Dark Energy as seen from the cosmological side
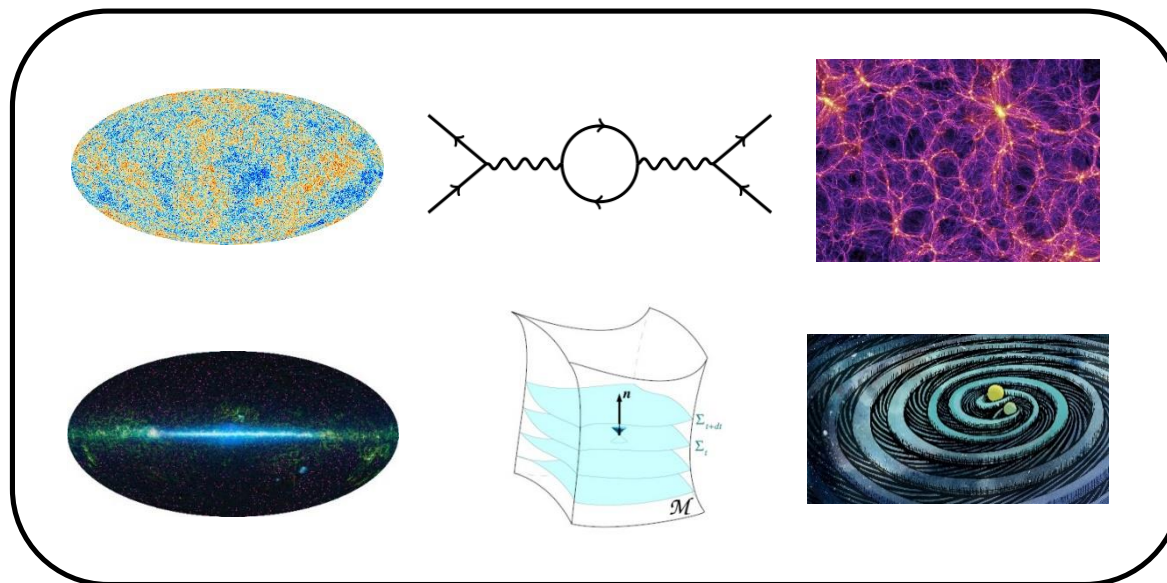

Johannes Noller

DAMTP, Cambridge

ICG, University of Portsmouth (from 02/21)

Dark Energy as seen from the cosmological side

Slide from Ian's talk

Dark Energy as seen from the cosmological side

Slide from Ian's talk

Dark Energy in numbers: How much?

Planck Collaboration '15

Dark Energy in numbers: How much?

Planck Collaboration '15

Supernova Cosmology Project '10

Dark Energy in numbers: What is it?
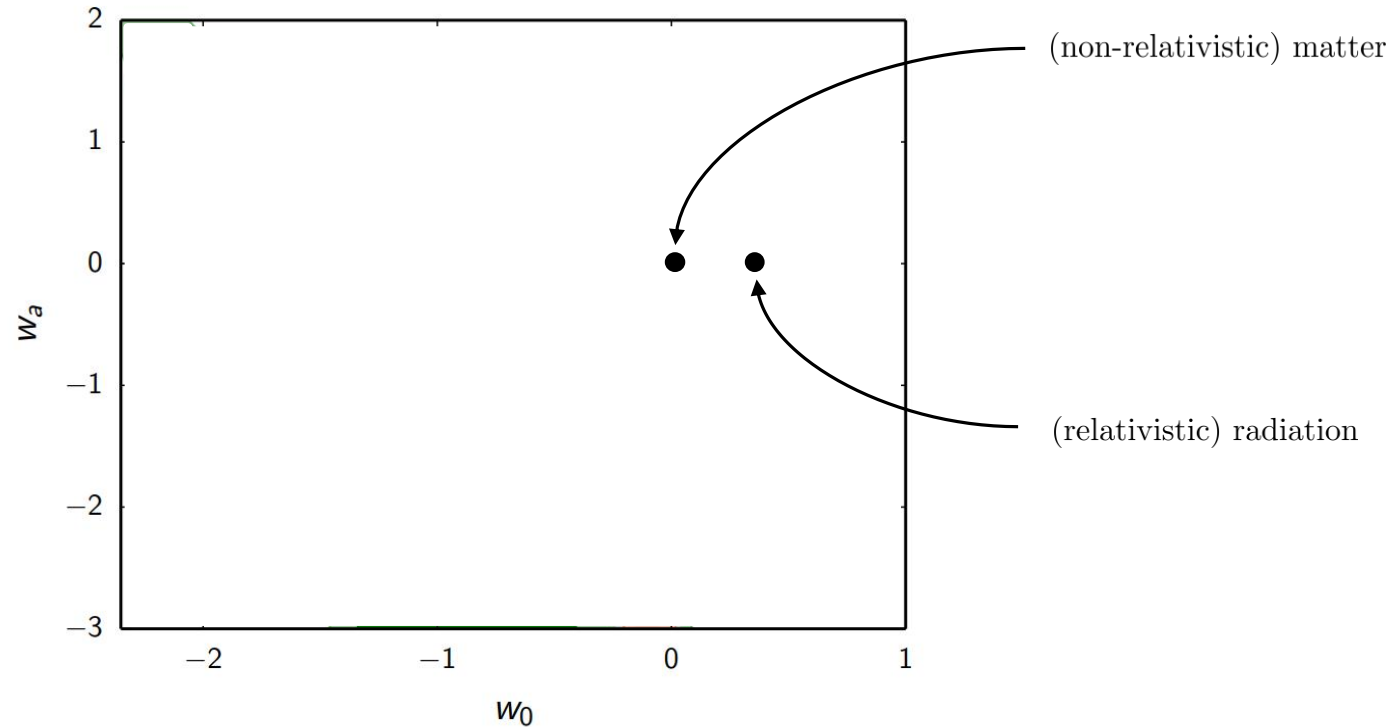
Planck Collaboration '15

The equation of state:

$$w = \frac{\text{pressure}}{\text{density}}$$

$$w = w_0 + (1 - a)w_a$$

Dark Energy in numbers: What is it?

Cosmological constant

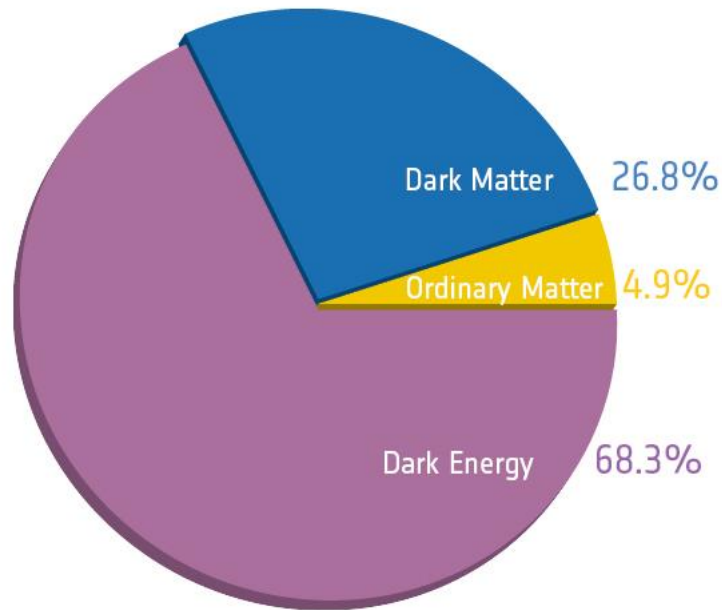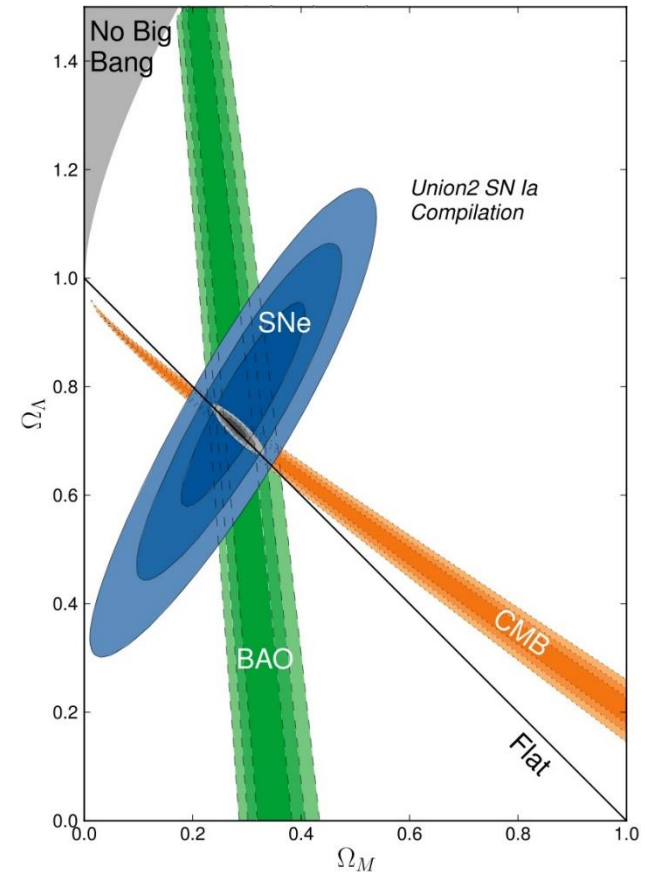$$G_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$$

(non-relativistic) matter

(relativistic) radiation

Planck+BSH
Planck+WL
Planck+BAO/RSD
Planck+WL+BAO/RSD

w_a

w_0

Planck Collaboration '15

The equation of state: $w = \dfrac{\text{pressure}}{\text{density}}$ $w = w_0 + (1-a)w_a$

Dark Energy: Challenges

The observational side:

Planck Collaboration '15

$$\nabla^2 \Phi = 4\pi \, G \, \rho, \qquad \frac{\Delta G}{G} \gg 1$$
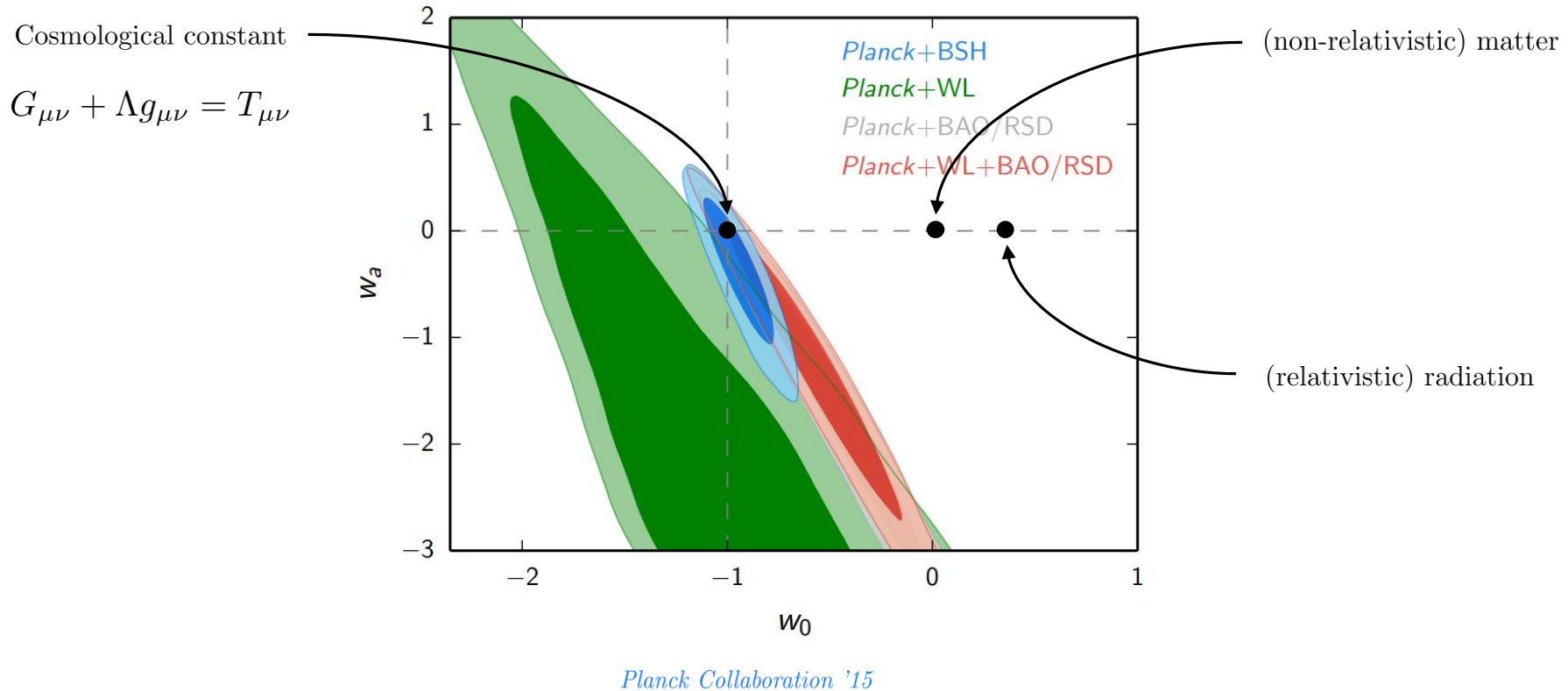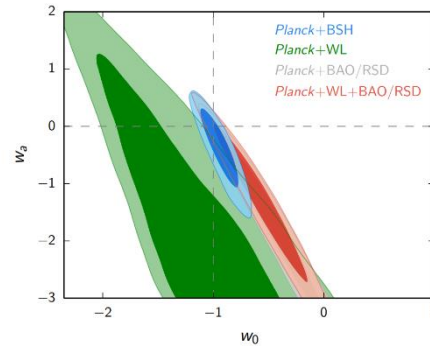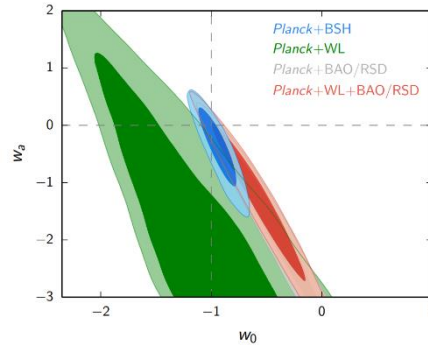
Large uncertainties for observables.

Dark Energy: Challenges

The observational side:

Planck Collaboration '15

Large uncertainties for observables.

$$\nabla^2 \Phi = 4\pi \, G \, \rho, \qquad \frac{\Delta G}{G} \gg 1$$

The theory side:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}^{mat} + T_{\mu\nu}^{DE} + \Lambda_{vac} g_{\mu\nu}$$

$$\bigcirc \;+\; \text{\textcircled{Y}} \;+\; \text{\textcircled{Y}} \;+\; \ldots \;\sim\; \Lambda_{vac} \int d^4 x \sqrt{-g}$$

Padilla '15

Image credit: BBC News '06

The problem is not fine tuning as such, but its radiative instability.

Probing Dark Energy = Testing GR
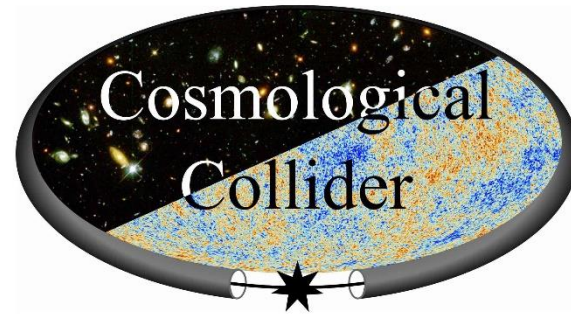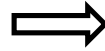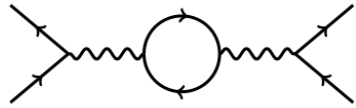
(on large scales)

GR as unique consistent theory
of a massless spin-2 field.

Probing GR = looking for new grav. particles.

Probing Dark Energy = Testing GR

(on large scales)

GR as unique consistent theory
of a massless spin-2 field.

Cosmological Collider

Probing GR = looking for new grav. particles.

Where do observational constraints come from:

Photons from the CMB probe
gravitational potential along line of sight

redshift space
62295 galaxies

400 h⁻¹ Mpc
200 h⁻¹ Mpc
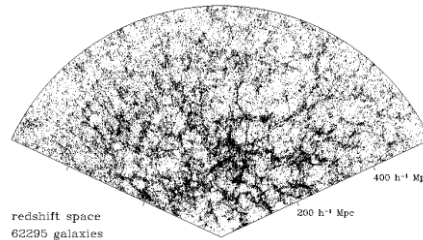
Large scale structure probes structure
formation via clustering and lensing
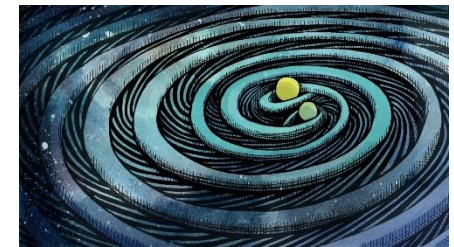
Gravitational wave propagation probes
interactions with dark energy

Probing Dark Energy: Gravitational waves
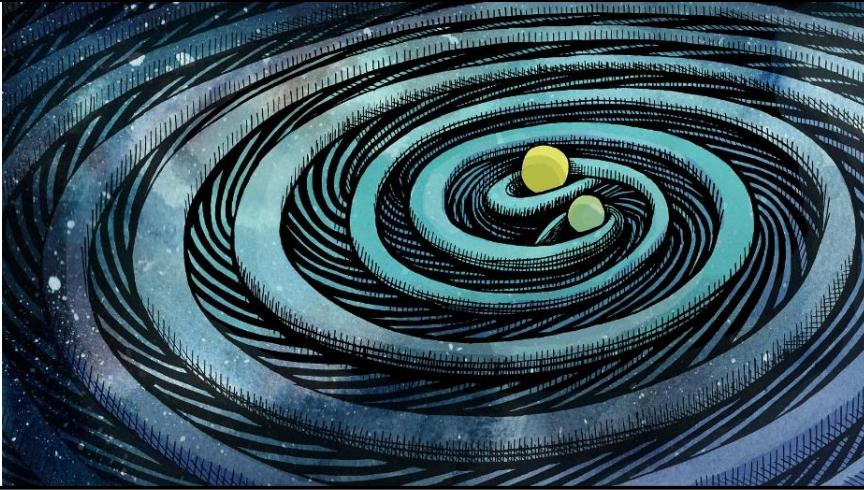
- Constraints on speed of GWs: $|c_{\mathrm{GW}}^2 - 1| \lesssim 10^{-15}$.

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

- New gravitational degrees of freedom can easily lead to $c_{\mathrm{GW}} \neq 1$.

- Resulting tight bounds on dark energy/modified gravity.

  *Baker, Bellini, Ferreira, Lagos, **JN**, Sawicki '17, Creminelli, Vernizzi '17,*
  Ezquiaga, Zumalacarregui '17, Sakstein, Jain '17 + many follow ups.

Probing Dark Energy: Gravitational waves

$$\mathcal{L}_2 = G_2, \quad \mathcal{L}_3 = G_3 \Box \phi, \quad \mathcal{L}_4 = G_4 R + G_{4,X} \left\{ (\Box \phi)^2 - \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi \right\},$$

$$\mathcal{L}_5 = G_5 G_{\mu\nu} \nabla^\mu \nabla^\nu \phi - \frac{1}{6} G_{5,X} \left\{ (\Box \phi)^3 - 3 \nabla^\mu \nabla^\nu \phi \nabla_\mu \nabla_\nu \phi \Box \phi + 2 \nabla^\nu \nabla_\mu \phi \nabla^\alpha \nabla_\nu \phi \nabla^\mu \nabla_\alpha \phi \right\}.$$

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

Horndeski theory as general ST theory

Horndeski '74, Deffayet, Gao, Steer, Zahariade '11

Probing Dark Energy: Gravitational waves

$$\mathcal{L}_2 = G_2, \quad \mathcal{L}_3 = G_3 \Box \phi, \quad \mathcal{L}_4 = G_4 R + G_{4,X} \left\{ (\Box \phi)^2 - \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi \right\},$$

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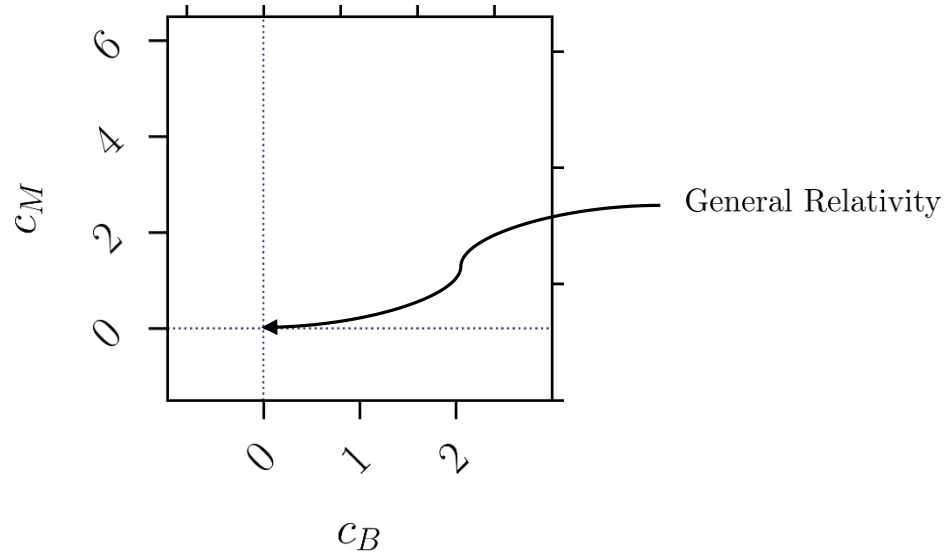
Horndeski theory as general ST theory

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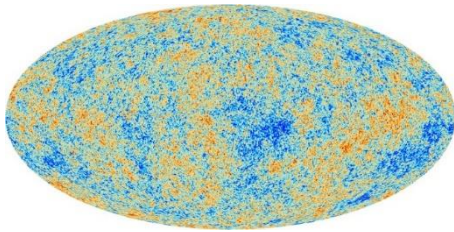$$\mathcal{L} = G_4(\phi) R + G_2(\phi, X) - G_3(\phi, X) \Box \phi$$

*Baker, Bellini, Ferreira, Lagos, **JN**, Sawicki '17, Creminelli, Vernizzi '17, Ezquiaga, Zumalacarregui '17, Sakstein, Jain '17 + many follow ups.*

Probing Dark Energy: CMB + LSS

weaker Gravity

↑

y-axis ~ what is the gravitational
constant G?

↓

stronger Gravity

General Relativity

c_M

c_B

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

**Photons from the CMB probe
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400 h⁻¹ Mpc
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**Large scale structure probes structure
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Probing Dark Energy: CMB + LSS

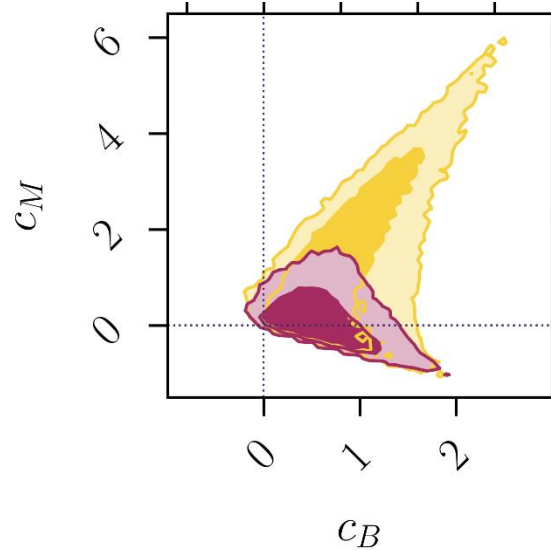JN, *Nicola '18a, 18b*

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$\uparrow$

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$\downarrow$

stronger Gravity

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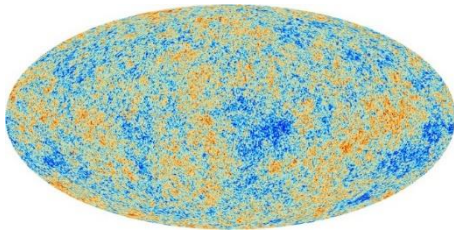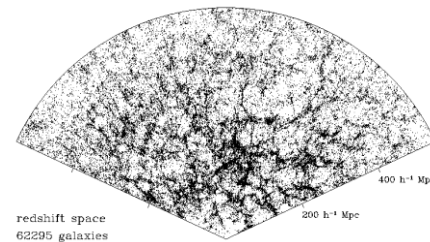
Probing Dark Energy: CMB + LSS + GW

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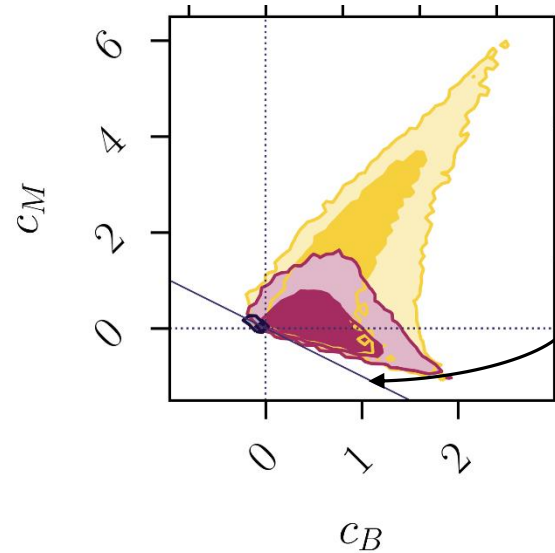
GW constraints

Creminelli et. al '19, **JN** *'20*

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

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

Probing Dark Energy: CMB + LSS + GW

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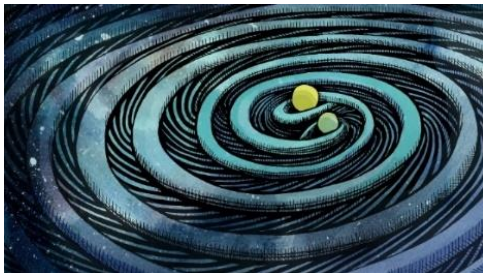
↓

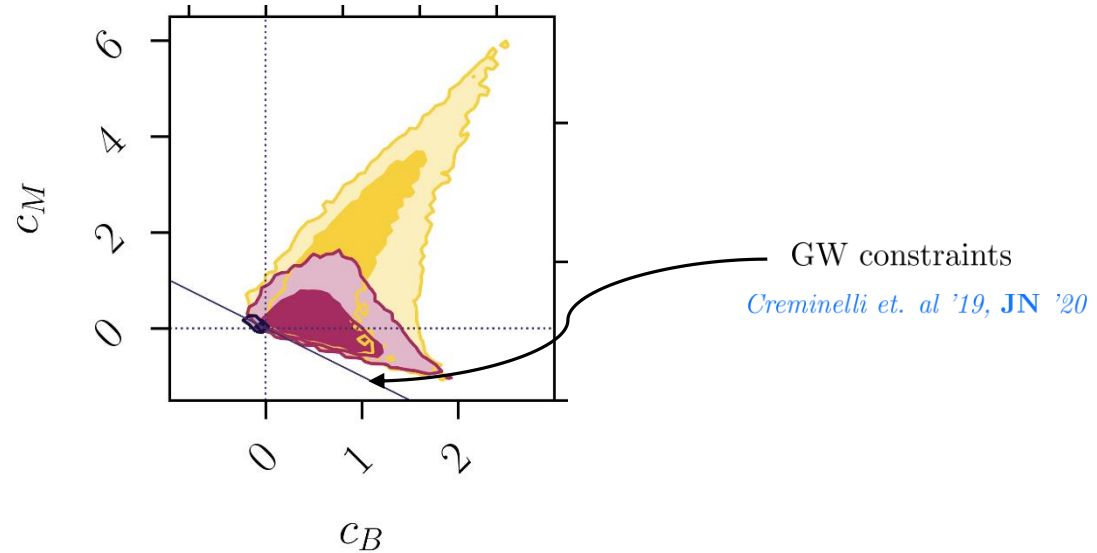stronger Gravity

GW constraints

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

⇩

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

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

Outlook + The Big Picture

Speed of GWs

| | PTA | LISA | LIGO | |

Frequency (Hz): 10^{-18} 10^{-13} 10^{-8} 10^{-2} 10^{2} 10^{43}

Distance (km): 10^{23} km 10^{13} km 10^{7} km 10^{3} km 10^{-38} km
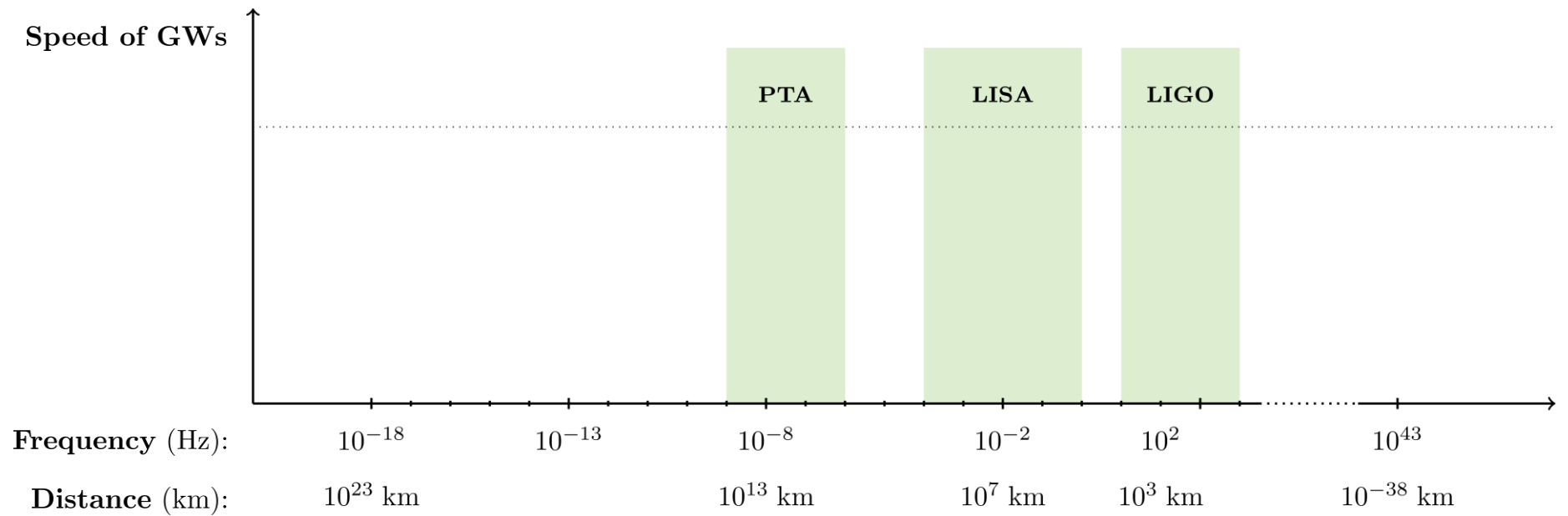
Outlook + The Big Picture

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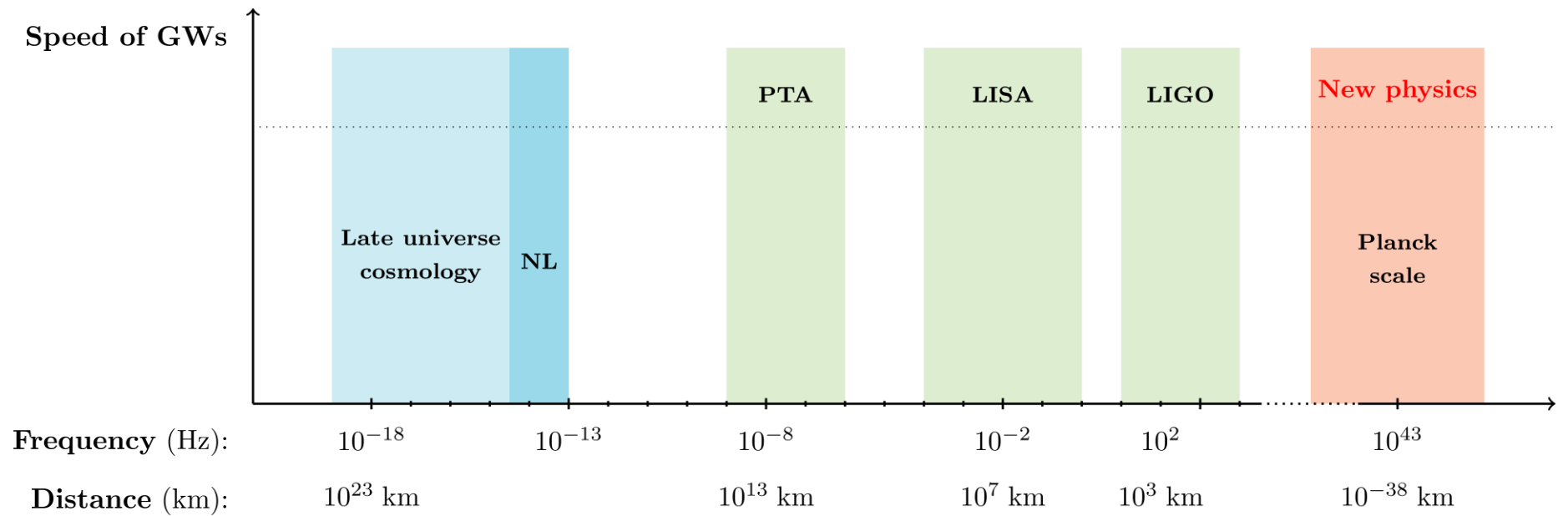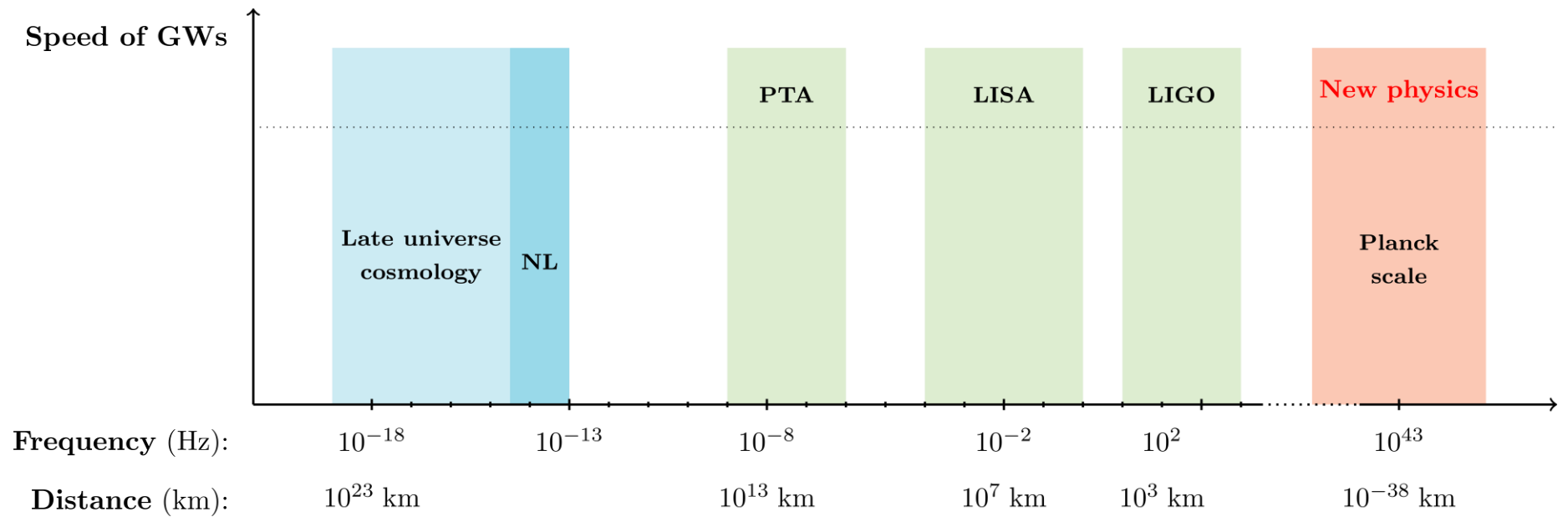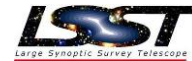
Plethora of upcoming cosmological data: + many more.

Outlook + The Big Picture

Speed of GWs

Frequency (Hz):	10^{-18}	10^{-13}	10^{-8}	10^{-2}	10^{2}	10^{43}

Late universe cosmology — NL — PTA — LISA — LIGO — New physics — Planck scale

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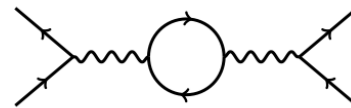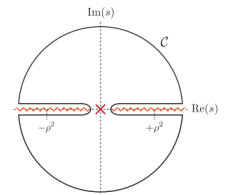**Plethora of upcoming cosmological data:** SKA LSST euclid + many more.

Novel theoretical "constraints" :

GW-induced constraints   Radiative stability of DE theories   'Positivity' bounds

Outlook + The Big Picture

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Plethora of upcoming cosmological data: **SKA** SQUARE KILOMETRE ARRAY **LSST** Large Synoptic Survey Telescope **euclid** + many more.
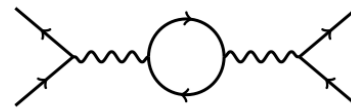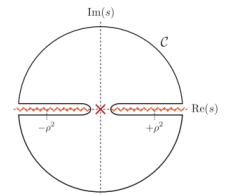
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