ΛCDM is alive and well!

A. Blanchard, J.-Y. Héloret, B.Lamine, S. Ilić, I.Tutusaus

Avignon, May 4th, 2023

Tensions for ΛCDM.

Successes of ΛCDM :

$\longrightarrow$ predictive

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H_0

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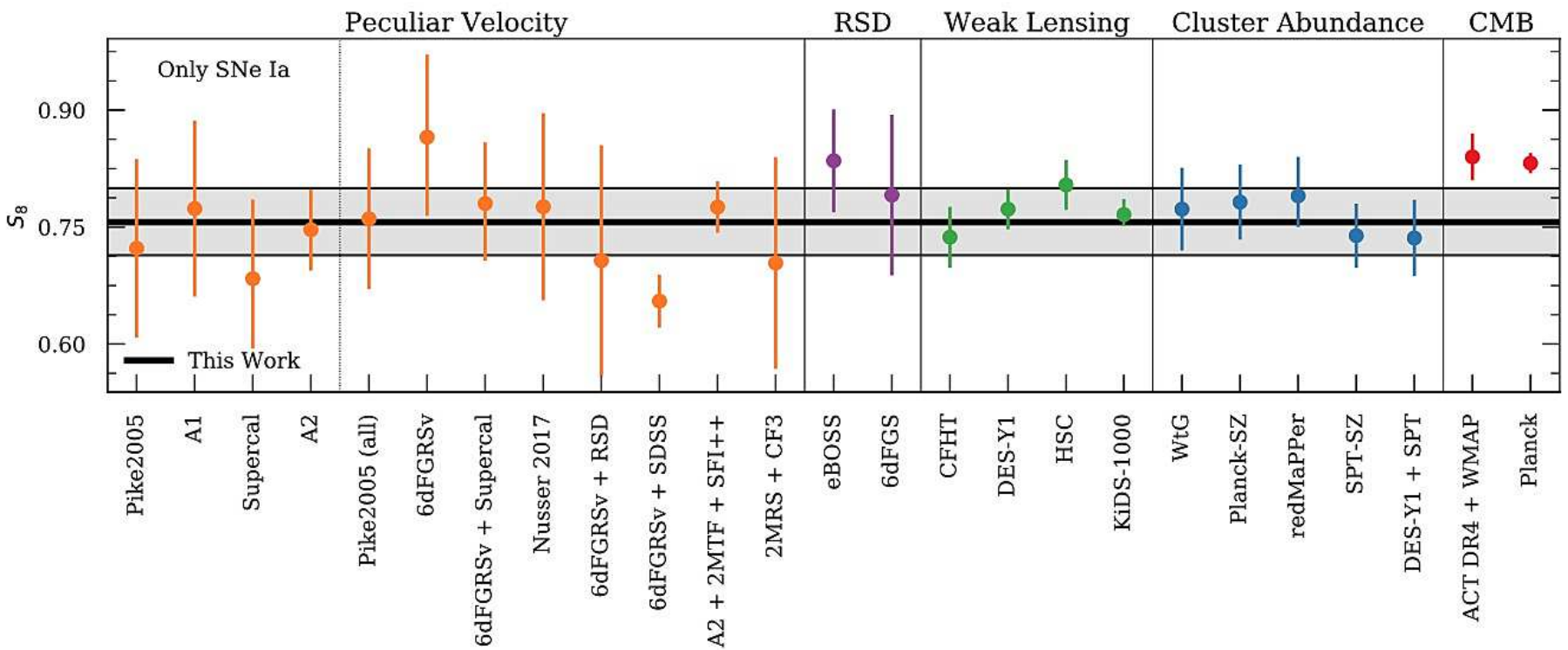
Tensions.
H_0
S_8

The amplitude of matter fluctuations tension, i.e. S_8 tension.



Stahl et al. (2021)

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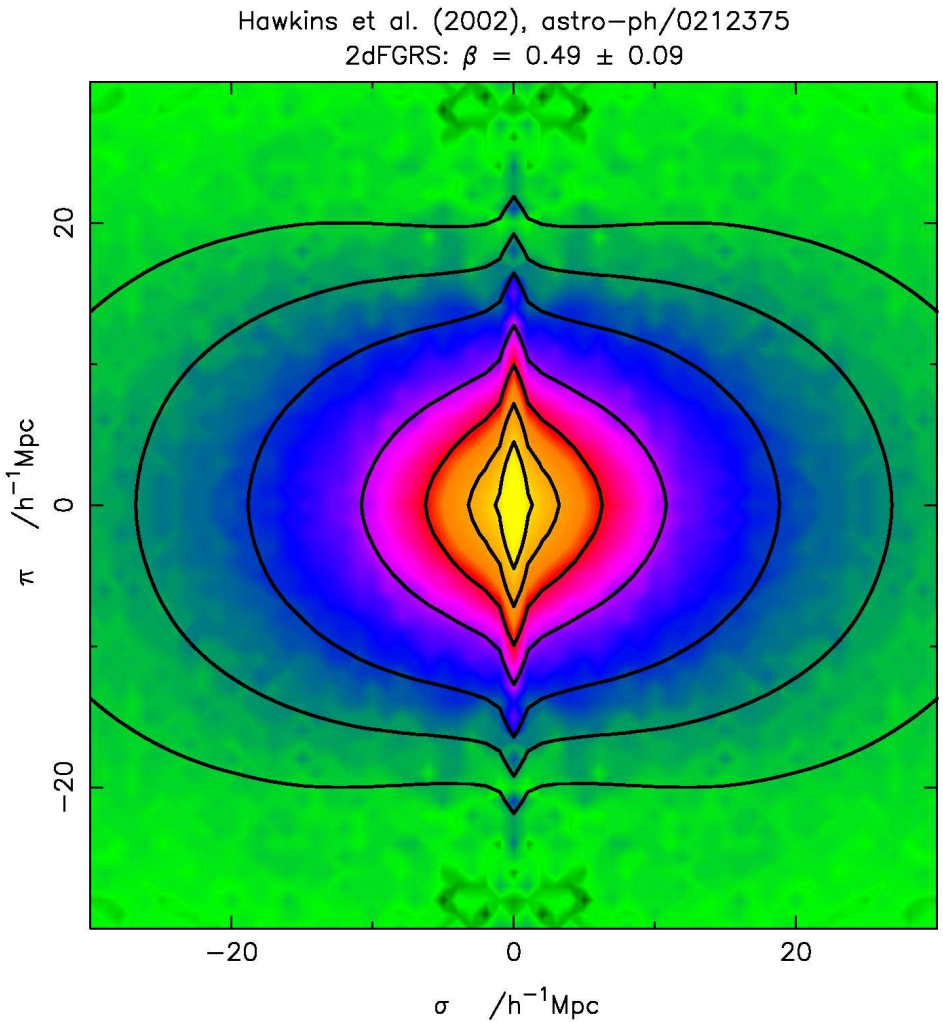

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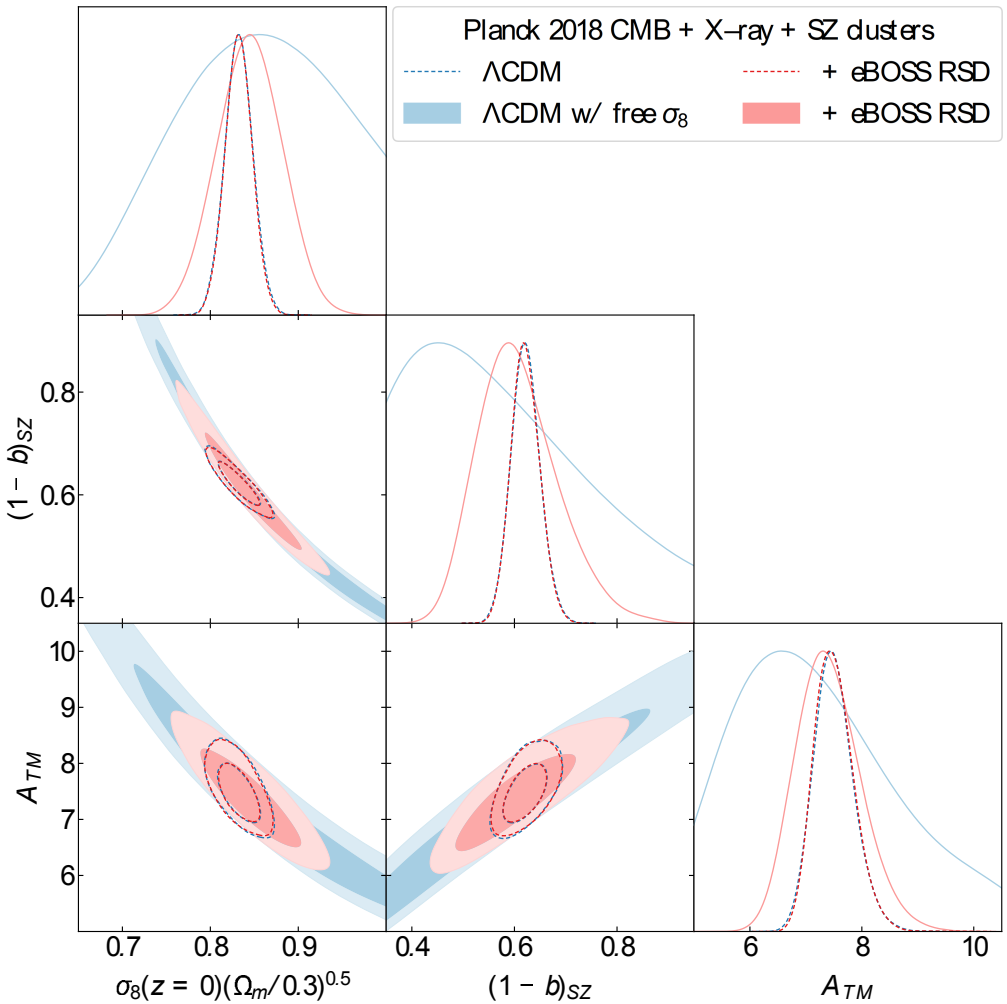
- Cosmological parameters from Planck CMB **but** σ_8

Constraining 1 – b, σ_8, S_8



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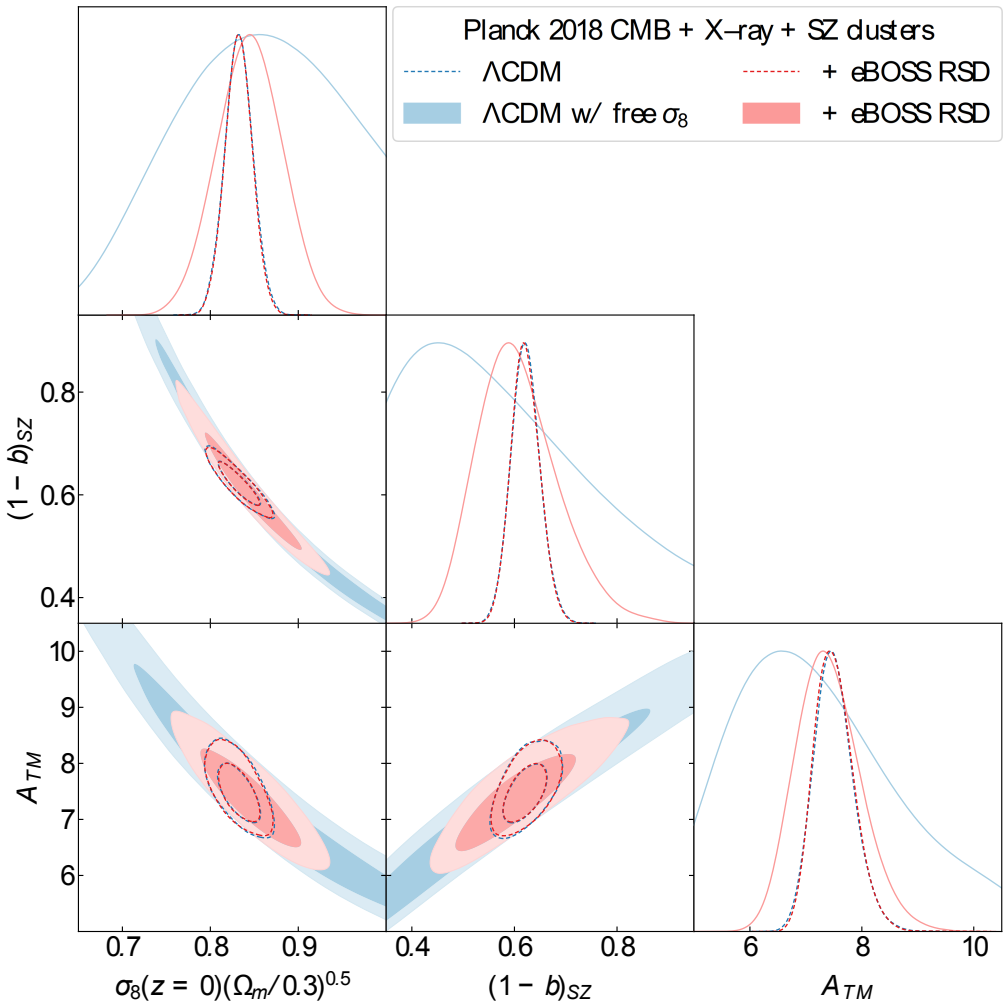

$$1 - b = 0.608 \pm 0.07$$

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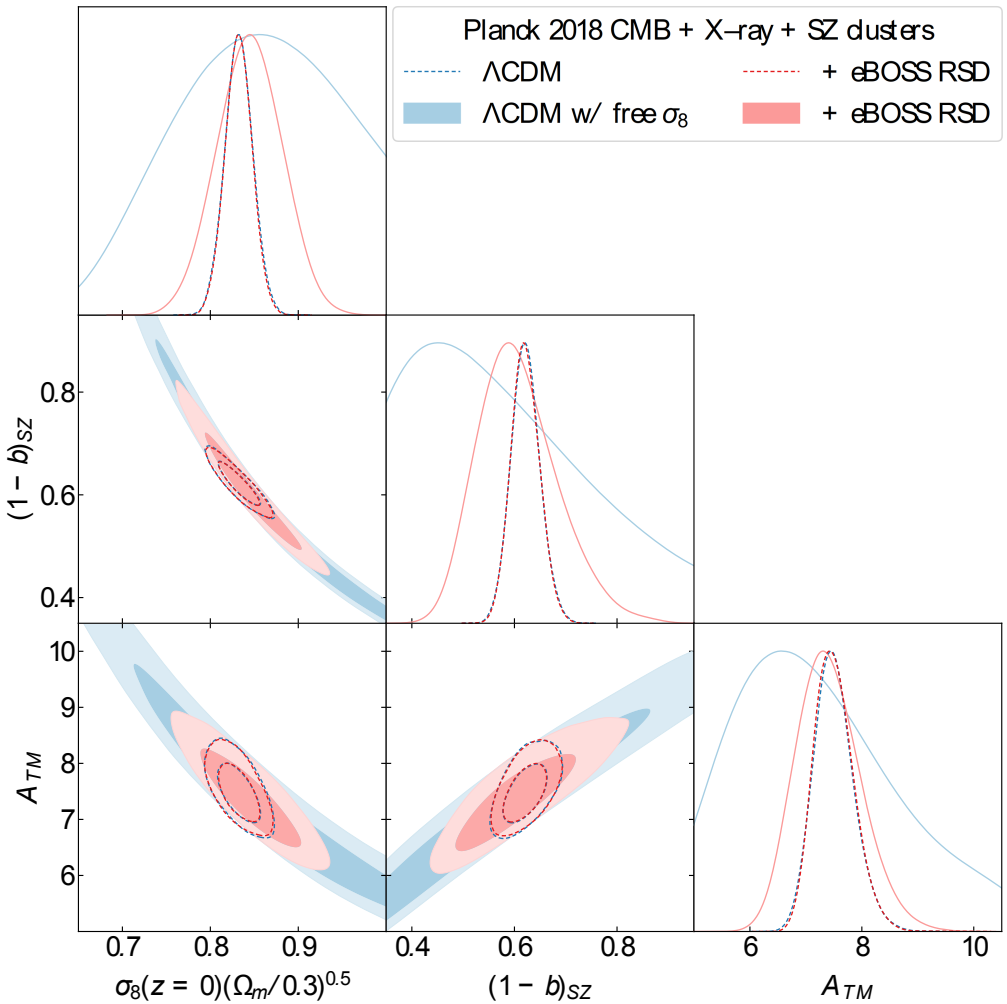

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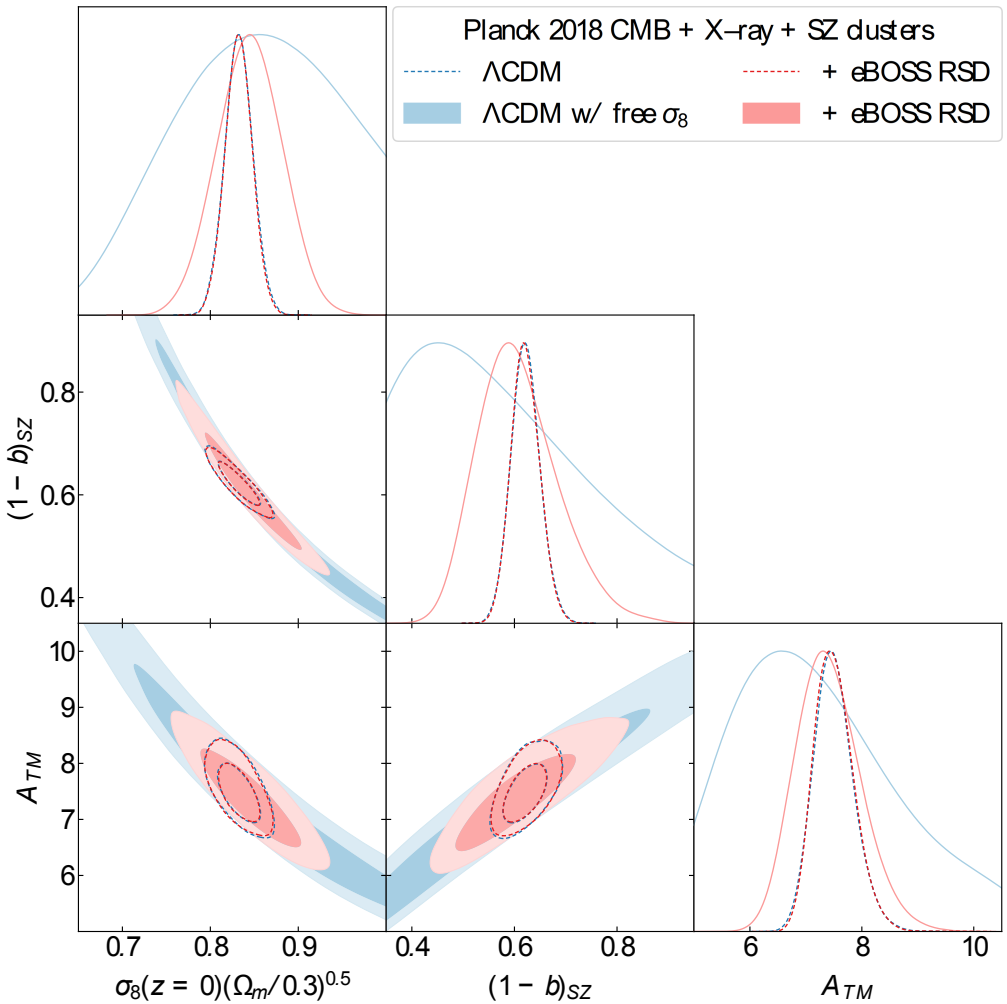

$$\boxed{1 - b = 0.608 \pm 0.07}$$

$$\boxed{S_8 = 0.841 \pm 0.038}$$ Planck : $S_8 = 0.828 \pm 0.016$

(Blanchard & Ilić 2021)

New cluster calibration: ACT DR5

arXiv:2304.10219

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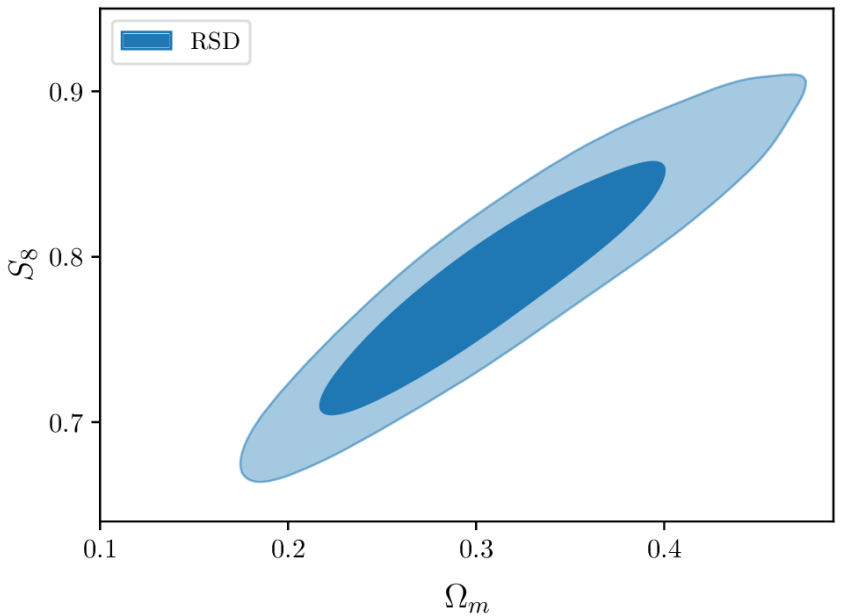
This translates to :

$$\boxed{S_8 = 0.818 \pm 0.027}$$

One step further: RSD from surveys

Survey	z	$f\sigma_8$	**Refs**
2MFT	0.001	0.51+/-0.085	[19]
6dFGS	0.067	0.423+/-0.055	[20]
SDSS DR13	0.1	0.48+/-0.16	[21]
2dFGRS	0.17	0.51+/-0.06	[22]
GAMA	0.18	0.36 +/- 0.09	[23]
WiggleZ	0.22	0.42+/-0.07	[24]
SDSS LRG60	0.25	0.35+/- 0.06	[25]
BOSS LOW Z	0.32	0.48+/-0.1	[26]
GAMA	0.36	0.44+/- 0.06	[23]
SDSS LRG 200	0.37	0.46+/- 0.04	[25]
WiggleZ	0.41	0.45+/-0.04	[24]
CMASS BOSS	0.57	0.453+/-0.02	[27]
WiggleZ	0.6	0.43+/-0.04	[24]
VIPERS	0.6	0.48+/-0.12	[28]
SDSS IV	0.69	0.447+/-0.039	[29]
VIPERS	0.76	0.44+/-0.04	[30]
SDSS IV	0.77	0.432+/-0.038	[31]
WiggleZ	0.78	0.38+/-0.04	[24]
SDSS IV	0.85	0.52+/-0.10	[32]
VIPERS	0.86	0.48+/-0.10	[28]
SDSS IV	0.978	0.379+/-0.176	[31]
SDSS IV	1.23	0.385+/-0.1	[31]
Fastsound	1.4	0.494+/-0.123	[33]
SDSS IV	1.52	0.426 +/-0.077	[34]
SDSS IV	1.944	0.364+/-0.106	[31]

RSD from surveys: constraints



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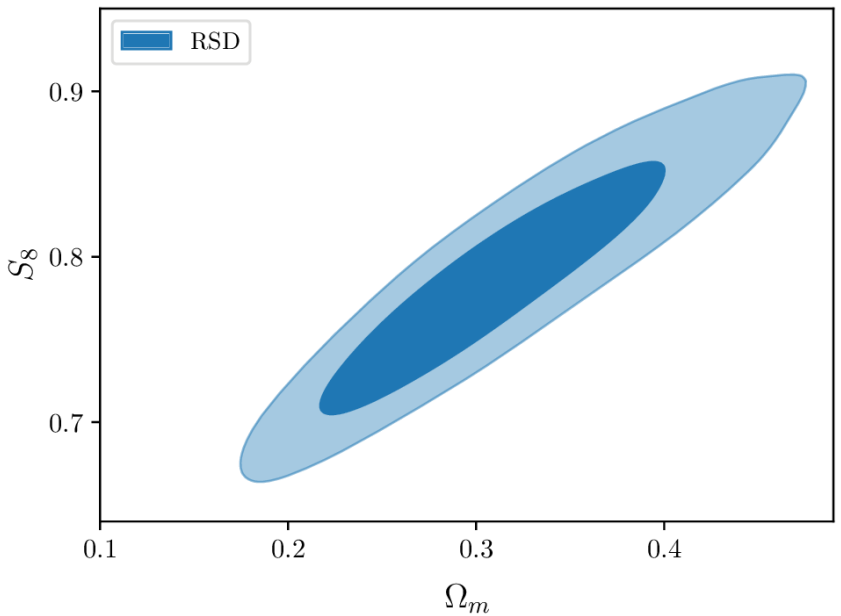

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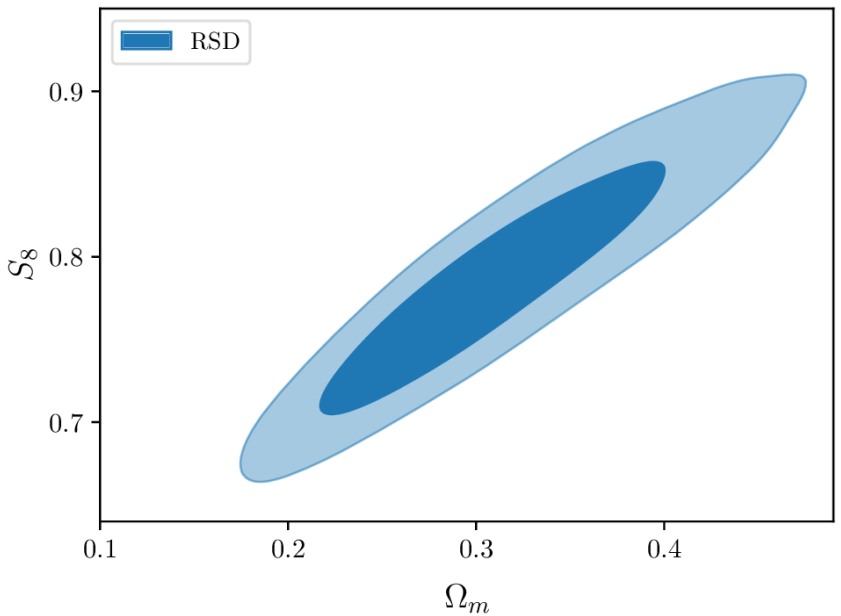

Not surprisingly strong degeneracy
Need to combine with other $low - z$ data

RSD from surveys+ DES3yr+ Pantheon+

Pantheon+: SNIa Hubble diagram (Brout et al., 2022), for ΛCDM):

$$\boxed{\Omega_M = 0.338 \pm 0.018}$$

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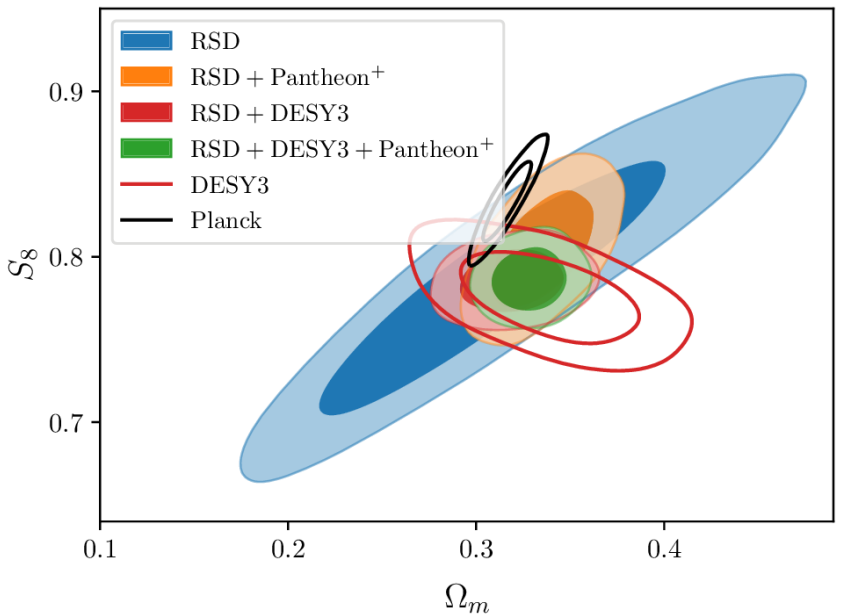

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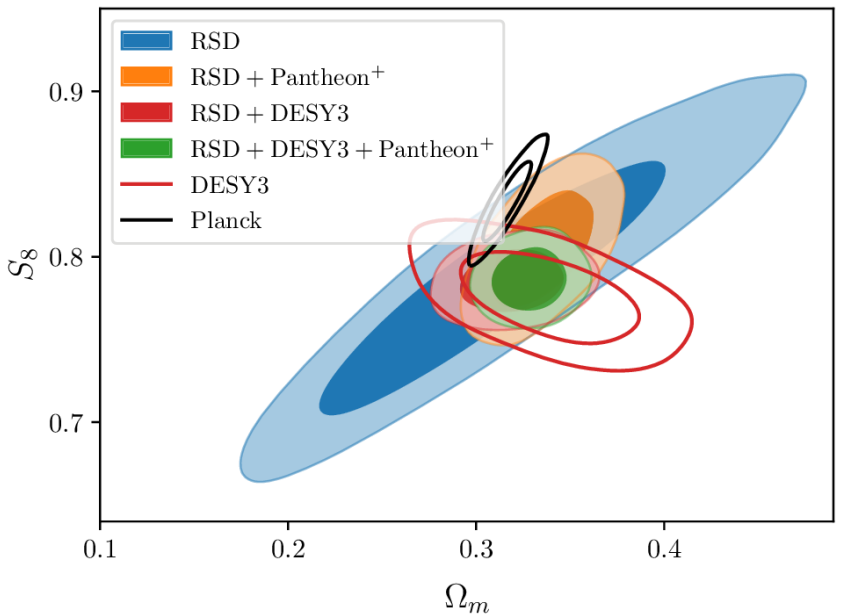

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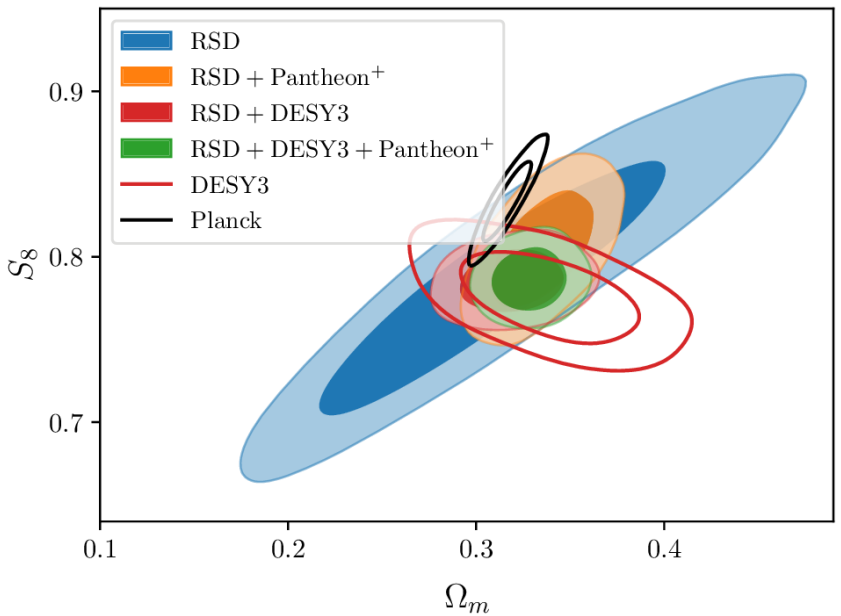

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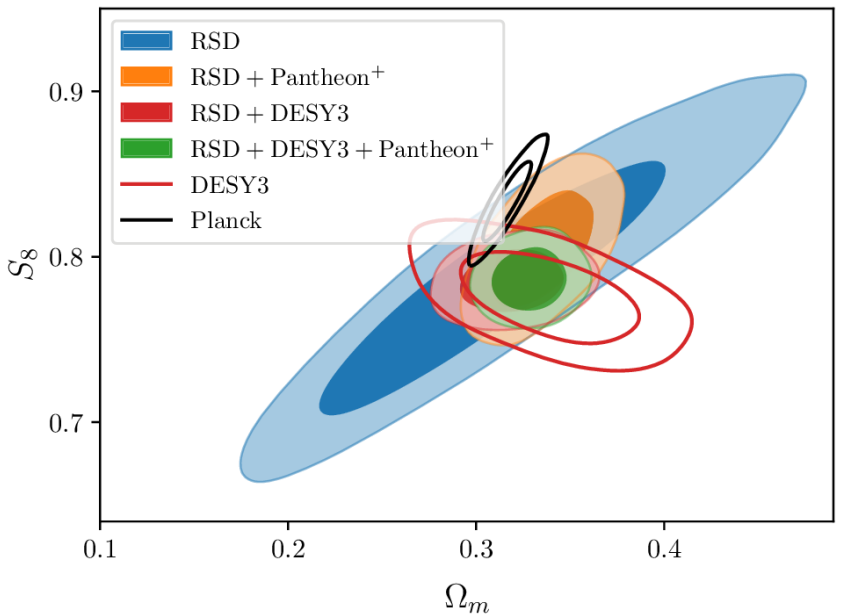

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Final tension with Planck: 1.9 σ

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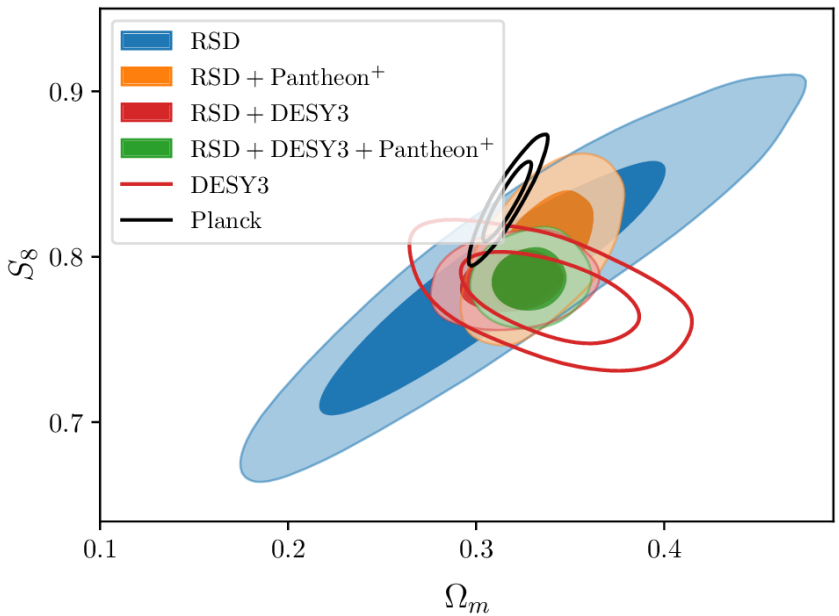

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Final tension with Planck: $1.9\ \sigma$

$$\boxed{\Omega_M = 0.327 \pm 0.013}$$

(arXiv:2205.05017)

DES conclusions

Beware of NL and baryons
Arico et al. :arXiv:2303.05537v1

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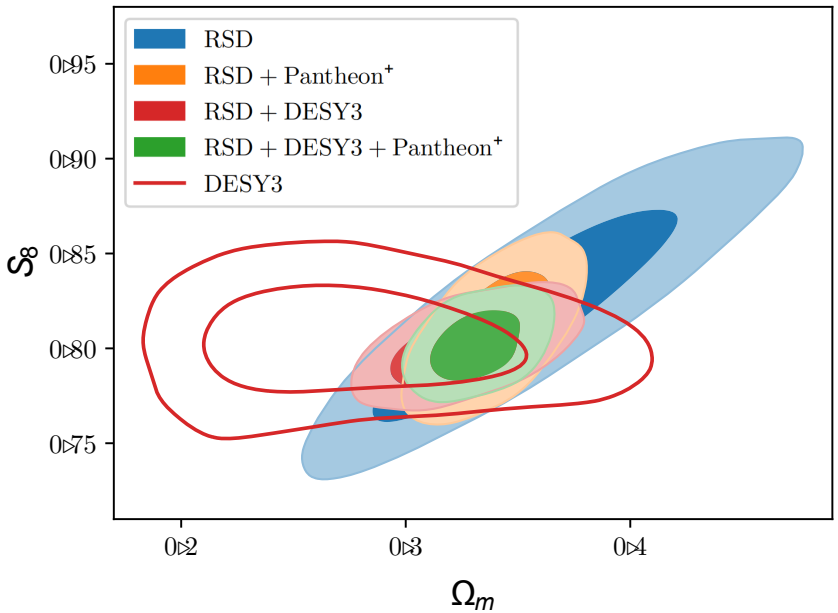

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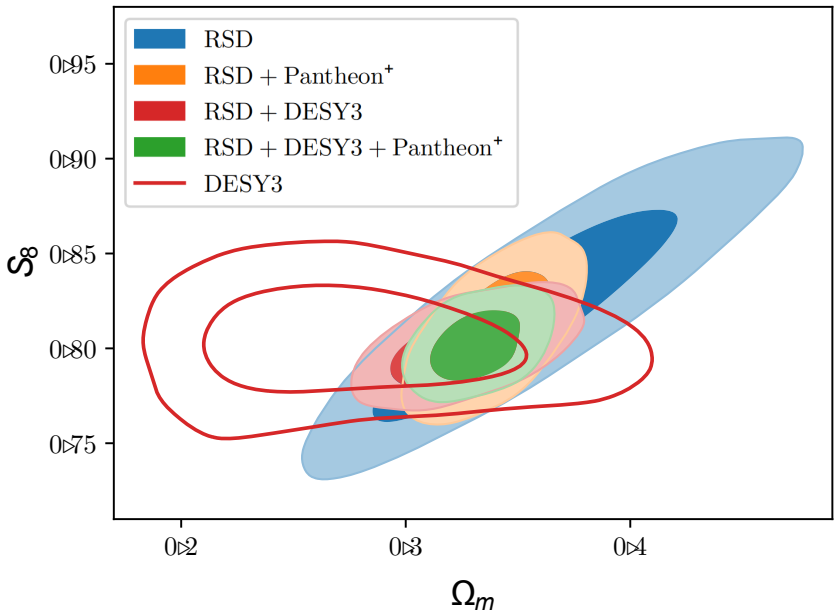

$$S_8 = 0.801 \pm 0.012$$

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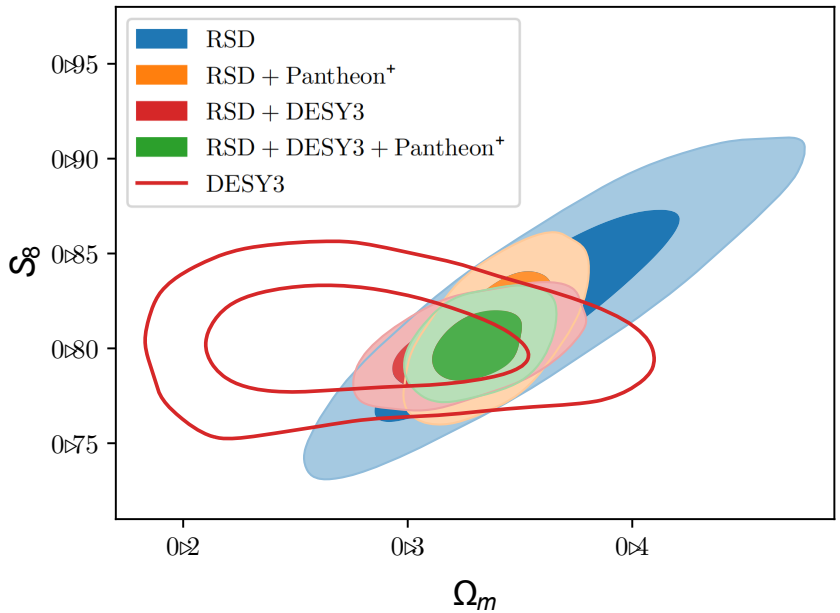

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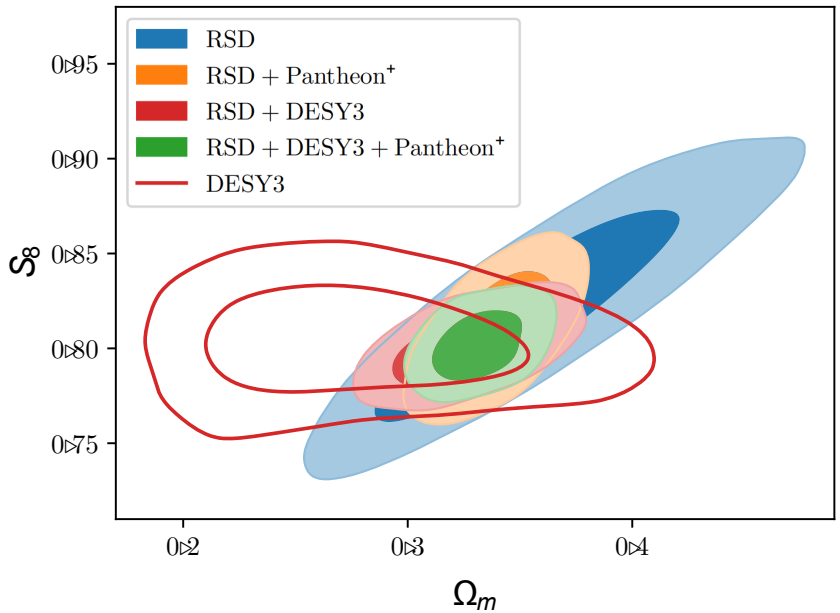

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Last word on S_8: ACT DR5

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Final nail in the coffin?

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Four pieces of evidence for **low z** $S_8 \sim 0.81$ (± 0.01)

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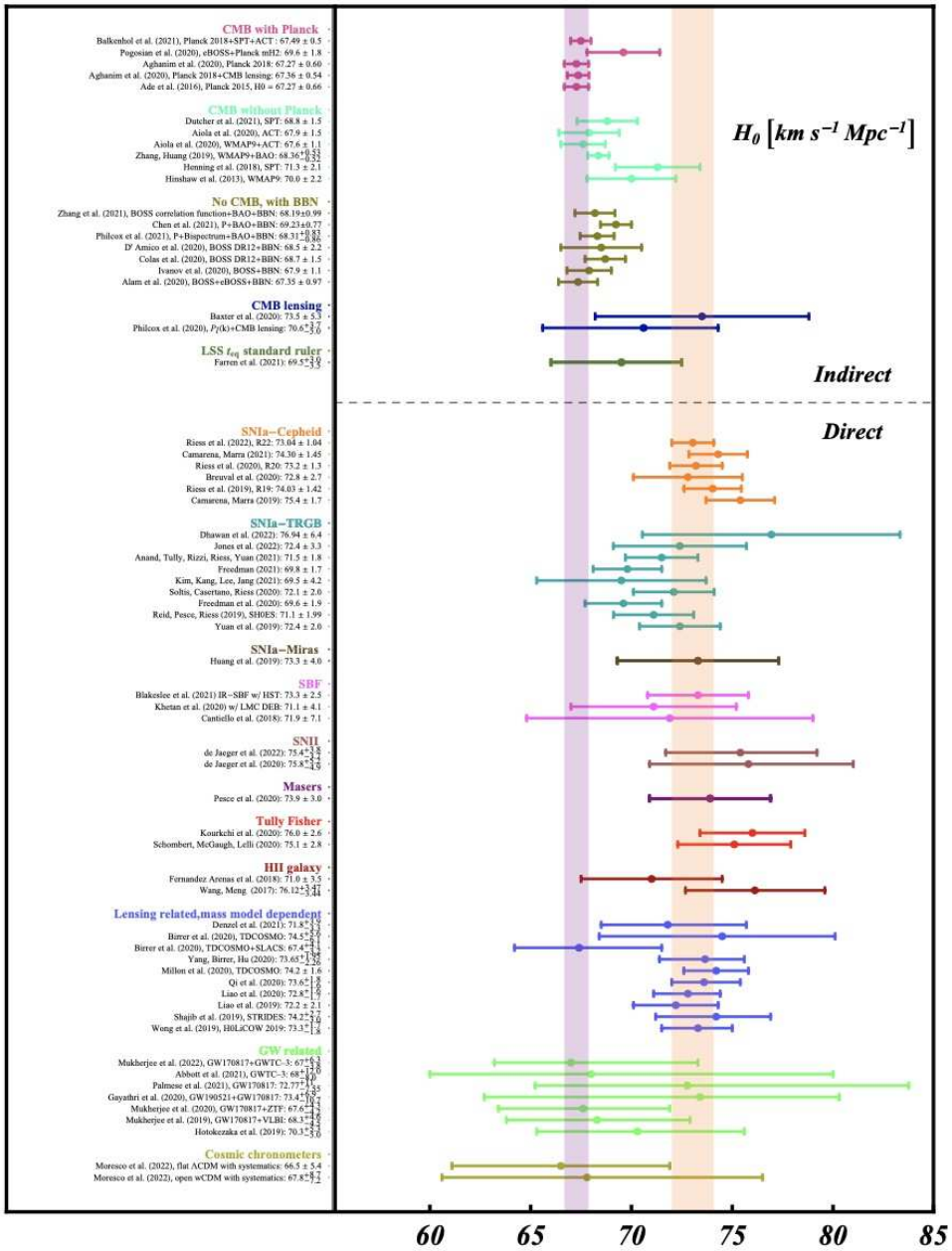
Consistent with LCDM Planck normalized!

H_0 tension


CMB with Planck
Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.5
Pogosian et al. (2020), eBOSS+Planck mH2: 69.6 ± 1.8
Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60
Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54
Ade et al. (2016), Planck 2015, H0 = 67.27 ± 0.66
CMB without Planck
Dutcher et al. (2021), SPT: 68.8 ± 1.5
Aiola et al. (2020), ACT: 67.9 ± 1.5
Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1
Zhang, Huang (2019), WMAP9+BAO: 68.36
Henning et al. (2018), SPT: 71.3 ± 2.1
Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2
No CMB, with BBN
Zhang et al. (2021), BOSS correlation function+BAO+BBN: 68.19±0.99
Chen et al. (2021), P+BAO+BBN: 69.23±0.77
Philcox et al. (2021), P+Bispectrum+BAO+BBN: 68.31
D' Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5
Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1
Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97
CMB lensing
Baxter et al. (2020): 73.5 ± 5.3
Philcox et al. (2020), P_T(k)+CMB lensing: 70.6
LSS t_{eq} standard ruler
Farren et al. (2021): 69.5
H_0 [km s^{-1} Mpc^{-1}]
Indirect
Direct
SNIa−Cepheid
Riess et al. (2022), R22: 73.04 ± 1.04
Camarena, Marra (2021): 74.30 ± 1.45
Riess et al. (2020), R20: 73.2 ± 1.3
Breuval et al. (2020): 72.8 ± 2.7
Riess et al. (2019), R19: 74.03 ± 1.42
Camarena, Marra (2019): 75.4 ± 1.7
SNIa−TRGB
Dhawan et al. (2022): 76.94 ± 6.4
Jones et al. (2022): 72.4 ± 3.3
Anand, Tully, Rizzi, Riess, Yuan (2021): 71.5 ± 1.8
Freedman (2021): 69.8 ± 1.7
Kim, Kang, Lee, Jang (2021): 69.5 ± 4.2
Soltis, Casertano, Riess (2020): 72.1 ± 2.0
Freedman et al. (2020): 69.6 ± 1.9
Reid, Pesce, Riess (2019), SHOES: 71.1 ± 1.99
Yuan et al. (2019): 72.4 ± 2.0
SNIa−Miras
Huang et al. (2019): 73.3 ± 4.0
SBF
Blakeslee et al. (2021) IR−SBF w/ HST: 73.3 ± 2.5
Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1
Cantiello et al. (2018): 71.9 ± 7.1
SNII
de Jaeger et al. (2022): 75.4
de Jaeger et al. (2020): 75.8
Masers
Pesce et al. (2020): 73.9 ± 3.0
Tully Fisher
Kourkchi et al. (2020): 76.0 ± 2.6
Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8
HII galaxy
Fernandez Arenas et al. (2018): 71.0 ± 3.5
Wang, Meng (2017): 76.12
Lensing related,mass model dependent
Denzel et al. (2021): 71.8
Birrer et al. (2020), TDCOSMO: 74.5
Birrer et al. (2020), TDCOSMO+SLACS: 67.4
Yang, Birrer, Hu (2020): 73.65
Millon et al. (2020), TDCOSMO: 74.2 ± 1.6
Qi et al. (2020): 73.6
Liao et al. (2020): 72.8
Liao et al. (2019): 72.2 ± 2.1
Shajib et al. (2019), STRIDES: 74.2
Wong et al. (2019), H0LiCOW 2019: 73.3
GW related
Mukherjee et al. (2022), GW170817+GWTC−3: 67
Abbott et al. (2021), GWTC−3: 68.5
Palmese et al. (2021), GW170817: 72.77
Gayathri et al. (2020), GW190521+GW170817: 73.4
Mukherjee et al. (2020), GW170817+ZTF: 67.6
Mukherjee et al. (2019), GW170817+VLBI: 68.3
Hotokezaka et al. (2019): 70.3
Cosmic chronometers
Moresco et al. (2022), flat ΛCDM with systematics: 66.5 ± 5.4
Moresco et al. (2022), open wCDM with systematics: 67.8
60
65
70
75
80
85

Measuring the Tension

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Let's assume that Cepheid's distances are biased by an unknown factor...

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$$\chi^2 = \sum \frac{(H_0 - \alpha_i \times H_{0,i})^2}{\sigma_i^2} \tag{1}$$

With H_0 from **SH0ES**, **TF**, **SBF**, CCHP, MCP, Miras, BAO, Planck

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Akaike Information Criterium (AIC):

$$\Delta \mathrm{AIC} = \Delta\chi^2 + 2\Delta p\,. \tag{2}$$

for model comparison.

Testing for bias in the Cepheid scale

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ΛCDM E4	19.2	–15.76	Planck
ΛCDM E5	4.3	–30.7	Planck +BAO

Conclusion: The E2 model is performing better than any alternative published model to solve the H_0 tension!

A (new) stress test for extensions...

With :

$$\Omega_M = 0.327 \pm 0.013$$

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using SH0ES: $H_0 = 73.3 \pm 1.04$ km/s/Mpc

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compared to Planck (+ext):

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4.7 σ away for ΛCDM

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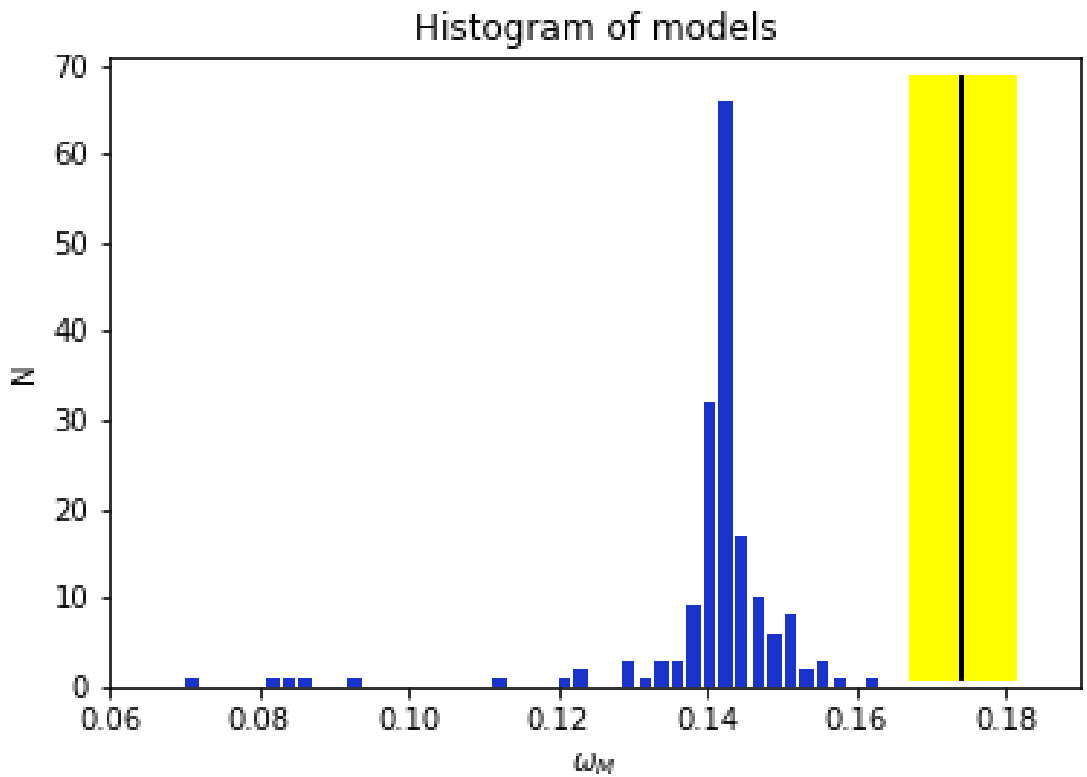

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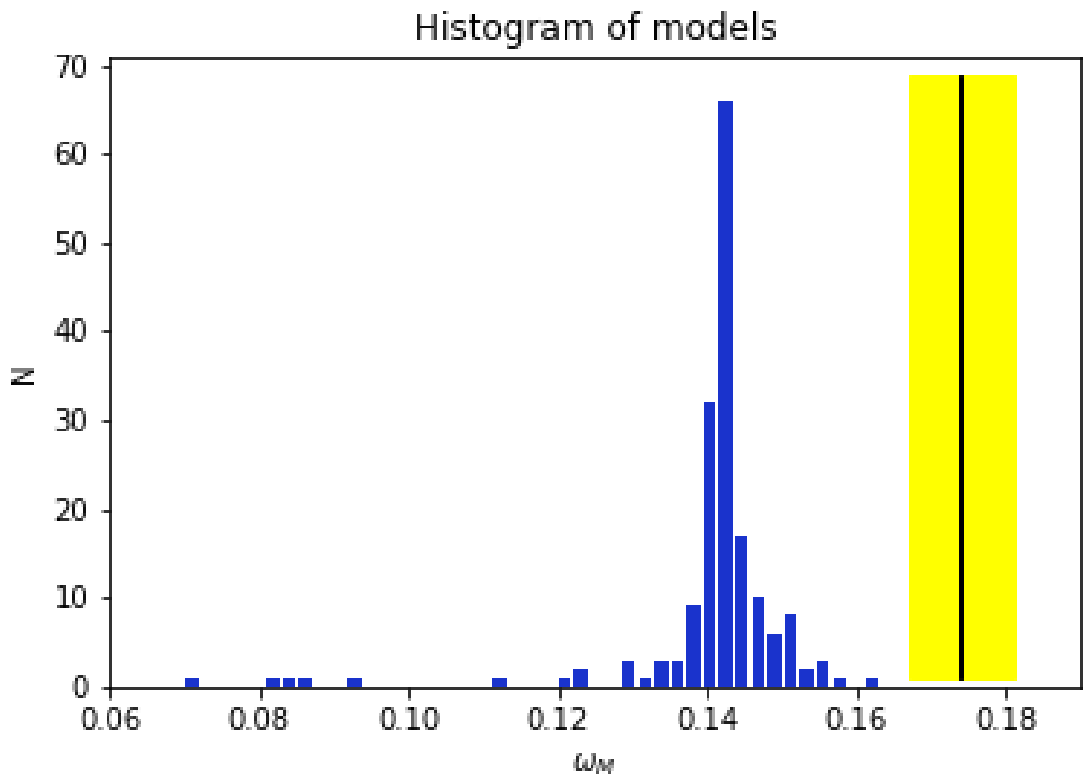

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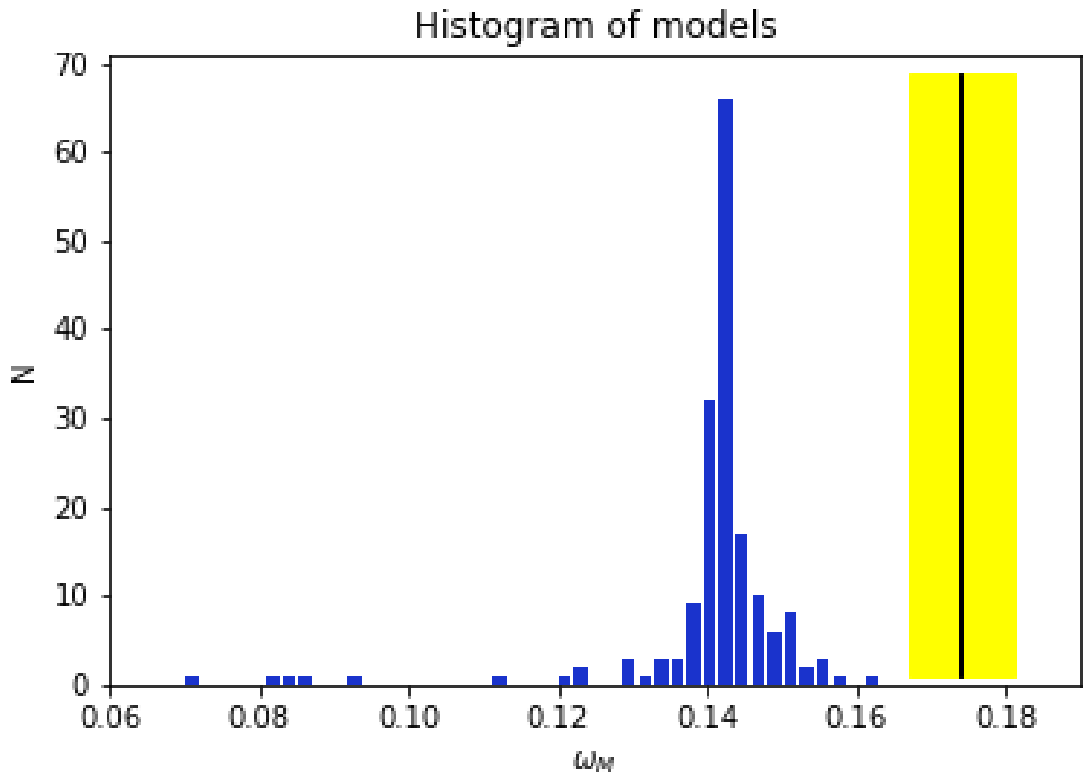

Take the recent EDS model : $\omega_M = 0.128 \pm 0.0037$ 3σ away with this test (and all published EDE models).

A (new) stress test for extensions...

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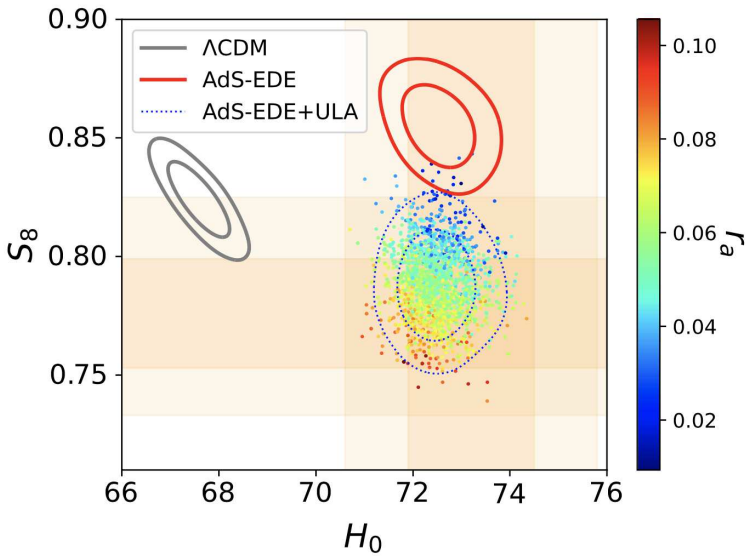

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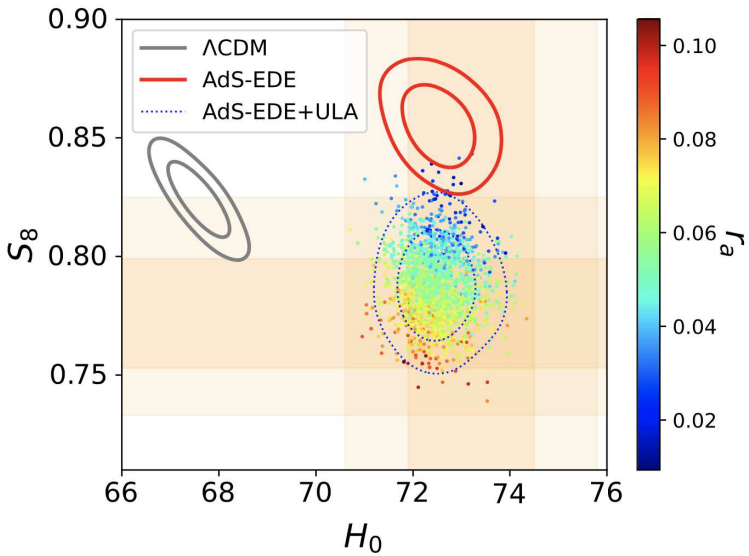

However ω_m value $> 2.6\sigma$ away.

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Thank You