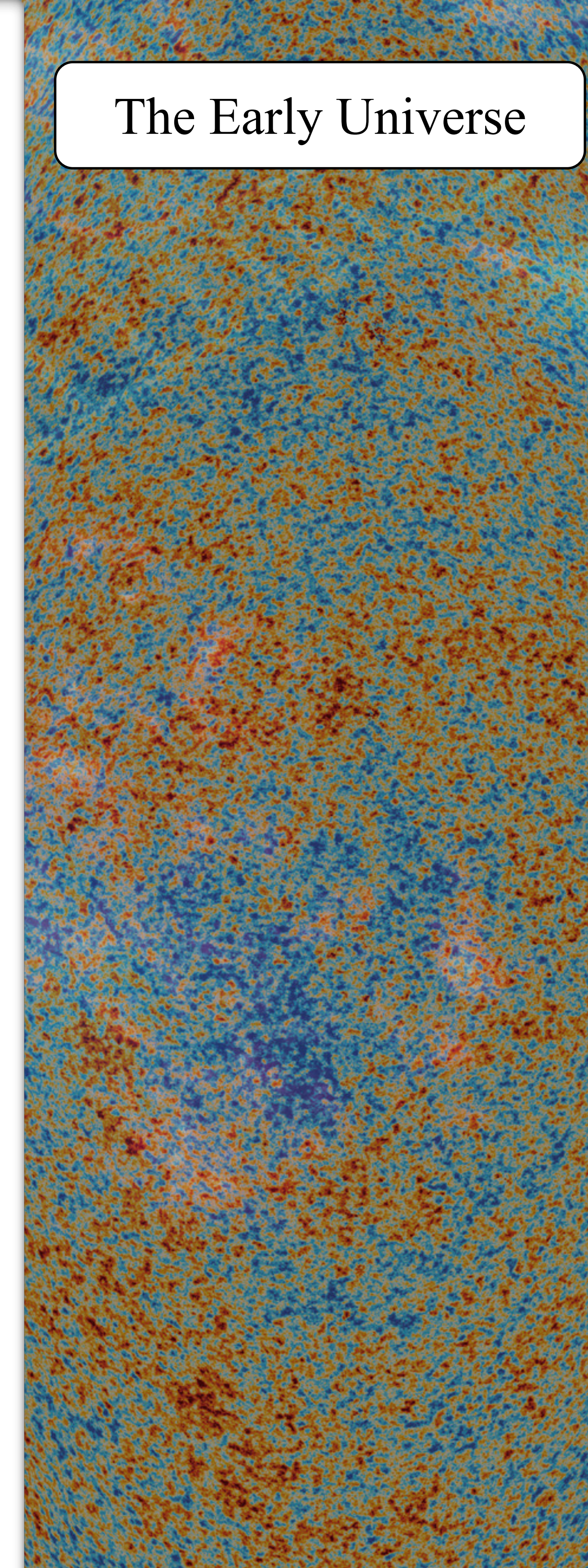


Tensions in Cosmology

Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

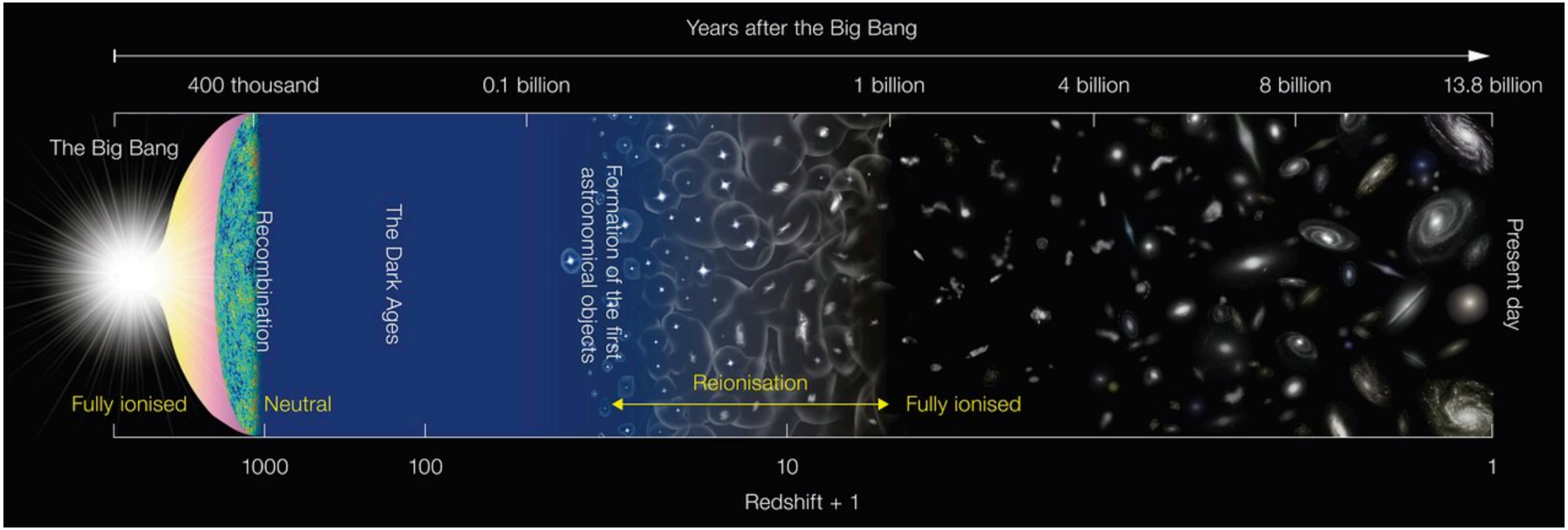
vivian.poulin@umontpellier.fr

Les Houches summer school
July, 28th & 29th 2025

The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology: GR+ Cosmological Principle

$\omega \equiv \Omega h^2, \; H_0 = 100h$ 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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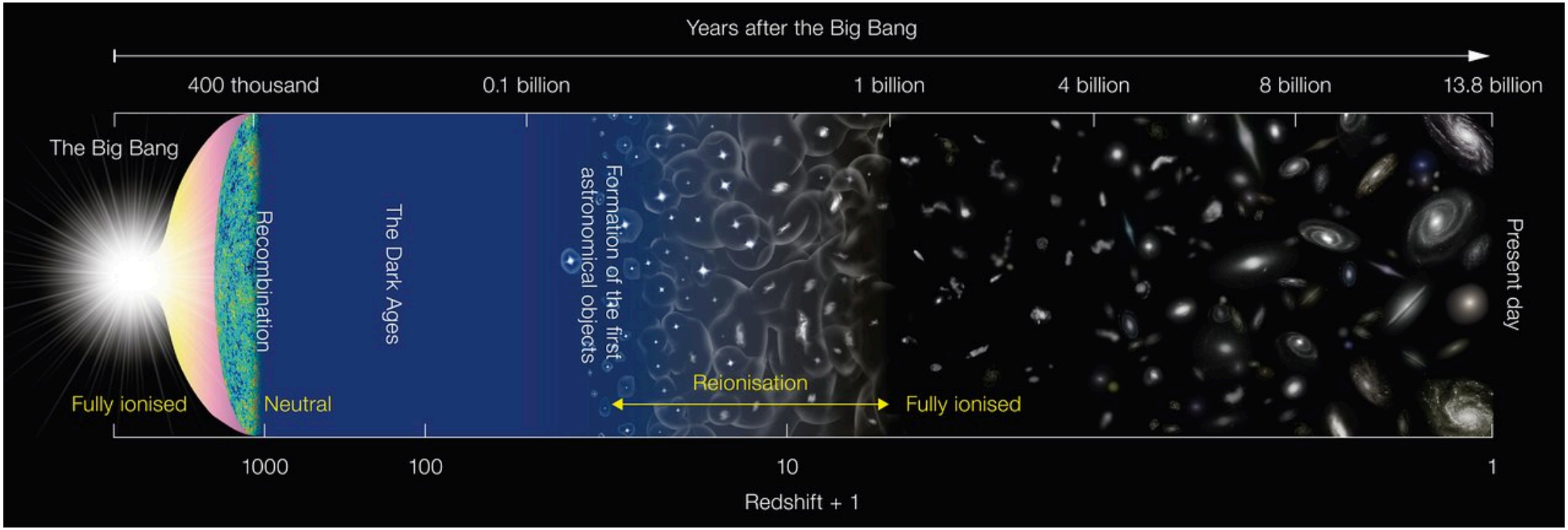
Expansion/Energy content



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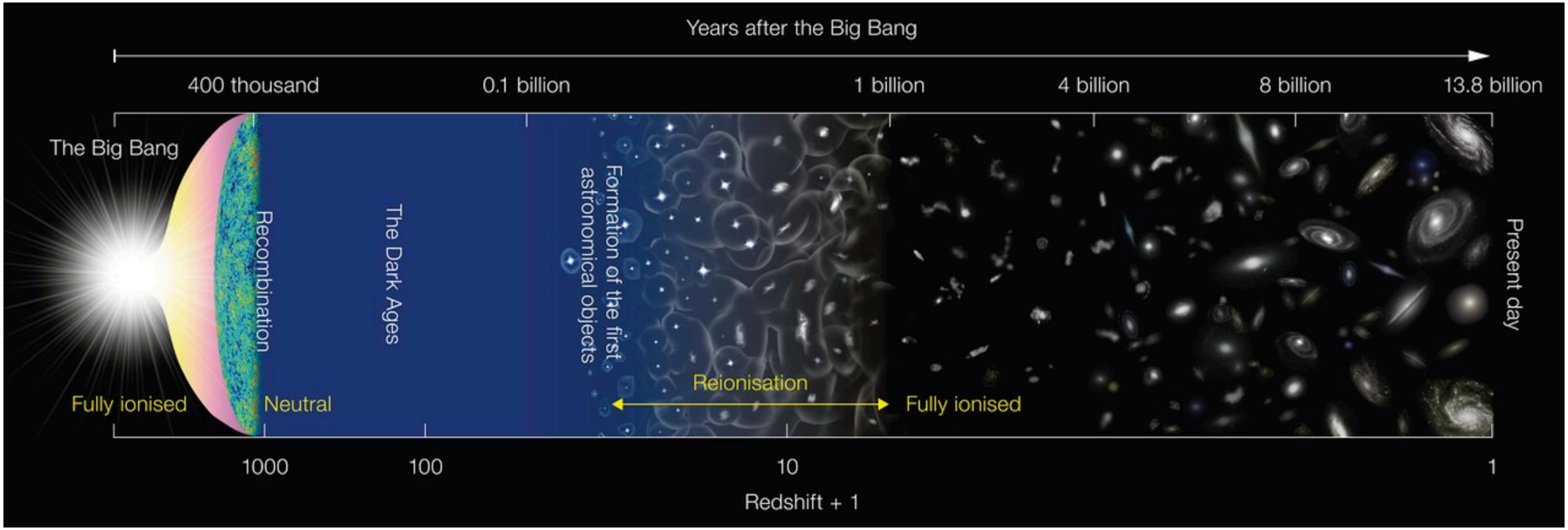

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Expansion/Energy content

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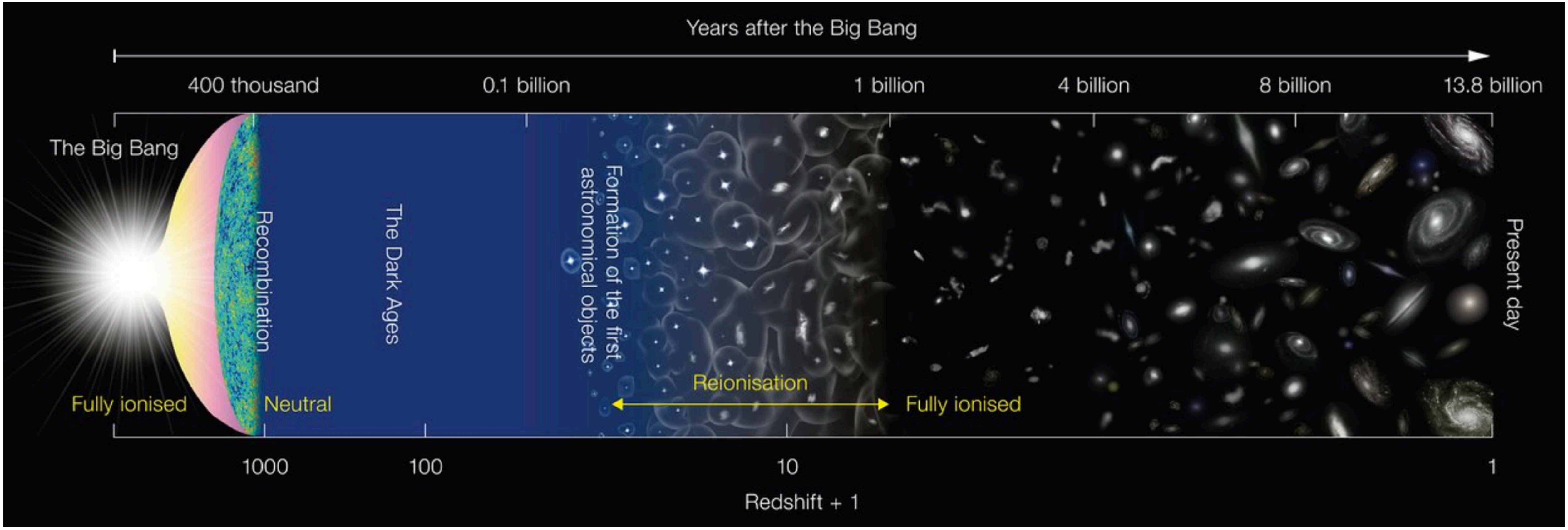
star formation



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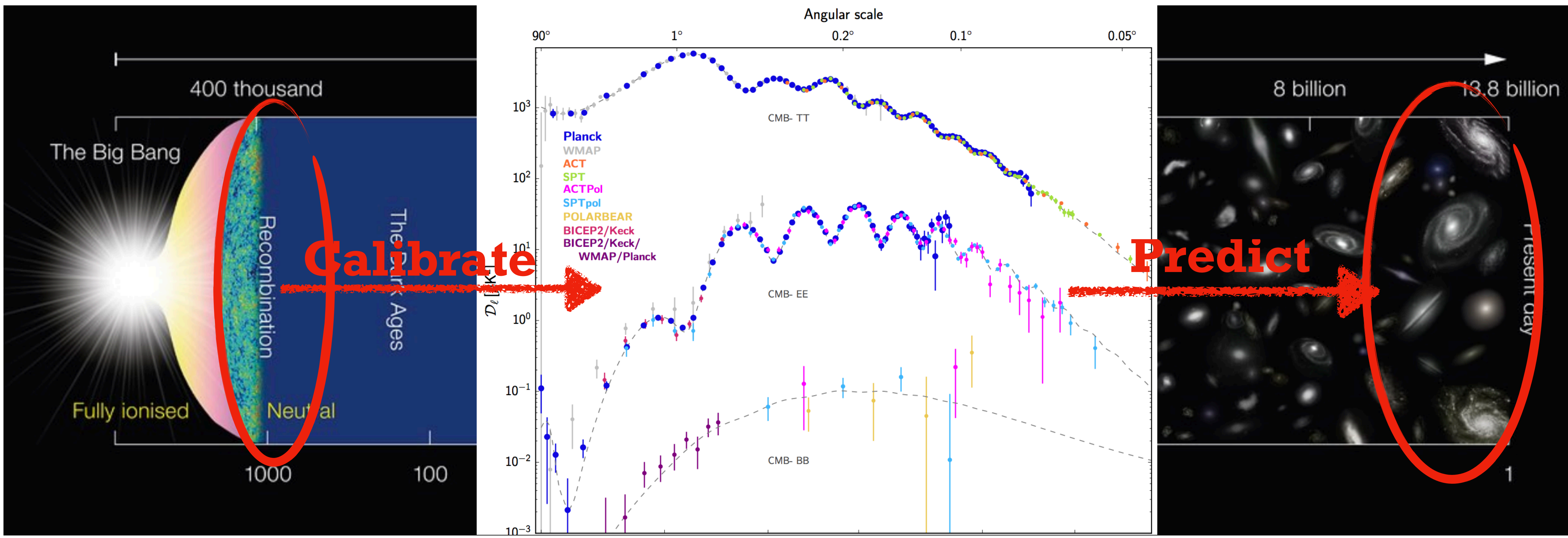

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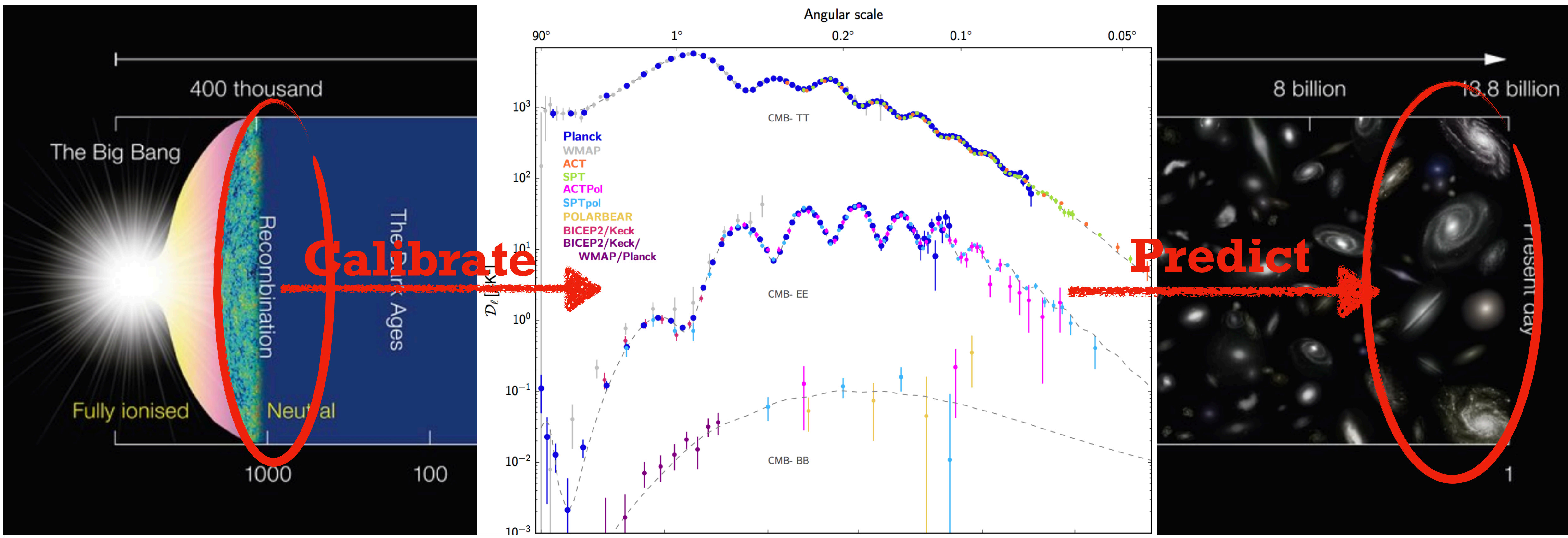

95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

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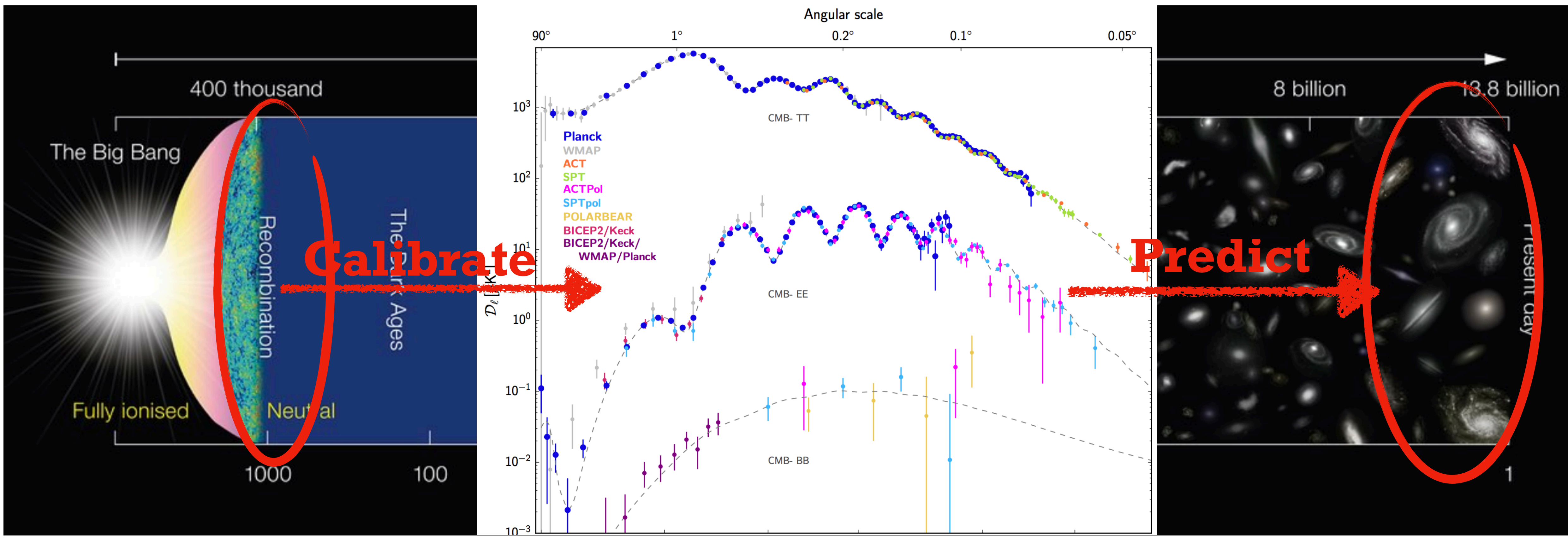
Expansion/Energy content — **Inflation** — **star formation**



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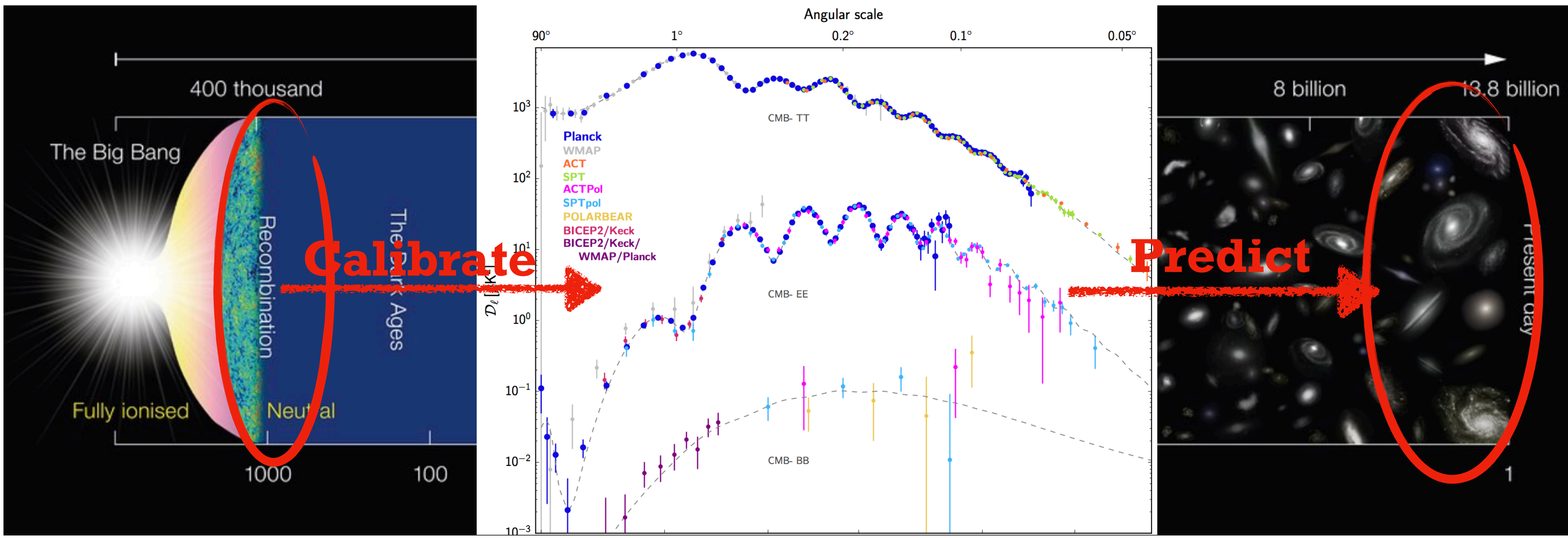

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The mechanism behind initial conditions is unknown.

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

Precision Cosmology or Cosmic Discordance?

The ΛCDM Cosmology is under extreme pressure

- 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?

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- Tensions in cosmological parameters?

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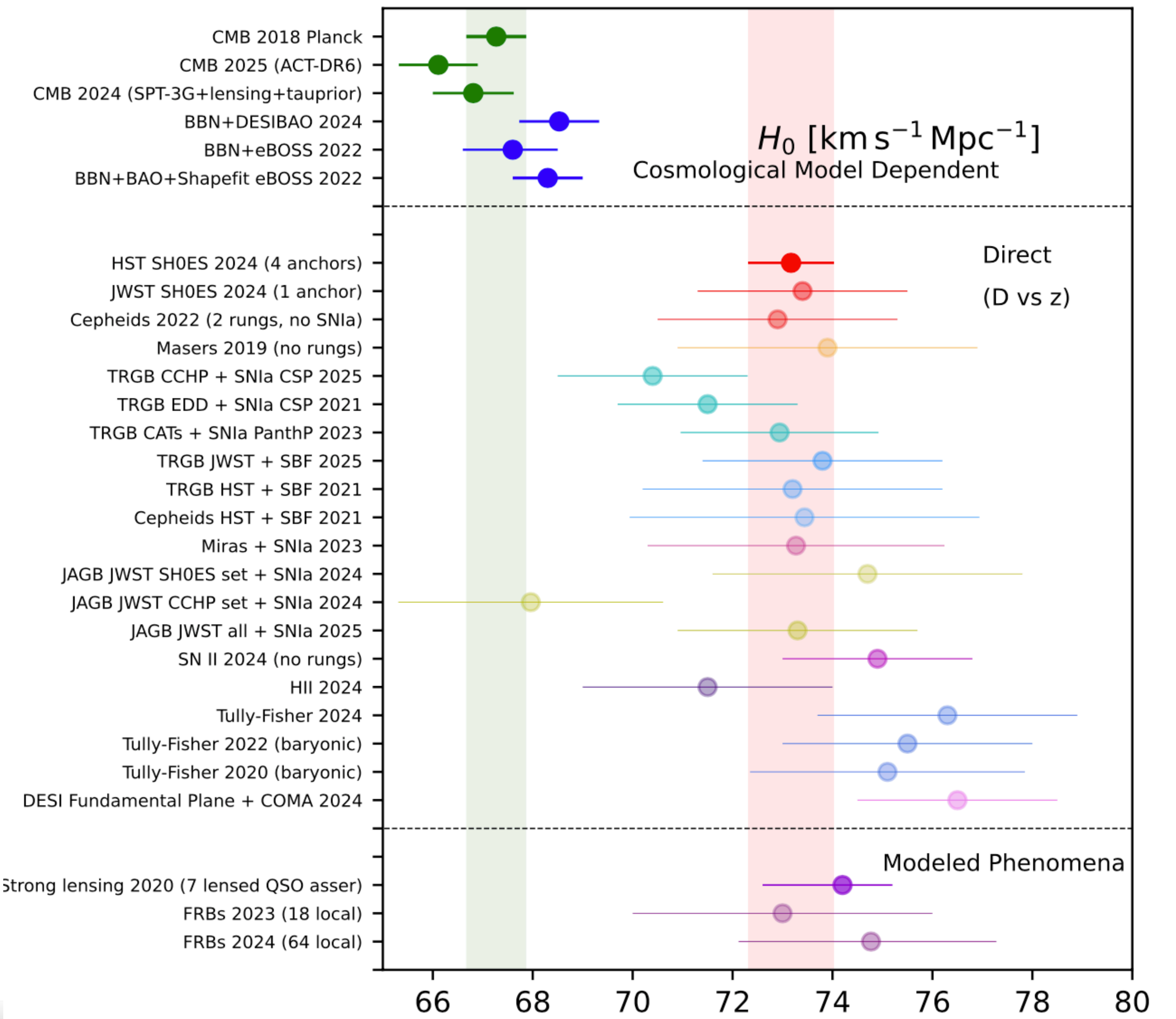
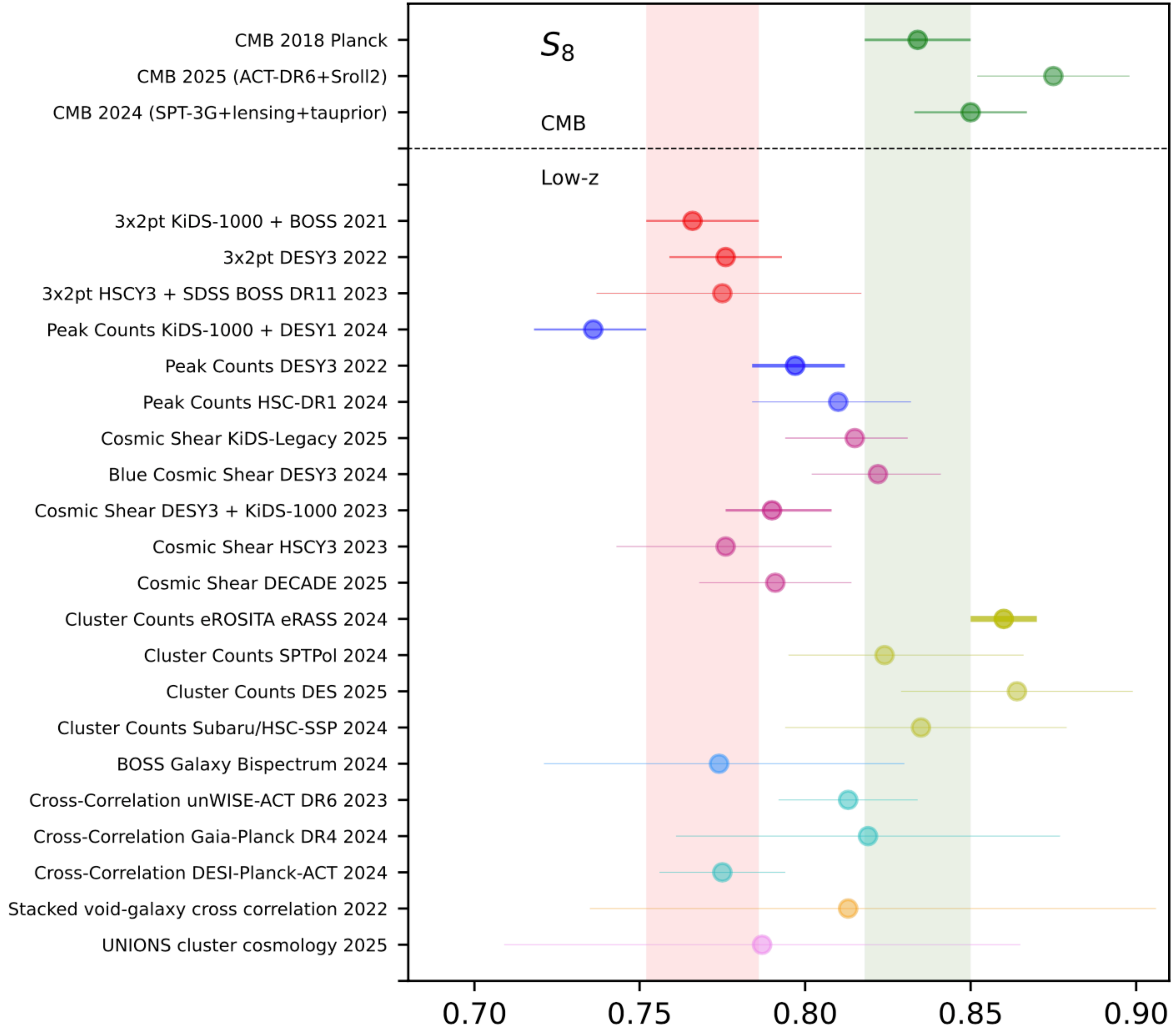
Is this a sign of a break down in the cosmological principle or GR?

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

The Hubble tension

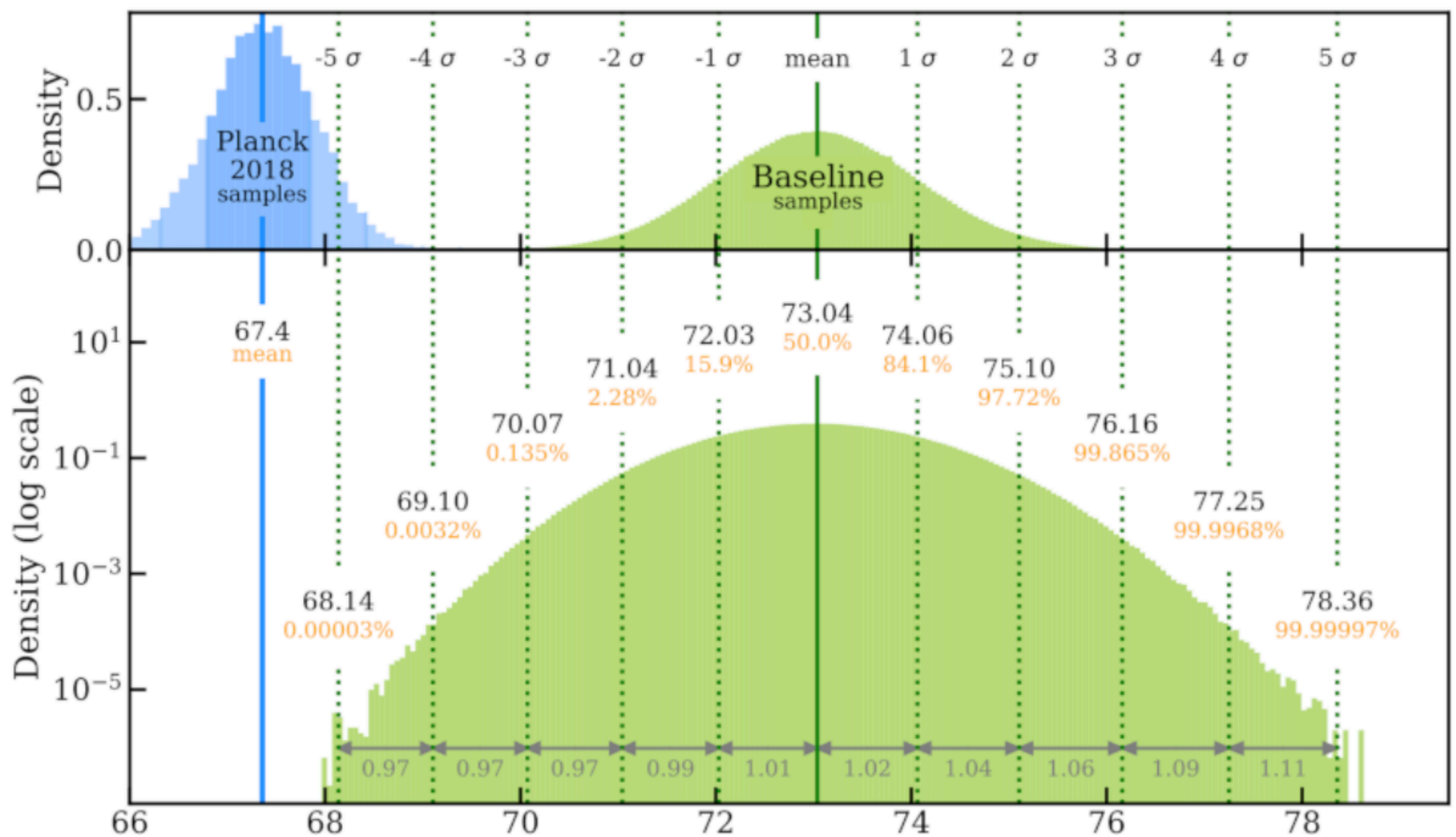


The S8 tension



The Hubble tension between SH0ES & *Planck*

There is a 5σ discrepancy between the SH0ES and *Planck* determination of the Hubble parameter



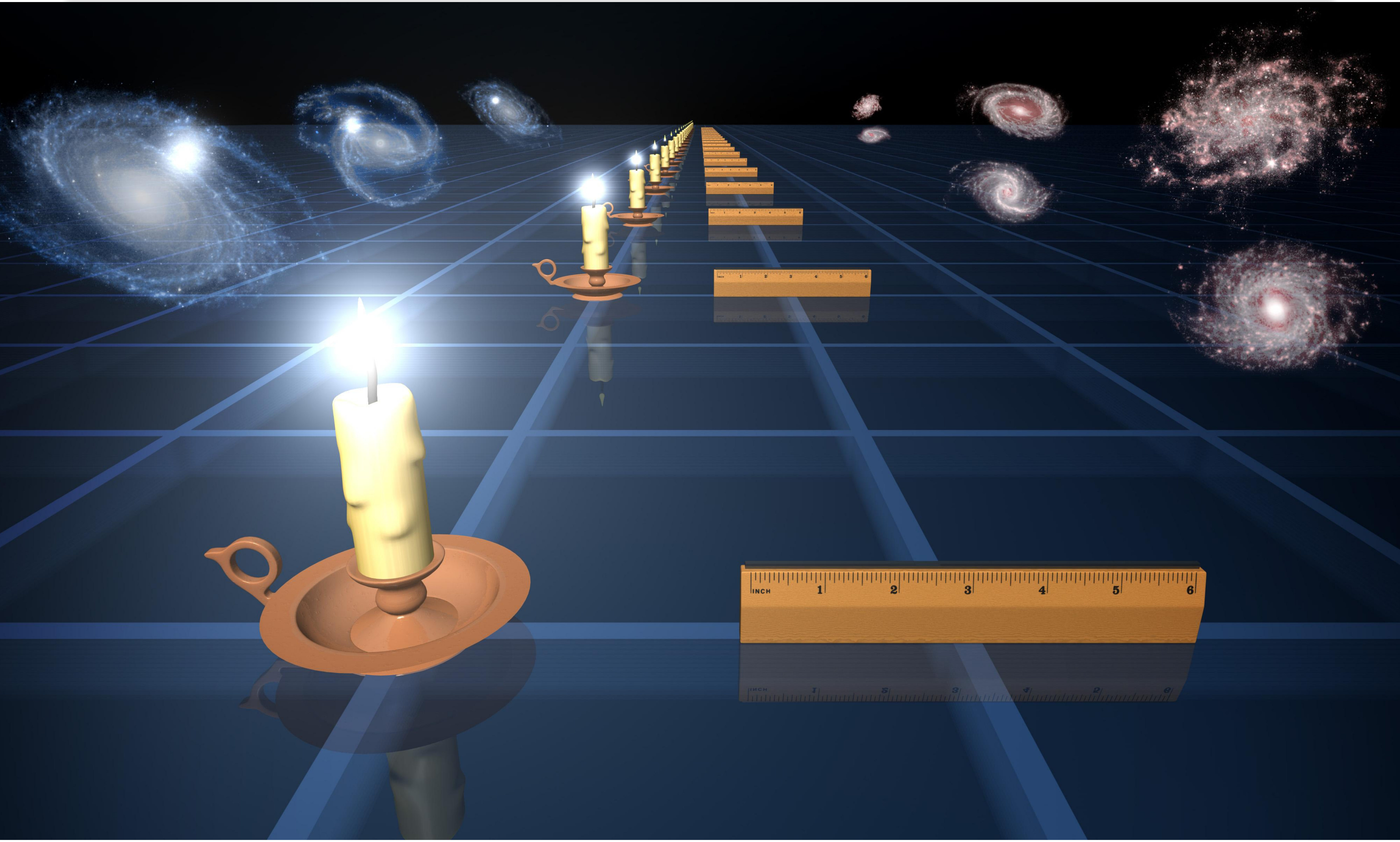
Riess et al. 2112.04510

$$H_0(\Lambda\text{CDM/Planck}) = 67.4 \pm 0.5$$ **km/s/Mpc**

$$H_0(\text{SH0ES}) = 73.04 \pm 1.04$$ **km/s/Mpc**

Is this first sign of a crack in ΛCDM?

Measuring distances in Cosmology



A tension between luminosity and angular distance

- The comoving distance $\chi = \int_{t_e}^{t0} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$ from imposing $ds^2 = dt^2 - a^2 d\chi^2 = 0$

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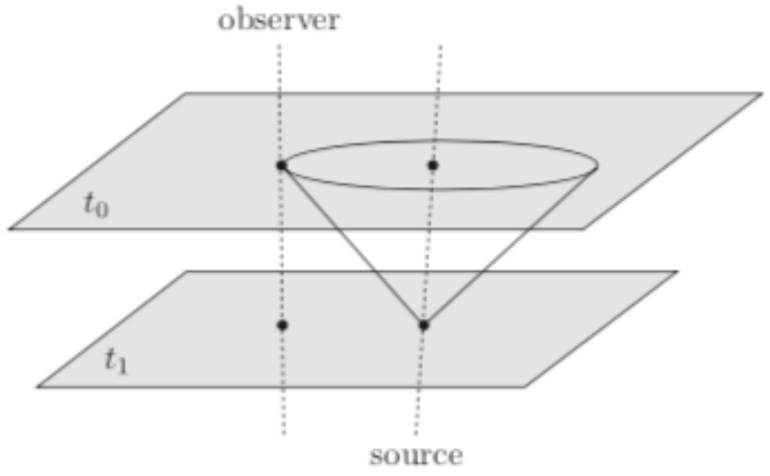
- The luminosity distance to a source of known flux and luminosity

$$F = \frac{L}{4\pi d_L(a)^2} \qquad d_L = \frac{\chi(a)}{a} = \chi(z)(1+z)$$



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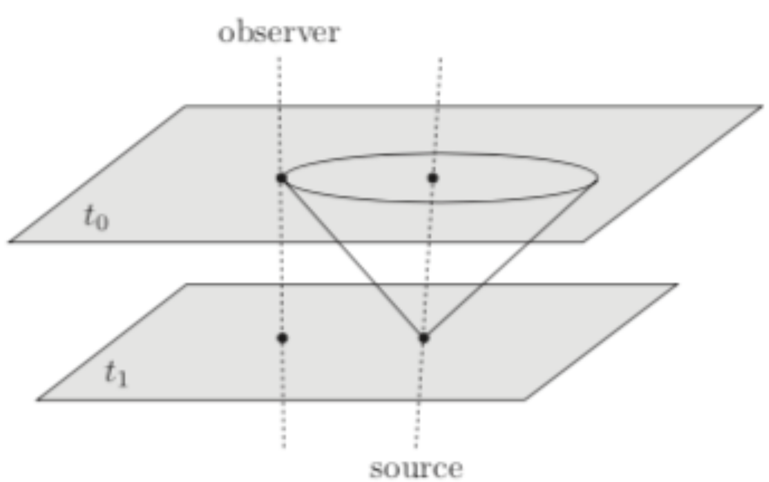
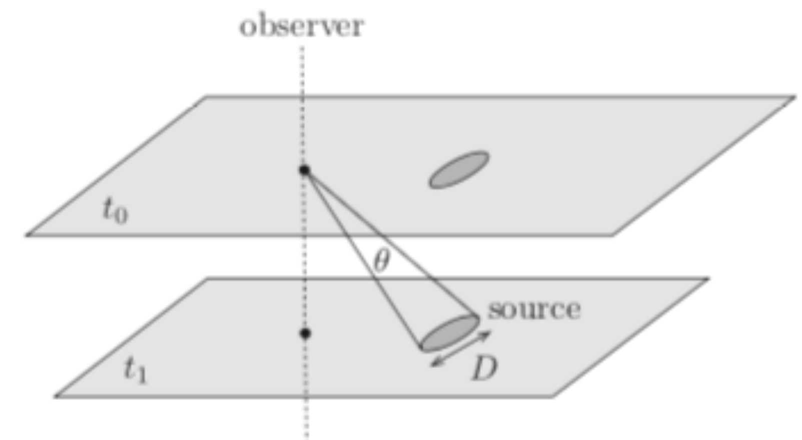


- The angular diameter distance to a source of known apparent and intrinsic size.

$$\delta\theta = \frac{D}{d_A} \qquad d_A = a\chi(a) = \frac{\chi(z)}{(1+z)}$$



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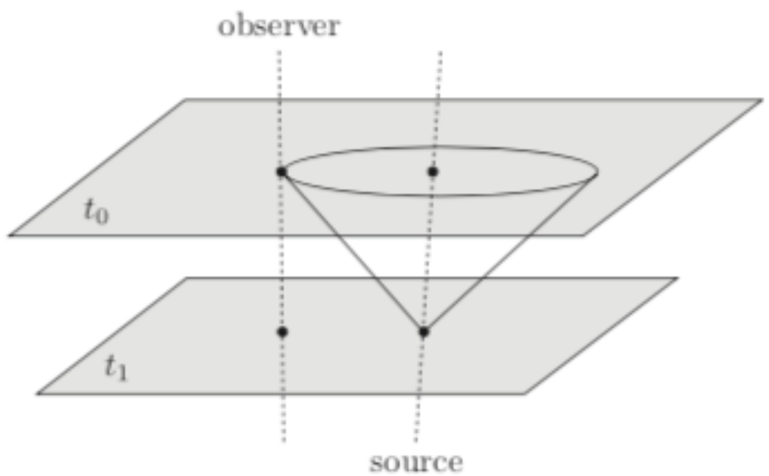

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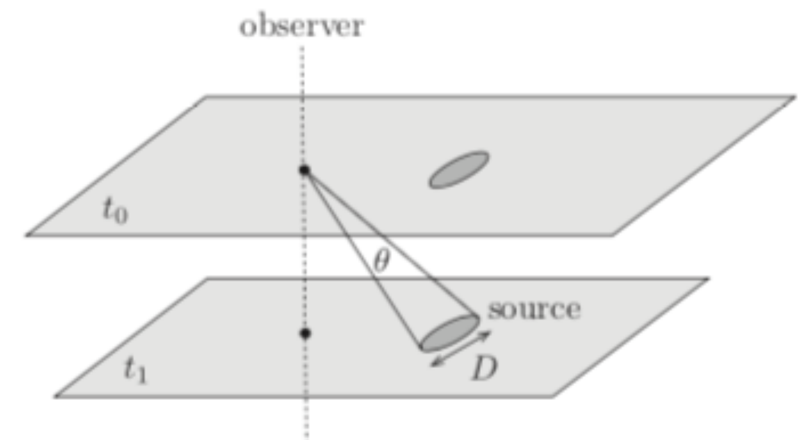

- In GR the Etherington distance-duality relationship imposes

$$d_A = d_L/(1+z)^2$$

$$d_A = \frac{1}{1+z}\int_0^z \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda}}$$

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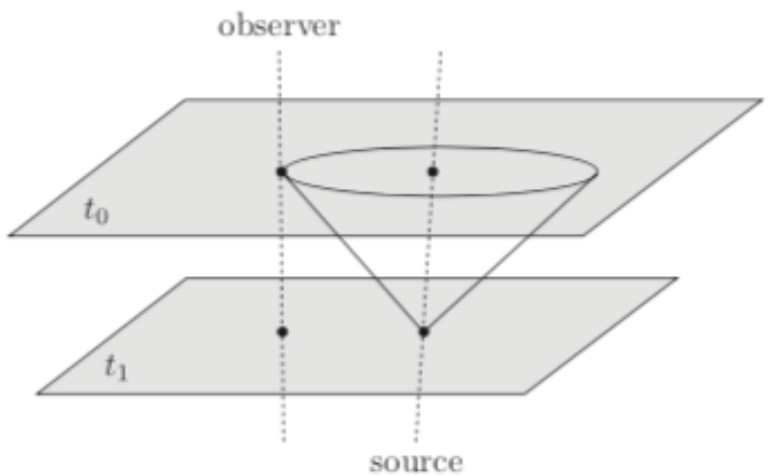

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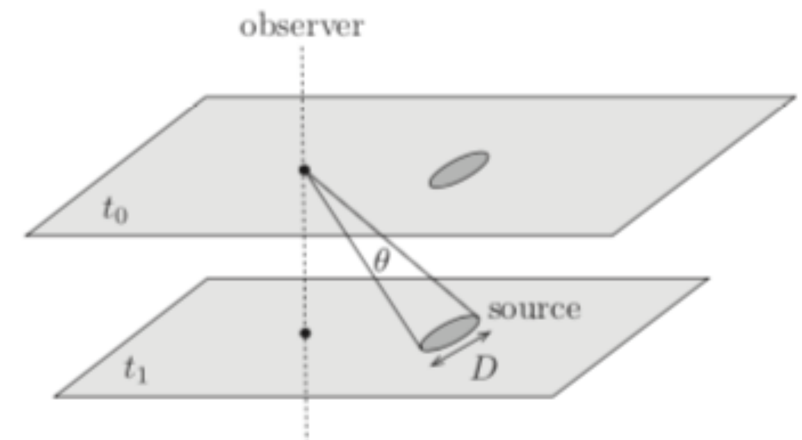

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Measuring H_0 == measuring distances

Mismatch in H_0 == wrong distance!

The cosmic distance ladder

- **Standard candle:** Object of known luminosity L

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

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

$$m - M = 5\log D_L[\text{Mpc}] + 25$$

*1 $\text{Mpc} = 3.2 \times 10^6\ \text{l.y.}$

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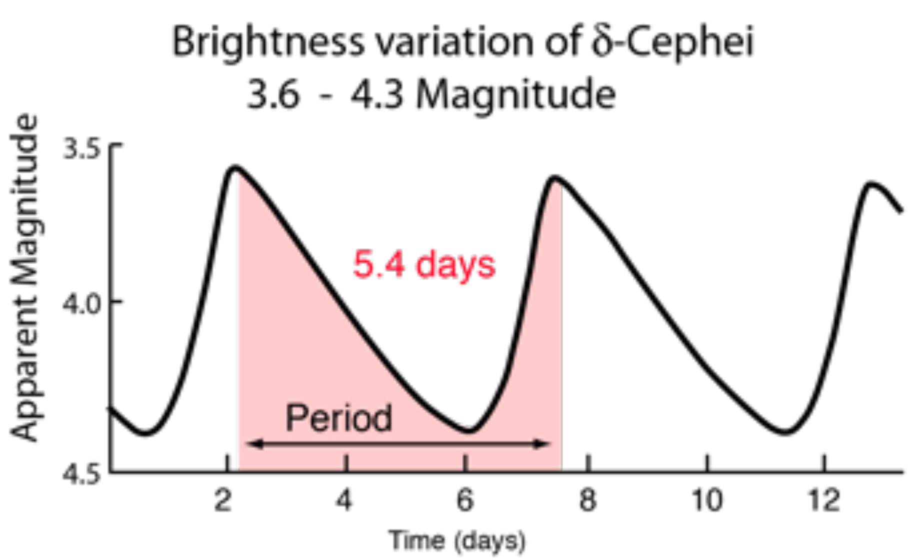
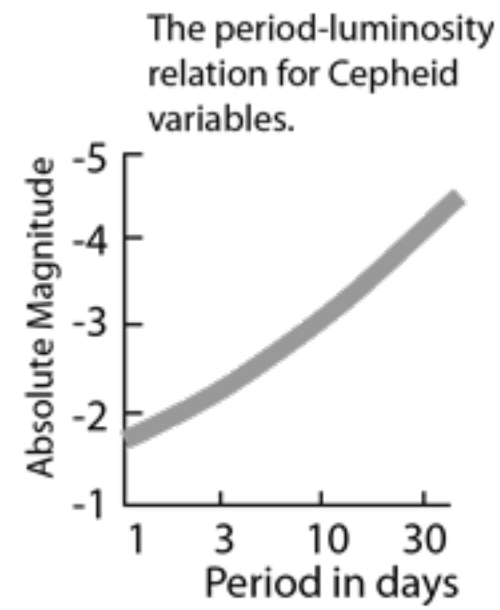
Cepheid stars

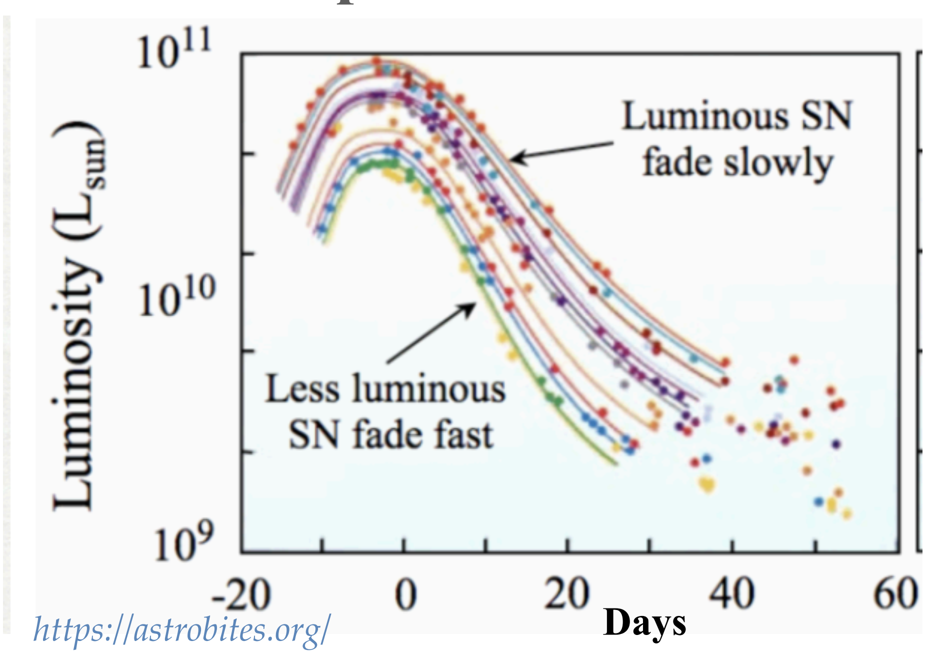




(D ~ 10³ -10⁶ l.y.)

- Pulsating stars
  Period-luminosity relation

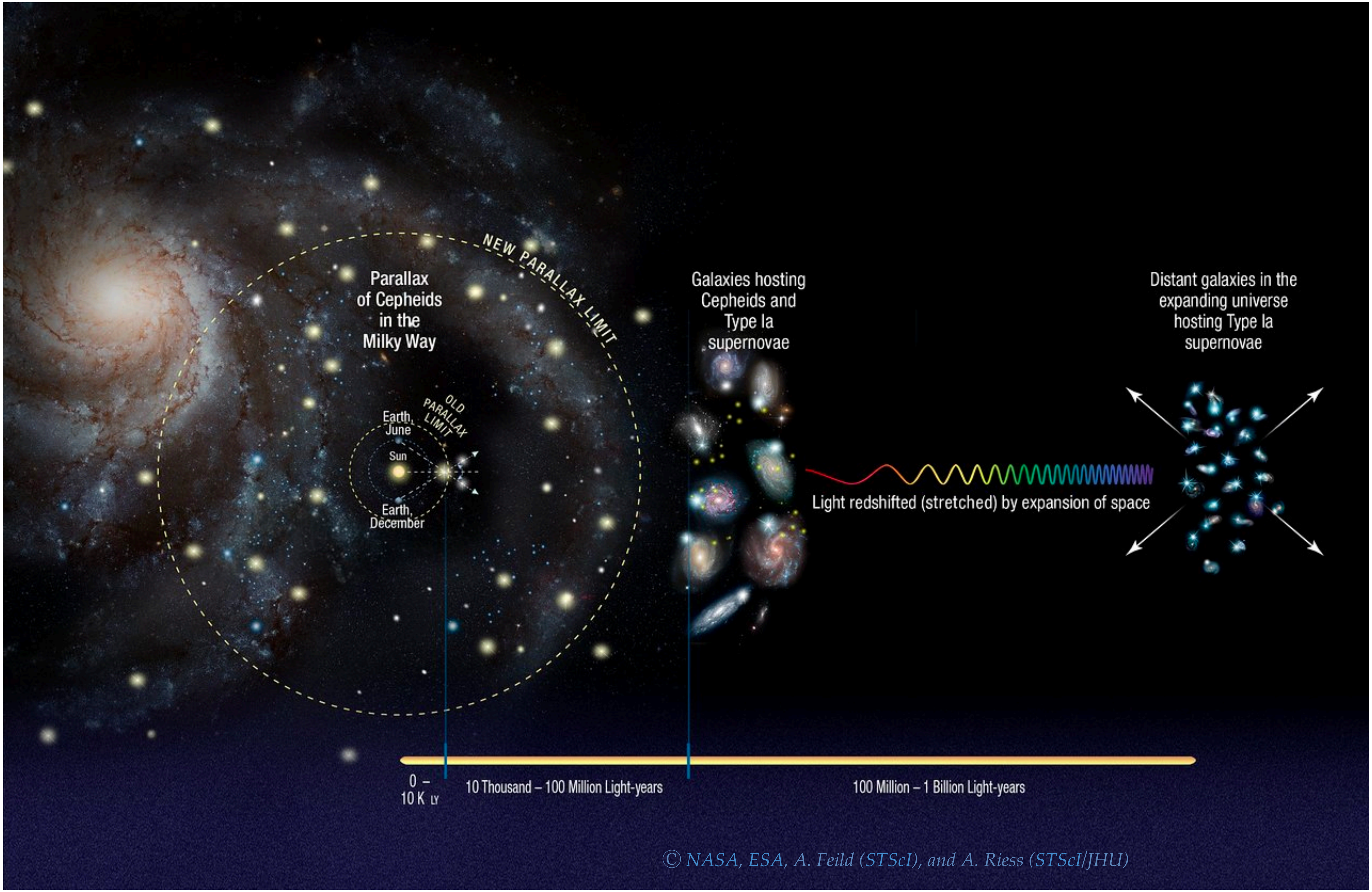
Supernovae Ia



(D ~ 10⁹ l.y.)

- Bright "standardizable" objects
  relation between peak & slope of the light curve

Three steps to the Hubble constant



The cosmic distance ladder

Different geometric calibrators: GAIA parallaxes, masers NGC 4258, DEB in the LMC

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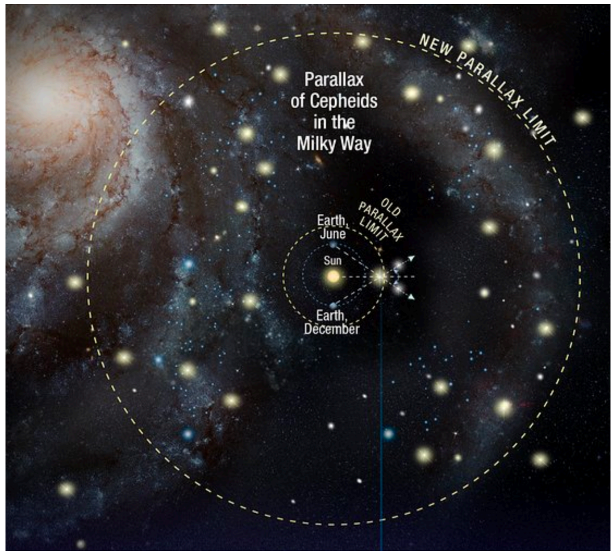

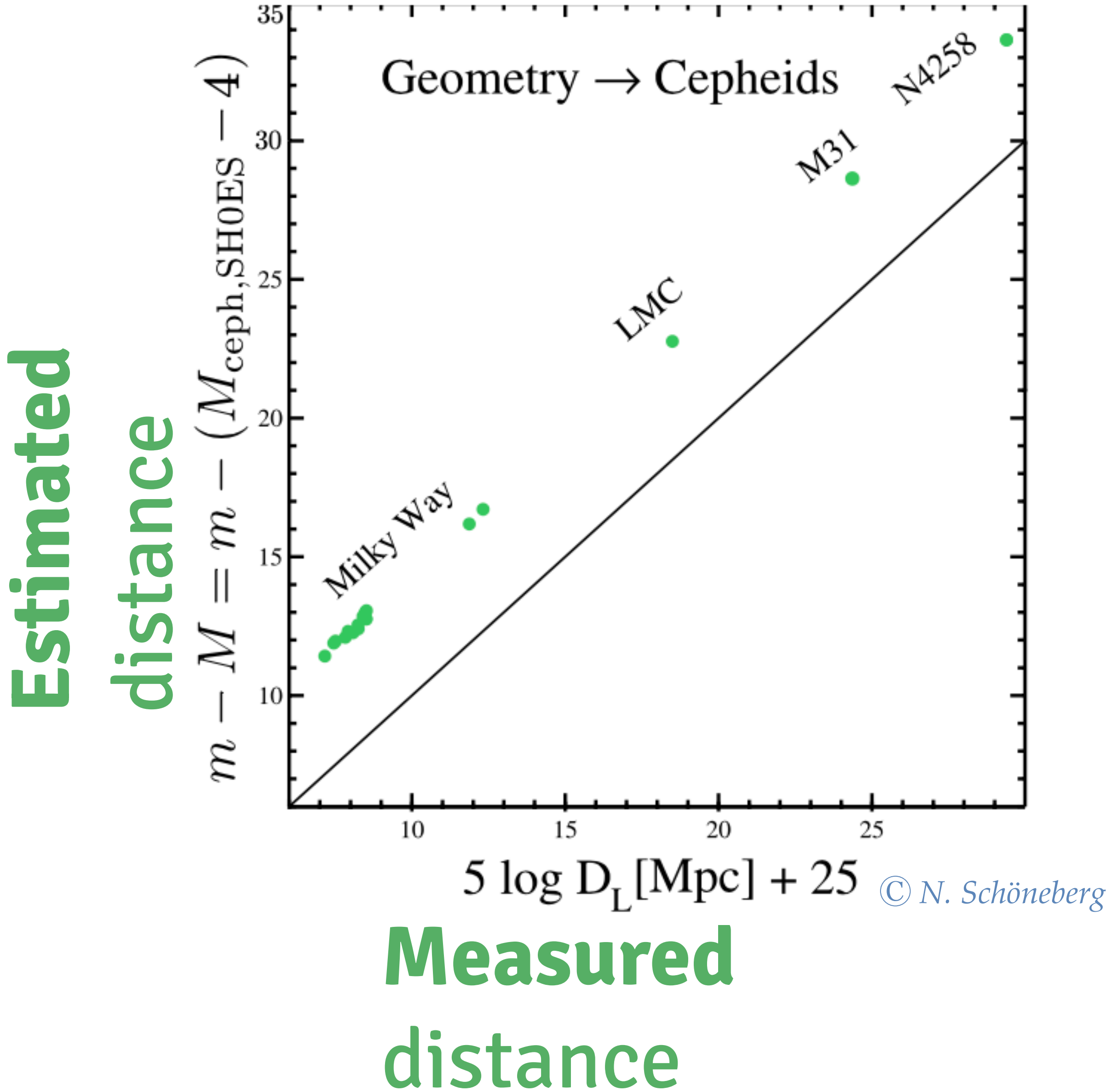

[Riess+1604.01424 (edited)]

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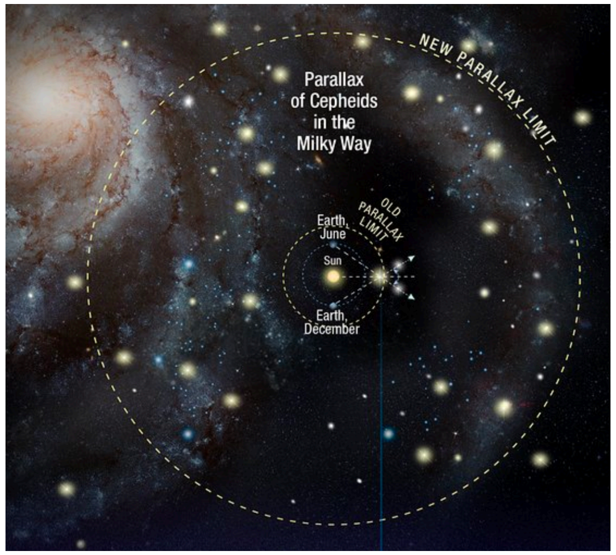

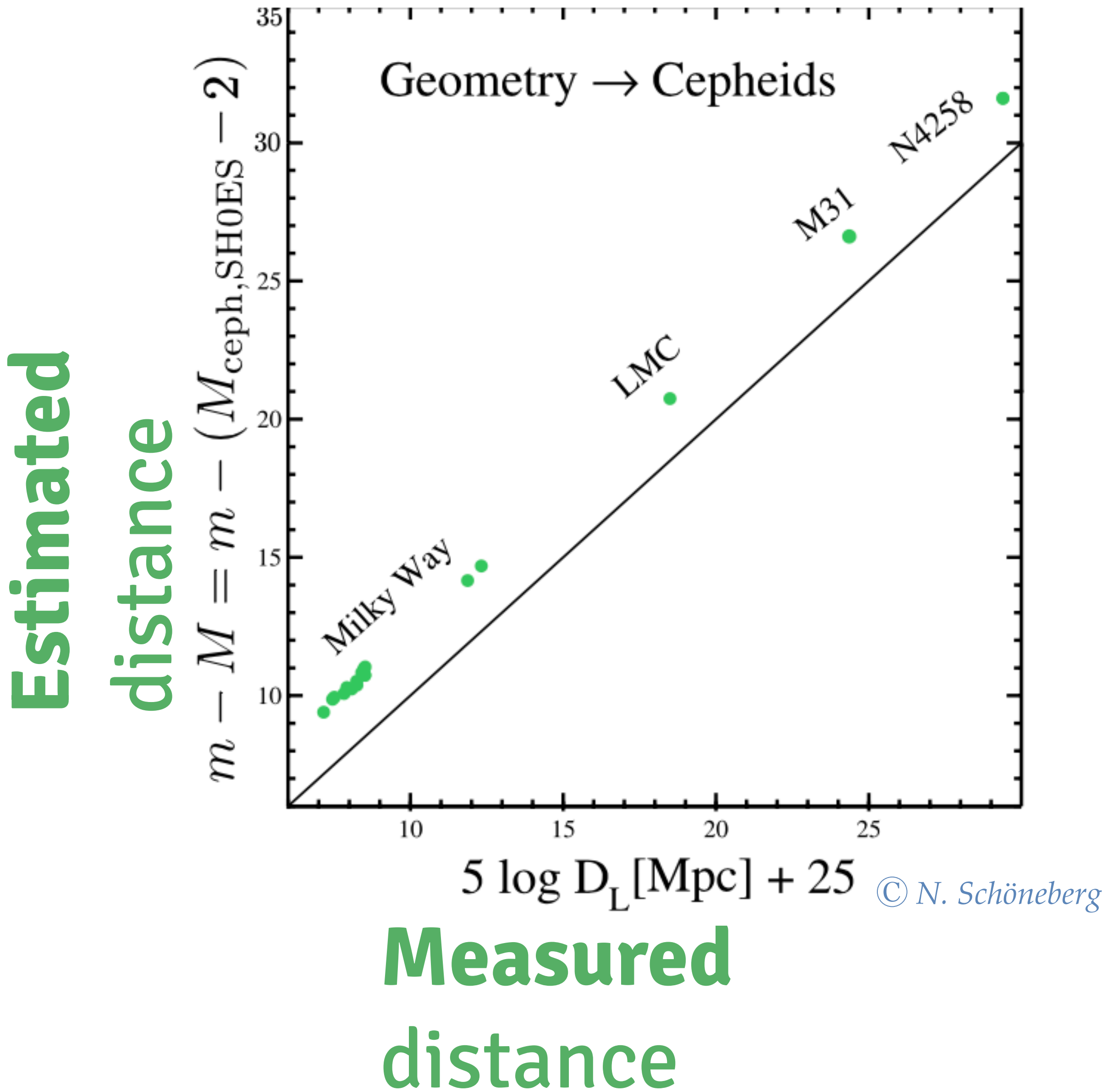

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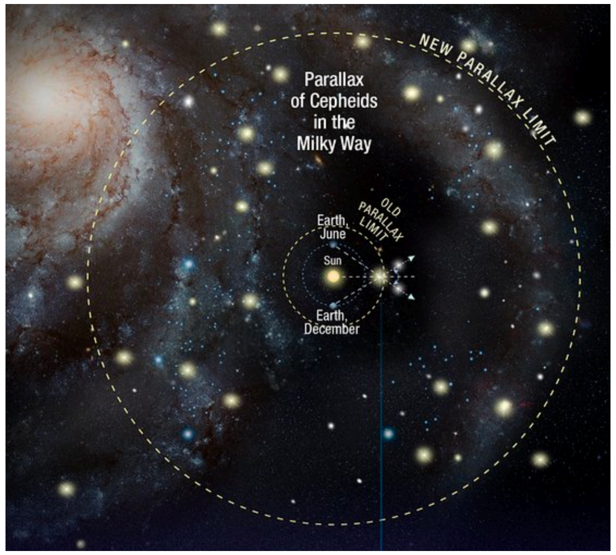

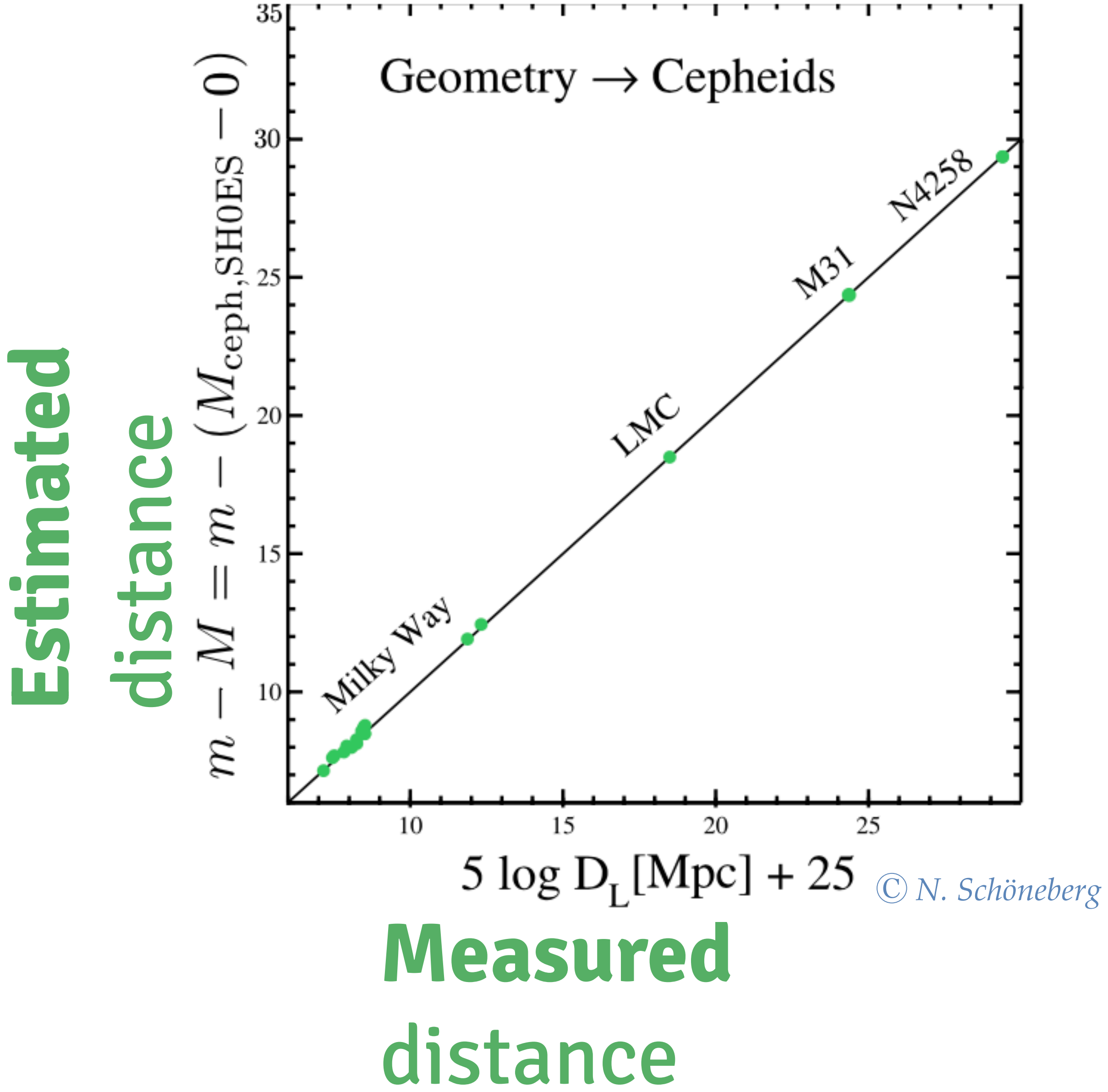

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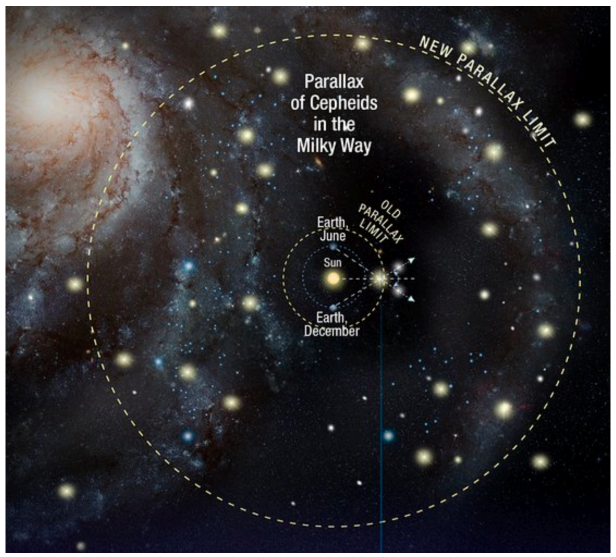

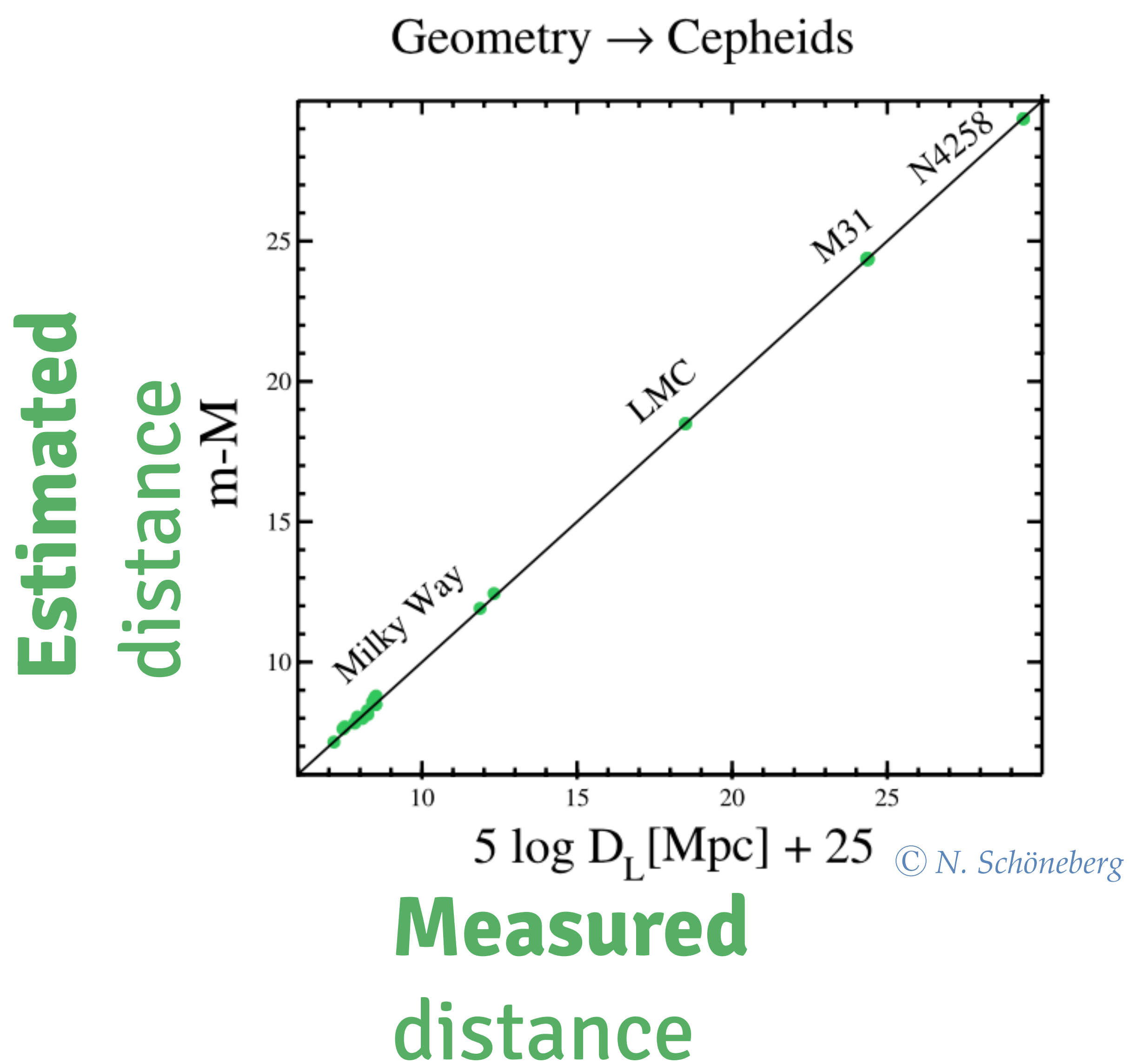

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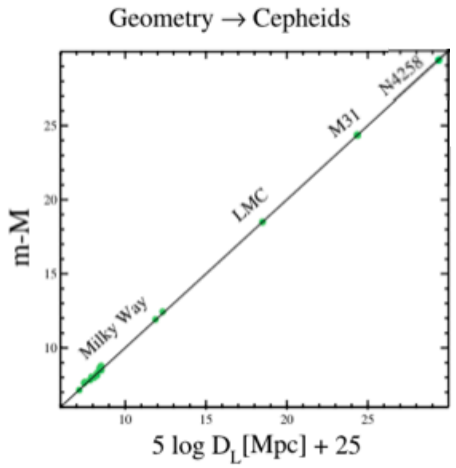
Three steps to the Hubble constant



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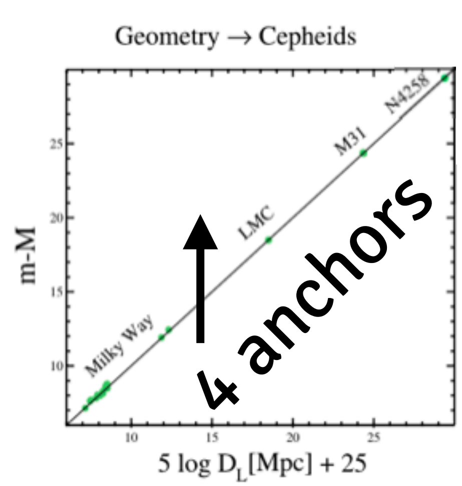

→ M_{ceph} (P-L relation)

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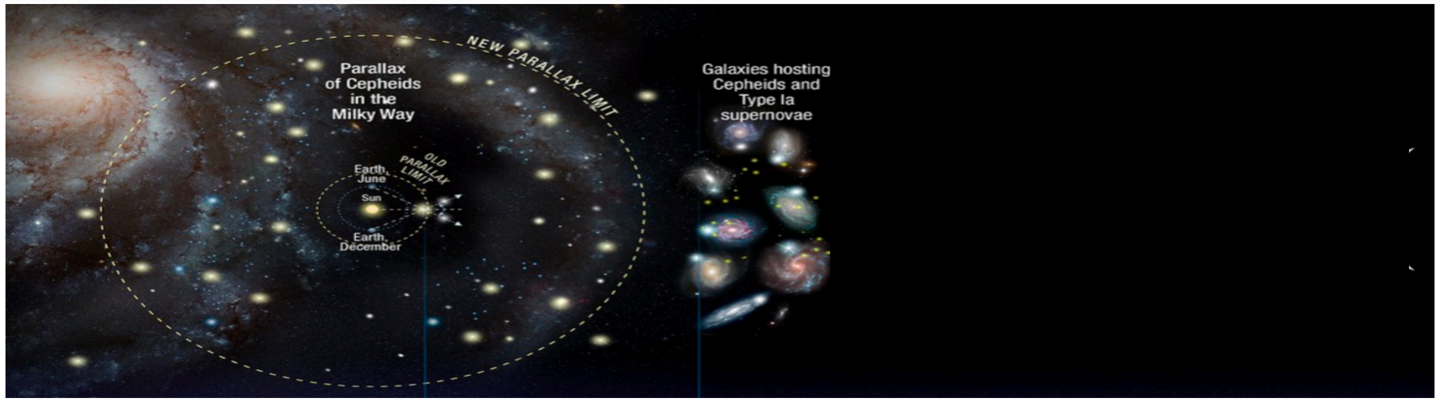

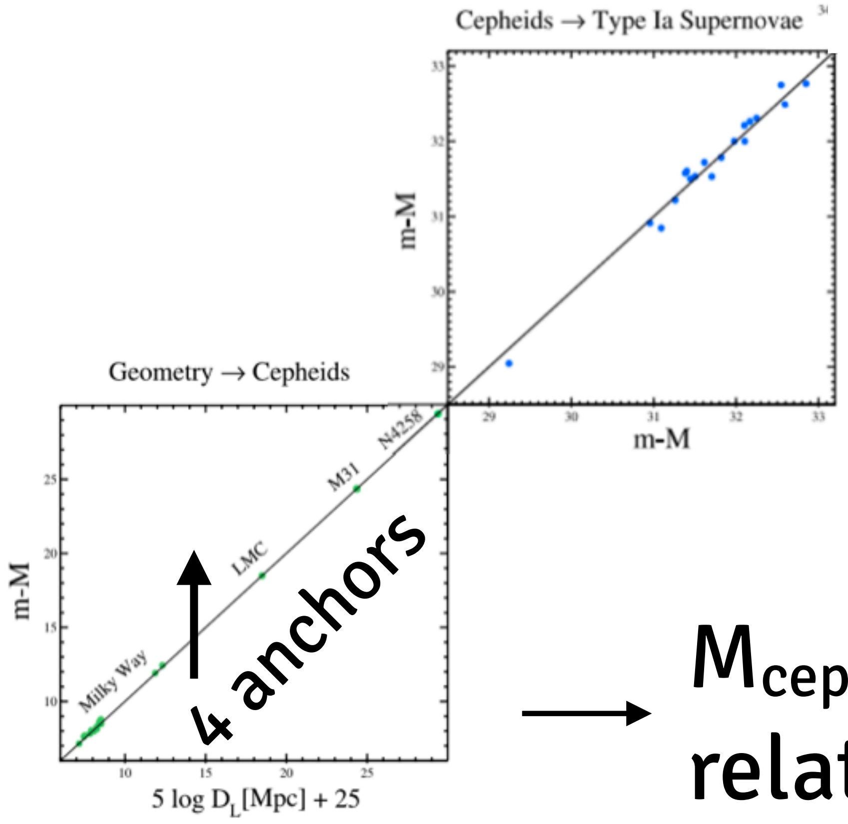

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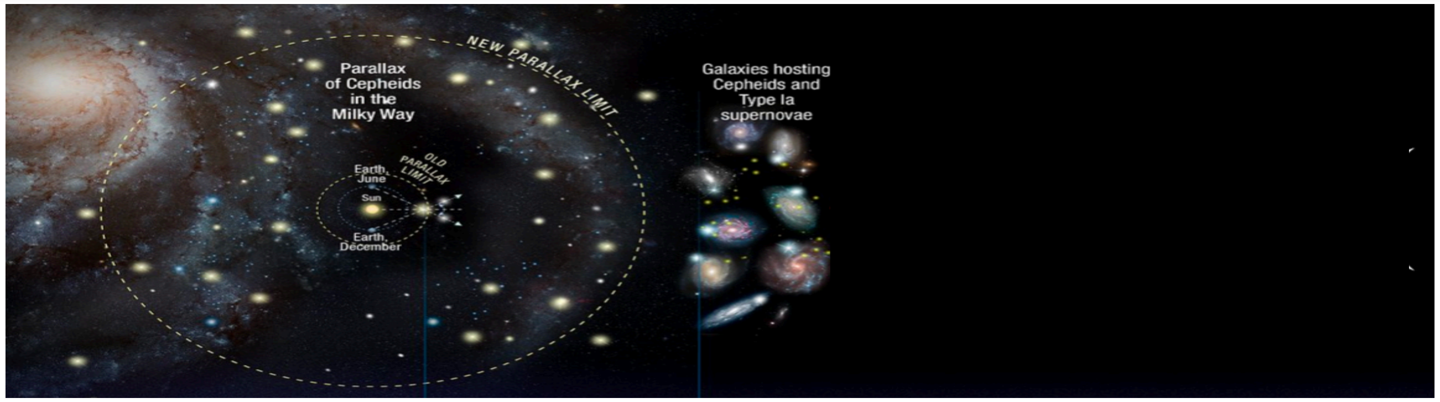

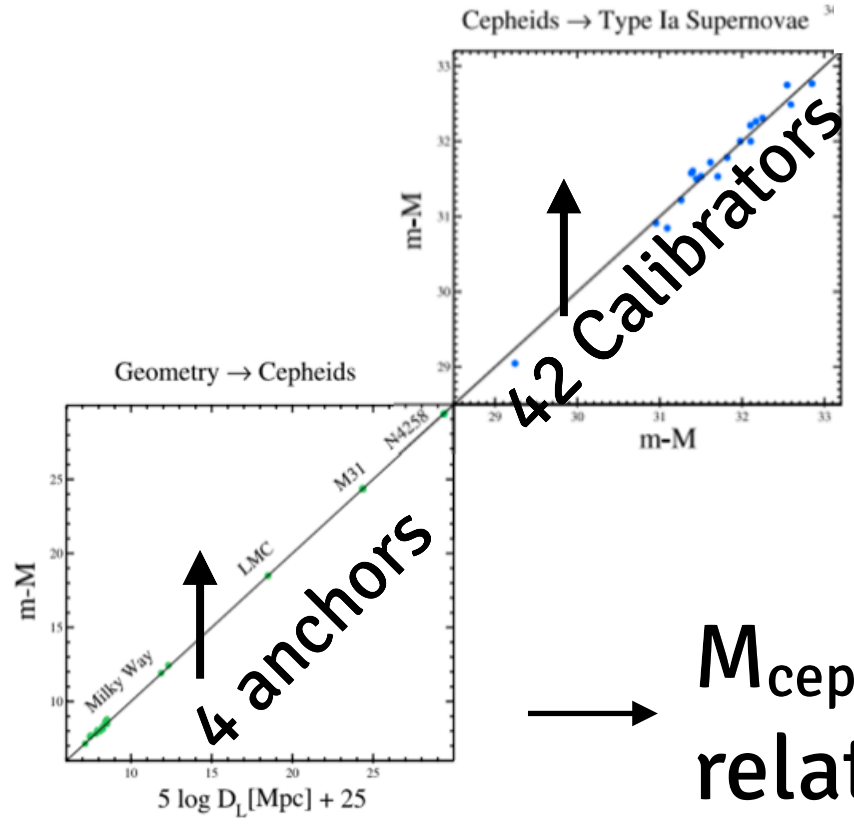

→ M_B

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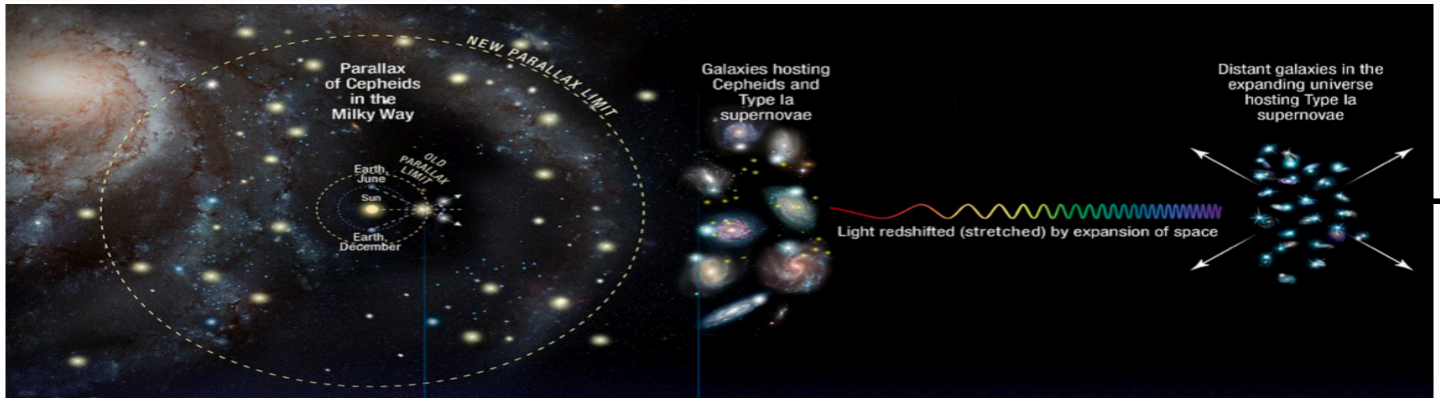
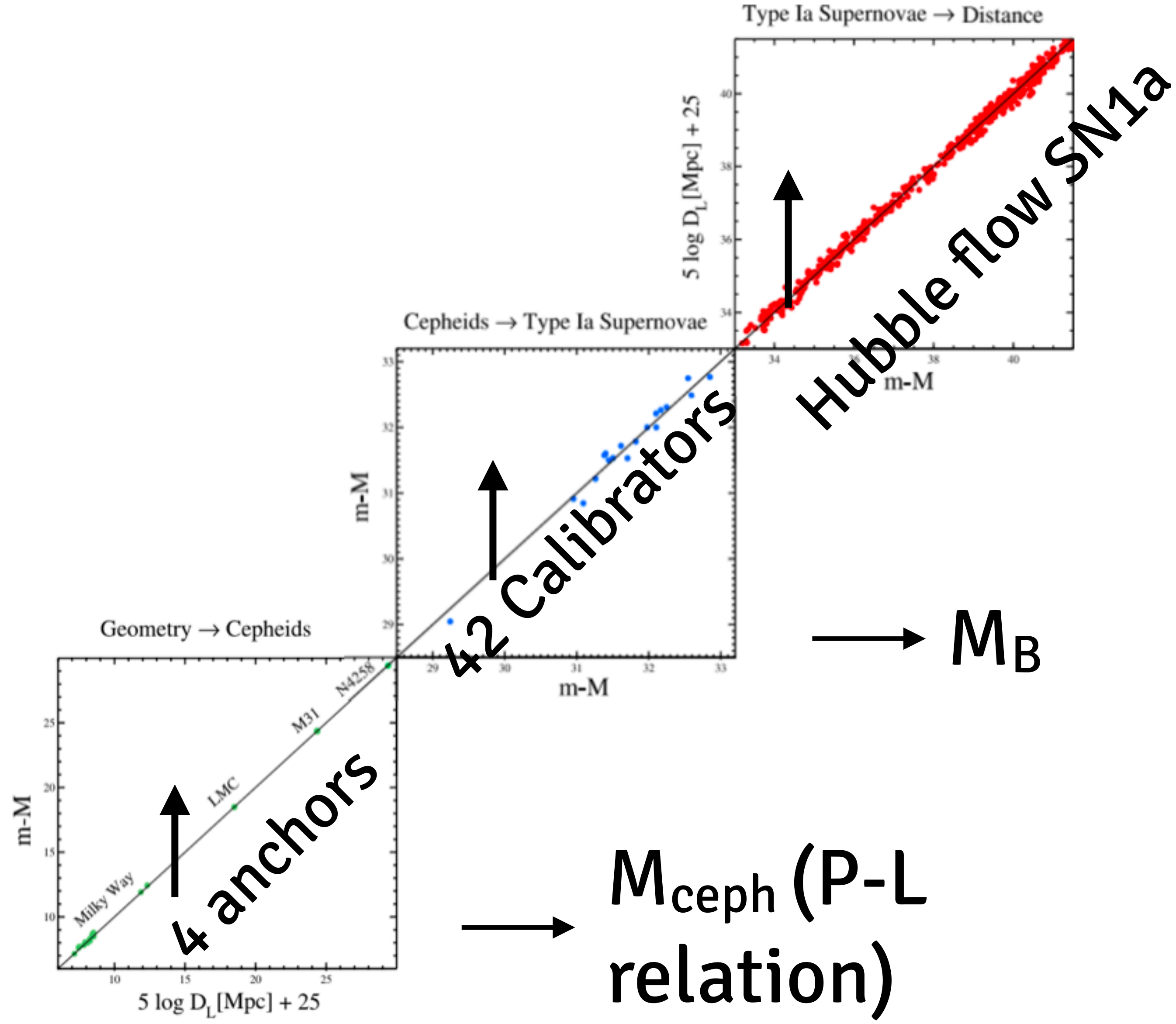


→ D_L + (measured) z



$$v \simeq cz \simeq H_0 D_L$$

→ M_B

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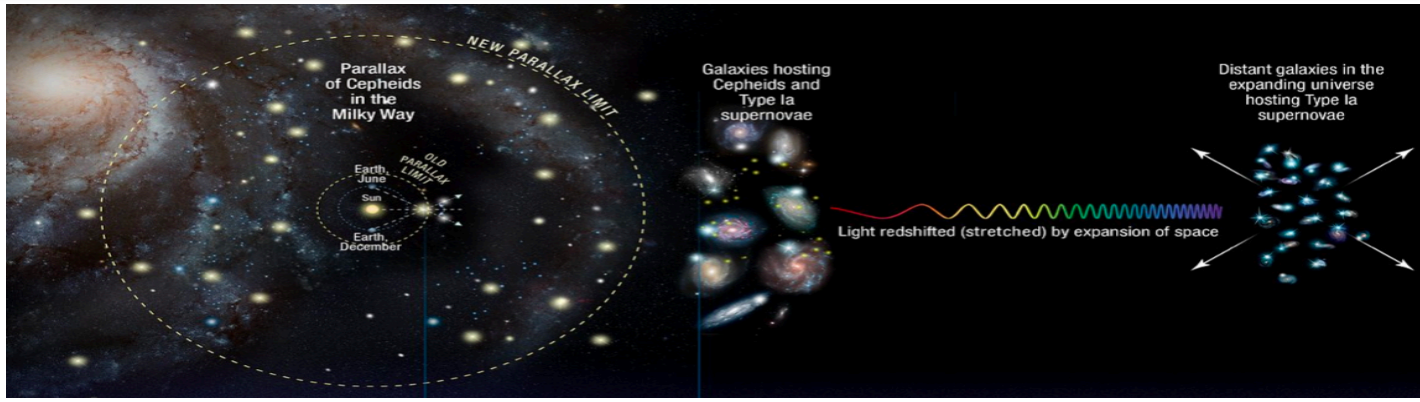
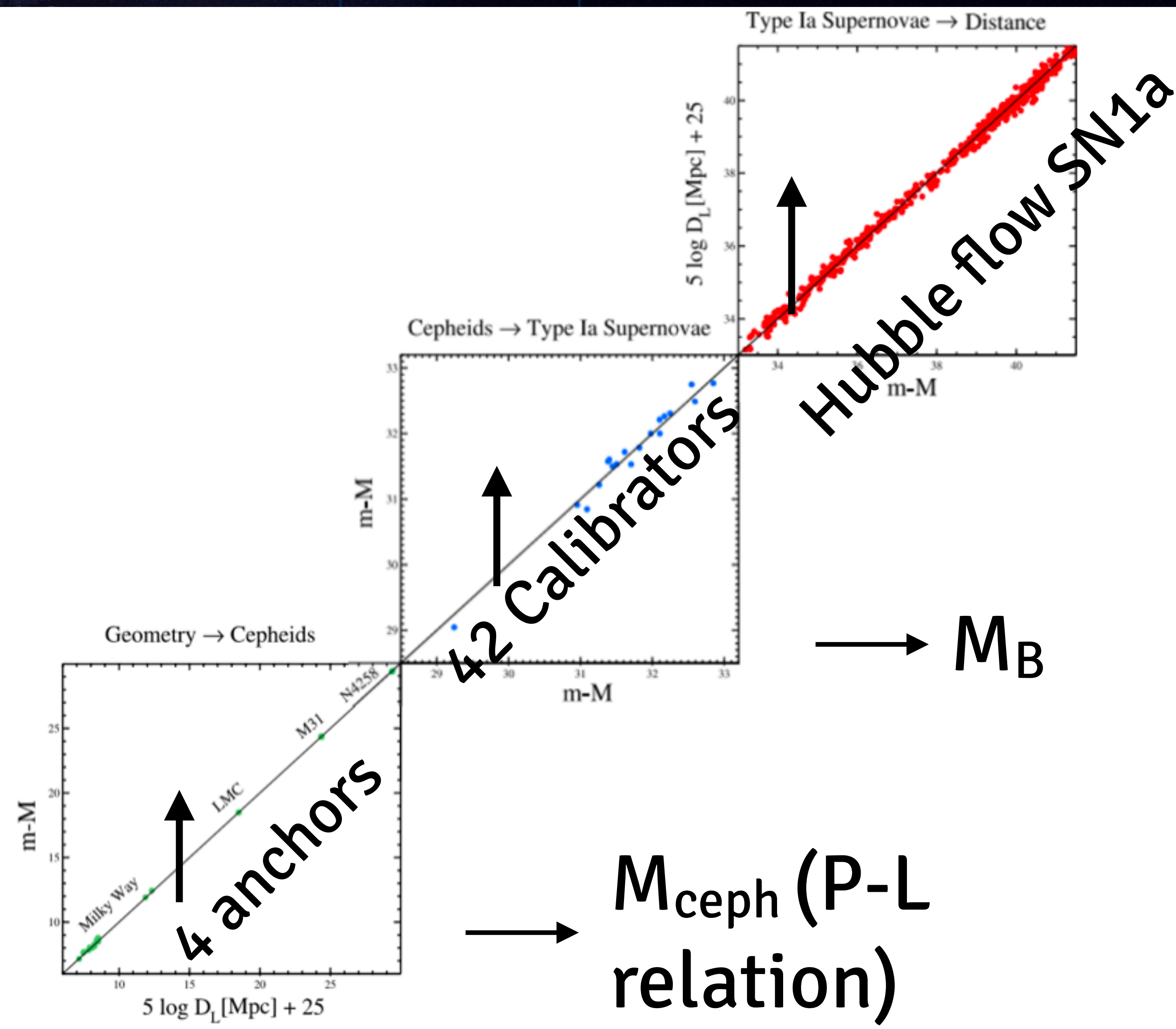


→ D_L + (measured) z



$$v \simeq cz \simeq H_0 D_L$$

$H_0 = 73 \pm 1$ km/s/Mpc

→ M_B

[Riess+1604.01424 (edited)]

→ M_{ceph} (P-L relation)

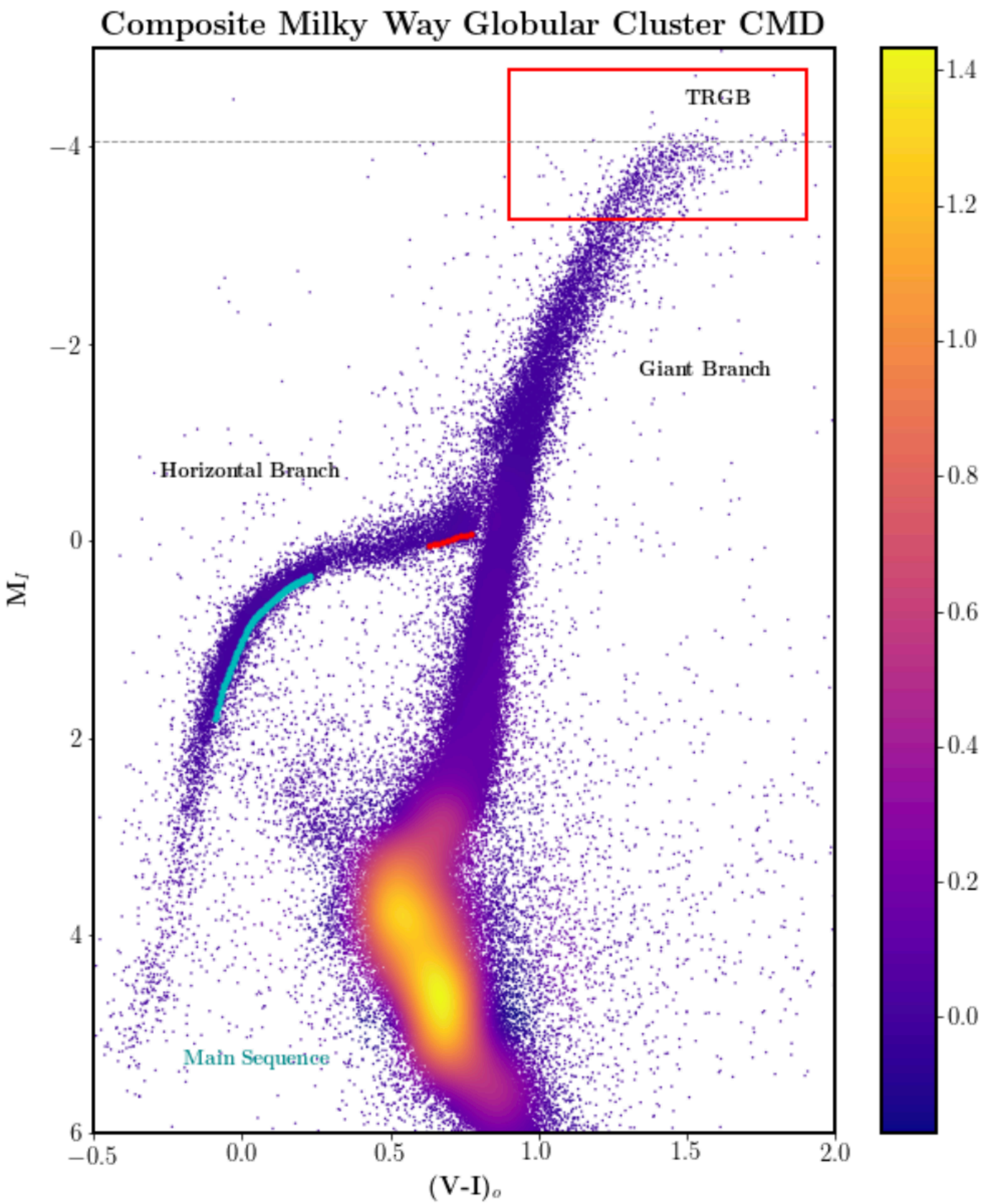
© N. Schöneberg

Systematics? A non-exhaustive list

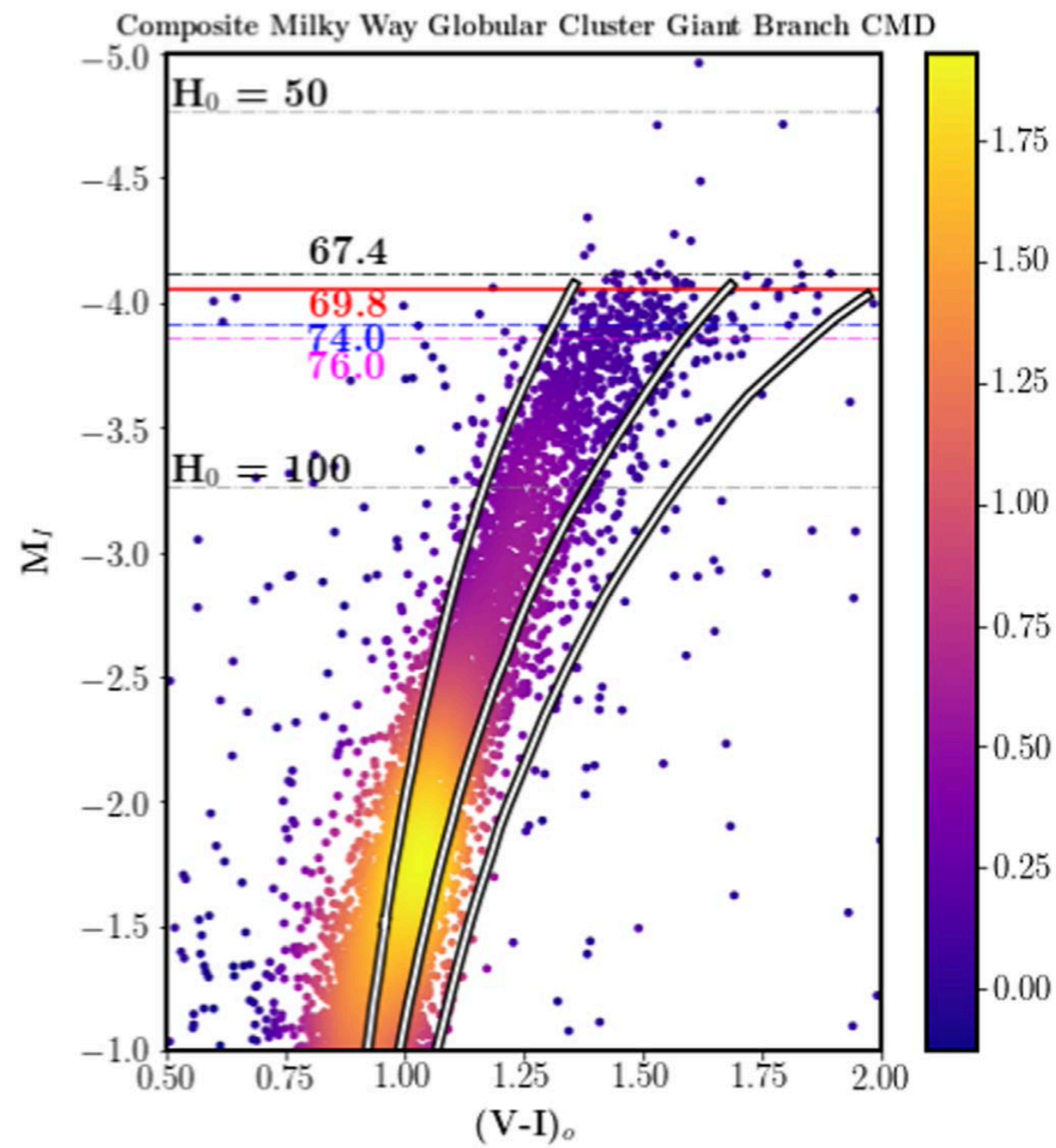
See review Di Valentino++ 2103.01183 for all relevant references

- 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*

Tip of the Red Giant branch

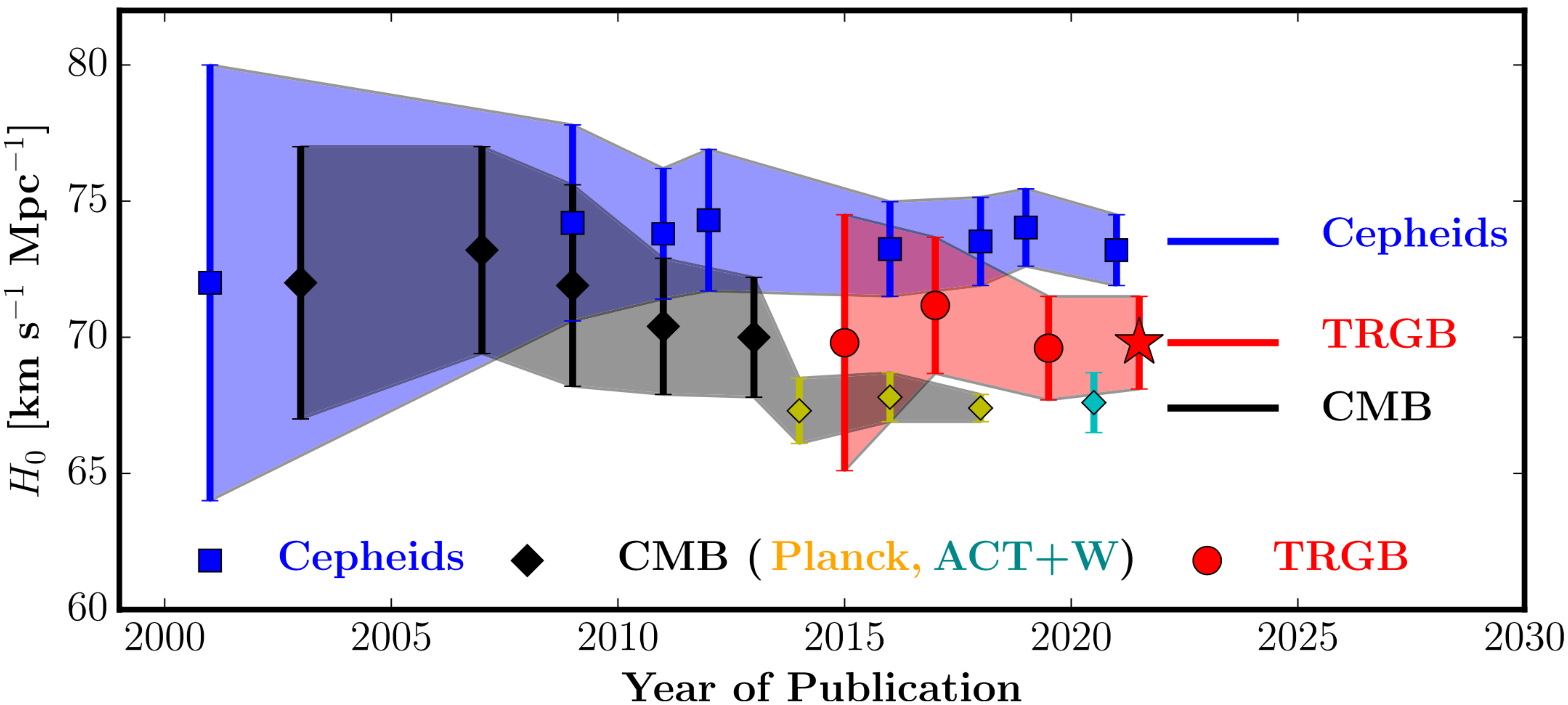


Absolute calibration of $M_{\rm TRGB}$



Freedman++ 2106.15656

The Chicago Carnegie Hubble Program



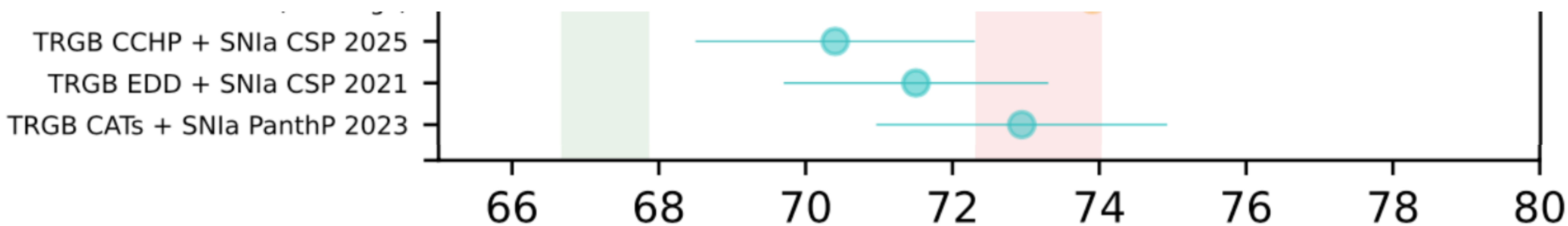
Freedman (2021)

Freedman++ 2106.15656

Tip of the Red Giant branch revisited

Table 5. Sources of Differences in H_0 Between TRGB analysis by CATs (Here), CCHP, EDD (in H_0)

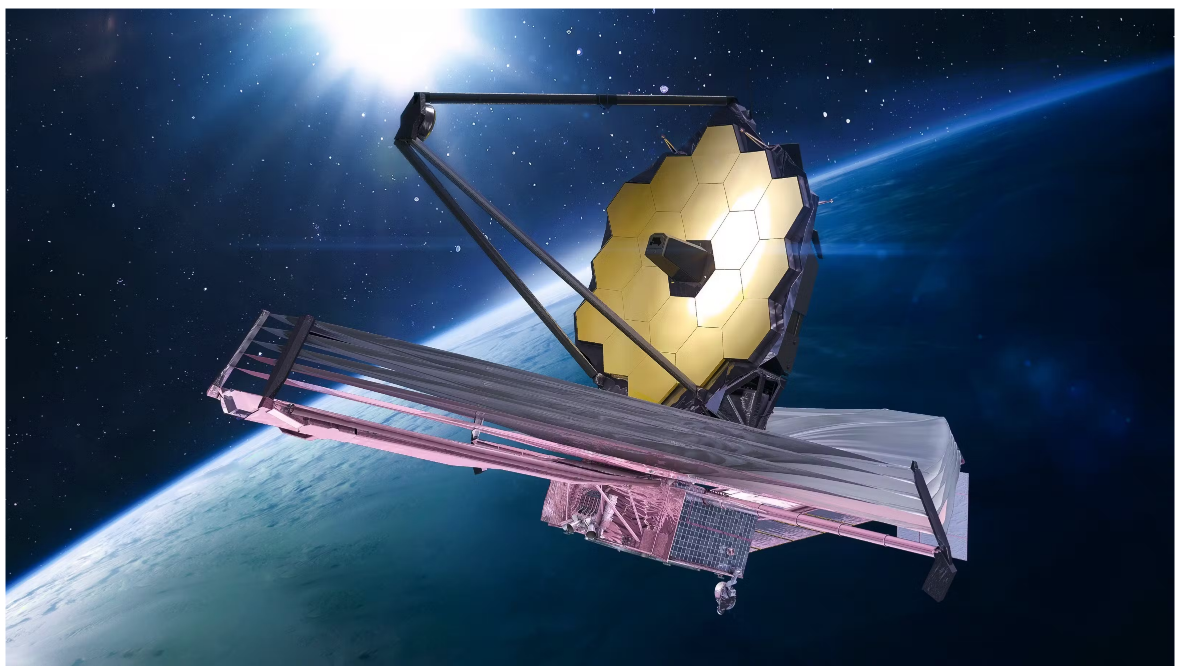
Term	ΔCCHP	ΔEDD
	(km/s/Mpc)	(km/s/Mpc)
SN Related		
1. Include SN 2021pit,2021rhu,2007on	0.6	1.3
2. No TRGB detected in N5584,N3021,N1309,N3370	0.0	0.0
3. Peculiar Flows (Pantheon+)	0.4	0.0
4. Hubble Flow Surveys (Pantheon+)	1.1	0.0
SN subtotal	**2.0**	**1.3**
TRGB Related		
5. Fiducial TRGB Calibration/Tip-Contrast Relation	1.4	−0.3
Total	**3.4**	**1.0**

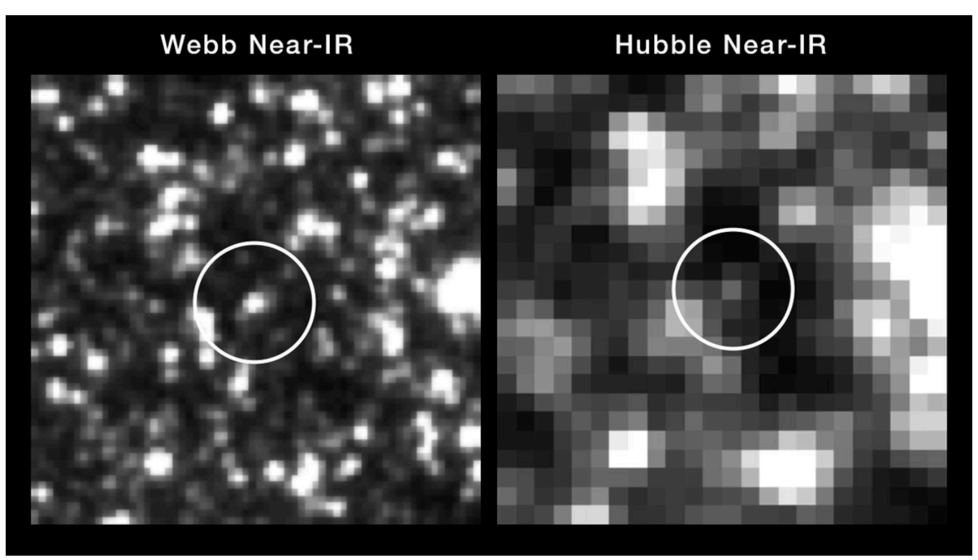


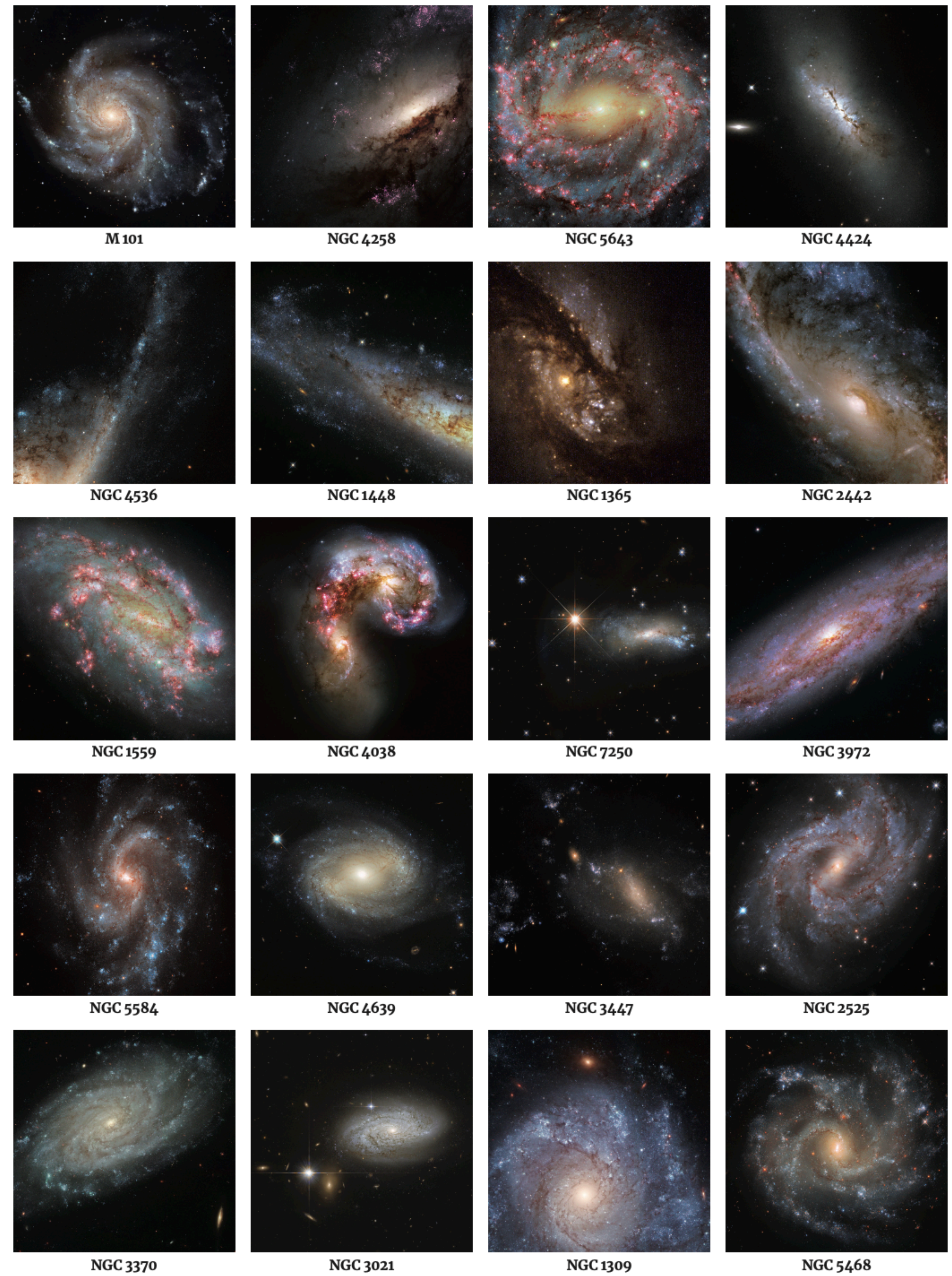
Scolnic++ 2304.06693

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.

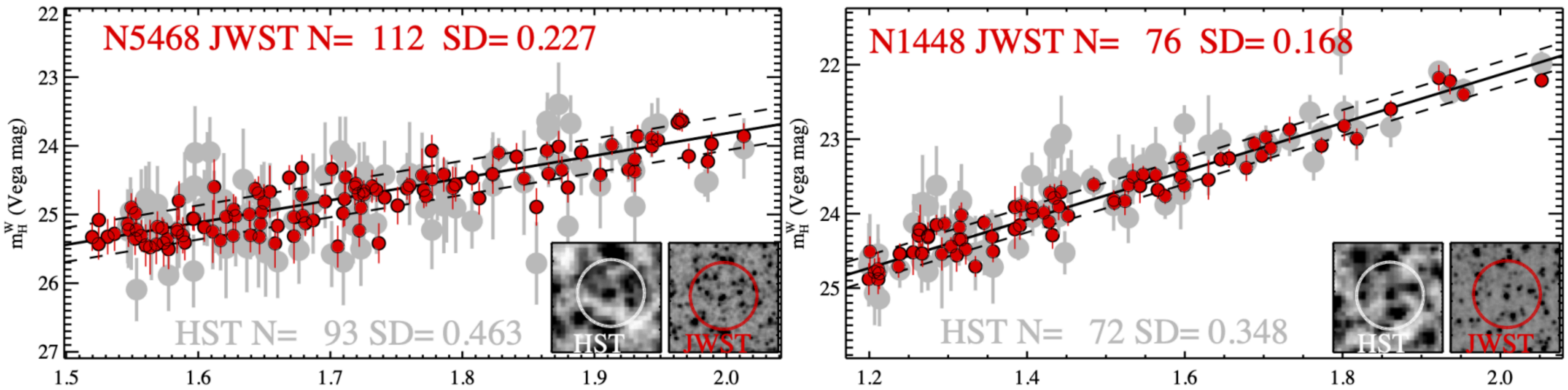






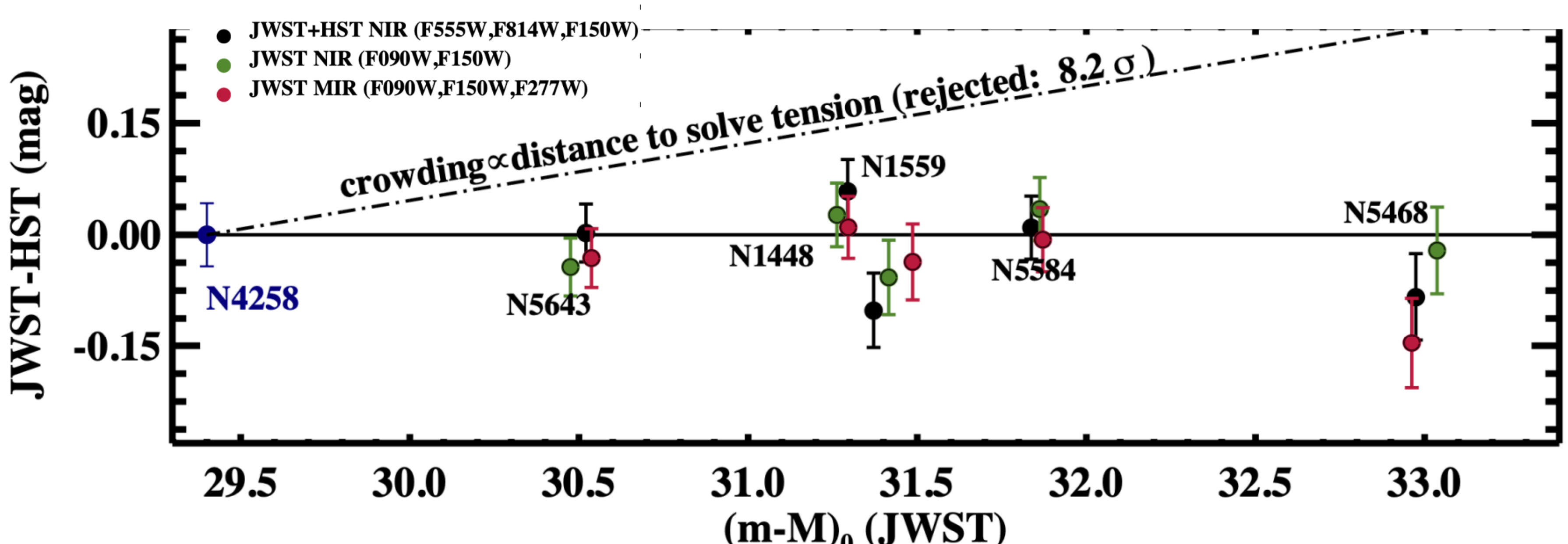
SHOES finds excellent agreement with HST

- From SH0ES: reanalysis of the PL relations in 8 SN1a hosts galaxies, excellent agreement with HST



Riess++ 2401.04773

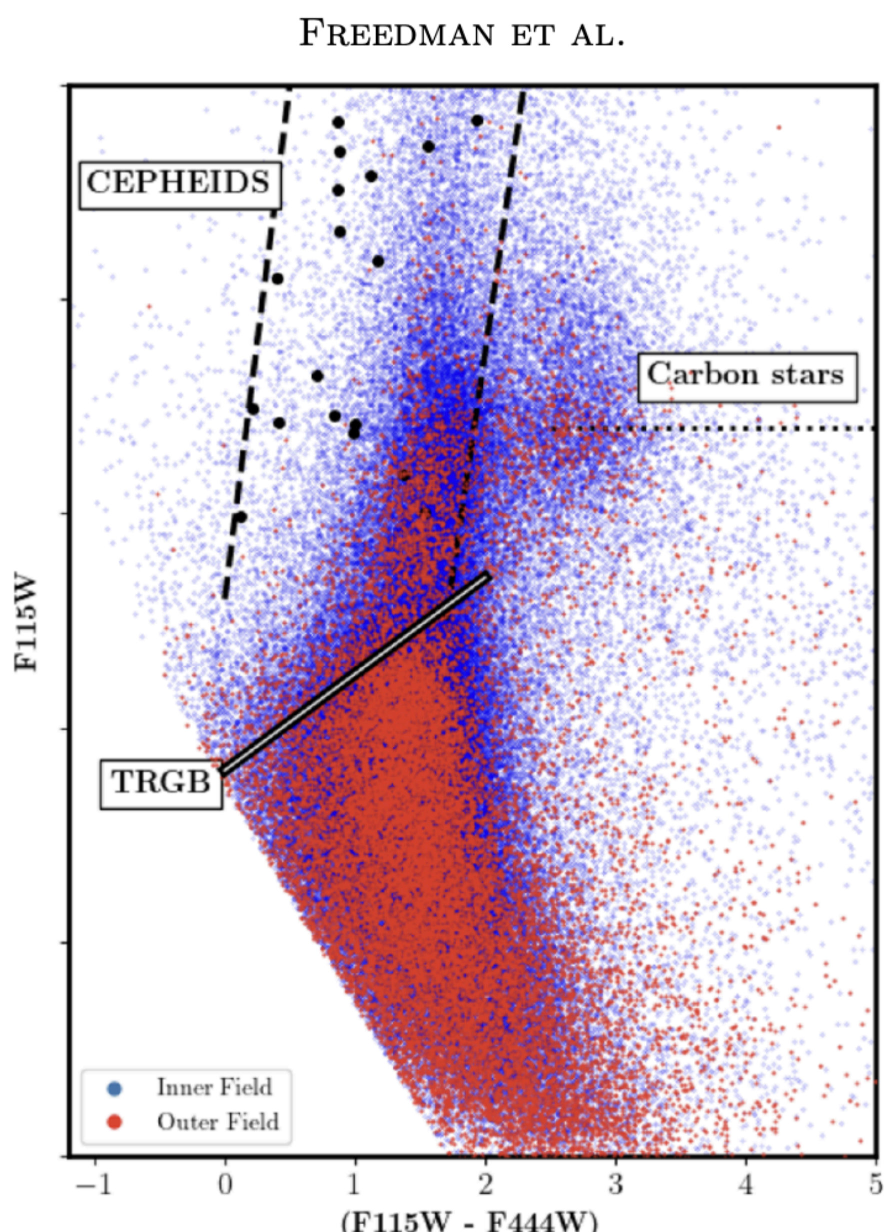
- Rejects "crowding" of cepheids as an explanation for the tension



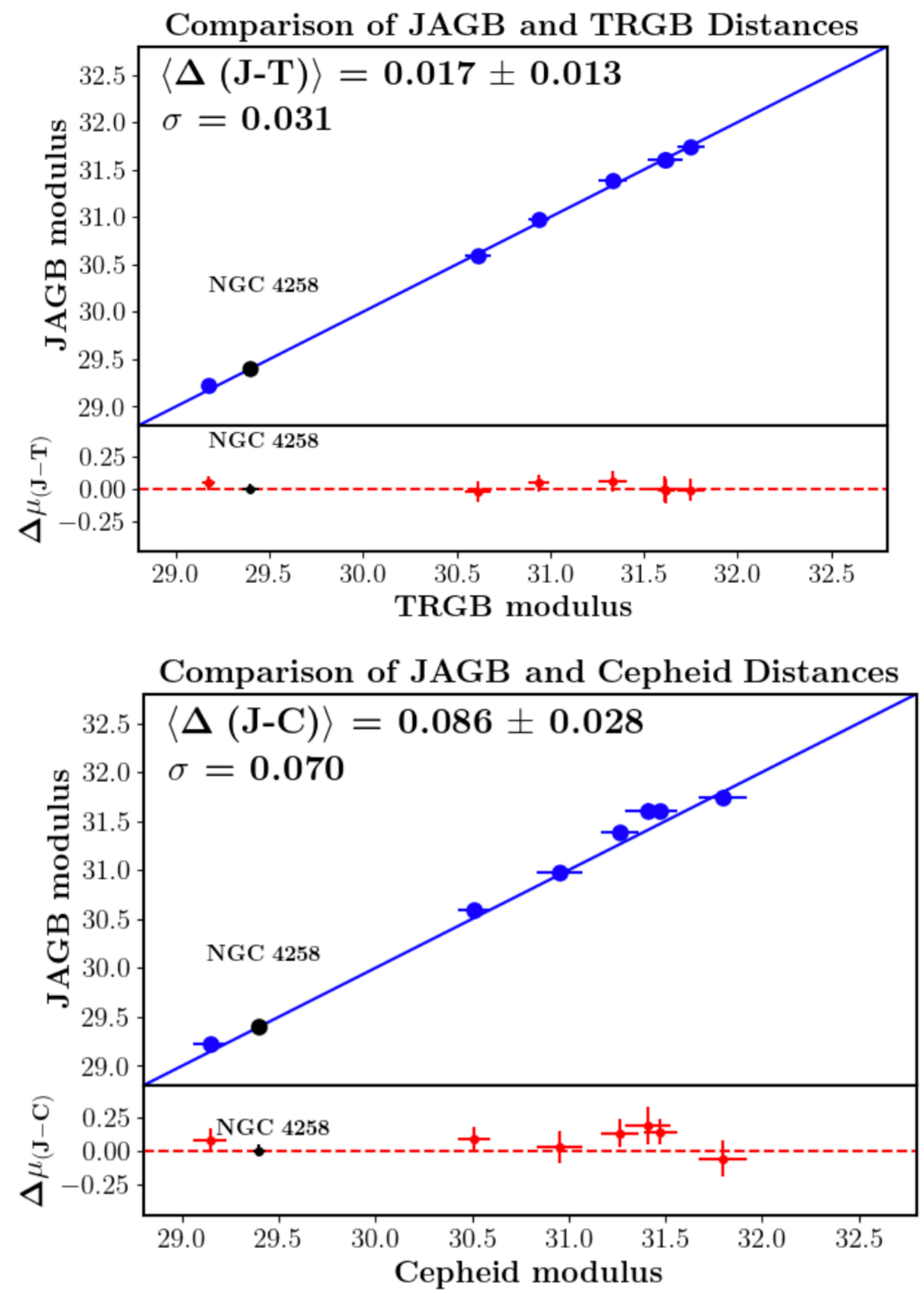
Riess++ 2401.04773

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.



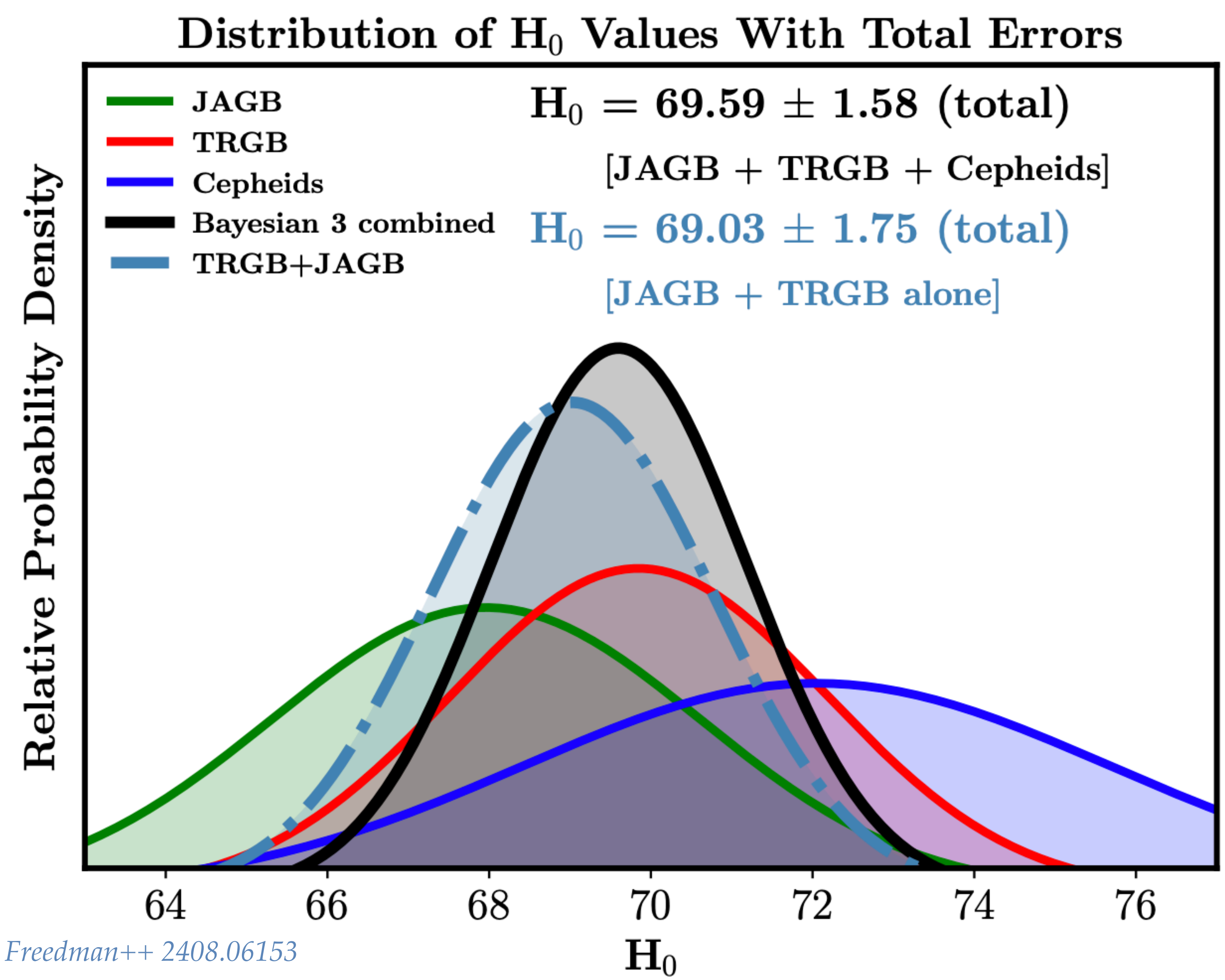
Freedman++ 2408.06153



- 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.

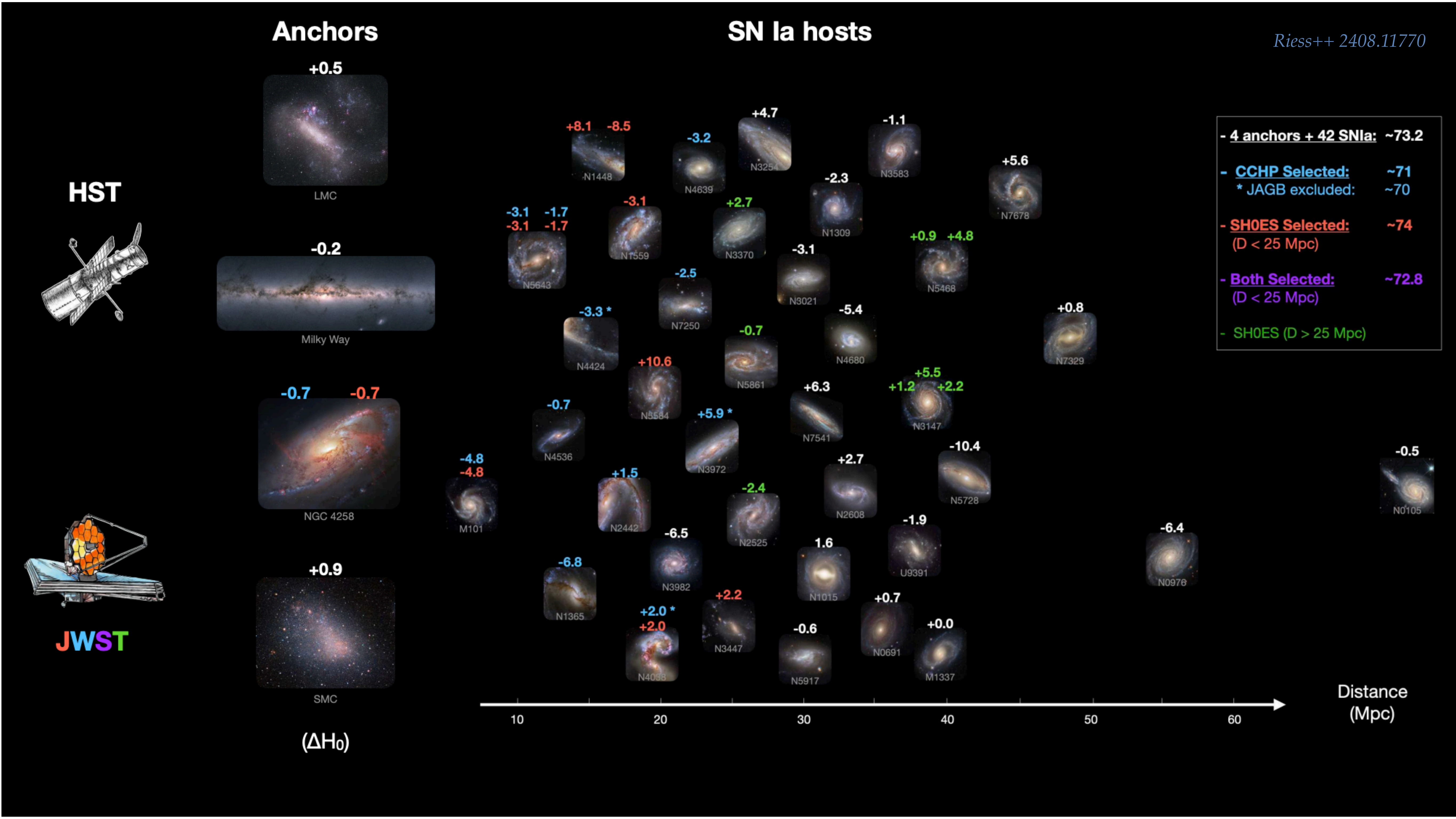


Freedman++ 2408.06153

Is this the end of the Hubble tension?

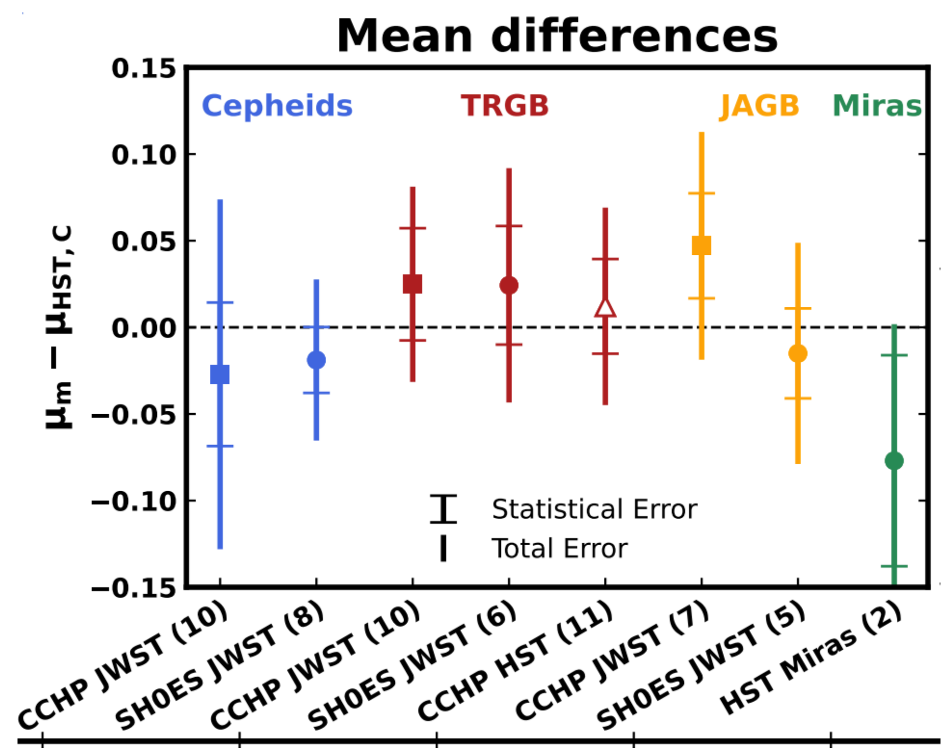
HST provides a 'complete' picture

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

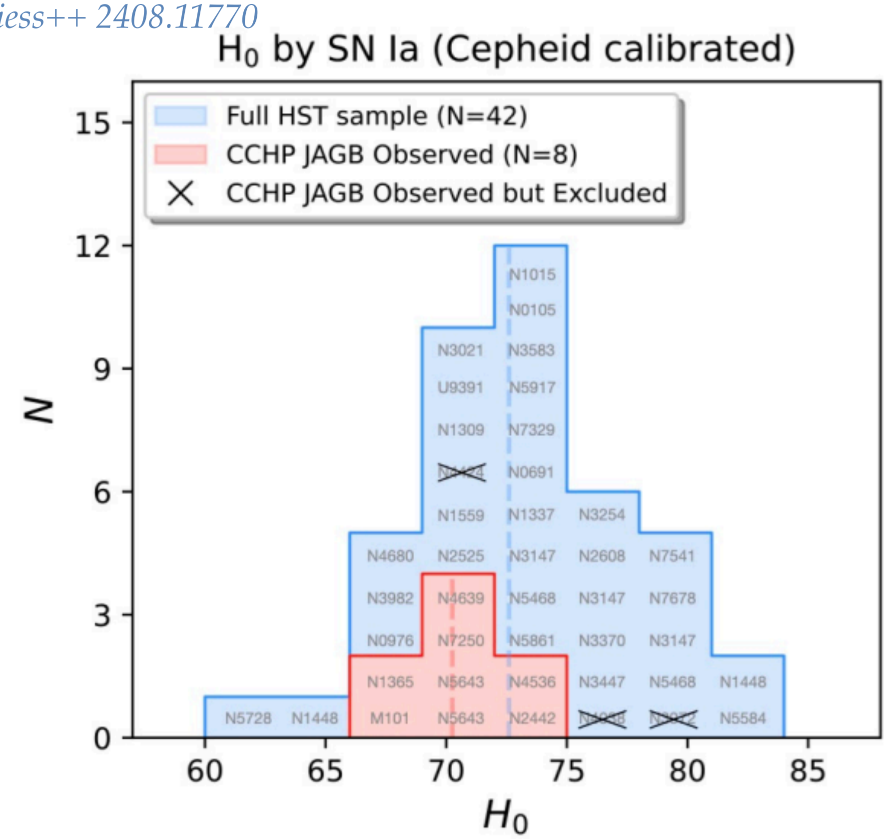


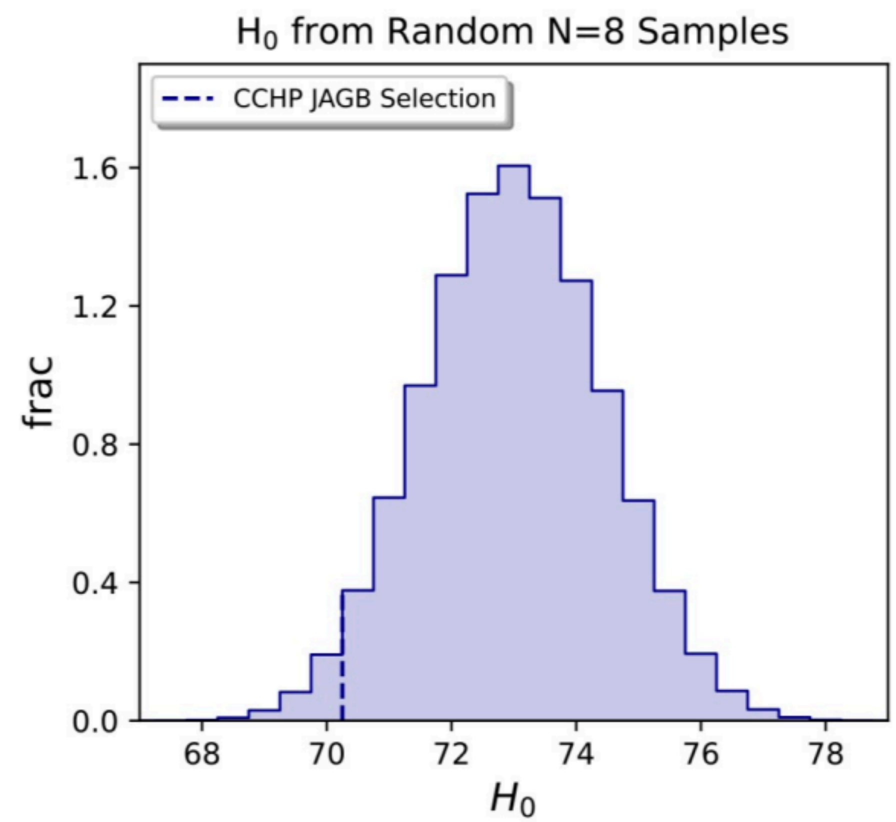
SHOES suggests a 'bias low' in CCHP samples

- 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!

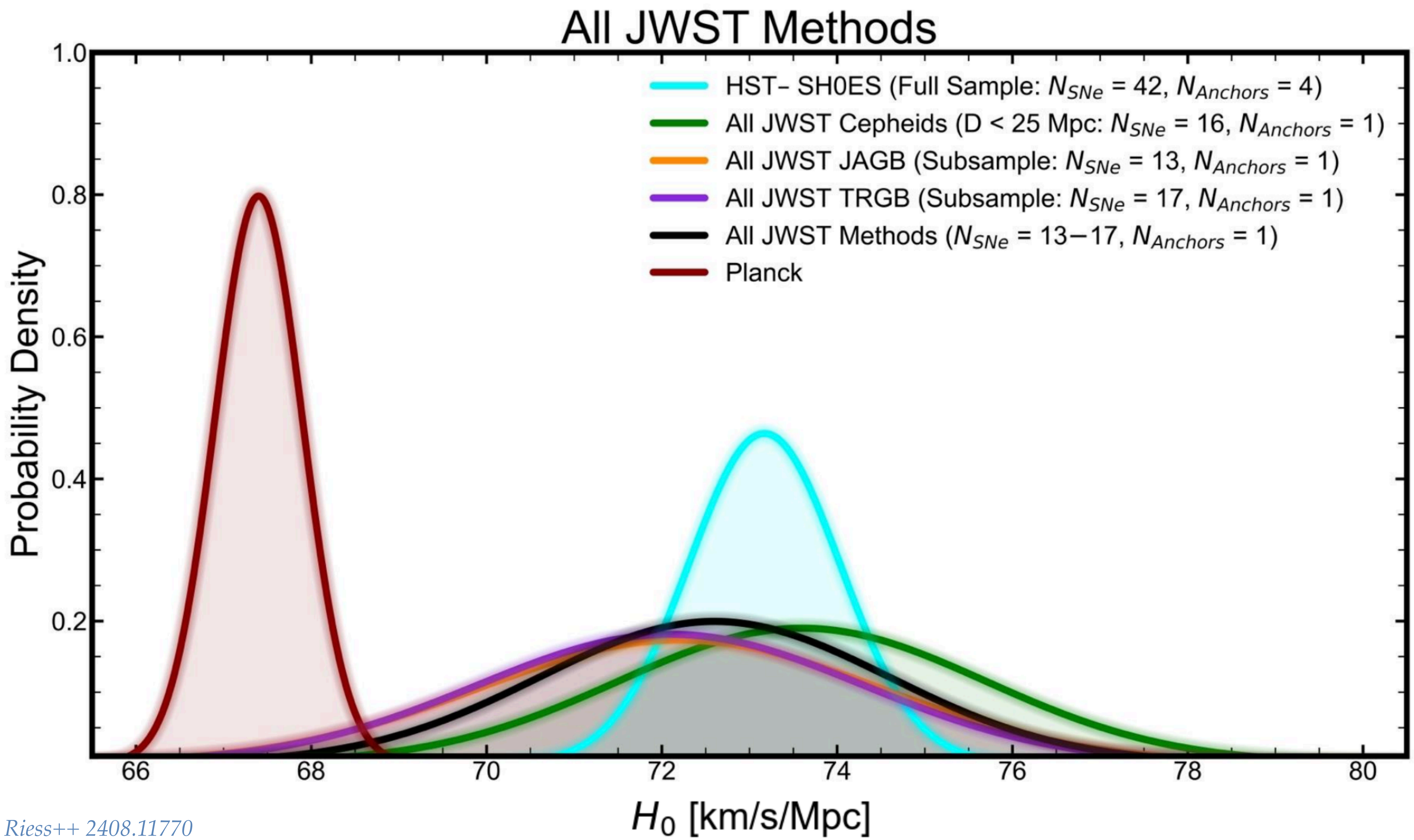


Riess++ 2408.11770





SHOES confirms the Hubble tension with JWST



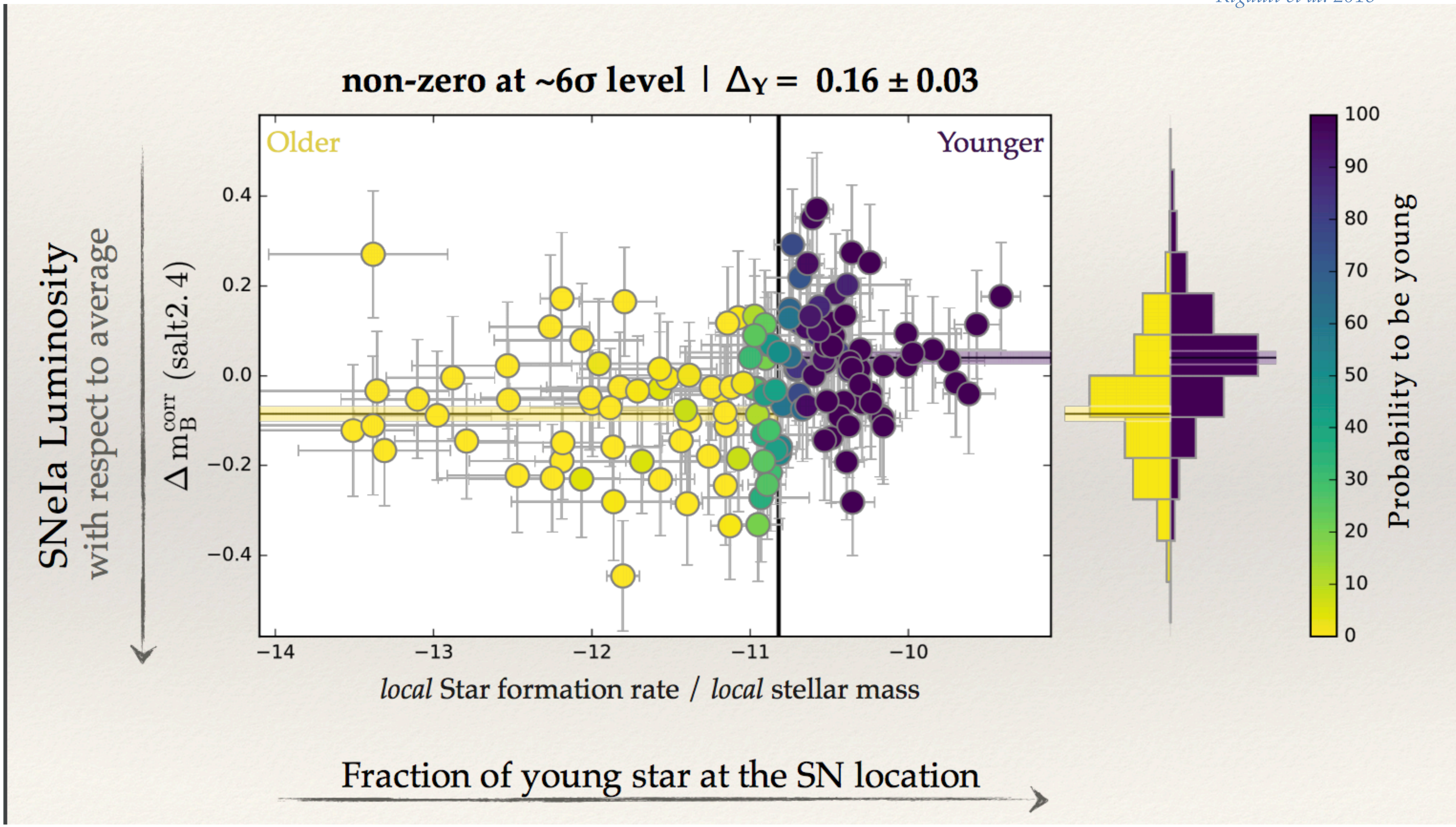
Riess++ 2408.11770

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

The Hubble tension is alive and well!

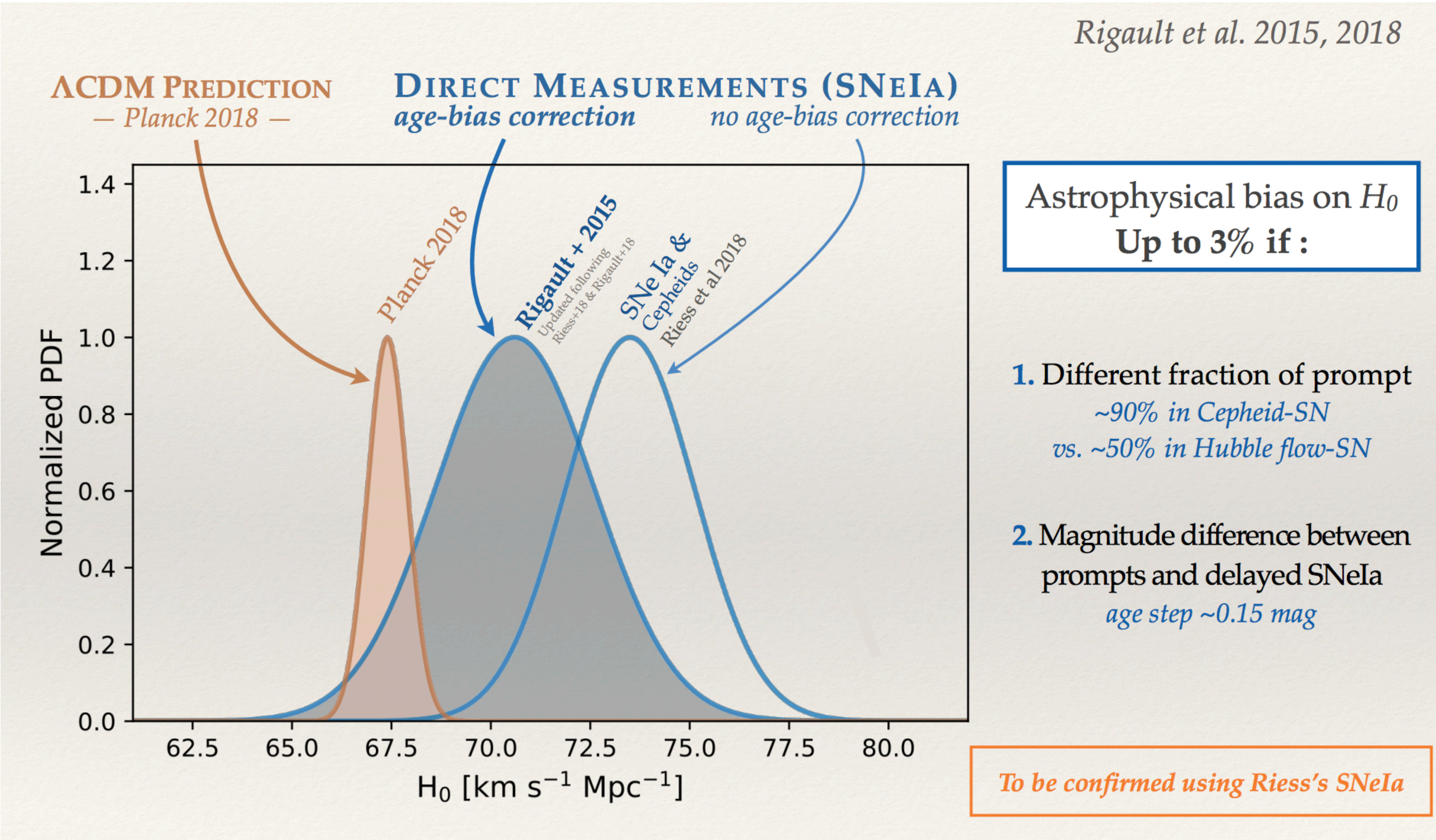
The progenitor bias

Rigault et al. 2018



Slide by M. Rigault, IAP 2018

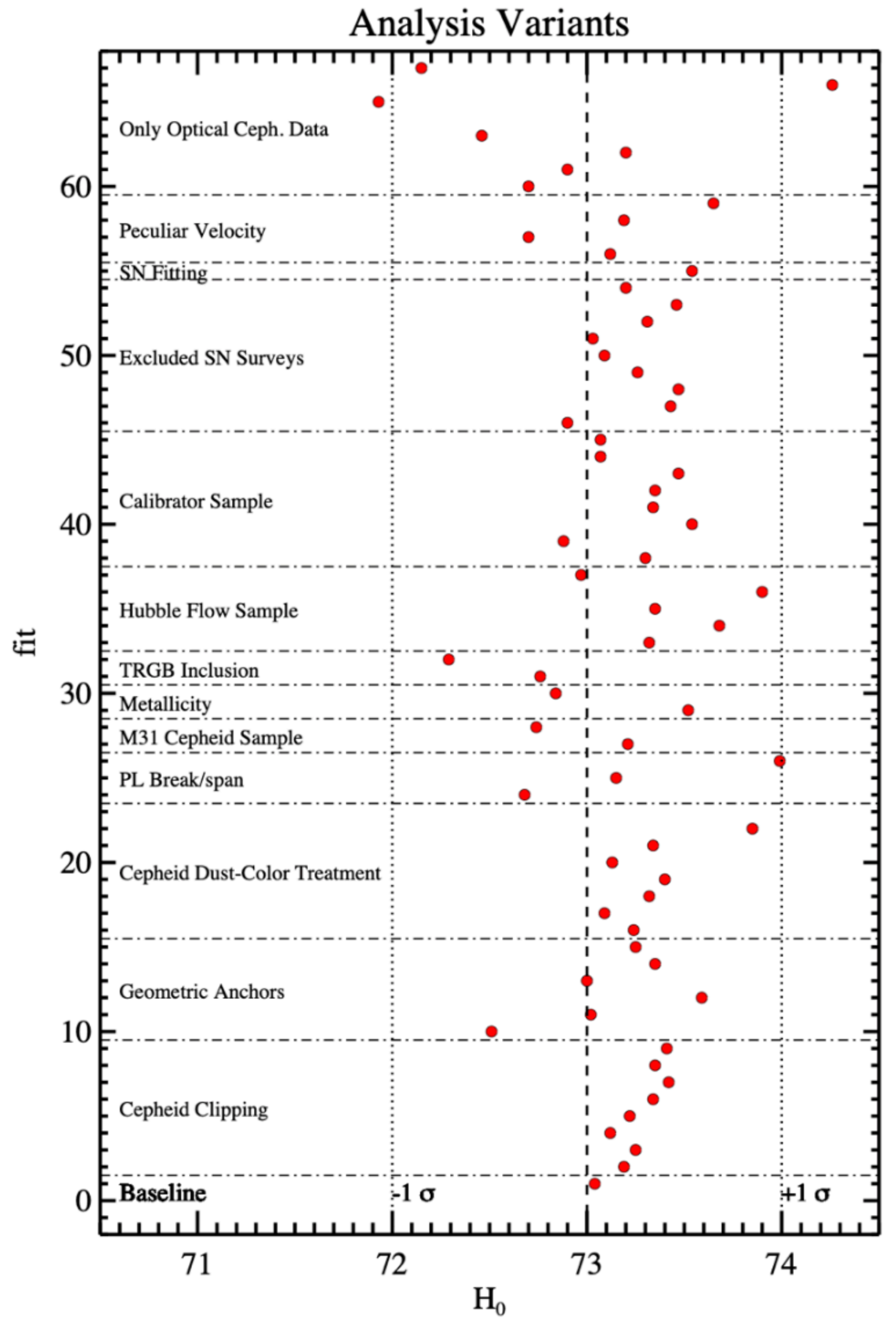
Impact for H_0



Slide by M. Rigault, IAP 2018

SHOES estimates of systematic uncertainties

Analysis Variants: 12 categories, 67 variants, bifurcations, extensions, etc



- Optical Cepheid data only (72.7)
- Different pec. vel map or none (73.1,72.7)
- SN scatter ind. wave+mass step (73.5)
- No pre-2000 SNe (73.2)
- closest half hosts (73.1)
- most crowded half (73.4)
- least crowded half (73.3)
- Skip "local hole" z>0.06 (73.4)
- All host types (73.3)
- include TRGB (consistent) jointly (72.5)
- No metallicity term (73.5)
- Break in PL at P=10 days (72.7)
- No dust correction (74.8)
- Individual host dust law (73.9)
- Free param dust law (73.3)
- Low R_V=2.5 dust law (73.2)
- Two of three anchors (73.0,73.4,73.2)
- No outlier rejection (73.4)

Bottom line: hard to get below 72.5, above 73.5, propagate dispersion as extra systematic

A local void?

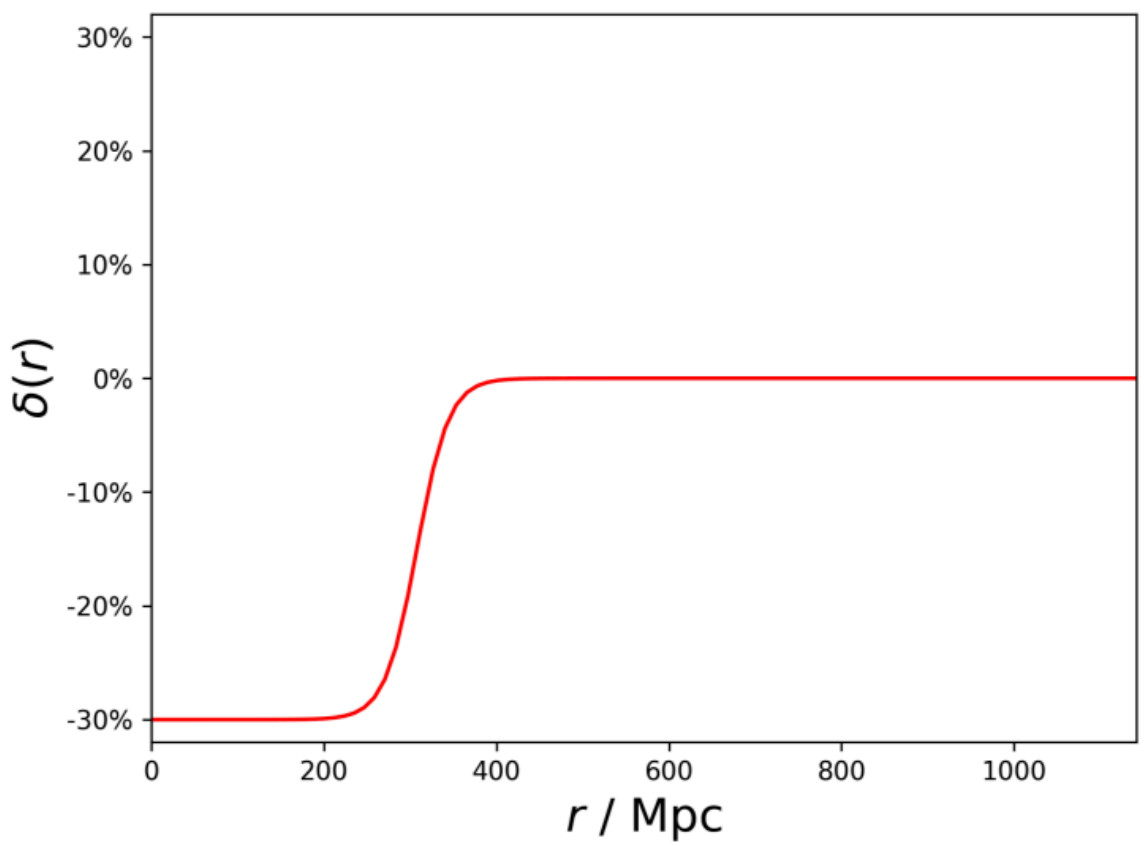
Kenworthy++ 1901.08681

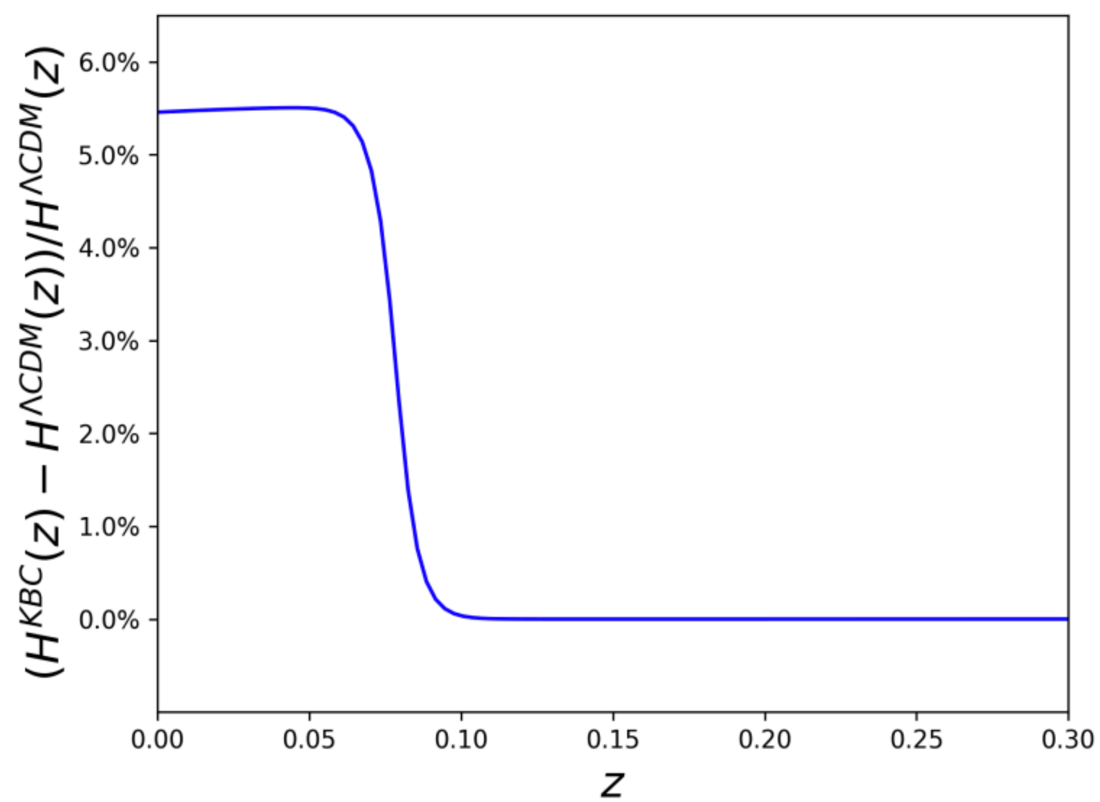
$$\frac{\Delta H}{H} = -\frac{1}{3}\delta \cdot f$$

$$ds^2 = -dt^2 + \frac{R'^2(r,t)}{1+2r^2k(r)\tilde{M}^2}dr^2 + R^2(r,t)d\Omega$$

$$\delta(r) = \delta_V \frac{1-\tanh((r-r_V)/2\Delta_r)}{1+\tanh(r_V/2\Delta_r)}$$

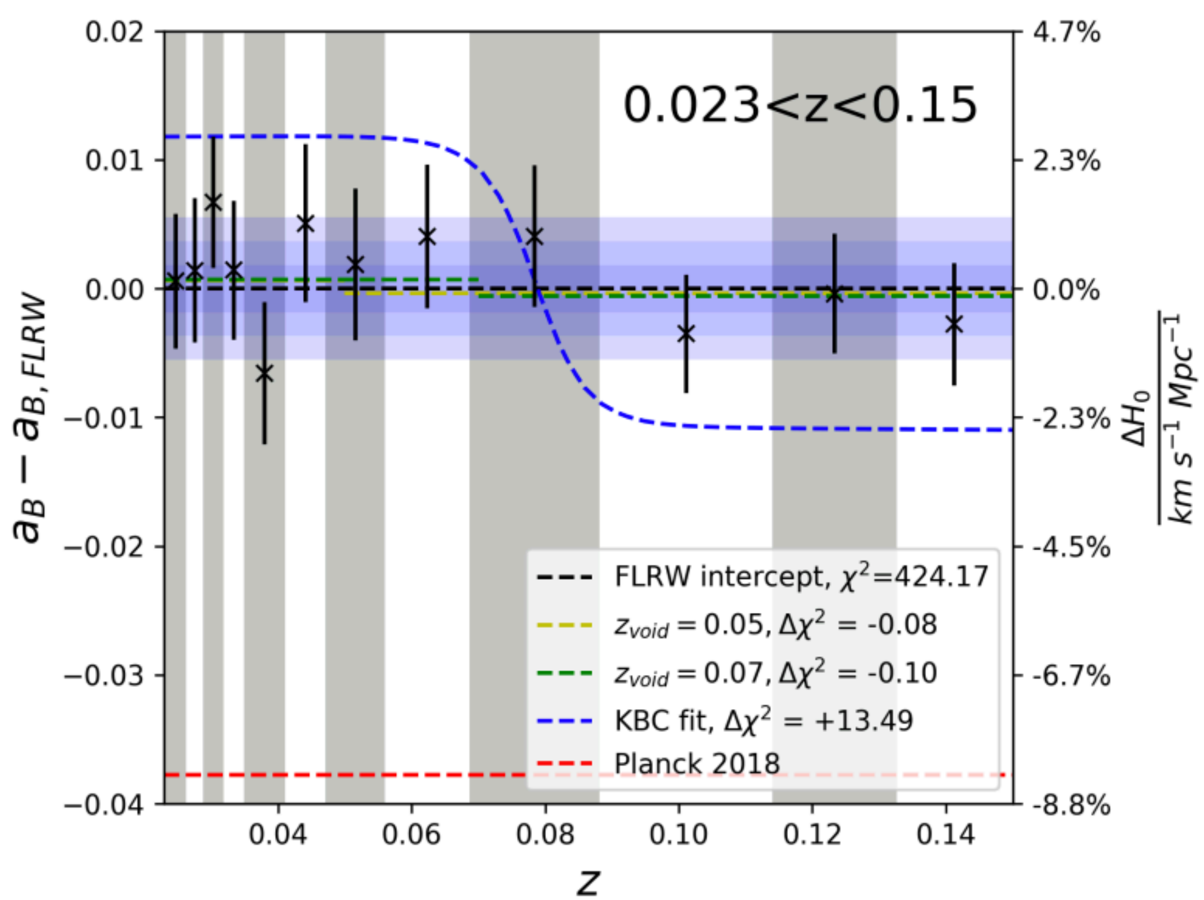
$$\frac{\dot{R}(r,t)^2}{R(r,t)^2} = H_0(r)^2 \cdot \left(\Omega_M(r)\frac{R_0(r)^3}{R(r,t)^3} + \Omega_k(r)\frac{R_0(r)^2}{R(r,t)^2} + \Omega_\Lambda(r)\right)$$

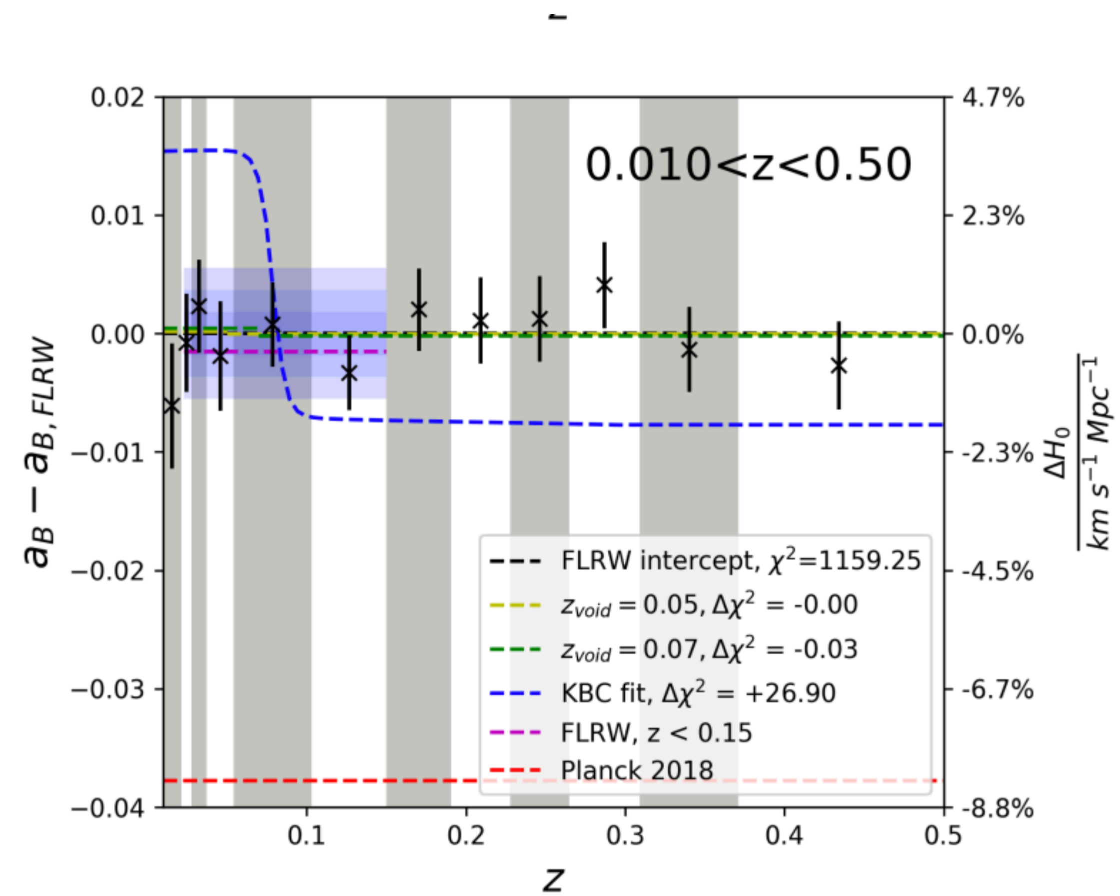




Incompatible with the SNIa data

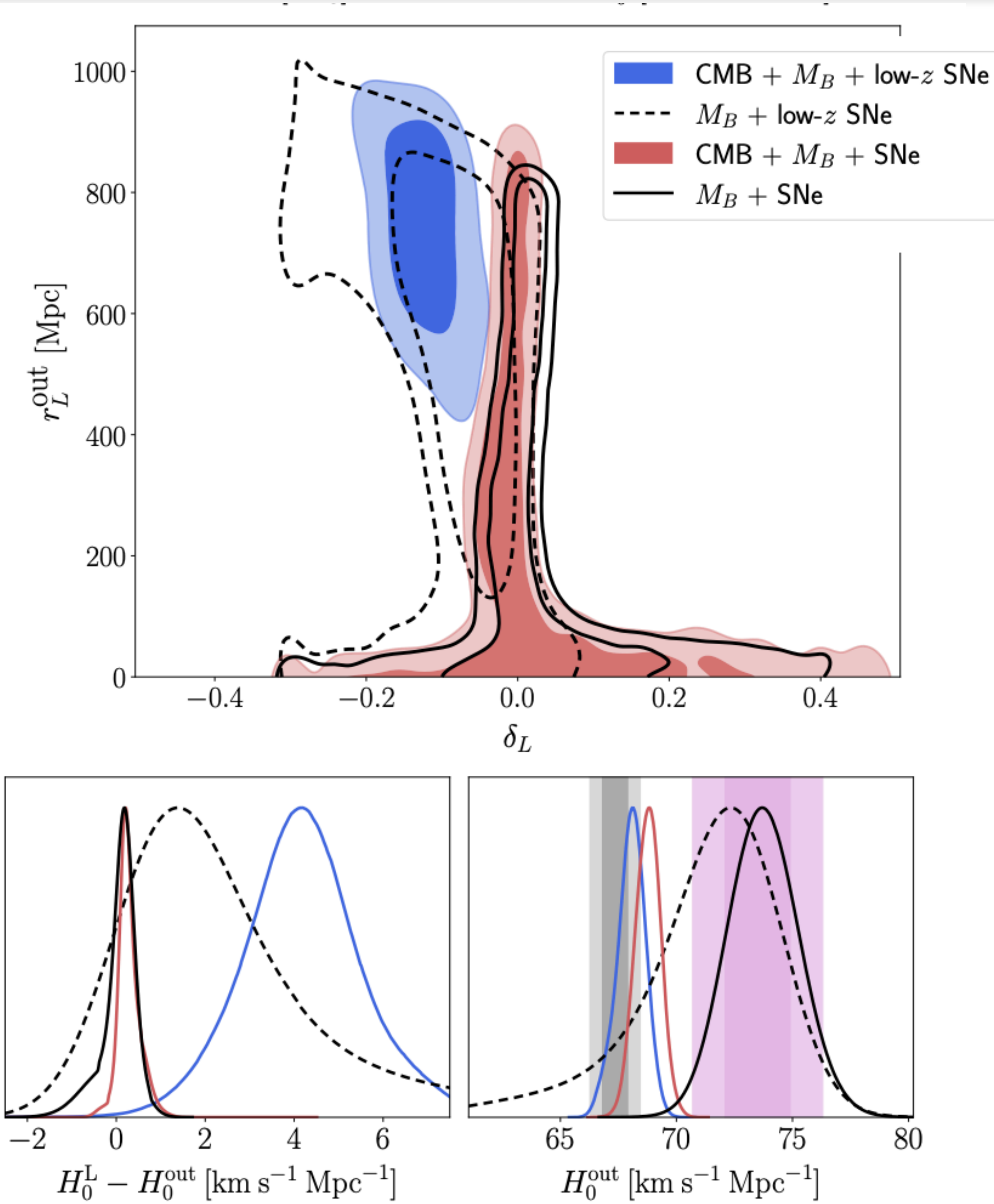
Kenworthy++ 1901.08681



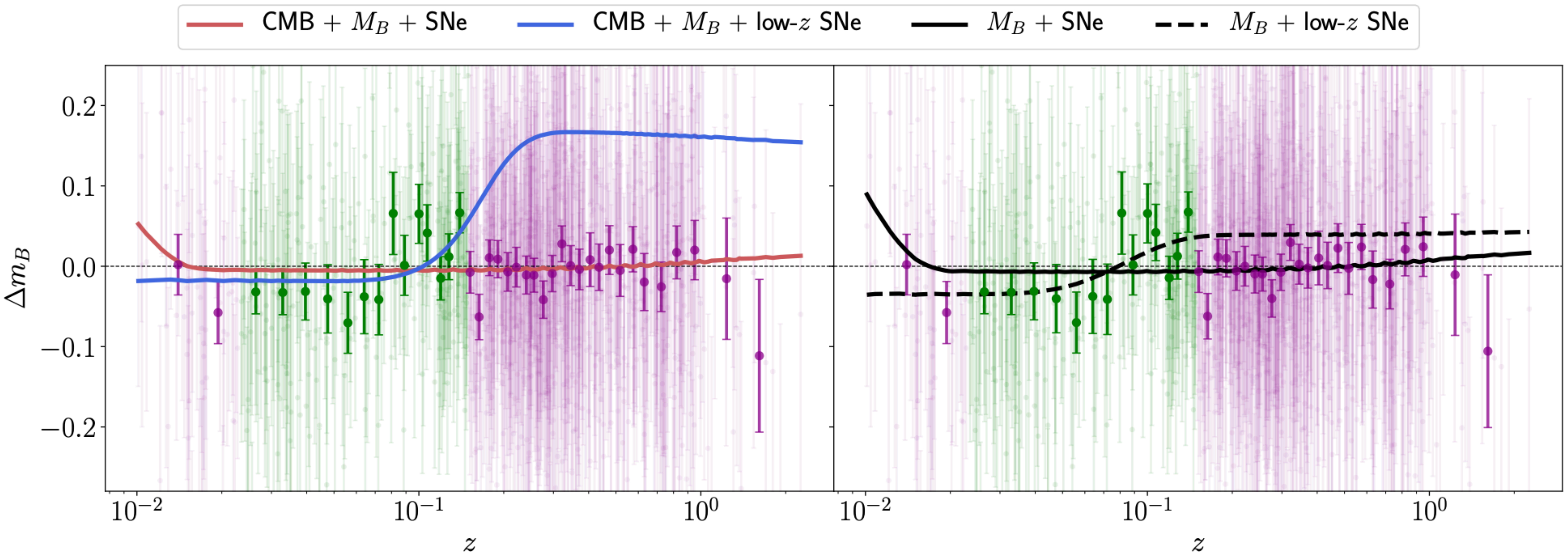


Impact of local void beyond KBC

Camarena++ 2205.05422



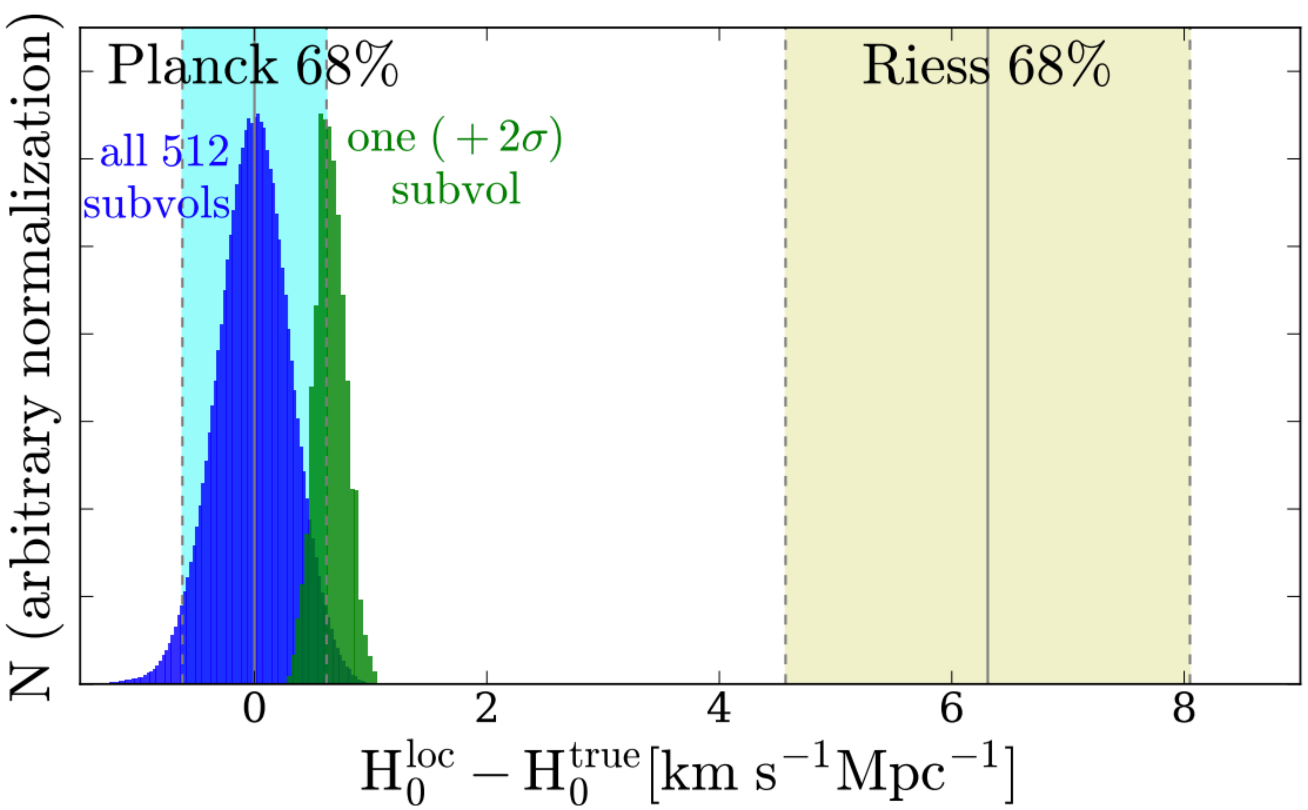
It cannot explain the Hubble tension



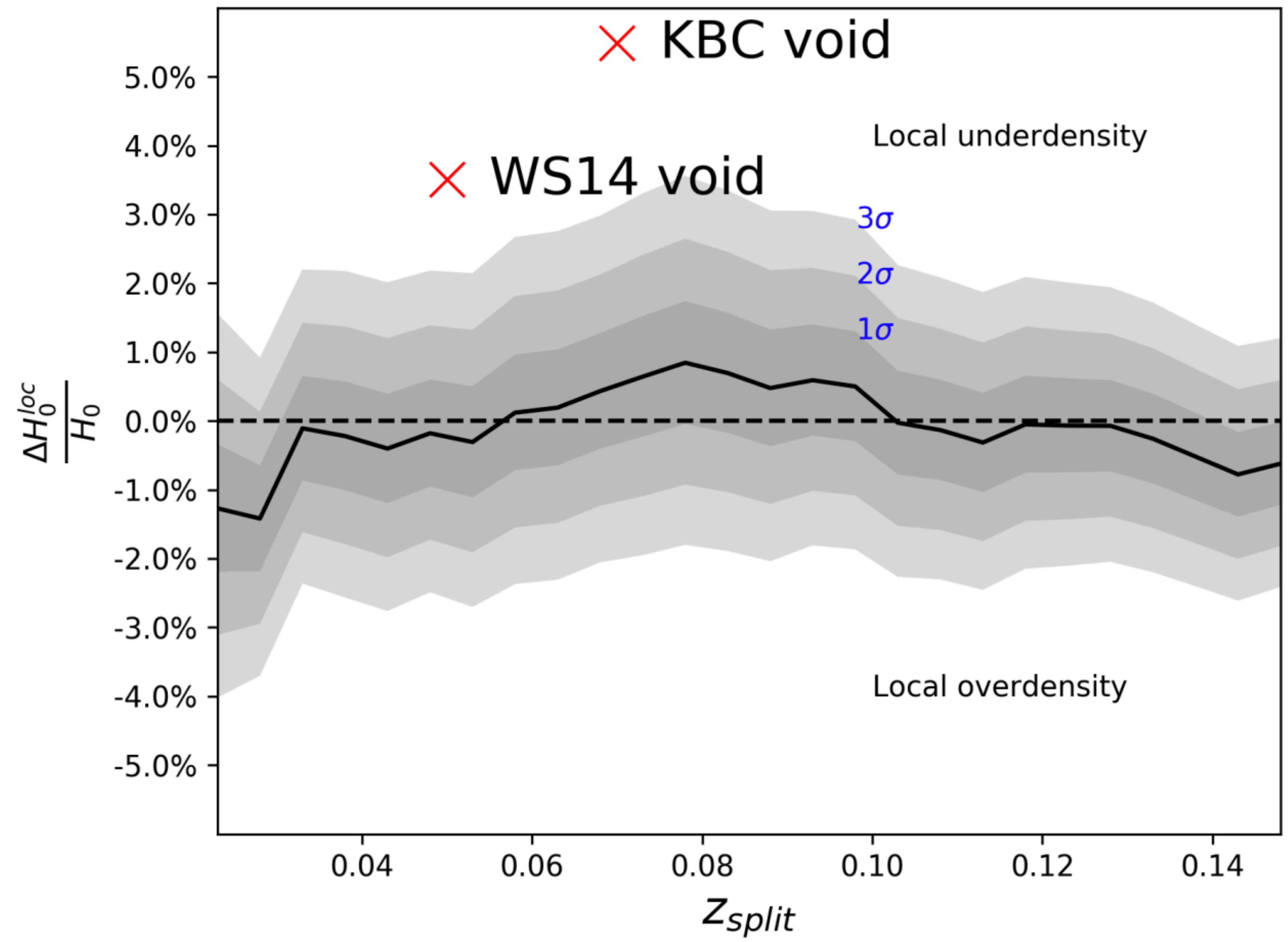
Camarena++ 2205.05422

Sample variance cannot explain the Hubble tension

$$\Delta H_0^{\rm loc} = \frac{1}{N}\sum_{i=1}^{N}\frac{v_{r,i}}{r_i}$$



Wu&Huterer 2309.05749

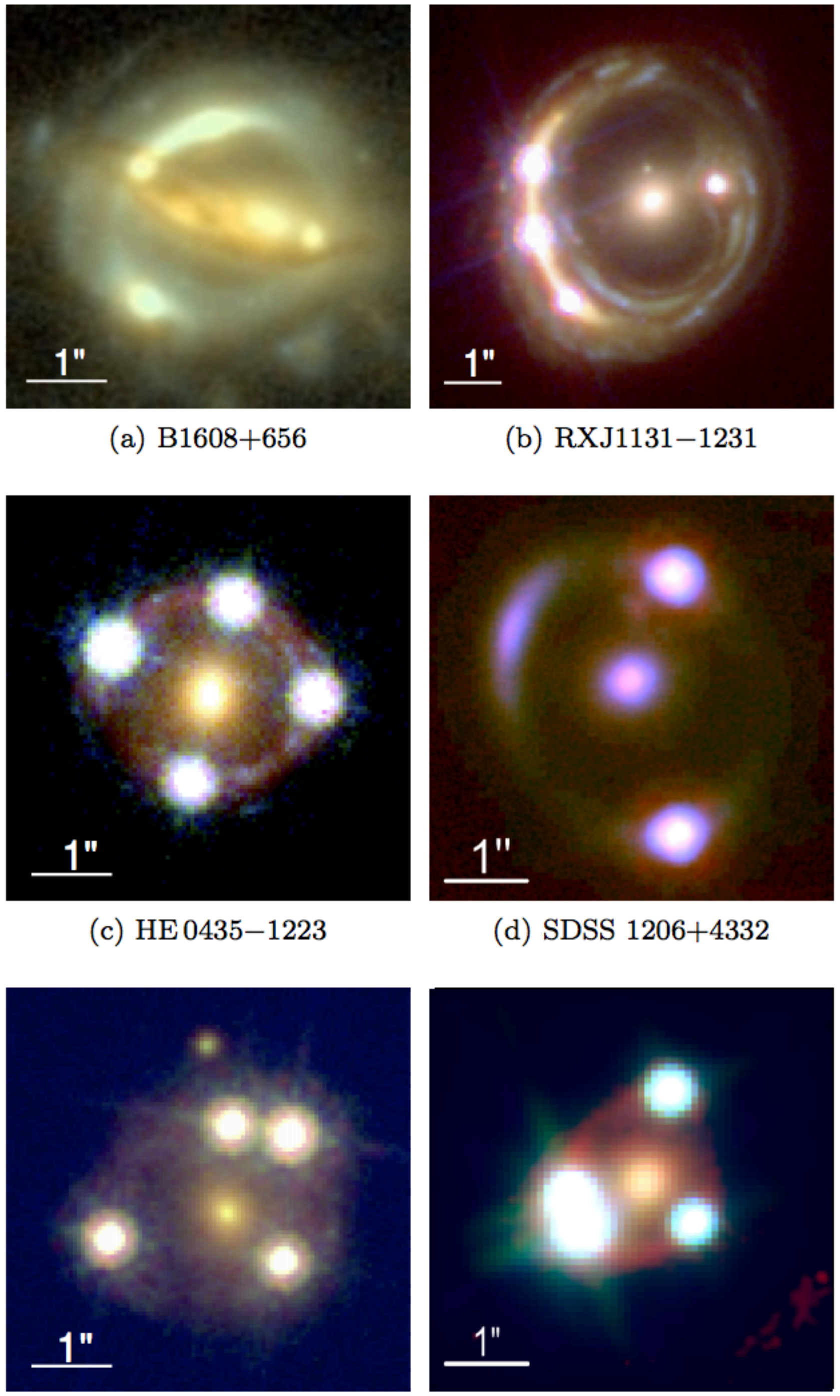


Kenworthy++ 1901.08681

$$\sigma_{\rm sample\,variance} = 0.31\,{\rm km\,s^{-1}Mpc^{-1}}$$

$$|H_0^{\rm Planck} - H_0^{\rm loc}|/\sigma_{\rm sample\,variance} \simeq 20.$$

Strongly lensed Quasars measurement of H0



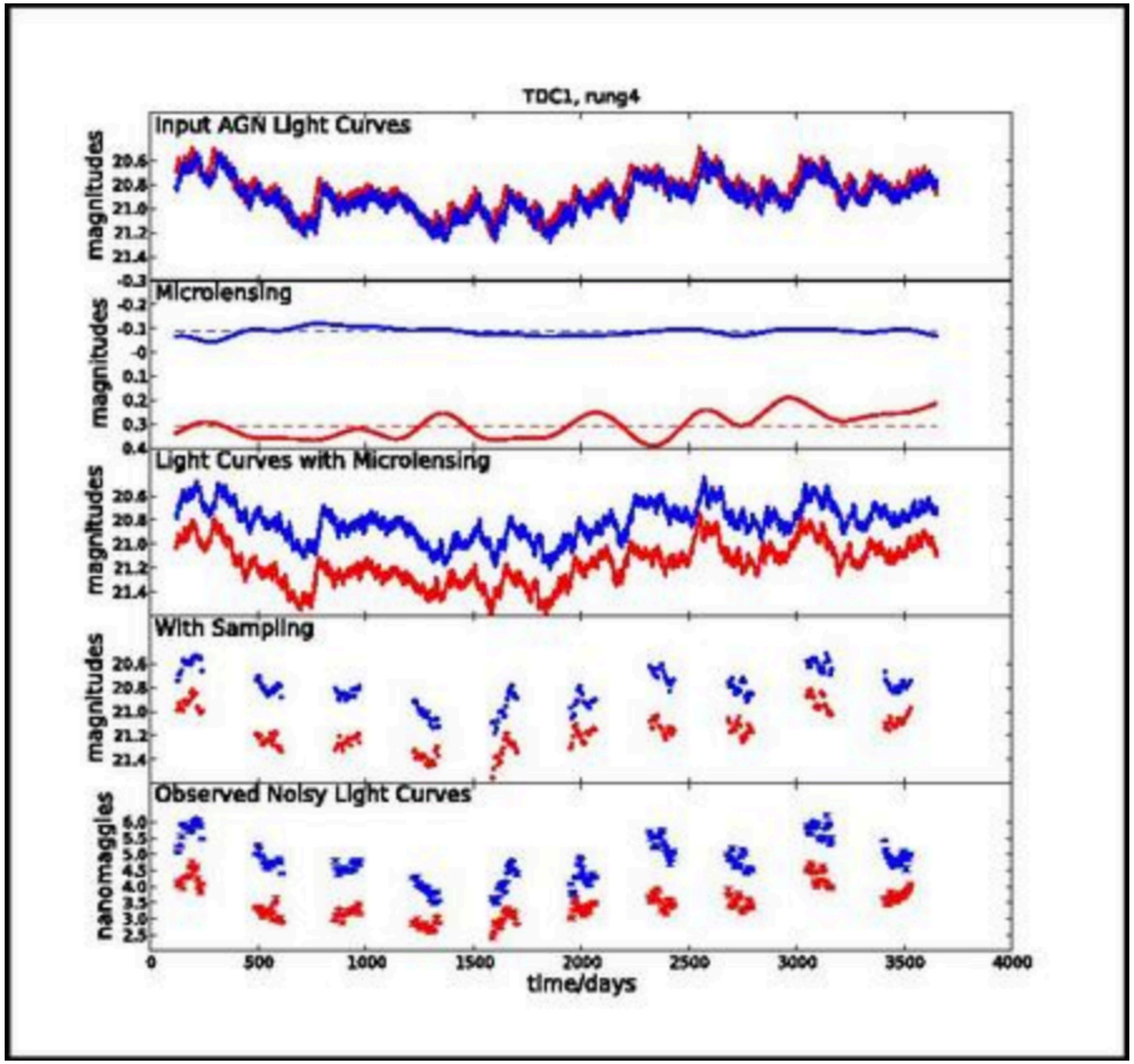
(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

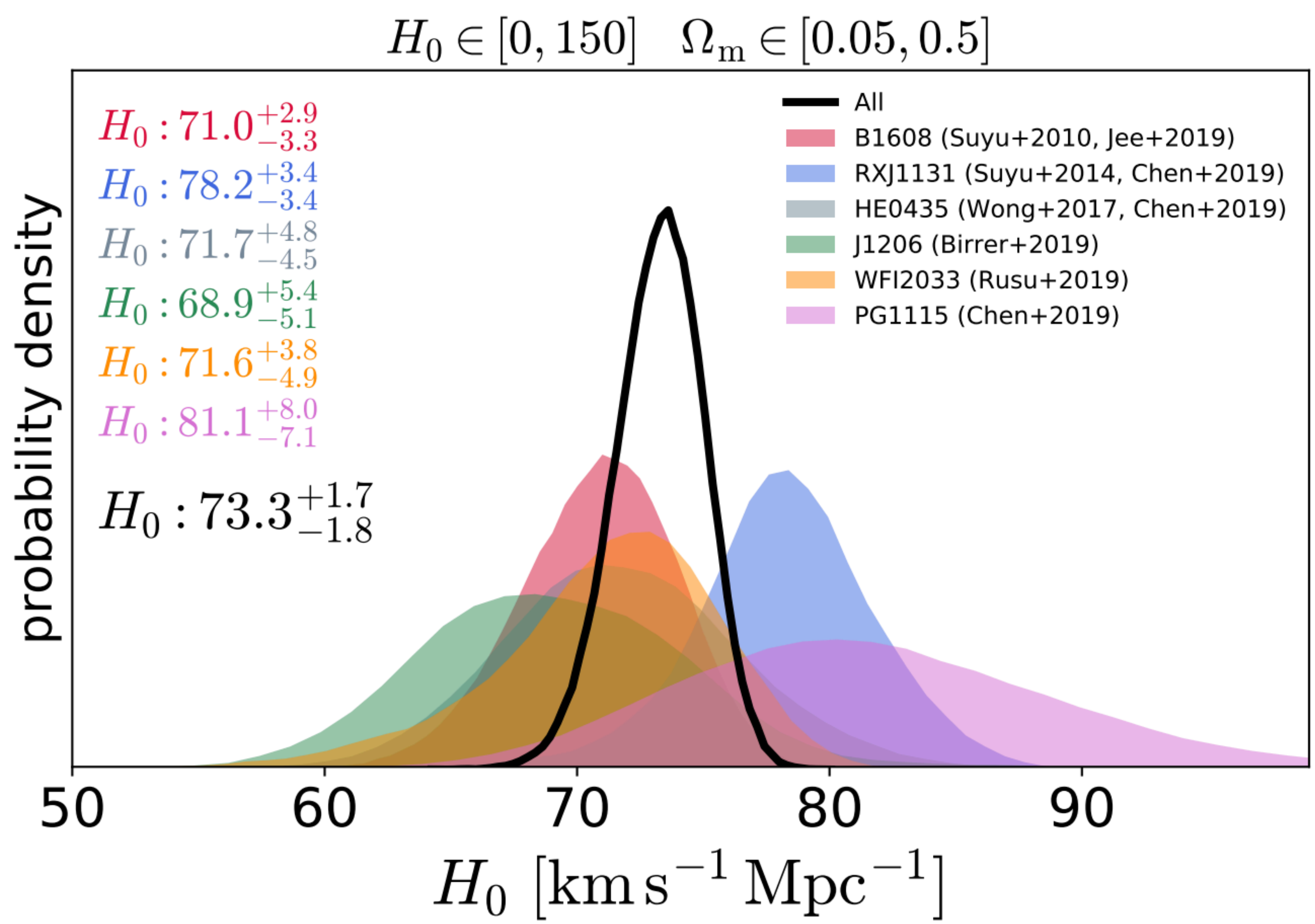
(e) WFI2033−4723 (f) PG 1115+080

Wong et al. 1907.04869

$$D_{\Delta t} \equiv (1+z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$$

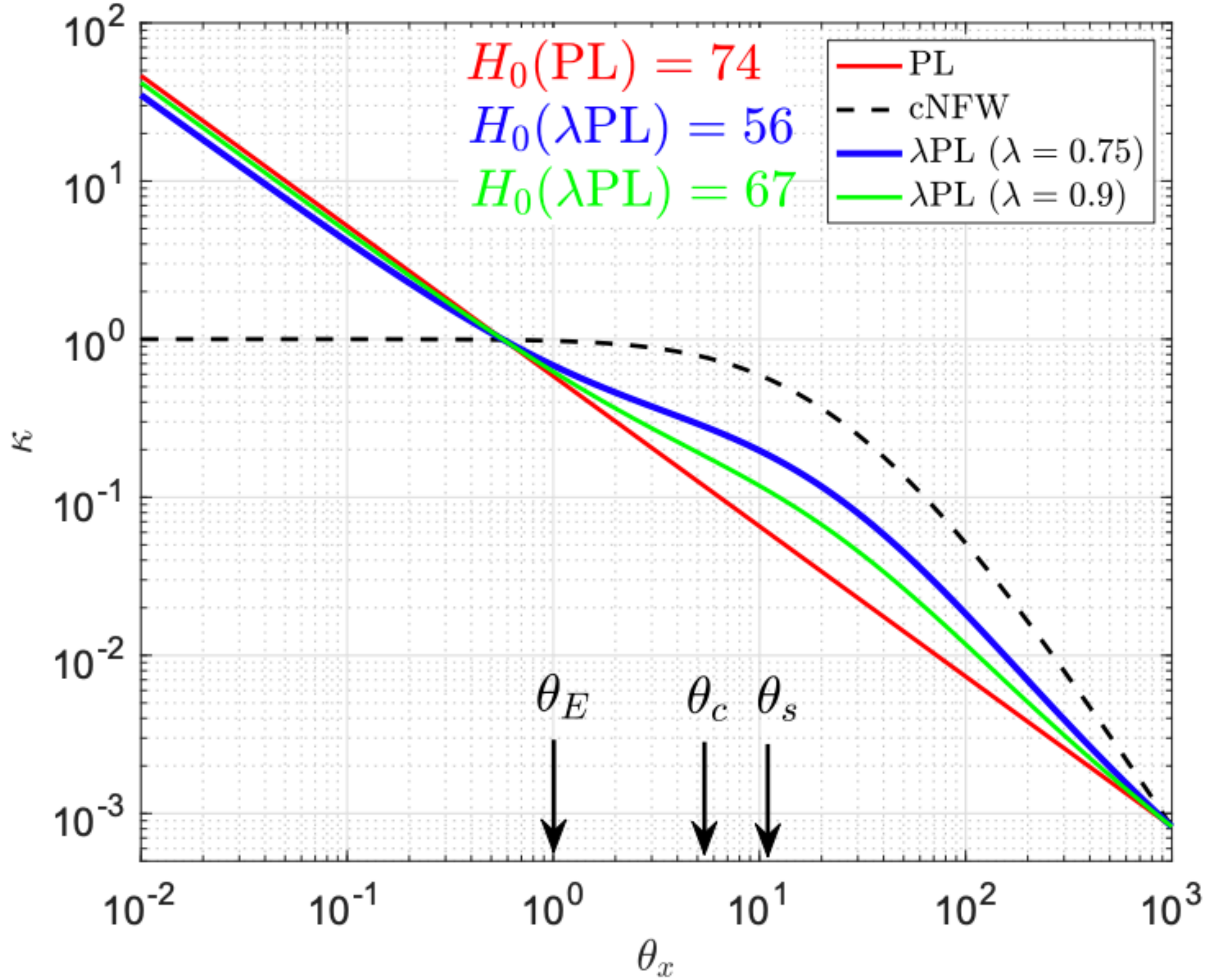


H0LiCOW: H_0 measurement to few %

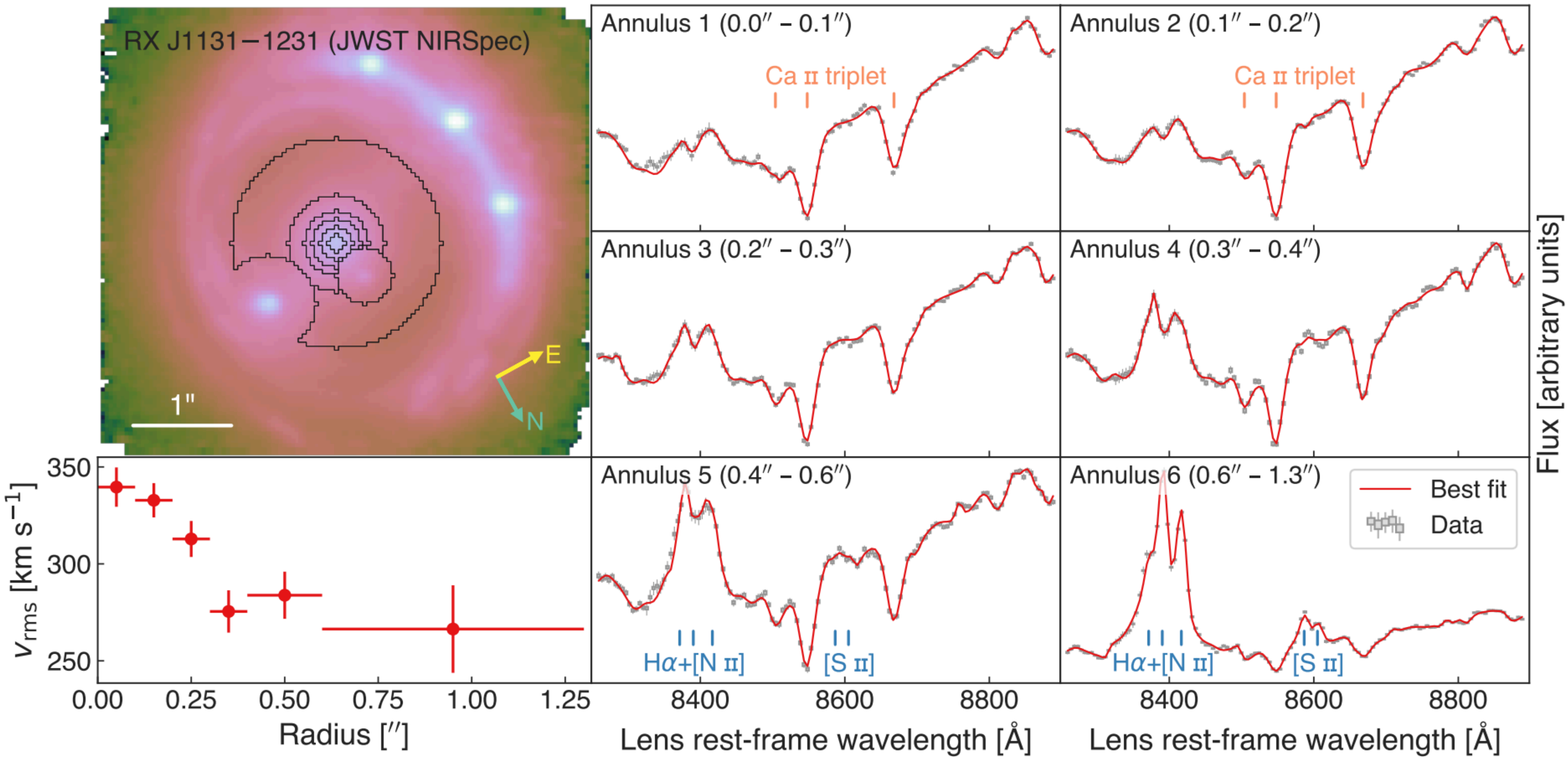


Wong et al. 1907.04869

The “mass-sheet” degeneracy

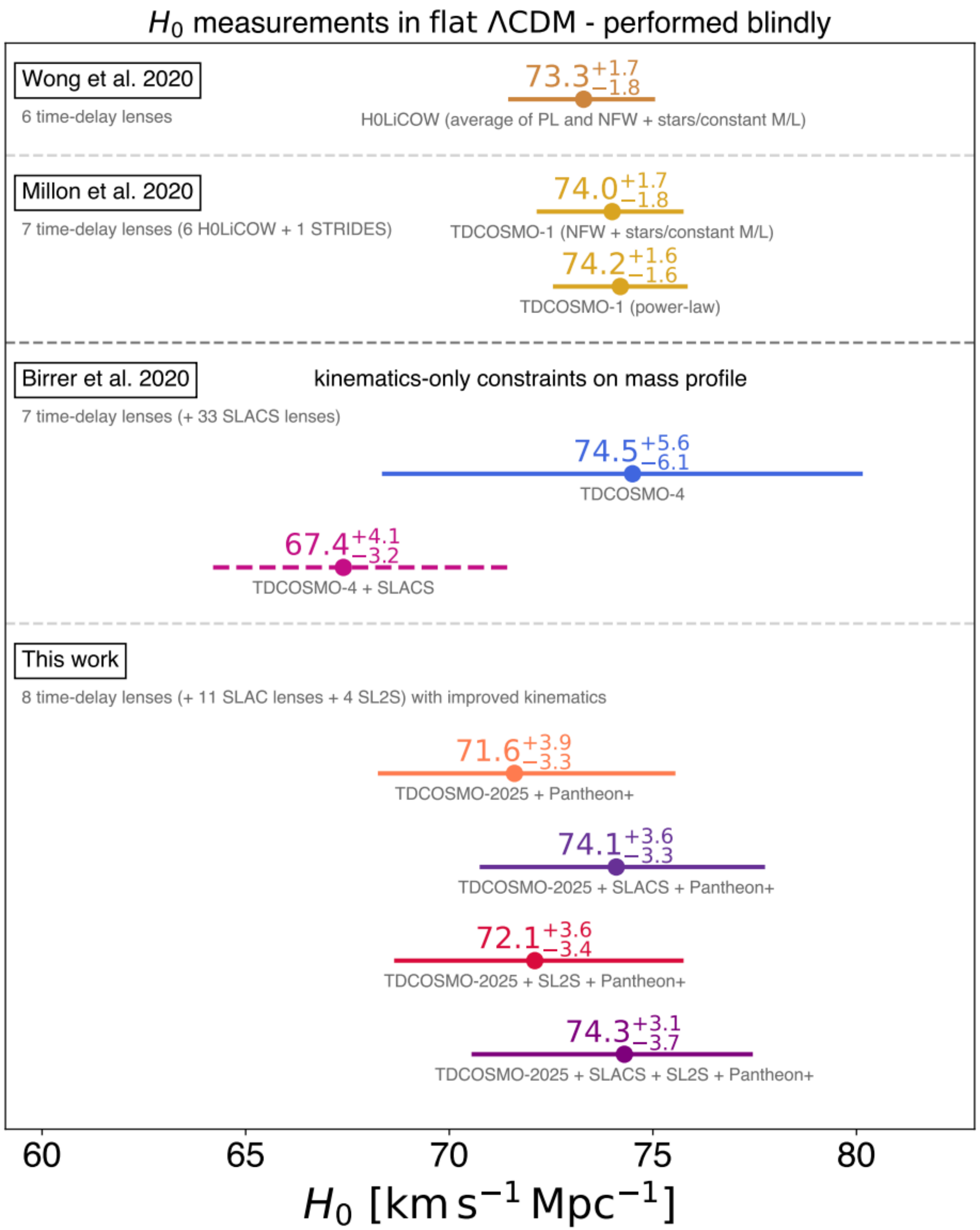


TDCosmo: Conservative H0 measurement



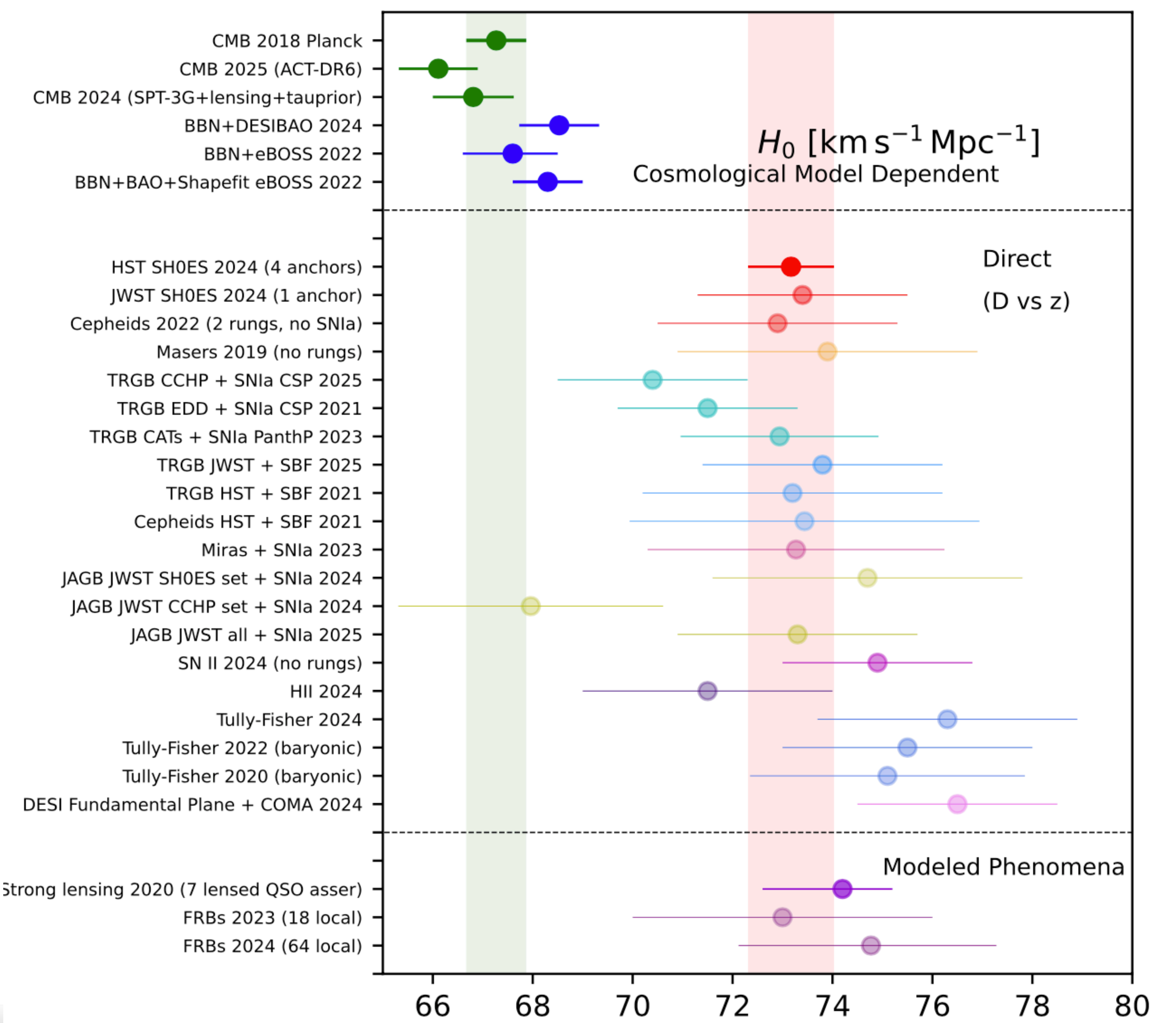
Birrer et al 2506.03023

High H_0 but large error bars



Birrer et al 2506.03023

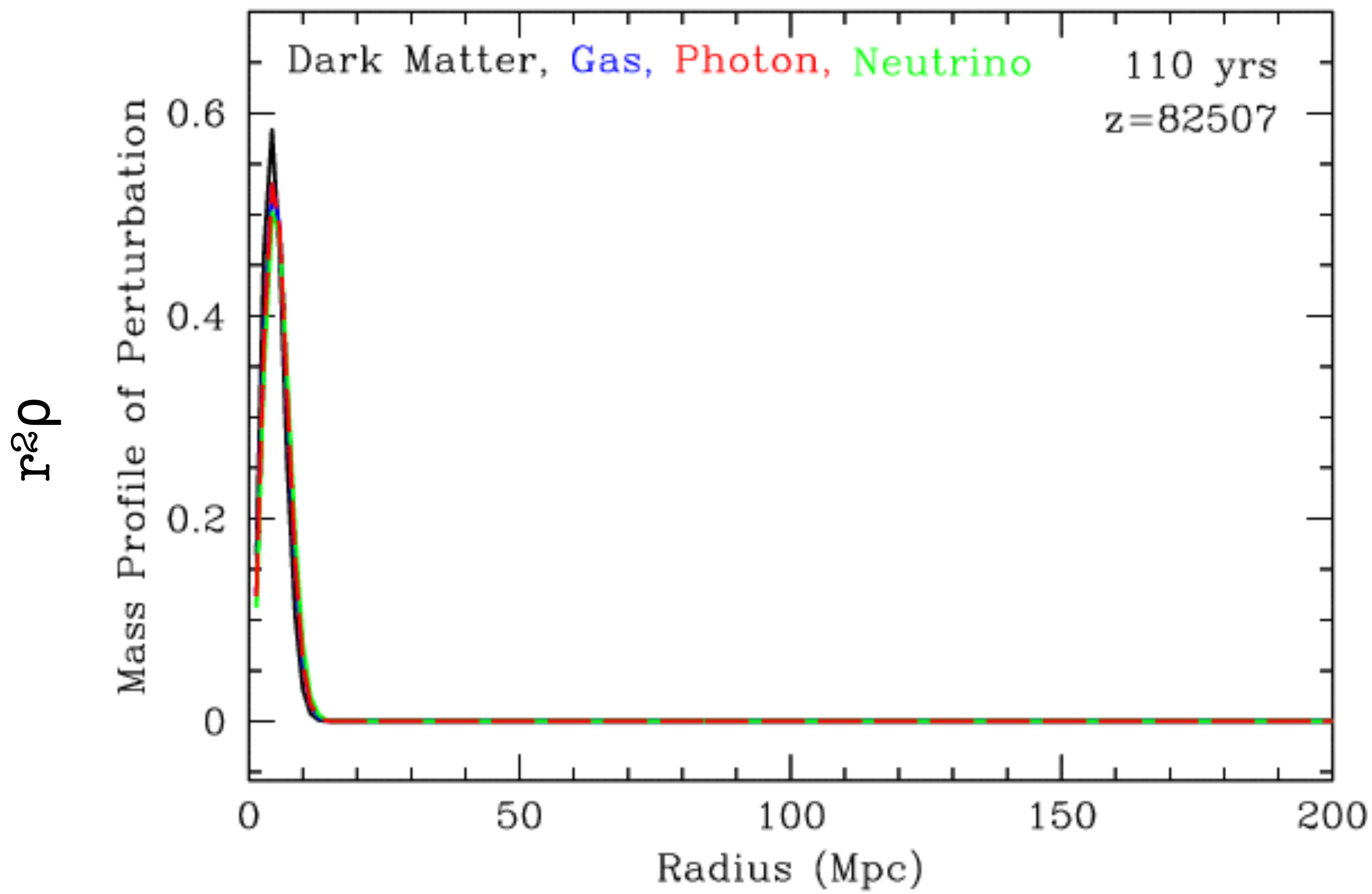
The Hubble tension



The BAO: a standard ruler in the sky

- Before recombination (380 000 yr): a tightly coupled photon-baryon plasma with acoustic waves.
- The 'sound horizon' is the distance travelled by sound wave until recombination.

$$r_s = \int_{t_{rh}}^{t_{\rm rec}} c_s(t)dt$$



credit: Bassett & Hlozek

© D. Eisenstein

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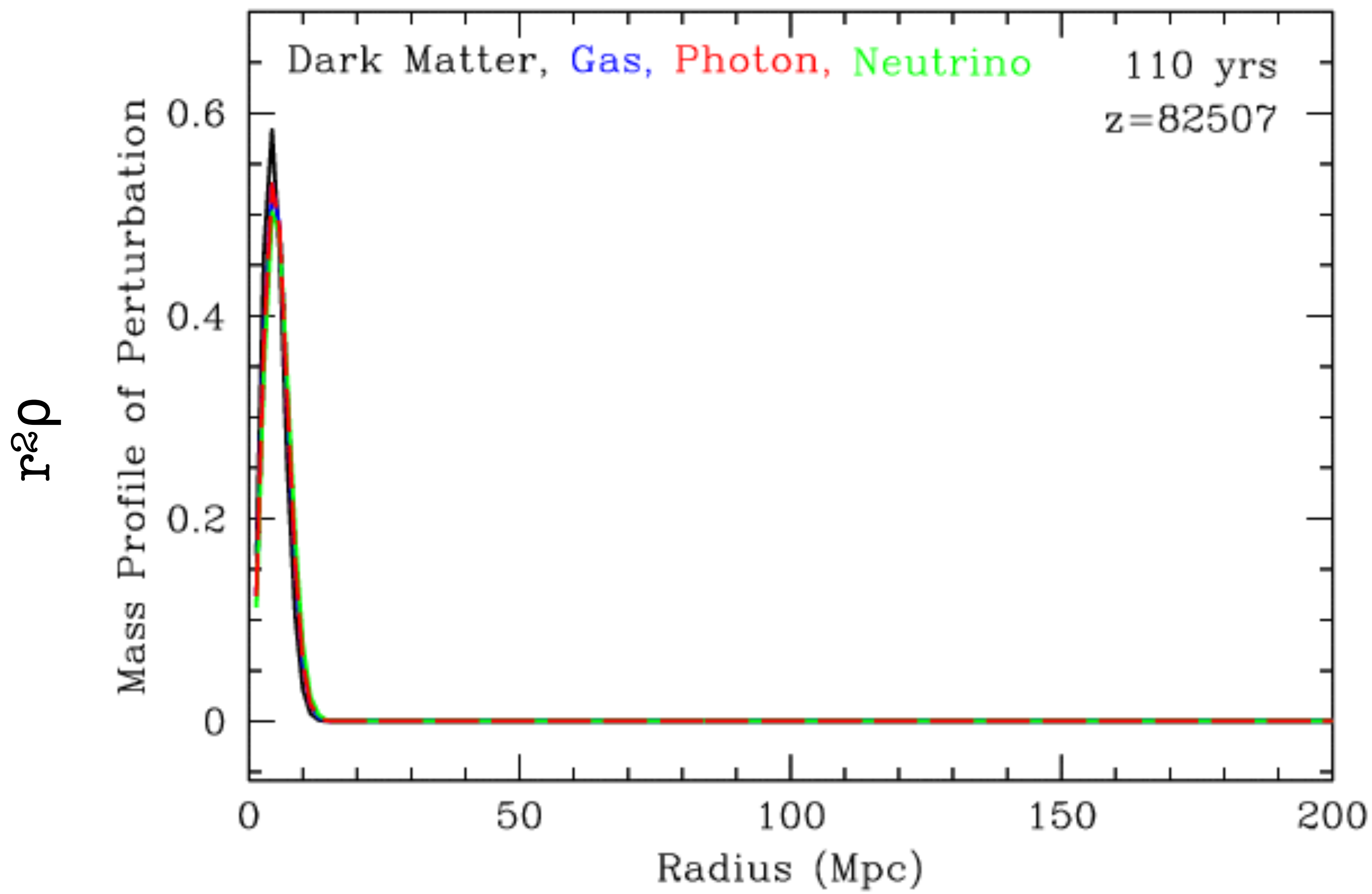

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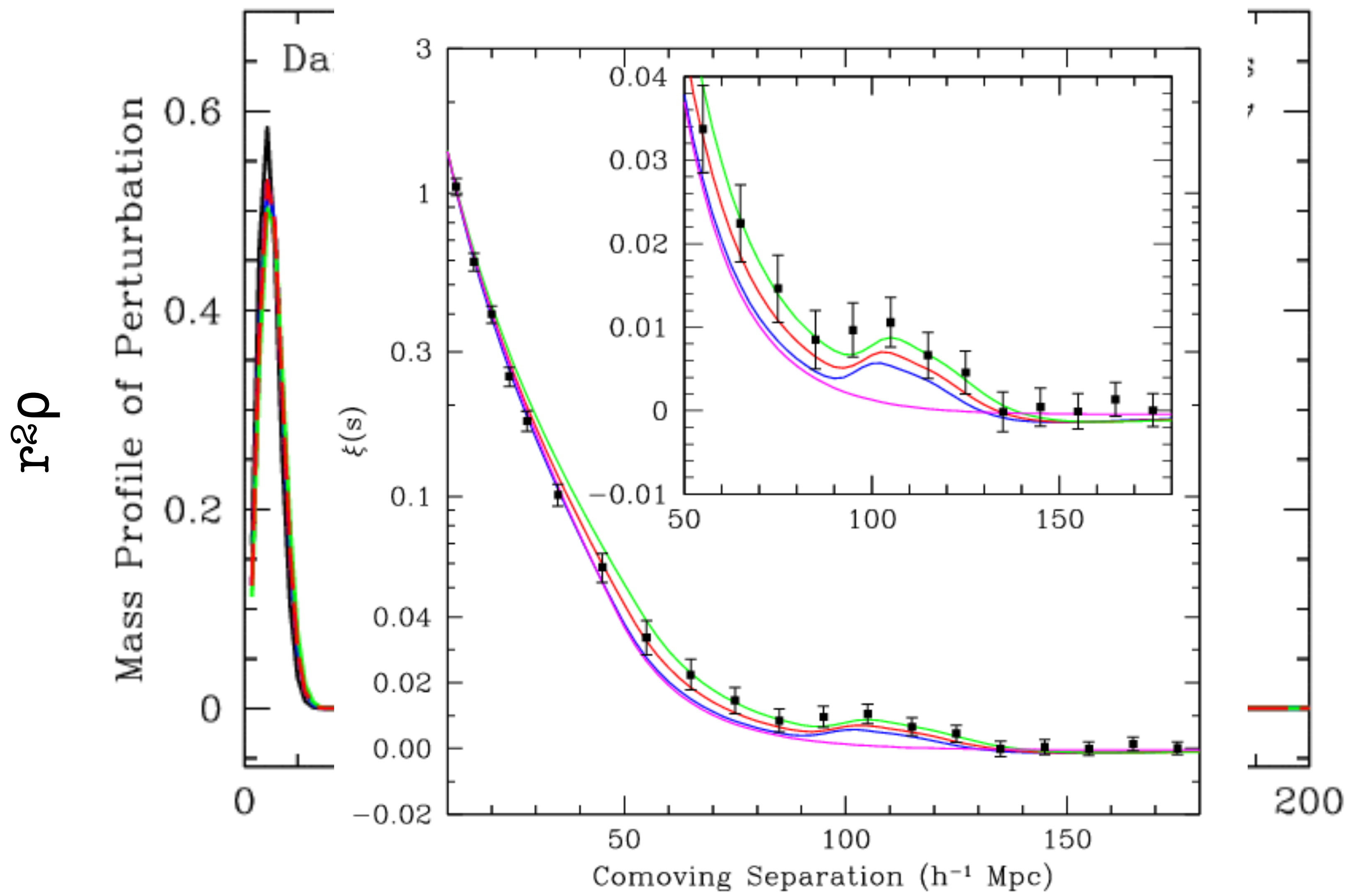
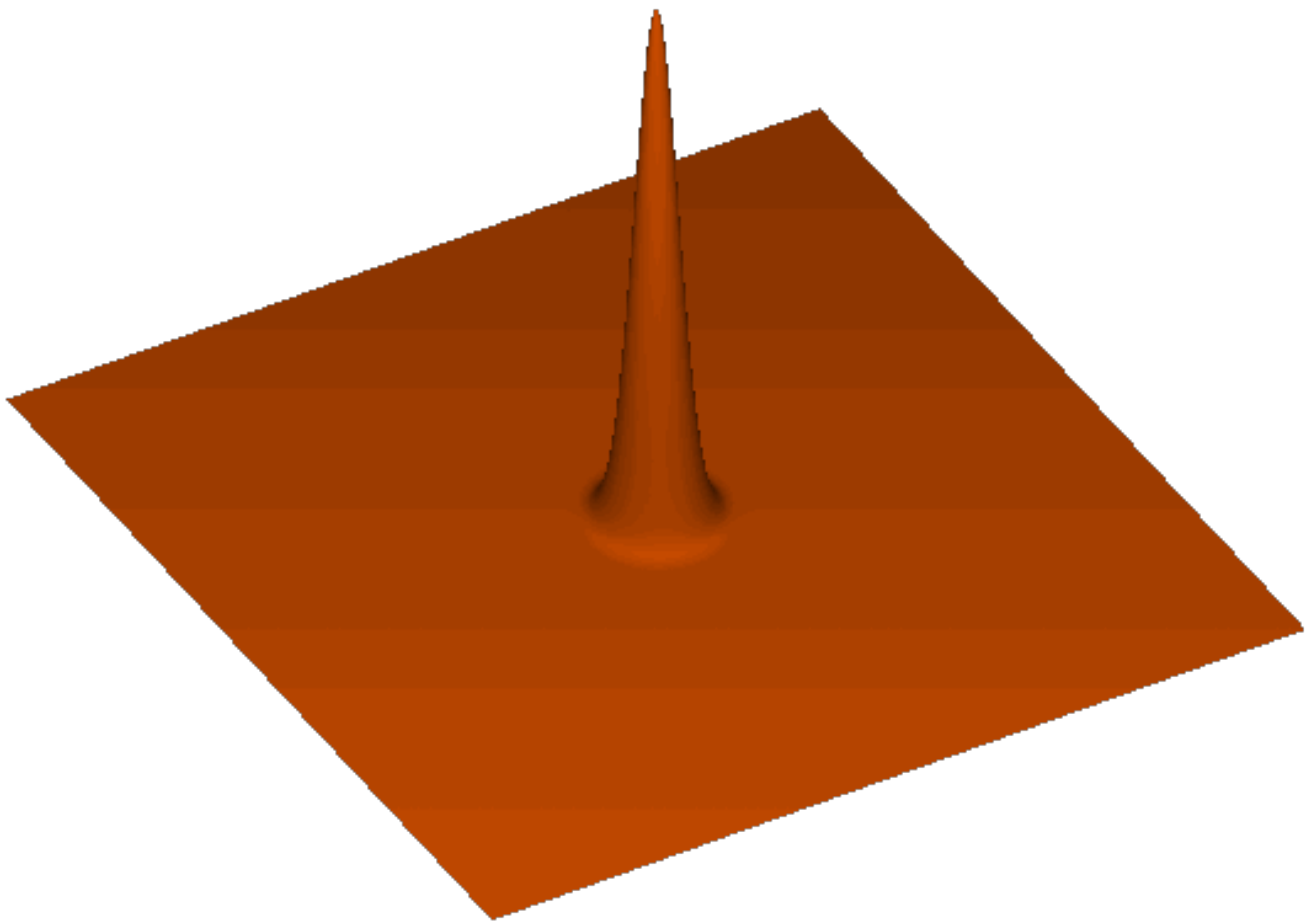


credit: Bassett & Hlozek

Eisenstein et al. 2005

Ⓒ *D. Eisenstein*

The BAO: a standard ruler in the sky



credit: Bassett & Hlozek

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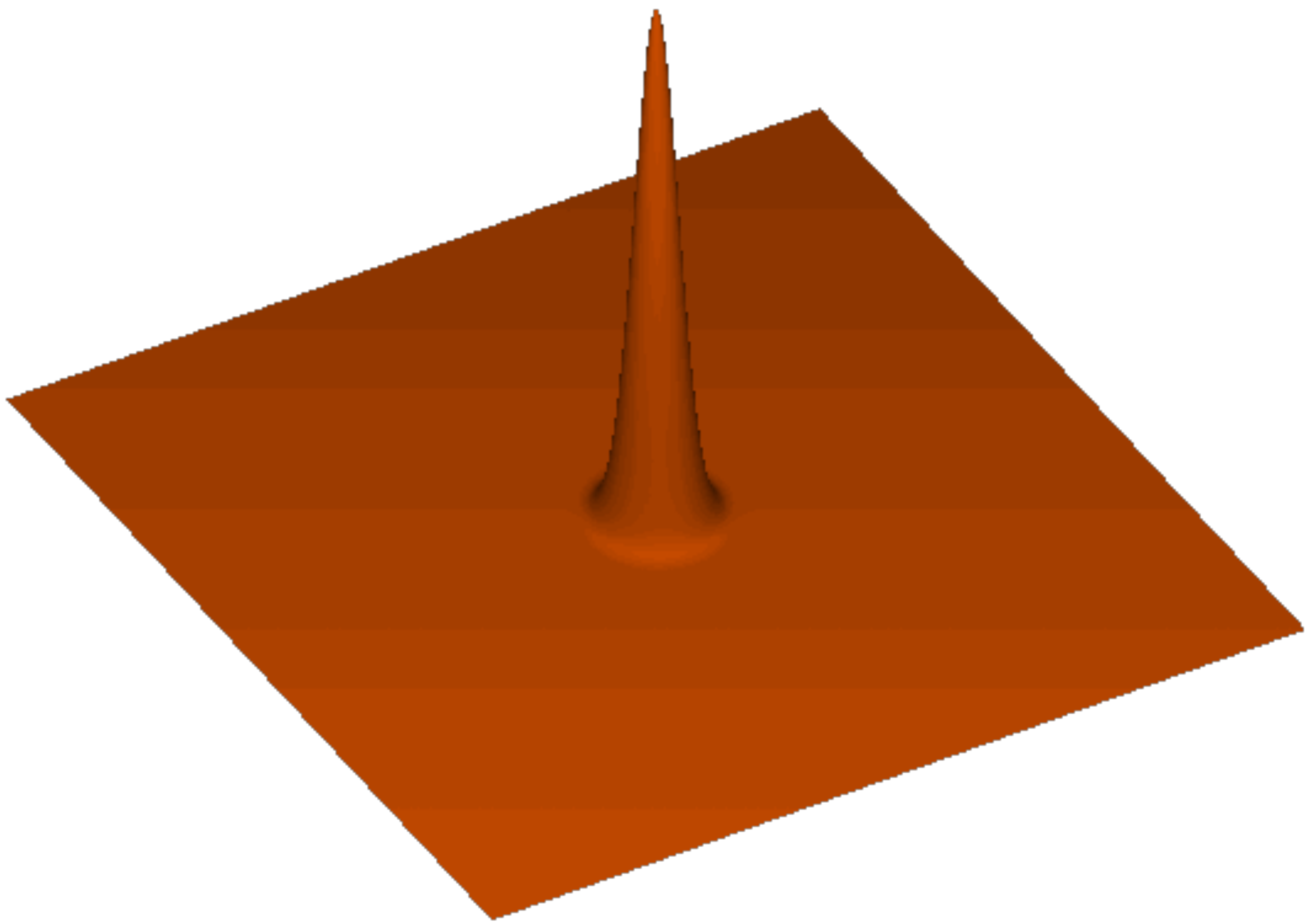

credit: Bassett & Hlozek

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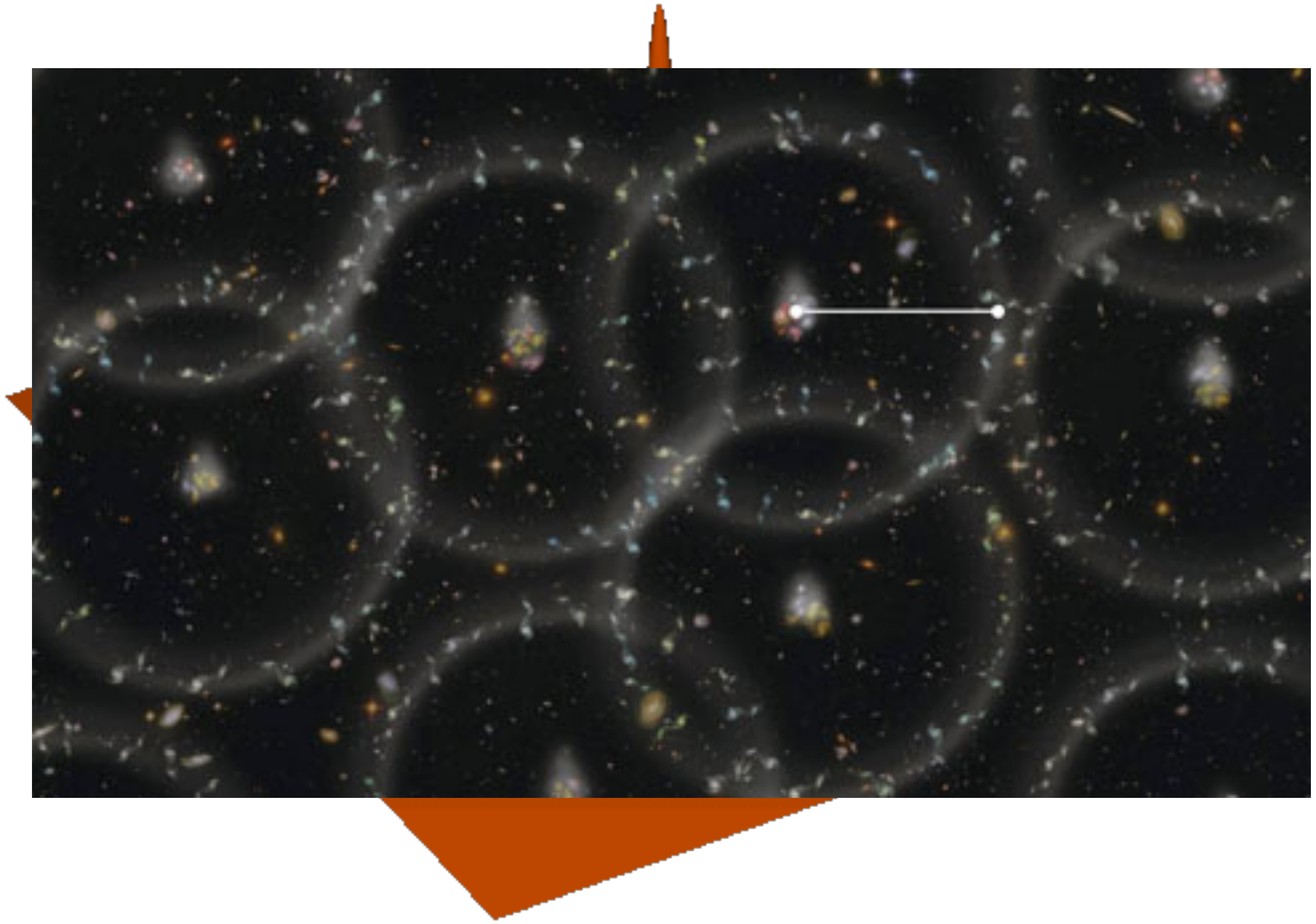
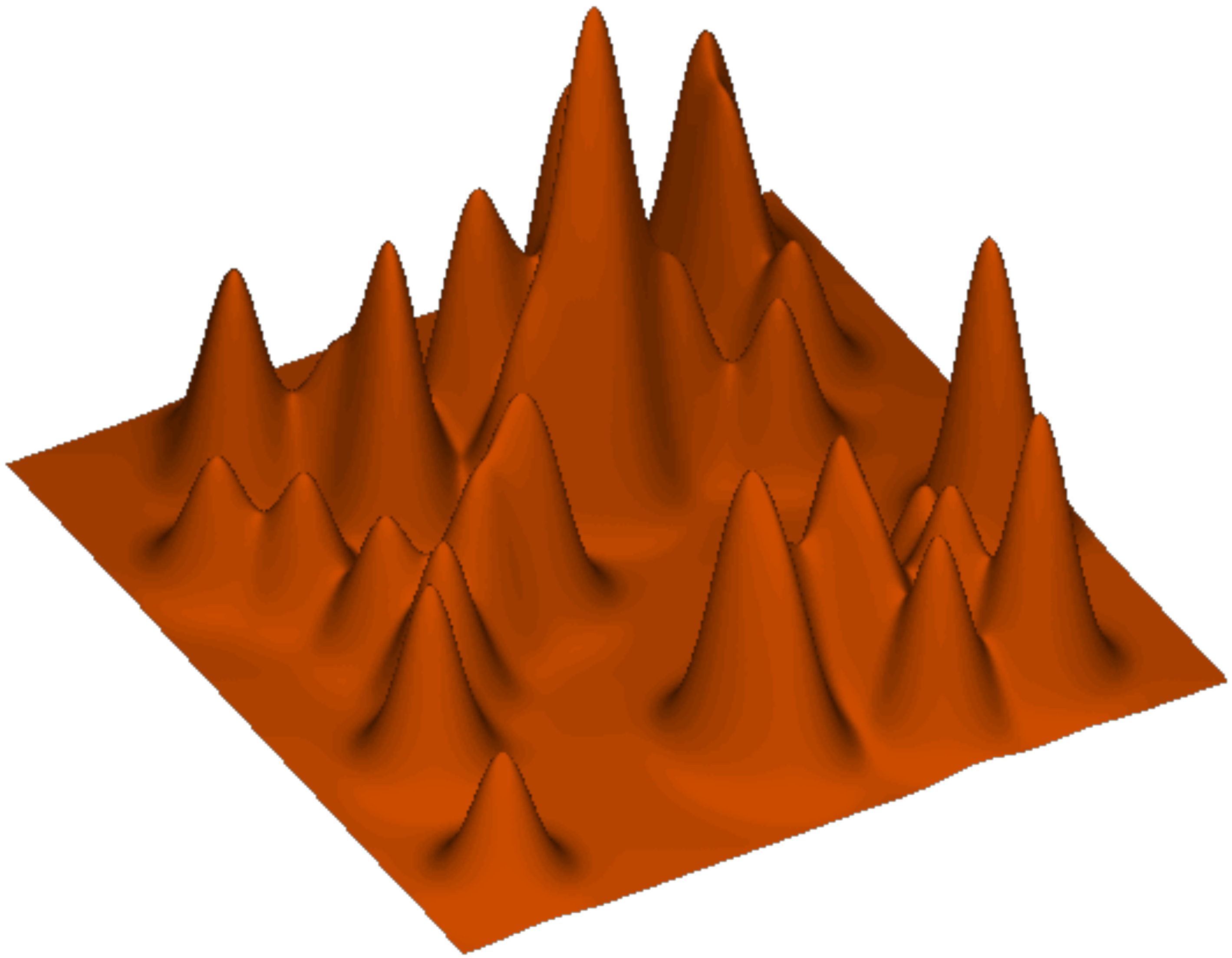


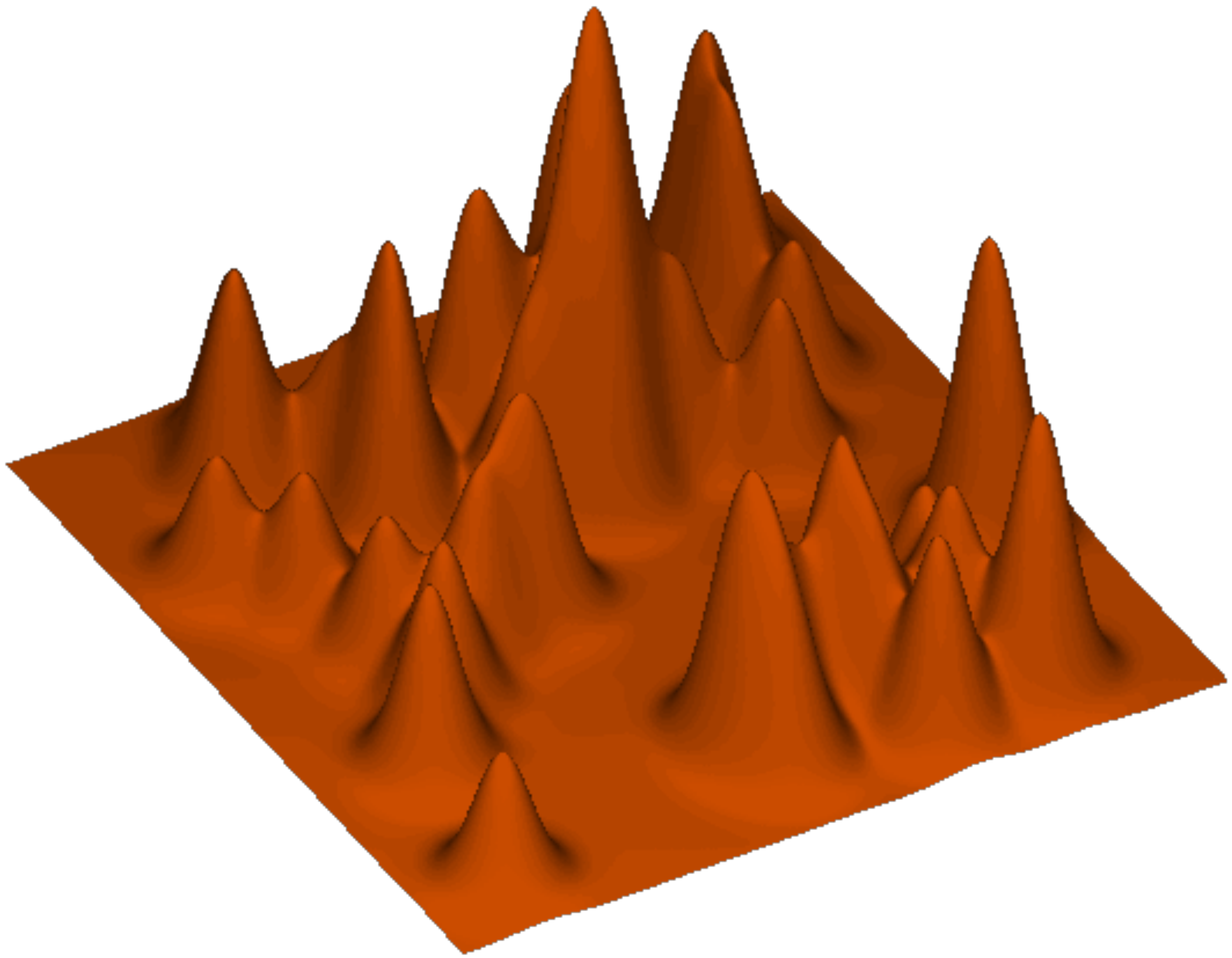
credit: Bassett & Hlozek

The BAO: a standard ruler in the sky



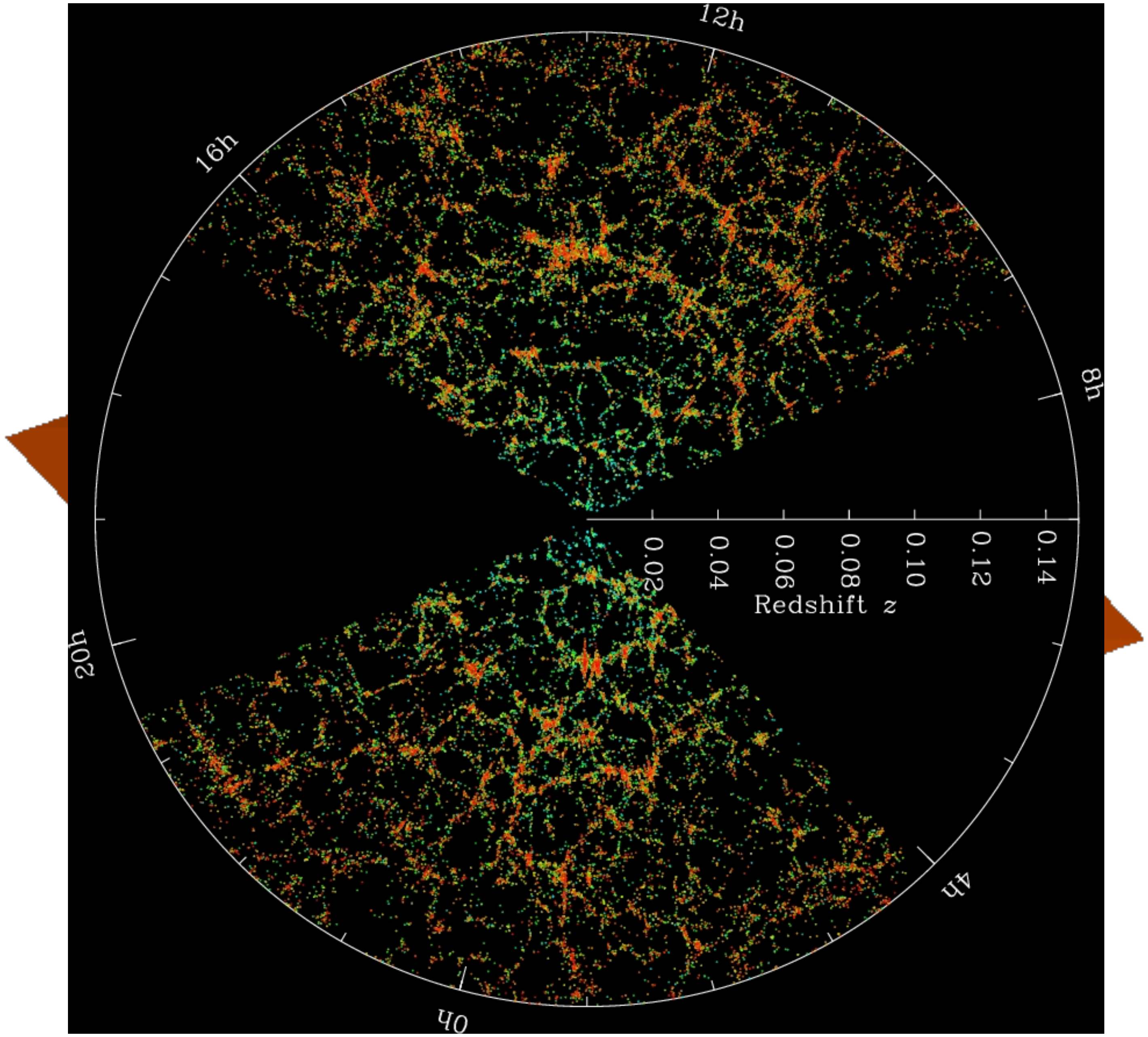
credit: Bassett & Hlozek

The BAO: a standard ruler in the sky



credit: Bassett & Hlozek

The BAO: a standard ruler in the sky

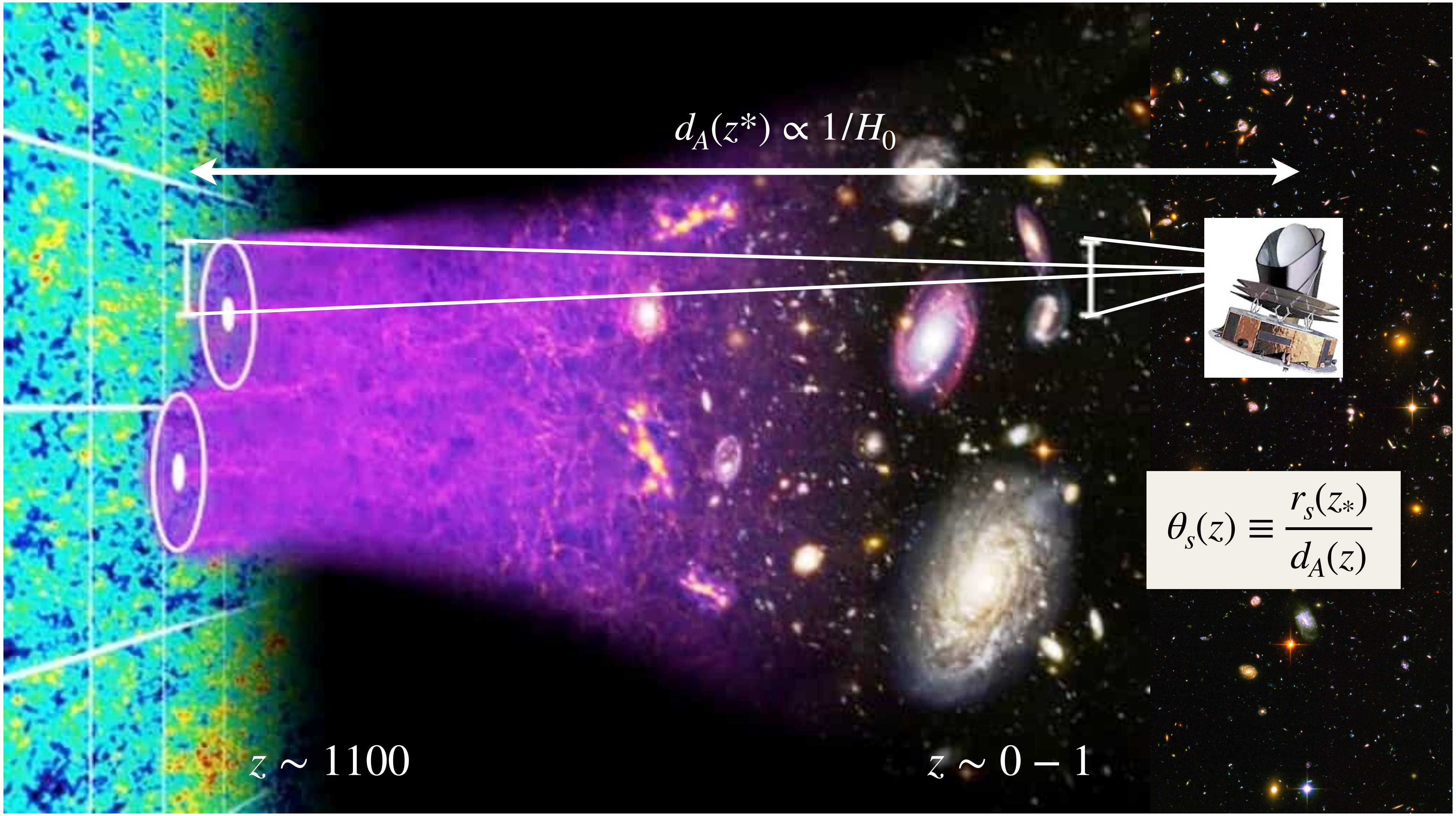


credit: SDSS collaboration

credit: Bassett & Hlozek

The BAO: a standard ruler in the sky

- The Baryonic Acoustic Oscillation: a standard ruler in the sky



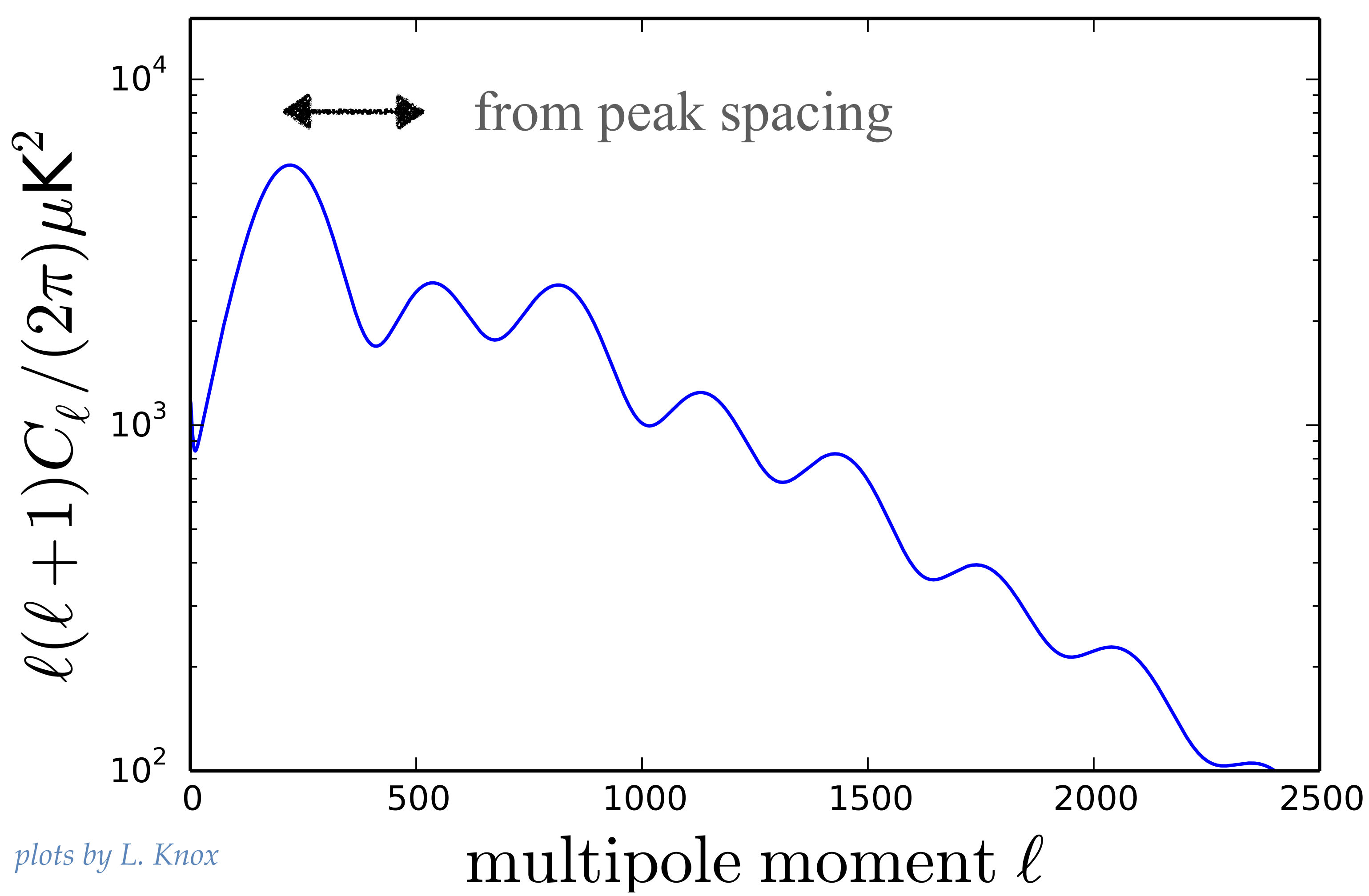
- *Planck* measures θ_s at 0.04% precision but r_s & d_A are model dependent.
- H_0 appears only in the angular diameter distance d_A.

Summary of other measurements: Verde++ 2311.13305

How does CMB data measure H0?

- Inference of H_0 comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_s sound horizon at last scattering ~1.0404



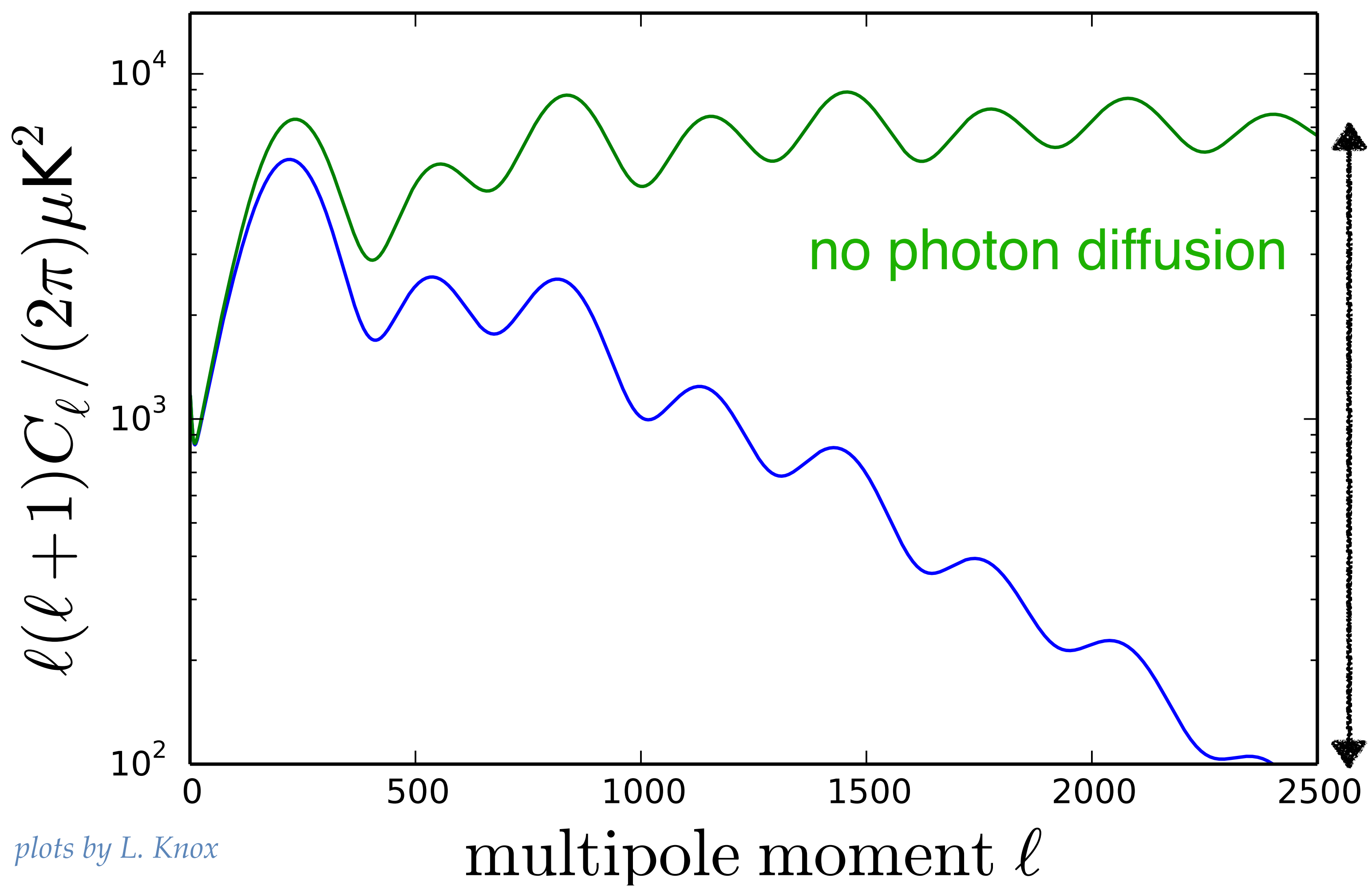
plots by L. Knox

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

How does CMB data measure H0?

- Inference of H_0 comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_d photon diffusion length at last scattering ~ 0.1609



"Silk Damping"

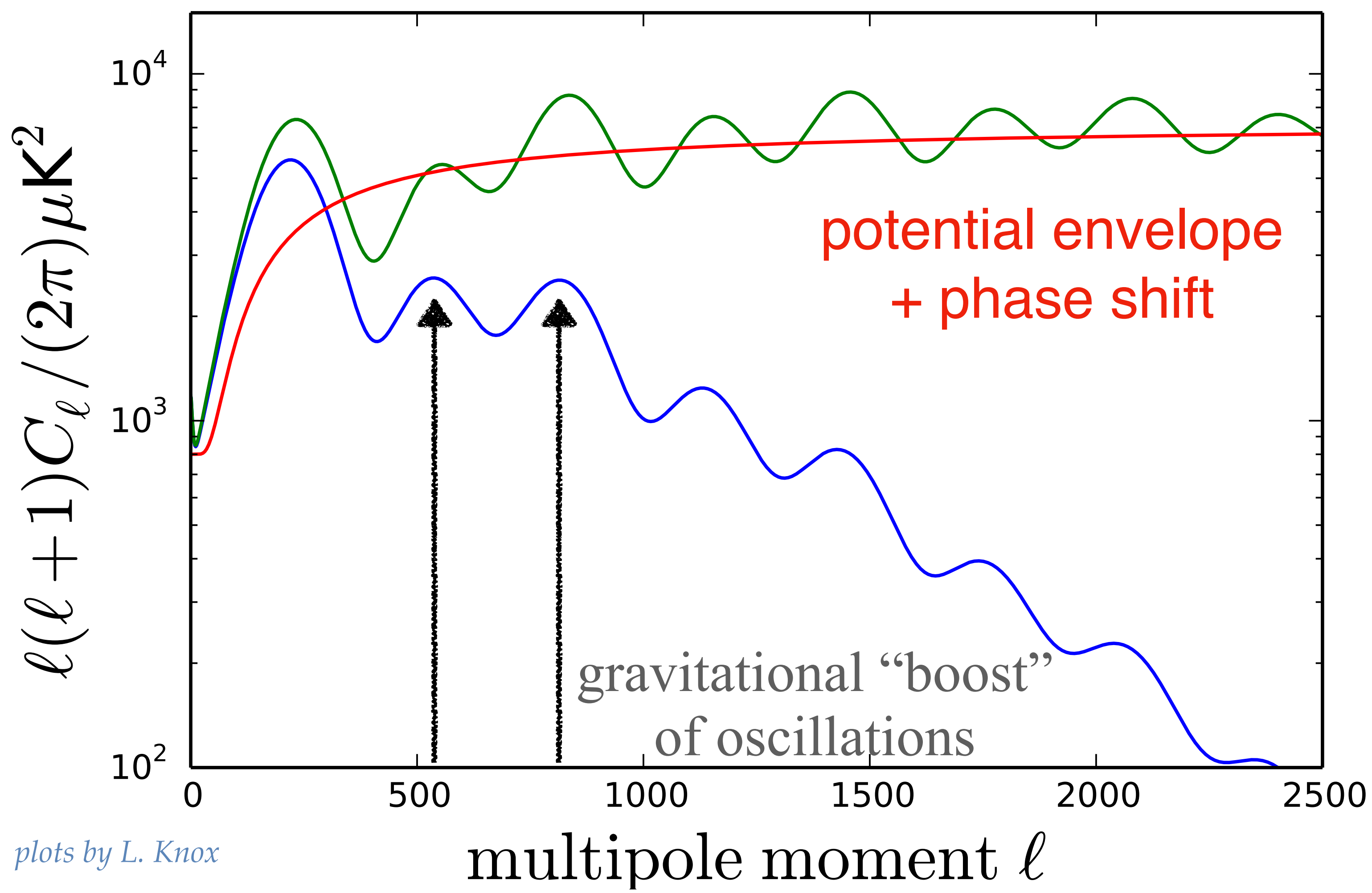
plots by L. Knox

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

How does CMB data measure H0?

- Inference of H_0 comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_{eq} horizon size at matter-radiation equality ~ 0.81

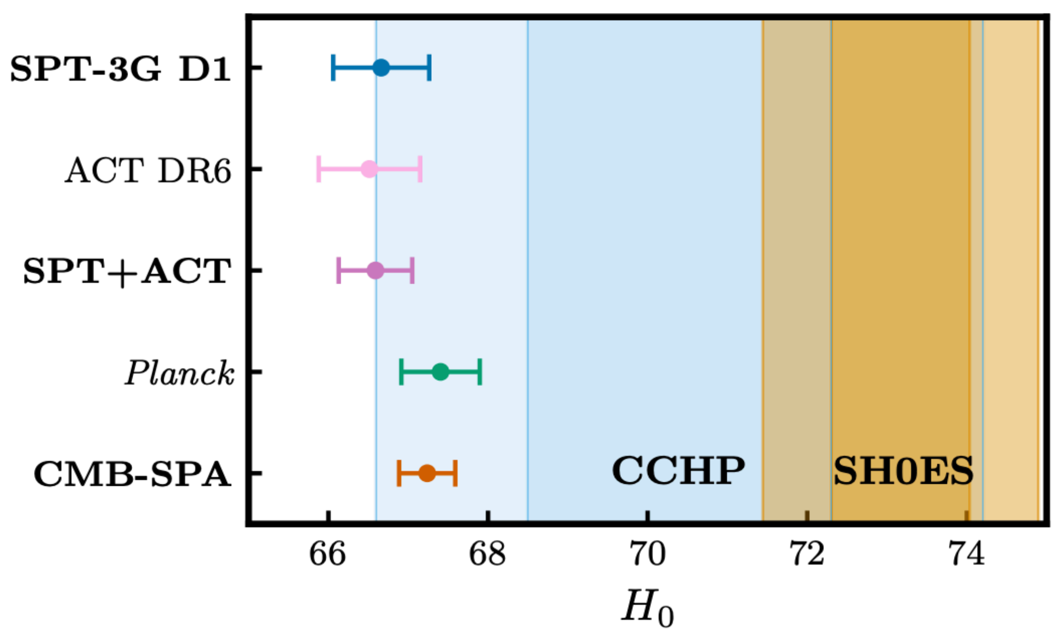


plots by L. Knox

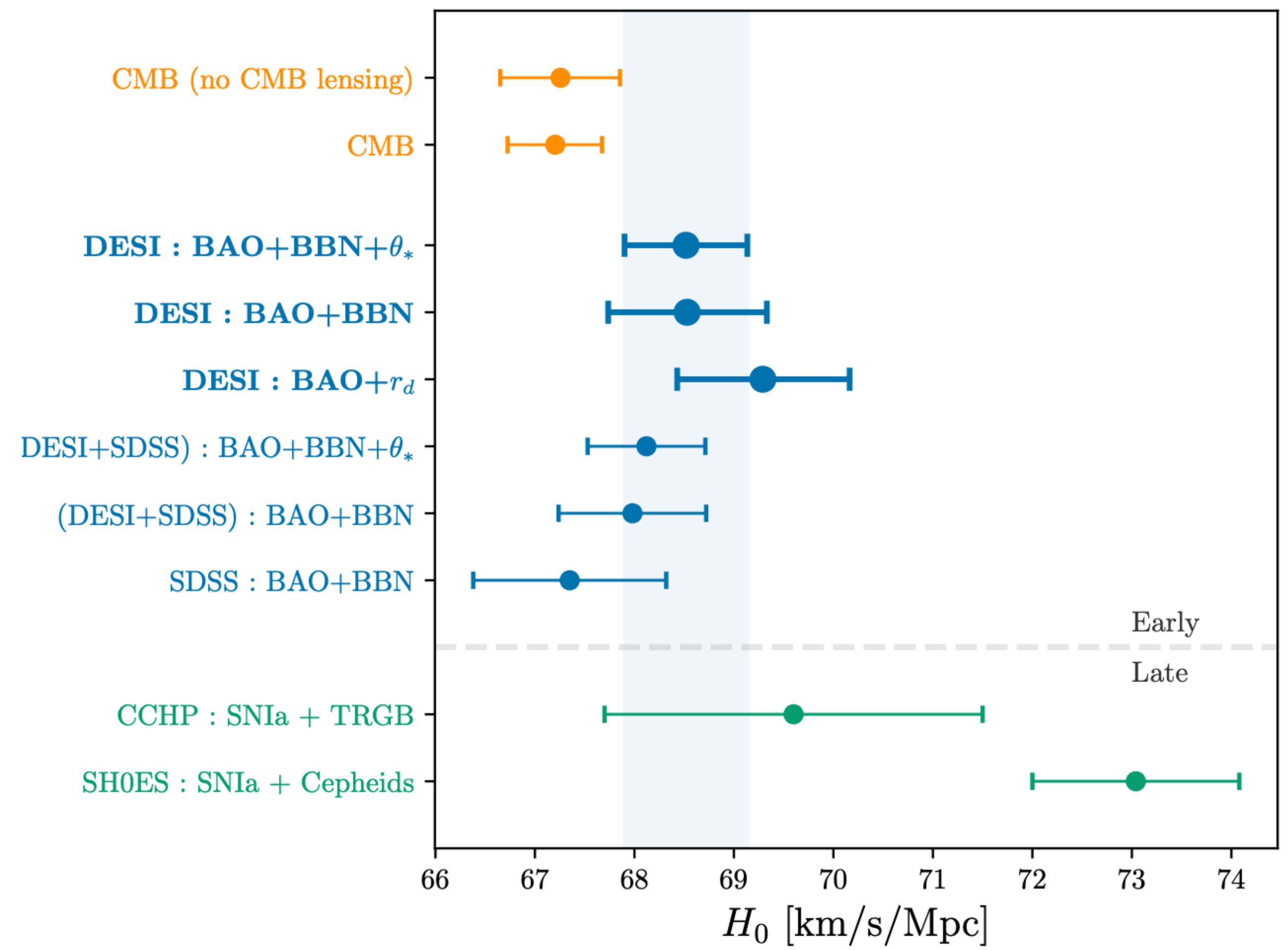
e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

CMB and BAO measurement of H_0

Comparing CMB measurements



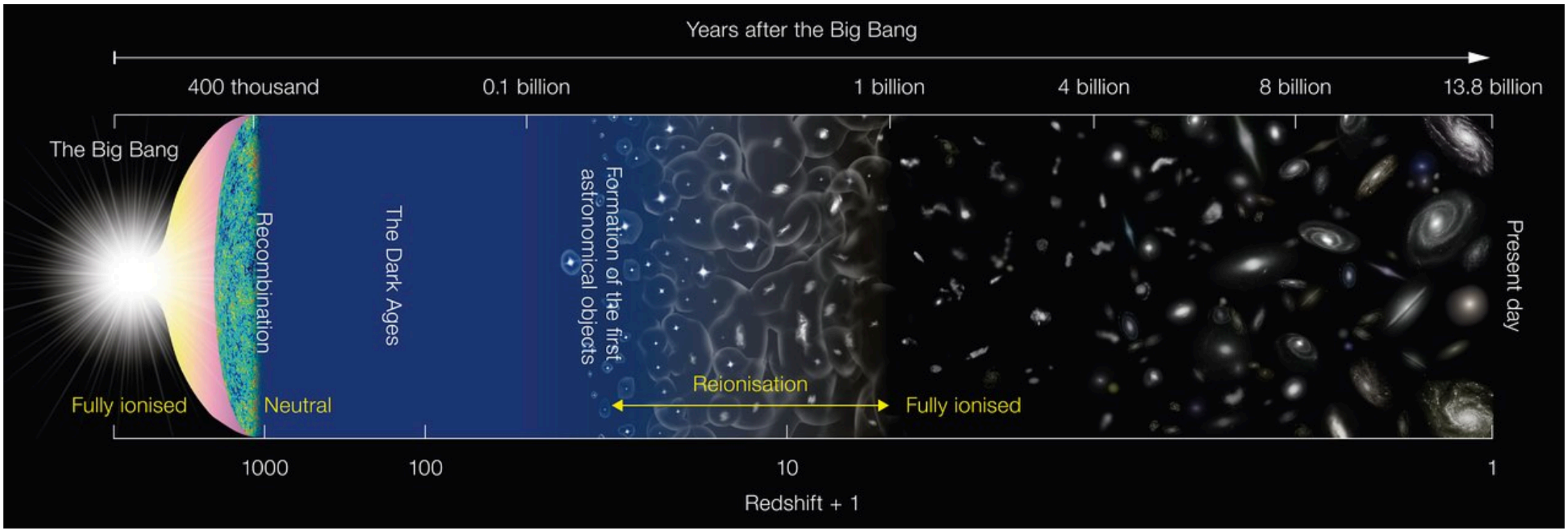
Comparing BAO+BBN measurements



- The measurement of H_0 in the ΛCDM model using the inverse-distance ladder is robust

Two ways of solving the Hubble tension

$$\theta_s = \frac{r_s}{r_A} = \frac{H_0 r_s}{\int_0^{z_*} 1/E(x)\mathrm{d}x}$$



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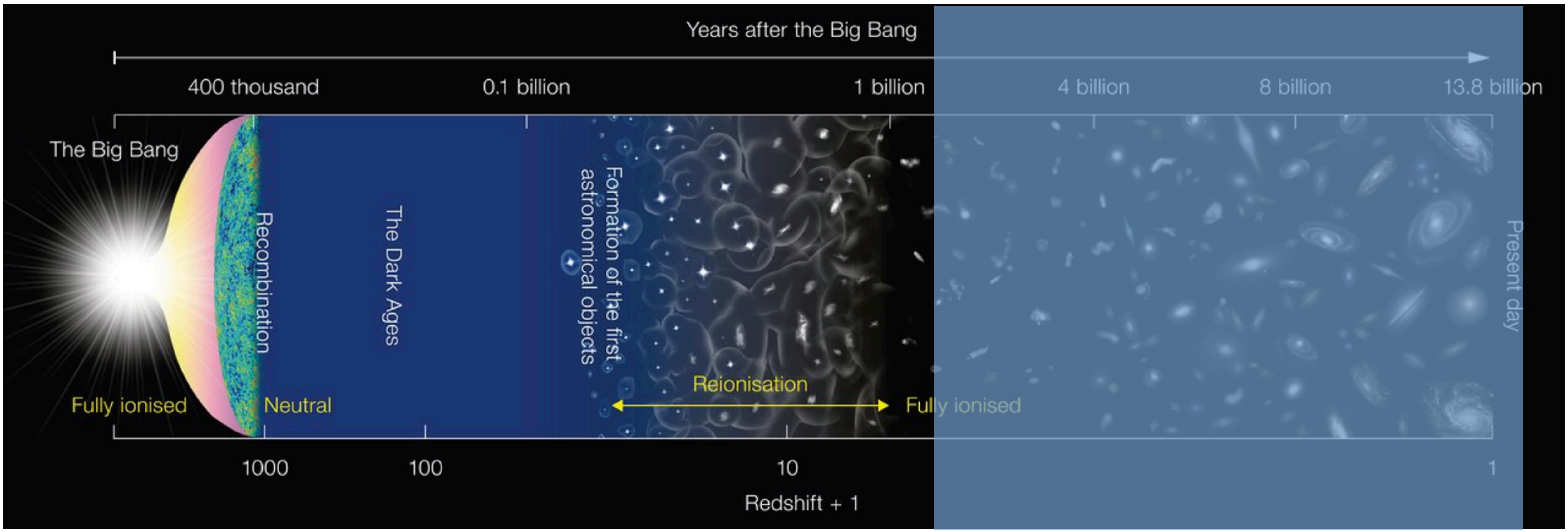
Late-universe models



$$\frac{H_0 \nearrow r_s}{\int_0^{z_*} 1/E(x) \searrow \mathrm{d}x}$$

Change expansion history

Two ways of solving the Hubble tension

Early universe models

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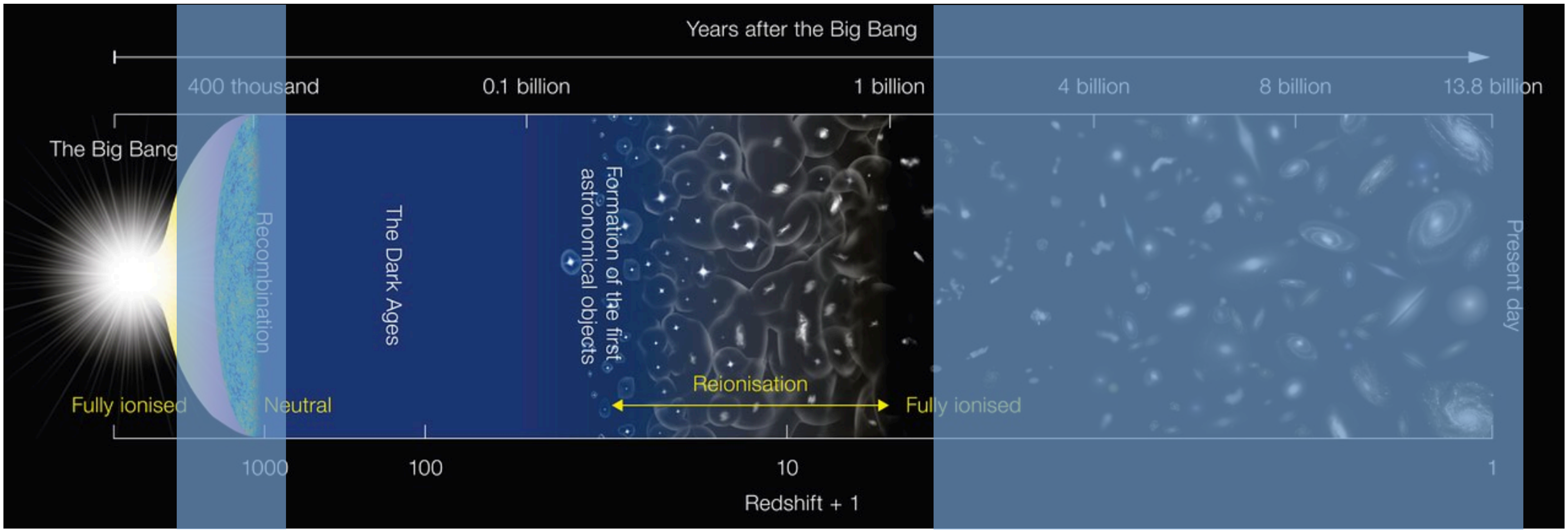

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Change calibrator

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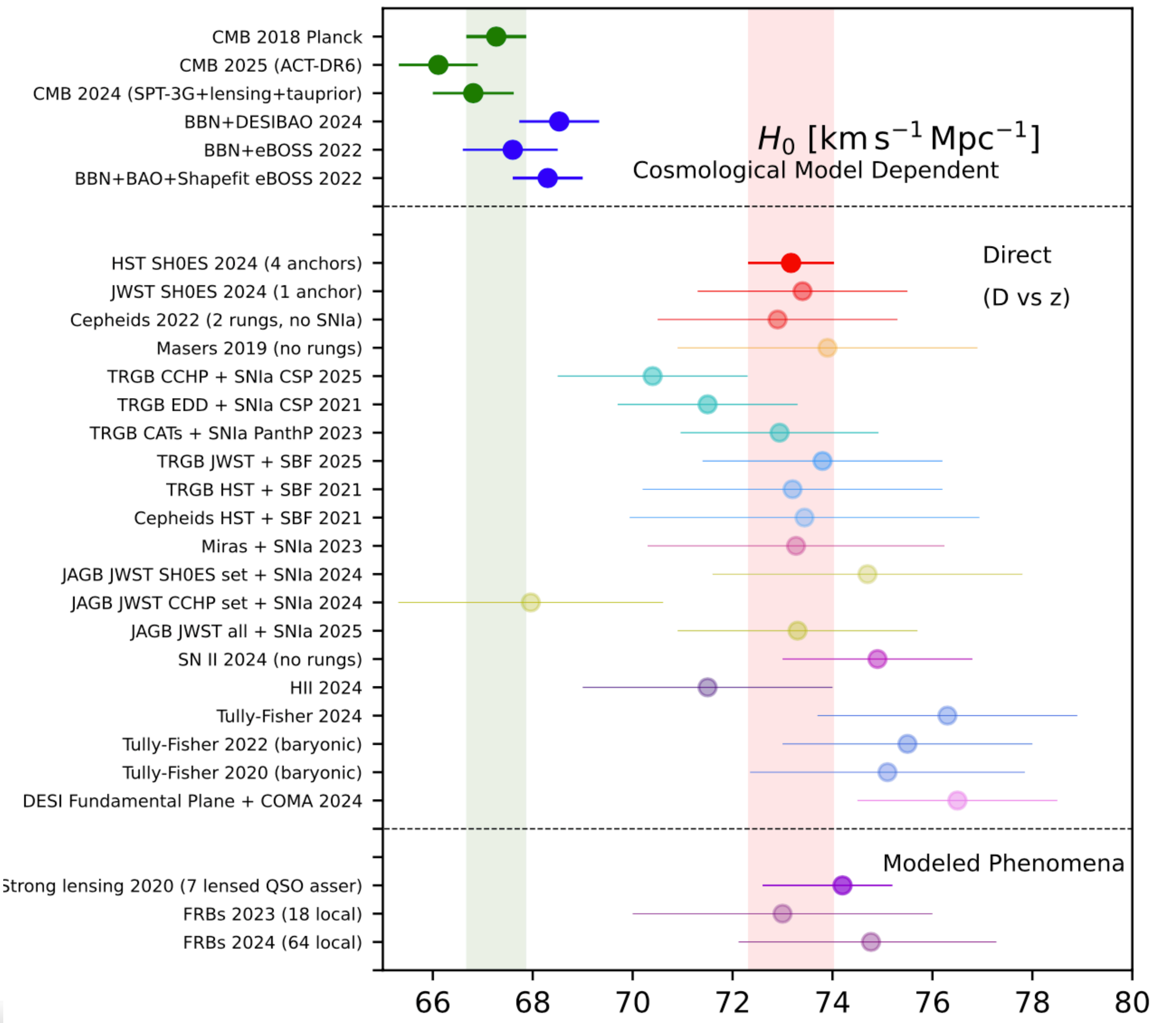
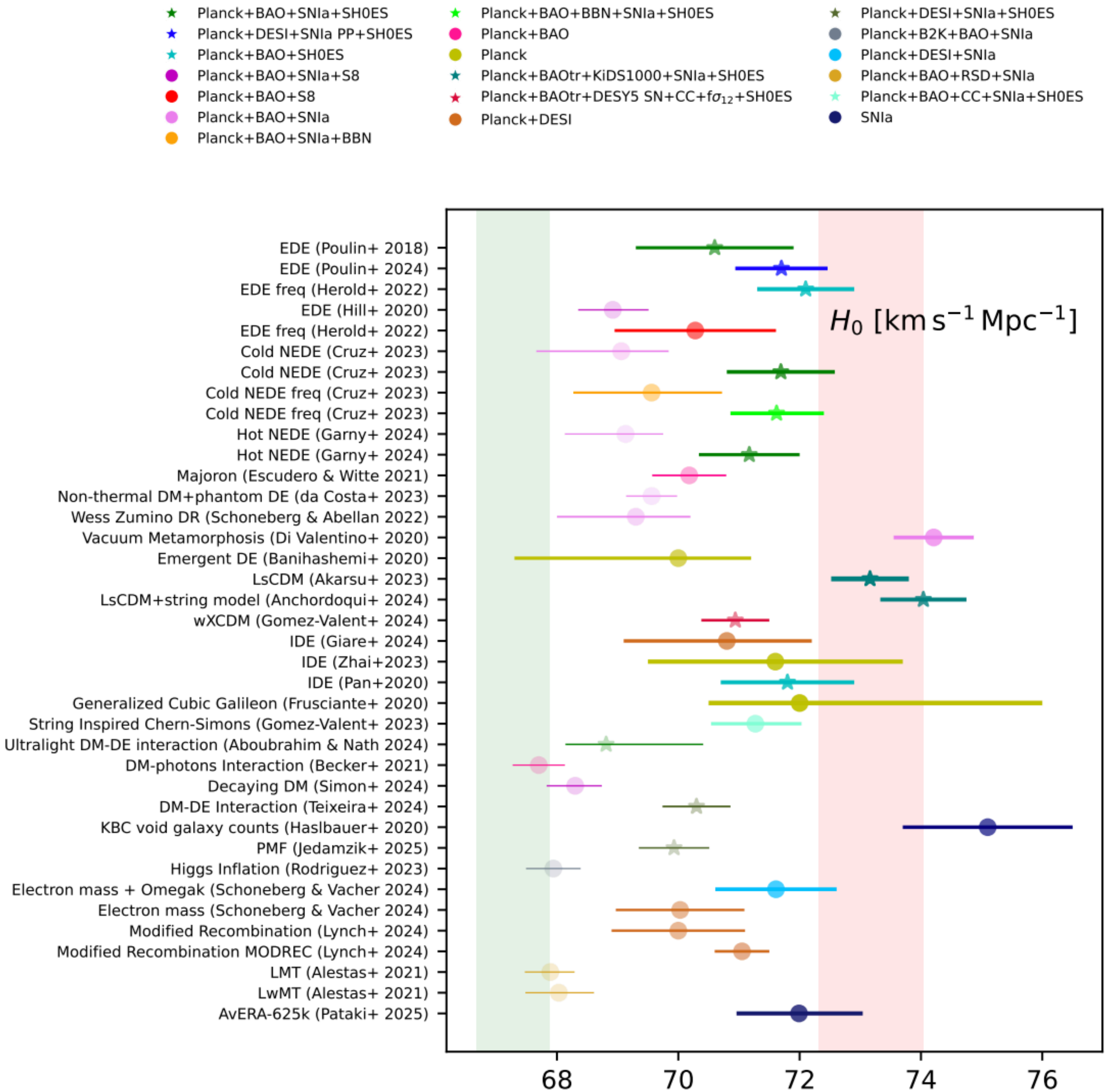
The Hubble tension





Planck+BAO+SNIa+SH0ES
Planck+DESI+SNIa PP+SH0ES
Planck+BAO+SH0ES
Planck+BAO+SNIa+S8
Planck+BAO+S8
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Planck+B2K+BAO+SNIa
Planck+DESI+SNIa
Planck+BAO+RSD+SNIa
Planck+BAO+CC+SNIa+SH0ES
SNIa
EDE (Poulin+ 2018)
EDE (Poulin+ 2024)
EDE freq (Herold+ 2022)
EDE (Hill+ 2020)
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Cold NEDE (Cruz+ 2023)
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Hot NEDE (Garny+ 2024)
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Majoron (Escudero & Witte 2021)
Non-thermal DM+phantom DE (da Costa+ 2023)
Wess Zumino DR (Schoneberg & Abellan 2022)
Vacuum Metamorphosis (Di Valentino+ 2020)
Emergent DE (Banihashemi+ 2020)
LsCDM (Akarsu+ 2023)
LsCDM+string model (Anchordoqui+ 2024)
wXCDM (Gomez-Valent+ 2024)
IDE (Giare+ 2024)
IDE (Zhai+2023)
IDE (Pan+2020)
Generalized Cubic Galileon (Frusciante+ 2020)
String Inspired Chern-Simons (Gomez-Valent+ 2023)
Ultralight DM-DE interaction (Aboubrahim & Nath 2024)
DM-photons Interaction (Becker+ 2021)
Decaying DM (Simon+ 2024)
DM-DE Interaction (Teixeira+ 2024)
KBC void galaxy counts (Haslbauer+ 2020)
PMF (Jedamzik+ 2025)
Higgs Inflation (Rodriguez+ 2023)
Electron mass + Omegak (Schoneberg & Vacher 2024)
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Modified Recombination (Lynch+ 2024)
Modified Recombination MODREC (Lynch+ 2024)
LMT (Alestas+ 2021)
LwMT (Alestas+ 2021)
AvERA-625k (Pataki+ 2025)
H_0 [km s^{-1} Mpc^{-1}]
68
70
72
74
76

The H_0 Olympics: A fair ranking of proposed models

Nils Schöneberg[a,*], Guillermo Franco Abellán[b], Andrea Pérez Sánchez[a], Samuel J. Witte[c], Vivian Poulin[b], Julien Lesgourgues[a]

[a] *Institute for Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, D-52056 Aachen, Germany.*
[b] *Laboratoire Univers & Particules de Montpellier (LUPM), CNRS & Université de Montpellier (UMR-5299), Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France.*
[c] *GRAPPA Institute, Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

Abstract

Despite the remarkable success of the Λ Cold Dark Matter (ΛCDM) cosmological model, a growing discrepancy has emerged (currently measured at the level of $\sim 4-6\,\sigma$) between the value of the Hubble constant H_0 measured using the local distance ladder and the value inferred using the cosmic microwave background and galaxy surveys. While a vast array of ΛCDM extensions have been proposed to explain these discordant observations, understanding the (relative) success of these models in resolving the tension has proven difficult – this is a direct consequence of the fact that each model has been subjected to differing, and typically incomplete, compilations of cosmological data. In this review, we attempt to make a systematic comparison of seventeen different models which have been proposed to resolve the H_0 tension (spanning both early- and late-Universe solutions), and quantify the relative success of each using a series of metrics and a vast array of data combinations. Owing to the timely appearance of this article, we refer to this contest as the "H_0 Olympics"; the goal being to identify which of the proposed solutions, and more broadly which underlying mechanisms, are most likely to be responsible for explaining the observed discrepancy (should unaccounted for systematics not be the culprit). This work also establishes a foundation of tests which will allow the success of novel proposals to be meaningfully "benchmarked".

Keywords: Hubble Tension, Dark Energy, Dark Matter Phenomenology, Dark Radiation, Early Dark Energy, Varying fundamental constants

The H_0 olympics: fairly ranking models

- We compare 17 different models suggested to resolve the Hubble tension.

Schöneberg (VP) ++ 2107.10291

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Late-Universe models	Dark Radiation models	Exotic Early Universe models
CPL Dark Energy	Free-streaming $N_{\rm eff}$	Early Dark Energy
Emergent Dark Energy	Self-Interacting $N_{\rm DR}$	New Early Dark Energy
Generalized Emergent Dark Energy	Mixture of $N_{\rm eff}+N_{\rm DR}$	Early modified Gravity
Decaying Dark matter to massless particles	DM-DR interaction + $N_{\rm DR}$	Primordial magnetic fields
Decaying Dark matter to massive particles	Self interacting $\nu + N_{\rm eff}$	Varying electron mass m_e
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- I/ Frequentist: Can a model give a good fit to all data including SH0ES and be favored over ΛCDM.
- II/ Bayesian: Can a model be favored over ΛCDM independently of SH0ES and "predict" a high H_0.

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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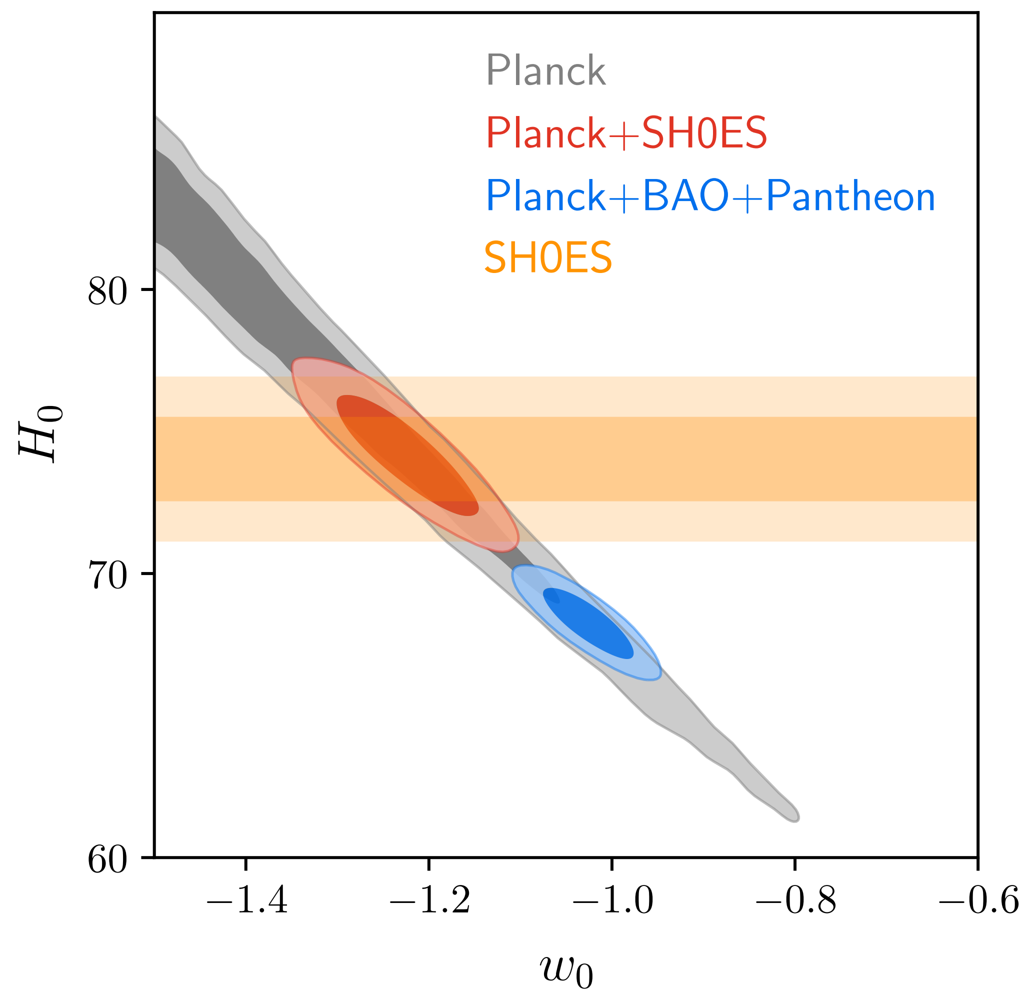

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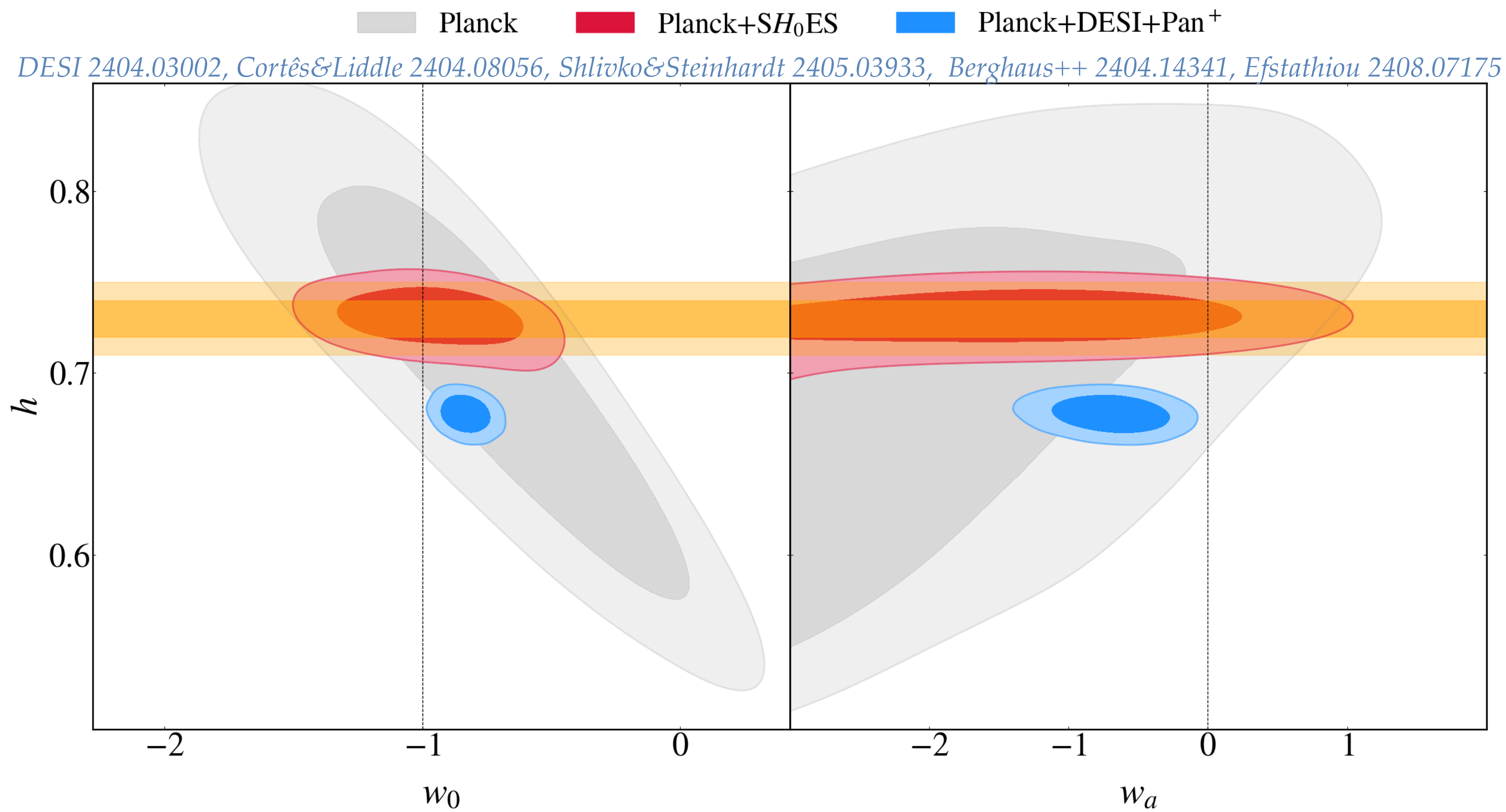
DESI 2404.03002, Cortês&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, Efstathiou 2408.07175



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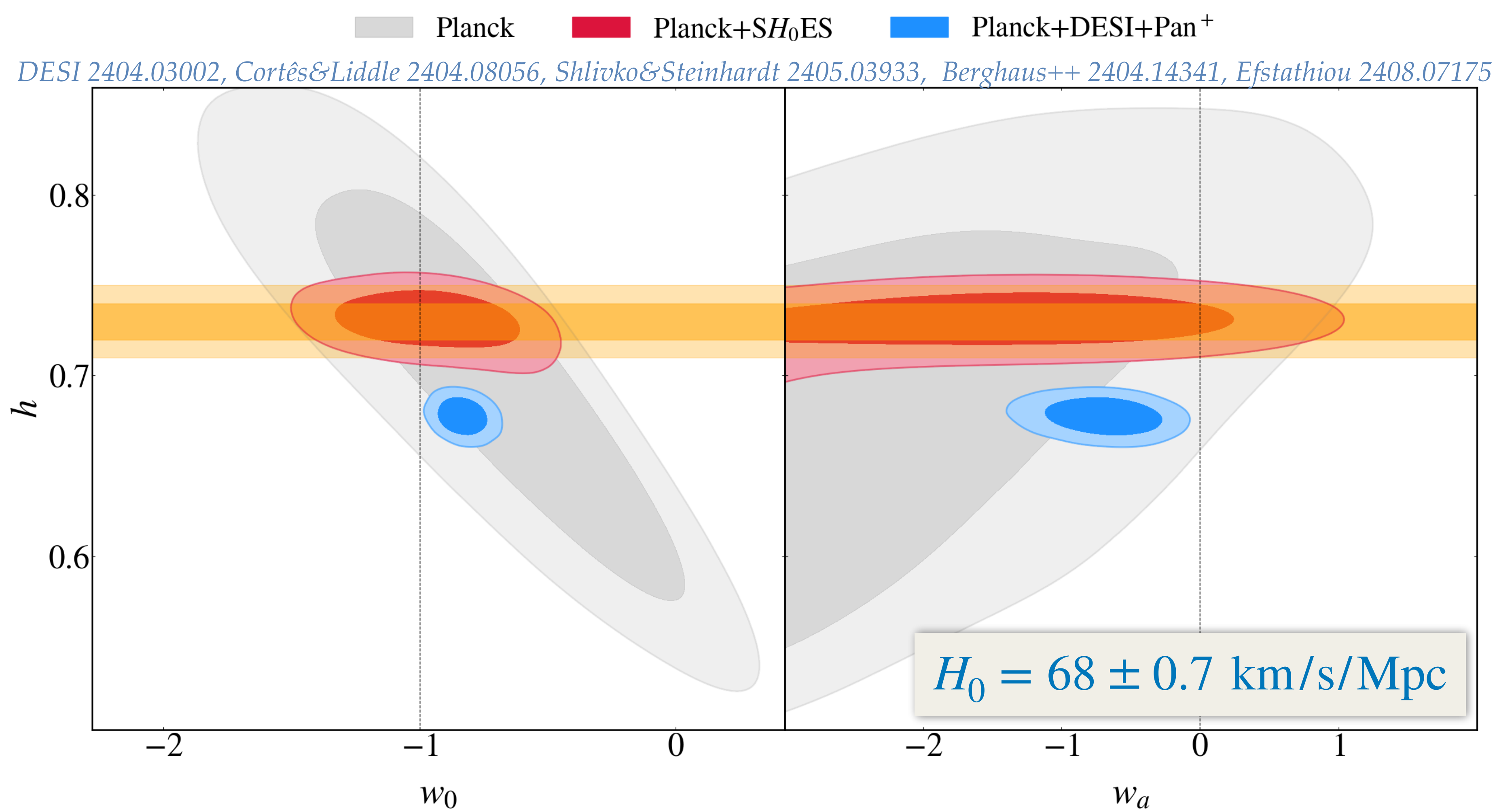

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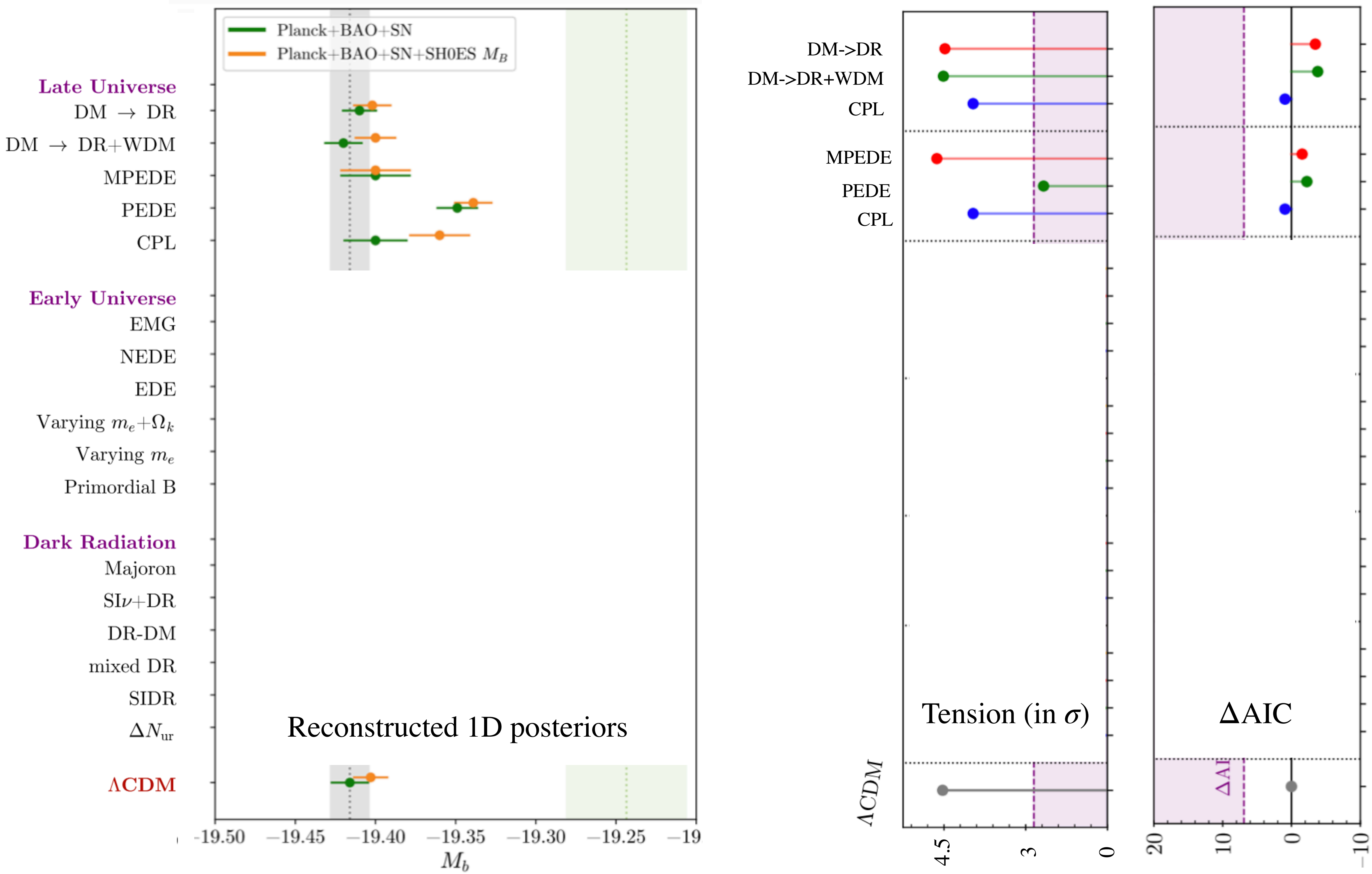

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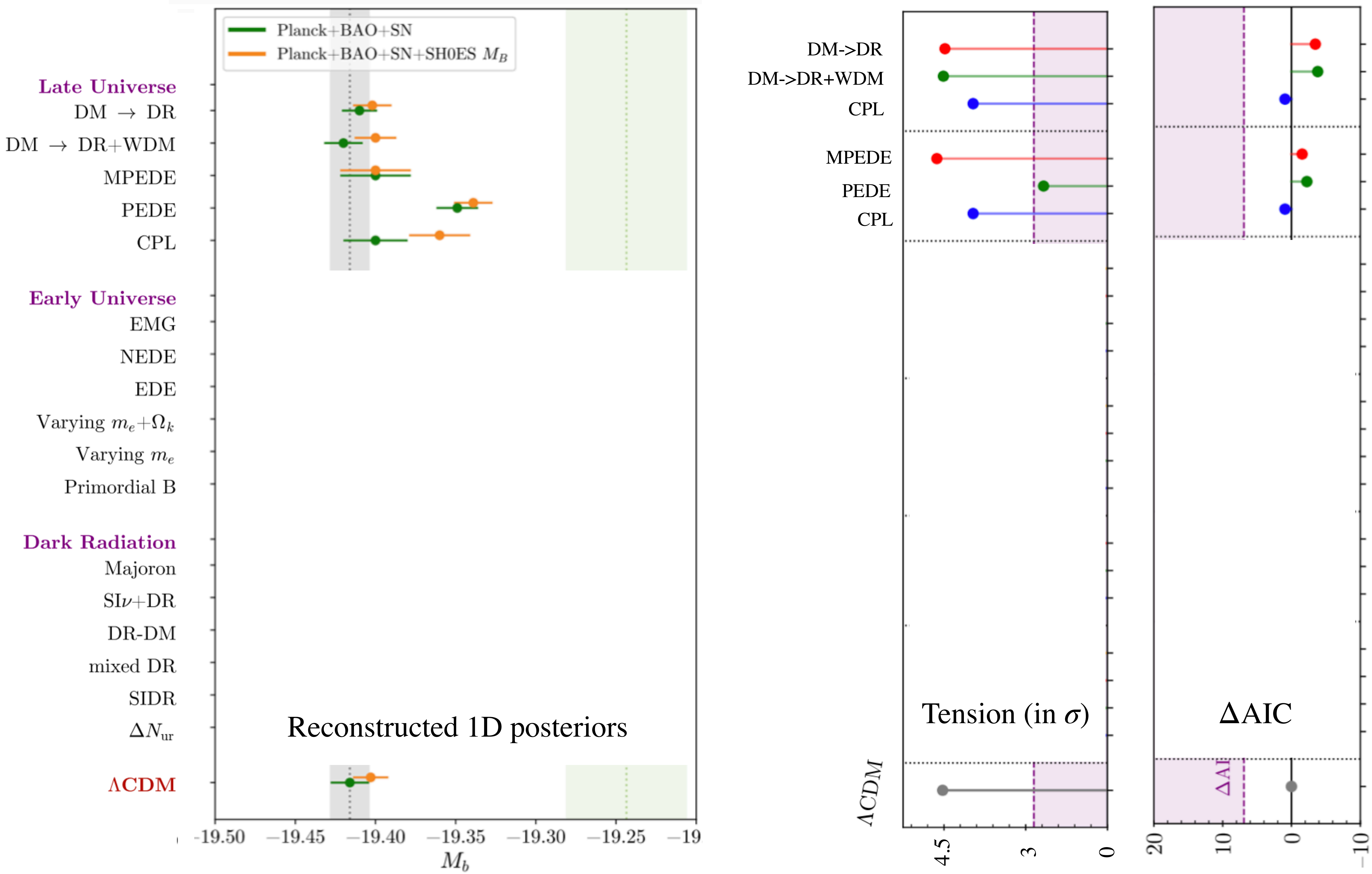

Late-universe models are excluded as a resolution to the tension (alone)

A ‘no-go’ theorem for 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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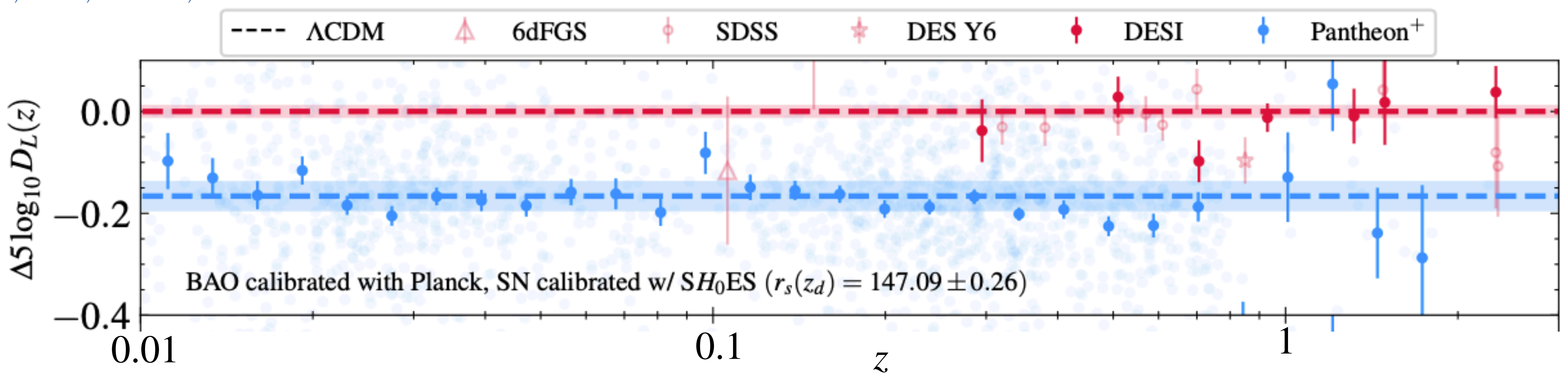
VP, Smith, Calderon, Simon 2407.18292



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Camarena&Marra 2101.08641, Efstathiou 2103.08723, Raveri 2309.06795

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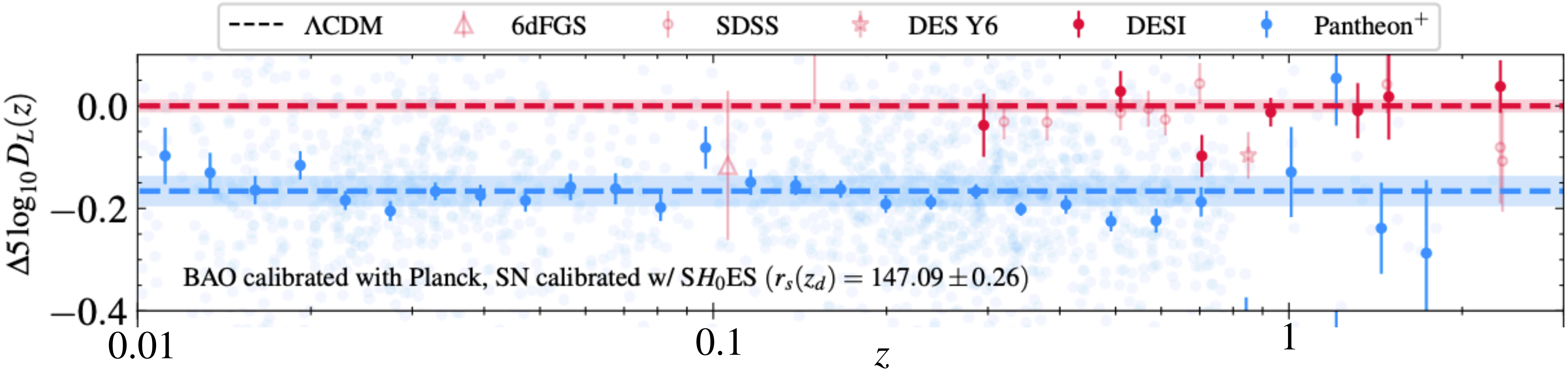

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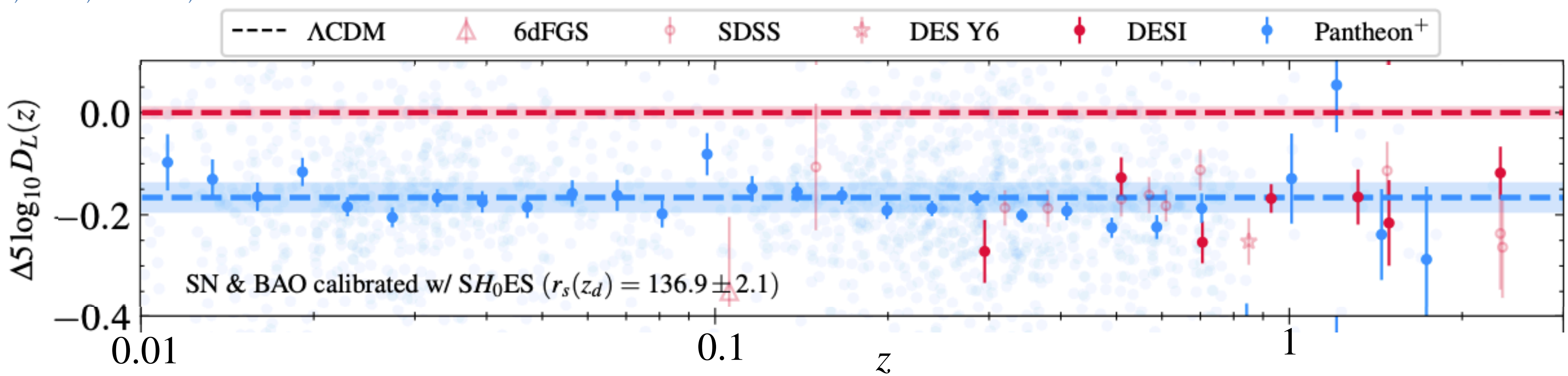

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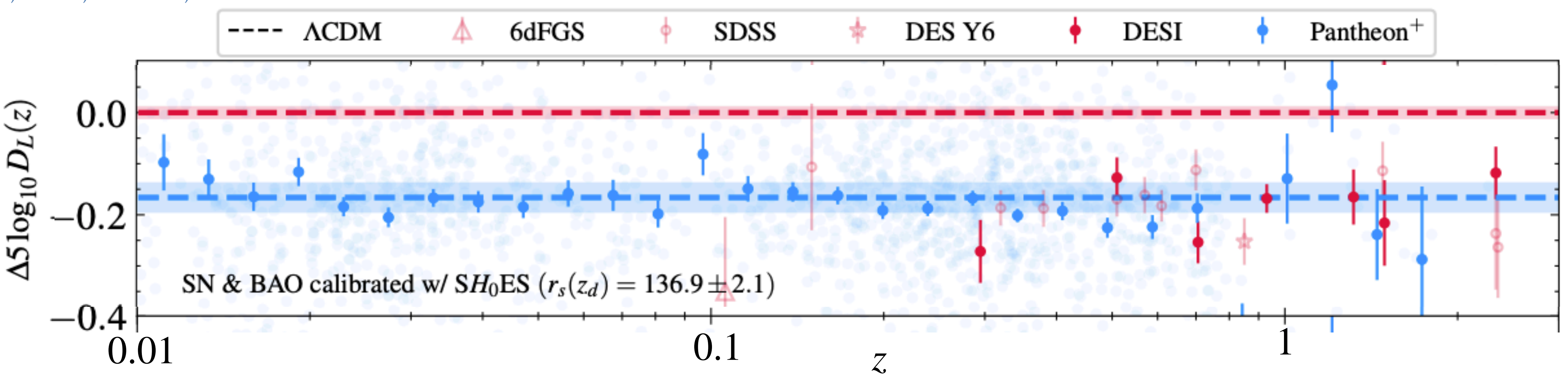

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- Solving the tension require to either change calibrators or break the DDR relation

- A single "constant" shift is currently sufficient ⇒ changing calibrators favored! *Teixeira (VP) ++ 2504.10464*

Impact of the Cosmic Calibration Tension

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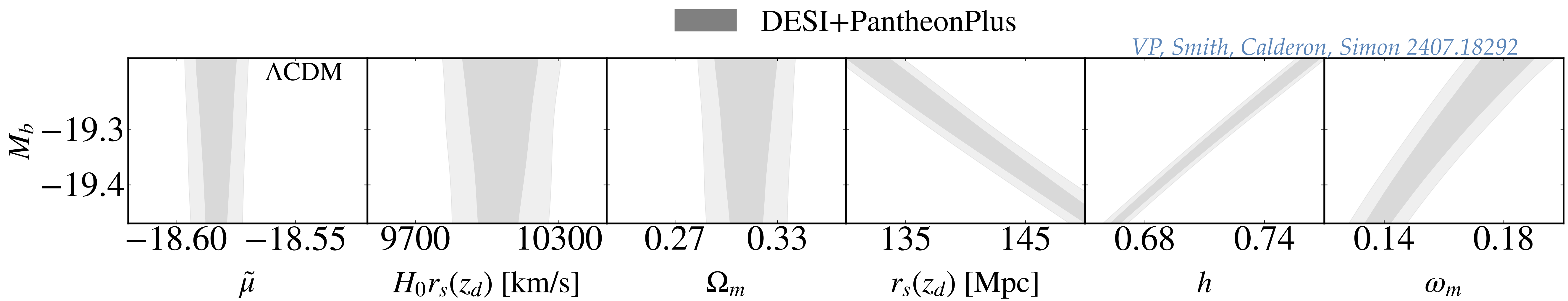

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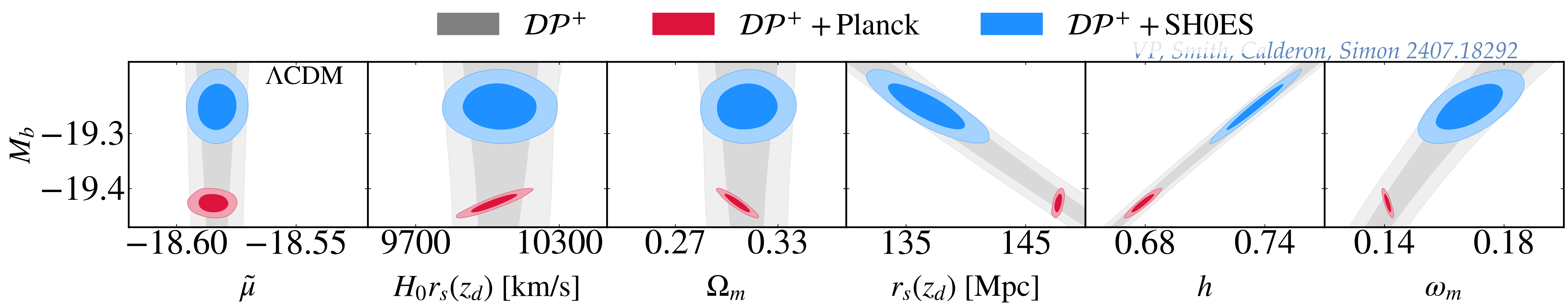

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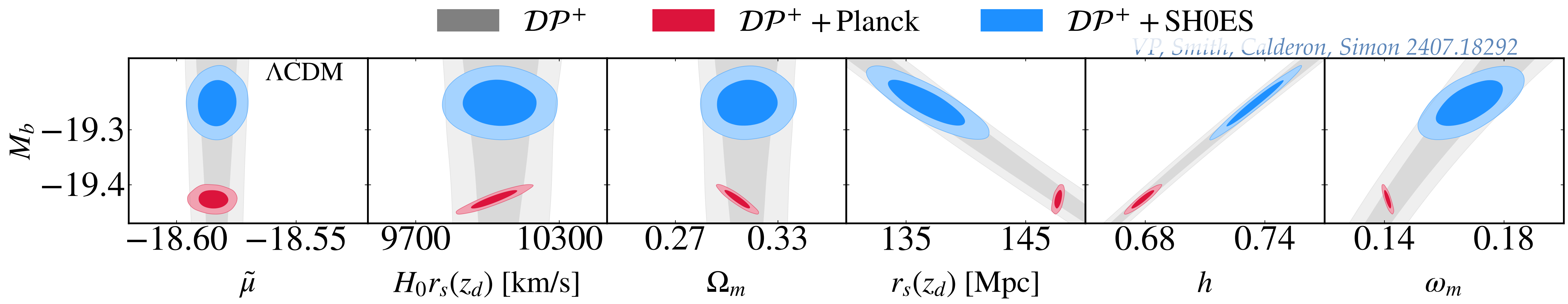

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- Challenge for new physics: Reduce the sound horizon and compensate the larger ω_m on the CMB

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

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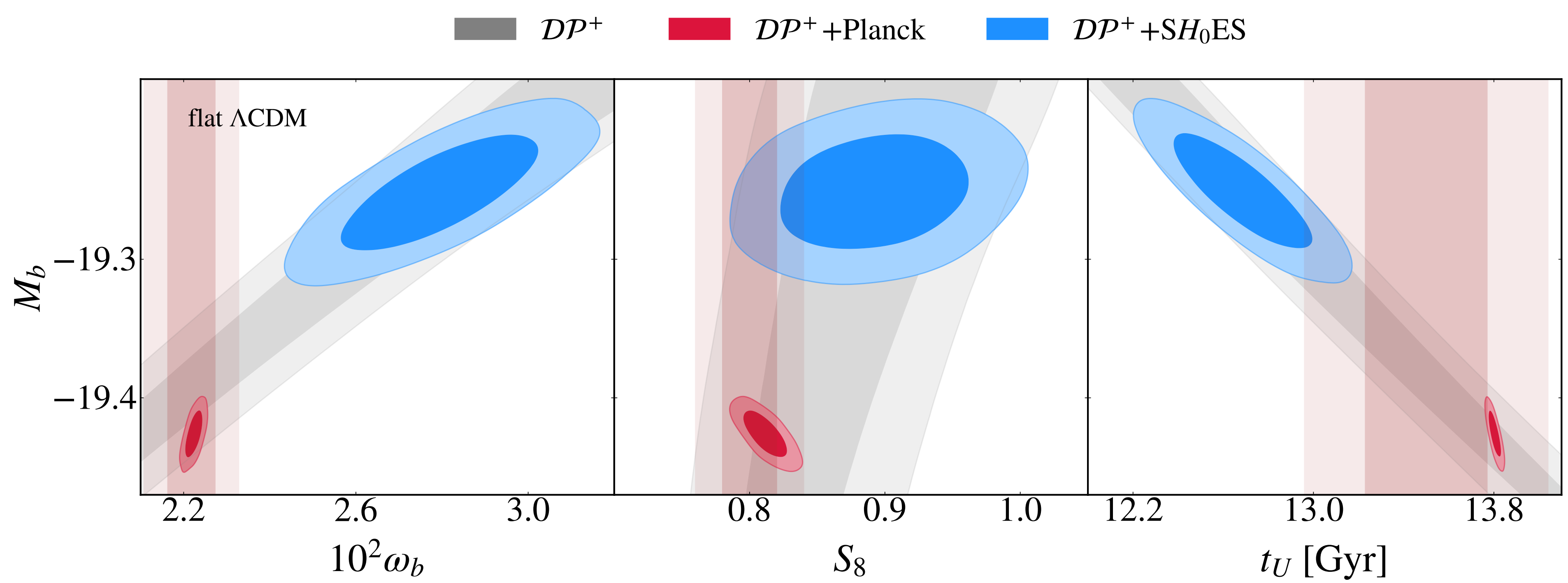
- Under ΛCDM, the SH_0ES calibration has further implications



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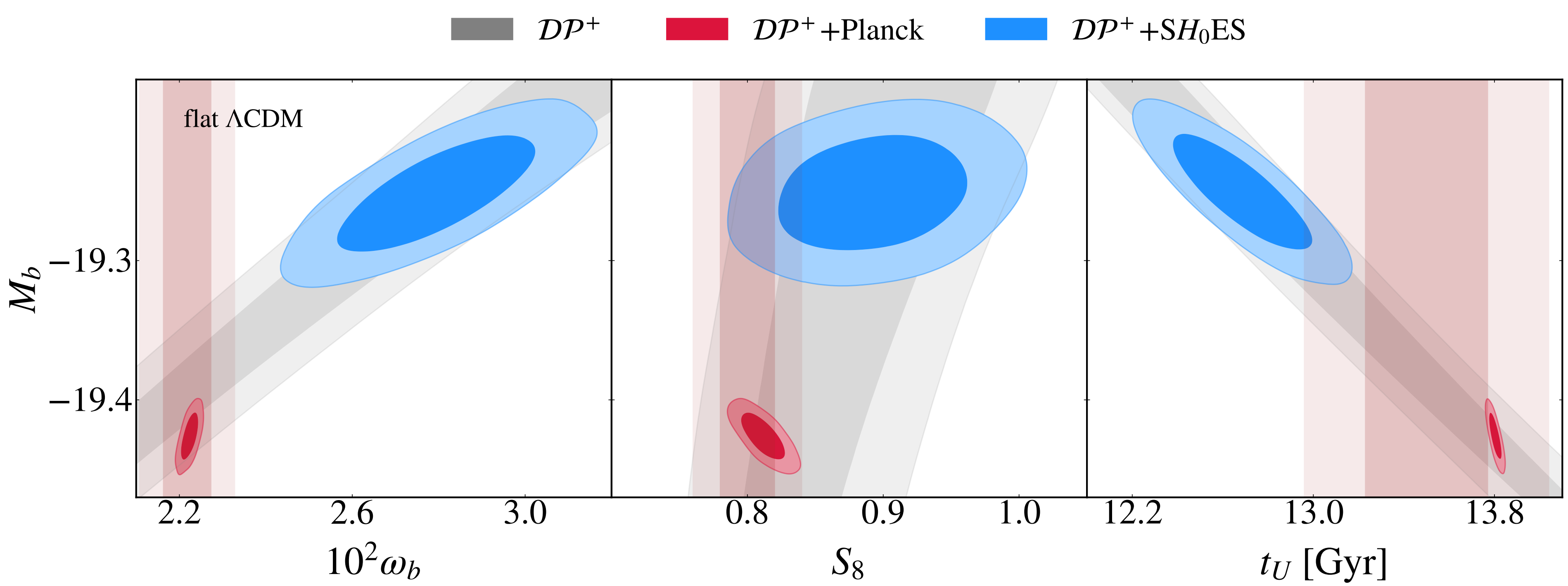

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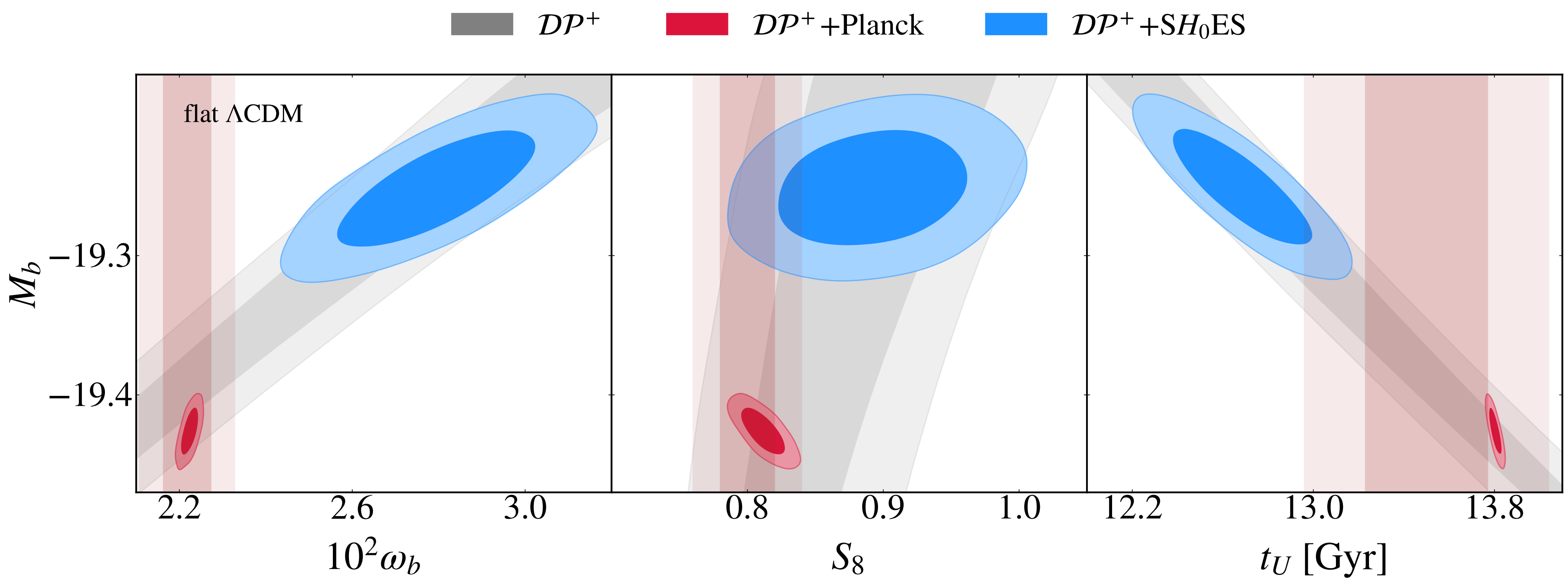

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Jedamzik & Pogosian 2010.04158

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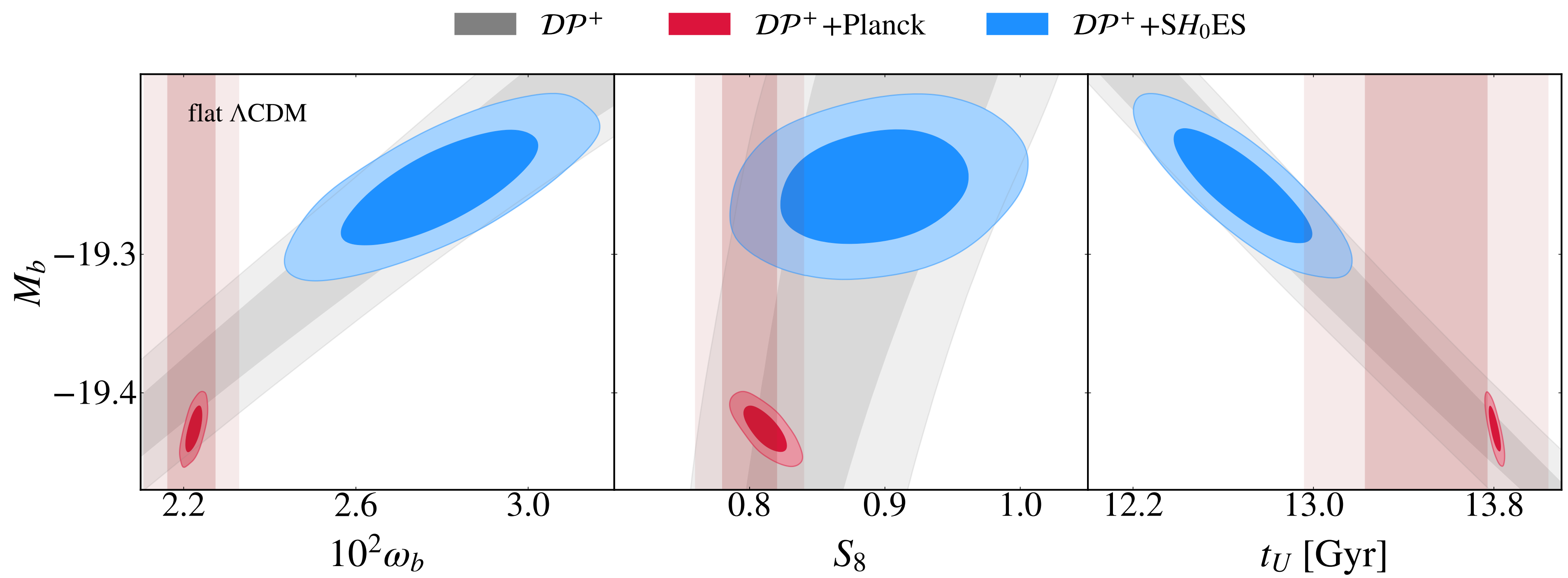

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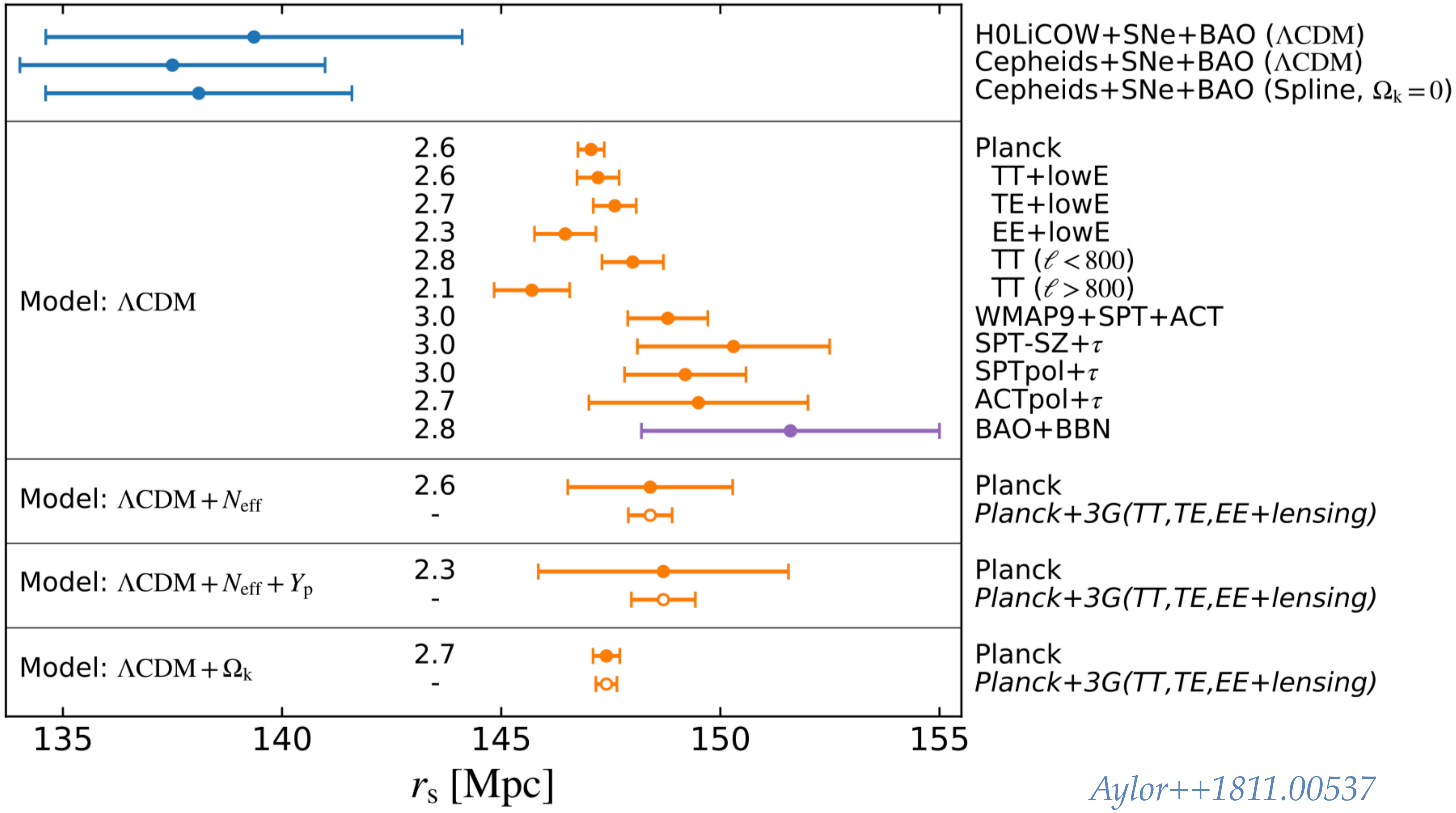
Jedamzik & Pogosian 2010.04158

- Age of the universe tension: t_U is younger by about 1 Gyr than in Planck/ΛCDM!

Bernal++ 2102.05066, Boylan-Kolchin 2103.15824, Vagnozzi 2105.10425

Solving the Cosmic Calibration Tension

- One can deduce the co-moving sound horizon r_s from H_0 and BAO: CMB estimate must decrease by ~ 10 Mpc



Aylor++1811.00537

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

Bernal++ 1607.05617, Knox & Millea 1908.03663

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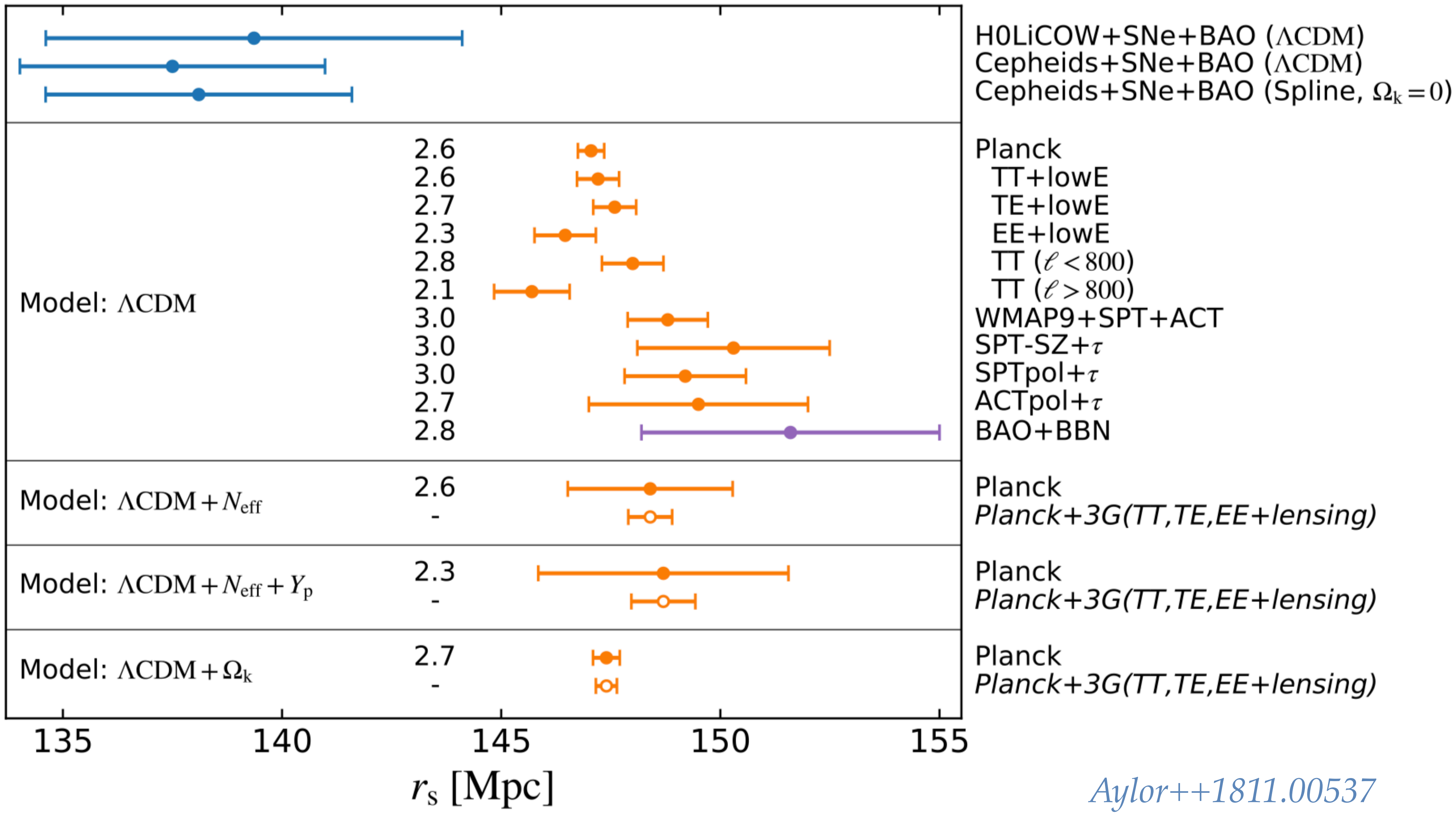

Aylor++1811.00537

affect c_s: DM-photon scattering? DM-b scattering?

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Bernal++ 1607.05617, Knox & Millea 1908.03663

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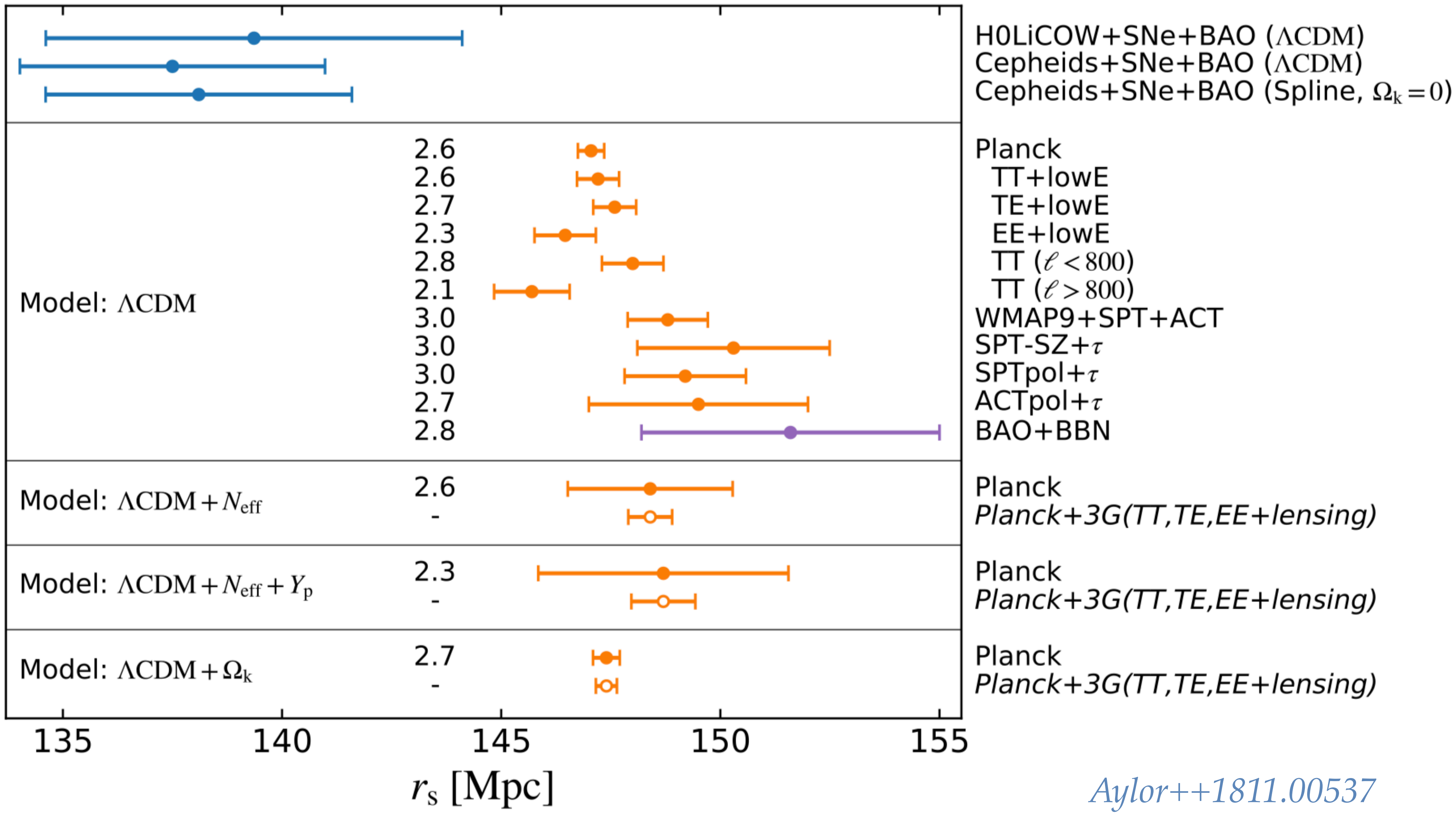

Aylor++1811.00537

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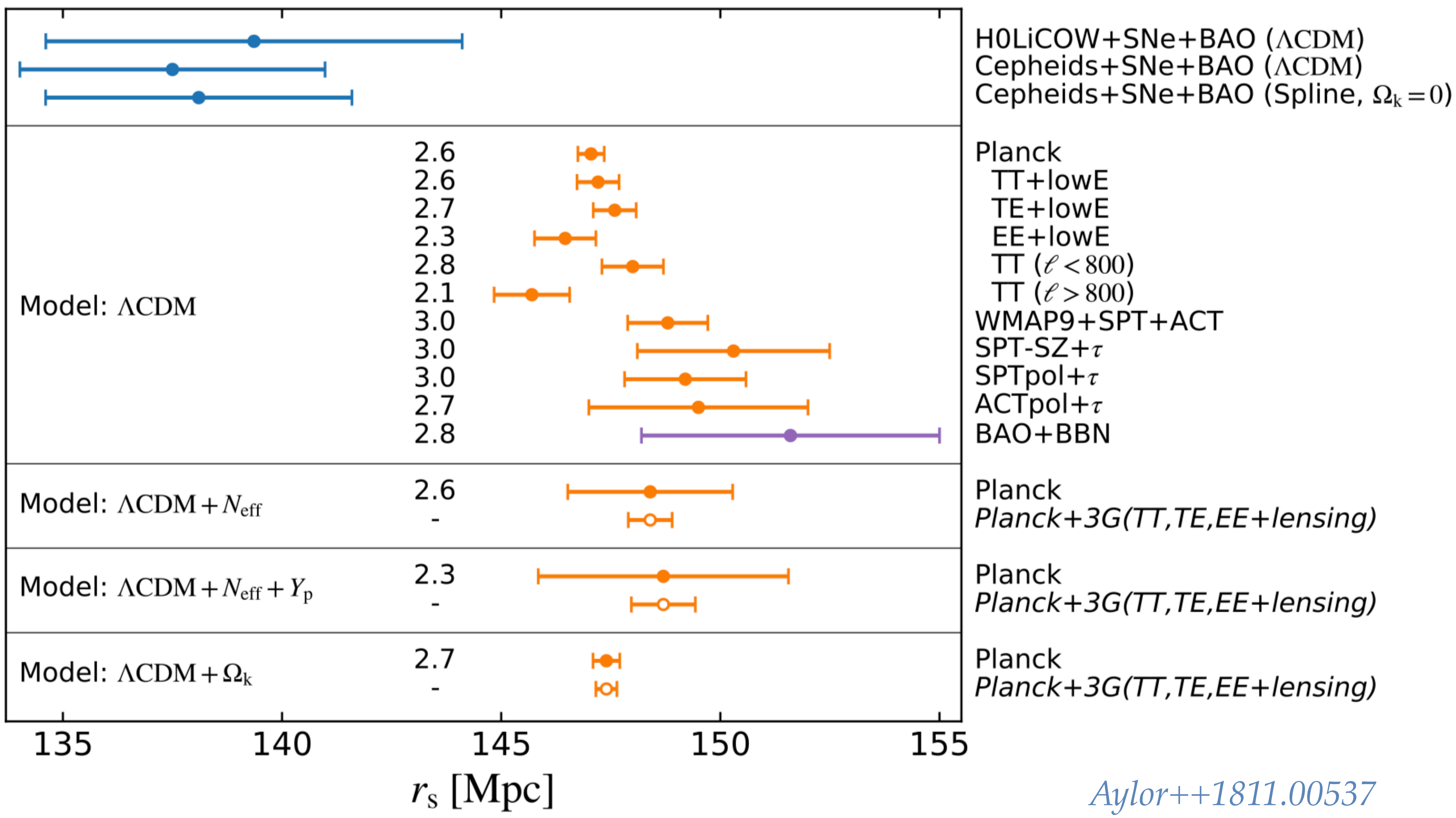

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increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?

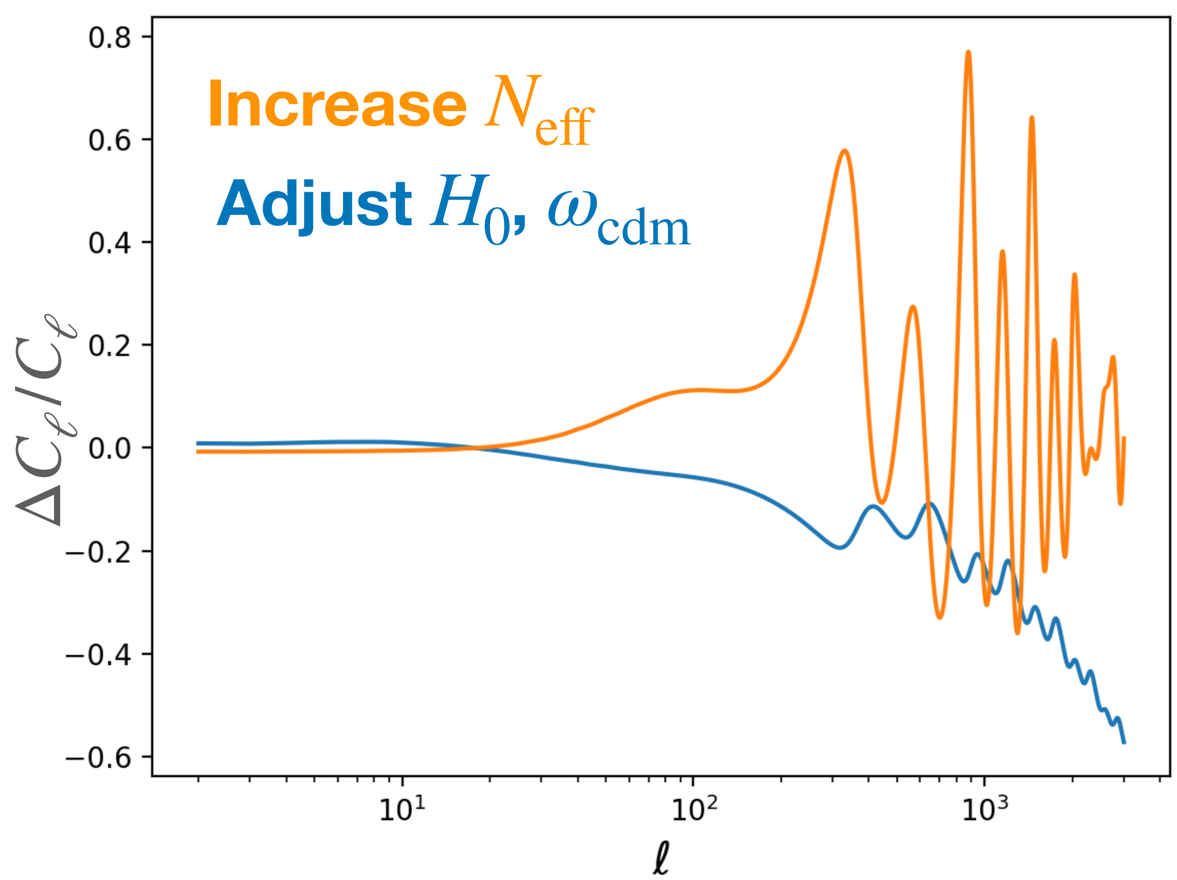
Bernal++ 1607.05617, Knox & Millea 1908.03663

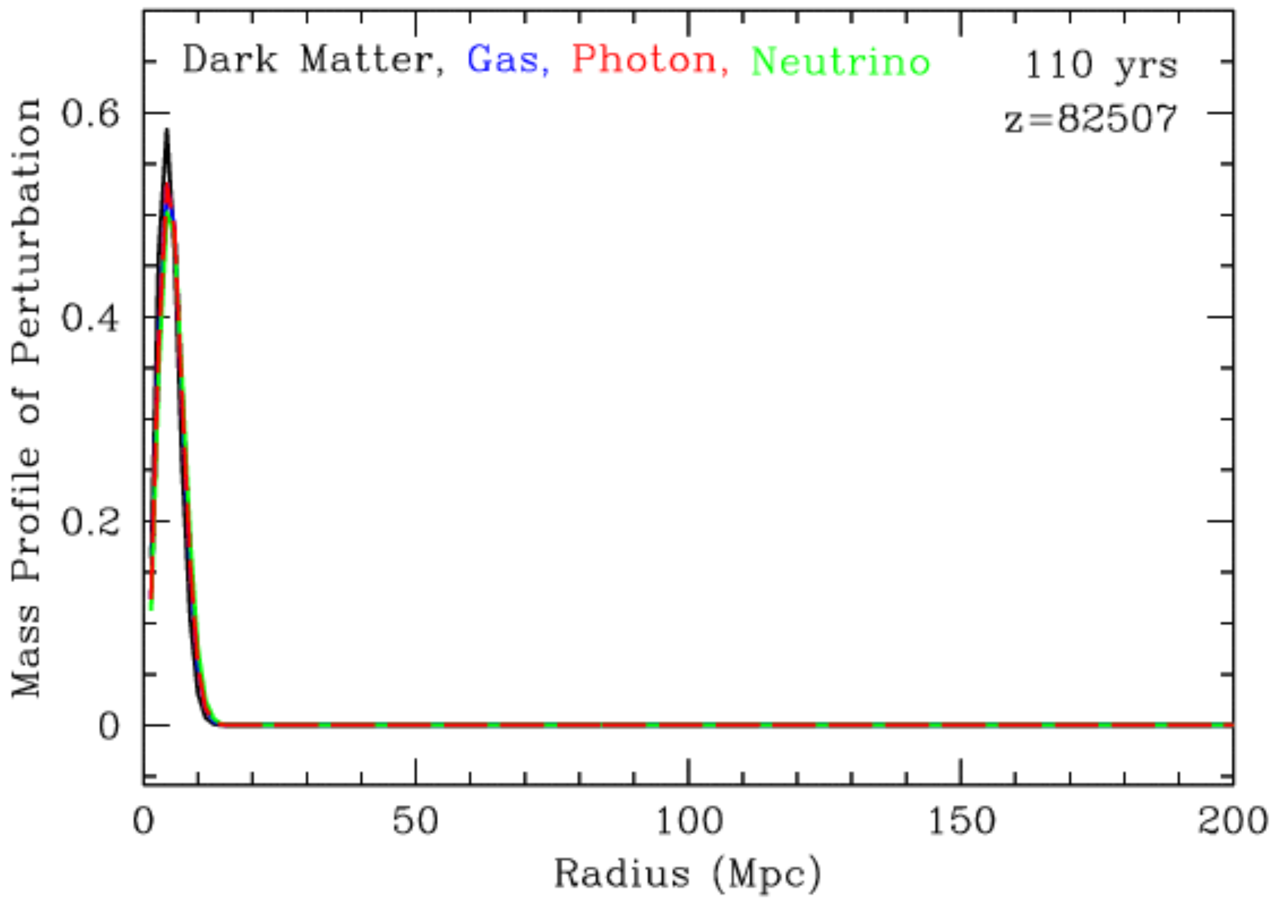
Relativistic species $N_{\rm eff}$

- Additional relativistic degrees of freedom can be parametrized by $N_{\rm eff}$

$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- Standard Model neutrinos behave as *free-streaming radiation* since T~1MeV with $N_{\rm eff} = 3.044$





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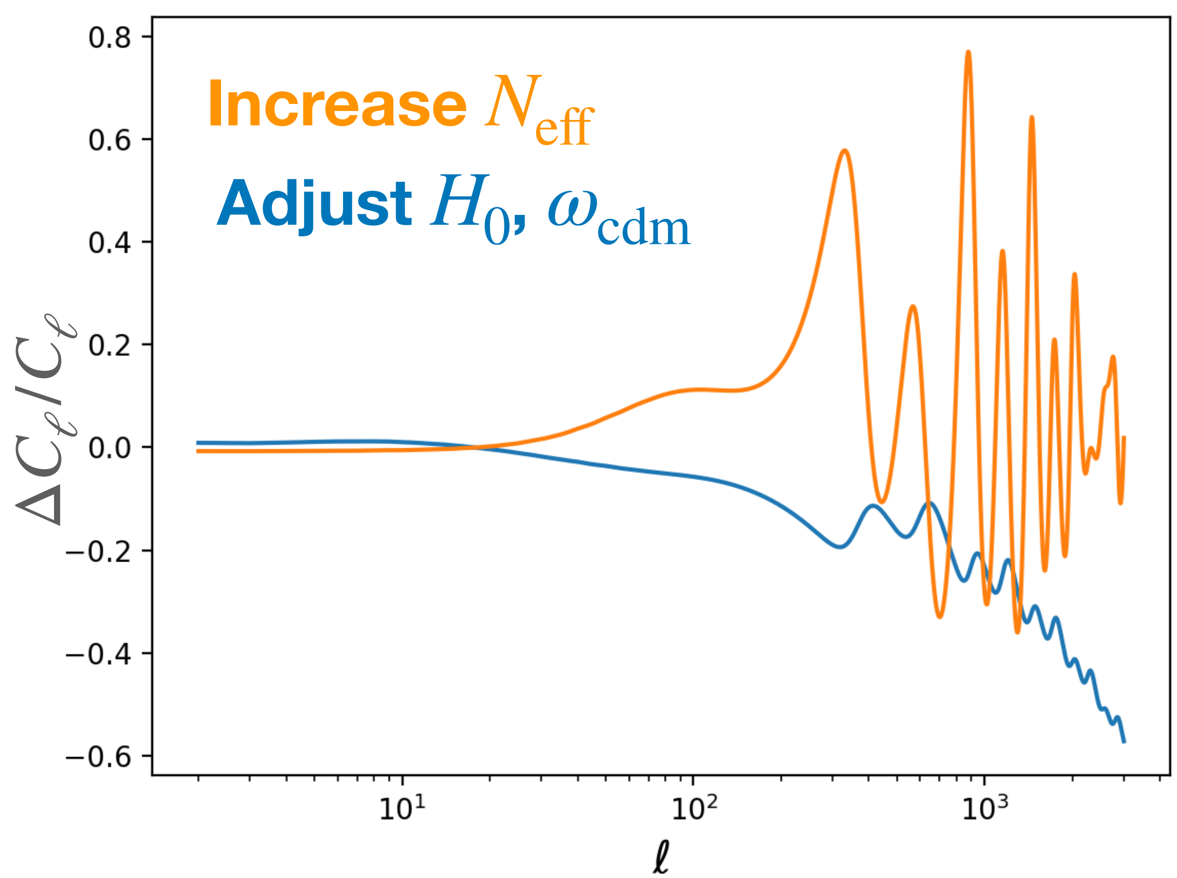

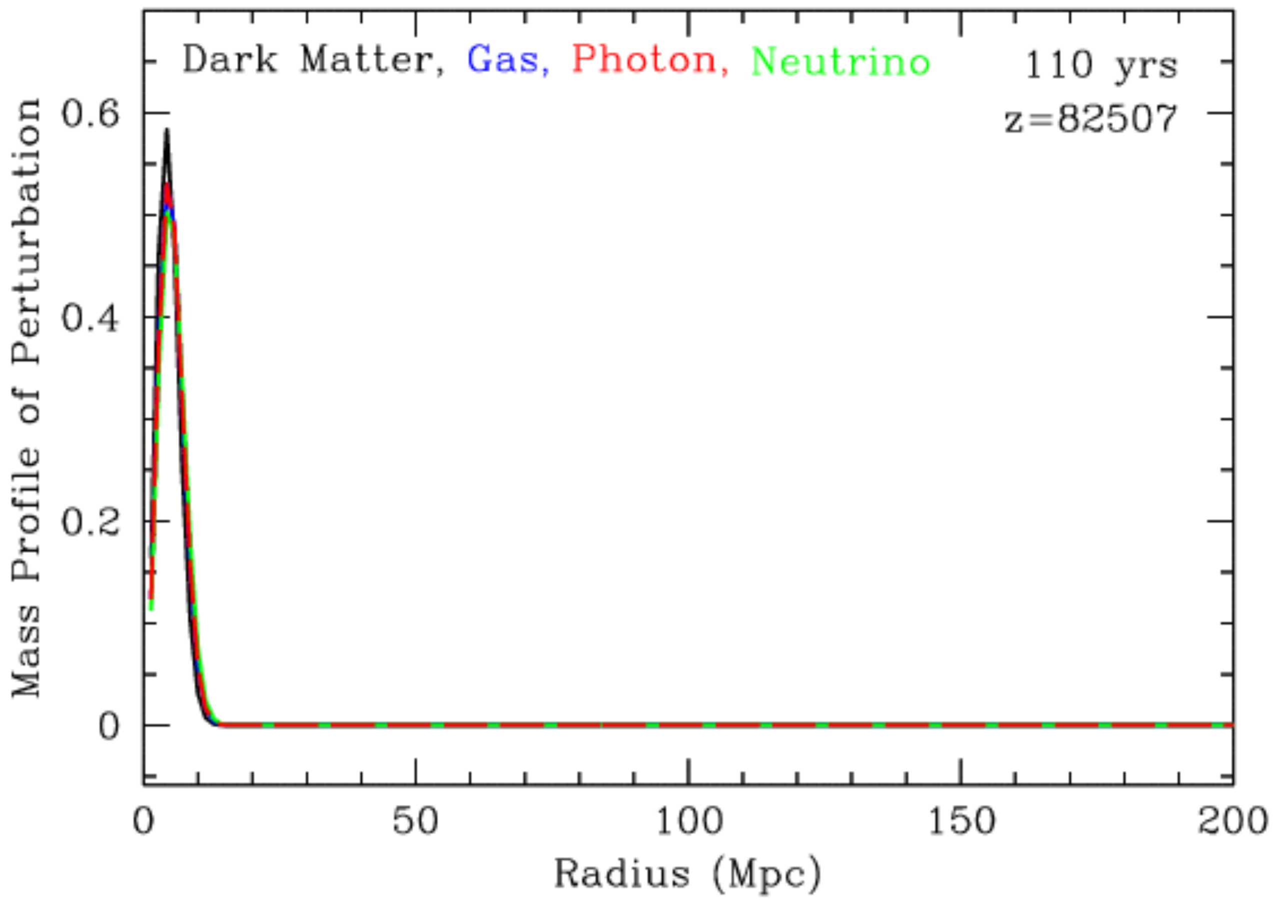

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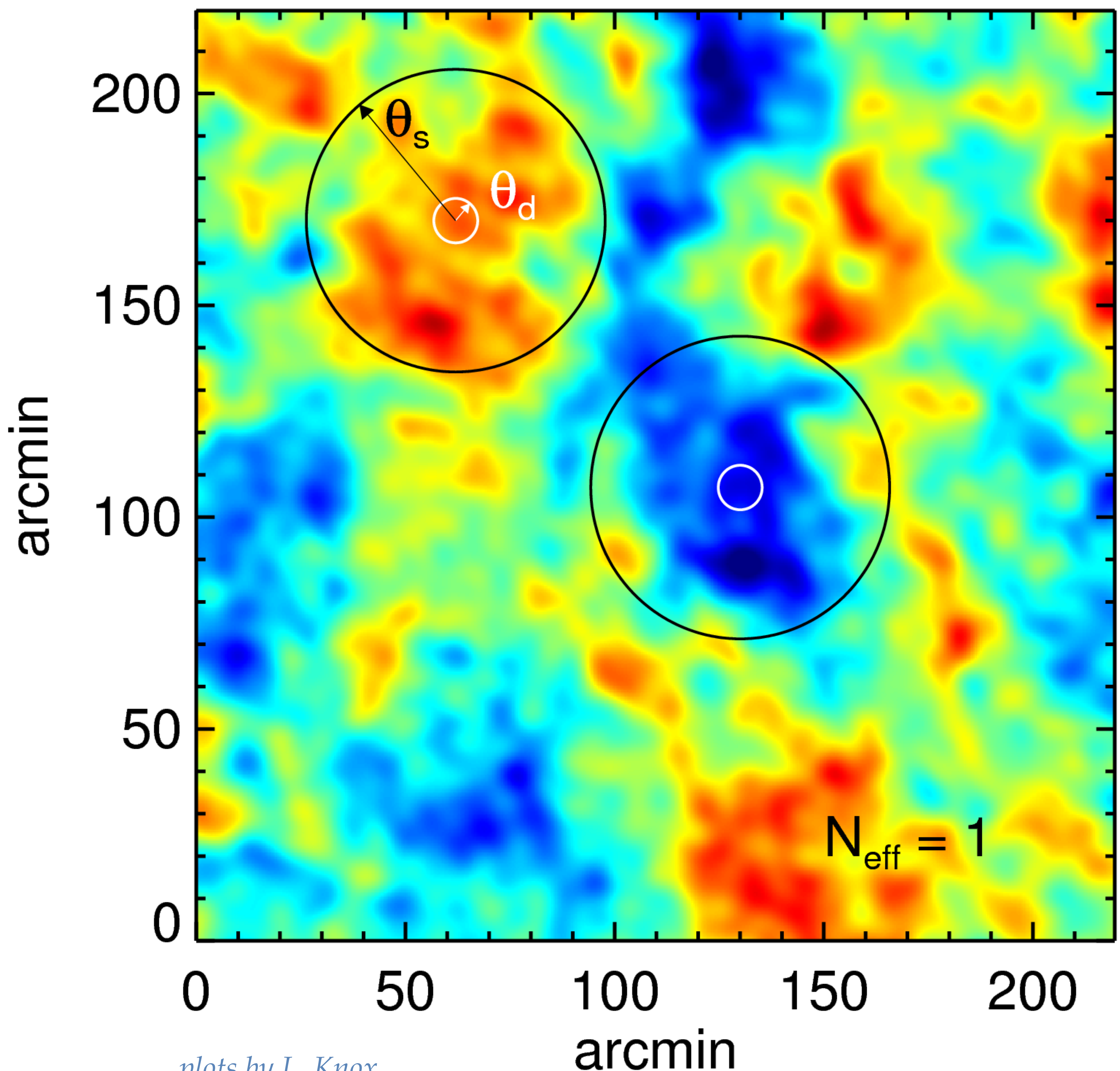
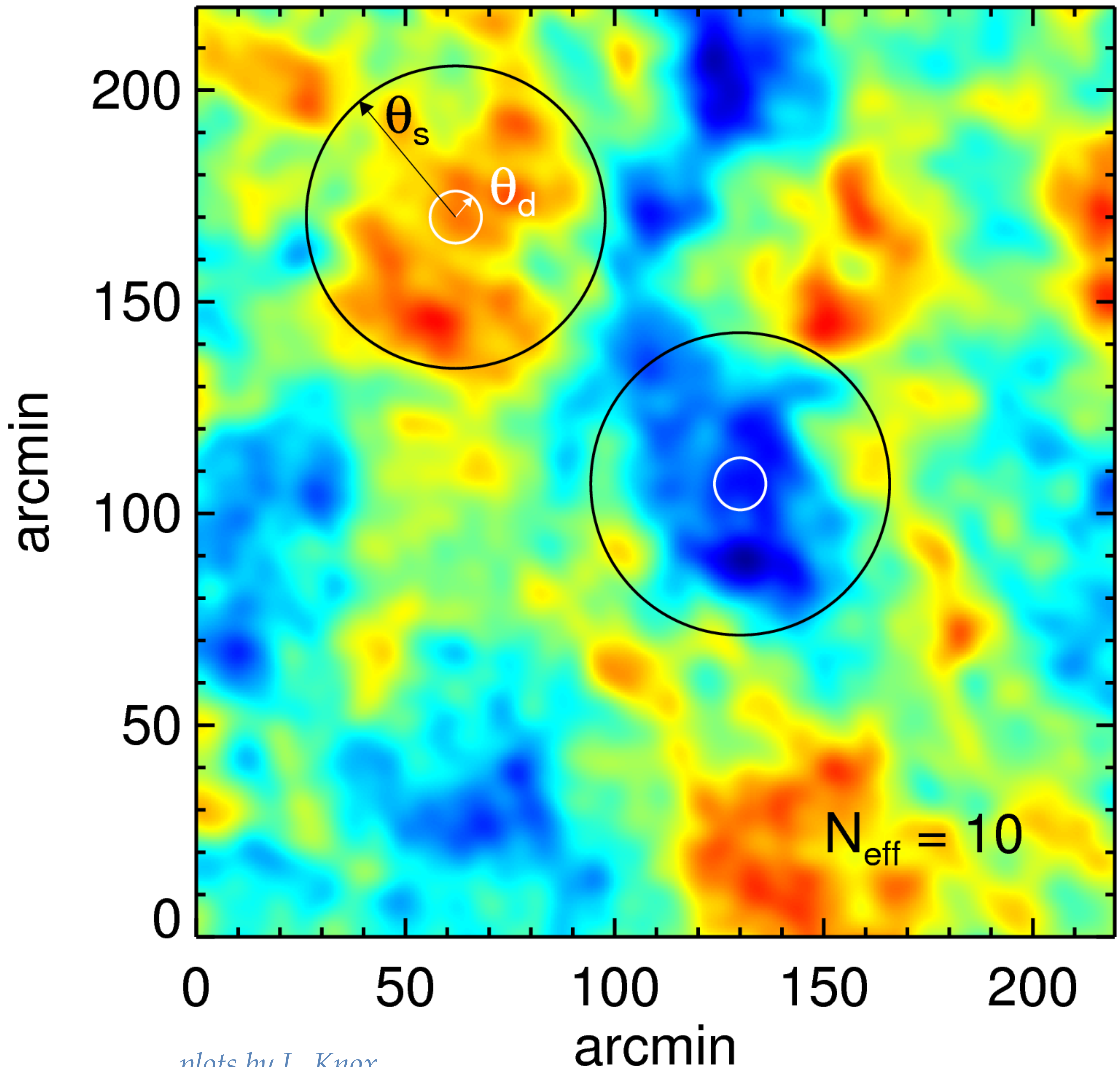


Vivia

plots by L. Knox



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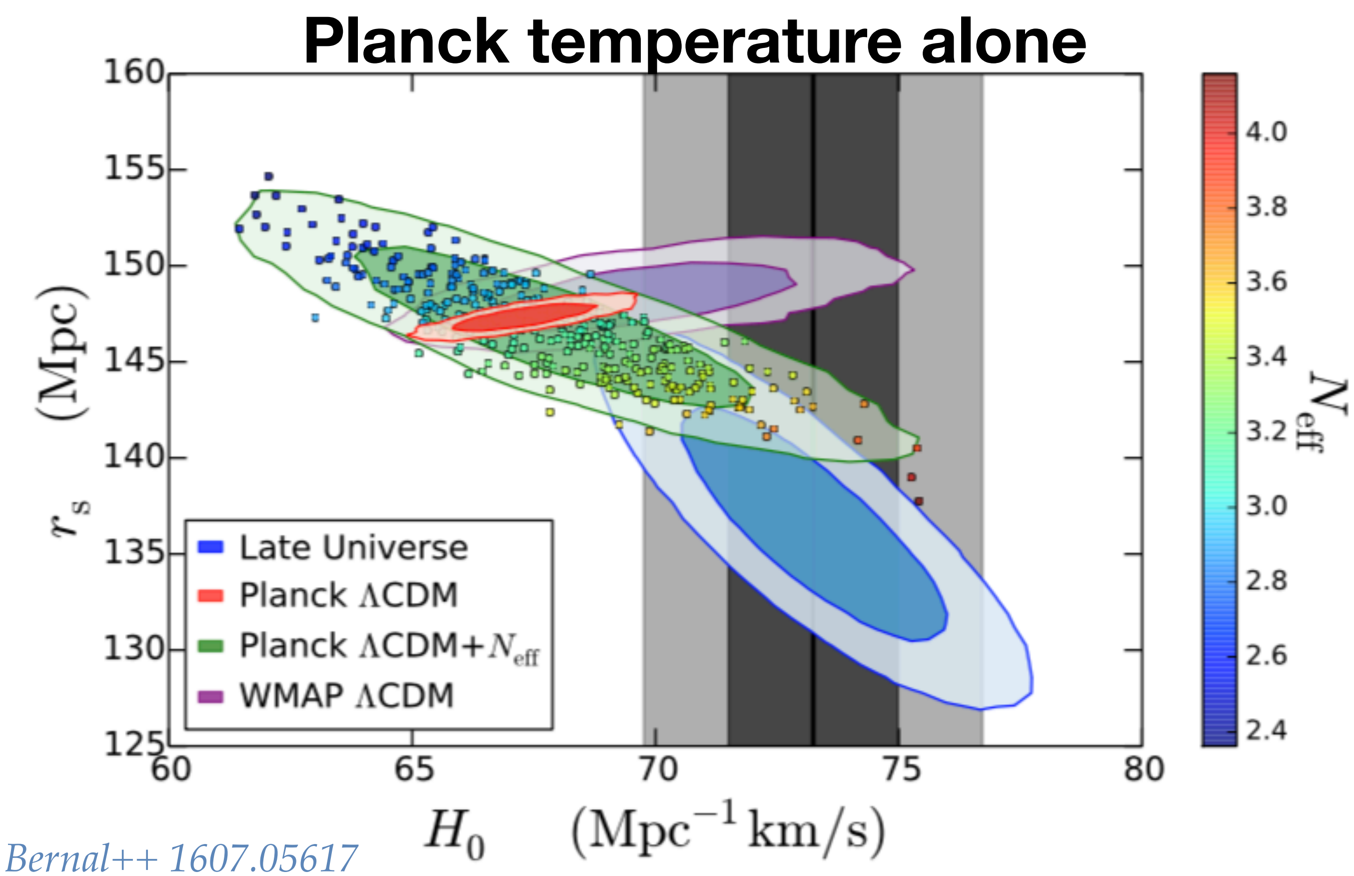

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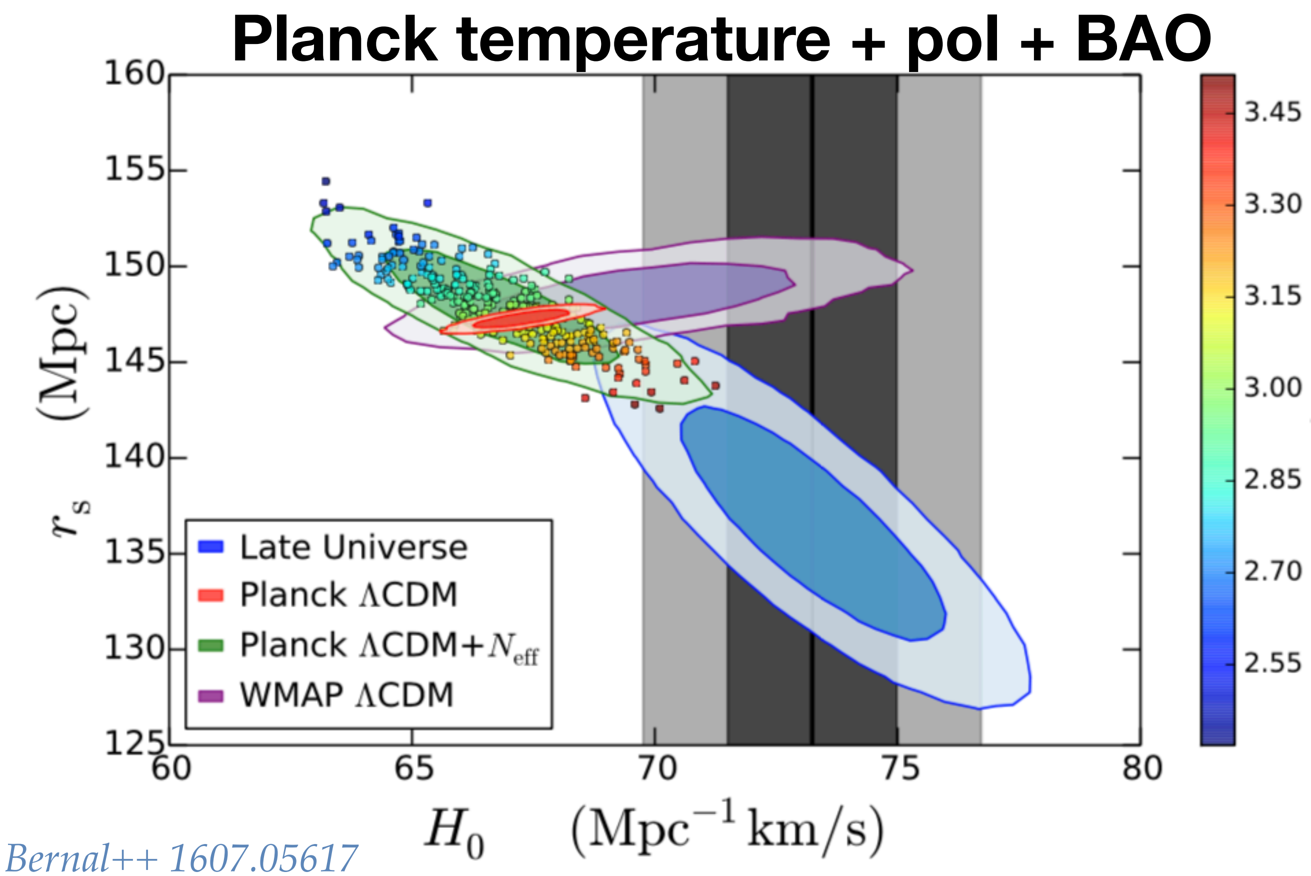

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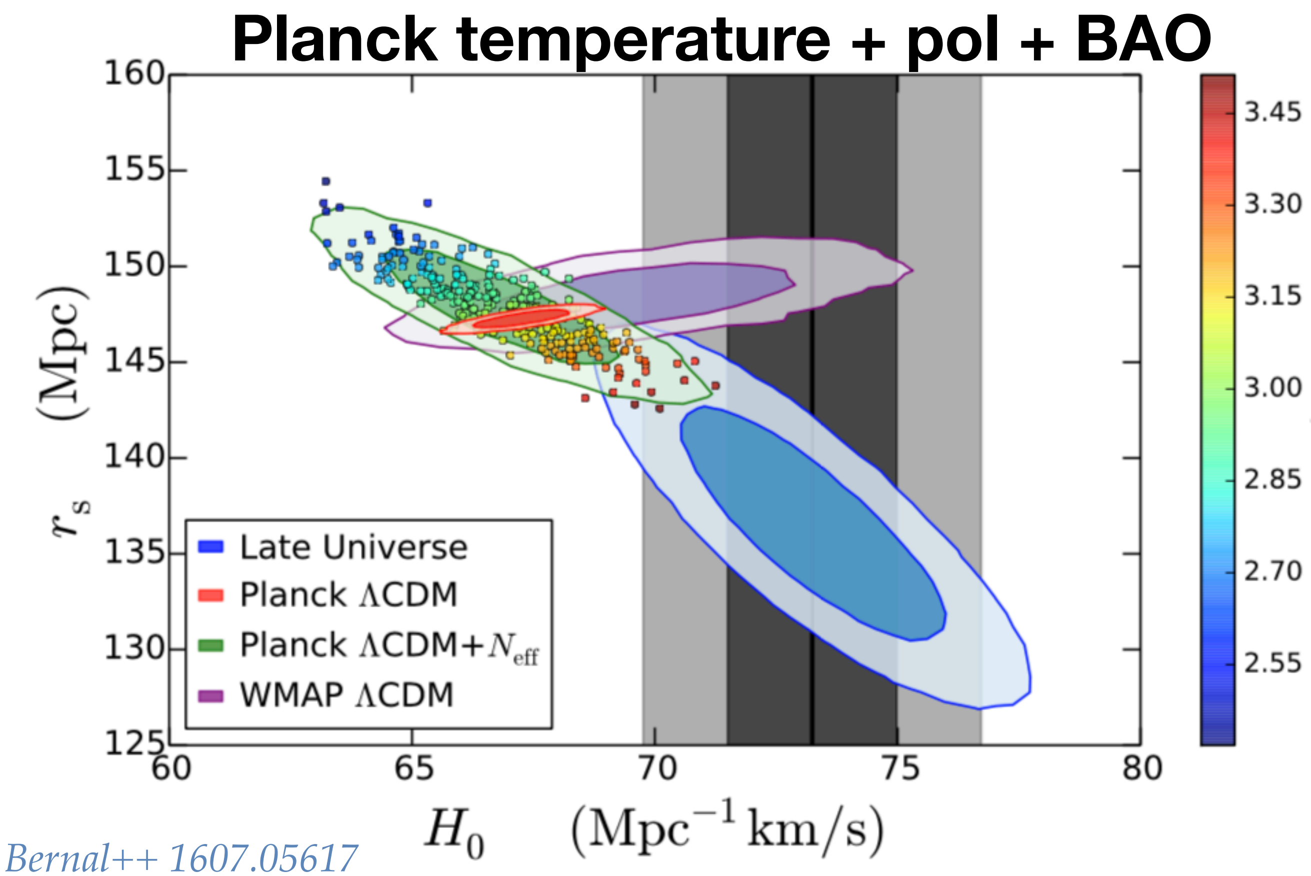

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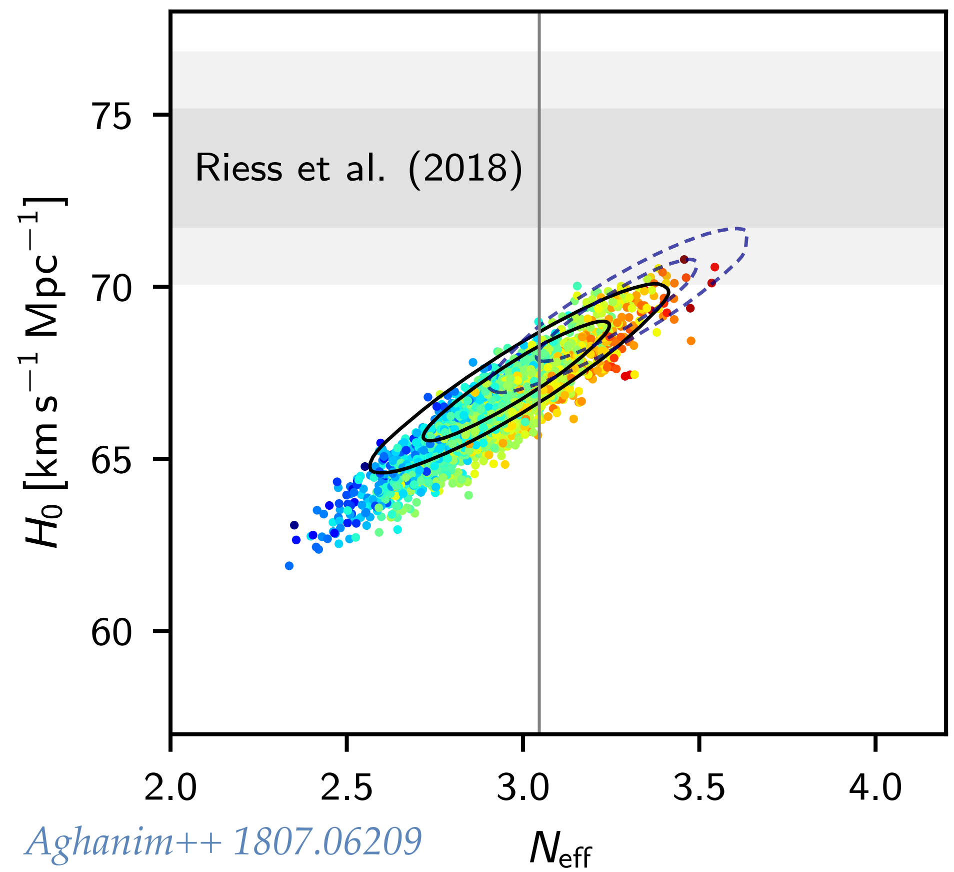

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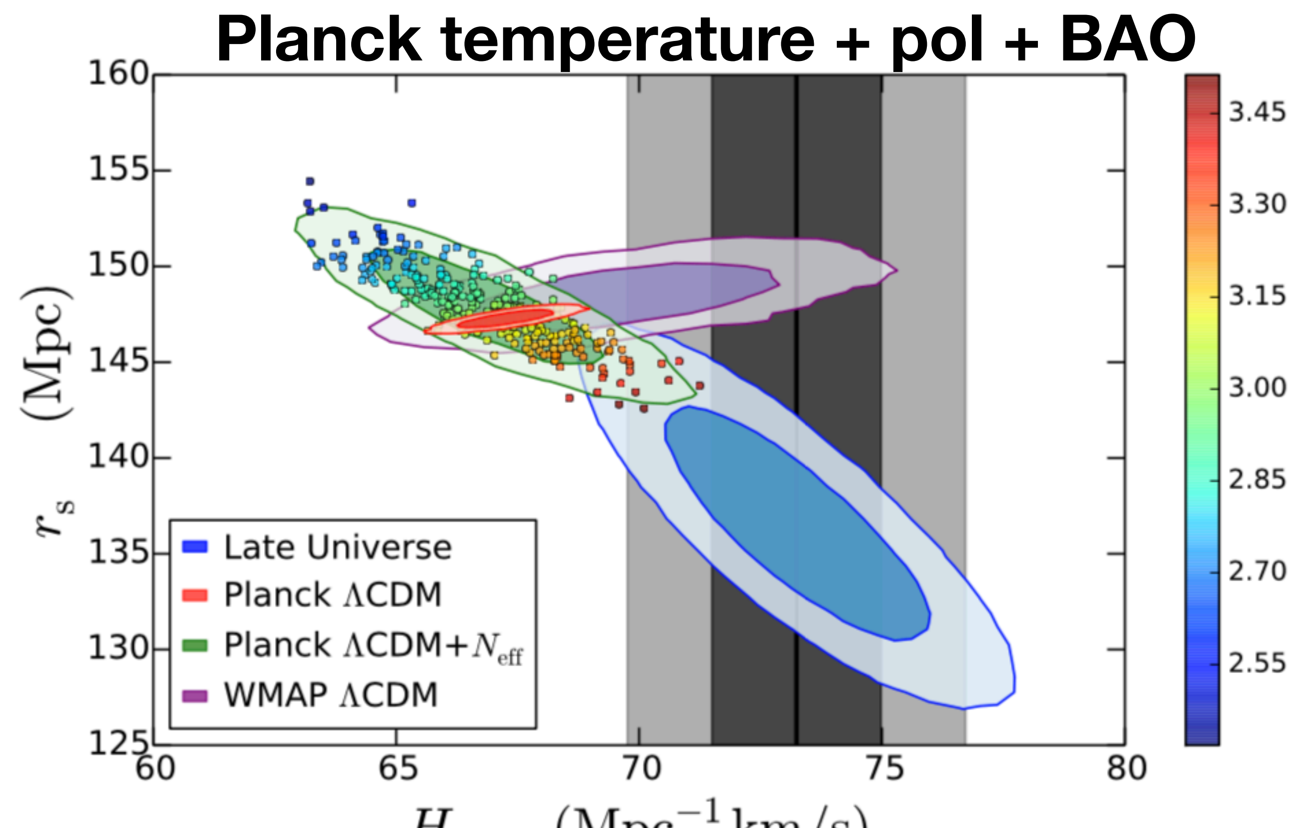

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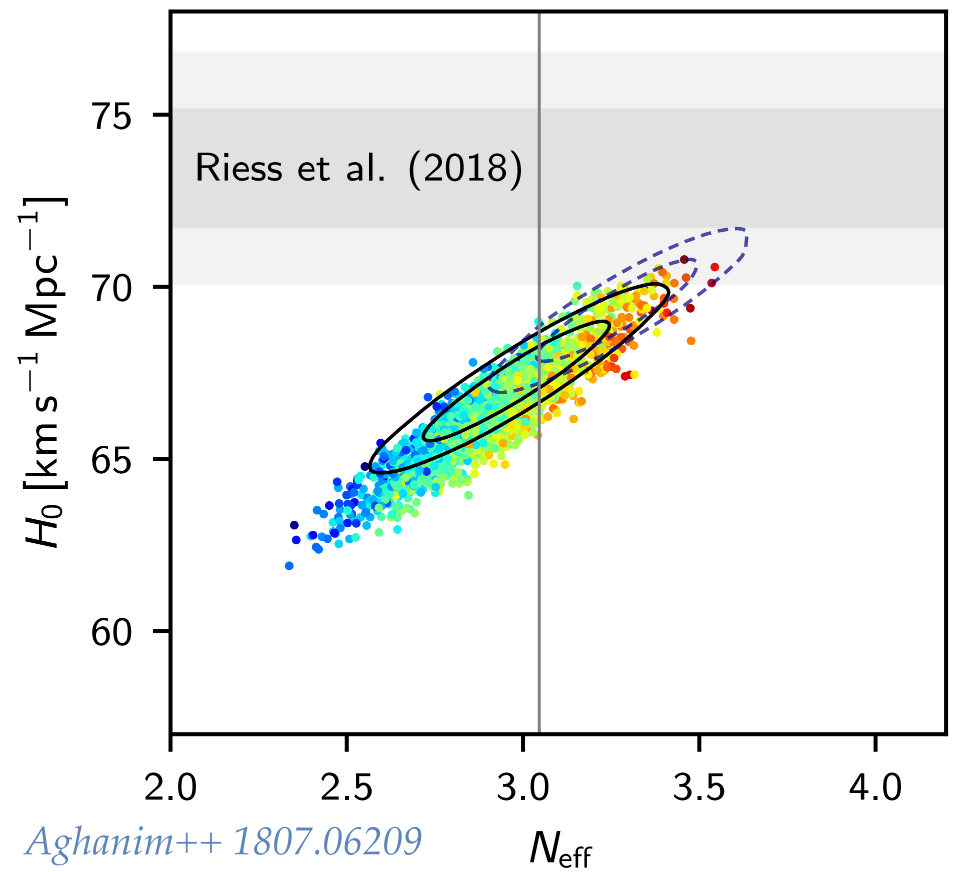

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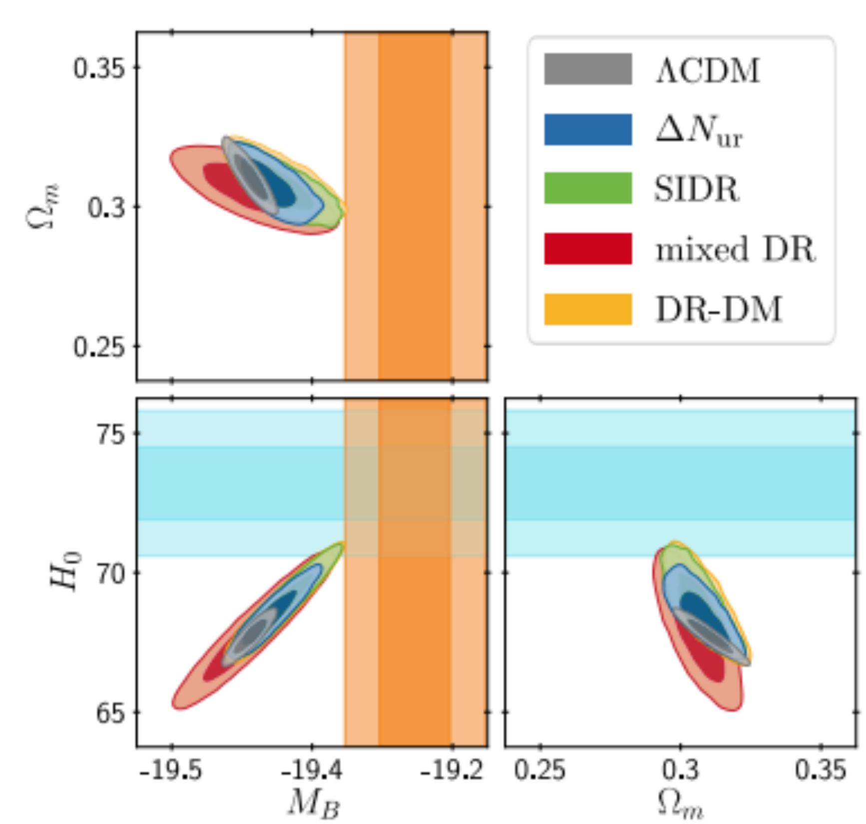
Planck+BAO constrains $N_{\rm eff} = 2.99 \pm 0.17$ and $H_0 = 67.3 \pm 1.1$ km/s/Mpc

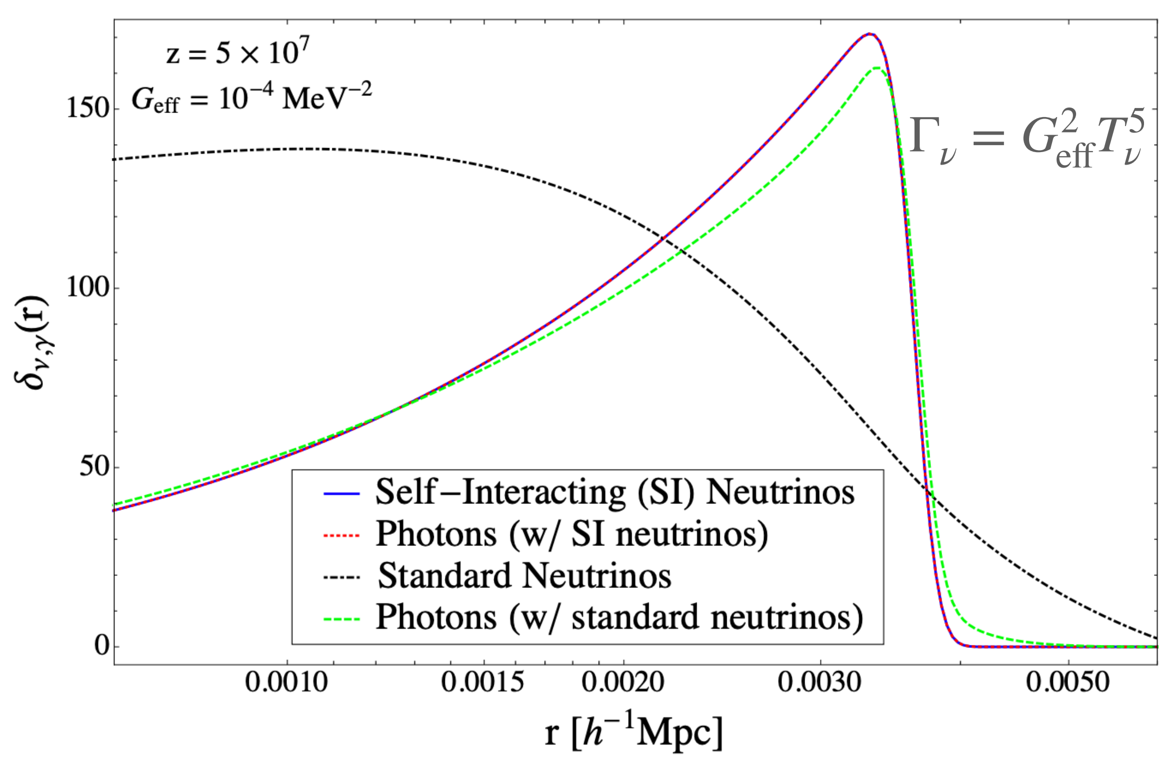
Is it possible to relax this bound?

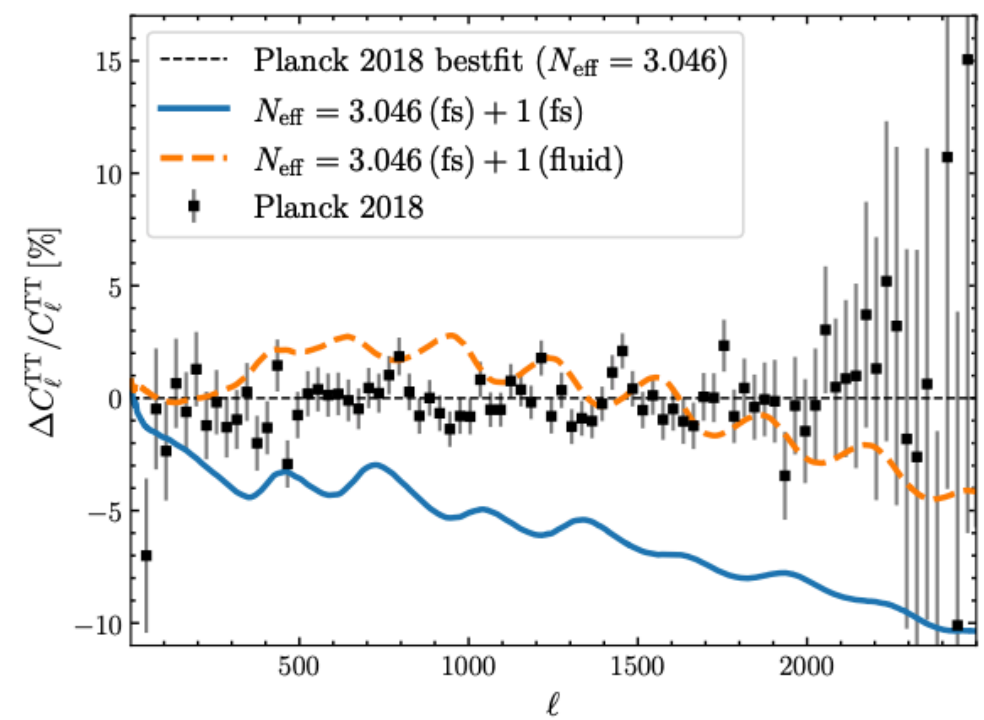
Introducing exotic ν-interactions

- Exotic ν self-interaction can erase free-streaming and make ν behaves as perfect fluid.
- Once interactions are switched on: γ-perturbations are enhanced / phase is washed-out.
- This helps a bit but not enough to explain H_0



Cyr-Racine++ 1306.1536





Interacting neutrinos could resolve H_0 tension

see also Ghosh ++1908.09843

$$\theta_{\rm peak} = \theta_s + \delta\theta \sim 0.6\left(\frac{\rho_\nu}{\rho_g}\right)$$

- Free-streaming neutrinos lead to a phase shift:
  Bashinsky&Seljak, astro-ph/0310198, Baumann++ 1508.06342
- Self-interacting neutrinos: no phase shift, θ_s is larger than in ΛCDM => larger H_0

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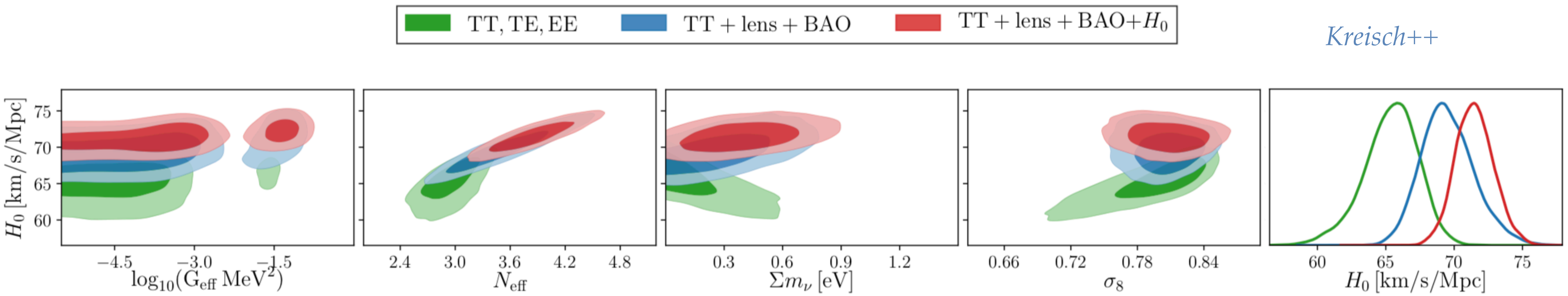

- 2015 data: solution requires 4 strongly interacting neutrinos with M ~ 0.4eV
- "For free": solve S_8 tension and reactor anomalies!
- BBN & Lab. requires majorana neutrinos and a heavy mediator coupled to ν_τ

Blinov++ 1905.02727

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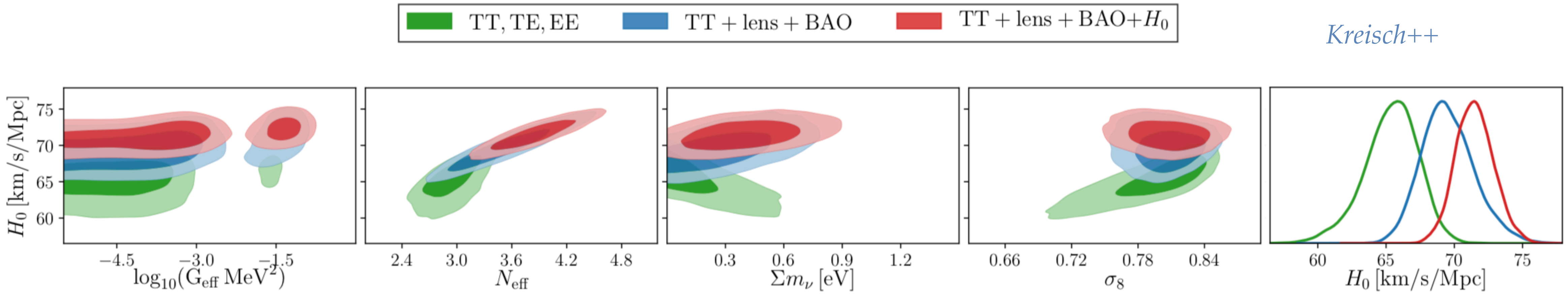

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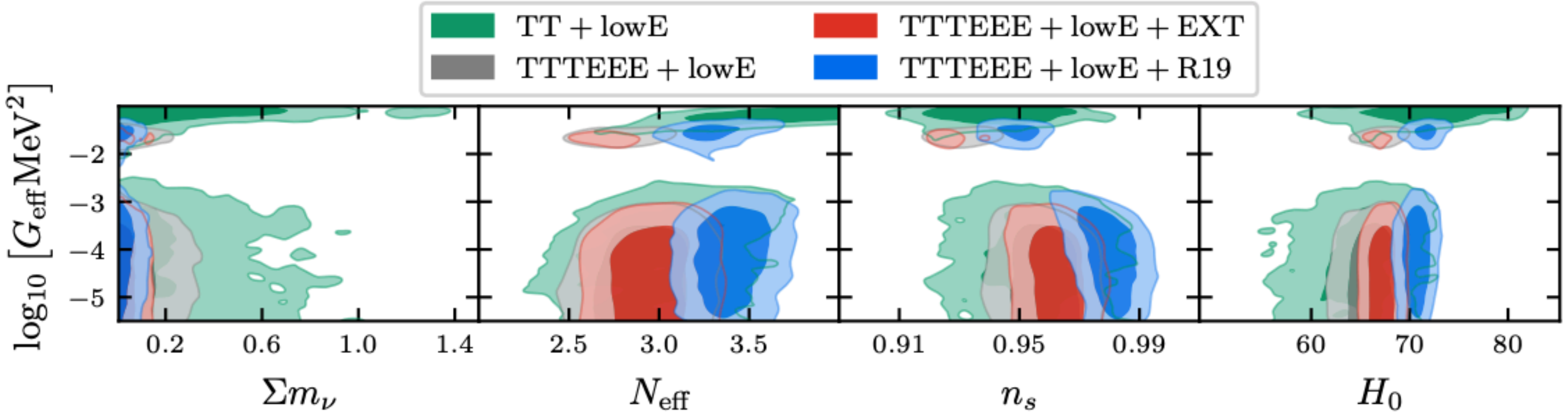
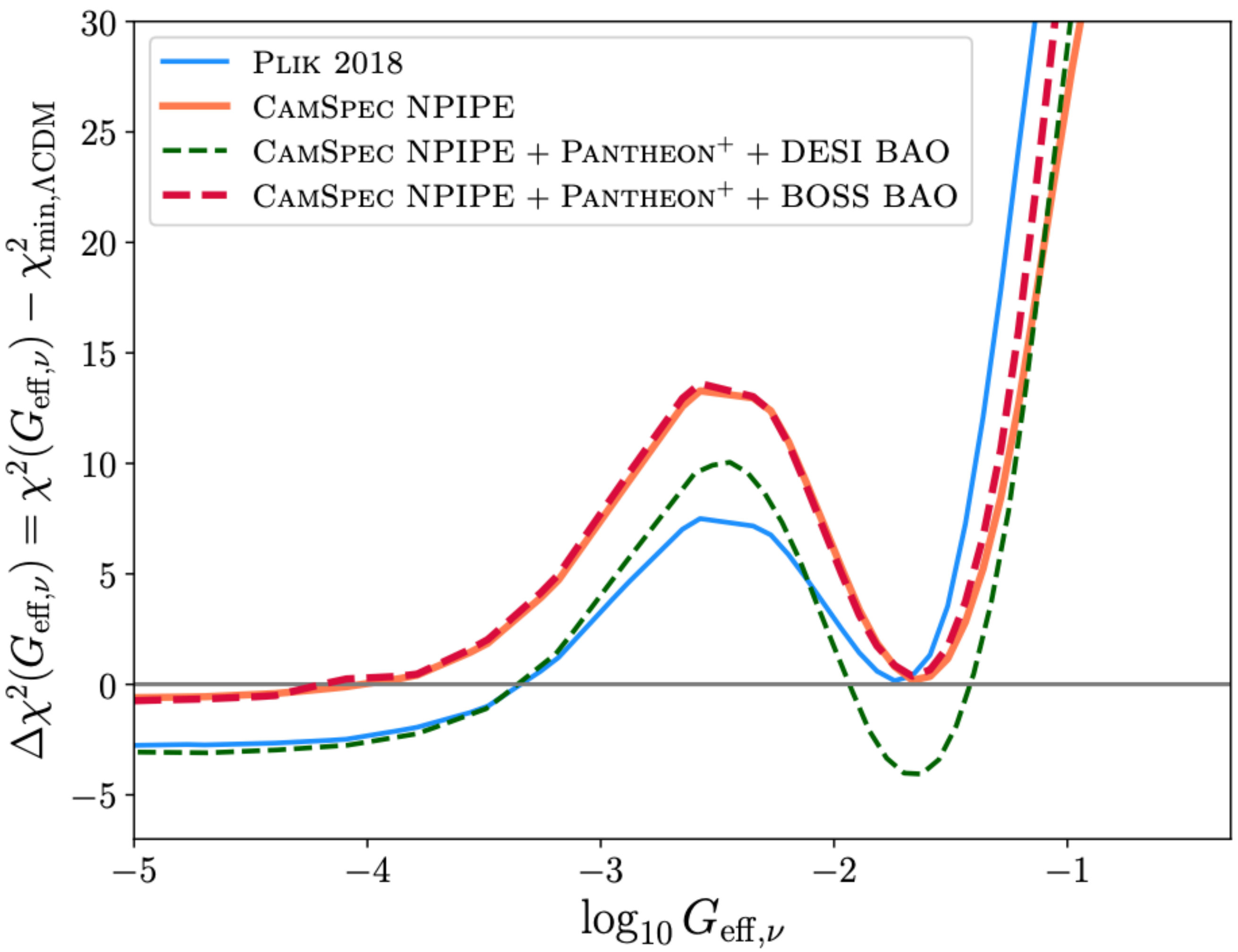
- 2018 Planck polarization data disfavor the strongly interacting mode.

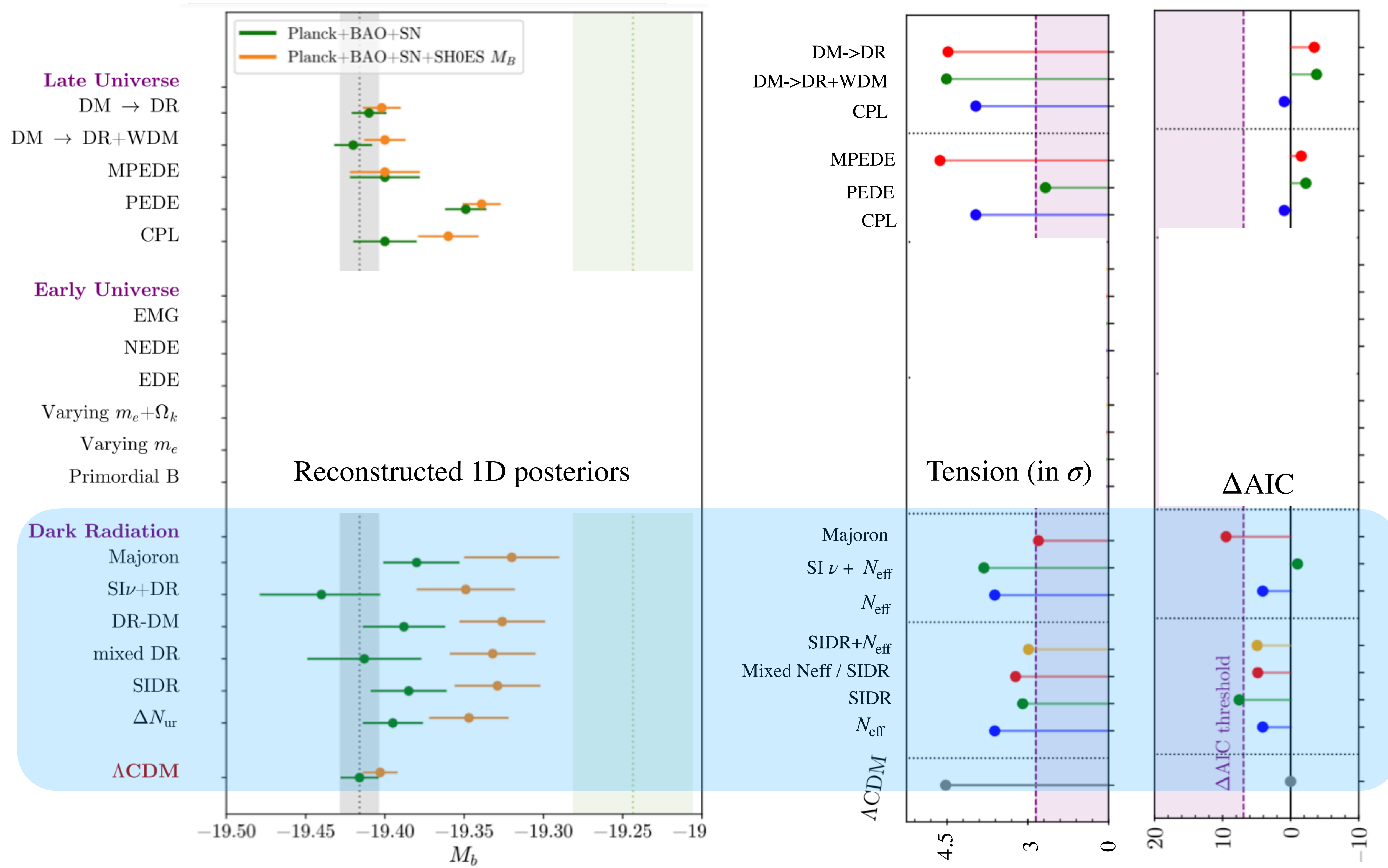


Update with NPIPE & DESI



	SIν	
	BOSS BAO	DESI BAO
$\log_{10}\mathrm{G}_{\mathrm{eff},\nu}$	$-1.63(-1.66)^{+0.13}_{-0.10}$	$-1.61(-1.66)^{+0.14}_{-0.11}$
$-2\log\mathcal{L}(\log_{10} G_{\mathrm{eff},\nu})$	$-1.66^{+0.14}_{-0.13}$	$-1.66^{+0.11}_{-0.13}$
H_0	$67.58(67.2)^{+0.91}_{-1.4}$	$68.6(68.0)^{+1.2}_{-1.4}$

Status of "$N_{\rm eff}$–like" solutions



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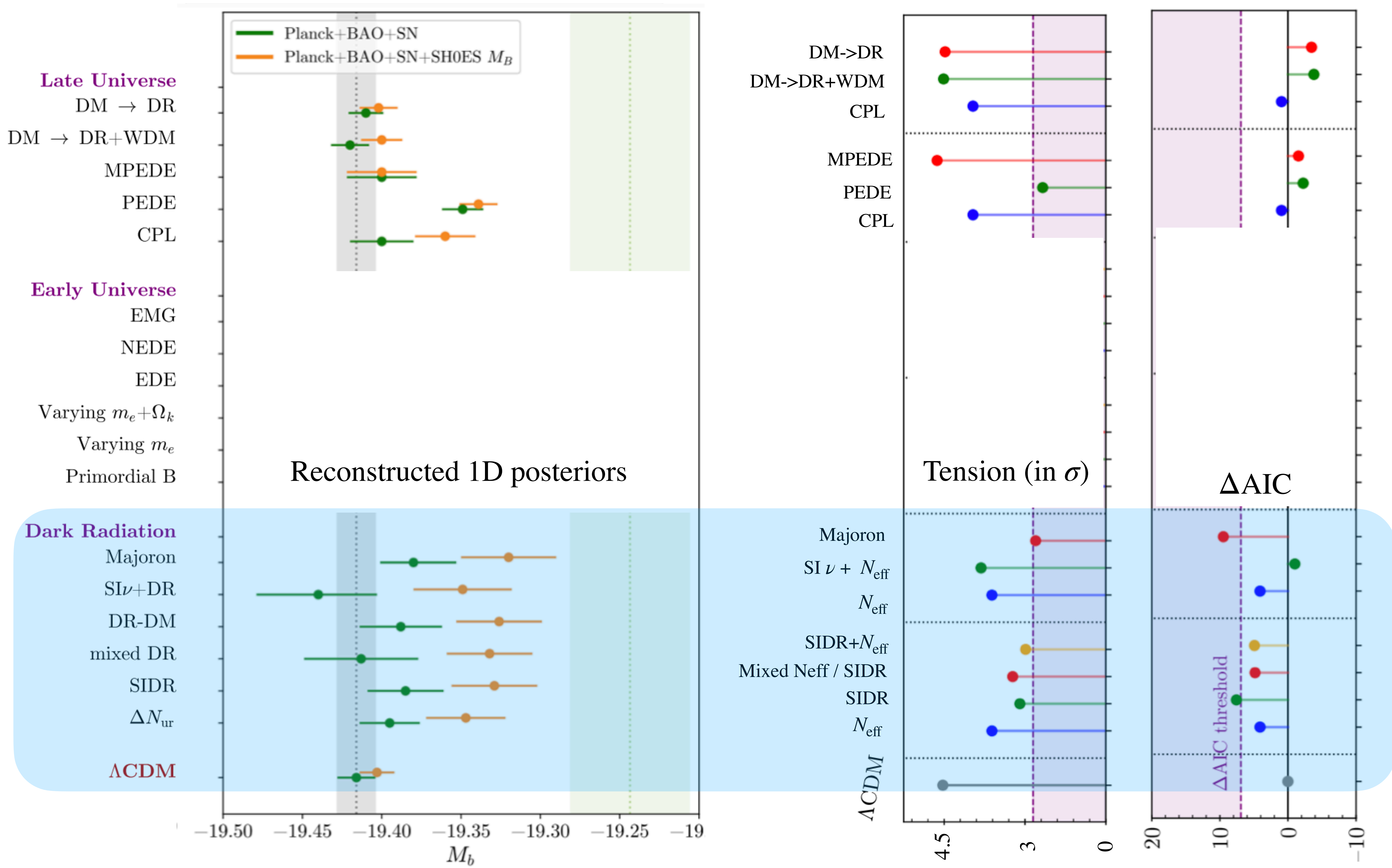
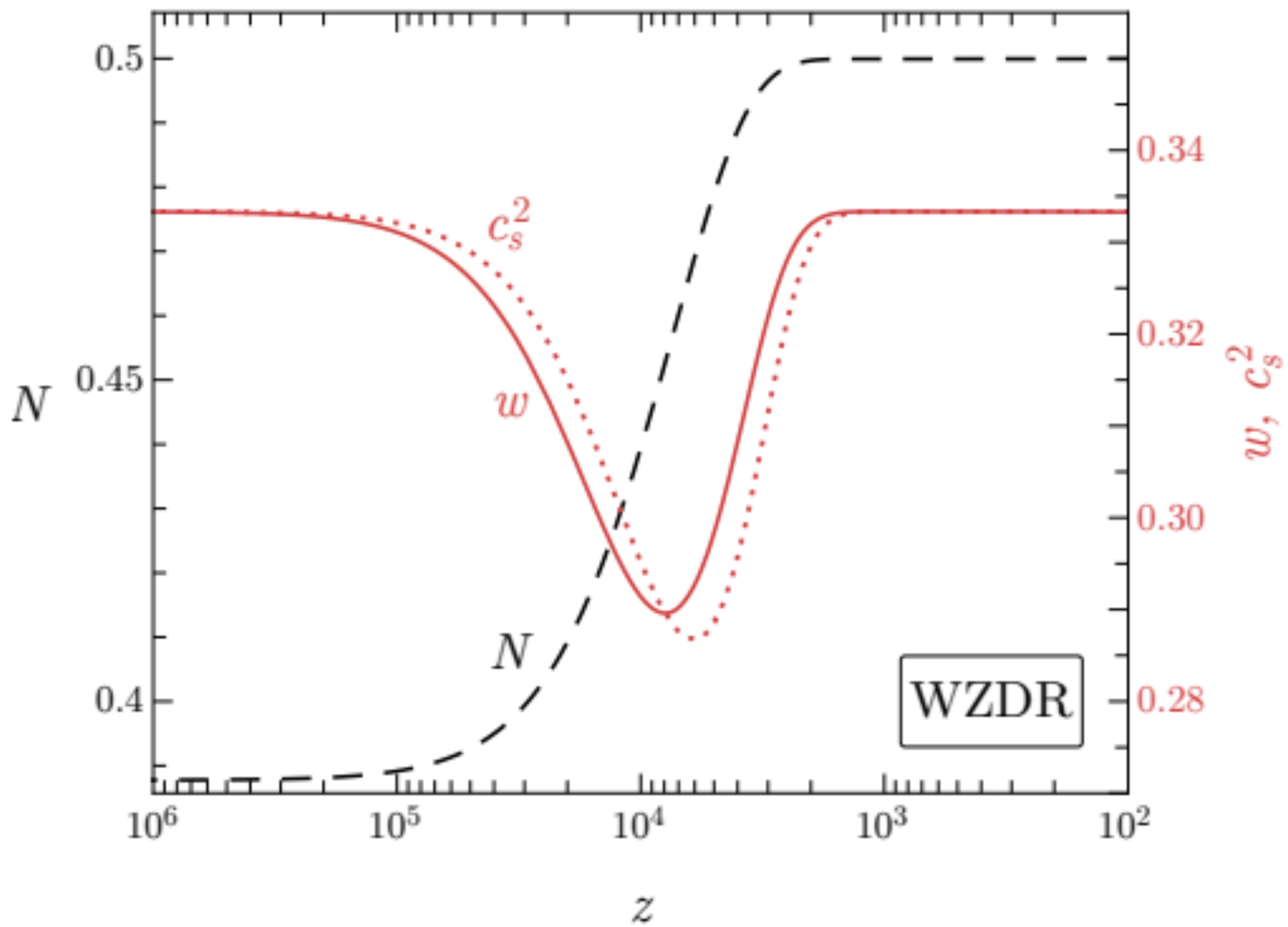
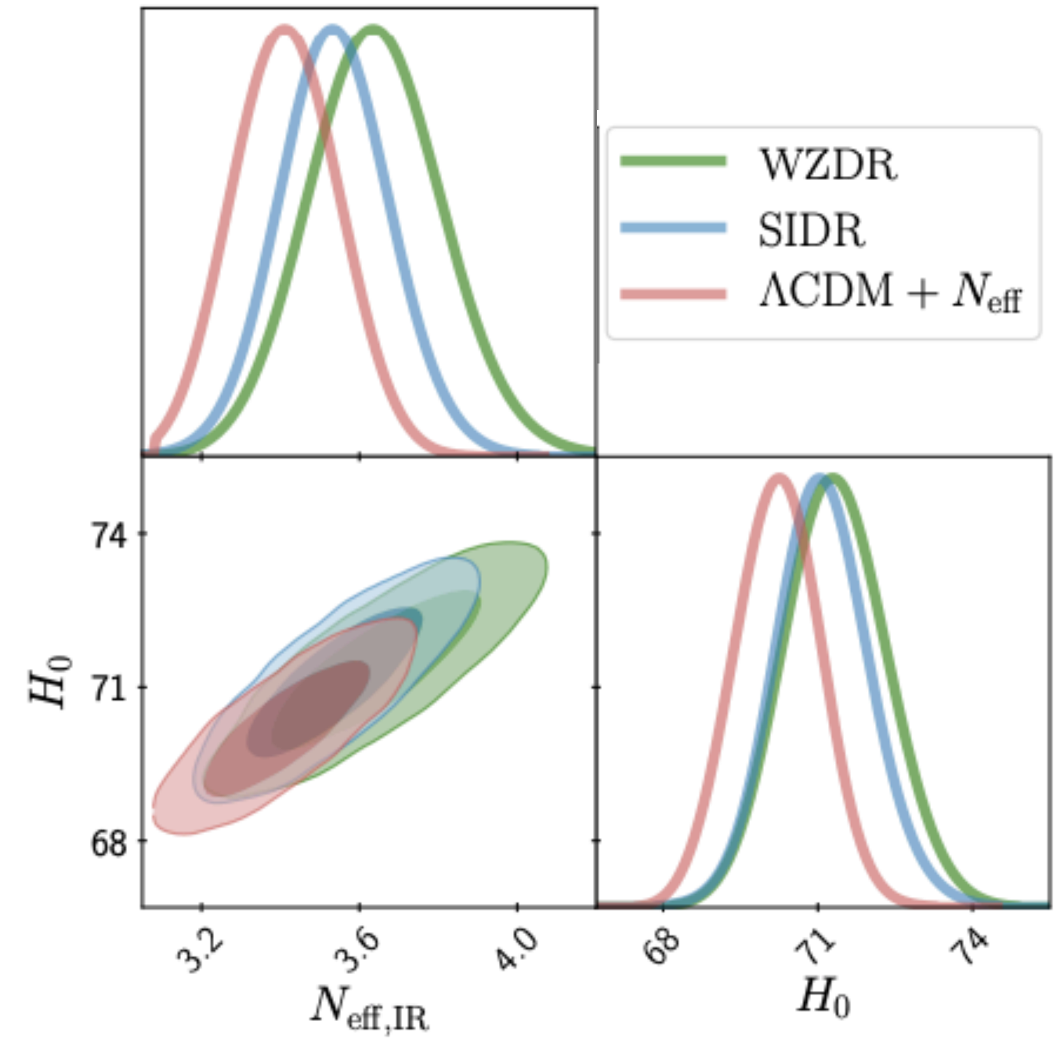


Extra-radiation can bring the tension down to the 3σ level but are not favored without H_0 prior

A step in resolving the H0 tension



Aloni++ 2111.00014



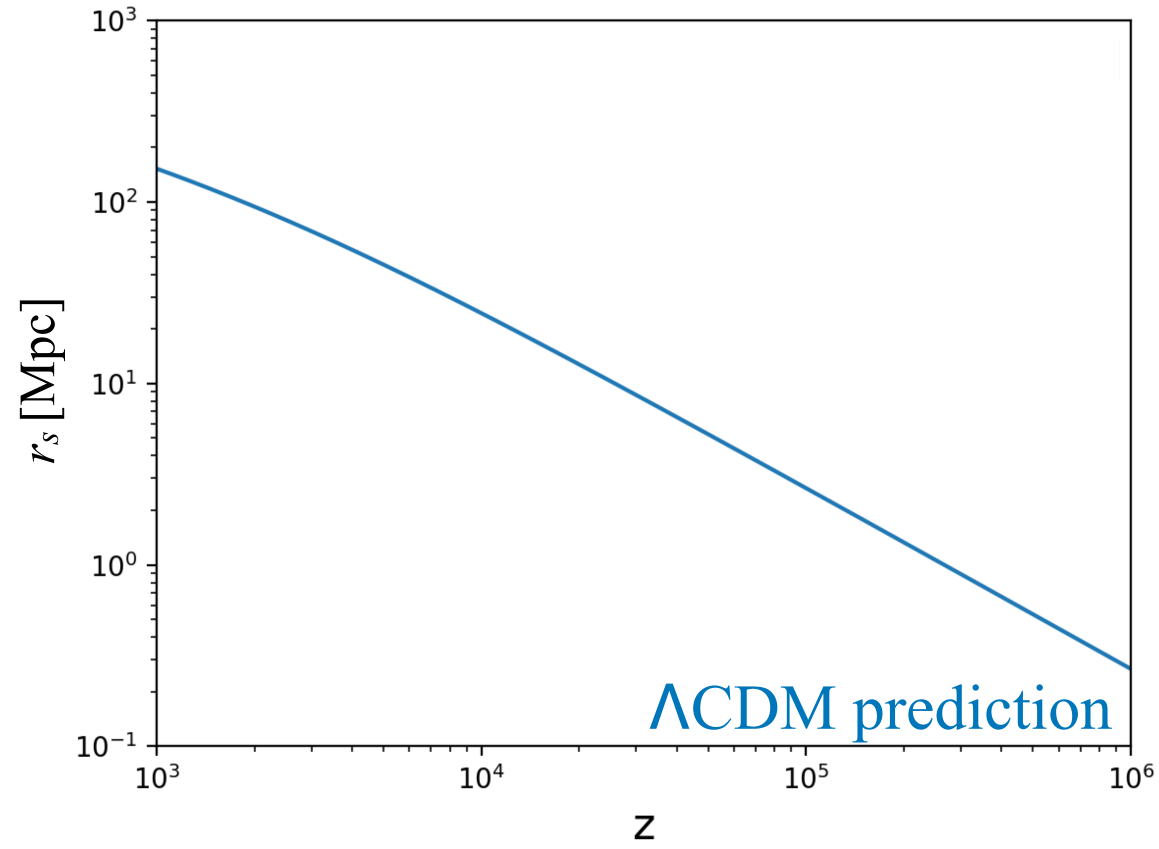
- If $N_{\rm eff}$ has a step around $z \sim 10^4$ e.g. from decoupling of a scalar ϕ with $m \sim 1$eV reheating a bath of fermion ψ.

$$\frac{N_{\rm IR}}{N_{\rm UV}} = \left(\frac{g_*^\phi + g_*^\psi}{g_*^\psi}\right)^{1/3} = \left(\frac{15}{7}\right)^{1/3} \simeq 1.29$$

- WZDR model provides a significantly better fit than standard $N_{\rm eff}$ or SIDR

Exotic energy injection to resolve the H_0 tension

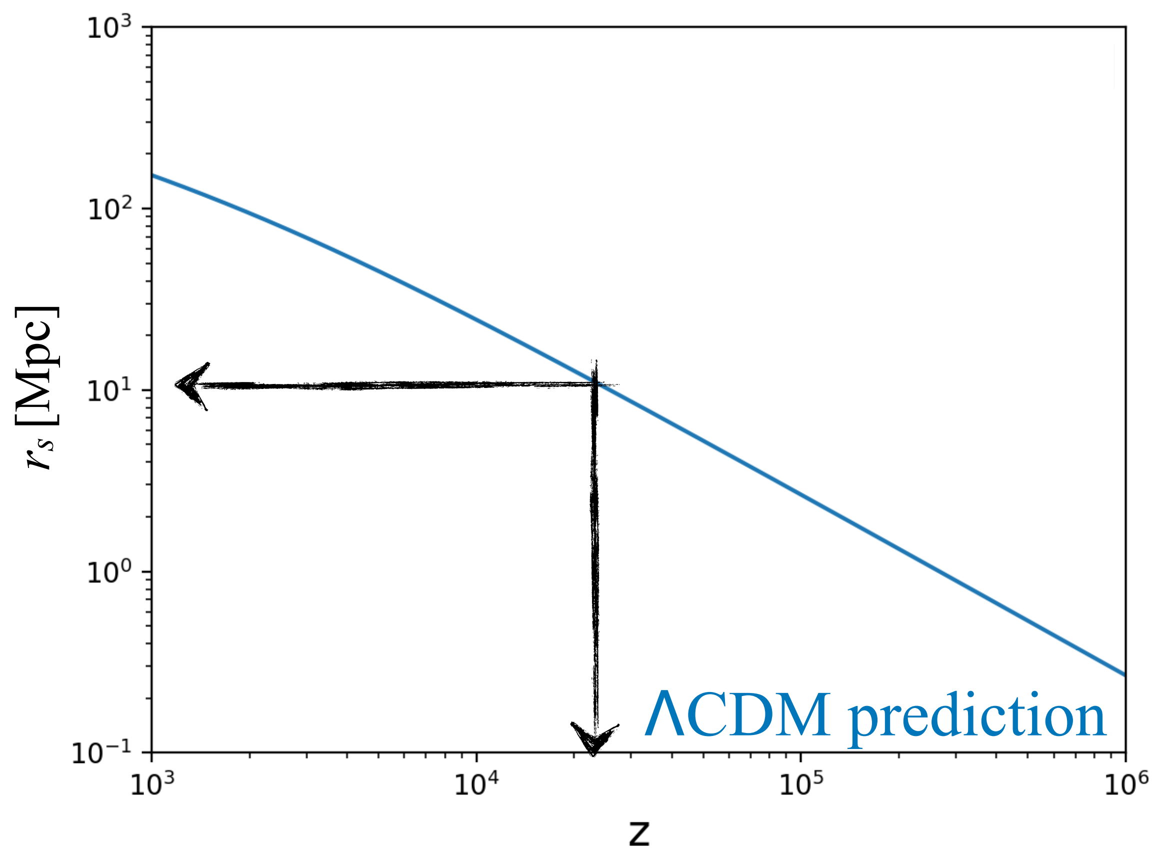
- r_s must decrease by $\sim$10Mpc.



See the `Hubble Hunter's guide' Knox&Millea 1908.03663

Exotic energy injection to resolve the H_0 tension

- r_s must decrease by ~10Mpc.
- r_s does not reach 10Mpc before ~ 25000 in ΛCDM



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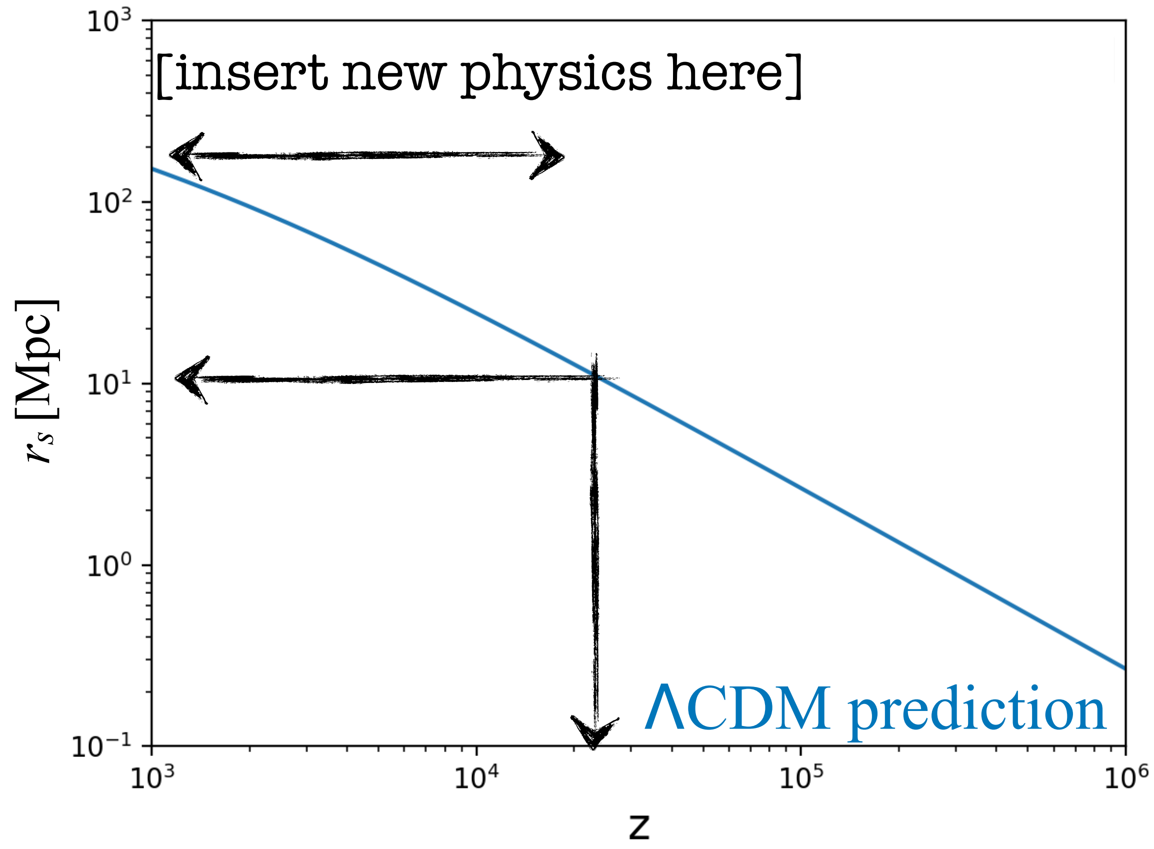

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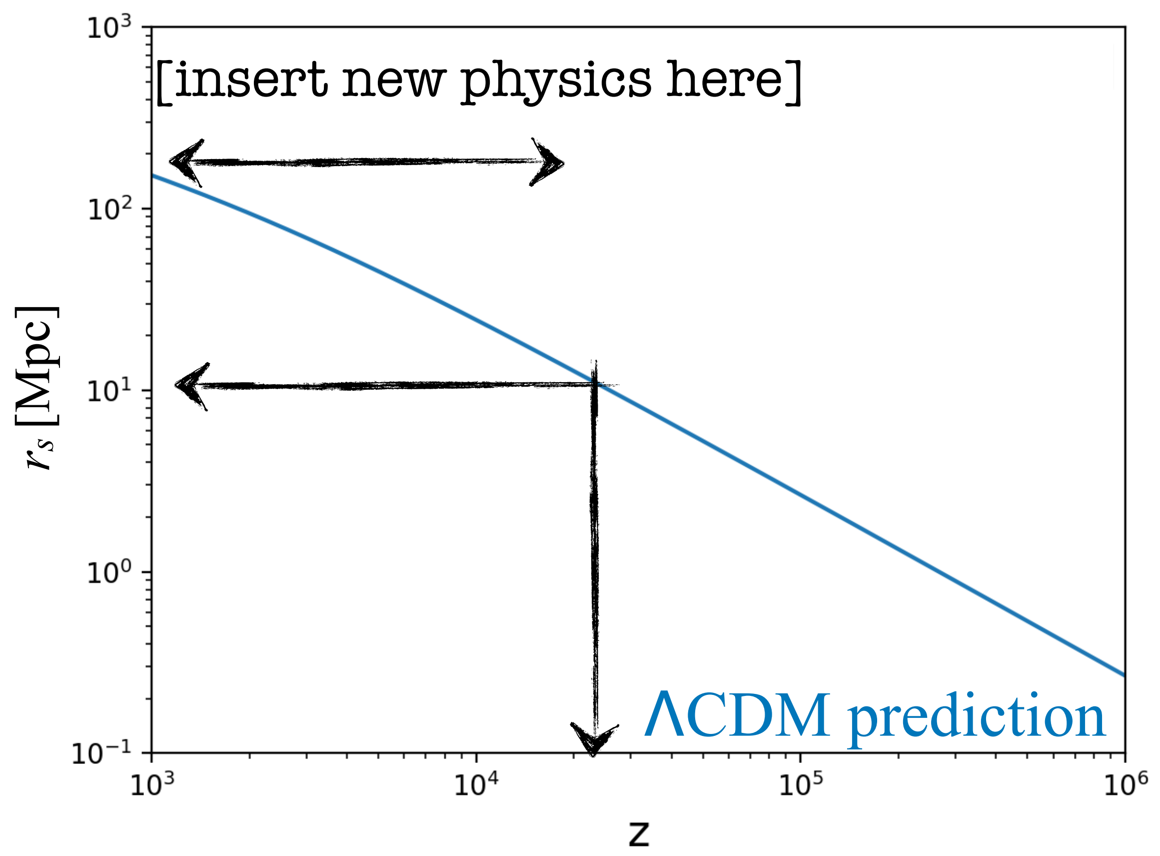


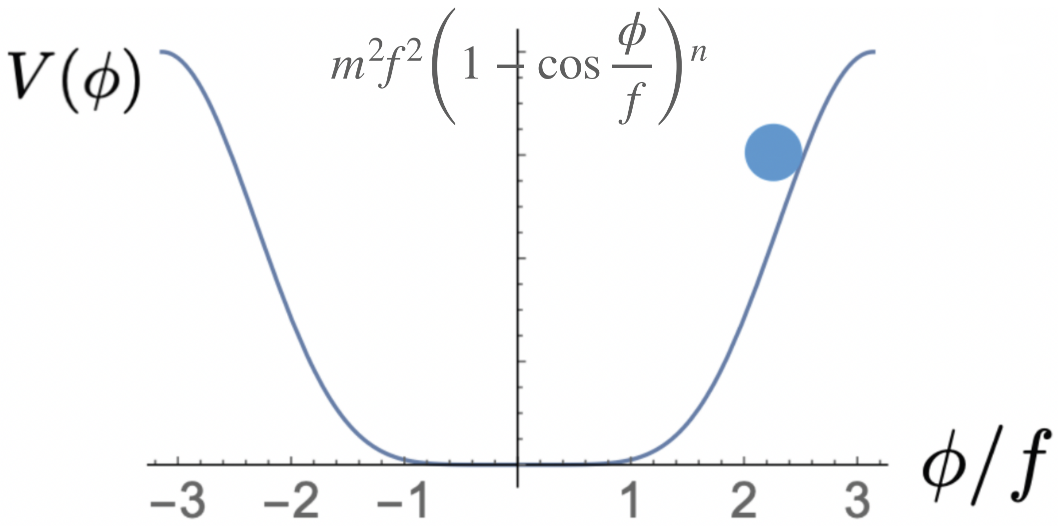
- Inject energy between recombination and $z \sim 2 \times 10^4$ to reduce r_s

See the `Hubble Hunter's guide' Knox&Millea 1908.03663

What is Early Dark Energy?

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

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



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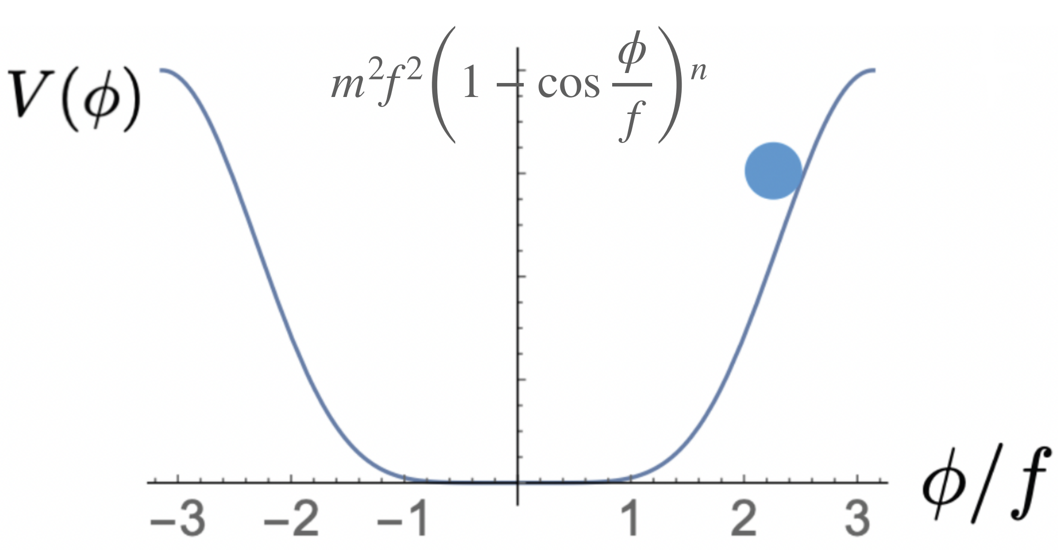

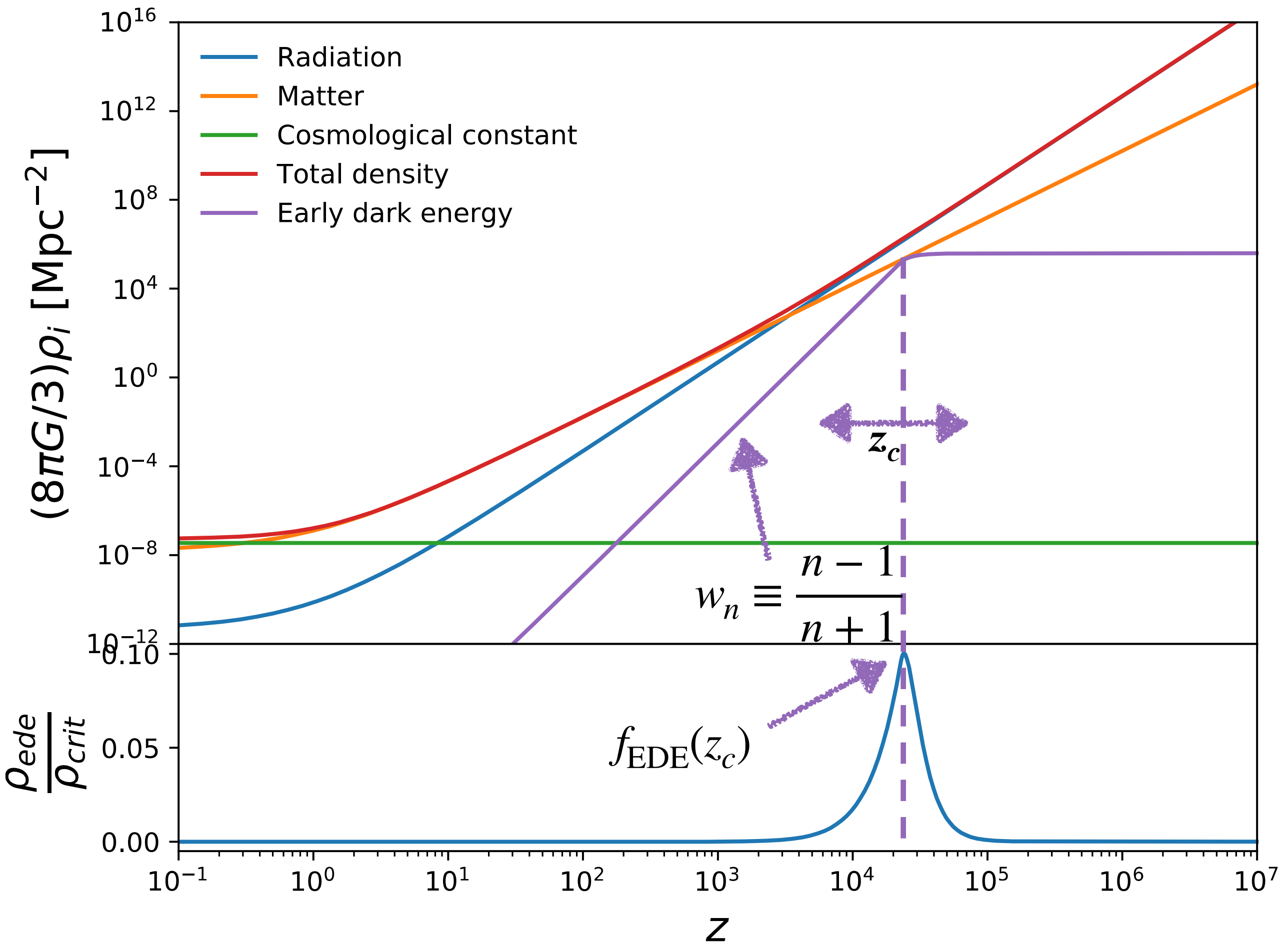

- Specified by $f_{\rm EDE}(z_c)$, z_c, $w(n)$, $c_s^2(k,\tau)$

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

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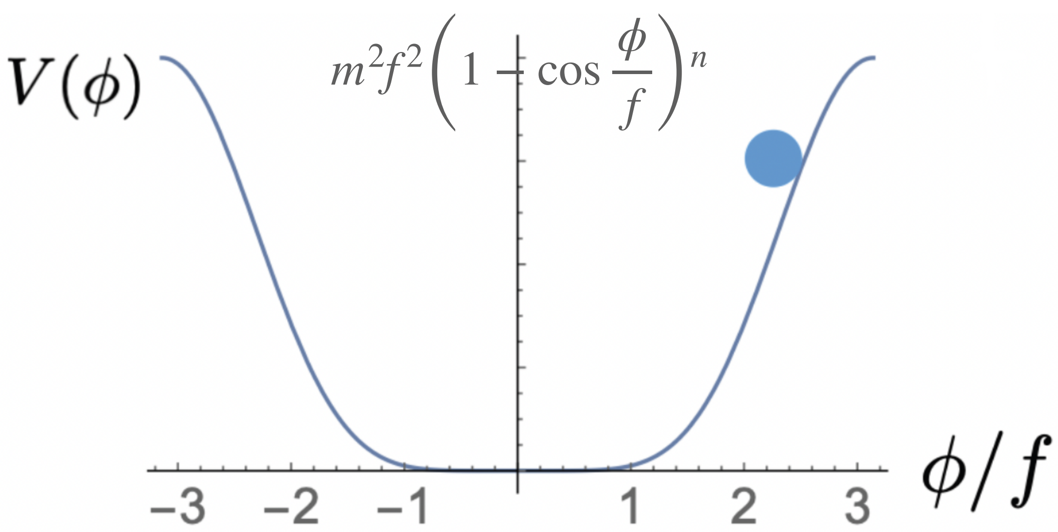

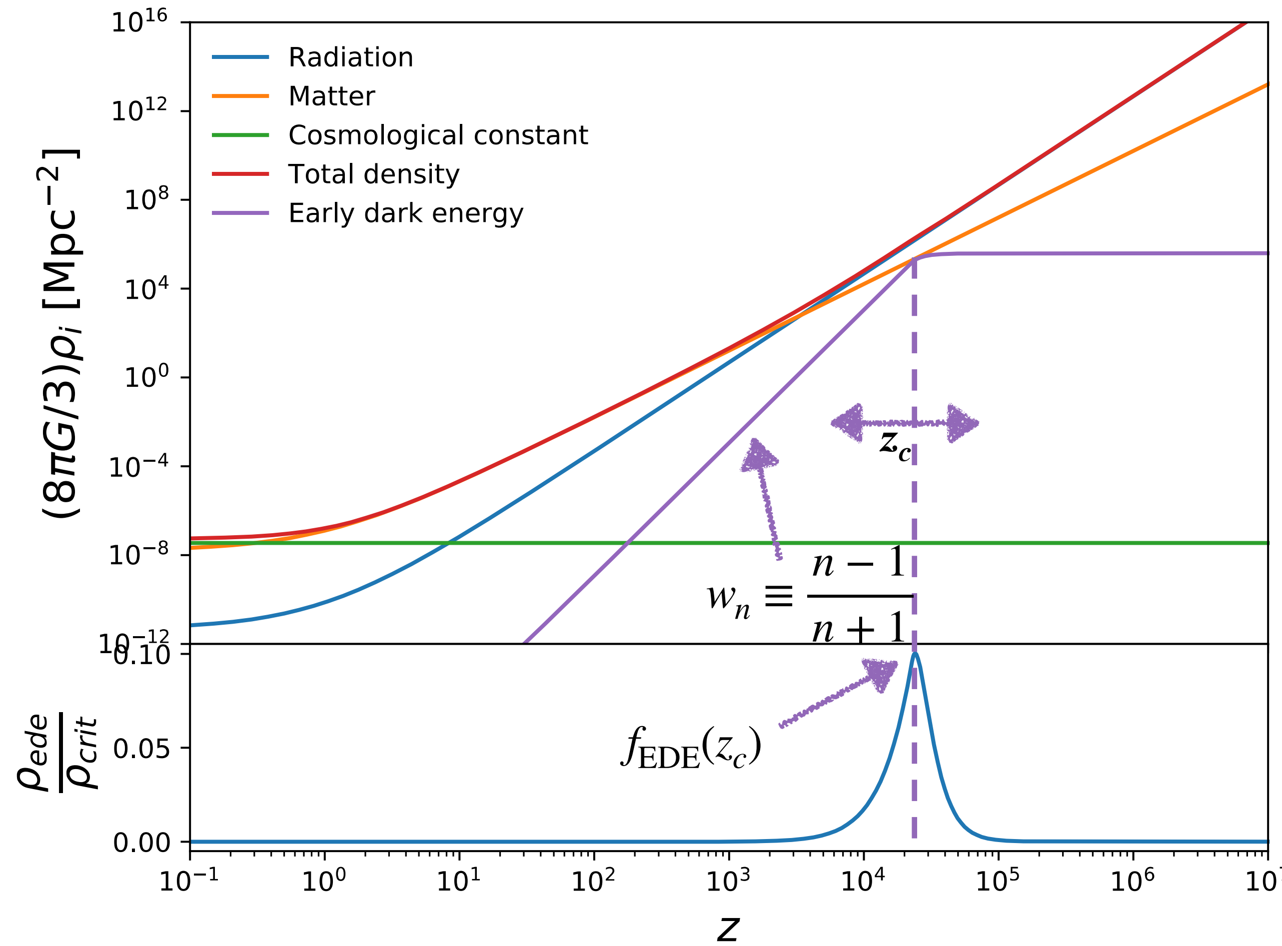

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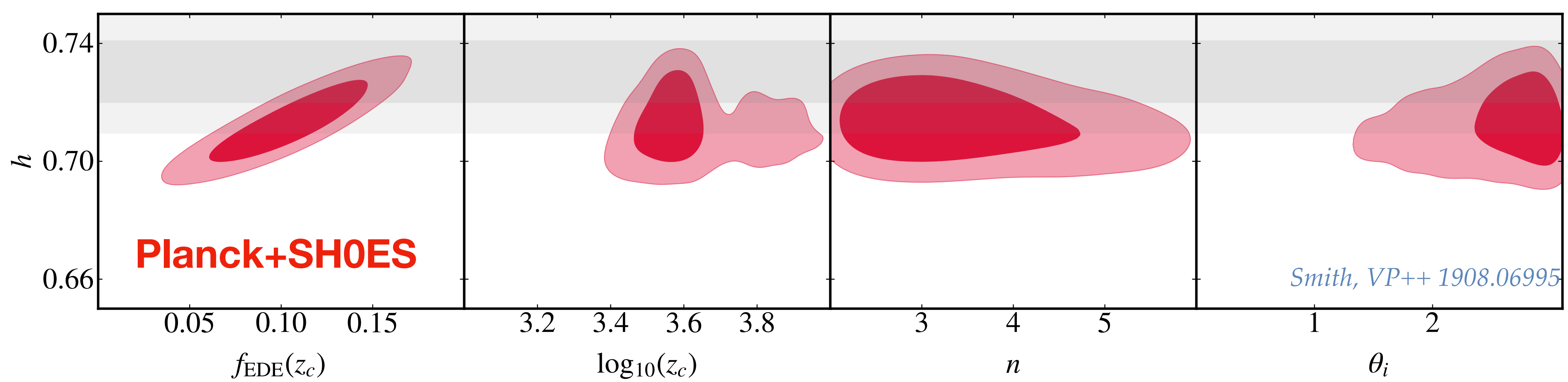
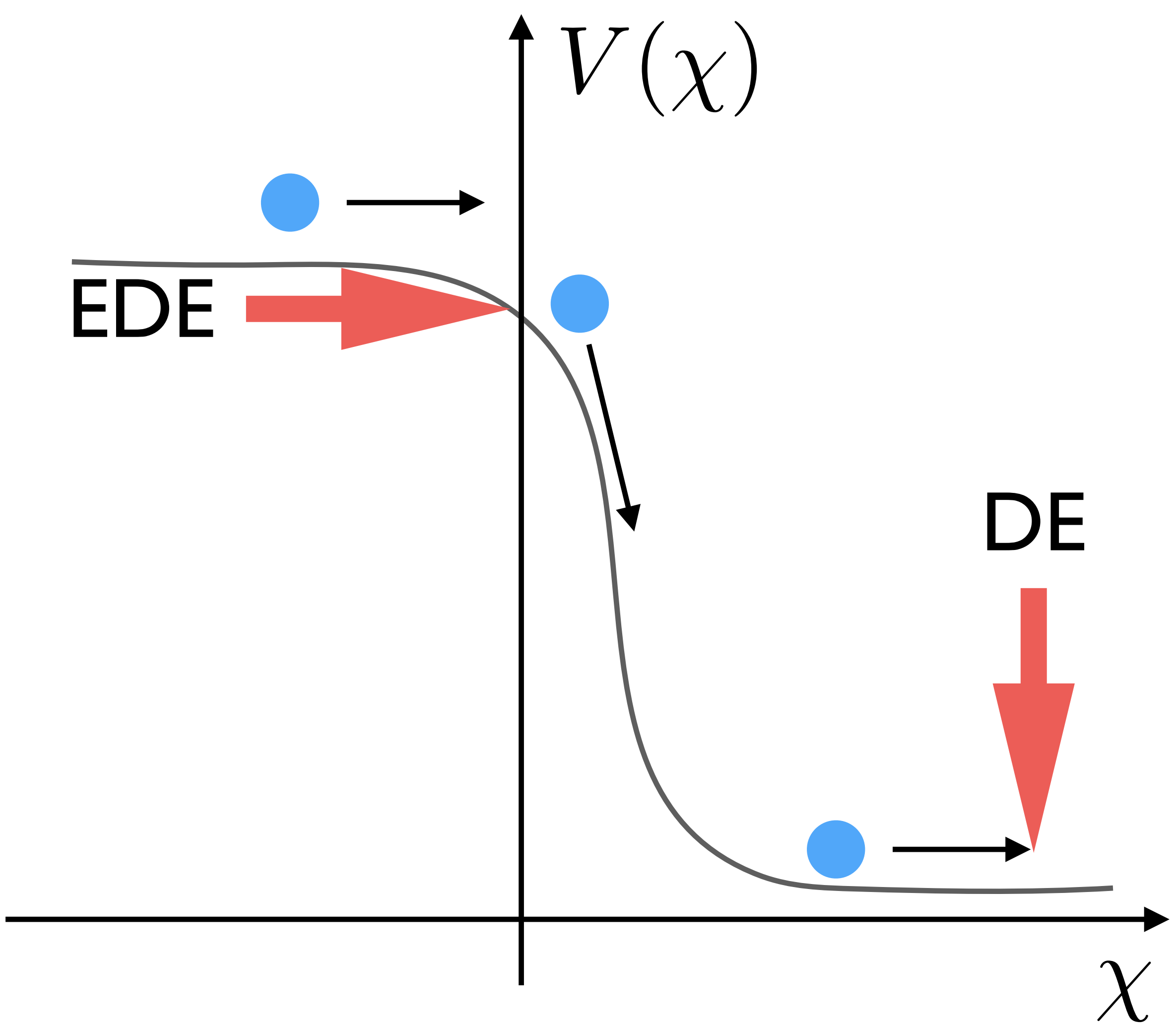


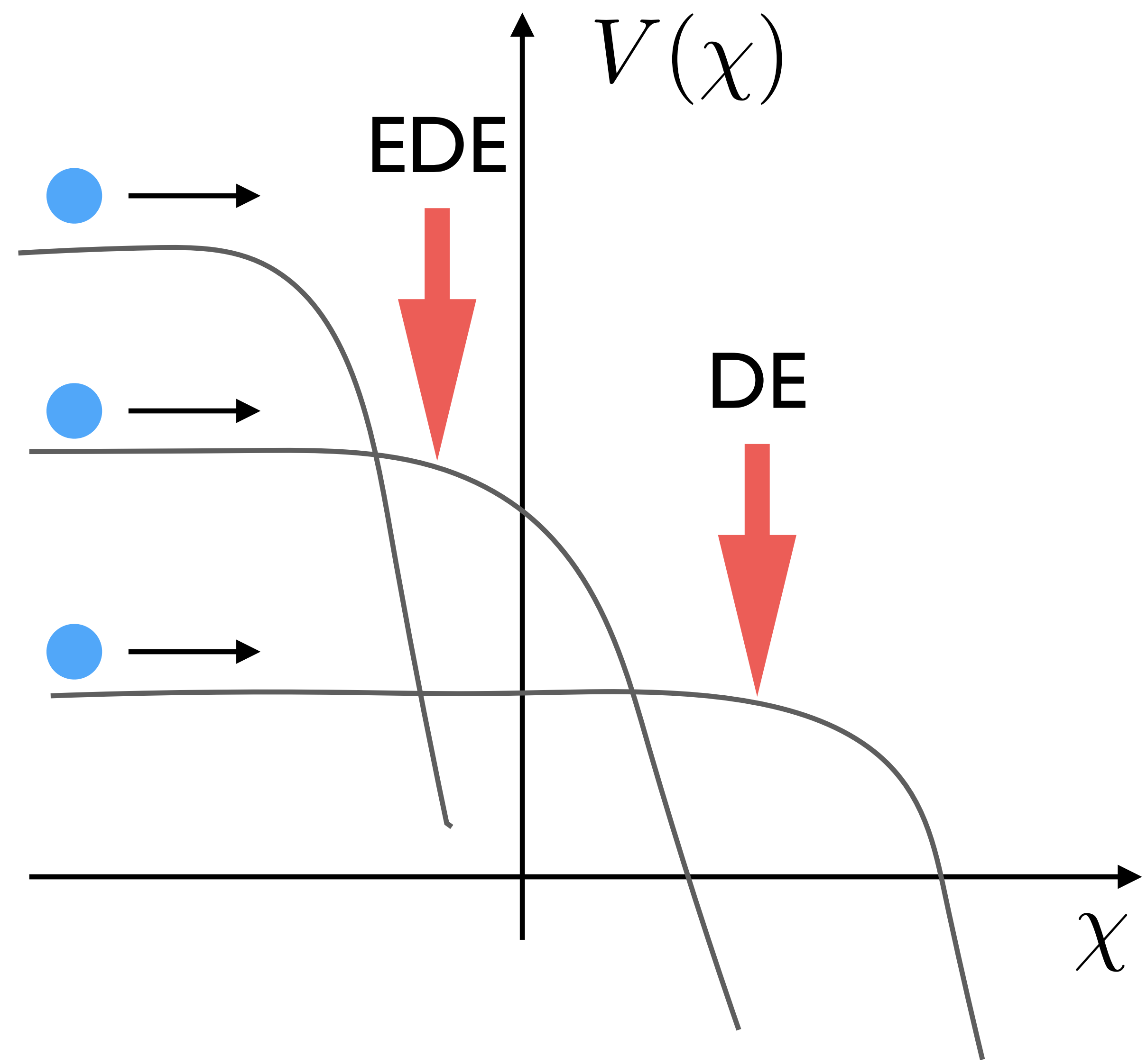
A New Understanding Of Dark Energy?

- The idea that DE altered the early universe is not new: explains the DE coincidence problem

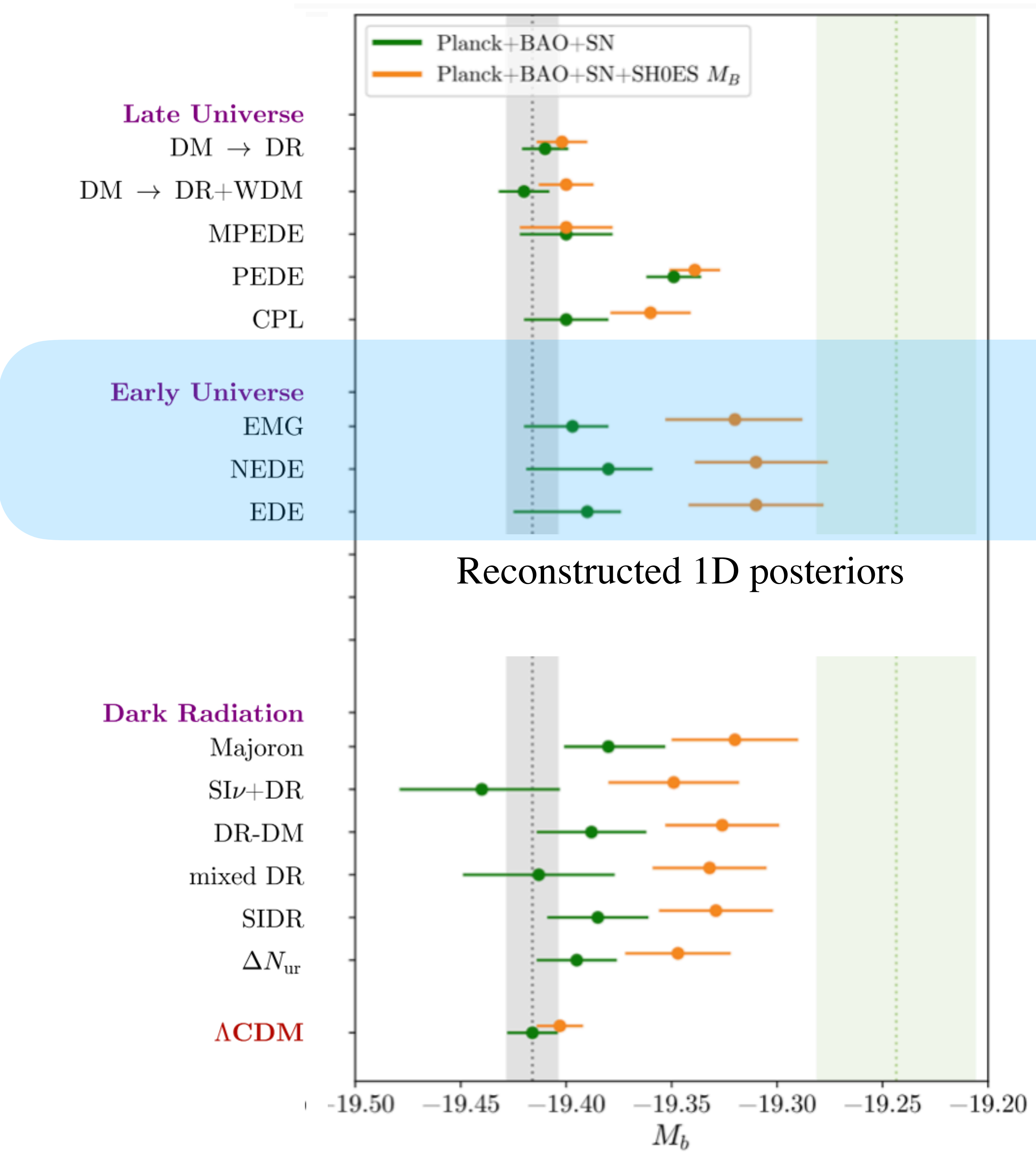
e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Bielefeld (Caldwell)++ 1305.2209, Kamionkowski++1409.0549

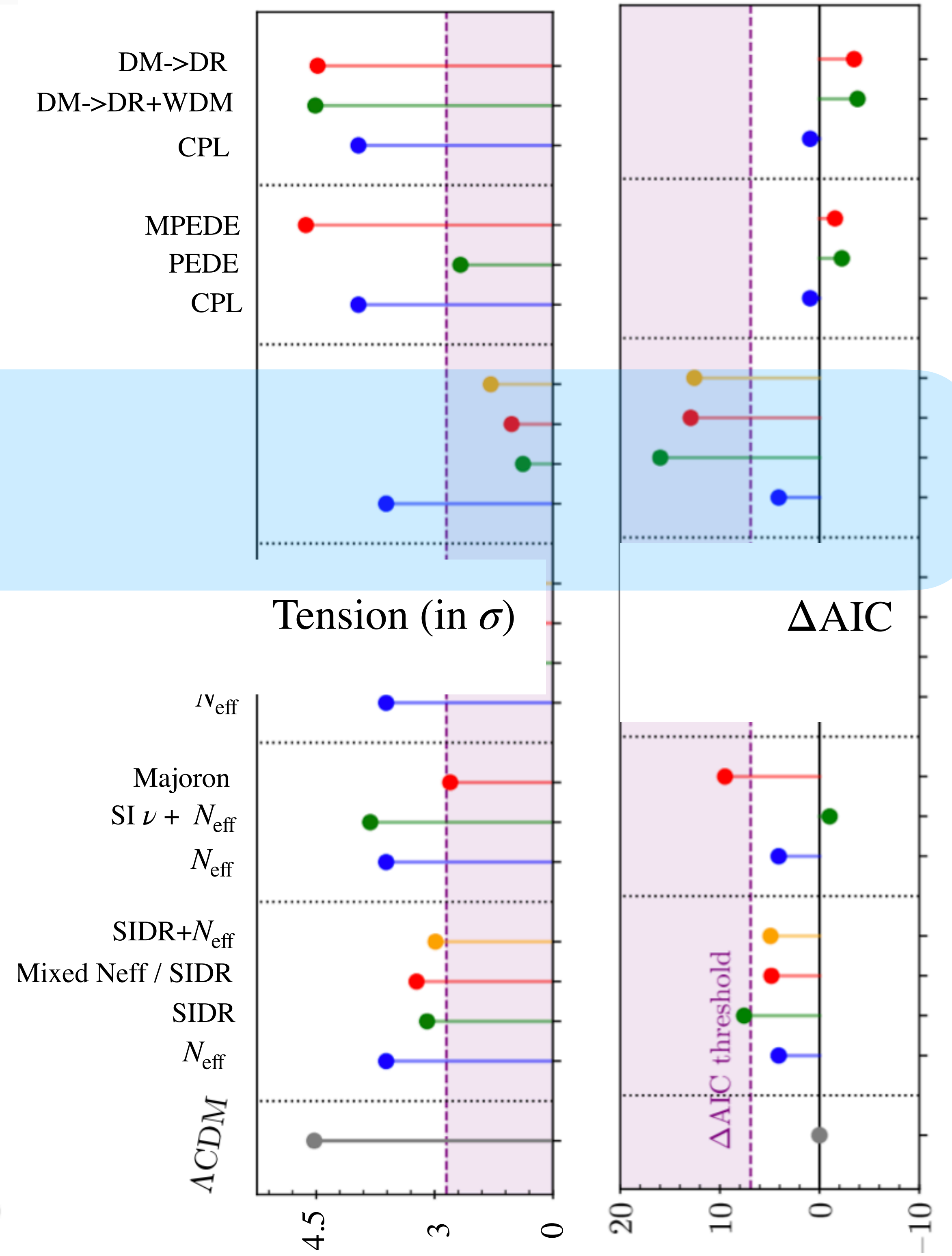
- Is their one field with a complicated potential or many fields with simple potentials?
- We know of Inflation, late-time Dark Energy: could there be more of such era to be discovered?



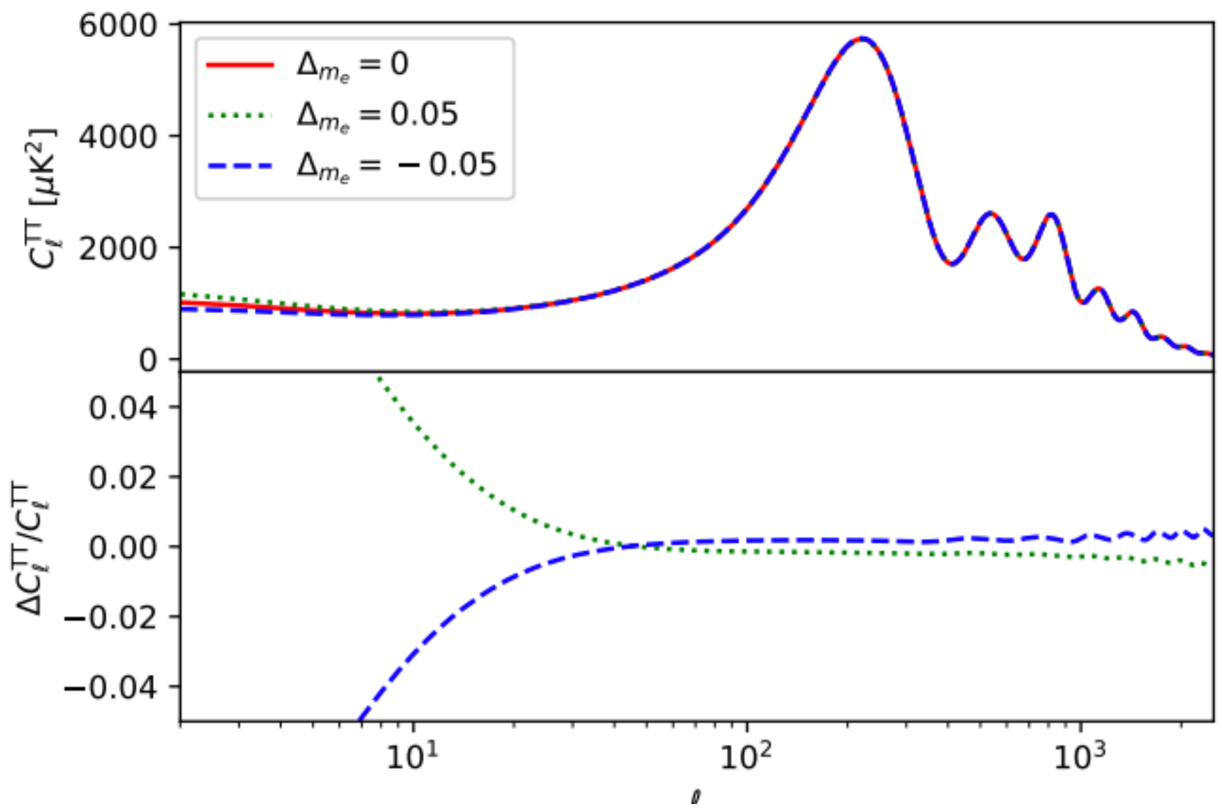


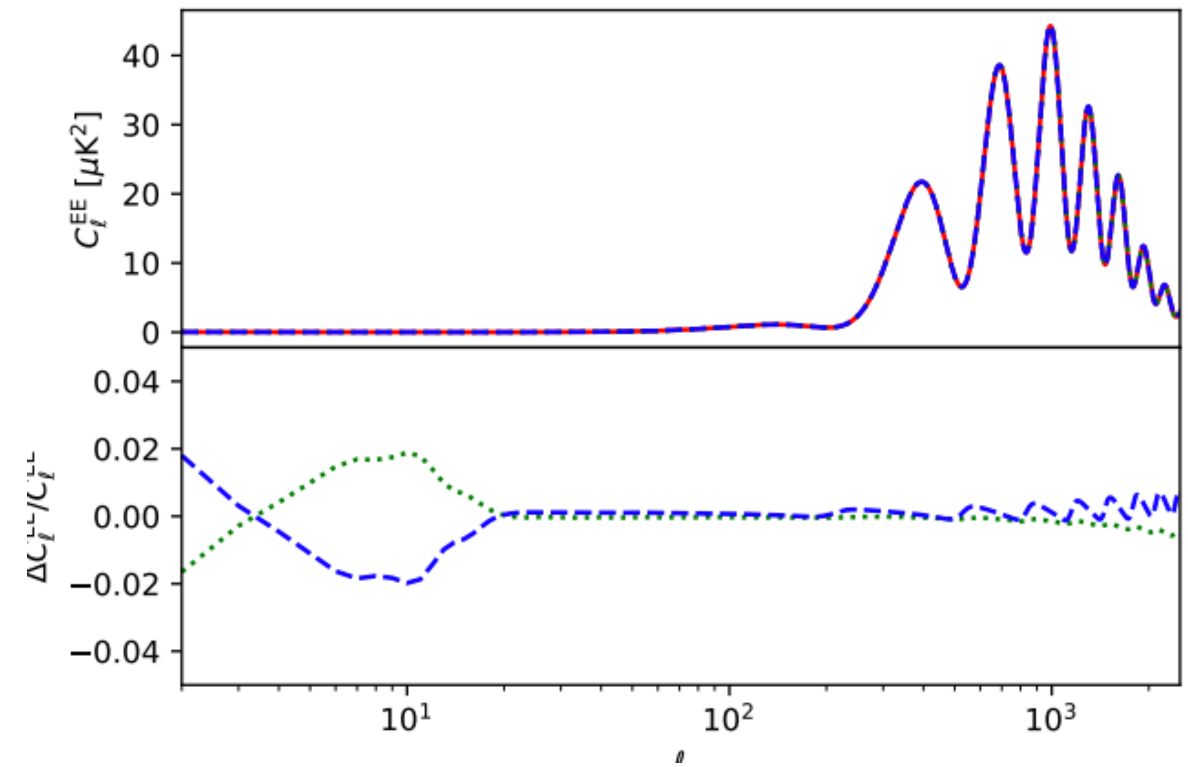
Status of "Exotic Energy Injection" solutions

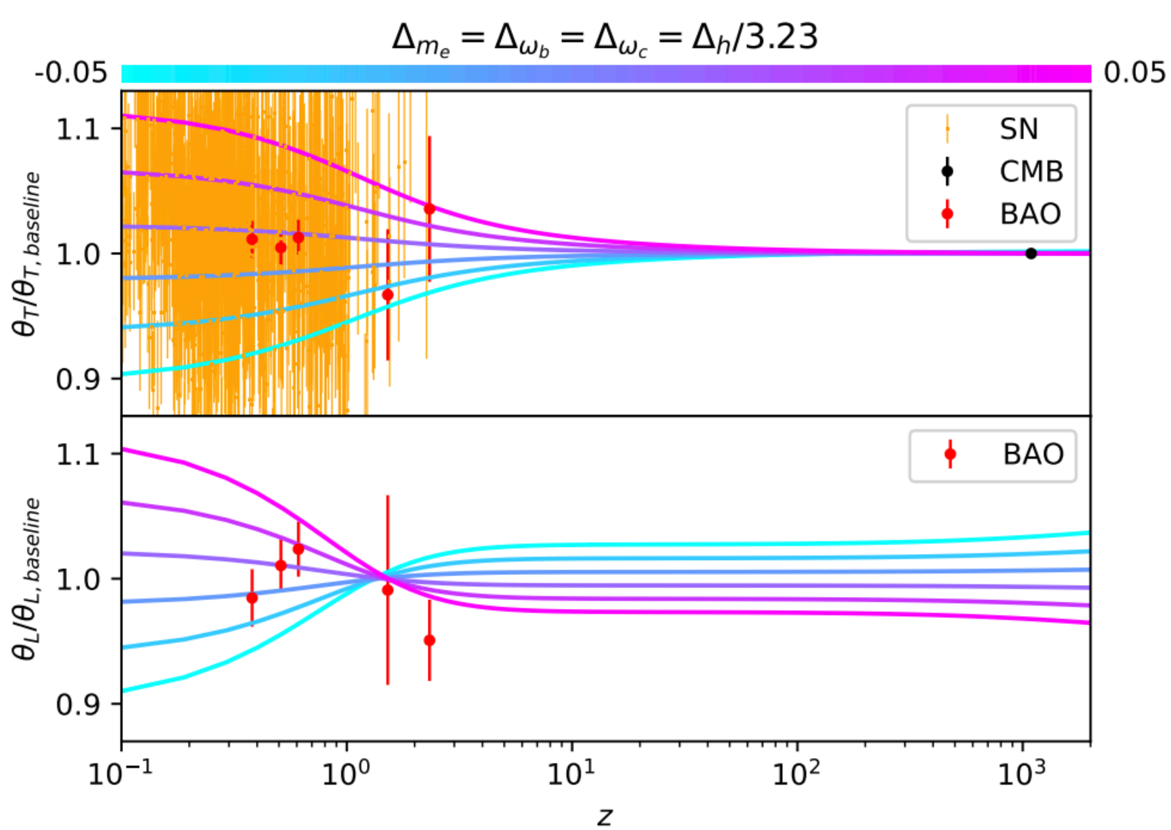


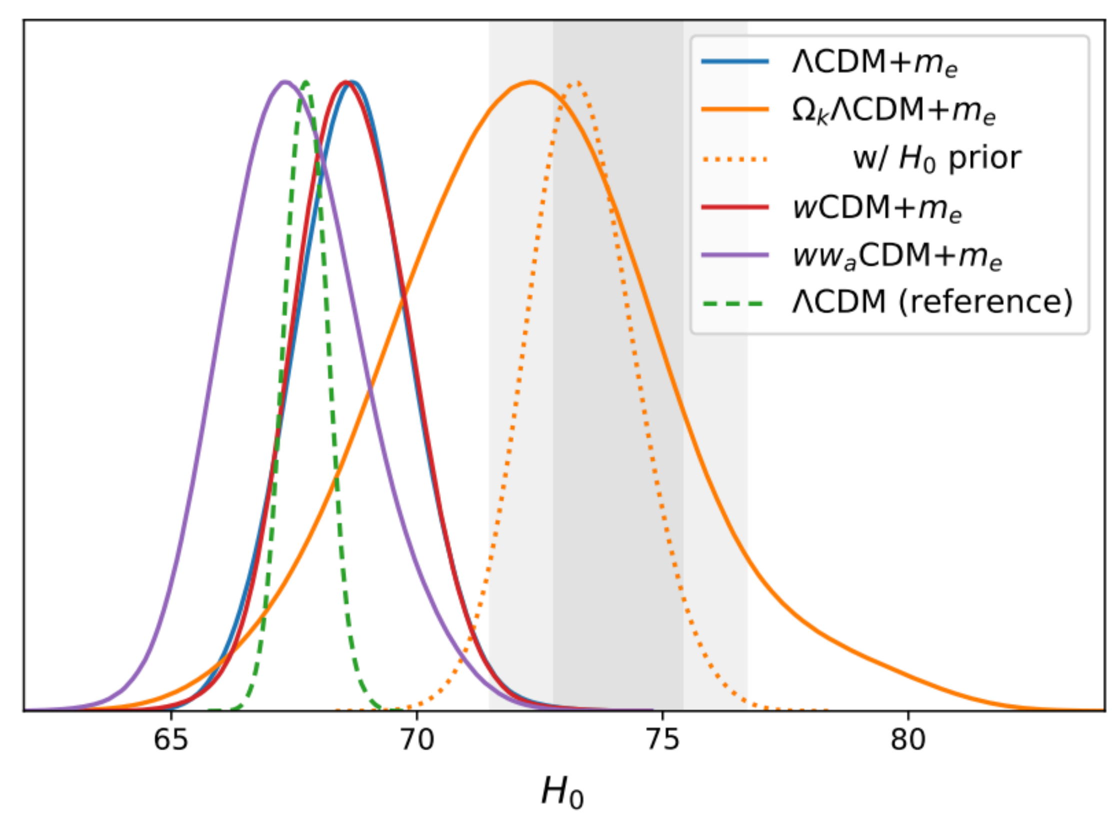


A higher m_e could resolve the H_0 tension

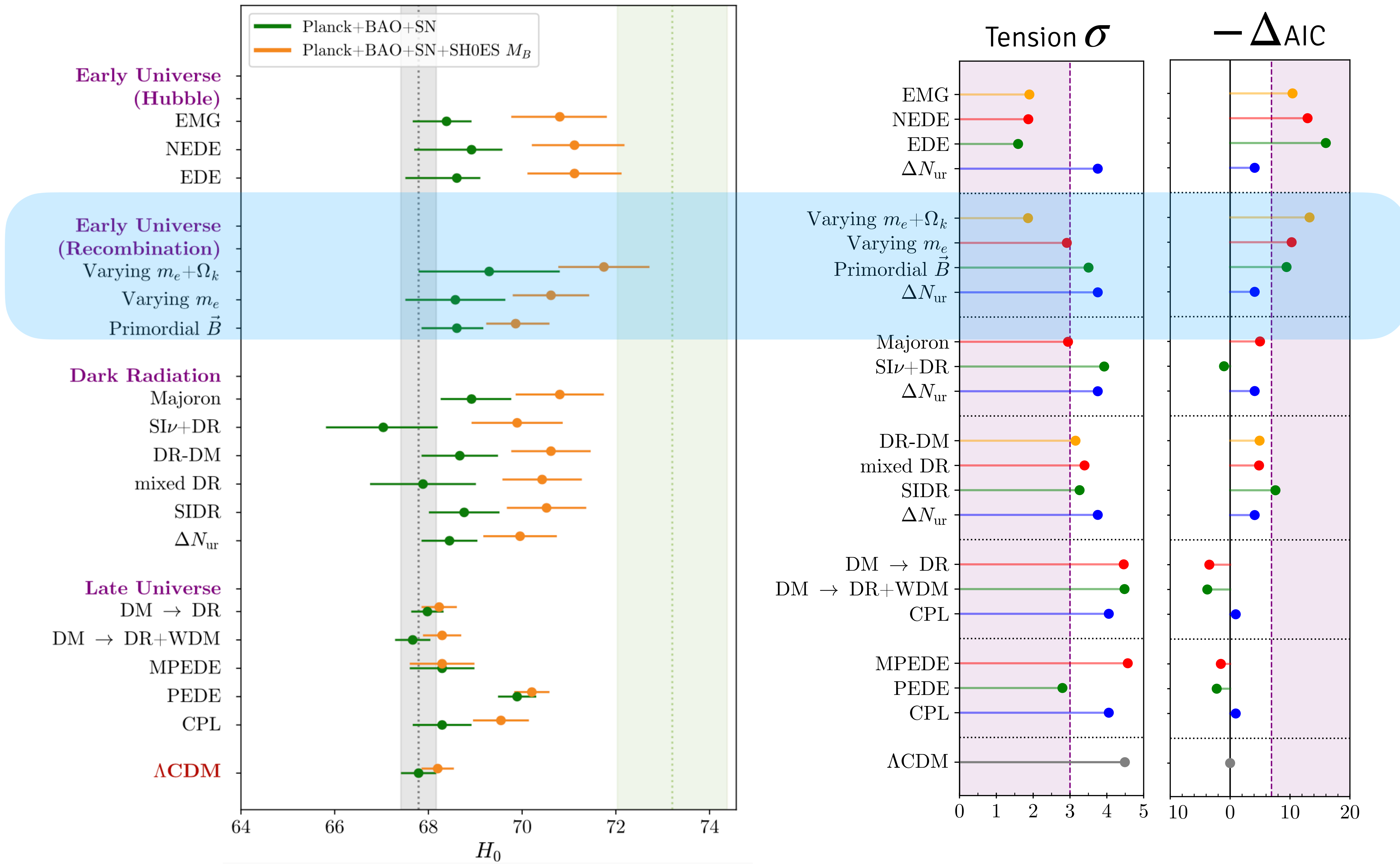








Status of "modified recombination" solutions



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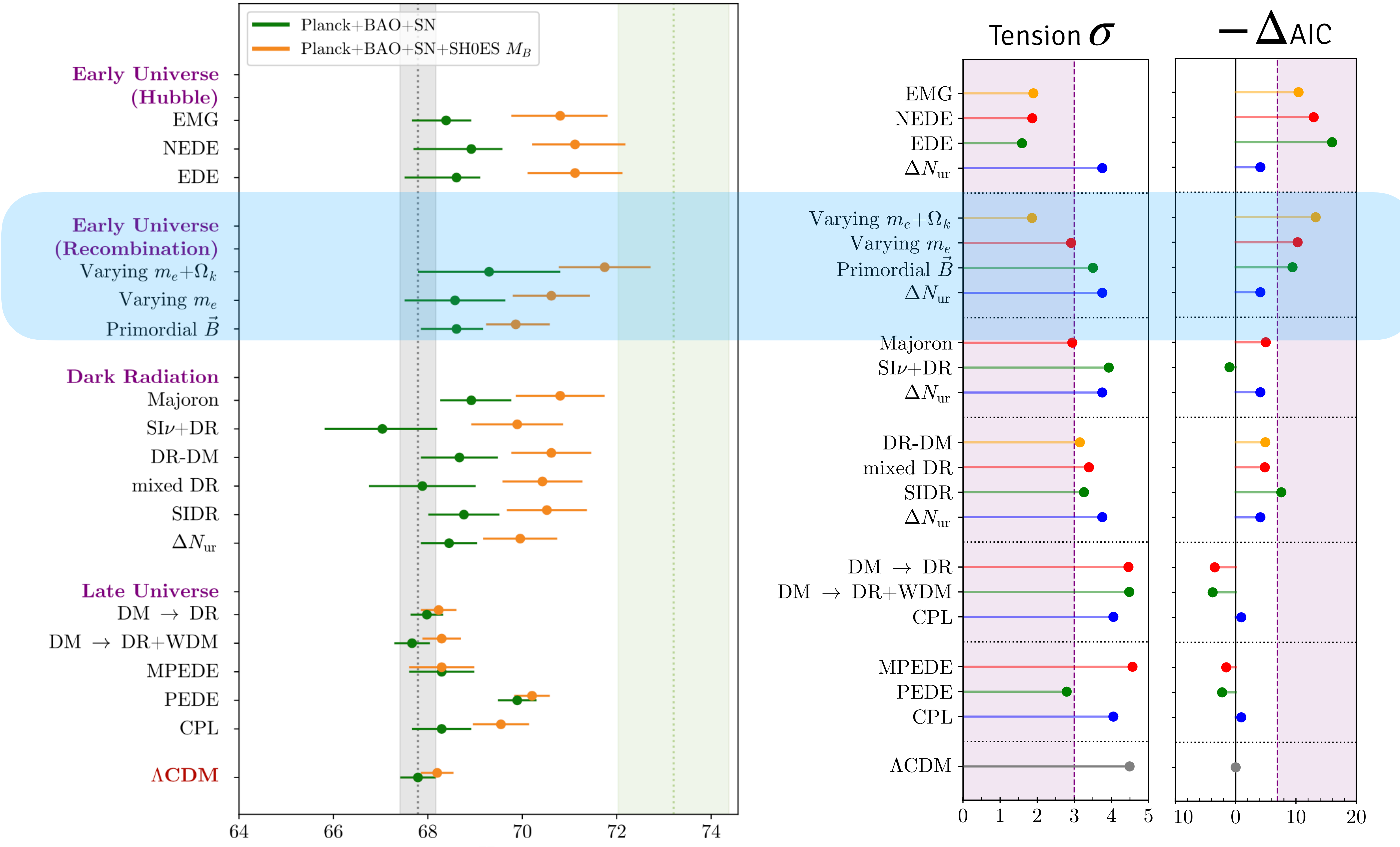
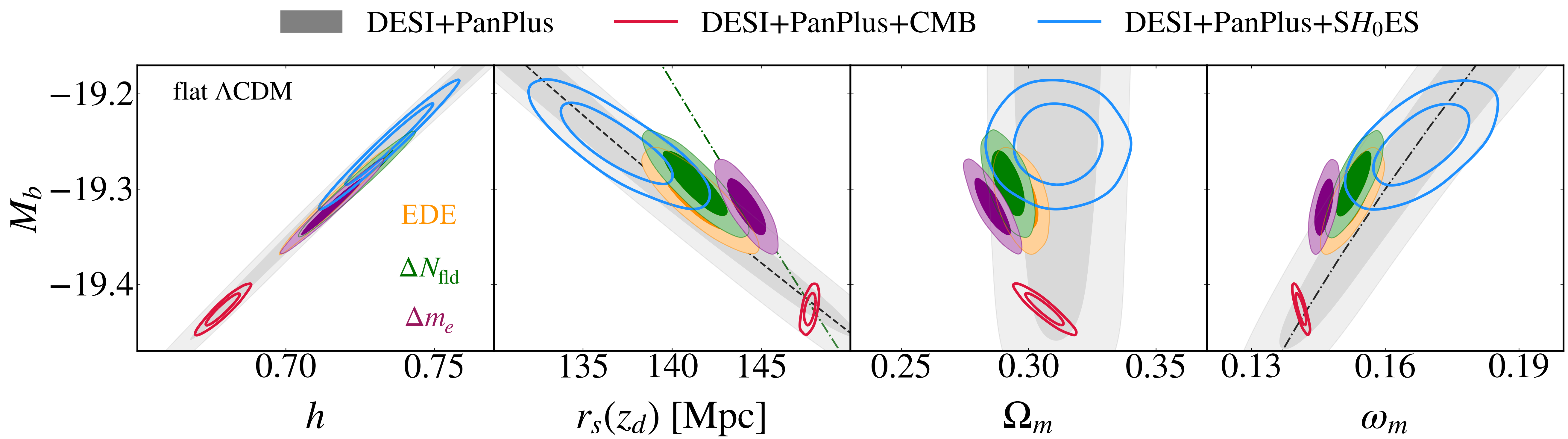


$m_e + \Omega_k$ **can bring the tension down to the 1.8σ level and is slightly favored without H_0 prior**

Can models respect degeneracies imposed by the distance ladder?



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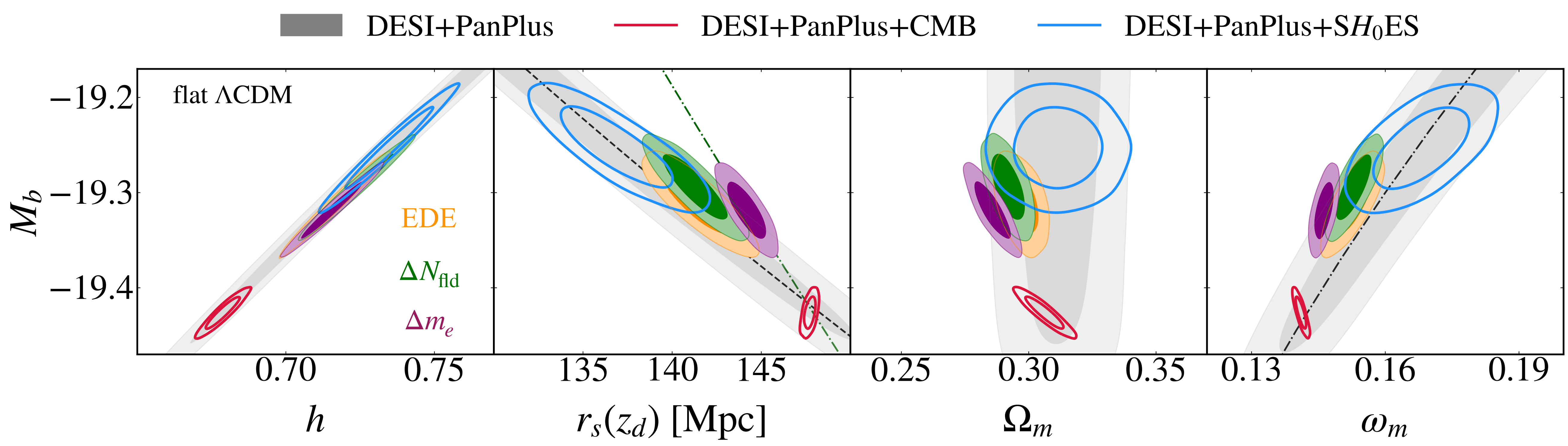

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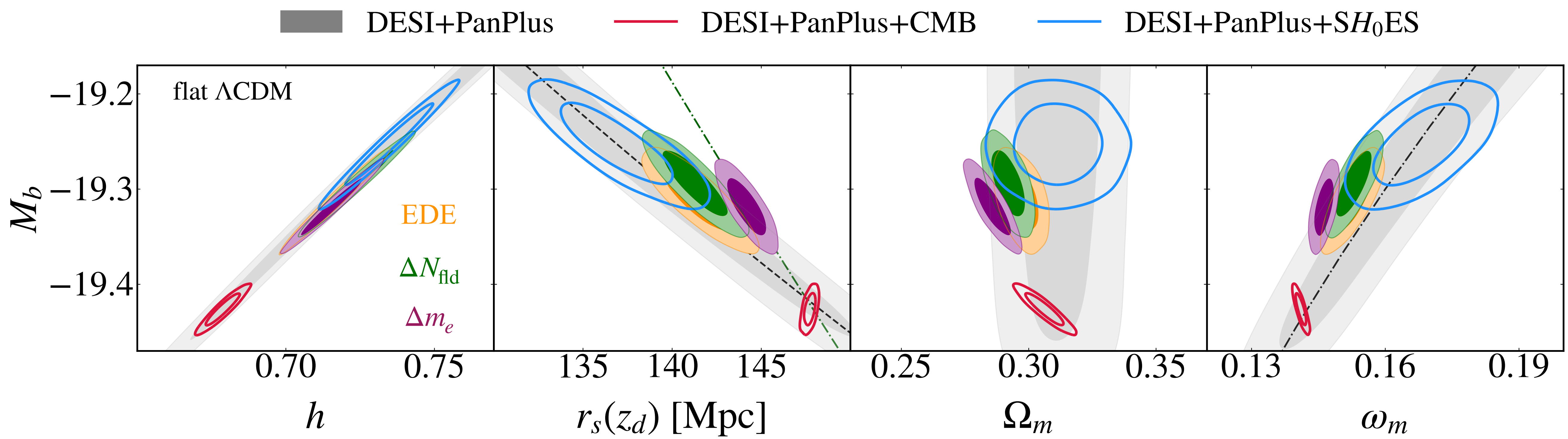
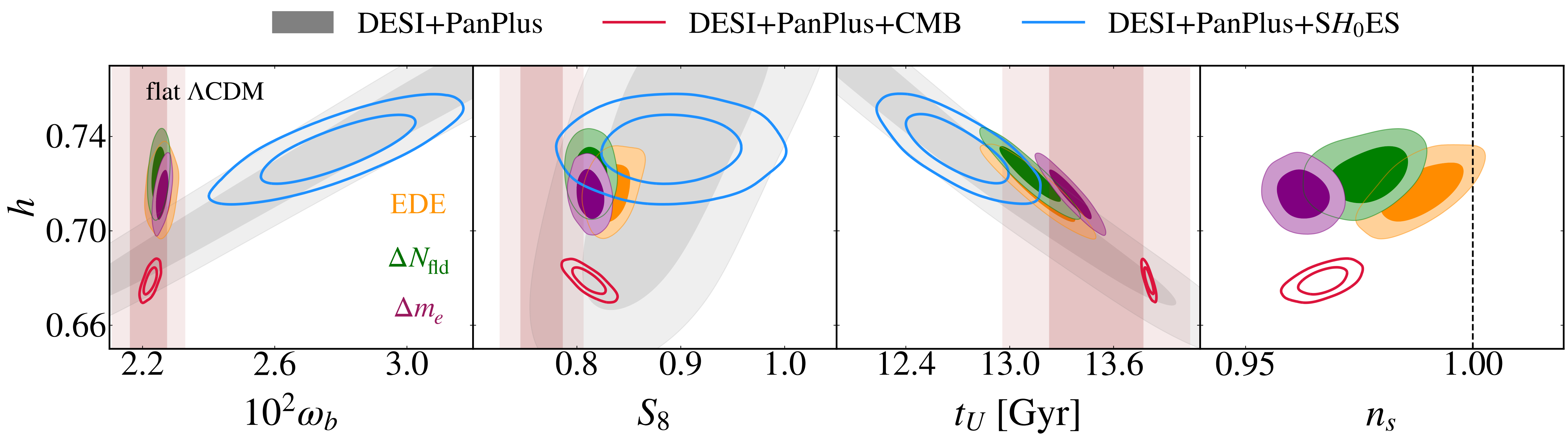


- Models affecting expansion history can reduce tension to $\sim 2-3\sigma$ level
- Models affecting solely the way recombination proceeds are disfavored: they lead to a low Ω_m

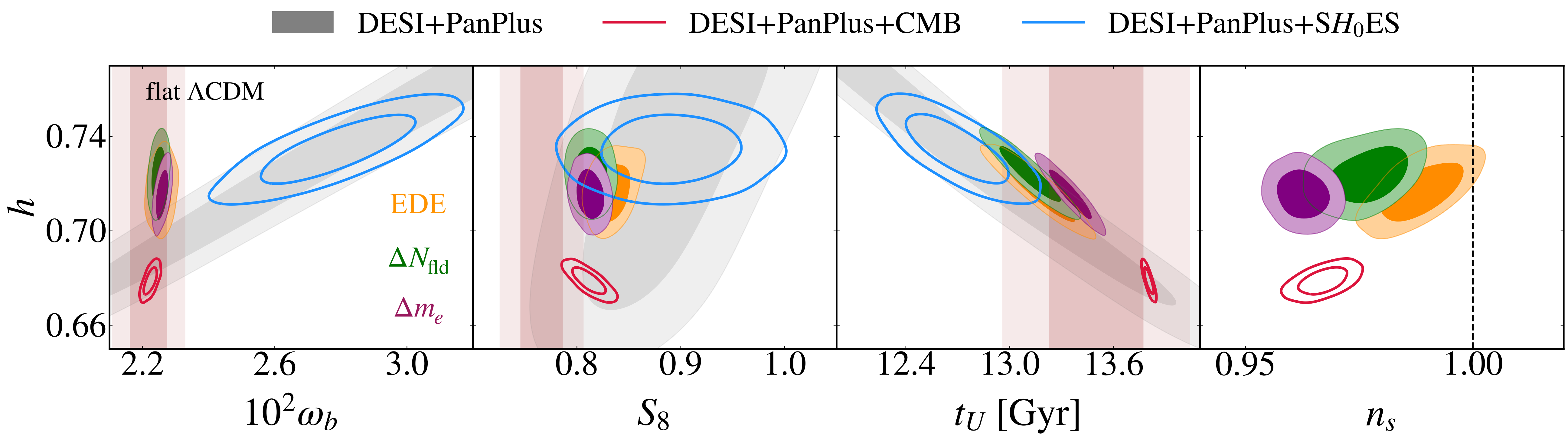
Lee (VP)++ PRL 2022, Lynch++ 2404.05715

Can models resolve the other tensions?



- No more tension with BBN but tension with weak lensing measurements at the $3-3.5\sigma$ level
- Age of the universe ~ 0.7 Gyr younger: problem with old objects? JWST?

Can models resolve the other tensions?

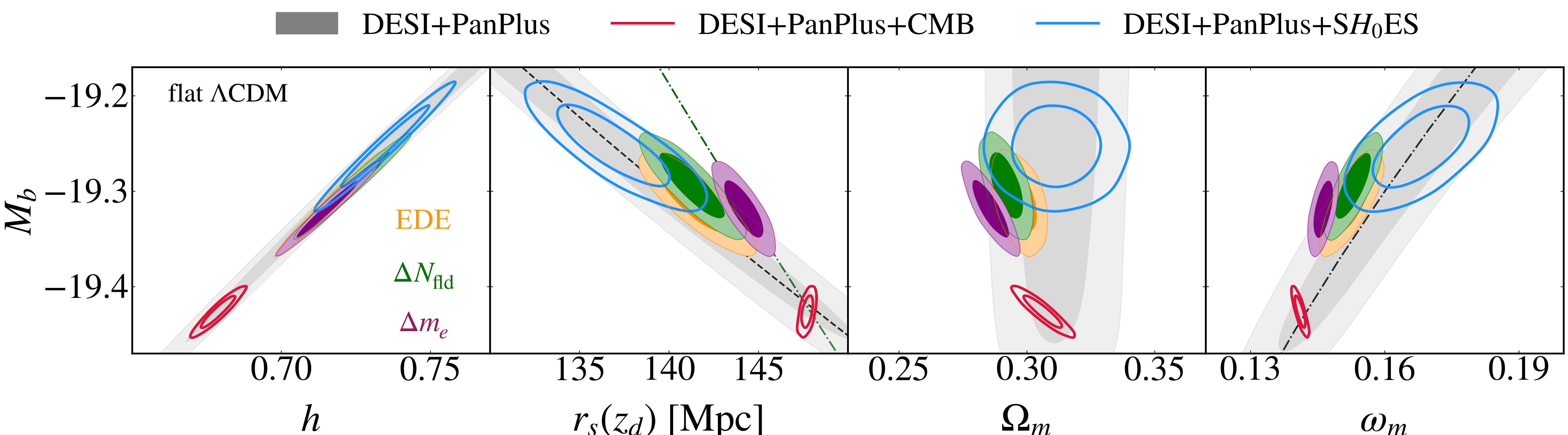


- No more tension with BBN but tension with weak lensing measurements at the $3-3.5\sigma$ level
- Age of the universe $\sim$ 0.7 Gyr younger: problem with old objects? JWST?
- n_s is degenerate with the angular damping scale $$\frac{\delta\theta_D}{\theta_D} \simeq 0.2\frac{\delta n_s}{n_s}\,.$$ *Smith&VP, 2309.03265*
- $\theta_D \sim \sqrt{H_0}$ while $\theta_s \propto H_0$: n_s must increase to compensate a higher H_0.

Synergy between early and late-time?

- Constraints to Ω_m are an important part of the problem: how to relax them?
- Hints of dynamical dark energy: could it play a role in the tensions?

  DESI 2404.03002, Cortês&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, Efstathiou 2408.07175
- Test: Open the late-time expansion history (w_0, w_a, Ω_k)



VP, Smith, Calderon, Simon 2407.18292

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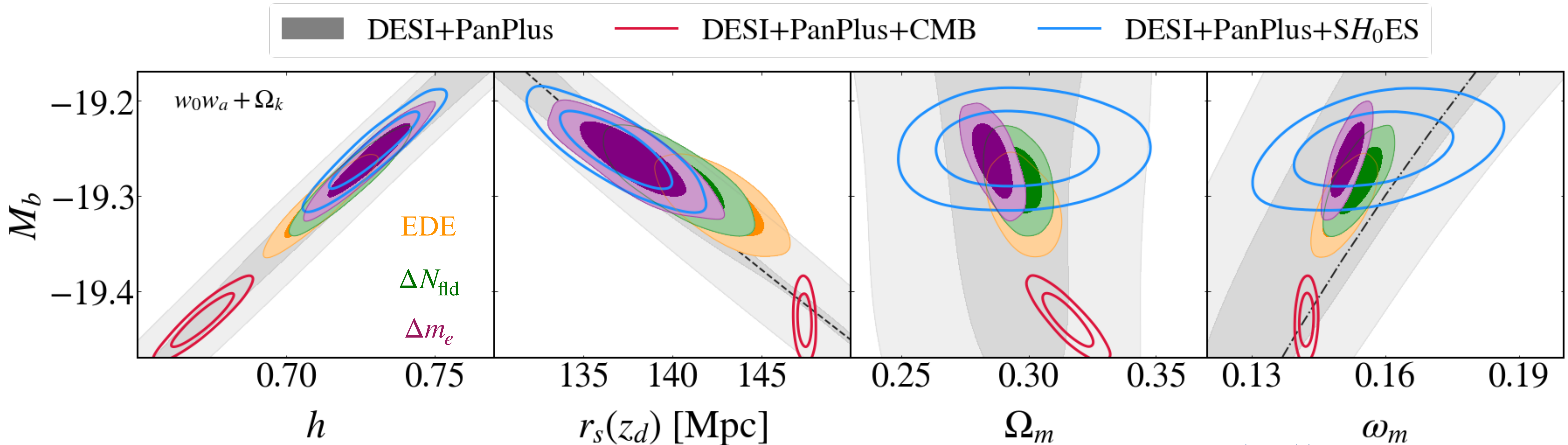

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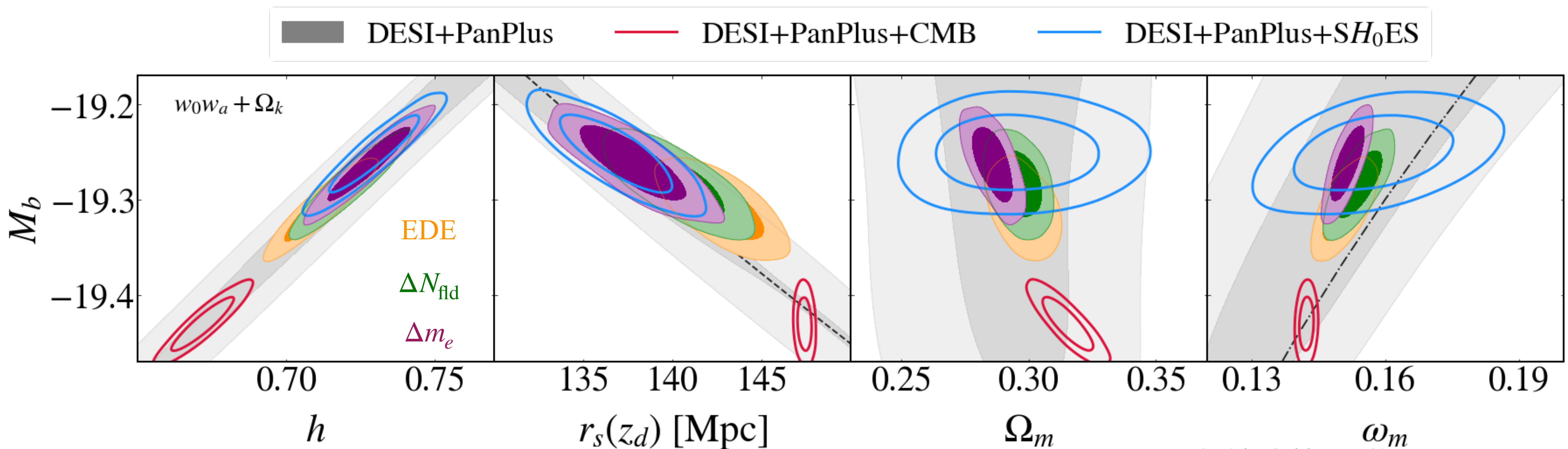

VP, Smith, Calderon, Simon 2407.18292

- Δm_e model has almost no tension with $\Omega_k \simeq -0.0114 \pm 0.0031$; No impact for EDE and $\Delta N_{\rm fld}$.

Sekiguchi++2007.03381

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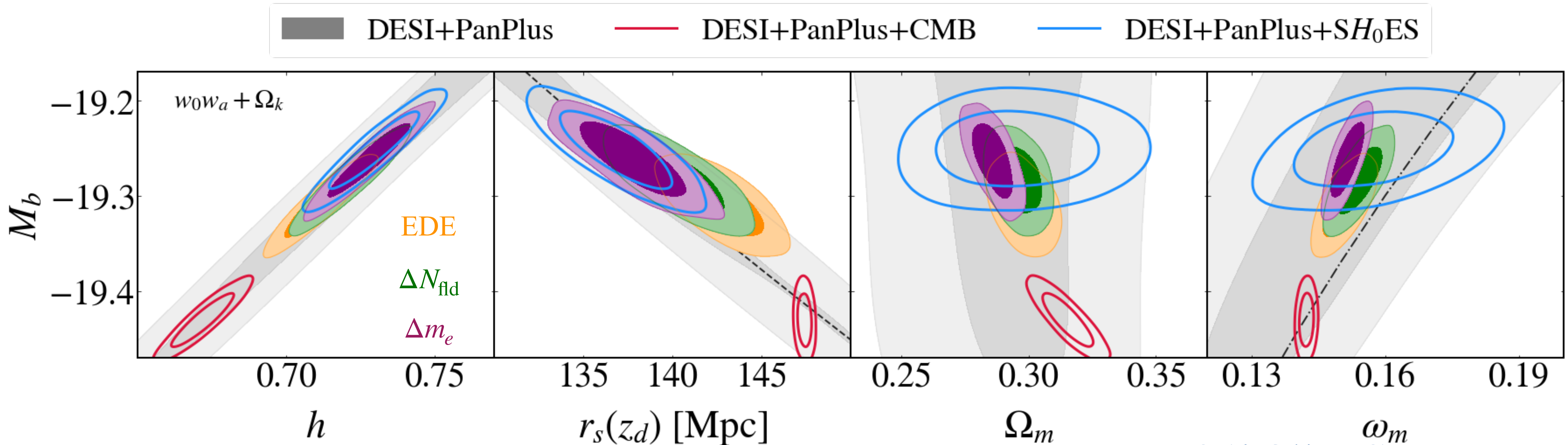

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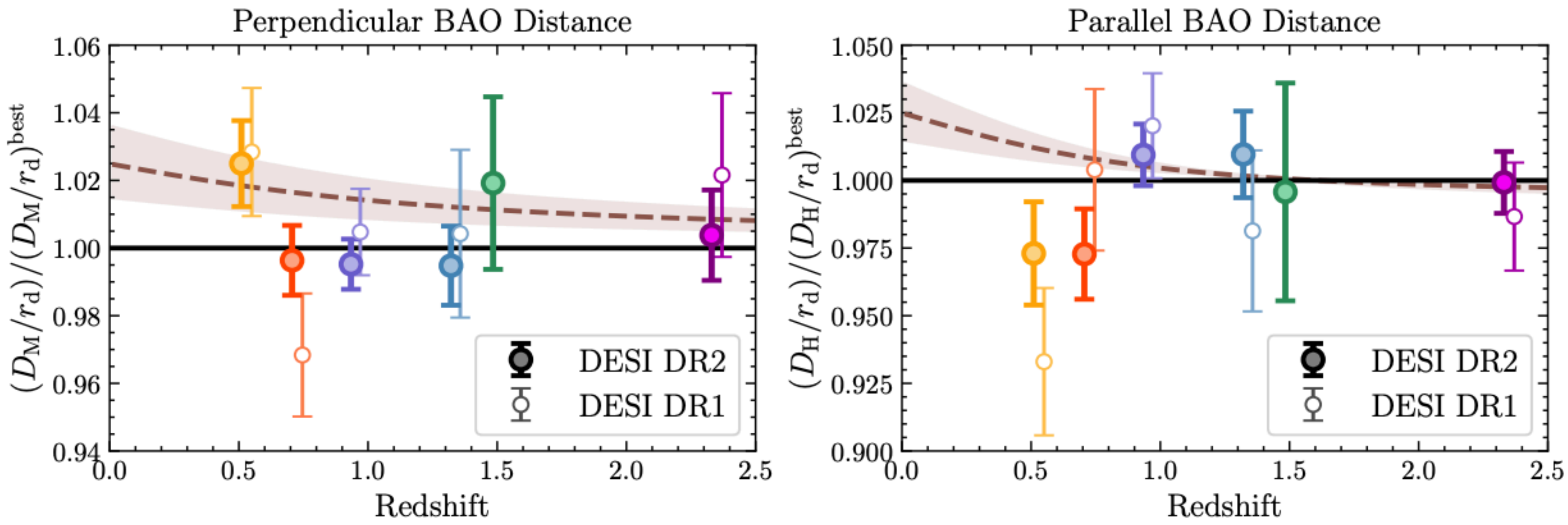
  Sekiguchi++2007.03381
- Localized energy injection boosting $H(z)$ or a broad change affecting several cosmic epochs?

DESI BAO measurements: hint of new physics?

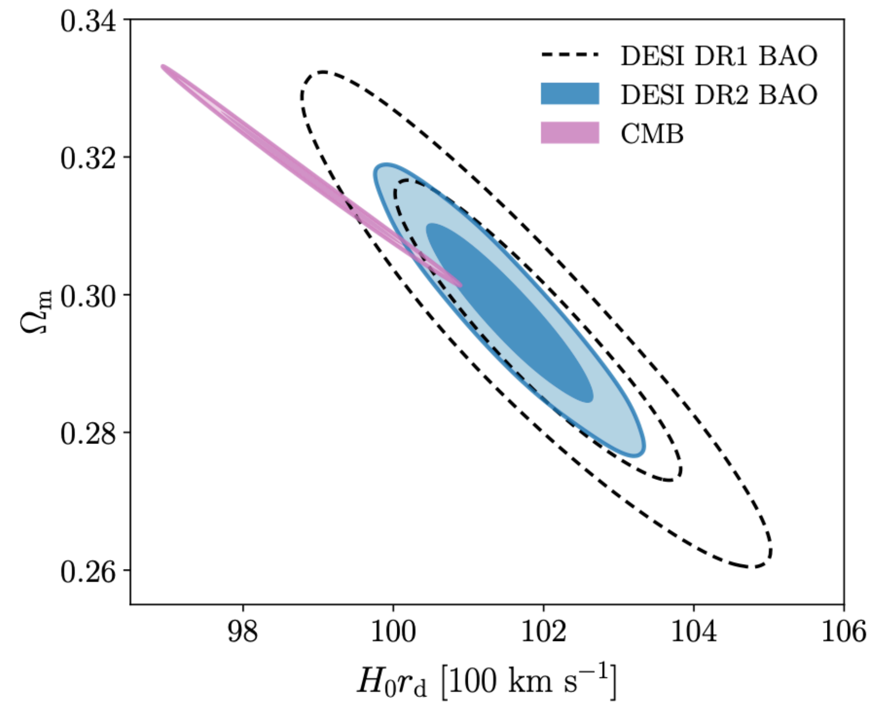
- Under ΛCDM, 2.3σ tension between CMB and BAO data



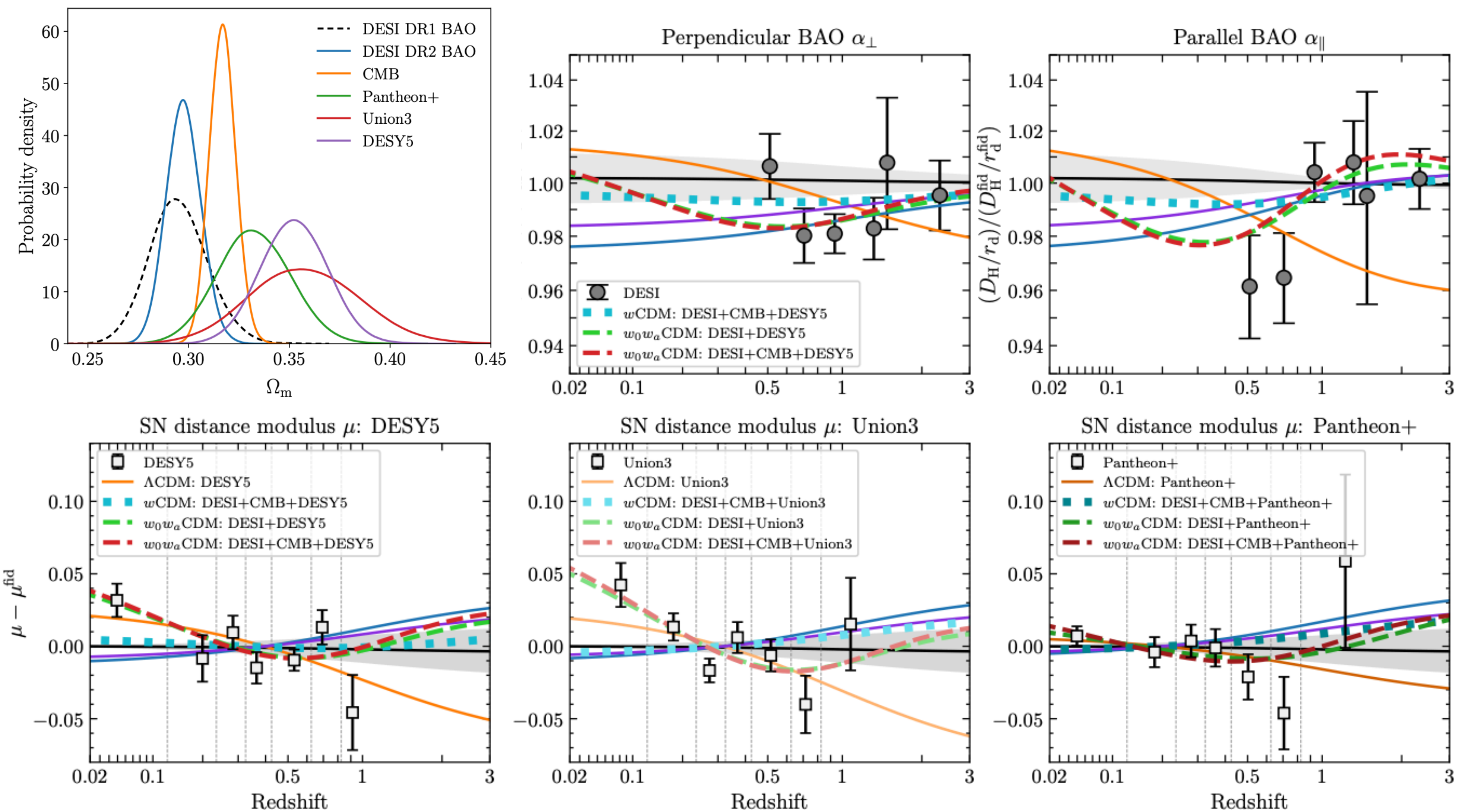
- Under ΛCDM, the BAO allows to measure Ω_m and $H_0 r_d$.

$$\frac{r_d}{D_M} \equiv \frac{H_0 r_s(z_d)}{\int_0^z dz\left(\Omega_m[(1+z)^3-1]+1\right)^{-1/2}}$$

$$\frac{r_d}{D_H} \equiv H_0 r_s(z_d)\sqrt{\Omega_m[(1+z)^3-1]+1}$$

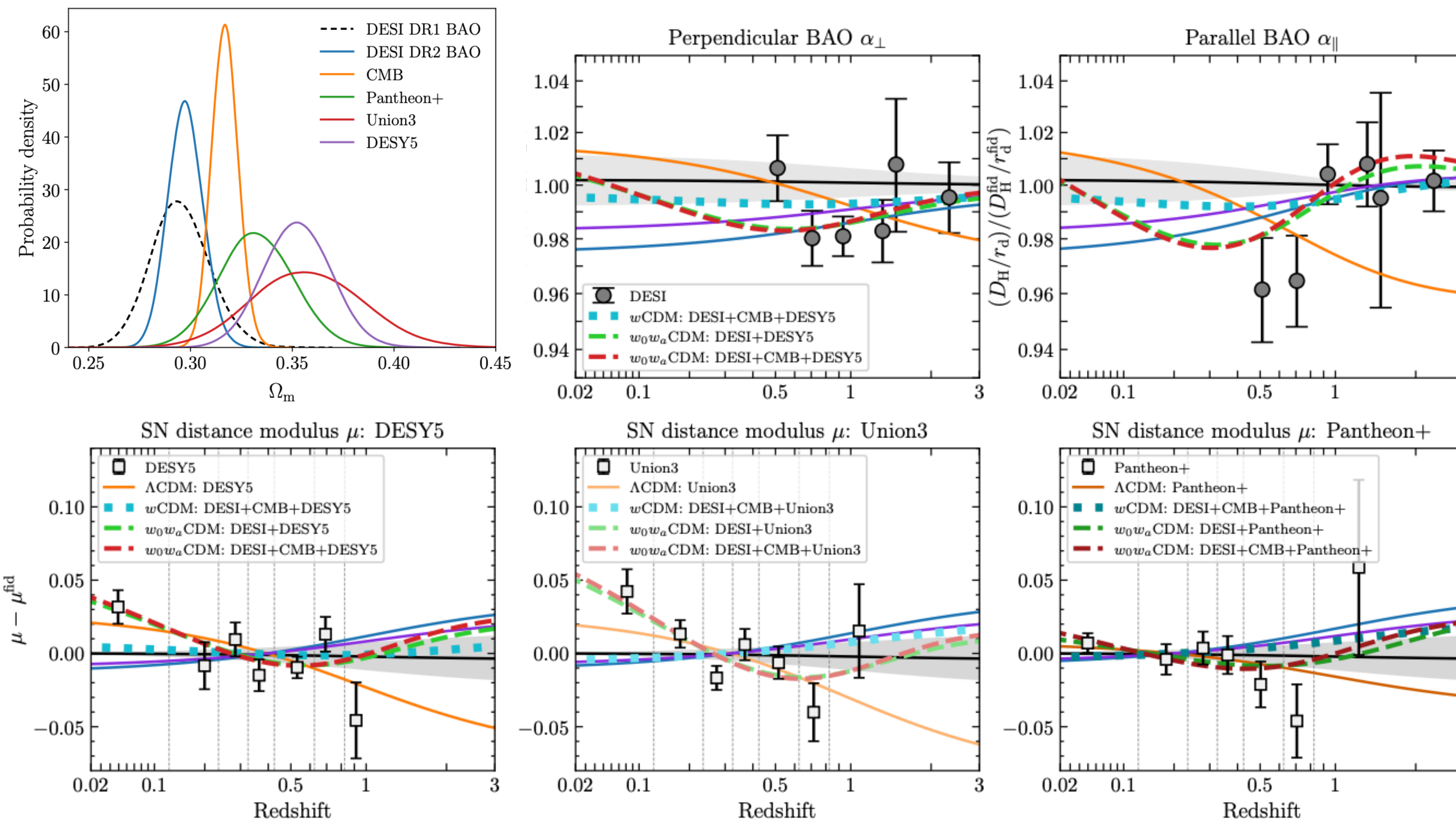


DESI vs SNIa



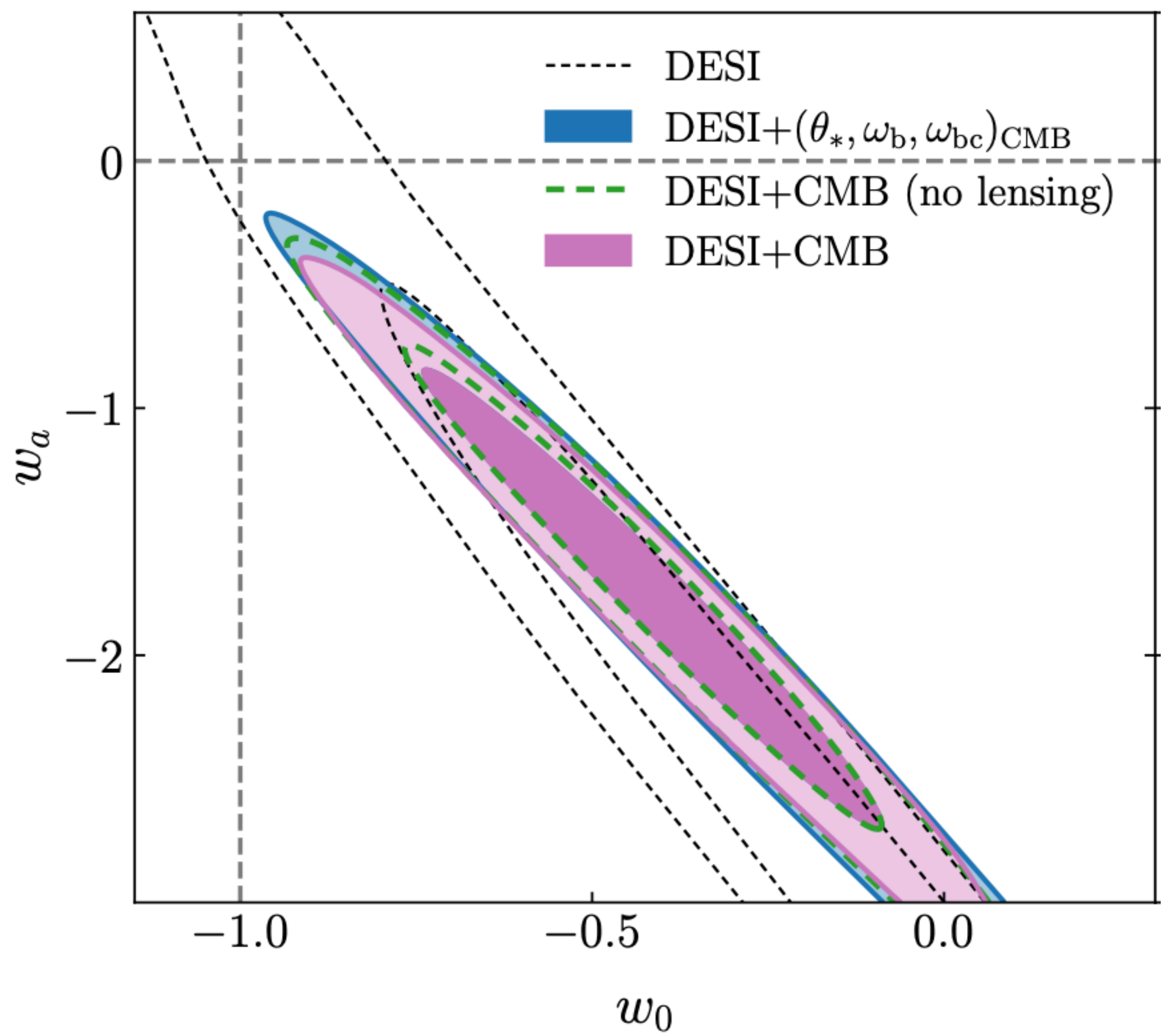
DESI DR1 BAO
DESI DR2 BAO
CMB
Pantheon+
Union3
DESY5
Probability density
Ω_m
Perpendicular BAO $\alpha_\perp$
Parallel BAO $\alpha_\parallel$
$(D_H/r_d)/(D_H^{fid}/r_d^{fid})$
DESI
wCDM: DESI+CMB+DESY5
w_0w_aCDM: DESI+DESY5
w_0w_aCDM: DESI+CMB+DESY5
SN distance modulus μ: DESY5
SN distance modulus μ: Union3
SN distance modulus μ: Pantheon+
$\mu - \mu^{fid}$
DESY5
ΛCDM: DESY5
wCDM: DESI+CMB+DESY5
w_0w_aCDM: DESI+DESY5
w_0w_aCDM: DESI+CMB+DESY5
Union3
ΛCDM: Union3
wCDM: DESI+CMB+Union3
w_0w_aCDM: DESI+Union3
w_0w_aCDM: DESI+CMB+Union3
Pantheon+
ΛCDM: Pantheon+
wCDM: DESI+CMB+Pantheon+
w_0w_aCDM: DESI+Pantheon+
w_0w_aCDM: DESI+CMB+Pantheon+
Redshift

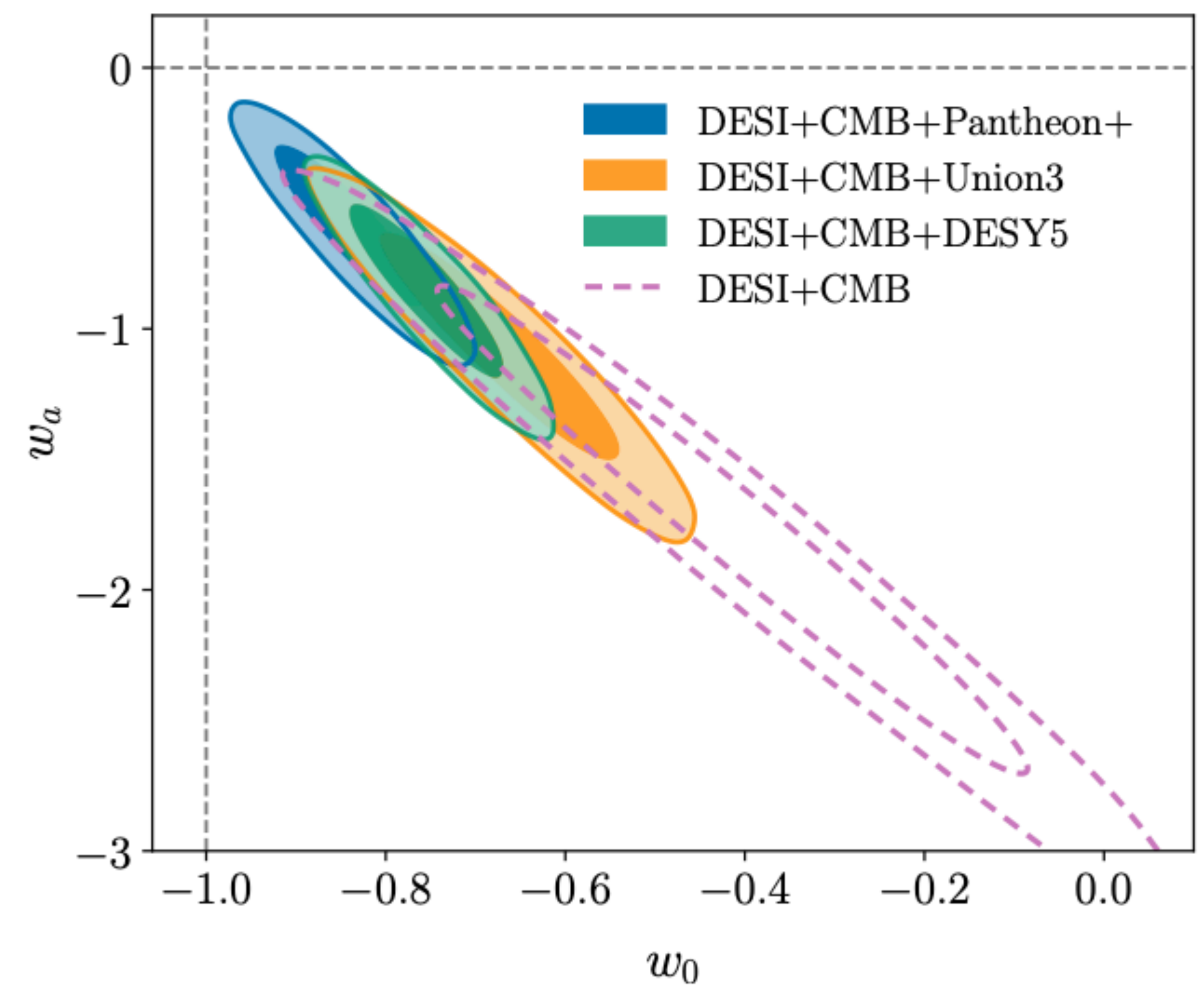
DESI vs SNIa



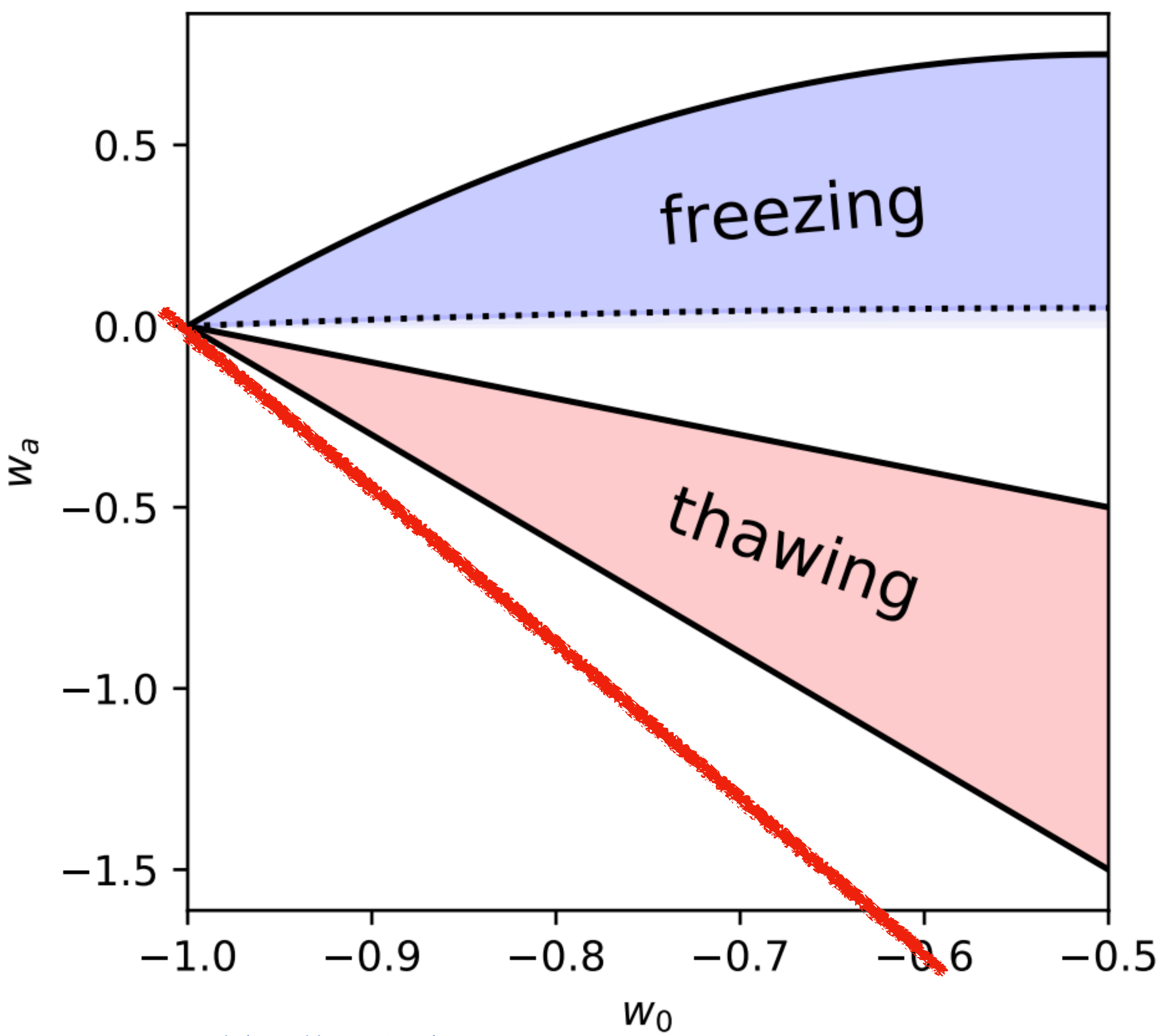
- DESI+CMB in tension at the $\sim 2-3\sigma$ level with SN1a in the determination of Ω_m

Evidence for dynamical dark energy

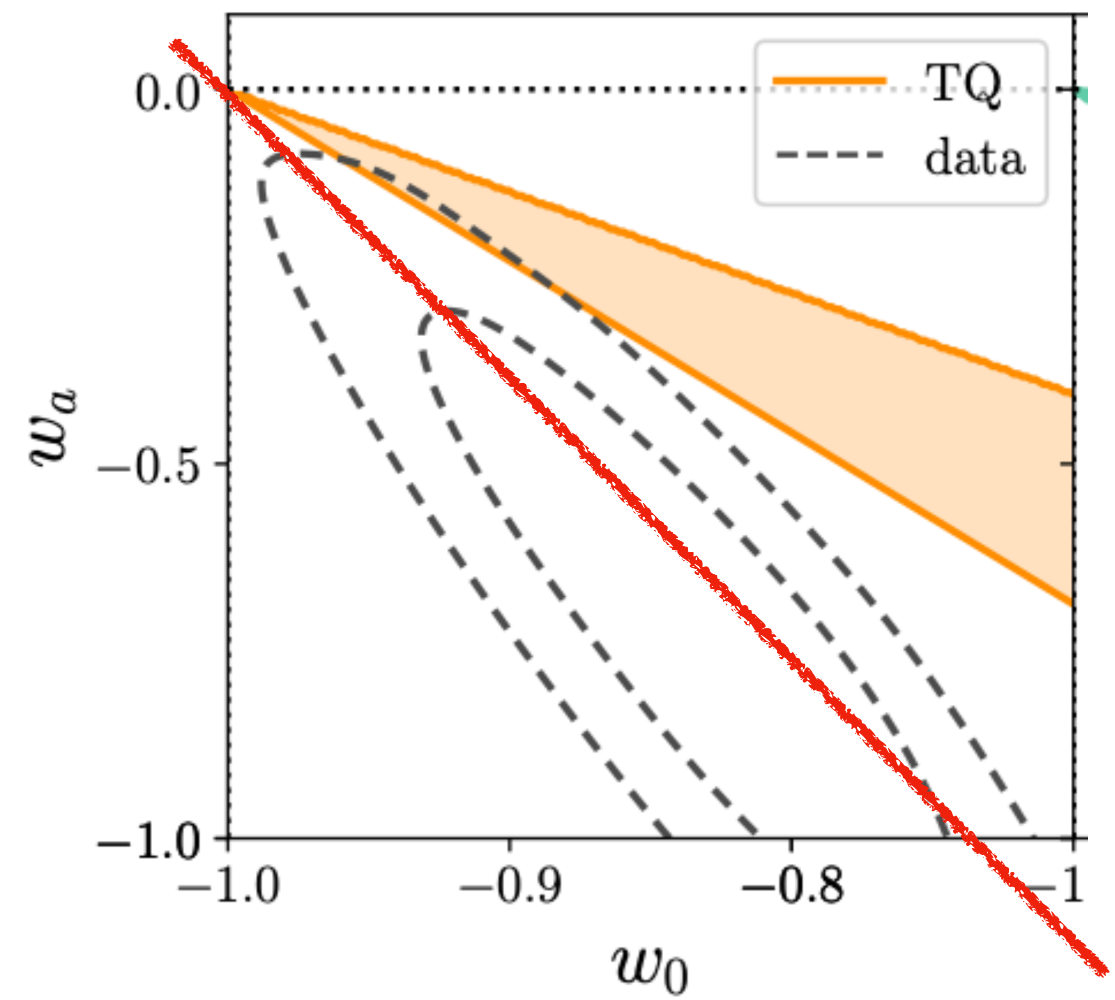




Evidence for non canonical quintessence



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)
$w_0 w_a$	−6.8 (−10.7)	−13.5 (−17.4)	−17.2 (−21.0)

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

Linder 0708.0024

WEIRD??

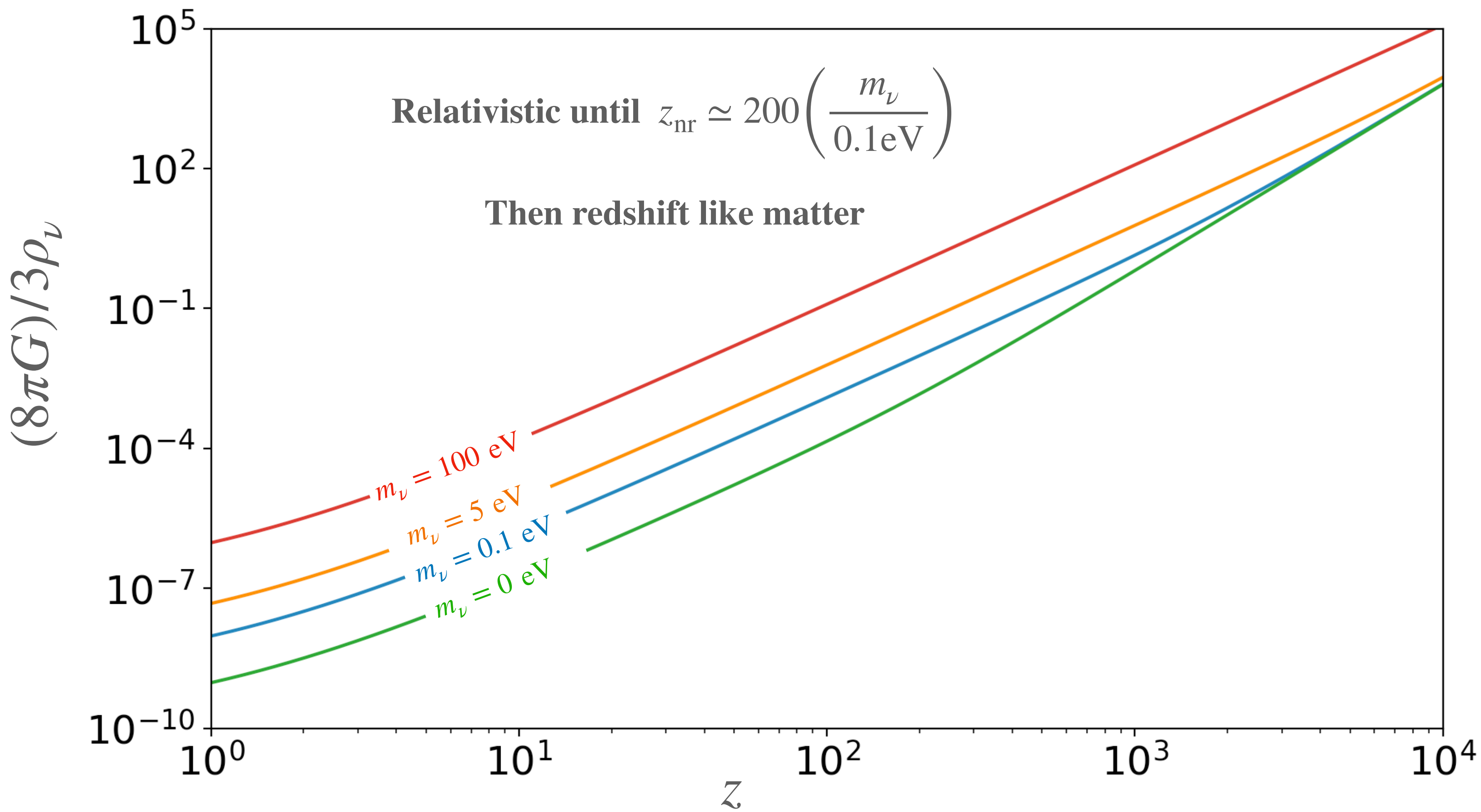
m_ν can affect cosmological distances

- ν can affect the homogeneous expansion

$$H(z) \equiv \frac{\dot{a}}{a} = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda + \ldots}$$

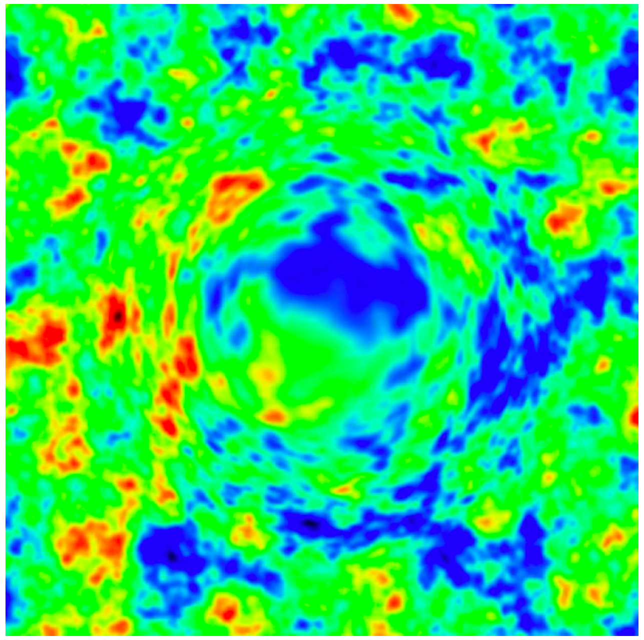
- Affect distance measurements via SN1a and BAO

$$D_M(z) = \int_0^z \frac{cdz}{H(z)}$$

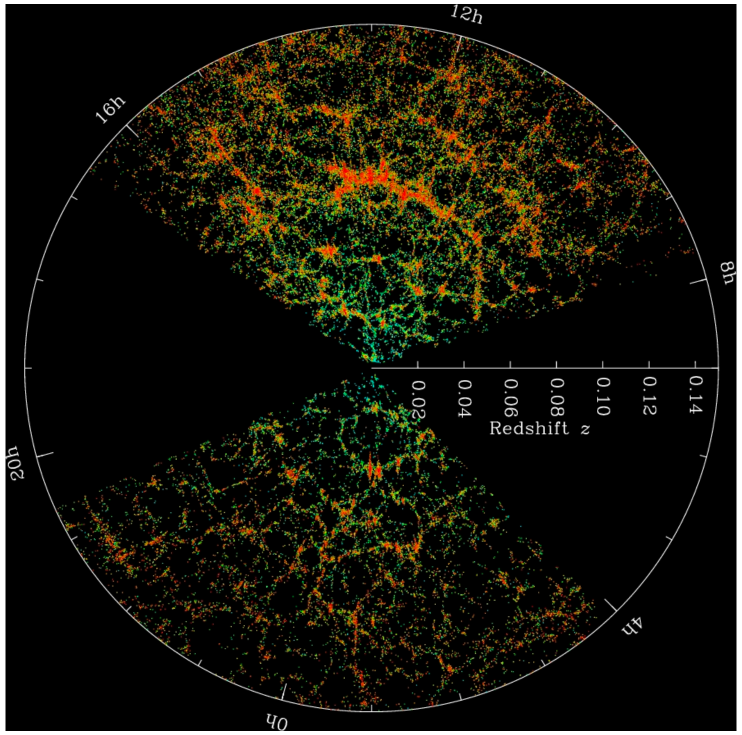


m_ν can affect probes of matter structuring

CMB weak lensing

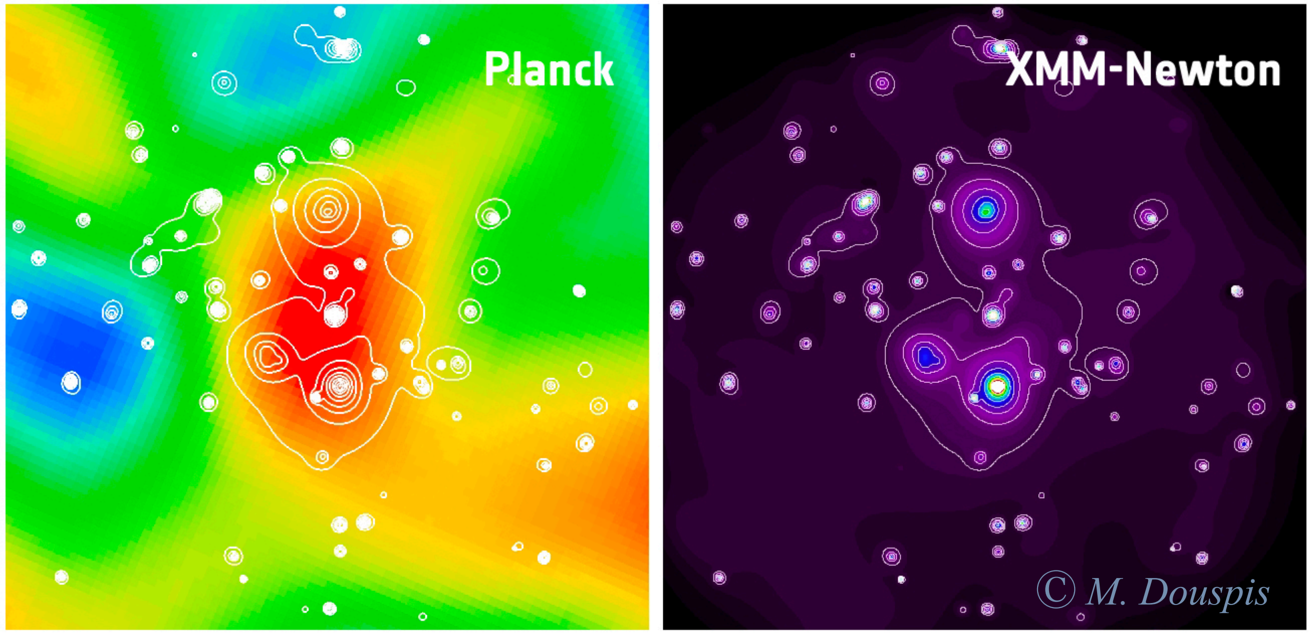


Galaxy correlation function (SDSS/BOSS)

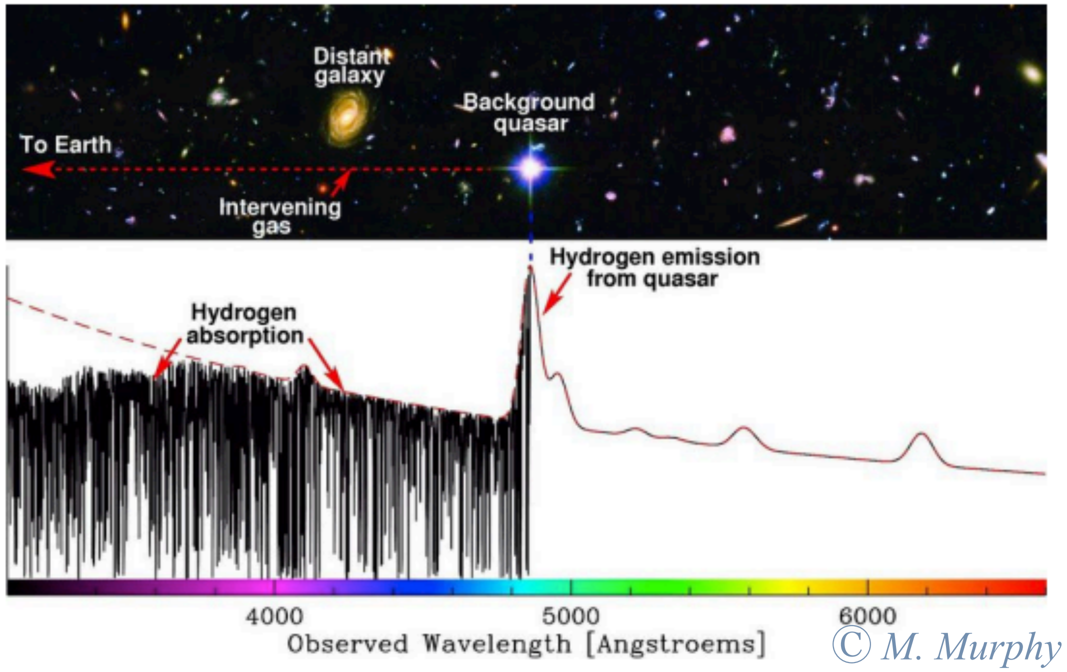


Galaxy weak lensing (KiDS / DES)

Galaxy cluster mass function

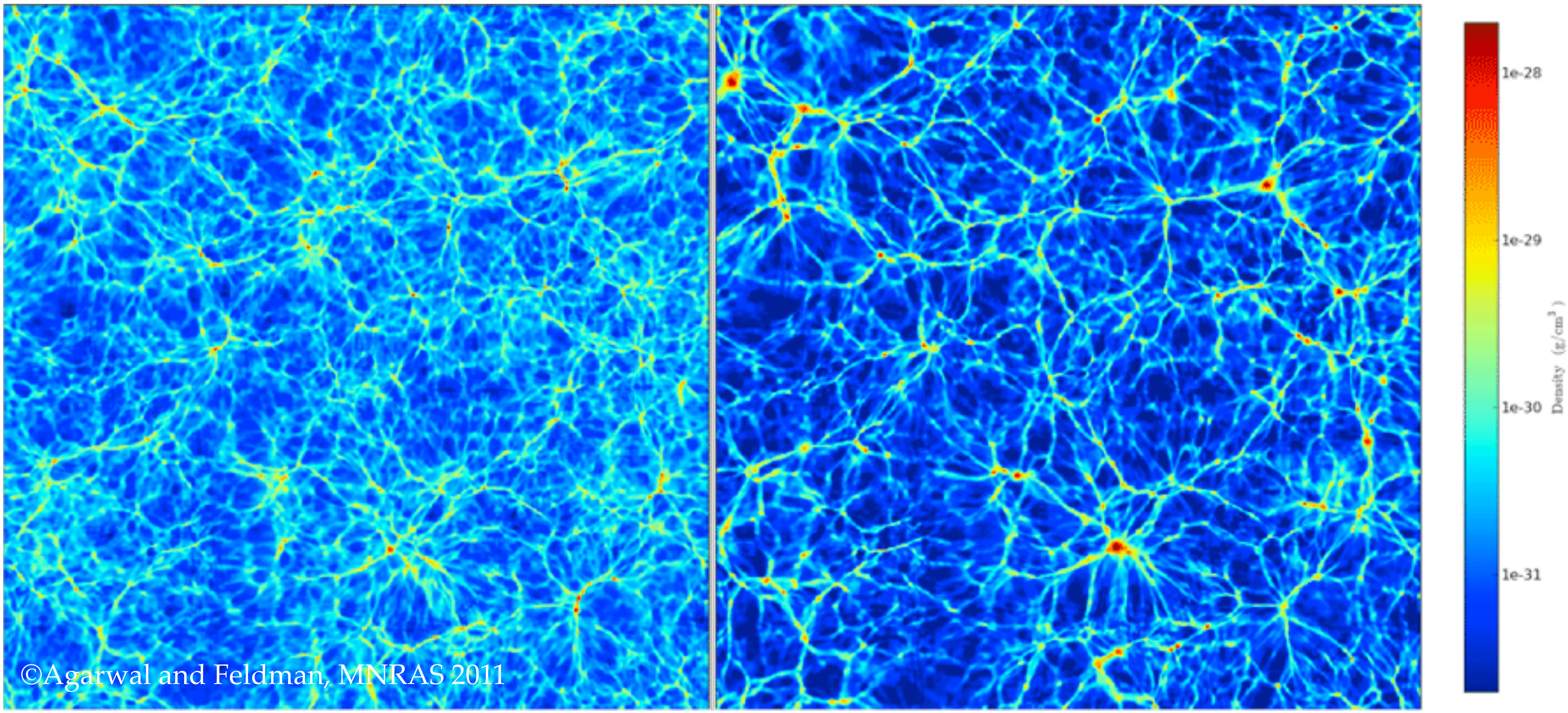


The Lyman-α forest (MIKE/HIRES)



m_ν suppresses the clustering of matter

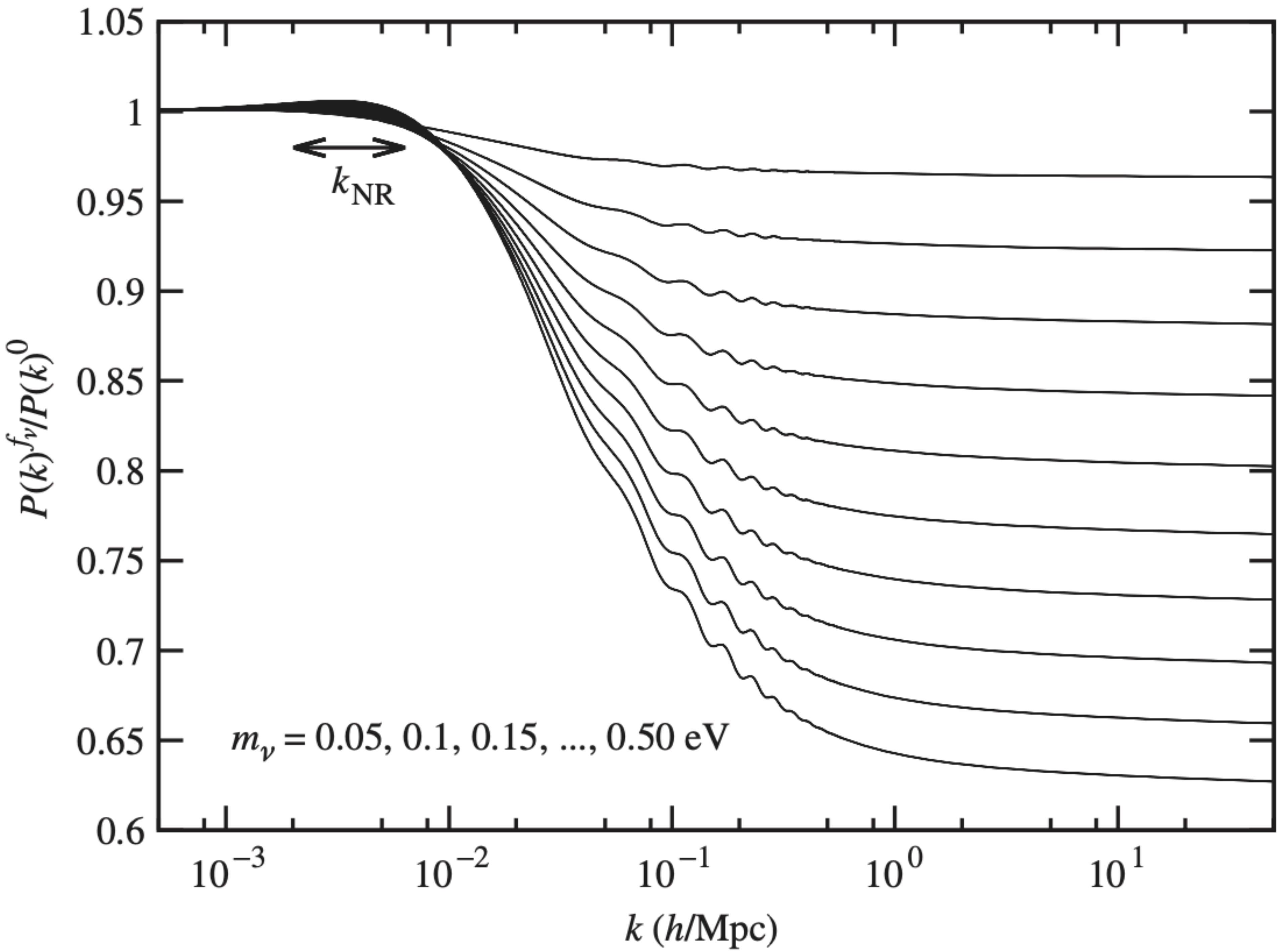
$M_\nu = 1.9$ eV $\qquad\qquad$ $M_\nu = 0$ eV



The density field is "smoother" on small scales

m_ν suppresses the matter power spectrum

For ν's suppression at $k \geq k_{\rm nr} \equiv 0.01\left(\frac{m_\nu}{1{\rm eV}}\right)^{1/2}\left(\frac{\Omega_m}{0.3}\right)^{1/2} h{\rm Mpc}^{-1}$ and amplitude $\frac{\Delta P}{P} \simeq -8\frac{\omega_\nu}{\omega_{\rm m}}$



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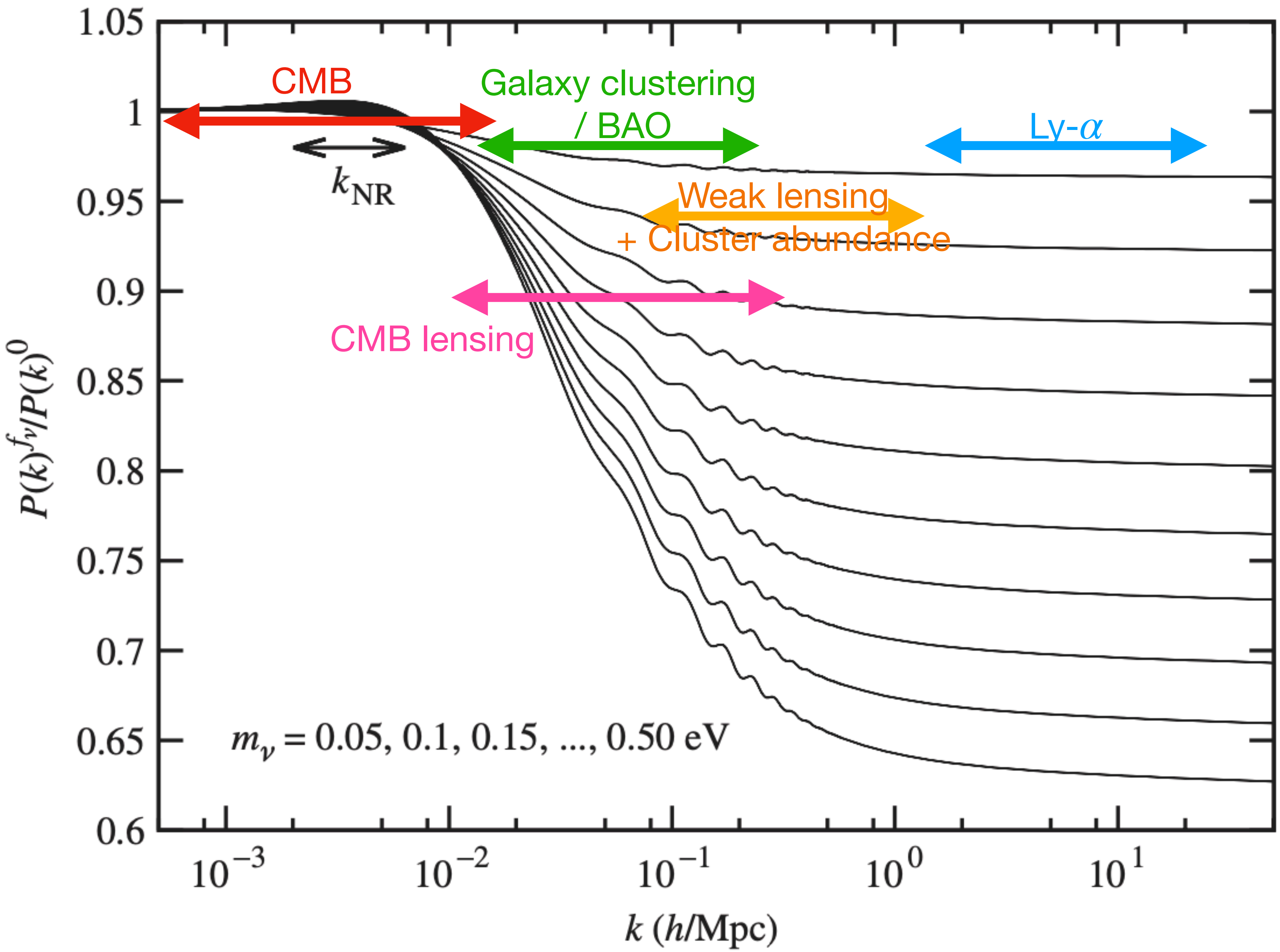
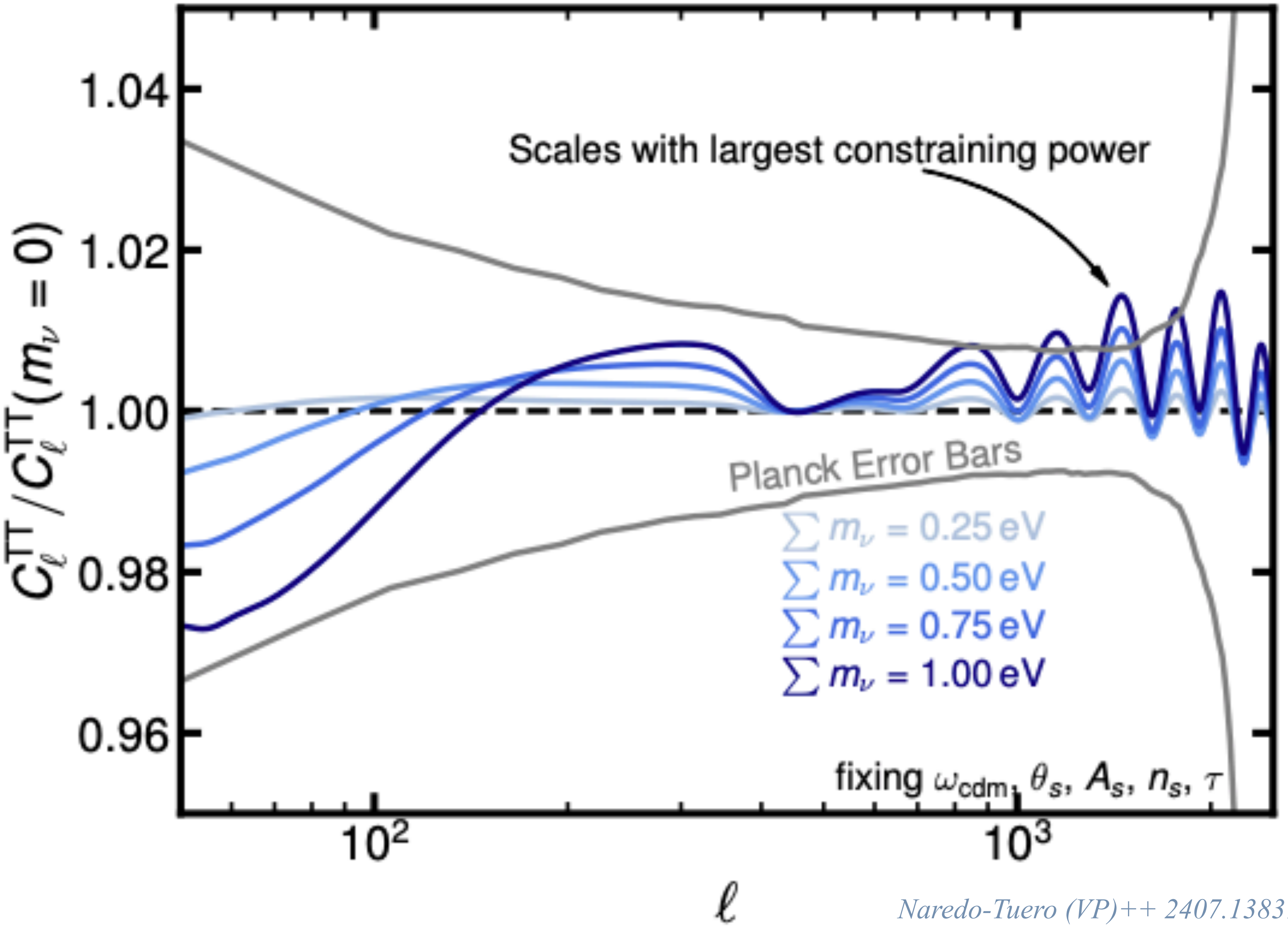


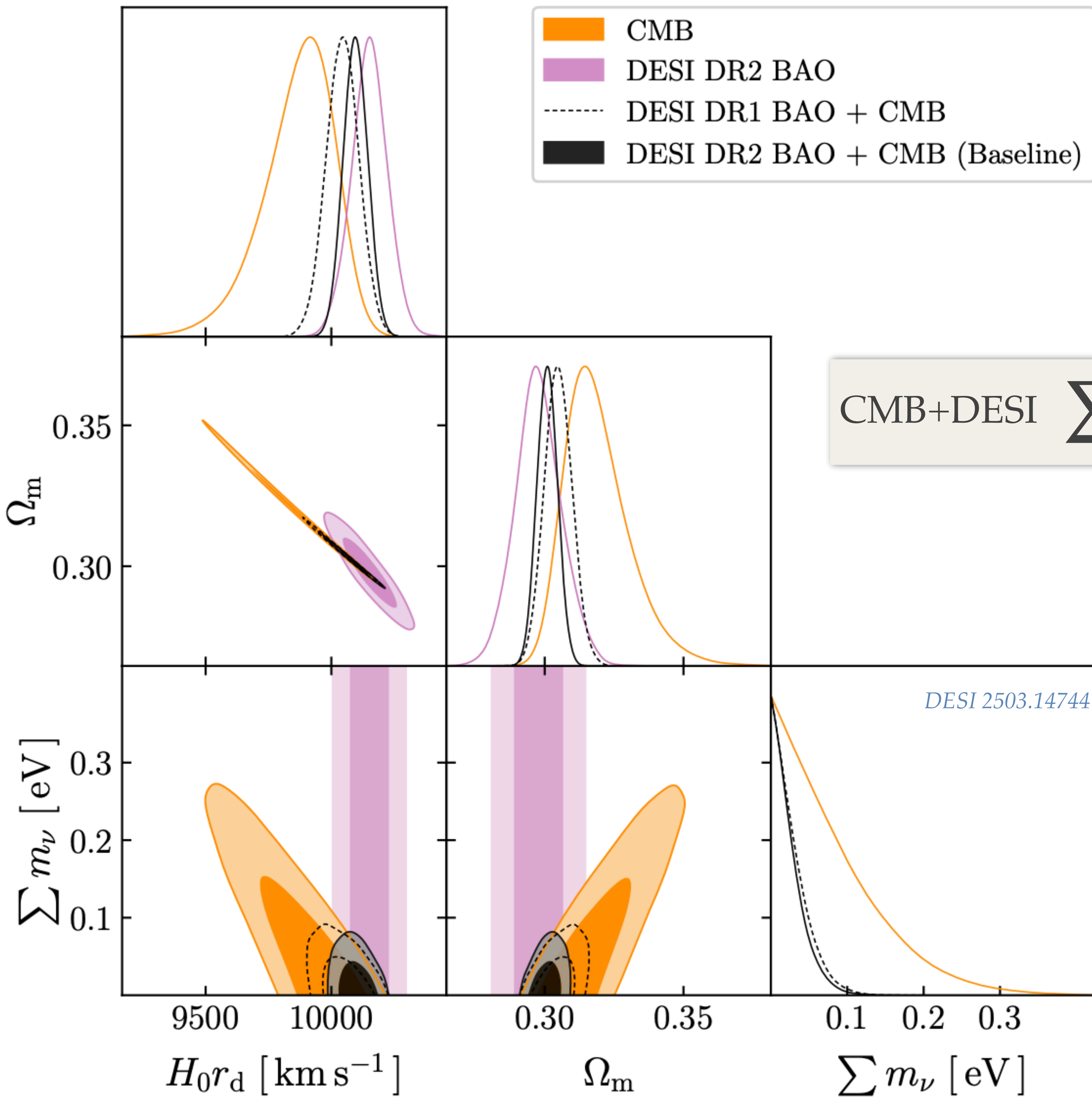
m_ν affects the CMB power spectrum

For $\sum m_\nu < 1$ eV, the main effect of neutrinos is to alter the lensing in the CMB



Naredo-Tuero (VP)++ 2407.13831

Strong constraints to M_ν from background effect



CMB+DESI $\sum m_\nu < 0.048$ eV

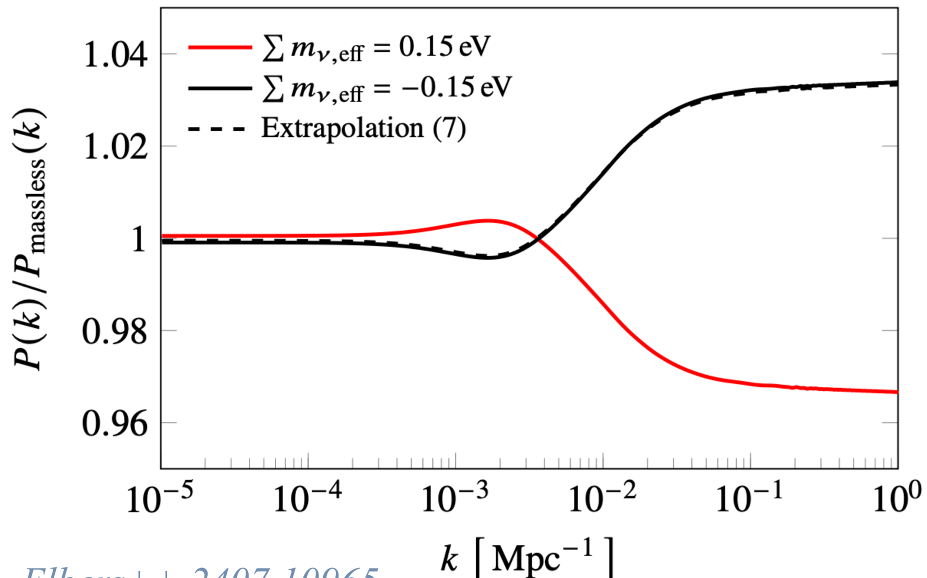
SPT 2506.20707

No ν's is good news?

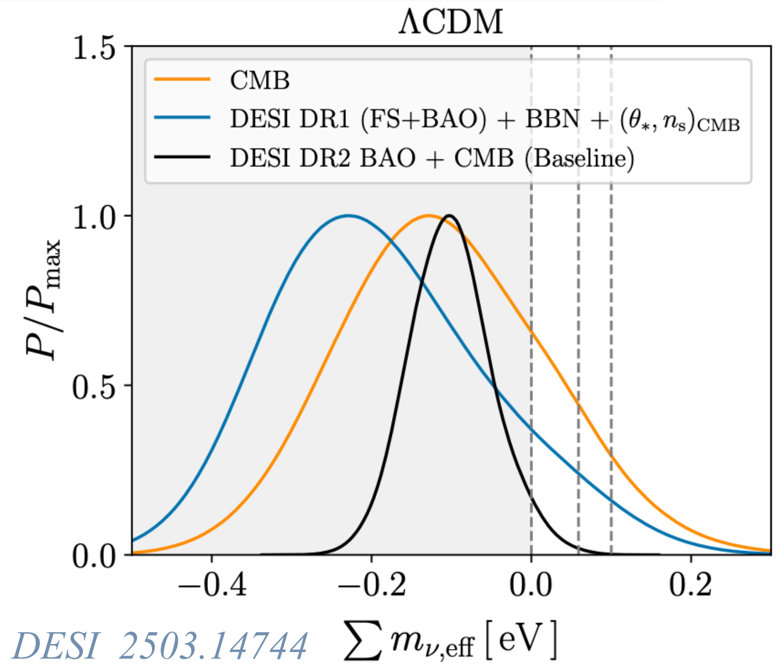
Craig++ 2405.00836

- When allowing for (effective) $m_\nu < 0$ eV

$$\sum m_{\nu,\mathrm{eff}} = -0.101^{+0.047}_{-0.056} \ \mathrm{eV}$$

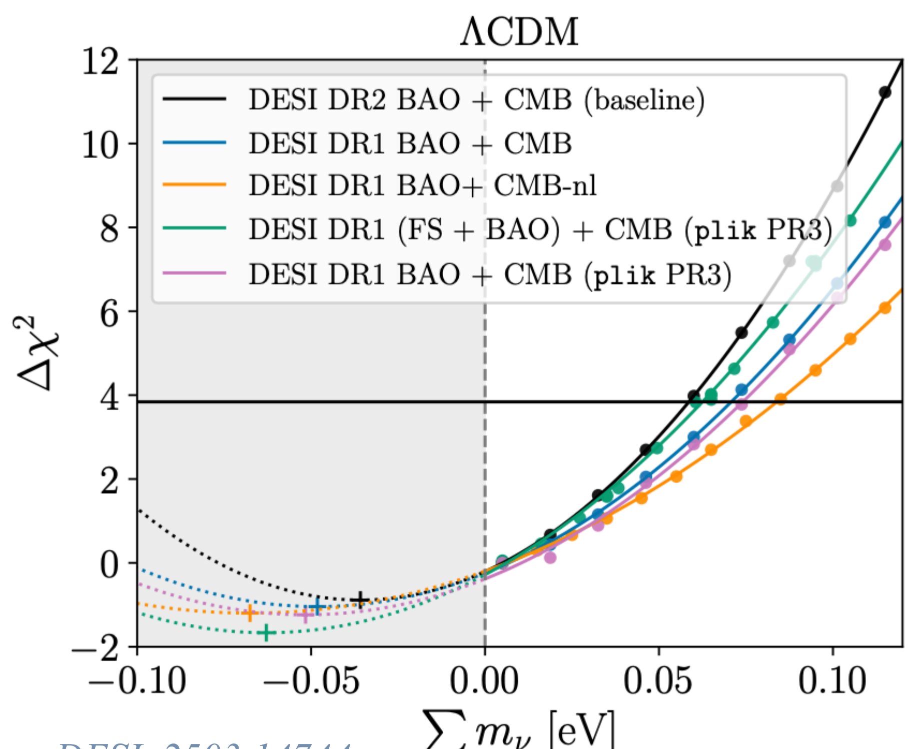


Elbers++ 2407.10965

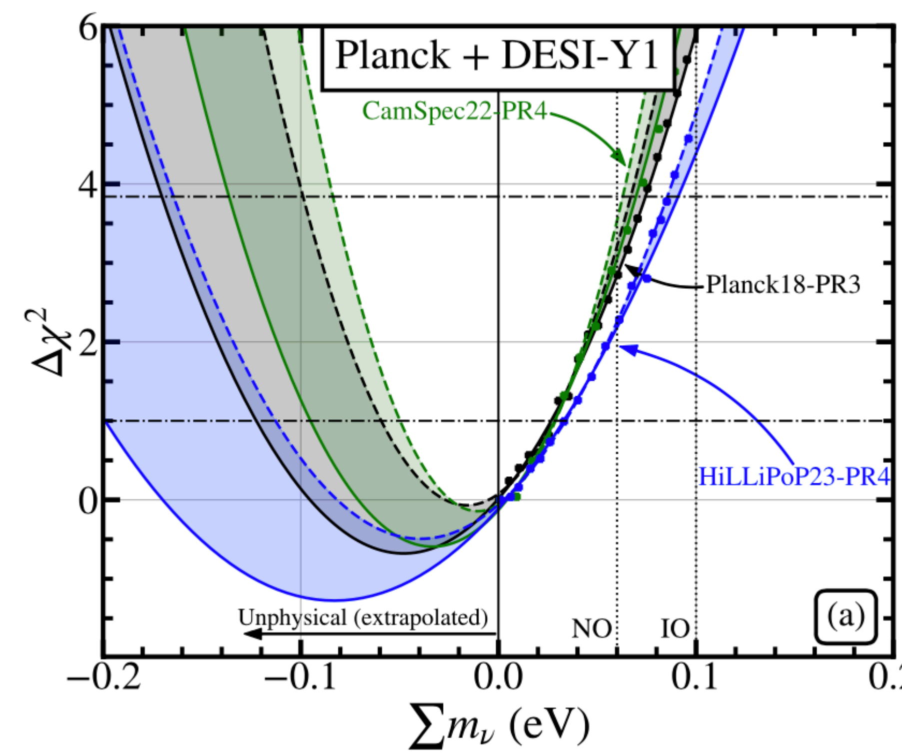


DESI 2503.14744

- Also seen in Frequentist analyses

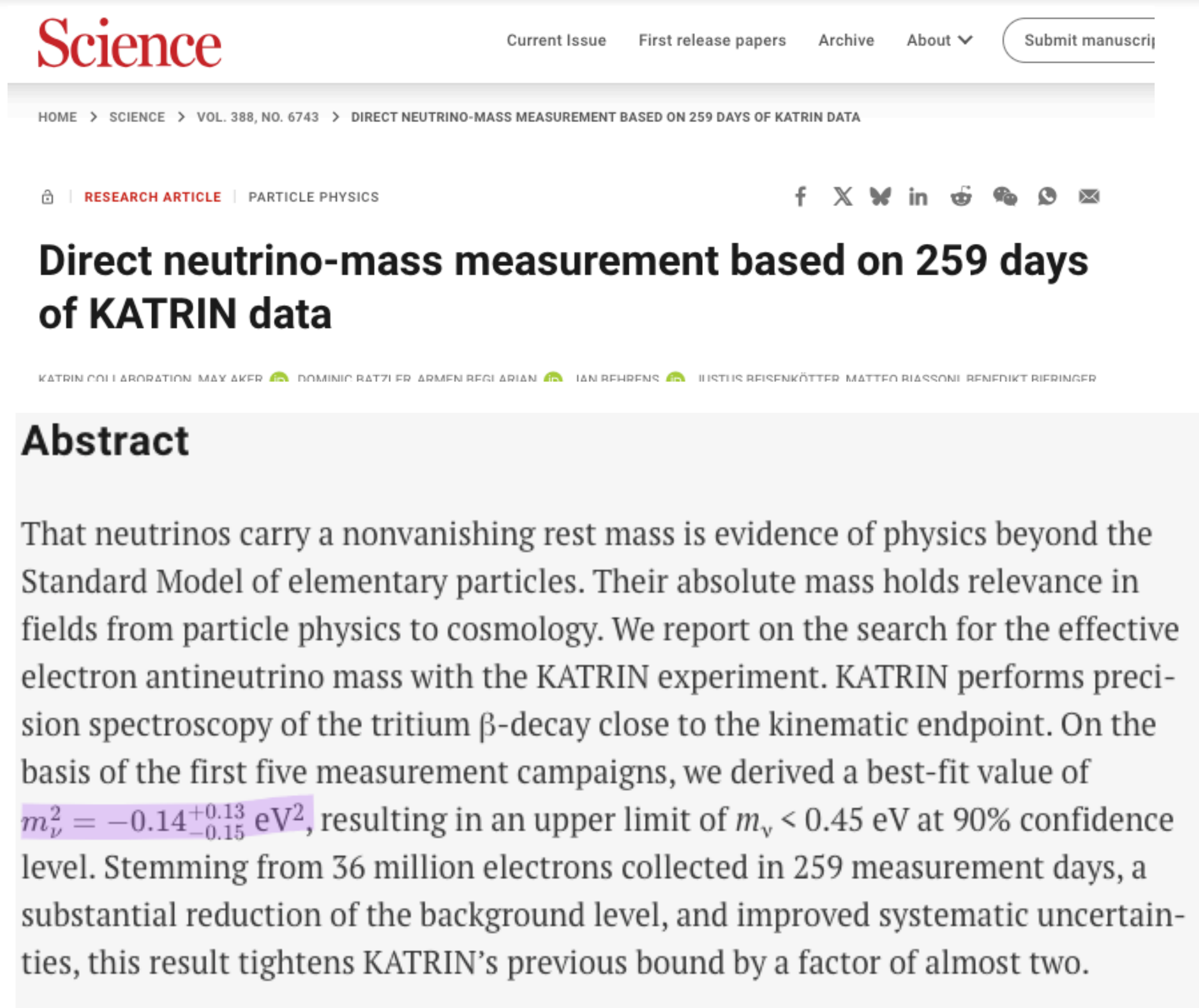


DESI 2503.14744



Naredo-Tuero (VP)++ 2407.13831

A statistical fluke?



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RESEARCH ARTICLE | PARTICLE PHYSICS

Direct neutrino-mass measurement based on 259 days of KATRIN data

KATRIN COLLABORATION, MAX AKER, DOMINIC BATZLER, ARMEN BEGLARIAN, JAN BEHRENS, JUSTUS BEISENKÖTTER, MATTEO BIASSONI, BENEDIKT BIERINGER

Abstract

That neutrinos carry a nonvanishing rest mass is evidence of physics beyond the Standard Model of elementary particles. Their absolute mass holds relevance in fields from particle physics to cosmology. We report on the search for the effective electron antineutrino mass with the KATRIN experiment. KATRIN performs precision spectroscopy of the tritium β-decay close to the kinematic endpoint. On the basis of the first five measurement campaigns, we derived a best-fit value of $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$, resulting in an upper limit of $m_\nu < 0.45$ eV at 90% confidence level. Stemming from 36 million electrons collected in 259 measurement days, a substantial reduction of the background level, and improved systematic uncertainties, this result tightens KATRIN's previous bound by a factor of almost two.

- Within Katrin, it is attributed to under fluctuations compatible with statistical fluke
- There are two main reasons driving this preference in CMB data, both still compatible with fluke

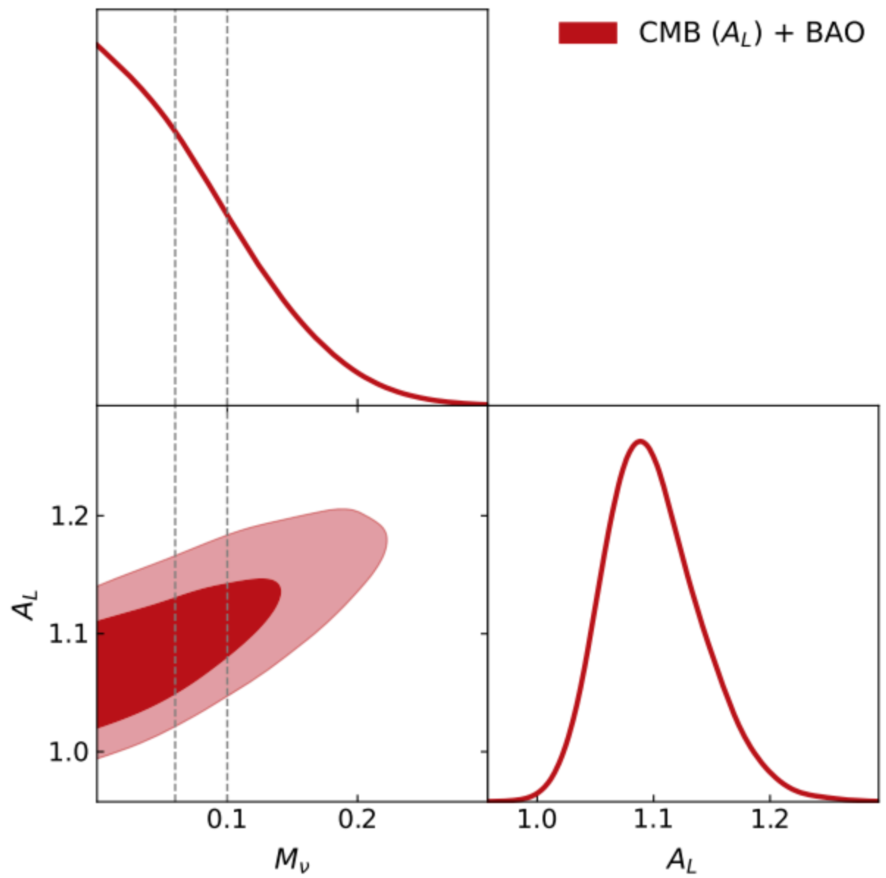
$m_\nu < 0$ is due to a "lensing anomaly" in Planck

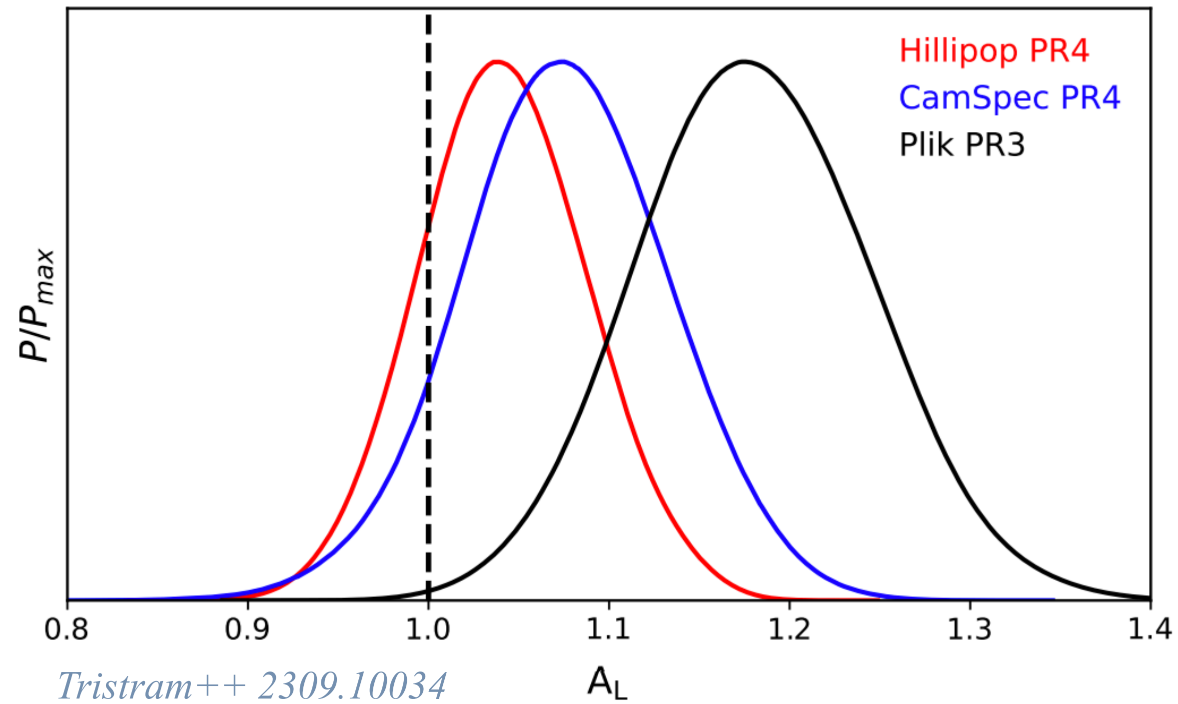
- Planck 2018 has an anomalous amount of lensing

$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}, \quad A_L = 1.180 \pm 0.065$$

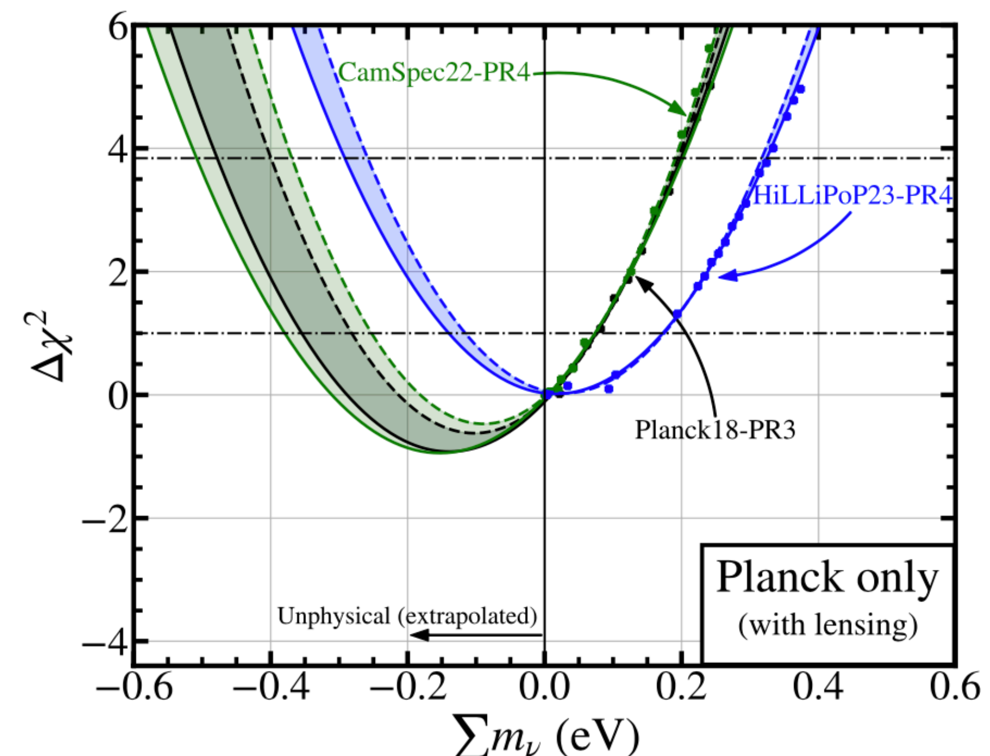
- This anomaly went down with PR4

$$A_L = 1.039 \pm 0.052$$





Tristram++ 2309.10034



Naredo-Tuero (VP)++ 2407.13831

- The preference for $m_\nu < 0$ goes away when using a newer version *Planck* data (NPIPE)

The role of the optical depth τ

- The amplitude is correlated with the optical depth to reionization τ

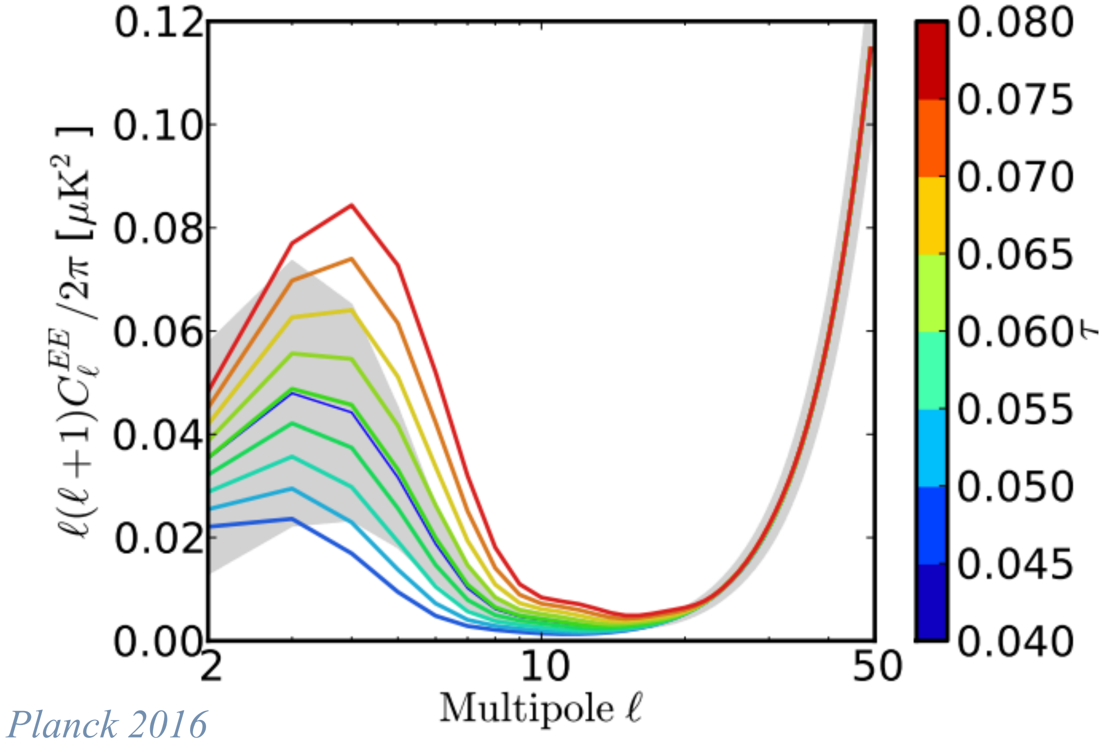
$$C_\ell \propto A_s \exp(-2\tau)$$

- The low-ℓ EE spectrum constrains

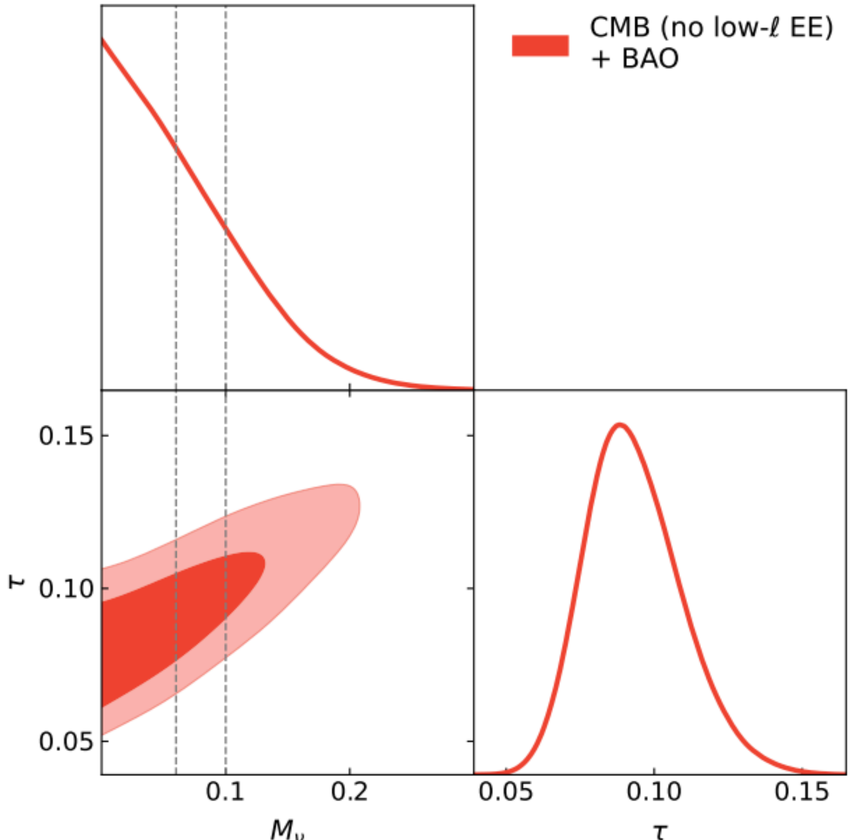
$$\tau = 0.0592 \pm 0.0062$$

- Without low$-\ell$ EE information,

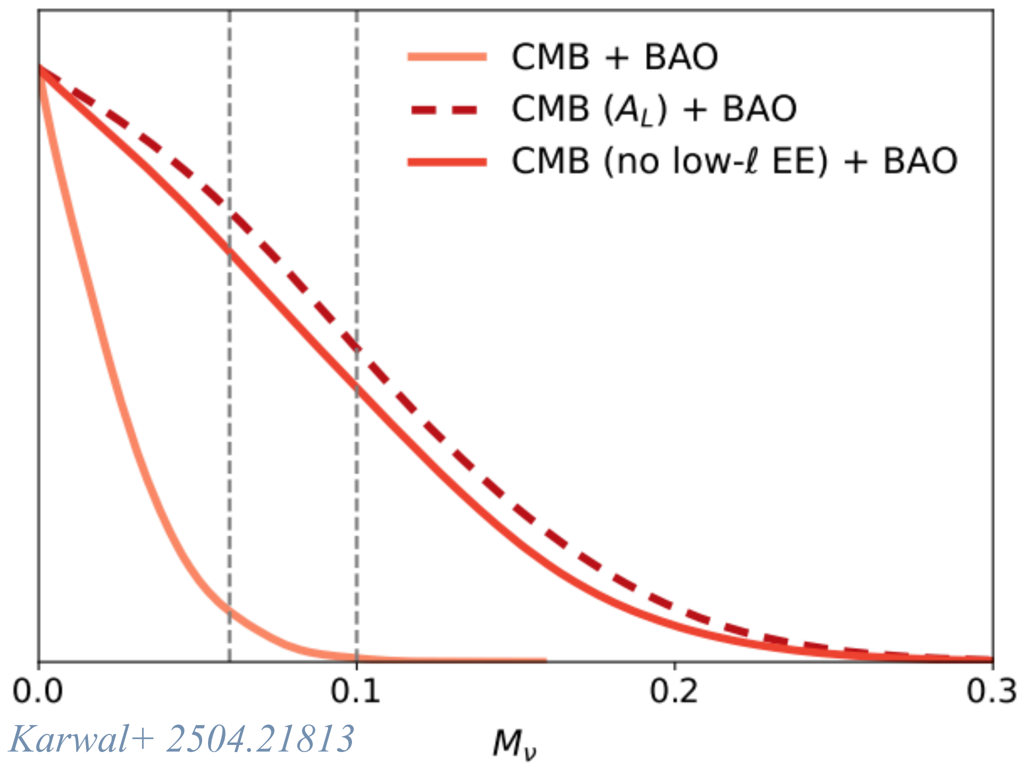
$$\tau = 0.09 \pm 0.012\,, \quad \sum m_\nu < 0.2 \text{ eV}$$



Planck 2016

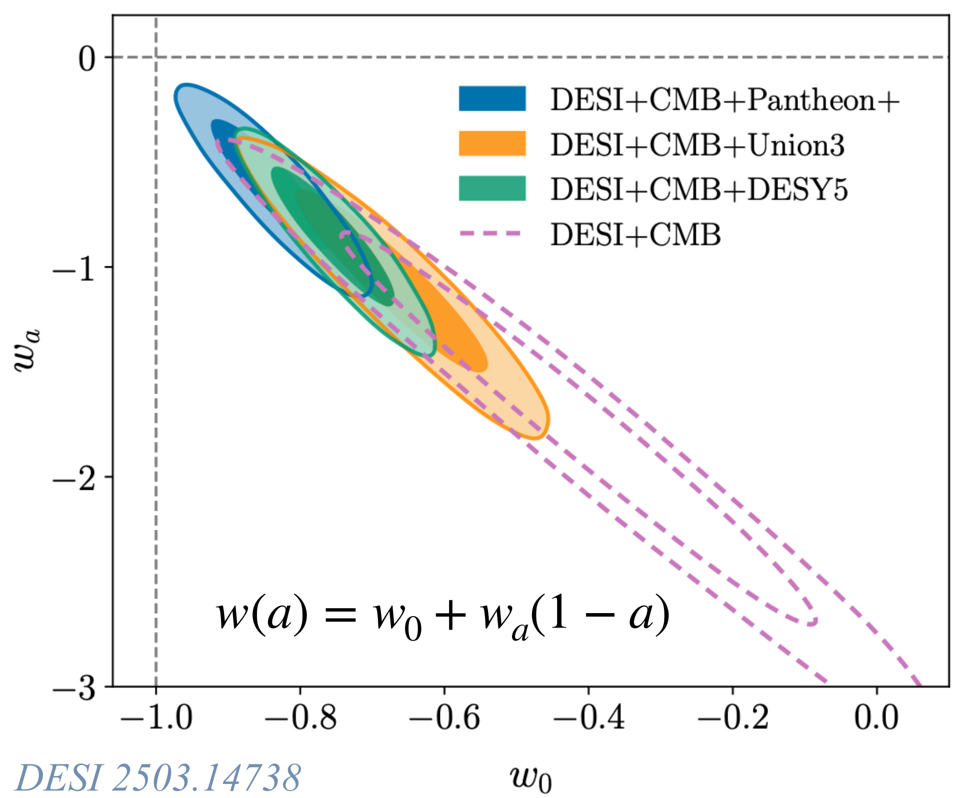


Karwal+ 2504.21813

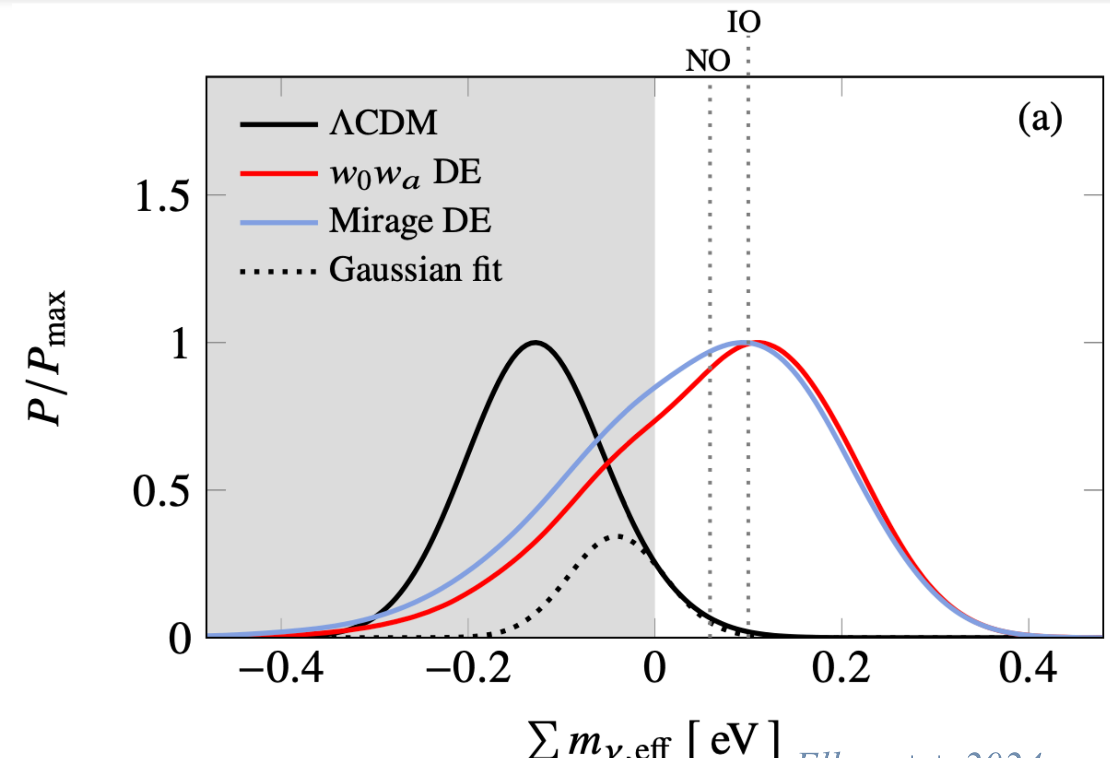


Karwal+ 2504.21813

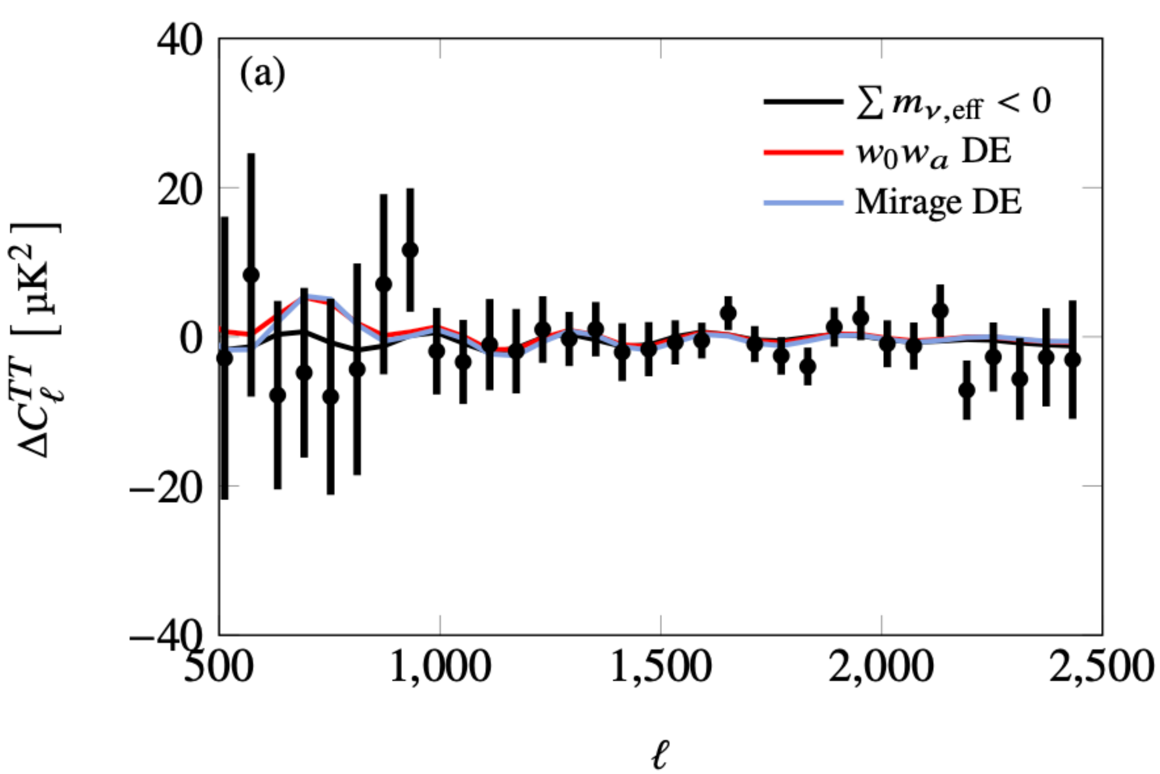
m_ν is degenerate with the effect of dark energy

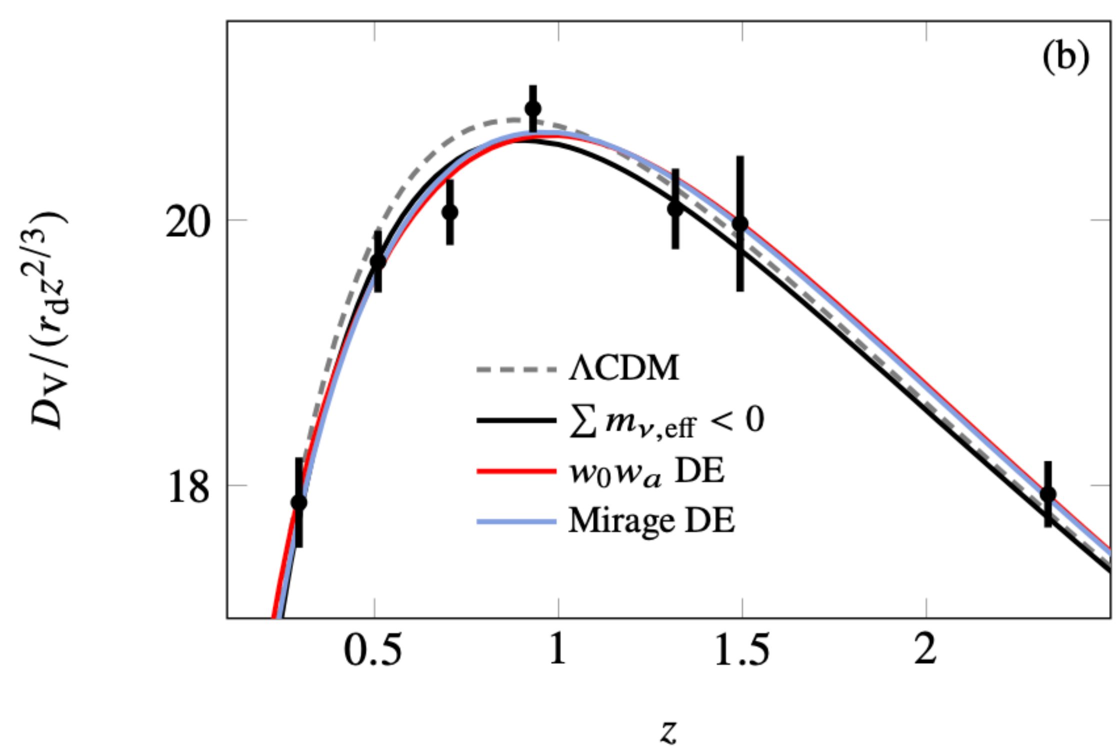


DESI 2503.14738



Elbers++ 2024





Summary of neutrino mass bounds

DESI 2503.14744, 2504.18464

- Despite anomalies, it is hard to get rid of the neutrino mass bound from cosmology

Flat ΛCDM (3 deg ν's)

Planck+DESI $\sum m_\nu < 0.064$ eV

Planck+ ACT +DESI $\sum m_\nu < 0.06$ eV

P+ ACT +SPT +DESI $\sum m_\nu < 0.048$ eV

$w_0 w_a$CDM (3 deg ν's)

Planck+DESI $\sum m_\nu < 0.163$ eV

Planck+ ACT +DESI $\sum m_\nu < 0.152$ eV

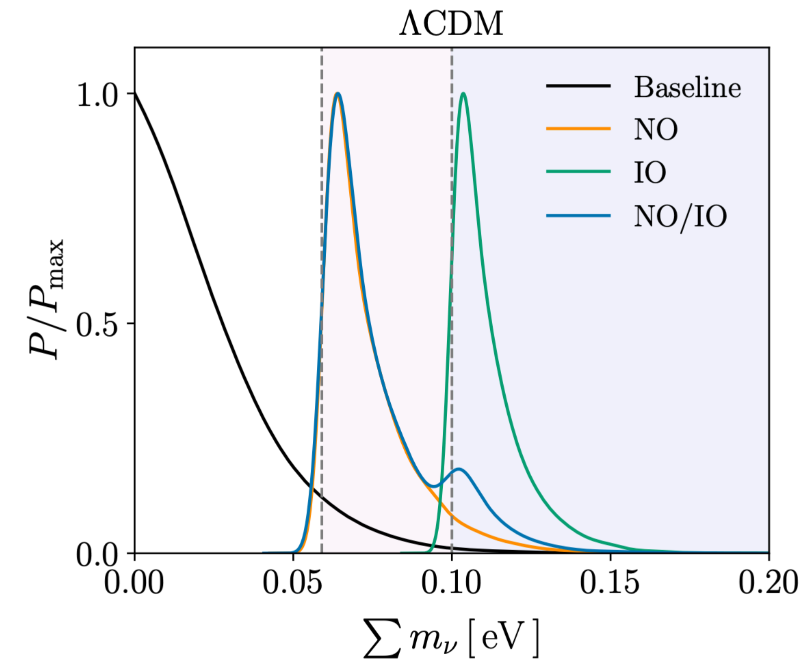
Planck+ ACT + SN1a $\sum m_\nu <$ 0.117-0.139 eV

- Enforcing neutrino mass ordering leads to a preference for NO over IO at 10 : 1

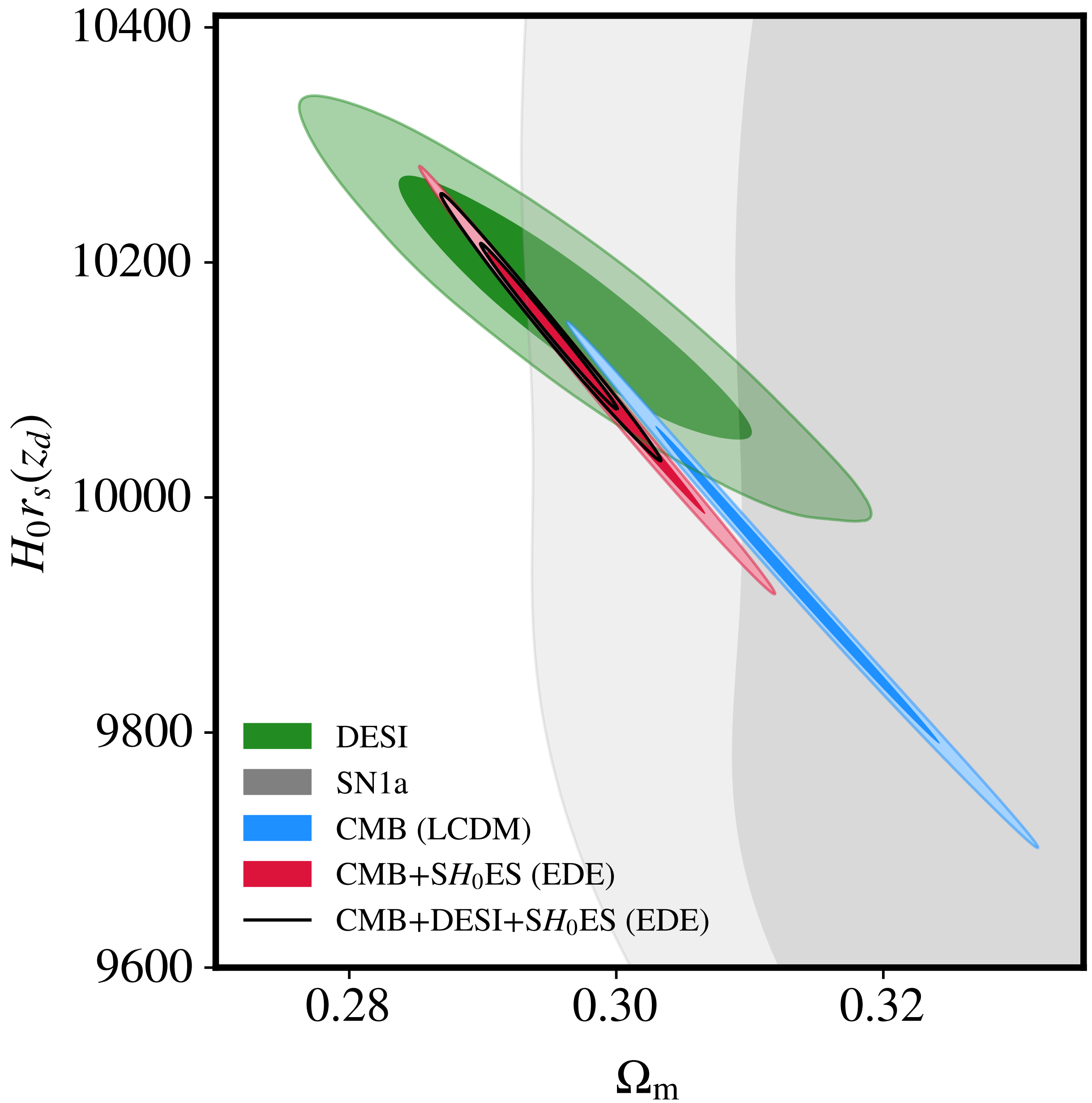
Planck + DESI + NuFIT6.0 (ΛCDM)

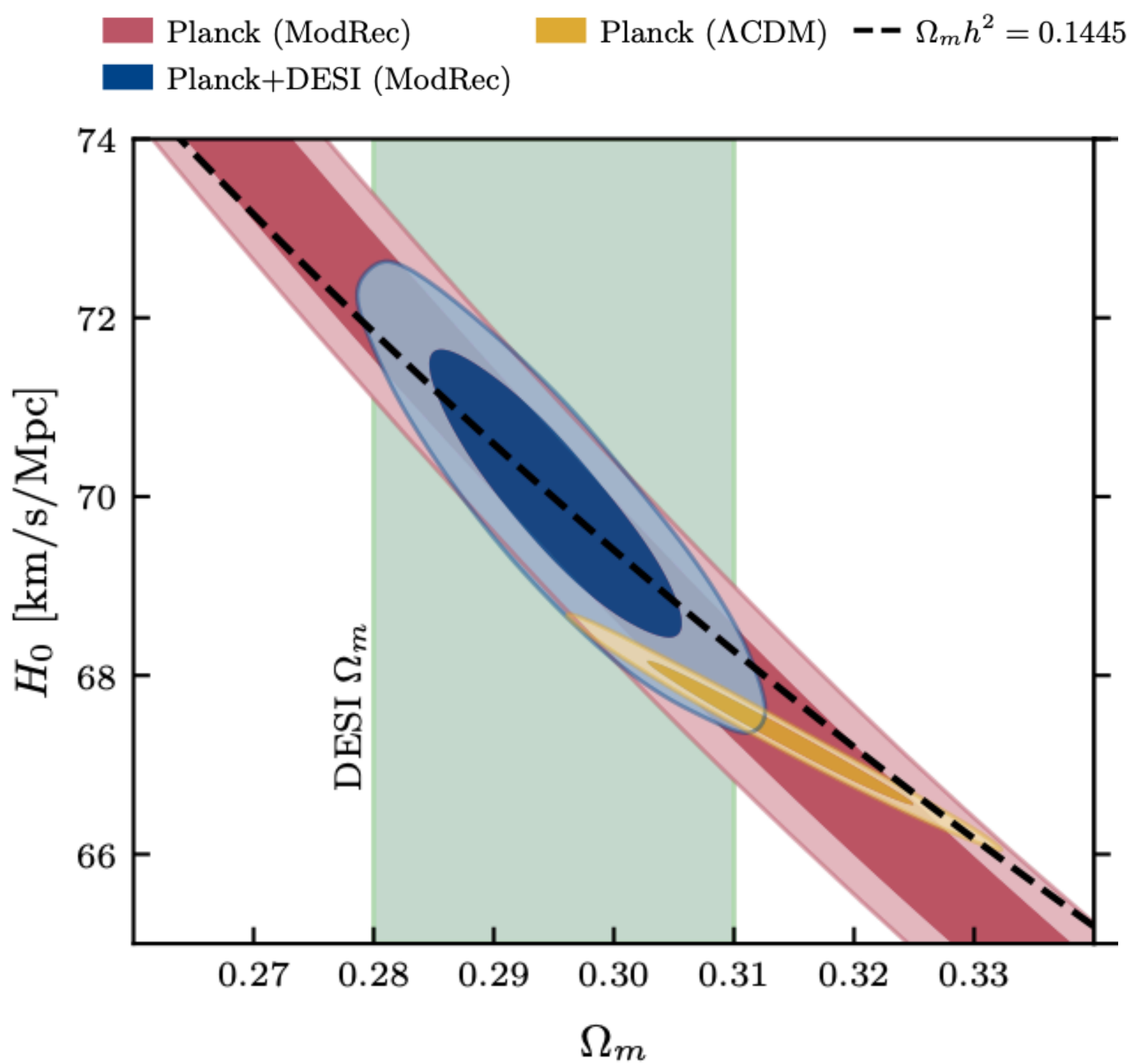
NO $\sum m_\nu < 0.101$ eV $\Rightarrow m_l < 0.023$ eV

IO $\sum m_\nu < 0.133$ eV $\Rightarrow m_l < 0.024$ eV



Early universe solution to the BAO tension

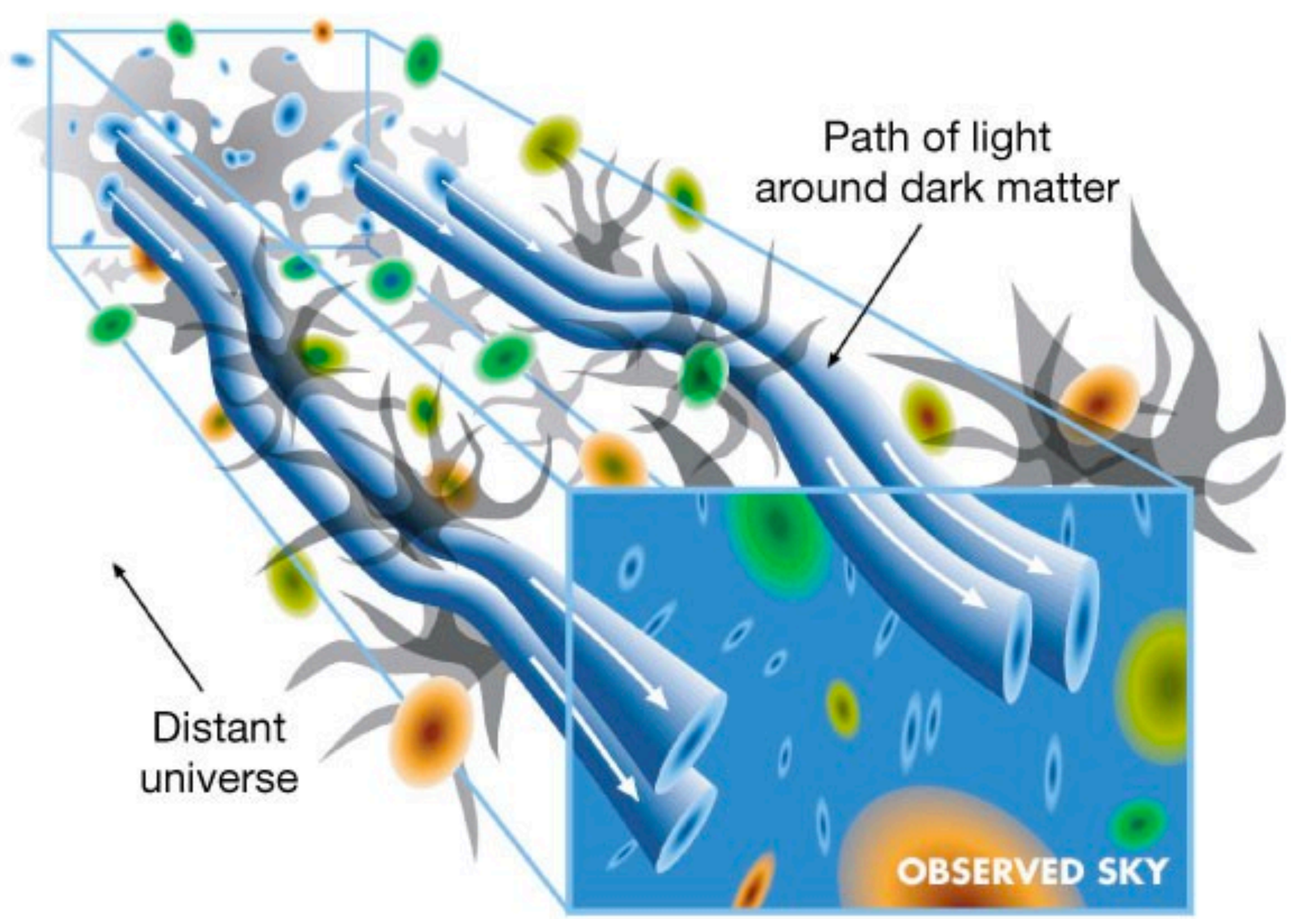


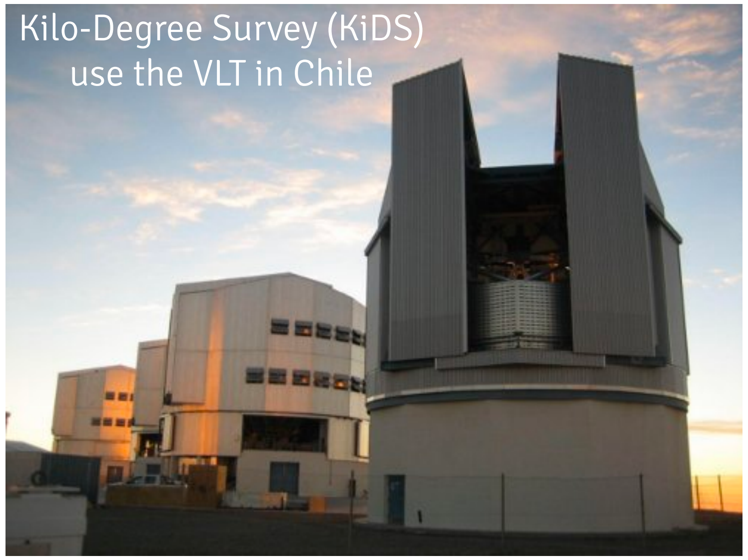


- Early universe solution can reduce $H_0 r_d$ and Ω_m
- An alternative explanation to DESI results? *Lynch&Chluba 2406.10202, Chaussidon++ 2503.24343*

Galaxy weak lensing

- “Weak gravitational lensing” observations measure the distortions in the shape of galaxies

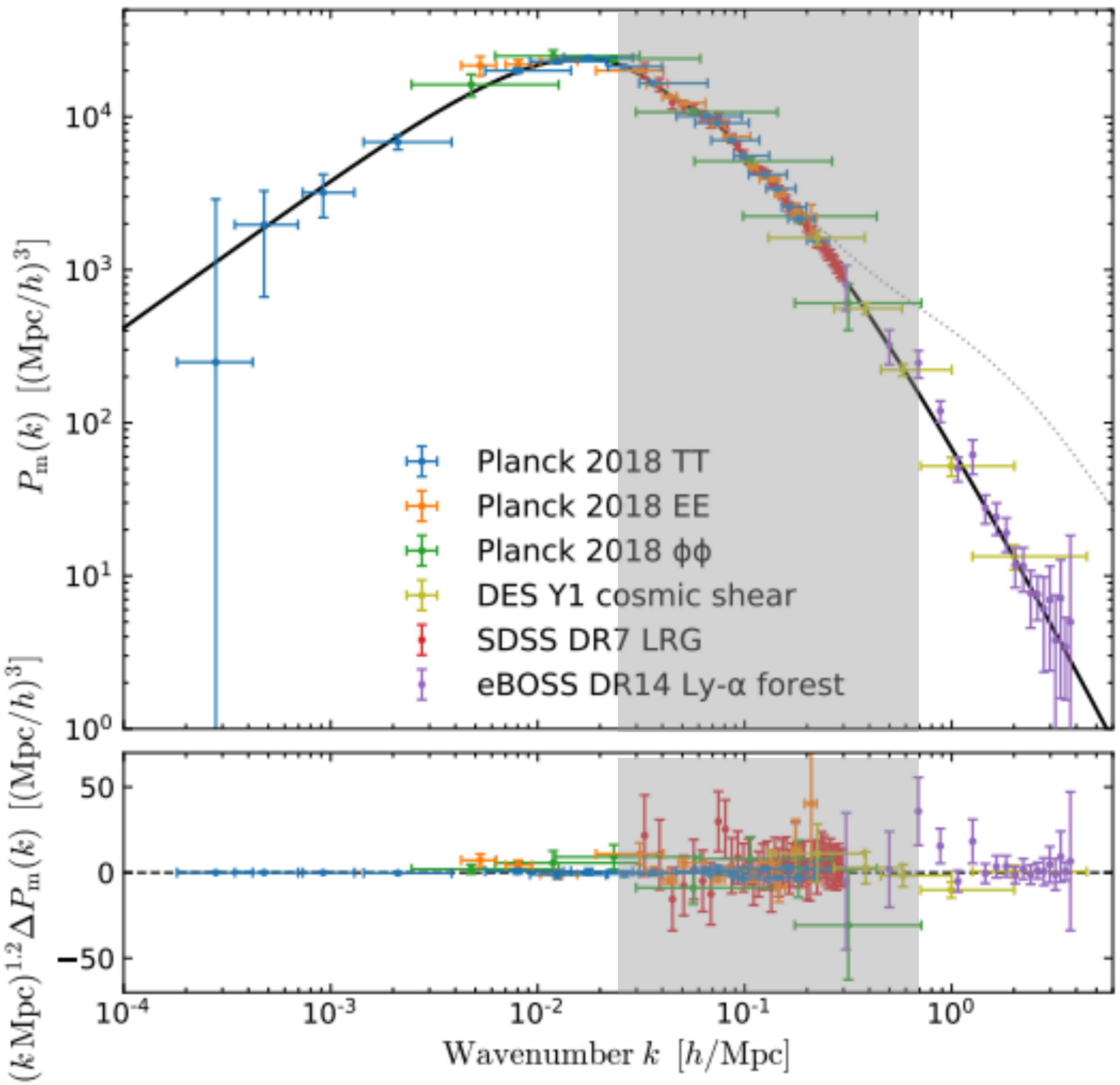




- There are three main WL observatory: DES, KiDS and HSC (Hawaii)
- New: Euclid!

The S_8 parameter

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



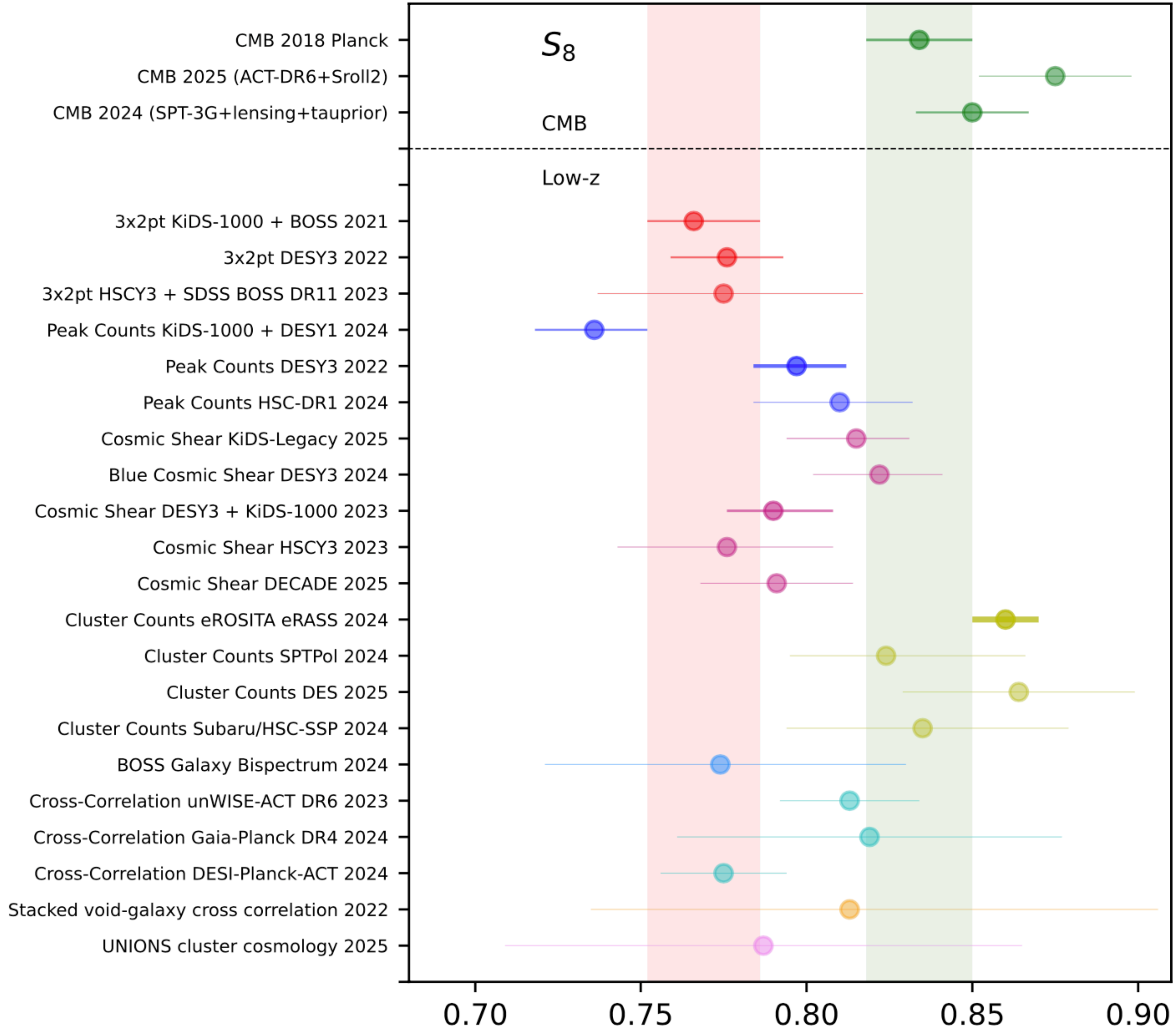
Chabanier 1905.08103

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

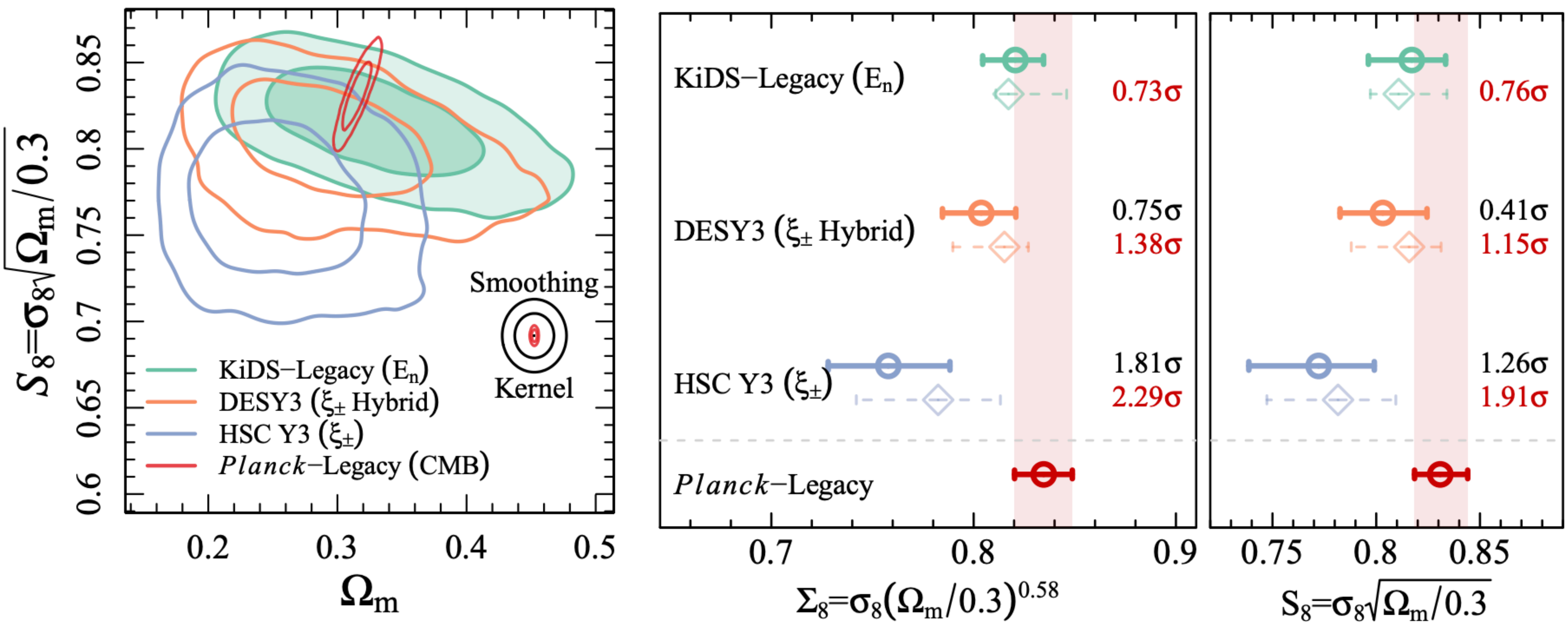
$$\sigma_8^2 = \int_0^\infty \frac{k^3}{2\pi^2} P_{\rm lin}(k) W^2(kR) d\ln k$$

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

The S8 tension

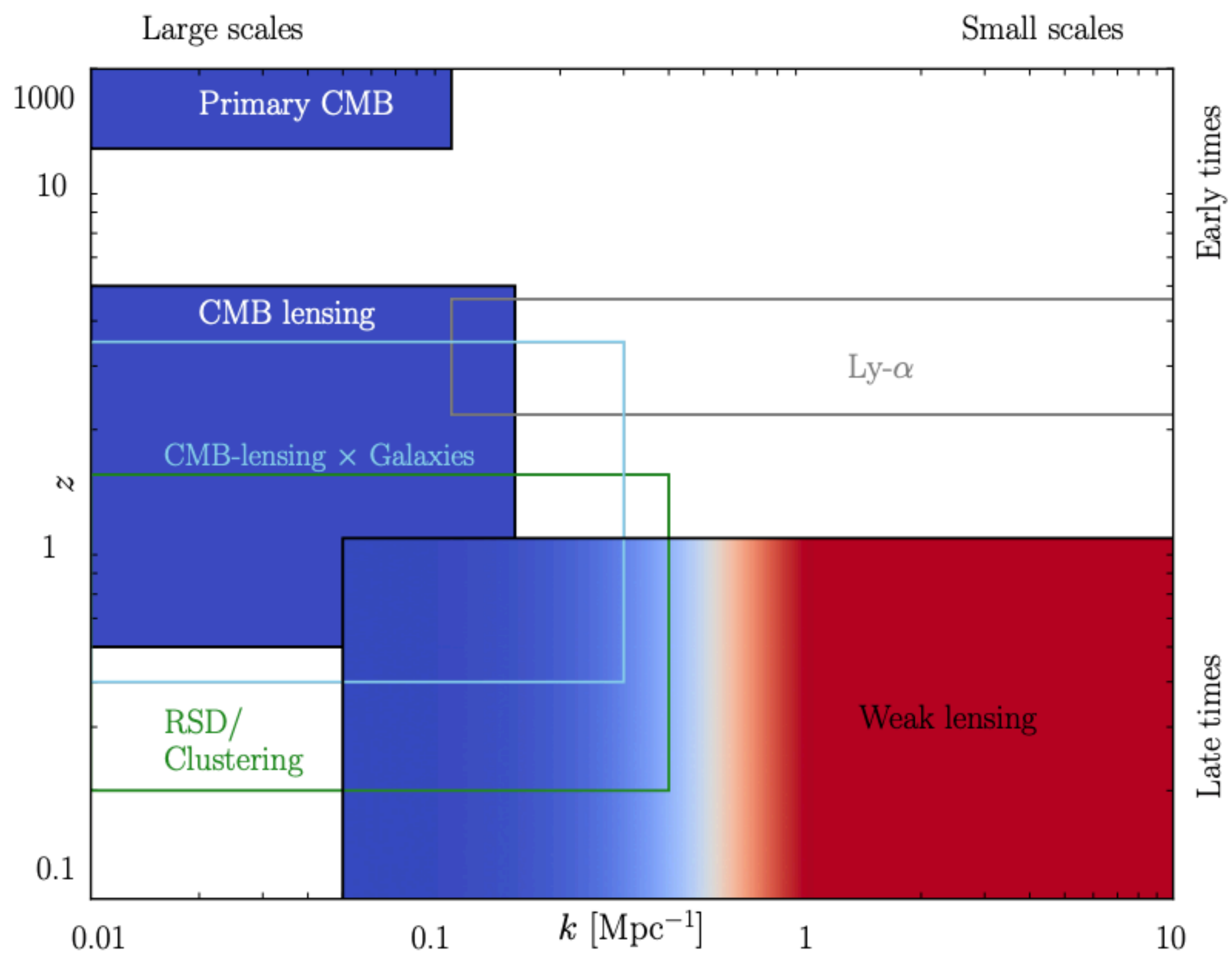


The S_8 tension revisited



- Latest results from KIDS Legacy: improved redshift calibration has resolved the tension

The general picture: what do we know about P(k,z)?



Preston++ 2305.09827

Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

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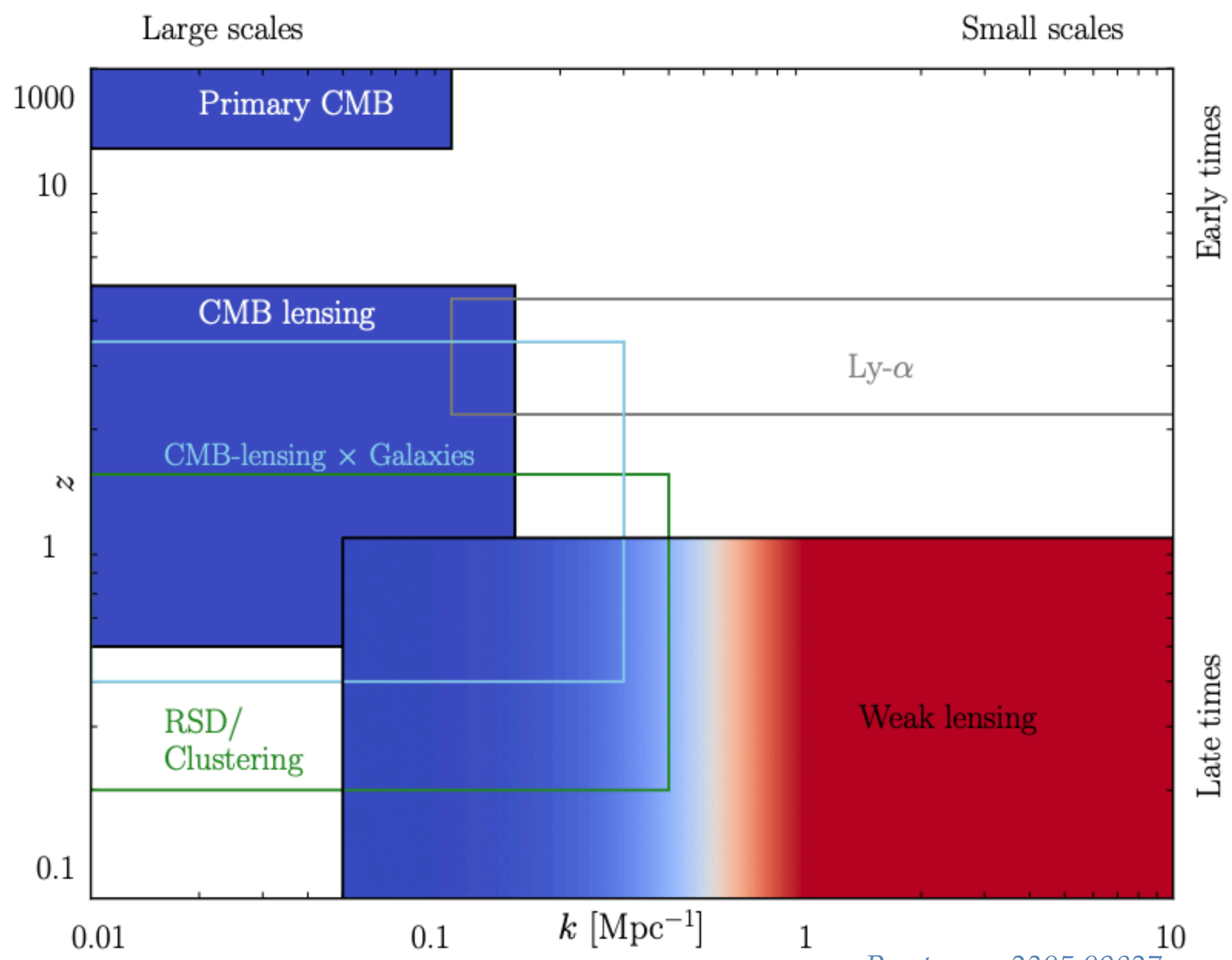


Preston++ 2305.09827

- 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 $^{-1}$

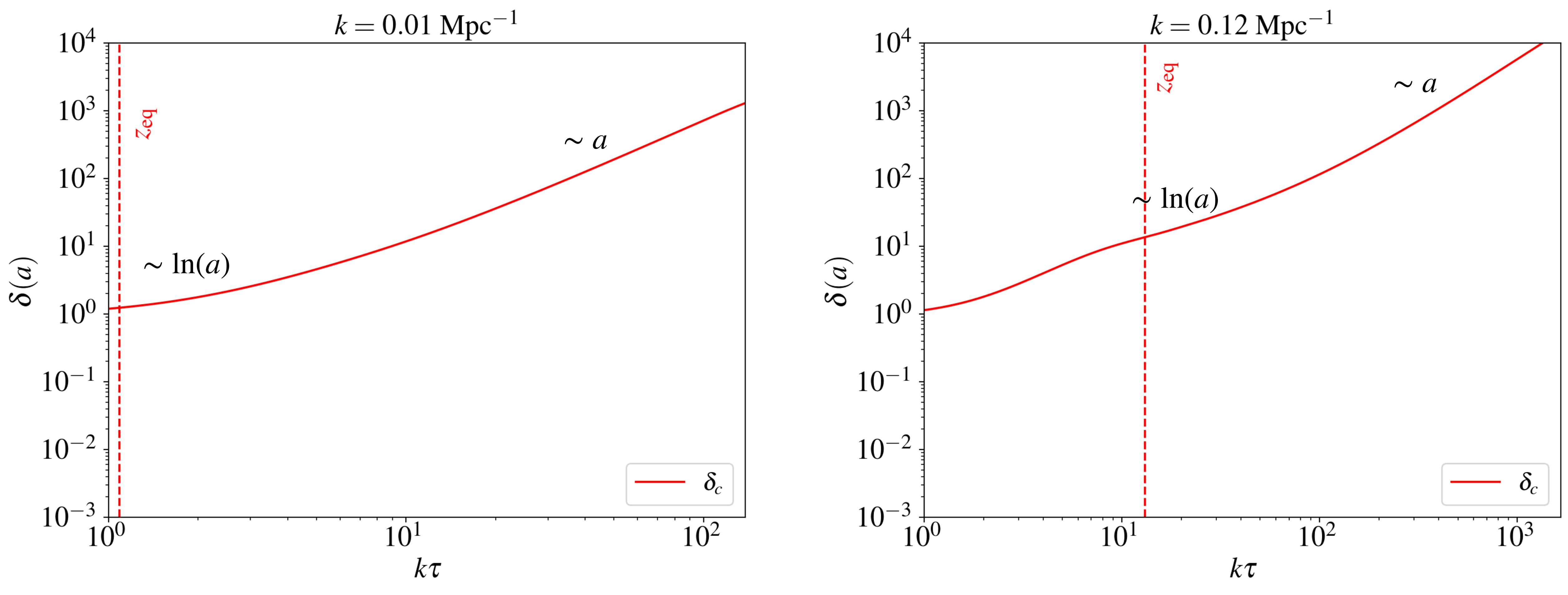
Goldstein++ 2303.00746 , K. Rogers & VP 2311.16377

The growth of CDM density perturbations

- Continuity & Euler equations for CDM perturbations (synchronous gauge):

$$\delta_c' = -\theta_c - \frac{1}{2}h', \qquad \theta_c' = -\frac{a'}{a}\theta_c \qquad \delta \equiv \delta\rho/\rho, \;\; \theta \equiv kv \equiv 0$$

- For pressure-less, collision-less fluid: within the horizon, scale-independent growth.



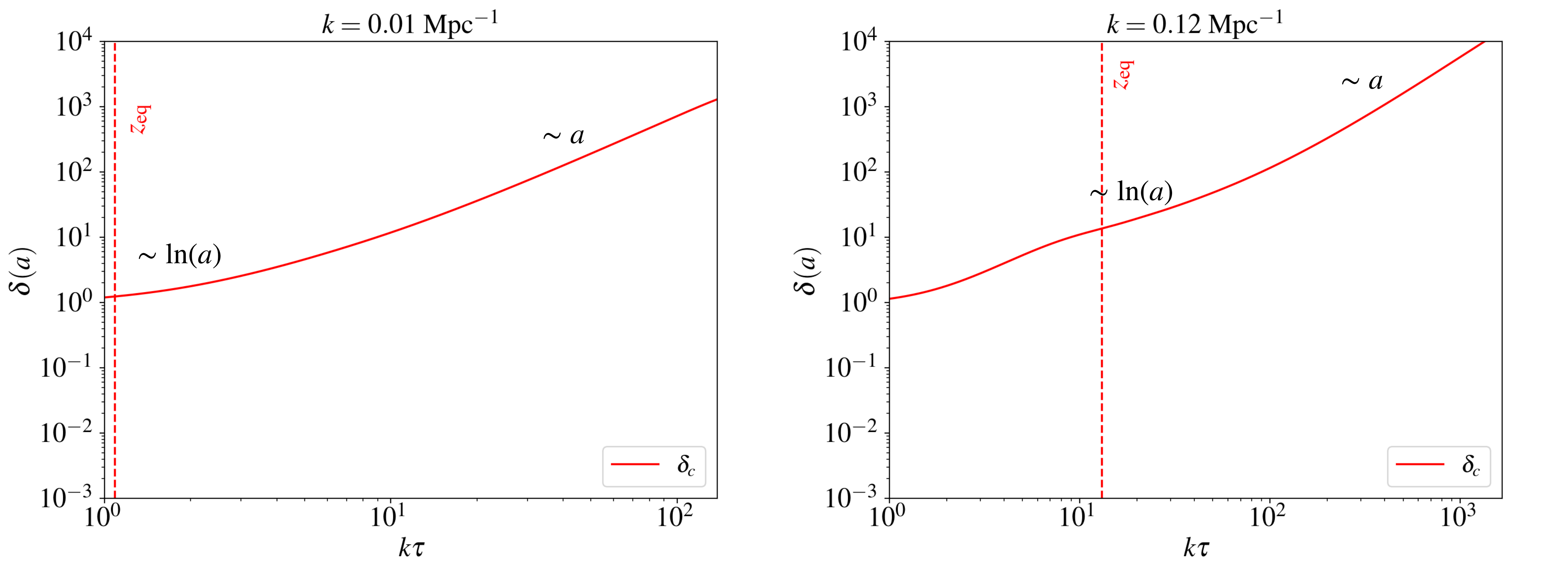
How to decrease power at small scales

- If non-zero pressure: $w = \frac{p}{\rho}$, $c_a^2 = \frac{p'}{\rho'}$, $c_s^2 = \frac{\delta p}{\delta \rho}$ can be non-zero

$$\delta'_{\rm ncdm} = -(1+w)\left(\theta_{\rm ncdm} - \frac{1}{2}h'\right) - 3\frac{a'}{a}(c_s^2 - w)\delta_{\rm ncdm}, \quad \theta'_{\rm ncdm} = -\frac{a'}{a}(1-3c_a^2)\theta_{\rm ncdm} + \frac{c_s^2}{1+w} - k^2\sigma_{\rm ncdm}$$

- One can write a formal equation driving the growth of perturbation on small scales:

$$k\tau \gg 1 \Rightarrow \qquad \delta''_{\rm ncdm} + \frac{a'}{a}\delta'_{\rm ncdm} + (k^2 - k_J^2)c_s^2\delta_{\rm ncdm} = 0 \qquad k_J \equiv \sqrt{\frac{3(a'/a)}{c_s^2}}$$



The case of neutrinos

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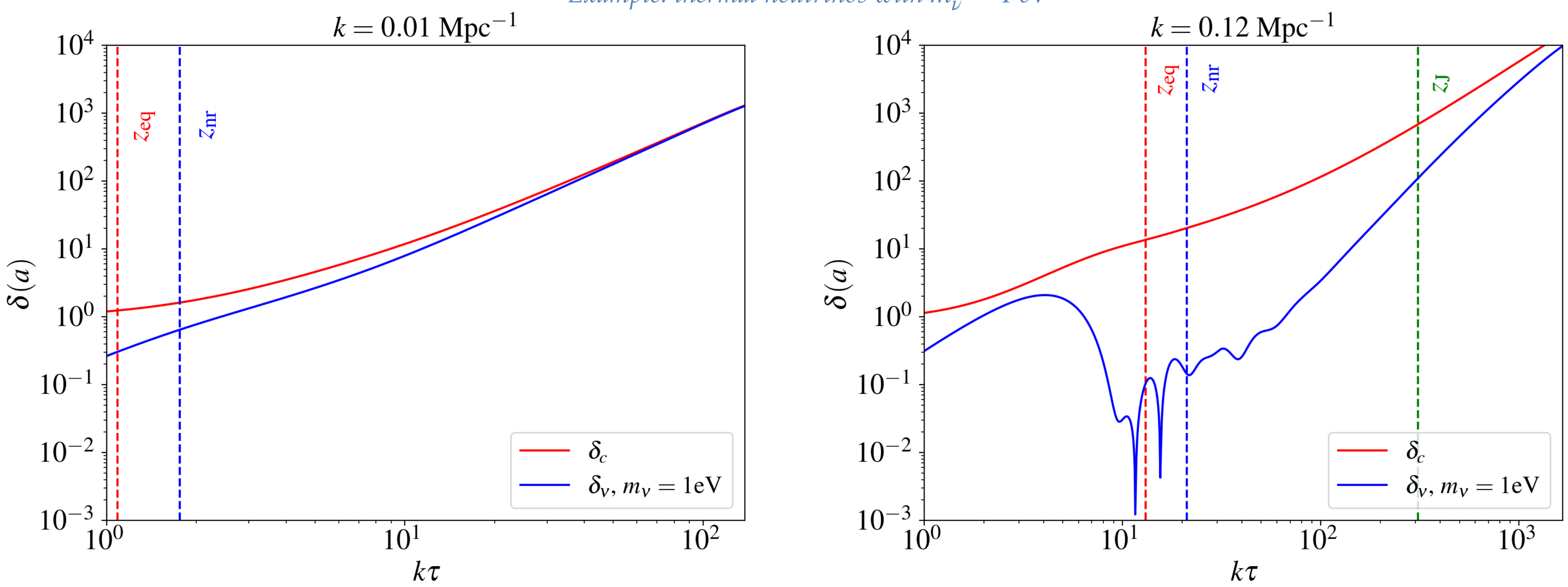
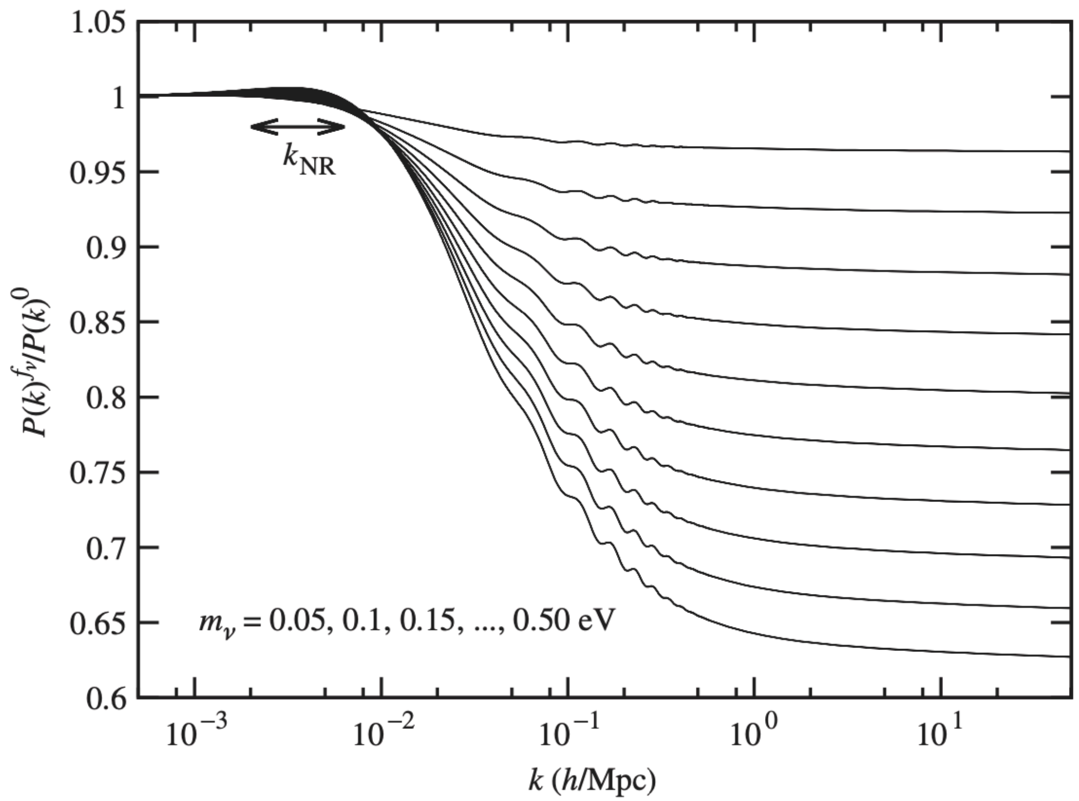
Example: thermal neutrinos with $m_\nu = 1$ eV



Could ν's explain the S_8 tension?

Power suppression: $k \geq k_{nr} \equiv 0.01 \left(\frac{m_\nu}{1\text{eV}}\right)^{1/2} \left(\frac{\Omega_m}{0.3}\right)^{1/2} h\text{Mpc}^{-1}$ with amplitude $\frac{\Delta P}{P} \simeq -8\frac{\omega_\nu}{\omega_m}$

Need $\sum m_\nu \sim 0.2$ eV to explain S_8



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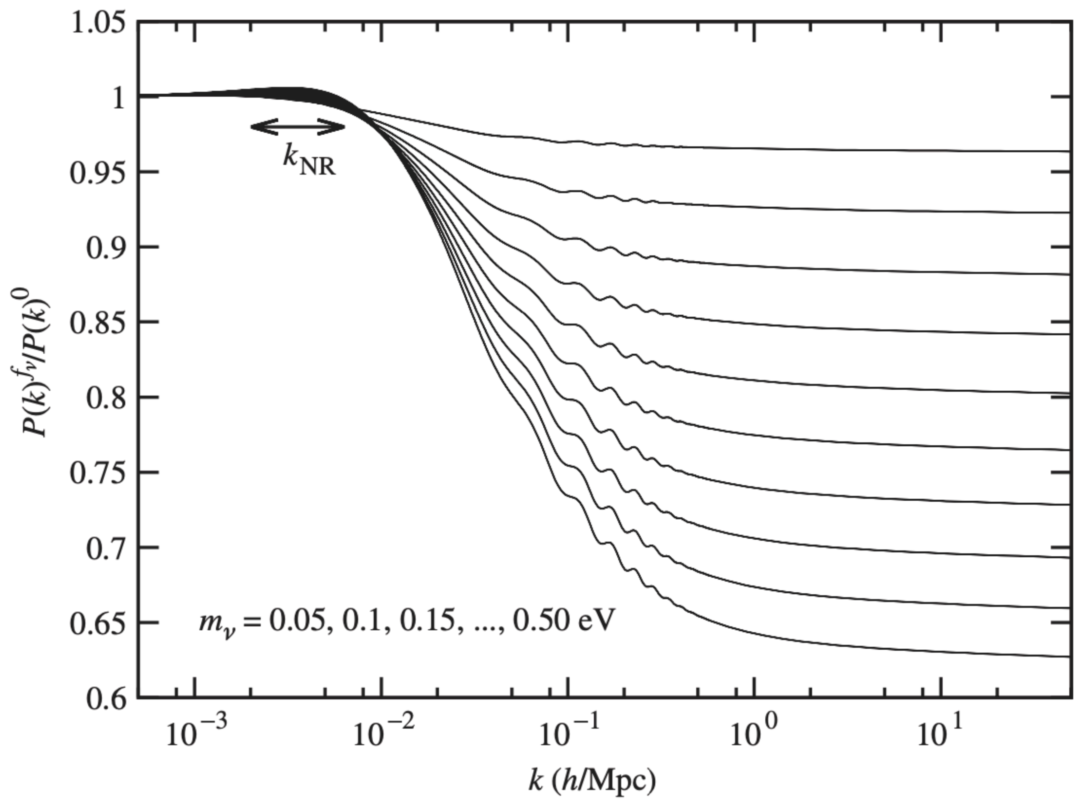
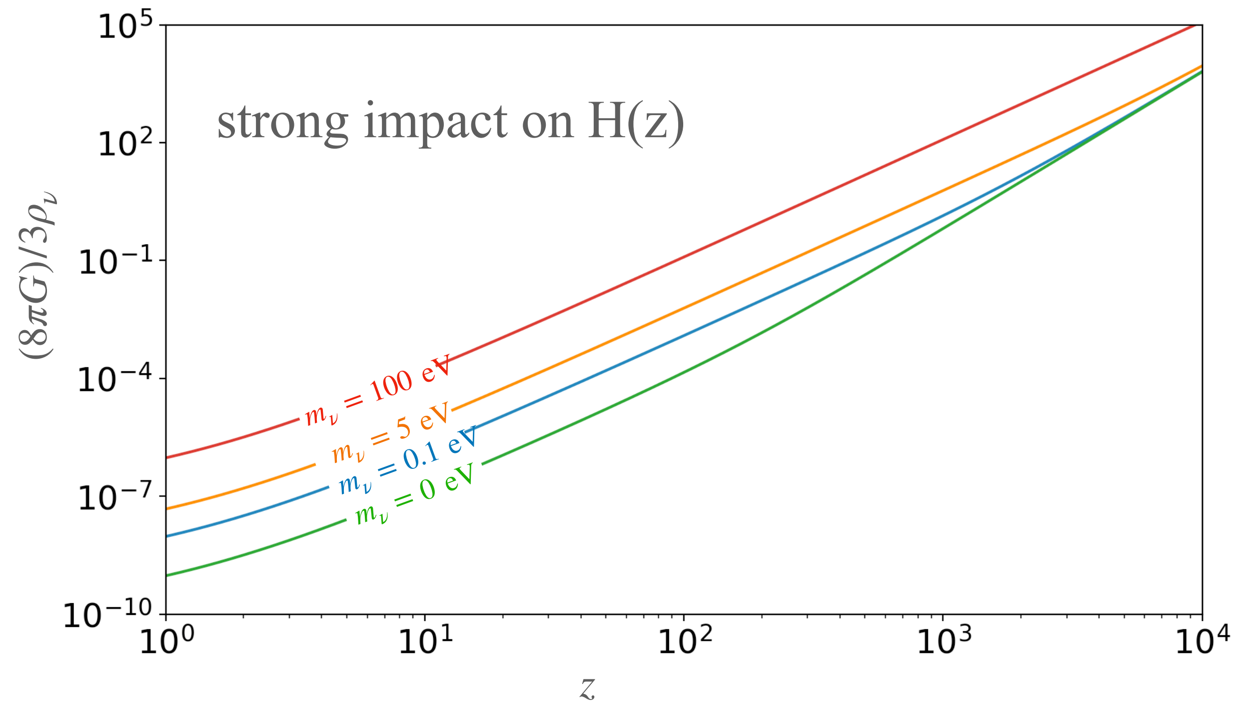
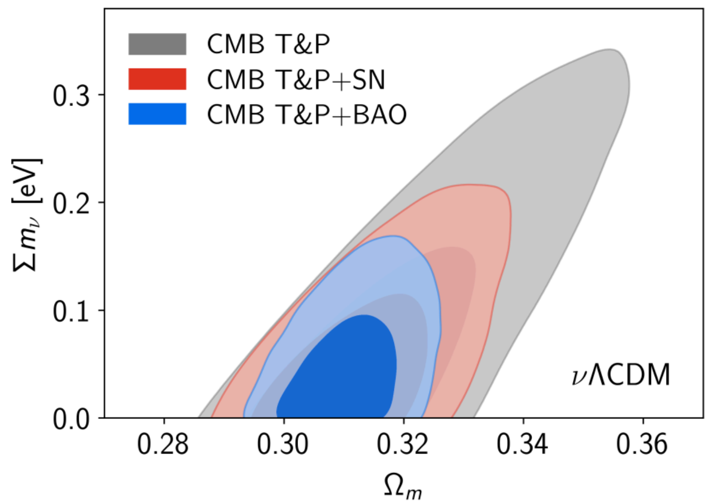




Planck 2018 + BAO < 0.12eV

Planck 1807.06205



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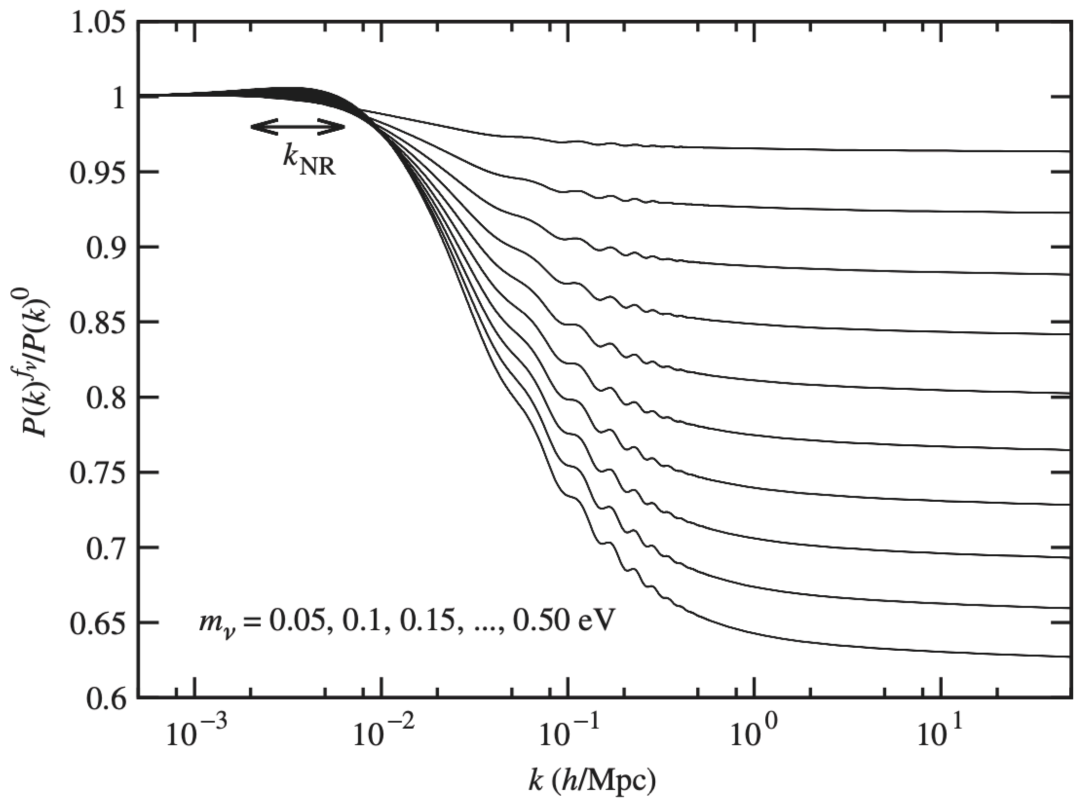
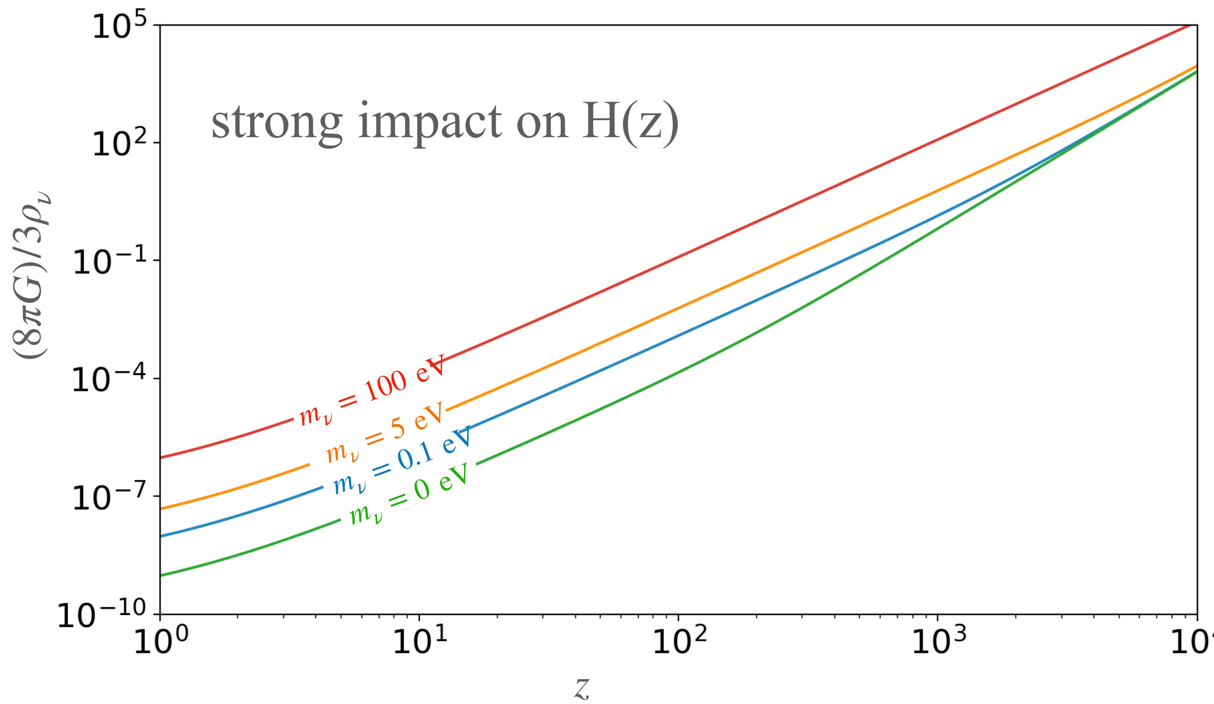




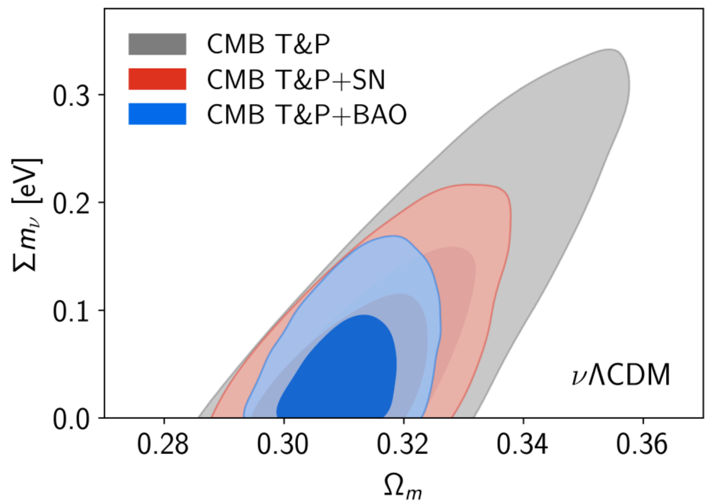
Planck 2018 + BAO < 0.12eV *Planck 1807.06205*

Planck 2018 + BAO + Ly$-\alpha$ < 0.089eV

Palanque-Delabrouille++ 1911.09073

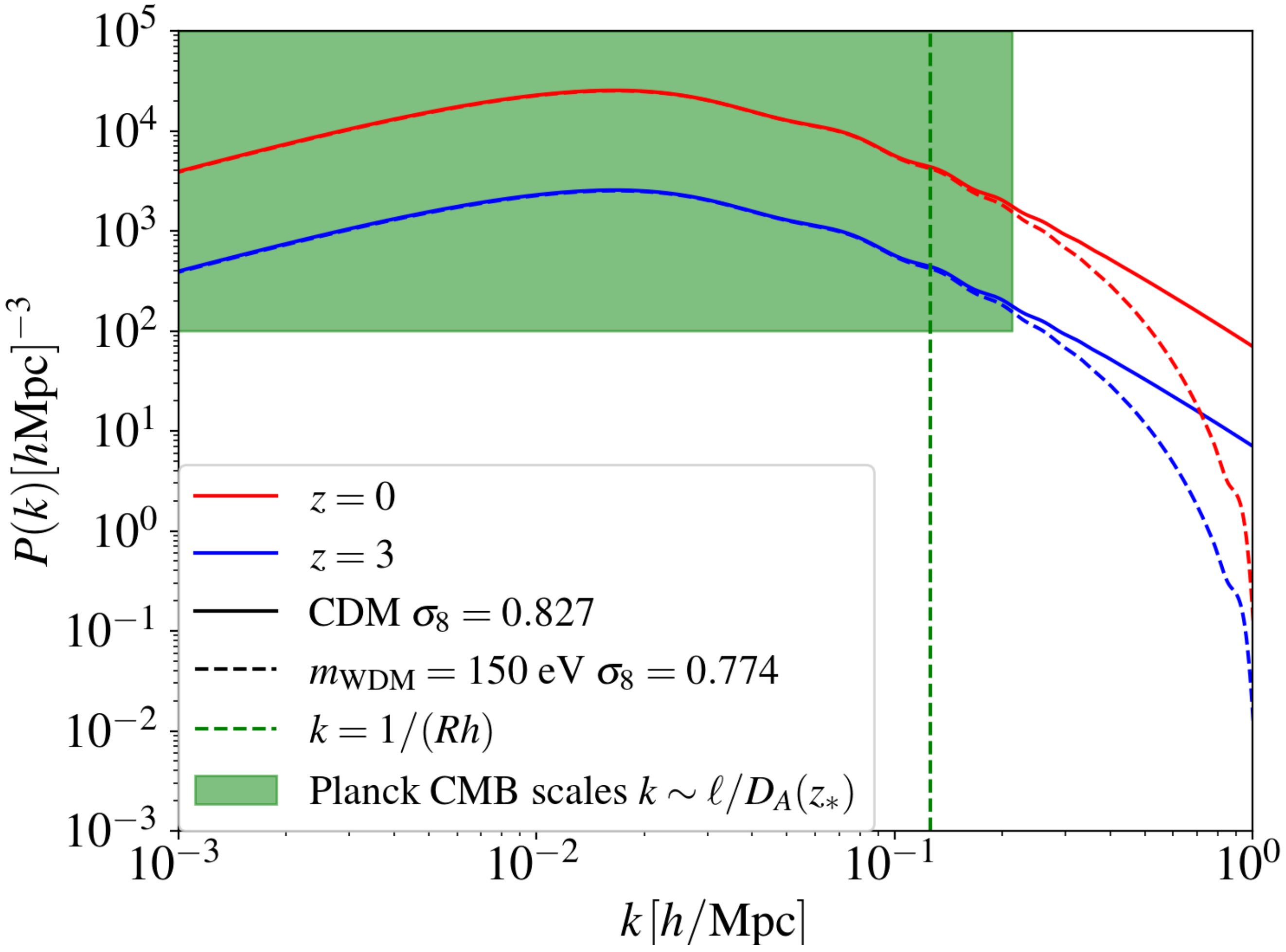
Planck 2018 + BOSS + eBOSS < 0.082eV

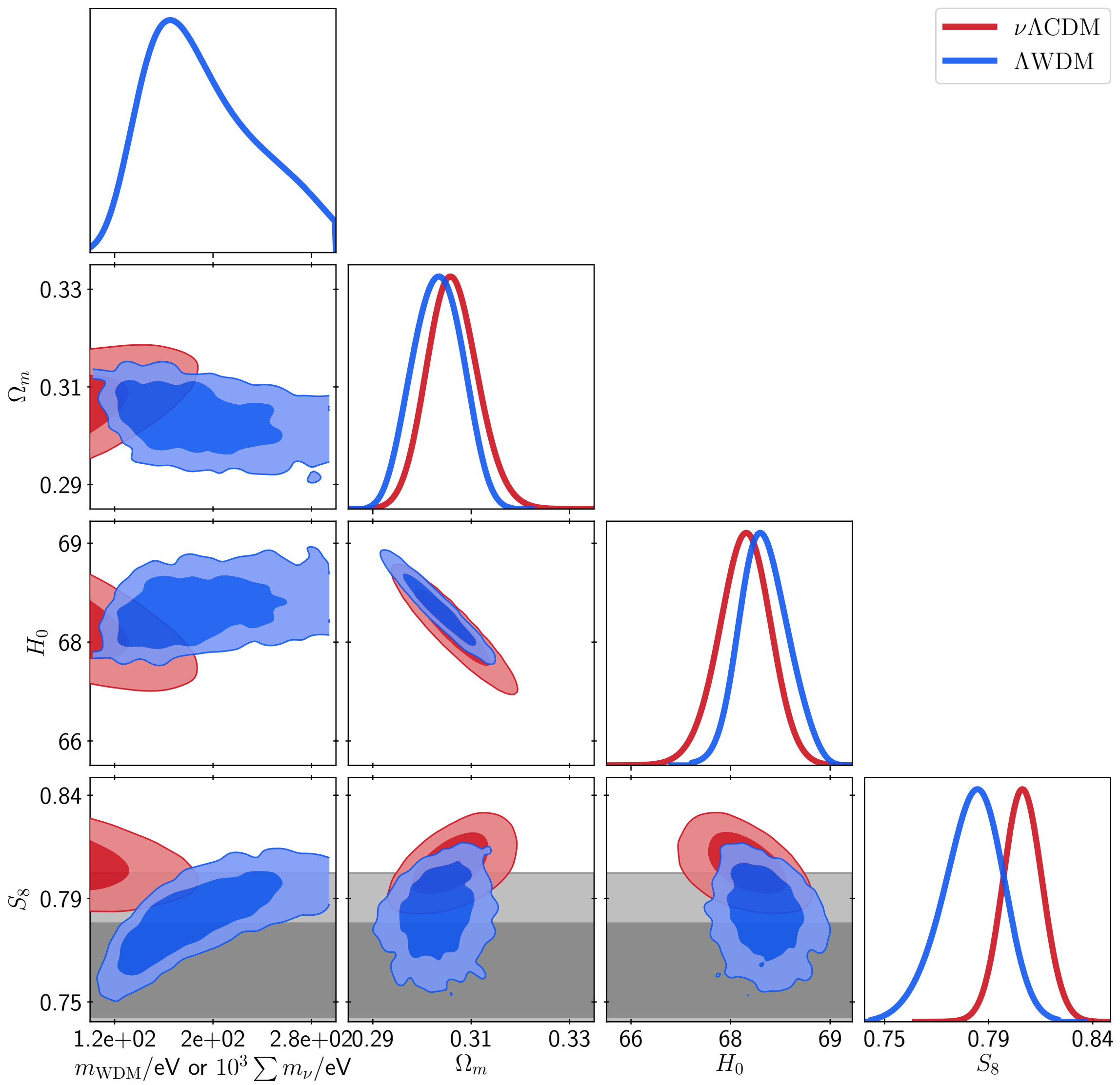
Brieden++ 2204.11868, Simon++ 2210.14931



The case of warm dark matter

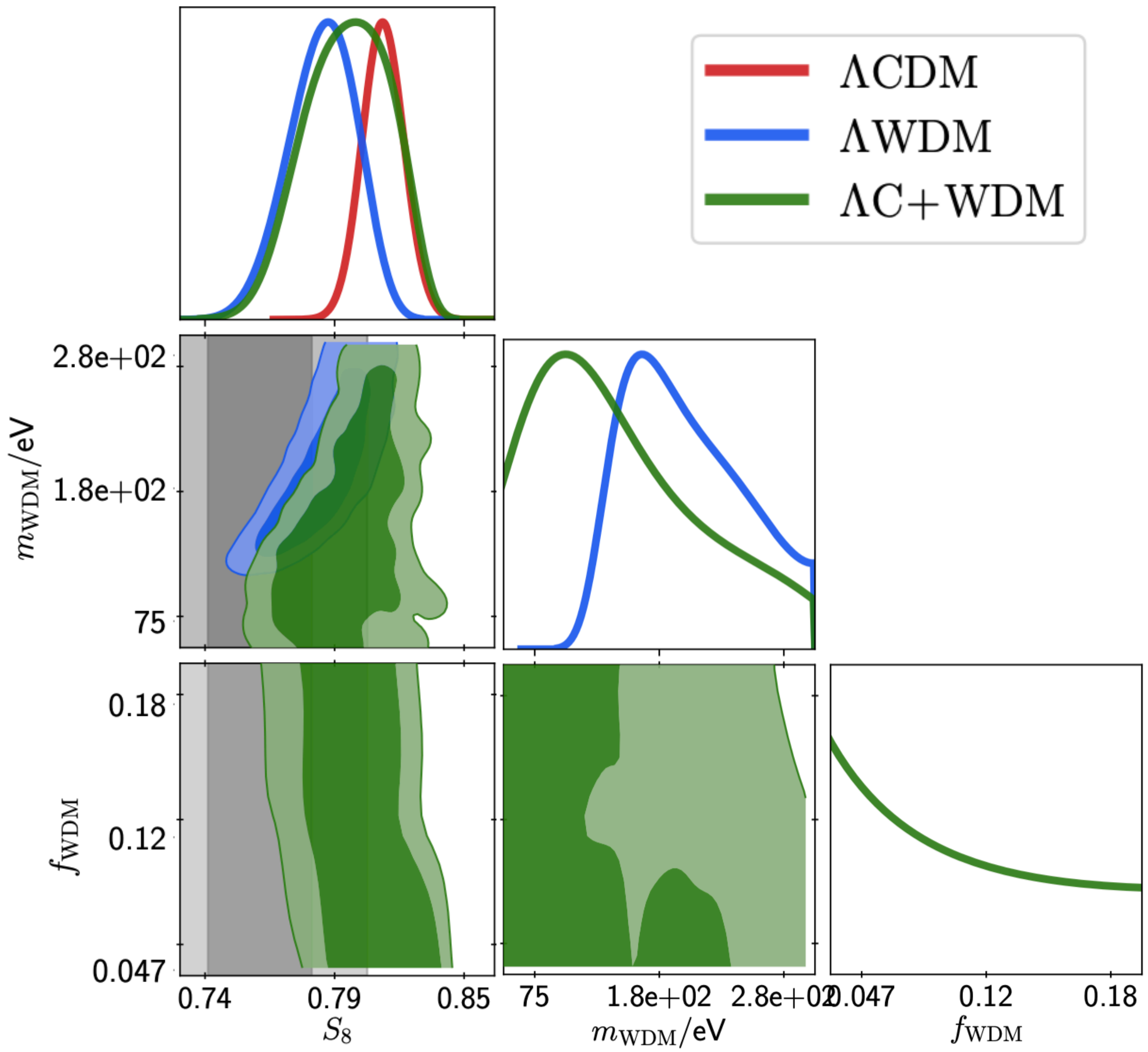
- For WDM: suppression at $k \geq k_{\rm FS} \sim 5\ {\rm Mpc}^{-1}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)\left(\frac{T_\nu}{T_{\rm WDM}}\right)$ *Viel++ astro-ph/0501562*
- Requiring $k_{\rm FS} \geq 0.1h/{\rm Mpc}$ and $\omega_{\rm ncdm} = \omega_{\rm cdm}$ leads to $m_{\rm WDM} \sim 100{\rm eV}$.



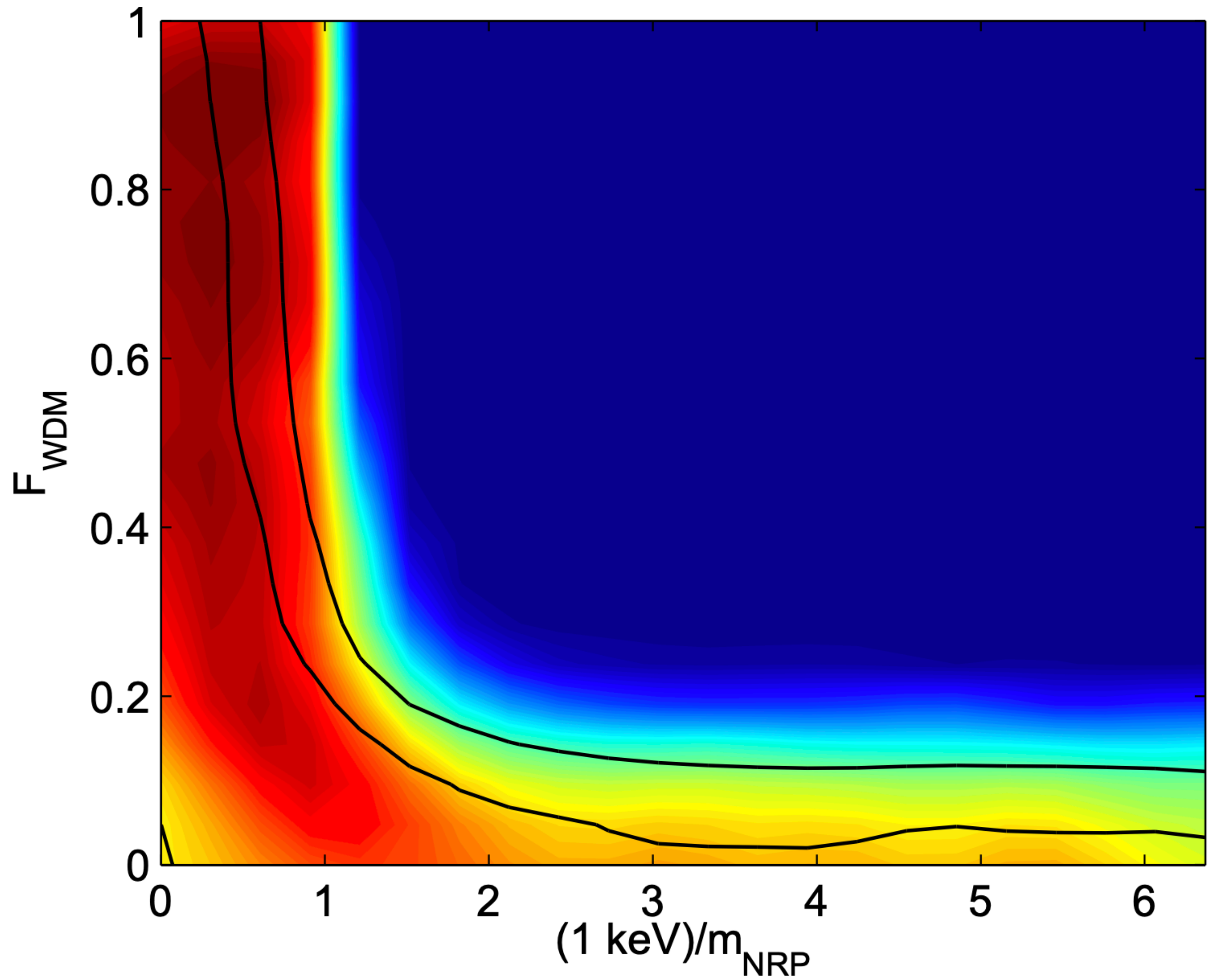


- CMB + BAO + S_8 $m_{\rm WDM} \simeq 192.2^{+31}_{-60}$ eV.
- Yet, exponential cutoff 'a la WDM' are excluded: $m_{\rm WDM} > 5$ keV. *Palanque-Delabrouille++ 1911.09073*

Fraction of Warm Dark Matter and S_8



Boyarski, Lesgourgues ++ 0812.0010



- A fraction of thermal WDM with $m \sim \mathcal{O}(100\text{eV})$ could explain low S_8: Ly-α restricts $f_{\rm WDM} \lesssim 0.2$

See also Gariazzo++ 1704.02991

- How to generate a fraction of WDM?
- Nb: similar results with fraction of fuzzy dark matter / tightly coupled fraction of DM

Chacko++ 1609.03569, Allali++ 2104.12798, Laguë++ 2104.07802

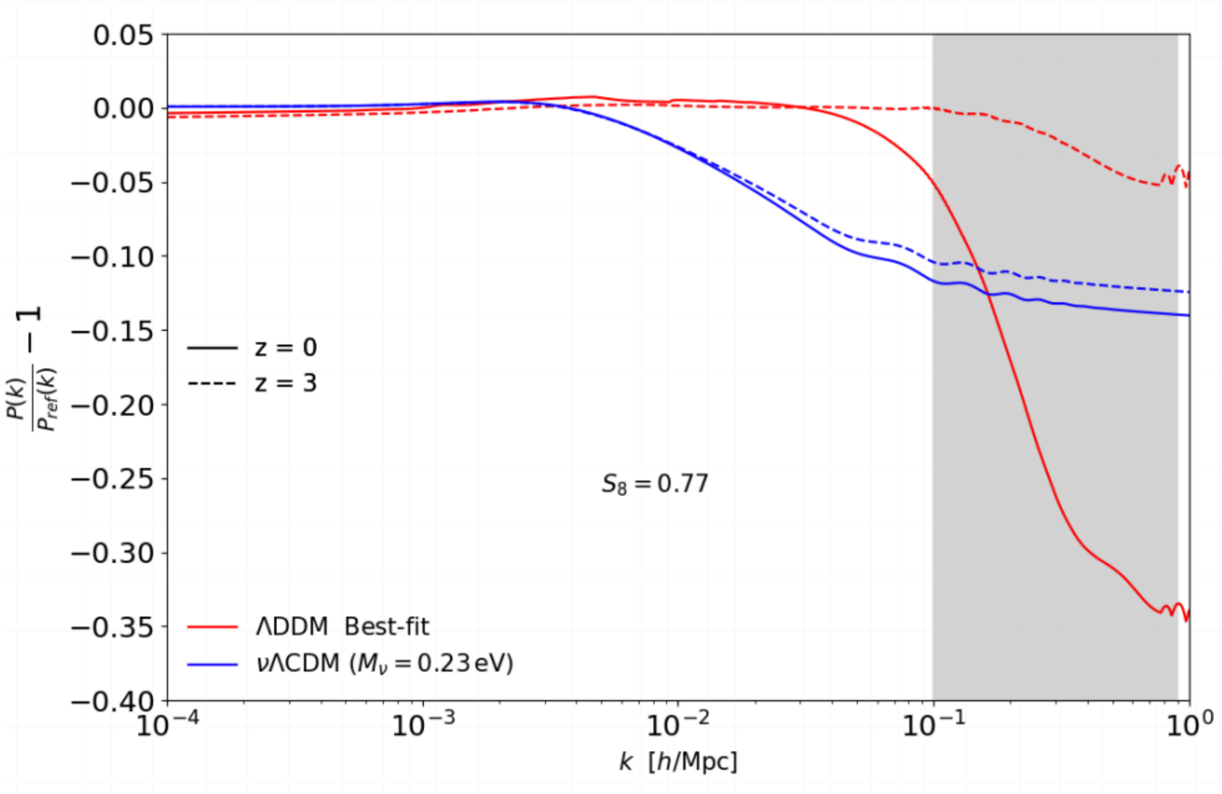
DM decays generate a late-time suppression

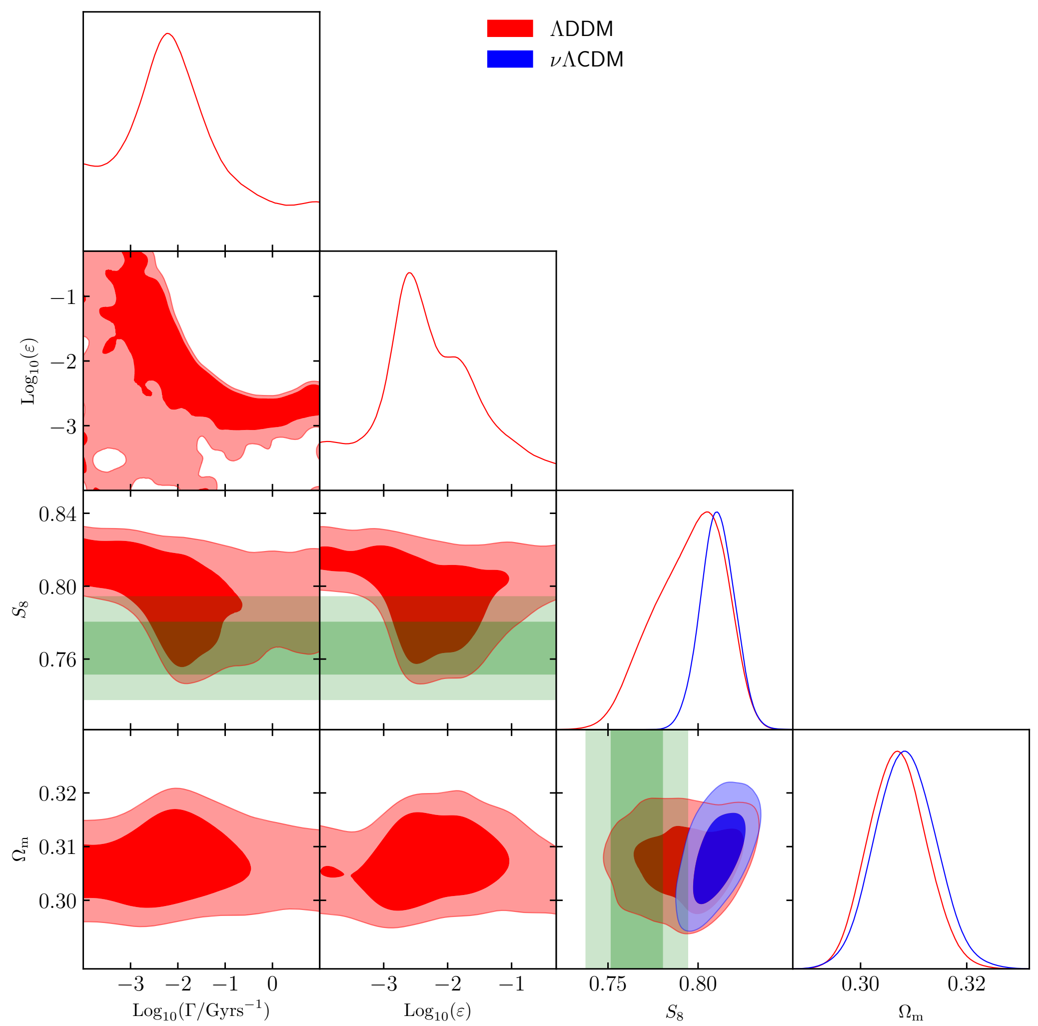
- Standard neutrinos are largely excluded as a solution: need $M_\nu \simeq 0.23$ eV but $M_\nu \lesssim 0.08 - 0.12$ eV

Palanque-Delabrouille++ 1911.09073 ; Brieden++ 2204.11868 ; Simon (VP)++ 2210.14931

- ΛCDM + two free parameters: the CDM decay rate Γ and the branching ratio to DR $\varepsilon \equiv \left(\frac{1}{2} - \frac{m^2_{\rm WDM}}{m^2_{\rm DCDM}}\right) \simeq v_{\rm wdm}/c$

$$\dot{\bar\rho}_{\rm dcdm} = -3\mathcal{H}\bar\rho_{\rm dcdm} - a\Gamma\bar\rho_{\rm dcdm},$$
$$\dot{\bar\rho}_{\rm dr} = -4\mathcal{H}\bar\rho_{\rm dr} + \varepsilon a\Gamma\bar\rho_{\rm dcdm},$$
$$\dot{\bar\rho}_{\rm wdm} = -3(1+w)\mathcal{H}\bar\rho_{\rm wdm} + (1-\varepsilon)a\Gamma\bar\rho_{\rm dcdm}.$$





- DM with $\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}$ Gyrs can explain low S_8 (1.3σ agreement) *Abellan++ 2008.09615 & 2104.03329*

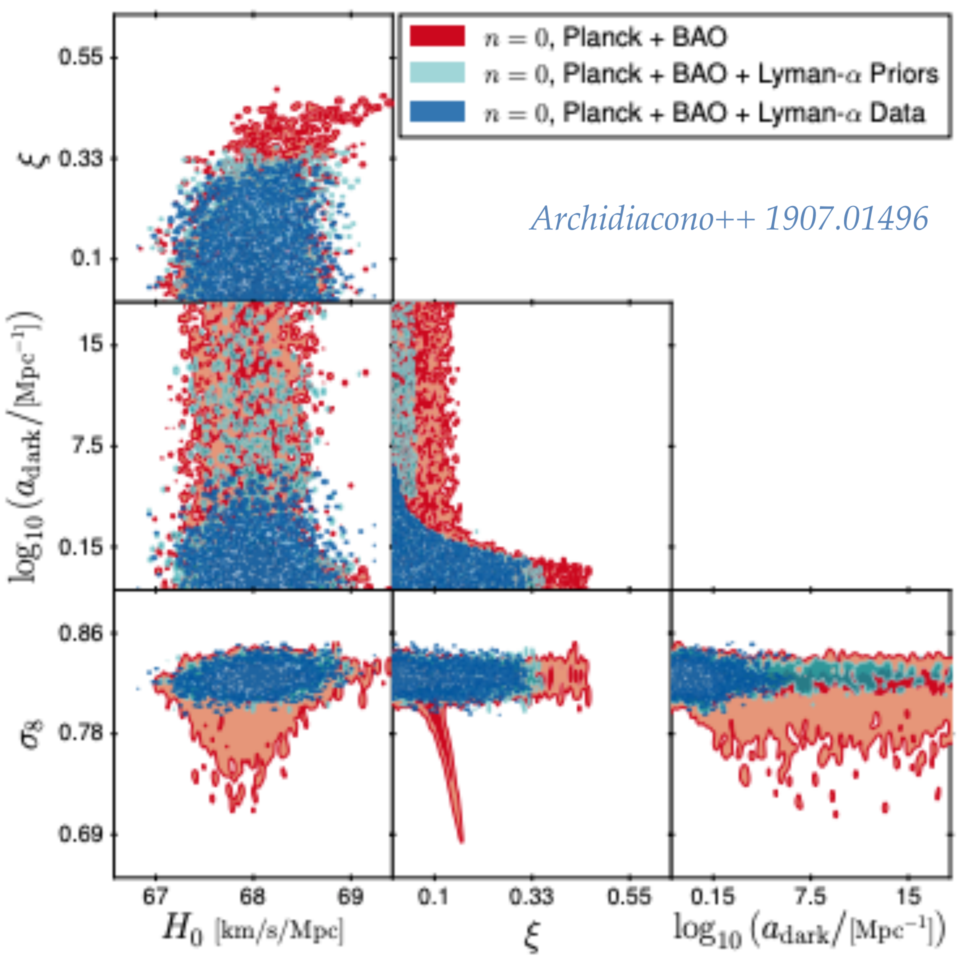
See also Davari&khosravi 2203.09439, Clark++ 2110.09562

The S_8 tension is a drag…

DM<=>DR

$$\dot{\delta}_{\rm DM} + \theta_{\rm DM} - 3\dot{\phi} = 0,$$
$$\dot{\theta}_{\rm DM} - k^2 c_{\rm DM}^2 \delta_{\rm DM} + \mathcal{H}\theta_{\rm DM} - k^2\psi = \Gamma_{\rm DM-DR}\left(\theta_{\rm DM} - \theta_{\rm DR}\right),$$

$$\Gamma_{\rm DR-DM} = -\Omega_{\rm DM} h^2 a_{\rm dark}\left(\frac{1+z}{1+z_d}\right)^n, \qquad \xi = T_{\rm DR}/T_\gamma$$

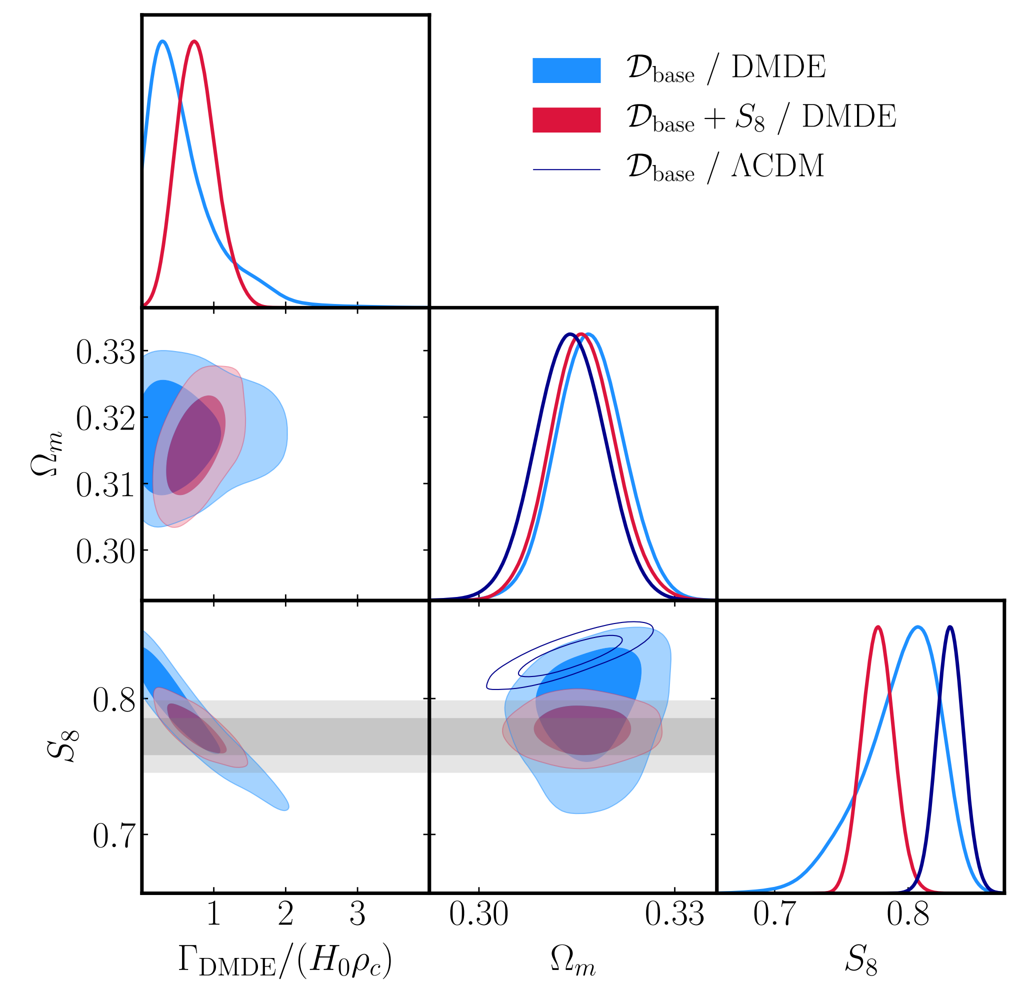


Archidiacono++ 1907.01496

DM<=>DE

VP, Bernal, Kovetz, Kamionkowski 2209.06217

$$\theta'_{\rm DM} = -\frac{a'}{a}\theta_{\rm DM} + k^2\psi + \Gamma_{\rm DMDE}(a)(\theta_{\rm DE} - \theta_{\rm DM}),$$
$$\theta'_{\rm DE} = -(1-3c_{s,{\rm DE}}^2)\frac{a'}{a}\theta_{\rm DE} + \frac{k^2 c_{s,{\rm DE}}^2}{(1+w_{\rm DE})}\delta_{\rm DE} + k^2\psi - \Gamma_{\rm DMDE}(a)R(\theta_{\rm DE} - \theta_{\rm DM}),$$

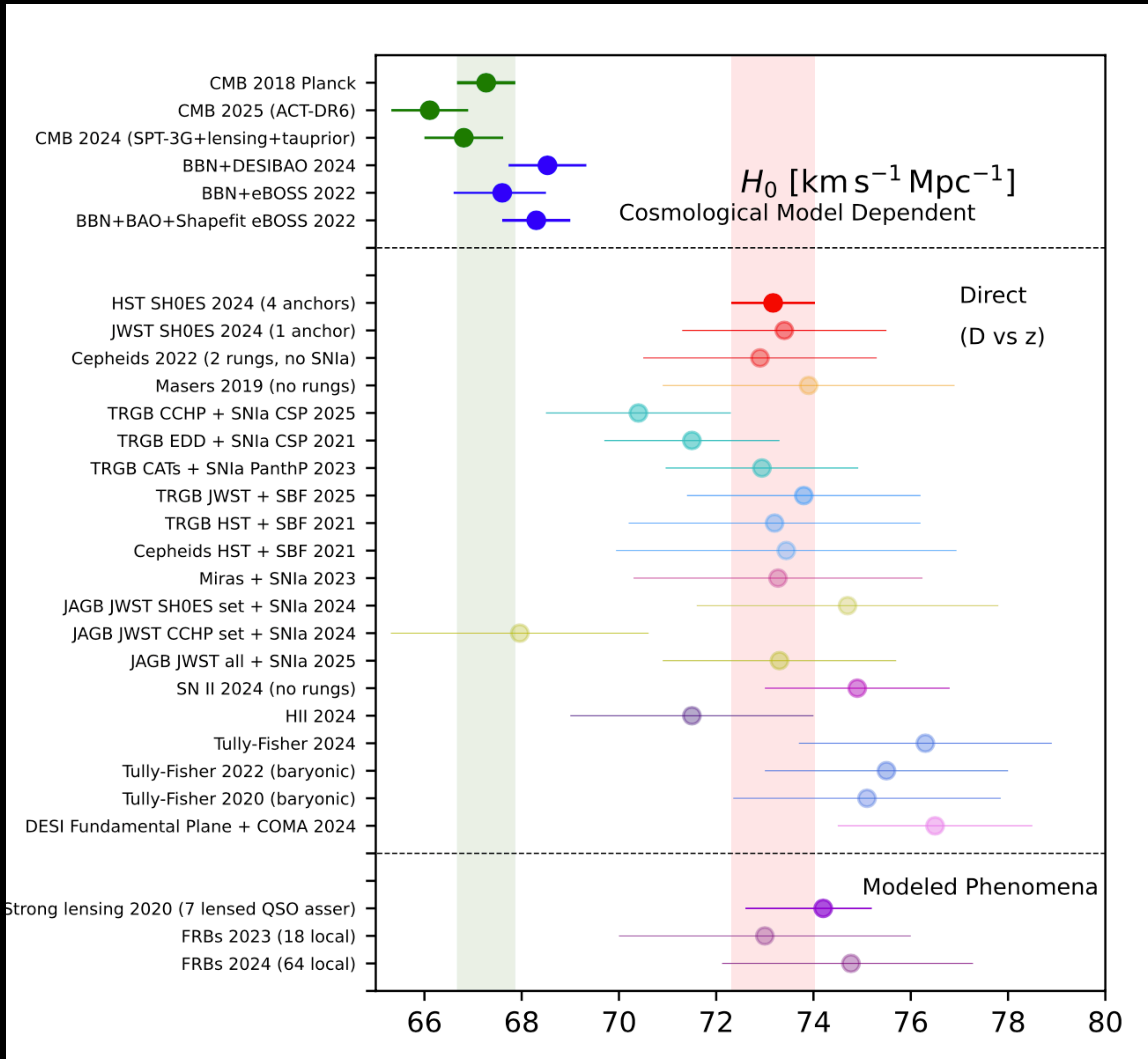


See also Di Valentino++ 1908.04281

- Non-Abelian dark matter model, Cannibal dark matter, also with sub-component of strongly interacting DM

Buen-Abad++1505.03542, Lesgourgues++1507.04351, Heimersheim++ 2008.08486, Chacko++1609.03569, Buen-Abad++ 1708.09406, Raveri++ 1709.04877

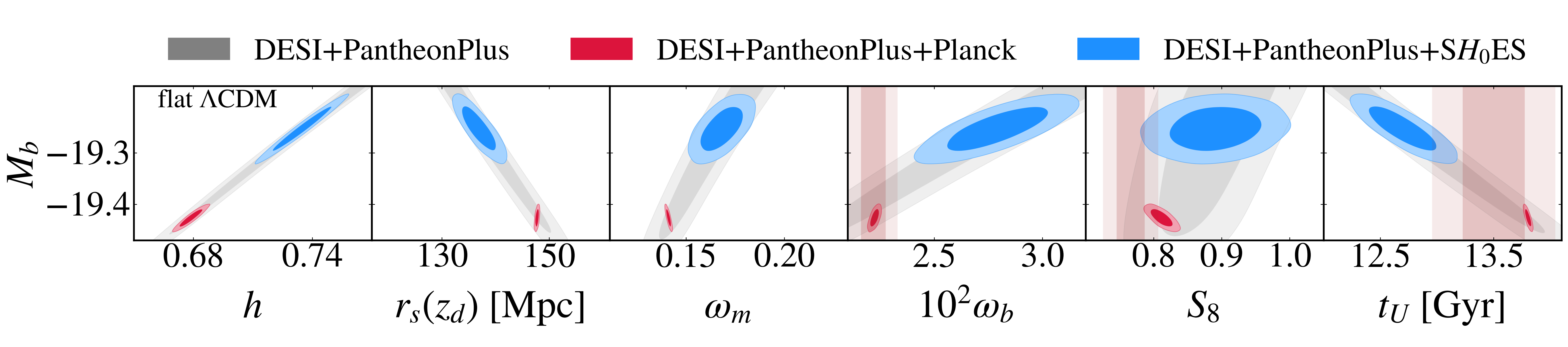
The Hubble tension



- We are still tracking "unknown unknowns"

Stop calling it H_0 tension!

- The "H_0 tension" should really be called cosmic calibration tension
- Calibrating the ladder has implications beyond the value of H_0: smaller t_U, larger ω_m, ω_b and S_8



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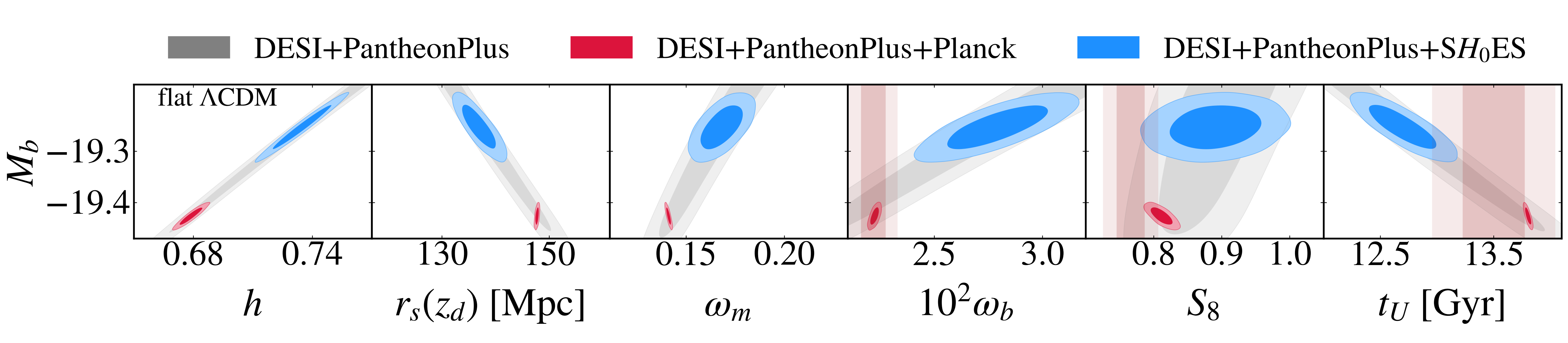

- New physics must reduce the sound horizon r_s and accommodate larger ω_m.
- Models affecting the pre-recombination expansion history favored but not fully successful
- Or maybe need new degrees of freedom at both early- and late-times?

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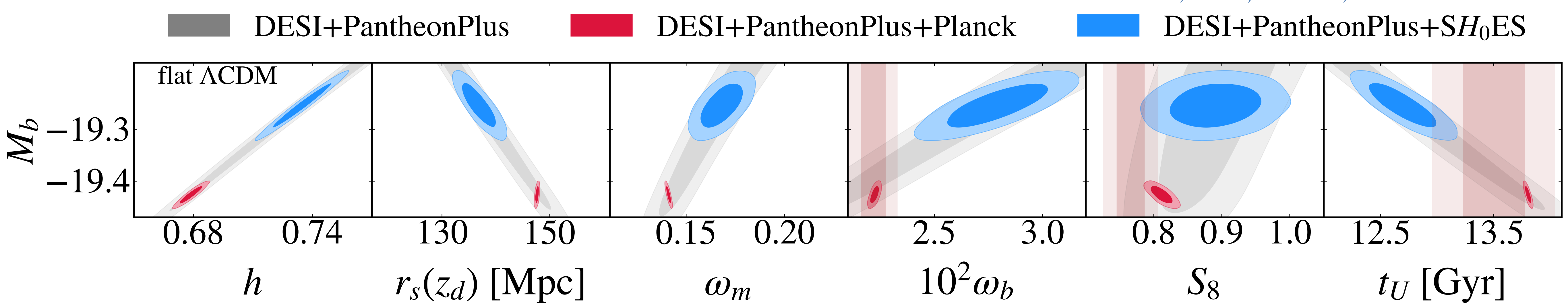
VP, Smith, Calderon, Simon 2407.18292



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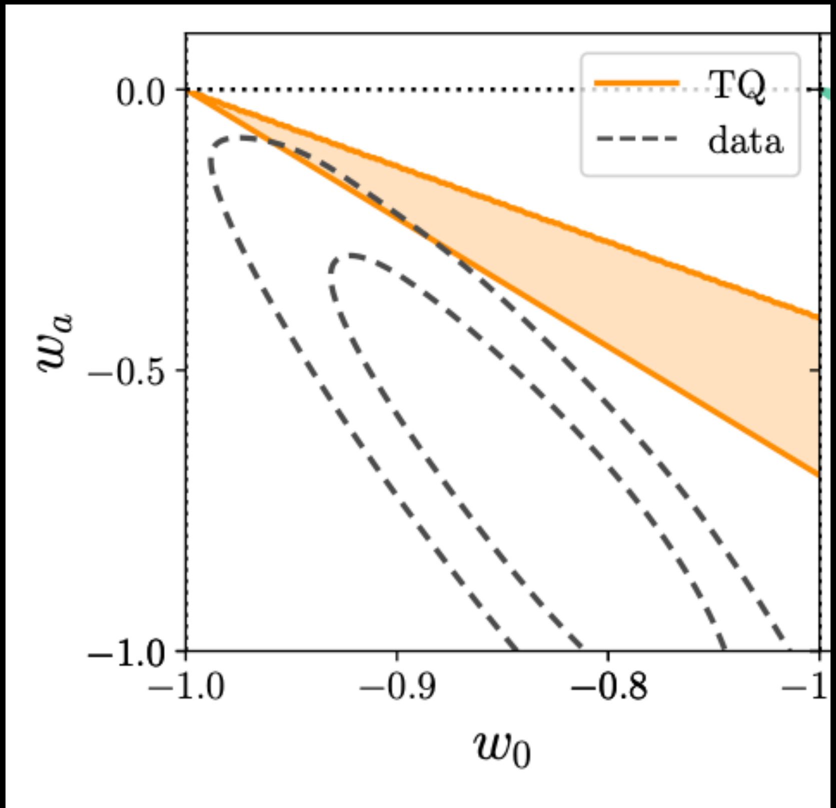
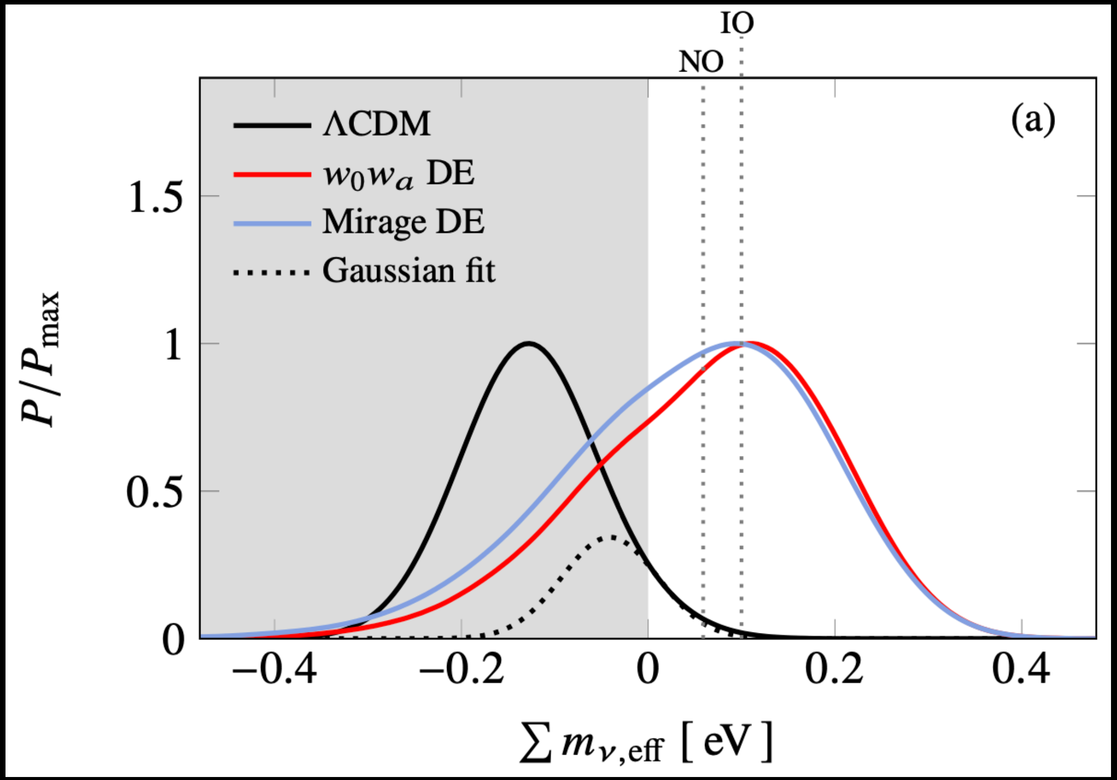
- Models affecting the pre-recombination expansion history favored but not fully successful
- Or maybe need new degrees of freedom at both early- and late-times?

- We haven't found the solution yet, but there is a lot we understand!

A new DESI tension?

- DESI + CMB in 2.3 σ tension, DESI+CMB in tension with SN1a at 2-3σ
- This can be explained by Dynamical Dark Energy ==> non-canonical quintessence
- Mirage Dark Energy is favored: weird?





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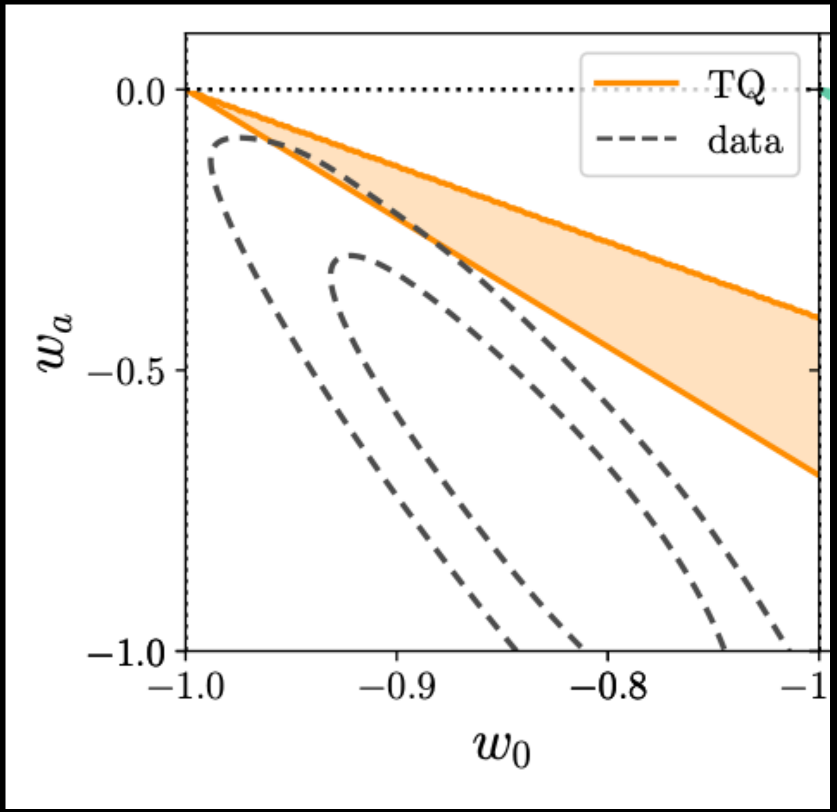

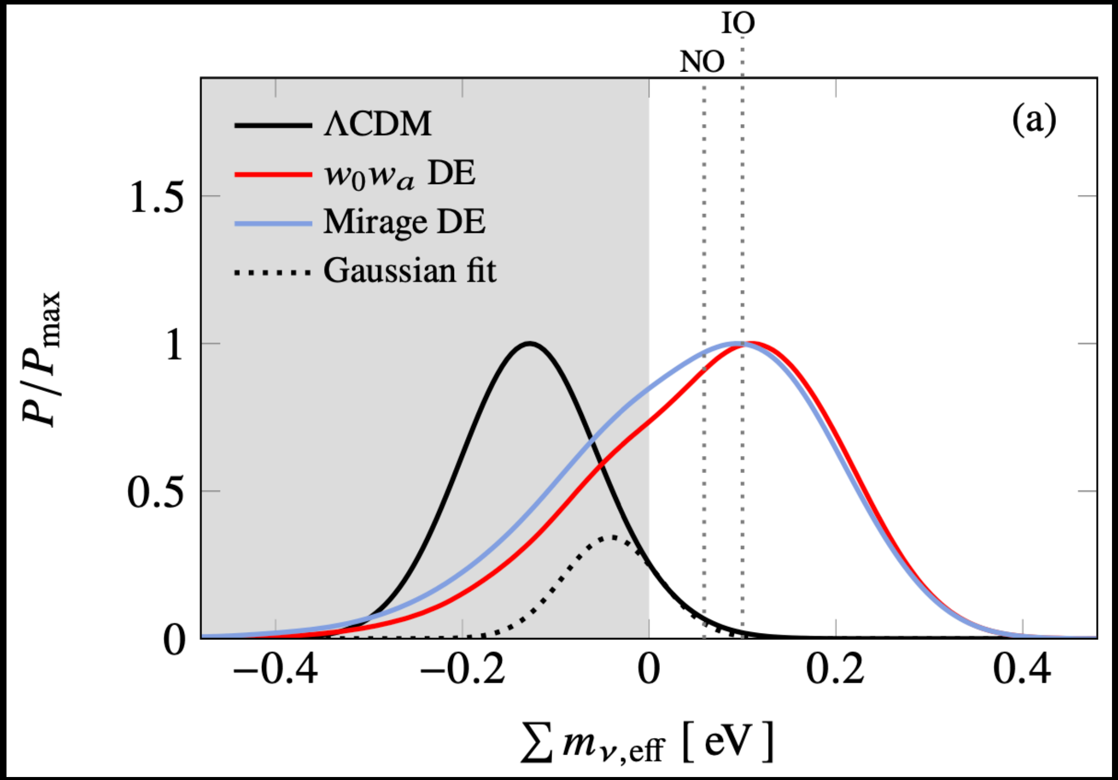

- Very strong bounds to M_ν due to impact on $d_A(z)$: P-ACT-SPT +DESI M_ν< 0.048 eV
- These relaxes (a bit) in extended cosmological models

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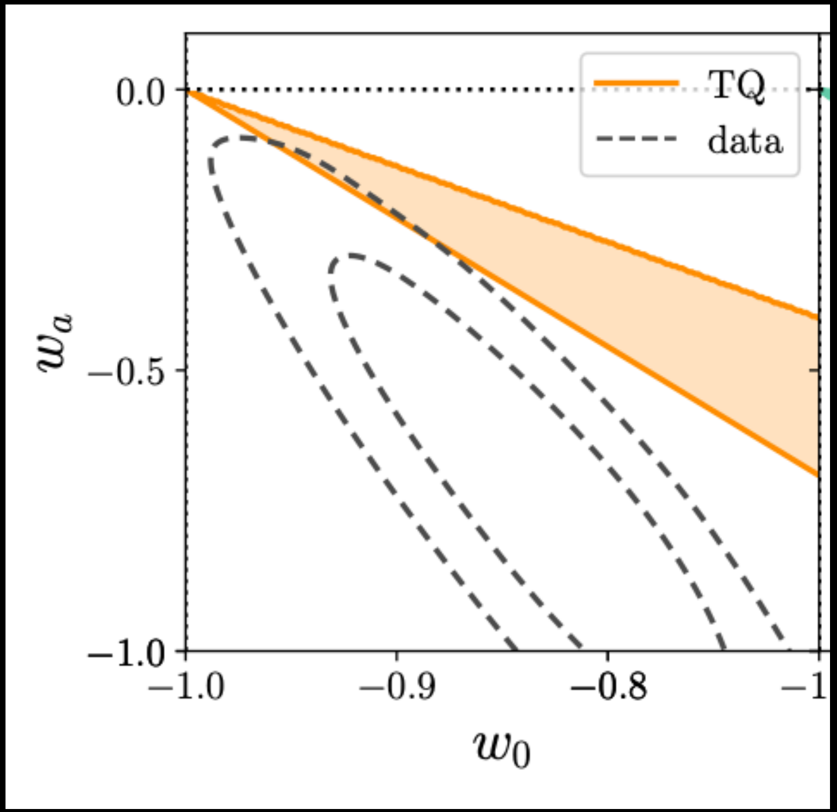

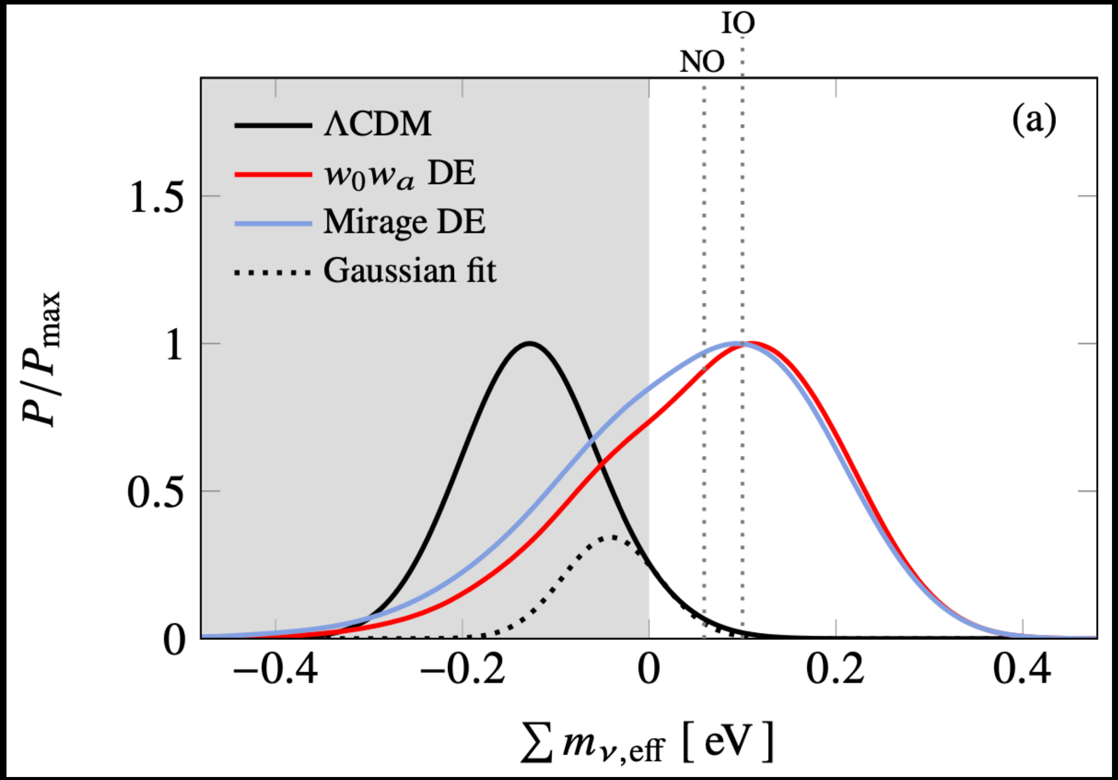

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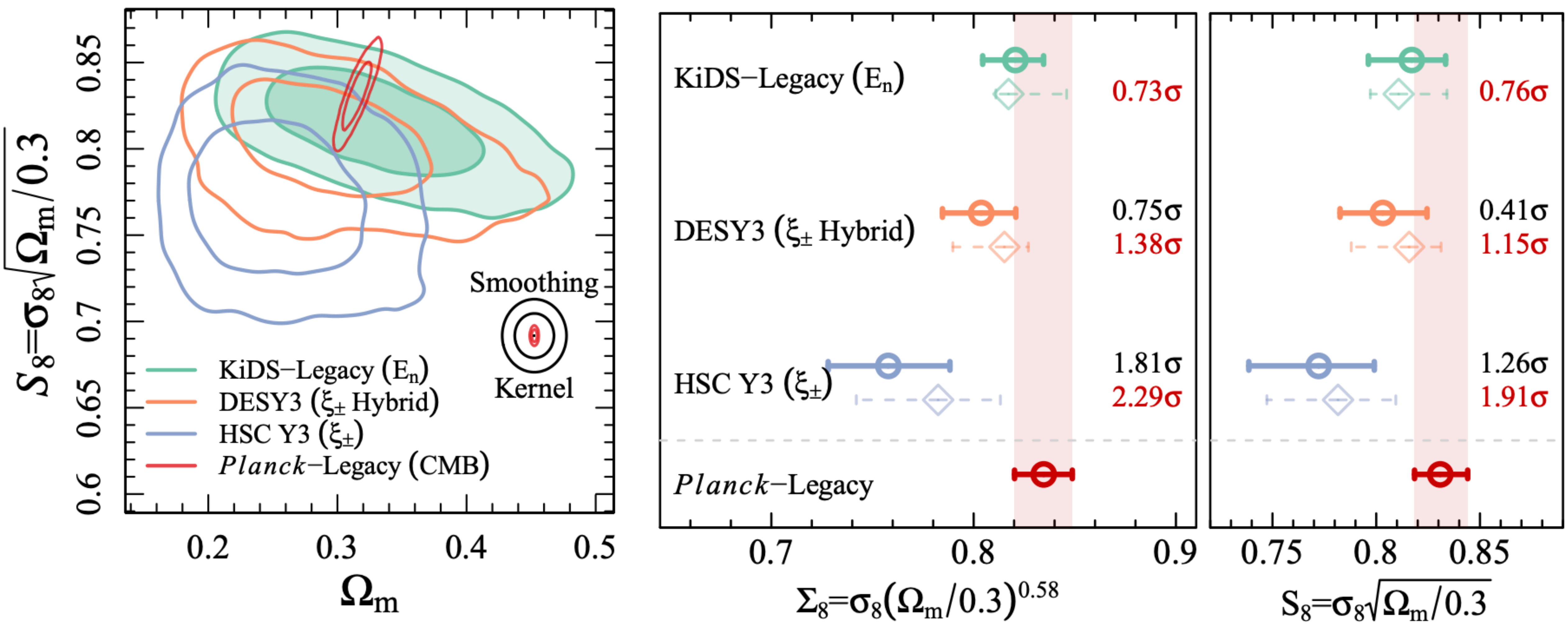
- These relaxes (a bit) in extended cosmological models

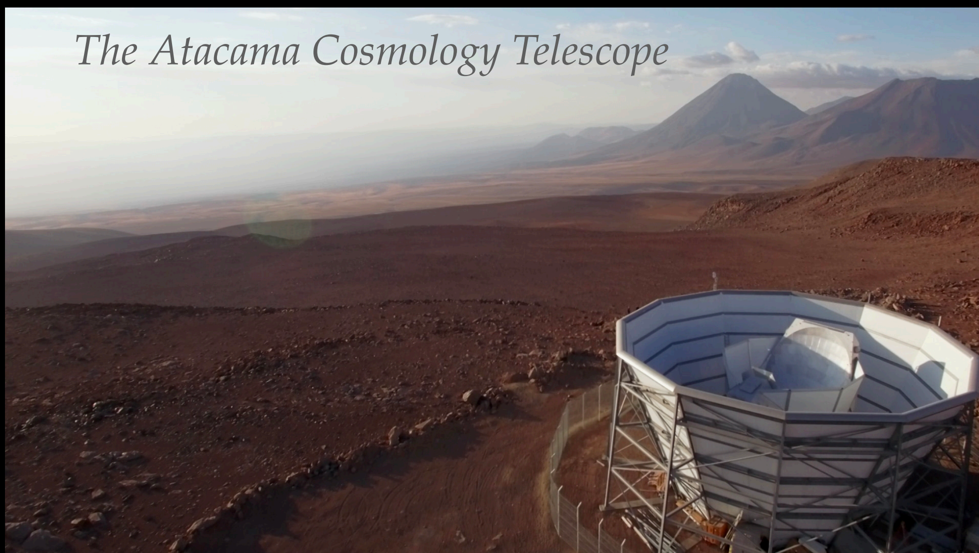
- Early universe models could explain BAO data but not large Ω_m from SNe

The S_8 tension is gone?



- But remember that the H_0 tension may imply some residual tension …
- See DM talks for more ideas for solutions

Cosmic tension: where are we going next?



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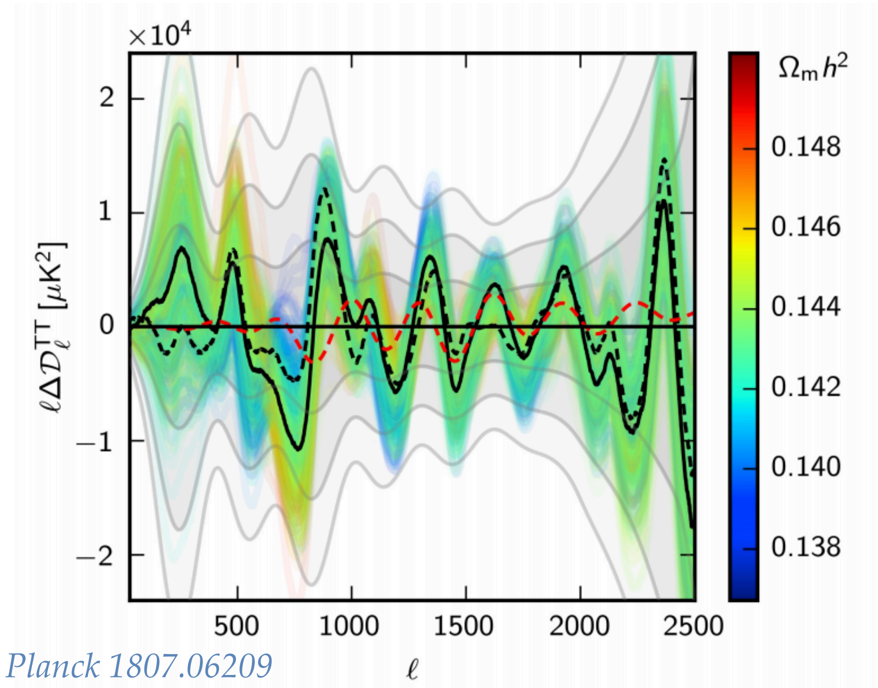
- New CMB data are coming: very sensitive to new physics around recombination!
- New LSS data are coming: measure $P(k, z)$, constrain baryonic feedback, neutrino masses?
- New JWST data + age of the universe? + gravitational wave measurements of H_0.

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$

Unless specified, Figs. from Di Valentino++ 1911.02087



Planck 1807.06209

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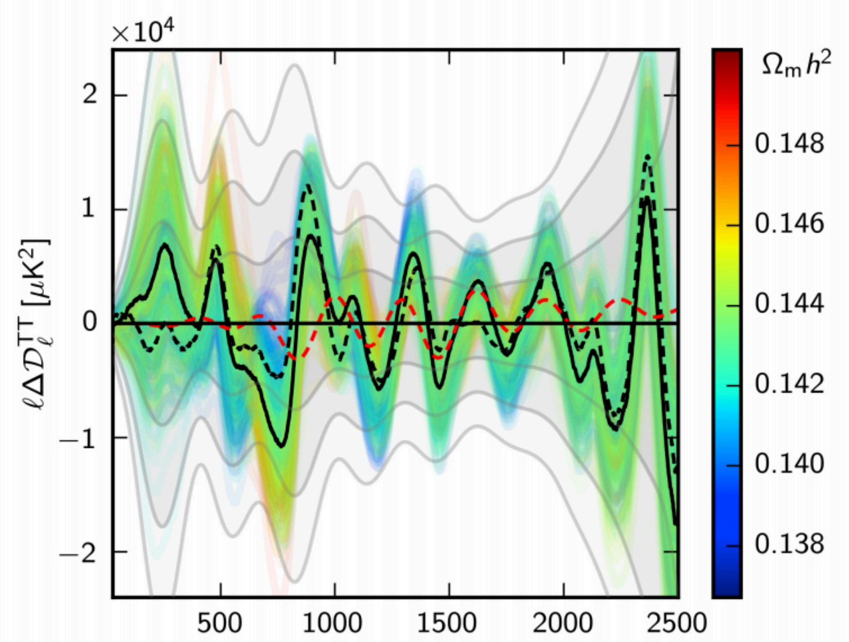
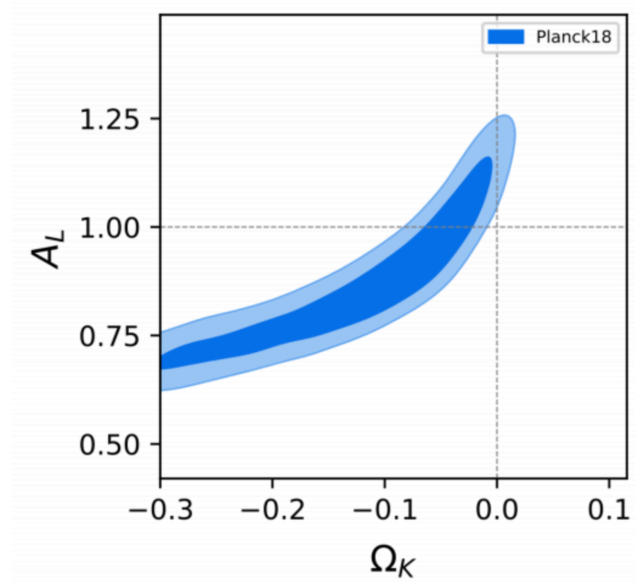
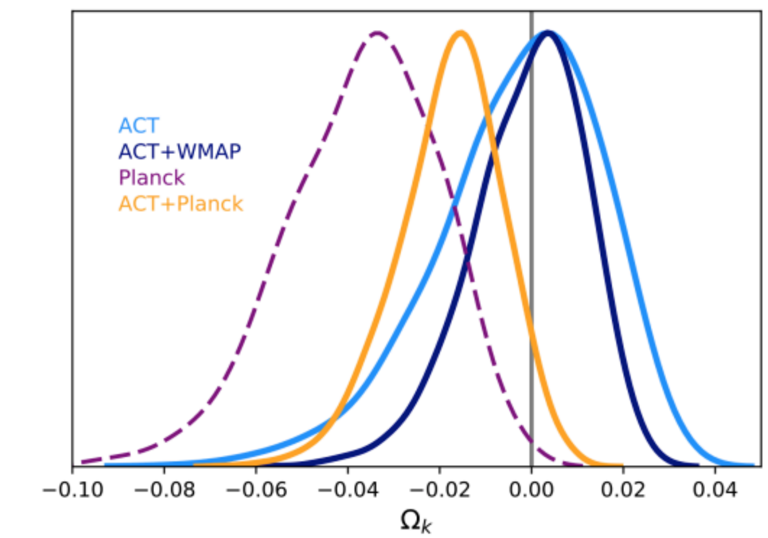


Planck 1807.06209





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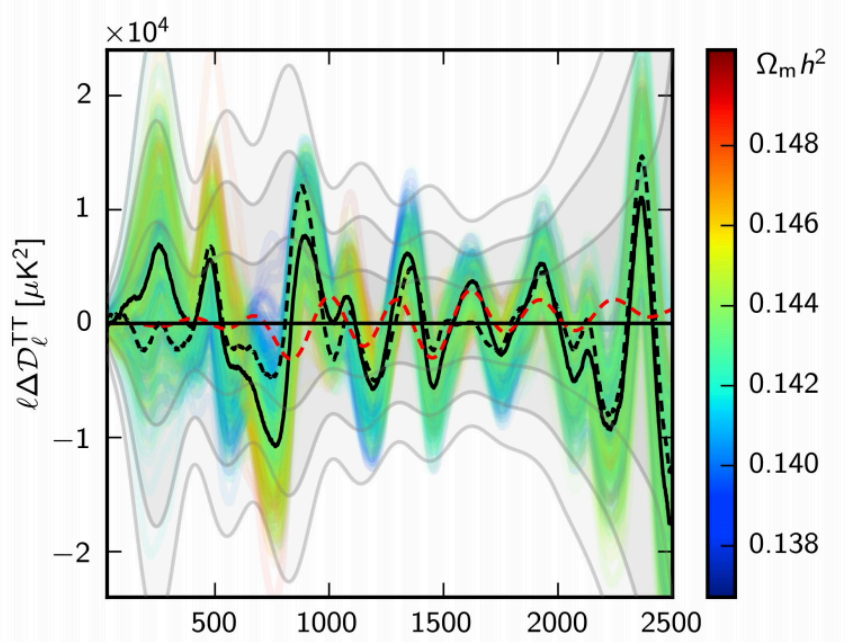
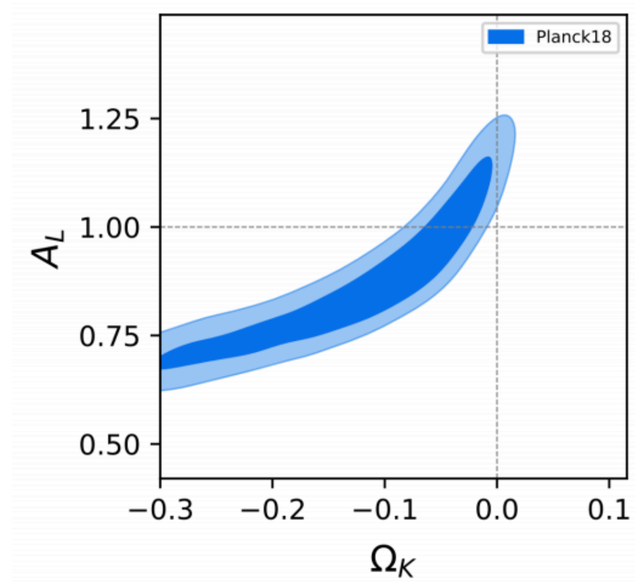
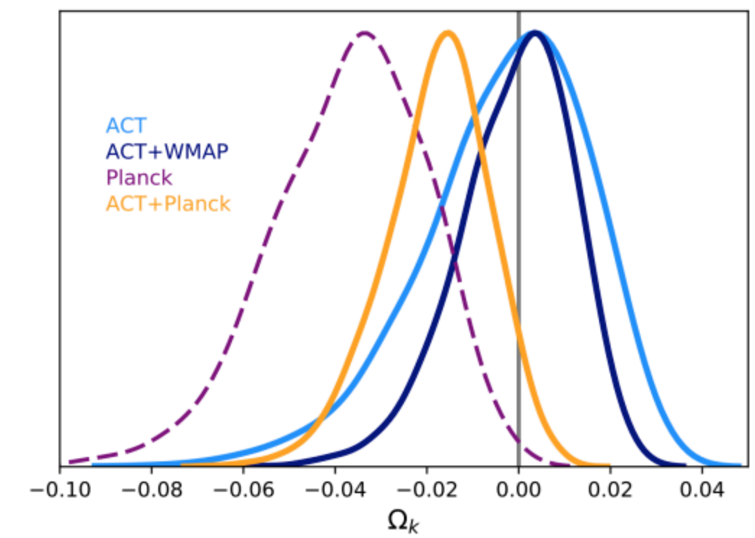
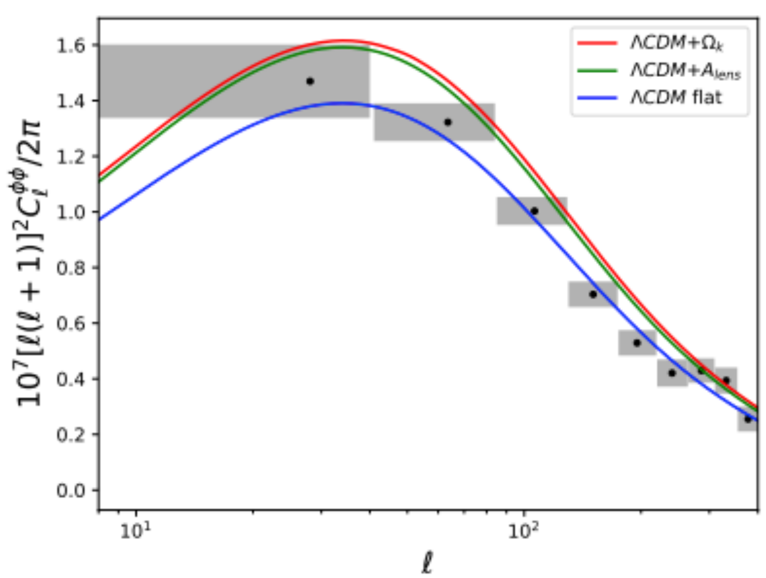


Planck 1807.06209

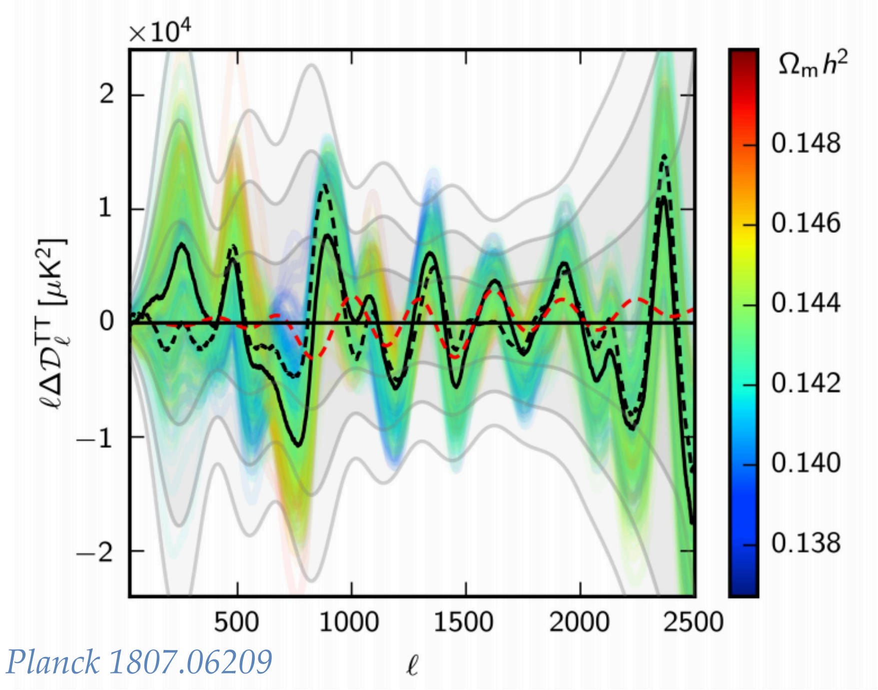






$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}$$

Unless specified, Figs. from Di Valentino++ 1911.02087



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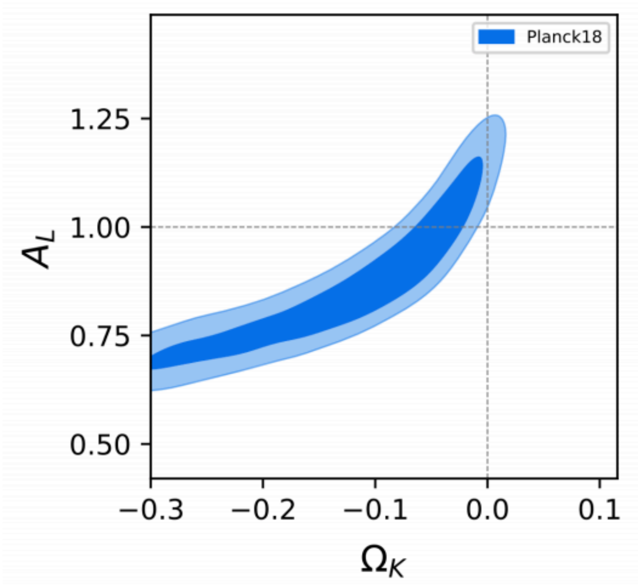
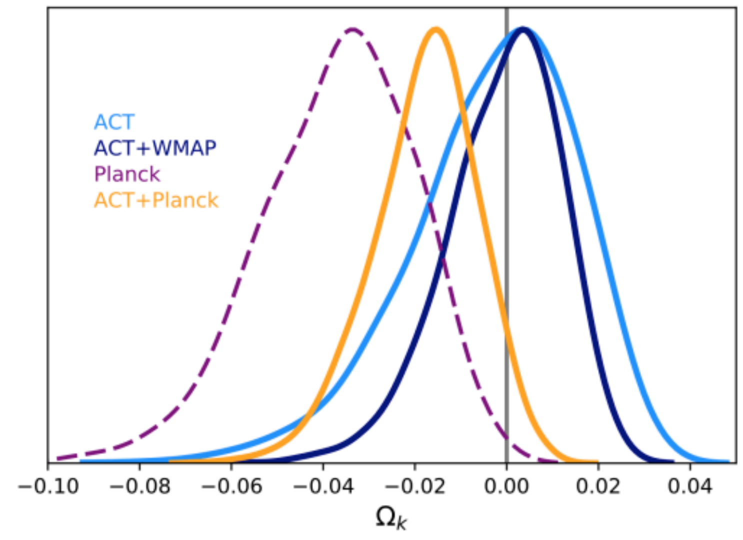
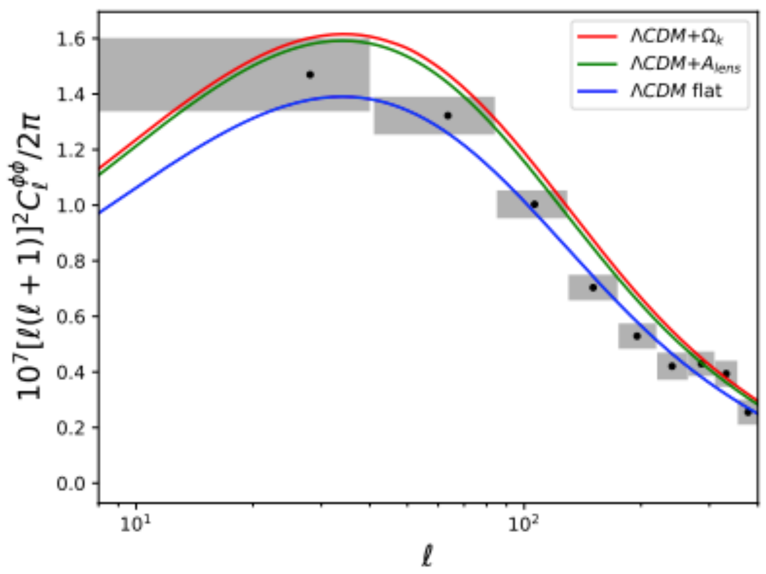
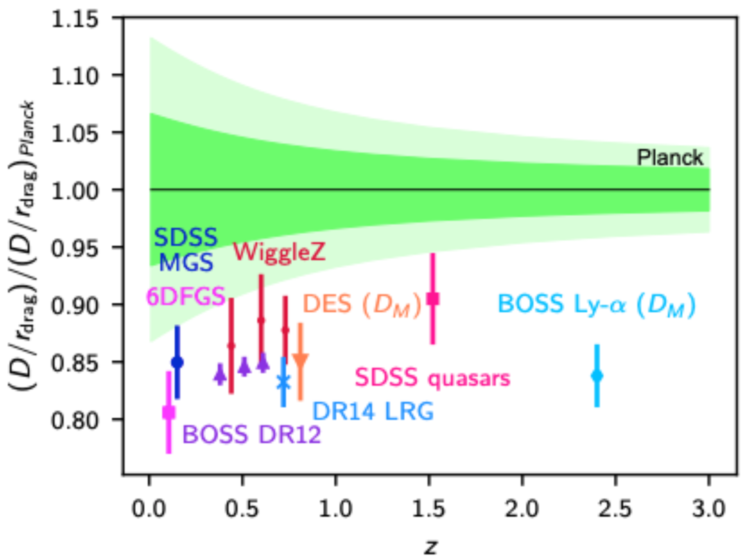


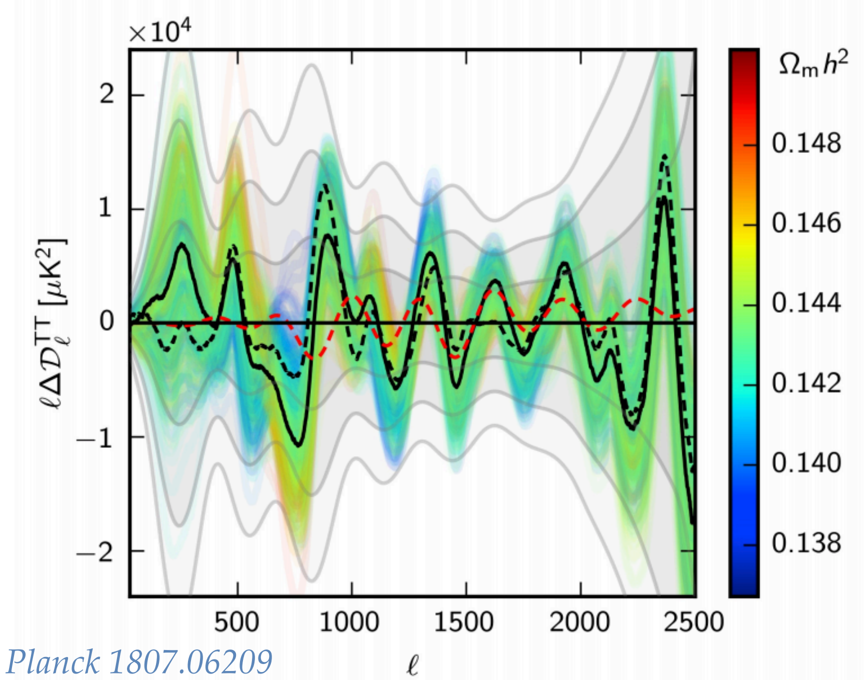






$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}$$

Unless specified, Figs. from Di Valentino++ 1911.02087



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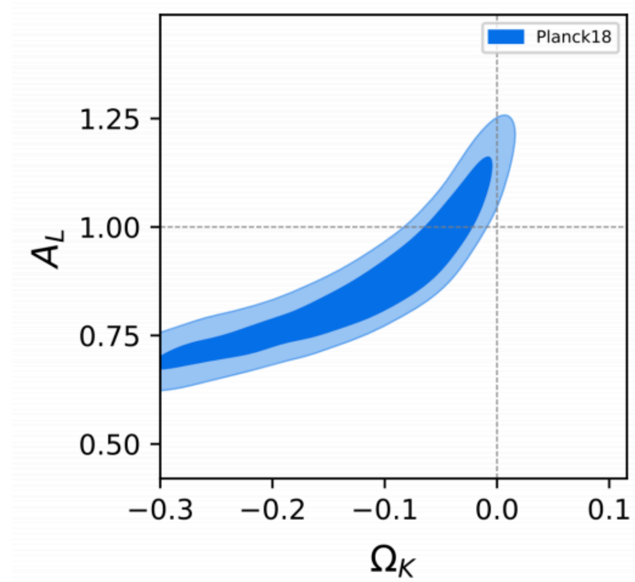

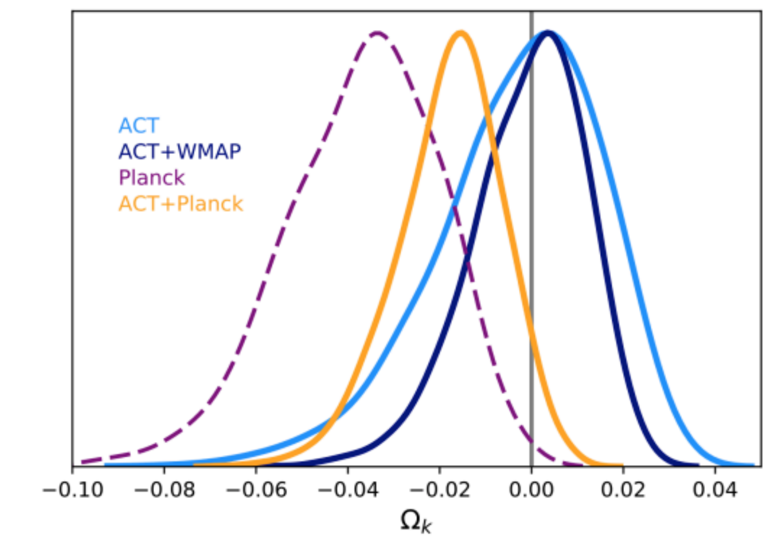

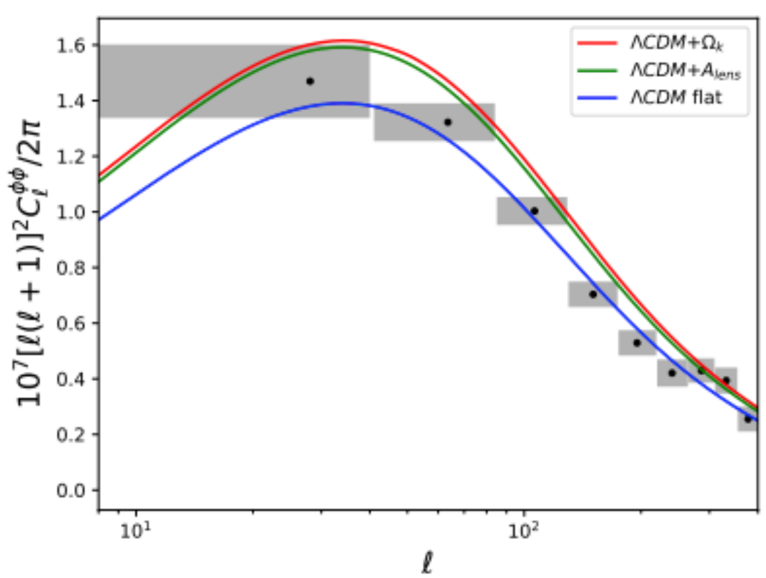

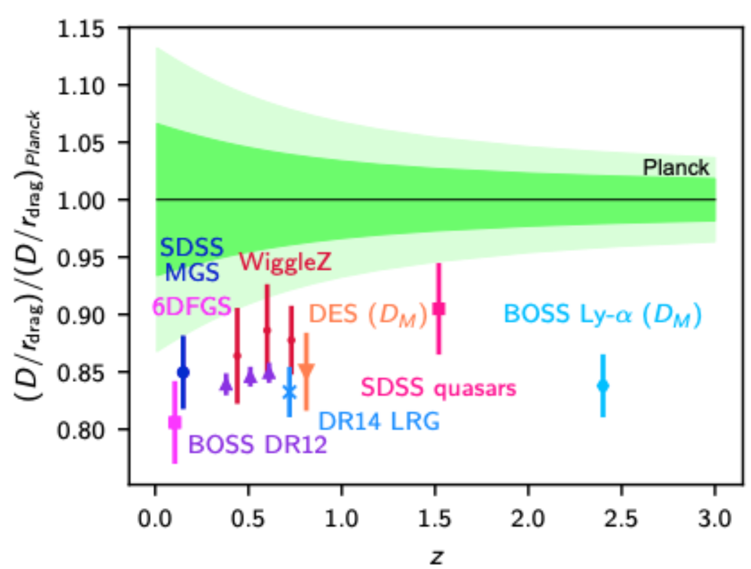

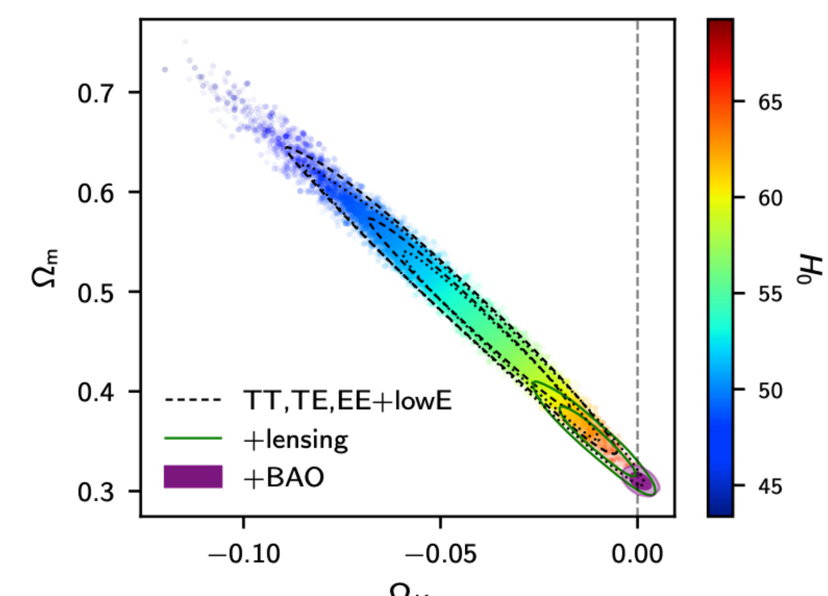

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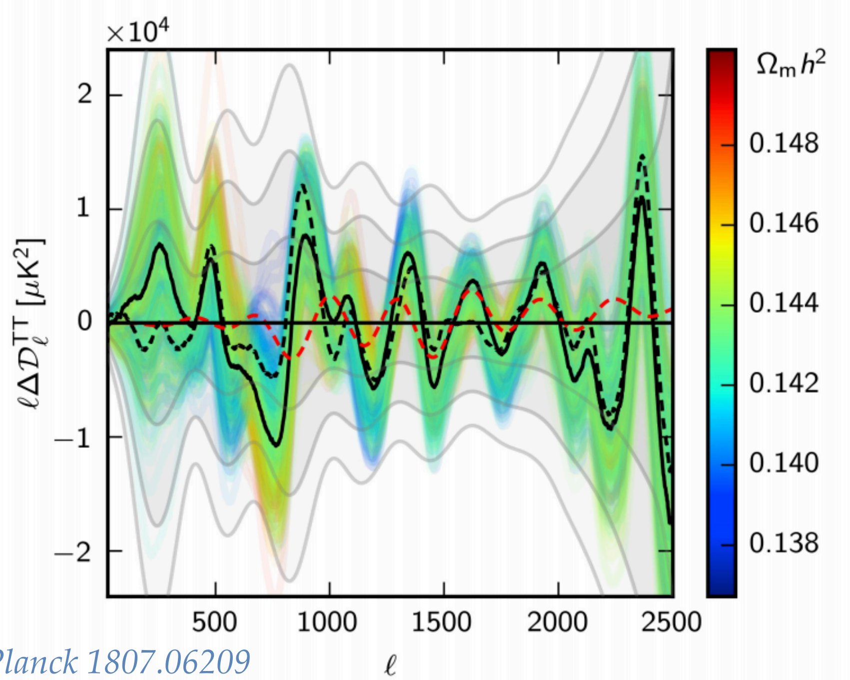
$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}$$

Unless specified, Figs. from Di Valentino++ 1911.02087



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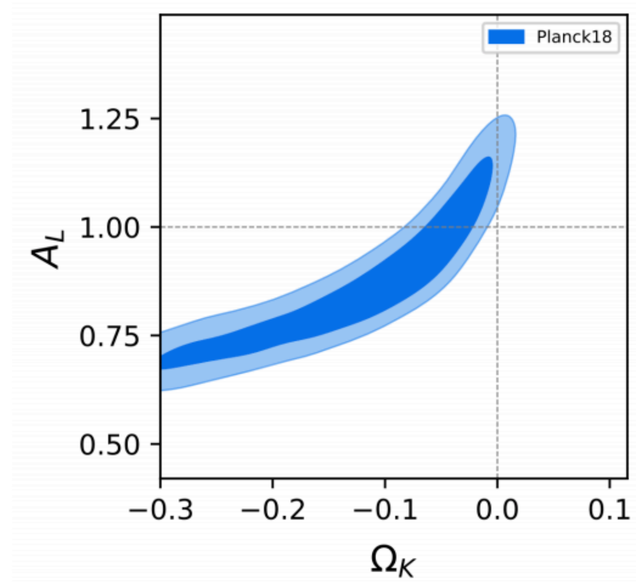

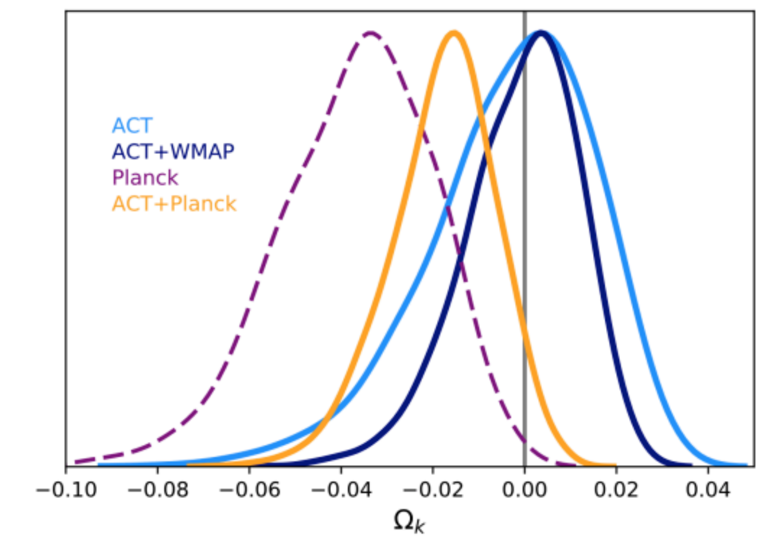

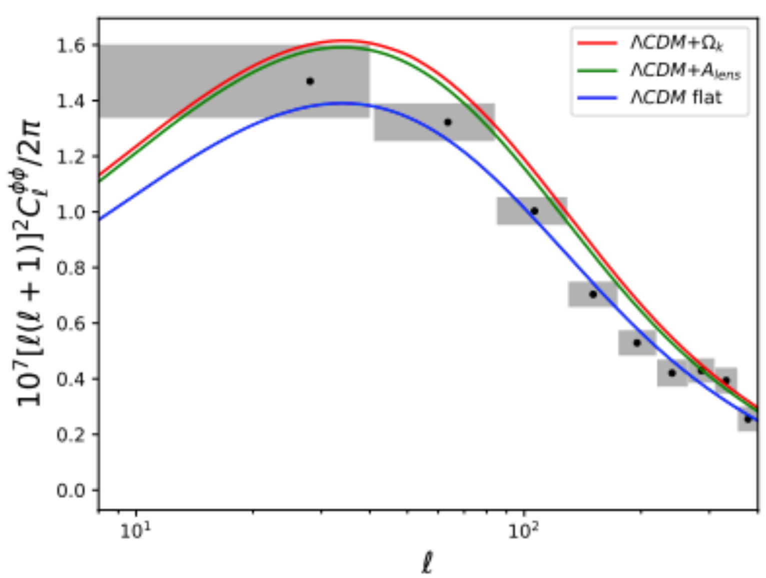

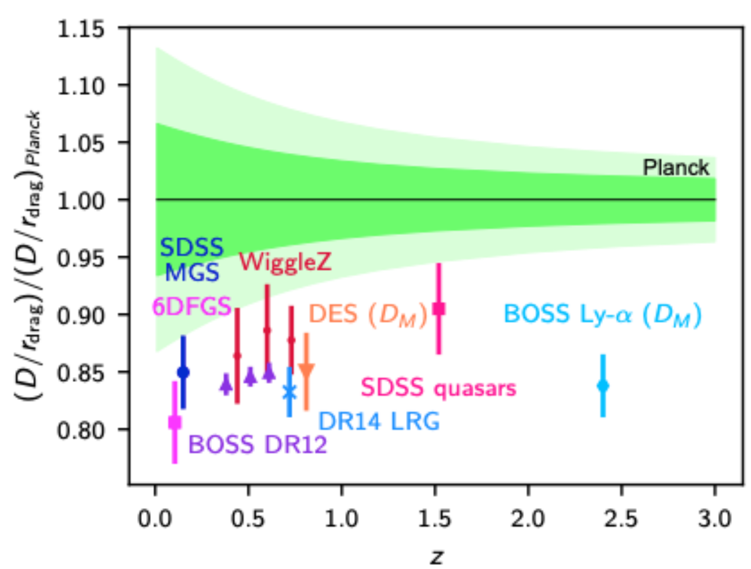

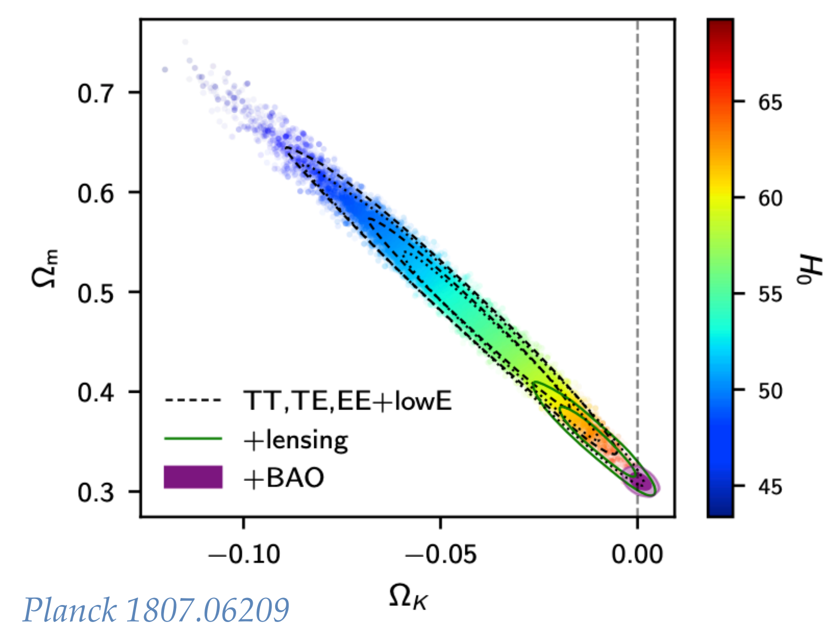

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- The Universe is flat unless of a true ‘cosmological crisis’.
- Flat universe is also supported by BOSS and Cosmic Chronometers. *Vagnozzi++2010.02230, 2011.11645*
- Nb: A_L could also be explained in modified gravity framework, it suffers from the same issues.