Title: Testing Gravity with Gravitational Waves

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Series: Cosmology & Gravitation

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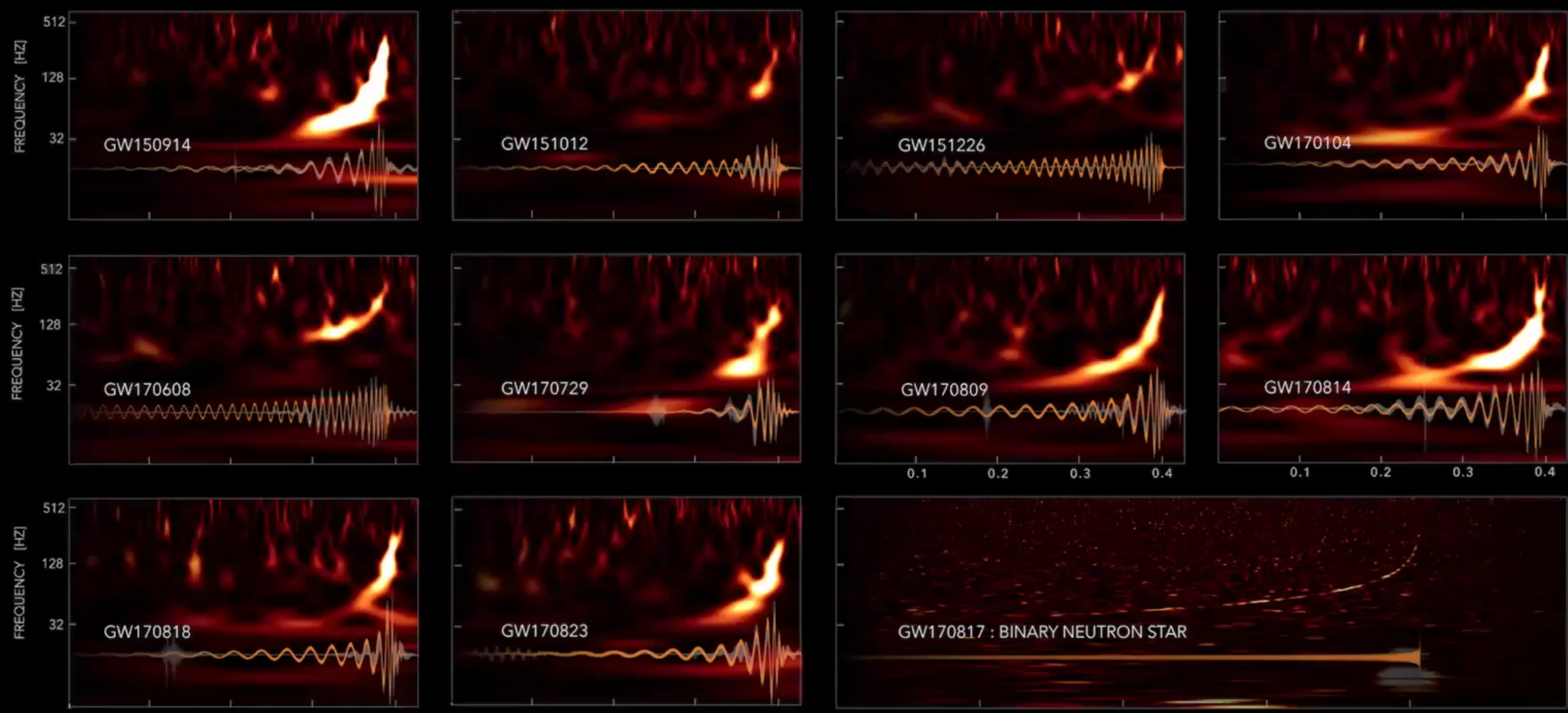
Abstract: Gravitational waves (GWs) have already proved immensely powerful for constraining cosmological extensions of GR, both from data-driven and theoretical perspectives. However, GWs really come into their own when used in combination with complementary electromagnetic data. Iâ€™ll start by reviewing some of the bounds on extended gravity theories from GW detections to date. I'll introduce the formalism, the phenomenology, and the astrophysical pitfalls of these tests. Finally, we'll explore the impact of future experiments like LISA and accompanying galaxy surveys on the remaining parameter space of modified gravity theories.

TESTING GRAVITY WITH GRAVITATIONAL WAVES



Tessa Baker, QMUL

OUTLINE

- Gravity theories & experiments.
- What have GWs taught us about cosmological gravity so far?
- What next?

(Last part based on 2007.13791.)

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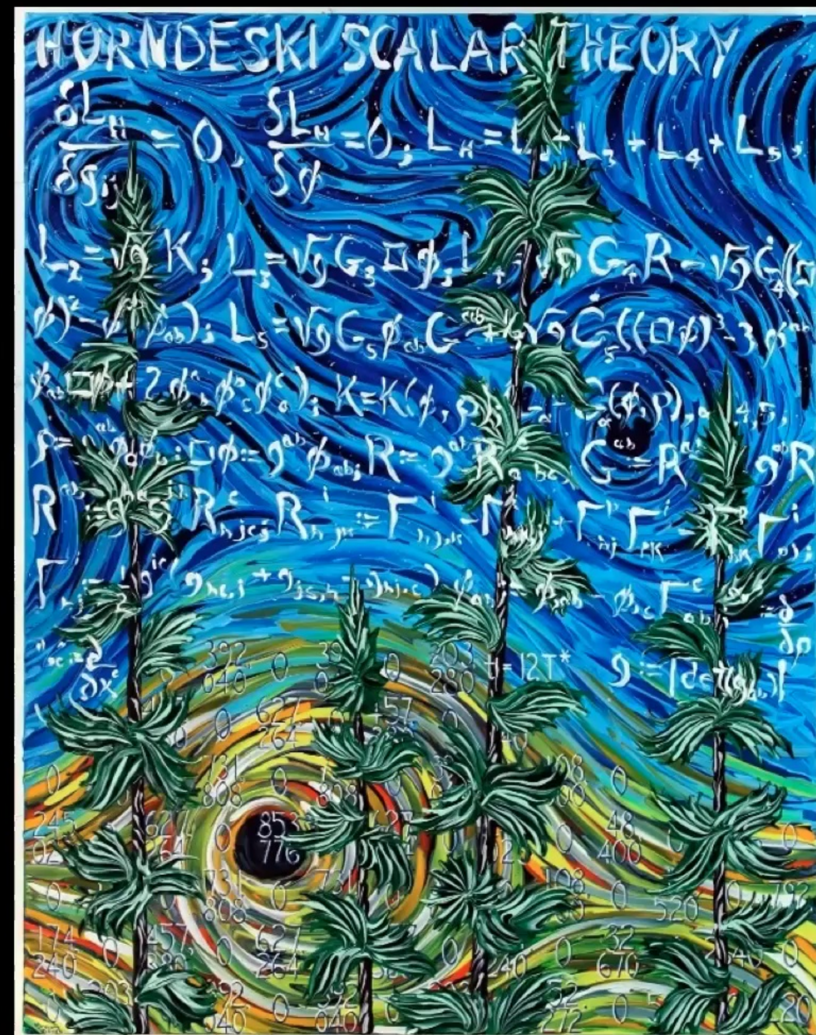


`Horndeski Scalar Theory--Past, Present & Future', G. Horndeski

LIGO IS CURRENTLY *OFFLINE*

www.ligo.org

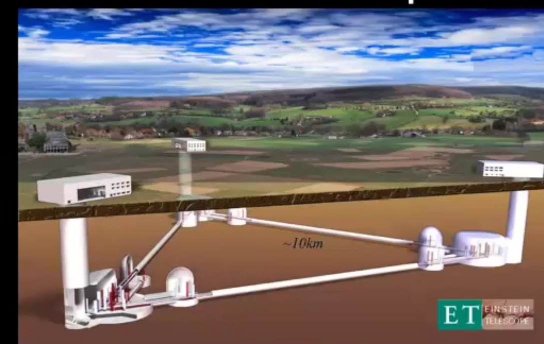
O3 operation ended on 27th March 2020 (~ 1 month early).

→ 56 new events

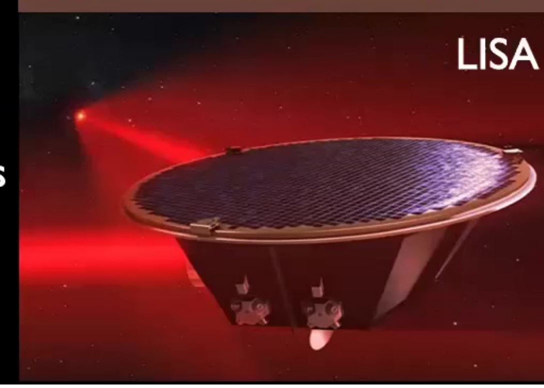
O4 was due to start ~ autumn 2021.

3rd-generation detectors: (2030+)

Einstein Telescope



~990,000 per year



~130 mergers per year

Cosmological Gravity Theories

- Motivated by: cosmic acceleration, effects on large-scale structure, dark matter substitute (less common).

- Designed to modify *weak-field* regime (large scales).

Many are *designed* to reduce to GR in the strong-field regime by **screening mechanisms**

Chameleon

Vainshtein

Symmetron, dilaton

Cosmological tests focus on GW *propagation* (not *generation)*

EXTENDED GRAVITATIONAL ACTION

HORNDESKI GRAVITY: The most general theory of gravity with one new fundamental scalar field, with 2nd-order equations.

$$S = \int d^4x \sqrt{-g} \left[\text{Messy function of } \phi \text{ and the metric g.} \right] + S_{\mathrm{Matter}}$$

Take linearised equations on FRW

$$\alpha_K(z),\ \alpha_B(z),\ \alpha_M(z),\ \alpha_T(z),\ \alpha_H(z)$$

Horndeski 'alpha' parameters.

1404.3713
1604.01386

THE HORNDESKI ALPHA PARAMETERS

Quantify typical features of non-GR behaviour:

$\alpha_T(z)$ speed of gravitational waves, $c_T^2 = 1 + \alpha_T$.

$\alpha_M(z) = \frac{1}{H}\frac{d\ln\, M^2(t)}{dt}$ running of effective Planck mass.

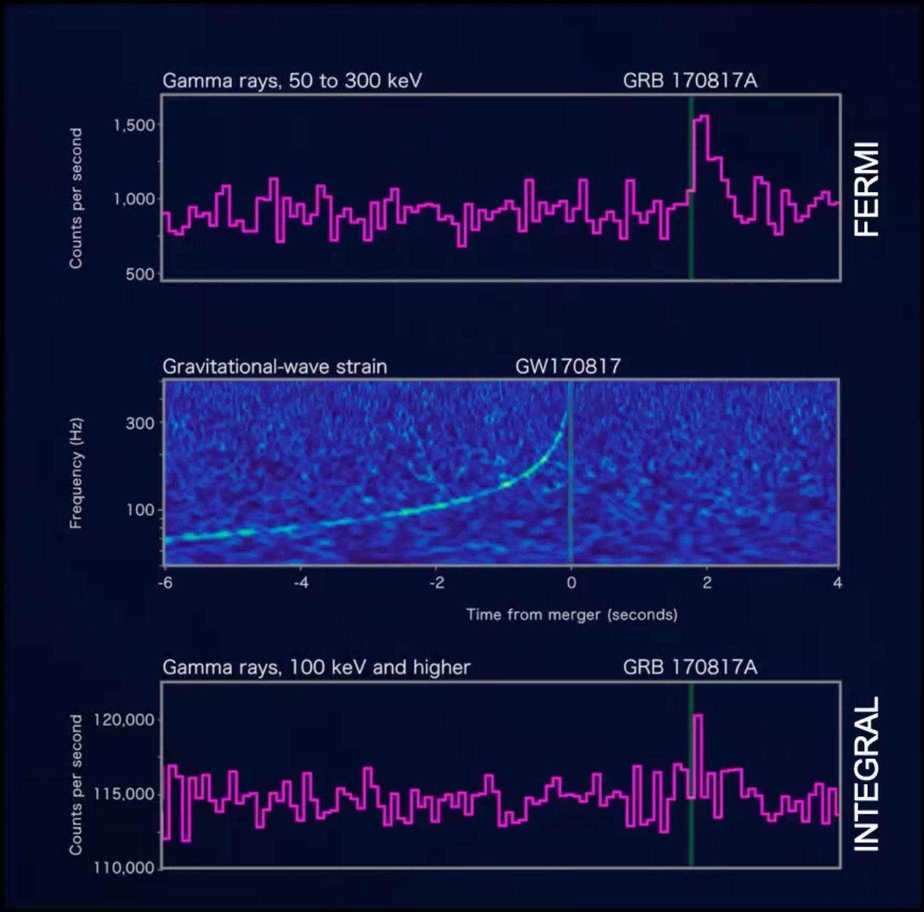
$\alpha_B(z)$ `braiding' – mixing of scalar + metric kinetic terms.

$\alpha_K(z)$ kinetic term of scalar field.

$\alpha_H(z)$ disformal symmetries of the metric.

$$\tilde{g}_{\mu\nu} = \Omega^2(X,\phi)g_{\mu\nu} + \Gamma(X,\phi)\partial_\mu\phi\partial_\nu\phi$$

MODIFIED PROPAGATION SPEED



GW170817 gave us $\delta t \simeq 1.7\,\mathrm{s}$.

Parameterise GW speed as: $c_T^2 = c^2\left[1 + \alpha_T(z)\right]$

Simple time-of-flight calculation $\delta t \simeq \frac{d}{c}\frac{\alpha_T}{2}$

$|\alpha_T| \leq 10^{-15}$ at z=0.01 OR $|\alpha_T| \lesssim 10^{-13}$

(conservative)

E.g. 1710.06394 + others.

MODIFIED PROPAGATION SPEED

Quintessence

K-essence

Bigravity

Massive Gravity

Brans-Dicke

f(R) KGB

Cubic Galileon

Horndeski

Generalised Proca

Einstein-Aether

DHOST

Horava-Lifschitz

TeVeS

Quintic Galileons

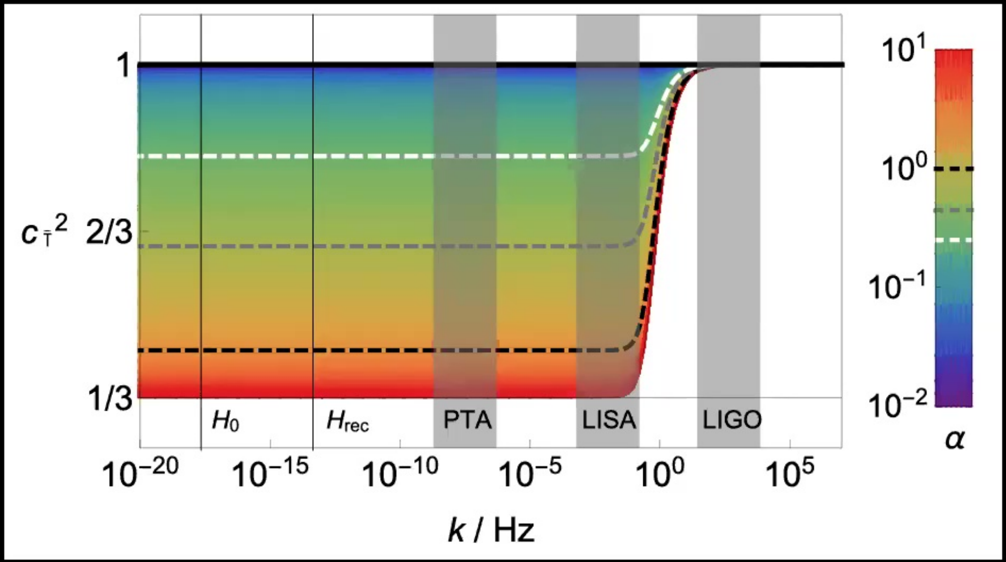
Quartic Galileons

Fab Four

SVT

MODIFIED PROPAGATION SPEED

Important caveat:



de Rham & Melville (2018) argue that $\alpha_T \to 0$ at high energies for a Lorentz invariant UV completion.

In Horndeski scalar-tensor theories this *could* mean:

$$\Lambda_{\mathrm{cut-off}} \sim (M_P\, H_0^2)^{1/3} \sim 260\,\mathrm{Hz}$$

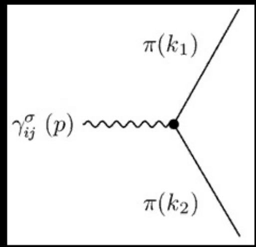
THEORETICAL BOUNDS

Initially `Beyond Horndeski' theories with $\alpha_H(z) \neq 0$ seemed to survive.

But then (Sept. 2018):

Gravitational Wave Decay into Dark Energy

Paolo Creminelli[a], Matthew Lewandowski[b], Giovanni Tambalo[c,d], Filippo Vernizzi[b]



1809.03483

In these models, gravitons can decay into the Horndeski scalar via $\gamma \to \pi\pi$ and $\gamma \to \gamma\pi$.

$$\Gamma_{\gamma\to\pi\pi} = \frac{p^7\,(1-c_s^2)^2}{480\pi\, c_s^7\,\Lambda_*^6}$$

⇒ Rules out Beyond Horndeski models **except** special cases with $c_s^2=1$.

$$\Rightarrow\ \alpha_H(z) \lesssim 10^{-10}$$

THE HORNDESKI ALPHA PARAMETERS

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$\alpha_M(z) = \frac{1}{H}\frac{d\ln M^2(t)}{dt}$ running of effective Planck mass.

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~~$\alpha_H(z)$ disformal symmetries of the metric.~~

What next for GW tests of gravity?

Propagation Effects

GW propagating on FRW background in modified gravity:

$$h''_{ij} + 2\,(1 + \alpha_M)\,\mathcal{H}\,h'_{ij} + (c_T^2\,k^2 + a^2\,m_g^2)\,h_{ij} = a^2\,\Gamma_C\,\gamma_{ij}$$

- h''_{ij} → Extra polarisation modes possible
- α_M → Modified `friction' → changes GW amplitude
- c_T^2 → Modified propagation speed
- m_g^2 → Graviton mass
- $a^2\,\Gamma_C\,\gamma_{ij}$ → Non-zero source term

Least constrained | Most generic | Best constrained | Rare

$|c_T/c - 1| \simeq 10^{-15}$ from GW170817

$m_g \lesssim 10^{-32}\,\mathrm{eV/c^2}$ from Solar System tests

Anomalous Luminosity Distances

GW propagating on FRW background in modified gravity:

$$h''_{ij} + 2\,(1 + \alpha_M)\,\mathcal{H}\,h'_{ij} + k^2\, h_{ij} = 0$$

Modified `friction'
→ changes GW amplitude

Let $h_{ij} = h\, e_{ij}$, and $h = h_{GR} \times B e^{iC}$.

Solving the wave eq. → **C = 0** (no phase shift)

→ **B =** **exp** $\left[\int_0^{\mathrm{z}} \frac{\alpha_M(z)}{1+\mathrm{z}}\,\mathrm{dz}\right]$

Anomalous Luminosity Distances

Let $h_{ij} = h\, e_{ij}$, and $h = h_{GR} \times B e^{iC}$.

Solving the wave eq. → **C = 0** (no phase shift)

$$\rightarrow \mathbf{B} = \exp\left[\int_0^{z} \frac{\alpha_M(z)}{1+z}\,dz\right]$$

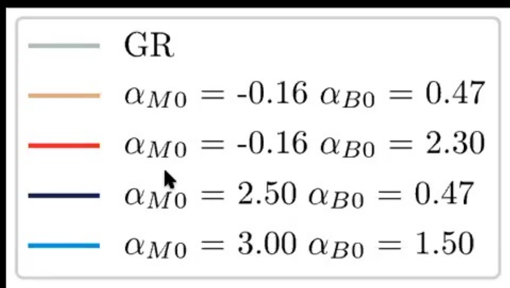
At lowest PN order, the GR amplitude is:

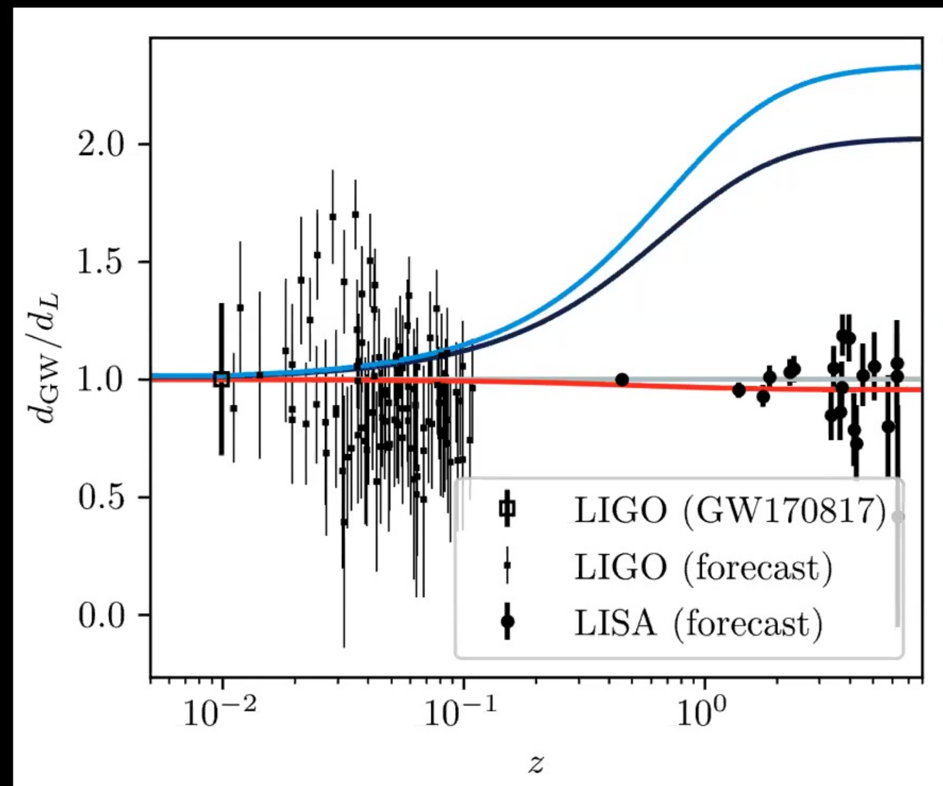
$$h_{MG} = \frac{4}{d_{GW}}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{5/3}\left(\frac{\pi f_{gw}}{c}\right)^{2/3}$$

$$\Rightarrow \quad d_{GW} = e^{[\cdots]}\, d_L$$

Effective GW luminosity distance.

LUMINOSITY DISTANCES

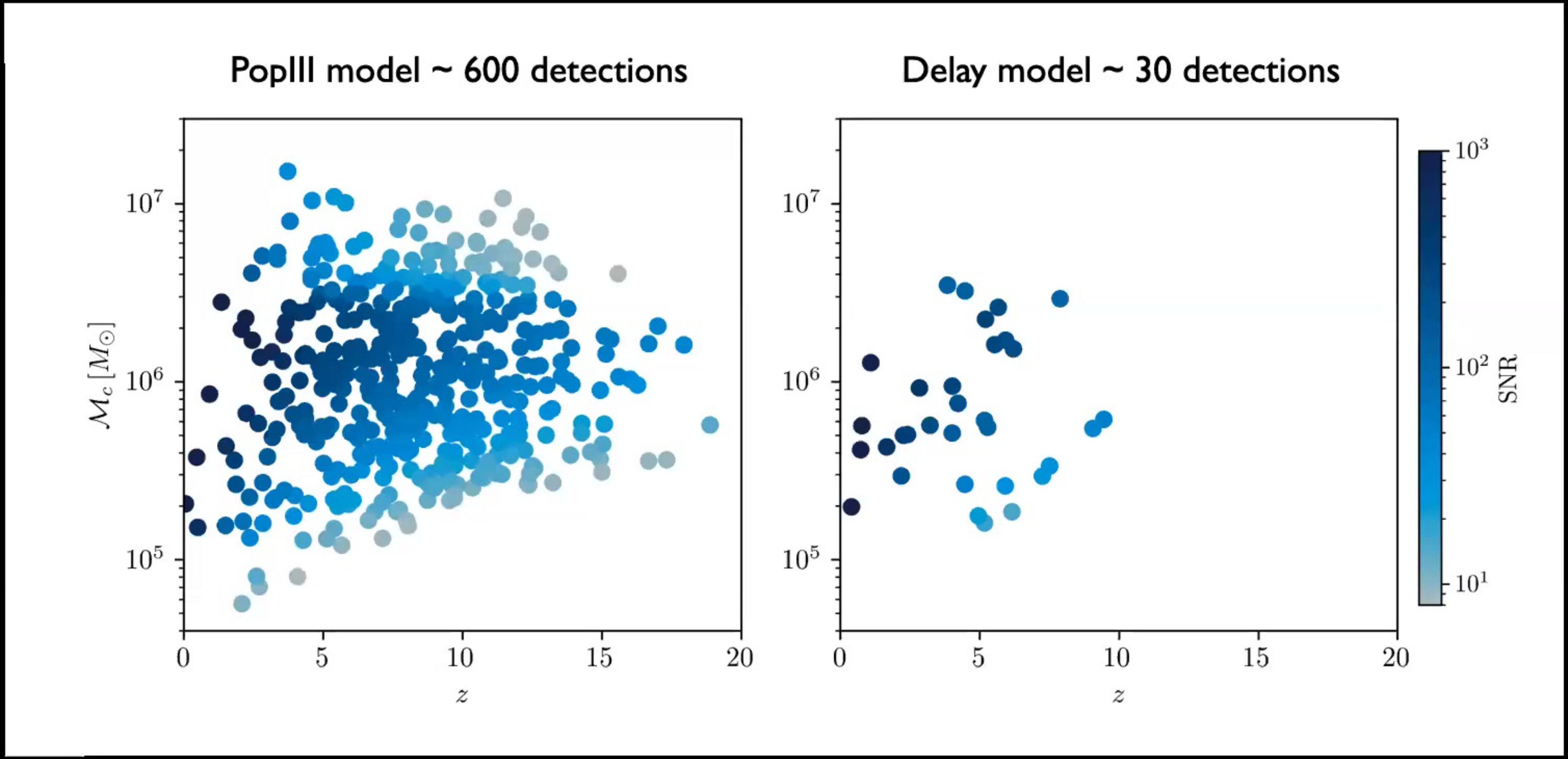




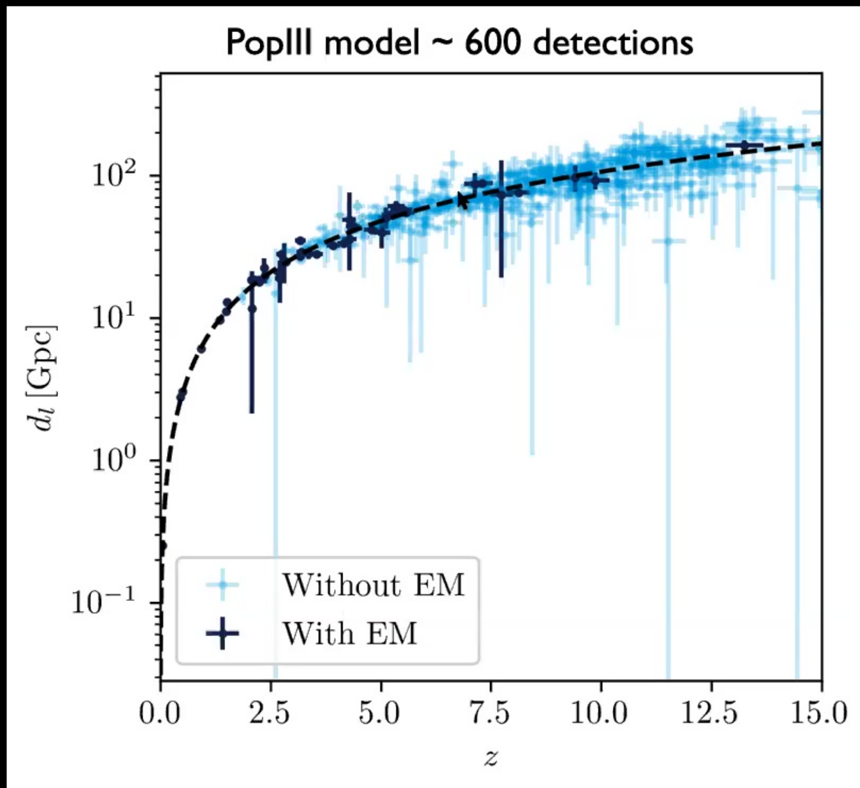
Here we have assumed a time-dependent ansatz for α_M :

$$\alpha_M(z) = \alpha_{M0}\,\Omega_\Lambda(z)$$

1. LISA SOURCES



2. EM COUNTERPARTS ARE PRECIOUS

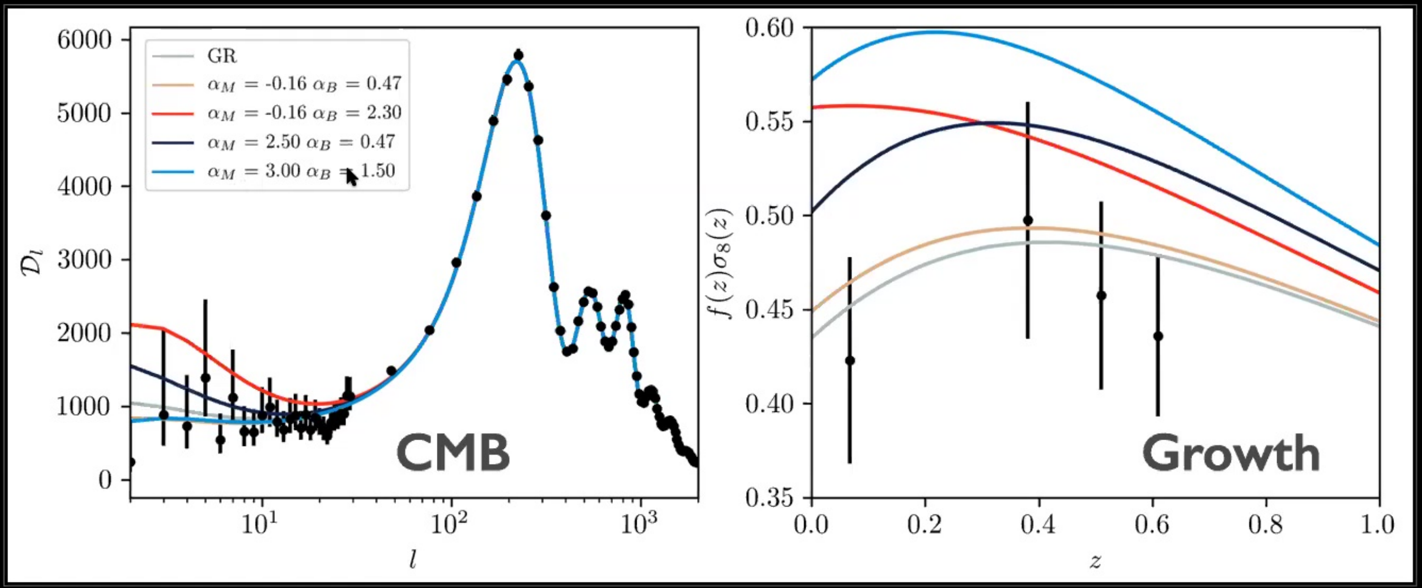


~ 10% of PopIII events have a counterpart

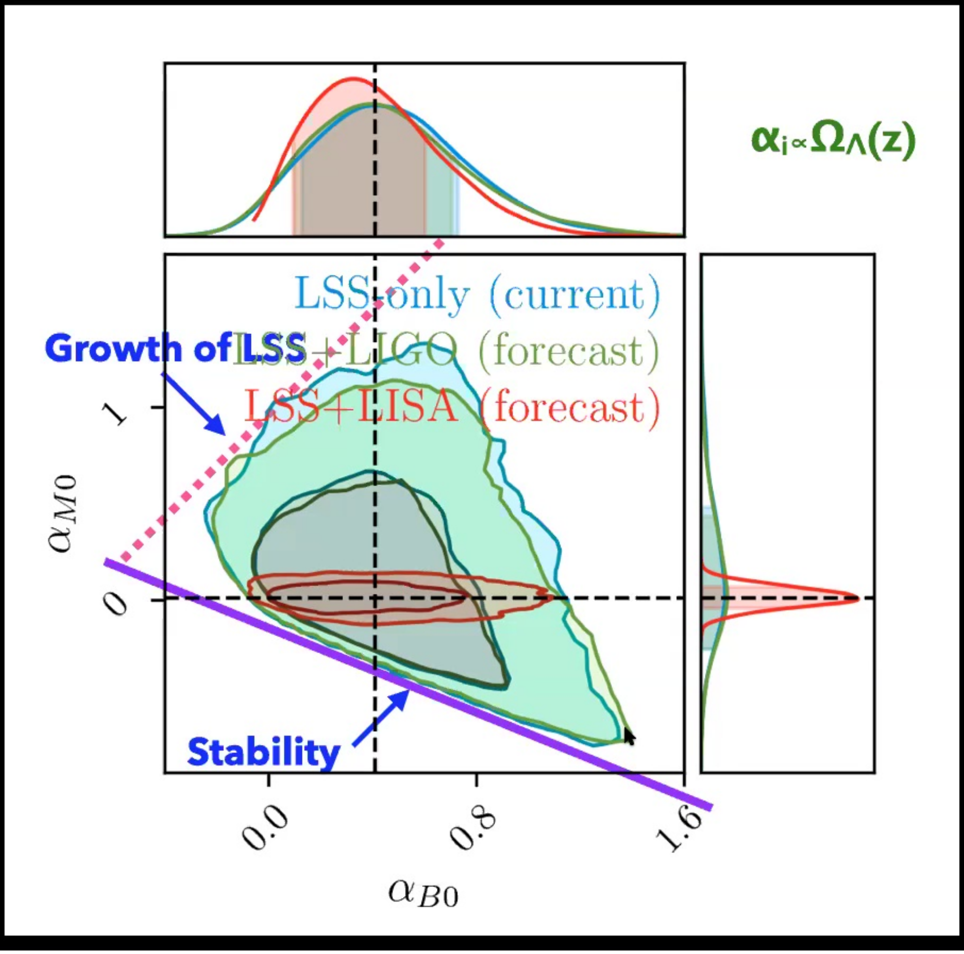
Here distributed as $\propto d_L^{-2}$

WHAT ABOUT EM PROBES?

- The GW luminosity distance probes $\alpha_M(z)$ only.
- CMB + LSS are sensitive to both $\alpha_M(z)$ and $\alpha_B(z)$.



CONSTRAINTS ON MG



For the popIII model.

Stability $\rightarrow c_s^2 \geq 0$

+ no-ghost condition

Experiment	$\sigma_{\alpha_{B0}}$	$\sigma_{\alpha_{M0}}$
LSS-only	0.59	0.73
LSS+LIGO (forecast)	0.60	0.68
LSS+LISA (pop. III)	0.49	0.11
LSS+LISA (delay)	0.50	0.15
LSS+LISA (no delay)	0.51	0.13

HOW GOOD IS THIS?

We find $\sigma_\alpha \sim 0.2$. How does this compare to other bounds?

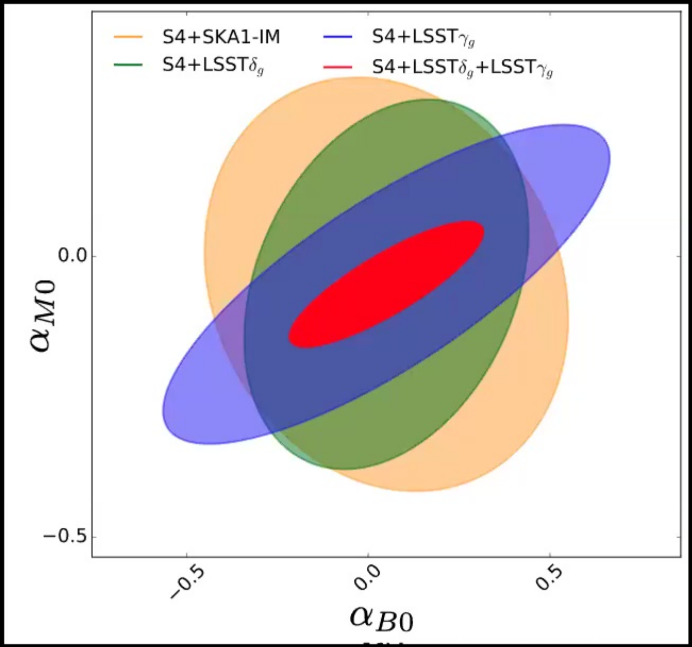
- 1 LIGO BNS : $\sigma_\alpha \sim 10$
- 100 LIGO BNS : $\sigma_\alpha \sim 1$

  Lagos et al. (2019)
- Current LSS alone : $\sigma_\alpha \sim 1 - 0.5$

  Noller & Nicola (2018)
- Future LSS : $\sigma_\alpha \sim 0.2$ →

  (Stage 4 CMB + LSST)

  Alonso et al. (2017)
- Future LSS +GWs : $\sigma_\alpha \sim 0.1 - 0.01$?



Alonso et al., 2016

CONCLUSIONS

little/no impact on observables

↓

~~$\alpha_T(z)$~~ $\alpha_M(z)$ $\alpha_B(z)$ $\alpha_K(z)$ ~~$\alpha_H(z)$~~

Refs: 1604.01386, 1710.06394, 1906.01593, 2007.13791.

CONCLUSIONS

little/no impact on observables ↓

~~$\alpha_T(z)$~~ | $\alpha_M(z)$ $\alpha_B(z)$ | $\alpha_K(z)$ | ~~$\alpha_H(z)$~~

- GW luminosity distances hold extra information on α_M .

→ Can we close off the Horndeski parameter space by combining future GW+EM data?

- Lots of nice astrophysics to learn along the way....

(SMBH population models, counterparts, source inclinations, etc.)

Refs: 1604.01386, 1710.06394, 1906.01593, 2007.13791.