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# As time goes by ...

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## ABSTRACT

A rather simple and non-technical exposition of our new approach to *Time*, *Quantum Physics*, *Black-Hole dynamics*, and *Cosmology*, based on non-critical string theory, is provided. A new fundamental principle, the *Procrustean Principle*, that catches the essence of our approach is postulated: the low-energy world is *unavoidably* an “open” system due to the spontaneous truncation of the *delocalized*, *topological* string modes in continuous interaction with the low-lying-*localized* string modes. The origin of space-time, the expansion of the Universe, the entropy increase and accompanied irreversibility of time, as well as the collapse of the wavefunction are all very neatly tied together. Possible observable consequences include: quantum relaxation with time of the Universal, fundamental constants, like the velocity of light  $c$  and the Planck constant  $\hbar$  decreasing towards their asymptotic values, and the cosmological constant  $\Lambda_C$  diminishing towards zero; possible violation of *CPT* invariance in the  $K^0 - \bar{K}^0$  system, possible apparent non-conservation of angular momentum, and possible loss of quantum coherence in SQUID-type experiments.

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“Physicists consider me an old fool, but I am convinced that the future development of Physics will depart from the present road”.

Albert Einstein

“It is my opinion that our present picture of physical reality, particularly in relation to the nature of *time*, is due for a grand shake up – even greater, perhaps, than that which has already been provided by present-day relativity and quantum mechanics”.

Roger Penrose  
in *The Emperor's New Mind*

## Prolegomena and Epimythion

During the last fifty years, high-energy physics has gone through many dramatic changes, mostly positive, that have led us to an unprecedented understanding of the subnuclear world. From the discovery of the pion ( $\pi$ ) to the discovery of the top quark ( $t$ ), and from the Lamb-shift to the LEP-shift(s), all very nicely accommodated in the *Standard Model*, the crown jewel of present day particle physics. So, the basic question arises: is that it? Certainly not! The Standard Model is certainly a very fundamental step in the right direction, but it leaves so much to be desired that its *Supersymmetric Grand Unified Theoretical* extension is, for at least *some* of us, an unavoidable *must*. As it is, for at least *some* of us (not necessarily the same *some* as above), unavoidable to replace point-like particles by *one-dimensional fundamental extended objects*, strings, *i.e.*, use *String Theory*. The *raison d'être* of string theory is rather well-known: natural, automatic unification of all interactions in nature, including *unavoidably* a consistent Quantum Theory of Gravity. The infrared limit of string theory seems, to many of us, the correct framework to resolve the usual conundrums of present day particle physics: *origin* of *all* masses, angles, coupling constants, electroweak breaking, etc. Then, is that it? Unless we are desperate to confirm Dante's "*O insensata cure dei mortal!*", we better refrain from answering yes to this question. Let me remind you that all our Modern Physics is based on two fundamental, *untouchable* principles: the *quantum* one and the (special) *relativity* one. Combined they have provided the spectacularly successful point-like Relativistic Quantum Field Theory (QFT) framework, the basis of particle physics. *Charmed away* by the phenomenal successes of relativistic QFT, we run into the danger of conveniently and tacitly neglecting some of the dark corners of quantum physics and relativity. The absence of a dynamical mechanism for the *collapse of the wavefunction*, related directly to the "measurement" problem of quantum mechanics and to the emergence of the classical world from the quantum one, the *arrow of time* shining by its absence from

presently available microscopic theories, the rather incomplete *black-hole physics*, not only do they prevent us from a crystal-clear picture of physical reality, but they do sustain a *Pirandelloish* mystery of reality.

During the last three years, together with John Ellis and Nick Mavromatos, we have attacked these problems from the premises of non-critical string theory. To our surprise, this line of research took us very soon to completely *uncharted waters* and we found ourselves facing a plethora of technical and physical problems. To our initial disbelief, we found that the *untouchable* principles of quantum mechanics and relativity needed to be touched! We are not talking here about some higher-order corrections to the Einstein-Hilbert action, or some extra corrections, to say, the Schrödinger equation. What we are talking about here is to *abandon* altogether the language of the wavefunction, to be replaced by the *density matrix*, as well as, to create dynamically an *arrow of time* at the microscopic level. In other words, not only providing each space point with a clock, á la Einstein, but inventing in addition a dynamical mechanism to synchronize all of them! All these admittedly seemingly *incredulous allegations* are springing off the very fundamental properties of string theory. String theory is consistently and dynamically endorsed with infinite symmetries (in sharp contrast with point-like QFT), which mix the different mass “levels”, including delocalized topological modes, thus triggering spontaneous truncation down to the *observable* localized low-energy string modes. This *unavoidable* truncation renders the low-energy observable system effectively “open”, thus inheriting the characteristic statistical properties: increase of entropy, irreversible time, collapse of the wavefunction, etc. In a way, “we can have our cake and eat it too”: we start from a complete, consistent string theory, according to all the rules of quantum theory, no violations of anything, and dynamically the low-energy *observable* world behaves *effectively* as an “open system”.

The reaction to our approach, as it was expected, varies from the very negative to the very positive! The tactics of *suppresio veri*,

*suggestio falsi*, and of “*no vogliamo capire*”, have been employed in abundance, which for us had a very positive outcome: understand much better our engaged technology and physical issues!

Since our approach touches upon issues that go beyond string theory or even high-energy physics, I have decided, after some initial resistance, to comply with the continuous urgings of several friends, *to say it like it is!* I have tried *willingly* and *deliberately* to minimize the technical details to the bare bones, and to sacrifice mathematical elegance, clarity, and rigor for the more familiar, at least to me, physical intuition. I would like to encourage very strongly the interested reader to have a look at Refs. [1, 2, 3] in which a much more technical review of our approach is provided and to which the present review will hopefully serve as a useful companion.

## Contents

<b>1</b>	<b>Remembrance of Things Past</b>	<b>1</b>
1.1	Black-body Radiation . . . . .	1
1.2	The Michelson-Morley Experiment . . . . .	2
1.3	Line Atomic Spectra . . . . .	4
<b>2</b>	<b>Recent Past and Present</b>	<b>6</b>
2.1	Black Holes . . . . .	6
2.2	Quantum Physics and Gravity . . . . .	9
2.3	Schrödinger’s Cat/EPR “Paradoxes” . . . . .	9
<b>3</b>	<b>Interlude (I) – Free Time</b>	<b>13</b>
<b>4</b>	<b>Present</b>	<b>19</b>
4.1	General string framework . . . . .	20
4.1.1	String equations of motion (E.O.M.) . . . . .	22
4.1.2	String target-space scattering amplitudes . . . . .	23
4.2	Critical versus non-critical string theory . . . . .	24
<b>5</b>	<b>Interlude (II) – Friction Time</b>	<b>30</b>
<b>6</b>	<b>Back to the Present</b>	<b>33</b>
6.1	The formalism . . . . .	34
6.2	The microscopic mechanism – A new fundamental Procrustean Principle . . . . .	38
<b>7</b>	<b>Future</b>	<b>45</b>
7.1	Density matrix mechanics . . . . .	45
7.2	Spontaneous collapse of the “wavefunction” – classical from quantum – the Aphrodite Mechanism . . . . .	52
7.3	A new theory of black-hole dynamics – No-Horizon Cosmology . . . . .	57
<b>8</b>	<b>Interlude (III) – Passatempo</b>	<b>65</b>
<b>9</b>	<b>Back to the Future</b>	<b>69</b>

# 1 Remembrance of Things Past

Towards the end of the last century, physics seemed to be in very good shape. Classical mechanics, Electromagnetic theory, and Thermodynamics were well under control and most physicists were taking a nohelic point of view that everything had been understood. There were a few “small” problems here and there, but it was widely believed that the existing “technology” would eventually resolve them. The most notable “small” problems were:

1. Black-body radiation: ultraviolet catastrophe.
2. Michelson-Morley experiment: no ether.
3. Line atomic spectra: do “a-toms” have substructure(?).

Let me remind you of the origin of these problems and their eventual resolution.

## 1.1 Black-body Radiation

According to classical physics, the average energy  $\langle \epsilon \rangle$  at temperature  $T$  of a harmonic oscillator of frequency  $w$  is given by

$$\langle \epsilon \rangle_T = \frac{\int_0^\infty d\epsilon \epsilon e^{-\epsilon/T}}{\int_0^\infty d\epsilon e^{-\epsilon/T}} = T, \quad (1)$$

which is *independent* of the frequency  $w$ . Integrating next over all frequencies one encounters the ultraviolet catastrophe. It took a very drastic and unheard off “action” to fix this problem. Indeed, Planck suggested that  $\epsilon$  is not a continuous variable but a *discrete* one instead:

$$\epsilon = n(\hbar w), \quad n \in Z^+, \quad (2)$$

where  $\hbar \approx 1 \times 10^{-34}(\text{J} \cdot \text{s})$  is a new dimensional parameter. In such a case, Eq. (1) is replaced by

$$\langle \epsilon \rangle_T = \frac{\sum_{n=0}^\infty (n\hbar w) e^{-n\hbar w/T}}{\sum_{n=0}^\infty e^{-n\hbar w/T}} = \frac{\hbar w}{e^{\hbar w/T} - 1} \quad , \quad (3)$$

which depends on the frequency  $w$ . Integration over all frequencies yields a finite result. The ultraviolet catastrophe has been averted. This bold suggestion – *quantize the energy* to resolve the black-body radiation problem – led to Quantum Physics, which is one of the two pillars of Modern Physics in the 20th century.

## 1.2 The Michelson-Morley Experiment

One of the niceties of Newtonian mechanics is the incorporation of the Galilean principle: all inertial frames are equivalent. The invariance of Newtonian mechanics under the Galilean transformations:  $\vec{x}' = \vec{x} - \vec{v}t$ ,  $t' = t + \text{const}$ , with  $\vec{v} = \text{const}$ , imply the absence of a preferred inertial reference frame and the existence of “universal” time or “universal” simultaneity. To avoid problems with causality, action at a distance or signals traveling with infinite velocity have to be incorporated.

On the other hand, electromagnetic theory as contained in Maxwell’s equations:

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho, \quad (4)$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad (5)$$

$$\vec{\nabla} \cdot \vec{B} = 0, \quad (6)$$

$$\vec{\nabla} \times \vec{B} = 4\pi\vec{j} + \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t}, \quad (7)$$

is not invariant under Galilean transformations! Let me take it a bit further, since there is a multi-moral story here. Except for the last term ( $\frac{1}{c^2} \frac{\partial \vec{E}}{\partial t}$ ) on the R.H.S. in Eq. (7), everything else was known to Coulomb, Faraday, and Ampere. It was Maxwell’s brilliant contribution to suggest the existence of this *extra tiny term* (with respect to all the other terms), undemanded by experiments at that time. This *tiny term* changed everything:

1. (a) The dimensional constant  $c$ , was found (by Maxwell) to be the velocity of light ( $\sim 300,000\text{km/sec}$ )!
- (b) The very existence of this dimensional constant ( $c$ ) led eventually to special relativity.



2. (a) A “symmetric” treatment of  $\vec{E}$  and  $\vec{B}$ , thus leading to electromagnetism (E-M).
  - (b) The prediction and subsequent discovery of electromagnetic waves.
3. E-M theory, in quantum form, became the archetype of modern gauge theories.

It was precisely the assumption that the velocity of light  $c$ , *remains constant* in all inertial frames, that made Einstein abandon the Galilean transformations and endorse the Lorentz transformations  $[x' = (x - vt)/\sqrt{1 - v^2/c^2}, t' = (t - vx/c^2)/\sqrt{1 - v^2/c^2}, y' = y, z' = z]$  which eventually changed profoundly our view of space and time. Indeed, if we had to insist on the validity of Maxwell’s equations, we had to abandon the Galilean relativity principle, and assume the existence of a preferable reference frame, the “ether-frame”. The Michelson-Morley experiment showed that we “ran out of ether”, thus vindicating the existence of some relativity principle which is nothing else but special relativity: “All laws of Physics are invariant under Lorentz transformations”. In this case, the Galilean invariants  $\Delta x = \Delta x'$ ,  $\Delta t = \Delta t'$  are replaced by only one invariant:  $ds^2 = c^2 dt^2 - d\vec{x}^2$ , with far reaching consequences:

- (a) We should not talk any more about space and time, but about space-time.
- (b) There is no “universal” time, thus the very idea of “simultaneity” becomes relative! Past, present, and future depend on the “eye” of the moving observer, for space-like events. There is no “action at a distance”, and signals cannot travel with infinite velocity; the velocity of light is the maximal, limiting, allowable velocity. As the Minkowski line element ( $ds^2$ ) indicates, there is a horizon, beyond which there is no possible communication.

While points (a) and (b) changed profoundly our view of the Universe, and (special) relativity is the second pillar of modern physics in the 20th century, a few comments should be made:

- (i) In Einstein’s Universe, events take place in a “*pre-fixed*” space-time: there is no arrow of time. After all, if time is another dimension to be adjunct to space, why should it have an *arrow*?

Does space have an *arrow*? Certainly not! Furthermore, notice that the Lorentz transformations are *effectively* two-dimensional, the transverse (to  $\vec{v}$ ) dimensions play no role! Then, recall the fact that in two-dimensional physical theories there is no distinction between  $(x, t) \leftrightarrow (t, x)$  and if  $x$  does not have an *arrow*, then why should  $t$  have one? It does not have an *arrow*!

- (ii) In accordance with the spirit of special relativity, all equations of (classical and quantum) physics, are time-symmetric: they are invariant under the transformation  $t \leftrightarrow -t$ .

This lack of an *arrow of time* in Einstein’s Universe seems to be in some conflict with common sense or “conscious” time. After all, central to our feelings of awareness is the sensation of progression of time: there is a definite past and an uncertain future. Our perception of time seems to be in severe discrepancy with the Einstein time of modern physics, where each uniformly-moving observer has her own idea of simultaneity! There is no unique concept of simultaneity and thus there is no definite past and undetermined future, the whole space-time is fixed. How is it possible then to reconcile the highly successful modern physical theory, based on Einstein’s relativity, and thus with no apparent arrow of time, with our gut-feeling of “flowing” time?

Somewhere something has to change!

### 1.3 Line Atomic Spectra

The idea of *Democritean* “a-toms”, gained progressively a lot of support during the 19th century, despite the vicious attacks by many well known figures of that epoch, *e.g.*, Mach. Eventually it was realized that the classical “solar system-like” picture of the atom á la Rutherford, led to severe problems. Circulating electrons radiate energy according to E-M theory, and thus eventually, unavoidably, collapse into the nuclear center. It took the genius of Bohr, Heisenberg, Schrödinger, and Dirac to figure it all out and led us to a completely new picture of the subatomic world, **the quantum world**, profoundly different from our classical view of reality. The notion of *wave-particle duality* is the *central dogma* of Quantum Physics. It is best expressed

by Heisenberg's *uncertainty principle*

$$\Delta x \cdot \Delta p \geq \hbar, \quad (8)$$

which emphasizes our inability to “measure” *simultaneously* the position and momentum of a particle, as precisely as we want. A sharp deviation from our classical view of the world! All the information about the system is embodied in its complex wave-function  $\Psi$ , and its evolution is described by some suitable wave-equation (Schrödinger, Klein-Gordon, Dirac, ...). An essential point of quantum reality is the principle of *complex linear superposition* or *quantum parallelism*, or *quantum coherence*, which is reflected in the specific forms that the relevant wave equations take. Any number of (quantum) states whatever, *irrespective* of how different they are, can coexist in any complex linear superposition. A “measurement”, or an “observation” on the system, *i.e.*, magnification of quantum effects at a classical level, consists of picking up one of the actual alternatives,  $\Psi_i$ , with classical probability  $P = |\Psi_i|^2$ , according to Born. This arguably strange picture of the subatomic world, quantum reality, seems to work perfectly well and constitutes together with special relativity, the foundations of modern physics. It came a long way from Planck's bold assumption of energy quantization and has led to the miracles of the quantum world.

Hopefully, by now I have convinced you that sometimes innocent looking “small” problems may carry the seed, if properly analyzed, of potentially big discoveries, and may act as *time* bombs ticking at the foundations of well established/accepted theories/views about the physical world.

## 2 Recent Past and Present

Towards the end of the 20th century, physics seems to be in very good shape. Quantum physics, in the form of Quantum Field Theory (QFT), has given us the Standard Model (SM): an  $SU(3) \times SU(2) \times U(1)$  gauge theory that describes strong ( $SU(3)$ ) and electroweak interactions ( $SU(2) \times U(1)$ ). All available experimental data are in remarkable agreement with the SM. Despite its phenomenal success, many people are under the impression that we have to go beyond the SM, at least for aesthetical and philosophical reasons. Grand Unified Theories (GUTs) try to unify all above interactions into one, Supersymmetry (SUSY) tries to establish a fermion-boson symmetry, and Supergravity GUTs try to put the whole thing together, including gravity. While these efforts are well justified and try to answer some big questions, I will assume here that some “effective supergravity” GUT theory will bring peace to the minds of these daring souls. My purpose is to concentrate on a few “small” problems here and there, which many physicists believe that the currently available “technology” will eventually resolve in a smooth fashion. On my list, the most pronounced “small” problems are:

1. Black holes: the Hawking catastrophe.
2. Quantum physics and gravity: do not mix.
3. Schrödinger’s cat / Einstein-Podolski-Rosen (EPR) “Paradoxes” : collapse of the wave-function  
nonlocality

Let me discuss now each of these problems and their possible consequences.

### 2.1 Black Holes

According to classical general relativity, neutral Black Holes (BH) are stable objects. Thanks to Hawking’s remarkable insight [4], we know that black holes radiate almost like a black body, when some form of quantum effects (in the semiclassical approximation) are taken into account, thus becoming unstable. A black hole of mass  $M$  may be

viewed as a thermodynamic system at a temperature  $T_{\text{BH}}$  and entropy  $S_{\text{BH}}$ , where [4, 5]

$$S_{\text{BH}} \sim M^2 \quad \text{and} \quad T_{\text{BH}} \sim 1/M \quad (9)$$

in accordance with the standard thermodynamic relation  $dM = TdS$ .

As the black hole radiates, it loses energy and eventually it “evaporates”. The lifetime of a black hole of mass  $M$  is given by

$$\tau_{\text{BH}} \propto M^3 \quad (10)$$

In Eqs. (9,10) I have used the so-called natural units:  $k_B = 1$ ,  $c = 1$ ,  $\hbar = 1$ , and  $G_N$ , the gravitational constant, which may be written as  $G_N = 1/M_{\text{Pl}}^2$ , has also been set to one. The Planck mass is  $M_{\text{Pl}} \approx 10^{19} \text{ GeV}$ . While the above analysis sounds and looks like standard thermodynamics, it contains the seeds of potentially profound and dramatic changes, both in quantum physics and general relativity! The central issue is *loss of information*. Imagine that our black hole can be described, according to quantum mechanics, by a *pure state*  $\Psi$ . As it *thermally radiates*, it evolves into a *mixed state*, which contains much less information about the black hole system, as compared to its initial state. A lot of information has been lost, which is in agreement with the huge entropy that characterizes a black hole (see Eq. (9))! After all, black body radiation is notoriously universal and independent of the specific details of the radiating body, thus clearly not the best form of information storage. Furthermore, this transition from a *pure* to a *mixed* state is not allowed in quantum mechanics, because it leads to a breakdown of our central *sacred quantum principle: quantum complex linear superposition* or *quantum coherence*. According to quantum mechanics, *purity is eternal!* The black hole evaporation, or *Hawking radiation* looks like an unprecedented attack at the very basis of quantum physics: quantum coherence. That is why I call it the *Hawking catastrophe*. Hawking himself was not slow to realize the profound significance of his discovery and suggested that we may have to abandon the principle of quantum coherence [6]. A rather bold proposal! He went further to suggest that we may have to abandon altogether the very notion of the wave-function  $\Psi$  to describe quantum states, and that we should replace it with the notion of density matrix  $\rho_{ij} (\sim \Psi_i \Psi_j^*)$ . This kind of dramatic change implies that we have to abandon the very idea of the

$S$ -matrix:  $\Psi_{\text{out}} = S\Psi_{\text{in}}$  and replace it by the  $\mathcal{S}$ , the superscattering matrix [6]:

$$\rho_{\text{out}} = \mathcal{S}\rho_{\text{in}} \quad (11)$$

J. Ellis, J. Hagelin, M. Srednicki, and myself [7] took it a bit further: if the idea of the wave-function is to be abandoned, then the corresponding wave-equation is to be abandoned and to be replaced by some form of equations for the density matrix  $\rho$ . It was known, since the early thirties, that the quantum wave equation could be cast in the form of Liouville-type equations, similar to ones describing statistical systems, which involve directly the density matrix:  $\partial\rho/\partial t = i[\rho, H]$ , where  $H$  is the Hamiltonian (evolution operator) describing our system. Our search for an appropriate generalization of the above equation lead us to the following **Master Equation** (ME) [7]:

$$\frac{\partial\rho}{\partial t} = i[\rho, H] + \delta\mathcal{H}\rho. \quad (12)$$

Here  $\delta\mathcal{H}$  is some appropriate, system-dependent operator, which basically renders the system “open”, and has to satisfy a lot of conditions in order to be acceptable: conservation of probability, conservation of energy, increasing or stationary entropy, etc. Very “tall-orders” to realize in practice, specifically if there is no consistent theory of quantum gravity. Nonetheless, “the cat is out of the bag” now, and the Hawking catastrophe has to be addressed and resolved one way or another. It should be stressed that our problem is at the fundamental level of the theory, and in a way, independent of the existence of astrophysical black holes. At very short distances, close to the Planck scale ( $l_{Pl} \sim 10^{-33}$  cm) the space-time metric, like any other quantum field, fluctuates violently thus destroying our “fixed” space-time notions and leads to the so-called *space-time foam* [8]. There is no “fixed” space-time at the Planck scale, only *space-time foam* due to quantum fluctuations, a dynamical effect beyond our control. Specifically, virtual black holes of Planck size certainly contribute to the space-time foam. As a particle moves through space-time foam, it encounters, in principle, these Planck-size black holes, which suck information and “evaporate”, thus “opening” the system (a particle in our example). This is the “microscopic” origin of the extra term  $\delta\mathcal{H}\rho$  in Eq. (12), which sums up the effects of space-time foam on the system and it turns it, *unavoidably*, into an “open” system.

While intuitively plausible, our analysis above has been criticized on the following grounds: Hawking’s radiation is based on some semiclassical approximation, in lack of a complete theory of quantum gravity, and thus should not be taken extremely seriously, specifically if it runs against big principles such as quantum coherence. It may all be some artifact of our unjustifiable approximations. This criticism, sound for the time being, brings me to another “small” problem.

## 2.2 Quantum Physics and Gravity

All efforts to extend our highly successful unified theories of gauge interactions (strong and electroweak) to include gravity into a consistent quantum dynamical framework, have badly failed, including supergravity theories. The problem being our inability to tame all kinds of infinities that emerge at each order in perturbation theory in sharp contrast with renormalizable gauge theories. While the standard gauge interactions are characterized by dimensionless coupling constants (*e.g.*, electric charge), the gravitational constant  $G_N$  is dimensional, thus preventing the usual renormalization program to apply. The theory has to be directly *finite*, no infinities are allowed because, if present, they are incurable. It should be stressed that this problem seems to bring us against a brick wall, since we have used all kinds of symmetries that we can envisage: space-time symmetries, internal symmetries (local or global), fermion-boson symmetry or supersymmetry (local or global), and still no acceptable quantum theory of gravity in sight.

This is a rather serious and threatening impasse.

## 2.3 Schrödinger’s Cat/EPR “Paradoxes”

While quantum physics seems to describe extremely accurately the microworld, its “blind” extension to the macroworld may lead to rather remarkable “paradoxes”, or even nonsensical answers. Quantum parallelism or quantum coherence, *if* assumed valid all the way to the macrocosmos, implies the coexistence of vastly different macroscopic states, in sharp contrast with common sense, everyday experi-

ence. A celebrated example of applying quantum physics all the way is Schrödinger’s cat [9]. In an “isolated” box, a cat coexists with a vial of poison and some lump of radioactive material, such that after some time  $\tau$  there is 50% probability that at least one nucleus has decayed, and by triggering a series of well-defined processes results in the breaking of the vial of poison and thus the death of the cat. According to standard Quantum Mechanics (QM), the system (cat + nucleus) is described by:

$$\Psi_{\text{system}}(t) = \frac{1}{\sqrt{2}}\Psi_{\text{cat}}^{\text{alive}}\Psi_{\text{nucl}}^{\text{stable}} + \frac{1}{\sqrt{2}}\Psi_{\text{cat}}^{\text{dead}}\Psi_{\text{nucl}}^{\text{decayed}}, \quad (13)$$

for  $t \geq \tau$ .

Before making any “measurement” (*e.g.*, opening the box), the system is described by Eq. (13), obeying standard quantum mechanics equations. Thus we have a certain moment where the cat is 50% dead and 50% alive, etc. Even if cats have “nine lives”, this is a kind of result difficult to swallow! Here we have an archetypal example of a microprocess (nuclear decay) perfectly described by QM, leading to a macroscopic *logical catastrophe*, if we insist that our combined macro-micro system is *QM-describable*! Of course, the crucial point here is our assumption that a macrosystem (*e.g.*, our cat) obeys the laws of quantum physics. But, on the other hand, the whole point of *reductionism*, the *tacit* dogma of modern physics, is that everything can be understood in terms of few elementary constituents and their interactions. So, if our cat is made of these elementary constituents, who is there to decide when and how the transition from the micro to the macro system occurs, in order to avoid situations where the cat is 50% alive and 50% dead? Ideally, what we are after is some *dynamical mechanism* that destroys quantum coherence for macroscopic systems by *spontaneous collapse of the wave function*, with a realistic time scale compatible with our notions of the macrocosmos. Here we have touched upon a rather big issue of quantum physics, that of the *collapse of the wavefunction* which presumably occurs when a “measurement” takes place. By its very nature, a “measurement” involves a macrosystem in “contact” with the “measured” microsystem, that triggers the microsystem to *jump* into one of its possible quantum states  $\Psi_i$  with classical probability  $|\Psi_i|^2$ . As is well known, this “quantum jump” process has made many people very skeptical,



including Schrödinger, of whether quantum physics in its standard-textbook form is the whole story. The dynamics of the *collapse of the wavefunction* do not seem to be completely and satisfactorily understood.

Another example exposing some of the possible inadequacies of standard quantum physics is the famous Einstein-Podolsky-Rosen (EPR) “paradox” [9]. Consider a spin-0 system (*e.g.*, a  $\pi^0$ ) decaying at rest into two photons, moving in opposite directions (conservation of linear momentum). Clearly, the total angular momentum of the system of the two photons has to be always zero. The wave function of the system of the two photons can be represented by:

$$\Psi_{\text{system}} \propto (\gamma_1)_+(\gamma_2)_- + (\gamma_1)_-(\gamma_2)_+ \quad (14)$$

where  $+(-)$  are the helicities of the photon with respect to some (unspecified) direction. Before making any “measurement” on the system, *e.g.*, measuring the helicity of the photon  $\gamma_1$ , the question “what is the helicity of any one of the photons?” is an empty one. The two photons are entangled in such a way that we can only describe them as lumped together in  $\Psi_{\text{system}}$ . Imagine now that some time after the parent decay, we “measure” the helicity of photon  $\gamma_1$  and we find it to be  $(-)$ , then we know, according to Eq. (14), with *certainty* that if we “measure” next the helicity of  $\gamma_2$ , it is going to be  $(+)$ . What has happened is that our first “measurement” has demolished/collapsed the  $\Psi_{\text{system}}$  down to the second term,  $(\gamma_1)_-(\gamma_2)_+$ :

$$(\gamma_1)_+(\gamma_2)_- + (\gamma_1)_-(\gamma_2)_+ \xrightarrow[\text{“jump”}]{\text{“measurement”}} (\gamma_1)_-(\gamma_2)_+ \quad (15)$$

While innocent looking, the above standard lore of quantum mechanics leads to some dramatic consequences. After the parent decay, the two photons go their ways and clearly they are well separated (they are not both at the same space point, for all times). How is it possible then, that the photon  $\gamma_2$  knows “instantaneously” the direction of its helicity, according to Eq. (15), *i.e.*, at the moment that the  $\gamma_1$  helicity is measured? Apparently we have to attribute some *nonlocality to the quantum jump!*

It should be *emphatically stressed* that the above analysis should not be taken to imply that we can use EPR-type experiments to send

signals faster than light! The *nonlocal influences* that arise in EPR-type experiments are not such that they can be used to send messages. In our particular example above, it is only the direction of the alternative polarizations which arrives faster than light (“instantaneously”), while which of the two possible directions (+ or –) has been picked up, arrives through “normal channels” of communicating the result of the first ( $\gamma_1$ ) polarization measurement. So, the nonlocal nature of the quantum jumps does not lead to any violation of causality! Actually, there is a whole new activity on the *basics* of quantum mechanics, due mainly to the ingenuity of John Bell, who through his inequalities established that no *local “realistic”* (e.g., “hidden variable”, or “classical type”) description can give the correct quantum probabilities [9]. Amazingly enough, a detailed series of experiments in the mid 1980’s, performed by A. Aspect and collaborators [10], have *vindicated* standard quantum mechanics, i.e., *the nonlocal nature of quantum jumps*, ruling out *local, realistic models*.

As far as we do *understand* and *accept the nonlocal nature of quantum physics*, there is no EPR-“paradox”. Alas, we have not finished yet. As has been emphasized repeatedly by Penrose [9], all the above analysis of the EPR-“paradox” and its satisfactory resolution in the framework of quantum mechanics is *non-relativistic in nature*. As I mentioned above, the two photons are well space-separated, thus the two measurements (measuring the helicity of  $\gamma_1$  and then measuring the helicity of  $\gamma_2$ ) correspond to space-like separated events. As such, as I emphasized in section 1, in accordance with special relativity, which measurement occurs first depends on the “eye” of the moving observer! Imagine that  $\gamma_1$  moves to the left and thus  $\gamma_2$  to the right. For an observer moving rapidly enough to the left, she will tabulate the events as follows: (1) measurement of the  $\gamma_1$  polarization and quantum jump, (2) measurement of the  $\gamma_2$  polarization. While for an observer moving rapidly enough to the right, it looks like: (1) measurement of the  $\gamma_2$  polarization and quantum jump, (2) measurement of the  $\gamma_1$  polarization. What is going on? There is some real conflict here: we are getting *two different pictures of physical reality!* Different measurements cause the nonlocal jump. According to Penrose [9], there is an essential conflict between our space-time picture of physical reality, including the nonlocal nature of quantum physics, and the spirit of special relativity. Let me appropriately call it the

*Penrose paradox* [9].

I am not aware of any better example showing so graphically the apparent inadequacies at the very foundations of QM and special relativity, in providing a complete and satisfactory picture of physical reality. The very issue of the apparent lack of “universal” simultaneity (or “universal” time) in special relativity, combined with the apparent nonlocal nature of the quantum jumps (“collapse of the wavefunction”) drive our sense of physical reality against the wall! While this state of affairs is rather upsetting and alarming, it indicates the profound intimacy between the very nature of time and the collapse of the wavefunction. A possible resolution of the Penrose paradox [9] should definitely try to shed light on this close intimacy.

Actually, we shouldn’t be that surprised by decoding the “message” contained in the Penrose paradox [9]. After all, the very notion of the collapse of the wavefunction is, for at least a few people, a *time asymmetric process*. Consider for example, after Penrose [9], a lamp emitting photons, which go through a half-silvered mirror, tilted at  $45^\circ$  with respect to a horizontal line that connects the lamp and a photocell. Clearly, the probability that the photocell detects a photon, *given* that the source emits one, is exactly  $(1/\sqrt{2})^2 = 1/2$ , so that 50% of photons are absorbed by the wall. A straightforward application of the standard QM rules, employing *time-reversal symmetry*, will give the same answer (1/2) for the probability that the lamp emitted a photon, *given* that the photocell detected a photon! Sheer nonsense! The *correct* experimental answer is of course 1. There are no off-wall photons registered by the photocell! This example shows dramatically that the “collapse of the wavefunction” is not as innocent as it looks, *i.e.*, just the amplitude squaring procedure, but something more sneaks into the whole process. It is hard to avoid thinking of some kind of *thermodynamic irreversibility*, implying some *entropy increase*, thus defining clearly *an arrow of time*, and thus turning the “collapse of the wavefunction” into a *non-relativistic process*!

Once more, somewhere, something has to change!

### 3 Interlude (I) – Free Time

It will be instructive to try to isolate the *possible common origin* of the three “small” problems discussed in the previous section. Let us start

with the Hawking catastrophe, endemic to black holes. The central issue here is the apparent loss of information, as reflected in the huge entropy (see Eq. (9)) characterizing black holes. The problem being that black holes have “*no hair*”: there are not many useful, suitable quantum numbers that may label the black hole. Mass ( $M$ ), angular momentum ( $\vec{L}$ ), and electric charge ( $Q$ ) are about the only “charges” that are measurable at *long distances*, beyond the black holes’s horizon, due to long-range forces (gravitational, electromagnetic). These long-range “charges” are scarcely enough to describe completely the state of a black hole, containing say, at least  $3M_{\odot}(\text{grams})N_{\text{Avogadro}}$  basic constituents. In other words, there is a large number of different configurations, all characterized by the same  $M$ ,  $\vec{L}$ , and  $Q$ ! That is why we are getting such a huge entropy  $\propto M^2$ . A possible cure for this situation is to invent more kinds of suitable “charges”. But we know that there are not that many new long-range interactions remaining to be discovered! Furthermore, the above discussion shows that we *practically* need an *infinite number* of new, suitable “charges”. Another apparent impasse? Not necessarily! Thanks to quantum mechanics it is possible to measure a specific kind of “charge”, let me call it the Aharonov-Bohm (AB) “charge”, at long distances, even if these “charges” are not necessarily due to long-range forces. We may make use of the celebrated AB effect [11], where *e.g.*, by measuring the phase shift that an electron (wavefunction) suffers when circulating around (but at a long distance outside) a solenoid, we may deduce the flux (solenoid’s AB “charge”) and thus the magnetic field *inside* the solenoid, which as is well known, vanishes outside the solenoid. For example, in a double-slit experiment, the existence of an “ideal” solenoid between the two slits and the screen will shift the total wave pattern on the screen by an amount

$$(\Delta\theta)_{\text{AB}} = \frac{Q\Phi}{\hbar}, \quad (16)$$

with  $Q$  denoting the electric charge of the projectile and  $\Phi$  the flux through the solenoid, which may be considered as solenoid’s AB “charge”. If this type of AB “charges” were available for a black hole, then by allowing suitable “projectiles” to circulate around (but far!) from a black hole, we could in principle measure all of its “charges”. If a black hole carries AB “charges”, because of its quantum nature, it is

called *quantum hair* [12]. While the need for a huge number of new long-range interactions has evaporated, the source of a huge number of different kinds of quantum hair remains enigmatic. A new impasse in the (BH) horizon! In this case we have come close to the brink. All our symmetries, space-time, internal, supersymmetry, have been exhausted and still we have no answer! Take, as we have *tacitly assumed*, a *point-like* particle: you can accelerate it ( $m$ ), kick it around ( $\vec{p}, \vec{L}$ ), give it some internal “charges” (electric, color, ...), “change” its spin (supersymmetric charge), make it “live” in a D-dimensional Universe with the D-4 extra dimensions curled up á la Kaluza-Klein, and still, we have a long way to go before its I.D. contains a practically infinite kind of lines, each for every (spontaneously broken) symmetry (AB “charge”). After all, in every point-like quantum field theory we have a number (usually small) of elementary fields participating in a finite number (usually small) of interactions, thus falling extremely short from the practically needed infinite amount of AB “charges”, for a complete description of a black hole. Of course, the situation is dramatically different if we abandon the idea of point-like particles as fundamental blocks and use instead *extended objects*. In such a case, the particle spectrum is going to be *dynamically* infinite (corresponding to all kinds of vibrational or other modes), thus providing the seeds for a practically infinite number of AB “charges”, corresponding to an infinite number of spontaneously broken generalized “gauge” symmetries due to the availability of an infinite number of generalized “gauge” bosons.

Actually, the above analysis of the cause of information loss in black holes, *i.e.*, the *no-hair theorem*, and its possible resolution by abandoning the *point-like nature* of elementary constituents and moving to *elementary* but *extended* fundamental blocks, applies equally well to our second “small” problem: no consistent theory of quantum gravity. Indeed, it is well known that most of the infinities that plague quantum field theories are due to the assumed point-like nature of the elementary fields-particles. A mere glimpse at Newton’s gravitational law, or Coulomb’s law, at very short distances, exhibits an “apparent” infinity as  $r \rightarrow 0$ ! As described in the previous section, in the case of Coulomb’s law, as contained in quantum electrodynamics, or more generally in gauge theories, we do have an algorithm, called *renormalization* to take care of all types of infinities, but apparently not so for

gravity. It seems that our tacit assumption of *point like elementary constituents* is, again, the stumbling block for a consistent quantum theory of gravity. The move to *elementary* but *extended* fundamental blocks, looks once more unavoidable!

Concerning the Schrödinger's cat and the EPR/Penrose “paradoxes” [9], *i.e.*, *the collapse of the wavefunction*, involving *nonlocal quantum jumps* of *non-relativistic nature*, a similar analysis applies as to the other two “small” problems above. Indeed, our assumption that the principles of quantum physics, mainly quantum coherence, applies all the way from the Planck scale to the cat-scale, is questionable. It should be that some *dynamics* intervene in the way that make it highly improbable for the cat to be described by a coherent wavefunction. But what can it be? Well, maybe we can, very naively, put our first “small” problem, the BH-Hawking catastrophe, to work to our advantage! Everybody knows that at Planck distances, quantum fluctuations of the metric destroy the *finesse* of our space-time and create space-time foam. Virtual, Planck scale BHs appear and disappear continuously, sucking information from our “system” (see Eq. (12)). Clearly, these (quantum) gravitational effects are proportional ( $(G_N E^2)^n$ ,  $n=1,2,\dots$ ) to the mass (or maybe energy) of our “system”. Thus, it is not inconceivable that “elementary systems” (*e.g.*, electrons) remain virtually unscathed by the Planck BH-Hawking catastrophe, while “complex systems” (*e.g.*, our cat) suffers a *spontaneous* collapse of their wavefunction. So an *effective Planck BH-Hawking catastrophe*, may be after all welcomed from the collapse of the wavefunction point of view. The word *effective* is of dramatic importance here: we discussed above that *point-like* QFT type of BH are unacceptable, too many profound problems, and we speculated that *extended objects* QFT type of BH may be the solution. The extra demand here is that this new type of BH dynamics, based on *extended objects QFT*, should allow in some appropriate limit for some controllable leakage of information, thus mimicking *effectively* the Planck BH-Hawking catastrophe and triggering the collapse of the wavefunction! Incidentally, this *effective Planck BH-Hawking catastrophe* triggering *spontaneous* collapse of the wavefunction, meets successfully the *demand*, discussed in the previous section, that some kind of thermodynamic irreversibility, accompanied by entropy increase, is involved somewhere in the “collapse of the wavefunction” process.

The need for *extended, fundamental objects*, as opposed to *point-like constituents*, for the collapse of the wavefunction is enforced by the EPR-Penrose “paradox”, involving nonlocal quantum jumps presumably of non-relativistic nature. The very straight connection between causality and the vanishing of any space-like correlations in point-like QFT, becomes much looser in the case of extended objects. After all, the infinitely sharp delta-functions, involved in the definition of space-like events, are smeared out over the extension of our fundamental objects, thus making it, at least intuitively plausible, for the quantum mechanical “instantaneous” influences, as observed in the EPR-type experiments, *e.g.*, by A. Aspect *et. al.* [10]. Furthermore, the very existence of *extended, fundamental objects*, entails the existence of some fundamental length, thus a *new dimensional “constant”* of nature. It is far from clear that our notions of special or general relativity based on point-like constituents (practically equivalent to the fact that  $c$ , the velocity of light, is the *only dimensional parameter* at the classical level), will hold true in the case of *extended, fundamental objects* (practically introducing a new fundamental dimensional “constant”: their size). Past experience shows (see Section 1) that moving from classical mechanics (no dimensional constants) to Maxwell’s equations (E-M theory) (one dimensional constant:  $c$ ) and asking for some common sense relativistic principle to hold true, shook dramatically the foundations of classical physics, specifically the very notion of *time*! So, it does not look inconceivable that we may be in for another “shake up” of our assumed solid foundations of modern physics, and specifically once more involving the notion of time. It is amusing to note that the very existence of a fundamental length, if interpreted as the modern version of the “ideal rigid body” of classical mechanics, defies the very notion of “relative simultaneity”! Its ends would always move simultaneously as observed from any frame, and it could therefore be used to establish “universal time”! It may be that special (or general) relativity is some *appropriate limit* of a more fundamental theory, and thus *approximately true* even if, in lots of circumstances, this approximation is *extremely accurate*! Thus, the hope exists that the dynamics of extended fundamental objects may lead to some new notion of *time*, encompassing the possibility of “universal simultaneity”, and allowing for space-like correlations, thus evading the EPR-Penrose paradox.

Before moving to the discussion of the simplest fundamental extended objects, *i.e.*, superstrings, it would pay to put forward what exactly are we expecting from a *complete theory of quantum physics*. Until now, our approach to the quantum world involves two components: the one component dubbed by Penrose [9] the **U**-part, involves the **U**nitary evolution of the system, in a *deterministic, continuous, time-symmetric* fashion, as described for example by the Schrödinger equation,

$$\mathbf{U} : \quad i\hbar \frac{\partial \Psi}{\partial t} = H\Psi, \quad (17)$$

with  $H$  the Hamiltonian operator of our system described by the wavefunction  $\Psi$ . Clearly such an evolution respects quantum coherence, as reflected by the quantum complex superposition principle implicit in Eq. (17). The second component, dubbed by Penrose [9] the **R**-part, involves the **R**eduction of the state-vector or collapse of the wavefunction, that enforces coexisting alternatives to resolve themselves into *actual* alternatives, one *or* the other,

$$\mathbf{R} : \quad \Psi = \sum_i c_i \Psi_i \longrightarrow \sum_i |c_i|^2 |\Psi_i|^2, \quad (18)$$

where  $|c_i|^2$  are classical probabilities describing *actual* alternatives. It is the **R**-part of quantum physics that introduces “uncertainties” and “probabilities”, thus involving *discontinuous, time-asymmetric quantum jumps* and leading to gross violations of quantum coherence. It is fair to say that almost universally, when physicists talk about quantum physics, they tacitly identify it with its **U**-part only! It is the **U**-part that has absorbed all our attention for about 70 years now, and in its more advanced form, relativistic quantum field theory, has become an icon of modern physics, with spectacular success, *e.g.*, the standard model  $SU(3) \times SU(2) \times U(1)$ . On the other hand, the **R**-part has been vastly and conveniently forgotten, tacitly assumed to be some mere technicality that gives us the right rules of “measurement” or “observation”: different aspects of a quantum system are simultaneously magnified at the classical level, and between which the system must choose. I strongly believe that this attitude has brought us finally to a dead end, *e.g.*, the *Penrose paradox*, and we need to reconsider our strategy. Actually, I believe that, maybe against the “mainstream”, there is no way to deduce the **R**-part from



the **U**-part, the **R**-part being a completely different procedure from the **U**-part, and effectively providing the *other “half”* of the interpretation of quantum mechanics. It is the (**U+R**) parts *together* that are needed for the spectacular agreement of QM with the observed facts. So, we are after some *New dynamics*, **N**, that provides a unified and comprehensible picture of the whole (**U+R**) process, by giving satisfactory answers to basic questions like: what constitutes “making a measurement”? Why and when are  $|\Psi_i|^2$  interpretable as probabilities? How does the classical world emerge from the quantum world? Let me schematically represent the above approach by

$$\mathbf{U} \oplus \mathbf{R} \subseteq \mathbf{N} \quad (19)$$

It should be stressed that the **N**ew dynamics involved in the **N**-equation (19), because they have to approach at appropriate limits the **U**-equation (17) and the **R**-equation (18), *i.e.*, almost anti-diametrical points of view, cannot be some smooth generalization of some wave dynamics. Apparently, the **N**-equation (19) has to contain seeds of *non-relativistic invariance* and *time asymmetry*, but in such a way that when the **R**-part or emergence of classicality is *neglected*, an approximately relativistic, time-symmetric (quantum field) theory emerges. *Neglect* in my thinking means that either we disregard completely the notion of space-time foam, *i.e.*, back to the “fixed” space-time, *topologically smooth* picture, *or*, in a more realistic way, we include the effects of space-time foam and prove *dynamically* that at large distances (compared to the Planck scale  $l_{Pl} \sim 10^{-33}$  cm) and for micro-objects (electrons, ...) an approximately relativistic time-symmetric (quantum field) theory springs out.

Let us move next to the discussion of the dynamics of superstrings, the simplest *extended, fundamental* objects, that are relevant to our program here, to develop a possibly complete picture of the quantum world. It should be stressed up front that superstrings are not only the *simplest/extended, fundamental objects*, but also the only ones whose dynamics have not been marred with grave problems.

## 4 Present

Superstring Theory (ST) [13], the theory of *one-dimensional extended fundamental objects*, is the *only* theory known to provide a consistent

framework for Quantum Gravity. The particle spectrum of *closed strings* contains *always* a massless spin-2 field that has all the right properties to be identified with the *graviton*, the carrier of the gravitational force. This remarkable property, combined with the natural existence in the closed string spectrum of massless spin-1 fields, identifiable as the mediators of the other forces (strong and electroweak), justify the singular excitement that superstring theory has created, as a prominent candidate for the **Theory Of Everything (TOE)**. The fundamental length of the string  $l_{\text{string}}$  is, as naturally expected in any theory of Quantum Gravity, determined by the gravitational constant

$$l_{\text{string}} \approx \mathcal{O}(\sqrt{G_N}) \approx \mathcal{O}\left(\frac{1}{M_{\text{Pl}}}\right) \approx \mathcal{O}(l_{\text{Planck}}) \approx \mathcal{O}(10^{-33} \text{ cm}). \quad (20)$$

Fundamental strings have indeed minuscule extensions, and for many practical purposes they can be safely assumed to be almost point-like. It is remarkable and non-trivial that the low-energy or infrared limit of string theory provides a *realistic, effective* supergravity, point-like quantum field theory, which is able to describe the low-energy (with respect to the Planck scale) world. Let me now describe some of the dynamics of string theory that I will need for my main purpose here, *i.e.*, to develop a new stringy-based quantum physics framework, which hopefully will be able to satisfy all the “*desiderata*” set up in section 3.

#### 4.1 General string framework

As a closed string moves in spacetime it sweeps out a two-dimensional surface, *world-sheet*, which is described by two variables,  $\sigma \in [0, \pi]$  and  $\tau$  (time) which runs on the real axis. It is very convenient to replace  $(\sigma, \tau)$  by a complex variable  $z = e^{i\sigma + \tau}$  which maps an initial state at  $\tau_i = -\infty$  to  $z = 0$  and turns “time-ordered” products into “radially-ordered” products. This “complexification” is of extreme technical importance, since it leads to the well-known theory of Riemann surfaces and complex analysis. At the classical level, we have to study “physics” on the Riemann sphere, while quantum corrections (loops) correspond to more complicated Riemann surfaces, torus, etc. of genus ( $\equiv$  handles on the sphere)  $g > 0$ . The use of just the complex plane as the world-sheet makes a lot of the fundamental properties of string dynamics, like *conformal invariance*, easier to grasp,

thanks to the simple fact that any analytic function of  $z$  corresponds to a conformal mapping on the  $z$ -plane! Clearly, the dynamics of one-dimensional extended fundamental objects is bound to be pretty constrained and complicated. After all, it is almost like treating an *infinite set of point-like particles* all at once! Writing down the complete *action* for a string moving in  $D$ -spacetime dimensions is a horrendous thing. Usually, one writes down an *effective action* in  $D$ -dimensions, that contains a lot of information relevant to low-energy physics and, depending on the level of sophistication, tries to encompass as many novel stringy properties as possible. While this approach is pretty good for “normal” type of particle physics, it is not good for us, because we are after *exactly* the properties that differentiate between a string theory from point-like QFT. Nevertheless, there is an equivalent way to discuss string physics. Concentrate first on the “physics” of the string world-sheet, and translate afterwards to the spacetime language. In other words, we have to work with two-dimensional  $(\sigma, \tau)$  QFT, which is simpler than  $D$ -dimensional QFT! One considers then a set of world-sheet bosonic fields  $X^\mu(\sigma, \tau)$ ,  $\mu = 0, 1, \dots, D-1$ , corresponding to the  $D$  spacetime coordinates of our space-time ( $X^0$ ), that in the string jargon is called *target space*. The *action*, consistent with two-dimensional reparametrization invariance and renormalizability, is given by

$$S_{2-d} = -\frac{T}{2} \int d^2\sigma \sqrt{h} h^{\alpha\beta} g_{\mu\nu}(X^\mu) \partial_\alpha X^\mu \partial_\beta X^\nu \quad (21)$$

where  $T$  is the string tension, sometimes written as  $T \equiv \frac{1}{2\pi\alpha'} = \mathcal{O}(1/l_{\text{string}}^2)$ ,  $h^{\alpha\beta}$  is the 2-d ( $\alpha, \beta = 1, 2$ ) world-sheet metric tensor, and  $g_{\mu\nu} = g_{\mu\nu}(X)$  is the *target space* metric (symmetric and traceless) tensor, which upon quantization provides the *graviton*. Notice that the action (21) has several worth discussing *symmetries*.

- (A) *Local*: beyond the standard 2-d reparametrization invariance, there is *conformal invariance*

$$h_{\alpha\beta} \rightarrow e^{\phi(\sigma, \tau)} h_{\alpha\beta} \quad (22)$$

with the *Liouville field*,  $\phi(\sigma, \tau)$ , decoupled at least at the classical level! It should be *emphatically* stressed that the *conformal invariance* of the action (21) is of fundamental importance and

it should remain valid *not only* at the classical level (where it is automatic) but to all orders in  $T$  or  $\alpha'$ .

- (B) *Global*: reflect the symmetries of the *background*,  $g_{\mu\nu}(X)$ , in which the string is propagating. For example, if we take  $g_{\mu\nu}(X) = \eta_{\mu\nu}$ , *i.e.*, the Minkowski metric, then *Lorentz*, or more generally, *Poincare invariance* emerges, as a *global* ( $\sigma, \tau$ -independent) 2-d symmetry, corresponding to a *local* ( $X^\mu$ -dependent) target space symmetry!

The action (21) should be seen as an action describing the dynamics of a bunch of 2-d (world-sheet) fields  $X^\mu(z)$ , corresponding to our real spacetime coordinates, while the “coupling constants”  $g_{\mu\nu}(X)$  of this *non-linear  $\sigma$ -model* should be seen as corresponding to physical (spacetime) fields, *e.g.*, the graviton in this particular case. The action (21) is a *very small part* of the complete 2-d action, able to describe, say, the Standard Model. Every physical field (particle)  $g(X)$  will appear multiplying a *vertex operator*  $V_g$ , *e.g.*,  $\partial_\alpha X^\mu \partial_\beta X^\nu$  for the graviton  $g_{\mu\nu}(X)$ , of suitable form such that it successfully and uniquely represents the particle on the world-sheet physics world. To complete our story we have to know how to derive the equations of motion (E.O.M.) for our physical (*i.e.*, target space) fields and how to calculate scattering amplitudes or, through the usual LSZ-trick, correlation functions in target space.

#### 4.1.1 String equations of motion (E.O.M.)

A characteristic property (for some, the defining property) of *conformal invariance* is the vanishing of the trace of the energy-momentum tensor describing our theory. For example in the case of the action (21), with  $g_{\mu\nu} = \eta_{\mu\nu}$ , the corresponding energy-momentum tensor is

$$T_{\alpha\beta} = \partial_\alpha X^\mu \partial_\beta X_\mu - \frac{1}{2} h_{\alpha\beta} h^{\alpha'\beta'} \partial_{\alpha'} X^\mu \partial_{\beta'} X_\mu, \quad (23)$$

which is automatically traceless,  $h^{\alpha\beta} T_{\alpha\beta} = 0$ , as a consequence of conformal invariance (Eq. (22)). The above result is valid at the classical level. When quantum corrections are taken into account, there are going to be extra terms in (23) and extra care has to be taken such that the tracelessness property (equivalent to conformal invariance)

remains still valid. In principle, quantum corrections introduce infinities that have to be removed through the renormalization programme, which one way or the other introduces a *scale* into the problem and thus breaks conformal (or scale) invariance. What we are after is a *finite*, not just *renormalizable*, 2-d **Conformal Field Theory** (CFT), which implies that all the  $\beta(g)$ -functions corresponding to the “couplings”  $g(X)$  (our physical target space fields) better be zero to all orders in perturbation theory. The vanishing of the  $\beta(g)$ -functions implies correspondingly the vanishing of a set of equations involving the  $g(X)$  “couplings”, which better be our E.O.M. (we cannot have two different sets of equations satisfied by the same fields) [14]

$$\beta_{g_i}(g)|_{2\text{-d world-sheet}} = \left. \frac{\delta S_{\text{eff}}}{\delta g_i} \right|_{D\text{-Target-space}} = 0 \quad (24)$$

Equation (24) is a *highly remarkable* equation: it relates a *basic* property of world-sheet physics (*2-d conformal invariance*) to the variation of the *effective* target-space action w.r.t. the physical fields, *i.e.*, the target space E.O.M.! It should be stressed, *at the outset*, that away from the conformal *fixed point* (*i.e.*, where all  $\beta_{g_i}(g) = 0$ ) a more general form of dynamics applies and, as we will discuss later, extra care is needed for its interpretation in terms of target-space physics.

#### 4.1.2 String target-space scattering amplitudes

Using the language of *vertex operators* (discussed above) to describe physical fields on the world-sheet, it is not difficult to motivate the form that the target-space scattering amplitude for  $N$ -particles takes [13]

$$A(g_1, p_1; \dots; g_N, p_N) = \kappa^{N-2} \int \mathcal{D}X(\sigma, \tau) \mathcal{D}h_{\alpha\beta}(\sigma, \tau) \exp(-S_{2\text{-d}}) \cdot \prod_{i=1}^N V_{g_i}(p_i) = \left\langle \prod_{i=1}^N V_{g_i}(p_i) \right\rangle, \quad (25)$$

with  $V_{g_i}(p_i) \equiv \int d^2\sigma \sqrt{h} V_{g_i}(\sigma, \tau) e^{ip_i \cdot X}$  the emission or absorption operator of a string state of type  $g_i$  and momentum  $p_i$ , and  $\kappa$  is a coupling constant. This *Golden Rule* of string theory is another highly remarkable relation, carrying us again from complicated  $D$ -spacetime scattering amplitudes to simple 2-d world-sheet correlation functions

$\langle \prod_{i=1}^N V_{g_i}(p_i) \rangle$ . Once more, it should be stressed that away from the conformal fixed point extra care should be taken in using Eq. (25) because, as we will see later, more general dynamics set in which may obscure its straightforward physical interpretation.

## 4.2 Critical versus non-critical string theory

String theory as a consistent theory of gravity should be able to take care of two fundamental problems:

- (A) Quantum Gravitational (QG) corrections to scattering processes, *in fixed spacetime backgrounds*, should be *finite* and *calculable*.
- (B) Quantum fluctuations of spacetime itself, alias *spacetime foam*, should be *tamed* and lead to *calculable* physical effects.

Traditionally, most of our efforts in string theory have been concentrated on problem (A). Building upon the deep insight of, most notably, G. Veneziano, Y. Nambu, M. Virasoro, A. Neveu, J. Schwarz, P. Ramond, J. Scherk, A. Polyakov, M. Green and others, it was finally proven in 1992 by S. Mandelstam [15] that indeed string theory provides *finite* and *calculable* QG corrections to any process, thus resolving problem (A). The method is standard by now [13, 14]: one chooses a suitable CFT on the world-sheet to represent the *fixed* spacetime background ( $g_{\mu\nu}(X)$ ) usually taken to be flat Minkowski spacetime ( $g_{\mu\nu} = \eta_{\mu\nu}$ ) *plus* all other physical fields (“backgrounds”)  $g_i(X)$ . In other words, the CFT has a *critical* or *fixed point*  $g_i^*$ , such that  $\beta_i(g_j^*) = 0$  represent successfully the E.O.M. of all the physical fields  $g_i(X)$  in target-space, according to Eq. (24). In such a case we say that we got a *critical string vacuum*, represented by the corresponding CFT. Higher-order QG corrections correspond to higher-genus effects, and generalizations of Eq. (25) are available in such a case, providing *finite* and *calculable* results, as advertised above. While all these developments are pretty remarkable, unfortunately they do not address problem (B), *i.e.*, the menace of the spacetime foam. In such a case, we need to take into account quantum transitions between *different* critical string vacua, and thus, at least “*temporarily*” we have to “live” away from the *critical* or *fixed* point, and consequently we have to generalize our notions of critical string theory to *non-critical*

*string theory*. Non-critical string theory, introduced in 1988 by I. Antoniadis, C. Bachas, J. Ellis, and myself [16], provided the *first exact* string solution(s) (“vacuum(a)”) corresponding to an *expanding Universe*, in sharp contrast with the “*static*” background solutions of the critical string. Since non-critical string theory [16, 17] is the *epicenter* of my discussions, it is useful to analyze its structure in some detail. In any closed string theory, as mentioned before, there is *unavoidably* the massless graviton multiplet  $\tilde{g}_{\mu\nu}$ , consisting of the spin-2 graviton  $g_{\mu\nu}$  (symmetric and traceless part of  $\tilde{g}_{\mu\nu}$ ), the spin-0 *dilaton*  $\Phi$  (containing the trace of  $\tilde{g}_{\mu\nu}$ ), and the *antisymmetric tensor* (of rank two)  $B_{\mu\nu}$  (containing the antisymmetric part of  $\tilde{g}_{\mu\nu}$ ), which only in four dimensions corresponds to a pseudo-scalar  $b$ , called sometimes the “axion”. In a way this is a “universal multiplet” contained in any closed string theory, and thus model independent. We shouldn’t be surprised by this “*universality*” because the graviton multiplet provides the spacetime “background” where all other physical (target-space) particles “live”. It is natural that we can have several theories “living” on the same spacetime background. Thus, if we are interested in quantum fluctuations of spacetime itself, *i.e.*, spacetime foam, *to first approximation* we can neglect all other fields, beyond the graviton multiplet, “putting” them into their corresponding ground state, and conveniently forgetting about them. The 2-d world-sheet action (21) becomes then [13]

$$S_{2-d} = -\frac{T}{2} \int d^2\sigma [\sqrt{h} h^{\alpha\beta} g_{\mu\nu}(X) \partial_\alpha X^\mu \partial_\beta X^\nu + B_{\mu\nu}(X) \epsilon^{\alpha\beta} \partial_\alpha X^\mu \partial_\beta X^\nu] - \frac{1}{2} \int d^2\sigma \sqrt{h} \Phi(X) R^{(2)} \quad , \quad (26)$$

with  $R^{(2)}$  the 2-d scalar curvature. It is worth emphasizing some subtle difference between the origin of the  $(g_{\mu\nu}, B_{\mu\nu})$  terms and the  $\Phi$  term. As is indicated in (26), the  $(g_{\mu\nu}, B_{\mu\nu})$  terms are, for dimensional reasons, proportional to the string tension  $T$ , while this is not the case for the  $\Phi$ -(dilaton) term. Since  $\frac{1}{T} (\propto \alpha')$  acts as a world-sheet perturbation expansion parameter, it becomes apparent that, if the  $(g_{\mu\nu}, B_{\mu\nu})$  terms appear at the “classical level”, the dilaton term appears at the next order, as an  $\mathcal{O}(\alpha')$  “quantum correction”! The first, rather obvious exact “solution” to (26) is the “Minkowski back-

ground”:

$$g_{\mu\nu}(X) = \eta_{\mu\nu}; \quad \Phi = \Phi_0, \quad B_{\mu\nu}(X) = 0 \quad (27)$$

with the condition for *conformal invariance* ( $\beta_\Phi = 0$ ) implying

$$D + c_I = 26 \quad (28)$$

where  $D$  is the target space dimension and  $c_I (\geq 0)$  is the “central charge” of the internal conformal system that, in principle, “complements” the  $X^\mu$  fields on the world-sheet, so that the 2-d world-sheet QFT is “conformal-anomaly” free. Clearly there is a  $D_{\max} = 26$ , the famous 26 dimensions that the (bosonic) string has to “live” in. It should be observed that the “backgrounds” (27) are *static*, *i.e.*, no explicit time ( $X^0$ ) evolution! Actually, this static “solution” corresponds to the *critical string vacuum*. Clearly the critical string vacuum solution is the string analogue of the usual “Minkowski” solution of the *conventional point-like QFT*, which is the infrared limit of the critical string. As such, the critical string inherits a “small problem” of conventional point-like QFT, mentioned in the previous sections, notably the lack of an *arrow* of time which becomes endemic to critical strings. Actually, in a way it may be even worse because it is possible to formulate *consistently* critical strings without a time-variable at all, *i.e.*, on the light-cone gauge with  $D = D_{\text{transverse}} = 24$ . In such a case the physical meaning of  $X^0$  is similar to the physical meaning of the longitudinal photons in quantum electrodynamics, not much!

Fortunately, there is another rather simple, non-trivial, *exact* solution to (26) describing a *non-critical string vacuum* [16]

$$g_{\mu\nu}(X) = \eta_{\mu\nu}; \quad \Phi = -2QX^0 + \Phi_0; \quad B_{\mu\nu}(X) = 0 \quad (29)$$

with the condition for *conformal invariance* ( $\beta_\Phi = 0$ ) reading now

$$(D + c_I) - (12Q^2) = 26 \quad (30)$$

where the “background charge”  $Q$  provides the “central charge deficit”  $\delta c = 12Q^2 \geq 0$ . In such a case there is no  $D_{\max}$  and the (bosonic) string may “live” in *any* dimension ( $\geq 26$ )! What really happens is that by turning the dilaton  $\Phi$  to be a *time-dependent* ( $X^0$ ) field, we get an *extra*  $Q$ -dependent contribution to the  $\beta_\Phi = 0$  condition, thus shifting the burden from  $(D + c_I)$  to  $Q$ , such that (30) is always satisfied for *any value of*  $(D + c_I) (\geq 26)$ ! It is amusing to notice



that *if and only if*  $D = 4$  there is another, closely related non-critical string vacuum (solution) [16], which “activates”  $B_{\mu\nu}$  by giving it also a time dependence, and corresponds to a well-known CFT on the world-sheet, namely the Wess-Zumino (WZ) model of an  $SO(3)$  (or  $SU(2)$ ) group manifold. The uniqueness of the WZ solution for  $D = 4$  follows from the simple observation that only for  $D = 4$ , *i.e.*, three space dimensions, the corresponding “maximal symmetric space” ( $S_3$ ) is a group manifold ( $SO(3)$ )! We have been able to prove [16] that the “linear dilaton” solution (29), amended with the (WZ) solution if  $D = 4$ , is the *unique* solution of the 1-loop (2-d)  $\beta$ -functions with  $\delta c \neq 0$  in the following sense [16]:

- (i) Every possible solution approaches asymptotically (large  $X^0$ ) the solution (29).
- (ii) Even if we include *moduli fields* of the CFT coupled to the dilaton  $\Phi$ , again all possible solutions, for large  $X^0$ , approach asymptotically (29) and constant values of the moduli fields [18].

The *universality* and *uniqueness* of the “linear dilaton” non-critical string vacuum is rather striking! Actually, there is more to it. The *effective* target-space  $D$ -dimensional action corresponding to the general action (26) may be written as

$$S_{\text{eff}}^D = \int d^D X \sqrt{-g} e^{-\Phi} \left\{ R^{(D)} + (D_\mu \Phi)^2 - \frac{1}{12} H^2 - \frac{1}{3} \delta c + \dots \right\} \quad (31)$$

with  $R^{(D)}$  the target-space scalar curvature,  $H_{\mu\nu\rho}$  the field strength of the antisymmetric tensor  $B_{\mu\nu}$ , and  $\delta c$  a generic “central charge deficit”. The form of the action (31) suggest that  $\delta c$  can be thought of as an *allowed* tree-level cosmological term, as well as dilaton potential. We are thus faced with a horrendous *fine-tuning problem*: there is a priori no theoretical reason why  $\delta c$  should be *ab initio* zero, in other words, “*static*” Minkowski spacetime and constant dilaton (*i.e.*, *critical strings*) are *very particular* “solutions” of the string equations of motion. It sounds much more reasonable to start *generically* with  $\delta c \neq 0$  and then prove *dynamically* that we are “relaxing” towards the  $\delta c = 0$  Minkowski “solution” asymptotically. Here “relaxing” refers to the dependence of at least some of the physical fields on some dynamical variable, like for example the “common sense” time, *i.e.*, time *with*

*an arrow*, as the cosmic time in an expanding Universe. It is heart-warming that the non-trivial solution (29) provides *automatically* and *generically*  $\delta c \neq 0$ , and a dependence of the dilaton  $\Phi$ -field on time  $X^0$ , even if at this moment  $X^0$  *looks like* arrow-less Einstein time. But it is not so! The “physical metric”, with a correctly normalized Einstein action is [16]

$$G_{\mu\nu} = e^{Q\Phi} g_{\mu\nu} = e^{Q\Phi} \eta_{\mu\nu} \quad (32)$$

thus implying a Robertson-Walker line element

$$ds^2 = c^2 dt_c^2 - t_c^2 d\vec{x}^2 \quad (33)$$

with the cosmic time  $t_c \propto e^{QX^0}/Q$ , in other words a *linearly expanding Universe* [16]! It is highly remarkable that an *exact, universal, and unique time-dependent* string solution exists, describing a *non-critical string vacuum*, with  $\delta c \neq 0$  and a *time-dependent dilaton* that corresponds to an *expanding Universe* [16]. It seems that we have all the prerequisites in place for a “quantum relaxation” mechanism towards  $\delta c = 0$  (critical string vacuum).

There is another, very interesting reason indicating that the “linear dilaton” solution (29) is really special: *the quantum origin of time* [19]. Usually, when one uses the classical (genus zero) 2-d action (26), one assumes that the two-dimensional metric  $h_{\alpha\beta}$  can always take the form  $h_{\alpha\beta} = e^\phi \hat{h}_{\alpha\beta}$ , with  $\phi$  the conformal factor and  $\hat{h}_{\alpha\beta}$  some fixed metric. The conformal factor decouples from the classical 2-d action, although this decoupling is not automatic when quantum corrections are taken into account. The decoupling occurs *also* at the quantum level *if and only if*  $\delta c = 0$ , otherwise,  $\phi$  becomes a dynamical degree of freedom, the Liouville field. Indeed, there is a quantum correction to the classical action (26) given by [20]

$$S_{2-d}^{\text{quantum}} = \int d^2\sigma \sqrt{\hat{h}} \{ -\hat{h}^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi + \sqrt{c_m - 25} \phi R^{(2)} + \dots \} \quad (34)$$

where  $c_m = 3 + c_I$  stands for “matter” central charge. It is impressive that quantum corrections create a kinetic term for the conformal factor  $\phi$ , thus turning it into a new dynamical degree of freedom. It is even more impressive that this kinetic term has the wrong sign: *minus!* We just have to notice that (34) can be readily absorbed in

(26) *if and only if* [19]

$$\phi = X^0; \quad \Phi \sim \sqrt{c_m - 25} \phi = \sqrt{c_m - 25} X^0 \quad (35)$$

*i.e., if and only if* the string started in the “linear-dilaton” vacuum of (29)! Furthermore, (34) implies a conformal anomaly contribution of the  $\phi$ -field:  $c_\phi = 1 - (c_m - 25)$ , or

$$c_m + c_\phi = 26 \quad (36)$$

which is nothing else but the conformal anomaly cancellation condition (30), reexpressed in terms of  $c_m (\equiv 3 + c_I)$  and thus  $c_m - 25 = \delta c = 12Q^2$ . Remarkably, turning  $\phi$  into a dynamical degree of freedom by moving to  $c_m > 25$ , not only do we “create” time by quantum corrections (34), but *also* conformal invariance is imposed *dynamically* (36), not put in by hand. This extra bonus was the missing link in identifying string theory with 2-d quantum gravity, and makes the whole picture much more logical and aesthetically appealing. Using this 2-d quantum gravity language, one can readily show [16] that the “matter” part of the vertex operator ( $e^{i\vec{p}\cdot\vec{X}}$ ) has to be “gravitationally dressed” by  $e^{i(p^0+iQ)\phi}$  in order to render a consistent reparametrization invariant conformal field theory in 2 dimensions. Thus, we explicitly see how time ( $\sim \phi$ ) is created and “runs”, while it is guaranteed that the total conformal weight is 1! It should be stressed that the dynamical appearance of the Liouville field at the quantum level is in *perfect agreement* with the origin of the dilaton ( $\Phi$ ) term in the action (26), which as emphasized there, should be considered an  $\mathcal{O}(\alpha')$  quantum correction! The deep connection between the dilaton ( $\Phi$ ), the Liouville field ( $\phi$ ) and time ( $X^0$ ) is, of course, reflected in (35).

It should be apparent by now that the “time”-variable of the non-critical string theory, as dynamically created by quantum corrections of the 2-d world-sheet QFT, stands on a very different footing compared to the ordinary space-dimensions ( $\vec{X}$ )! Actually, that is exactly what we were after in order to resolve the *arrow* of time problem: space and time are indeed different! As long as  $\delta c = c_m - 25 = 12Q^2 \neq 0$ , we do live in an “expanding Universe”, with an *arrow* of time, and we do asymptotically “reach” a critical string vacuum (Minkowski background), where  $\delta c = 0$  and where (34) just provides us with an Einstein-time of the proper *negative* signature! This way of

looking at things provides a very satisfactory picture: the “idealized” Minkowski background of special relativity, with all its Einstein-time consequences, is only *asymptotically reachable* and thus *approximately true*, although its phenomenal success of the last 90 years strongly suggests that we are not very far from it! In other words, time has an *arrow* as long as we are away from the critical string vacuum, *i.e.*, away from criticality, *i.e.*, *out of equilibrium* (non-critical string vacuum), while it becomes Einsteinian at *equilibrium* (critical string vacuum), in full accordance with our standard notions of non-equilibrium quantum statistical mechanics, that we now turn our attention to.

## 5 Interlude (II) – Friction Time

It is very encouraging that in the case of non-critical string theory the notion of *out-of-equilibrium* emerges because, as we discussed in Section 3 (Interlude (I)), such notion may be required for a “complete” understanding of Quantum Physics along the lines of (19). **Non-Equilibrium Quantum Statistical Systems** [NEQSS] involve generically an *observed* “open” (sub)system in contact with an *unobserved* reservoir. The main characteristics of the *observed (sub)system* relevant to our discussion here are: (i) the existence of a “microscopic” arrow of time related to (ii) an increase in the entropy,  $\Delta S_{\text{entr}} > 0$ , in accordance with the Second Thermodynamic Law, due to (iii) dissipation, which is also responsible for (iv) the “collapse” of the wave function:  $\Psi_{(\text{sub})\text{system}} \xrightarrow{\text{collapses}} \sum_i |c_i|^2 |\Psi_i|^2$ . Of course, this is exactly what we are after, as discussed in section 3. As indicated there, identifying the *observed* “open” (sub)system with the *low-energy, propagating* particles and the *unobserved* reservoir with the *microscopic event horizons* (unobservable even in principle) of the spacetime foam, may get us somewhere. But, what are the conditions so that the wonderful properties (i)-(iv) are realizable in practice? Thanks to the work of Misra and Prigogine (MP) [21] and their collaborators, we know the answer. In the MP theory [21] one assumes the existence of a *non-unitary*  $\Lambda$ -transformation such that

$$\tilde{\rho} = \Lambda \rho; \quad \partial_t \tilde{\rho} = \Phi(L) \tilde{\rho} \quad (37)$$

where  $\tilde{\rho}$  refers to the phase-space density matrix describing the “open” (sub)system, and  $\Phi(L) \equiv \Lambda^{-1} L \Lambda$  is the Liouvillean of the (sub)system,

while  $\partial_t \rho = L\rho$  refers to the corresponding quantities of the *whole, closed* system ((sub)system $\oplus$ reservoir). Then, MP have proven [21] that *under certain conditions* the dynamic “open” (sub)system ( $\tilde{\rho}$ ) *admits* an internal time variable with an “arrow”, related to the increase of the “open” (sub)system entropy

$$\tilde{S} = -\text{Tr} \tilde{\rho} \ln \tilde{\rho}; \quad \partial_t \tilde{S} \geq 0. \quad (38)$$

They have also pointed out the strong bond that exists between their notion of *time-irreversibility* and *nonlocality*, a kind of *inverse* “butterfly effect”. This very last point is of immense importance for us, because as we discussed in section 3, and will be the focus of our attention a bit later, our rather restricted ability to “measure” things *only* locally, prevents us of taking into account the effects of extended, non-local (in spacetime), solitonic string states, characteristically present in spacetime foam, thus *necessarily* rendering our “idealized”, “local” system, *open!* Let us consider [3] the simplest possible “open” system, the *dissipative* (e.g., *friction*) *motion* of a single particle, as described by the *open-version* of Lagrange equations, involving non-conservative forces ( $\mathcal{F}_i$ ),

$$\text{[2nd – order formalism]} : \quad \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = \mathcal{F}_i(t, q_i, \dot{q}_i) \quad (39)$$

or equivalently

$$\begin{aligned} \text{[1st – order formalism]} : \quad \dot{q}_i &= \frac{\partial H}{\partial p_i} \\ \dot{p}_i &= -\frac{\partial H}{\partial q_i} + F_i ; \quad \mathcal{F}_i(t, q_i, \dot{q}_i) = F_i(t, q_i, p_i), \end{aligned} \quad (40)$$

where as usual,  $L$  and  $H$  refer to the Lagrangian and Hamiltonian functions, and the dots indicate time derivatives. Let us extend our study to the statistical evolution of the phase-space density function  $\rho = \rho(q, p, t)$ , dropping from now on the twiddle over  $\rho$  for simplicity. The generalized Liouville equation for “open” systems reads in our case [3]

$$\frac{\partial \rho}{\partial t} + \{\rho, H\} + F_i \frac{\partial \rho}{\partial p_i} + \rho \frac{\partial F_i}{\partial p_i} = 0 \quad (41)$$

with  $\{, \}$  indicating the usual Poisson brackets. As is well known, we are facing here a troublesome problem: while the “physical energy”  $E$  is not conserved ( $\dot{E} \neq 0$ ) because of the existence of dissipative (*e.g.*, friction) environmental effects that “open” the system,  $H$ , the generator of time-translations, is conserved  $\dot{H} = \{H, H\} = 0$ . In other words, we don’t know anymore how  $E$  relates to  $H$ ! Fortunately, there is a whole new branch of NEQSS that has been developed [22], under the name of *Lie-Admissible Algebras* (L-A-A), suitable to provide a satisfactory answer. One has to generalize the notion of Poisson bracket  $\{, \}$ , or in the quantum case, of the Lie product  $[, ]$ , to *symbolically*  $\{\{, \}\}$  and  $(, )$  respectively. The new “products” satisfy linearity, generalized Jacobi identities, and most importantly, in their quantum version, the *Lie-Admissivity* property [22]

$$(A, B) - (B, A) = 2[A, B] \quad (42)$$

which shows immediately that while  $[H, H]$  is zero,  $(H, H)$  *does not* have to vanish! In such a case we get for any dynamical quantity  $A$

$$\dot{A} = \{A, H\} + \frac{\partial A}{\partial p_i} G_{ij} \frac{\partial H}{\partial p_j} \equiv \{\{A, H\}\} \quad (43)$$

with  $G_{ij} \equiv \delta_{ij}(F_i/(\frac{\partial H}{\partial p_i}))$ , assuming of course  $\partial H/\partial p_i = \dot{q}_i \neq 0$ . For this simple dissipative statistical mechanical system, the MP function  $\Phi$  defined in (37) reads [3]

$$\Phi = i \sum_{i=1}^N \left( \frac{\partial H}{\partial q_i} \frac{\partial}{\partial p_i} - \frac{\partial H}{\partial p_i} \frac{\partial}{\partial q_i} \right) + \sum_{i,j=1}^N \frac{\partial H}{\partial p_i} G_{ij} \frac{\partial}{\partial p_j} \quad (44)$$

or equivalently (41) reads

$$\partial_t \rho = -\{\rho, H\} + \sum_{i,j=1}^N \dot{q}_i G_{ij} \frac{\partial \rho}{\partial p_j}. \quad (45)$$

Remarkably enough, Constantopoulos and Ktorides (CK) [23] have proven that *all* the MP [21] conditions for time irreversibility etc, are satisfied, *if and only if*,  $G_{ij}$  is *real* and *symmetric*, *i.e.*  $G_{ij} = G_{ji}^*$ . In other words, we are after a *Lie-Admissible* NEQSS with *real* and *symmetric*  $G_{ij} \equiv \delta_{ij}(F_i/(\frac{\partial H}{\partial p_i}))$ . Well, we will show next

that we got one such NEQSS: non-critical string theory, endorsed with the Zamolodchikov metric  $G_{ij}$  [24], which happens to be *real* and *symmetric* for *unitary* 2-d CFT, as is always the case in string theory!!!

## 6 Back to the Present

During the last three years, J. Ellis, N. Mavromatos, and myself have utilized non-critical string theory as the right framework to address all presently cumbersome problems analyzed in the previous sections. Our strategy is the following [1, 2, 3]: use the most general formalism of 2-d world-sheet *unitary* and *renormalizable* QFT, generically referred to as 2-d world-sheet  $\sigma$ -models, *without* the restriction of being *necessarily* conformal field theories. A qualification is needed here right away: as we discussed towards the end of section 4 (around Eqs. (34)-(36)), the “conformal anomaly” condition (36) is *always* satisfied, thanks to the cerberian behavior of the “activated” Liouville mode, which turns conformal invariance into a “derived”, dynamical property. What we are discussing here is the rest of the system, *i.e.*, *not* including the Liouville mode, which is used as a dynamical evolution parameter – time – as (35) indicates. A very rough analogy would be to allow a small ball to roll between two points A and B lying on the rim of a hemisphere, starting at rest, say, at A and finishing at B assuming the dynamical energy relation  $V_A = V_B$ . We know that total energy conservation implies that for every point on the ball trajectory, the sum of the dynamical energy and the kinetic energy  $T$  is constant, *i.e.*, *always*:  $V + T = V_A = V_B$ . *Nevertheless*, we learn a lot about the ball’s motion by concentrating our studies on the dependence of  $V$  with time, *e.g.*, decreases some of the time and increases the rest of it, etc. In our string case, the “magic” number of 26 seems to be always conserved (corresponding to the total energy of the ball), while  $c_m$  and  $c_\phi$  may change appropriately (corresponding to  $V$  and  $T$  respectively). Thus we have the right to concentrate on studies of the ever changing “matter” part,  $c_m$ , and get invaluable information about the system out of it. The deep question of why  $c_m$  *starts changing at all*, corresponding to the small “push” we have to give to our ball at A to start rolling, will be addressed in due time!

## 6.1 The formalism

Let us start [2, 3] with a 2-d CFT represented on the world-sheet by the action  $S_0(r)$ , where  $\{r\}$  refers to the “matter” fields (*e.g.*,  $X^\mu : \mu = 1, \dots, D$ ) spanning a  $D$ -dimensional target-space manifold of *Euclidean signature*, *i.e.*, there is no time-variable! As usual, let us perturb our system, or more properly in string theory, let us deform it, by “turning on” some string background  $g(r)$  represented on the world-sheet by the (1,1) (in order to satisfy global scale invariance), but not necessarily *exactly marginal*, vertex operator  $V_g(r)$ . Exactly marginal operators, in technical jargon, means that their Operator Product Expansion (OPE)  $V_g \otimes V_g$  does not contain a term of the form  $C_{ggg}V_g$ , *i.e.*,  $C_{ggg} = 0$ . In plain language, it means that such deformations never get the system out of the *critical line*. In critical string theory, only *exactly marginal* vertex operators appear/are allowed, because there is no dynamical Liouville mode ( $c_\phi = 0$ ), thus  $c_m$  has to remain *always* constant!

Using our small ball analogy, this means that the ball may, *at most*, move on a flat surface (equipotential surface), *i.e.*,  $V = \text{constant}$ , or in the string language,  $c_m = \text{constant}$ . Actually here lies the whole *clue* of our approach: by deforming our original system (CFT), with *not* exactly marginal vertex operators, we are allowing  $c_m$  to change, by “utilizing” the Liouville field ( $c_\phi \neq 0$ ). Let us see how this works [2, 3]. The existence of a non-exactly marginal vertex operator, *i.e.*,  $C_{ggg} \neq 0$  implies the existence of an “anomalous” scaling dimension  $\alpha_g = -gC_{ggg} + \mathcal{O}(g^2)$ . Thus, global scale invariance, a rather *untouchable* fundamental prerequisite, is in jeopardy, unless the Liouville mode comes to the rescue, “dressing” appropriately our non-exactly marginal operator, so that it keeps its (1,1) scaling dimensions *intact*! Indeed, to first order in  $\alpha'$ , we get [2, 3]

$$\int d^2z g V_g(r) \rightarrow \int d^2z g e^{\alpha_g \phi} V_g(r) = \int d^2z g V_g(r) - \int d^2z g^2 C_{ggg} V_g(r) \phi + \dots \quad (46)$$

indicating clearly that global scale invariance is guaranteed *if and only if*  $g(r)$  gets *renormalized*, implying a non-vanishing  $\beta$ -function for  $g$

$$g_R \equiv g - C_{ggg} \phi g^2 \rightarrow \dot{g}_R = \frac{dg_R}{d\phi} \equiv \beta_g = -C_{ggg} g_R^2 + \dots \neq 0 \quad (47)$$

with  $\phi(\sigma, \tau)$  the Liouville mode, apparently playing the role of a *local*



*renormalization group scale* on the world-sheet

$$\phi(\sigma, \tau) \equiv \ln \Lambda(\sigma, \tau). \quad (48)$$

But, as we discussed in detail in section 4 (around Eqs. (34-36)),  $\phi$  *acquires dynamics* through integration over world-sheet covariant metrics  $h_{\alpha\beta} = e^\phi \hat{h}_{\alpha\beta}$ ,  $\hat{h}_{\alpha\beta} = \text{fixed}$ , and becomes an extra target coordinate with, in the case of  $c_m \geq 25$ , negative metric, *i.e.*, the time-coordinate,  $X^0$  (35). Thus, by combining (35) and (48) we arrive at the highly remarkable *dynamical* relation [2, 3]

$$\phi(\sigma, \tau) = X^0(\sigma, \tau) = \ln \Lambda(\sigma, \tau) \quad (49)$$

which clearly indicates the *singularly double* role of the *dynamical* Liouville field  $\phi$ , “active” only in the non-critical string theory, as the time variable, as well as the local renormalization group (RG) dynamical scale that “flows” or “runs” along the RG trajectories of the 2-d world-sheet  $\sigma$ -models. This is the “microscopic” explanation of the quantum origin of time discussed in section 4 and, as (47) indicates, the Liouville “dressing” makes the string background  $g(r)$  be time-dependent,  $g(r, \phi) = g(r, X^0)$ . Since the time variable  $X^0$  is of a very different origin (in fact of *quantum* origin) compared with the *classical*  $\vec{X}$ -fields representing the space-coordinates denoted above collectively as  $\{r\}$ , we should not be surprised that time “flows” irreversibly, while space does not. It looks like that we are on the right track.

The above analysis can be easily generalized to an arbitrary number of string backgrounds  $\{g_i\}$ , with corresponding vertex operators  $\{V_{g_i}\}$  and  $\beta$ -functions  $\beta_i \equiv \dot{g}_i$ . We shouldn’t forget the double role of the  $g_i$ ’s: they represent physical fields of target-space (graviton, photon, electron, ...), as well as coupling-constants (or functions) of the 2-d world-sheet  $\sigma$ -model. Viewing them as coupling constants, we can consider them as the coordinates spanning the manifold of all *unitary* and *renormalizable* 2-d world-sheet  $\sigma$ -models  $G \equiv \{g_i\}$ , which is endorsed with a Zamolodchikov ( $Z$ ) metric [24]:

$$G_{ij}(g) = 2|z|^4 \langle V_{g_i}(z) V_{g_j}(0) \rangle \quad (50)$$

which is *real* and *symmetric*, due to the unitarity of the  $\sigma$ -models on the world-sheet. Furthermore, there is a function  $C(g)$  defined on  $G$ , such that

$$\frac{\delta C(g)}{\delta g_i} = G_{ij} \beta^j \quad (51)$$

and thus

$$\partial_t C(g) = -\beta^i G_{ij} \beta^j \leq 0 \quad (52)$$

where the last step (“positivity” of  $G_{ij}$ ) follows from the *unitarity* of the  $\sigma$ -models on the world-sheet, and for shorthand,  $X^0$  has been replaced by  $t$ . Zamolodchikov’s  $C$ -theorem [24] (51,52) shows that at fixed points ( $\beta_i(g^*) = 0$ )  $C(g) = \text{constant}$ , and actually, it corresponds to the “central charge” of the CFT representing the  $\sigma$ -model at the critical point  $g^*$ . It is also apparent from (52) that *if* any of the  $\beta_i$  is different from zero, then the system “runs” irreversibly into *smaller* values of central charge  $C$ ! This *irreversible* “flow” along the RG trajectory (52) is of particular importance for us for two main reasons. Firstly, the identification of time with the local RG scale ( $\ln \Lambda(\sigma, \tau)$ ) that *irreversibly* “flows” along the RG trajectories, provides us with a remarkably simple and aesthetically appealing solution to the *arrow* of time problem! The non-vanishing  $\beta_i$  (see (47)) is the origin of the time-“flow” or *arrow* of time, and if it hits a fixed point ( $\beta_g = 0$ ), presumably corresponding to a critical string vacuum, time stops to “flow”, it becomes *arrow-less*, *i.e.*, it becomes Einstein time! Secondly, if we take into account the deep connection [14, 25] that exists between  $S_{\text{eff}}^{\text{Target-space}}[g_i]$ , where  $g_i$  play the role of physical fields, and  $C(g_i)$

$$S_{\text{eff}}^{\text{Targ.sp.}}[g_i] = C(g_i) \quad (53)$$

it implies that the “roll-over” towards smaller values of  $C$  is nothing else but the usual “roll-over” towards smaller values of the effective potential  $V_{\text{eff}}$ ! Maybe the example of a small “rolling” ball used in the beginning of the section as an analogy for a “running” central charge was not “off-the-wall” as it may have sounded. Combining now (51) and (53), we get [2, 3]

$$\frac{\delta S_{\text{eff}}^{\text{Targ-Sp.}}[g_i]}{\delta g_i} = \frac{\delta C}{\delta g_i} = G_{ij} \beta^j \quad (54)$$

which give us, recalling the fact that  $\delta S_{\text{eff}}/\delta g_i$  are just the Lagrange equations,

$$\frac{d}{dt} \frac{\partial \mathcal{L}(g_i, \dot{g}_i)}{\partial \dot{g}_i} - \frac{\partial \mathcal{L}}{\partial g_i} = G_{ij} \beta^j \quad (55)$$

which is nothing else but (39), describing the *dissipative motion* of particles, involving *non-conservative forces*  $\mathcal{F}_i \equiv G_{ij} \beta^j = G_{ij} \dot{g}^j$ , in

full accord with the definition of  $G_{ij}$  provided by (43)!!!! Considering next the *target-space density matrix*  $\rho = \rho(g_i, p_i)$ , with  $p_i$  the conjugate momenta of  $g_i$  ( $p_i = \partial\mathcal{L}/\partial\dot{g}_i$ ), we get, thanks to the renormalizability of the world-sheet  $\sigma$ -model,

$$\frac{d\rho[g_i, p_i, t]}{d \ln \Lambda} = \frac{d\rho[g_i, p_i, t]}{d\phi} = \frac{d\rho[g_i, p_i, t]}{dt} = 0$$

which yields

$$\frac{\partial\rho}{\partial t} + \dot{g}_i \frac{\partial\rho}{\partial g_i} + \dot{p}_i \frac{\partial\rho}{\partial p_i} = 0 \quad (56)$$

Using the equations of motion, in their 1st order or Hamiltonian form, similar to (40), it is easy to see that (56) is identical to (41), but with  $\partial F_i/\partial p_i = 0$ . Thus, by following the steps between (41) and (45), (56) may be cast in the form [26], similar to (45),

$$\begin{aligned} \partial_t \rho &= -\{\rho, H\} + \sum_{i,j=1}^N \dot{g}_i G_{ij} \frac{\partial\rho}{\partial p_j} \\ &= -\{\rho, H\} + \delta\mathbb{H}\rho \end{aligned} \quad (57)$$

which is nothing else but the highly desirable master equation (ME) (12), but with  $\delta\mathbb{H}$  *explicitly prescribed* [26]

$$\delta\mathbb{H}\rho = \sum_{i,j=1}^N \dot{g}_i G_{ij} \frac{\partial\rho}{\partial p_j} \quad (58)$$

a rather remarkable result. Before losing (in)sight, let us reiterate the following: in the framework of non-critical string theory, and *assuming that some  $\beta_{g_i} \neq 0$* , we have found that time is of quantum origin (48), and as such it has an *arrow*, related (49) to the irreversible RG flow (52) on the world-sheet. The Liouville equation (57) for the target-space density matrix, takes its *Lie-Admissible-open-system form* (45) but with  $G_{ij}$  identifiable with the Zamolodchikov metric (50), *real and symmetric*, thus fulfilling the Misra-Prigogine conditions [21], so that the wonderful properties (i)-(iv) (discussed in the beginning of section 5) are inherited by our system! The self-consistency of the whole picture is striking: the *irreversibility* of the RG flow, identifiable with *time-irreversibility*, is *due* to the “positivity” of  $G_{ij}$ , *i.e.*, *real and symmetric*  $G_{ij}$ , emerging from the *unitarity* of the 2-d world-sheet  $\sigma$ -models, which is *exactly* the same condition that CK [23]

found, such that the MP conditions are met and thus entailing the existence of microscopic time with an *arrow!!!* Furthermore, as we will discuss shortly, the increase of entropy (as demanded by the Second Thermodynamic Law) is *automatic* thanks to the “*positivity*” of the  $G_{ij}$ ! *Amazing*. We will find it very useful in the following to encode the above correspondence between non-critical strings and dissipative systems, in a lexikon-like way

$$\begin{array}{ll}
\sigma\text{-models “coupling constant”} & \longleftrightarrow \text{dissipative, Lie-Admissible} \\
\text{phase space } (g_i, p_i) & \text{particle statistical system} \\
& \text{phase space } (q_i, p_i) \\
(\text{Non})\text{-criticality of strings} & \longleftrightarrow (\text{Non})\text{-conservative forces} \\
(G_{ij}\beta^j \neq 0) & \longleftrightarrow (\mathcal{F}_i \neq 0) \\
C(g_i) & \longleftrightarrow S_{\text{eff}}[q_i] \\
\text{E.O.M.: } \frac{\delta C}{\delta g_i} = G_{ij}\beta^j & \longleftrightarrow \frac{\delta S_{\text{eff}}}{\delta q_i} = \mathcal{F}_i
\end{array} \tag{59}$$

Before we enjoy and discuss further the fruits of our labor, we have to deal with the rather *pressing* question of who provides us and how with the *underlying central assumption* of all our formalism:  $\beta_i \neq 0$ ?

## 6.2 The microscopic mechanism – A new fundamental Procrustean Principle

In order to take into account the effects quantum fluctuations of space-time, *i.e.*, spacetime foam, we have to *allow* for quantum transitions between different critical string vacua (CFT’s). Since each critical string vacuum (CFT) corresponds to a critical or fixed point of the  $G$ -space, where all  $\beta_i(g) = 0$ , once we decide to move from one critical point to another, we will, in principle, *unavoidably* go through non-critical points of  $G$ -space, where at least some of the  $\beta_i(g) \neq 0$ ! Actually, all the formalism [2, 3] of non-critical string theory developed just above takes into account exactly this point, and the renormalization group (RG) trajectories discussed above are just the trajectories that connect two fixed points, with in principle a lot of non-critical points in between. While some “**Grand Old String Theorists**” (GOSTs) may get a bit worried and upset about allowing non-critical points ( $\beta_i(g) \neq 0$ ) into string theory, they really shouldn’t! Let me explain. In the past, conformal invariance was fixed by hand by not allowing

the Liouville field  $\phi$  to get activated, and it had been just there disconnected and forgotten. We found in recent years, that this “negligence” of the Liouville field was a very special case, and really unjustifiable. The Liouville field is “activated” in any “realistic” string solution (*i.e.*, expanding Universe) and its central charge, automatically and naturally takes care of conformal invariance, *i.e.*, dynamically establishes conformal invariance. A much more satisfactory state of affairs. In such a case, “running” along the RG trajectory between two different critical or fixed points, *with  $\phi$  as the RG scale*, assures that the *whole* system (“matter”  $\oplus$  Liouville field) is conformally invariant *at every point of the RG trajectory*. In our analogy with the “rolling” of the small ball, it corresponds to the conservation of the total energy ( $V + T$ ) along every point of the ball trajectory. On the other hand, the “running” corresponds to a *dynamical* evolution of our “matter” system that we are really interested in, *i.e.*, not just “playing around” a given fixed point, but moving all the way from one fixed point to another. In our analogy with the small “rolling” ball example, it corresponds to leaving the ball “run” its course, as it moves from one “height” to another, in principle significantly different. We, kind of, bring to *completion* the close analogy that exists between string theory, viewed as 2-d world-sheet  $\sigma$ -model and 2-d statistical mechanical system *at a critical or fixed point*, by just extending the analogy beyond the *critical point!* The *dynamically recovered* conformal invariance unleashes our hands and allows us to treat string theory as a genuine statistical mechanical system. In such a case, we have to consider *not only Exactly Marginal Operators* (EMO), that *at most* can take you along a critical line, but also **R**elevant **O**perators (RO) that “run” away from a given fixed point, and **IRR**elevant **O**perators (IRRO), that “run” towards a fix point. In the small “rolling” ball analogy, they correspond to pushing the ball away from the inverted bottom, or bottom, of the hemisphere respectively. Both relevant and irrelevant operators are characterized by  $\beta(g_i) \neq 0$ , positive for RO and negative for IRRO, while as discussed previously,  $\beta_i(g) = 0$  for EMO. Thus in the case of non-critical strings, and by their close correspondence with a genuine statistical mechanical system, we have to allow the existence of IRR and R operators as possible fluctuations or deformations, in other words, we have to allow  $\beta_i(g) \neq 0$ . Thus we shouldn’t be surprised after finding all these wonderful analogies with

(non)equilibrium quantum statistical mechanics, that the *desiderata* for understanding the *arrow* of time and the “collapse” of the wavefunction may be met in non-critical string theory. The captivity, at the critical point, is over!

Let me describe now the microscopic mechanism that we think is at work, providing *effectively* non-vanishing  $\beta$ -functions ( $\beta_i(g) \neq 0$ ). I will use the two-column format, so that the one-to-one correspondence between world-sheet phenomena and target-space phenomena remains apparent during the whole process. For the “doubting Thomasses”, in the section 8 I will discuss very briefly, since it has been discussed and reviewed *numerous times* by now [1, 2, 3], a “toy” 2-D (*space-time*) black-hole model, due to Witten [27], where *all* the forthcoming two-column steps have been worked out, by us, *explicitly* and in *excruciating detail*.

## WORLD-SHEET

Topological “defects”

Need:

$\left\{ \begin{array}{l} \text{“Monopoles” [28, 29]} \\ \text{“Antimonopoles at infinity”} \\ \text{“Instantons” [30, 31]} \end{array} \right.$

existence of:

“monopoles” / “instantons” *imply*

the existence of:

“gauge symmetries”

Increase *usually* available symmetries

*e.g.*: usual Virasoro algebra:

$$[L_m, L_n] = (m - n)L_{m+n} + \dots$$

is contained in the  $W_\infty$  algebra [33]

$$[W_m^i, W_n^j] = [jm - in]W_{m+n}^{i+j-2} + \dots$$

Close to the 't Hooft-Polyakov monopole center, and in *sharp contrast* with the would-be *Dirac-monopole singularity*, the corresponding order parameter(s) vanish ( $\langle W \rangle = 0$ ), thus enlarging the symmetry, *i.e.*, we are getting the primordial Big Symmetry ( $\Omega$ ) which corresponds to a Topological Field Theory [35], involving “surface” terms a la Chern-Simons or Wess-Zumino (WZ)

## TARGET-SPACE

spacetime foam, containing microscopic event horizons due to creation and annihilation of microscopic (Planck size) black holes

$\longleftrightarrow$

$\left\{ \begin{array}{l} \text{black-hole [29]} \\ \text{black-hole quantum decay [32, 31]} \end{array} \right. \left\{ \begin{array}{l} \text{horizon} \\ \text{“singularity”} \end{array} \right.$

$\longleftrightarrow$

Increase available local symmetries

*e.g.*: Black holes with “W-hair” [1, 34] (infinite dimensional, commuting, conserved charges)

$\longleftrightarrow$

Close to the would-be (spacetime) classical “singularity” the spacetime metric (order parameter) vanishes ( $\langle g_{\mu\nu} \rangle = 0$ ), one of many vanishing order parameters, thus getting us to the primordial Big Symmetry ( $\Omega^T$ ) which corresponds to a Topological Field Theory [27, 36, 37]

(...continued)

## WORLD-SHEET

Primordial Big Symmetry ( $\Omega$ )  
 “breaks down” [37] (via “instantons”) to  $W_\infty$  symmetry (thus a “relic” of topological symmetries)

“Area-preserving diffeomorphisms [34] of  $G$ -manifold phase-space”

any available deformation operator is Exactly Marginal Operator (EMO)

## BUT

$V_g = ((V_g)^{\text{“light”}} \oplus \sum_i \text{“}W_i\text{”}) =$   
 (due to  $W_\infty$  symmetry  $\uparrow$ )  
 = Exactly Marginal Operator (EMO)

*thus*

$(V_g)^{\text{“light”}}$  cannot be EMO

*and*  
 “effectively” becomes  
*a*

Relevant operator!

## TARGET-SPACE

Primordial big symmetry ( $\Omega^T$ ) “breaks down” [37, 31, 3] (via  $\langle g_{\mu\nu} \rangle \neq 0, \dots$ ) to  $(spacetime) \oplus$  topological-states (“relics” of the topological phase)

*Quantum coherence* [34, 1] ( $\delta\mathcal{H} = 0$ )!

$g = (g)_{\text{local}} \oplus \sum_i \text{“}g_{W_i}\text{”}$   
 $\uparrow$  *nonlocal,*  
*“topological”,*  
*extended*  
*states*

The “ $g_{W_i}$ ”, because of their *delocalized nature*, they neither appear as well-defined asymptotic states nor can they be integrated out in a *local* path-integral formalism, thus defying their detection in *local* scattering experiments [26, 2, 3]

*thus*  
 “effectively”  $g$  becomes

$(g)_{\text{local}}$



(...continued)

## WORLD-SHEET

implying [26, 2, 3]

$$\begin{aligned} \beta_g &= (\beta_g)^{\text{“light”}} + \sum_i \beta^{\text{“}W_i\text{”}} = 0 \\ \implies (\beta_g)^{\text{“light”}} &\neq 0 \end{aligned}$$

## TARGET-SPACE

*Unavoidably implying spontaneous truncation*

$$\begin{aligned} \rho_{(g)_{\text{local}} + \text{“}g_{W_i}\text{”}} &\longrightarrow \tilde{\rho}_{(g)_{\text{local}}} \\ (\text{system}) & \quad (\text{sub})\text{system)} \\ (\delta\mathcal{H})^{\text{“light”}} &\neq 0 \\ \text{“effectively” quantum} & \\ \text{coherence loss for} & \\ \text{local/“light” subsystem} & \text{ [26, 2, 3]} \end{aligned}$$

---

Some explanations are due. It shouldn't be surprising that topological non-trivial “solutions” of target-space, like black-holes, correspond to topological nontrivial structure on the world-sheet, including “monopoles” and “instantons”. What else could it be? Furthermore, there is a one-to-one correspondence [29] between the “monopole” charge and the black-hole mass. Actually, “instantons” may cause transitions between “monopoles” of different charges, corresponding to higher-genus (quantum level) corrections to black-hole masses, thus triggering *quantum decay* [2, 3, 31, 32] of the black hole. The accommodation of topological non-trivial structure on the world-sheet, needs gauge symmetry, which forces the Virasoro algebra to become a  $W_\infty$  algebra, which through the Evans-Giannakis-Ovrut (EGO) mechanism [38], translates to infinite dimensional, commuting, conserved charges on target-space, that endorse the black-hole. The pipe-dreaming of section 3 becomes a reality: non-critical strings provide non-trivial, infinite dimensional symmetries, whose corresponding conserved charges characterize the identity of the black hole. Thus, enabling the B.H. to absorb all information, in a coherent way, and then, through normal *quantum decay* [32], and not through *thermal Hawking radiation*, to spit it out coherently, through a very *constrained decay-cascade* [39], due to the severe obligation of the decay process to respect a whole set of selection rules. The *common* origin of the “melting” of the singularity (“Dirac-like” in the “monopole”

case and “space-like” in the B.H. case), due to the enhancement of the infinite symmetries as we approach the “singularity” and thus unavoidably rendering *both* world-sheet and target-space actions *topological*, is fascinating. Normal QFT, 2-d (world-sheet) or  $D$ -dimensional (target-space), based on Riemannian metrics, cannot sustain such an incredible amount of infinite symmetry and they dissolve to topological field theories! The infinite symmetries that characterize string theories, away from the “classical” singularity, *i.e.*, in the “spacetime” phase, are nothing else but a subgroup of the “infinite” symmetries in the topological phase! Thus, we should not be surprised that in the “spacetime” phase we may encounter [34] nonlocal, topological, extended states, *i.e.*, states with *definite, discrete*  $E$  and  $\vec{p}$  (extendable over *all space* and *all time*, thanks to the uncertainty principle!), the “relics” [37] of spontaneously broken infinite symmetries, something like the Goldstone bosons of spontaneously broken global symmetries. It is exactly the very existence [34] of these delocalized states which, since they *cannot be accounted* by a *local* observer, renders the *local* system *unavoidably, open* [2, 3, 26]! Undoubtedly, we have discovered [2, 3, 26] here a very interesting, new and of *pure stringy origin* phenomenon, which is the source of the conceptual changes that may be needed at the foundations of Quantum Physics and Relativity. It seems very likely that we are uncovering [2, 3, 26] a *new fundamental principle*, beyond the *wave-particle duality* (or *uncertainty principle*) of Quantum Mechanics and the *Relativity principle*, which in a way completes the set of our big sacred principles. It may be expressed in a very general, *abstract* way as follows.

*In our “low-energy” world our available “tools”, made of the lowest lying, propagating string modes, are localized, thus the available “measurements”/ “experiments” are necessarily localized. As such, we cannot take into account the **complete** effects of the topological, extended (over all space-time) states, in continuous interaction with the low-energy propagating particles. Thus, a **spontaneous truncation** occurs in a natural, unavoidable and **dynamical** way, that renders a local system wide open. We “measure” only what fits in our “apparatus”, and thus let me call it, appropriately, the **Procrustean Principle**.*

Technically, such a procedure would amount to integrating out the topological modes in a String Field Theory path-integral. Since a

second quantized String Field Theory is not yet at hand, a first quantized  $\sigma$ -model approach [13] can be adopted instead, in which such an integration would appear as turning on a “*spontaneously truncated*” background of propagating light string modes only [2, 3].

After this rather detailed discussion of the *formalism*, and of the *microscopic mechanism* at work in non-critical string theory, responsible for the “openness” of the “low-energy” world available to us, it is appropriate to discuss some of the rather dramatic consequences that may lie in our

## 7 Future

It became apparent in the previous section that non-critical string theory may furnish the appropriate framework to address and correlate all the “deep” problems that have plagued us for almost a century now: “arrow” of time, “collapse” of the wavefunction, quantum gravitational dynamics, including black-holes. As it was conjectured in section 3, the resolution of these problems seems to cast down the *shibboleths* of conventional physics, but in a very intriguing way.

### 7.1 Density matrix mechanics

The central issue of non-critical string theory, viewed as a **Non-Equilibrium-Quantum-Statistical-System** (NEQSS), is the derivation (see (57),(58)) of the Liouville equation for an “open” system, which becomes

**A Master EquatioN** (AMEN) [26]:

$$\partial_t \rho = -\{\rho, H\} + \left(\frac{1}{M_{Pl}}\right) G_{ij} \beta^j \frac{\partial \rho}{\partial p_i} = i[\rho, H] + \left(\frac{1}{M_{Pl}}\right) iG_{ij}[g_i, \rho] \beta^j,$$

implying

$$\delta \# \rho = \left(\frac{1}{M_{Pl}}\right) G_{ij} \beta^j \frac{\partial \rho}{\partial p_i} = \left(\frac{1}{M_{Pl}}\right) iG_{ij}[g_i, \rho] \beta^j \quad (60)$$

where the second term holds in the quantum formulation. As I have indicated explicitly, the extra term in the standard Liouville equation is at least of  $\mathcal{O}(1/M_{Pl})$  with respect to the standard term  $[\rho, H]$ . Since the origin of this extra term is due to the mixing (triggered by

the  $W_\infty$ -symmetries) between the “low-energy world” ( $E$ ) particles and the massive ( $\mathcal{O}(M_{Pl})$ ), higher level, topological string modes, we naturally expect  $(\beta^j)^{\text{“light”}}$ , a concise “measure” of non-marginality, to be proportional to this mixing, *i.e.*,  $(\beta^j)^{\text{“light”}} \approx \mathcal{O}((E/M_{Pl})^n)$ , with  $n$  some small positive integer. A “tiny” extra term indeed! But as Maxwell taught us (see section 1, after (7)) “Beware of *tiny* terms bearing changes”! Indeed, this time too the consequences are rather far-reaching. To start with, even the mere presence of this “tiny”  $\delta\mathbb{H}$  term, eroding the wave-behavior of matter, entails the abandoning of *even the notion* of the wavefunction  $\Psi$  and replacing it by the density matrix  $\rho$ . Consequently, we have to [2, 3, 26] abandon the notion of the  $S$ -matrix:  $|\alpha, +\infty\rangle = S|\alpha, -\infty\rangle$  and replace it by the  $\mathcal{S}$ -matrix:  $\rho_+ = \mathcal{S}\rho_-$ , with  $\mathcal{S} = SS^\dagger + \delta\mathcal{S}$ . While these remarks sound suspiciously similar to the remarks made in section 2 (around (11),(12)), there is a *big difference*. There we didn’t have any consistent quantum gravity dynamics, we didn’t know if our conclusions were true or artifacts of semiclassical approximations, and we didn’t have any slight clue of how to calculate  $\delta\mathbb{H}$ , etc. Here we have a consistent quantum gravity framework, and a microscopic mechanism that explains how, starting from a *consistent* and *complete* (non-critical) string theory at the quantum level, we end up *unavoidably* and *necessarily* with an *effectively* “open” non-equilibrium quantum statistical system. As such, we can work out the explicit form of  $\delta\mathbb{H}$  or  $\delta\mathcal{S}$  and thus we are able to provide new rules for performing calculations. A very different picture from the murky point-like QFT picture indeed! Furthermore, the specific structure/form of the AMEN (60) leads *immediately* to the following properties, *independently* of the specific system under consideration [2, 3, 26]:

(I) *Conservation of Probability  $P$*

$$\partial_t P = \int dp_i dg^i \text{Tr} \left[ \frac{\partial}{\partial p_i} (G_{ij} \beta^j \rho) \right] = 0 \quad (61)$$

(II) *Conservation of Energy, on the average*

$$\partial_t \langle\langle E \rangle\rangle \equiv \partial_t [\text{Tr}(\rho E)] = \partial_t (p_i \beta^i) = 0 \quad (62)$$

where the last equality is due to the *renormalizability of the  $\sigma$ -model*. The latter implies that any dependence on the renormalization group scale in the  $\beta^i$  functions is implicit through

the renormalized couplings. Renormalizability replaces the time-translation invariance of conventional target-space field theory.

(III) *Increase in Entropy*

$$\partial_t S \equiv \partial_t [-\text{Tr}(\rho \ln \rho)] = (\beta^i G_{ij} \beta^j) S \geq 0 \quad (63)$$

where the last inequality follows from the *unitarity of the  $\sigma$ -model*, as explained in section 6, see (50).

These are three properties of fundamental importance for us, because we are not talking about any random “open” system, in which *generically* energy conservation for the (sub)system is not guaranteed, but for a specific “open” system that we claim describes the microcosmos and thus we cannot afford energy non-conservation, and indeed we do get energy conservation! Actually, it is intuitively easy to understand why. Our “light” system interacts with the massive topological models of *definite, discrete  $E$* , of the order of  $M_{Pl}$ , thus the “light” system cannot excite them and consequently, on the average, the  $E_{\text{light}}$  is conserved! Similarly, the increase in entropy due to the “*positivity*” of  $G_{ij}$  is nothing else but the Zamolodchikov’s  $C$ -theorem [24] condition for irreversible RG flow (see (51,52)), *i.e.*, for irreversible time “flow”, as it should be in any NEQSS, like non-critical strings, where the monotonic increase in entropy may be used to define the “arrow” of time. It is highly remarkable that two fundamental properties of world-sheet physics, renormalizability and unitarity are responsible for two fundamental properties of target-space physics, *conservation of energy* and *monotonic increase of entropy* (implying *an arrow of time*) respectively.

However, the renormalizability of the theory, which guarantees energy conservation, does not guarantee the conservation of angular momentum (see second Ref. in [3]). Unlike string contributions to the increase in entropy, which cannot cancel, the *apparent* non-conservation of angular momentum may vanish in some backgrounds, though not in one cosmological background that we have studied (see second Ref. in [3]). Namely, in the case of a maximally symmetric  $D$ -dimensional, non-static Universe with  $\partial_t R(t) \equiv -H(t)R(t)$  where  $H(t)$  is a Hubble parameter, we find (see second Ref. in [3])

$$\partial_t \langle\langle J^{\alpha\beta} \rangle\rangle = -\frac{3D}{8\pi^2} H(t) R(t) \langle\langle J^{\alpha\beta} \rangle\rangle \quad (64)$$

showing a decrease of the average angular momentum in an expanding Universe. This amounts to a *derivation* of *Mach's Principle*.

To discuss further some general properties of density matrix mechanics, I will use again the two-column format employed in the last section, in order to keep crystal clear the correspondence between world-sheet phenomena and target space phenomena.

**WORLD-SHEET**

“Monopoles”/“Instantons”

Trigger *Renormalization* ( $\ln \Lambda(\sigma, \tau)$  or  $t$ -dependence) of the  $k$ -parameter(s), *i.e.*, the levels of the Kac-Moody “currents” defining the CFT, expressible as  $\theta_{\text{QCD}}$ -like angles in the case of the Wess-Zumino type CFT, due to “Instanton” (IRR)  $\oplus (V_g)_{\text{light}}(\mathbb{R})$  deformations [31, 2, 3]:

$$k \stackrel{t \rightarrow \infty}{\propto} e^{(\beta_g)gt} \rightarrow \infty,$$

while  $k \stackrel{t \rightarrow 0}{\rightarrow} k_{\text{top.phase}}$ , a small finite number, *e.g.*, 2. In other words, a *monotonic increase* of  $k$  with time  $t$ , as we move away from the topological phase [31, 2, 3].

The correlation functions  $\langle V_1 \cdots V_N \rangle$  get “non-perturbative” contributions (“valleys”, ...) [31]

**TARGET-SPACE**

$\longleftrightarrow$  spacetime foam

$\longleftrightarrow$  Generates irreversible time-“flow” by getting the (sub)system out of equilibrium, thus triggering *dynamically quantum relaxation* of all the “constants” [2, 3] of Nature towards their asymptotic (critical string vacuum) values;  $c, \hbar, l_{\text{string}}, \Lambda_C$  all become *monotonically decreasing* functions of  $k$ , *i.e.*, of  $t$ , as we move way from the topological phase [2, 3].

The scattering amplitudes  $A(1, 2, \dots, N)$  get non-standard (*i.e.*, beyond those included in (25)) contributions leading [31] to  $\rho(t) = \mathcal{S}(t)\rho(0)$ , with  $\mathcal{S}(t)$  containing a factor  $e^{-\gamma t}$ , where  $\gamma$  represents generically the small anomalous dimension of the deformation at hand. This extra exponential damping with time of the  $\mathcal{S}$ -matrix leads, of course, to the *spontaneous collapse* of the “wave function” [31, 2, 3].

A few explanations are in order. Having convinced ourselves that  $\delta\mathbb{H} \neq 0$ , *i.e.*, that we are dealing with an “open” system in the low-energy world, it is only natural that  $\delta\mathcal{S} \neq 0$  and thus non-factorization of the  $\mathcal{S}$ , triggers the *spontaneous collapse* of the wavefunction, irrespectively of the nitty-gritty microscopic details! Still, it is very interesting that the topological non-trivial structure on the world-sheet, including “monopoles” and “instantons”, contributes to the correlation functions and while this is nothing unusual at the world-sheet level, when these contributions are elevated to the target-space level, they go far beyond [31, 2, 3] usual QFT contributions. Furthermore, the NEQSS nature of the low-energy world makes it apparent that we are “running” towards (but not yet there) the “chosen” (critical string vacuum) fixed point. Thus, the “coupling constants”  $g_i$  (our stringy backgrounds) evolve continuously with time, and so do the associated world-sheet QFTs and thus their generic parametrizations (*i.e.*, the  $k$ ’s) become time-dependent [31, 2, 3]. The case corresponding to the Wess-Zumino CFTs is illuminating because  $k_{\text{WZ}} \rightarrow \theta_{\text{QCD}}$ -like angle, and we know that “instanton” effects *renormalize*  $\theta_{\text{QCD}}$ ! Correspondingly, the “constants” of Nature that characterize a given (critical string) vacuum, would depend on the parametrization of this vacuum, *i.e.*, will be  $k$ -dependent and thus  $t$ -dependent [2, 3]. Actually, it is intuitively simple to determine their generic behavior with time. Close to the topological phase, *i.e.*,  $t \rightarrow 0$ , one expects the dominance of the topological, extended states, thus the dominance of *nonlocal effects*, making it easy to communicate at *any distance*, thus suppressing the “horizon”. In other words allowing the velocity of light  $c \rightarrow \infty$ ! As time goes by, the influence of the topological modes decreases and  $c \rightarrow$  finite. The above discussion shows rather clearly that  $c = c(t)$  is a *monotonically decreasing* function of  $t$ . In the same spirit, the closer we get to the topological phase, the easier it is for the (sub)system to become “closed” and “complete”, *i.e.*, standard quantum mechanics at its full strength, with maximal  $\hbar$ ! Again,  $\hbar = \hbar(t)$  is a *monotonically decreasing* function of  $t$ , because getting away from the topological phase the influence of the topological modes diminishes, as does the “strength” of standard quantum mechanics,  $\hbar$ ! The time-dependence of the string as it approaches the ultraviolet fixed point is reflected in a computation of the string position-momentum uncertainty relation in the  $\sigma$ -model deformed by



propagating low-lying string modes and “instantons”. The result for the position-momentum uncertainty, defined appropriately to incorporate curved gravitational backgrounds, is a generalization of the standard uncertainty principle (8), and can be expressed as [2, 3], for large enough  $t$

$$(\Delta X \cdot \Delta P)_{\min} \equiv \hbar_{\text{eff}}(t) = \hbar [1 + \mathcal{O}(1/k(t))] \quad (8')$$

The case of the fundamental length  $l_{\text{string}}$  is similar. Close to the topological phase, the string tension  $T \rightarrow 0$ , or  $\alpha' \rightarrow \infty$ , or  $l_{\text{string}} (\sim \sqrt{\alpha'}) \rightarrow \infty$ , while away from the topological phase  $\alpha' \rightarrow \text{finite}$ , thus  $l_{\text{string}}$  gets smaller as time “runs”. Furthermore, since the *fundamental* string length,  $l_{\text{string}}$  contributes an *extra term* to Heisenberg’s uncertainty principle, and since close to the topological phase the uncertainty principle works at “full strength”, we naturally expect  $l_{\text{string}} \rightarrow \infty$  as  $t \rightarrow 0$ , while  $l_{\text{string}} \rightarrow \text{finite}$  as  $t \rightarrow \infty$ , once more a *monotonic decrease* with time. Indeed, we get [2, 3] a generalization of (20) that reads, for large enough  $t$

$$l_s(t) = l_s [1 + \mathcal{O}(1/k(t))] \quad (20')$$

Concerning the cosmological constant  $\Lambda_C$ , keep in mind that, as (31) indicates,  $\Lambda_C$  is proportional to  $\delta c$ , while through (35),(36),  $\delta c = c_m - 25 = 12Q^2$ , which is *monotonically decreasing* [2, 3] with time, towards its (critical string) vacuum value  $\delta c = c_m - 25 = 0$ , thanks to the irreversible RG trajectory flow, alias Zamolodchikov’s  $C$ -theorem (52)!

It should be stressed that the above properties are rather general, as based on first principles. Indeed, Zamolodchikov’s  $C$ -theorem (52) *entails* an irreversible decrease with time of the  $C$ -function, whose dependence on the  $k$ -parameters for large  $k$  is of the form  $C_0 + \mathcal{O}(1/k)$ , for physically *relevant* CFTs. Thus we get a monotonic increase with time of  $k$ -parameters! It looks like based upon very general and powerful first principles of string theory, the “constants” of Nature,  $c, \hbar, l_{\text{string}}, \Lambda_C$ , *irreversibly* and *monotonically* decrease with time [2, 3]. It looks very plausible that the Master Equation (60) is nothing else but the long-sought **N**-equation (19)!

Having discussed at length *density matrix mechanics*, the “answer” of non-critical string theory to the fundamental question of how quantum physics and gravity best mix, we need to move on to provide

“answers” to the other “small” problems discussed in section 2 and elaborated further in section 3.

## 7.2 Spontaneous collapse of the “wavefunction” – classical from quantum – the Aphrodite Mechanism

It must have been pretty clear by now that we have in our hands all the right ammunition to attack the problems related to the **R** part of quantum mechanics (see (18)) such as the Schrödinger’s cat “paradox”, the EPR “paradox” and more generally the emergence of the classical world from the quantum world *dynamically* and *spontaneously* as it should be (see section 3). The spontaneous “openness” of the low-energy world, due to the spontaneous truncation of the topological, extended modes, coupled to the low-energy propagating particles (the **P**rocrustean principle discussed in section 6), is the long-sought “panacea”!

Before discussing the rôle of topologically non-trivial configurations on the world-sheet in the suppression of coherence at large times, we review a similar phenomenon in Hall conductors, namely the suppression of spatial correlations by “de-phasons” [40]. A black-hole model is analogous to a fractional Hall conductor [41], with the Wess-Zumino level parameter  $k$  corresponding to the transverse conductivity. Hall systems generally are described by appropriate  $\sigma$ -models with Wess-Zumino  $\theta$ -terms, defined on the two-dimensional space of electron motion [40]. The fields of such  $\sigma$ -models, which are space-time coordinates in the black-hole case, correspond to electrons propagating in the plane, with the transverse and longitudinal conductivities  $\sigma_{\mu\nu}$  corresponding to background fields in the black-hole case. The Wess-Zumino terms are associated with instantons that renormalize non-perturbatively these conductivities [42]:

$$\beta_{\mu\nu} = \frac{d\sigma_{\mu\nu}}{d \ln L} \neq 0 \quad (65)$$

where  $L$  is an infrared cut-off on the instanton size that serves as a renormalization group scale [42].

We believe that localization in Hall systems is directly related to our problem of quantum coherence. In the **I**nteger **Q**uantum **H**all **E**ffect (IQHE) model [40], impurities are responsible for the localization of the electron wave function in the plane. The localization is

achieved formally by representing collectively the effects of impurities on electron trajectories via extended, static scattering centres termed “de-phasons”, which trap the electron waves into localized states with sizes  $O(1/\sqrt{\rho})$ , where  $\rho$  is the de-phason density. As a result, the electron correlation functions are suppressed at large spatial separations:

$$\propto \exp[-(x - y)^2 \rho] \quad (66)$$

at zero magnetic field ( $\theta = 0$ ). As the magnetic field is varied so that the transverse conductivity becomes a half-integer (in units of  $e^2/h$ ), corresponding to a discrete value of the instanton angle  $\theta = \pi$ , the property of the de-phasons to destroy phase coherence between the advanced and the retarded electron propagators is lost. Quantitatively [40], the expectation value of an electron loop that encircles a de-phason, in the presence of a magnetic field, is proportional to  $e^{-(x-y)^2 \rho \cos \frac{\theta}{2}}$ . Thus, for  $\theta = \pi$  the “effective de-phason density”  $\rho \cos(\theta/2)$  vanishes, and the electrons delocalize implying a non-zero longitudinal conductivity. This delocalization property is responsible for the transition between two adjacent plateaux of the transverse conductivity in the Hall conductivity diagram [40]. These ideas can be extended to the Fractional QHE [43] via the three-dimensional anyonic Chern-Simons theories, which are closer to our black-hole interests. In fact, it appears to be the zero-field Hall effect that describes physics at the space-time singularity. For example, the massive topological modes of the  $SL(2, R)/U(1)$  black-hole model (see section 8) are the analogues of the de-phasons. As discussed earlier in this section, the “instantons” renormalize the Wess-Zumino level-parameter  $k$  (c.f.  $\theta$ ), changing the mass and size of the black hole. The delocalized phase at  $\theta = \pi$  may be identified with the “topological” phase at the space-time singularity [37], which is an infrared fixed point. The propagating “tachyon” mixes in this limit, as we have discussed above, with the delocalized topological modes of the string that are analogous to the de-phasons. The localization properties are consistent with shrinking of the world-sheet as one approaches the ultraviolet fixed point that corresponds to a flat target space-time where the tachyons are normal localized fields that do not mix with topological modes.

Our formalism for [2, 3, 31] the time evolution of the density matrix is analogous to the Drude model of quantum friction [44], with the massive string modes playing the rôles of ‘environmental

oscillators'. In the language of world-sheet  $\sigma$ -model couplings  $\{g\}$ , the reduced density matrix of the observable states is given, relative to that evaluated in conventional Schrödinger quantum mechanics, by an expression of the form

$$\rho(g, g', t)/\rho_S(g, g', t) \simeq e^{-\eta \int_0^t d\tau \int_{\tau' \simeq \tau} d\tau' \beta^i G_{ij} \beta^j} \simeq e^{-Dt(\mathbf{g}-\mathbf{g}')^2+\dots} \quad (67)$$

where  $\eta$  is a calculable proportionality coefficient, and  $G_{ij}$  is the Zamolodchikov metric (50) in the space of couplings. In string theory, the identification of the target-space action with the Zamolodchikov  $C$ -function  $C(\{g\})$  [24] enables the Drude exponent to be written in the form (52)  $-\beta^i G_{ij} \beta^j = \partial_t C(\{g\})$ , which also determines the rate of increase of entropy (63)  $\dot{S} = \beta^i G_{ij} \beta^j S$ . In the string analogue of the Drude model (67) the rôle of the coordinates in (real) space is played by the  $\sigma$ -model couplings  $g^i$  that are target-space background fields. Relevant for us is the tachyon field  $T(X)$ , leading us to interpret  $(g - g')^2$  in (67) as [31]

$$(g - g')^2 = (T - T')^2 \simeq (\nabla T)^2 (X - X')^2 \quad (68)$$

for small target separations  $(X, X')$ . Equation (68) substituted into (67) gives us a suppression very similar to the IQHE case (66).

The effect of the time-dependences (67,68) is to suppress off-diagonal elements in the target configuration space representation of the out-state density matrix :

$$\rho_{out}(x, x') = \hat{\rho}(x)\delta(x - x') \quad (69)$$

This behaviour can be understood intuitively as [31] being related to the apparent shrinking of the string world sheet in target space, which destroys interferences between strings localized at different points in target configuration space, c.f. the de-phasons in the Hall model [40]. This behaviour is generic for string contributions to the space-time foam, which make the theory supercritical locally, inducing renormalization group (target time) flow. Calculations in simplistic models [31], as well as dimensional analysis (see in particular the discussion below (60)), indicate that the **Dumping** (or **Drude**) coefficient  $D$  in (67) is given by [45, 31]  $D \approx N \left( \frac{m^6}{M_{Pl}^2} \right)$ , where  $N$  is the number of microconstituents of mass  $m$ . Inserting this value of  $D$  in (67), and

taking into account (68), we arrive at a spontaneous collapse of the system “wave-function” with the following characteristics: localization of the center-of-mass coordinate  $X_{\text{C.M.}}$  within the Bohr radius  $a_B$  ( $\sim 0.53\text{\AA}$ ) within  $\mathcal{O}(10^{-7}\text{sec})$ , iff  $N(\approx M_{Pl}/m) \approx \mathcal{O}(N_{\text{Avogadro}})$ ! A rather remarkable result. For us [45, 31],  $N_{\text{Avog}} \approx 10^{24}$  is an *indicative* number of constituents for systems showing characteristics of “classical” behavior! What we find here is exactly that: we get a spontaneous, *quick* collapse of the wave-function, for  $N \approx M_{Pl}/m$ , not very different from  $N_{\text{Avog}}$ . It is incredible that the *smallness* of Newton’s gravitational constant, with respect to the other interaction coupling constants, or equivalently, the *vast difference* between the low-energy masses (GeV-TeV region) and the Planck mass ( $10^{19}$  GeV), is responsible for the *almost exact* quantum mechanical behavior of *microsystems* ( $N \ll 1$ ), electrons, quarks, ..., while it demolishes in no time the wavefunction of *macrosystems* ( $N \sim N_{\text{Avog}}$ ). The Schrödinger’s cat is either dead or not, as the case may be [45, 31], but not half-dead, half-alive, anymore. There is no Schrödinger’s cat in density matrix mechanics. Clearly, such a dynamical mechanism, triggering the *spontaneous collapse* of the wavefunction, will have far-reaching consequences for the “measurement” problem in Quantum Mechanics. I cannot resist of making a side comment here. The *vast disparity* between  $m_{\text{(light)}}$  and  $M_{Pl}$ , known as the notorious *gauge hierarchy* problem in particle physics, has been the main motivation for practical uses of supersymmetry and supergravity. Actually, in *no-scale supergravity* [46], one gets *naturally* and *dynamically* a relation of the form  $m_{\text{light}} \approx e^{-1/\alpha} M_{Pl}$ , with  $\alpha$  some characteristic fine-structure-like constant; while the cosmological constant  $\Lambda_C$  is *at most* of  $\mathcal{O}(M_W^4)$ , even after the spontaneous breaking of supersymmetry. Recalling also the fact that the *no-scale supergravity framework* seems to be the infrared limit of string theory [47], corresponding to flat-directions ( $\beta_g = 0$  on a continuous, critical line, not at just a point!), it looks like the *gauge hierarchy problem*, was a *blessing in disguise*! In fact, since the spontaneous collapse of the wavefunction in non-critical string theory is a well tabulated dynamical mechanism, it leads to some, as it should, specific experimental predictions. Namely, the exponential decay with time of the electronic currents in a SQUID with a Josephson Junction at very low temperatures [45, 31], as well as CPT-violating effects in the  $K^0 - \bar{K}^0$  system [7, 48, 49, 50]. While CPT-invariance is a *basic*

theorem of point-like QFT, this is *not necessarily* the case in non-critical string theory. The CPT-theorem is based on *locality*, *Lorentz invariance*, and *unitarity*. The first two assumptions are not automatically satisfied in non-critical string theory, thus it is appropriate to re-open the possibility of CPT-violation. It goes far beyond my purposes here to discuss these very interesting proposals, since they have been discussed very clearly and in full detail in the recent literature [48, 49, 50]. It suffices to say that these experiments are under the way to completion and we may know something not in the very far future.

Concerning the EPR “paradox”, the very existence of the *delocalized*, topological, extended states in continuous interaction with the low-energy world particle states, turns the low-energy world into an *effective nonlocal theory*, in accord with Aspect’s experimental results [10]. In a way we are dealing *effectively with a nonlocal hidden variable theory* provided by the non-trivial mixing of the low-energy particle modes to the massive, topological modes induced by the *infinite symmetry* content of non-critical string theory. In an intuitive way, as the two photons, decay products of the  $\pi^0$  (see (14)), run away in spacetime, still they are entangled through the topological extended states, and thus when “something” happens to one photon, say  $\gamma_1$ , the other “feels” the *influence instantaneously* due exactly to the *very nature* of the delocalized, topological states. Furthermore, because the very existence of the topological states is the *main reason* for the *arrow* of time, through the **P**rocrustean principle, and thus the *un-relativistic* behavior of the **R**-part of quantum mechanics (18), clearly the Penrose “paradox” gets automatically resolved! If the two “observers” wish, they may “log on” to the indisputable irreversible time “flow”, that characterizes the **R**-part of quantum mechanics, and thus straighten out their differences, *getting a universal picture of physical reality*, as it should be!

As has been repeatedly emphasized above, the dynamical origin of the spontaneous collapse of the wavefunction provides a very appealing resolution to the “classical” versus “quantum” world problem. The “*coherent phase*” *erosion factor* (second RHS of (60)) depends *explicitly* on the mass (maybe more precisely on the energy) of the system under consideration, and while it is *virtually harmless* for microsystems (*e.g.*, electrons, photons, ...) it becomes *dominant* for

macrosystems ( $N_{\text{const}} \sim N_{\text{Avog}}$ ). Thus the natural emergence of the “classical” world from the “quantum” world. It is amazing, how lucky the founding fathers of quantum mechanics were. How lucky? About  $(M_{\text{Pl}}/m_{\text{light}})^n$ ,  $n = 1, 2, \dots$ , in other words *very lucky!*

Very recently (see second Ref. in [3]), we have been able to show the emergence of *almost-time-reversible* local field theory structures, associated with decoherence-induced pointer states in the coupling constant space, as a result of the inevitable couplings to the unobservable non-propagating solitonic string states. Thus, we satisfy successfully the last *desideratum* of section 3, concerning the *dynamical* appearance, at large distances, of an *almost* relativistic QFT.

This is our answer [2, 3, 26] to the often asked question: why does quantum mechanics seem to work so *extremely* well? It is just a matter of scale! Since the *de-phasing, erosion mechanism* in target-space is due to the existence of spacetime foam, thus implying the emergence of the “classical” world from the foam, like another Aphrodite, it is appropriate to call this mechanism the **Aphrodite mechanism**, an immediate consequence of the **Procrustean principle**. It seems that the ancient Greeks had their mythology straight!

### 7.3 A new theory of black-hole dynamics – No-Horizon Cosmology

The emerging new picture of black-hole dynamics in non-critical string theory is not hard to spell. Black holes correspond [29] to topological defects on the world-sheet, *e.g.*, monopole-antimonopole pairs, where the monopole, say placed at the origin of the complex plane (or the south pole of the Riemann sphere) corresponds to the black-hole (event) horizon, while the antimonopole placed at infinity (or the North pole of the Riemann sphere) corresponds to the region of the *would be* classical space-singularity. The existence [29] of topological defects on the world-sheet presume the non-trivial enlarging of the world-sheet symmetries, *e.g.*, the existence of  $W_{1+\infty}$  symmetries, that through the EGO mechanism [38] are elevated to target-space (spontaneously broken) local symmetries. Thus, the stringy black holes are endorsed *naturally* with infinite *quantum hair*, *e.g.*, “W-hair” [34, 1], of the Aharonov-Bohm (AB) type discussed in section 3, thus enabling them to absorb *coherently* vast amounts of information [34, 1].

Any type of interaction/perturbation with/of the black hole will bring it to some different level, vis-à-vis the infinity of AB “charges” that are needed for the complete characterization of the black hole identity. The black hole decay, due to quantum effects [32], is also an orderly process, characterized by a vast set of selection rules [39], and thus there is no information loss! Indeed, string black holes, like massive string modes, are unstable under quantum corrections. Regularization of divergent integrals over large tori, related to modular invariance, a *purely stringy effect*, induce a non-zero  $Im(M_{\text{BH}}) \propto 1/\tau_{\text{BH}}$ , *i.e.*, causing the decay of the black hole [32]. An explicit calculation shows that the 4-D black-hole lifetime [32, 51] is given by  $\tau_{\text{BH}} \propto M^3$ , very similar to Hawking’s result (10)! Of course, in our case we have a *normal, ordinary, coherent* decay process, like  $\Delta^{++} \rightarrow p\pi^+$ , and not Hawking’s, thermal-like radiation. The formal proof [34, 1] of these statements rely on the fact that, *e.g.*, the  $W_{1+\infty}$  symmetry on the world-sheet is just an area-preserving diffeomorphism on the phase-space of the “coupling constants”, in other words, imply vanishing of  $\delta\mathcal{H}$  (see (60)), thus no information loss! On the other hand, we should be able [39] to “measure” all the AB “charges”, as explained in section 3, in order to get the *complete* picture. Since this is practically impossible, the *Procrustean principle* intervenes and *effectively* “opens” the black hole system, turning it into a NEQSS! Actually, we have proven explicitly [51] that when we “sum over” the unobservable AB “charges”, *e.g.*, “*W-hair*”, we are getting back the standard Beckenstein-Hawking formula (9). The proof goes like this [51]: stringy black holes, like the massive string modes, are characterized by a level-multiplicity

$$N(M_{\text{BH}}) \stackrel{M_{\text{BH}} \rightarrow \infty}{\approx} e^{2\pi\sqrt{\alpha'}} e^{\sqrt{2+Q^2}M} \approx e^{2\pi\alpha' M_{\text{BH}}^2} \quad (70)$$

thus implying a 4-D black-hole entropy (by “summing over” the AB “charges”)

$$S_{\text{BH}} \sim \ln N(M_{\text{BH}}) \sim M_{\text{BH}}^2, \quad (71)$$

which is nothing else but (9)! Of course, here we have an explicit *microscopic mechanism* that explains how starting from a *consistent* and *complete* quantum theory of gravity, we end up with some *apparent loss of information*, carried away by the topological modes, due to our “confinement” in a local, low-energy world! In a way, it looks like the



well-known *energy crisis* or the *energy catastrophe* of 1929, that led eventually to the discovery of the neutrino. A *continuous* spectrum as a function of the electron energy, implies that either  $\beta$ -decay is a two-body process, in which case *energy is not conserved*, *i.e.*, the *energy crisis* or *energy catastrophe* supported strongly by Bohr; or it is a three-body process involving a new particle (*neutrino*) that entails the partitioning of the available energy between the neutrino and the electron, resulting in a continuous electron energy spectrum, as suggested by Pauli. Bohr was wrong! The so-called *Hawking catastrophe* (discussed in section 2), as far as non-critical string theory is concerned, descends to the same level as the *energy catastrophe* above, where the role of the *elusive neutrino* is played by the *delocalized, topological states*. While the thermodynamic laws of black holes *are derivable* in non-critical string theory, they are just that: thermodynamic laws, *i.e.*, a coarse-grain approximation, neglecting the nitty-gritty details of the involved topological modes. Actually, this new picture [1, 2, 3] provides a crystal-clear answer to the frequently asked question: what is the fate of the black hole? The answer is: it disappears into the spacetime foam! Indeed, as the black hole decays *coherently*, it loses mass and eventually it becomes indistinguishable [29] from the virtual black holes that are part of the spacetime foam, having transmitted all its information to its decay products, which include the topological modes [29]. Another frequently asked question is: what happens to the physically intuitive Hawking mechanism for the evaporation of the black hole, where near the BH horizon a particle-antiparticle pair is spontaneously generated and then one falls into the BH, while the other arrives at the “observer” at infinity, who thinks that the BH radiates? The answer is again simple: stringy black holes, because of the vast amount of “charges” they carry, are *extreme black holes*, like the usual *extreme Reissner-Nordström* black holes whose main characteristic is the absence of Hawking radiation. Thus their “horizons” are not an *attractive* place to be (the gravitational attraction is balanced by the “charges” repulsion), and no member of the particle-antiparticle pair is able to fall into the black hole, and thus the particle-antiparticle pair is spontaneously annihilated, and the “observer” at infinity sees nothing!

Concerning the black hole “classical” space-singularity, the new stringy black-hole theory provides a very satisfactory and aesthetically

appealing answer: there is no space-singularity! Let me explain. As we discussed in the previous section, as we approach the would-be classical “singularity”, spacetime dissolves ( $\langle g_{\mu\nu} \rangle = 0$ ) and the standard Riemannian-like notions of spacetime break down, leaving topological field theory as the only suitable description of this classical “singular” region [37]. In a way, the region of infinitely many symmetries cannot support a spacetime interpretation, it suffers a phase transition characterized by the vanishing of  $\langle g_{\mu\nu} \rangle$ , and thus becomes topological. It looks like the new theory of black-hole dynamics has the potential of providing satisfactory answers to all the standard problems of black-hole physics. Furthermore, black-hole dynamics are intimately related to the questions concerning the “*initial singularity*” in the early Universe, and thus we shouldn’t be surprised that we may get satisfactory answers to cosmological problems, as well. After all, in many cases, and in non-critical string theory in particular, cosmological solutions (*e.g.*, (29)) are related to black-hole solutions by a Minkowski rotation ( $r \leftrightarrow t$ ) (see section 8). Indeed, very near the would-be classical *initial singularity*, spacetime dissolves ( $\langle g_{\mu\nu} \rangle = 0$ ) and thus the spacetime description is replaced by some topological field theory characterized by infinitely many symmetries. This topological field theory corresponds to the *eternal topological phase*, that is *always there*, since there is no notion of time in this phase, let it be! Dynamical, energetically favorable, spontaneous breakdown [37] of some of the infinitely many symmetries in the topological phase, leads to an *expanding spacetime* ( $\langle g_{\mu\nu} \rangle \neq 0$ ) Universe [37]. *Why spacetime?* Because the metric tensor (together with many other fields) gets a non-zero vacuum expectation value, thus allowing a “standard” description of our Universe. *Why expanding?* The topological phase, or the region very-very close to it, is characterized by a very high value of “central charge deficit”  $\delta c = c_m - 25 = 12Q^2$  (see (30),(35),(36)) “rolling” down irreversibly along the RG trajectory, according to Zamolodchikov’s *C*-theorem [24] (52). This fact, combined with our interpretation of the RG scale as time (49), makes  $Q^2$  a monotonically decreasing function of  $t$ , and thus through (32) leads to an initially fast ( $Q^2(t \rightarrow 0) \gg 1$ ) and much later slow ( $Q^2(t \rightarrow \infty) \rightarrow 0$ ) *expanding* Universe. A rather dynamical and natural explanation [2, 3] of the origin of the expansion of the Universe. Furthermore, very close to the topological phase ( $t \rightarrow 0$ ), as discussed above, the velocity of light  $c \rightarrow \infty$  (not un-

related to the fact that  $\delta c(t \rightarrow 0) \rightarrow \infty$ ) implying that the horizon distance  $d$  in co-moving coordinates over which an observer can look back  $d = \int c(t)dt \rightarrow \infty$ , or much larger than the naive estimate  $d = ct = (\text{constant})t$ . In other words, as  $t \rightarrow 0$ , *all* regions were *comunicado*, and *not* as naive extrapolations of the standard Big-Bang cosmology suggest that there were, say at  $t \approx 10^{-35}$ sec about  $10^{80}$  *incomunicado* regions! This is the simplest, to me, solution [2, 3] of the *horizon problem*. As,  $t \rightarrow 0$ , there are *no horizons*, because  $c \rightarrow \infty$  and thus the light-cone gets *flat-open*. Actually, the similarity with the EPR paradox is striking: (a) the *no-horizon* embryonic Universe *makes it possible* to define initially a “coherent” wavefunction  $\Psi_{\text{Universe}}$ , corresponding to the  $\Psi_{\text{system}}$  (14) of the two photons, implying that initially all the regions in the Universe were in “contact” and in entanglement, while (b) later on “measurements” on one local region led to a controllable disentanglement through the *influences* of the topological modes, that trigger any other “disconnected” local region to (quantum) “jump” on a specific, strongly inter-related state, corresponding to the “quantum jump” that photon  $\gamma_2$  suffers, after “measuring” photon  $\gamma_1$ . The presently observed smoothness, *i.e.*, homogeneity and isotropy of our Universe, as measured by the variation of the cosmic background radiation ( $\Delta T_0/T_0 \approx 10^{-5}$ ), over angular scales covering effectively the whole sky, should be as surprising as the two-photon correlations in Aspect’s experiment [10]! It is just *nonlocality*, a fact of quantum mechanical life, that finds a very interesting microscopic explanation through the existence of the topological modes, *i.e.*, the Procrustean principle, in non-critical string theory. It should be stressed that in the *non-critical* Universe, the origin of horizons, *i.e.*, light-cones, is *dynamic* as occurring during the phase transition from the topological phase ( $c \rightarrow \infty$ ) to the spacetime phase ( $c \rightarrow \text{finite}$ ). An appropriate name would be **NO-HOR izon cosmology** implying *not the absence of horizons*, but *the existence of dynamically created horizons!*<sup>1</sup> Furthermore, if the dependence on  $t$  of the velocity of light  $c = c(t)$  is a smooth function (as it is for  $t \gg 0$ ) we can always redefine [2, 3] it to be 1, thus avoiding any conflicts with special relativity. The variation of  $c$  with cosmic time  $t$  should have some experimental consequences in phenomena

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<sup>1</sup>Any similarity with the *no-scale supergravity framework* [46], implying *not the absence of (mass) scales*, but *the existence of dynamically created (mass) scales*, is *not accidental!*

that evolve strongly with cosmic time, and are due to processes in the very early, fast expanding, violent Universe. We have already mentioned one, *i.e.*, the absence of horizons at the very beginning ( $t \rightarrow 0$ ) due to the very fact that as  $t \rightarrow 0$ ,  $c = c(t)$  becomes a singular function, and cannot be reset to 1! Studies of other phenomena are in progress. Concerning the problem of the presently large entropy content of our Universe, *no-horizon cosmology* provides a very simple answer [2, 3]. It is the entropy that has been generated according to (63) while the *non-critical Universe* ( $\beta^i \neq 0$ ) “rolls down” its RG trajectory, starting at the topological phase (infrared fixed point) and *eventually* arriving at the critical string vacuum (ultraviolet fixed point). We should be very pleased that we are not yet at the UV-fixed point, because that would mean the End of Time! Clearly, by having turned our “low-energy *observable* world” into an “open” NEQSS, the increase in entropy, as irreversible time “flows”, should be no paradox. A very different situation, indeed, from the *quite* adiabatically (*isoentropically*) expanding standard Big-Bang Universe! Of course, at very late times, presumably like the ones we are now living, the rate of increase of entropy is reduced significantly ( $\beta^i \rightarrow 0$ ), as (63) indicates, thus implying asymptotically a standard Big-Bang adiabatically expanding Universe. In a way, all the information that the delocalized topological modes have carried away, since the *beginning of time*, is quantitatively expressed by the presently large entropy content of our Universe. It should be stressed that the generation of entropy in the non-critical Universe is only natural since we are dealing with an “open” system. Furthermore, the rate of increase of entropy (63) is tremendously enhanced very close to the topological phase ( $Q^2(t \rightarrow 0) \gg 1$ ) since there the topological modes are very “active”, carrying away a lot of information, thus leading to a fast increase of entropy. This huge production of entropy at the very first stages of the non-critical Universe, just out of the Topological Phase, has some very desirable, long-sought features. It leads to the natural dilution of all kinds of problematic, undesirable, either topological defects (*e.g.*, monopoles, domains, etc.) or particles (gravitini, hidden sector “cryptons”, etc.), thus helping to provide swiftly an *environmentally clean*, smooth Universe. In addition, it certainly helps to diminish dynamically the *space-curvature*  $k_s$ .

The *space curvature*  $k_s$  in the non-critical Universe is either *zero*,

as (33) implies for any  $D$  (including  $D = 4$ ), *or* in the particular case of  $D = 4$  there is another possibility available,  $k_s \propto 1/k$ , with  $k$  the level parameter of the world-sheet Wess-Zumino (WZ) model on the group manifold  $SO(3)$  (see discussion after (30)). If we insist on a WZ type of solution, since the level parameter  $k \rightarrow \infty$  for large ( $\gg 1$  in stringy or Planck units) space-times, it follows that  $k_s (\propto 1/k) \rightarrow 0$ . Thus, in either case ((33) or WZ type of solution) the net outcome is that for large space-times [19]

$$(k_s)_{l \gg l_{\text{string}}} = 0 \quad (72)$$

*i.e.*, a *spatially-flat* Universe! This is the dynamical, stringy, microscopic resolution of the *flatness problem*, as provided by the **NO-HORIZON COSMOLOGY**, in full accord with the huge production of entropy at the initial stages of the non-critical Universe, as discussed above.

Concerning the cosmological constant  $\Lambda_C$ , we have argued (second Ref. of [34]) that the infinite set of string symmetries that preserve quantum coherence may also be responsible for the vanishing of the cosmological constant. If this is indeed true, then we expect that, as in the case of quantum coherence, the Procrustean Principle intervenes and renders the cosmological constant *effectively* non-zero, and “*running*”. Indeed, its dynamical evolution with time (for any  $D$ ) is given by [2, 3]

$$\Lambda(t) = \frac{\Lambda(0)}{1 + t \left( \frac{\Lambda(0)}{D-1} \right)} \quad (73)$$

with  $\Lambda(0) = 2/\alpha'$ , implying an asymptotically-free cosmological constant  $\beta$ -function, thereby leading *dynamically* and *fastly* to a vanishing cosmological constant at the ultraviolet fixed point on the world-sheet, corresponding to the critical string vacuum,  $\delta c = 0$ . This is the microscopic realization of the quantum relaxation mechanism [2, 3] for the vanishing of the cosmological constant, advocated at the beginning of this section. While it is premature to discuss quantitatively the implications of this specific mechanism for the vanishing of  $\Lambda_C$ , it is amusing to point a few relevant points. The present age of the Universe is about  $10^{60}$  in natural (Planck) units. Another point is that one-loop calculations at the point-like field theory level in *no-scale supergravity models* [46], discussed above in conjunction with

the resolution of the Schrödinger’s cat problem, yield a negative contribution to the cosmological constant that is  $\mathcal{O}((M_W/M_{Pl})^4) \sim 10^{-60}$  in Planck units. Finally, we note that astrophysical and cosmological observations are *compatible* with a present-day value of about  $10^{-120}$  in Planck units. Moreover, a cosmological constant of this order of magnitude could even be a welcome adjunct to Cold Dark Matter models. Thus it may be even *desirable* that the cosmological constant  $\Lambda_C$  has not yet completely relaxed [2, 3, 52]! It is highly remarkable that **NO-HORIZON COSMOLOGY** in conjunction with the no-scale framework [46], both crucial parts of non-critical string theory, may eventually lead through (73), not only to a natural, dynamical resolution of the cosmological constant problem, but also to some observable consequences as well!

In a few words, the Universe according to [2, 3] non-critical string theory is a very dynamical NEQSS, where the very origin of space-time, the subsequent expansion, the huge entropy generation, the large-scale smoothness, and the apparent vanishing of the space-curvature  $k_s$  and of the cosmological constant  $\Lambda_C$  are *all* due to a *universal quantum relaxation mechanism*: irreversible “flow” along the RG trajectory, starting at the infrared fixed point (eternal topological phase) and ending up at the ultraviolet fixed point (critical string vacuum). Once more, I would like to stress the fact that critical string vacua are *derivable* dynamically in non-critical string theory, and that the apparent similarity of our Universe to a critical-string vacuum asymptotically is only due to the diminishingly small  $\beta$ -functions,  $\beta_i \approx \mathcal{O}((E/M_{Pl})^n)$ ,  $n = 1, 2, \dots$ , at large times. Actually, the Hubble expansion parameter, in the *no-horizon cosmology*, owes its origin to the non-vanishing of the  $\beta_i$ -functions, thus one very naively may expect  $H \propto \beta_i$ , *e.g.*,  $H \propto E^2/M_{Pl} \approx T^2/M_{Pl}$  at large times, providing a possible microscopic explanation of a well-known result in Standard Big-Bang cosmology! In addition, the apparently small “anomalous dimensions” of the “matter” deformations may eventually lead in target-space to *quasi-scale-invariant* energy density perturbations  $\delta\rho/\rho$ , responsible eventually for galaxy formation and other non-trivial cosmic structures observed in our Universe. The NEQSS nature of the non-critical Universe provides a new angle for looking at the cosmic texture problem.

## 8 Interlude (III) – Passatempo

Until now I have tried to present the physics of non-critical string theory as generally as possible, and willingly and consciously I have avoided the use of explicit models. As an “existence” proof, together with John Ellis and Nick Mavromatos, we have “derived” explicitly most of the physics I presented in the previous sections in the case of a 2-D (*space-time*) stringy black hole, due to E. Witten [27]. This “toy” laboratory shouldn’t be taken lightly, as it may take us a long way towards understanding how non-critical string theory applies to the real world. There are many reasons supporting this allegation. Two-dimensional stringy black holes may be considered as spherically symmetric four-dimensional black holes [51], which as is well-known, are the studying ground of full-fledged 4-D black hole dynamics. Using the techniques of matrix models [53] one may sum up the effects of higher genera and provide (quasi) exact solutions, avoiding the usual traps of perturbation theory. The embedding of the 2-d world-sheet into space-time is easier to handle and the one-to-one correspondence between topological defects on the world-sheet and stringy black holes becomes apparent [29, 41]. Furthermore, one relies heavily, again, on the “linear dilaton” solution (29), which is valid for  $c_m = 1$ , provided that  $X^0 \leftrightarrow X^1$ ! In addition, the world-sheet CFT corresponds [27] to a *gauged* Wess-Zumino model based on a  $SL(2, R)/[U(1)$  or  $O(1, 1)]$  coset space, not unrelated to the existence of a “linear dilaton” non-critical string vacuum, as discussed in subsection 4.2. Actually, there is a deep reason for the frequent appearance of the gauged WZ type models. Non-compact groups/symmetries on the world-sheet, leading to very interesting non-trivial backgrounds/physics in target space, are usually represented by unacceptable non-unitarity current algebras. Only some very specific cosets of the non-compact groups turn out to be *unitary*, and the *natural framework* to study them, by providing explicit Lagrangians, are the *gauged* Wess Zumino models on the corresponding coset spaces! So, it looks that in whatever we do, if we want to take into account non-trivial topological configurations in  $D$ -dimensional *target-space* (*e.g.*, taking into account space-time foam), we better have on the world-sheet a piece of the CFT corresponding to some gauge WZ coset space. I do hope that by now I have provided enough evidence and arguments that the Witten 2-D

stringy black hole should be taken very seriously, specifically in its world-sheet representation, as most of its properties may be independent of the target-space dimension, modulo trivial rescalings of the different quantities with  $D$ , as follow from simple dimensional analysis. As I have emphasized above, together with John Ellis and Nick Mavromatos, we have gone through all the “steps” that I have presented previously in the two-column format, and we have tabulated our results elsewhere [1, 2, 3]. So there is no need here to repeat them again, except for emphasizing a few crucial points.

The action of the model is [27]

$$S_0 = \frac{k}{2\pi} \int d^2z [\partial r \bar{\partial} r - \tanh^2 r \partial t \bar{\partial} t] + \frac{1}{8\pi} \int d^2z R^{(2)} \Phi(r) \quad (74)$$

where  $r$  is a space-like coordinate and  $t$  is time-like,  $R^{(2)}$  is the scalar curvature, and  $\Phi$  is the dilaton field. The customary interpretation [27] of (74) is as a string model with  $c_m = 1$  matter, represented by the  $t$  field, interacting with a Liouville mode, represented by the  $r$  field, which has  $c_m < 1$  and is correspondingly space-like. As an illustration of the approach outlined in the previous sections, however, we reinterpret [31, 2, 3] (74) as a fixed point of the renormalization group flow in the local scale variable  $t$ . In our interpretation, the “matter” sector is defined by the spatial coordinate  $r$ , and has central charge  $c_m = 25$  when  $k = 9/4$ . Thus the model (74) describes a critical string in a dilaton/graviton background. The fact that this is static, i.e. independent of  $t$ , reflects the fact that one is at a fixed point of the renormalization group flow.

The Witten 2-D black hole [27] is endorsed with  $W$ -hair [34, 1], due to the existence of a non-trivial  $W_{1+\infty}$  algebra, that is, a “coupling constant” phase space area-preserving symmetry, thus implying  $\delta \mathcal{H} = 0$ , *i.e.*, no loss of quantum coherence [34, 1]! Nevertheless, Chaudhuri and Lykken have argued [54] that the exactly-marginal deformation that turns on a static tachyon background for the Witten black hole necessarily involves the higher-level topological string modes, that are non-propagating delocalized states, which are interrelated by an infinite-dimensional  $W$  symmetry. This is a consequence of the operator product expansion of the tachyon zero-mode operator  $\mathcal{F}_{-\frac{1}{2},0}^c$  [54]:

$$\mathcal{F}_{-\frac{1}{2},0}^c \circ \mathcal{F}_{-\frac{1}{2},0}^c = \mathcal{F}_{-\frac{1}{2},0}^c + W_{-1,0}^{hw} + W_{-1,0}^{lw} + \dots \quad (75)$$



where we only exhibit the appropriate holomorphic part for reasons of economy of space. The  $W$  operators and the ... denote level-one and higher string states.

Since a “local” observer cannot take into account this mixing of the tachyon with the delocalized modes, she truncates them, thus unavoidably getting an effective loss of coherence. Furthermore, we have *explicitly* identified [29, 2, 3] the topological defects on the world-sheet as “monopoles” and “instantons”, that correspond to black holes in target space and have worked out their contributions to world-sheet correlation functions using the respectful “valley”-method of non-perturbative physics [31, 2, 3]. Then, when these “valley”-improved world-sheet correlation functions get translated to target-space correlation functions, they lead immediately to *non-factorizable*  $\mathcal{S}$ , as we have advocated above [31, 2, 3]. In the particular case of the Witten 2-D black hole [27], the space-time foam is represented [29, 41] on the world-sheet by a *Quantum Hall fluid*, and thus many of the remarkable properties of Quantum Hall fluids get transmitted to black hole physics [41], as we have emphasized in section 7.

Concerning the problem of the black hole “singularity” [24], it has been shown that the conformal field theory action close to the singularity can be rewritten in the form [27, 36, 37]:

$$S = -\frac{k}{4\pi} \int d^2x D_i a D_i b + i \frac{k}{2\pi} \int d^2x w \epsilon^{ij} F_{ij} \quad (76)$$

where the singularity is parametrized [27] by the limit  $uv = 1$  of the Kruskal-Szekeres coordinates  $u$  and  $v$  which have been written in the forms  $u = \exp(w)$ ,  $v = \exp(-w)$ , and  $a, b$  are diagonal elements in the general  $2 \times 2$   $SL(2, R)$  matrix - the off-diagonal elements being  $u$  and  $-v$  with  $ab + uv = 1$ . In equation (76),  $F_{ij}$  is the field strength of the  $U(1)$  gauge potential  $A_i$ , and the indices  $i, j$  take two values, corresponding to the two dimensions of the space-time, and the two variables  $a$  and  $b$  both vanish at the singularity. The exciting and key observation [27, 36, 37] is that the residual theory resembles a *topological field theory*, namely the dimensionally-reduced form of a Chern-Simons theory in three dimensions.

That a topological field theory should emerge at the singularity was perhaps not surprising for at least one reason. It is thought that topological field theories correspond to an unbroken phase of

gravity, in which the metric vanishes, and it is precisely at the singularity that there is no physically-meaningful metric. Here there is an analogy with the core of a magnetic monopole, where the vacuum expectation value of the Higgs field vanishes at the centre of a topologically-non-trivial solution of the field equations, and the underlying gauge symmetry is restored. In the same way, we expect that a non-zero value of the metric is at least one of a possibly infinite number of order parameters that mark the spontaneous breakdown of a higher stringy symmetry, which should become manifest in the associated topological field theory.

As described in previous sections, we have identified [34, 1] the essential symmetry that safeguards quantum coherence as a  $W$ -symmetry, with an infinite set of associated conserved charges that are in principle measurable [39]. Indeed, there is evidence that the topological field theories relevant to space-time singularities have a high degree of symmetry that includes  $W$ -symmetry!

It should be noticed that in the case of 2-D stringy black holes [27], their mass  $M_{\text{BH}} \propto (k-2)^{-1/2}$  and the velocity of light  $c \propto c_0 \sqrt{\frac{k}{k-2}}$ , where  $k = k(t)$  is the level parameter of the Wess-Zumino-Witten model (74), thus showing *explicitly* [2, 3] some of our repeatedly stressed points: (1) for large space-times, corresponding to  $k(t \rightarrow \infty) \rightarrow \infty$ , the black-hole mass diminishes, through quantum decay [32], and eventually the black hole is absorbed in the space-time foam [29], while the velocity of light  $c \rightarrow c_0$ , its critical string vacuum, asymptotic value; (2) as  $k(t \rightarrow 0) \rightarrow 2$ , *i.e.*, very close to the topological phase, the velocity of light  $c(t \rightarrow 0) \rightarrow \infty$ , due to the dominance of the topological, delocalized modes and the eventual breakdown of our naive space-time interpretation of the “classical” singularity! Interestingly enough, as (76) indicates *explicitly*, one basic, fundamental property of gauged Wess Zumino-type models on coset spaces is their *topological nature*, that enables them to metamorphise into a topological field theory, upon hitting a would be target space “classical” singularity.

## 9 Back to the Future

Non-critical string theory seems to provide a suitable framework [1, 2, 3] for addressing all the “small” problems discussed in section 2. The suggested resolution of these problems is characterized by its simplicity and its universality. Indeed, as we conjectured in section 3, we do find that black hole dynamics, the collapse of the wavefunction, and quantum gravity are so internally correlated that a satisfactory resolution of one of these “small” problems naturally implies a resolution to the others. We believe that the essential brand new element that non-critical string theory brings in is the *Procrustean Principle*. The issue of *nonlocality*, which hovers around in conventional Quantum Mechanics, becomes the *central issue* in non-critical string theory. It is exactly the *conflict* between the limited ability of the “local” observer, “who cannot see beyond his (her) nose”, and the existence of *delocalized, topological* states in continuous interaction with the low-energy string modes, that eventually lead to spontaneous truncation, thus “opening” the low-energy observable system (*the Procrustean Principle*) with all its consequences discussed previously. It is of fundamental importance to understand that the possible extension/modification of quantum mechanics and (special) relativity suggested by non-critical string theory is of a very original and somehow subtle nature. If we *tacitly assume* that we are living in a *fixed* (Minkowski) *space-time*, then *critical* string theory may provide a *complete* framework for calculating consistently quantum gravitational corrections, but inherits all other “small” problems of point-like QFT. We claim [1, 2, 3] that the *tacit assumption* or *premise* of a *fixed* (Minkowski) *space-time* is false, and that this idealistic premise has to be replaced by one that takes into account the existence of space-time foam. This possibility exists *only* in non-critical string theory where space-time foam is naturally taken into account and the Minkowski background of critical strings is *replaced* by the “linear dilaton” background, similar to (29). In such a case, one automatically has to use the general approach (19), outlined in section 3, which takes a very concise form [26] (60), as explained in section 7. In the non-critical string theory framework, critical string vacua correspond to fixed points of the RG trajectory, while the big question of why our Universe looks so much like a Minkowski background (critical vacuum) gets a very rea-

sonable answer: the  $\beta_i$ -functions responsible for the RG “flow” are diminishingly small:  $\mathcal{O}((m_{\text{light}}/M_{Pl})^n)$ ,  $n = 1, 2, \dots!$  In a way, we have extended the two big principles of modern physics, the quantum principle and the relativity principle to

### Three Big Principles

#### (I) *Particle–Wave duality*

- It leads to the introduction of a new *dimensional* constant of nature, the Planck constant  $\hbar$ , with dimensions of *action*, diminishingly small with respect to the classical world natural units.
- It leads to the *uncertainty principle*

$$\Delta X \cdot \Delta p \geq \hbar$$

which implies that “we cannot measure simultaneously the position and momentum of a particle”, and thus making the quantum world *very different* from the classical world.

#### (II) *The laws of nature are **locally** form-invariant under changing of inertial frames*

- It leads to the promotion of the velocity of light  $c$  to a universal dimensional constant of nature, with  $1/c$  diminishingly small with respect to the classical world natural units.
- It leads asymptotically to *restricted horizons*

$$ds^2 = c^2 dt^2 - d\vec{x}^2$$

which implies that “we cannot send signals traveling faster than light”, and thus turning the Newtonian-Galilean notion of absolute “simultaneity” into a “relative” (observer-dependent) one.

I conjecture now that the third (*missing*) big principle should read as follows

#### (III) *The laws of nature are effectively **nonlocal** – there is no **closed** system (a physical extension of Goedel’s theorem)*

- It leads to the promotion of the string fundamental length  $l_{\text{string}}$  to a universal dimensional constant of nature, diminishingly small with respect to the classical world natural units.
- It leads to the *Procrustean Principle*

$$g = (g)_{\text{local}} \oplus \left( \sum_i "g_{W_i}" \right)_{\text{nonlocal}}$$

with  $g$  the (non-critical) string backgrounds, which implies that “we cannot measure it *all*”, because we are *locally* confined, thus we spontaneously truncate the system, *i.e.*, we “open” it, triggering a monotonic increase of entropy, as recorded in the apparent “*arrow*” or “*irreversibility*” of time.

A clarifying remark is *badly* needed here. String theory is of course based on *local* quantum field theory on the *world-sheet*, and as far as “*world-sheet physics*” is concerned, the two Big Principles *Quantum* (I) and *Relativity* (II) remain *exact, intact, untouchable* according to the *old scriptures!* Nevertheless, *locality* on the world-sheet is *not equivalent* to *locality* in target spacetime. Thus, the third, Goedelian-like, Big Principle of (target spacetime) *Nonlocality* (III) intervenes and renders *approximate*, as far as “*target spacetime physics*” is concerned, the *Quantum* (I) and *Relativity* (II) principles, in sharp discord with the *old scriptures!* After all, the scriptures should not be something just carved in dead stone, but instead we should allow, as past experience has abundantly taught us, for some revamping and/or addition of a few *new* lines.

It is worth emphasizing that the above three big principles are mainly concerned about *information*: loss of information (I,III) or transmission of information (II). Thus we shouldn’t be surprised that NEQSS, as described by non-critical string theory, play a fundamental role in describing our Universe. Actually, as is well-known, in string theory the different constants of nature,  $c, \hbar, l_{\text{string}}$  are interrelated, and thus the common origin ( $k = k(t)$ ) of their quantum-relaxation towards their asymptotic values, is only natural. Since all the constants of nature are functions of the level parameter  $k$  characterizing the world-sheet CFT (*e.g.*, see (74),(76)), it is only natural that all the above big principles and their consequences may be eventually “derived” from the following

## Protean Principle

There is an Eternal Topological phase of our Universe, *classically* perceived as the *initial singularity*, corresponding to a suitable topological field theory on the world-sheet characterized by some level parameter(s)  $k$ , ...

Well, it is about *time* to stop. There is a question that we are unable to answer at this *time*: does non-critical string theory have anything to do with the “works” of the real Universe?  
Only *time* will tell,

but you must remember this,  
a (standard) model, is just a model,  
a (point-like QF) theory, is just a theory  
the fundamental (non-critical) strings apply  
as *time* goes by ...

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