Reconstructed Gravity and Cosmological Tensions

Alessandra Silvestri
Instituut Lorentz, Leiden U.

Universiteit Leiden

Tensions in Cosmology, Corfu' , 8-11 September 2022

NWO

How does Gravity look like on large scales?

How does Gravity look like on large scales?

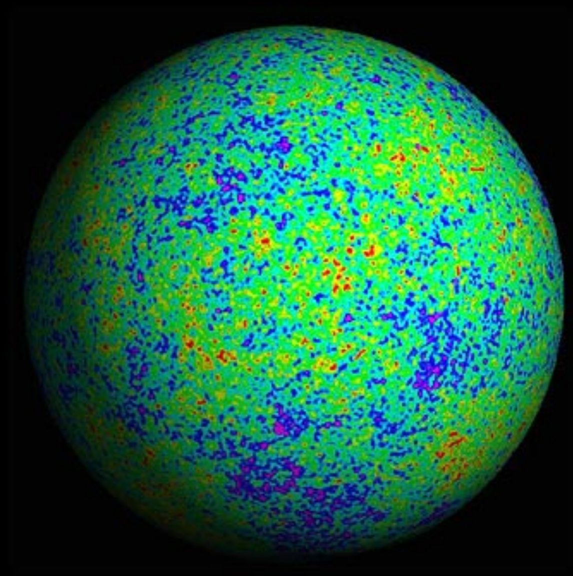
What can current cosmological data already tell us about this?

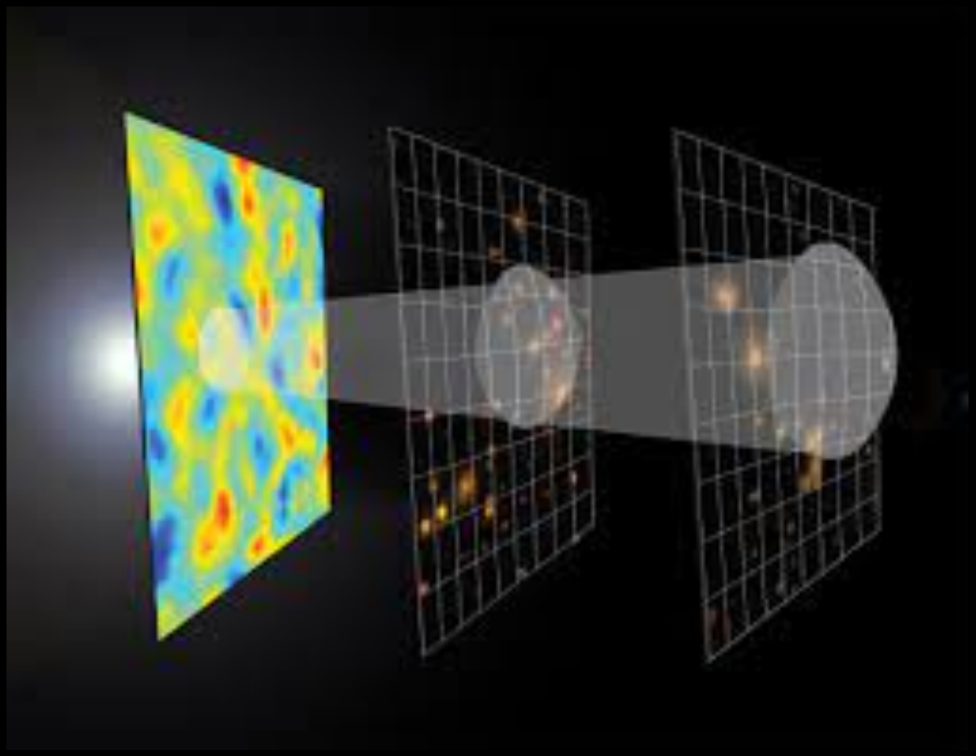
How does Gravity look like on large scales?

What can current cosmological data already tell us about this?

arXiv:2107.12990, 2107.12992

The gamefield





CMB

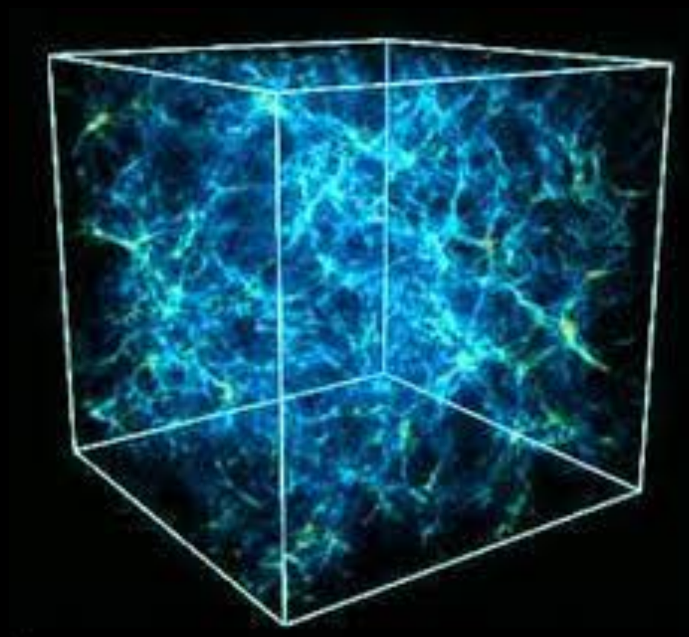
temperature, polarization from Planck 2018

lensing from Planck 2018

BAO (& RSD)

BAO from eBOSS DR16 and 6dF

RSD from eBOSS



SNIa

Pantheon

SH0ES prior on magnitude

LSS

GC, WL, GCxWL from DES Y1

The theoretical framework

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

Expansion:

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

Clustering:

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

Lensing:

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

The theoretical framework

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

Expansion:

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

Clustering:

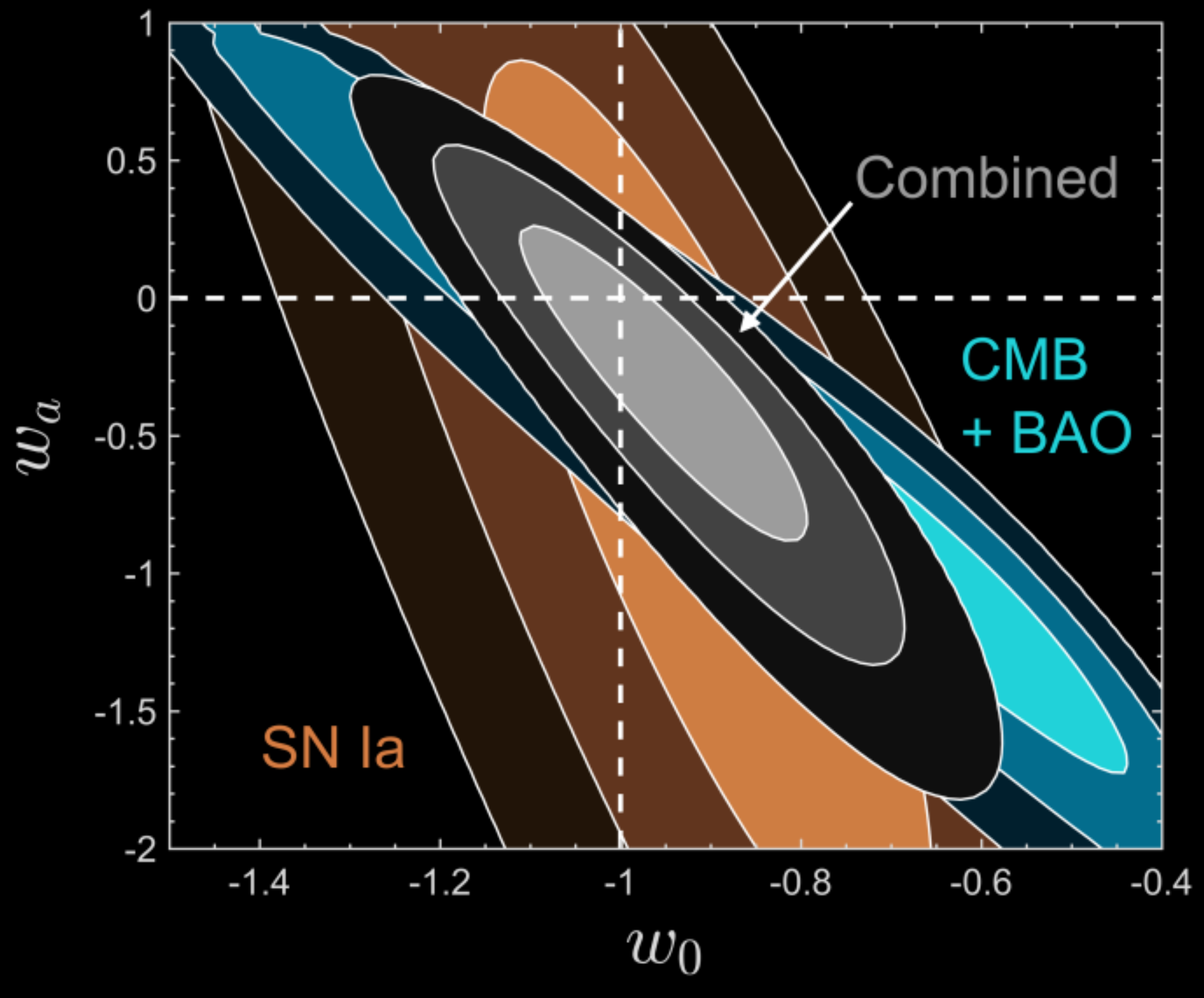
$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\delta$$

Lensing:

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

What can current data tell us about w, μ, $\sum$?

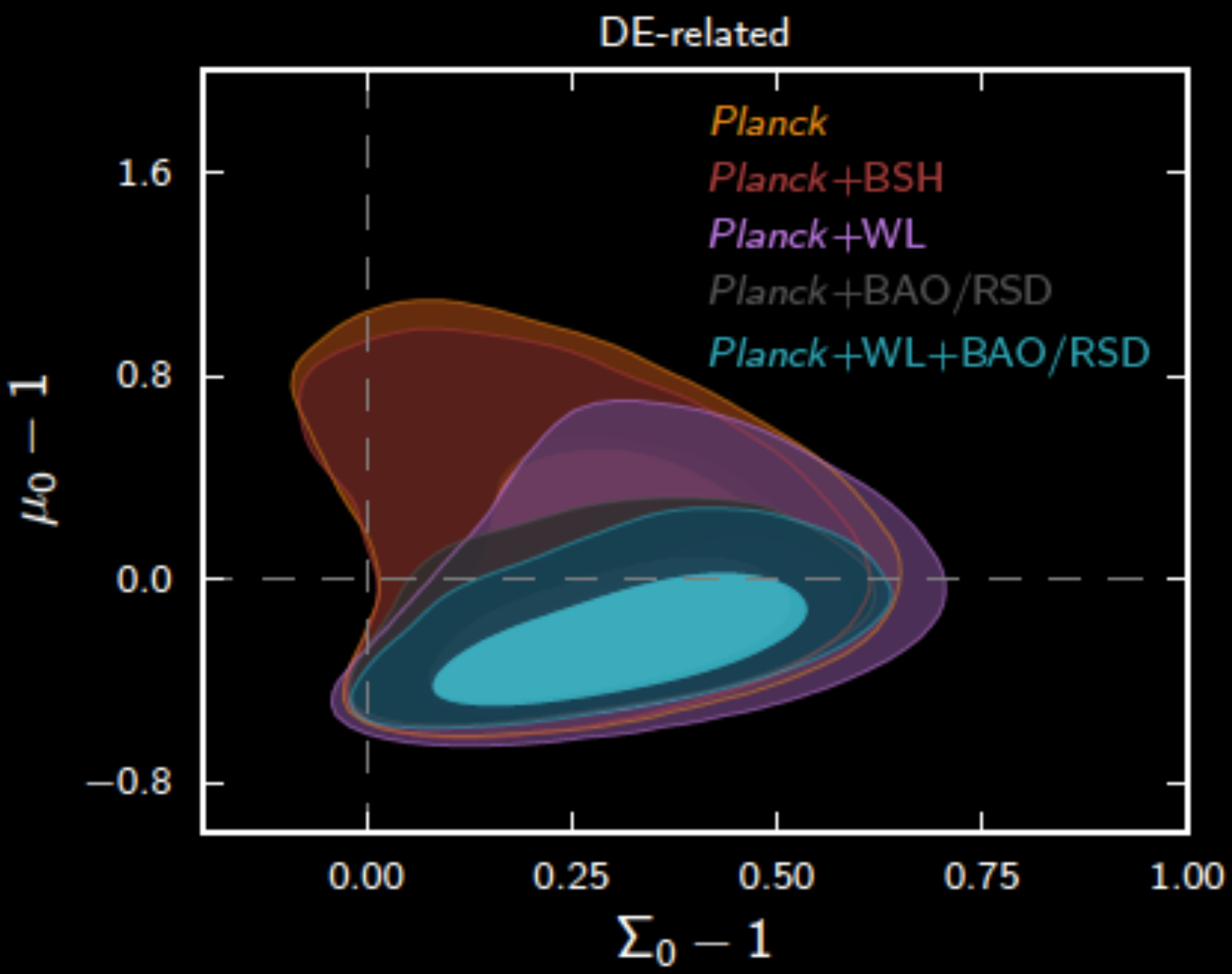
$$w(a) = w_0 + w_a(1 - a)$$



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

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

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



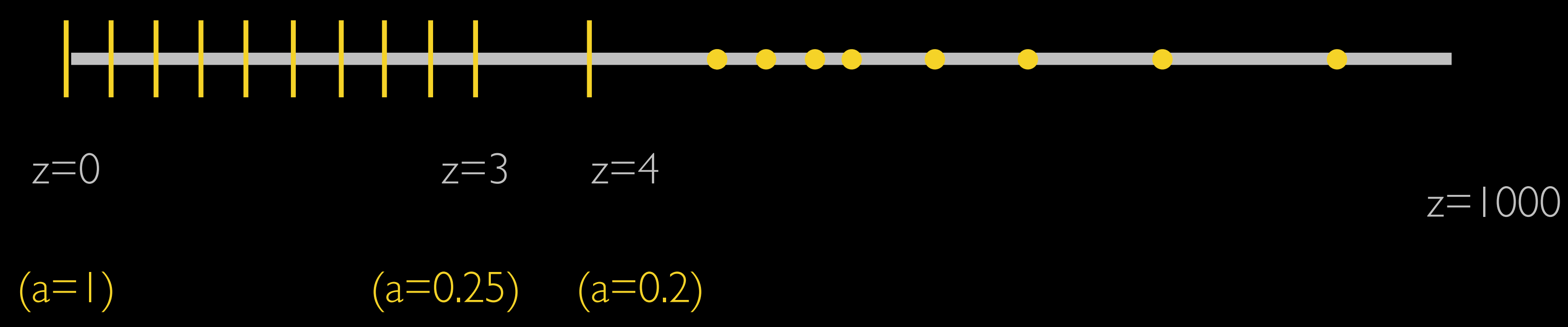
Planck 2018

Can we maximize the information gain and minimize the theoretical bias?

Reconstructing Gravity

We bin the functions in time:

$$\Omega_X^i, \mu_i, \Sigma_i$$



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

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

$A_{\rm lens}$

$M_{\rm SN}$

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

$$S=\int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R+\Lambda(\tau)-c(\tau)a^2\delta g^{00}+\right.$$
$$\left.+\gamma_1(\tau)\frac{m_0^2H_0^2}{2}(a^2\delta g^{00})^2-\gamma_2(\tau)\frac{m_0^2H_0}{2}(a^2\delta g^{00})\delta K^\mu_\mu\right\}+S_m[g_{\mu\nu},\chi_i].$$

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

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

Raveri, Bull, AS, Pogosian, PRD 2017

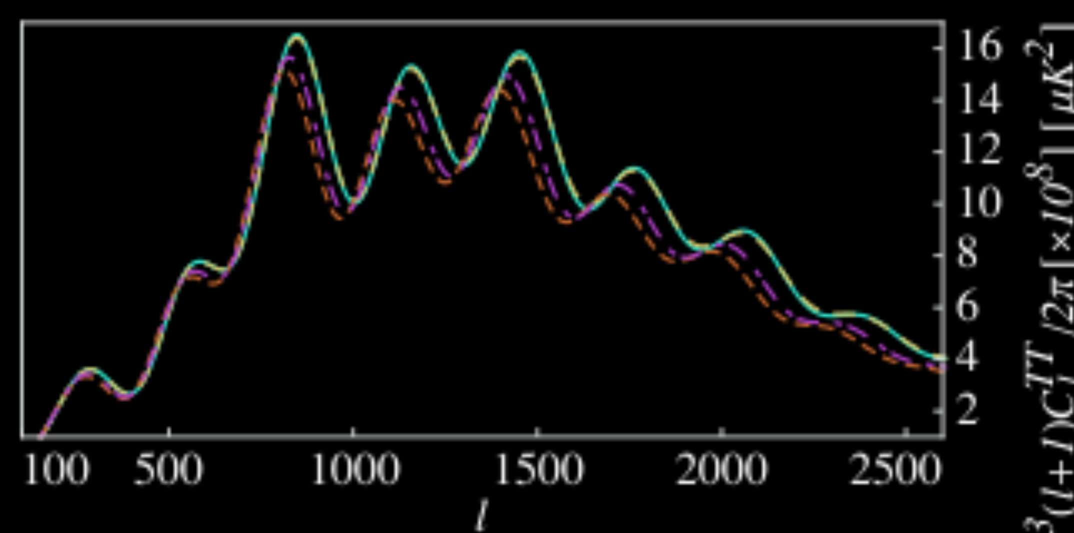
Sampling Horndeski

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R + \Lambda(\tau) - c(\tau)a^2\delta g^{00} + \right.$$
$$\left. + \gamma_1(\tau)\frac{m_0^2H_0^2}{2}(a^2\delta g^{00})^2 - \gamma_2(\tau)\frac{m_0^2H_0}{2}(a^2\delta g^{00})\delta K^\mu_\mu\right\} + S_m[g_{\mu\nu},\chi_i].$$

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

Saving only **viable** models:

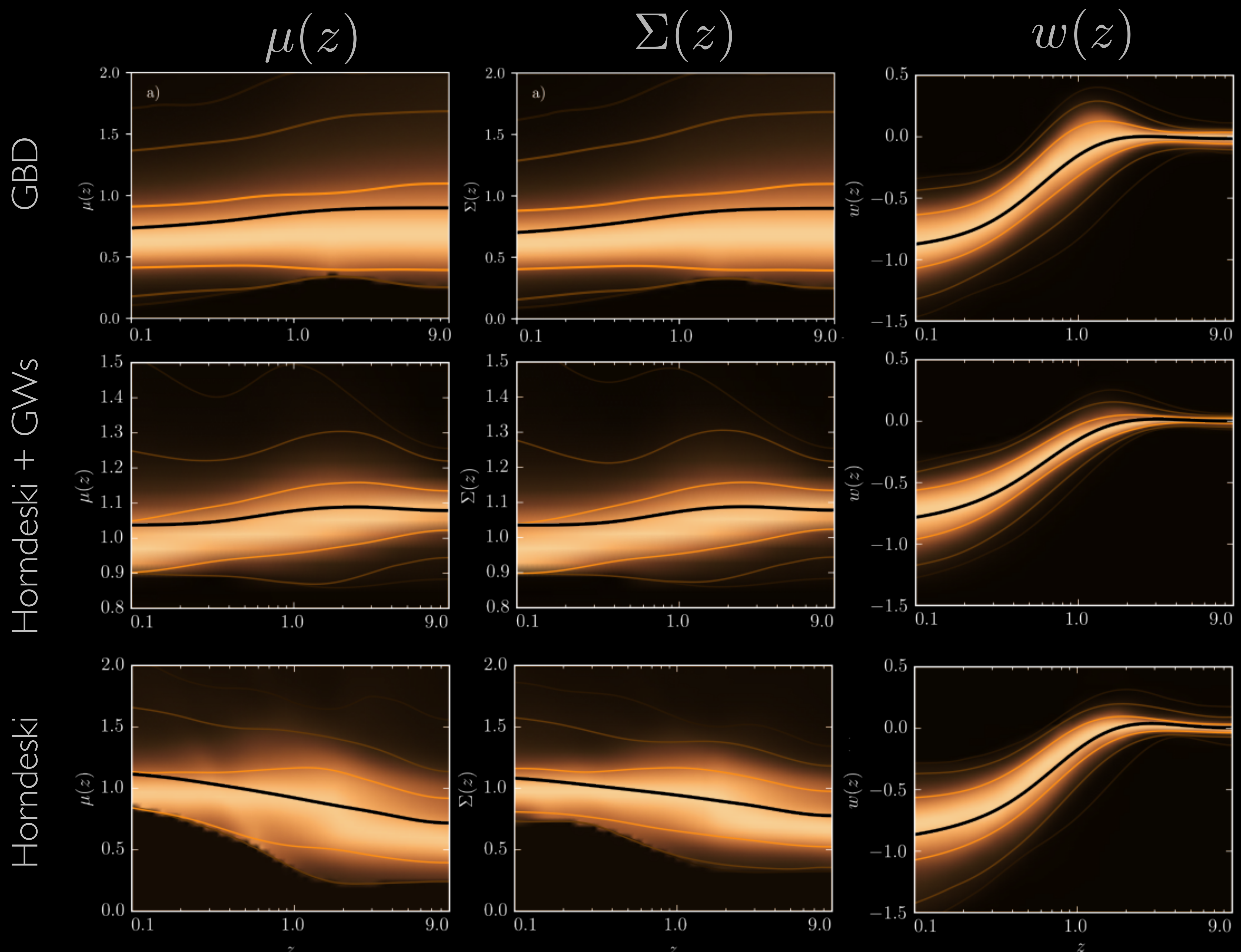
$10^4 - 10^6$ models



EFTCAMB

Raveri, Bull, AS, Pogosian, PRD 2017

Theoretical priors - Horndeski

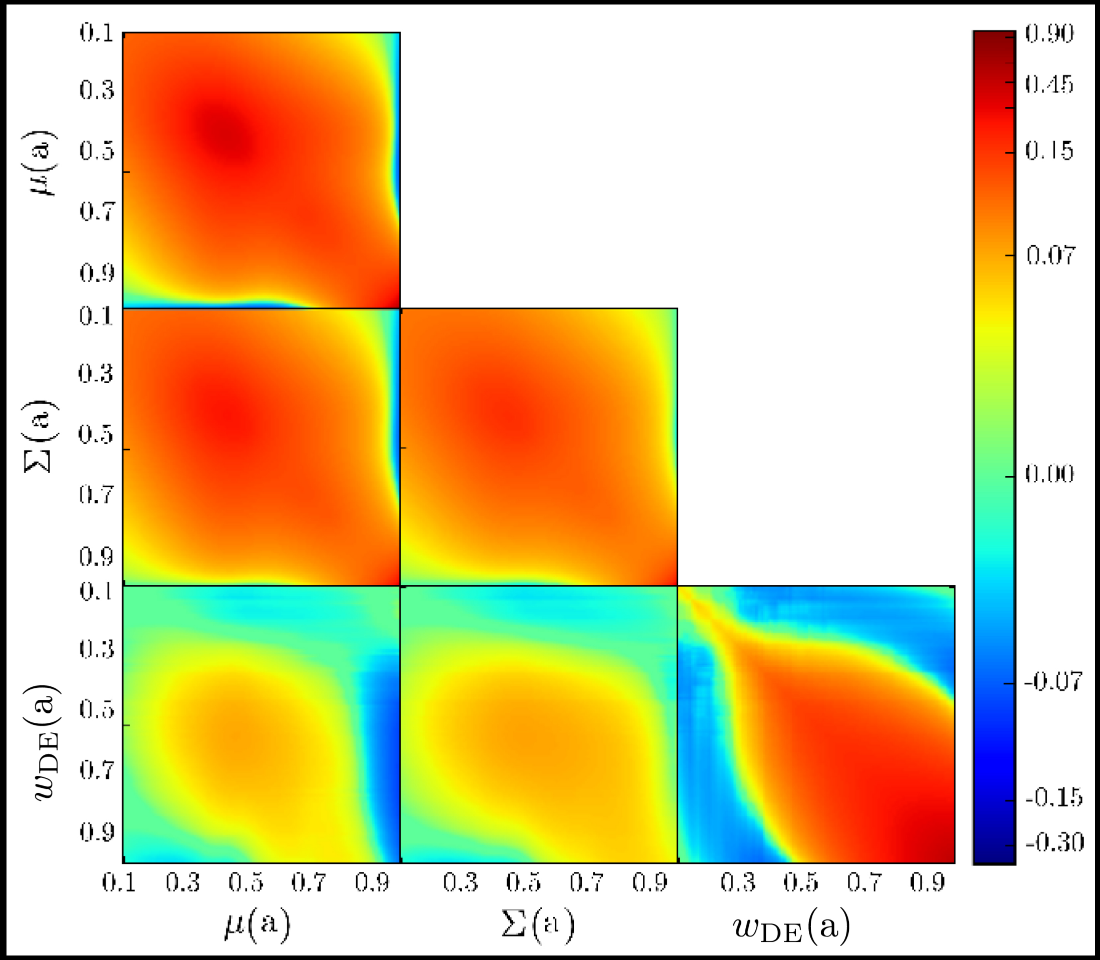


Folding in the Theoretical Prior

So, let us introduce the Horndeski prior, correlating the values of the different functions at the different bins, as a Gaussian prior:

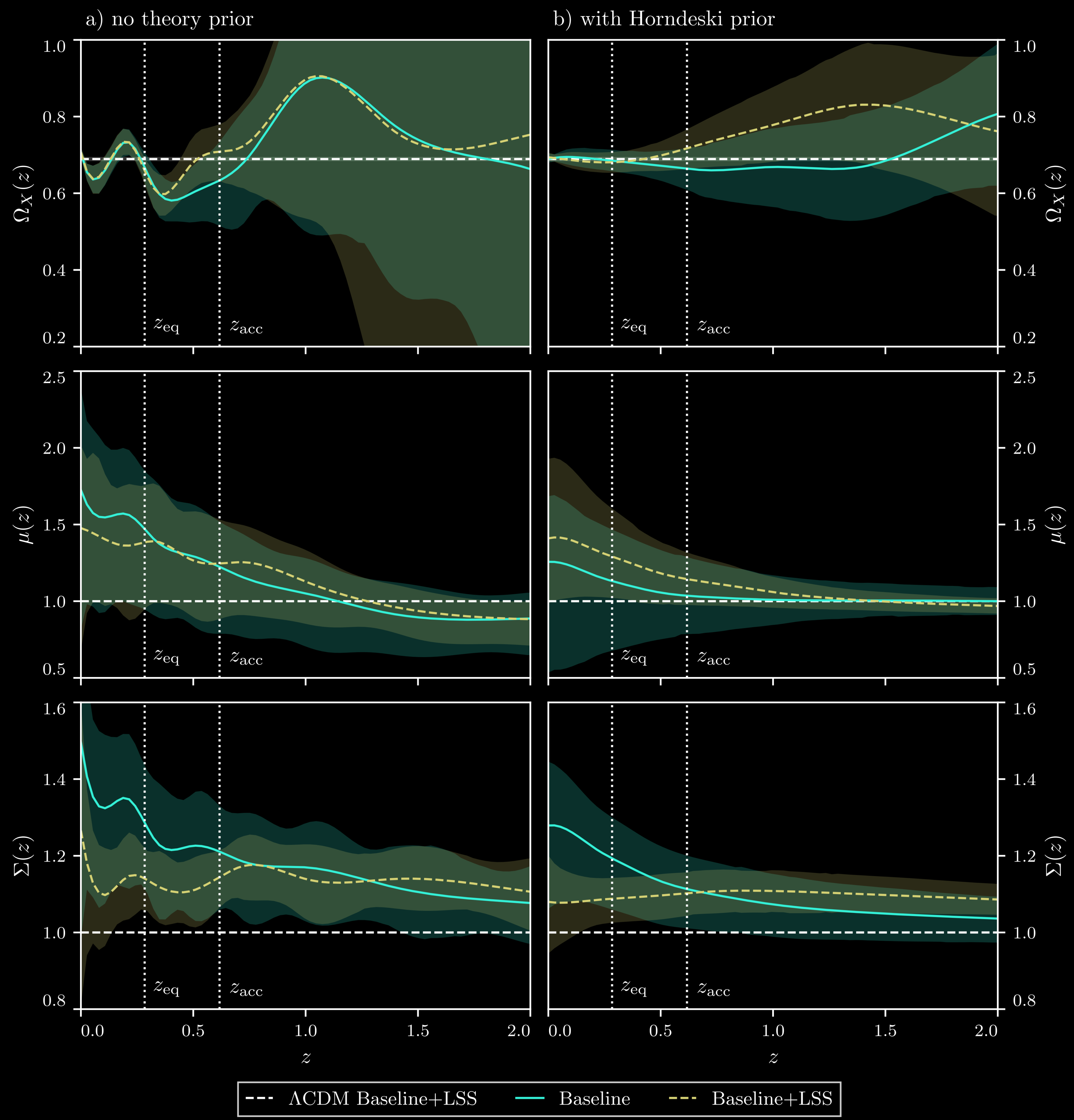
$$\mathcal{P}_{\rm prior} \propto \exp\left[-\left(\mathbf{f}-\mathbf{f}_{\rm fid}\right)\mathcal{C}^{-1}\left(\mathbf{f}-\mathbf{f}_{\rm fid}\right)^T\right]$$

Theory Correlation Matrix

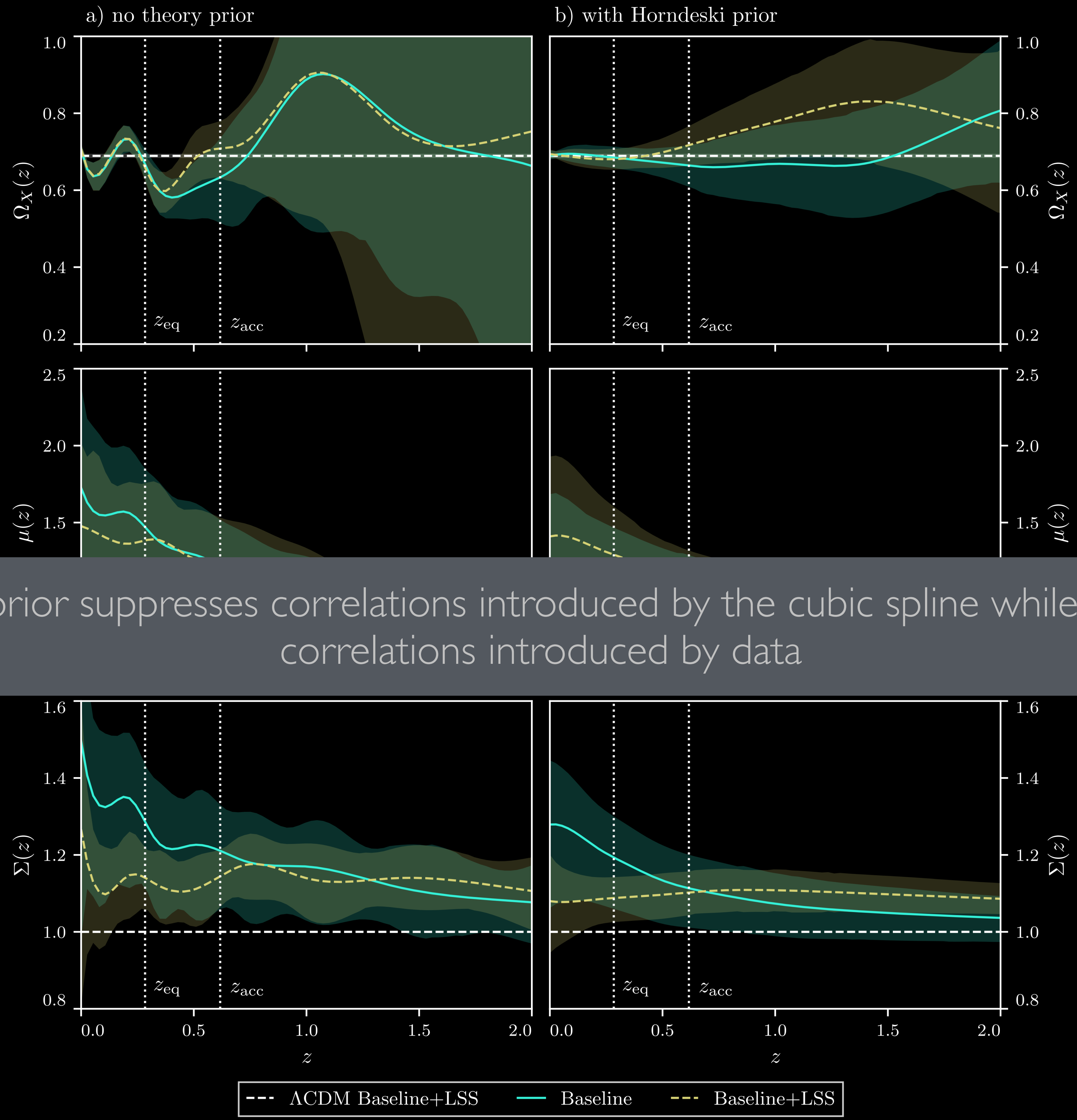


This will help with convergence of the reconstruction procedure, AND CLEAN UNPHYSICAL FEATURES

Reconstructed Gravity

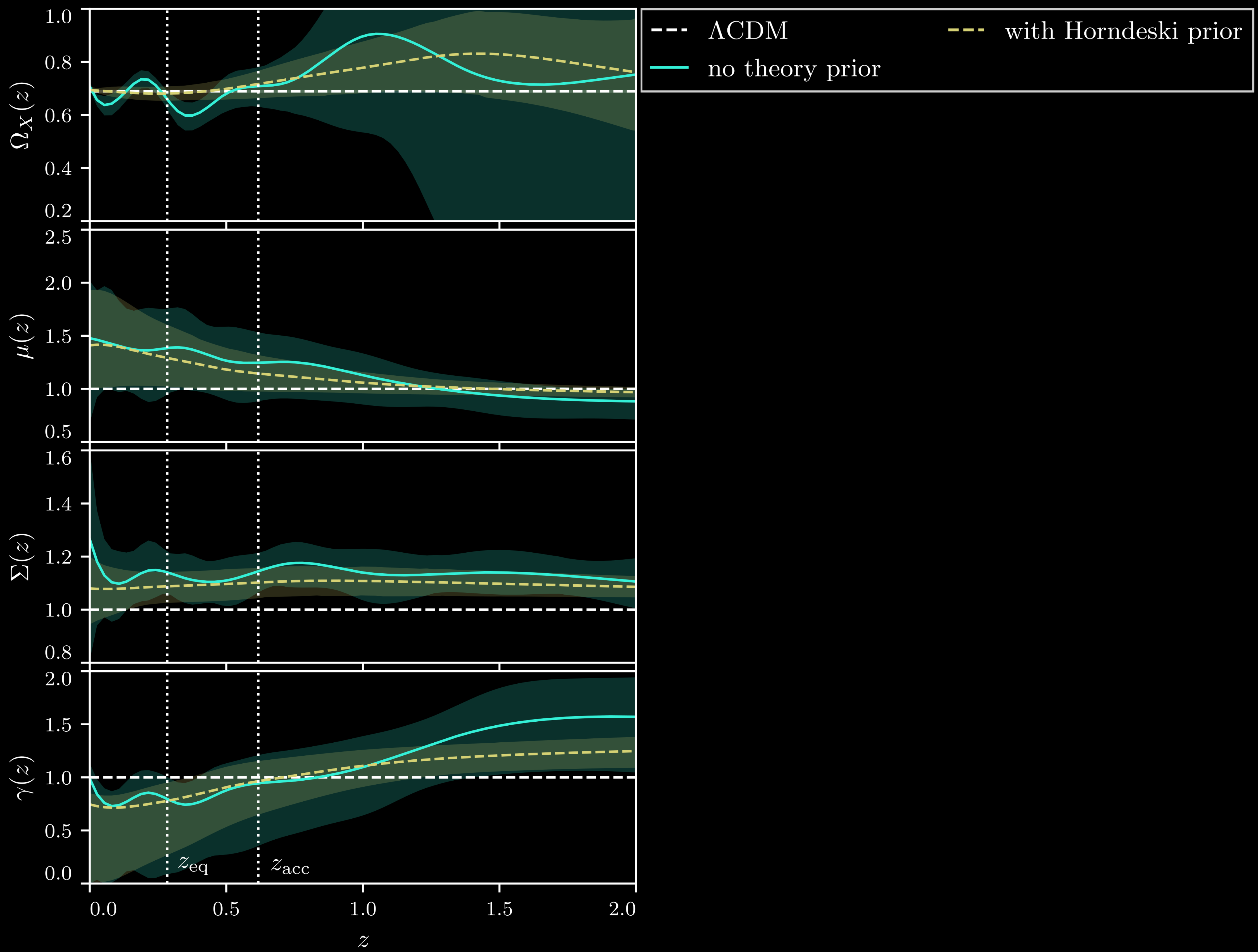


Reconstructed Gravity

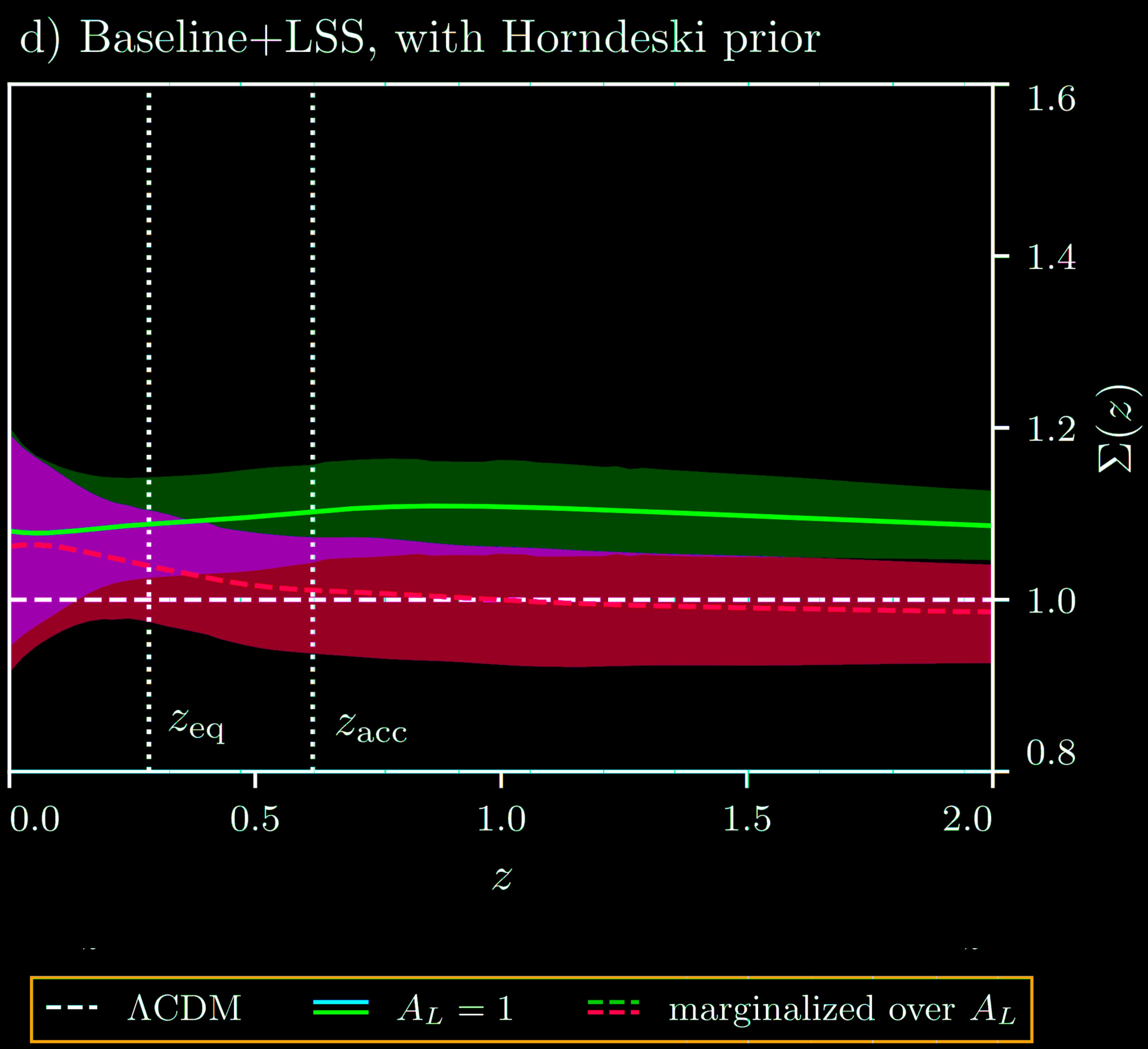


The theory prior suppresses correlations introduced by the cubic spline while retaining the correlations introduced by data

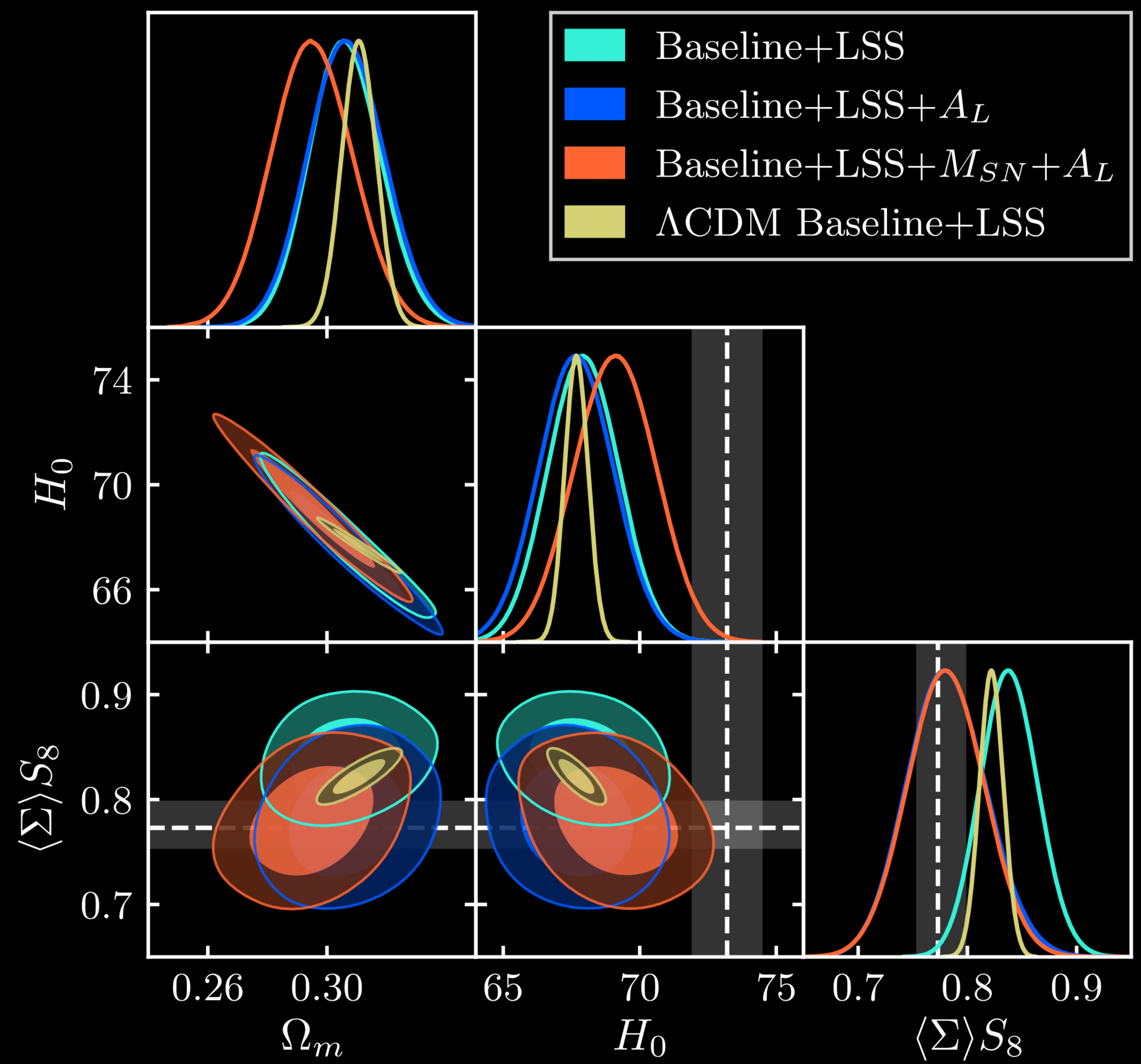
Reconstructed Gravity



A closer look at ∑

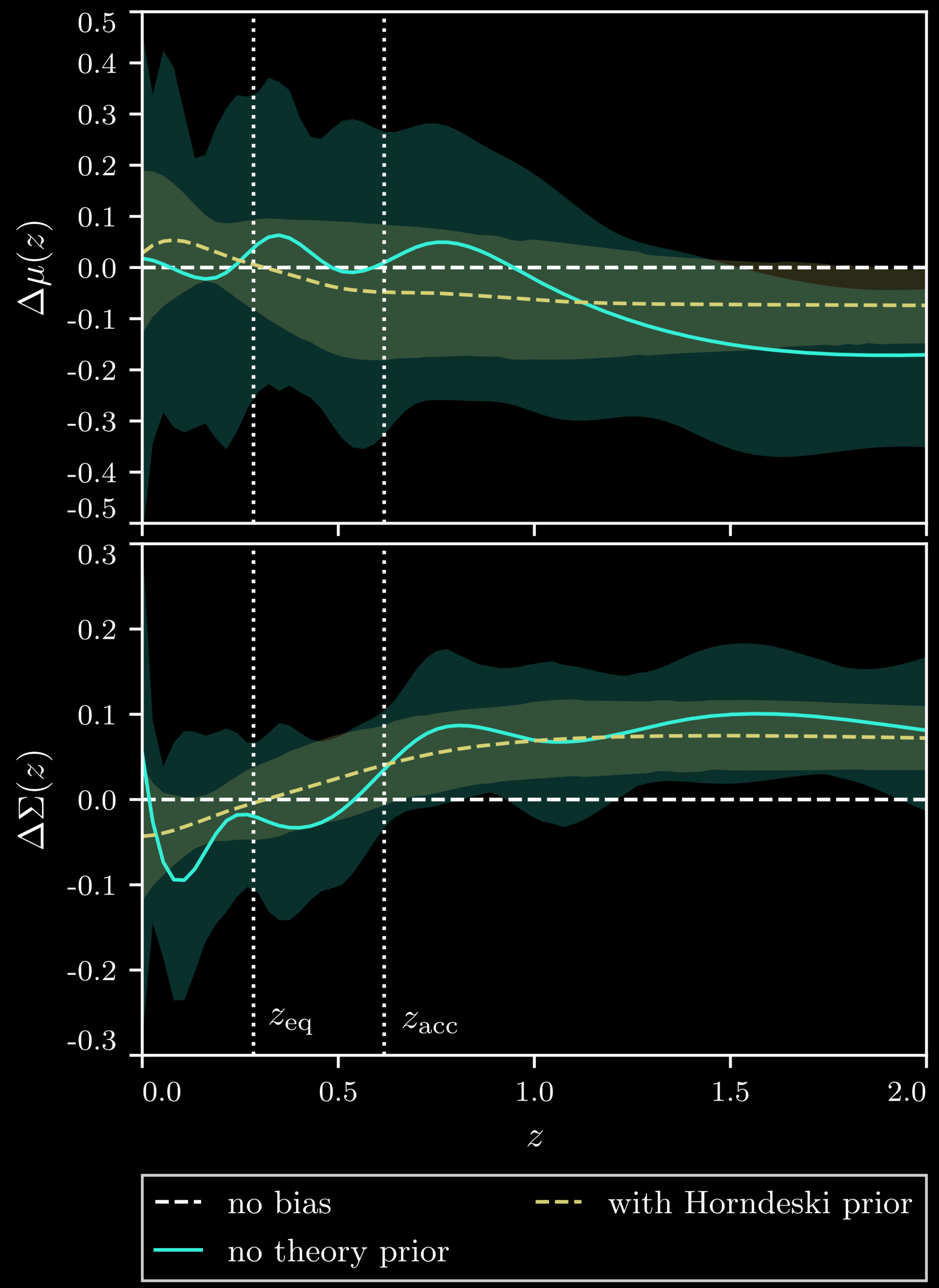


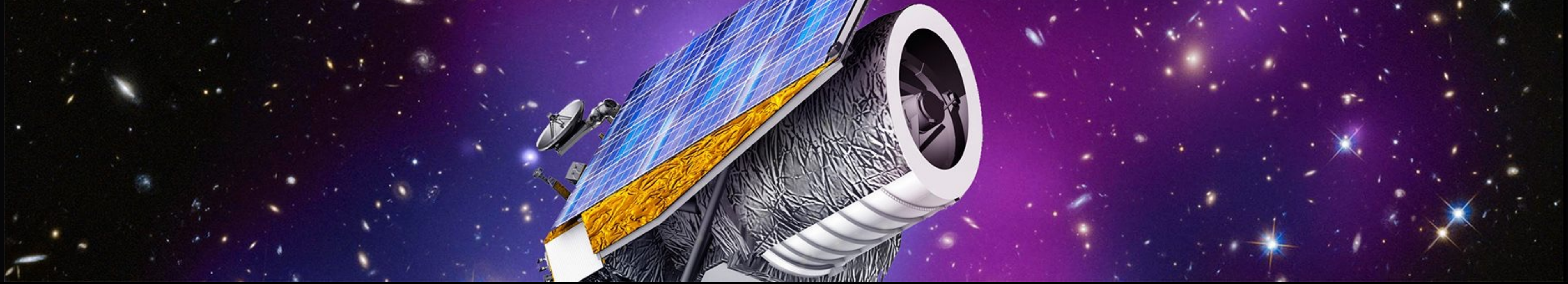
How about the tensions?



How good are common parametrizations?

$$\mu = 1 + \mu_0 \frac{\rho_{\rm DE}}{\rho_{\rm tot}(a)}$$





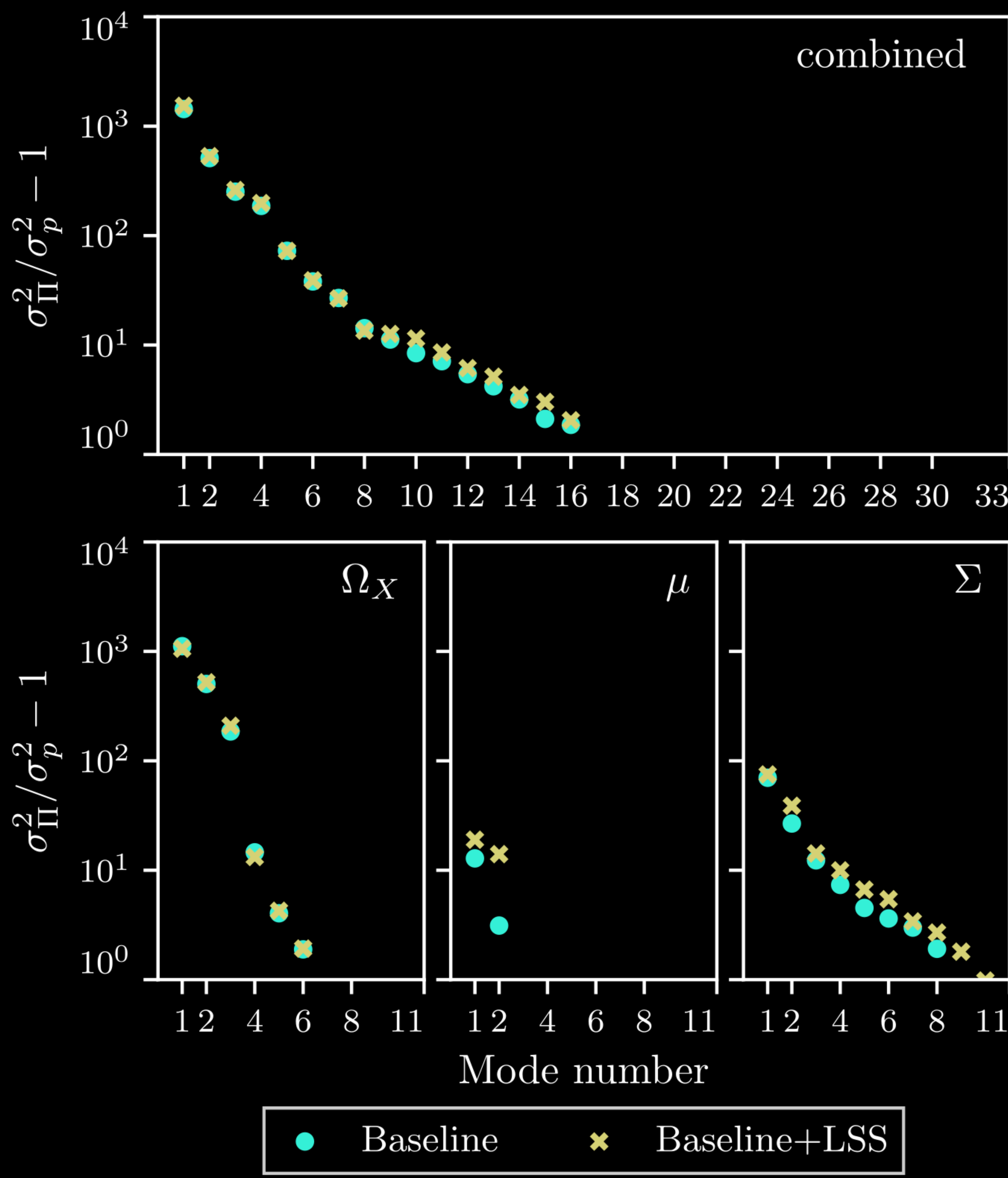
Current cosmological data can already constrain **15 combined modes of gravity** on large scales!

(Oversimplified) parametrization are prone to missing out on this.

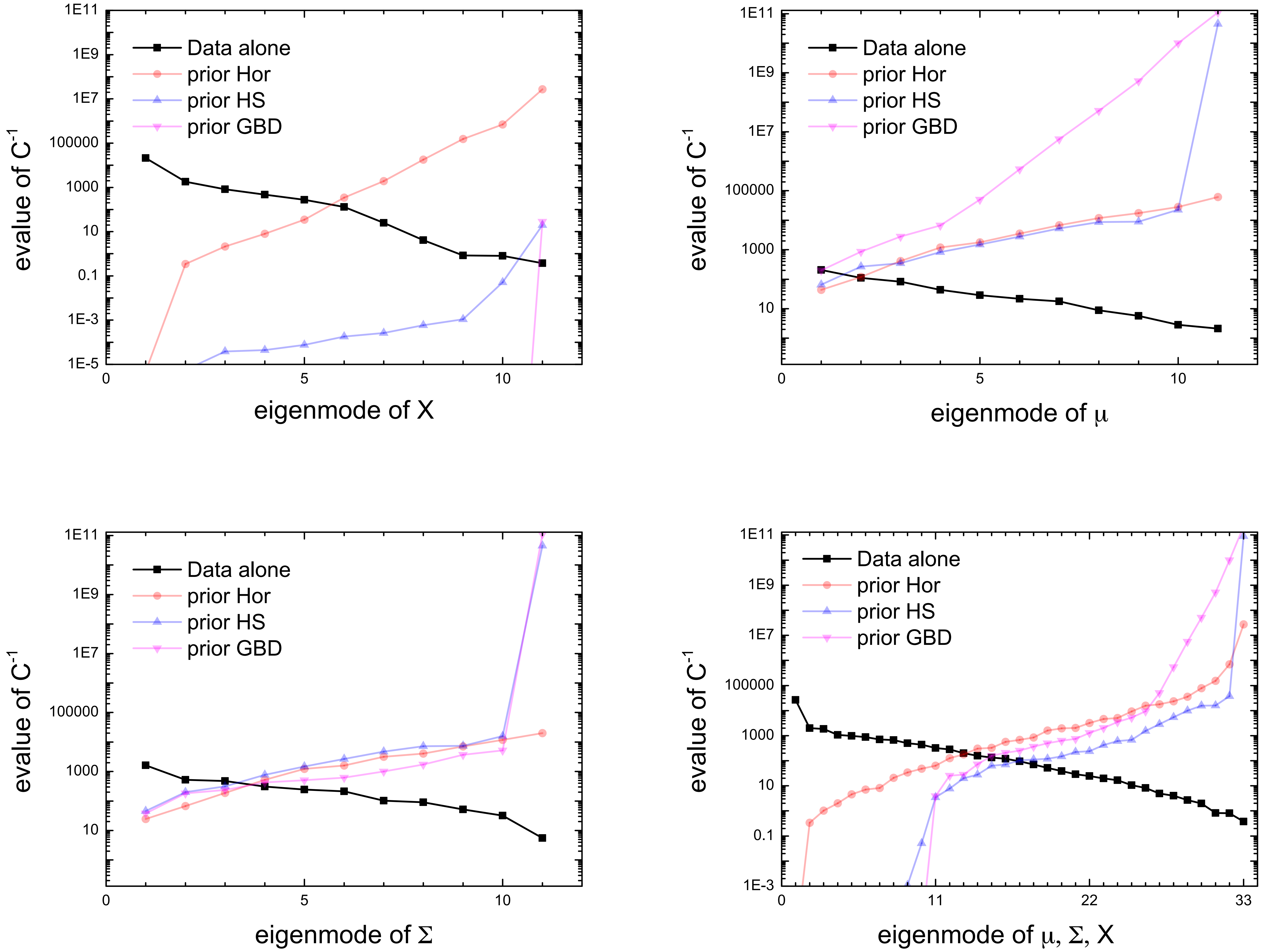
The ongoing/upcoming generation of LSS observations will see a tremendous leap in sensitivity.

Future interferometers will allow us to fold in also complementary information from tensors.

Appendix



combined
$\sigma^2_{\Pi}/\sigma^2_p - 1$
10^0
10^1
10^2
10^3
10^4
1 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 33
Ω_X
μ
Σ
1 2 4 6 8 11
Mode number
Baseline
Baseline+LSS



evalue of C^{-1}
eigenmode of X
Data alone
prior Hor
prior HS
prior GBD
1E11
1E9
1E7
100000
1000
10
0.1
1E-3
1E-5
0
5
10
evalue of C^{-1}
eigenmode of μ
Data alone
prior Hor
prior HS
prior GBD
1E11
1E9
1E7
100000
1000
10
0
5
10
evalue of C^{-1}
eigenmode of Σ
Data alone
prior Hor
prior HS
prior GBD
1E11
1E9
1E7
100000
1000
10
0
5
10
evalue of C^{-1}
eigenmode of μ, Σ, X
Data alone
prior Hor
prior HS
prior GBD
1E11
1E9
1E7
100000
1000
10
0.1
1E-3
0
11
22
33

Theoretical prior correlations