# Dark Energy at the Speed of Gravitational Waves

## New probes of gravity and cosmic acceleration

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

# gravity

ˈgravɪti/

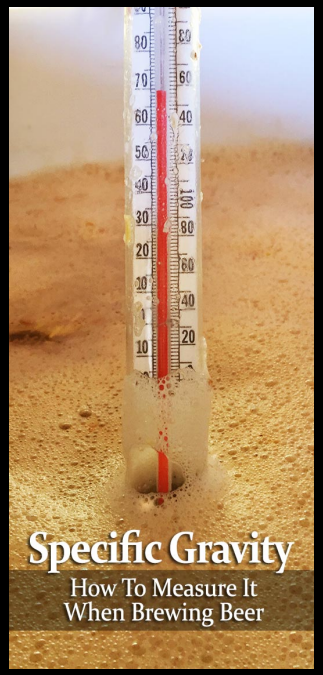
*noun*

1. [Physics]
   the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.

2. extreme importance; seriousness.

3. in the context of fermenting alcoholic beverages, refers to the specific gravity, or relative density compared to water, of the wort or must at various stages in the fermentation.

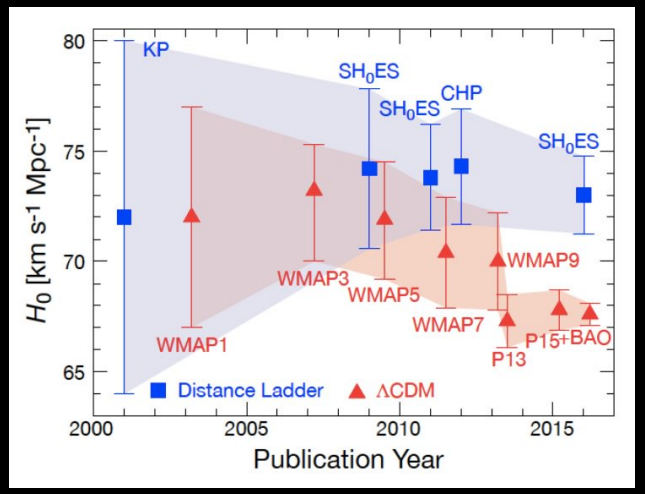
$$\boxed{\frac{d}{dt}\text{gravity} \propto \text{alcohol }\%}$$



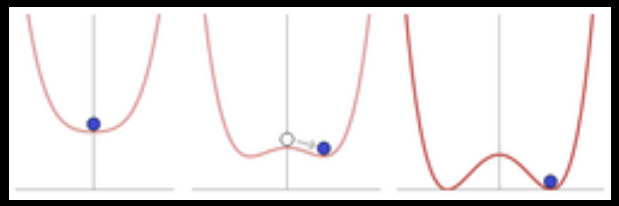

Sources: google (1,2), wikipedia (3)

# The case for modified gravity

- Alternatives to $\Lambda$
  - Inflation again? $n_s \neq 1$
  - $\Lambda$CDM tensions $\longrightarrow$




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

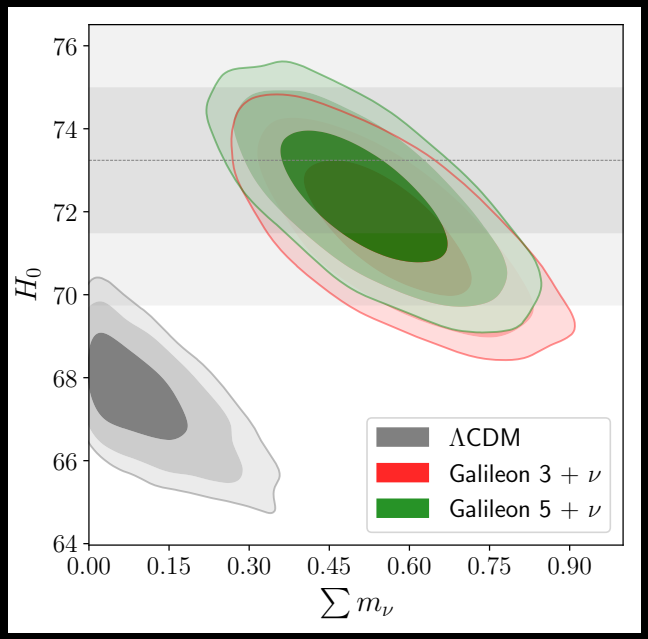


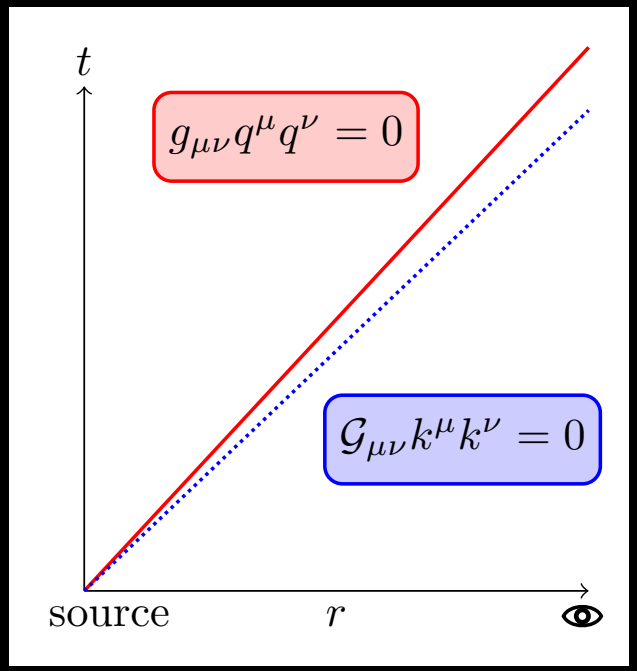
$\sim 36\%$ *of unresolved problems in physics involve gravity*

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

- Test gravity on all regimes by
  - *confirming standard predictions* ✓
  - *ruling out competing theories*

# Main results: highly testable DE models




Self-accelerating Galileon:

- solves $H_0$ while fitting CMB, ISW, old BAO
- some tension with new BAO
- $\Sigma\nu \gtrsim 0.6$ eV

DE with GW signatures:

- Anomalous speed $\gtrsim \mathcal{O}(10\%)$
- case $c_g = 1$ ruled out by ISW effect $(8.2\sigma)$
- $\sigma(c_g) \to 10^{-12} - 10^{-17}$

# Scalar-Tensor gravity

⋆ First-generation: $f(\phi)R + K[(\partial\phi)^2, \phi]$

$\supset$ quintessence, $f(R)$, Brans-Dicke (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 $\phi$, $X \equiv -(\partial\phi)^2/2$

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

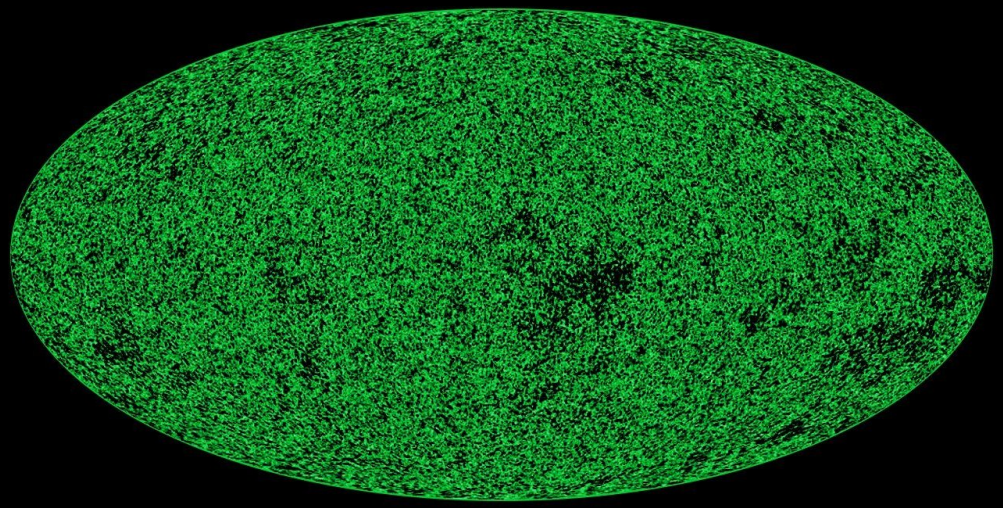
$\supset$ GR, quint/k-essence, Brans-Dicke, $f(R)$, chameleons...

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

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

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

# Cosmological Tests and Dark Energy



with

E. Bellini, P. Ferreira, J. Lesgourgues, I. Sawicki (1605.06102)

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

PLANCK

# Horndeski in four words (Bellini & Sawicki '14)

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

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

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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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Standard kinetic term $\rightarrow c_S^2$

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Kinetic Mixing of $g_{\mu\nu}$ & $\phi$

**$M_p$ running: $\alpha_M$**

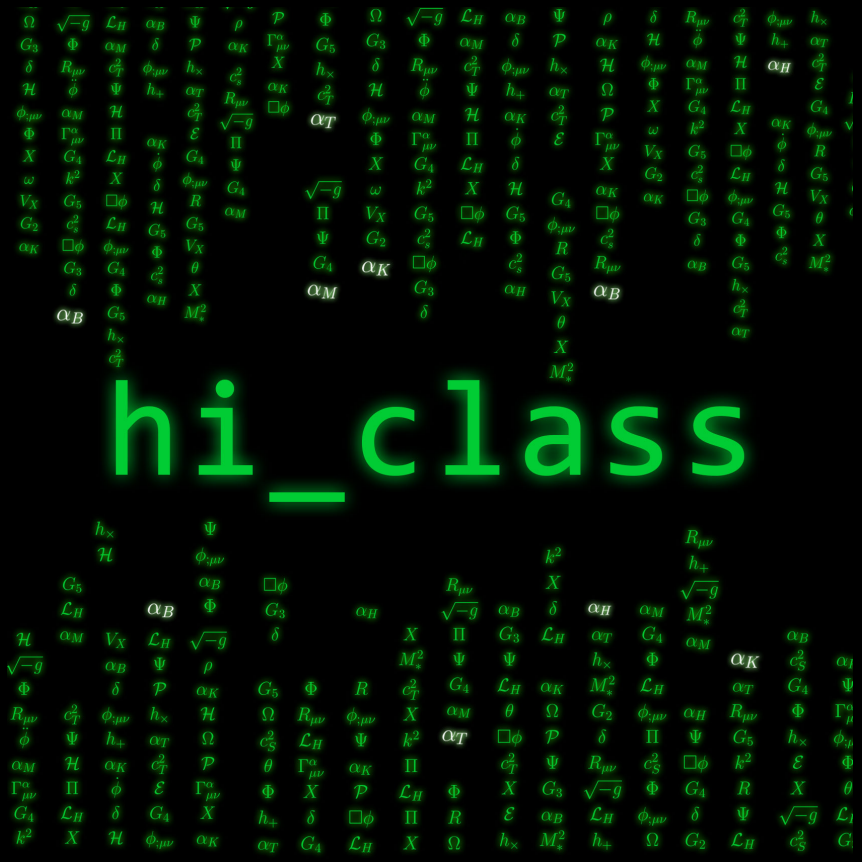
Variation rate of effective $M_p$

**Tensor speed excess: $\alpha_T$**

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:
   - ⋆ New models trivially added
   - ⋆ Compatible massive $\nu$'s...
2. Accuracy:
   - ⋆ Full linear dynamics + ICs
   - ⋆ Tested - Bellini+ (in prep.)
3. Speed: MCMC-able

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

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

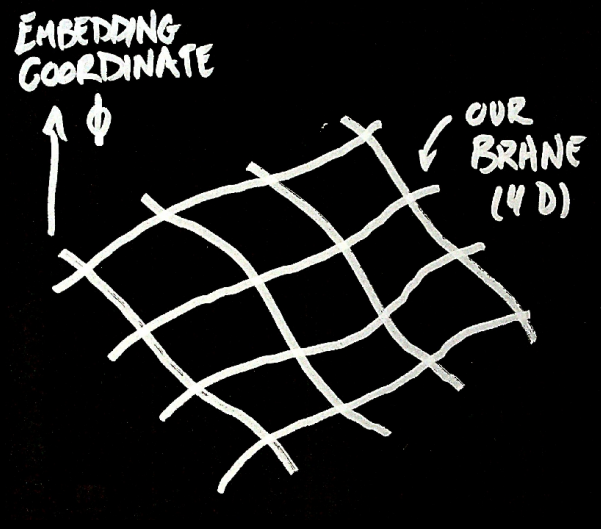
**"Simplest" Horndeski theory with all ingredients**

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

$\boxed{G_2, G_3 \propto X}$ and $\boxed{G_4, G_5 \propto X^2}$ $(X \equiv -(\partial\phi)^2/2)$

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

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



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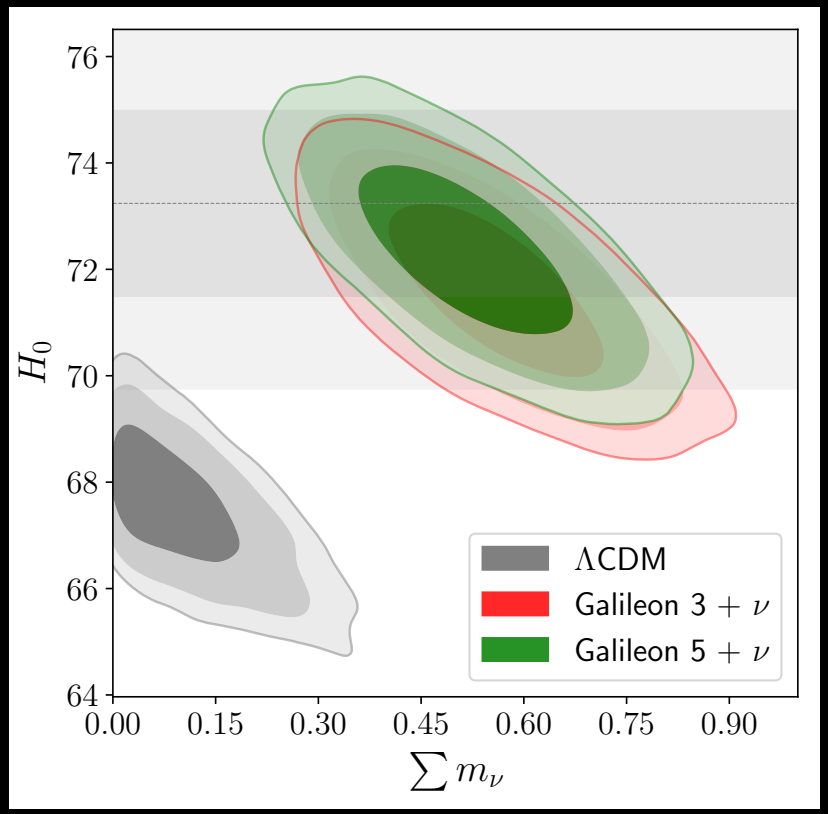


- $H_0$ compatible ($\Lambda$CDM 3.4$\sigma$!)
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- tension with current BAO data

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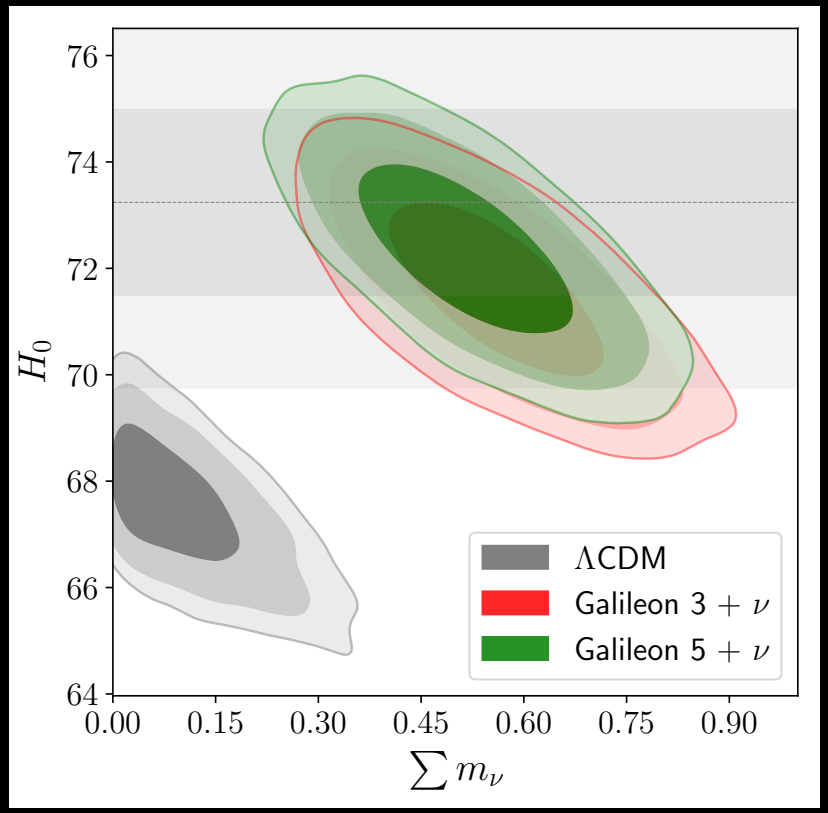


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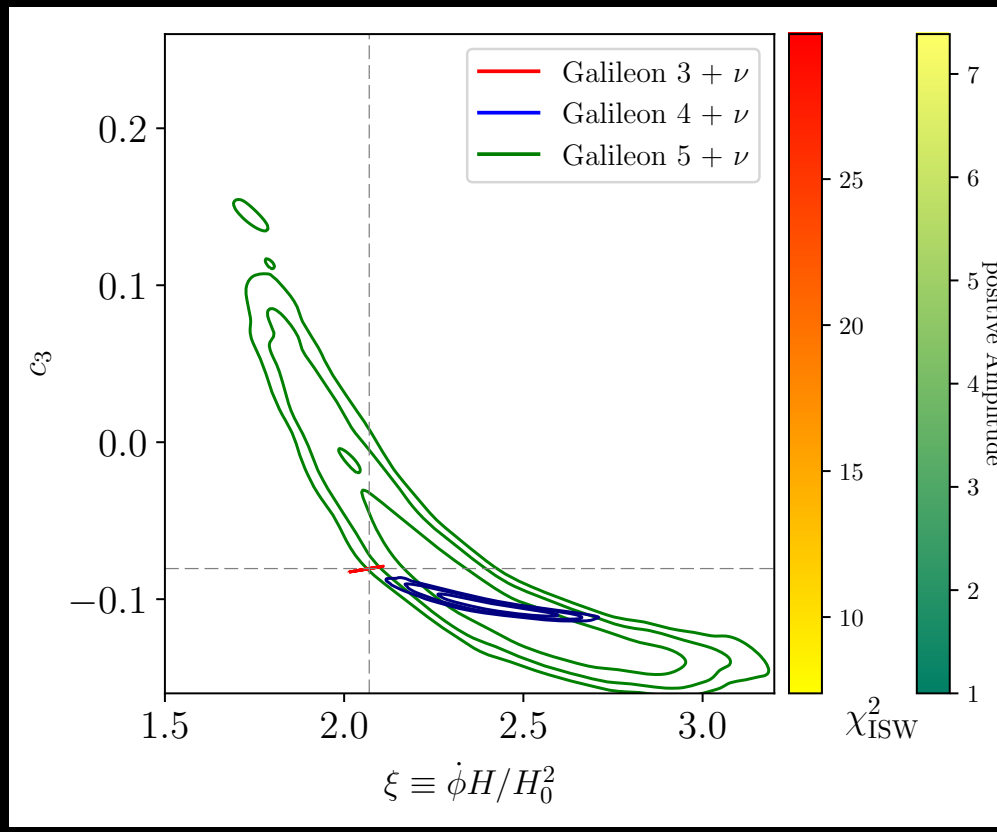
ISW from WISE-Planck:

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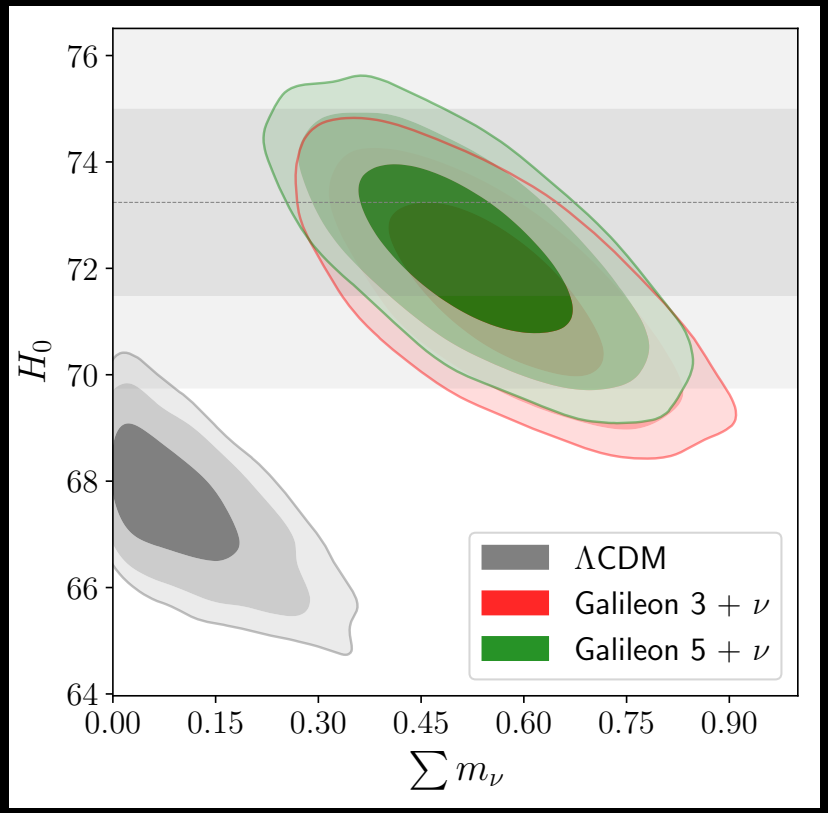


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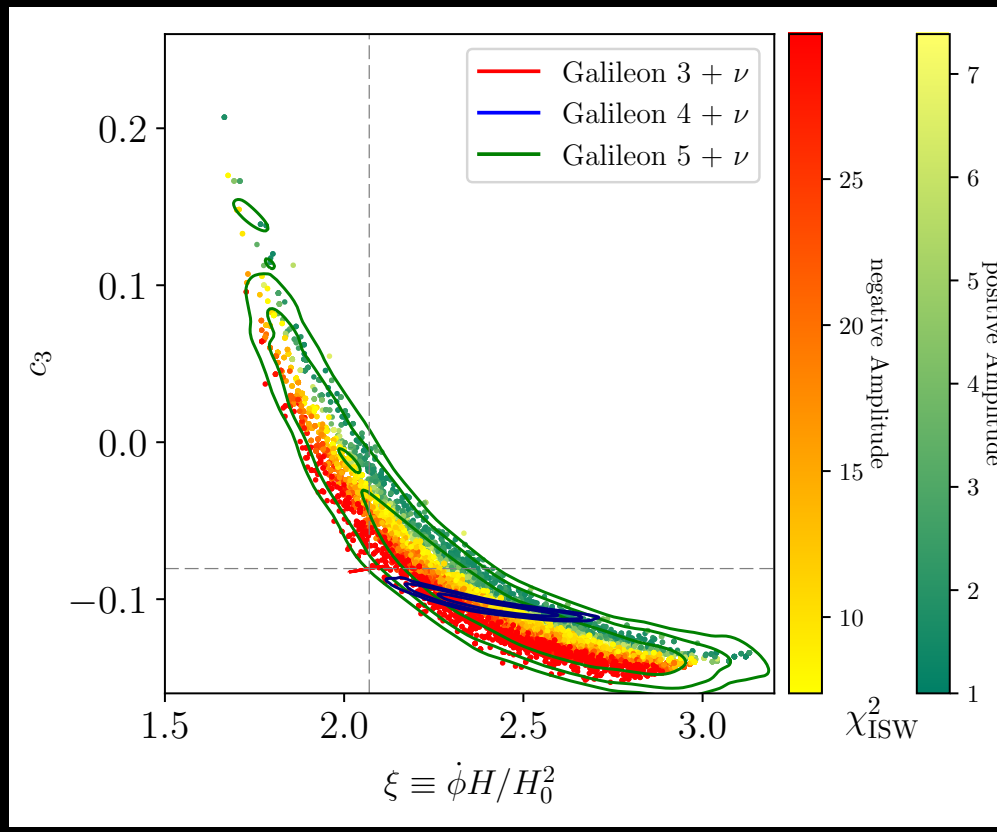


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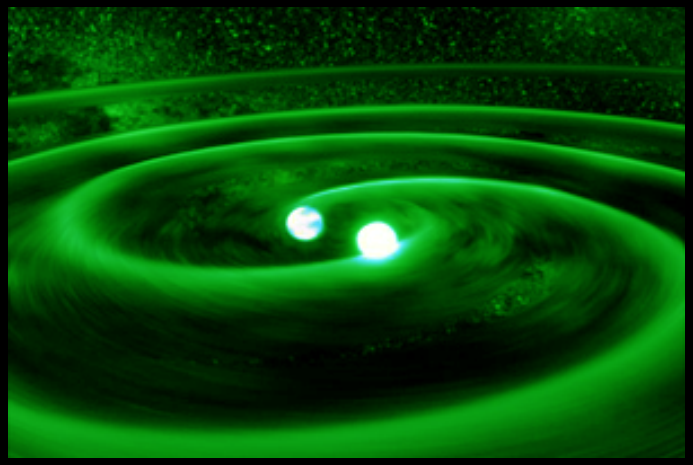
# Gravitational Waves



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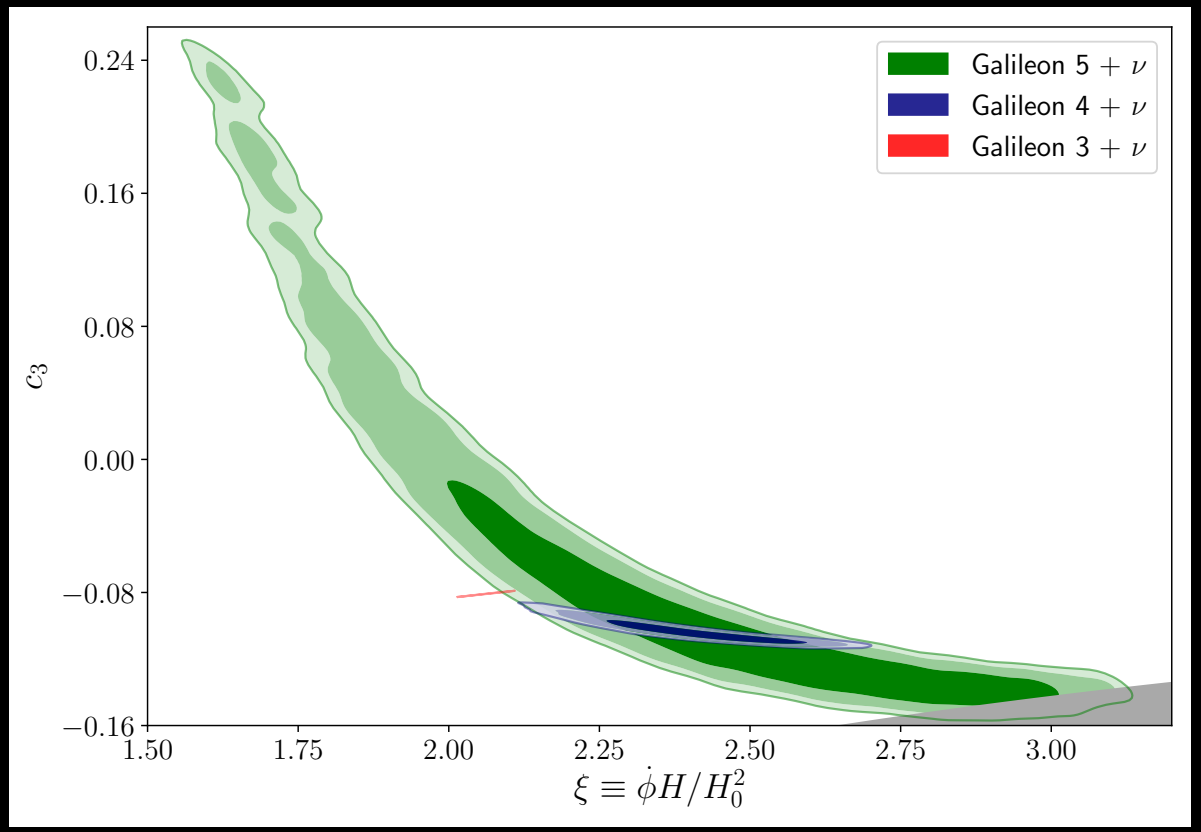
NASA

# Viable Galileons affect GWs!

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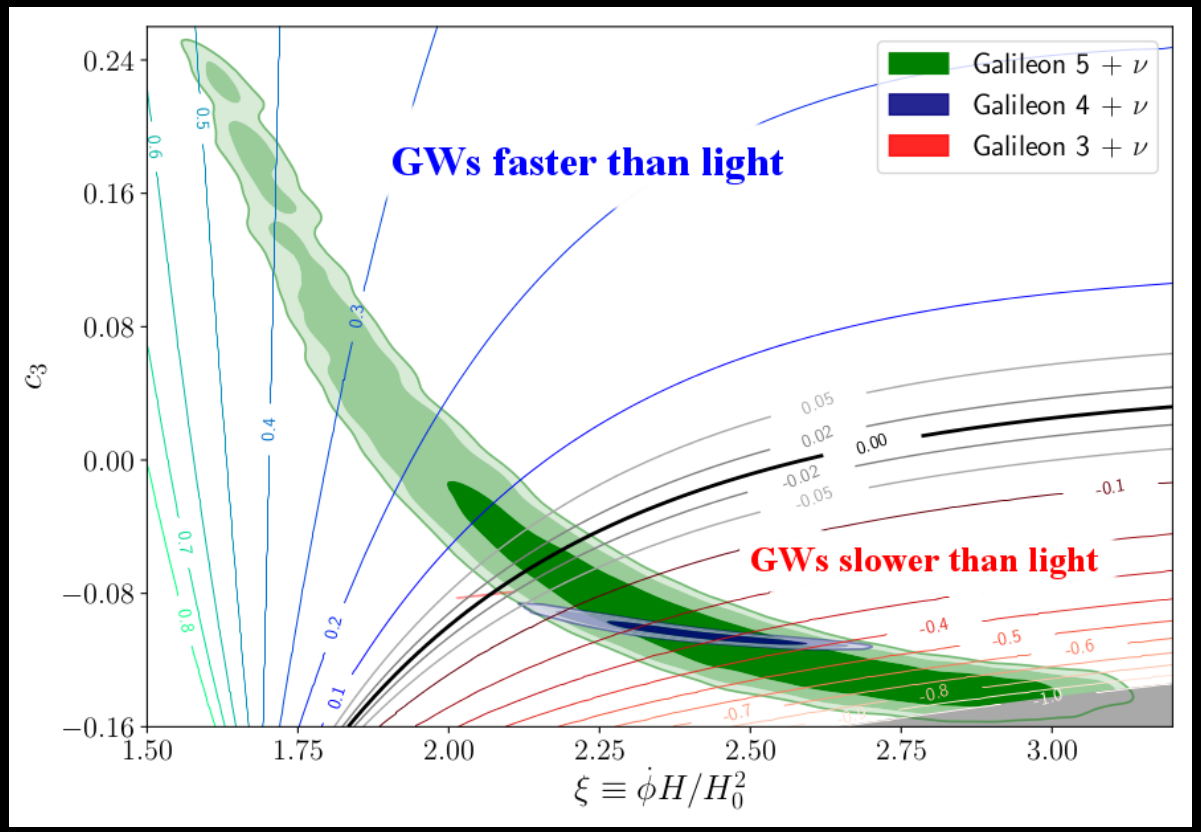


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**GWs on FRW** (Bellini+Sawicki, Gleyzes+ '14)

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

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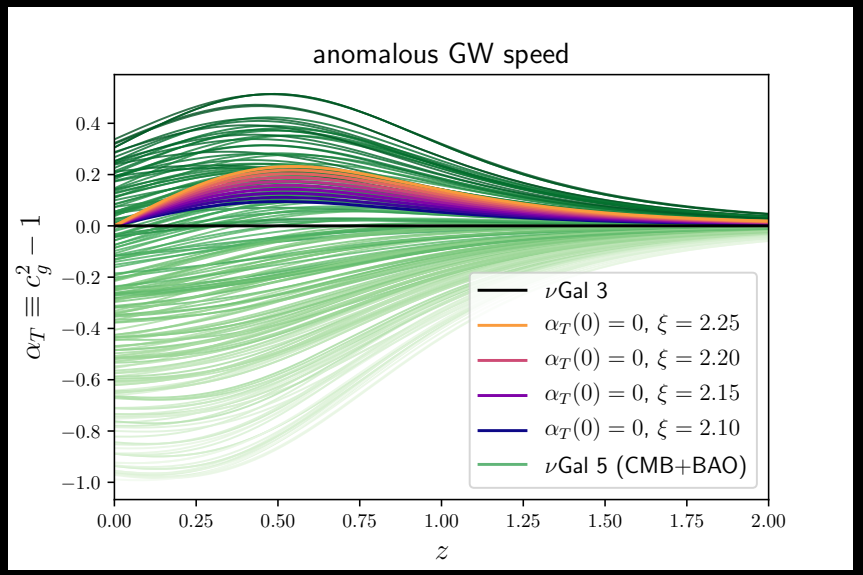
- Galileons with $\alpha_T(z) = 0$

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



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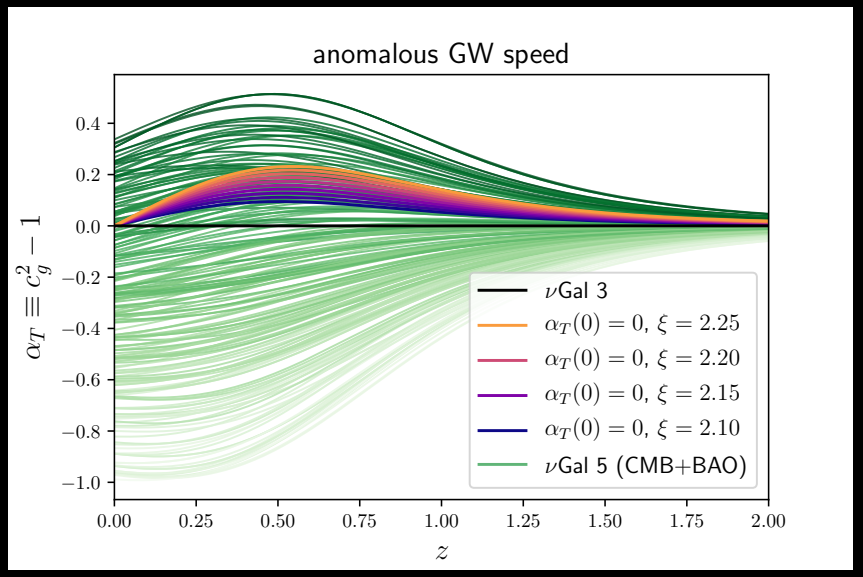



No waveform distortion $\Rightarrow$ <u>need EM counterpart</u>

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

Massive gravity tested with GW alone: $m_g < 7.7 \cdot 10^{-23} eV$ (LIGO '17)

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

# The fate of scalar-tensor gravity (Bettoni, Ezquiaga, Hinterbichler, MZ '16)

**Multi-messenger event (e.g. short-hard Gamma Ray Burst)**

$$\frac{\Delta t}{s} \sim 10^{17}\left(\frac{c_g}{c}-1\right)\left(\frac{D}{200\mathrm{Mpc}}\right)$$

(Will '14, Lombriser & Taylor '15)

- Clear measurement

  $\Rightarrow$ rule out $G_4, G_5$ spectacularly!

- Galileon $\Rightarrow$ Impossible detection

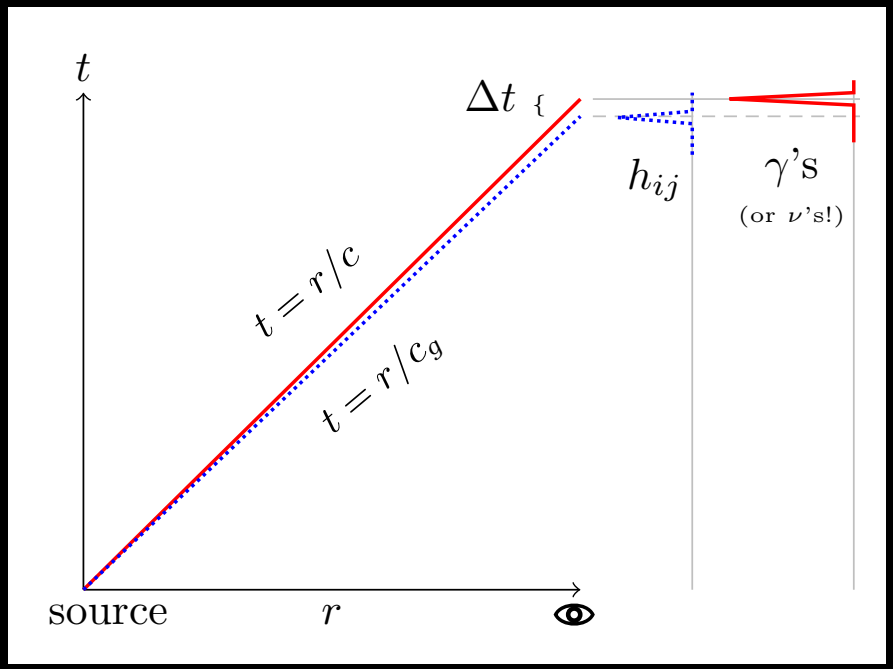
  $\alpha_T \sim 0.1 \Rightarrow \Delta t \sim 10^9 y$!

- LIGO: EM-GW event in 2 years

  (Chen & Holz '13)

- Monitor periodic sources

  (Cutler+ '03, Cooray Seto '04, Bettoni+'17)



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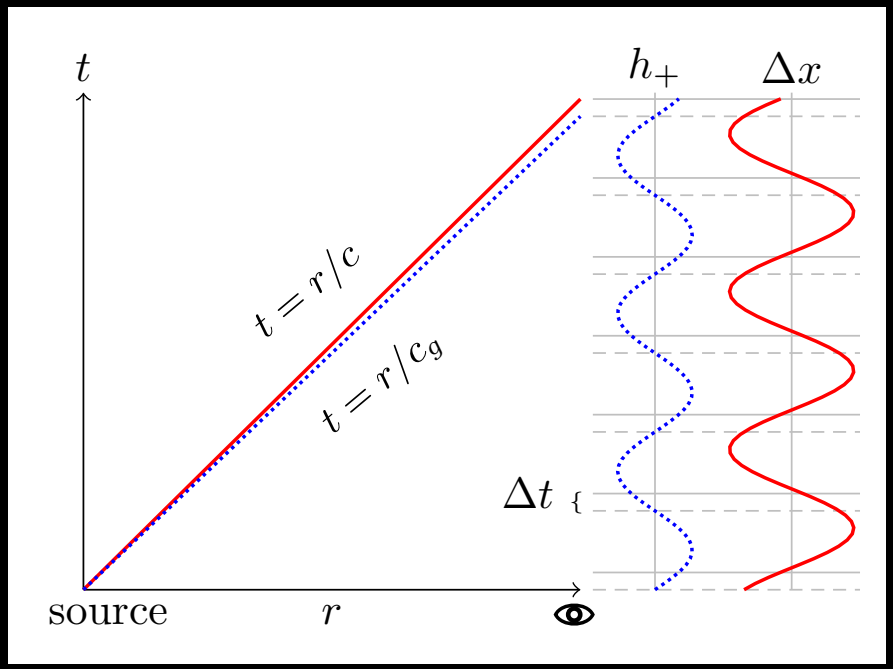

# GW 1708xx $\Rightarrow$ $|\alpha_T| \lesssim 10^{-1\mathrm{x}}$

See also GW 121117:

# Anomalous propagation speed (Babichev, Mukhanov, Vikman '08)

- Canonical scalar field: $\mathcal{L} = X \equiv -(\partial\phi)^2/2$

$$\Box\phi = 0 \quad \rightarrow \quad c_s^2 = 1$$

- Non-canonical ($\phi$-dependence): $\mathcal{L} = f(\phi)X$

$$f\Box\phi - f'(\partial\phi)^2 = 0 \quad \rightarrow \quad c_s^2 = 1$$

$\exists$ transformation $\tilde{\phi}(\phi) : \begin{cases} \tilde{\mathcal{L}} \rightarrow \tilde{X} \\ \tilde{c}_s \rightarrow 1 \end{cases}$

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- Non-canonical (K-essence): $\mathcal{L} = F(X)$

$$\big(\underbrace{F' g^{\mu\nu} - F'' \phi^\mu \phi^\nu}_{\text{effective metric } \mathcal{G}^{\mu\nu}}\big)\phi_{;\mu\nu} = 0 \quad \rightarrow \quad c_s^2 = \frac{1}{1 - \dot{\phi}^2 F''/F'}$$

$c_s \neq 1 \;\Leftrightarrow\; \mathcal{G}^{\mu\nu} \neq \Omega g^{\mu\nu}$ (not proportional metrics)

# Conditions for anomalous speed (Bettoni, Ezquiaga, Hinterbichler, MZ '16)

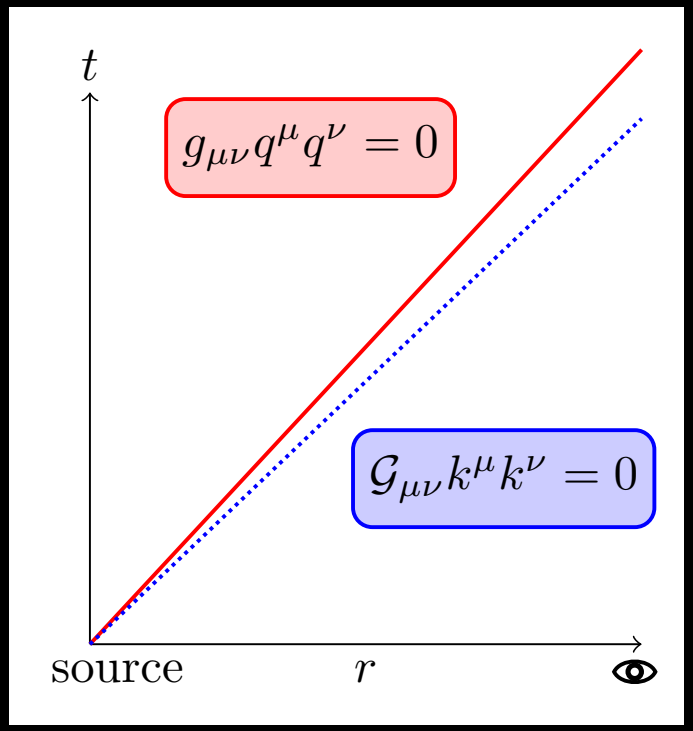
**GW effective metric** - any background, $k^2 \gg |R_{\mu\nu}|$

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

1) VEV for $\phi(x) \to \mathcal{D}_{\mu\nu} \propto \phi_{,\mu}\phi_{,\nu},\ \phi_{,\mu\nu}\cdots$

2) Disformal eff. metric $\quad \mathcal{G}_{\mu\nu} \neq \Omega g_{\mu\nu}$

Kinetic term $\supset$ Weyl tensor (in EoM)




Linear + transverse + traceless perturbations:

- $R^{TT}_{\mu\nu} \propto \Box h^{TT}_{\mu\nu} \Rightarrow \mathcal{G}_{\mu\nu} \propto g_{\mu\nu}$
- $R^{TT}_{\mu\alpha\nu\beta} \propto \partial_\beta\partial_\alpha h^{TT}_{\mu\nu}$ + perm. $\Rightarrow$ Need Weyl tensor in EoM
- $\nabla\nabla\nabla\phi$ from $\phi_{\mu\nu}\phi^{\mu\nu}$ - beyond Horndeski (de Rham & Matas '16)

# Binary classification of theories (Bettoni, Ezquiaga, Hinterbichler, MZ '16)

**$c_g = c$ exact!**

- GR
- Massive Gravity
- Horndeski $G_2, G_3, G_4(\phi)$
- Conformal deriv. coupling $C(X)$

**$c_g \neq c$**

- Bigravity*
- Horndeski $G_4(X), G_5$
- $G^3$ beyond Hornd. (Gleyzes + '14)
- Some DHOST (de Rham&Matas '16)

- Bigravity: $\sqrt{-g}R[g_{\mu\nu}] + \sqrt{-f}R[f_{\mu\nu}] + \cdots$

  $f_{\mu\nu} \neq g_{\mu\nu}$ (FRW) $\Rightarrow c_f \neq c_g \longrightarrow$ hidden by GW oscillations

  (See A. Davis' Talk, Max, Platscher, Smirnov '17)

- Ths. conformally related to GR: $\boxed{g_{\mu\nu} \to \Omega(X,\phi)^2 g_{\mu\nu}}$

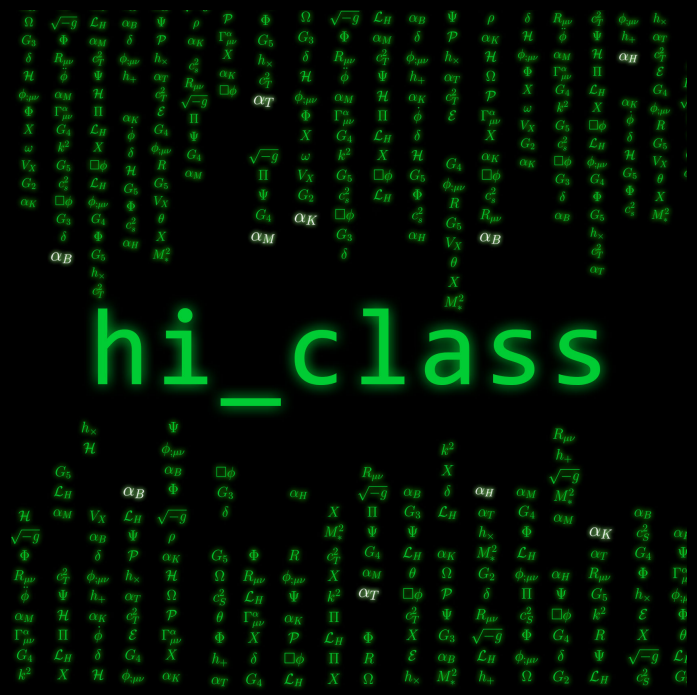
  $\star$ $G_4(\phi)$ (Brans-Dicke & $f(R)$, Chameleons...)

  $\star$ First theory beyond Horndeski (MZ&Garcia-Bellido '13)

# Testing Dark Energy at the Speed of GWs

merci beaucoup!

- Scalar-tensor cosmology well understood
  - ⋆ Description of general theories
  - ⋆ Fast, flexible and accurate software
- Interesting Dark Energy models
  - ⋆ Solution to $H_0$?
  - ⋆ Test with $\nu$'s, Solar System...
- GW+EM $\rightarrow$ critical test for ST theories
  - ⋆ $\phi$ VEV + Weyl $\rightarrow$ disformal
  - ⋆ <u>*either* $c_g = c$ or not</u>
  - ⋆ rule out with GRB (<u>soon?</u>)

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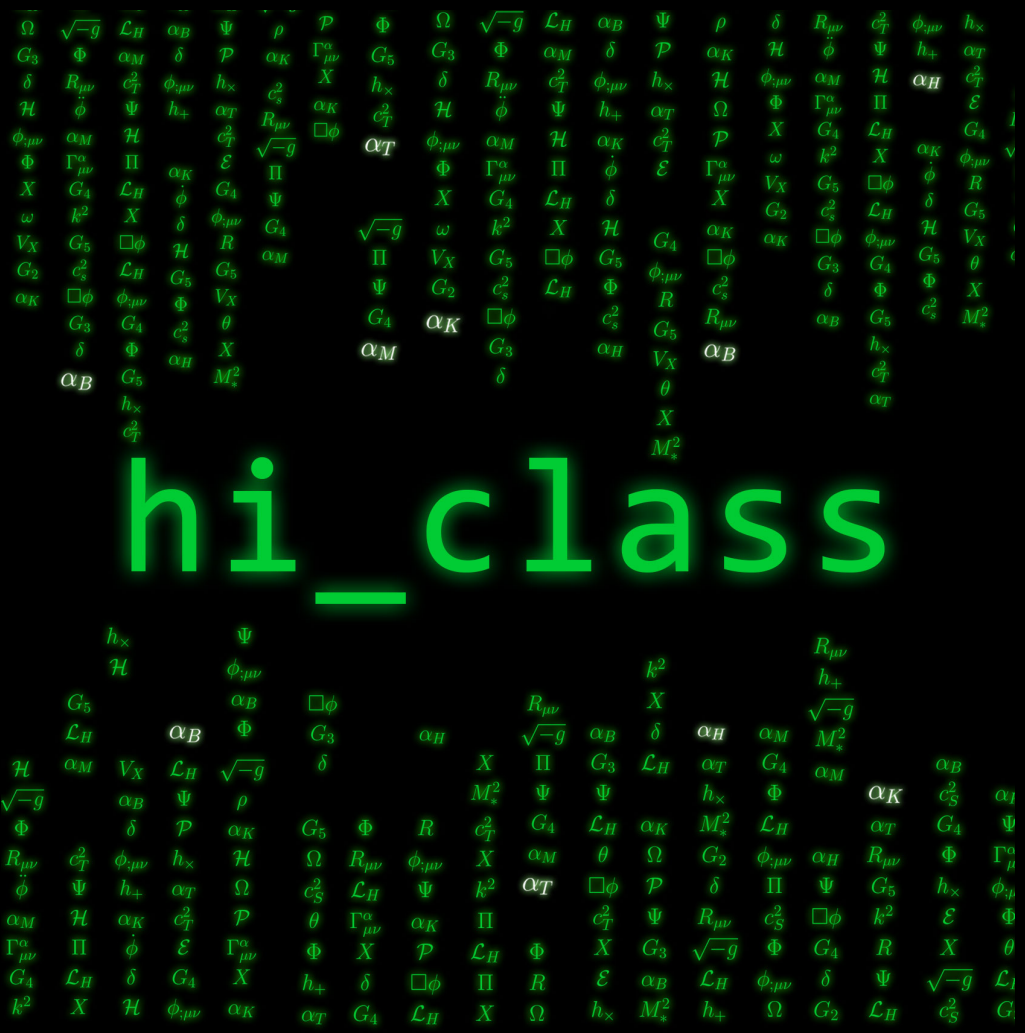
# Back up Slides

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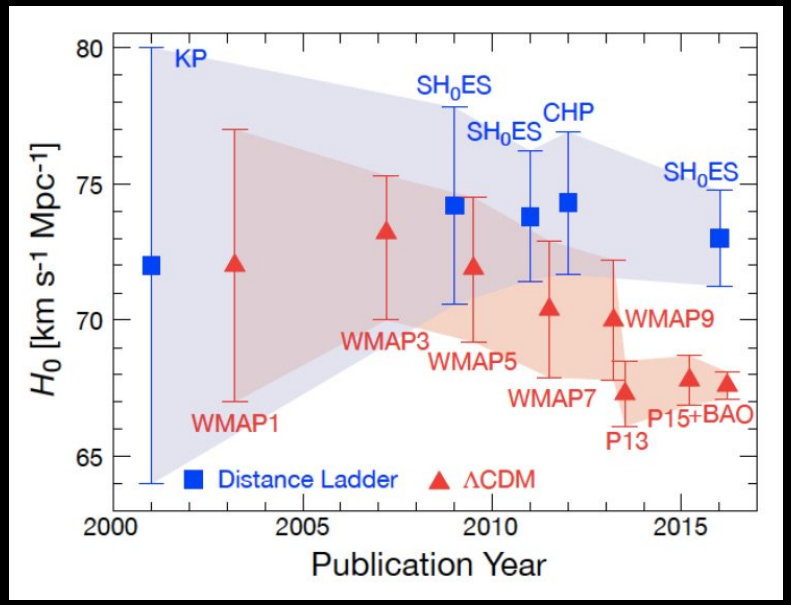
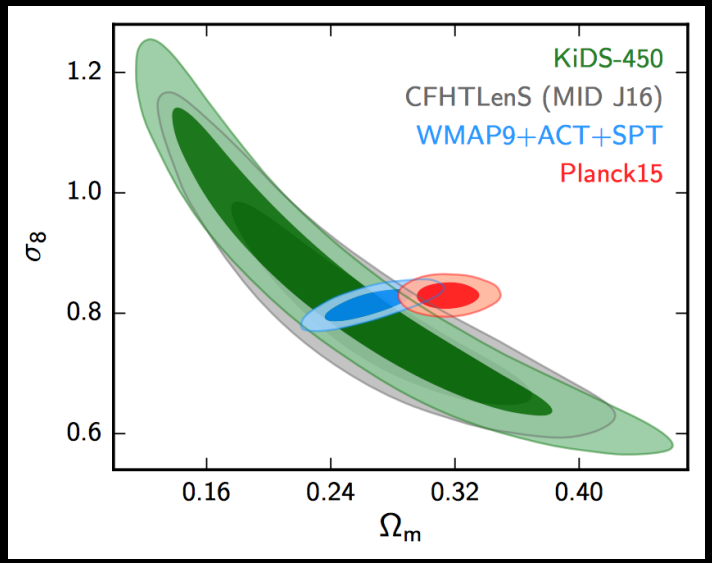
# Tensions in $\Lambda$CDM

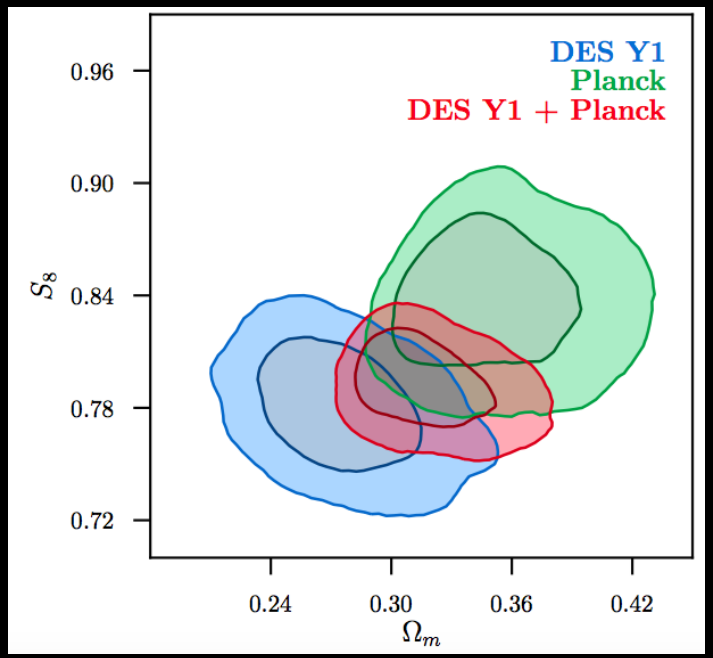
- $H_0 \sim 3.4\sigma$ (HST) $\longrightarrow$
- Weak Lensing
  $\gtrsim 2.9\sigma$ (KiDS)
- DES $\rightarrow$ no tension (?)

Systematics or new physics?




(W. Freedman - Nature '17)



# Continuous GW sources

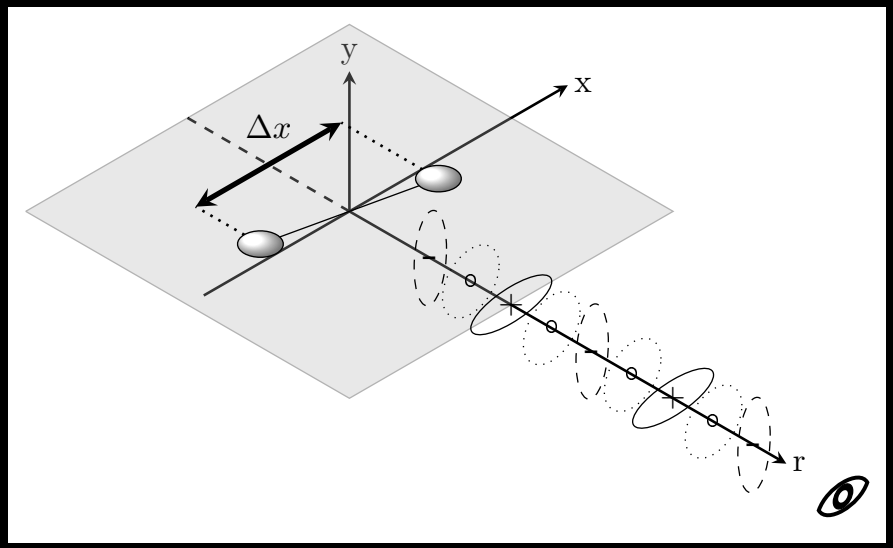
(Bettoni, Ezquiaga, Hinterbichler, MZ '16)

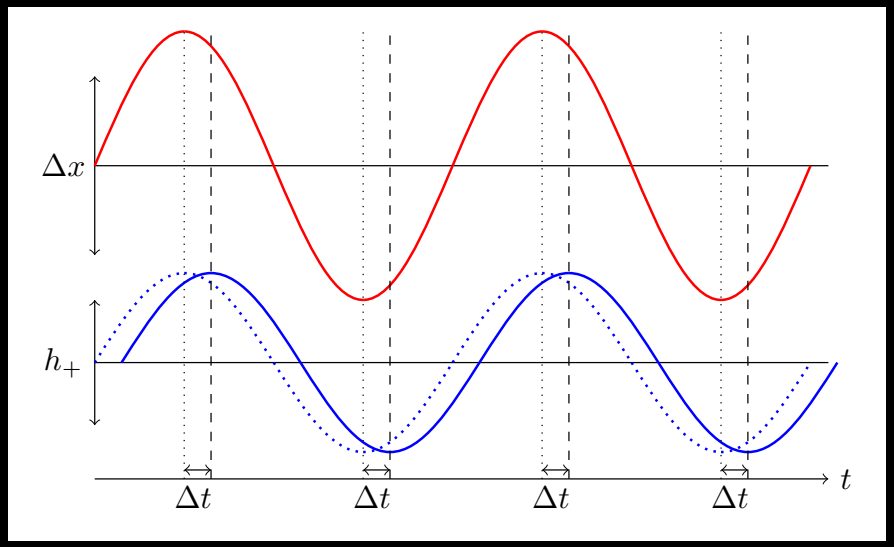
## WDS J0651+2844 (Brown+ '11)

- Eclipsing binary WD
- $T = 765.206543(55)s$
- $\dot{T} = (-8.2 \pm 1.7) \cdot 10^{-12}$

(Hermes+ '12)

$\supset$ LISA verification binaries




$$\Delta t = \frac{r(t)}{c}\left(\frac{c}{c_g} - 1\right)$$

- $r_0 \sim 1\text{kpc} \rightarrow$ phase lag

  Test $c_g \neq c$ at $10^{-12}$ level
- $v_{\text{rel}} t \rightarrow$ frequency shift
- Solar motion (Finn+Romano '13)

# hi_class in practice

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

a) $\boxed{\text{Full theory} + \text{IC}}$

b) *or* $\boxed{\text{Parameterize } w(z), \alpha_i(z)}$

Full theory has more info

- Background $\longrightarrow$ often very constraining
- <u>Non-linear effects</u>
- Other regimes: GWs, strong gravity, Solar System, QM, Lab...

# hi_class: status and prospects

## Public (www.hiclass-code.net)

1. Parameterized $H$, $\alpha$

   $\alpha \propto \Omega$, Planck param...

   ☛ your model here!
2. Iterface with MontePython (parameter estimation)
3. Tested: $\delta C_\ell \lesssim 0.5\%$, $\delta P_k \lesssim 0.1\%$

## Private (coming soon)

1. Theories with $G_2 - G_4$:

   Brans-Dicke, Galileons...

   ☛ your model here!
2. Early Modified Gravity

## Development/test

1. Theories with $G_5$
2. Quasi-static approximation
3. MG initial conditions

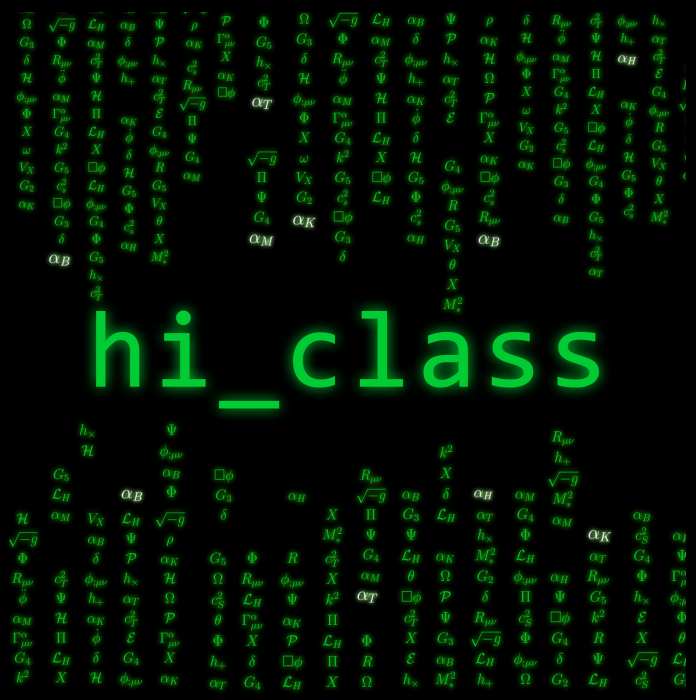
## Prospects

1. beyond Horndeski:

   $G^3$, EST, massive gravity
2. Non-linear (PT, N-body)
3. Curvature, Newt. gauge...

# The hi_class academy

Coming soon!

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- Set of interrelated projects:
  - ⋆ Theory & model building
  - ⋆ Implementation and phenomenology
  - ⋆ Compare with data
- Collaboration → Publishable results
  - ⋆ Review of models
  - ⋆ Observational constaints
- Stay tuned for more info!