ROAD TO THE MULTIVERSE PAVED BY QUANTUM INTERACTIONS

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INTRODUCTION

- Why multiverse?
  - Emerges naturally in some physical theories
  - It could solve some open cosmological questions (i. e. cosmological constant problem)
  - Depends on the definition of a universe
- Physical multiverse
  - Appropriate multiverse scenario to make observational predictions
  - It need some kind of non standard interaction between universes (classical or quantum)
  - It is not related with a particular multiverse theory

➢ Quantum correlations between universes

- Classically disconnected universes
- Quantum entanglement ➔ effects of other universes on our own
- Consideration of the multiverse as a whole

➢ We need to make a simple model for the multiverse: the universes and the interactions between them

- Third quantization scheme
- Different models

1) Decoherence due to the enviroment made of other universes ➔ Master equation

2) Curvature Principle ➔ Curvature invariant for each universe

3) Multiverse of interacting harmonic oscillators ➔ Wigner quantization

THIRD QUANTIZATION FORMALISM

- Analogy with quantum field theory
  - WDW as K-G in superspace ➔ Wavefunction as the field to quantize
  - Creation and annihilation of universes ➔ baby universes
- Minisuperspace: Homogeneous and isotropic models ➔ FLRW metric
  - Scale factor as a time variable

$$\left(\partial_{aa} + \frac{\Omega_0^2}{\hbar^2} a^{2(q+1)} \right) \phi(a) = 0$$

➔ harmonic oscillator (time dependent frequency)

where $\Omega_0^2 = 4\pi G \rho_0$ y $q = \frac{3}{2}(1-\omega)$

- Wavefunction of the multiverse $H|\Psi\rangle = i\hbar\partial_a|\Psi\rangle$

  where $H = \frac{1}{2}\hat{P}_\phi^2 + \frac{\Omega^2(a)}{2}\hat{\phi}^2$

- Creation and annihilation operators $\begin{cases} b = \sqrt{\frac{\Omega(a)}{2\hbar}}\left(\hat{\phi} + \frac{i}{\Omega(a)}\hat{P}_\phi\right) \\ b^+ = \sqrt{\frac{\Omega(a)}{2\hbar}}\left(\hat{\phi} - \frac{i}{\Omega(a)}\hat{P}_\phi\right) \end{cases}$

So, the Hamiltonian $\mathrm{H} = \beta_- b^2 + \beta_+ {b^\dagger}^2 + \beta_0\left(b^\dagger b + \frac{1}{2}\right)$

DECOHERENCE IN THE MULTIVERSE

- The interaction can be represented by a total Hamiltonian

$$H = H_P + H_\varepsilon + H_{int}$$

where

- $H_P = \frac{1}{2} P_\Phi^2 + \frac{\Omega^2(a)}{2} \Phi^2$
- $H_\varepsilon = \sum_{i=1}^{N} \frac{1}{2} p_{\phi_i}^2 + \frac{\omega_i^2}{2} \phi_i^2$
- $H_{int} = \sum_i \lambda_i \Phi_P \otimes f(\phi_i)$ → $f(\phi_i) \equiv \phi_i$ Linear interaction; $f(\phi_i) \equiv \phi_i^2$ Quadratic interaction

- Master equation

$$\partial_a \rho_P = -i[\tilde{H}_P, \rho_P] - i\gamma[\Phi, \{P_\Phi, \rho_P\}] - D[\Phi, [\Phi, \rho_P]] - f[\Phi, [P_\Phi, \rho_P]]$$

with $\tilde{H}_P \equiv H_P + \frac{\tilde{\Omega}^2}{2}\Phi^2$

- Correlation function $\langle \phi^k(a)\phi^k(a')\rangle_b = \underbrace{\nu(a,a')}_{\text{noise kernel}} - \underbrace{i\eta(a,a')}_{\text{dissipation kernel}}$

- Solution to WDW + dissipation kernel ⟶ Lamb shift
- Solution to WDW + dissipation kernel ⟶ Normal-diffusion coeficient

- Calculating…

$$\begin{cases} \Omega^2(a) = c_1 f(a,q) \\ D(a) = c_2 g(a,q) \end{cases}$$

INTERACTION OF A UNIVERSE WITH ITS QUANTUM FLUCTUATIONS

- Creation and annihilation operators → thermal bath / squeezed state

- The expressions for the noise and dissipation kernel involves the spectral density ➔ encapsulates the physical properties of baby universes

$$J(\omega) = J_0^2 \omega^3 e^{-\omega/\Lambda}$$

- Results
  - Linear interaction $\begin{cases} c_1 \sim \mathrm{cte} \\ c_2 \sim N \end{cases}$
  - Quadratic interaction $\begin{cases} c_1 \sim N \\ c_2 \sim N^2 \end{cases}$
  - Scale for the decoherence $a_D = \dfrac{1}{\sqrt{c_2}}$

➔ Decoherence scale: very small, more in quadratic interaction

➔ Lamb shift: constant or dependent on the strenght of fluctuations

INTERACTION OF A UNIVERSE WITH OTHER UNIVERSES

- The squeezing effect asymptotically dissappears

- We choose the spectral density as $J(\Omega) \sim \delta(\Omega' - \Omega_0)$

- So, we obtain $\begin{cases} c_1^p \approx \Omega_0 \\ c_2^p \approx 2N \end{cases}$

➔ Decoherence is very effective for a large number of universes

➔ Lamb shift: same order energy density of the Universe (without interactions)

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effective energy of the Universe turns out to be approximately zero

THERMODYNAMICAL QUANTITIES

- Interaction with enviroment → effectively non unitary evolution

- The previous master equation can be solved with the Gaussian ansatz → the solution depens on cofficient c_2

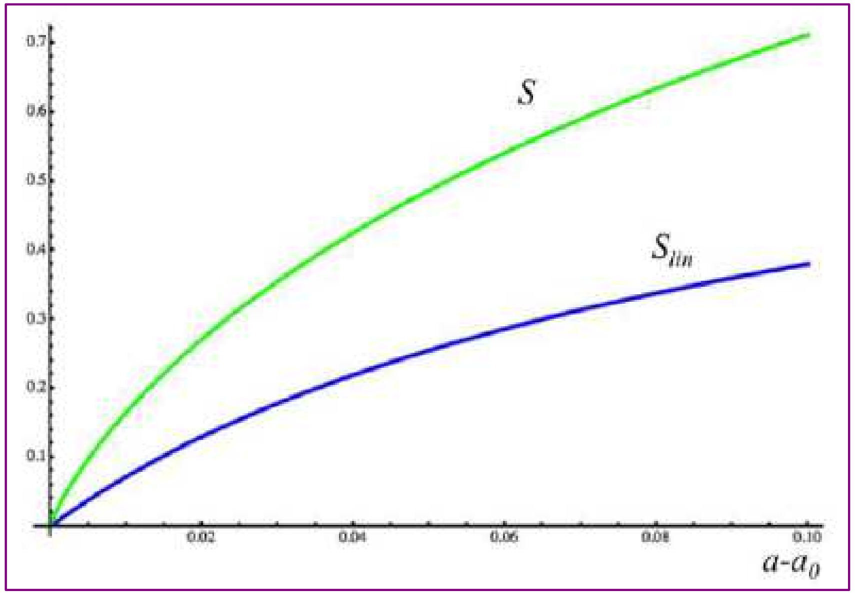
- Considering an initial pure state

- This coefficient allow us to obtain thermodynamical properties of the parent universe

➢ Entropy of a parent universe interacting with the environment

$$S_{lin} = 1 - \zeta$$

$$S = -\frac{1}{p_0}(p_0 \ln p_0 + q_0 \ln q_0)$$



➔ Interaction with the environment → evolution to a mixed state → loss of information

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Decoherence process → Universe described in terms of the semiclassical branch which we live in

➔ Total system retains all information

CURVATURE PRINCIPLE

- Each universe described in terms of a curvature invariant ➔ sensitive to the vacuum energy

- Hamiltonian evolution that reflects the interaction between universes

- We consider the third quantization formalism for homogeneous and isotropic universes → WDW as a harmonic oscillator

$$\ddot{\phi} + \frac{\dot{M}}{M}\dot{\phi} + \omega\phi = 0 \quad \text{with} \quad M(a) = a \quad \text{and} \quad \omega(a) = \frac{a}{\hbar}\sqrt{a^2\Lambda - 1}$$

- The total Hamiltonian is given by

$$H_T = H_1 + H_2 + H_I \quad \text{where} \quad \begin{cases} H = \dfrac{1}{2M}p_\phi^2 + \dfrac{M\omega^2}{2}\phi^2 \\ H_I = \dfrac{Ma^4k}{2}(\phi_2 - \phi_1)^2 \end{cases}$$

- A non-trivial choice of canonical transformation to $(\Phi_1, \Phi_2, P_1, P_2)$

$$H_N = \frac{1}{2M}P_1^2 + \frac{M\Omega_1^2}{2}\Phi_1^2 + \frac{1}{2M}P_2^2 + \frac{M\Omega_1^2}{2}\Phi_1^2$$

where
$$\begin{cases} \Omega_1^2 = a^4 f(\Lambda_1, \Lambda_2, k) \\ \Omega_2^2 = a^4 g(\Lambda_1, \Lambda_2, k) \end{cases}$$

- H_N represents dynamical evolution of non-interacting universes
- Normal modes of oscillation
- Vacuum energy associated with new frecuencies

➢ Considering two "nearby" universes

$$\Lambda_1 = \Lambda + \varepsilon$$
$$\Lambda_2 = \Lambda - \varepsilon$$

So $\begin{cases} \Omega_1^2 \approx a^4 \Lambda_1^{\rm ef} \\ \Omega_2^2 \approx a^4 \Lambda_2^{\rm ef} \end{cases}$ $\xrightarrow{k = -\frac{\Lambda}{2}}$ $\begin{cases} \Lambda_1^{\rm ef} \approx \dfrac{2\varepsilon^2}{\Lambda} \approx 0 \\ \Lambda_2^{\rm ef} \approx \Lambda - \dfrac{2\varepsilon^2}{\Lambda} \approx \Lambda \end{cases}$

- Point of view of an internal observer that perceives its universe as isolated → value of the cosmological constant as proper of the universe

- Observer in universe 1: see a nearly zero value of the cosmological constant → cannot identify to any effect of its universe

- Mechanism for reducing the cosmological constant of a universe by means of the interaction of different universes

➢ We also extend this study to a general quadratic potential

MULTIVERSE OF INTERACTING HARMONIC OSCILLATORS

- Multiverse can exhibit collective phenomena → new perspective
- Considering N de Sitter universes interacting → represented in third quantization as harmonic oscillators
- Asuming "nearest interaction" and the interaction governed by Hooke's law

$$\hat{H} = \sum_{r=1}^{N} \left(\frac{\hat{p}_r^2}{2M} + \frac{M\omega^2}{2}\hat{\phi}_r^2 + \frac{Mc}{2}(\hat{\phi}_r - \hat{\phi}_{r+1})^2 \right)$$

$$\Downarrow$$

$$\hat{H} = \sum_{r=1}^{N} \left(\frac{1}{2M}\hat{P}_r\hat{P}_r^\dagger + \frac{M\omega_r^2}{2}\hat{\Phi}_r\hat{\Phi}_r^\dagger \right)$$

with $\omega_r^2 = \omega^2 + 4c\sin^2\left(\frac{\pi r}{N}\right)$

➔ We can follow a more general quantization procedure

➢ Canonical commutation relations replaced by compatibility conditions

➢ In addition to the standard solution, it alllow us to obtained more solutions → be described by means of representations of Lie superalgebras

➢ Defining the operators
$$\begin{cases} a_r^- \equiv \sqrt{\frac{M\omega_r}{2}}\hat{\Phi}_r + \frac{i}{\sqrt{2M\omega_r}}\hat{P}_r^\dagger \\ a_r^+ \equiv \sqrt{\frac{M\omega_r}{2}}\hat{\Phi}_r^\dagger - \frac{i}{\sqrt{2M\omega_r}}\hat{P}_r \end{cases}$$

the Hamiltonian takes the form $\hat{H} = \sum_{r=1}^{N} \frac{\omega_r}{2}\{a_r^-, a_r^+\}$

➢ Compatibility condition $[\hat{H}, a_r^\pm] = \pm\omega_r a_r^\pm$

➢ These relations have solutions in a particular Lie superalgebra → We can diagonalize the Hamiltonian and obtain the energy spectrum

- We consider a multiverse with explicit interaction or without it

- For the given representation the spectrum of the Hamiltonian splits into a large number of different levels for both cases (different each other)

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Even in the case without explicit interaction → there are quantum interactions with no classical analogue

- The energy levels depends strongly on the interaction between universes

- Given some conditions, the ground state of the new spectrum approaches to zero

- The collective phenomena of the multiverse provide a mechanism to fix the cosmological constant to a value arbitrarly close to zero

CONCLUSIONS

- The interaction of a parent universe with a multiverse environment → parallel development to quantum optics
  - Decoherence effect permit the emergence of a classical Universe
  - An analogue effect to Lamb shift, provide a mechanism that allows to reduce the value of the cosmological constant, due to the interaction of the Universe with a multiverse environment
  - We also show the entropy increase of the state of the Universe → loss of information that is mantained in the whole multiverse
- By means of the Curvature Principle we obtain a reduction of the value of the cosmological constant in the Universe, due to the interaction with other universe

- We can consider collective phenomena in the multiverse → give us new tools to understand cosmological issues
  - Take N universes in the multiverse as harmonic oscillators, and use the Wigner Quantum System → quantum interaction in the multiverse without classical analogue
  - The interactions between universes produce new energy levels for the Hamiltonian → In any case we can fix the vacuum energy to a value arbitrary close to zero
  - So, the vacuum energy of a universe depends not only on the interaction between universes but also on the structure of the multiverse as a whole
- These simple models show that an interacting multiverse could solve some cosmological problems and open the door to a new range of effects that could give physical predictions of the multiverse

Thank you for your atention!