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Long range quantum gravity and galactic dynamics

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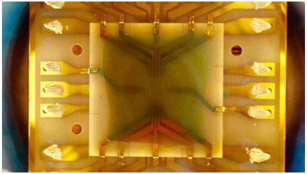
Based on:
M. Cadoni, MT, *arXiv:1904.08209*
M. Cadoni, MT, *arXiv:1904.11835*

Outline

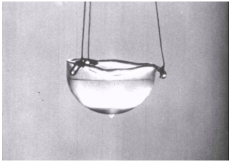
- Long range quantum mechanics and the universe
- Long range quantum gravity effects
- One-dimensional quantum mechanical model for galactic dynamics
- Macroscopic effects of long-range quantum gravity at galactic scales
- A generalized thermal equivalence principle
- Conclusions

Long-range quantum mechanics and the universe

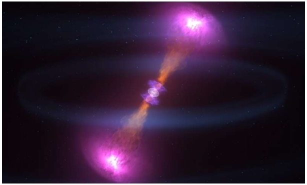
– Quantum mechanics determines the macroscopic behaviour of many physical systems



BEC: The chip of rubidium atoms from MAIUS 1 experiment.



Superfluid helium.



Neutron stars merging. Credits LIGO

– Long-range quantum effects $\rightarrow$ Bose-Einstein condensates, neutron stars, entanglement, Pauli exclusion principle...

– Quantum gravity $\rightarrow$ Planck scales.

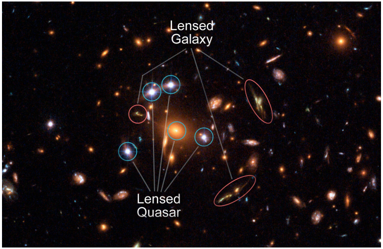
– Can quantum gravity effects determine the large scale structure and dynamics of the Universe?

Long-range quantum mechanics and the universe

- Hints from emergent gravity [Sakharov (1965), Jacobson (1995), Dvali (2012), Padmanabhan (2015), Verlinde (2016)]: spacetime and gravity are a macroscopic manifestation of microscopic quantum gravity degrees of freedom.

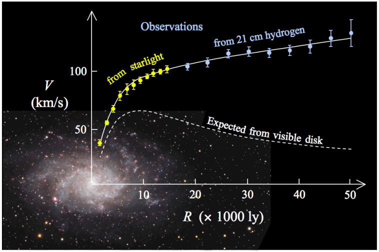
- Known and unknown universe: hints of long range quantum gravity
  - ΛCDM model: 70% $\rightarrow$ dark energy, 25% $\rightarrow$ dark matter, 5% $\rightarrow$ baryonic matter.
  - Indirect evidence of dark matter effect in the universe

The bullet cluster. Credits: Chandra/NASA Collaboration.



Gravitation lensing effects in the galaxy cluster SDSS J1004+4112. Credits: ESA, NASA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech).

- Galaxy rotation curve



Rotation curve of M33 galaxy. Credits: Wikipedia

The asymptotic value of stars velocity approaches the form (Tully-Fisher relation)

$$v^2 \approx \sqrt{\frac{a_0 G_N m_B}{6}}$$

where $a_0 = 1.2 \times 10^{-12} ms^{-2} \approx H/2\pi$, where H is the Hubble radius and m_B is the baryonic mass.

- Tully-Fisher relation: no dark matter is needed!

Long-range quantum gravity effects: symmetries

– We consider our universe as made only by dark energy (DE) and baryons.

– Without baryonic matter, the universe is described by the de Sitter (dS) metric

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2, \quad f(r) = 1 - \frac{r^2}{L^2},$$

where $d\Omega^2$ is the metric of the 2−sphere and $L = \sqrt{3/\Lambda}$. Note $L = 1/H$.

– The cosmological acceleration H is related to L by $H = 1/L$.

– The dS spacetime properties: isometry group $SO(1,4)$ inherited from its embedding in $\mathbb{R}^{1,4}$ which acts as conformal transformations of the 3−sphere at infinity. In FLRW form and in the flat slicing we have

$$ds^2 = -dt^2 + e^{\frac{2t}{L}} d\vec{y}^{\,2},$$

where $d\vec{y}^{\,2}$ is the flat metric on $\mathbb{R}^3$.

- With the introduction of (point-like) baryonic matter m_B, the metric function will be

$$f(r) = 1 - \frac{r^2}{L^2} - \frac{2Gm_B}{r}.$$

- Conformal symmetry breaking $\rightarrow$ generation of a new length scale r_0:
  - $r_0 = R_s = 2Gm_B$ IF the dark energy does not react to the presence of baryonic matter
  - *Emergent gravity scenario*: r_0 is a *mesoscopic* scale. It can depend on the Planck length l_p, R_s and L (note however $l_p \ll r_0 < L$).

- Analogy with condensed matter systems:
  - DE is considered as a system of size L characterized by a microscopic scale $l_p \ll L$ (i.e. the dimension of its elementary constituents)
  - Baryonic matter is considered as an impurity of size R_s
  - Excitations in the "DE medium" due to the reaction of DE to the presence of baryonic matter plays the role of phonons.

Long range quantum gravity

- Relevance of quantum effects: we compare the Compton wavelength λ_c associated to the impurity with r_0.

- If DE does not react to baryonic matter, $r_0 \sim R_S$ and $\lambda_c = \hbar/m_B$. In this case $\lambda_c \simeq r_0$ determines the typical scale of quantum gravity effects to be of the order of l_p.

- If DE reacts to baryonic matter, to evaluate λ_c we must consider a test mass m at distance r from m_B and its classical Newtonian energy, $V_N(r) = -\frac{Gmm_B}{r}$. The typical scale of quantum gravity effects is determined by

$$\lambda_c \simeq \frac{\hbar}{|V_N|} \simeq r_0.$$

- Quantum effects are negligible for $r \ll r_0 R_s m/\hbar$ and become relevant for $r \simeq r_0 R_s m/\hbar$. At scales $r = r_0$ quantum effects become relevant when $m = \hbar/R_s$.

- It is possible to have quantum gravity effects at large (galactic) scales generated by the presence of baryonic matter!

Long range quantum gravity and Bose-Einstein condensates

- Evidences from GR and various quantum gravity models: the gravitational interaction should be mediated by bosonic spin-2 particles [Cadoni (2018)].

- DE excitations $\rightarrow$ bosonic quantum states in thermal equilibrium with the dS spacetime described by a Bose-Einstein distribution with zero chemical potential at temperature $T_{dS} = \frac{\hbar}{2\pi L}$,

$$N(\varepsilon) = \frac{1}{e^{\frac{\varepsilon}{T_{dS}}} - 1},$$

  where ε is the energy of the excitations.

- The dS universe (as well as black holes Dvali (2012), Casadio (2017)) can be considered as a quantum critical state representing a BEC (see [Binetruy (2012) ,Cadoni (2017), Cadoni (2018)] for corpuscolar gravity picture).

- Bosonic (soft) excitations arise when $N = \mathcal{O}(1)$. We expect their spectrum to be of the type

$$\varepsilon = \frac{\hbar\alpha}{r},$$

  where α will depend on both Gm_B and L $\alpha < 1$ for soft DE bosonic excitations.

One-dimensional quantum mechanical model for galactic dynamics

- Emergent gravity scenario: spacetime and DE have some elastic properties [Sakharov (1965), Padmanabhan (2015), Verlinde (2016)].

- The DE excitations are collective modes of DE, i.e. quasi particles with effective mass m^* subject to an effective potential $V(x)$.

- The presence of the baryonic mass m_B at scales r will generate an elastic response of the DE medium and, consequently, the harmonic oscillator effective potential,

$$V(x) = \frac{1}{2} K(r, L)\, x^2.$$

- K should be proportional to the absolute value of the Newtonian potential energy $|V_N(r)|$ of the mass m^* in the potential generated by the baryonic mass m_B.

- The proportionality factor must have dimensions of length^{-2} defining a pivotal distance $\langle x \rangle$ such that $V(x = \langle x \rangle) = |V_N(r)|$. In particular, we take the geometric mean between r and L, $\langle x \rangle = \sqrt{rL}$.

One-dimensional quantum mechanical model for galactic dynamics

- The elastic constant takes the following form

$$K = \frac{2Gm_B m^*}{r^2 L}.$$

- The energy spectrum of the DE excitations is given by the energy levels ε_n of the one-dimensional quantum harmonic oscillator of mass m^*,

$$\varepsilon_n = \left(n + \frac{1}{2}\right) \frac{\hbar}{r} \sqrt{\frac{2Gm_B}{L}},$$

where the ground state energy is

$$\varepsilon_0 = \frac{\hbar}{r} \sqrt{\frac{Gm_B}{2L}}.$$

- The energy of DE bosonic excitations only depends on Gm_B, L and r. The value of the coupling constant α is $\alpha \simeq \sqrt{Gm_B/L}$.

- We can now evaluate the value of r_0: by using $N = \mathcal{O}(1)$ and the value of ε, one finds

$$r_0 \simeq \sqrt{R_s L} = \sqrt{Gm_B L}.$$

- For $m_B \sim 10^{11} M_\odot$, $r_0 \sim kpc$.

Macroscopic effects of long-range quantum gravity at galactic scales

- New potential term at scales $r_0 \rightarrow$ generation of a new "dark force", "dark acceleration" felt by stars in galaxies.

- Dark matter effects are associated to the response of DE "medium" to the presence of baryonic matter.

- No dark matter to explain galactic phenomenology: the total acceleration of stars in galaxies (elliptic, spheric and spiral) is [Lelli (2017), McGaugh (2018)]

$$a_{tot} = a_B + a_{DF}, \qquad a_{DF} = \frac{a_B}{e^{\sqrt{\frac{a_B}{a_0}}} - 1},$$

  where a_0 is a fitting parameter whose (universal) value is $a_0 = 1.2 \times 10^{-10} ms^{-2} \sim H/2\pi$. a_{tot} measured in a survey of rotation curves of 153 galaxies in the SPARC database. The Newtonian gravitational potential, a_B is estimated from baryons as observed in stars, gas and dust.

- a_{DF} is generated by the pressure P of the gas of DE bosonic excitations in the sphere of radius r.

- $a_{DF} \sim PV/r \sim PV\varepsilon \sim CN(\varepsilon)\varepsilon^2$, where V is the volume of the sphere, $\varepsilon \sim 1/r$ and TS is negligible at galactic scales, $r \ll L$.

Macroscopic effects of long-range quantum gravity at galactic scales

- To calculate C we consider the limit in which the number of soft DE bosonic excitations becomes very large, $N \gg 1$, i.e. when $r_0 \lesssim r < L$.

- In this limit, $2\pi L\varepsilon \to 0$ and, at leading order in $2\pi L\varepsilon$, we have $N(\varepsilon_{DF}) = (2\pi L\varepsilon)^{-1}$.

- The behaviour of DE bosonic excitations should match that of the dS universe, i.e. $\varepsilon = \hbar/L$ and a_{DF} must become the cosmological acceleration $a_{DF} = H = 1/L$ [Cadoni (2017), Cadoni (2018)].

- This requirement determines the constant C to be $C = \frac{2\pi}{\hbar^2} L$.

- This corresponds to the transition from an excited system to the critical phase of a Bose-Einstein condensate (dS universe). Putting all together we find [Cadoni (2019)]

$$a_{DF} = \frac{2\pi a_B}{e^{2\pi\sqrt{\frac{a_B}{H}}} - 1},$$

where $a_B = Gm_B/r^2$ is the Newtonian acceleration experienced by the test mass.

A generalized thermal equivalence principle

- Smolin proposal: the MOND theory corresponds to a quantum gravity, cosmological constant-dominated, regime in which the equivalence principle does not hold in its usual form [Smolin (2017)].

- The fate of the classical equivalence principle in the region $a_B \ll a_0$: does a quantum extension of Einstein's equivalence principle exist?
  - *Thermal Equivalence Principle* (TEP) [Smolin (2017)]: it incorporates the universality of free fall by asserting that *the temperature T seen by an observer is related to his acceleration a by the Deser-Levin (DL) formula*

    $$T = \sqrt{T_{dS}^2 + \left(\frac{\hbar a}{2\pi c}\right)^2}$$

    where T_{dS} is the dS temperature and a the observer acceleration.

  - *Generalized Thermal Equivalence Principle* (GTEP) [Cadoni (2019)]: TEP + *whenever we have a thermal ensemble at temperature T of quantum gravity degrees of freedom, the macroscopic acceleration produced on a test mass is given by the Deser-Levin formula*,

    $$a = \frac{2\pi c}{\hbar}\sqrt{T^2 - T_{dS}^2}.$$

A generalized thermal equivalence principle: applications

- *Black Holes*: astrophysical black holes correspond to the limiting case $T \gg T_{dS}$ and $a = \frac{2\pi c}{\hbar} T$. If the typical energy of the quanta is $\varepsilon = \frac{\hbar c}{R_s}$, the previous relation leads to

$$a = \frac{c}{2\hbar}\varepsilon.$$

- *dS spacetime*: similar to black holes, with T_{BH} (ε_{BH}) replaced by T_{dS} (ε_{dS}).

- *Long-range quantum gravity*:
  - expanding the DL formula near a temperature $T_1 = \sigma T_{dS}$ where $\sigma > 1$ and of order 1, we find, at leading order in T^2,

$$a = \rho H + \eta \frac{L}{\hbar^2} T^2,$$

    where H is the cosmological acceleration and ρ, η are dimensionless constants. The typical energy of an excitation of the thermal bath is $\varepsilon \sim T$, the second term becomes

$$a \sim \eta \frac{L}{\hbar^2} \varepsilon^2.$$

  - We consider the contribution of a single quantum mode $(N(\varepsilon) \sim 1)$ and to fix the proportionality constant $\eta = C = 2\pi/\hbar^2$.

- For $N(\varepsilon) \sim 1$, $a_{DF} = a_B$ then $\varepsilon_0 = \frac{\hbar}{r}\sqrt{\frac{Gm_B}{2L}}$ and a_{DF} exactly matches the phenomenological result of McGaugh *et al.* (MOND).

Conclusions

- We have argued that long-range quantum gravity effects could play a relevant role at galactic scales.
- Existence of a huge number of extremely soft bosonic excitations:
  - their wavelength is much bigger than the size of the cosmological horizon
  - they are in thermal equilibrium with de Sitter spacetime
- Excitations distribution and energy:
  - explain why dark matter effects arise at galactic scales (leaving unaltered Newtonian gravity at small scales)
  - allow to find the correct value of r_0.
- Derivation of the total radial acceleration of stars in galaxies in agreement with the phenomenological relation obtained by McGaugh *et al.* and MOND theory.
- We have also proposed a GTEP and found the same formula.
- It is also possible to build an effective fluid description in a GR framework for an infrared-modified theory of gravity.
- Possible studies on the origin of the dark energy and the cosmological implications for our model are left for future studies.

Thank you for your attention!

Gratzias po s'attentzioni vostra!