The H_0 Olympics: a fair ranking of proposed models

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Based on:

arXiv:2107.10291, submitted to Physics Reports

In collaboration with Nils Schöneberg, Andrea Pérez Sánchez, Samuel J. Witte, Vivian Poulin and Julien Lesgourgues

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Laboratoire Univers & Particules Montpellier

Challenges to the ΛCDM paradigm

Several discrepancies emerged in recent years

- S_8 with weak-lensing data (2-3σ)
  KiDS-1000 2007.15632

- H_0 with local measurements (5σ)
  Riess++ 2012.08534

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Unaccounted systematics?

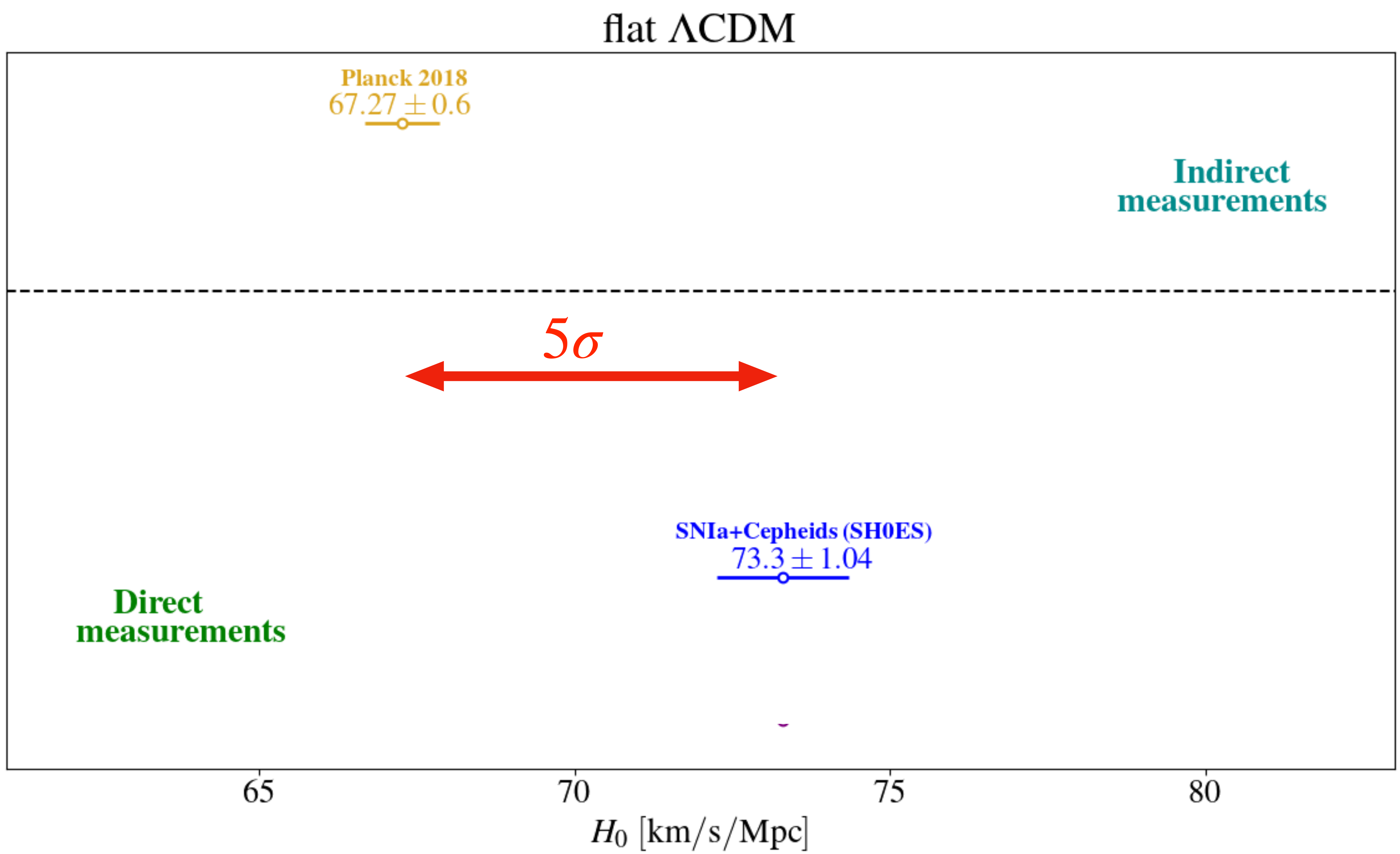
- Less exotic explanation ✅
- Difficult to account for all discrepancies ❌

Physics beyond ΛCDM?

- Reveal properties about the dark sector ✅
- Very challenging ❌

The H_0 tension

Planck (*under ΛCDM*) and SH0ES measurements are now in **5σ tension !**



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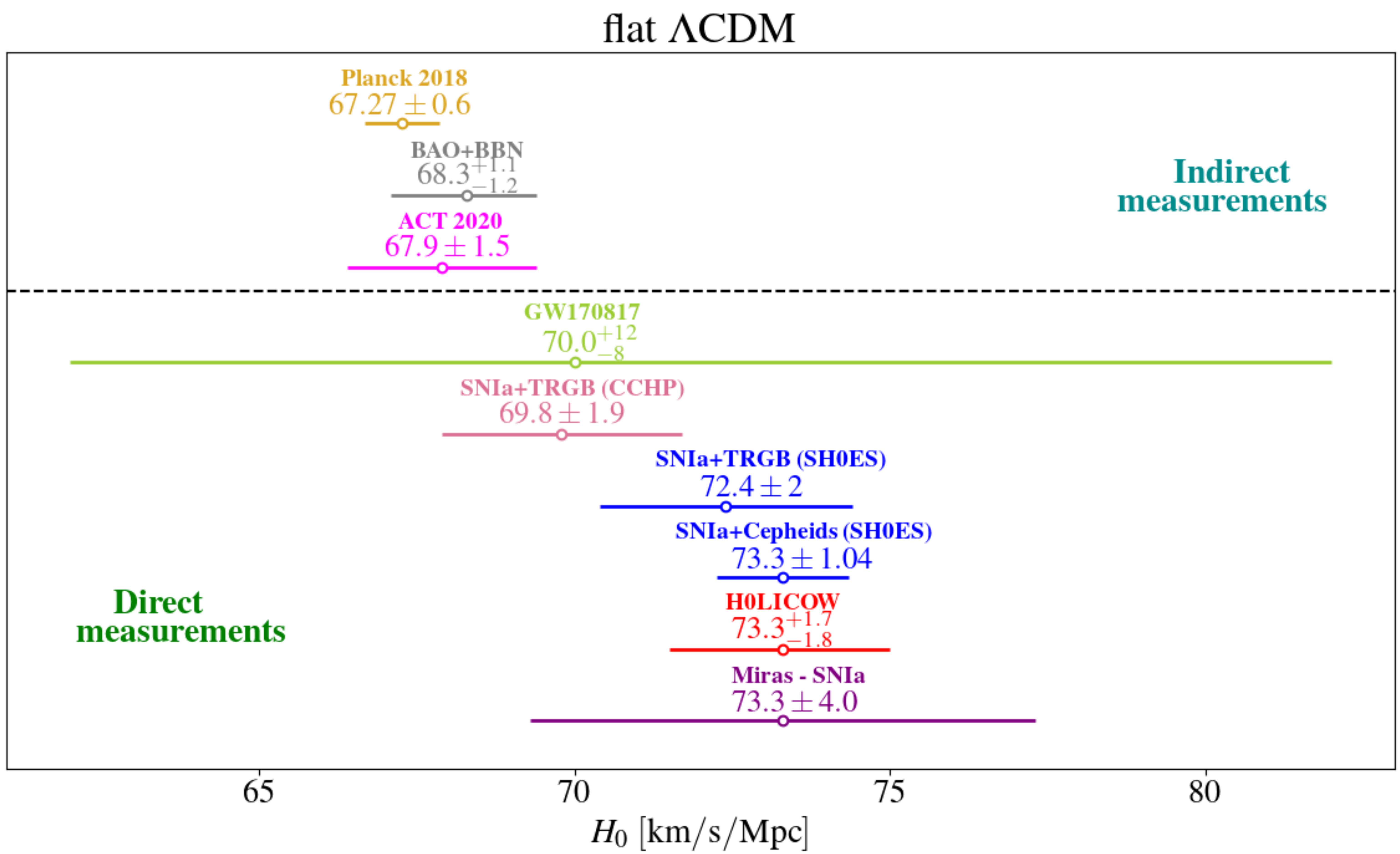
High- and low-redshift probes are typically discrepant



Lost in the landscape of solutions

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- Di Valentino, Mena++ 2103.01183 ⟶ recent review of solutions, more than 1000 refs !

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]

Relieving the Hubble tension with primordial magnetic fields

Karsten Jedamzik[1] and Levon Pogosian[2,3]

The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions

Christina D. Kreisch,[1,*] Francis-Yan Cyr-Racine,[2,3,†] and Olivier Doré[4]

Rock 'n' Roll Solutions to the Hubble Tension

Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]

The Hubble Tension as a Hint of Leptogenesis and Neutrino Mass Generation

Miguel Escudero[1,*] and Samuel J. Witte[2,†]

Can interacting dark energy solve the H_0 tension?

Eleonora Di Valentino,[1,2,*] Alessandro Melchiorri,[3,†] and Olga Mena[4,‡]

Dark matter decaying in the late Universe can relieve the H_0 tension

Kyriakos Vattis, Savvas M. Koushiappas, and Abraham Loeb

A Simple Phenomenological Emergent Dark Energy Model can Resolve the Hubble Tension

Xiaolei Li[1,2] and Arman Shafieloo[1,3]

Early recombination as a solution to the H_0 tension

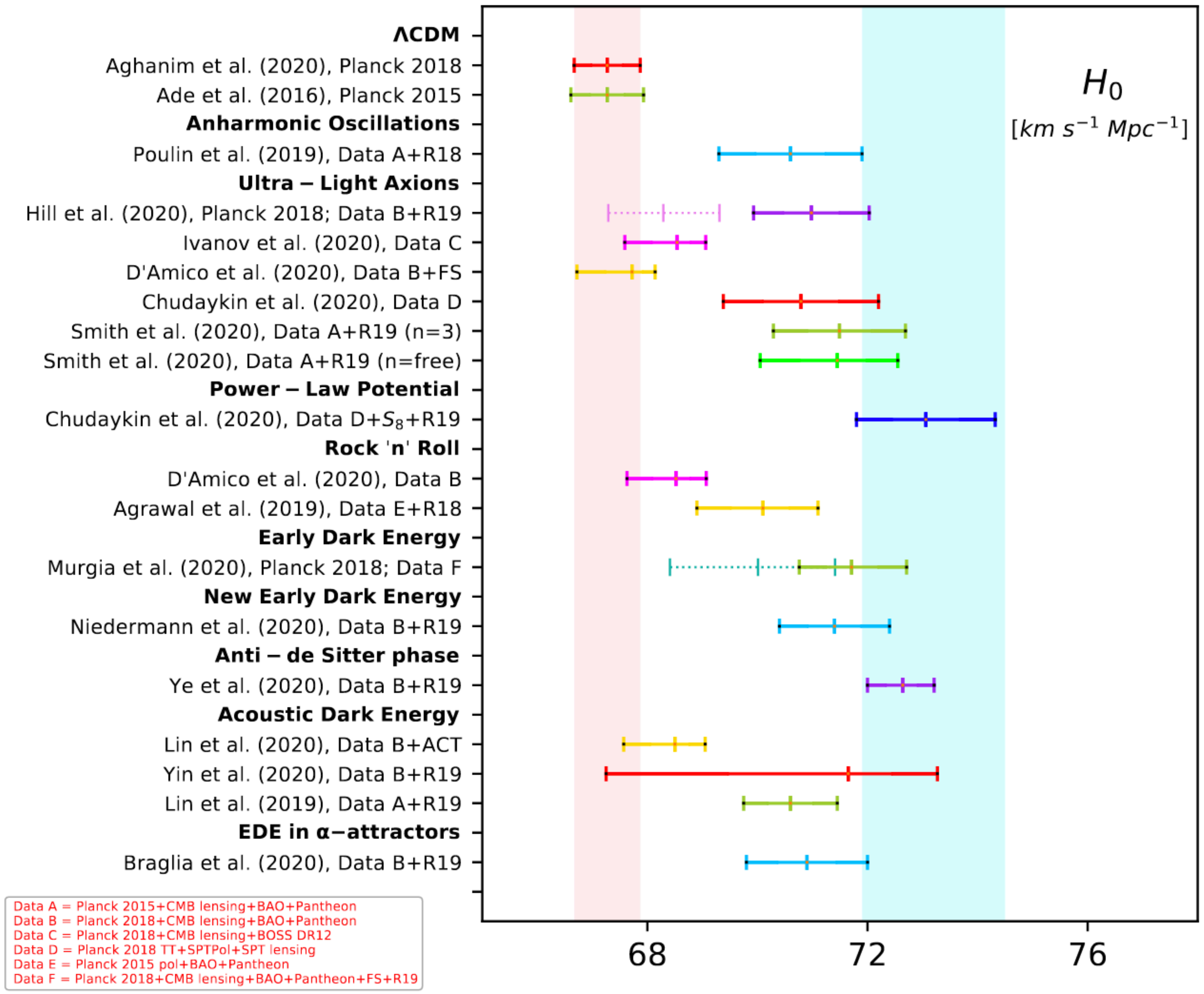
Toyokazu Sekiguchi[1,*] and Tomo Takahashi[2,†]

Early modified gravity in light of the H_0 tension and LSS data

Matteo Braglia,[1,2,3,*] Mario Ballardini,[1,2,3,†] Fabio Finelli,[2,3,‡] and Kazuya Koyama[4,§]

Lost in the landscape of solutions

It proves difficult to compare success of the different proposed solutions, since authors typically use differing and incomplete combinations of data



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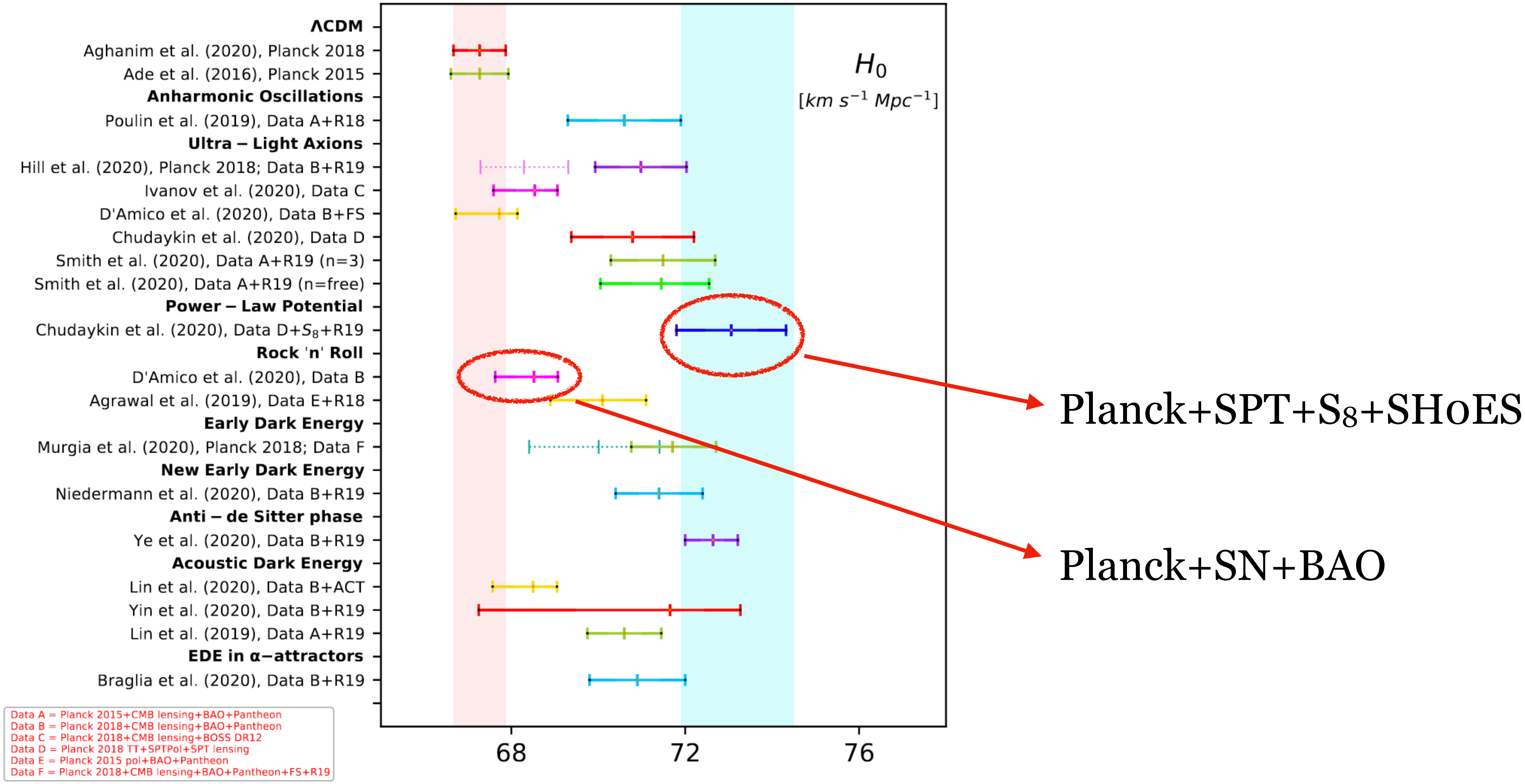

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The H_0 Olympics

Goal: Take a representative sample of proposed solutions, and quantify the relative success of each using certain metrics and a wide array of data

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Early universe

w Dark radiation

- ΔN_{eff}
- Self-interacting DR
- Mixed DR
- DM-DR interactions
- Self-interacting ν_s+DR
- Majoron-ν_s interactions

wo Dark radiation

- Primordial B
- Varying m_e
- Varying $m_e+\Omega_k$
- Early Dark Energy
- New Early Dark Energy

Late universe

- CPL dark energy
- PEDE
- MPEDE
- Fraction DM → DR
- DM → DR +WDM

Model-independent treatment of the SH0ES data

The cosmic distance ladder method *doesn't directly measure H_o.*

It directly measures the intrinsic magnitude of SNIa M_b at redshifts $0.02 \leq z \leq 0.15$, and then infers H_o by comparing with the apparent SNIa magnitudes m

$$m(z) = M_b + 25 - 5\mathrm{Log}_{10} H_0 + 5\mathrm{Log}_{10}(\hat{D}_L(z))$$

where

$$\hat{D}_L(z) \simeq z\left(1 + (1 - q_0)\frac{z}{2} - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0)z^2\right)$$

Depends on the model!

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Quantifying model success

Criterion 1: Can we get high values of H_0 without the inclusion of a SH0ES prior?

Gaussian tension GT

$$\frac{\bar{x}_D - \bar{x}_{SH0ES}}{\sqrt{\sigma_D^2 + \sigma_{\rm SH0ES}^2}} \text{ for x} = \mathrm{H_0} \text{ or } \mathrm{M_b}$$

We demand $\mathrm{GT} < 3\sigma$

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Caveats:

- Only valid for gaussian posteriors ❌
- Doesn't quantify quality of the fit ❌

Quantifying model success

Criterion 2: Can we get a good fit to all the data in a given model?

$\mathbf{Q_{DMAP}}$ tension

$$\sqrt{\chi^2_{\rm min,D+SH0ES} - \chi^2_{\rm min,D}}$$

Raveri&Hu 1806.04649

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Caveats:

- Accounts for non-gaussianity of posteriors ✅
- Doesn't account for effects of over-fitting ❌

Quantifying model success

Criterion 3: Is a model M favoured over ΛCDM?

Akaike Information Criterium ΔAIC

$$\chi^2_{\text{min,M}} - \chi^2_{\text{min,}\Lambda\text{CDM}} + 2(N_M - N_{\Lambda\text{CDM}})$$

We demand $\Delta\text{AIC} < -6.91$ *

*Corresponds to weak preference according to Jeffrey's scale

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We demand $\Delta\mathrm{AIC} < -6.91$ *

Caveats:

- Simple to use and prior-independent ✅

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Steps of the contest

Compare all models against
- Planck 18 TTTEEE+lensing
- BAO (BOSS DR12+MGS+6dFGS)
- Pantheon SNIa catalog
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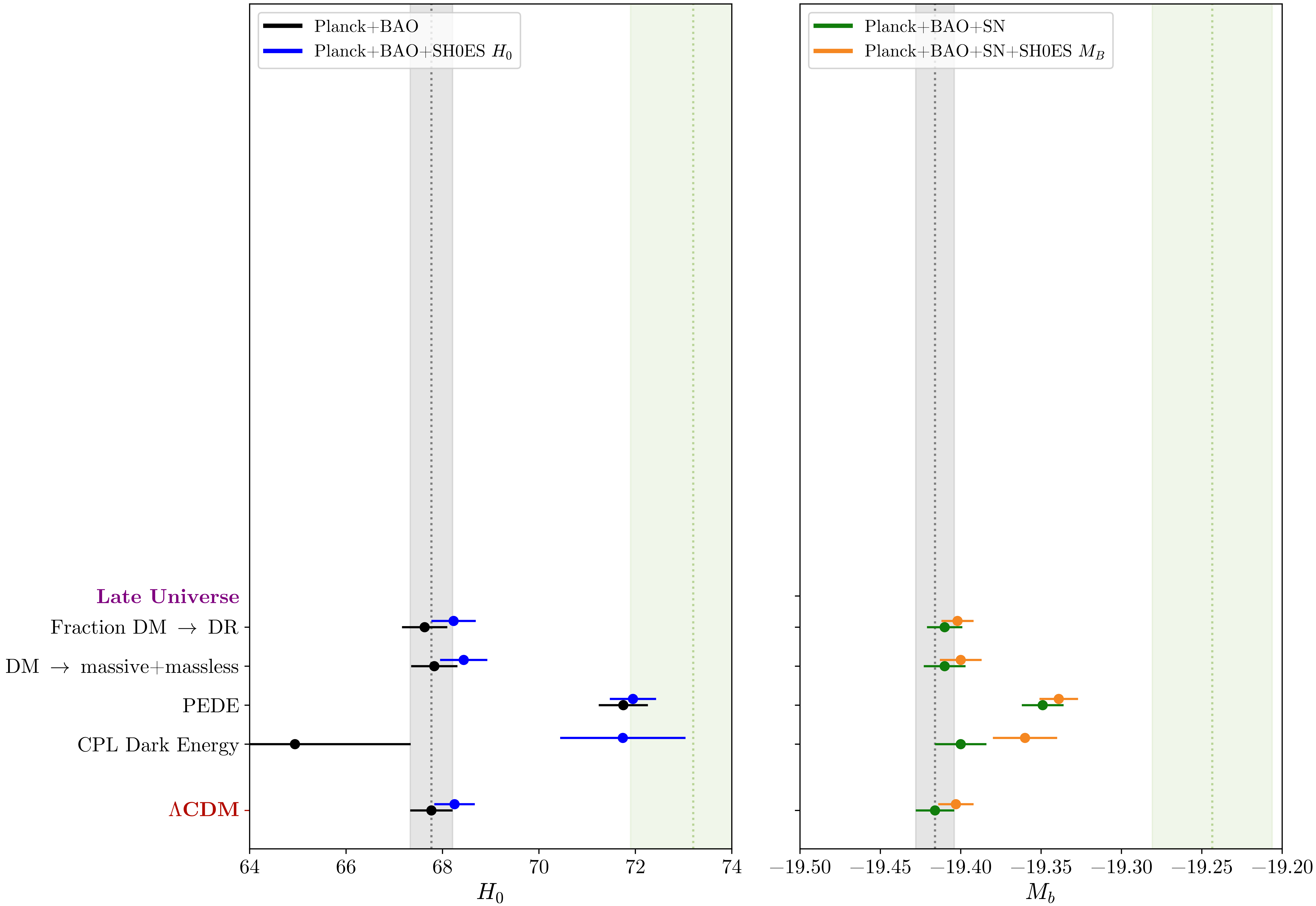
Finalists receive bronze, silver or golden medals if they satisfy one, two or three criteria, respectively

Results of the contest



Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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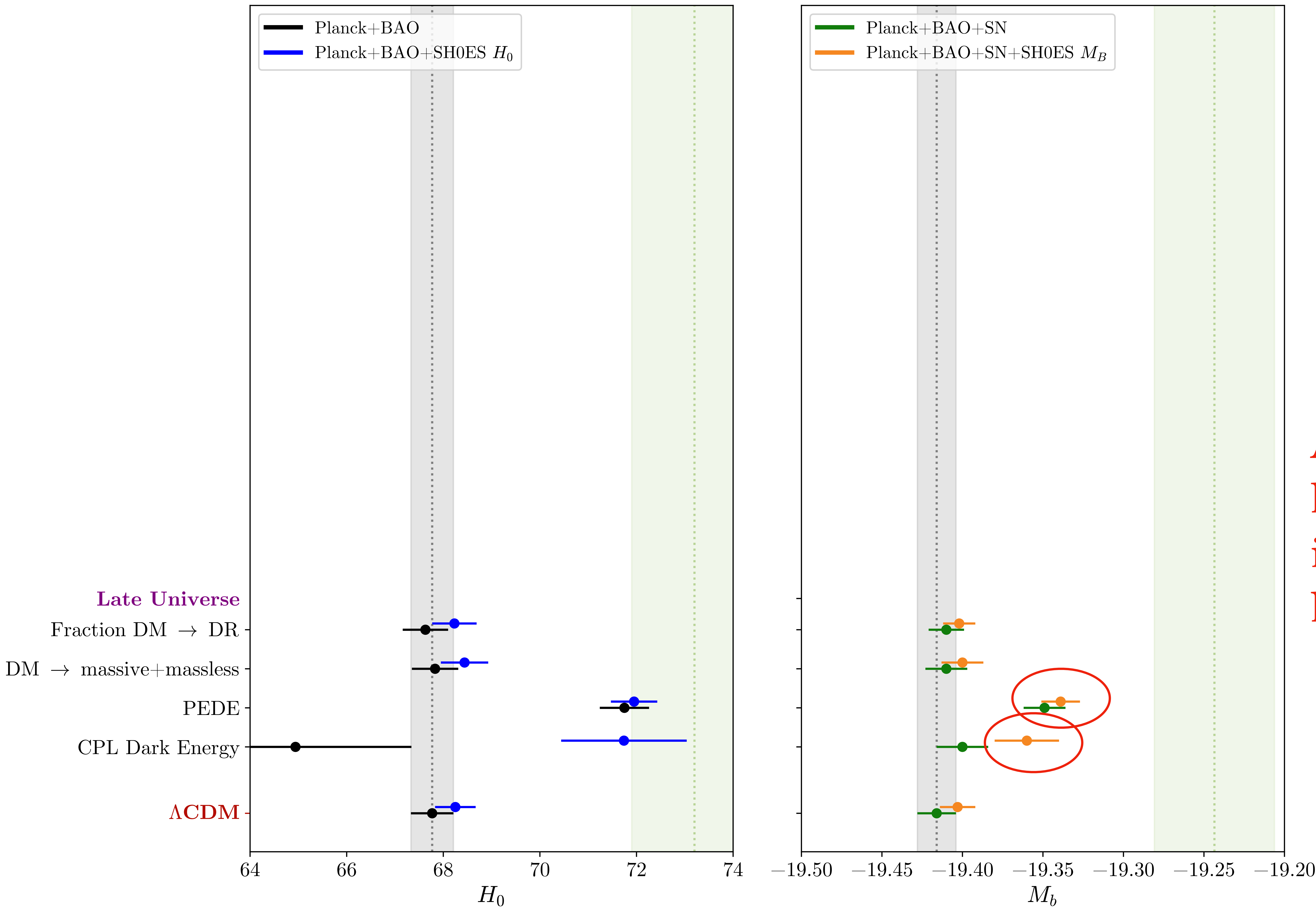
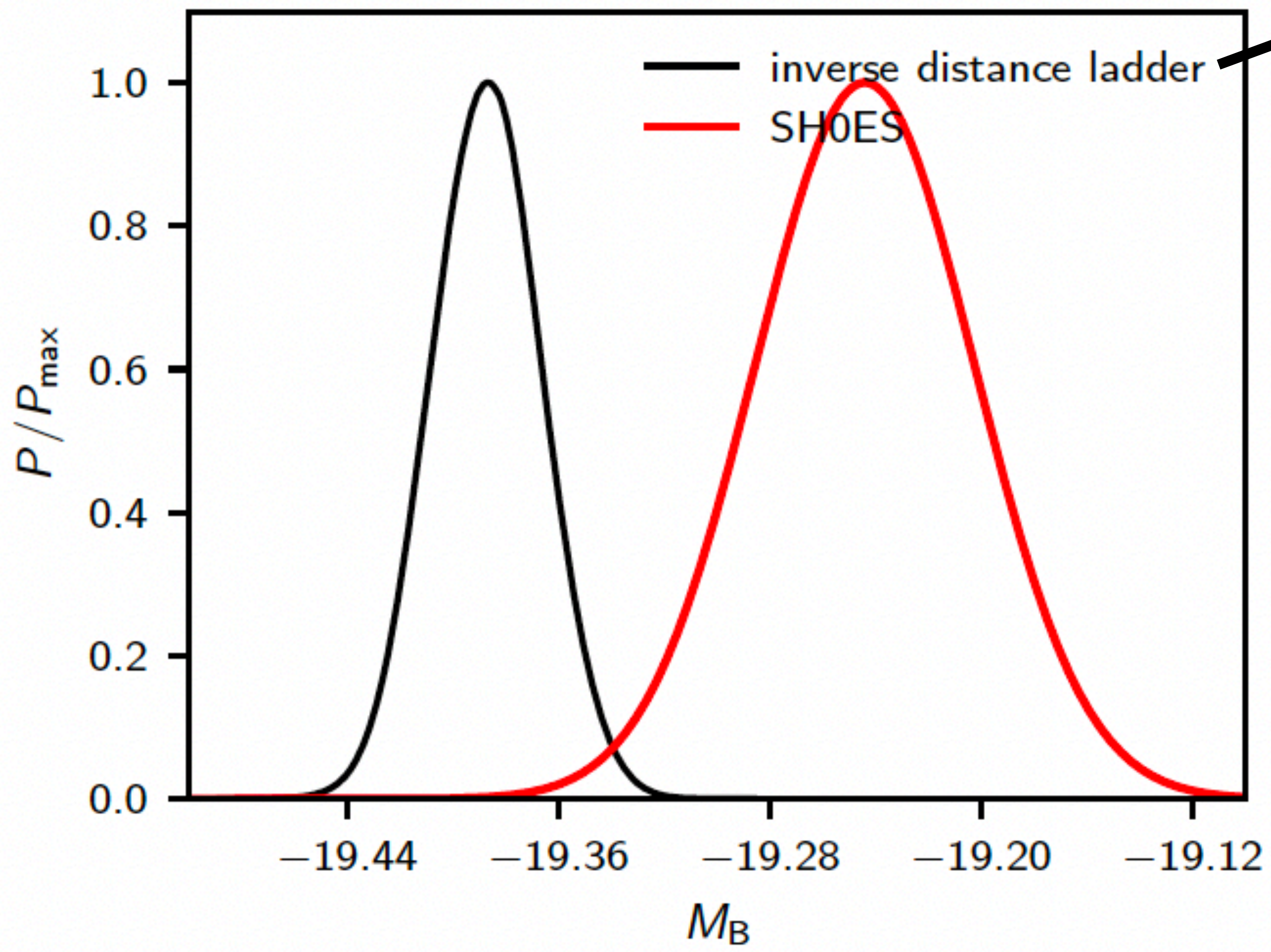


Adding Mb prior has a strong impact on late solutions!

Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

Late-time solutions are disfavoured by BAO+SNIa



Efstathiou 2103.08723

Given r_s, obtain D_A using BAO data

$$\theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)}, \quad \theta_d(z)^{\parallel} = r_s(z_{\rm drag})H(z)$$

$$D_L(z) = D_A(z)(1+z)^2$$

Obtain M_b from calibration const. of SNIa

$$m(z) = 5{\rm Log}_{10}{\rm D_L}(z) + {\rm const}$$

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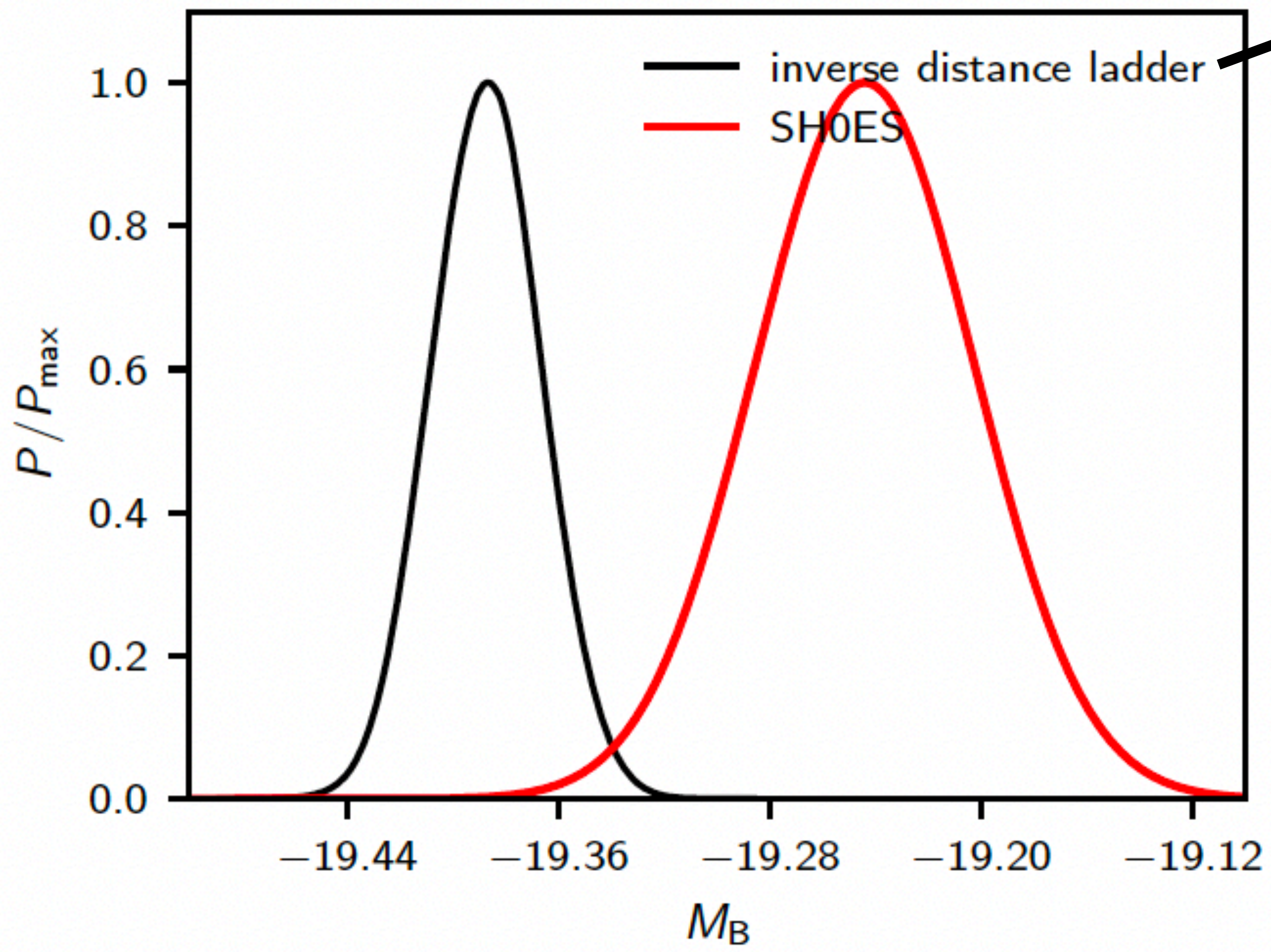

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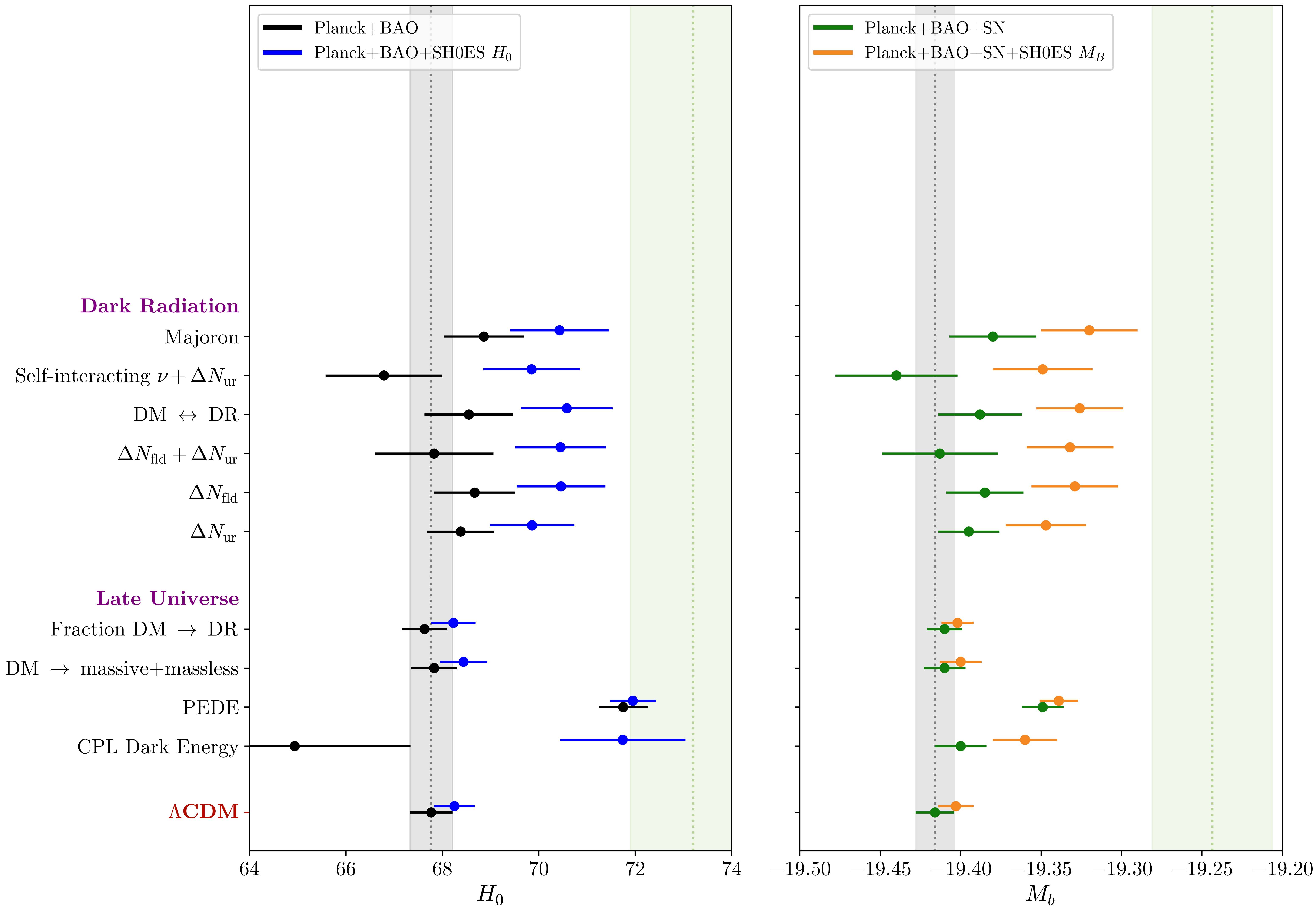
For $r_s^{\Lambda CDM} = 147$ Mpc, inverse distance ladder disagrees with SH0ES

To make the two determinations agree, one is forced to reduce r_s

Ex: *Early Dark Energy or exotic neutrino interactions*

Results of the contest



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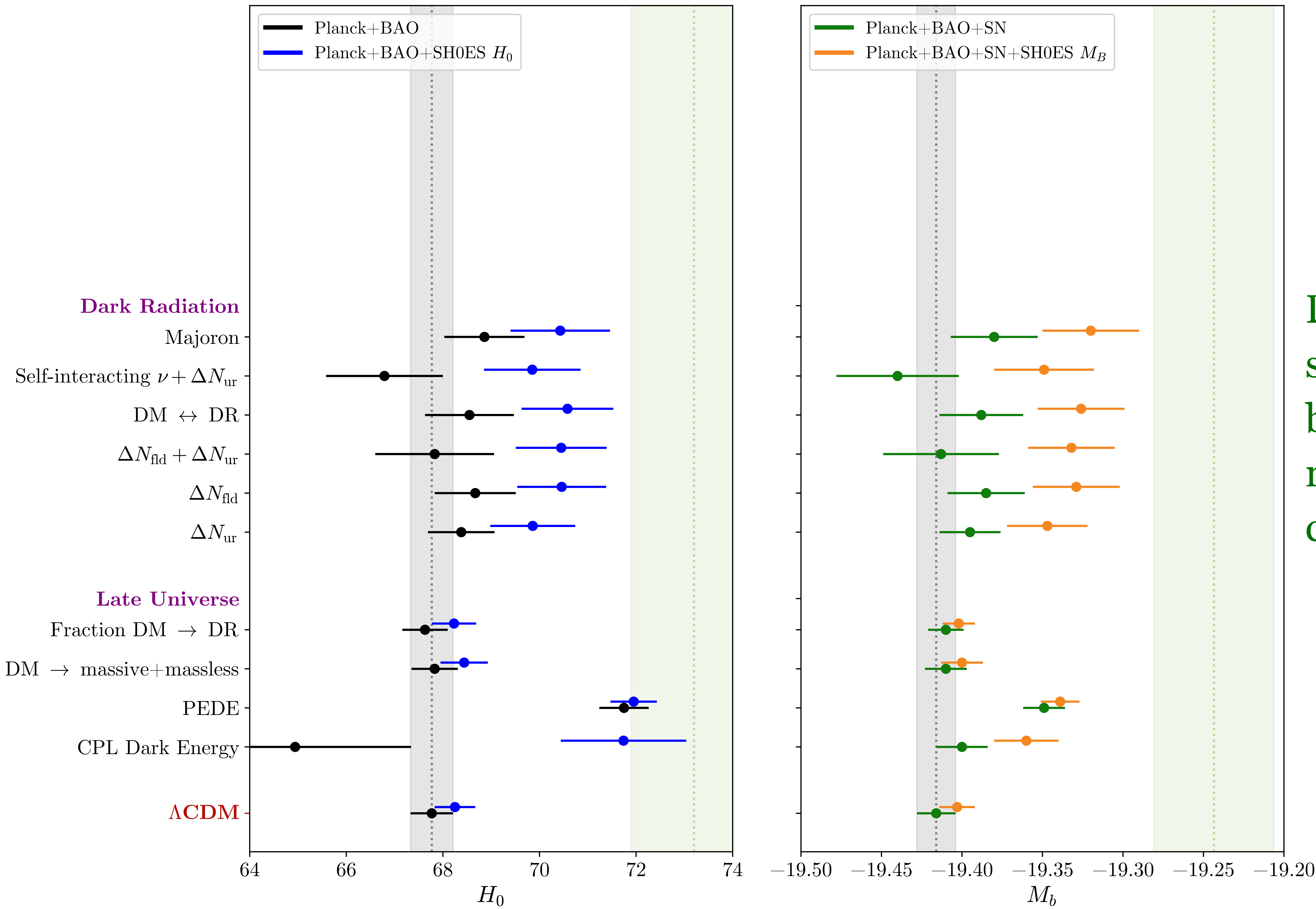

Dark radiation solutions work better, but remain very constrained

Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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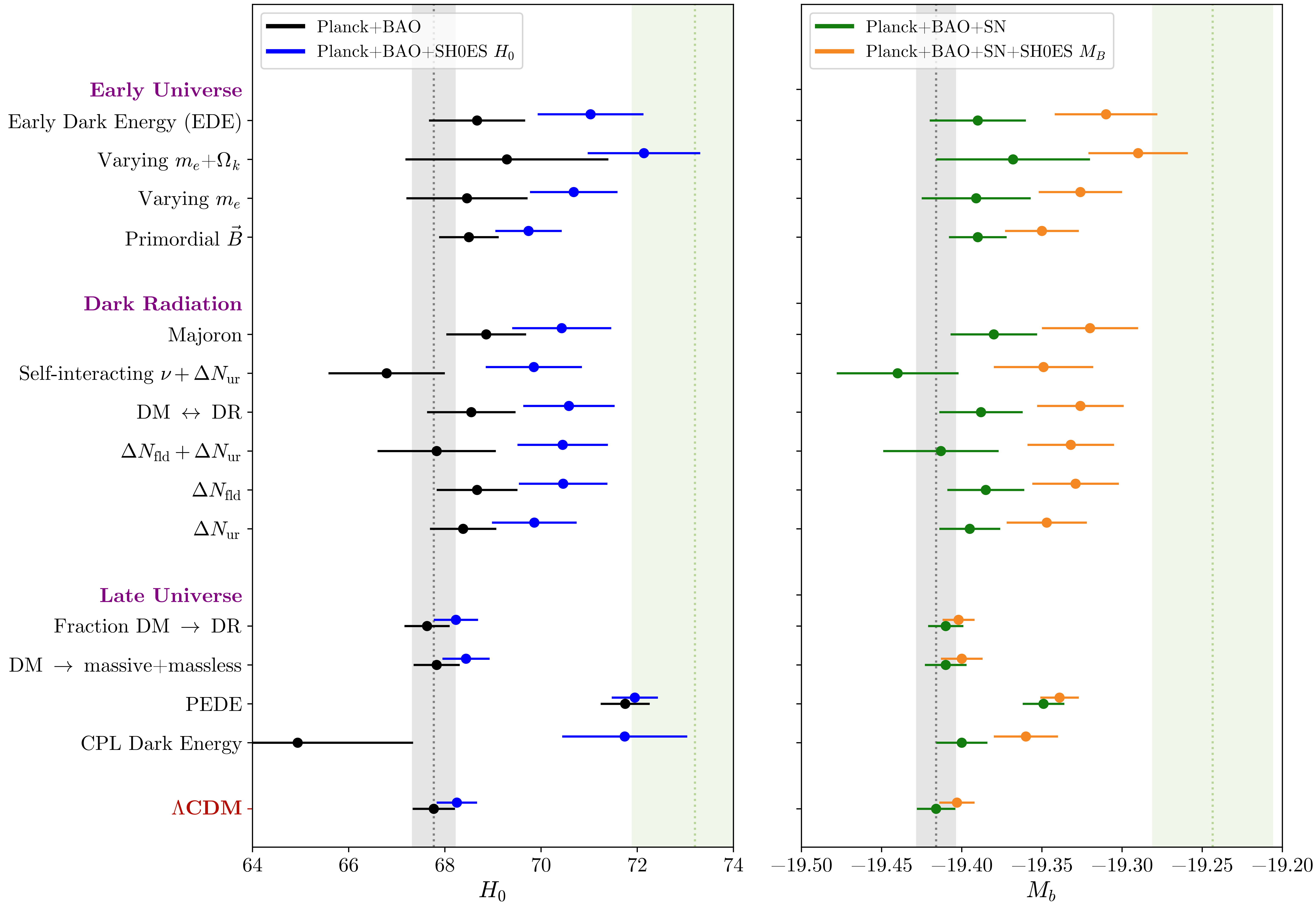

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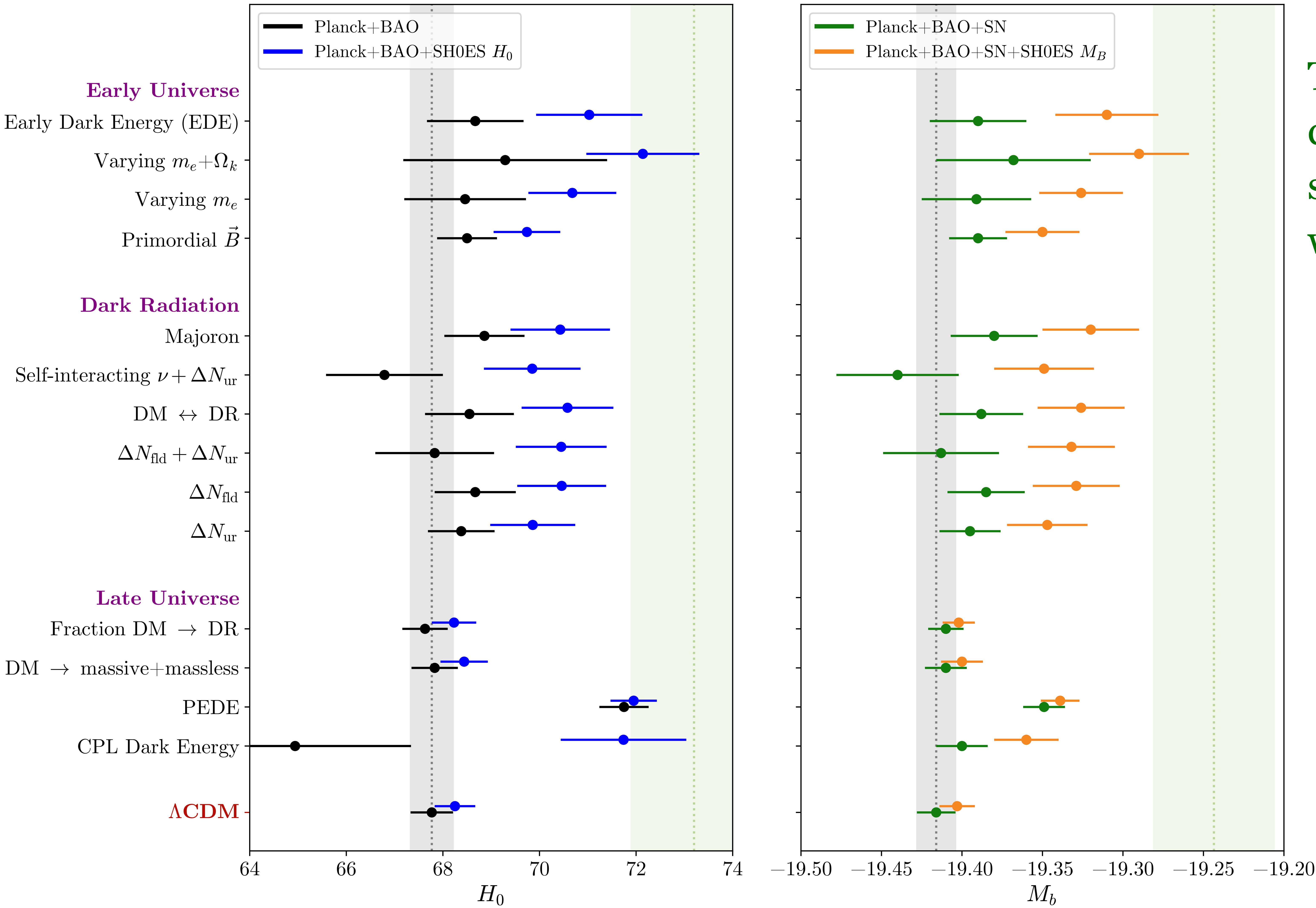

This is the category of solutions that work the best

Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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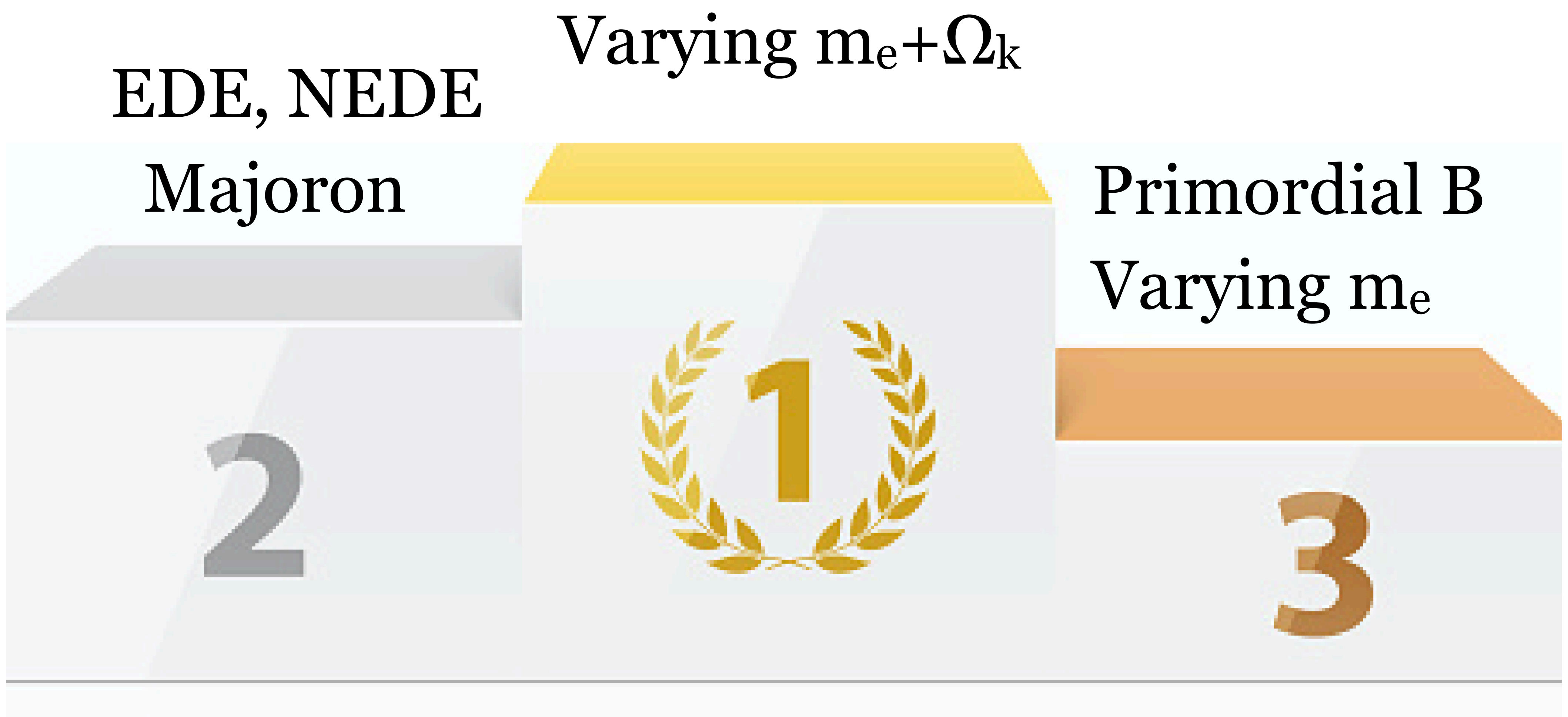
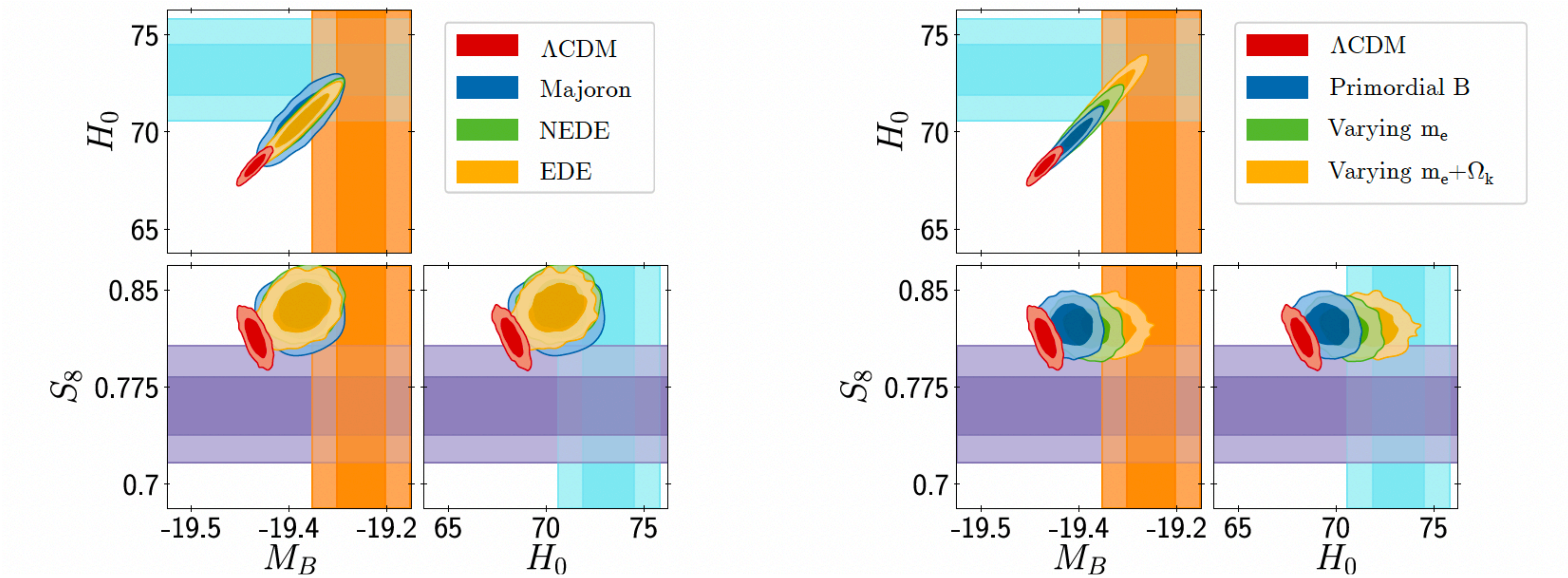


Results of the contest

Unfortunately, the most successful models are unable to explain the S_8 tension



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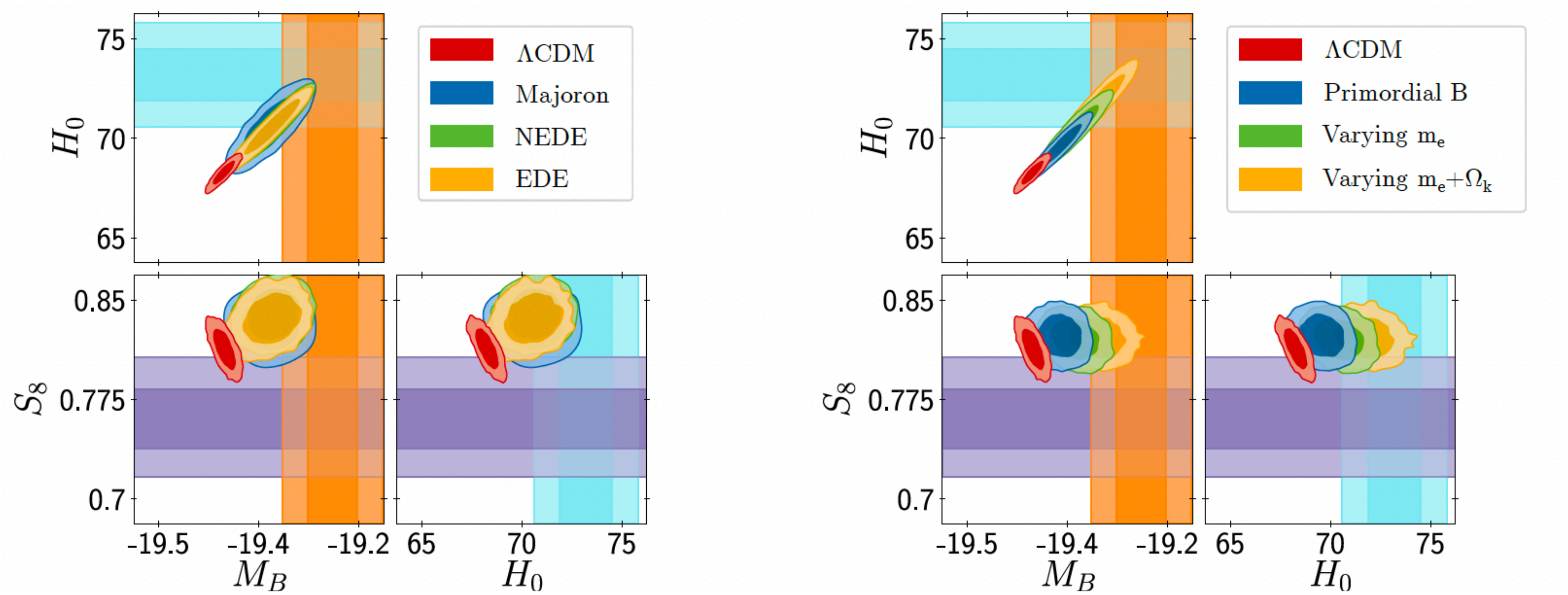

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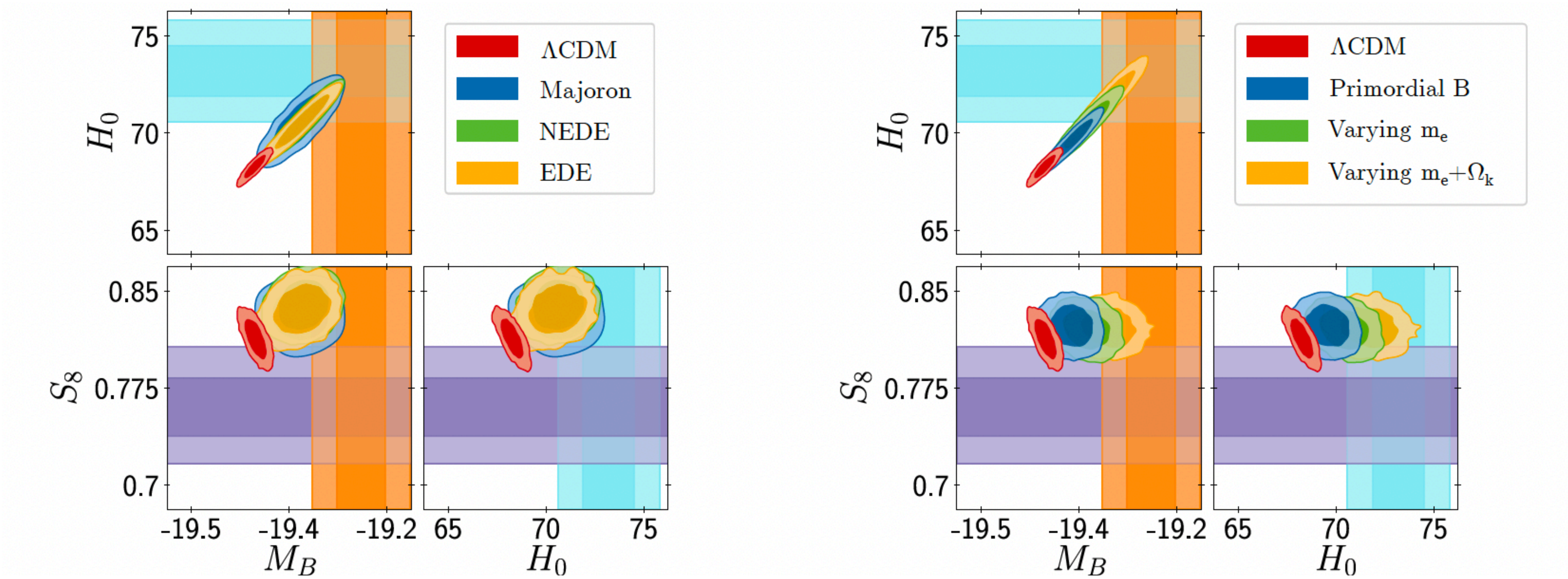

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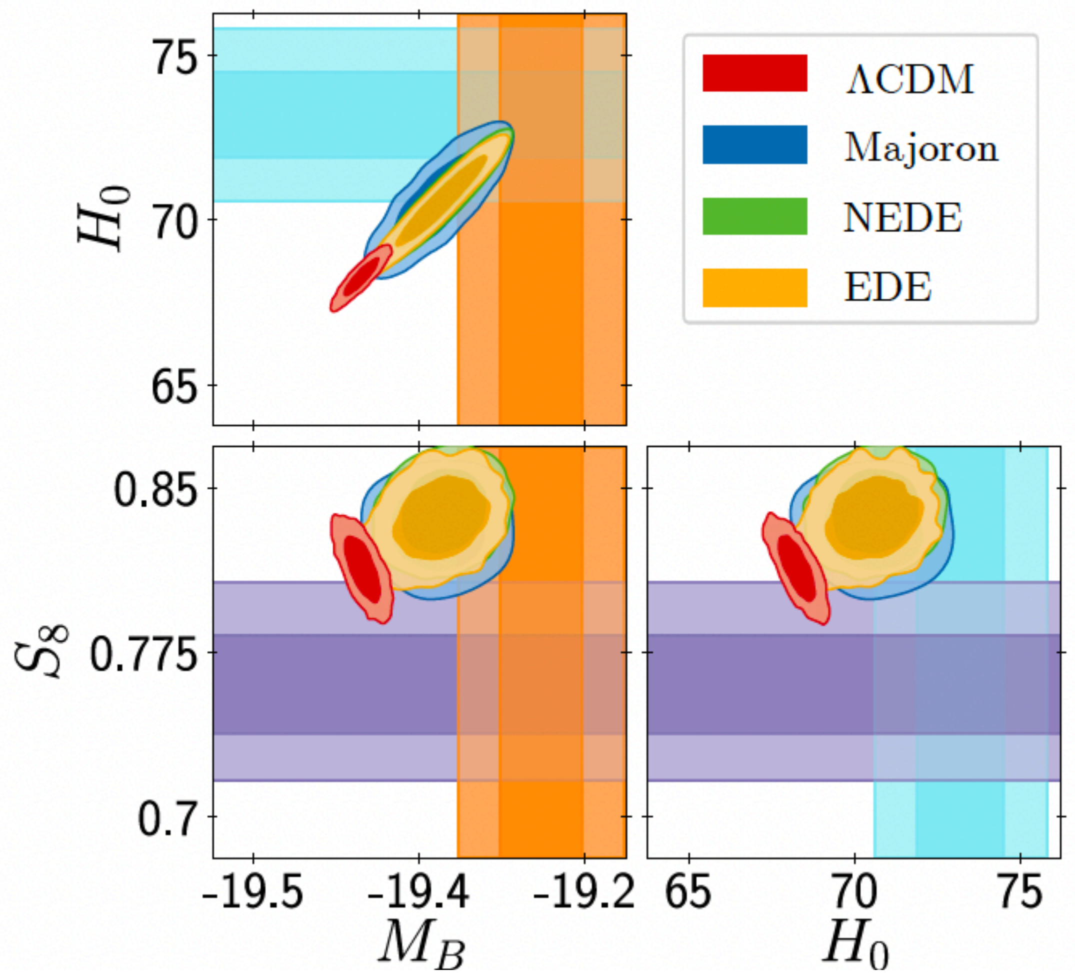

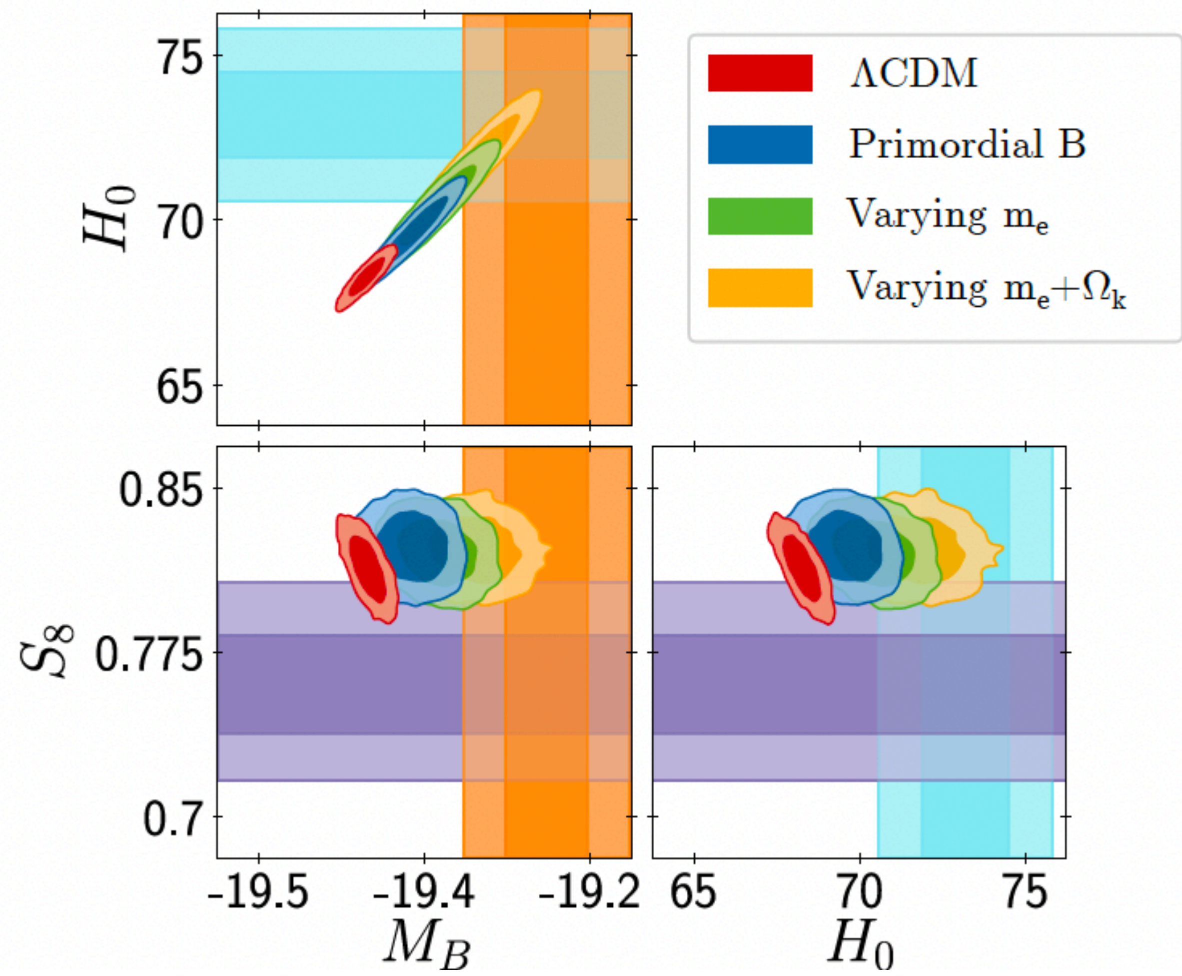

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Is there any model that could explain the S_8 anomaly?

⟶ 2-body DM decay

GFA, Murgia, Poulin 2102.12498

GFA, Murgia, Poulin, Lavalle 2008.09615

Conclusions

- ΛCDM provides a remarkable fit to many observations, but there exists a 5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

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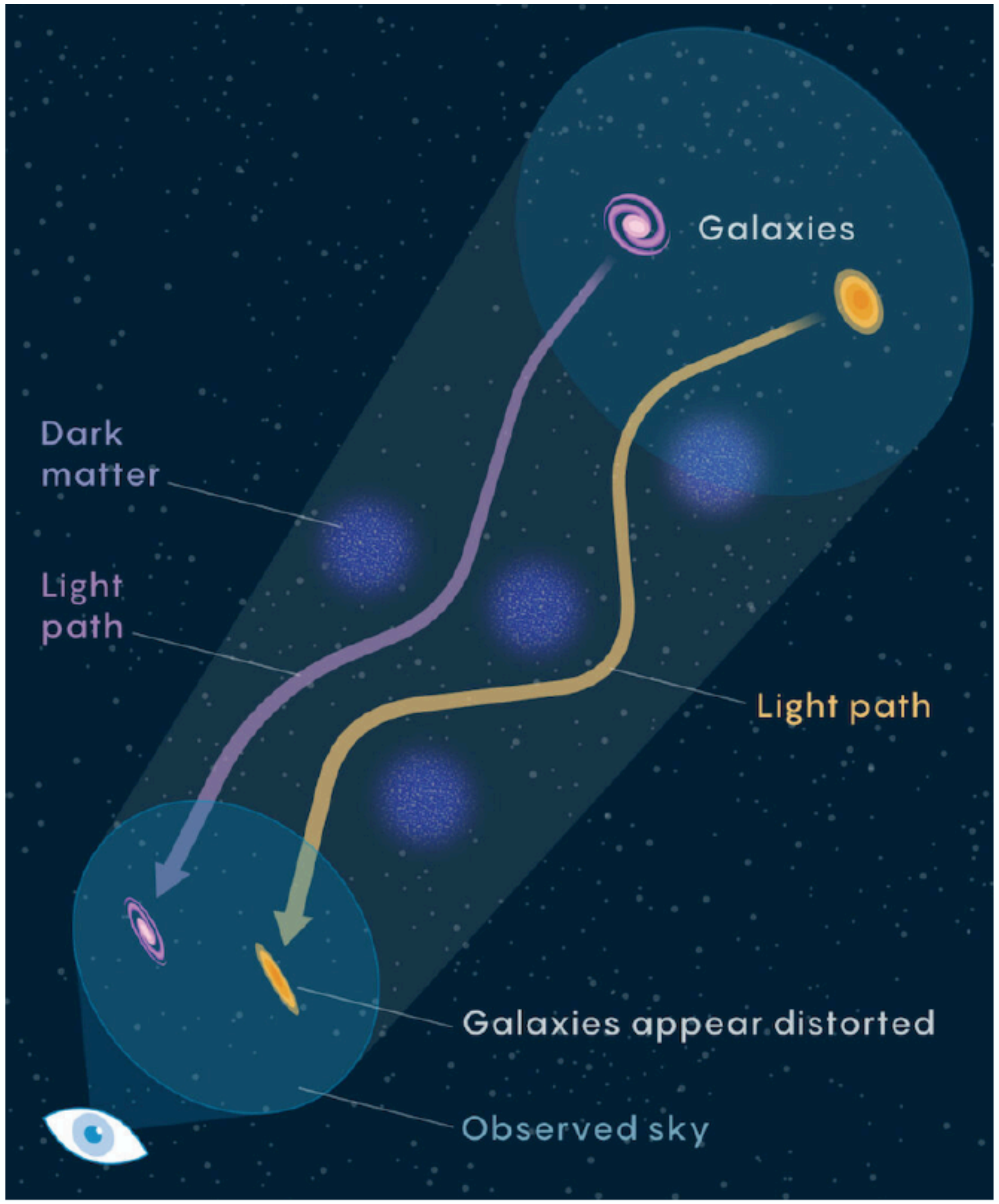
We might be on the verge of the discovery of a rich dark sector!

BACK-UP SLIDES

The S_8 tension

Weak-lensing surveys are mainly sensible to $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$



KiDS+BOSS+2dfLenS*:

$$S_8 = 0.766^{+0.020}_{-0.014}$$

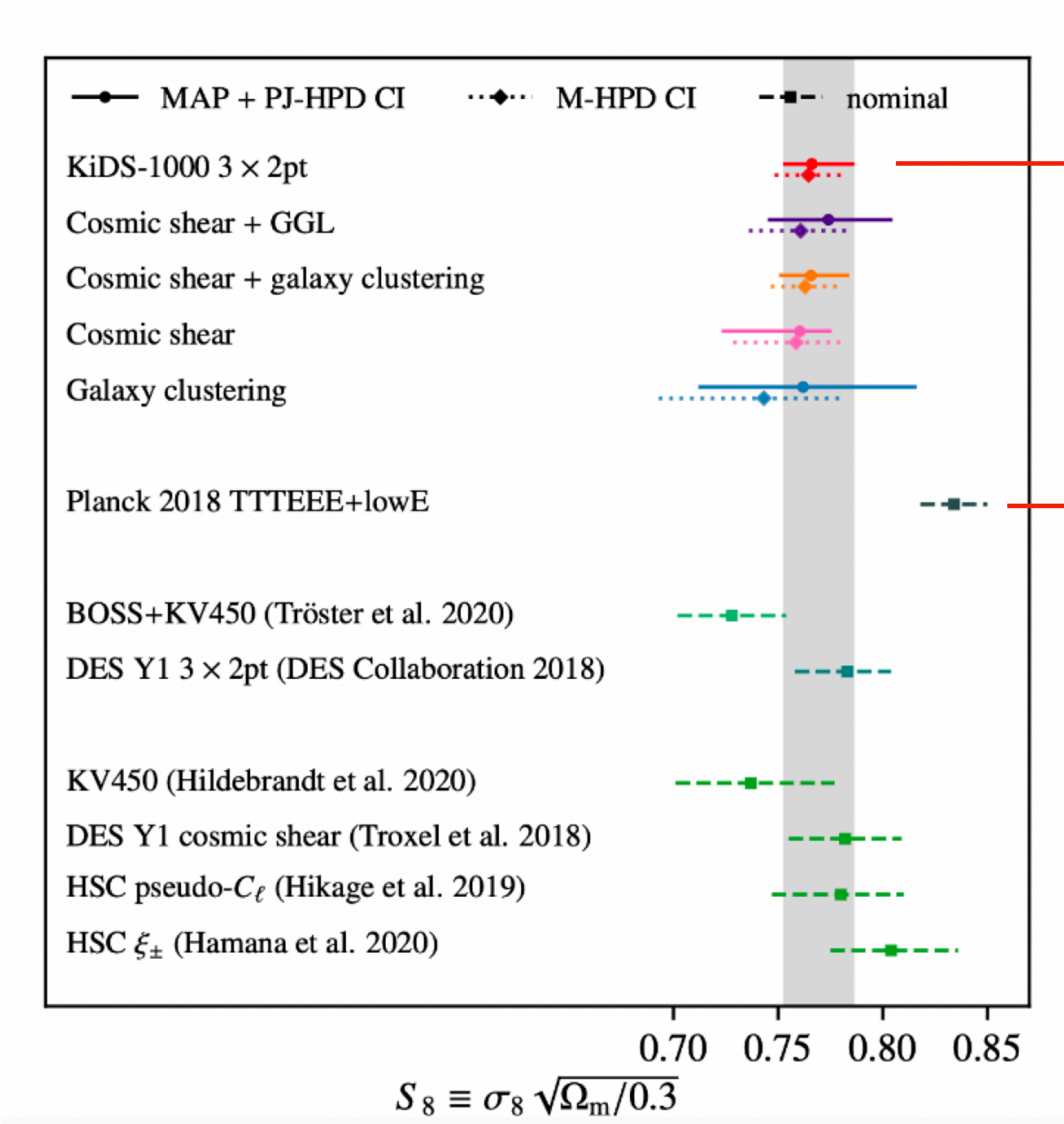
Planck (*under ΛCDM*):

$$S_8 = 0.830 \pm 0.013$$

$\rightarrow \sim \mathbf{2-3}\sigma$ tension

*Other surveys such as DES, CFHTLens or HSC yield similar results

The S₈ tension



$$S_8 = 0.766^{+0.020}_{-0.014}$$

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$$\Longrightarrow \sim 3\sigma \text{ tension}$$

Di Valentino++ 2008.11285

How does SH0ES determine H_0?

$$v = H_0 D$$

From spectrometry

$$1 + z = \frac{\lambda_{obs}}{\lambda_{emit}}$$

Distance to some standard candle, e.g. supernovae Ia

$$\mathrm{Flux} = \frac{\mathrm{L}}{4\pi \mathrm{D}_\mathrm{L}^2}$$

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Focus on small z*, for which distances are approx. model-independent

$$D_L = (1+z)\int_0^z \frac{c\,dz'}{H(z')} \xrightarrow{z\ll 1} czH_0^{-1} \simeq vH_0^{-1}$$

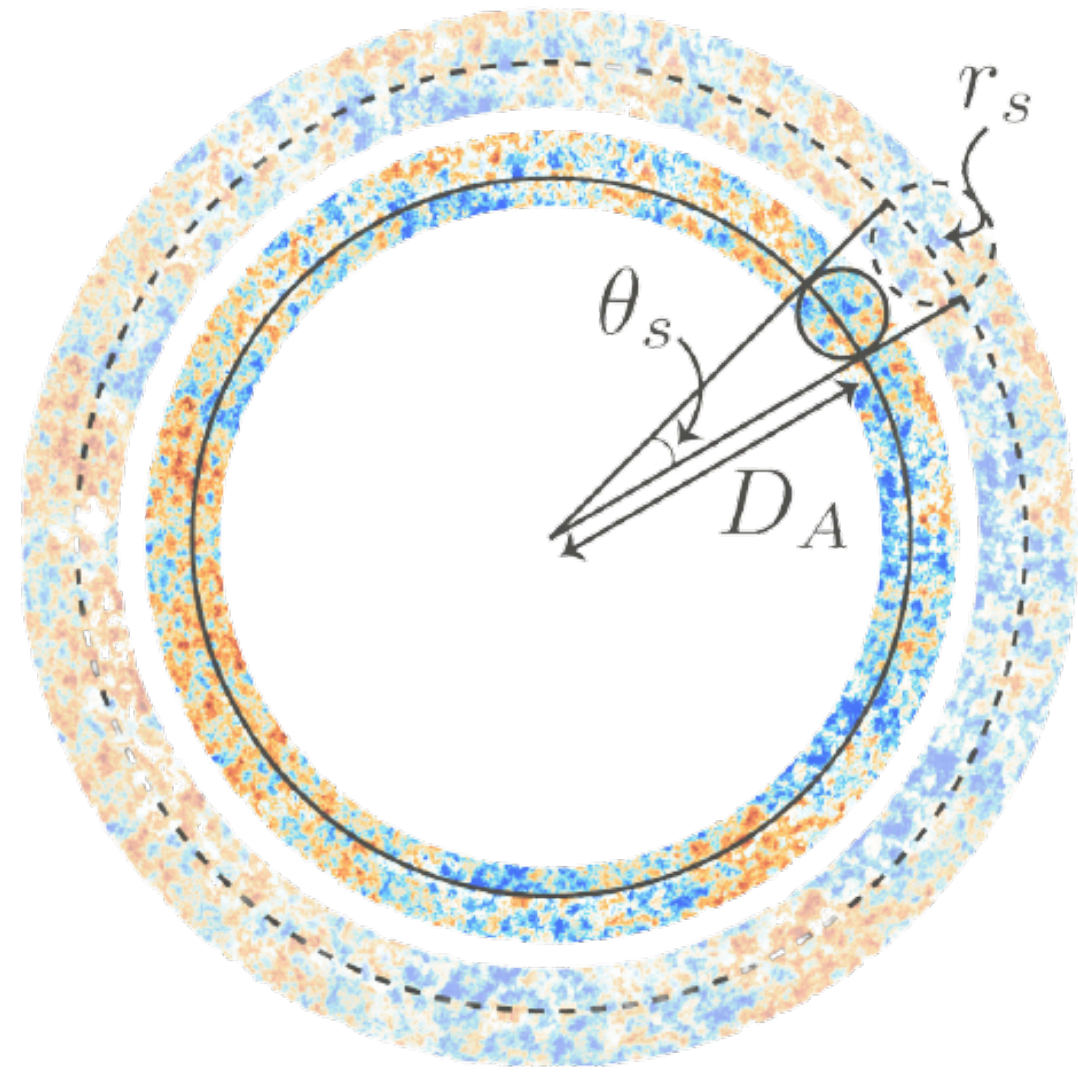
$$\text{where } \mathrm{H^2(z)} = \frac{8\pi \mathrm{G}}{3}\sum_{\mathrm{i}} \rho_{\mathrm{i}}(\mathrm{z})$$

*But not too small, to make sure peculiar velocities are negligible

How does Planck determine H_0?

Angular size of the sound horizon is measured at the 0.04 % precision

$$\theta_s = \frac{r_s(z_{\rm rec})}{D_A(z_{\rm rec})} = \frac{\int_0^{\tau_{\rm rec}} c_s(\tau) d\tau}{\int_{\tau_{\rm rec}}^{\tau_0} c d\tau}$$



T. Smith

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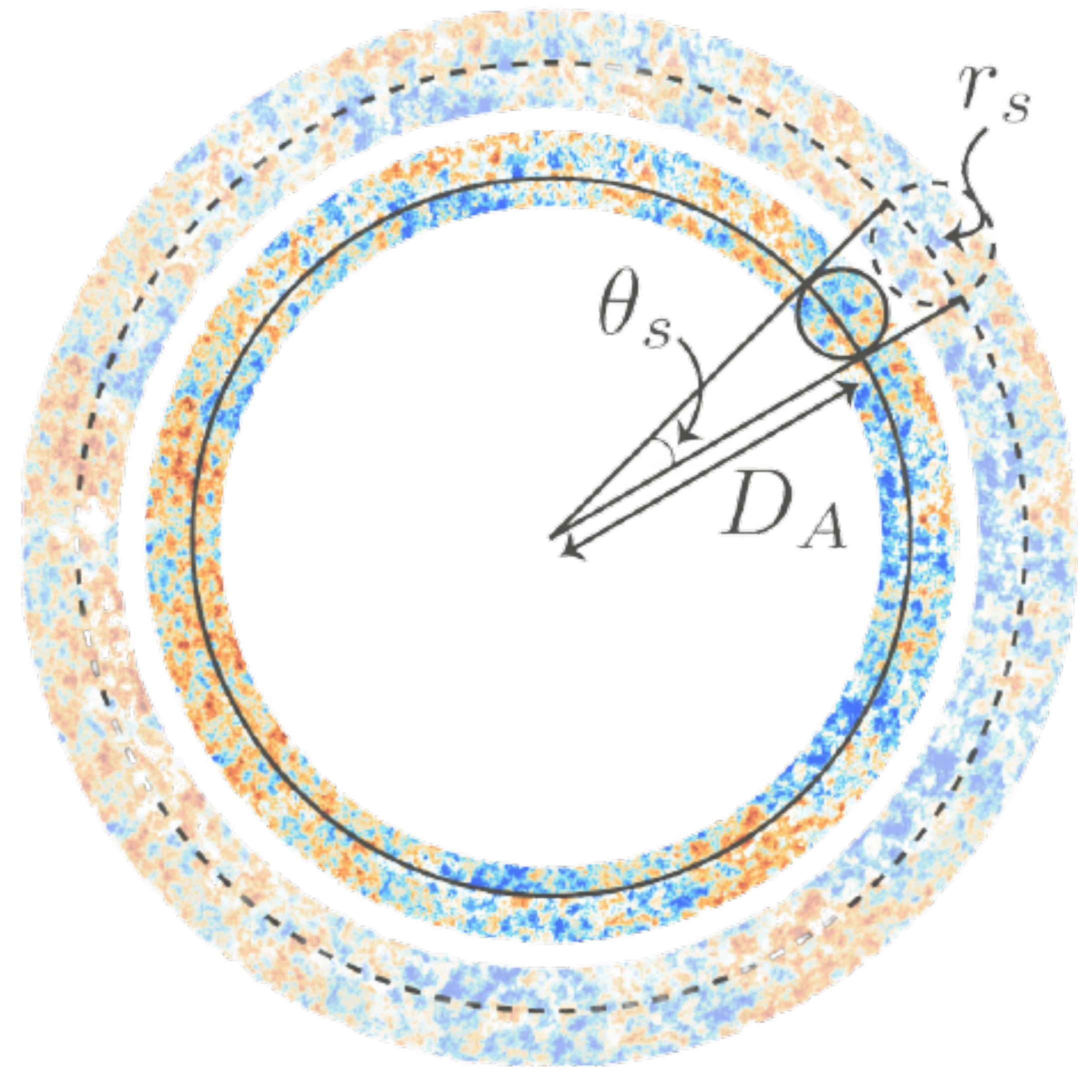
with $D_A \propto 1/H_0 = 1/\sqrt{\rho_{\rm tot}(0)}$

model prediction of r_s + measurement of $\theta_s \longrightarrow H_0$



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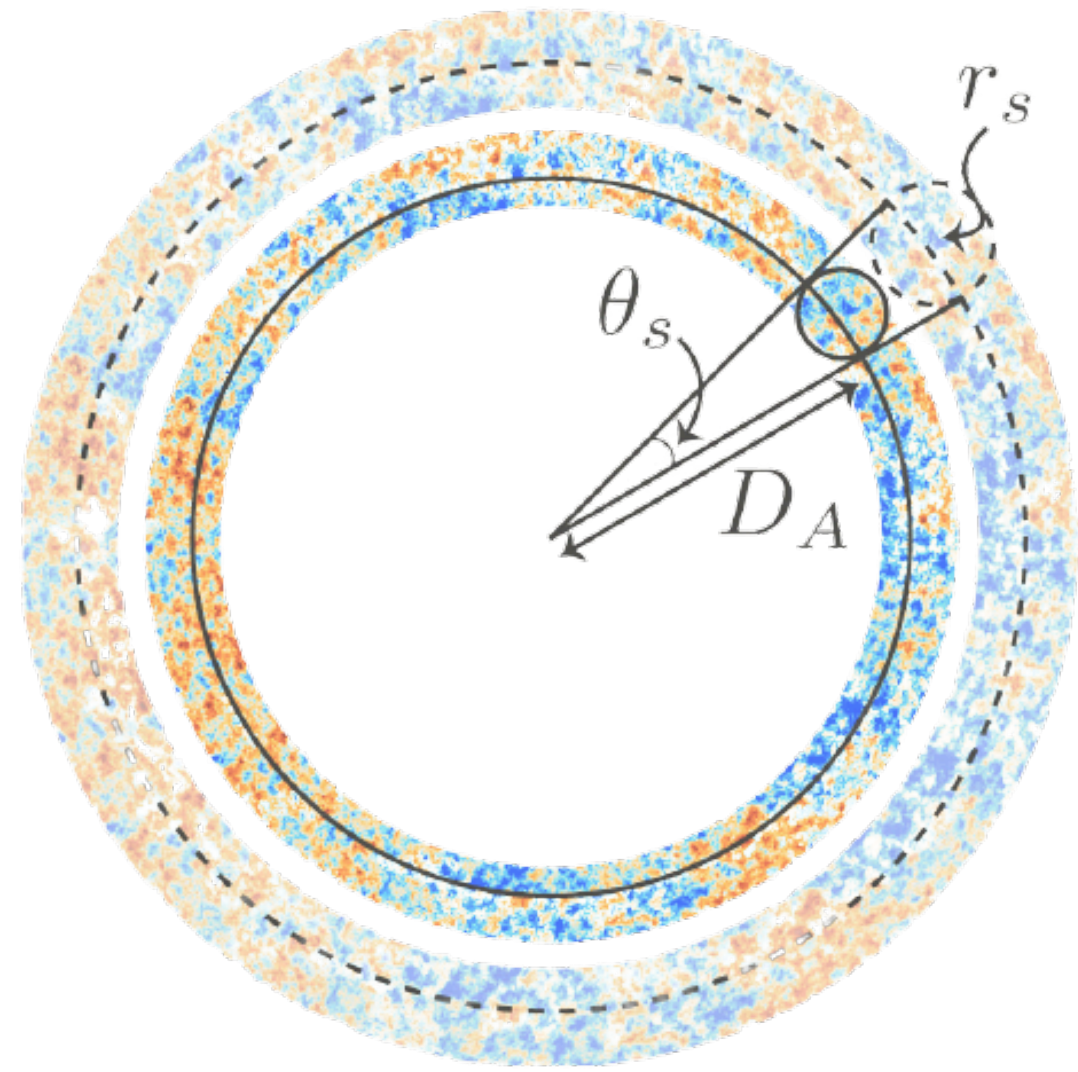

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Early-time solutions

Decrease $r_s(z_{rec})$ at fixed θ_s to decrease $D_A(z_{rec})$ and increase H_0

Ex : $\Delta N_{eff} > 0$

Late-time solutions

$r_s(z_{rec})$ and $D_A(z_{rec})$ are fixed, but $D_A(z < z_{rec})$ is changed to allow higher H_0

Ex : $w < -1$

H_0 Olympics: testing against other datasets

Role of Planck data: We replaced Planck by WMAP+ACT and BBN+BAO

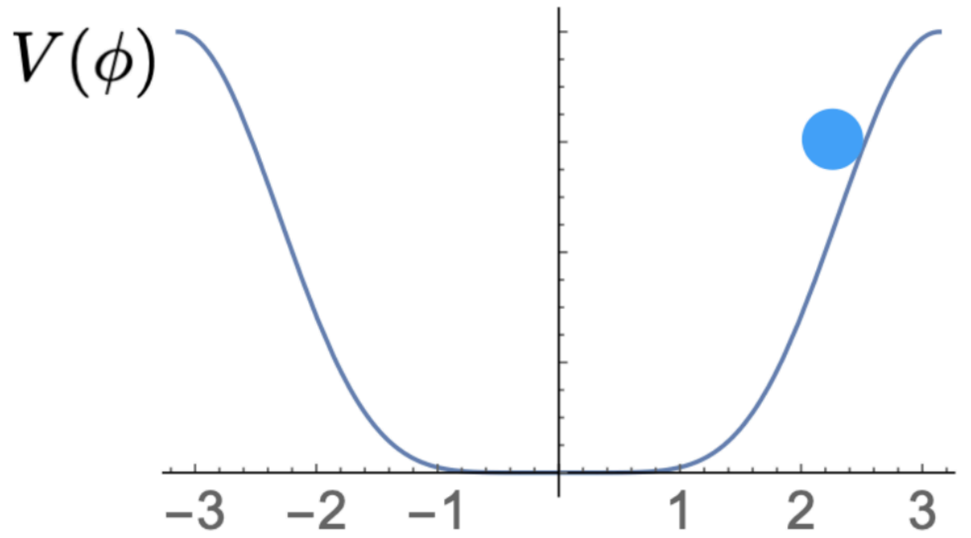
⟶ No significant changes (*notable exceptions are EDE and NEDE*)

Adding extra datasets: We included data from Cosmic Chronometers, Redshift-Space-Distortions and BAO Ly-α.

⟶ No huge impact, but decreases performance of finalist models

Early Dark Energy

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$



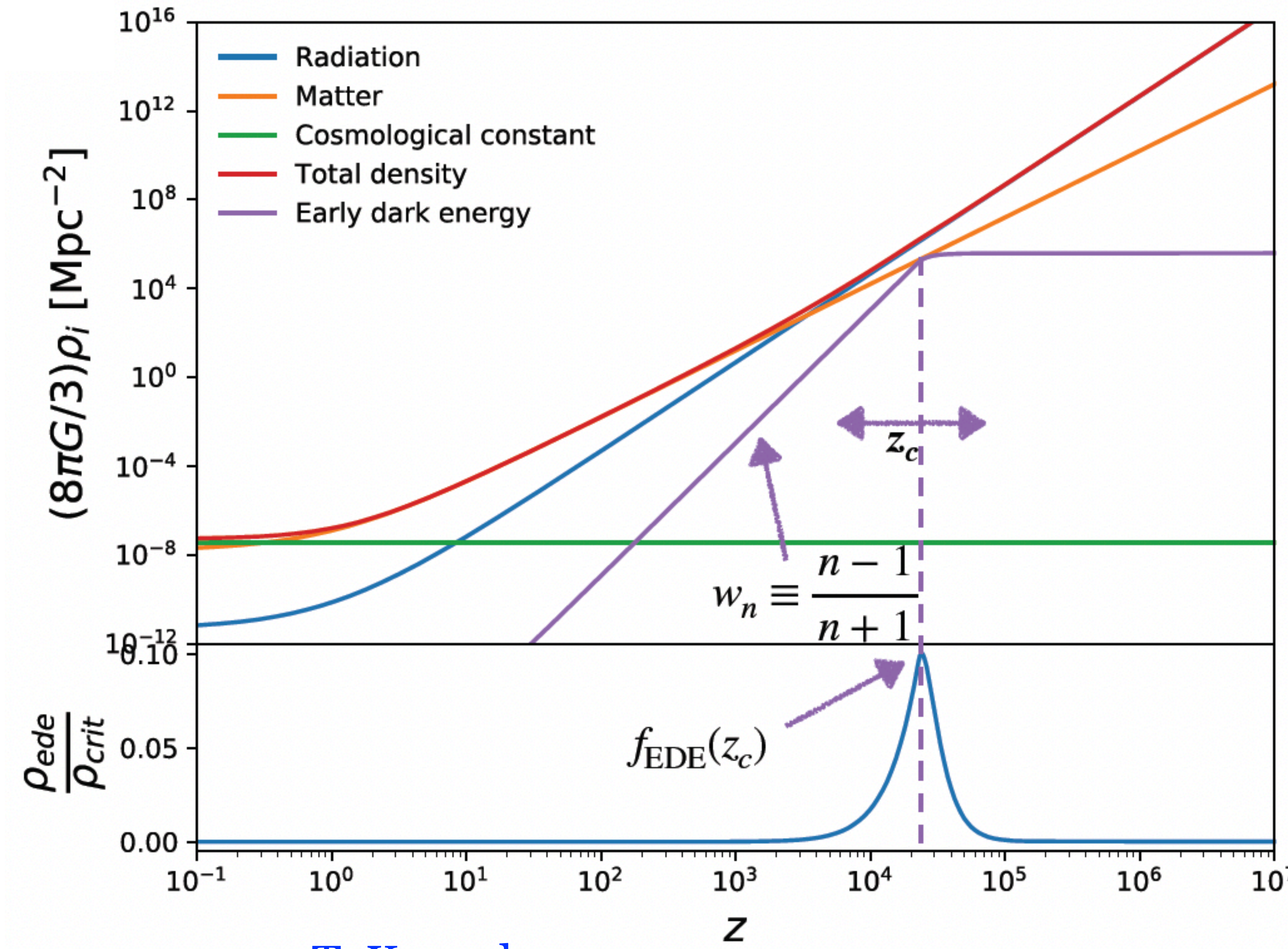
Scalar field initially frozen, then dilutes away equal or faster than radiation

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

+ perturbed linear eqs.

The model is fully specified by

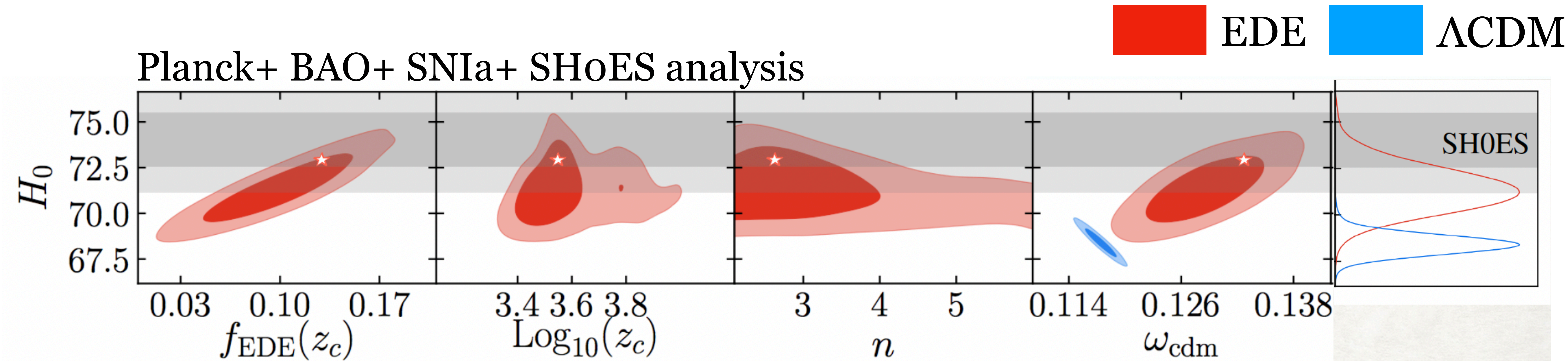
$$\{f_{\rm EDE}(z_c),\ z_c,\ n,\ \phi_i\}$$



T. Karwal

Early Dark Energy

Early Dark Energy can resolve the H_0 tension if $f_{EDE}(z_c) \sim 10\,\%$ for $z_c \sim z_{eq}$



Poulin++ 1811.04083 Smith++ 1908.06995

Some caveats

1. *Very fine tuned?*

⟶ Proposed connexions of EDE with neutrino sector and present DE

Sakstein++ 1911.11760 Freese++ 2102.13655

2. Increased value of $\omega_{cdm} = \Omega_{cdm} h^2$, *exacerbates S_8 tension*

Jedamzik++ 2010.04158.