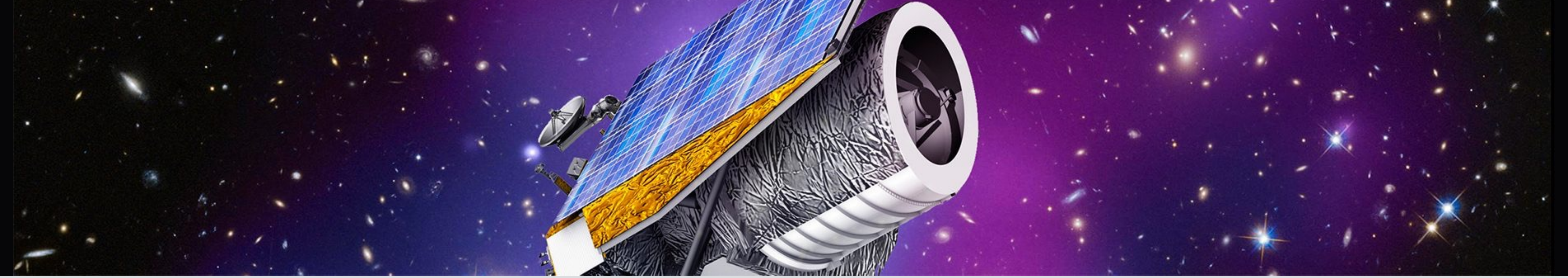


Precision and Accurate Cosmology with Euclid: what awaits us

Alessandra Silvestri
Leiden University

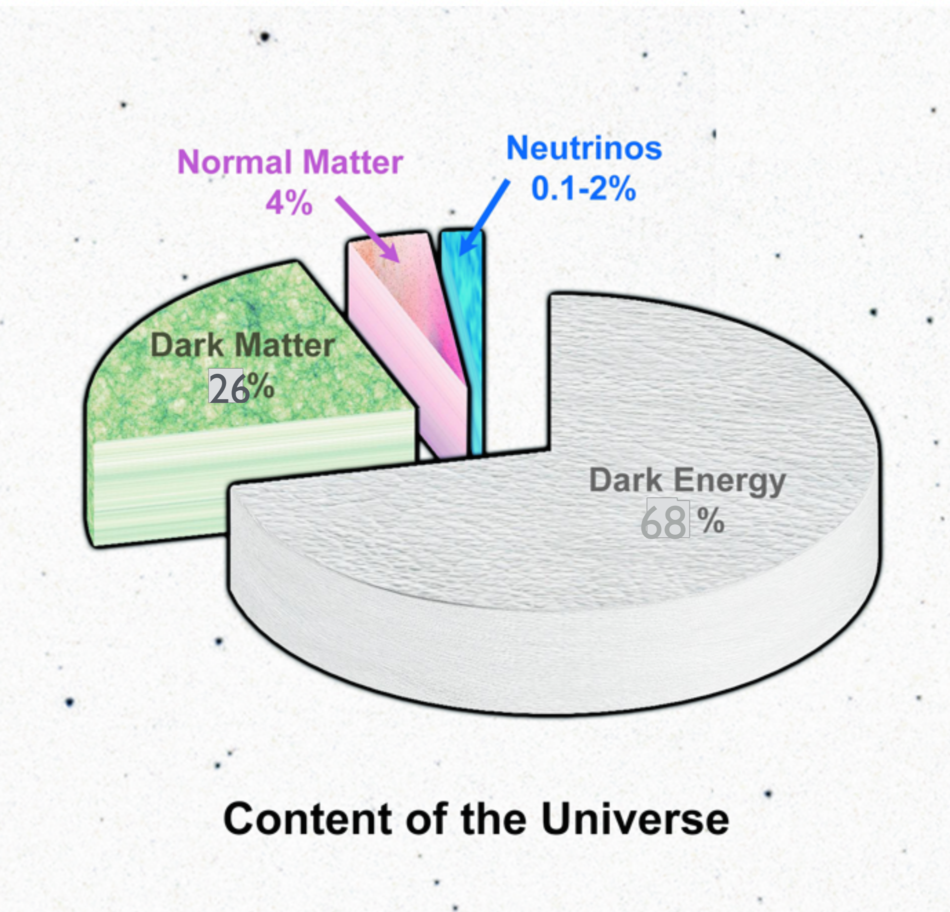
Astroparticle Symposium, Paris-Saclay, November 3, 2022

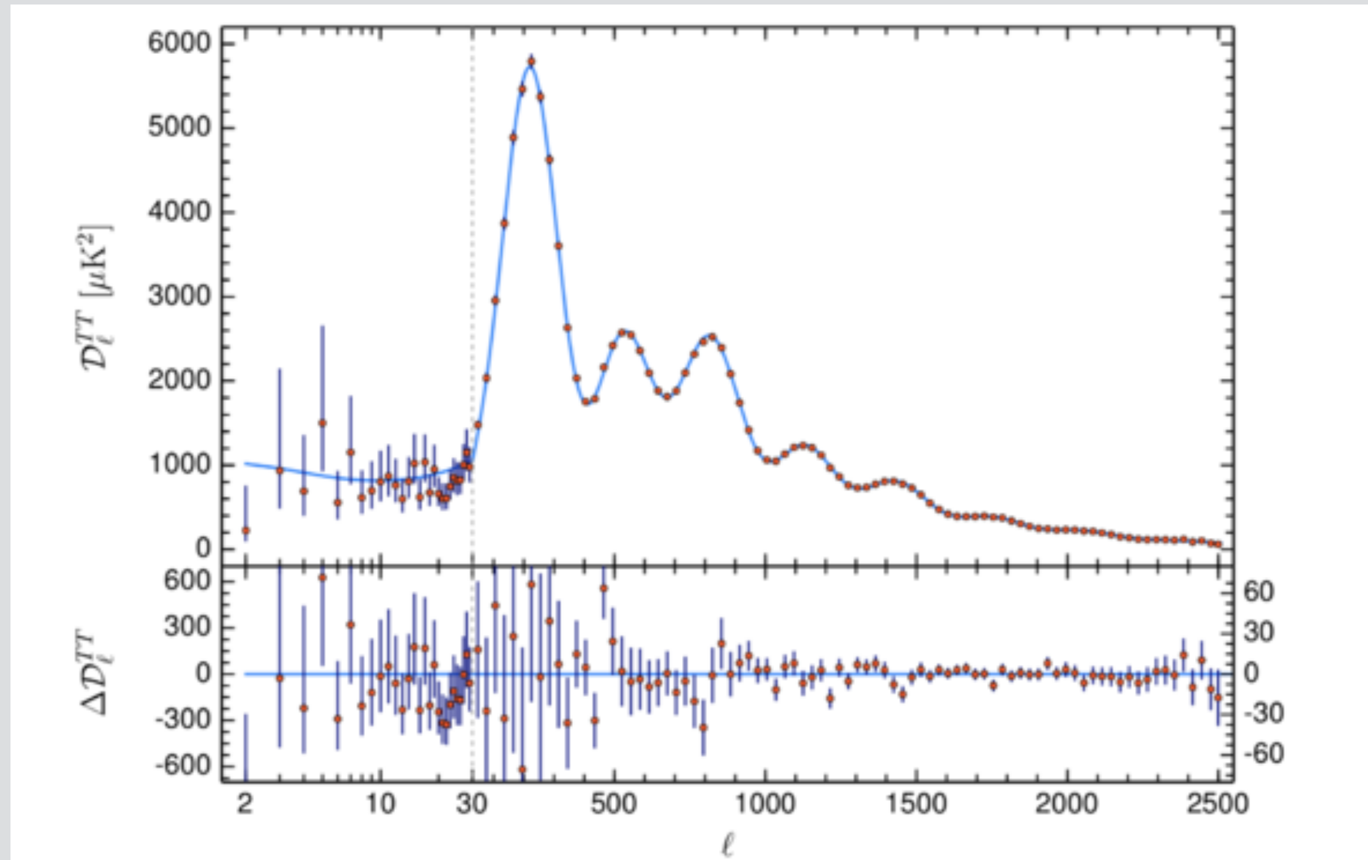
The standard model of Cosmology

LCDM: 6 parameters to describe it all!

based on General Relativity

Parameter	TT+lowE 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022
$\Omega_c h^2$	0.1206 ± 0.0021
$100\theta_{MC}$	1.04077 ± 0.00047
τ	0.0522 ± 0.0080
$\ln(10^{10} A_s)$	3.040 ± 0.016
n_s	0.9626 ± 0.0057





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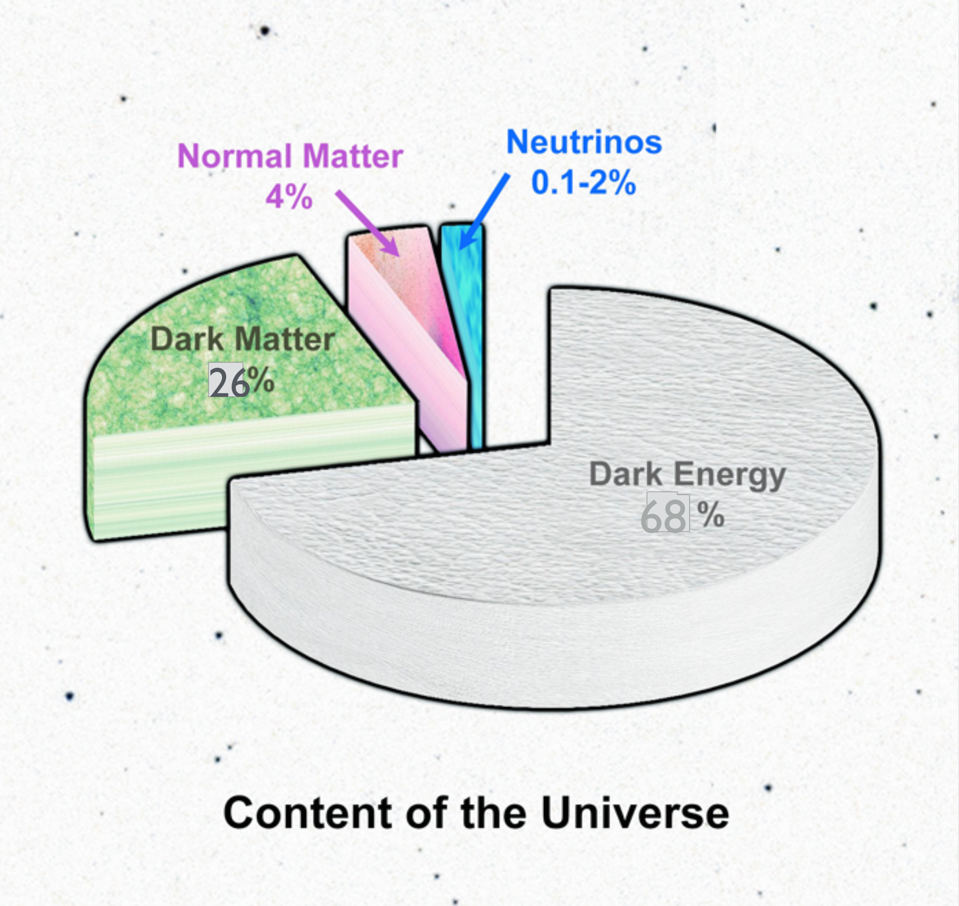

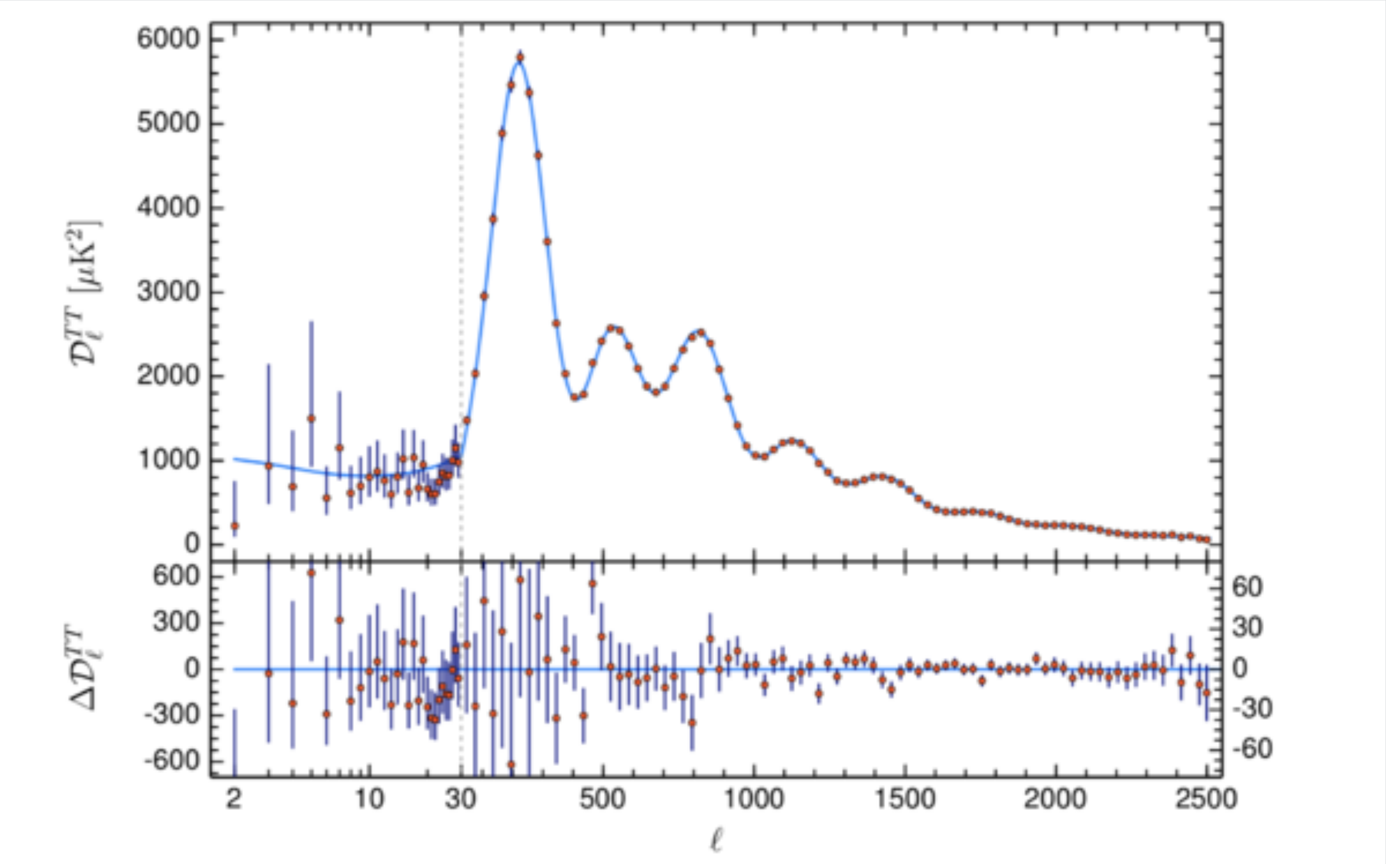

measured at percent level !

The standard model of Cosmology

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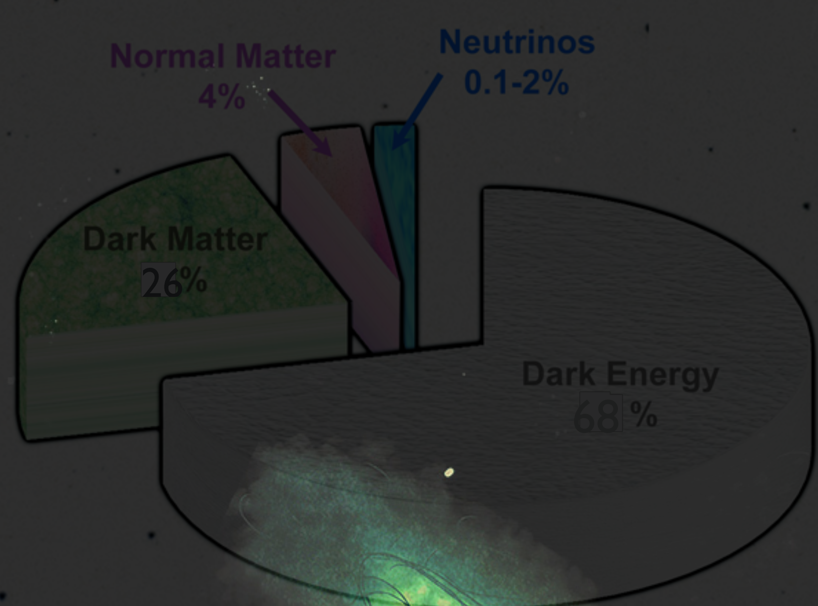
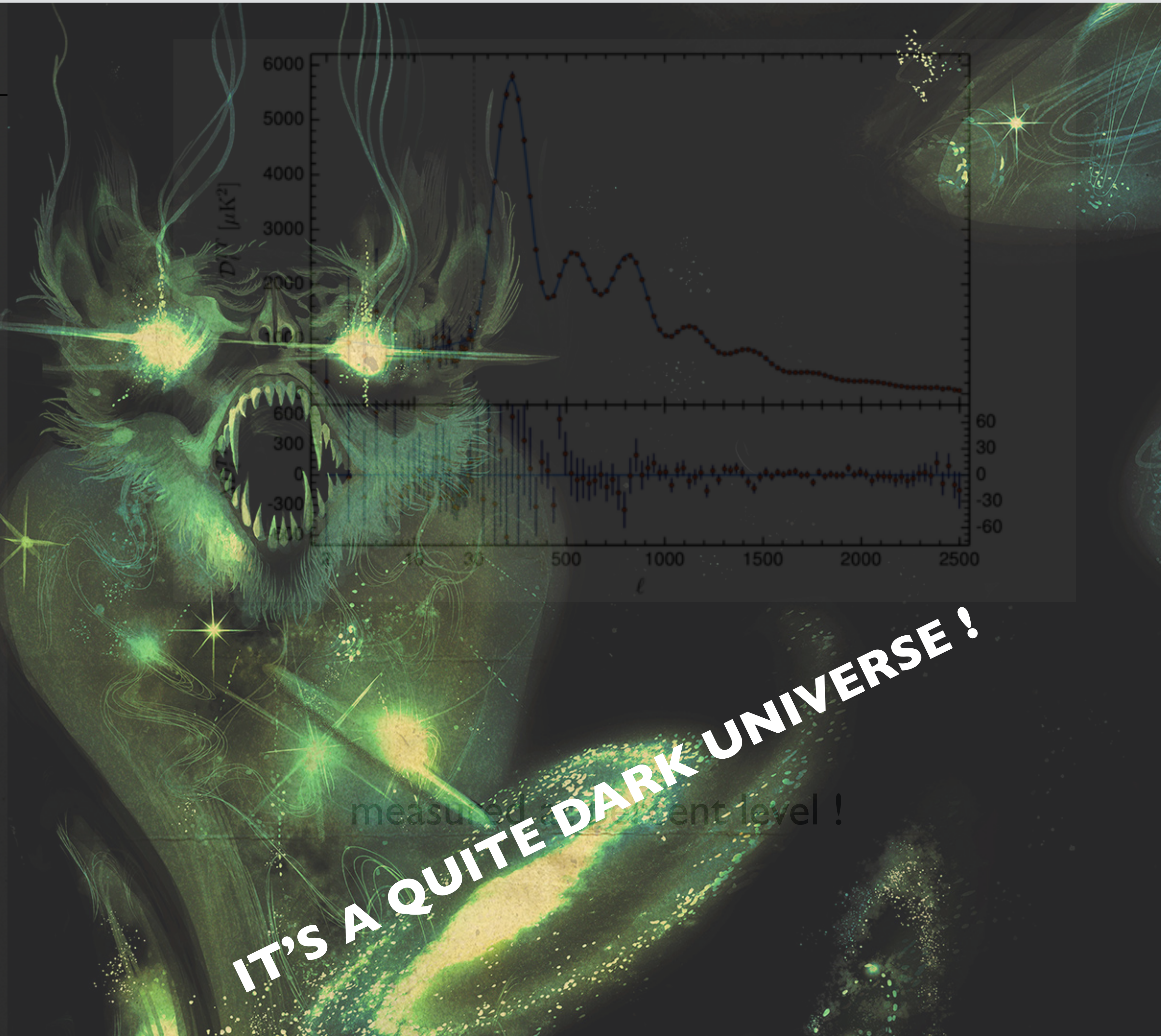
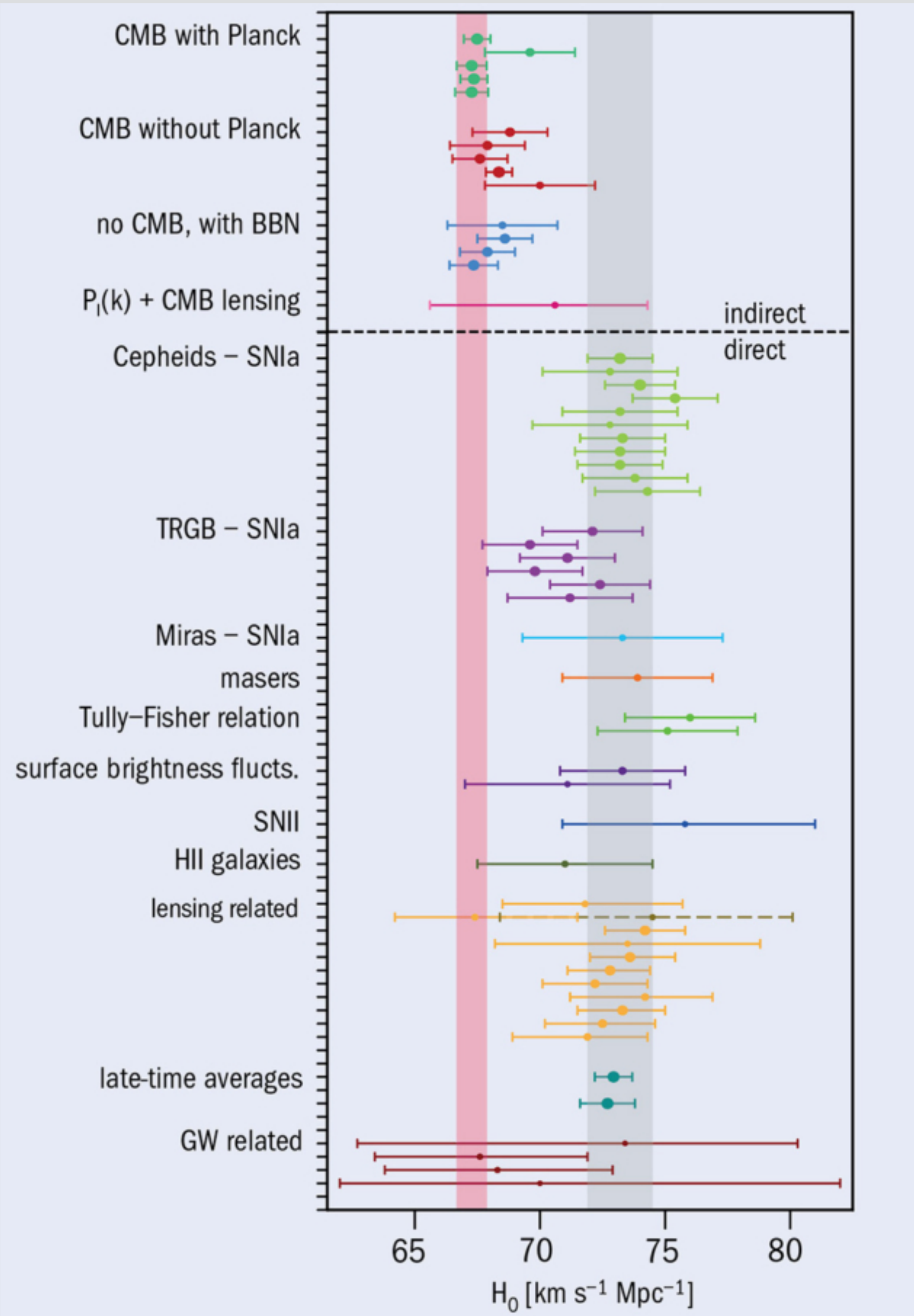


Content of the Universe

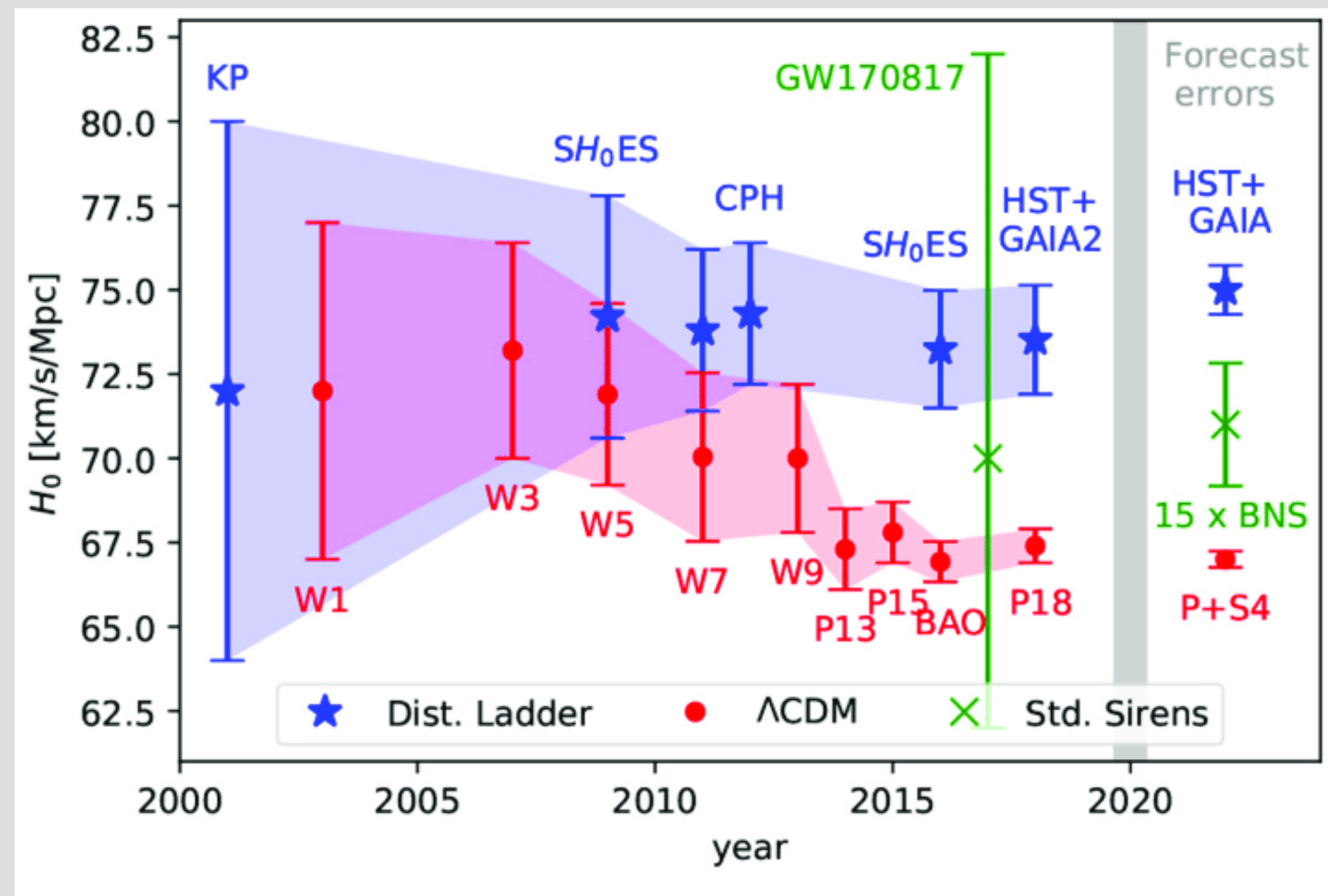
credit: NASA/JPL Caltech



Cosmological Tensions



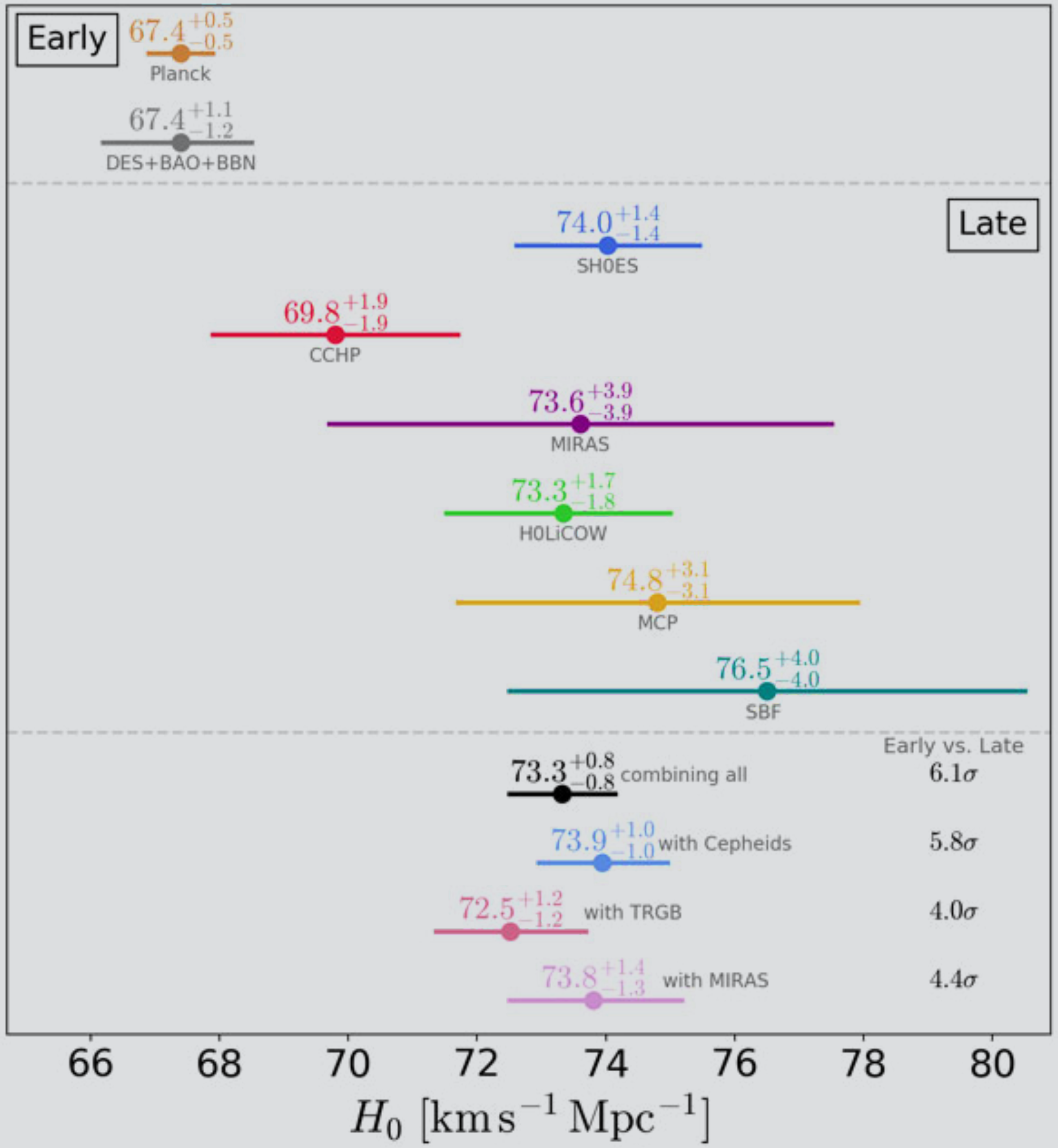
Hubble tension



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

di Valentino et al., Class. Quantum Grav. **38**, 1523001 (2021)

Cosmological Tensions



Vivien Bonvin / HOLiCOW Team

Early: relying on details of LCDM model at z>1000

CMB inferences of H_0 depend on cosmological model (connecting early Universe to today)

BAO inferences of H_0 depend on anchoring of sound horizon (at drag epoch)

Late: relying on details of LCDM model at low z

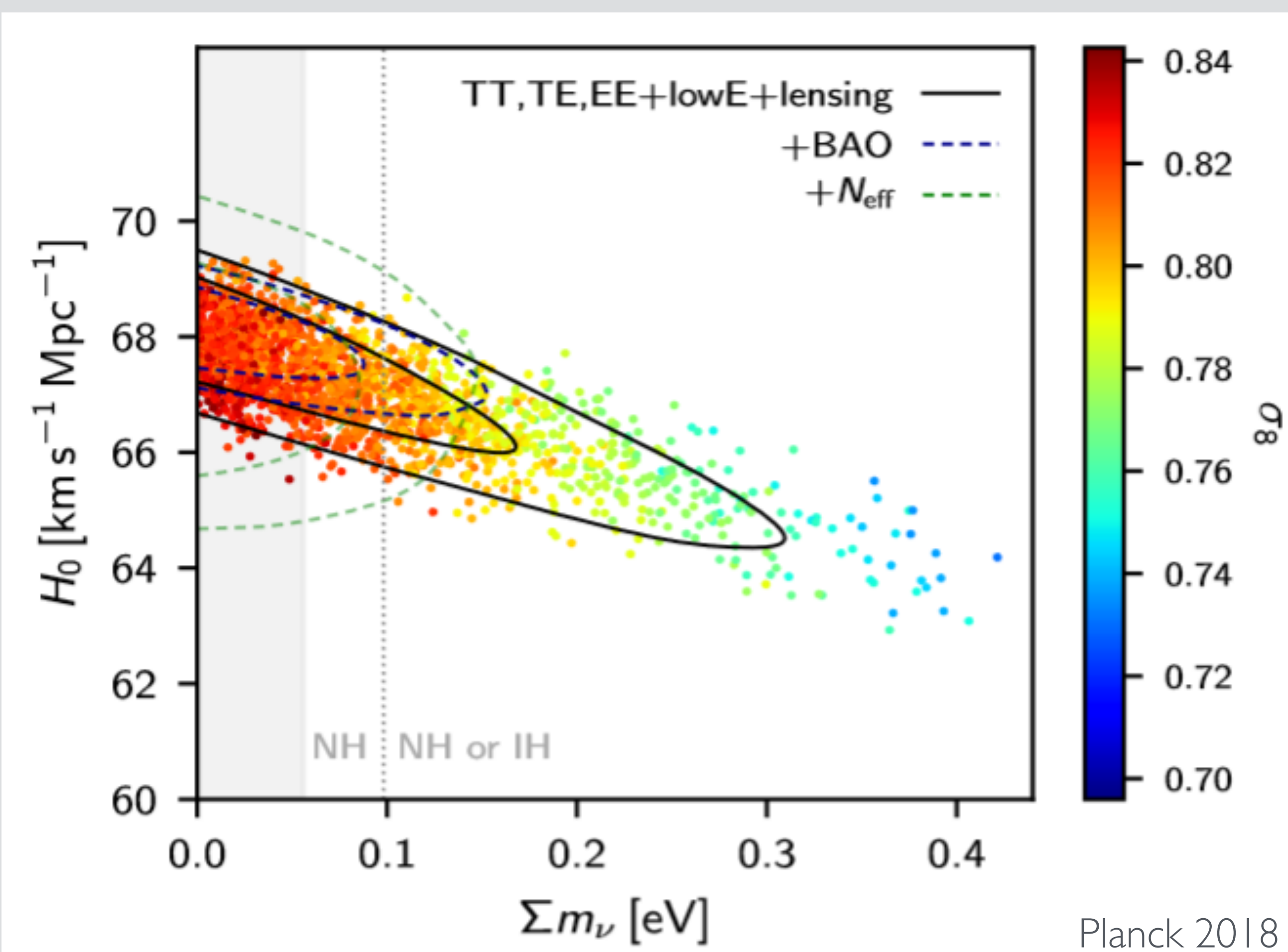
SNe inferences of H_0 depend on calibration of absolute magnitude (via distance ladder)

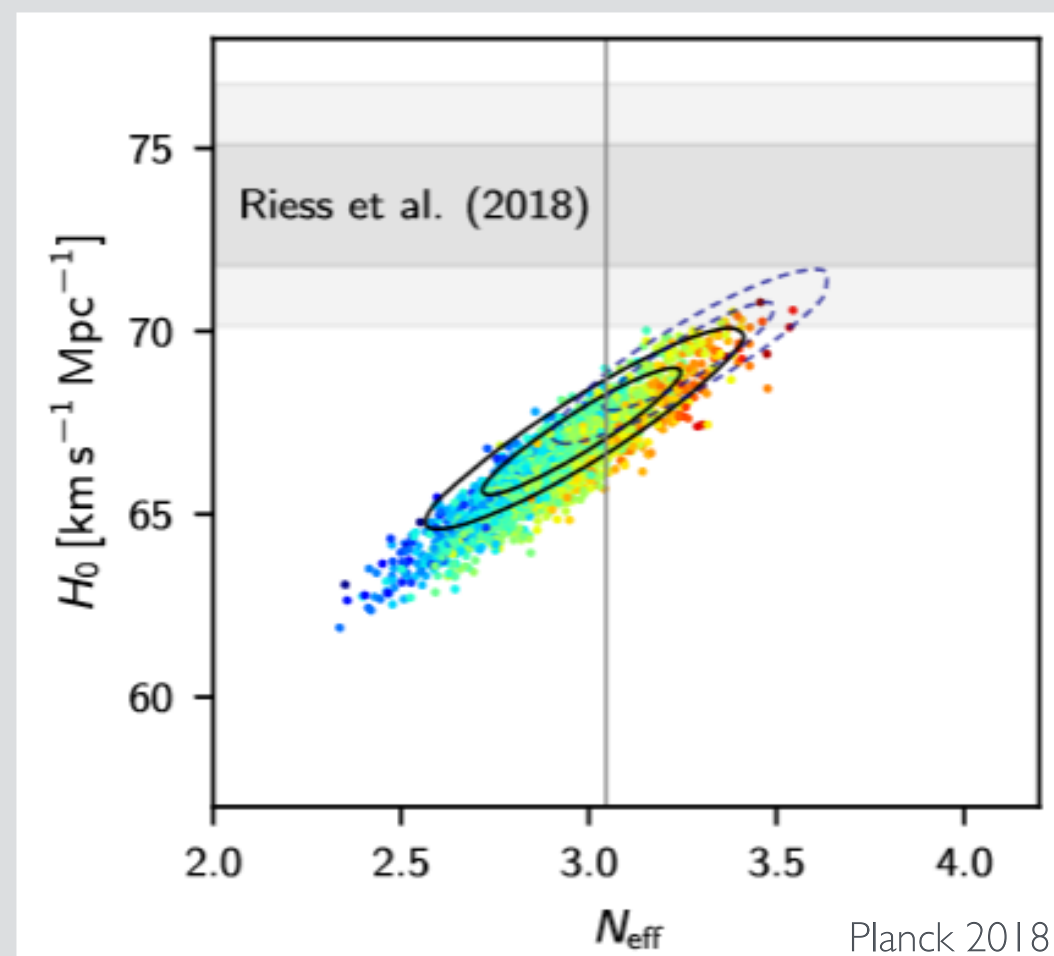
SLTD inferences of H_0 are effectively calibration dependent (cause of strong dependence on lens mass model)

Systematics or new Physics?

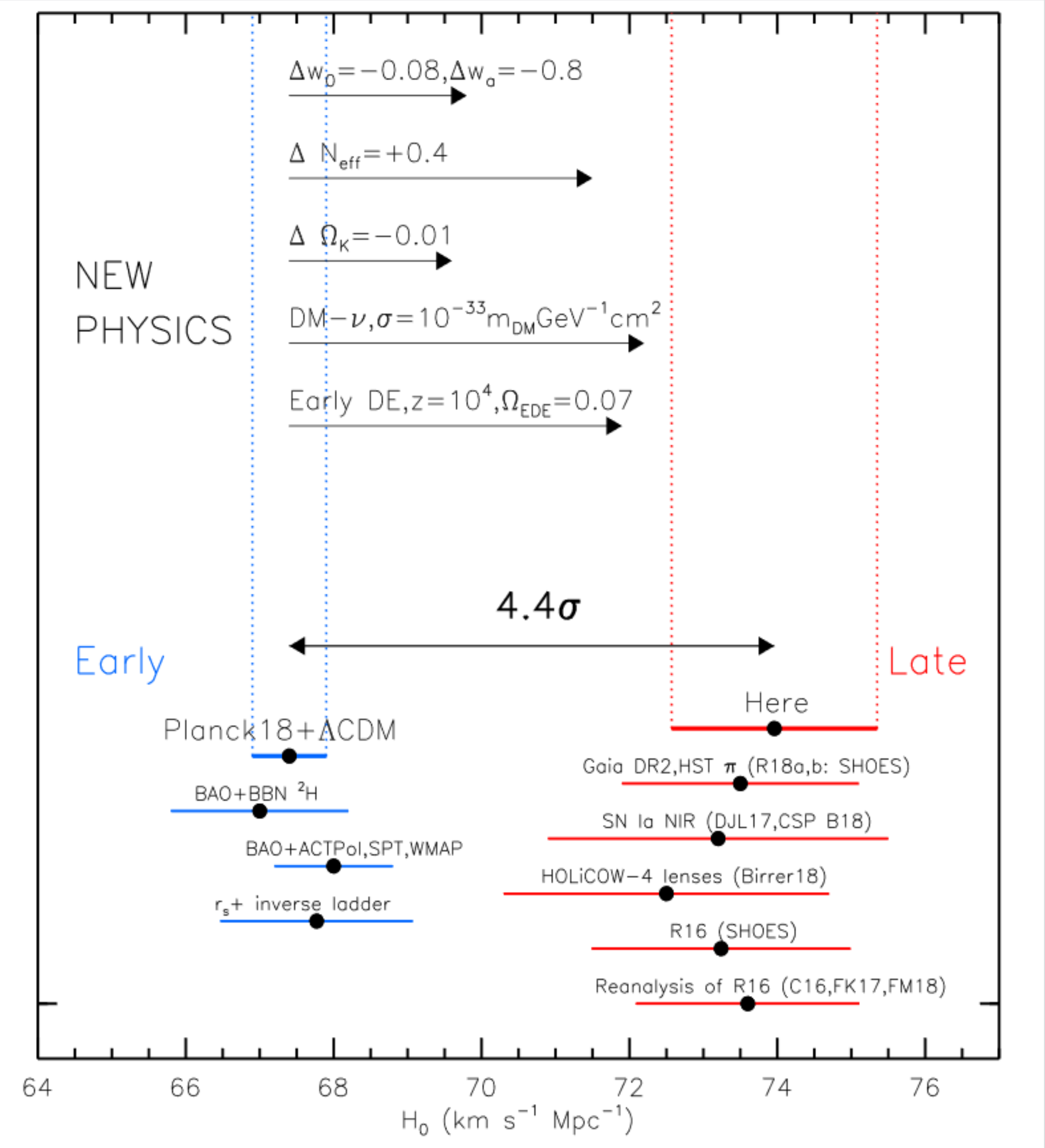
SYSTEMATICS: many sources of systematics have been taken into account, especially by the SH0ES team. There remain the possibility of some unknown/ underestimated systematics….

NEW PHYSICS: extensions of the standard model of Cosmology (early DE, late DE, neutrino sector, etc..) can alleviate somewhat the tension





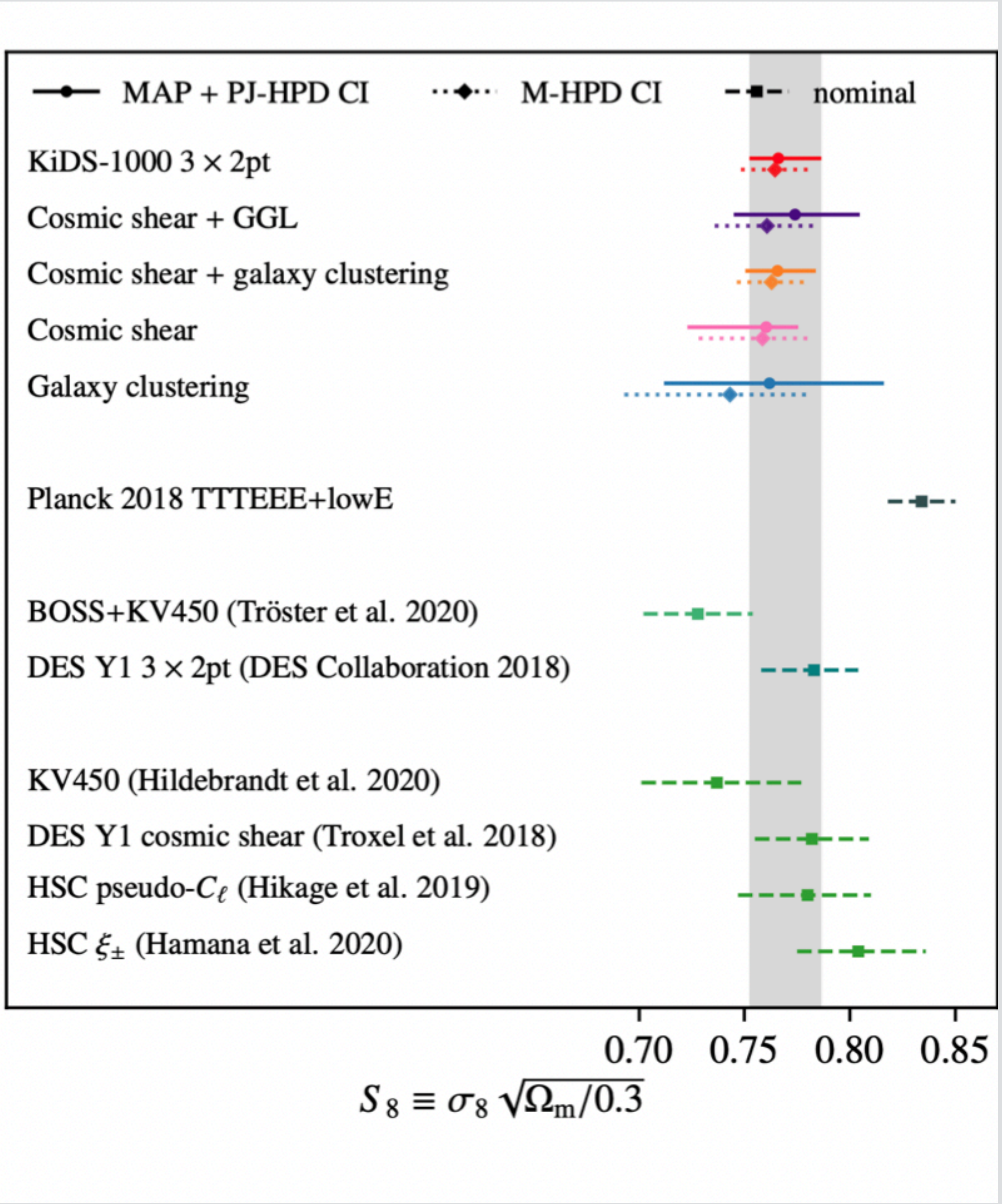
Systematics or new Physics?

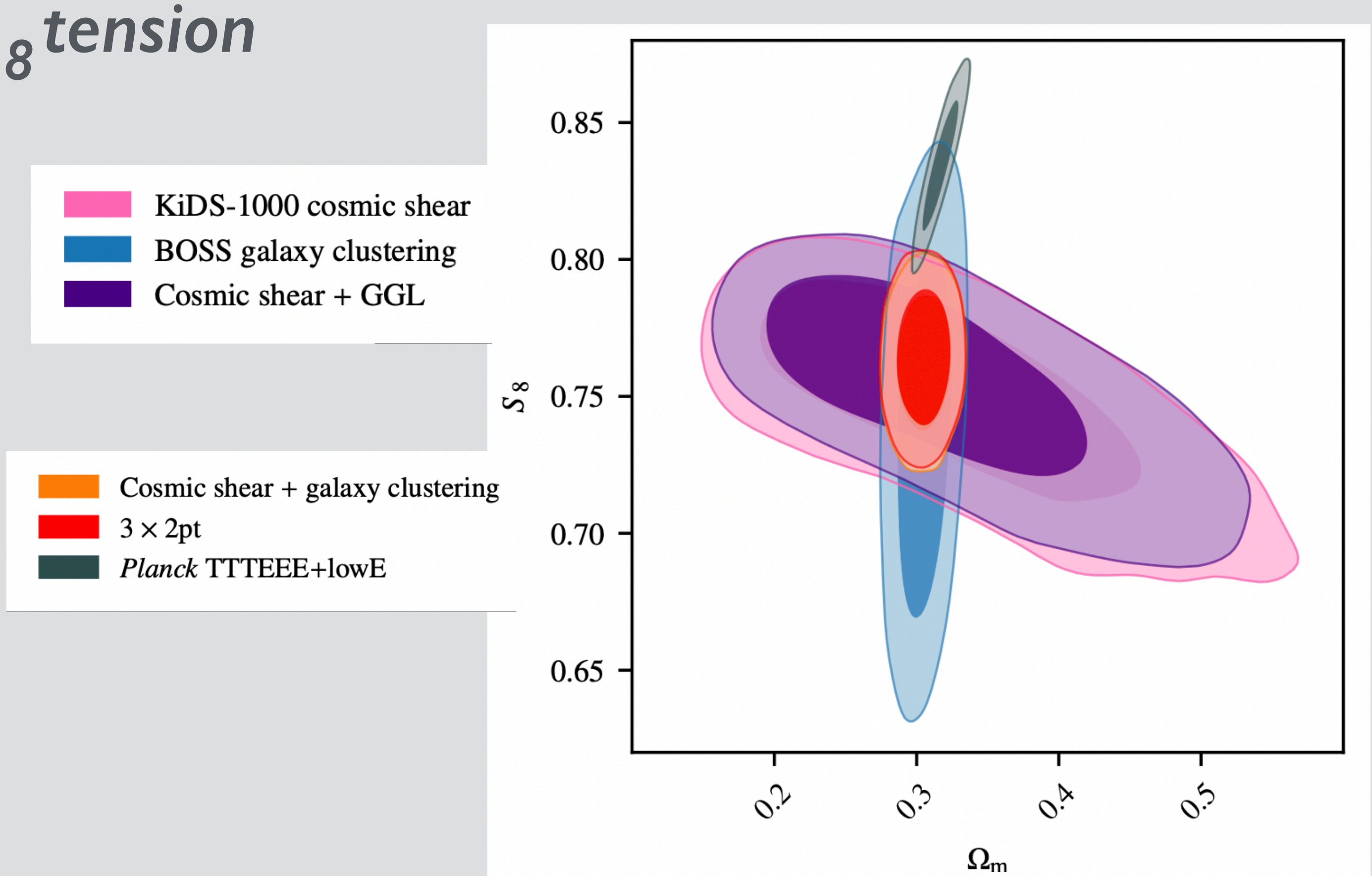


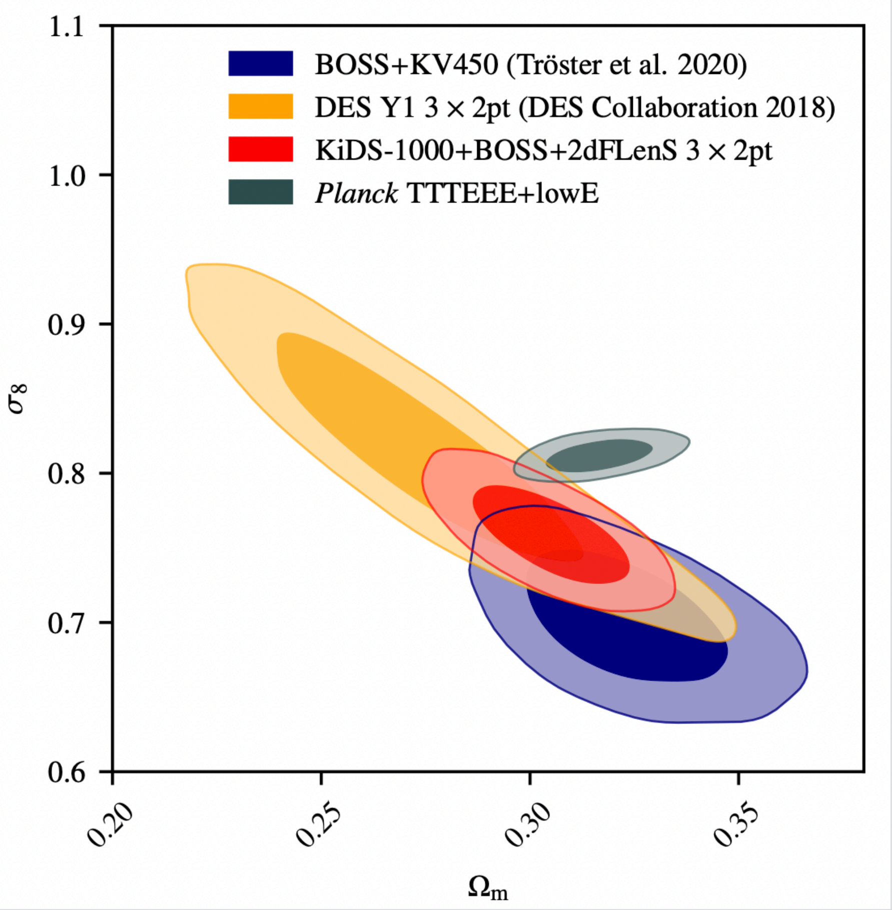
Riess et al., *Astrophys.J.* 876 (2019) 1, 85

Cosmological Tensions

S_8 *tension*







C. Heymans et al., "KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints," 7, 2020

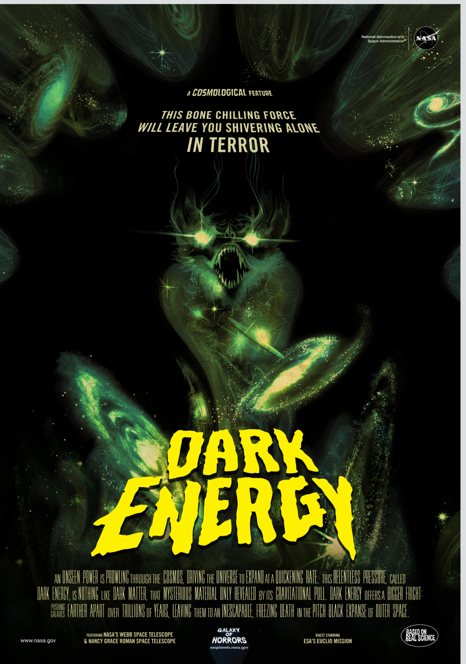
Long standing questions

How does Gravity look like on large scales?

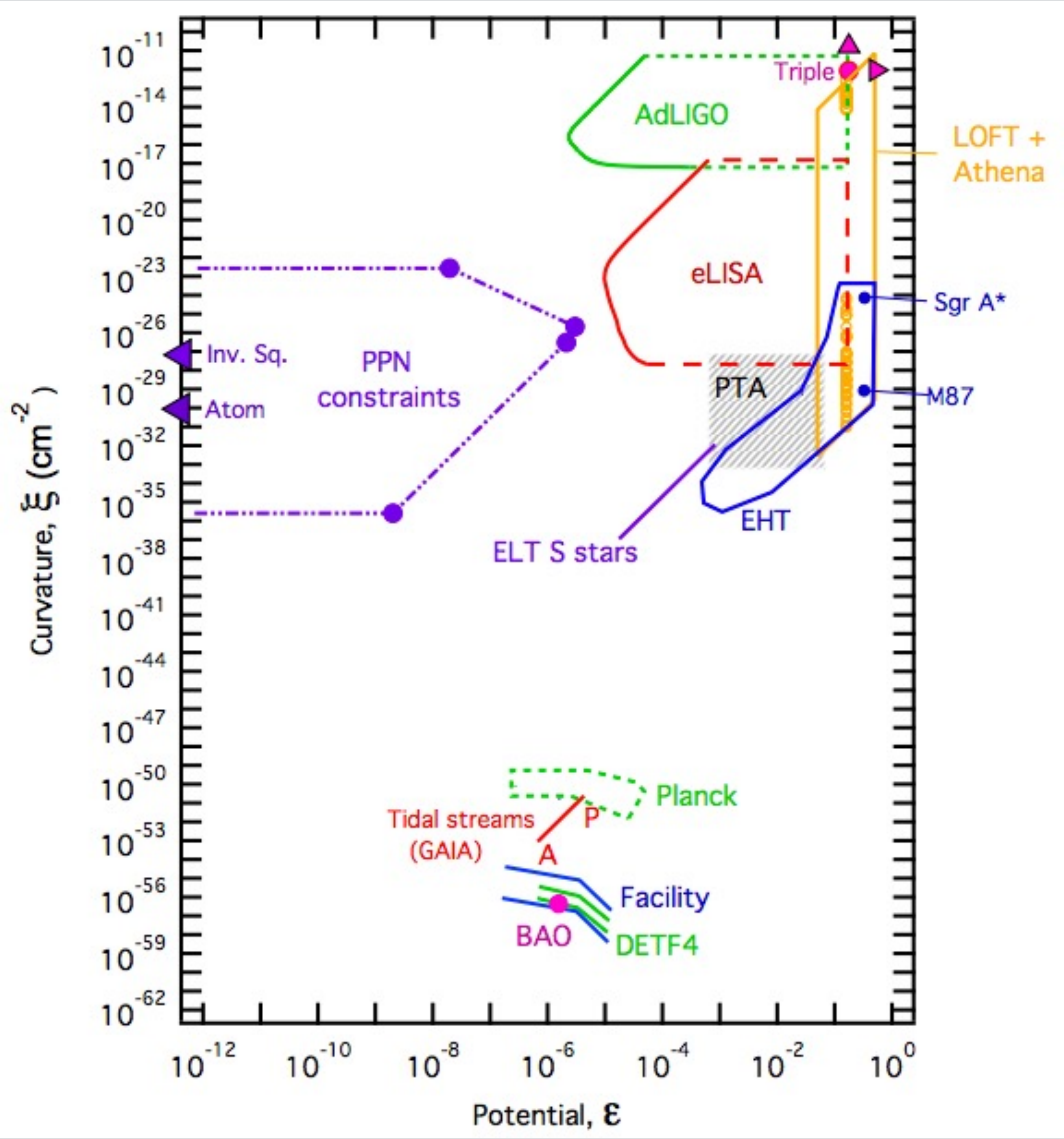
What is the nature of dark matter?

What is the physics of dark energy?

How about inflation?

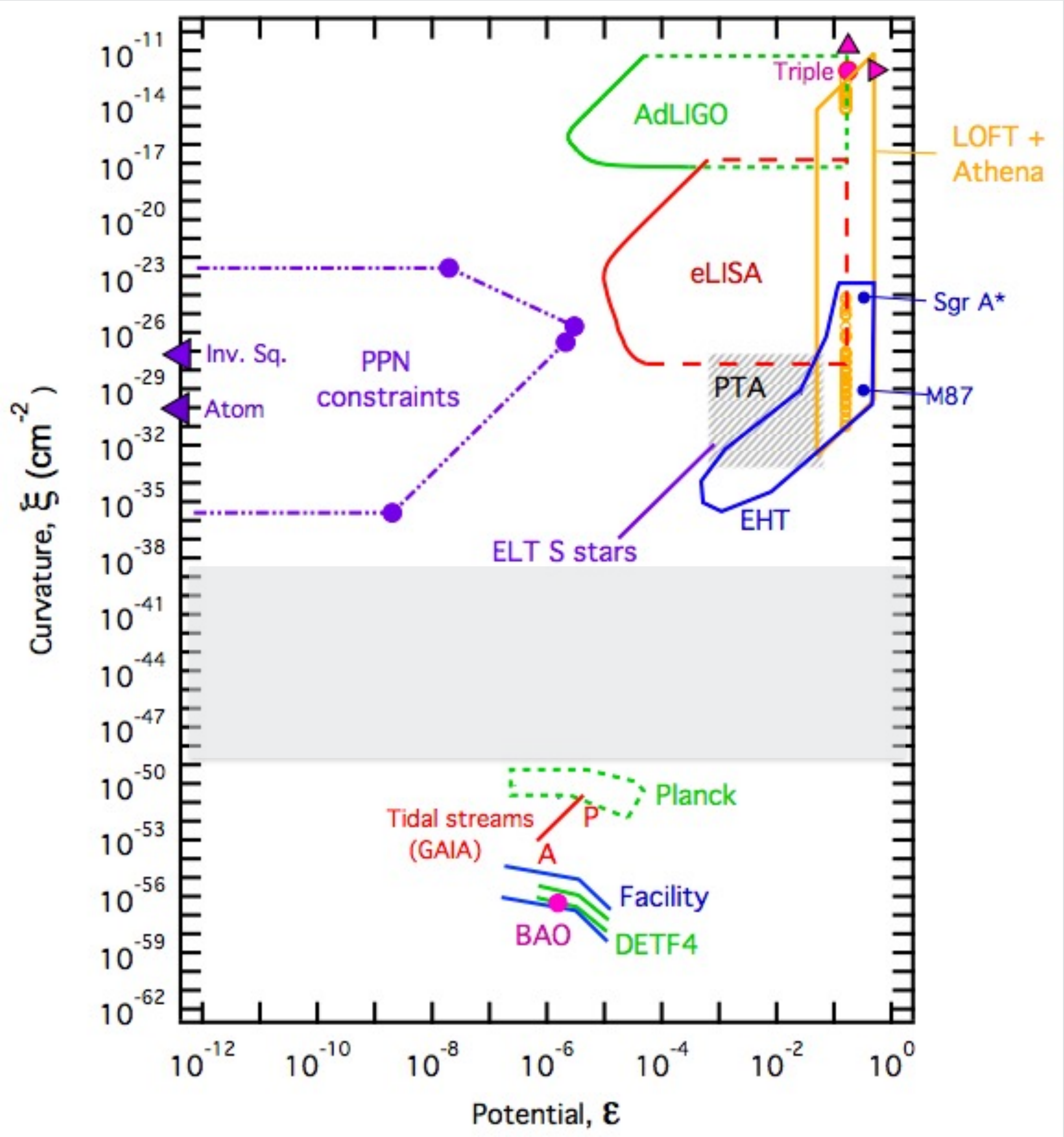


Tests of Gravity



Baker, Psaltis, Skordis, Astrophys.J. 802 (2015)

Tests of Gravity



Baker, Psaltis, Skordis, Astrophys.J. 802 (2015)

Are we really sure that GR correctly describes gravity on cosmological scales?

What has data told us so far ?

Theoretical Framework

We can capture the large scale behavior of gravity in few **phenomenological functions**:

Expansion:

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

Clustering:

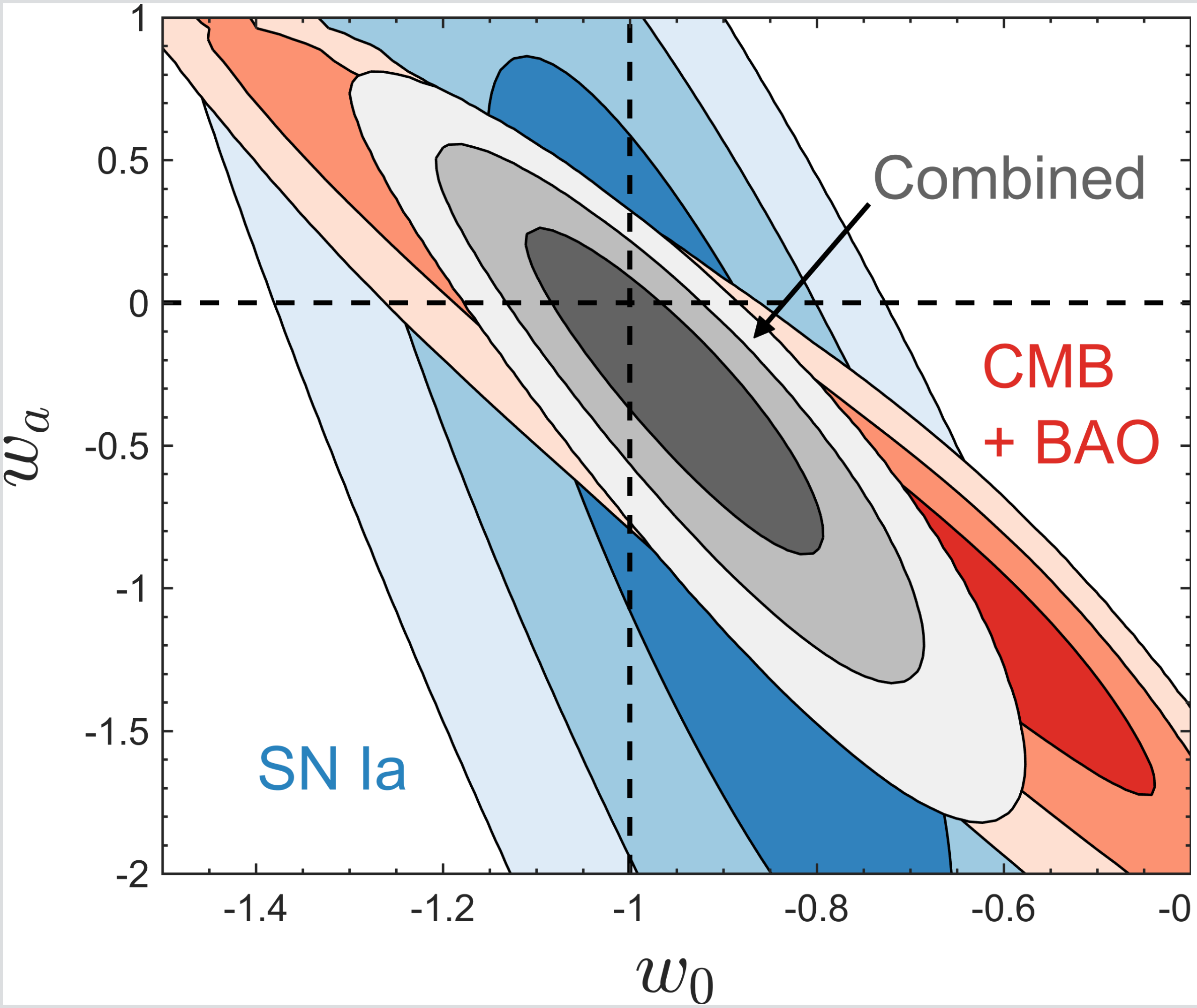
$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\delta$$

Lensing:

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

expansion

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

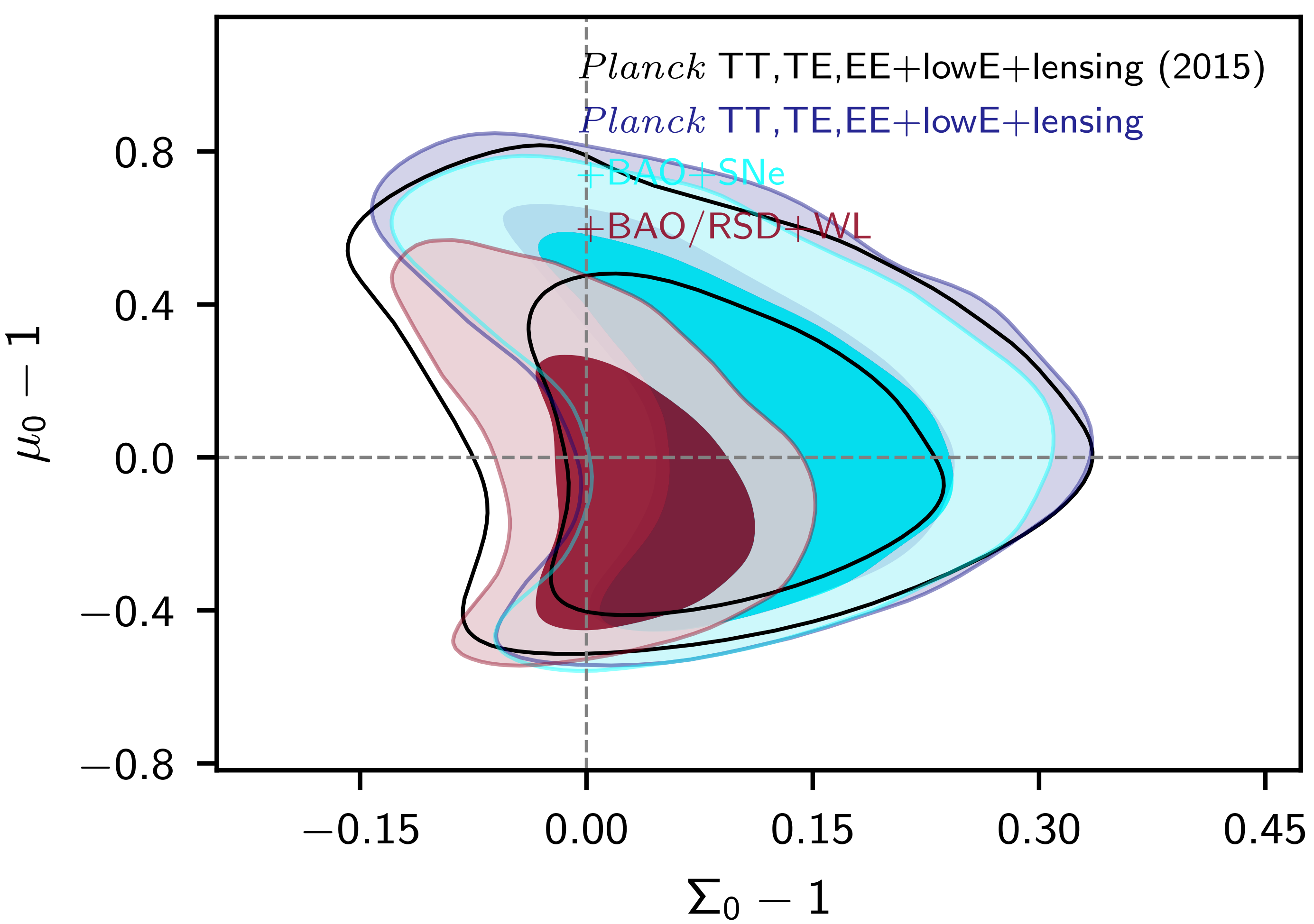


Huterer et al., Rep. Prog. Phys., 2017

clustering and lensing

$$\mu(a) = \mu_0 + \mu_a(1-a)$$

$$\Sigma(a) = \Sigma_0 + \Sigma_a(1-a)$$

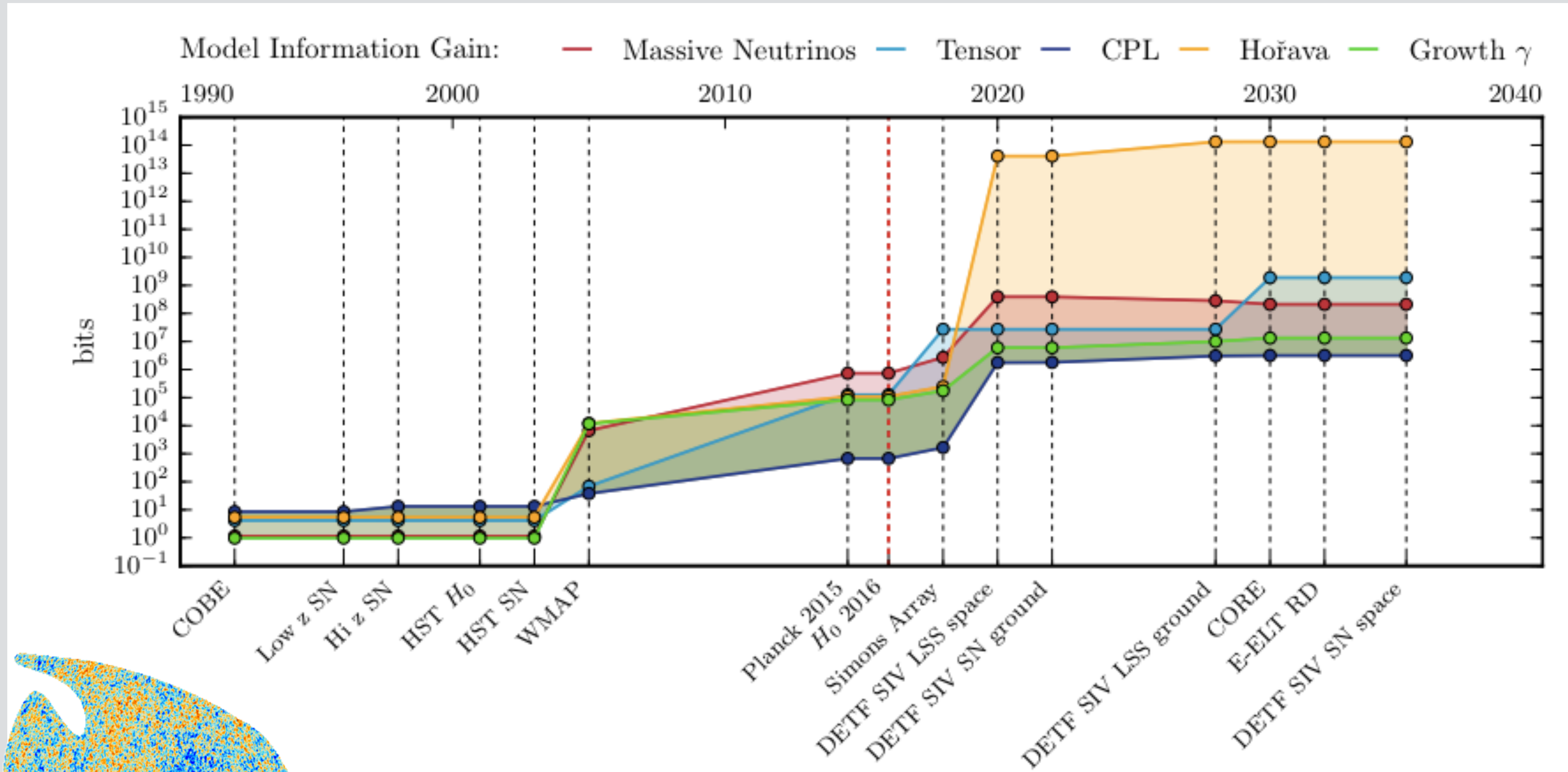


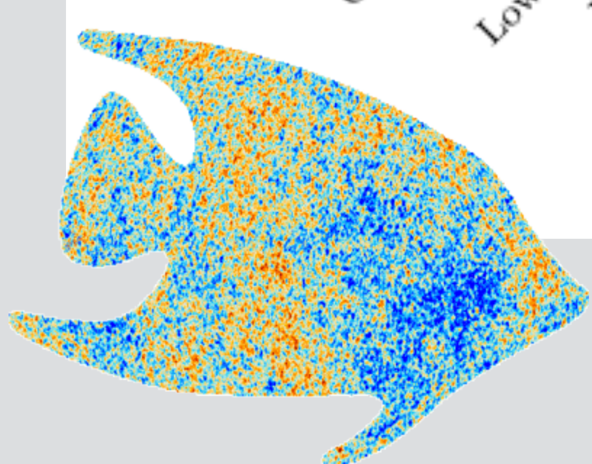
Planck 2018

What awaits us?

Information Gain in Cosmology

…

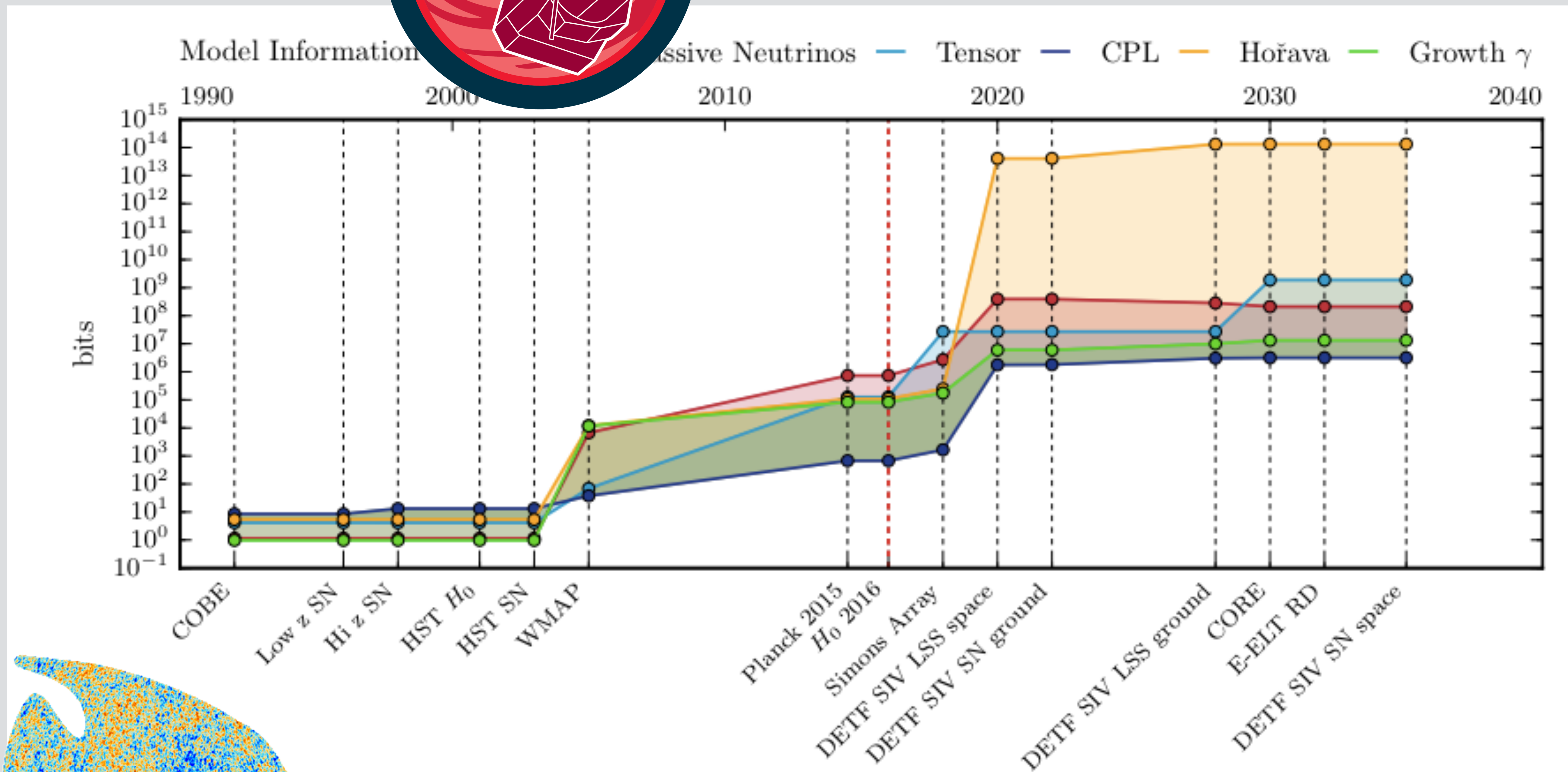


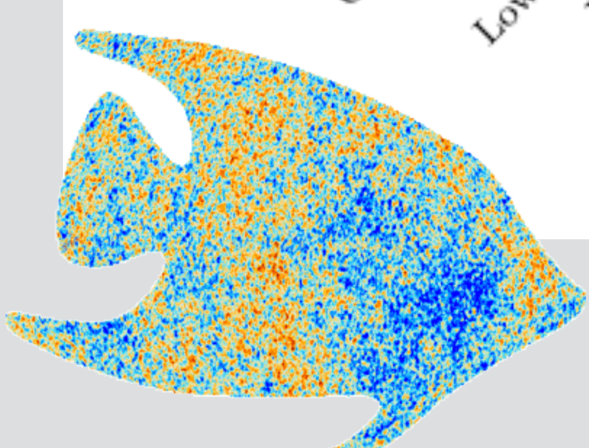


Model cumulative Information Gain

Raveri, Martinelli, Zhao, Wang, **CosmicFish**/arXiv:1606.06273

Information Gain in Cosmology

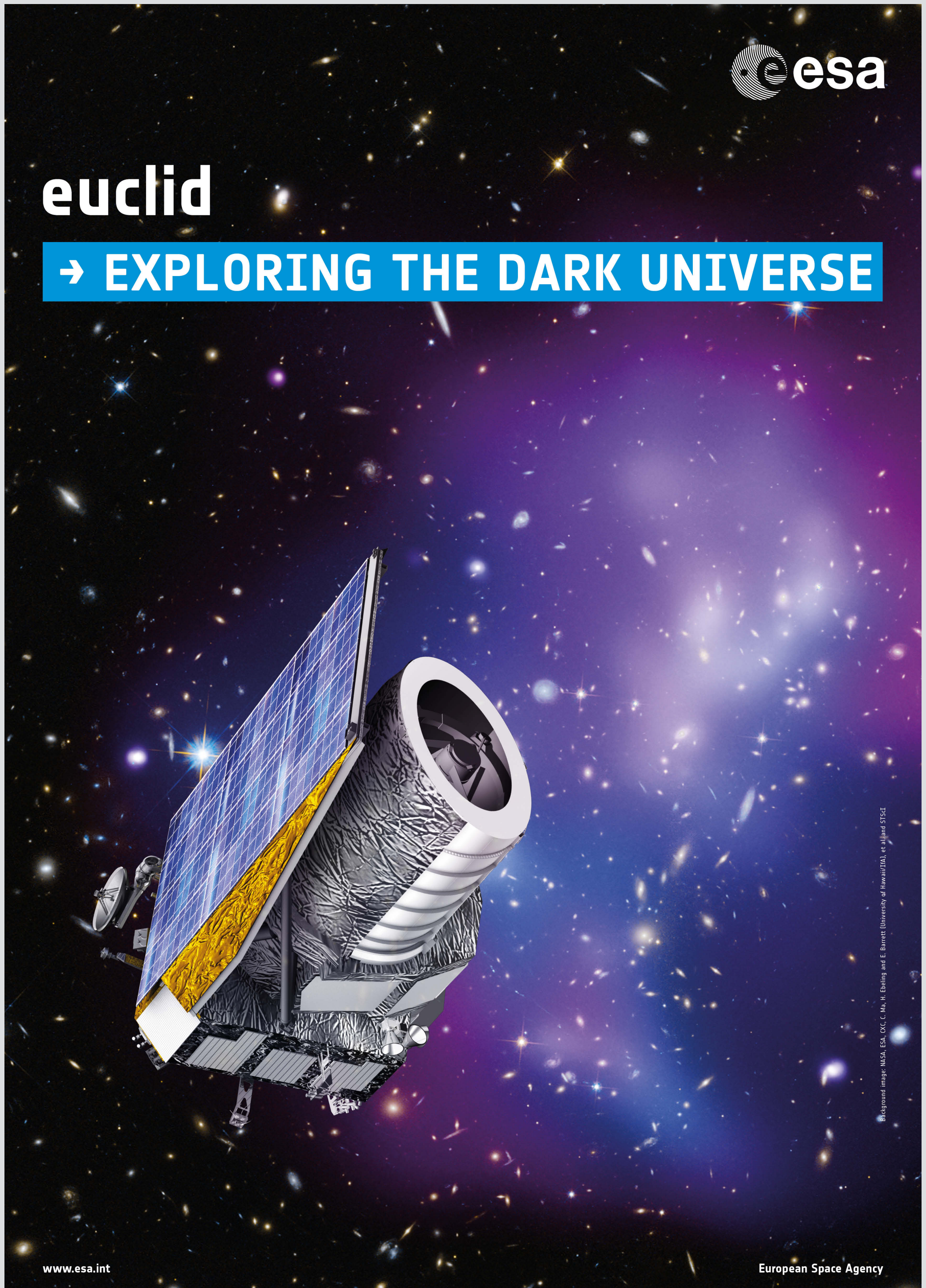




Model cumulative Information Gain

Raveri, Martinelli, Zhao, Wang, **CosmicFish**/arXiv:1606.06273

Euclid



Euclid is an **ESA M-class** mission designed to explore the dark universe using:

- ***Weak lensing*** by large scale structure
- ***Clustering*** of galaxies

It will do so with an **Optical + NIR imaging survey** resulting in shapes and photometric redshifts for $2\text{x}10^9$ galaxies. And a **slitless NIR spectroscopic** survey for $35\text{x}10^7$ galaxies.

$$A_{\text{survey}} = 15\,000\ \text{deg}^2$$

Spectroscopic survey:

$N_{\text{gal}} \approx 10^7$

$\sigma_z \approx 0.01(1+z)$

$z \in [0.9, 1.8]$

Photometric survey:

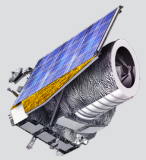
$N_{\text{gal}} \approx 10^9$

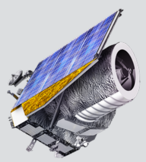
$\sigma_z \approx 0.05(1+z)$

$z \in [0, 2.5]$

Euclid

Euclid will be equipped with a **1.2m diameter Silicon Carbide mirror telescope** made by Airbus, feeding 2 instruments built by the Euclid Consortium:

 a high quality panoramic visible imager (**VIS**)

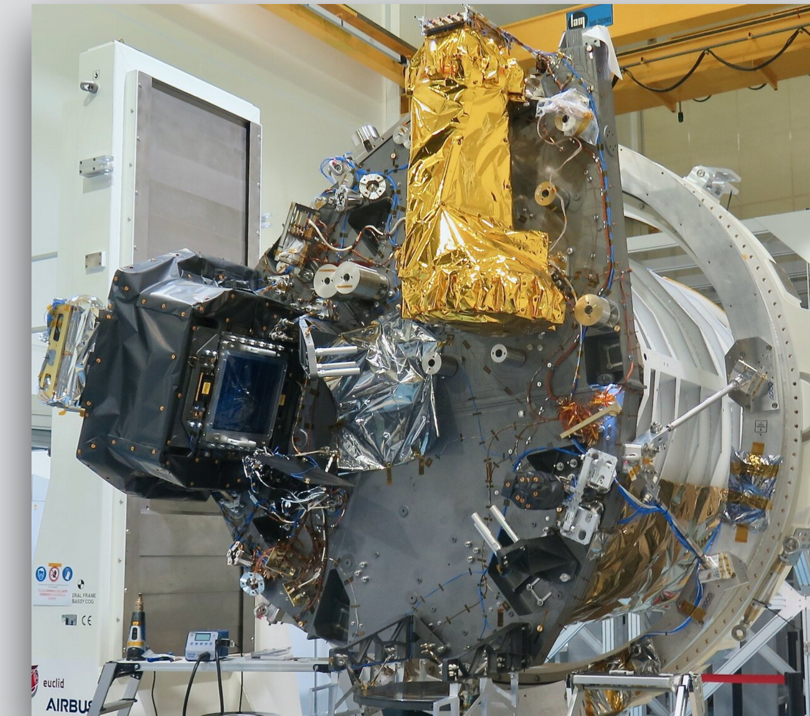
 a near infrared 3-filter (Y, J, H) photometer (**NISP-P**) & a slitless spectrograph (**NISP-S**)

With these instruments physicists will probe the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of DM and the 3D distribution of structures from spectroscopic redshifts of galaxies.

During the 6 years of the survey, Euclid will collect **more than 500,000 visible and NIR images** that will be transferred to Earth on a daily basis cadence.

About 10 billion sources will be observed by Euclid, out of which more than 1 billion will be used for weak lensing, and about 30 million galaxy redshifts will be obtained. The Science Ground Segment is a most challenging part of this mission and represents about 50% of the resources provided by the Euclid Consortium.

Euclid



Euclid launch → start of survey → DR1: 2500 deg^2 → DR2: 7500 deg^2 → DR3: 15000 deg^2

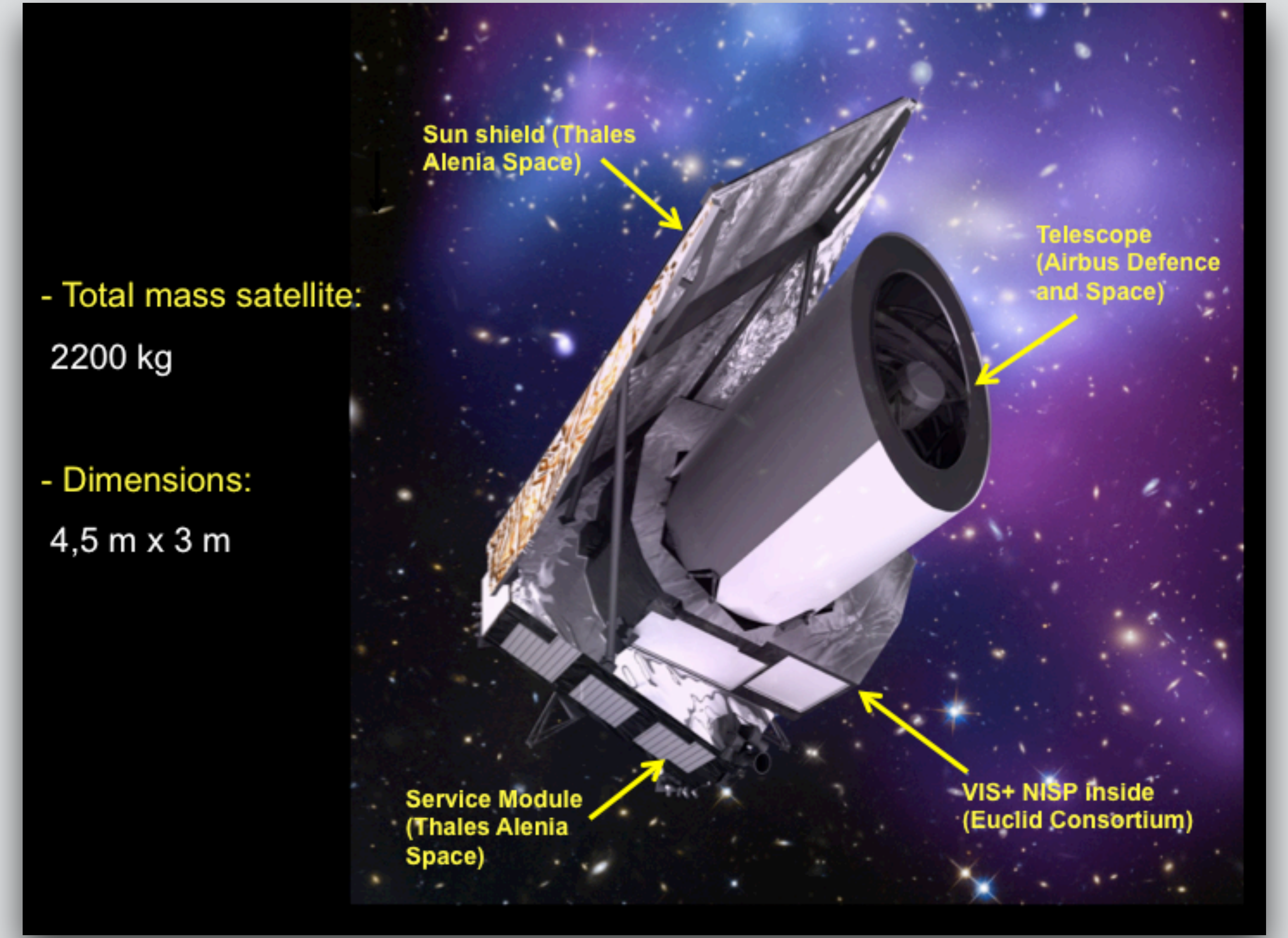
Q3/2023

Q1/2024

The supporting structure of the telescope's secondary mirror for ESA's Euclid spacecraft being brought together for final integration and optical alignment at Airbus in Toulouse, France. Credit: Airbus

The VIS and NISP instruments on Euclid's payload module. Credit: Airbus

Euclid



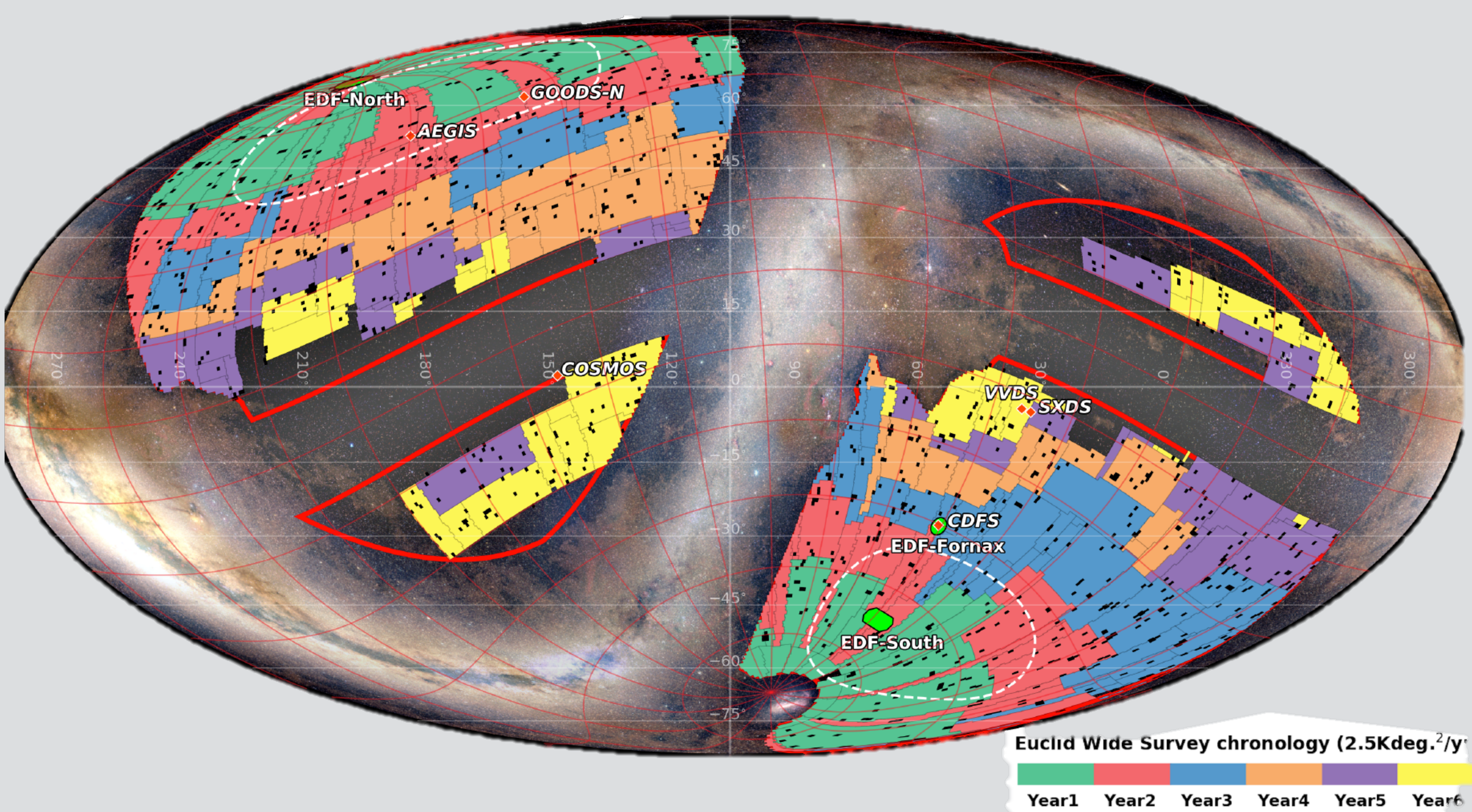
Overview of the spacecraft. These artist views are based on the CAD drawings by Thales Alenia Space, Italy and Airbus (Defence and Space) , France.- © ESA

The telescope is a 1.2 m on axis 3-mirror Korsch cold telescope providing a field of view of 1.25 x 0.727 deg^2. M1 is maintained at temperature below 130K with thermal stability better than 50mK. The mirrors and structures are all made in Silicon Carbide, a material with excellent thermo-elasticity and stifness and immune to radiations. The telescope design comprises a 3 degree-of-freedom mechanism for M2 focus and tilt correction that allows Airbus Defence and Space division to meet all requirements on the image quality for weak lensing science (ellipticity, FWHM, R^2 and encircled energy) .

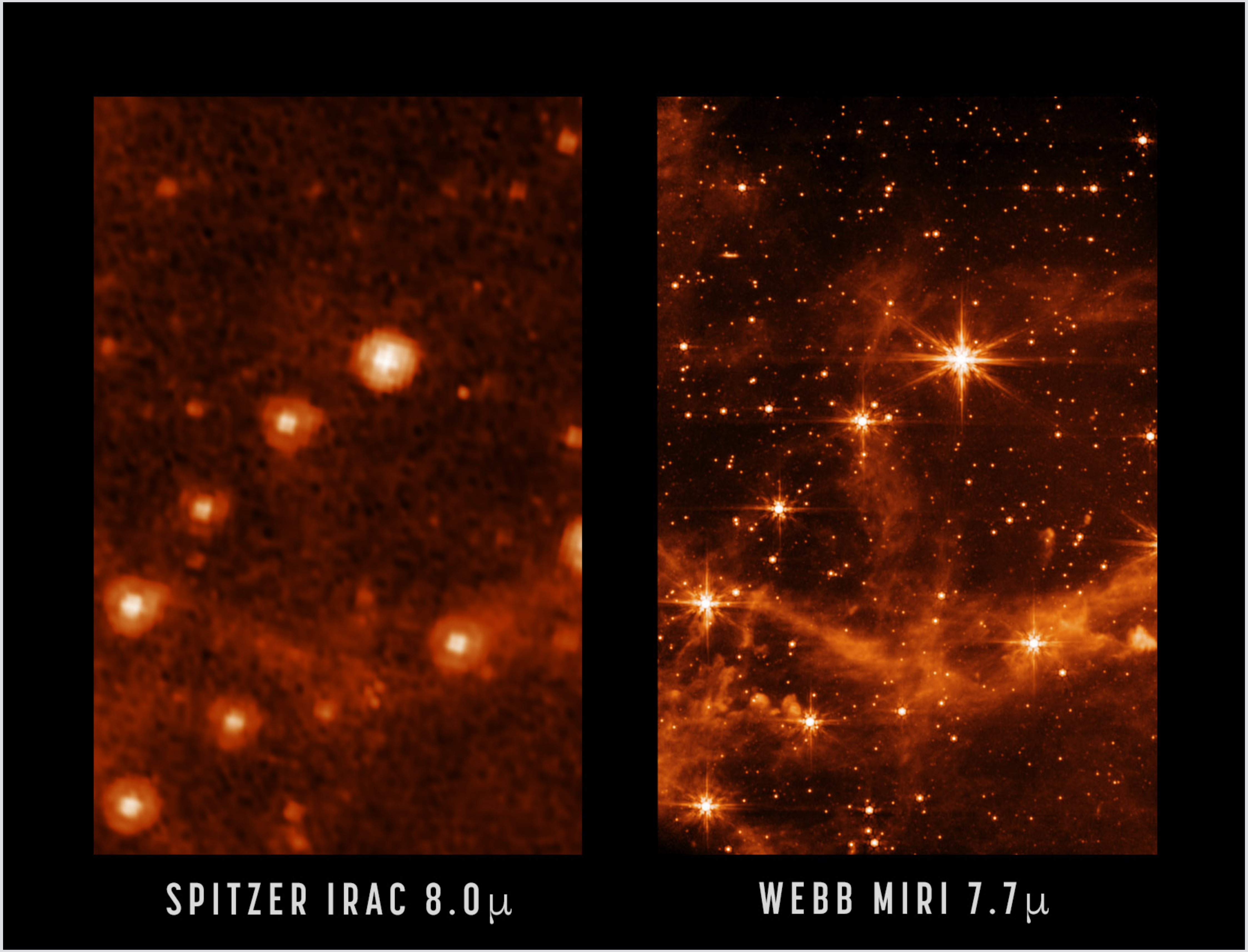
Once at its nominal L2 Sun-Earth Lagrangian position, Euclid will start a 6 years observing campaign completing:

- One **Euclid Wider Survey** covering **15,000 deg^2** of the darkest sky (away from Galaxy and Solar System contamination). This is the core of the DE mission, out of which weak lensing, baryon acoustic oscillations and redshift space distortion signal will be measured.

- Three **Euclid Deep Fields** about 2 magnitude deeper than the wide survey, covering around **40 deg^2** in total. These will be used primarily for calibrations of the wide survey data, but will also extend the scientific scope of the mission to faint high redshift galaxies, quasars and AGNs.



A taste of what is to come…



Credit: NASA/JPL-Caltech (left), NASA/ESA/CSA/STScI (right)

Euclid

Euclid will explore how the Universe evolved over the past 10 billion years to address questions related to fundamental physics and cosmology on the nature of **Dark Energy**, **Dark Matter** and **Gravity**. It will also provide insightful information on the physics of the **Early Universe** and on the **Initial Conditions** which seed the formation of cosmic structure.

On more quantitative terms, the Main Scientific Objectives are:

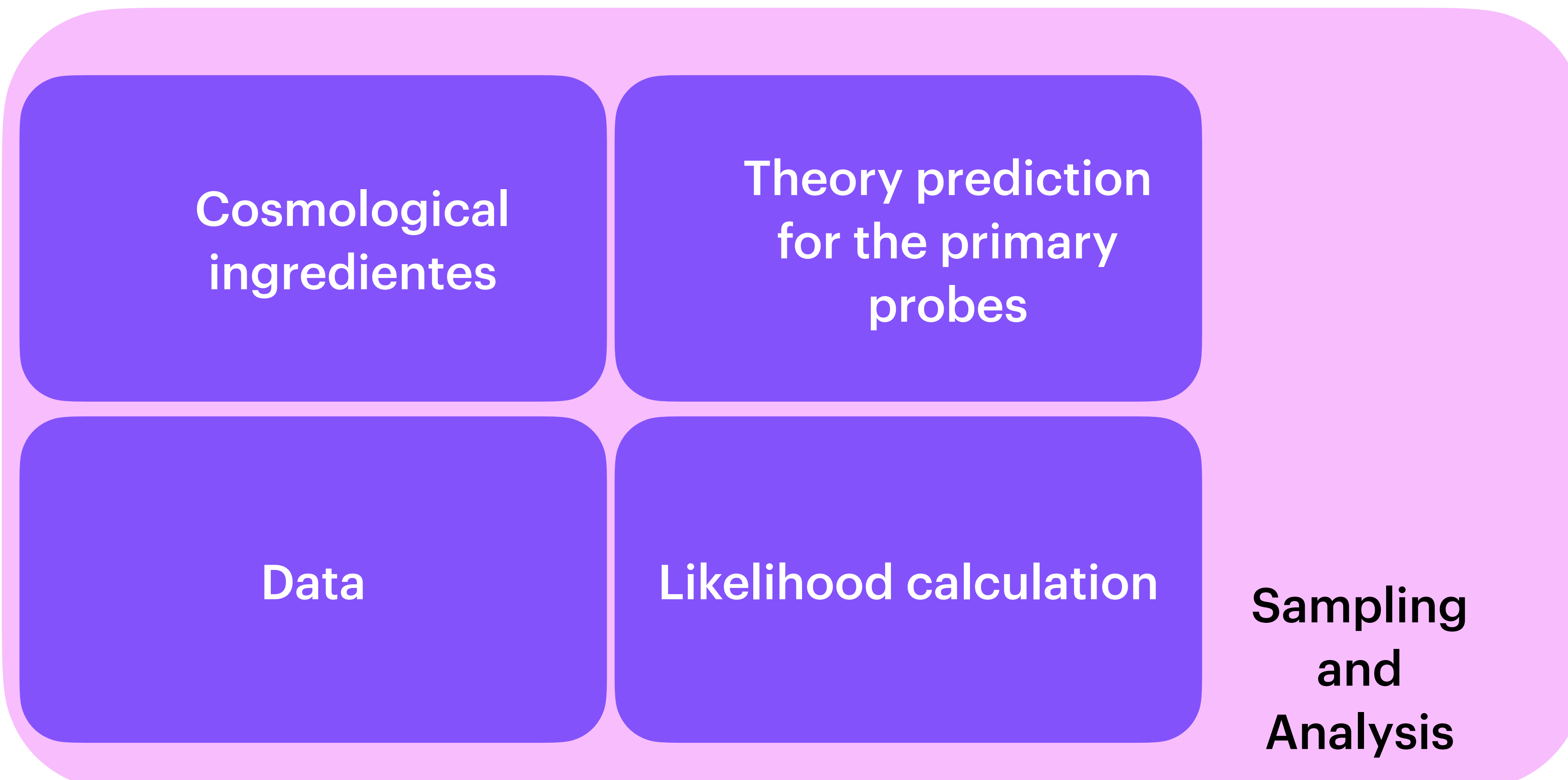
Understand the nature of Dark Energy and Dark Matter by:

- Reach a dark energy *FoM* > 400 using only weak lensing and galaxy clustering; this roughly corresponds to 1 sigma errors on w_p and w_a of 0.02 and 0.1, respectively.
- Measure γ, the exponent of the growth factor, with a 1 sigma precision of < 0.02, sufficient to distinguish General Relativity and a wide range of modified-gravity theories
- Test the Cold Dark Matter paradigm for hierarchical structure formation, and measure the sum of the neutrino masses with a 1 sigma precision better than 0.03eV.
- Constrain n_s, the spectral index of primordial power spectrum, to percent accuracy when combined with Planck, and to probe inflation models by measuring the non-Gaussianity of initial conditions parameterised by f_{NL} to a 1 sigma precision of ~2.

Cosmology and Fundamental Physics with the Euclid Satellite, *Living Rev. Relativity, **16**, (2013), 6*

The code: CLOE

Cosmology Likelihood for Observables in Euclid



courtesy of Guadalupe Cañas-Herrera (IST:L, TWG)

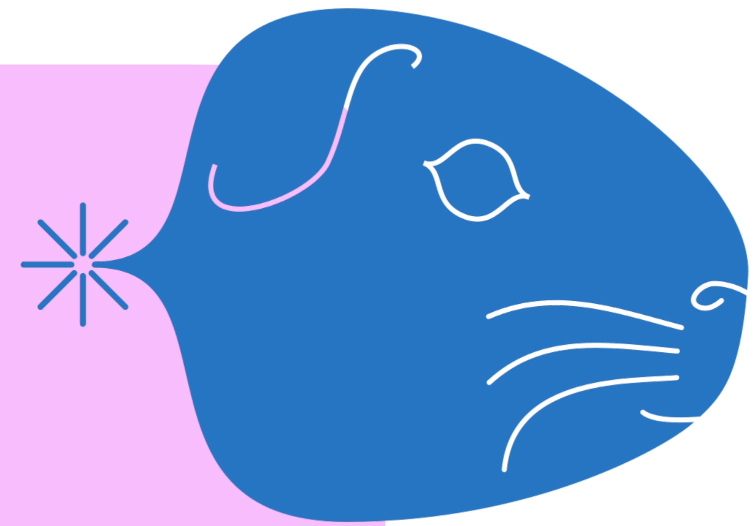
Inspired by V. Pettorino

The code: CLOE

Cosmology Likelihood for Observables in Euclid

Cosmological ingredientes

Theory prediction for the primary probes



Data

Likelihood calculation

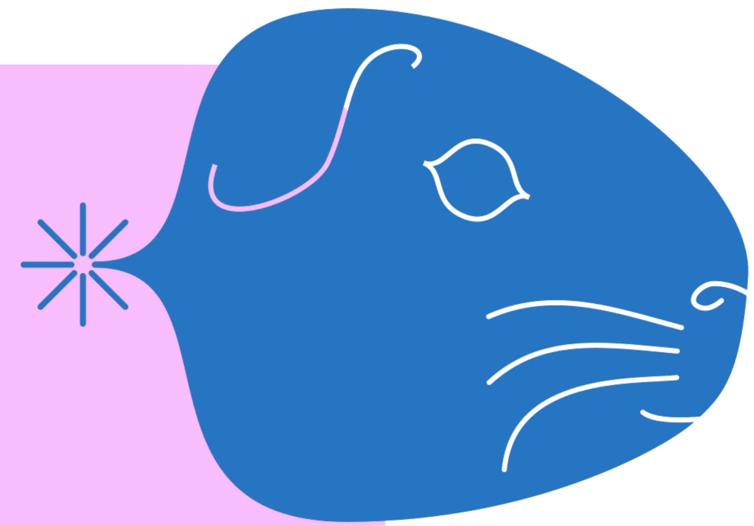
Sampling and Analysis

The code: CLOE

Cosmology Likelihood for Observables in Euclid

Cosmological ingredientes

Theory prediction for the primary probes



Cobaya

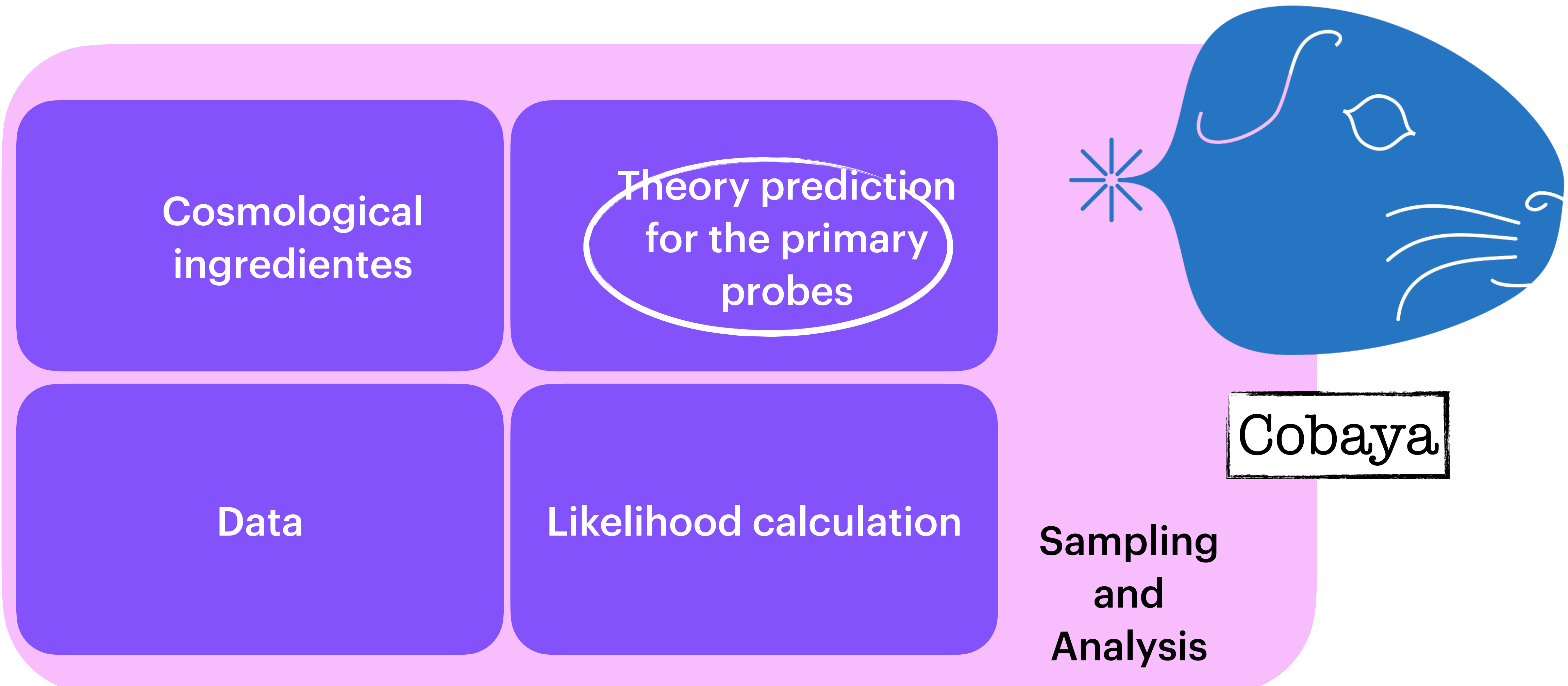
Data

Likelihood calculation

Sampling and Analysis

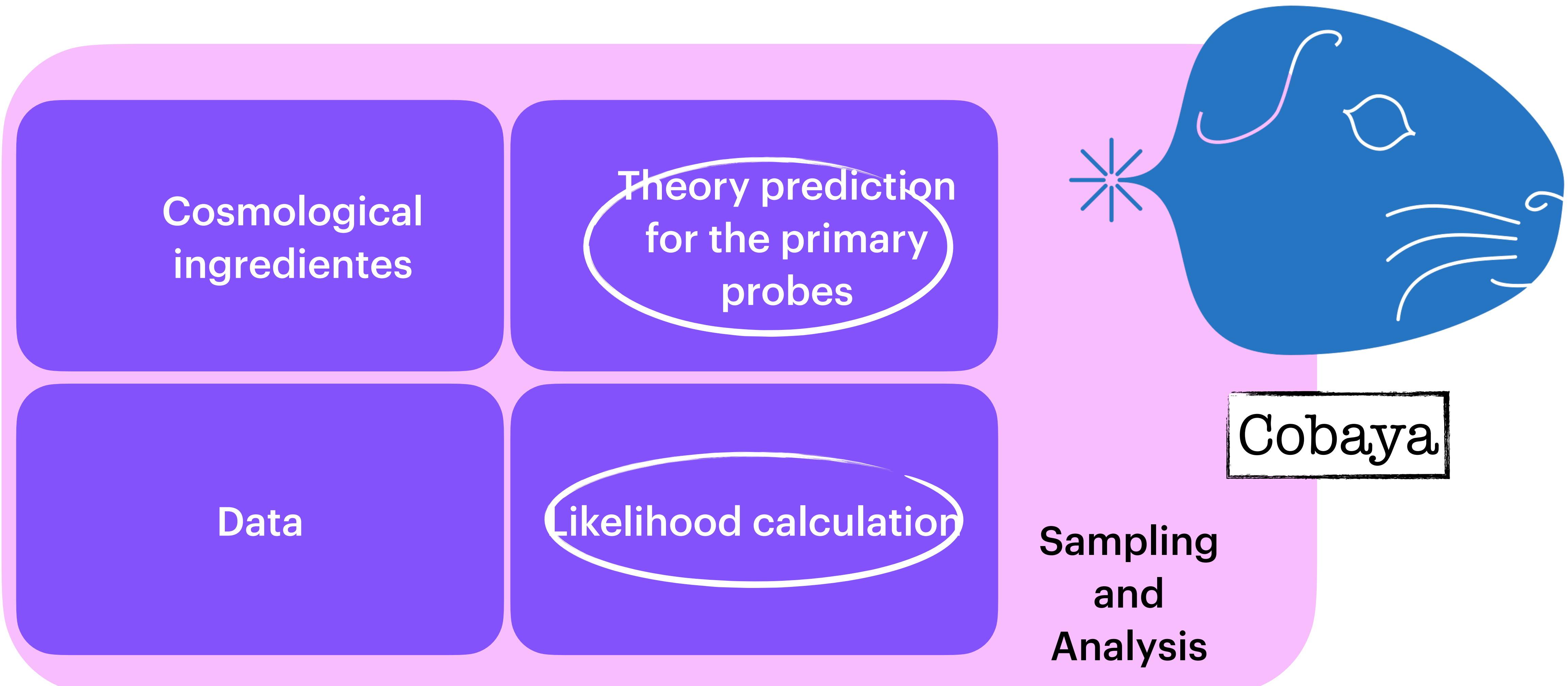
The code: CLOE

Cosmology Likelihood for Observables in Euclid



The code: CLOE

Cosmology Likelihood for Observables in Euclid



courtesy of Guadalupe Cañas-Herrera (IST:L, TWG)

Inspired by V. Pettorino

Synergies

The European Space Agency selected *Euclid* in 2011. The American National Science Foundation (NSF) officially approved Rubin in 2014, though some parts began earlier construction with private financing. As both are modern observatories dedicated to surveying large, overlapping fractions of the celestial sky for cutting-edge cosmology, discussions of synergies between the two have been ongoing essentially since their conception.

In addition to the fact that they will be taking data simultaneously, two aspects of these experiments drive most of the synergies: different angular resolutions, and different wavelength coverage.

- Angular Resolution: The ground-based Rubin Observatory will have roughly 0.7", atmospheric-seeing-limited angular resolution, while *Euclid* will have an optical wavelength band with angular resolution of order 0.2".
- Spectral Resolution and Coverage: The space-based *Euclid* will have three infrared bands and a spectrometer, but a single optical band, which will benefit from the additional spectral resolution in the optical afforded by the five separate Rubin bands in the optical. This is illustrated in figure 1.

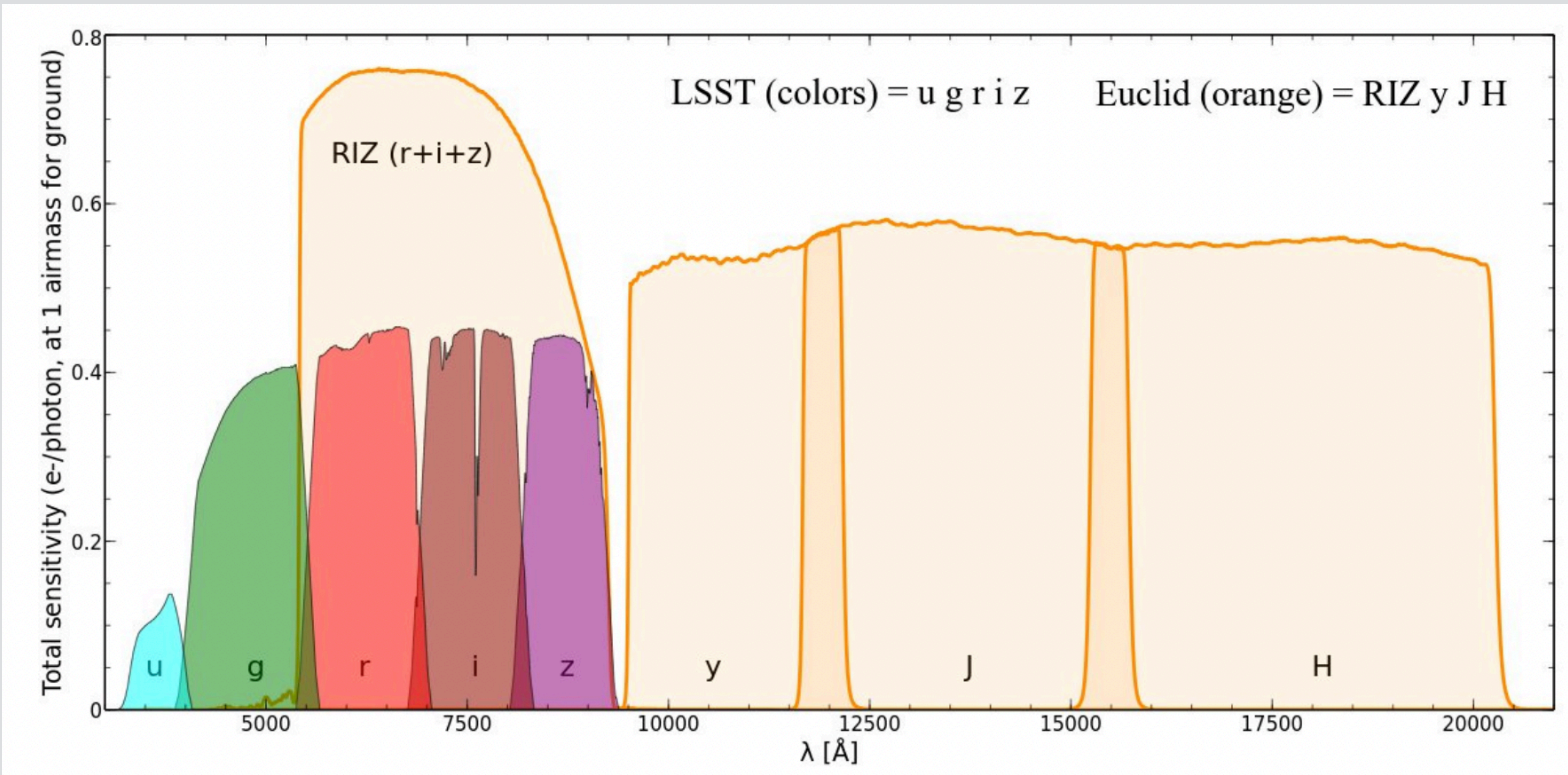
4. SUPERNOVAE

Cosmological measurements using type Ia supernovae could greatly benefit from the synergy of Rubin and *Euclid*. The goal would be to convolve the high cadence, deep, multi-band imaging photometry of Rubin with near-infrared photometry and spectroscopy from *Euclid* to provide important information about host galaxies and improve the photometry and classification of Rubin transients.

Spectroscopic redshifts could be provided by *Euclid* using NISP-S for a fraction of supernovae host galaxies (Rhodes *et al.* 2017). This could help in understanding and removing systematic biases observed using photometry only. SNe Ia standardization could greatly benefit from the knowledge of the overall color, morphology, and metallicity of host galaxies derived from VIS and NISP data. Furthermore, high resolution imaging from VIS and NISP could enable local measurements of host galaxy properties (e.g. local star-formation specific rate), key parameters to improve the knowledge of type Ia supernovae as "standard candles".

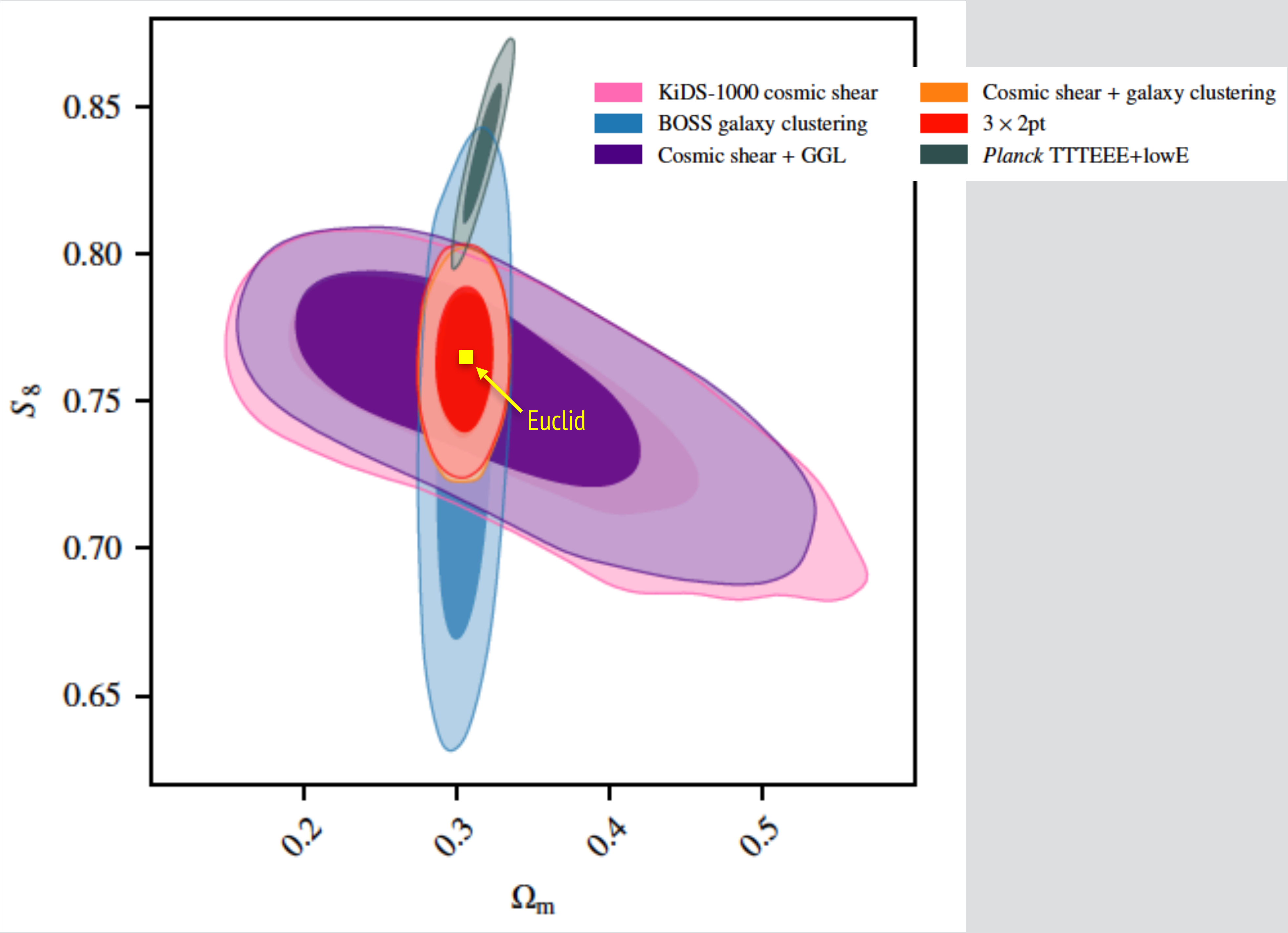
Euclid measurements could also lead to improvement of classification and photometry of Rubin transients by supplying serendipitous spectra (from NISP-S) for many long-lived Rubin transients such as superluminous supernovae, hence providing a training set for classification. Combining a few serendipitous NIR *Euclid* data points overlapping with Rubin could improve our understanding of Type Ia supernovae in the near-infrared domain using model-fitting of joint data of the second luminosity peak of type Ia SN in the NIR (Rhodes *et al.* 2017).

Synergies



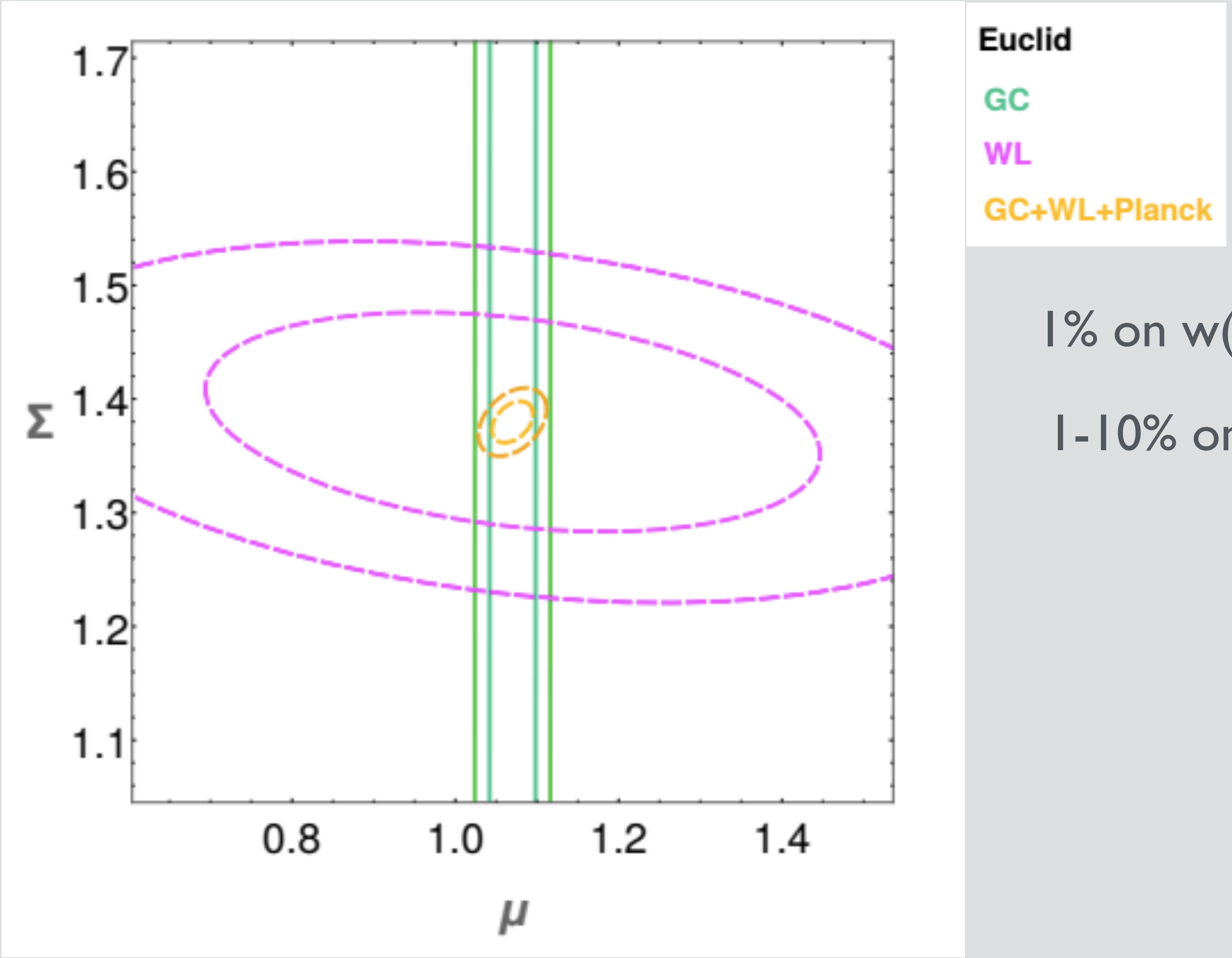
It is only with supplementary optical band data from ground-based experiments such as Rubin, DES and CFHT that Euclid will be able to get a full complement of photometric redshifts.

Euclid will be a major step forward!



Heymans et al. (2021)

Euclid will be a major step forward!



1% on w(a)

1-10% on μ, Σ

But we must achieve precision & accuracy

Everything matters!

Is it Gaussian?

Do we need data compression?

$$\ln \mathcal{L}(\mathbf{p}) = -\frac{1}{2} \sum_{ij} [D_i - T_i(\mathbf{p})]\, C^{-1}{}_{ij}\, [D_j - T_j(\mathbf{p})]$$

Data vector:
shapes
redshifts
PSF errors
...

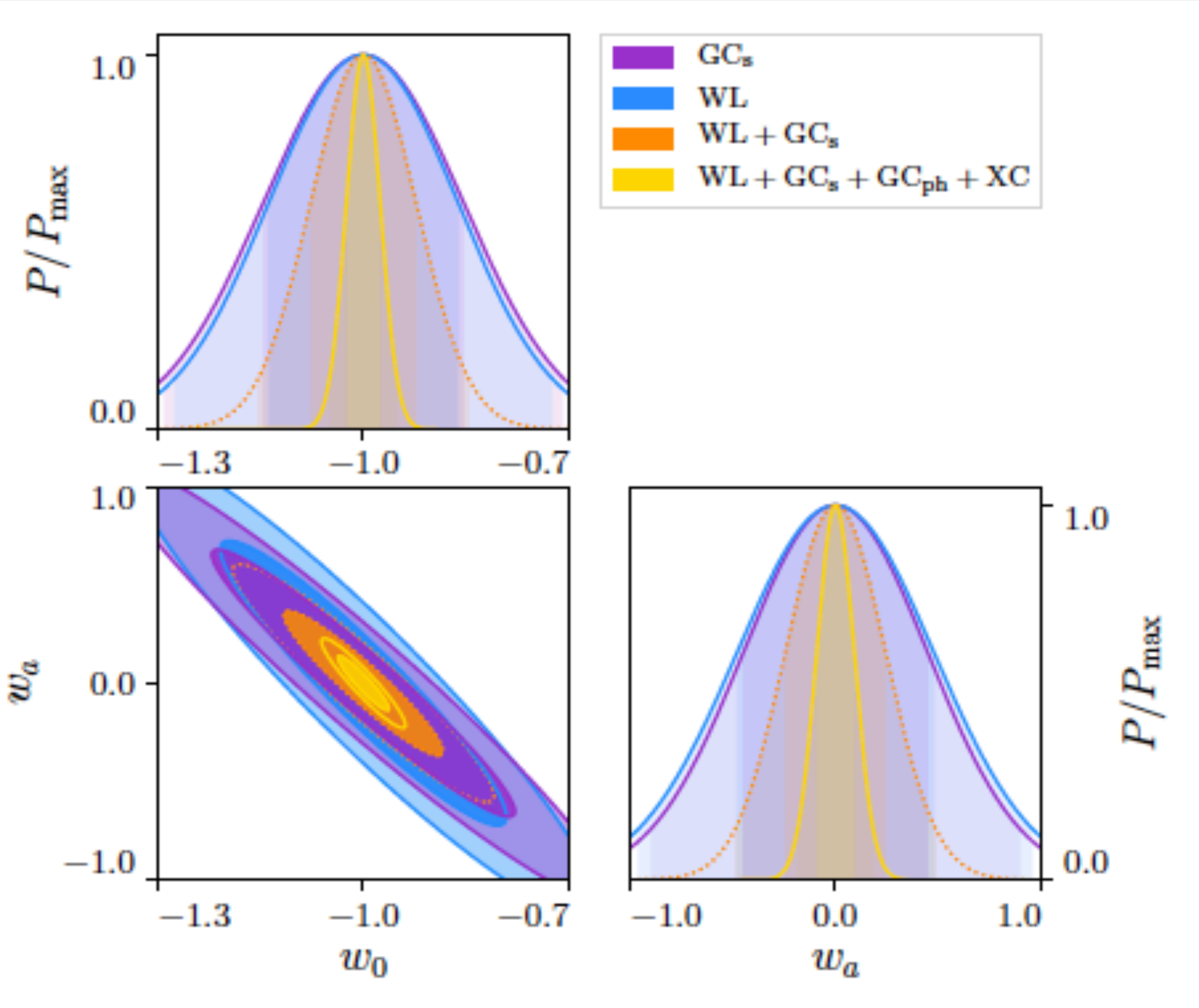
Covariance
cosmology
survey properties
...

Theory vector:
cosmology
new physics!
baryon physics
intrinsic alignments
...

courtesy of Henk Hoekstra

Probe combination

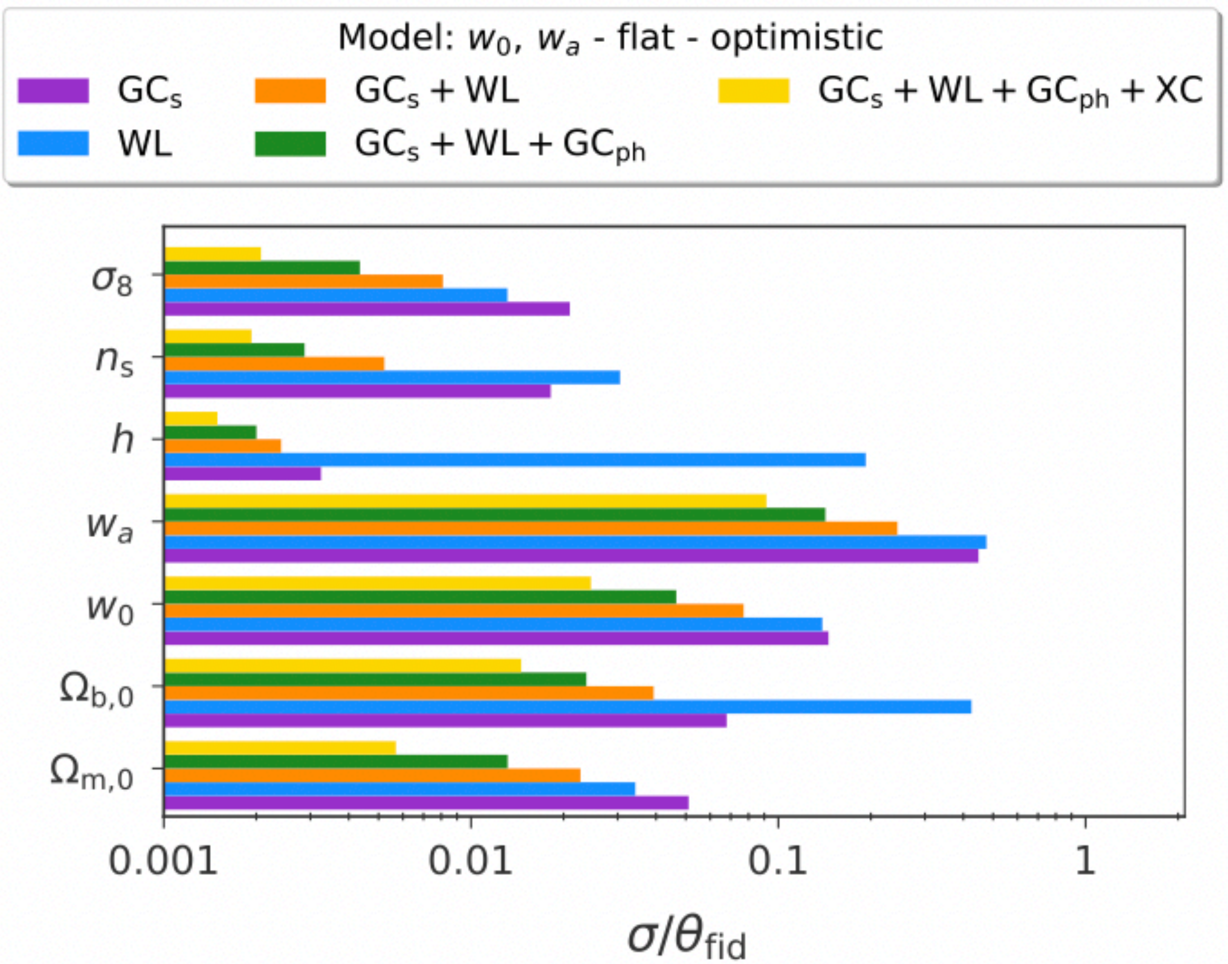
Percent precision on the dark energy equation-of-state requires the combination of probes.

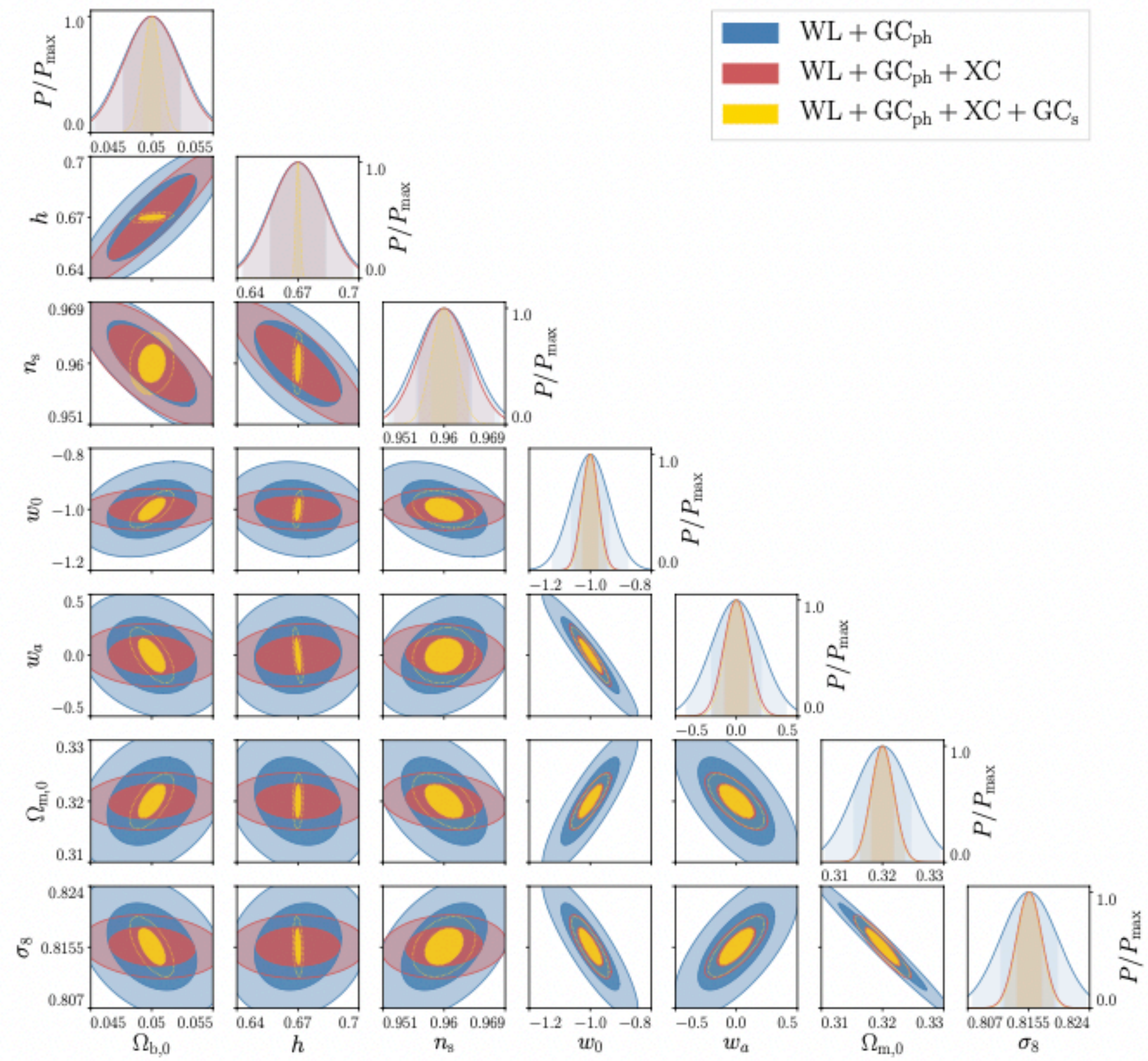


Euclid Collaboration: Blanchard et al. (2020)

Probe combination

The combination of photometric probes gives very competitive constraints, giving sub-% constraints on standard parameters, as well as tight constraints on non-standard ones (e.g. DE)

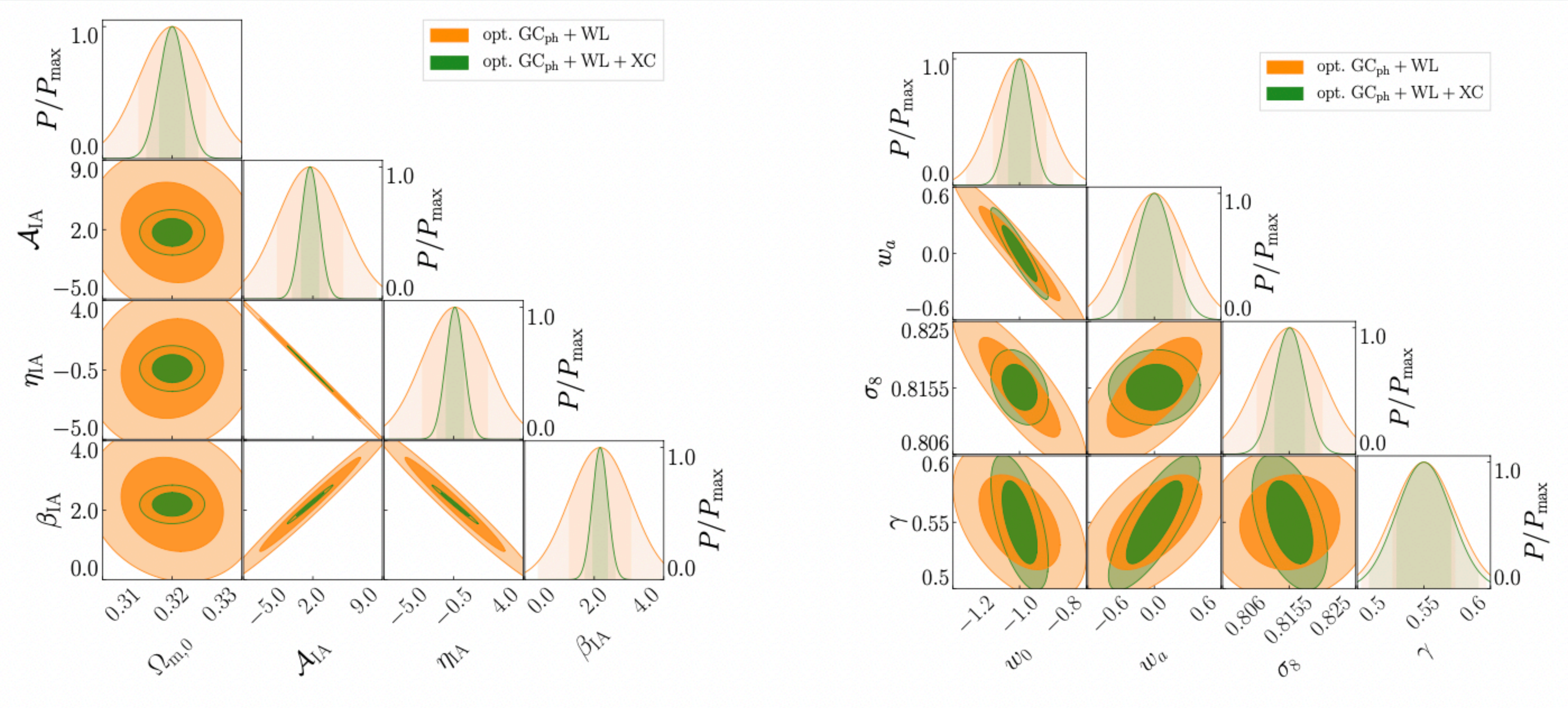




Euclid preparation VII: Forecast Validation for Euclid Cosmological Probes,
A.Blanchard et al. (A&A 642, A191, 2020)

Probe combination

The full 3x2pt combination of photometric observables gives considerable improvement in the constraining power, in particular on DE parameters, thanks to the breaking of degeneracies with nuisance parameters (galaxy bias and IA)



Euclid: The importance of galaxy clustering and weak lensing cross-correlations within the photometric Euclid survey, *I. Tutusaus et al.* (A&A 643, A70, 2020)

Non-linearities

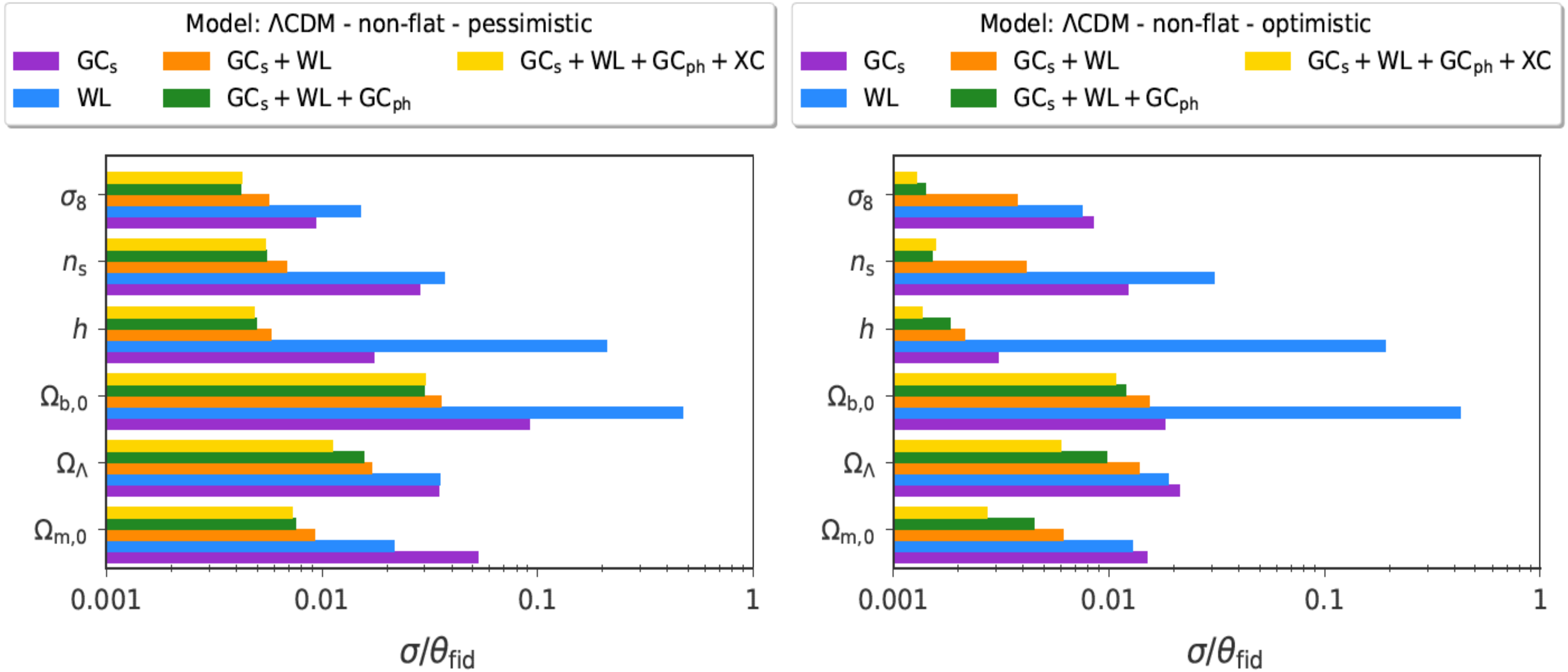
Including small scales helps a lot …

Pessimistic settings:

$$k_{\max}(\mathrm{GC_s}) = 0.25\,h\,\mathrm{Mpc}^{-1},$$
$$\ell_{\max}(\mathrm{WL}) = 1500,$$
$$\ell_{\max}(\mathrm{GC_{ph}}) = \ell_{\max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 750,$$

Optimistic settings:

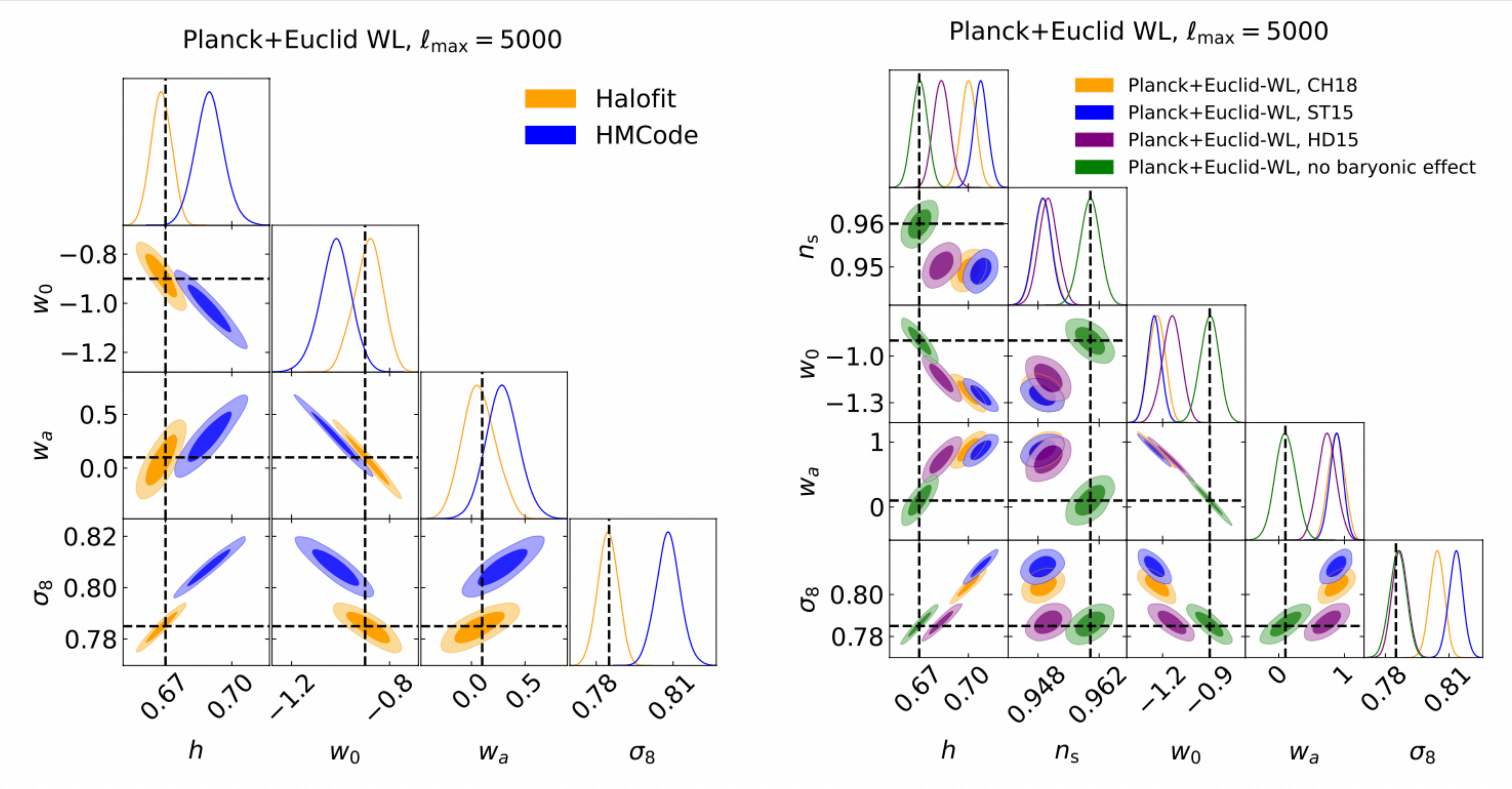
$$k_{\max}(\mathrm{GC_s}) = 0.3\,h\,\mathrm{Mpc}^{-1}, \text{with fixed } \sigma_\mathrm{p} \text{ and } \sigma_\mathrm{v},$$
$$\ell_{\max}(\mathrm{WL}) = 5000,$$
$$\ell_{\max}(\mathrm{GC_{ph}}) = \ell_{\max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 3000.$$



Euclid Collaboration: Blanchard et al. (2020)

…as long as you apply correct modelling!

a mismatch between the cosmological models assumed for numerical simulations and reality, as well as a bad modelling of astrophysical effects on small scales, would hinder the accuracy of the results.

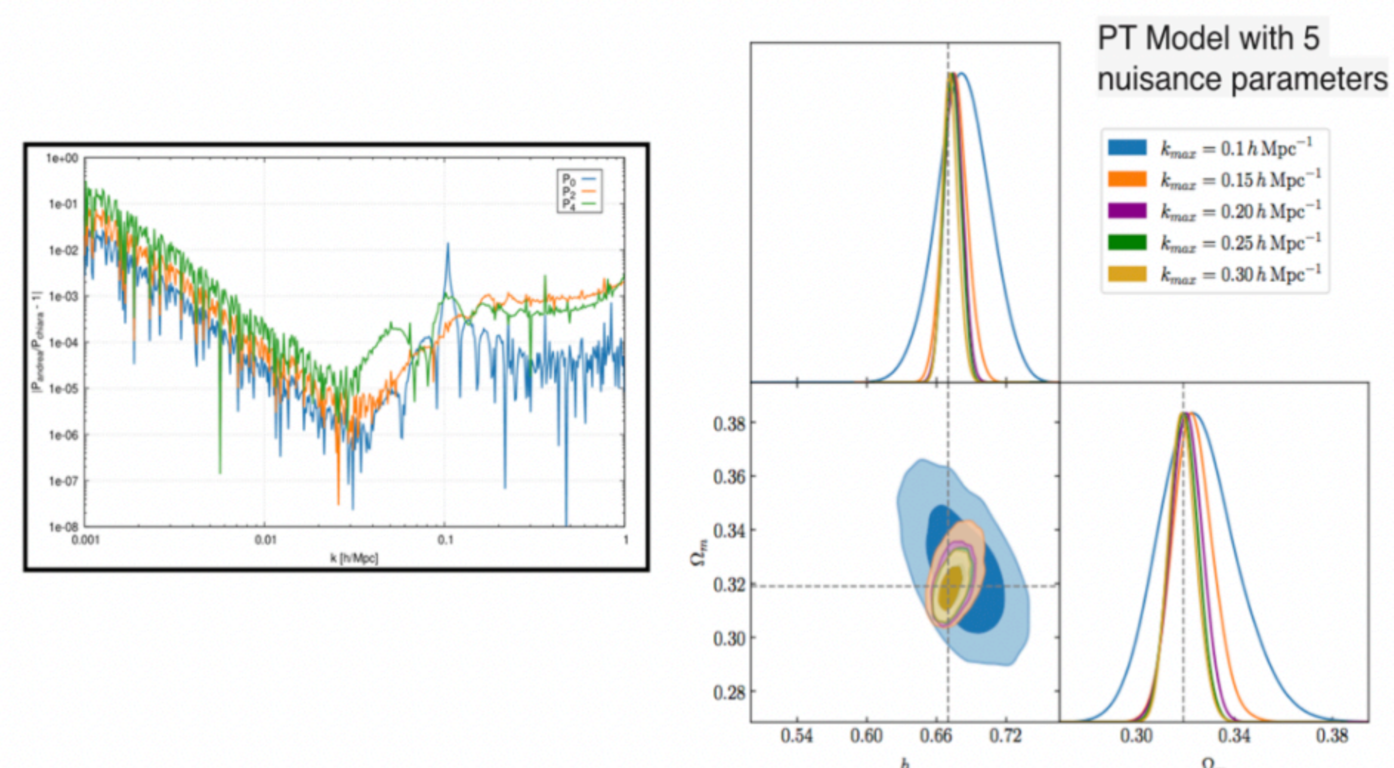


Euclid: Impact of non-linear and baryonic feedback prescriptions on cosmological parameter estimation from weak lensing cosmic shear, *M.Martinelli et al.* (A&A 649, A100, 2020)

Non-linearities

Euclid: the precision vs accuracy challenge

- Euclid should measure key cosmological parameters (e.g. the DE equation of state) to **percent or sub-percent accuracy**
- This requires the nonlinear, high S/N scales
- Without bespoke & accurate nonlinear modelling, Euclid's error budget will be dominated by **theoretical systematics → the precision vs accuracy problem**



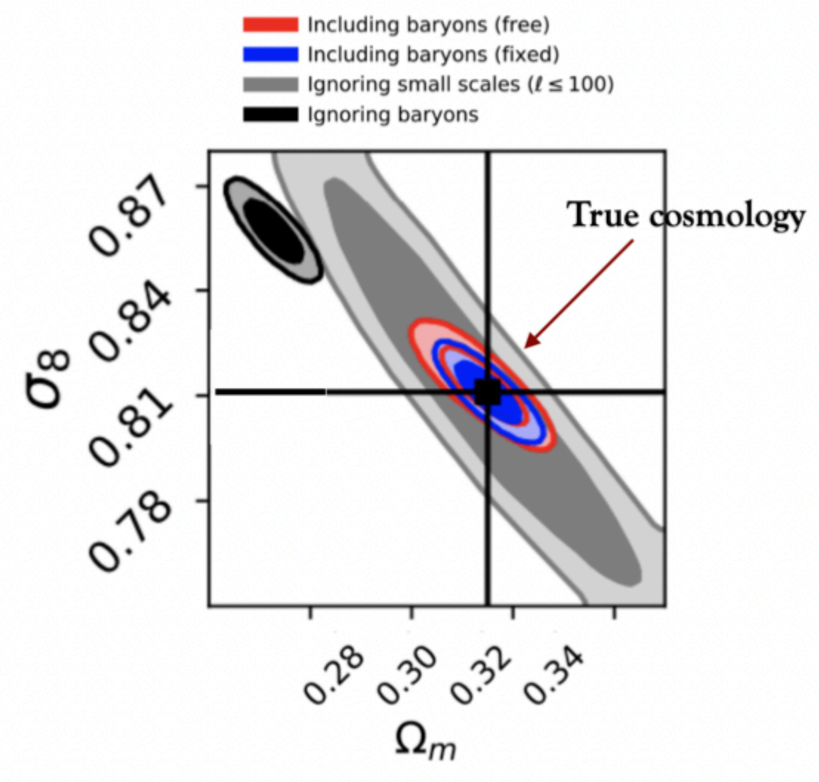
Plots: C. Moretti and A. Pezzotta, on behalf of the GC-SWG WP:NL modelling challenge

courtesy of Alkistis Pourtsidou (IST:NL)

Non-linearities

WL analysis

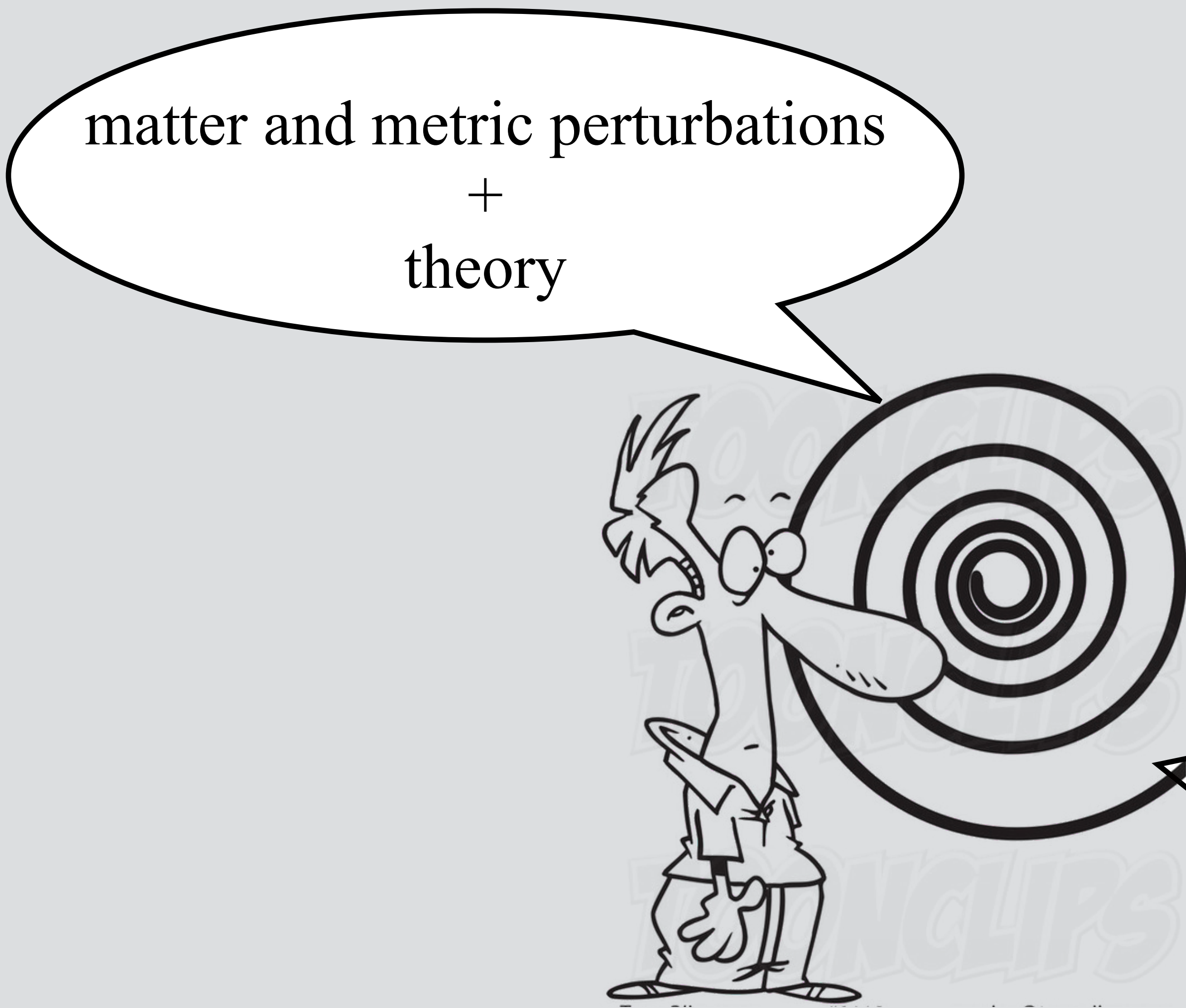
- Modelling with emulators, e.g. Euclid Emulator, bacco, etc.
- Need accurate nonlinear modelling of dark matter clustering *and* baryonic feedback (and Intrinsic Alignments ...)
- We probe up to k ~ 5 Mpc/h to exploit Euclid's WL sensitivity
- Inaccurate nonlinear modelling results in biased (wrong) parameter inference
- Validation with simulations and null tests are essential



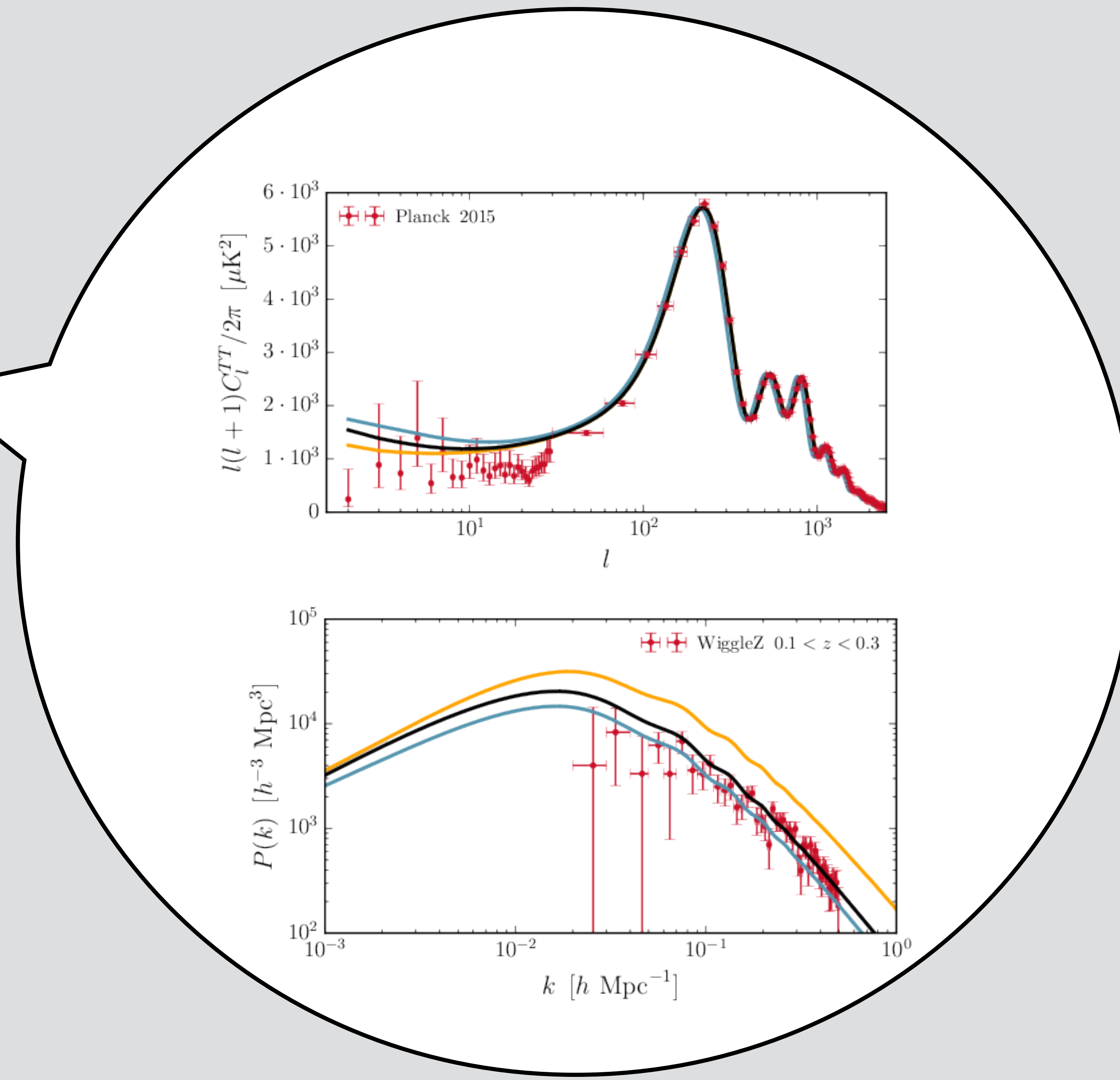
Forecasts by A. Schneider et al (2020)

courtesy of Alkistis Pourtsidou (IST:NL)

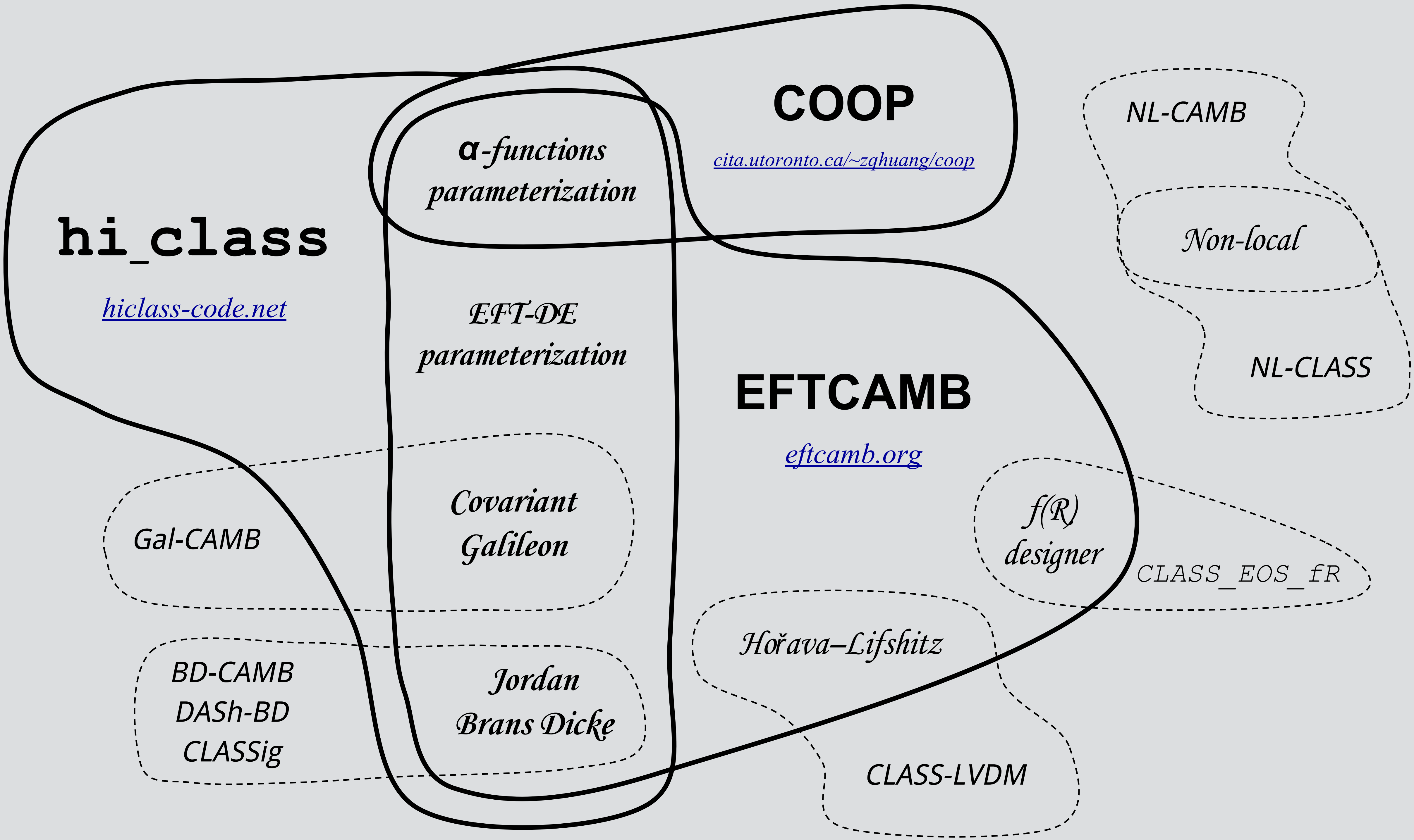
From Theory to Observables



EINSTEIN-BOLTZMANN
SOLVER
e.g. CAMB



Validation of codes for late time cosmology



Phys. Rev. D 97, 023520 (2018), arXiv:1709.09135

Theoretical landscape

Beyond LCDM

with focus on DE/MG !

Can we maximize the information gain and at

the same time minimize the theoretical bias?

DISCLAIMER: personal research ahead!

Can we maximize the information gain and at

the same time minimize the theoretical bias?

Reconstructing Gravity

We bin the functions in time:

$$\Omega_X^i \quad \mu_i \quad \Sigma_i$$

The three functions are represented by their values at **11 discrete** values **(nodes)** of a, with a **cubic spline** used to interpolate between them.

From the 11 nodes, 10 are distributed uniformly in the interval a ∈ [1, 0.25] (corresponding to z ∈ [0, 3]) with another one at a = 0.2 (z = 4).

The functions are made to approach their ΛCDM values at higher redshifts (studying earlier times deviations from GR is generally possible within the same framework) .

The data

And we fit all the resulting parameters, along with the standard cosmological ones to two combinations of data sets:

CMB: Planck2018 temperature, polarization and the reconstructed CMB weak lensing spectra

SN: Pantheon sample 0.01<z<2.3

BAO: eBOSS DR16 BAO compilation + 6dF, covering 0.07<z<3.5

RSD: eBOSS joint measurement of BAO and RSD for LRGs, ELGs and QSOs

DES: DES-Y1 3x2pt correlation functions of galaxy clustering, cosmic shear, galaxy-galaxy lensing; sources in 0.2<z<1.3 (with non-linear cut)

BASELINE: CMB + SN + BAO

BASELINE+LSS: CMB + SN + BA0-RSD + DES

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BASELINE: CMB + SN + BAO

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$A_{\rm lens}$

$M_{\rm SN}$

Correlated Prior

We would like to add a **theory-motivated correlation prior**, to (mildly) correlate the values of the functions in neighbouring bins.

This will ease convergence for high number of nodes and smooth out (unphysical) variations of the functions with redshift.

We focus on **Horndeski gravity**

Sampling Horndeski

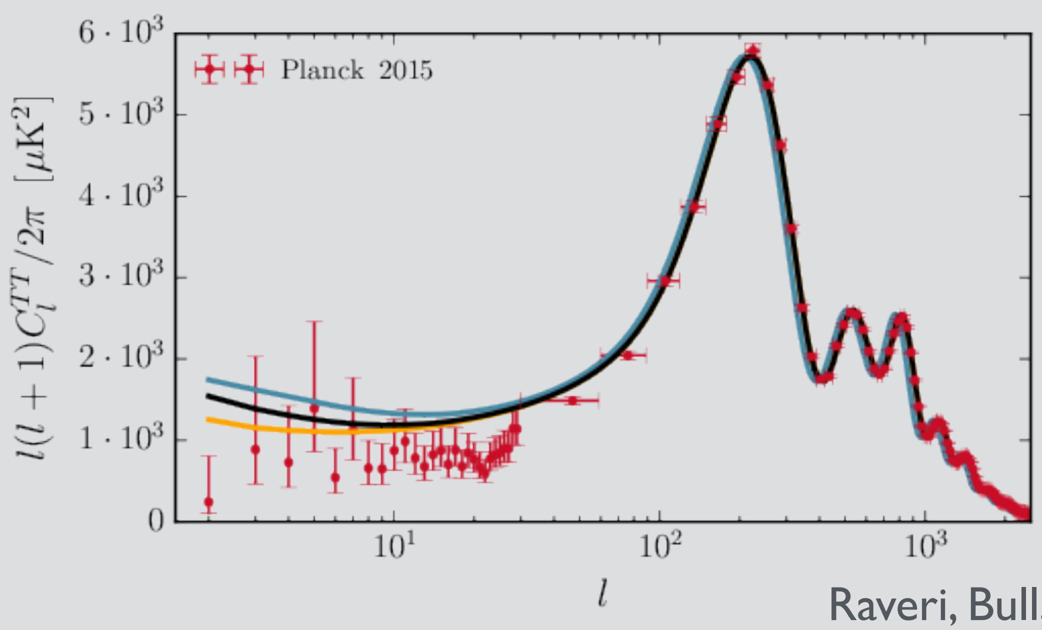
$$S^{(2)} = \int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]+\Lambda(\tau)-c(\tau)a^2\delta g^{00}+\right\}$$

$$\left\{\gamma_1(\tau)\frac{m_0^2H_0^2}{2}\left(a^2\delta g^{00}\right)^2-\gamma_2(\tau)\frac{m_0^2H_0^2}{2}a^2\delta g^{00}\delta K^\mu_\nu\right\}+S_m[g_{\mu\nu},\chi_i]$$

$$f(a) = \frac{\sum_{n=0}^{N}\alpha_n(a-a_0)^n}{1+\sum_{n=0}^{M}\beta_m(a-a_0)^m}$$

$$\begin{cases} a_0 = 0, 1 \\ \alpha_n, \beta_m \epsilon [-1, 1] \\ M + N = 9 \end{cases}$$

$10^4 - 10^6$ models



Raveri, Bull, AS, Pogosian, PRD 2017

Sampling Horndeski

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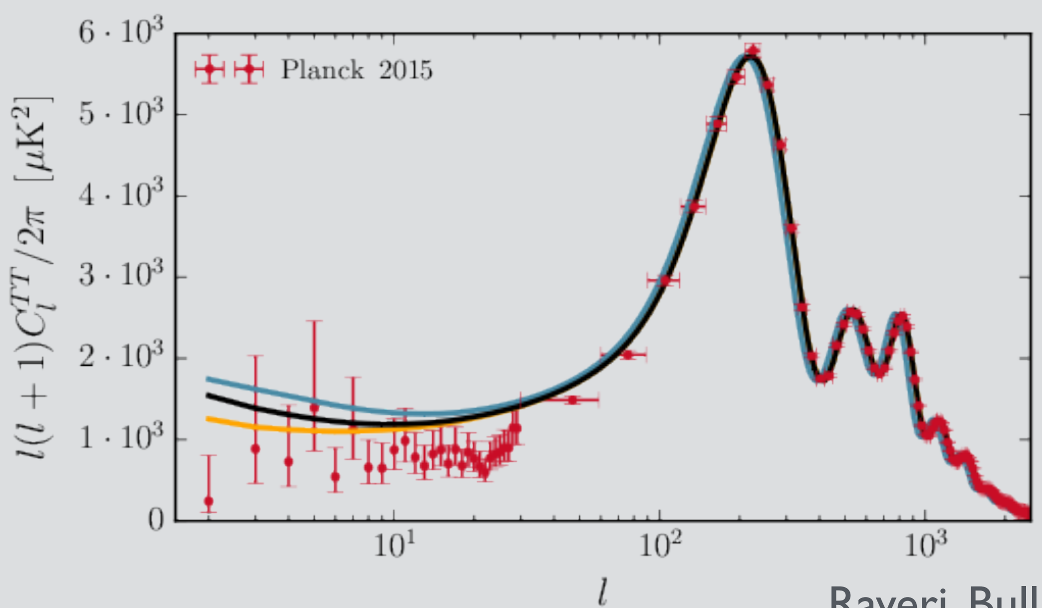
$$\left\{\gamma_1(\tau)\frac{m_0^2H_0^2}{2}\left(a^2\delta g^{00}\right)^2-\gamma_2(\tau)\frac{m_0^2H_0^2}{2}a^2\delta g^{00}\delta K_\nu^\mu\right\}+S_m[g_{\mu\nu},\chi_i]$$

$$f(a)=\frac{\sum_{n=0}^{N}\alpha_n(a-a_0)^n}{1+\sum_{n=0}^{M}\beta_m(a-a_0)^m}\qquad\begin{cases}a_0=0,1\\ \alpha_n,\beta_m\epsilon[-1,1]\\ M+N=9\end{cases}$$

Saving only **viable** models:

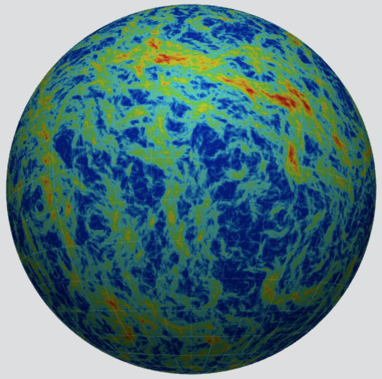
$10^4 - 10^6$ models

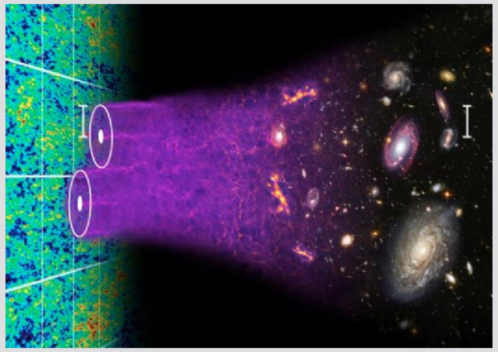


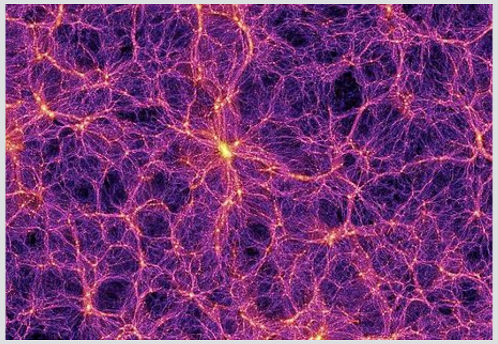
EffectiveFieldTheory CAMB

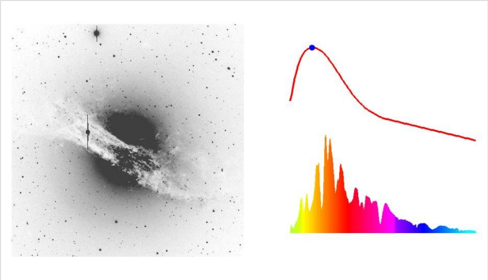
Raveri, Bull, AS, Pogosian, PRD 2017

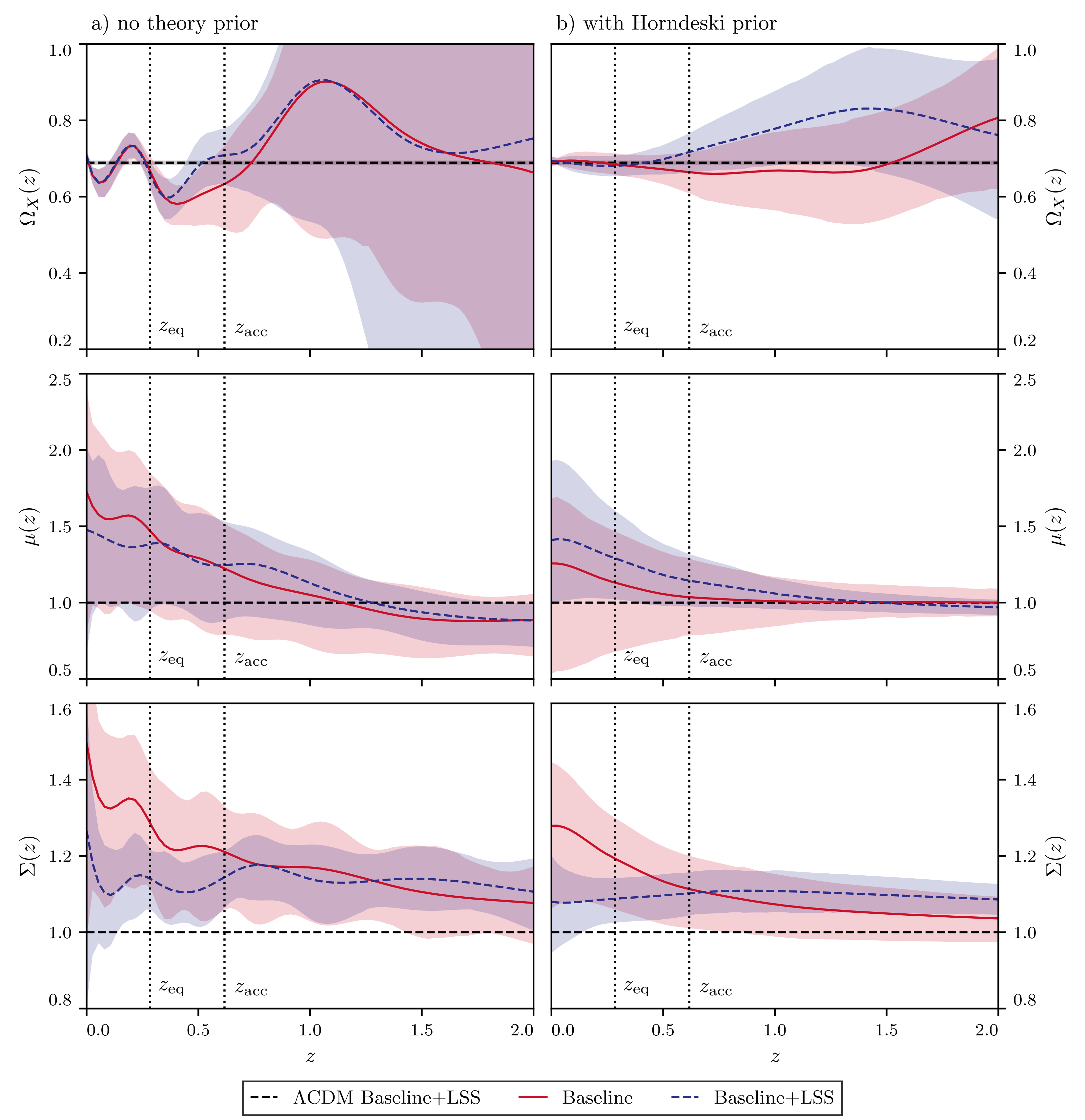
Reconstructed Gravity





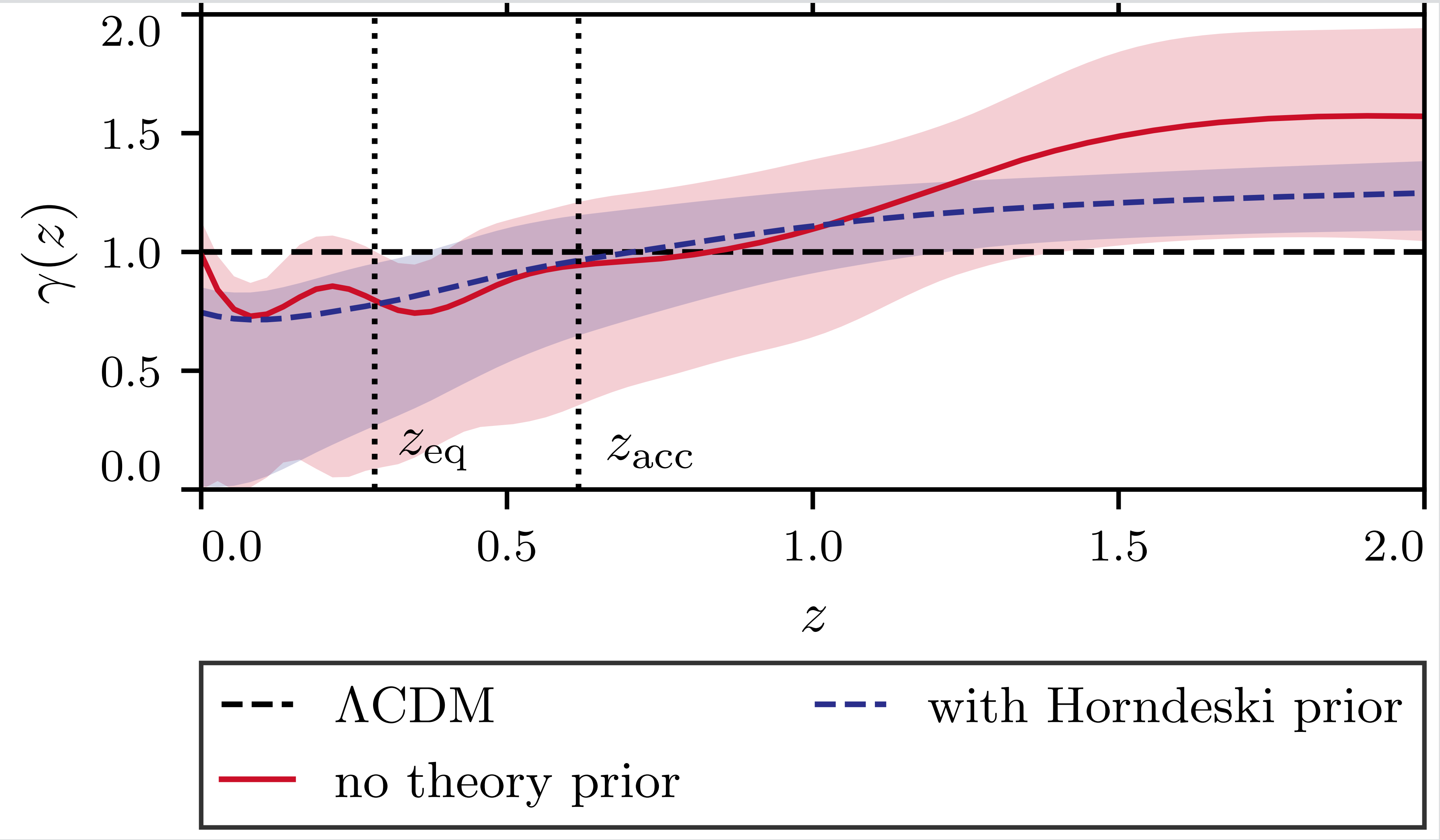






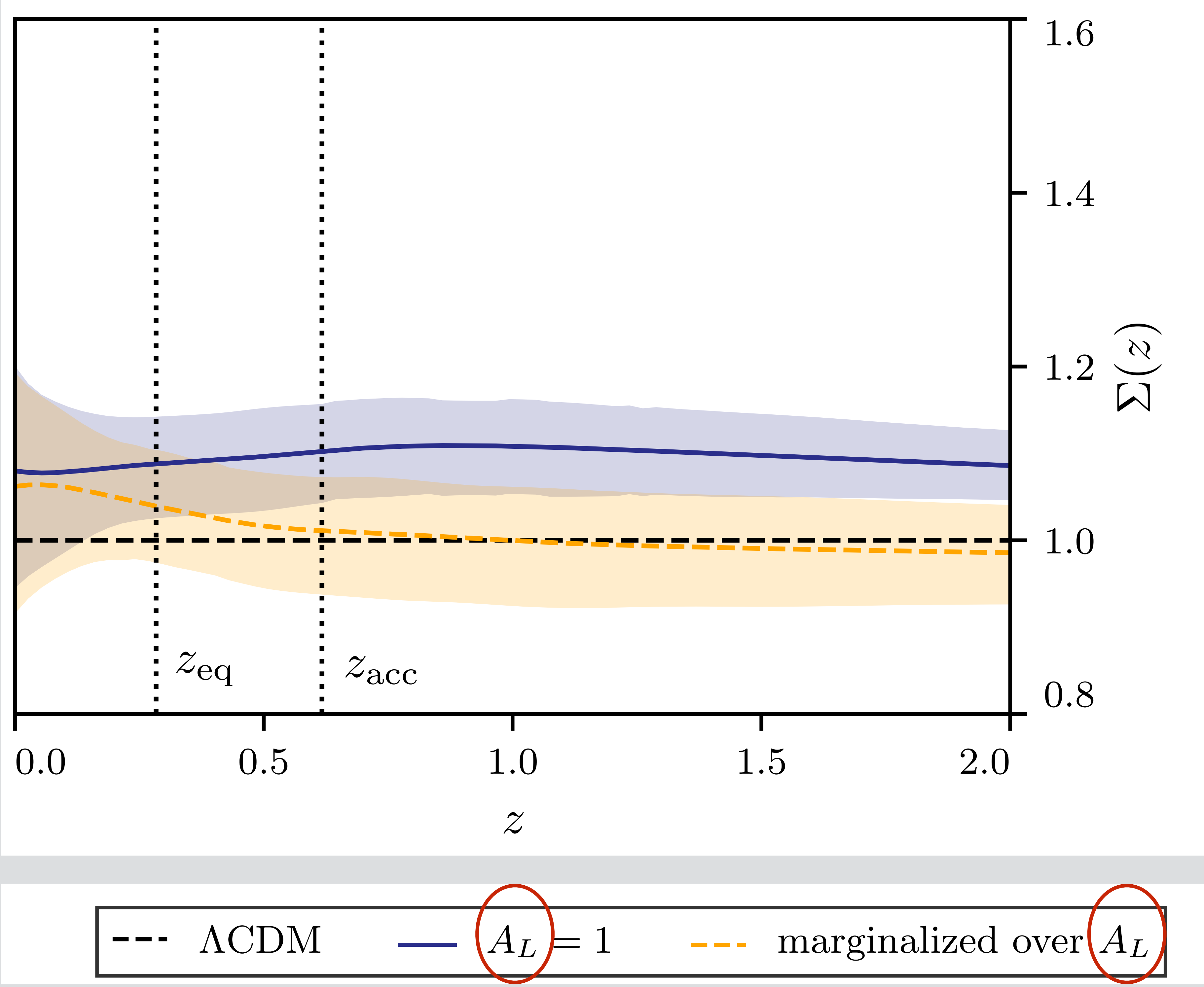
Pogosian et al., Nature Astronomy (2022), arXiv:2107.12992

Reconstructed Gravity - gravitational slip

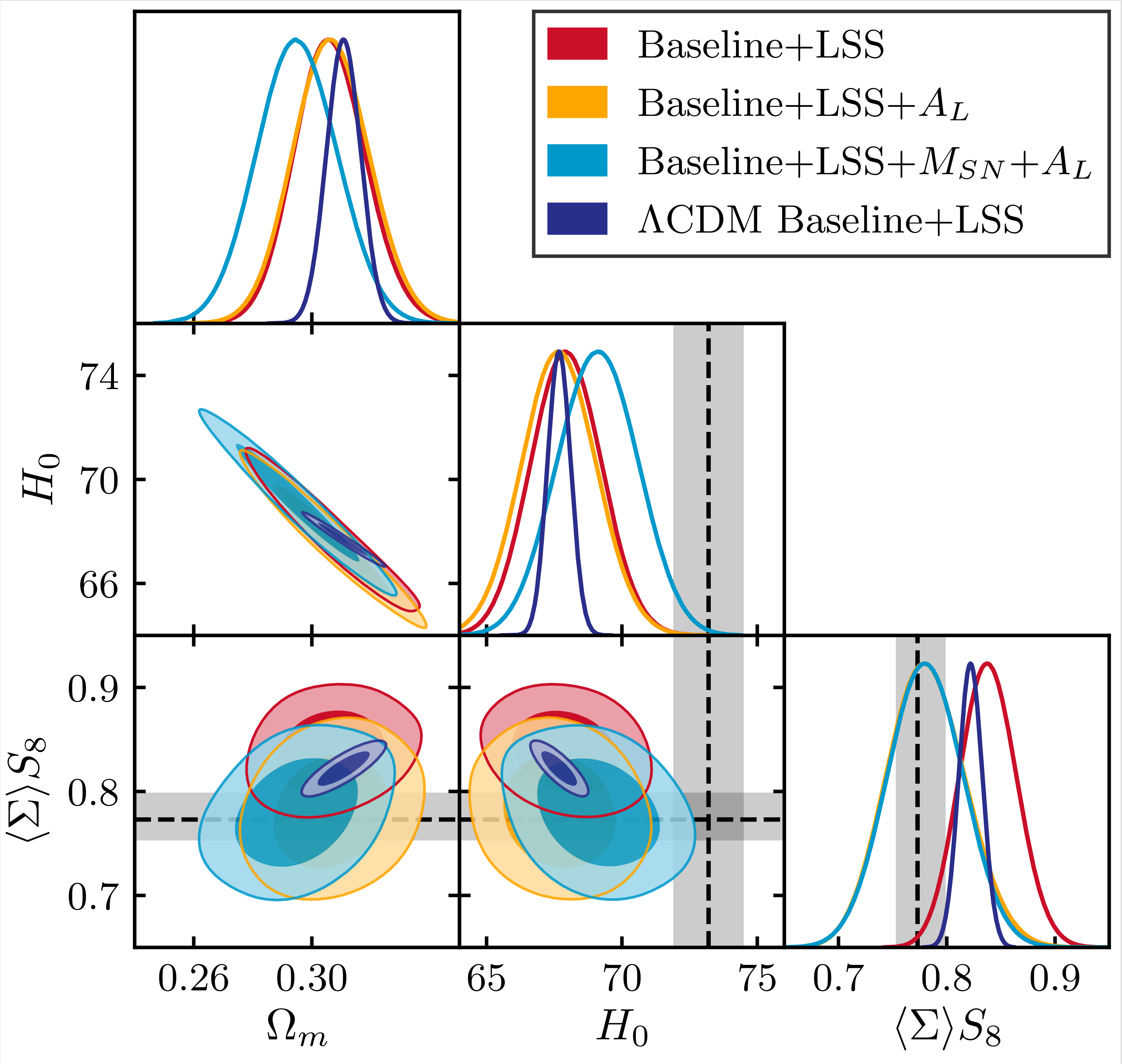


$$\gamma = \frac{2\Sigma}{\mu} - 1$$

A closer look at Σ



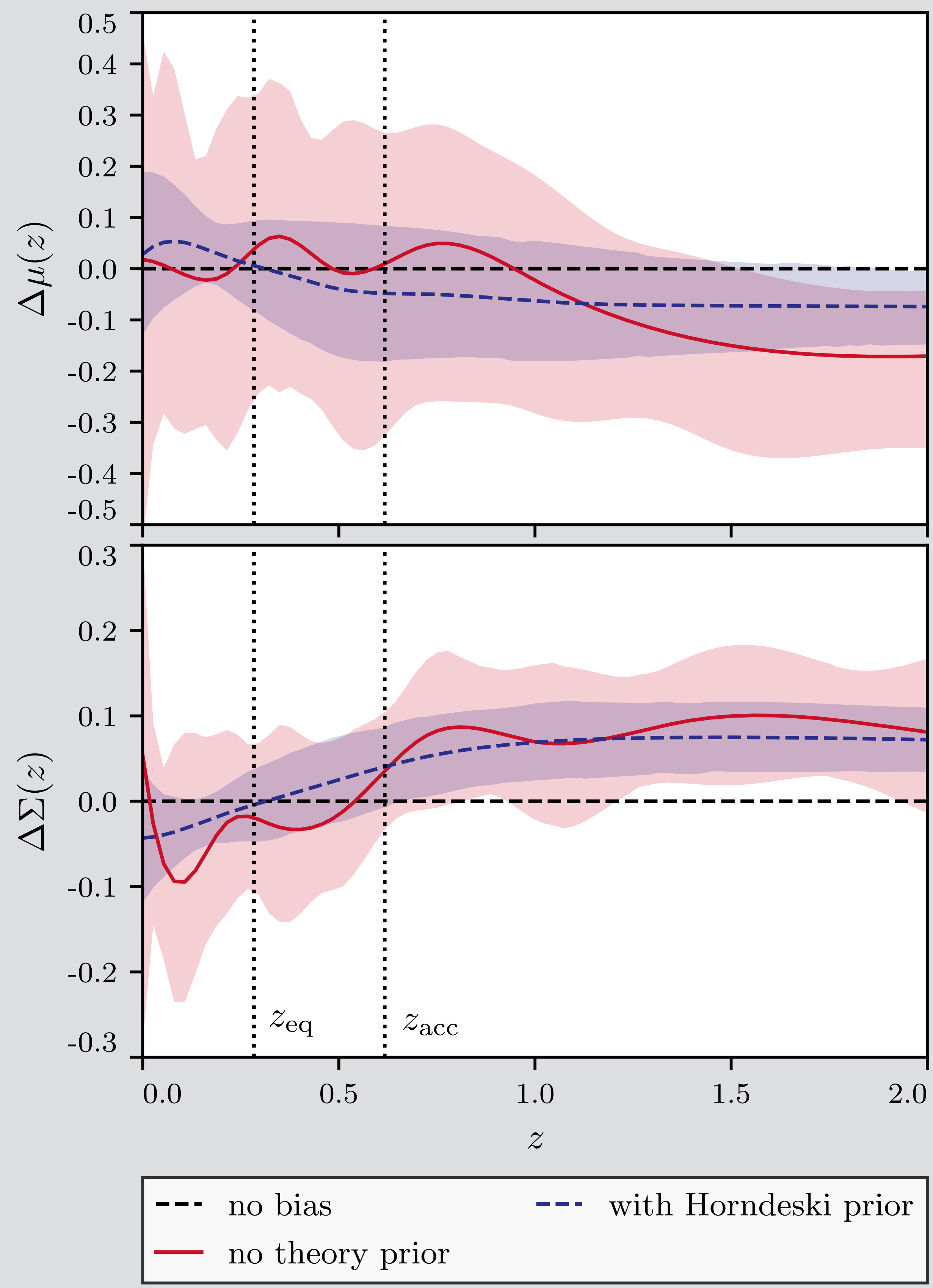
How about the tensions?



How ~~good~~ bad are common parametrizations?

$$\mu(a) = 1 + \mu_0 \Omega_{\mathrm{DE}}(a)$$

$$\Sigma(a) = 1 + \Sigma_0 \Omega_{\mathrm{DE}}(a)$$



Exciting and busy times are awaiting us, as we prepare to play ball with the Universe!