Dark energy in the laboratory

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based on 1711.03356, 1902.07555 with
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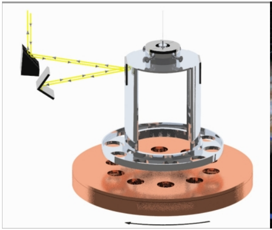
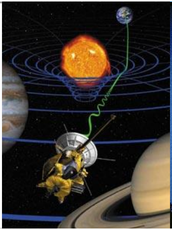
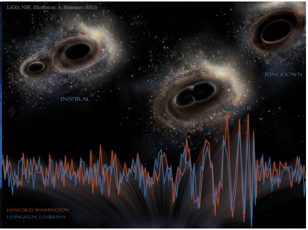
Exploring gravity in the Universe

Gravity is described by General relativity which is the unique Lorentz invariant theory of massless spin-2 interaction `[Weinberg]`

General relativity has been tested on many scales

- **Millimeter range:** Laboratory experiments tests of fifth forces and equivalence principle
- **150 million km range (1 a.u.):** Cassini probe test of fifth forces
- **400 000 km range:** Lunar ranging tests of strong equivalence principle and time variation of Newton's constant
- **10-100 Mpc range:** Gravitational wave emissions from black hole and neutron star mergers

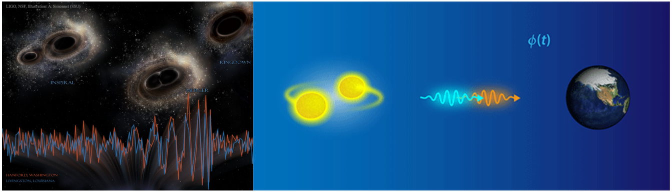





Exploring gravity in the Universe

The detection of gravitational waves has opened a new window on the gravitational physics of our universe

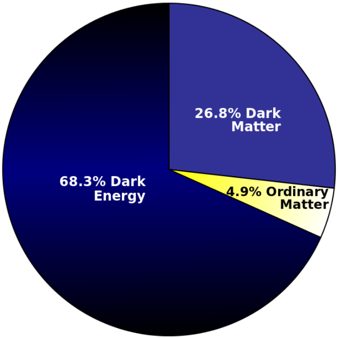
We do not find any inconsistency of the data with the predictions of general relativity and improve our previously presented combined constraints by factors of 1.1 to 2.5. [VIRGO Collaboration (2019)]



The multi-messager detections improves the constraints on various modified gravity models

- gravitational waves propagates $|c_{GW} - c| < 10^{-15}c$
- Rules out many Effective Field Theory for dark energy [Gubitosi, Piazza, Vernizzi]

Beyond Einstein gravity



We need to go beyond Einstein gravity because we do not have a good understanding of dark energy and dark matter which are necessary for explaining the Baryon Acoustic Oscillations and the Cosmic Microwave Background

With the coming age of precision cosmology, it is needed to understand gravity effective field theories and their connection with observations

Gravity effective field theories

Therefore it is important to develop a theoretical framework allowing to test the prediction of effective field theory models

We will be working in the context of an effective field theory assuming :

- Standard QFT (local, unitary, lorentz invariant, ...)
- The low-energy DOF: graviton, usual matter fields
- Standard symmetries: General relativity as we know it

$$\mathcal{S}_{eff} = \mathcal{S}_{eff}^{gravity} + \mathcal{S}_{eff}^{matter}$$

$$\mathcal{S}_{eff}^{gravity} = \frac{1}{16\pi G_N} \int d^4x \sqrt{g}\mathcal{R} + \cdots$$

Particles couple to a unique metric $g_{\mu\nu}$: $\mathcal{S}_{eff}^{matter}(\psi_i, g_{\mu\nu})$

Gravity is the best effective field theory

[J. D. Bjorken, ``The Future of particle physics,'' hep-ph/0006180]

> *I also question the assertion that we presently have no quantum field theory of gravitation. It is true that there is no closed, internally consistent theory of quantum gravity valid at all distance scales, but such theories are hard to come by, and in any case, are not very relevant in practice. But as an open theory, quantum gravity is arguably our best quantum field theory, not the worst. Feynman rules for interaction of spin-two gravitons have been written down, and the tree-diagrams (no closed loops) provide an accurate description of physical phenomena at all distance scales between cosmological scales, down to near the Planck scale of* 10^{-33} *cm.*

The S-matrix approach to Classical Post-Minkowskian contributions shows that one can use loop computation to get accurate results.

Gravity is the best effective field theory

[J. D. Bjorken, ``The Future of particle physics,'' hep-ph/0006180]

> *One way of characterizing the success of a theory is in terms of bandwidth, defined as the number of powers of ten over which the theory is credible to a majority of theorists (not necessarily the same as the domain over which the theory has been experimentally tested).From this viewpoint, quantum gravity, when treated—as described above—as an effective feld theory, has the largest bandwidth; it is credible over 60 orders of magnitude, from the cosmological to the Planck scale of distances.*

Gravity effective field theories

The effective field theory of gravity contains an infinite numbers of higher derivative terms

$$S_{eff}^{gravity} = \int_{\mathcal{M}_4} d^4x\,\sqrt{-g}\,\left(\Lambda^4 + \frac{1}{16\pi G_N}\mathcal{R} + M_*^4 \sum_{L\geqslant 1} c_L \left(\frac{R}{M_*^2}\right)^{L+1}\right)$$

- All these terms are allowed by the symmetries of the theory
- They arise as local counter-terms to L-loop ultraviolet divergences from the perturbative expansion of ultraviolet complete theories of quantum gravity (like string theory)

The typical scale M_* of these higher derivative corrections is unknown. The scale is $M_* \leqslant M_{\text{Planck}}$

It is difficult to derive these coupling from top-bottom approach but these couplings can be determined by experimental measurements if one knows how to make contact with measurable effects

Gravity effective field theories : infrared physics

$$S_{eff}^{gravity} = \int_{\mathcal{M}_4} d^4x \, \sqrt{g} \, \left(\Lambda^4 + \frac{1}{16\pi G_N} \mathcal{R} + M_*^4 \sum_{L \geqslant 1} c_L \left(\frac{R}{M_*^2} \right)^{L+1} \right)$$

In the infrared we have the propagation of a *massless spin 2*: the graviton
Non-local effects lead to **very distinct** signatures that we can identify **without** knowing the high-energy behaviour of the theory.

There are physical consequences independent of the UV completion

- The contributions to the *classical* (post-Minkowskian) 2-body interactions [this workshop]
- Eikonal limit of gravity amplitudes [cf. Talks Veneziano, di Vecchia, Parra-Martinez]
- IR Quantum induced infrared effects (e.g. quantum contribution to the bending angle [Donoghue et al.; Bjerrum-Bohr et al.])
- Effects of higher-derivative terms (e.g. R^2 and R^3 [Accettulli Huber, et al.; Cristofoli], &c. to potential)

Effective field theory : R^2 contributions

$$S^{gravity}_{eff} = \int_{\mathcal{M}_4} d^4x \, \sqrt{g} \, \left(\Lambda^4 + \frac{1}{16\pi G_N}\mathcal{R} + c_0 \mathcal{R}^2 + c_1 (R_{\mu\nu})^2 + c_2 (R_{\mu\nu\rho\sigma})^2 \right)$$

The R^2 corrections to the effective actions of gravity are important because

- They are the first UV quantum corrections to pure gravity with matter
- The $\mathcal{R}^2$ Starobinsky model for inflation agree well with the Planck data
- The (dimensionless) coefficients in the effective action are very loosing constrained by observations

Effective field theory : R^2 contributions

$$S_{eff}^{gravity} = \int_{\mathcal{M}_4} d^4x \, \sqrt{g} \left(\Lambda^4 + \frac{1}{16\pi G_N} \mathcal{R} + c_0 \mathcal{R}^2 + c_1 (R_{\mu\nu})^2 + c_2 (R_{\mu\nu\rho\sigma})^2 \right)$$

It is known for a long time [Stelle] that in four dimensions

- The $(R_{\mu\nu\rho\sigma})^2$ term is the topological Euler characteristic + Ricci terms
- $(R_{\mu\nu})^2 - \mathcal{R}^2/3$ induces a spin-2 ghost of mass $m_{\text{ghost}} \sim M_{\text{Pl}}/\sqrt{c_1}$
- $\mathcal{R}^2$ induces a spin-0 scalaron of mass $m_{\text{scalaron}} \sim M_{\text{Pl}}/\sqrt{c_0}$
- These corrections induce a modification of the $1/r$ law

$$V(r) = -\frac{G_N M}{r} \left(1 + \frac{1}{3} e^{-m_{\text{scalaron}} r} - \frac{4}{3} e^{-m_{\text{ghost}} r} \right)$$

Recall that $8\pi G_N M_{\text{Pl}}^2 = 1$

The scalaron

The $\mathcal{R}^2$ action is equivalent to the EH action coupled to the scalar field ϕ

$$S_\phi = \int d^4x \sqrt{g} \left(\frac{1}{2}(\partial\phi)^2 - V(\phi) - \left(e^{\frac{\phi}{\sqrt{6}M_{\rm Pl}}} - 1 \right) T_\mu^{\text{matter}\,\mu} \right)$$

- For $c_0\mathcal{R} \ll M_{\rm Pl}^2$ then $\phi \ll M_{\rm Pl}$

$$\mathcal{R} \simeq -\frac{\phi}{\sqrt{6}2c_0} M_{\rm Pl} + O(\phi^2/M_{\rm Pl}^2)$$

$$V(\phi) \simeq \lambda^4 M_{\rm Pl}^4 + \frac{4\lambda^4 M_{\rm Pl}^3}{\sqrt{6}} + \frac{1}{24}\left(32\lambda^4 + \frac{1}{c_0}\right) M_{\rm Pl}^2\phi^2 + O(\phi^3 M_{\rm Pl})$$

- The scalaron has a *universal* coupling to matter $\beta = \frac{1}{\sqrt{6}}$

$$\left(e^{\frac{\beta\phi}{M_{\rm Pl}}} - 1 \right) T_\mu^{\text{matter}\,\mu}$$

other scalar fields (moduli) have different values of β

The low-energy milli-eV sector

The cosmological model has (Planck 2018)

- Cosmological constant

$$\rho_{\Lambda_0} = (\lambda M_{\mathrm{Pl}})^4 \simeq (2.3\,10^{-3}\,eV)^4 \Leftrightarrow \lambda \simeq 4 \times 10^{-31}$$

- Neutrino : 3 families of masses

$$m_1 + m_2 + m_3 < 0.12\,eV$$

- Mass difference from oscillations

$$m_2^2 - m_1^2 = 7.5\,10^{-5}\,eV^2$$

and

$$m_3^2 - m_1^2 = 2.524\,10^{-3}\,eV^2 \qquad \text{or} \qquad m_3^2 - m_2^2 = 2.514\,10^{-3}\,eV^2$$

Effective field theory : R^2 models

$$S_{eff}^{gravity} = \int_{\mathcal{M}_4} d^4x\,\sqrt{g}\,\left(\Lambda^4 + \frac{1}{16\pi G_N}\mathcal{R} + c_0\mathcal{R}^2 + c_1(R_{\mu\nu})^2\right)$$

With $\Lambda = \lambda M_{\text{Pl}}$ let's assume that

$$c_0 \simeq \lambda^{-2} \simeq 10^{62}; \qquad |c_1| \simeq 1$$

- No ghosts at low-energy since $m_{\text{ghost}} \propto M_{\text{Pl}}/\sqrt{c_1} \simeq M_{\text{Pl}}$
- The scalaron has a mass of the milli-electron Volt range $m_{\text{scalaron}} \propto M_{\text{Pl}}/\sqrt{c_0} \simeq \lambda M_{\text{Pl}} \simeq 10^{-3}\,eV$

That would naturally link the observed cosmological constant to the gravitational sector and to laboratory observations of modified gravity

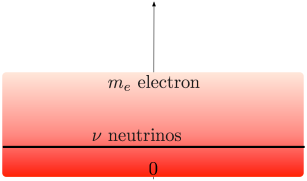
$$V(r) = -\frac{G_N M}{r}\left(1 + \frac{1}{3}e^{-\alpha\lambda M_{\text{Pl}} r}\right)$$

This is *not* a solution to the cosmological constant problem (i.e. the smallness of the measured value)

Running of the vacuum energy

For this we consider the physics at low-energy in the meV regime

- We integrate out all the fields from the electron mass and above
- We still have the neutrinos of mass $m_i \ll m_e$ and *by assumption* the scalaron of mass m



In the *decoupling substraction scheme* the vacuum energy is affected by the quantum loops due to the particles which have not been integrated out

$$\frac{d\rho_\Lambda(\mu)}{d\log\mu^2} = \beta^{1-\text{loop}} = \frac{m^4}{64\pi^2} - \sum_{i=1}^{3}\frac{m_i^4}{32\pi^2}$$

Running of the vacuum energy

The energy density for $m_i, m \leqslant \mu \leqslant m_e$ when all the particle with mass above the electron having decoupled and with contribution from the neutrinos and scalaron is

$$\rho_\Lambda(\mu) = \rho_\Lambda(m_e) + \left(\frac{m^4}{64\pi^2} - \sum_{i=1}^{3} \frac{m_i^4}{32\pi^2}\right) \log\left(\frac{\mu^2}{m_e^2}\right)$$

For the dark energy since today Hubble scale $H_0 \sim 10^{-42}\mathrm{GeV}$, we need the low-energy regime where $\mu < \min(m, m_f)$ where the neutrinos and the scalaron have decoupled.

Running of the vacuum energy

There is no well identified scale in cosmology (some say it is set by the Hubble scale).

We identify the vacuum energy as measured on large scale in the Universe with the 1PI result corresponding to the very low energy limit $\mu < \min(m, m_f)$ to m_e

$$\rho_{\text{vac}} = \rho_\Lambda(m_e) + \frac{m^4}{64\pi^2}\log\left(\frac{m_e^2}{m^2}\right) - \sum_{i=1}^{3}\frac{m_i^4}{32\pi^2}\log\left(\frac{m_e^2}{m_i^2}\right)$$

where ρ_{vac} is the vacuum energy which appears in the classical equations of motion of the theory. This is the dark energy density $(\lambda M_{\text{Pl}})^4$ measured by cosmological probe

$$\rho_{\text{vac}} = \lambda^4 M_{\text{Pl}}^4 \simeq (2.3\,10^{-3} eV)^4$$

This is *assuming* the cosmological constant problem i.e. that a lot of cancellations have already occurred in $\rho_\Lambda(m_e)$

The sequestring the scalaron mass :astrophysical datas

In the Universe, the galaxy clusters with a density constrast of around 500 play the role of "separate Universes"

In Galaxy clusters the neutrinos and the scalaron do not interact a lot and they don't participate to the dark energy density.

They have decoupled from the Hubble flow and host a gas at a temperature larger T than $100keV$.

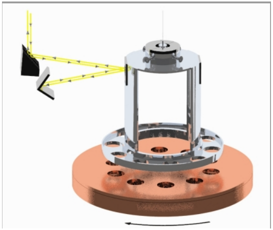
We apply Weinberg anthropic reasoning to galaxy clusters If the vacuum energy there were very negative, space-time would collapse inside the cluster in less than a Hubble time. We get that

$$|\rho_\Lambda(T)| \leqslant 200(\lambda M_{\rm Pl})^4 \Longrightarrow m \leqslant \bar m_\nu \simeq 5\times 10^{-3} eV$$

with the "average" neutrino mass

$$\bar m_\nu^4 \log(\bar m_\nu^2) = \sum_{i=1}^{3} m_i^4 \log(m_i^2)$$

The sequestring the scalaron mass : lower bound



The Eöt-Wash experiment gives the best lower bound on the scalaron mass

$$V(r) = -\frac{G_N M}{r}\left(1 + \frac{1}{3}e^{-mr}\right)$$

gives that no change for $r \geqslant 68\mu m$ this implies that

$$m \gtrsim (68\mu m)^{-1} \simeq 1.22\lambda M_{\rm Pl}$$

The bound from Gravity Probe B or the precession of the pulsar B in the PSR J0737-3039 system give very low lower bounds.

Testing dark energy in the laboratory

- Under the hypothesis that the dark energy scale is related to the coefficient of c_0 in the gravity effective action we have that the mass for the scalaron is in the range

$$4\mu m \lesssim m^{-1} \lesssim 68\mu m$$

- the mechanism is proposing a way to see the cosmological constant in the modification of the Newton force

$$V(r) = -\frac{GM}{r}\left(1 + \frac{1}{3}e^{-mr}\right);$$

- This prediction will be soon tested by a new run of the Eöt-Wash experiment testing the $1/r^2$ law till $40\mu m$ may be less

Conclusion

- if our bound is not satisfied then this means that the cosmological constant problem is not linked to the gravity sector the way we assumed
- If the scalaron has a very large mass then it will decouple but then we need an extra scalar field to compensate for contributions from the neutrinos
- On the theoretical front $\mathcal{R}^2$ are very important for inflation. They are rather robust models.
- There are other model of modified gravity model on the market. Which are described by low-energy EFT.
- The GW measurement brings new way to test them and we need to understand how to go back and forth between data and model
- For these models the UV completion of such models is not yet understood and some of them are rather tricky to obtain from string theoy

The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

Gravitational scattering, inspiral, and radiation

May, 18 2020 - July, 5 2020

The workshop will gather theoretical physicists working on connected, yet different aspects of gravitational waves. Major themes will be:

1 - to deepen links, and foster new collaborations, between the quantum gravitational scattering amplitude and the GR community, leading to improved perturbative approaches to the two-body system;

2 - to identify new synergies between the GR analytical and numerical communities which can improve the construction of waveform templates for the analysis of LIGO/Virgo data;

3 - to connect low frequency properties of the gravitational wave spectrum to recent progress in soft-graviton theorems, including predictions for gravitational memory, asymptotic symmetries, and logarithmic enhancements;

4 - to explore the implications of LIGO/Virgo data for modified gravity theories.

Topics:

- Analytic and numerical methods for the general relativistic two-body problem
- High energy gravitational scattering and radiation
- New approaches to gravitational amplitudes
- Soft theorems and their use for computing GW signals
- Alternative theories of gravity

Organizing Committee:
Dimitri Colferai (University of Florence),
Claudia de Rham (Imperial College London),
Alessandro Nagar (INFN, Turin),
Donal O'Connell (University of Edinburgh),
Pierre Vanhove (CEA, Saclay),
Gabriele Veneziano (CERN),
Alexander Zhiboedov (CERN)

Contact person: Dimitri Colferai

GGI: http://www.ggi.infn.it/

Deadline for applications: January, 31 2020