Probing gravity and dark energy in the era of multi-messenger cosmology

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Instituut Lorentz, Leiden U.

LISA NL meeting

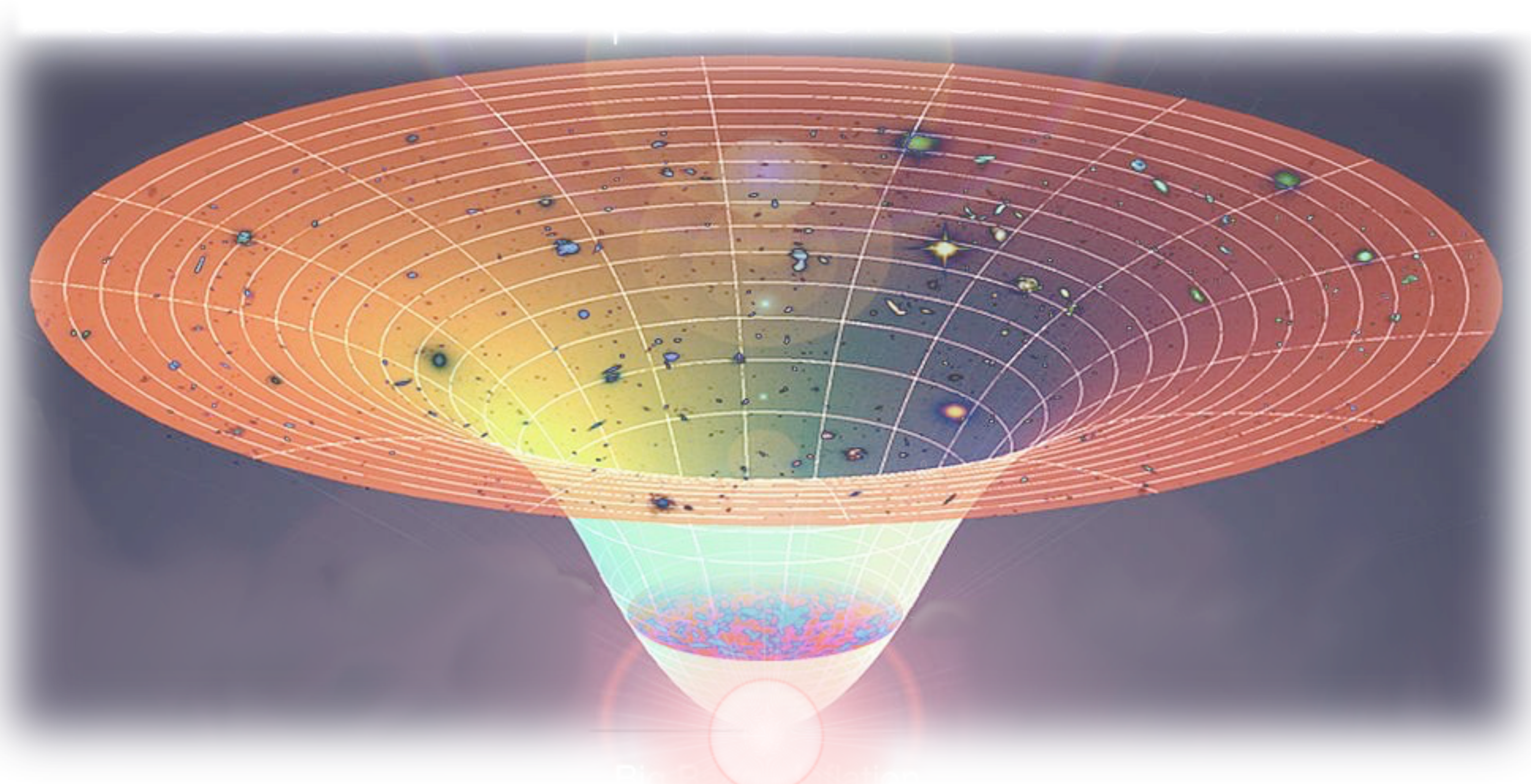
Leiden, October 1, 2021

The standard model of Cosmology

ΛCDM: 6 parameters to describe it all!

based on General Relativity

$$\{\Omega_b h^2, \Omega_c h^2, 100\theta_{\mathrm{MC}}, \tau, ln(10^{10} A_s), n_s\}$$ **measured at percent level!**



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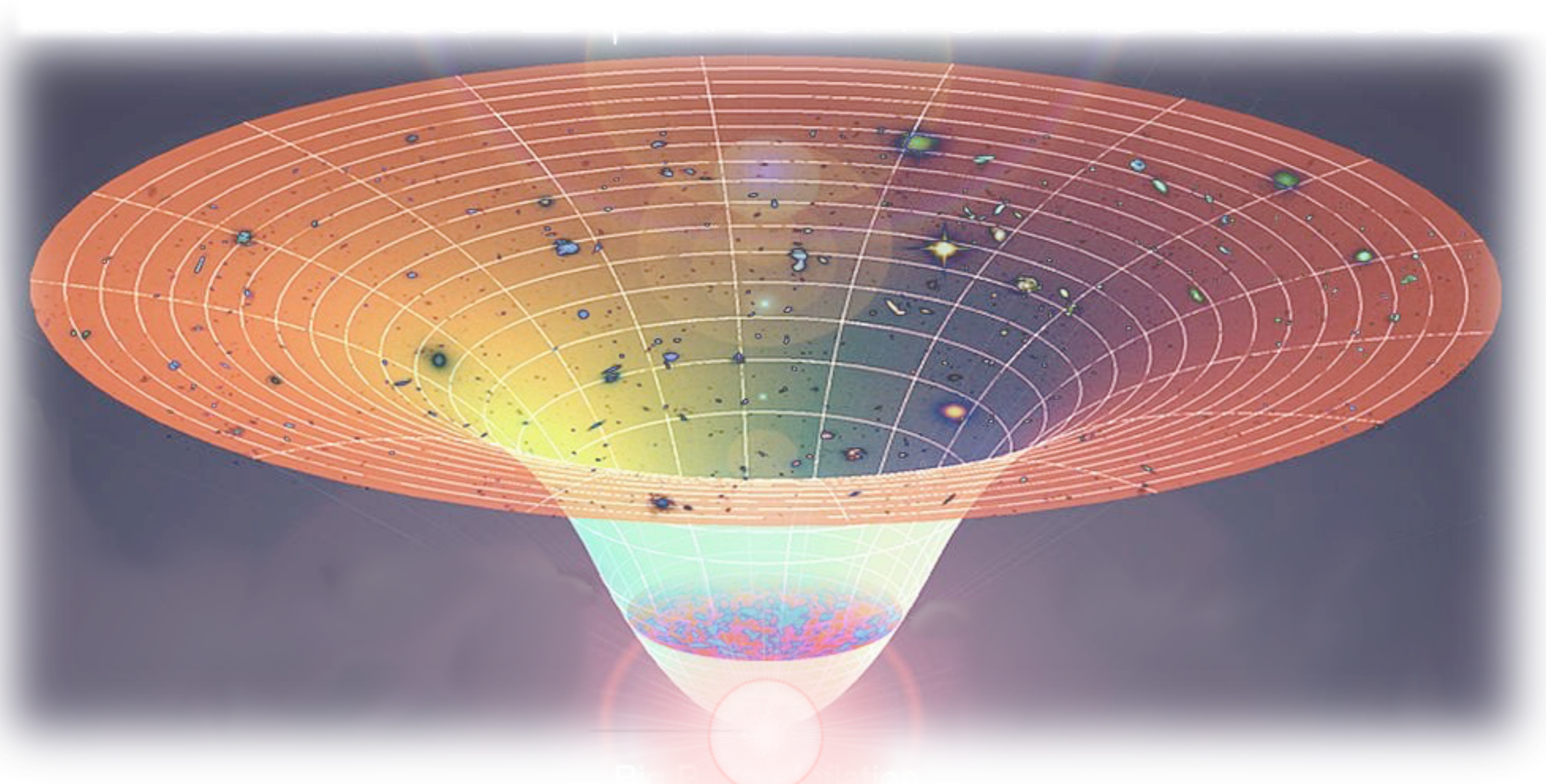
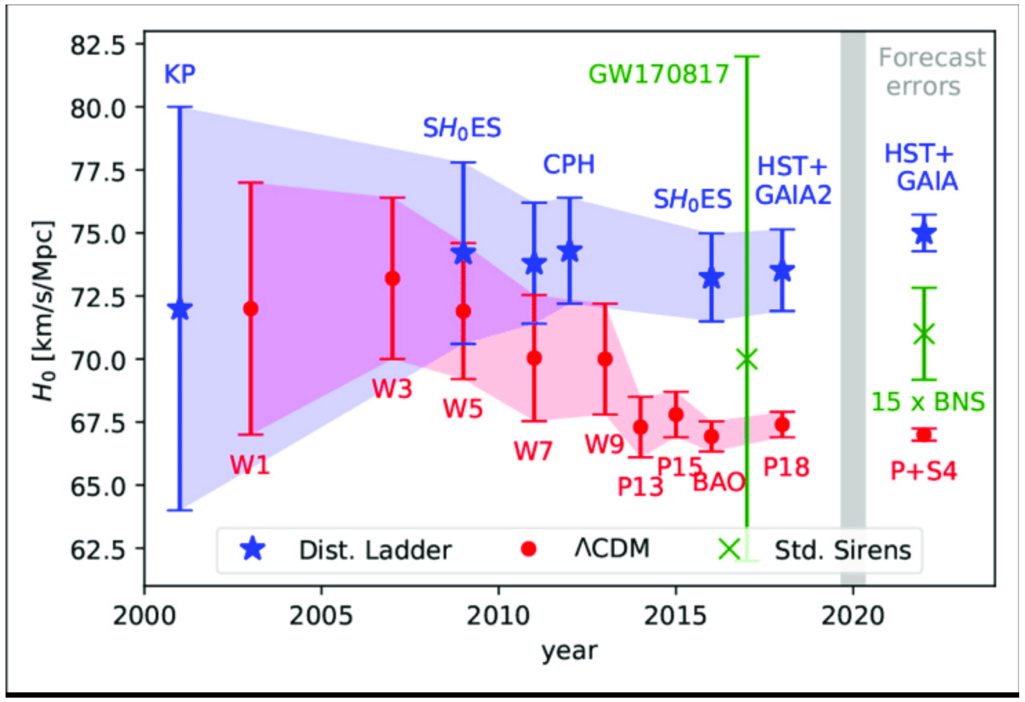
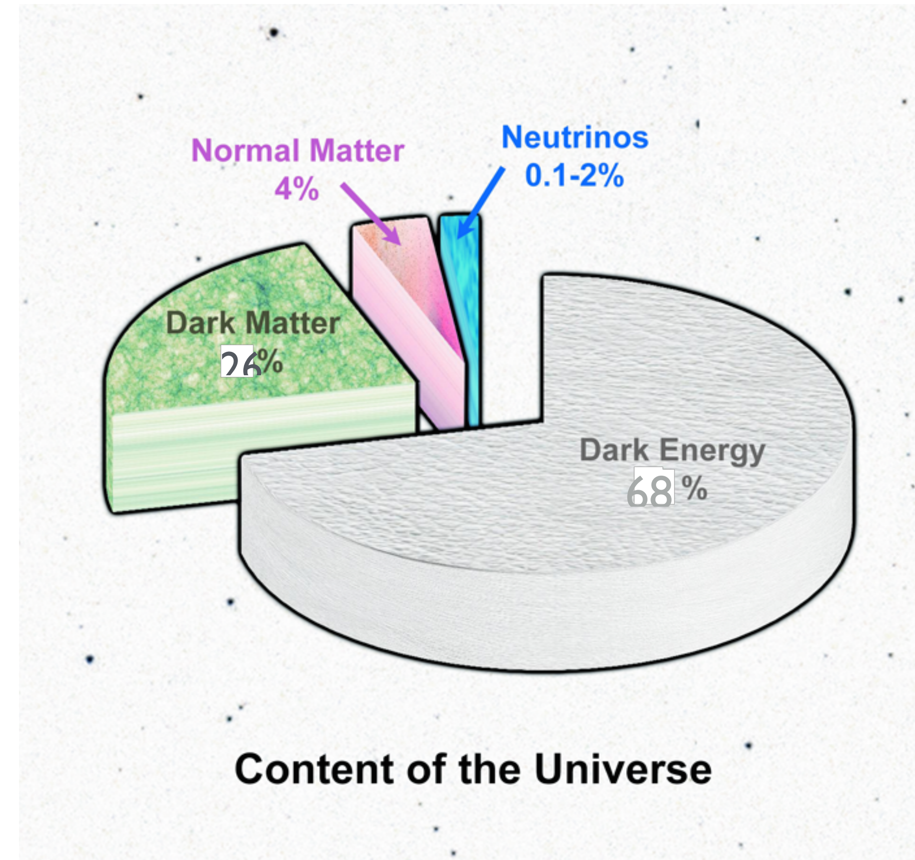


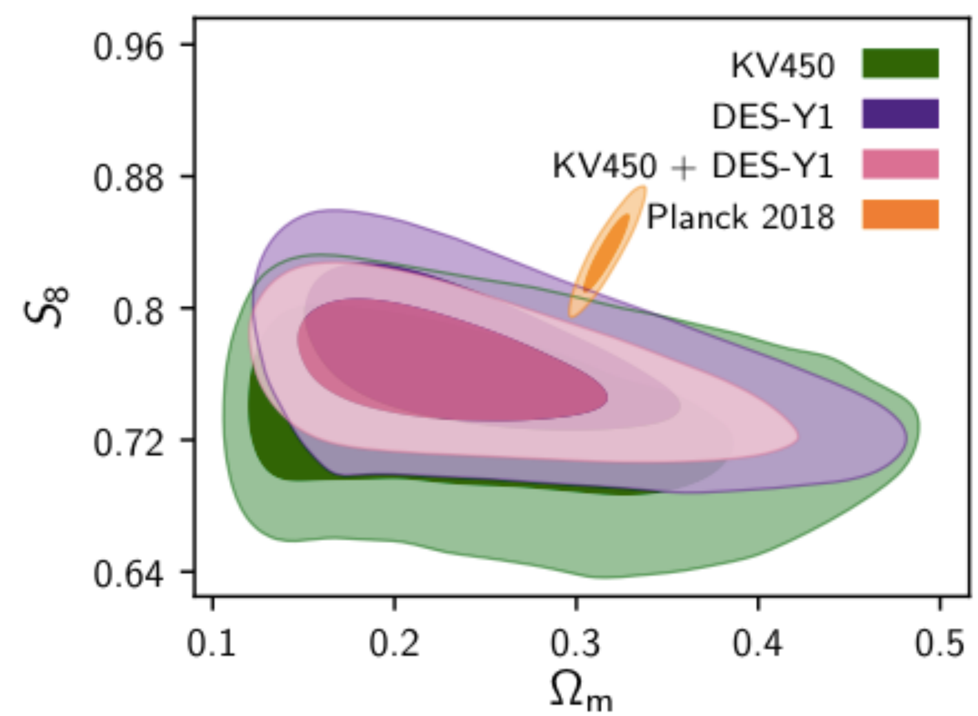
Why looking any further?



Ezquiaga et al., Front.Astron.Space Sci. (2018)



S.Joudaki et al., Astron.Astrophys. 638 (2020)



We face a mix of long standing fundamental questions (DM, DE, physics of inflation) and new tantalizing "curiosities" that make us question all aspects of our standard model as well as exploring new probes.

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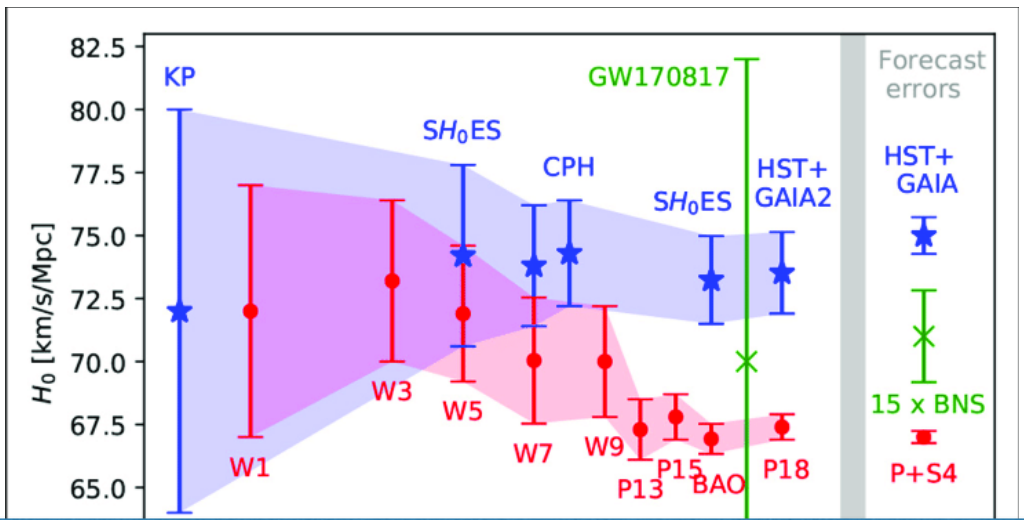

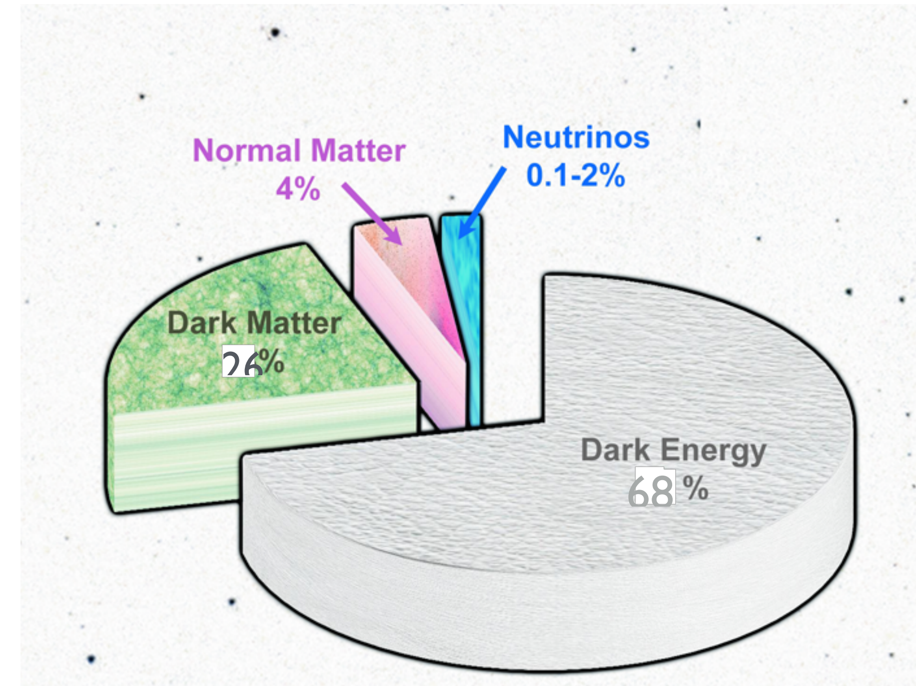

Because we can !

Upcoming surveys will provide us with a swath of data that will allow us to test gravity on cosmological scales with <u>unprecedented</u> precision.

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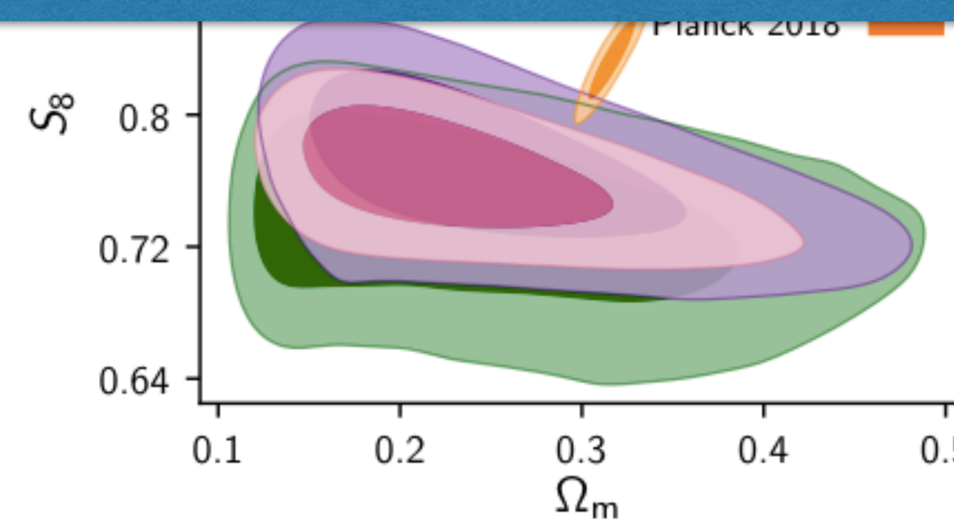
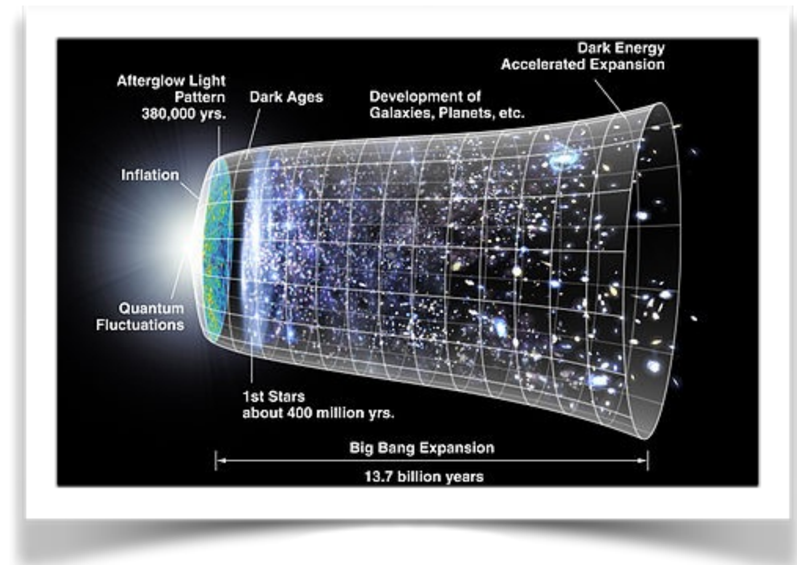


The Standard Model of Cosmology

Einstein eqs. applied to the background FLRW metric of our Universe $ds^2 = -dt^2 + a^2(t)d\bar{x}^2$ give the Friedmann eq.:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r}{a^4} + \rho_\Lambda^0\right)$$



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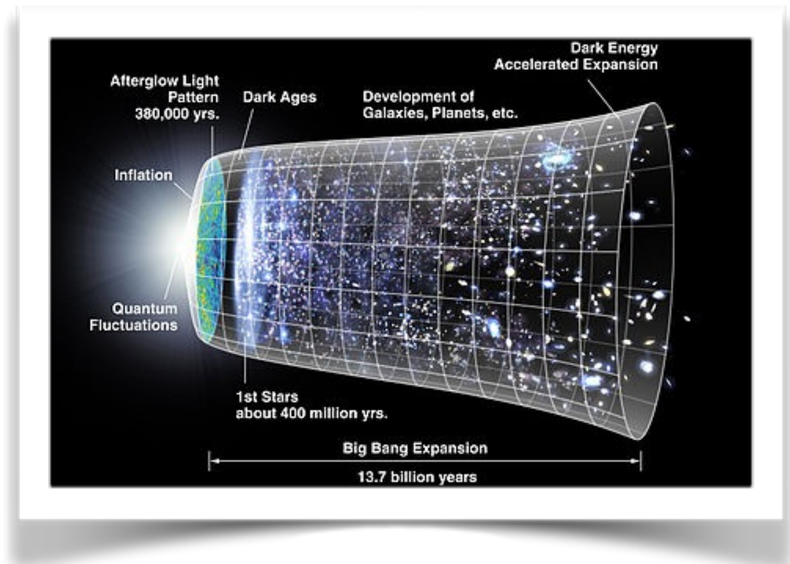
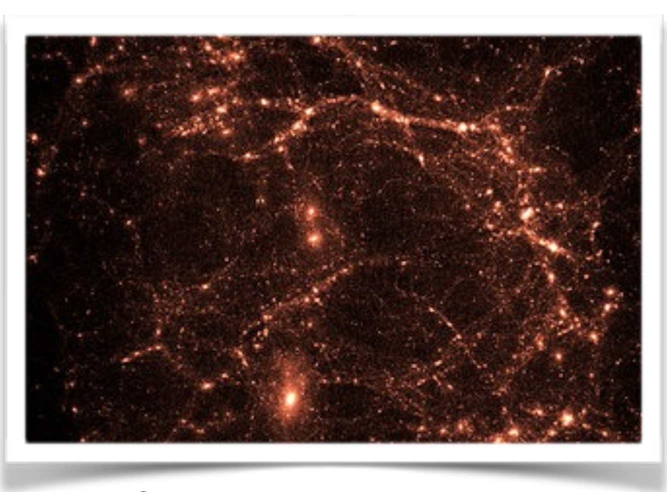
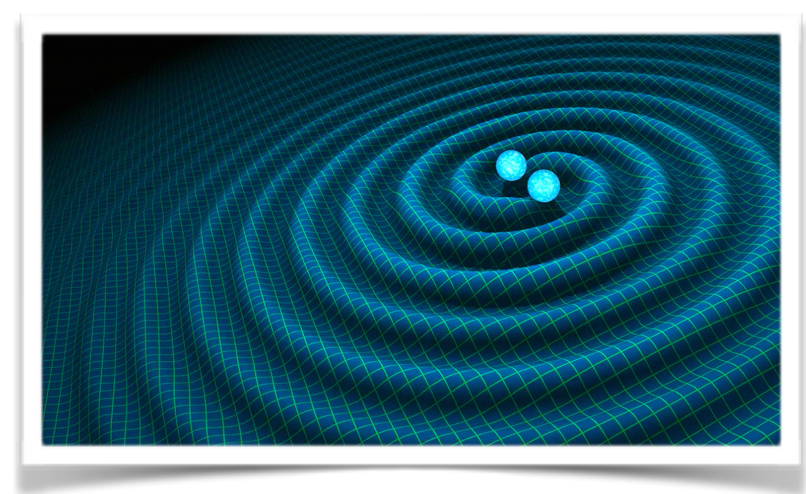


If we now include **perturbations**

$$ds^2 = -\left[1 + 2\Psi(t,\vec{x})\right]dt^2 + a^2(t)\left[1 + 2\Phi(t,\vec{x})\right]d\vec{x}^2 + h_{ij}(t,\vec{x})dx^i dx^j$$

the Einstein equations at **linear** level are **decoupled**:





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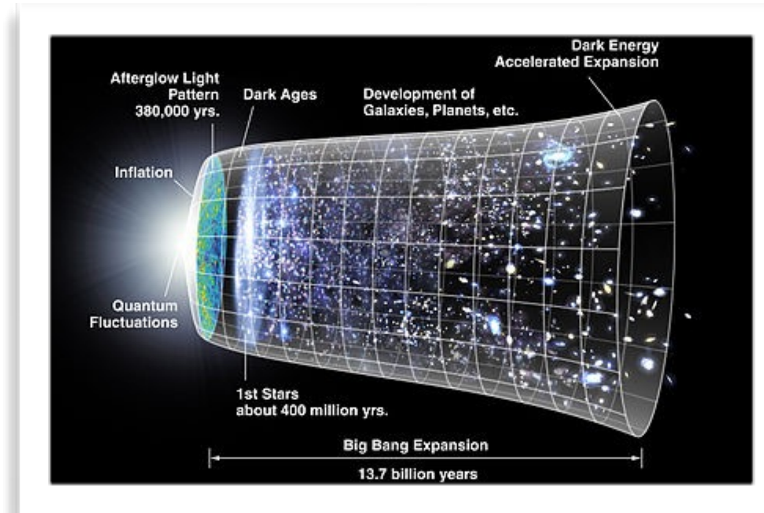

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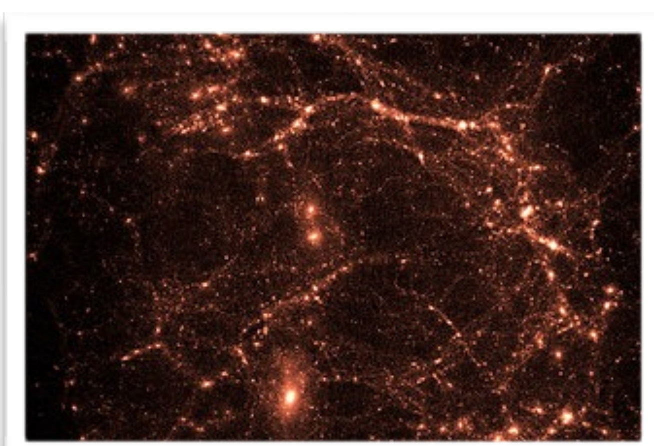

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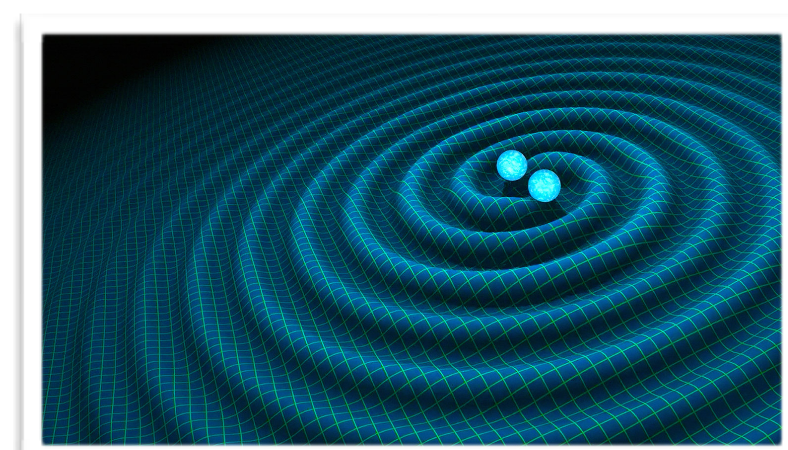

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Beyond LCDM ?

Let me focus on dark energy and modifications of gravity

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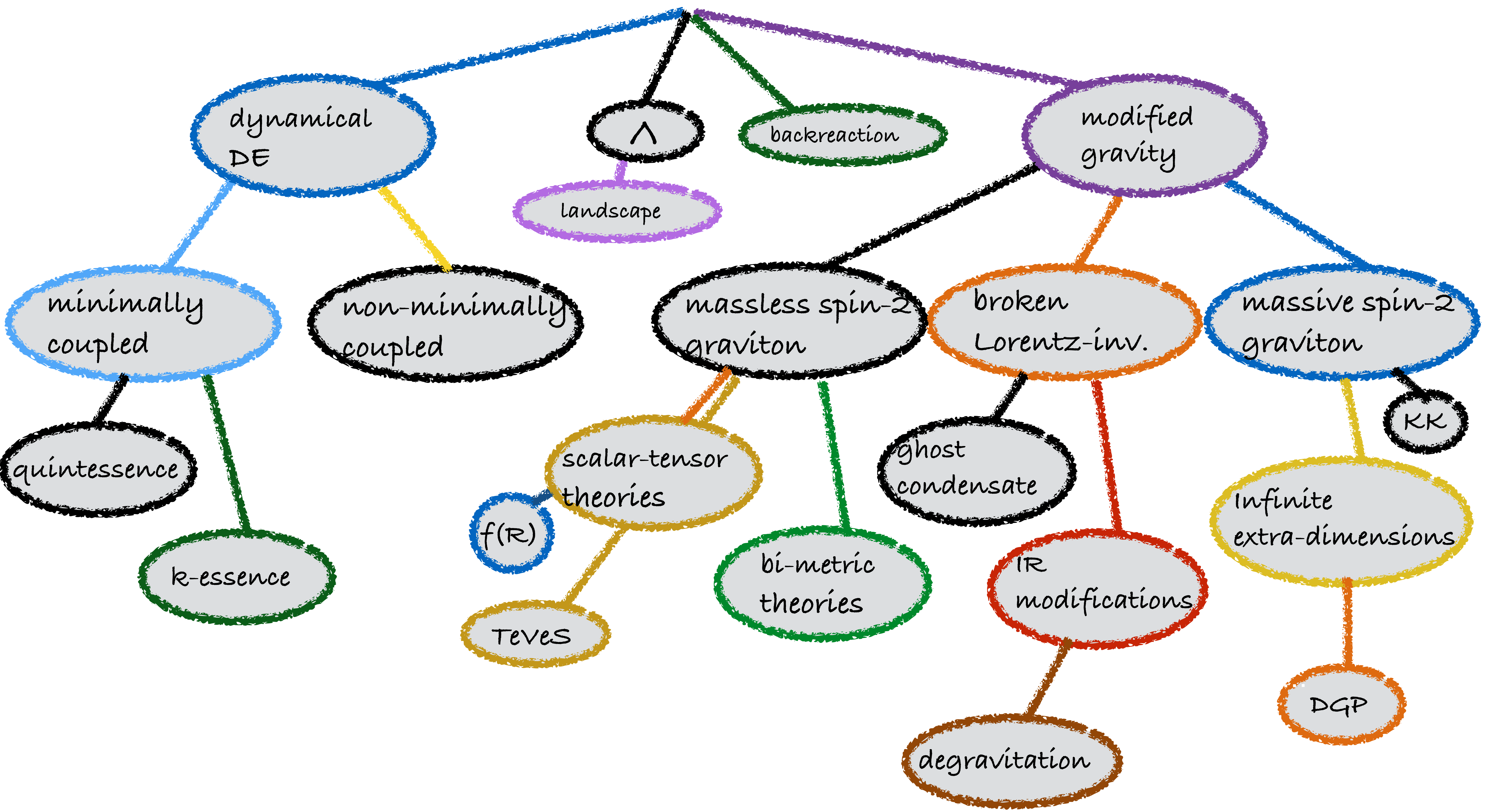
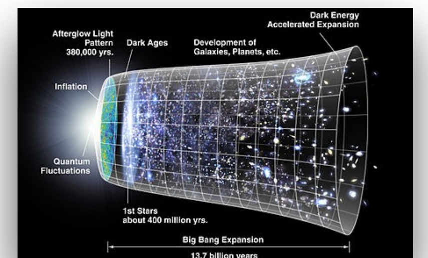


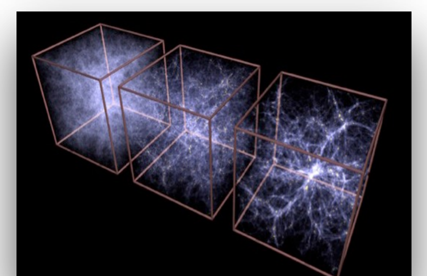
Beyond LCDM - LSS frontier

The equations for (linear scalar) perturbations become significantly more complicated. Yet we can capture the effects in few phenomenological functions:



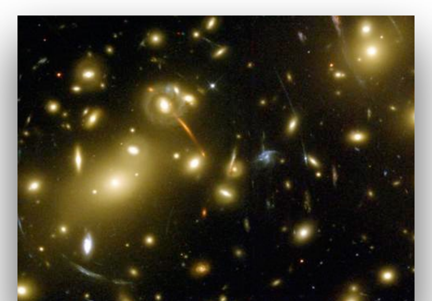
Expansion:

$$\frac{H^2}{H_0^2} = \frac{\Omega_r}{a^4} + \frac{\Omega_M}{a^3} + \Omega_{\rm DE} a^{-3\int(1+w_{\rm DE}(a))}$$



Clustering:

$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\delta$$



Lensing:

$$k^2(\Phi+\Psi) = -\Sigma(a,k)\frac{a^2}{M_P^2}\rho\delta$$

for scalars only!

AS, Pogosian, Buniy, PRD 2013

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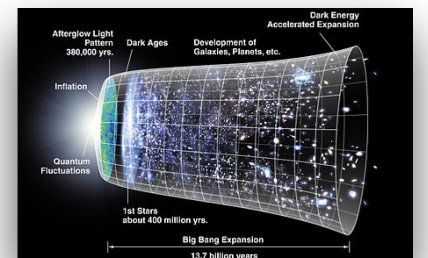

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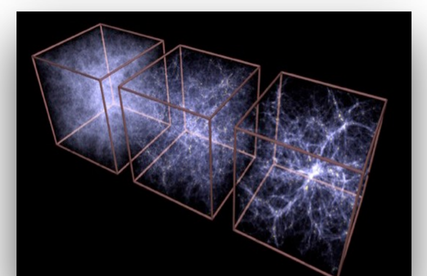

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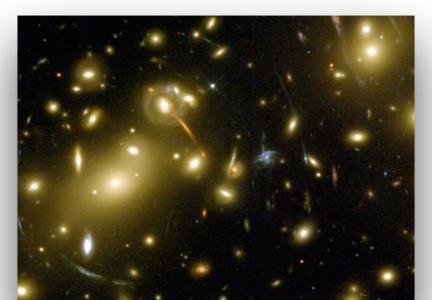

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Ongoing and upcoming wide field imaging and spectroscopic redshift surveys are in line to map more than a 100 cubic-billion-light-year of the Universe: exquisite measurements of **expansion rate** & reconstruction of cosmic structure **growth rate** and **lensing** to ~ O(1)% over wide redshift range.

among several:

euclid

ESA M-class mission, O(€1 Billion), to be launched in 2022/2023

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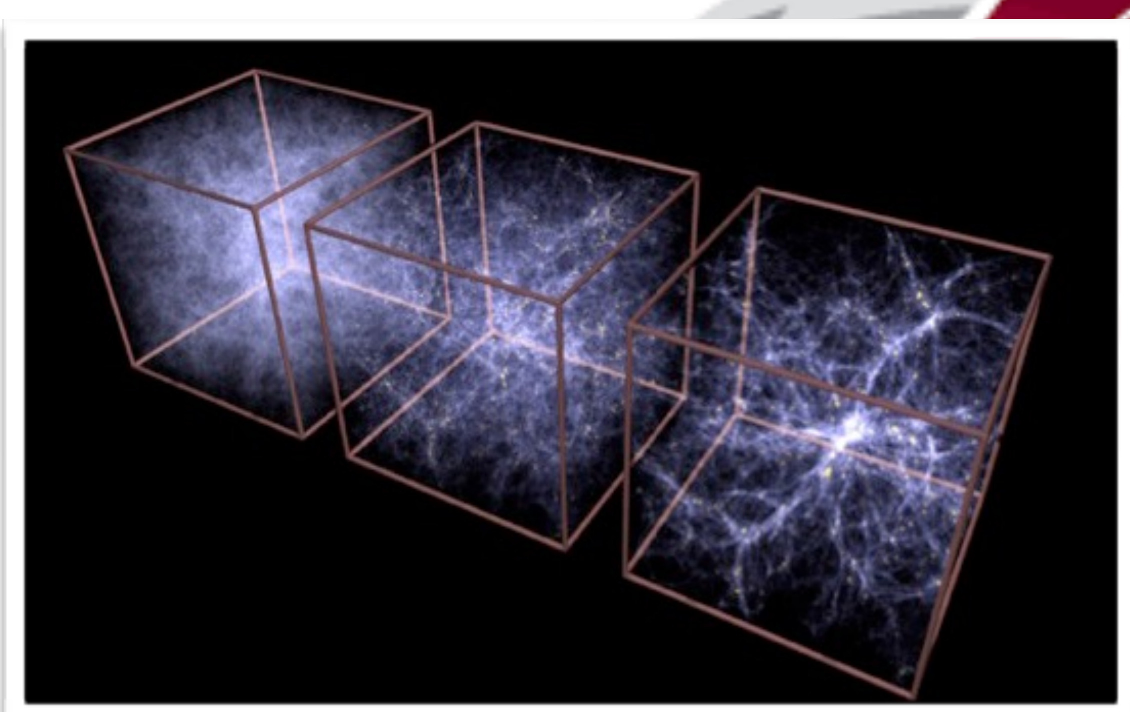

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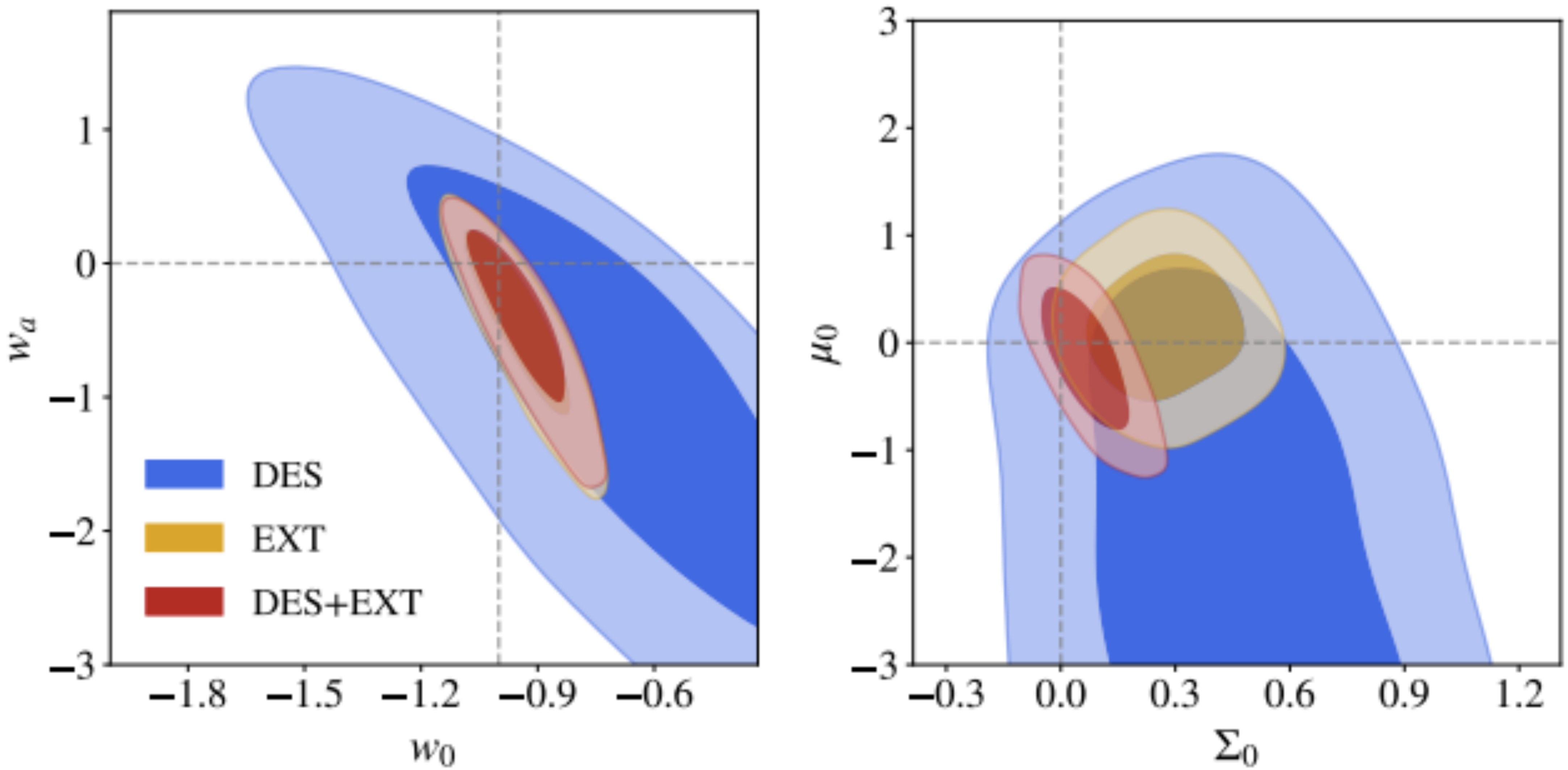
Beyond LCDM - LSS frontier

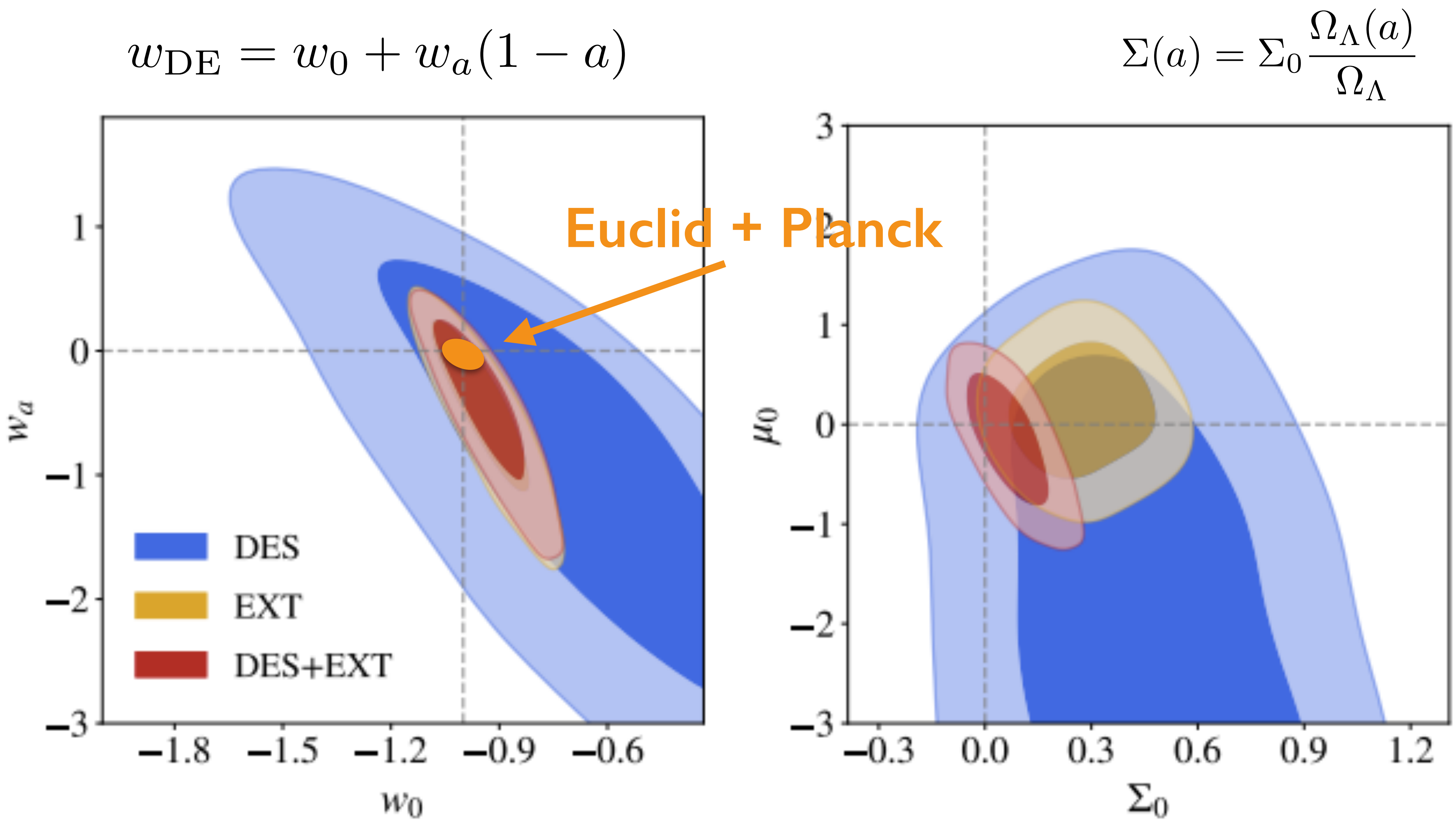
$$w_{\rm DE} = w_0 + w_a(1-a)$$

$$\Sigma(a) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$



DES year 1

Beyond LCDM - LSS frontier



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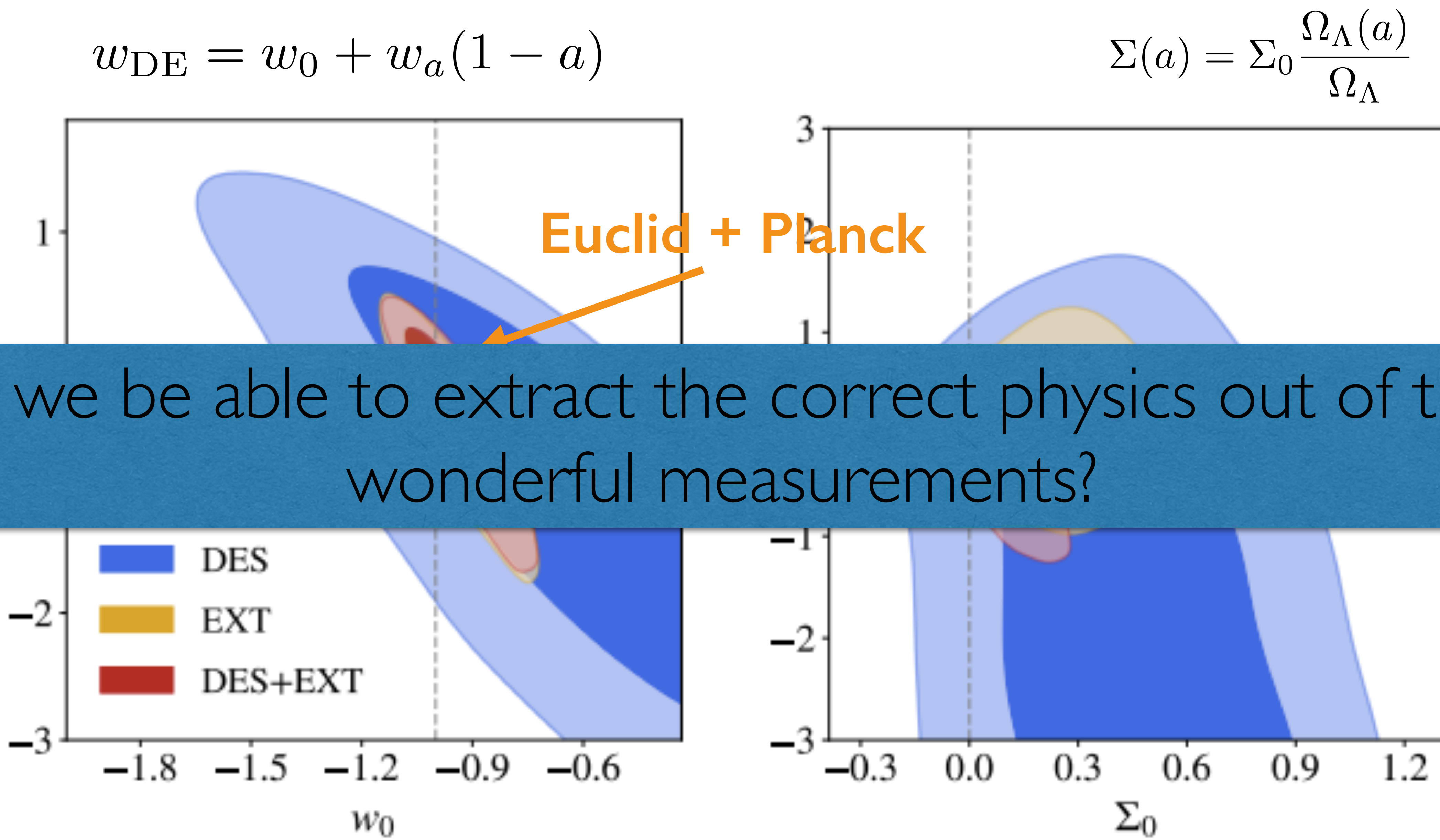

Will we be able to extract the correct physics out of these wonderful measurements?

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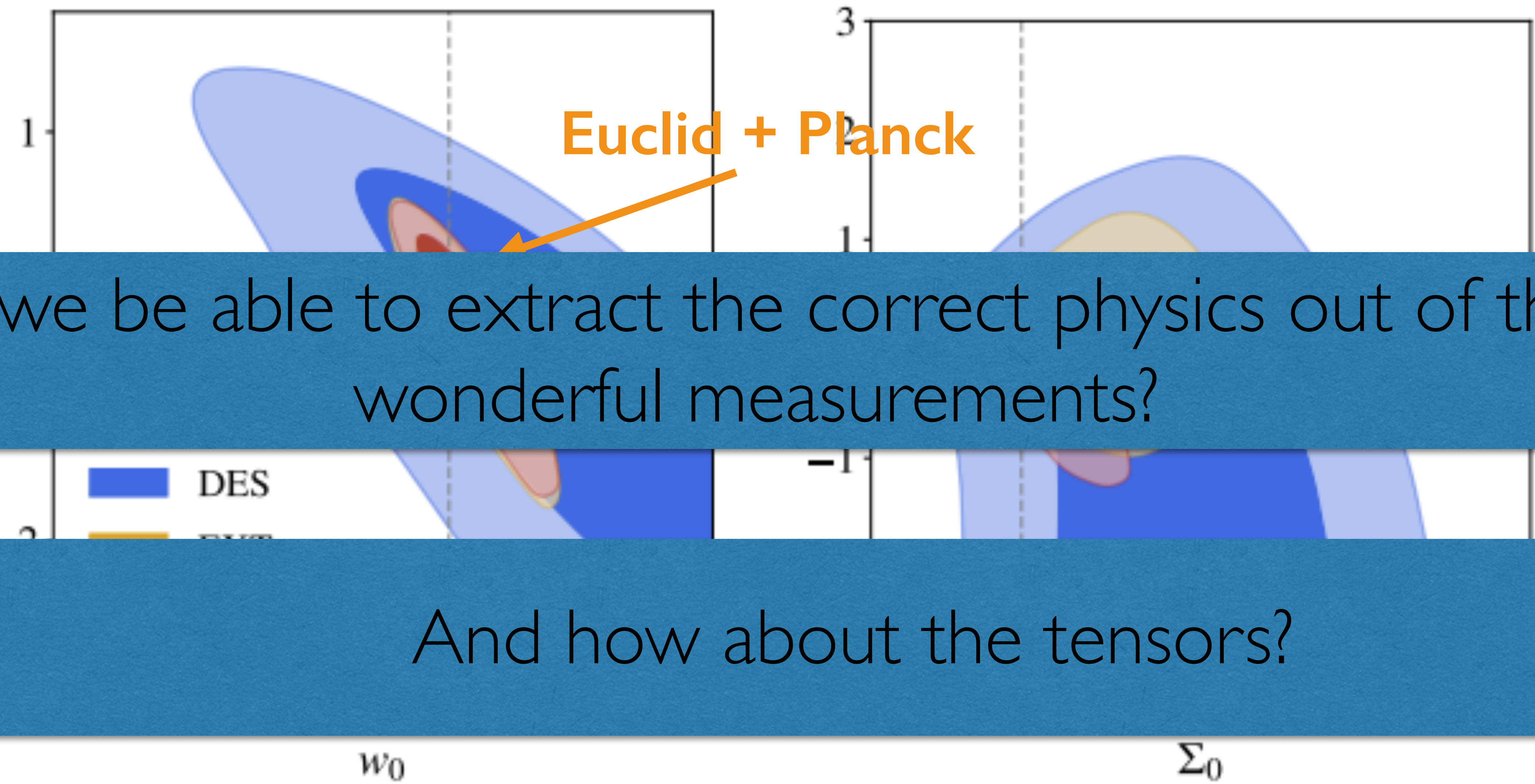

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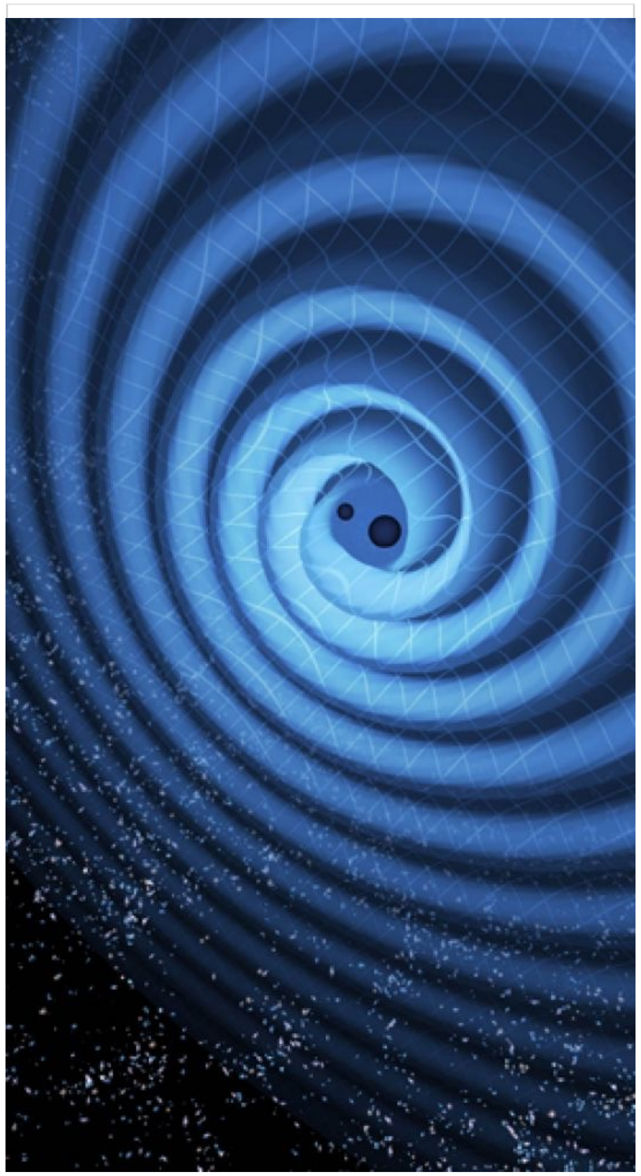
And how about the tensors?

DES year 1

GW170817

& GRB170817A



Using the observed **time-delay** btw GRB and GW,

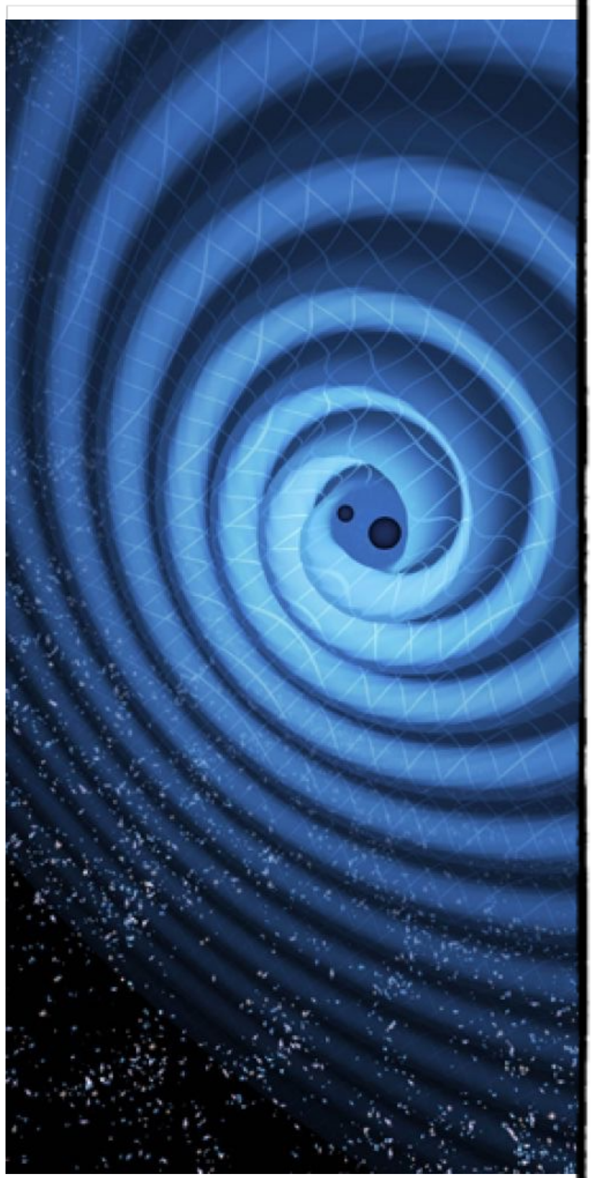
$(1.74 \pm 0.05)\mathrm{s}$, they placed very stringent limits on the speed of gravity:

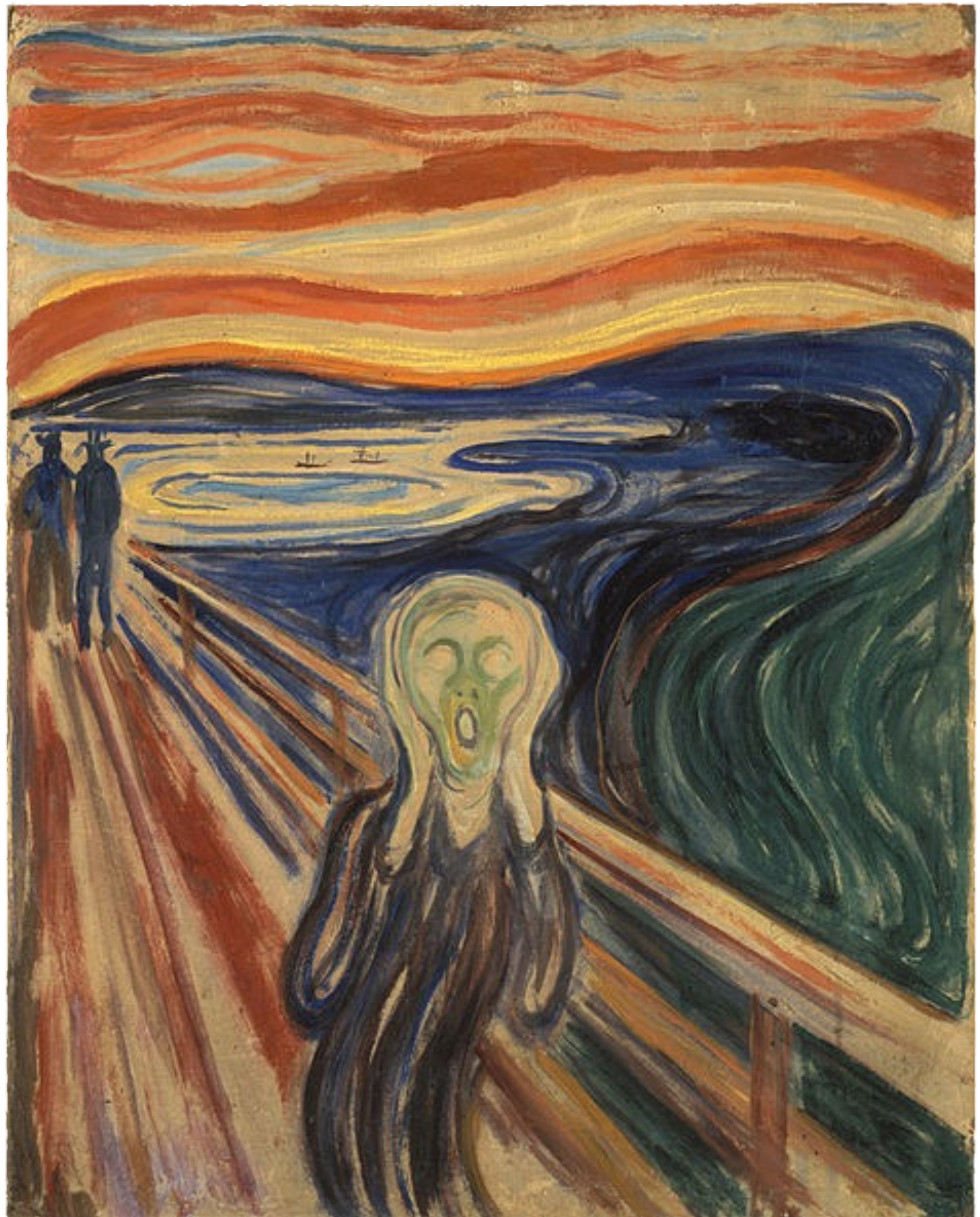
$$-3 \cdot 10^{-15} < \frac{c_T^2}{c^2} - 1 < 7 \cdot 10^{-16}$$

and just like that, many modified gravity models were ruled out* !

GW170817

170817A





The scream, E. Munch

W,

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Effective Field Theory of Dark Energy

A unified action for linear perturbations

$$S^{(2)} = \int dx^3\, dt\, a^3 \frac{M_*^2}{2} \left\{ \delta K_{ij} \delta K^{ij} - \delta K^2 + (1 + \alpha_T) \delta_2 \left(\sqrt{h} R / a^3 \right) + \alpha_K H^2 \delta N^2 + 4 \alpha_B H \delta K \delta N \right\}$$

$$\alpha_M \equiv H^{-1} \frac{d \ln M_*^2}{dt}$$

α_M Running of Planck's constant, generated by non-minimal coupling

α_T Deviation of speed of GWs from unity; non-zero whenever there is a non-linear derivative coupling of the scalar field to the metric. Same non-linearity is responsible for non-zero anisotropic stress.

α_K Quantifies the independent dynamics of the scalar-field

α_B Signals a coupling between the metric and the scalar-field

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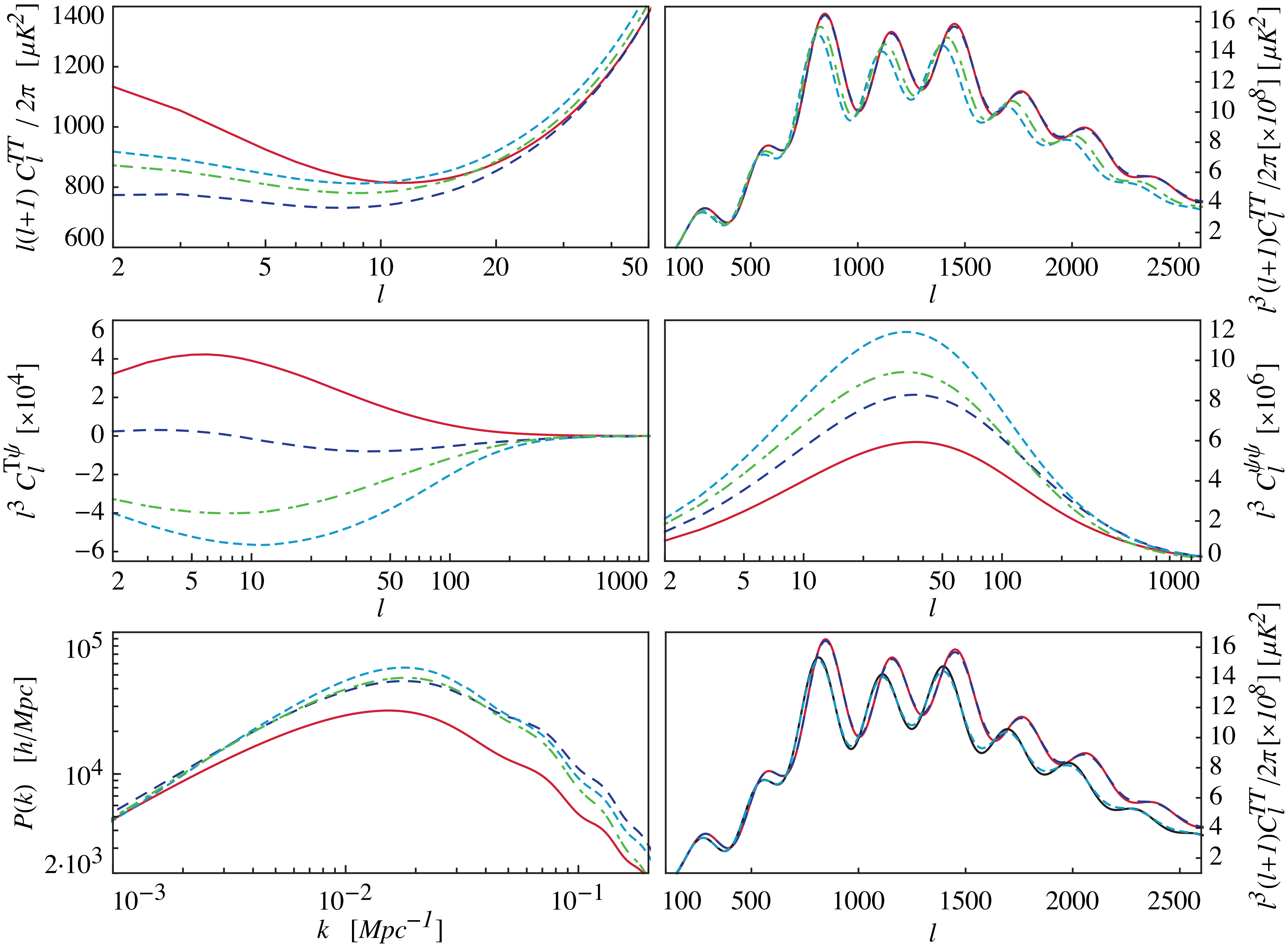
$$\alpha_M \equiv H^{-1} \frac{d \ln M_*^2}{dt}$$

- Guided by symmetry principles
- Unified and physically informed framework
- Unified treatment of vast range of observables

LSS in Beyond LCDM with EFTCAMB



eftcamb.org

sub-percent precision spectra

Gravitational Waves Phenomenology

From the same unified action, we can now study also the propagation of tensors:

$$\ddot{h}_{ij} + \underline{(3 + \alpha_M)}\, H\dot{h}_{ij} + \underline{(1 + \alpha_T)}\, k^2 h_{ij} = 0$$

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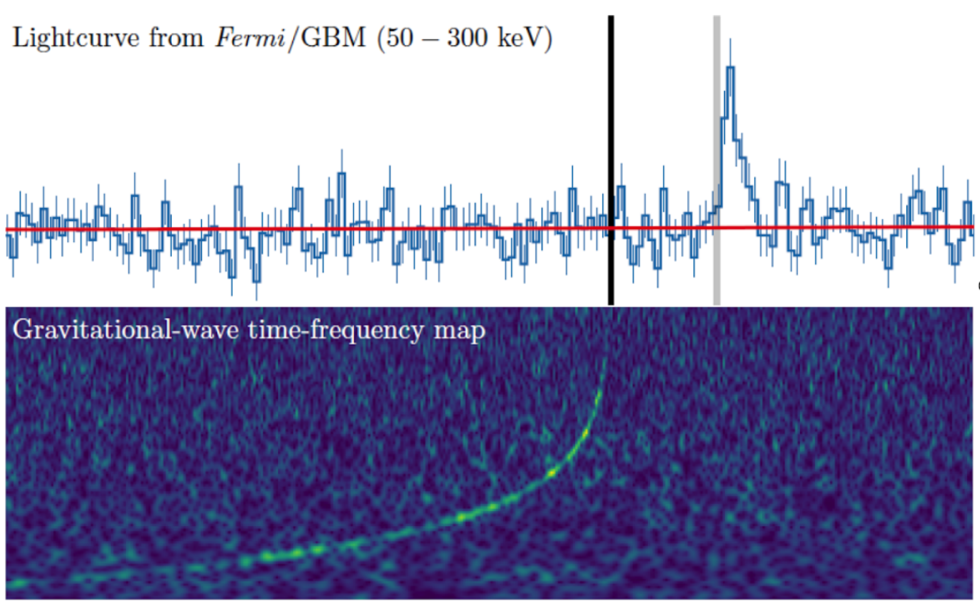
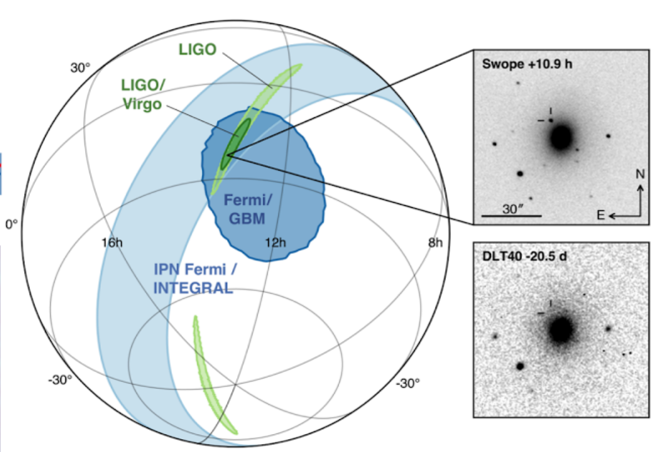
<u>GW170817 +GRB170817A</u>





$$-3 \cdot 10^{-15} < \frac{c_T^2}{c^2} - 1 < 7 \cdot 10^{-16}$$

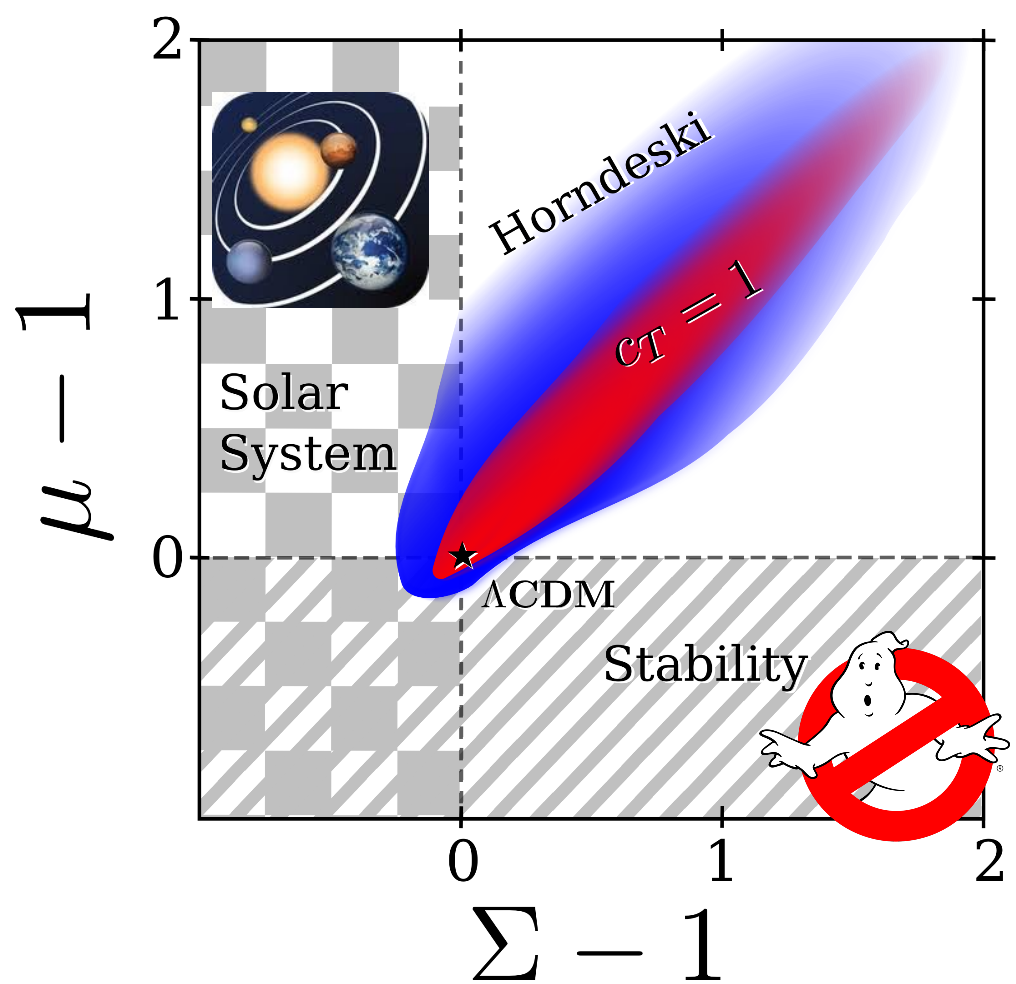
$$\alpha_T = 0$$

Creminelli & Vernizzi, PRL 2017
Ezquiaga, Zumalacarregui, PRL 2017
Baker et al., PRL 2017

This cuts a big chunk of interesting, self-accelerating models

Modified Gravity after GW170817
& GRB170817A

- A modified propagation of GW and a gravitational slip $\mu \neq \Sigma$ are intertwined



More specifically, a standard speed of propagation implies:

$$\Phi(k \ll Ma) = \Psi(k \ll Ma)$$

No gravitational slip on large scales for scalar-tensor theories!

Pogosian & Silvestri PRD 2016

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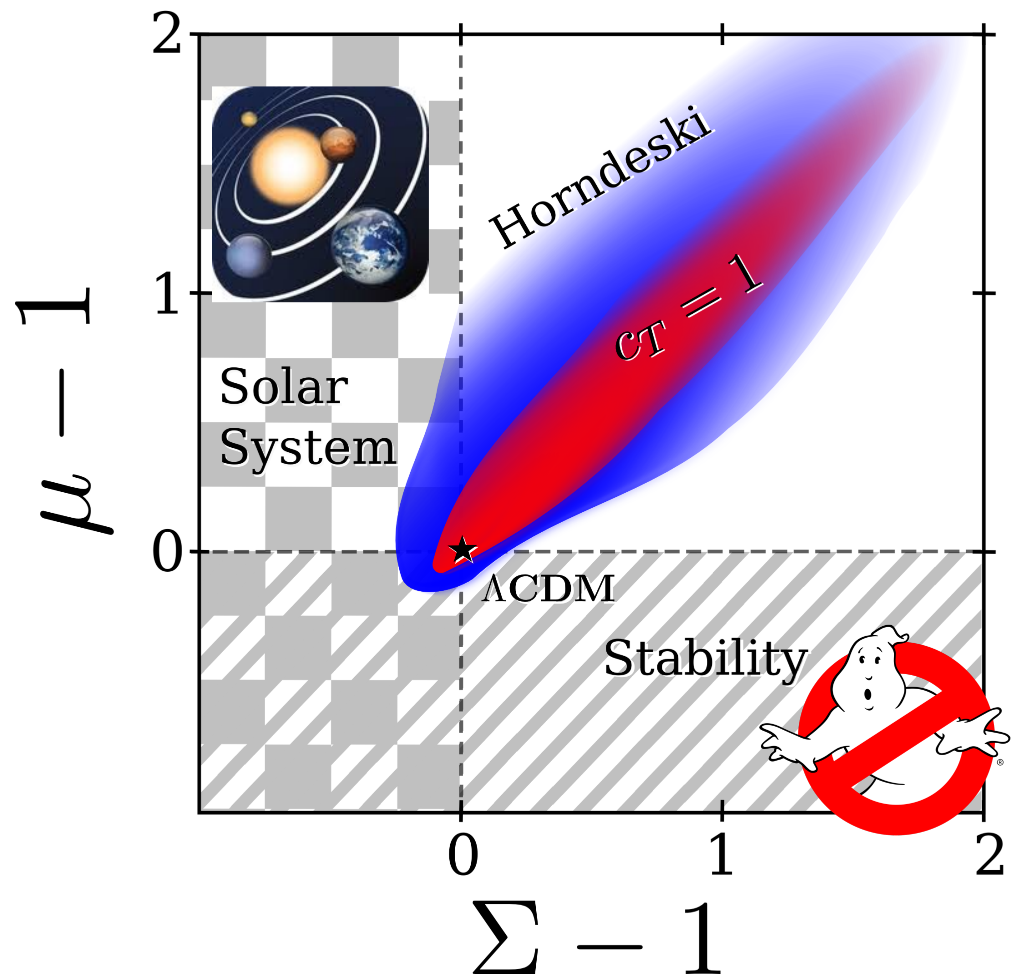

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Euclid will measure this slip with ~1-10% accuracy.

Were we to find a non-null value, then we would detect some "beyond scalar-tensor".

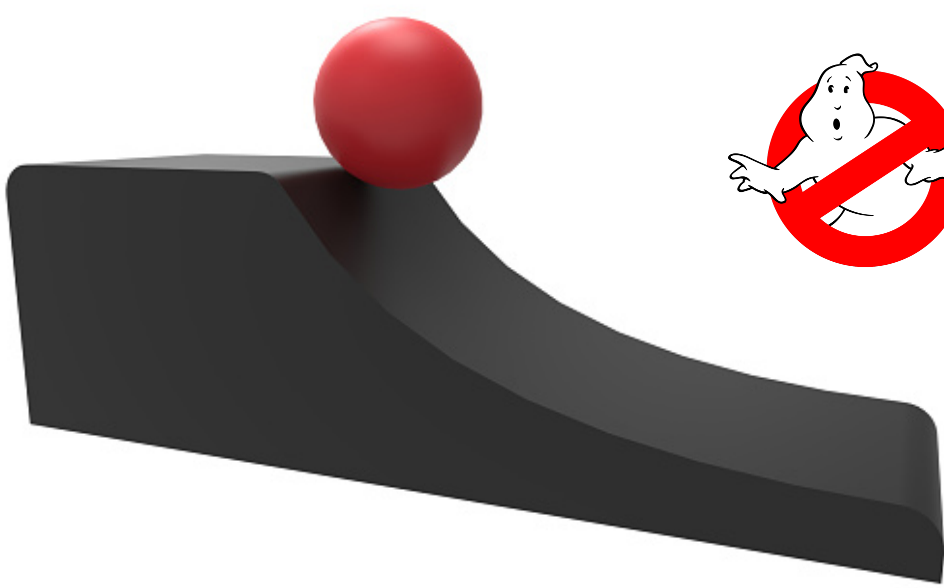
Pogosian & Silvestri PRD 2016

Theoretical Priors

Expanding the given action up to second order in the perturbations, and removing spurious DOFs, we can inspect the dynamics of perturbations:

$$S^{(2)}_{\xi,h^T} = \frac{1}{(2\pi)^3}\int d^3k\,dt\,a^3\left\{\left[\mathcal{L}_{\dot{\xi}\dot{\xi}}\dot{\xi}^2 - k^2 G\xi^2\right] + \frac{A_T}{8}\left[\left(\dot{h}^T_{ij}\right)^2 - \frac{c_T^2}{a^2}\left(h^T_{ij}\right)^2\right]\right\}$$

and the avoidance of instabilities translate into a set of precise conditions on the free functions:



$$\mathcal{L}_{\dot{\xi}\dot{\xi}} > 0$$

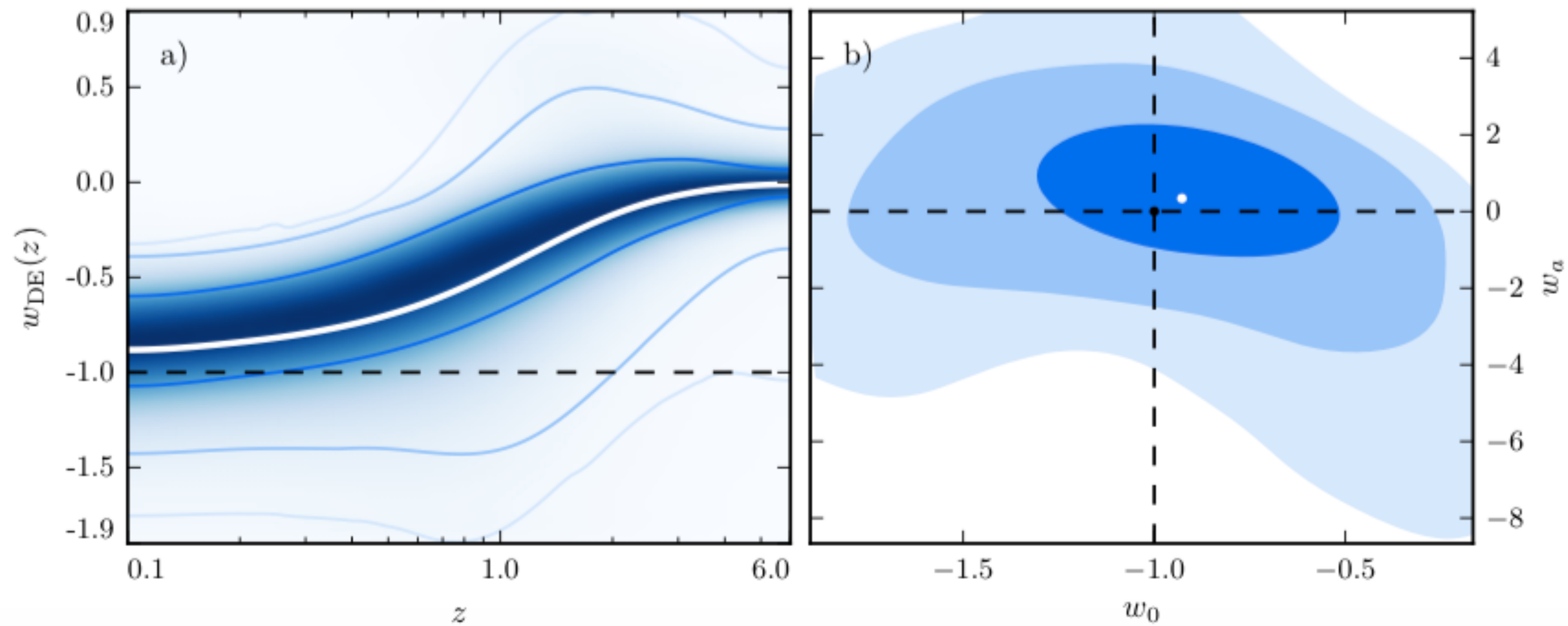
$$c_s^2 \equiv \frac{G}{\mathcal{L}_{\dot{\xi}\dot{\xi}}} > 0$$

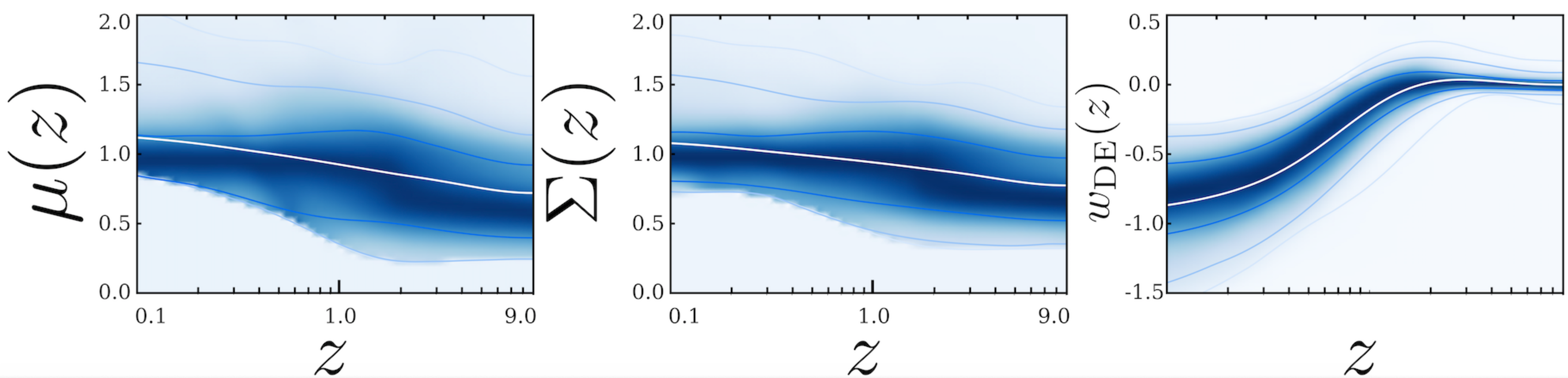
$$A_T > 0$$

$$c_T^2 > 0$$

Frusciante, Papadomanolakis, AS, JCAP 1607 (2016).

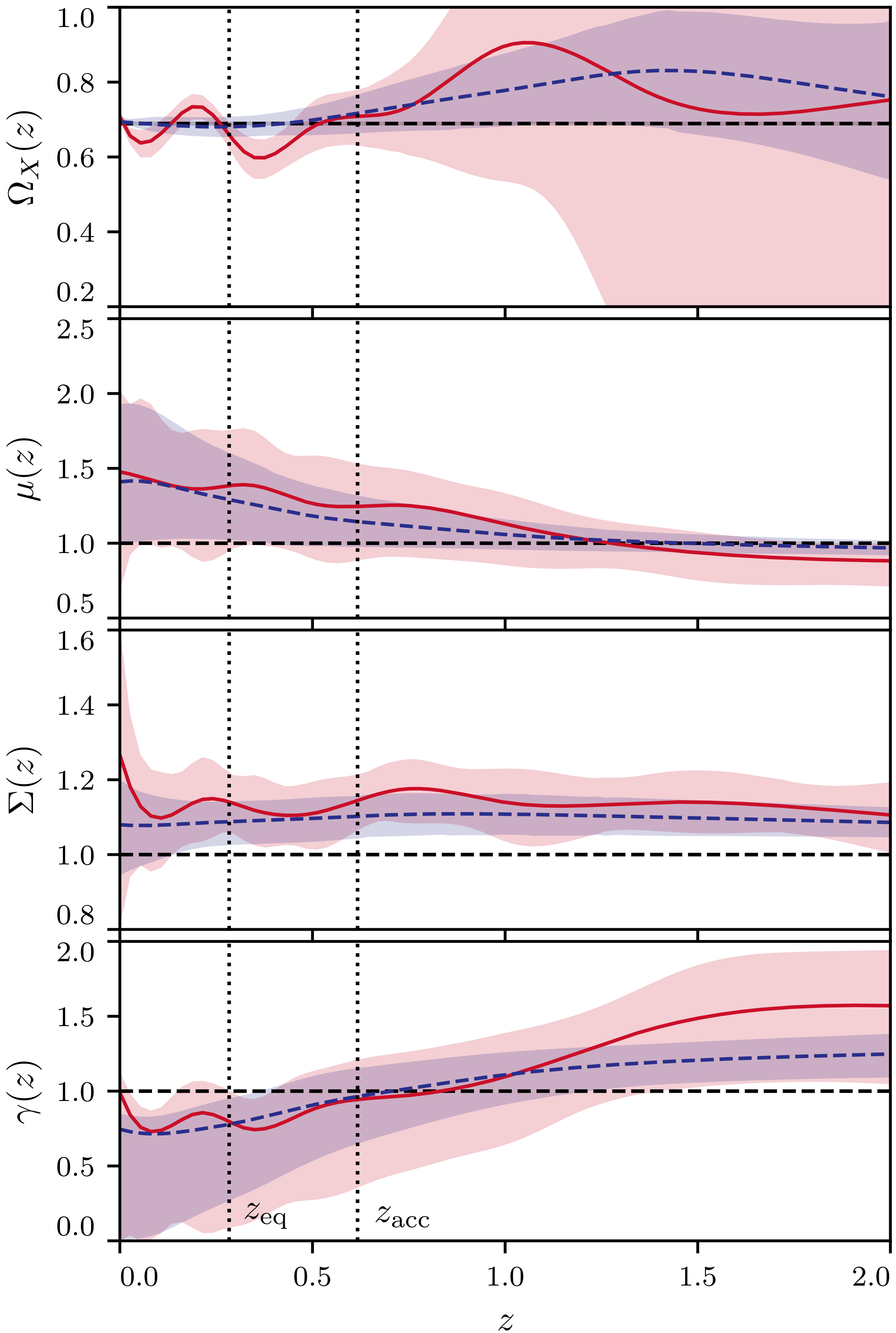
Theoretical Priors for LSS





Espejo et al., PRD 2019

Reconstruction with theoretical priors



Pogosian, Peirone, Zhao, Li, Raveri, Koyama, AS,
arXiv:2107.12990
arXiv:2107.12992

First joint non-parametric reconstruction of gravity from Large Scale Structure data, under guidance of theoretical viability conditions.

#weak lensing
DES
#Planck 2015 TT, lowTEB, lowl
#BAO Likelihoods
BAO: 6DF, MGS, eBOSS DR12 (in 9 bins by YTW), eBOSS DR14 (a
z_eff by GBZ),
eBOSS DR12 Lyman alpha
#Others:
Pantheon
WiggleZ_MPK

GW & beyond LCDM

So, we are left with:

$$\ddot{h}_{ij} + \underline{(3 + \alpha_M)}\, H\dot{h}_{ij} + (1 + \cancel{\alpha_T})\, k^2 h_{ij} = 0$$

Amendola et al., JCAP 08 (2018) 030; Belgacem et al., Phys.Rev.D 98 (2018)

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then, inside the horizon

$$h \propto \frac{1}{\tilde{a}} \qquad \frac{\dot{\tilde{a}}}{\tilde{a}} = \frac{3 + \alpha_M}{2} H$$

$$d_L^{\mathrm{GW}}(z) = \frac{a(z)}{\tilde{a}(z)} d_L^{\mathrm{EM}}(z)$$

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$$d_L^{\mathrm{GW}}(z) = \frac{a(z)}{\tilde{a}(z)} d_L^{\mathrm{EM}}(z)$$

$$d_L^{\mathrm{GW}}(z) = \frac{M_*(0)}{M_*(z)} d_L^{\mathrm{EM}}(z)$$

Amendola et al., JCAP 08 (2018) 030; Belgacem et al., Phys.Rev.D 98 (2018)

GW & beyond LCDM

So, we are left with:

$$\ddot{h}_{ij} + (3 + \alpha_M)\, H\dot{h}_{ij} + (1 + \alpha_T)\, k^2 h_{ij} = 0$$

then, inside the horizon

$$h \propto \frac{1}{\tilde{a}} \qquad \frac{\dot{\tilde{a}}}{\tilde{a}} = \frac{3 + \alpha_M}{2} H \qquad (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

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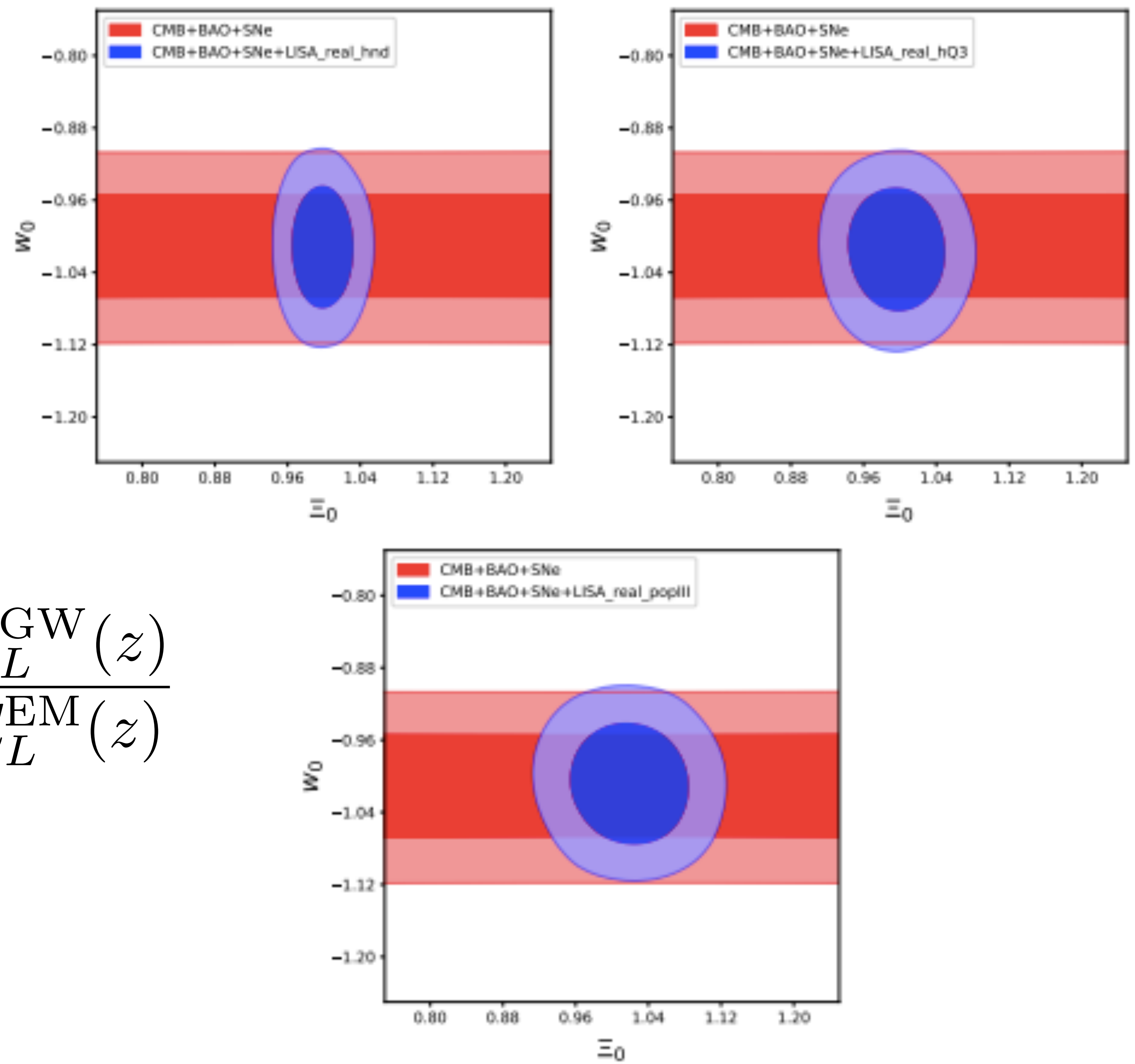
GW & beyond LCDM



$$\Xi(z) \equiv \frac{d_L^{\rm GW}(z)}{d_L^{\rm EM}(z)}$$

LISA Cosmology Working Group, JCAP 07 (2019)

Alice Garoffolo

Detecting DE fluctuations ?

We pick up additional, theory-dependent corrections from inhomogeneities along the line of sight:

$$\frac{\Delta d_L^{\rm SN}}{\bar{d}_L^{\rm SN}} = -\,\kappa - (\phi+\psi) + \frac{1}{\chi}\int_0^{\chi} d\tilde{\chi}\,(\phi+\psi) + \phi\left(\frac{1}{\chi\mathcal{H}}\right) + v_{\parallel}\left(1-\frac{1}{\mathcal{H}\chi}\right) - \left(1-\frac{1}{\chi\mathcal{H}}\right)\int_0^{\chi} d\tilde{\chi}\,(\phi'+\psi')$$

A.Garoffolo et al., JCAP 11 (2020)

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$$\Delta_\varphi(\hat{\theta},z) \equiv \frac{\Delta d_L^{\mathrm{SN}}(\hat{\theta},z)}{\bar{d}_L^{\mathrm{SN}}} - \frac{\Delta d_L^{\mathrm{GW}}(\hat{\theta},z)}{\bar{d}_L^{\mathrm{GW}}} = \frac{M_P'}{\mathcal{H}M_P}\left(\phi - v_\parallel + \int_0^\chi d\tilde{\chi}\,(\phi'+\psi')\right) - \frac{M_{P,\varphi}}{M_P}\delta\varphi - \frac{M_{P,X}}{M_P}\delta X$$

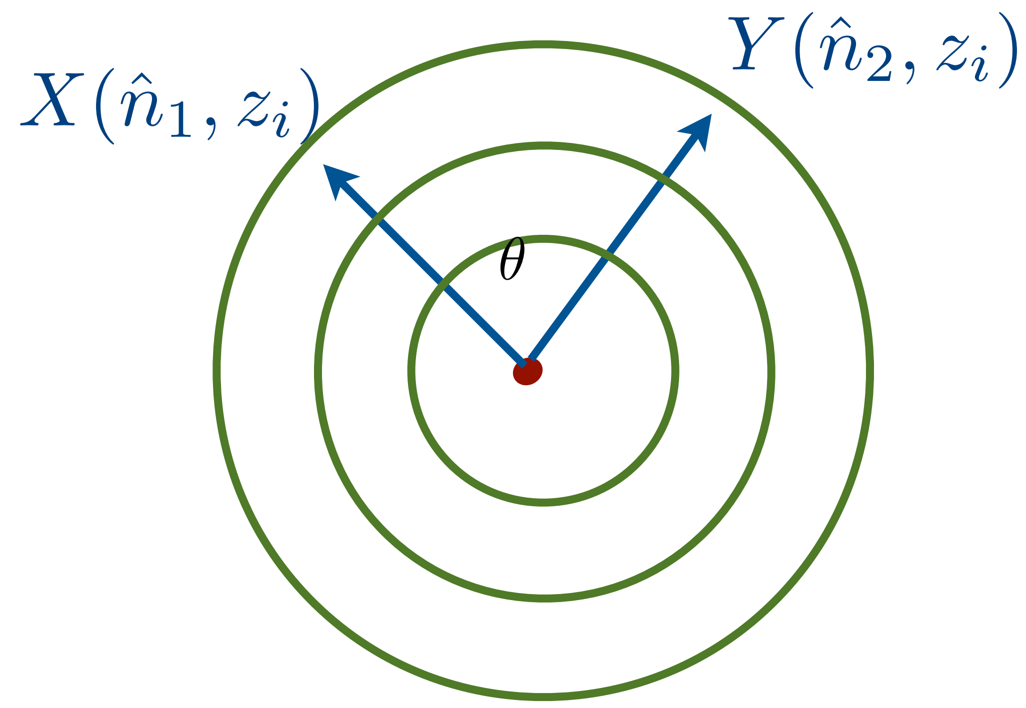
A.Garoffolo et al., JCAP 11 (2020)

Detecting DE fluctuations ?

<X Y>$_\theta$

X,Y: GWs, SNIa

$$C_\ell^{XY}$$



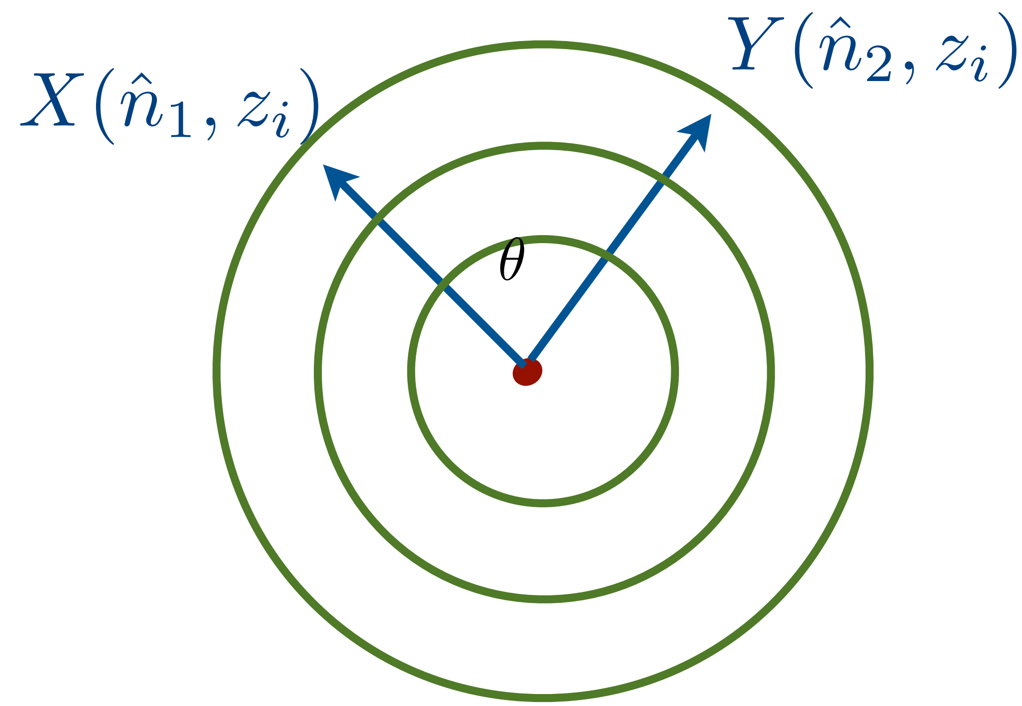
Detecting DE fluctuations ?

$\langle X\ Y \rangle_\theta$

X,Y: GWs, SNIa

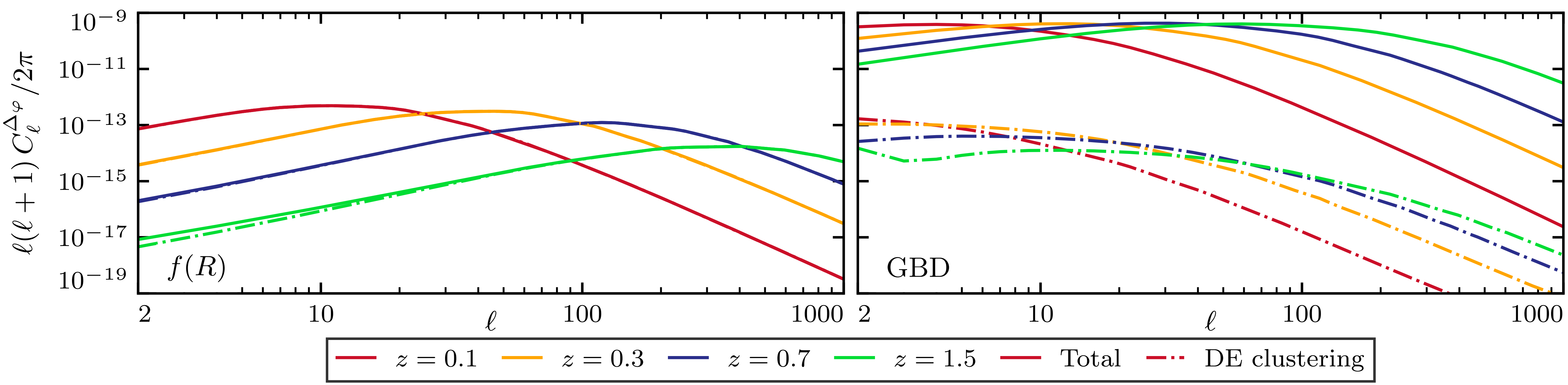
↓

$$C_\ell^{XY}$$



$$C_\ell^{\Delta\varphi} = C_\ell^{\mathrm{SN}} + C_\ell^{\mathrm{GW}} - 2C_\ell^{\mathrm{SN-GW}}$$

EffectiveFieldTheory with CAMB

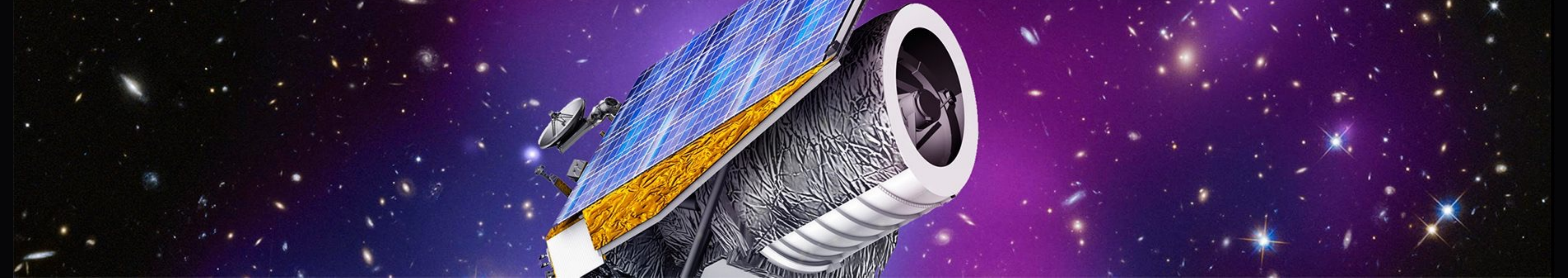


futuristic, but exciting!

$$N_i^{\rm eff} = \frac{N_i}{\sigma_{d_L}^2 / d_L^2}$$

	GR	$f(R)$		GBD	
	$N_{\rm GW}^{\rm eff}$	$N_{\rm GW}^{\rm eff}$	$N_{\Delta_\varphi}^{\rm eff}$	$N_{\rm GW}^{\rm eff}$	$N_{\Delta_\varphi}^{\rm eff}$
$z = 0.1$	10^7	10^7	10^{14}	10^7	10^{12}
$z = 0.3$	10^8	10^8	10^{15}	10^8	10^{11}
$z = 0.7$	10^8	10^8	10^{16}	10^8	10^{12}
$z = 1.5$	10^7	10^7	10^{17}	10^7	10^{12}
w/o z	10^7	10^7	10^{19}	10^7	10^{14}

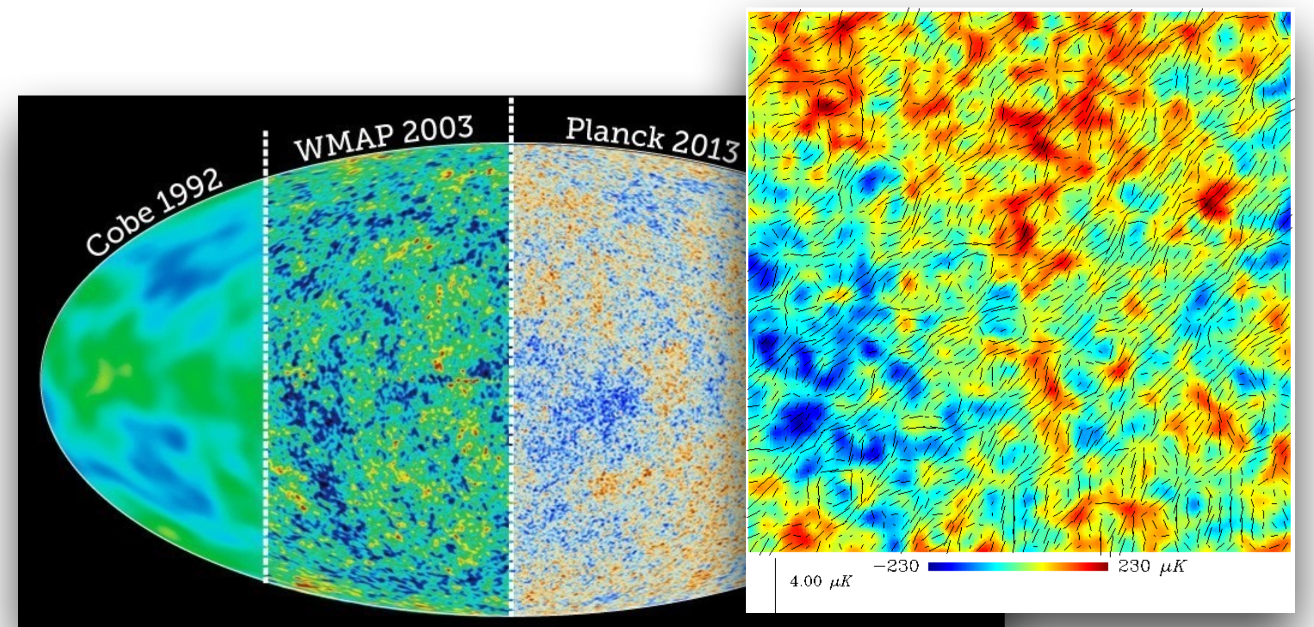
TABLE I. Effective number of events for a 5-σ detection of $C_\ell^{\rm GW}$ and $C_\ell^{\Delta_\varphi}$.



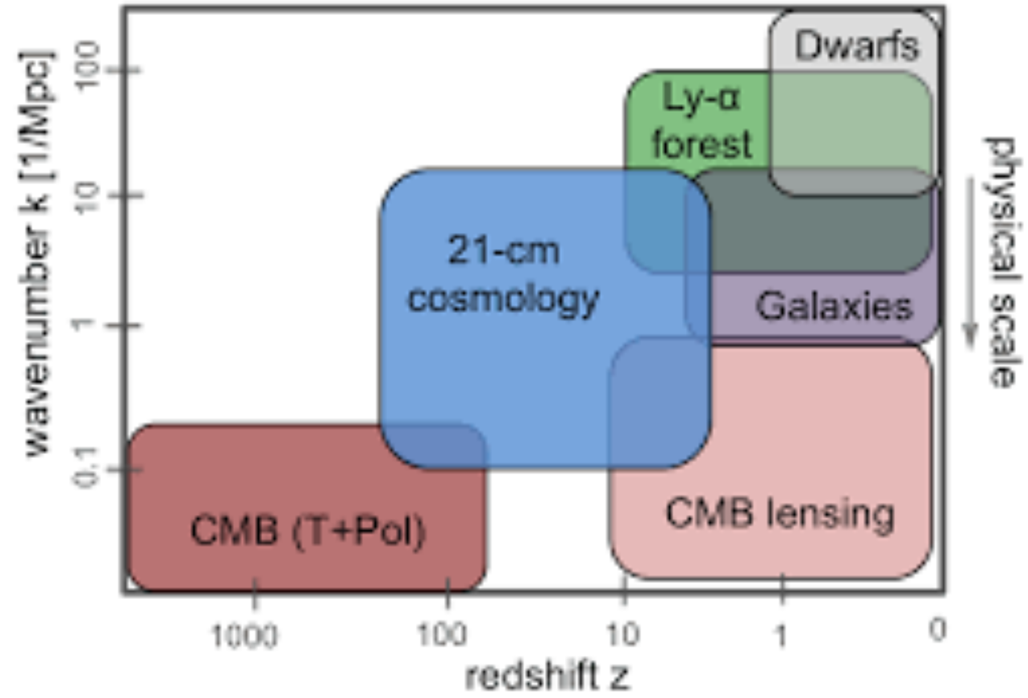
Towards precise and accurate Cosmology

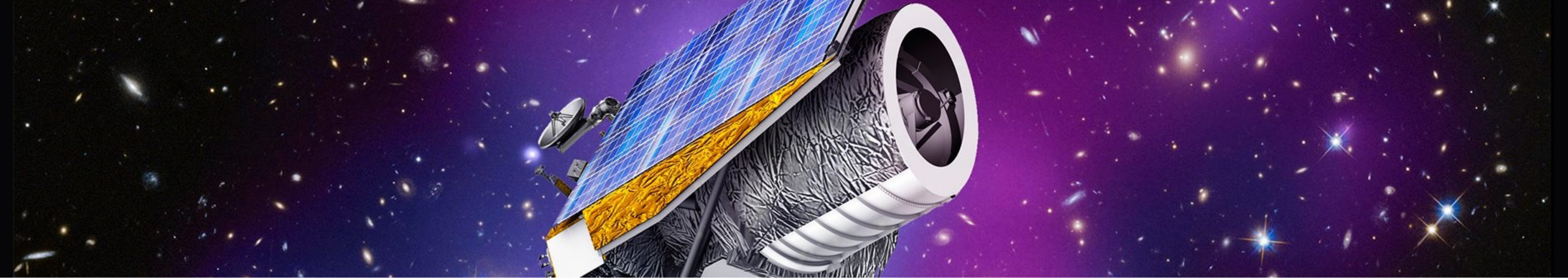
Cosmology is a versatile tool that can test broad classes of theoretical scenarios.
The next decade of observations will see a tremendous leap in sensitivity.

Synergy will be the key!

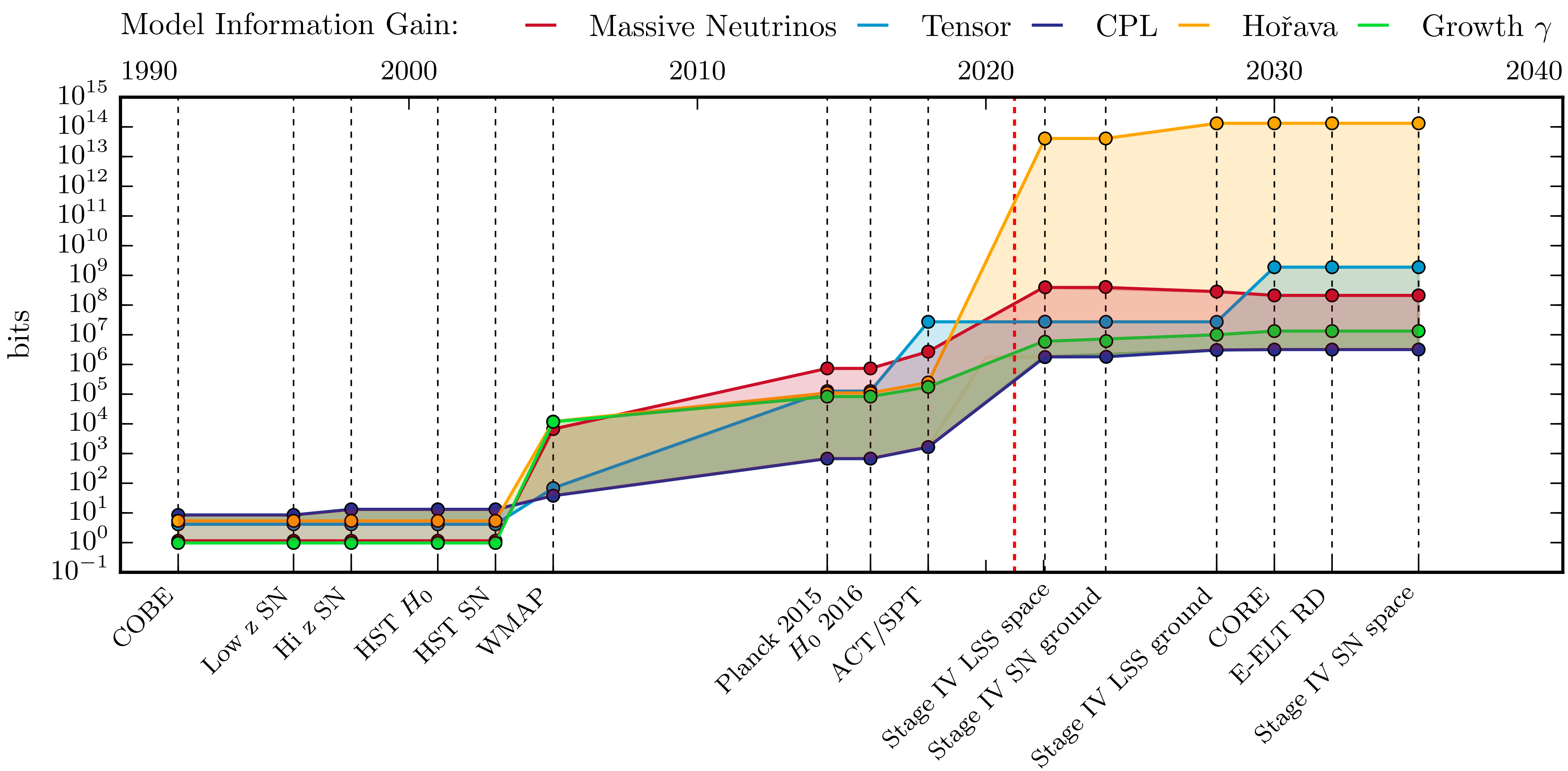


CMB S4

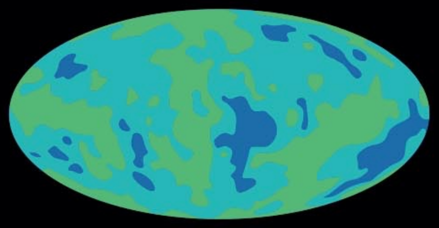




Towards precise and accurate Cosmology



courtesy of M. Raveri, & M. Martinelli (CosmicFish, https://cosmicfish.github.io/)



KEEP
CALM
AND
TEST
GRAVITY

the EFTCAMB team

THANK YOU
for hosting me !