The H_0 Olympics: a fair ranking of proposed models

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Based on:

arXiv:2107.10291, accepted in Physics Reports

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

Tensions in cosmology

With the era of precision cosmology, several discrepancies have emerged

- 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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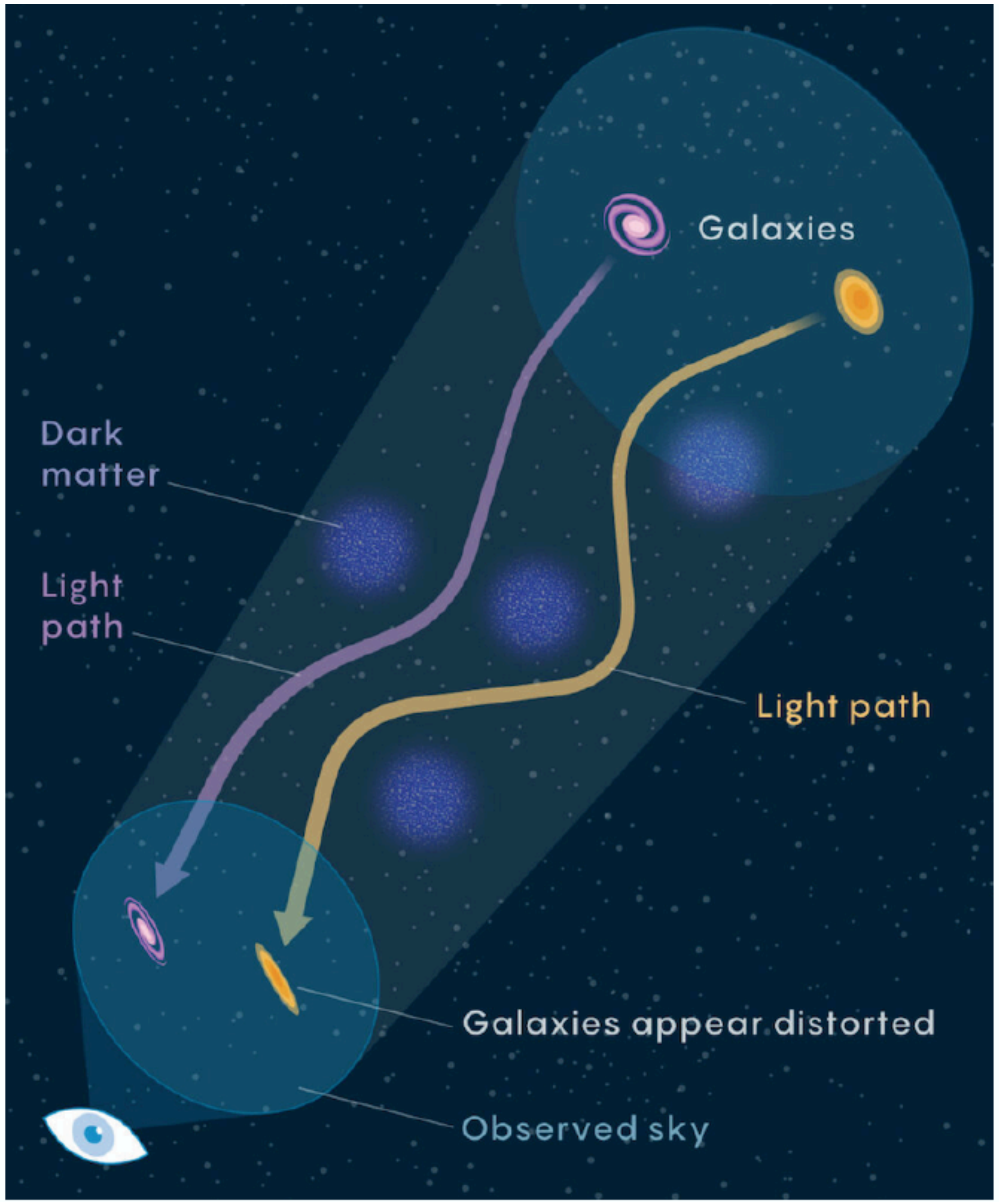
Unaccounted systematics?

Physics beyond ΛCDM?

The S₈ 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*):

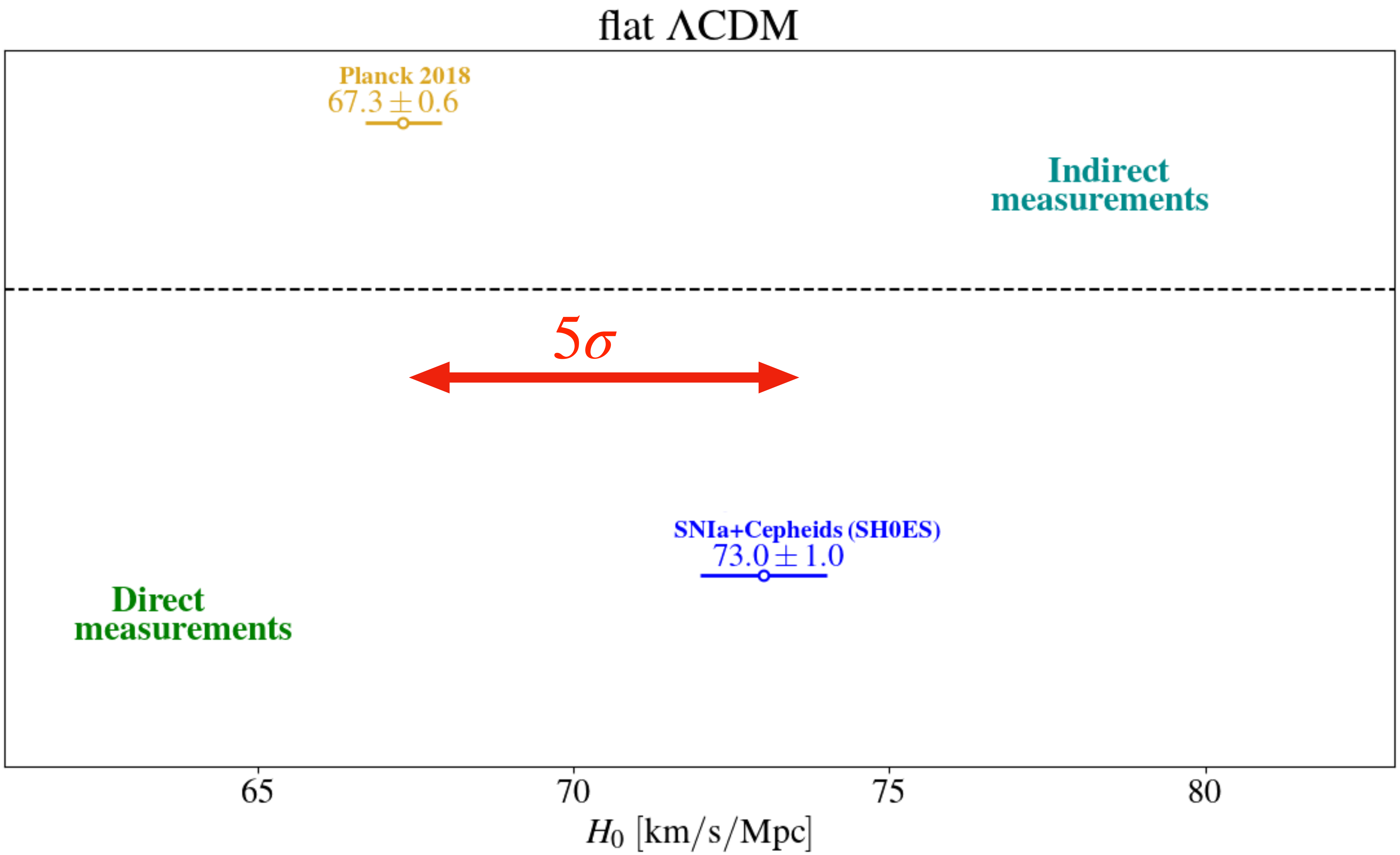
$$S_8 = 0.830 \pm 0.013$$

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

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

The H_0 tension

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



The H_0 tension

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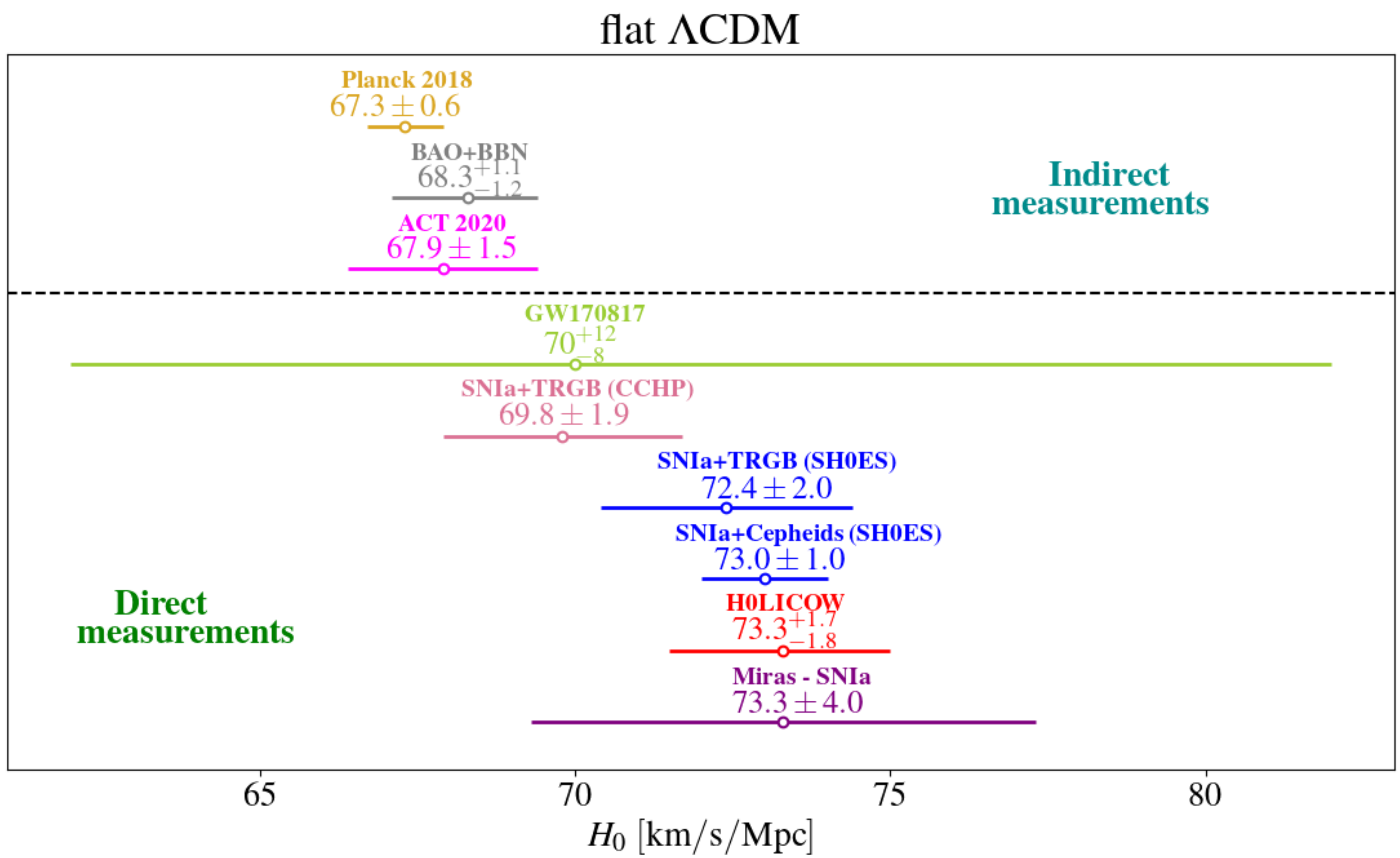
High- and low-redshift probes are typically discrepant



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

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

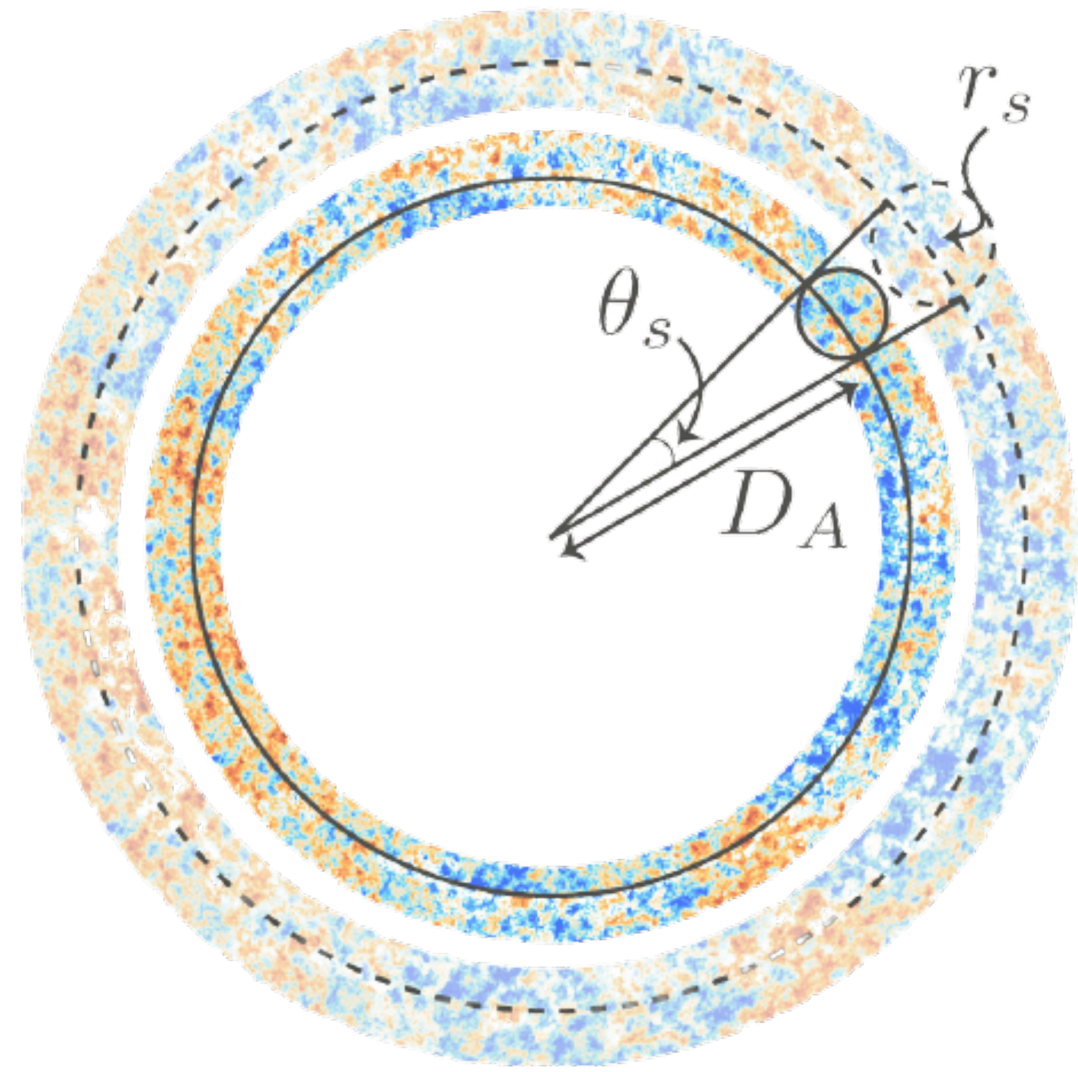
$$\text{where } \mathrm{H}^2(\mathrm{z}) = \frac{8\pi \mathrm{G}}{3}\sum_\mathrm{i} \rho_\mathrm{i}(\mathrm{z})$$

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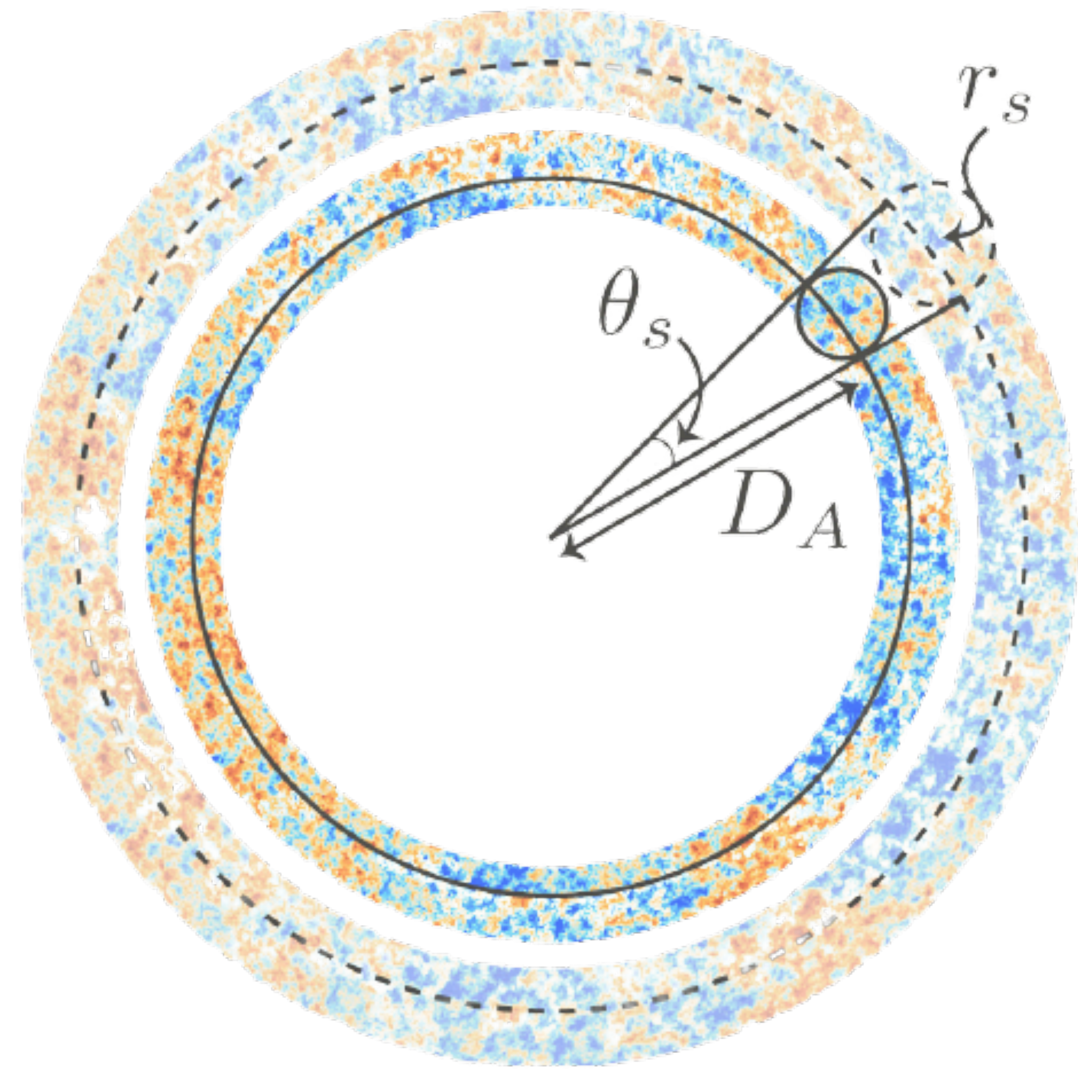
with $\mathrm{D_A} \propto 1/\mathrm{H_0} = 1/\sqrt{\rho_{\rm tot}(0)}$

model prediction of $\mathrm{r_s}$ + measurement of $\theta_\mathrm{s} \longrightarrow \mathrm{H_0}$



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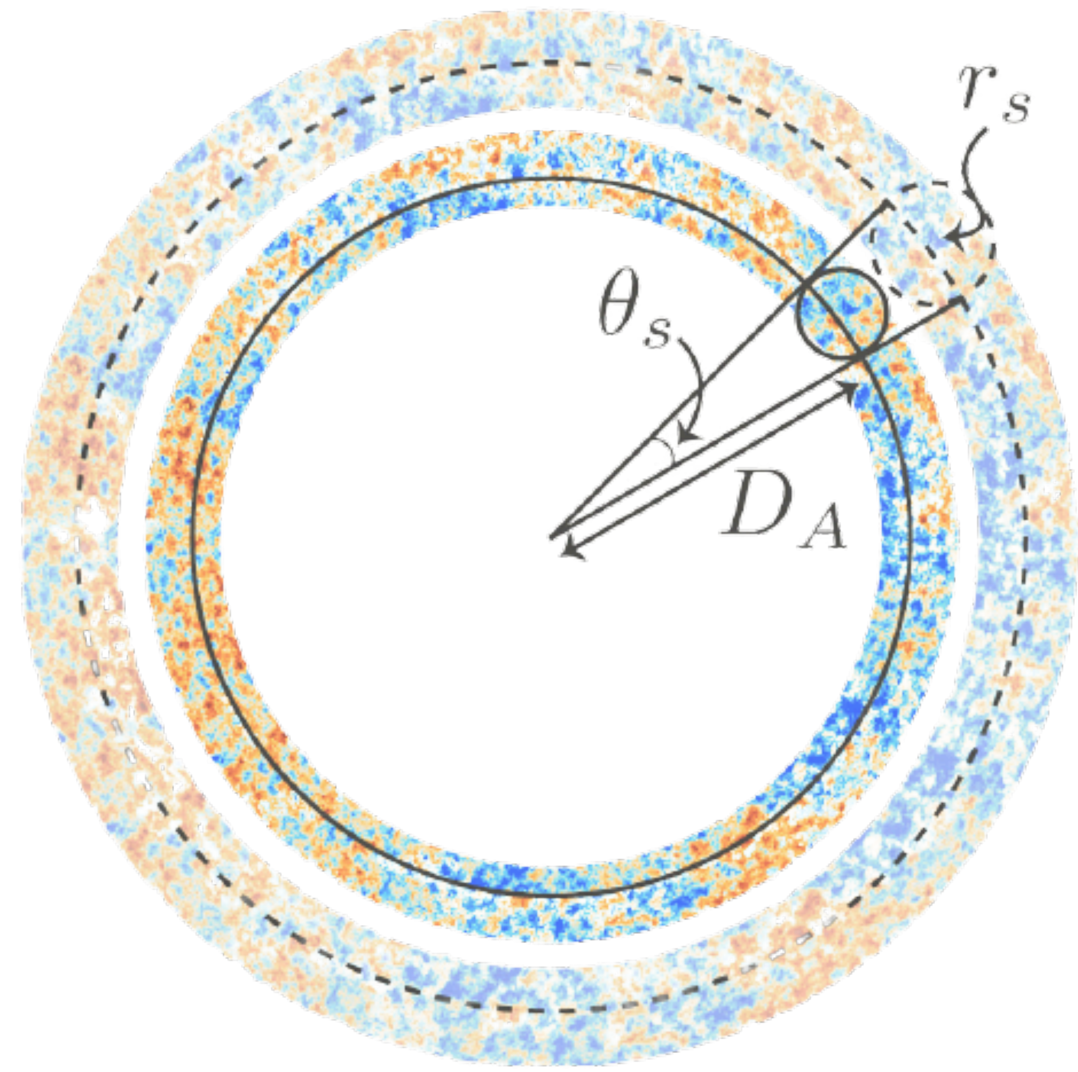

model prediction of r_s + measurement of θ_s $\longrightarrow$ H_0

T. Smith

Early-time solutions

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

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

Late-time solutions

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

$\mathbf{Ex : w < -1}$

Lost in the landscape of solutions

- Cosmological tensions have become a very hot topic (specially the H_0 tension)

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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 Tensic

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

Early recombination as a solution to the H_0 tension

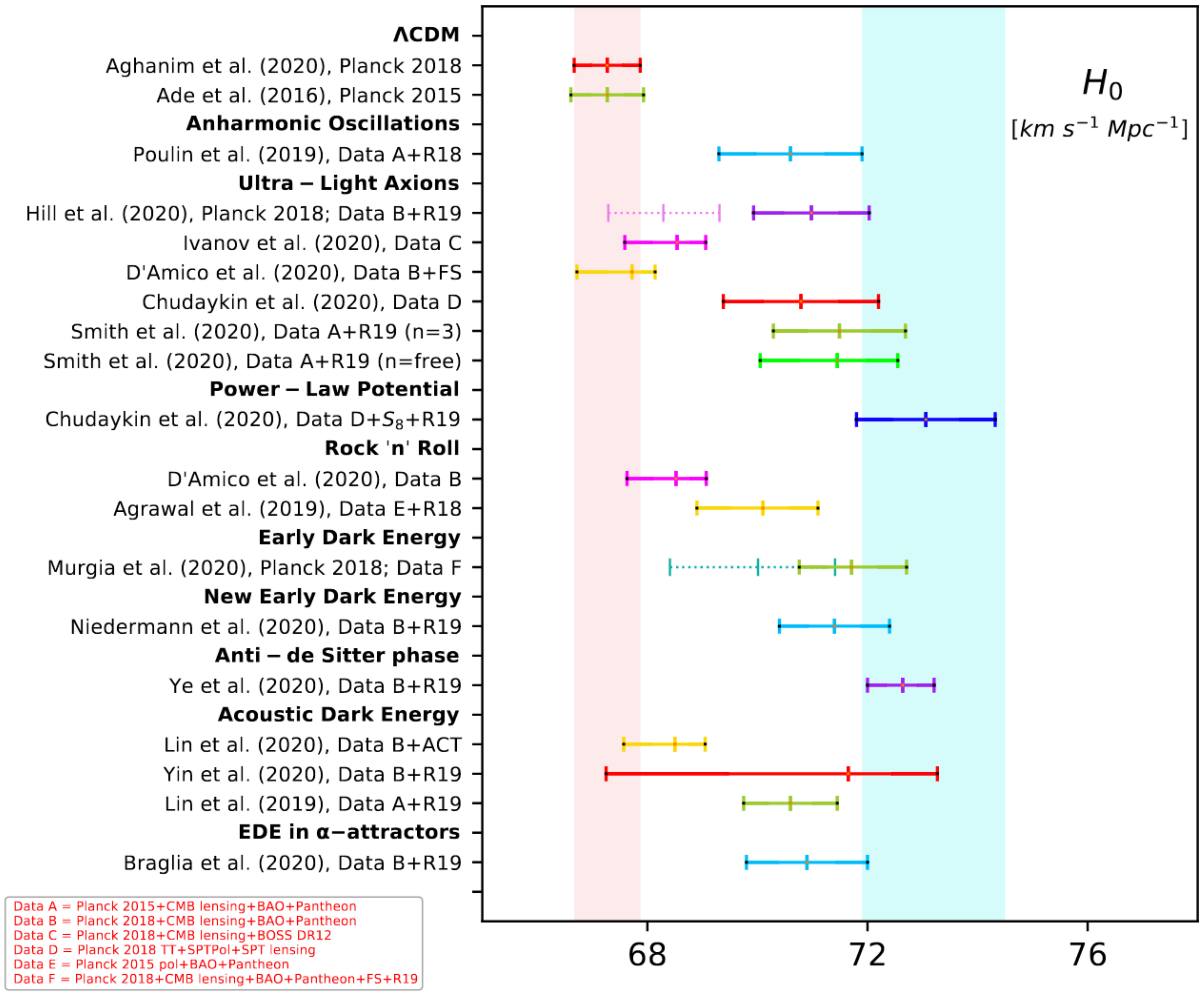
Toyokazu Sekiguchi[1,*] and Tomo Takahashi[2,†]

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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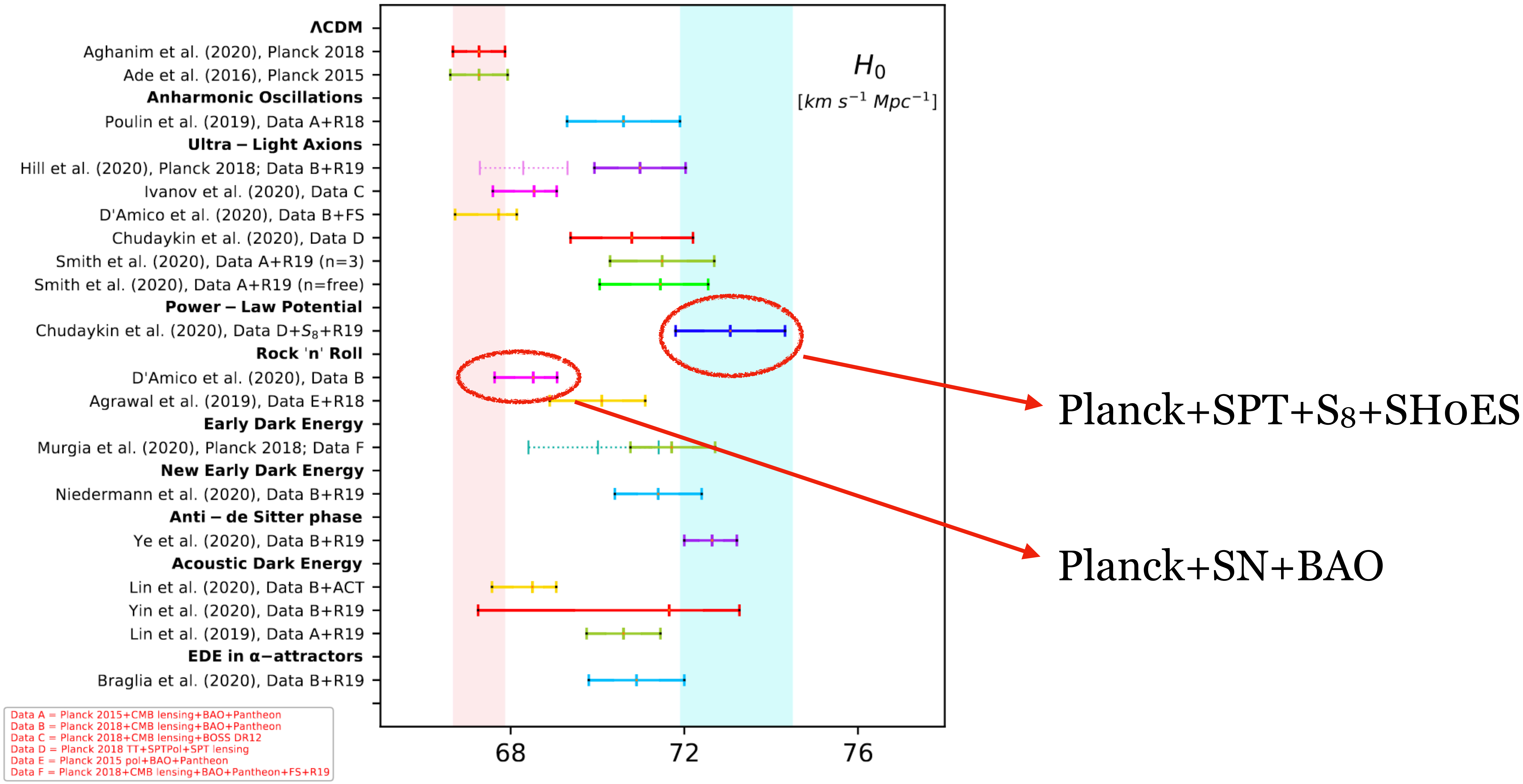

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The H_0 Olympics

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

with Dark radiation

- Free-streaming DR (ΔN_{eff})
- Self-interacting DR (ΔN_{fluid})
- Mixed DR ($\Delta N_{eff}+\Delta N_{fluid}$)
- DM-DR interactions
- Self-interacting ν_s
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no Dark radiation

- Primordial B fields
- Varying m_e
- Varying $m_e+\Omega_k$
- Early Dark Energy (EDE)
- New Early Dark Energy (NEDE)
- Early Modified Gravity (EMG)

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Late universe

- CPL dark energy
- Phenomenological Emergent Dark Energy (PEDE)
- Modified PEDE
- 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

$$m(z) = M_b + 25 - 5\mathrm{Log}_{10}\mathrm{H}_0 + 5\mathrm{Log}_{10}(\hat{\mathrm{D}}_\mathrm{L}(\mathrm{z}))$$

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 (or Mb) from a data combination D not including a SH0ES prior?

Gaussian tension GT

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

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

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

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?

Q_{DMAP} tension

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

Raveri&Hu 1806.04649

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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 $\Delta\mathrm{AIC}$

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

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

*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

1

Compare **all models** against

- Planck 2018 TTTEEE+lensing
- BAO (BOSS DR12+MGS+6dFGS)
- Pantheon SNIa catalog
- SH0ES

Steps of the contest

2

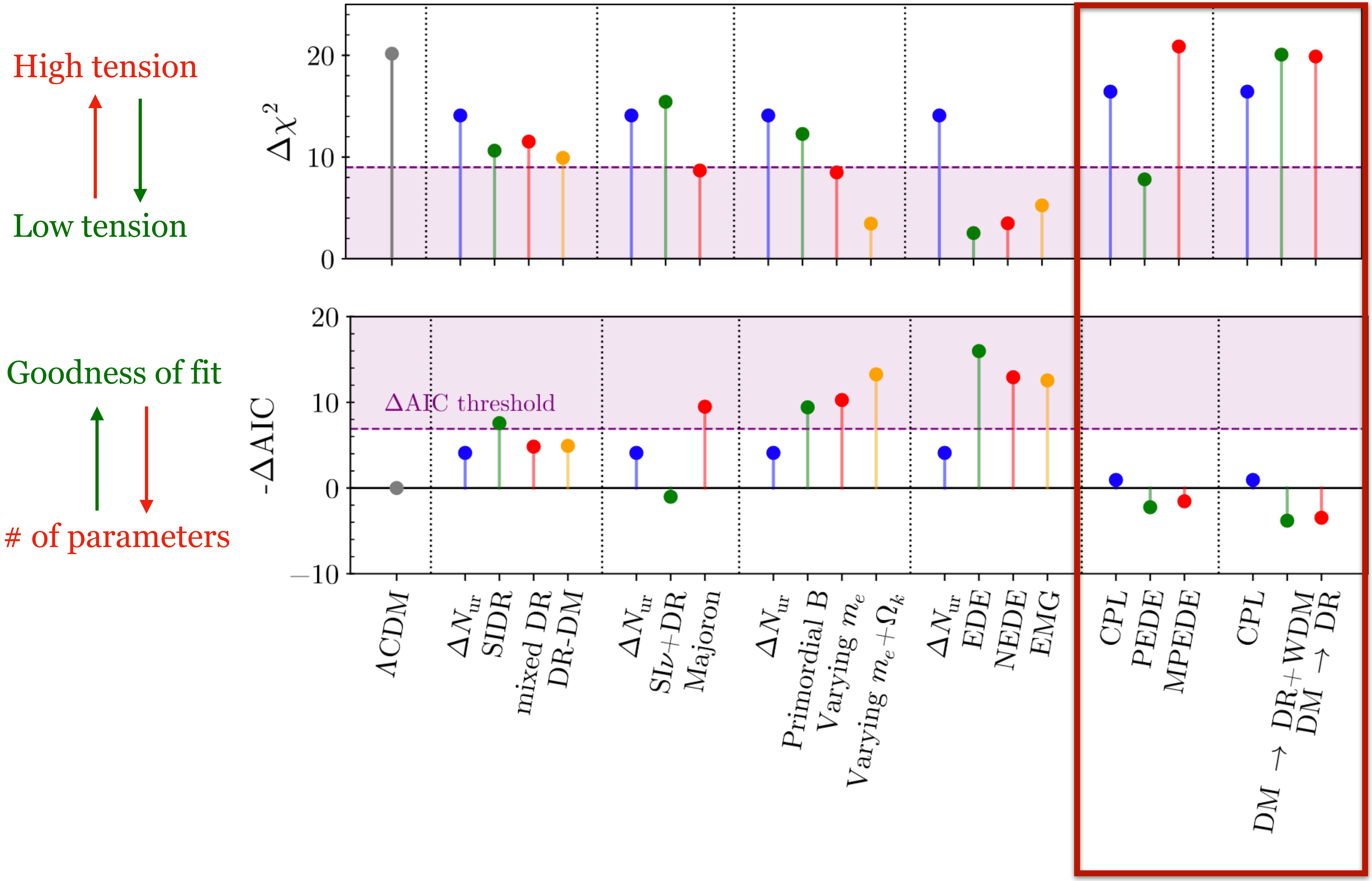
As long as $\Delta \text{AIC} < 0$, models go into **finalist** if criterium 2 or 3 are satisfied

Steps of the contest

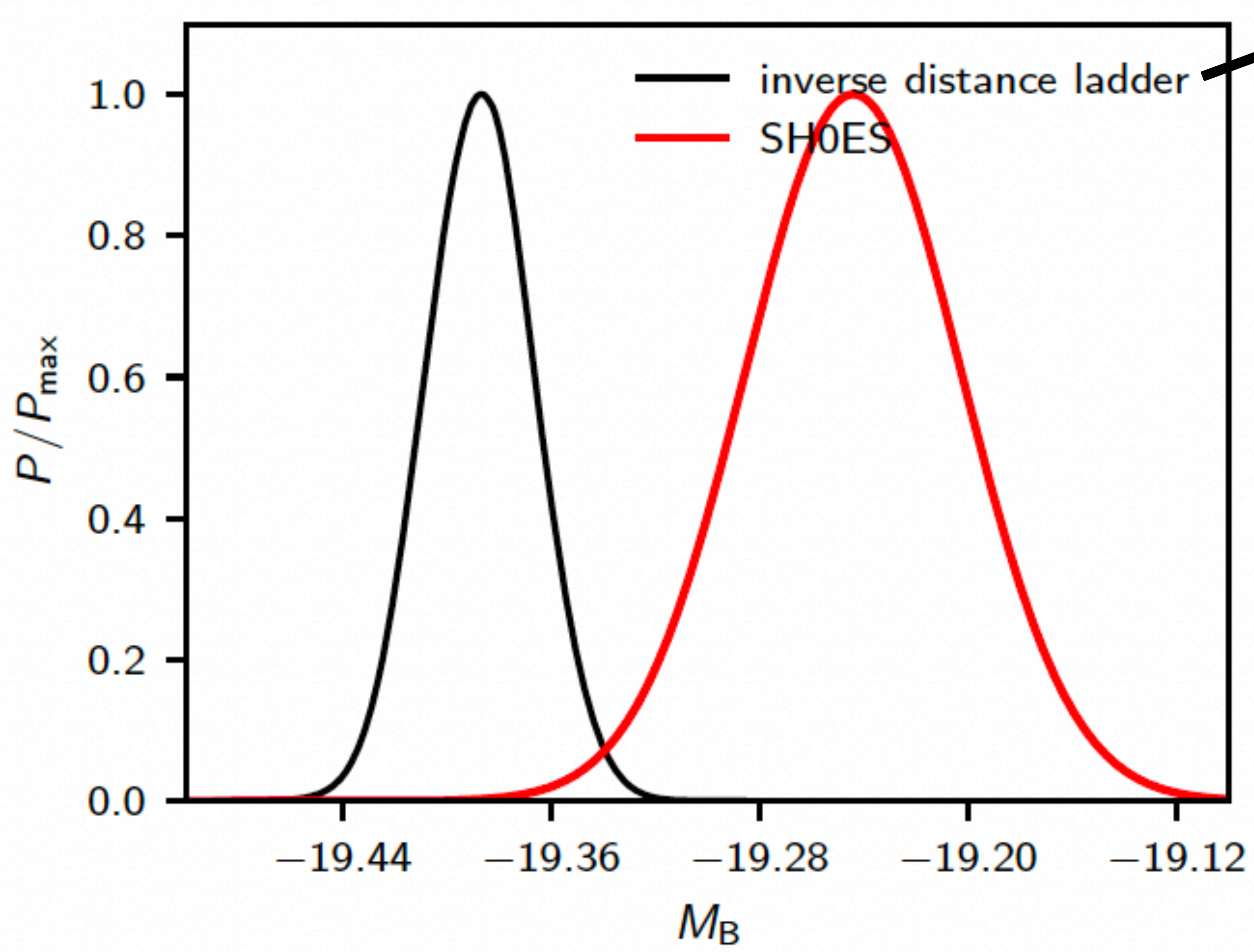
3

Finalists receive **bronze**, **silver** or **golden** medals if they satisfy **one**, **two** or **three** criteria, respectively

Results: late-time solutions



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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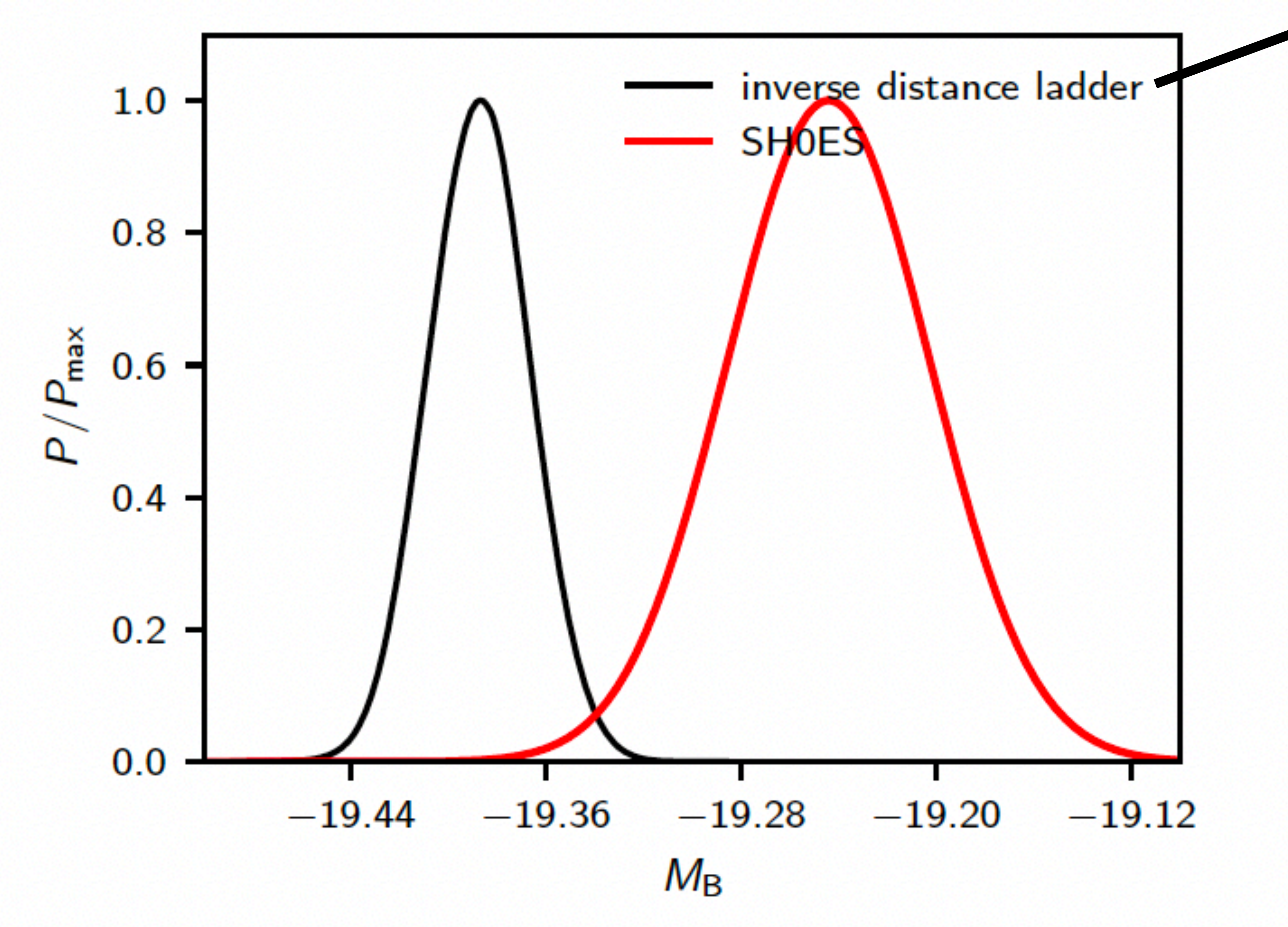

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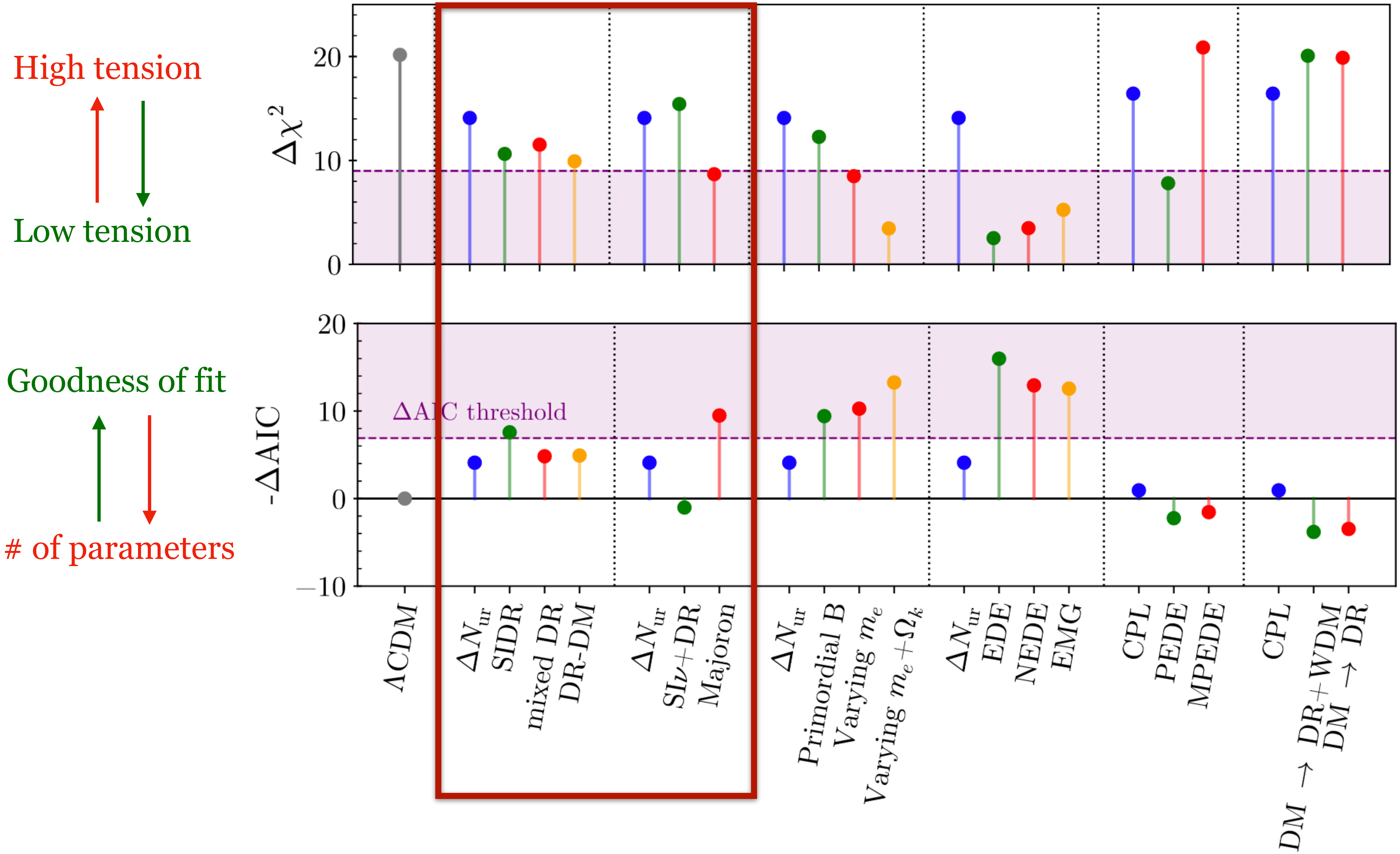
For $r_s^{\Lambda CDM} = 147$ Mpc, inverse distance ladder disagrees with SH0ES

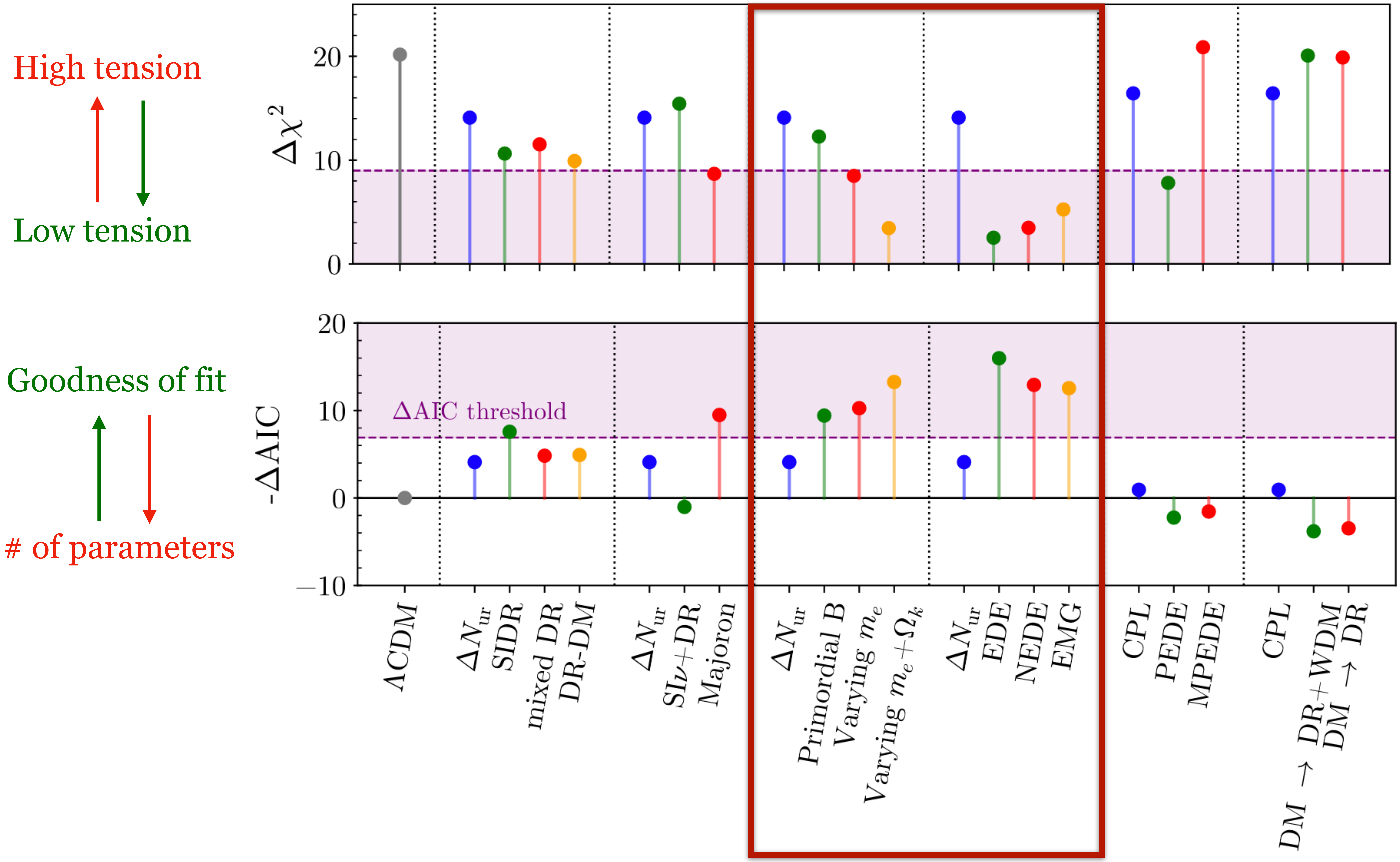
To make the two determinations agree, one is forced to reduce r_s

Ex: *Early Dark Energy or varying electron mass*

Results: early-time solutions with Dark Radiation



Results: early-time solutions without Dark Radiation



Results of the contest

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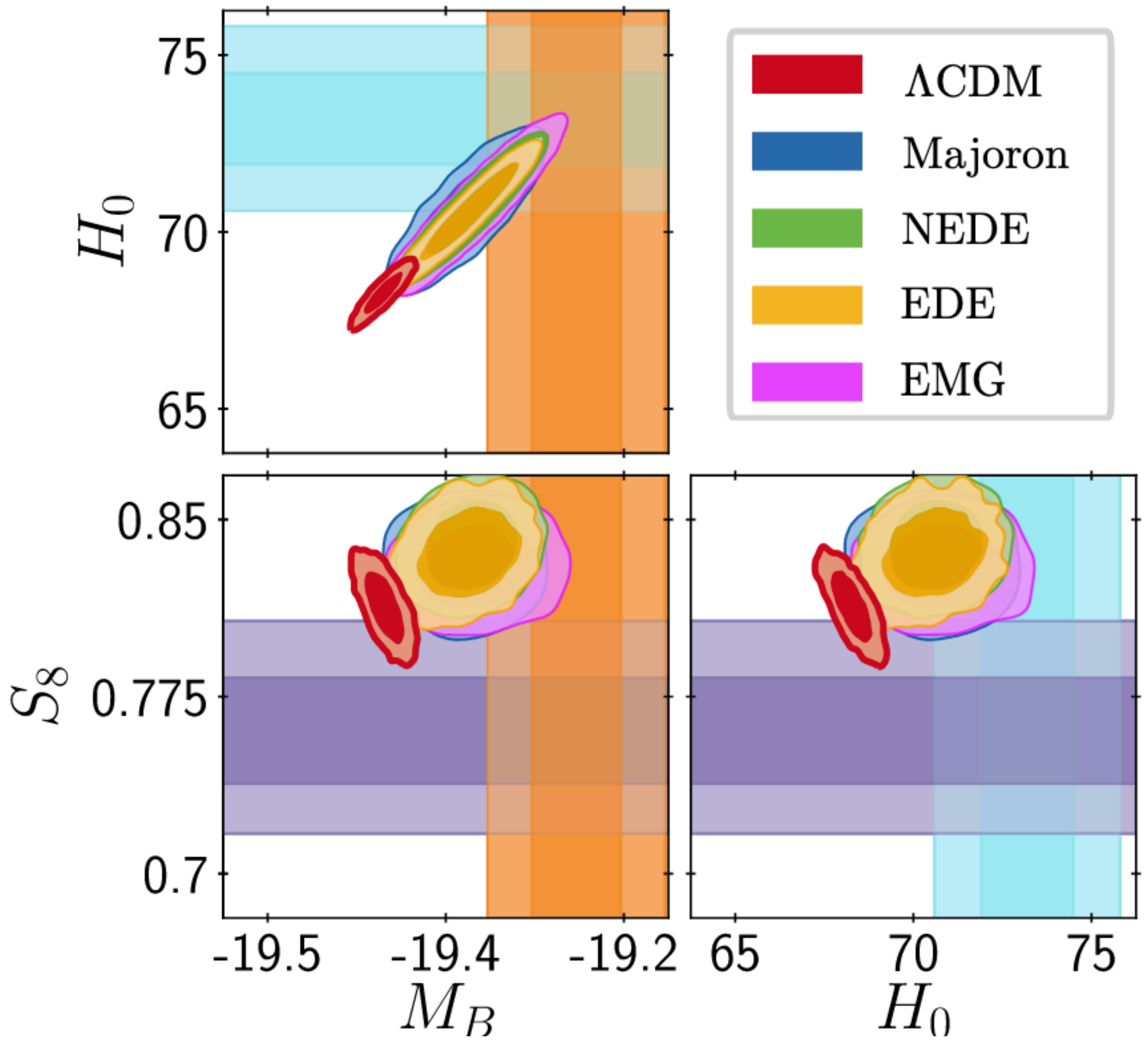
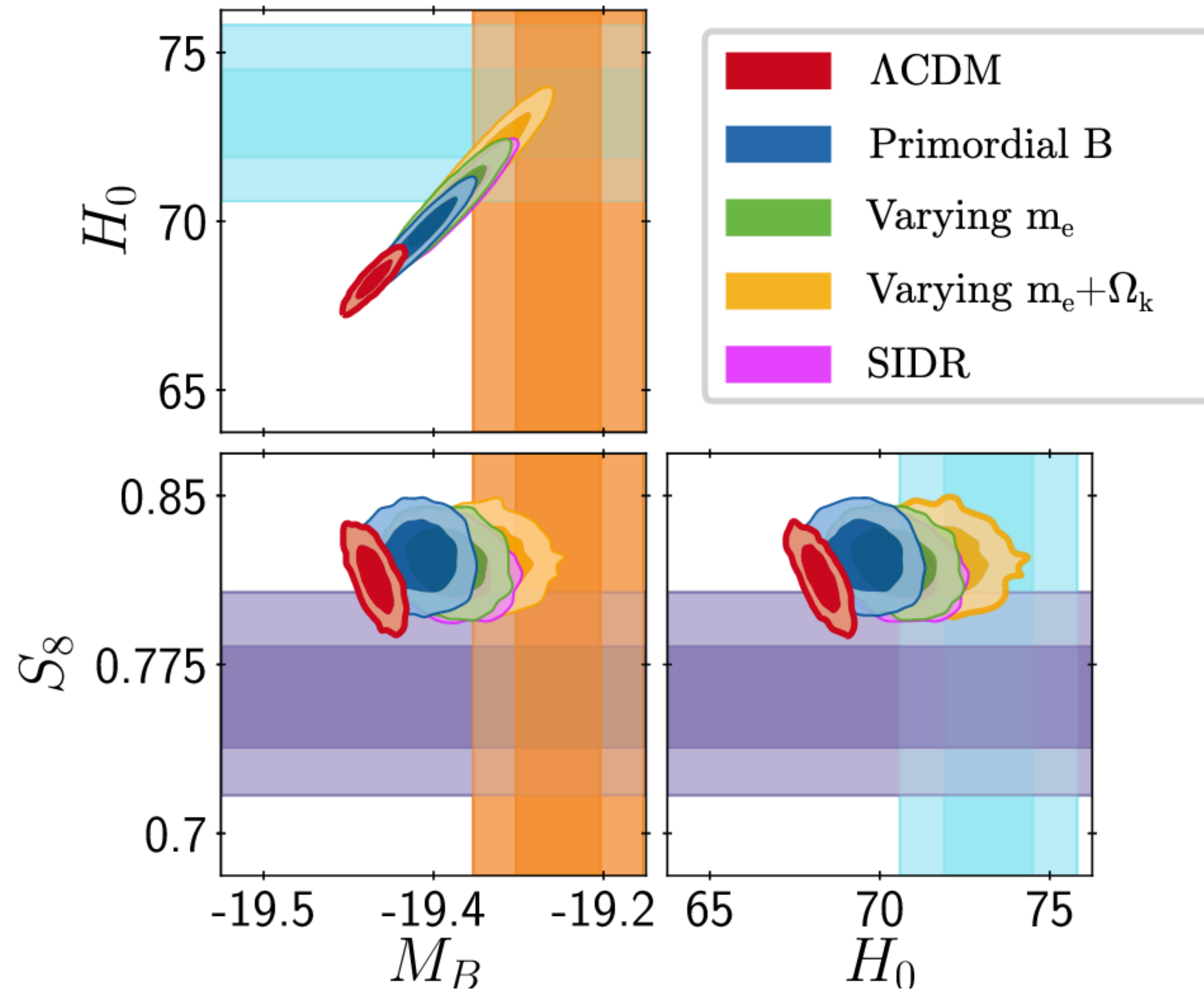
Unfortunately, the most successful models face strong fine-tuning problems, and are unable to explain the S_8 tension





Conclusions

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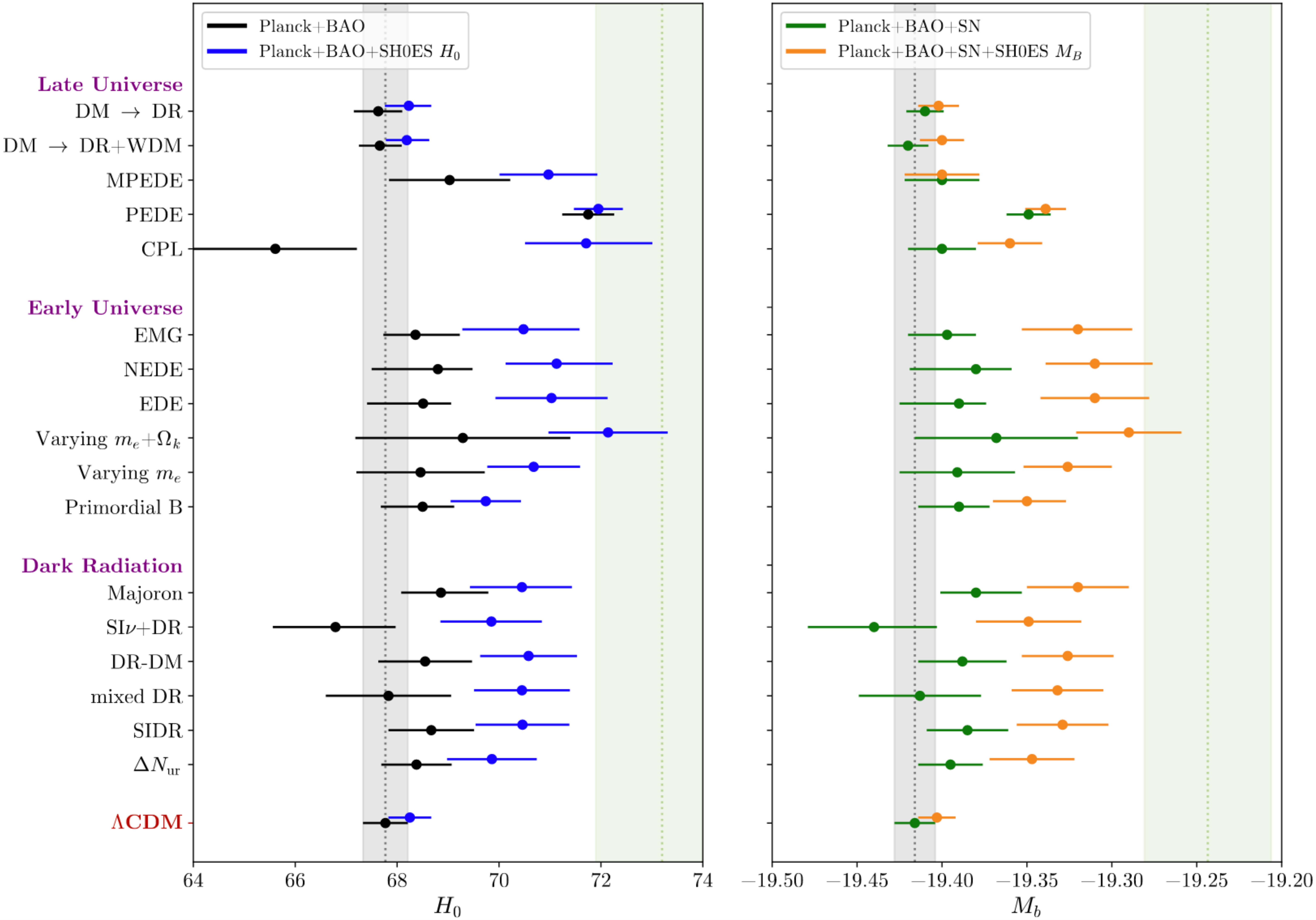
We might be on the verge of the discovery of a rich dark sector!

BACK-UP SLIDES

Reconstructed values of H_0



H_0 Olympics: testing against other datasets

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

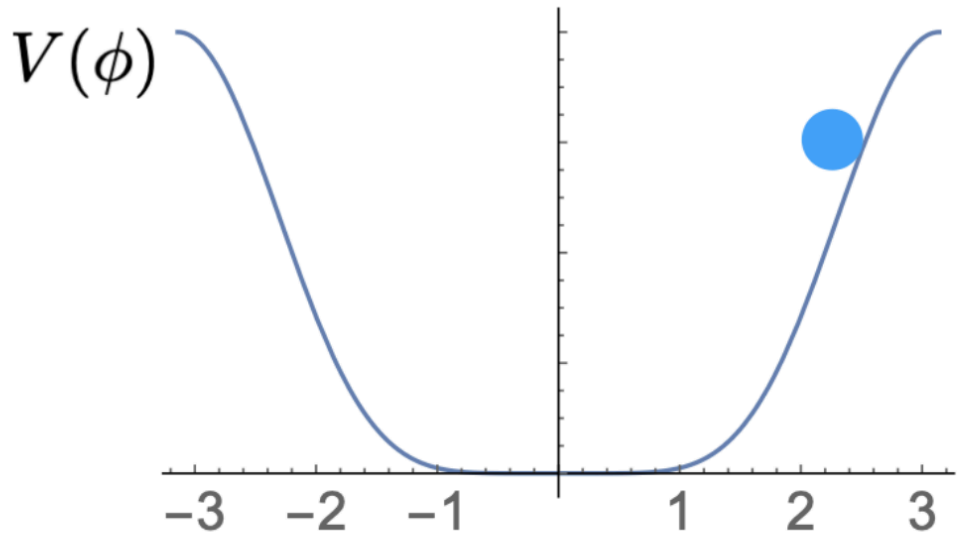
⟶ No significant changes (*notable exceptions are EDE and NEDE*)

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

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



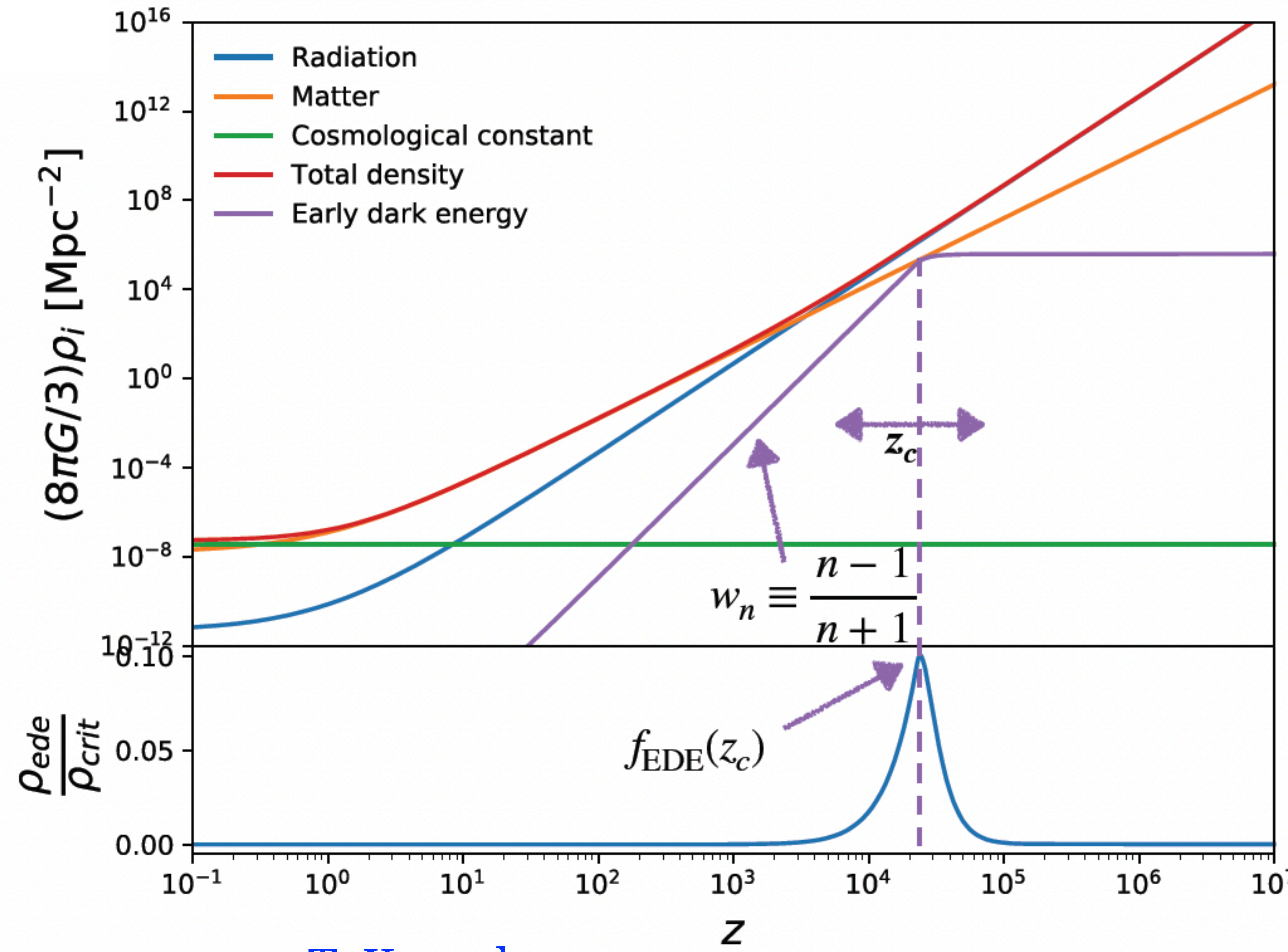
Scalar field initially frozen, then dilutes away equal or faster than radiation

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

+ perturbed linear eqs.

The model is fully specified by

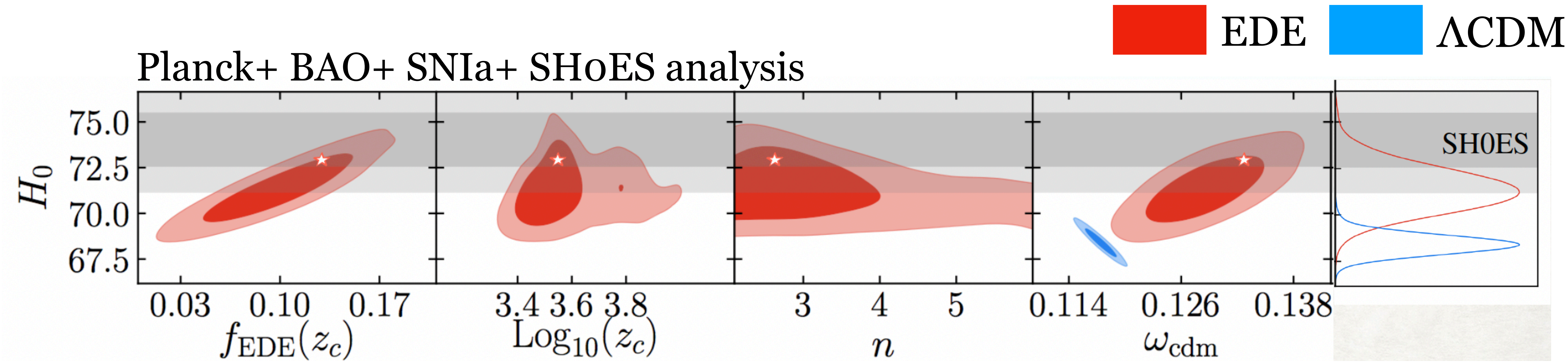
$$\{f_{\rm EDE}(z_c),\ z_c,\ n,\ \phi_i\}$$



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

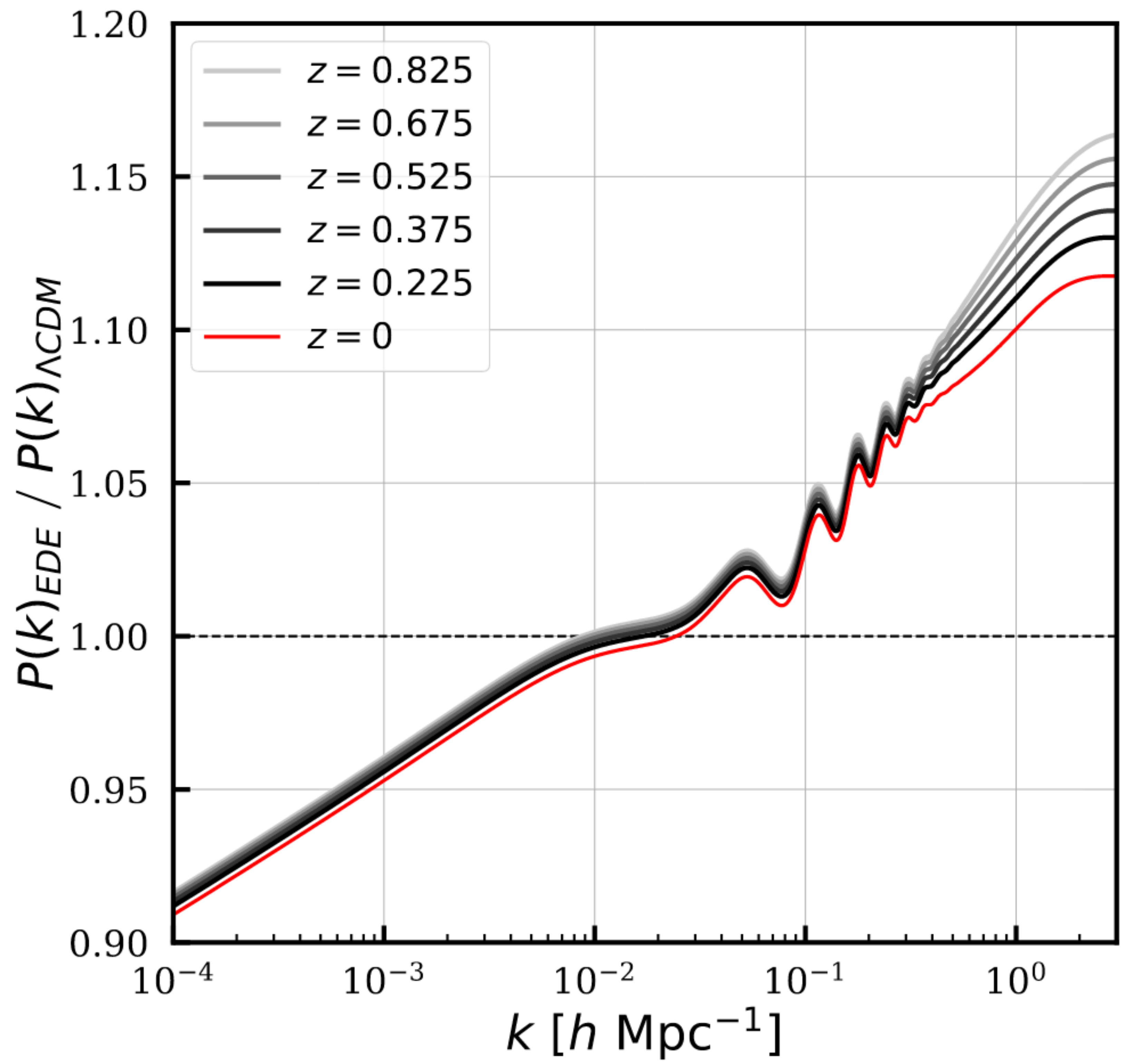
Sakstein++ 1911.11760 Freese++ 2102.13655

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

Jedamzik++ 2010.04158.

Is EDE solution ruled out?

EDE solution increases power at small k (*with a corresponding increase in* S_8), rising mild tension with Large Scale Structure (LSS) data



Hill++ 2003.07355

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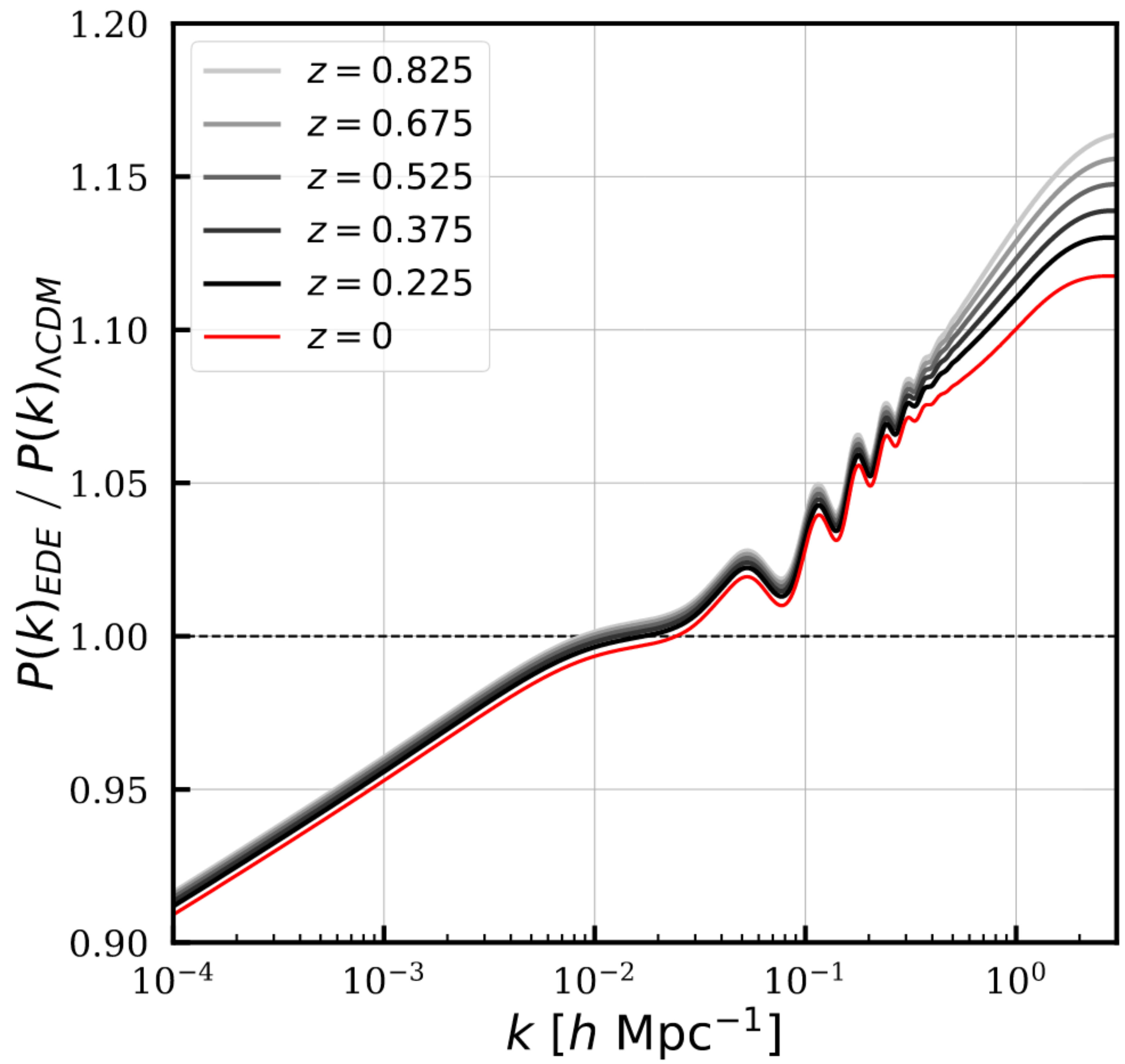
When LSS data is added to analysis, EDE detection is reduced from 3σ to 2σ

In addition, EDE is not detected from Planck data alone



D'amico++ 2006.12420
Ivanov++ 2006.11235

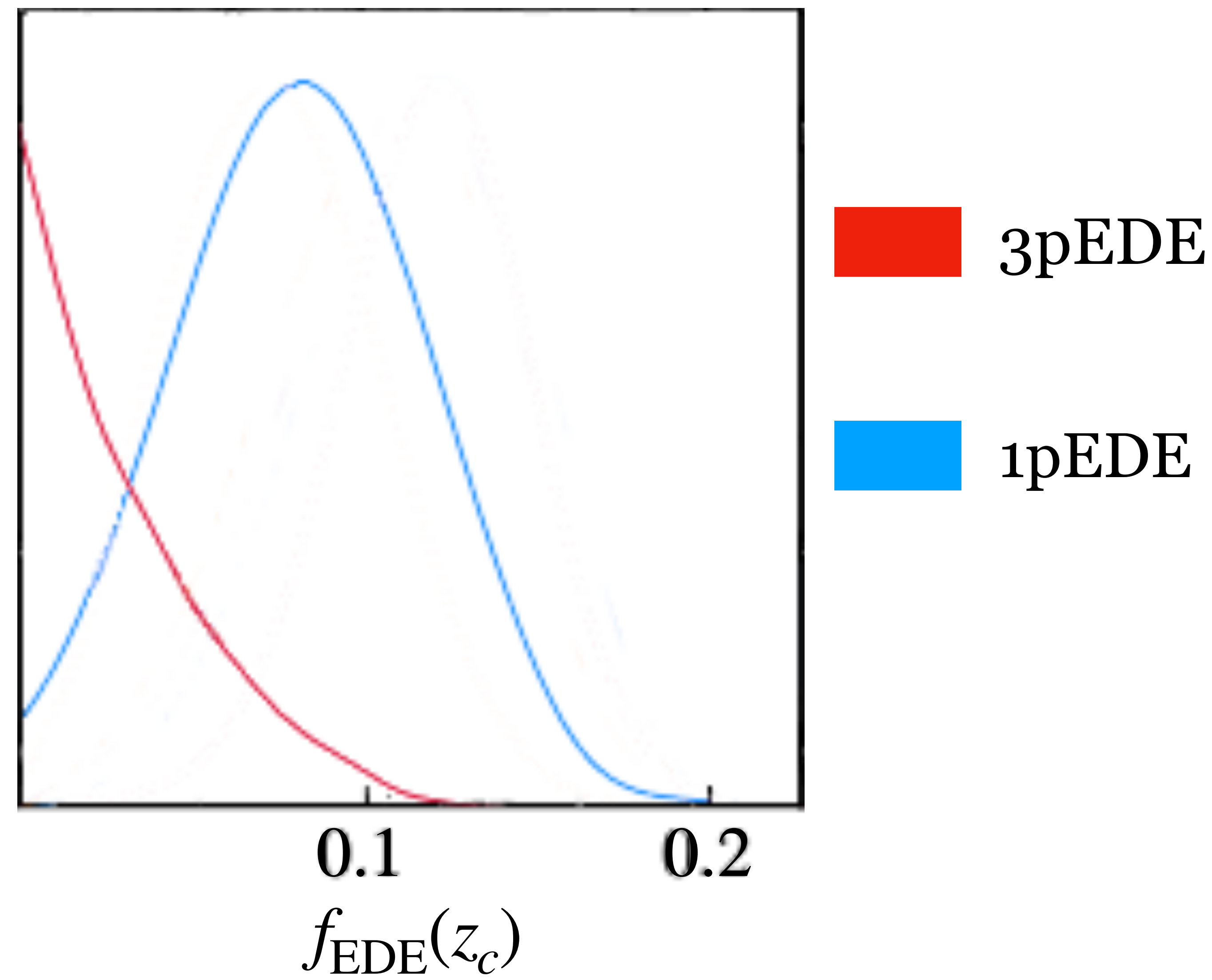
Hill++ 2003.07355

Answer: no, EDE solution is still robust

1. Why EDE is not detected from Planck alone?

χ^2 degeneracy in Planck between ΛCDM and EDE :
For $f_{\rm EDE} \lesssim 4\,\%$, parameters z_c and $\phi_{\rm i}$ become irrelevant,
so posteriors are naturally weighted towards ΛCDM

Planck 2018



Murgia, GFA, Poulin 2107.10291

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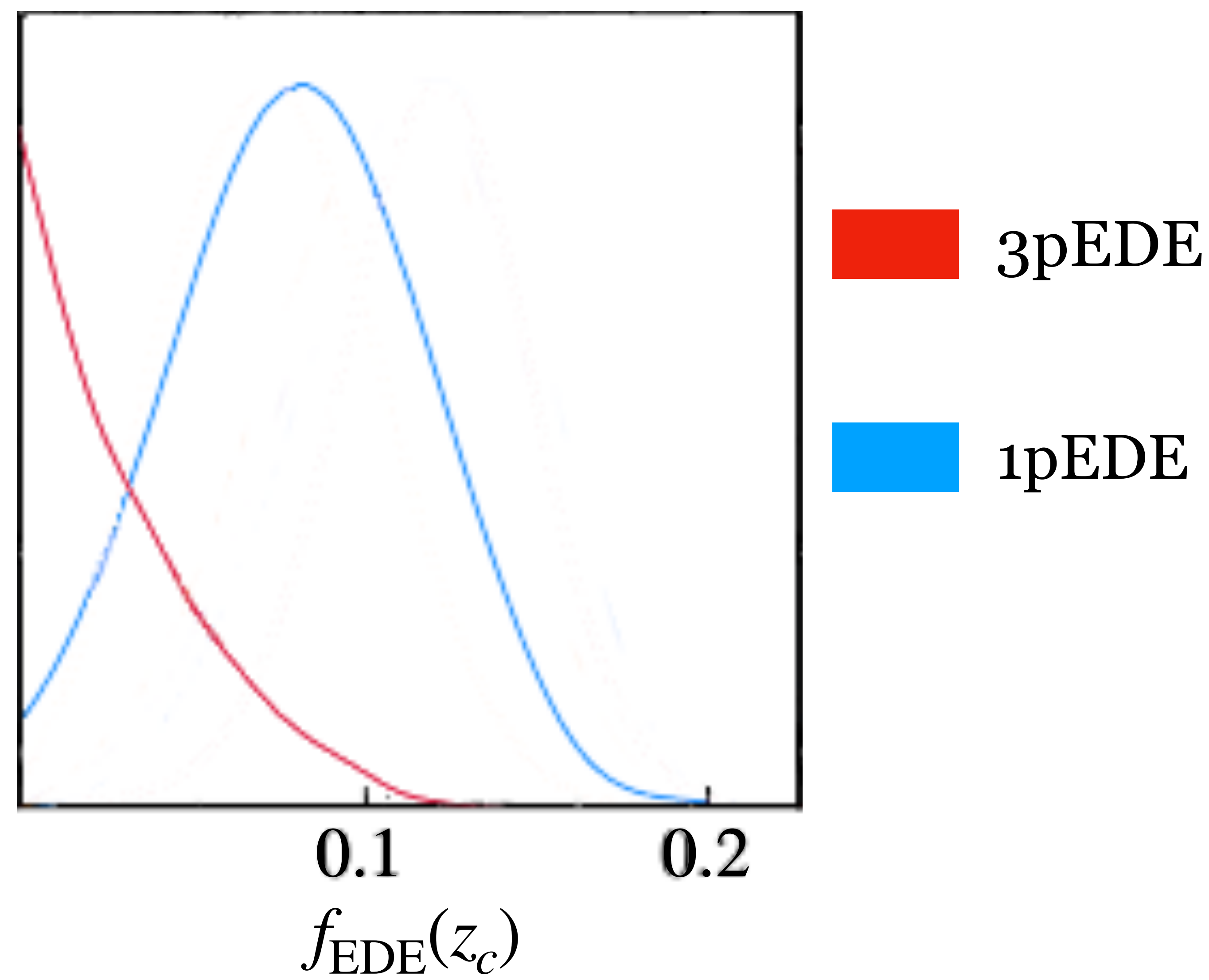
To avoid this Bayesian volume effect, consider a
1 parameter EDE model (1pEDE):
Fix z_c and ϕ_i and let f_{EDE} free to vary

Planck 2018



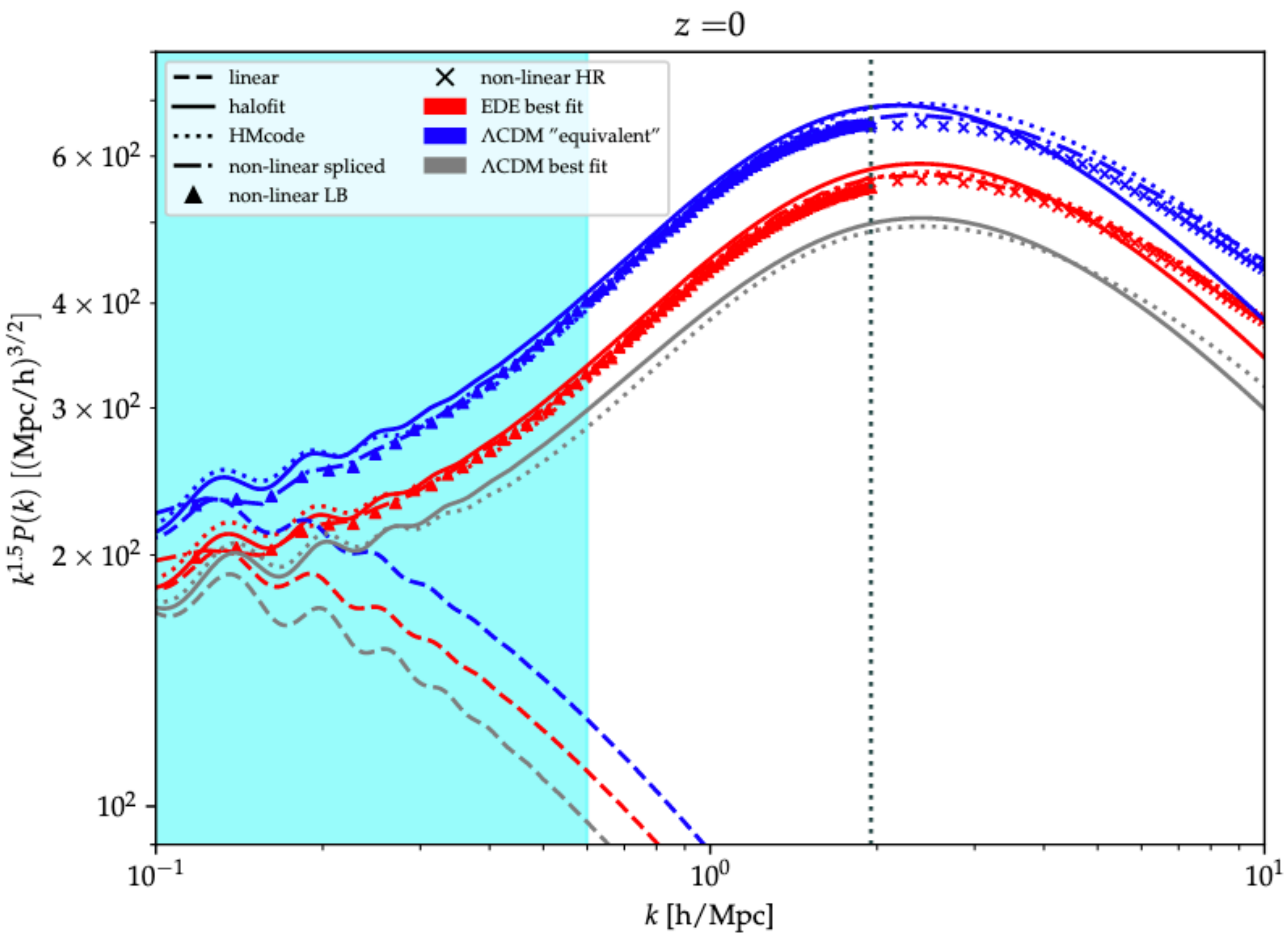
Within 1pEDE, we get a 2σ detection of EDE from *Planck data alone*

$$f_{\rm EDE} = 0.08 \pm 0.04 \qquad H_0 = 70 \pm 1.5\ \text{km/s/Mpc}$$

Murgia, GFA, Poulin 2107.10291

Answer: no, EDE solution is still robust

2. Is LSS data constraining enough to rule out EDE?



EDE non-linear P(k)* from halofit agrees well with results from N-body simulations

*Intrinsic effect of EDE is a power suppression, but the shift of the ΛCDM params. leads to an enhancement

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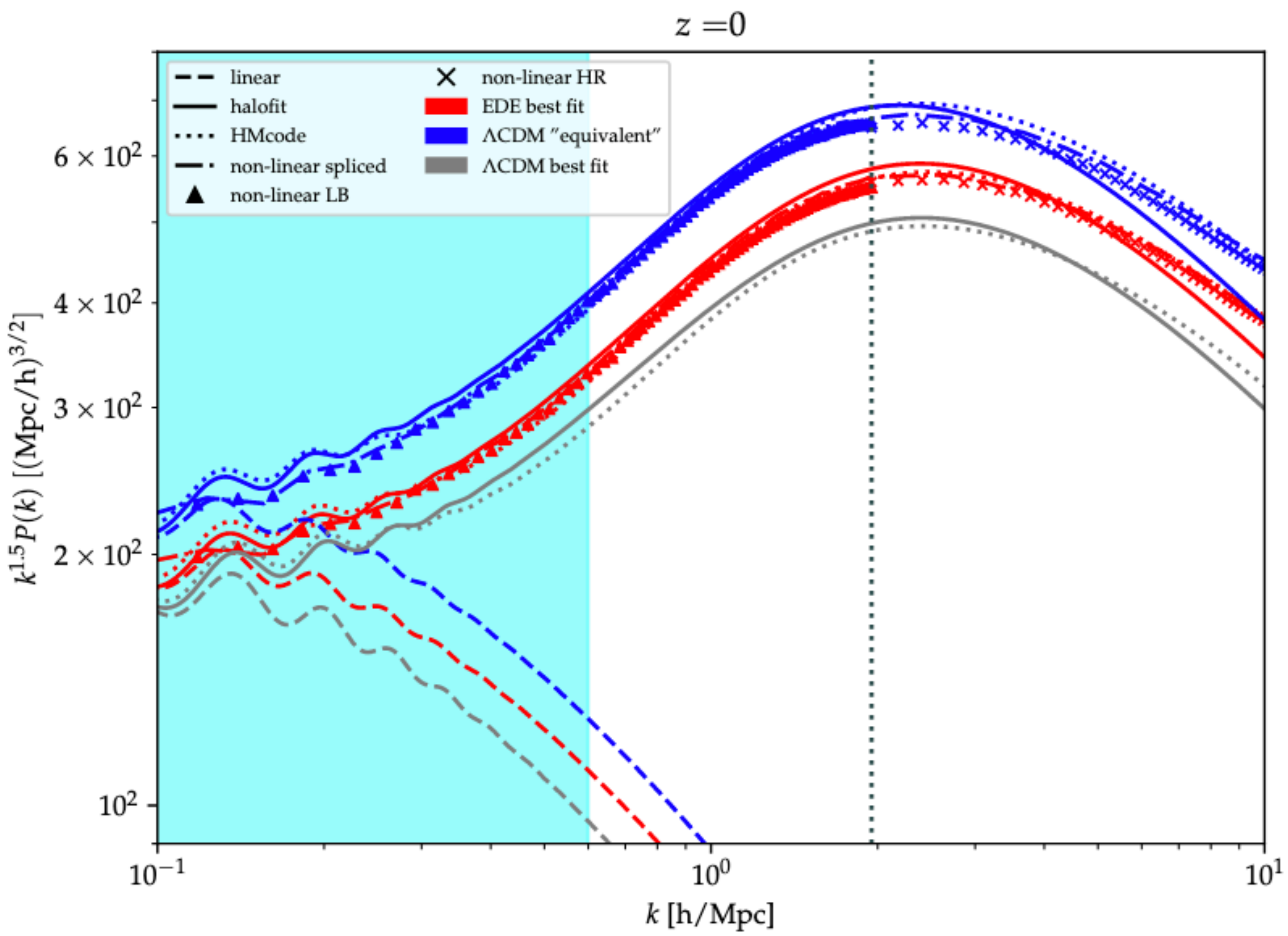


EDE non-linear P(k)* from halofit agrees well with results from N-body simulations

1pEDE tested against Planck+BAO+SNIa+SH0Es and WL data from KiDS/Viking+DES: S_8 tension persists, but fit is not significantly degraded wrt ΛCDM, and solution to the H_0 tension survives

Murgia, GFA, Poulin 2107.10291

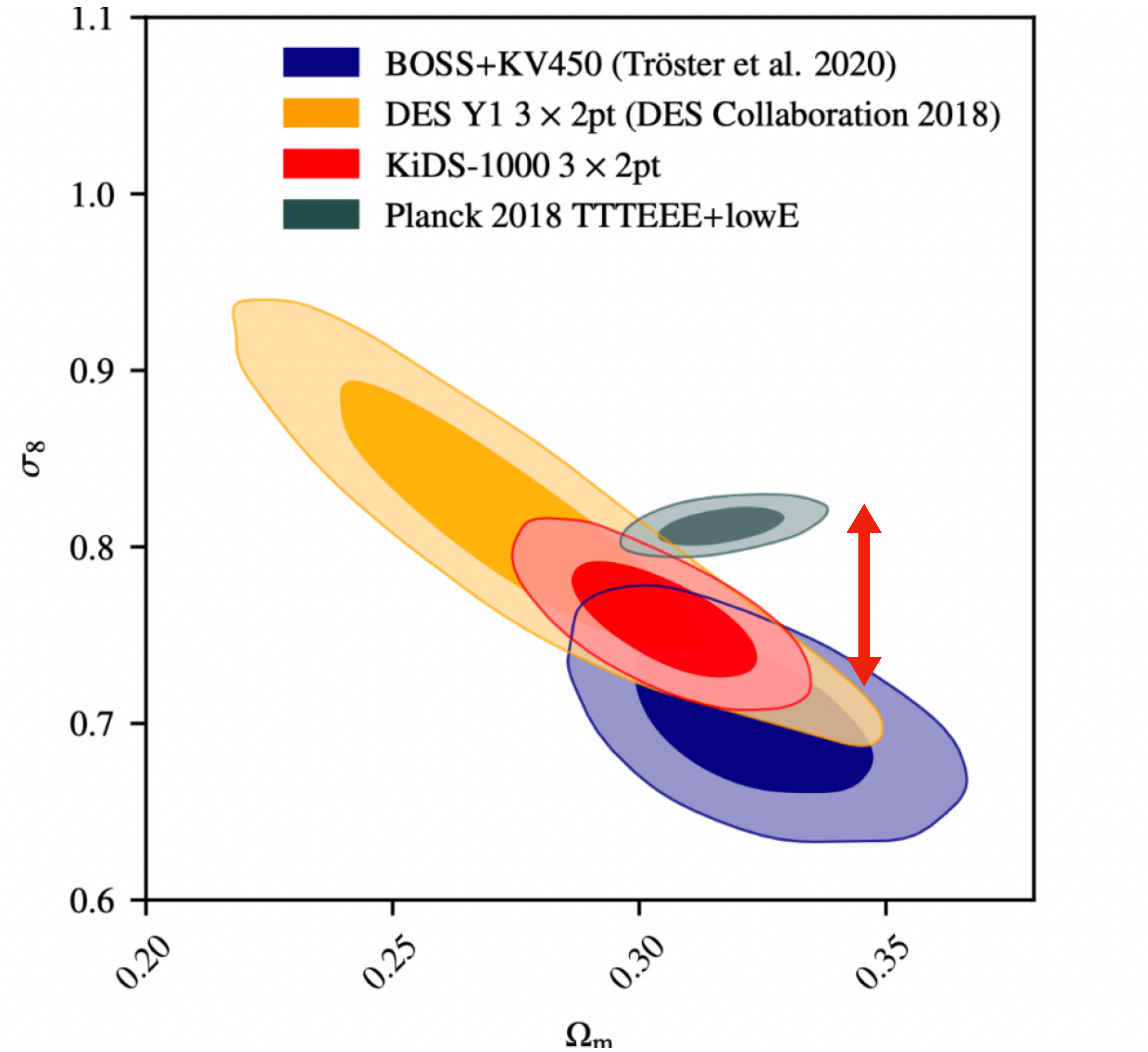
$$f_{\rm EDE} = 0.09^{+0.03}_{-0.02} \qquad H_0 = 71.3 \pm 0.9 \ \text{km/s/Mpc}$$

*Intrinsic effect of EDE is a power suppression, but the shift of the ΛCDM params. leads to an enhancement

What is needed to resolve the S_8 tension?

Di Valentino++ 2008.11285

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$



Ω_m should be left unchanged

$$\sigma_8 = \int P_m(k, z=0) W_R^2(k) d\ln k$$

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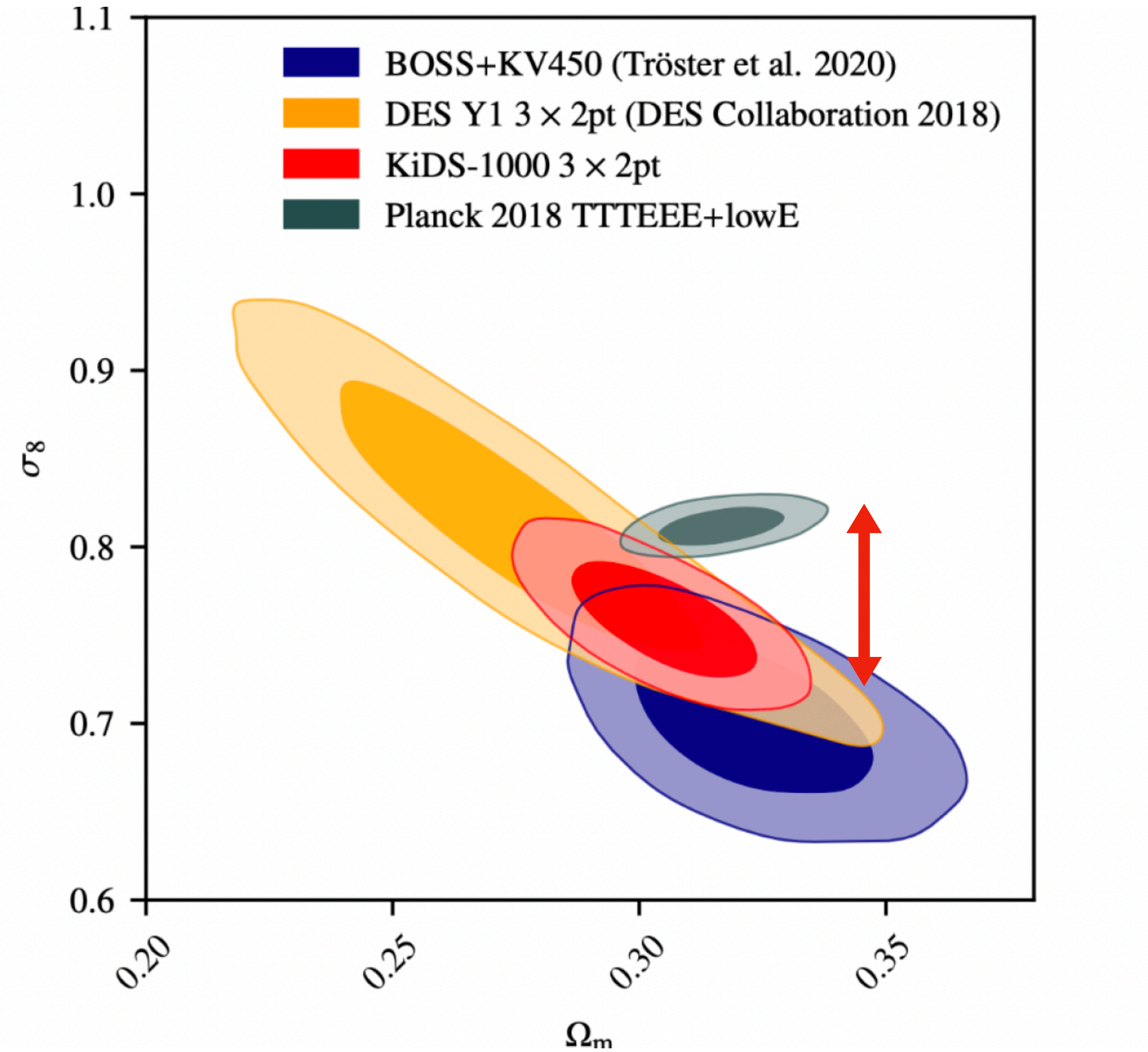

Ω_m should be left unchanged

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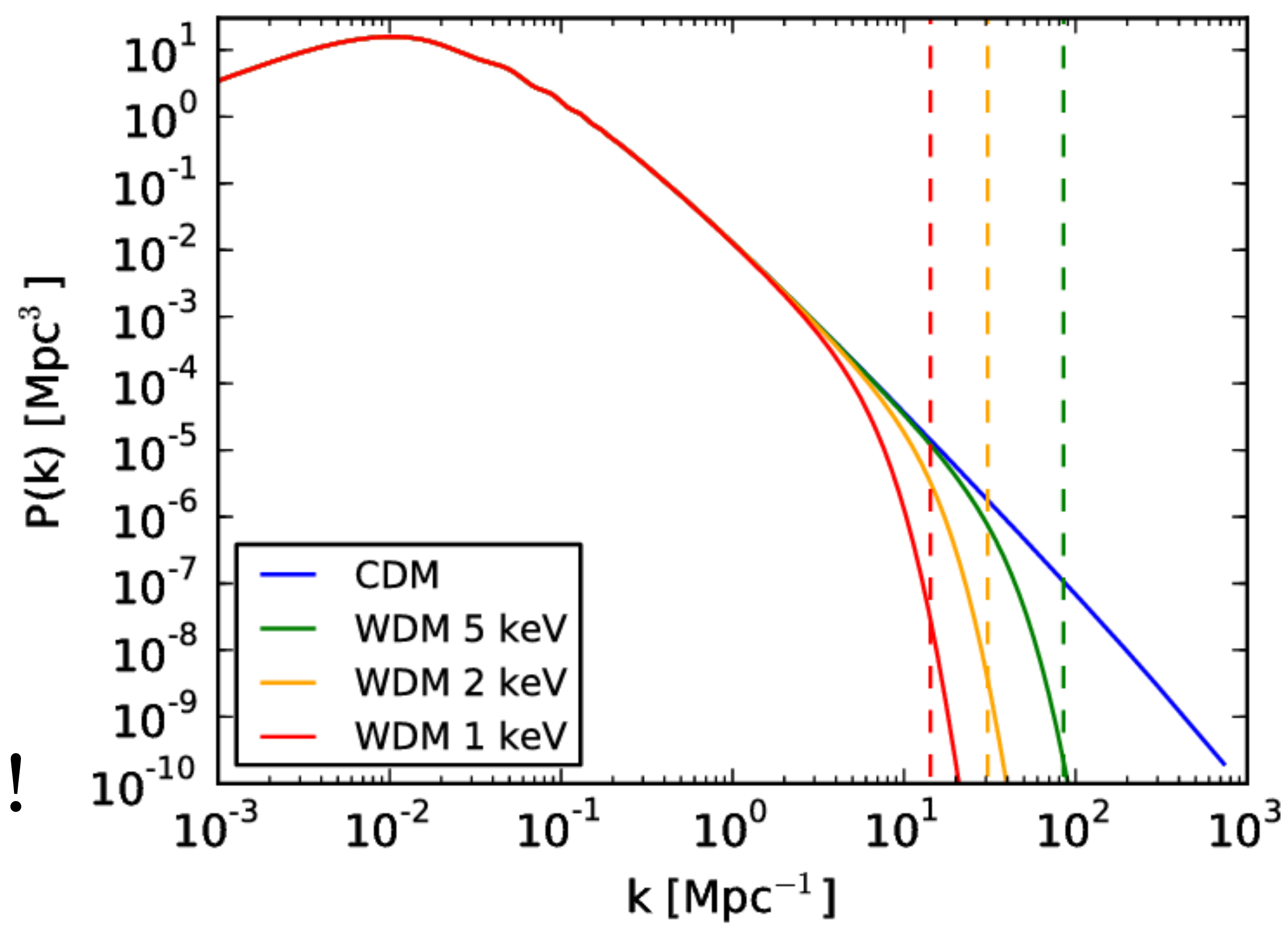
↓

Need to suppress power at scales $k \sim 0.1 - 1\ h/\mathrm{Mpc}$

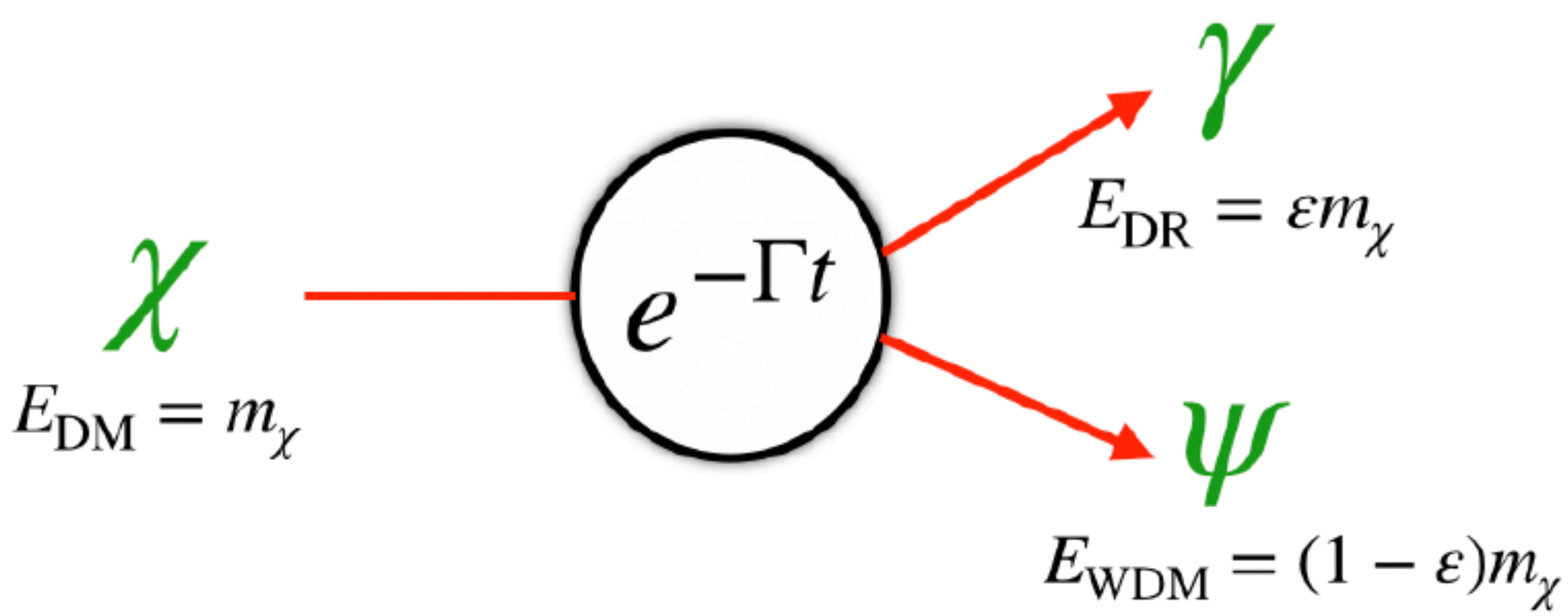
Ex: Warm Dark Matter

Very constrained by many probes!



2-body Dark Matter decay

We explore DM decays to massless (Dark Radiation) and massive (Warm Dark Matter) particles, $\chi(\mathrm{DM}) \to \gamma(\mathrm{DR}) + \psi(\mathrm{WDM})$



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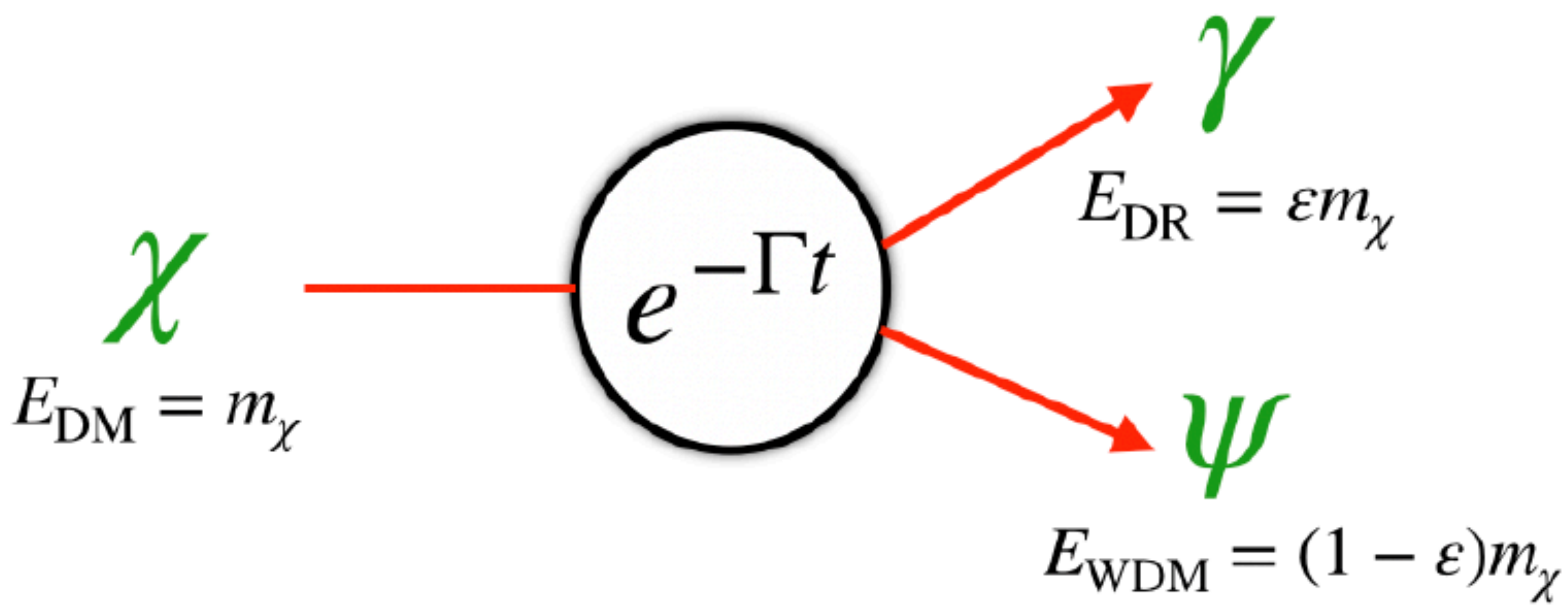
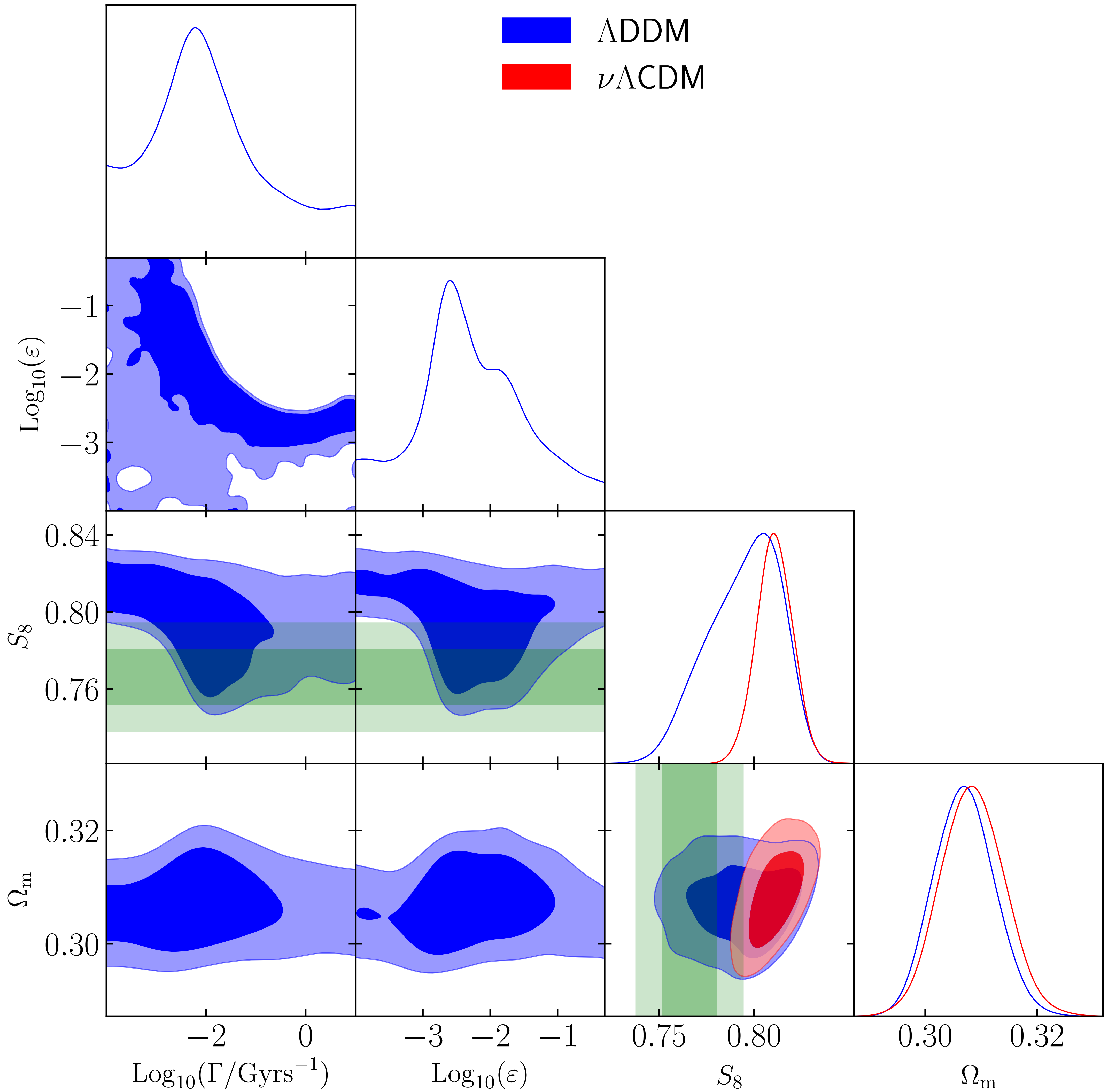


The model is fully specified by:

$$\{\Gamma,\ \varepsilon\} \quad \text{where} \quad \varepsilon = \frac{1}{2}\left(1 - \frac{\mathbf{m}_\psi^2}{\mathbf{m}_\chi^2}\right) \begin{cases} = \mathbf{0} \ \text{for } \Lambda\mathrm{CDM} \\ = \mathbf{1/2} \ \text{for DM} \rightarrow \mathrm{DR} \end{cases}$$

Explaining the S_8 tension



GFA, Murgia, Poulin 2102.12498

- MCMC analysis using Planck+BAO+SNIa+prior on S_8 from KIDS+BOSS+2dfLenS

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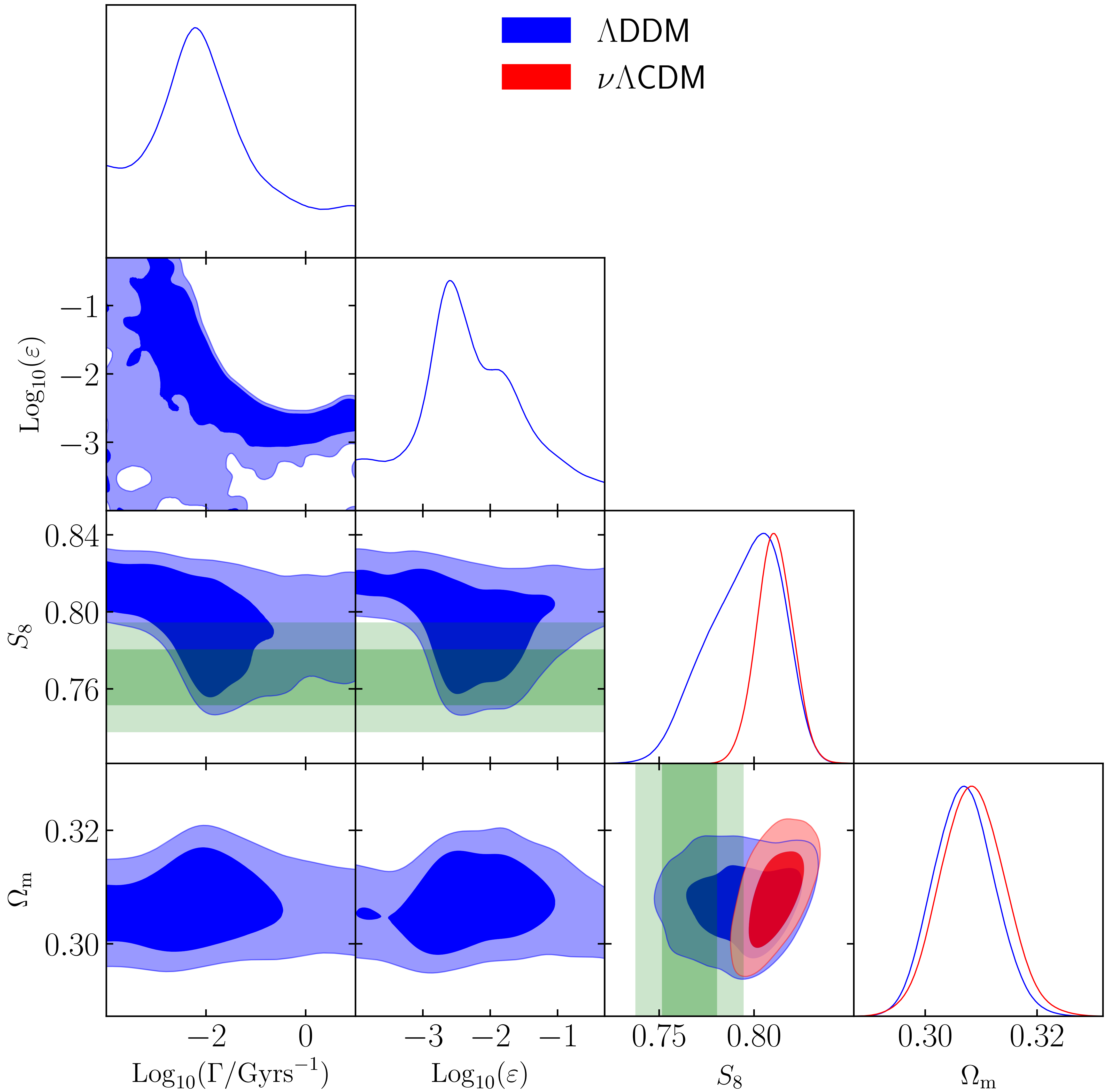


GFA, Murgia, Poulin 2102.12498

- MCMC analysis using Planck+BAO+SNIa+prior on S_8 from KIDS+BOSS+2dfLenS

- Reconstructed S_8 values are in excellent agreement with WL data!

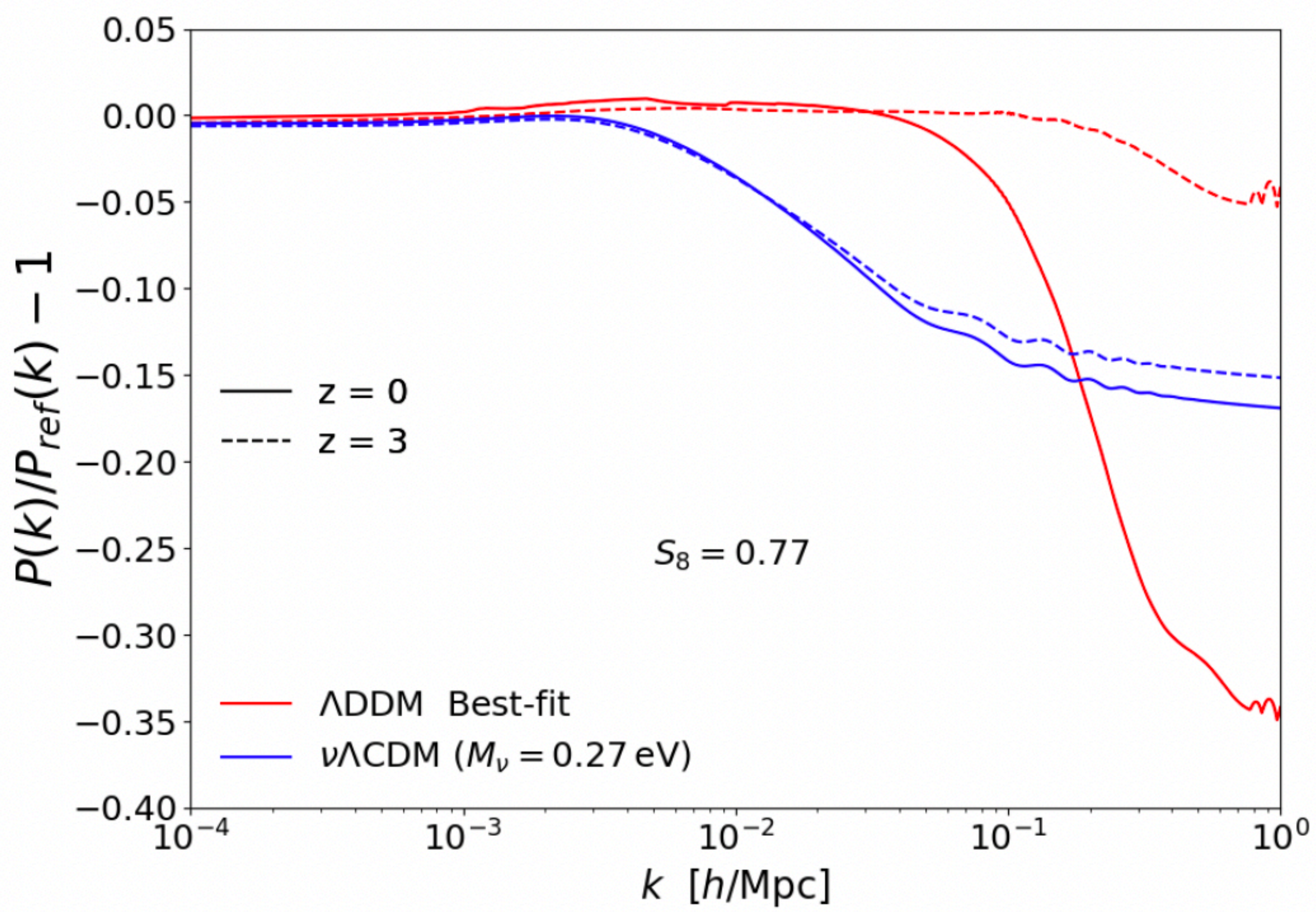
	$\nu\Lambda$CDM	ΛDDM
$\chi^2_{\rm CMB}$	1015.9	1015.2
$\chi^2_{S_8}$	5.64	0.002

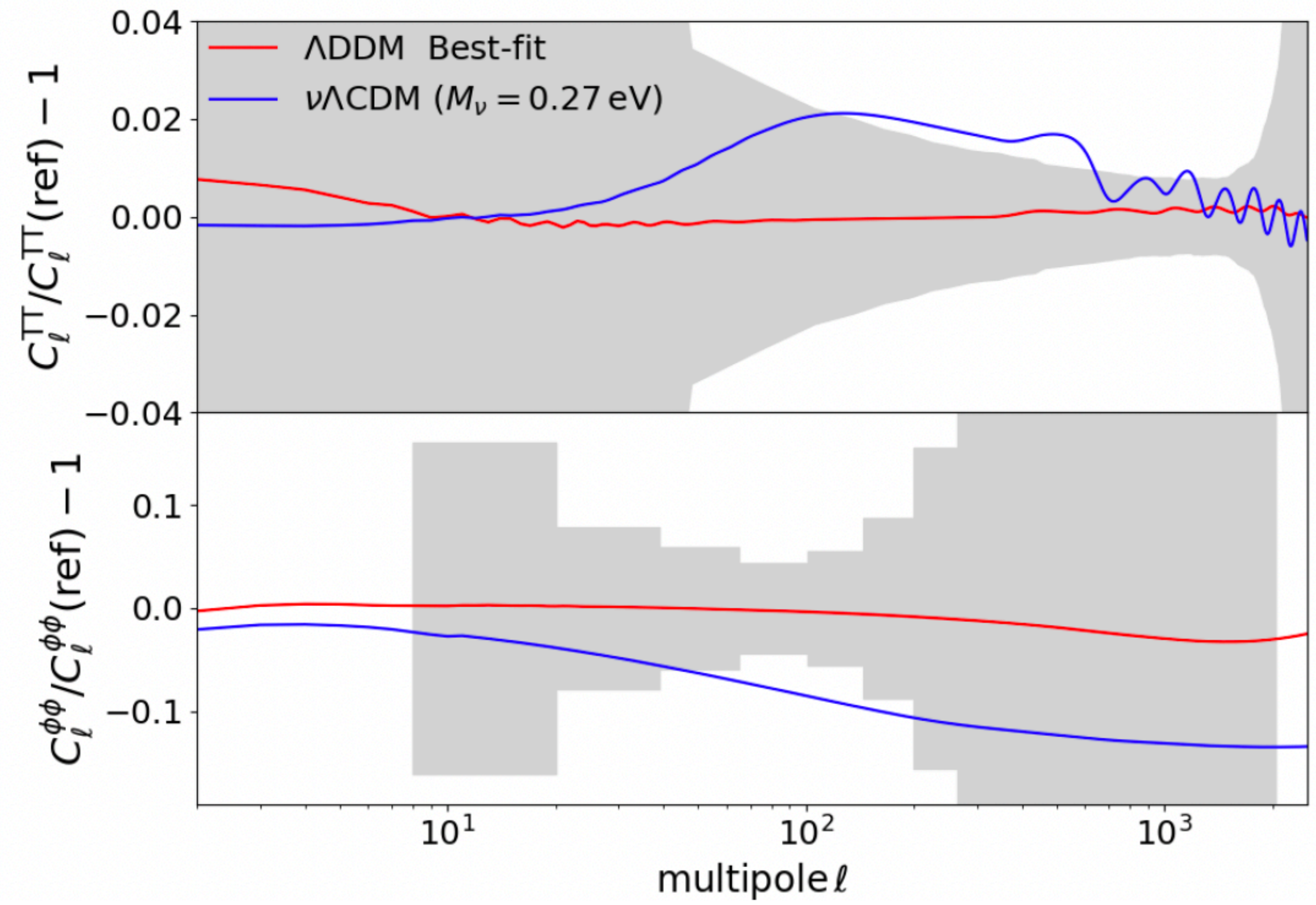
$$\longrightarrow \Delta\chi^2_{\rm min} \simeq -5.5$$

$$\Gamma^{-1} \simeq 55\ (\varepsilon/0.007)^{1.4}\ \mathrm{Gyr}$$

Why does the 2-body DM decay work better than massive neutrinos?

The 2-body decay gives a better fit thanks to the time-dependence of the power suppression and the cut-off scale





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