Cosmological tests of Einstein and Euler

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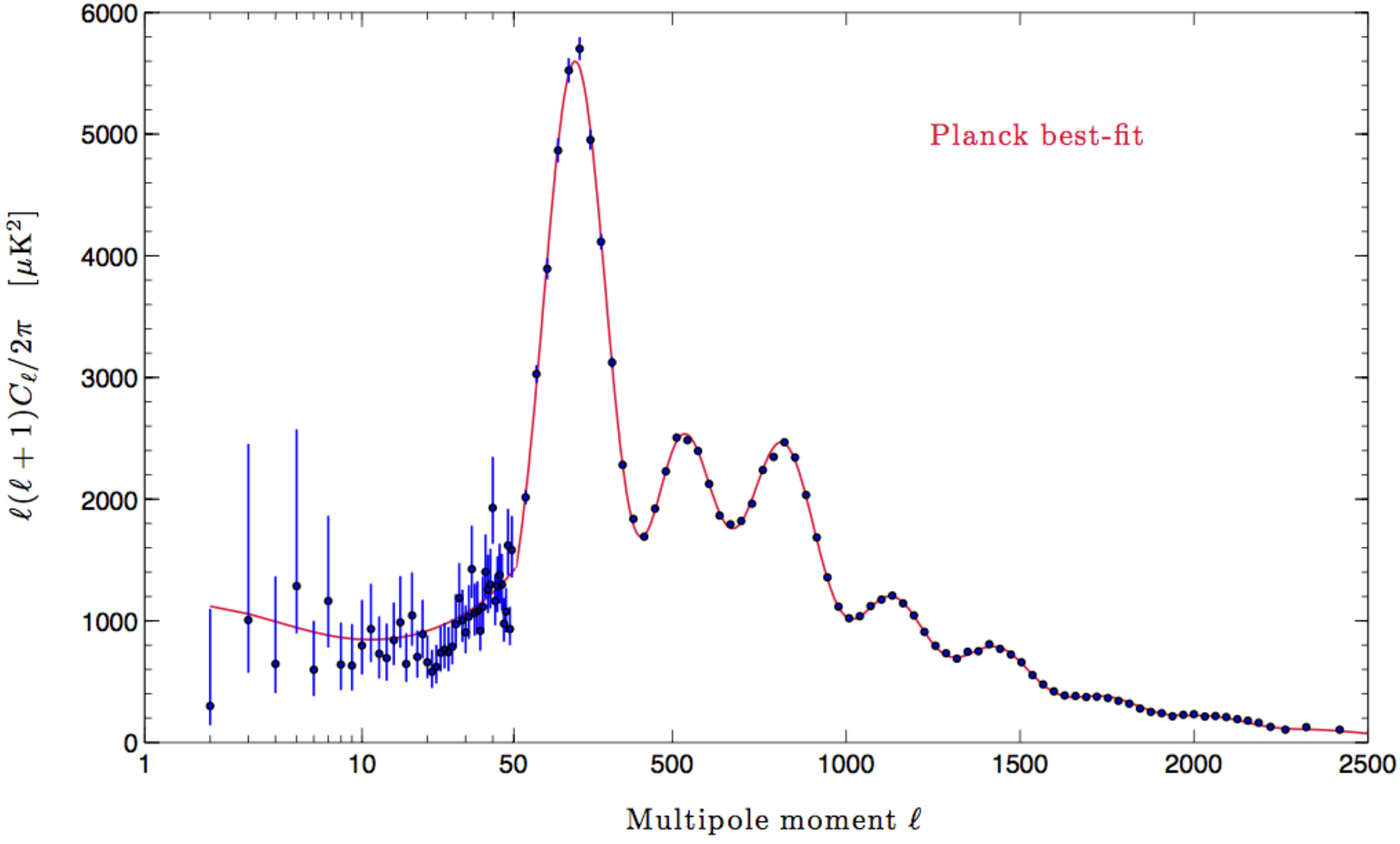
LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy
M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP
C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy

Why are we testing Einstein?

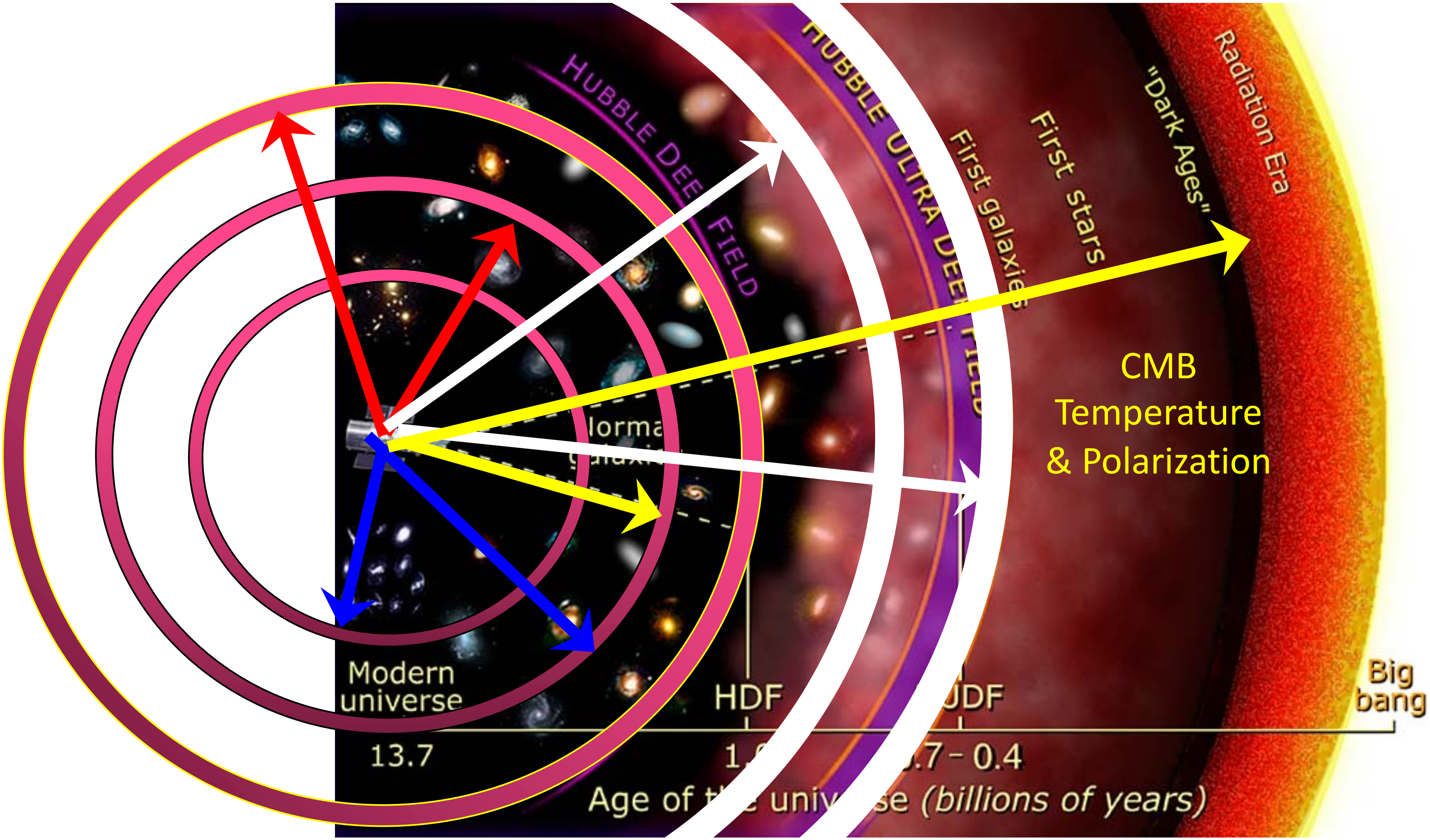


Reasons to keep an open mind about LCDM

- Lambda → (How) does the vacuum gravitate? What sets the observed value of Lambda?
- CDM
- Other good general reasons
  - GR is not well-tested on cosmological scales
  - No theory of Quantum Gravity
  - No theory of the Big Bang
- Lesser, specific problems
  - Tensions between datasets
  - Missing satellites, (non)cuspy halos, JWST high-z galaxies, …

Because we can: tomography with DESI, Euclid, LSST, SKA,…

Weak gravitational lensing of galaxies



21 cm

Galaxy counts, redshifts

25 years of Dark Energy

- The field of dark energy and modified gravity matured over the past two decades
- Discussions evolved from specific models (quintessence, f(R), DGP,…) to general classes of theories, such as Horndeski and effective field theory approaches
- Frameworks and numerical tools developed for testing gravity using data from galaxy surveys (MGCAMB, EFTCAMB, HiCLASS, …)
- Extensive N-body simulations of structure formation in scalar-tensor theories with different types of screening

No compelling alternative to LCDM so far

What's next?

What can we learn about gravity from DESI, Euclid, Rubin and SKA that we could not with SDSS, KiDS and DES?

- Can simultaneously measure <u>many</u> more parameters
  - from constraining *ad hoc* models, such as (w_0, w_a) and Ω^γ to Bayesian reconstruction of functions

- Opportunity to get less model-dependent answers to general questions:
  - Is the expansion history consistent with ΛCDM?
  - Is the dynamics of structure formation consistent with GR?
  - Is there evidence of new interactions?
  - What alternative gravity theories are allowed?
  - Is there evidence of screened modified gravity?

Testing the expansion history: the (effective) Dark Energy

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left\{ \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm M}}{a^3} + \frac{\rho_{\rm DE}(a)}{\rho_c} \right\}$$

Is working with $w_{\rm eff}$ justified when testing gravity?

$$\boxed{w_{\rm DE}^{\rm eff} = p_{\rm DE}^{\rm eff}/\rho_{\rm DE}^{\rm eff}}$$

$$\dot{\rho}_{\rm DE}^{\rm eff} + 3H(\rho_{\rm DE}^{\rm eff} + p_{\rm DE}^{\rm eff}) = 0 \quad \overset{?}{\Longrightarrow} \quad \rho_{\rm DE}(a) = \rho_0 \exp\left[\int_a^1 3(1+w(a'))\frac{da'}{a'}\right]$$

Working with $w_{\rm eff}$ assumes that the effective density doesn't change sign, but it can in modified gravity

Modified gravity: a scalar-tensor theory

$$S = \int d^4x\sqrt{-g}\Big[\frac{F(\phi)R}{16\pi G} - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \mathcal{L}_M\Big]$$

$$\begin{aligned} G_{\mu\nu} &= 8\pi G F^{-1}\left\{T^M_{\mu\nu} + T^\phi_{\mu\nu} + \nabla_\mu\nabla_\nu F - g_{\mu\nu}\Box F\right\} \\ &= 8\pi G\left\{T^M_{\mu\nu} + (T^{\rm eff}_{\rm DE})_{\mu\nu}\right\}\ , \end{aligned}$$

Effective dark energy density:

$$\rho^{\rm eff}_{\rm DE} = F^{-1}\left\{\frac{1}{2}\dot\phi^2 + V(\phi) - 3H\dot F + (1-F)\rho_M\right\}$$

Effective dark energy equation of state:

$$w^{\rm eff}_{\rm DE} = \frac{\dot\phi^2/2 - V(\phi) + 2H\dot F + \ddot F}{\dot\phi^2/2 + V(\phi) - 3H\dot F + (1-F)\rho_M}$$

Testing the expansion history: the (effective) Dark Energy

Is working with w_{eff} justified when testing gravity?

$$w_{\rm DE}^{\rm eff} = p_{\rm DE}^{\rm eff}/\rho_{\rm DE}^{\rm eff}$$

$$\dot{\rho}_{\rm DE}^{\rm eff} + 3H(\rho_{\rm DE}^{\rm eff} + p_{\rm DE}^{\rm eff}) = 0 \overset{?}{\Longrightarrow} \rho_{\rm DE}(a) = \rho_0 \exp\left[\int_a^1 3(1+w(a'))\frac{da'}{a'}\right]$$

Parametrizing the effective dark energy evolution in terms of w_{eff} can bias the studies of modified gravity. It's safer to work directly with $\boldsymbol{\rho}_{eff}$:

$$\frac{H^2}{H_0^2} = \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm M}}{a^3} + \Omega_{\rm DE}X(a)$$

Phenomenology of modified gravity (scalar-tensor theories)

"Spacetime tells matter how to move; matter tells spacetime how to curve."

John A. Wheeler (1911-2008)

In GR, relativistic and non-relativistic matter follow the same geodesics

Modified gravity: photons and matter respond to different spacetimes

Non-relativistic matter

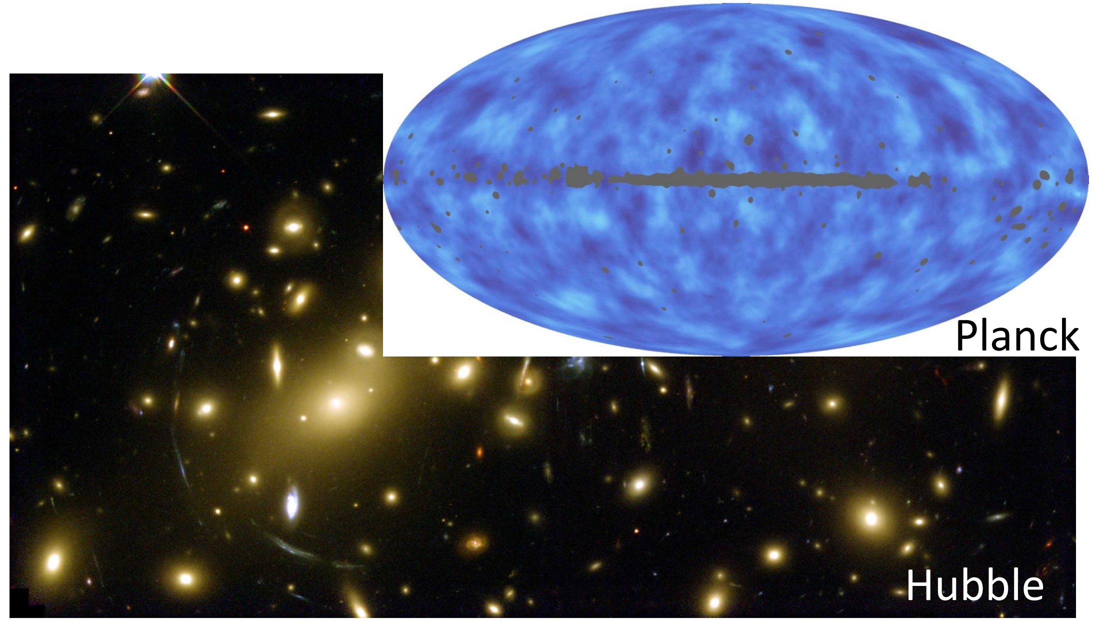
- sources the curvature perturbation $\boldsymbol{\Phi}$
- responds to the Newtonian potential $\boldsymbol{\Psi}$
- $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$ are NOT the same in scalar-tensor theories
- feels a "fifth force" mediated by the scalar field

Photons

- respond to $(\boldsymbol{\Phi}+\boldsymbol{\Psi})/2$
- do not feel a "fifth force"

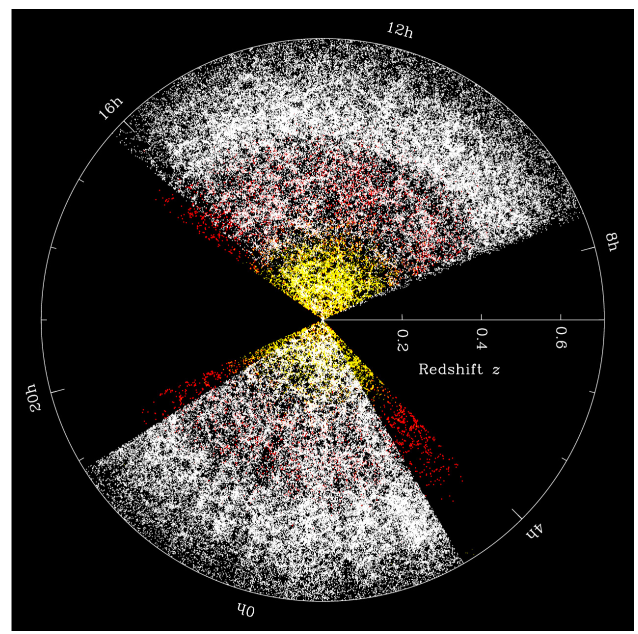
Weak Gravitational Lensing

$$\text{Distortion} \propto \int dz\ \partial_{\perp}(\Phi + \Psi)$$



Redshift space distortions due to peculiar motion

$$V' + V = \frac{k}{aH}\Psi$$



Cosmological phenomenology of modified gravity as implemented in MGCAMB

https://github.com/sfu-cosmo/MGCAMB

Modified Einstein's equations:

($\boldsymbol{\mu}$ = $\boldsymbol{\Sigma}$ = $\boldsymbol{\gamma}$ = 1 in LCDM)

$$\begin{aligned} -k^2\Psi &= 4\pi\, \mu(a,k)G\, a^2\delta\rho \quad \text{“}G_{matter}\text{”} \\ \Phi &= \gamma(a,k)\,\Psi \\ -k^2\left(\frac{\Phi+\Psi}{2}\right) &= 4\pi\, \Sigma(a,k)G\, a^2\delta\rho \quad \text{“}G_{light}\text{”} \end{aligned}$$

A smoking gun of new gravitational physics:

$$\boxed{G_{matter} \neq G_{light} \quad \text{or} \quad \Phi \neq \Psi}$$

Effective dark energy density:

($X(a)$ = 1 in LCDM)

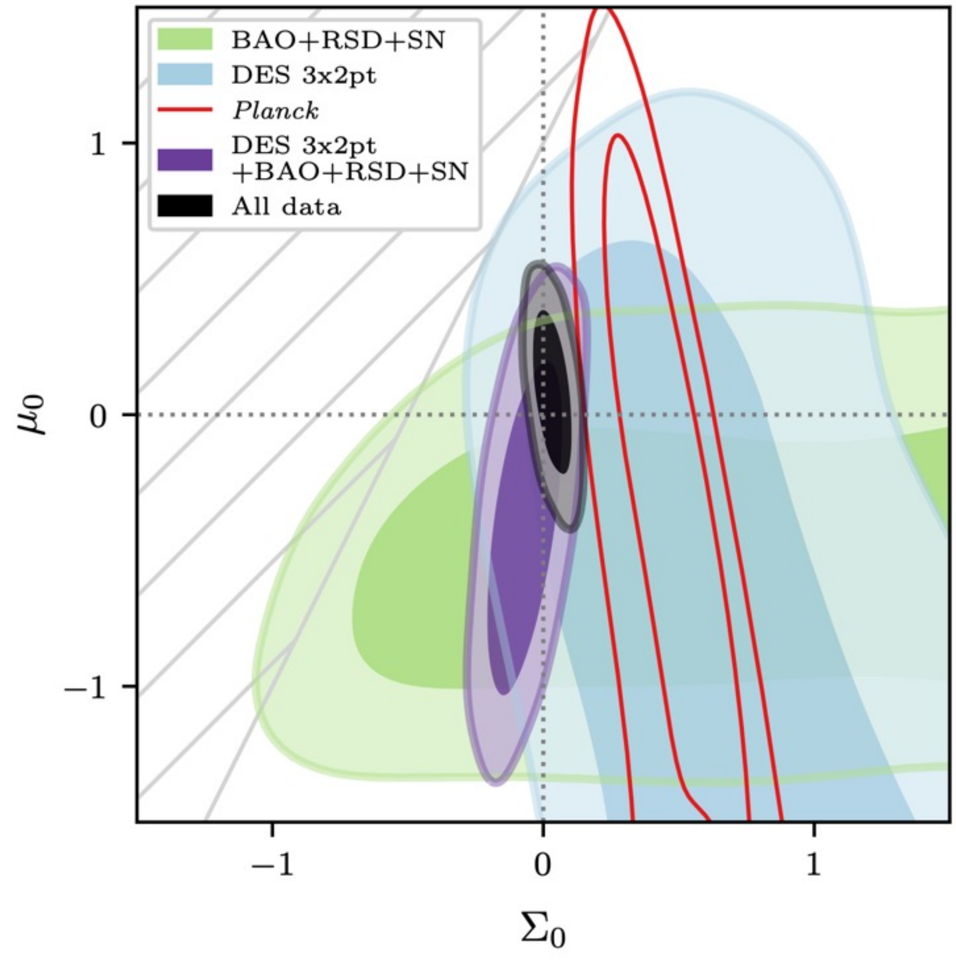
$$\frac{H^2}{H_0^2} = \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm M}}{a^3} + \Omega_{\rm DE}X(a)$$

Dark Energy Survey Year 3 Constraints on $\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$

$$\mu = 1 + \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}\ , \quad \Sigma = 1 + \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$

Assumed LCDM expansion history (w = -1)

Used MGCAMB



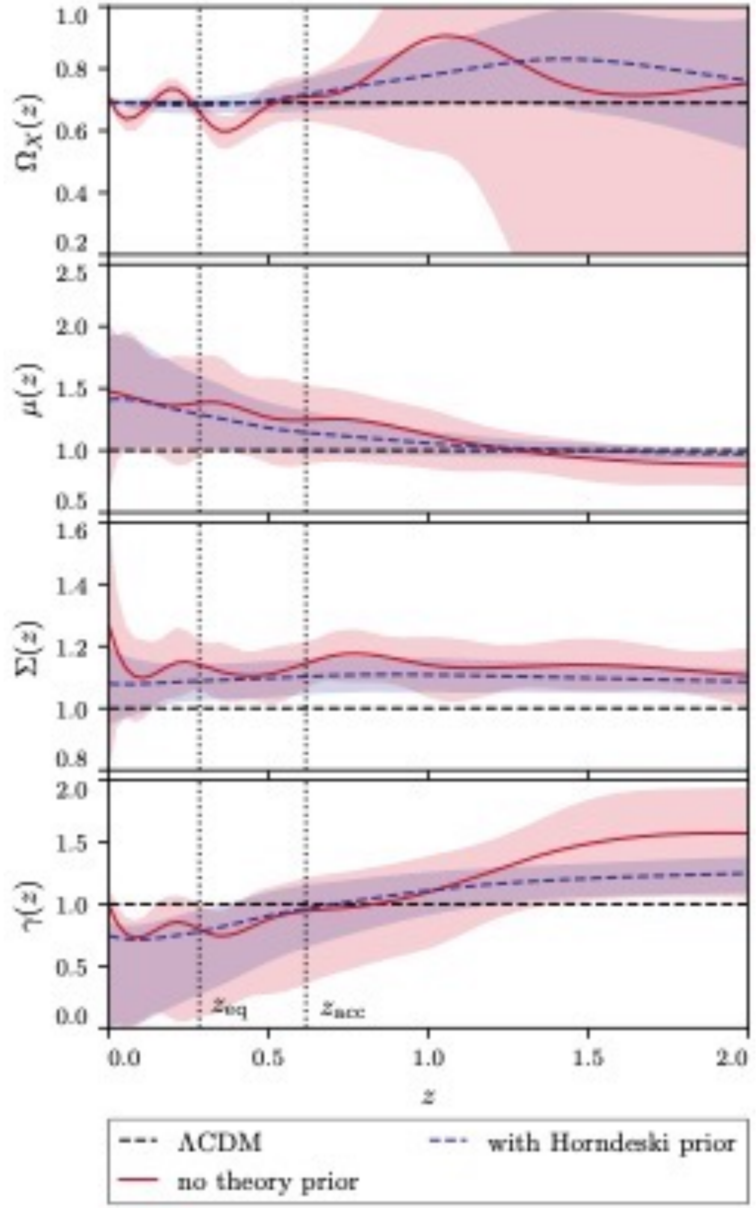
Dark Energy Survey Year 3 Results: Constraints on extensions to ΛCDM with weak lensing and galaxy clustering, arXiv:2207.05766

What can X(a), μ(a,k) and Σ(a,k) tell us about Gravity?

- *Ad hoc* parameterizations provide only a crude consistency test of LCDM
- Treating Σ and μ as completely independent is unphysical and opens the possibility of false detections (e.g. caused by systematics)
- In any specific gravity theory, functions X(a), μ(a,k) and Σ(a,k) are derived from the same Lagrangian and are not independent
- Our approach: simultaneously reconstruct all three functions from the data with and without a prior covariance derived from general scalar-tensor theories

Reconstructing gravity from Planck+DES+RSD+BAO+SN

- First simultaneous reconstruction of $\mu(a)$, $\Sigma(a)$ and $\Omega_X(a)$
- With and without a Horndeski prior: a way to separate features consistent with theory from potential systematics
- Current data can constrain 15 eigenmodes relative to the prior
- Late-time modified gravity is unlikely to resolve the tensions
- Implications for scalar-tensor theories

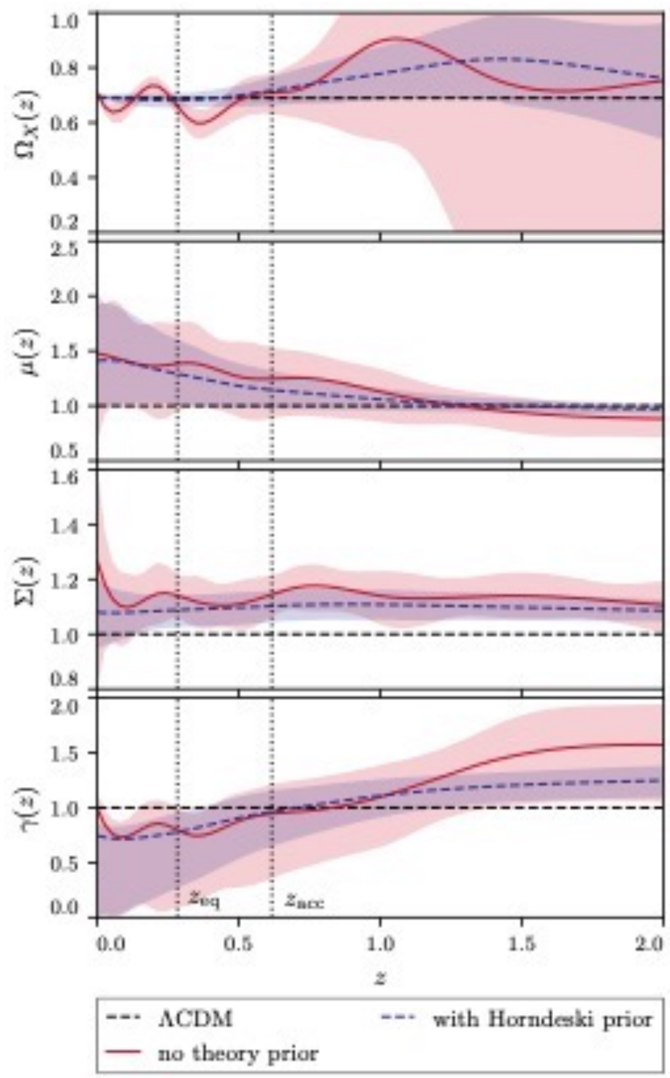


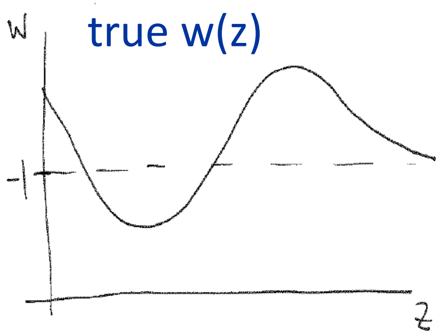
Imprints of cosmological tensions in reconstructed gravity, LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

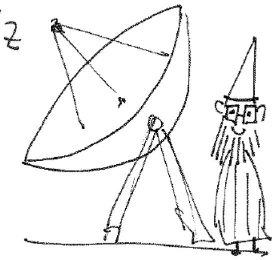
Principal reconstructed modes of dark energy and gravity, M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP

A lot to unpack…

- The correlated prior method
- The Horndeski prior
- The imprint of tensions
- Implications for theory



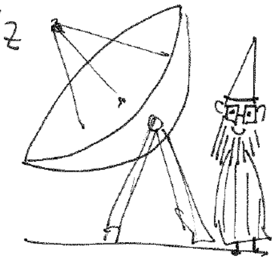




MCMC fit
using many w-bins

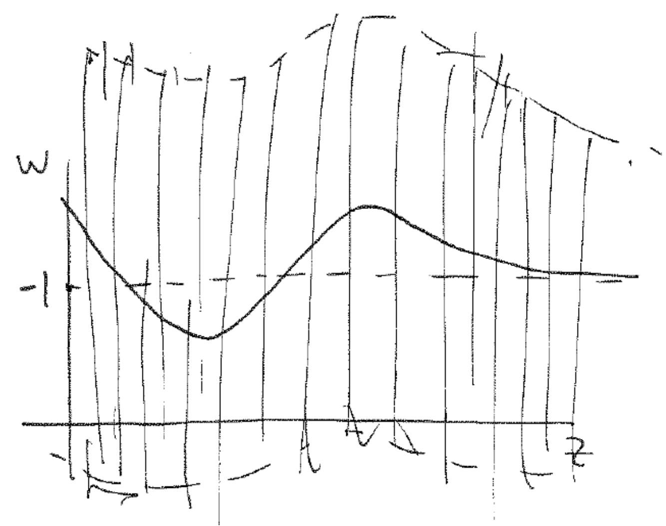
no prior

true w(z)

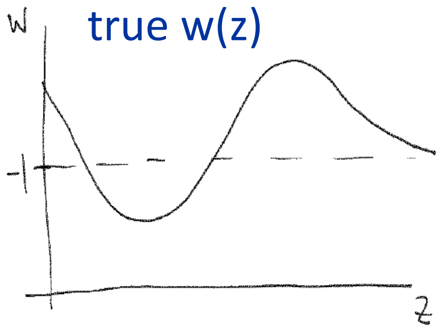


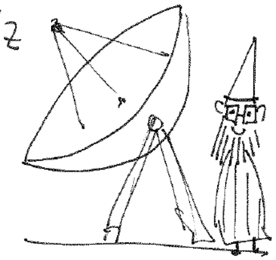
MCMC fit
using many w-bins

reconstructed w(z)



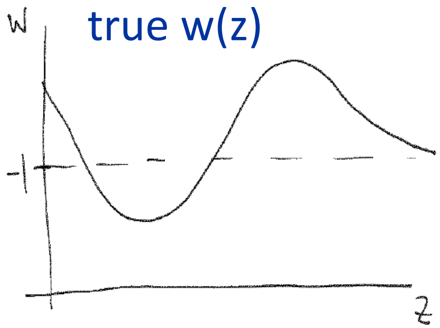
- large variance
- zero bias

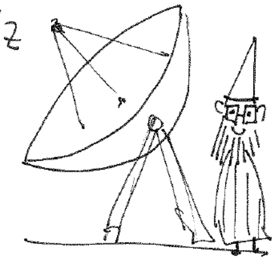




$$\chi^2_{\rm prior} = -2\ln\mathcal{P}_{\rm prior} = (\mathbf{w}-\mathbf{w}^{\rm fid})^T\mathbf{C}^{-1}(\mathbf{w}-\mathbf{w}^{\rm fid})$$

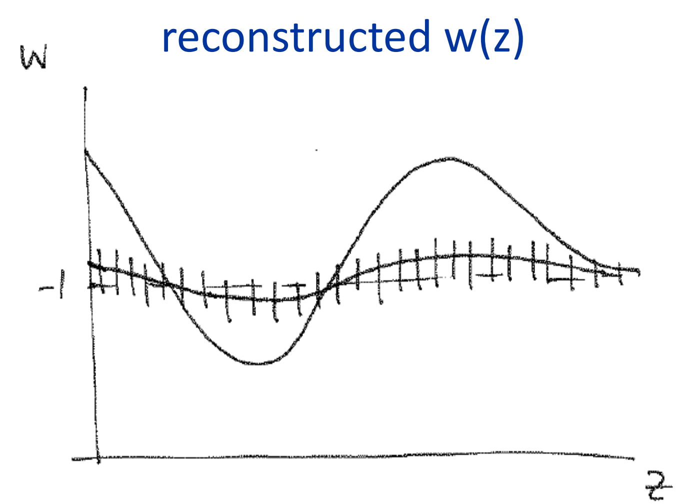
MCMC fit
using many w-bins





Excessively strong prior

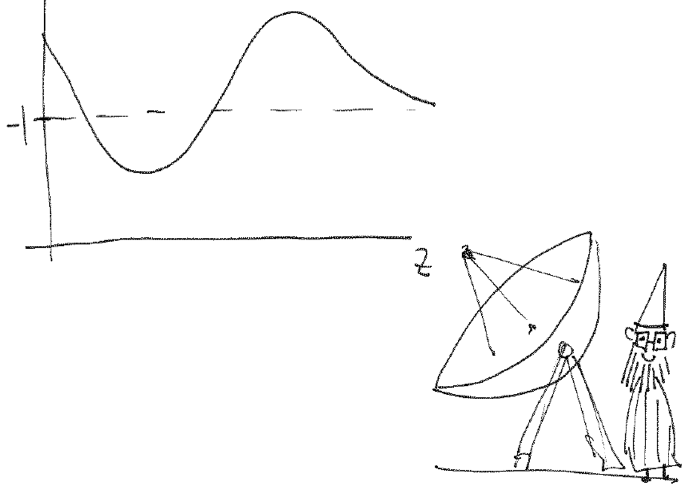
MCMC fit
using many w-bins



○ tiny error bars (small variance)

○ large bias

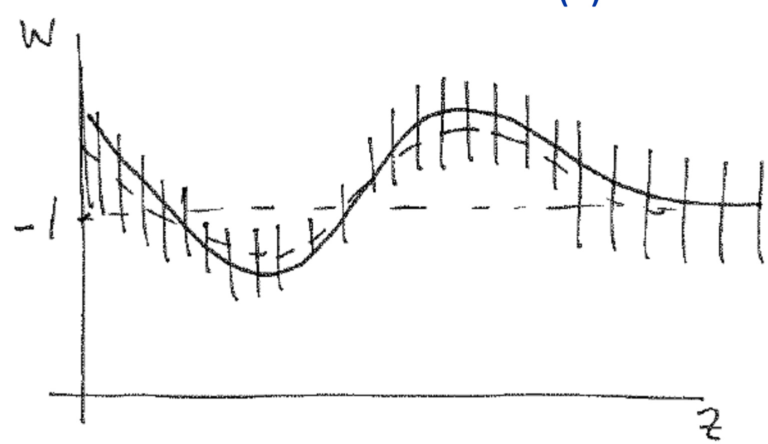
true w(z)



“optimal” prior?

MCMC fit
using many w-bins

reconstructed w(z)



○ moderate variance

○ insignificant bias, i.e. the bias
is smaller than the variance

What is a reasonable prior?

In the Bayesian approach, priors should be Informed by theory, e.g. scalar fields

M. Raveri, P. Bull, A. Silvestri, LP, arXiv:1703.05297, PRD
J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121

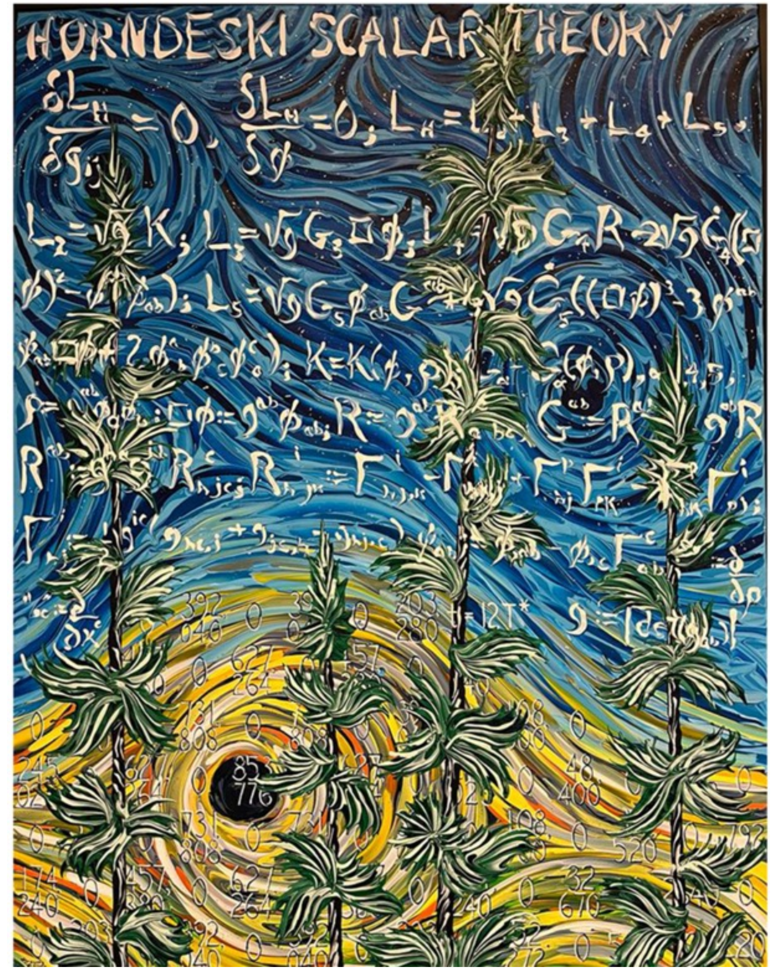
Advantages of the correlated prior approach

- Smooth features (well constrained by the data) not biased by the prior
- Noisy features (poorly constrained by the data) determined by the prior
- Clear Bayesian interpretation of the results, e.g. how many eigenmodes one gained by adding data to the prior

Fables of Reconstruction, Crittenden, Zhao, LP, Samushia, Zhang, 1112.1693, JCAP'12

General Scalar-Tensor Theories

G. W. Horndeski, Int. J. Theor. Phys (1974)
C. Deffayet, X. Gao, D. A. Steer, and G. Zahariade, PRD (2011)



The Horndeski Lagrangian

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \mathcal{L}_i + \mathcal{L}_{\mathrm{m}}[g_{\mu\nu}] \right]$$

$$\mathcal{L}_2 = K(\phi,\, X)\,, \qquad X = -\phi^{;\mu}\phi_{;\mu}/2$$

$$\mathcal{L}_3 = -G_3(\phi,\, X)\Box\phi\,,$$

$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right],$$

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

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https://doi.org/10.1007/s10773-024-05558-2

REVIEW

50 Years of Horndeski Gravity: Past, Present and Future

Gregory W. Horndeski[1] · Alessandra Silvestri[2]

Received: 15 January 2024 / Accepted: 16 January 2024

Abstract
An essay on Horndeski gravity, how it was formulated in the early 1970s and how it was 're-discovered' and widely adopted by Cosmologists more than thirty years later.

Keywords Scalar-tensor field theories · Horndeski gravity · Lagrangians · Modified gravity · Dark energy

50 Years of Horndeski Gravity, Waterloo, Canada, July 15-19, 2024

Generating priors using the “EFT” of Horndeski

$$S = \int \mathrm{d}^4x \sqrt{-g} \left\{ \frac{m_0^2}{2}\Omega(t)R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2}\left(\delta K^i{}_i{}^2 - \delta K^i{}_j \delta K^j{}_i + 2\delta g^{00}\delta R^{(3)}\right) \right\} + S_{matter}[g_{\mu\nu}]$$

Gubitosi et al 1210.0201; Bloomeld et al 1211.7054, 1304.6712; EFTCAMB (Hu et al) 1312.5742

Generating priors using the "EFT" of Horndeski

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2} \Omega(t) R + \Lambda(t) - c(t) \delta g^{00} + \frac{M_2^4(t)}{2} (\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2} \delta g^{00} \delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2} \left(\delta K^i{}_i{}^2 - \delta K^i{}_j \delta K^j{}_i + 2 \delta g^{00} \delta R^{(3)} \right) \right\} + S_{matter}[g_{\mu\nu}]$$

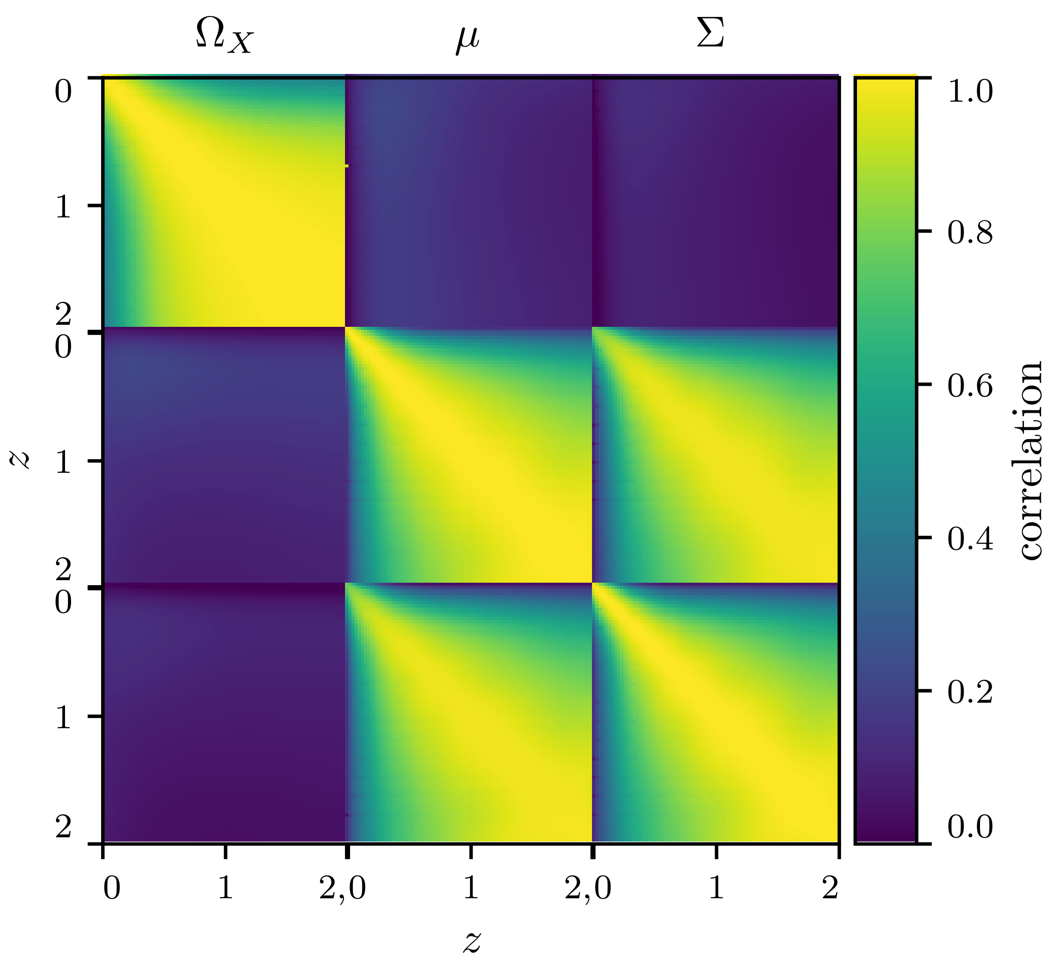
Gubitosi et al 1210.0201; Bloomeld et al 1211.7054, 1304.6712; EFTCAMB (Hu et al) 1312.5742

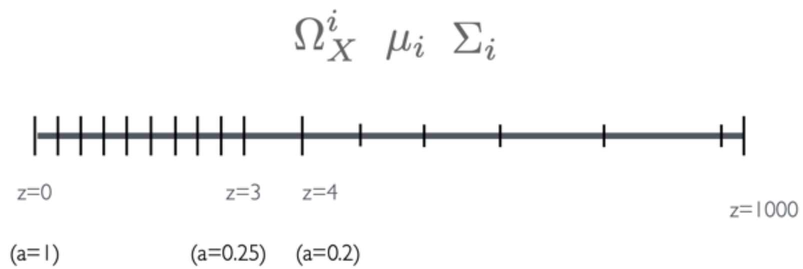
- Generate an ensemble of EFT functions
  - Parameterize the EFT functions as Pade polynomials (9th order)
  - Sample the coefficients, filter out unphysical solutions
- Filter out models with
  - unacceptable background expansion histories
  - unacceptable gravitational wave speed
  - unacceptable variations of the Newton's constant

J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121, PRD

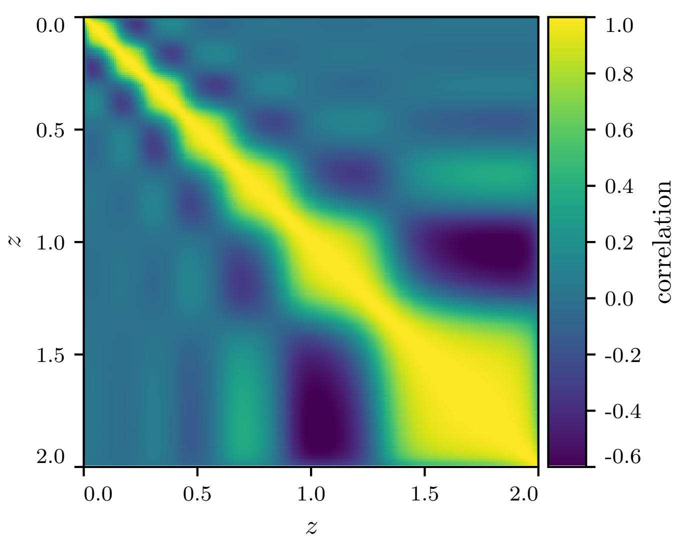
The Horndeski correlation prior on $\Omega_X(a)$, $\mu(a)$ and $\Sigma(a)$

$\Omega_X(z) = \Omega_{DE}\, X(z)$



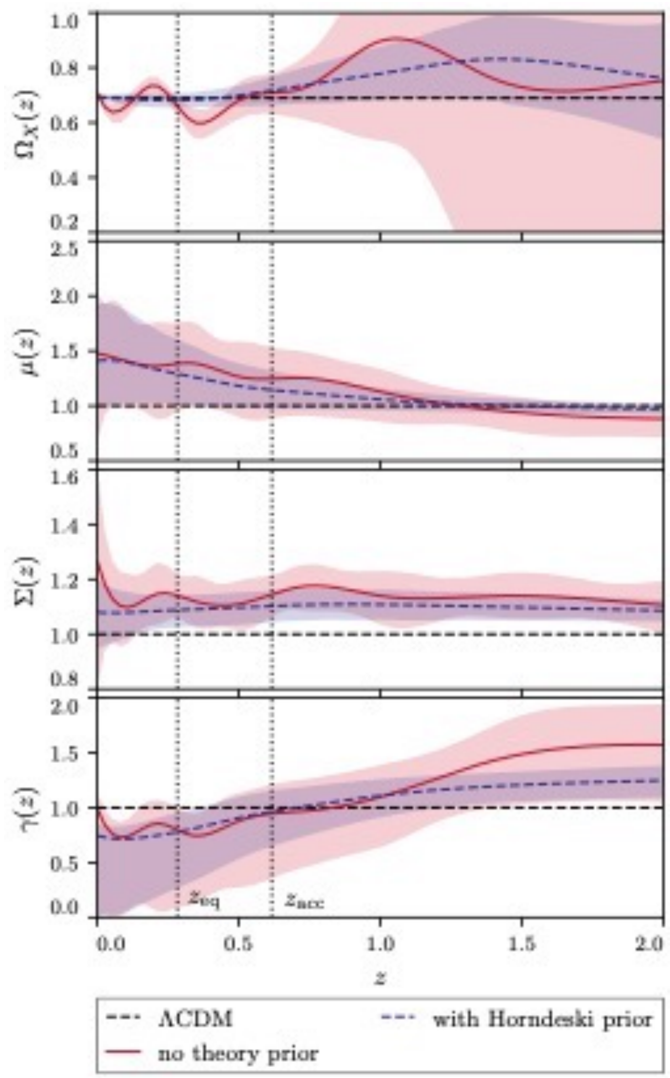


The implicit correlation Introduced by cubic spline



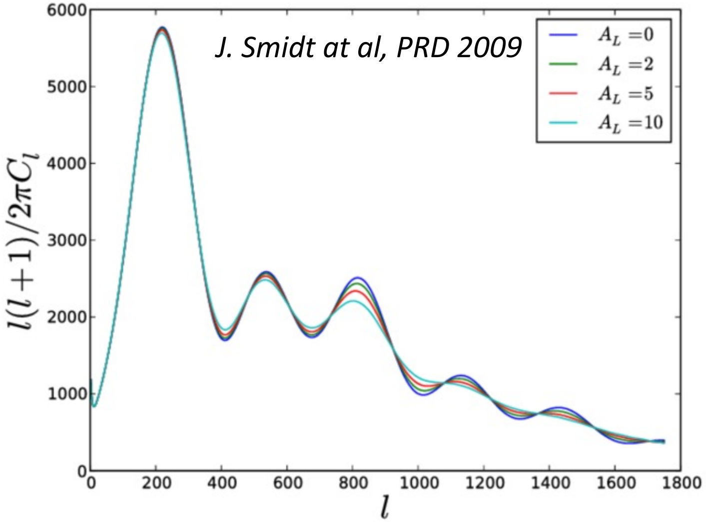
A lot to unpack...

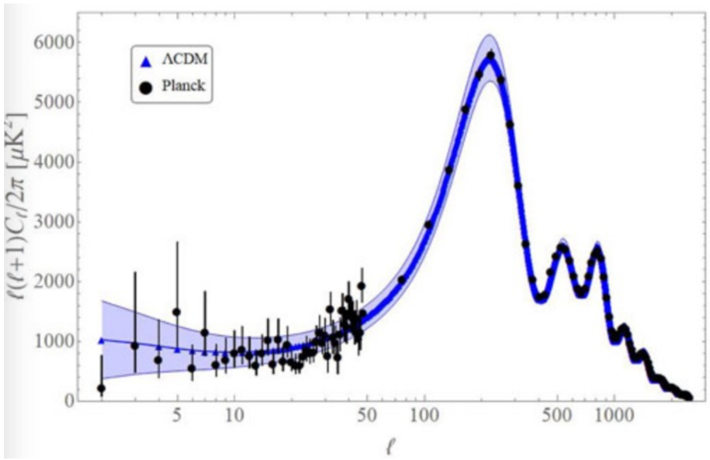
- The correlated prior method
- The Horndeski prior
- The imprint of tensions
- Implications for theory



A quick refresher of relevant tensions

- A_L - the weak lensing effect on the acoustic peaks in the CMB temperature anisotropy spectrum (TT) appears to be stronger than predicted (yet the reconstructed CMB lensing agrees with the model)
- S_8 – large scale structure surveys see matter more clustered than predicted by the CMB best fit model
- Low-ell CMB TT - the observed CMB temperature anisotropy correlation on large angular scales is below the prediction
- H_0 – the value inferred from CMB does not agree with the value obtained from Cepheid-calibrated supernovae





Agullo, Kranas1, Sreenath, Front. Astron. Space Sci., 2021

Reconstruction results: $\Omega_X(z)$, $\mu(z)$ and $\Sigma(z)$

$$-k^2\Psi = 4\pi\ \mu(a,k)G\ a^2\delta\rho$$
$$\Phi = \gamma(a,k)\ \Psi$$
$$-k^2\left(\frac{\Phi+\Psi}{2}\right) = 4\pi\ \Sigma(a,k)G\ a^2\delta\rho$$

(!) Current data can constrain 15 eigenmodes relative to the Horndeski prior

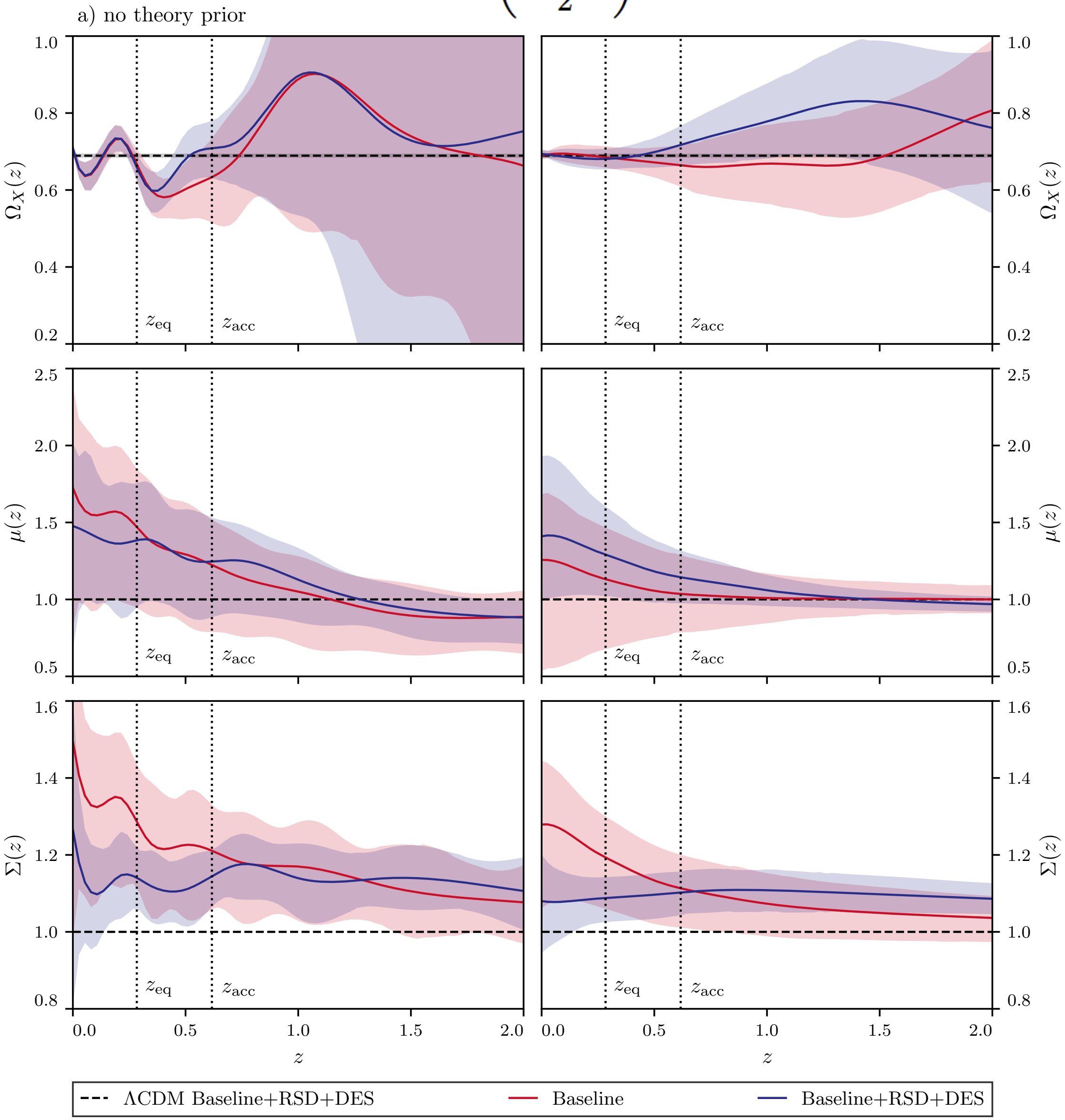
Wiggles in $\Omega_X(z)$ are driven by BAO and SN, but disappear when the Horndeski prior is applied

$\Sigma(z) > 1$ for two reasons:

- at lower z, to compensate for the deficit at low-ell CMB TT;
- at higher z, to alleviate the CMB TT lensing anomaly (A_L)

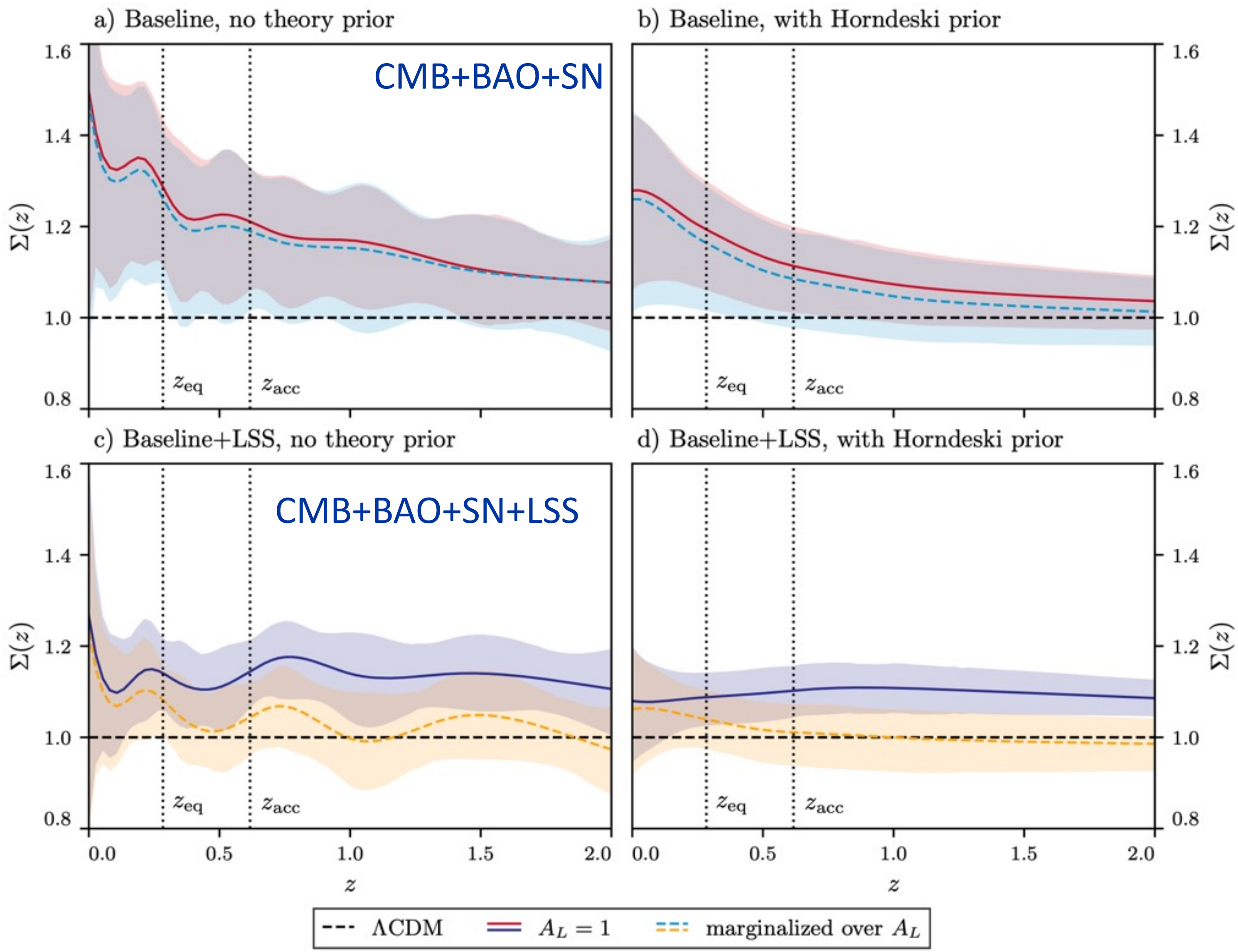
$\mu(z) > 1$ at lower z due to the correlation with $\Sigma(z)$

minor preference for $\mu(z) < 1$ at higher z, driven by S_8, which disappears after Horndeski prior



LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

Reconstruction results: $\Sigma(z)$ with and without A_L



LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

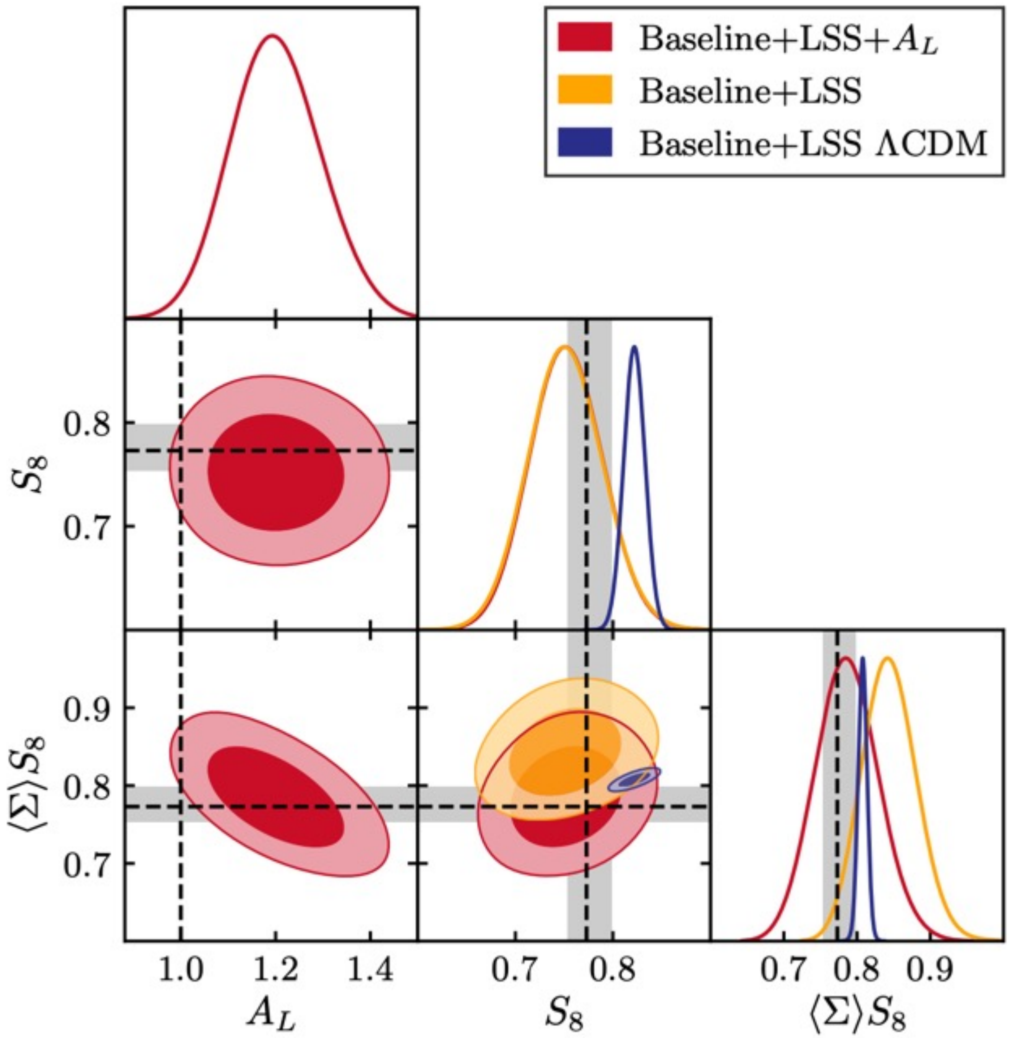
Implications for the S_8 tension

$$
\begin{aligned}
-k^2\Psi &= 4\pi\ \mu(a,k)G\ a^2\delta\rho \\
\Phi &= \gamma(a,k)\ \Psi \\
-k^2\left(\frac{\Phi+\Psi}{2}\right) &= 4\pi\ \Sigma(a,k)G\ a^2\delta\rho
\end{aligned}
$$

Weak lensing constrains $\langle\boldsymbol{\Sigma}\rangle$ S_8

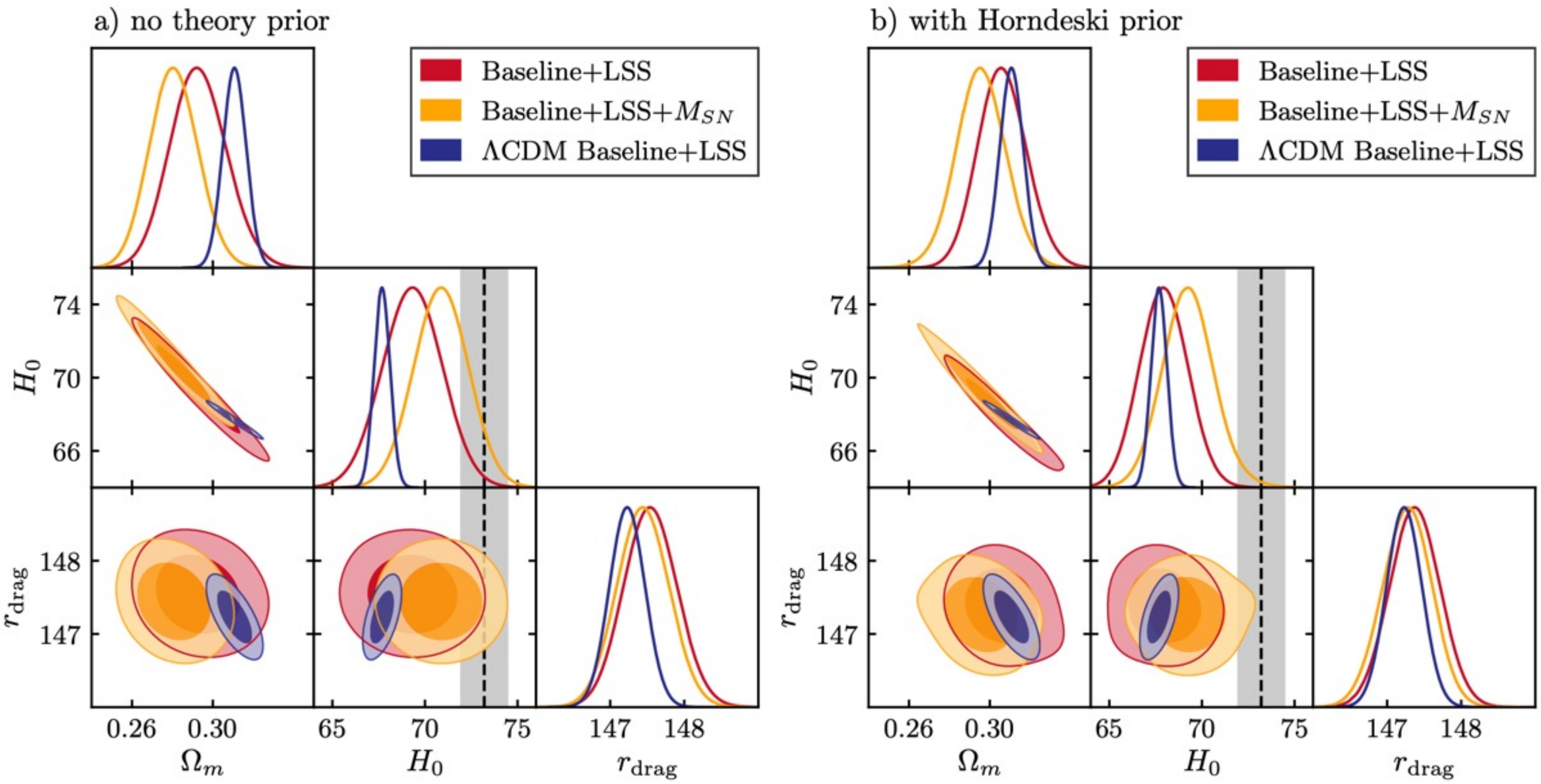
Allowing for a non-zero $\boldsymbol{\Sigma}$ reconciles the Planck and DES estimates of S_8, <u>but</u> the tension in $\langle\boldsymbol{\Sigma}\rangle$ S_8 remains

The tension goes away if A_L is added as a parameter, i.e. if the CMB lensing anomaly is eliminated "by hand"



LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

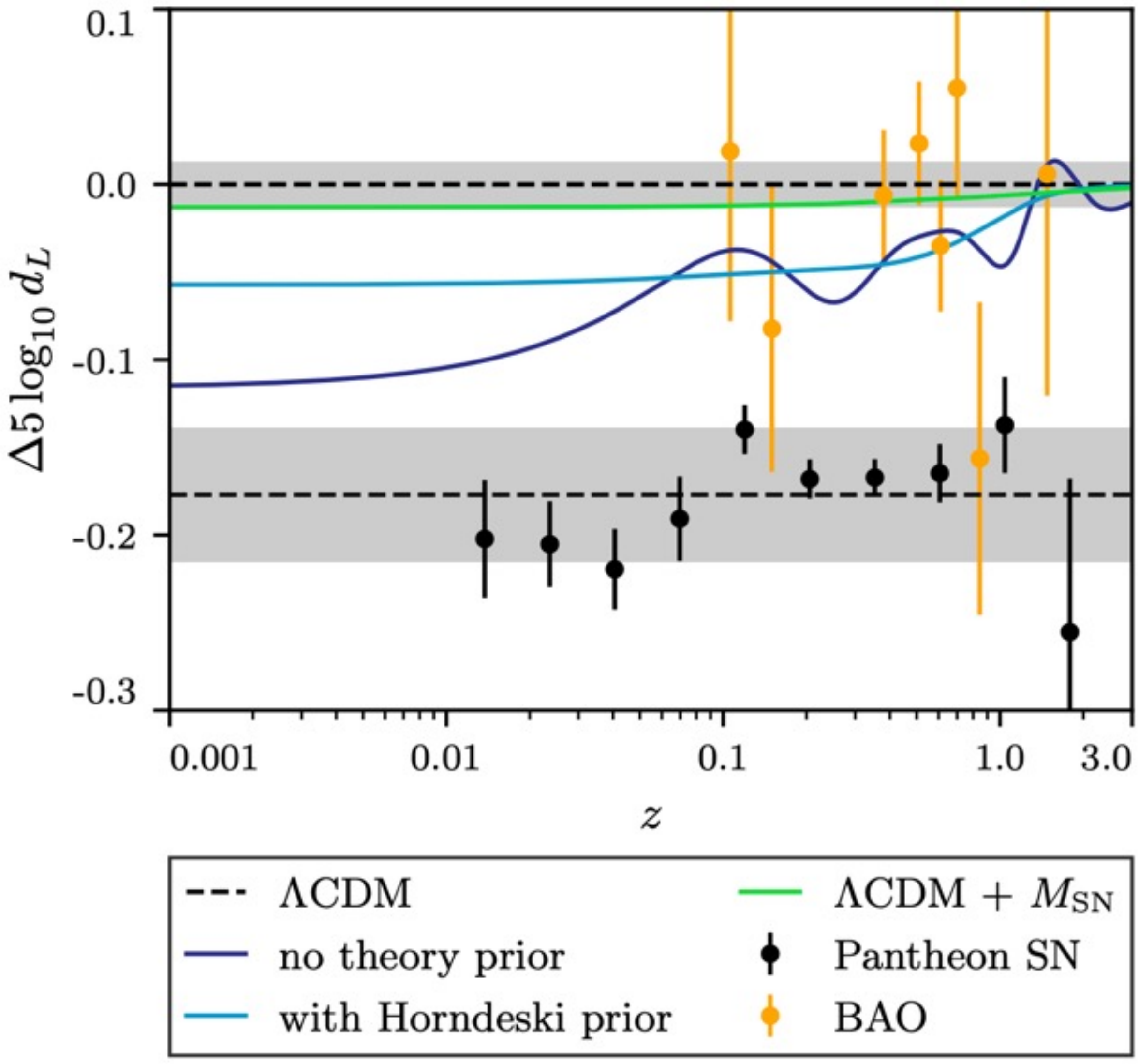
Implications for the H_0 tension



- Allowing for a flexible effective dark energy reduces the tension and increases the uncertainty
- The Horndeski prior makes it more difficult to relieve the tension

LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

Why it is difficult to solve the H_0 tension with late-time dark energy



LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)

The Hubble Tension

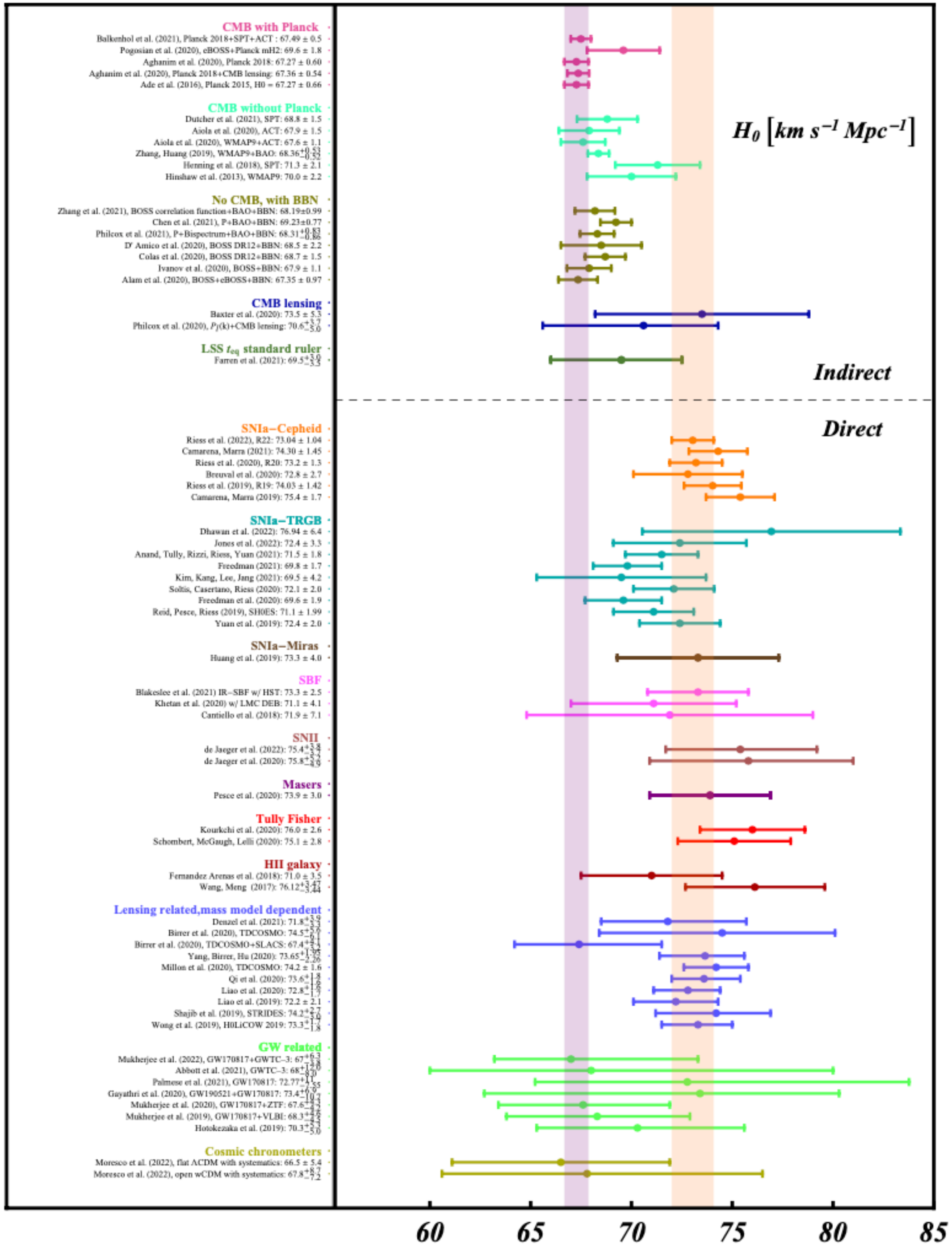
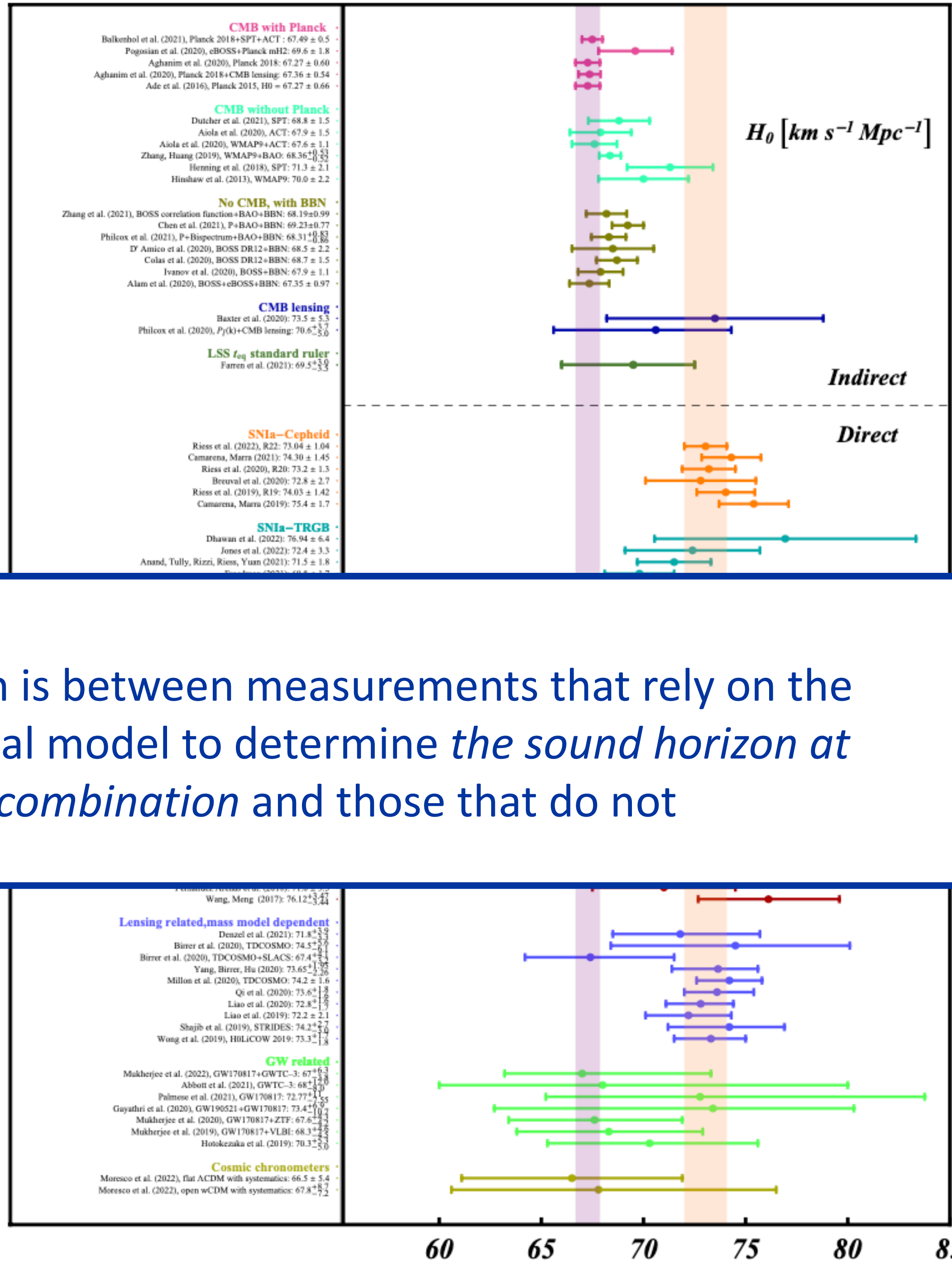


Table from arXiv:2203.06142

The Hubble Tension



The tension is between measurements that rely on the conventional model to determine *the sound horizon at recombination* and those that do not

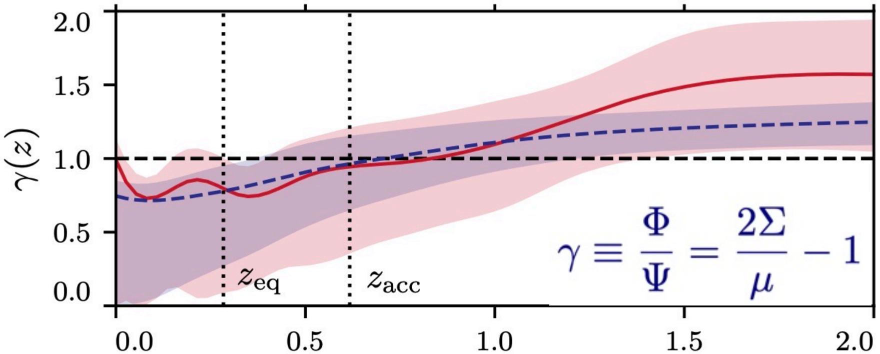
Table from arXiv:2203.06142

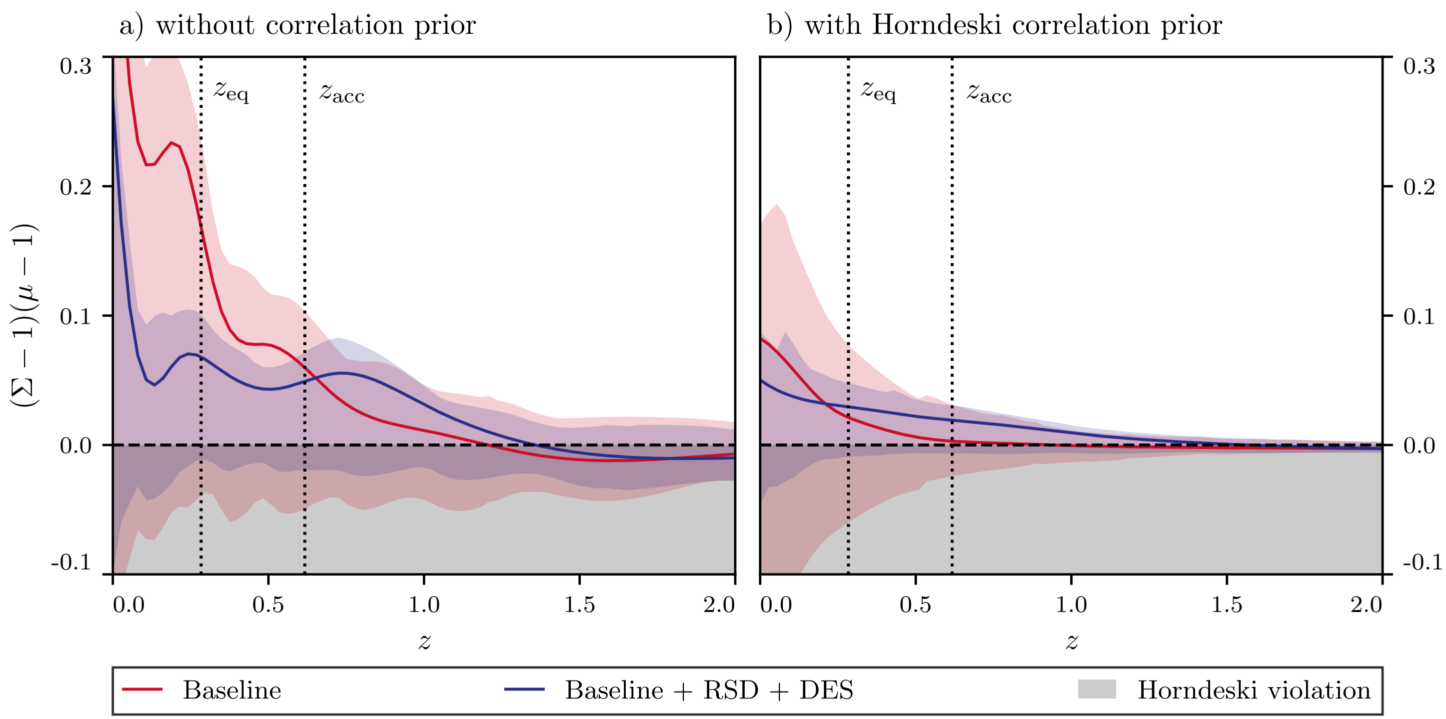
What can cosmology tell us about gravity? Constraining Horndeski with Σ, μ, γ

LP & Silvestri, arXiv:1606.05339, PRD

- γ >1 would rule out Brans-Dicke type theories
- $\Sigma \neq \mu$, or $\gamma \neq 1$, can only be due to $c_T \neq 1$ or a fifth force
- $(\Sigma - 1)(\mu - 1) \geq 0$, as expected in Horndeski

gravitational slip $\gamma(z)$

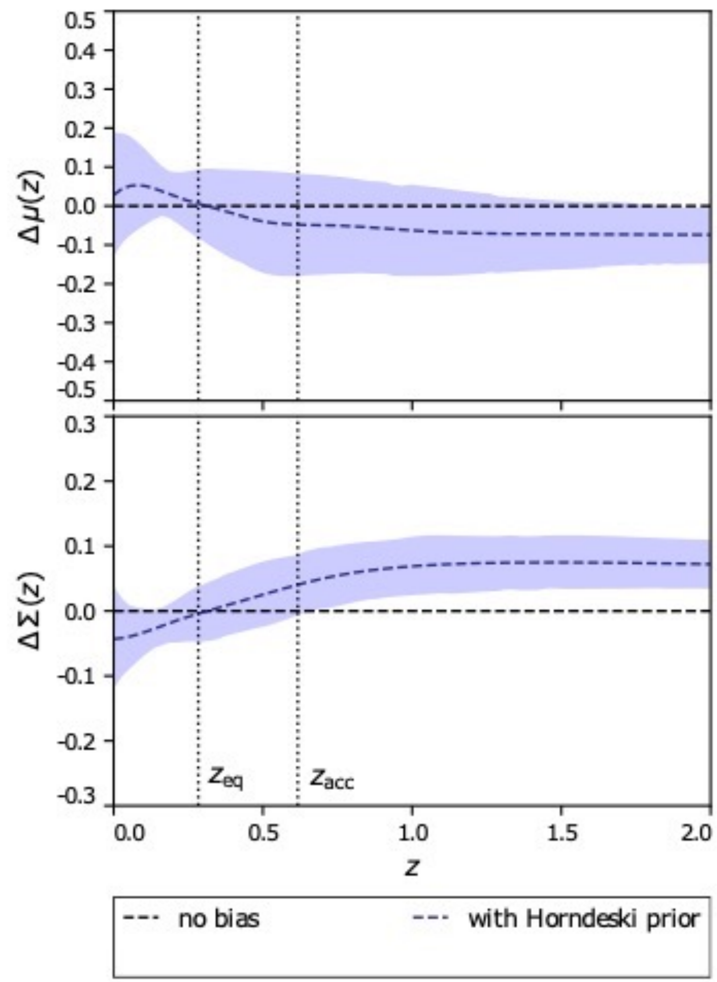




How ~~good~~ bad are common parametrizations?

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

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



M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP

Next step: beyond linear perturbations

Extend MGCAMB to model non-linearities using the Reaction method
M. Cataneo, L. Lombriser, C. Heymans, A. J. Mead, A. Barreira, S. Bose, B. Li, arXiv:1812.05594, MNRAS (2019)

Goal: non-linear matter power spectrum in a modified cosmology $P_{NL}(k,z)$

Step 1: given a linear $P_L(k,z)$ in a modified cosmology, find initial conditions of the LCDM cosmology that gives the same linear $P_L(k,z)$

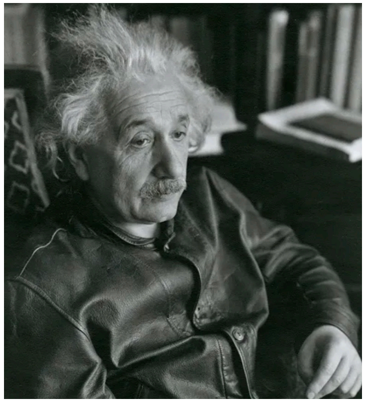
Step 2: Generate $P_{NL}(k,z)$ for the LCDM cosmology in Step 1 (using well-established methods)

Step 3: Multiply $P_{NL}(k,z)$ a 'Reaction' factor that incorporates the nonlinear effects of fifth forces, screening mechanisms and other deviations from LCDM, computed using the halo model and nonlinear perturbation theory

Use a 4-parameter model for the reaction function:
B. Bose, M. Tsedrik, J. Kennedy, L. Lombriser, A. Pourtsidou, A. Taylor, arXiv:2210.01094

- q1: sets the screening scale
- q2: controls the halo mass dependency of the screening scale
- q3: controls the environment dependency of the screening scale
- q4: calibrates any existing Yukawa suppression scale

Z. Wang, D. Saadeh, K. Koyama, LP, B. Bose, in preparation



Modified Einstein vs Modified Euler

The above reconstruction assumed that all matter (CDM and baryons) follow the same geodesics, *i.e.* the modified gravity affects all matter universally

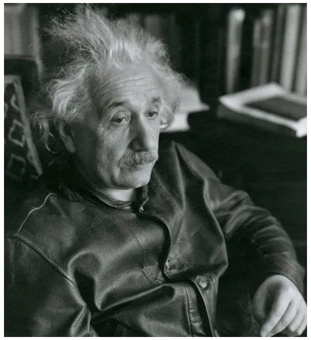
What if gravity was not modified, but there was a force acting only on CDM? Could we tell the difference?

A case study: Generalized Brans-Dicke vs Coupled Quintessence

$$S^{\rm GBD} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{A^{-2}(\phi)}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\rm m}(\psi_{\rm DM},\psi_{\rm SM},g_{\mu\nu})\right]$$

$$S^{\rm CQ} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\rm SM}(\psi_{\rm SM},g_{\mu\nu}) + \mathcal{L}_{\rm DM}(\psi_{\rm DM},A^2(\phi)g_{\mu\nu})\right]$$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy



Modified Einstein vs Modified Euler

baryon frame, quasistatic approximation

Generalized Brans-Dicke (GBD)		Coupled Quintessence (CQ)	
$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) - \beta k^2\delta\phi$	(21)	$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right)$	(30)
$k^2(\Phi - \Psi) = -2\beta k^2\delta\phi$	(22)	$k^2(\Phi - \Psi) = 0$	(31)
$\dot\delta_b + \theta_b = 0$	(23)	$\dot\delta_b + \theta_b = 0$	(32)
$\dot\theta_b + \mathcal{H}\theta_b = k^2\Psi$	(24)	$\dot\theta_b + \mathcal{H}\theta_b = k^2\Psi$	(33)
$\dot\delta_c + \theta_c = 0$	(25)	$\dot\delta_c + \theta_c = 0$	(34)
$\dot\theta_c + \mathcal{H}\theta_c = k^2\Psi$	(26)	$\dot\theta_c + (\mathcal{H}+\beta\dot\phi)\theta_c = k^2\Psi + k^2\beta\delta\phi$	(35)
$\delta\phi = -\dfrac{\beta(\rho_c\delta_c + \rho_b\delta_b)}{m^2 + k^2/a^2}$	(27)	$\delta\phi = -\dfrac{\beta\rho_c\delta_c}{m^2 + k^2/a^2}$	(36)
$\Box\phi = V_{,\phi} + \beta(\rho_c + \rho_b) \equiv V^{\text{eff}}{}_{,\phi}$	(28)	$\Box\phi = V_{,\phi} + \beta\rho_c \equiv V^{\text{eff}}{}_{,\phi}$	(37)
$\ddot\delta + \mathcal{H}\dot\delta = 4\pi G a^2\rho\delta\left[1 + \dfrac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\right]$	(29)	$\ddot\delta + \mathcal{H}\dot\delta = 4\pi G a^2\rho\delta\left[1 + \dfrac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\left(\dfrac{\rho_c}{\rho}\right)^2\left(\dfrac{\delta_c}{\delta}\right)\right]$	(38)

$$G_{\text{eff}}^{\text{GBD}} = G\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\right]$$

$$G_{\text{eff}}^{\text{CQ}} = G\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\left(\frac{\rho_c}{\rho}\right)^2\left(\frac{\delta_c}{\delta}\right)\right]$$

$\Sigma = A^2 \simeq 1$, $\mu > 1$, $\eta < 1$

$\Sigma = \mu = \eta = 1$

Note a switch in notation: $\eta = \gamma$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy

Theory vs practice

In theory, equations suggest that η could be the smoking gun

- Weak lensing probes $\Phi + \Psi$
- Redshift space distortions probe θ_b , hence Ψ

$$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi$$

- Combine WL and RSD to measure η

Note a switch in notation: $\eta = \gamma$

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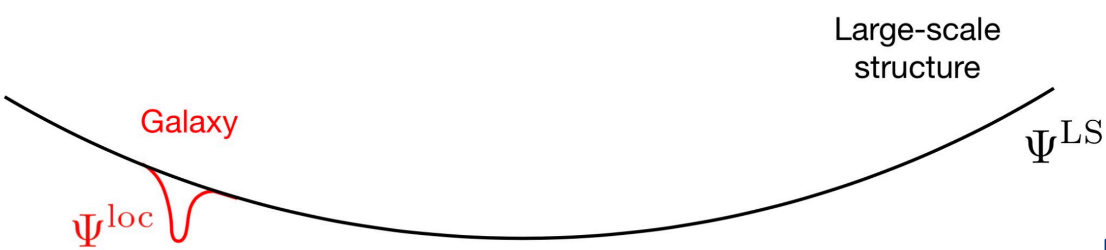
- Combine WL and RSD to measure η

In practice, the baryons we see are confined to galaxies made mostly of CDM



RSD of galaxies is not a measure of the true Ψ

$$\text{GBD}: \quad \dot{\theta}_g + \mathcal{H}\theta_g = k^2\Psi^{\rm LS}\,,$$

$$\text{CQ}: \quad \dot{\theta}_g + \mathcal{H}\theta_g = k^2\Psi^{\rm LS} + \frac{\rho_c}{\rho}k^2\beta\delta\phi \equiv k^2\Psi^{\rm eff}$$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy

Fitting μ and Σ to RSD+WL (assuming Euler is valid)

RSD: $$P^{\rm gal}(k,\mu_k,z) = \left(b^2+\mu_k^2 f\right)^2 P_{\delta\delta}(k,z)$$

WL: $$P^{(\Phi+\Psi)}(k,z) = 9H_0^4\Omega_m^2(1+z)^2\Sigma^2(k,z)P_{\delta\delta}(k,z)$$

Generalized Brans-Dicke

$$G_{\rm eff}^{\rm GBD} = G\left[1+\frac{2\tilde{\beta}^2k^2}{a^2m^2+k^2}\right]$$

$$\mu^{\rm fit} = \frac{G_{\rm eff}^{\rm GBD}}{G} = \mu^{\rm GBD} > 1\,,$$

$$\eta^{\rm fit} = \frac{2\Sigma^{\rm fit}}{\mu^{\rm fit}} - 1 = \frac{2}{\mu^{\rm fit}} - 1 = \eta^{\rm GBD} < 1$$

Coupled Quintessence

$$G_{\rm eff}^{\rm CQ} = G\left[1+\frac{2\tilde{\beta}^2k^2}{a^2m^2+k^2}\left(\frac{\rho_c}{\rho}\right)^2\left(\frac{\delta_c}{\delta}\right)\right]$$

$$\mu^{\rm fit} = \frac{G_{\rm eff}^{\rm CQ}}{G} > 1$$

$$\eta^{\rm fit} = \frac{2\Sigma^{\rm fit}}{\mu^{\rm fit}} - 1 = \frac{2}{\mu^{\rm fit}} - 1 < 1$$

One would measure η < 1 in both cases!

Note a switch in notation: $\eta = \gamma$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy

Is it possible to measure the true Ψ ?

Observed galaxy distribution

Redshift-space distortion

The "standard" terms: $$\Delta(\mathbf{n}, z) = \delta_g - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}_b \cdot \mathbf{n})$$

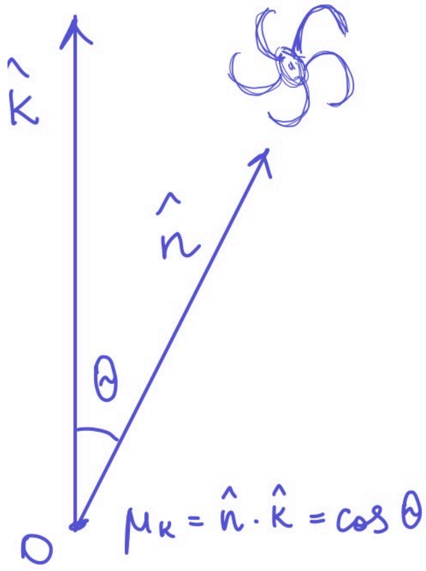
Leading order corrections:

$$\Delta^{\rm rel}(\mathbf{n}, z) = \frac{1}{\mathcal{H}}\partial_r\Psi + \frac{1}{\mathcal{H}}\dot{\mathbf{V}} \cdot \mathbf{n} + \left(1 - 5s + \frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\mathbf{V} \cdot \mathbf{n} + \ldots$$

Gravitational redshift

Yoo, Fitzpatrick, Zaldarriaga, Phys. Rev. D80, 083514 (2009)
Yoo, Phys. Rev. D82, 083508 (2010)
Bonvin, Durrer, Phys. Rev. D 84, 063505 (2011)
Challinor, Lewis, Phys. Rev. D84, 043516 (2011)

Observed galaxy distribution



The "standard" terms: $$\Delta(\mathbf{n},z) = \delta_g - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}_b\cdot\mathbf{n})$$

In Fourier space: $$\Delta(\mathbf{k},z) = b\,\delta(\mathbf{k},z) - \frac{1}{\mathcal{H}}\mu_k^2\,\theta_b(\mathbf{k},z)$$

Even power of μ_k

Leading order corrections:

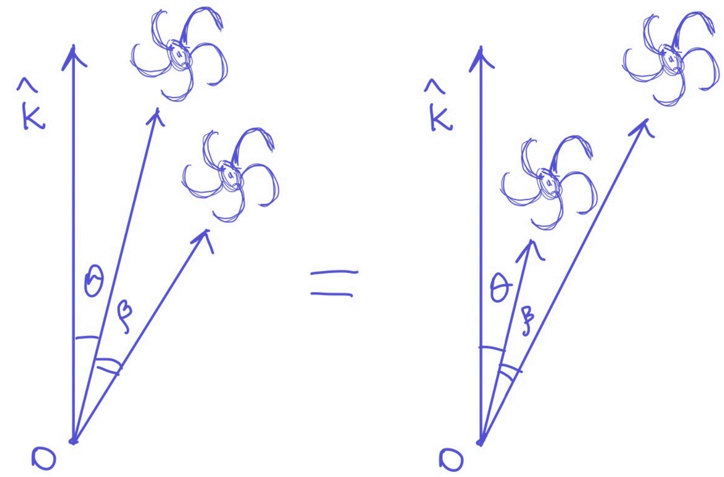
$$\Delta^{\rm rel}(\mathbf{n},z) = \frac{1}{\mathcal{H}}\partial_r\Psi + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \left(1-5s+\frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\mathbf{V}\cdot\mathbf{n} + \ldots$$

$$\Delta^{\rm rel}(\mathbf{k},z) = i\mu_k\left[-\frac{k}{\mathcal{H}}\Psi(\mathbf{k},z) + \left(1-5s+\frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\frac{\theta_g(\mathbf{k},z)}{k} + \frac{\dot{\theta}_g(\mathbf{k},z)}{k\mathcal{H}}\right] + \ldots$$

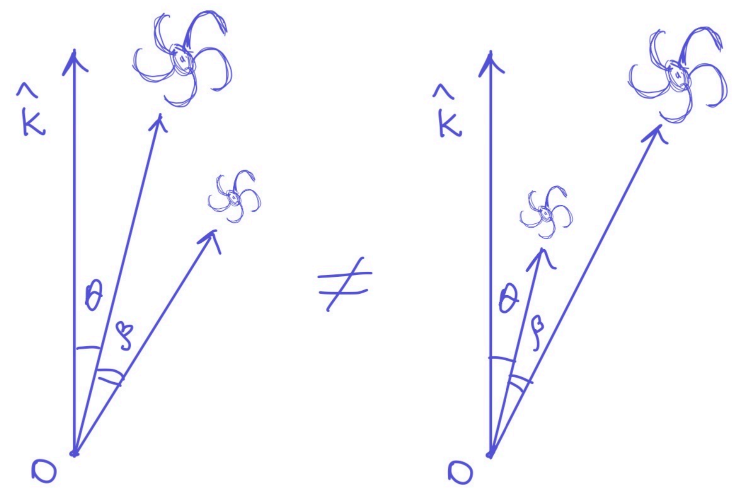
Odd power of μ_k

Can one isolate the dipolar distortion?

No, if galaxies are indistinguishable



Yes, if galaxies are distinguishable



C. Bonvin, L. Hui, E. Gaztanaga, arXiv:1309.1321, Phys Rev D

Multipole expansion of correlation between two galaxy populations: B (bright) and F (faint)

$$P_{\rm BF}^{\rm gal}(k,\mu_k,z) = \sum_\ell P_{\rm BF}^{(\ell)}(k,z)\mathcal{L}_\ell(\mu_k)$$

monopole: $$P_{\rm BF}^{(0)}(k,z) = \left[b_{\rm B}b_{\rm F} + \frac{1}{3}(b_{\rm B}+b_{\rm F})f_m + \frac{1}{5}f_m^2\right]P_{\delta\delta}(k,z)\,,$$

quadrupole: $$P_{\rm BF}^{(2)}(k,z) = \left[\frac{2}{3}(b_{\rm B}+b_{\rm F})f_m + \frac{4}{7}f_m^2\right]P_{\delta\delta}(k,z)\,,$$

hexadecapole: $$P_{\rm BF}^{(4)}(k,z) = \frac{8}{35}f_m^2 P_{\delta\delta}(k,z)\,,$$

dipole: $$P_{\rm BF}^{(1)}(k,z) = i\,\alpha\left(f_m,\dot{f}_m,\Theta_{\rm B},\Theta_{\rm F}\right)\frac{\mathcal{H}}{k}P_{\delta\delta}(k,z) + \boxed{i(b_{\rm B}-b_{\rm F})\frac{k}{\mathcal{H}}P_{\delta\Psi}(k,z)}\,,$$

octupole: $$P_{\rm BF}^{(3)}(k,z) = i\,\beta\left(f_m,\Theta_{\rm B},\Theta_{\rm F}\right)\frac{\mathcal{H}}{k}P_{\delta\delta}(k,z)\,,$$

C. Bonvin, P. Fleury, arXiv:1803.02771, JCAP

S. Castello, N. Grimm, C. Bonvin, arXiv:2204.11507, PRD

D. Sobral-Blanco and C. Bonvin, arXiv:2205.02567, MNRAS

Galaxy – galaxy lensing correlation

Gravitational slip:
$$\frac{P_{\delta(\Phi+\Psi)}(k,z)}{P_{\delta\Psi}(k,z)} = 1+\eta(k,z)$$

Galaxy dipole: $P^{(1)}_{BF}$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

Distinguishing coupled quintessence from scalar-tensor gravity

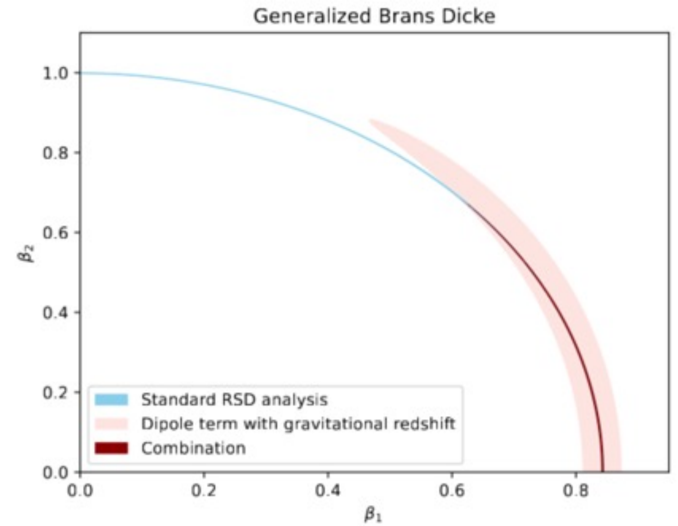
Forecast for SKA:

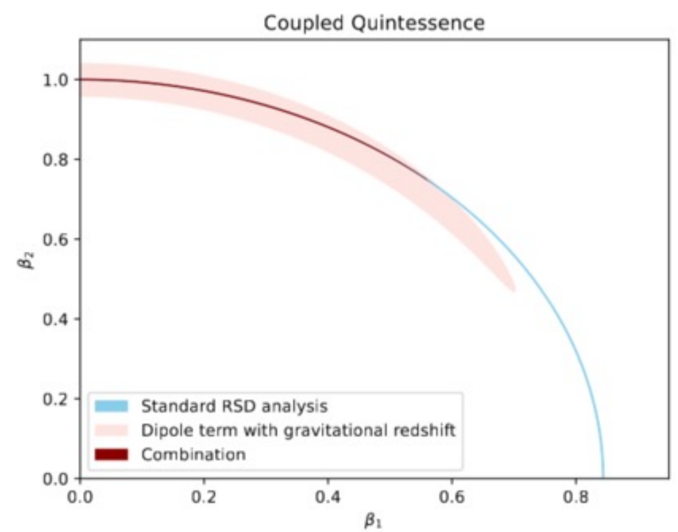
β_1 - the coupling between all matter and scalar field in Generalized Brans-Dicke

β_2 - the coupling CDM and scalar field in coupled quintessence

β_1 and β_2 are fully degenerate If only even multipoles of galaxy correlation function is used

Adding the dipole breaks the degeneracy





C. Bonvin, S. Castello, L. Damn, H. Mirpoorian, LP, Z. Wang, in preparation

Summary

One can already learn a lot more from today's data than w_0, w_a, Σ_0 and μ_0

The new version of MGCAMB includes the option for reconstructions and correlated priors

Nonlinear extension of MGCAMB is coming out soon

Need to measure relativistic corrections (gravitational redshift) to distinguish a modification of gravity from a dark matter force. This may be possible with DESI, more likely with SKA