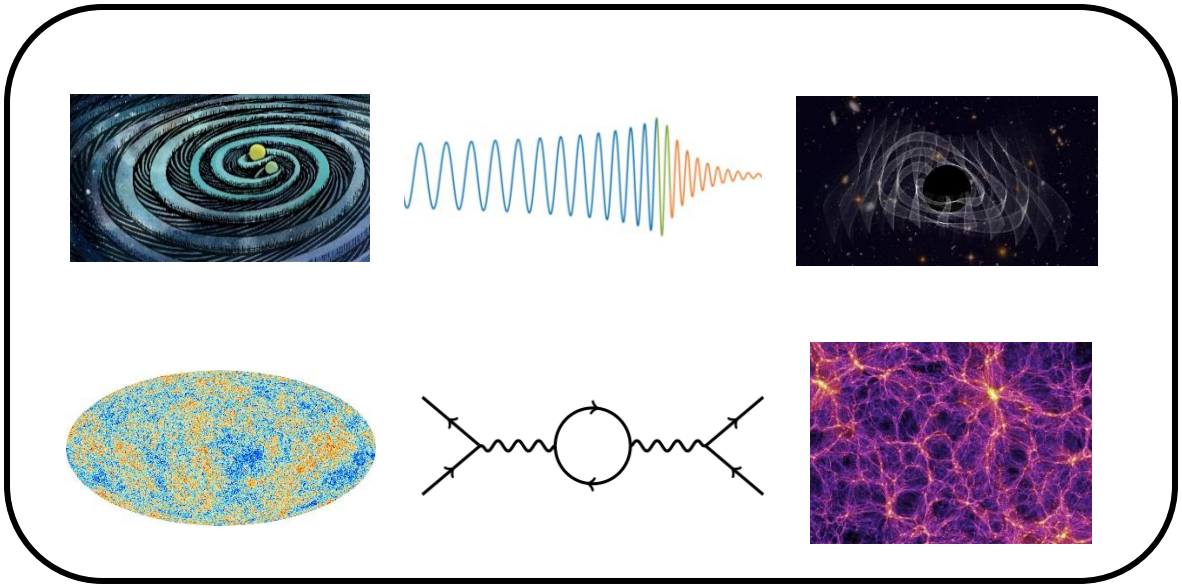
# Testing Gravity on all scales



**Johannes Noller**

ICG, University of Portsmouth (currently)
University College London (from autumn)

# Gravitational EFTs

GR/ΛCDM/MG/...

# Gravitational EFTs

UV completion
Quantum Gravity

GR/ΛCDM/MG/...

# Gravitational EFTs

UV completion
Quantum Gravity

GR/ΛCDM/MG/...

# Gravitational EFTs

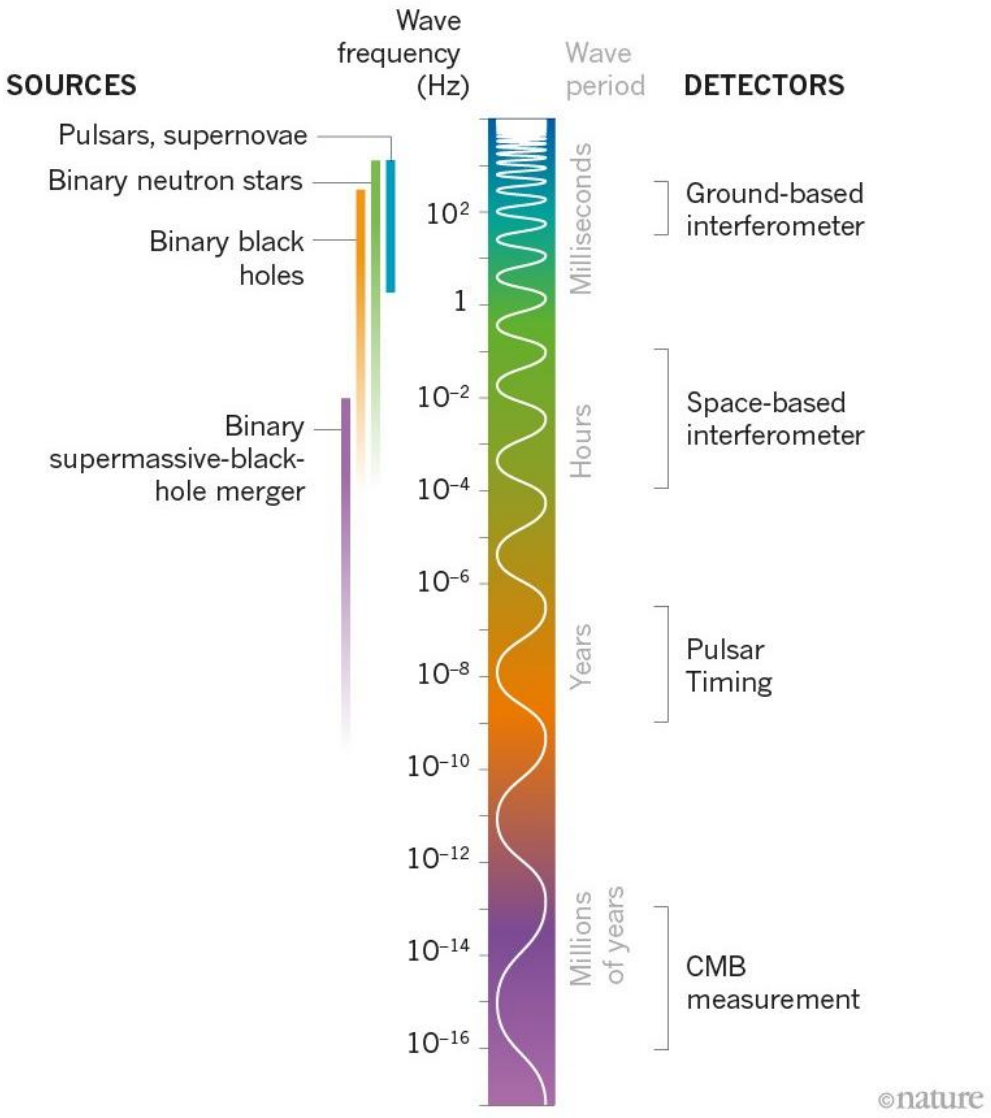
UV completion
Quantum Gravity

GR/ΛCDM/MG/...

Vacua/Solutions

EFTs around vacua

# Gravity's rainbow

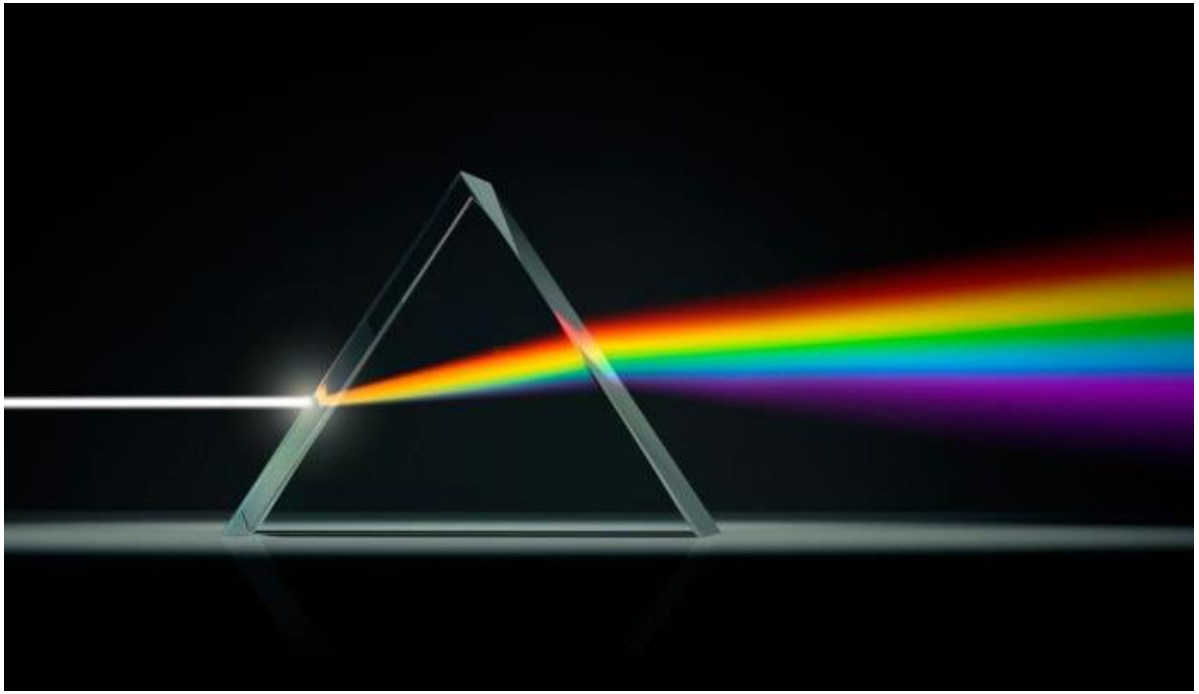



3

1

2

# Gravity's rainbow



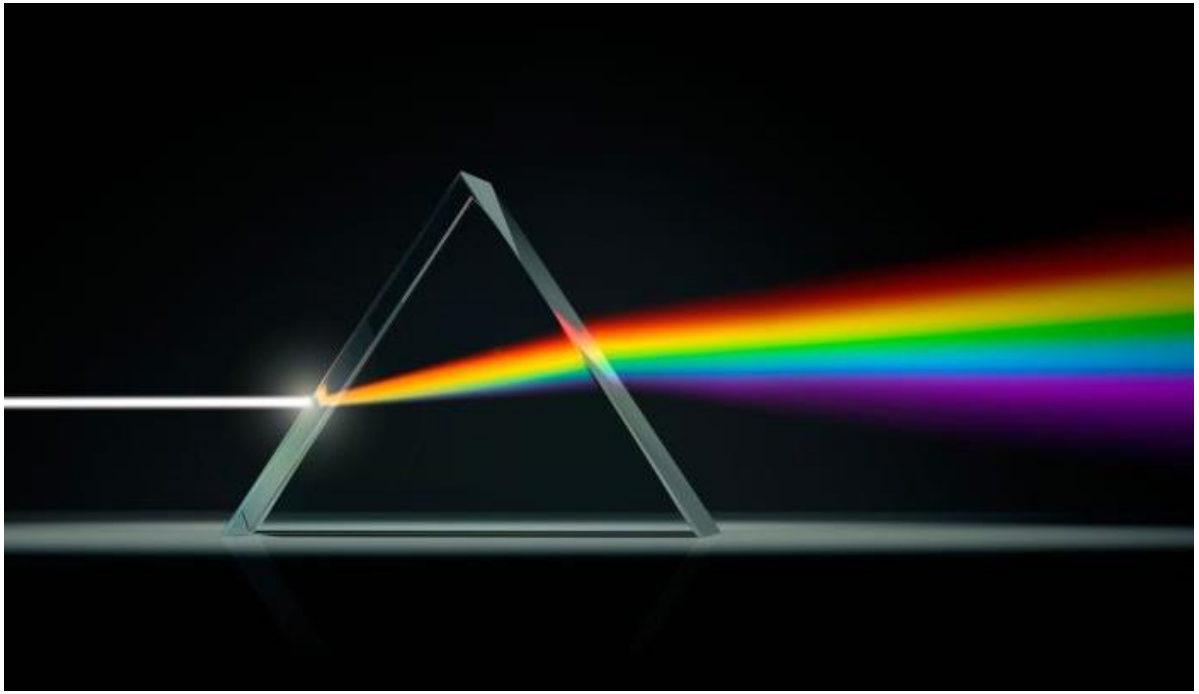
Gravitational wave 'h'

$$\ddot{h} + \underbrace{3H(1-\delta(f))\dot{h}}_{\text{Hubble friction}} + \underbrace{\left[(c^2+\alpha_T(f))k^2}_{\text{GW speed}} + \underbrace{m_g^2}_{\text{GW mass}}\right] h = 0$$

ΛCDM prediction

New physics

# Gravity's rainbow

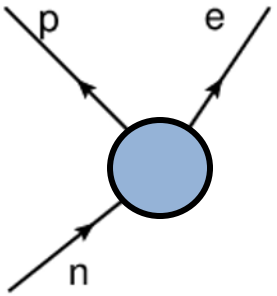


**Modified Dispersion Relation:** $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$

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

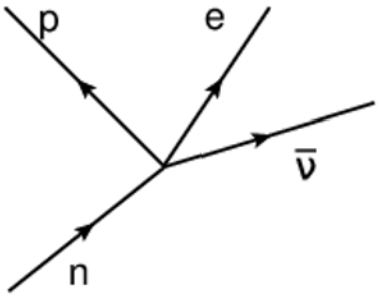
# The reach of a theory

# The reach of a theory



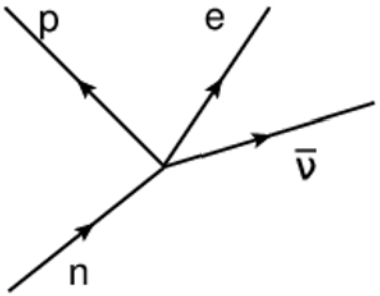

Neutron decay

# The reach of a theory




**Fermi theory**

# The reach of a theory




**Fermi theory**

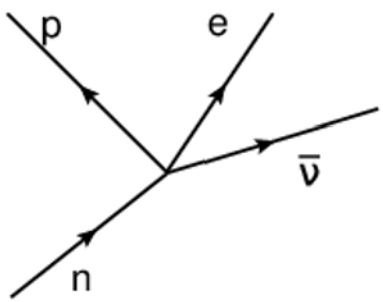
**Scattering amplitude:**

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

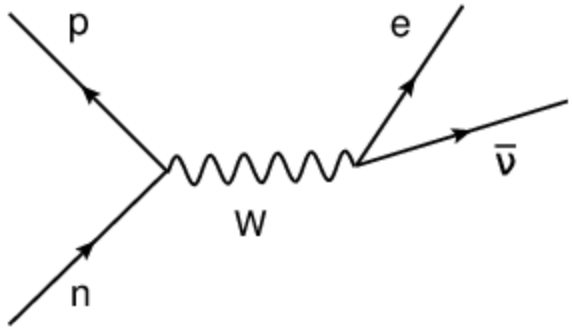
**Energy scaling:**

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

# The reach of a theory




**Fermi theory**




**Electro-weak theory**

**Scattering amplitude:**

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

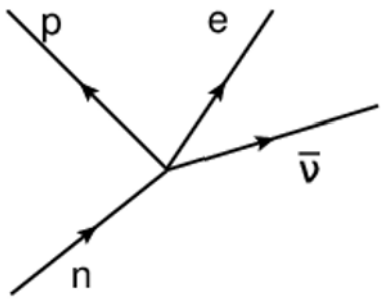
**Energy scaling:**

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

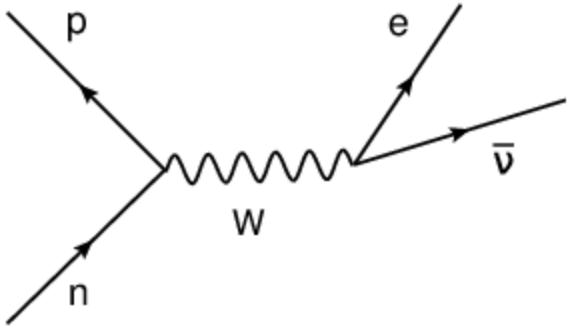
**The scale of new physics:**

$$m_{\text{W}} \sim 80 \text{ GeV}$$

# The reach of a theory




**Fermi theory**

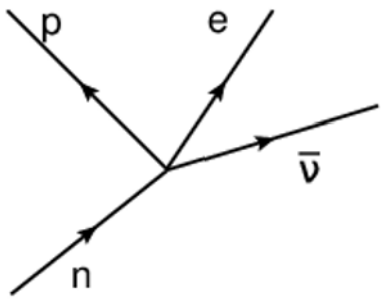



**Electro-weak theory**

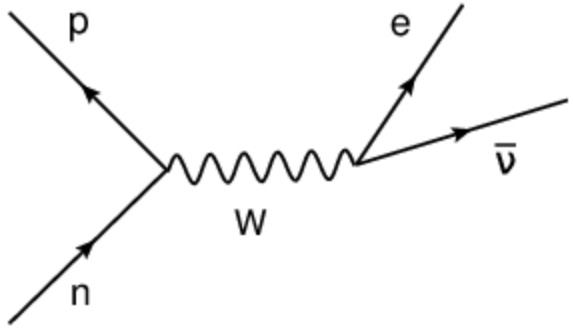
**Fermi theory:**

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

# The reach of a theory




**Fermi theory**




**Electro-weak theory**

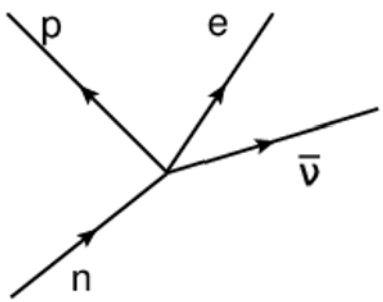
**Fermi theory:**

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

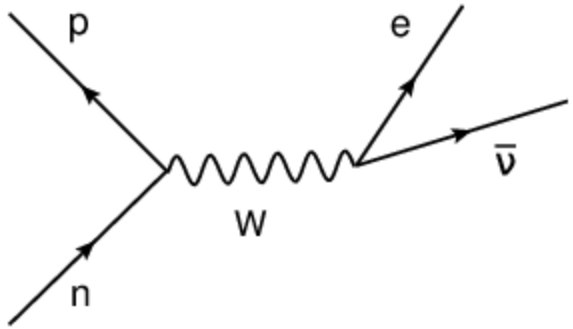
**General Relativity:**

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

# The reach of a theory




**Fermi theory**




**Electro-weak theory**

**Fermi theory:**

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

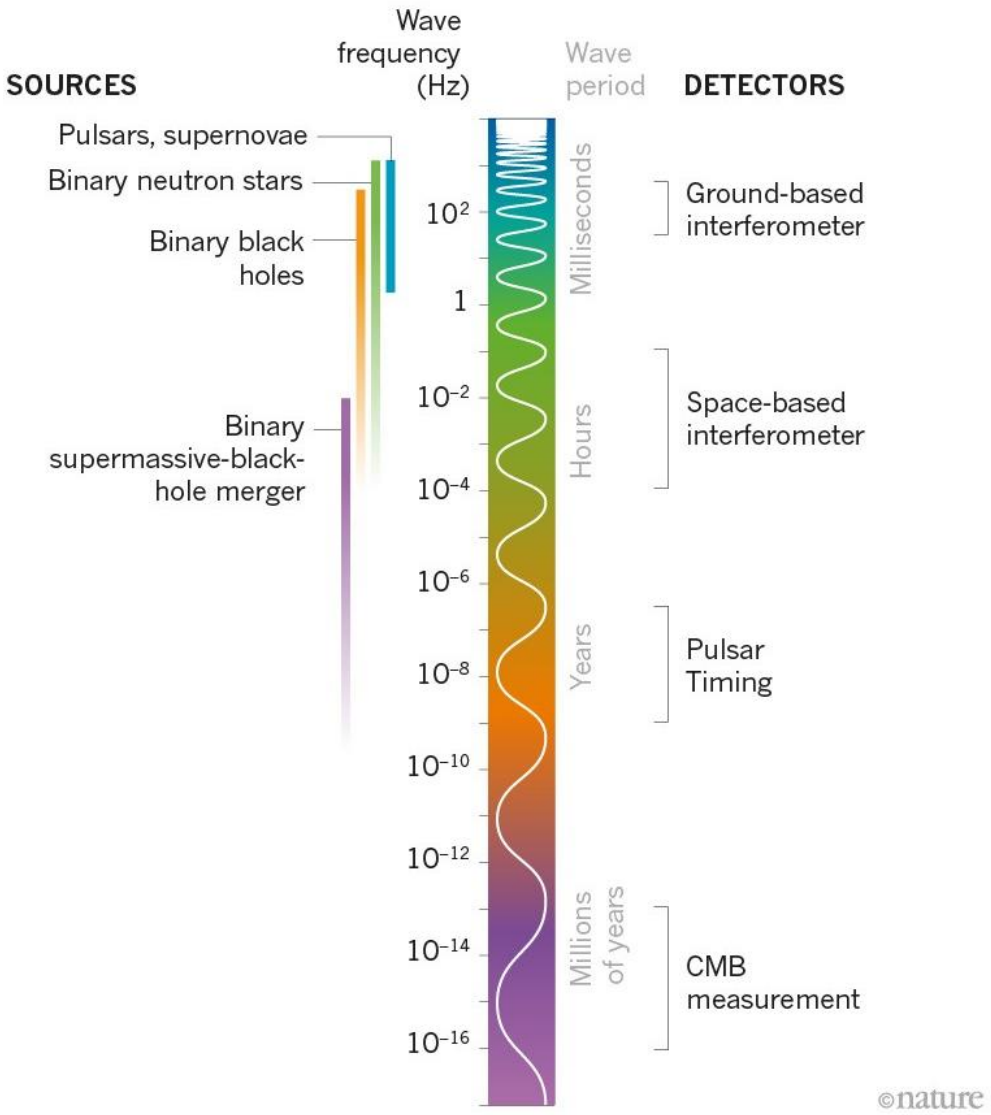
**General Relativity:**

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

**Dark Energy EFT:**

$$\mathcal{A} \sim \left(\frac{E}{10^{-12}\ \text{eV}}\right)^p$$

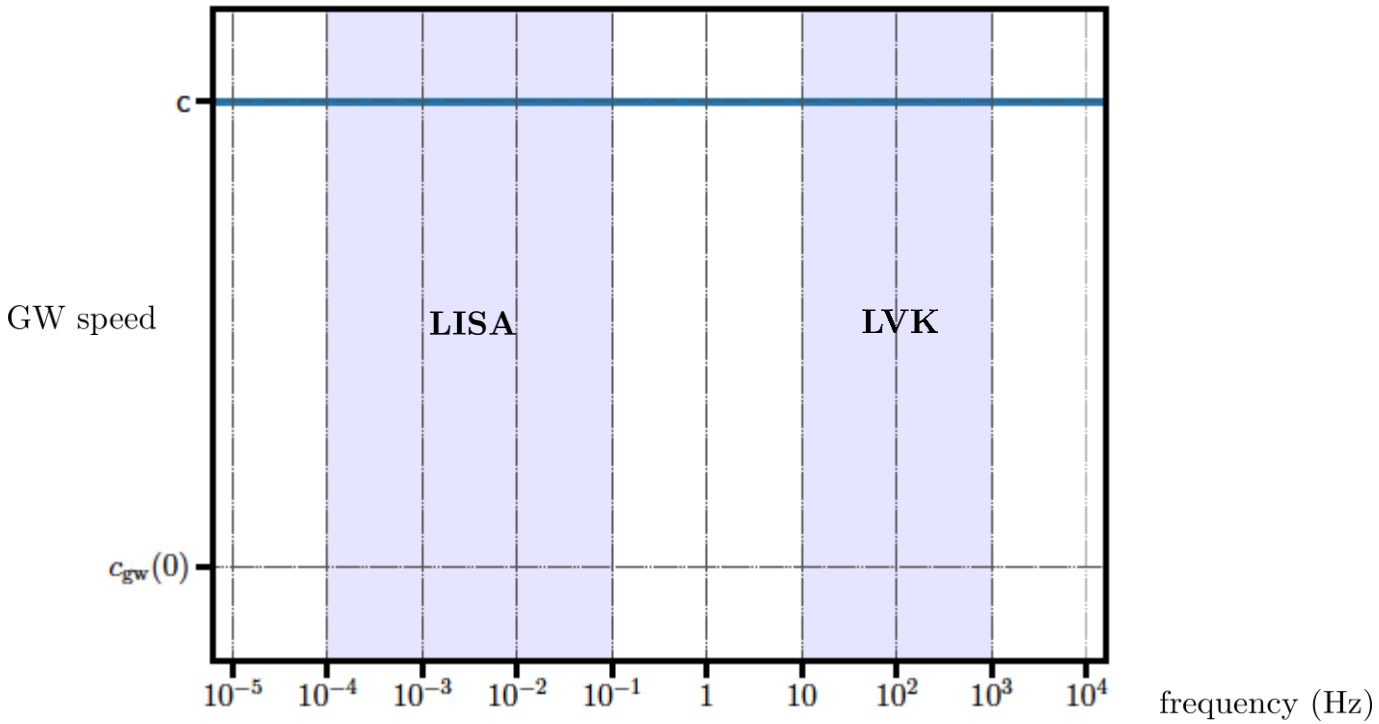
# Gravity's rainbow




**UV completion**

**Dark Energy phase**

# The speed of gravity



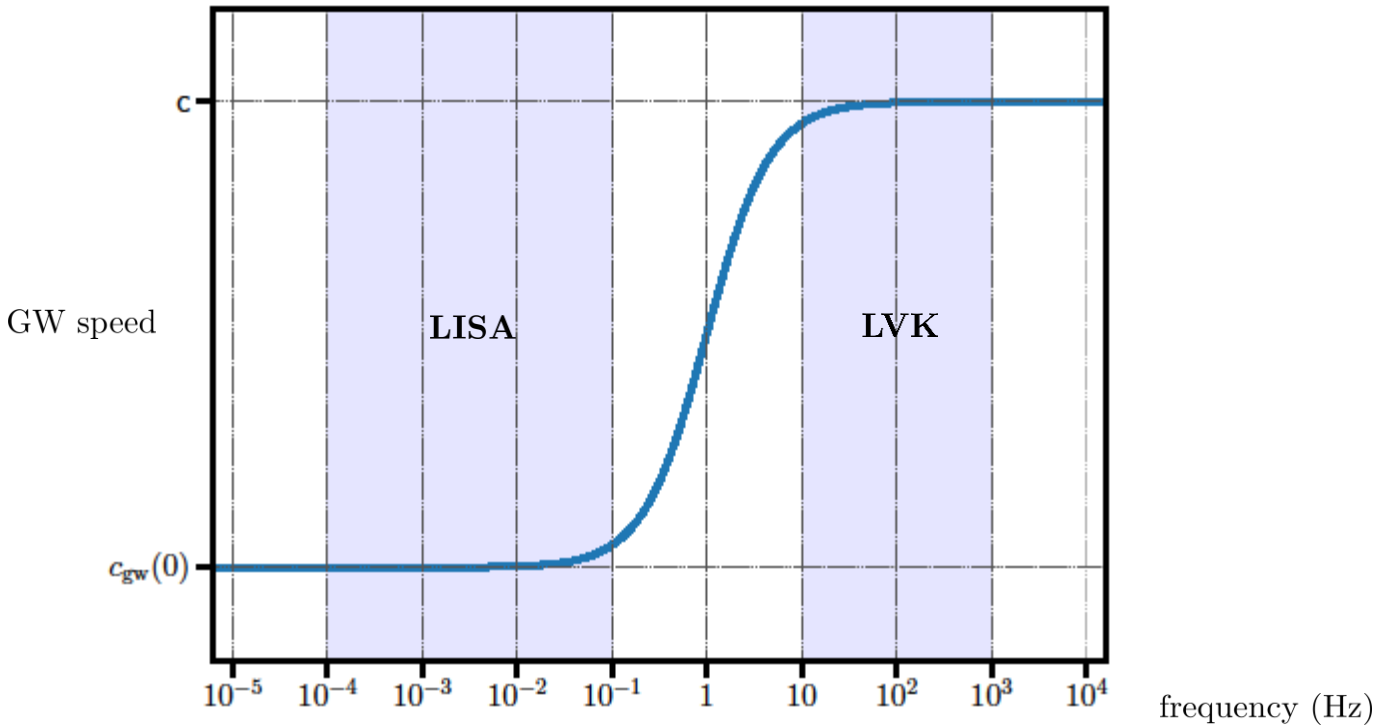

$$\delta c_{\rm GW} \equiv \frac{c_{\rm GW} - c}{c} \qquad \Rightarrow \qquad |\delta c_{\rm GW}| \lesssim 10^{-15}$$

*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 $c_{\rm gw}(0) \neq c$**

$\Downarrow$

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

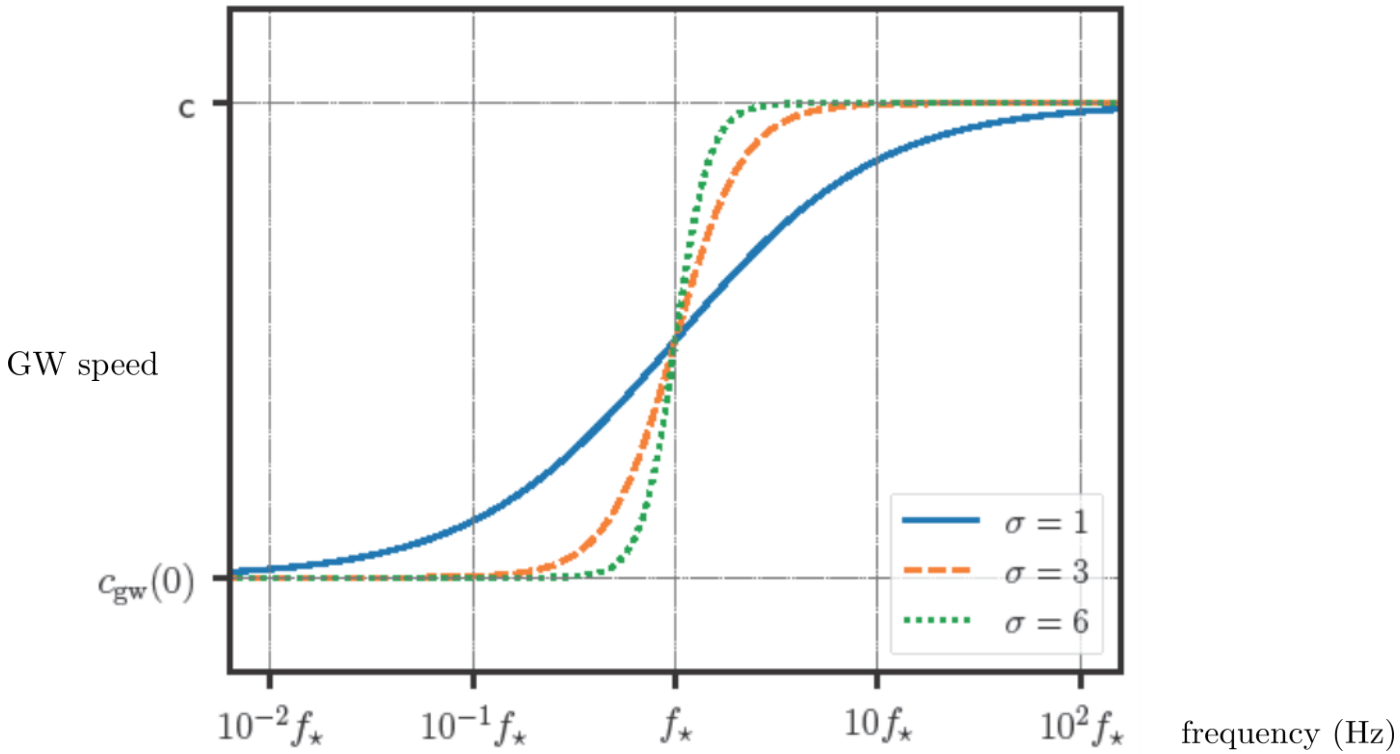
*de Rham, Melville '18*

$\Downarrow$

**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*

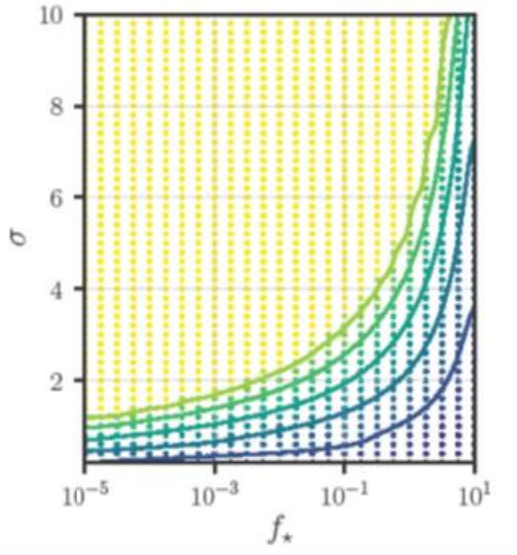
# The speed of gravity: A template

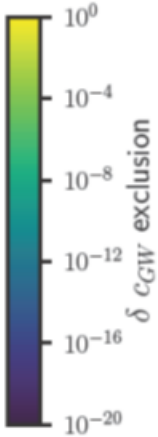



*Harry, JN '22*

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

# LVK & LISA constraints

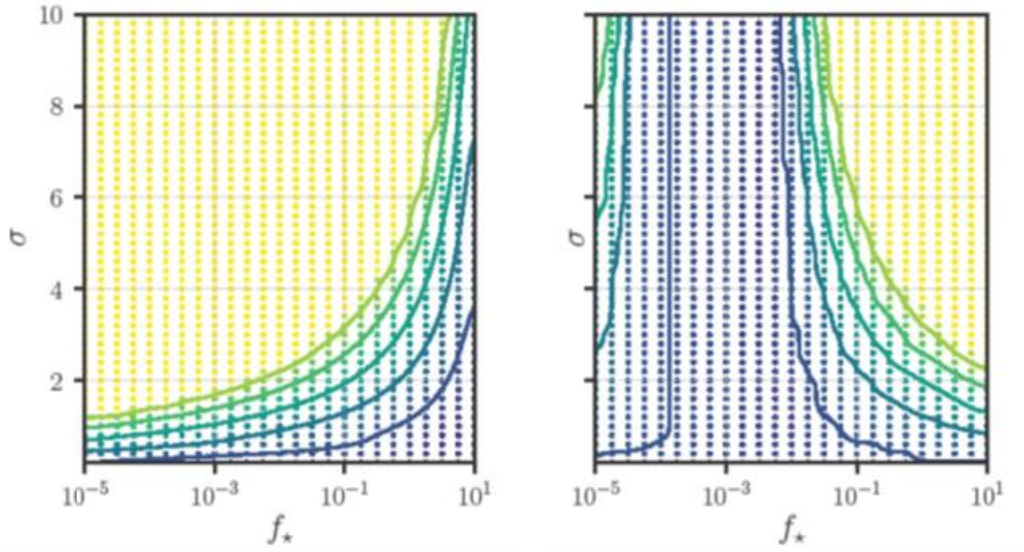


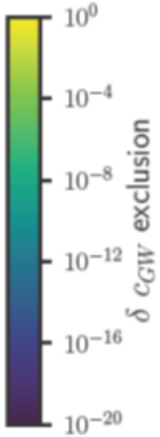




*Harry, JN '22*

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

# LVK & LISA constraints

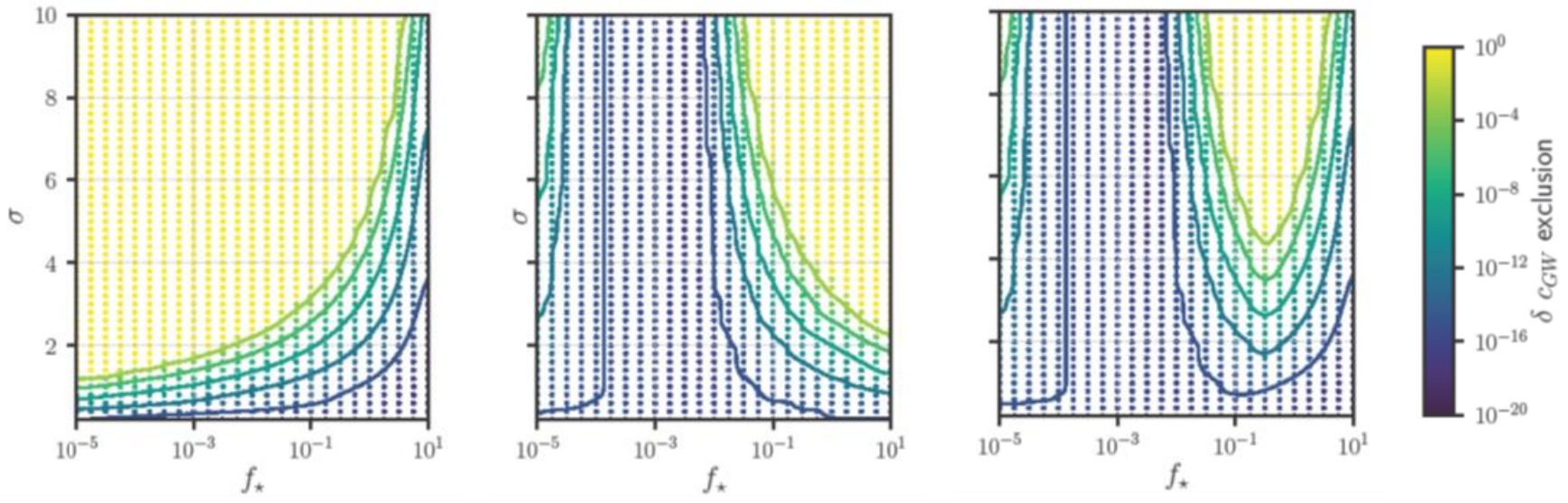



*Harry, JN '22*

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

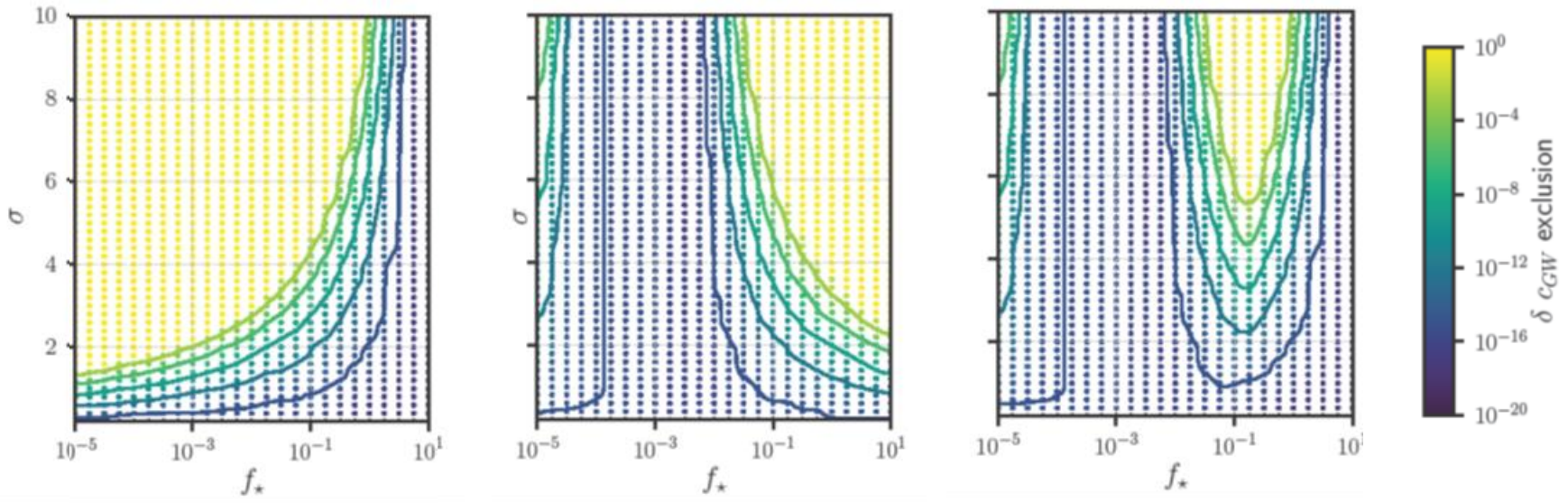
# LVK & LISA constraints




*Harry, JN '22*

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

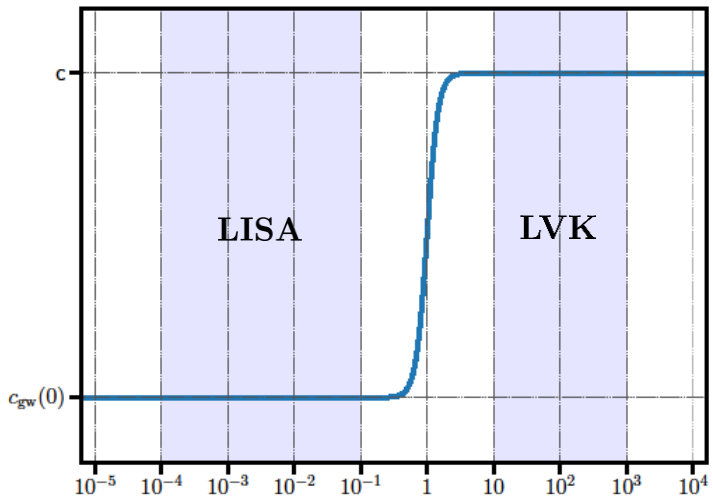
# ET & LISA constraints

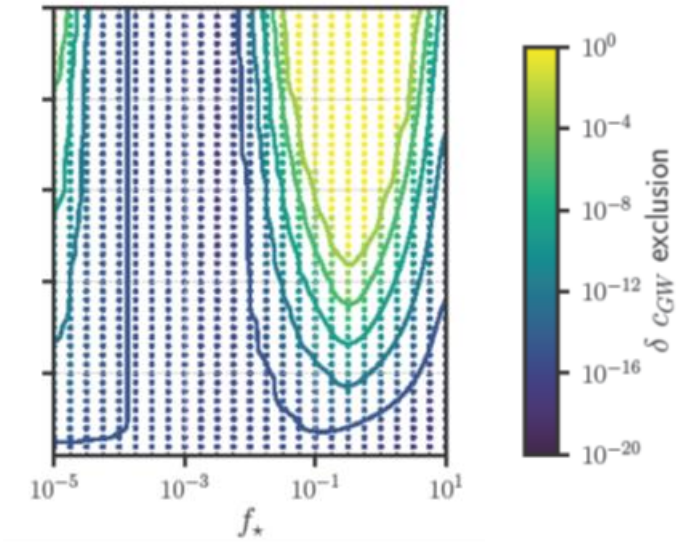



*Harry, JN '22*

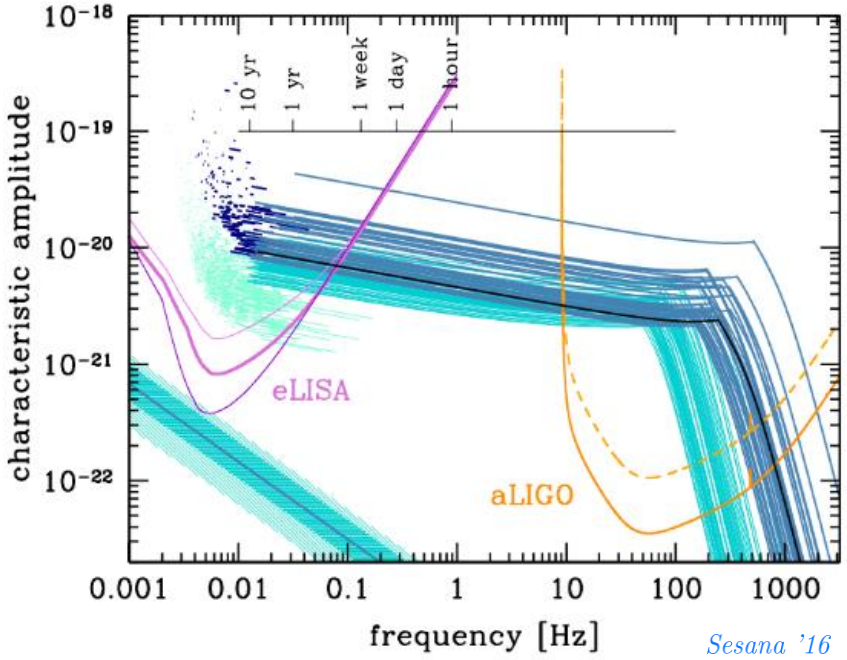
$$\delta c_{\rm GW}(f) = \delta c^{(0)}_{\rm GW}(\tfrac{1}{2} - \tfrac{1}{2}\tanh\left[\sigma \cdot \log\left(f/f_\star\right)\right])$$

# Multiband constraints



# Multiband constraints




*Sesana '16*

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

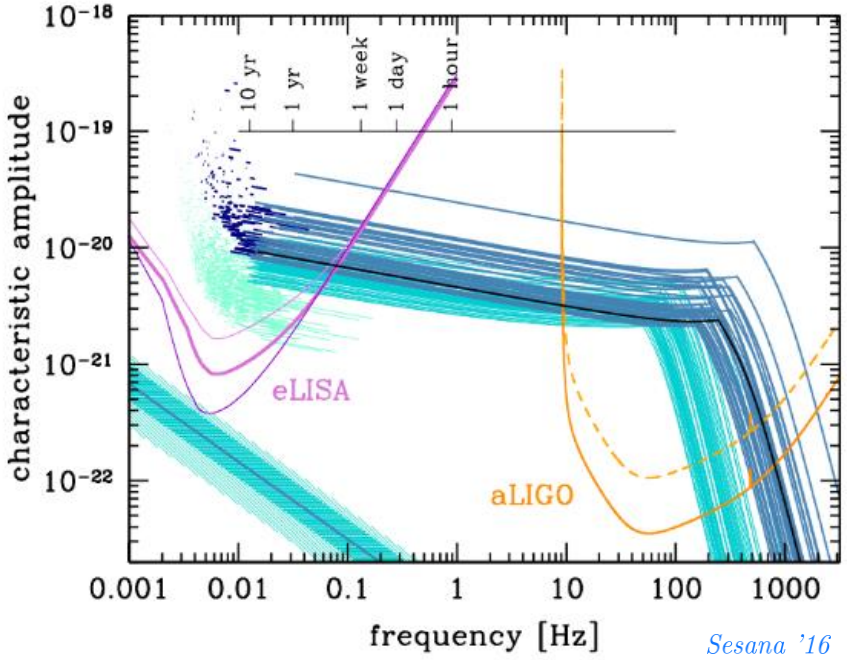
**Predict arrival time in LVK band with** $\sim 10s$ **accuracy.**

*Sesana '16*

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

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

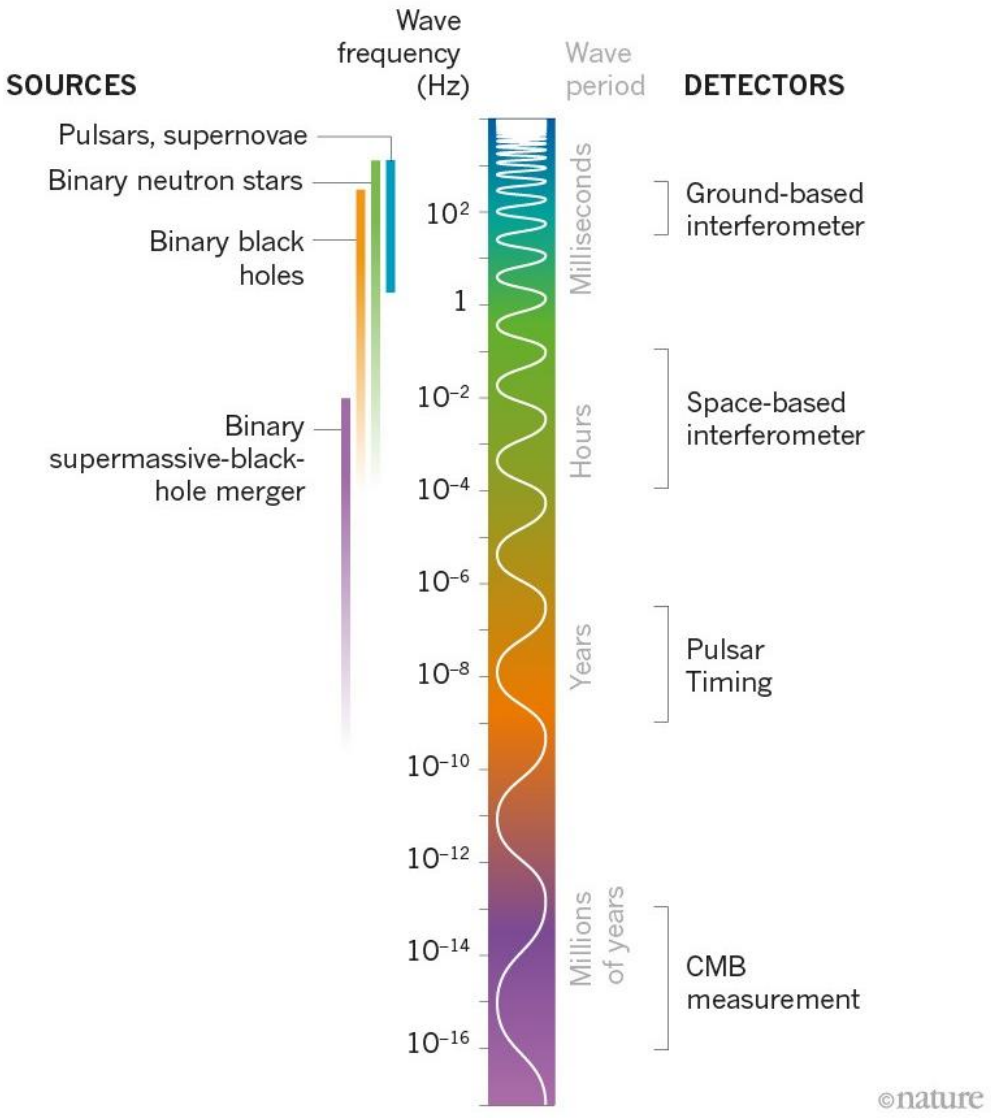
# Multiband constraints




**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** $|\delta c_{\rm gw}| \gtrsim 10^{-8}$.

# Gravity's rainbow

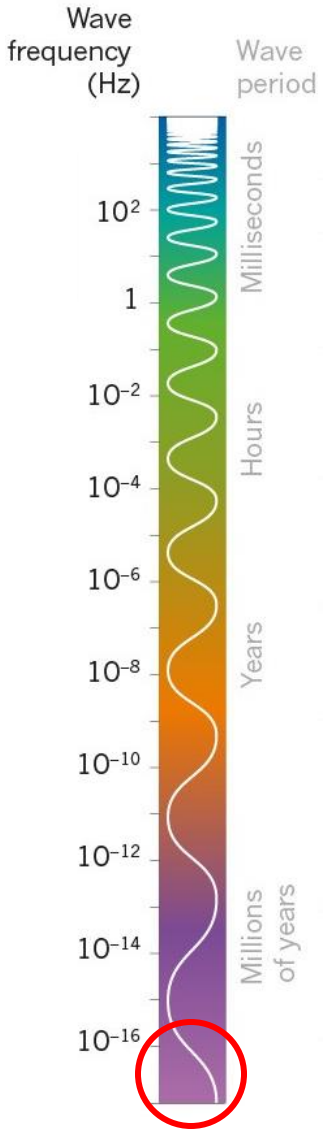



3

1

2

# Gravity's rainbow

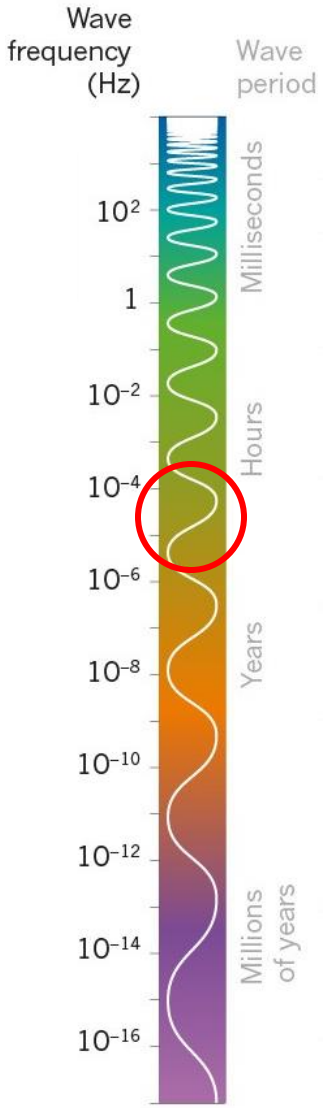



$$\nabla^2\Phi = 4\pi G a^2 \mu(\delta c_{\rm gw}, \ldots)\delta\rho$$

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, ...*

# Gravity's rainbow




$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{r^2}{32\pi c_T G_{\rm gw}} \int \mathrm{d}\Omega \, \langle \partial_t \gamma_{ij} \partial_t \gamma_{ij} \rangle$$

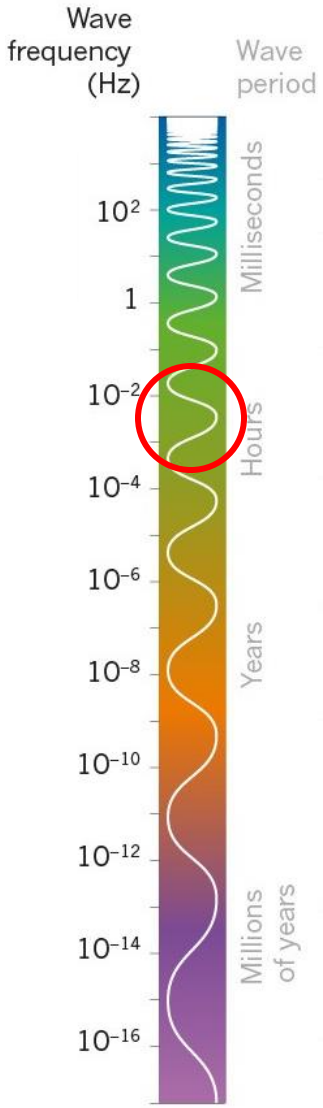
**Hulse-Taylor binary** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-2}$

*Beltran, Piazza, Velten '15*

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, ...*

# Gravity's rainbow




**Ultra-compact binaries** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-12}$

*Littenberg, Cornish '19*

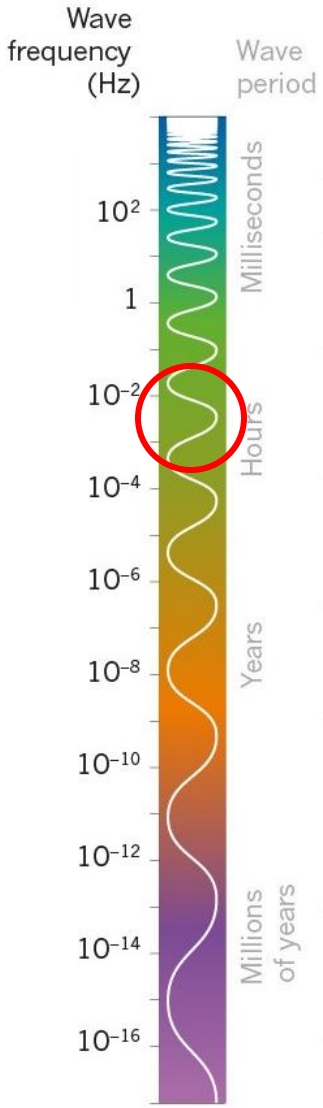
**Hulse-Taylor binary** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-2}$

*Beltran, Piazza, Velten '15*

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, ...*

# Gravity's rainbow




**BH ringdown** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-4}$

*Sirera Lahoz, JN '23*

**Ultra-compact binaries** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-12}$

*Littenberg, Cornish '19*

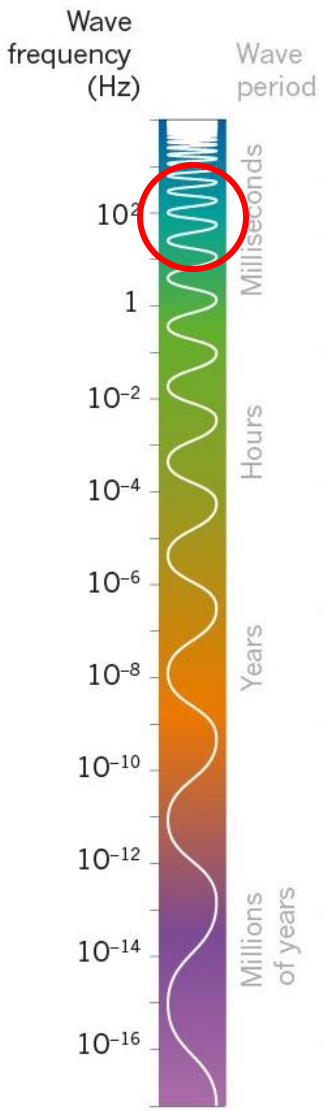
**Hulse-Taylor binary** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-2}$

*Beltran, Piazza, Velten '15*

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, ...*

# Gravity's rainbow




**GW170817** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-15}$

*LVK, Fermi, Integral, . . . '17*

**BH ringdown** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-4}$

*Sirera Lahoz, JN '23*

**Ultra-compact binaries** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-12}$

*Littenberg, Cornish '19*

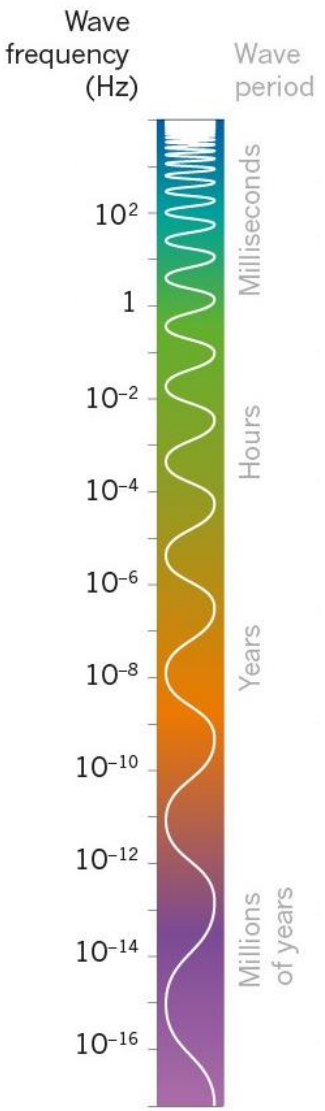
**Hulse-Taylor binary** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-2}$

*Beltran, Piazza, Velten '15*

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, . . .*

# Gravity's rainbow




**Gravitational Cherenkov** $\Rightarrow$ $\delta c_{\rm gw} \gtrsim -10^{-15}$

*Moore, Nelson '01*

**GW170817** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-15}$

*LVK, Fermi, Integral, ... '17*

**BH ringdown** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-4}$

*Sirera Lahoz, JN '23*

**Ultra-compact binaries** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-12}$

*Littenberg, Cornish '19*

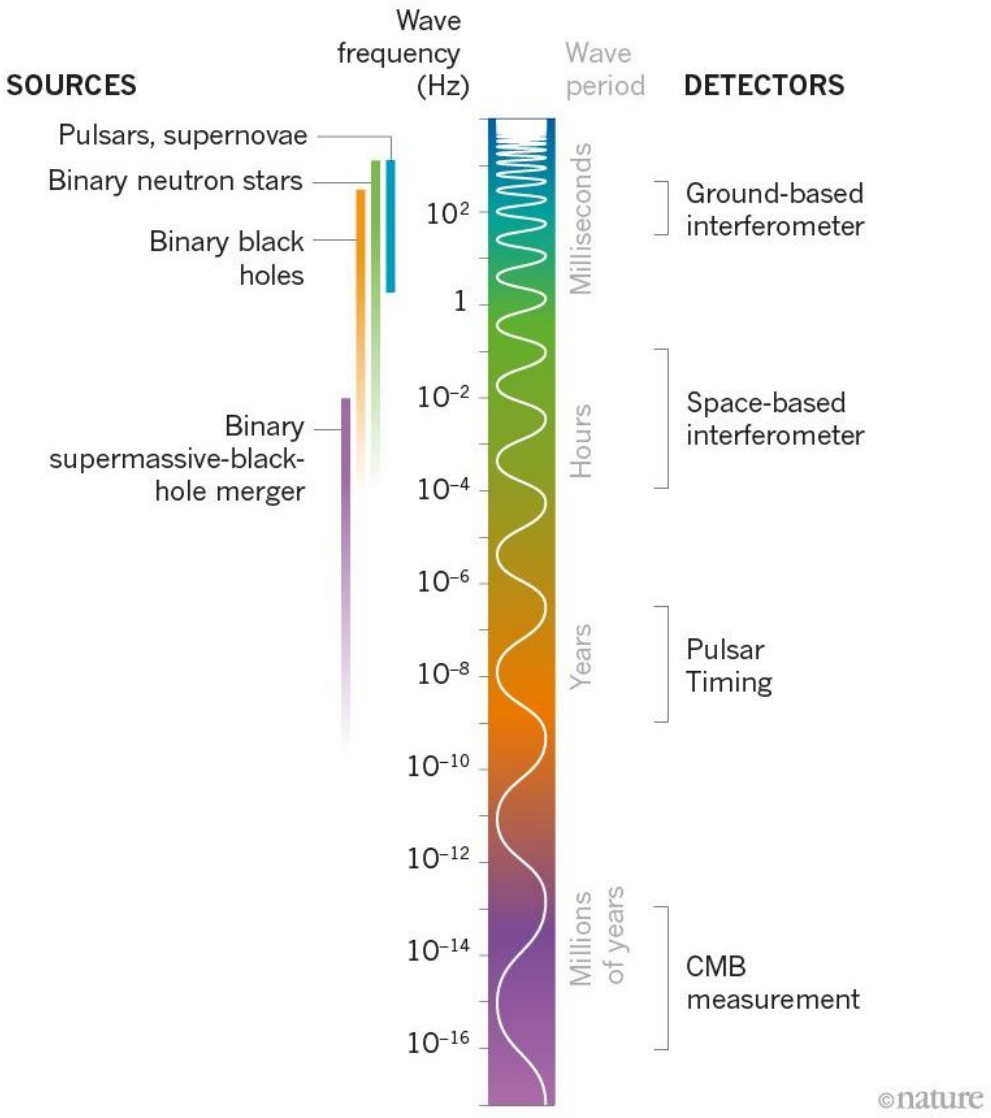
**Hulse-Taylor binary** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 10^{-2}$

*Beltran, Piazza, Velten '15*

**Cosmological structure formation** $\Rightarrow$ $|\delta c_{\rm gw}| \lesssim 1$

*Raveri, Baccigalupi, Silvestri, Zhou '14, Bellini, Cuesta, Jimenez, Verdde '15, JN, Nicola '18, ...*

# Gravity's rainbow



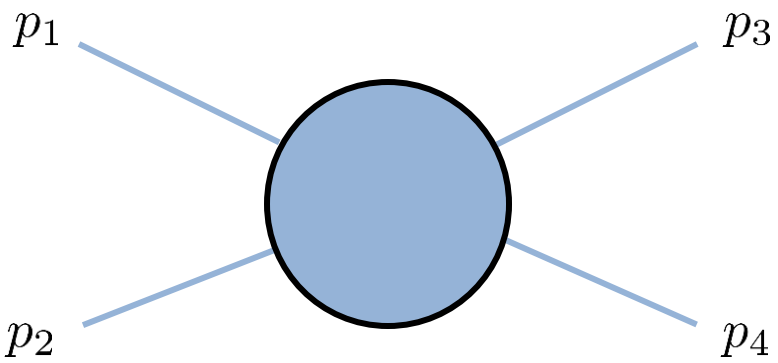

3

1

2

# Positivity

**Theoretical bounds that any**
*unitary, local and causal*
**gravitational theory has to satisfy**




**Scattering amplitude:** $\mathcal{A}$

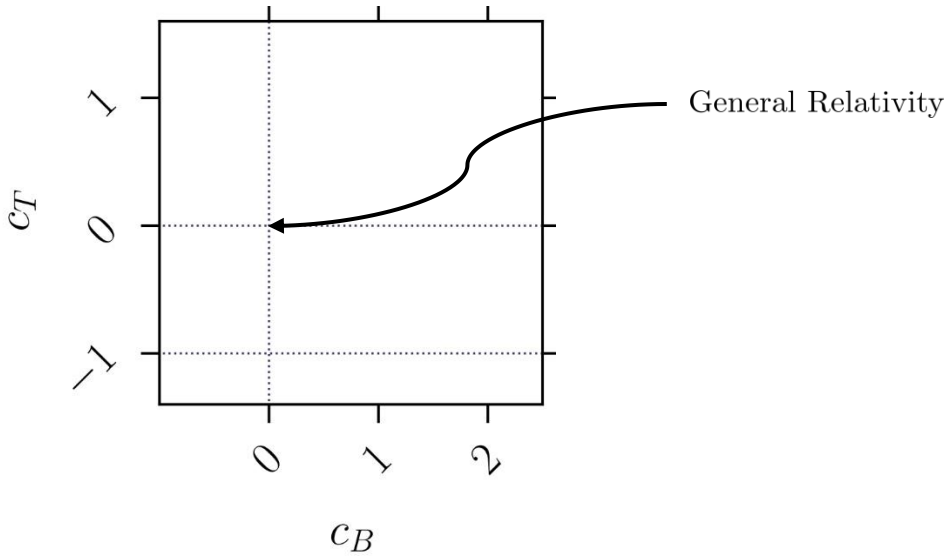
# A case study

GWs faster than photons

y-axis $\sim$ what is the speed of gravitational waves?



Photons faster than GWs




x-axis $\sim$ how much does the graviton interact with DE scalar?

---

$$\mathcal{L} = G_2 + G_4 R + G_{4,X} \left\{ (\Box\phi)^2 - \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi \right\},$$

where $G_i \equiv G_i(X)$ and $X \equiv -\frac{1}{2}\nabla^\mu \phi \nabla_\mu \phi$

# A case study

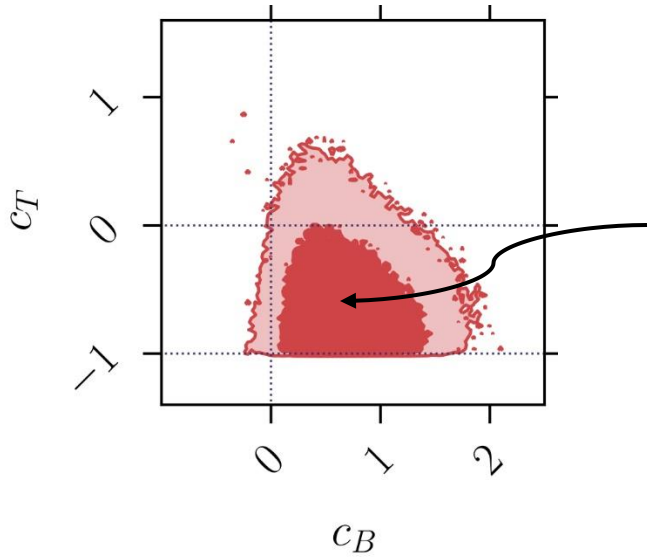
GWs faster than photons

↑

y-axis ∼ what is the speed of gravitational waves?

↓

Photons faster than GWs




Data constraints from CMB and LSS

**JN**, *Nicola '18*

x-axis ∼ how much does the graviton interact with DE scalar?

# A case study

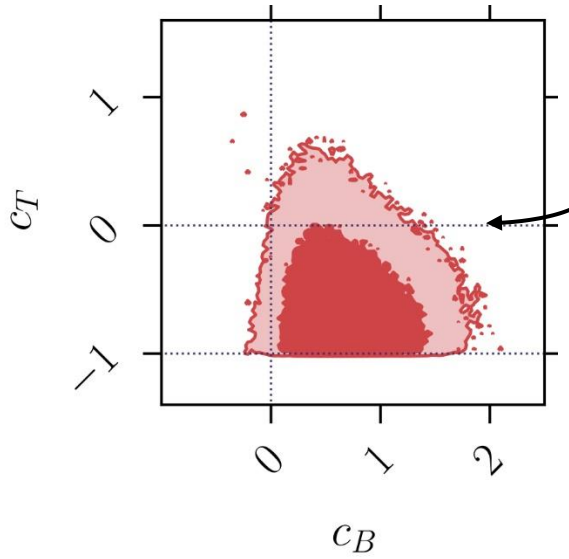
GWs faster than photons

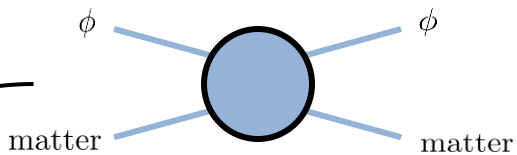
↑

y-axis ∼ what is the speed of gravitational waves?

↓

Photons faster than GWs




*de Rham, Melville,* **JN** *'21*

x-axis ∼ how much does the graviton interact with DE scalar?

# A case study

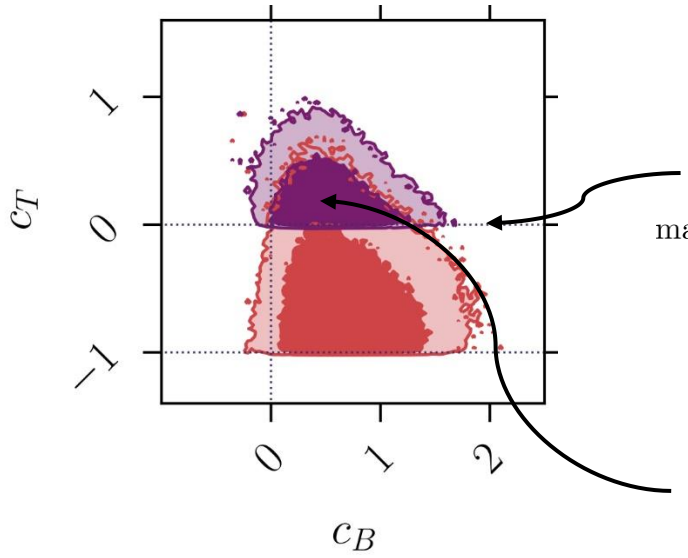
GWs faster than photons

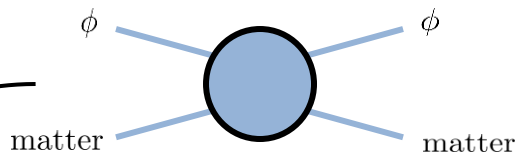
↑

y-axis ∼ what is the speed of gravitational waves?

↓

Photons faster than GWs



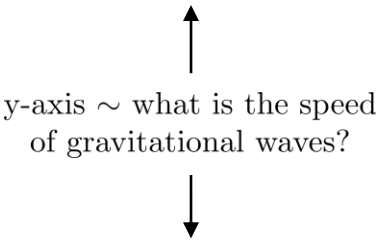

*de Rham, Melville,* **JN** *'21*

Data constraints with this positivity prior

x-axis ∼ how much does the graviton interact with DE scalar?

# A case study

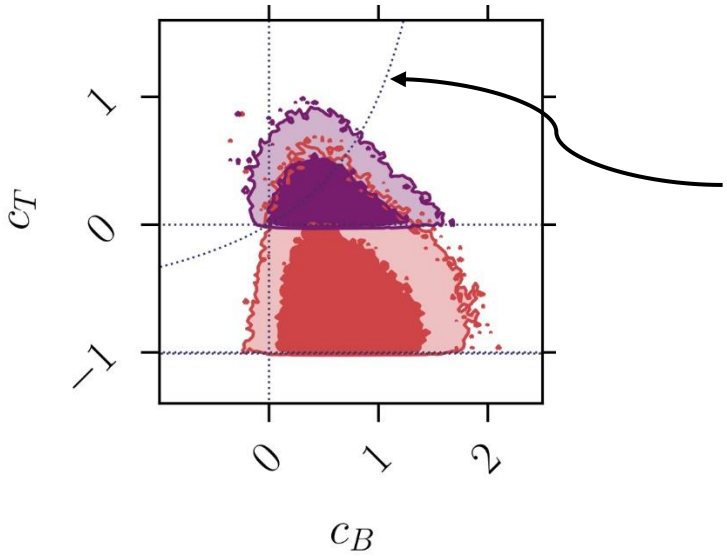
GWs faster than photons

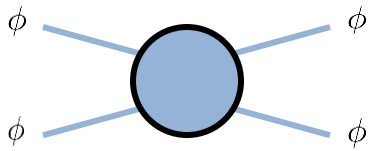


y-axis $\sim$ what is the speed of gravitational waves?



Photons faster than GWs




*Melville,* **JN** *'19*

x-axis $\sim$ how much does the graviton interact with DE scalar?

# A case study

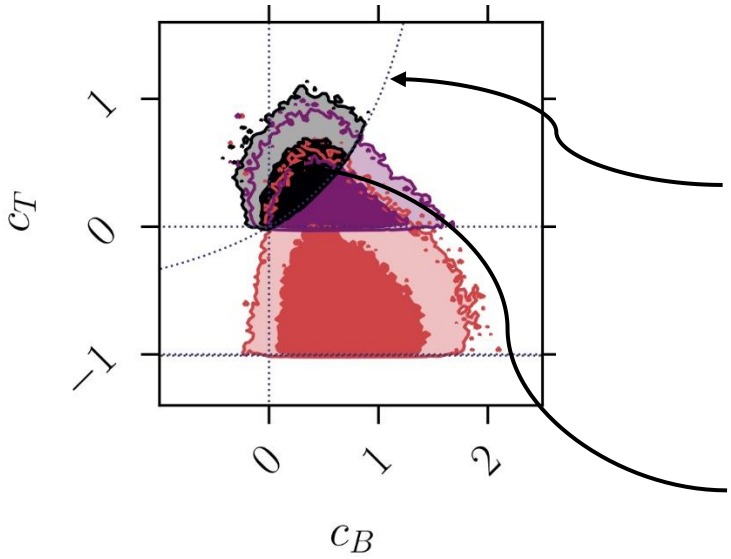
GWs faster than photons

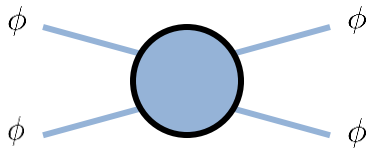
↑

y-axis ∼ what is the speed of gravitational waves?

↓

Photons faster than GWs




*Melville,* **JN** *'19*

Data constraints with both positivity priors

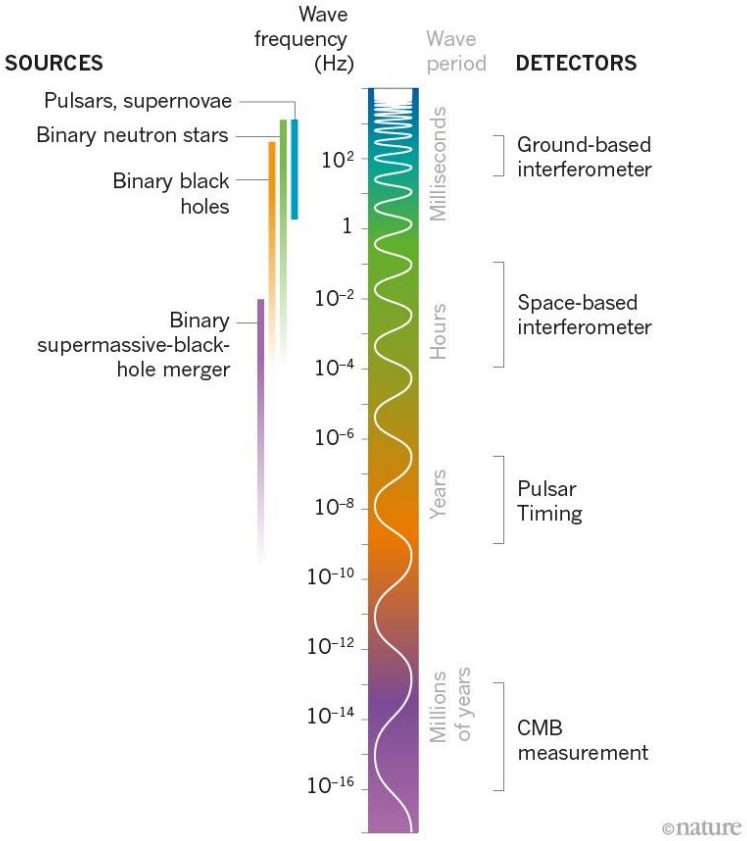
x-axis ∼ how much does the graviton interact with DE scalar?

---

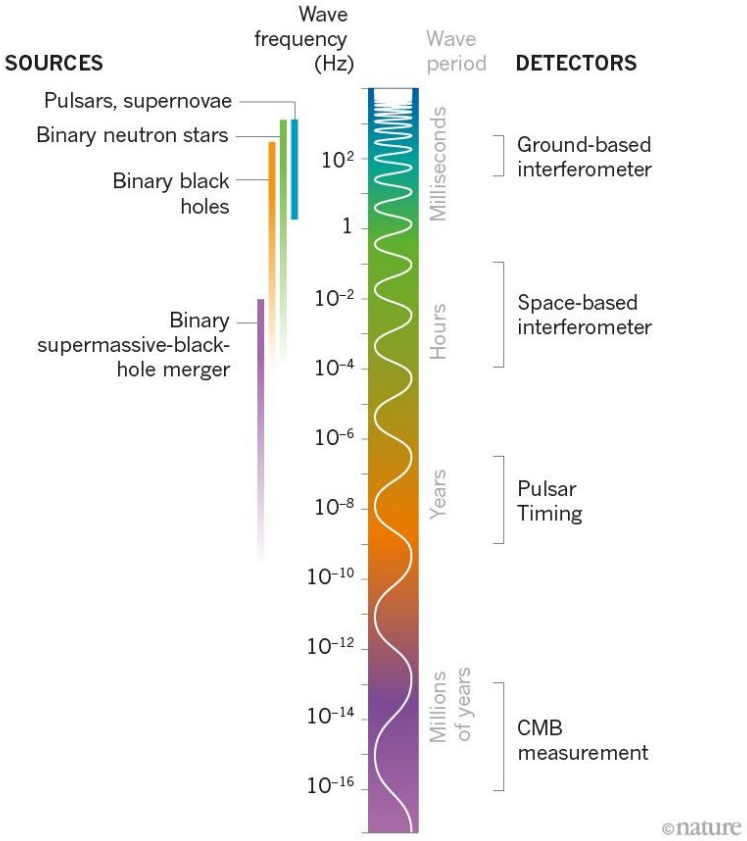
**Key observations:**

- Positivity priors tighten constraints.
- Physical vs. unphysical parameter space.
- Alternative perspective: IR test of UV physics.

# Testing Gravity on all scales



# Testing Gravity on all scales




# Thank you!