Deep Space

Valentijn, Edwin A.; Visser, Manus; van den Broeck, Chris; Brouwer, Margot; Verlinde, Erik

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Theoretical physics has not progressed much in the last decennia — some call it a crisis. Likely, a break-through in our own laboratories is out of reach: the highest man-made information density on Earth is produced by the high energy accelerators at CERN. But these accelerators have to be ~10^{15} times more powerful to reach the possible ultimate unit of information corresponding to the Planck length of a staggeringly small 10^{-35} meters.

Verlinde heroically *postulates* that the information of dark energy at the scale of the Planck length fills the whole Universe and is entangled, making the universe one big information processing machine. The jury is still out whether his theory is correct, but at least his predictions for dark matter distributions are consistent with our lensing results with OmegaCAM[28]. A theory of this kind seems promising, as it seems to solve the three most outstanding problems in physics:

1) the unknown connection between the theories of Einstein's general relativity and quantum mechanics,
2) no detection so far of the dark matter particle and
3) no understanding of the nature of dark energy, which accelerates the expansion of our Universe.

Unfortunately, there is no way to reach this unit of information with our particle accelerators. This enormous gap in reaching all the domains in the Information Universe is sobering — an instructive table is in the Appendix.

However, nature provides us with incredible laboratories in deep space, allowing us to observe extremely high energy events, such as the bending of light around black holes and the gravitational waves caused by merging black holes and neutron stars.

Here, we observe domains of the Powers of Two beyond 2^{128}.

CHAPTER 4

DEEP SPACE

BY EDWIN A. VALENTIJN

and contributions by:

Manus Visser
Chris van den Broeck
Margot Brouwer
Erik Verlinde

E. A. Valentijn, *Powers of Two*,
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66 bits
$2^{66} = 7 \times 10^{19}$ states
9 exabytes

The Desert

66-400 BITS

CERN's Large Hydron Collider (LHC) in Geneva is currently the record holder in acquiring huge amounts of experimental science data. The reason is simple: the target particles are extremely rare and are searched for in an ocean of other events. In 2019 CERN's advanced tape storage system Castor held 330 petabytes, in a very sustainable way compared to the energy-consuming spinning disks. CERN is already planning for tape systems two times bigger in 2022, and five times bigger in 2026.

Next to the tapes, the disk-based distributed storage system of 200 petabytes was copied around four times to other sites over the world to deliver 830 petabytes. Assuming that future data will be copied four times to other sites, CERN is actively planning for and implementing 9,000 petabytes, which is an amazing 9 exabytes.

This is equivalent to the number of **states** of a 66-bit string. In Information Universe speak, one could say that CERN's LHC experiment works at the 66-bit level. This is amazing but also sobering, as the ultimate limit in physics is at the Planck length, which requires around a 400-bit string to address all states in the universe. This enormous domain from CERN's 66-bit to 400-bit is called **'the desert'**.

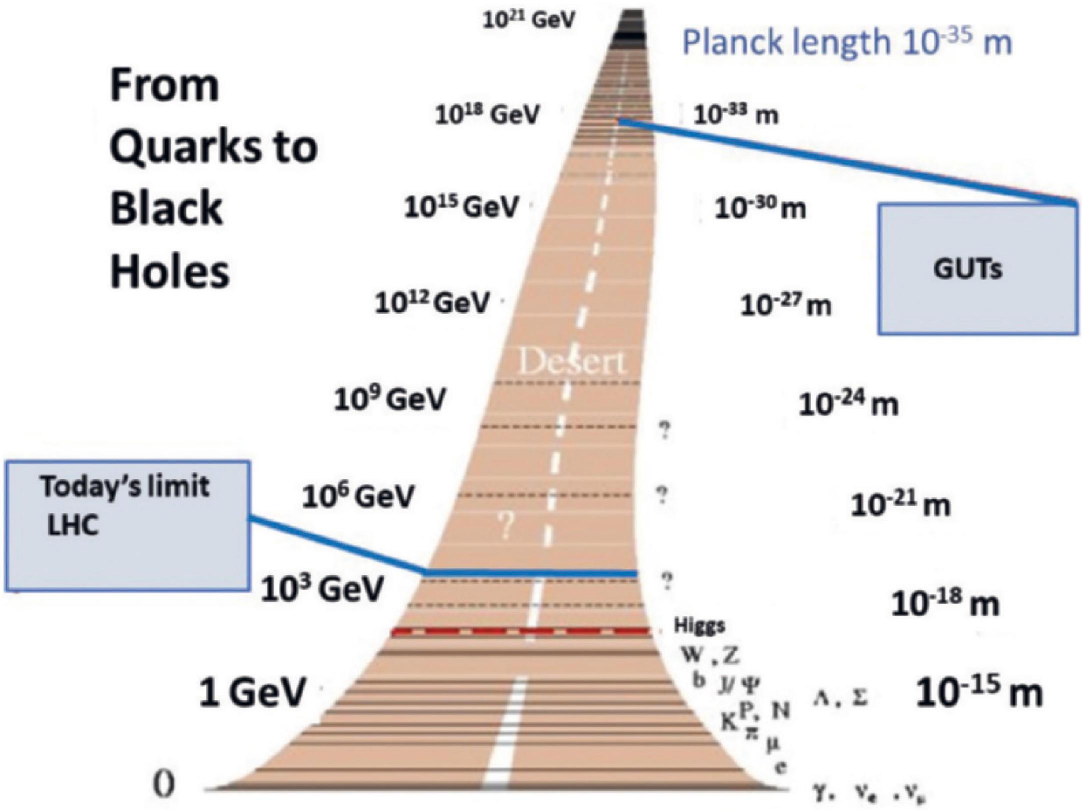
The number of states scales with a typical size in meters of the information-carrying unit. This is depicted on the right side of 't Hooft's graph. On the left side the scale indicates the energy expressed in tera-electronvolt (TeV). The desert stretches up to 10^{15} times the current maximum energy of particles observable at CERN. Unreachable. The hope is that these high energy particles leave some trace at lower energies, detectable by accelerators.

UNREACHABLE

Most of the deep high energy universe is unreachable by human-built experiments as it exists in the domain beyond 128-bits — which in current **cryptography** is considered impossible to decipher without the key.

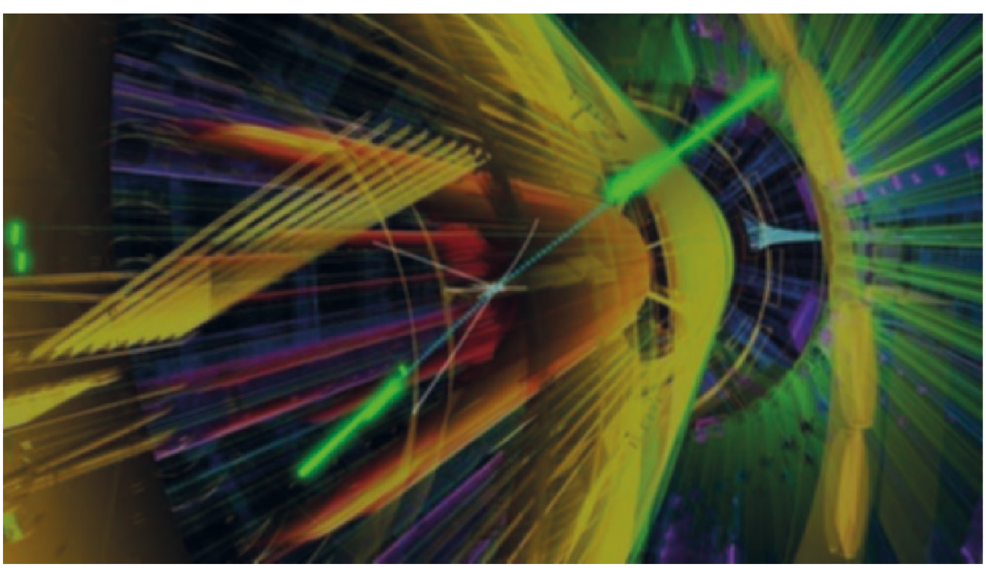
CERN LHC
Credit CERN LHC

At CERN (Geneva) scientists are searching for highly energetic fundamental particles and ultimately for a Grand **Unified Theory** (GUT) which is extremely remote in **information density** space.



THE DESERT

"The ride through the desert" **after 't Hooft 2003(!), showing the relation between the energy of a particle, from 1 up to 10^{23} giga-electronvolts (GeV), and its typical size in meters. In 2017 LHC's world record is 13 tera-electron-volts — even with ten times higher energies, there remains an enormous domain of unexplored information space: the desert. If a dark matter particle exists, it might hide there.**
Credit Gerard 't Hooft



Detecting the Higgs Boson in the LHC in an ocean of other collision remnants at the CERN-Atlas experiment.
Credit CERN

Information density
The Desert
Cryptography
States
Dark matter
Unified theory

1001 1000 1100 1100 0011 0110 0011 1011 0110 0011 1100 0011 0110 0011 1011 0110 0011 1100 0011 1100 1100 1101 1011 1110 1001 1000 1100 0011 0110 0011 1011 1100 0011 0110 0011 1100 0011 1100 1100 1101 1011 1110 1100 0001 1110 0111 1000 0110 0111 1000 1011 1000 1101 0001 1011 1110 1011 1100 0001 0101 1100 0111 0011 1000 01

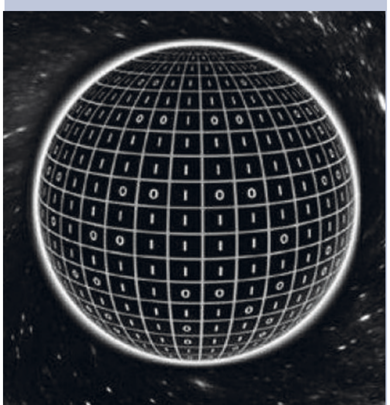
Black Hole

BY MANUS VISSER

258 bits
2^{258} = $4\text{x}10^{77}$ states
in a 1 solar mass black hole

MINDBOGGLING ENTROPY

How much information is stored in black holes? Do black holes destroy or leak information? A black hole whose mass is equivalent to our Sun's has an event horizon radius of 3 kilometers. Its entropy is mindboggling: $4\text{x}10^{77}$ or 2^{258} bits, a number equal to the total amount of particles in our Universe!



Remarkably, the mass of the black hole is fully determined by the amount of bits that can be projected on its surface. A tiny fraction of this information leaks out through Hawking radiation. A solar mass black hole has a temperature of only 60 nanokelvins, which means it absorbs more photons from the **Cosmic Microwave Background (CMB)** than it emits.

Black holes are the most compact objects in our universe. They have extremely high **information densities** and actually store the ultimate amount of information space can host. If you try to store more information inside a black hole, by throwing in an object, its size will increase.

So how much information do black holes carry? Imagine a black hole as a spherical object. At a certain radius r, the gravity of the black hole is so strong that even light cannot escape: the event horizon. The surface area of this spherical boundary (given by: $4\pi r^2$) tells you everything there is to know about the black hole: its total information content or entropy S. This was first proposed by Jacob Bekenstein[29]. The entropy of black holes is simply:

$$S = \frac{k_B\, c^3}{G\, \hbar} \frac{\text{Area}}{4}$$

This magic formula is the "$E=mc^2$" of the black hole, and connects the information content or **entropy** in physical (in vivo) and communication (in vitro) systems. Strangely, this formula might also form a basis for a **unified theory**, as it contains the four fundamental constants of nature dictating the four very different realms of physics: thermodynamics (Boltzmann's constant k_B), relativity (speed of light c), quantum mechanics (Planck's constant ħ) and gravity (Newton's constant G).

It is amazing that all the properties of a black hole relate to its surface area, rather than its volume. This is identified as the **holographic** principle: the information inside a 3D black hole volume can be described in one dimension less, on the 2D surface of the event horizon. The surface area is then measured in the smallest length unit we know of in physics: the Planck length = $1.6\ 10^{-33}$ cm, the smallest unit of information in our Universe. Verlinde uses this principle to derive his **Emergent Gravity** and even **dark matter**.

BLACK-BODY RADIATION

It is very satisfying that the laws describing black holes mimic those of particles in gas form. However, the most convincing evidence that black holes are thermodynamic objects is a famous calculation by Stephen Hawking. He showed that, if quantum effects are taken into account, black holes emit **black-body radiation**. Although classically nothing can escape from a black hole, quantum mechanically particles can tunnel through the event horizon. Black holes are not black after all. In fact, they slowly evaporate! For every black hole, this Hawking radiation is perfectly thermal: it has a standard black-body spectrum that does not contain any information about the specific black hole that emitted it, except its total mass. Therefore, it seems that the written information in this book would be lost when it is thrown into a black hole, since it cannot be recovered by analyzing the Hawking radiation. However, according to quantum theory, information is a conserved quantity that can never truly be lost. Physicists are still debating this "black hole information paradox", arguing whether information can truly be destroyed by black holes. But what type of information is associated with black holes? It is fair to say that we do not yet know what the correct quantum description of black holes is. In string theory one can compute the entropy of certain idealized black holes from counting microscopic states. But for more realistic black holes, it remains an open question, from what type of information they are made.

Credit Warren Johnston

Black hole
Information density
4π
Entropy
Unified theory
Holography
Emergent Gravity
Dark matter
CMB
Black-body radiation

RINGDOWN

A newly formed black hole undergoing "ring-down". Spacetime in its vicinity is vibrating in a specific way. In the next few years, as detector sensitivities improve, it will be possible to study gravitational wave signals from ringdown in sufficient detail for us to tell the difference between the black holes of classical general relativity and modifications thereof, for instance as a result of macroscopic quantum effects.
Credit *NASA/Goddard/UMBC/Bernard J.Kelly, NASA/Ames/Chris Henze, CSC Government Solutions LLC/Tim Sandstrom*

UNRAVELING BLACK HOLES WITH GRAVITATIONAL WAVES

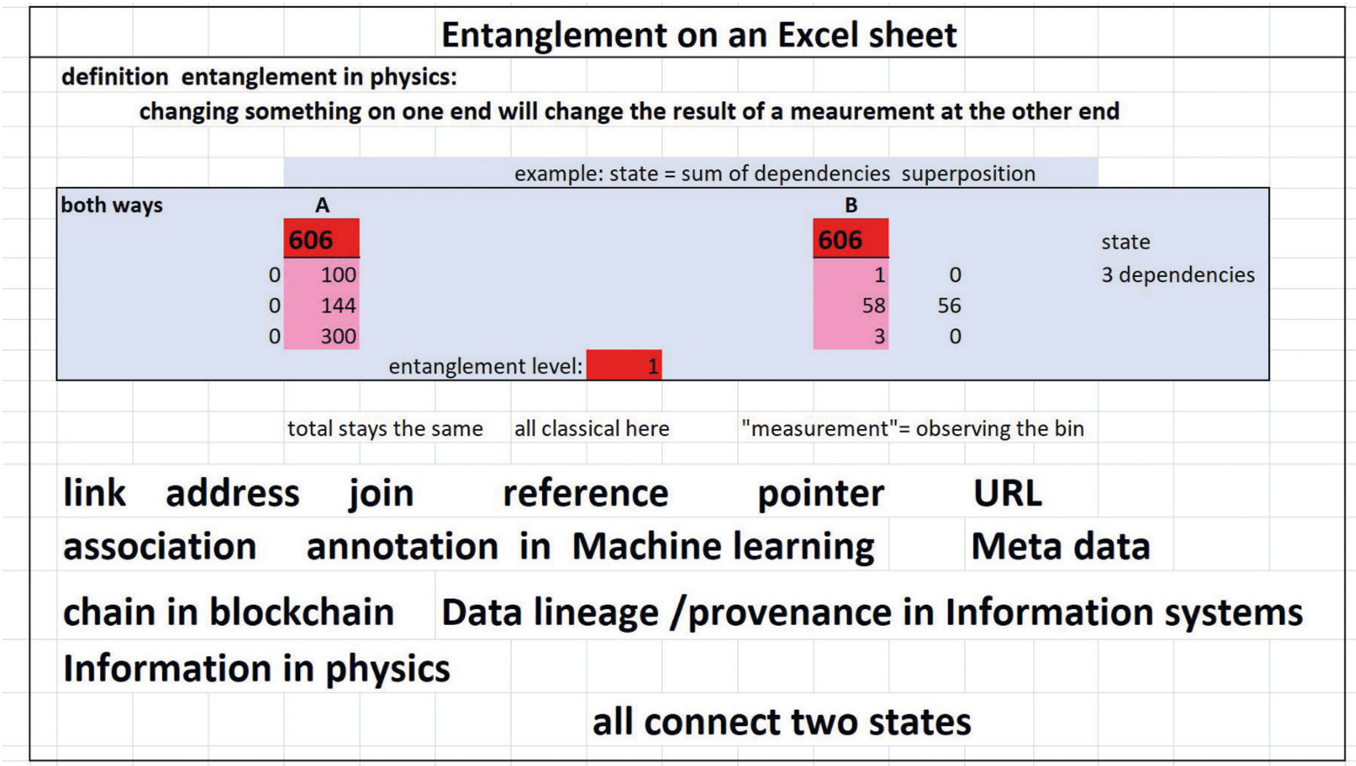
BY CHRIS VAN DEN BROECK

Detections of gravitational waves by LIGO and Virgo have become commonplace. In one case, the merger of two neutron stars was seen nearly simultaneously in gravitational waves and gamma rays, among other things showing that the speed of light equals the speed of gravity to one part in 10^{15}. However, most of the signals being detected appear to be from mergers of two black holes. These are perfect laboratories for testing the fundamental physics of gravity: here we observe empty spacetime whose curvature is a million times stronger than in any other astrophysical scenario, and is evolving on a timescale of milliseconds. This has given us access to a regime of gravity where Einstein's general relativity does not just provide minor corrections to Newton's theory of gravity; instead it takes center stage. For now, Einstein's theory holds up.

The next step is to answer the question: are the massive compact objects we observe really the "standard" black holes of classical general relativity? A range of possible alternative objects have been put forward, such as dark matter stars, or gravastars that resemble pockets of dark energy. Prompted by Hawking's information paradox, alternatives to black holes such as firewalls and fuzzballs were proposed. The latter are particularly exciting, since they open up the possibility of directly seeing quantum gravity at work.

When two black hole-like objects merge, a single, highly excited object is formed which undergoes "ringdown". This is similar to a chunk of metal being struck by a hammer: the object will vibrate with particular characteristic frequencies and damping times that are unique to its shape and composition. Observing gravitational waves from ringdown will enable us to tell the difference between Einstein's "ordinary" black holes and alternatives. For objects like fuzzballs, which don't have a horizon, there is also the possibility that gravitational waves falling in will bounce around many times inside the object, at regular times leaking out again as gravitational wave "echoes". Should such anomalies be observed, it would be a watershed moment in our fundamental understanding of gravity.

Gravitational waves
Black hole
General Relativity
Dark matter
Dark energy

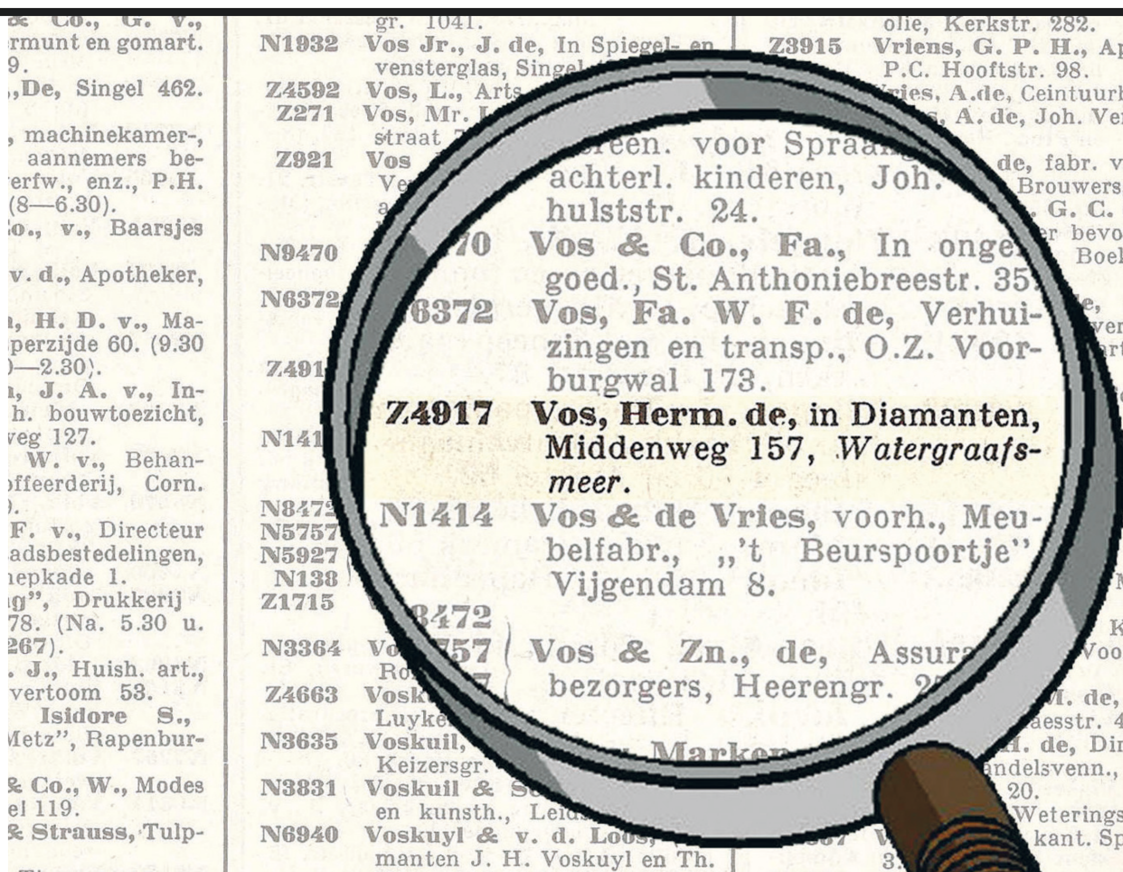


ENTANGLED STATE

With a simple equation one can create an entangled state on an Excel sheet (in vitro) — following the basic definitions/properties of entangled states in physics (in vivo), allthough the signal on the Excel sheet is classically transmitted by electrons in the computer hosting the Excel.

Snippet from my presentation at the ***Information Universe Conference 2018****.*

Credit Ron de Wit



Links — addresses
Artificial Intelligence
Cryptography
Data-centric
Open Science
Metadata
Astro-WISE
Virtual Observatory
DNA
Apoptosis
Entanglement
Complexity
FAIR
Standards
Unified theory

LINKS

THE UNIVERSE AS A SPREADSHEET

In Information Technology **links** are applied with an ever-increasing **complexity**. A link is nothing other than an address such as printed in old-fashioned telephone books. Addresses come in many flavours, but they all are fundamentally the same thing. Addresses are applied to programme computer chips (memory addresses), on the internet (URLs), in text and files (references), in databases (joins or associations) and in **Artificial Intelligence**, as annotations for data and to train neural networks. In blockchain technology, like the bitcoin, addresses are put in a block, which in turn are put into a chain, allowing computers to fully trace the sources. As we don't trust each other, everything is **encrypted** allowing only limited access to these links.

We use links to build whole worlds of complex information systems: in so-called **data-centric** data federations, **links** act as a workhorse to facilitate globally distributed storage and processing. For instance in the European Union, the Commission has recently decreed the **Open Science** paradigm: all research results and original data should become publicly available, following the **FAIR** principles — Findable, Accessible, Interoperable and Reusable. In fact, this implies that all these data should have administrated **links** and **Metadata**. Astronomers are quite advanced with such an approach (**Astro-WISE**, **Virtual Observatory**), but we know it takes dozens of years of work defining and implementing **standards** and protocols. It is a major, mainly sociologically oriented, project management task to achieve this for all fields.

There is no physical theory which describes what a **link** is: "we are just doing something" and thereby build huge systems (in vitro), which are like super spreadsheets. But in fact, nature (in vivo) does the same: e.g. a cell reads its **DNA**. By complex exchange of information with its environment — amongst others involving **apoptosis**, a programmed cel death — it determines and lives out its identity. In physics links are perceived as entanglement. This suggests we are hitting something very deep: **links** in Information Technology and even **entanglement** in physics appear to be a building block in the Information Universe — the in vivo – in vitro cross-over — is there any difference? In my view, a **Unified theory** should encompass information not only as a building block, but also as a carrier of links.

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0111 1000 1011 1000 1101 0001 1011 1110 1011 1100 0001 0101 1100 0111 0011 1000

256 bits
2^{256} = 10^{77} states
All matter

The CMB

BY MARGOT BROUWER

How much information does the entire Universe contain? In every cube of 1.3 x 1.3 x 1.3 millimetres there is one photon from the **Cosmic Microwave Background (CMB)** flying around: here on Earth, in the space between planets, in between the stars and galaxies — everywhere. It is amazing: CMB photons are filling space everywhere in the universe. You can watch them on the screen of an old analogue TV set with an antenna on your roof — *see* page 18 Multicellular Life — although they were emitted 13.8 billion years ago.

Where do all these **CMB** photons come from? At the dawn of time, when our Universe was more than 1,000 times smaller than it is now, all matter was compressed into a hot dense plasma emitting **black-body radiation**. All photons continuously bounced off the charged electrons like balls in a pinball machine, unable to escape. Finally, 370,000 years after the **Big Bang**, the cosmos had expanded and cooled enough for the protons and electrons to combine into neutral hydrogen atoms. The photons were freed, and able to start their nearly eternal journey through space. Now, for each normal particle, there are billions of CMB photons. This means that CMB photons totally dominate the information content of our Universe, with a staggering 5×10^{77} units.

Still, the average separation of around 1.3 millimetres implies that the average total **information density** of the Universe is approximately equal to the text you are reading right now. The overall (Information) Universe is rather empty! Obviously, we are not counting unknown components, such as **dark matter**. In his theory of **Emergent Gravity**, Erik Verlinde postulates that **dark energy** carries even more information than the CMB.

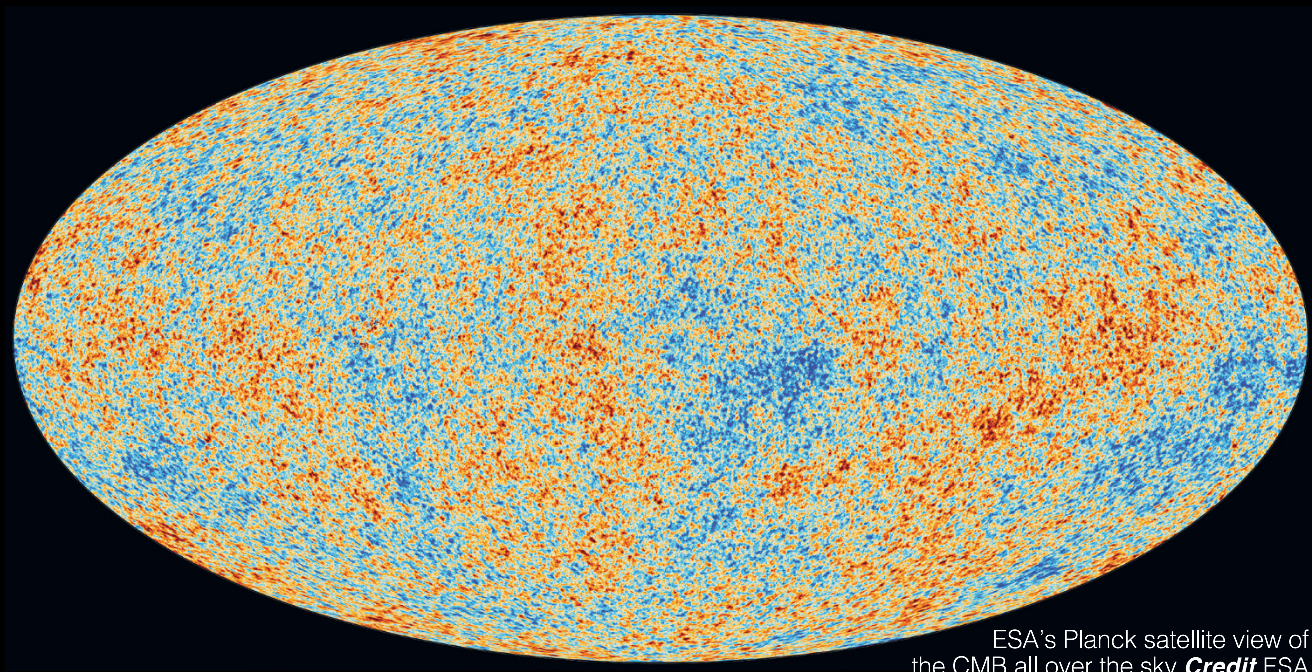
256 LINES

Almost all the information in the Universe is contained in photons emitted when the Universe was just a new-born. A barcode of 256 lines would have a unique code (address) for all of them.

Credit Creative Commons Zero

Credit Olcay Ertem

Comparing a 370,000-year-old Universe to the present is like comparing a baby of one day old to a 100-year-old woman.

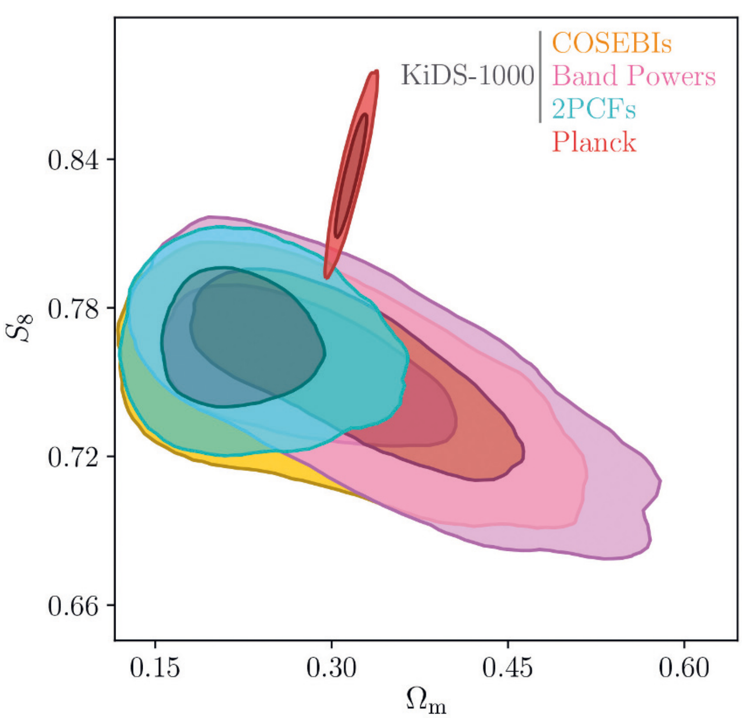


ESA's Planck satellite view of the CMB all over the sky ***Credit*** ESA

BABY PICTURE

CMB photons escaped from the primordial plasma when the Universe was a baby of only 370,000 years old. This is a picture of that early moment. Now, 13.8 billion years later, we use the CMB to figure out what the early Universe looked like, particularly with how much structure (S_8) and visible+dark matter (Ω_m) it started. We compare this baby picture to other measurements, such as weak gravitational lensing in our local present-day, Universe (the old woman), to test our current cosmological model: ΛCDM. Until recently the data matched very well. But as we acquired more Big Data of galaxies in the local Universe with our own Kilo-Degree Survey (KiDS) (see page 67: From terabytes to two numbers), an inconsistency between the Planck and KiDS/DES surveys emerged in the values of S_8 and Ω_m. This might imply the need for physics which transcends General Relativity, perhaps in a new unified gravity plus quantum theory. Astronomers are quite excited about it, and ESA's Euclid satellite will shed more light on this.

I can't wait!



KiDS-1000 (2020) — the latest results from 1000 square degrees of Kilo-Degree Survey data, showing a discrepancy between their lensing measurements and the Planck CMB data, indicating that our present day universe has ~10% less structure than predicted by **ΛCDM**. ***Credit*** Marika Asgari et al. 2020 and the KiDS collaboration (arXiv:2007.15633)

Big Bang
Black-body radiation
Information density
Emergent Gravity
Dark matter
Dark energy
Unified theory
CMB
Lensing
Big Data
ΛCDM
General relativity

0011 0101 1001 1000 1100 1100 0011 0110 0011 1011 0110 0011 1100 0011 0100 0011 1011 0110 0011 1100
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399 bits
2^{399} = 10^{120} states
Everything

Cosmic event horizon

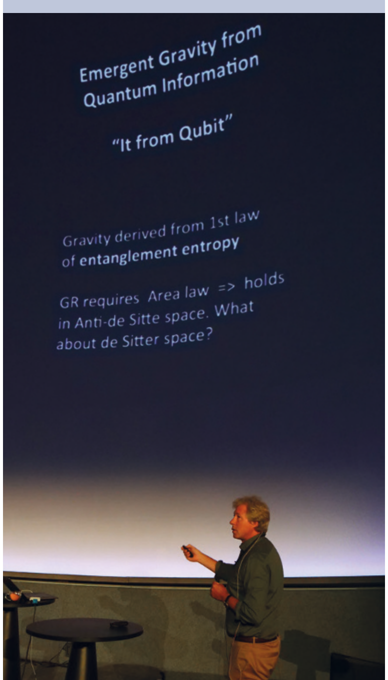
BY ERIK VERLINDE

How much information is contained in our Universe? In 1998 astronomers discovered that the Universe is expanding at an accelerating rate. This means that, for galaxies beyond a particular distance, the space between us and these galaxies expands faster than the speed of light. Light emitted by these galaxies will never reach the Earth. So, similar to **black holes**, our Universe has a “Event Horizon” beyond which current events can never be known to us. To compute the amount of information inside the cosmic event horizon we can use the same **holographic** laws that Bekenstein and Hawking[29,30] discovered for the **entropy** of black hole horizons: the amount of information in the Universe is given by the area of the cosmic horizon measured in terms of the Planck length. This enormous number is of the order of $10^{120} = 2^{399}$ — a lot of information! But where is this information stored? Is there some way we can see or access it?

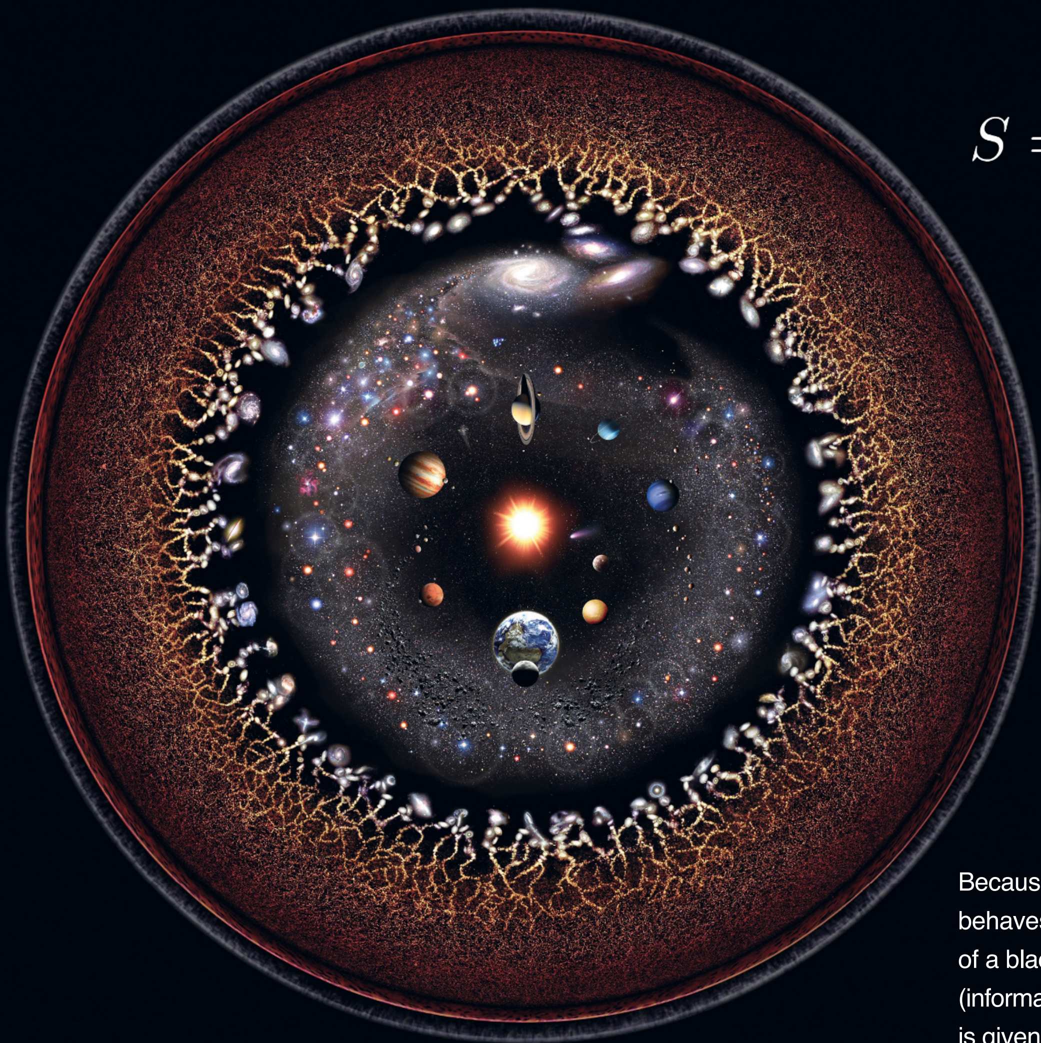
To explain the accelerated expansion of the Universe, one needs to postulate that space contains a kind of mysterious energy, called **dark energy**. One can think of dark energy as the energy of the vacuum: even empty space is filled with energy. In fact, in our current Universe dark energy accounts for close to 70% of the total energy. Dark energy can’t be seen directly, nor can it be used in any way by human beings. Also at present there is no good theoretical understanding of what dark energy is made of. Yet, it gives the largest contribution to the value of the Hubble constant. Moreover, its presence is responsible for the appearance of a cosmological horizon. It is therefore natural to assume that the total amount of information in the Universe is actually carried by the dark energy that is filling empty space. Unfortunately this means that we can not access this information: it is hidden from us, just as the dark energy itself is. We can, however, use it in an attempt to build a **unified theory** of physics based on information.

2^{399}

In my information theory of **Emergent Gravity**, the information content of the entire Universe is 2^{399}: the highest power described in physics. This information is completely dominated by dark energy, and might help us to devise a unified description of the Universe.



Erik Verlinde at the 2018 Information Universe conference.



$$S = \frac{k_B\, c^3}{G\, \hbar} \frac{\text{Area}}{4}$$

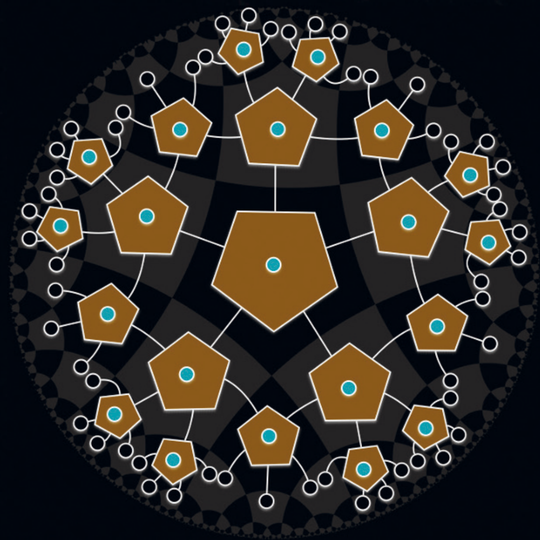
Because the cosmological horizon behaves similarly to the horizon of a black hole, the total entropy (information content) of the Universe is given by the same equation: its area in terms of the Planck length. ***Credit*** Pablo Carlos Budassi

NEW THEORETICAL UNDERSTANDING

The presence of dark energy adds an enormous amount of information to our Universe, which has to be taken into account in deriving the gravitational laws. The additional information associated to dark energy leads to modifications compared the gravitational laws derived by Newton and Einstein at galactic and cosmic scales. In fact, one can show that these modifications have precisely the correct size to explain the phenomena observed in galaxies (and clusters) that are currently attributed to **dark matter**.

The large amount of information associated with dark energy also influences the structure and evolution of the Universe at cosmological distances and very early times. It thus appears that a new theoretical understanding of our Universe is emerging, which is based information and promises to shed a completely new light on the origin of spacetime, matter and all forces of Nature.

Black hole
Holography
Entropy
Dark energy
Unified theory
Emergent Gravity
Dark matter



Credit F. Pastawski, B. Yoshida, D. Harlow en J. Preskill.

Credit Angela Miller

MISSING MASS

Space itself can be described as a network of tiny "bits" of information, all entangled with each other. This quantum **entanglement** of space is what allows us to move from one place to another. The amount of shared information (entanglement **entropy**) between two volumes is defined by the surface area that separates them. As we just saw, this *area law* ($A \sim R^2$) is essential to deriving Newton's and Einstein's laws of gravity ($F \sim R^{-2}$). In my view, it is not just space that has entanglement entropy — **dark energy** produces it too. Since dark energy is spread throughout space, this entropy is not related to its surface, but to its *volume*. Around a mass distribution — such as a galaxy — part of this entropy is removed. The resulting "vacuum" pulls the surrounding information inwards, causing an additional gravitational pull. This extra gravity, caused by the interaction between normal matter and dark energy, exactly describes the behaviour of the "missing mass" currently attributed to **dark matter**!

It is observed in galaxies that dark matter only starts playing a role beyond a specific scale. In theories like Modified Newtonian Dynamics (MOND), this scale is seen as a new fundamental constant of nature. In my theory, however, this is simply the scale at which the information of the dark energy (described by a volume law: R^3) begins to dominate the information removed by matter (described by an area law: R^2). In my theory, this is no more fundamental than the fact that a mouse can ventilate his body-heat more easily than an elephant. It simply shows the balance between area and volume, which causes stress at a specific scale. So, for the same reason an elephant has a sensitive and wrinkled skin (its volume/area ratio by-pass a critical scale), "dark matter" arises at large scales in the Universe. In this way gravity, quantum mechanics, dark energy and dark matter can all be described in one theory, based on perceiving the Universe in terms of information.

General Relativity
4π
Unified theory
Bit
Entanglement
Entropy
Dark energy
Dark matter
Emergent Gravity
Black hole

EMERGENT GRAVITY

BY ERIK VERLINDE

The biggest mystery in theoretical physics is: "How can we combine gravity (described by **general relativity**) and quantum mechanics into one **unified theory**?" Bekenstein and Hawking[29,30] found a profound clue in this cosmic mystery when they discovered that black holes can be described in terms of **entropy**, a concept derived from thermodynamics. So, just like the heat in a cup of coffee emerges from the combined movements of its molecules, gravity might emerge from the combined behaviour of the "atoms" of spacetime. If gravity, like heat, does not exist on quantum scales, the need for a unified theory dissolves! Now, how does **gravity emerge** from information? From **black holes** we know that the information in a spherical volume with radius R is equal to the number of **bits** N that fit on its surface area $A = 4\pi R^2$. Each bit covers an area of a squared Planck length l_p^2 which can be expressed in terms of the fundamental constants as $c^2 / \hbar G$, so the number of bits on the surface of a sphere is:

$$N = A / l_p^2 = (4 \pi R^2 c^3) / (\hbar G).$$

Here c is the speed of light, ħ the Planck constant, and G… well, normally G would be interpreted as Newton's gravitational constant, but now it simply defines how many bits fit on a surface! Say that our volume contains a mass M with an energy $E=Mc^2$. How is this energy described by the information on the surface? Since the surface/horizon has thermodynamic properties, the bits behave like particles in a gas: their total energy is equal to the total number N of particles (bits) in the gas times its temperature T and the Boltzmann constant k_B:

$$E = N k_B T.$$

By combining this with our first equation, we get a strange expression for the mass:

$$M = E / c^2 = \tfrac{1}{2} N k_B T / c^2 = R^2 / G \, (2 \pi c k_B T) / \hbar.$$

What does this all mean? That will become apparent when we place a particle of mass m at distance R from our original mass M. Quantum physicist Bill Unruh discovered that a particle will undergo an acceleration **a** exactly equal to the yellow part of the expression for the mass M, because it experiences a type of Hawking radiation with temperature T. Thus we can simply derive the acceleration at the surface:

$$\mathbf{a} = G M / R^2 \longrightarrow F = m \mathbf{a} = G M m / R^2.$$

We have derived Newton's law of gravity, purely from the information properties of our system! Gravity is not one of the four fundamental forces; it emerges from bits like heat emerges from molecules.