Status of ΛCDM and cosmic tensions

Vivian Poulin

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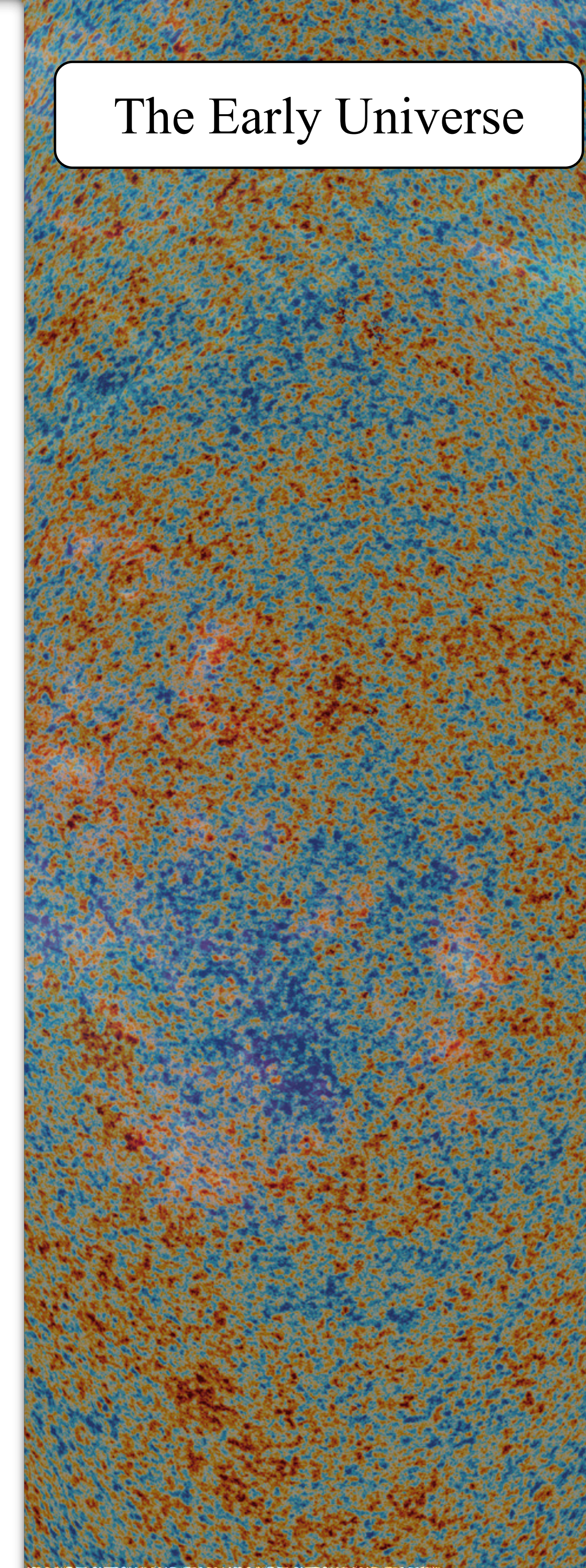
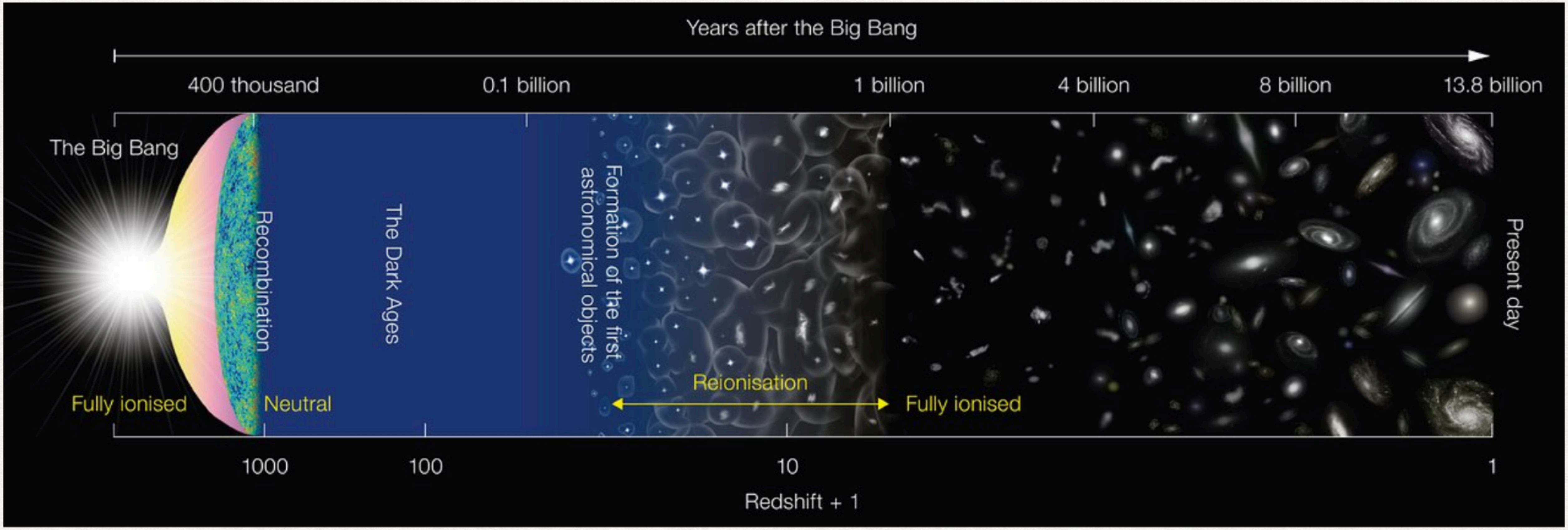


ModIC24 workshop
IFPU, Trieste, Italy
May 13th, 2024

The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology: GR + Cosmological Principle

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



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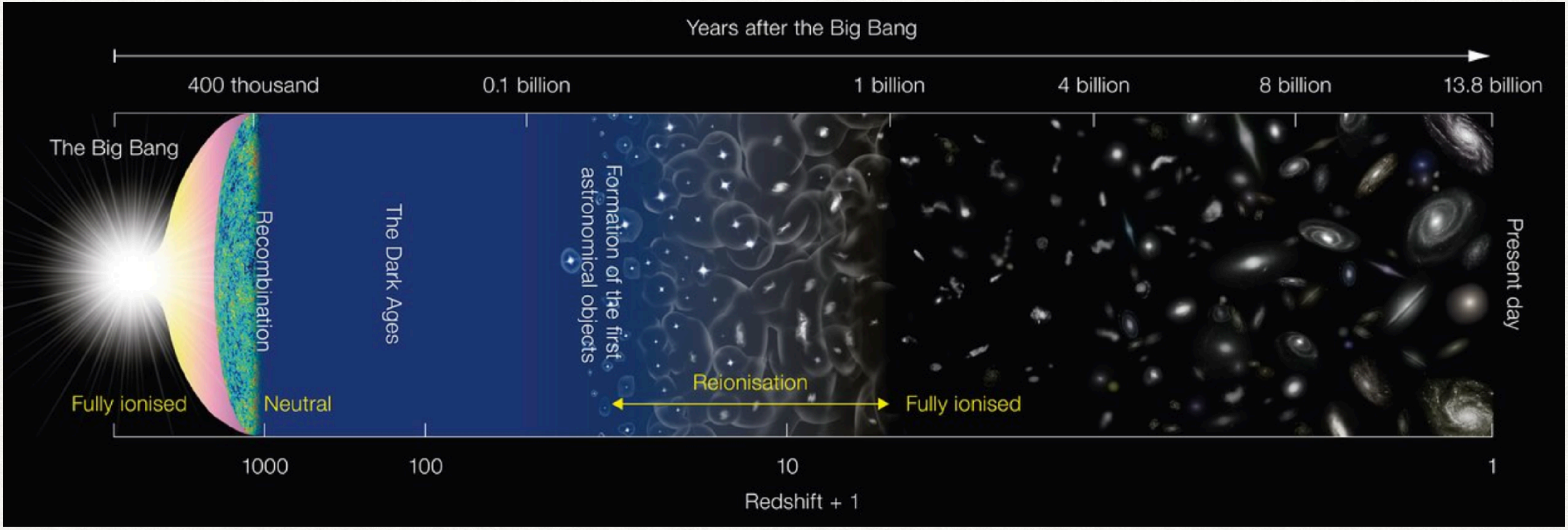
matter content



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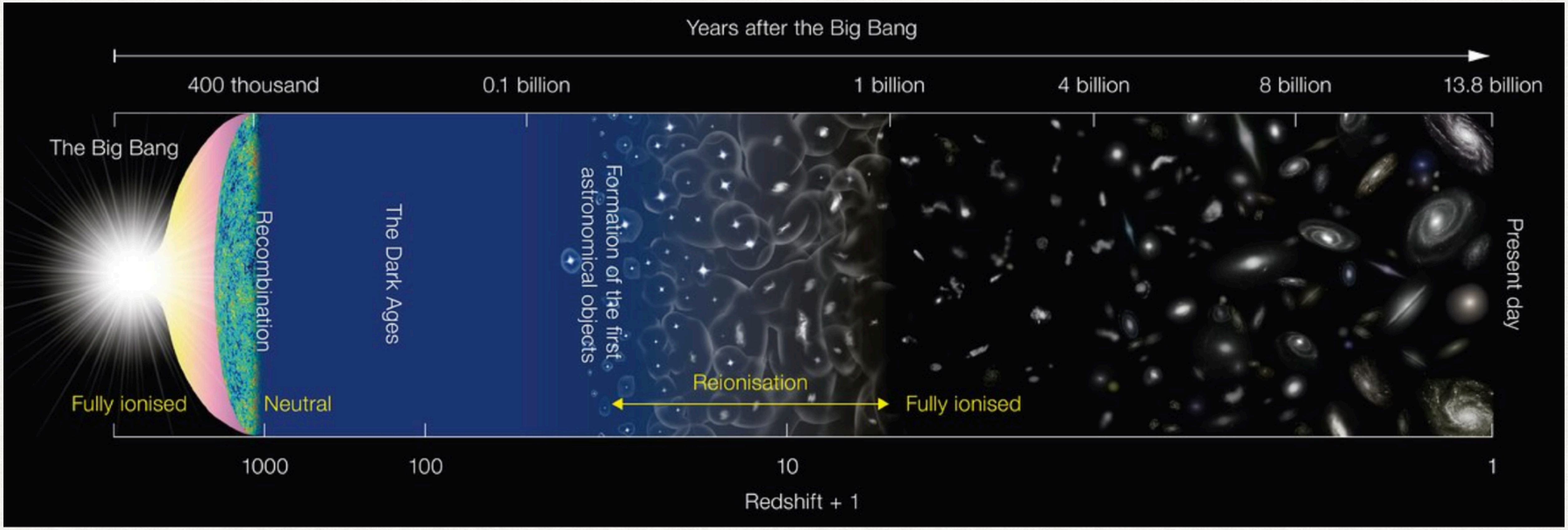

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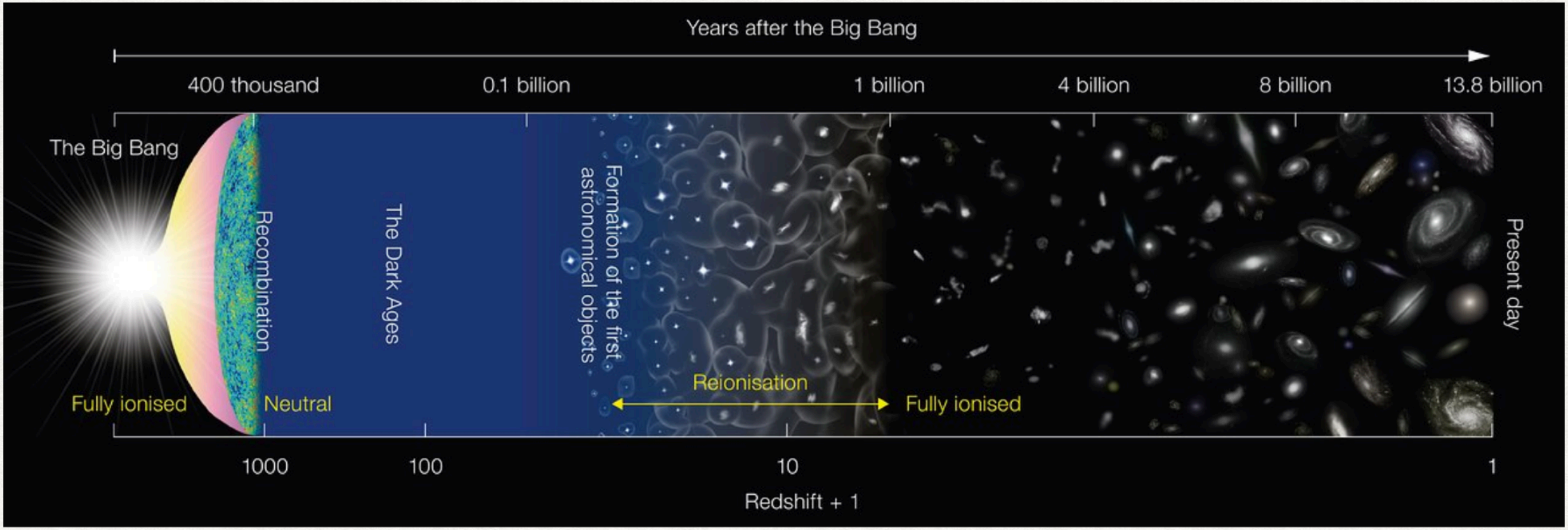

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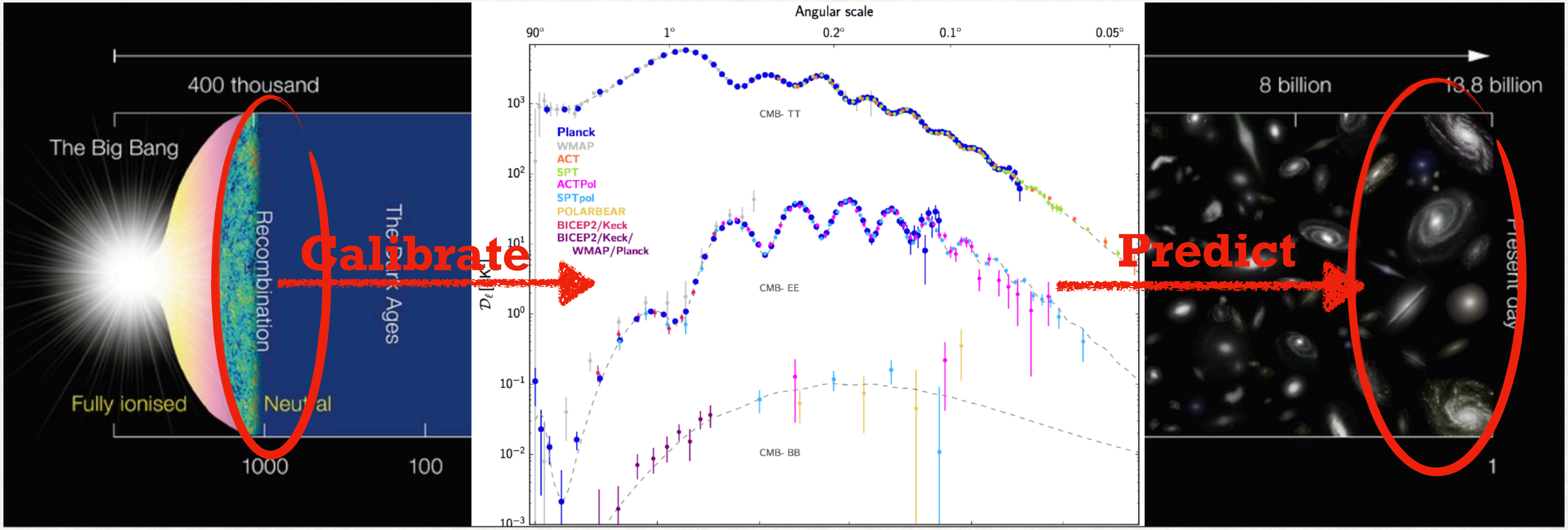

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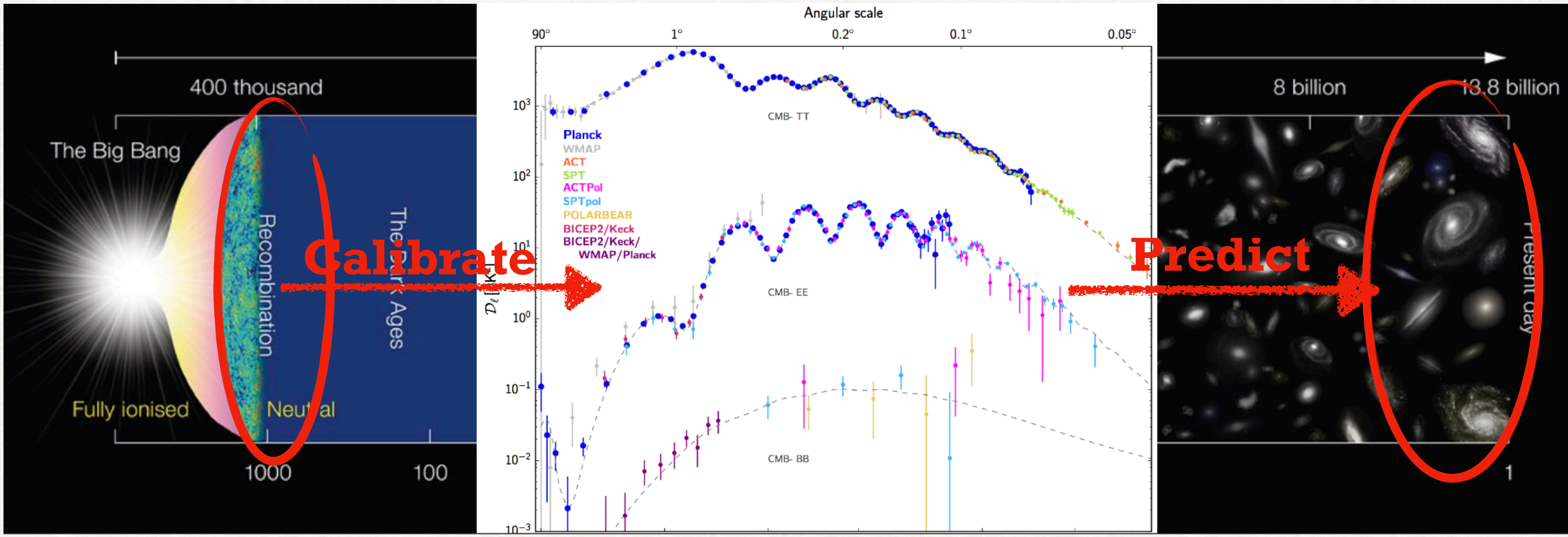

95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

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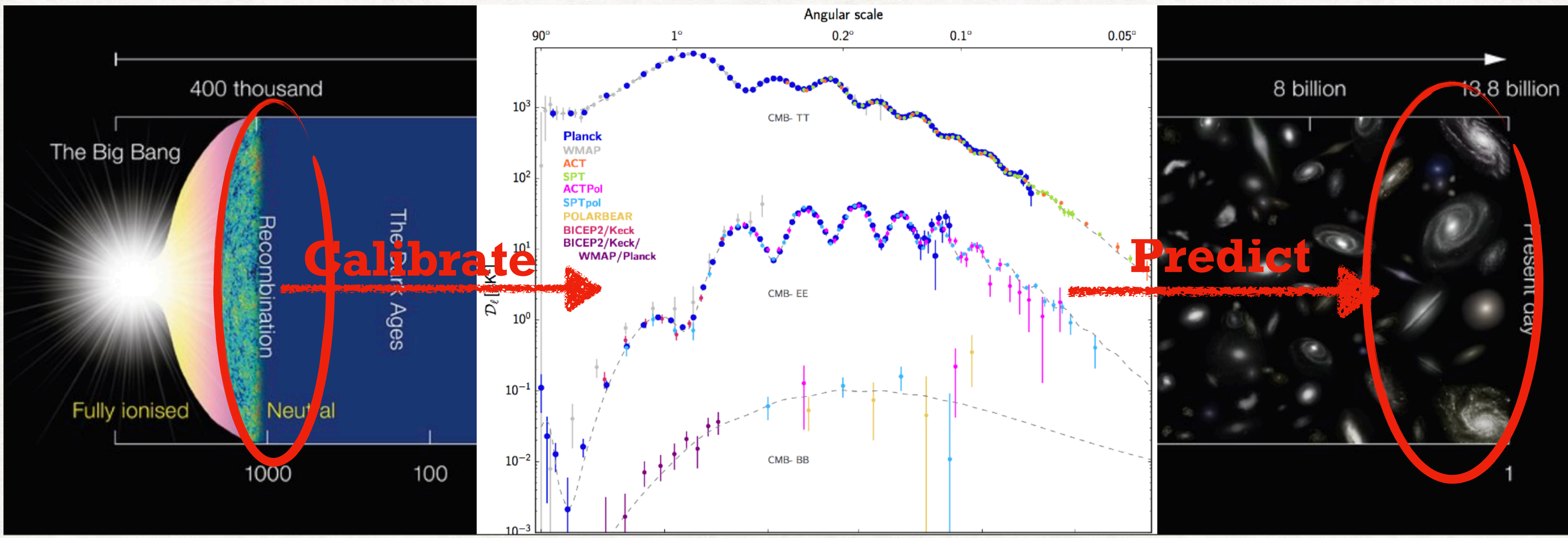

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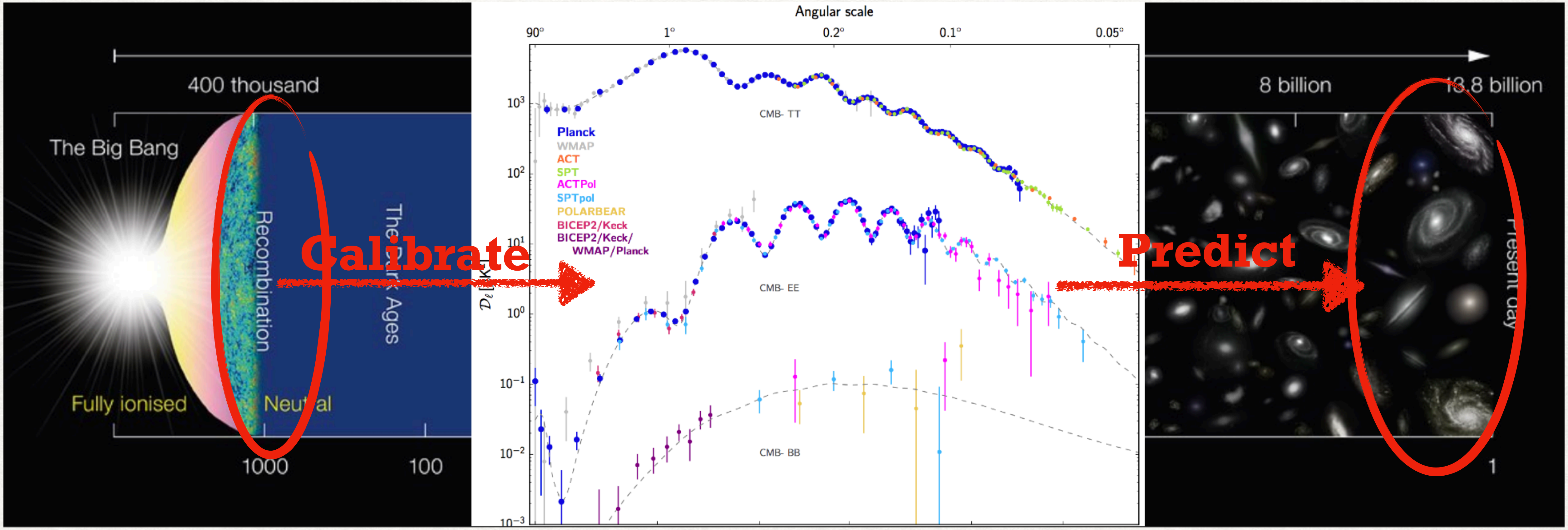

95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

The mechanism behind initial conditions is unknown.

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

Precision Cosmology or Cosmic discordance?

The ΛCDM Cosmology is under extreme scrutiny

- 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?

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?

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

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

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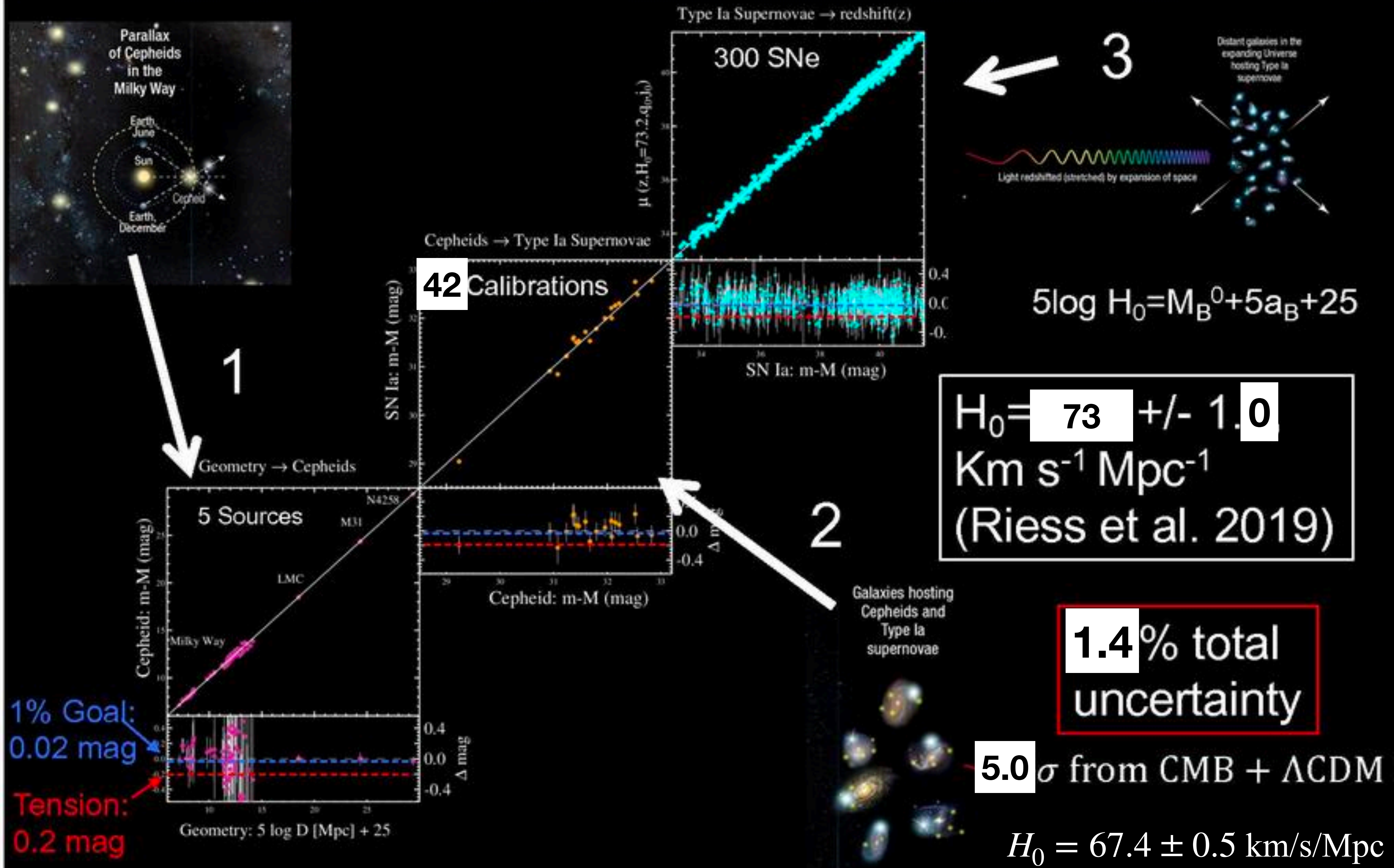
The Hubble Constant in 3 Steps: Present Data



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
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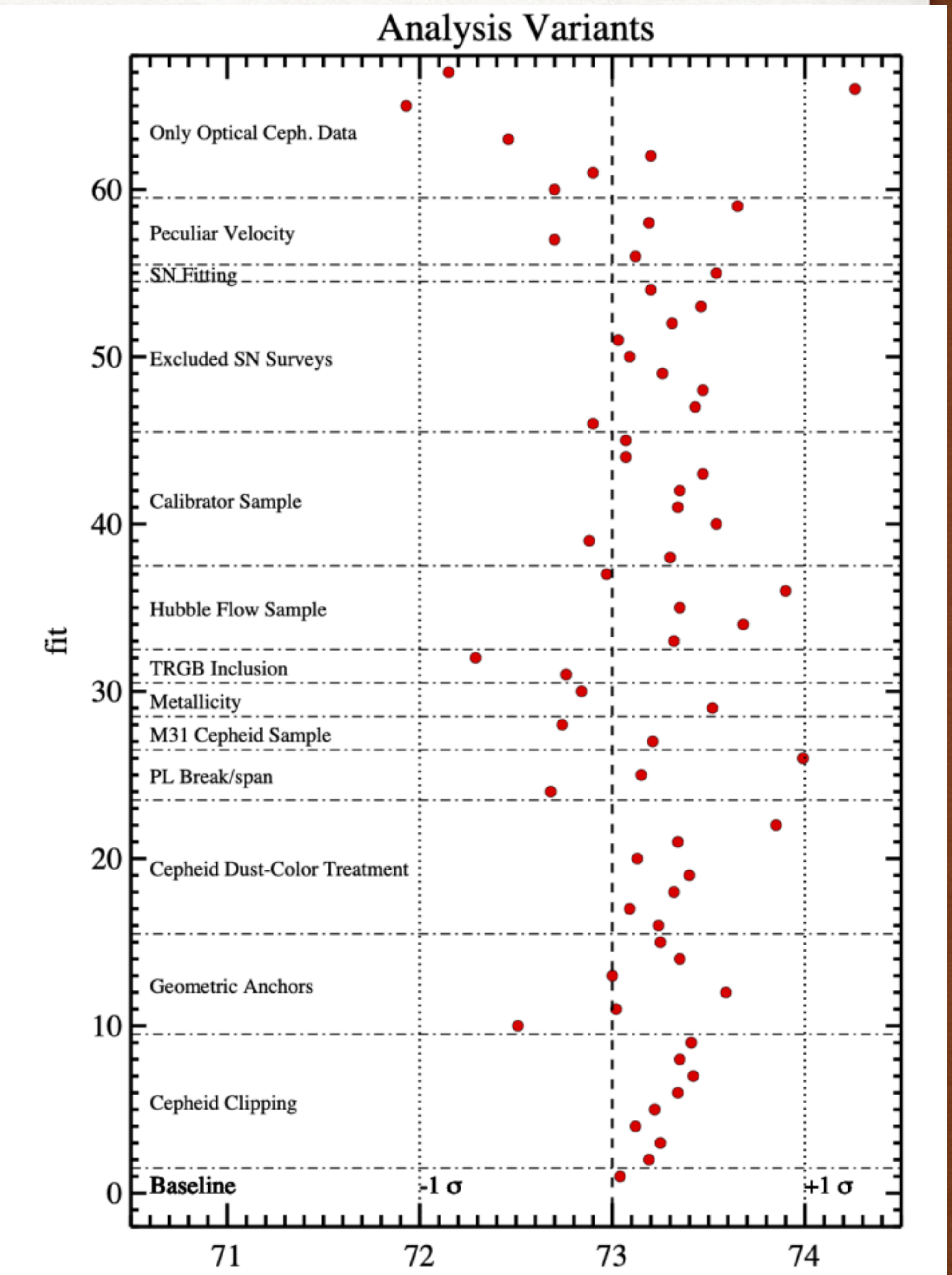

Riess et al. 2112.04510

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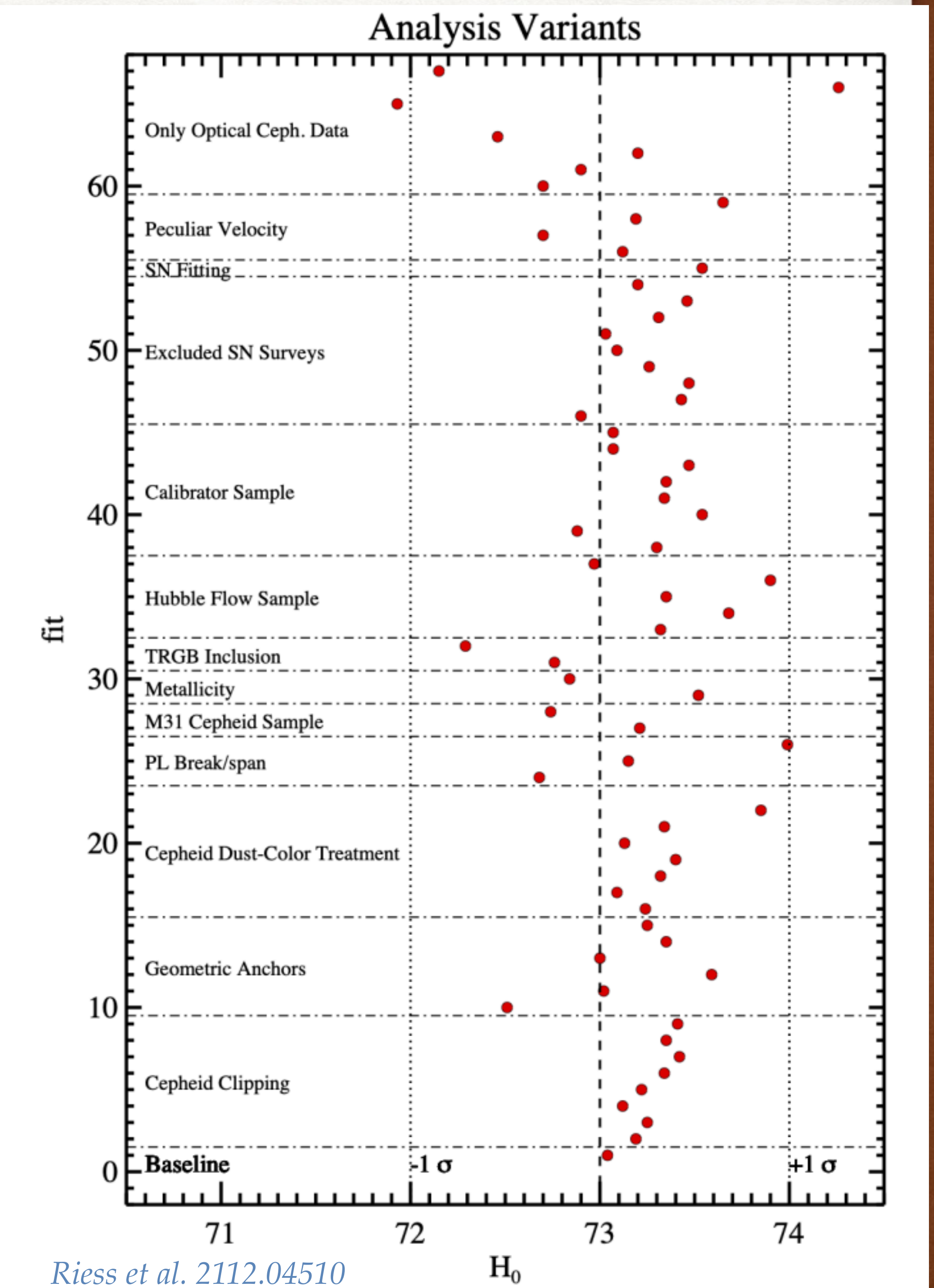
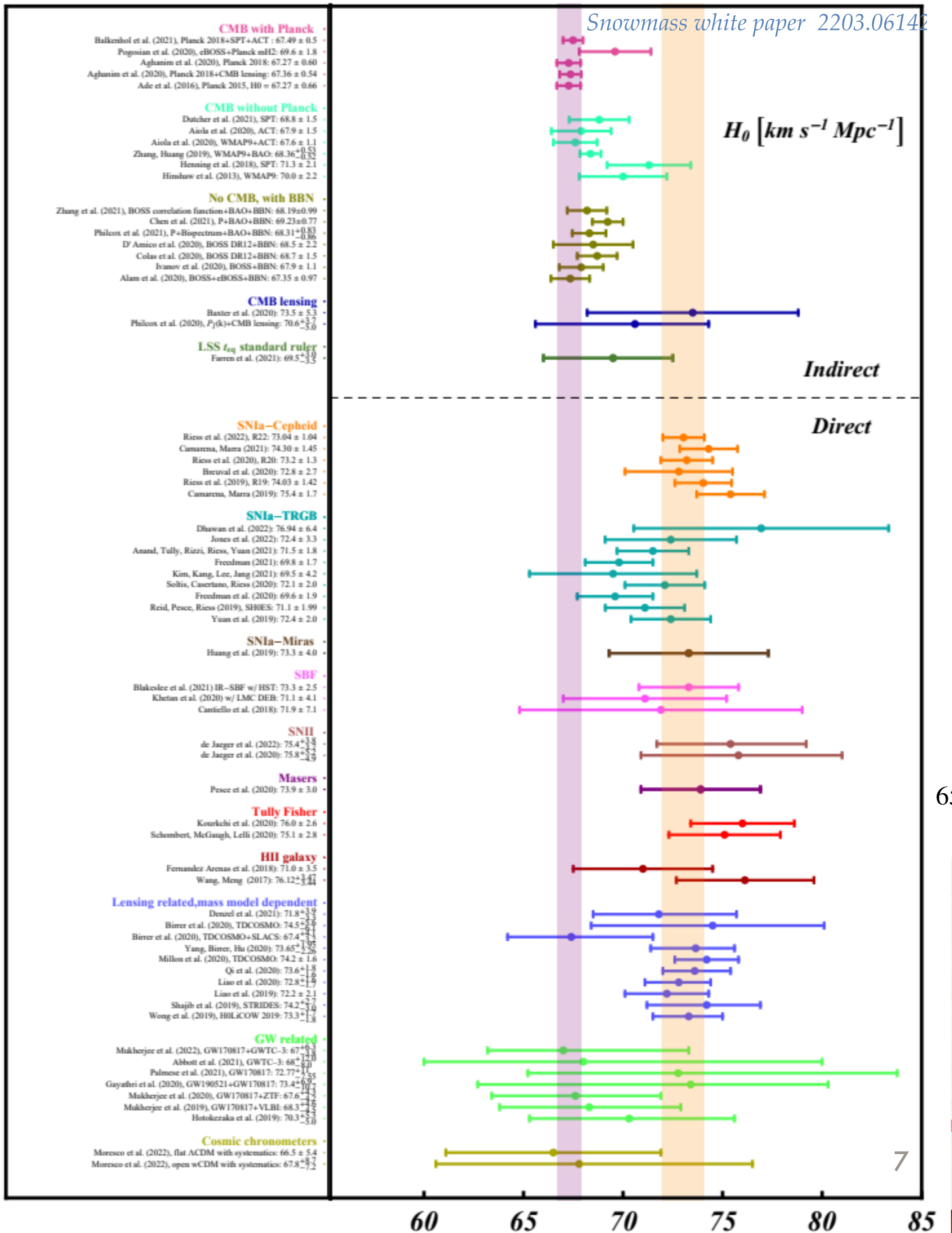
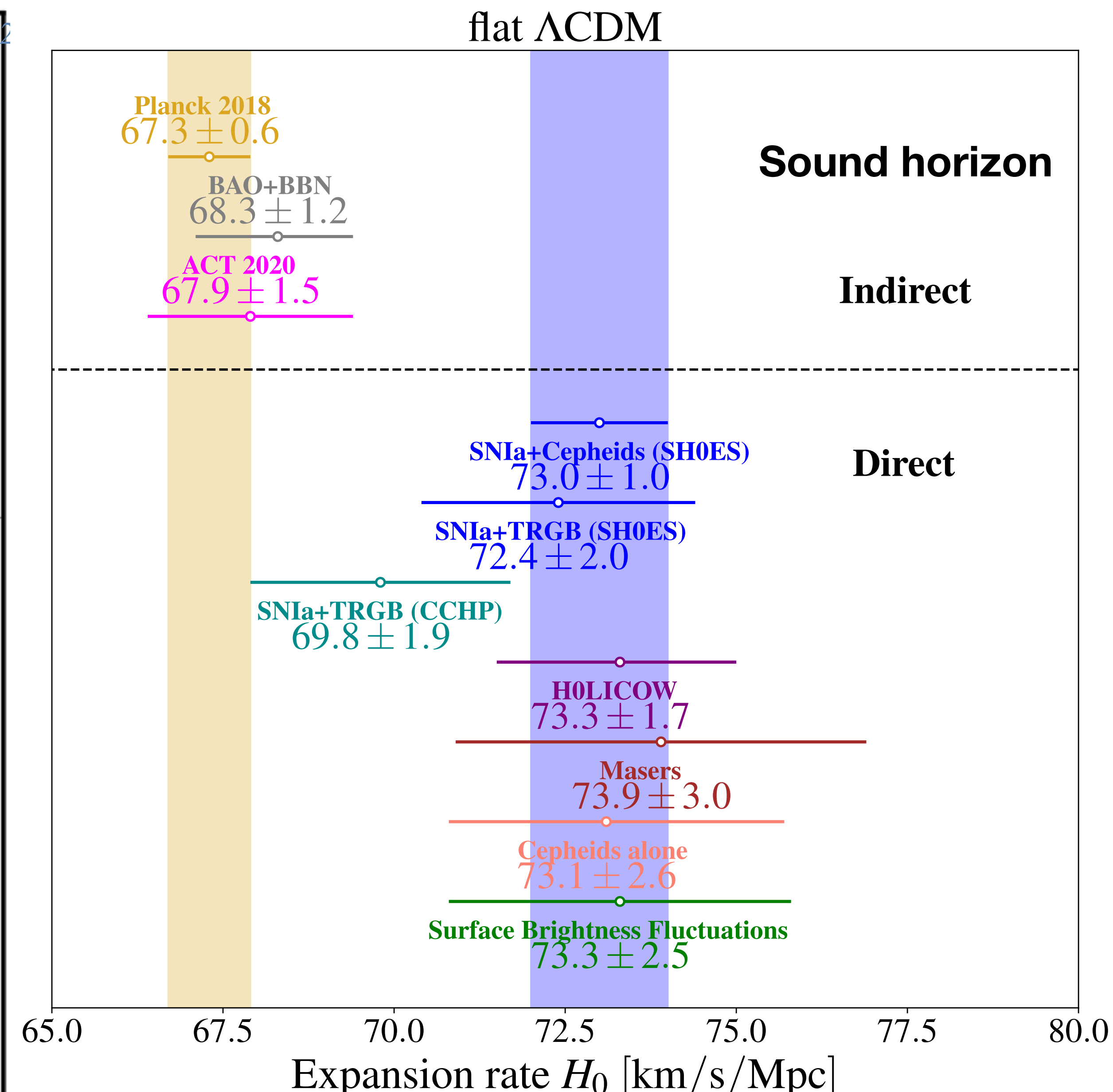


Riess et al. 2112.04510

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

The Hubble tension beyond SHOES & Planck





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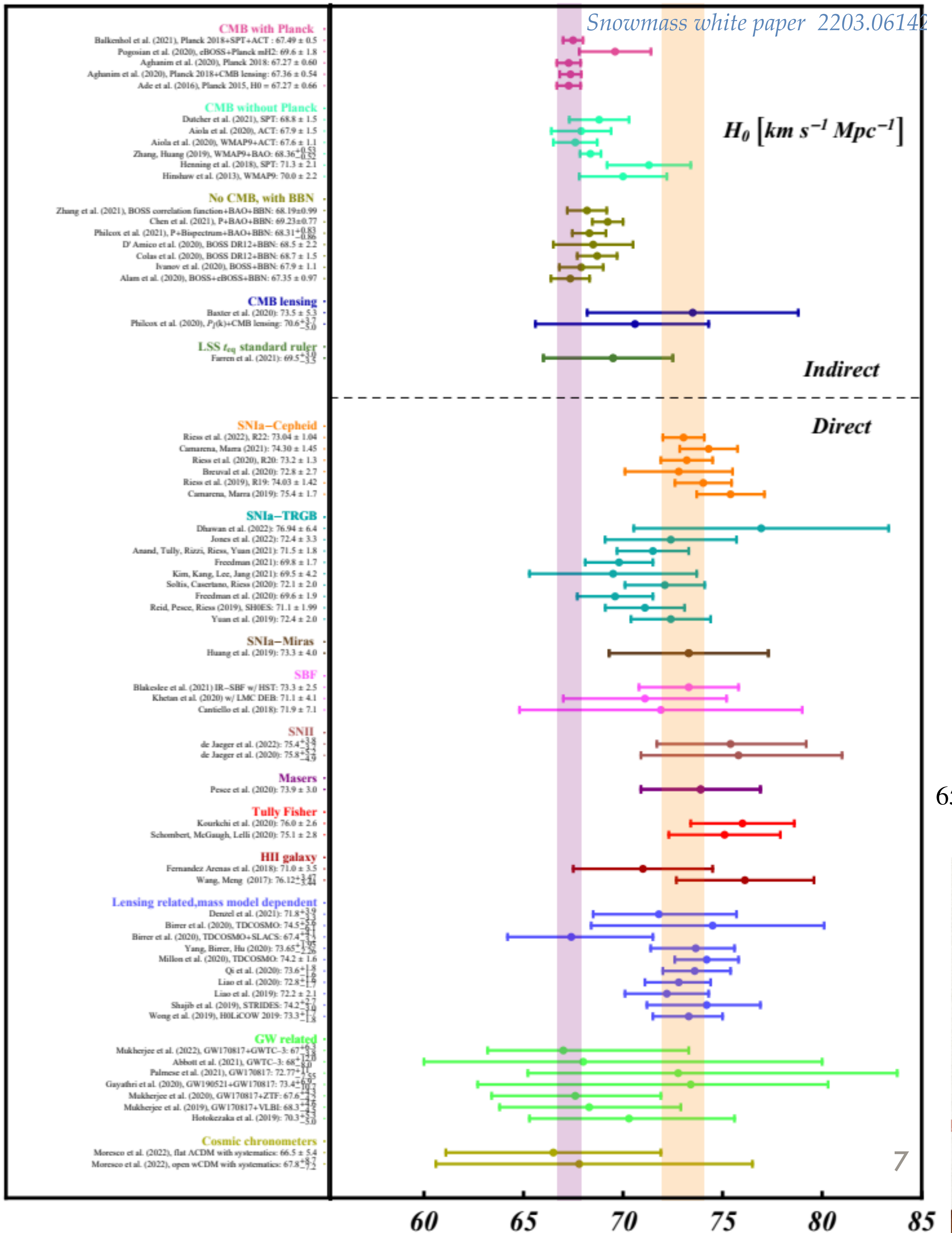
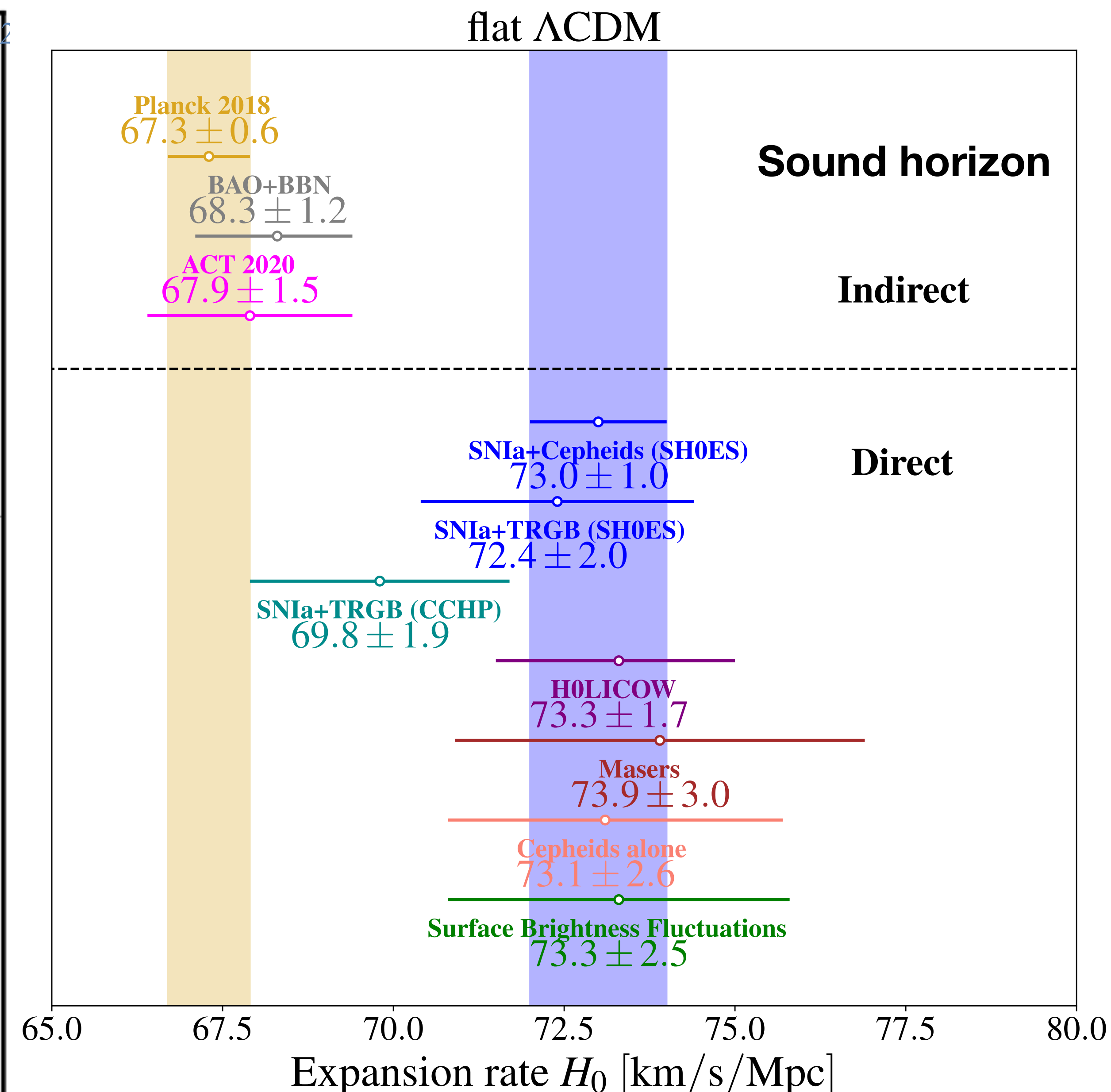
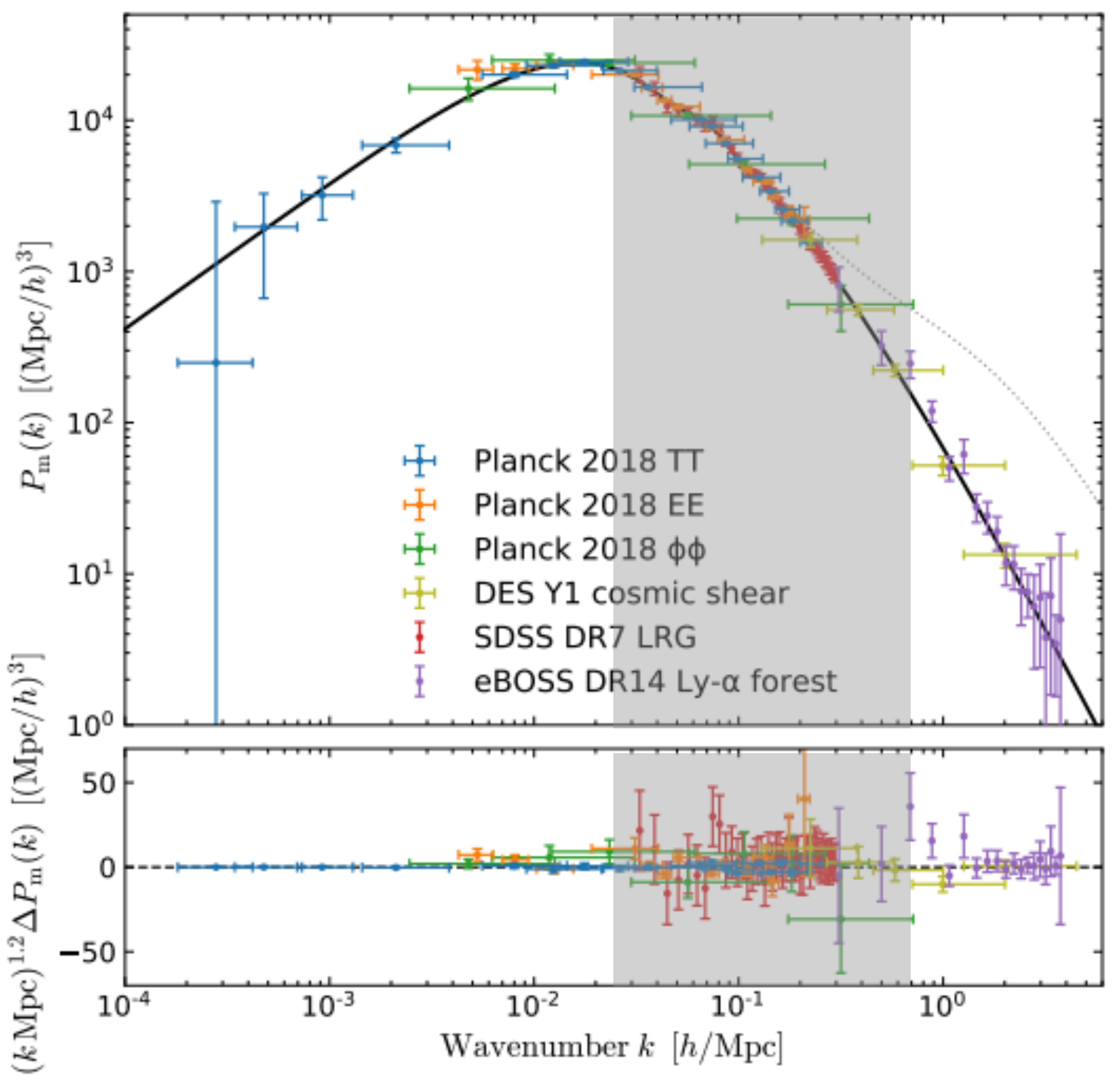




- High-accuracy measurements (very different systematics) indicate large H_0
- Some debate around H0LICOW results

The S_8 parameter



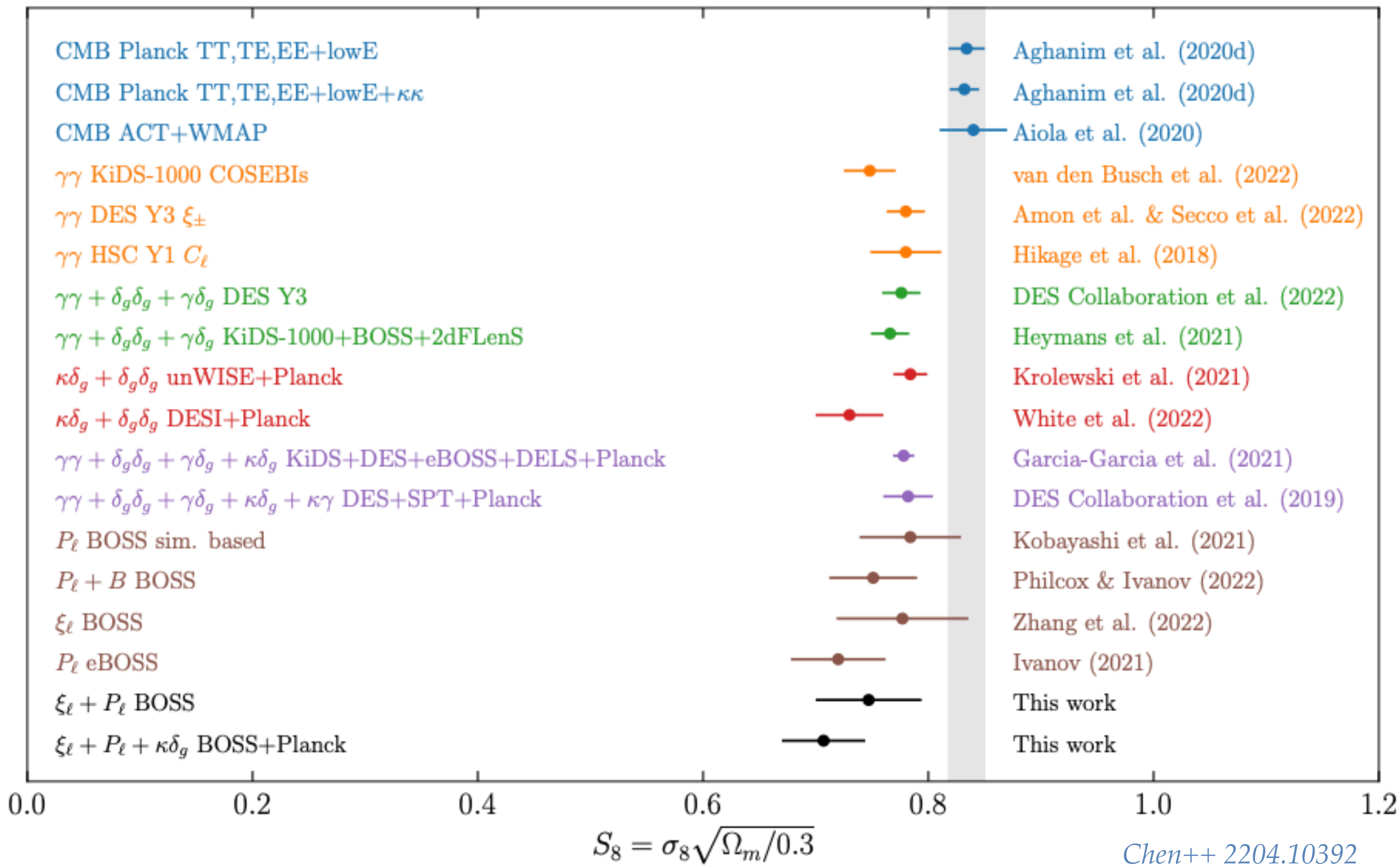
Chabanier 1905.08103

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

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

- The S_8 parameter quantifies how “clumpy” the universe is on scales of $\sim$ 30 million-ly

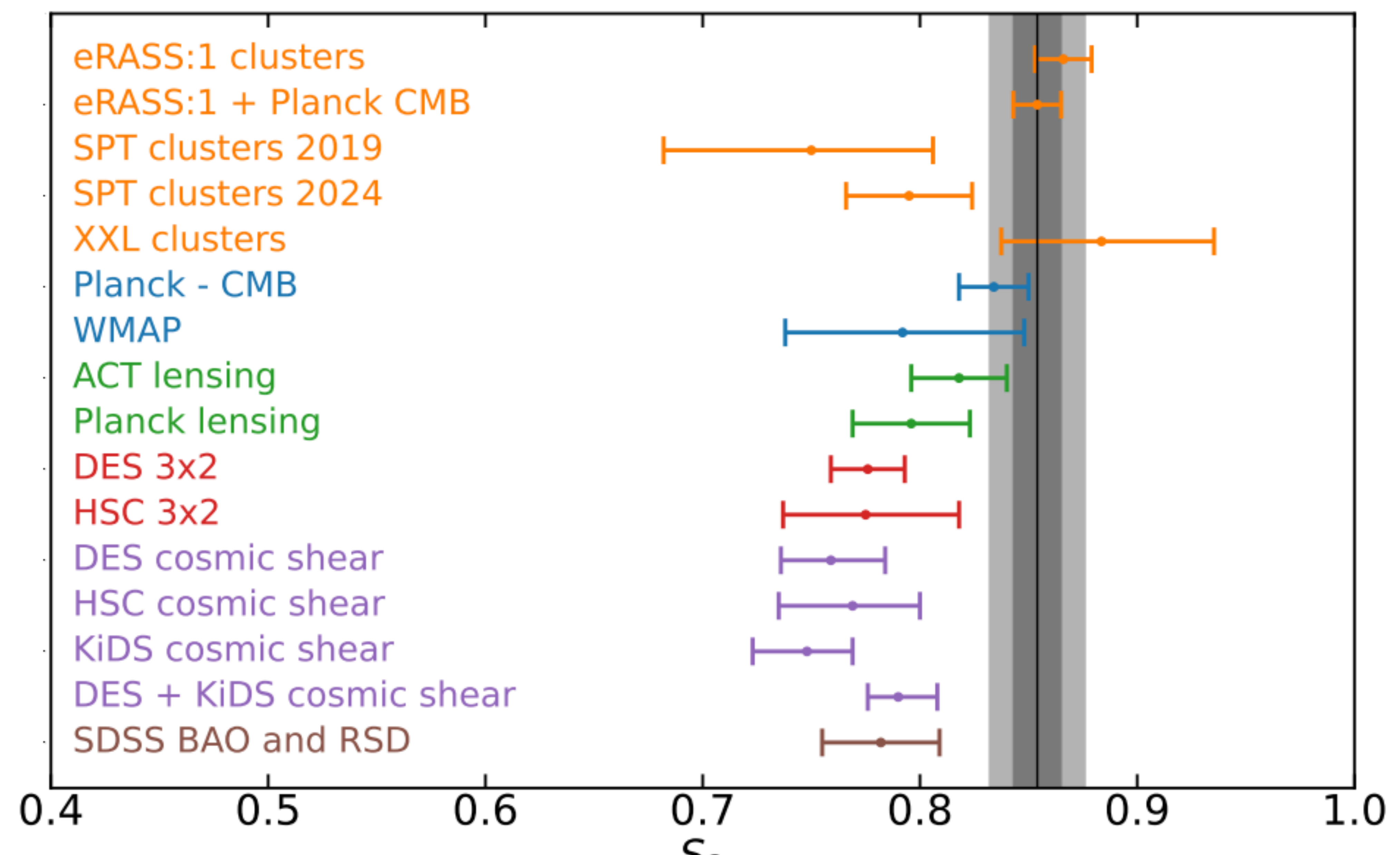
The S_8 tension



Chen++ 2204.10392

There is a 2-3σ tension between S_8 from WL x GC measurements and *Planck*

Is there a S_8 tension after all?



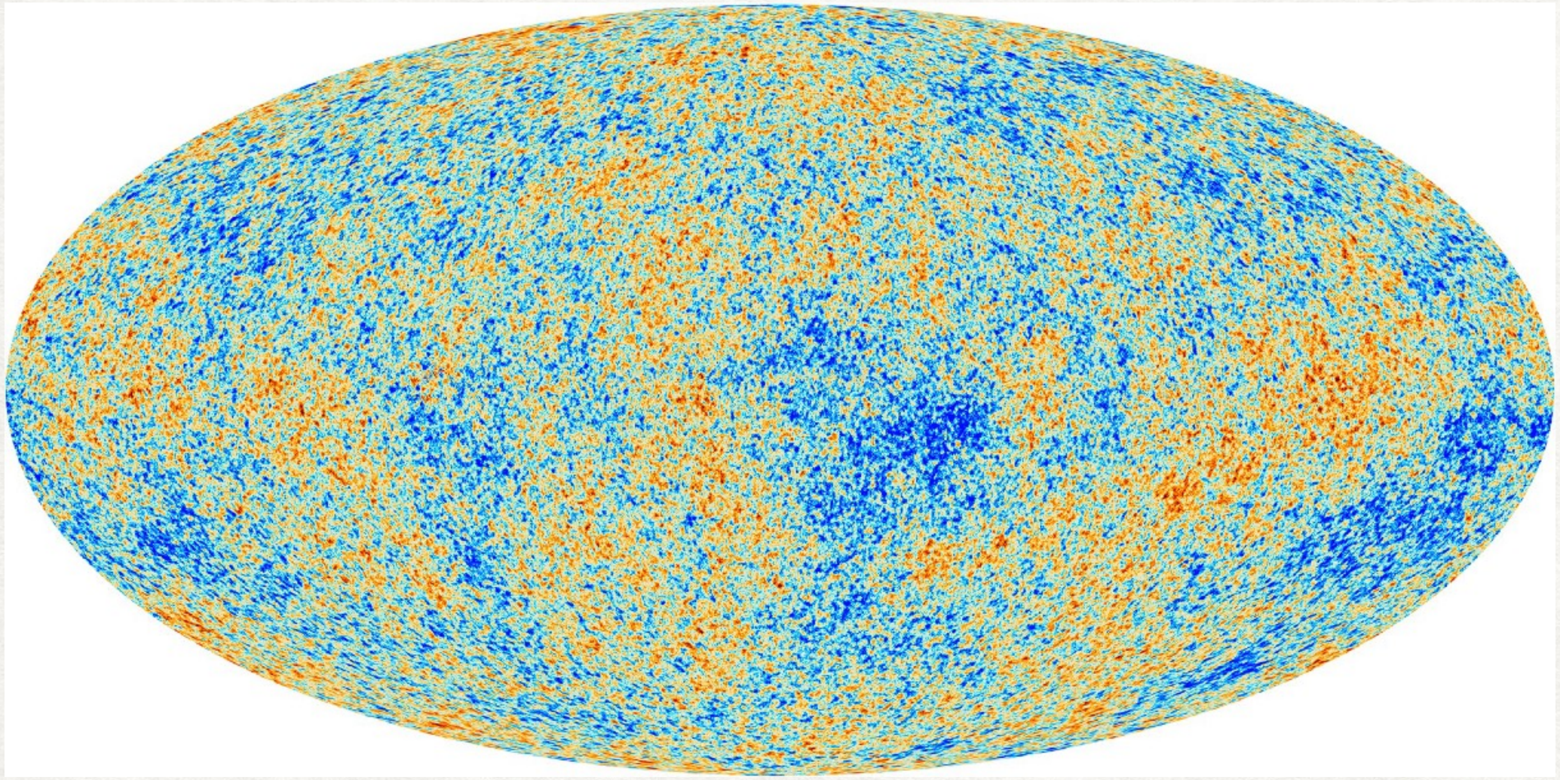
Ghirardini 2402.08458

- Latest S_8 from galaxy cluster number counts by eROSITA is not in tension with Planck

- A potential systematic in WL surveys was already pointed out: intrinsic alignements, non-linear modeling, baryonic feedback could play a role. *Amon& Efstathiou 2206.11794, Aricò++ 2303.05537, Abbott++ 2305.17173*

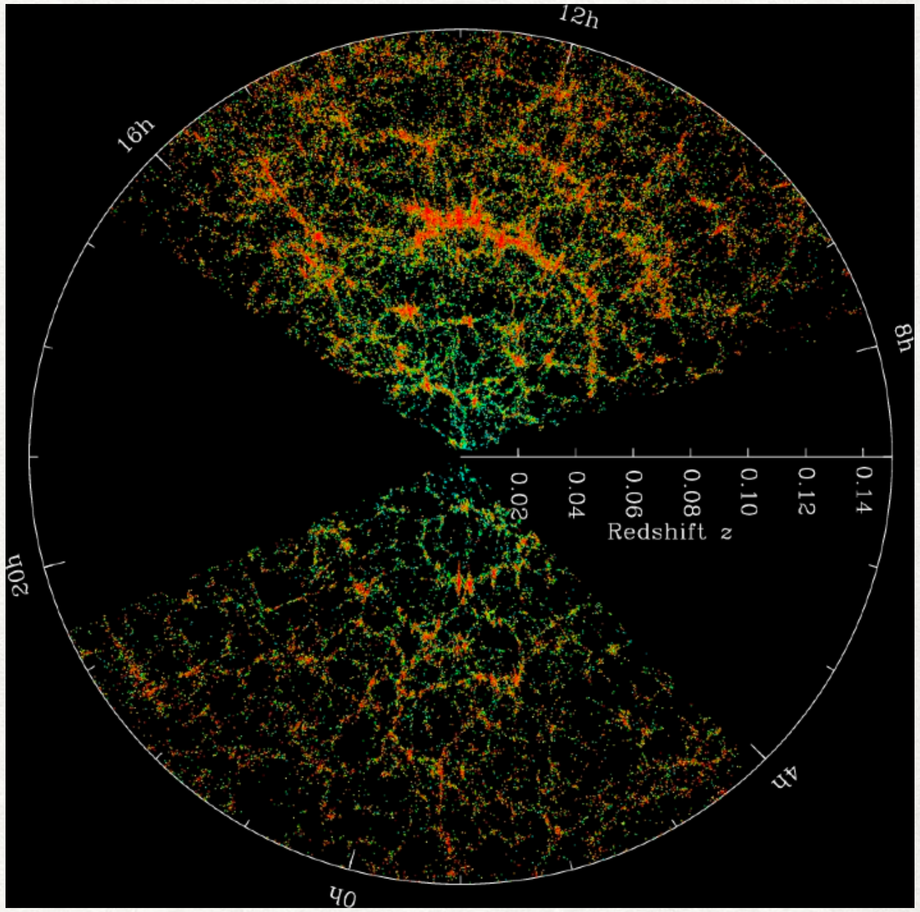
The BAO: a standard ruler in the sky

- Sound horizon r_s: distance travelled by sound-waves in the plasma until recombination
- The acoustic size of the sound horizon θ_s is seen through CMB anisotropies and galaxy surveys
- It can be used to measure distances and infer H_0 given a model.



Planck 1807.06209

$z \sim 1100$



BOSS/SDSS collaboration

$z \sim 0 - 1$

How does CMB data measure H_0?

- The sound horizon r_s is determined from the acoustic peaks given a model
- H_0 appears only in the angular diameter distance d_A.

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

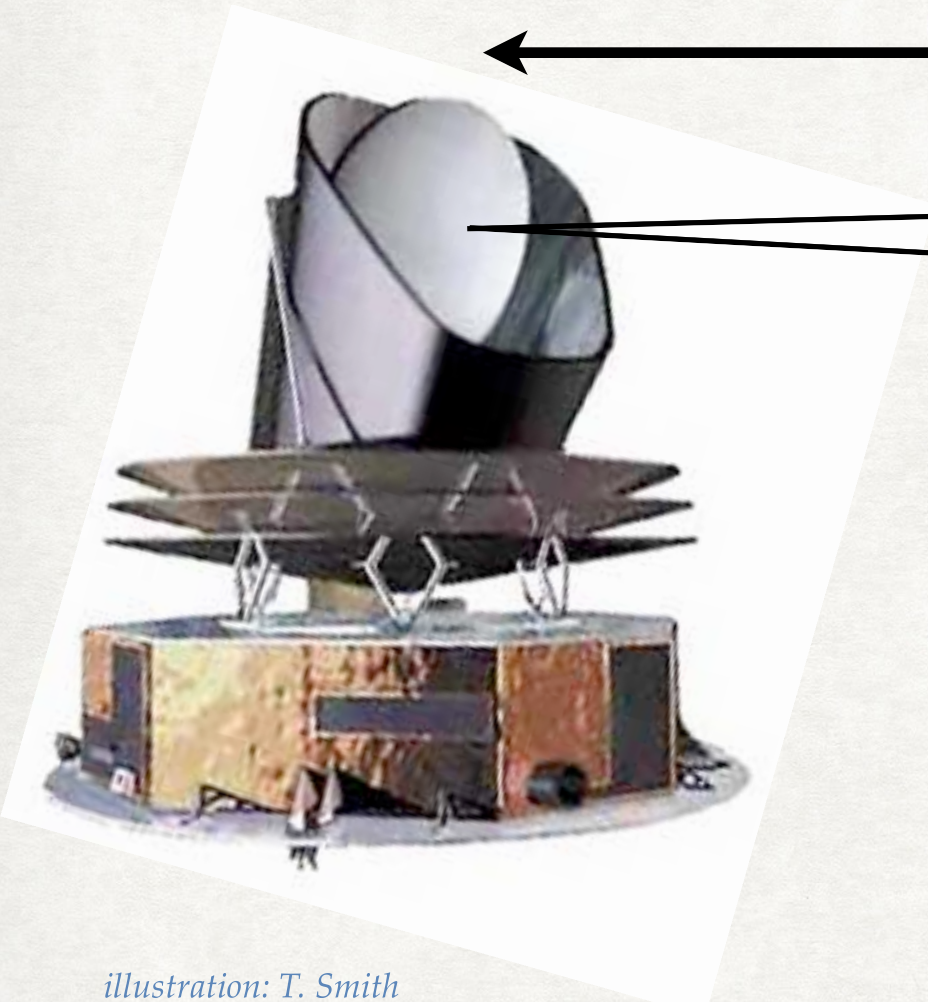


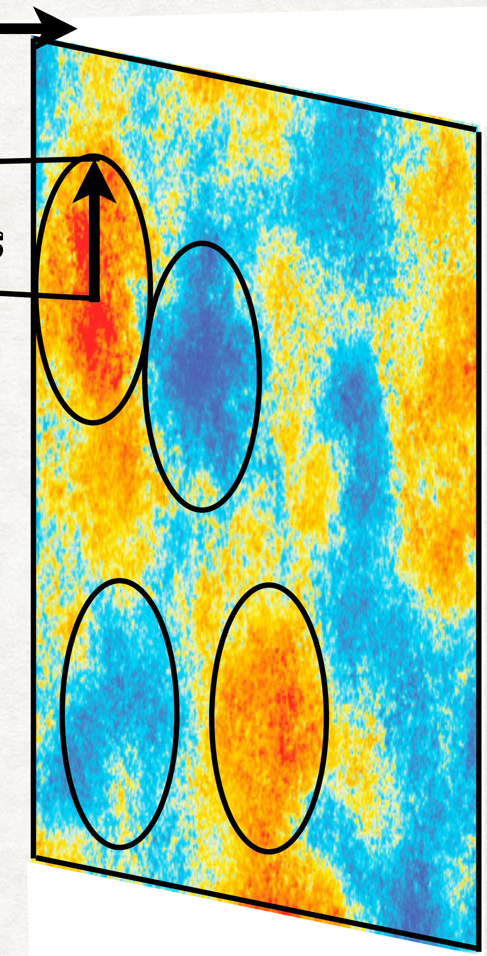
illustration: T. Smith

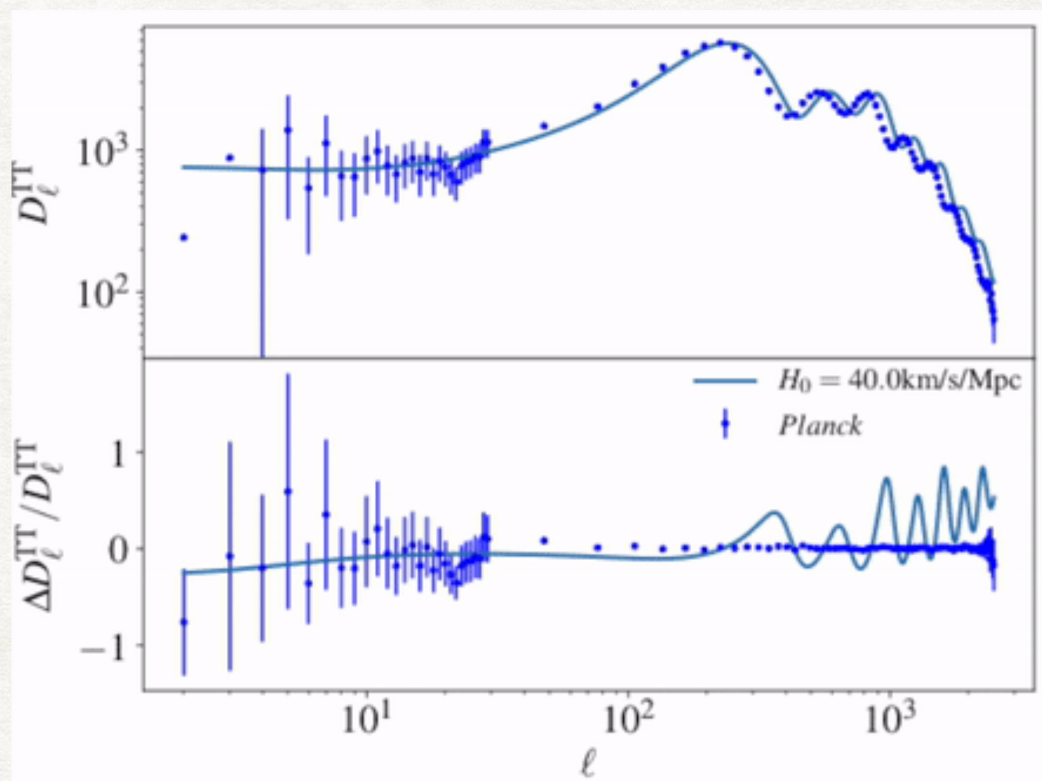
$d_A \propto 1/H_0 = 1/\sqrt{\rho_{\rm tot}(0)}$

$\theta_s \simeq 1^\circ$

0.04% precision!

r_s





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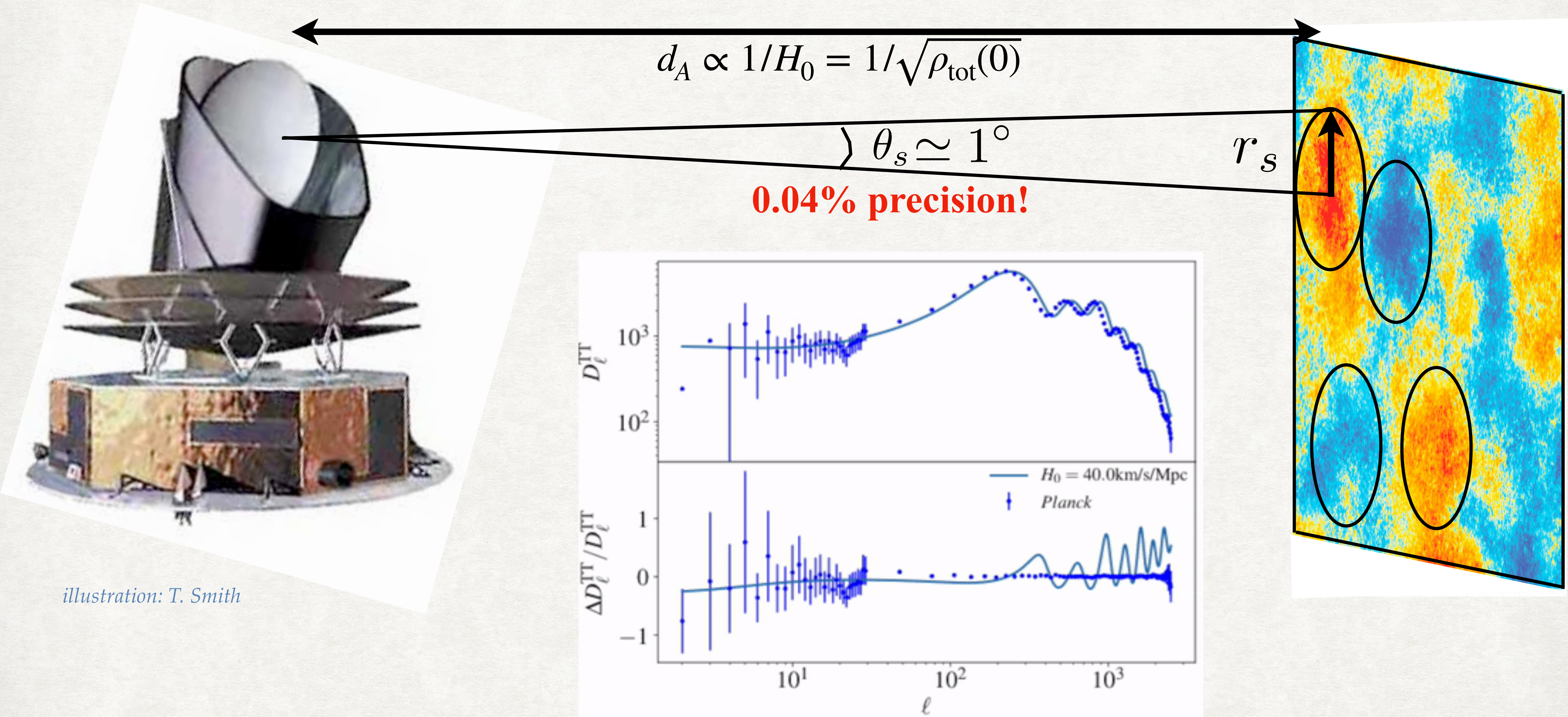

illustration: T. Smith

Geometrical degeneracy in the late-universe!

- ‘phantom dark energy’ $w < -1$, DE phase transition, DE-DM interaction, decaying/annihilating DM, and many more…

$$\theta_s \equiv \frac{H_0 \nearrow r_s(z_*)}{\int_0^{z_*} 1/E(z') \searrow dz'} \qquad E(z) \equiv \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(z) + \cdots}$$

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

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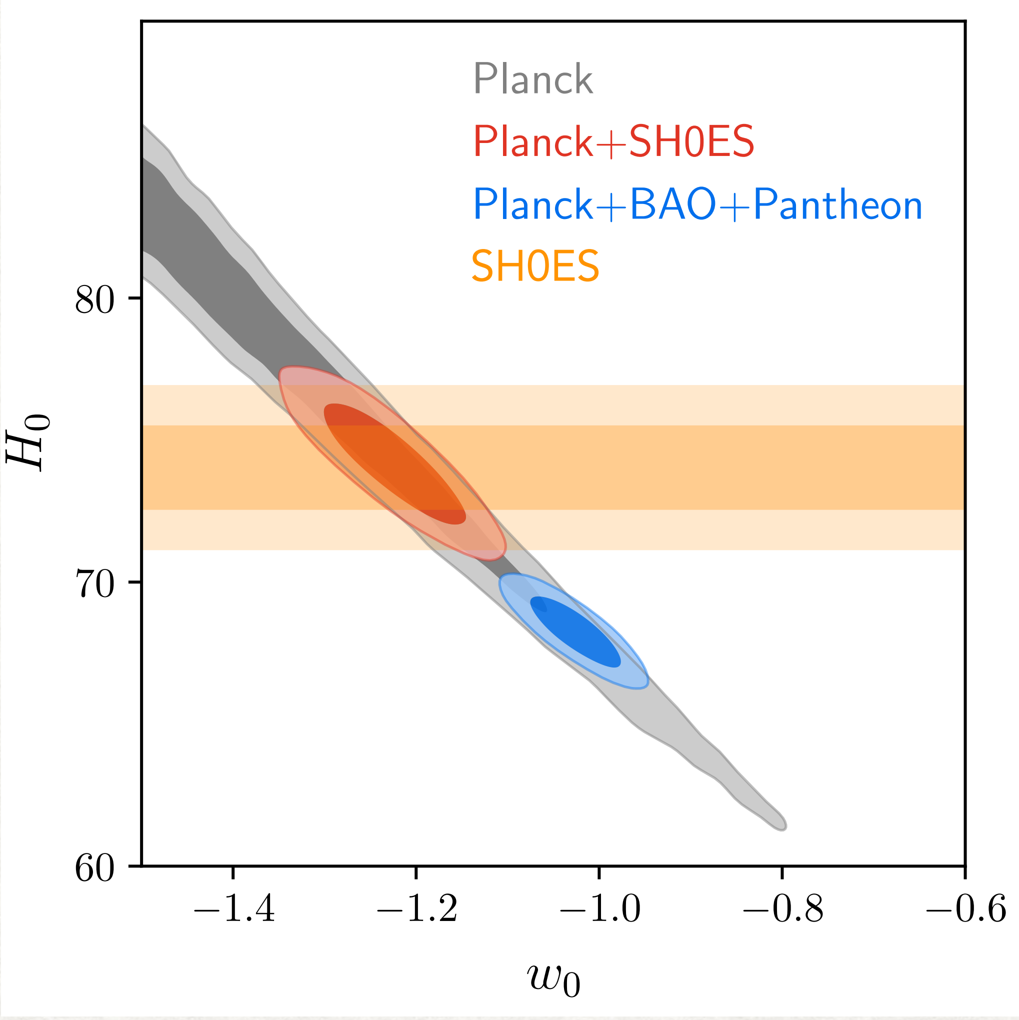
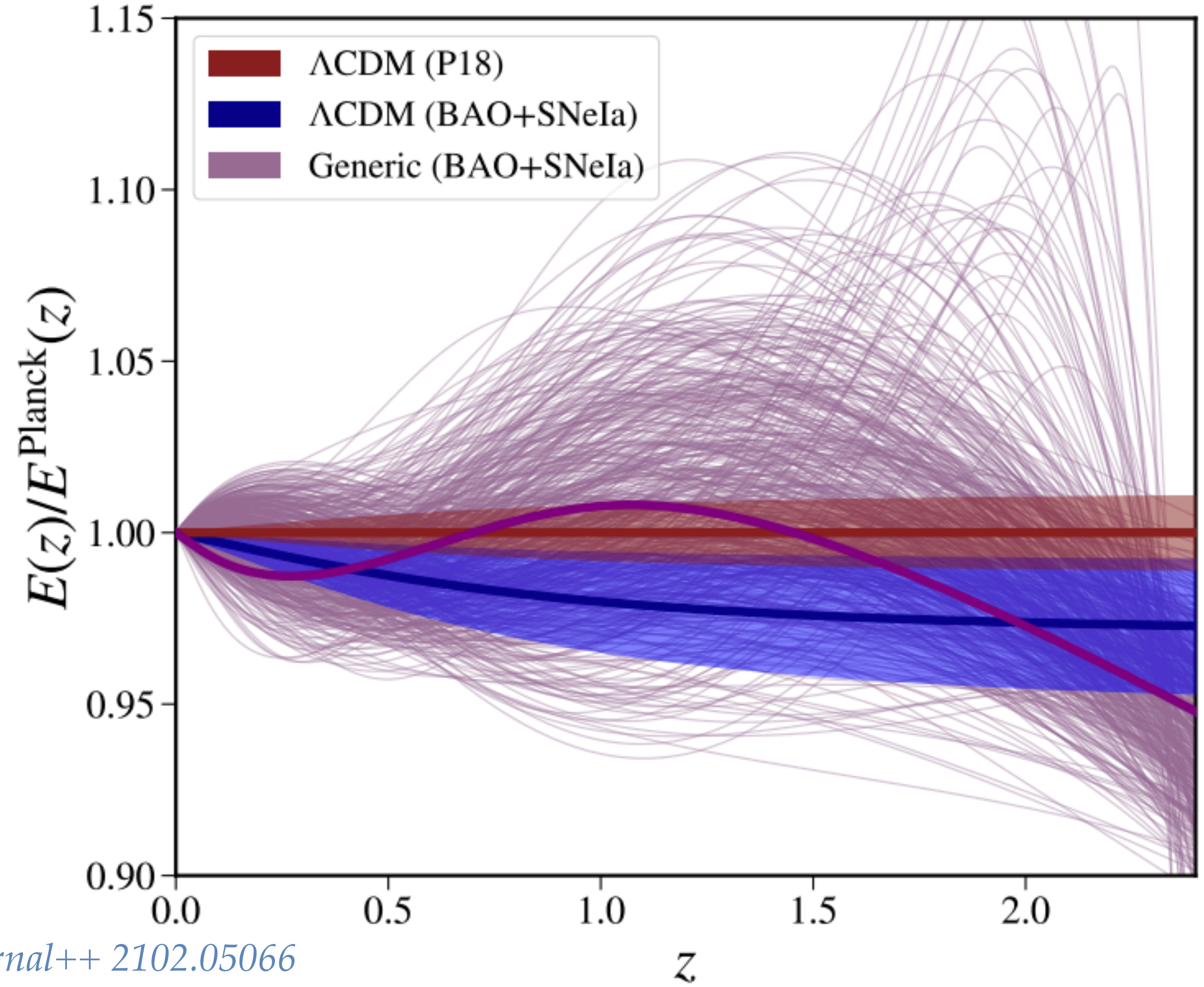
- Planck can easily accommodate a higher H_0: problem with BAO and Pantheon

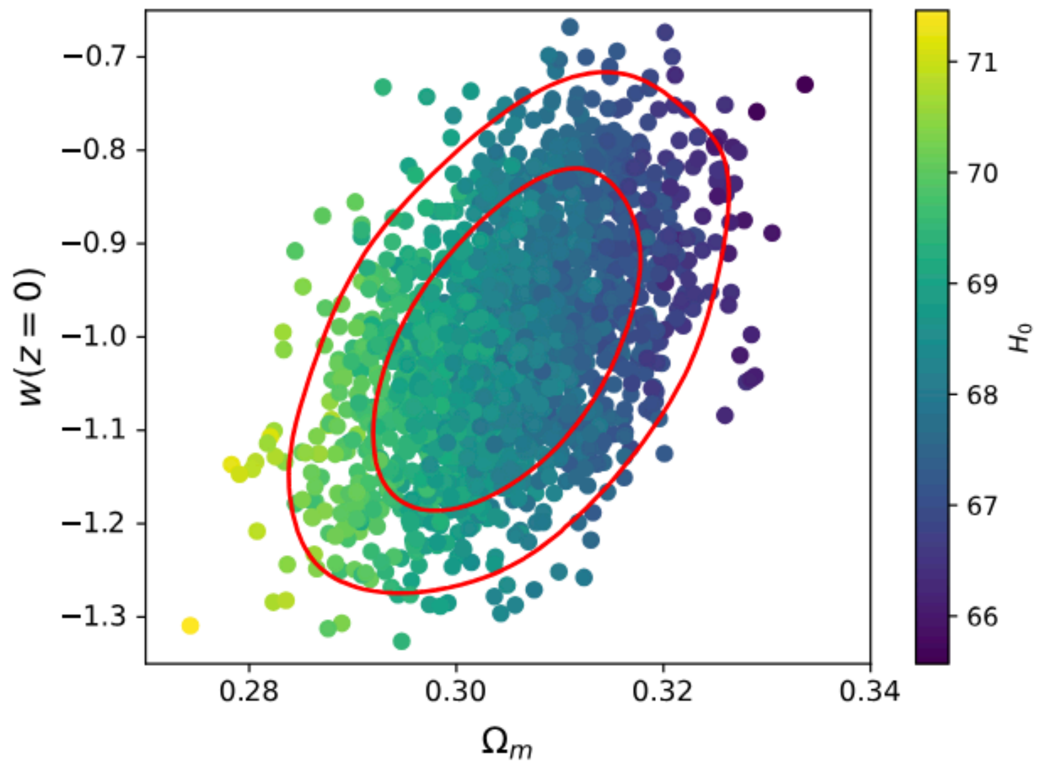


BAO and SNIa constrain the expansion history

- Uncalibrated BAO and SN1a can constrain the shape of the expansion history to high-accuracy



Bernal++ 2102.05066



Keeley & Shafieloo 2206.08440

- Tight constraints on $\Omega_m = 0.316^{+0.009}_{-0.005}$ even if the dark energy equation of state is let free to vary ($\Omega_\Lambda = 1 - \Omega_m$).
- It is impossible to play with the late-time expansion history to explain H_0 — VP++ 1803.02474 Keeley & Shafieloo 2206.08440
- This conclusion is NOT affected by the latest DESI + SN1a data — Calderon++ 2405.04216

The tension is truly between **calibrators**!

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

SN1a: $\mu(z) = 5\mathrm{Log}_{10} D_L(z) + M_b$

- In GR: $D_A = D_L/(1+z)^2$ ==> it is impossible to resolve the tension without changing calibration!

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Planck

SHOES

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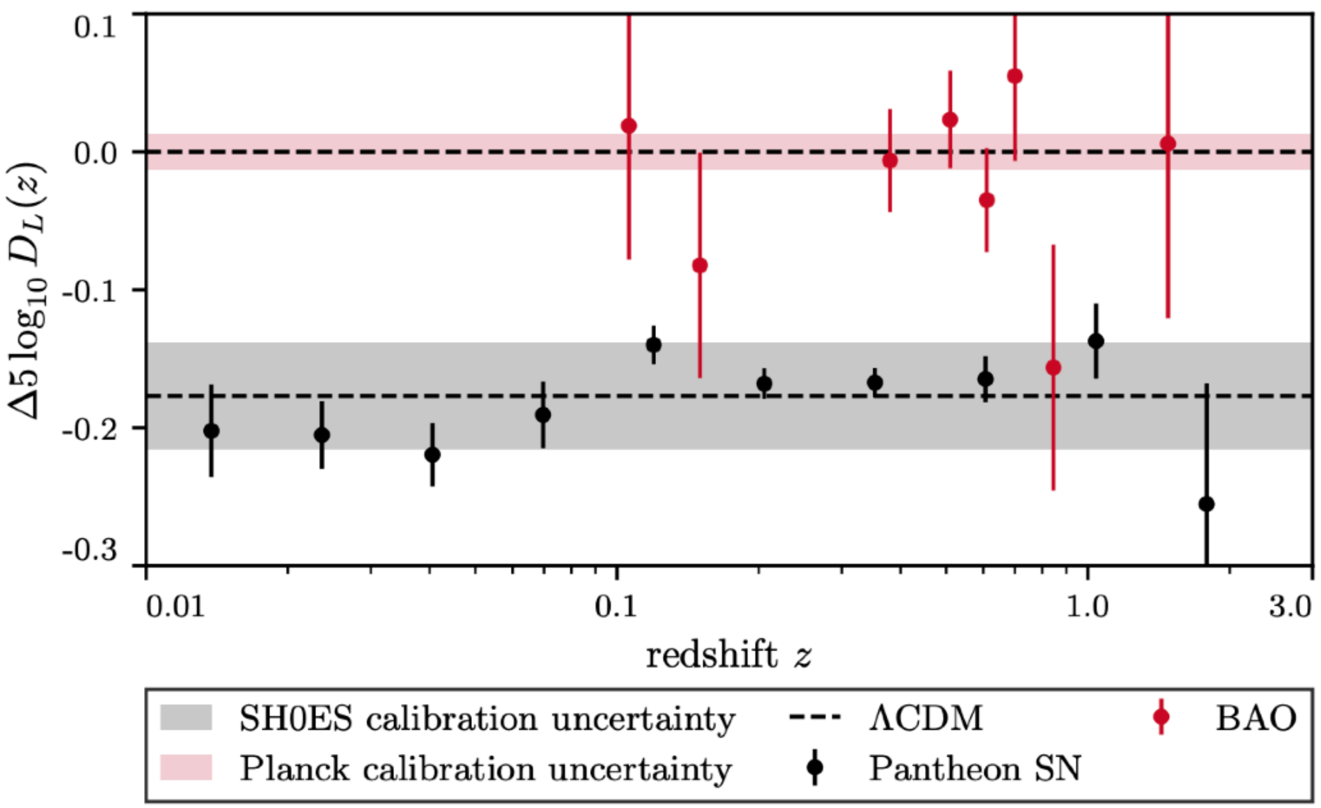
Raveri 2309.06795



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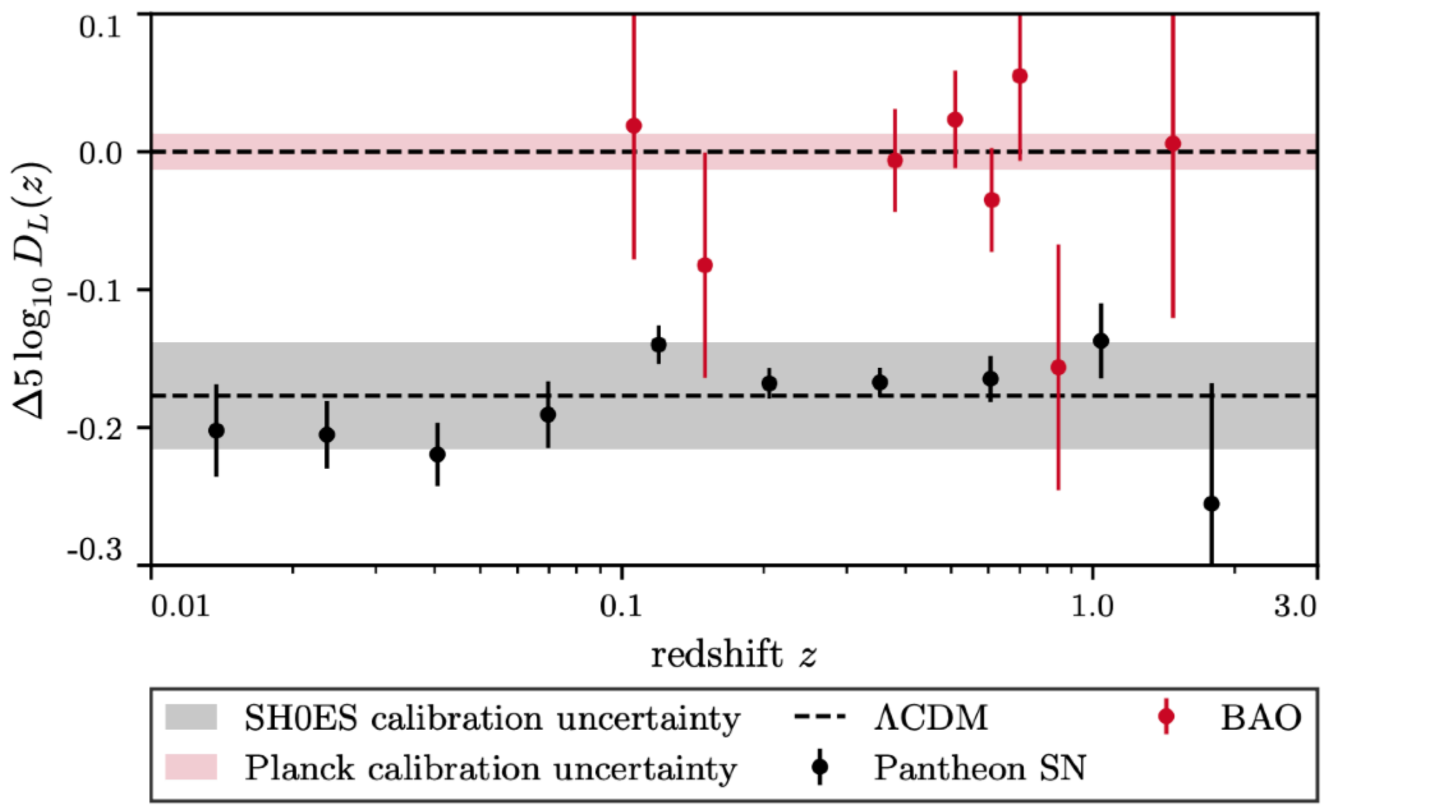

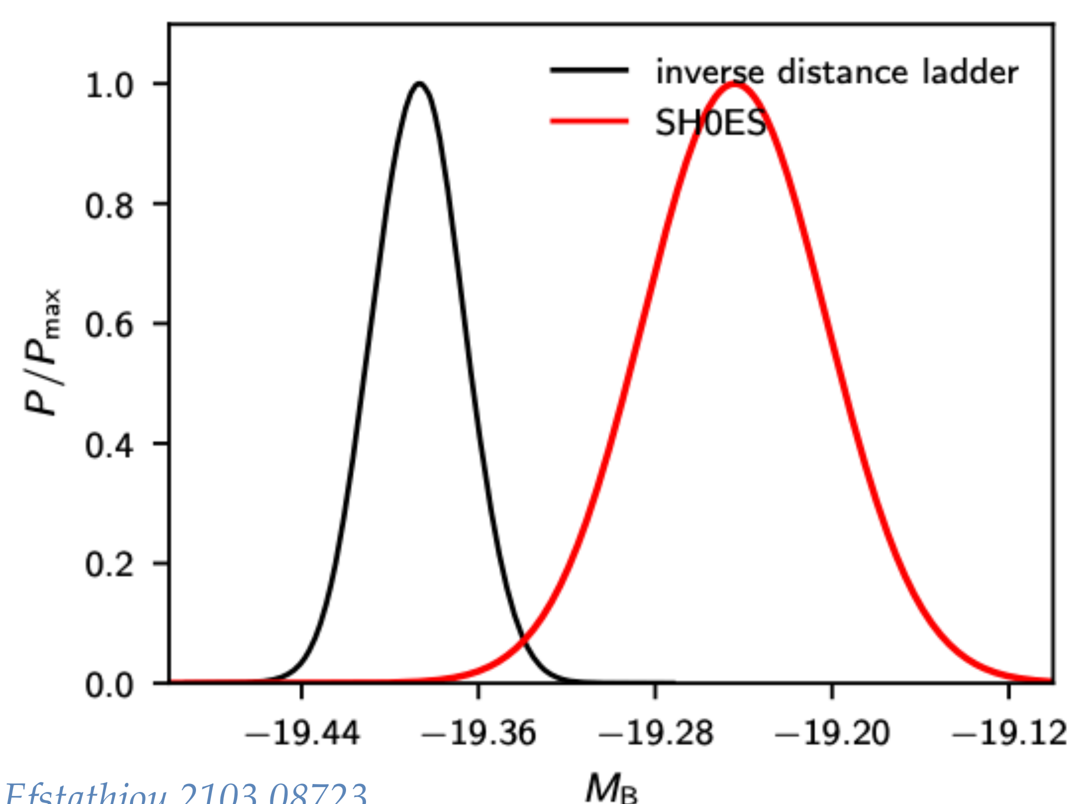

Efstathiou 2103.08723

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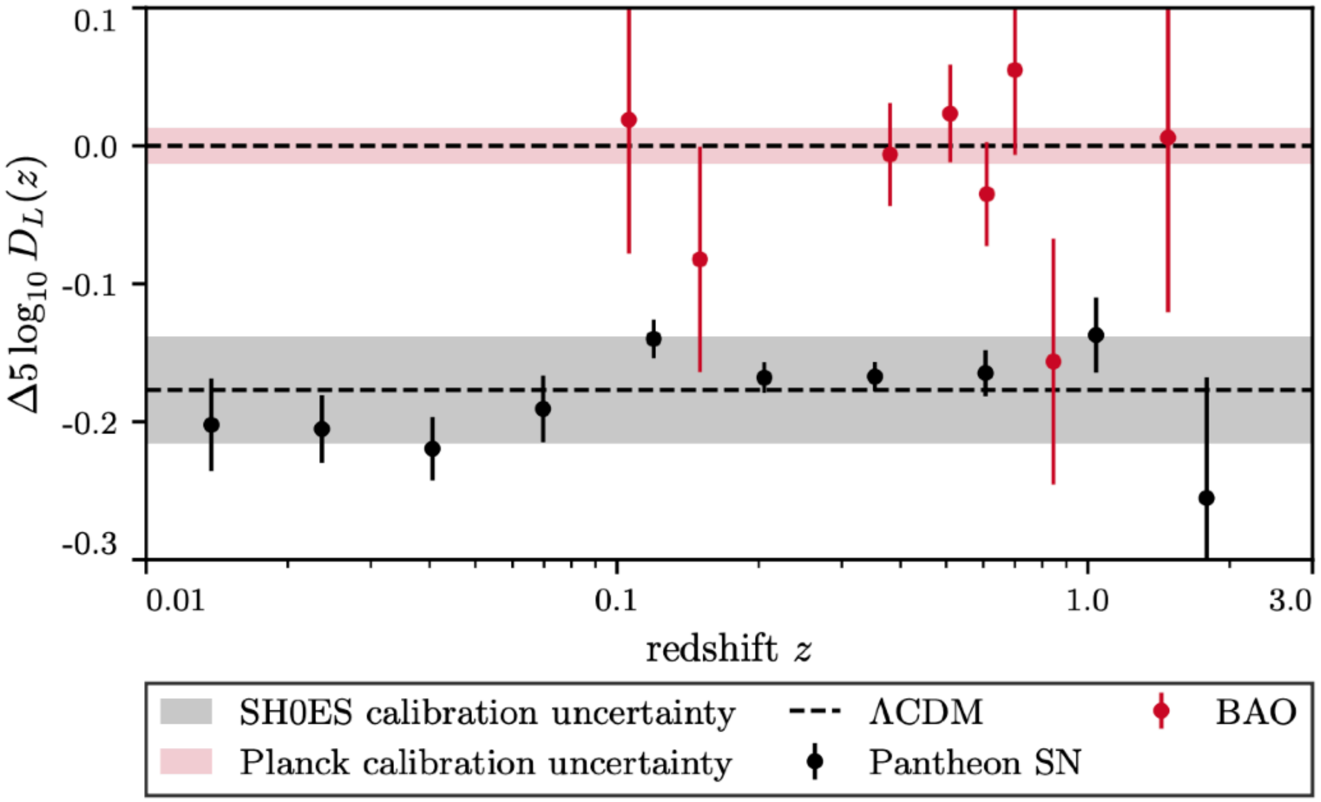
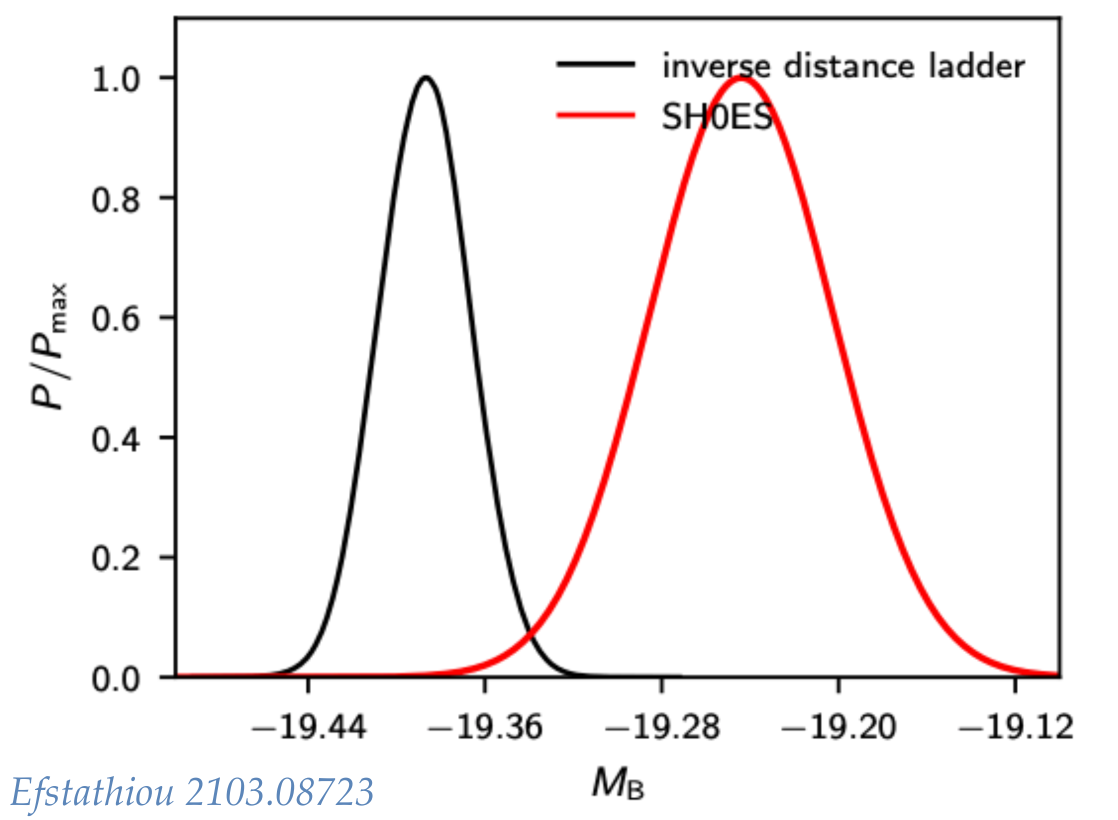


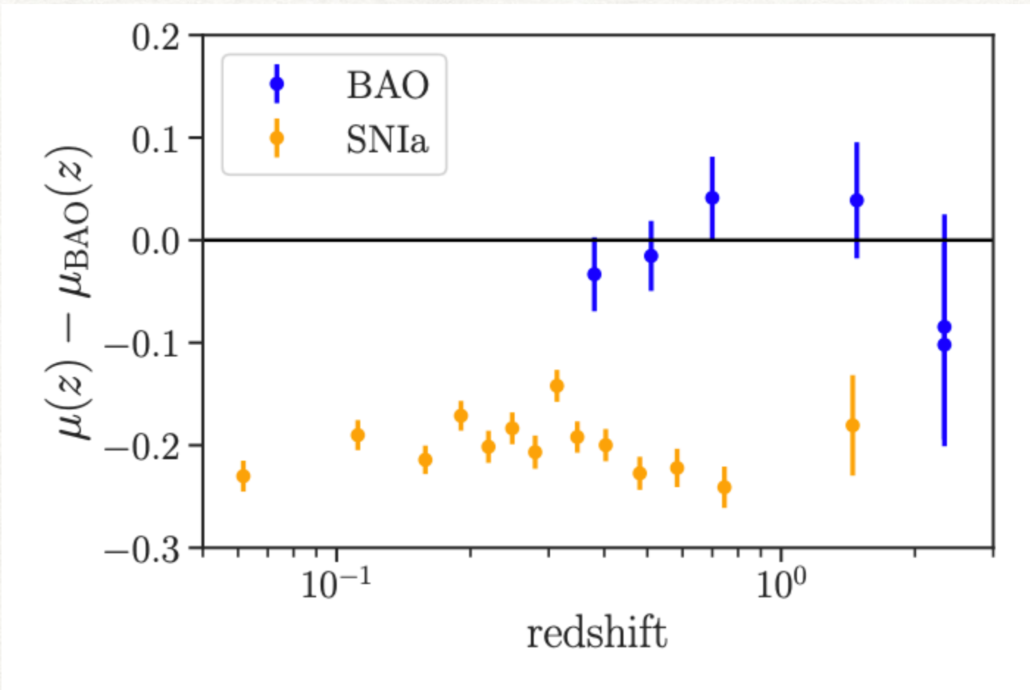


Efstathiou 2103.08723

- Assuming r_s(ΛCDM) and M_b(SH0ES), $D_A(z)$ and $D_L(z)$ are incompatible!
- Two possibilities: break EDDR or change calibrators? *Tutusaus++, 2311.16862*

Could the DDR be violated?

Tutusaus++, 2311.16862



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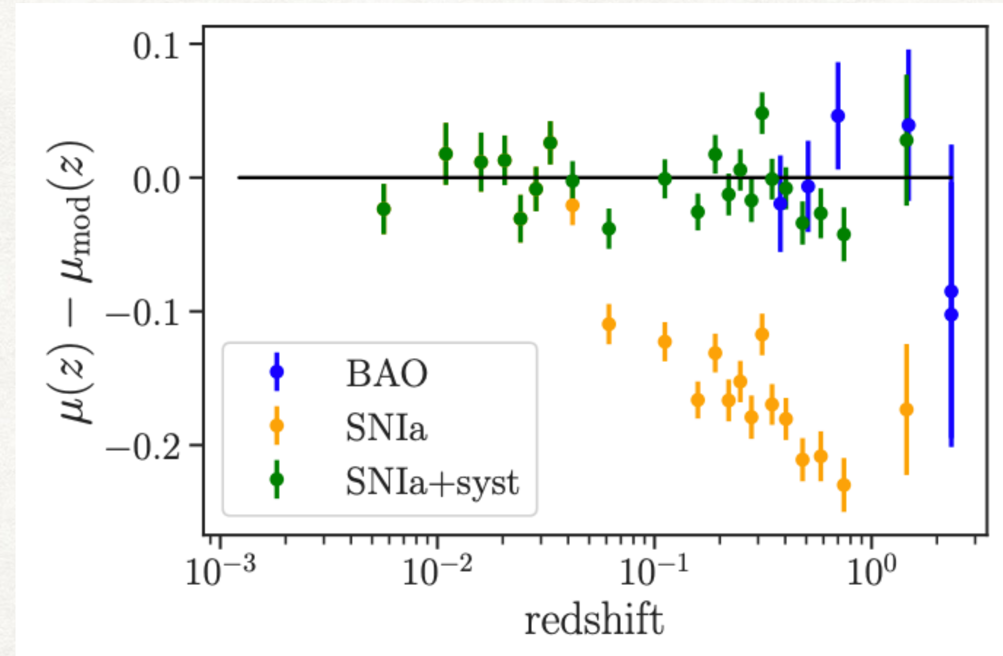

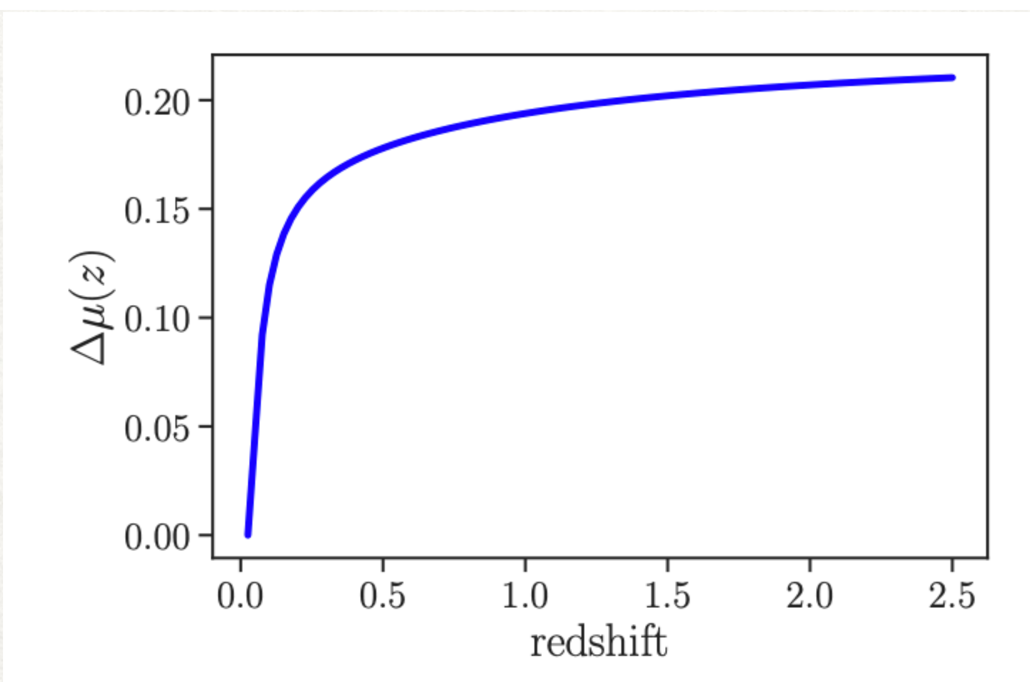

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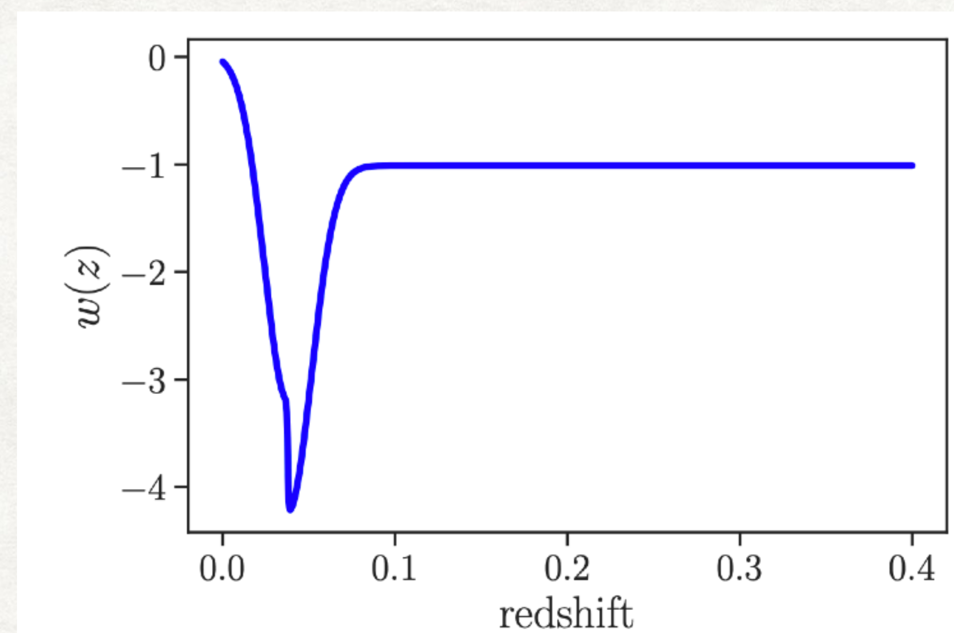
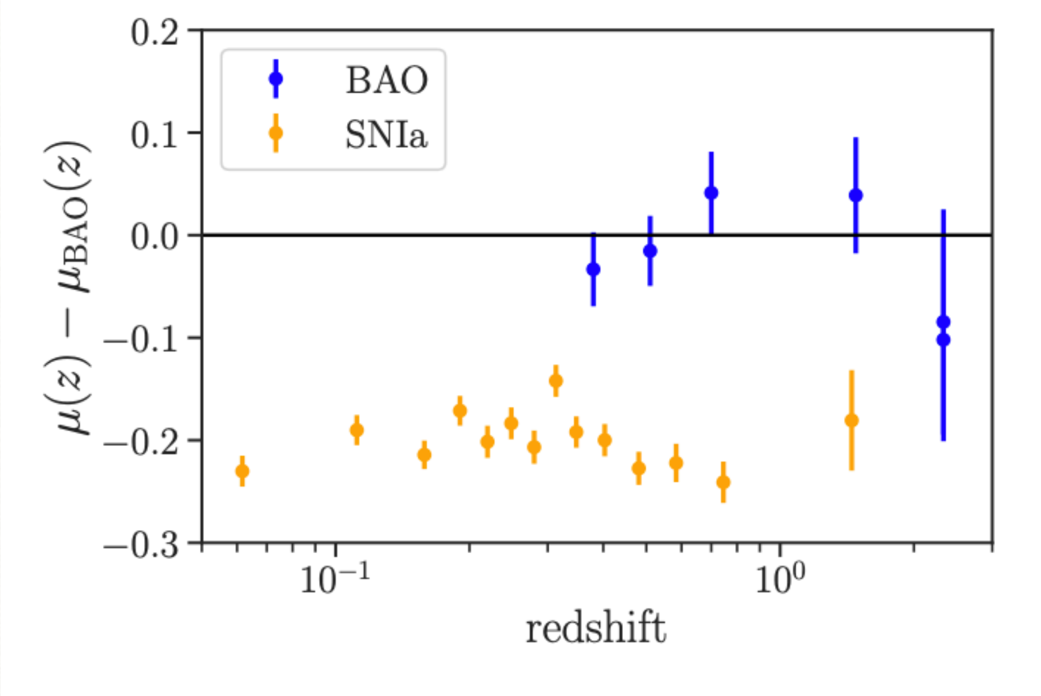


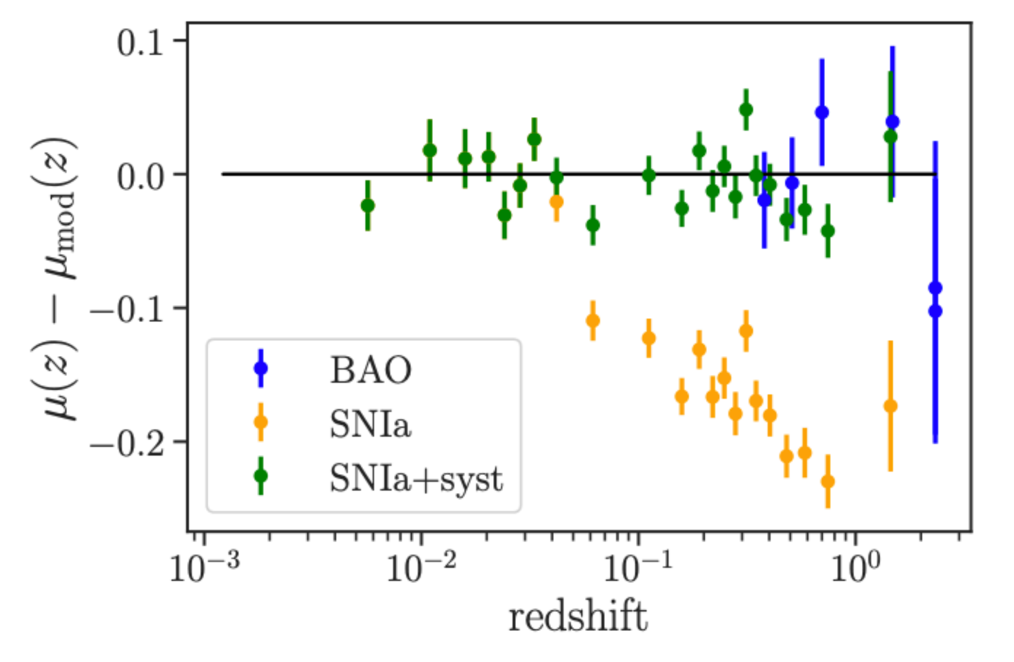
Could the DDR be violated?

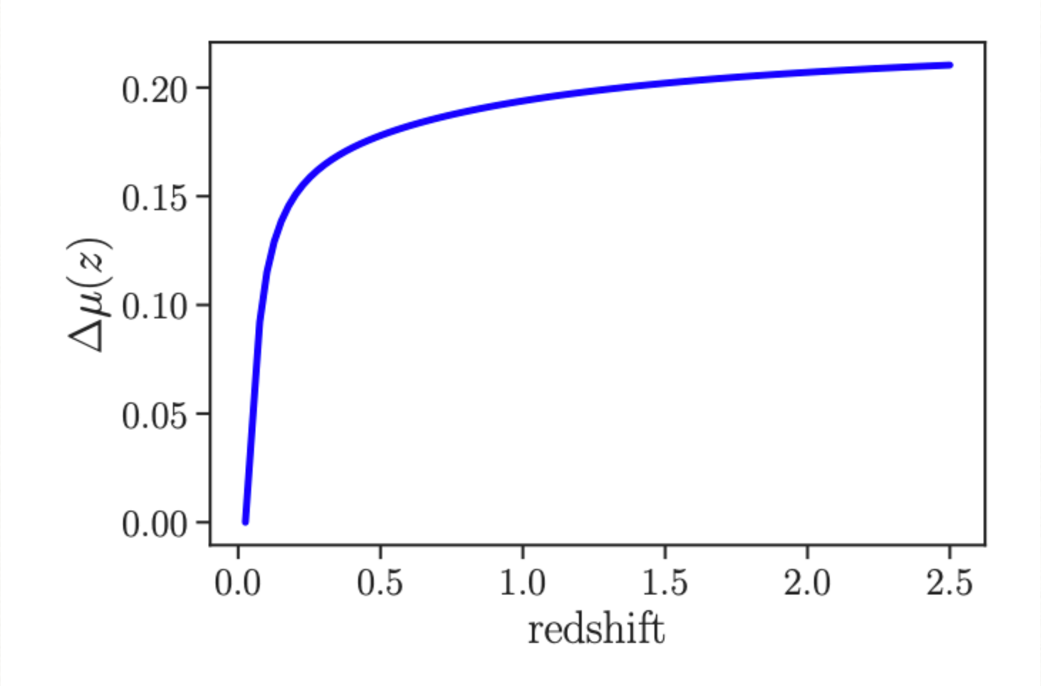
- Photon number not conserved? e.g. “dust” or exotic physics like photon-axion conversion?

Tutusaus++, 2311.16862



=>





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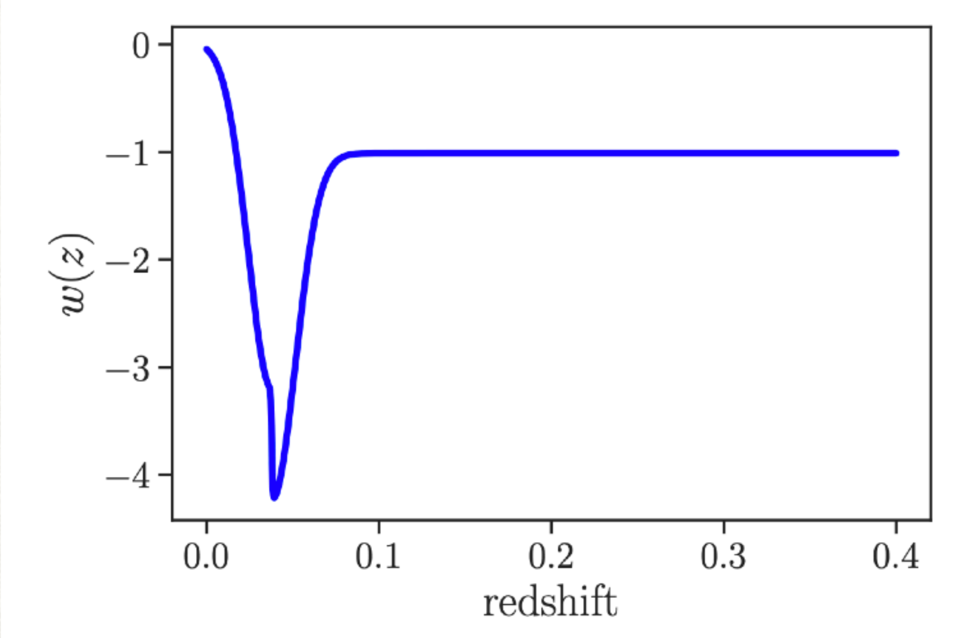
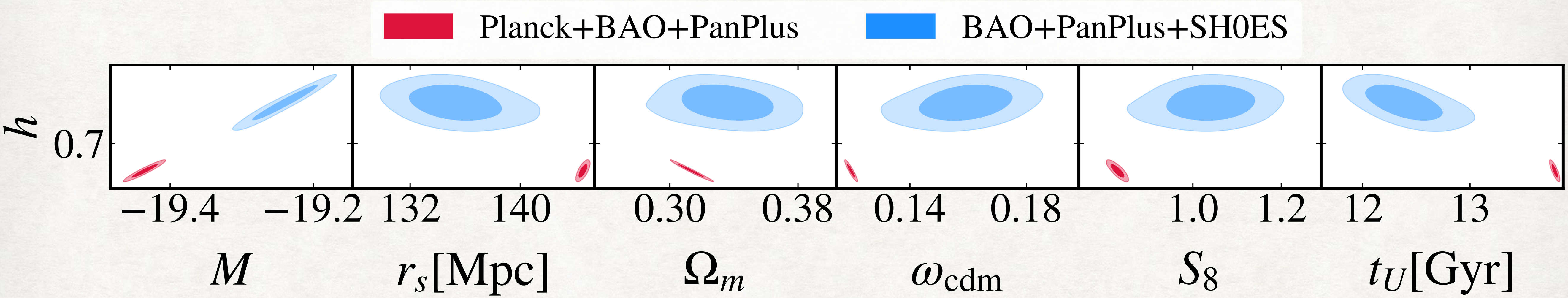


- Possibly, but it would not affect “non-SN1a-based” measurements.

The trouble beyond H_0

Bernal++ 2102.05066, Jedamzik & Pogosian 2010.04158, Vagnozzi 2105.10425



- Decrease r_s by ~ 10 Mpc and compensate for the higher $\omega_{\rm cdm}$ and $S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$

- Since Ω_m and H_0 are unchanged (fixed by late-time) t_U will decrease! Age of the universe tension?

This is model independent as long as late-time dynamics is unchanged

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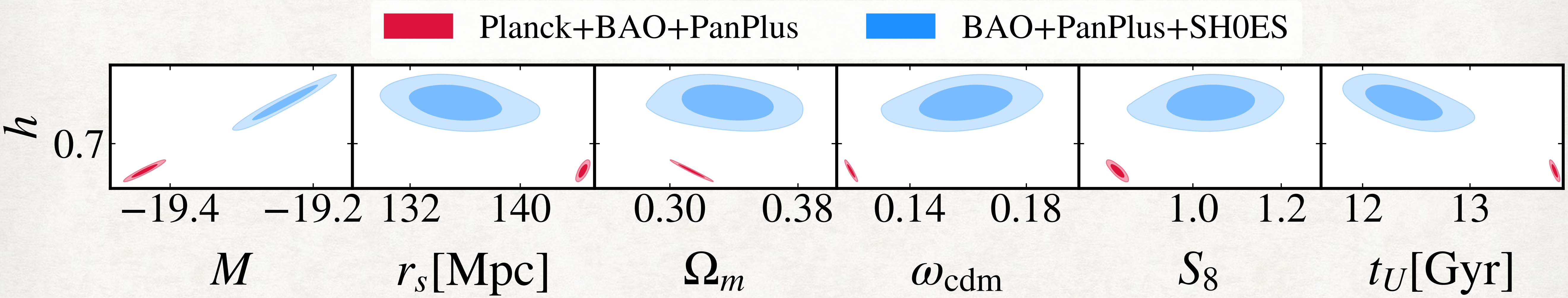

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This is model independent as long as late-time dynamics is unchanged

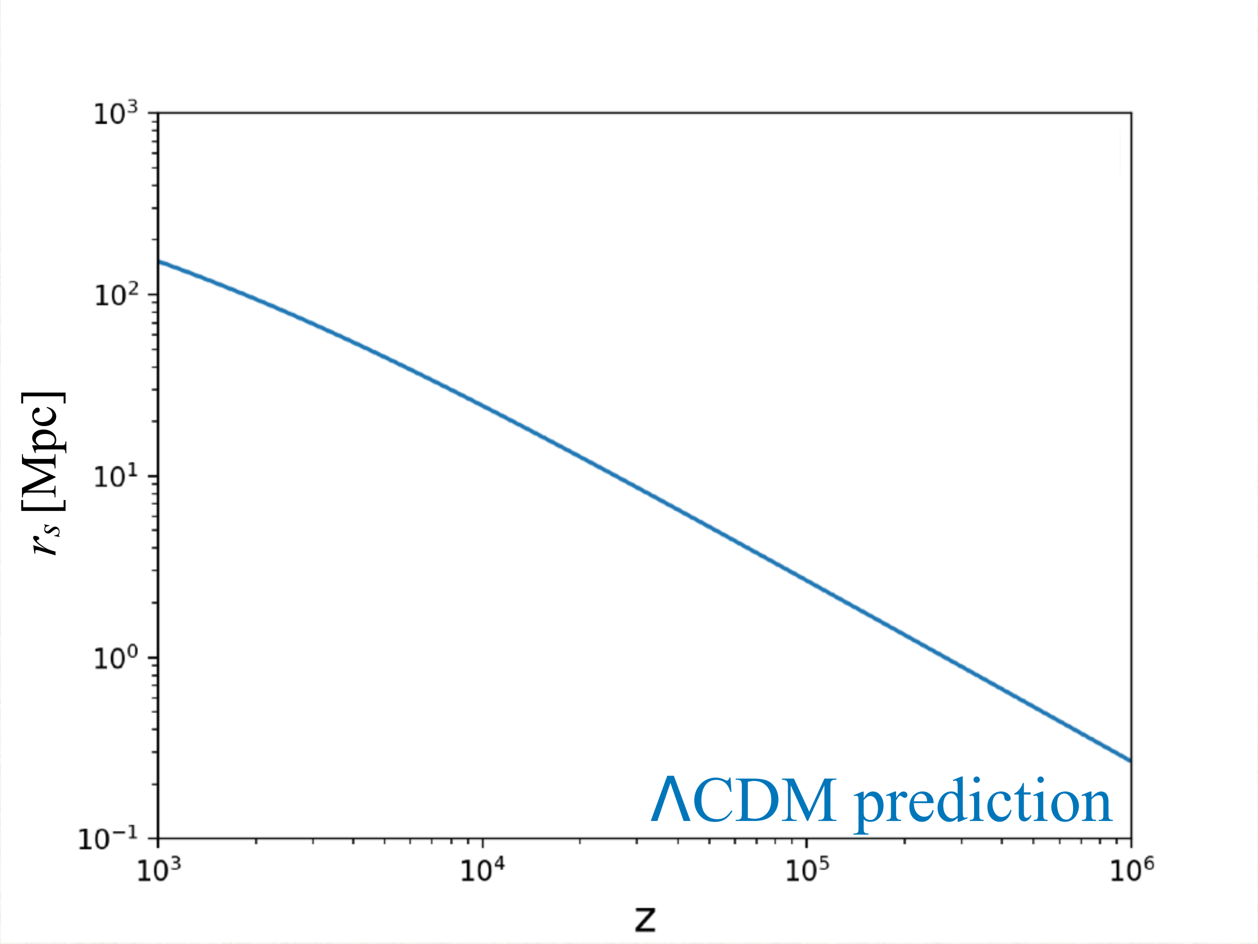
- Question: how to reduce the sound horizon while compensating the impact of a larger $\omega_{\rm cdm}$ on the CMB?

- Hints of $N_{\rm eff}$ or Early Dark Energy?

How to resolve the Hubble tension

- Sound horizon r_s: distance travelled by sound-waves in the plasma until recombination

$$r_s = \int_{\infty}^{z_*} dz \frac{c_s(z)}{8\pi G/3\sqrt{\rho_{\rm tot}(z)}}$$



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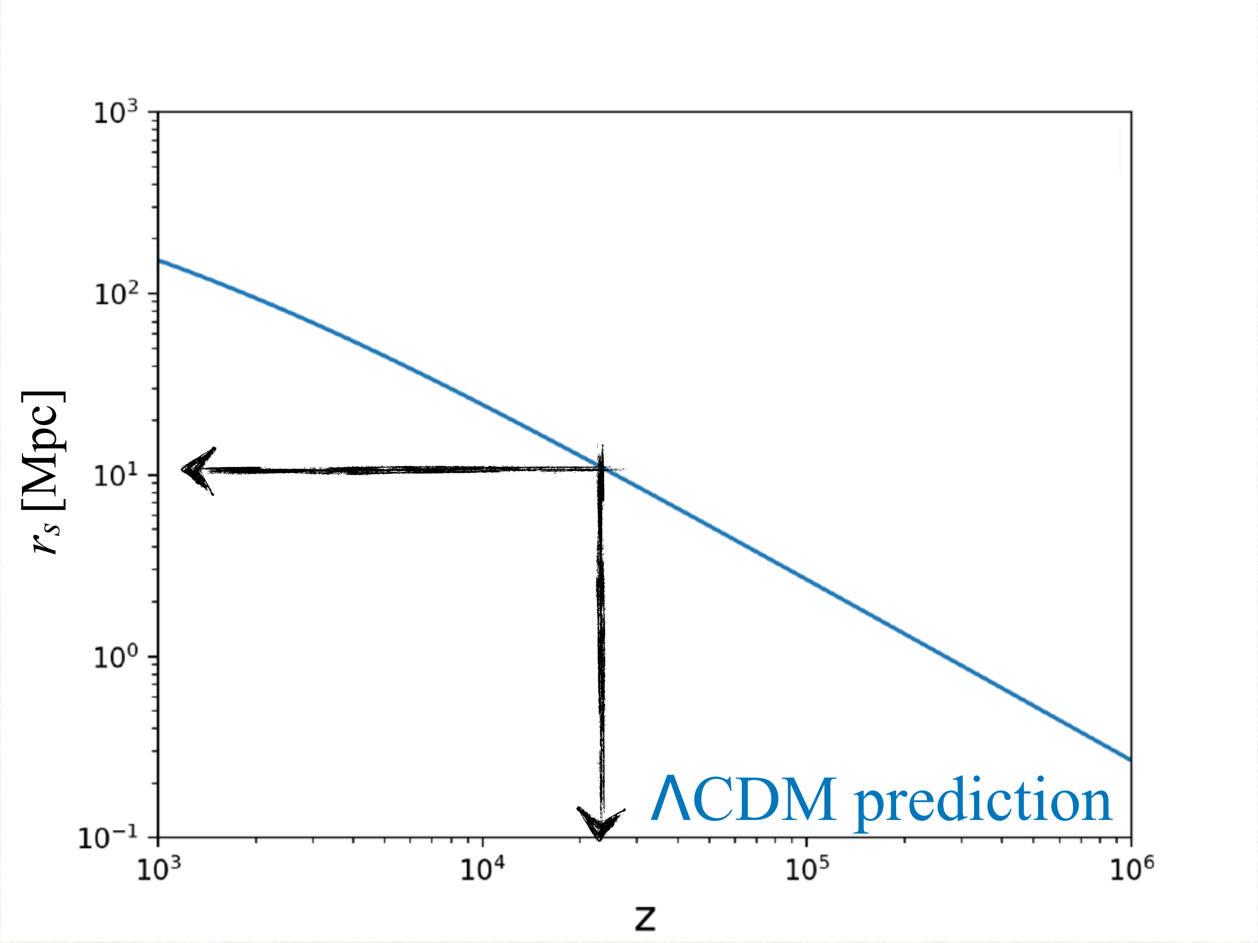

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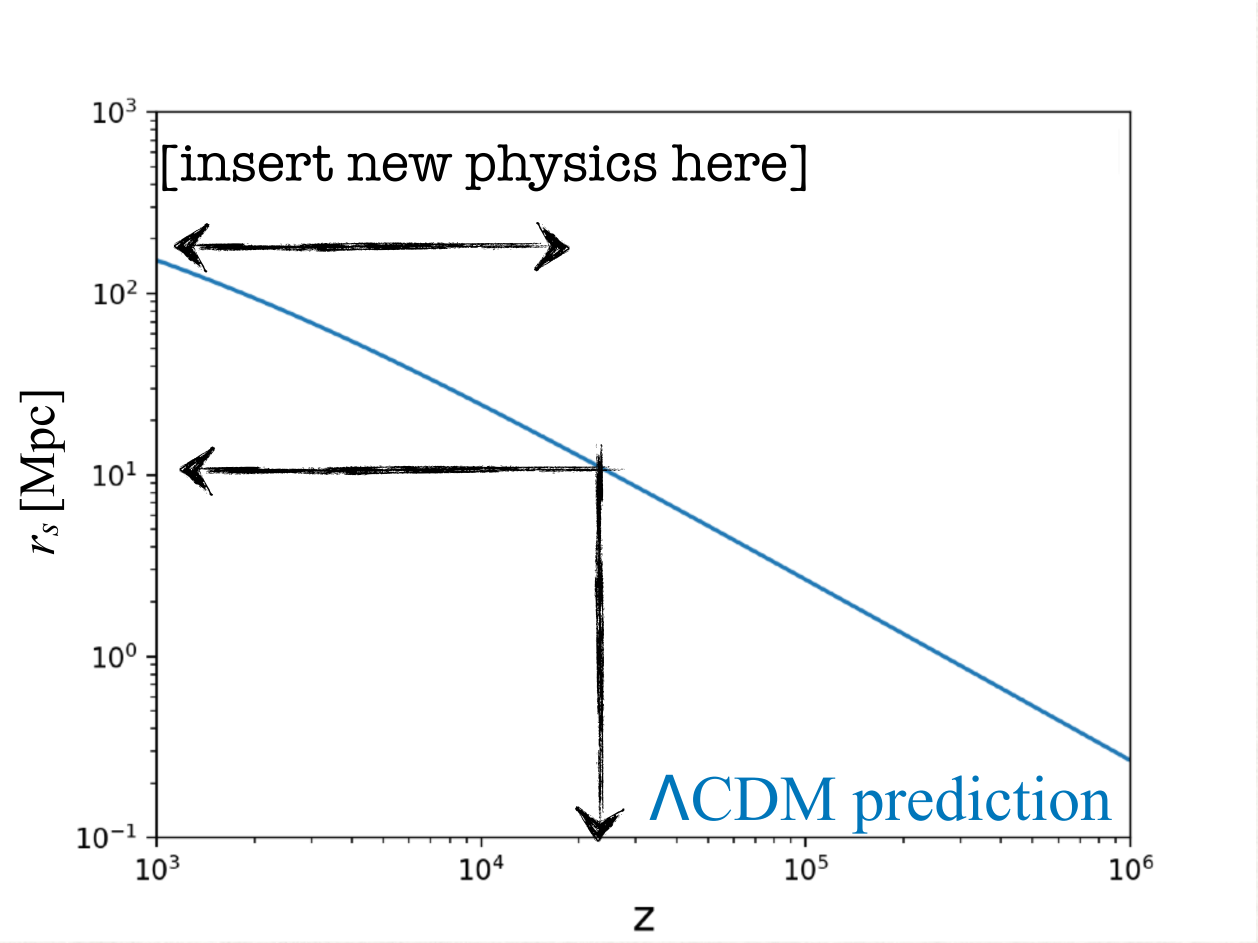

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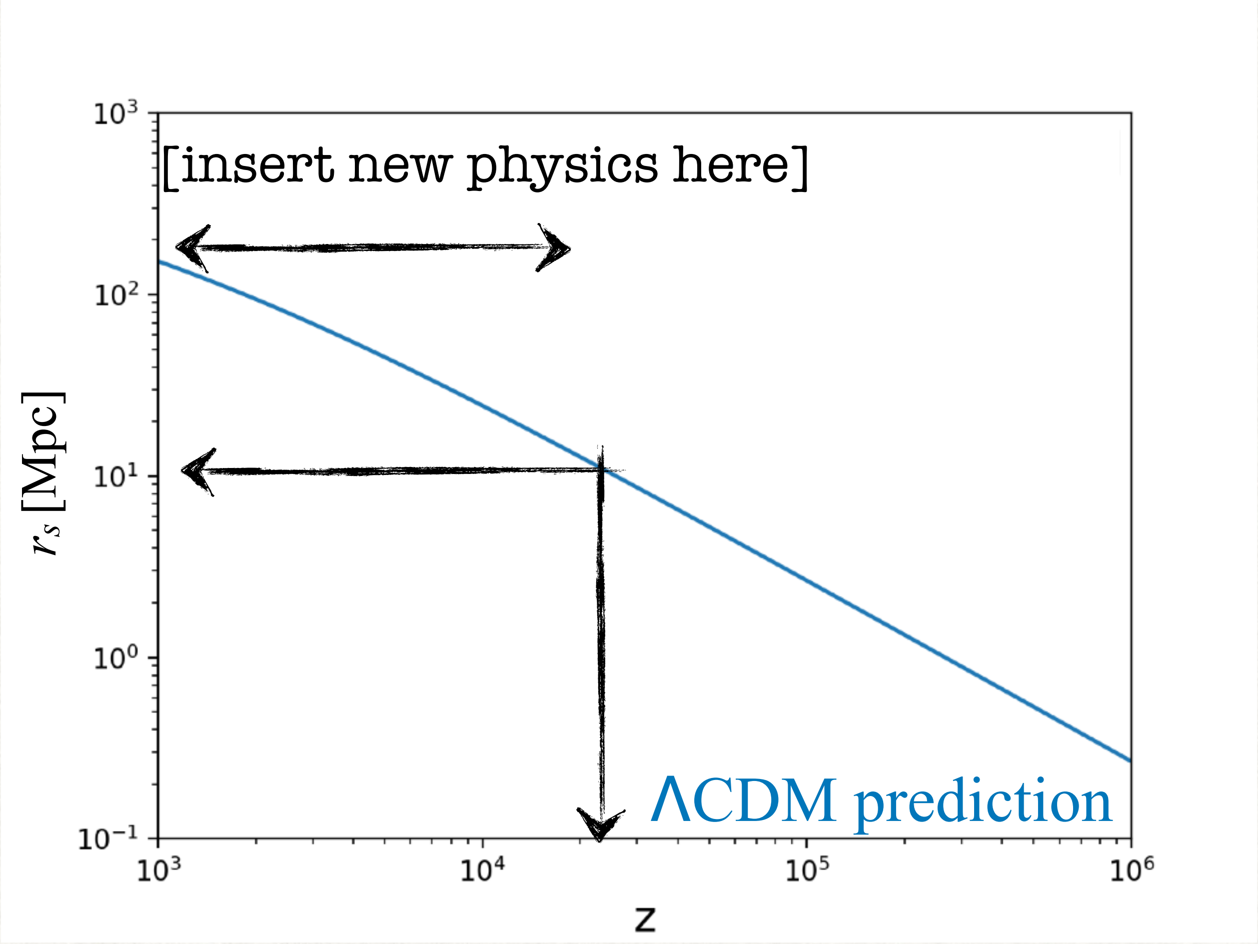

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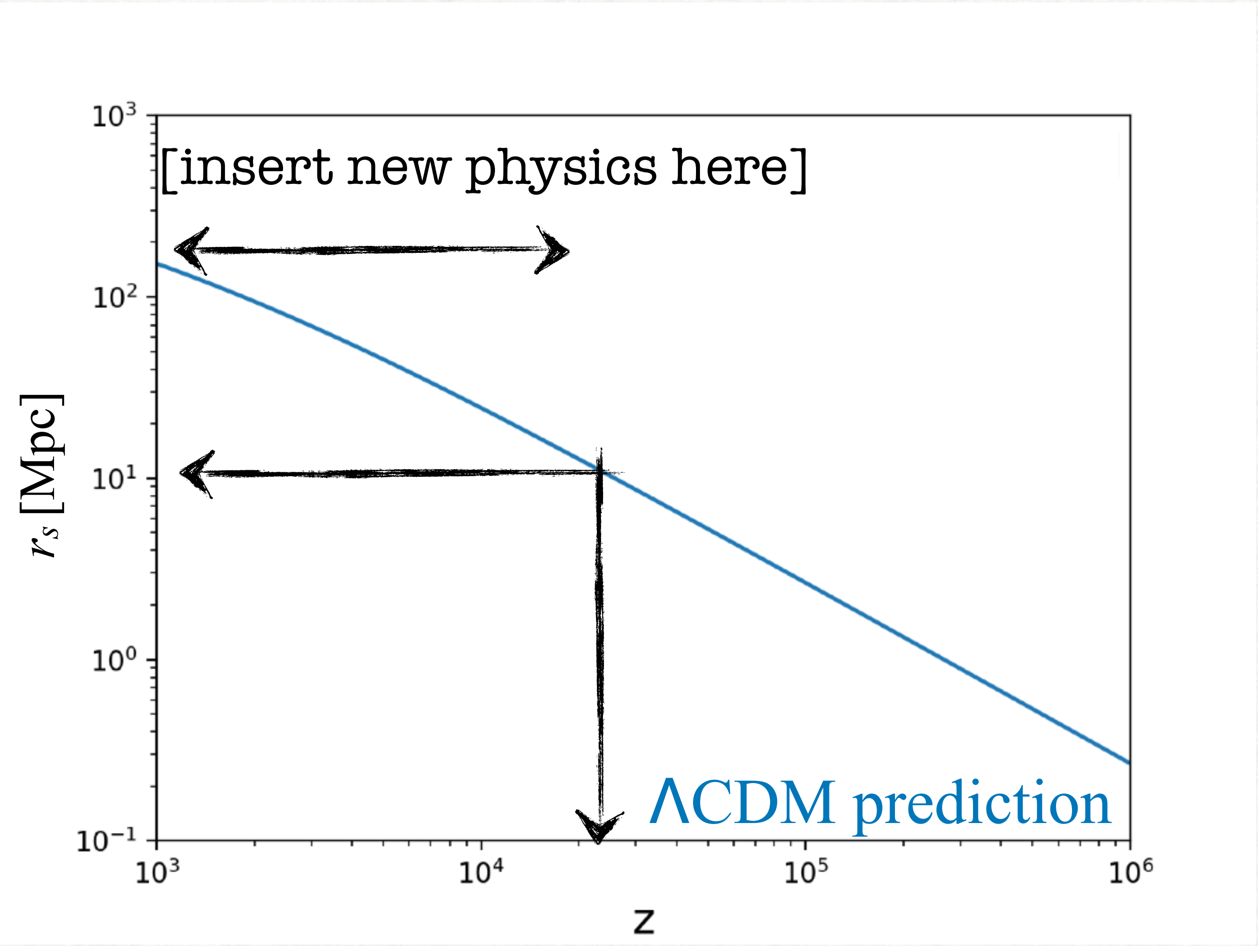

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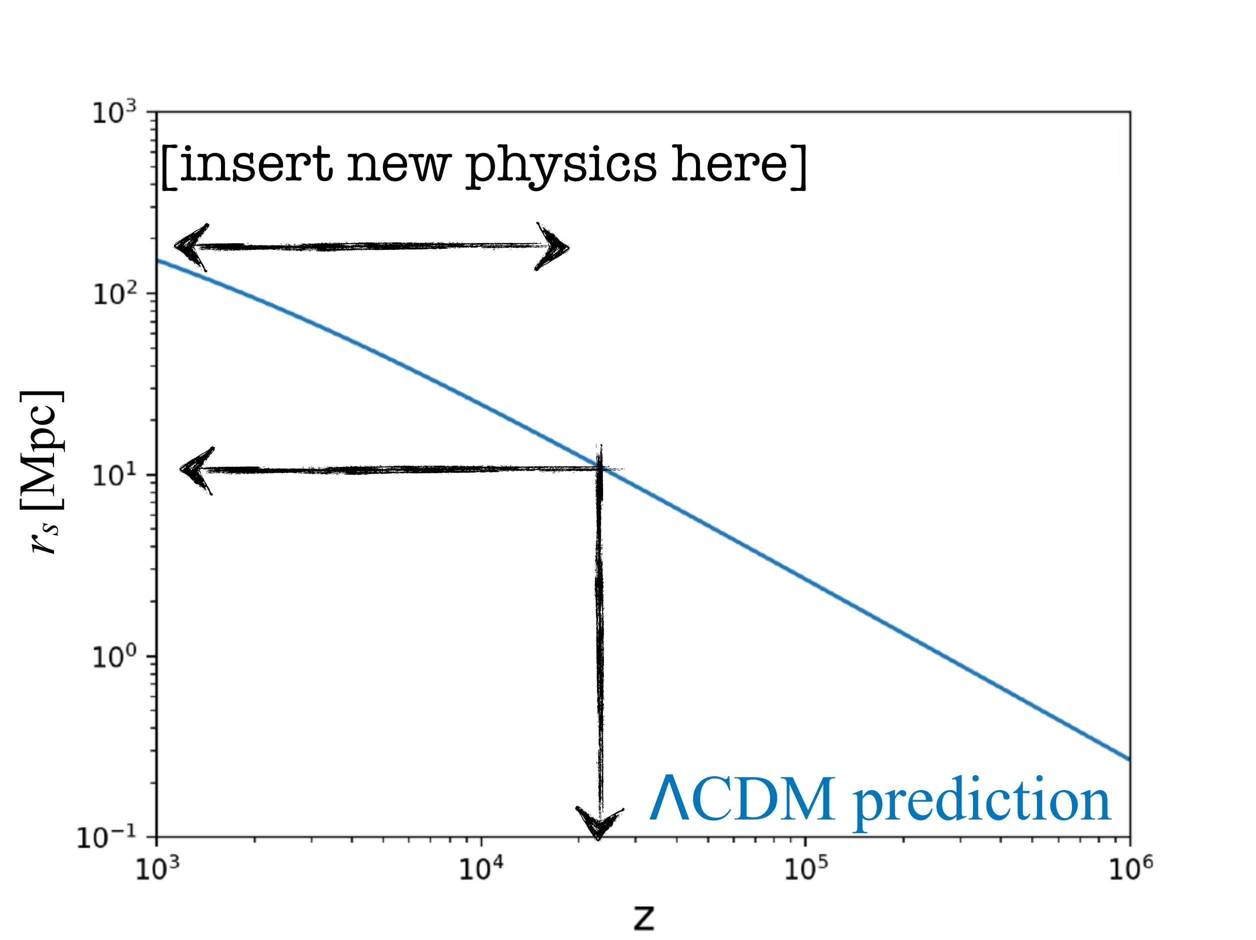
increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?



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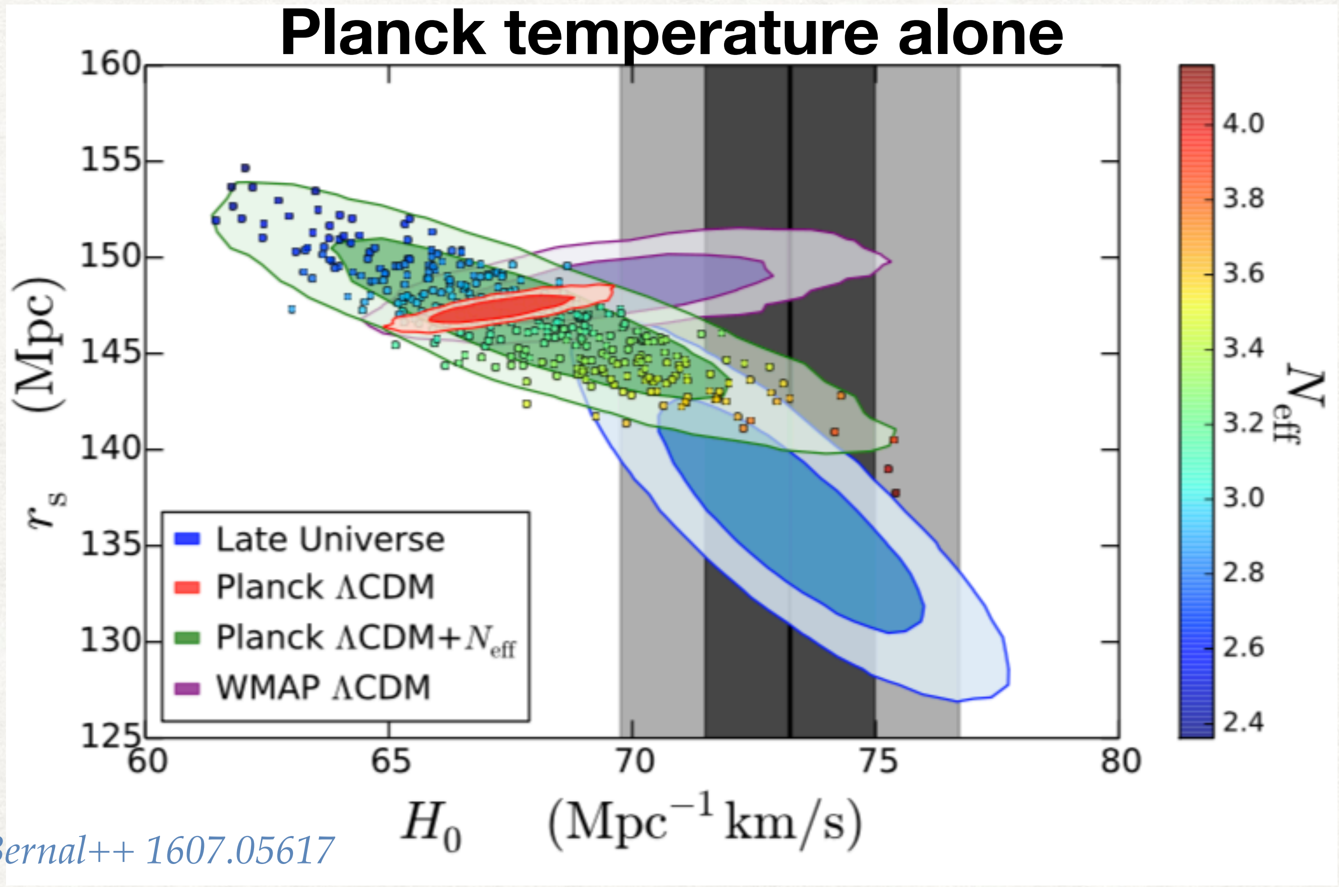
Extra-relativistic degrees of freedom $N_{\rm eff}$

- $\Delta N_{\rm eff}$ (free-streaming) ~$0.5 - 1$ is needed



Bernal++ 1607.05617

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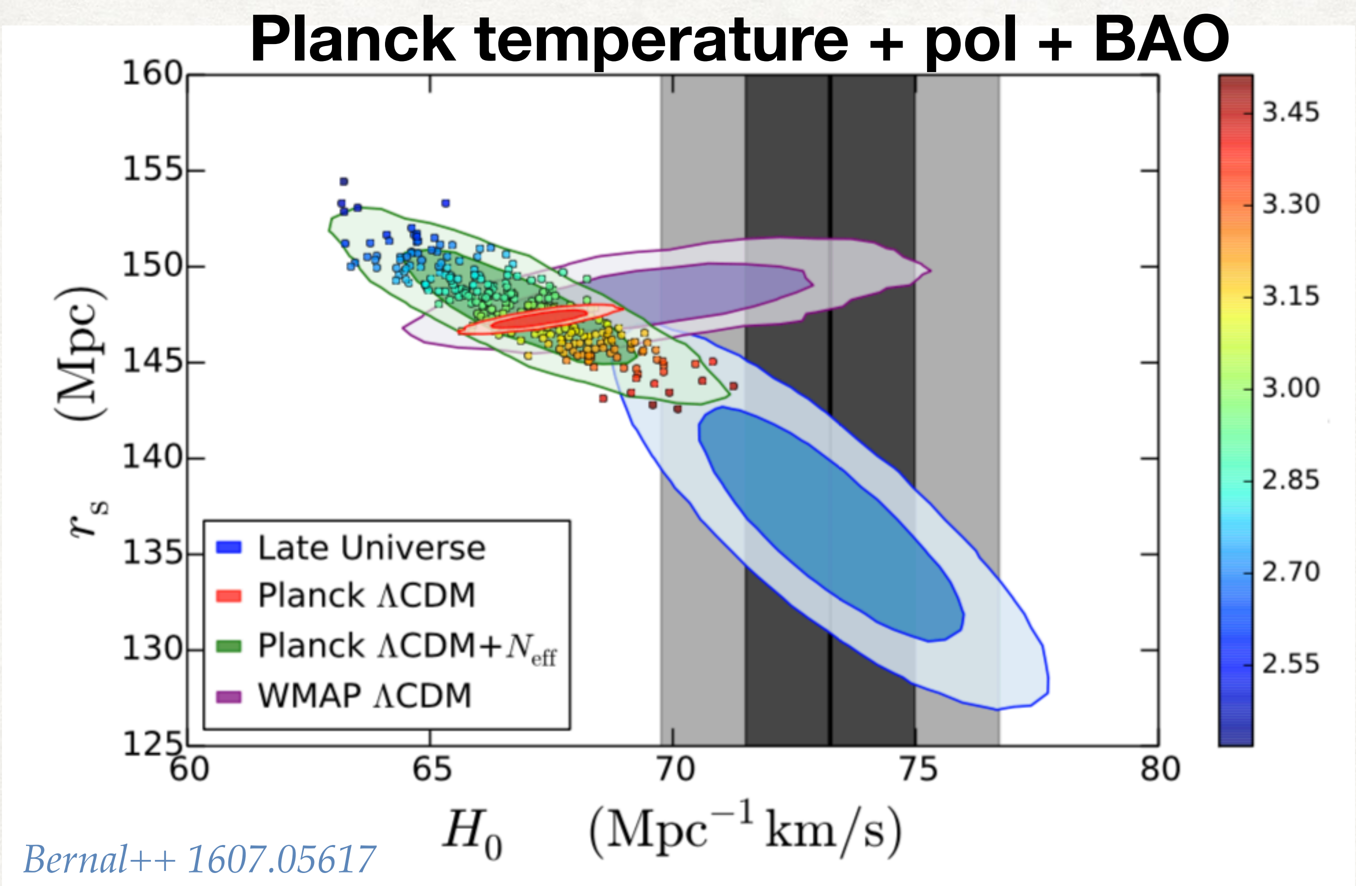

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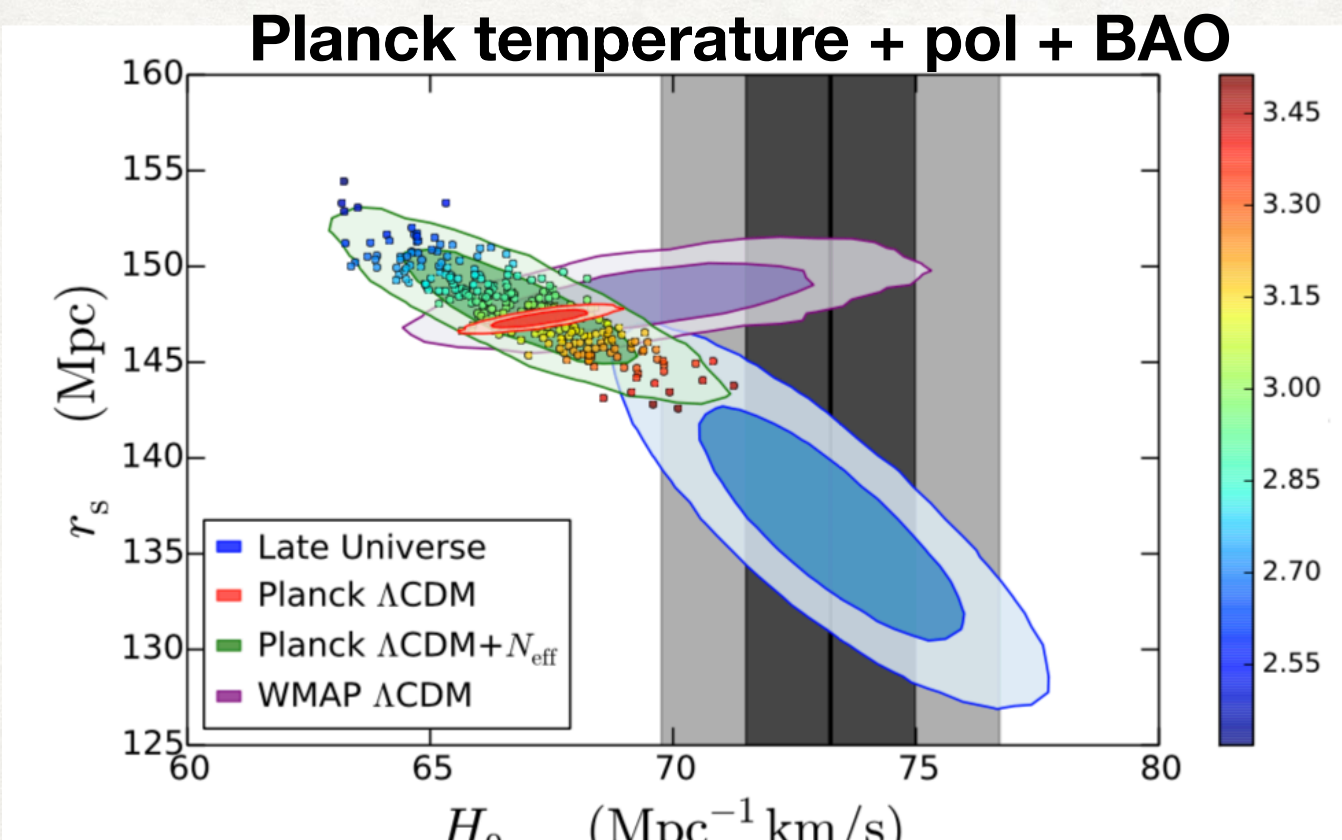

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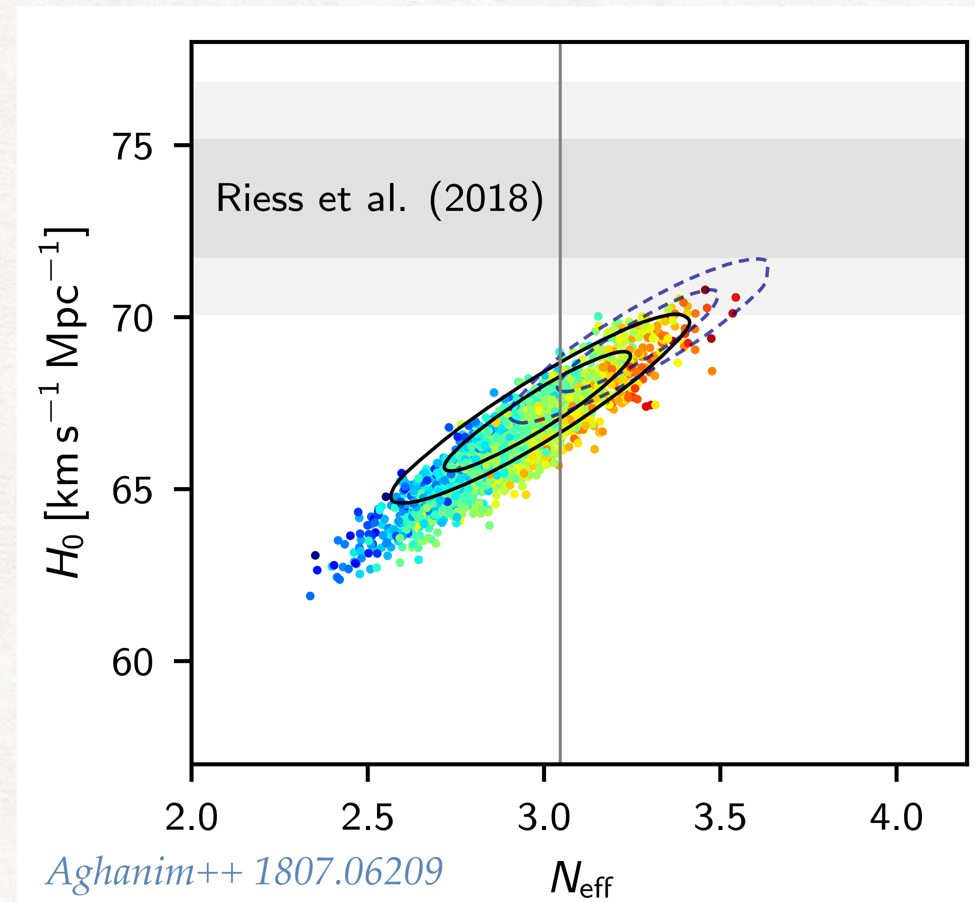

Aghanim++ 1807.06209

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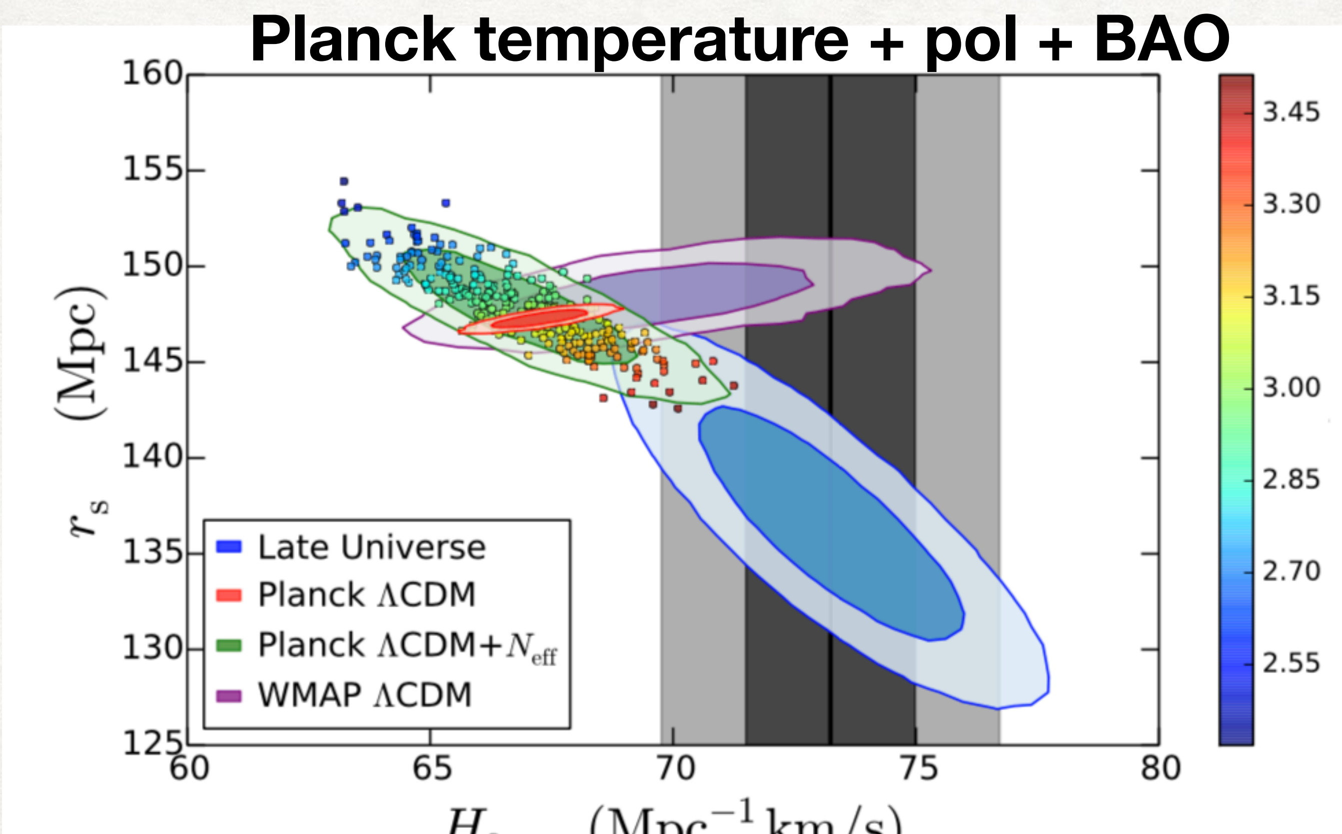
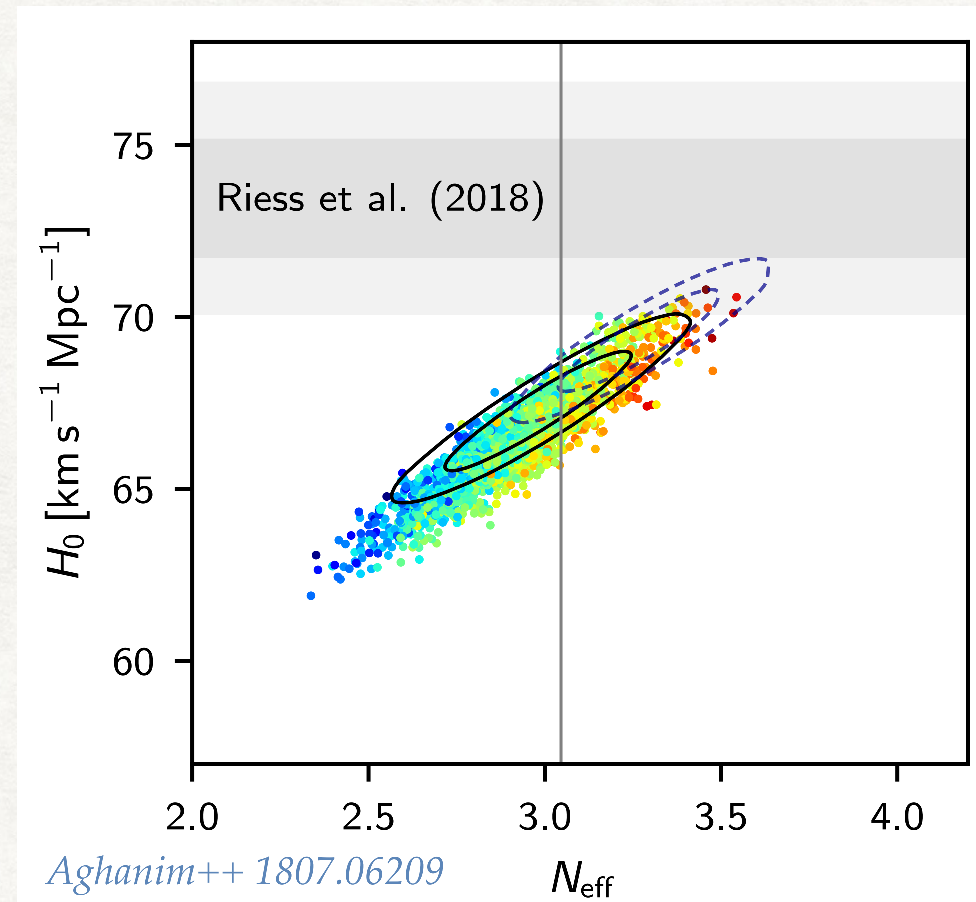


Bernal++ 1607.05617



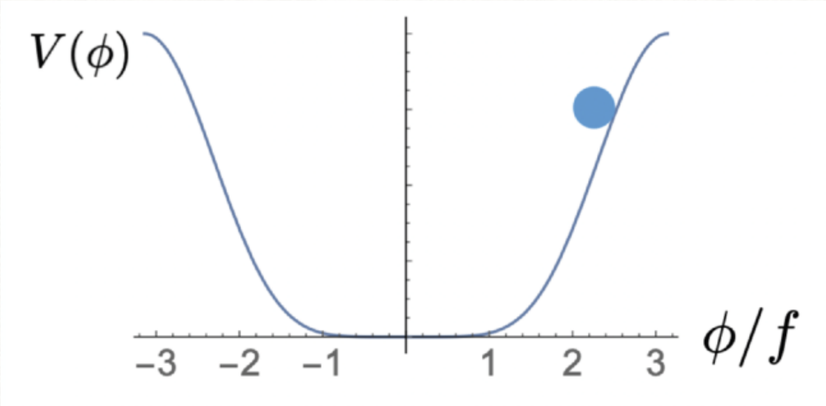
Aghanim++ 1807.06209

- Planck+BAO constrains $N_{\rm eff} = 2.99 \pm 0.17$ and $H_0 = 67.3 \pm 1.1$ km/s/Mpc
- Exotic neutrino interactions cannot help anymore *Camarena&Cyr-Racine 2403.05496*
- => Need for a "localized" energy injection *Aloni++ 2111.00014, Joseph++ 2207.03500, Shöneberg++ 2306.12469*

What is Early Dark Energy?

- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$$



VP++ 1811.04083

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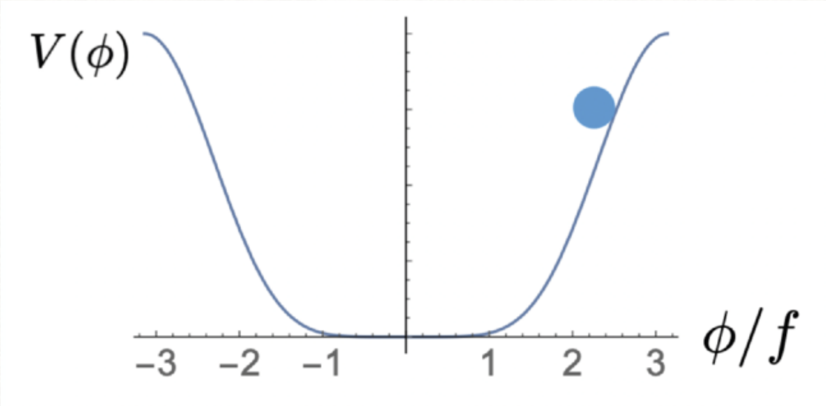

VP++ 1811.04083

- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$

Karwal& Kamionkowski 1608.01309, VP, Smith,Karwal++ 1806.10608 & 1811.04083; Smith, VP++ 1908.06995

- α-attractors: $V(\phi) = f^2 \left[\tanh(\phi/\sqrt{6\alpha}M_{\rm pl})\right]$

Linder 1505.00815, Braglia++ 2005.14053

- Early MG: $(M_{\rm pl}^2 + \xi\phi^2)R + \lambda\phi^4$
  leads to a similar phenomenology if $\xi > 0$

Braglia++ 2011.12934

- First-order phase transition (NEDE model)

Niedermann&Sloth 1910.10739, 2006.06686, 2009.00006, 2112.00770; Freese&Winkler 2102.13655

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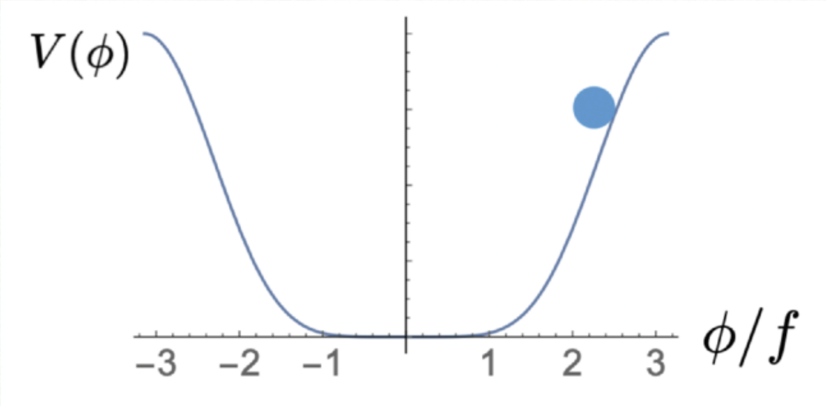

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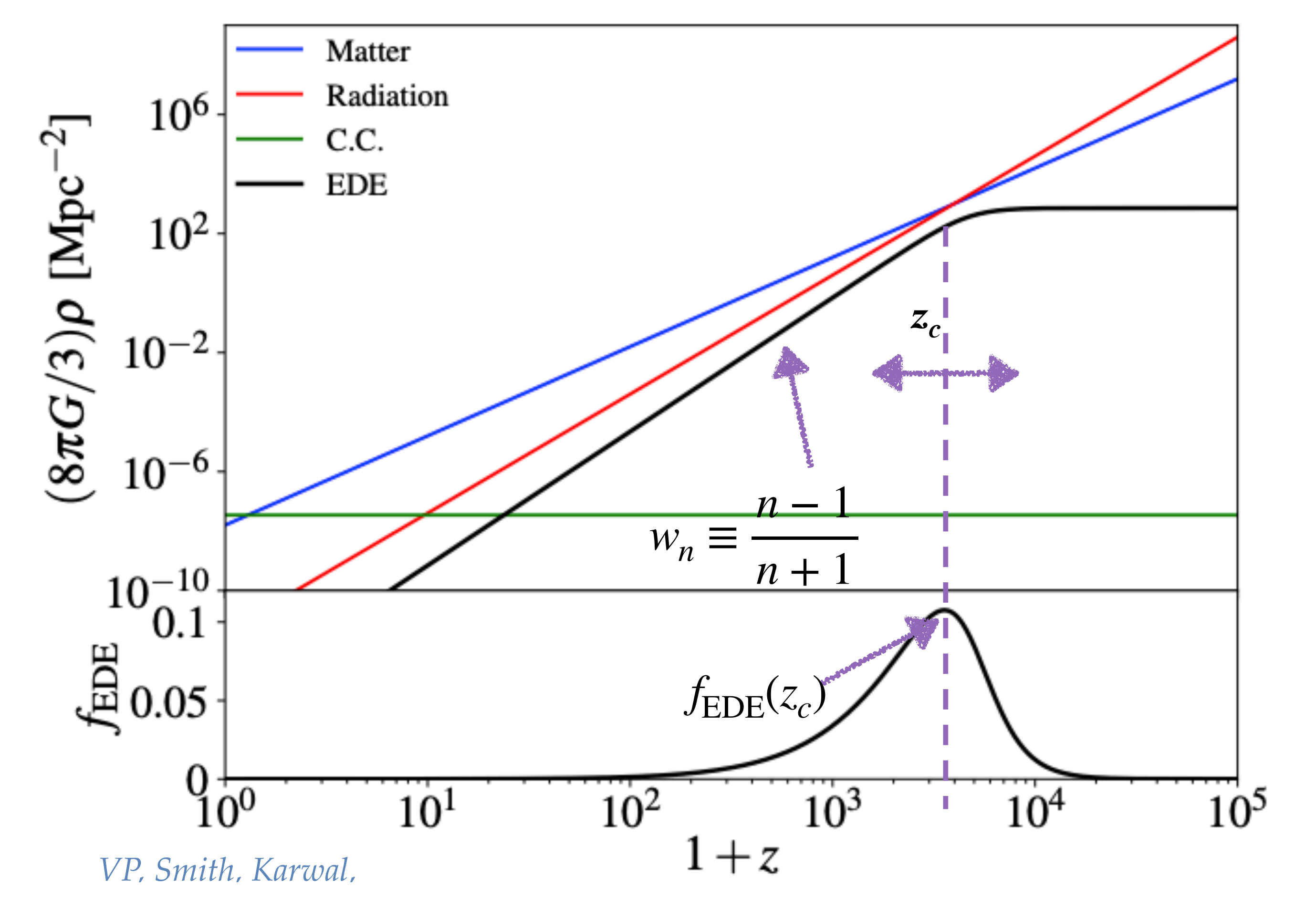
- Specified by $f_{\rm EDE}(z_c)$, z_c, $w(n)$, $c_s^2(k,\tau)$

$$\begin{cases} z > z_c \Rightarrow w_n = -1 \\ z < z_c \Rightarrow w_n = (n-1)/(n+1) \end{cases}$$

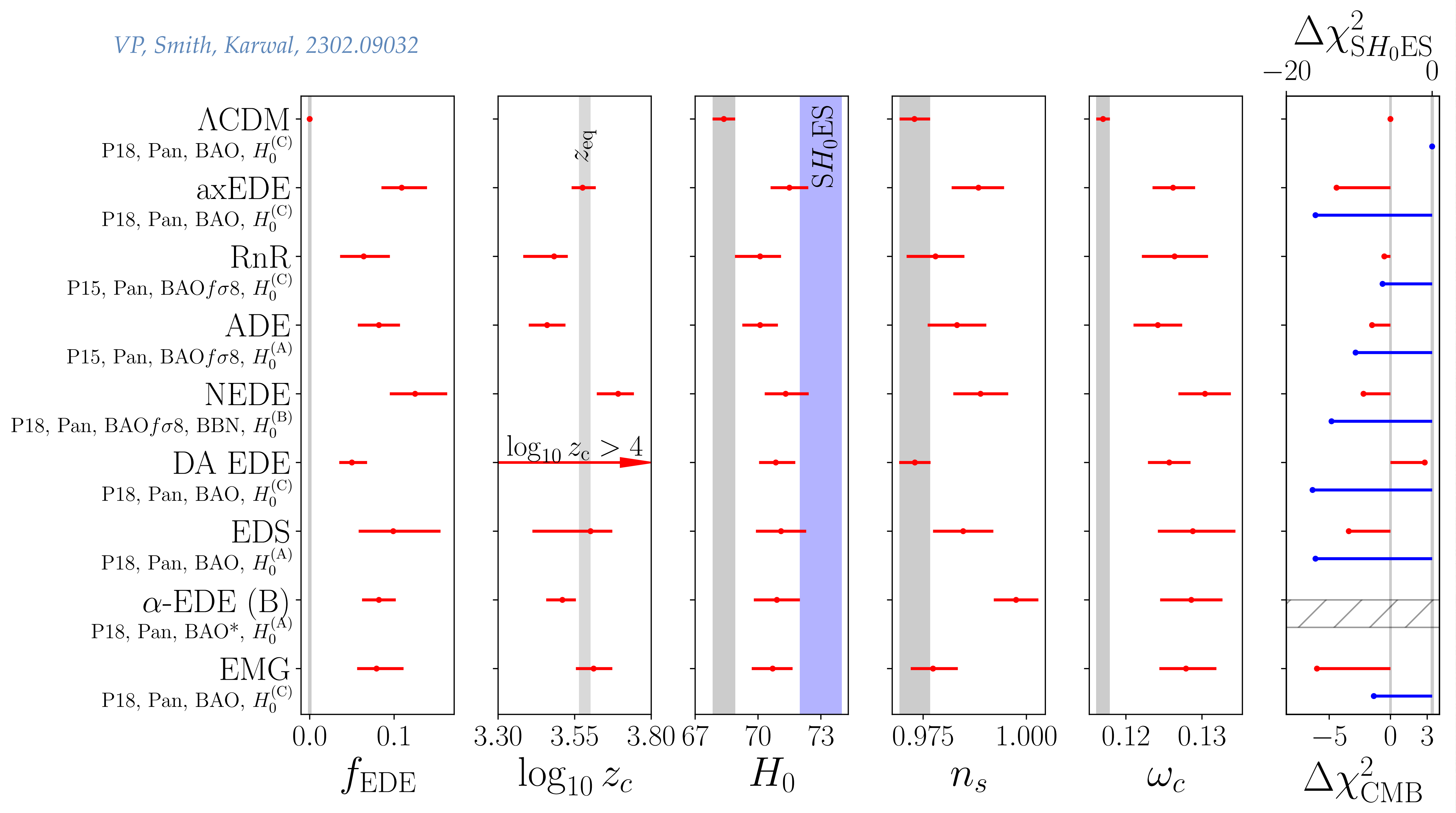
$n = 1$: matter, $n = 2$: radiation, etc.



VP, Smith, Karwal,

Status of EDE solutions with Planck 2018

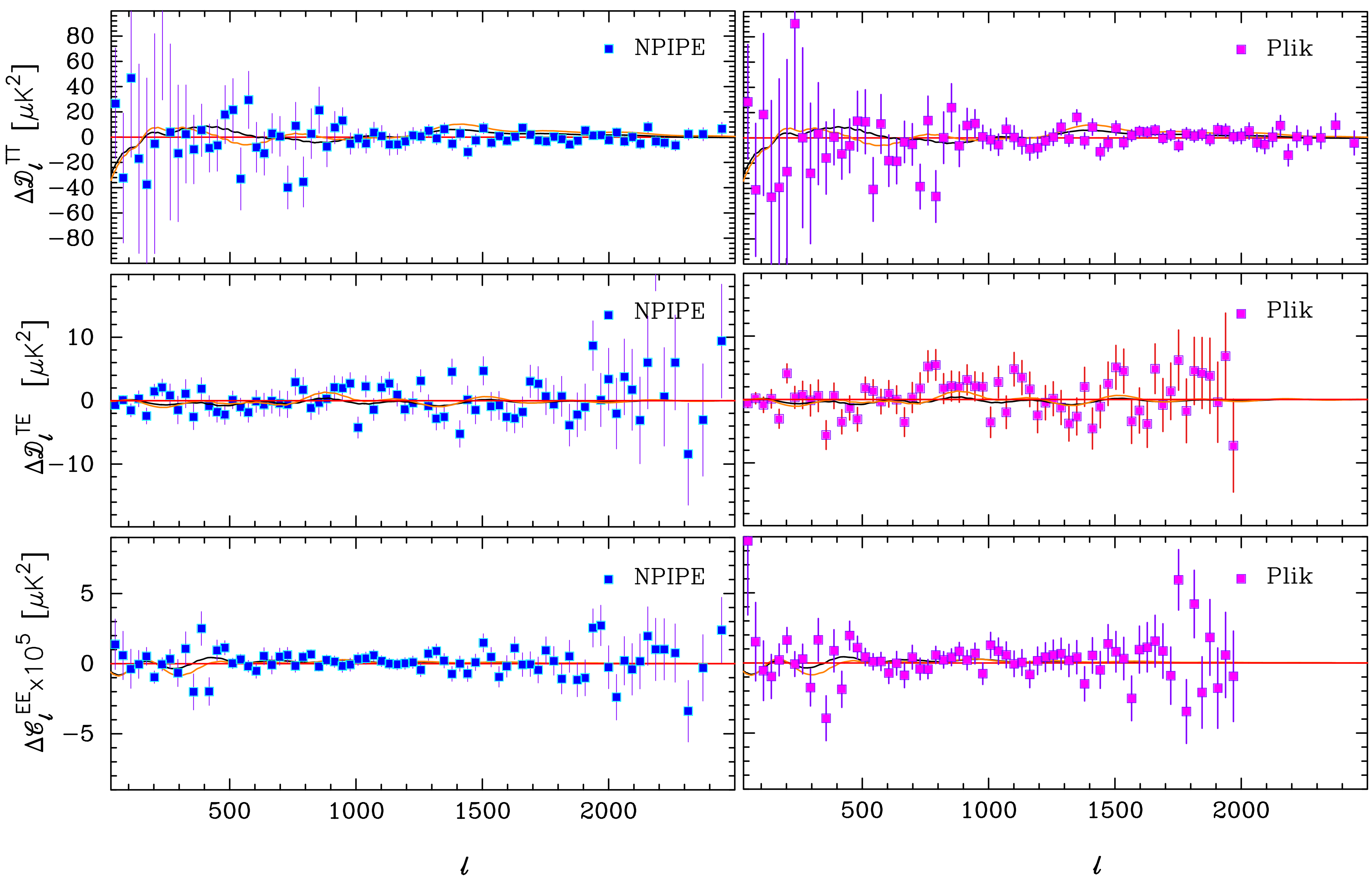
- *Planck* + BAO + Pantheon + SH0ES : a good fit with strong preference over ΛCDM



- Similar background properties although not all models yield the same overall improvement

NPIPE Planck maps can improve constraints on EDE

- New NPIPE maps: 80% sky, $\ell < 2500$, lower noise/systematics — *Planck 2007.04997*
- ~10% precision gain in ΛCDM, no $A_{\rm lens}$ anomaly — *Rosenberg++ 2205.10869, Tristram++ 2309.10034*



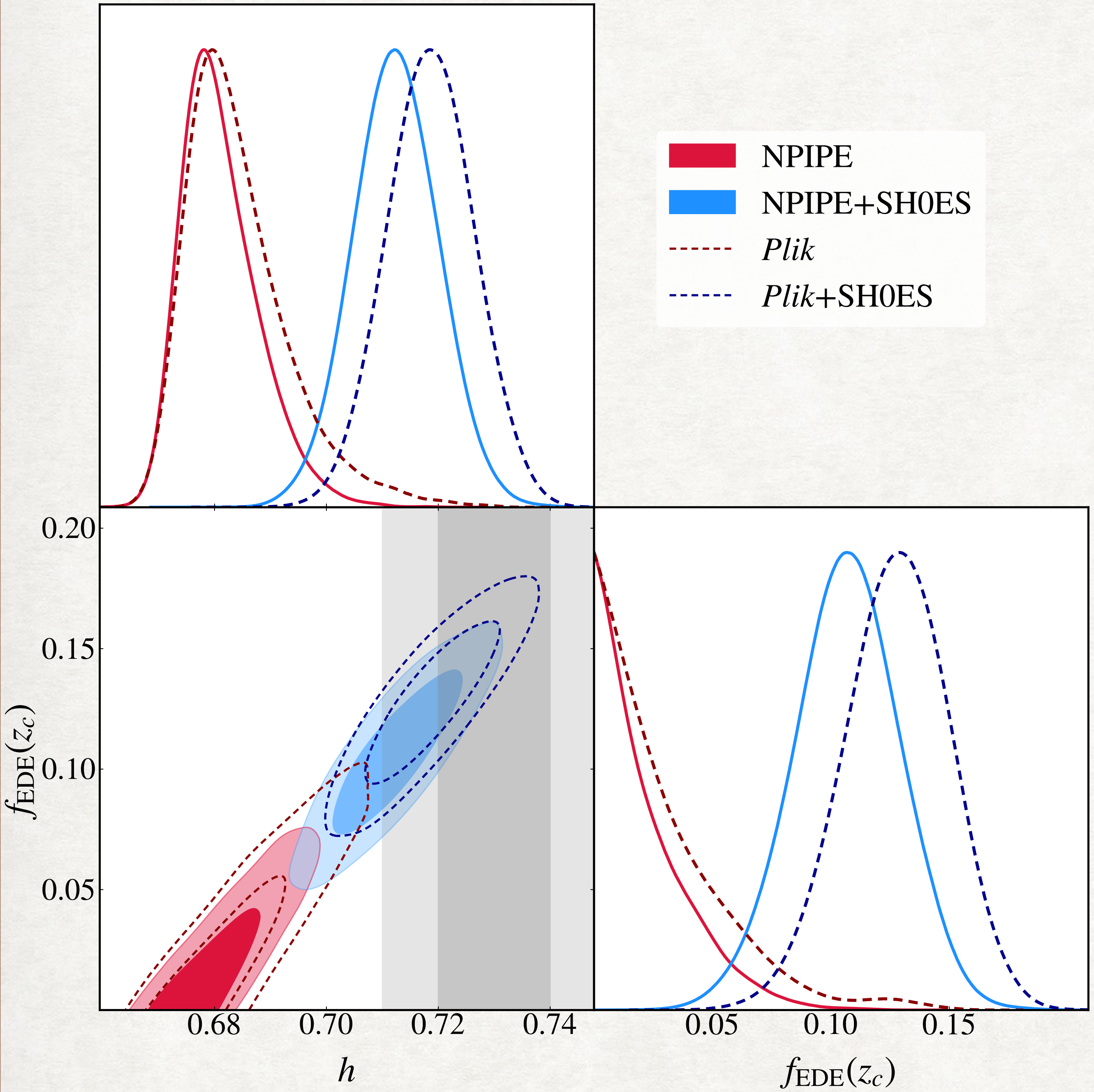
Efstathiou, Rosenberg, VP 2311.00524

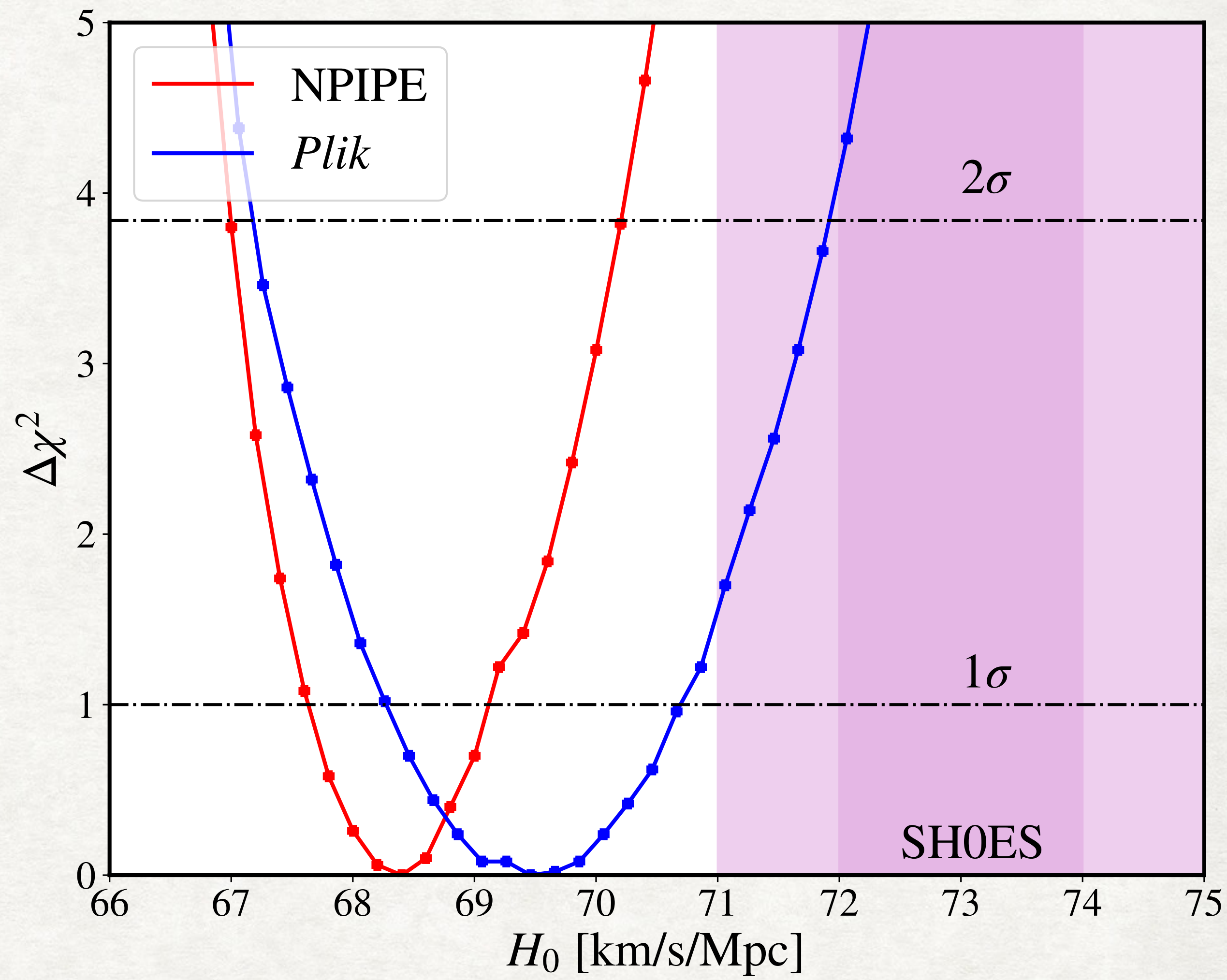
See also Calderón++ 2302.14300

Updated constraints from CamSpec NPIPE 2020

- Residual tension now exceeds 3.5σ: the axion-like EDE is now severely constrained.

Efstathiou, Rosenberg, VP 2311.00524





- This does NOT mean that all EDE models are excluded!
  ==> Need to test better theoretically motivated potentials or model-independent reconstructions of the potential.

ModIC: the way forward… but not new

Samsing, Linder, Smith 1208.4845

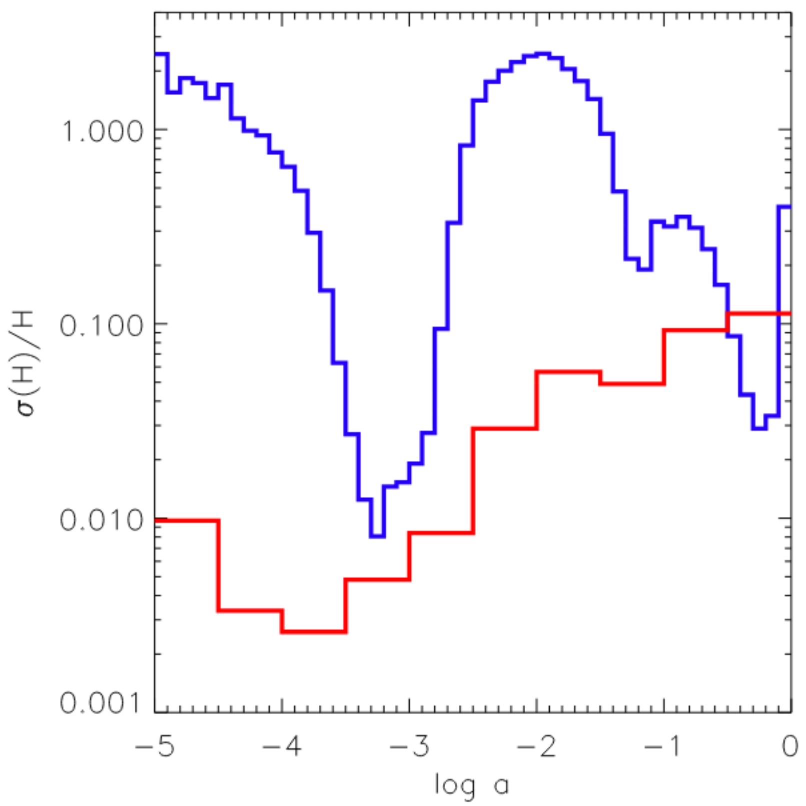


FIG. 4. The fractional precision with which the expansion history can be determined by projected Planck CMB data is plotted vs scale factor, for two different bandwidths. The top (bottom) curve is for 10 (2) bins per decade in scale factor. Subpercent precision can be achieved around decoupling but large swaths of the cosmic history will remain unknown.

Hojjati, Linder, Samsing 1304.3724

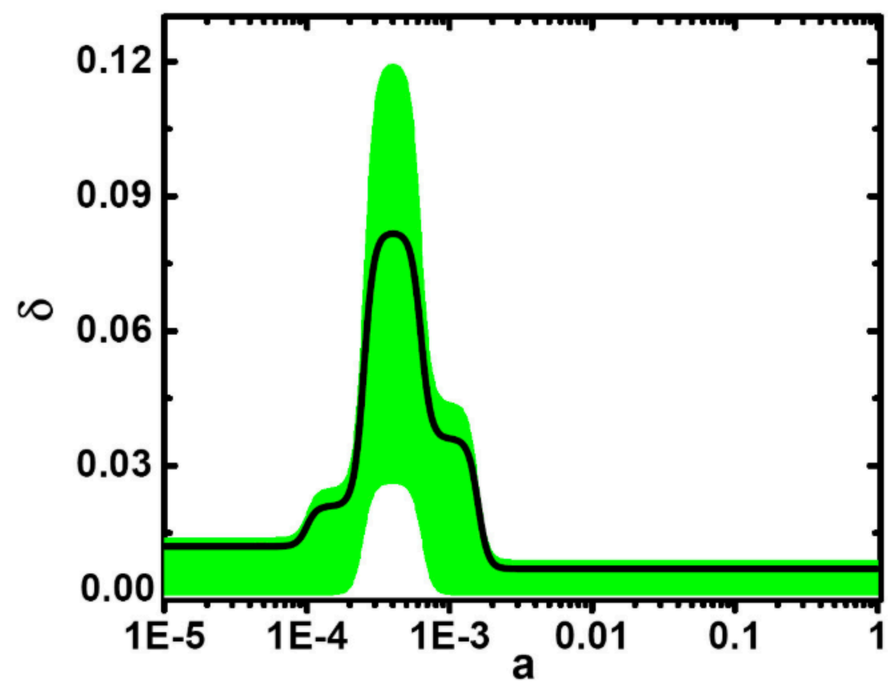
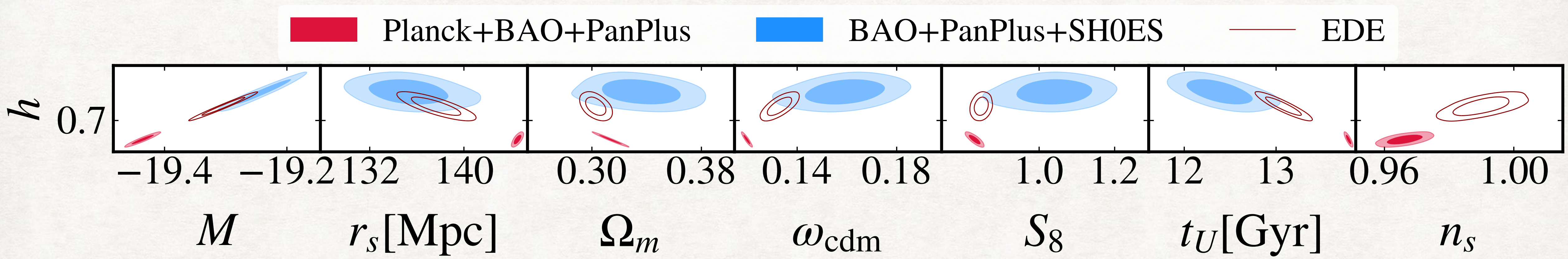


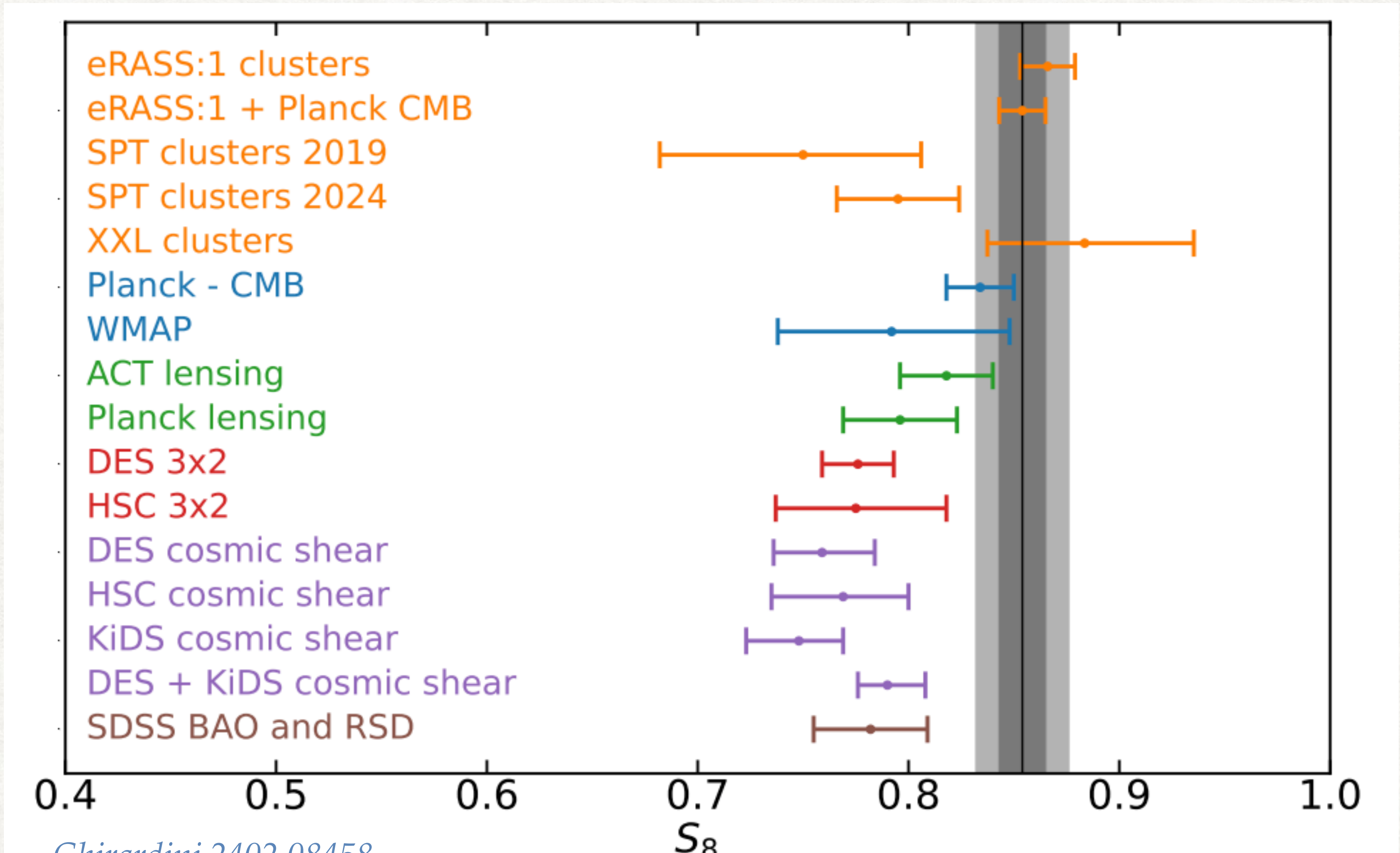
FIG. 3. Reconstruction of the expansion history deviations $\delta(a)$ from ΛCDM is shown, with the mean value (solid line) and 68% uncertainty band (shaded area).

- Already attempts at reconstruction of the early expansion history showing hints of deviations!
- Need to go beyond “background-only” approach

The Hubble tension makes the S_8 tension worse

Hill et al. 2003.07355, Ivanov++ 2006.11235 , d'Amico++ 2006.12420

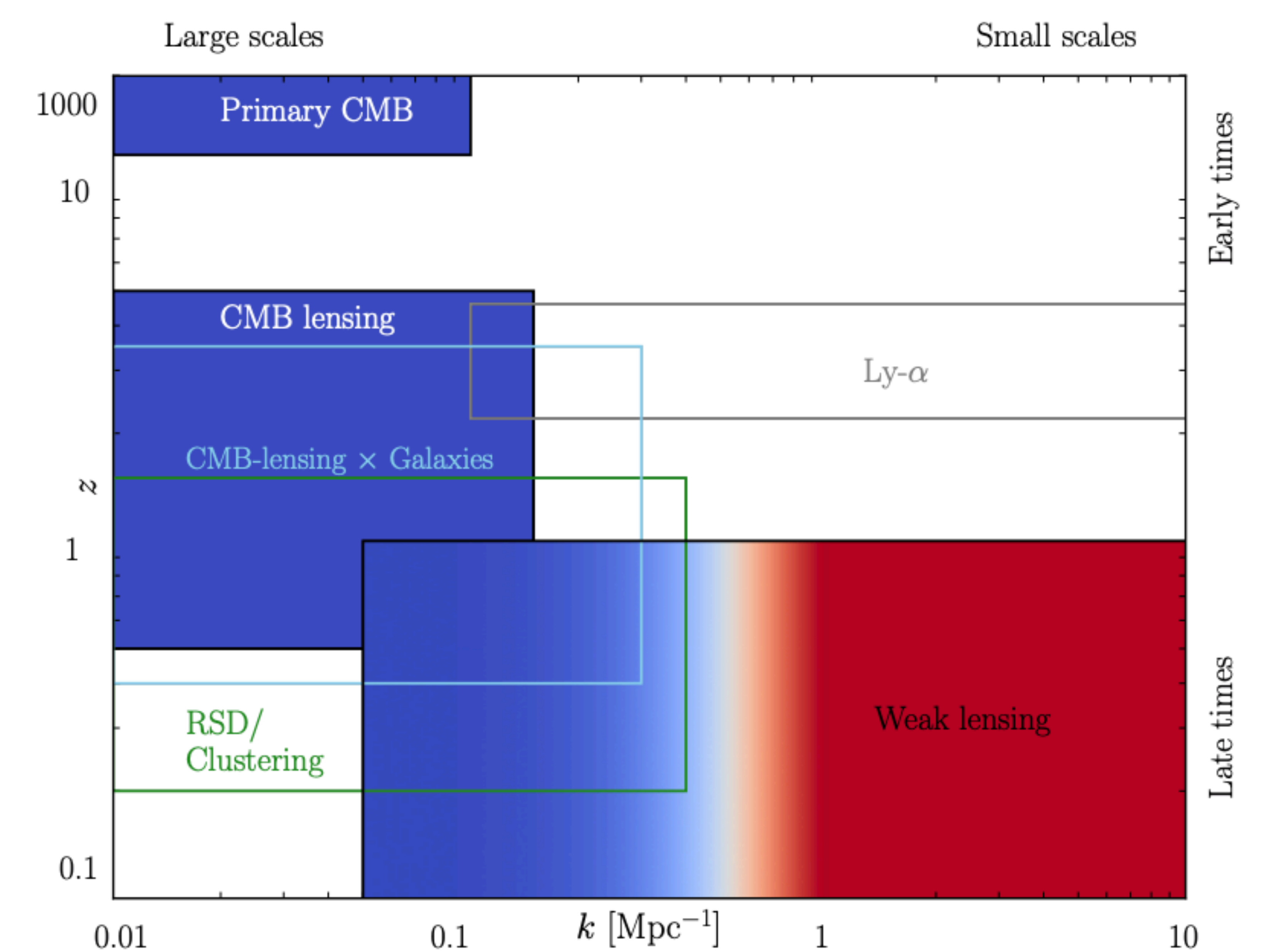




Ghirardini 2402.08458

- If no systematic in WL surveys, the low S_8 measurements constrain solutions to H_0 tension

How to resolve the tension about the S_8 tension



Preston++ 2305.09827

Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

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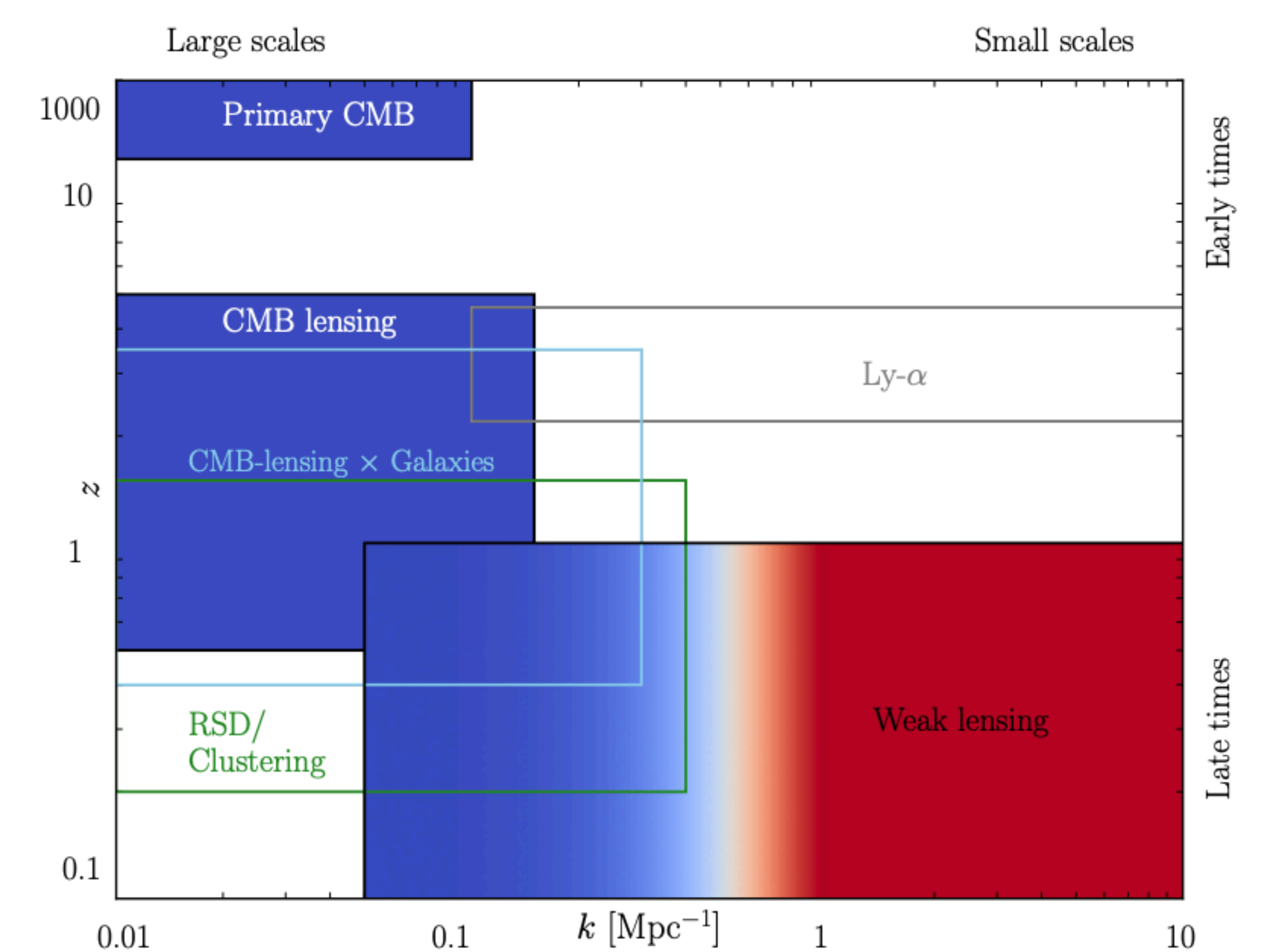


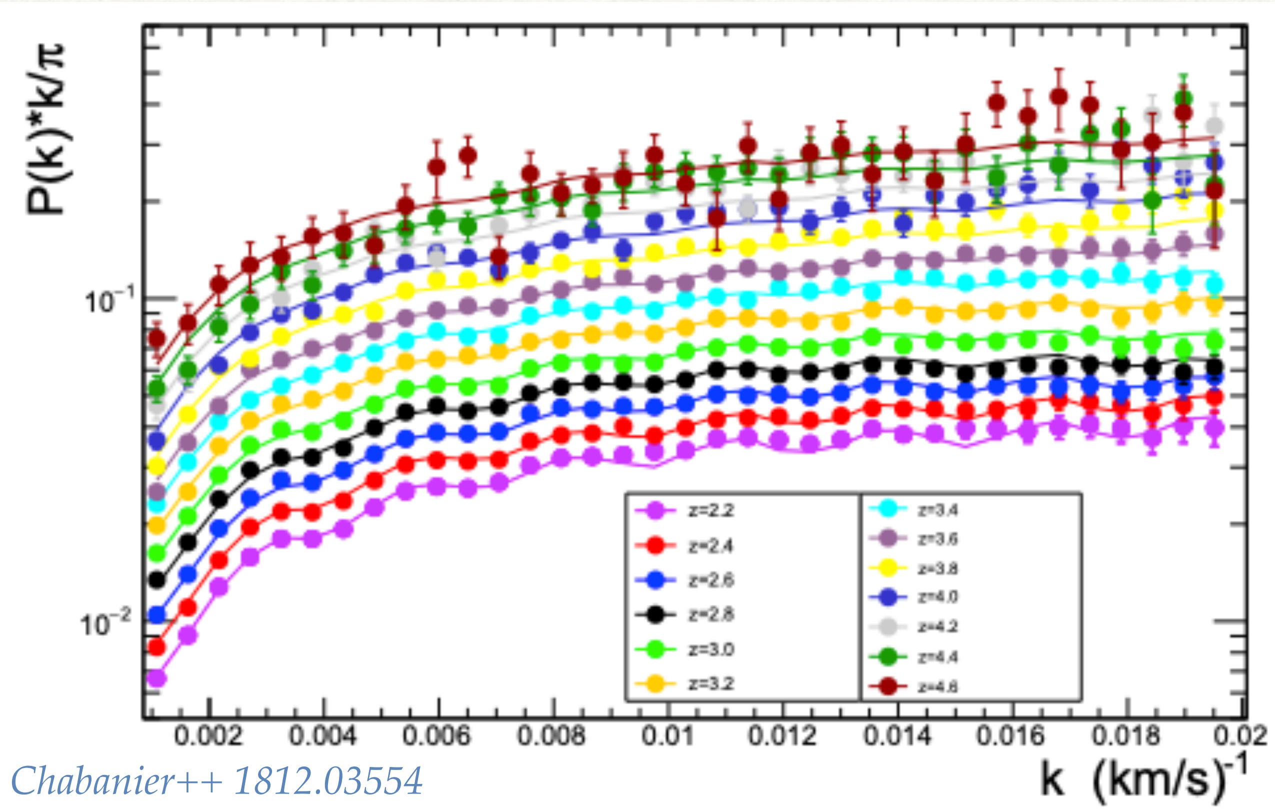
Preston++ 2305.09827

- KIDS/DES measure smaller scales than eROSITA! Power suppression at $k \gtrsim 0.5$ h/Mpc?
- Lyman-α data also favor (strongly) a power suppression at $z \sim 3$ and $k \sim 0.7$ Mpc $^{-1}$

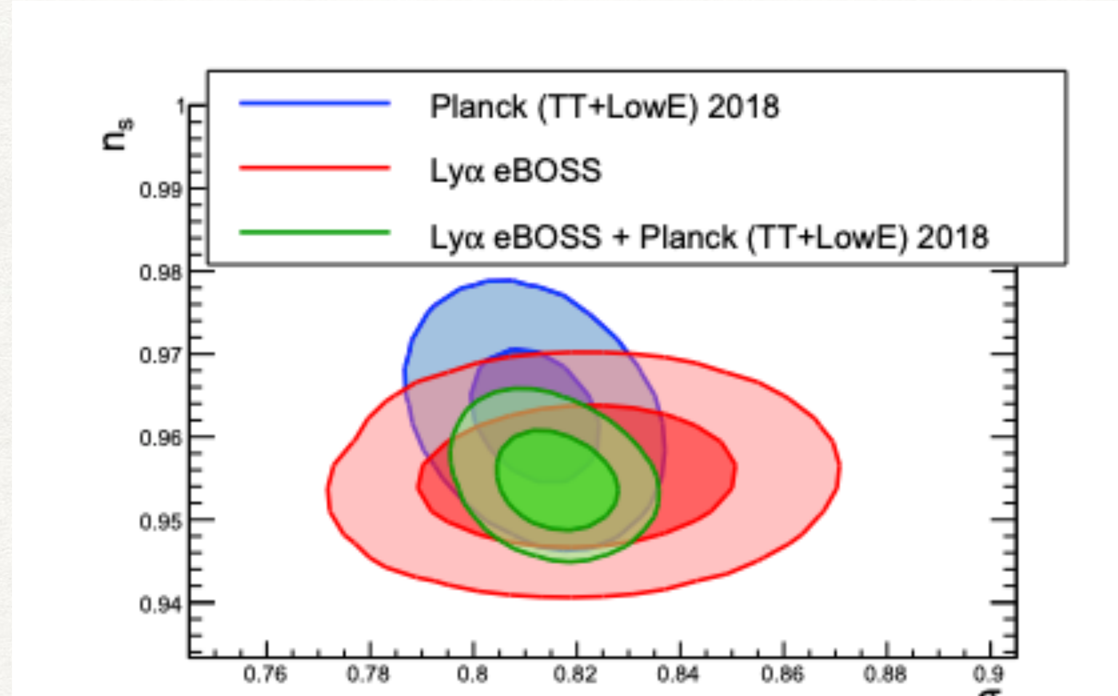
Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

Strong tension between Planck and eBOSS Lya?

- eBOSS Lya ~ 200 000 QSO at $z = 2 - 5$



Chabanier++ 1812.03554



Chabanier++ 1812.03554

- Measurements of tilt n_L & amplitude Δ_L^2 at $z = 3$, $k \simeq 1h/\mathrm{Mpc}$

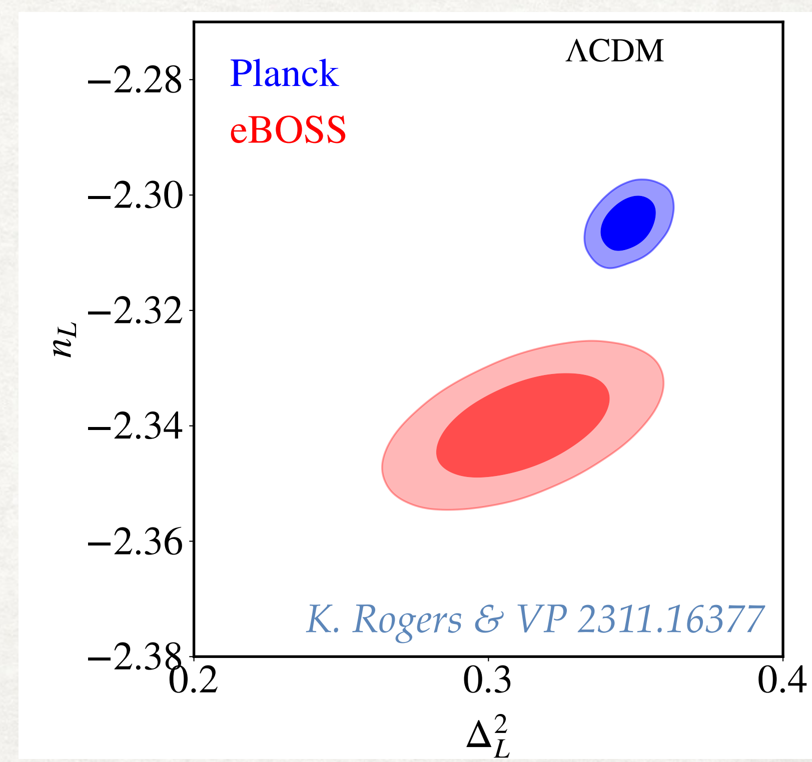
  McDonald astro-ph/0407377, Pedersen ++ 2209.09895, Goldstein++ 2303.00746

- No tension on ΛCDM parameters but 4.8σ tension on n_L & Δ_L^2

  See also Palanque-Delabrouille+ 1911.09073

- Hint for model resolving σ_8 tension?

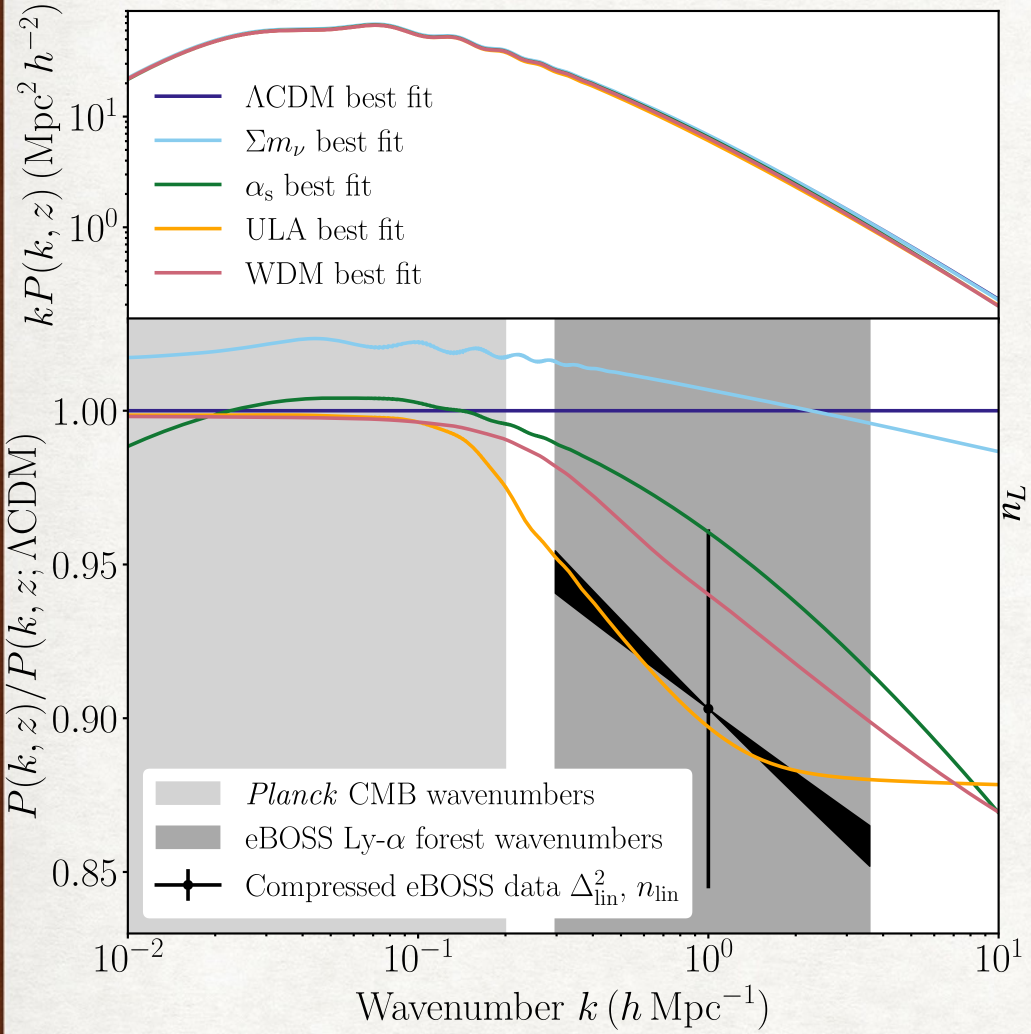
  See also Fernandez++ 2309.03943

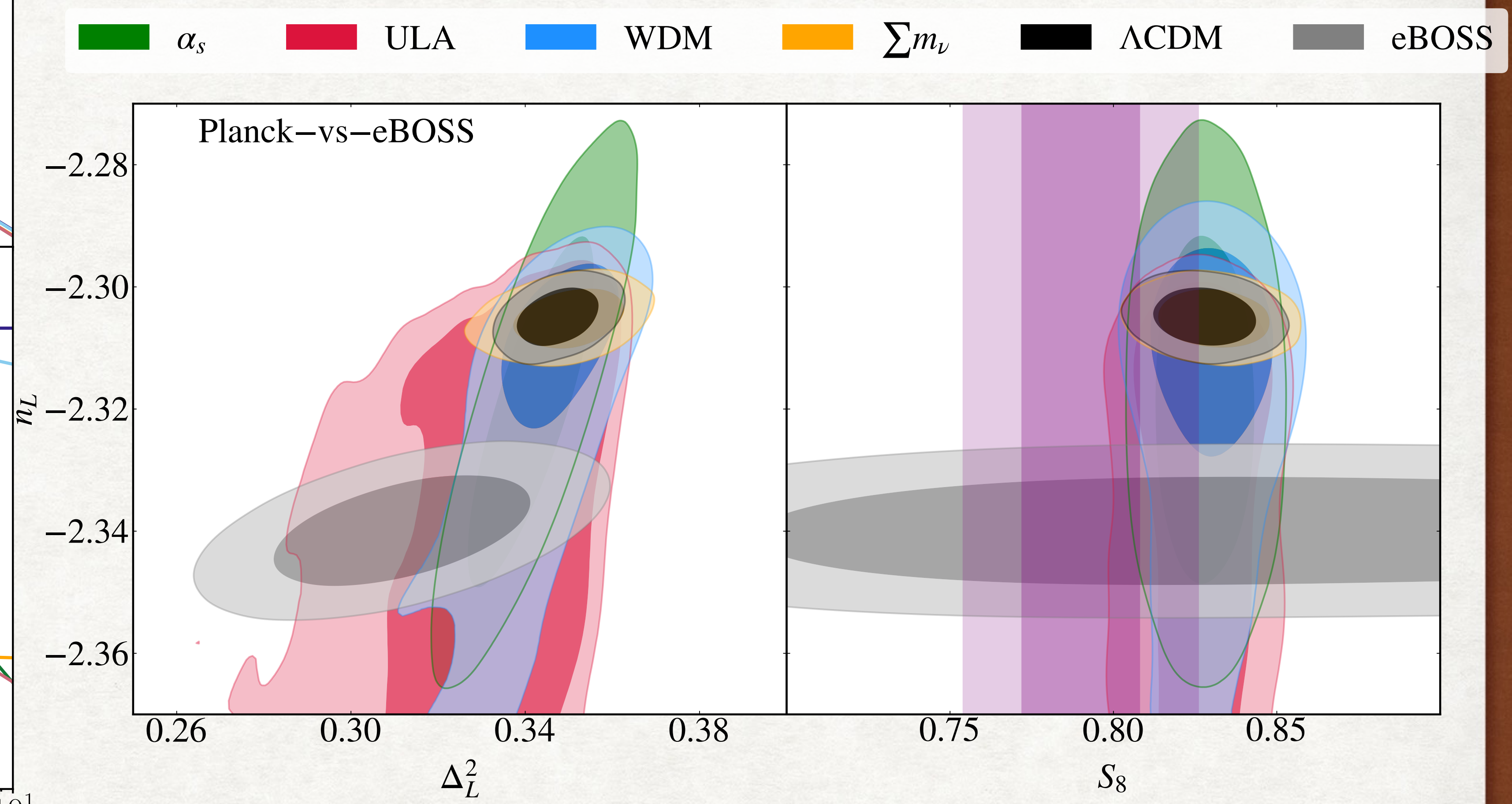


K. Rogers & VP 2311.16377

New physics in eBOSS data?

K. Rogers & VP 2311.16377





- Models with power suppression: running α_s, fraction of WDM and ULA all favored

See also Palanque-Delabrouille+ 1911.09073

- Require $\alpha_s \sim 0.01$ or $\{f_{\rm ULA} \sim 1\,\%\,, m_{\rm ULA} \sim 10^{-26}\mathrm{eV}\}$ or $\{f_{\rm WDM} \sim 1\,\%\,, m_{\rm WDM} \sim 100\mathrm{eV}\}$

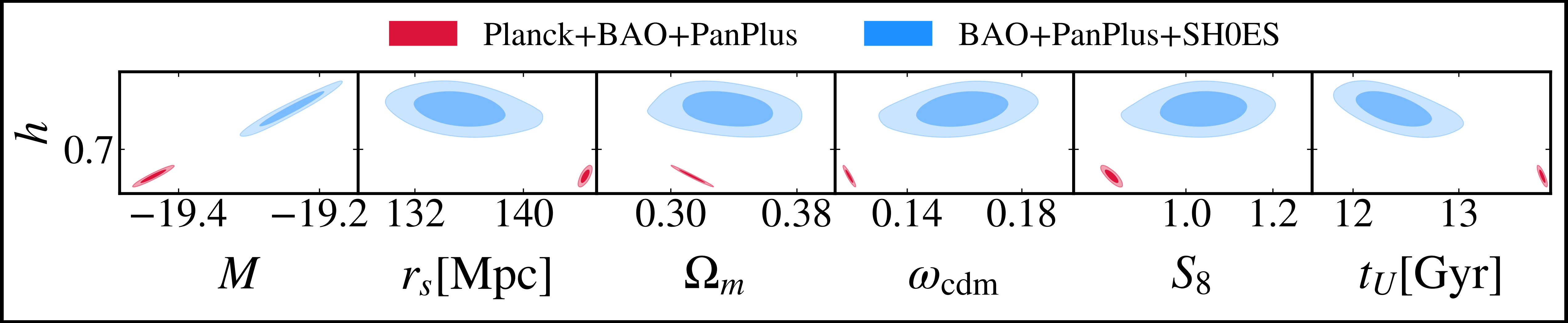
Rogers++ 2301.08361

- TBC with small scales Ly-α (XQ100 & MIKE / HIRES)
- H_0 and S_8 may be two (related or not) new degrees of freedom ? Connection between EDE and ULA?

The Hubble tension: what do we know so far?

- Despite its great success, the ΛCDM model is purely parametric: DM, DE, inflation still unknown
- H_0 is in 5σ tension and S_8 is in 3σ tension: first clue about physics beyond ΛCDM?

- DDR require that a new physics solution before or around the time of recombination.
- Increase Hubble rate or accelerate recombination to reduce the sound horizon r_s.



- It has implications beyond H_0: smaller t_U, larger $\omega_{\rm cdm}$ and larger S_8
- **A**dditional dynamics to reduce the growth of matter perturbations, WDM/ULA … or baryons?

Cosmic tensions: where are we going next?

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- New CMB data are coming: very sensitive to new physics around recombination!
- New LSS data are coming: measure $P(k, z)$, improve "baryons", neutrino masses?
- JWST and gravitational wave measurements of H_0.