Scalar-tensor theories after GW170817

Eugeny Babichev
Laboratory for Theoretical Physics, Orsay

XXth International Seminar on High Energy Physics “Quarks-2018”
27 May - 2 June 2018
Modification of gravity

Why modify gravity?

✦ Cosmological constant problem: vacuum energy is huge. How to cancel it?

✦ Dark energy problem: the present-day acceleration of the Universe. What is the cause? Also coincidence problem.

✦ Dark matter problem.

✦ Inflation
Modification of gravity

Why modify gravity?

✦ Make gravity renormalisable

✦ Theoretical curiosity

✦ Establishing benchmarks to compare with GR
Many ways to modify gravity

- Old-school (vanilla) scalar tensor theory, $f(R)$  
  (Talk by A. Starobinsky)

- Galileons, Horndeski (and beyond) theory, KGB, Fab-four …

- Higher dimensions, brane worlds

- Massive and bi -gravity, massive spin-2  
  (Talk by M. Volkov)

- Horava gravity, Khronometric  
  (Talk by S. Mukohyama, A. Barvinsky)

- Non-local models  
  (Talk by S. Vernov)

- Gravity with torsion  
  (Talk by V. Nikiforova)
Modification of gravity

Why scalar tensor models?

✦ Simple (the simplest?)

✦ Many theories related to scalar-tensor theories in specific regimes:
  ▶ Massive (bi) gravity
  ▶ Kaluza-Klein reduction of higher-dimensional theories (i.e. DGP)
  ▶ Vector-scalar theories
Motivation: to attack problems in cosmology

- Cosmological constant problem: vacuum energy is (naively) huge due to the zero-point energy of the vacuum and/or due to the phase transitions. How to cancel it?

- Dark energy problem: the present-day acceleration of the Universe. What is the cause? Additionally — coincidence problem.

- Dark matter problem. Probably not so appealing anymore.

- Inflation
Attempts to solve the problems

- Modifying general relativity?
  The only nontrivial Lagrangian made of metric solely in 4D is GR+c.c. \( R - \Lambda \)

- Simplest modification of General relativity: one extra degree of freedom

\[
R \rightarrow \phi R - \frac{\omega}{\phi} \partial_\mu \phi \partial^\mu \phi \rightarrow A(\phi) R - f(\phi) \partial_\mu \phi \partial^\mu \phi - V(\phi)
\]


- Models of inflation (Starobinsky model, Higgs inflation …) ( Talks by A. Starobinsky, A. Toporenski, A. Tokareva)

- Dark energy models (Quintessence, Non-minimal quintessence, k-essence, …) — an alternative to Lambda-term in cosmology

- Relativistic MOND — an alternative to CDM

- Dynamical adjustment mechanism of vacuum energy  (Dolgov model)
Can scalar tensor theory help to solve CC problem?

Weinberg’s no-go theorem:
It is impossible to screen the spacetime curvature from the net cosmological constant with the help of a scalar field (adjustment mechanism).

Assumptions:
- Poincaré invariance of the vacuum fields
- ...
- ...
More general theories?

Pure scalar sector:

\[-\partial_\mu \phi \partial^{\mu} \phi - \frac{1}{2} m^2 \phi^2 \rightarrow -\partial_\mu \phi \partial^{\mu} \phi - V(\phi) \rightarrow K(\partial_\mu \phi \partial^{\mu} \phi, \phi)\]

- canonical scalar theory
- nonlinear potential
- k-essence

More non-linear

\[(\partial_\mu \phi \partial^{\mu} \phi) \Box \phi \rightarrow (\Box \phi)^2 \partial_\mu \phi \partial^{\mu} \phi - 2 \Box \phi \partial_\mu \phi \partial_\nu \phi \nabla^\mu \nabla^\nu \phi + ... \rightarrow\]

- Monge-Ampère
- “galileon”

\[(\Box \phi)^3 \partial_\mu \phi \partial^{\mu} \phi - 3(\Box \phi)^2 \partial_\mu \phi \partial_\nu \phi \partial^{\mu} \partial^{\nu} \phi + ...\]

- even more complicated
- “galileon”

we don’t want to have extra d.o.f.
More general theories (Scalar-tensor)?

EOMS contain no more than second derivatives!

\[ S = \int d^4x \ F \left[ g, \partial g, \partial^2 g, \varphi, \partial \varphi, \partial^2 \varphi \right] \]

Horndeski theory[1974]

\[ E[g, \partial g, \partial^2 g, \varphi, \partial \varphi, \partial^2 \varphi] = 0 \]

\[ G_2(X, \phi), \ G_3(X, \phi), \ G_4(X, \phi), \ G_5(X, \phi) \]

\[ L_2 = G_2(X, \phi) \]
\[ L_3 = G_3(X, \phi) \Box \phi \]
\[ L_4 = G_4(X, \phi) R + G_{4,X}(X, \phi) \left[ (\Box \phi)^2 - (\nabla \nabla \phi)^2 \right] \]
\[ L_5 = G_{5,X}(X, \phi) \left[ (\Box \phi)^3 - 3 \Box \phi (\nabla \nabla \phi)^2 + 2 (\nabla \nabla \phi)^3 \right] - 6 G_5(X, \phi) \ G_{\mu \nu} \nabla^\mu \nabla^\nu \phi \]
\[ X \equiv (\partial \phi)^2 \]
Modern scalar-tensor theories

Extension of Horndeski: + 2 extra functions

EOMS contain three derivatives

Degenerate Higher-Order Scalar-Tensor (DHOST) theories

or

Extended scalar-tensor (EST) theories

beyond Horndeski

\[ \mathcal{L}_4^{bH} = F_4(X, \phi) \varepsilon^\mu_{\alpha \gamma} \varepsilon^\nu_{\beta \delta} \partial_\mu \phi \partial_\nu \phi (\nabla_\alpha \nabla_\beta \phi) (\nabla_\gamma \nabla_\delta \phi) \]

\[ \mathcal{L}_5^{bH} = F_5(X, \phi) \varepsilon^\mu_{\alpha \gamma} \varepsilon^\nu_{\beta \delta} \partial_\mu \phi \partial_\nu \phi (\nabla_\alpha \nabla_\beta \phi) (\nabla_\gamma \nabla_\delta \phi) (\nabla_\rho \nabla_\sigma \phi) \]

\( G_4, G_5, F_4, F_5 \) are related

\[ g_{\mu \nu} \rightarrow C g_{\mu \nu} + D \partial_\mu \phi \partial_\nu \phi \]

\( C(X, \phi), D(X, \phi) \)

Zumalacárregui & García-Bellido’14
Gleyzes et al’15
Deffayet et al’15
Langlois and Noui’15
Crisostomi et al’16
Motohashi et al’16

talk by M. Yamaguchi
Horndeski, beyond Horndeski and beyond^2 Horndeski

DHOST I/EST
+C(X)

beyond Horndeski
+ \{F_4(X, \phi) \leftrightarrow F_5(X, \phi)\}

Horndeski theory
G_2(X, \phi), G_3(X, \phi), G_4(X, \phi), G_5(X, \phi)

\( g_{\mu\nu} \rightarrow C g_{\mu\nu} + D \partial_\mu \phi \partial_\nu \phi \)
Features of galileons:

- Kinetic nonlinearity of EOMs

\[ \Box \phi + \mathcal{E}_{gal} = 0 \]

If the theory is (almost) shift-symmetric (the action is invariant with respect to \( \phi \rightarrow \phi + \text{const} \)), the scalar field naturally takes a non-constant value \( \dot{\phi} \neq 0 \)

*The assumption of Poincaré invariance in the Weinberg no-go theorem can be avoided.*

- Possibility to violate energy conditions (in particular the Null energy condition)
Self-accelerating Universe (Dark energy problem): galileon Dark energy

Inflation (inflation driven by galileon) (Talk by S. Sushkov)

Alternatives to inflation (Bounce and Genesis) (Talk by V. Volkova)

Dark matter (Improving MOND)

Cosmological constant problem (Fab4, Fab5, 3Graces, self-tuning, Well-Tempered Cosmological Constant)
Screening mechanisms (Vainshtein mechanism,…) to restore GR in Solar system

Modification of neutron stars, while dwarfs structures (breaking of Vainshtein mechanism)

Scalarisation: black holes and neutron stars spontaneously acquire hairs

Non-GR black holes, hairy solutions…

Wormholes  (Talks by O. Evseev, S. Mironov)
Speed of propagation

\[ G_3 : \quad (\partial_\mu \phi \partial_\nu \phi) \square \phi \supset \Gamma \partial \phi \sim \partial g \partial \phi : \quad \text{kinetic mixing (braiding)} \]

Speed of propagation of the scalar mode changes \( c_s \neq 1 \)
graviton mode speed is not modified \( c_g = 1 \)

\[ \sim (\nabla_\mu \nabla_\nu \phi)(\nabla^\mu \nabla^\nu \phi) : \quad c_s \neq 1, \ c_g \neq 1 \]

On nontrivial background both scalar and tensor modes have speed of propagation different from 1
GW170817 / GRB170817A

Horndeski theories

The no-hair theorem

Breaking the hypotheses

Parenthesis: Did GW170817 kill Horndeski gravity?

Fermi

LIGO

Gamma rays, 50 to 300 keV

Counts per second

Gravitational-wave strain

Frequency (Hz)

Time from merger (seconds)
$40 \text{ Mpc}$

$1.74 \text{ sec}$

$\frac{|c_g - c_{light}|}{c_{light}} < 10^{-15}$
Consequences of GW170817 / GRB170817A, graviton speed = speed of light:

I. Is generalised scalar-tensor theory dead?

II. Cosmology, Black holes, Neutron stars...
Cosmology / local physics

- Dark energy
- Self-tuning (CC problem)

Inflation and alternatives

- Black holes
- Wormholes
- Neutron stars
- Scalarisation

Constraints on the theory
Constraint on the deviation of the graviton speed from the speed of light: $|c_{\text{grav}}/c_{\text{light}} - 1| < 10^{-15}$ for weakly curved backgrounds

Surviving DHOST/EST theory contains 4 arbitrary functions

$$\mathcal{L} = G_2(X, \phi) + G_3(X, \phi) \Box \phi : \quad c_s = c_{\text{light}}$$

$$+ G_4(X, \phi) \quad \text{changes speed of graviton: } c_s \neq c_{\text{light}}$$

However can be compensated by beyond Horndeski piece $F_4(X, \phi)$, so that $c_s = c_{\text{light}}$

One extra function which correspond to conformal transformation of the metric $C(X)$

[Creminelli,Vernizzi’17, Ezquiaga,Zumalacarregui’17, Langlois et al’17, …]
Cosmology and scalar-tensor theories

\[ G_2(X), G_3(X), G_4(X), G_5(X) \]

\[ G_2(X, \phi), G_3(X, \phi) \]

\[ G_2(X, \phi), G_3(X, \phi), G_4(X, \phi), G_5(X, \phi) \]

\[ c_g = c_{\text{light}} \]

\[ c_g \neq c_{\text{light}} \]

DHOST I/EST

Beyond Horndeski

Horndeski theory
Exact Schwarzschild-de-Sitter black holes in beyond Horndeski (DHOST/EST) theory.

Non-trivial scalar field.

Speed of gravity = speed of light in the vicinity of black hole, provided that it is true asymptotically.

Stable black holes: no ghosts, no gradient instability.
Further constraints?

Time-dependent cosmological scalar field

Time-dependent scalar field in and around black holes and stars

Breaking of the Vainshtein mechanism inside stars

Anomalous mass-to-radius relation; I/C is also modified

Hairy black holes

Modified motion of stars around BHs; Modified shadow of black holes

White dwarfs with non-GR masses

Different gravitational signal from merging of black holes and neutron stars

(Talk by A. Zakharov)
Theoretical issues

- Well-posedness of the Cauchy problem (hyperbolicity)?
- Absence of ghosts?
- Globally Hamiltonian is not bounded from below?
- Caustics
- Quantum corrections and loop corrections?
Conclusions

- GW170817 constraints Dark energy and self-tuning scalar-tensor theories
- Nevertheless moderns scalar-tensor theories are not dead
- It is possible that in near(est) future scalar-tensor theories will be constrained further
- On the other hand one can hope to find smoking guns from observations of LIGO/VIRGO and Event horizon telescope
- Theoretical issues