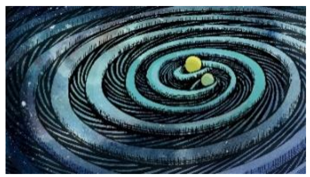
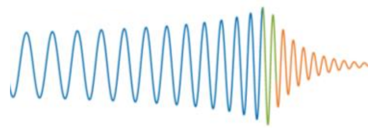
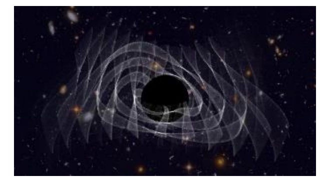
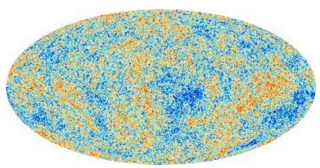
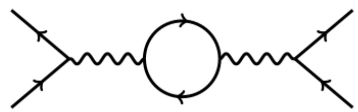
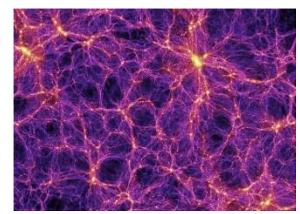
A tale of two speeds

(GW propagation and ringdown tests of $c_{\rm GW}$)

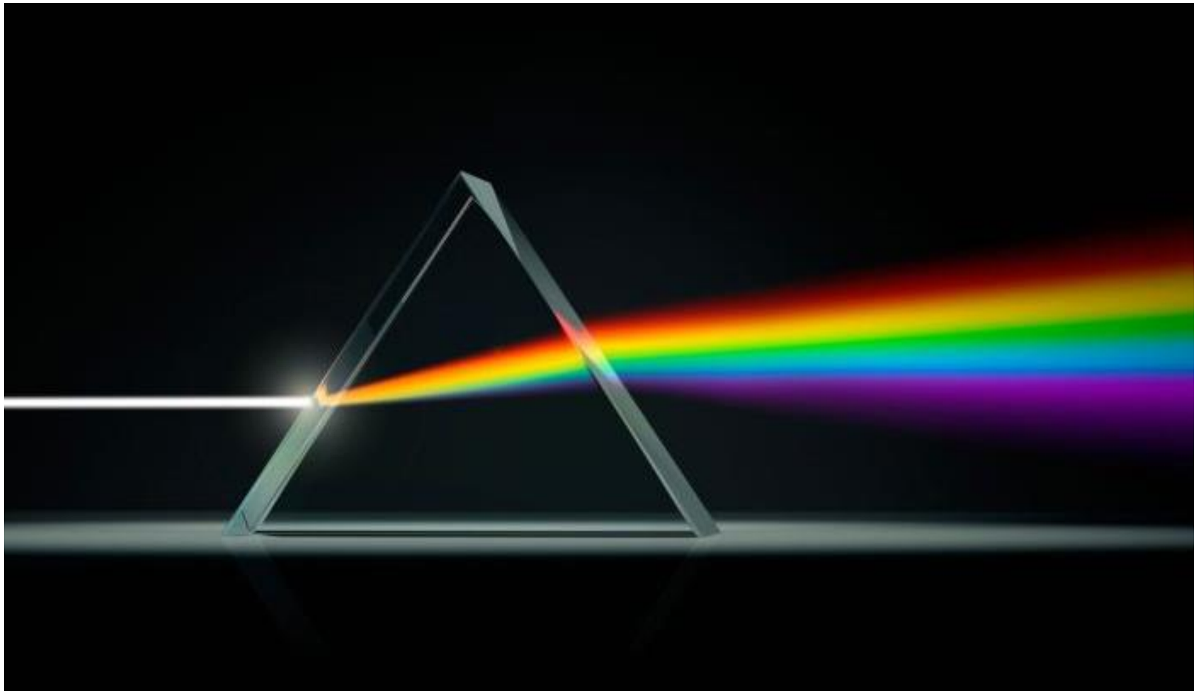
Johannes Noller

University College London (since October)

ICG, University of Portsmouth (until October)

Compact Objects Workshop, Institut Pascal, 09/11/2023

Gravity's rainbow



Gravitational wave 'h'

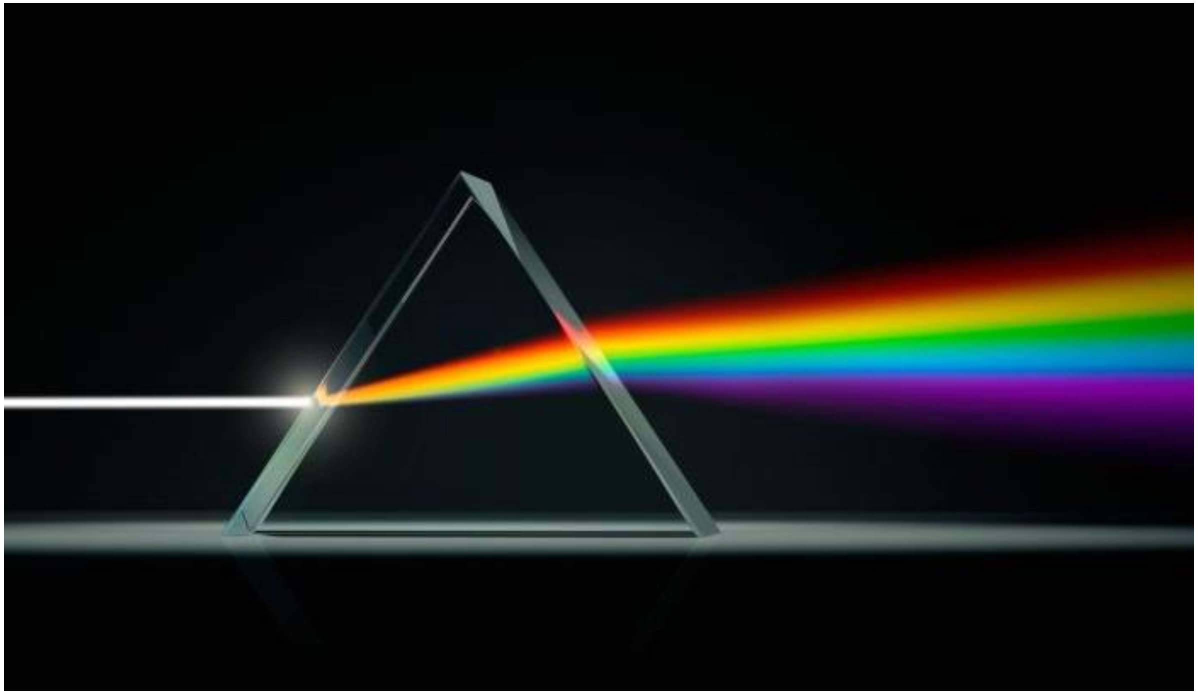
$$\ddot{h} + 3H(1 - \delta(f))\dot{h} + \left[(c^2 + \alpha_T(f))k^2 + m_g^2\right] h = 0$$

Hubble friction — GW speed — GW mass

ΛCDM prediction

New physics

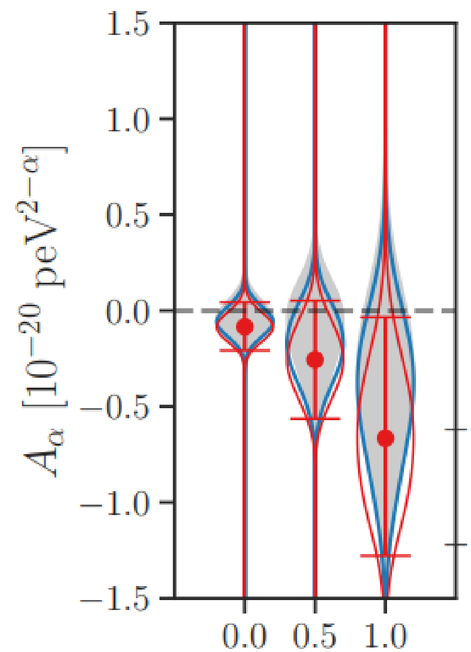
Gravity's rainbow



Modified Dispersion Relation: $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$

Physical meaning of $\{A_\alpha, \alpha\}$: $E^2 = p^2c^2\left[1 \pm \left(\frac{p}{p_\star}\right)^{\alpha-2}\right] \iff c_{\rm gw}^2 = c^2\left[1 \pm \left(\frac{f}{f_\star}\right)^{\alpha-2}\right]$

Gravity's rainbow



LVK "Tests of General Relativity" GWTC-3 (2021)

$\Rightarrow m_g \lesssim 10^{-23}$ eV

Tomasz Baka

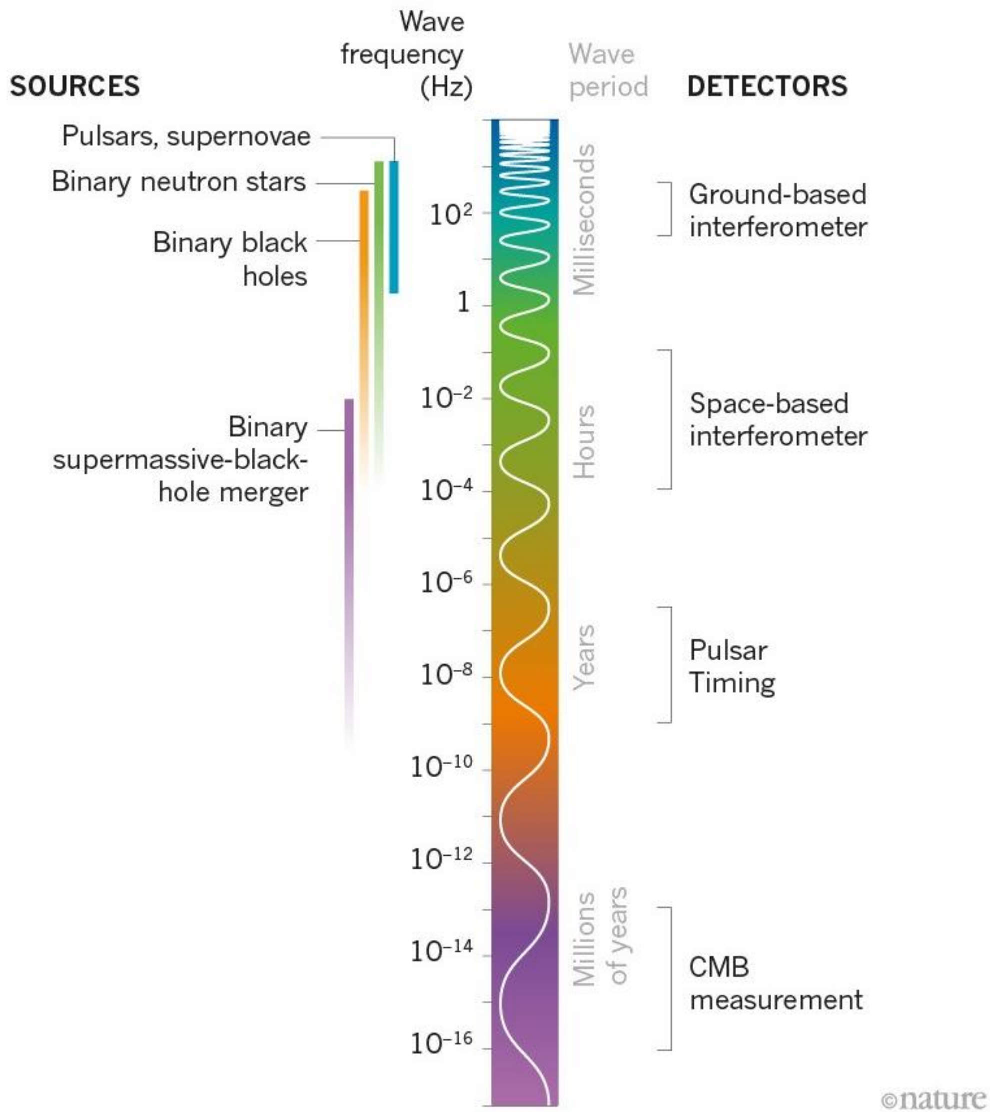
Balazs Cirok

Haris Maliyamveettil

Modified Dispersion Relation: $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$

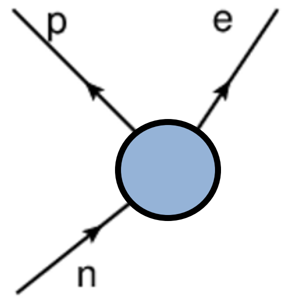
Physical meaning of $\{A_\alpha, \alpha\}$: $E^2 = p^2c^2\left[1 \pm \left(\frac{p}{p_\star}\right)^{\alpha-2}\right] \iff c_{\mathrm{gw}}^2 = c^2\left[1 \pm \left(\frac{f}{f_\star}\right)^{\alpha-2}\right]$

Gravity's rainbow



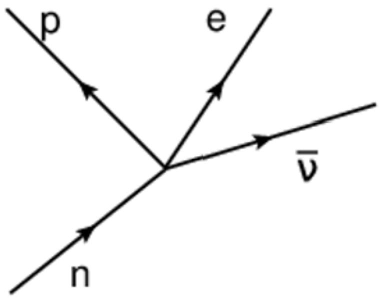
The reach of a theory

The reach of a theory



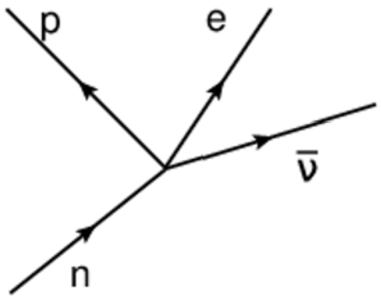
Neutron decay

The reach of a theory



Fermi theory

The reach of a theory

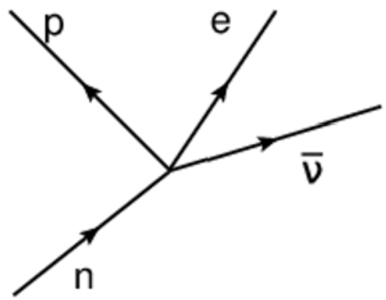


Fermi theory

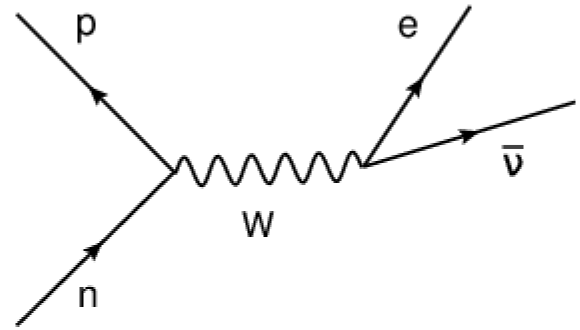
Scattering amplitude: $$\mathcal{A} \Rightarrow \frac{d\sigma}{d\Omega} \sim \frac{\text{Scattered flux}}{\text{Incident flux}}$$

Energy scaling: $$\mathcal{A} \sim \left(\frac{E}{\text{TeV}}\right)^4$$

The reach of a theory



Fermi theory



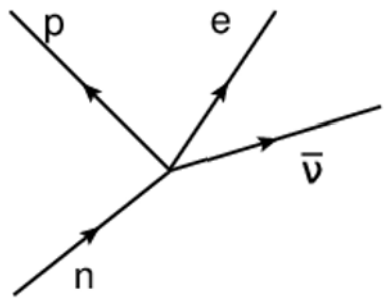
Electro-weak theory

Scattering amplitude: $\mathcal{A} \Rightarrow \frac{d\sigma}{d\Omega} \sim \frac{\text{Scattered flux}}{\text{Incident flux}}$

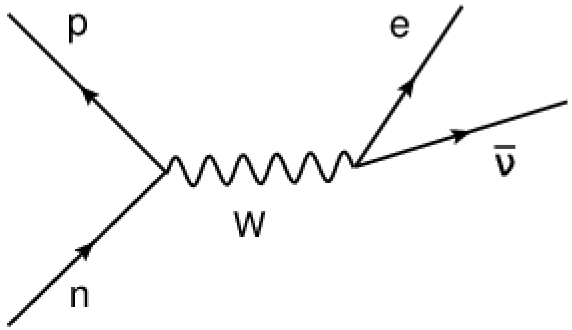
Energy scaling: $\mathcal{A} \sim \left(\frac{E}{\text{TeV}}\right)^4$

The scale of new physics: $m_{\text{W}} \sim 80 \text{ GeV}$

The reach of a theory



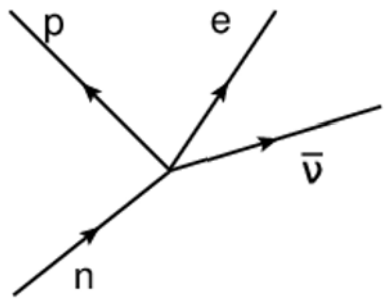
Fermi theory



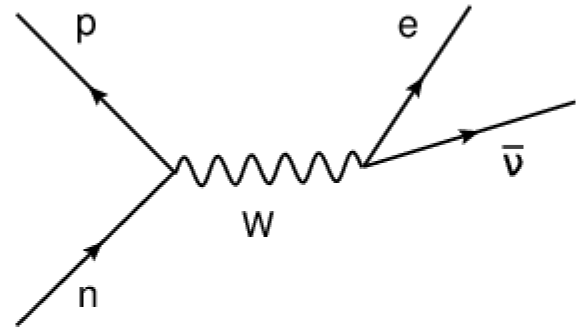
Electro-weak theory

Fermi theory: $\mathcal{A} \sim \left(\frac{E}{\mathrm{TeV}}\right)^4$

The reach of a theory



Fermi theory

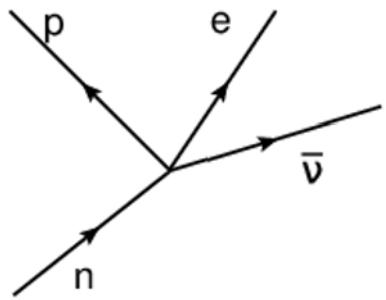


Electro-weak theory

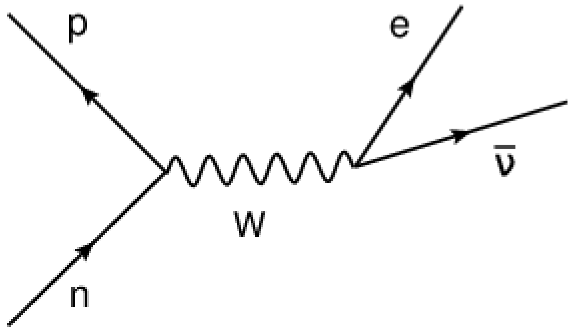
Fermi theory: $$\mathcal{A} \sim \left(\frac{E}{\text{TeV}}\right)^4$$

General Relativity: $$\mathcal{A} \sim \left(\frac{E}{M_{\text{Pl}}}\right)^2 \sim \left(\frac{E}{10^{15}\ \text{TeV}}\right)^2$$

The reach of a theory



Fermi theory



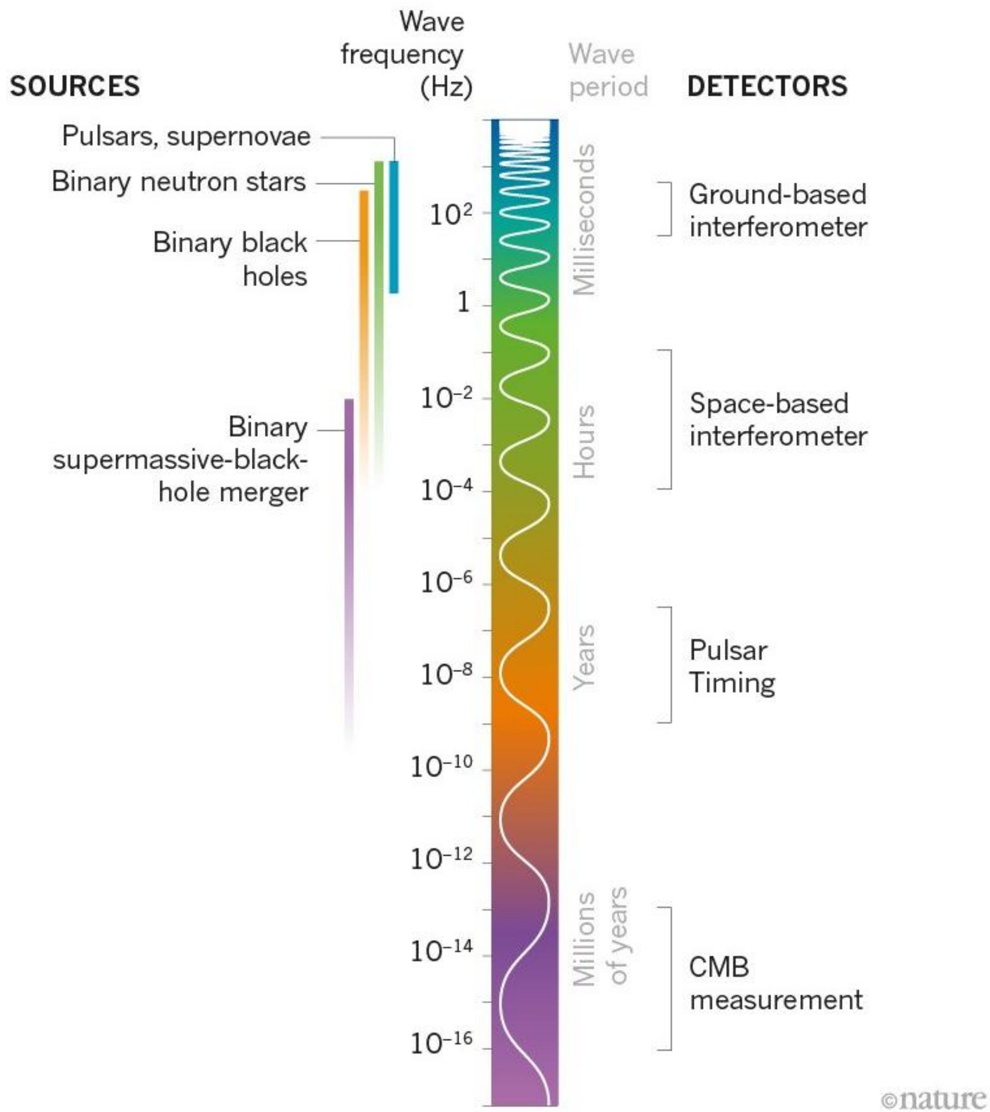
Electro-weak theory

Fermi theory: $\mathcal{A} \sim \left(\frac{E}{\mathrm{TeV}}\right)^4$

General Relativity: $\mathcal{A} \sim \left(\frac{E}{M_{\mathrm{Pl}}}\right)^2 \sim \left(\frac{E}{10^{15}\ \mathrm{TeV}}\right)^2$

Dark Energy EFT: $\mathcal{A} \sim \left(\frac{E}{10^{-12}\ \mathrm{eV}}\right)^p$

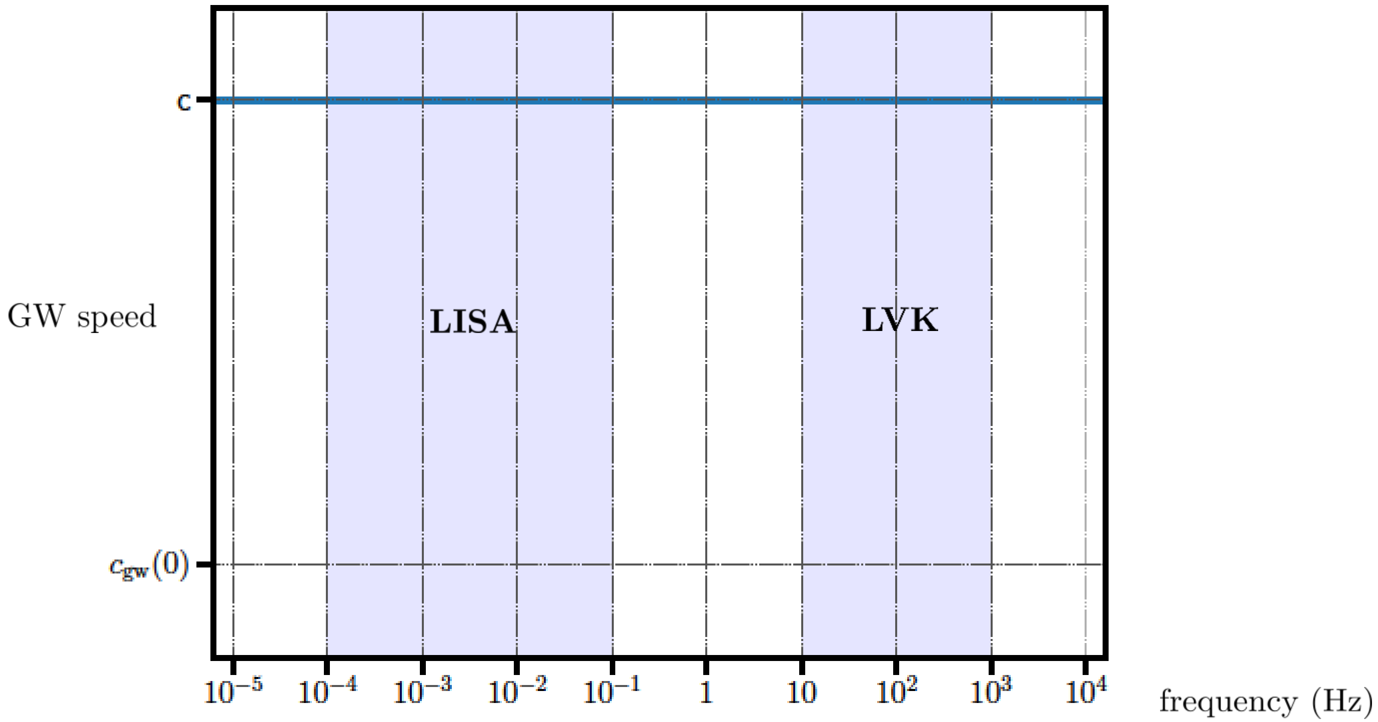
Gravity's rainbow



UV completion

Dark Energy phase

The speed of gravity



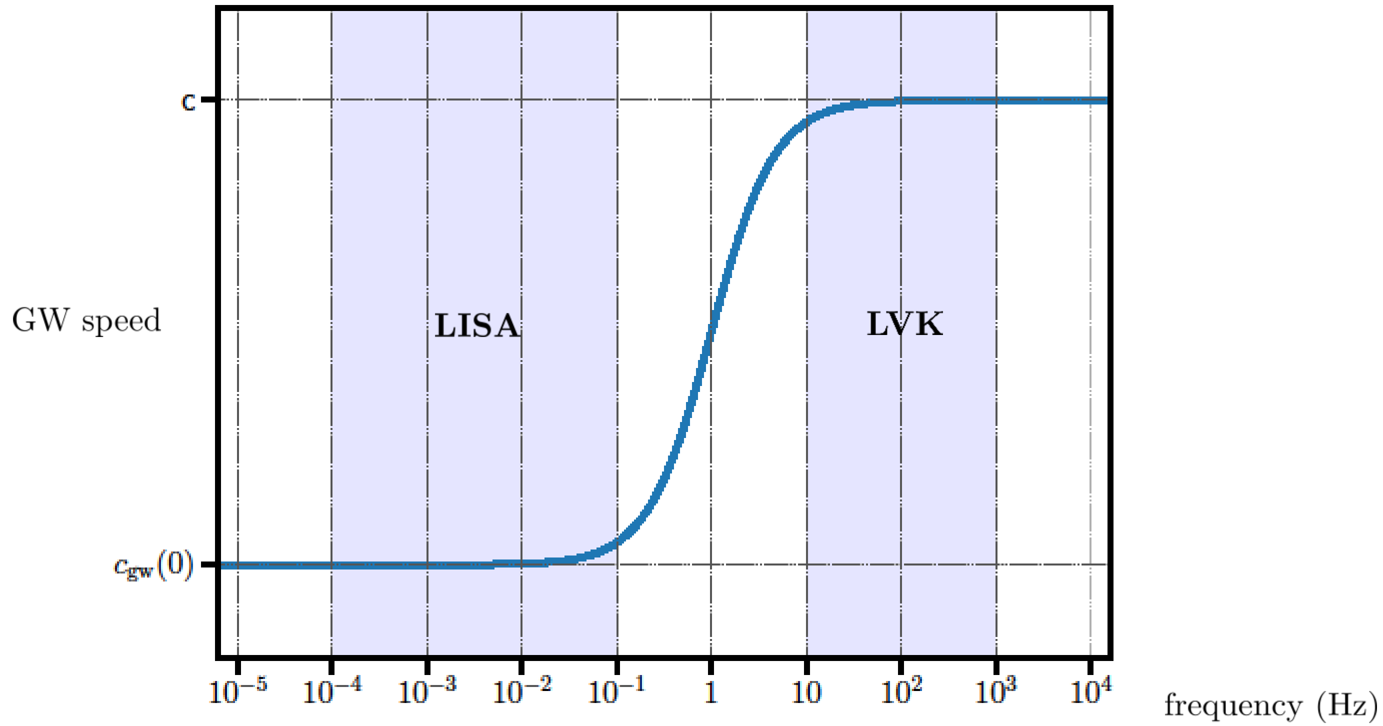
$$\delta c_{\rm GW} \equiv \frac{c_{\rm GW} - c}{c} \qquad \Rightarrow \qquad |\delta c_{\rm GW}| \lesssim 10^{-15}$$

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

⇒ **Strong constraints on dark energy/modified gravity theories and their interactions.**

Creminelli, Vernizzi '17, Baker, Bellini, Ferreira, Lagos, JN, Sawicki '17,
Ezquiaga, Zumalacarregui '17, Sakstein, Jain '17, ++

The speed of gravity



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

$\Downarrow$

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

de Rham, Melville '18

$\Downarrow$

Can we test this with GW observations?

Ringdown constraints

Background ansatz:

$$ds^2 = -\left(1 - \tfrac{2M}{r}\right) dt^2 + \frac{1}{\left(1 - \tfrac{2M}{r}\right)} dr^2 + d\Omega^2,$$

$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

Sergi Sirera Lahoz

Ringdown constraints

Background ansatz:

$$ds^2 = -\left(1 - \tfrac{2M}{r}\right) dt^2 + \frac{1}{\left(1 - \tfrac{2M}{r}\right)} dr^2 + d\Omega^2,$$

$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

$$\delta\phi(r) = \varphi_c \left(\frac{2M}{r}\right)$$

Ringdown constraints

Background ansatz: $$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \frac{1}{\left(1 - \frac{2M}{r}\right)} dr^2 + d\Omega^2,$$

$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

$$\delta\phi(r) = \varphi_c \left(\frac{2M}{r}\right)$$

Modified RW equation: $$\frac{d^2 Q}{dr_*^2} + \left[\omega^2(1 + \alpha_T) - (1 - \frac{2M}{r})(V_{RW} + \delta V)\right] Q = 0,$$

Ringdown constraints

Background ansatz: $$ds^2 = -\left(1-\tfrac{2M}{r}\right)dt^2 + \frac{1}{\left(1-\tfrac{2M}{r}\right)}dr^2 + d\Omega^2,$$

$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

$$\delta\phi(r) = \varphi_c\left(\frac{2M}{r}\right)$$

Modified RW equation: $$\frac{d^2Q}{dr_*^2} + \left[\omega^2(1+\alpha_T) - (1-\tfrac{2M}{r})(V_{RW}+\delta V)\right]Q = 0,$$

Modified potential: $$\delta V = \alpha_T\left[\frac{M(2r-5M)}{r^3(r-2M)} + \frac{(\ell+2)(\ell-1)}{r^2} - \frac{r-2M}{2r}\left(\left(\frac{\delta\phi''}{\delta\phi'}\right)^2 - \frac{\delta\phi'''}{\delta\phi'}\right) + \frac{r-5M}{r^2}\frac{\delta\phi''}{\delta\phi'}\right].$$

Sirera Lahoz, JN '23

Ringdown constraints

Background ansatz:

$$ds^2 = -\left(1 - \tfrac{2M}{r}\right) dt^2 + \frac{1}{\left(1 - \tfrac{2M}{r}\right)} dr^2 + d\Omega^2,$$

$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

$$\delta\phi(r) = \varphi_c \left(\frac{2M}{r}\right)$$

Modified RW equation:

$$\frac{d^2 Q}{dr_*^2} + \left[\omega^2 (1 + \alpha_T) - \left(1 - \tfrac{2M}{r}\right)(V_{RW} + \delta V)\right] Q = 0,$$

Tensor speed excess:

$$\alpha_T = -\left(1 - \frac{2M}{r}\right) \frac{G_{4X} - G_{5\phi}}{G_4} \delta\phi'^2$$

Sirera Lahoz, JN '23

Ringdown constraints

Background ansatz:

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \frac{1}{\left(1 - \frac{2M}{r}\right)} dr^2 + d\Omega^2,$$

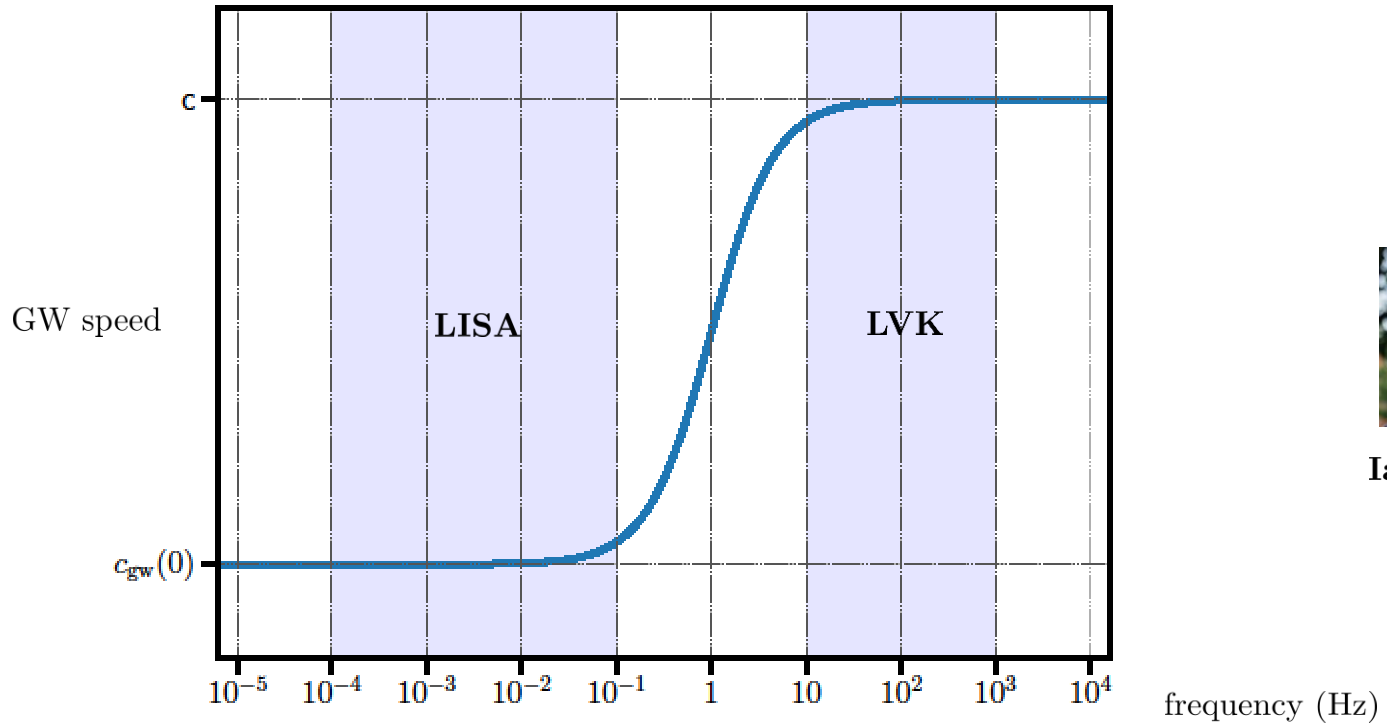
$$\bar{\phi} = \phi_0 + \delta\phi(r),$$

$$\delta\phi(r) = \varphi_c \left(\frac{2M}{r}\right)$$

Detector(s)	Ringdown SNR (ρ)	Error on α_T
LVK	10 [136–138]	1
ET / CE	10^2 [138–141]	10^{-1}
pre-DECIGO	10^2 [142]	10^{-1}
DECIGO / AEDGE	10^3 [143, 144]*	10^{-2}
LISA	10^5 [137, 145]	10^{-4}
TianQin	10^5 [145]	10^{-4}
AMIGO	10^5 [130]	10^{-4}

Sirera Lahoz, JN '23

The speed of gravity



Ian Harry

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

$\Downarrow$

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

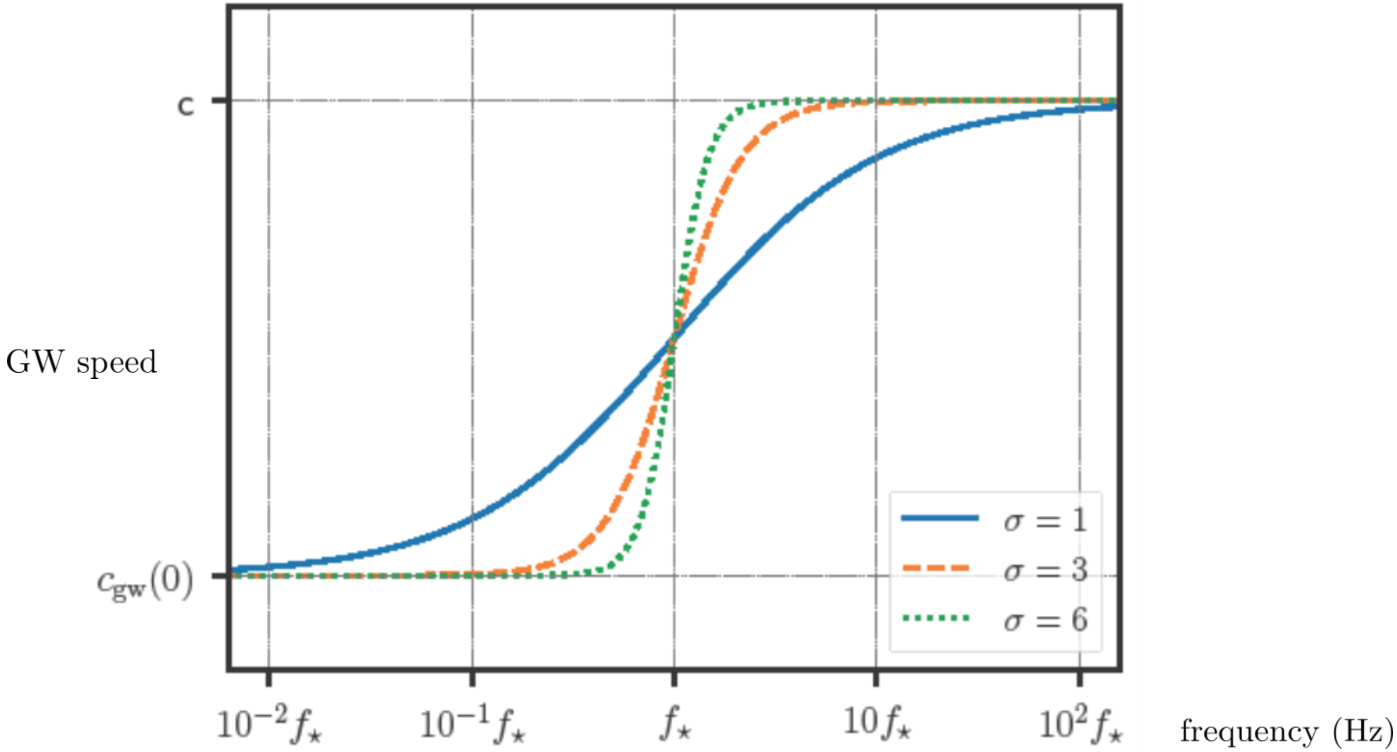
de Rham, Melville '18

$\Downarrow$

Can we test this with GW observations?

Baker, Calcagni, Chen, Fasiello, Lombriser, Martinovic, Pieroni, Sakellariadou, Tasinato, Bertacca, Saltas '22 Harry, JN '22, Baker, Barausse, Chen, de Rham, Pieroni, Tasinato '22

The speed of gravity: A template



Harry, JN '22

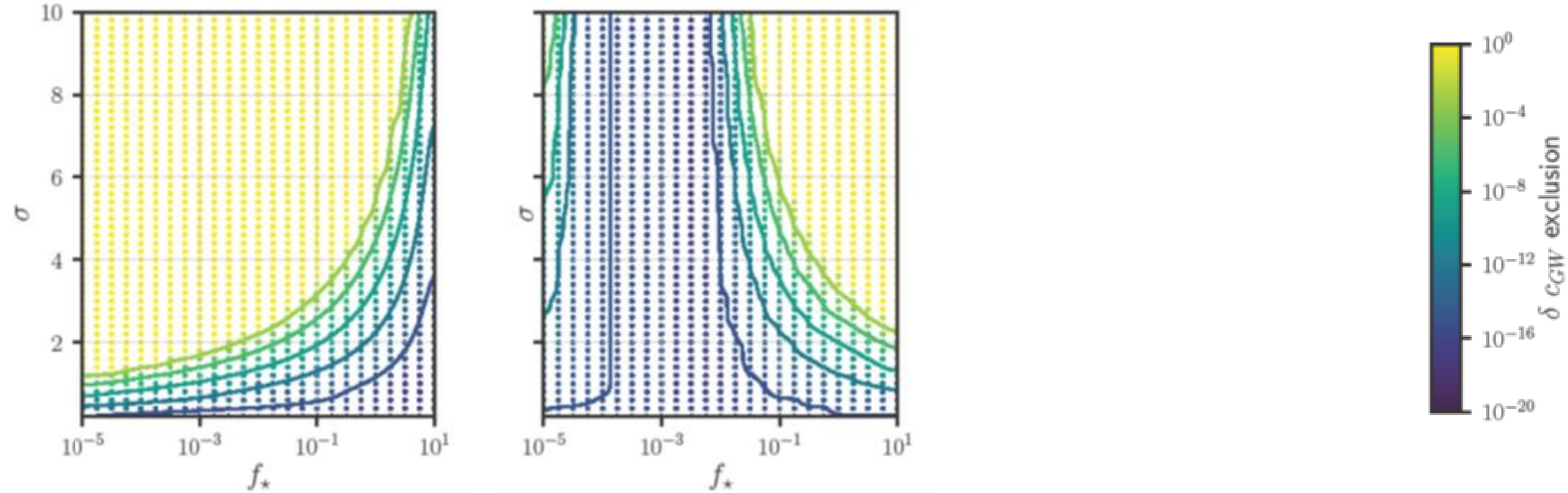
$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)} \left(\tfrac{1}{2} - \tfrac{1}{2} \tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

LVK & LISA constraints

Harry, JN '22

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

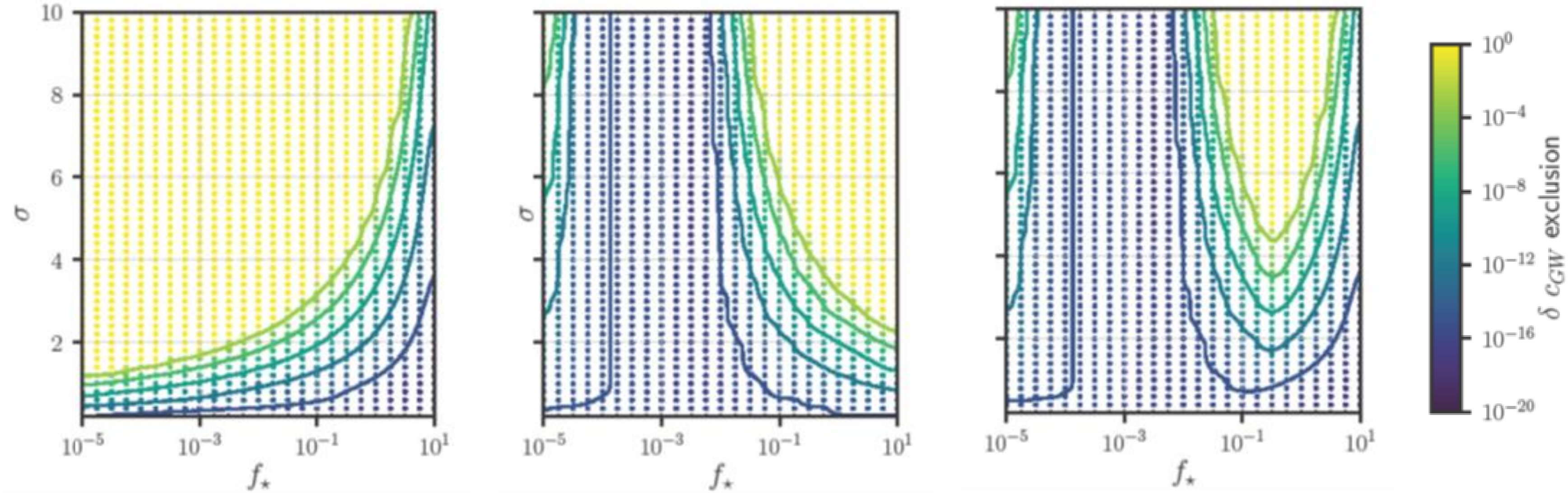
LVK & LISA constraints



Harry, JN '22

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

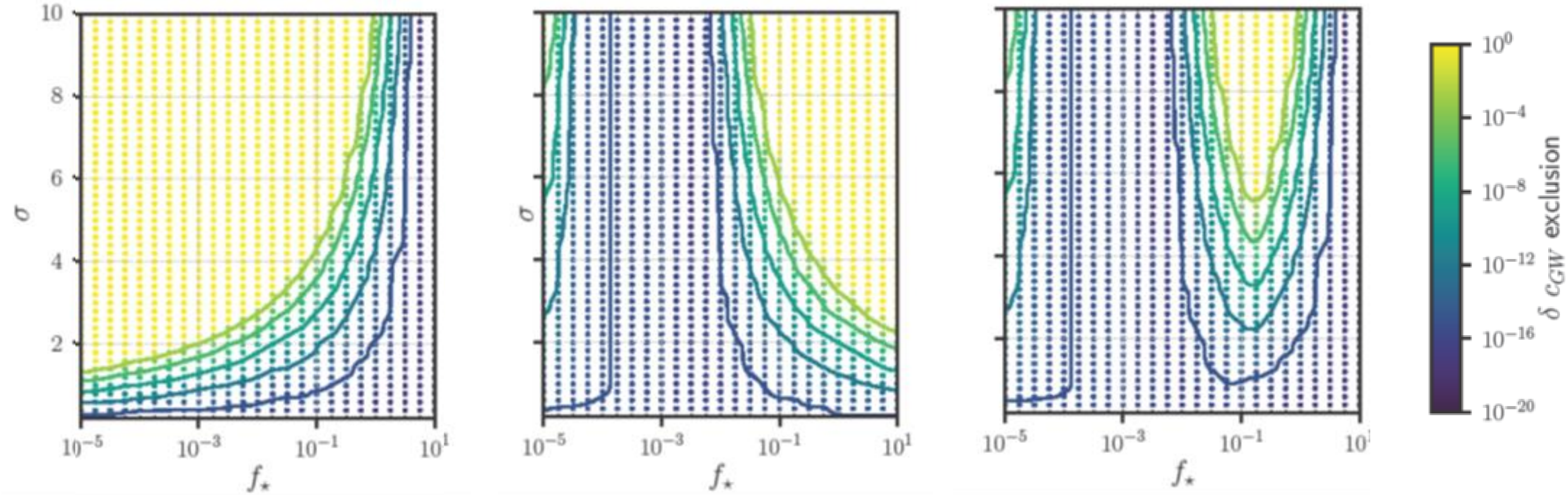
LVK & LISA constraints



Harry, JN '22

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

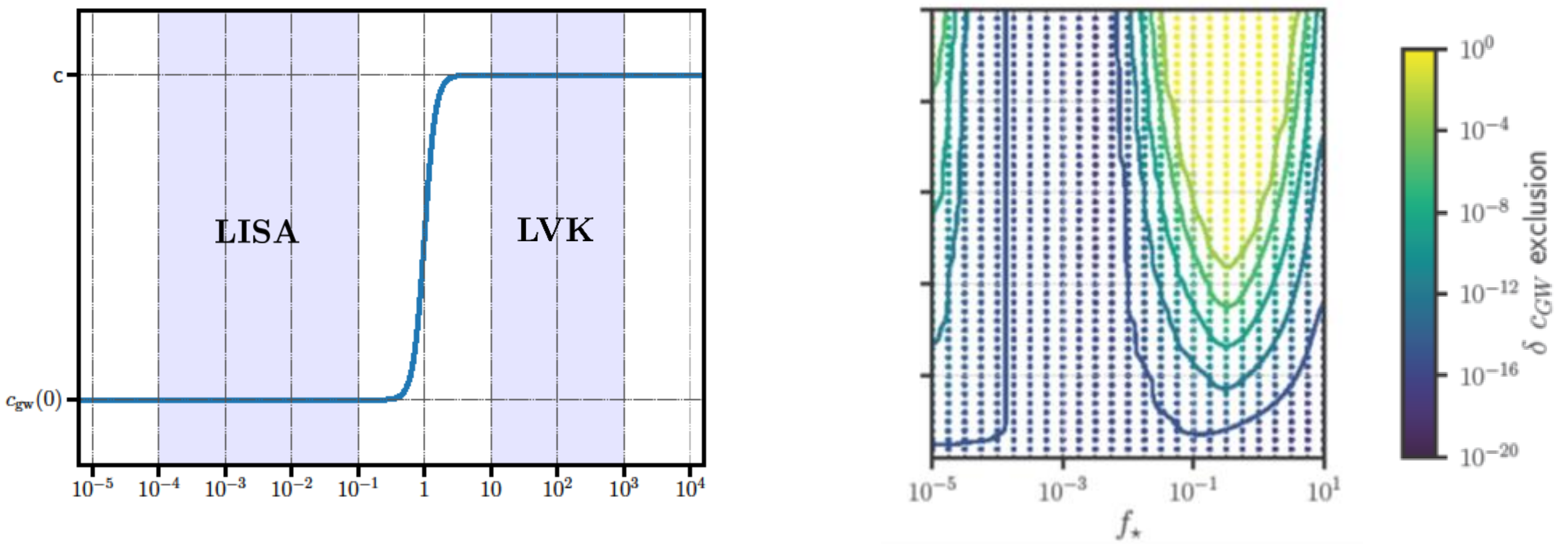
ET & LISA constraints



Harry, JN '22

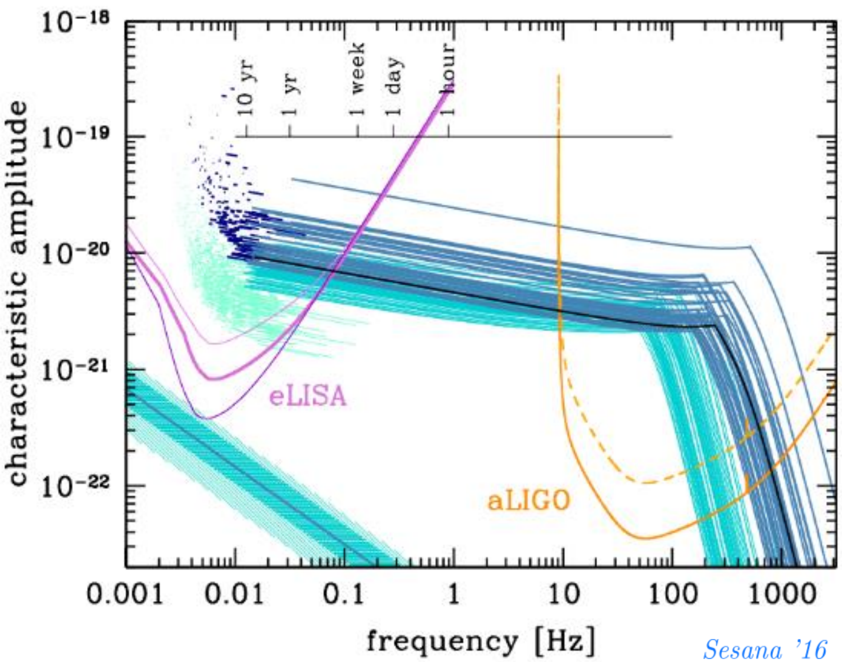
$$\delta c_{\rm GW}(f) = \delta c_{\rm GW}^{(0)}\left(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right]\right)$$

Multiband constraints



Harry, JN '22

Multiband constraints



Sesana '16

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

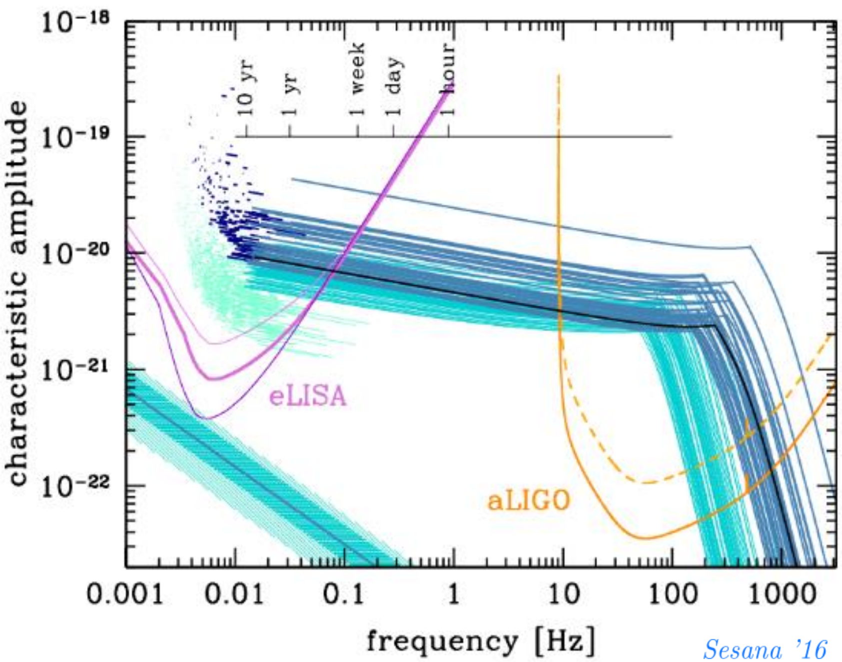
Predict arrival time in LVK band with $\sim 10s$ accuracy.

Sesana '16

Therefore $|\delta c_{\rm gw}| \sim 10^{-16}$ detectable for source at ~ 400 Mpc.

Harry, JN '22, Baker, Barausse, Chen, de Rham, Pieroni, Tasinato '22

Multiband constraints



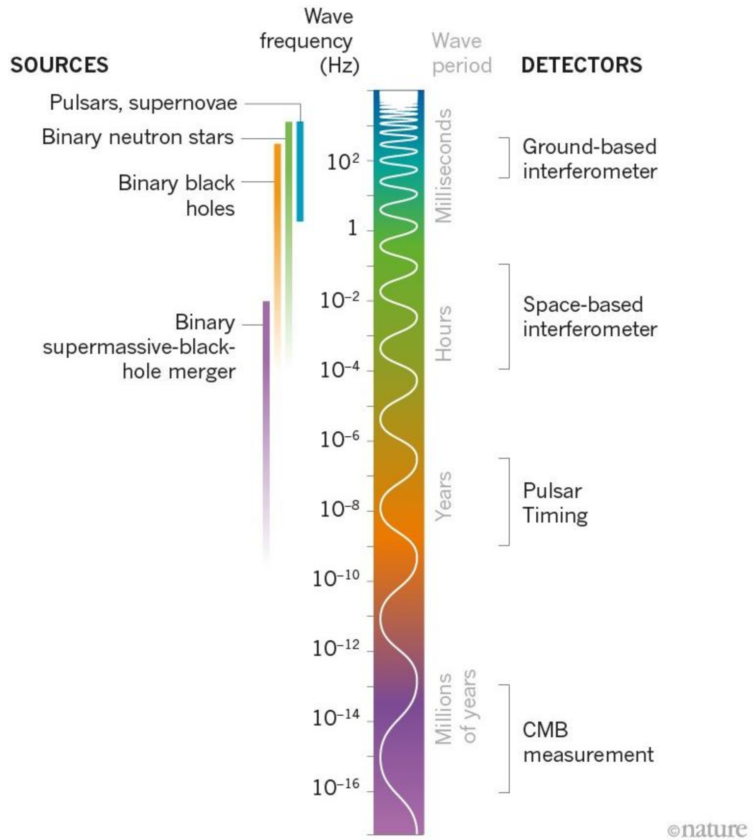
Sesana '16

LVK/LISA multiband observations can:

- **Constrain** $|\delta c_{\rm gw}| \lesssim 10^{-16}$.
- **Measure** $10^{-16} \lesssim |\delta c_{\rm gw}| \lesssim 10^{-9}$.
- **No multiband signal for** $|\delta c_{\rm gw}| \gtrsim 10^{-8}$.

Harry, JN '22

A tale of two speeds



Thank you!