MPIK - 10.12.2018

One wave to rule (out) them all?

On how GW astronomy is challenging scalar DE

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In collaboration with:

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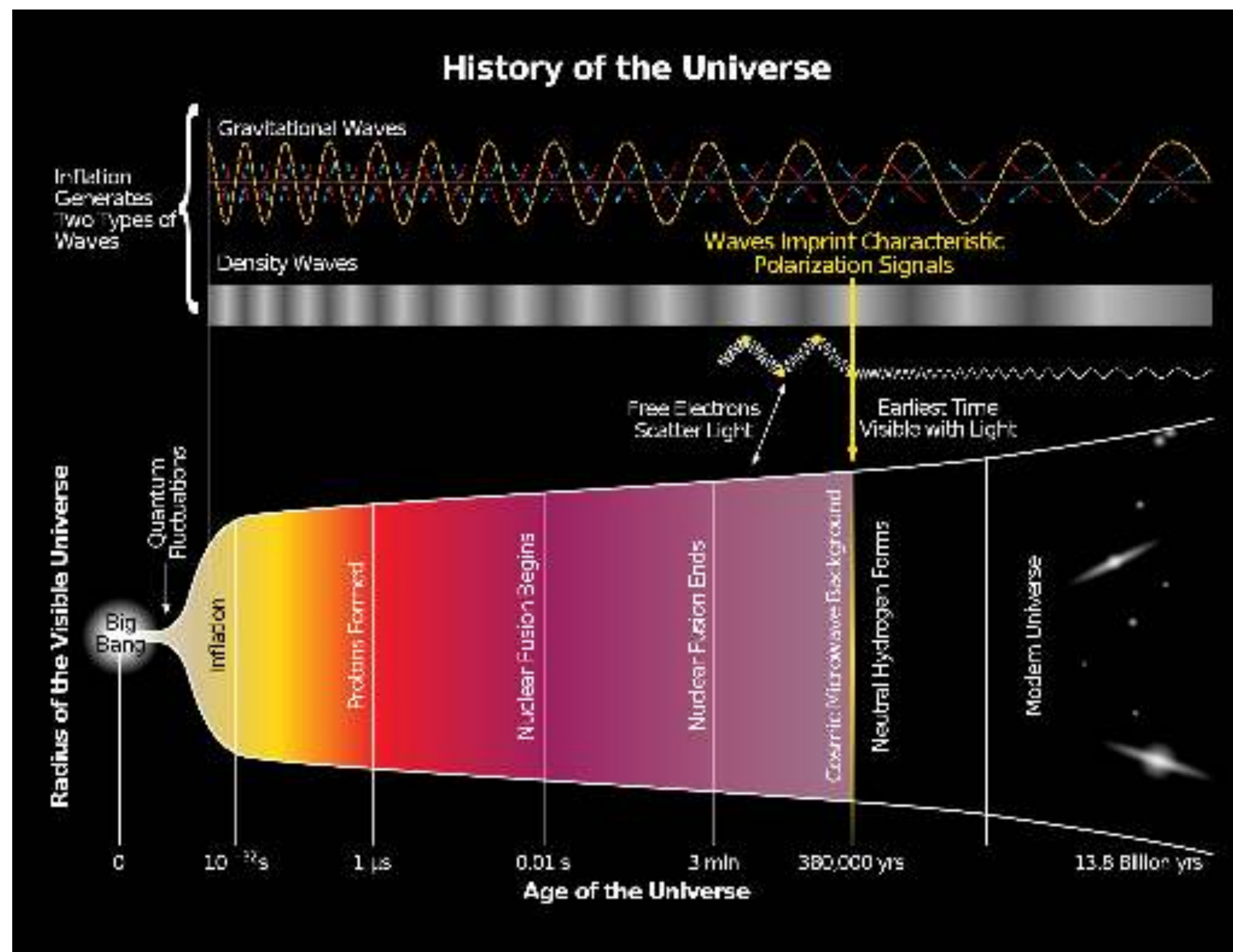
Introduction

- Modern cosmology is living a golden age
- Universe evolution well encompassed by ΛCDM model

General Relativity & Λ & DM & SM particles

- In agreement with observations on a very broad range of scales
- BBN, CMB, LSS, Solar System, …



Introduction

- **However, this success is also a curse**: ΛCDM is an effective description that is not showing much of its fundamental nature.

General Relativity & Λ & DM & SM particles

- So far DM has been elusive despite all the experimental and theoretical efforts. Neither direct nor indirect detection so far.
- The Cosmological Constant is still a theoretical puzzle

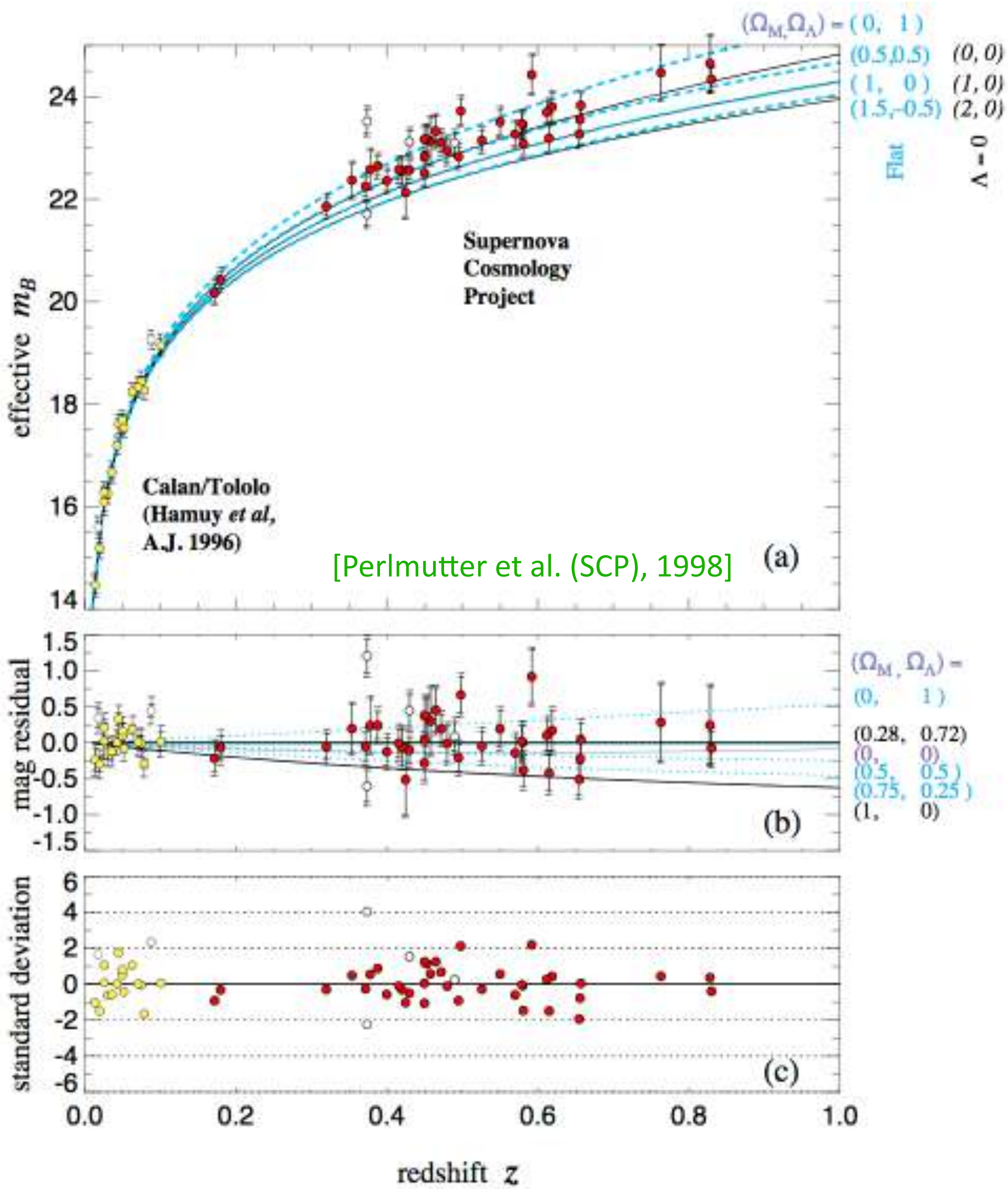
20 years of acceleration

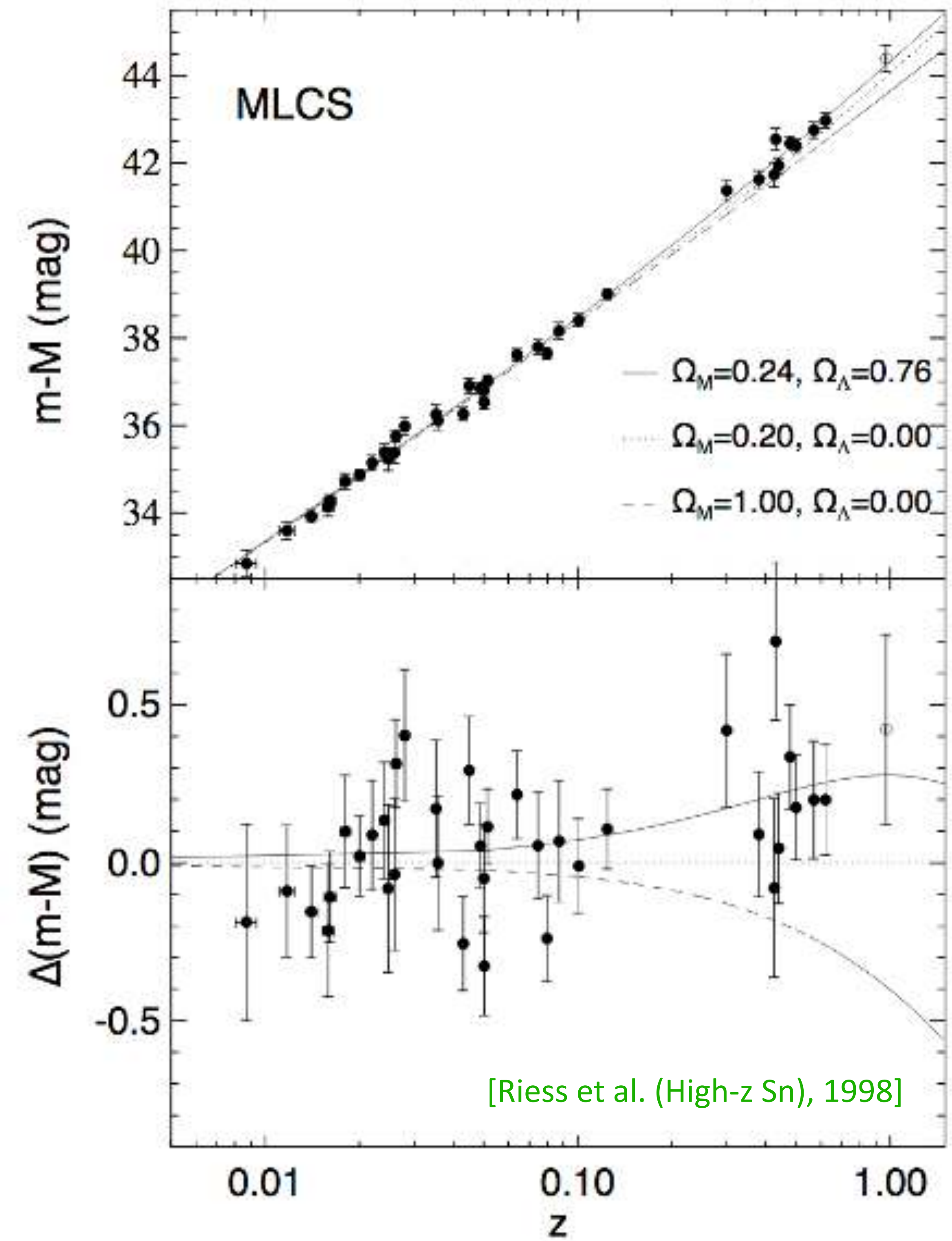
"The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is non-zero and positive"

"For a flat universe prior the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7σ and 9σ […]. A universe closed by ordinary matter is formally ruled out"

20 years of acceleration

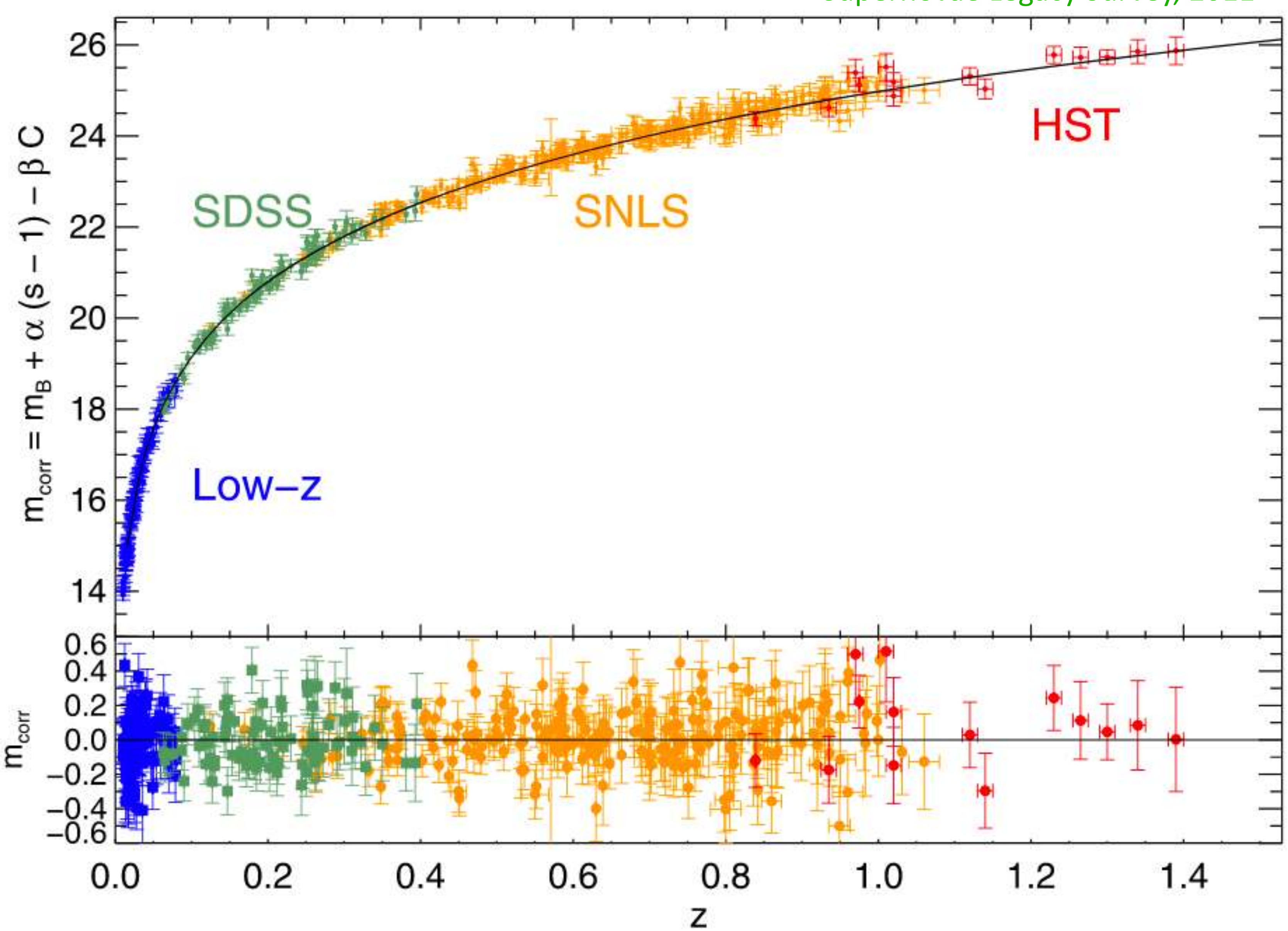
December 1998 $m_B^{\text{effective}} \equiv \mathcal{M}_B + 5 \log \mathcal{D}_L(z; \Omega_M, \Omega_\Lambda)$ May 1998





20 years of acceleration

Supernovae Legacy Survey, 2011



More evidences of DE

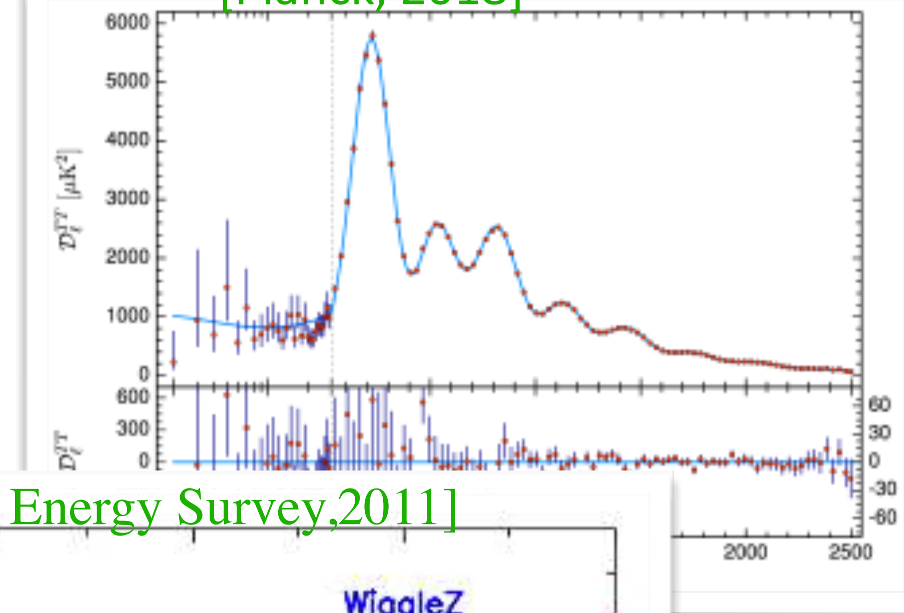
Probes of acceleration:

- CMB
- Supernovae
- baryon acoustic oscillations
- weak lensing
- Clusters

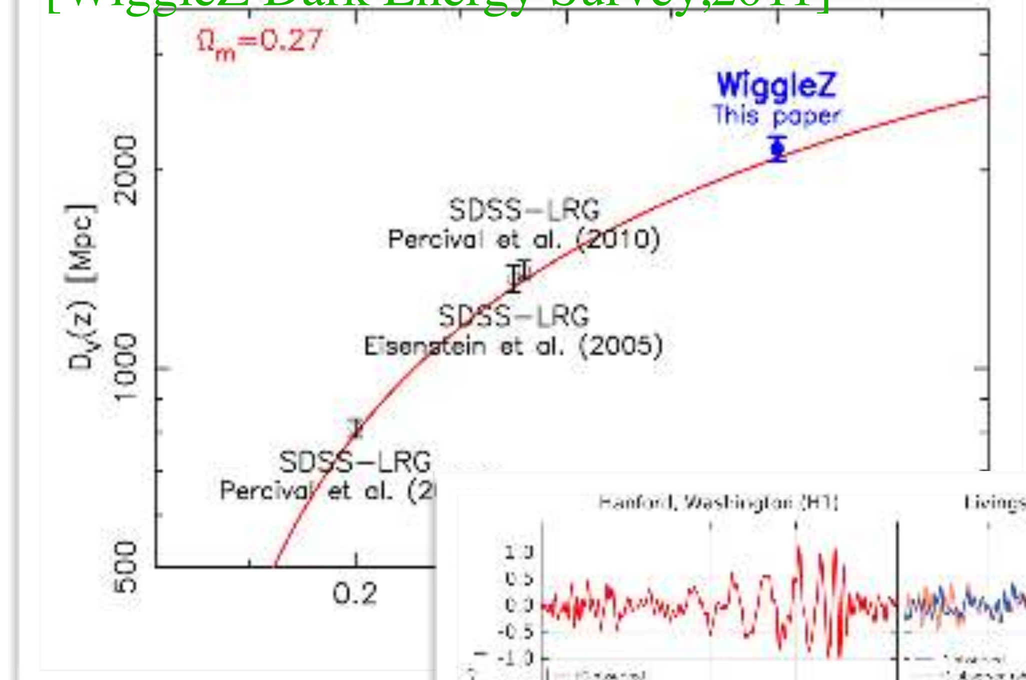
New probes of acceleration:

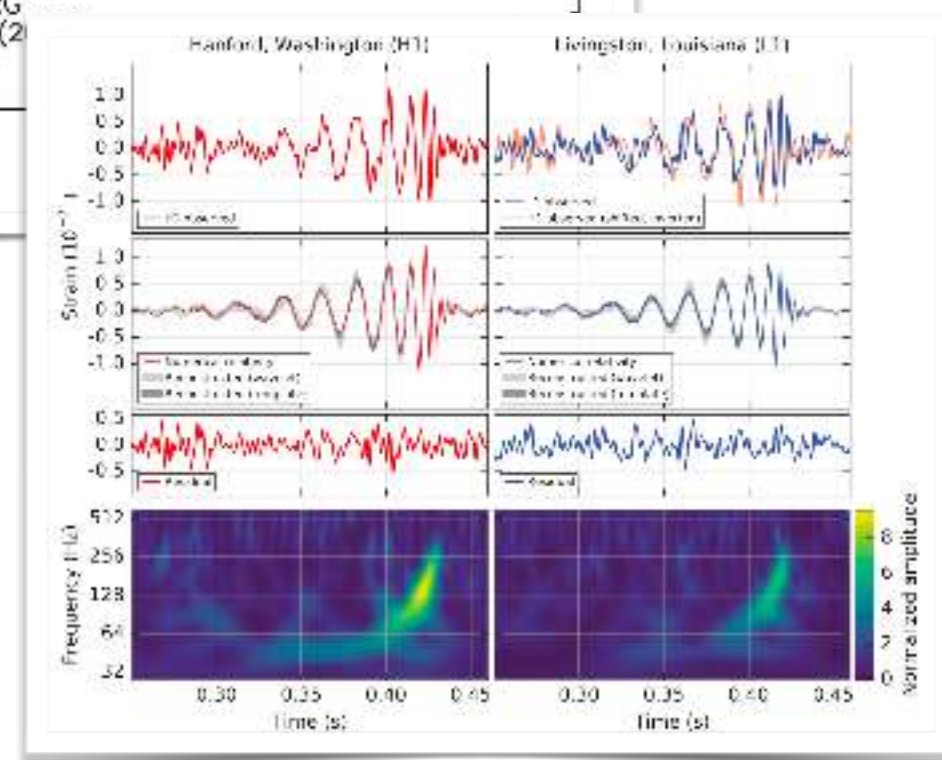
- 21cm lines
- Gravitational waves

[Planck, 2018]



[WiggleZ Dark Energy Survey,2011]





[LIGO, 2016]

More evidences of DE

Probes of acceleration:

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- Supernovae
- baryon acoustic oscillations
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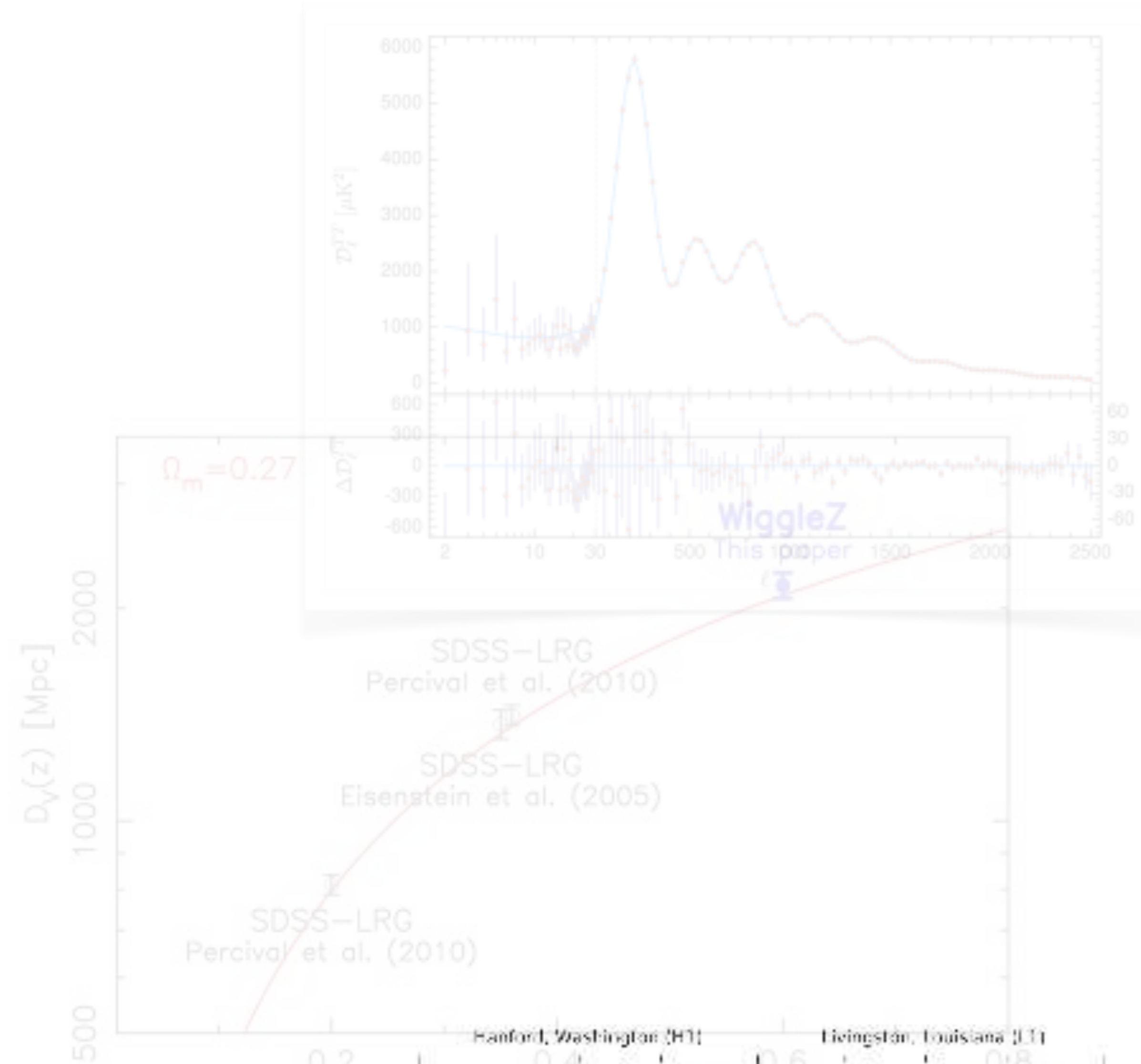
- Clusters



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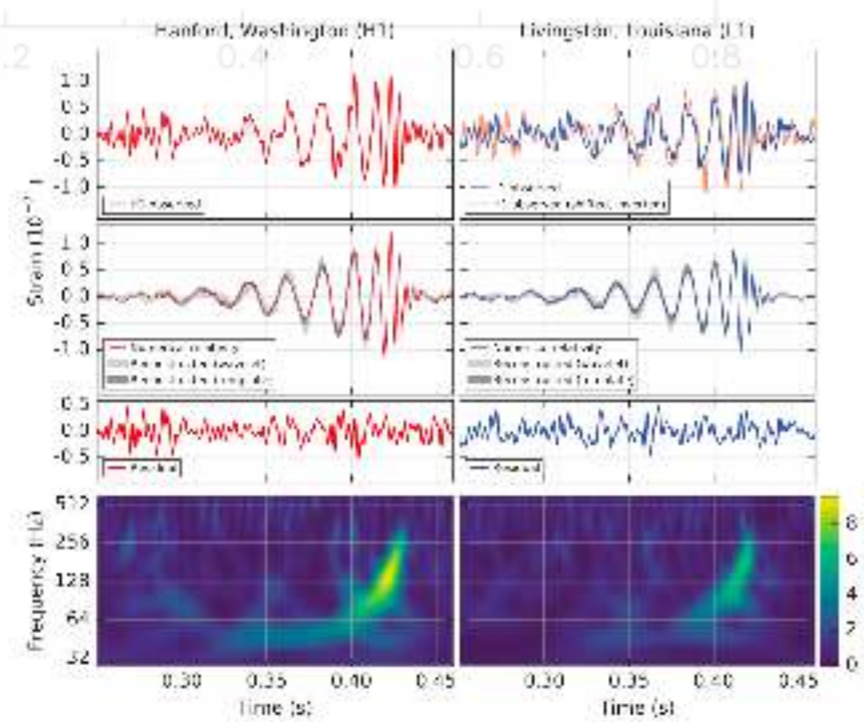

GW170817 & GRB170817A

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

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CrossMark

An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: *Fermi*-GBM Detection of GRB 170817A

A. Goldstein[1], P. Veres[2], E. Burns[3,17], M. S. Briggs[2,4], R. Hamburg[2,4], D. Kocevski[5], C. A. Wilson-Hodge[5], R. D. Preece[2,4], S. Poolakkil[2,4], O. J. Roberts[1], C. M. Hui[5], V. Connaughton[1], J. Racusin[6], A. von Kienlin[7], T. Dal Canton[3,17], N. Christensen[8,9], T. Littenberg[5], K. Siellez[10], L. Blackburn[11], J. Broida[8], E. Bissaldi[12,13], W. H. Cleveland[1], M. H. Gibby[14], M. M. Giles[14], R. M. Kippen[15], S. McBreen[16], J. McEnery[6], C. A. Meegan[2], W. S. Paciesas[1], and M. Stanbro[4]

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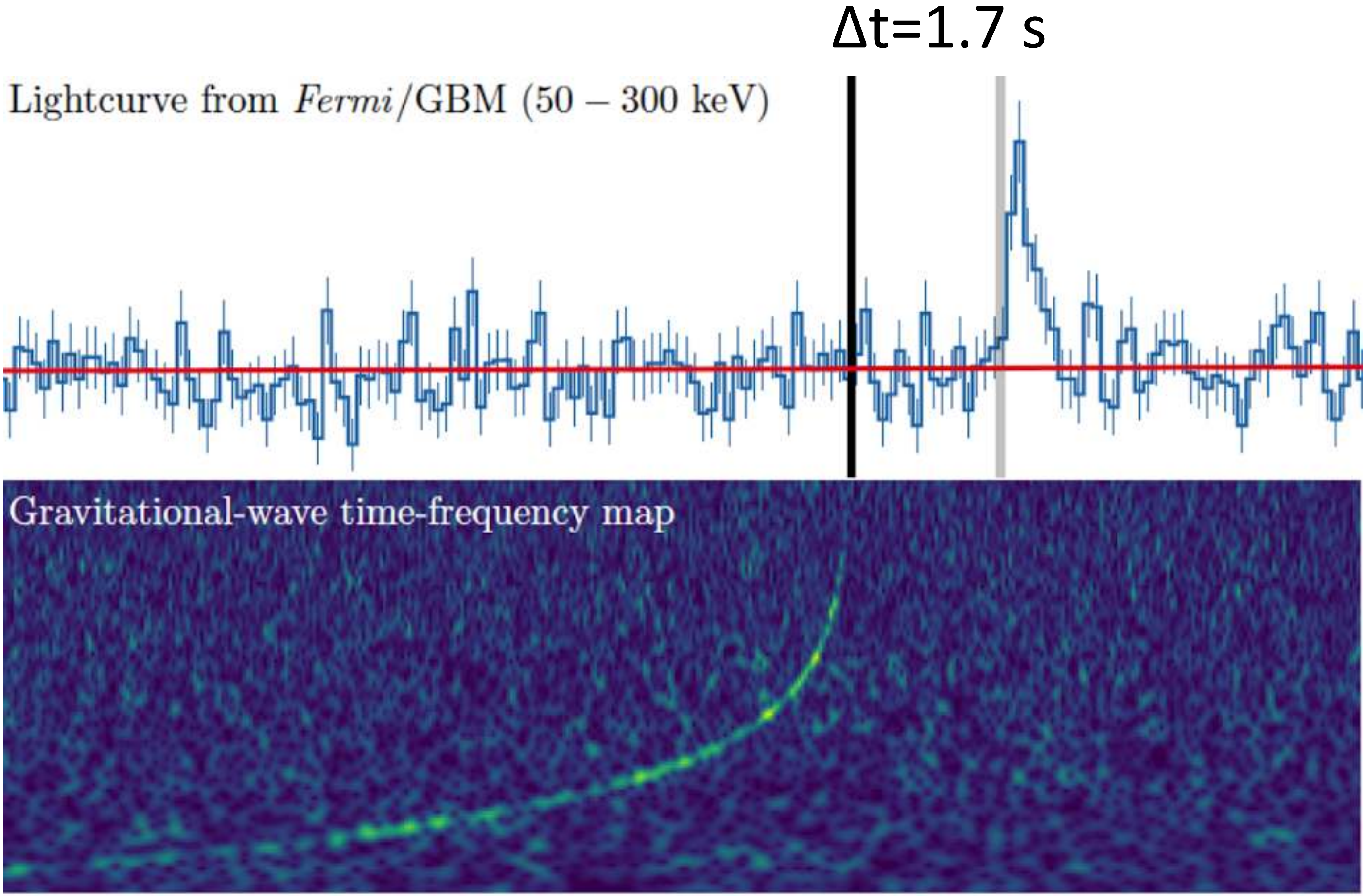
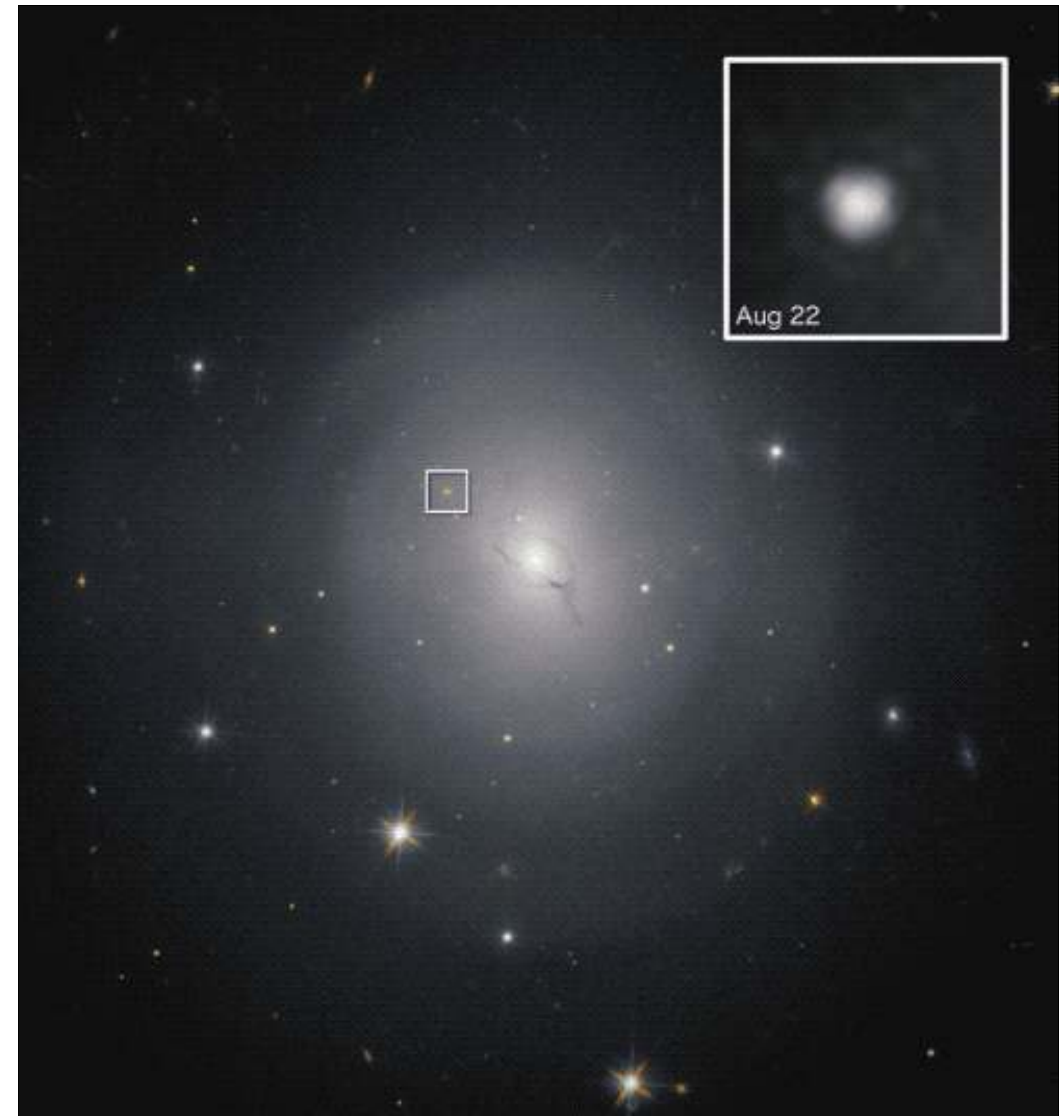


GW170817 & GRB170817A

- Located 40 Mpc (z=0.008) from us
- Low energy, $\lambda \sim 10000\,\mathrm{km}$
- Speed of GW measured:



[NGC 4993 HST]

$$-3 \times 10^{-15} \leq \frac{c_T}{c_\gamma} - 1 \leq 7 \times 10^{-16}$$

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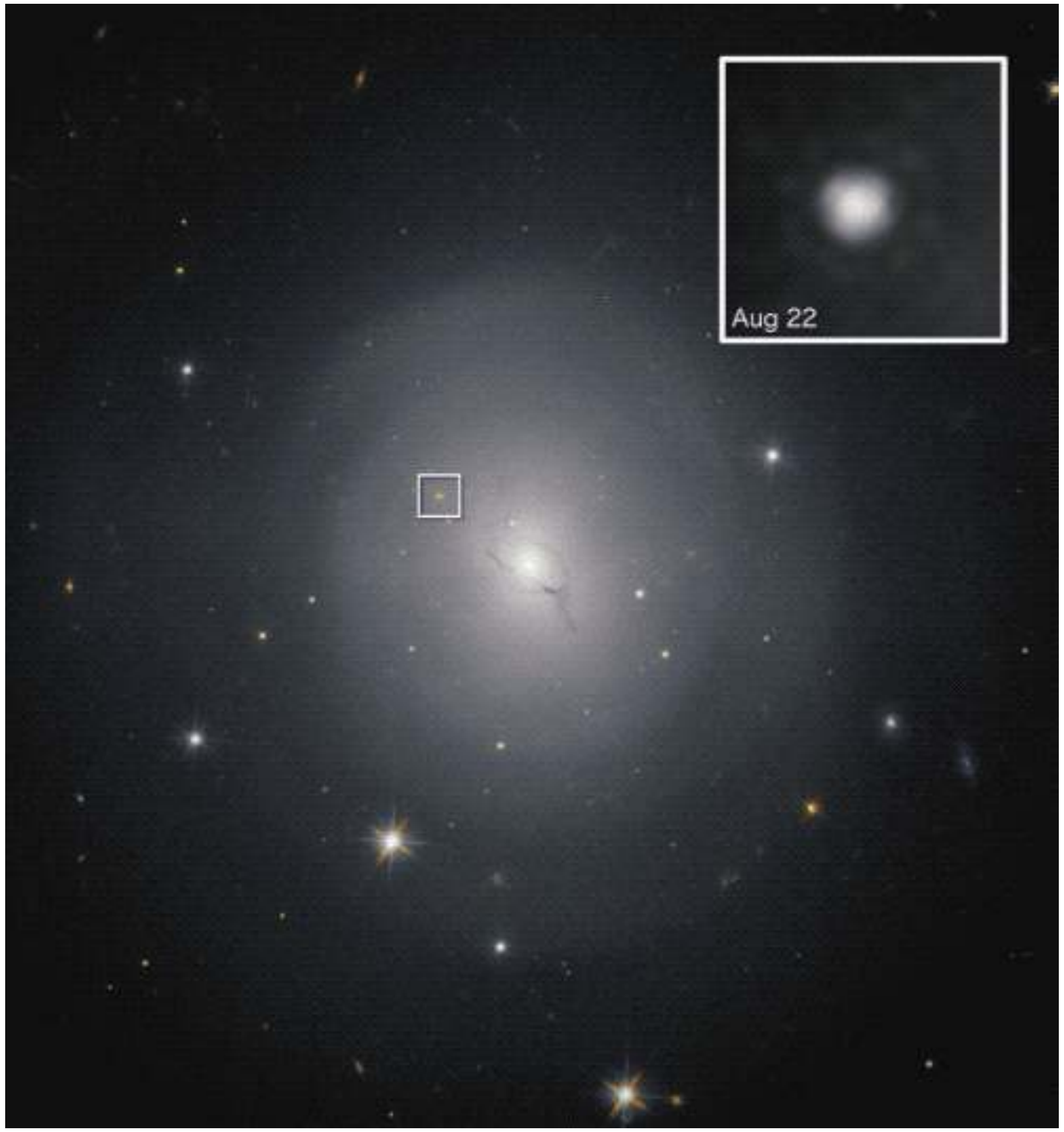
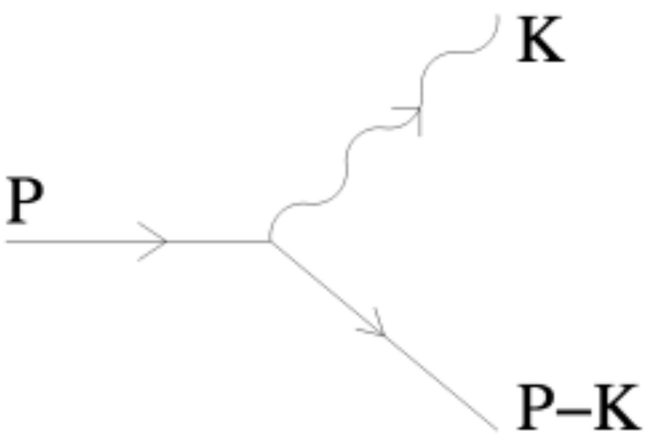


[NGC 4993 HST]

$$-3 \times 10^{-15} \leq \frac{c_T}{c_\gamma} - 1 \leq 7 \times 10^{-16}$$

Previous constraints

- Cherenkov radiation $c - c_{\rm gw} < 2 \times 10^{-15} c$



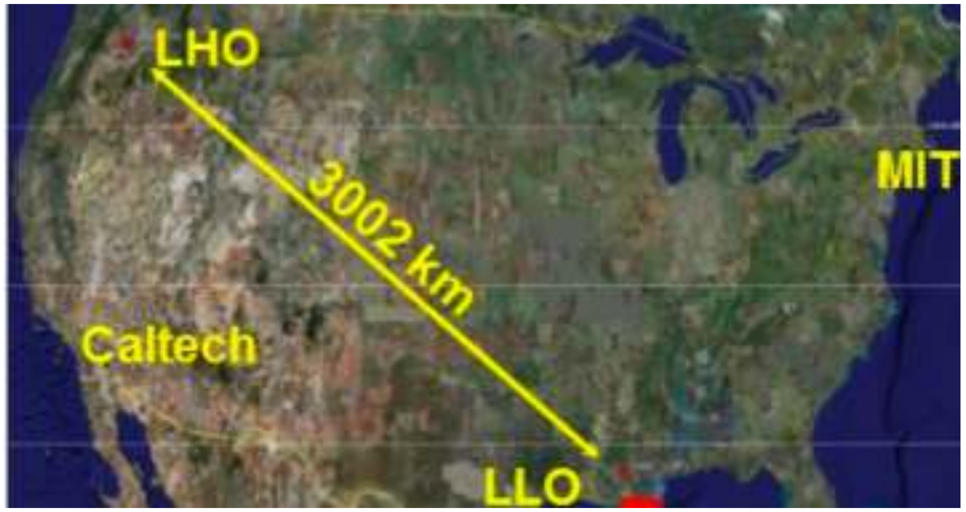
[Moore & Nelson et al., 2001]

- Binary pulsars $0.995 \lesssim c/c_{gw} \lesssim 1$

[Jiménez et al., 2015]

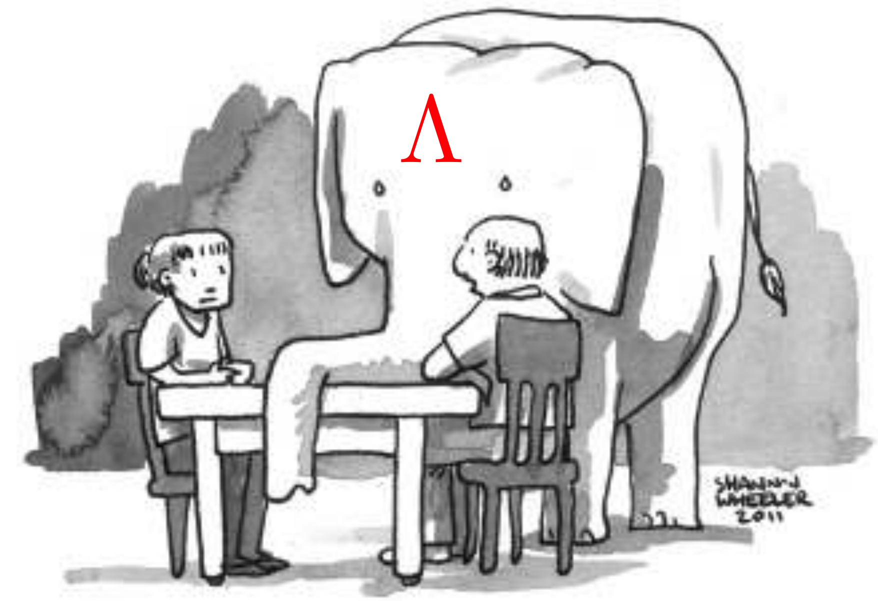
- Time delay between LIGO detectors

[Cornish et al., 2017] $0.55c < c_{\rm gw} < 1.42c$



Caveat: these constraints are either in the high frequency regime or in regions where screening is occurring or indirect.

Cosmological constant



We have a successful candidate

$$G_{\mu\nu} = 8\pi G T^{(m)}_{\mu\nu} - \Lambda g_{\mu\nu}$$

For which $c_T = c$. So, why bother?

Λ is know to suffer from several issues. It is a measure of our ignorance on gravity! [Martin, 2012]

- Value is at odds with quantum (vacuum fluctuations) and classic (phase transitions) expectations $\Lambda \sim 10^{-29} g/cm^3$ $\Lambda \sim 10^{-43} GeV^4$
- Coincidence problem $\Omega^0_\Lambda \sim \Omega^0_m$

Beyond Λ

But can be something that is not lambda?

We do not solve Λ problems but we adventure beyond GR boundaries

However, Lovelock theorem:

- One metric
- Diffeomorphism invariance
- 4 dimensions
- local theory
- Second order equation

GR

[Lovelock, 1971]

From GR to scalar-tensor theories

- Extra "matter" fields

Scalar, Vector, Tensor fields
(Includes also. $f(R)$)

- Non local theories

$$R\left(\frac{1}{\Box^2}\right)R\,,\ldots$$

- Higher derivatives

$$f(R, R_{\mu\nu}, R_{\mu\nu\alpha\beta})$$

- Breaking symmetries

Einstein-Aether,
Horava-Lifschitz

- …

In most cases, it reduces to specifying the nature of the new d.o.f. and their couplings to matter or gravity.

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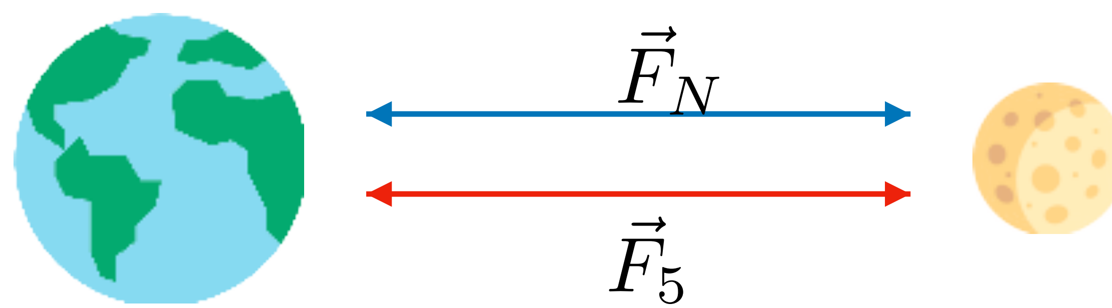
From solar system to cosmology

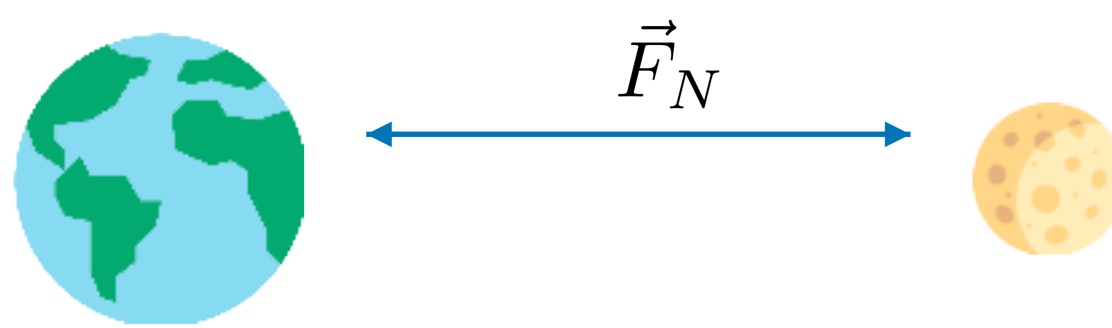
Reproduce the cosmological ΛCDM background

Equation of state $w \sim -1$

Modified growth of structures $\vec{F}_5 \propto Q\vec{\nabla}\phi$ Fifth forces



Satisfy solar system tests $Q \sim 0$ Screening mechanisms



From GR to scalar-tensor theories

Not all possible interactions are viable:

Lagrangians with more than one time derivative induce linear instabilities in the Hamiltonian [Ostrograski (1850)]

But there is a loophole in the argument:

Horndeski theorem!

[Horndeski (1974)]

The Horndeski theorem

The most general action for a metric and a scalar field that gives second order field equations in four dimensions is:

[Horndeski (1974), Deffayet (2011)]

$$S_{\rm H} = \sum_{i=2}^{4} \int d^4x \sqrt{-g} \mathcal{L}_i(g_{\mu\nu}, \phi)$$

The Horndeski theorem

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-

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- $\mathcal{L}_4 = G_4(\phi, X)R - G_{4,X}(\phi, X)[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2]$
-

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- $\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi +$
  $\frac{G_{5,X}}{6}\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]$

Horndeski, beyond Horndeski and beyond beyond Horndeski: DHOST theories

Degenerate theories:

The **degeneracy** of the Lagrangian is the most fundamental starting point in order to build theories that do not propagate extra d.o.f. but contains accelerations

Beyond Horndeski

Using this criteria more general theories have been found that do not propagate any unwanted extra d.o.f.: DHOST theories [Crisostomi, Koyama, Langlois, Noui, Gao and more (2013-2018)]

Other, analogous approach is EFT for DE

[Senatore, Luty, Creminelli, Vernizzi, Piazza, Gubitosi, Raveri and more (2013-2018)]

Why these complicated models?

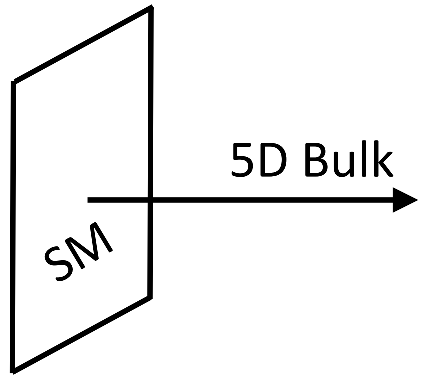
Horndeski action from limit of more fundamental theories

- Decoupling limit of massive gravity $g_{\mu\nu} \supset \partial_\mu \partial_\nu \phi$

[De Rham, Gabadadze, Tolley (2010)]

- Extra dimensions, DGP

[Dvali, Gabadadze, Porrati (2000)]



Gravitons interact with scalars via $\partial_\mu \partial_\nu \phi$

GW anomalous speed

Horndeski predicts *anomalous propagation of GW*

Derivative couplings and GW speed

$$\mathcal{L} = G(X)R + G'(X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

Perturb the variables $g_{\mu\nu} \to g_{\mu\nu} + h_{\mu\nu}\,, \quad \phi \to \phi + \varphi$ and expand to second order

$$\mathcal{L}^{(2)} \propto h_{\alpha\beta}^{TT}\left(\mathcal{G}_{\mu\nu}\partial^\mu\partial^\nu\right)h^{\alpha\beta}_{TT}$$

Effective metric for GW

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

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Effective metric for GW

GR $\qquad \mathcal{G}_{\mu\nu} = \qquad g_{\mu\nu}$

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

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Effective metric for GW

BD $\qquad \mathcal{G}_{\mu\nu} = f(\phi)g_{\mu\nu}$

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

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Effective metric for GW

HL $$\mathcal{G}_{\mu\nu} = G(X)g_{\mu\nu} + G'(X)\partial_\mu\phi\partial_\nu\phi$$

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

GW anomalous speed

Derivative couplings and GW speed

Expand effective metric using a time-like scalar field derivative

$$\mathcal{L} = \frac{1}{2}\left\{\left[G - G'\dot{\phi}^2\right)\left(\dot{h}_{ij}^{TT}\right)^2 - G\left(\vec{\nabla} h_{ij}^{TT}\right)^2\right\}$$

From which one can read the speed of GW

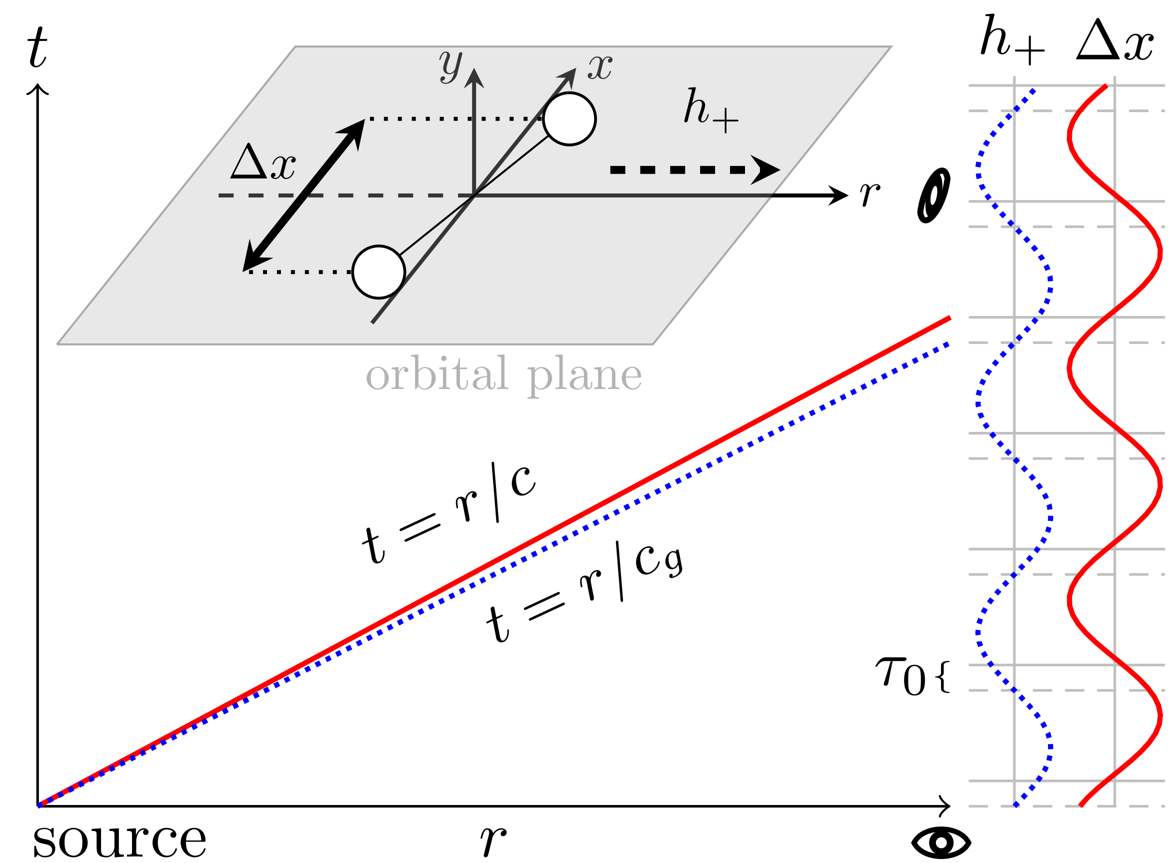
$$c_T^2 = \frac{1}{1 - \frac{G'}{G}\dot{\phi}^2}$$

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

Phase lag test

Test with eclipsing binaries: LISA $\sim 10^{-4} - 10^{-1}\mathrm{Hz}$

- Nearby sources
- EM cunterpart
- Periodic sources of GW & EM
- Test the phase lag:



$$\Delta\Phi(t) = 2\omega\frac{r(t)}{c}\left(\frac{c}{c_{gw}} - 1\right)$$

[DB, Ezquiaga, Hinterbichler, Zumalacarregui(2016)]

GW anomalous speed

Horndeski action and GW (On FLRW background)

$$c_T = \frac{w_4}{w_1} = \frac{2G_4 - 2\ddot{\phi}XG_{5,X} - 2XG_{5,\phi}}{2(G_4 - 2XG_{4,X} - 2X(\dot{\phi}HG_{5,X} - G_{5,\phi})}$$

[De Felice & Tsujikawa, 2011]

How do we reconcile with LIGO/Fermi observations?

- **Forget** about Horndeski: $G_4(\phi, X) = f(\phi)\,, \quad G_5(\phi, X) = 0$
- Tune G_4 and G_5 functions: is **background dependent**

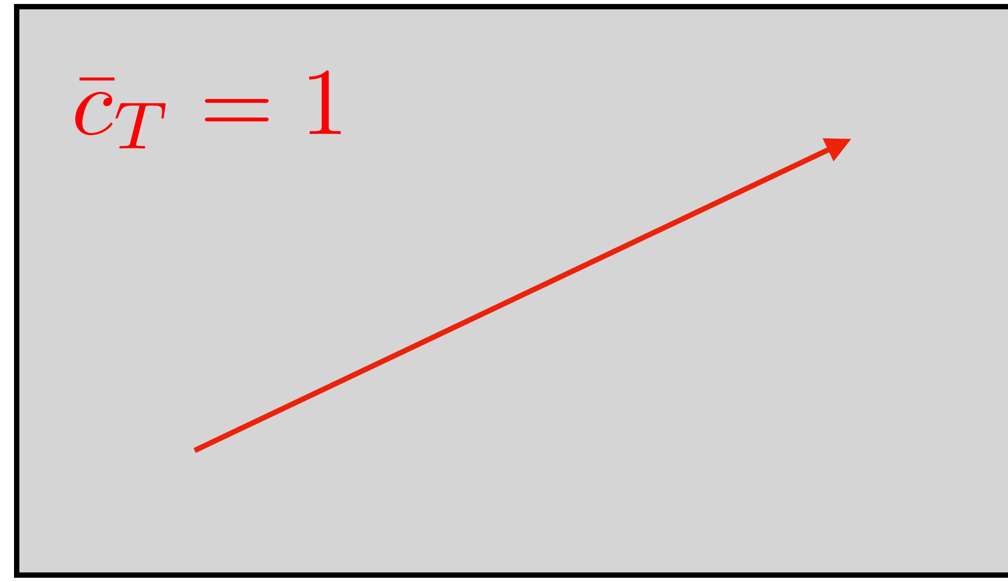
[Ezquiaga & Zumalacarregui, 2017]
[Creminelli & Vernizzi, 2017]
[Sakstein & Jain, 2017]
[Baker at al., 2017]

Caveat

- Use scalar field equation & assume spatial flatness

$$\mathcal{E} = A\ddot{\phi} + B = 0$$

$$c_T^2 - 1 = \frac{\mu}{2\dot{\phi}\,(3\,H\mu - \kappa_G)\,\mathcal{K}_{,X}}\mathcal{E}_\phi,$$



- Get algebraic relations and gives a non trivial HL with ct=1

- Effect of LSS $c_T = \bar{c}_T + \delta c_T$

[Copeland et al., 2018]

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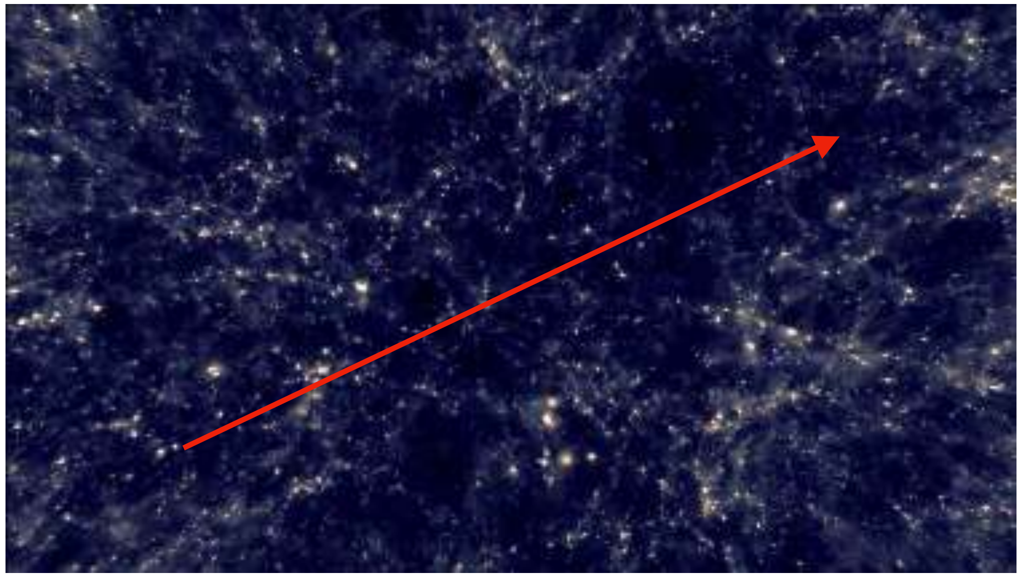

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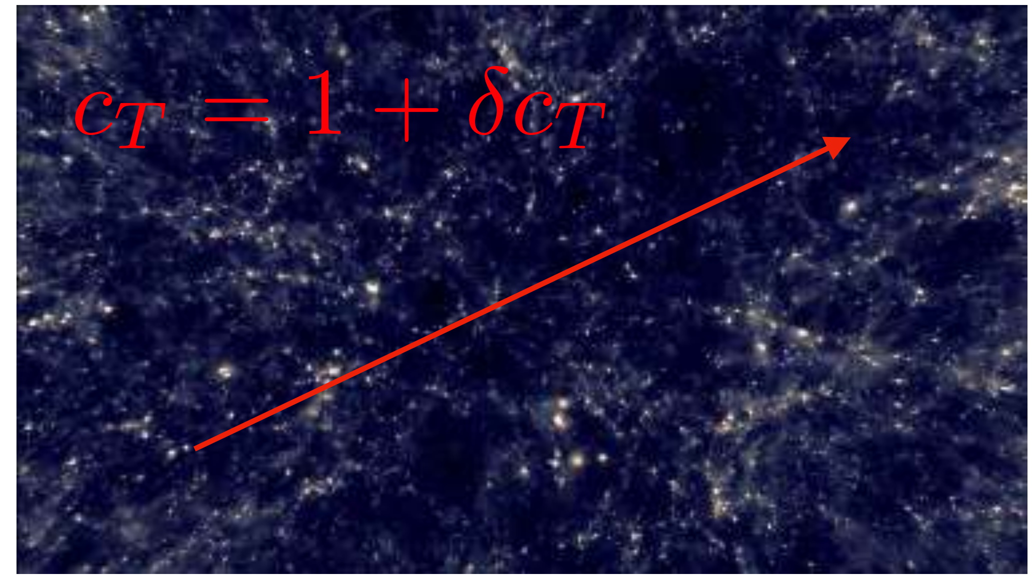

- Get algebraic relations and gives a non trivial HL with ct=1
- Effect of LSS $\quad c_T = \bar{c}_T + \delta c_T$

$$\Rightarrow \delta c_T \sim 10^{-3}$$

[Copeland et al., 2018]

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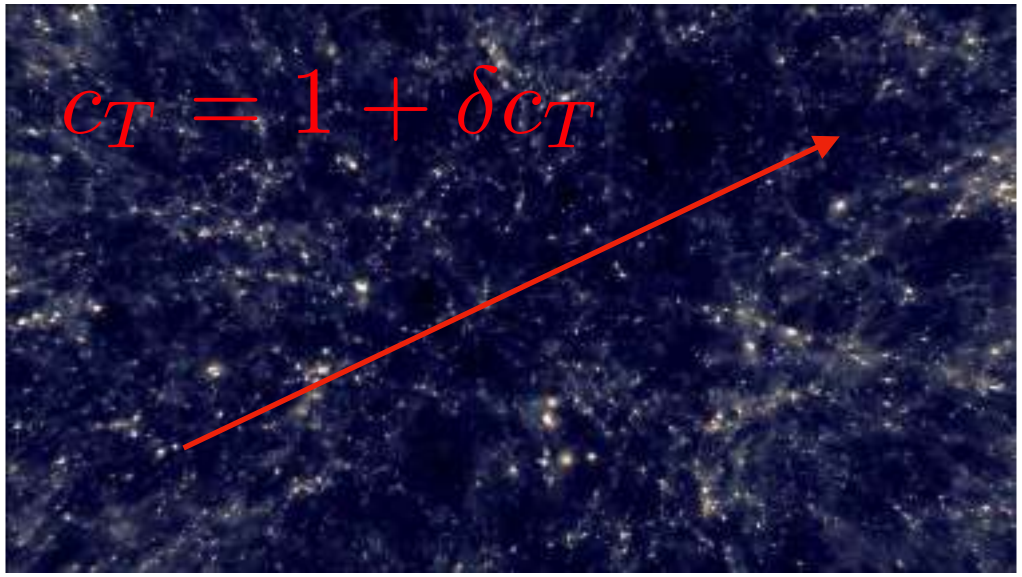

- Get algebraic relations and gives a non trivial HL with ct=1
- Effect of LSS $\quad c_T = \bar{c}_T + \delta c_T$

$$\Rightarrow \delta c_T \sim 10^{-3}$$

- So.. not quite working…

[Copeland et al., 2018]

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- **Forget** about Horndeski: $G_4(\phi, X) = f(\phi)\,, \quad G_5(\phi, X) = 0$
- Tune G_4 and G_5 functions: is **background dependent**
- Go to DHOST: admit $c_T = 1$ exactly, but **suffer at small scales** [Langlois et al., 2017]
- Dynamical mechanism for which $c_T = 1$ is an **attractor**

Doppelgänger Dark Energy

Compatibility with GW

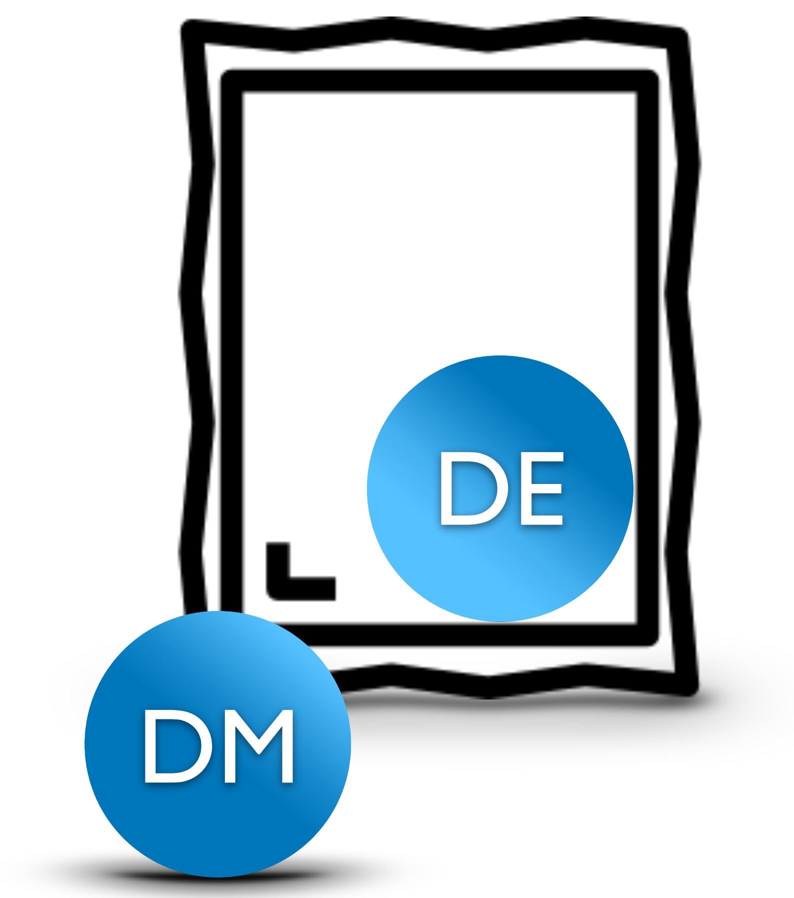
- Look for a dynamical tuning: relax to $c_T = 1$ today but not in the past in a non trivial Horndeski scenario

Scaling solution

- Assume that DM and DE look alike

$$\rho_{DE} = c\rho_{DM}$$

- DM-DE interaction is needed



[Amendola, DB,Domenech, Gomes (2018)]

DDE recipe

- Impose scaling $\rho_{DE} = c\rho_{DM}$
- Look for solutions $\rho_{DE} = \rho_{DE}(G_i)$
- Check that these are attractor
- Stability & consistency checks $c_s^2 > 0\,, \quad c_{gw}^2 > 0$
- Impose the GW constraint $c_{gw}|_{DDE} = 1$

Look for DDE solutions

DM-DE interaction

$$\frac{d\rho_{DM}}{dt} + 3H\rho_{DM} = Q(\phi)\frac{d\phi}{dt}\rho_{DM}$$

$$\frac{d\rho_\phi}{dt} + 3H(1+w_\phi)\rho_\phi = -Q(\phi)\frac{d\phi}{dt}\rho_{DM}$$

DM-DE interaction as an **effective metric**

$$S = \int d^4x\,\sqrt{-\bar{g}}\left\{\sum_i \bar{\mathcal{L}}_i(\bar{g},\phi) + \bar{\mathcal{L}}_{DM}(g_{\mu\nu}B(\phi)) + \bar{\mathcal{L}}_{SM}\right\}$$

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Complicated. Use a trick:Invert metric $g_{\mu\nu} = B(\phi)^{-2}\bar{g}_{\mu\nu}$

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Complicated. Use a trick:Invert metric $g_{\mu\nu} = B(\phi)^{-2}\bar{g}_{\mu\nu}$

Baryons are now coupled but since they are subdominant we neglect them… (for the moment!)

Doppelgänger Dark Energy

- **Uncoupled DM** behaves as a pressure less fluid $\rho_{DM} \propto a^{-3}$
- **DDE condition** $\rho_\phi \propto \rho_{DM} \propto a^{-3}$
- Friedmann equations

$$6H^2 G_4 = \rho_\phi + \rho_{DM}$$

Impose scaling

$$\frac{d\ln\rho_\phi}{dN} = \frac{d\ln\rho_{DM}}{dN} = -3$$

- Need to solve

$$\frac{d\ln G_4}{dN} = \frac{d\ln G_4}{d\phi}\frac{d\ln\phi}{dN} + \frac{d\ln G_4}{dX}\frac{d\ln X}{dN} = 3w_{eff}$$

Doppelgänger Dark Energy

- Solving and knowing the functional dependence $\rho_\phi(G_i)$

$$G_2(\phi, X) = \phi^{p_2} a_2(Y) \quad , \quad G_3(\phi, X) = \phi^{p_3} a_3(Y)$$
$$G_4(\phi, X) = \phi^{p_4} a_4(Y) \quad , \quad G_5(\phi, X) = \phi^{p_5} a_5(Y)$$

$$Y = X\phi^p \,, \; p = p_4 - p_2 - 2 \,, \; p_3 = p_4 - 1 \,, \; p_5 = 2p_4 - p_2 - 1$$

- Y is constant on (DDE) scaling solution
- The most general solutions of DDE in the Horndeski Lagrangian that greatly extends previous results

Doppelänger Dark Energy

- Compute the speed of tensor

$$c_T^2 = \frac{a_4 - p_5 Y a_5}{a_4 - 2Y a_{4,Y} + p_5 Y a_5 - (6 + p_2 - 3p_4)\, Y^2 a_{5,Y}}$$

- Instead of arbitrarily tuning the coefficients to satisfy the constraint we exploit the attractor nature of the DDE solution i.e. we require:

$$a_{4,Y}\big|_s = 0 = a_{5,Y}\big|_s \quad \& \quad a_5 = 0 \text{ or } p_5 = 0$$

- On the scaling solution the **Horndeski functions** are in a **minimum**
- Out of the scaling (i.e. in the past) GW speed can be different than 1

Effect of baryons

- In general baryons will tend to bring out of scaling solution

$$\delta c_T^2 = \frac{\delta Y^{n-1}}{Y_s^{n-1}} \frac{2Y_s^n a_{4,Y^n}|_s}{a_4|_s}$$

- Horndeski function must have a minimum, e.g.

$$a_4(Y) = \frac{M_{pl}^2}{2}\left(1 + c_4\left(1 - \frac{Y}{Y_s}\right)^n\right)$$

- From this we get how many derivatives must vanish

$$\delta c_T^2 \approx -n\,10^{-n+1} c_4 < 10^{-15}$$

- In order not to be affected by baryons n>16!

Conclusions

GW 170817 and GRB strongly constrained Horndeski action.

- **Reduced** theory space $G_4(\phi, X) = f(\phi)\,, \quad G_5(\phi, X) = 0\,, \quad G_2(\phi, X)\,, \quad G_3(\phi, X)$
- Affects also **large scales**: $c_{gw} = 1 \Rightarrow \eta \equiv -\dfrac{\Phi}{\Psi} = 1$ [Amendola et al.,2017]

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

[Ezquiaga & Zumalacarregui,2017]

Conclusions

However:

- **Attractor solutions** with $c_{gw}(z=0.008)=1$ but free in the past can be found albeit with tuning
- The parameter space is still very rich: **Yukawa couplings**, screening, G_N^{eff}
- **Caveat?** GW produced very close to the **cut-off scale of the EFT** (wait for LISA?) [De Rham & Melville, 2018]
- Constraint only apply to visible sector. **DM-DE (derivative) couplings**
- Is there a **symmetry** protecting the speed of GW?

Conclusions