Modified Gravity: Where are We?

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Introduction

Why modifying gravity ?... To test the limits of General Relativity.

General Relativity is a beautiful theory...

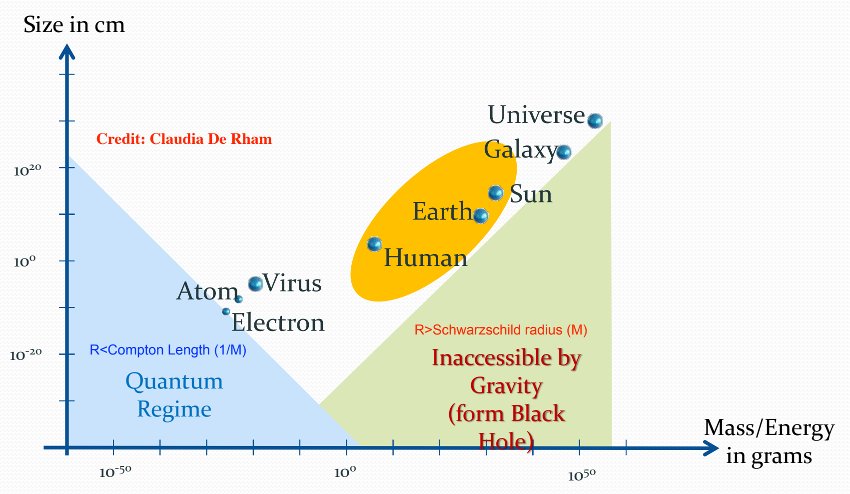
In total agreements with today observations

... But it is an EFT which comes with limitations

- Planck scale : need of a UV completion of General Relativity.
- Very large (cosmological) scales : the problem of dark energy ?
  - Accelerated expansion of the universe leads to troubles

$\Longrightarrow$ Going beyond General Relativity : Modifications of GR to test the gravitational interaction at these different scales and to propose deviations that we could eventually constrain with observations...

Narrow window of tests of General Relativity (Credit : C. De Rham)



Uniqueness of General Relativity with a cosmological constant :

- Hypothesis 1 : Space-time is of dimension 4
- Hypothesis 2 : Gravity is described by a metric (spin 2) only
- Hypothesis 3 : Euler-Lagrange equations are diff-covariant and second order

$\Longrightarrow$ Lovelock theorem (1971) : Einstein gravity + Cosmological constant

$$S[g_{\mu\nu}] = \frac{c^4}{16\pi G_N} \int d^4x \sqrt{-g}\,(R - 2\Lambda)$$

Any alternative theories rely on relaxing of these hypothesis...

Scalar-Tensor Theories : Landscape

Relax some of the hypothesis of Lovelock Theorem

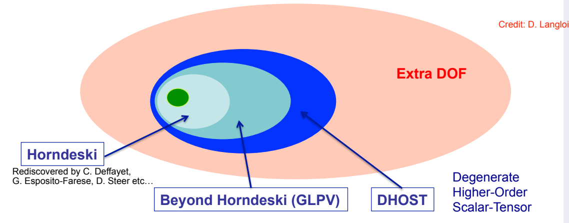
- Gravity comes with a scalar field ϕ : a fifth force which could be expected to be responsible for dark energy (in context of cosmology) $\Longrightarrow$ Scalar-Tensor theories
- Equations of motion are not necessarily second order PDE

Motivations

- Adding a scalar is the simplest possibility to start with
- Related to other scenarii : massive gravity, bi-gravity, vectors, extra-dimensions, Lorentz-breaking theories... Where a scalar is propagating.

⋆ The landscape of Scalar-Tensor theories has evolved and developed a lot in the last 20 years and they date back from Brans-Dicke in the 60's

From Brans-Dicke to DHOST Theories : a long story



The Lagrangians depend on ϕ, the kinetic energy $X \equiv g^{\mu\nu}\phi_\mu\phi_\nu$ and $\phi_{\mu\nu}$

- First-order theories (Green area) : $L[g_{\mu\nu}, \phi] = F(\phi)R + G_2(\phi, X)$
- Higher-order : $L[g_{\mu\nu}, \phi] = G_2 + G_3\Box\phi + G_4 R + 2G_{4X}\left[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2\right] + \cdots$

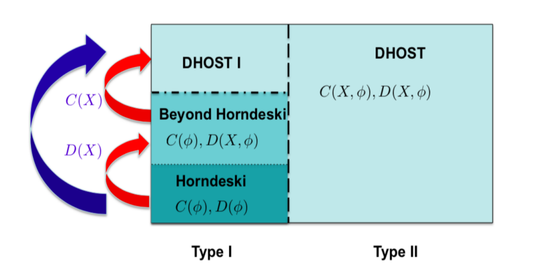
Brans, Dicke (1961) - Damour, Esposito-Farese (1992) - Armendariz-Picon, Damour, Mukhanov (1999) - Armendariz-Picon, Mukhanov, Steinhardt (2000) - Dvali, Gabadadze, Porrati (2000) - Horndeski (1974) - Nicolis, Rattazzi, Trincherini (2008) - Deffayet, Esposito-Farese (2009) - Deffayet, Deser, Esposito-Farese (2009) - Deffayet, Gao, Steer, Zahariade (2011) - Kobayashi, Yamaguchi, Yokoyama (2011) - Chamseddine, Mukhanov (2013) - Zumalacarregui, Garcia-Bellido (2013) - Gleyzes, Langlois, Piazza, Vernizzi (2015)-Langlois, Noui (2016) - Crisostomi, Koyama, Tasinato (2016) - Ben Achour, Langlois, Noui (2016) - Motohashi, Noui, Suyama, Yamaguchi, Langlois (2016) - de Rham, Matas (2016) - Crisostomi, Klein, Roest (2017) - etc.

Disformal Transformations : the metric is not unique !

Disformal transformations of the metric

$$g_{\mu\nu} \longmapsto \tilde{g}_{\mu\nu} = C(\phi, X) g_{\mu\nu} + D(\phi, X)\phi_\mu \phi_\nu \,, \qquad S[g_{\mu\nu}, \phi] = \tilde{S}[\tilde{g}_{\mu\nu}, \phi]$$

Degeneracy is preserved by disformal transformations : one identifies disformal classes.



- Type I are equivalent to Horndeski up to a disformal coupling to matter.
- Type I Lagrangians are disformally related to $L = {}^{(4)}R + \lambda\, {}^{(3)}R$ where ${}^{(3)}\Sigma = \{\phi = t\}$!

Phenomenology

A simple example and its phenomenology : the cubic Galileon theory

$$L[g_{\mu\nu},\phi] = F(\phi)R + \phi_\mu\phi^\mu - \frac{1}{2\Lambda^3}X\Box\phi$$

- It comes with a new scale Λ (which defines a domain of validity)
- Self-accelerating solutions with H_0 the Hubble constant today

$$\Lambda \sim (M_{\rm P} H_0^2)^{1/3} \sim 300\, Hz\,.$$

- Vainshtein screening : the scalar field is screened around a body (mass $\mathcal{M}$) below

$$r_V \sim \frac{1}{\Lambda}\left(\frac{\mathcal{M}}{M_P}\right)^{1/3}$$

Dvali, Gabadadze, Porrati (2000) - Reviews : Babichev, Deffayet (2013) - Kobayashi (2019)

Quadratic action for the perturbations ζ (scalar) and γ_{ij} (tensors)

- One considers a cosmological background $a(t)$ with self-acceleration

$$S = \int dt\, d^3x\, a^3 \left\{ \frac{M^2}{2} A \left[\dot{\zeta}^2 - c_s^2 \frac{(\partial\zeta)^2}{a^2} \right] + \frac{M^2}{8} \left[\dot{\gamma}_{ij}^2 - c_T^2 \frac{(\partial\gamma_{ij})^2}{a^2} \right] \right\}$$

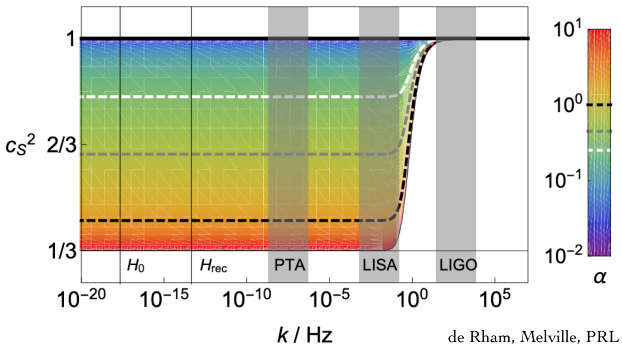
- Tensor modes do not propagate at speed of light in general : $c_T^2 = \frac{G_4}{G_4 - XA_1}$
- GW feel the fifth force and propagate in a medium

DHOST After GW170817 : $|c_T - 1| < 3.10^{-15}$

- Severe constraints on DHOST actions if taken strictly : $A_1 = 0$ etc.
- But rainbow argument : limit of validity of DHOST at GW scale

Langlois, Mancarella, Noui, Vernizzi (2017) - Creminelli, Vernizzi (2017) - Ezquiaga, Zumalacarregui (2017) - Sakstein, Jain (2017) - de Rham, Melville (2018) - Creminelli, Lewandowski, Tambalo, Vernizzi (2018) - Creminelli, Tambalo, Vernizzi, Yingcharoenrat (2018 and 2019)

Gravitational Rainbow ?



de Rham, Melville, PRL (2018)

Gravitational Rainbow by de Rham and Melville (2018)

GW170817 probes DHOST Theories at its limit of validity : $\Lambda = (H_0^2 M_P)^{1/3} \sim 300 Hz$

Discussion

Classification of scalar-tensor theories

- Full classification of DHOST theories with NO GHOST
- Very interesting applications to (late time) cosmology and limitations

Applications to Black Holes

- Scalar-Tensor theories to test GR at the strong field regime
- Background solutions are modified
- Perturbations about these solutions : subtle entanglement between the scalar and the polar gravitational mode
- New techniques for computation of QNM (see Hugo Roussille)

Babichev, Charmousis (2013) and Babichev, Charmousis, Lehebel (2016-2017-2018) - Van Aelst, Gourgoulhon, Granclement, Charmousis (2020) - Anson, Babichev, Chamousis, Hassaine (2021) - Ben Achour, Liu, Mukohyama, Noui (2020) - etc...