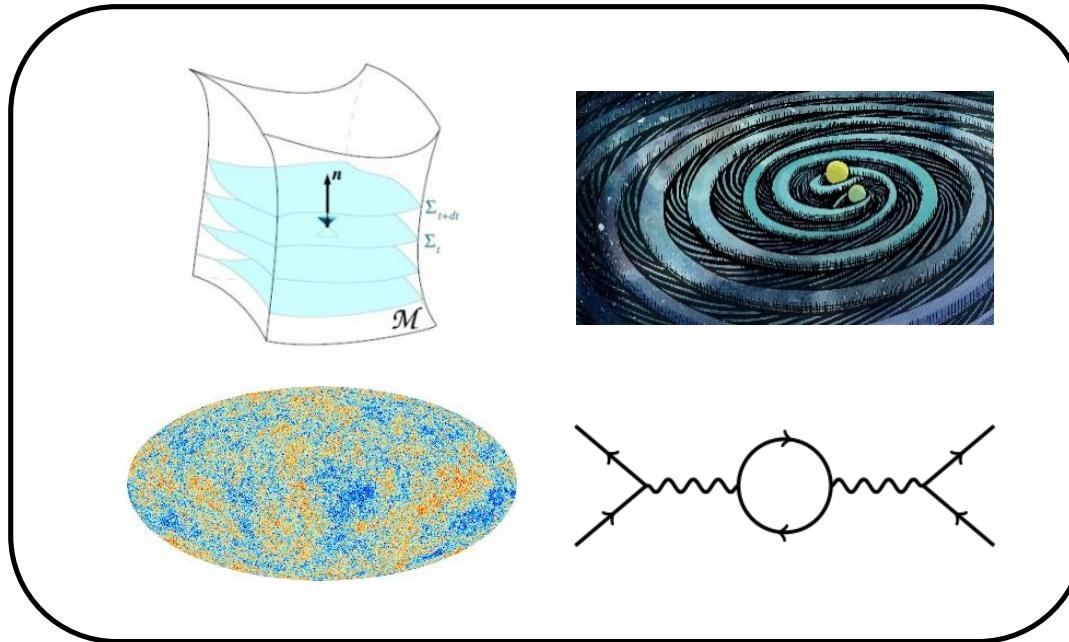


# Precision constraints for dark energy and modified gravity

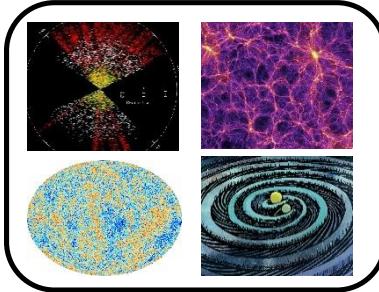


Work in collaboration with: **S. Melville, A. Nicola, T. Baker, E. Bellini, P. Ferreira, M. Lagos, I. Sawicki.**

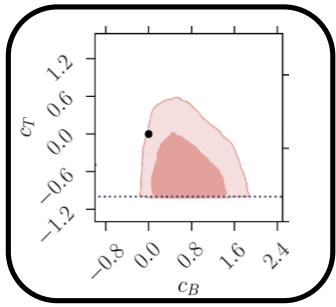
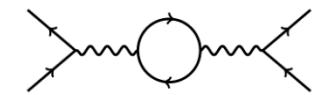
**Johannes Noller**  
ETH Zürich, Switzerland

**ETH** zürich

# Testing gravity



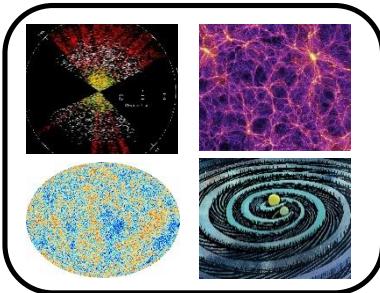
$$\begin{aligned} \mathcal{S} = & \int d^4x \sqrt{-g} \left[ G_4 R + G_2 \right. \\ & + m^2 \phi + \frac{c_3}{\Lambda_3^3} G_3 \square \phi \\ & \left. + G_{4,X} \left( (\square \phi)^2 - (\partial \phi)^2 \right) \right] \end{aligned}$$



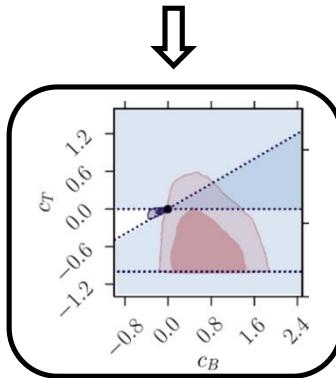
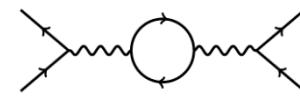
$$\begin{aligned} G_{2,XX} > 0, \quad G_{4,X} < 0, \quad G_{4,XX} > 0 \\ \text{Im } \mathcal{M}(k_1 k_2 \rightarrow k_1 k_2) = 2 E_{\text{CM}} P_{\text{CM}} \sigma_{\text{tot}} \end{aligned}$$



# Testing gravity

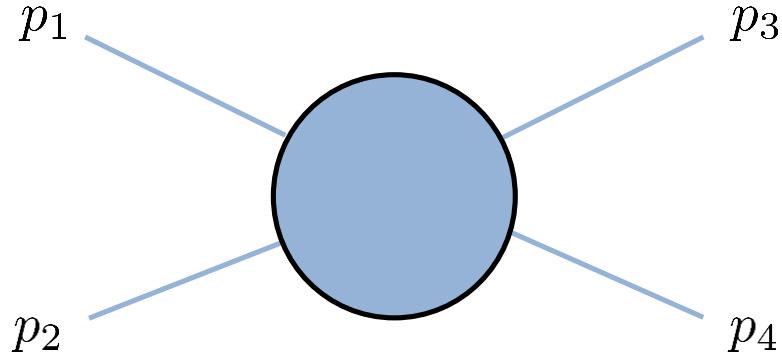


$$\begin{aligned} \mathcal{S} = & \int d^4x \sqrt{-g} \left[ G_4 R + G_2 \right. \\ & + m^2 \phi + \frac{c_3}{\Lambda_3^3} G_3 \square \phi \\ & \left. + G_{4,X} \left( (\square \phi)^2 - (\partial \phi)^2 \right) \right] \end{aligned}$$



# Positivity bounds

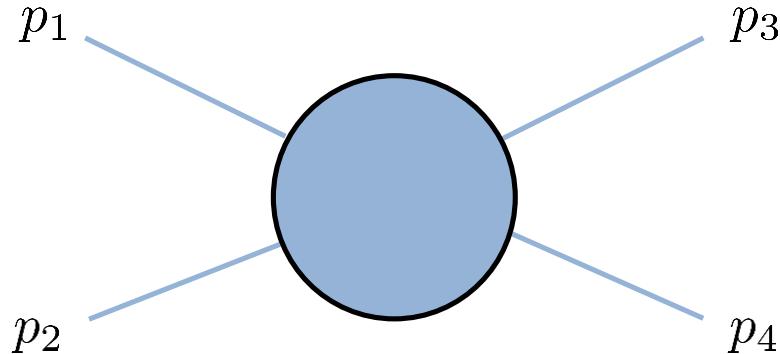
Theoretical bounds that any  
*unitary, local and causal*  
gravitational theory has to satisfy



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

# Positivity bounds

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



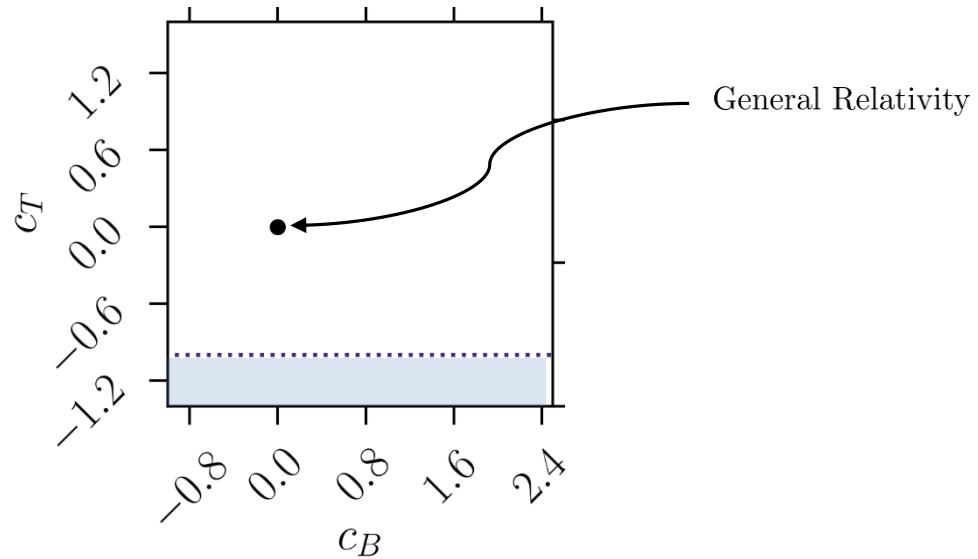
**Scattering amplitude:**  $\mathcal{A} = \textcolor{red}{c}_{ss}s^2 + \dots$ , where  $s = -(p_1 + p_2)^2$

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



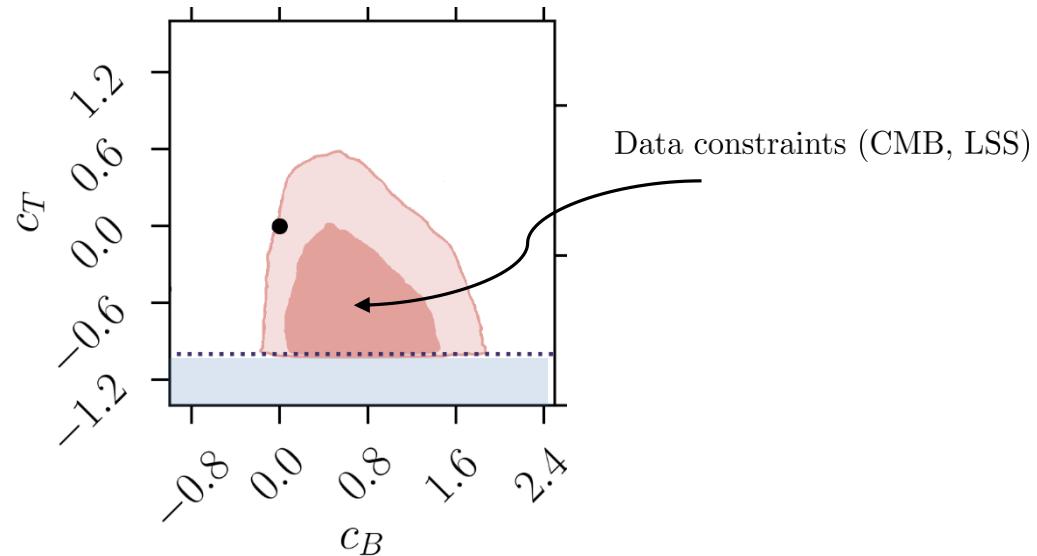

# A case study

super-luminal  
↑  
y-axis  $\sim$  what is the speed  
of gravitational waves?  
↓  
sub-luminal



# A case study

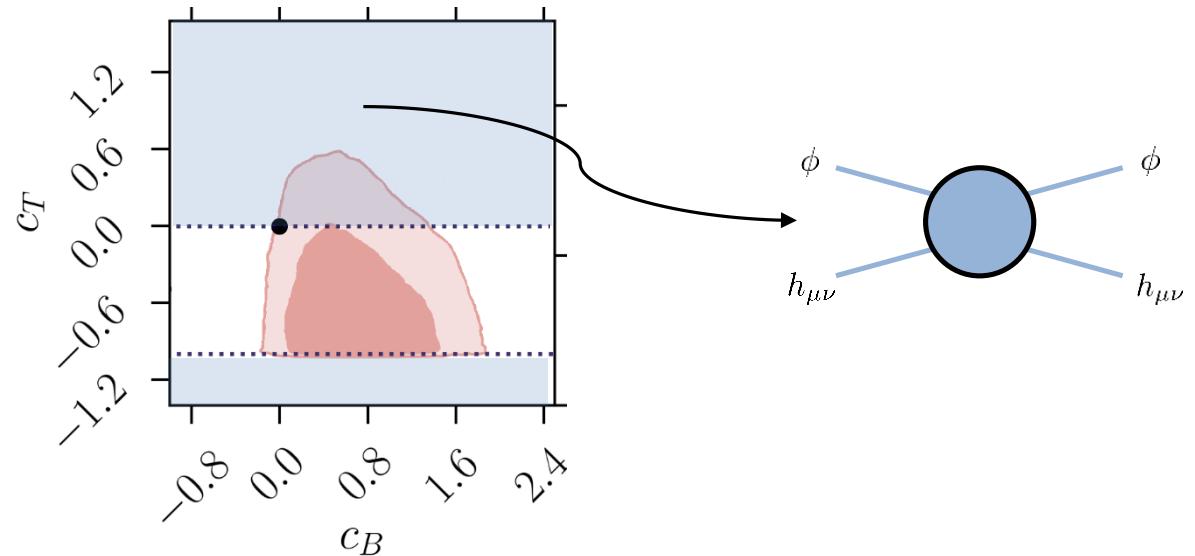
y-axis  $\sim$  what is the speed  
of gravitational waves?



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

# A case study

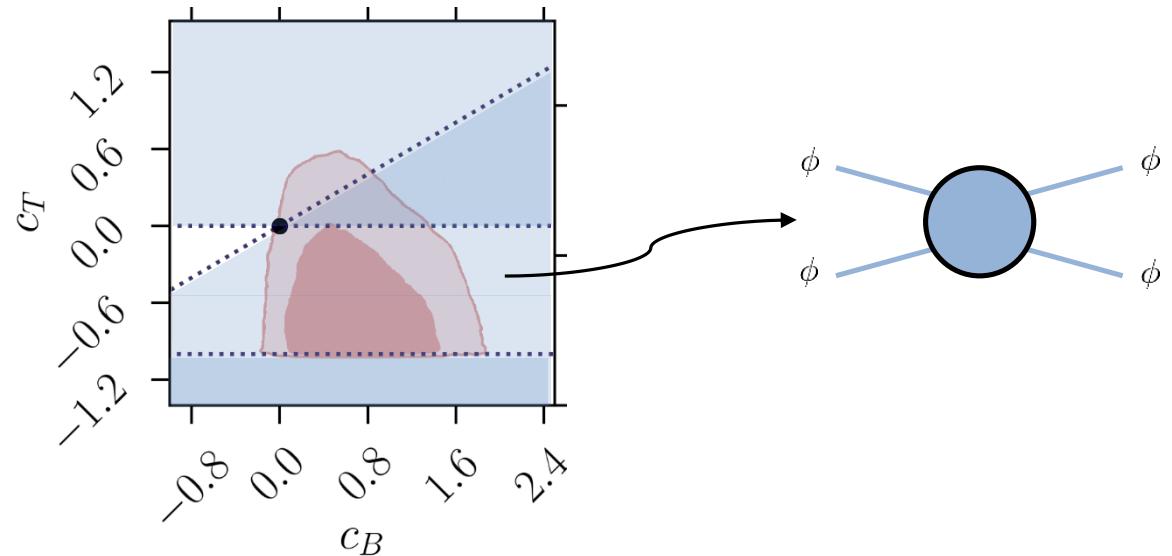
y-axis  $\sim$  what is the speed  
of gravitational waves?



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

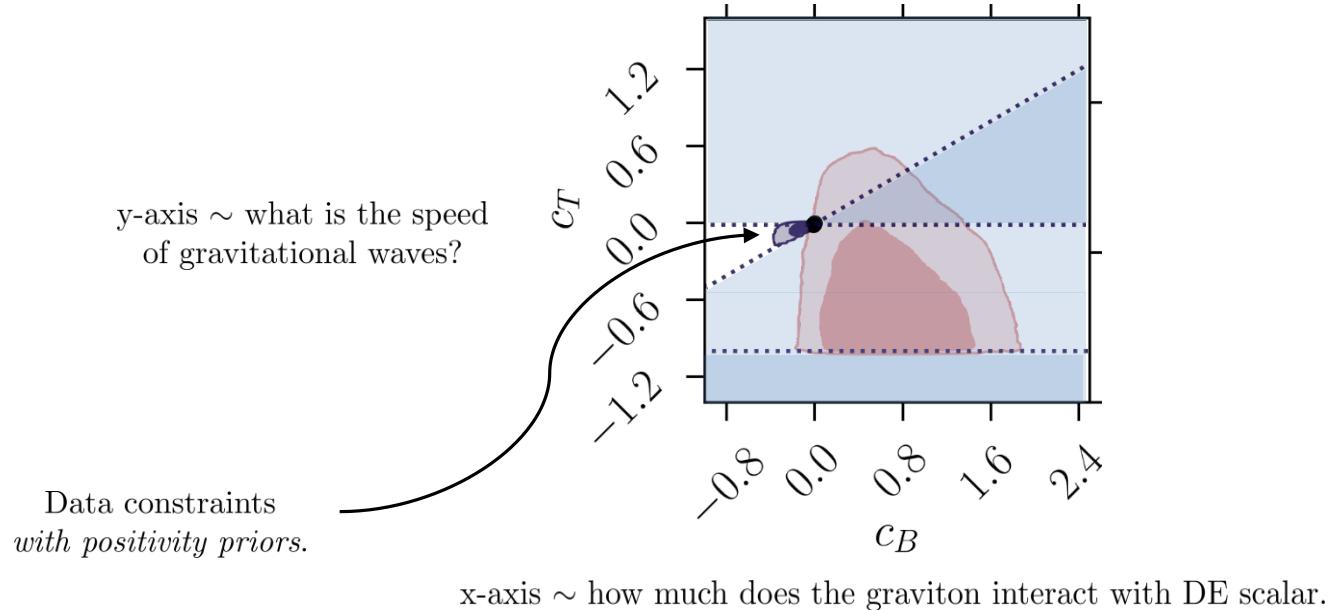
# A case study

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

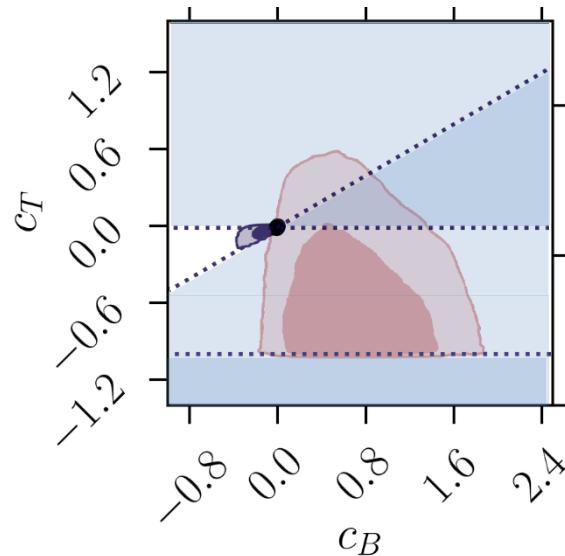


x-axis  $\sim$  how much does the graviton interact with DE scalar.

# A case study



# A case study

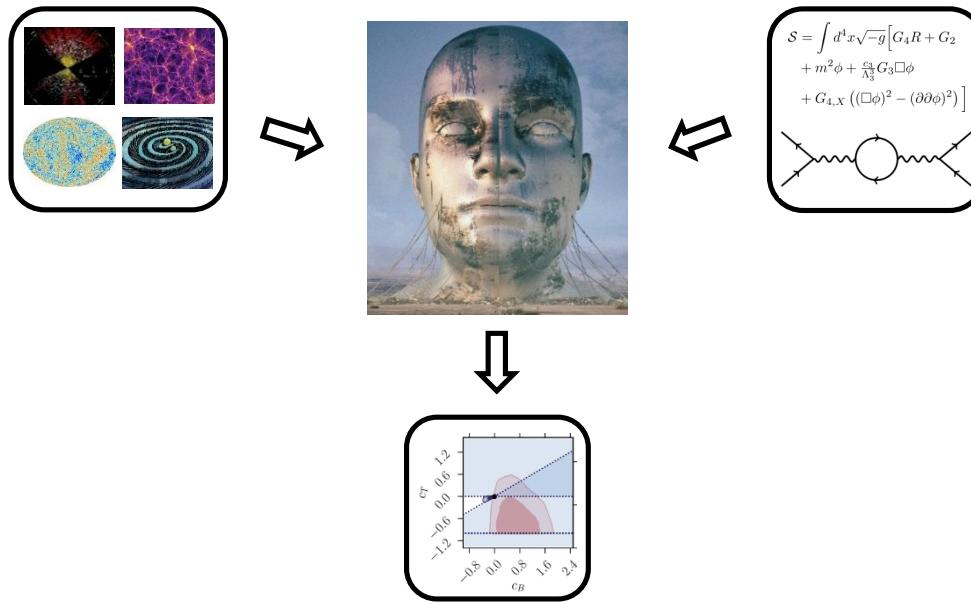


Constraints	Improvement
Present cosmological data (CMB, LSS)	x 1
Forecast <b>future data</b> (+ CMB S4, LSST, SKA)	<b>x 20</b>
Present data + 2 (out of many!) <b>positivity constraints.</b>	<b>x 110</b>

*JN, Nicola '18b*  
*Alonso, Bellini,  
Ferreira, Zumalacarregui '17*

*Melville, JN '19*

# Precision constraints for DE and MG



- Current cosmological data constraints for dark energy at  $\mathcal{O}(1)$  level – no ‘precision cosmology’ yet.
- Additional ‘theoretical’ constraints – e.g. positivity, (radiative) stability – can drastically improve bounds.
- Together with the next generation of surveys, expected to reach percent level precision.

**Thank you!**