Dark Energy after GW170817 Revisited

Investigating gravitational wave propagation and phenomenology in (beyond)-Horndeski theories after GW17081

arXiv:1810.08239, or see the poster

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in collaboration with

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Hot topics in Modern Cosmology.
Spontaneous Workshop XIII 5 - 11 May 2019, Cargese

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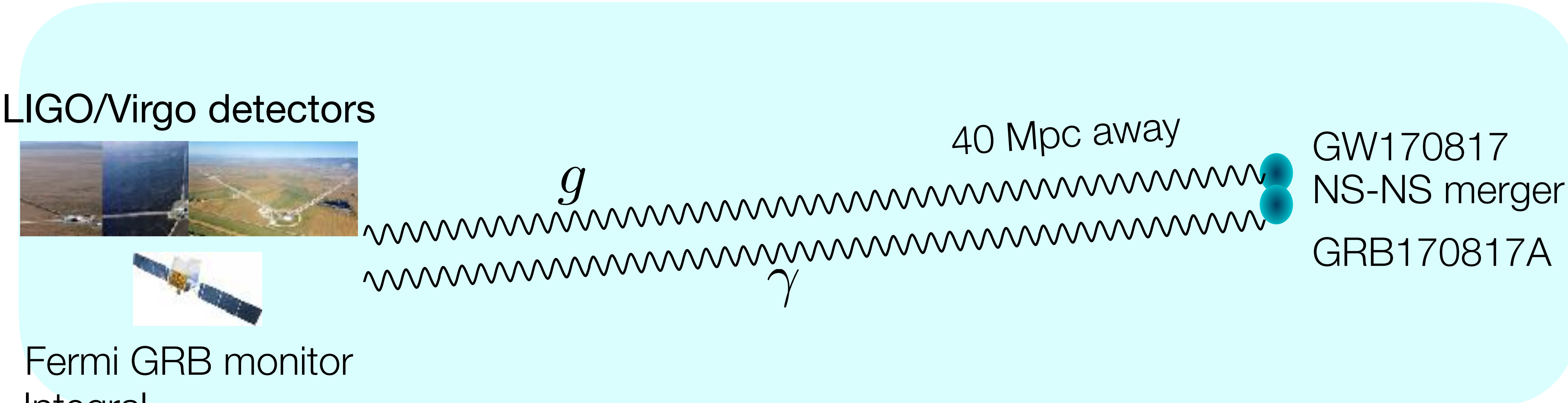
New test of GR: Gravitational waves



Integral

within 1.7 seconds of Grav. Wave

$$\alpha_T = |c_T^2 - 1| \approx \frac{2\Delta t}{d_S}$$

$$d_S \sim 40Mpc$$

$$\alpha_T \leq 10^{-15}$$

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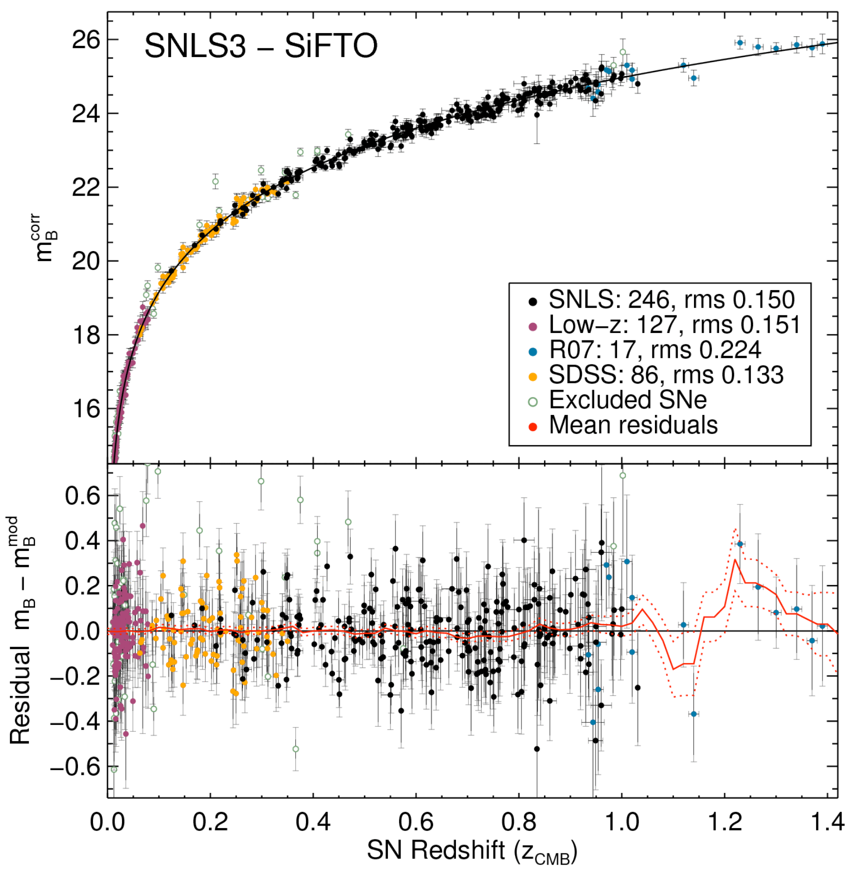
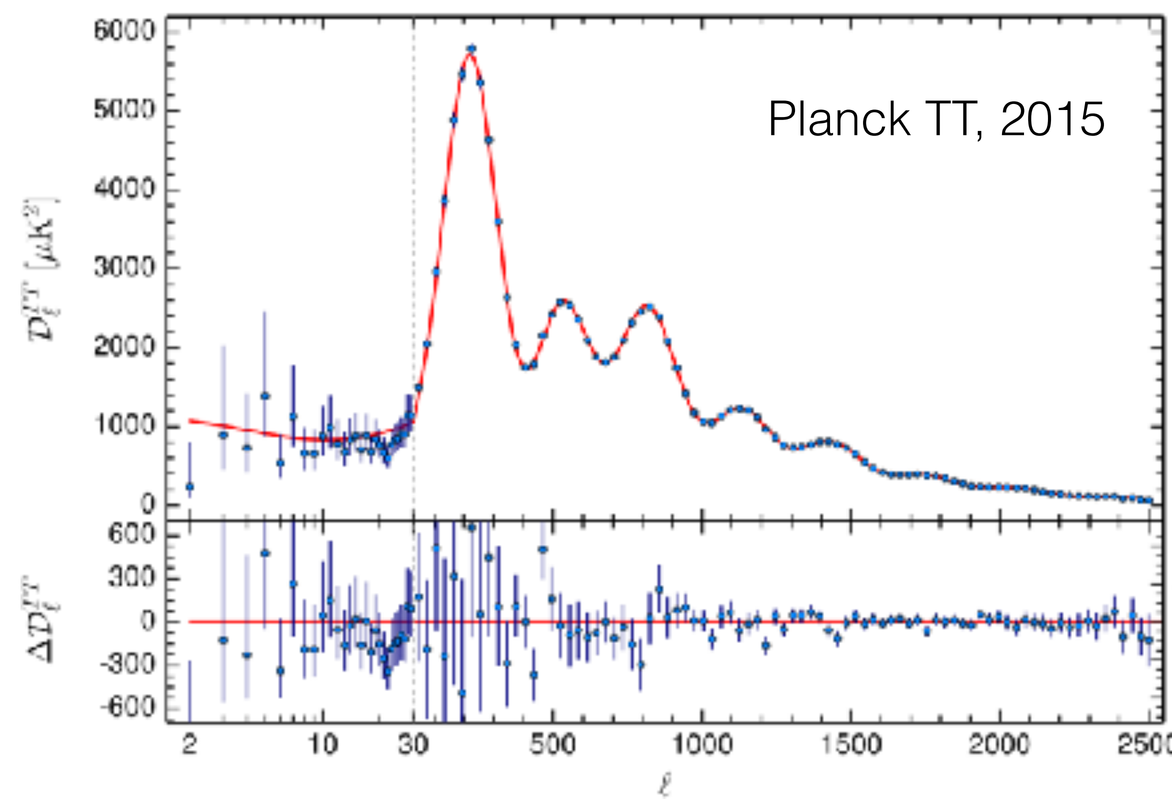
Dark Energy as breakdown of GR





If not Λ then what?

Dynamical fields: e.g. Quintessence, k-essence,…

Field-theoretical: e.g. Massive gravity, Galileons, Chameleons, Horndeski etc.

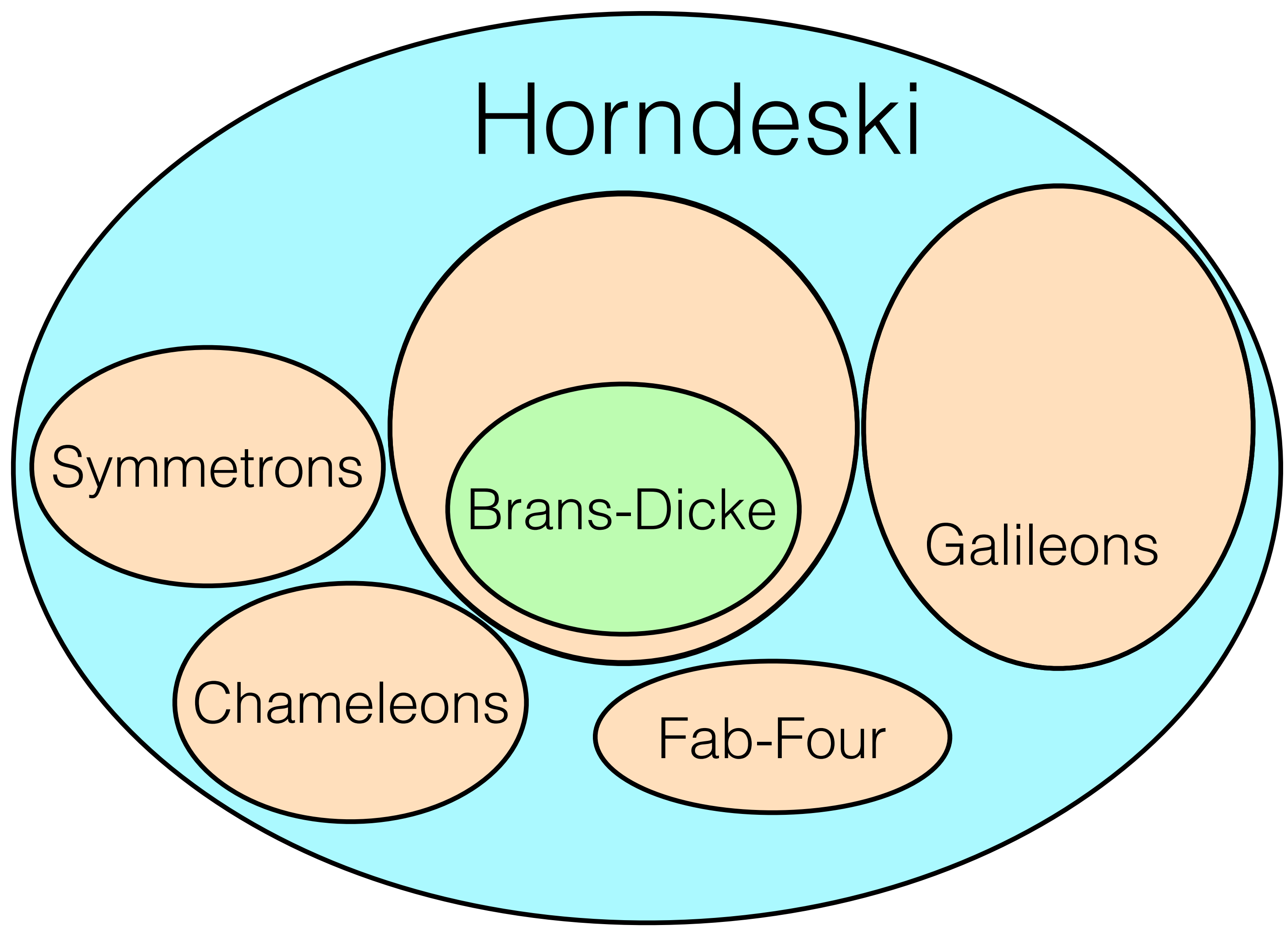
Horndeski theory

Horndeski, Int.J.Theor.Phys. 10, 363 (1974)

- Most general scalar-tensor theory with 2nd order field equations
- Fields: $g_{\mu\nu}$ and ϕ
- Four free functions: $G_2(\phi, X)$ $G_3(\phi, X)$ $G_4(\phi, X)$ $G_5(\phi, X)$

where: $X = -\frac{1}{2}(\nabla\phi)^2$

Gregory Horndeski, self-portrait



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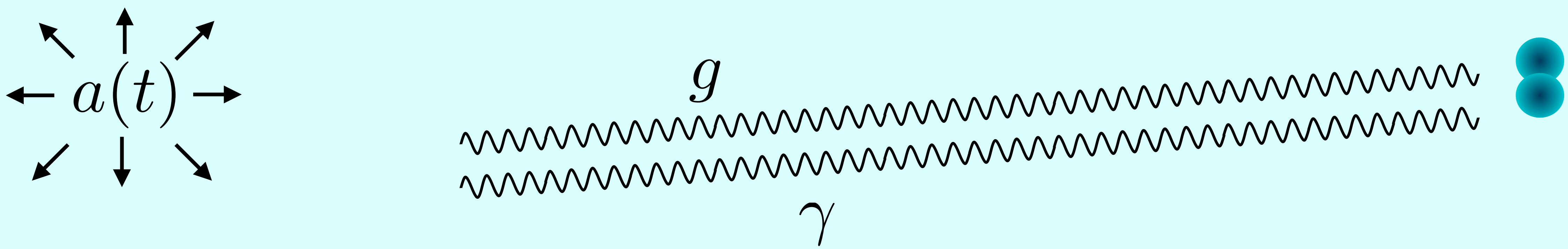
Gravitational waves through FRW universe



$$ds^2 = -a^2 d\tau^2 + a^2 \left(\gamma_{ij} + h_{ij}\right) dx^i dx^j$$

$$h^i{}_i = \vec{\nabla}_j h^j{}_i = 0$$

$$\ddot{h}^i{}_j + \frac{\dot{a}}{a}\left(2+\alpha_M\right)\dot{h}^i{}_j - \left(1+\alpha_T\right)\left(\vec{\nabla}^2 - 2\kappa\right) h^i{}_j = \frac{16\pi G a^2}{M_*^2} T^i{}_j$$

EFT of DE parameters

[arXiv:1810.08239](https://arxiv.org/abs/1810.08239)

Horndeski theory

Grav. waves speed excess

$$\Longrightarrow \quad \alpha_T \propto 2X\left[2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X}\right]$$

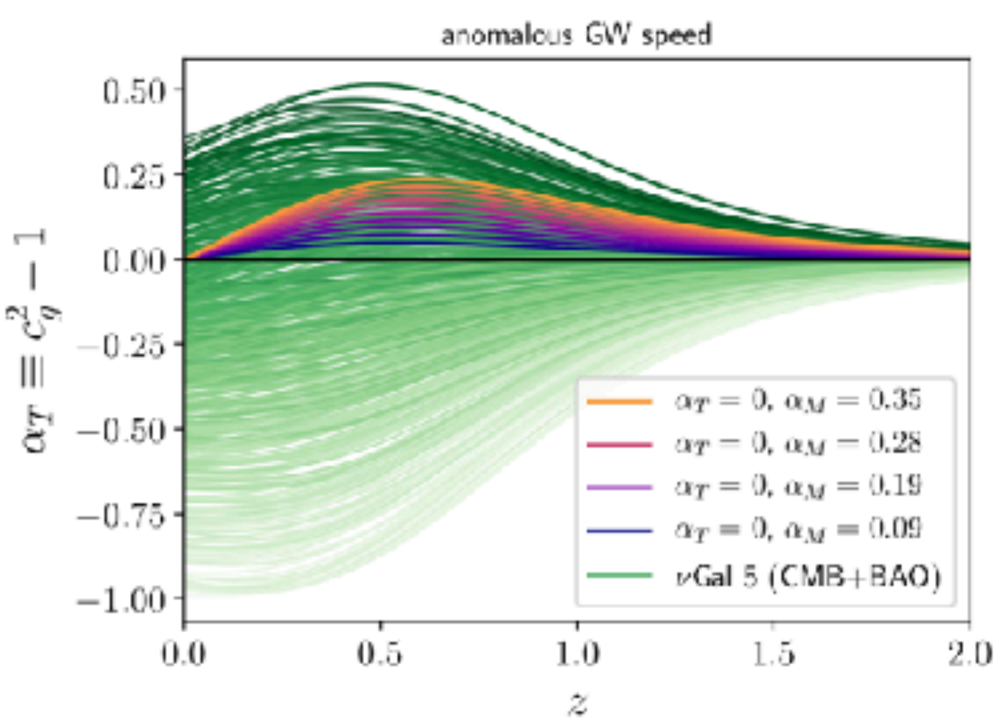
Baker et al. (2017)

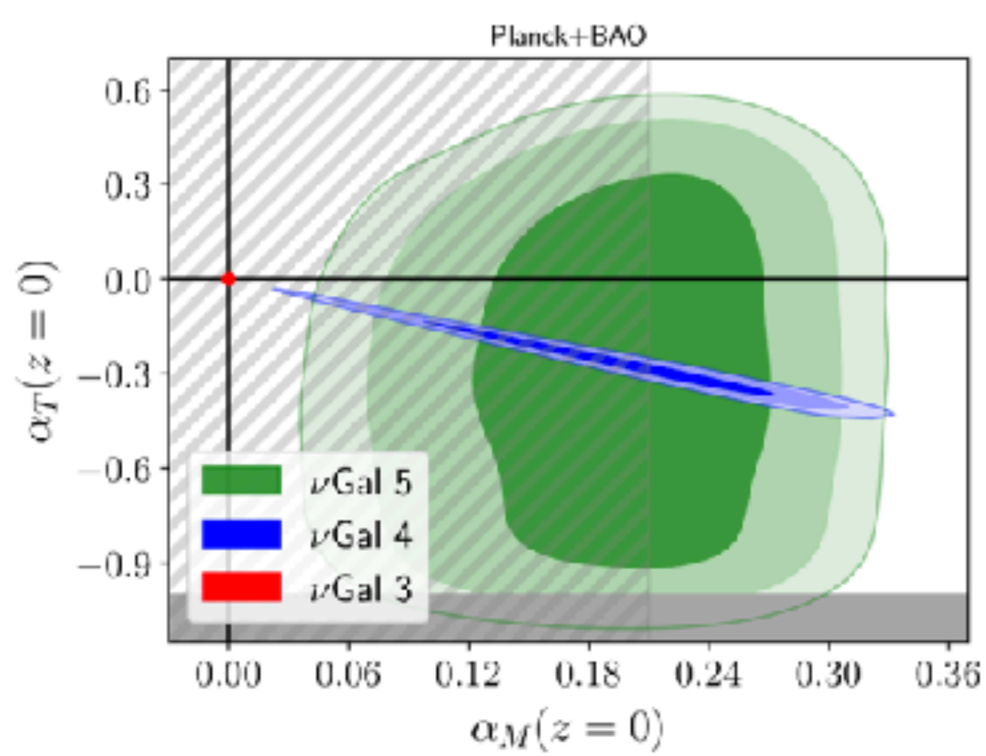
Creminelli & Vernizzi (2017)

Ezquiaga & Zumalacarregui (2017)

Jain & Sakstein (2017)

Trivial case: $G_4 = G_4(\phi)$ and $G_5 = 0$





Ezquiaga & Zumalacarregui (2017)

Special initial condition dependent cases may exist for which $\alpha_T = 0$ $\Longrightarrow$ fine-tuning…

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Michael Kopp, (slides stolen from) Constantinos Skordis, Institute of Physics, Prague

Horndeski: Non-trivial case

Copeland, Kopp, Padilla, Saffin & C.S., PRL 12, 061301 (2019)

$$\alpha_T \propto 2X\left[2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X}\right]$$

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↑

Use EOM of ϕ

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Use EOM of ϕ → $\alpha_T \propto \sum_{ij} C_{ij}(\phi, X) H^i \dot{H}^j = 0$

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Flat universe

$\Rightarrow$

$$G_5 = -6\mu/\sqrt{|X|}$$

$$G_4 = \kappa_G^2 + \frac{3}{2}\mu f(\phi)\sqrt{|X|}$$

$+G_2, G_3$

GW ok!

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Spatially curved universe

$$\alpha_T \propto \sum_{ij} \left(C_{ij}(\phi, X) + \frac{\kappa}{a^2} D_{ij}\right) H^i \dot{H}^j = 0$$

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If $\kappa \neq 0 \Rightarrow D_{ij} = 0$

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If $\kappa \neq 0 \Rightarrow D_{ij} = 0$ BUT: $D_{01} = 0$ Iff $G_{5,X} = 0$

$\langle \vec{\nabla}^2 \Phi \rangle \sim \kappa \Rightarrow$ potential problem…

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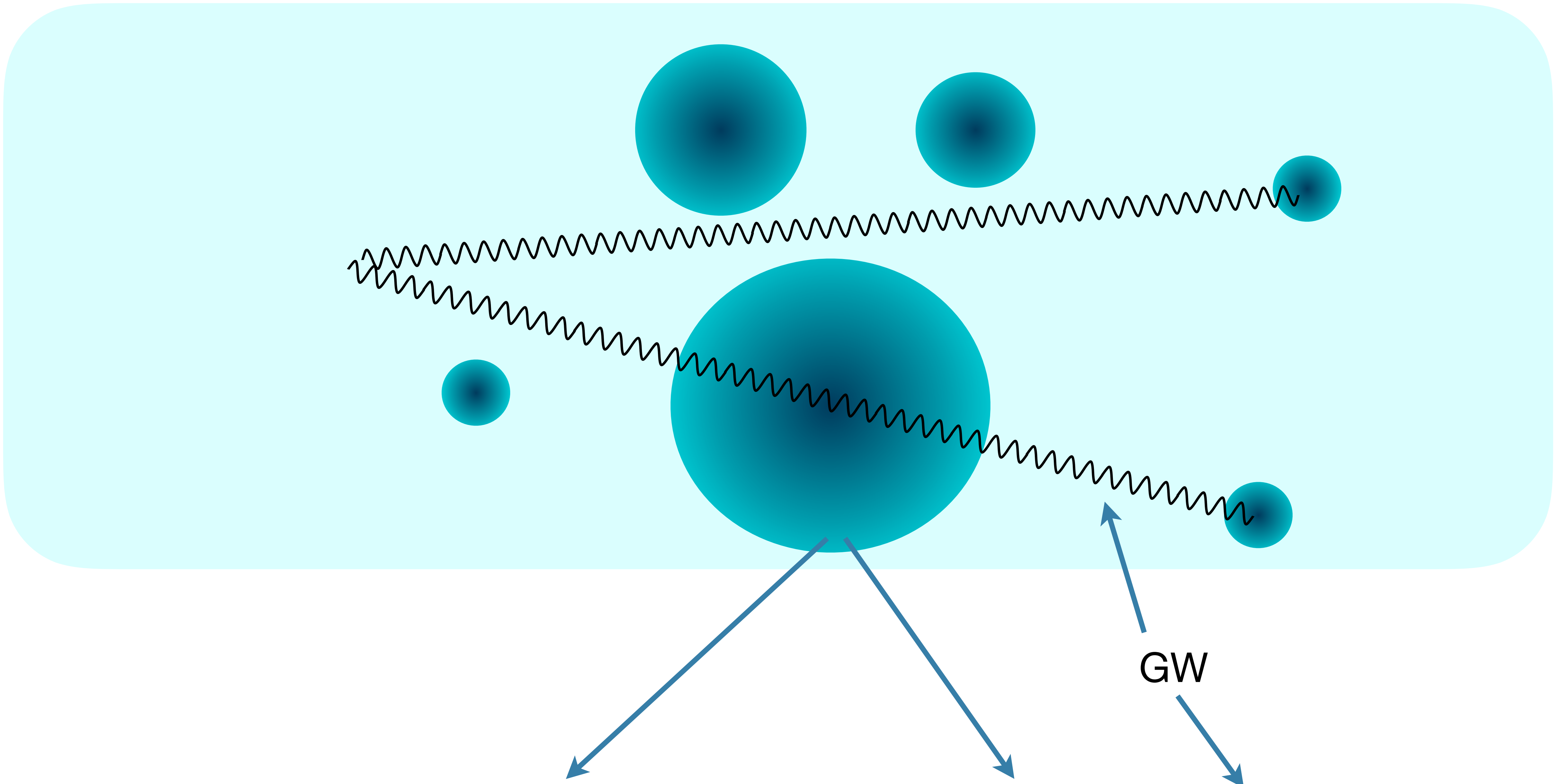
Moving through structure



$$ds^2 = -a^2\left(1+2\Psi\right)d\tau^2 + a^2\left(1-2\Phi\right)\left[\gamma_{ij}+h_{ij}\right]dx^i dx^j$$

$$h_{ij} \ll \Phi, \Psi \sim 10^{-5} \qquad \epsilon_h = \frac{h_{ij}}{\Phi} \sim 10^{-17}\frac{40Mpc}{d} \ll 1$$

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Horndeski: Non-trivial theory

Copeland, Kopp, Padilla, Saffin & C.S., PRL 12, 061301 (2019)

For LIGO wavelengths: $\lambda \sim 1000km$

Inhomogeneity scale: $r \geq 100Mpc$

$$\Rightarrow \quad \epsilon_\lambda = \frac{\lambda}{r} \ll 10^{-18}$$

$$\partial\Phi \sim \frac{\Phi}{r} \qquad \partial h \sim \frac{h}{\lambda}$$

Hierarchy of scales

$$\partial^2 h \gg \Phi\partial^2 h \gg \Phi^2\partial^2 h \gg \partial\Phi\partial h \gg h\partial^2\Phi$$

Tensor mode eq.

$$(1-2\Psi)\left(\ddot{h}^i{}_j + 2\frac{\dot{a}}{a}\dot{h}^i{}_j\right) - (1-2\Phi)\,(1+\alpha_T)\,\vec{\nabla}^2 h^i{}_j + \ldots = 16\pi G T^i{}_j$$

$$\alpha_T \sim H_0^{-2}\vec{\nabla}^2\Phi + \ldots \sim \frac{\Phi}{(H_0 r)^2} \sim 10^{-3} \gg 10^{-15} \qquad \Rightarrow \quad \text{No-Go}$$

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Beyond Horndeski

Gleyzes, Langlois, Piazza, Vernizzi (2013)

Zumalacarregui & Garcia-Bellido (2013)

- Most general scalar-tensor theory with 3rd order field equations
- additional constraints remove d.o.f.
- Fields: $g_{\mu\nu}$ and ϕ
- Six free functions: $K(\phi, X)$ $G_3(\phi, X)$ $G_4(\phi, X)$ $G_5(\phi, X)$ $F_4(\phi, X)$ $F_5(\phi, X)$

Trivial case

Baker et al. (2017)

$$\alpha_T = 0 \longrightarrow G_{5,X} = F_{5,X} = 0 \qquad F_{4,X} = G_{4,X} - G_{5,\phi}$$

Beyond Horndeski: non-trivial case

Copeland, Kopp, Padilla, Saffin & C.S., PRL 12, 061301 (2019)

$$\alpha_T \left[G_4, G_5, F_4, F_5, \ddot{\phi}\right]$$

↑

Use EOM of ϕ ⟶ $\alpha_T \propto \sum_{ij} C_{ij}(\phi, X) H^i \dot{H}^j = 0 \quad \Rightarrow \quad C_{ij} = 0$

$\Rightarrow$ non-trivial cases with $G_4, G_5, F_4, F_5 \neq 0$

Creminelli & Vernizzi (2018)

Graviton decay into scalars (so that no GW should have been detected)

Unless: $m_4^2 = -\frac{1}{2}\mathcal{G}_T \alpha_T - X^2 F_4 + 3HX^2\dot{\phi}F_5 \to 0$

If $\alpha_T = 0 \quad \Rightarrow \quad F_4 = F_5 = 0$ RULED OUT

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