THE ROYAL SOCIETY
Queen Mary University of London
erc European Research Council

Gravitational Wave Propagation Beyond LCDM

Tessa Baker, Queen Mary University of London

10th LISA Cosmology WG workshop
Stavanger, 06/06/23

Image: Oleksii Topolianskyi

Outline

- GW propagation phenomenology
- GW propagation speed
- GW friction

Image: Karoline Vargdal

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- GW propagation speed
- GW friction

Look out for question boxes

Image: Karoline Vargdal

GW propagation — assumptions

Standard picture used for propagation work so far:

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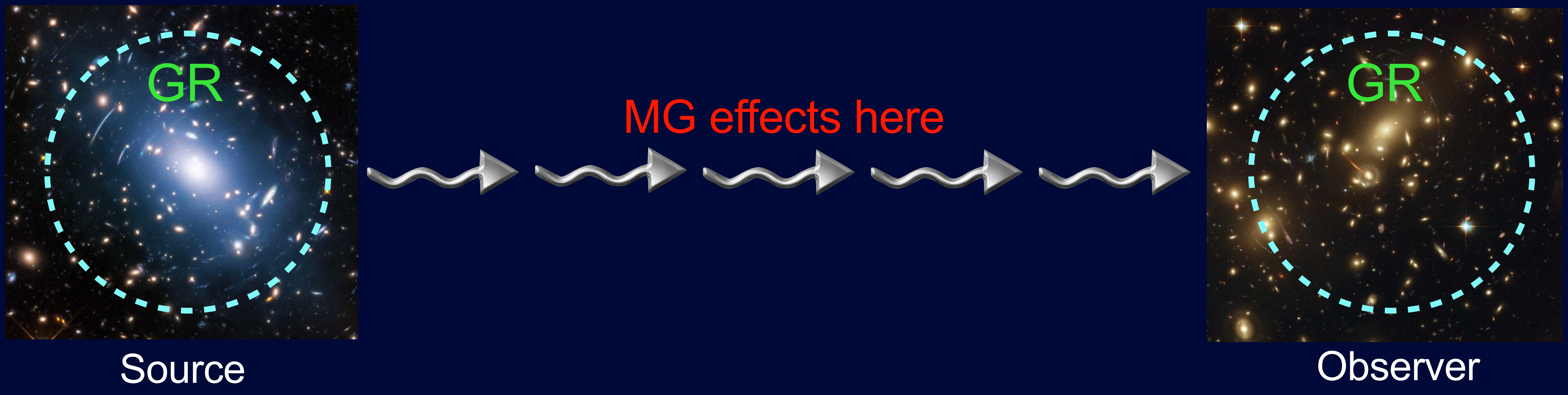

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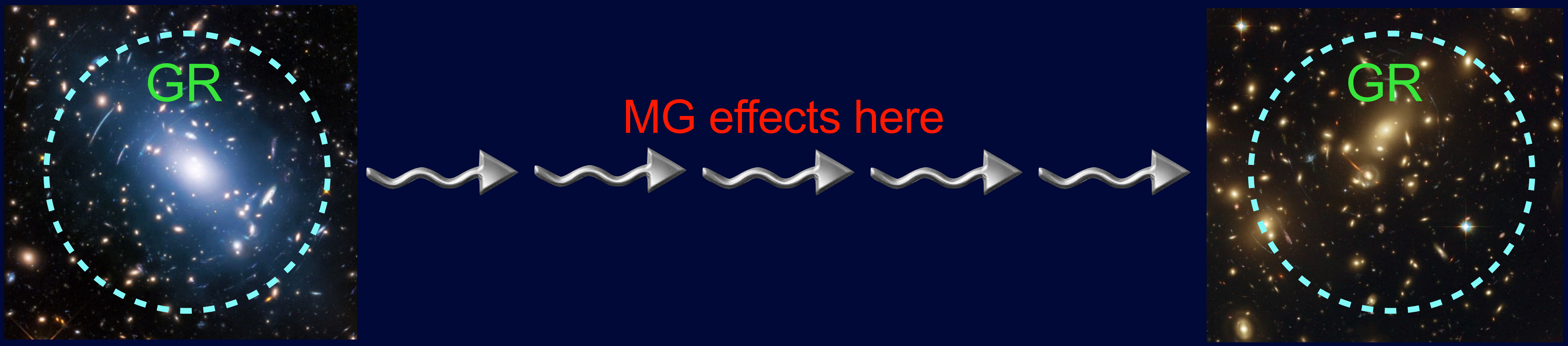

Source Observer

- Modified *generation* — are there some simple features we could include?
  Or must it be full numerical relativity?

GW propagation — assumptions

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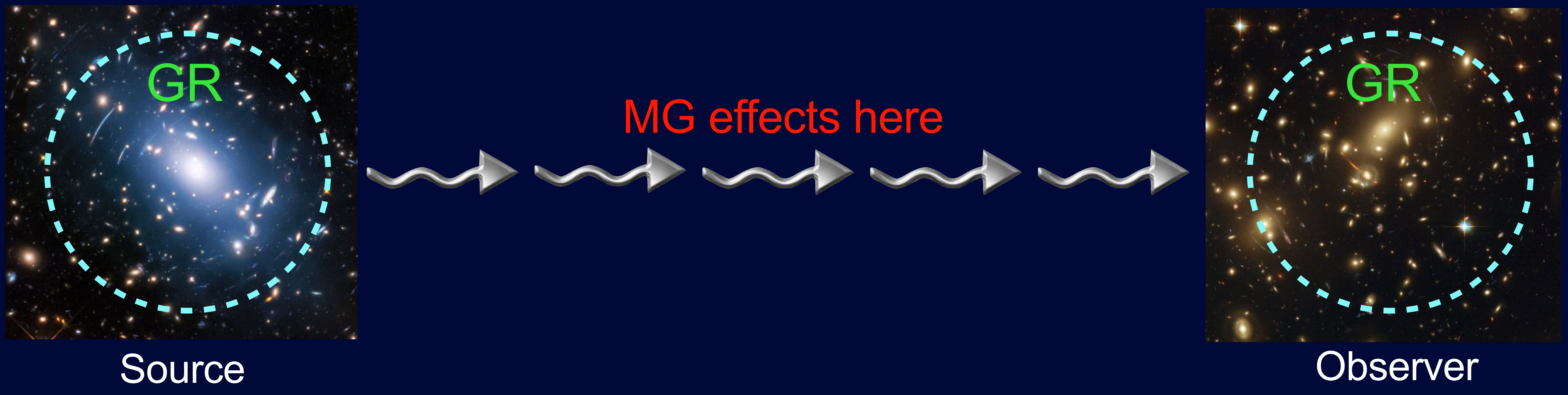

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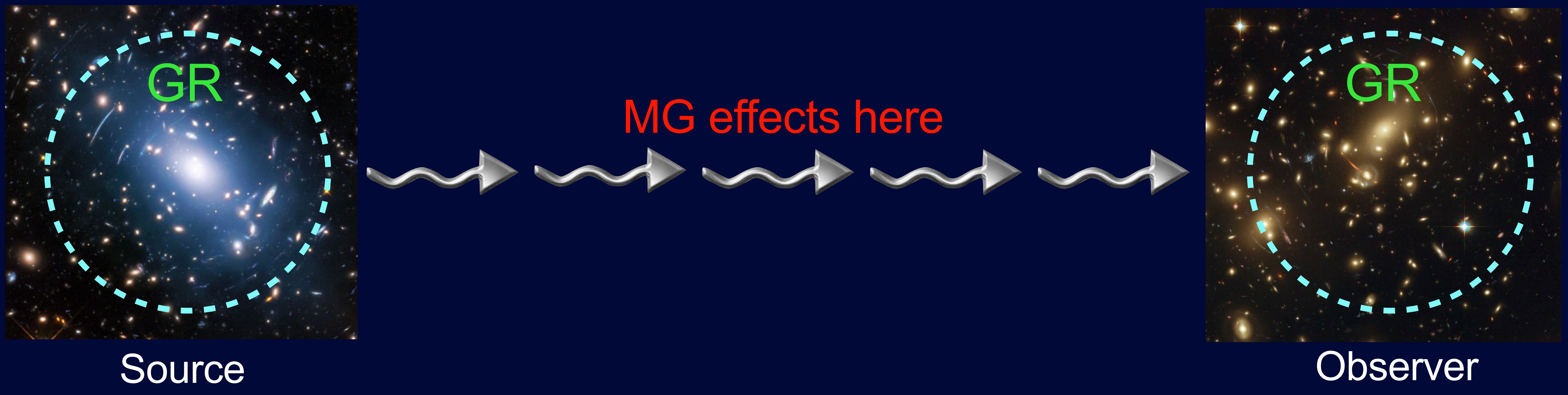

- Modified *generation* — are there some simple features we could include?
  Or must it be full numerical relativity?
- If **both** modified propagation + generation, does one dominate the waveform?
- If the waveform is significantly modified, would we detect it? (→ Talk to LISA waveform or data analysis WGs)

GW propagation

GW propagating on FRW background in GR:

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

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Hubble factor

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GW propagating on FRW background in modified gravity:

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

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Modified `friction'
→ changes GW amplitude

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- h''_{ij}: Extra polarisation modes possible
- $\nu(z)$: Modified `friction' → changes GW amplitude
- c_T^2: Modified propagation speed
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$m_g \lesssim 10^{-22}\mathrm{eV/c^2}$ from GW dispersion

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

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- Is it still worth testing the graviton mass & RHS source terms?

GW propagation speed

(the updated story)

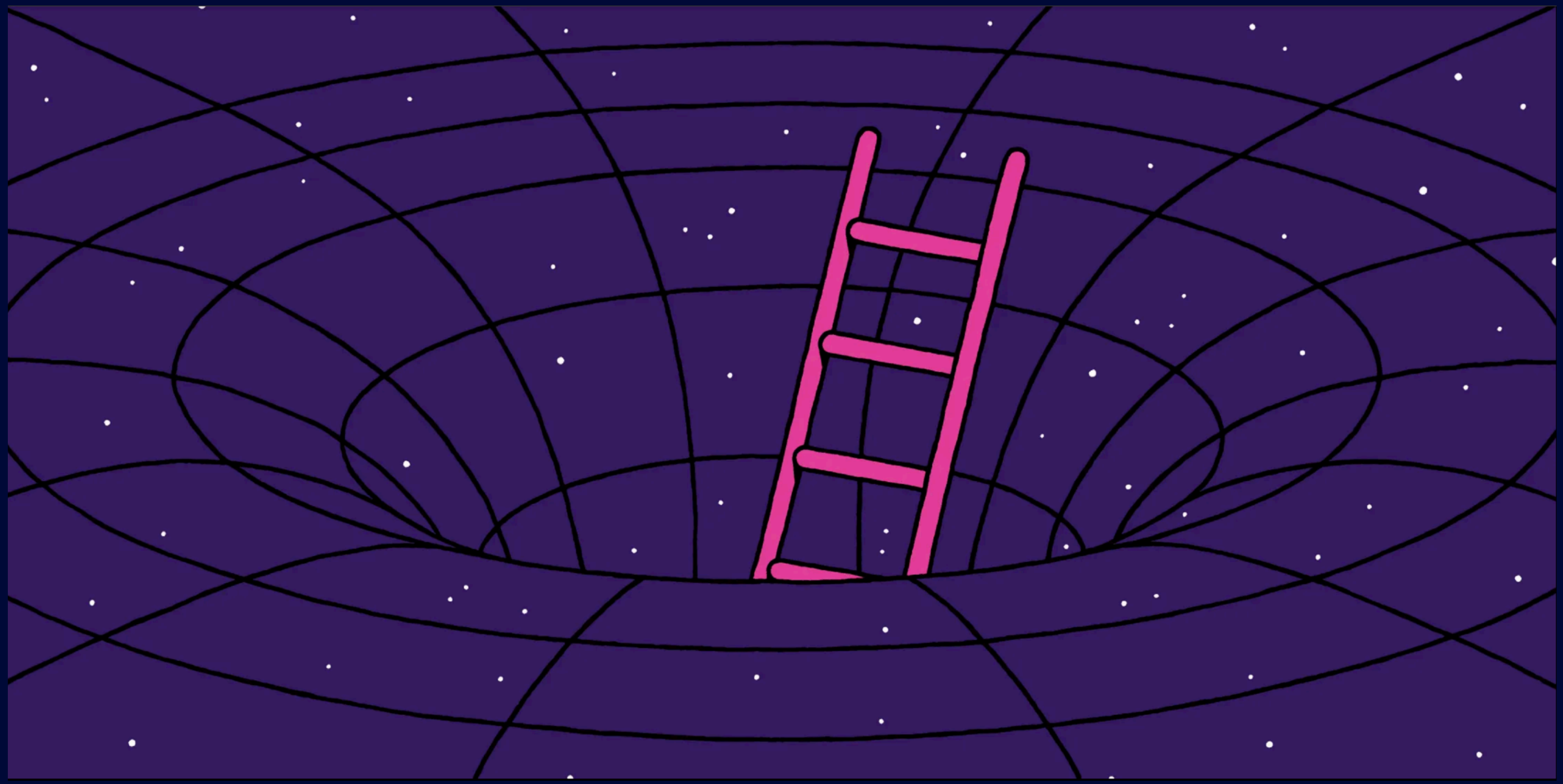
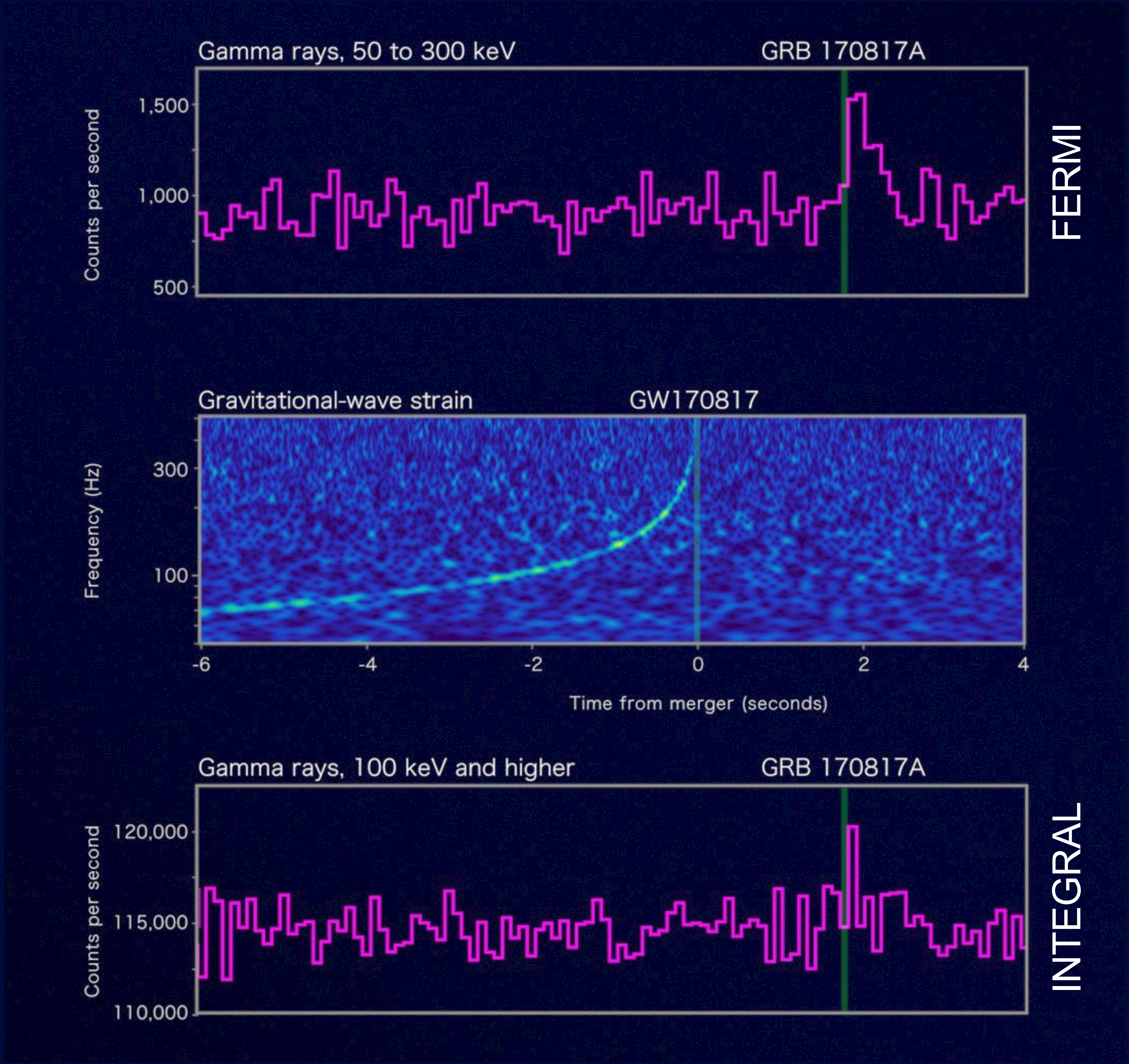


Illustration: Lennard Kok

1710.06394
1710.05832
1710.05834

Propagation speed with GW170817



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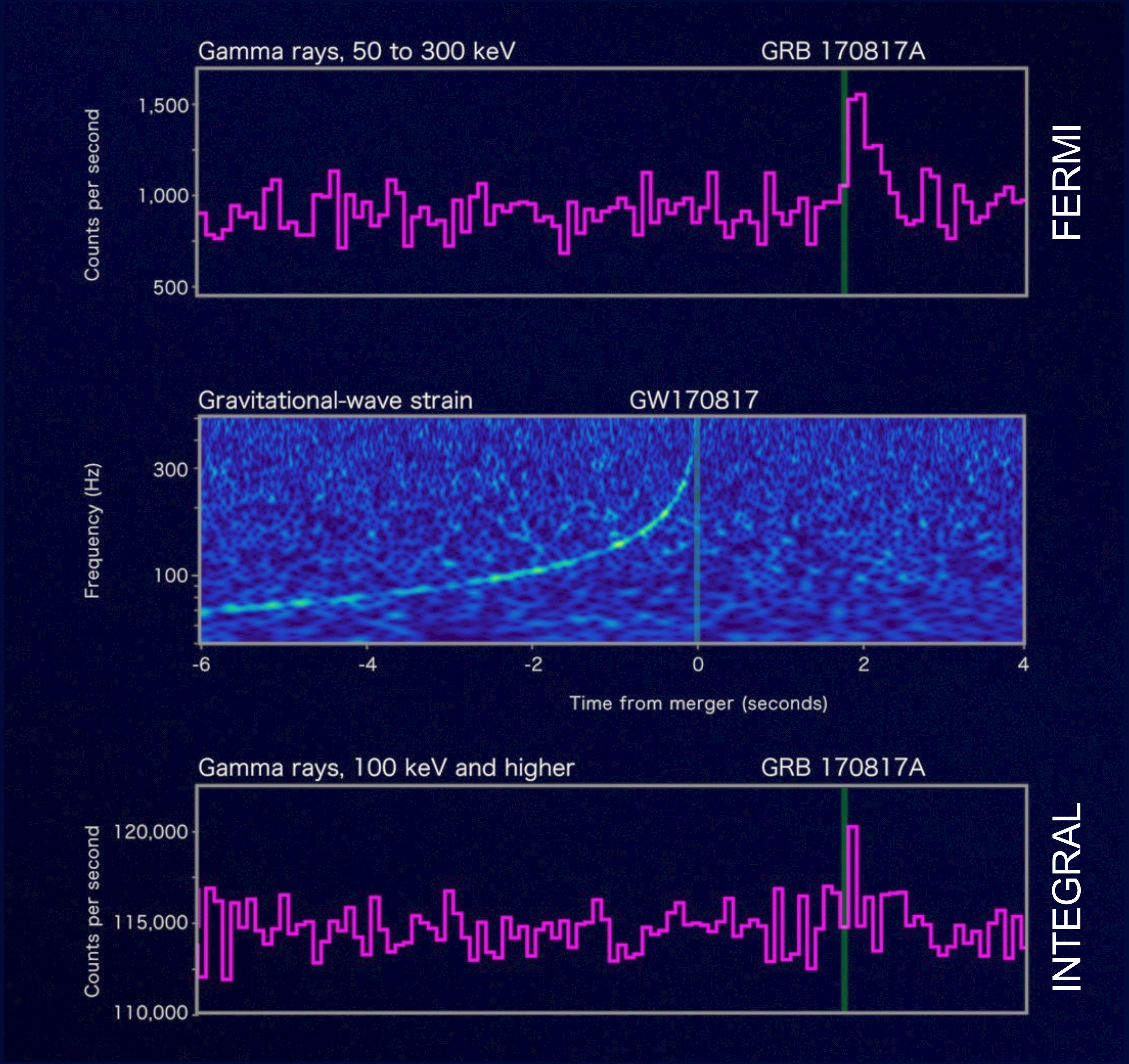

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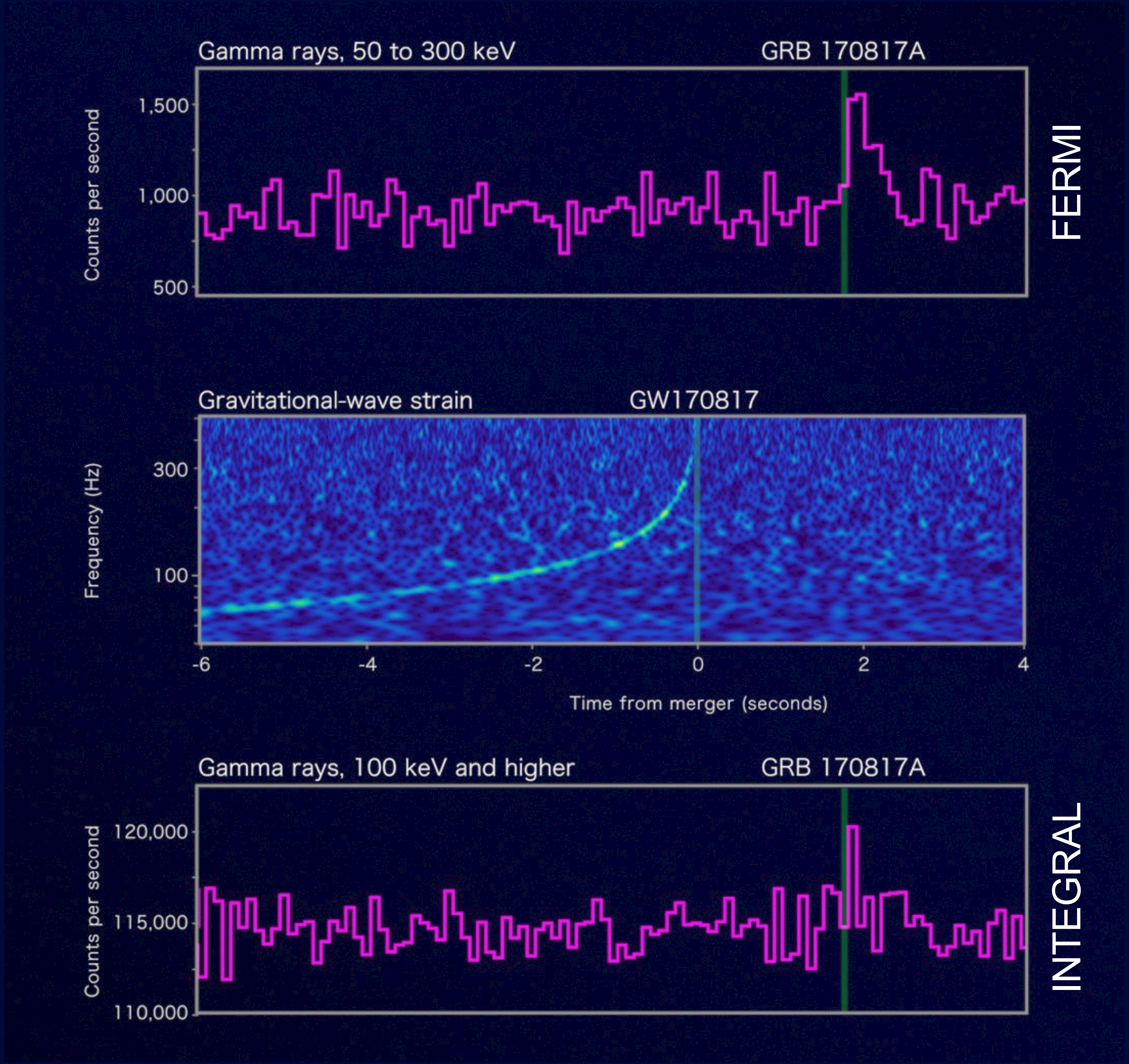

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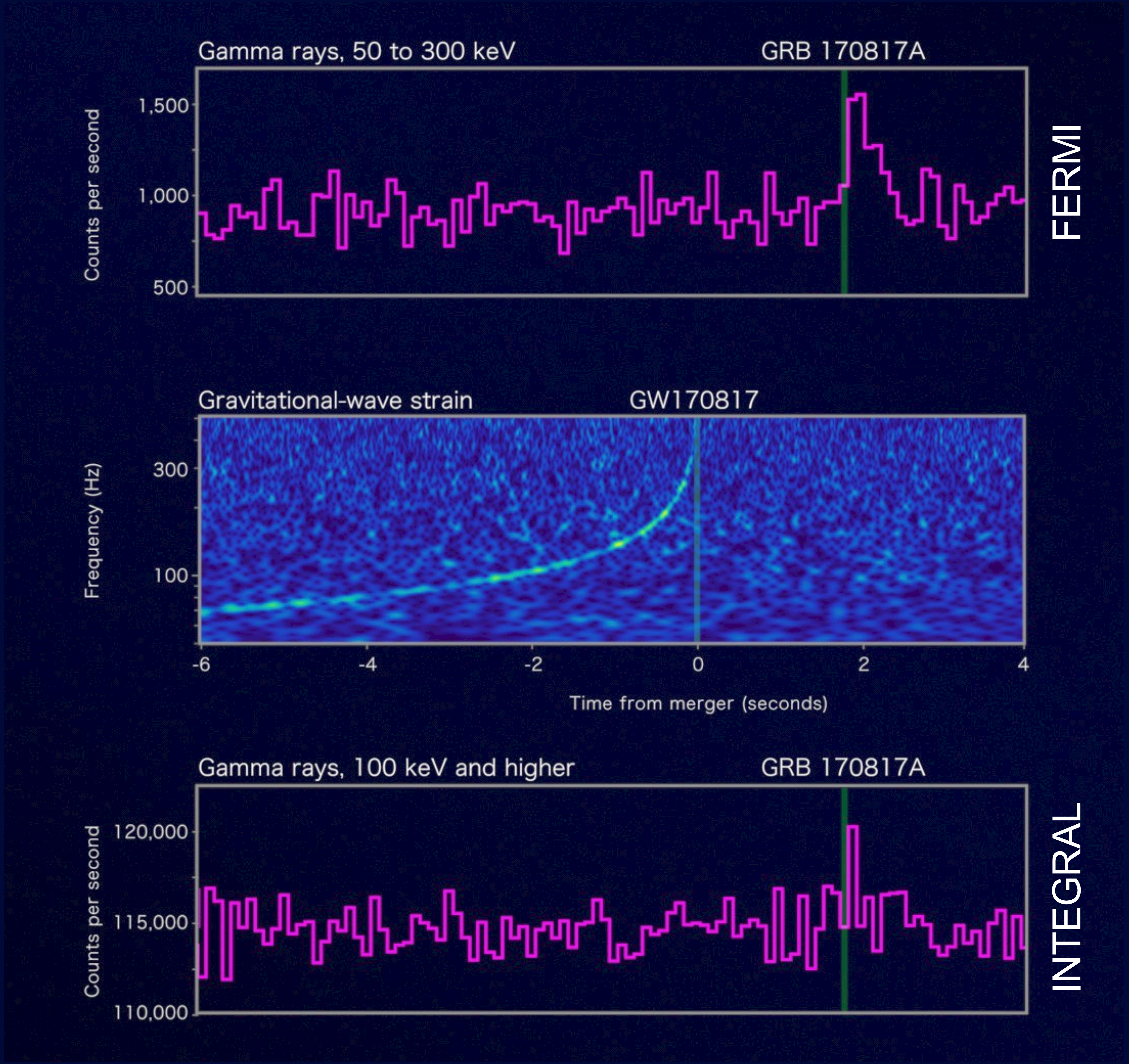

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- Claim — this ruled out chunks of the **Horndeski** model space.

Horndeski = general 'parent theory' of all* gravity models with scalar fields

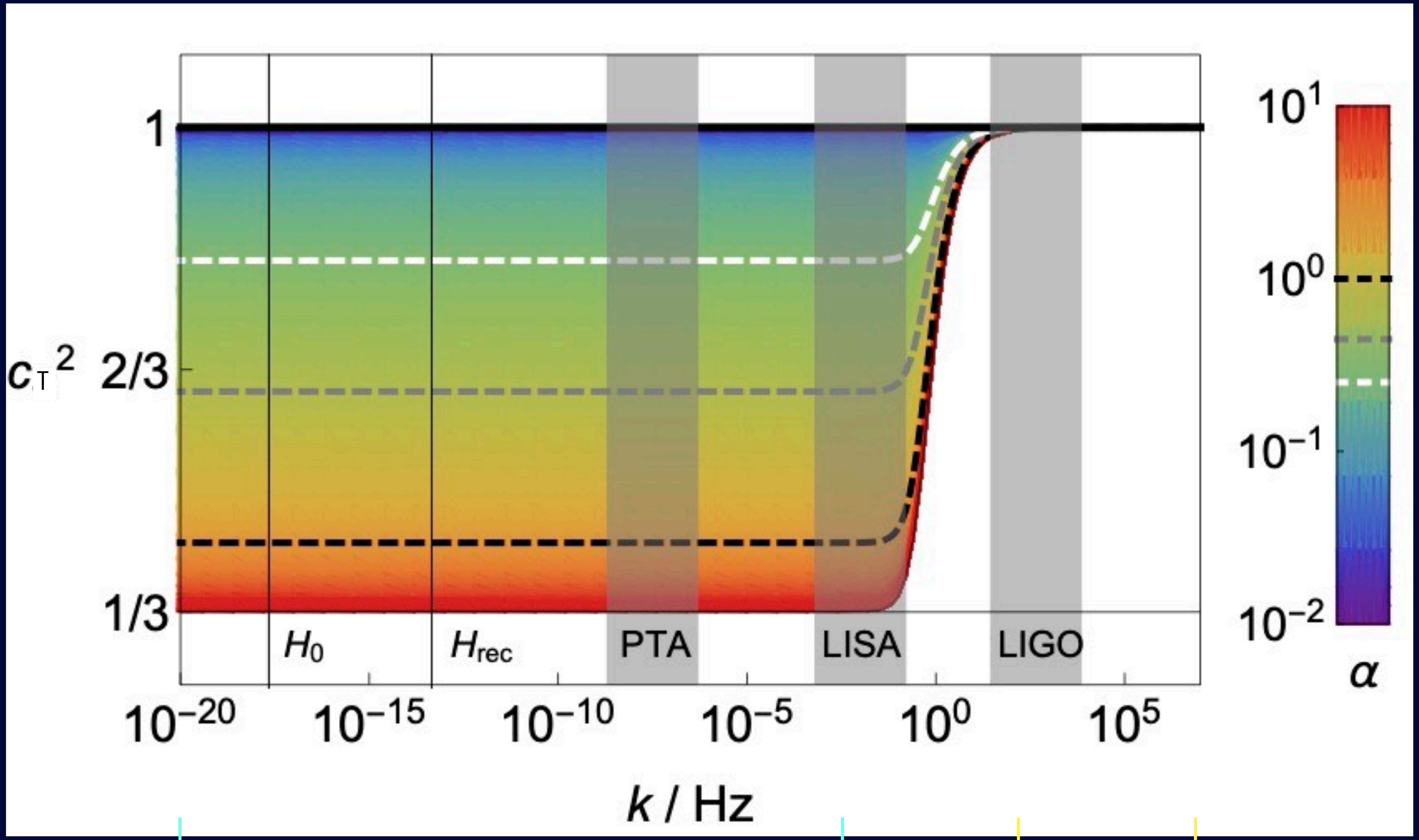
*slight oversimplification

Running propagation speed

- But when viewed as an EFT, the Horndeski family has an energy cut-off scale (where the theory breaks down)

Cut-off scale:

$$\Lambda_{EFT} \sim 260\,\mathrm{Hz}$$



de Rham & Melville (2018)

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$c_T \rightarrow c$ here (Lorentz invariance required at high energies)

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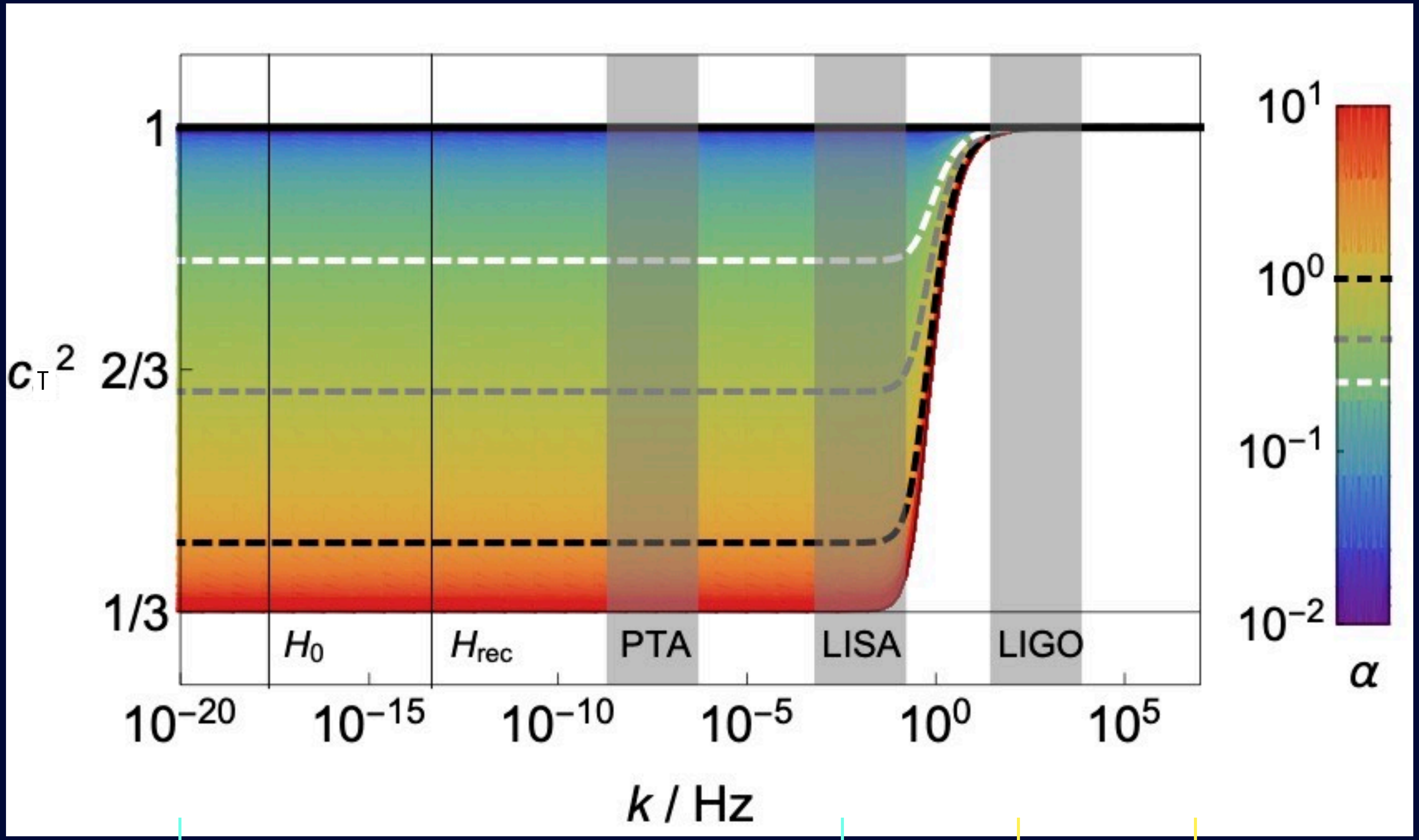

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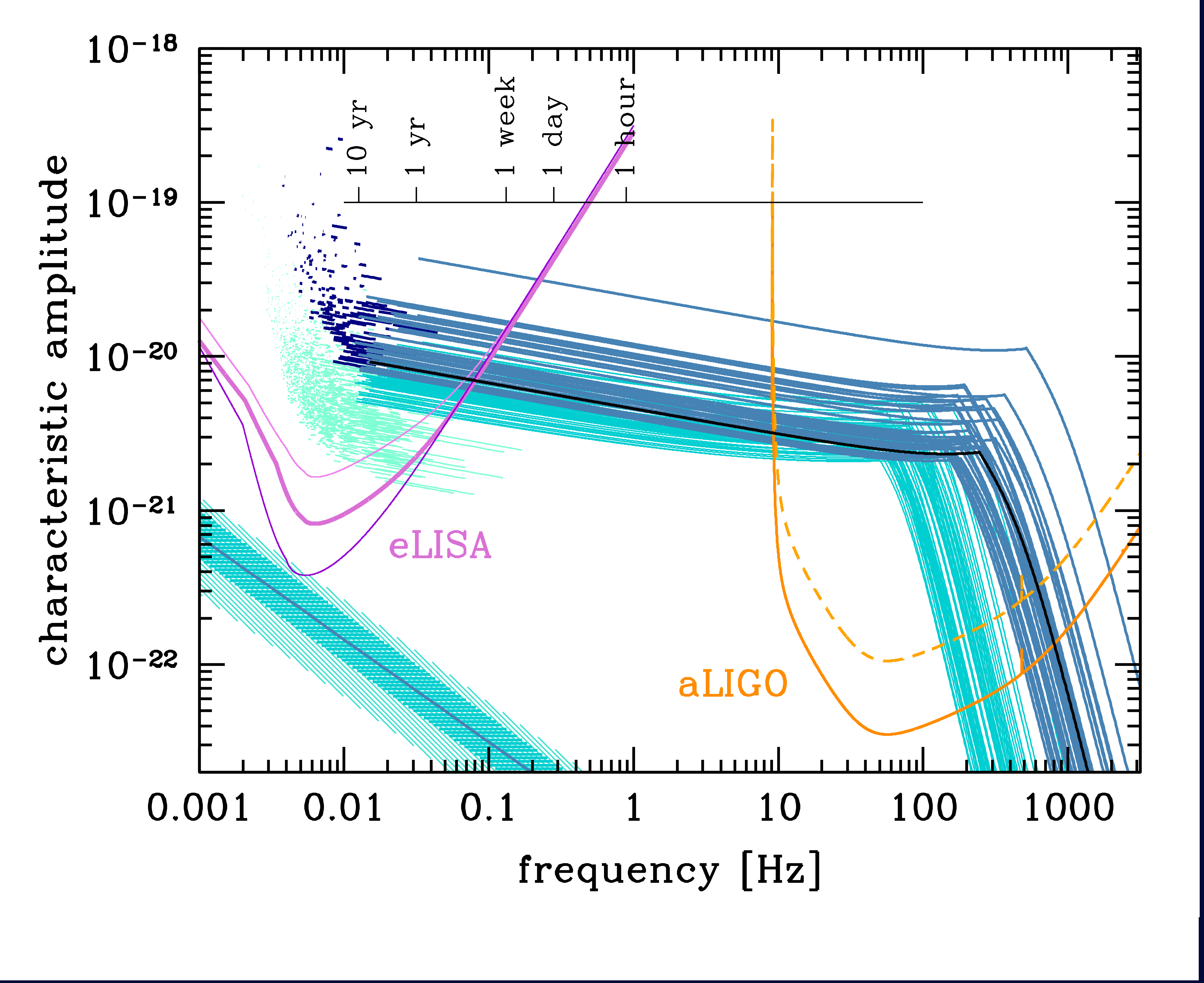
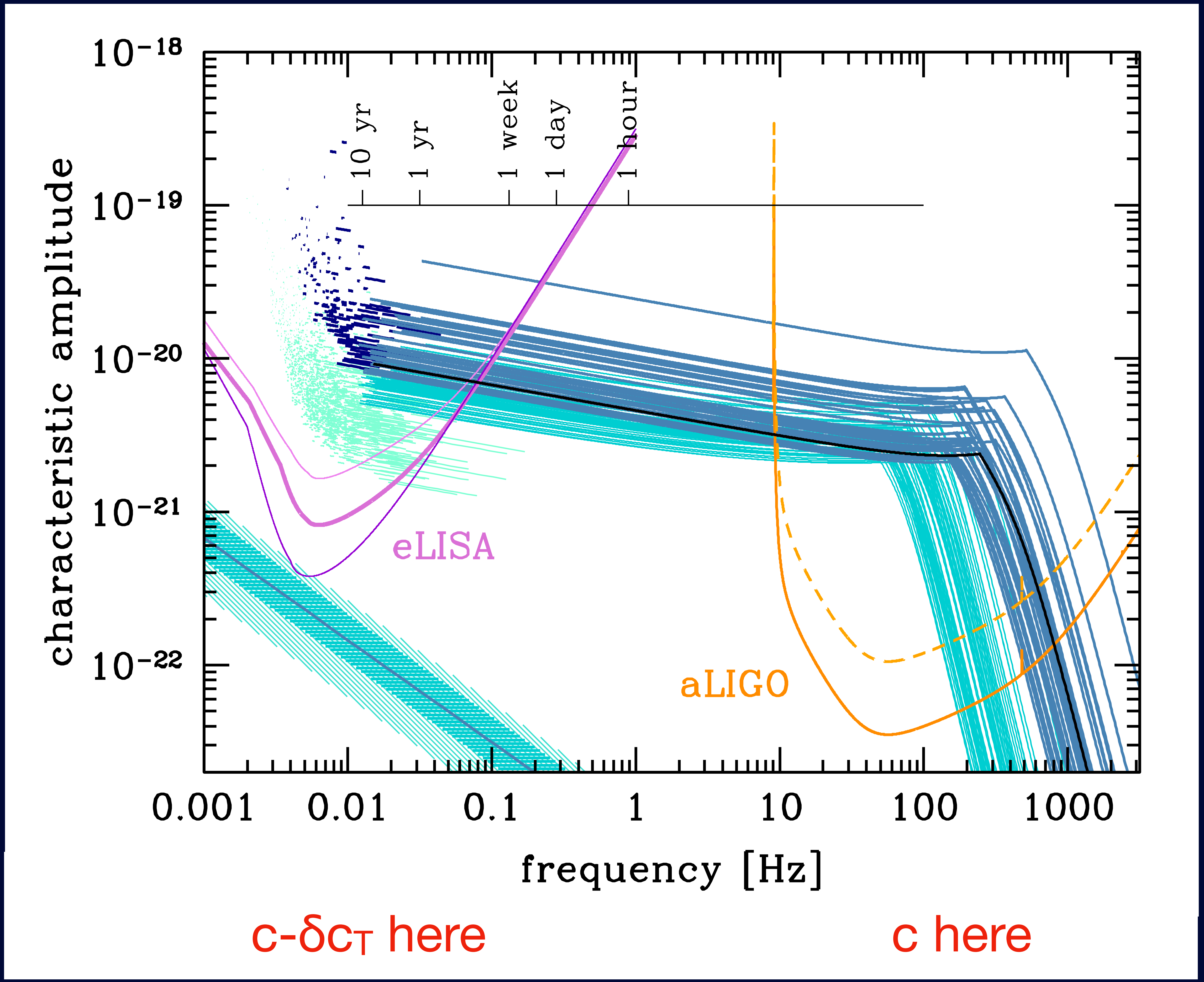
- So the question of GW propagation speed *at low frequencies* is back on the table.

Constraints from multiband sources



A. Sesana, 2016

Constraints from multiband sources



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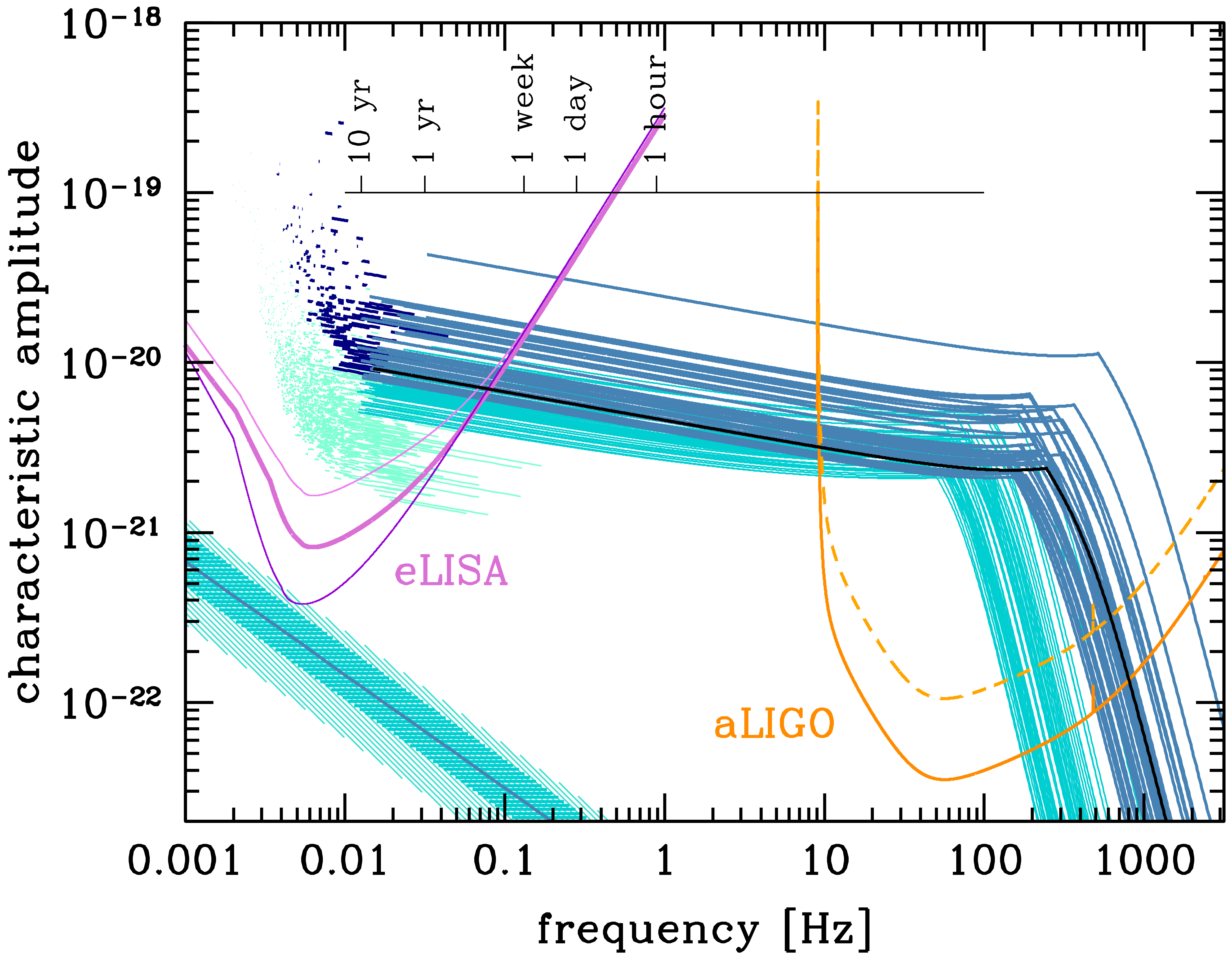

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c-δc_T here

c here

A change in the speed of propagation causes a a shift in coalescence time of the binary:

$$t - t_c = \tau_{\mathrm{GR}} + \frac{D}{c}\,\frac{\delta c_T}{c} + \text{subleading corrections}$$

Large (~ billion years) → $\frac{D}{c}$

Tiny, e.g. 10^{-15} → $\frac{\delta c_T}{c}$

(TB, Barausse, Chen, de Rham, Pieroni,Tasinato, 2022.)

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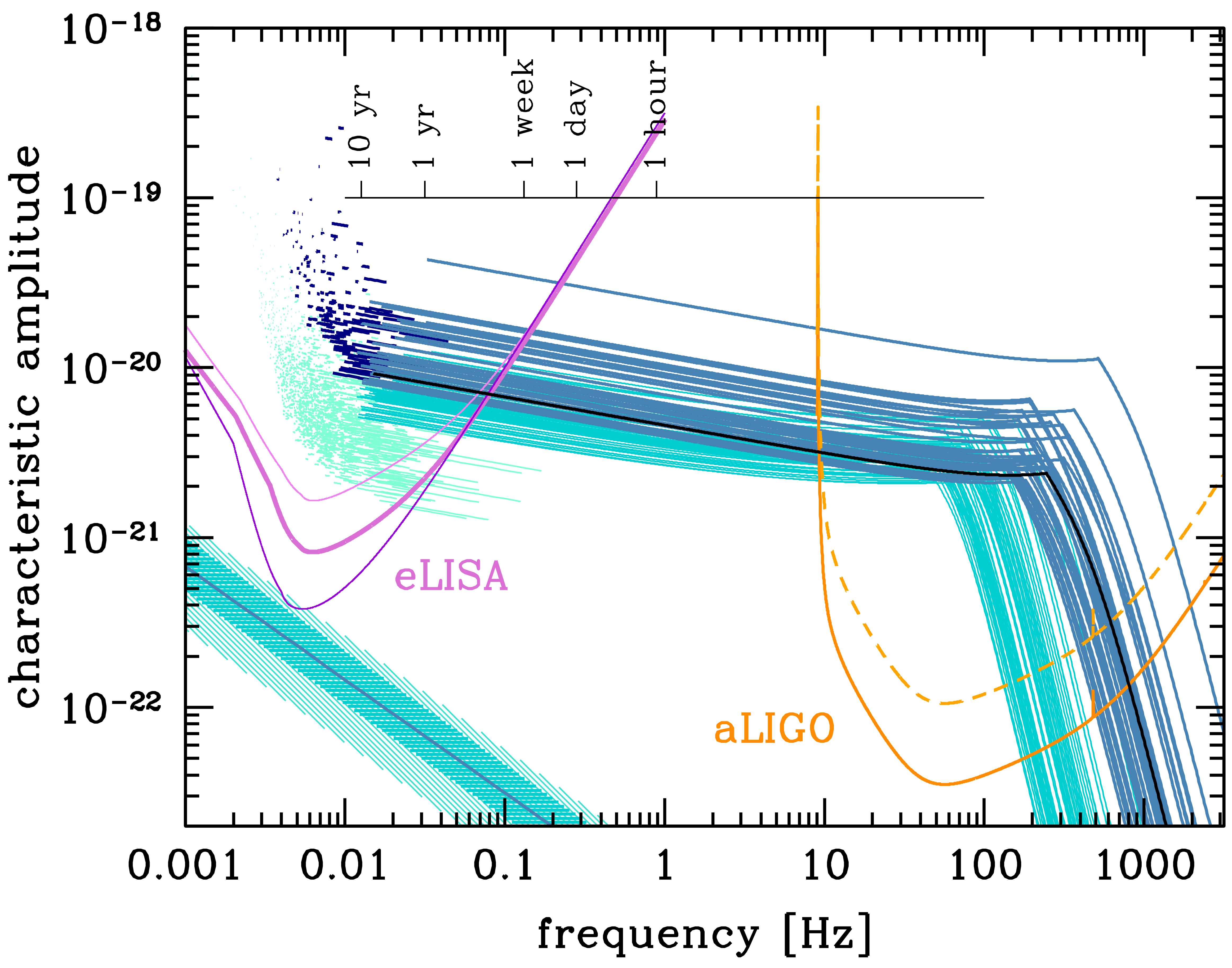

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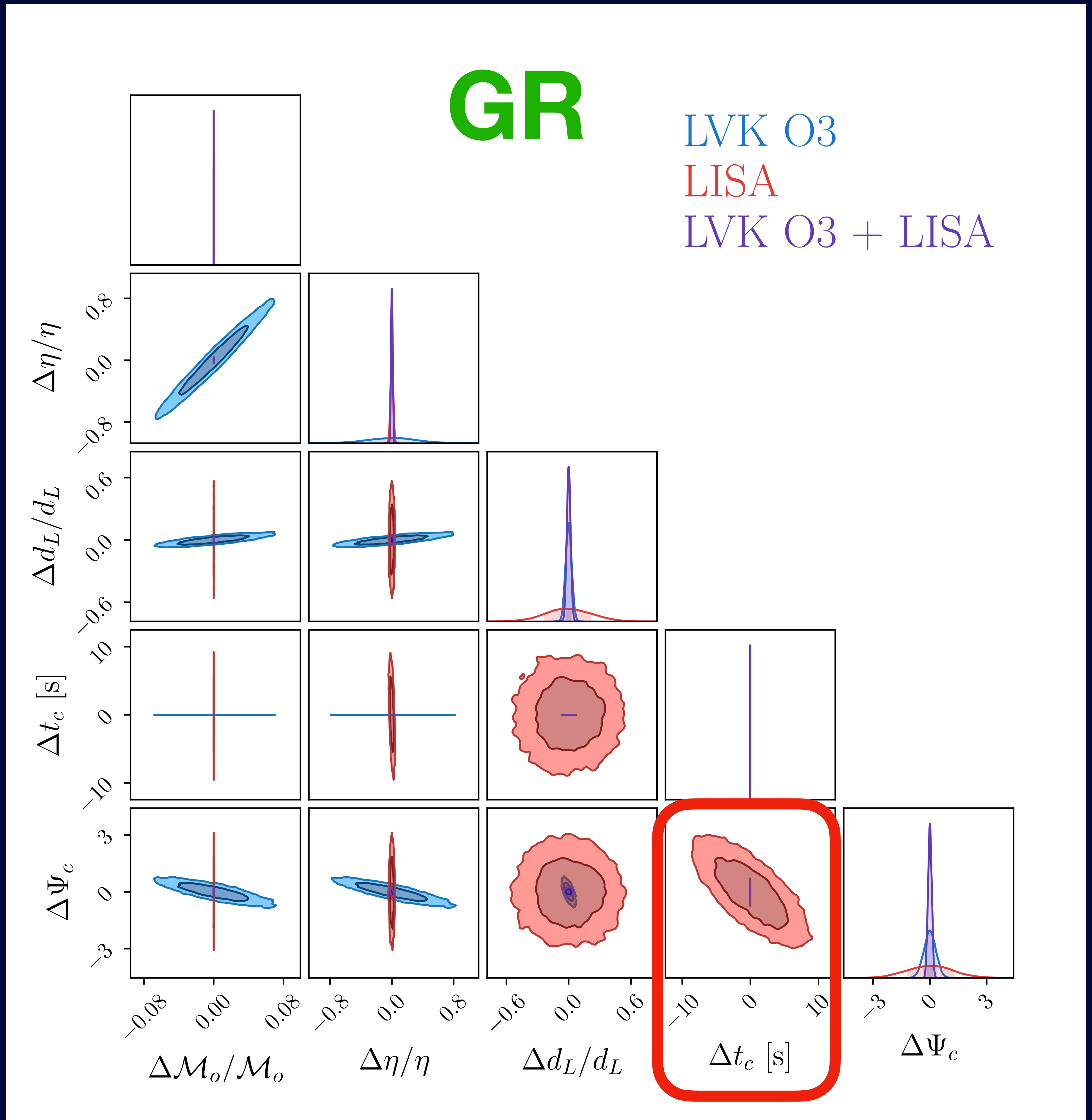
E.g. for GW150914, coalescence time is shifted by ~ 2 minutes.

(TB, Barausse, Chen, de Rham, Pieroni, Tasinato, 2022.)

Multiband Results



LISA forecasts coalescence time to accuracy ~10s

LVK measures it to accuracy ~ ms

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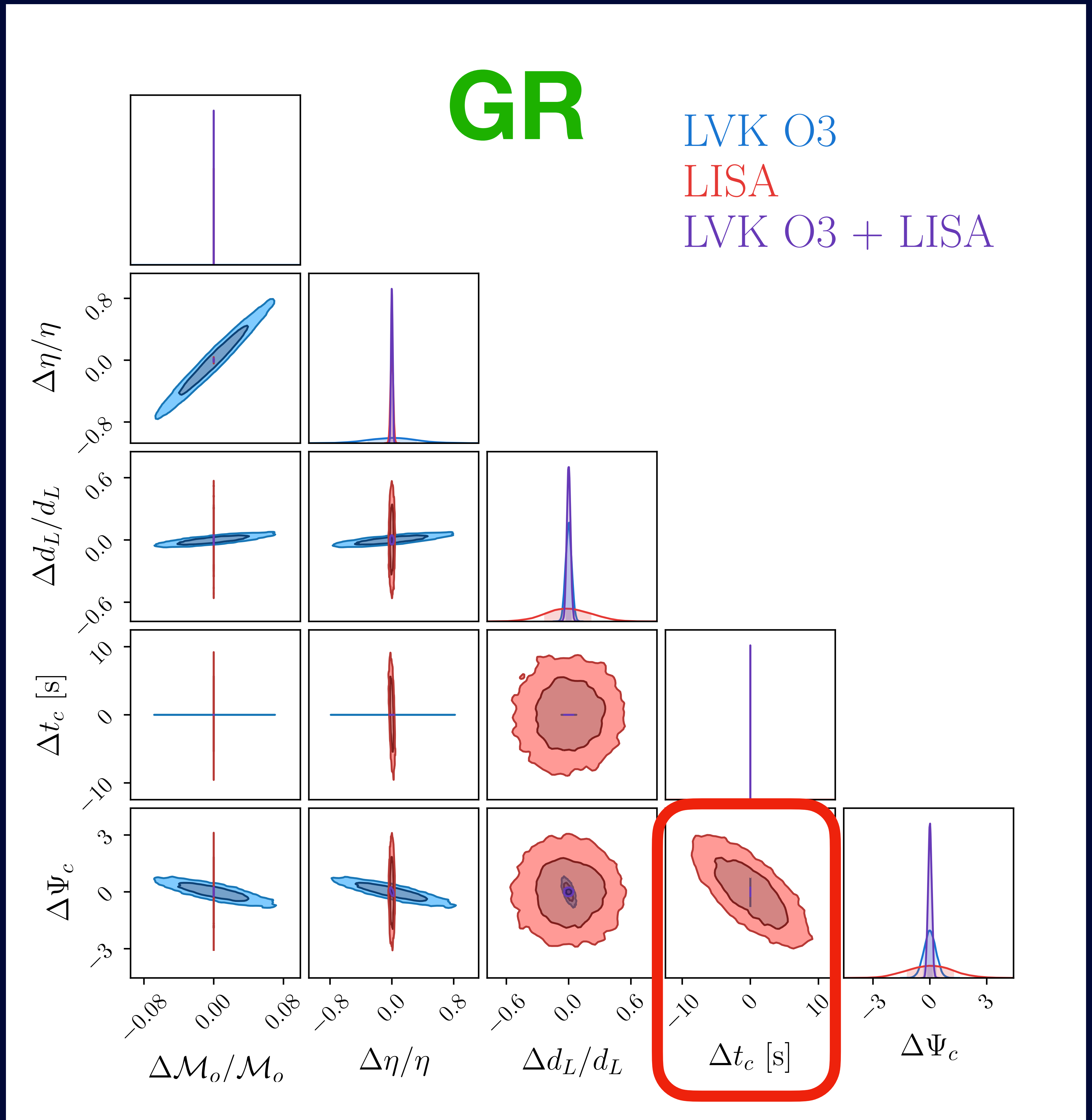

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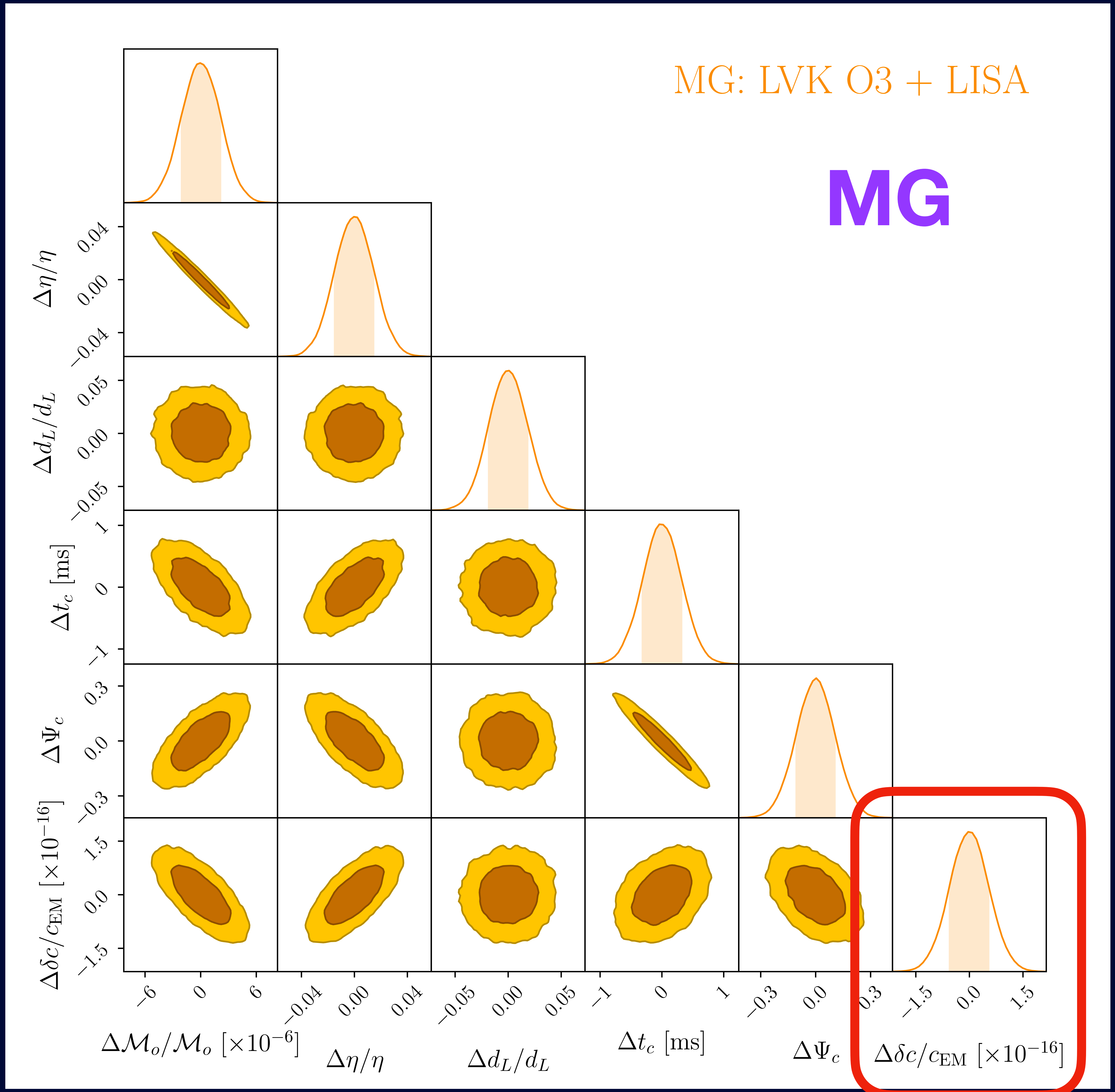
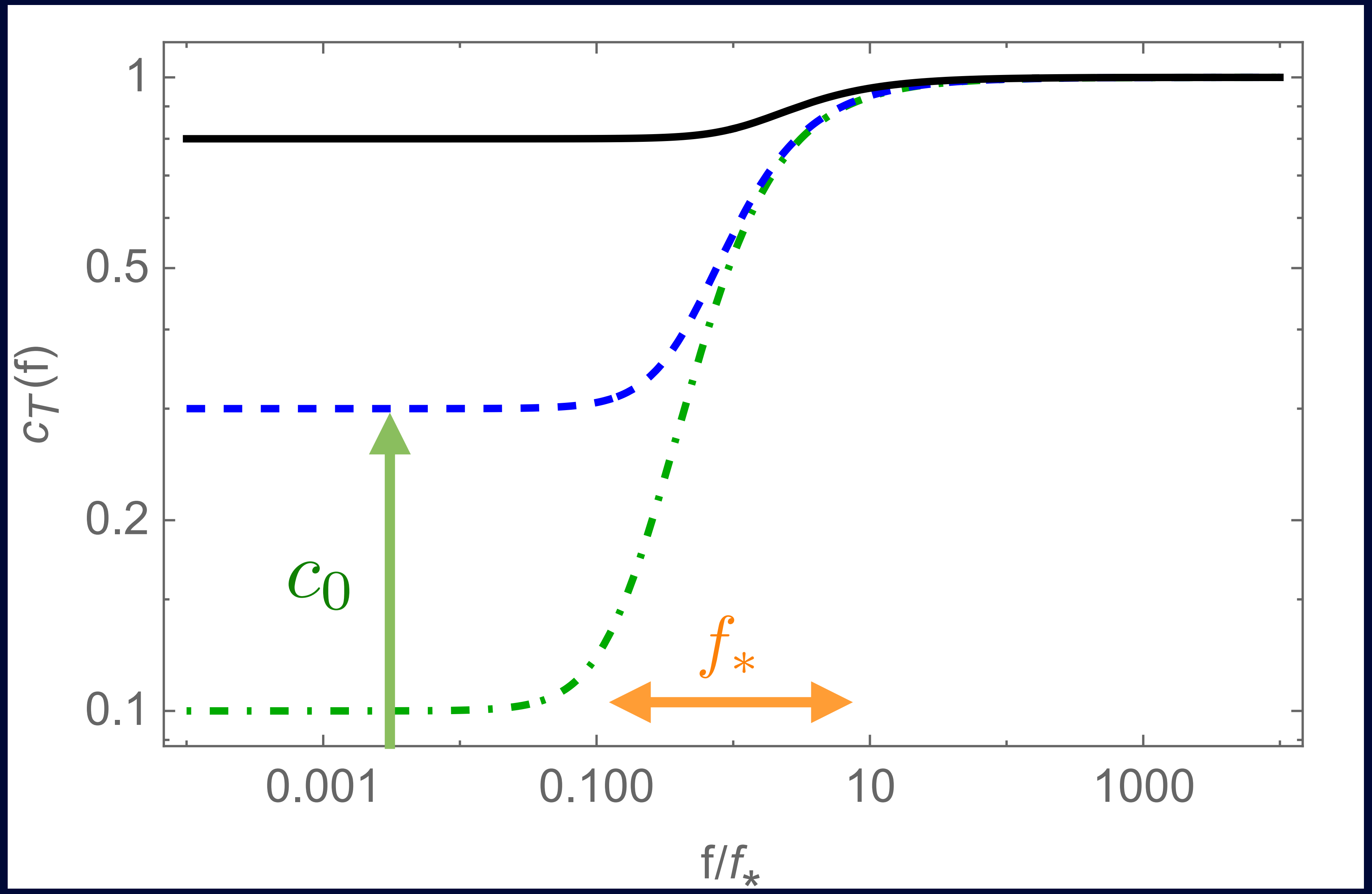


Hence multiband observations constraint cT *very* tightly.

Waveform-only constraints

Both amplitude and phase of waveform modified: $\tilde{h}^{\rm MG}(f_o) = A^{\rm MG}(f_o)\,\exp\left[i\Psi^{\rm MG}(f_o)\right]$



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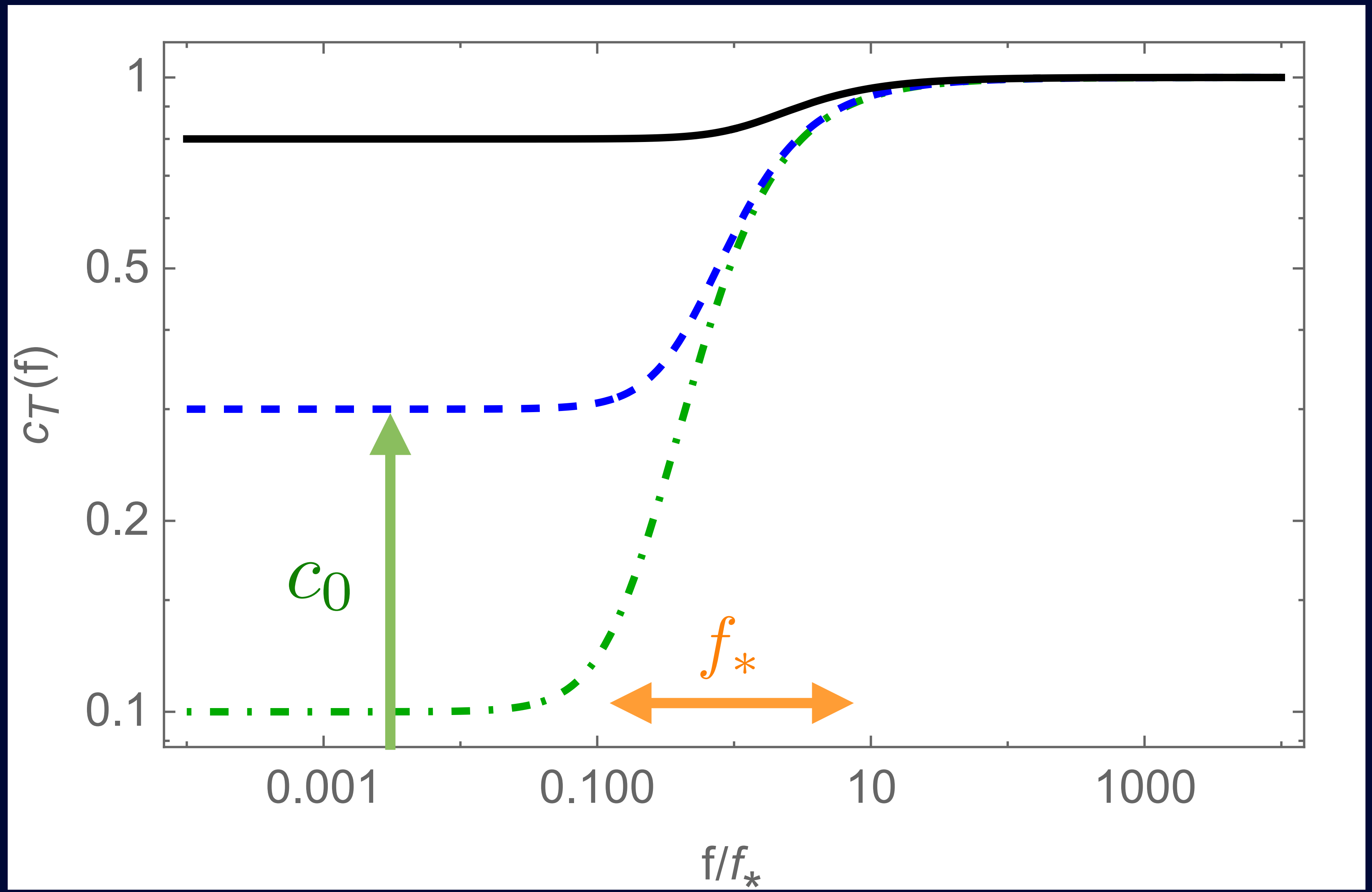

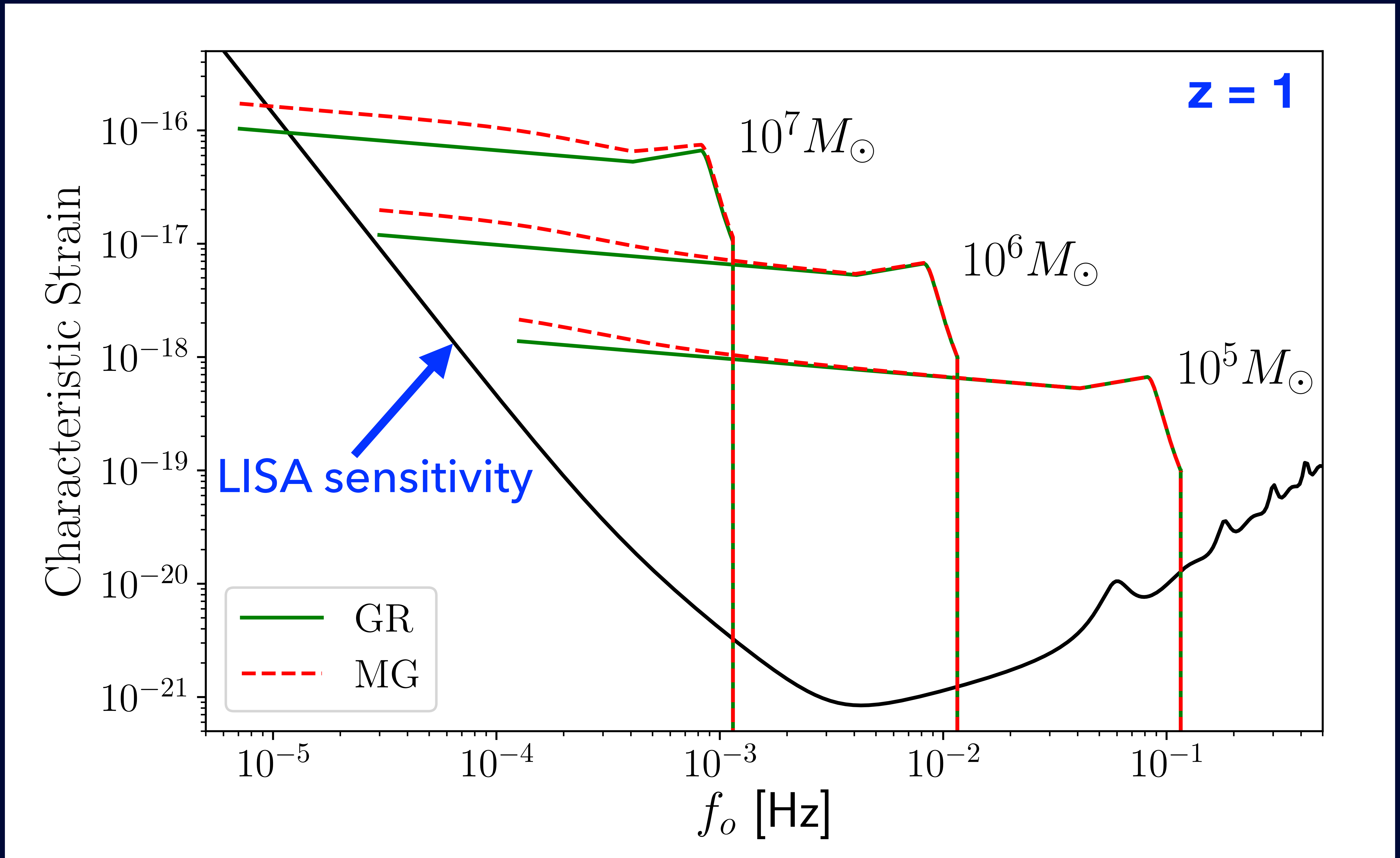

(TB, Calcagni, Chen, Fastello, Lombriser, Pieroni,Tasinato, Saltas for the LISA CosWG, 2022.)

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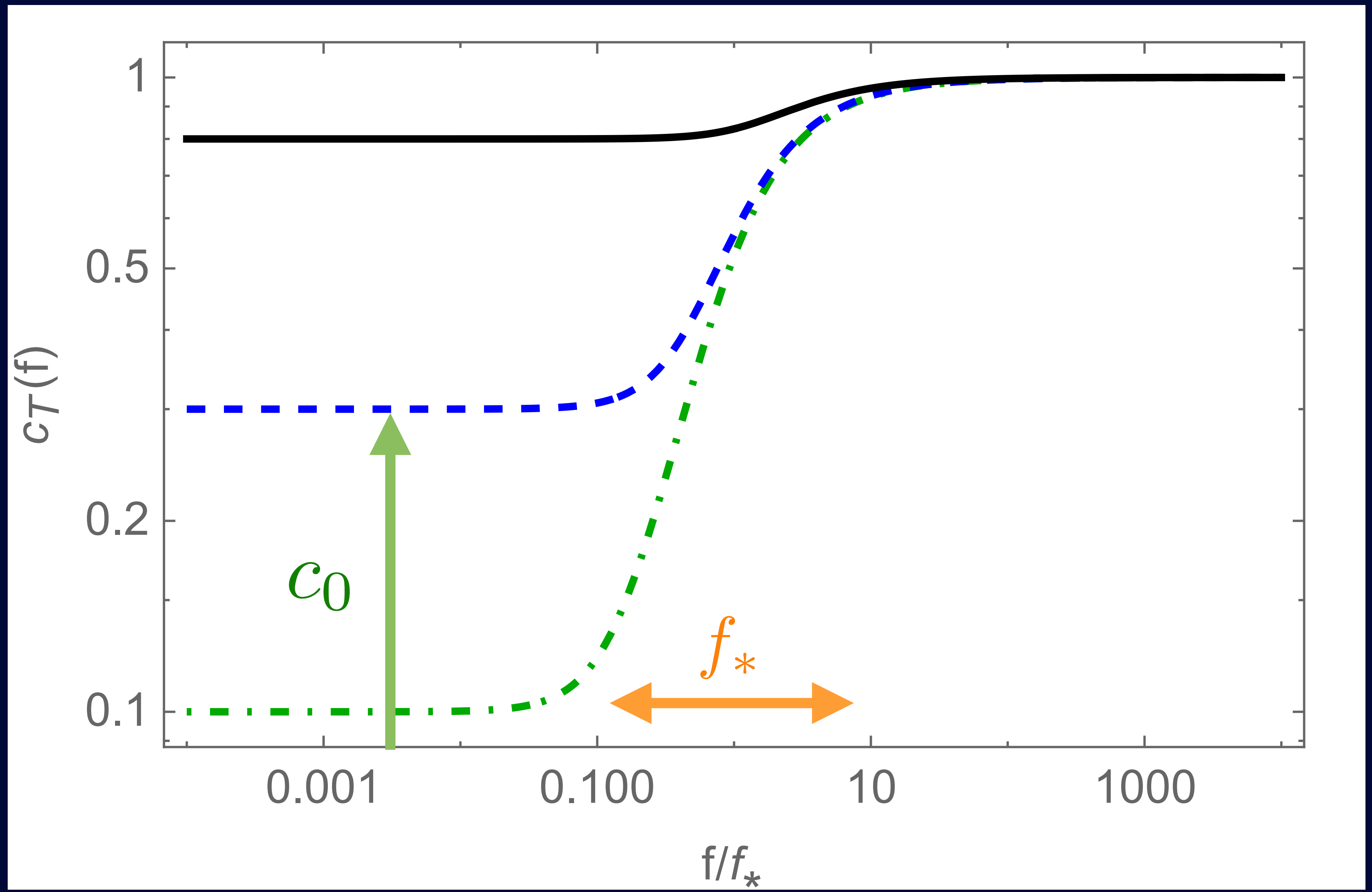

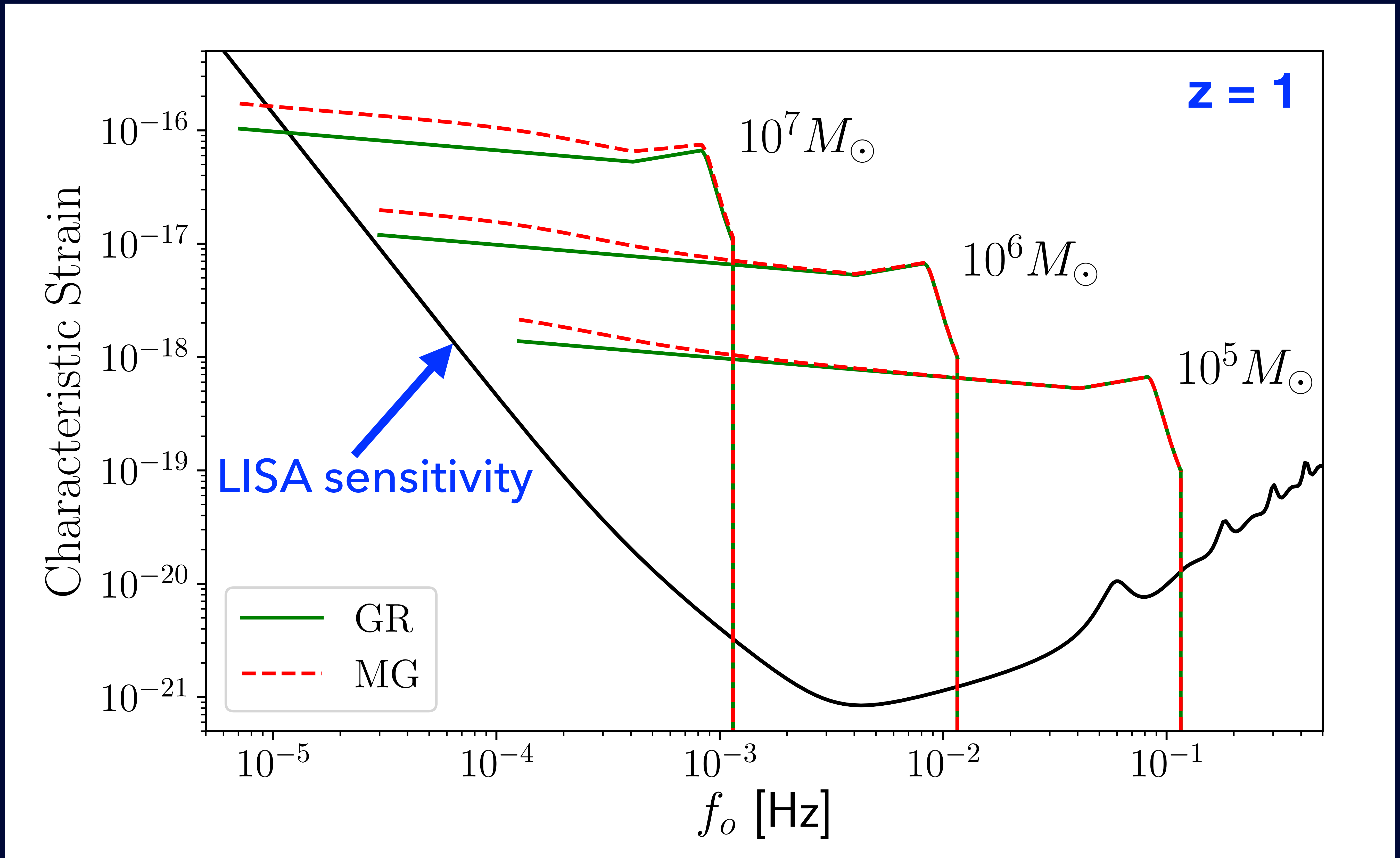

In this case, $\delta c_T/c$ is constrained to ~ 10^{-4}.

(Compare to 10^{-15} for multiband case.)

But these sources are guaranteed.

(TB, Calcagni, Chen, Fastello, Lombriser, Pieroni, Tasinato, Saltas for the LISA CosWG, 2022.)

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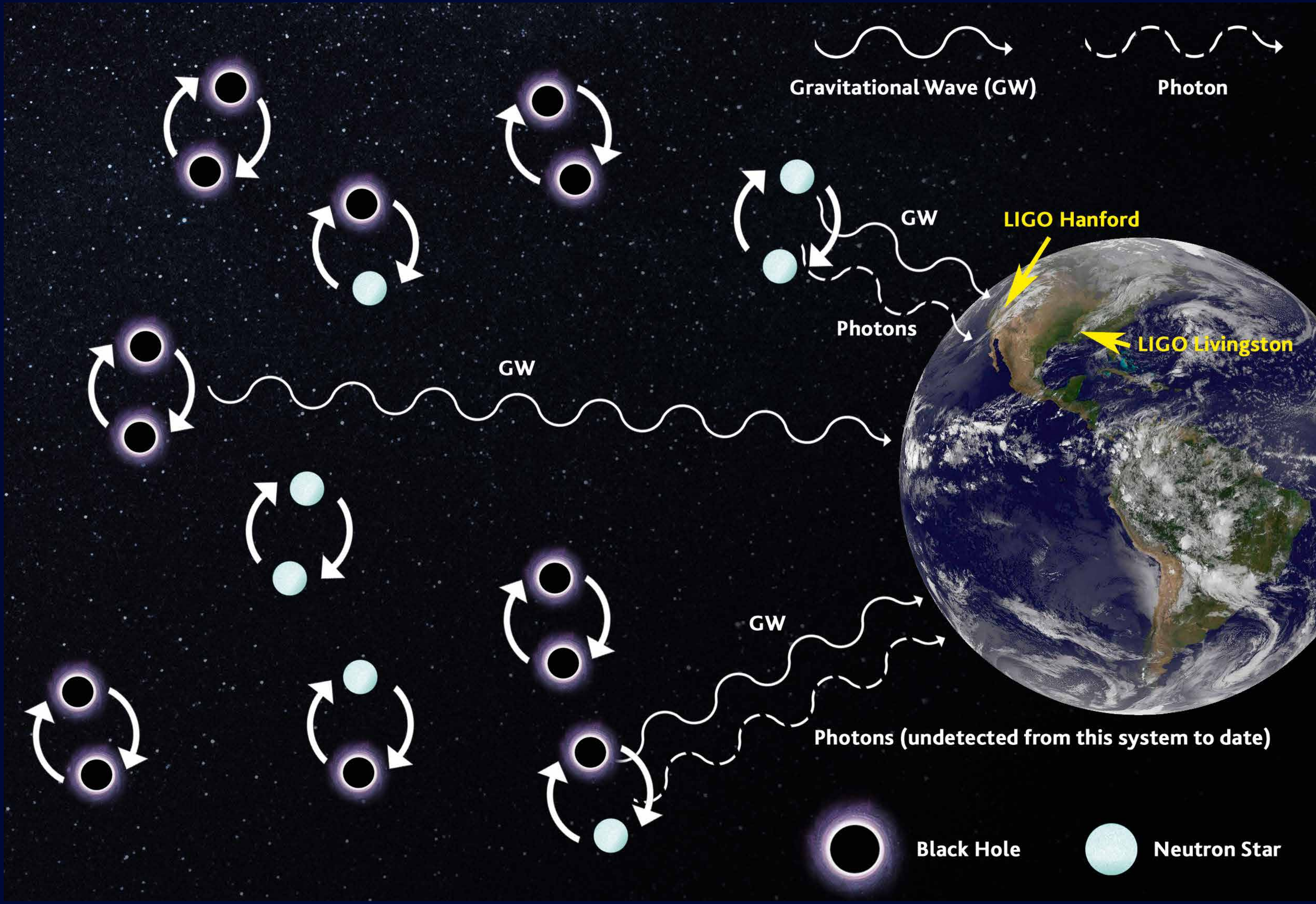
- Multiband sources: how many are likely? How many would we need to have a confident detection/bound?
- Inverse chirps: do we need to build an analyses which can find these?
- Real data analysis: so far, individually extracted events only. How does LISA's global fit impact these numbers?

GW Friction
with bright & dark sirens



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GW luminosity distances

Deviations from GR affect GW luminosity distances:

$$\tilde{h}_{+,\times}(f) \;\propto\; \frac{\mathcal{M}_z^2}{d_L}\,(\pi\,\mathcal{M}_z\,f)^{-\frac{7}{6}} \;\times\; \text{(polarisation angles)} \;\times\; \text{(inclination factor)}$$

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GW Luminosity distance $\quad \dfrac{d_{\rm GW}}{d_L} \neq 1$

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Belgacem et al. (2018)

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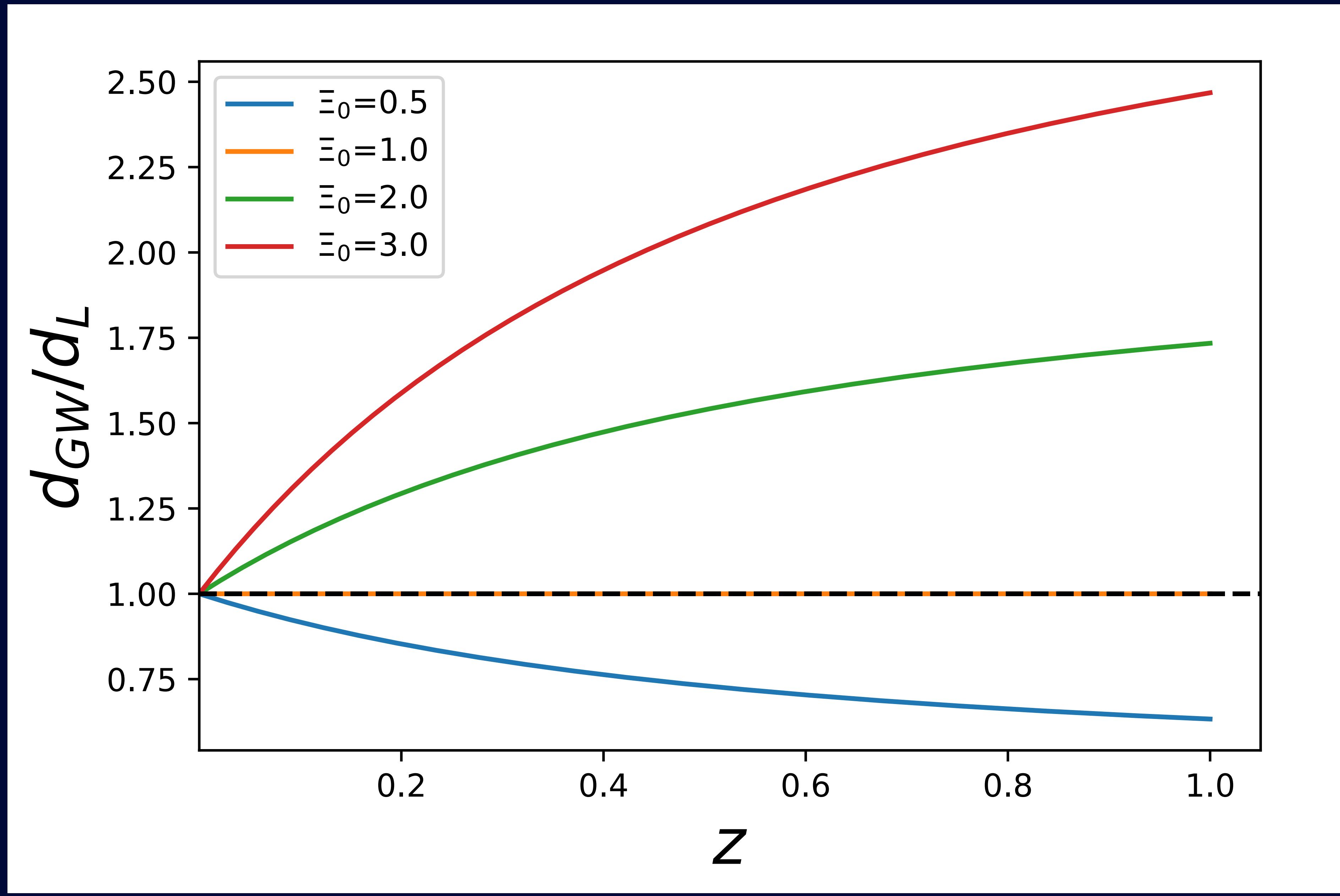

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- Is this an adequate parameterisation for LISA sources? Should we parameterise $\nu(z)$ or $\frac{d_{\rm GW}}{d_L}$?

Bright & dark sirens

$$\frac{d_{\rm GW}}{d_L} = \Xi_0 + \frac{(1-\Xi_0)}{(1+z)^n}$$

or

$$\frac{d_{\rm GW}}{d_L} = \exp\left[\int_0^z \frac{\nu(\tilde{z})}{1+\tilde{z}}\,d\tilde{z}\right]$$

To obtain d_L we need a redshift & a cosmological model (see Chiara's talk).

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Bright sirens

EM counterpart → single redshift

Strong constraints from one event

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Bright sirens

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Strong constraints from one event

Dark sirens (incl. spectral sirens)

No EM counterpart

Galaxy catalogue → many possible redshifts

Need to stack events & lines of sight

Friction constraints from GW170817

This would constrain GW friction, *but* it needs to be at a 'reasonable' distance to be useful.

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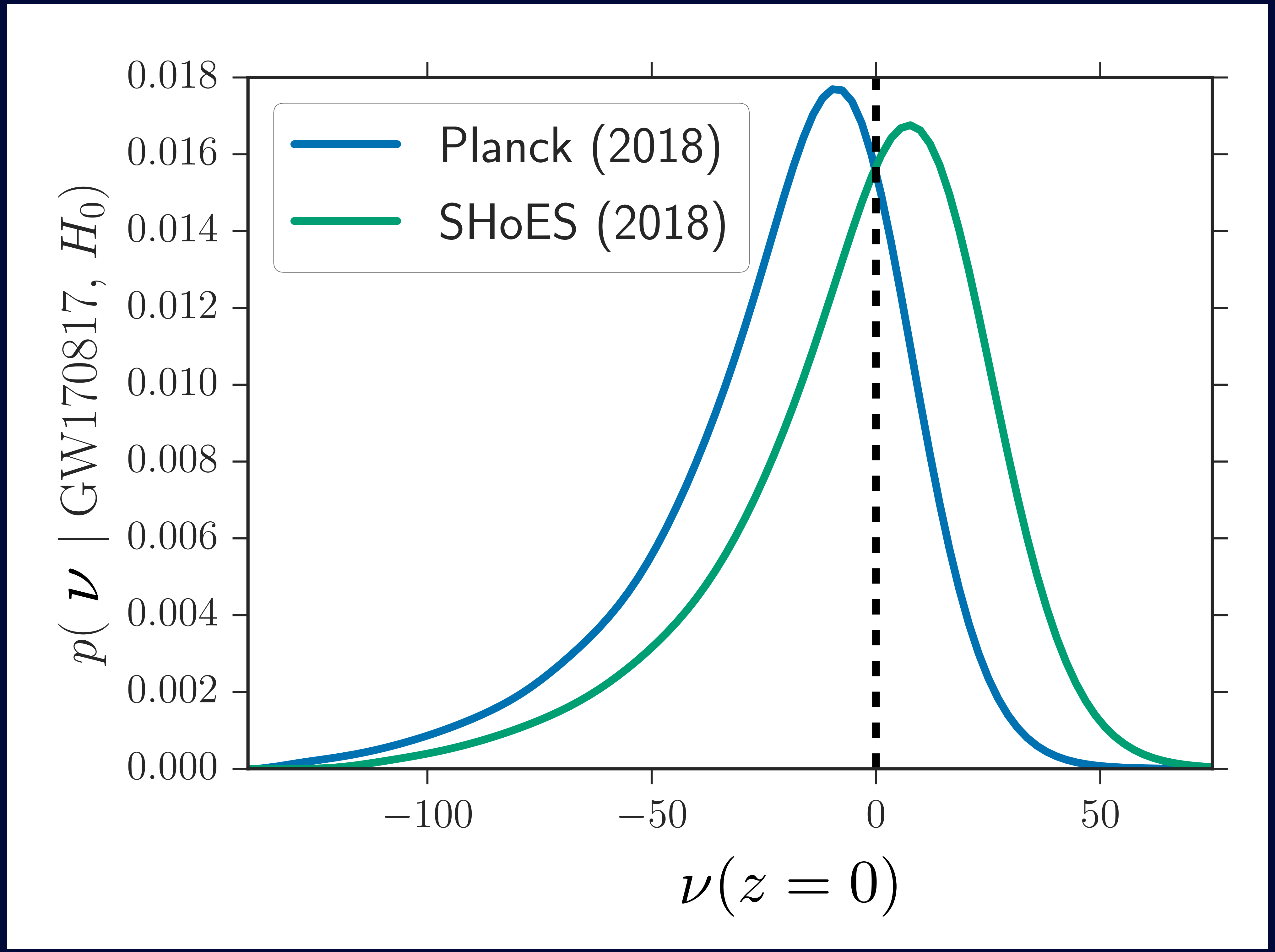
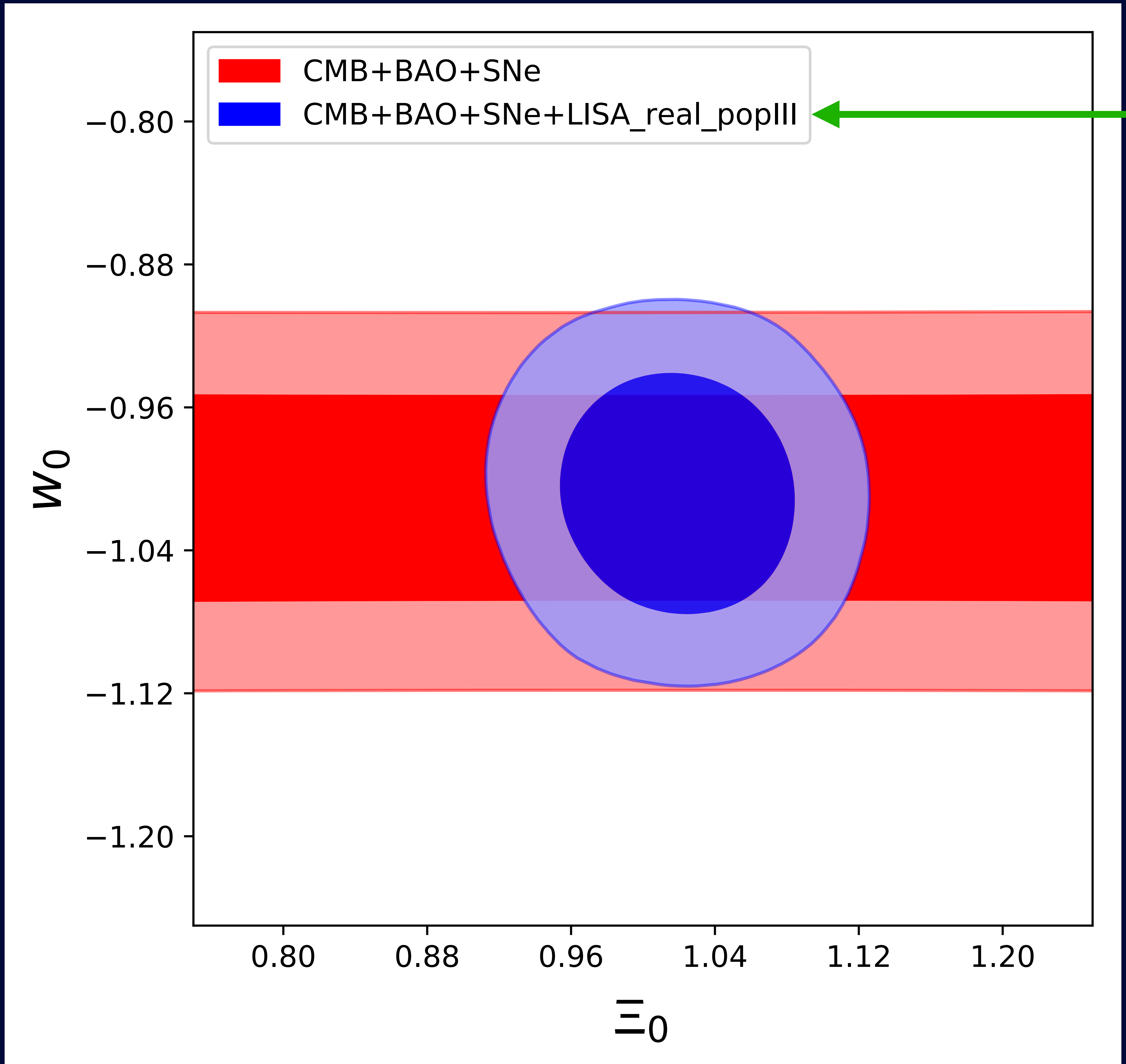
Lagos et al. (2018)



weak constraints only (GW170817 nearby)

Friction forecast for LISA sources + counterparts

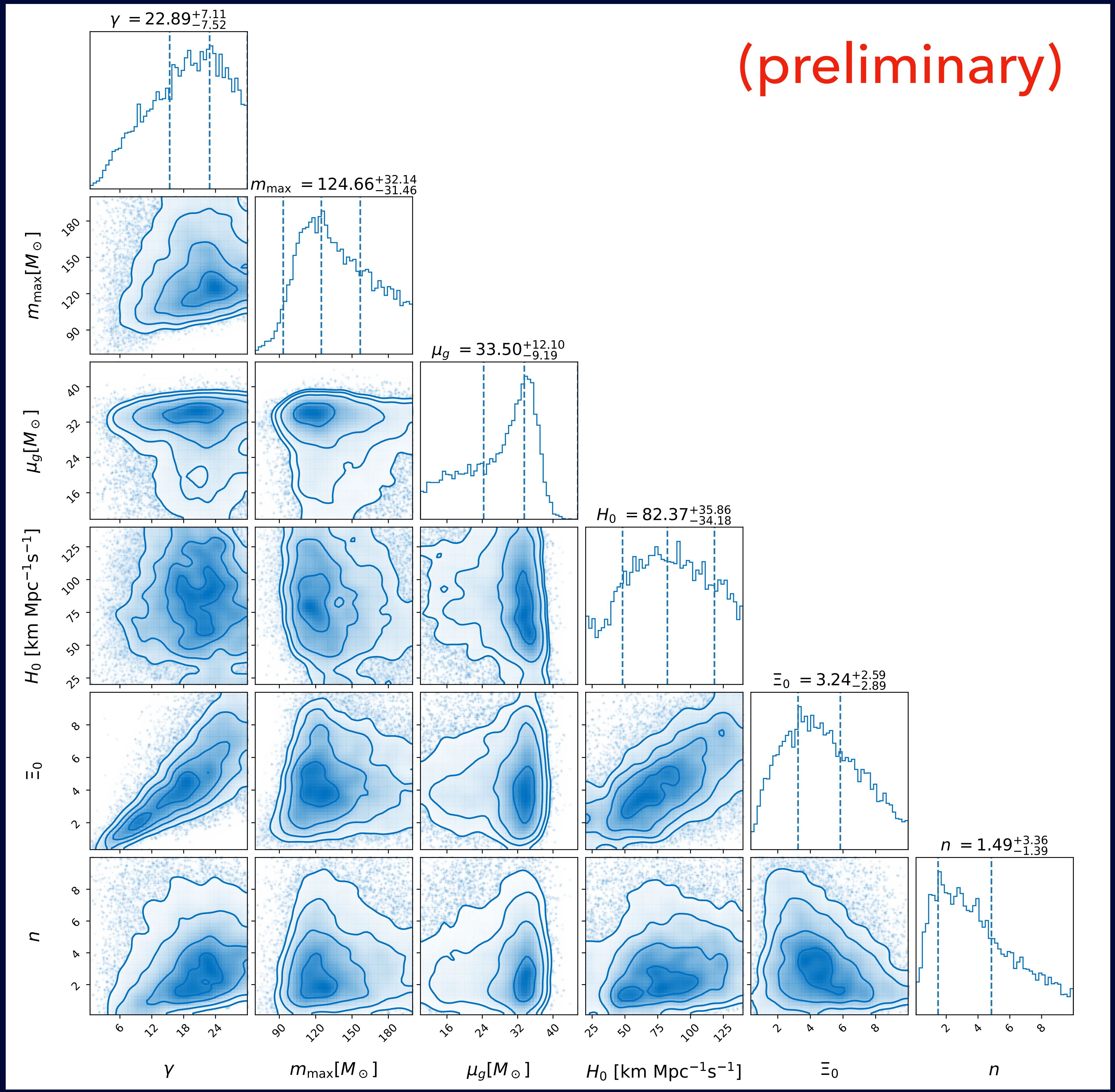


Some dependence on population model.

Belgacem et al., LISA CosWG (2019).

Dark Sirens: GWTC-3 BBHs

Figure: A Chen



Parameters describing black hole mass distribution

We use the code **gwcosmo** (Gray et al.), extended for MG by Anson Chen.

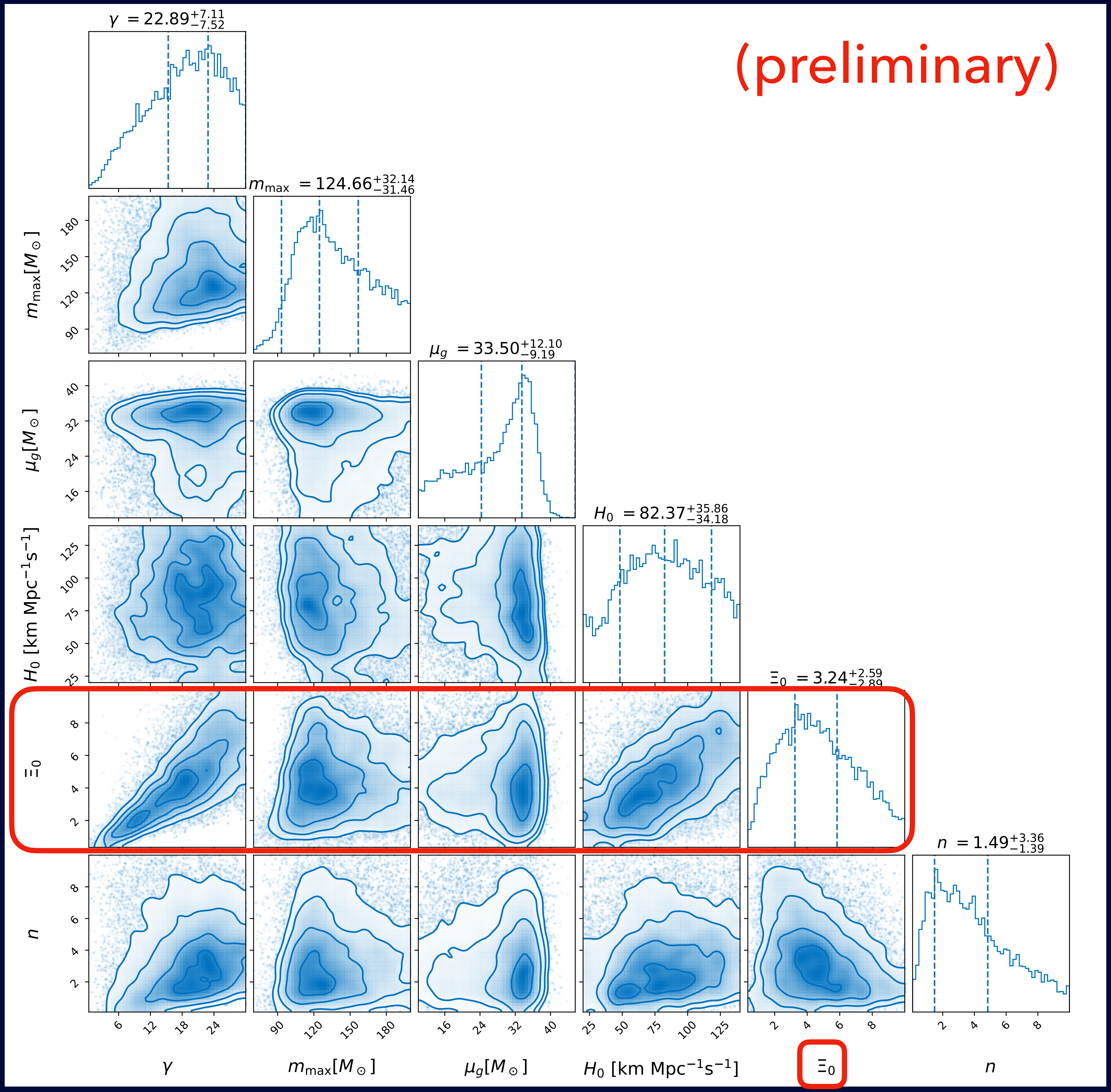
See also LISA dark sirens forecast by Laghi et al. (2021)

Chen, Gray & TB (in prep)

Dark Sirens: GWTC-3 BBHs

Figure: A Chen

Parameters describing black hole mass distribution



Chen, Gray & TB (in prep)

We use the code **gwcosmo** (Gray et al.), extended for MG by Anson Chen.

See also LISA dark sirens forecast by Laghi et al. (2021)

GW Friction Questions

- Bright vs dark sirens: which is most useful for LISA binaries?
  Depends on: rarity of LISA EM counterparts vs catalogues completeness at high redshift.

- Are there exploitable features in the SMBH mass distribution?

Bonus Question

- What MG phenomenology can we probe with polarisation data?

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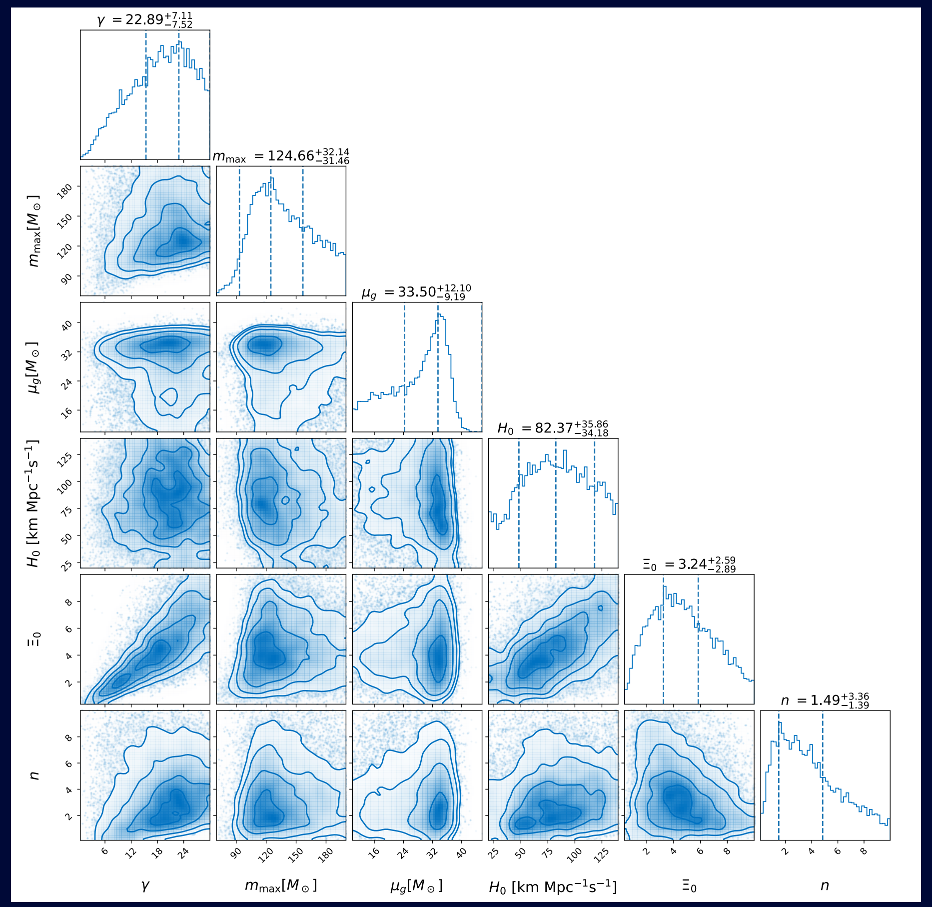
Conclusions

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

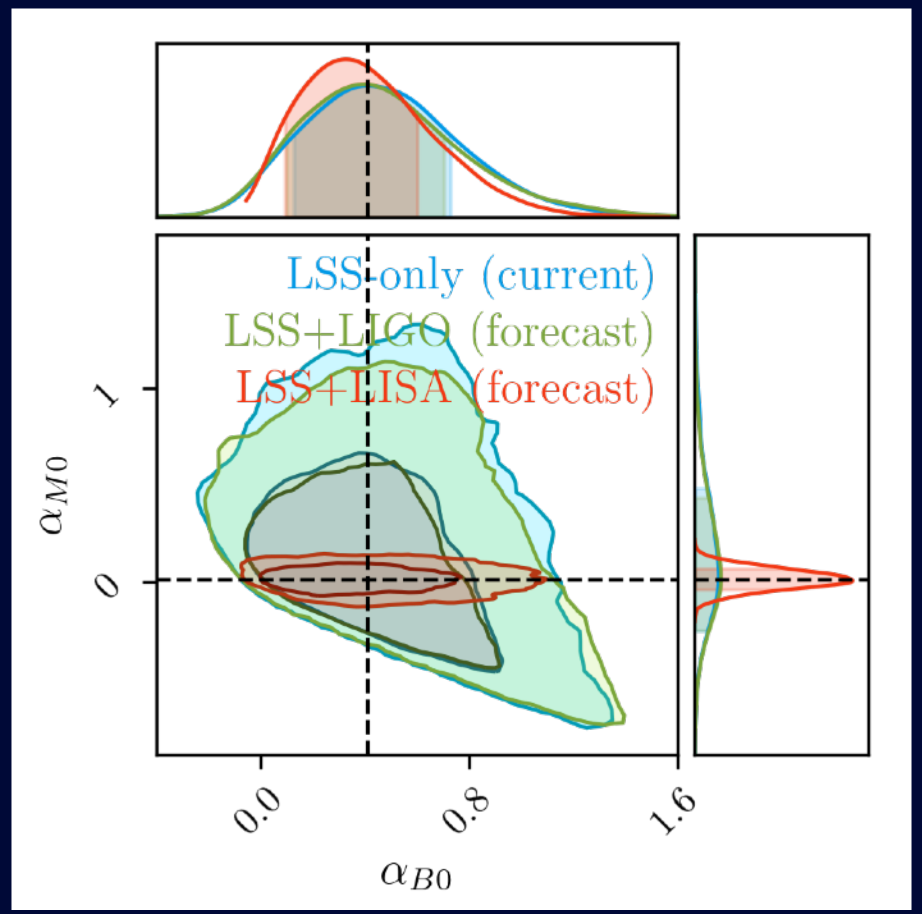
Modified friction

Modified propagation speed

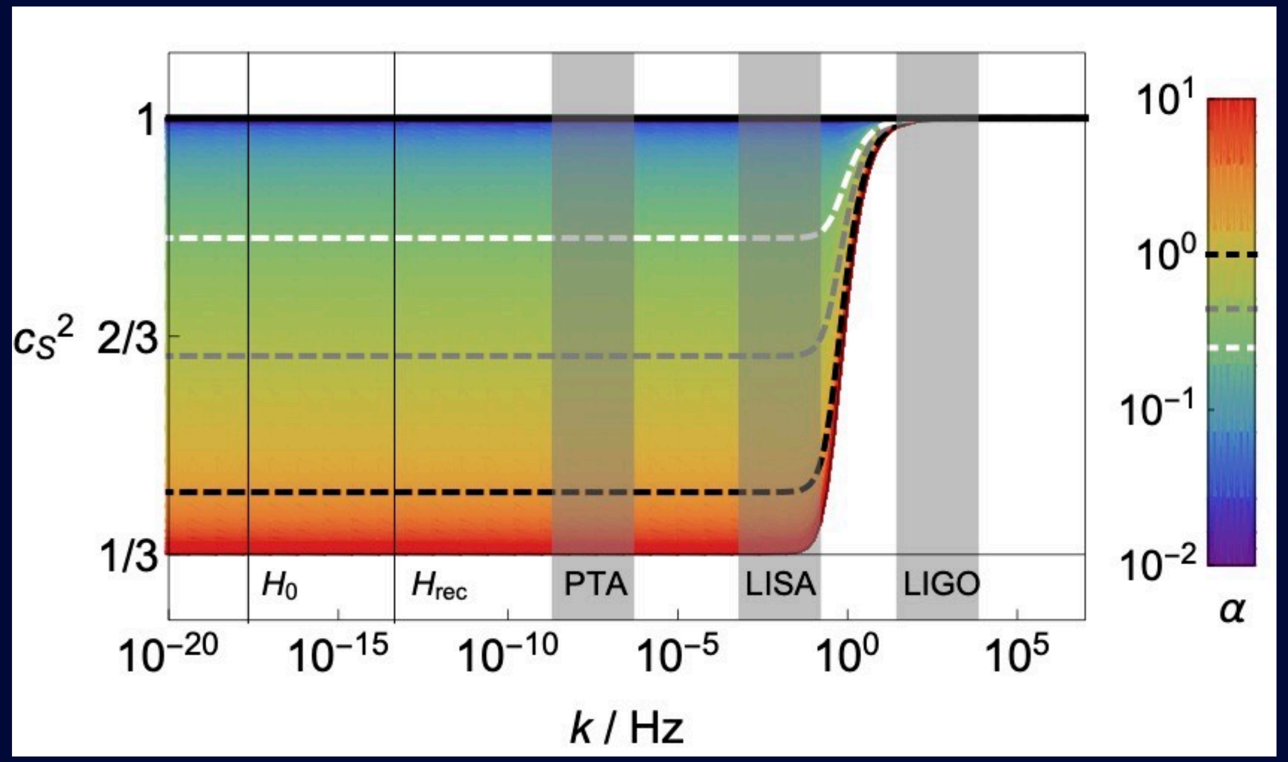
Dark Sirens



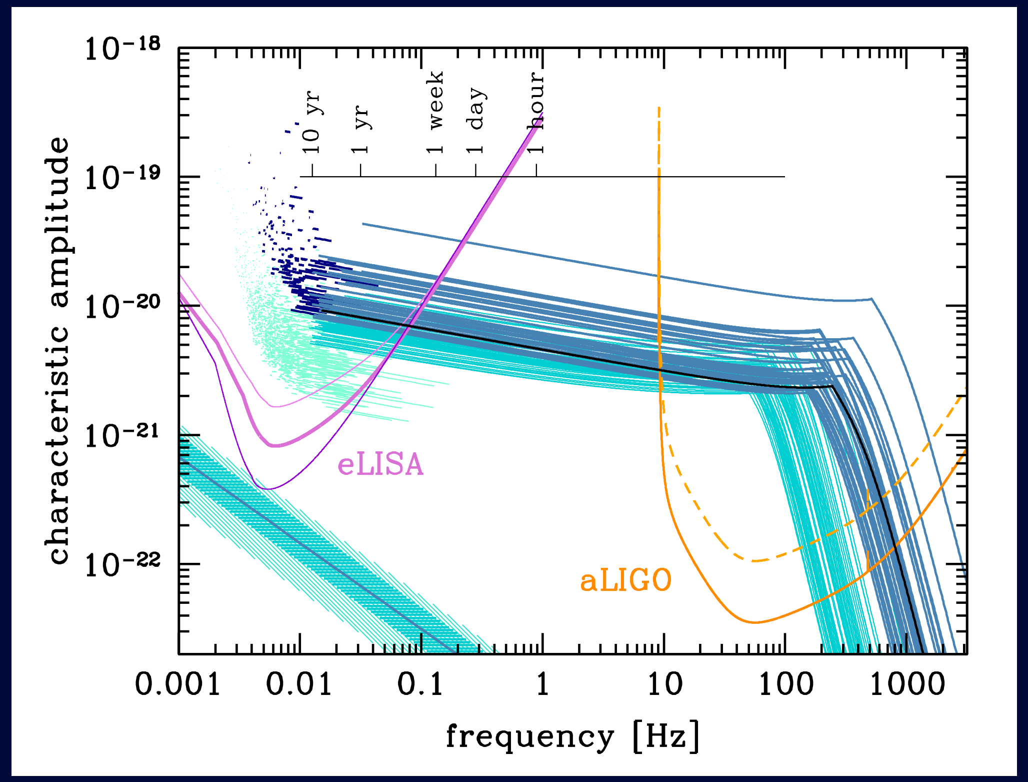
Bright Sirens



Running GW speed & dispersion

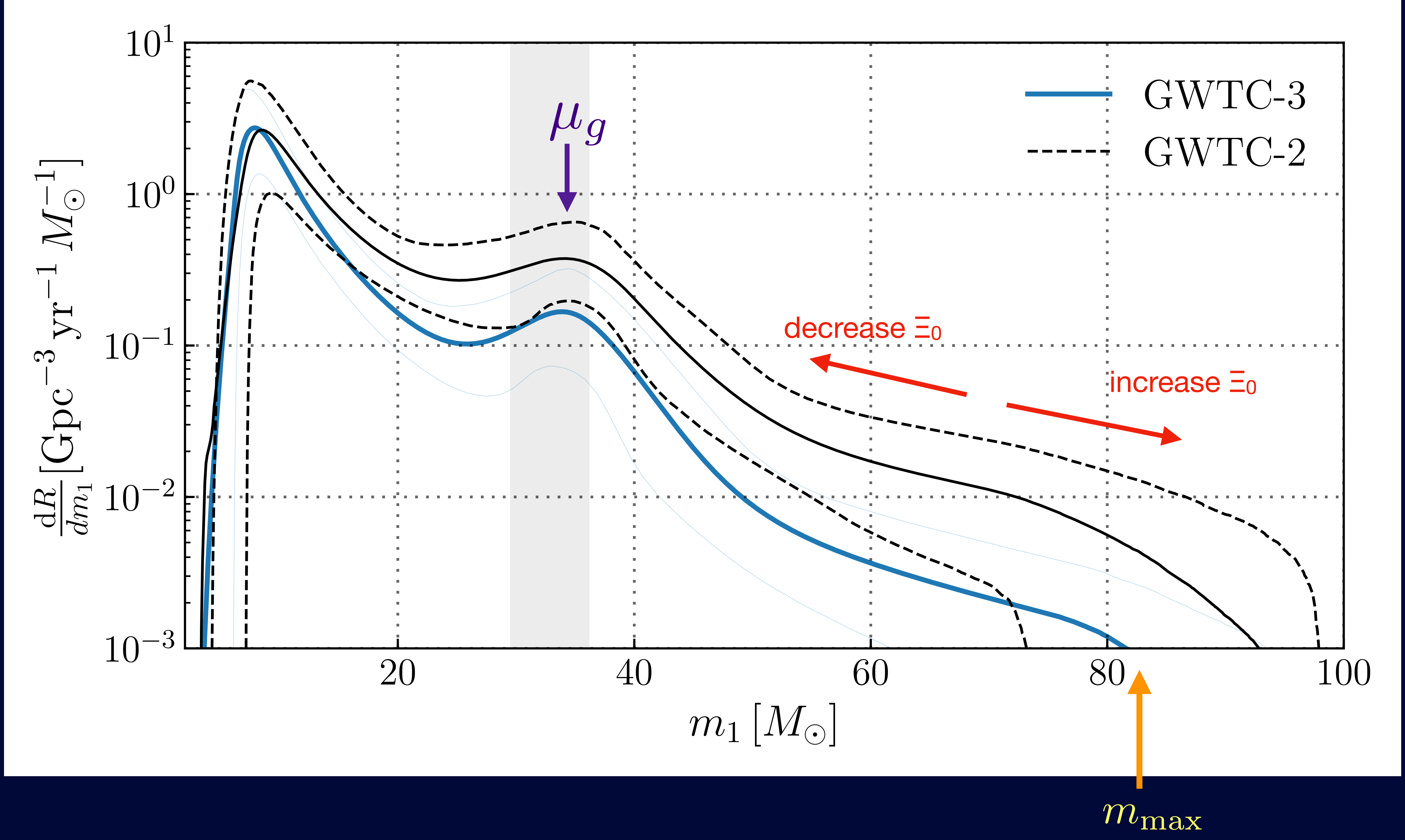


Effects on merger time & waveform



BBH mass distribution

Abbott et al. 2022



Modified dispersion relations

Parameterised GW dispersion relation: $E^2 = p^2c^2 + A_\alpha\, p^\alpha c^\alpha$

$\alpha = 0 \quad \Rightarrow$ Graviton mass term

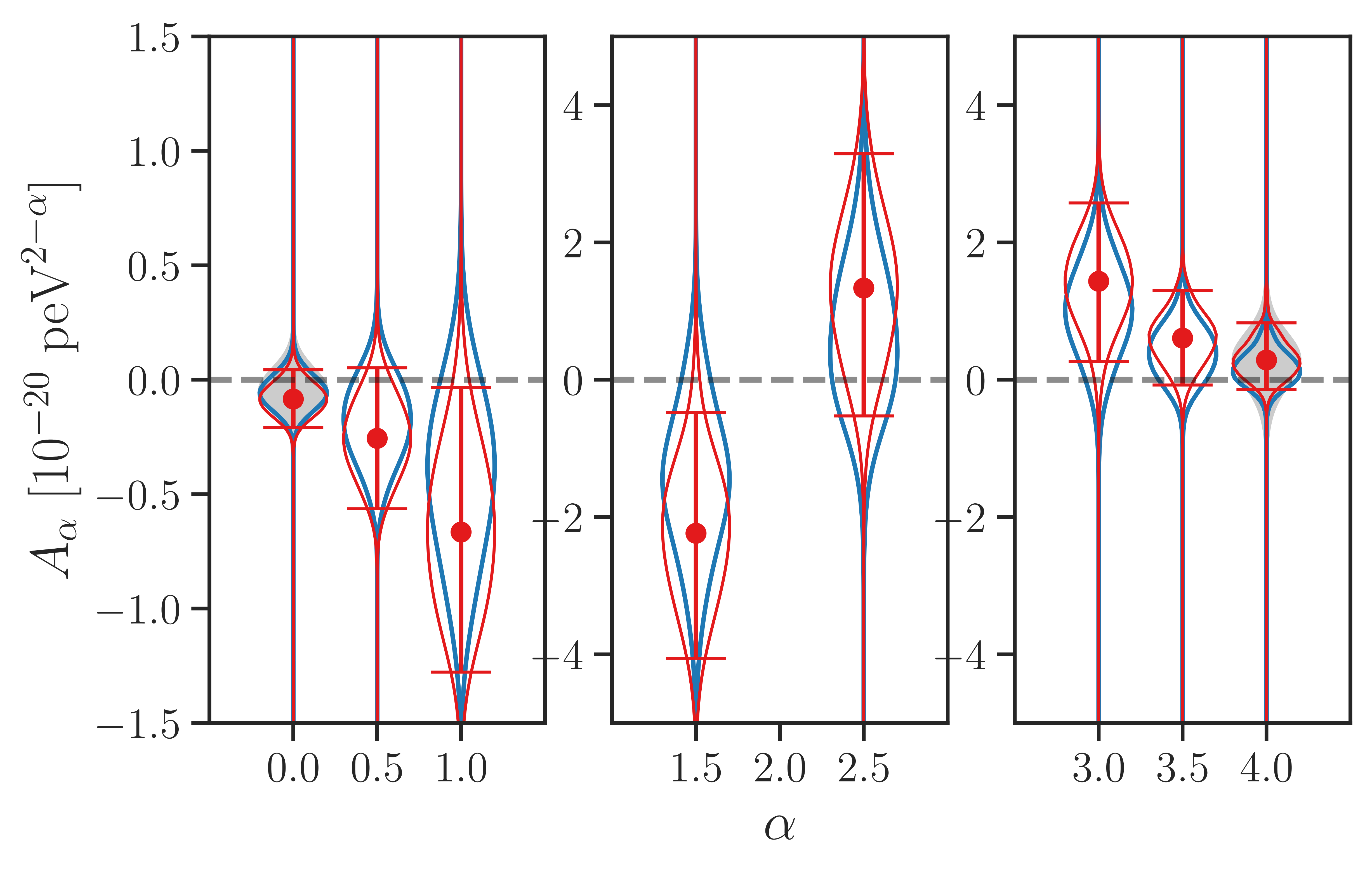
$\alpha = 2 \quad \Rightarrow$ Frequency-independent change to speed

LIGO constraints:

Red = GWTC-3

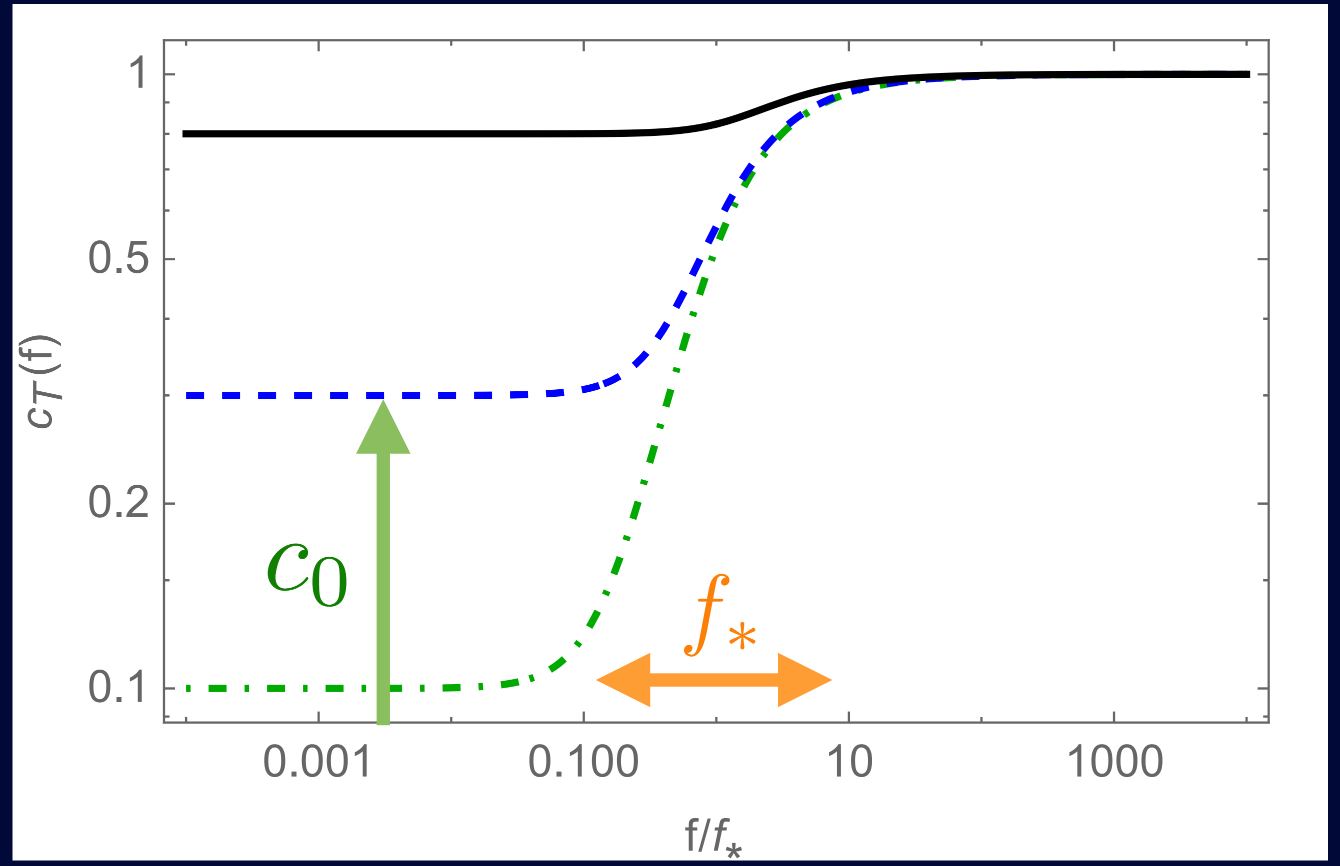
Blue = minus two events with subtleties

Grey = GWTC-2 (O1+O2+O3a)

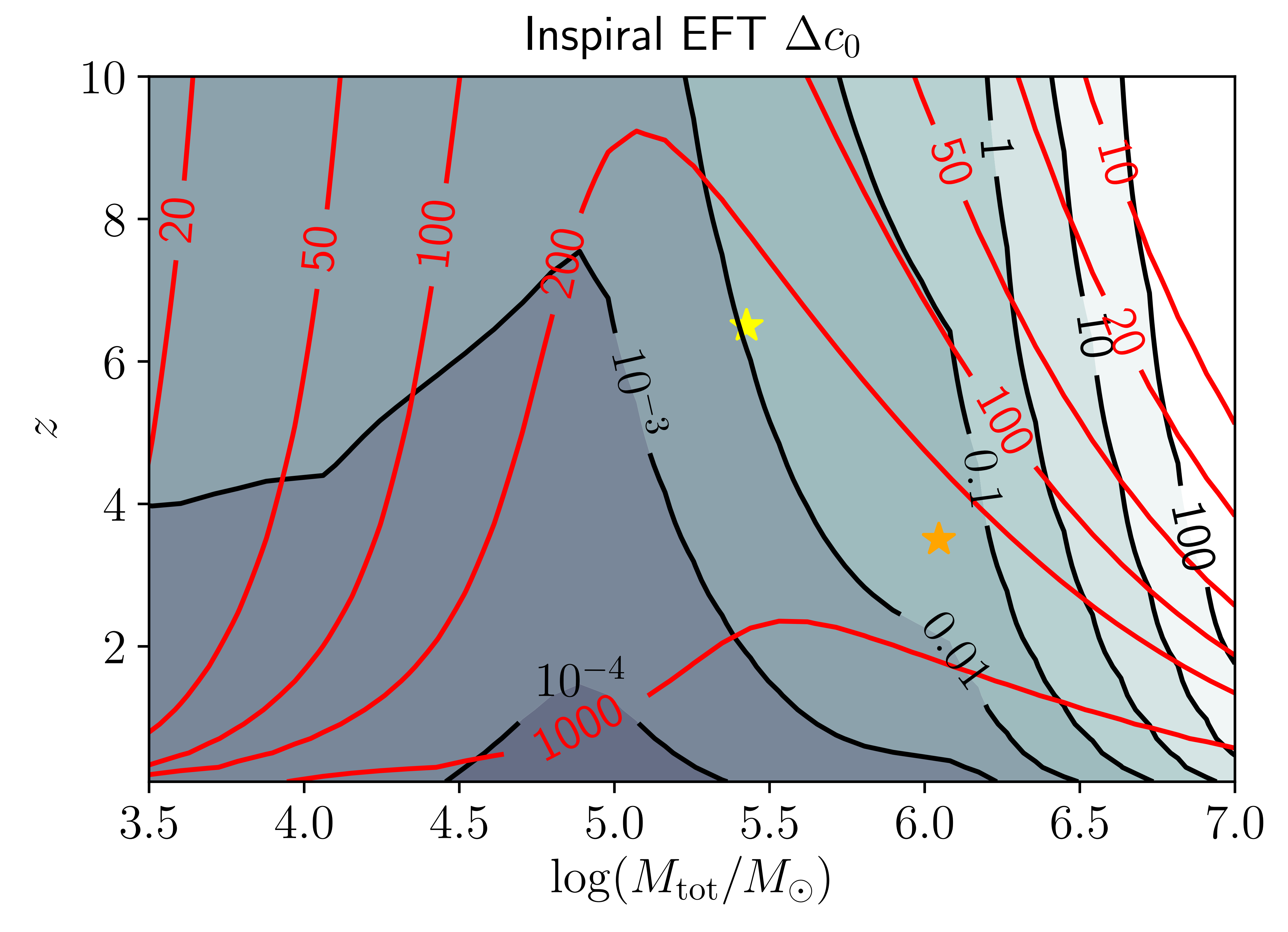


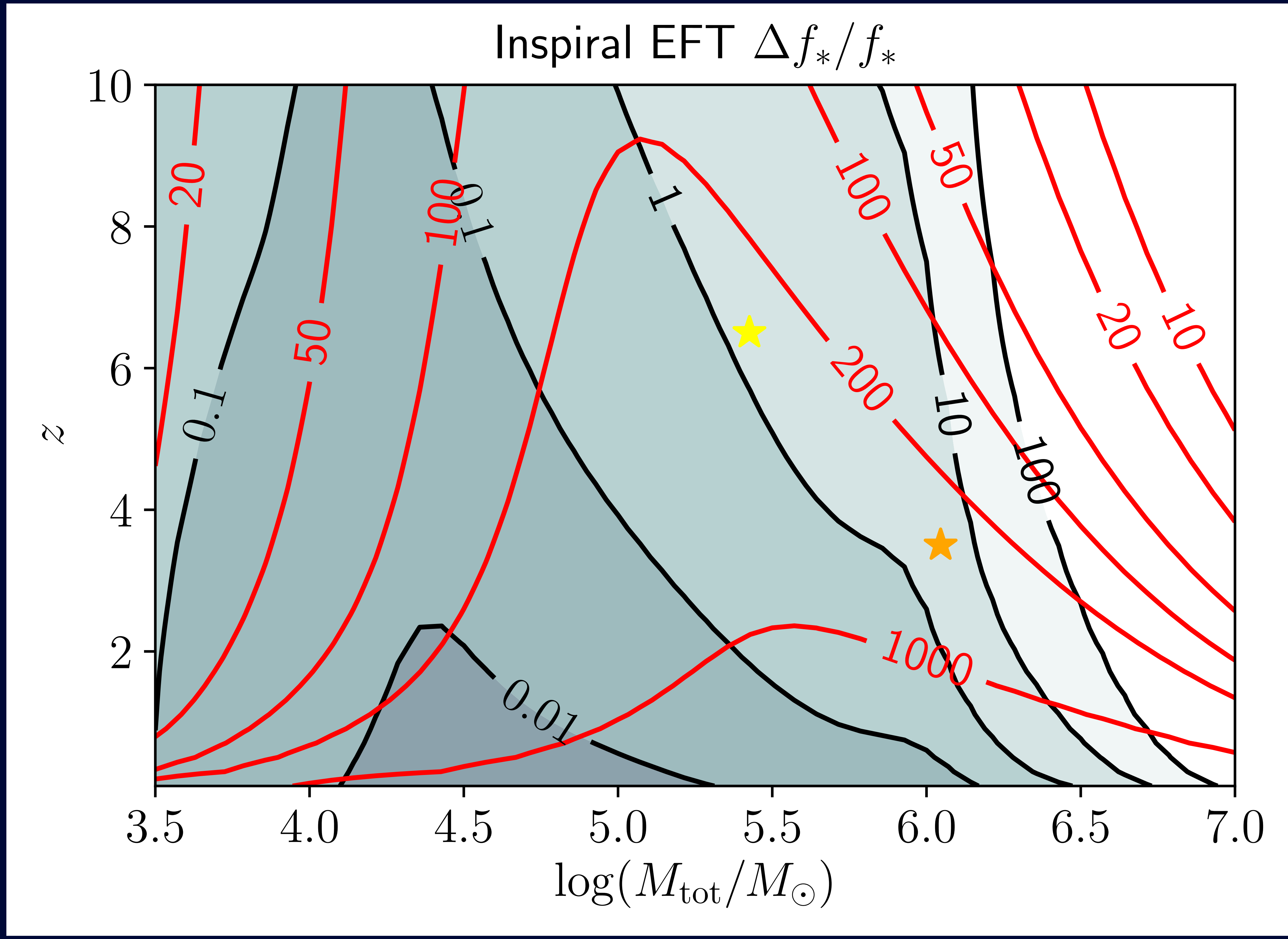
Waveform-only constraints

Reminder:

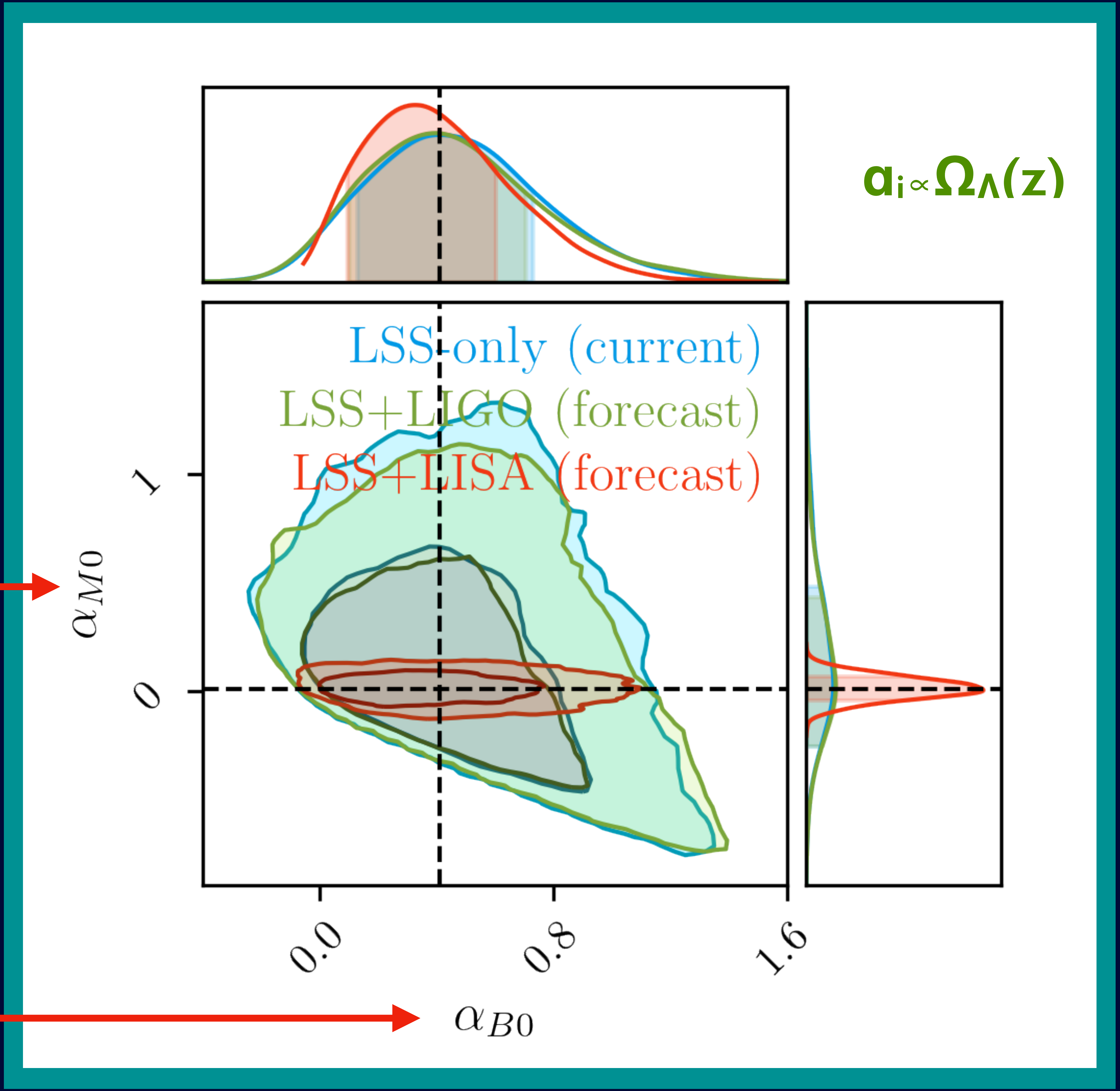


Red contours → SNR





Friction forecast for LISA sources



Equivalent to ν_0

Another MG parameter impacting LSS (no effect on GWs)

TB & Harrison (2020)