Probing the speed of gravity with LVK, LISA, and joint observations

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What is the speed of gravity?

- We know it must be close to c. Use the variable:

$$\delta c_{\mathrm{GW}} \equiv \frac{c_{\mathrm{GW}} - c}{c}$$

What is the speed of gravity?

- The tightest bound on the speed of gravity came from GW170817.
- EM signal and GW signal arrived within seconds of each other from 40Mpc away. Even if we assume that there was a small delay in the emission time we place a very strong bound:

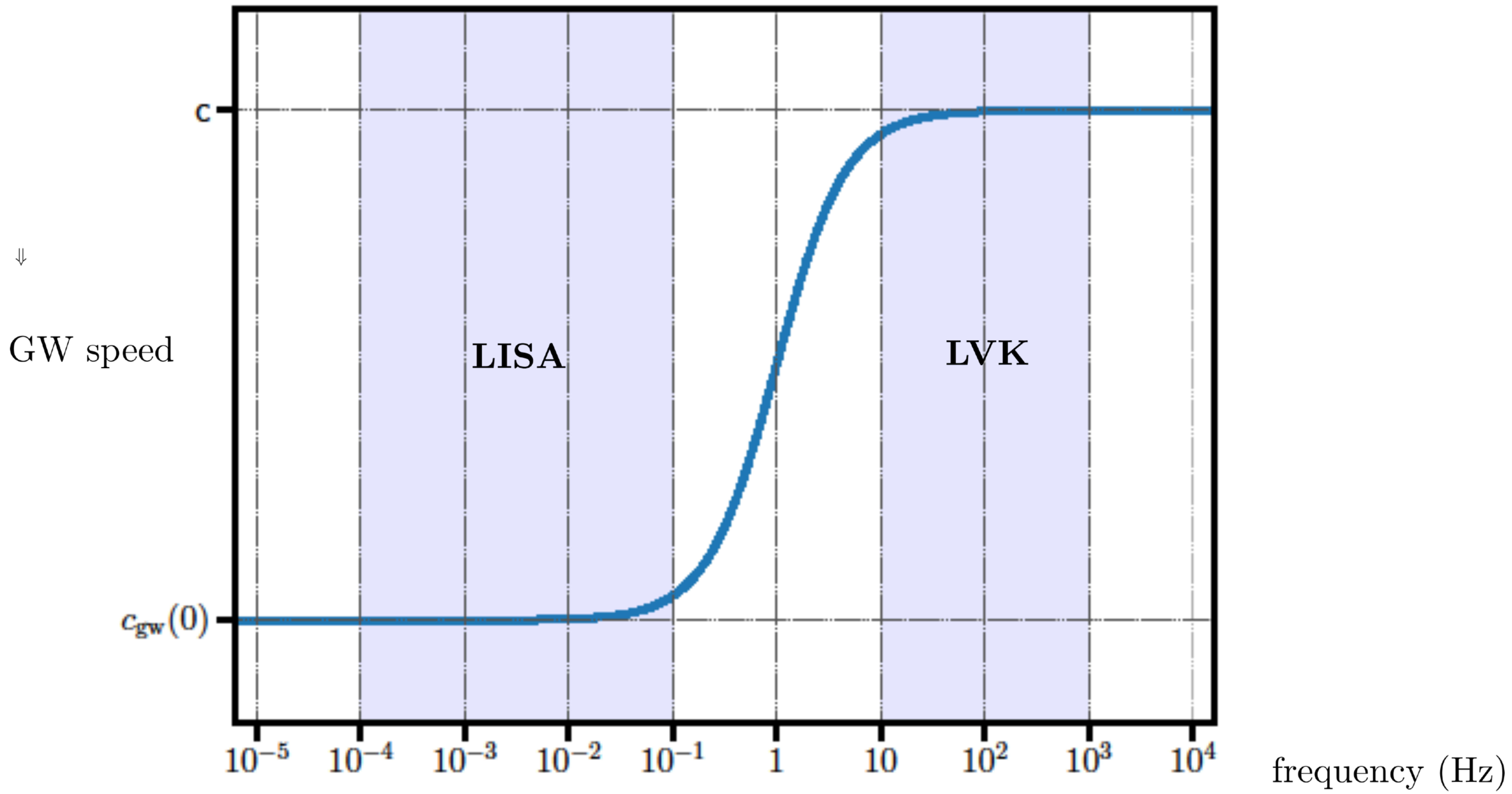
$$|\delta c_{\mathrm{GW}}| \lesssim 10^{-15}$$

LIGO & Virgo Collaborations '17, Fermi, IGAL '17

What is the speed of gravity?

- The GW170817 observation placed strong constraints on many theories of gravity.
- However (as a cynical data scientist) it seems that the more theories we constrain the more theories seem to pop up!
- In particular, LVK constraints only cover gravitational waves around 10 - 1000Hz. There are other constraints at other frequencies, but they are considerably weaker.
- What if the speed of gravity is frequency dependent?
- Johannes says I shouldn’t be cynical here. There is a good theoretical motivation for a speed of gravity that diverges from c at low frequencies, but asymptotes back to c before the LVK window.

A frequency-dependent speed of gravity



Dark energy theory with $c_{gw}(0) \neq c$

Frequency-dependent c_{gw} transition close to LVK/LISA band(s)

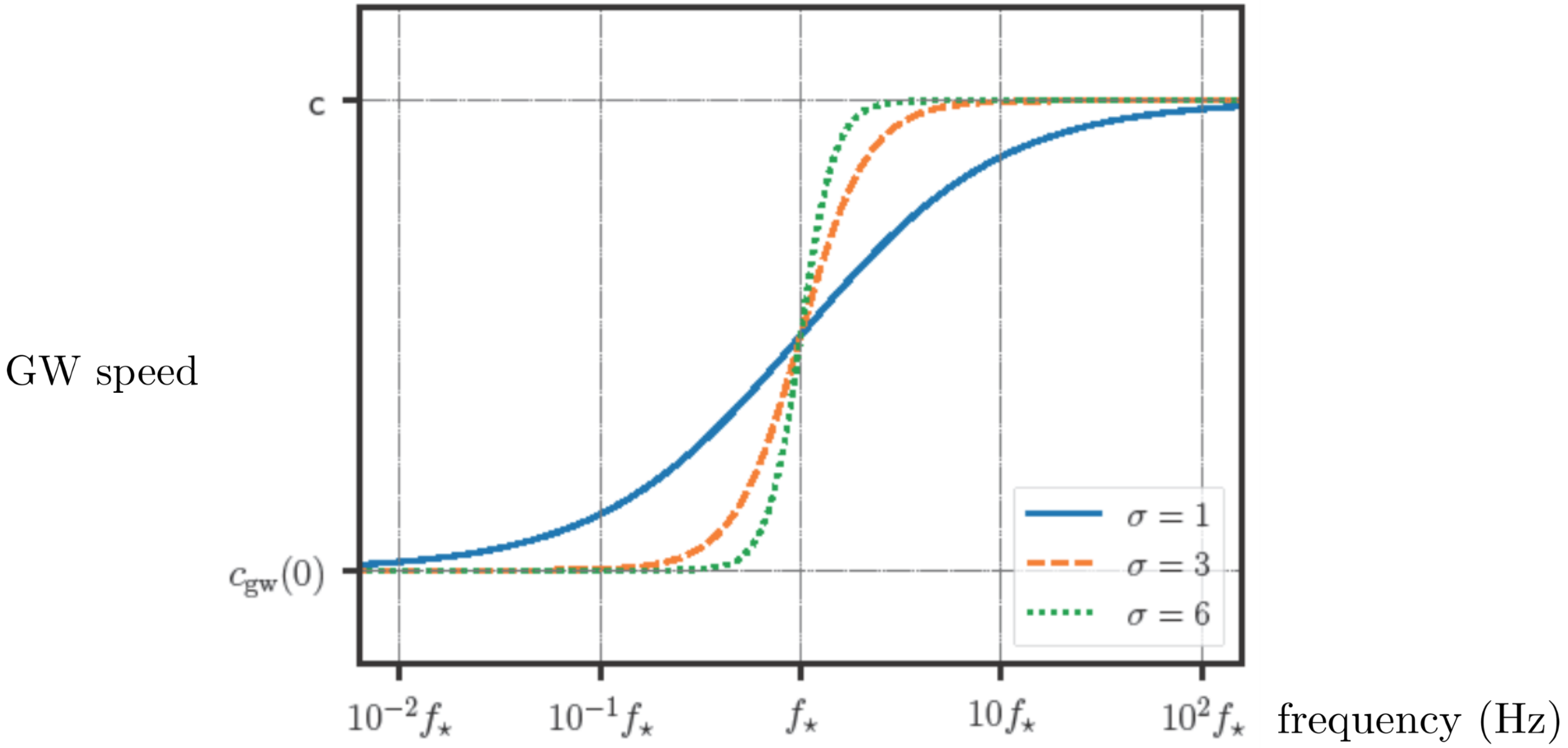
de Rham, Melville '18

Our goal in this work:

If there is a frequency-dependent speed of gravity, how well could we constrain it with gravitational-wave observations?

Can we place constraints with existing observations?

Step 1 - We need to parameterise this!



$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)} \left(\frac{1}{2} - \frac{1}{2} \tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

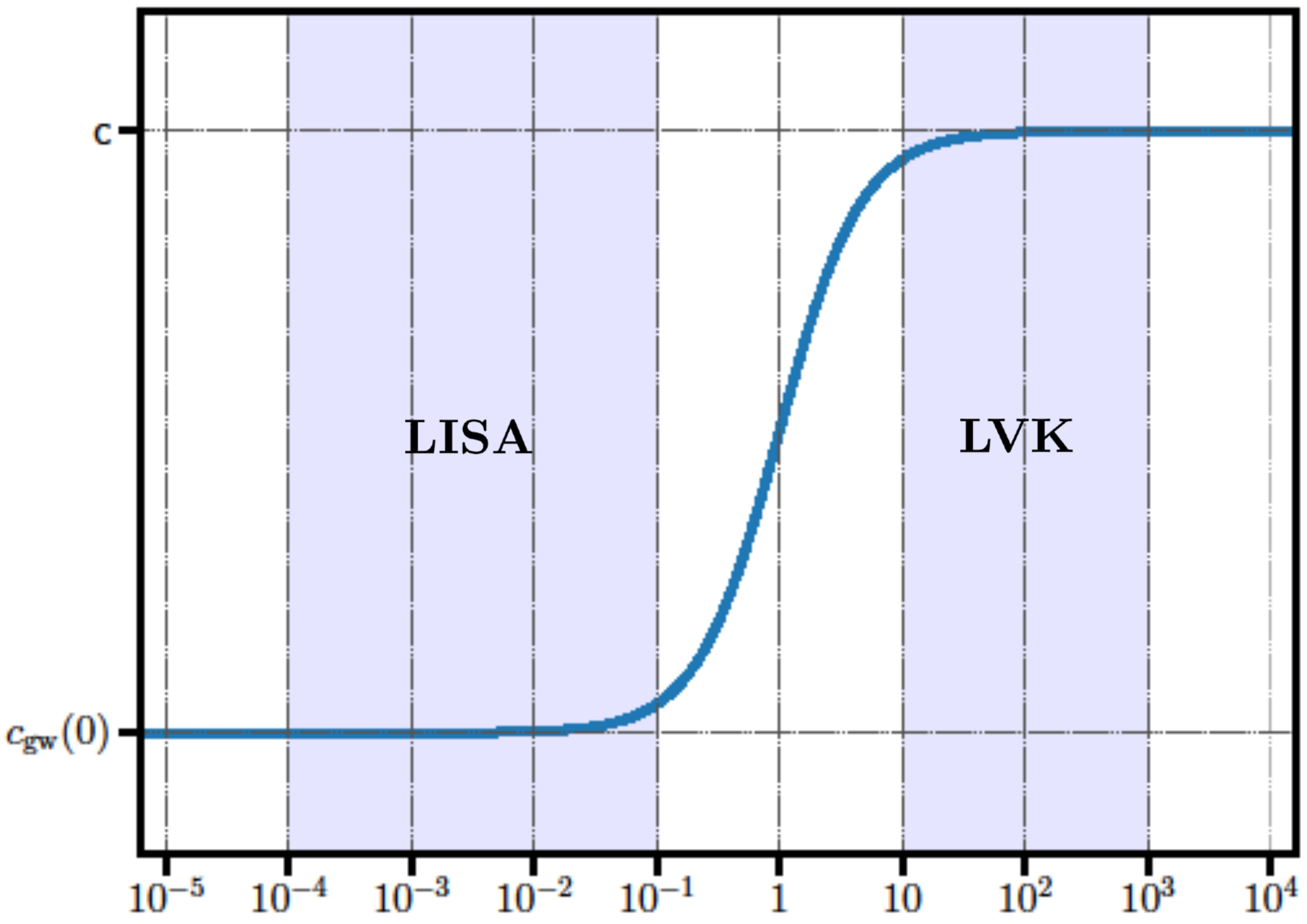
Step 2 - What effect would such a variation have?

- There are some subtle effects in the observed GW signal due to this, BUT:
- The main effect is that the travel time of the GW signal depends on frequency.
- For a signal whose frequency is evolving through the LISA/LVK band, this will stretch/squeeze the observed signal.
- For a source at 400Mpc and $\delta c_{gw} = 10^{-9}$ the travel speed will be a year longer/shorter than a wave travelling at c.

Constraints in the LVK band

- We assume that the transition frequency is below the LVK band and that c_{gw} is asymptoting to c in the LVK band.
- We should be ***more*** sensitive to a varying c_{gw} than a constant non-c value.
    - If a signal is shifted by O(ms) in the LVK band it could be observed.
- Can we place a tighter constraint than 10^{-15} on δc_{gw} if we assume it is varying?

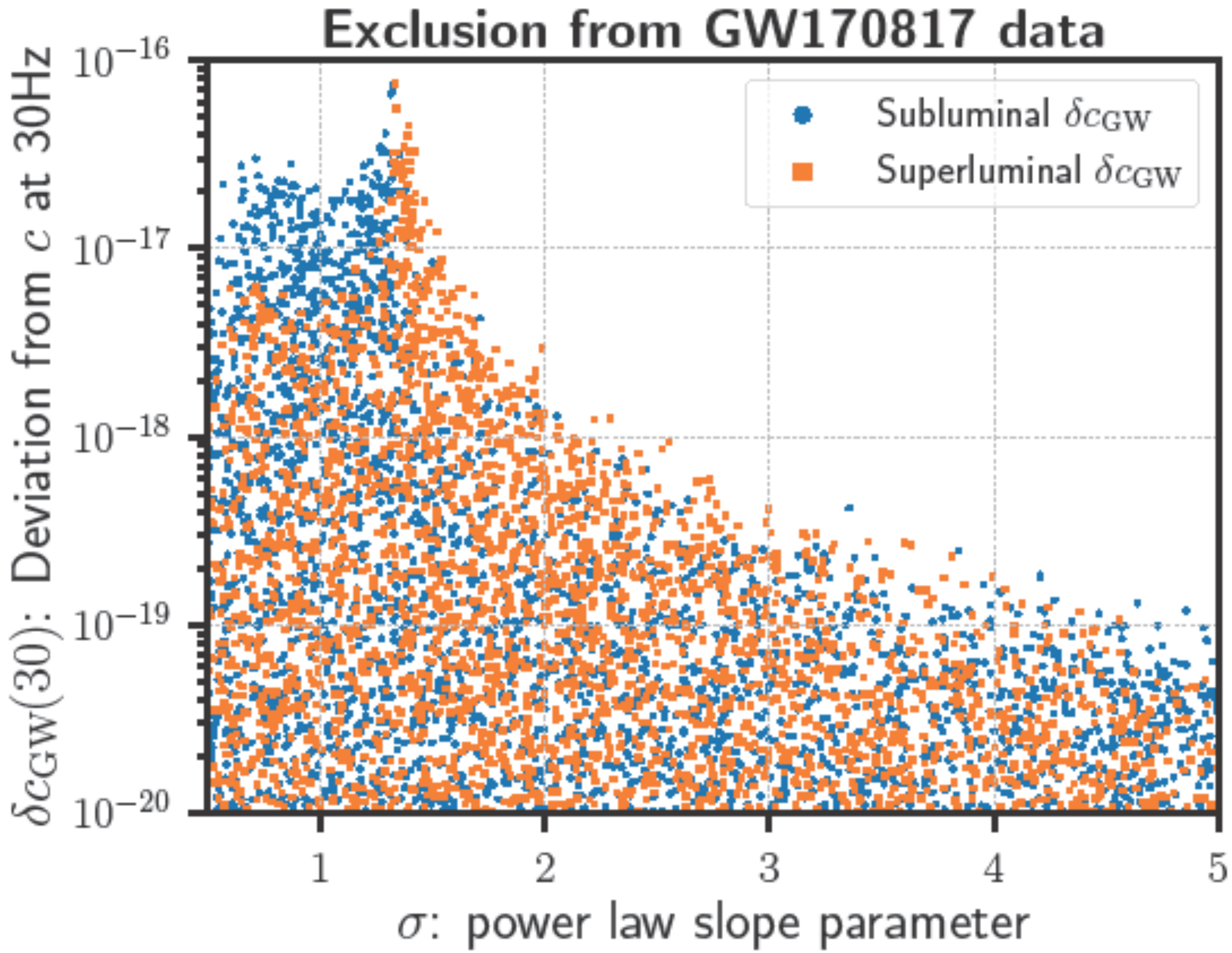
Constraints in the LVK band



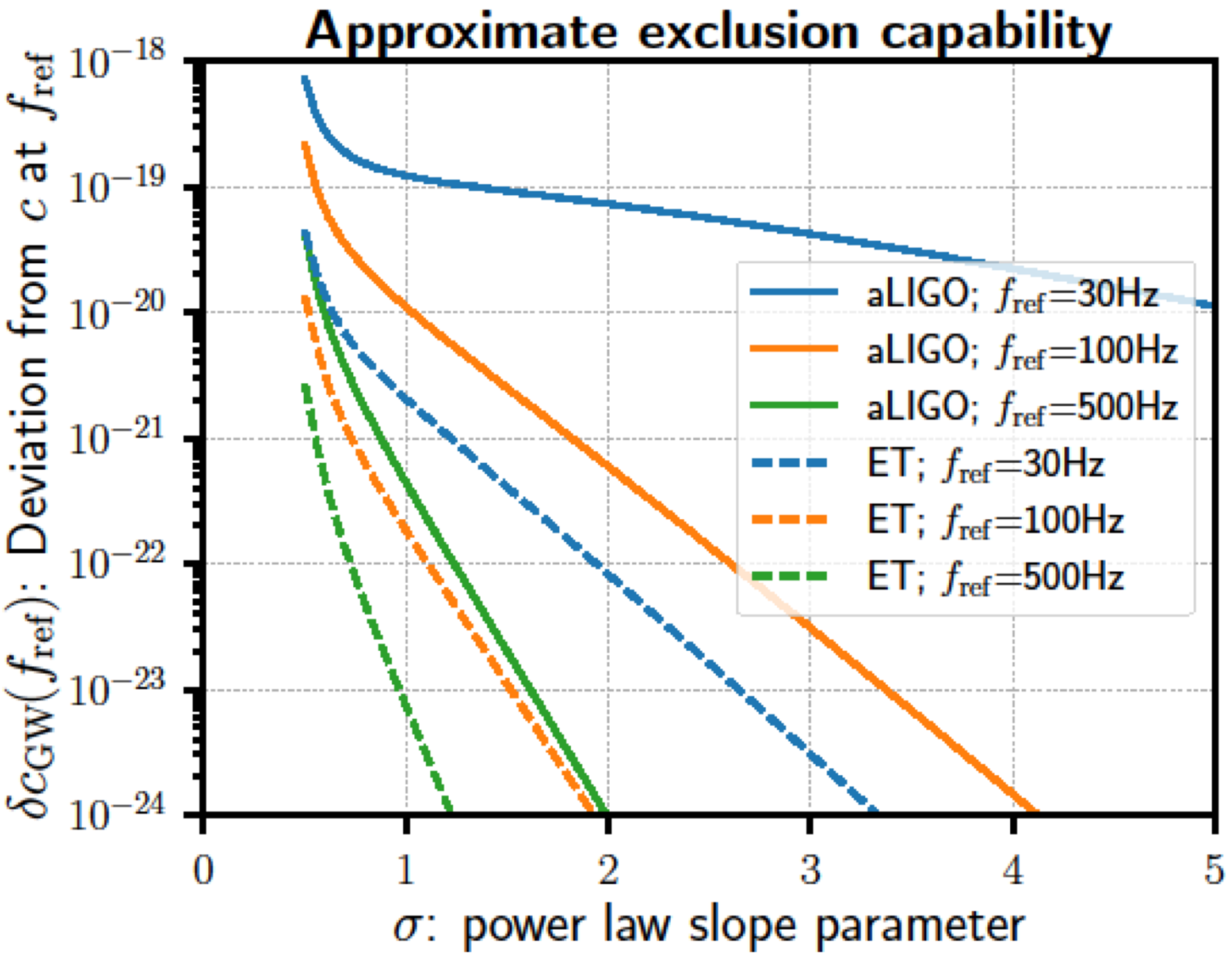
Asymptotic limit of template in LVK band:

$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}(f_{\rm ref}) * \frac{f_{\rm ref}^{2\sigma}}{f^{2\sigma}}$$

Results - Bayesian inference



Predicting exclusion capability with ET

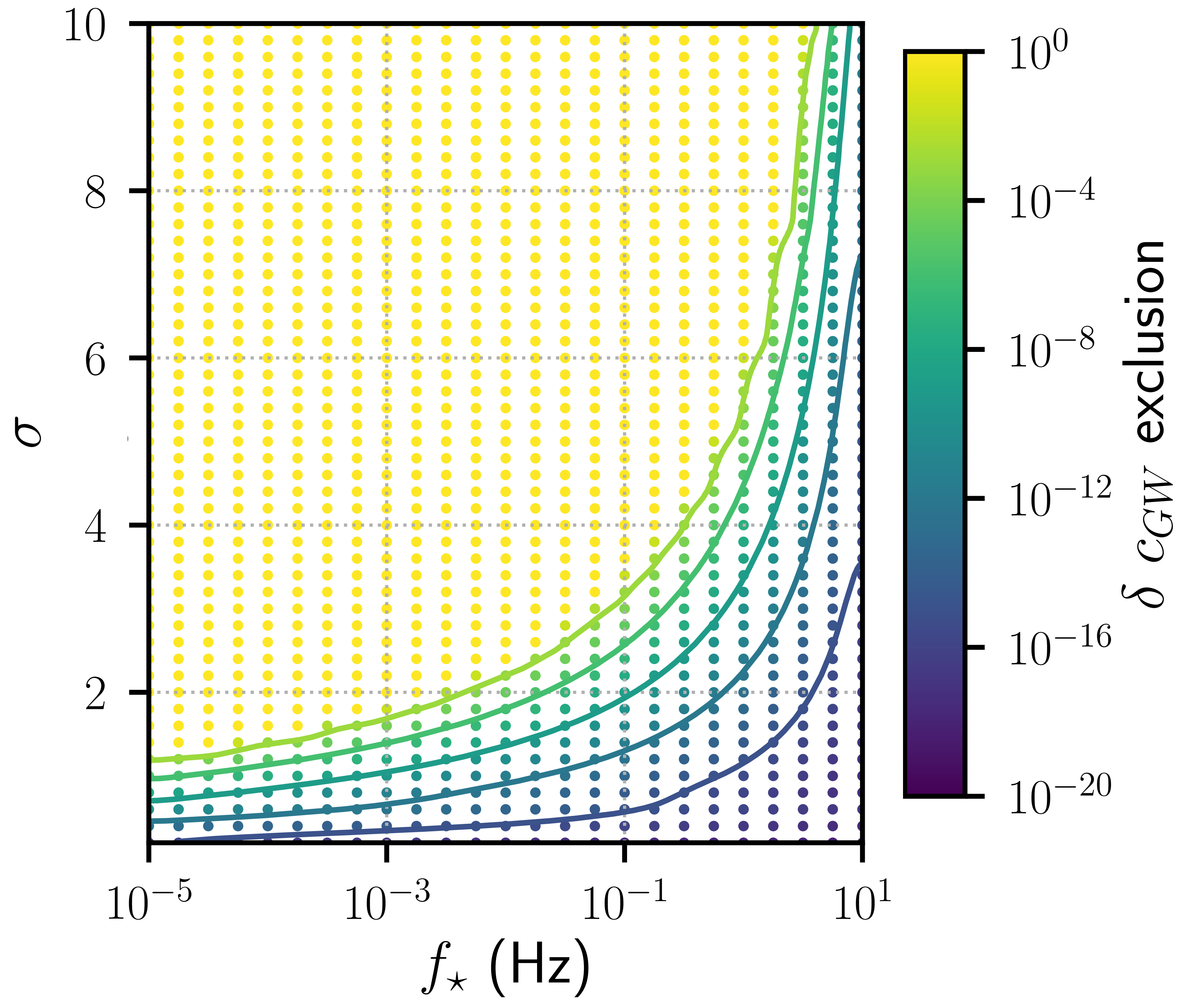


'Distinguishability':

$$\langle h_{\mathrm{MG}} - h_{\mathrm{GR}} | h_{\mathrm{MG}} - h_{\mathrm{GR}} \rangle \geq 1$$

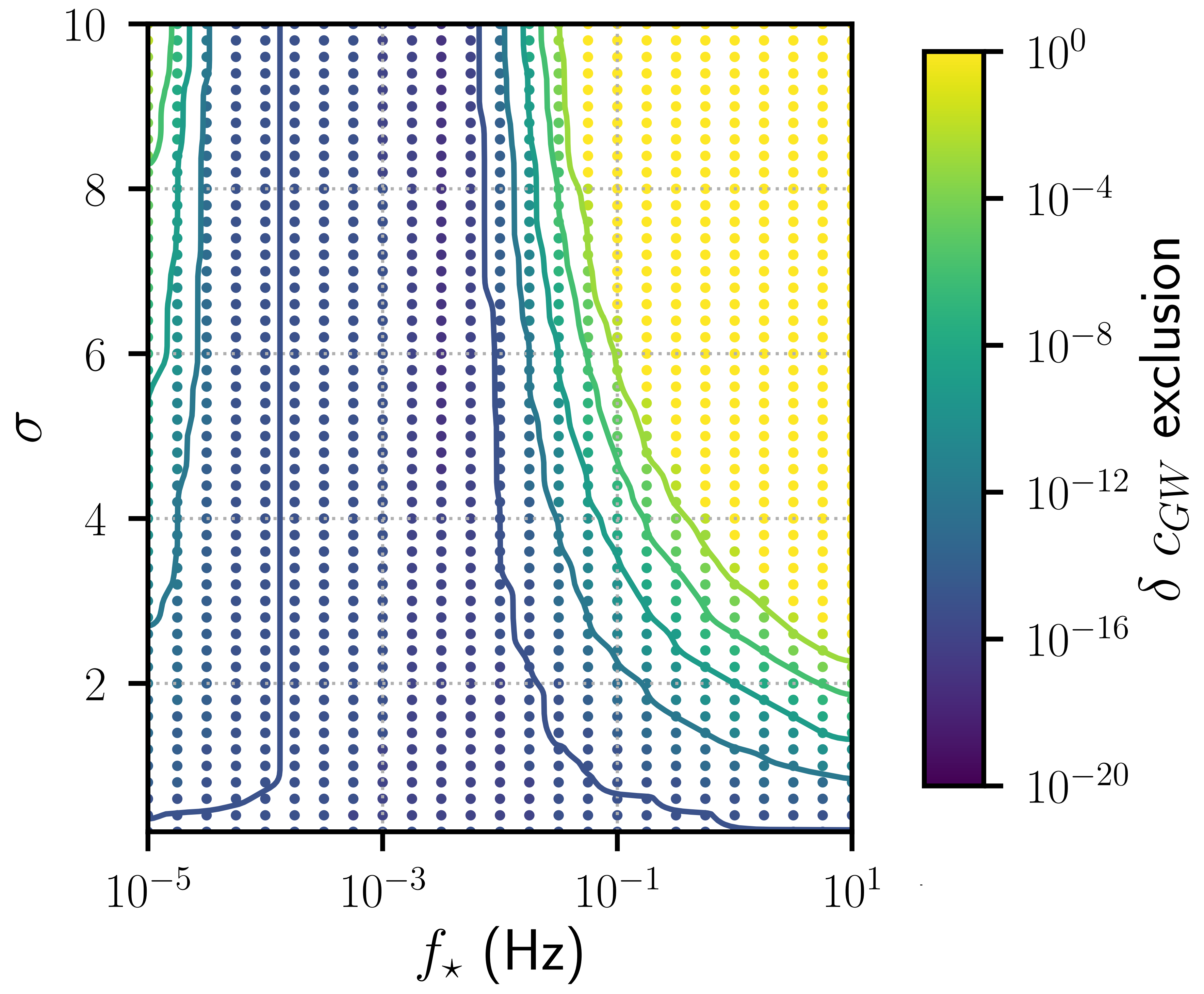
Lindblom, Owen, Brown '08

How will LISA help?



$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)}\left(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

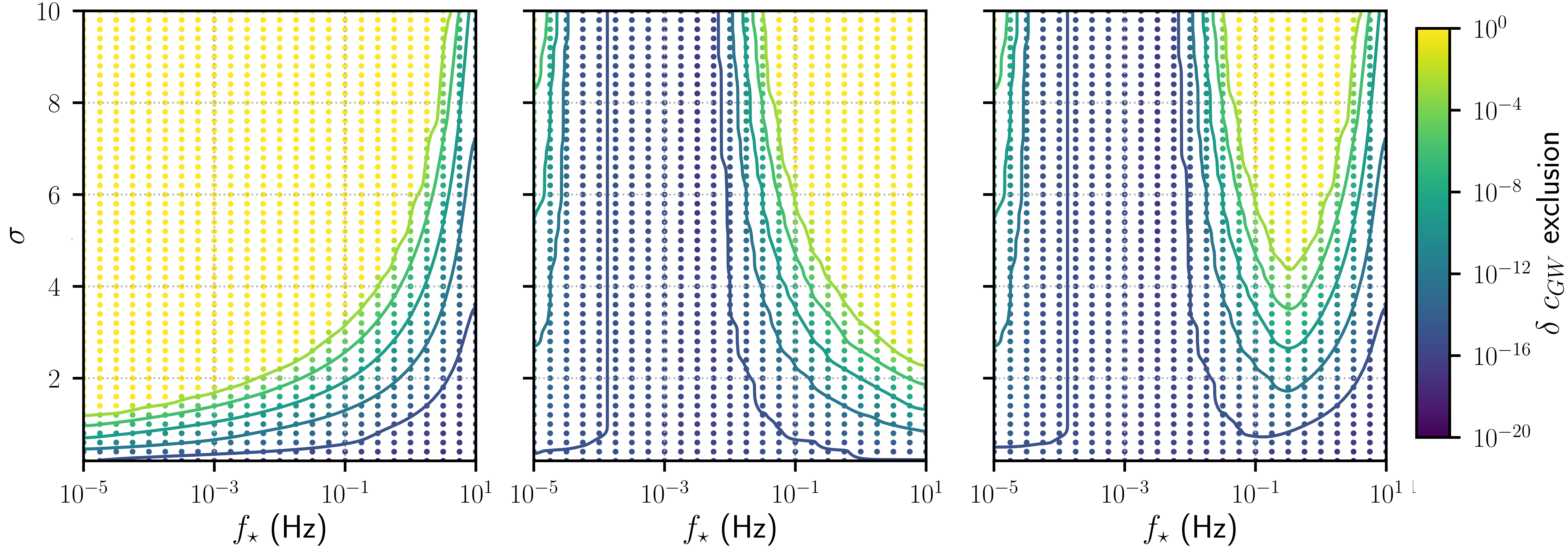
How will LISA help?



LISA only

$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)}\left(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

How will LISA help?



LVK only

LISA only

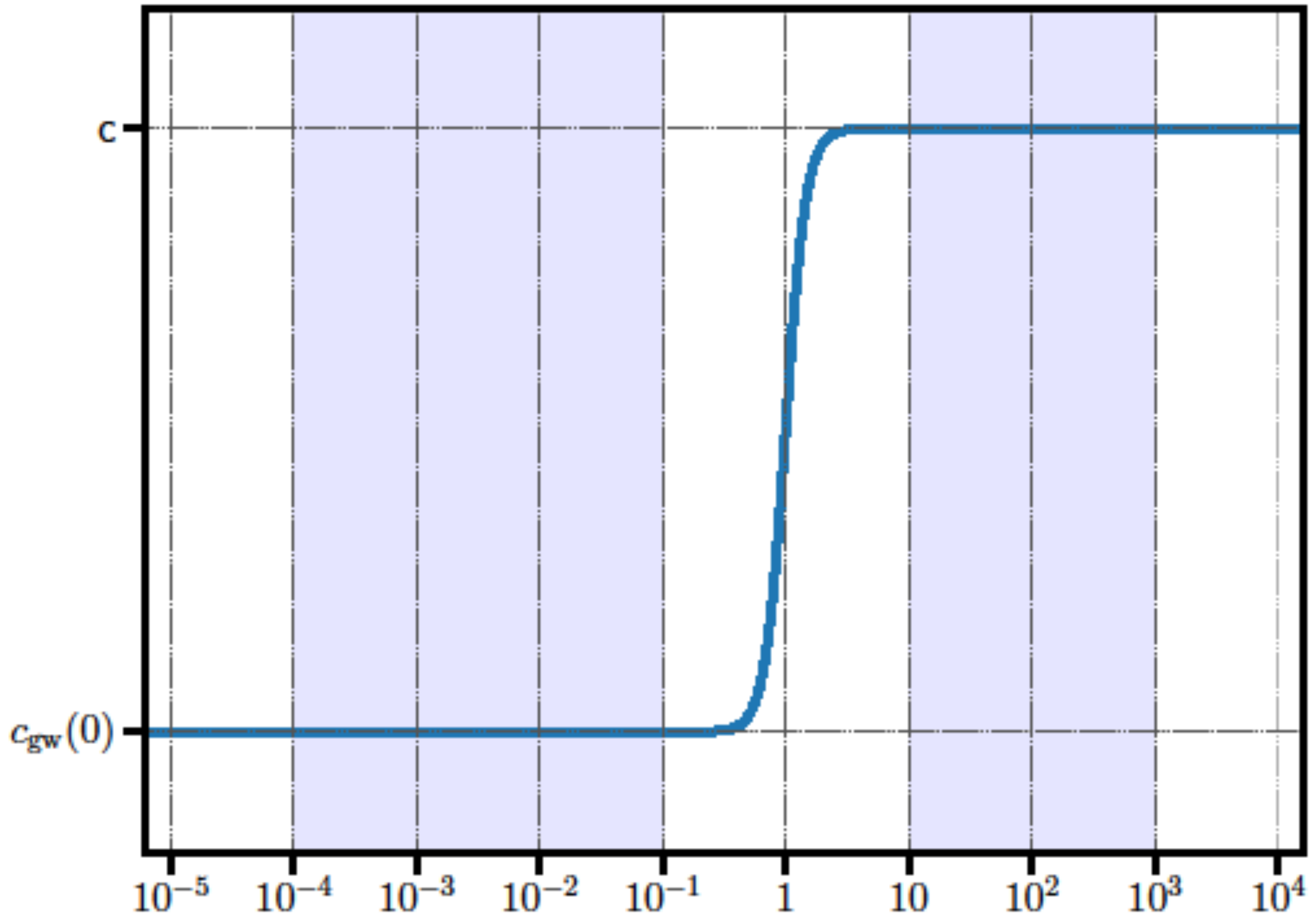
LVK *and* LISA

$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)}\left(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

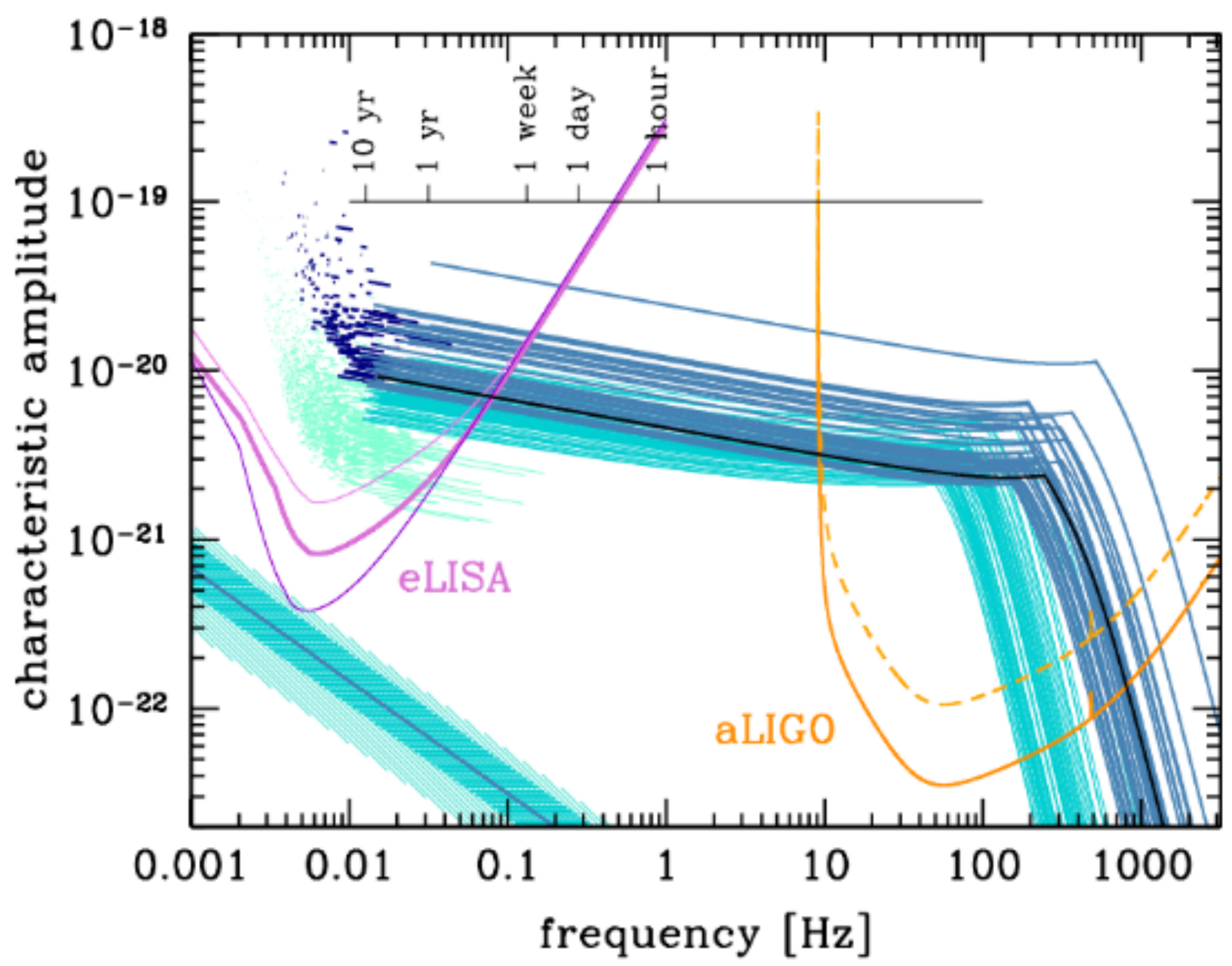
How will LISA help?

$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)}\left(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

What would be left?



Multiband constraints



Sesana '16

Predict arrival time in LVK band with $\sim 10^2$ accuracy.

Sesana '16

Multiband sources visible in LISA ***and*** LVK bands (GW150914)

Therefore $|\delta c_{gw}| \sim 10^{-15}$ detectable for source at ~ 400 Mpc.

Conclusion

- Frequency dependent c_{gw} with transition near LVK/LISA bands is a generic consequence of large classes of dark energy models.
- We can constrain $|\delta c_{gw}| \lesssim 10^{-17}$ in both LVK and LISA bands, even for mild frequency dependence.
    - We note that LVK bounds are even tighter if using the population of black holes rather than the binary neutron star, and LVK results can be used to get such a bound.
- Very sharp transitions around 0.1-1Hz can evade these bounds. Constrain up to $|\delta c_{gw}| \lesssim 10^{-15}$ with multi band observations.
- Gen.Rel.Grav. 54 (2022) 10, 133
- ArXiv: 2207.10096