Modified gravity in Cosmology & Astrophysics

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Astroparticules
et Cosmologie

Introduction

- So far, **GR** seems compatible with all observations.

- Several motivations for exploring **modified gravity**
  - Quantum gravity effects
  - Understand cosmological acceleration (or possibly dark matter)
  - Explore alternative gravitational theories
  - **Testing gravity**

- Modified gravity actively studied in two main contexts:
  - In cosmology (alternative to the cosmological constant, exotic early Universe models)
  - In astrophysics: compact objects (black holes, neutron stars)

Modified gravity

It is rather difficult to modify gravity:

1. The theory must be **internally consistent** (e.g. no problematic instabilities)

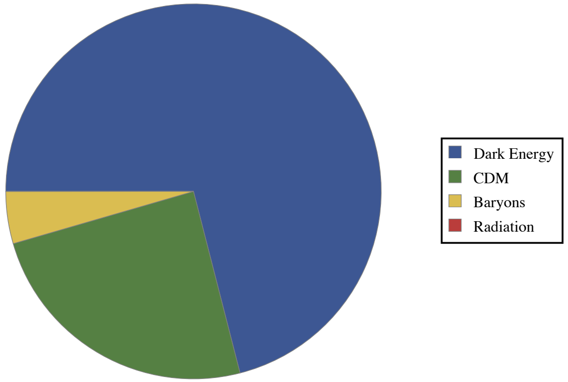
2. The theory **must look like GR** in all regimes where GR has been tested

   Lab tests, Solar system, Binary pulsars (and now binary BH)

3. Hopefully (but not necessarily), the theory should **account for the observed acceleration** and exhibit some **distinctive signatures**.

Modified gravity in Cosmology

- **Goal: Explain** the observed **cosmological acceleration** without cosmological constant

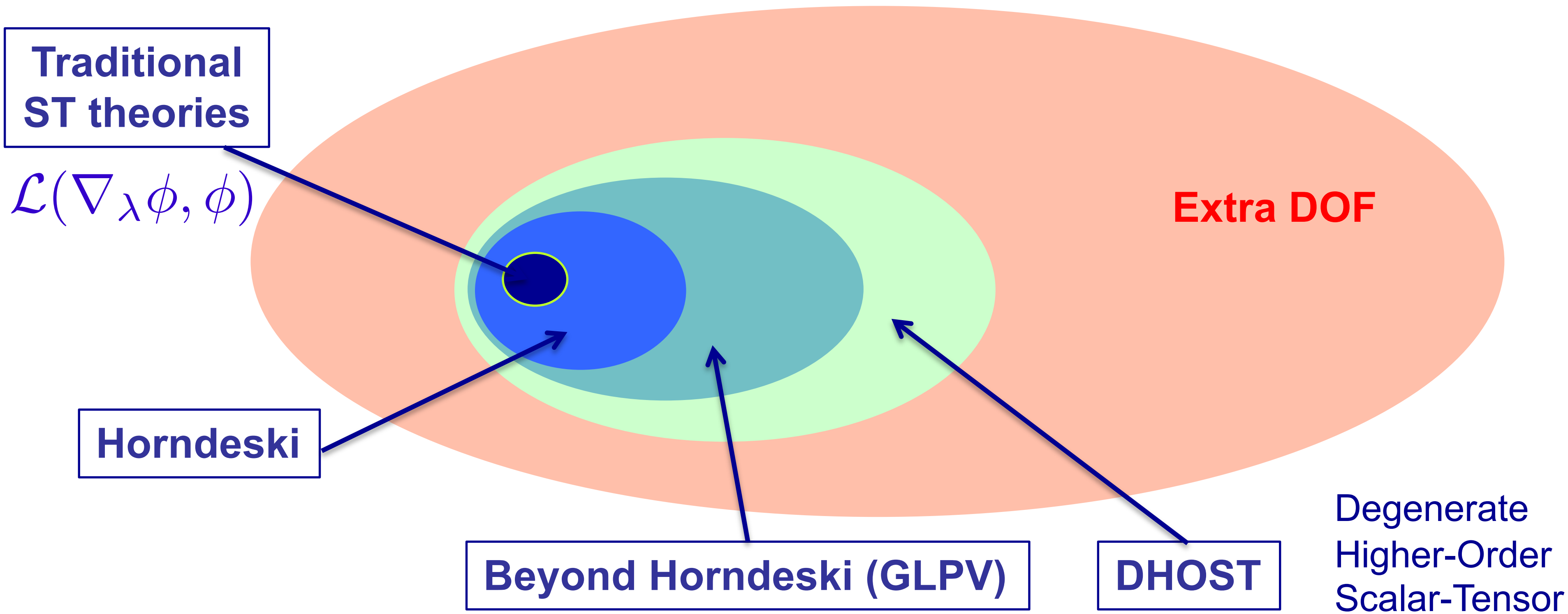


- Most models are based on scalar-tensor theories:
  - Traditional models: $\mathcal{L}(\nabla_\lambda \phi, \phi)$
  - Generalised models: $\mathcal{L}(\nabla_\mu \nabla_\nu \phi,\ \nabla_\lambda \phi,\ \phi)$

- New phenomenology on cosmological scales

Higher order scalar-tensor theories

- Generalized theories: $\mathcal{L}(\nabla_\mu\nabla_\nu\phi,\, \nabla_\lambda\phi,\, \phi)$
- **DHOST:** most general family of covariant scalar-tensor theories with a **single scalar DOF**



Modified gravity in Cosmology

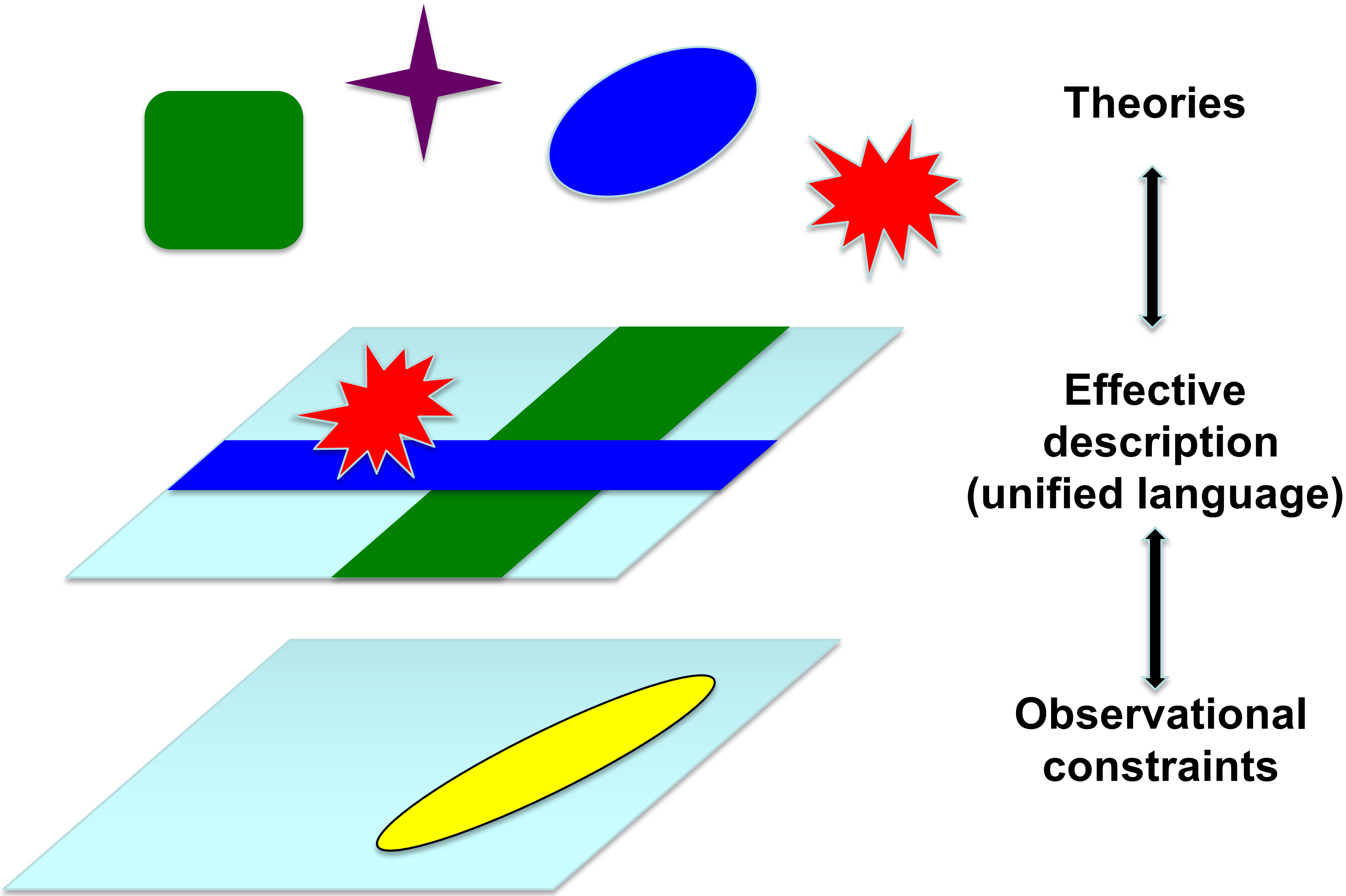
- **Internal consistency of the model**
  - No problematic instabilities

- **Potential new signatures:**
  - Speed of gravitational waves different from *c*
    [but GW170817 has probed only wavelengths 10^3 km]
  - Evolution of perturbations differs from Lambda-CDM predictions

- Many models: effective approach that can describe all (or most) models is useful

- Future observations: Euclid, LSST…

Effective description of dark energy

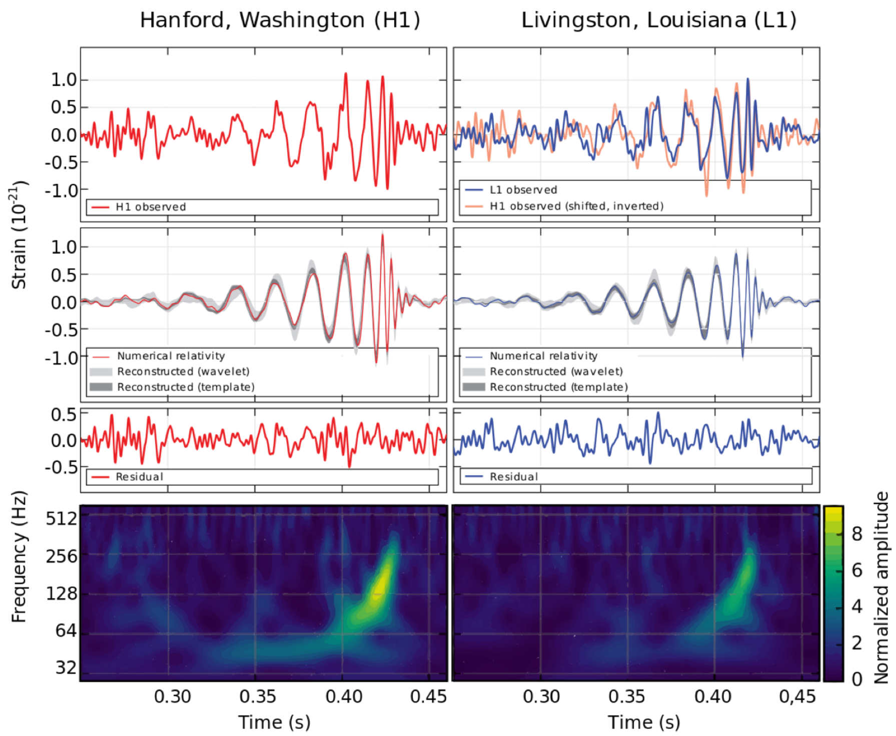


Modified gravity in Astrophysics

- Explore modified gravity in the strong-field regime

- Compact objects:
  - Black holes
  - Neutron stars

- New probe
  Gravitational waves



Black holes in modified gravity

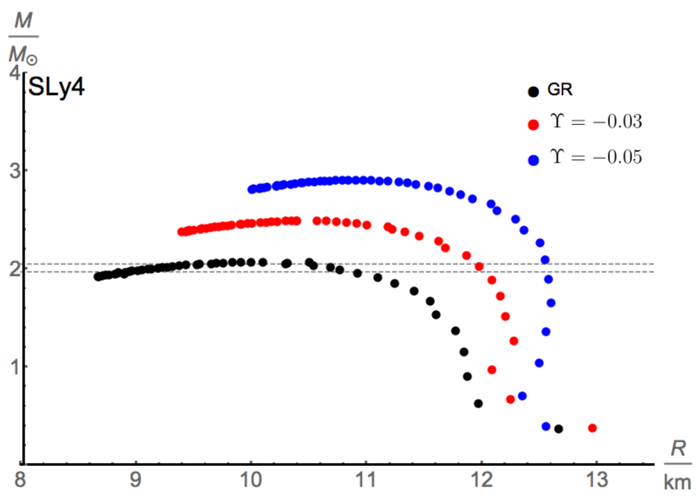
- Static solutions
  - Various **exact solutions**
  - Extra field: scalar field or vector field
- Linear perturbations:
  - Odd-parity & even-parity modes
  - **Quasi-normal modes**
- Rotating solutions
  - Kerr or Kerr-like solutions ?
  - Perturbations
- Description of **binary systems**

Neutron stars in modified gravity

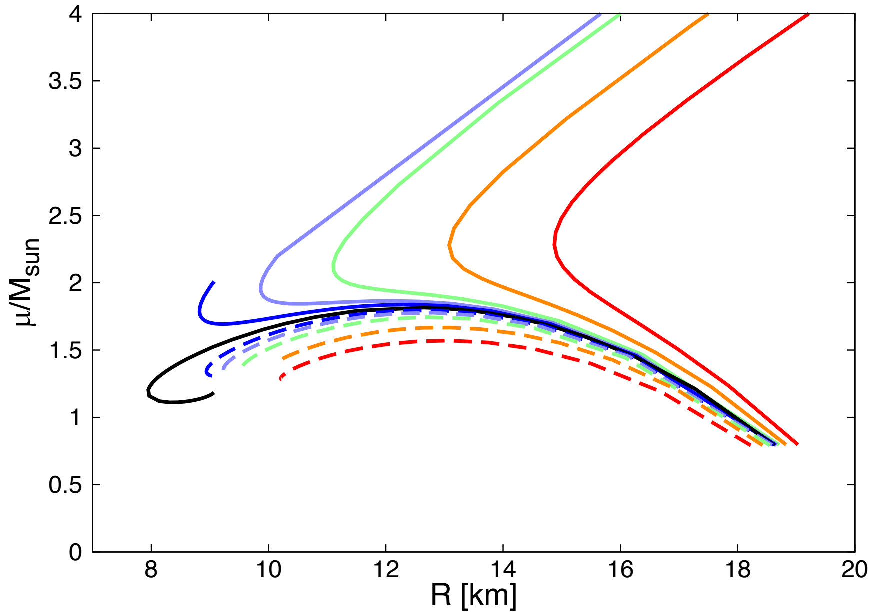
- Internal solution

  System analog to Tolman-Oppenheimer-Volkov equations

- Mass-radius relations



Sakstein, Babichev, Koyama, DL & Saito '16



Kobayashi & Hiramatsu '1803

Conclusions

- Exploring modified gravity is ubiquitous in works on cosmology and compact objects.
- There is no compelling theory of modified gravity at present but parametrized models enable us to test GR.
- In cosmology, general family of scalar-tensor theories, encompassing most theories of interest, as well as an **effective framework** to connect theories to the phenomenology of cosmological perturbations.
- Deviations from GR in the context of compact objects (e.g. neutron stars & black holes) is more diverse and more complex.