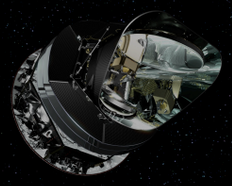
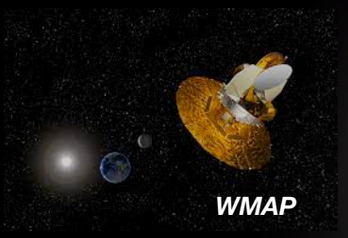


Planck



WMAP

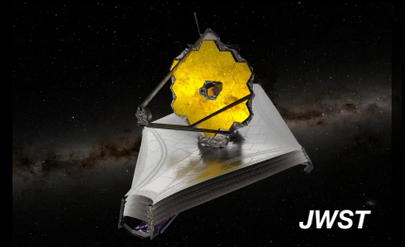
ACT

SPT

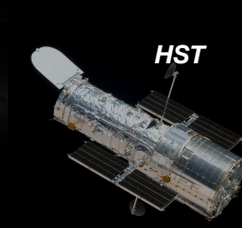
DES

BOSS/SDSS

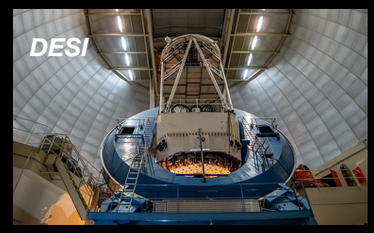
KiDS/VLT



JWST



HST



DESI

Summary of recent results in Cosmology: tensions in ΛCDM?

Vivian Poulin

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CNRS & Université de Montpellier

vivian.poulin@umontpellier.fr

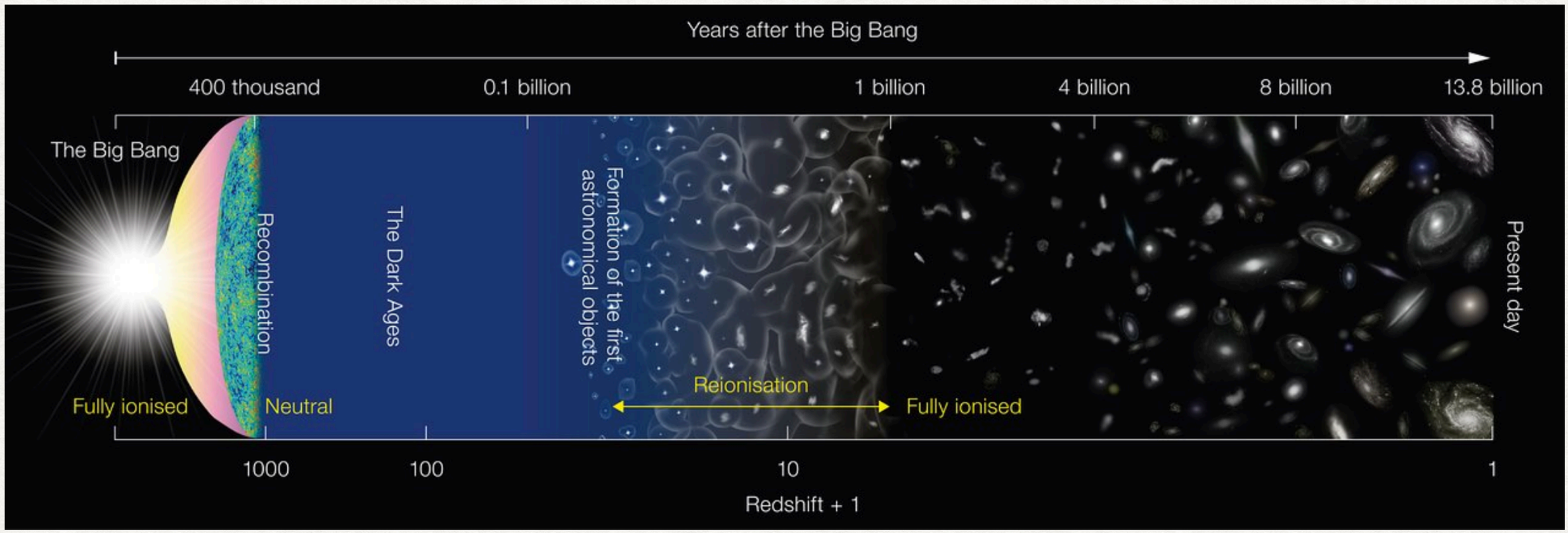
SUPPORTED BY FUNDING FROM THE EUROPEAN RESEARCH COUNCIL (ERC) UNDER THE EUROPEAN UNION'S HORIZON-ERC-2022 (GRANT AGREEMENT NO. 101076865)

NFTD Episode 10
Montpellier, France
September 10th, 2025

The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology: GR + Cosmological Principle

$\omega \equiv \Omega h^2, \;\; H_0 = 100h \text{ km/s/Mpc}$ $\quad \{H_0, \;\; \omega_b, \;\; \omega_{\rm cdm}, \;\; A_s, \;\; n_s, \;\; \tau_{\rm reio}\}$ $\quad \Omega_\Lambda = 1 - \Omega_m$



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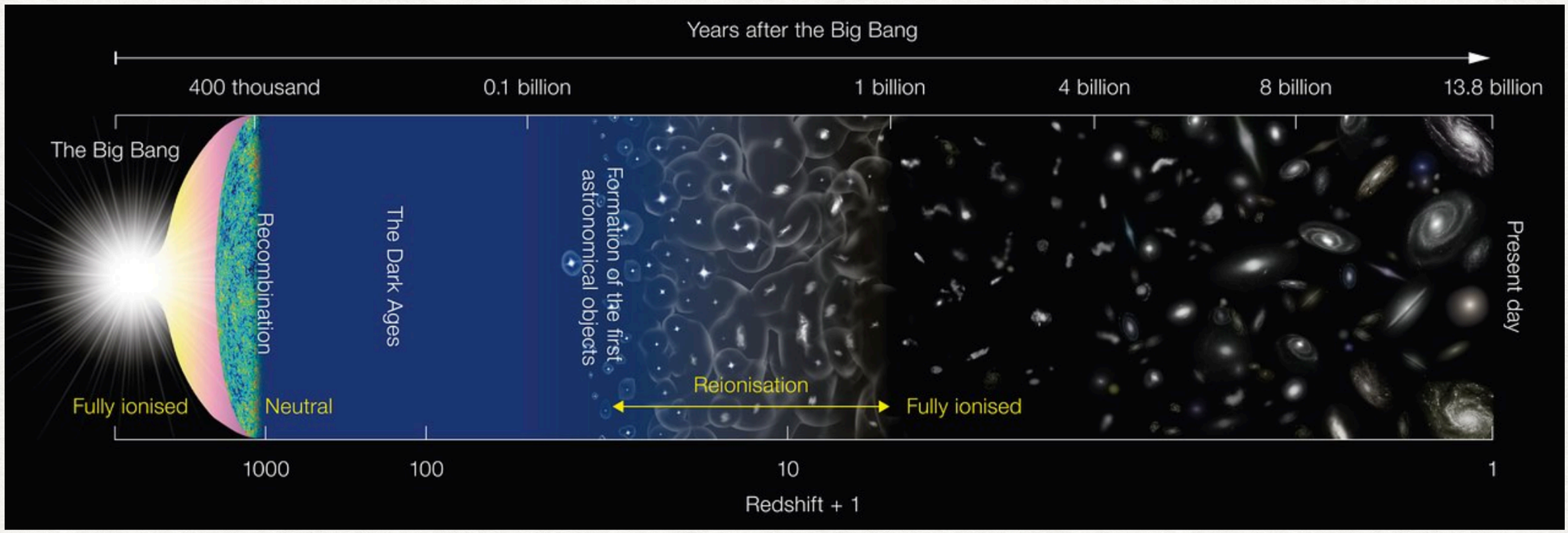
Expansion/matter content



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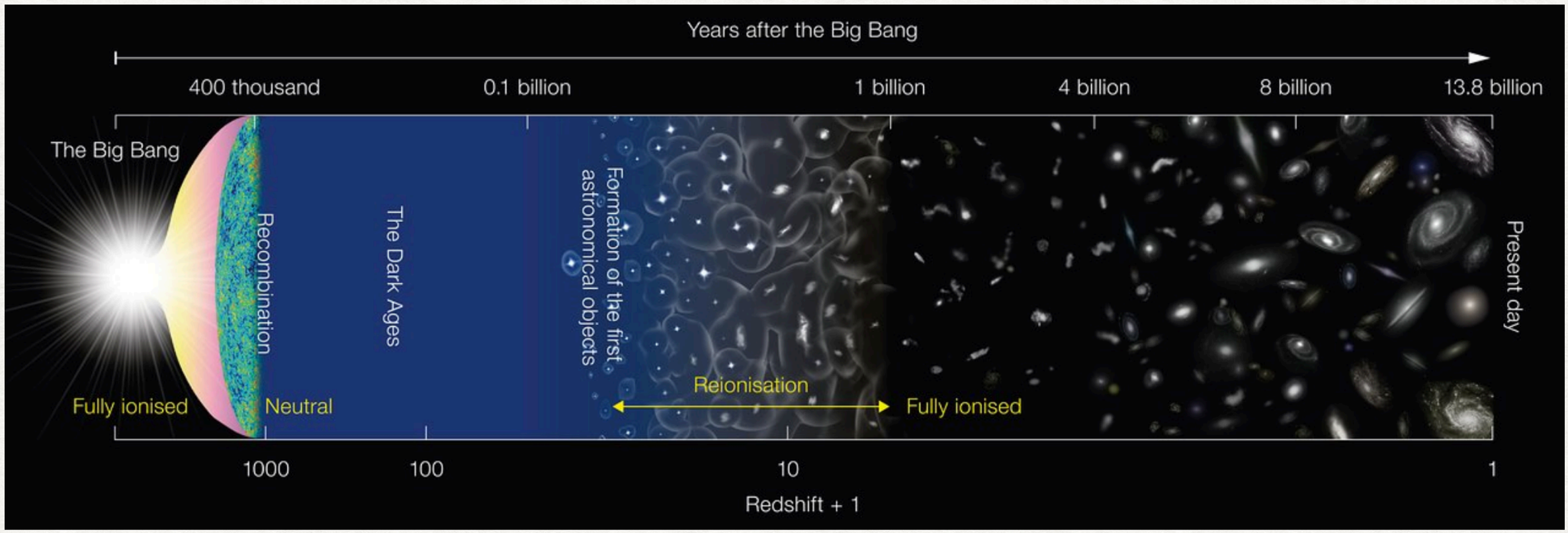
Expansion/matter content **Inflation**



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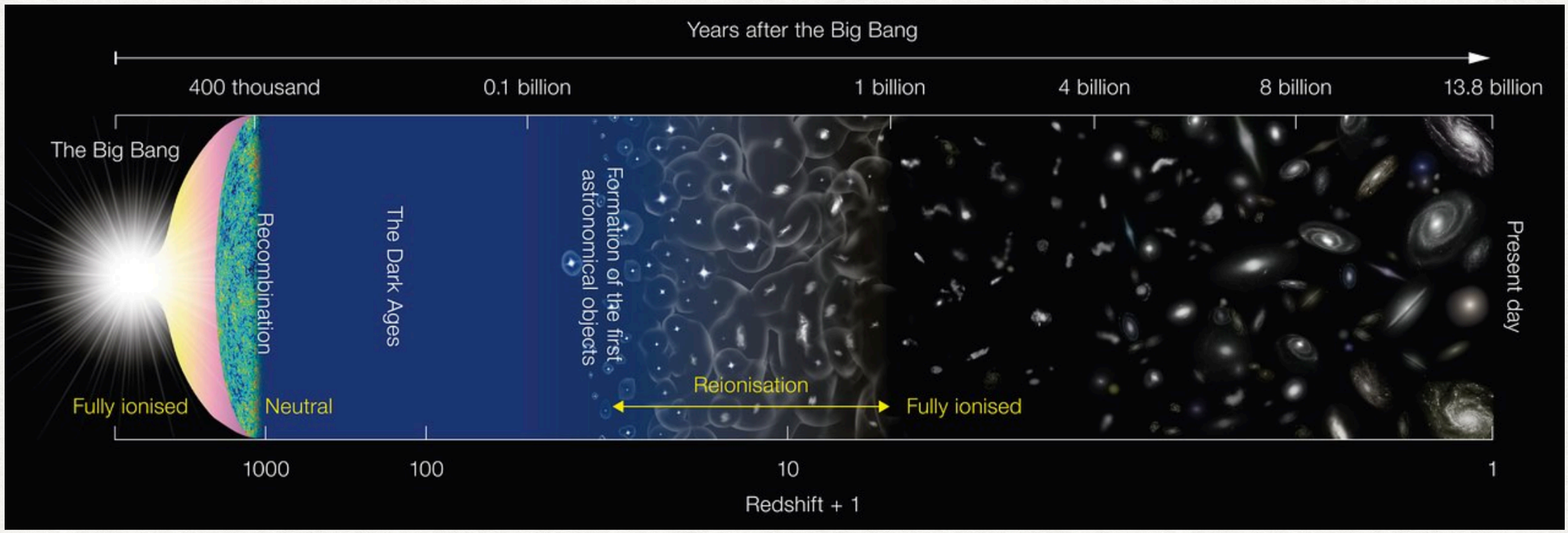
Expansion/matter content **Inflation** **star formation**



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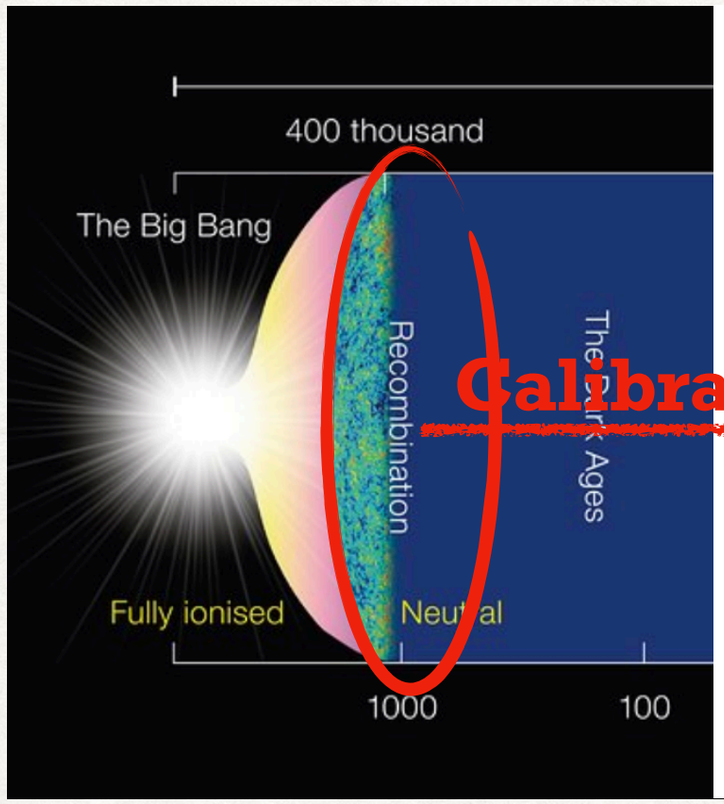
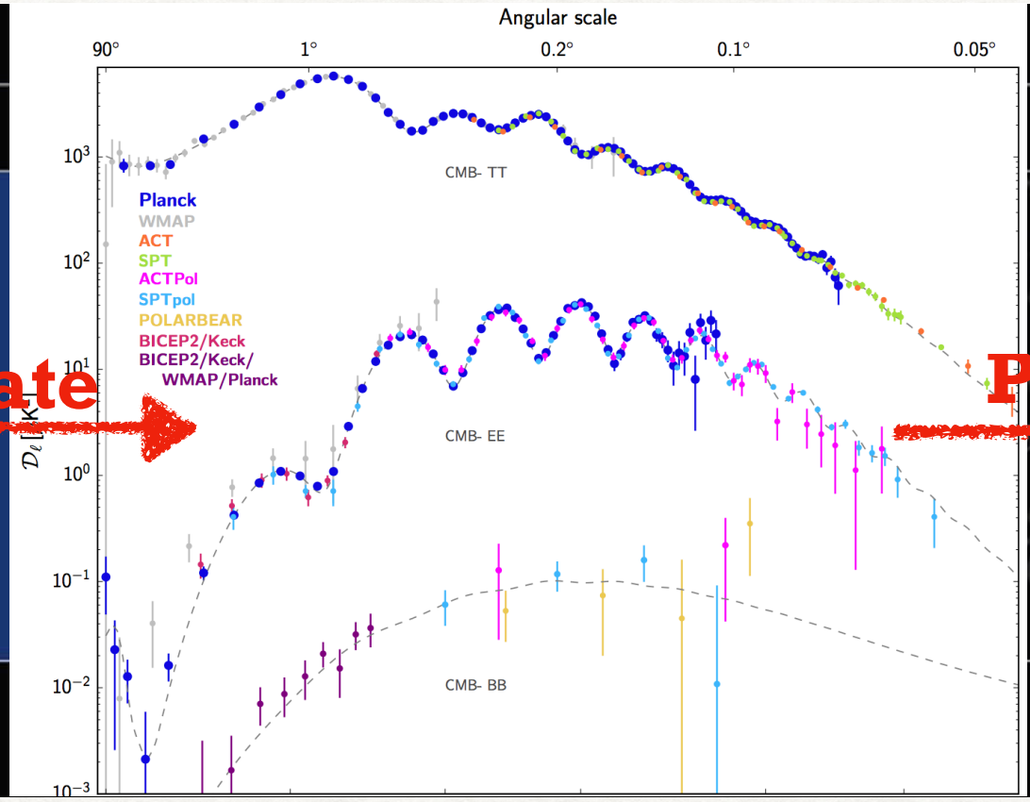
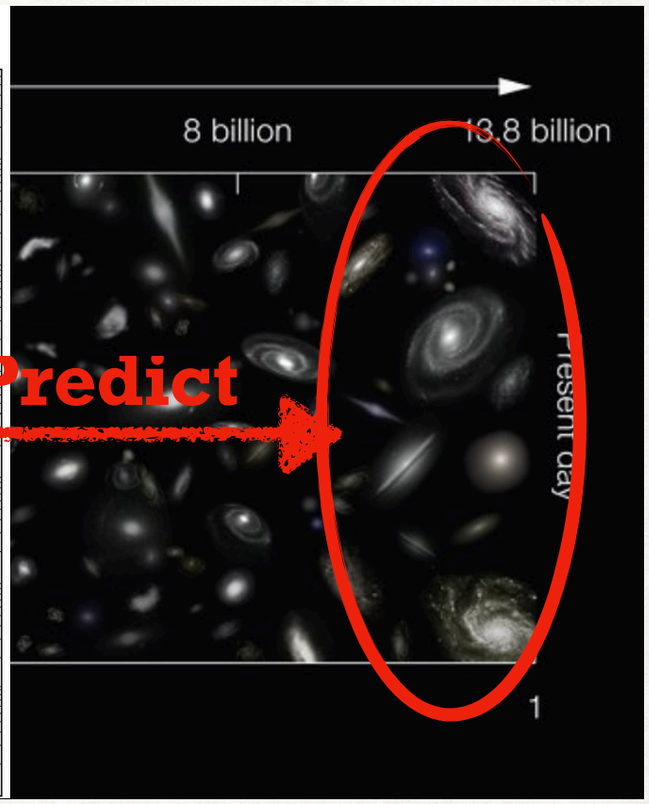
Expansion/matter content — **Inflation** — **star formation**



Calibrate



Predict



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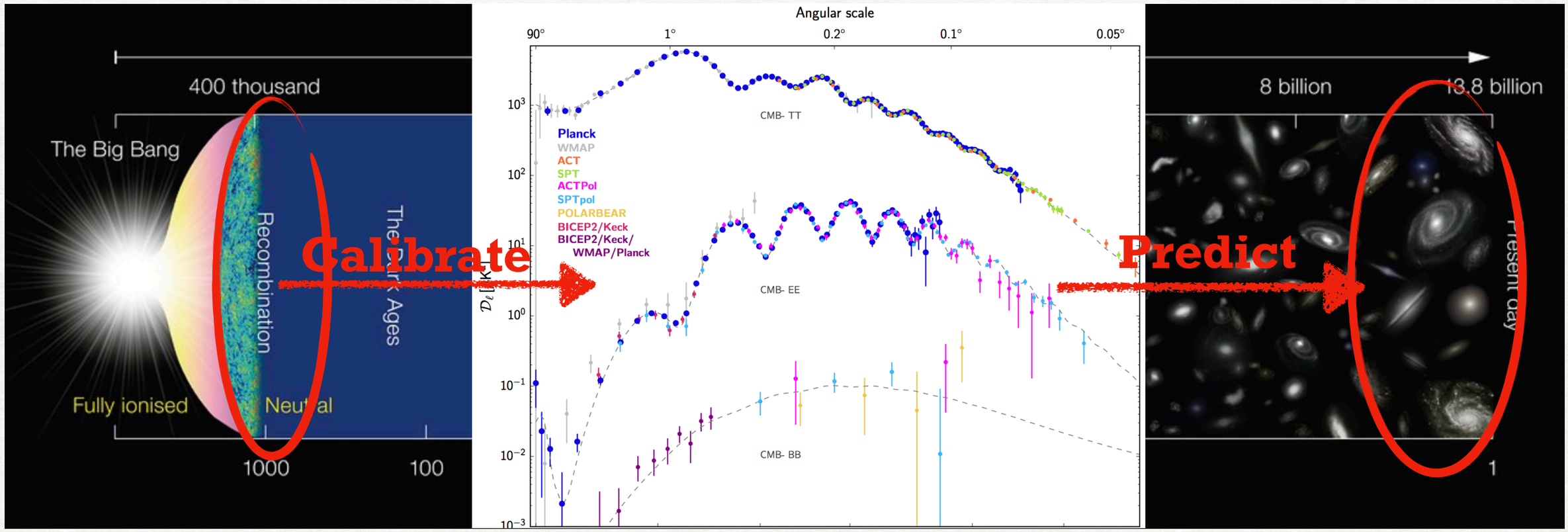

95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

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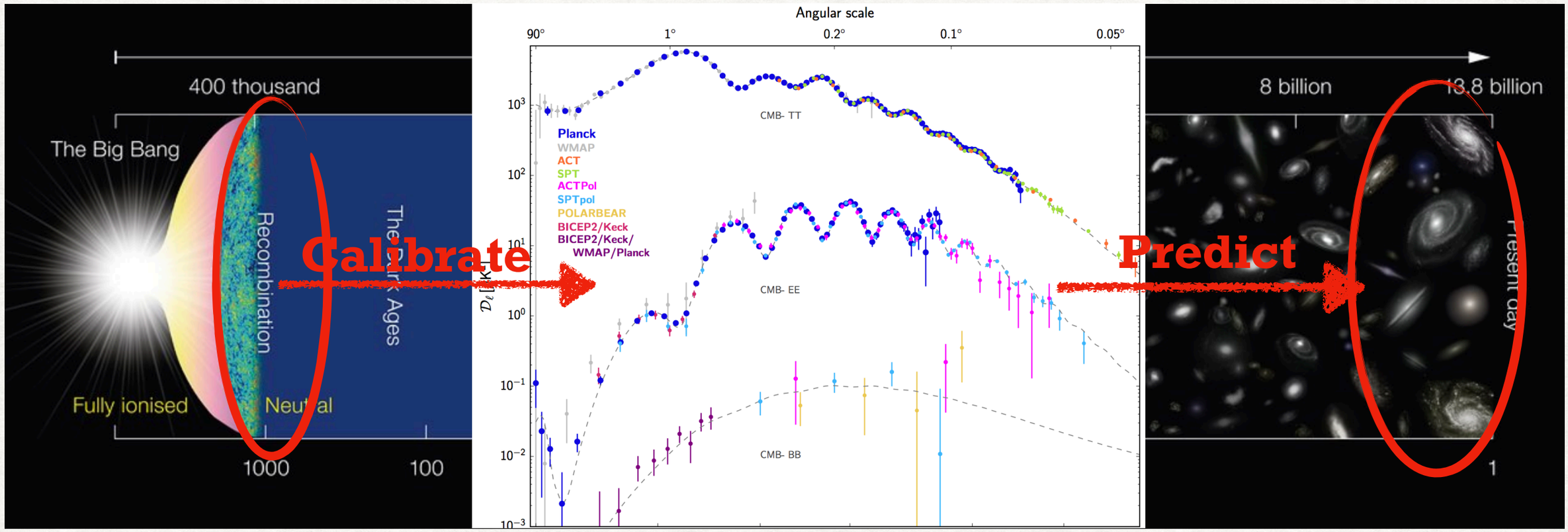

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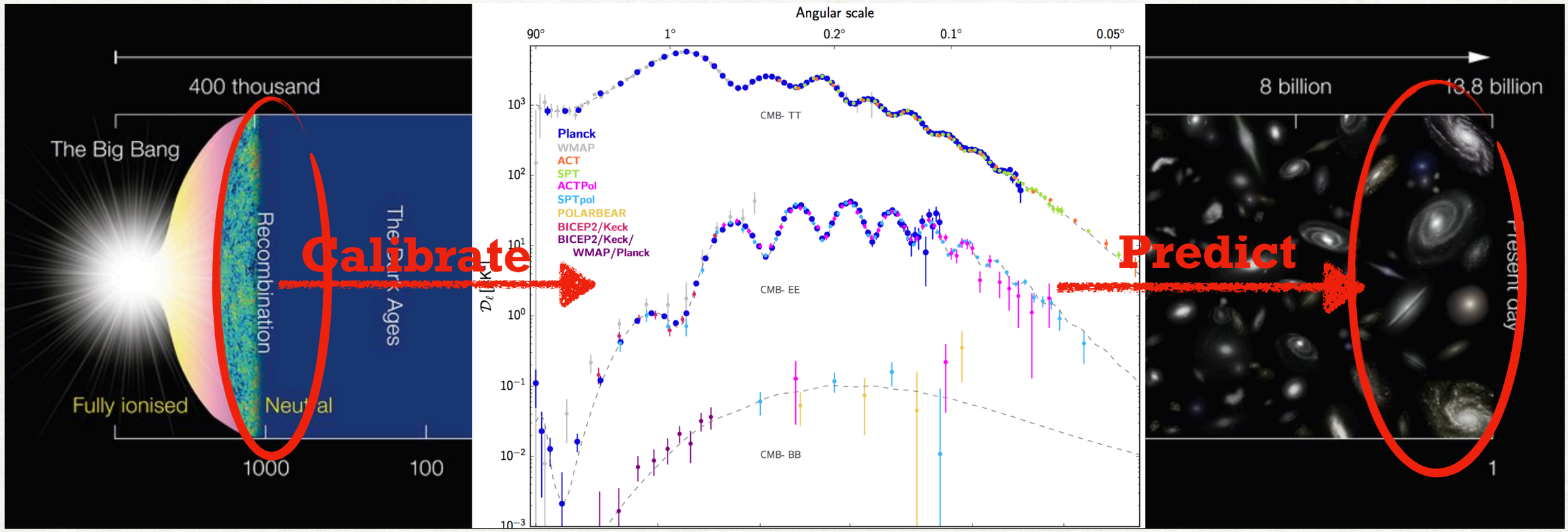
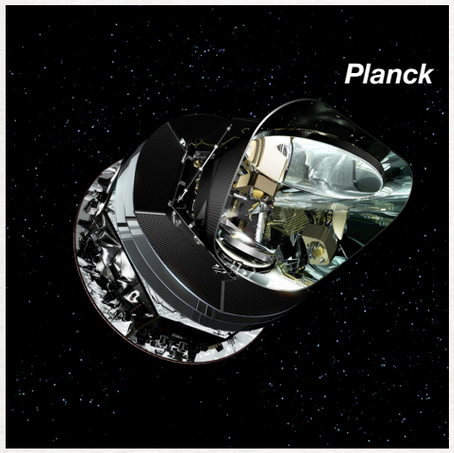


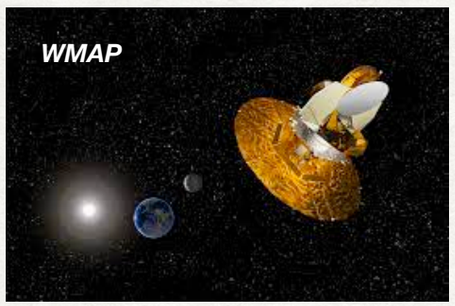
95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

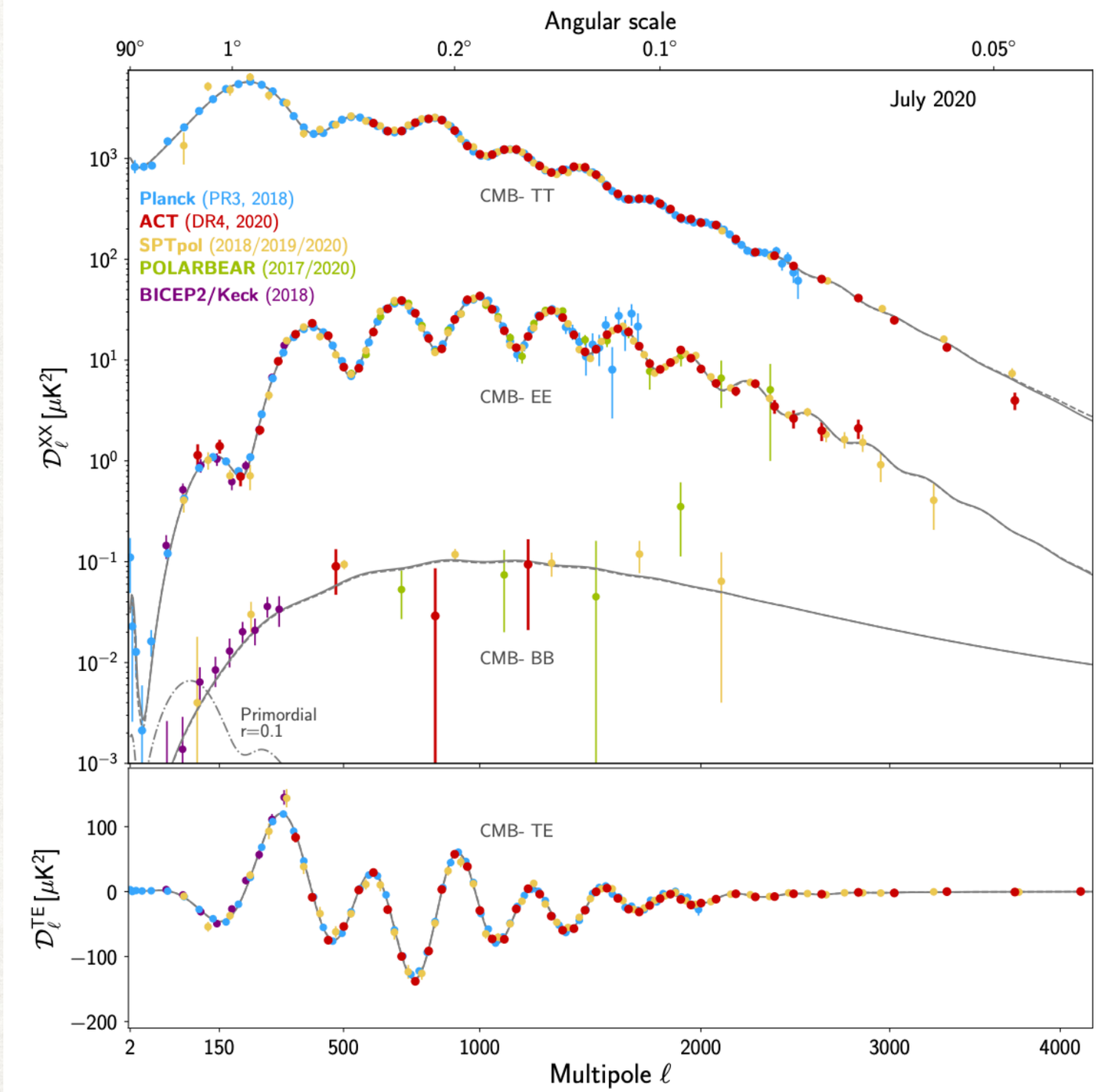
The mechanism behind its initial conditions is unknown.

How star formation happened and re-ionized the universe is unknown.

The Era of Precision Cosmology







- ΛCDM can fit a wide variety of CMB data within 2σ: Planck, ACT, SPT-3G

Precision Cosmology or Cosmic discordance?

The ΛCDM Cosmology is under extreme scrutiny… and starts showing cracks

- Cosmic dipole anomaly? The universe is not isotropic?

  Colin++ 1703.09376, 1808.04597, Secrest++ 2009.14826, Alari++ 2207.05765 , Guandalin++ 2212.04925

- Cosmic void? The universe is not locally homogeneous?

  Wu&Huterer 1706.09723, Kenworthy++ 1901.08681, Cai++ 2012.08292, Camarena++ 2205.05422

- Tensions in cosmological parameters H_0 and S_8?

  Abdalla++ 2203.06142

- Anomalies in *Planck* and ACT? Evidence for a curved universe?

  Di Valentino++ 1911.02087, Calderón++ 2302.14300

- Hints of dynamical dark energy?

  Union3 2311.12098, DES 2401.02929, DESI 2404.03002

- (Too) High redshift galaxies with JWST?

  Labbé++ 2207.12446, Boylan-Kolchin 2208.01611

Are these the first signs of the nature of DM and DE?

Is this a sign of a break down in the cosmological principle or GR?

Today I will highlight

- The "Hubble tension" and its implications

- DESI results on Dark Energy: a new hint for the Hubble tension?

- Update on the clustering tension S_8

Calibrating the ladder: the "direct" way

- SN1a act as standard candles to measure distances and determine H_0

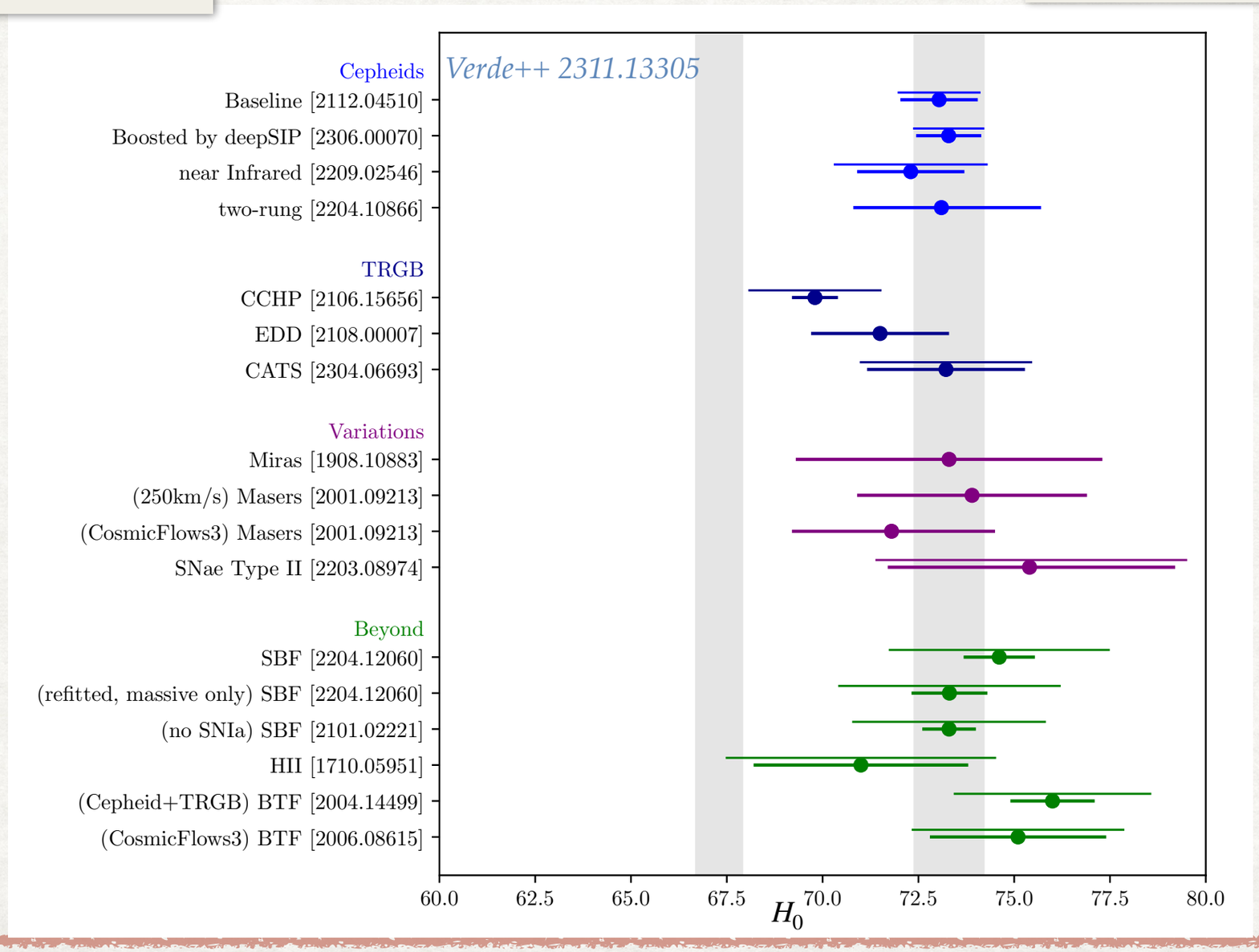
Measured

Requires calibration

$$F(z) = \frac{L}{4\pi D_L(z)^2}$$

$$m \equiv -2.5\log F/F_{\rm ref} + \text{const}.$$
$$M \equiv -2.5\log F(10\ \text{pc})/F_{\rm ref} + \text{const}.$$

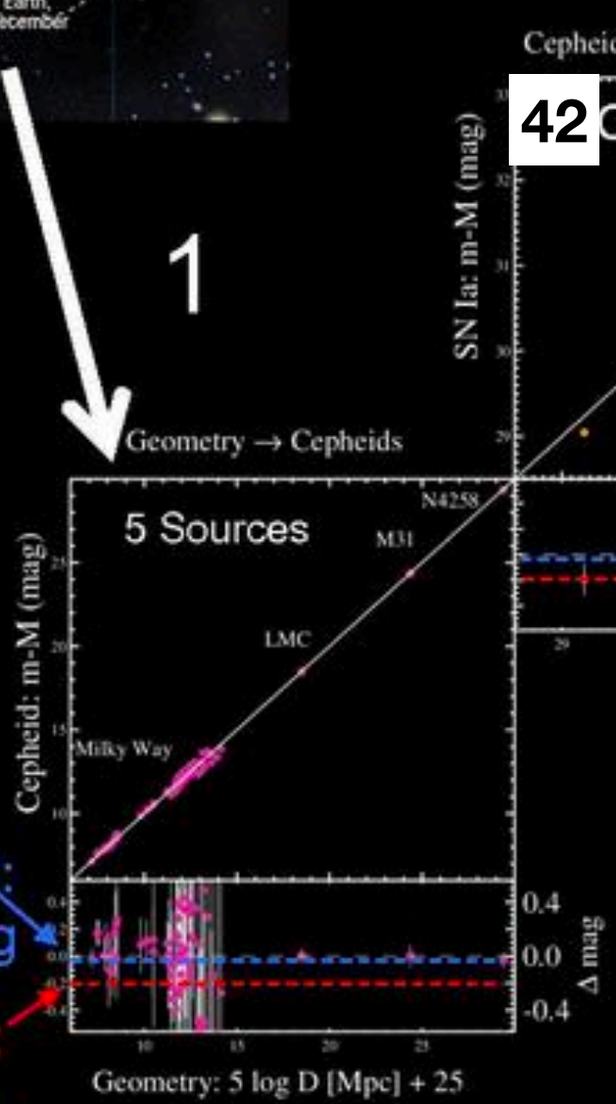
$$m - M = 5\log(D_L/10\text{pc})$$
$$D_L \sim czH_0^{-1}, \quad z \ll 1$$



The Hubble Constant in 3 Steps: Present Data

1

Geometry → Cepheids

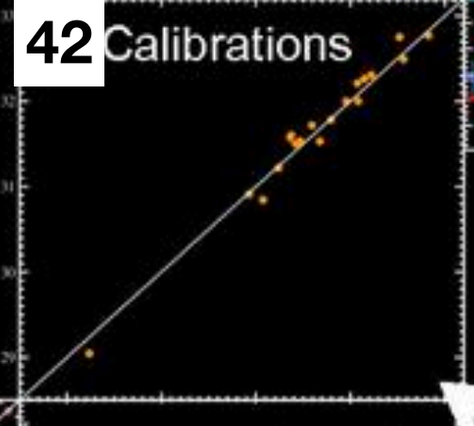


1% Goal: 0.02 mag

Tension: 0.2 mag

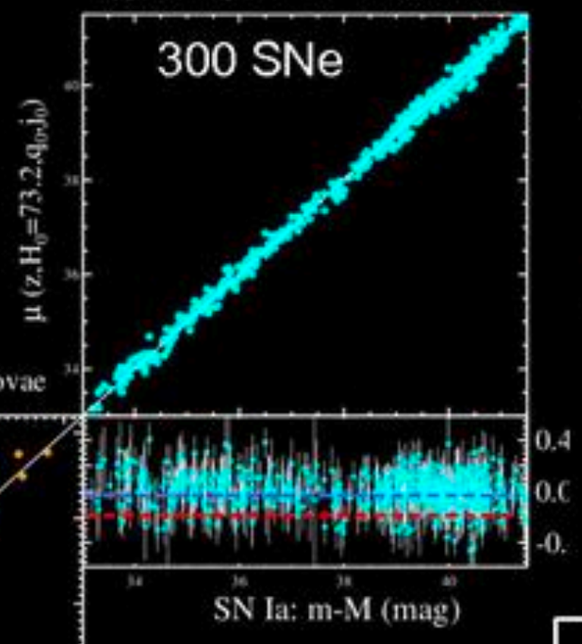
Cepheids → Type Ia Supernovae

42 Calibrations

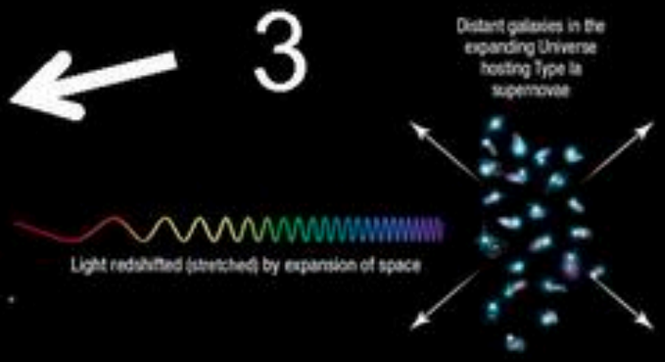


2

Type Ia Supernovae → redshift(z)



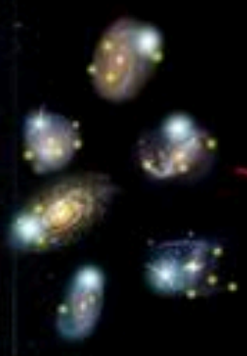
3



$5\log H_0 = M_B^0 + 5a_B + 25$

$H_0 = 73 \pm 1.0$ Km s^{-1} Mpc^{-1} (Riess et al. 2019)

Galaxies hosting Cepheids and Type Ia supernovae



1.4% total uncertainty

5.0 σ from CMB + ΛCDM !

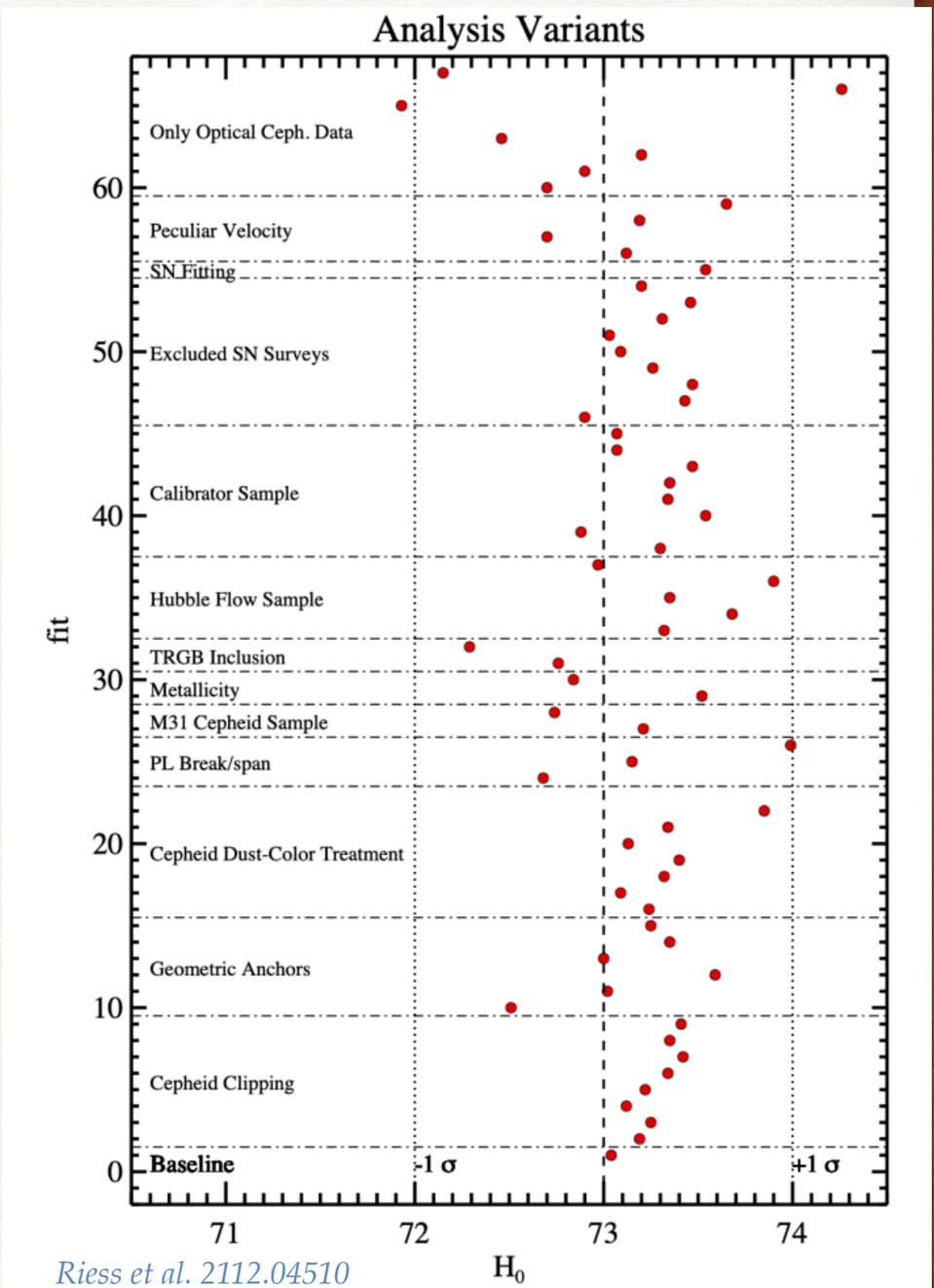
$H_0 = 67.4 \pm 0.5$ km/s/Mpc

Adapted from slide by A. Riess, KITP July 2019

Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

- SH0ES builds a 3 steps distance ladder: anchors => cepheids => SN1a
- Are there issues with distance anchor? (GAIA, LMC, NGC4258)
  Efstathiou++ 2007.10716, Soltis++2012.09196
- Are there issues with cepheids?
  - Cepheids vs TRGB: disagreement?
    Freedman++ 2106.15656, Anand++ 2108.00007
  - Effect of Dust? *Mortsell++ 2105.11461*
  - Cepheid crowding? *Riess++ 2401.04773*
  - Is the metallicity correction correct? *Efstathiou++ 2007.10716*
- Are there issues with SN1a? different populations of SN1a between "cepheid-SN1a calibrator" and Hubble flow SN1a?
  Rigault++ 1412.6501, Jones++1805.05911, Brout&Scolnic 2004.10206
- Are there issues with the CMB? *Di Valentino++ 1911.02087, Calderón++ 2302.14300*



Riess et al. 2112.04510

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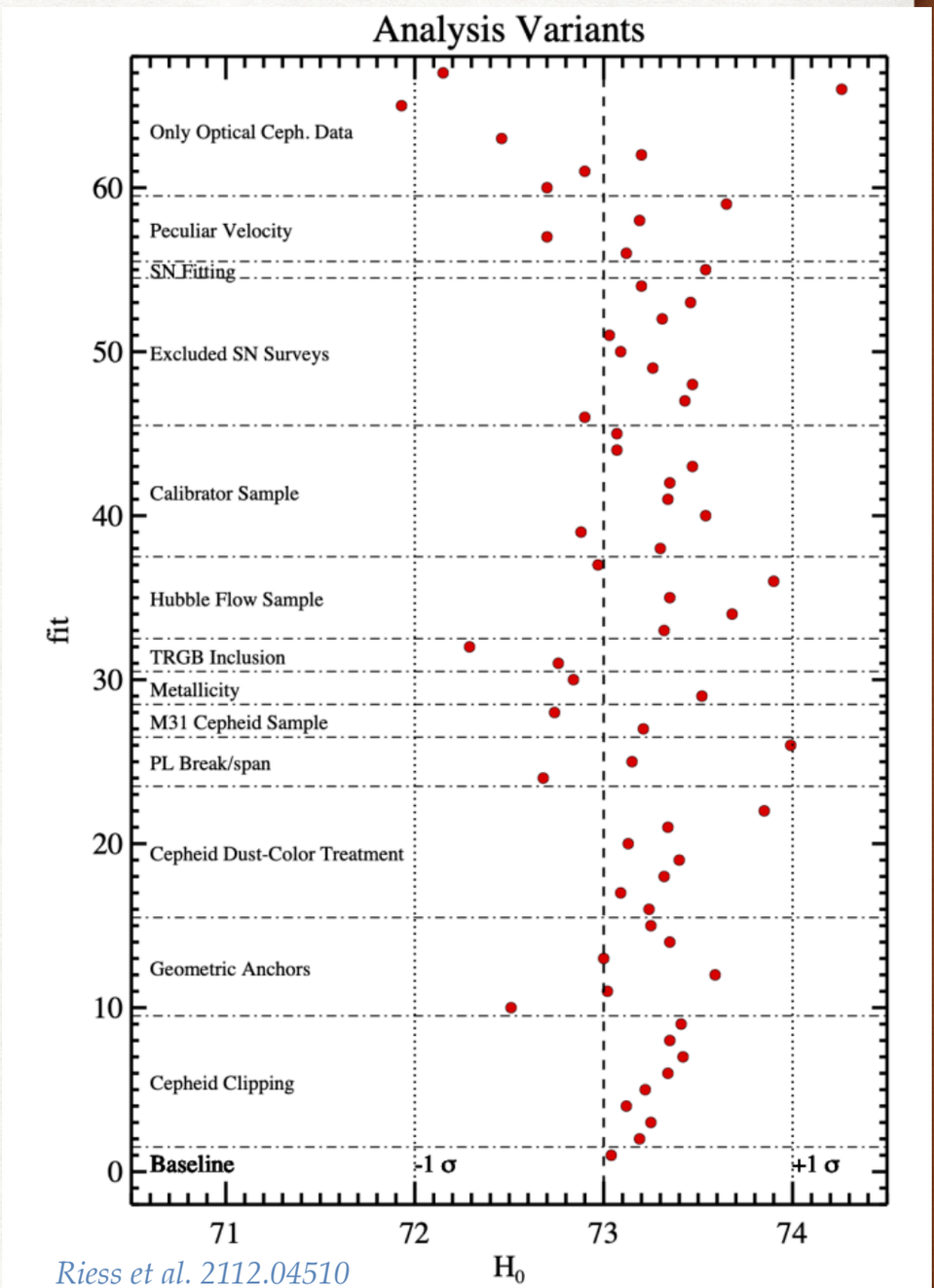
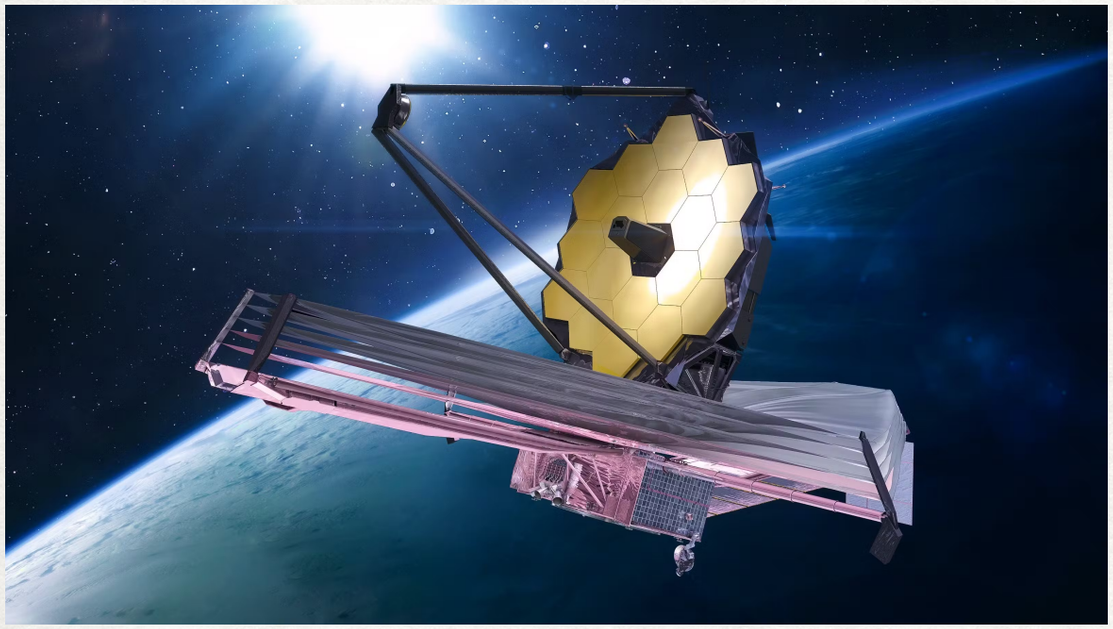
The question of systematics is not settled, but it is not easy to "hide" a 5σ bias!

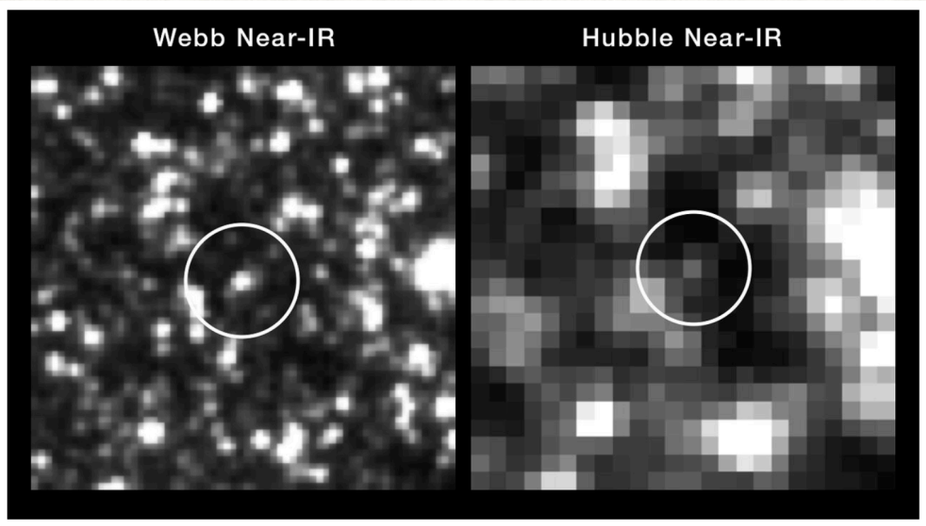


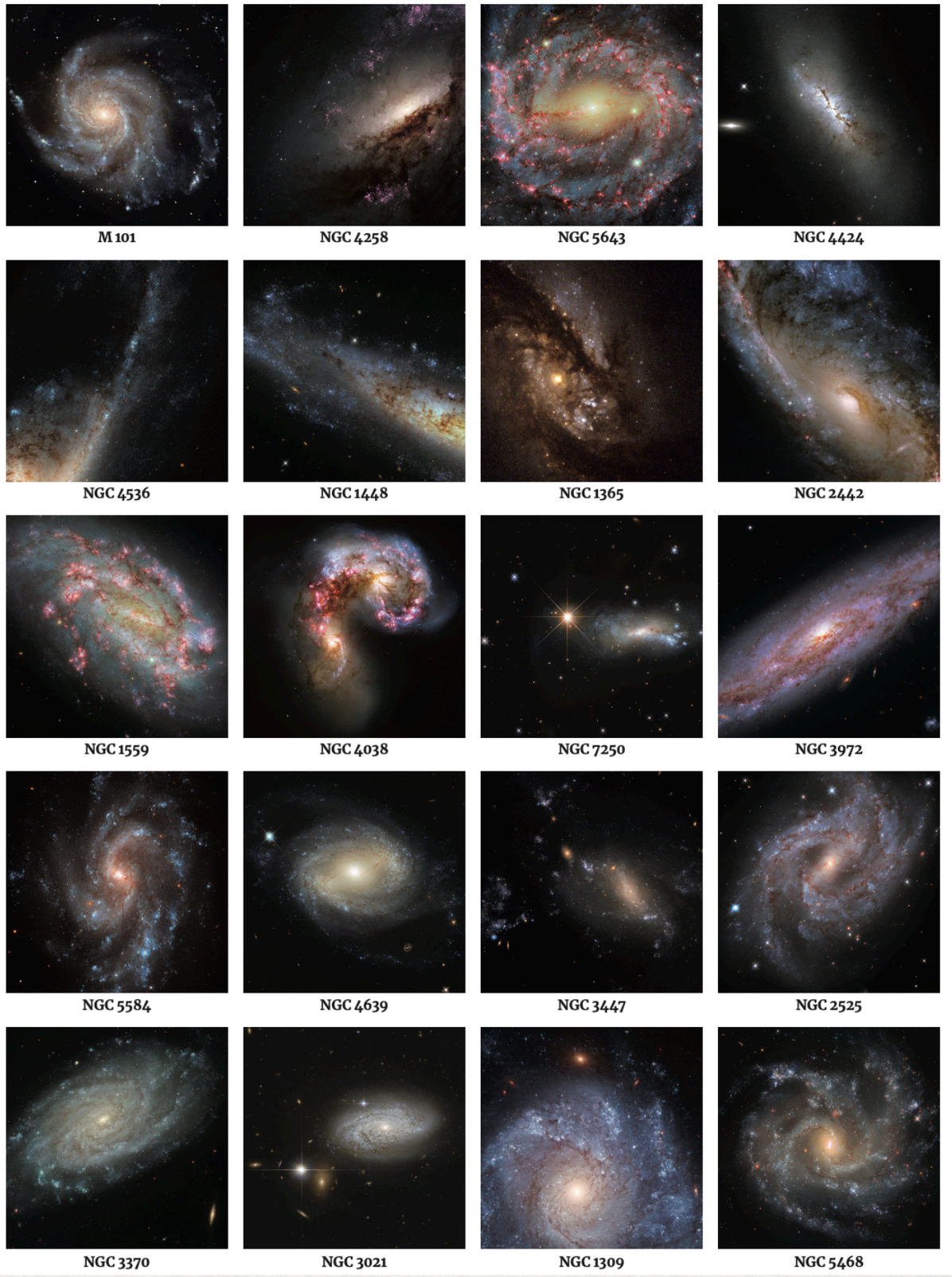
Riess et al. 2112.04510

JWST and the Hubble tension

- First analyses with JWST from CCHP and SH0ES.
- Re-observations of 20 key galaxies to check HST results + develop new calibration method.



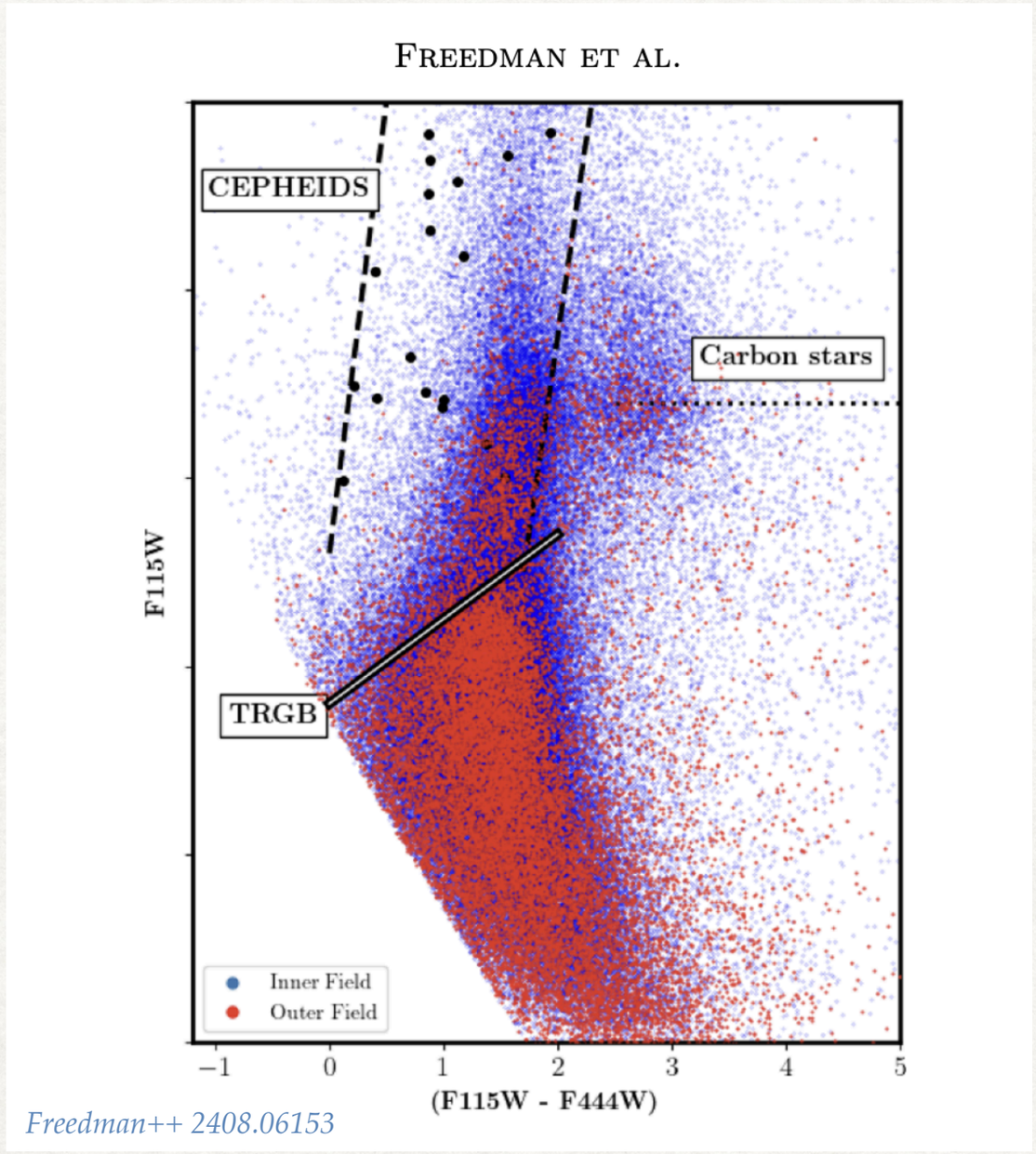




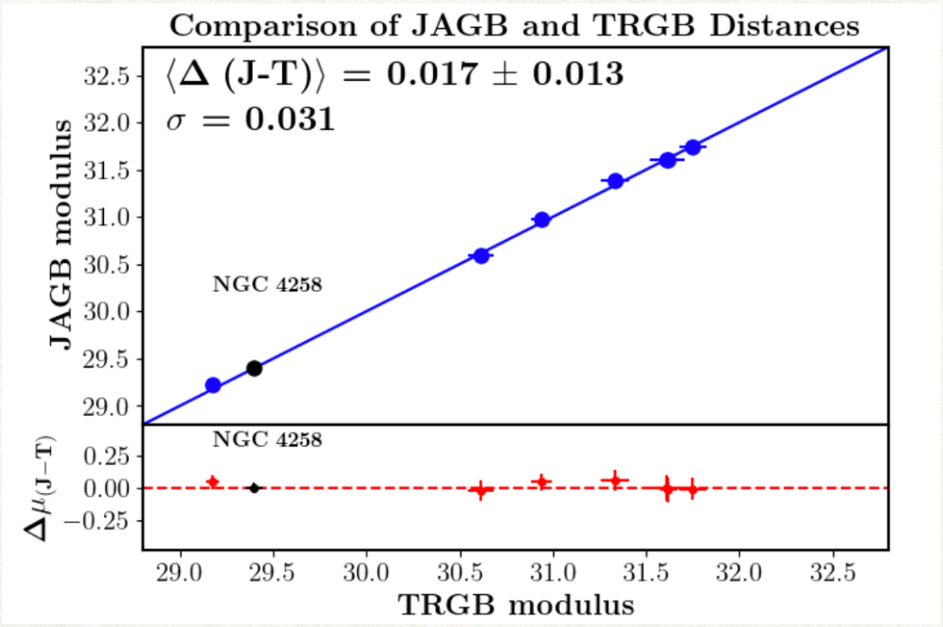
V. Poulin - LUPM (CNRS / Montpellier)

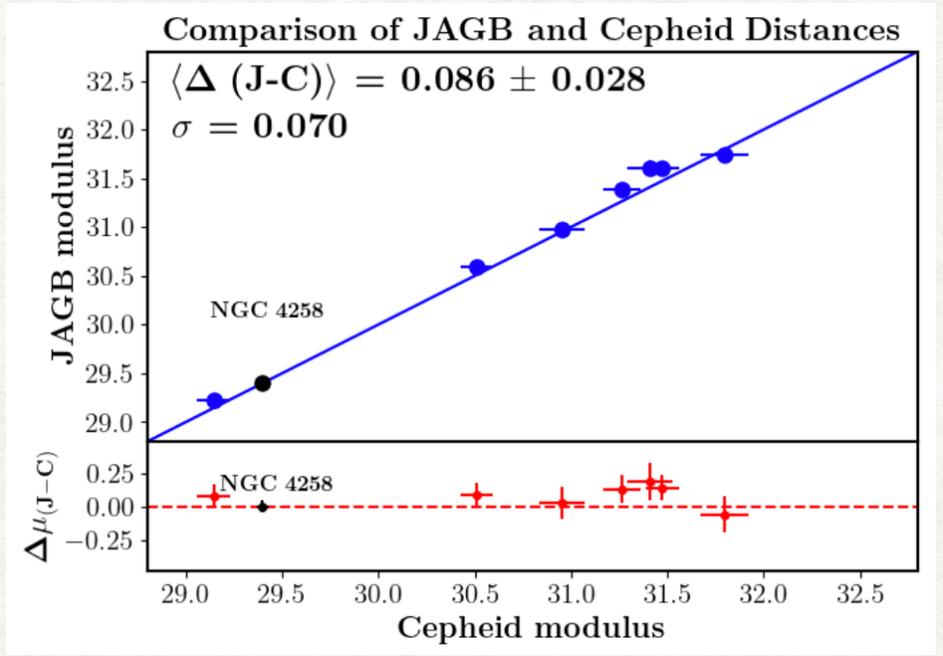
CCHP: 3 JWST-only measurements of H_0

- Observations of 10 SN1a hosts + 1 anchor to re-calibrate cepheids, TRGB and a new 'JAGB' method.



Freedman++ 2408.06153

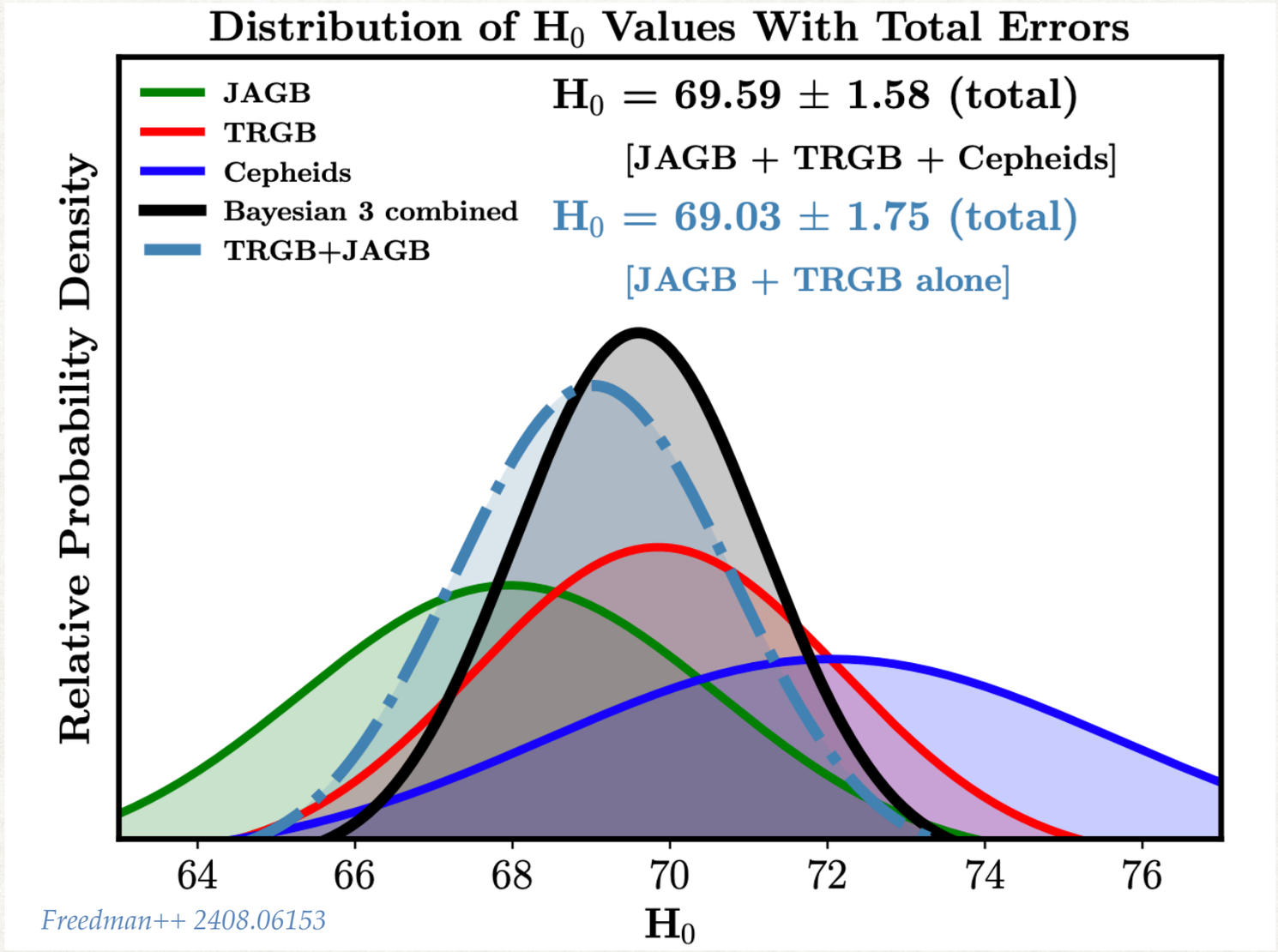




- Finds a bias in the cepheids distance while TRGB and JAGB distance are in good agreement

CCHP finds no Hubble tension

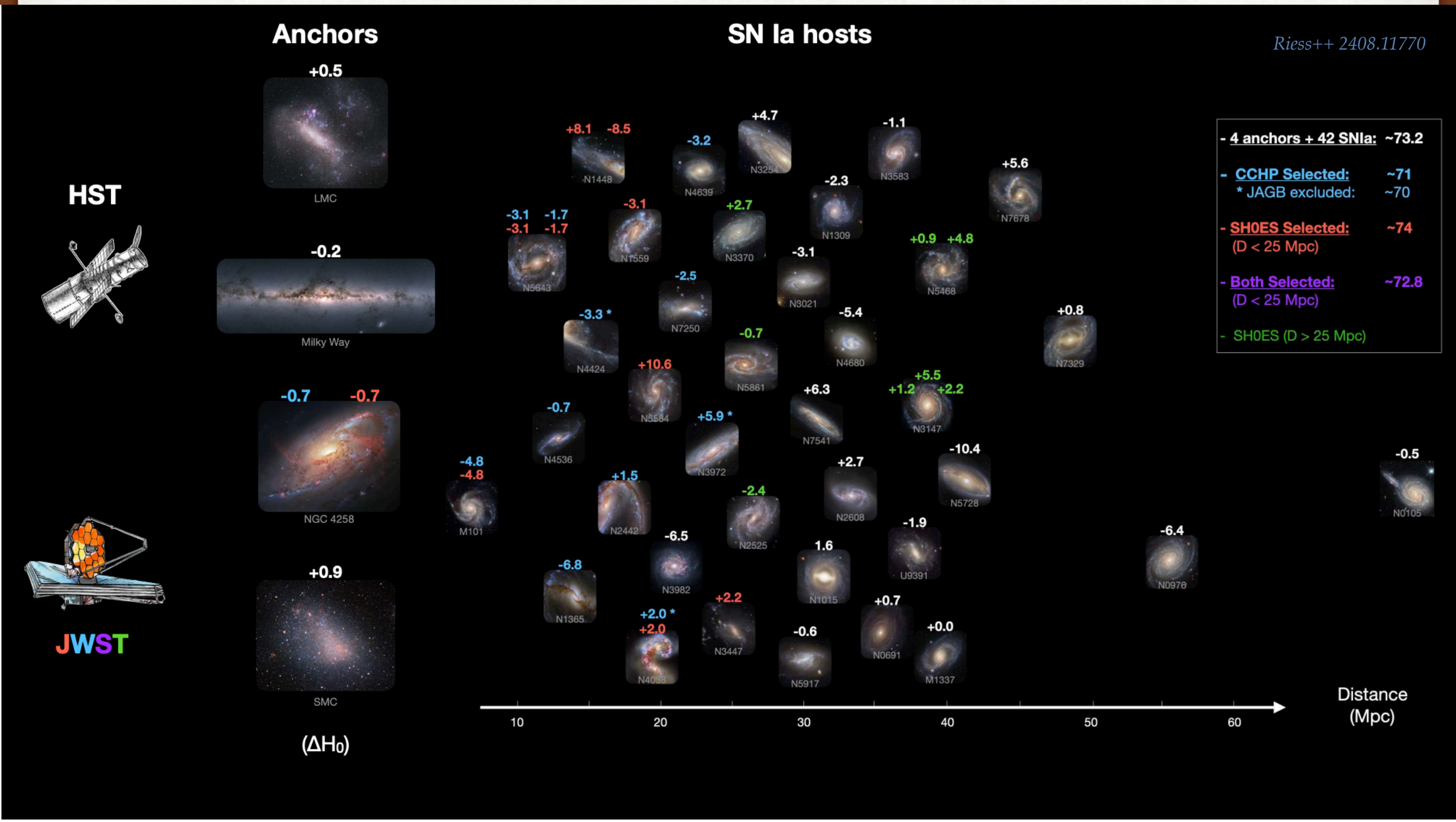
- JAGB and TRGB value of H_0 in good agreement with ΛCDM, Cepheids are 'biased high'.
- Error bars are large: JWST alone is not (yet) as good as HST, only 10 hosts galaxies and one anchor.



Is this the end of the Hubble tension?

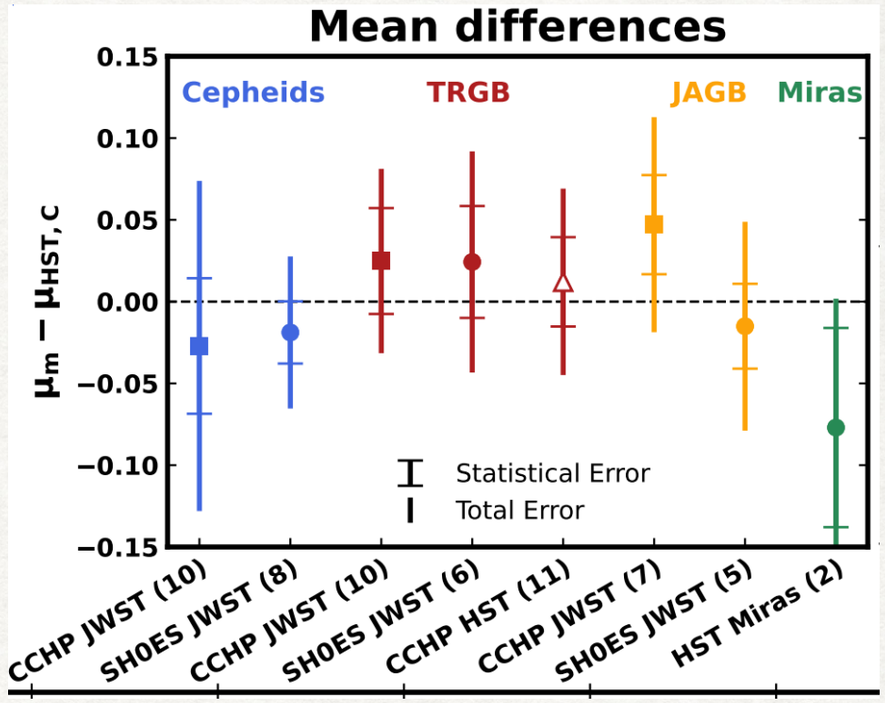
HST provides a 'complete' picture

- JWST measures (very well) a sub-sample of the full HST sample

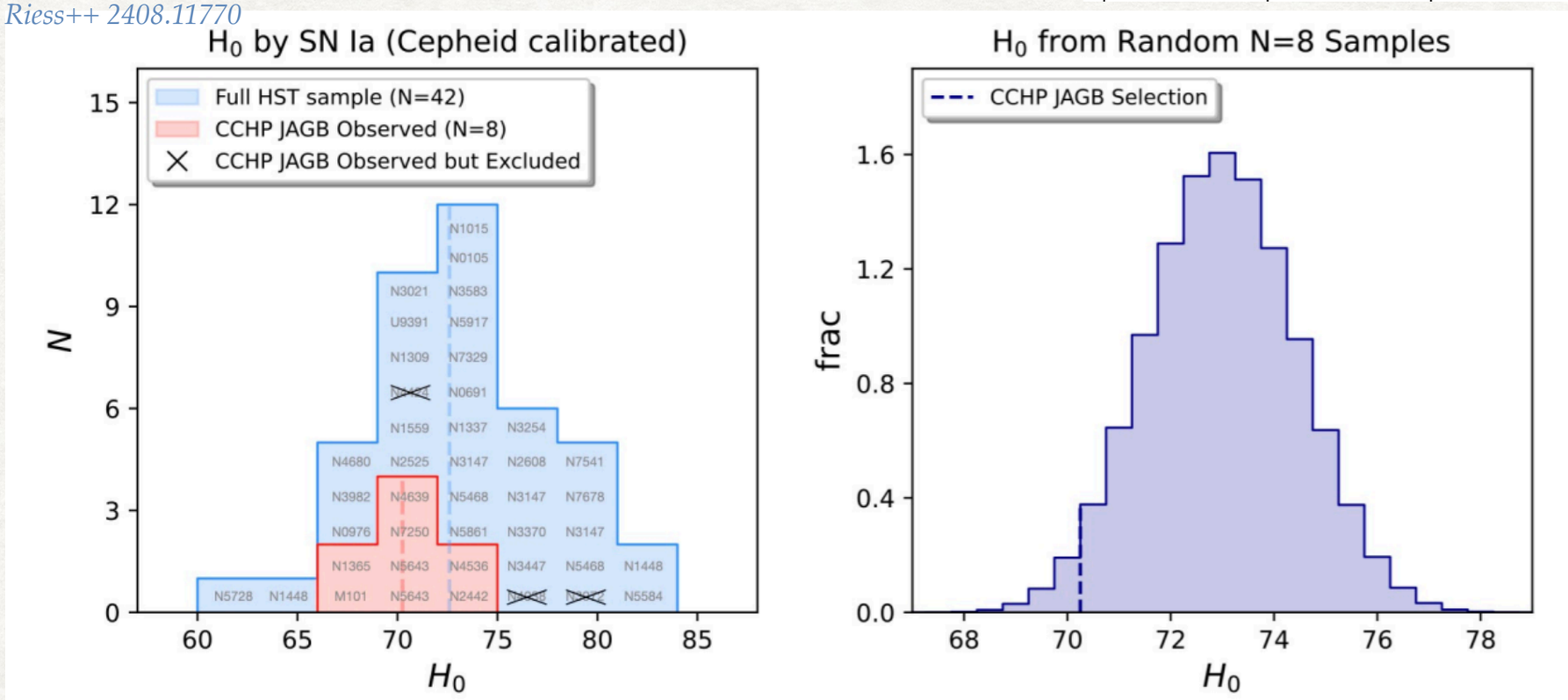


SHOES suggests a 'bias low' in CCHP samples

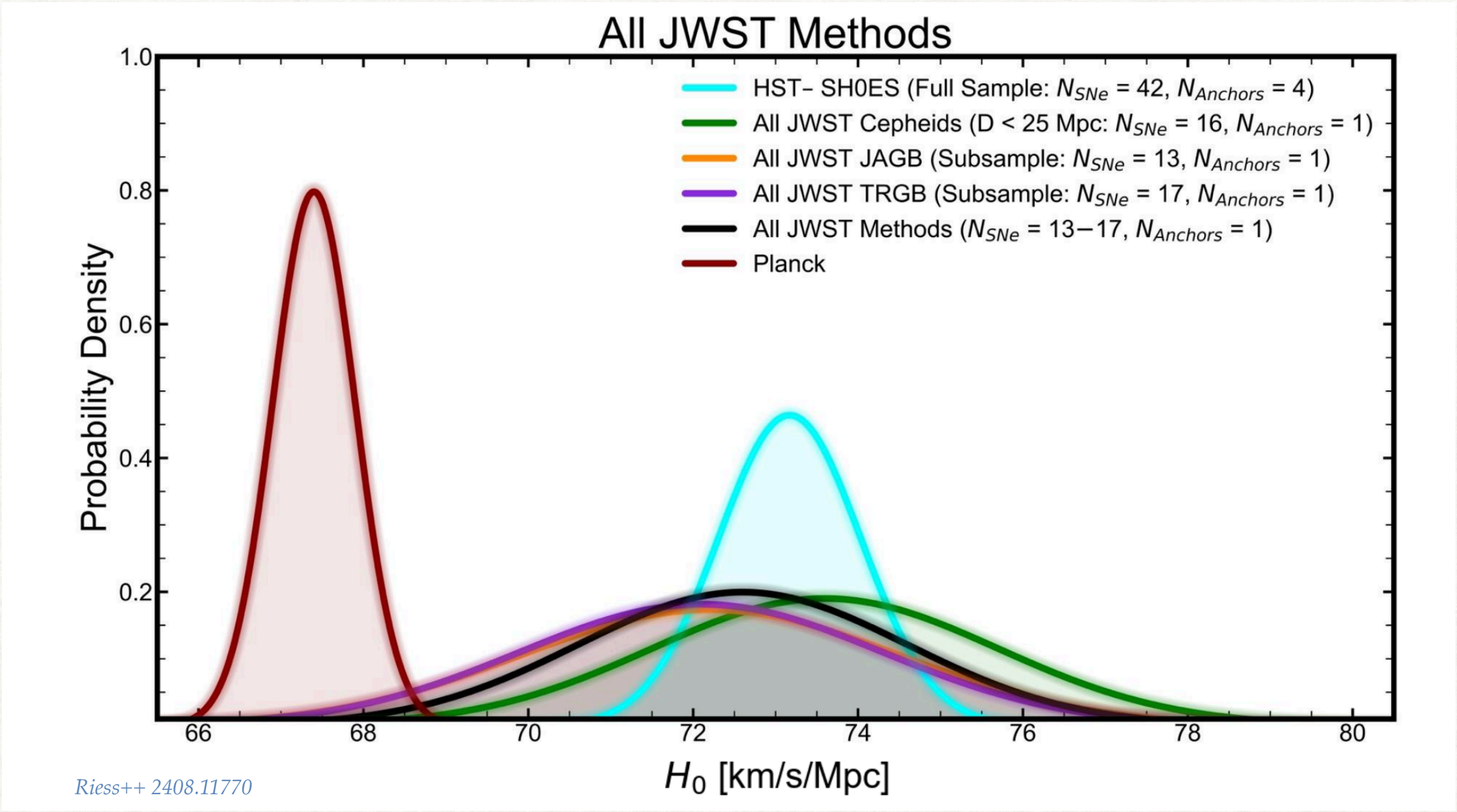
- JWST in very good agreement ($< 1\sigma$) between cepheid distances and all other methods from HST
- Identified a missing source of error in the CCHP cepheid
- JAGB sample of host galaxies is 'biased low' and this is expected!



Riess++ 2408.11770



SH0ES confirms the Hubble tension with JWST

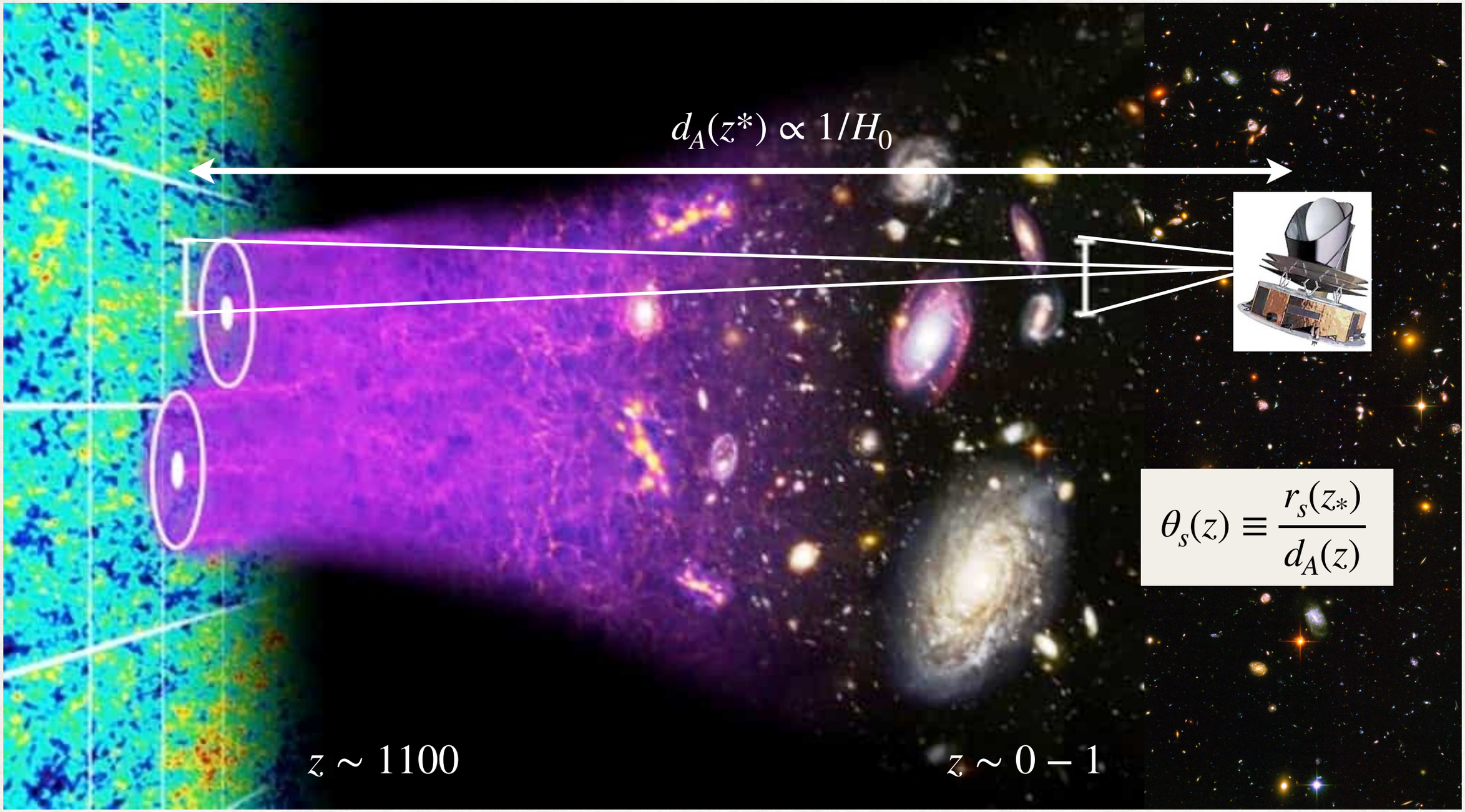


Riess++ 2408.11770

- The situation will be settled by (re-)measuring the remaining SN1a host galaxies and anchors.

The Hubble tension is alive and well!

Calibrating the ladder: the "indirect" way

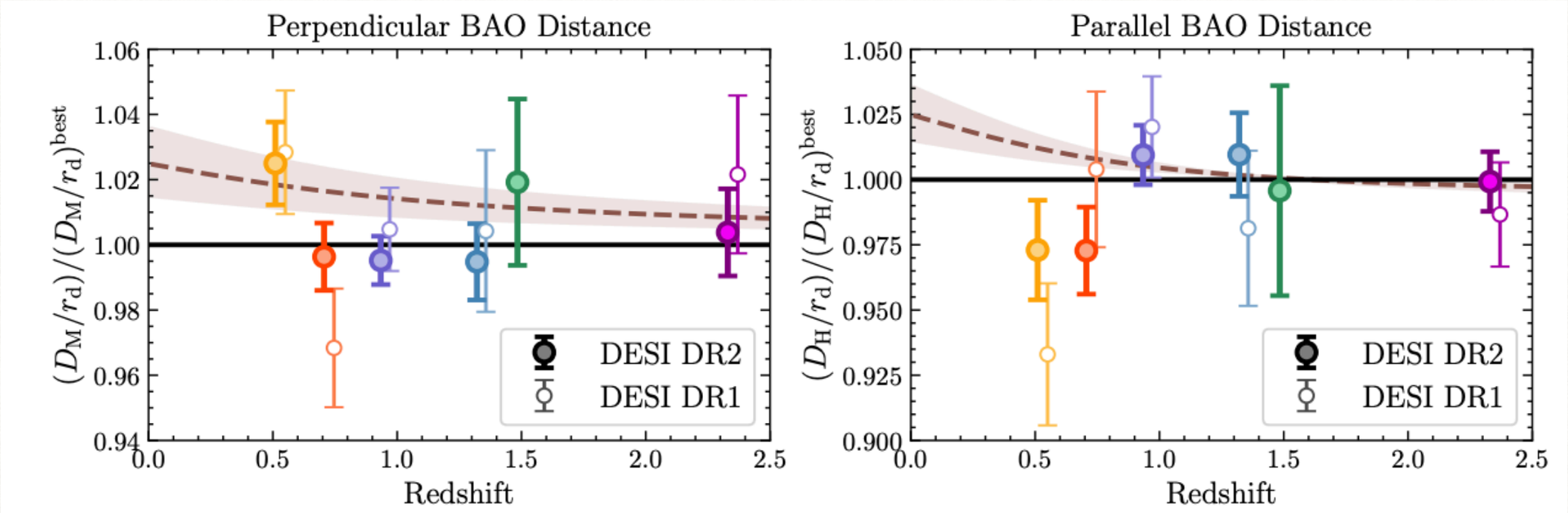


- *Planck* measures θ_s at 0.04% precision but r_s & d_A are model dependent.
- H_0 appears only in the angular diameter distance d_A.

Summary of other measurements: Verde++ 2311.13305

DESI BAO measurements: hint of new physics?

- Under ΛCDM, 2.3σ tension between CMB and BAO data



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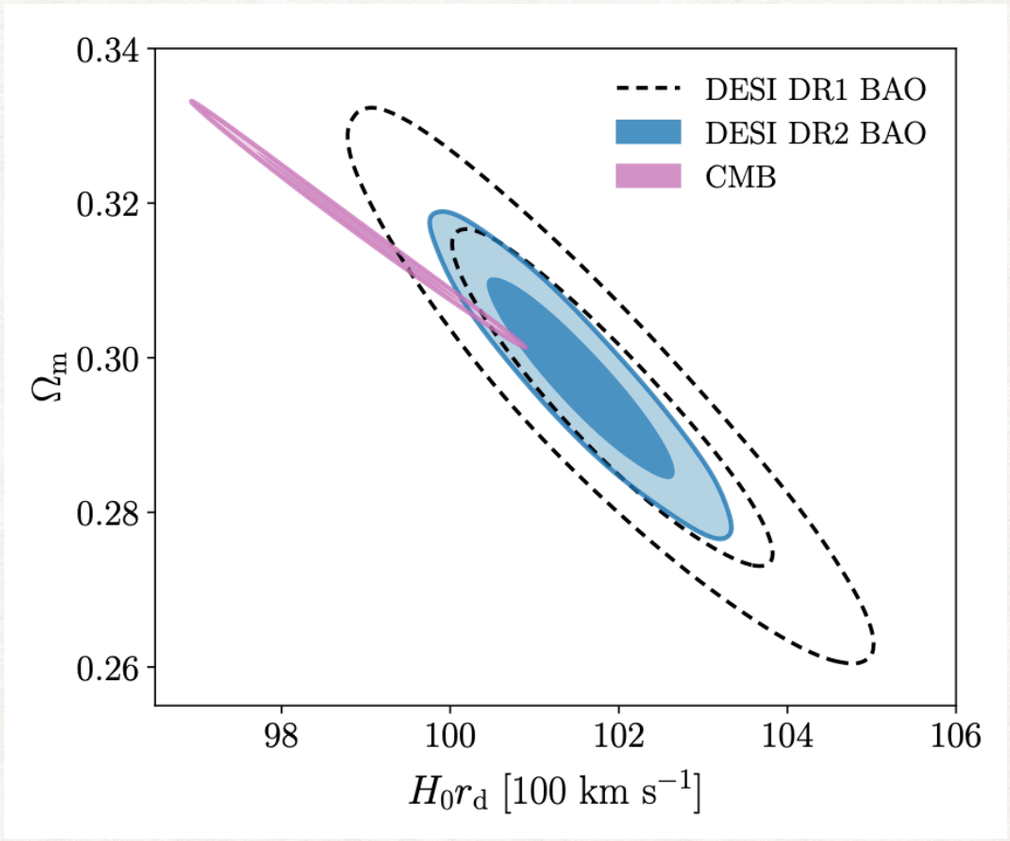

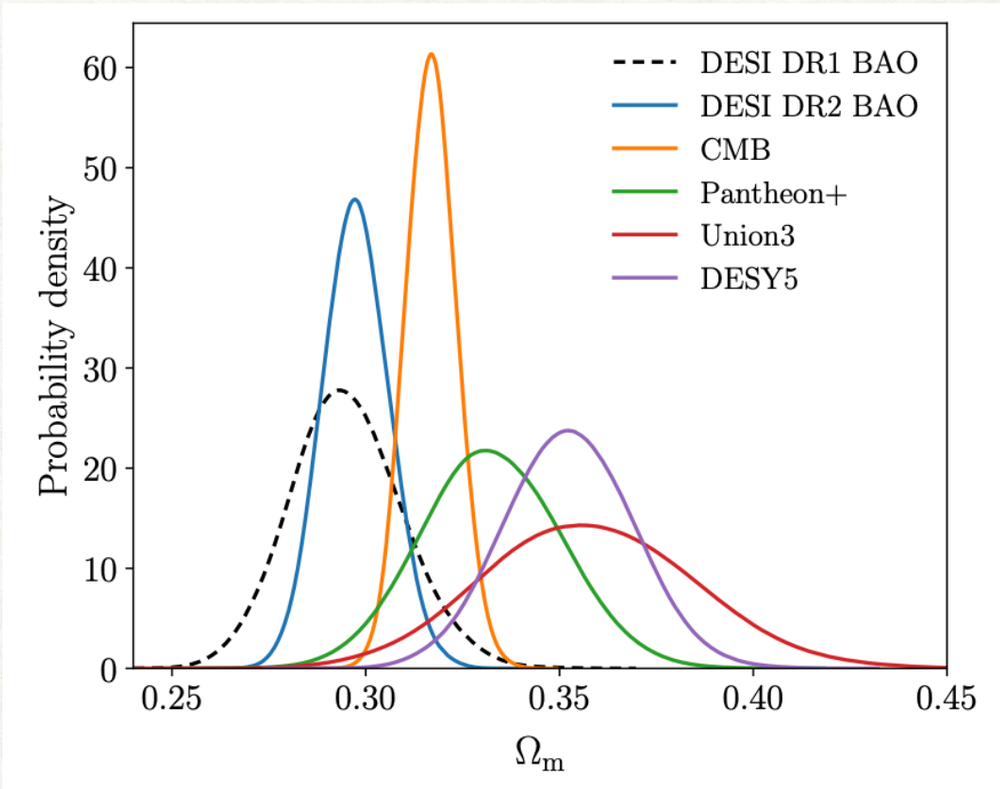

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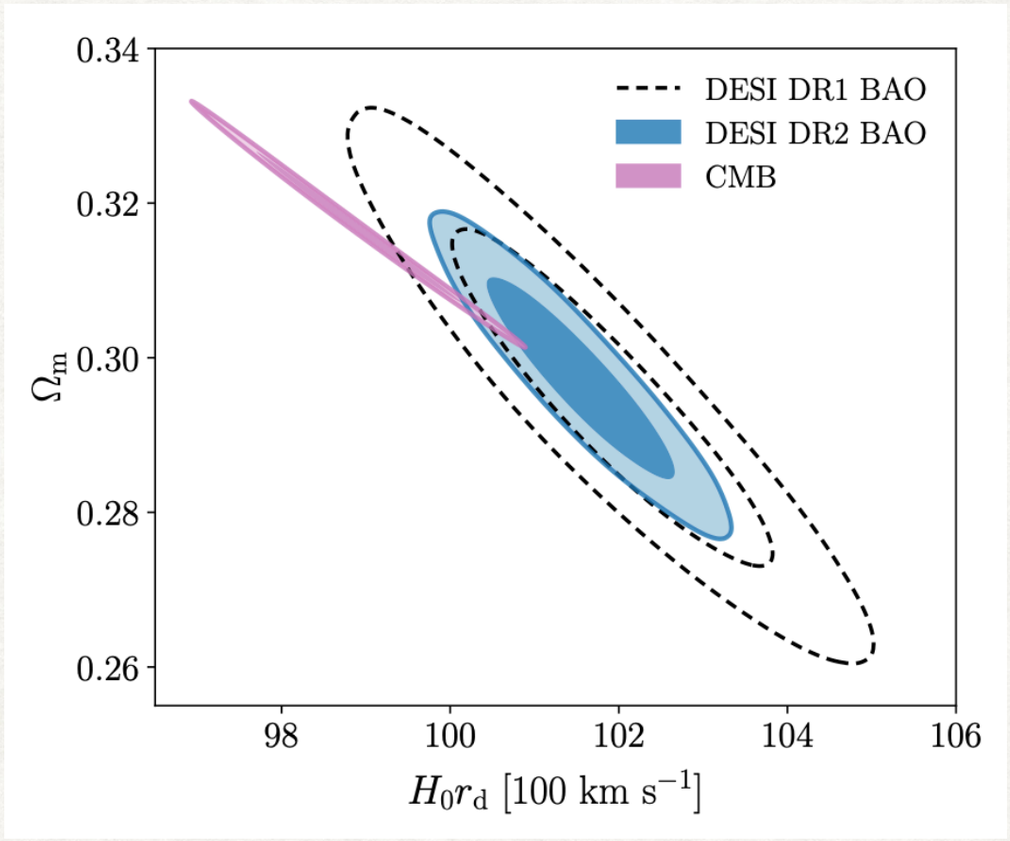
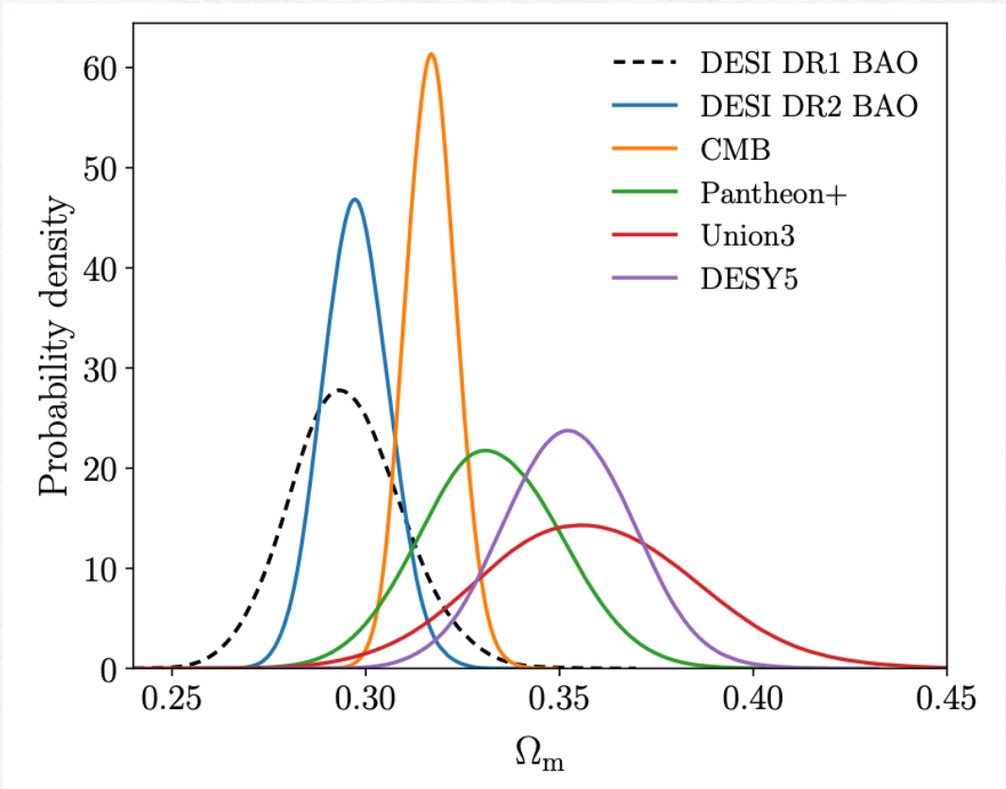


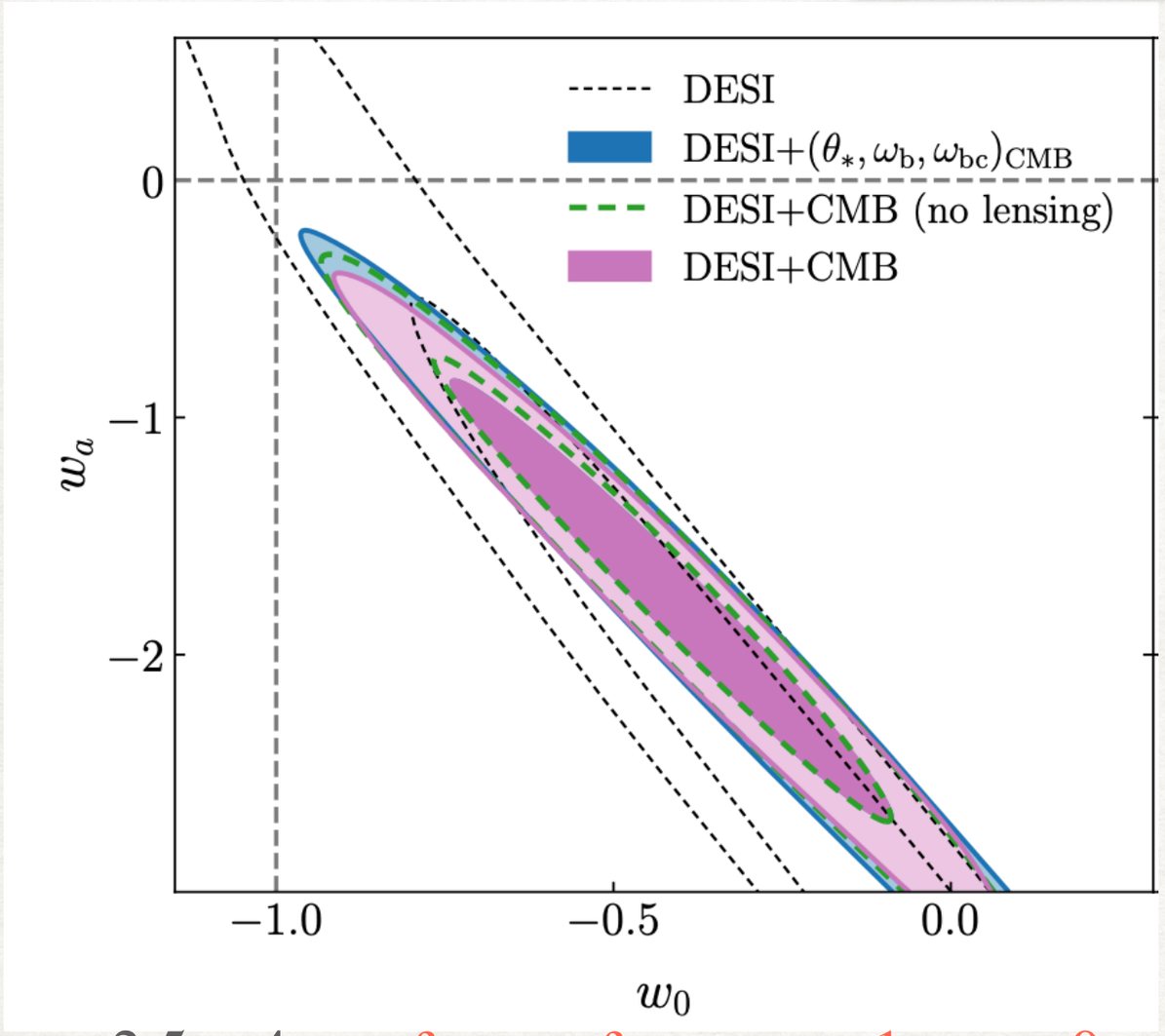


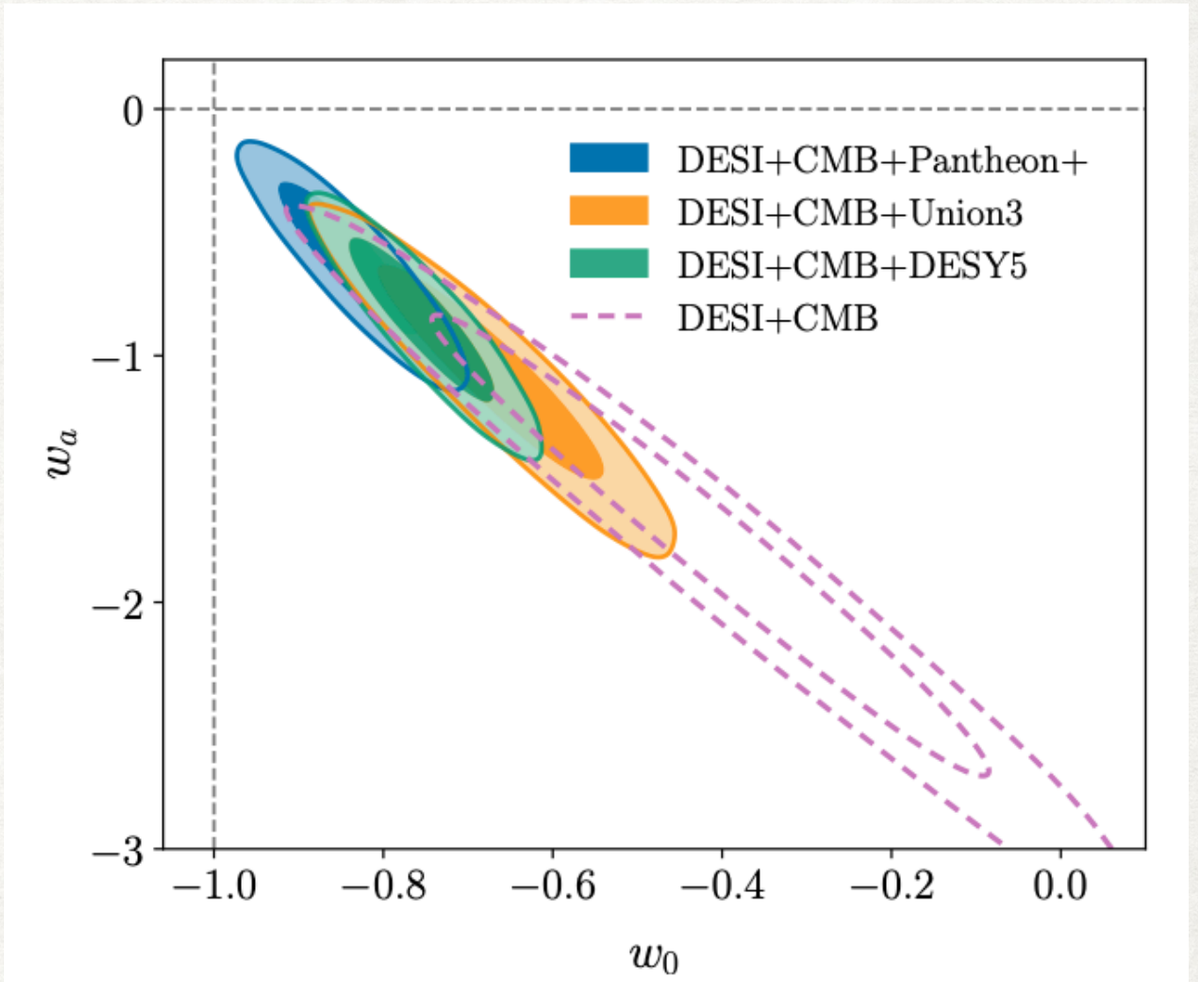
- DESI+CMB in tension at the $\sim 2-3\sigma$ level with SN1a in the determination of Ω_m

Evidence for dynamical dark energy

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

Chevallier, Polarski 2001; Linder 2002



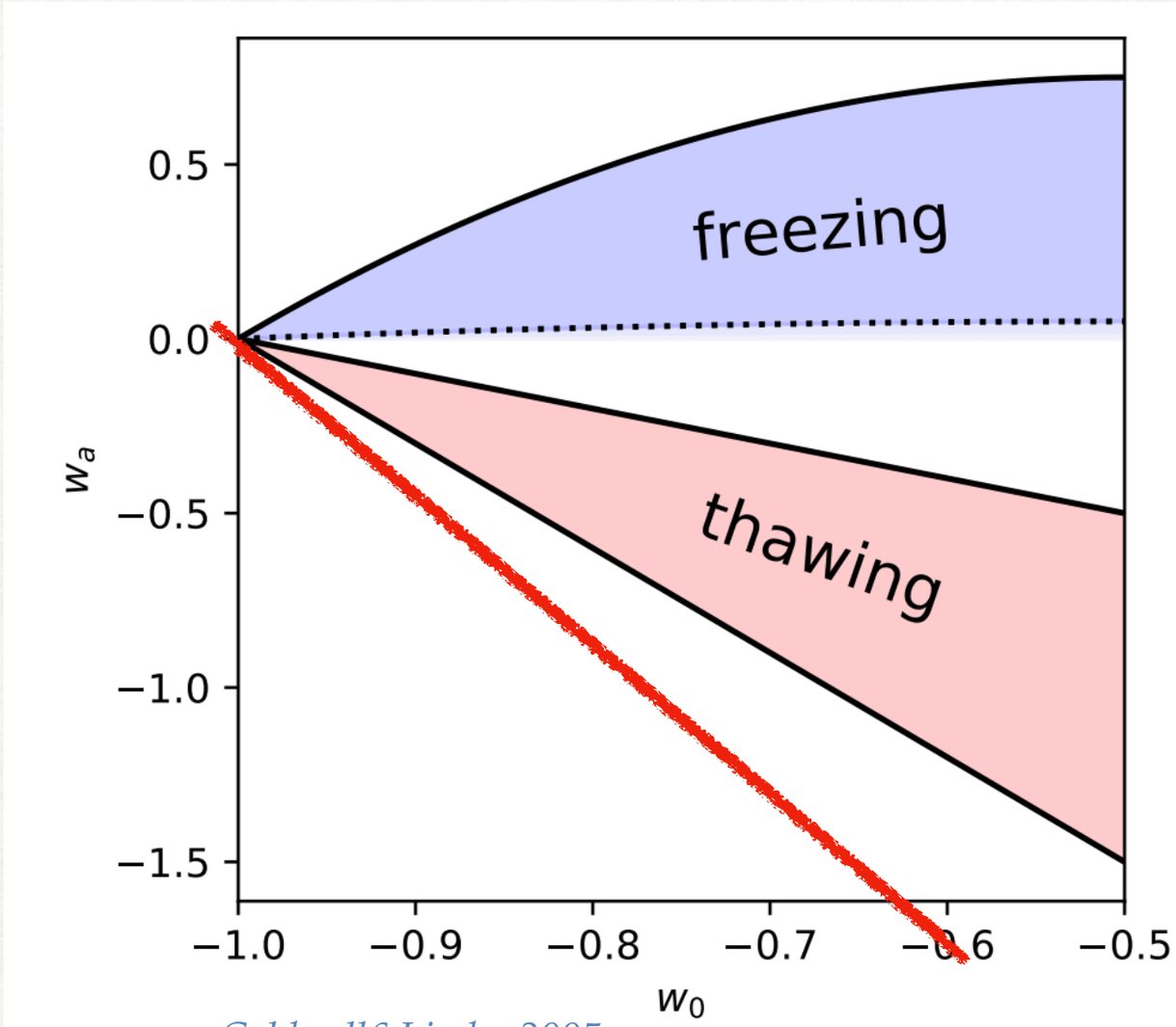


- $2.5-4\sigma$ preference for $w_0 > -1, w_a < 0$, reduce to $2-3.5\sigma$ with SDSS.

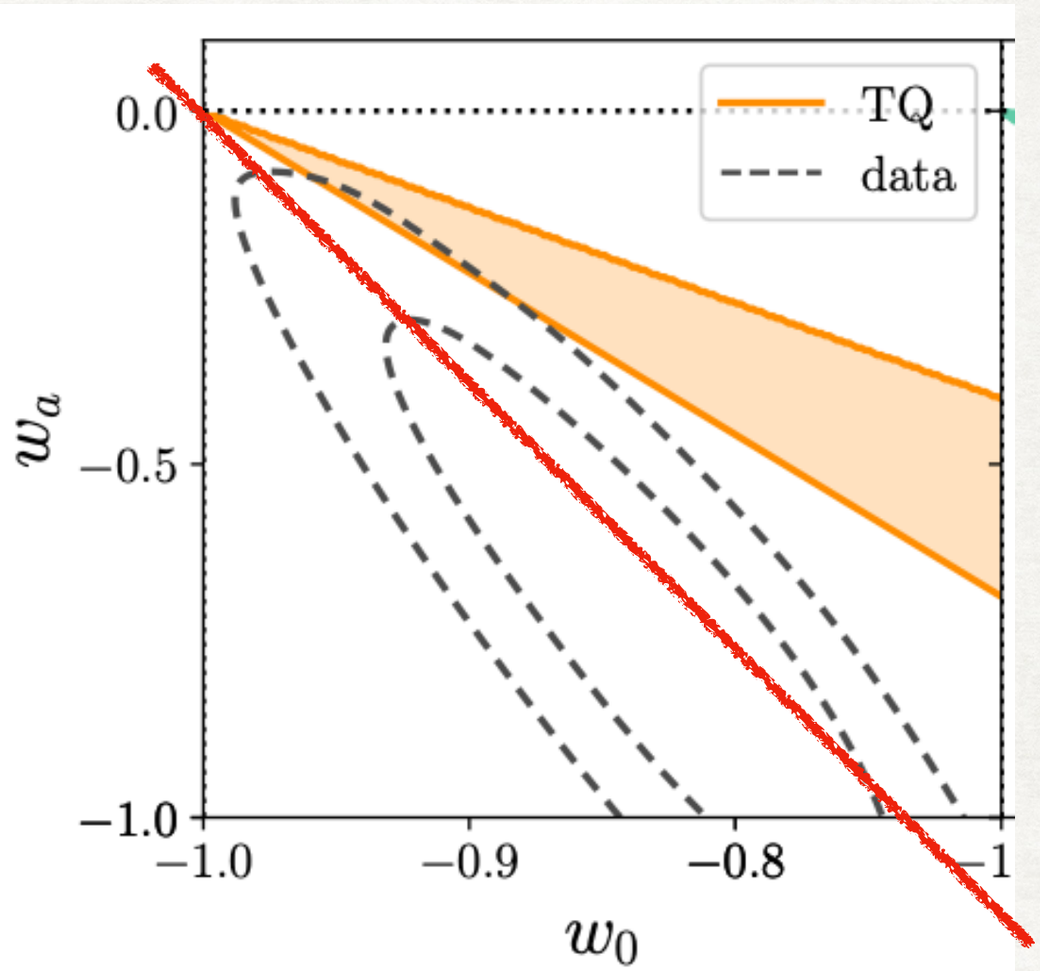
See also Cortês&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, DESI 2405.04216, 2405.13588, Efstathiou 2408.07175

- Can this hint for phantom dark energy help resolve the Hubble tension?

Evidence for non canonical quintessence



Caldwell&Linder 2005



Wolf++ 2409.17019

$$\langle w \rangle = -1 \Rightarrow \quad w_a \approx -3.66(1 + w_0)$$

Linder 0708.0024

A mirage of dynamical dark energy?

DESI+CMB:	+PantheonPlus		+Union3		+DESY5	
DE classes	ΔDIC ($\Delta\chi^2$)					
Thaw. (Cal.)	+0.4	(−1.6)	−0.6	(−2.5)	−5.8	(−7.1)
Thaw. (Alg.)	−1.0	(−2.9)	−4.6	(−6.9)	−10.1	(−13.2)
Emergent	+2.1	(−0.05)	+1.8	(−0.1)	+0.2	(−1.5)
Mirage	−9.1	(−10.5)	−13.8	(−16.2)	−18.7	(−20.7)
w_0w_a	−6.8	(−10.7)	−13.5	(−17.4)	−17.2	(−21.0)

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WEIRD??

A "late-time" solution to the Hubble tension?

Assumed from LCDM

Measured

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

$$d_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + \cdots}}$$

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$H_0 \uparrow \Rightarrow \Omega_X(z) \downarrow$

- 'phantom dark energy' $w < -1$, DE-DM interactions, decaying DM, and many more…

[http://arxiv/insert_your_favorite_ model_here.com]

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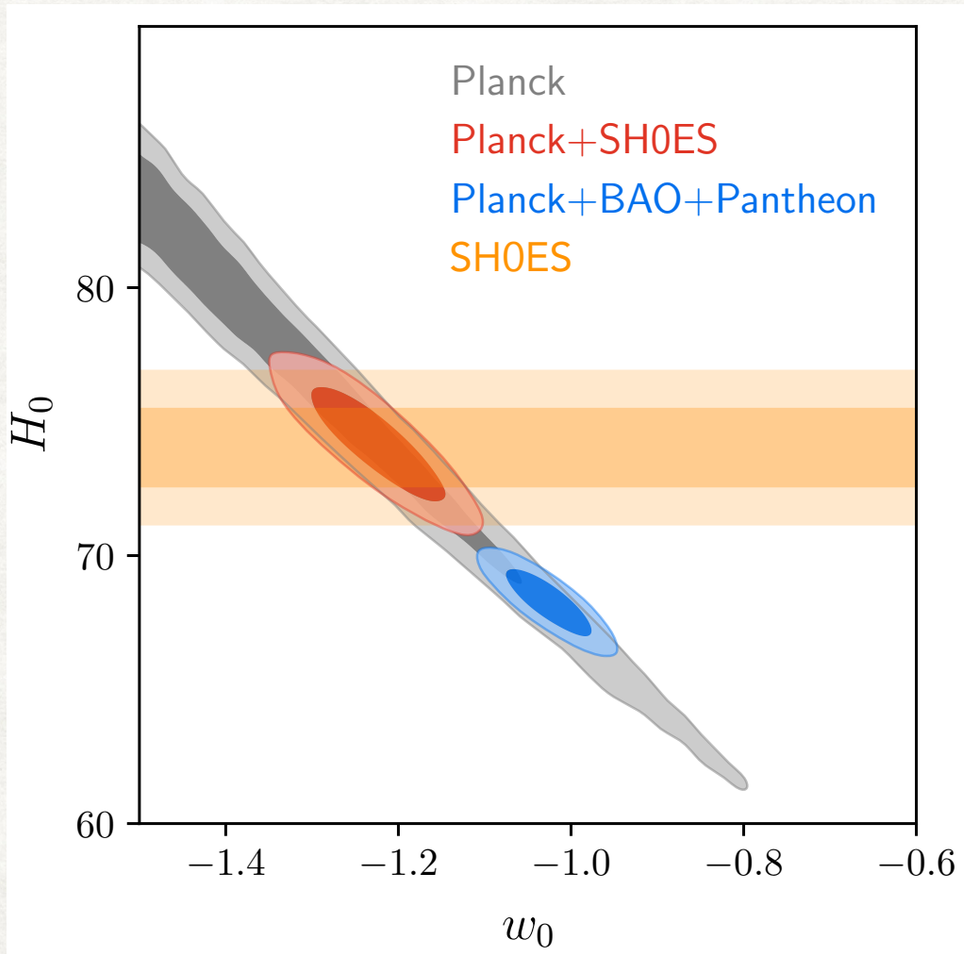

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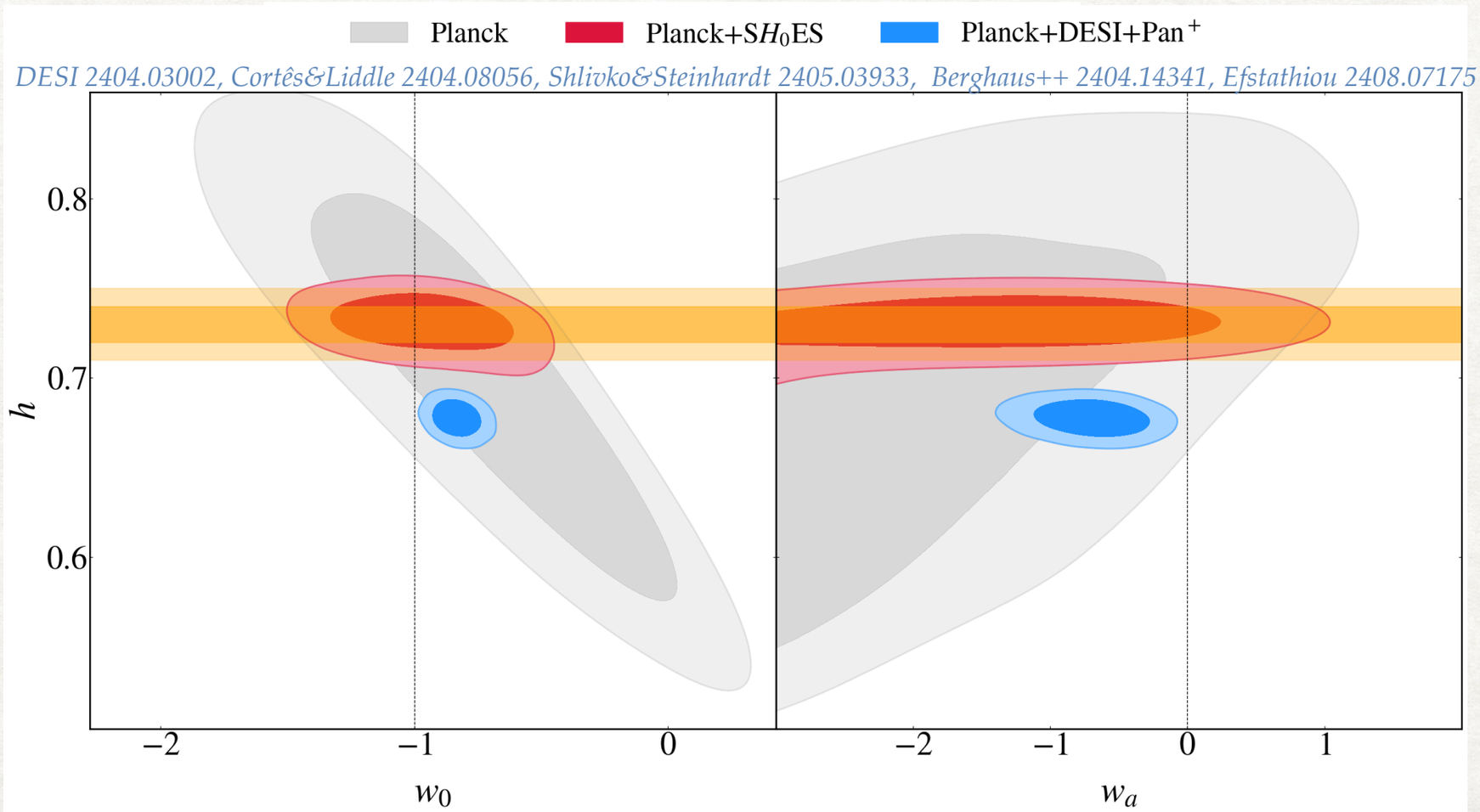

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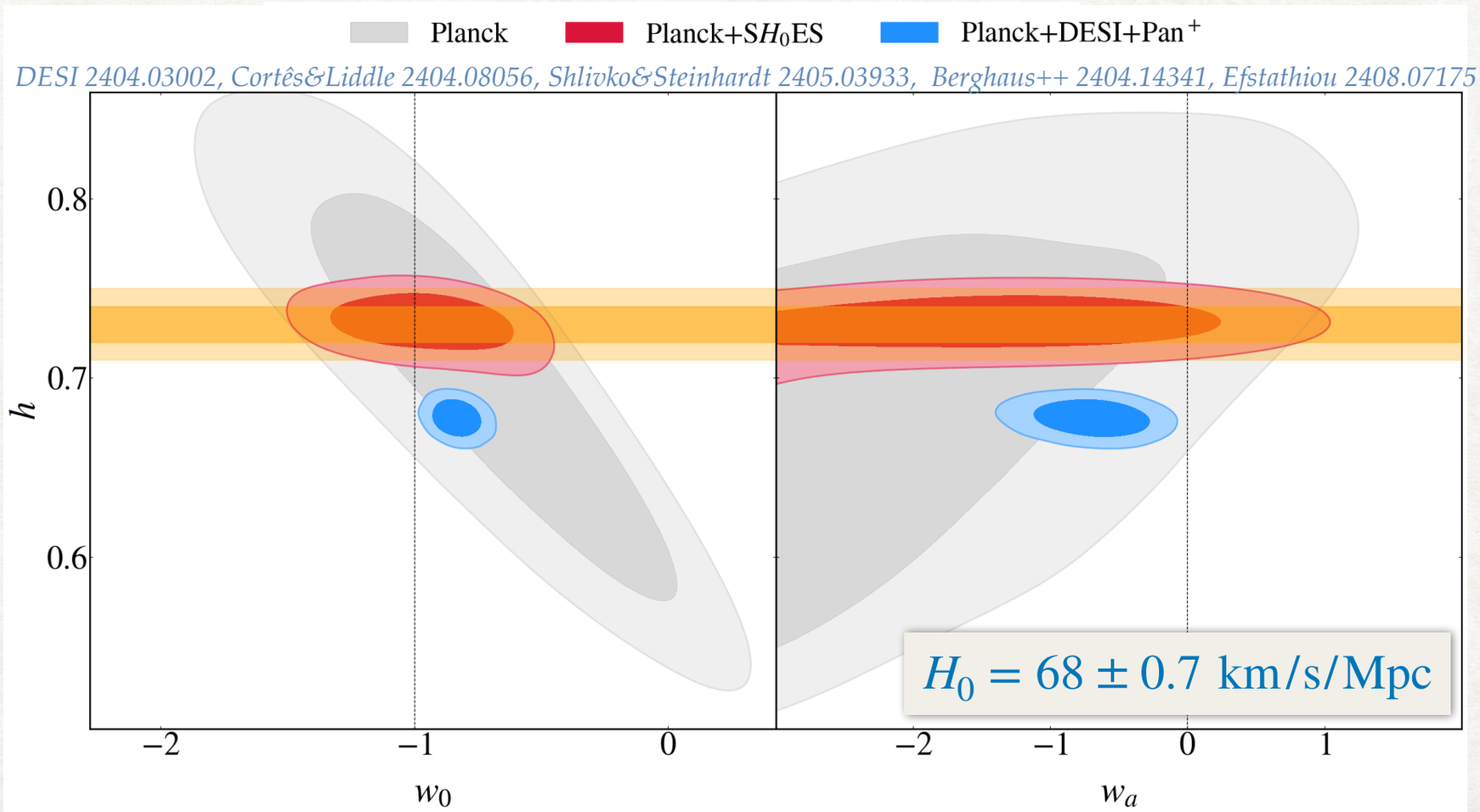

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A "no-go" theorem against late-time solutions

BAO: $\theta_d(z) = \dfrac{r_s(z_{\rm drag})}{D_A(z)}$

SN1a: $m(z) = 5\log_{10}\big(D_L(z)\big) + M_b$

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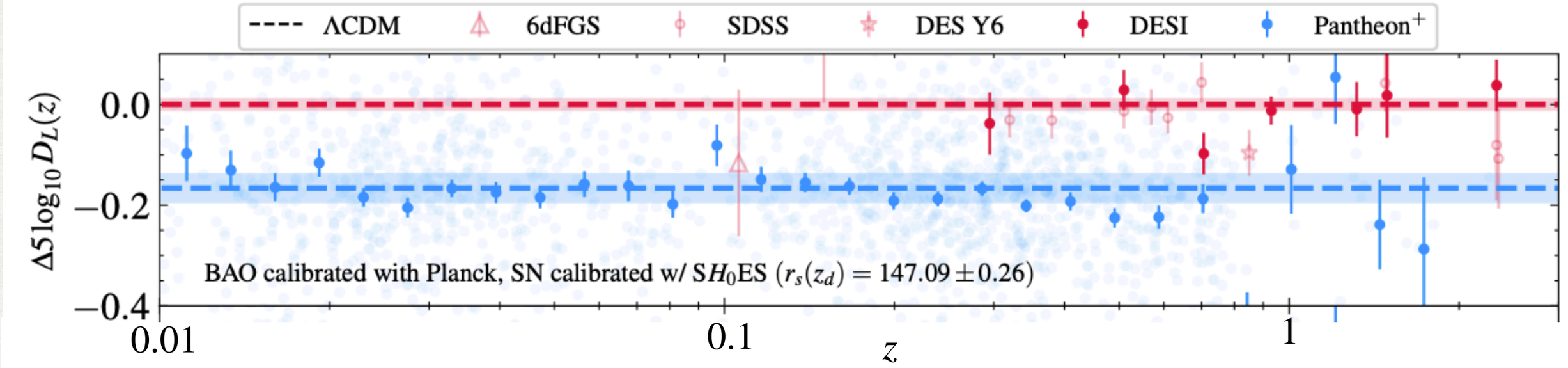
VP, Smith, Calderon, Simon 2407.18292



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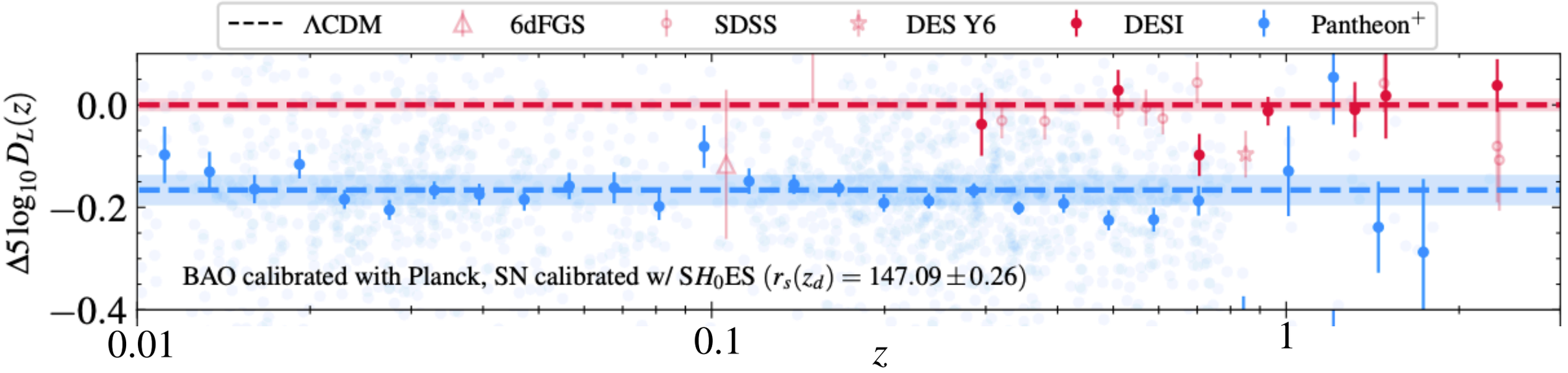

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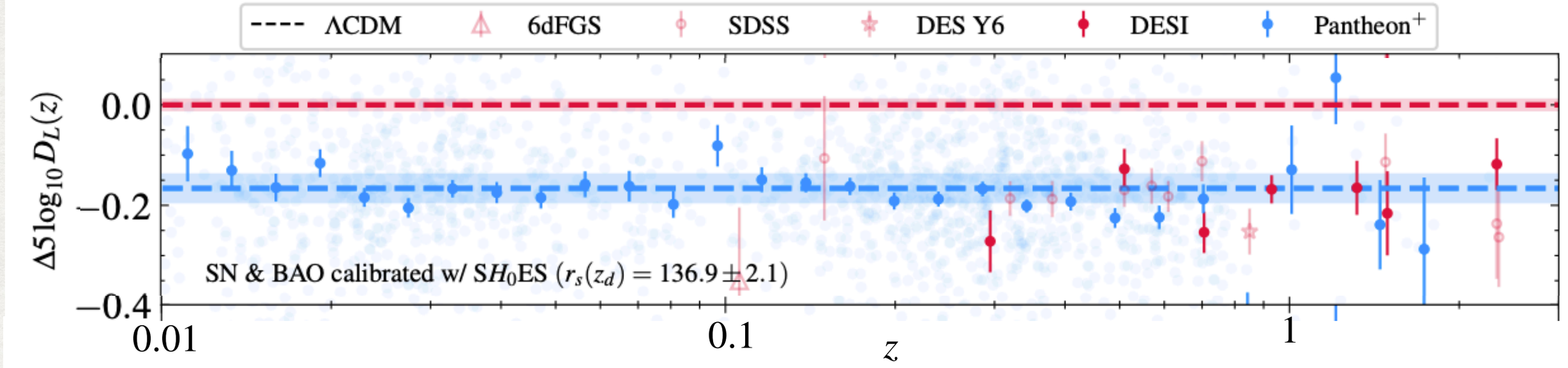

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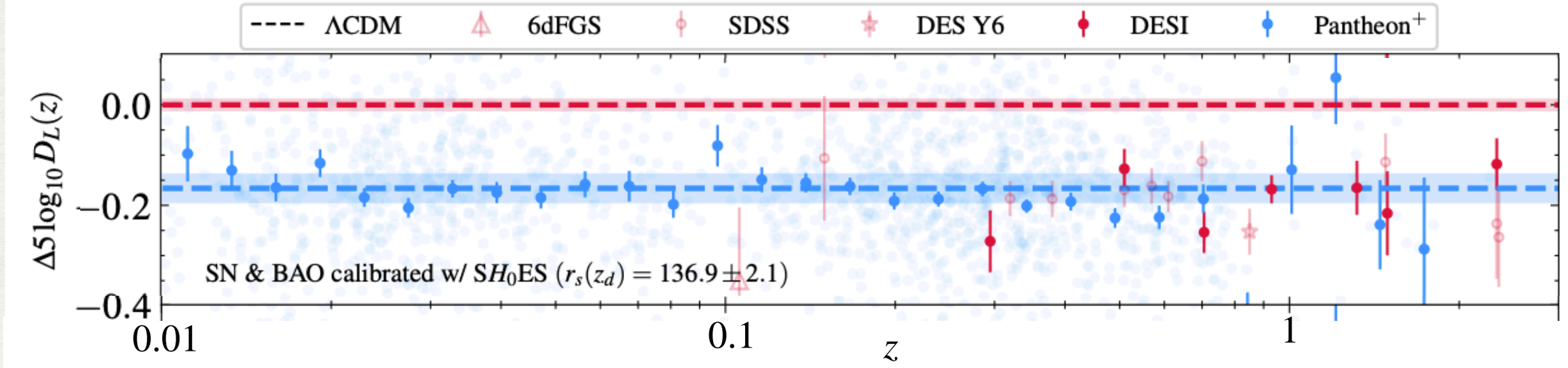

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- Solving the tension require to either change calibrators or break the DDR relation
- A single "constant" shift is currently sufficient ⇒ changing calibrators favored! *Teixeira (VP) ++ 2504.10464*

The cosmic calibration tension

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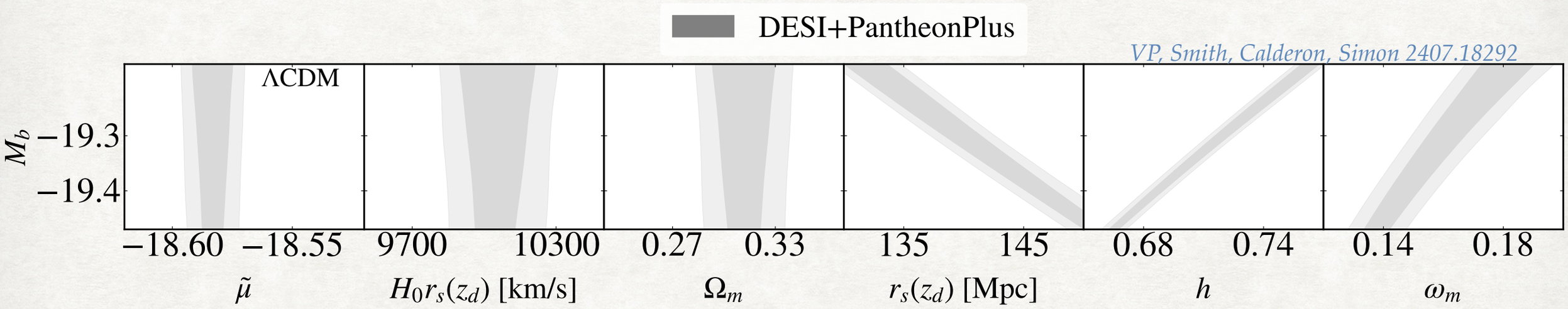

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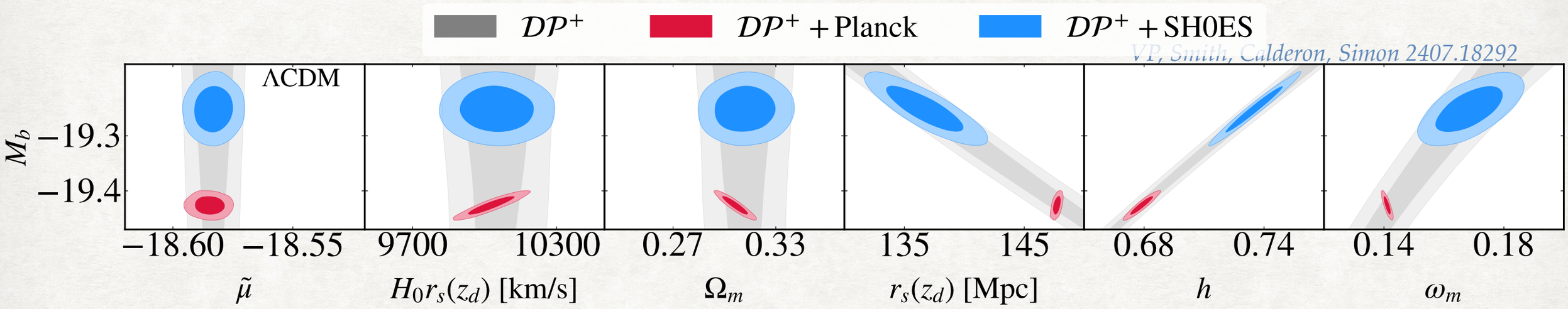

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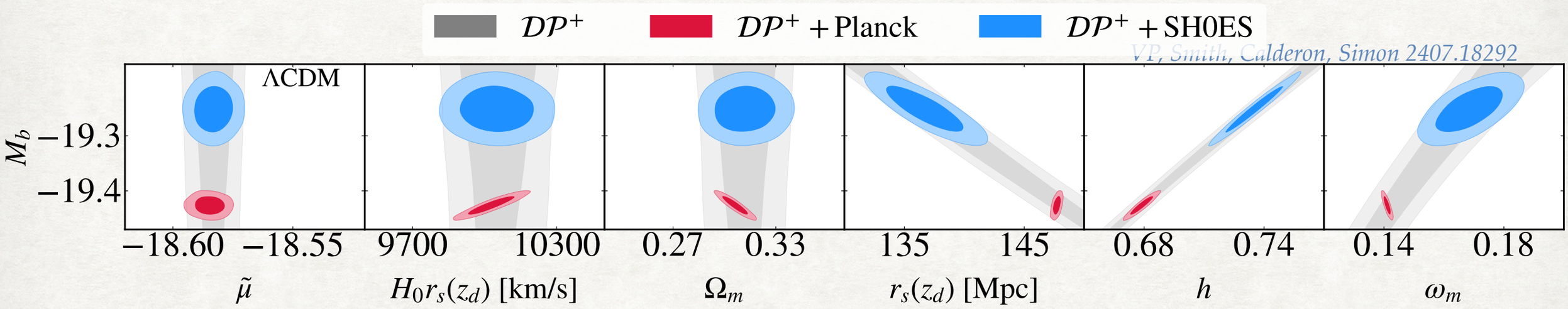

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- Challenge for new physics: Reduce the sound horizon and compensate the larger ω_m on the CMB

See also Jedamzik++ 2010.04158, Blanchard++ 2205.05017, Pedrotti++ 2408.04530

How to resolve the cosmic calibration tension

Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291

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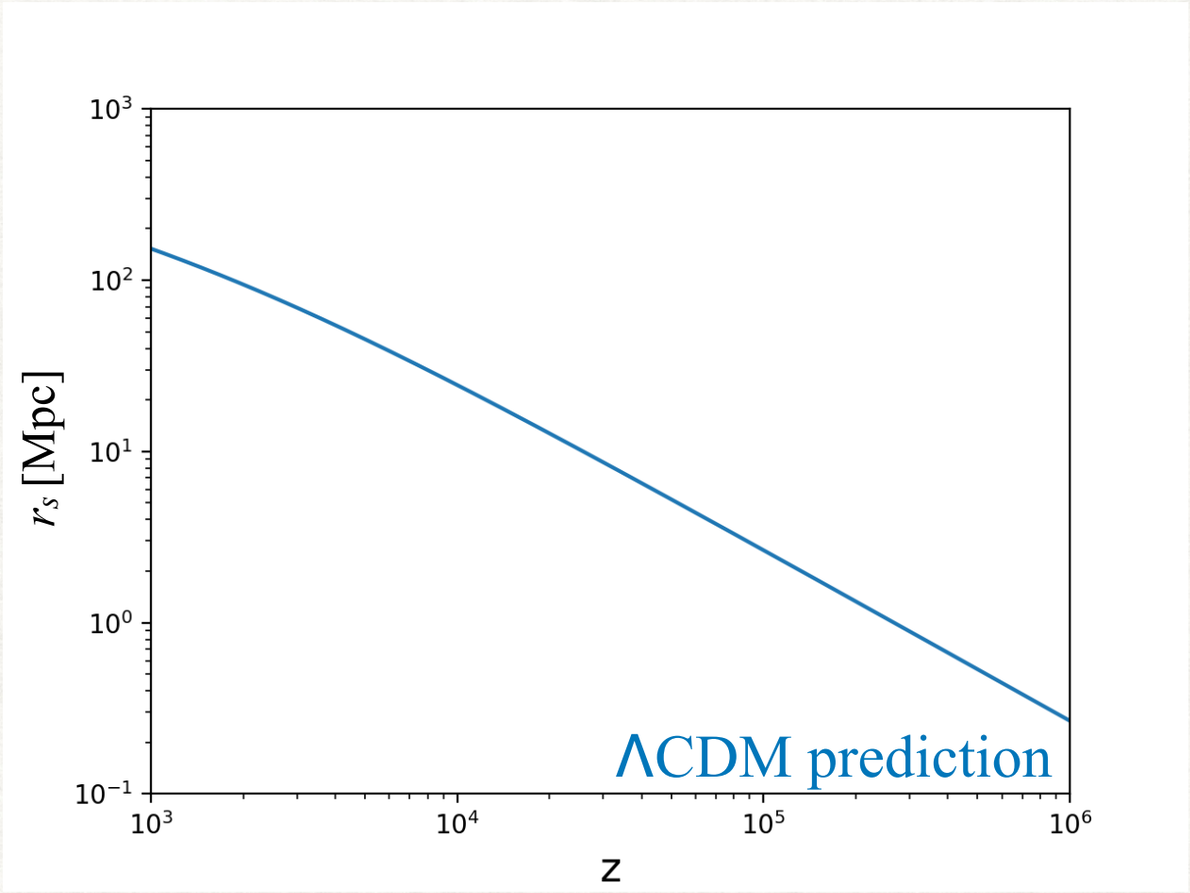

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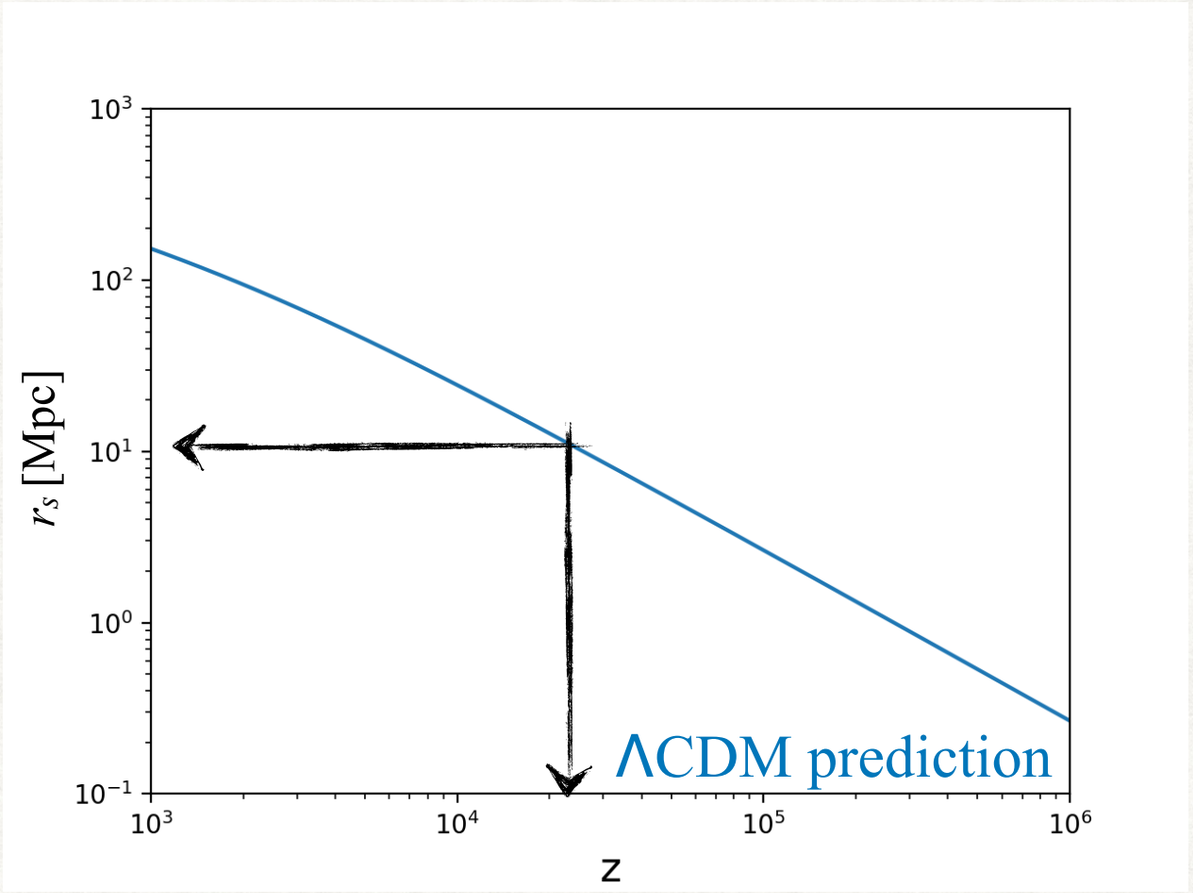

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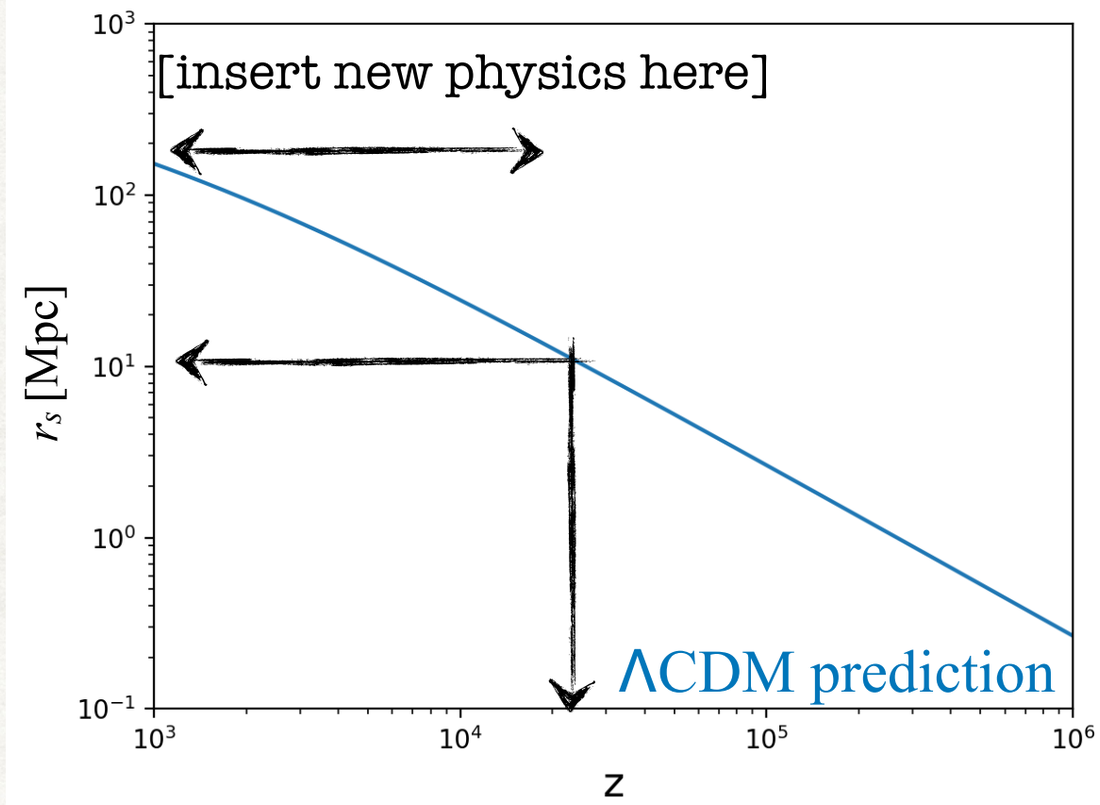

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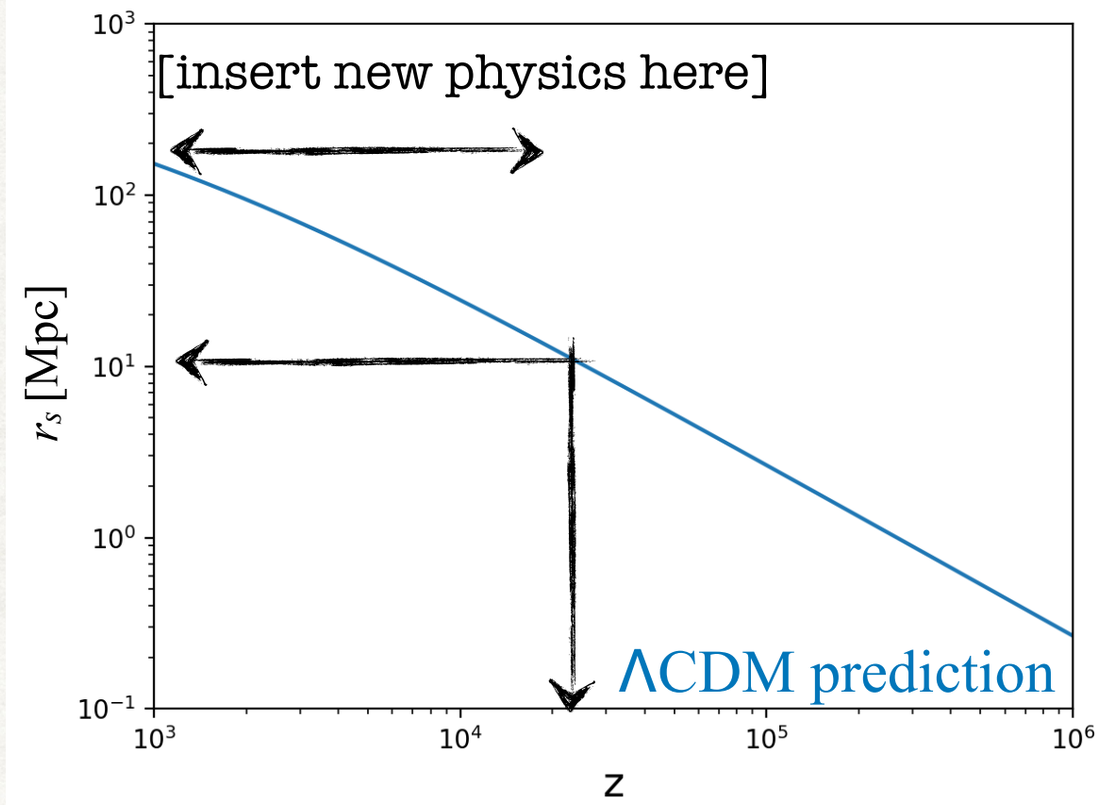

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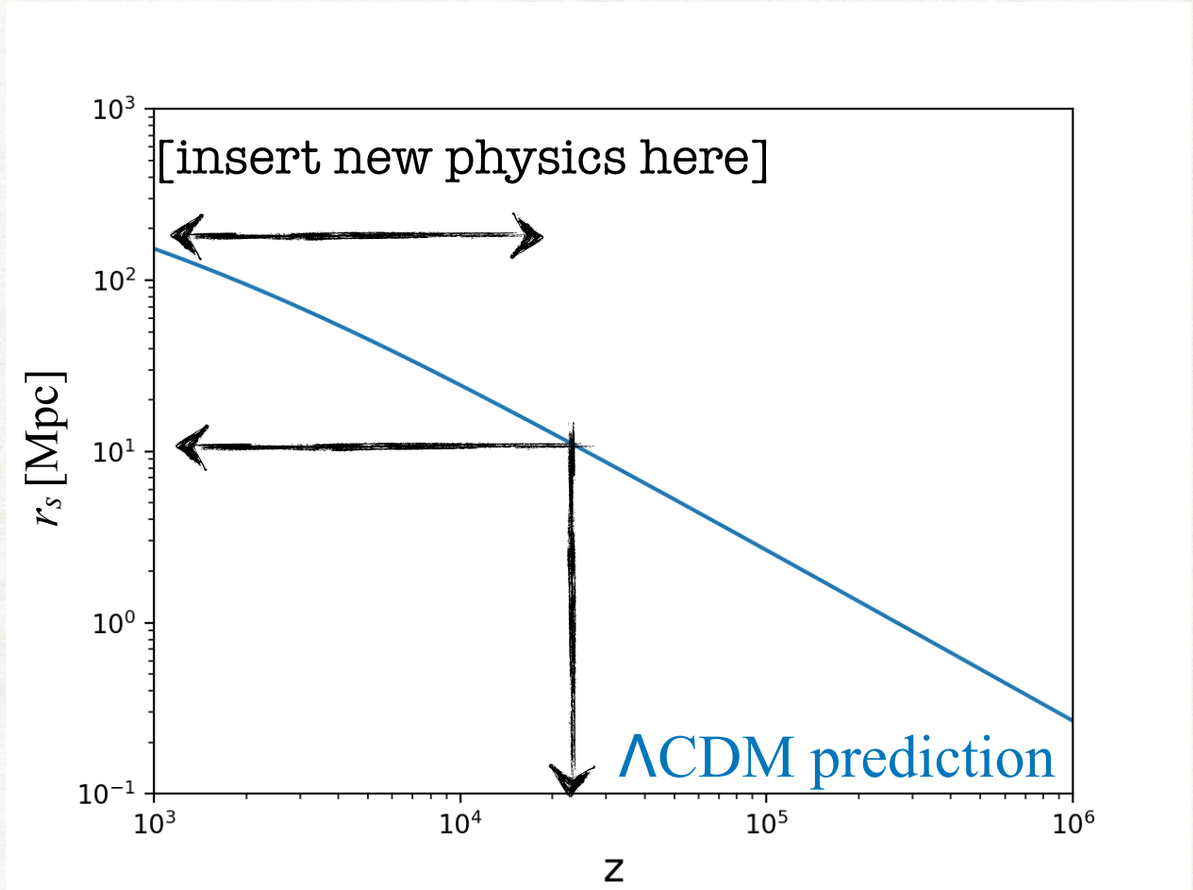

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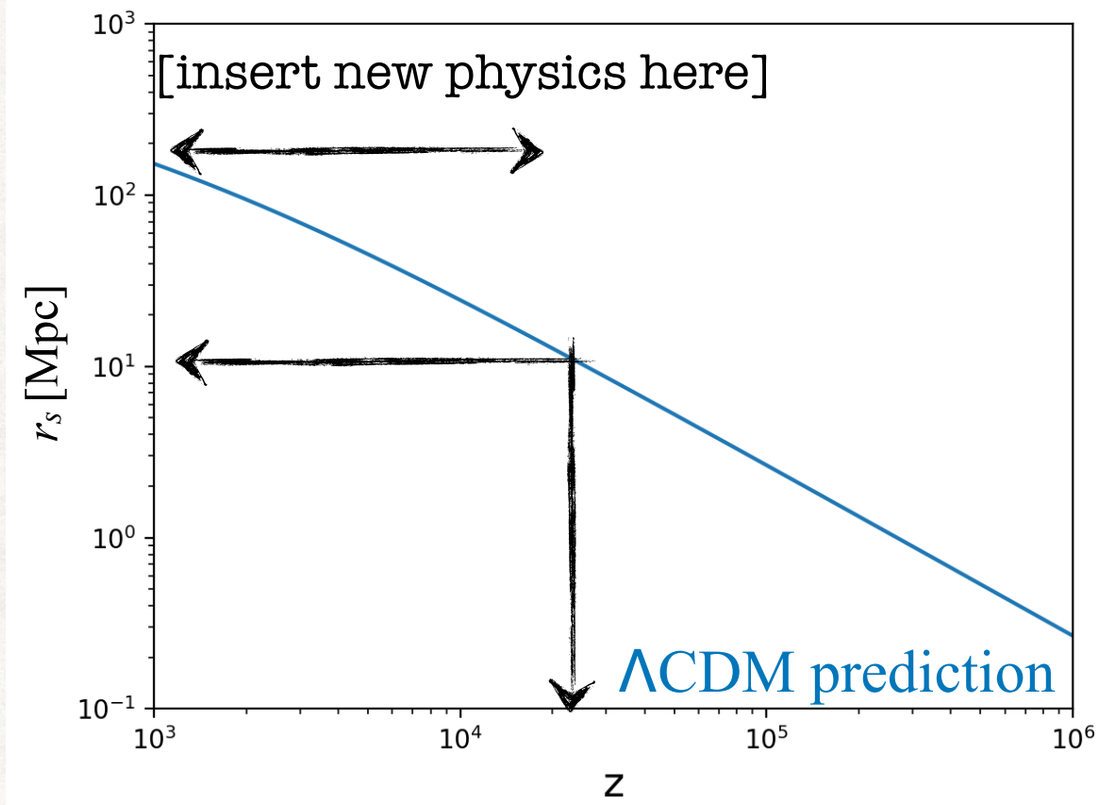
increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?



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Three models as examples

- Exotic expansion history via early dark energy: boost in $H(z \sim 3500) \sim 5\,\%$ through scalar-field

  VP, Smith, Karwal, 2302.09032

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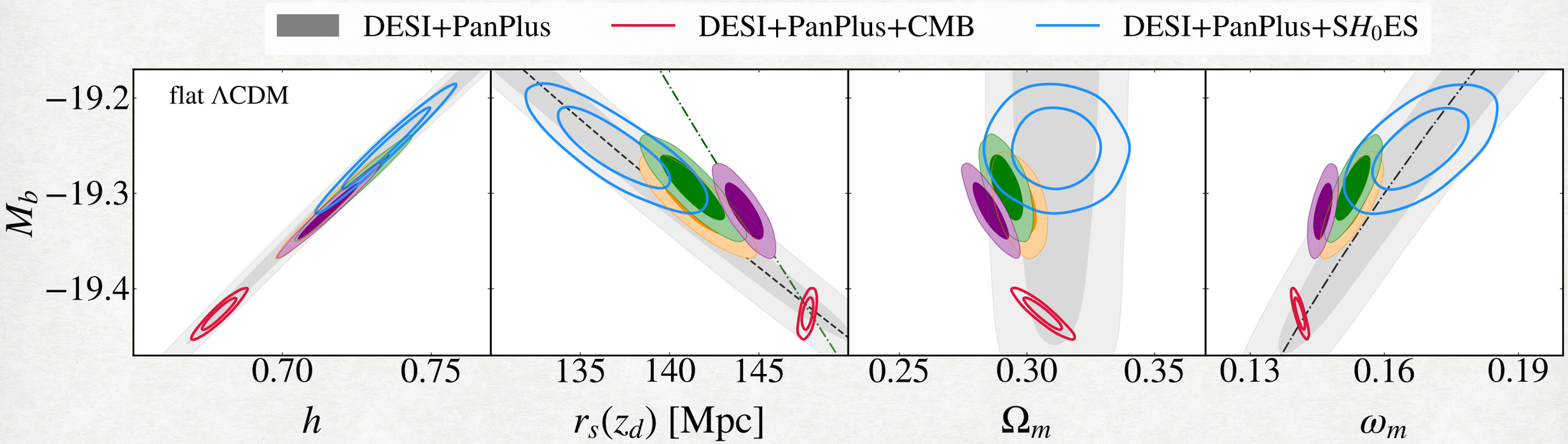

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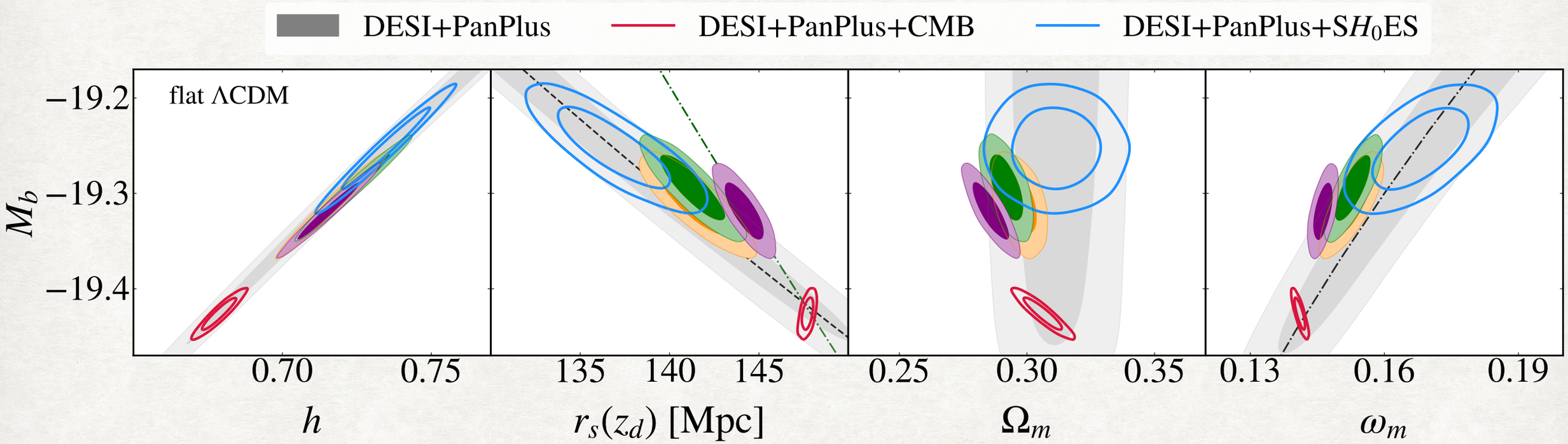

- Models affecting expansion history can reduce tension to $\sim 2-3\sigma$ level

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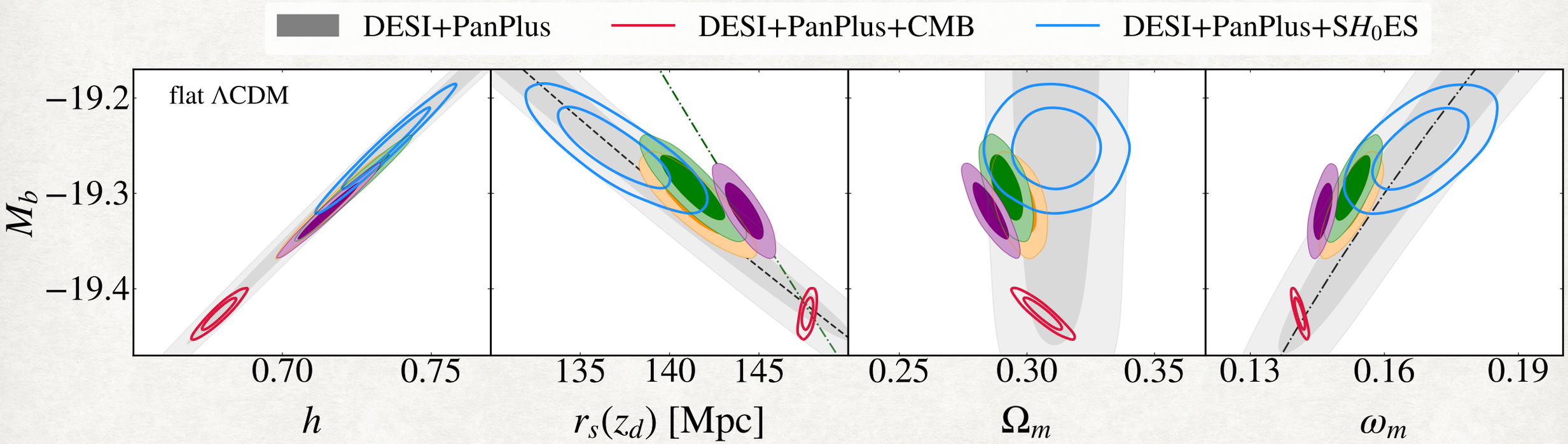
- Exotic recombination via electron mass increase $\dfrac{\Delta m_e}{m_e}(z \sim 1000) \sim 5\,\%$

Hart&Chluba 1912.03986



- Models affecting expansion history can reduce tension to $\sim 2-3\sigma$ level

- Models affecting solely the way recombination proceeds are disfavored: they lead to a low Ω_m

Lee (VP)++ PRL 2022, Lynch++ 2404.05715

Model-independent Implications beyond H_0

- Exotic expansion history via early dark energy: boost in $H(z \sim 3500) \sim 5\,\%$ through scalar-field

  VP, Smith, Karwal, 2302.09032

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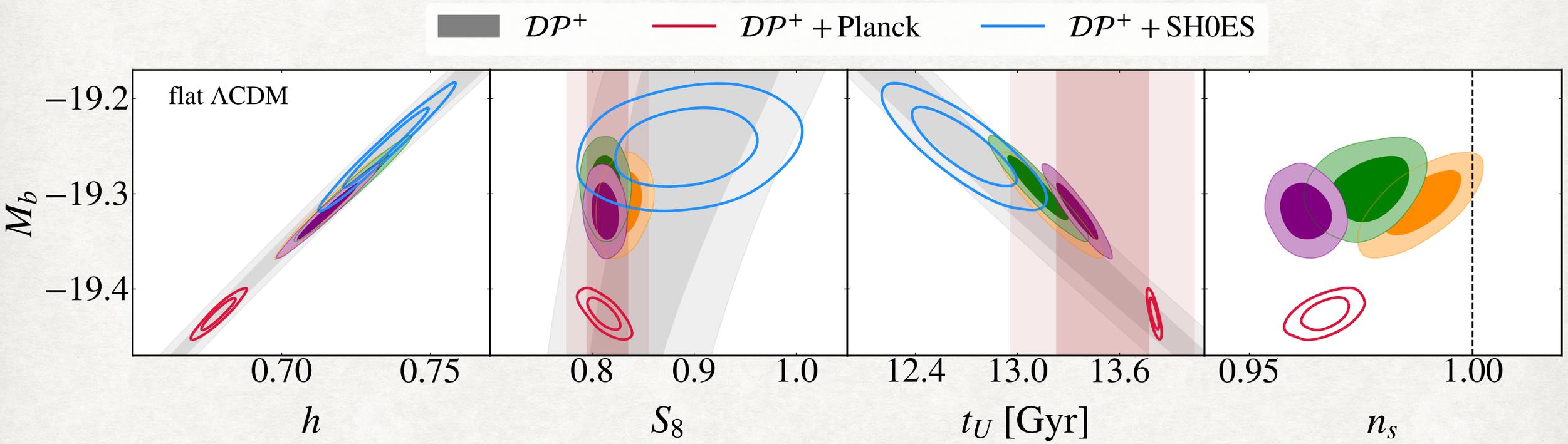
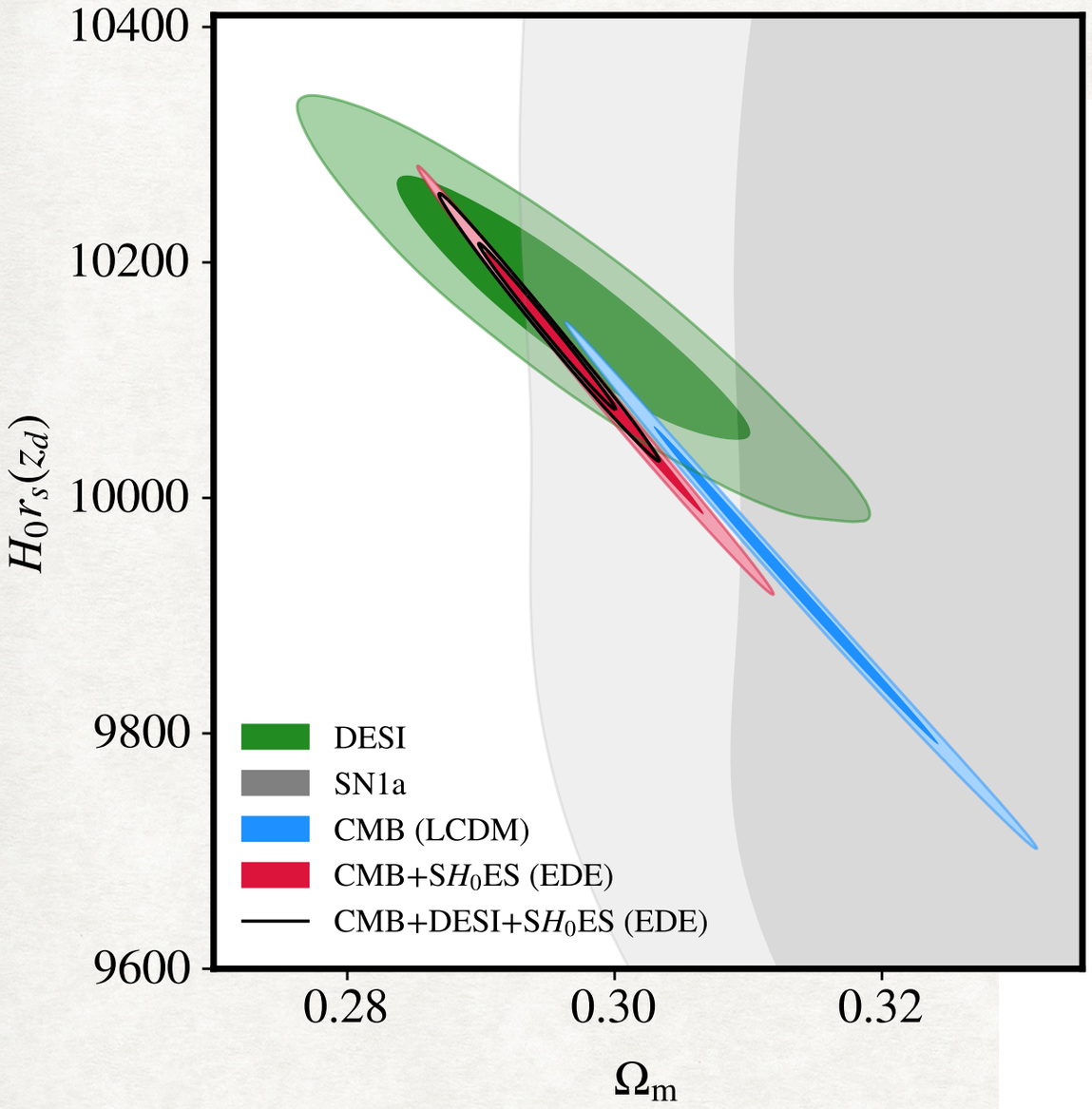
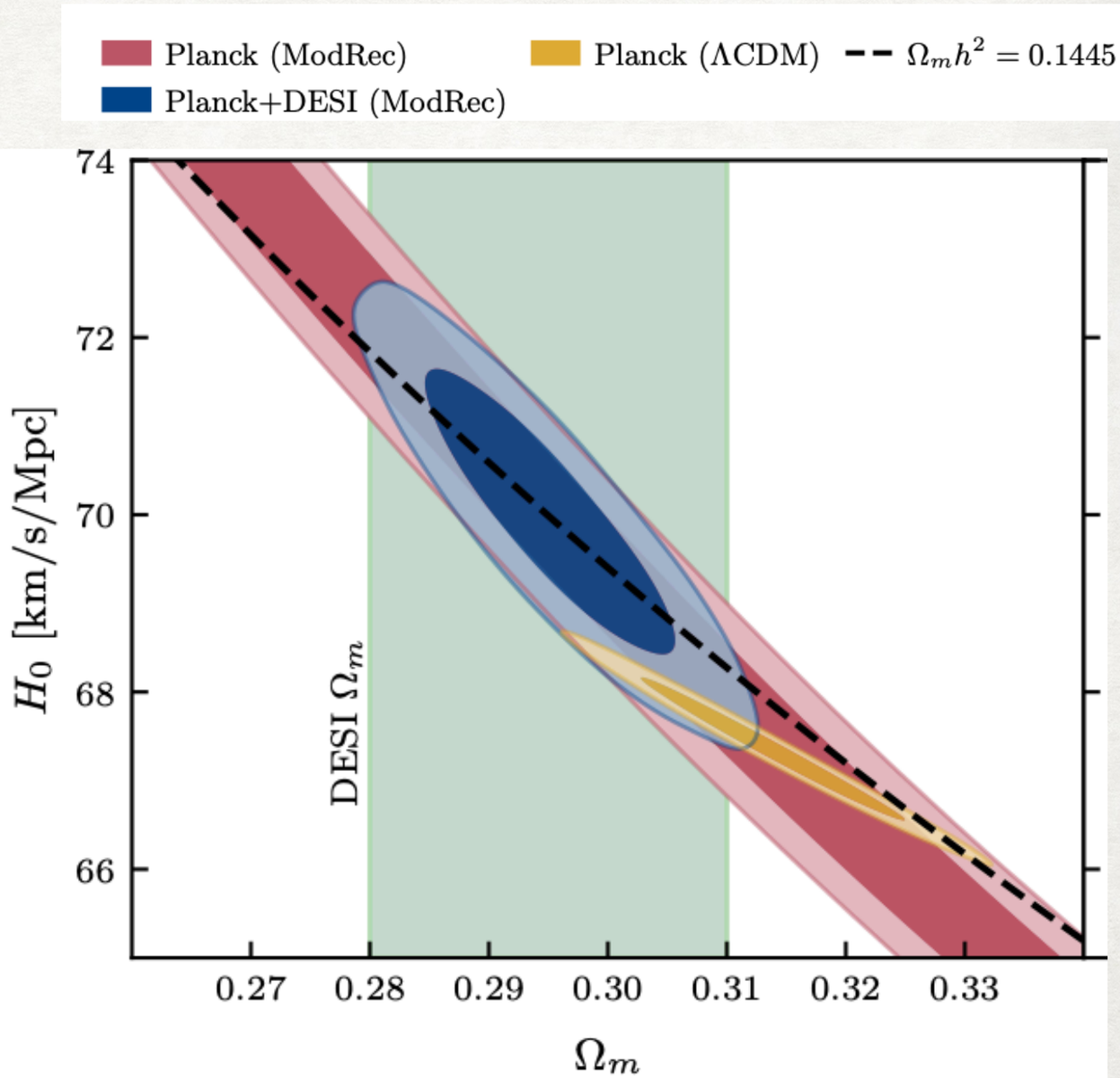


- No more tension with BBN but tension with weak lensing measurements at the $3 - 3.5\sigma$ level
- Age of the universe $\sim$ 0.7 Gyr younger: problem with old objects? JWST?
- n_s increases! Back to being compatible with 1? It can be probed with future CMB experiments

Early universe solution to the BAO tension

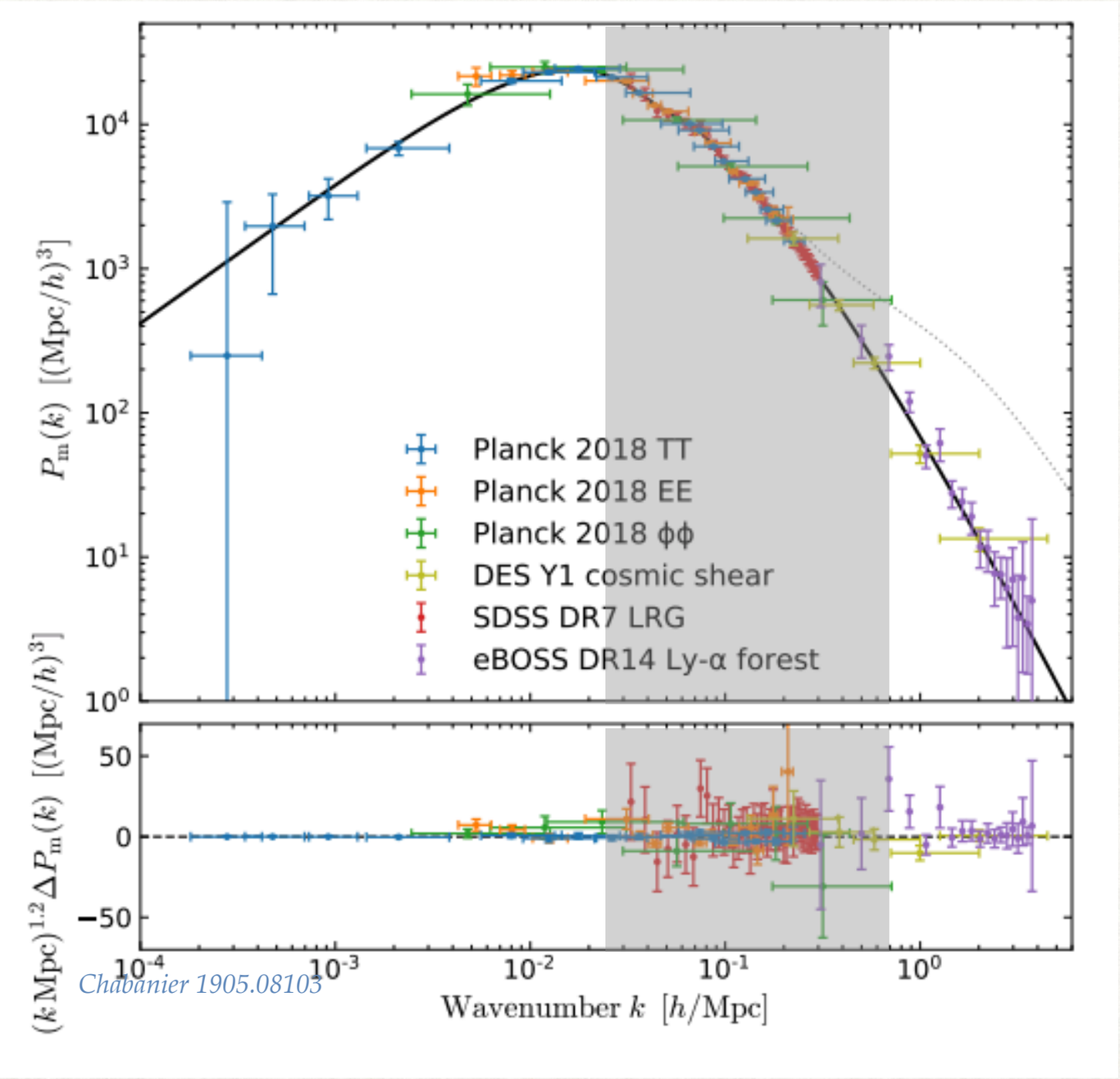




- Early universe solution can reduce $H_0 r_d$ and Ω_m
- An alternative explanation to DESI results? *Lynch&Chluba 2406.10202, Chaussidon++ 2503.24343*

The S_8 parameter

- WL observations are mostly sensitive to the 'S_8 parameter'.

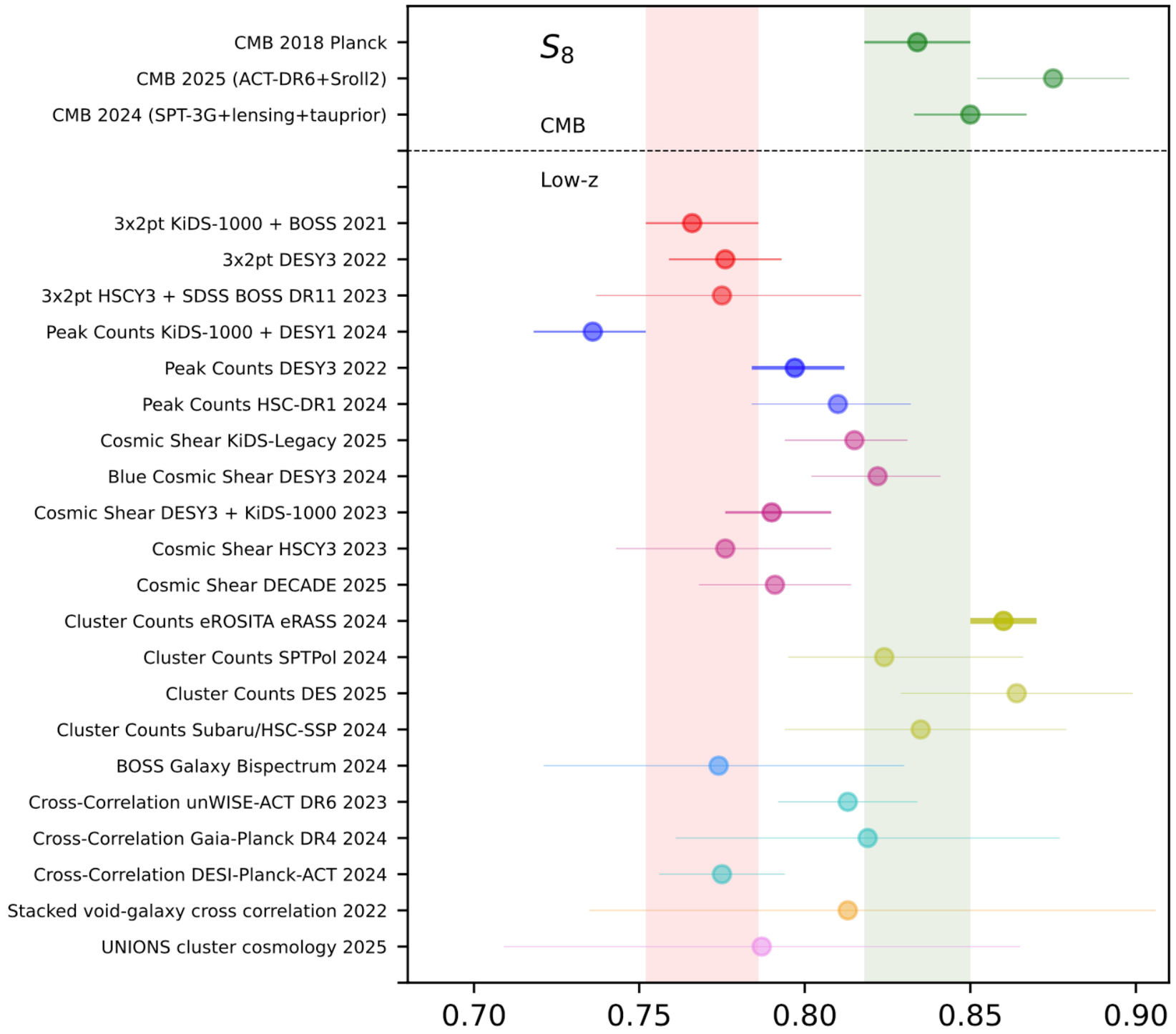


Chabanier 1905.08103

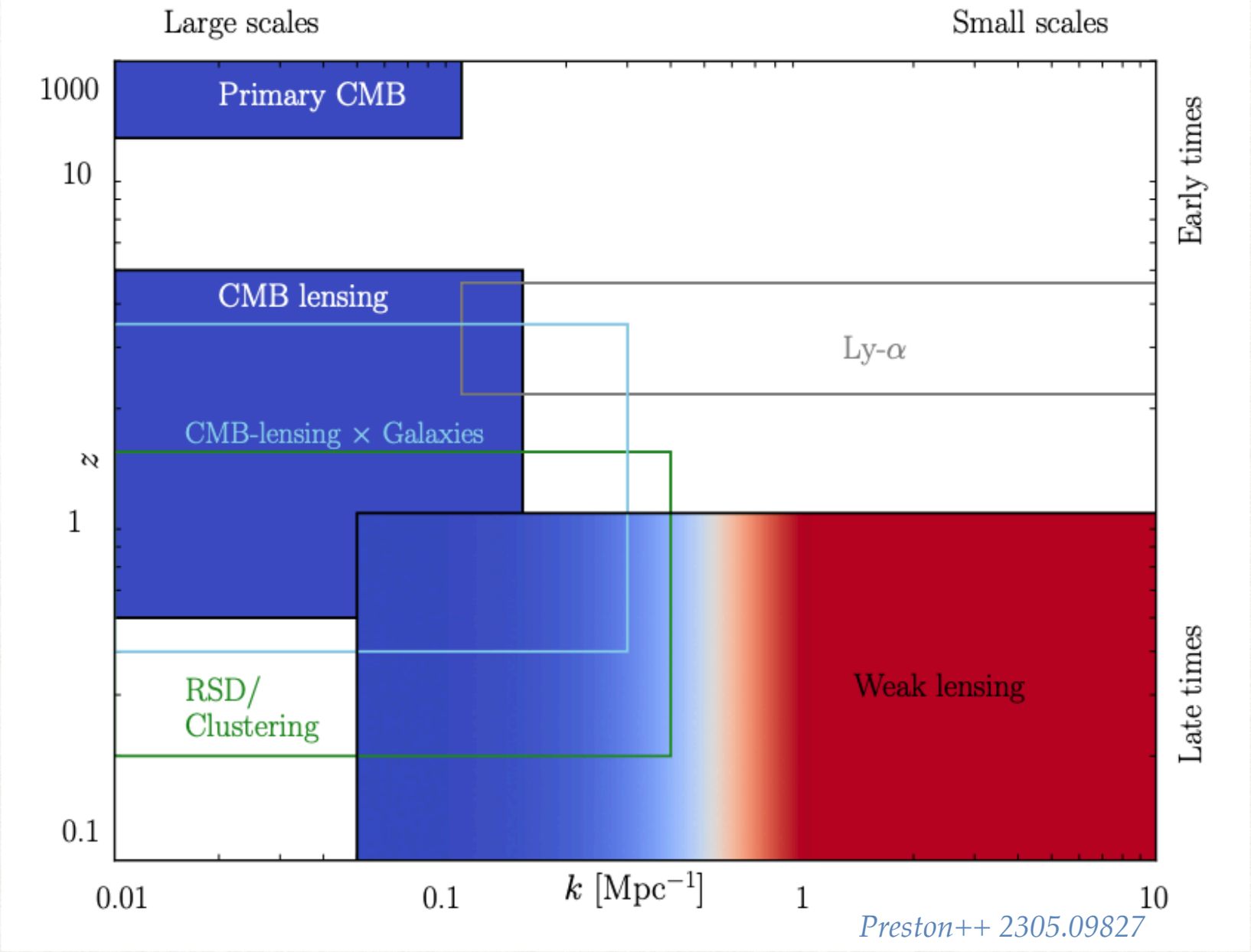
$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.5}$$

$$\sigma_8^2 = \int_0^\infty \frac{k^3}{2\pi^2} P_{\rm lin}(k) W^2(kR) d\ln k$$

The S_8 tension



What do we know about P(k,z)?



Preston++ 2305.09827

Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

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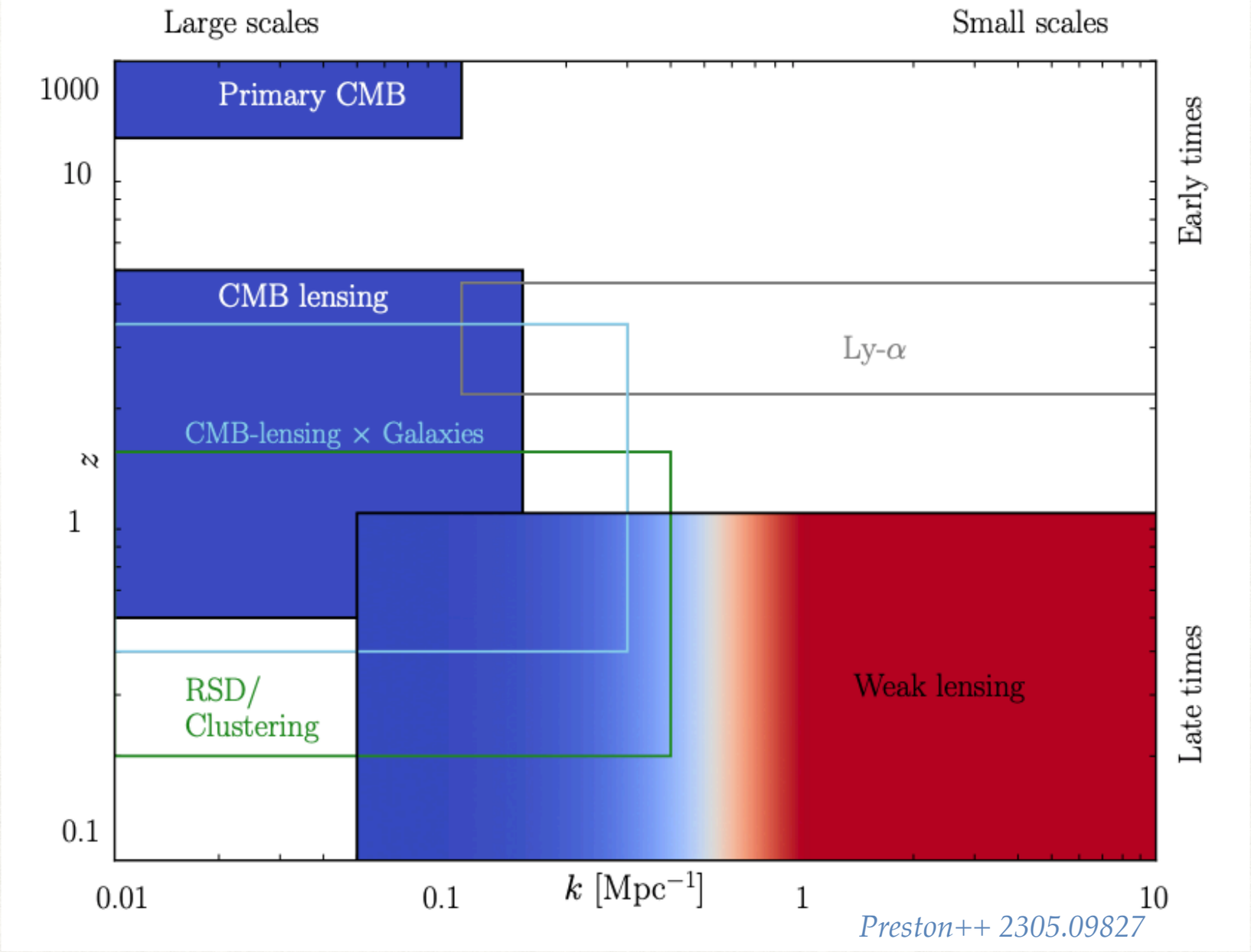
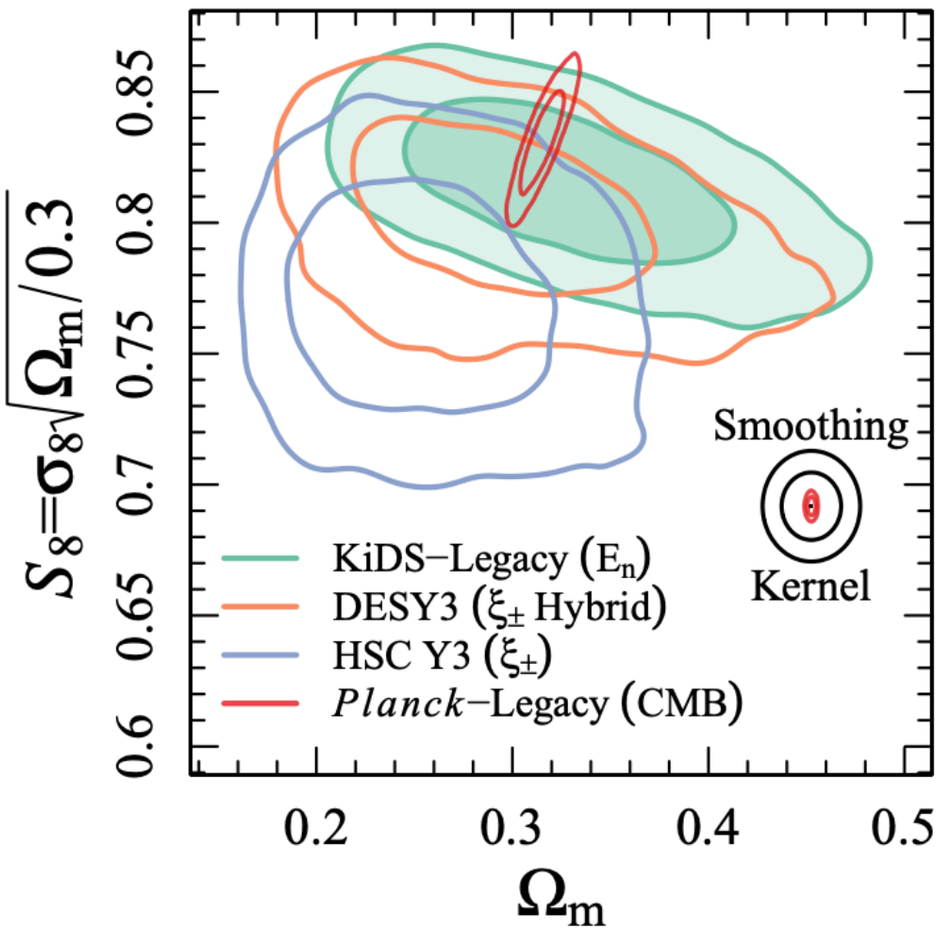


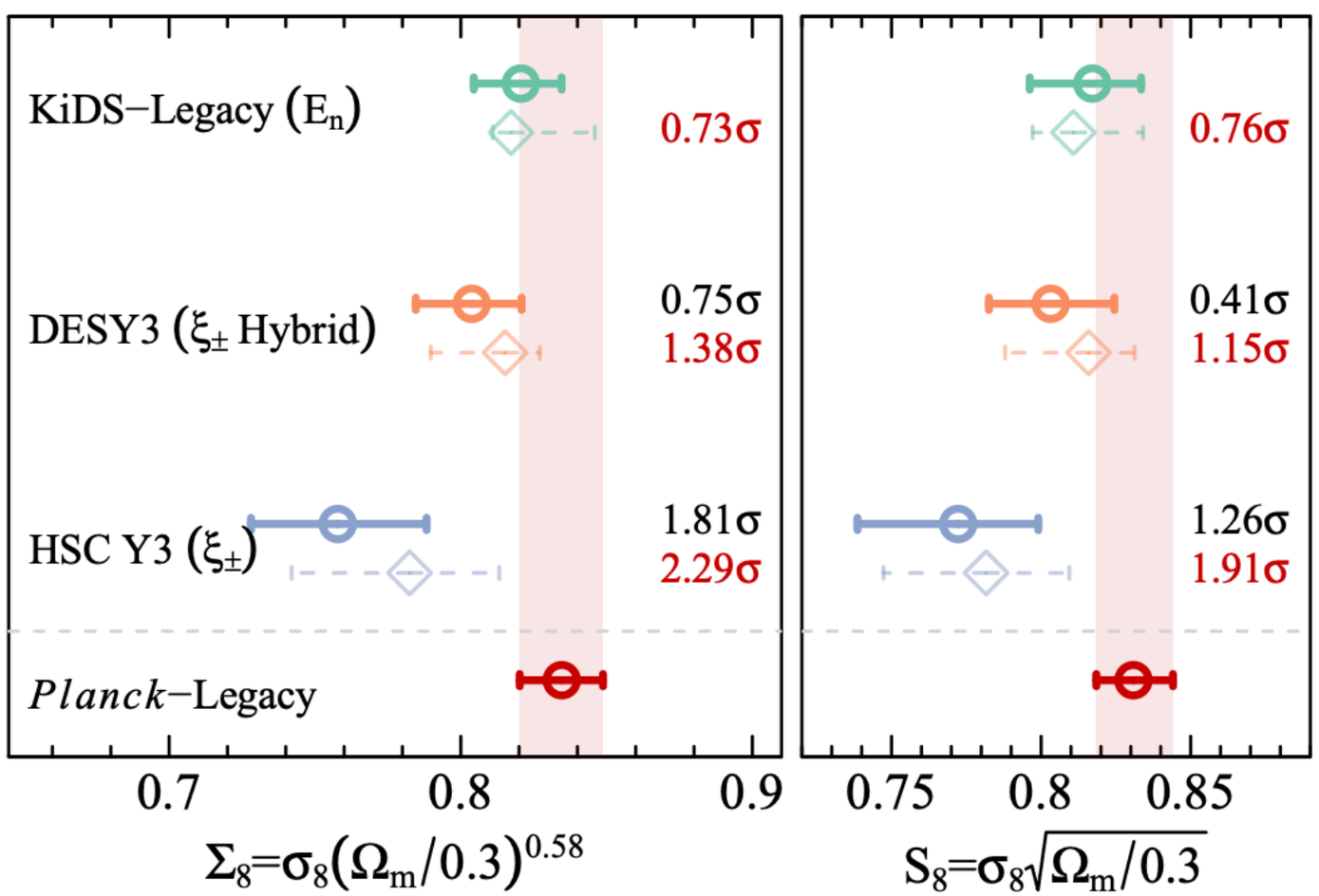
Preston++ 2305.09827

- Weak lensing measure smaller scales than galaxy cluster number counts! Power suppression at $k \gtrsim 0.5$ h/Mpc?
- Lyman-α data may or may not favor a power suppression at $z \sim 3$ and $k \sim 0.7$ Mpc $^{-1}$

Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

The S_8 tension revisited





- Latest results from KIDS Legacy: improved redshift calibration has removed the tension in their data

Cosmology at a crossroad: Precision or discordance?

- Despite its great success, the ΛCDM model is purely parametric: DM, DE, inflation still unknown
- H_0 at 5σ in tension, SN1a/BAO at 3-4σ, S_8 at <2σ in tension: clues about physics beyond ΛCDM?
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- Barring systematics/statistical fluke, the challenge is immense... but worth it!

Cosmology: where are we going next?

- New CMB data are coming: very sensitive to new physics around recombination! (And inflation)
- New LSS data are coming: check DESI result, check S_8 results, measure $\sum m_\nu$.
- JWST and gravitational wave measurements of H_0.