Perturbations of Black Holes in General Relativity and Beyond

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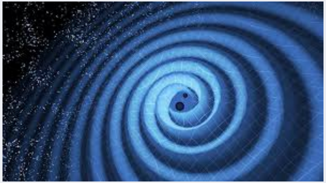
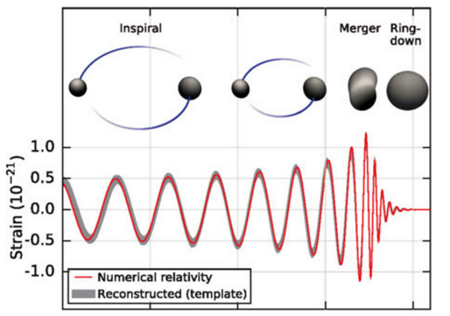
Motivations

Why perturbations of Black Holes ?... We (will) have an access to them !



Coalescence of Black Hole Binaries is decomposed in three phases

1. Inspiral : BH are "far" away
2. Merger : peak of GW emission
3. Ringdown : relaxation to equilibrium



[Ligo-Virgo]

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

General Relativity is a beautiful theory...

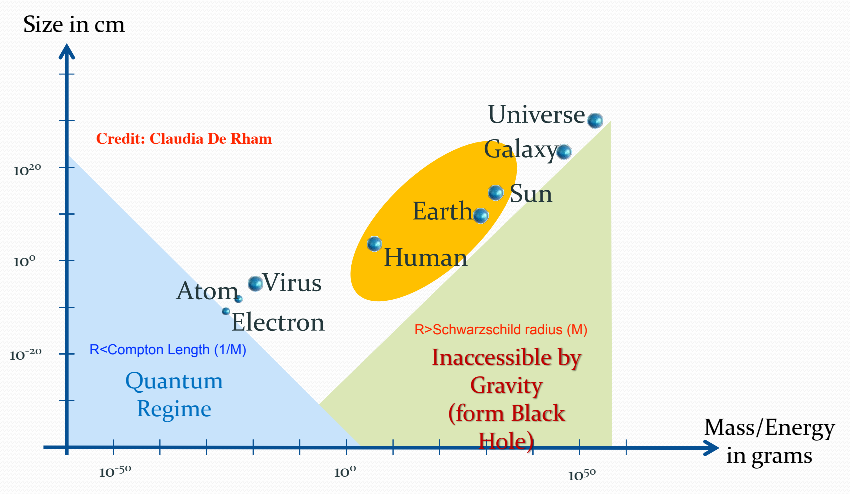
In total agreements with today observations

... 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)



Modified Gravity

Uniqueness of General Relativity with a cosmological constant :

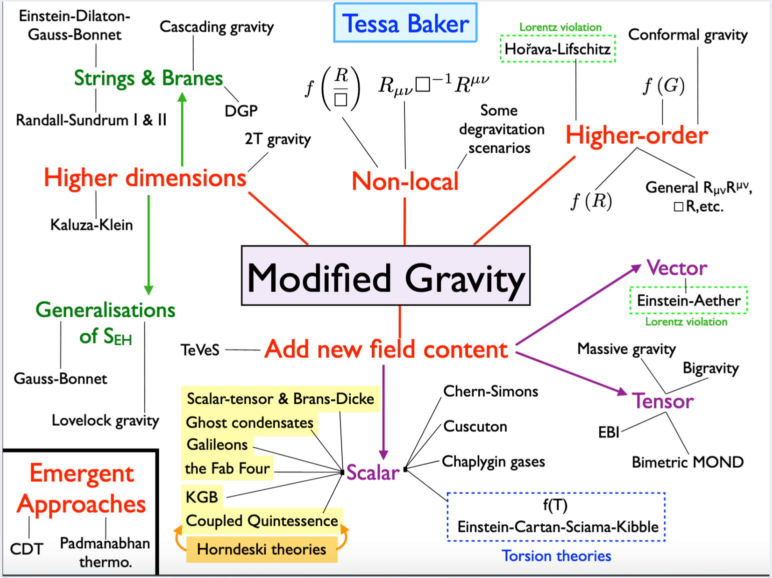
- Hypothesis 1 : Space-time is of dimension 4
- Hypothesis 2 : Gravity is described by a metric (spin 2) only
- Hypothesis 3 : Euler-Lagrange equations are diff-covariant and second order

$\Longrightarrow$ 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...

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



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

Black Holes

On Black Hole Solutions in modified gravity

The No-Hair Theorem of General Relativity

- Hypothesis 1 : Space-time is of dimension 4
- Hypothesis 2 : Stationary (regular) Space-Time and Asymptotically Flat
- Hypothesis 3 : Matter is Electromagnetism Fields

$\Longrightarrow$ Black Holes are described by M, J and Q

Black Holes in Scalar-Tensor Theories

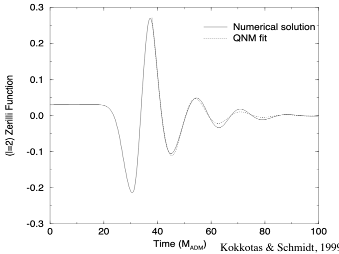
- A Scalar Hair "gravitating" around the new Black Hole
- Solutions found by C. Charmousis and E. Babichev etc...
- Few (analytic and numerical) rotating solutions $\rightarrow$ To be developed ?

$\Longrightarrow$ Could we see deviations from GR solutions in images or orbits ?

The Ringdown and Quasi-Normal Modes

Ringdown phase : Relaxation to equilibrium

- They are obtained from linear perturbations theory of Einstein theory about a Black Hole solution (the remnant in binaries)
- Gravitational waveform = (almost) Sum of complex exponentials (oscillation and damping) which are the Quasi-Normal Modes
- QNM are "Vibrations" of the Black Hole with dissipation into GW



Kokkotas & Schmidt, 1999

QNM in Modified Gravity

Ideal playground to constrain or reveal deviations from General Relativity, and test alternative theories of gravitation

Two types of modifications

- New background solutions : deviations from the "classical" Kerr metric
- New dynamics of linear perturbations : modified Einstein equations

$\Longrightarrow$ Modifications in the QNM spectrum : deviations vs. new modes

The problem is extremely interesting but very hard

"The era of ringdown physics is not quite here yet, but it is around the corner [...] Calculations of QNM in modified gravity are laborious [...] Little works on BH perturbations" [E. Berti et al, 1801.03587][L. Barak et al, 1806.05195]

$\Longrightarrow$ A timely problem for future observations with Need of new ideas !

Example : a very interesting new effect !

In General Relativity : minimal coupling makes perturbations universal !

Any spin s field ψ propagate in the background metric $g_{\mu\nu}$

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\psi + m_{\rm eff}^2\,\psi = 0\,.$$

In Scalar-tensor theories : the coupling is no more universal

In particular, gravitons feel the scalar field and their speed is reduced so that

$$\tilde{g}^{\mu\nu}\nabla_\mu\nabla_\nu\psi + m_{\rm eff}^2\,\psi = 0\,, \quad \tilde{g}_{\mu\nu} = A(\phi)g_{\mu\nu} + B(\phi)\phi_\mu\phi_\nu\,.$$

- $\tilde{g}_{\mu\nu}$ might not be a black hole anymore ! The species live in different space-time
- If $\tilde{g}_{\mu\nu}$ is still a black hole, it might have a different horizon radius :

$$R_s = 2GM/c^2\,, \qquad \text{with different } c\,!$$

Conclusion

Deviations from General Relativity : Observations vs. Constraints

GW open a Novel Access to the strong gravitational field regime

Need of a theoretical guide to look at eventual deviations

$\Longrightarrow$ Parametrize the space of (physically consistent) deviations

- Find universal features
- Find universal methods

Which are independent on the modified theory of gravity one is considering...

- Then, compare to future observations (new detectors)...