General Relativity and Beyond

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General Relativity

- GR: spacetime is dynamical
  Minkowski metric Diag$(-1,1,1,1)$ is replaced by $g_{\mu\nu}$

$$ds^2_{\text{Flat}} = \eta_{\mu\nu}\, dx^\mu dx^\nu \Rightarrow ds^2_{\text{GR}} = g_{\mu\nu}\, dx^\mu dx^\nu$$

- Einstein Equations: equations of motion for the metric field

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$\text{Curvature} = \left[L^{-2}\right] = \partial\left(g^{-1}\partial g\right) + \left(g^{-1}\partial g\right)\left(g^{-1}\partial g\right)$$

"*Matters (EMT) tells spacetime (metric) how to curve*" (Wheeler)

- Once the matter content is provided,

  a solution of Einstein equations gives the metric

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Einstein's GR: 1915-2015 a century of success

A single free parameter: $G \sim 1/M_{\rm pl}^2$

- Matter coupling Weak Equivalence principle (10^{-13})
- Post Newtonian solar system tests (weak field) ($10^{-3} - 10^{-5}$)
- Indirect GWs emission test: binary pulsar (10^{-3})
- Newton's Law tested at small distance down to 10^{-2}mm
- GR as an EFT: quantum corrections suppressed as

  $E/\Lambda, \qquad \Lambda \sim \left(10^{-33}\,\text{cm}\right)^{-1} \sim M_{pl} \sim 10^{19}$ GeV

  irrelevant at any accesible energy scales

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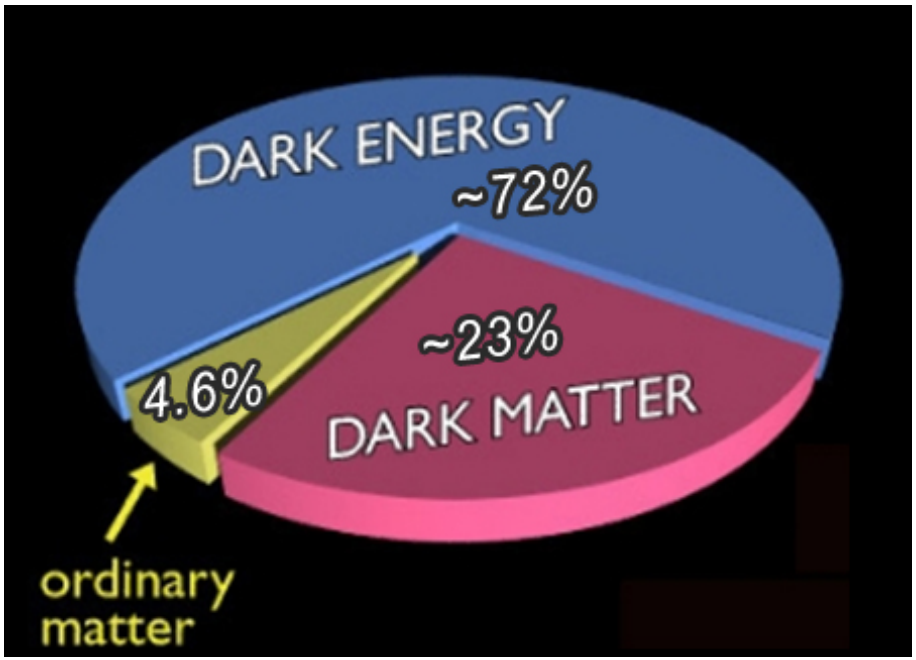
The Dark Side of GR

A snapshot of Universe's matter content



The Universe is dominated by an unknown component:

Dark Energy $p = w\,\rho$ with $w \sim -1$

The negative dark energy's pressure is the driving the present acceleration of the Universe

The Dark Side of GR

Simplest explanation: dark energy is just a cosmological constant

$$S_\Lambda = -\int d^4x\,\sqrt{g}\,\Lambda\,, \qquad T_{\mu\nu} = -\Lambda\, g_{\mu\nu}\,, \quad p = -\Lambda\,, \quad \rho = \Lambda$$

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How is it possible to modify GR ?

Modify what and at what scale ?

$$\int d^4x\sqrt{g}\left[M_{pl}^2 R(g) + \mathcal{L}_{matter}(g,\phi)\right]$$

Where ?

Dark energy scale $H_0^{-1} \approx 4.2$ Gpc or $H_0 \approx 10^{-33}$ eV

Modification in the infrared: large distance and low energy

What ?

- Modify the way matter couple to gravity is modified

  though: equivalence principle is well established
- New "gravitational" fields that couple with $g_{\mu\nu}$ are introduced
  Scalars, vectors, tensors ...
- $g_{\mu\nu}$ is still the only "gravitational" field but $R(g)$ is modified
- Add non derivative terms for $g_{\mu\nu}$

Example: Massive Gravity

Field theory side

- In gauge theories we can give mass m to gauge bosons ($W^{\pm}$, Z) effectively controlling the interaction range:

$$\text{unbroken phase} \qquad \frac{1}{r}$$

$$\text{unbroken phase} \qquad \frac{e^{-m\,r}}{r}$$

Is GR gauge theory alike and a massive gravity phase exists ?

Large distance modification of GR

- In a massive gauge theory $\Lambda = m\,g^{-1}$

for massive gravity then $\Lambda_2 = (m\,M_{pl})^{1/2} \sim 10^{-3}$ eV $<< M_{pl}$

- Is there an Higgs mechanism for gravity ?

dynamical spontaneous breaking with $\Lambda >> \Lambda_2$

People involved and Collaborations

M. Celoria; PhD student at GSSI

D. Comelli; INFN Ferrara

S. Matarrese, N. Bartolo; University of Padova and INFN Padova

F. Nesti; Ruder Bosskovic Institute, University of Zagreb, Croatia

K. Koyama and M. Crisostomi; Institute of Cosmology and Gravitation, University of Portsmouth, UK