Tensions in Cosmology
"The sword of Damocles over the ΛCDM"

Adrià Gómez-Valent

PPGCosmo UFES, 15 May 2023

INFN
Istituto Nazionale di Fisica Nucleare

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

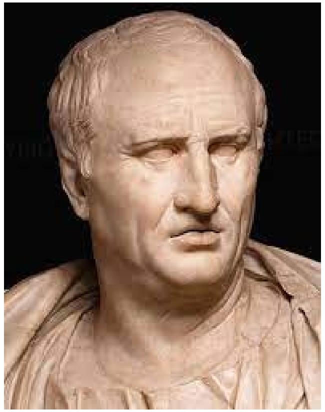
The sword a.k.a the tensions

Dionysius a.k.a New Physics

The servants a.k.a the wealth of cosmological data supporting the standard paradigm

Damocles a.k.a the ΛCDM

Cicerone a.k.a the physicists



FAQ

OR

Pillars of the ΛCDM

a) General Relativity

b) Symmetries of the spacetime: Isotropy+Homogeneity at large scales → FLRW metric

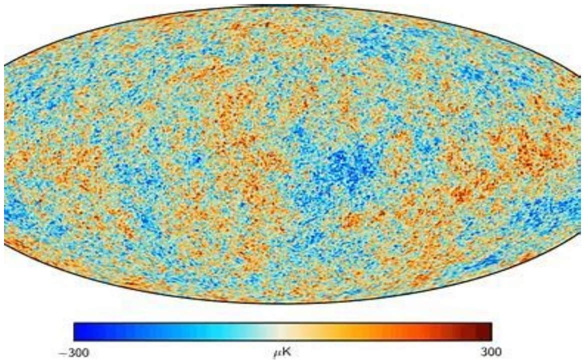
$$ds^2 = -dt^2 + \frac{a^2 dr^2}{1 - k\frac{r^2}{r_0^2}} + a^2 r^2 (\sin^2\theta d\varphi^2 + d\theta^2)$$

c) Energy content: standard model of particle physics with some extension to account for the neutrino masses and CDM + cosmological constant Λ

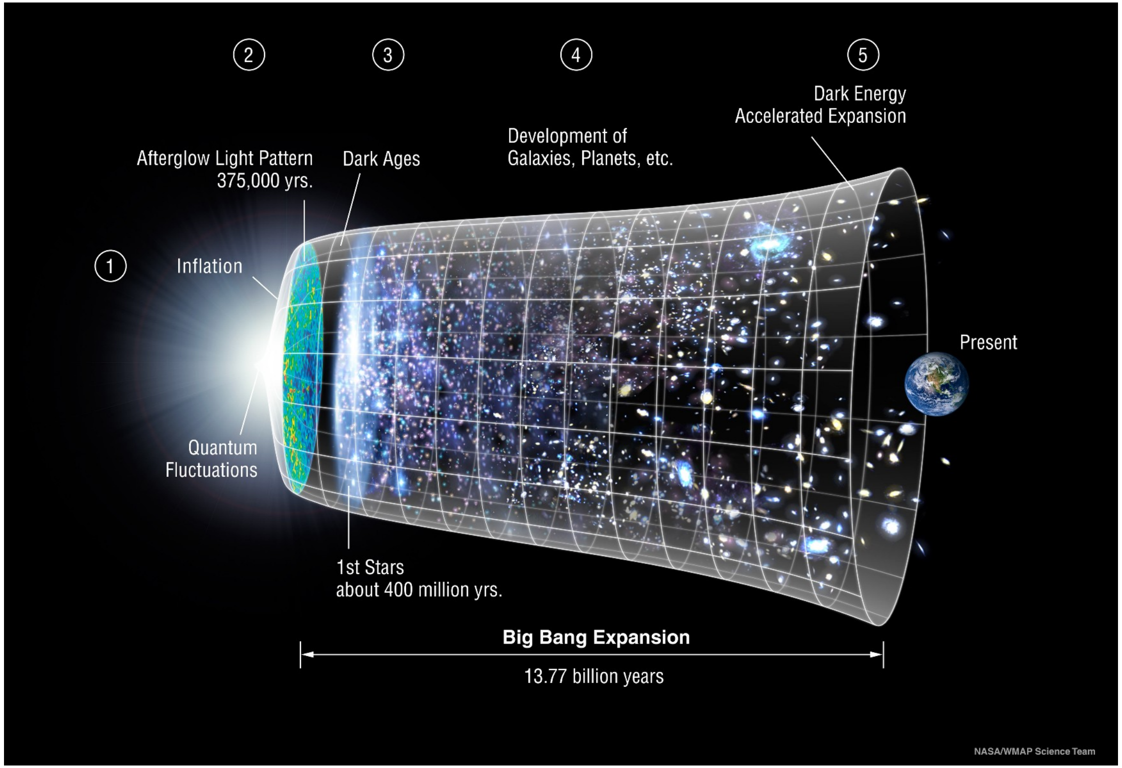
d) Inflationary model

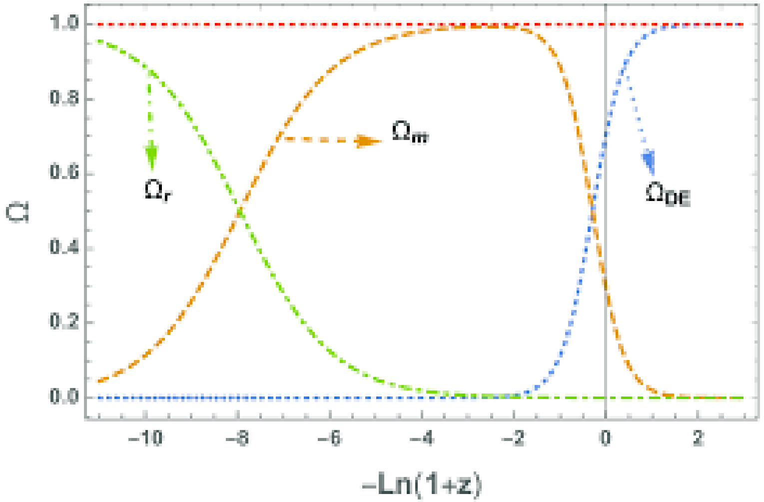
e) Six free parameters

Parameter	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042



The cosmic history in a (tiny) nutshell





Cosmic distances

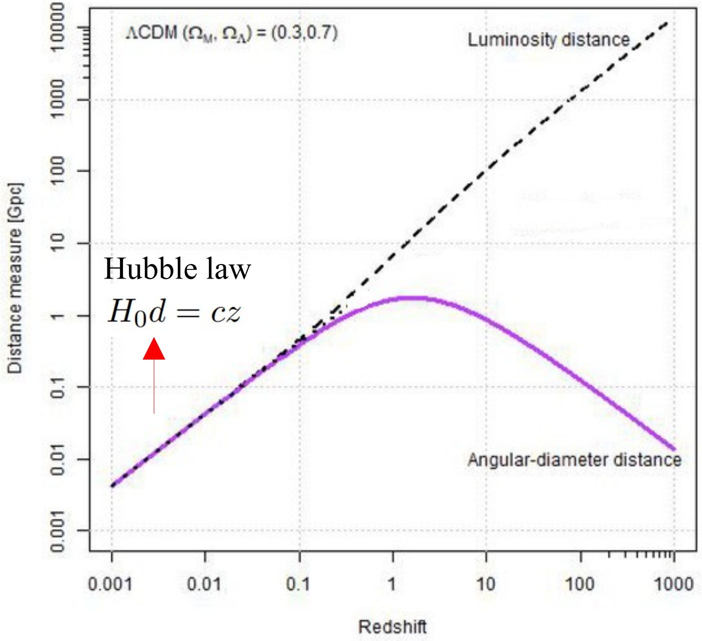
Redshift z=a[-1]-1

Luminosity distance
[useful for standard candles]

$$\mathcal{F} = \frac{\mathcal{L}}{4\pi D_L^2} \qquad D_L(z) = \frac{c(1+z)}{\sqrt{\Omega_k H_0^2}} \sinh\left(\sqrt{\Omega_k H_0^2}\int_0^z \frac{dz'}{H(z')}\right)$$

Angular diameter distance
[useful for standard rulers]

$$\mathrm{D}_A = \frac{L}{\delta\theta} \qquad D_A(z) = \frac{D_L(z)}{(1+z)^2}$$



Growth of structures

Primordial power spectrum + (linear) evolution

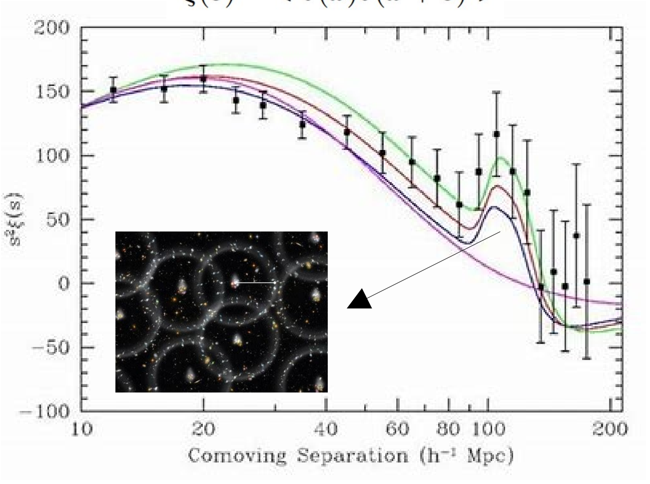
$$P(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$\delta_i = \delta\rho_i/\rho_i$$

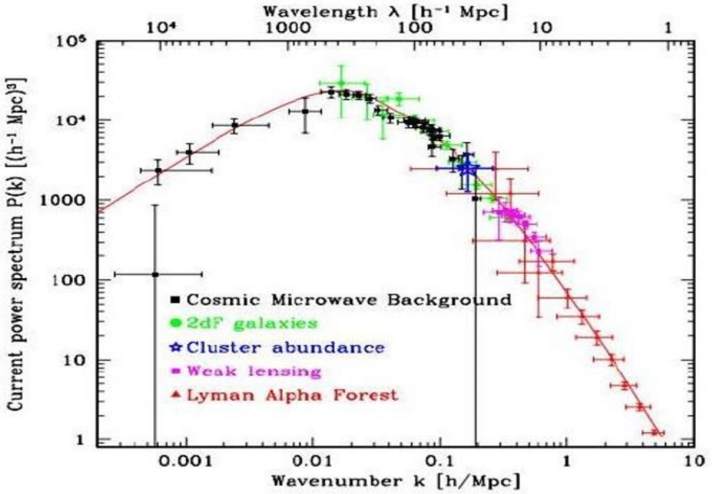
$$\frac{d^2\delta_i}{da^2} + \left(\frac{3}{a} + \frac{1}{H}\frac{dH}{da}\right)\frac{d\delta_i}{da} - \frac{3\Omega_m}{2a^2}\delta_i = 0$$

Two-point correlation function

$$\xi(s) = < \delta(x)\delta(x+s) >$$



Matter power spectrum

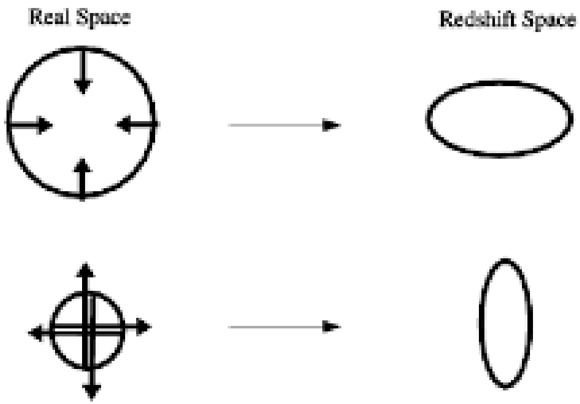


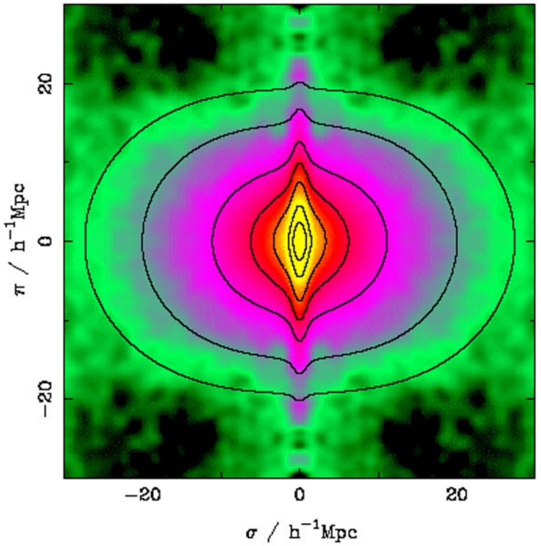
Redshift-space distortions and BAO

Large scales: Kaiser effect

$$\delta_s^{(g)}(k) = \delta_r^{(g)}(k)\left(1 + \frac{f}{b}\mu^2\right)$$

Small scales: FoG effect





Alcock-Paczynski effect, introduces an additional anisotropy when the fiducial cosmology is not the correct one.

Galaxy surveys provide information about:

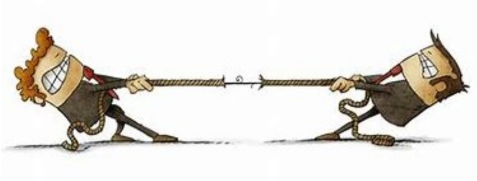
$$f = \frac{d\ln\delta_m}{d\ln a} \qquad r_s(z_d) = \int_{z_d}^{\infty}\frac{c_s(z)\,dz}{H(z)}$$

$$\sigma_8^2 = \frac{1}{2\pi^2}\int_0^{\infty} dk k^2 P(k)[W(kR_8)]^2$$

$R_8 = 8h^{-1}$ Mpc

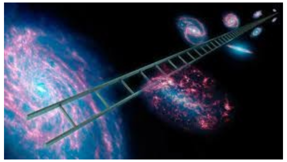
BAO	$D_A(z)/r_d$	$r_d H(z)$
RSD	$f(z)\sigma_8(z)$	

Outline of Part I



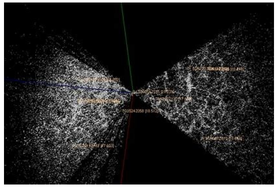
H_0 tension

- The direct cosmic distance ladder
- The inverse cosmic distance ladder
- Low-redshift anchors: GWs, CCH and strong lensed systems



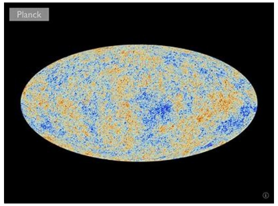
LSS tension

- Redshift-space distortions
- Weak lensing measurements
- Is σ_8 a correct LSS estimator?



CMB anomalies and others

- Constraints from low vs high multipoles
- Lack of power at low ls in the TT spectrum
- CMB lensing anomaly
- Cosmic birefringence



Hubble tension

Why is H_0 important?

It sets the characteristic time and distance scales in the universe

- Hubble function: $H(z) = \frac{\dot{a}}{a} = -(1+z)^{-1}\frac{dz}{dt}$.
- Hubble-Lemaître parameter: $H_0 \equiv H(z=0)$.
- Hubble law: $v = H_0 d = cz$
- Cosmic distances:

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{d\tilde{z}}{E(\tilde{z})} \quad ; \quad d_A = \frac{d_L(z)}{(1+z)^2}$$

- Age of the Universe:

$$T_{\rm Univ} = \frac{1}{H_0}\int_0^\infty \frac{d\tilde{z}}{(1+\tilde{z})E(\tilde{z})}$$

Edwin Hubble (1929)

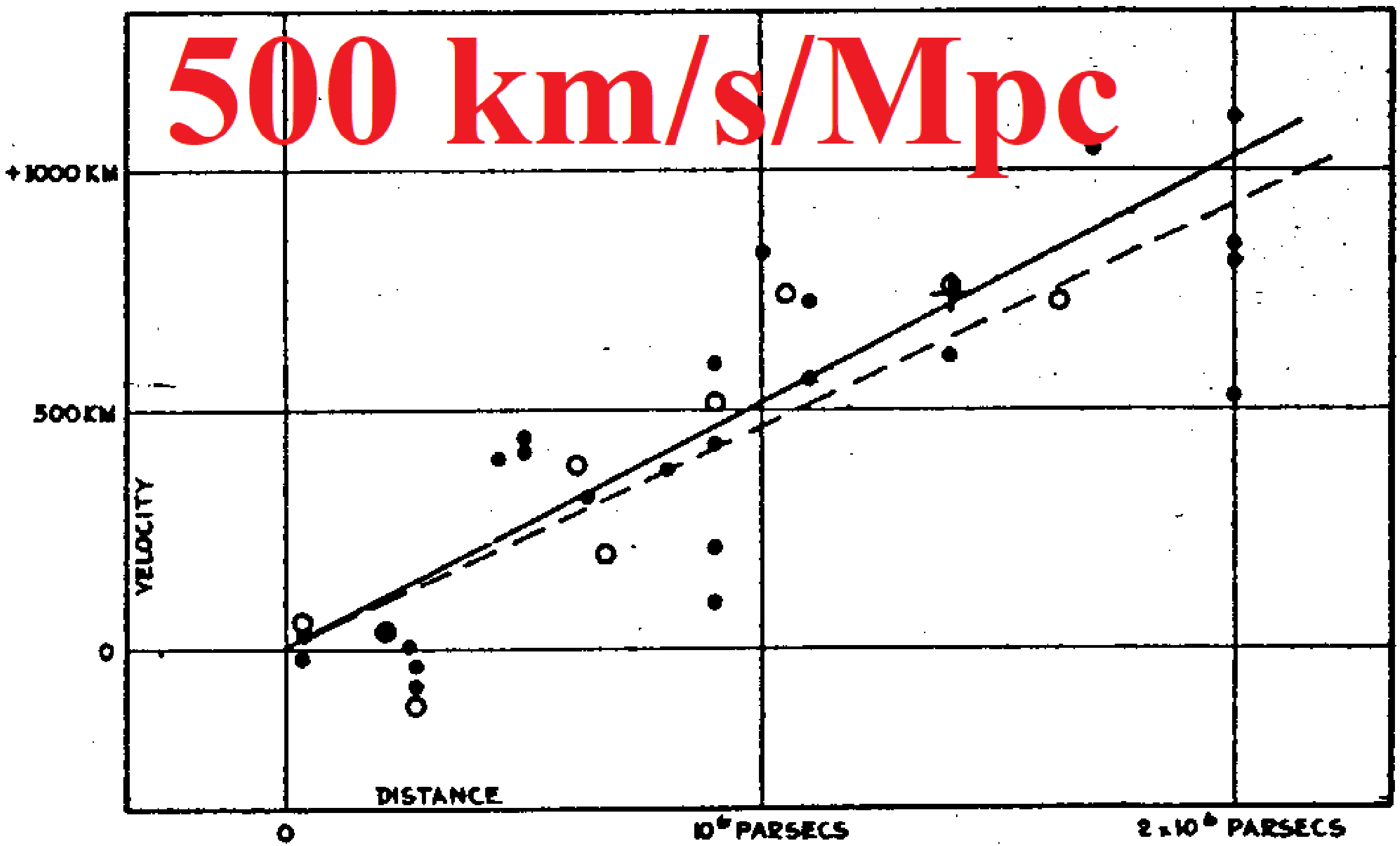
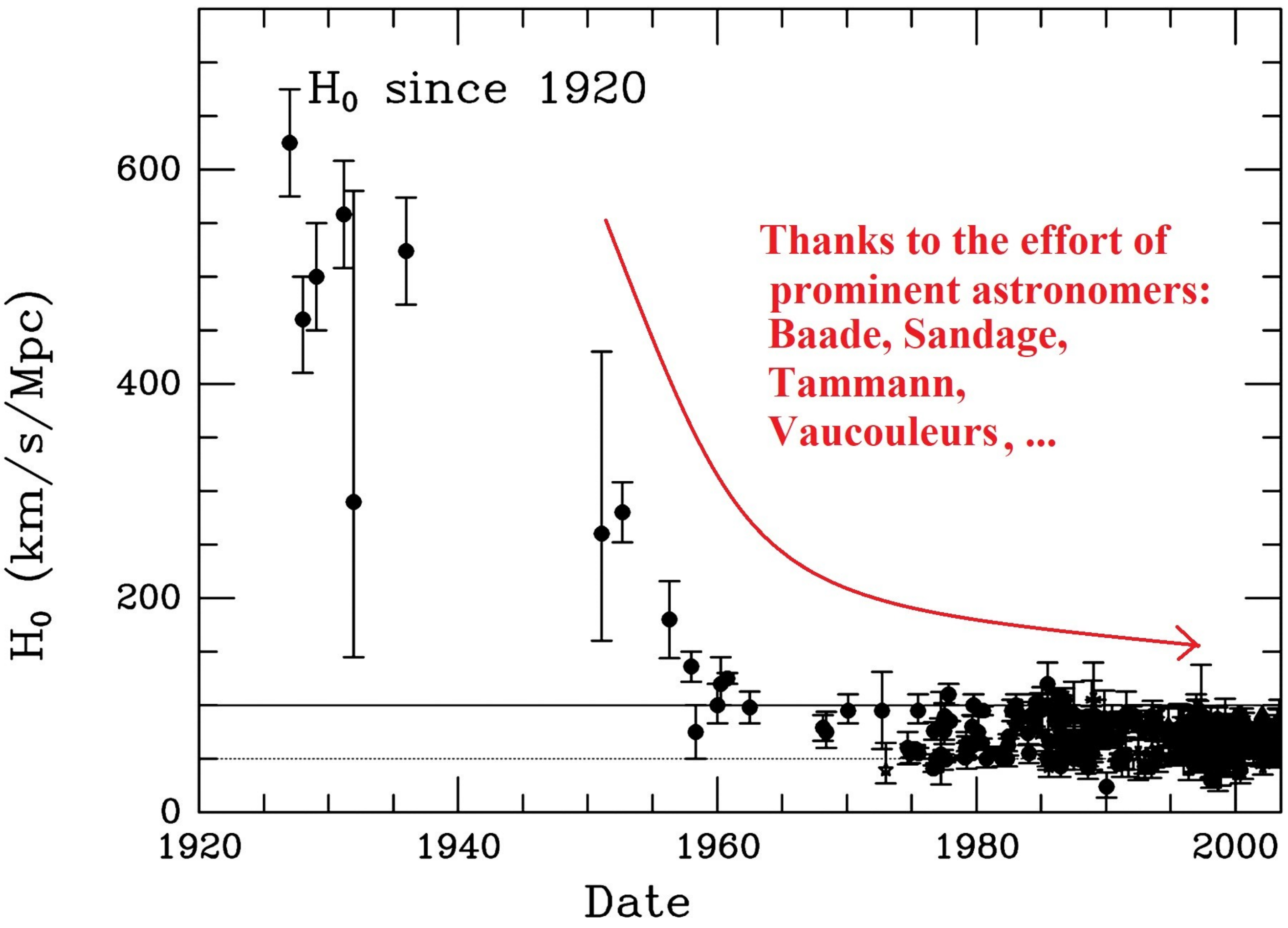


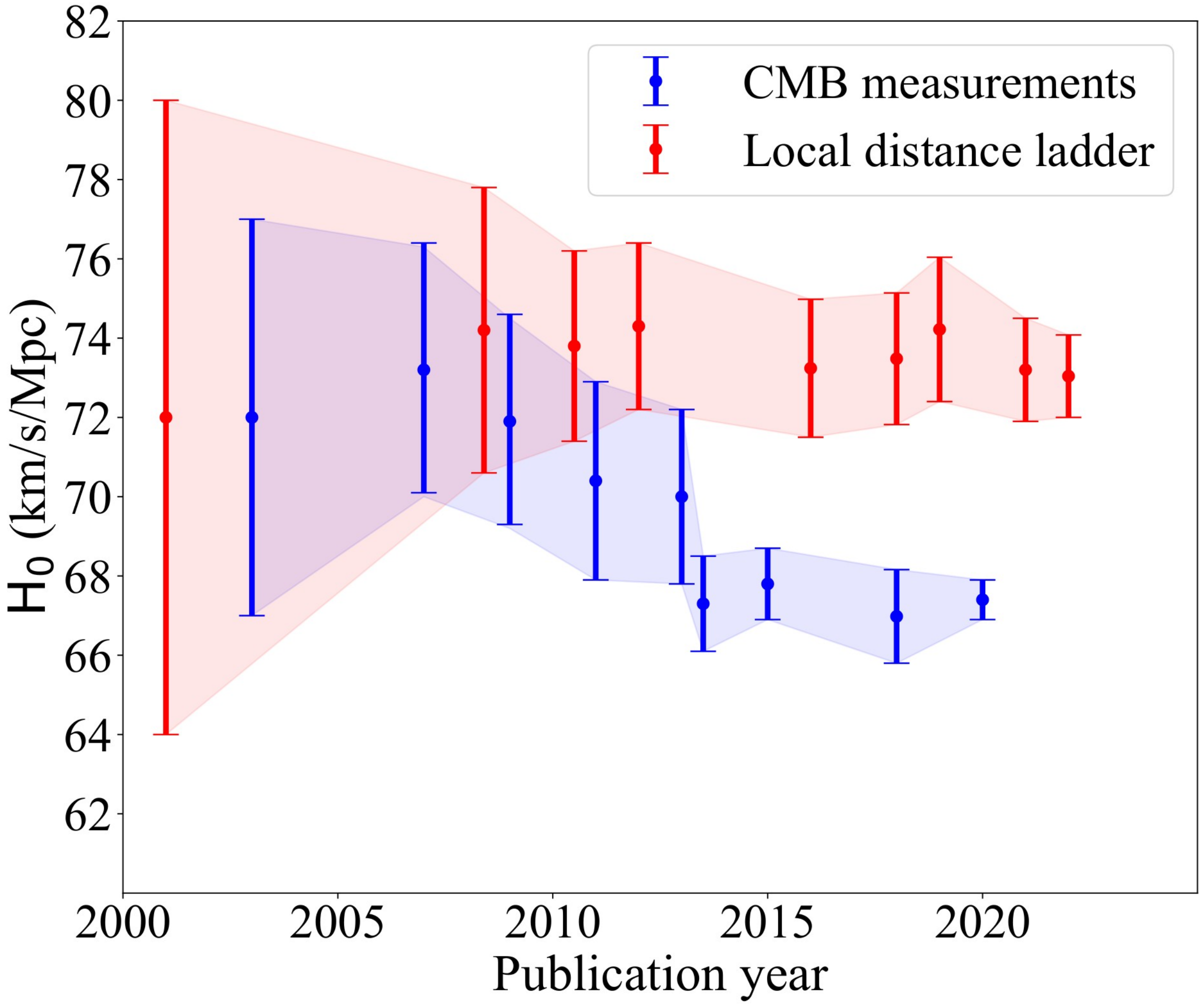
FIGURE 1



H_0 since 1920
Thanks to the effort of
prominent astronomers:
Baade, Sandage,
Tammann,
Vaucouleurs, ...
H_0 (km/s/Mpc)
0
200
400
600
1920
1940
1960
1980
2000
Date

H_o (km s^{-1} Mpc^{-1})	Technique	Reference
94 ± 11[a]	Lens 0957 + 561	Grogin & Narayan (1996)
81 ± 8	Cepheids in 4 Virgo spirals	van den Bergh (1995a)
80 ± 12	SB fluctuations	Jacoby et al. (1992)
78 ± 11	Globulars in M87	Whitmore et al. (1995)
76 ± 7	PN in Virgo Cluster	Jacoby (1996)
75 ± 8	PN in Fornax cluster	McMillan et al. (1993)
74 ± 14	Tip of RG branch	Sakai et al. (1996)
73 ± 6 ± 7	SNe II exp. photospheres	Kirshner (1996)
73 ± 6	D_n -σ (Vir, For, Leo)	Mould (1996)
70 - 74	Tully-Fisher	Giovanelli (1996)
70 ± 13	Novae in Virgo	Della Valle & Livio (1995)
66 ± 12	IR Tully-Fisher	Malhotra et al. (1996)
65 ± 6	SN Ia lightcurves	Riess et al. (1996)
64 ± 3	4 SNe Ia	Hamuy et al. (1996)
55 ± 17	Sunyaev - Zel'dovich effect	Birkinshaw & Hughes (1994)
55 - 60	SNe Ia (theory)	van den Bergh (1995b)
52 ± 9	SNe Ia (1937C)	Saha et al. (1994)
52 ± 8	SNe Ia (1972E)	Saha et al. (1995)
43 ± 11	Galaxy diameters	Sandage (1993a)

~5σ tension between SH0ES and Planck/ΛCDM



Direct cosmic distance ladder

ANCHORS

Milky Way	LMC	NGC 4258
(30 kpc) parallaxes	(50 kpc) DEBs	(7.2 Mpc) Maser

Calibration of Cepheids, Mira Variables, TRGB

HOST GALAXIES

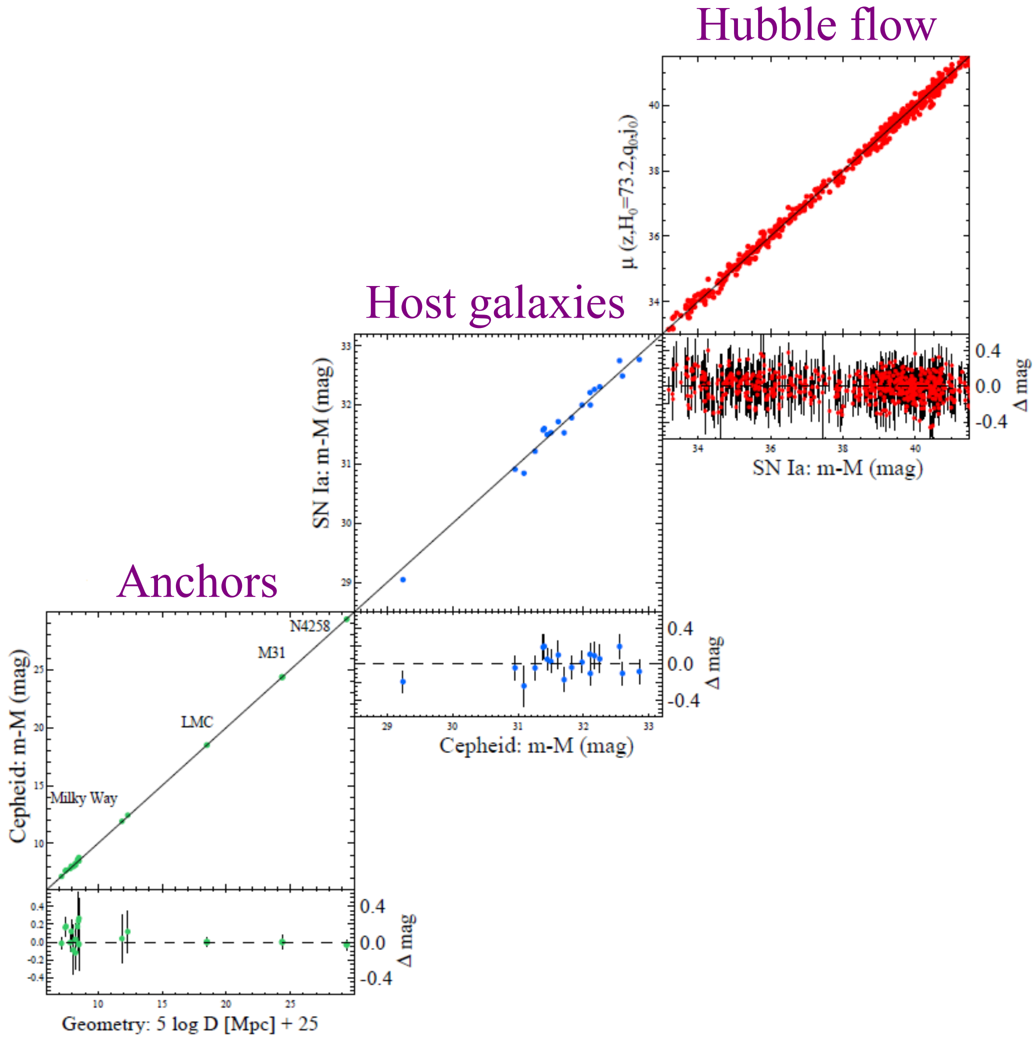
Cepheids/Miras/TRGBs + SNIa
42 , up to now
($z<0.01$; $d<40$ Mpc)

Calibration of SNIa

HUBBLE FLOW

SNIa
($0.02<z<0.15$; $d<600$ Mpc)

Hubble's law


Hubble flow
Host galaxies
Anchors
μ (z,H0=73.2,q0,j0)
SN Ia: m-M (mag)
Δ mag
Cepheid: m-M (mag)
Geometry: 5 log D [Mpc] + 25
N4258
M31
LMC
Milky Way

For stardardizable objects like SNIa:

$$m(z_{\rm HD}) = M + 25 + 5\log_{10}\left(\frac{D_L(z_{\rm HD})}{1\,{\rm Mpc}}\right)$$

And for SNIa in the Hubble flow:

$$D_L(z) = \frac{cz}{H_0}\left[1 + \frac{z}{2}(1-q_0)\right] + \mathcal{O}(z^3)$$

The calibration of SNIa in the host galaxies, combined with the SNIa in the Hubble flow, allows for a model-independent measurement of the Hubble constant

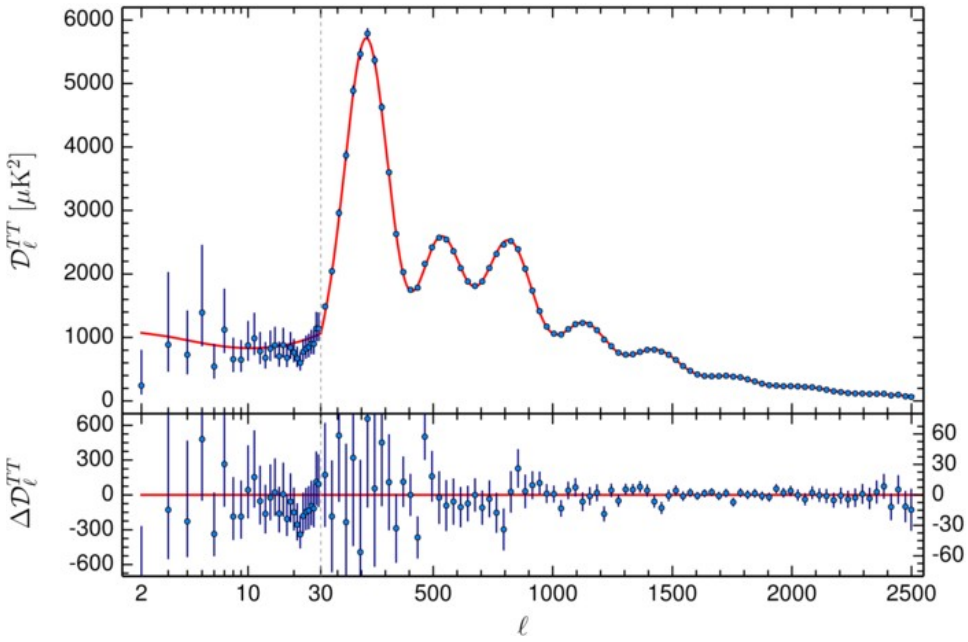
HST Key Project, HST Calibration Program, SH0ES

Year	Authors	$H_0\,(km/s/Mpc)$
2001	Freedman et al.	70 ± 8
2006	Sandage et al.	62.3 ± 5.2
2009	Riess et al.	74.2 ± 3.6
2016	Riess et al.	73.24 ± 1.74
2018	Riess et al.	73.48 ± 1.66
2019	Riess et al.	73.5 ± 1.4
2022	Riess et al.	73.04 ± 1.04

M = -19.253 ± 0.027 mag

A.G. Riess et al., ApJL, 934, 1, L17 (2022)

Planck/ΛCDM measurement of H_0



CMB allows the model-independent measurement of

$$\theta_* = \frac{r_d}{D_A(z_*)}$$

But the measurement of the two quantities in the ratio is model-dependent. In particular, the derived value

$$\boxed{H_0 = (67.36 \pm 0.54)\,\mathrm{km/s/Mpc}}$$

N. Aghanim et al., A&A, 641, A6 (2020)

Inverse cosmic distance ladder

Prior from Planck/ΛCDM on r_d + BAO data $H(z_i)r_d$ $D_A(z_i)/r_d$

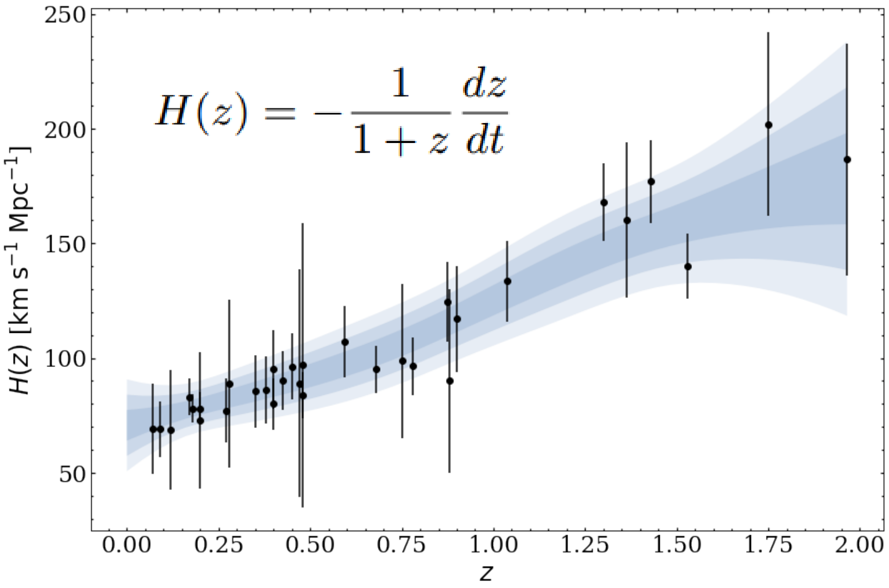
+ cosmography

Data	$H_0\,(km/s/Mpc)$
Planck 2013 prior, BOSS BAO, JLA SNIa	67.3 ± 1.1
Planck 2015 prior, BOSS BAO, Pantheon SNIa	68.57 ± 0.93
Planck 2018 prior, 6dFGS+SSDS MGS+BOSS BAO, DES SNIa	67.77 ± 1.30

Also in tension with the local distance ladder measurement

É. Aubourg et a., PRD, 92, 123516 (2015)
S.M. Feeney et al. PRL. 122, 061105 (2019)
E. Macaulay et al., MNRAS, 486, 2184 (2019)

Cosmic chronometers to anchor H_0



CCH + BAO + SNIa → measurement of r_d and M

	CCH+SNIa	CCH+BAO	CCH+SNIa+BAO
M [mag]	$-19.344^{+0.116}_{-0.090}$		$-19.314^{+0.086}_{-0.108}$
Ω_k	$-0.07^{+0.27}_{-0.21}$	-0.10 ± 0.18	$-0.07^{+0.12}_{-0.15}$
r_d [Mpc]		$141.9^{+5.6}_{-4.9}$	142.3 ± 5.3

$H_0 = (71.5 \pm 3.1)$ km/s/Mpc

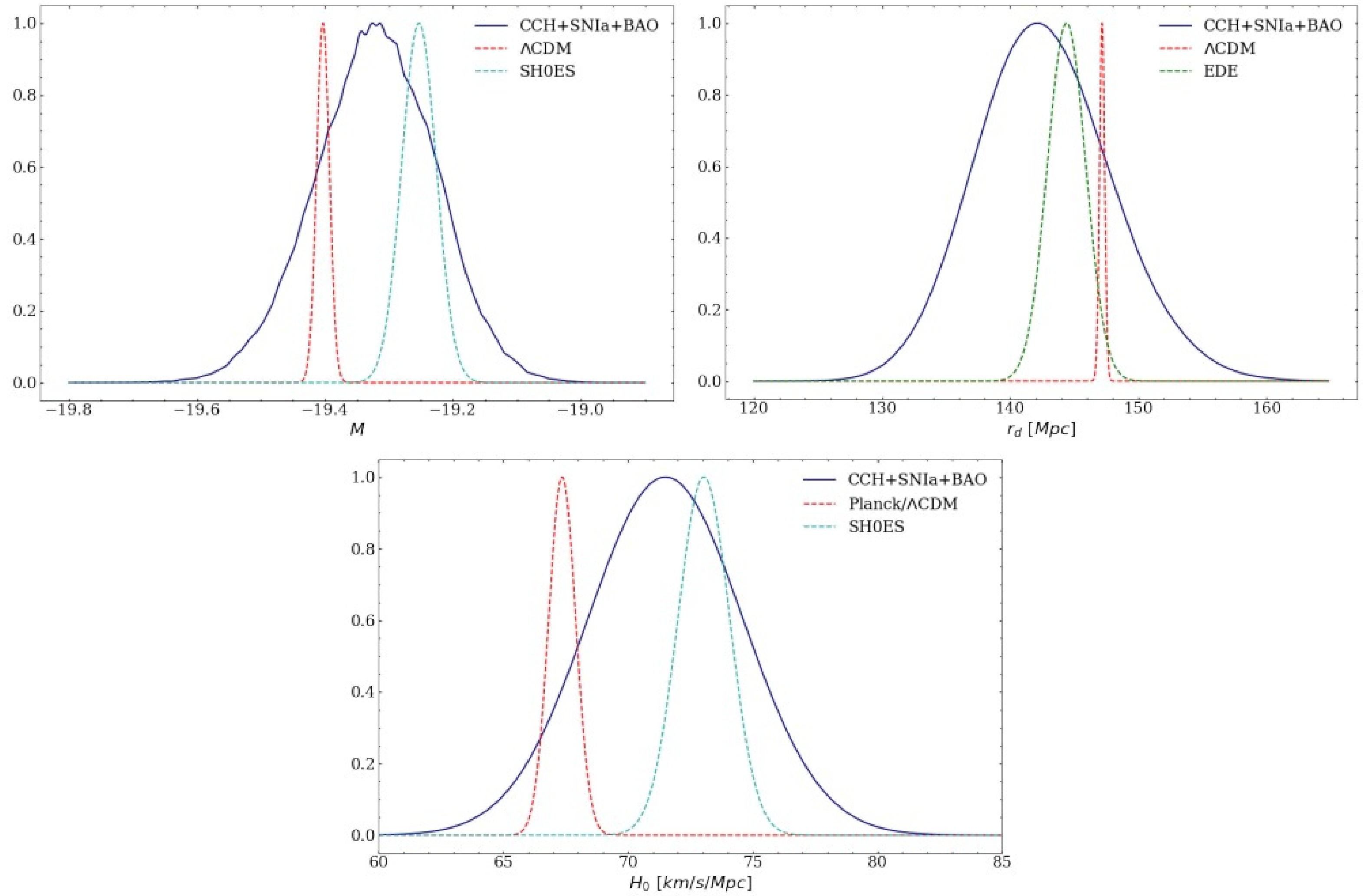
A. Favale, A. Gómez-Valent, M. Migliaccio, [arXiv:2301.09591]

See also:

B. Haridasu,V.V. Lukovic, M. Moresco, N. Vittorio, JCAP 10, 015 (2018) [arXiv:1805.03595]

A. Gómez-Valent, L. Amendola, JCAP 04, 051 (2018) [arXiv:arXiv:1802.01505]

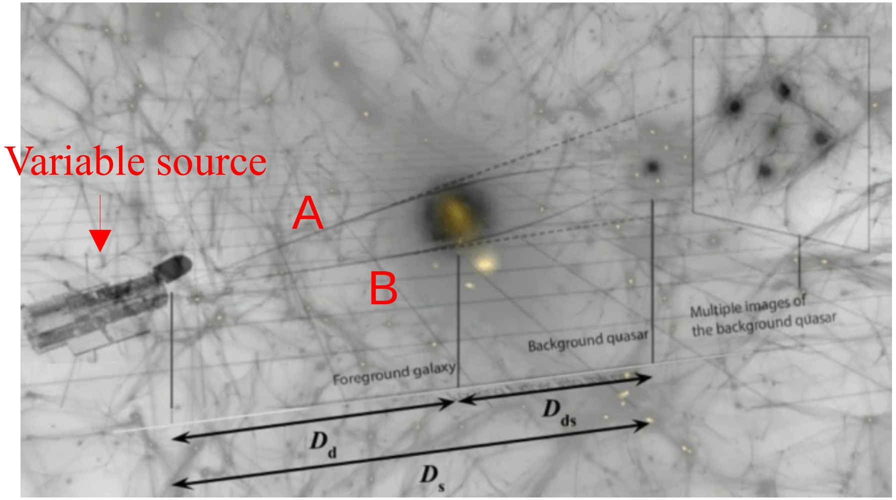
A. Gómez-Valent, Phys. Rev. D 105, 043528 (2022) [arXiv:2111.15450]

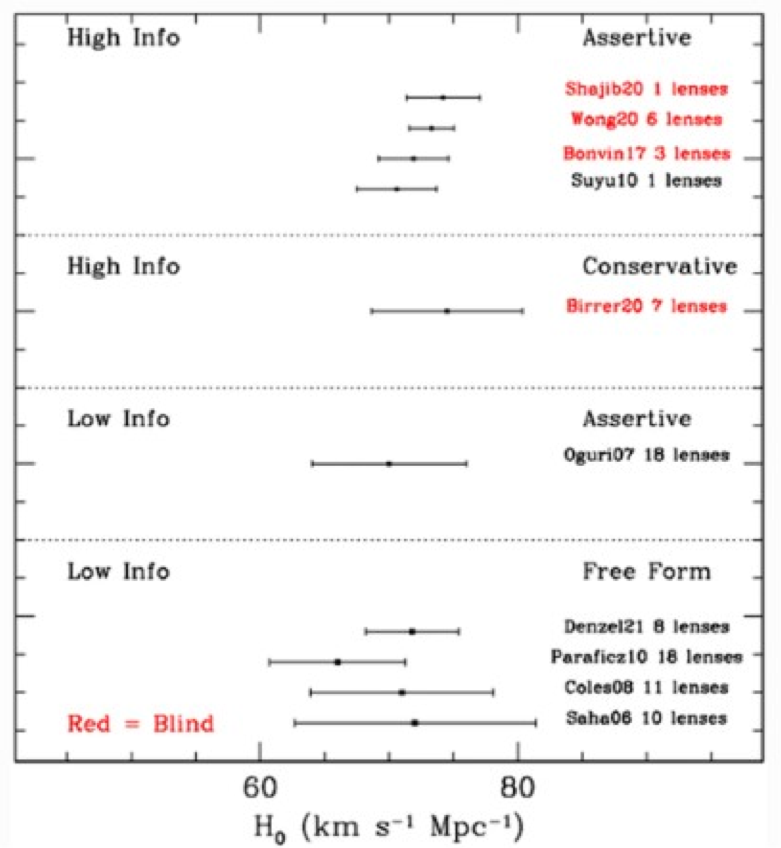

CCH+SNIa+BAO
ΛCDM
SH0ES
M
CCH+SNIa+BAO
ΛCDM
EDE
r_d [Mpc]
CCH+SNIa+BAO
Planck/ΛCDM
SH0ES
H_0 [km/s/Mpc]

Strong lensing and H_0

Time delay　　Diff. Fermat's potential　　Time-delay distance

$$\Delta\tau_{AB} = \frac{D_{\Delta t}}{c}\Delta\Phi_{AB}. \qquad D_{\Delta t} \equiv (1+z_d)\frac{D_d D_s}{D_{ds}}$$





T. Treu, S.H. Suyu, P.J. Marshall, Astron. & Astrophys. Rev. 30, 8 (2022) [arXiv:2210.15794]

(Bright) Standard Sirens

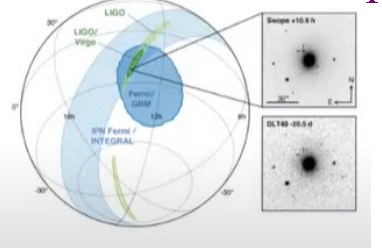
GW170817 event (NS-NS merger): GW
GRB 170817A: electromagnetic couterpart

$v = cz = H_0 D$

GRB

GW

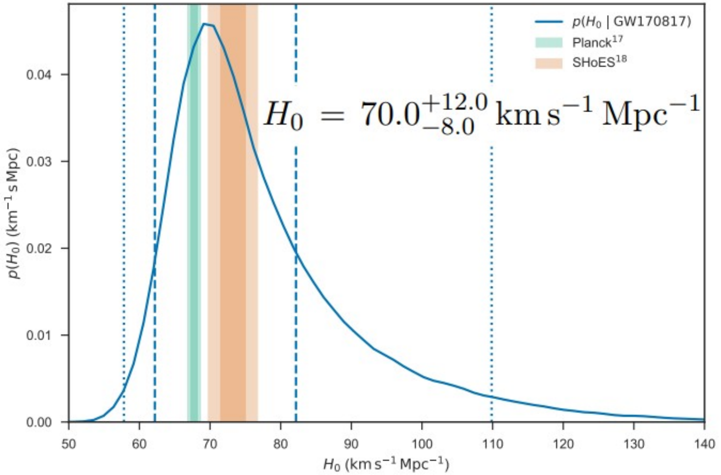
Redshift: EM follow-up, NGC 4993



Cosmological distance

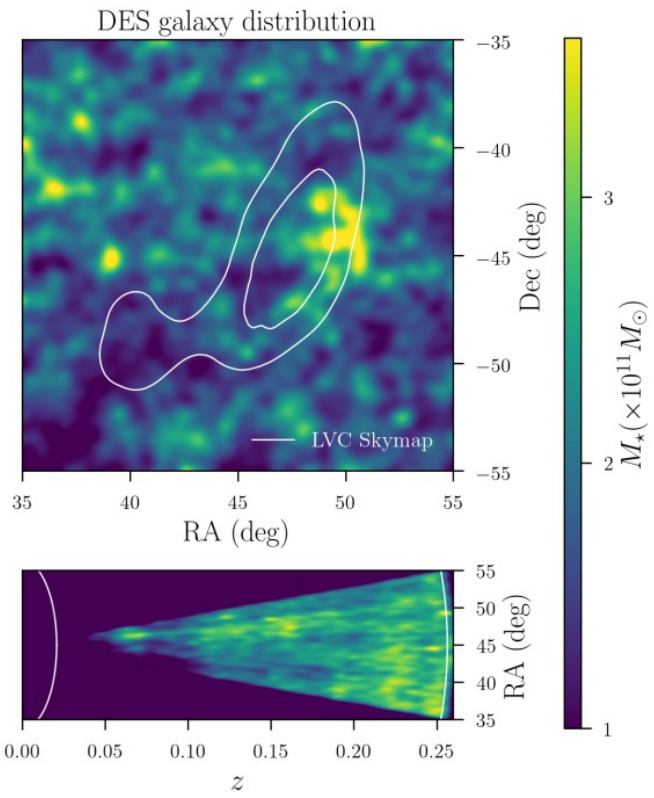
$$D = \frac{5}{96\pi^2}\frac{c}{h}\frac{\dot{f}_{GW}}{f_{GW}^3}$$

- D is the luminosity distance to the GW source
- h is the detector strain and dimensionless amplitude of the GW
- f_{GW} is the chirp frequency of the GW
- $\dot{f}_{GW}$ is the changing rate of GW chirp frequency



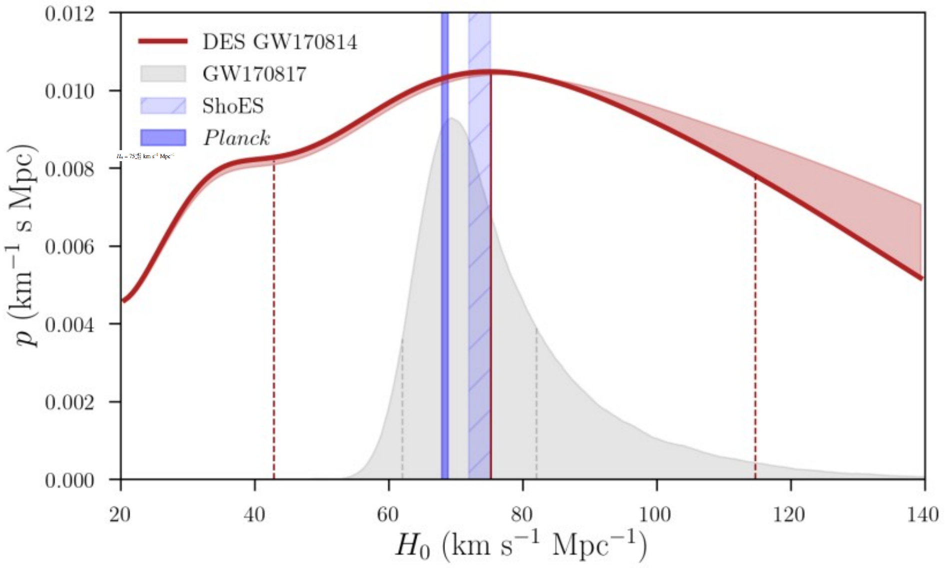
T.D. Abbott et al., Nature 551, 85 (2017) [arXiv:1710.05835]

(Dark) Standard Sirens



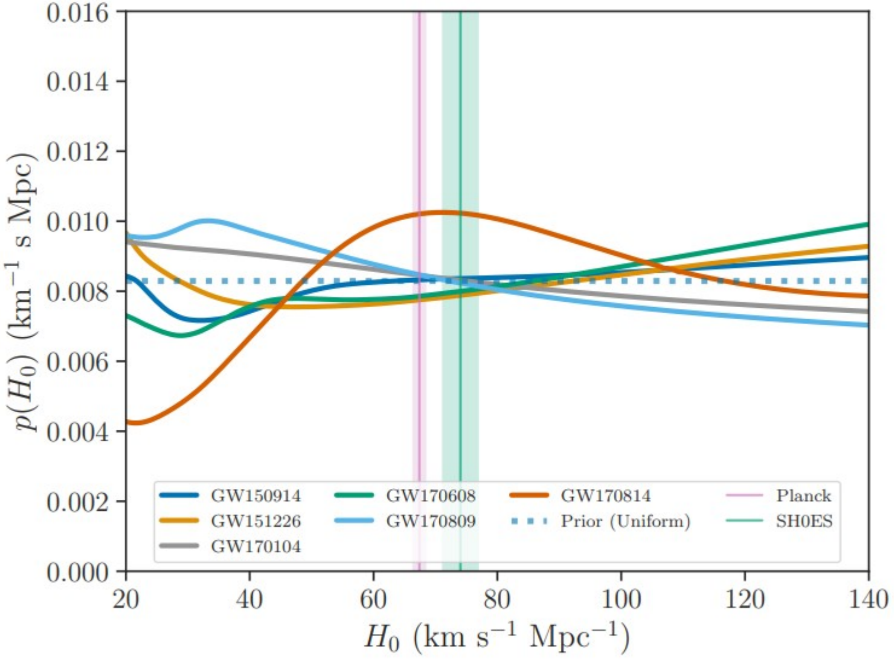
GW170814 event (BH-BH merger)

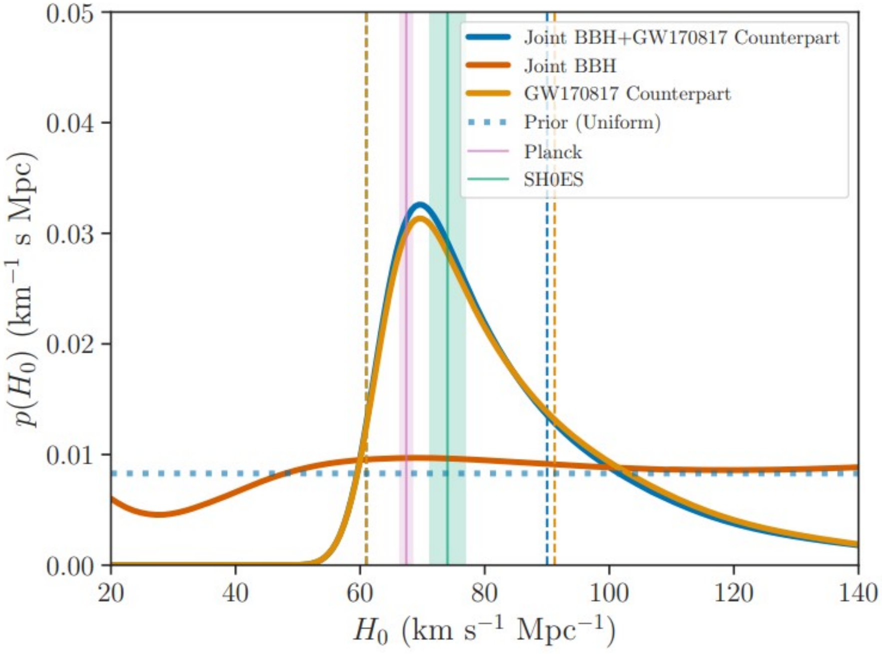
$$H_0 = 75^{+40}_{-32}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$



B. Schutz, Nature, 323, 310 (1986)
M. Soares-Santos et al., Astrophys. J. Lett. 876, L7 (2019) [arXiv:1901.01540]

Combining bright and dark sirens





B.P. Abbott et al., Astrophys.J. 909, 218 (2021) [arXiv:1908.06060]

Tension with LSS

First hint of tension with LSS

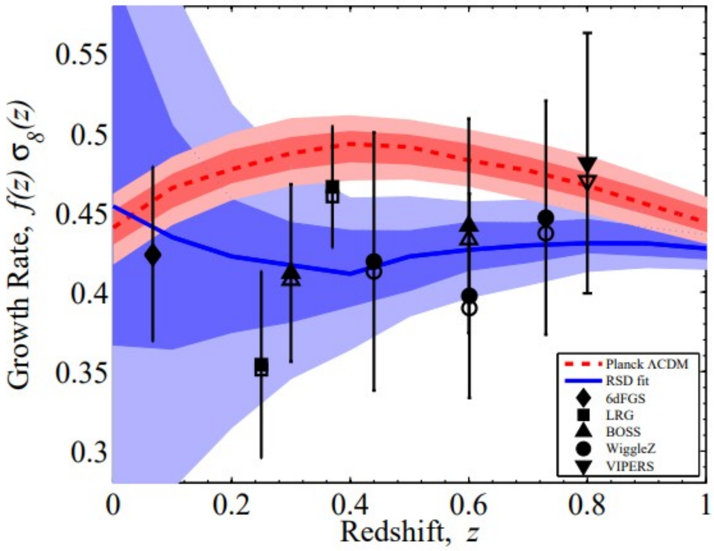
A Lower Growth Rate from Recent Redshift Space Distortion Measurements than Expected from Planck

E. Macaulay*
Department of Physics & Astronomy, University of Sussex, Falmer, BN1 9QH, UK and Astrophysics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK

I. K. Wehus†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA and Astrophysics, University of Oxford, DWB, Keble Road, Oxford, OX1 3RH, UK

H. K. Eriksen‡
Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway

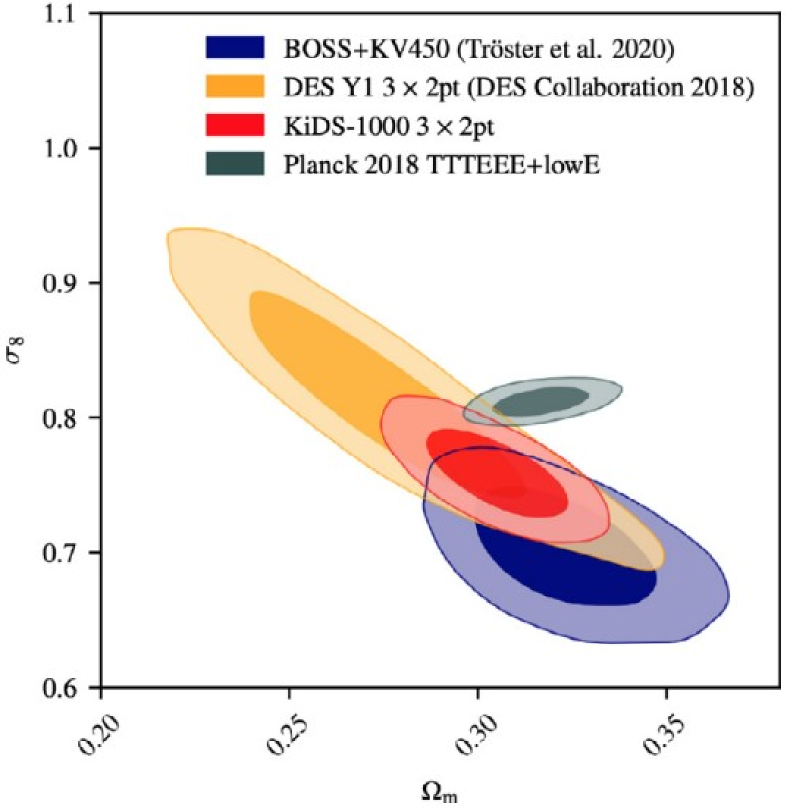
We perform a meta-study of recently published Redshift Space Distortion (RSD) measurements of the cosmological growth rate, $f(z)\sigma_8(z)$. We analyse the latest results from the 6dFGS, BOSS, LRG, WiggleZ and VIPERS galaxy redshift surveys, and compare the measurements to expectations from Planck. In this Letter we point out that the RSD measurements are consistently lower than the values expected from Planck, and the relative scatter between the RSD measurements is lower than expected. A full resolution of this issue may require a more robust treatment of non-linear effects in RSD models, although the trend for a low σ_8 agrees with recent constraints on σ_8 and Ω_m from Sunyaev-Zeldovich cluster counts identified in Planck.

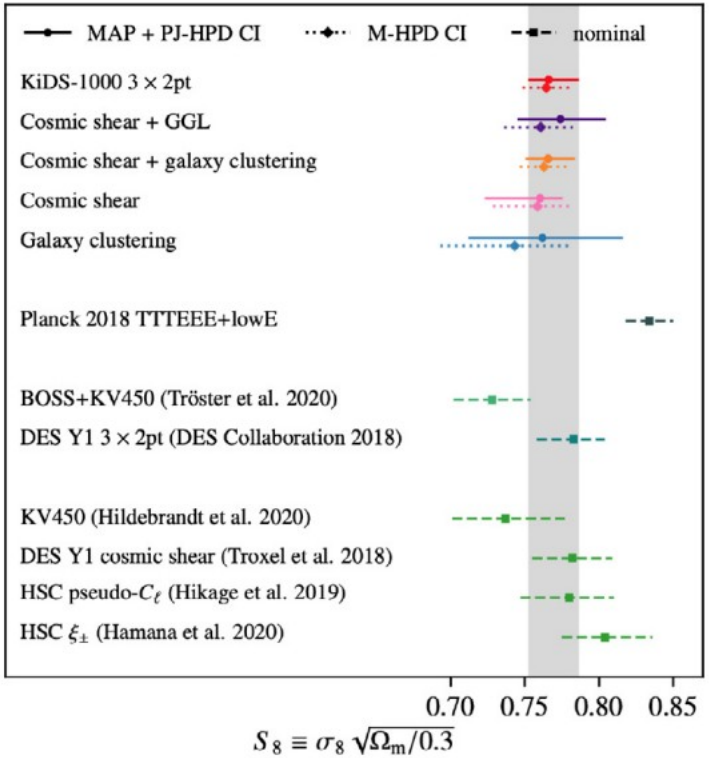


E. Macaulay et al., Phys. Rev. Lett. 111, 161301 (2013) [arXiv:1303.6583]

See also:
S. Nesseris et al., Phys. Rev. D, 96, 023542 (2017) [arXiv:1703.10538]
W. Lin, M. Ishak, Phys. Rev. D, 96, 083532 (2017) [arXiv:1708.09813]
A. Gómez-Valent, J. Solà, MNRAS 478, 126 (2018) [arXiv:1801.08501]
C. Garcia-Quintero et al., Phys. Rev. D, 100, 123538 (2019) [arXiv:1910.01608]

Weak lensing measurements





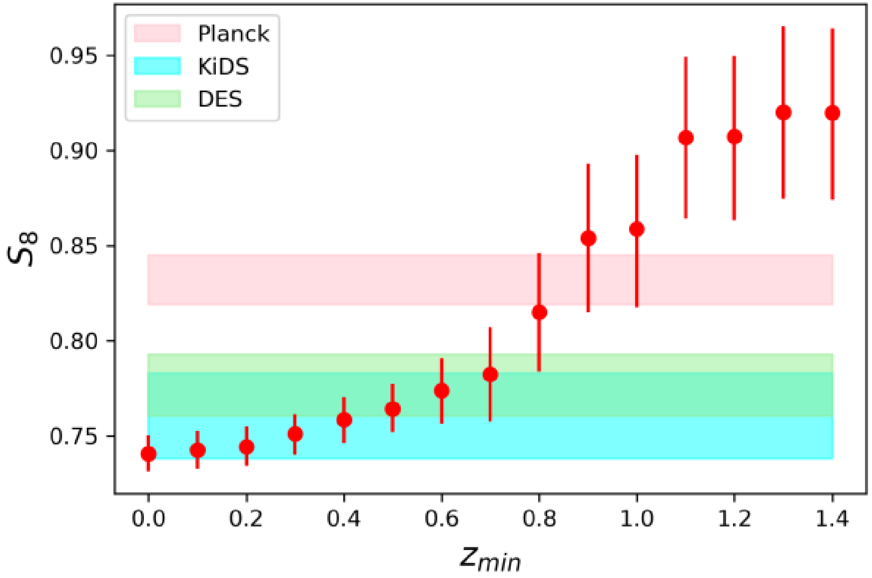
E. Di Valentino et al., Astropart. Phys. 131, 102604 (2021) [arXiv:2008.11285]

Late-time tension?

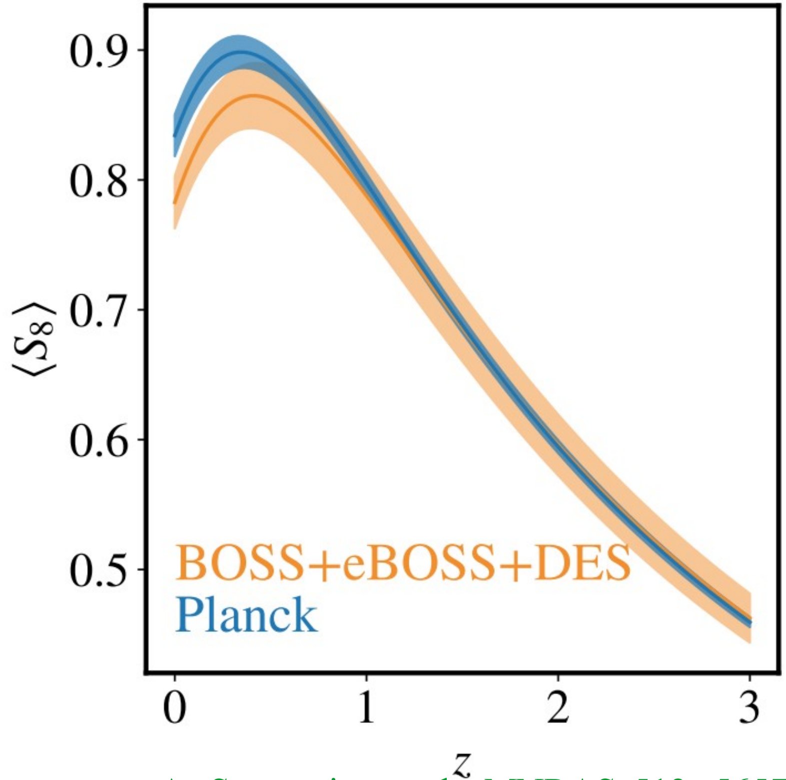
$$S_8 := \sigma_8 \sqrt{\Omega_m/0.3}$$

$$\Omega(z) := \frac{\Omega_m(1+z)^3}{1-\Omega_m+\Omega_m(1+z)^3}$$

$$f\sigma_8(z) = \sigma_8\, \Omega^{\frac{6}{11}}(z) \exp\left(-\int_0^z \frac{\Omega^{\frac{6}{11}}(z')}{1+z'}\mathrm{d}z'\right)$$



S.A. Adil et al. [arXiv:2303.06928]



A. Semenaite et al., MNRAS 512, 5657 (2022) [arXiv:2111.03156]

Is σ_8 a good LSS estimator to perform comparisons between models?

$$\sigma_8^2 = \frac{1}{2\pi^2}\int_0^\infty dk k^2 P(k)[W(kR_8)]^2$$ with R_8=8h^{-1} Mpc

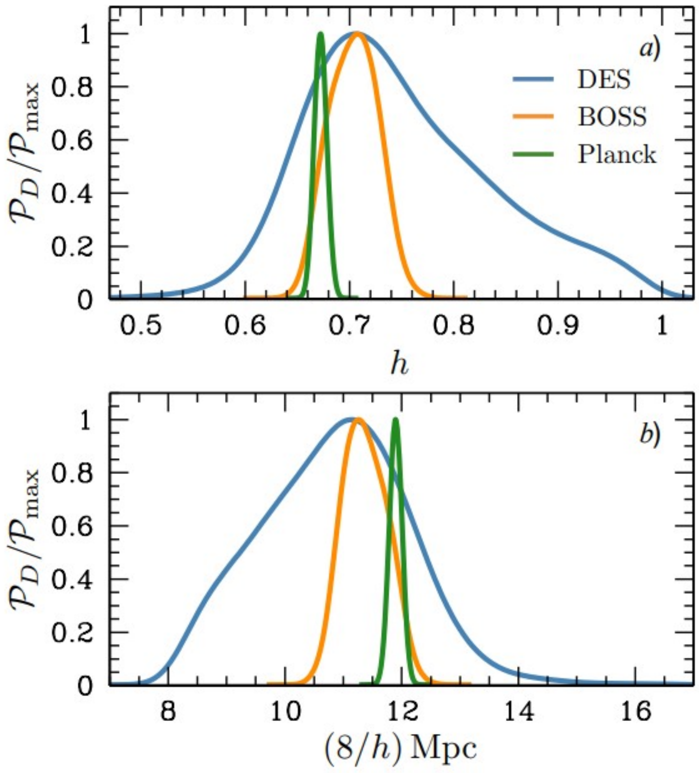
Imagine we have two different model with the same preferred shape of P(k) but with different posteriors of H_0

We will have two different values of σ_8, even if the power spectra are identical!

This fact might intertwine the two tensions in a non-trivial way, maybe even biasing our conclusions

New estimators σ_{12} and S_{12}

A.G. Sanchez et al., Phys. Rev. D 102, 123511 (2020) [arXiv:2002.07829]



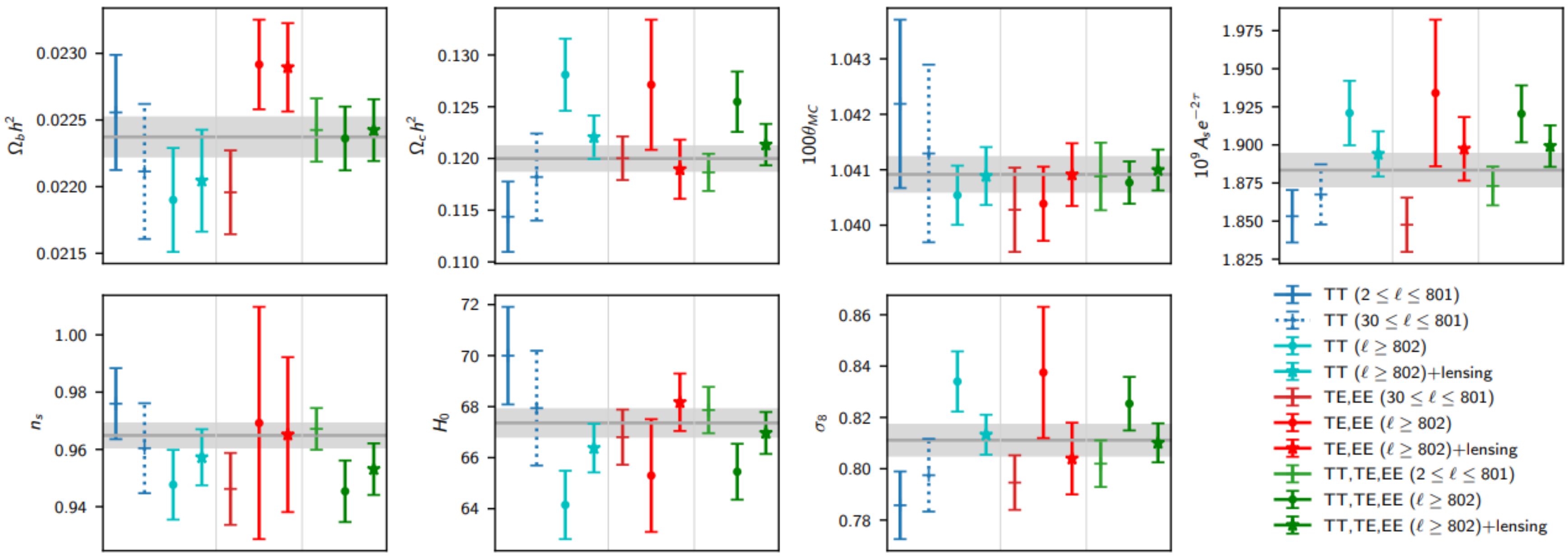
In order to obtain more representative results we might need to define a LSS estimator evaluated at a fixed scale (independent from h).

$$\sigma_{12}^2 = \frac{1}{2\pi^2}\int_0^\infty dk k^2 P(k)[W(kR_{12})]^2$$ with R_{12}=12 Mpc

$$S_{12} = \sigma_{12}\,(\omega_{\rm m}/0.14)^{0.4}$$

CMB anomalies and others

ΛCDM best-fit values from high- and low-l

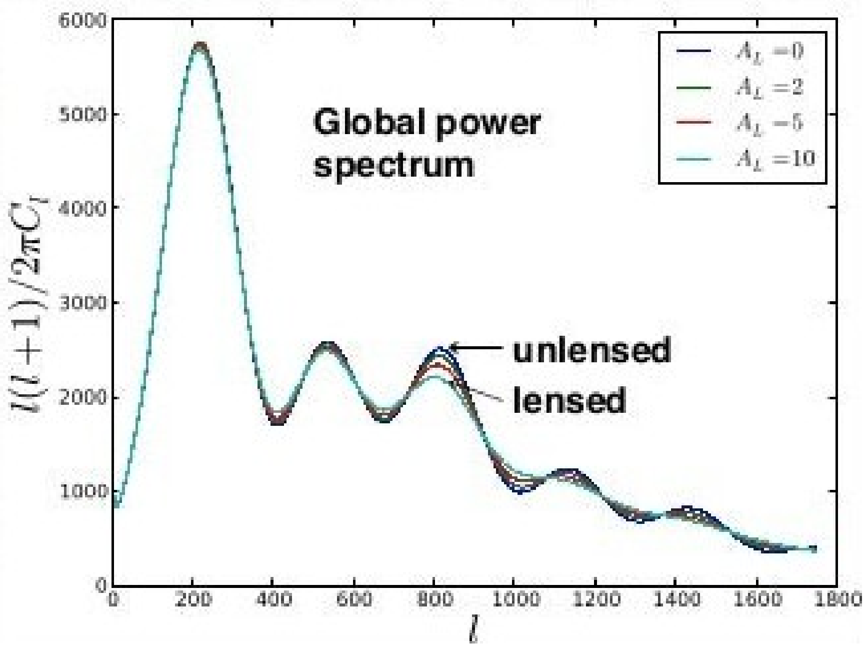


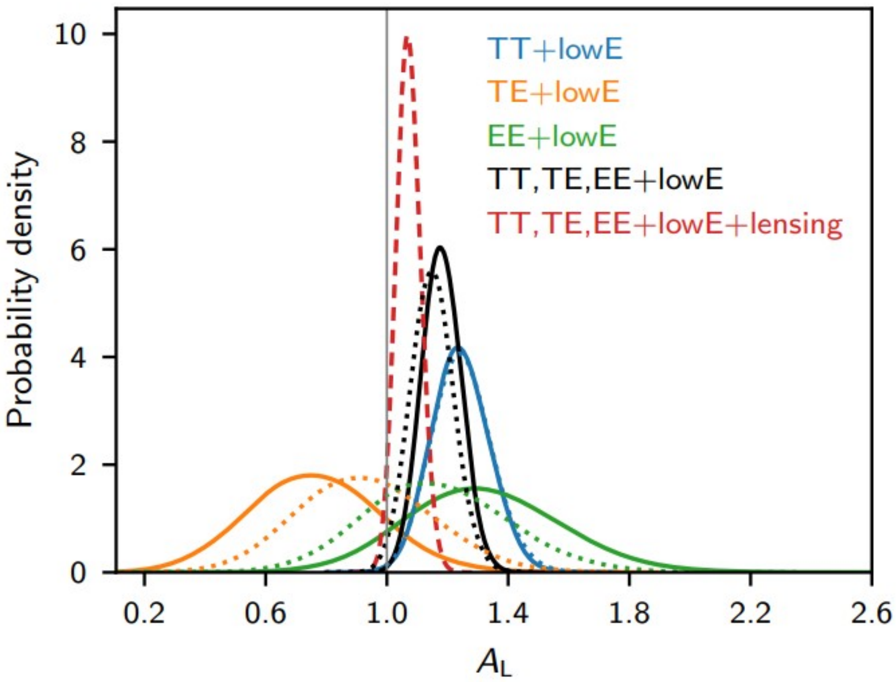
$\gtrsim 2\sigma$ tension between the best-fit values obtained from the high-l and low-l TT analyses

N. Aghanim et al., Astron. Astrophys. 641, A6 (2020) [arXiv:1807.06209]

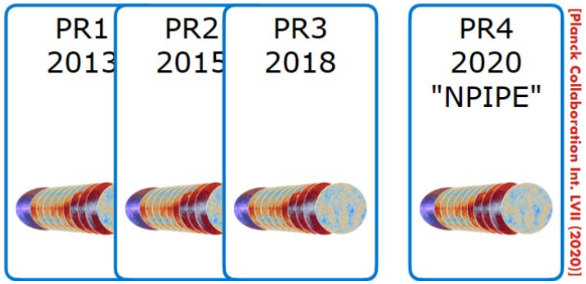
CMB lensing anomaly

The CMB lensing produces a smoothing of the CMB peaks at large multipoles



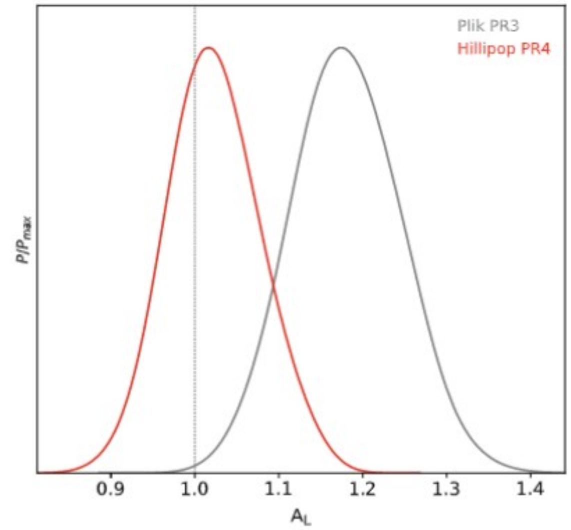


$$A_L = 1.243 \pm 0.096 \quad (68\%, \textit{ Planck} \text{ TT+lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\%, \textit{ Planck} \text{ TT,TE,EE+lowE})$$

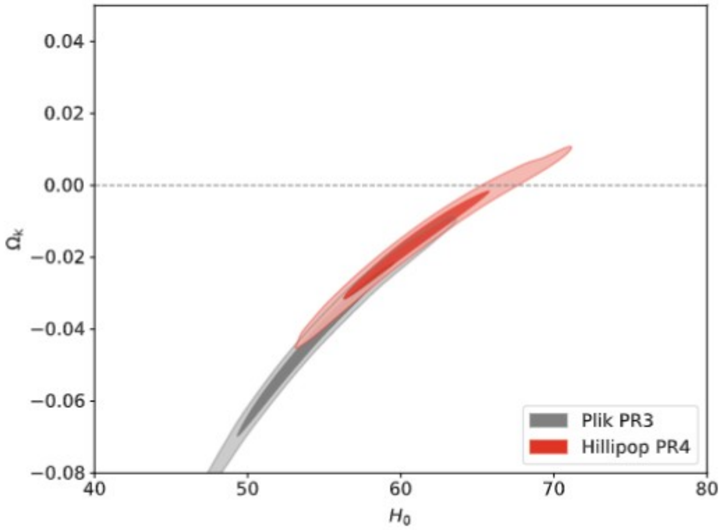


Taken from a talk by *Tristam Matthieu* (work in prep.)
Conference: Future Science with CMB x LSS

- **A_{lens}**



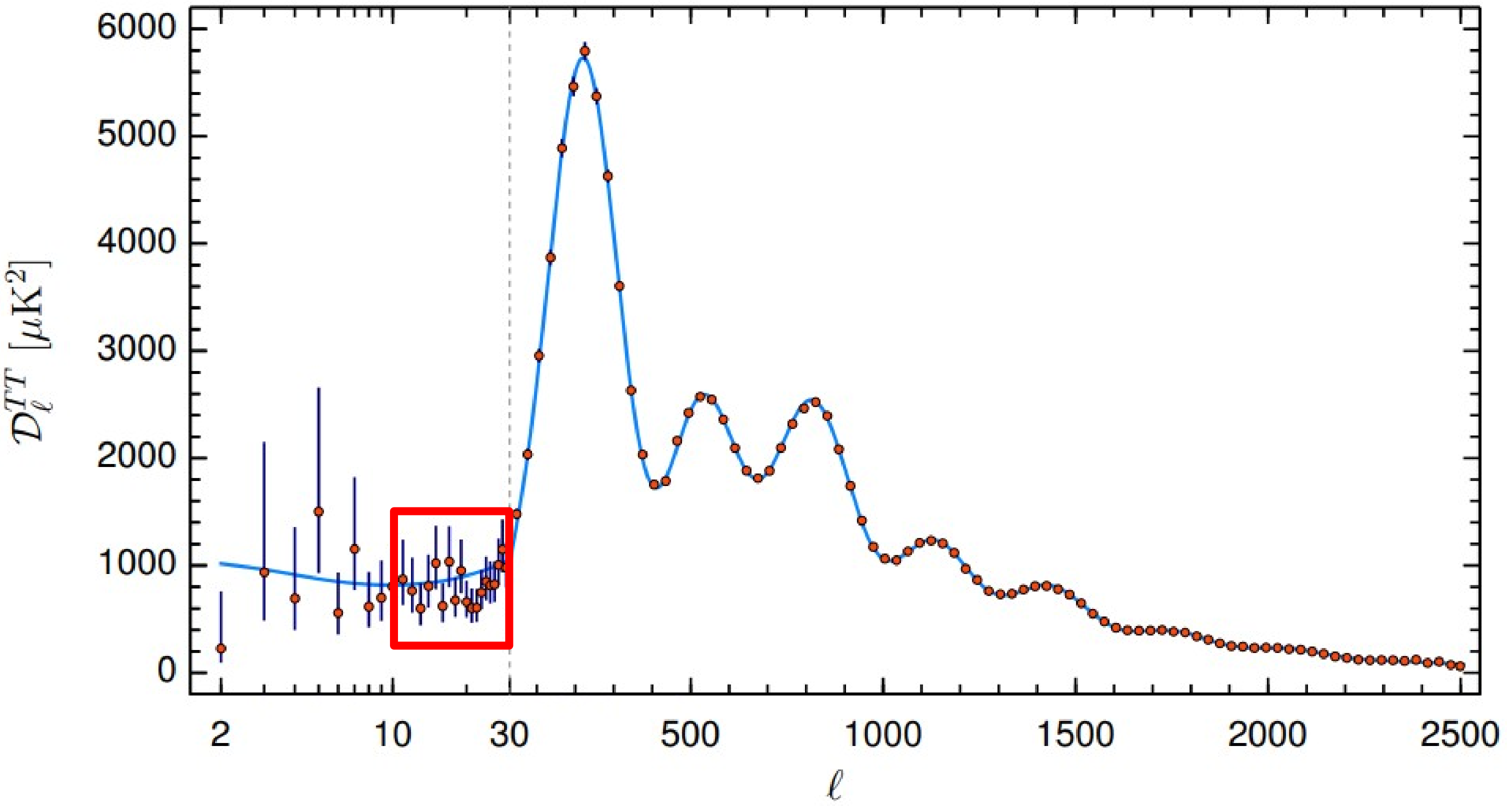
- **curvature Ω_K**



But still:

- **low H_0** compared to SNIa
- **high S_8** compared to LSS

Lack of power at large scales



Cosmological birefringence: new parity violating force in nature?

$$\mathcal{L} \supset -\frac{g_\phi}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$$ with $$\widetilde{F}^{\mu\nu} \equiv \tfrac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

→ Rotation of the linear polarization plane of CMB photons, which introduces a non-null correlation between the E/B modes.

N. Aghanim et al., Astron.Astrophys. 596, A110 (2016) [arXiv:1605.08633] → $\beta = 0.35 \pm 0.28$ deg
Y. Mimami, E. Komatsu, Phys.Rev.Lett. 125, 221301 (2020) [arXiv:2011.11254] → $\beta = 0.35 \pm 0.14$ deg
P. Diego-Palazuelos et al., Phys.Rev.Lett. 128, 091302 (2022) [arXiv:2201.07682] → $\beta = 0.30 \pm 0.11$ deg
J.R. Eskilt, E. Komatsu, Phys.Rev.D 106, 063503 (2022) [arXiv:2205.13962] → $\beta = 0.34 \pm 0.09$ deg

Fifth forces in the *dark* sector

Based on:

** A. Gómez-Valent, V. Pettorino, L. Amendola, Phys.Rev.D 101, 123513 (2020) [arXiv:2004.00610]
** A. Gómez-Valent, Phys.Rev.D 106, 063506 (2022) [arXiv:2203.16285]
** A. Gómez-Valent, Z. Zheng, L. Amendola, C. Wetterich, V. Pettorino, Phys. Rev.D 106 (2022) 10, 103522 [arXiv:2207.14487]
** L.W.K. Goh, A. Gómez-Valent, V. Pettorino, M. Kilbinger, [arXiv:2211.13588]

Outline of Part II

* Basics of coupled dark energy with a conformal coupling:
background and perturbation eqs.

* Impact on the CMB temperature and matter power spectra

* Cosmological constraints on a constant and time-dependent couplings

Coupled dark energy (CDE)

$$\nabla^\mu T^\phi_{\mu\nu} = +Q_\nu$$
$$\nabla^\mu T^{\rm dm}_{\mu\nu} = -Q_\nu$$

with $\quad Q_\nu = \kappa\beta T^{\rm dm}\nabla_\nu\phi$

Background equations

$$\bar\rho'_{\rm dm} + 3\mathcal{H}\bar\rho_{\rm dm} = -\beta\kappa\bar\rho_{\rm dm}\phi'$$

$$m_{\rm dm}(\phi) = m^{(0)}_{\rm dm} e^{\beta\kappa(\phi^{(0)}-\phi)}$$

$$\phi'' + 2\mathcal{H}\phi' + a^2\frac{dV}{d\phi} = \beta\kappa a^2\bar\rho_{\rm dm}$$

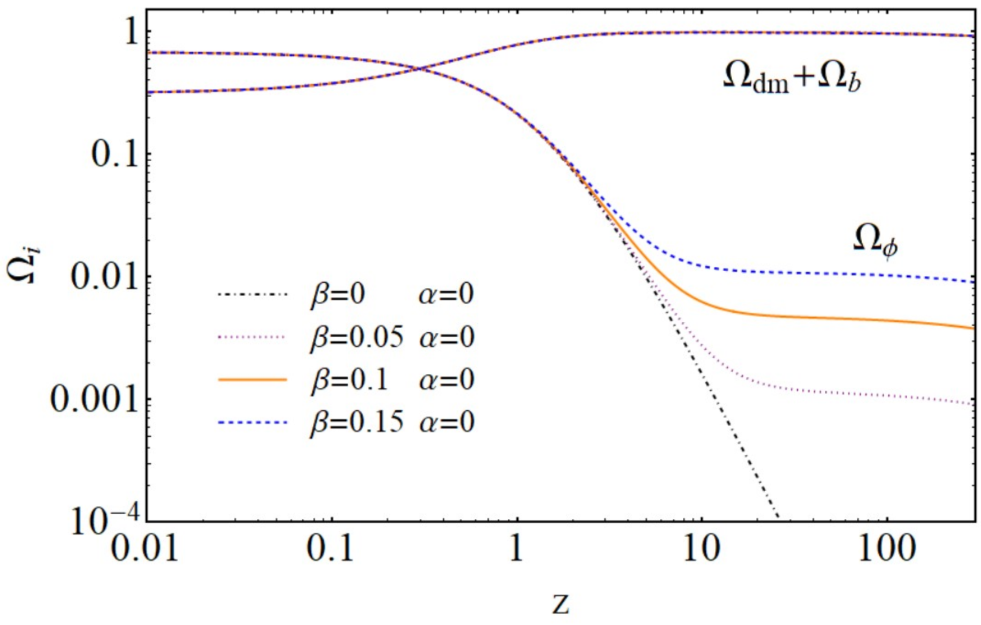
Linear perturbation equations

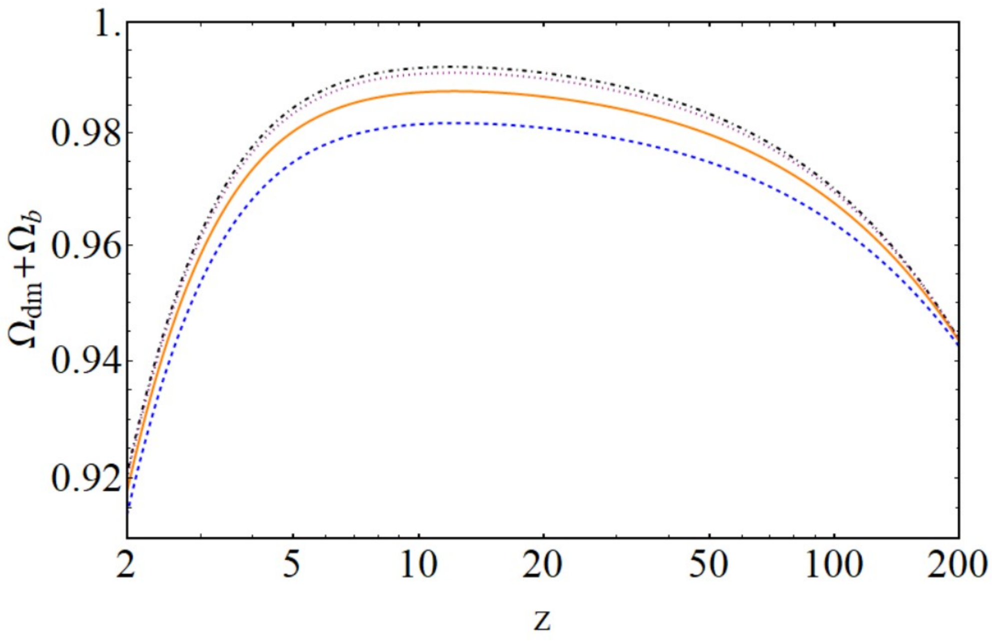
$$\delta''_{\rm b} + \mathcal{H}\delta'_{\rm b} - \frac{\kappa^2 a^2}{2}[\bar\rho_b\delta_b + \bar\rho_{\rm dm}\delta_{\rm dm}] = 0$$

$$\delta''_{\rm dm} + \left[\mathcal{H} - \frac{\beta\kappa\phi' k^2}{k^2 + a^2 m_\phi^2}\right]\delta'_{\rm dm} + (\delta'_b - \delta'_{\rm dm})\frac{\beta\kappa\phi' a^2 m_\phi^2}{k^2 + a^2 m_\phi^2} - \frac{\kappa^2 a^2}{2}\left[\bar\rho_b\delta_b + \bar\rho_{\rm dm}\delta_{\rm dm}\left(1 + \frac{2\beta^2 k^2}{k^2 + a^2 m_\phi^2}\right)\right] = 0$$

$$\delta''_{\rm dm} + [\mathcal{H} - \beta\kappa\phi']\,\delta'_{\rm dm} - \frac{\kappa^2 a^2}{2}\left[\bar\rho_b\delta_b + \bar\rho_{\rm dm}\delta_{\rm dm}(1 + 2\beta^2)\right] = 0$$

C. Wetterich, A&A 301, 321 (1995)
L. Amendola, PRD 62, 043511 (2000) [astro-ph/9908023]





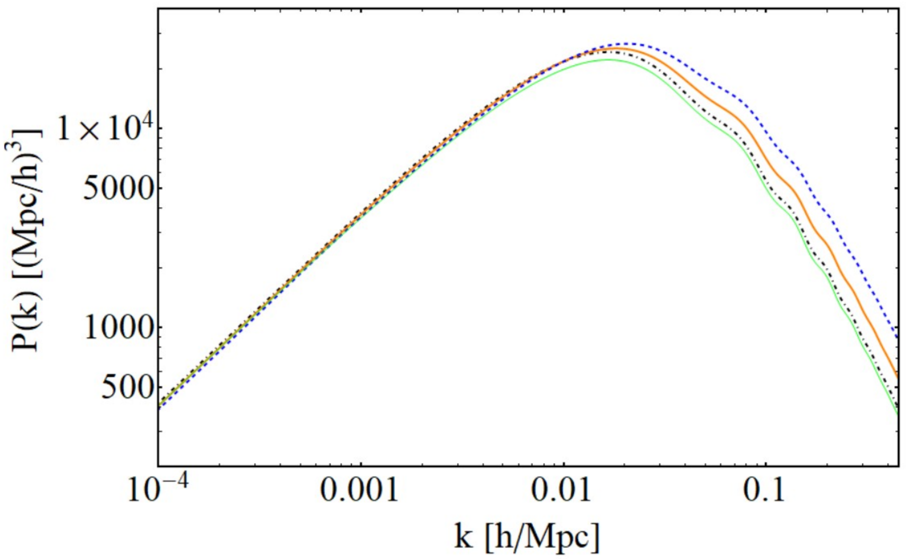
$$(\Omega_{dm}, \Omega_\phi) = (1 - 2\beta^2/3, \quad 2\beta^2/3)$$

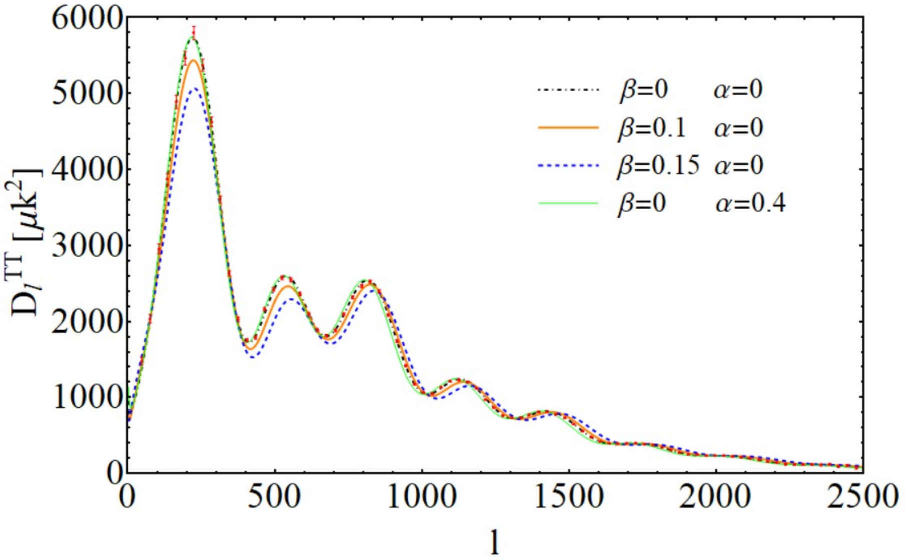
$$q = \frac{1}{2} + \beta^2$$

Scaling solution during matter-domination

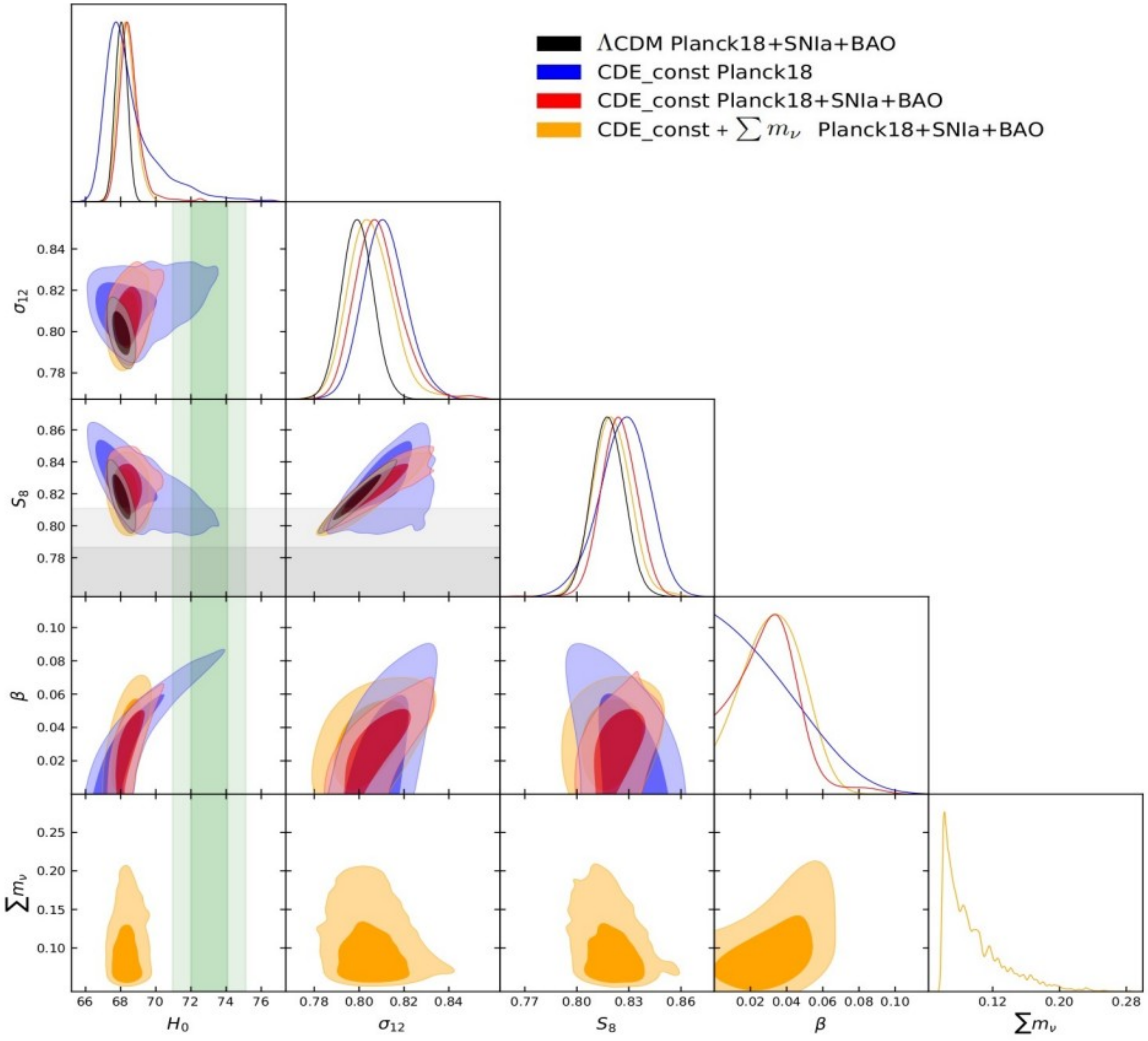
The universe is more decelerated

A flat potential $V_0 \sim (M_{pl}H_0)^2$





** A. Gómez-Valent, V. Pettorino, L. Amendola, Phys.Rev.D 101, 123513 (2020)

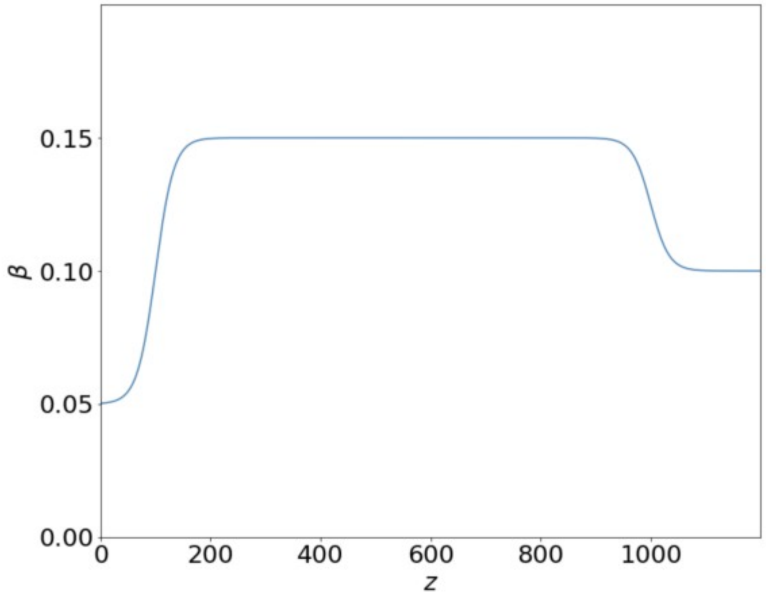


**A. Gómez-Valent, Z. Zheng, L. Amendola, C. Wetterich, V. Pettorino, PRD 106 (2022) 10, 103522 [arXiv:2207.14487]

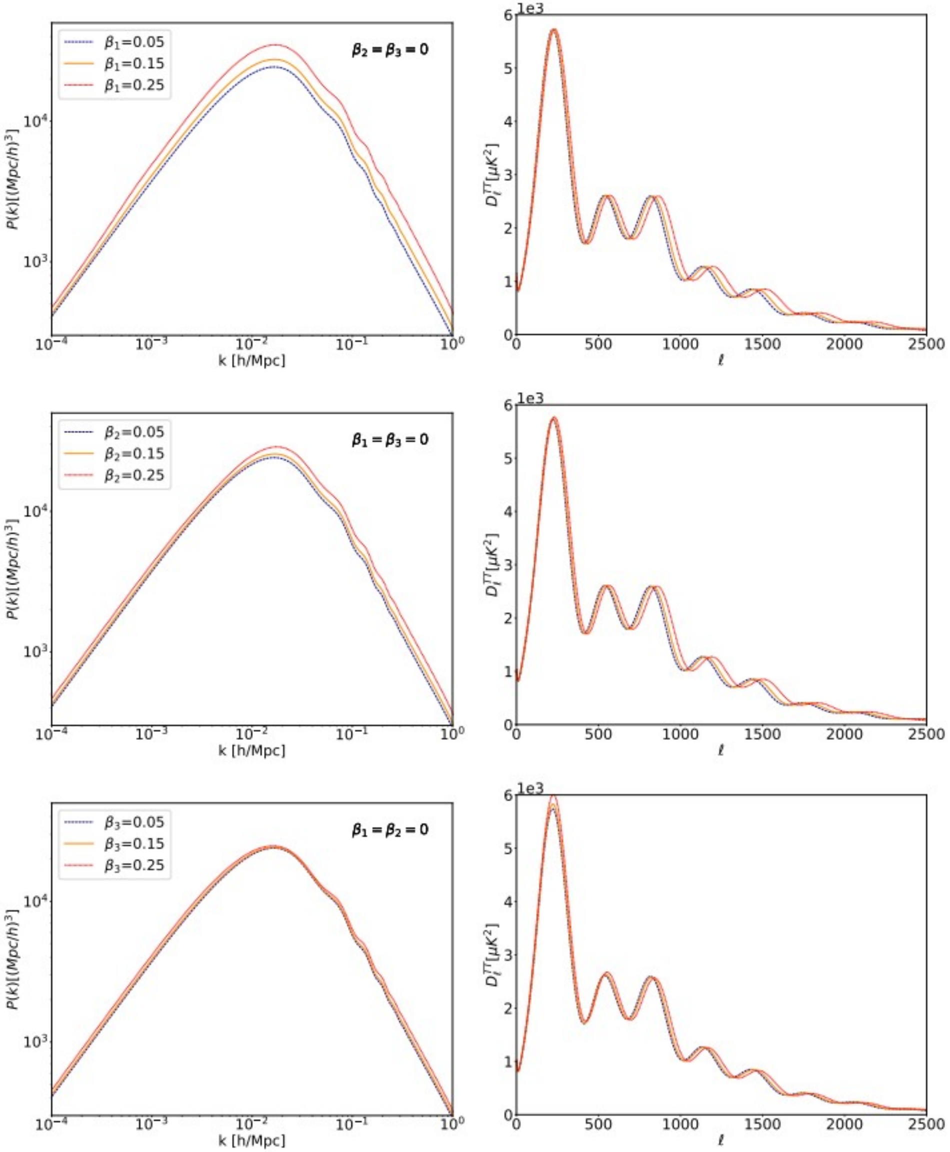
What if we depart from the β=const. scenario?

$$\beta(z) = \frac{\beta_1 + \beta_n}{2} + \frac{1}{2}\sum_{i=1}^{n-1}(\beta_{i+1} - \beta_i)\tanh[s_i(z - z_i)]$$

Are the data sensitive to the evolution of β?



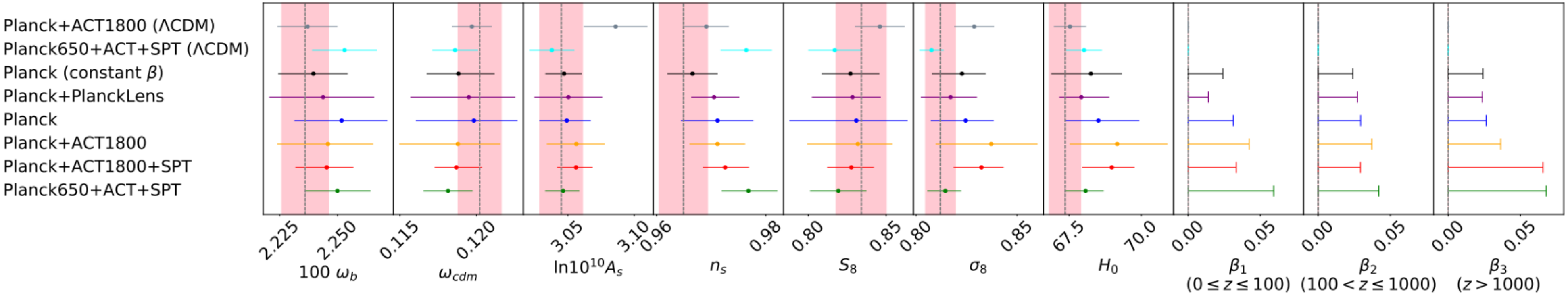
L.W.K. Goh, A. Gómez-Valent, V. Pettorino, M. Kilbinger, [arXiv:2211.13588]



The coupling at the various epochs have a different impact on the cosmological observables

The model should be sensitive to data from different redshifts

CMB constraints from Planck, ACT and SPT



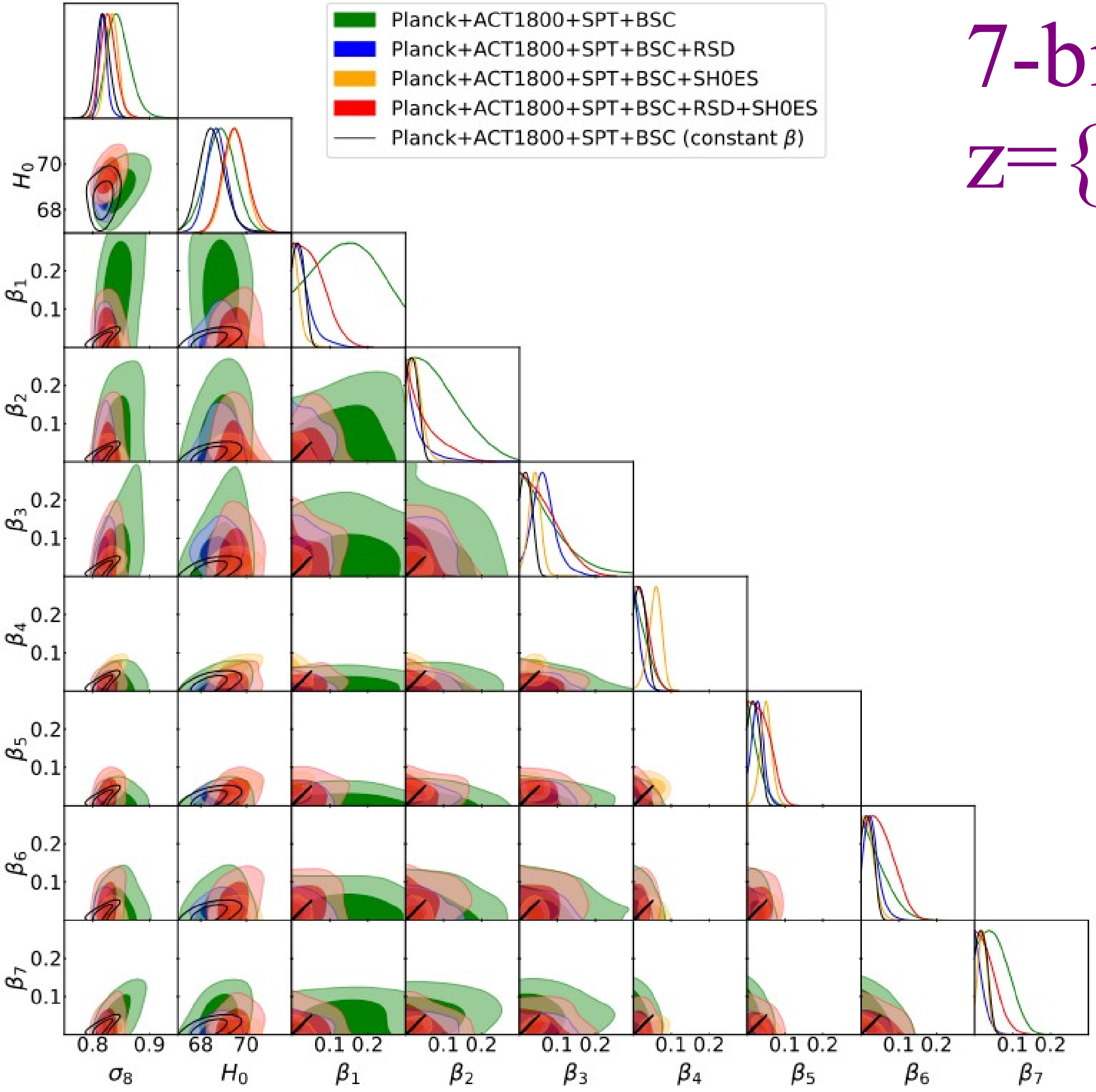
	S_8 tension	H_0 tension
ΛCDM	3.1σ	4.8σ
β=const.	1.8σ	2.9σ
Tomo β	1.3σ	2.7σ

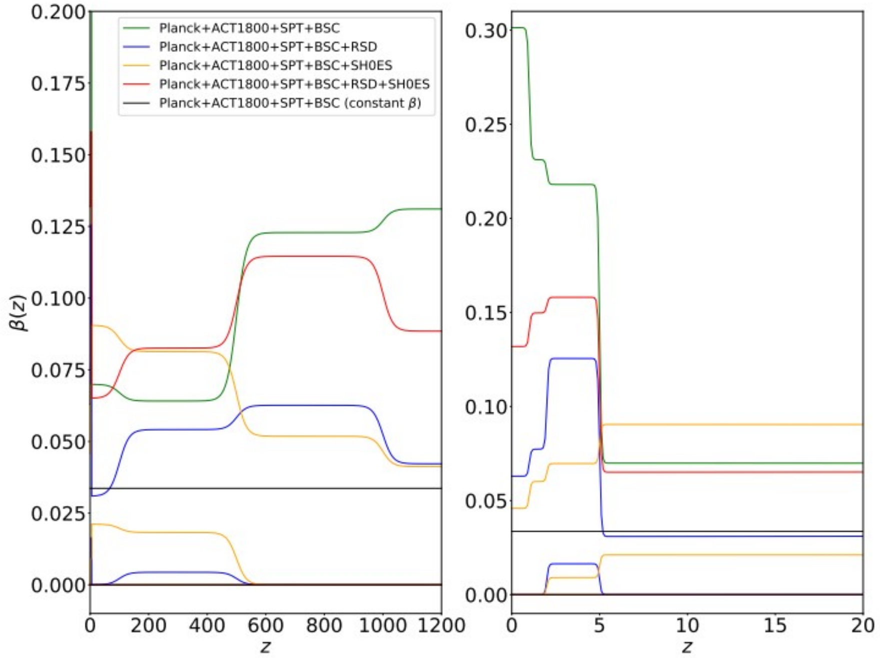
→ H_0 tension quantified by comparing the Planck vs SH0ES values

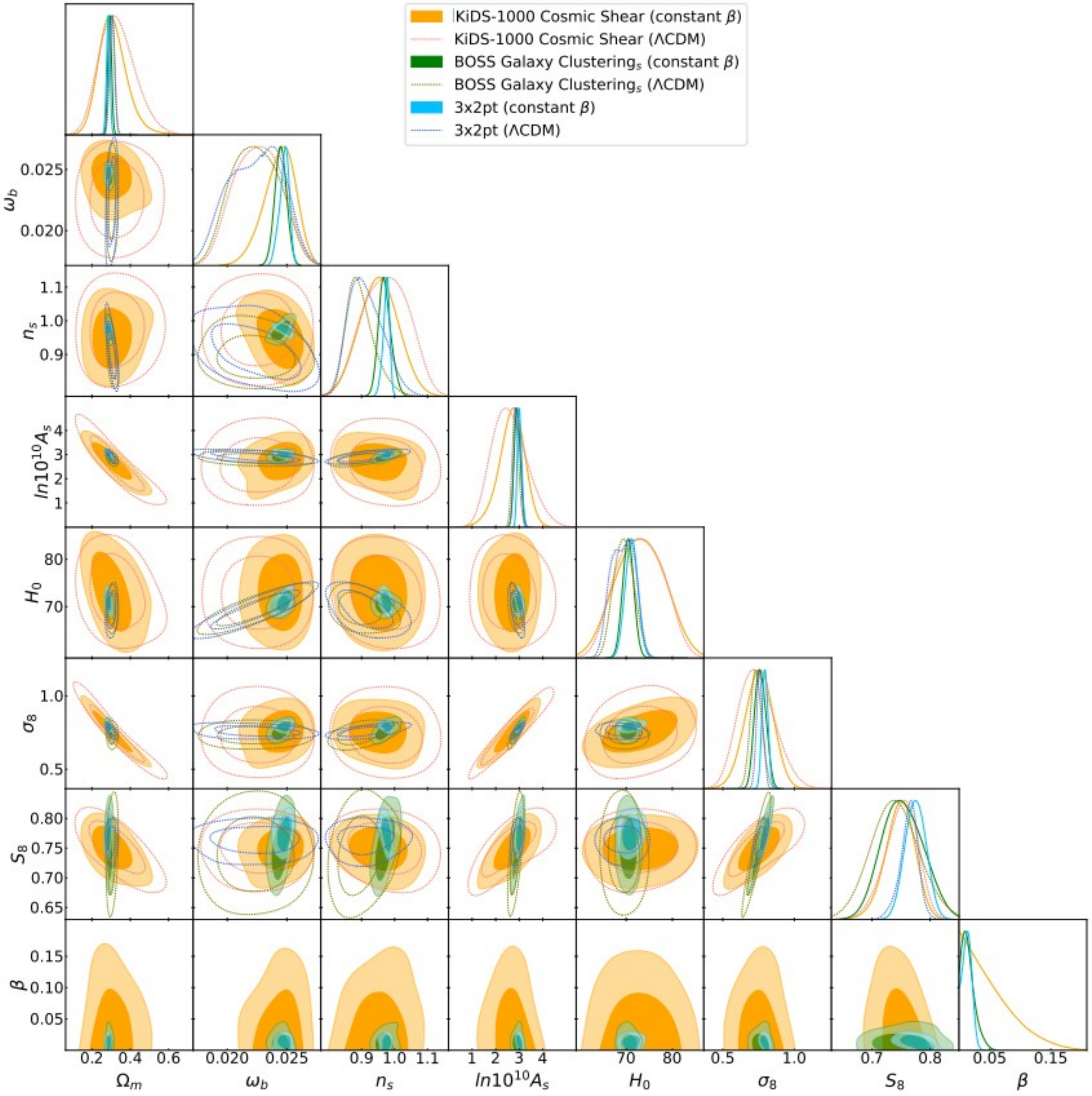
→ S_8 tension quantified by comparing the Planck vs 3x2pt values

→ But no Bayesian preference for CDE!

7-bin tomographic model
z={0,1,2,5,100,500,1000}







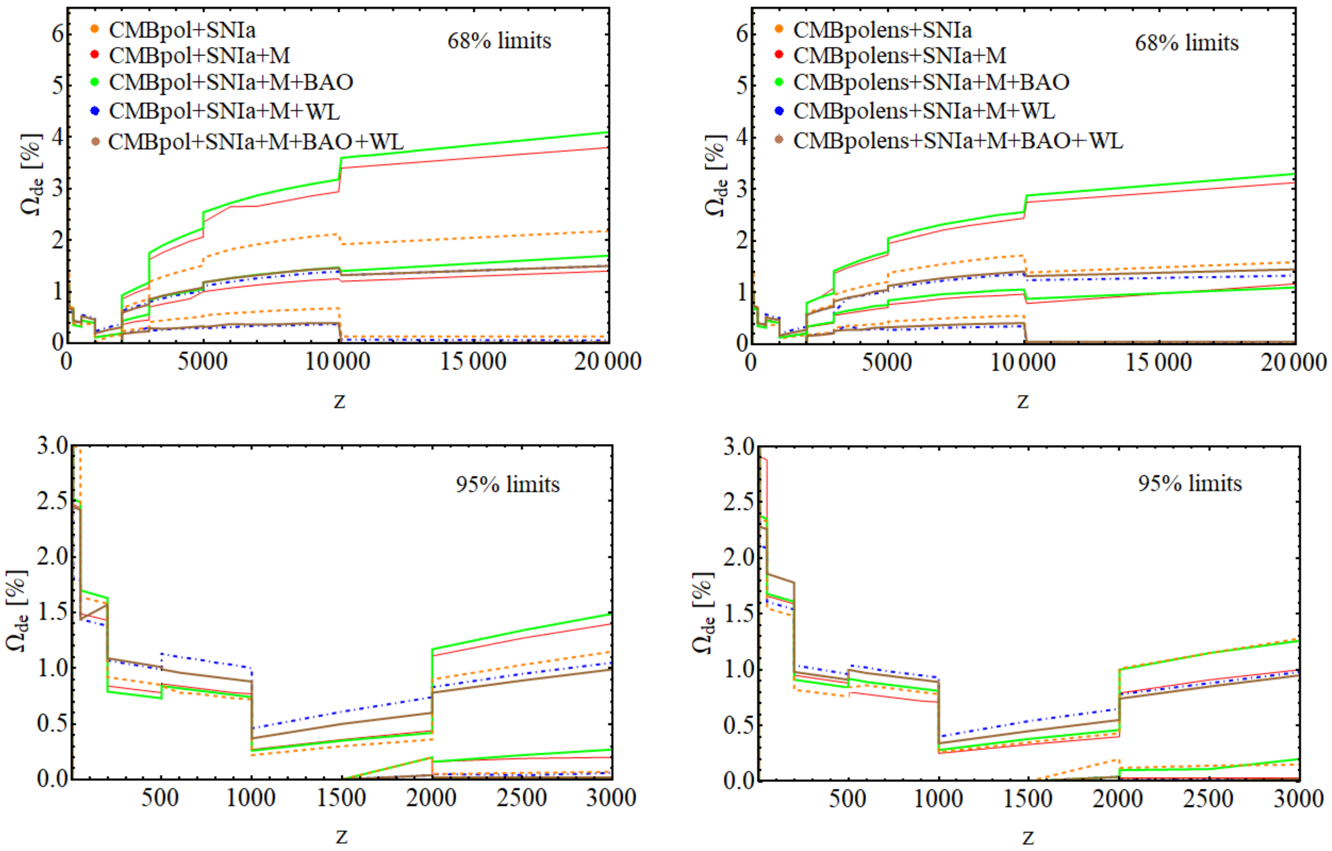
Weak lensing vs galaxy clustering

Uncoupled early dark energy

Based on:

** A. Gómez-Valent, Z. Zheng, L. Amendola, V. Pettorino, C. Wetterich, PRD 104, 083536 (2021) [arXiv:2107.11065]
** A. Gómez-Valent, PRD 106, 063506 (2022) [arXiv:2203.16285]
** A. Gómez-Valent, Z. Zheng, L. Amendola, C. Wetterich, V. Pettorino, PRD 106, 103522 (2022) [arXiv:2207.14487]

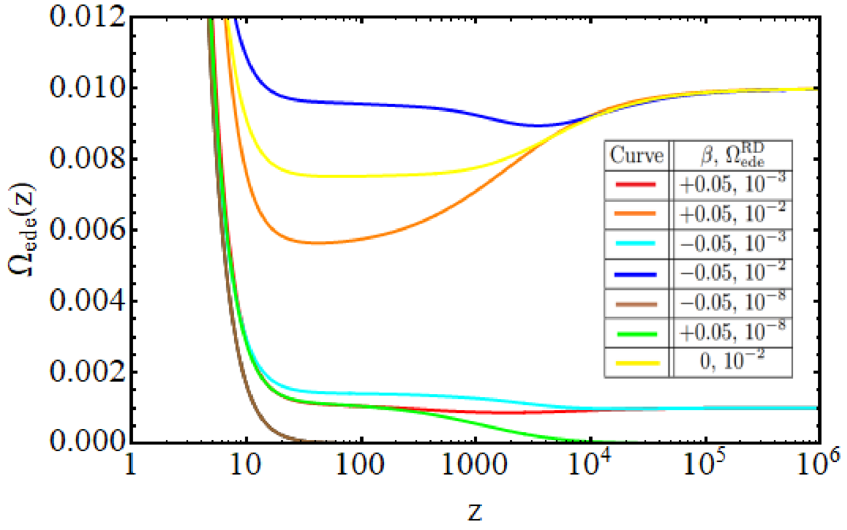
Constraints on the fraction of (uncoupled) EDE



** A. Gómez-Valent, Z. Zheng, L. Amendola, V. Pettorino, C. Wetterich, Phys.Rev.D 104, 083536 (2021)

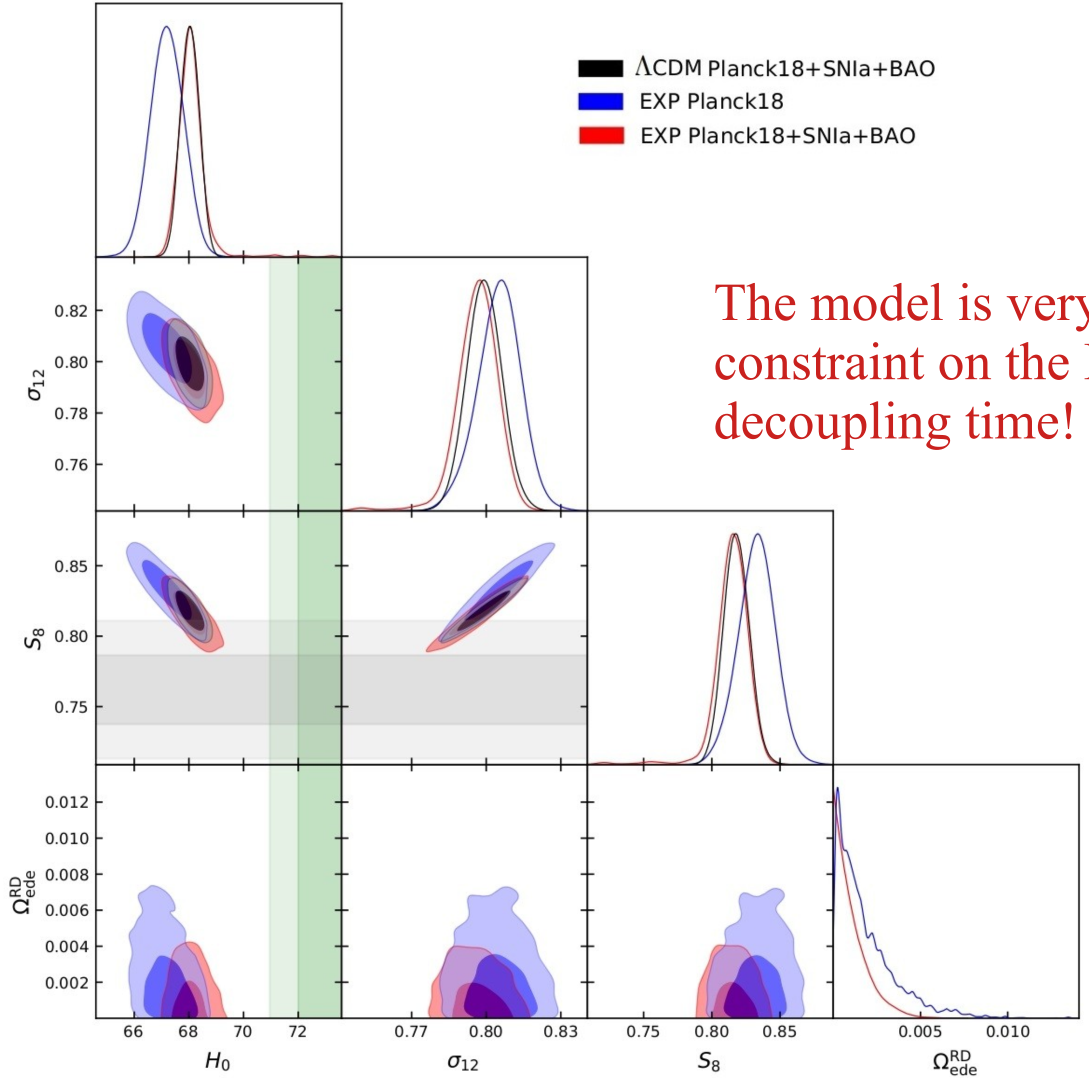
Uncoupled EDE with an exponential potential

$$V(\phi) = V_0 + \frac{\Omega_{\rm ede}^{\rm RD}\rho_r(a_{\rm ini})}{3(1-\Omega_{\rm ede}^{\rm RD})}\exp\left[\frac{-2\kappa}{\sqrt{\Omega_{\rm ede}^{\rm RD}}}(\phi-\phi_{\rm ini})\right] \qquad \Omega_{\rm ede}^{\rm MD} = 3\Omega_{\rm ede}^{\rm RD}/4$$



- The matter-radiation equality happens later in time.
- There is no fifth force.
- Matter perturbations are suppressed. $\delta_m \sim a^{1-\frac{9}{20}\Omega_{\rm ede}^{\rm RD}}$
- r_d is decreased

** A. Gómez-Valent, Z. Zheng, L. Amendola, V. Pettorino, C. Wetterich, Phys.Rev.D 104, 083536 (2021)
**A. Gómez-Valent, Z. Zheng, L. Amendola, C. Wetterich, V. Pettorino, PRD 106, 103522 (2022) [arXiv:2207.14487]



The model is very limited by the tight constraint on the EDE fraction at the decoupling time!

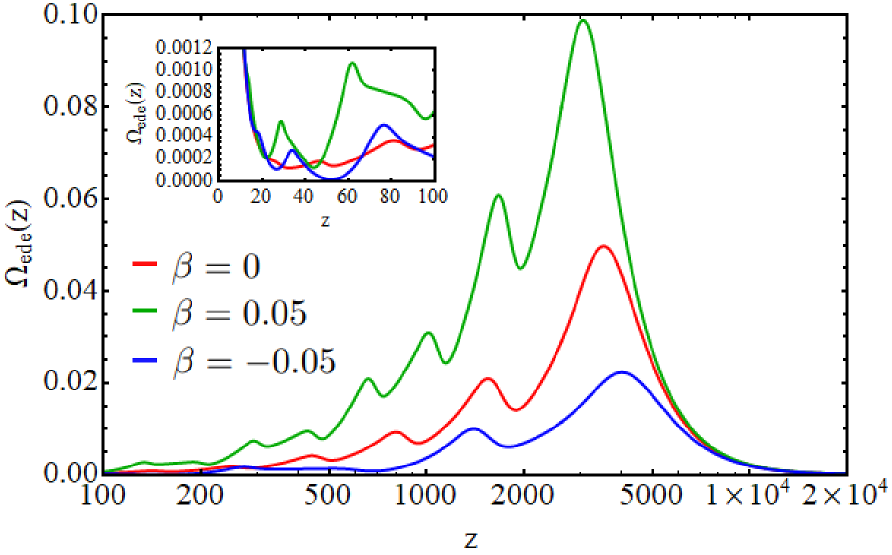
Ultra-light axion-like EDE (ULA)

$$V(\phi) = V_0 + m^2 f^2 [1 - \cos(\phi/f)]^3$$

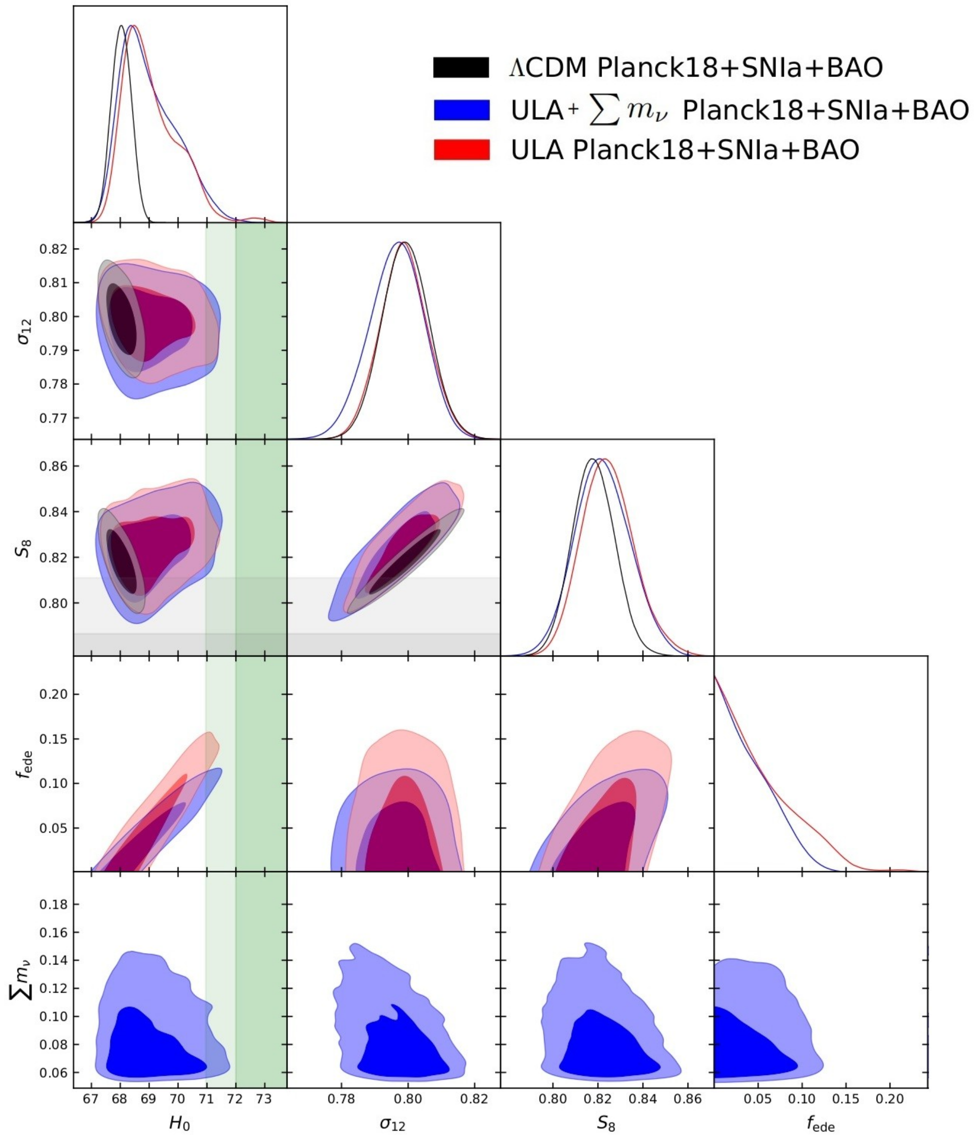
V. Poulin et al., Phys. Rev. D 98, 083525 (2018)
V. Poluin et al. Phys. Rev. Lett. 122, 221301 (2019)

The model loosens the H_0 tension, but requires more DM and a larger n_s

J.C. Hill et al., Phys. Rev. D 102, 043507 (2020)

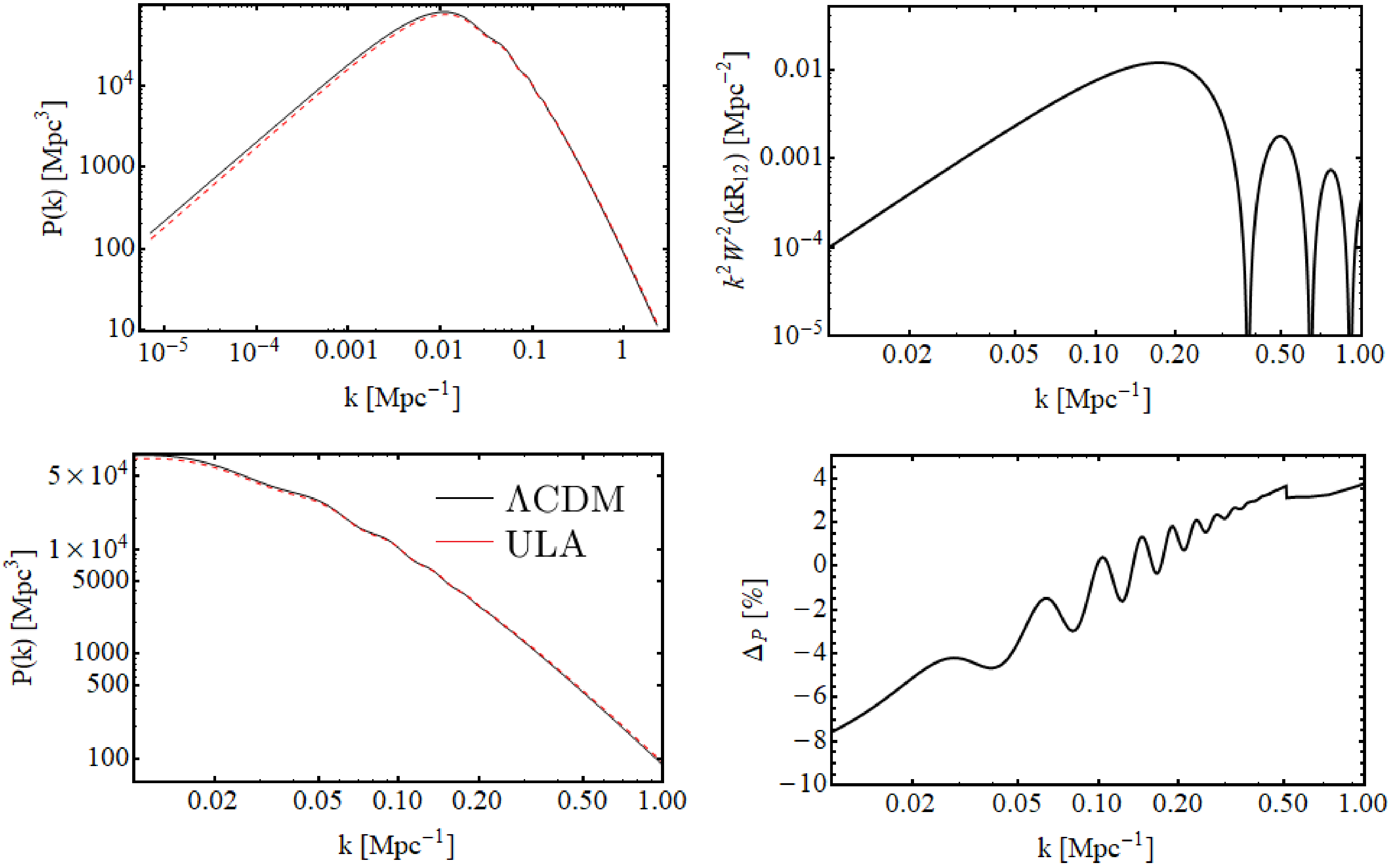


Does the tension with LSS worsen?



- The S_8 tension increases when we increase H_0
- But is S_8 a good LSS estimator? Maybe not...
- At linear scales the amount of structure is actually comparable to the one in the ΛCDM, see the posterior of σ_{12}.
- Massive neutrinos do not help that much...

** A. Gómez-Valent et al., PRD 106, 103522 (2022) [arXiv:2207.14487]



P(k) [Mpc^3]
k [Mpc^{-1}]
$k^2 W^2(kR_{12})$ [Mpc^{-2}]
k [Mpc^{-1}]
P(k) [Mpc^3]
k [Mpc^{-1}]
ΛCDM
ULA
Δ_P [%]
k [Mpc^{-1}]

Conclusions

→ The ΛCDM, despite being a successful model, is plagued with theoretical issues and tensions with observations.
→ Future measurements (LSST, Euclid, etc.) and reanalysis of current data will be important to assess the impact of potential systematics.
→ The search for model-independent measurements of the quantities of interest and independent from the main drivers of the tensions is of utmost importance.
→ It is crucial to quantify the tensions with observations and between models in a rigorous way: use correct statistical tools and meaningful physical quantities.
→ We have analyzed the state-of-the-art constraints on fifth forces in the dark sector and dark energy
→ We have seen that CDE can alleviate the tensions, but there is no preference from the Bayesian perspective.
→ Contrary to what is usually argued in the literature, EDE can loosen the H_0 tension without worsening the tension with the LSS.