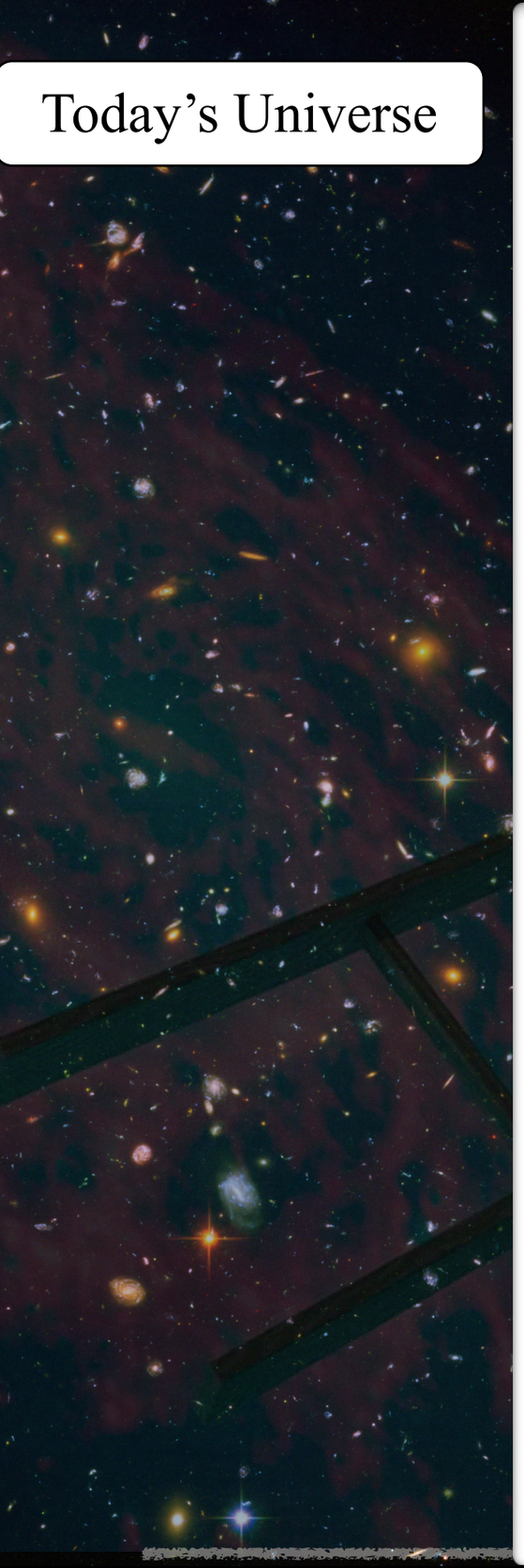
Today's Universe



The cosmic calibration tension

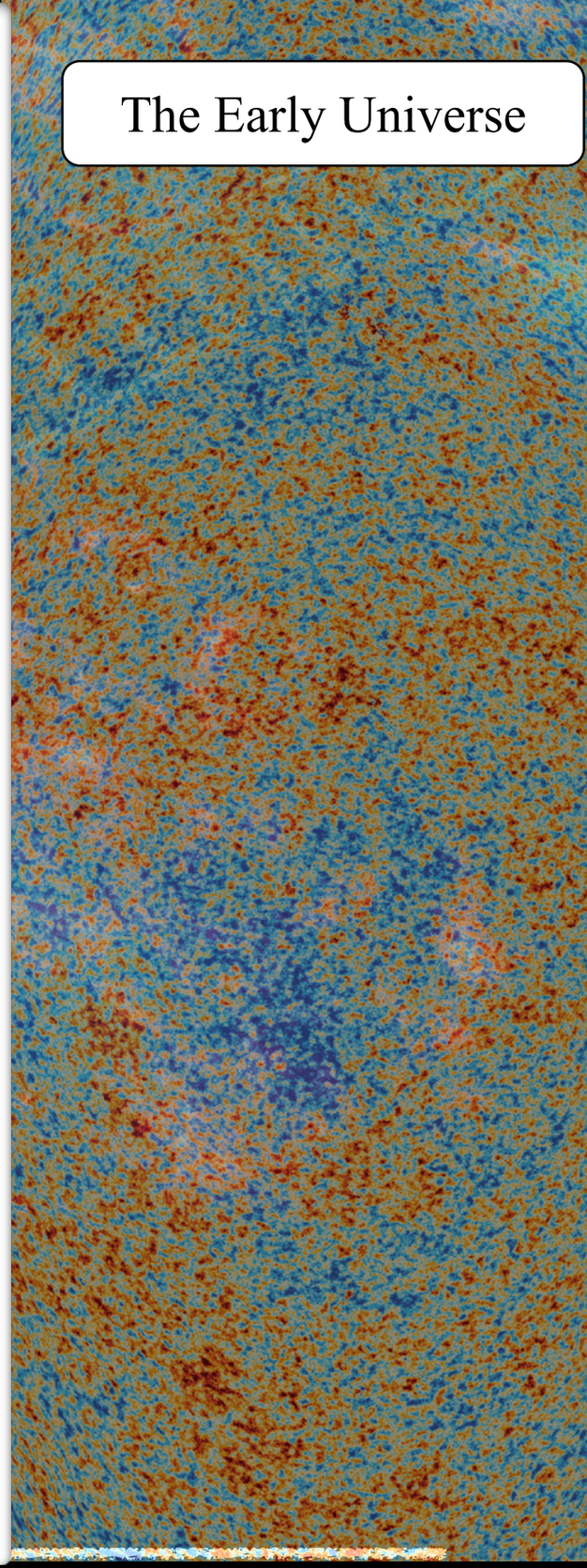
And why we should stop calling it "Hubble tension"

Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

vivian.poulin@umontpellier.fr

The Early Universe



EuCAPT Rapid Response Workshop
CERN (online)
September, 12th 2024

LUPM LABORATOIRE MONTPELLIER UNIVERS & PARTICULES
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erc European Research Council Established by the European Commission

Calibrating the Ladder: the "direct" way

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

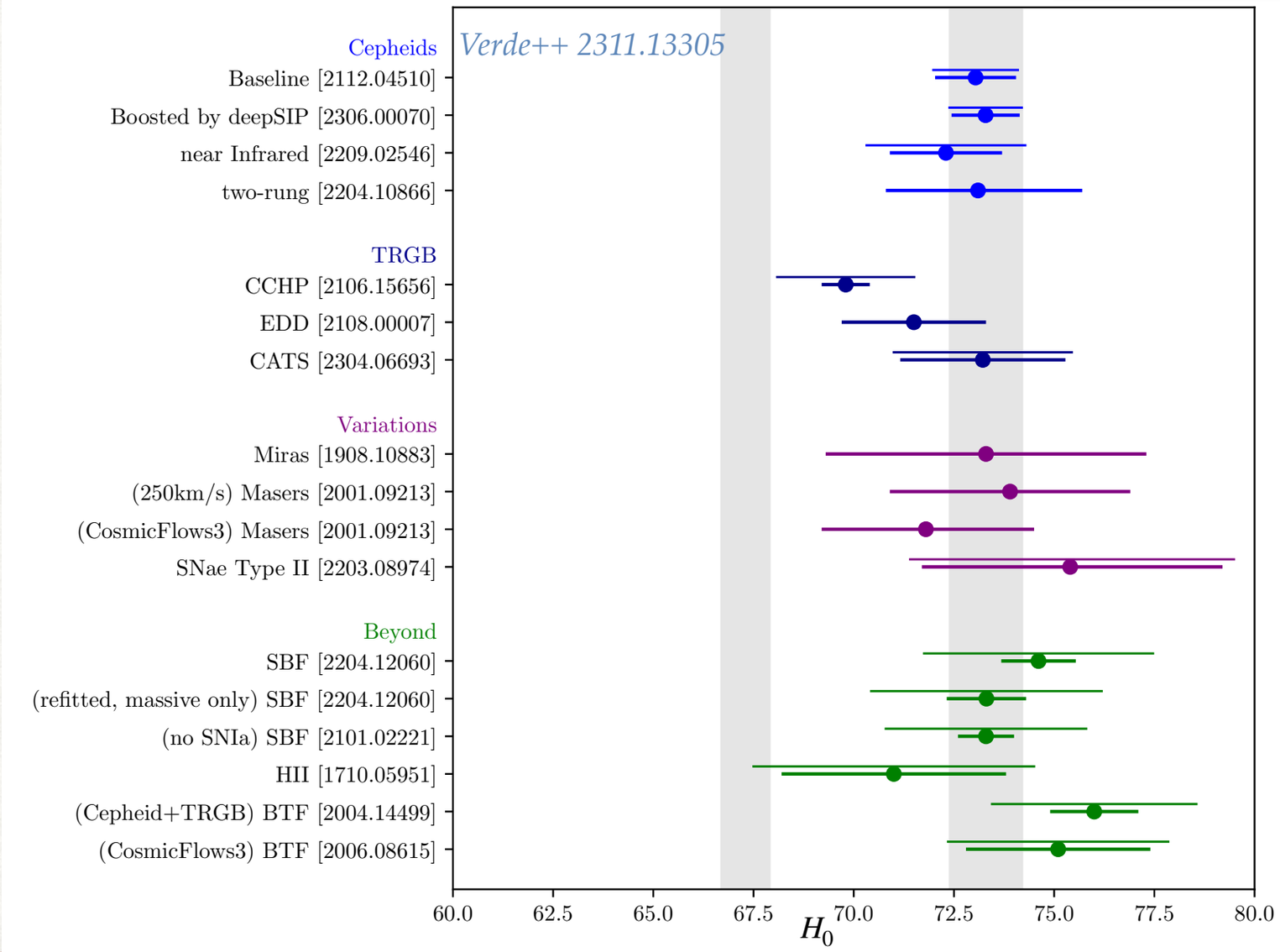
Measured

Requires calibration

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

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

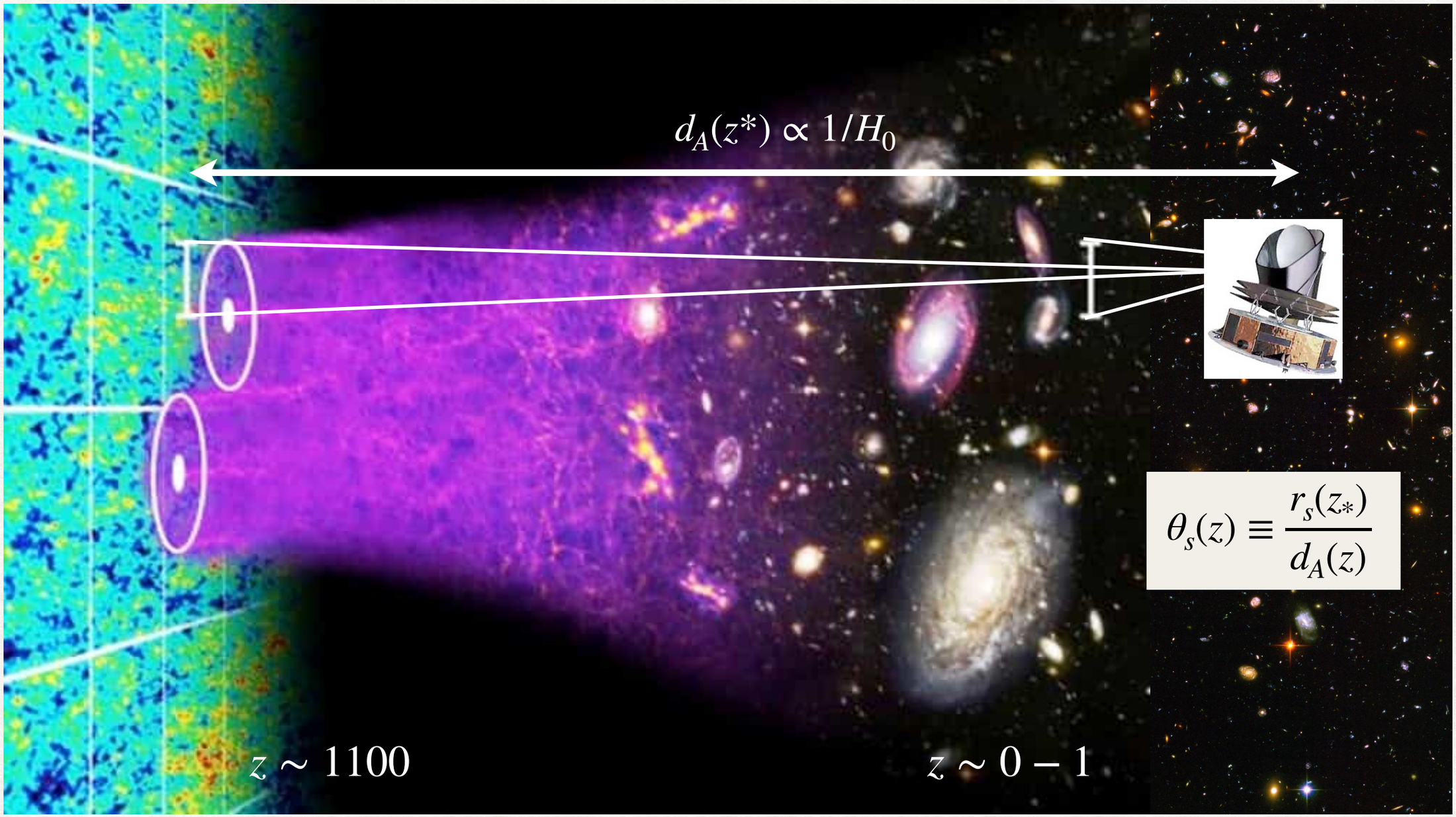
$$m - M = 5\log(D_L/10\text{pc})$$
$$D_L \sim czH_0^{-1}, \quad z \ll 1$$



Adapted from slide by A. Riess, KITP July 2019

Calibrating the ladder: the "indirect" way

- 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*

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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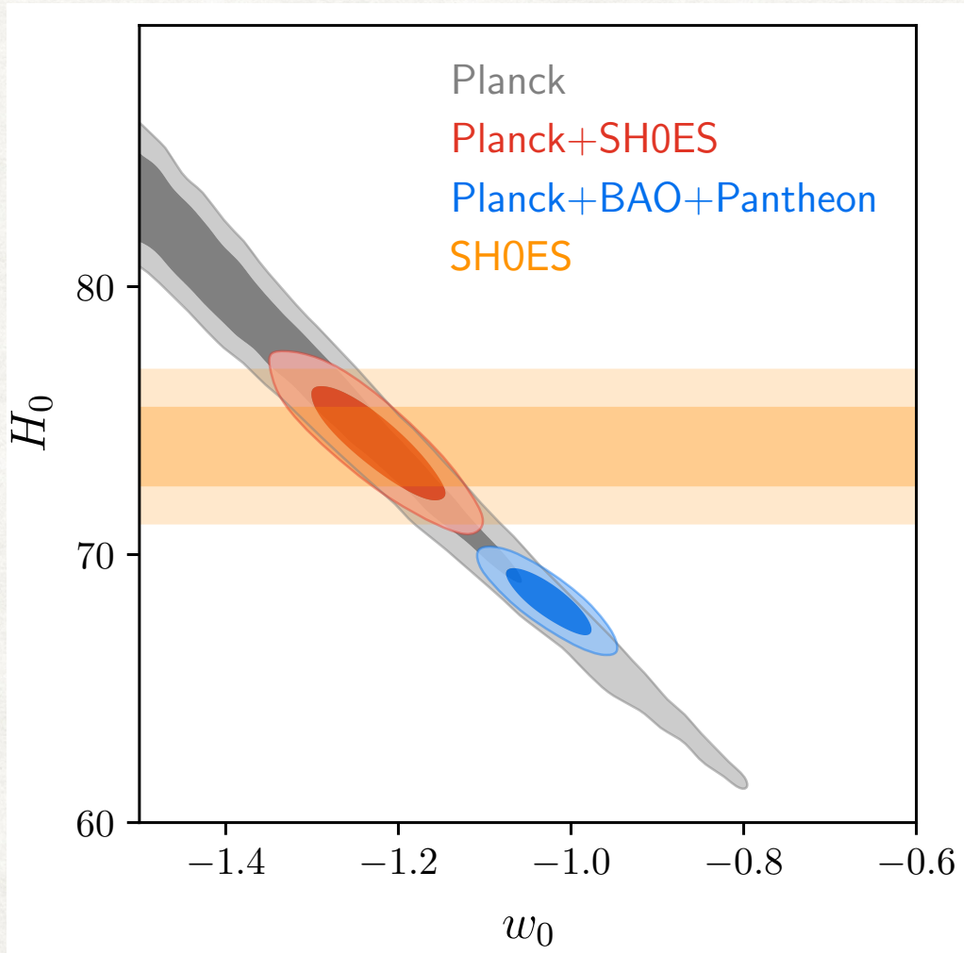

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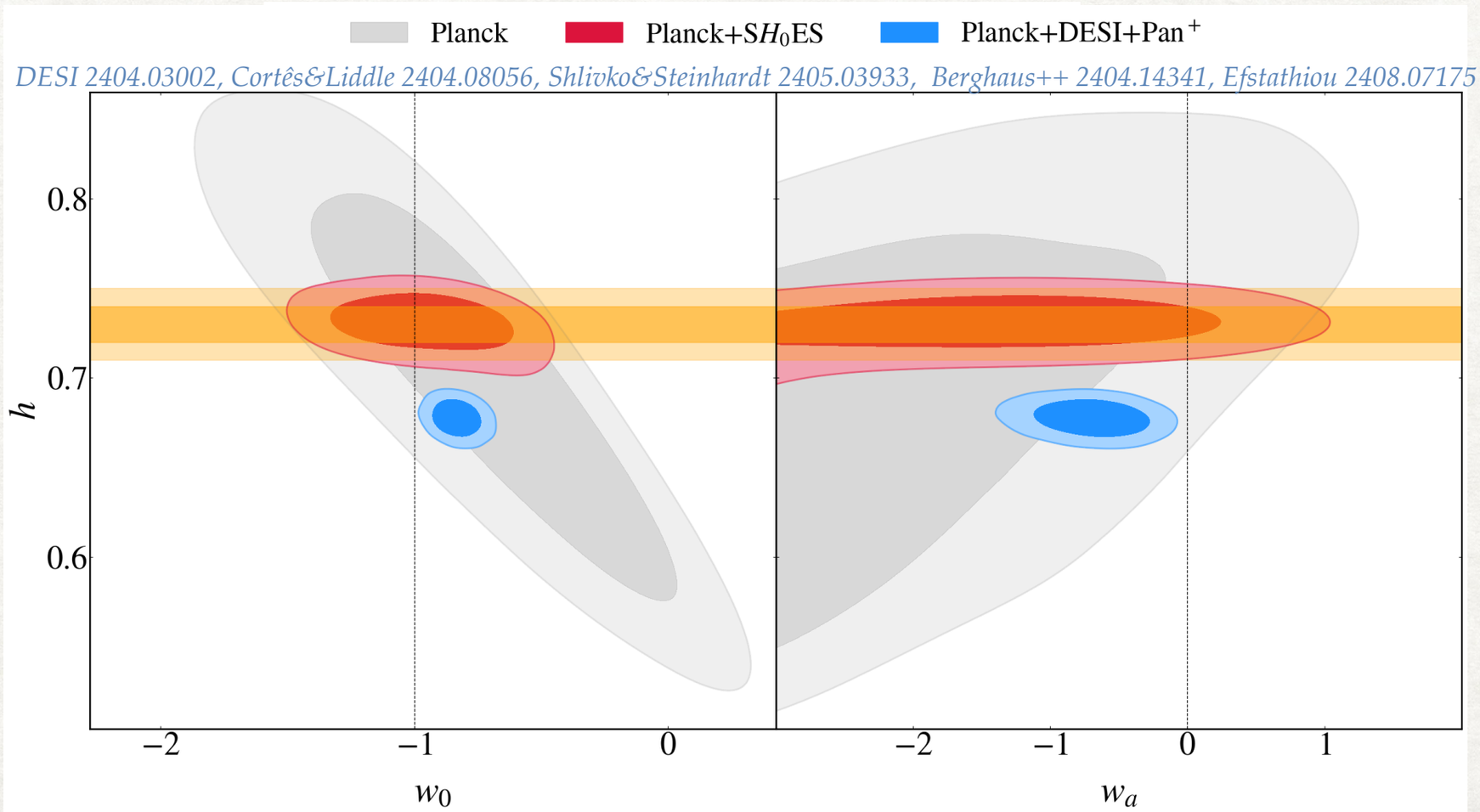

DESI 2404.03002, Cortês&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, Efstathiou 2408.07175

The tension is truly between **calibrators**!

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

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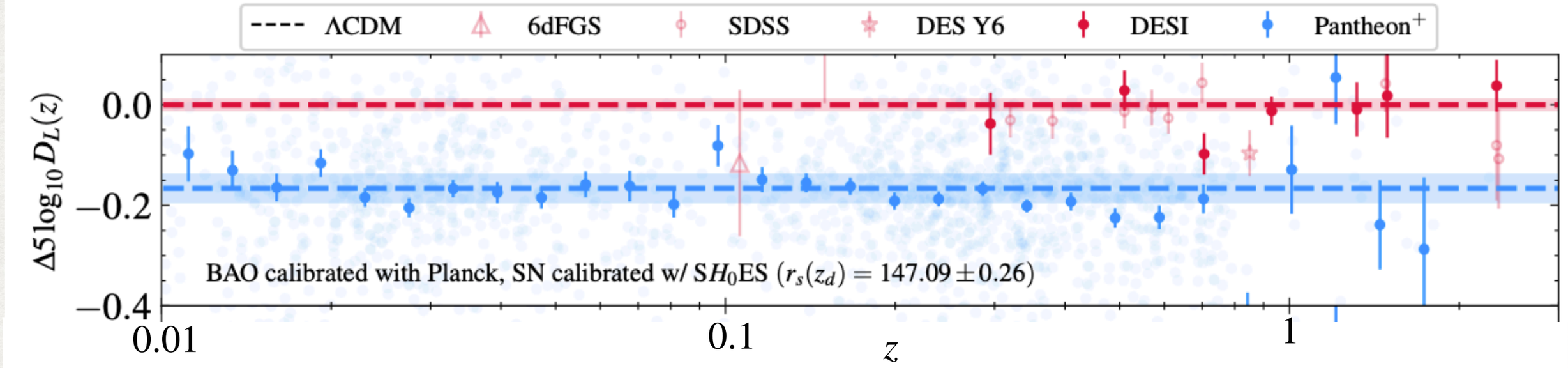
VP, Smith, Calderon, Simon 2407.18292



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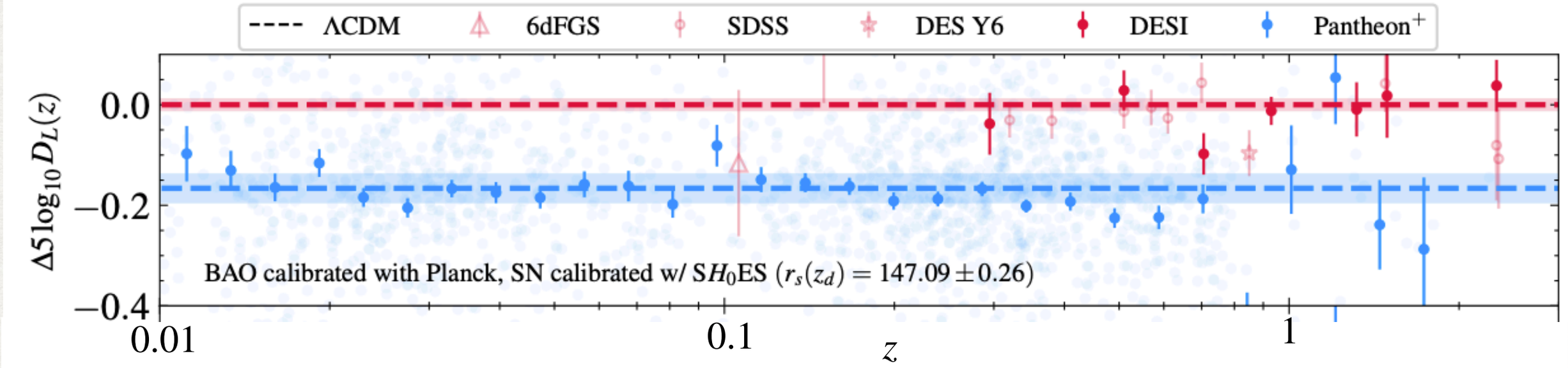

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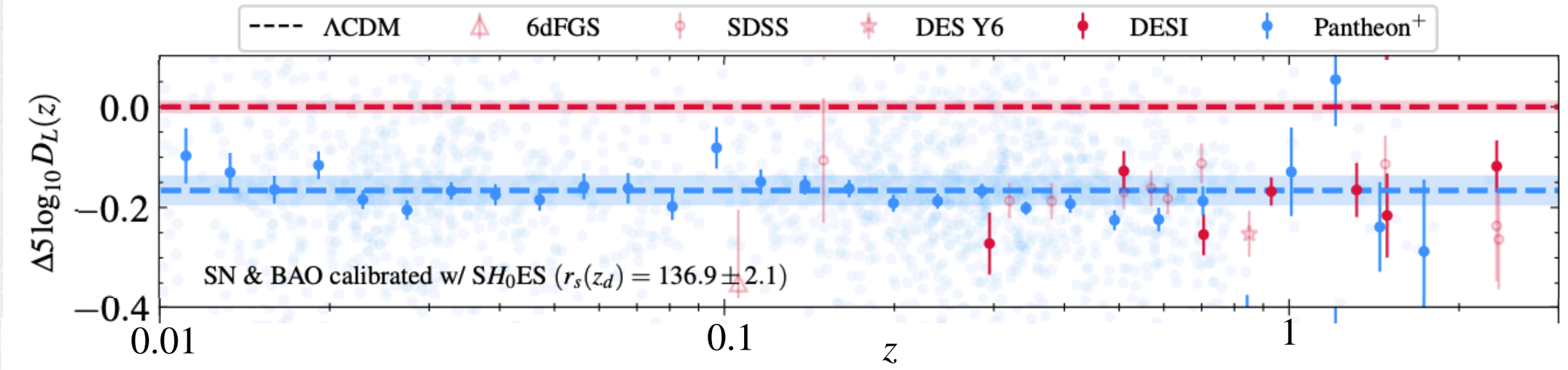

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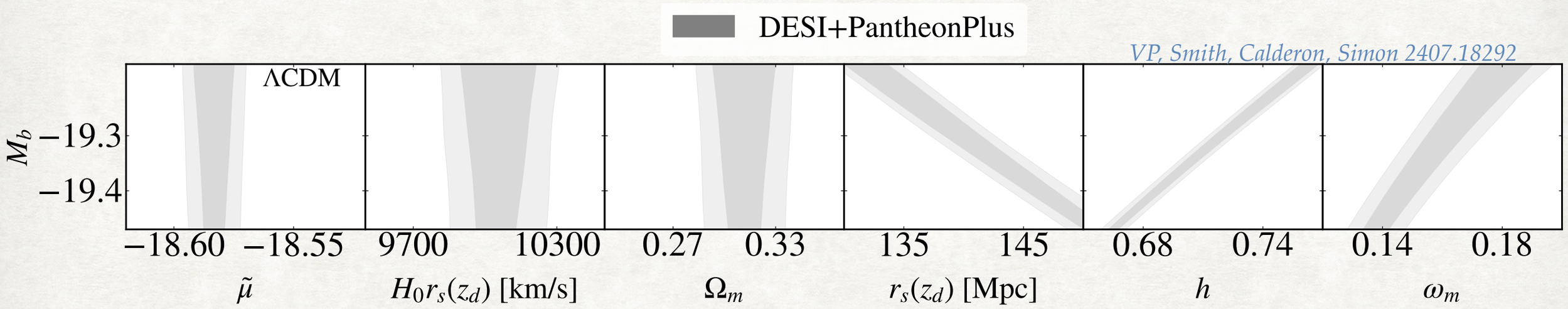

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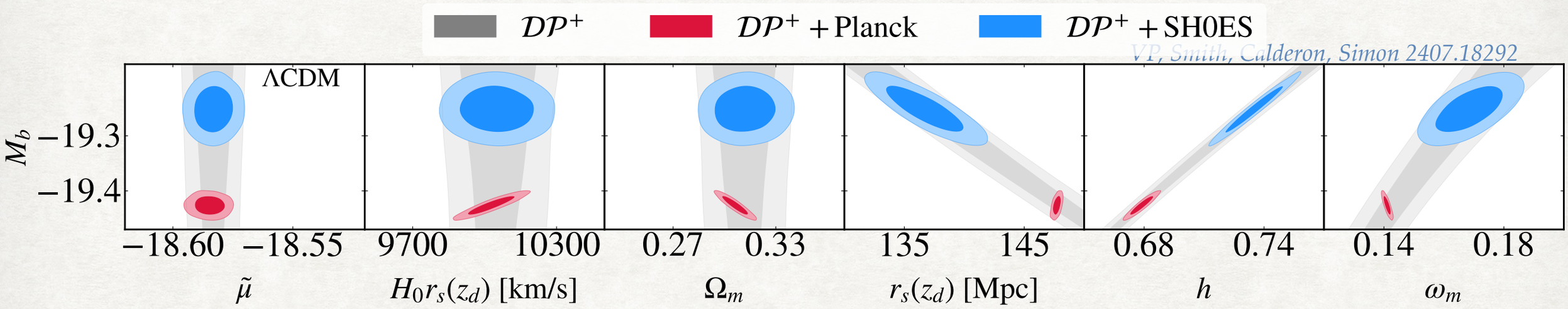

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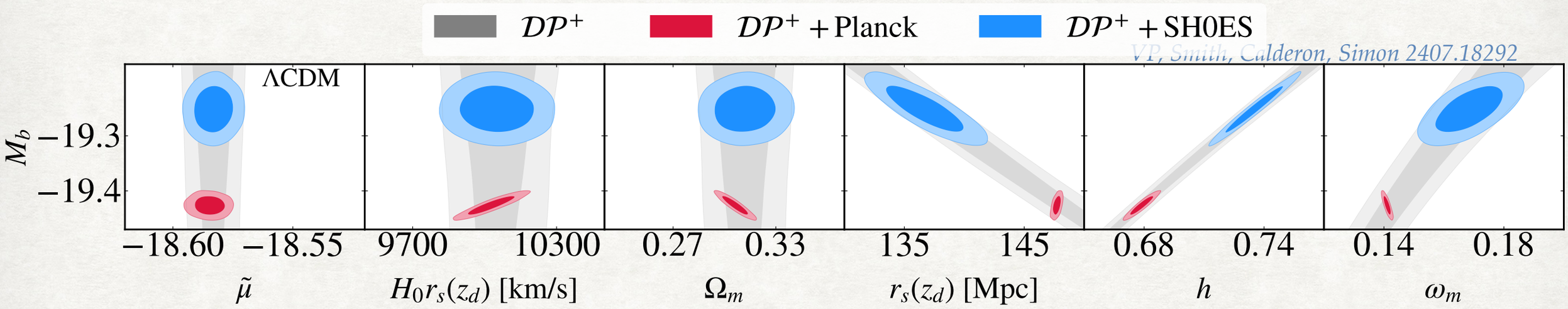

VP, Smith, Calderon, Simon 2407.18292

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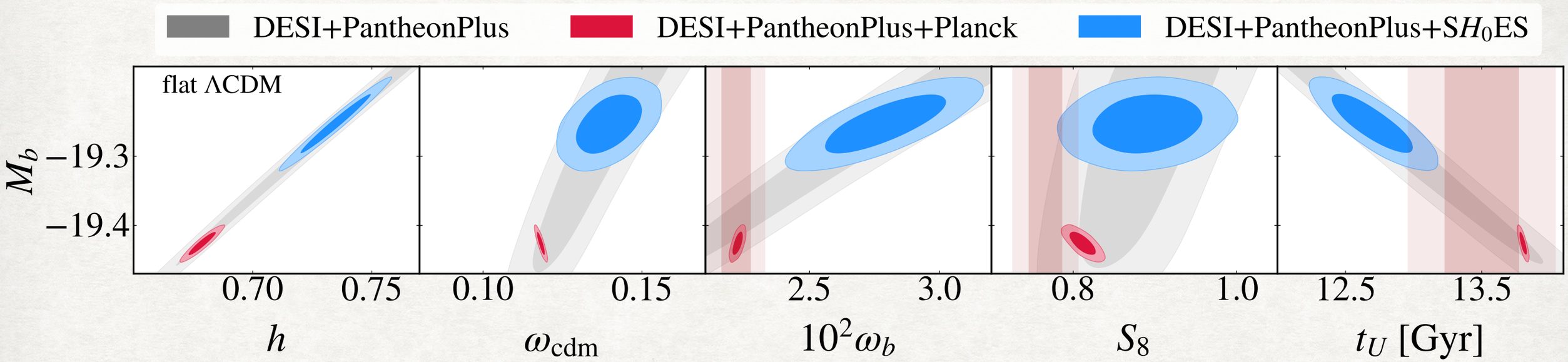
- Calibrating the BAO and SN1a leads to measurement of H_0 and $\omega_m = \Omega_m h^2$
- The Hubble tension could have been called "physical matter density tension" (or "Dark Energy tension")
- Challenge for new physics: Reduce the sound horizon and compensate the larger ω_m on the CMB

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

The Hubble tension beyond H_0

- Under ΛCDM, the SH_0ES calibration implies additional tensions!



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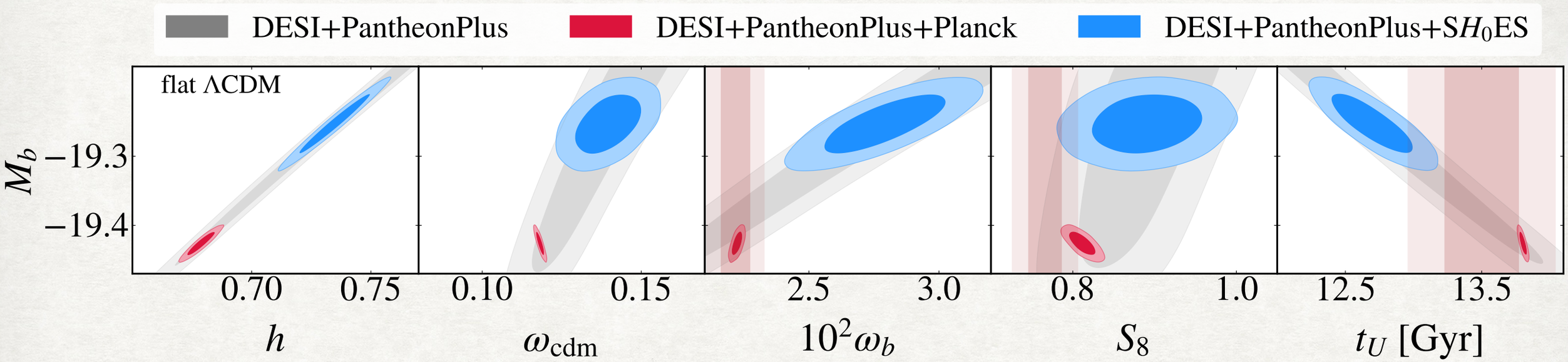

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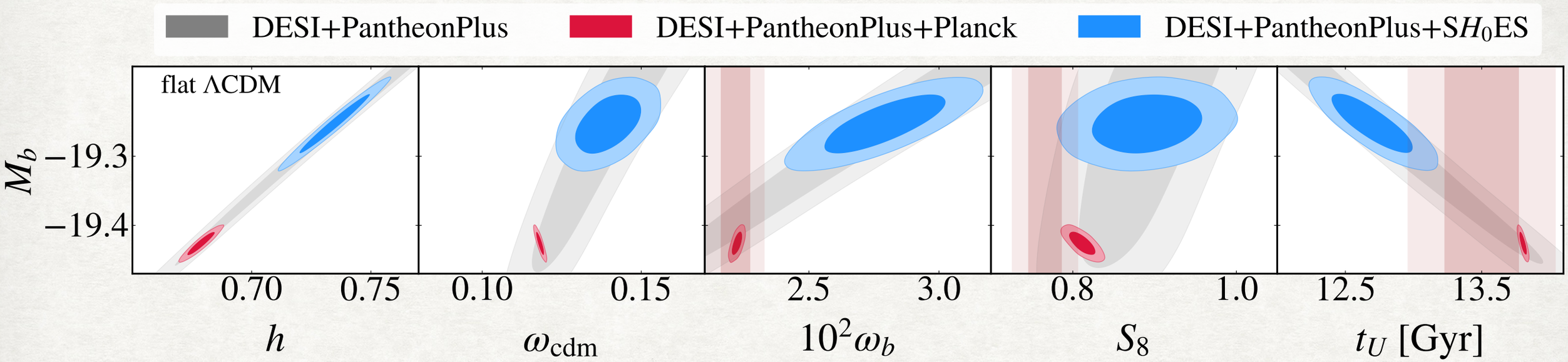

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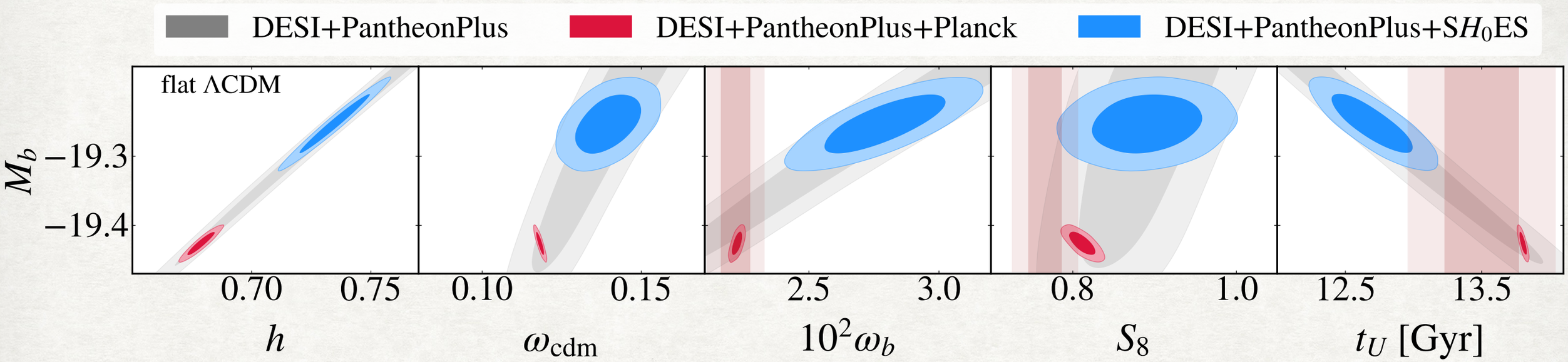

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Bernal++ 2102.05066, Boylan-Kolchin 2103.15824, Vagnozzi 2105.10425

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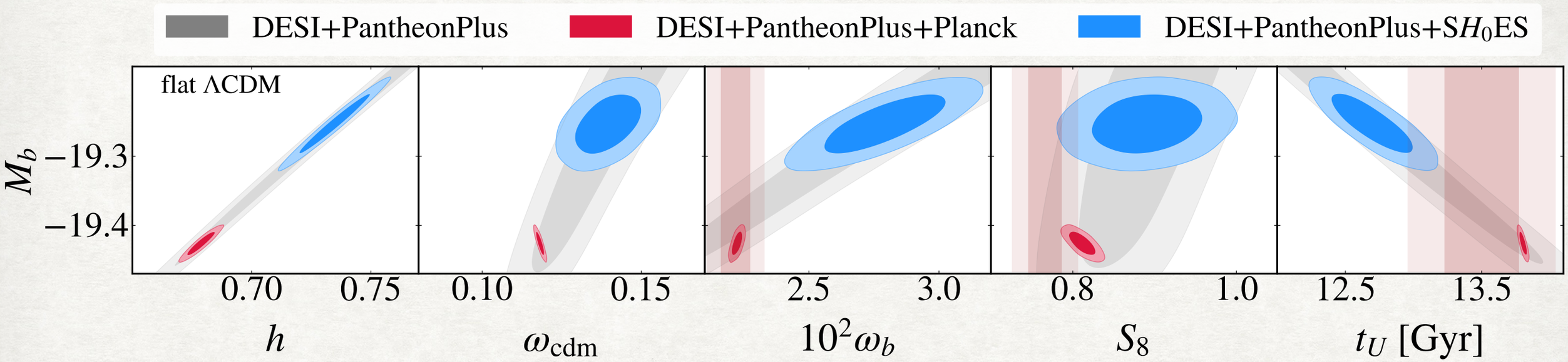

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- Another challenge for new physics: remove those additional tensions! *See also Vagnozzi 2308.16628*

How to resolve the cosmic calibration tension

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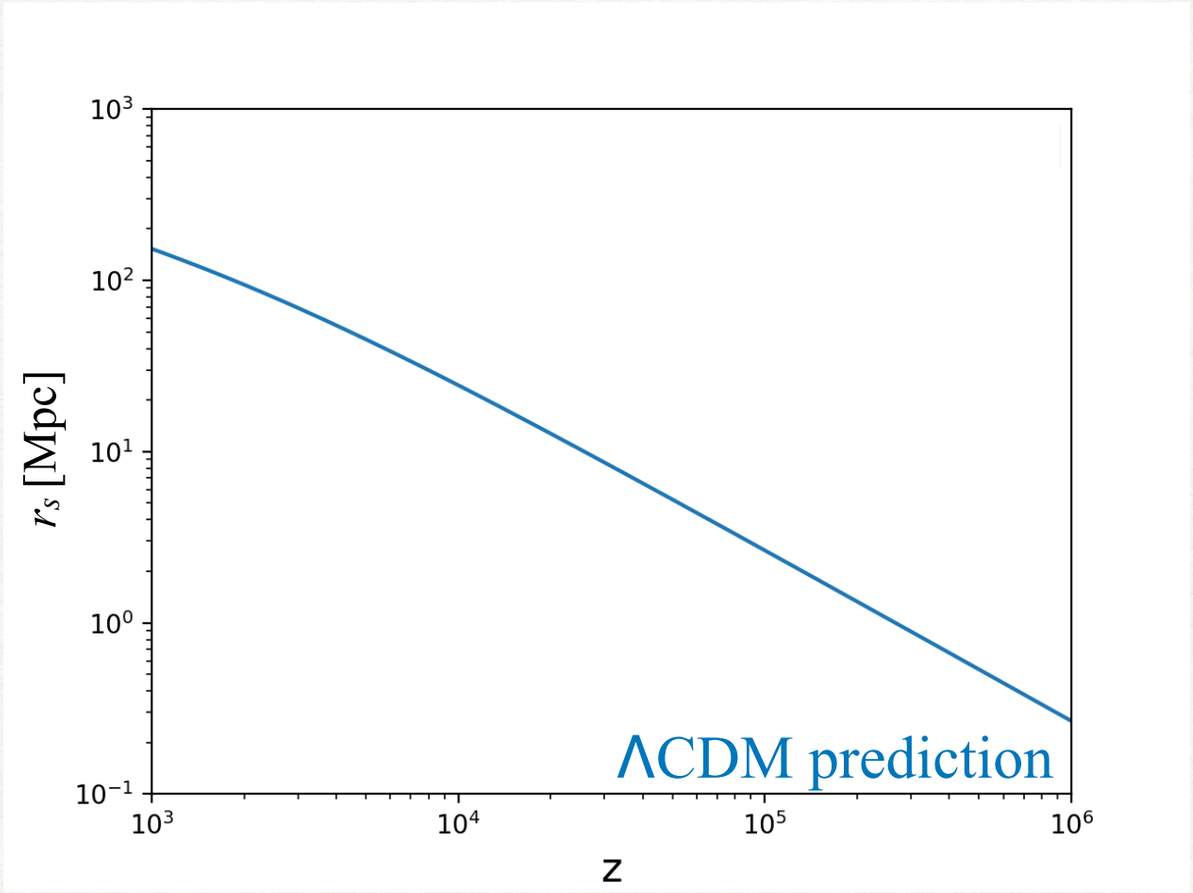

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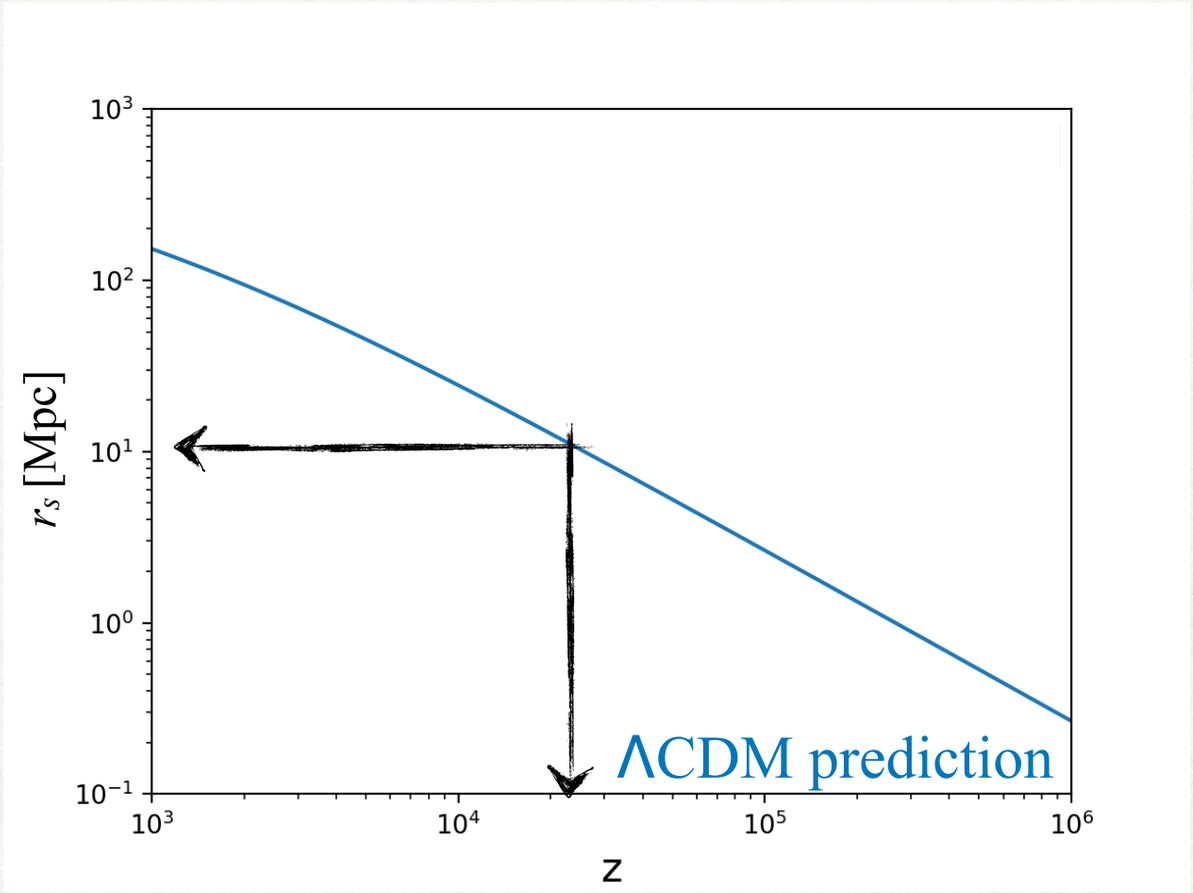

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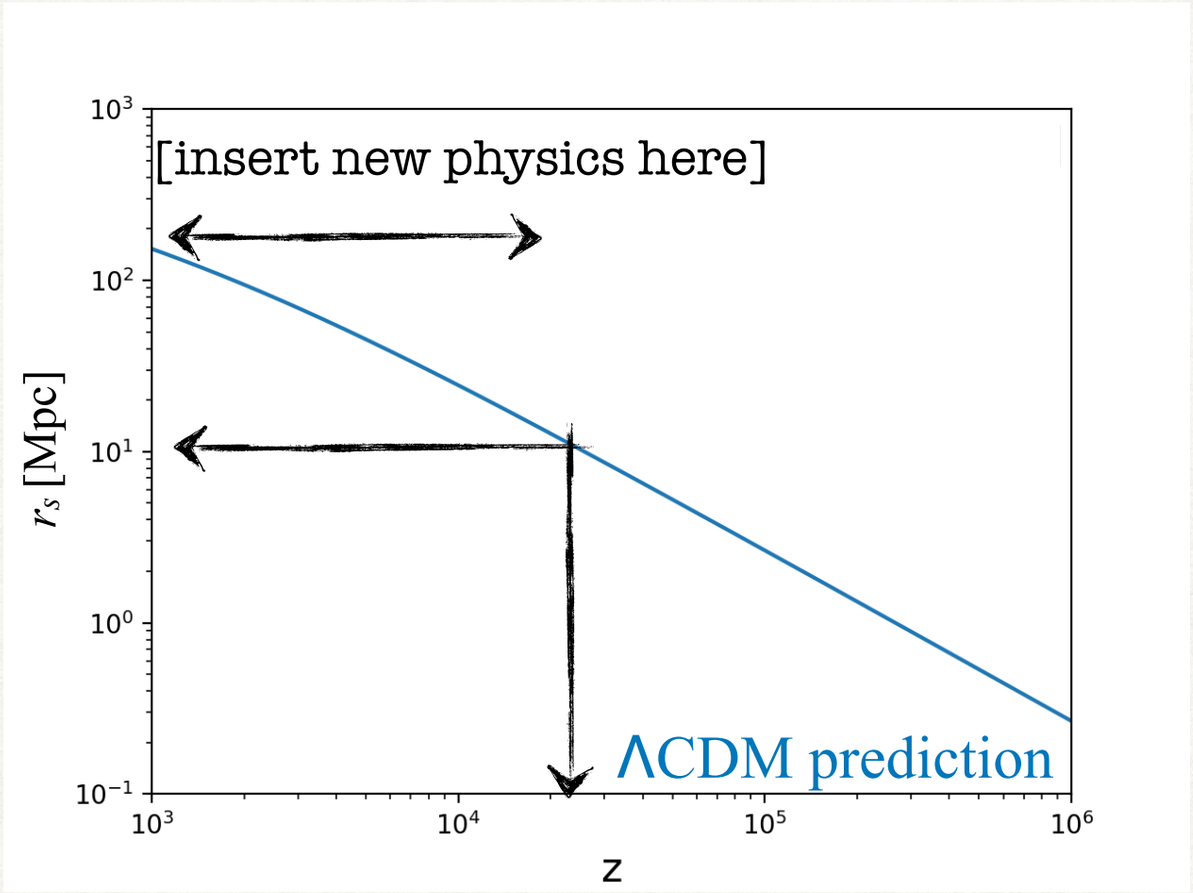

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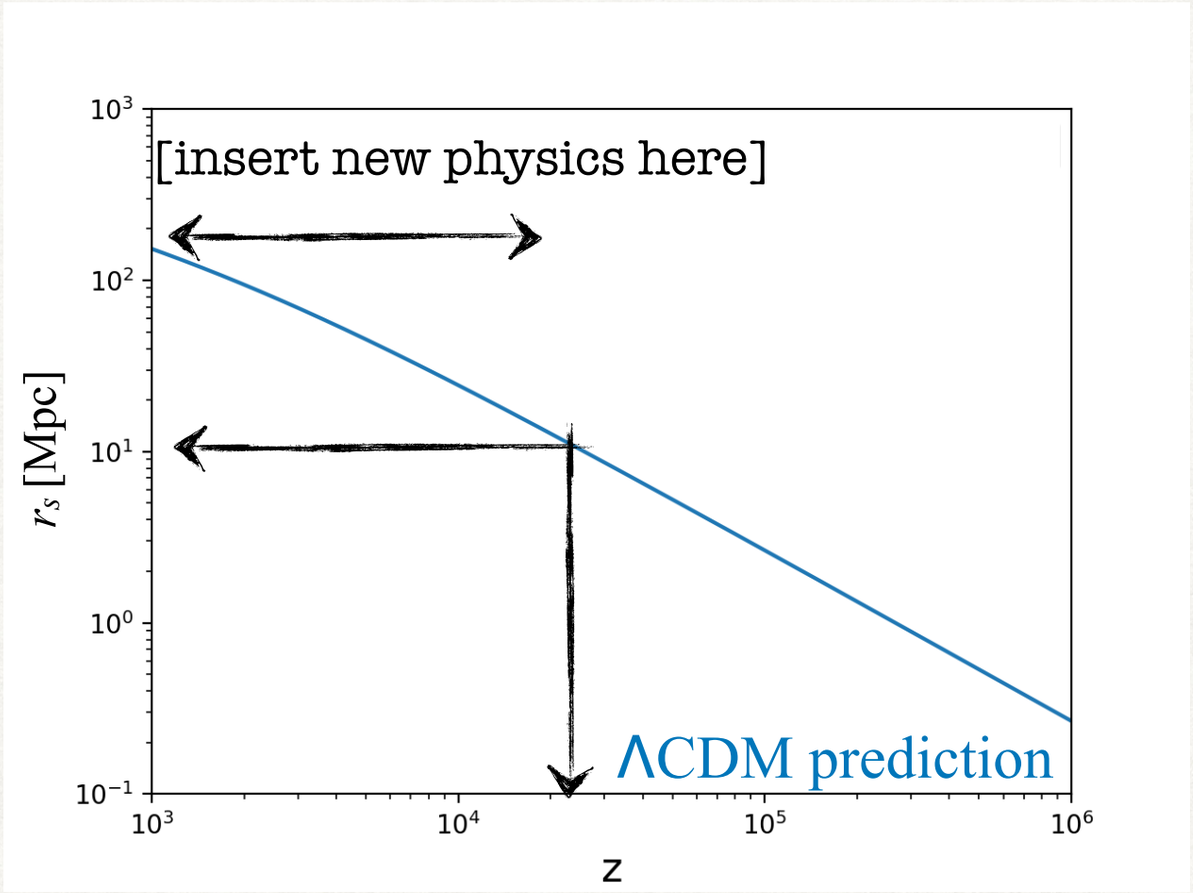

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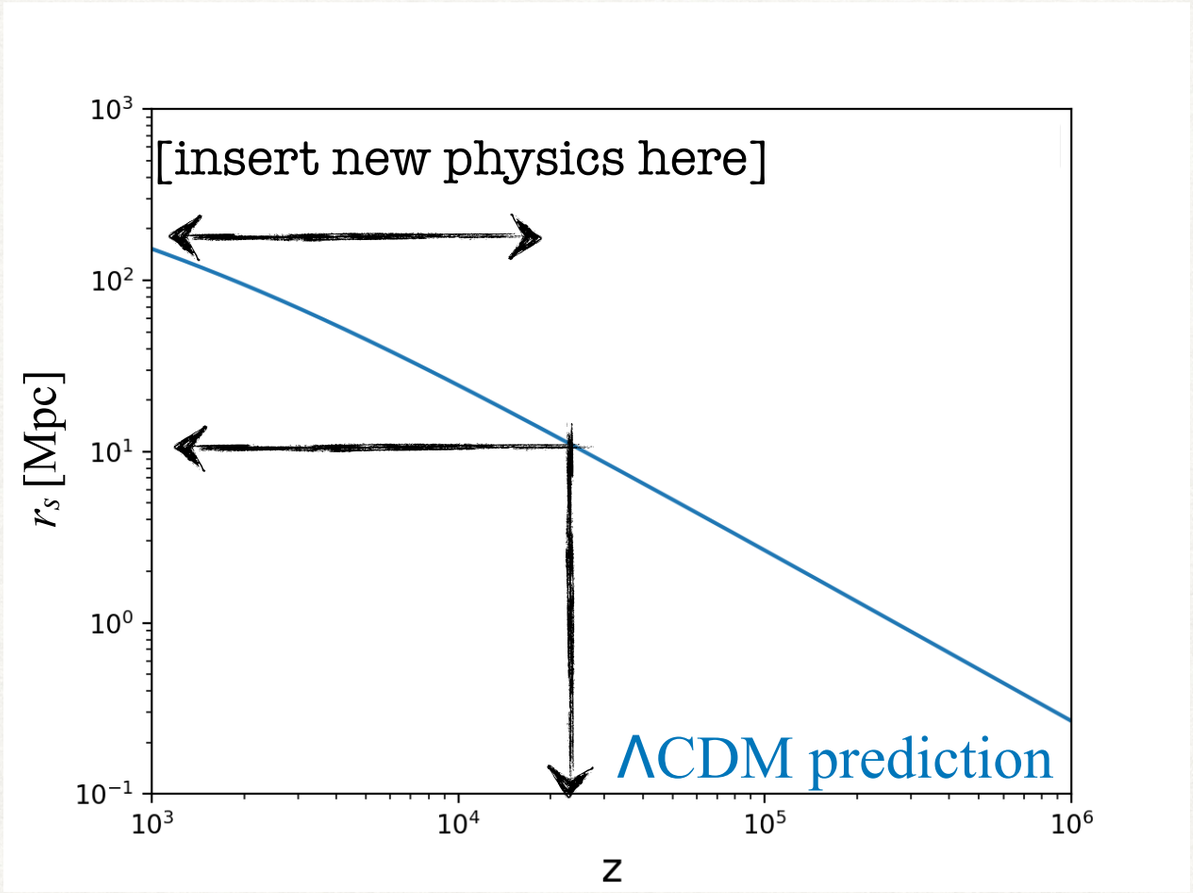

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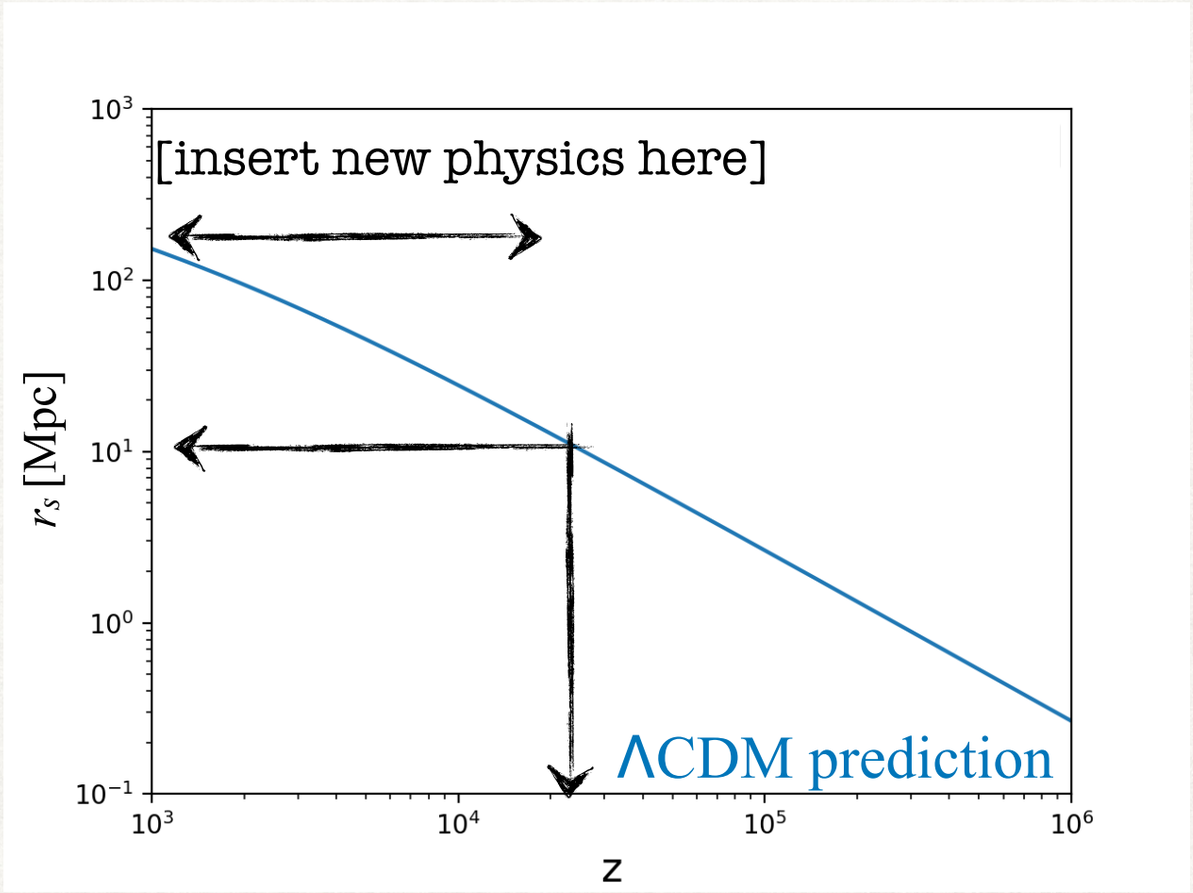

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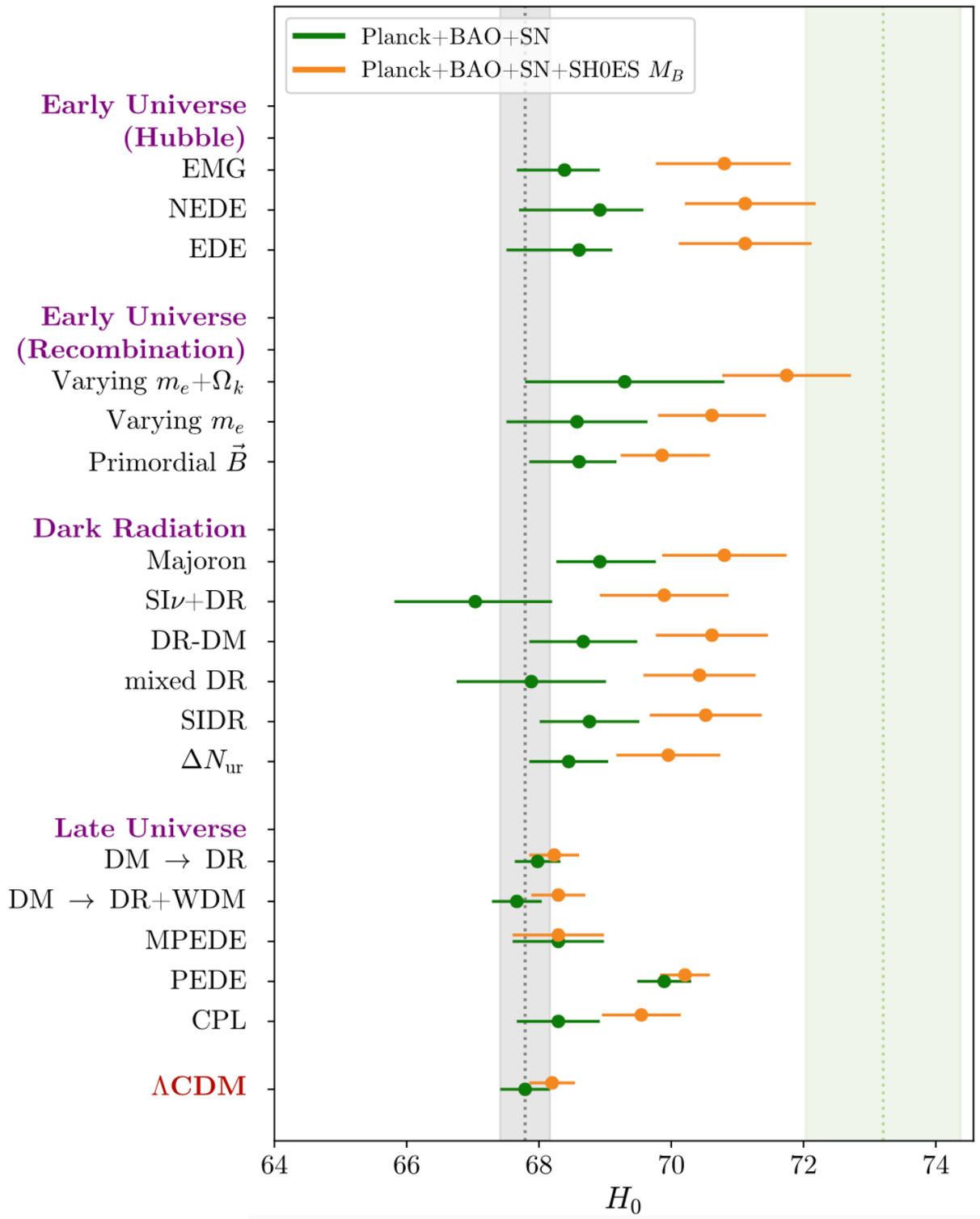
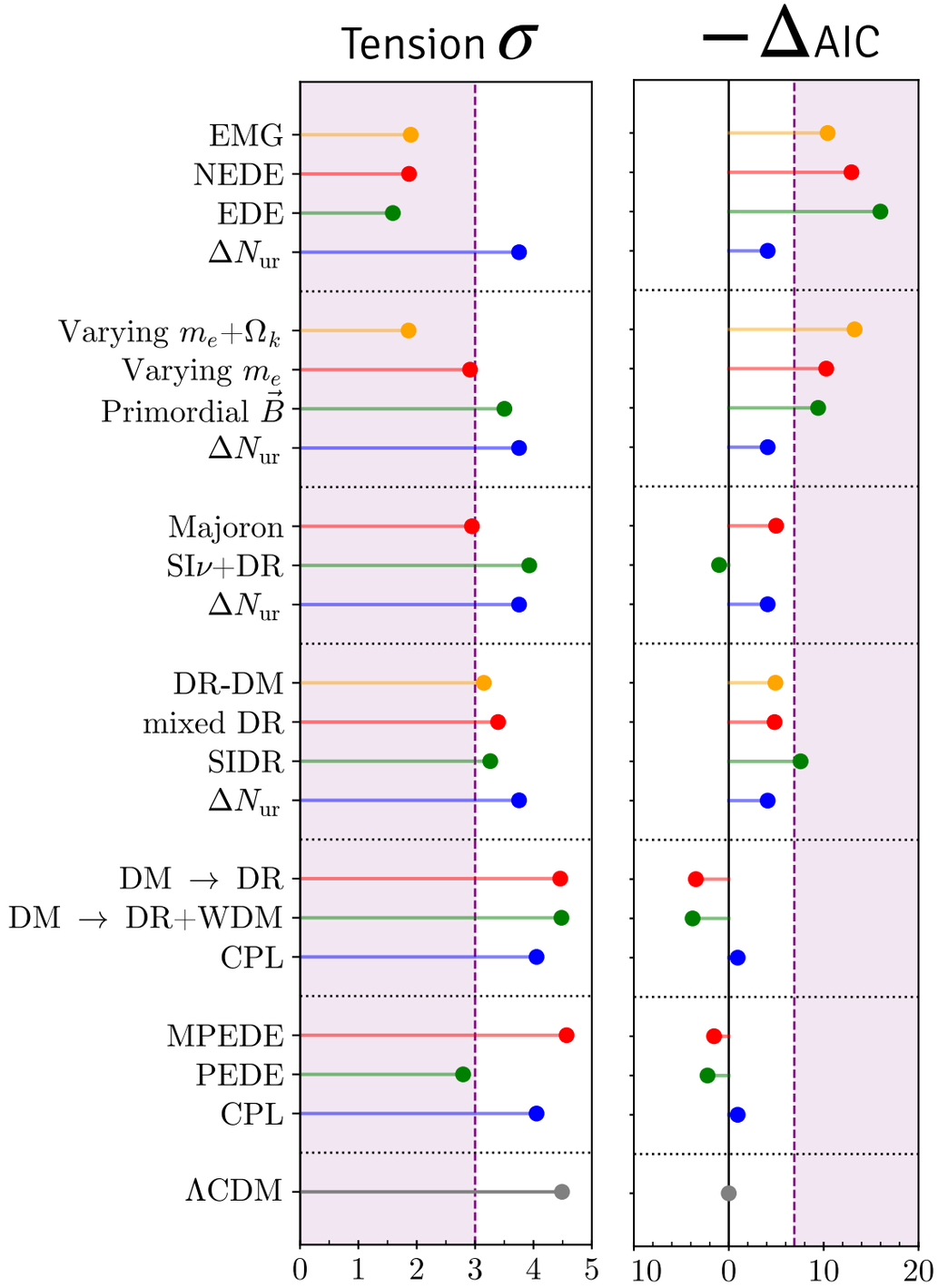
increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?

The H_0 olympics: fairly ranking models





Schöneberg (VP) ++ Phys. Report. 2107.10291

Can models respect degeneracies impose by the distance ladder?

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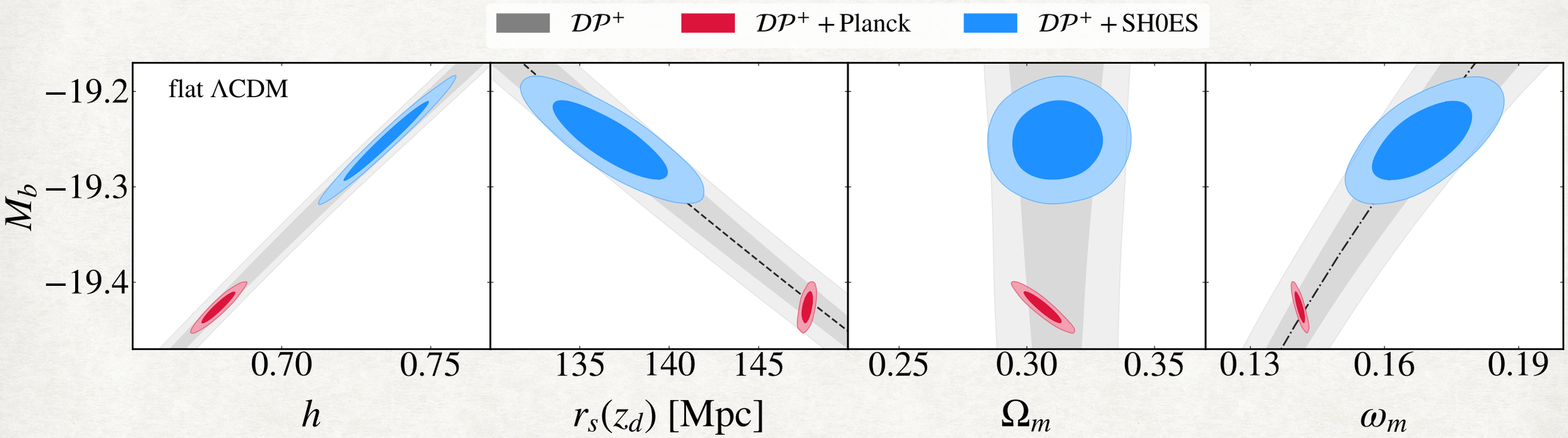

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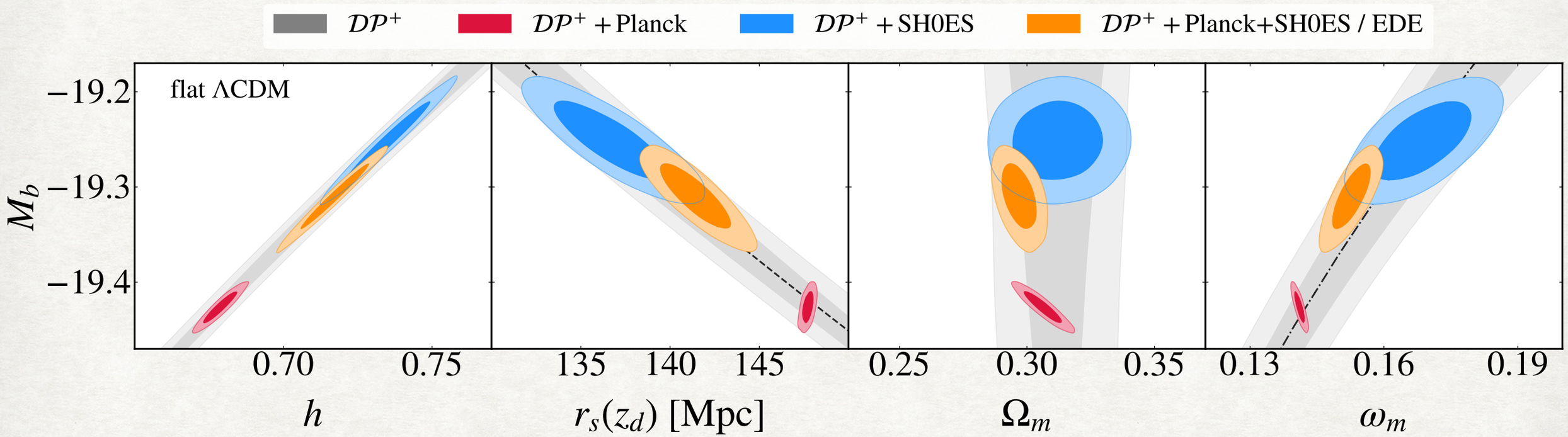

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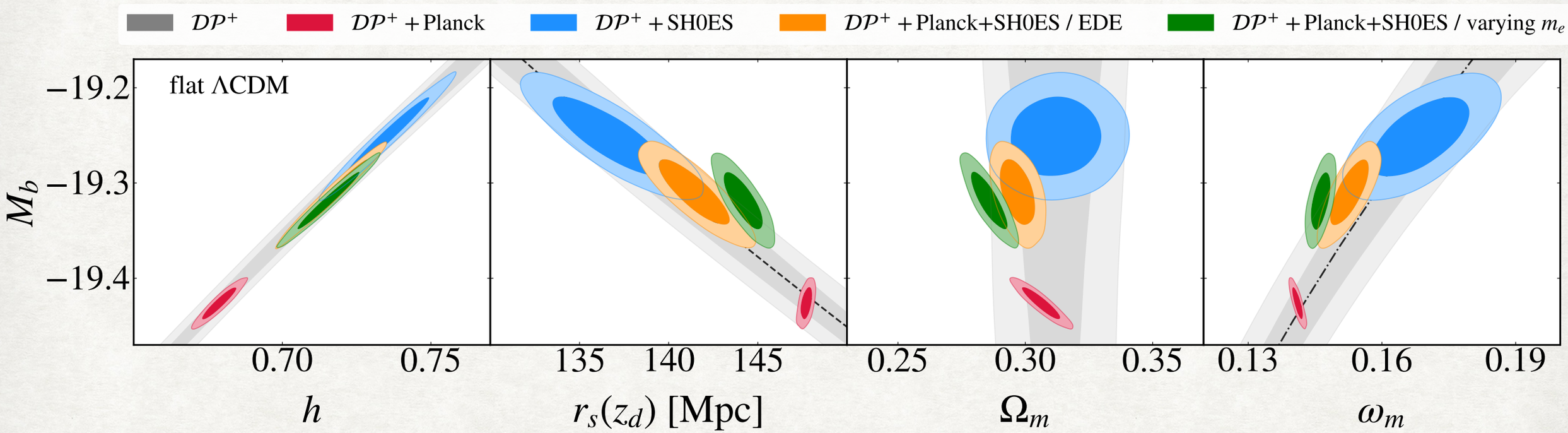

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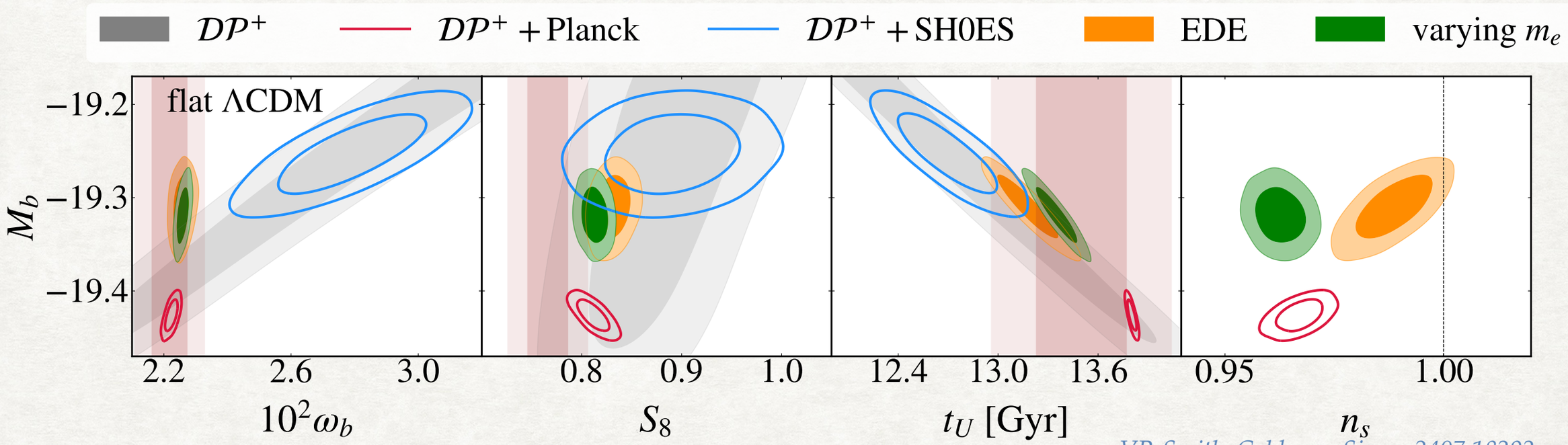
- Models affecting solely recombination are disfavored: they lead to low Ω_m
  Lee (VP)++ PRL 2022, Lynch++ 2404.05715

Consequences beyond H_0

- What is the impact of new physics beyond H_0?



VP, Smith, Calderon, Simon 2407.18292

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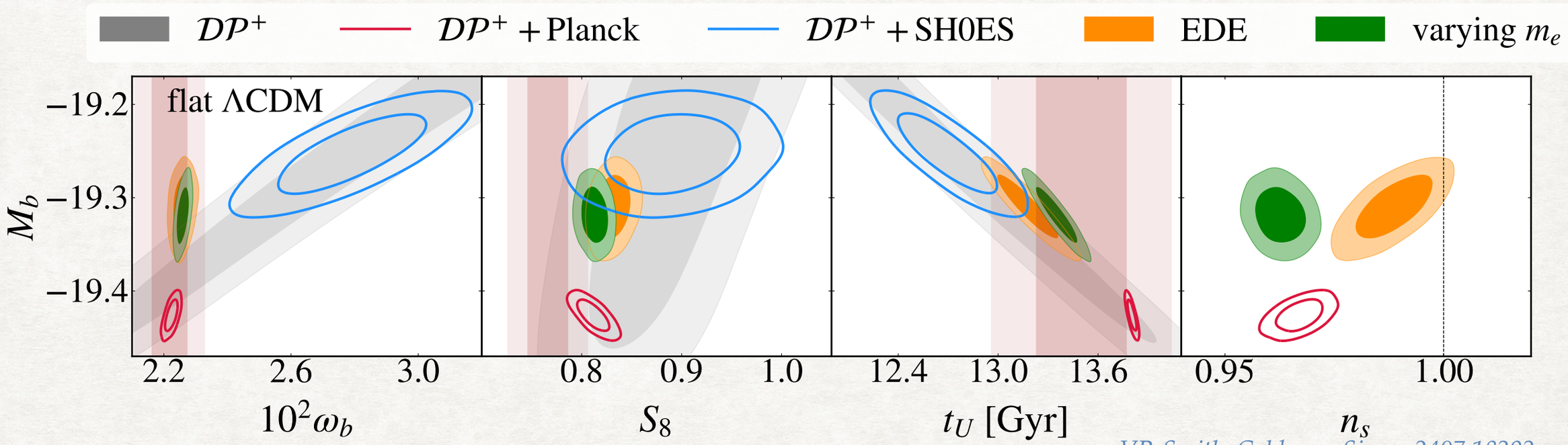

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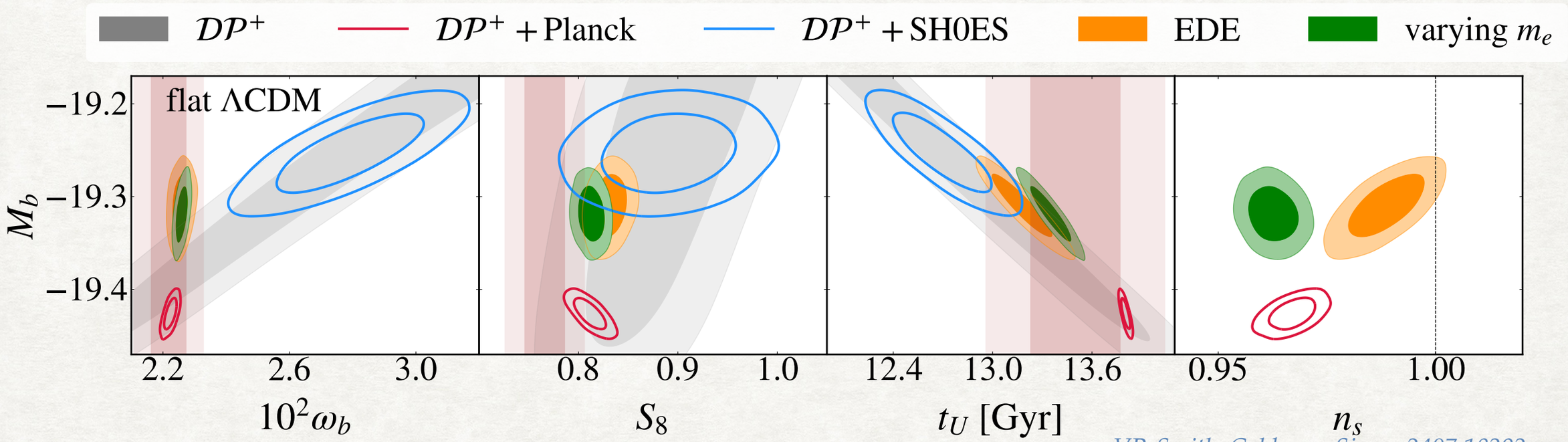

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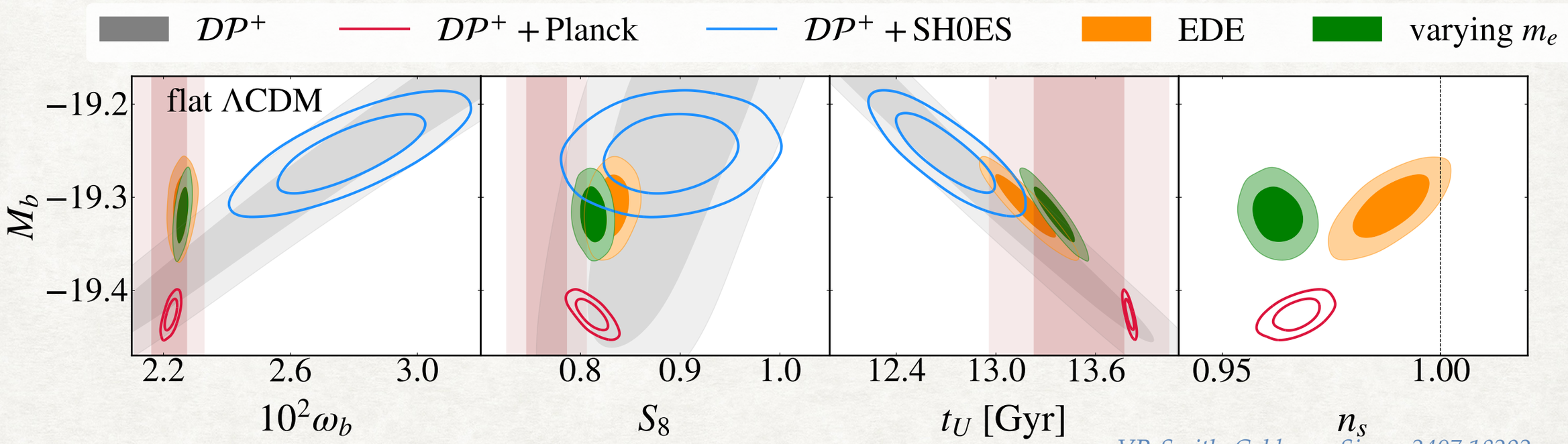

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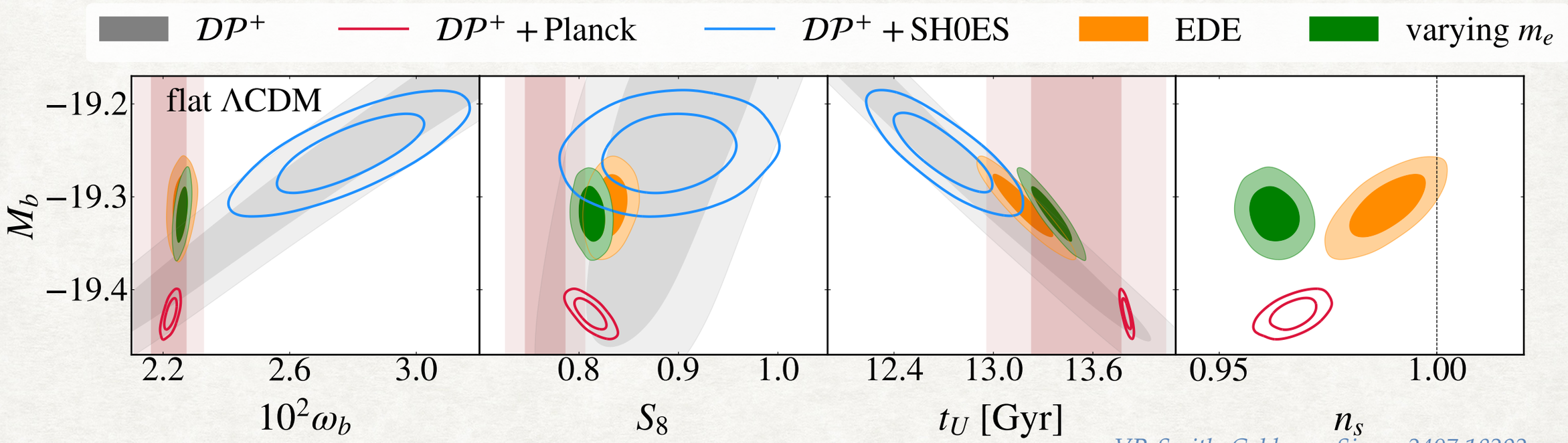

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- n_s increases in EDE! Back to being compatible with 1? Constraints from LSS?

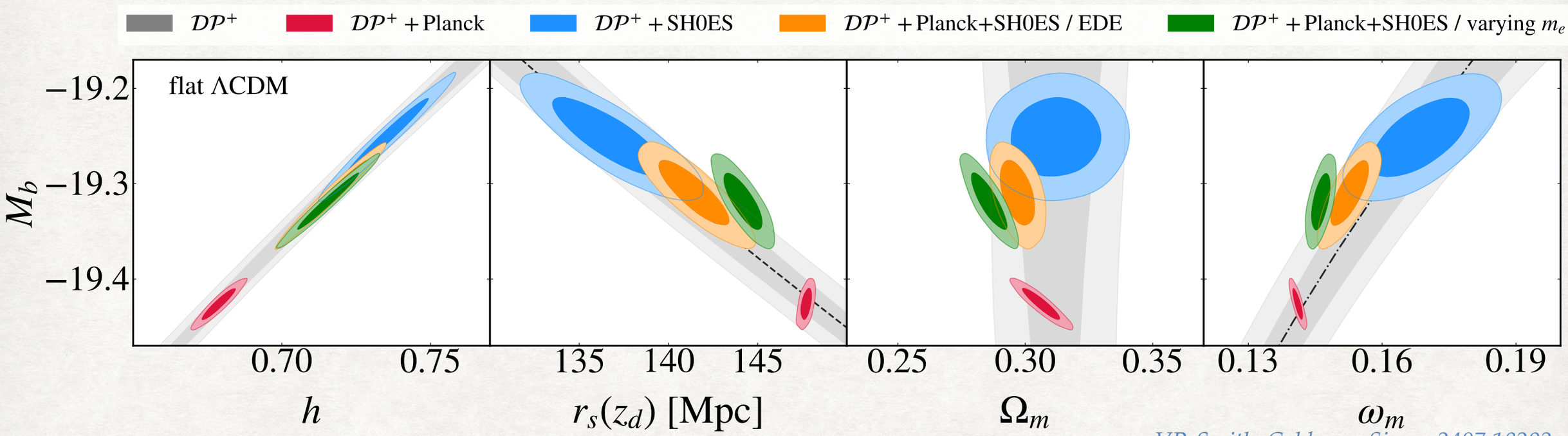
  Gen Ye++ 2103.09729, 2205.02478, Goldstein++ 2303.00746

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)



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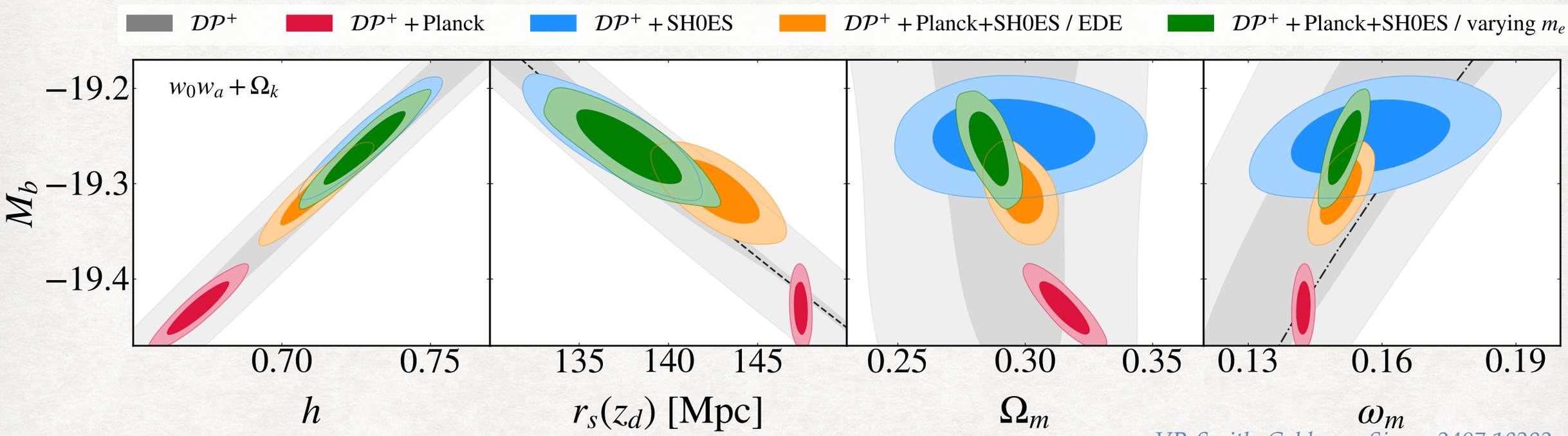

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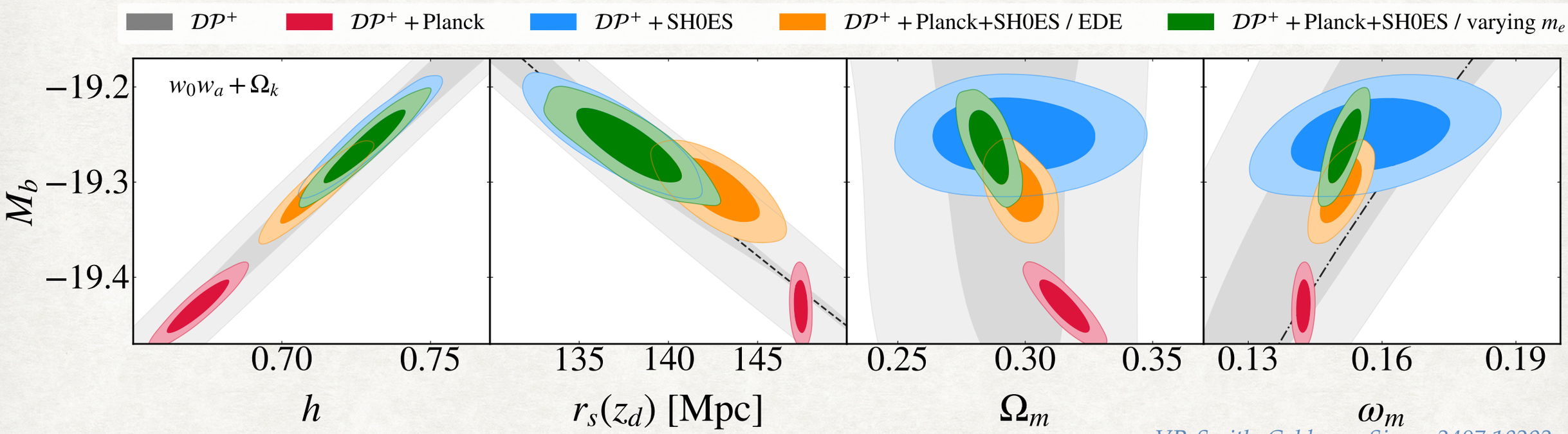

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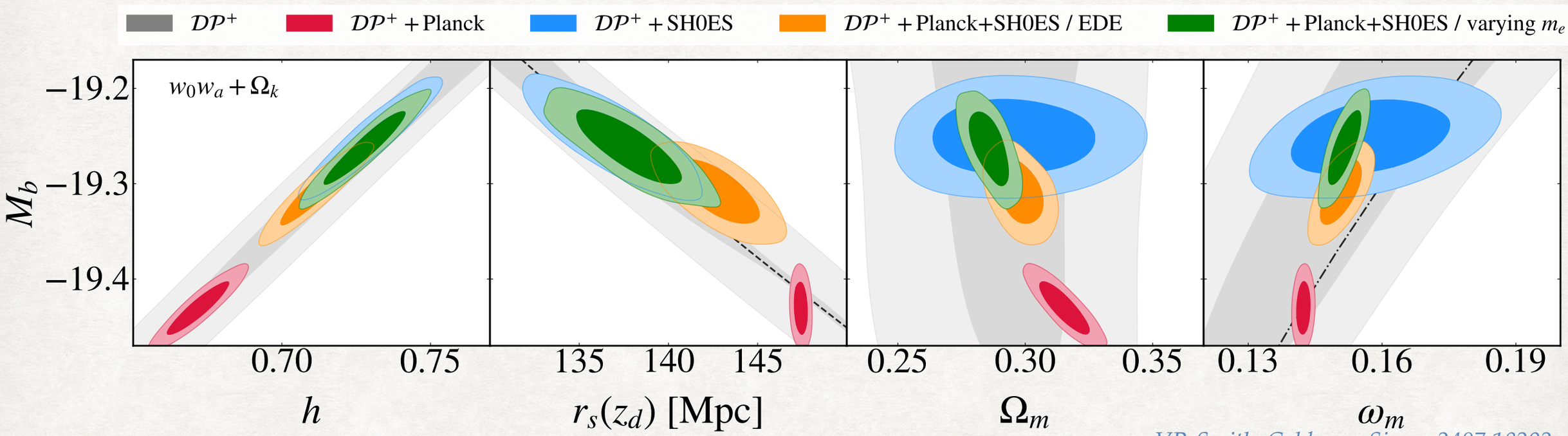

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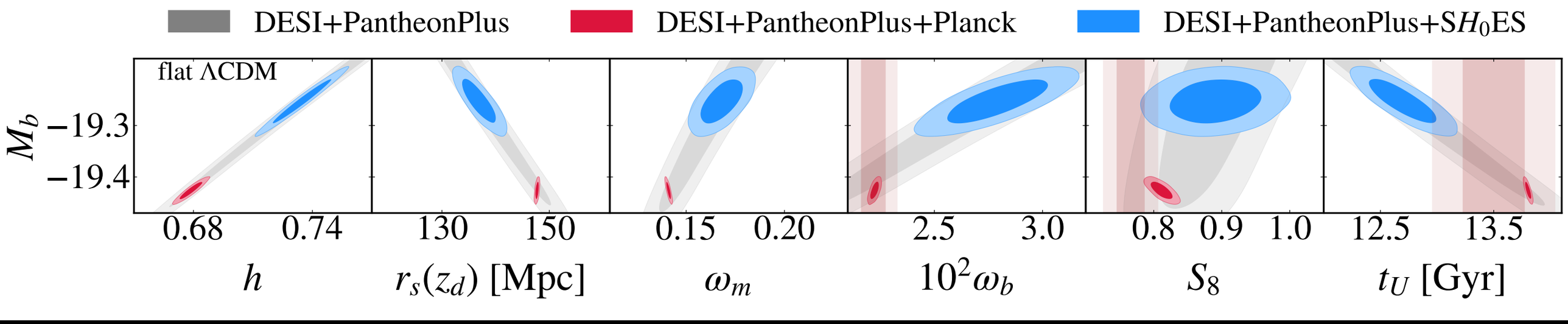
- Localized energy injection or a broad change affecting several cosmic epochs?

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 and larger S_8



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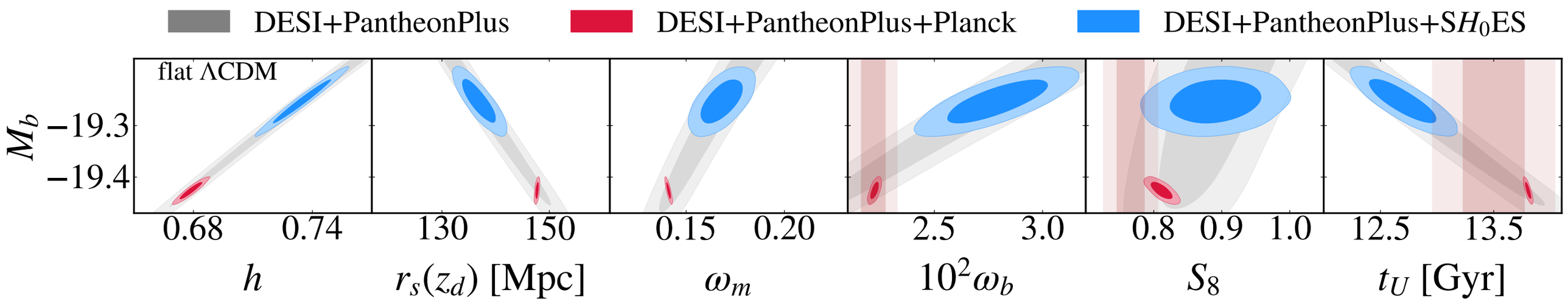

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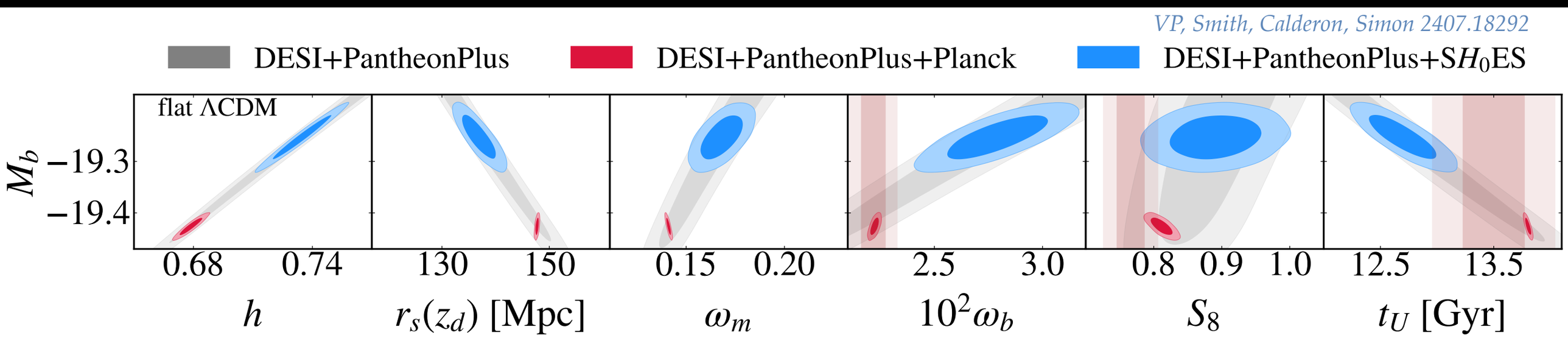

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- We haven't found the solution yet, but there is a lot we understand!