TESTING COSMOLOGICAL GRAVITY WITH GW170817

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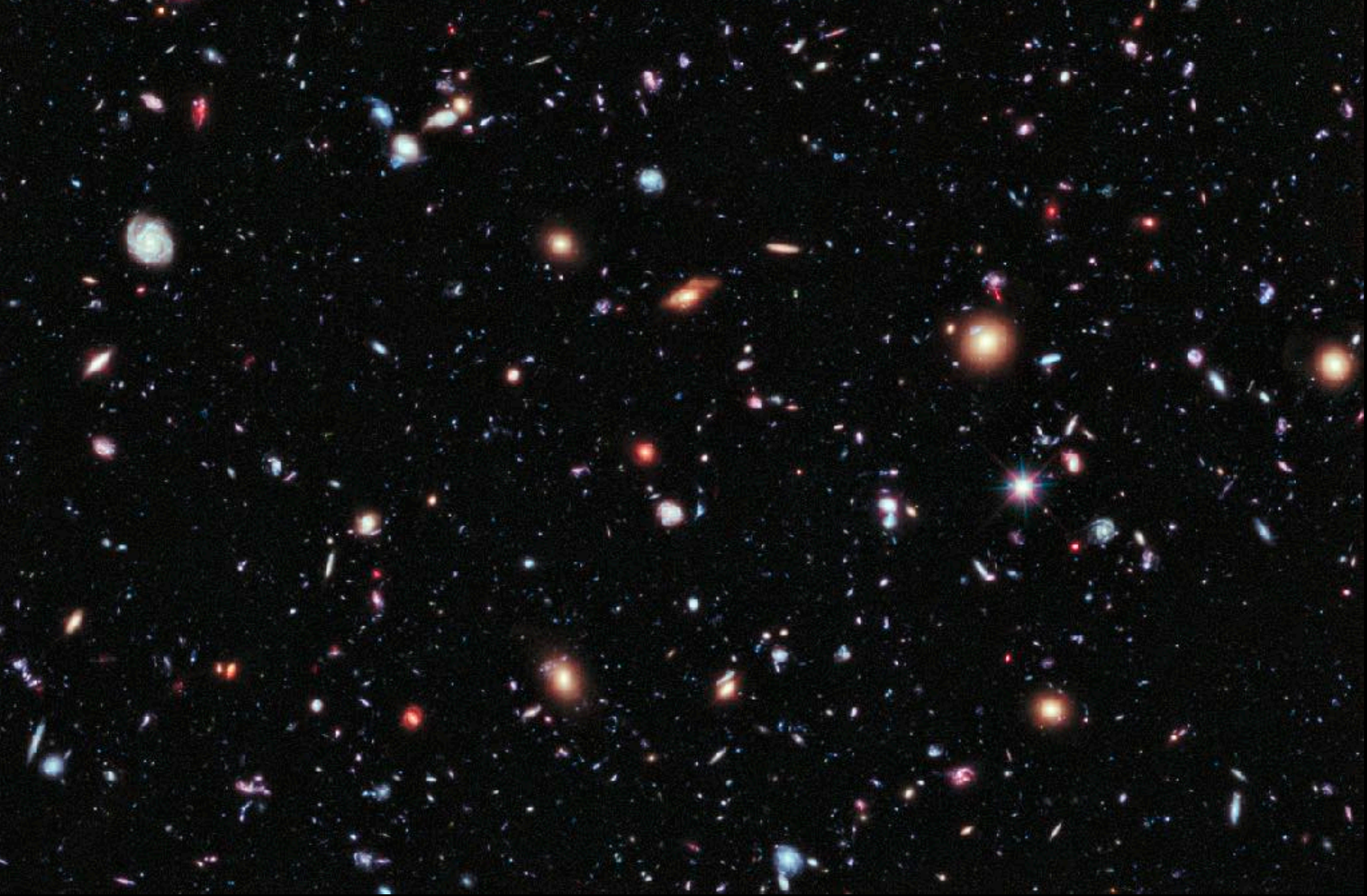
Outline

- What parameters do we want to measure?
- What did we learn from GW170817?
- Bonus material: what next?

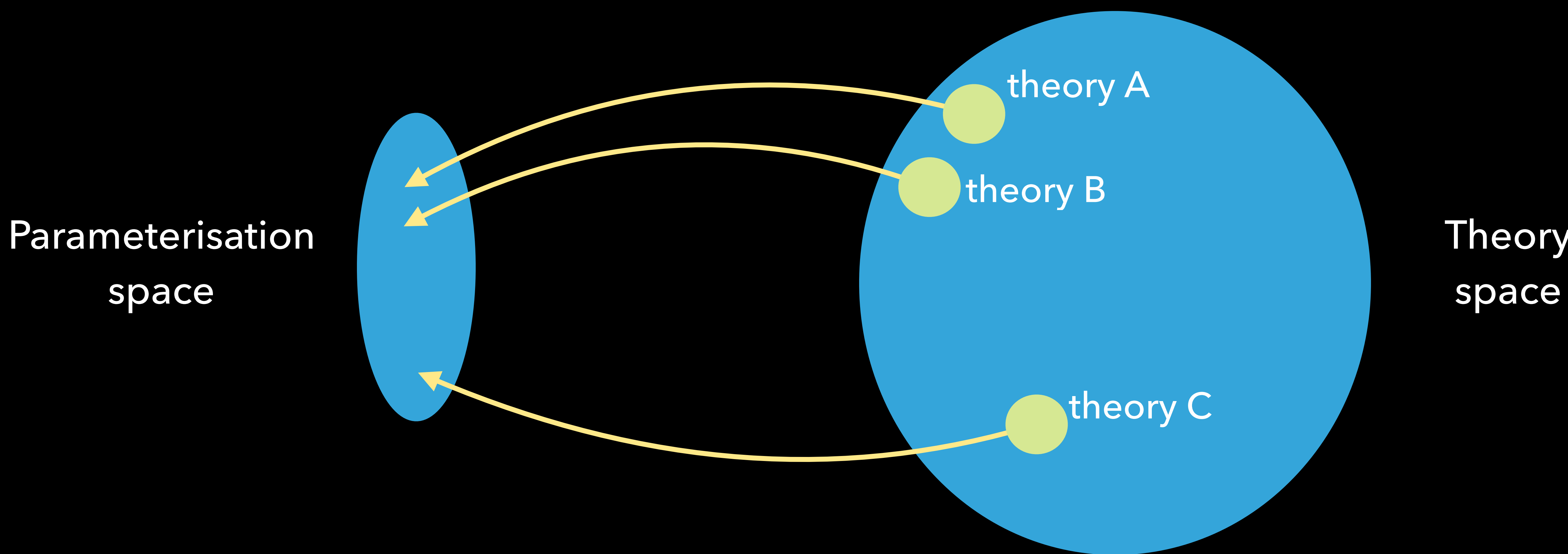
This talk: *cosmological gravity.*



Parameters for Testing Gravity

Model-Independent Methods

- We want a *parameterisation* of modified gravity model space.



- EFT mindset: **Must** include all terms consistent with symmetries.
- MG models involve new degrees of freedom. Today: one scalar only.

Extended Gravitational Action

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

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:

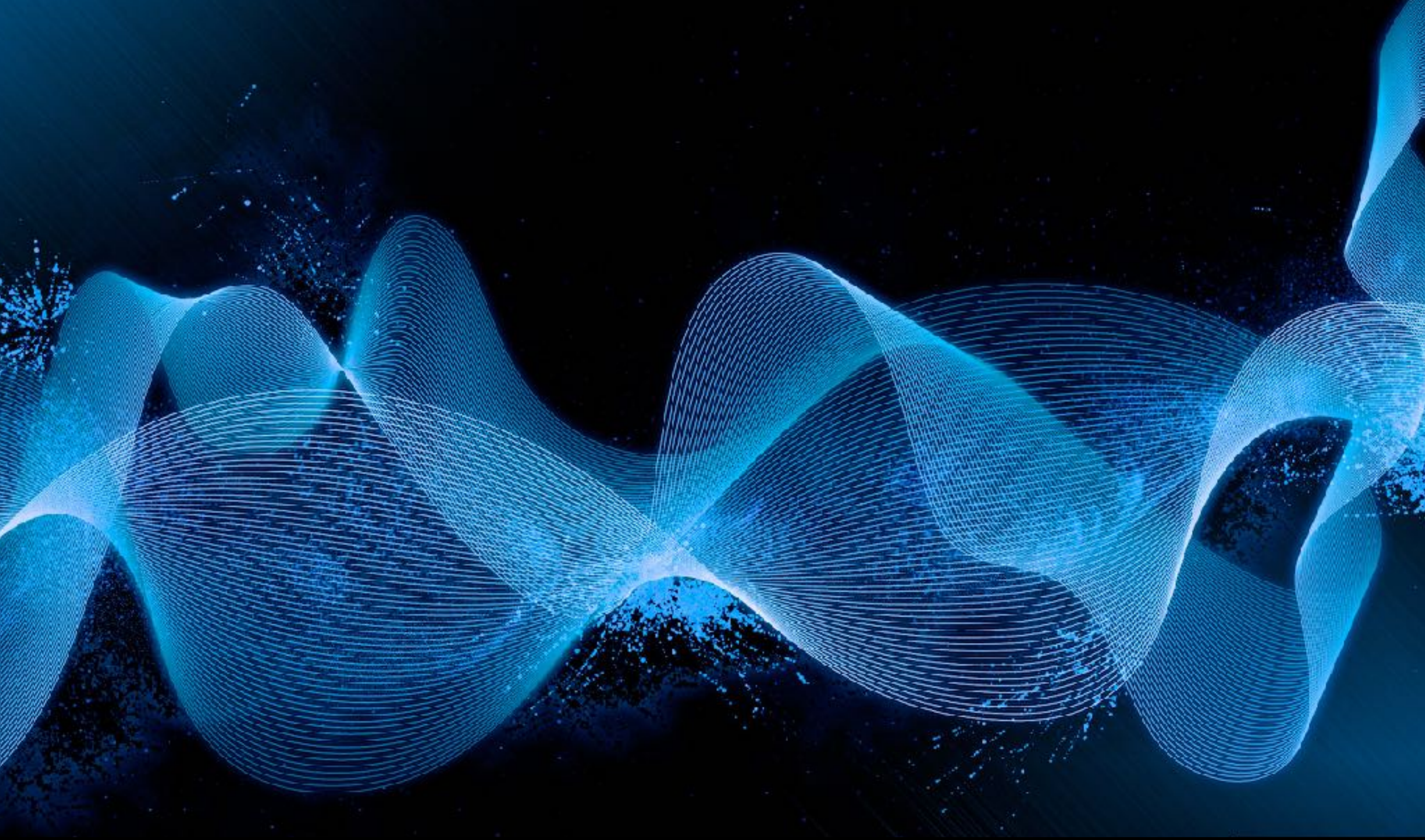
$\alpha_T(z)$ speed of gravitational waves, $c_T^2 = 1 + \alpha_T$.

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

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

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

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



Constraints from GW170817

GW170817 & GRB170817a

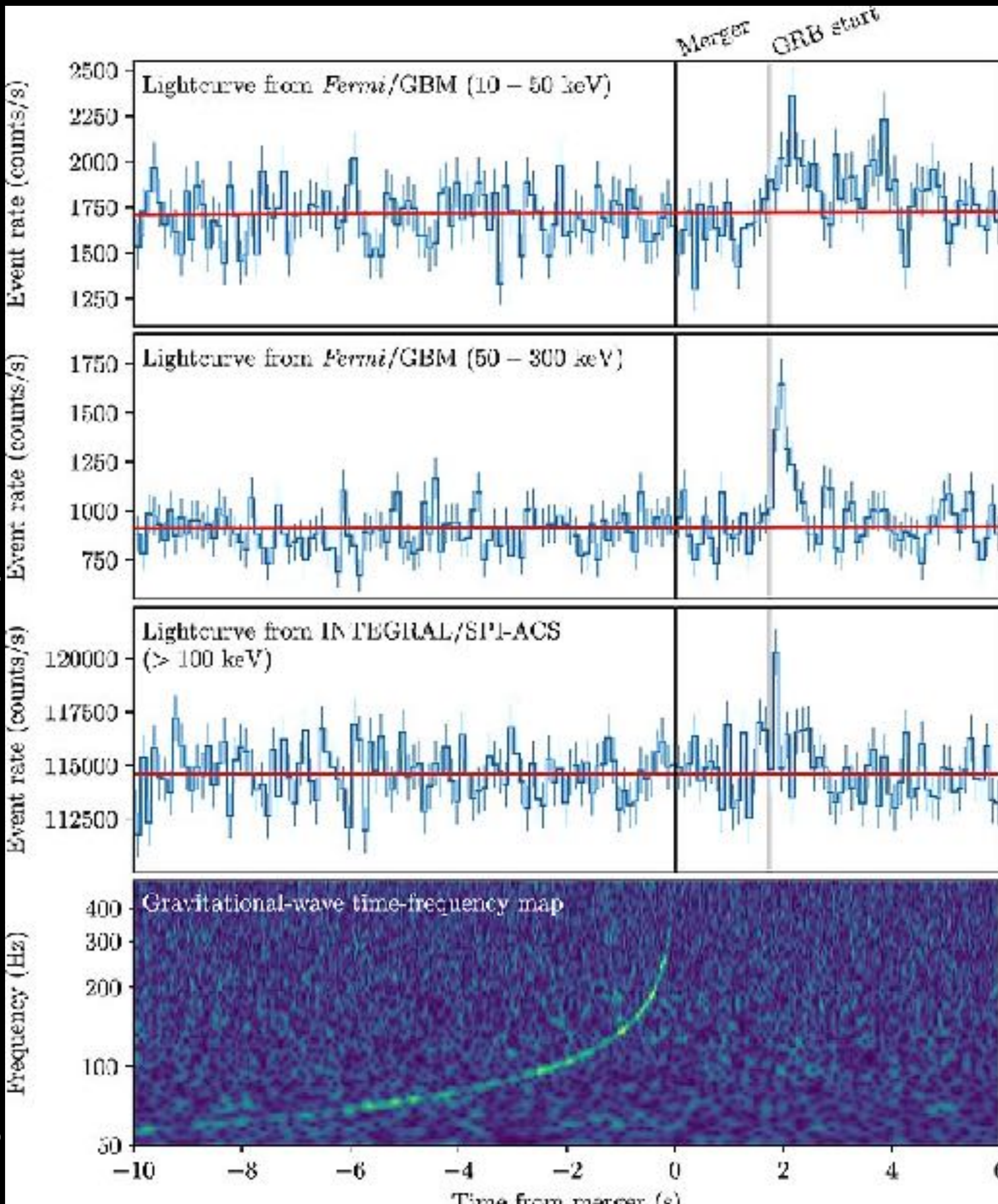


Image: LIGO-VIRGO Collaboration, ApJ 848:2 (2017).

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

$$\Delta t \simeq 1.7\,\mathrm{s}$$

$$\Rightarrow |\alpha_T| \lesssim 10^{-15}$$

More conservative:

$$|\alpha_T| \lesssim 10^{-12}$$

E.g. 1710.06394 + others.

Get-Outs

Gravitational Rainbows: LIGO and Dark Energy at its Cutoff

Claudia de Rham[1,2,*] and Scott Melville[1,†]

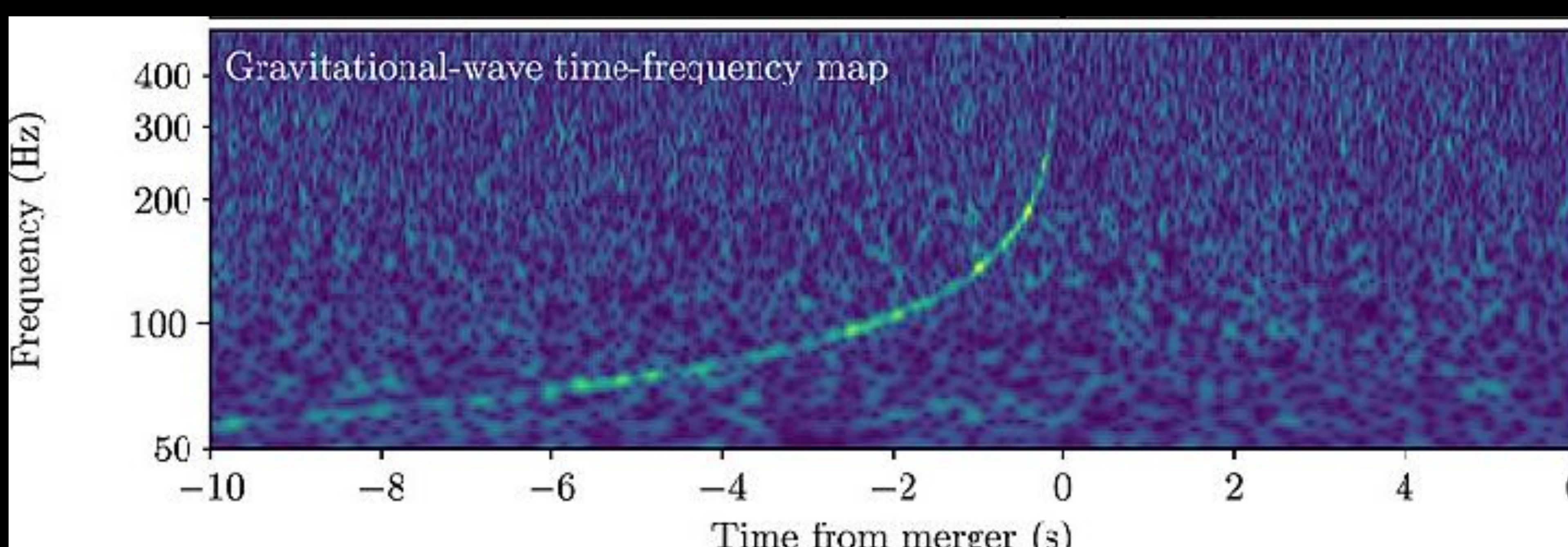
[1] *Theoretical Physics, Blackett Laboratory, Imperial College, London, SW7 2AZ, U.K.*
[2] *CERCA, Department of Physics, Case Western Reserve University, 10900 Euclid Ave, Cleveland, OH 44106, USA*

(Dated: June 26, 2018)

The recent direct detection of a neutron star merger with optical counterpart has been used to severely constrain models of dark energy that typically predict a modification of the speed of gravitational waves. We point out that the energy scales observed at LIGO, and the particular frequency of the neutron star event, lie very close to the strong coupling scale or cutoff associated with many

$$\Lambda_{\text{cutoff}} \sim \left(M_{\text{Pl}}\,H_0^2\right)^{1/3} \sim 260\,\text{Hz}$$

for Horndeski.



1809.03484
1906.07015

Survivors?

Initially theories with $\alpha_H(z) \neq 0$ seemed to survive.

But then (Sept. 2018):

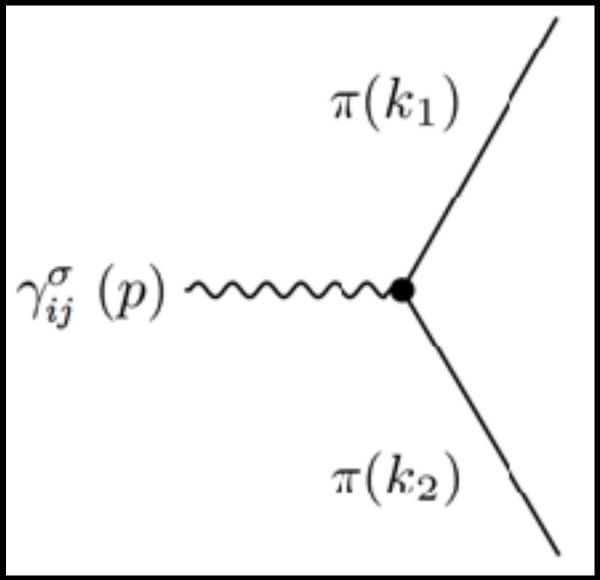
Gravitational Wave Decay into Dark Energy

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

Gravitons can decay into scalar field via $\gamma \to \pi\pi$ and $\gamma \to \gamma\pi$.

⇒ Rules out theories with non-zero $\alpha_H(z)$.

Except for a few special cases: $\Gamma_{\gamma\to\pi\pi} \propto (c_s^2 - 1)$



$$c_s^2 = -\frac{(2-\alpha_B)\left[\dot{H} - \frac{1}{2}H^2(\alpha_B + 2\alpha_M)\right] - H\dot{\alpha}_B + \rho_m + p_m}{H^2(\alpha_K + \frac{3}{2}\alpha_B^2)}$$

What Next?

Modified GW Propagation

Propagation in FRW + GR :

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

Modified GW Propagation

Propagation in FRW + Horndeski :

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

↑ enhanced Hubble damping

$$h_{MG} = e^{-D}\, h_{GR}$$ where $$D = \frac{1}{2}\int_0^z \frac{\alpha_M}{1+\tilde{z}}\, d\tilde{z}$$

↓

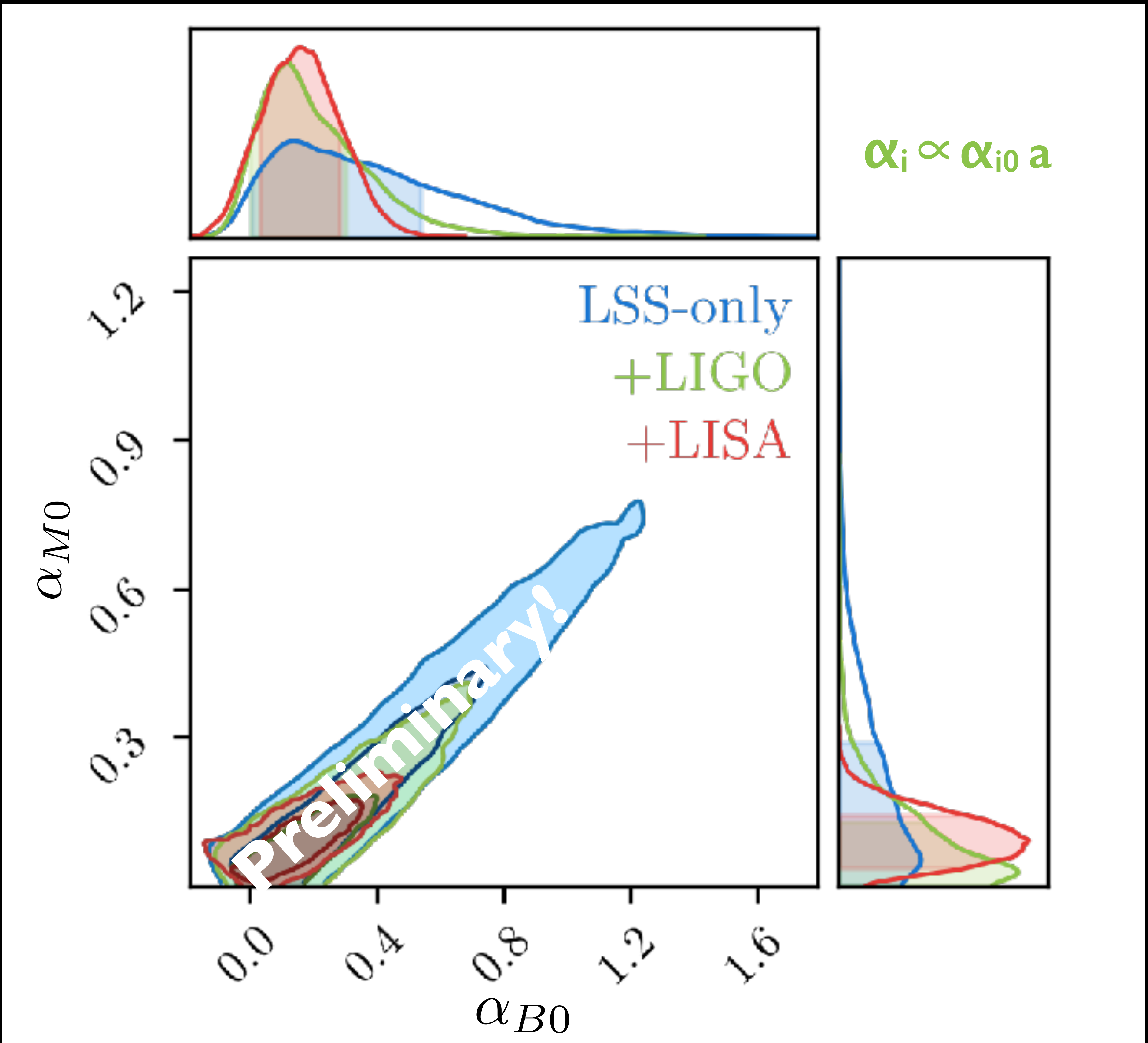
$$h_{GR} \propto \frac{1}{d_L(z)}$$

$$\Rightarrow h_{MG} \propto \frac{1}{d_{GW}(z)}$$

from GW amplitude ↓ from EM counterpart/ host + a d_L-z relation ↓

$$d_{GW}(z) = e^{D}\, d_L(z)$$

Constraints on GR Deviations



$\alpha_i \propto \alpha_{i0}\, a$

Best-fit:

$$\alpha_{B0} \simeq 0.2^{+0.2}_{-0.2}$$

$$\alpha_{M0} \simeq 0.1^{+0.1}_{-0.1}$$

TB & Ian Harrison, in prep.

Conclusions

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

$\alpha_K(z)$: only impacts ultra-large scales

- GWs can improve constraints on MG parameters by ~ 1 order of magnitude over EM cosmology alone.
- Not discussed today:
  - graviton mass
  - non-standard polarisations
  - getting redshifts for GW sources

Refs: 1604.01386, 1710.06394, TB & Harrison in prep.