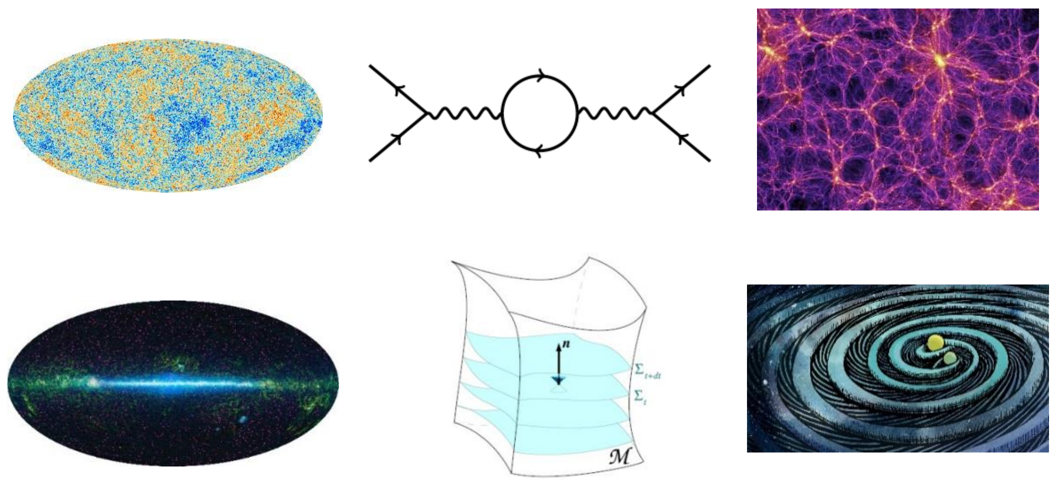
Testing gravity on all scales

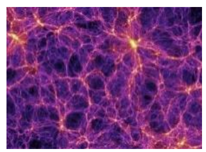


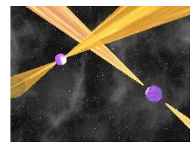
Johannes Noller

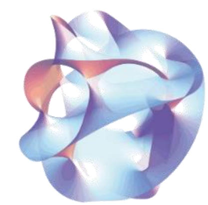
ICG, University of Portsmouth
DAMTP, University of Cambridge

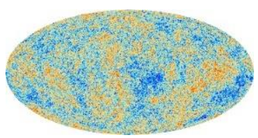
69th Copernicus Webinar, 16/11/2021

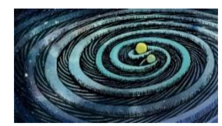
Gravity across scales











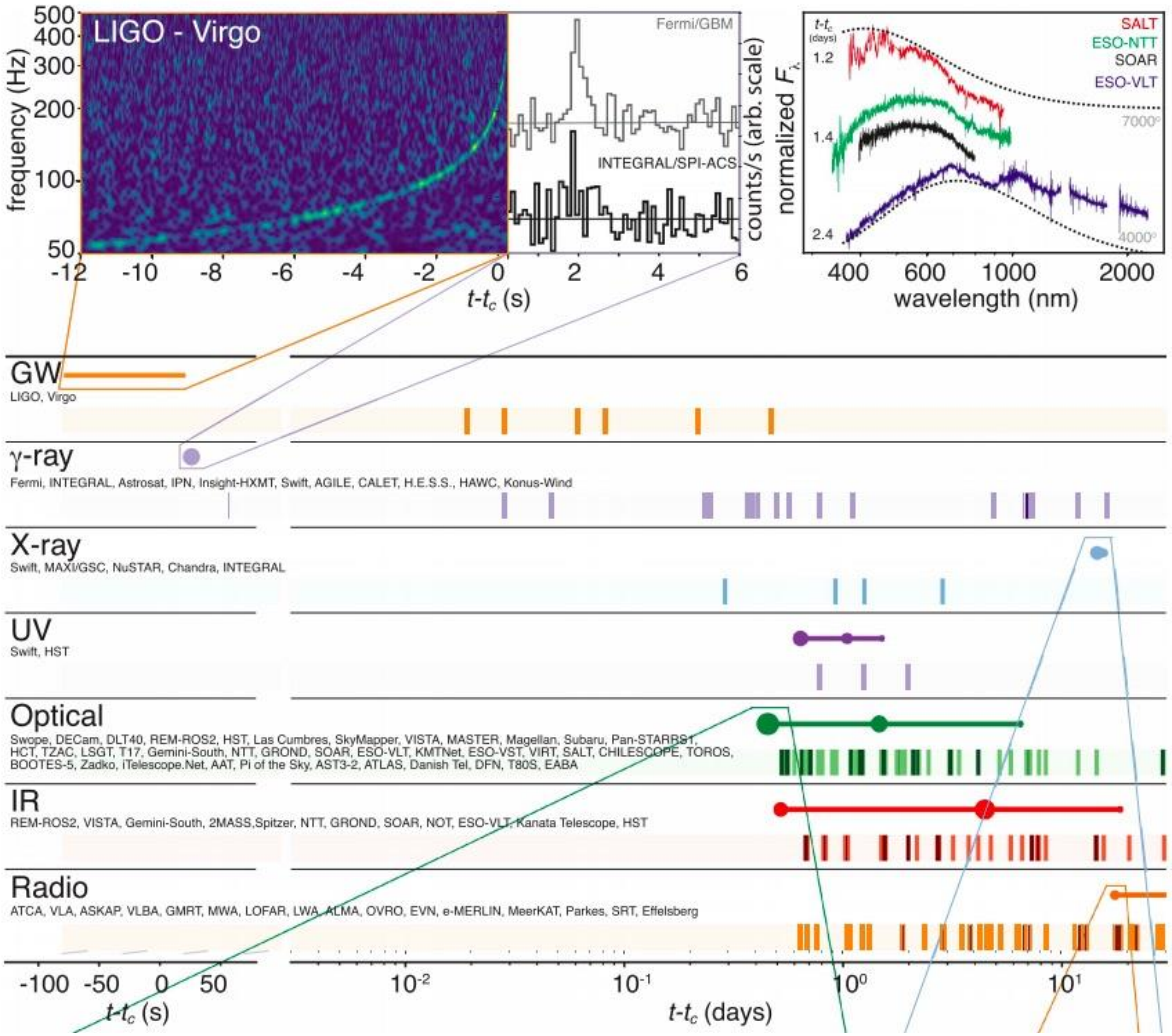
Frequency (Hz):	10^{-18}	10^{-13}	10^{-8}	10^{-2}	10^{2}	10^{43}
Distance (km):	10^{23} km	10^{18} km	10^{13} km	10^{7} km	10^{3} km	10^{-38} km

Gravity across scales

"The elegant logic of general relativity theory, and its precision tests, recommend GR as the first choice for a working model for cosmology. But the Hubble length is fifteen orders of magnitude larger than the length scale of the precision tests, at the astronomical unit and smaller, a spectacular extrapolation."

Jim Peebles, IAU 2000

GW170817



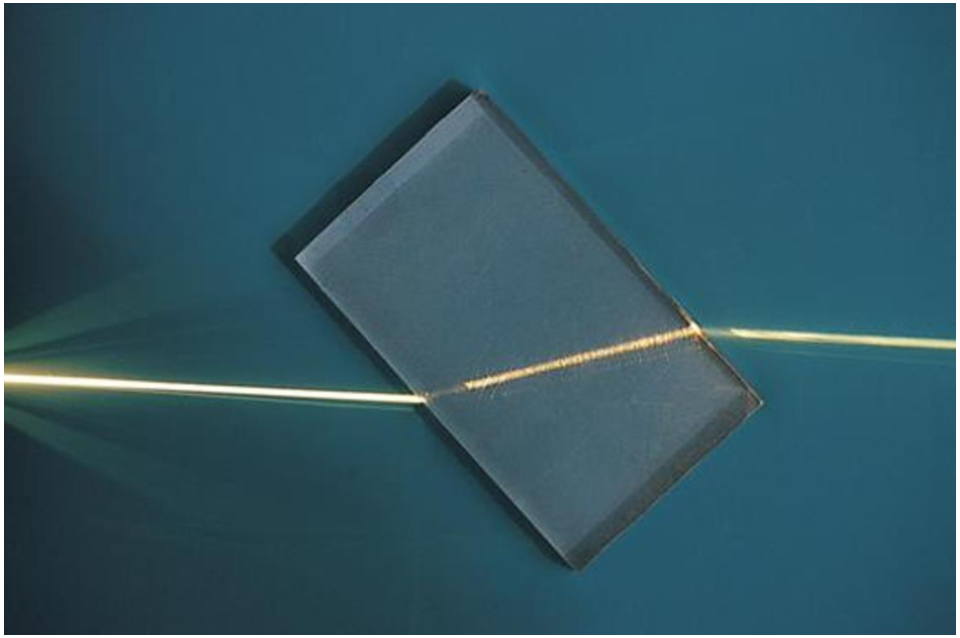
Abbott et al '17

The speed of gravitational waves

$$ds^2 = -dt^2 + a^2(t)\left[\delta_{ij} + \gamma_{ij}\right] dx^i dx^j$$

$$\Downarrow$$

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + c_{\rm GW}^2 k^2 \gamma_{ij} = 0$$



Constraints on speed of GWs: $|c_{\rm GW}^2 - 1| \lesssim 10^{-15}$.

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

The speed of gravitational waves

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + c_{\rm GW}^2 k^2 \gamma_{ij} = 0$$

$$\mathcal{L} = G_2 + G_3 \Box\phi + G_4 R + G_{4,X}\left\{(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right\} + G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$
$$- \frac{1}{6}G_{5,X}\left\{(\Box\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right\}.$$

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

Horndeski '74, Deffayet et al. '11

$$\Downarrow$$

$$\mathcal{L} = G_4(\phi)R + G_2(\phi, X) - G_3(\phi, X)\Box\phi$$

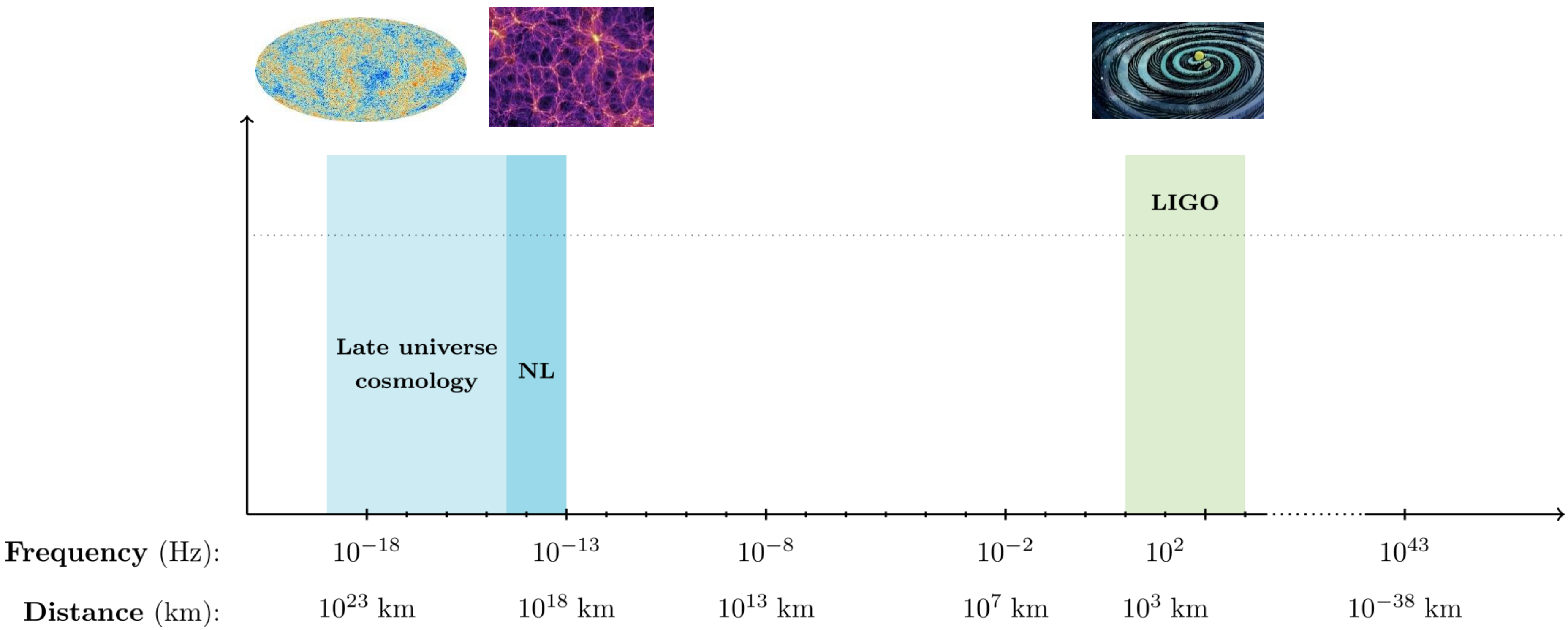
*Baker, Bellini, Ferreira, Lagos, **JN**, Sawicki '17, Creminelli, Vernizzi '17, Ezquiaga, Zumalacarregui '17, Sakstein, Jain '17*

Also see: Deffayet, Pujolas, Sawicki, Vikman '10, Amendola et al. '12, Linder '14, Saltas et al. '14, Beltran Jimenez et al. '15, Sawicki et al. '16, Bettoni et al. '16, Lombriser, Lima '16, Cornish et al. '17, ...

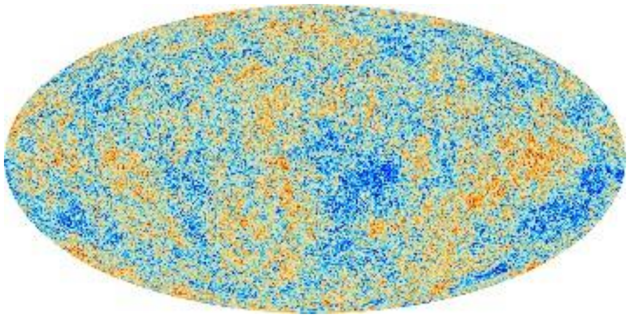
Constraints on speed of GWs: $|c_{\rm GW}^2 - 1| \lesssim 10^{-15}$.

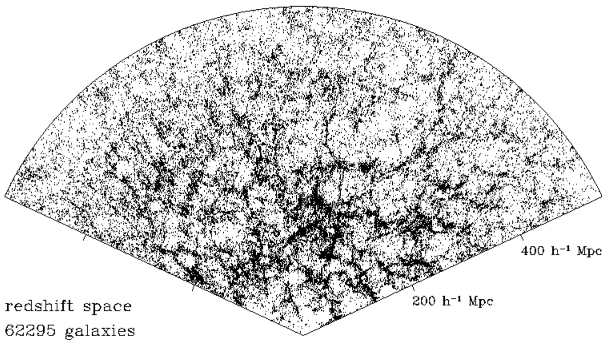
LIGO & Virgo Collaborations '17, Fermi, IGAL '17

Gravity across scales



Probing Dark Energy: CMB + LSS

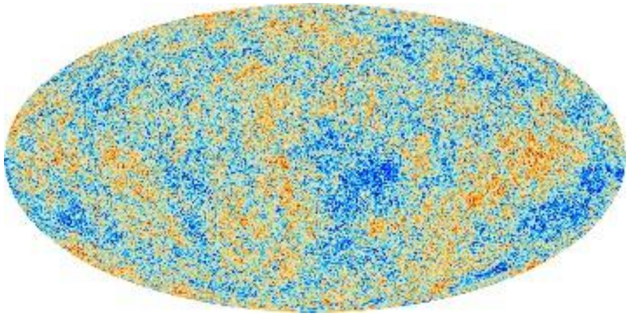


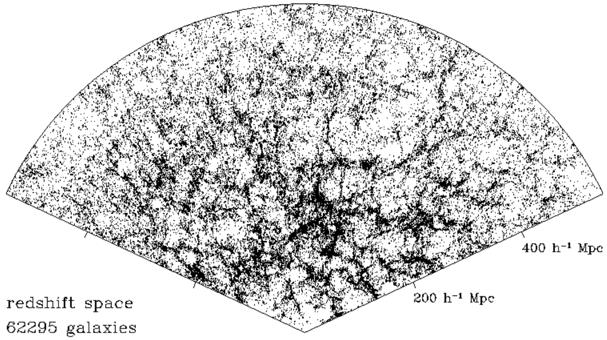


Metric fluctuations: $$ds^2 = a^2(\tau)\left[-(1+2\Phi)d\tau^2 + (1-2\Psi)dx_i dx^i\right]$$

Free-falling particles: $$\frac{1}{a}\frac{d(a\boldsymbol{v})}{d\tau} = \boldsymbol{\nabla}\Phi \quad \text{(CDM)} \qquad\qquad \frac{d(\boldsymbol{v})}{d\tau} = \boldsymbol{\nabla}_\perp(\Phi+\Psi) \quad \text{(photons)}$$

Probing Dark Energy: CMB + LSS





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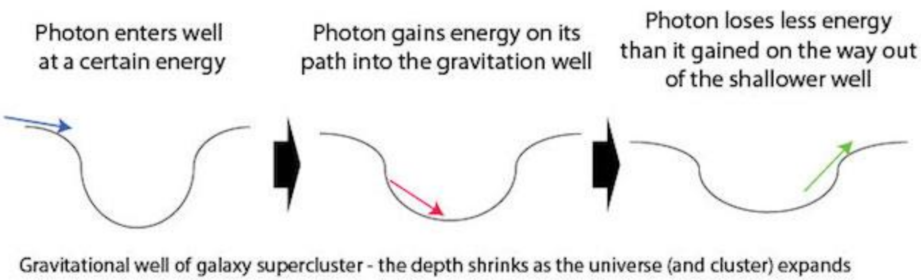
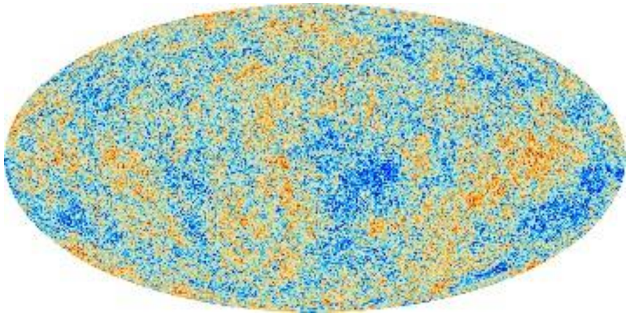
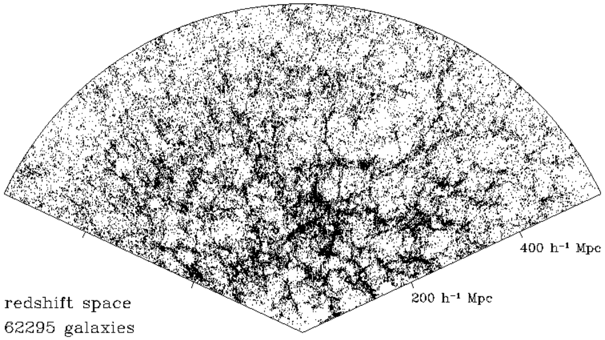
ISW effect: $$\frac{\delta T}{T} = \text{initial conditions} + \int_{\tau_\star}^{\tau_0} d\tau(\dot{\Phi}+\dot{\Psi})$$



Probing Dark Energy: CMB + LSS





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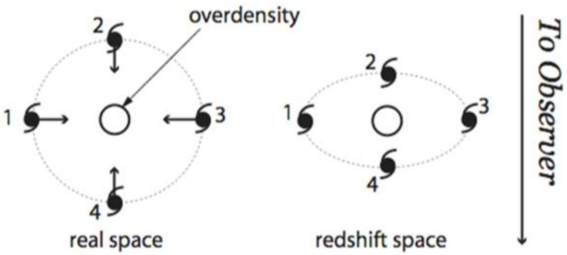
Free-falling particles: $$\frac{1}{a}\frac{d(a\boldsymbol{v})}{d\tau} = \boldsymbol{\nabla}\Phi \quad \text{(CDM)} \qquad\qquad \frac{d(\boldsymbol{v})}{d\tau} = \boldsymbol{\nabla}_\perp(\Phi+\Psi) \quad \text{(photons)}$$

Poisson equation: $$\nabla^2\Phi = 8\pi G_N(t)\delta\rho$$

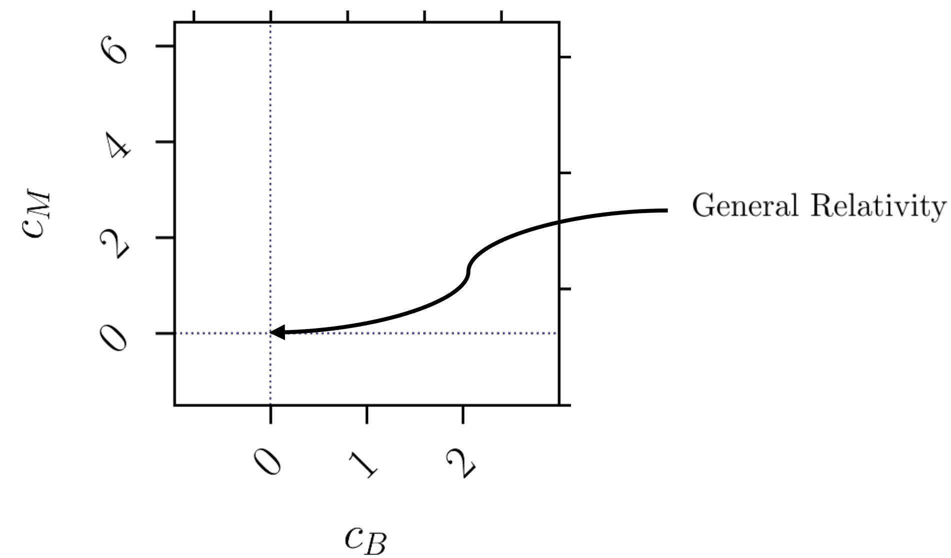


Probing Dark Energy: CMB + LSS

weaker Gravity

y-axis $\sim$ what is the gravitational constant G?

stronger Gravity



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

Parametrisation: $\alpha_{M,B} = c_{M,B}\Omega_{\rm DE}$ $\Longrightarrow$

α_i framework *Bellini, Sawicki, '14*

improved param. *Traykova, Bellini, Ferreira, Garcia-Garcia,* **JN***, Zumalacarregui '21*

Probing Dark Energy: CMB + LSS

JN, *Nicola '18a, 18b*

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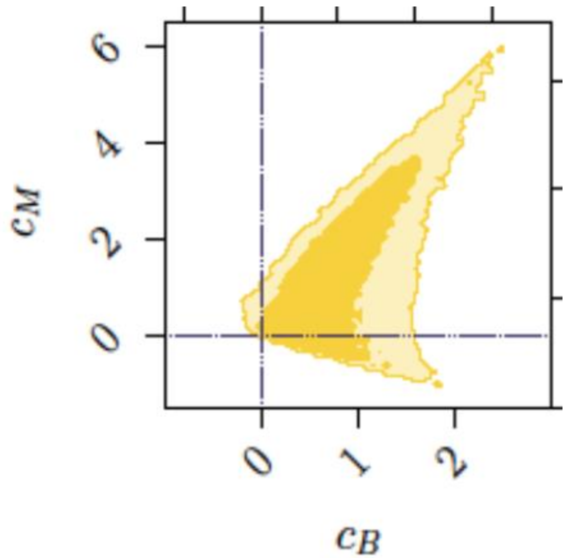

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Probing Dark Energy: CMB + LSS

JN, *Nicola '18a, 18b*

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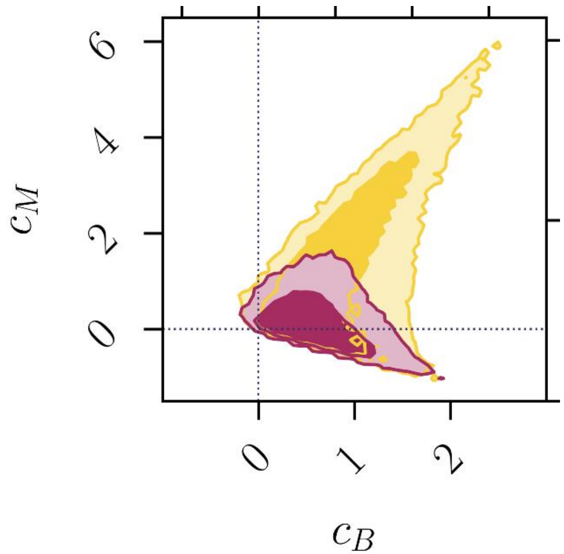
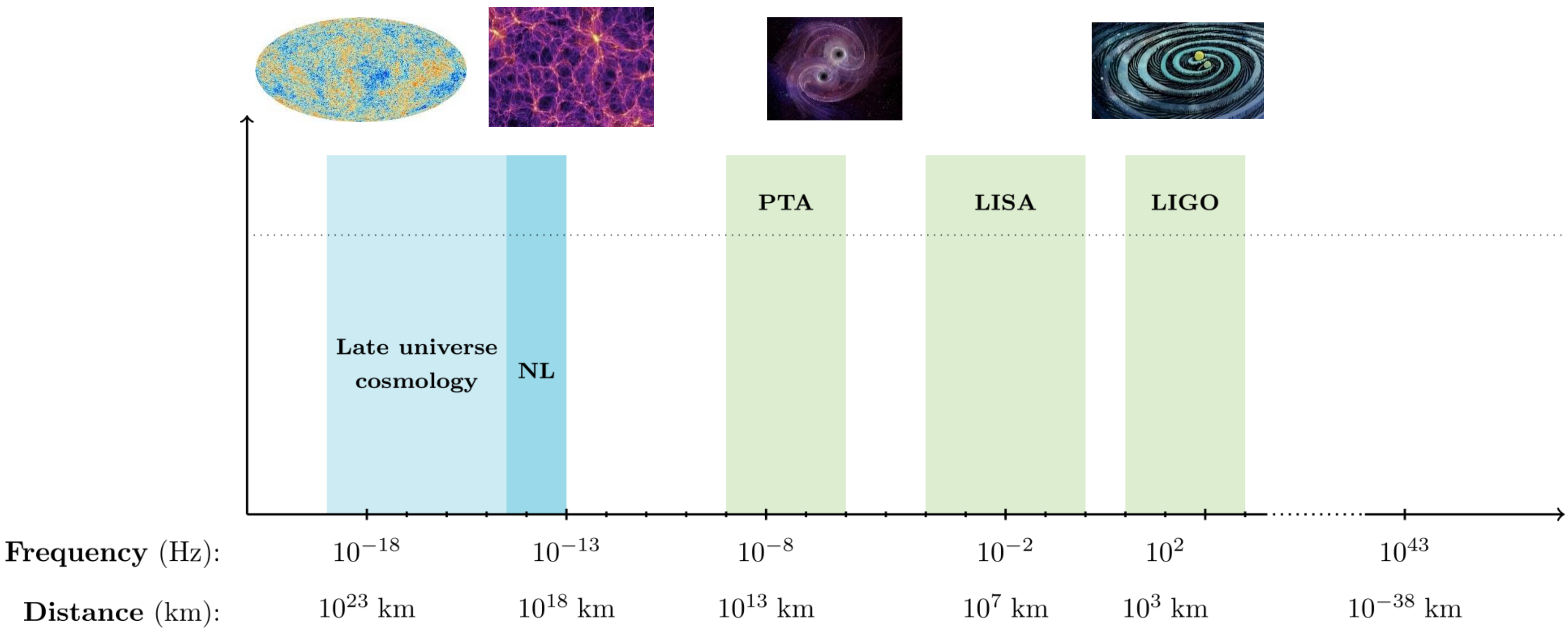
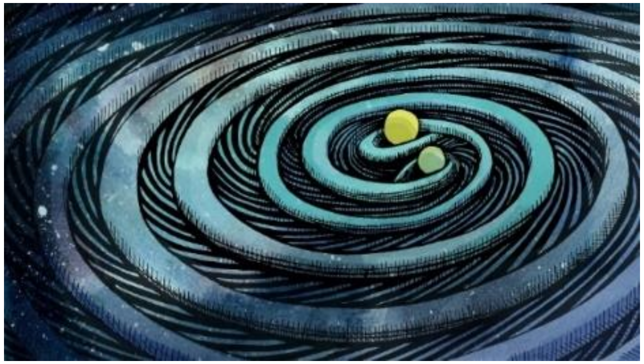


x-axis ∼ how much does the graviton interact with DE scalar?

Gravity across scales



Probing Dark Energy: CMB + LSS + GW



π fluctuations: $\ddot{\pi} + c_s^2 k^2 \pi = 0$

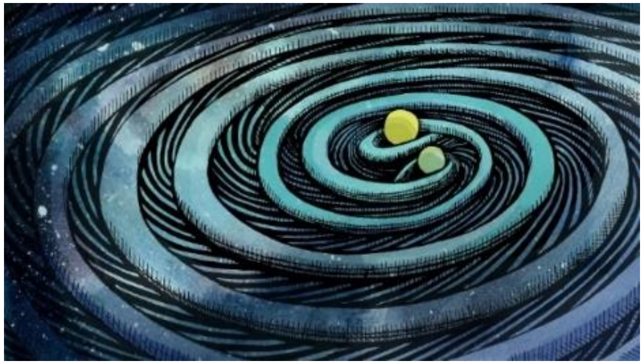
Background: $\gamma_{ij} = M_{\rm Pl} h_0^+ \cos[\omega(t-z)]\epsilon_{ij}^+$

Amplitude: $h_0^+ \sim \frac{4}{r}(GM_c)^{5/3}(\pi f_{\rm gw})^{2/3}$

DE fluctuations: $\ddot{\pi} + c_s^2[k^2 + \beta(c_M, c_B, h_0^+)\cos[\omega(t-z)]\epsilon_{ij}^+\partial^i\partial^j]\pi = 0$

Creminelli, Tambalo, Vernizzi, Yingcharoenrat '19

Probing Dark Energy: CMB + LSS + GW



Instability triggered within $r \sim 10$ Mpc for SMBH & $|c_M + c_B| \gtrsim \mathcal{O}(10^{-1})$.

Background: $h_0^+ \sim \frac{4}{r}(GM_c)^{5/3}(\pi f_{\rm gw})^{2/3}$ $\gamma_{ij} = M_{\rm Pl} h_0^+ \cos[\omega(t-z)]\epsilon_{ij}^+$

DE fluctuations: $\ddot{\pi} + c_s^2[k^2 + \beta(c_M, c_B, h_0^+)\cos[\omega(t-z)]\epsilon_{ij}^+\partial^i\partial^j]\pi = 0$

Creminelli, Tambalo, Vernizzi, Yingcharoenrat '19

Probing Dark Energy: CMB + LSS + GW

JN *'20*

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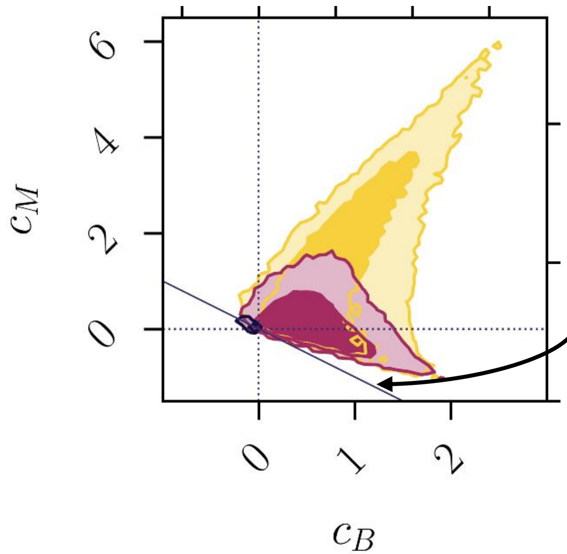
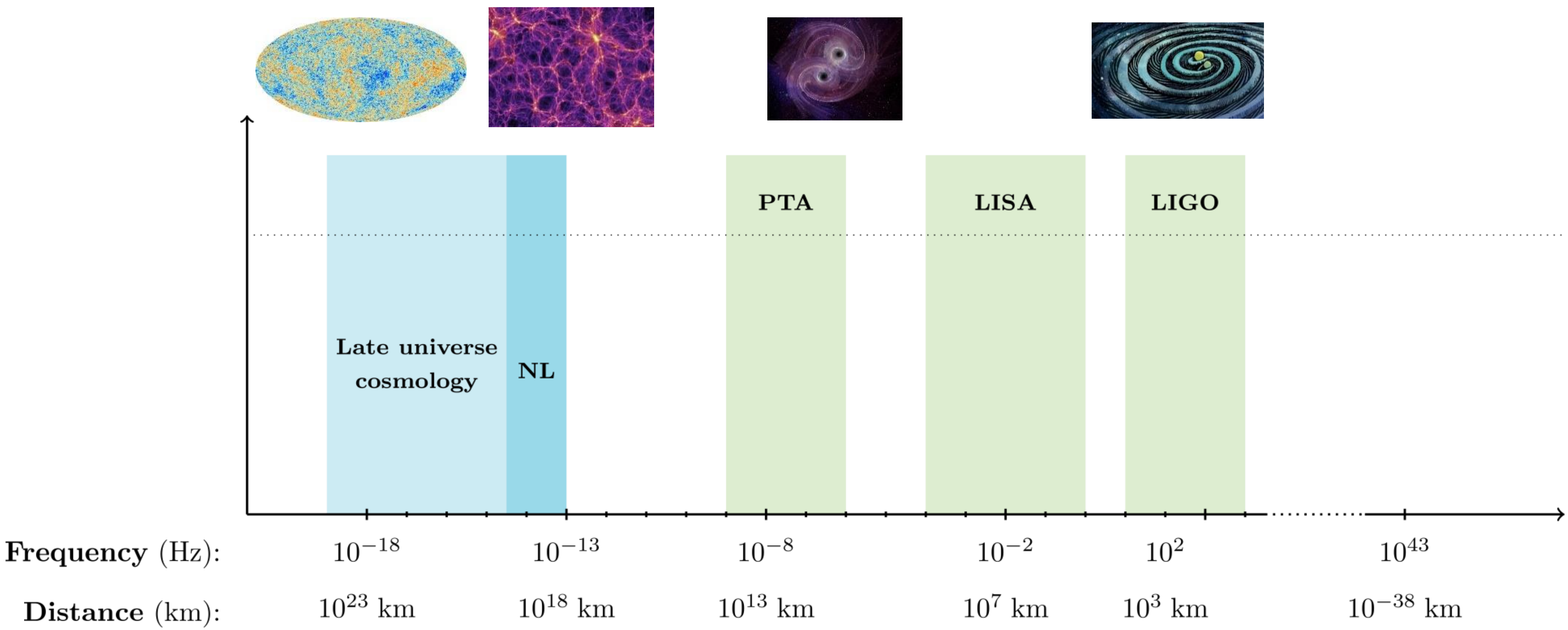


GW constraints

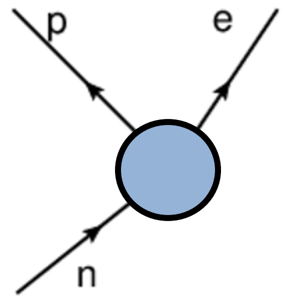
x-axis ~ how much does the graviton interact with DE scalar?

Demanding healthy GW-DE interactions can be used to constrain dark energy

Gravity across scales

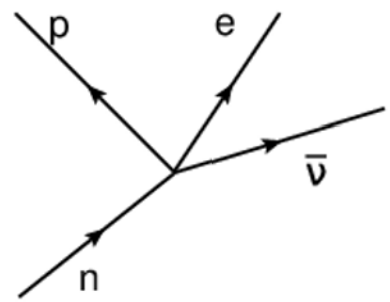


The reach of a theory



Neutron decay

The reach of a theory

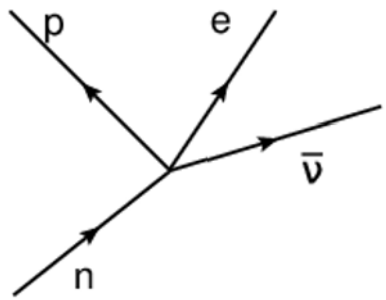


Fermi theory

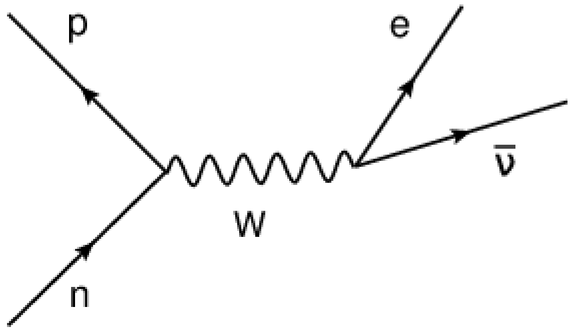
Scattering amplitude: $\mathcal{A} \sim \frac{d\sigma}{d\Omega} \sim \frac{\text{Scattered flux}}{\text{Incident flux}}$

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

The reach of a theory



Fermi theory



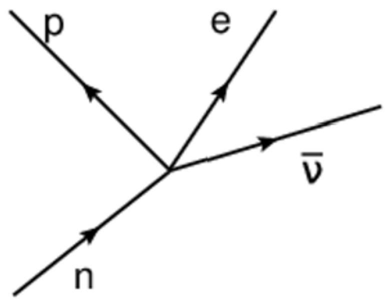
Electro-weak theory

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

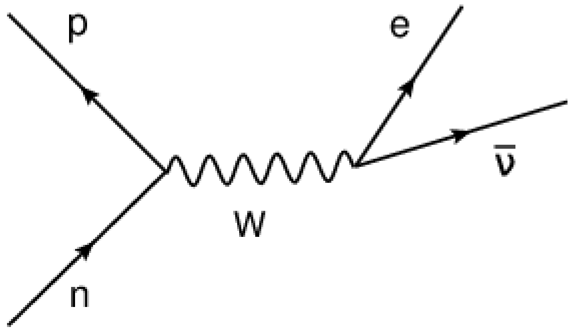
Energy scaling: $\mathcal{A} \sim \left(\frac{E}{\text{TeV}}\right)^4$

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

The reach of a theory



Fermi theory



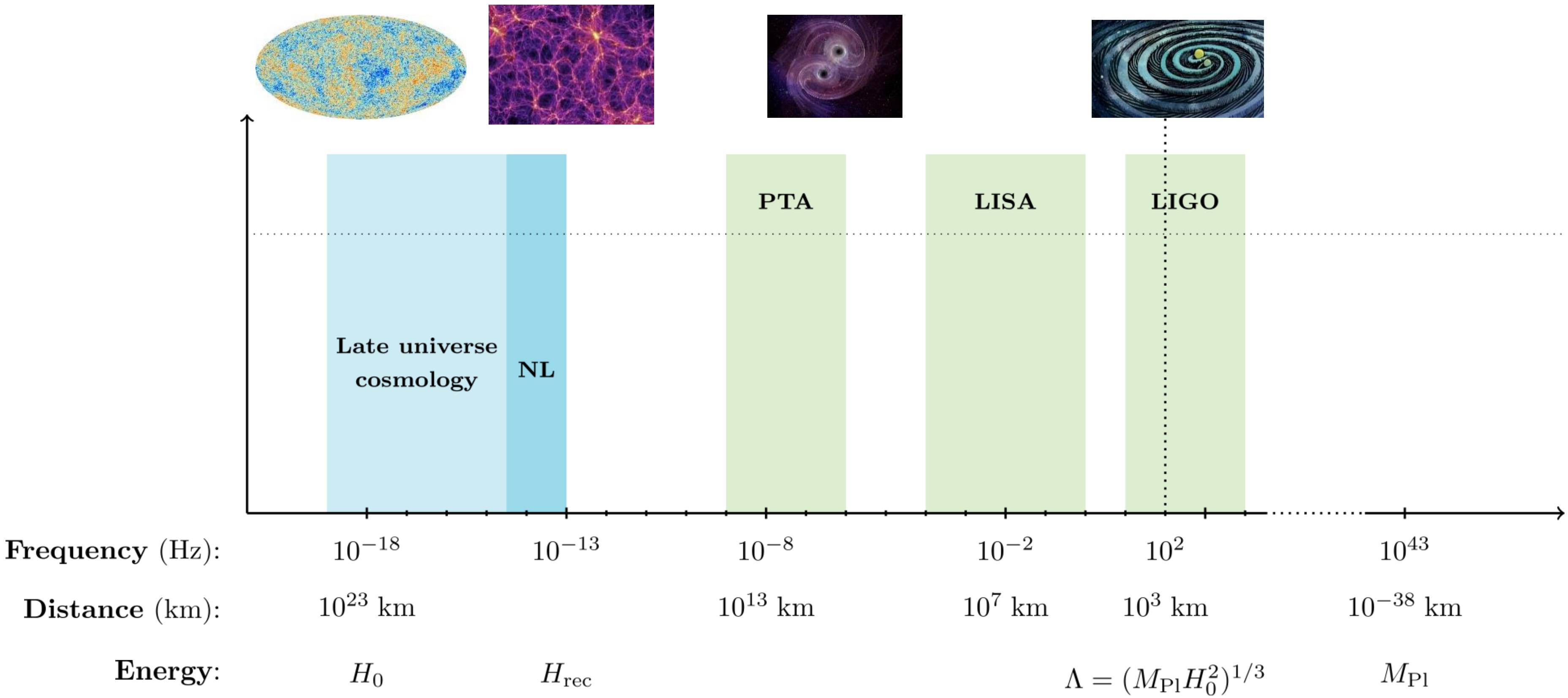
Electro-weak theory

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

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: $$\mathcal{A} \sim \left(\frac{E}{10^{-12}\ \text{eV}}\right)^6$$

Gravity across scales



$$\mathcal{L} = -\tfrac{1}{2}(\nabla\phi)^2 + M_{\rm Pl}^2 R + \frac{1}{\Lambda^6}(\nabla\phi)^2(\Box\phi)^2 + \dots$$

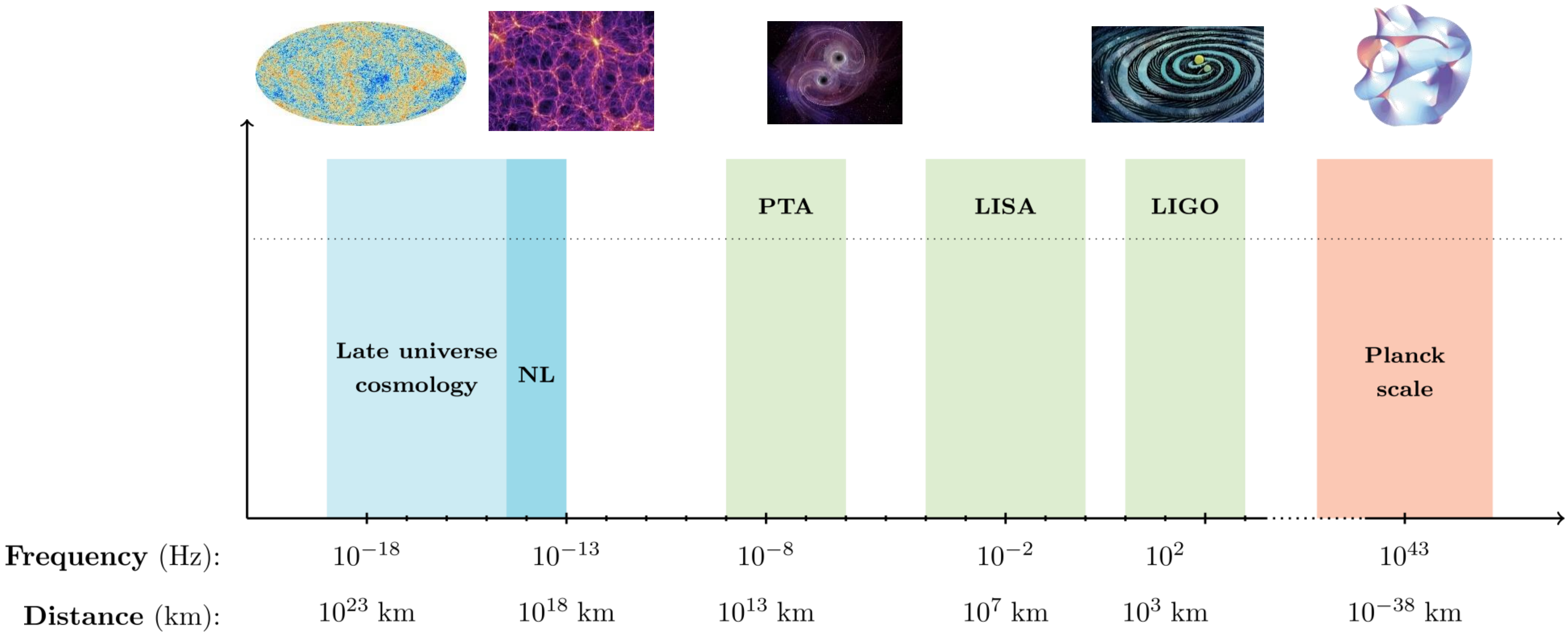
Connecting LIGO and cosmological scales non-trivial

de Rham, Melville '18

Raise cutoff + test dark energy with black holes

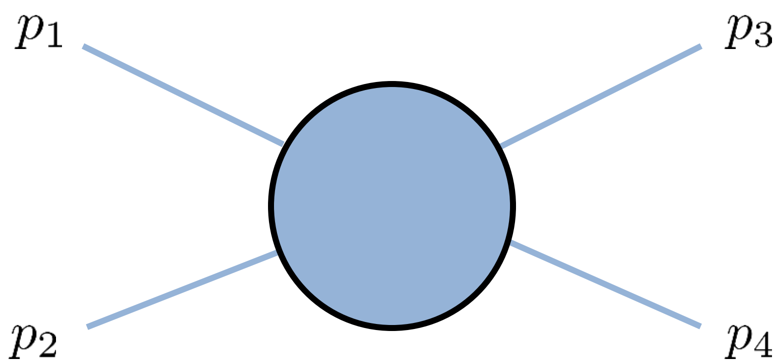
JN, *Santoni, Trincherini, Trombetta '19*

Gravity across scales



Positivity bounds

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



Scattering amplitude: $\mathcal{A} = c_{ss} s^2 + \ldots$, where $s = -(p_1 + p_2)^2$

$$c_{ss} = \frac{1}{2\pi i} \oint_{\mathcal{C}} ds \frac{\mathcal{A}(s)}{s^3} = \ldots = \frac{4}{\pi} \int_0^\infty ds \frac{\sigma(s)}{s^2}$$

Cauchy's theorem

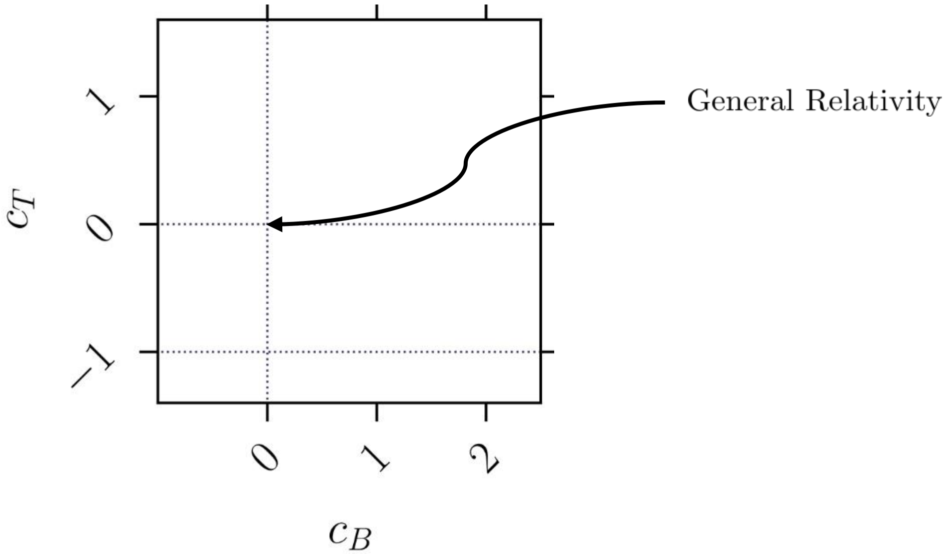
positive(!)

A case study

GWs faster than photons

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

Photons faster than GWs



x-axis ∼ 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

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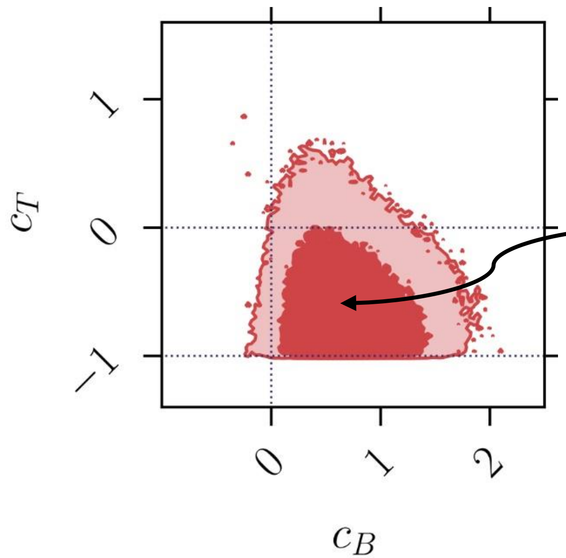


Data constraints from CMB and LSS

JN, *Nicola '18*

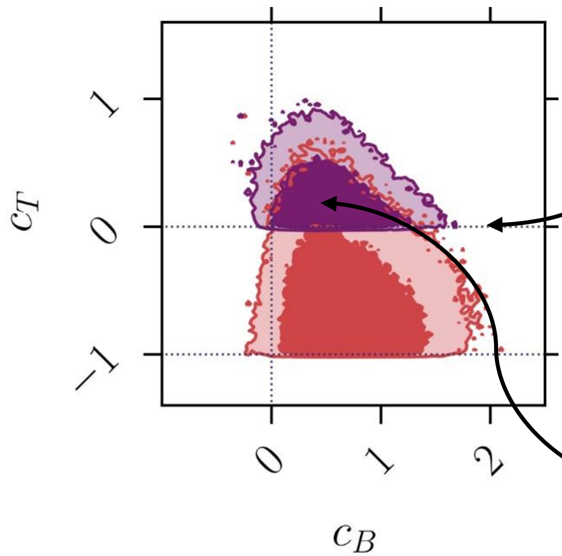
x-axis ~ how much does the graviton interact with DE scalar?

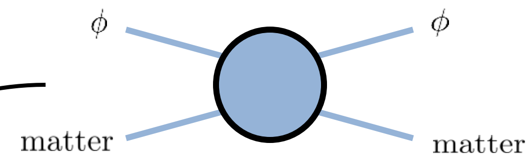
A case study

GWs faster than photons

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

Photons faster than GWs





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

Data constraints with this positivity prior

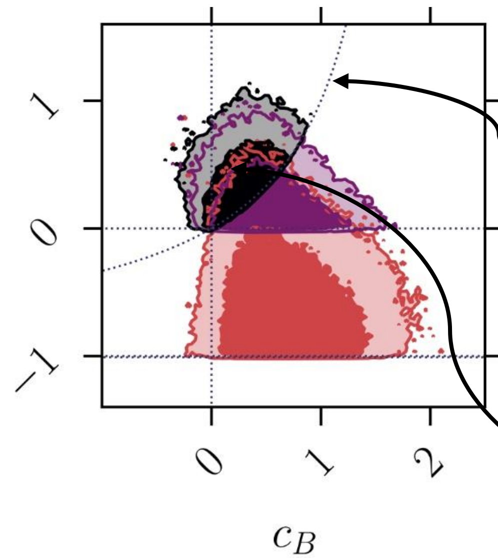
x-axis ~ how much does the graviton interact with DE scalar?

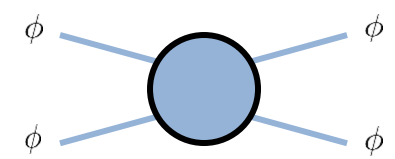
A case study

GWs faster than photons

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

Photons faster than GWs





Melville, **JN** *'19*

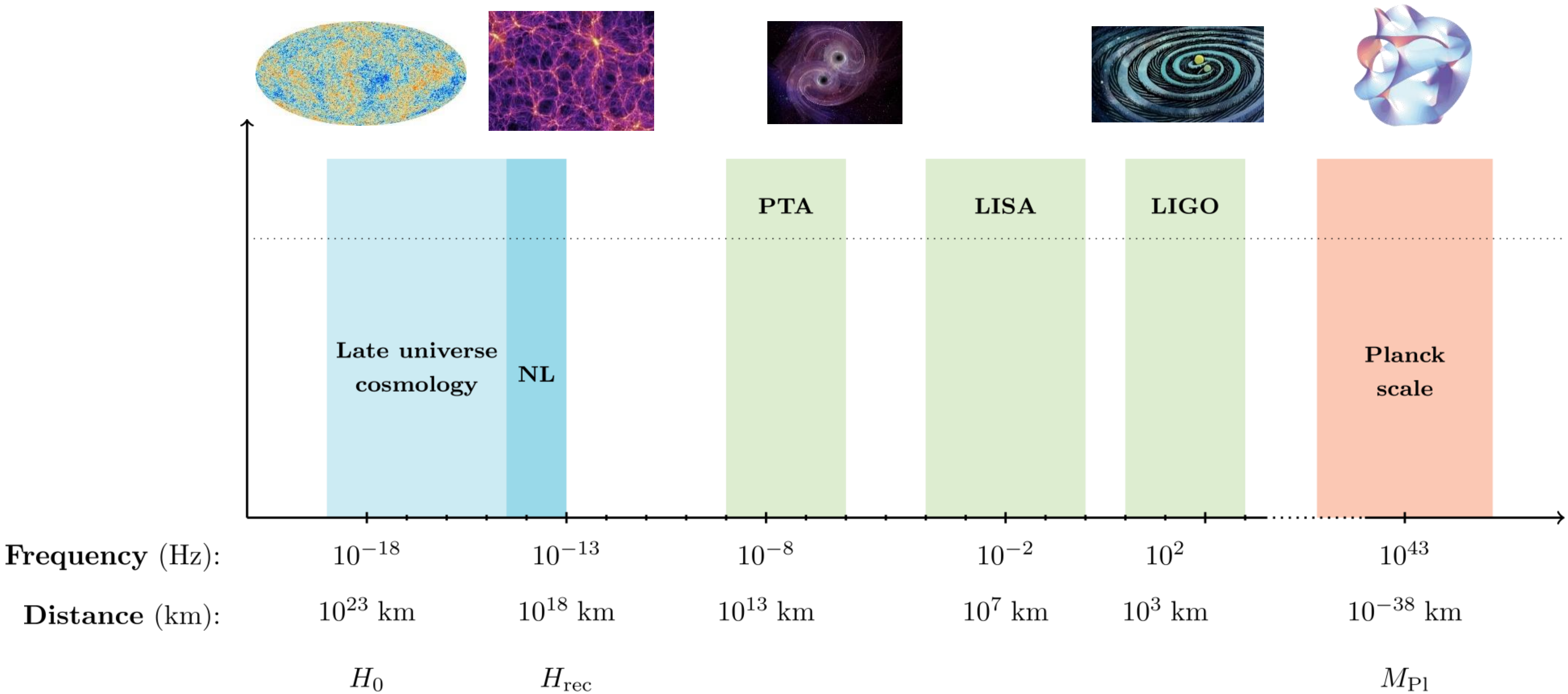
Data constraints with both positivity priors

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



Thank you!