Reconstructing non-minimally coupled gravity from cosmological data

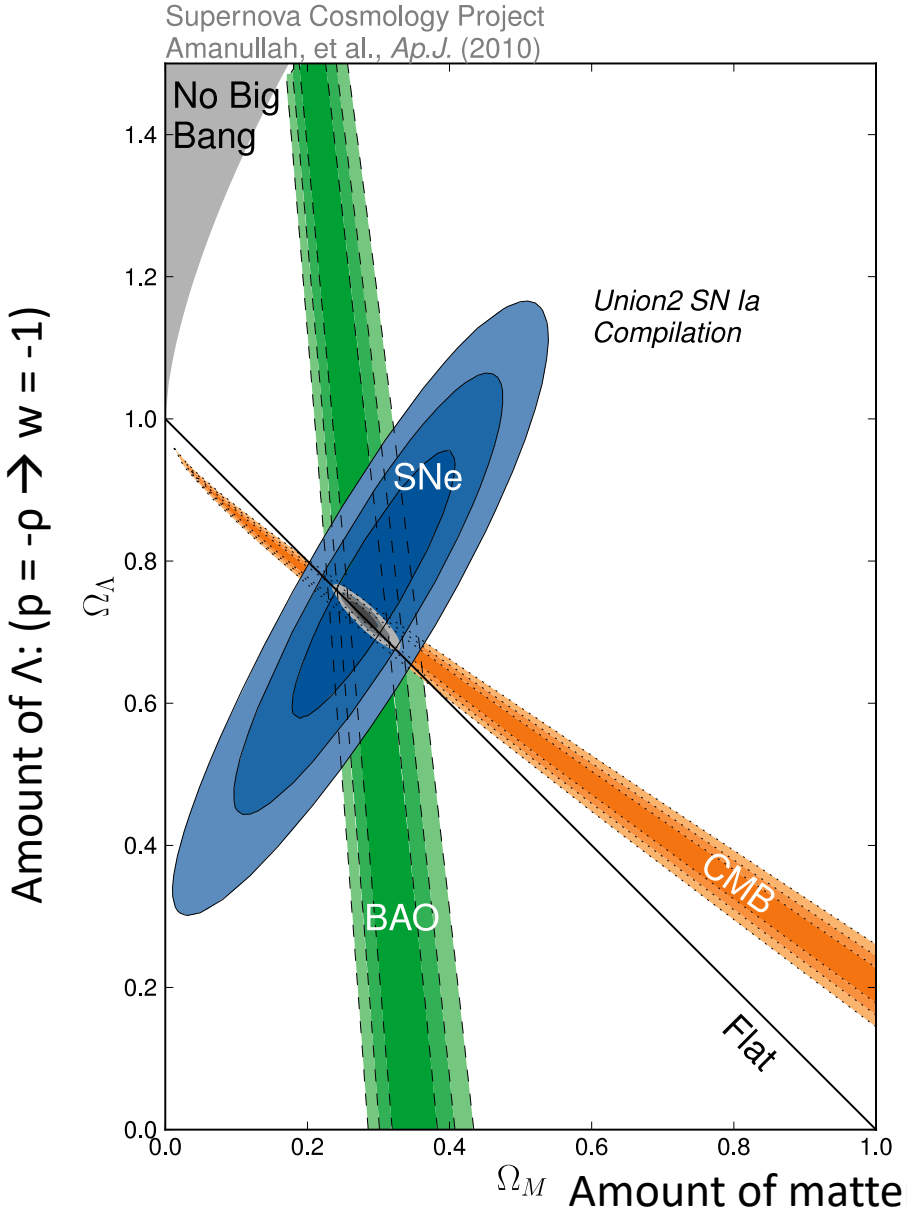
Martin Kunz
University of Geneva

with Anton Chudaykin, Gen Ye and Camille Bonvin

and with the Euclid Collaboration



Dark Energy



Physics Nobel prize 2011:

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

GR: accelerating expansion if $p < -\rho/3$

- Λ is unique natural extension (Lovelock) – should be there
- we know that for Λ: $p = -\rho$
- the data is (fairly) consistent with Λ

why look elsewhere?!

- ***Because we can (test LCDM)***
- ***Because of tensions***

Constraints on a dark energy fluid

DESI collaboration, arXiv:2404.03002

$p = w\,\rho$



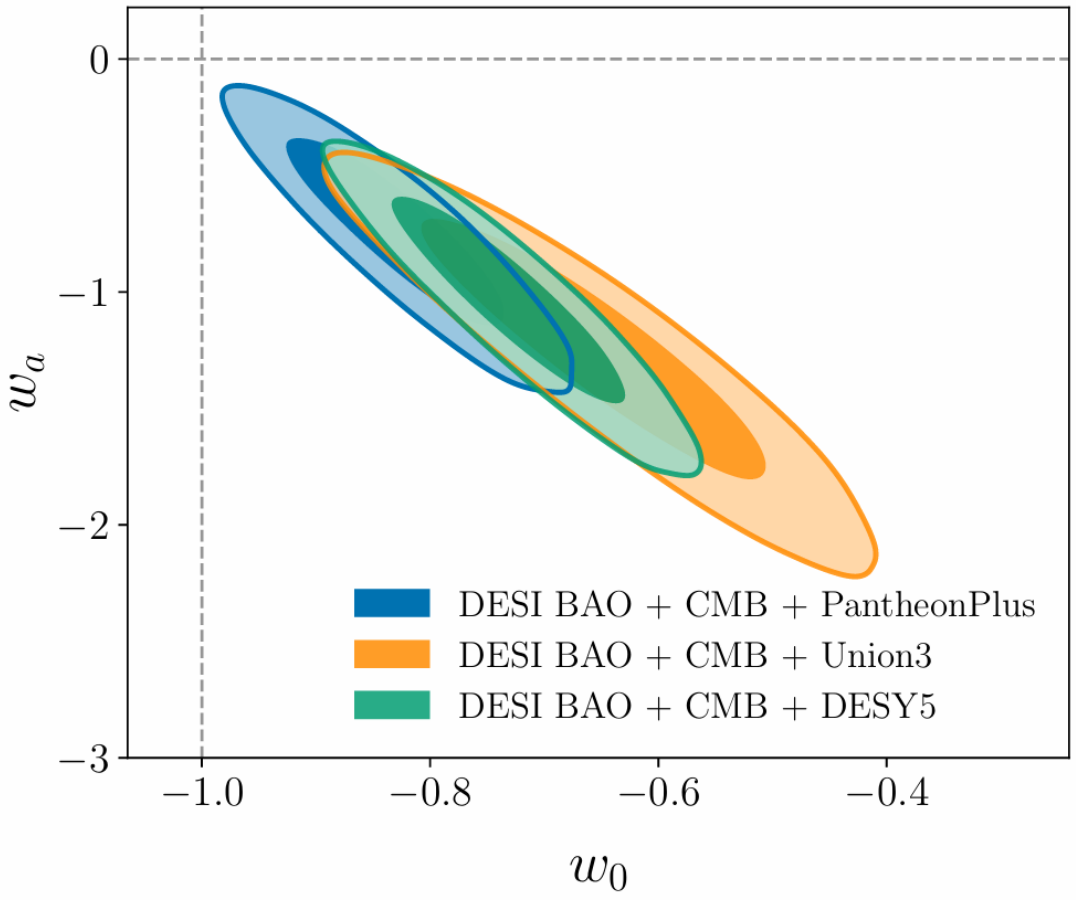
Ω_m

($\Omega_{DE} = 1-\Omega_m$)

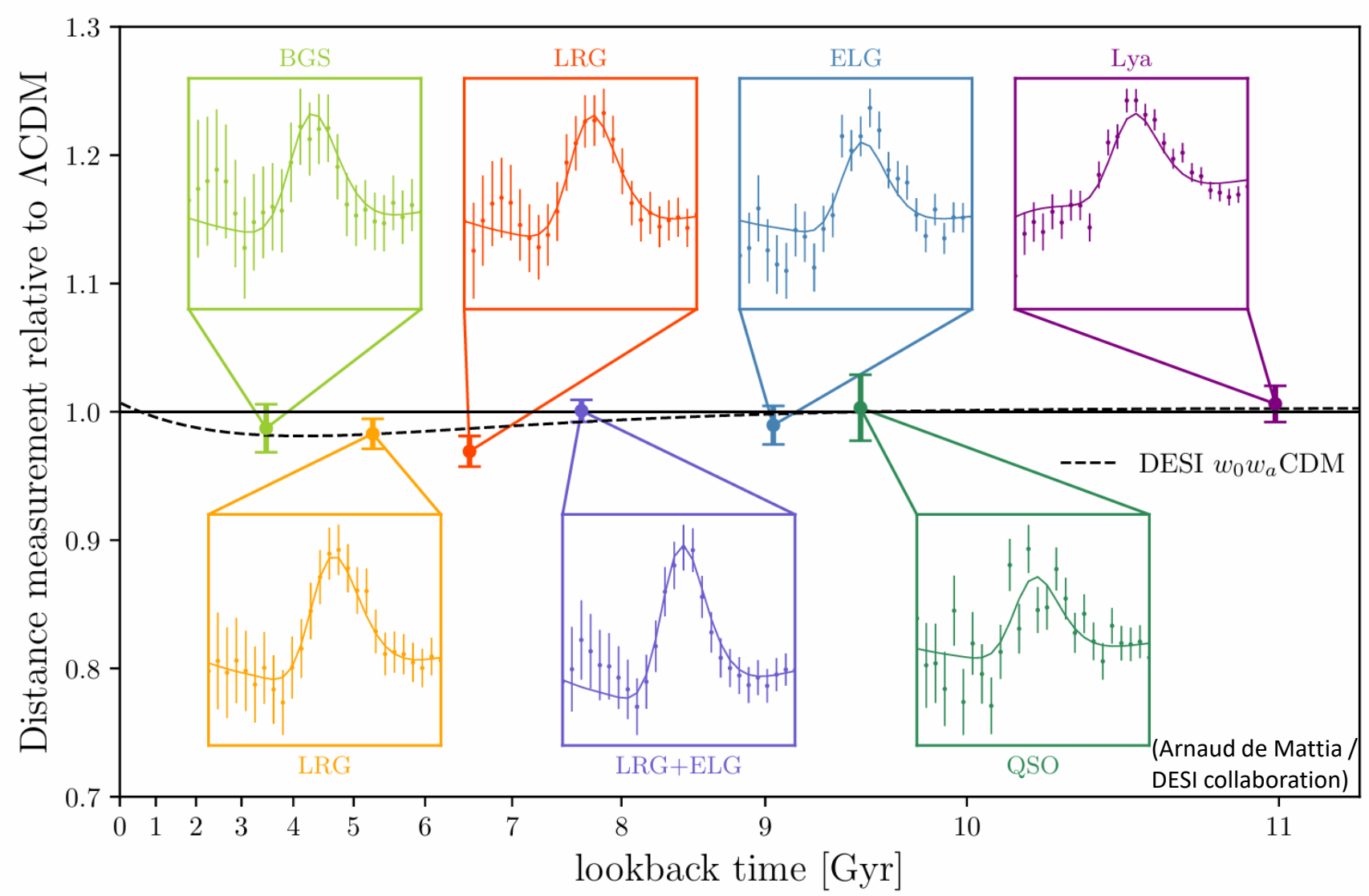
But dark energy could evolve …

$p = w\,\rho$ and $w(a) = w_0 + (1-a)\,w_a$

Λ : $w_0 = -1$ and $w_a = 0$



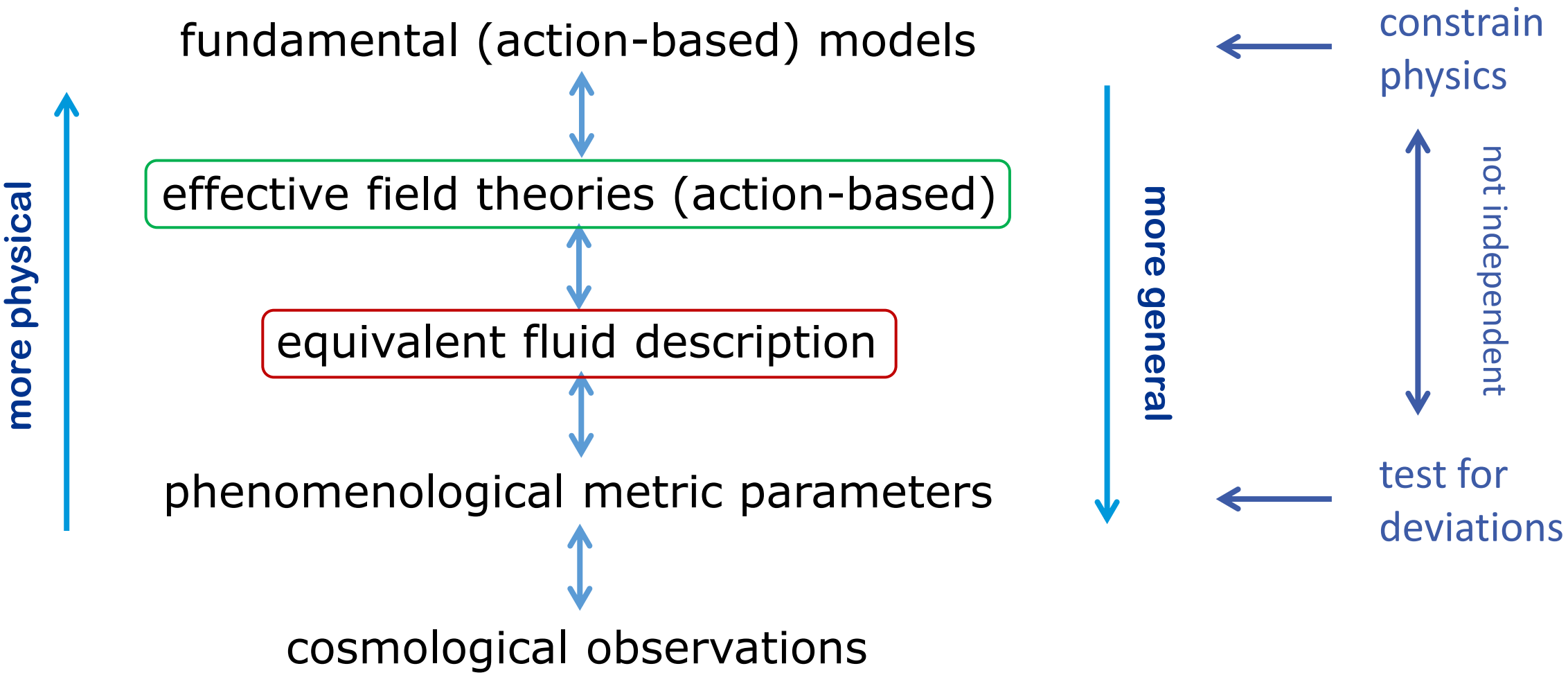
How does the DESI data look like?



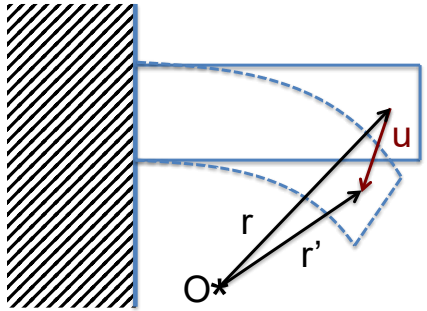
- Preference for w_0w_a model rests on few BAO points (specifically the two LRG data points).
- Replacing those with older data at equal constraining power reduces deviation to 1.8σ (Chudaykin & MK, 2407.02558)

- But evidence is contained not only in BAO but also in CMB and SN-Ia, corresponding to a shift in Ω_m if ΛCDM is assumed.
- It also did not go away with more DESI data.
- Conclusion: need ***more*** data! ☺
- And should use ***consistent*** model.

How to model Dark Energy?



effective theory of elasticity



- either build detailed model at molecular level
- or effective model of deformations

effective d.o.f → deformation tensor: $u_{ij} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$

vanishes because of definition of 'no deformation'

expand energy in terms of deformation: $E = E_0 + \lambda_1^{ij}(\mathbf{x}) u_{ij} + \lambda_2^{ijkl}(\mathbf{x}) u_{ij} u_{kl} + \dots$

$\lambda_2^{ijkl}(\mathbf{x}) = \left. \frac{\partial^2 E}{\partial u_{ij} \partial u_{kl}} \right|_0$

apply symmetry constraints: isotropy + homogeneity → λ_2 scalar const.

$$E = E_0 + \frac{1}{2}\lambda \left(u_i^i\right)^2 + \mu u_{ij} u^{ij} = E_0 + \frac{1}{2} K \left(u_i^i\right)^2 + \mu \left(u_{ij} - \frac{1}{3}\delta_{ij} u_k^k \right)^2$$

lessons:
- valid only in a certain regime (eg. no big deformations, not crystals)
- can be written in different ways, some better for physical interpretation

effective theory of dark energy

(Cheung et al, 2008; Gubitosi et al, 2013, Bloomfield et al 2013, …)

$$S = \int d^4x\,\sqrt{-g}\Bigg\{\frac{M_p^2}{2}\Big[1+\Omega(t)\Big]R + \Lambda(t) - c(t)\,a^2\,\delta g^{00}$$
$$+\frac{M_p^2 H_0^2}{2}\,\gamma_1(t)\left(a^2\,\delta g^{00}\right)^2 - \frac{M_p^2 H_0}{2}\,\gamma_2(t)\,a^2\,\delta g^{00}\,\delta K^{\mu}{}_{\mu}$$
$$-\frac{M_p^2}{2}\,\gamma_3(t)\left[\left(\delta K^{\mu}{}_{\mu}\right)^2 - \delta K^{\mu}{}_{\nu}\,\delta K^{\nu}{}_{\mu} - \frac{a^2}{2}\,\delta g^{00}\,\delta R\right]\Bigg\}$$
$$+ S_m\left[g_{\mu\nu}, \chi_m\right].$$

An alternative notation is (Bellini & Sawicki 2014, Gleyzes et al 2015)

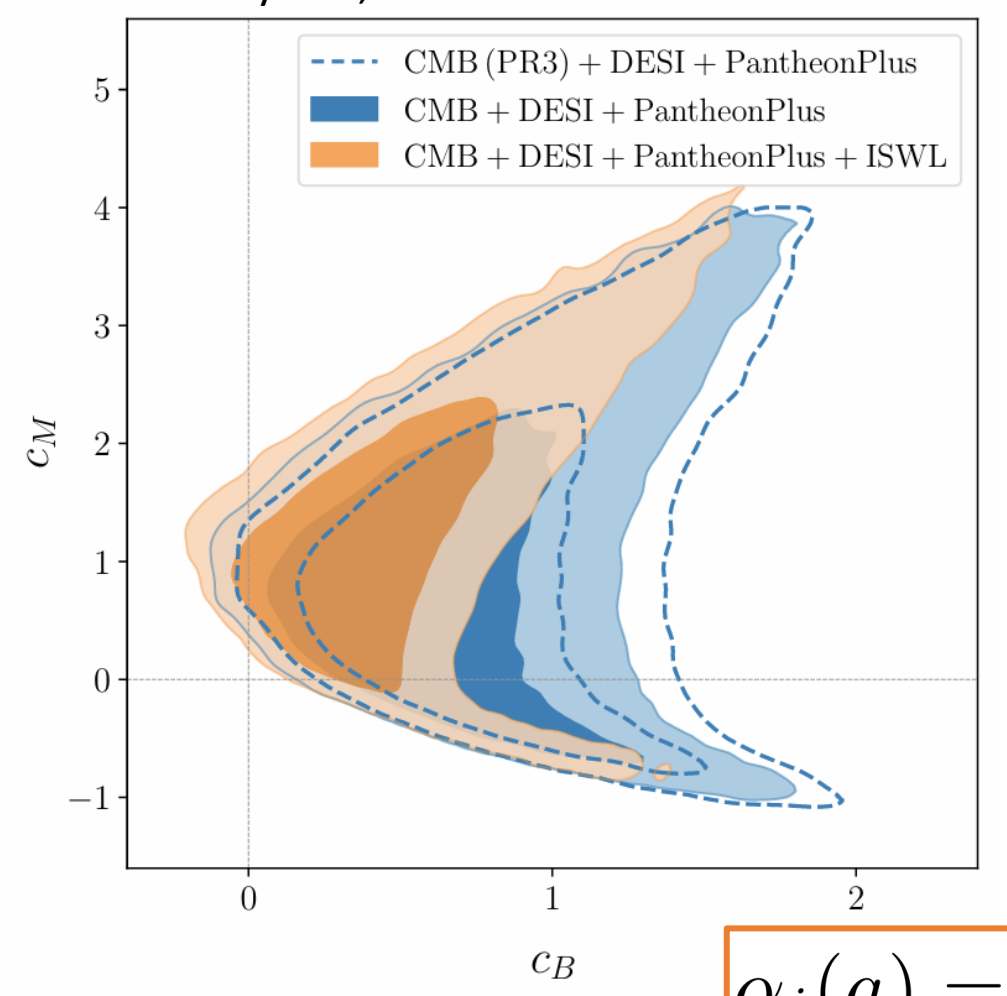
$$S^{(2)} = \int d^3x dt a^3\,\frac{M^2}{2}\Big[\delta K_{ij}\delta K^{ij} - \delta K^2 + (1+\alpha_T)\left(R\frac{\delta\sqrt{h}}{a^3} + \delta_2 R\right)$$
$$+\alpha_K H^2\delta N^2 + 4\alpha_B H\,\delta K\,\delta N + (1+\alpha_H)R\,\delta N\Big]$$

Some comments:

- The two notations are effectively equivalent.
- In the 'top' form, c(t) can be determined, **Ω** and **Λ** determine non-minimal coupling or the evolution of the Planck mass (**α_M**) and the background, **w_{eff}**
- **γ_1** is mostly related to the 'kineticity' **α_K** ~ $1/c_s^2$
- **γ_2** is mostly related to the 'kinetic gravity braiding' **α_B**
- Models with non-zero α_M or α_B can cross w = -1
- γ_3 and α_T are proportional and determine the speed of gravitational waves, but GW170817 places strong constraints; we set them to zero.
- Extensions are possible but strongly constrained by stability.

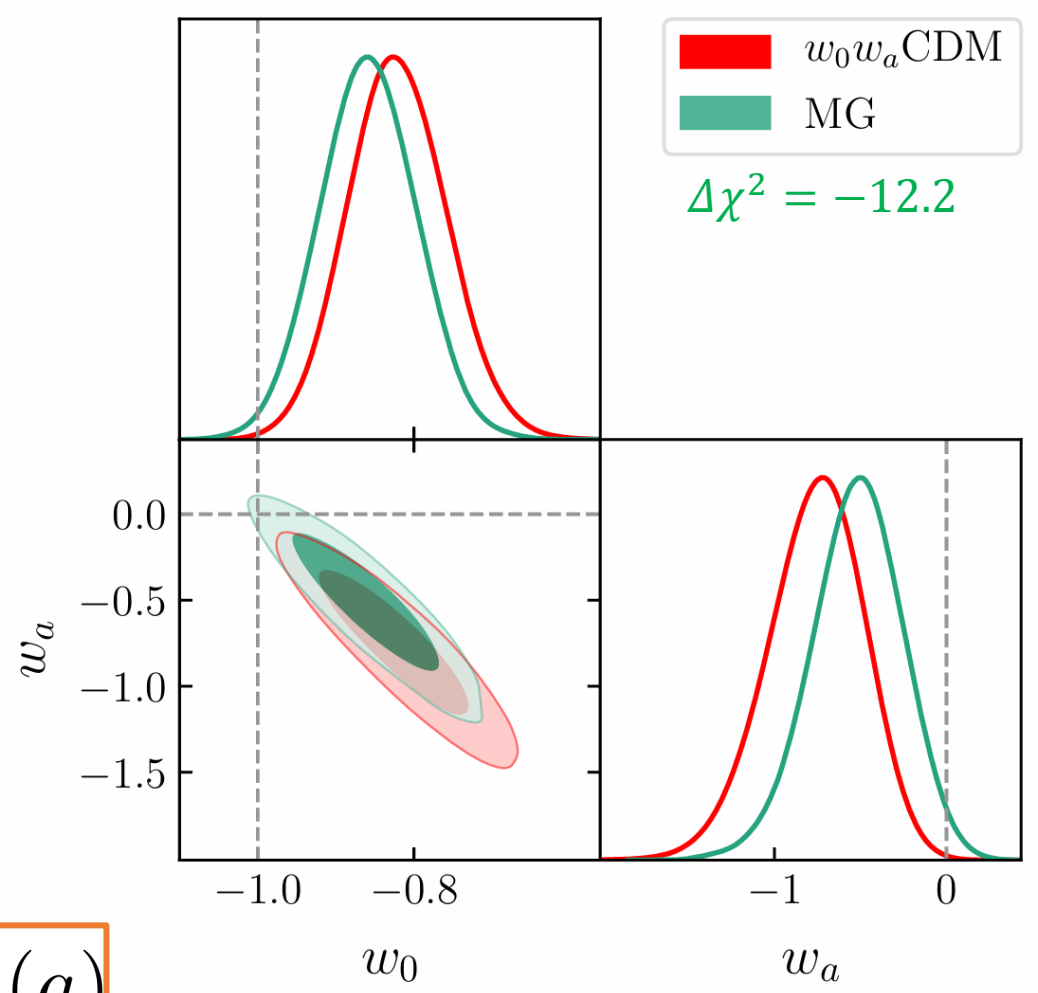
Using a consistent model

Chudaykin+, arXiv:2503.09893



$\Delta\chi^2 = -8.8$

$\Delta\chi^2 = -12.2$



$$\alpha_i(a) = c_i \Omega_{\rm DE}(a)$$

(Chudaykin, MK, arXiv:2407.02558)

What is the right evolution for the α_i?

- We don't know, but it might be important (constant w vs w_0/w_a)

→ Use a flexible and smooth scheme like a spline interpolation with many knots

- Constraints are not very strong, and bins can be strongly (anti-)correlated.

→ We want to avoid spurious oscillations that blow up the uncertainty band.

→ Introduce a correlation function that limits the expected function space

$$\xi(|a-a'|) \equiv \langle [f(a)-\bar{f}(a)][f(a')-\bar{f}(a')] \rangle \,, \quad \xi(\delta a) = \frac{\xi_0}{1+(\delta a/a_c)^2}$$

'CPZ prior'

$$\chi^2_{\rm prior} = -\frac{1}{2}\sum_{i,j}(f_i-\bar{f}_i)C^{-1}_{ij}(f_j-\bar{f}_j)$$

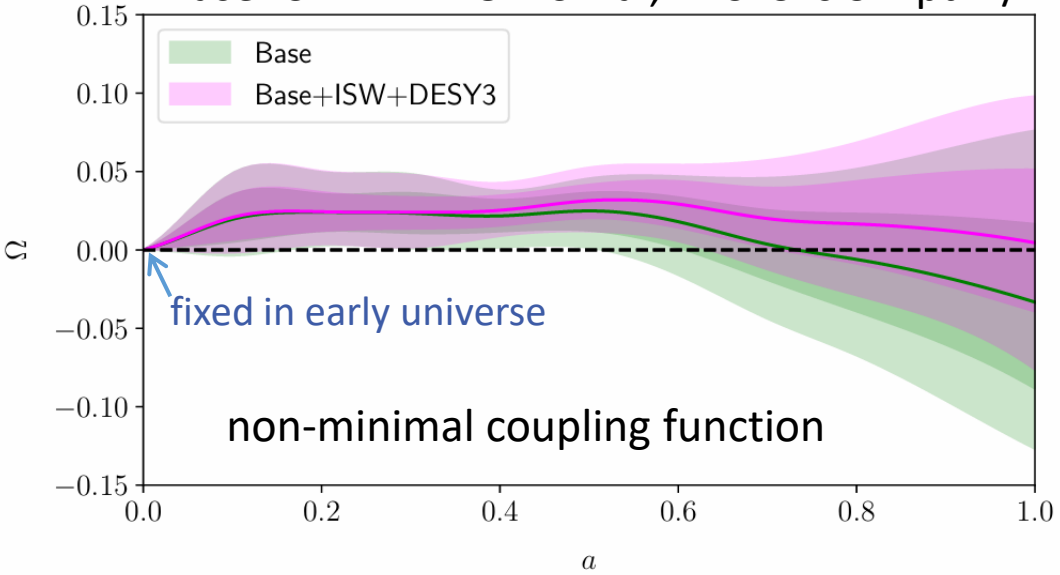
- Choice of CPZ prior, a_c=0.3 and ξ_0 from literature
- f_i and C_{ij} are averaged from f(a) and $\xi(|a-a'|)$
- $\bar{f}$ is a floating average matched to the correlation length

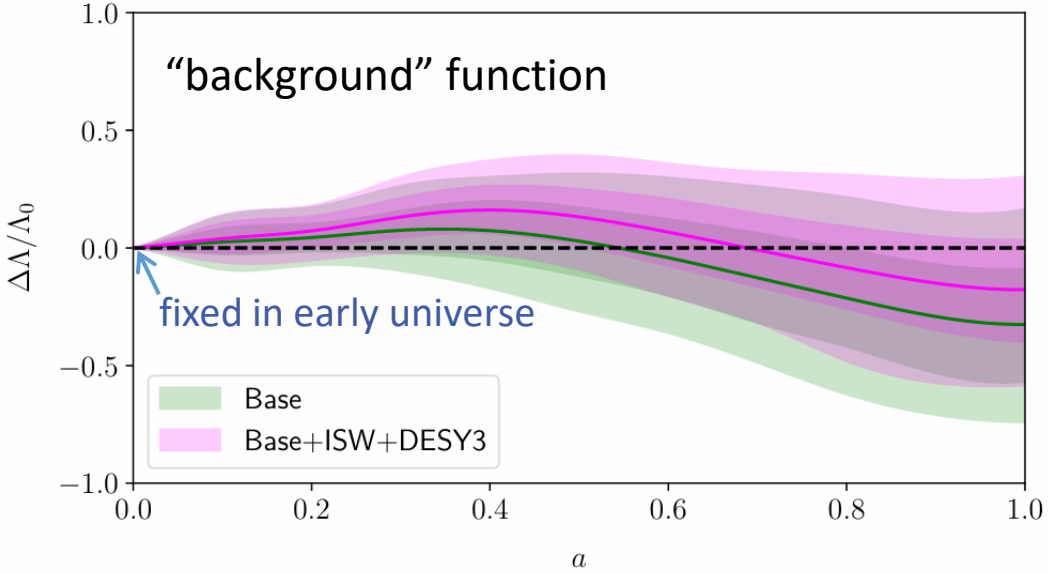
→ function cannot vary rapidly on scales smaller than a_c

Constraining non-minimal coupling

Base: CMB + BAO + SNIa ; DESY3 is 3x2pt w/ linear scale cuts

Ye, Chudaykin, Bonvin, MK, arXiv:2605.12415



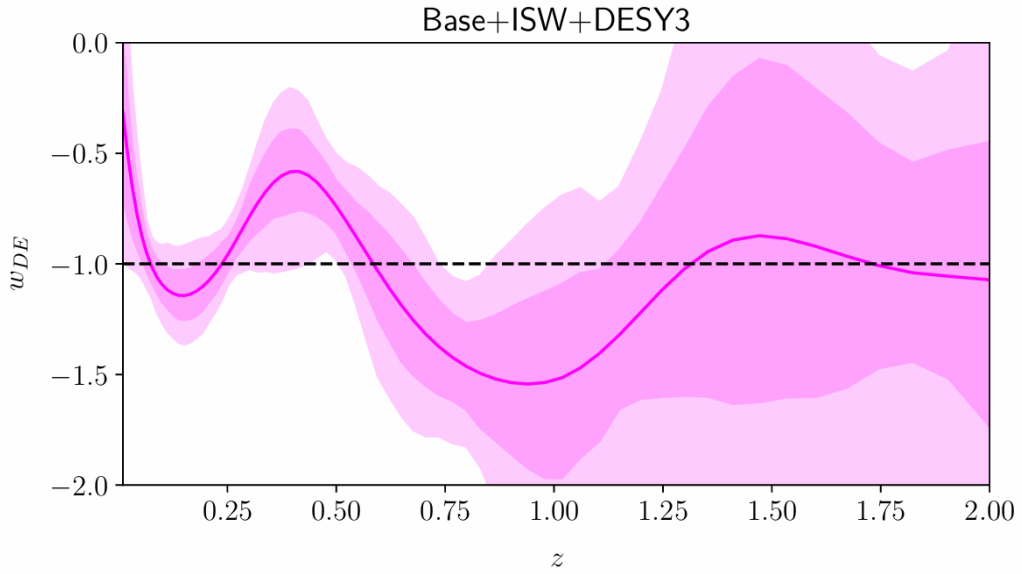


a = 1/(1+z)

Functions are fixed to zero at a=0.

Non-minimal coupling is positive (2.8σ), probably to allow for phantom-crossing.

The background evolution depends non-trivially on these functions, but we can compute *w*.



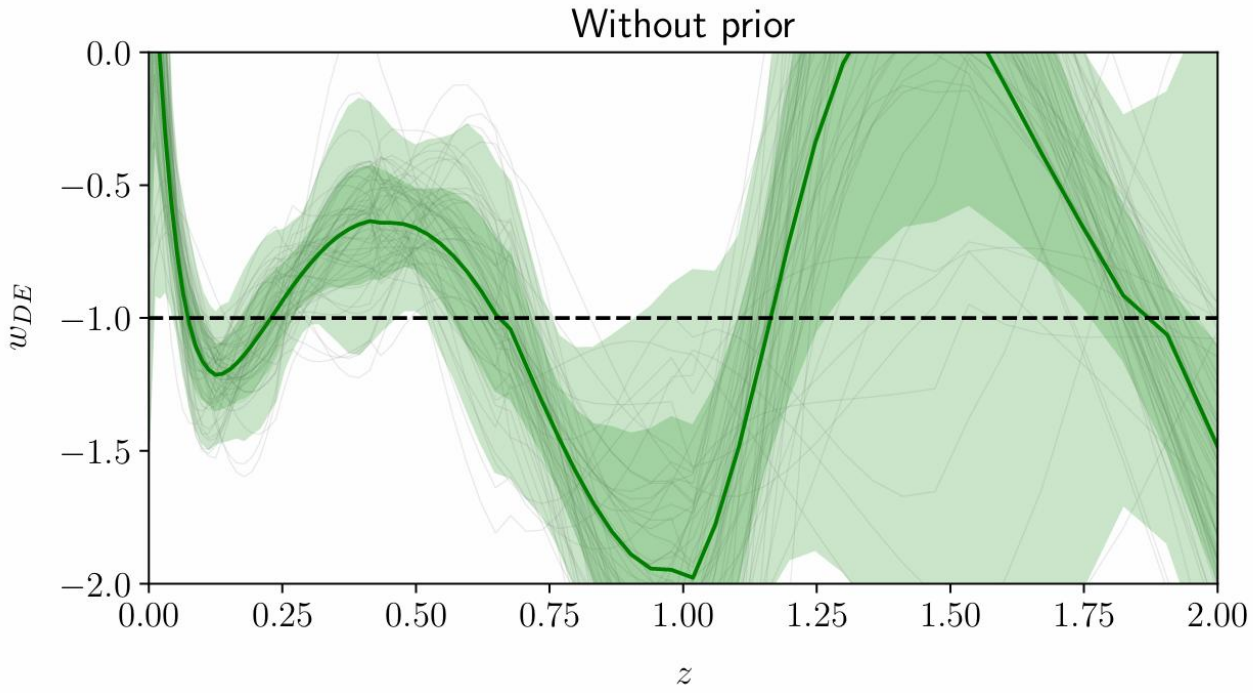
$$w_{\rm DE}(a) = \frac{\Lambda + (\ddot{\Omega} + 2H\dot{\Omega})}{2c - \Lambda - 3H\dot{\Omega}}$$

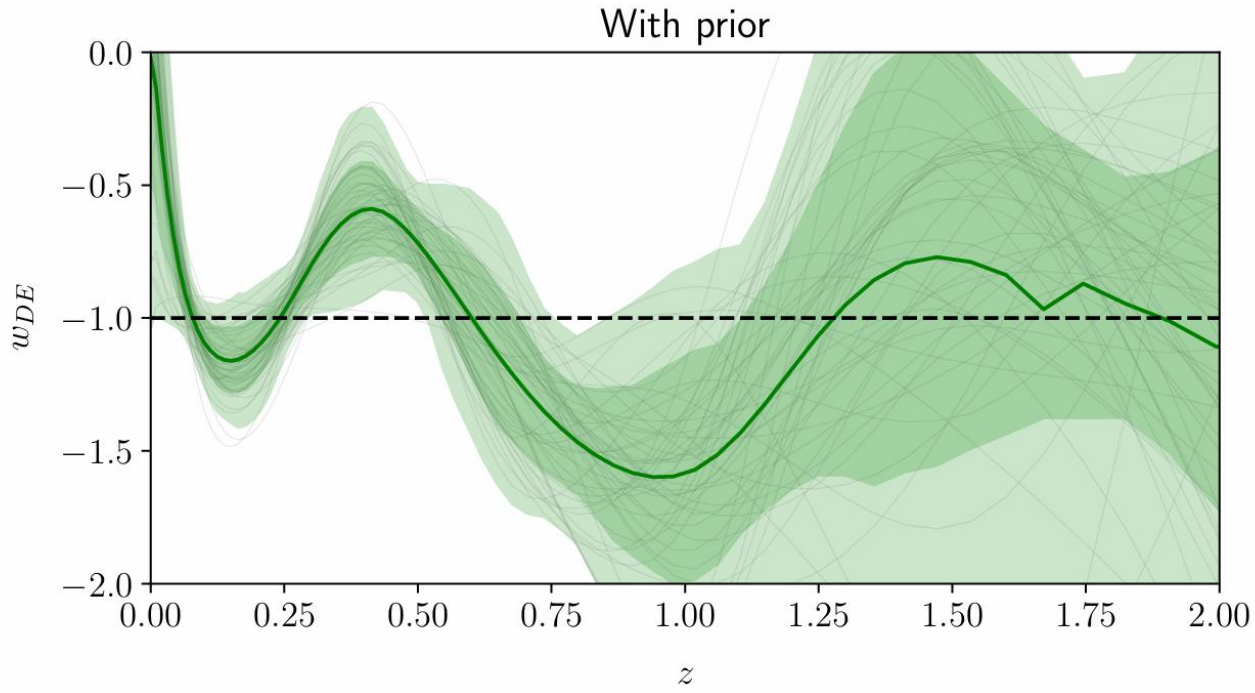
Need c > 0 for stability
→ Cannot cross if Ω is constant

Also, clustering and lensing are weaker than in GR for Ω > 0

Impact of smoothness prior

Does the smoothness prior actually make the results smoother?





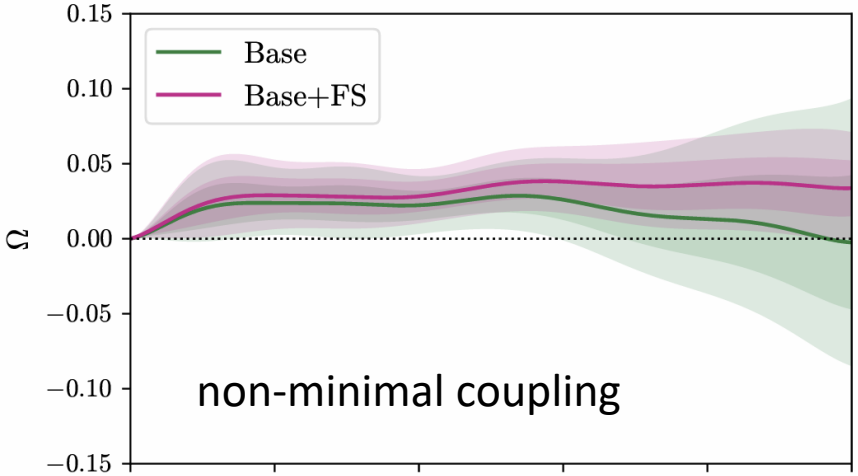
Could it be even smoother?

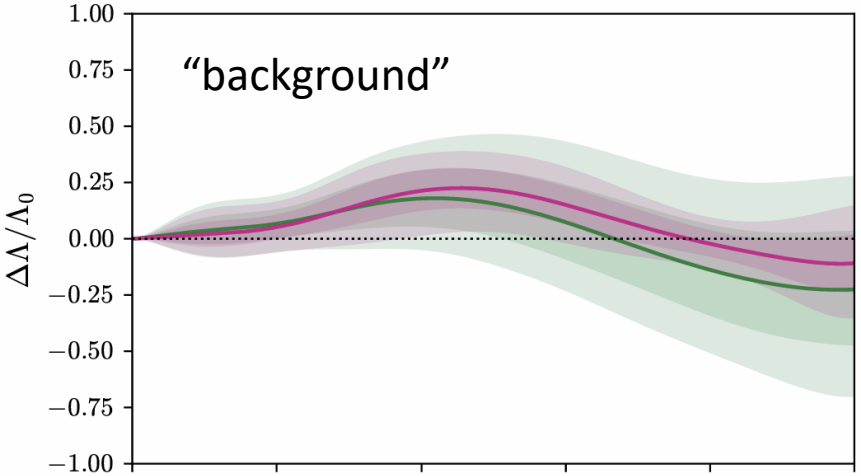
- Could we set the parameters by including them as free parameters?
- Other methods to reduce spurious oscillations?

Varying more EFT functions

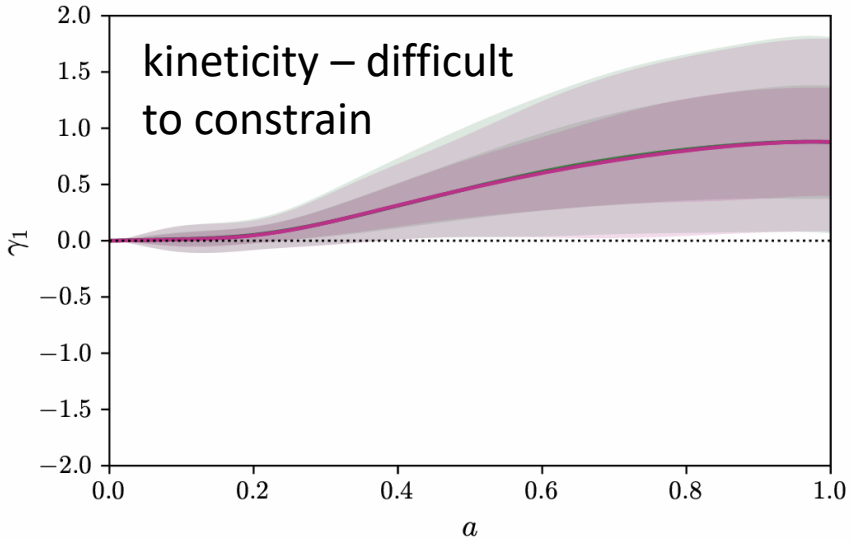
ONGOING / PRELIMINARY

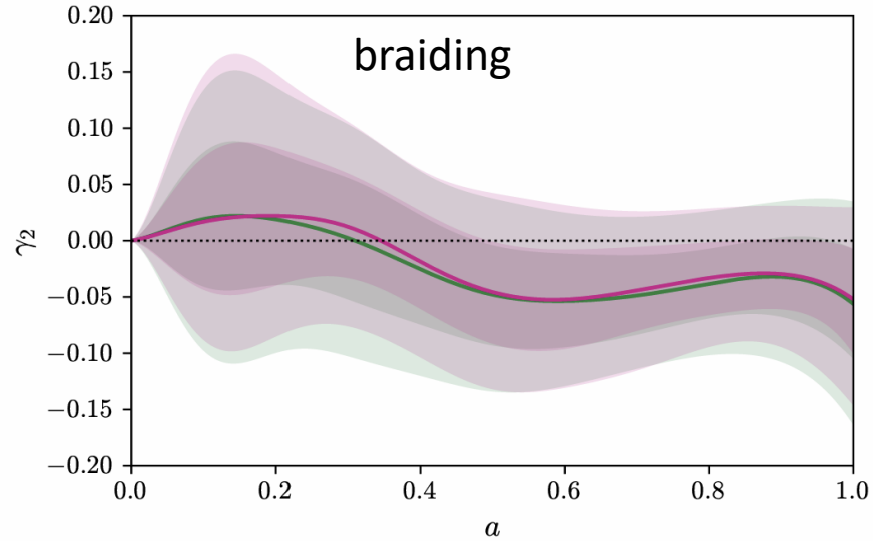
→ Horndeski with luminal GW; Ye, Chudaykin, Bonvin, me + Silvestri group (Maria Luisa Gallavotti, Stan Verhoeve, Dani de Boe)

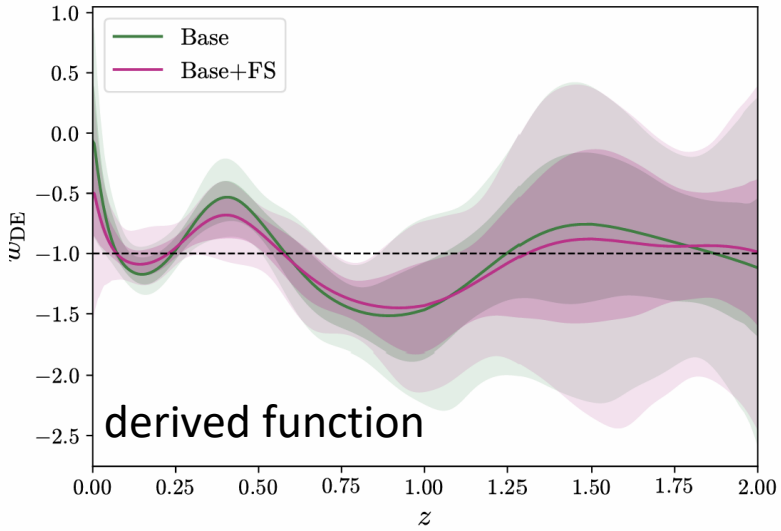




- 'Base' is now the previously extended data set (purple).
- No significant change in Ω and Λ visible w/o FS data.
- Kineticity is badly constrained.
- The DESI DR1 full matter $P^l(k)$ shape for l=0,2,4 (FS) reduces error bars on Ω and Λ.







And so?

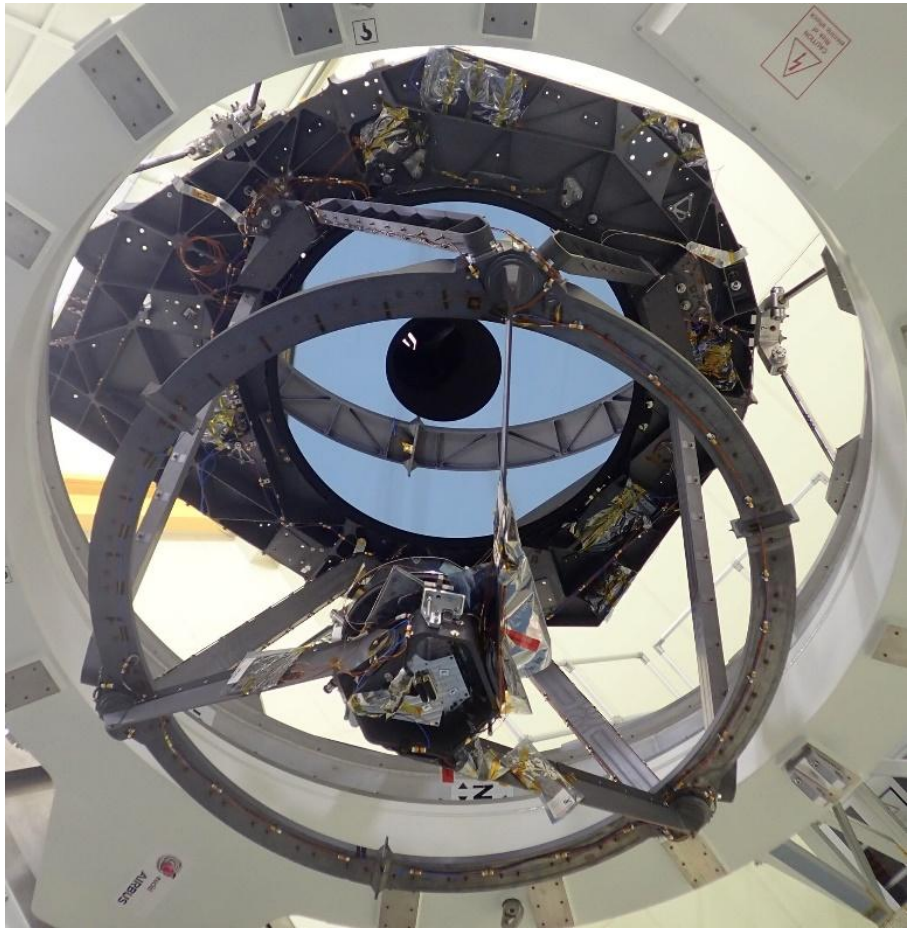
- The incredibly simple ΛCDM model provides a good description of what we observe in the Universe.
- But theorists think that the cosmological constant Λ has to be ‘too simple’.
- We have been looking for more than two decades for a signal of new physics.
- And maybe now we start to see such a signal – but more data is needed to be sure.
- Luckily, the next decade will literally flood us with data.

Euclid, an ESA M-class mission



© ESA / Euclid Consortium / NASA / TAS-I

- Ca 4.7m tall, 3.7m wide
- 1988kg launch mass
- 1.2m primary mirror
- Near-infrared & optical instruments
- Launch: July 1st, 2023 on SpaceX Falcon 9
- Daily data rate of ca 100GB compressed data
- Nominal mission duration of 6 years, extension possible.



‘eye of Euclid’ ©Airbus

Euclid main science objectives

Table 1: Euclid Primary Science Objectives – see RD10 for a full description.

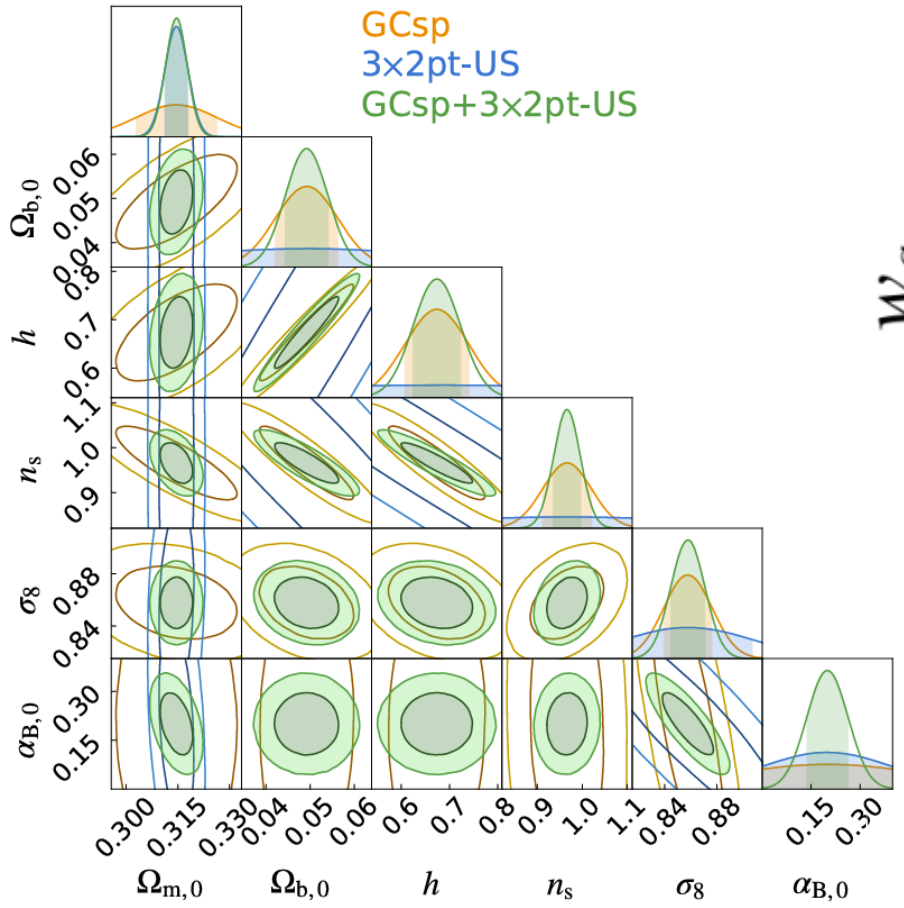
Sector	Euclid Targets
Dark Energy	• Measure the cosmic expansion history to better than 10% for several redshift bins from $z = 0.7$ to $z = 2$. • Look for deviations from $w = -1$, indicating a dynamical dark energy. • Euclid *alone* to give $FoM_{DE} \geq 400$ (roughly corresponding to 1-sigma errors on w_p, & w_a of 0.02 and 0.1 respectively)
Test of Gravity	• Measure the growth index, γ, to a precision better than 0.02 • Measure the growth rate to better than 0.05 for several redshift bins between $z = 0.5$ and $z = 2$ • Separately constrain the two relativistic potentials φ and ψ • Test the cosmological principle
Dark Matter	• Detect dark matter halos on a mass scale between 10^8 and $>10^{15}$ M_{Sun} • Measure the dark matter mass profiles on cluster and galactic scales. • Measure the sum of neutrino masses, the number of neutrino species and the neutrino hierarchy with an accuracy of a few hundredths of an eV
Initial Conditions	• Measure the matter power spectrum on a large range of scales in order to extract values for the parameters σ_8 and n_s to 0.01. • For extended models, improve constraints on n_s and α with respect to Planck alone by a factor 2. • Measure the non-Gaussianity parameter f_{NL} for local-type models with an error better than ± 2.

DE/MG

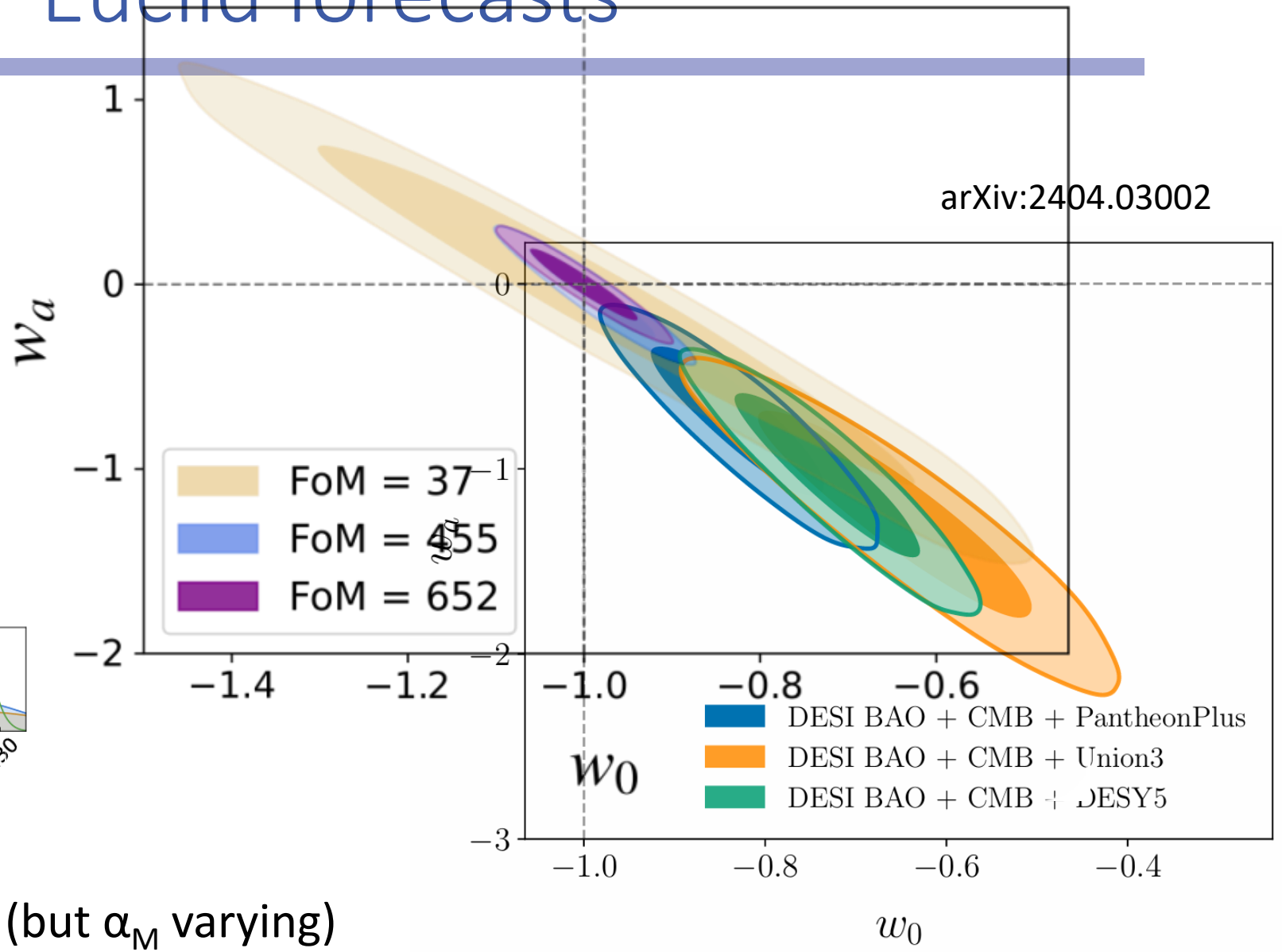
Euclid forecasts

Euclid. I. Overview of the Euclid mission, arXiv:2405.13491

Euclid Collaboration, arXiv:2506.03008



arXiv:2404.03002



α_B = 0.2 +/- 0.06 ; α_M = 0 (fixed)

Currently α_B = 0.45 +0.17/-0.41 (but α_M varying)

Conclusions

- Do we see first hints of a dynamical dark energy? We need more data to be sure, but also good methodological approaches.
- Euclid is producing copious amounts of data, with DR1 releases in 11/2026 (Foundation) and 06/2027 (Cosmology).
- Decades of development, but still many things to think about :
  - Fast inference methods (including emulators), flexible 'parametrisations' and generally AI/ML methods are important
  - Is this the 'best' way to constrain DE/MG?
  - Simply finding stuff in the data deluge is hard – there is just too much data ☺
- Much is still to be discovered, and much new data is coming!



DR1 Foundation: November 12

→ **In a week!**


Thank you!