

# Tests of Gravity and Dark Energy with Cosmology & Gravitational Waves

## Lecture 3: tests with GW propagation

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BERKELEY CENTER *for*  
COSMOLOGICAL PHYSICS



Mesoamerican Center for Theoretical Physics

October 2018

Further reading

- “Dark Energy in light of Multi-Messenger GW astronomy” 1807.09241
- “*hi-class: Horndeski in the Cosmic Linear Anisotropy Solving System*” 1605.06102
  - “Modified Gravity and Cosmology” 1402.5031

**gravity**

'gravɪtɪ/

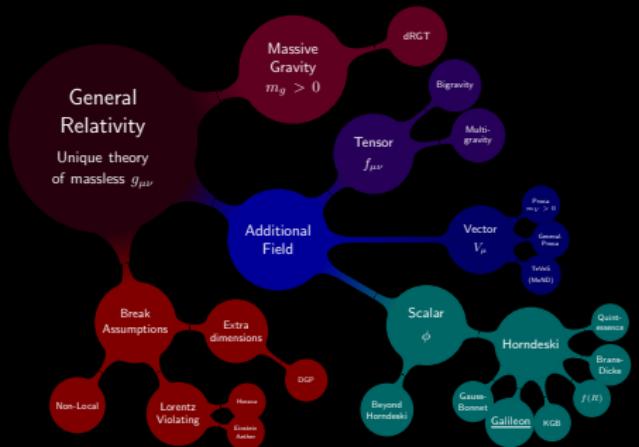
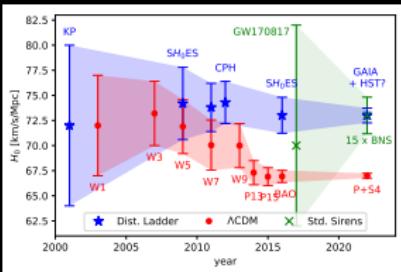
*noun*

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.

Sources: google (1,2)

# Recap from yesterday

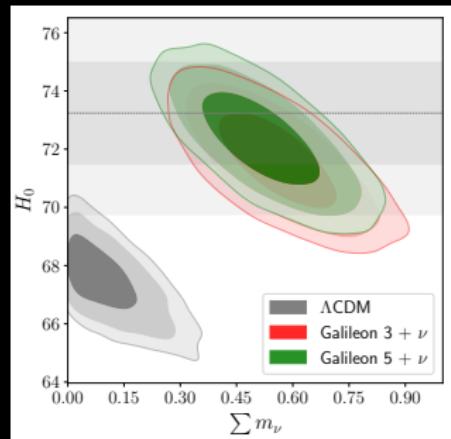
- Gravity is important:  $\exists$  good reasons for beyond GR
- Tensions in  $\Lambda$ CDM: new physics?
- Many theories available
  - general frameworks
  - flexible tools
- Most theories very predictive!
- Test theories in every regime: cosmology, local gravity, GWs...



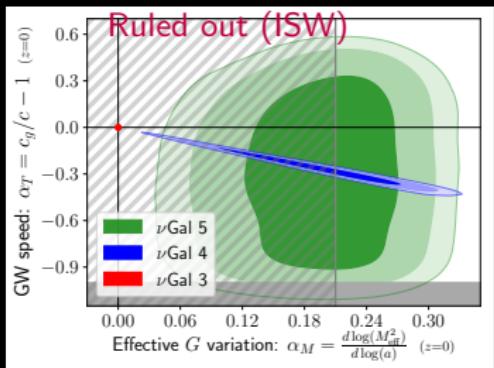
# Recap from yesterday

Self-accelerating Galileon  $\longrightarrow$  modifies GW propagation

Planck(w. lensing)+BAO:

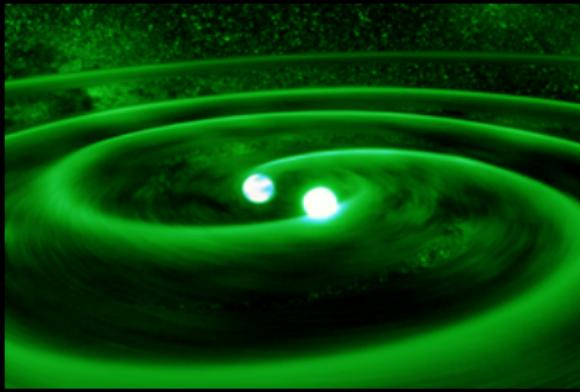


$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{c_g^2, \text{ GW}} \vec{\nabla}^2 h_{ij} + 3H(1 + \alpha_M)\dot{h}_{ij} = 0$$



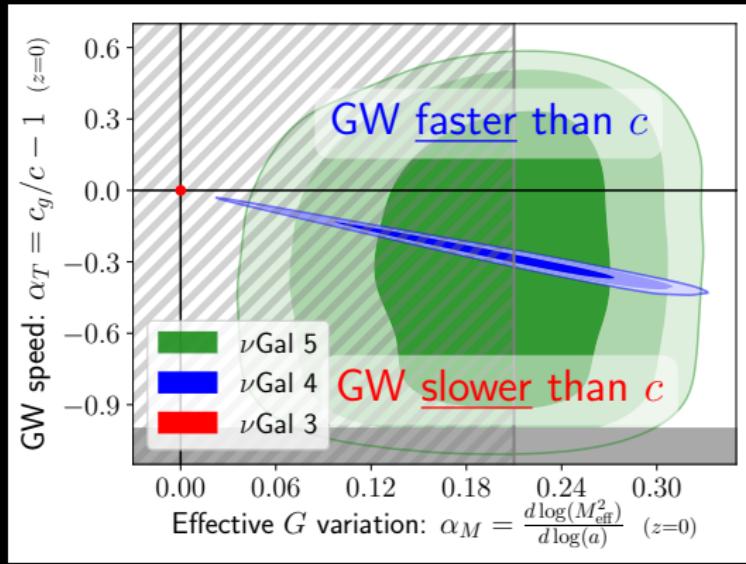
- $H_0$  compatible ( $\Lambda$ CDM  $3.4\sigma$ !)
- if  $\sum m_\nu \approx 0.6$  eV
- slight tension with other data
- ISW effect (from Planck×WISE):
  - kills  $\nu$ Gal3 ( $8.2\sigma$ )
  - non-standard GW propagation

# Gravitational Waves



NASA

# Viable Galileons affect GWs!



$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{c_g^2, \text{ GW}} k^2 h_{ij} + 3H(1 + \alpha_M)\dot{h}_{ij} = 0 \quad (\text{tensors})$$

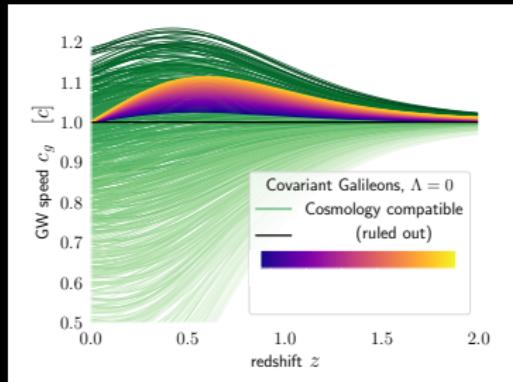
# No way out from GWs

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

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

- Can't fine tune  $|\alpha_T(z)| \lesssim 10^{-15}$
- Simple Galileons w.  $\alpha_T(z) = 0$   
⇒ ruled out by ISW ( $\approx 8\sigma$ )

No self-acceleration (Lombriser & Taylor '15)



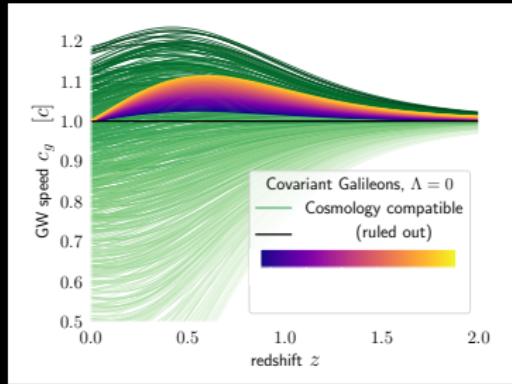
(↑ Ezquiaga & MZ '17)

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No self-acceleration (Lombriser & Taylor '15)

(↑ Ezquiaga & MZ '17)

No waveform distortion ⇒ 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)

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

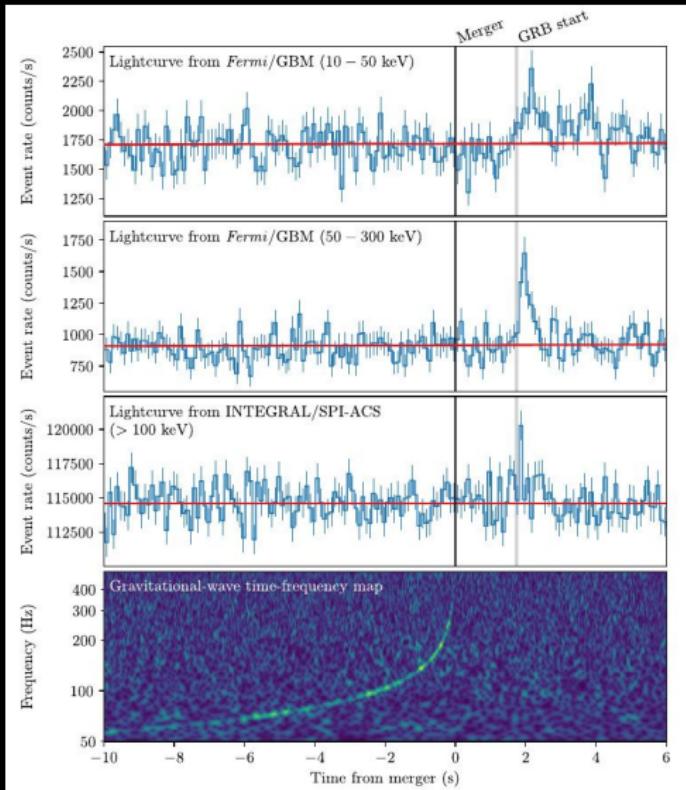
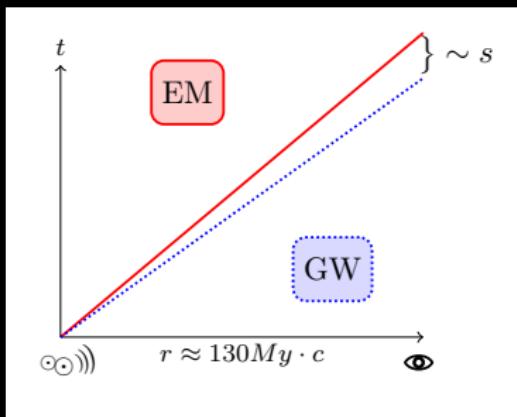
# Universal speed limit

GW170817 + GRB170817A

Bound on the GW speed:

$$-3 \cdot 10^{-15} \leq \frac{c_g}{c} - 1 \leq 6 \cdot 10^{-16}$$

(LIGO+Fermi+... 1710.05834)



# Coincident Signals: GW170817 and its Aftermath

## GW170817 + GRB170817A

Bounds:  $\left| \frac{c_g}{c} - 1 \right| \lesssim 10^{-15}$   
(LIGO+Fermi+... 1710.05834)

Theories:  $\Delta c_g/c \sim 0.1 - 1\%$

## Strongest constraints on DE & Modified Gravity

[2] arXiv:1710.05901 [pdf, other]

### Dark Energy after GW170817

Jose María Ezquiaga (1 and 2), Miguel Zumalacárcel (2 and 3) ((1) Madrid IFT, (2) UC Berkeley, (3)

Comments: 9 pages, 3 figures

Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)

[3] arXiv:1710.05893 [pdf, other]

### Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor

Jeremy Sakstein, Bhuvnesh Jain

Comments: 5 pages, two figures

Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)

[4] arXiv:1710.05877 [pdf, ps, other]

### Dark Energy after GW170817

Paolo Creminelli, Filippo Vernizzi

Comments: 5 pages

Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)



J Craig Wheeler  
@ast309

Follow

New LIGO. Source with optical counterpart. Blow your sox off!

7:25 PM - Aug 18, 2017

3 47 88

304 (2017)  Selected for a Viewpoint in Physics  
PHYSICAL REVIEW LETTERS 22 DECEMBER 2017

Dark Energy After GW170817: Dead Ends and the Road Ahead  
Jose María Ezquiaga<sup>1,2,\*</sup> and Miguel Zumalacárregui<sup>2,3,4,†</sup>

251302 (2017)  Selected for a Viewpoint in Physics  
PHYSICAL REVIEW LETTERS 22 DECEMBER 2017

Dark Energy after GW170817 and GRB170817A

Paolo Creminelli<sup>1</sup> and Filippo Vernizzi<sup>2</sup>

See also Baker, Bellini, Ferreira, Lagos, Noller, Sawicki '17, many others

$\mathcal{O}(50)$  papers on MG after GW170817 (and counting)

Miguel Zumalacárregui (Berkeley)

Tests of Gravity & DE with cosmology & GWs

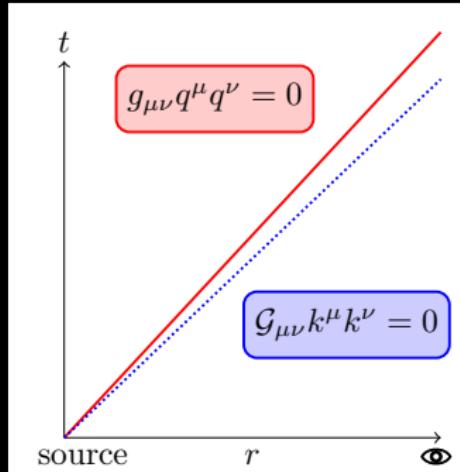
# Conditions for variable $c_g$

(Bettoni, Ezquiaga, Hinterbichler & MZ '16)

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

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

$$\text{GW eq} \propto \left( \underbrace{C\square + D_{\mu\nu}\partial^\mu\partial^\nu}_{G_{\mu\nu}\partial^\mu\partial^\nu} \right) h_{ij}$$



# Conditions for variable $c_g$

(Bettoni, Ezquiaga, Hinterbichler & MZ '16)

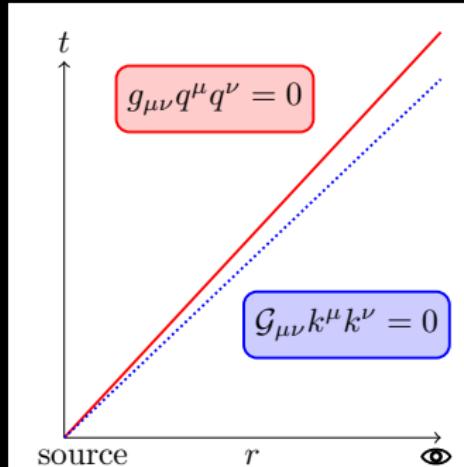
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1) Non-trivial  $\phi(x) \rightarrow \mathcal{D}_{\mu\nu} \propto \partial_\mu\phi\partial_\nu\phi \dots$

Cosmology  $\rightarrow \dot{\phi} \sim H_0$



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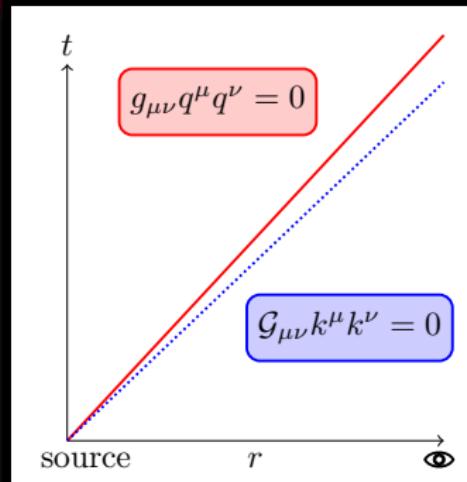
1) Non-trivial  $\phi(x) \rightarrow \mathcal{D}_{\mu\nu} \propto \partial_\mu\phi\partial_\nu\phi \dots$

Cosmology  $\dot{\phi} \sim H_0$

2)  $\phi$ -derivatives couple to Riemann Curvature

$$R_{\mu\alpha\nu\beta} \rightarrow \underline{\partial_\mu\partial_\nu} h_{\alpha\beta}^{\text{TT}} \quad (R_{\mu\nu} \rightarrow \square h_{\mu\nu}^{\text{TT}})$$

i.e. non-canonical kinetic term

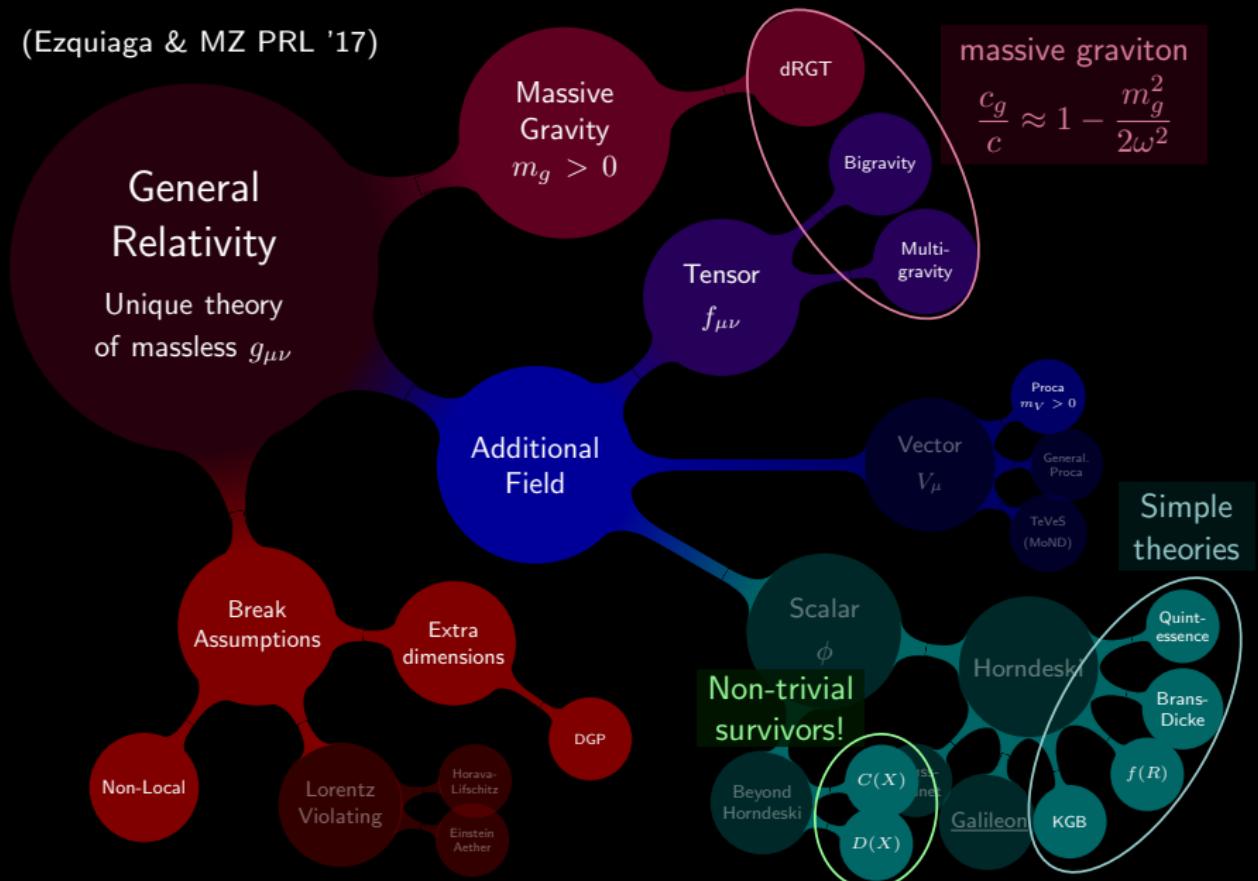


(1,2)  $\Rightarrow \phi$  changes the effective medium in which GWs propagate.

(2)  $\Rightarrow$  binary classification of theories

# DE after GW170817

(Ezquiaga & MZ PRL '17)



- Canonical kinetic term (quint/k-essence/KGB)

$$\sqrt{-g}R[g_{\mu\nu}] + \dots$$

- Conformally related to canonical: Brans-Dicke-like

$$\sqrt{-g}f(\phi)R[g_{\mu\nu}] = \sqrt{-\tilde{g}}\tilde{R}[\tilde{g}_{\mu\nu}] \quad \text{for} \quad \tilde{g}_{\mu\nu} = \mathcal{C}(\phi)g_{\mu\nu}$$

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## Conformal extension

$$\tilde{g}_{\mu\nu} = \mathcal{C}(\phi, X)g_{\mu\nu}$$

- Starting theory  $c_g = c$  ✓
- Transform preserving  $c_g/c$  ✓

↪ quartic DHOST theory!

*First beyond Horndeski th.* (MZ+ '13)

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▷ quartic DHOST theory!

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### Disformal tuning

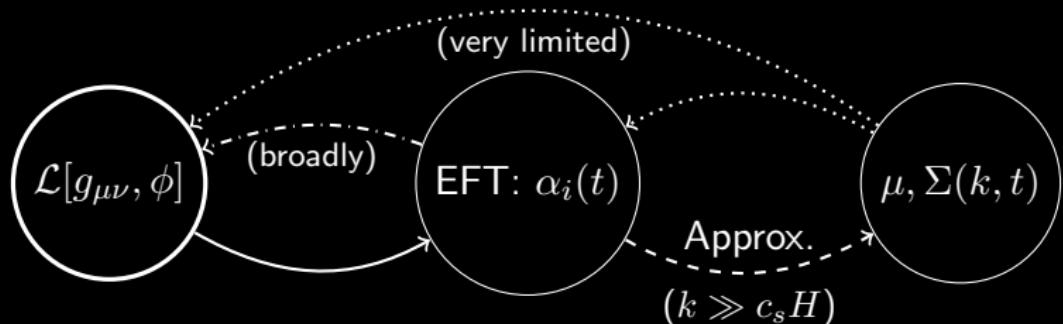
$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \mathcal{D}\phi_\mu\phi_\nu$$

- Starting theory  $c_g \neq c$  ☠
- Transform compensate  $\Delta c_g$  ✓

$$\tilde{c}_g^2 = c_g^2(\tilde{X})/(1 + 2\mathcal{D}\tilde{X})$$

▷ quartic GLPV theory

# What's left after GW170817?



## Lagrangian

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

## Effective Theory

- $\alpha_T = 0$
- all other  $\alpha$ 's free

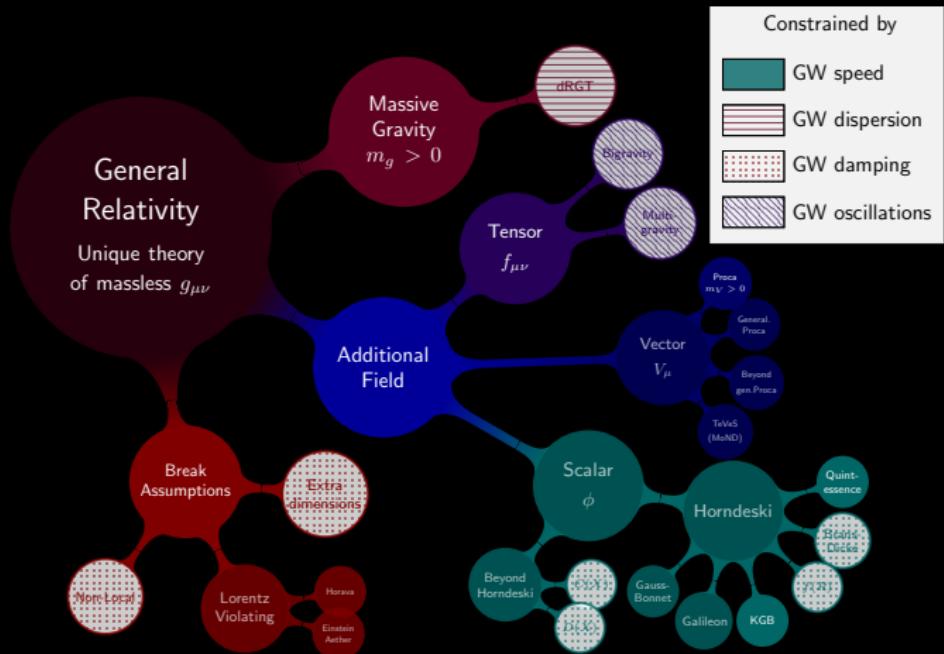
## Parameterization

- Everything goes!

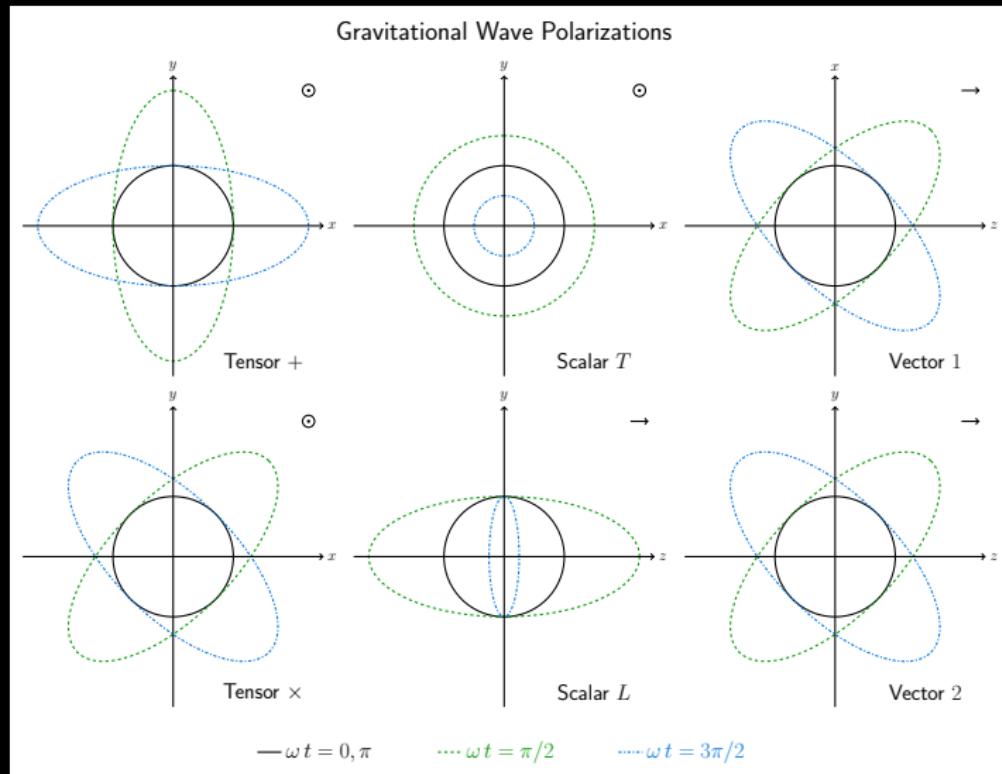
# Tests with GW propagation

(Nishizawa '17, Ezquiaga & MZ '18)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$



# GW polarizations (any beyond GR Th.) (cf. Capozziello's lecture 2)



Caution: screening suppresses emission/reception of non-GR polarizations.

# GW damping (scalar-tensor,...)

(Amendola+ '17)

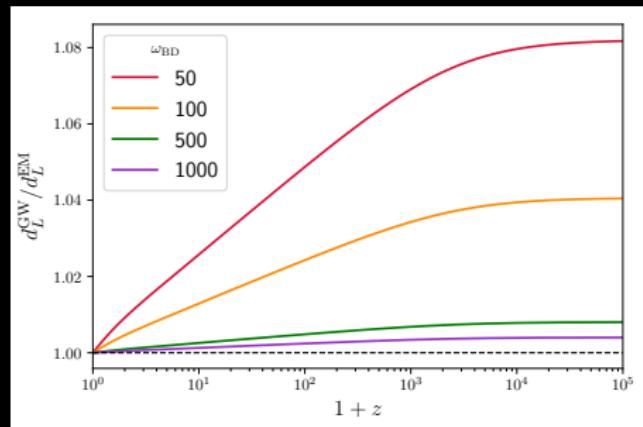
$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \boxed{\underbrace{(1 + \alpha_M) \dot{h}_{ij}}_{\text{damping}}} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

Friction  $\rightarrow$  damps GW amplitude

$$\begin{aligned} \frac{d_L^{em}(z)}{d_L^{gw}(z)} &= \exp \left[ \frac{1}{2} \int_0^z \frac{\alpha_M(z')}{1+z'} dz' \right] \\ &= \frac{M_*(0)}{M_*(z)} \end{aligned}$$

$$\alpha_M \equiv \frac{d \ln(M_*^2)}{d \ln(a)} \quad (\text{Planck mass running})$$

$$\text{Brans-Dicke: } M_*^2 = 2G_4 \propto \phi$$



(ratio of lum. dist. for Brans-Dicke)

# GW dispersion (massive gravity...)

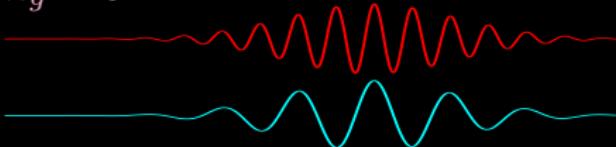
(Review: de Rham + '16)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T) k^2 h_{ij}}_{\text{speed}} + 3H \underbrace{(1 + \alpha_M) \dot{h}_{ij}}_{\text{damping}} + \boxed{\underbrace{m_g^2 h_{ij}}_{\text{dispersion}}} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

Mass: energy dependent velocity

$$v_g^2(E) \approx 1 - \frac{m_g^2}{E^2}$$

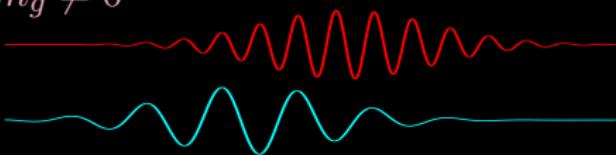
$$m_g = 0$$



Shifts the phase of lower frequencies

$$m_g^2 \leq 7.7 \cdot 10^{-23} \text{ eV}/c^2$$

$$m_g \neq 0$$



from GW170104 (no EM signal needed!)

Similar tests for Lorentz-violation:  $E^2 = c^2 k^2 + k^n / \Lambda^{n-2}$

# GW oscillations (bigravity, multigravity)

(Max et al '16)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + \underbrace{3H(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

Additional metric with mass mixing:

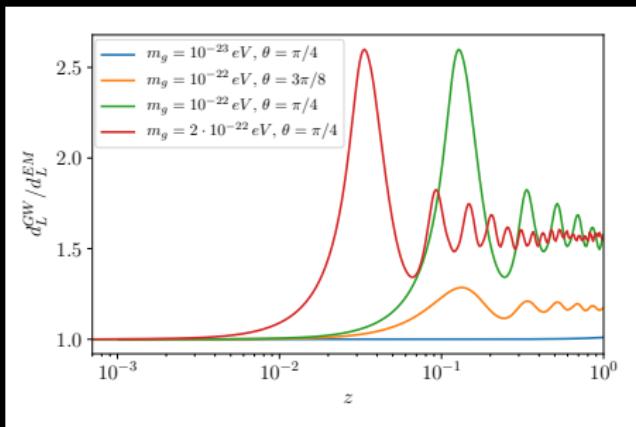
$$\left\{ \begin{pmatrix} \square & 0 \\ 0 & \square \end{pmatrix} + \begin{pmatrix} m_g^2 & \mu^2 \\ \mu^2 & m_f^2 \end{pmatrix} \right\} \begin{pmatrix} h \\ f \end{pmatrix} = 0$$

Diagonalize into propagation states

$$\begin{pmatrix} \tilde{h} \\ \tilde{f} \end{pmatrix} = \begin{pmatrix} \cos \theta_g & \sin \theta_g \\ -\sin \theta_g & \cos \theta_g \end{pmatrix} \begin{pmatrix} h \\ f \end{pmatrix}$$

$$\frac{\text{missing GW}}{\text{produced GW}} = \sin^2(2\theta_g) \left( \frac{m_g^2 L}{4E} \right)$$

Very similar to neutrino oscillations

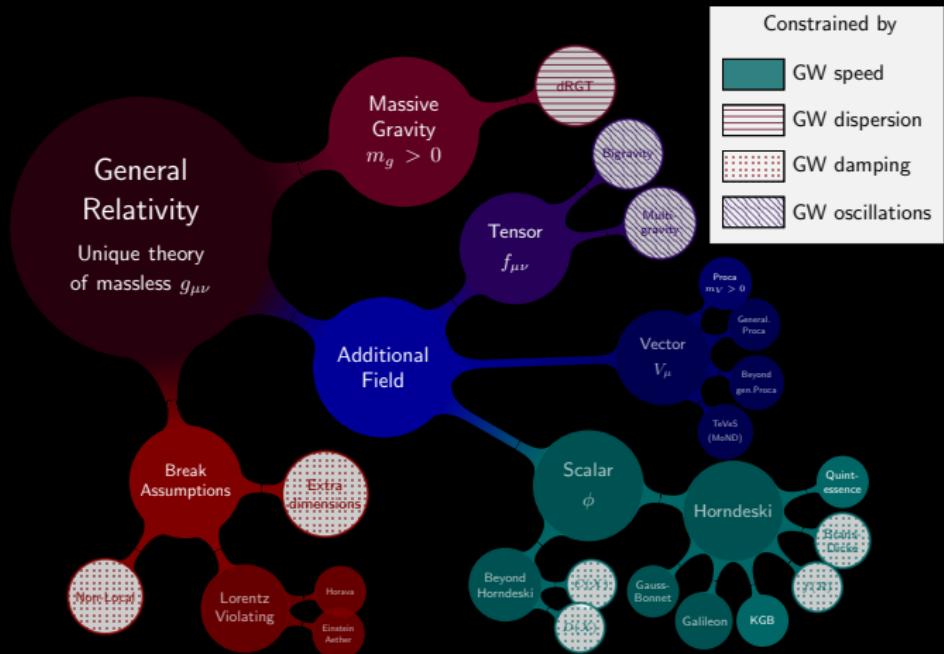


(ratio of lum. dist. for bigravity,  
cf. Max et al '16)

# Tests with GW propagation

(Nishizawa '17, Ezquiaga & MZ '18)

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# Standard Sirens (all theories)

Emitted GWs in GR (weak field)

$$\bar{h}_{ij} = \frac{2G}{d_L^{gw}} \ddot{M}_{ij} \Big|_{t_r}$$

$$(\bar{h}_{ij} = h_{ij} - h/2\eta_{ij})$$

- $M_{ij} = \int dy^3 y_i y_j T^{00}$  (quadrupole)

- $t_r = t - x/c$  (retarded time)

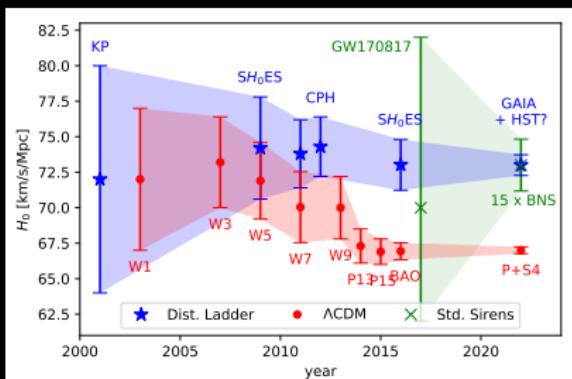
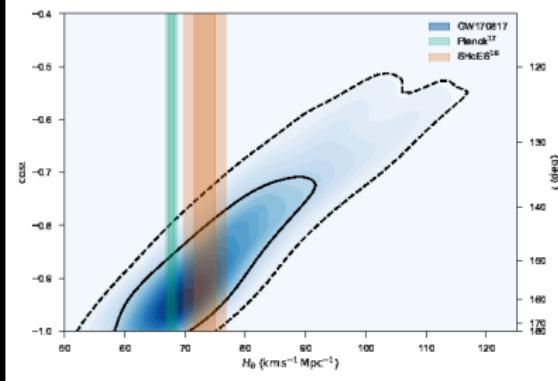
- degenerate with inclination  $\iota$

$$h_+ \propto \frac{(1 + \cos \iota)^2}{2d_L^{gw}}, \quad h_\times \propto \frac{\cos \iota}{2d_L^{gw}}$$

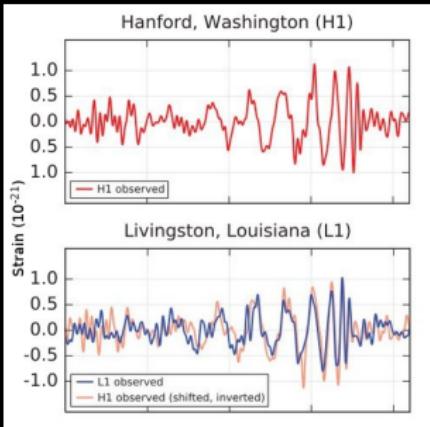
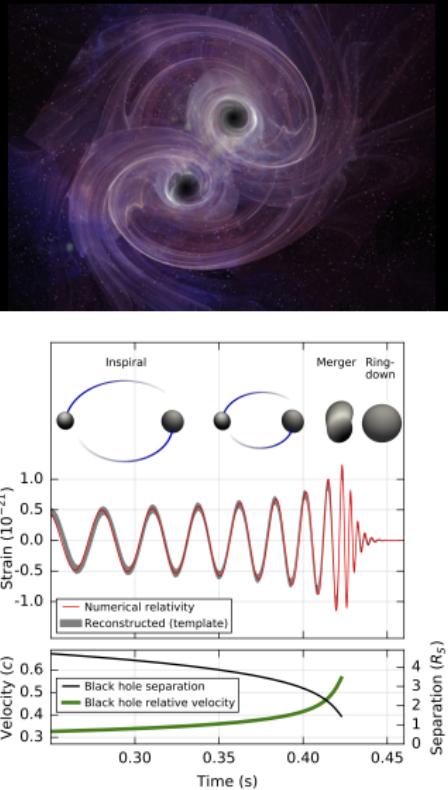
- Need EM counterpart  $\rightarrow z!$

Hard measurement, well known theory!  
(complementary to standard candles)

GW170817 measurement of  $H_0$



# The GW era has begun

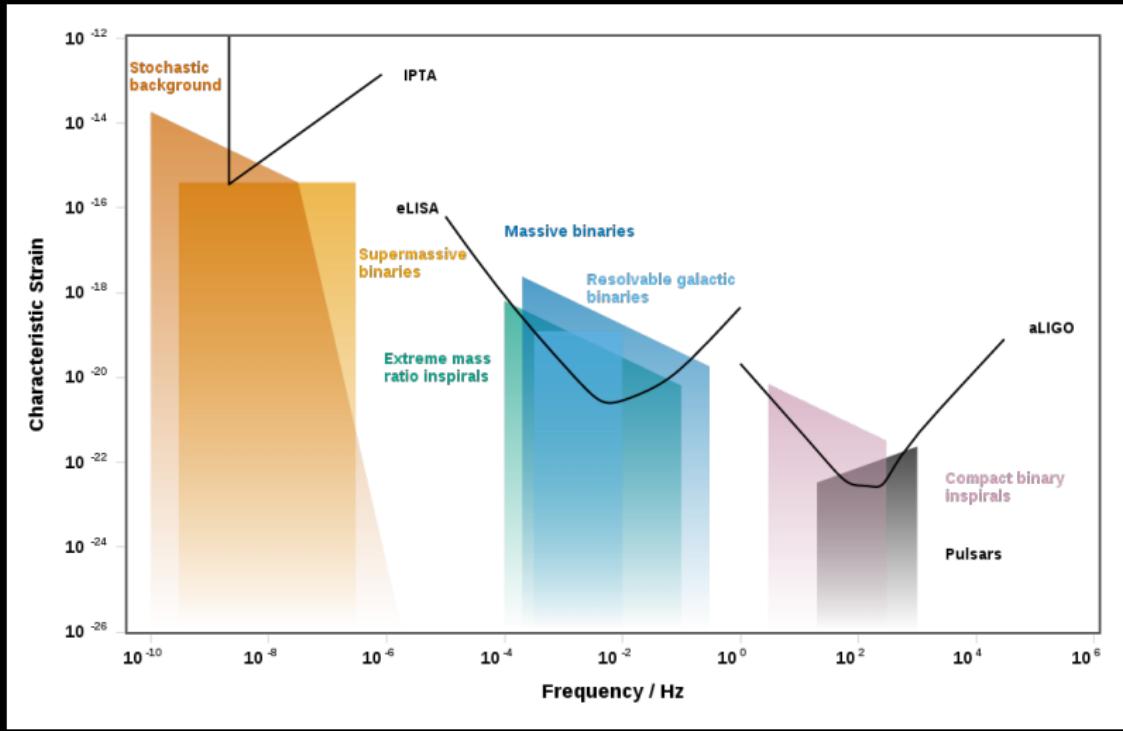


images from the LIGO collaboration

Miguel Zumalacárregui (Berkeley)

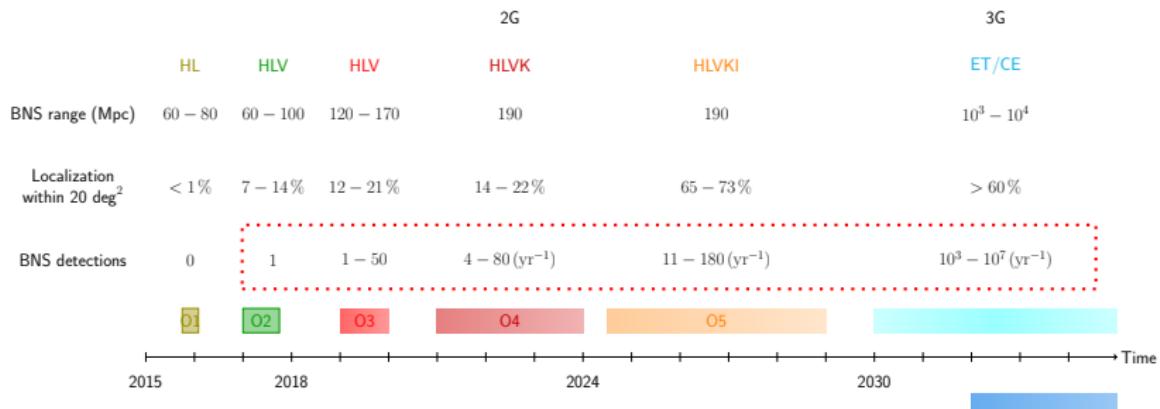
Tests of Gravity & DE with cosmology & GWs

# The GW spectrum



# GWs: a bright and loud future ahead!

Multi-messenger GW astronomy timeline



(from Ezquiaga & MZ '18)

gravity  
'gravɪti/  
*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.

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

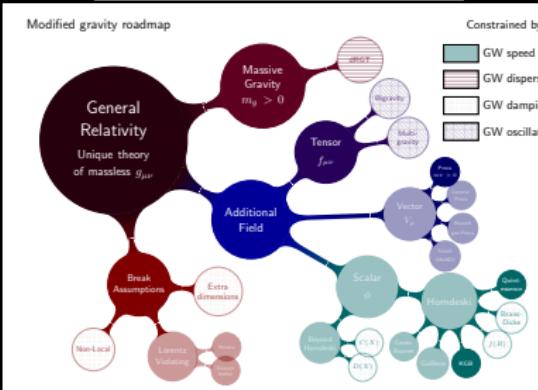
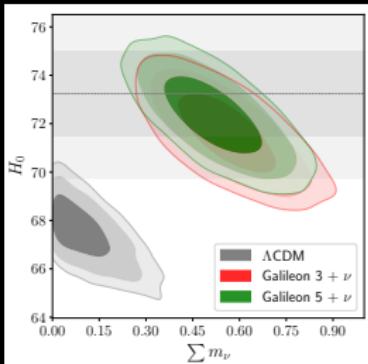
⇒ ∃ at least a useful “test” of gravity!



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

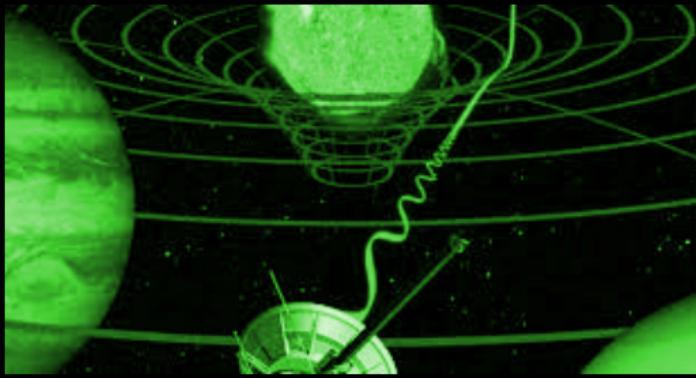
# Conclusions

- $\exists$  Interesting Dark Energy models
  - ★  $\Lambda$ CDM tensions?
  - ★ Very predictive!
- GW propagation  $\rightarrow$  critical test of gravity
  - ★ Dead ends after GW170817
  - ★ Many other tests!
- Complementarity is essential:
  - ★ Cosmology, cross-correl. (ISW...)
  - ★ Gravitational Waves
  - ★ Solar System
- Need to go back to our blackboards...



[www.hiclass-code.net](http://www.hiclass-code.net)

## Bonus Track



How to satisfy local gravity tests?

Cassini/NASA

# New gravity → new forces

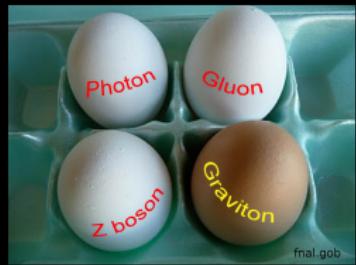
Scalar-tensor theories

⇒ scalar mediated force

★ Point Particle, coupled to  $\tilde{g}_{\mu\nu}[\phi]$ :

$$\ddot{x}^\alpha = - \left( \Gamma_{\mu\nu}^\alpha + \underbrace{\mathcal{K}_{\mu\nu}^\alpha}_{\gamma^{\alpha\lambda} (\nabla_{(\mu} \gamma_{\nu)}{}_\lambda - \frac{1}{2} \nabla_\lambda \gamma_{\mu\nu})} \right) \dot{x}^\mu \dot{x}^\nu$$

$$\Rightarrow \boxed{F_\phi^i \approx f[\phi] \nabla^i \phi} + \mathcal{O}(v^i/c)$$



# Subtle the Force can be

$$F_\phi^i \approx f[\phi] \nabla^i \phi$$

"You must feel the Force around you;  
here, between you, me, the tree, the rock,  
everywhere, yes"

*Master Yoda*

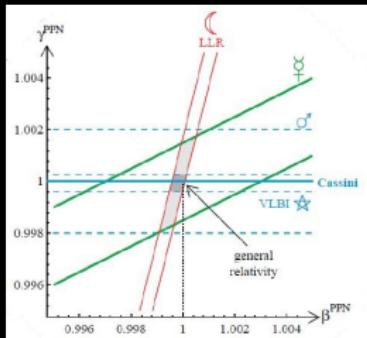


# Subtle the Force can be

$$F_\phi^i \approx f[\phi] \nabla^i \phi$$

"You must feel the Force around you;  
here, between you, me, the tree, the rock,  
everywhere, yes"

*Master Yoda*



## Screening Mechanisms

$$\left| \frac{F_\phi}{F_G} \right| \ll 1 \text{ when } \begin{cases} \rho \gg \rho_0 \\ r \ll H_0^{-1} \end{cases}$$

# May the force *not* be with you

$\rho \gg \rho_0$  Chameleon Screening - Khoury & Weltman (PRL 2004)

Yukawa force:  $\phi \propto \frac{1}{r} e^{-\phi/m_\phi}$  with  $m_\phi(\rho)$  increases with  $\rho$

(see also Symmetron - Pietroni PRD '05, Hinterbichler Khoury PRL '10)

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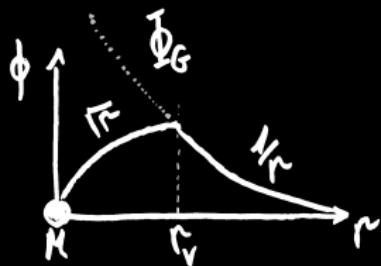
$r \ll H_0^{-1}$  Vainshtein Screening - Vainshtein (PLB 1972)

$\mathcal{L} \supset (\partial\phi) + \square\phi X/m^2 + \alpha\phi T_m$  Non-linear derivative interactions

$$\Rightarrow \square\phi + m^{-2} ((\square\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}) = \alpha M\delta(r)$$

$$\phi \propto \begin{cases} r^{-1} & \text{if } r \gg r_V \\ \sqrt{r} & \text{if } r \ll r_V \end{cases}$$

Vainshtein radius  $r_V \propto (GM/m^2)^{1/3}$



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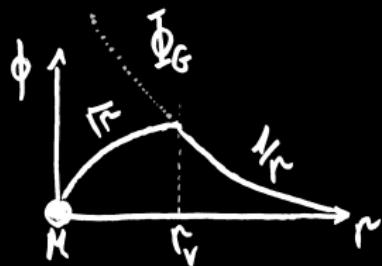
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