

# Modifying Gravity: Why? How? Observational Signatures?

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Based on works in collaboration with (mainly) D. Langlois and many other collaborators (Europe and Japan)

## Overview (*Intended not to be too technical...*)

- 1. Introduction : Why modifying Gravity ?  
→ Testing the Limits of General Relativity
- 2. Modified Gravity : How modifying Gravity ?  
→ (Higher Order) Scalar-Tensor Theories
- 3. Observational Signatures ?  
→ Cosmology (Dark energy)  
→ Astrophysics (Stars, Black Holes ...) [*See [David Langlois 's Talk](#)*]
- 4. Conclusion

*N.B. : Very few references to lighten the slides. Do not hesitate to ask...*

## Introduction : Why ?

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# Why modifying gravity ?...

General Relativity is a beautiful theory...

In total agreements with today observations : GW, BH images, etc...



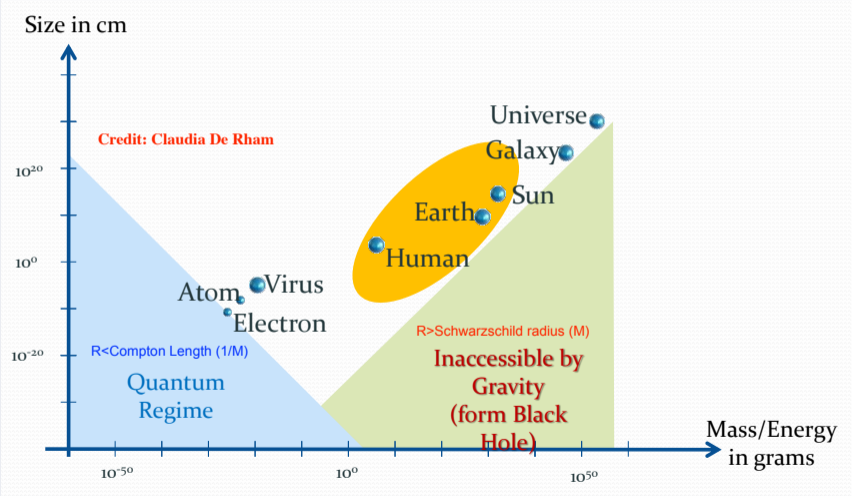
### GR is an Effective Field Theory which comes with limitations

- Planck scale : need of a UV completion of General Relativity.
  - Singularities in Big Bang Cosmologies and Black Holes
- Very large (cosmological) scales : the problem of dark energy ?
  - Accelerated expansion of the universe leads to troubles

⇒ Going beyond General Relativity : Modifications of GR

- (1) to test the gravitational interaction at different scales,
- (2) to propose alternative theories,
- (3) to predict deviations that we could eventually constrain with observations...

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



## Modified Gravity : How ?

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## 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

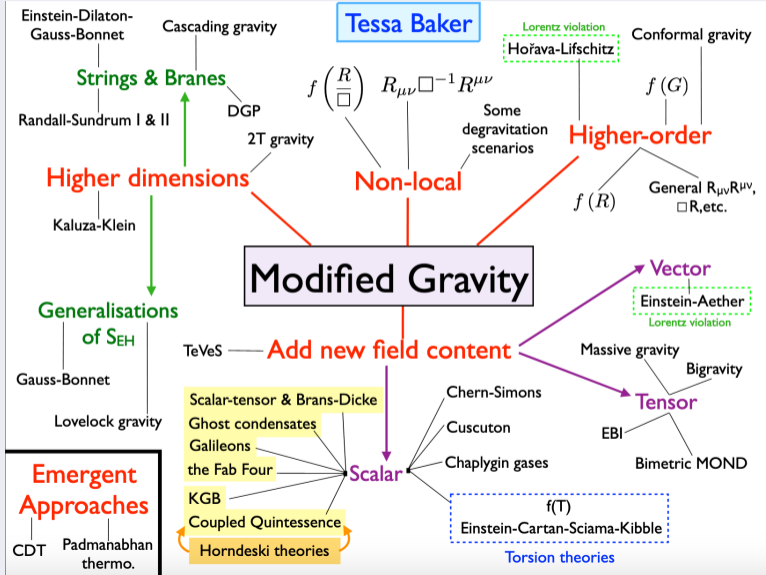
⇒ Lovelock theorem (1971) : Einstein gravity + Cosmological constant

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

This uniqueness theorem makes General Relativity so beautiful !

Any alternative theories rely on relaxing (at least) one of these hypotheses...

# A wide Landscape of Modified Theories (Credit : T. Baker)



# Scalar-Tensor theories : the gravitons and the scalar

## Relax some of the hypotheses of Lovelock Theorem

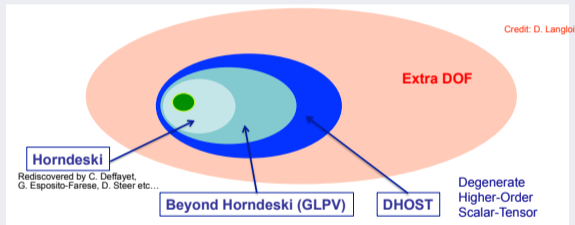
- Gravity comes with a scalar field  $\phi \implies$  Scalar-Tensor theories  
It drives a fifth force which could be expected to be responsible for dark energy in the context of cosmology for instance
- Equations of motion are not necessarily second order PDE

## Motivations

- Adding a scalar is the simplest possibility to start with
- Related to other scenarii in some “limit” :  
→ massive gravity, bi-gravity, vectors, extra-dimensions, Lorentz-breaking theories... where a scalar is propagating.
- Higher order equations lead to a new and very interesting phenomenology

# From Brans-Dicke to DHOST Theories : a long story

- ★ 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 (green area)



## DHOST : Classification of “Healthy” Higher derivative Lagrangians

$$S[g_{\mu\nu}, \phi] = \int d^4x \sqrt{-g} \mathcal{L}(R, R_{\mu\nu}; \phi, \partial_\mu \phi, \partial_\mu \partial_\nu \phi).$$

# Degenerate Higher Order Scalar Tensor Theories

## Case of Quadratic DHOST Theories

The DHOST action  $S[g_{\mu\nu}, \phi]$  whose E.o.M. are not necessarily second order

$$L[g_{\mu\nu}, \phi] = F(\phi, X) R + P(\phi, X) + Q(\phi, X) \square\phi + \sum_{i=1}^5 A_i(\phi, X) L_i$$

$$L_1 = \phi_{\mu\nu} \phi^{\mu\nu}, \quad L_2 = \square\phi^2, \quad L_3 = \phi^\mu \phi_{\mu\nu} \phi^\nu \square\phi, \quad L_4 = (\phi^\mu \phi_{\mu\nu})^2, \quad L_5 = (\phi^\mu \phi_{\mu\nu} \phi^\nu)^2$$

## Important Properties of Higher Order Scalar Tensor Theories

→ Metric not uniquely defined due to disformal transformations

$$g_{\mu\nu} \longrightarrow \tilde{g}_{\mu\nu} \equiv C(\phi, X) g_{\mu\nu} + D(\phi, X) \phi_\mu \phi_\nu.$$

→ Possibility of non-minimal couplings to matter :  $L_{\text{mat}}[\psi] = \tilde{g}^{\mu\nu} \partial_\mu \psi \partial_\nu \psi + \dots$

→ Possibility of having "Multi-horizons" Black Holes

## Observational Signatures ?

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# Dark Energy without Cosmological Constant : beyond standard model

Cosmological background :  $\phi(t)$  responsible for the acceleration

FRLW geometry :  $ds^2 = -dt^2 + a(t)^2 dx^2$  and  $\phi(t)$

Self-accelerating solutions preceded by a matter dominated era

Modified equation of state for dark energy :  $P = w_{DE}(\phi)\rho$

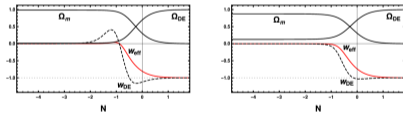


FIG. 1: Evolution of the parameters  $w_{DE}$ ,  $w_{eff}$ ,  $\Omega_{DE}$ , and  $\Omega_m$  as functions of  $N = \ln(a)$  for various choices

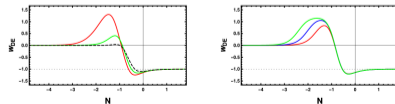


FIG. 2: Evolution of the dark energy ratio  $w_{DE} = P_{DE} / \rho_{DE}$  as a function of  $N = \ln(a)$  for various choices

## Stability of physical degrees of freedom

After integrating out gauge degrees of freedom

$$S = \int dt d^3x a^3 \left\{ \frac{M^2}{2} [A\dot{\zeta}^2 - B \frac{(\partial\zeta)^2}{a^2}] + \frac{M^2}{8} [\dot{\gamma}_{ij}^2 - \frac{1 + \alpha_T}{a^2} (\partial\gamma_{ij})^2] \right\}$$

One scalar propagates in addition to the usual two gravitational waves.

## Propagation of gravitational waves

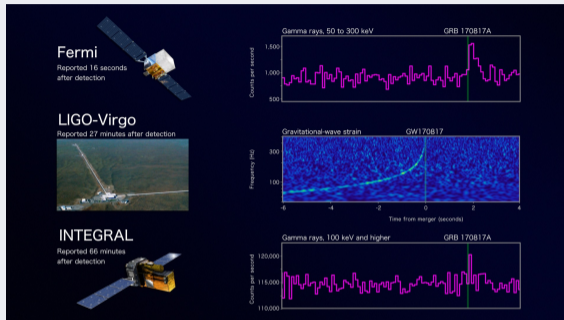
GW feel the fifth force and propagate in a medium (full of scalar field) :

$$\ddot{\gamma}_{ij} + (3 + \alpha_M)H\dot{\gamma}_{ij} + (1 + \alpha_T)\frac{k^2}{a^2}\gamma_{ij} = 0$$

The speed of propagation is different from speed of light :

$$c_T^2 = 1 + \alpha_T$$

# DHOST after GW170817 : what is the status of this Constraint ?



$$\text{Constraint : } c_T - 1 \leq 10^{-15} : \alpha_T \approx 0$$

Severe constraints on DHOST actions if taken strickly

But rainbow argument : limit of validity of DHOST at GW scale

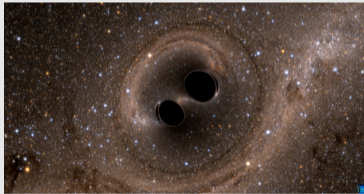
# Conclusion

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## Higher-Order Scalar Tensor Theories : DHOST Theories

- Have been fully classified
- Offer alternative theories to General Relativity
- Have been applied intensively to cosmology (primordial to late time) and then have been constrained a lot

## New directions : Testing Gravitation in the Strong Field Regime with GW



⇒ New Black Hole solutions and Modified GW form and QNM spectrum