Dark Energy at the Speed of Gravitational Waves

New probes of gravity and cosmic acceleration

Miguel Zumalacárregui

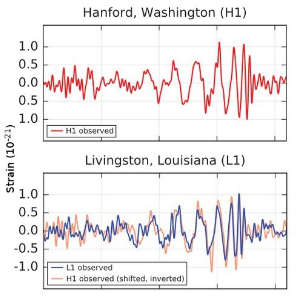
Nordita & BCCP

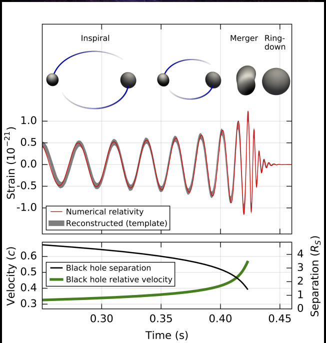
Theoretical Cosmology in the Light of Data - July 2017

with A. Barreira, F. Montanari, J. Renk (1707.xxxxx)

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

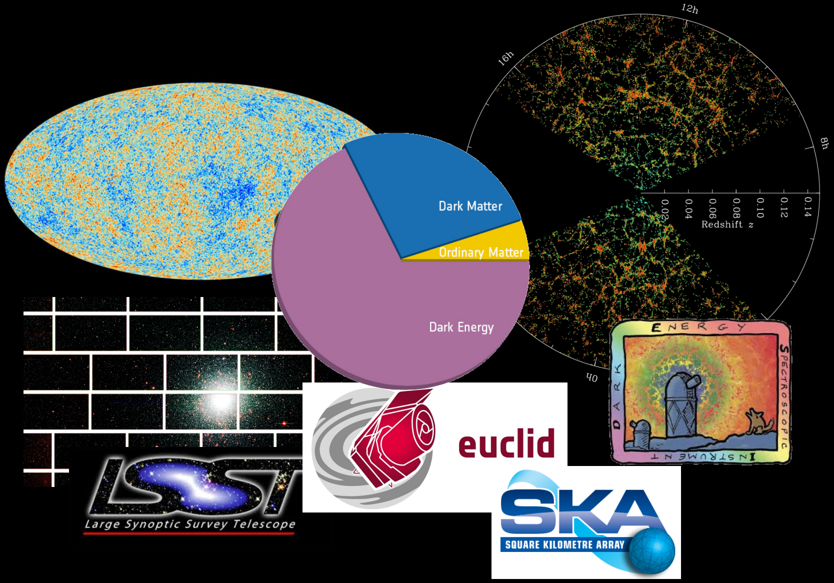
A New Era for Gravity





images from the LIGO collaboration

Great Opportunities for Cosmology



ΛCDM very successful *but*...

H_0 in tension

- Cepheids+SNe (distance ladder)

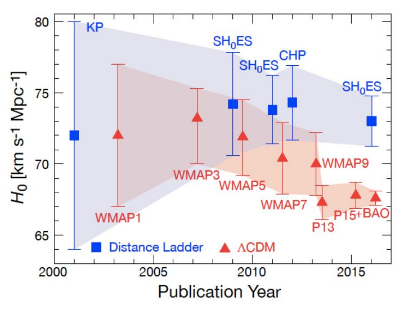
  $$H_0 = 73.24 \pm 1.74$$

  (Riess *et al.* '16)

- CMB+BAO+ΛCDM

  $$H_0 = 66.93 \pm 0.62$$

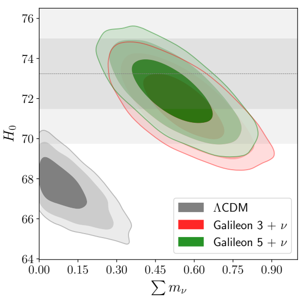
  (Planck '15)

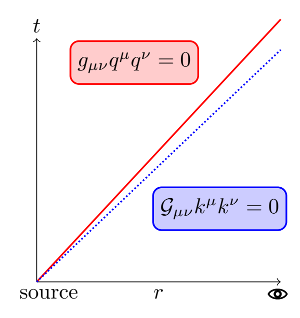


(W. Freedman - Nature '17)

- 3.4σ tension $\Rightarrow$ Either systematic effects or new physics
- Also tension between Planck + Weak Lensing surveys

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 (8.2σ)
- $\sigma(c_g) \to 10^{-12} - 10^{-17}$

The case for modified gravity

- Alternatives to Λ?

  Inflation again? $n_s \neq 1$

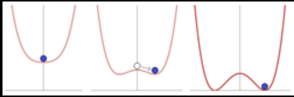
- Interesting theoretical questions

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

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

  proxy for inflation/quantum gravity?

  cosmological constant problems?



- Test gravity on all regimes by

  - *confirming standard predictions* ✓

  - *ruling out competing theories*

How to modify gravity

Lorentz + QM $\Rightarrow$ restrictions on massless graviton interactions!

(Weinberg '64)

Einstein gravity: only covariant metric theory with 2$^{\text{nd}}$ order eqs.

(Lovelock '71)

Need to give up some of the assumptions:

- Add degrees of freedom:
  - Massive gravity: $\rightarrow$ 5 d.o.f. $\rightarrow$ very tough!
  - Scalar-tensor: $\rightarrow$ 2+1 d.o.f.
  - vector-tensor, tensor-vector-scalar (TeVeS), $\cdots$
- Lorentz violation, Non-local interactions, $\cdots$

Scalar-Tensor gravity

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

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

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 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...

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 $\boxed{2^{nd} \text{ order Eqs.}}$

$4\times$ 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...

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 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...

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 ϕ, $X \equiv -(\partial\phi)^2/2$

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

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

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

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 $\boxed{2^{nd} \text{ order Eqs.}}$

$4\times$ 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...

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 ϕ, $X \equiv -(\partial\phi)^2/2$

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

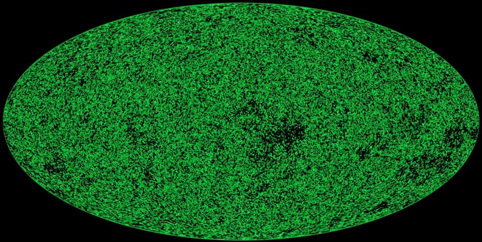
$\supset$ GR, quint/k-essence, Brans-Dicke, $f(R)$, chameleons...

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.xxxx)

PLANCK

Horndeski in four words (Bellini & Sawicki '14)

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

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

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory-specific relations:

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

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory-specific relations:

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

Kineticity: α_K

Standard kinetic term $\rightarrow c_S^2$

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory-specific relations:

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

Kineticity: α_K

Standard kinetic term $\to c_S^2$

Braiding: α_B

Kinetic Mixing of $g_{\mu\nu}$ & ϕ

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory-specific relations:

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

Kineticity: α_K

Standard kinetic term $\to c_S^2$

Braiding: α_B

Kinetic Mixing of $g_{\mu\nu}$ & ϕ

M_p running: α_M

Variation rate of effective M_p

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory-specific relations:

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

Kineticity: α_K

Standard kinetic term $\to c_S^2$

Braiding: α_B

Kinetic Mixing of $g_{\mu\nu}$ & ϕ

M_p running: α_M

Variation rate of effective M_p

Tensor speed excess: α_T

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

Horndeski in the Cosmic Linear Anisotropy Solving System

hi_class

www.hiclass-code.net

1. Flexibility:
   - $\star$ New models trivially added
   - $\star$ Compatible massive ν's, etc...
2. Accuracy:
   - $\star$ Full linear dynamics + ICs
   - $\star$ Tested - Bellini+ (in prep.)

$$\boxed{\delta C_\ell \lesssim 0.5\%,\ \delta P_k \lesssim 0.1\%,\ \delta H \lesssim 0.01\%}$$

3. Speed:
   - $\star$ $2\times$ QS approx. $\rightarrow$ speed up

(MZ, Bellini, Sawicki, Lesgourgues, Ferreira '16)

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

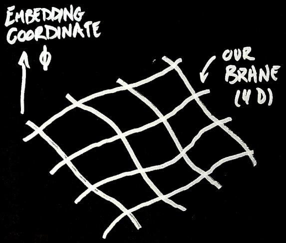
"Simplest" Horndeski theory with all ingredients

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

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

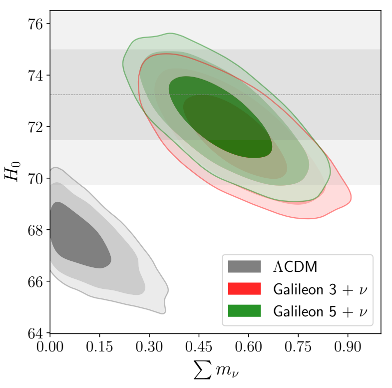
- Related to
  - ⋆ Massive Gravity: $\phi \rightarrow$ helicity 0
  - ⋆ DGP/extra dim: $\phi \leftrightarrow x^5$ coord.
- Vainshtein screening
  - $\Rightarrow$ GR recovered on small scales
- Self-accelerating solutions $(\Lambda = 0)$

(e.g. Barreira '14)



Self-accelerating Galileon gravity $\rightarrow$ talk by Janina Renk (week 4)

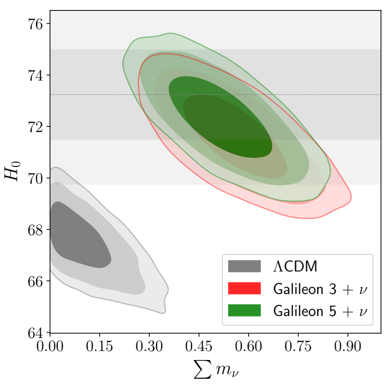
Planck+BAO:



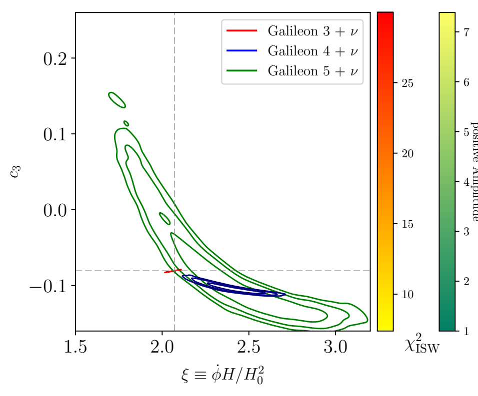
- H_0 compatible (ΛCDM 3.4σ!)
- $\Sigma m_\nu \approx 0.6$ eV
- tension with current BAO data

Self-accelerating Galileon gravity $\rightarrow$ talk by Janina Renk (week 4)

Planck+BAO:



ISW from WISE-Planck:



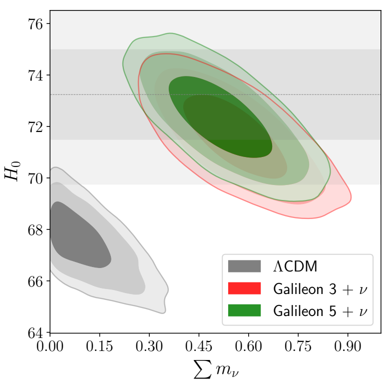
- $\underline{H_0 \text{ compatible}}$ (ΛCDM 3.4σ!)
- $\Sigma m_\nu \approx 0.6$ eV
- tension with current BAO data

- ISW $\rightarrow G_4, G_5 \neq 0$ (8.2σ)

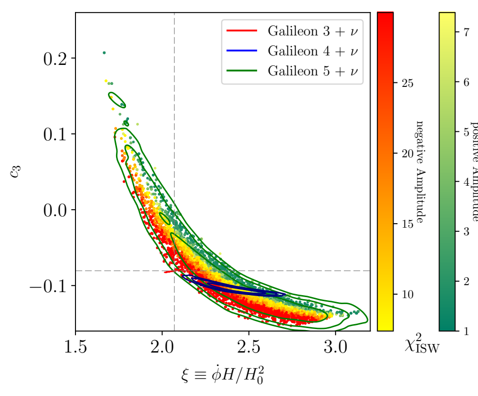
  $\underline{\text{non-standard GW propagation}}$

Self-accelerating Galileon gravity → talk by Janina Renk (week 4)

Planck+BAO:



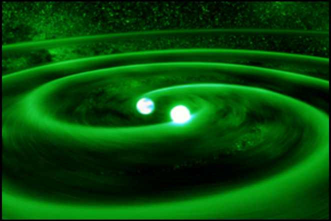
ISW from WISE-Planck:



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

- ISW $\to G_4, G_5 \neq 0$ (8.2σ)
  non-standard GW propagation

Gravitational Waves



with

D. Bettoni, JM Ezquiaga, K. Hinterbichler

1608.01982

NASA

There is no way out from GWs

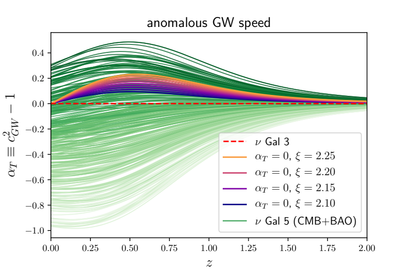
GWs on FRW (Bellini+Sawicki, Gleyzes+ '14)

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

Time dependence:

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

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



There is no way out from GWs

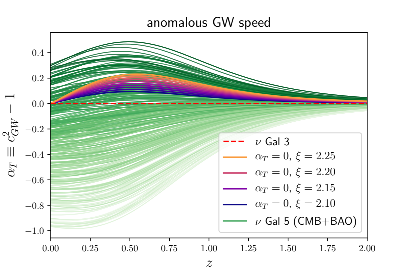
GWs on FRW (Bellini+Sawicki, Gleyzes+ '14)

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

Time dependence:

- Can't fine tune $\alpha_T(z_i) = 0$
- 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 can be tested with GW alone:

$$\omega^2 = k^2 + m_g^2 \quad \Rightarrow \quad \omega \approx k + \frac{m_g^2}{2k^2} + \cdots$$

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

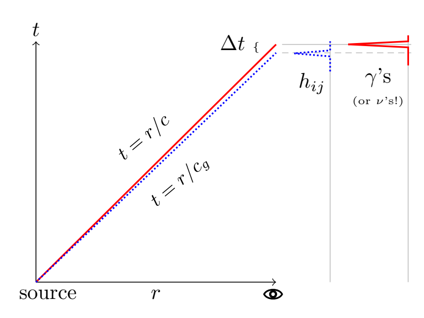
Multi-messenger event (e.g. short-hard Gamma Ray Burst)

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

(Will '14, Lombriser+Taylor '15)

- Clear measurement

  $\Rightarrow$ rule out G_4, G_5 spectacularly!



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

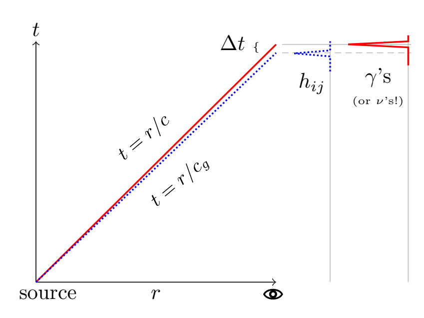
  $\Rightarrow$ rule out G_4, G_5 spectacularly!

- 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)



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

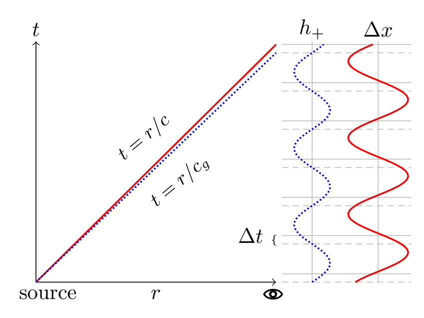
  $\alpha_T \sim 0.1 \Rightarrow \Delta t \sim 10^9 y$!

- LIGO: EM-GW event in 2 years

  (Chen & Holz '13)

- Monitor periodic sources

  (Cutler+ '03, Cooray Seto '04)



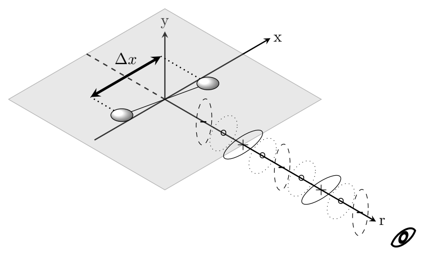
Continuous GW sources (Bettoni, Ezquiaga, Hinterbichler, MZ '16)

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



Continuous GW sources

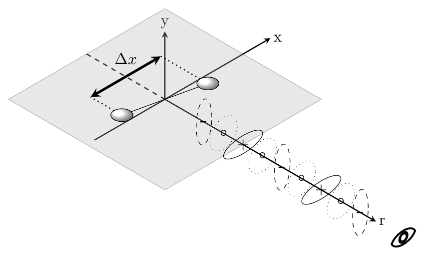
(Bettoni, Ezquiaga, Hinterbichler, MZ '16)

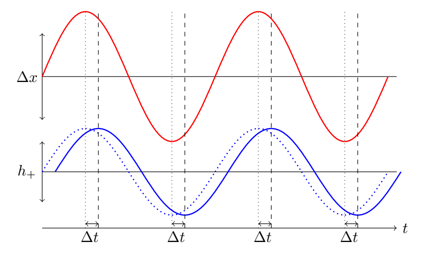
WDS J0651+2844 (Brown+ '11)

- 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 $\boxed{c_g \neq c \text{ at } 10^{-12} \text{ level}}$

- $v_{\rm rel} t$ $\rightarrow$ frequency shift
- Solar motion (Finn+Romano '13)

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

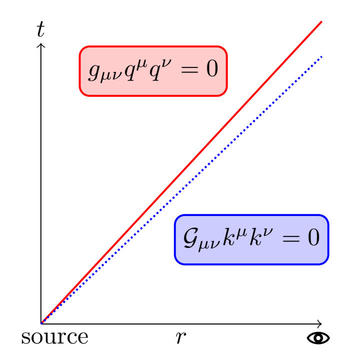
GW effective metric - any background, short scales

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

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

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

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



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

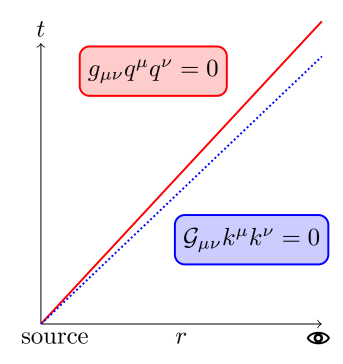
GW effective metric - any background, short scales

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

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

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

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



$c_g = c$ exact!

- GR
- Massive Gravity
- Brans-Dicke, Horndeski G_3
- $C(X)$ (Bekenstein 92, MZ+Garcia-Bellido 13)

$c_g \neq c$

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

Testing Dark Energy at the Speed of GWs

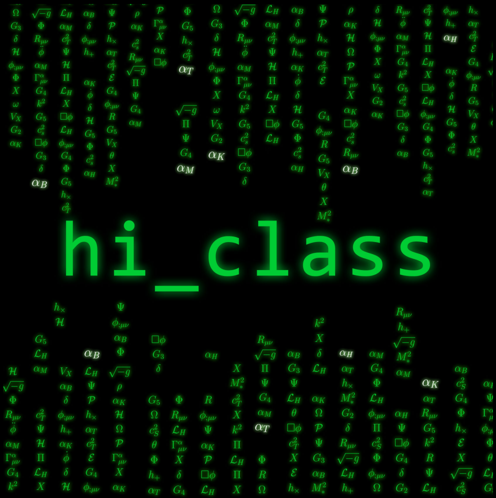
- Scalar-tensor cosmology well understood
  - ⋆ Description of general theories
  - ⋆ Fast, flexible and accurate software
- Interesting Dark Energy models
  - ⋆ Solution to H_0?
  - ⋆ Test with ν's, Solar System...
- GW+EM $\rightarrow$ critical test for ST theories
  - ⋆ *either* $c_g = c$ or not
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

Tack så mycket!

hi_class

www.hiclass-code.net

Back up Slides



www.hiclass-code.net

hi_class in practice

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

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

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

Full theory has more info

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

hi_class: status and prospects

Public (www.hiclass-code.net)

1. Parameterized H, α

   $\alpha \propto \Omega$, 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!

- 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!

www.hiclass-code.net