Gravitational Wave and cosmological tests of Gravity and Dark Energy

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MARIE CURIE ACTIONS

IPhT SACLAY

DESI - C3 telecon - 22 February 2018

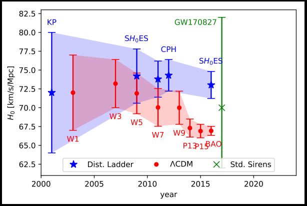
with JM Ezquiaga, (1710.05901 PRL)

D. Bettoni, JM Ezquiaga, K. Hinterbichler (1608.01982 PRD)

A. Barreira, F. Montanari, J. Renk (1707.02266 JCAP)

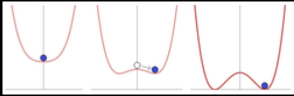
The case for modified gravity

- Alternatives to Λ
  - Inflation again? $n_s \neq 1$
  - ΛCDM tensions $\longrightarrow$



(Adapted from Fredman '17)

- Interesting theoretical questions
  - *proxy for inflation/quantum gravity?*
  - *cosmological constant problems?*



$\sim 36\%$ *of unsolved problems in physics involve gravity*

(see www.wikipedia.org/wiki/List_of_unsolved_problems_in_physics)

- Test gravity on all regimes

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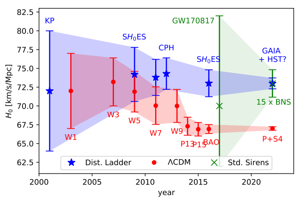

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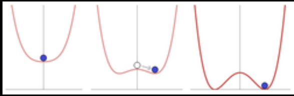

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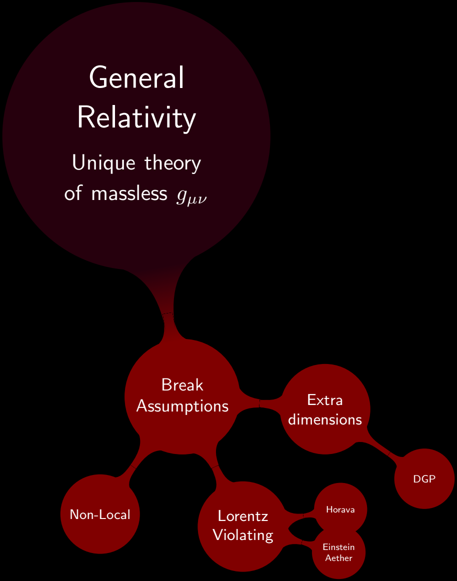

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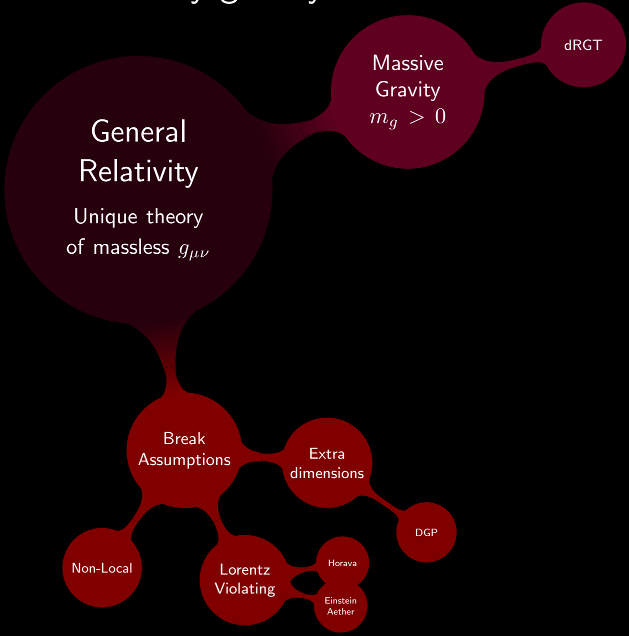

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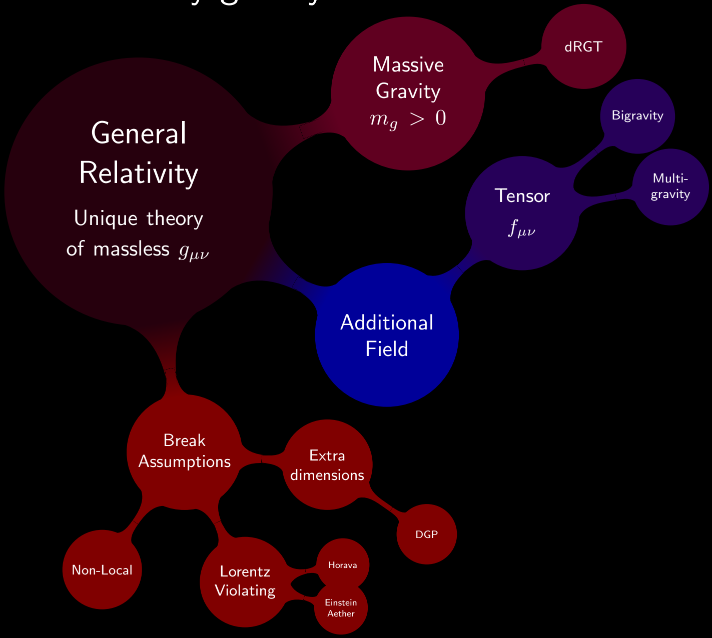

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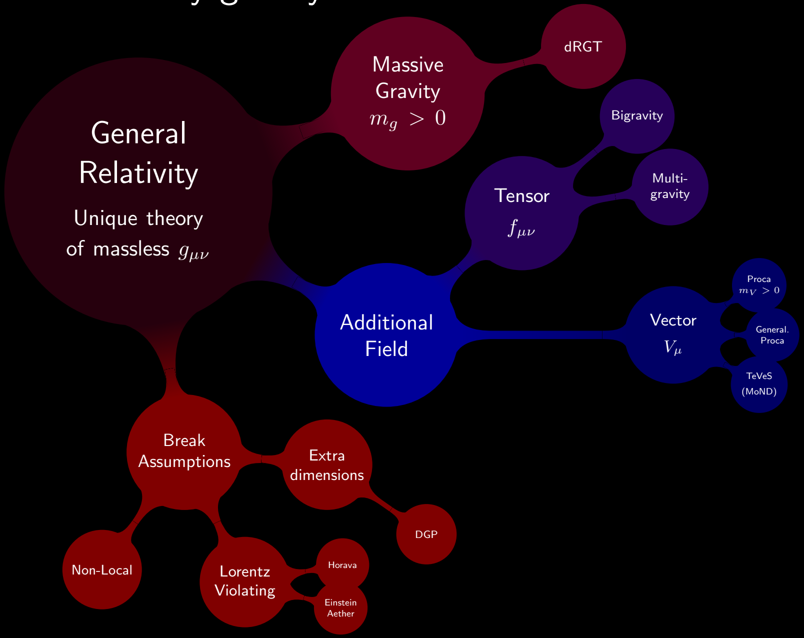

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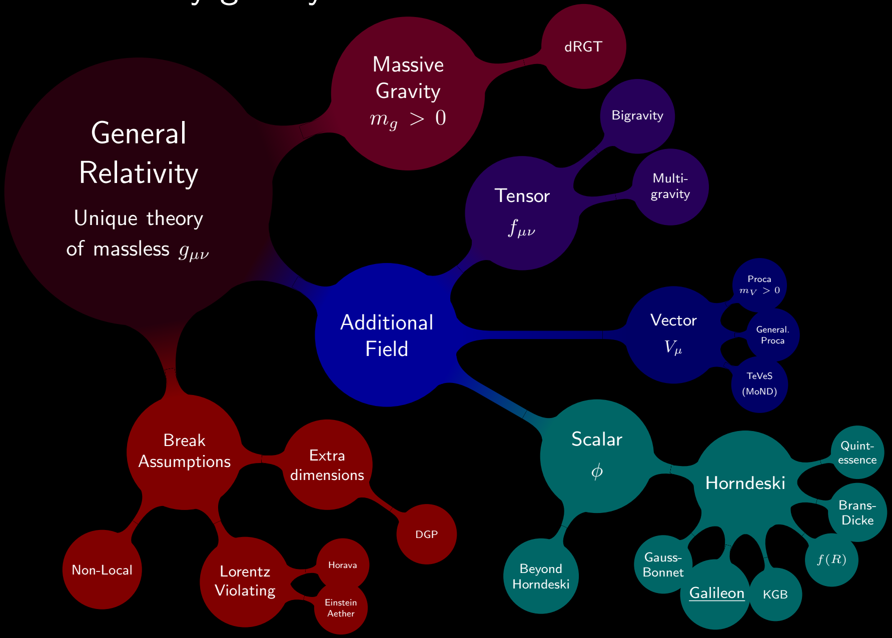


Test gravity: 3 approaches

1 - Model from Lagrangian

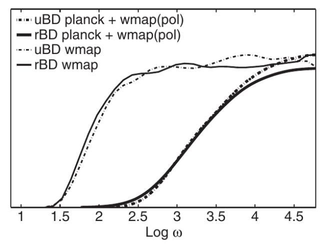
$$\underbrace{\sqrt{-g}\left\{\frac{1}{16\pi G}R[g_{\mu\nu}] + \mathcal{L}_m\right\}}_{\text{Theory (Lagrangian)}} \rightarrow \underbrace{G_{\mu\nu} = 8\pi G T_{\mu\nu}}_{\text{Equations}} \rightarrow \underbrace{H(t), P(k,t)}_{\text{Solutions}}$$

- Specific, self-consistent
- Variable freedom: parameters + ICs $\rightarrow$ several free functions
- Fully predictive: expansion history, N-body, GWs...

Example: Brans-Dicke

$$\mathcal{L} \propto \phi R - 2\Lambda - \frac{\omega}{\phi}(\partial\phi)^2$$

(Avilez & Skordis '14)



Test gravity: 3 approaches

1. Model from Lagrangian

2 - Parameterize the solutions

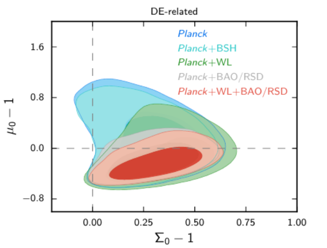
$$\nabla^2\Psi = 4\pi G a^2 \mu(a,k)\rho\Delta\,, \qquad \nabla^2(\Phi+\Psi) = 8\pi G a^2 \Sigma(a,k)\rho\Delta$$

- Fully general
- Vast functional freedom: 2 functions of 2 variables
- Only linear regime, no expansion history

Example: (Planck '15 DE paper)

$$\mu = 1 + \mu_0\Omega_{de}(a)$$

$$\Sigma = 1 + \Sigma_0\Omega_{de}(a)$$



Test gravity: 3 approaches

1. Model from Lagrangian
2. Parameterize the solutions

3 - Effective theory approaches

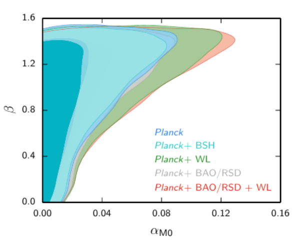
$$\mathcal{L} = \sum_i \alpha_i(t)\mathcal{O}_i$$

- Rather general: locality, covariance, d.o.f. # & type
- Large functional freedom $\mathcal{O}$(few) functions, 1 variable
- Limited info from other regimes GWs (no expansion history)

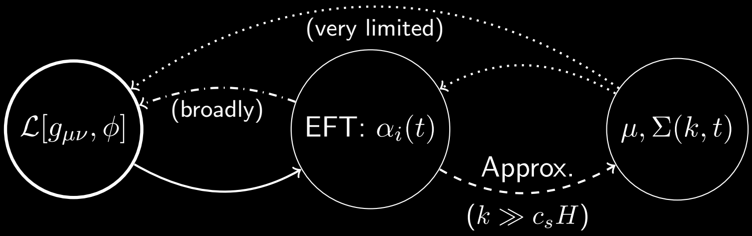
Example: (Planck '15 DE paper)

$$\alpha_M = \frac{a}{\Omega+1}\frac{d\Omega}{da} = -\alpha_B$$

$$\Omega(a) = \exp\left[\frac{\alpha_{M,0}}{\beta}a^\beta\right] - 1$$



Connecting approaches (Gubitosi+, Bloomfield+ '14)



Outline:

1. Tools for general theories (Horndeski in CLASS)
2. EFT & Lagrangian models (Galileon)
3. GW constraints on Lagrangians and EFT

Horndeski in EFT language (Bellini & Sawicki '14)

$$\underbrace{\ddot{h}_{ij} + 3H(1+\alpha_M)\dot{h}_{ij}}_{\delta(\sqrt{-g}M_*^2\dot{h}_{ij}^2)} + \underbrace{(1+\alpha_T)}_{c_T^2,\ \text{GW}} k^2 h_{ij} = 0 \qquad \text{(tensors)}$$

$$\underbrace{\alpha_K}_{\text{diagonal}}\ \delta\ddot{\phi} + 3H\ \underbrace{\alpha_B}_{\text{mixing}}\ \ddot{\Phi} + \underbrace{\left(\quad\cdots\quad\right)}_{\alpha_K,\alpha_B,\alpha_M,\alpha_T} = 0 \qquad \text{(scalar field)}$$

Theory-specific relations:

$$G_2 - G_3\Box\phi + G_4 R + G_{4,X}\left[\nabla\nabla\phi\right]^2 + G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[\nabla\nabla\phi\right]^3$$

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Kineticity: α_K

Standard kinetic term $\to c_S^2$

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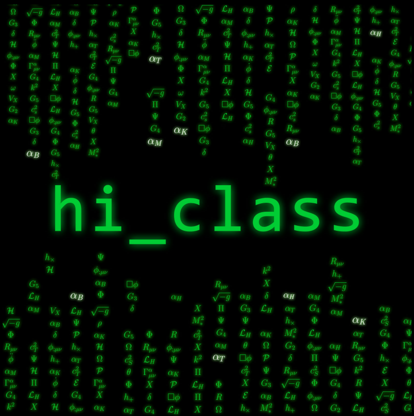
Variation rate of effective M_p

Tensor speed excess: α_T

GW at $c_g^2 = 1 + \alpha_T$

Horndeski in the Cosmic Linear Anisotropy Solving System

Goals: $\begin{cases} \star \text{ DE/MG predictions in as much detail as } \Lambda\text{CDM} \\ \star \text{ public tool, valid for a large class of theories} \end{cases}$



1. Flexibility:
   - $\star$ New models trivially added
   - $\star$ Compatible massive ν's...
2. Accuracy:
   - $\star$ Full linear dynamics + ICs
   - $\star$ Tested to $\mathcal{O}(0.1\%)$ (Bellini+ '17)
3. Speed: MCMC-able

www.hiclass-code.net (MZ, Bellini, Sawicki, Lesgourgues, Ferreira '16)

hi_class in practice

$$\left.\begin{matrix} G_2,\, G_3,\, G_4,\, G_5 \\ \phi(t_0),\, \dot\phi(t_0) \end{matrix}\right\} \longrightarrow \left\{\begin{matrix} \text{Kineticity } \alpha_K \\ \text{Braiding } \alpha_B \\ M_p \text{ running } \alpha_M \\ \text{Tensor speed } \alpha_T \end{matrix}\right\} \longrightarrow \left\{\begin{matrix} D_A(z) \\ C_\ell \\ P(k) \\ \dots \end{matrix}\right.$$

a) Full theory + IC

b) *or* Parameterize $w(z), \alpha_i(z)$

Analogy with Quintessence

$\underline{V(\phi), \phi_0, \dot\phi_0}$ *vs* $\underline{w(z)}$

EFT tests

(Alonso, Bellini, Ferreira, MZ '16)

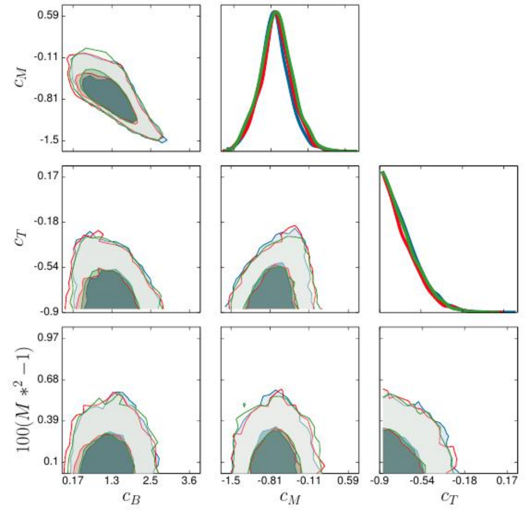
Horndeski parameterization

- $\boxed{\alpha_i = c_i \cdot \Omega_{de}(z)}$

- Current: (Bellini+ '15)

$$\Delta c_i \sim 1$$

CMB+BAO+RSD+PK



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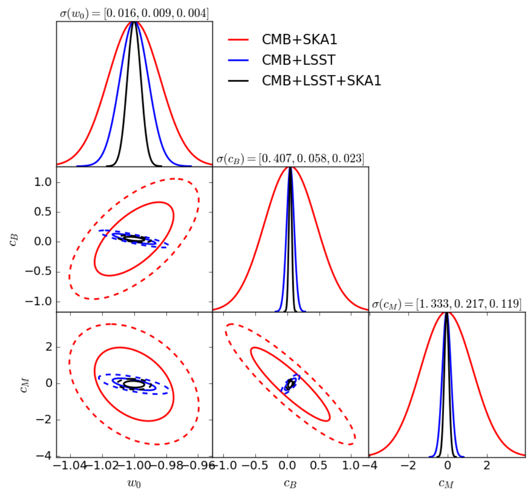
- CMB S4 + SKA
- + LSST
- + DESI-like



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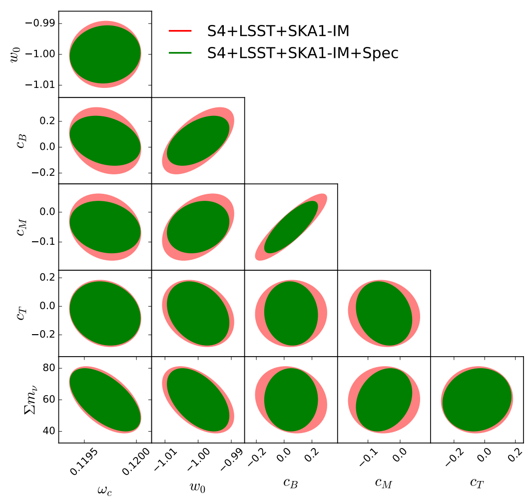


Galileon gravity (Nicolis+ '08, de Rham Tolley '10...)

Horndeski's Theory, with

$\boxed{\Lambda = 0}$ + simple choice of $G_i(X,\phi)$: (recall: $X \equiv -(\partial\phi)^2/2$)

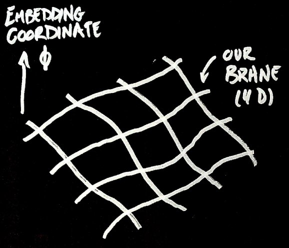
$\frac{M_p^2}{2}R - X - c_3 \frac{X}{M^3}\nabla^2\phi$ → Gal3 (cubic): 0 extra params

$+ c_4 \frac{X^2}{M^6}\left(\frac{M_p^2}{2}R + \frac{2}{X}\left[\nabla\nabla\phi\right]^2\right)$ → Gal4 (quartic): 1 extra params

$+ c_5 \frac{X^2}{M^9}\left(G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{3X}\left[\nabla\nabla\phi\right]^3\right)$ → Gal5 (quintic): 2 extra params

- Related to
  - ⋆ Massive Gravity: $\phi \to$ helicity 0
  - ⋆ DGP/extra dim: $\phi \leftrightarrow x^5$ coord.
- Screening: $\Rightarrow \sim$ GR on small scales
- Self-accelerating solutions $(\Lambda = 0)$

(de Felice Tsujikawa '10, Barreira+ '14)



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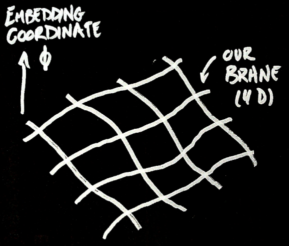

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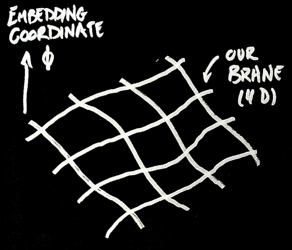

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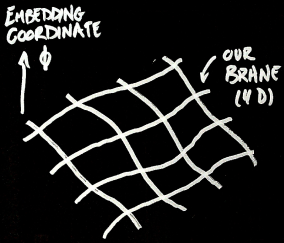
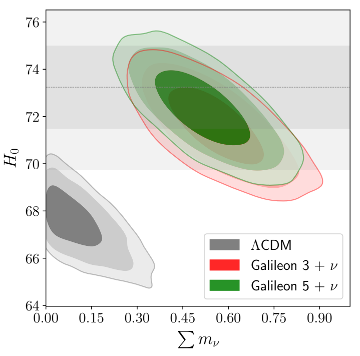


$\Lambda = 0$ Galileon Gravity

(Barreira+ '14, Renk+ 17')

Planck+BAO:



- H_0 compatible (ΛCDM 3.4σ!)
- if $\Sigma m_\nu \approx 0.6$ eV
- slight tension with other data

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(Barreira+ '14, Renk+ 17')

$\longrightarrow$ modifies GW propagation

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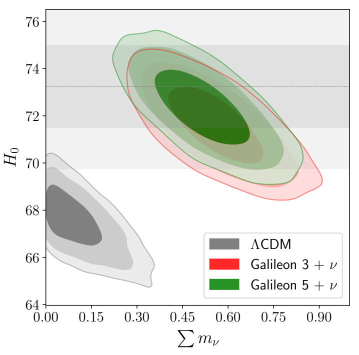

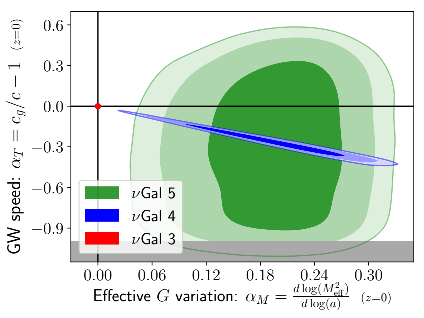

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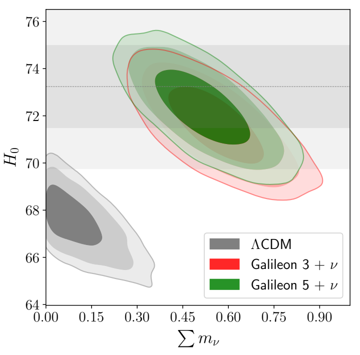

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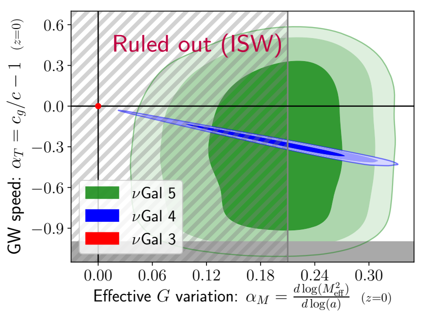


- ISW effect (from Planck×WISE):
  - $\rightarrow$ kills νGal3 (8.2σ)
  - $\rightarrow$ <u>non-standard GW propagation</u>

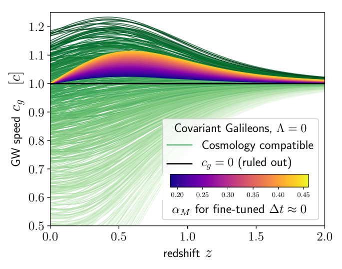
No way out from GWs

GWs on FRW (Bellini+Sawicki, Gleyzes+ '14)

$$\ddot{h}_{ij} + \underbrace{(1+\alpha_T)}_{c_g^2 \neq c} k^2 h_{ij} + \cdots = 0$$

- Can't fine tune $\alpha_T(z) = 0$
- Galileons with $\alpha_T(z) = 0$

  $\Rightarrow$ ruled out by ISW (8.2 σ)



No waveform distortion $\Rightarrow$ need EM counterpart

$$\omega^2 = (1+\alpha_T)k^2$$

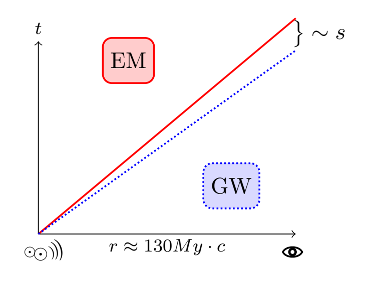
Massive gravity tested with GW alone: $m_g < 7.7 \cdot 10^{-23} eV$ (GW170104)

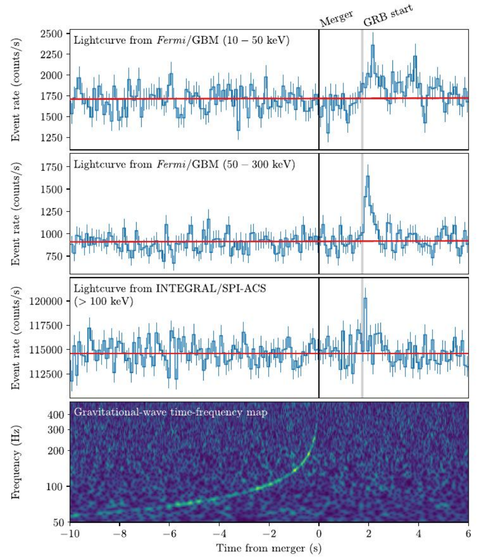
$$\ddot{h}_{ij} + k^2 h_{ij} + m_g^2 h_{ij} = 0 \quad \Rightarrow \quad \omega \approx k + \frac{m_g^2}{2k^2}$$

GW 170817 + GRB 170817A (LIGO+Fermi+$\cdots$ 1710.05834)

Very precise bound :

$$-3 \cdot 10^{-15} \leq \alpha_T \leq 6 \cdot 10^{-16}$$





Conditions for variable c_g (Bettoni, Ezquiaga, Hinterbichler & MZ '16)

Operationally: $\ddot{h}_{ij} + c_g^2 \vec{\nabla}^2 h_{ij} + \cdots = 0$

GW effective metric - any background, $k^2 \gg |R_{\mu\nu}|$

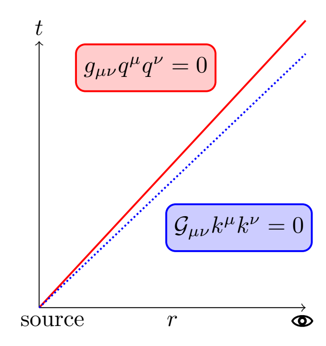
$$\text{GW eq} \propto \big(\underbrace{\mathcal{C}\Box + \mathcal{D}_{\mu\nu}\partial^\mu\partial^\nu}_{\mathcal{G}_{\mu\nu}\partial^\mu\partial^\nu}\big) h_{ij}$$

1) Non-trivial $\phi(x)$ configuration (any)

Dark Energy $\to \dot{\phi} \sim H_0$

2) ϕ-derivatives coupled to curvature

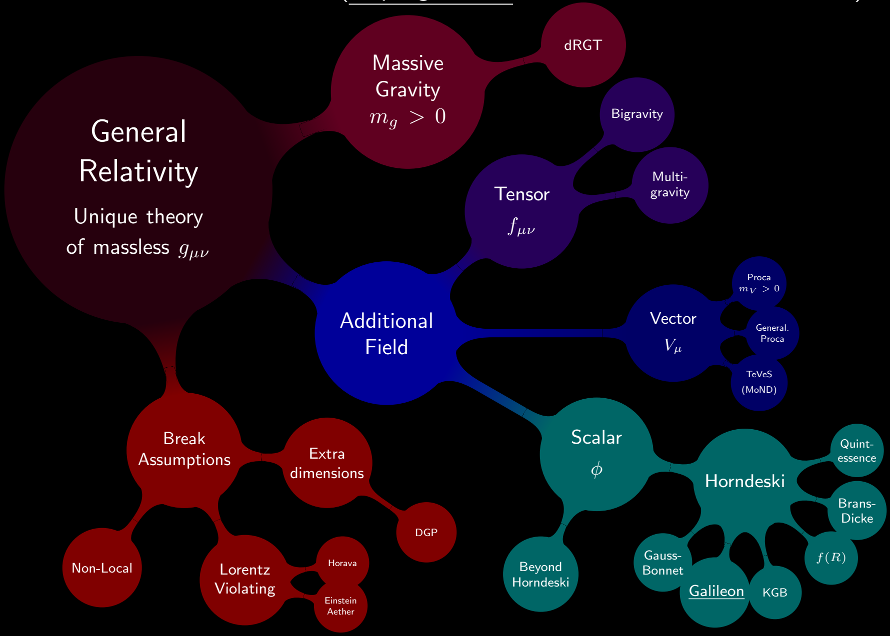
Modified Gravity: $\mathcal{D}_{\mu\nu} \propto \partial_\mu\phi\partial_\nu\phi \cdots$



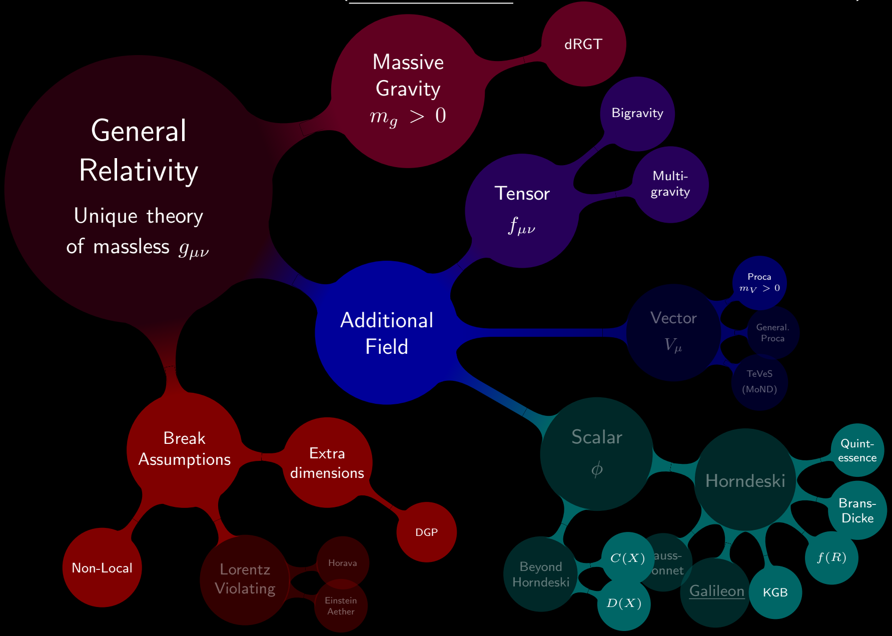
(1,2) $\Rightarrow$ ϕ changes the effective medium in which GWs propagate.

(2) $\Rightarrow$ binary classification of theories

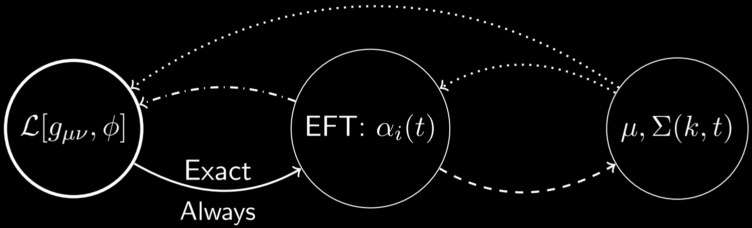
DE after GW170817 (Ezquiaga & MZ, Creminelli & Vernizzi - '17 PRL)



DE after GW170817 (Ezquiaga & MZ, Creminelli & Vernizzi - '17 PRL)



What's left after GW170817?



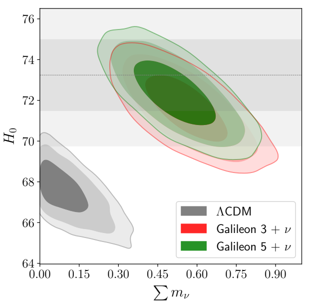
Lagrangian
- All Simple Ths.
- 2 special Ths.
- massive GR (?)

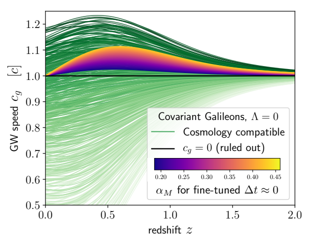
Effective Theory
- $\alpha_T = 0$
- all other α's free

Parameterization
- Everything goes!

Conclusions

- $\exists$ Interesting Dark Energy models
  - $\star$ ΛCDM tensions?
  - $\star$ Very predictive!
- GW propagation $\rightarrow$ critical test of gravity
  - $\star$ *either* $c_g = c$ or not
  - $\star$ Dead ends after GW170817
- Complementarity is essential:
  - $\star$ Cosmology
    Cross-correlations (e.g. ISW)
  - $\star$ Gravitational Waves
- Need to go back to our blackboards...





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Scalar-Tensor gravity

⋆ Old-School: $\frac{f(\phi)R}{16\pi G} - \frac{1}{2}(\partial\phi)^2 - V(\phi) \supset$ Quintessence/Inflation,

$\supset$ Brans-Dicke, $f(R)$ (Jordan '59, Brans & Dicke '61)

⋆ Horndeski's Theory (1974)

$g_{\mu\nu}$ + $\boxed{\phi}$ + Local + 4-D + Lorentz theory with $\boxed{2^{nd}\text{ order Eqs.}}$

4× functions $G_i(X,\phi)$ of ϕ, $X \equiv -(\partial\phi)^2/2$

$$\mathcal{L}_H = G_2 - G_3\nabla^2\phi + G_4 R + G_{4,X}\left[\nabla\nabla\phi\right]^2 + G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[\nabla\nabla\phi\right]^3$$

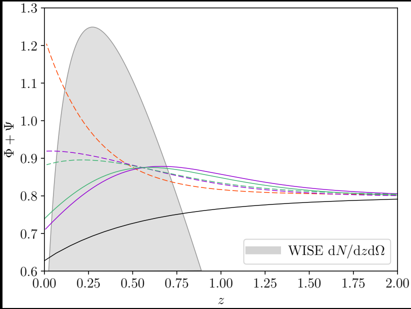
$\supset$ GR, quint/k-essence, Brans-Dicke, $f(R)$, chameleons...

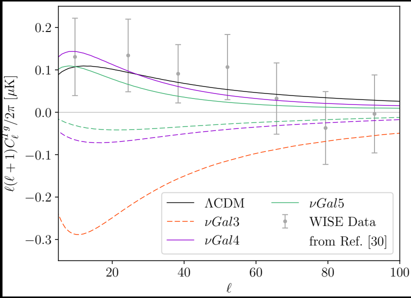
kinetic gravity braiding, covariant Galileon, Gauss-Bonnet...

⋆ Beyond Horndeski $\rightarrow$ *discovered by accident!*

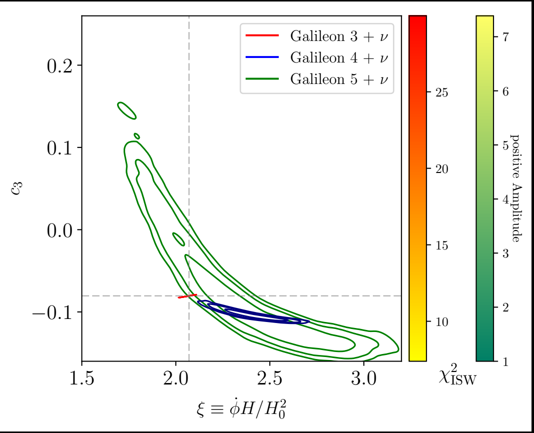
(MZ & Garcia-Bellido '13, Gleyzes *et al.* '14, Langlois & Noui '15)

Galileon and Integrated Sachs-Wolfe effect (Renk+ '17)

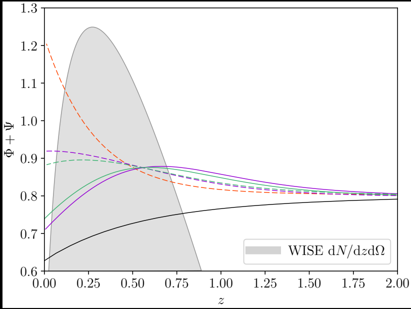




$$\Delta_\ell^{\rm ISW} = \int_{\tau_*}^{\tau_0} d\tau(\Phi' + \Psi')j_\ell$$



Galileon and Integrated Sachs-Wolfe effect (Renk+ '17)



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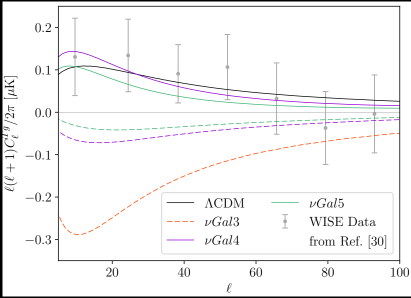
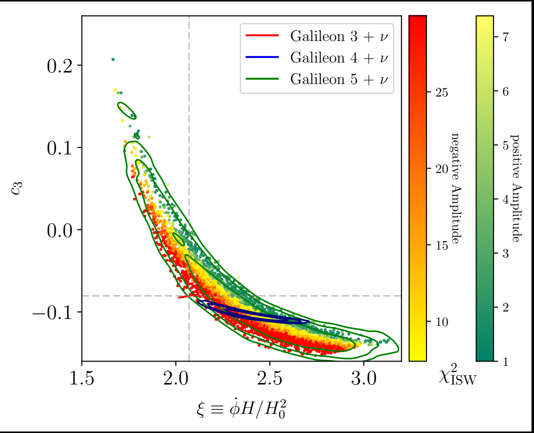
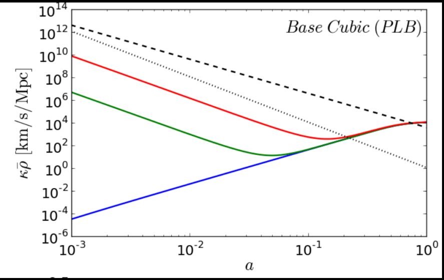


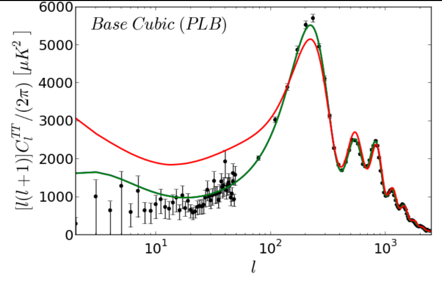


Galileon: Tracker solution (Barreira+ '14)

$$\text{Symmetry } \phi \to \phi + C \quad \Rightarrow \text{conserved } \mathcal{J}^{\mu} \quad \Rightarrow \mathcal{J}^{0} \propto a^{-3} \to 0$$

$$\dot{\phi}(t)H(t) = \xi \cdot H_0^2 M_P = \text{constant}$$





- Evolution to tracker: no fine tuning
- Tracker by $z_T \sim \infty$, $z_T \approx 6$, $z_T \approx 2.5$ (Ω_{de} small but relevant)
- Inviable if out of tracker late (i.e. while Ω_{de} significant)
- Indistinguishable if reached earlier