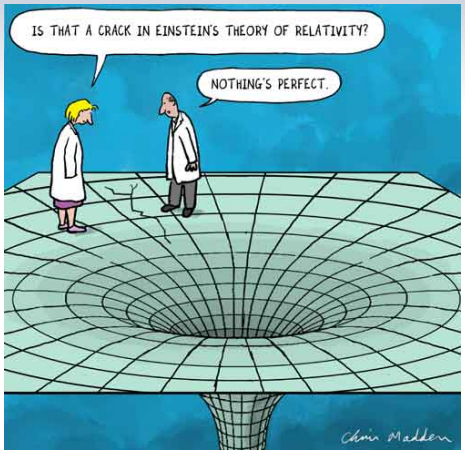
Scalar-Tensor Theories : Evading the Ghosts...



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Travail en collaboration avec

.

D. Langlois, C. Charmousis, M. Crisostomi, F. Vernizzi,

and many others (Japan, UK, China,...)

Gravity : beauty and limits ?

Einstein gravity : from 1915 to 2015...

1915 : Gravity results from deformations of space-time

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

2015 : First detection of gravitational waves by LIGO
Total agreement with theoretical predictions

Gravity : a success story

A beautiful theory with a happy end...

- Space-time is described in terms of (curved) geometry
- Gravity field results from deformations of space-time
- Agreements with observations : Planck, LIGO, Microscope...

... But open issues in "extreme" regimes

- Very short (Planck) scale : singularities ?
  - Big bang singularity at the origin of the universe
  - Black hole singularity behind the horizon
  - $\Longrightarrow$ Breakdown of the theory ? Need of quantization ?
- Very large (cosmological) scale : dark energy ?
  - Accelerated expansion of the universe leads to troubles
  - Signature of a modification of gravity laws ?

Robustness of gravity

Uniqueness of gravity + cosmological constant

- Hyp.1 : Space-time is of dimension 4 (+ symmetries)
- Hyp.2 : Gravity is described by a metric only
- Hyp.3 : Euler-Lagrange equations are second order
- Lovelock theorem : Einstein gravity + Cosmological constant

No much room available...

... Drop out one of the hypothesis above with :

- Theoretical/Experimental constraints
- Eventually, explain dark energy with fine tuning
- Almost no modifications at "small" scales (solar system)

Try to modify gravity

I like the idea that space-time is 4-dimensional

However, we assume that

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

Motivations

- Adding a scalar is the simplest case, but there are more complicated scenarii (bi-gravity, vectors,...) $\rightarrow$ including a scalar
- Higher order equations because the dynamics of gravity is governed by an action with second order derivatives : $\partial_\mu \partial_\nu g_{\rho\sigma} \rightarrow \partial_\mu \partial_\nu \phi$
- Let's see with a very simple example...

Toy-model : classical mechanics

Dynamics of a point like particle $q(t)$

$$\underline{\text{Action}} : \quad S[q(t)] = \int dt \, \left(\dot{q}^2 - \omega^2 q^2 + \alpha \ddot{q}^2\right)$$

$$\underline{\text{EoM}} : \quad \ddot{q} + \omega^2 q - \alpha \dddot{\ddot{q}} = 0 \, .$$

Degrees of Freedom

- One needs 4 initial conditions : $q(0)$, $\dot{q}(0)$, $\ddot{q}(0)$ and $\dddot{q}(0)$
- Hence, two degrees of freedom : two particles propagate !

Ostrogradski ghost

- The energy of the system is unbounded from below
- The extra DoF is called a ghost : quantum instability !

Evading Ostrogradski instability

Coupling several particles

- Only one particle : no way to escape - It's a theorem !
- Two particles : there is a different story. One can construct higher order actions with higher order EoM... With no Ostrogradski ghost ! Necessary and sufficient conditions : DEGENERACY
- A simple example

$$S[q_1(t), q_2(t)] = \int dt \left(\dot{Q}^2 - \omega^2 q_1^2 \right) , \quad Q = q_1 + \alpha \dot{q}_2$$

Higher derivative gravity

Charmousis, Crisostomi, Langlois, KN

- "In general", higher derivative gravity propagate ghosts...
- The two "gravitons" cannot combine to get rid of the ghost
- No way out to go beyond Einstein without breaking symmetries

Scalar-Tensor theories

Classification of scalar-tensor theories with no-ghost

$$S[g_{\mu\nu}, \phi] = S_{EH}[g_{\mu\nu}] + \int d^4x \, L[\phi, \partial_\mu\phi, \partial_\mu\partial_\nu\phi]$$

Langlois, KN - Crisostomi, Koyama, Tasinato

- Complete theoretical classification of DHOST theories
- They encompass many very well-known theories : Horndeski, Mimetic, Khronometric, Horava, etc...
- There are new theories with higher-order EoM

Constraints from GW detections (binary of neutron stars)

- GW propagates at speed of light (with uncertainty 10^{-15} !)
- Graviton decay ?

F. Vernizzi 's talk

Explicit DHOST theories

Full action compatible with GW detection : $c_g = 1$

$$S = \int d^4x\sqrt{g}\,[P + Q\Box\phi + G_N R + A_1\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi + A_2\phi^\mu\phi_{\mu\nu}\phi_\rho\phi^{\rho\nu} + A_3(\phi_\mu\phi^{\mu\nu}\phi_\nu)^2]$$

- $\phi_\mu = \partial_\mu\phi$ and $\phi_{\mu\nu}$ are second (covariant) derivatives
- The functions P, Q, G_N and A_α depend on ϕ and $X = \phi_\mu\phi^\mu$
- A_I are not independent

Conclusion and beyond

Systematic study of large class of modified gravity theories

- Scalar-Tensor theories $S[g_{\mu\nu}, \phi]$ where ϕ responsible for dark force
- Theoretical classification of DHOST theories with NO GHOST
- Physical effects that could be measured in principle...

Effective theories for quantum gravity

- Effective description of quantum effects at very strong gravity
- Theories with Lorentz symmetry breaking

Going further

Include scalar-tensor theories in numerical analysis to compute GW templates $\Longrightarrow$ New tests of general relativity...