Scalar-tensor theories after GW170817

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Modification of gravity

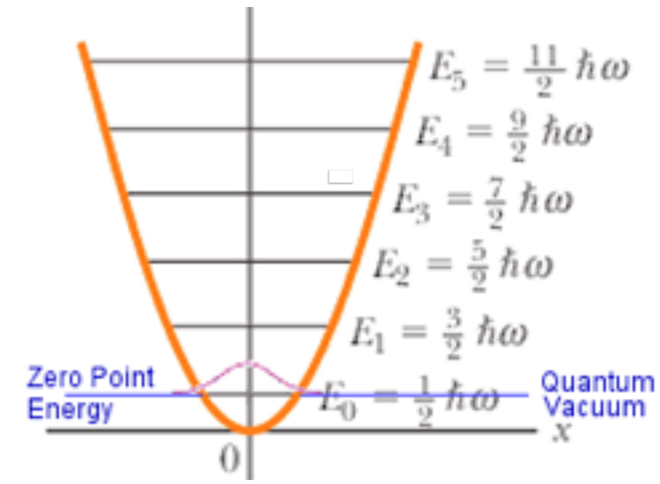
Why modify gravity?

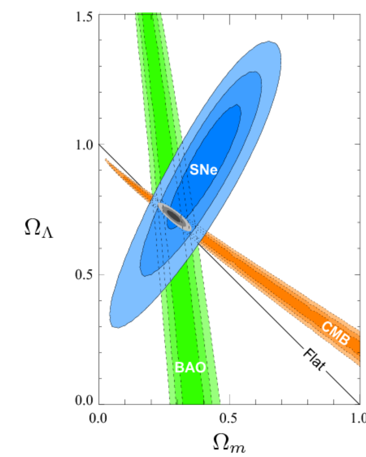
- ✦ Cosmological constant problem: vacuum energy is huge. How to cancel it?

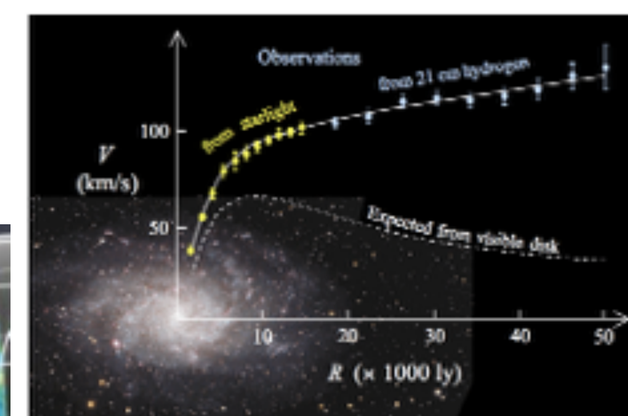
- ✦ Dark energy problem: the present-day acceleration of the Universe. What is the cause? Also coincidence problem.

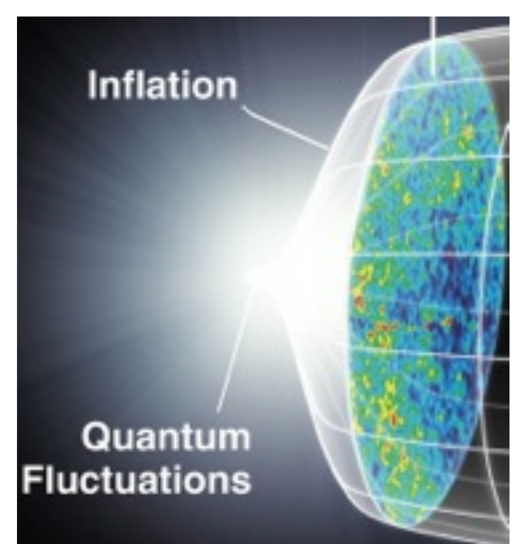
- ✦ Dark matter problem.

- ✦ Inflation









Modification of gravity

Why modify gravity?

- ✦ Make gravity renormalisable
- ✦ Theoretical curiosity
- ✦ Establishing benchmarks to compare with GR

Modification of gravity

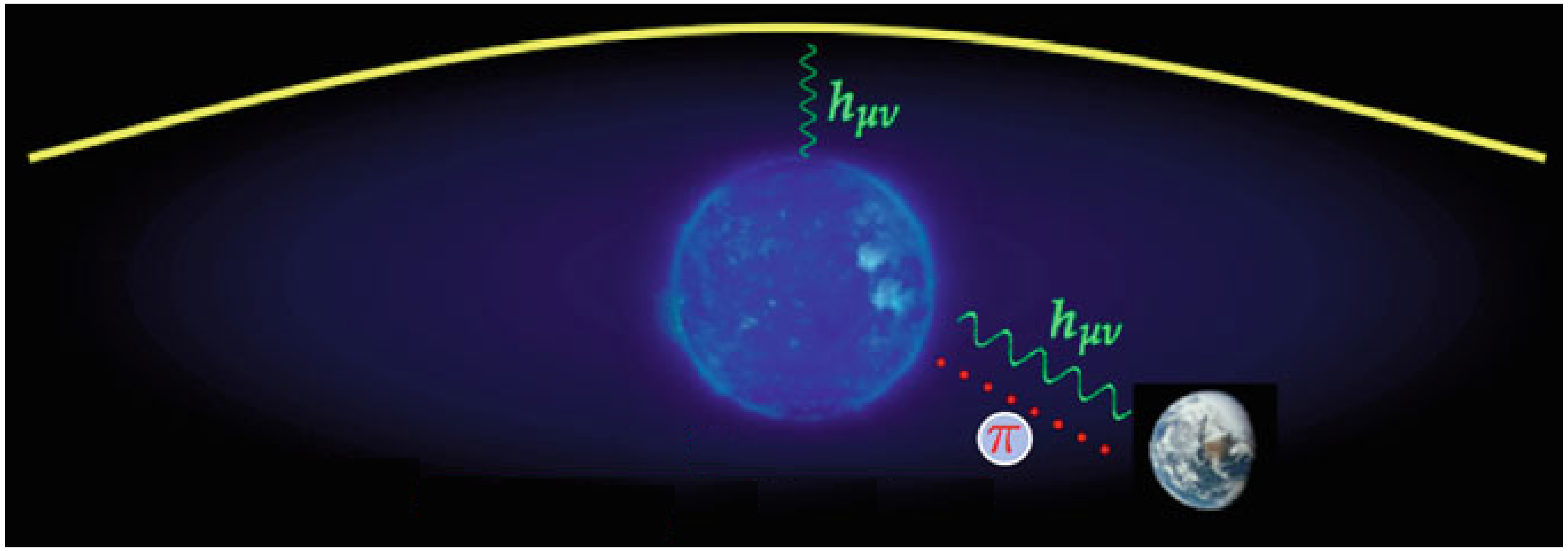
Many ways to modify gravity

- ✦ 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

$$R \to \quad \phi R - \frac{\omega}{\phi}\partial_\mu \phi \partial^\mu \phi \to \quad A(\phi)R - f(\phi)\partial_\mu \phi \partial^\mu \phi - V(\phi)$$

GR [1915] Brans-Dicke[1961] "Generalised scalar-tensor"

- 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
- …
- …

Modern scalar-tensor theories

More general theories?

Pure scalar sector:

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

canonical scalar theory — nonlinear potential — k-essence

More non-linear

$$(\partial_\mu\phi\partial^\mu\phi)\Box\phi \rightarrow \quad (\Box\phi)^2\partial_\mu\phi\partial^\mu\phi - 2\Box\phi\,\partial_\mu\phi\partial_\nu\phi\nabla^\mu\nabla^\nu\phi + \ldots \rightarrow$$

Monge-Ampère — "galileon"

$$(\Box\phi)^3\partial_\mu\phi\partial^\mu\phi - 3(\Box\phi)^2\partial_\mu\phi\partial_\nu\phi\partial^\mu\partial^\nu\phi + \ldots$$

even more complicated "galileon"

we don't want to have extra d.o.f.

Modern scalar-tensor theories

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]

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

$$G_2(X,\phi),\ G_3(X,\phi),\ G_4(X,\phi),\ G_5(X,\phi)$$

$$\mathcal{L}_2 = G_2\left(X,\phi\right)$$
$$\mathcal{L}_3 = G_3\left(X,\phi\right)\Box\phi$$
$$\mathcal{L}_4 = G_4(X,\phi)\,R + G_{4,X}(X,\phi)\left[(\Box\phi)^2 - (\nabla\nabla\phi)^2\right]$$
$$\mathcal{L}_5 = G_{5,X}\left(X,\phi\right)\left[(\Box\phi)^3 - 3\Box\phi\left(\nabla\nabla\phi\right)^2 + 2\left(\nabla\nabla\phi\right)^3\right] - 6G_5\left(X,\phi\right)\,G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$
$$X \equiv (\partial\phi)^2$$

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

$$\mathcal{L}_4^{bH} = F_4(X,\phi)\,\varepsilon^{\mu\alpha\gamma}{}_{\sigma}\varepsilon^{\nu\beta\delta\sigma}\partial_\mu\phi\partial_\nu\phi\,(\nabla_\alpha\nabla_\beta\phi)\,(\nabla_\gamma\nabla_\delta\phi)$$

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

G_4, G_5, F_4, F_5 are related

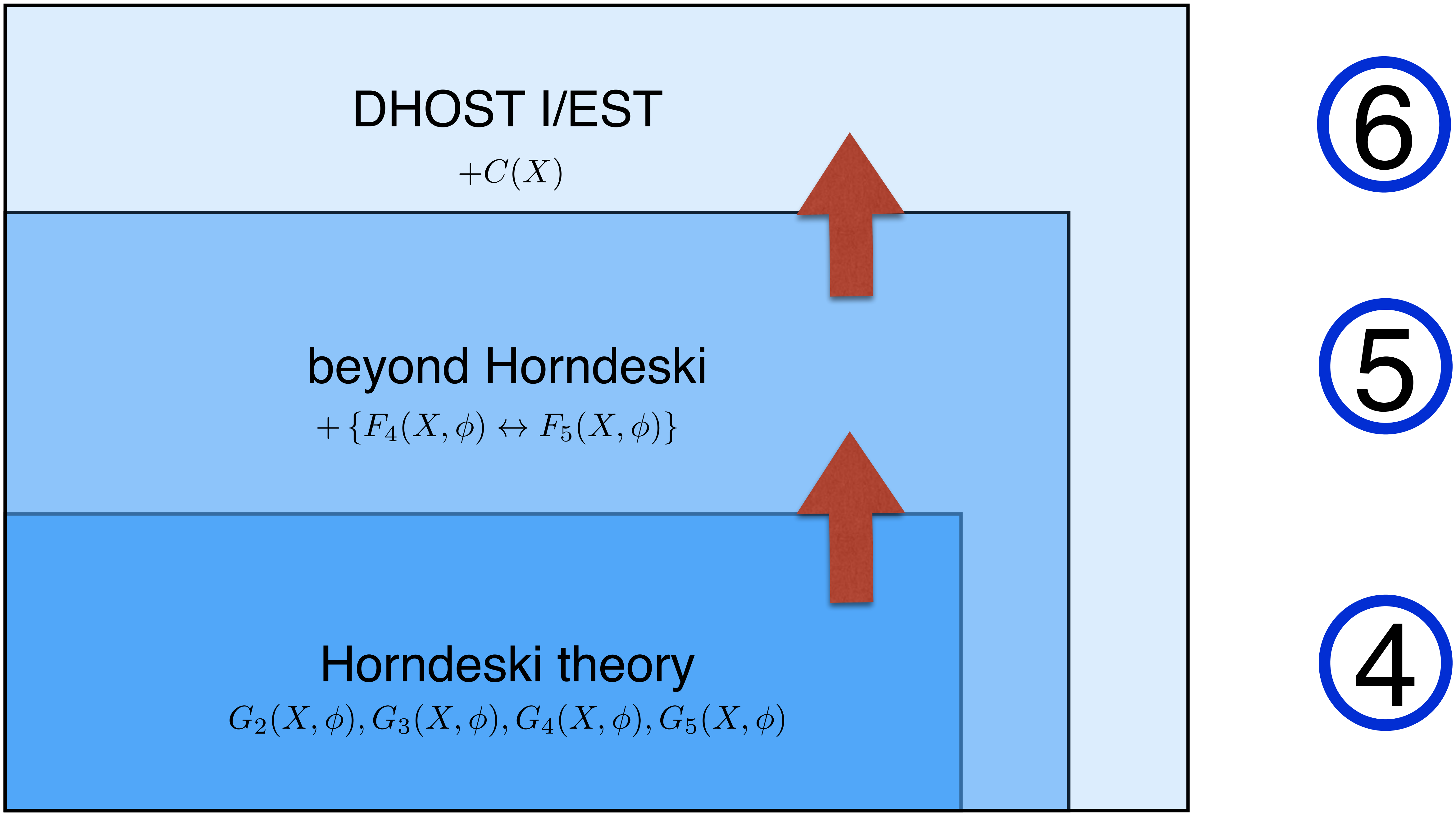
Zumalacárregui&García-Bellido'14
Gleyzes et al'15
Deffayet et al'15
Langlois and Noui'15
Crisostomi et al'16
Motohashi et al'16

$$g_{\mu\nu} \longrightarrow Cg_{\mu\nu} + D\partial_\mu\phi\partial_\nu\phi$$

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

talk by M. Yamaguchi

Horndeski, beyond Horndeski and beyond^2 Horndeski



$$g_{\mu\nu} \quad \longrightarrow \quad C g_{\mu\nu} + D\partial_\mu\phi\partial_\nu\phi$$

Horndeski and beyond

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 $\phi \to \phi + \mathrm{const}$), 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)

Interesting cosmology

- 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)

Interesting local physics

- 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

$$G_3: \quad (\partial_\mu\phi\partial^\mu\phi)\Box\phi \ \supset\ \Gamma\partial\phi \ \sim\ \partial g\partial\phi: \quad \text{kinetic mixing (braiding)}$$

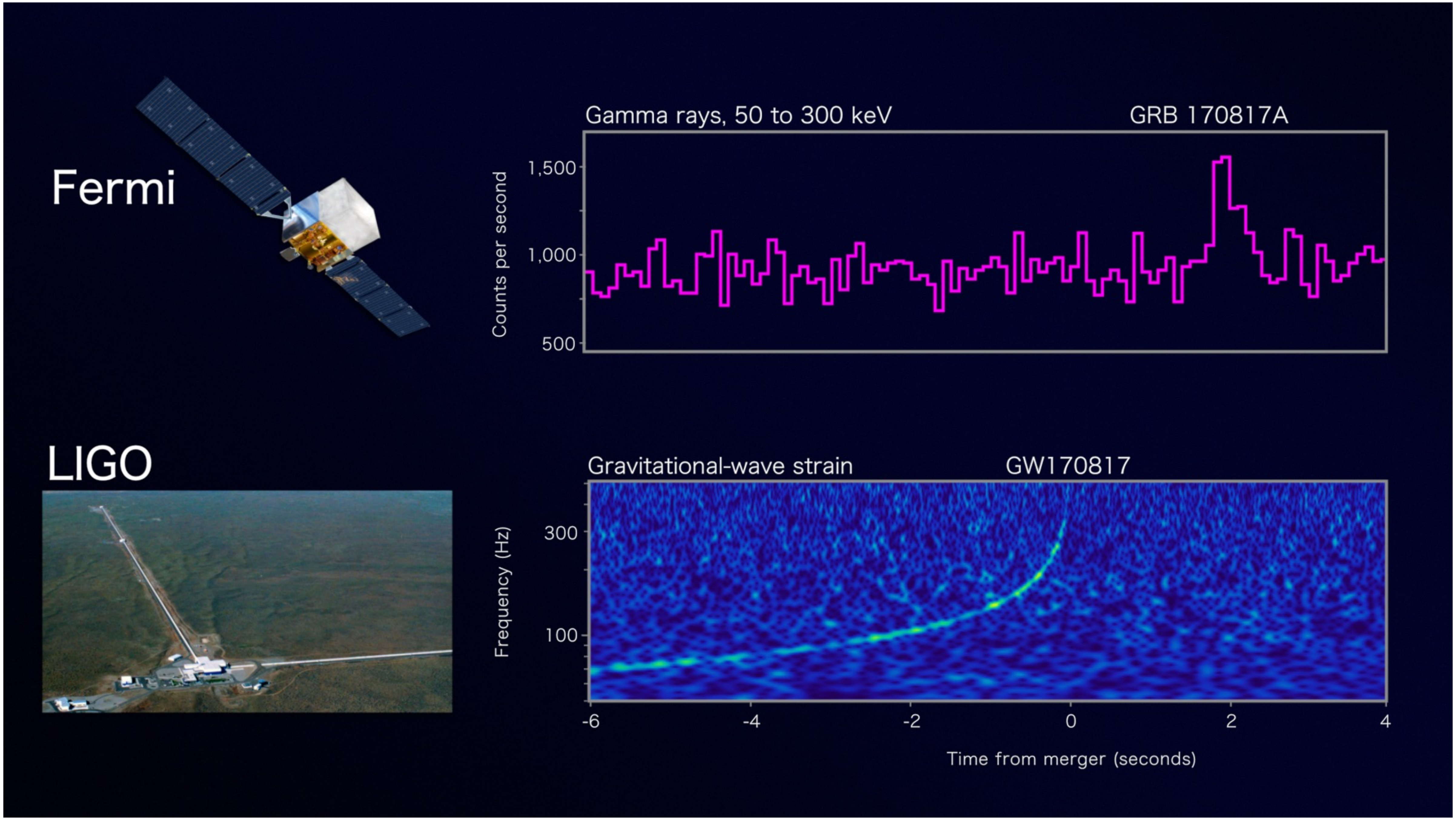
Speed of propagation of the scalar mode changes $c_s \neq 1$

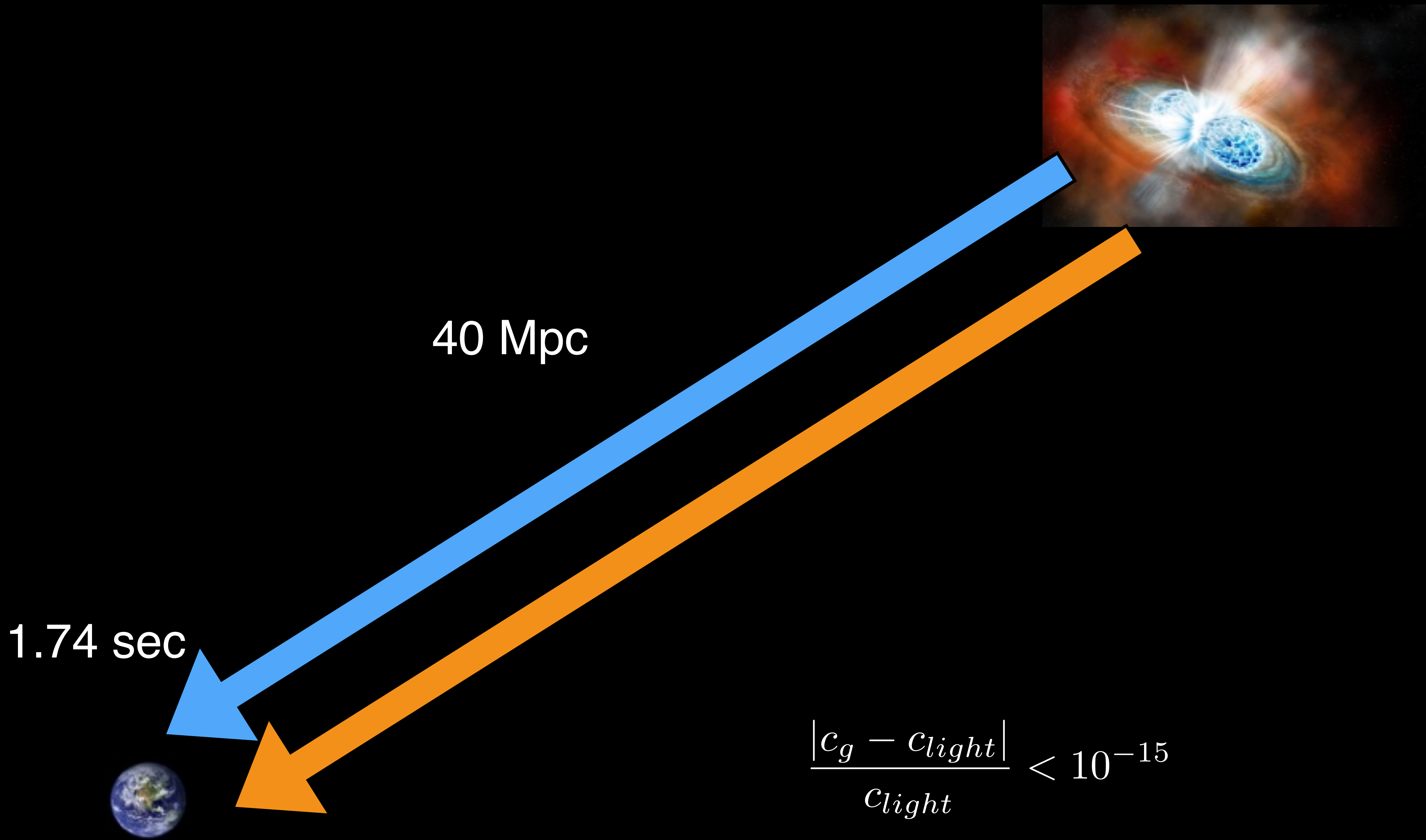
graviton mode speed is not modified $c_g = 1$

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

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

GW170817/GRB170817A




40 Mpc
1.74 sec
$$\frac{|c_g - c_{light}|}{c_{light}} < 10^{-15}$$

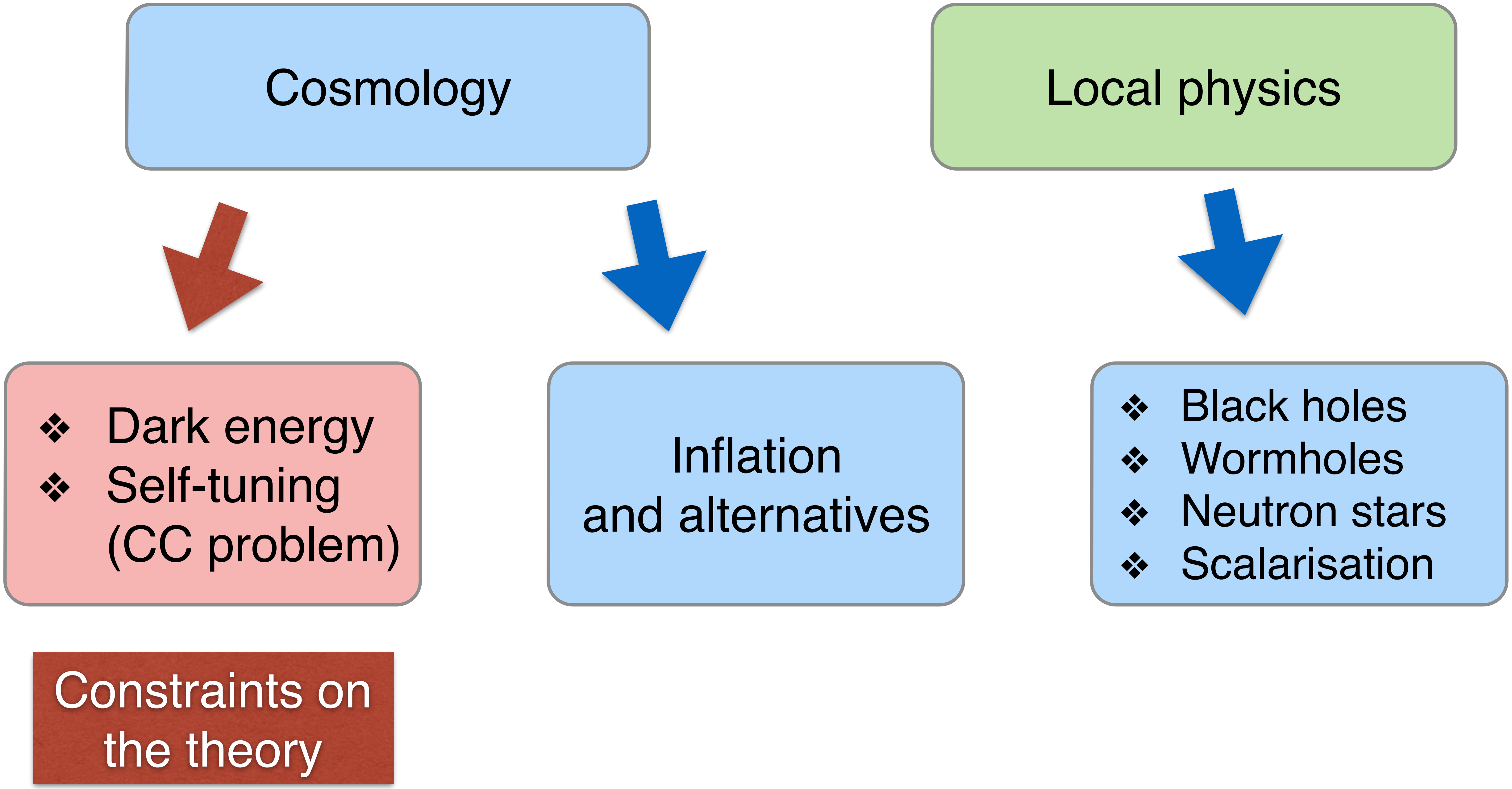
Consequences of GW170817 / GRB170817A,

graviton speed = speed of light:

I. Is generalised scalar-tensor theory dead?

II. Cosmology, Black holes, Neutron stars…

Cosmology / local physics



GW170817/GRB170817A

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

- Surviving DHOST/EST theory contains 4 arbitrary functions

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

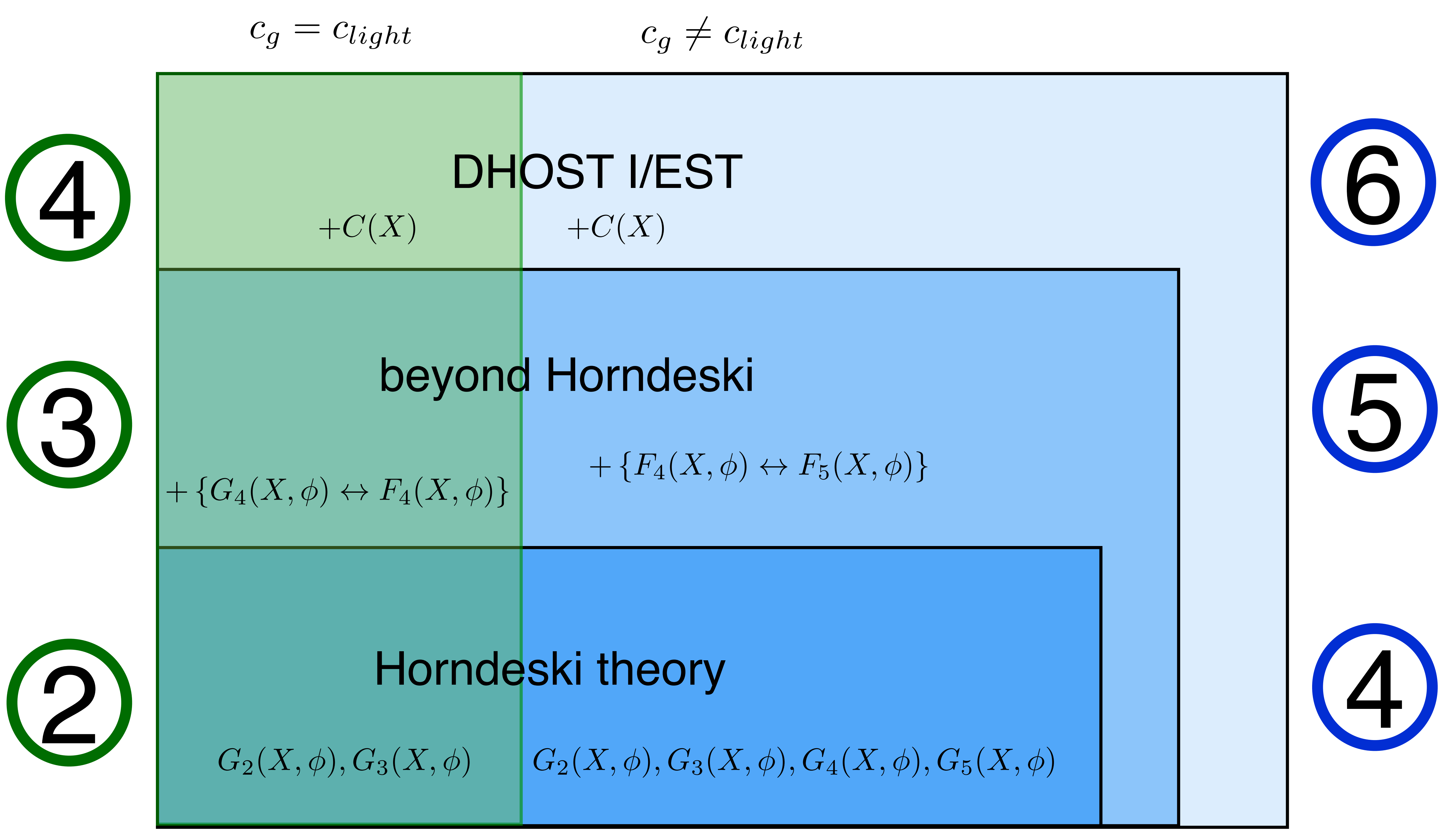
$$+G_4(X,\phi) \ \text{changes speed of graviton} : c_s \neq c_{light}$$

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

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



Black holes after GW170817

- 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

Hairy black holes

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

white dwarfs with
non-GR masses

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

(Talk by A. Zakharov)

Different gravitational signal from merging of
black holes and neutron stars

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