The H_0 Olympics: a fair ranking of proposed models

Guillermo Franco Abellán
Laboratoire Univers et Particules de Montpellier

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

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

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

Unaccounted systematics?

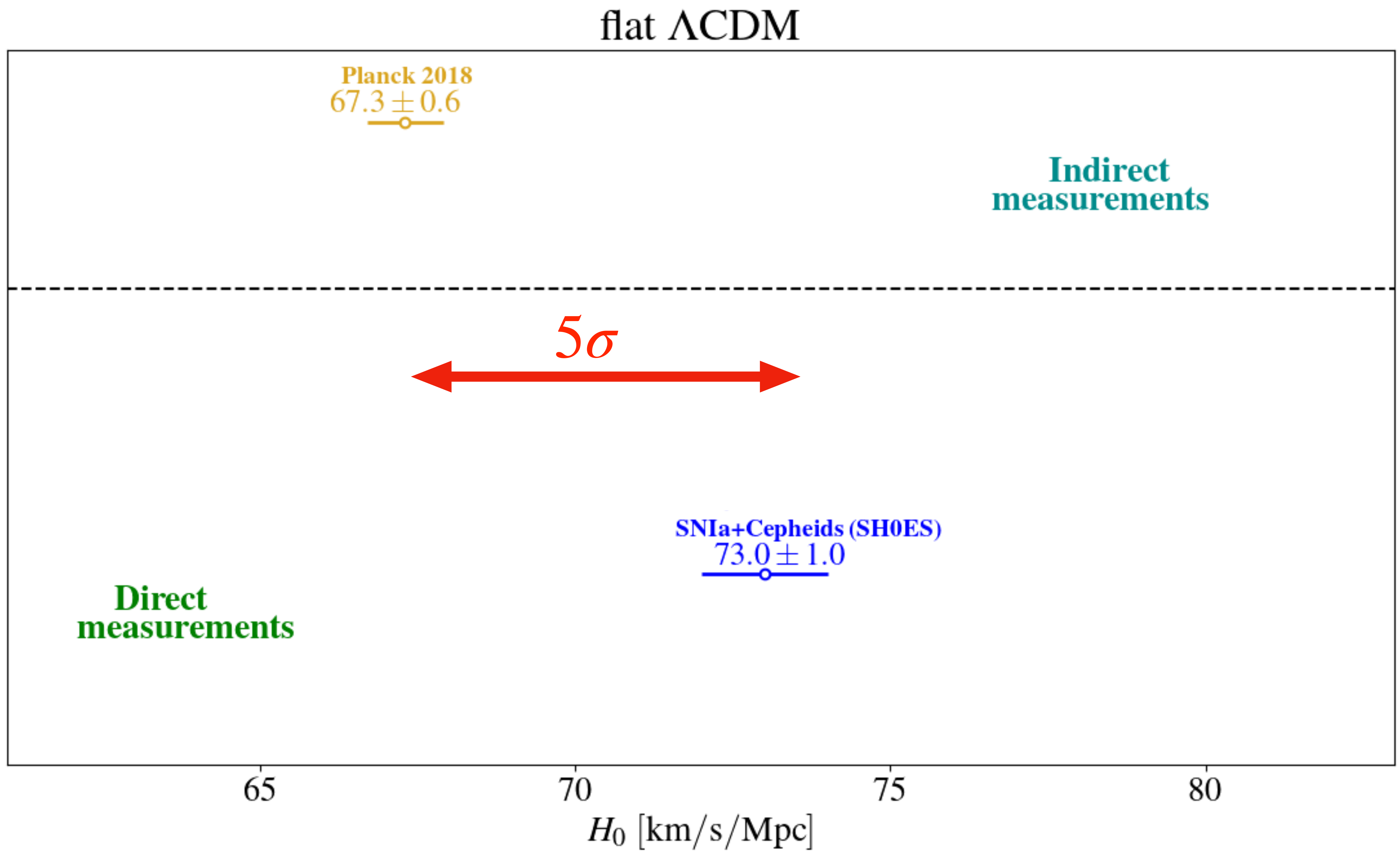
- Less exotic explanation ✅
- Difficult to account for all discrepancies ❌

Physics beyond ΛCDM?

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

The H_0 tension

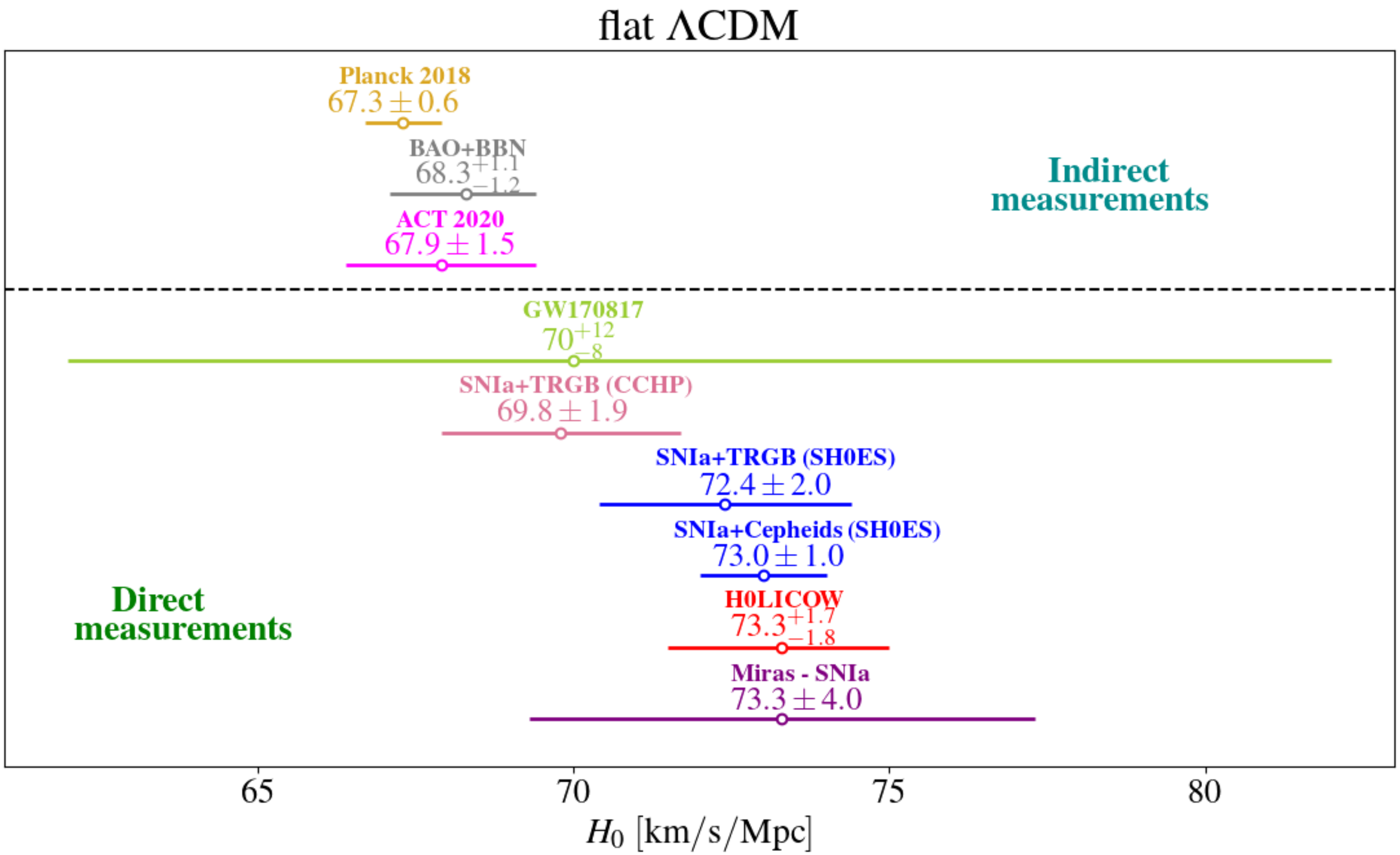
Planck (*under ΛCDM*) and SH0ES measurements are now in **5σ tension !**



The H_0 tension

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

High- and low-redshift probes are typically discrepant



Lost in the landscape of solutions

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

Lost in the landscape of solutions

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

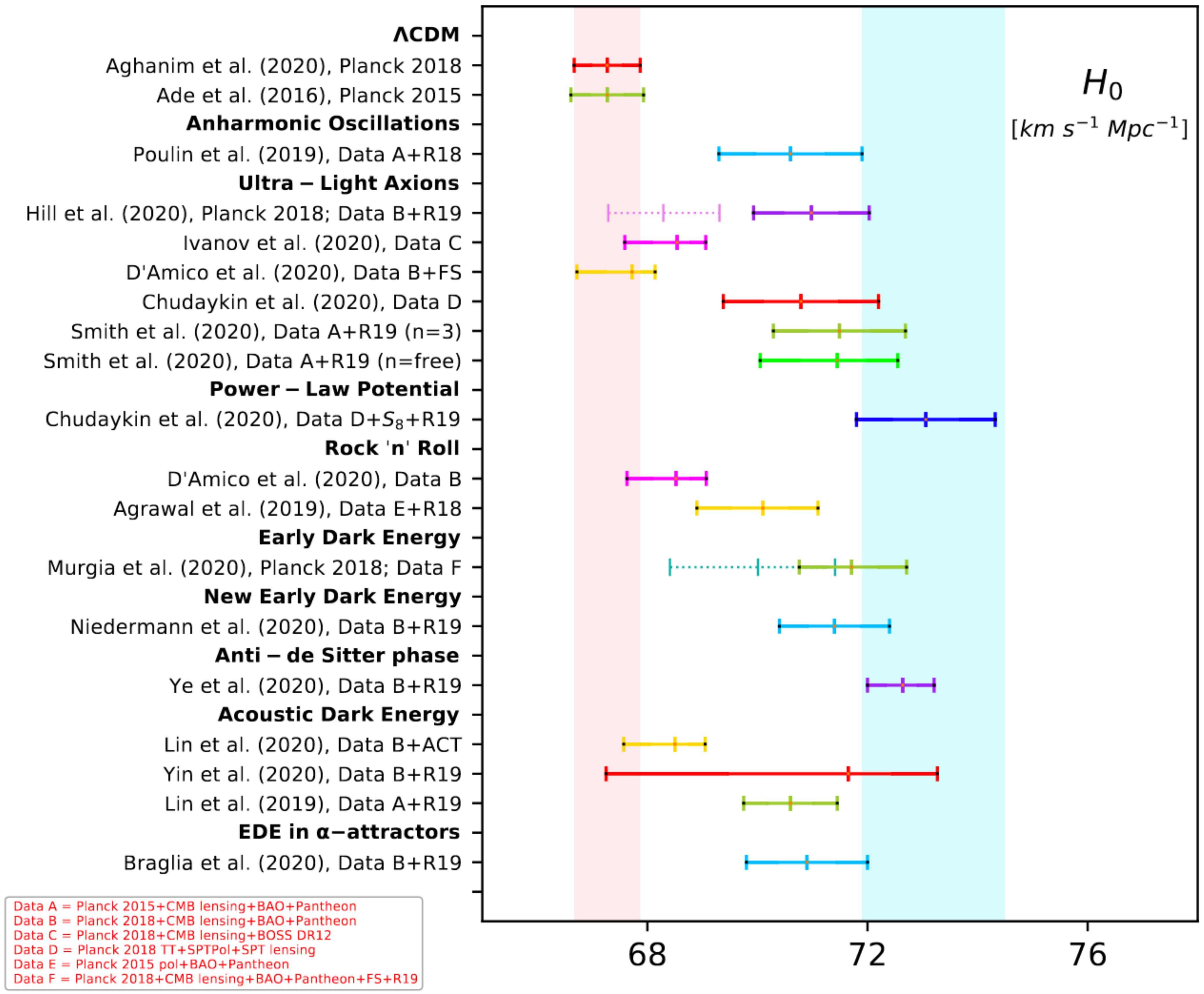
Toyokazu Sekiguchi[1,*] and Tomo Takahashi[2,†]

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

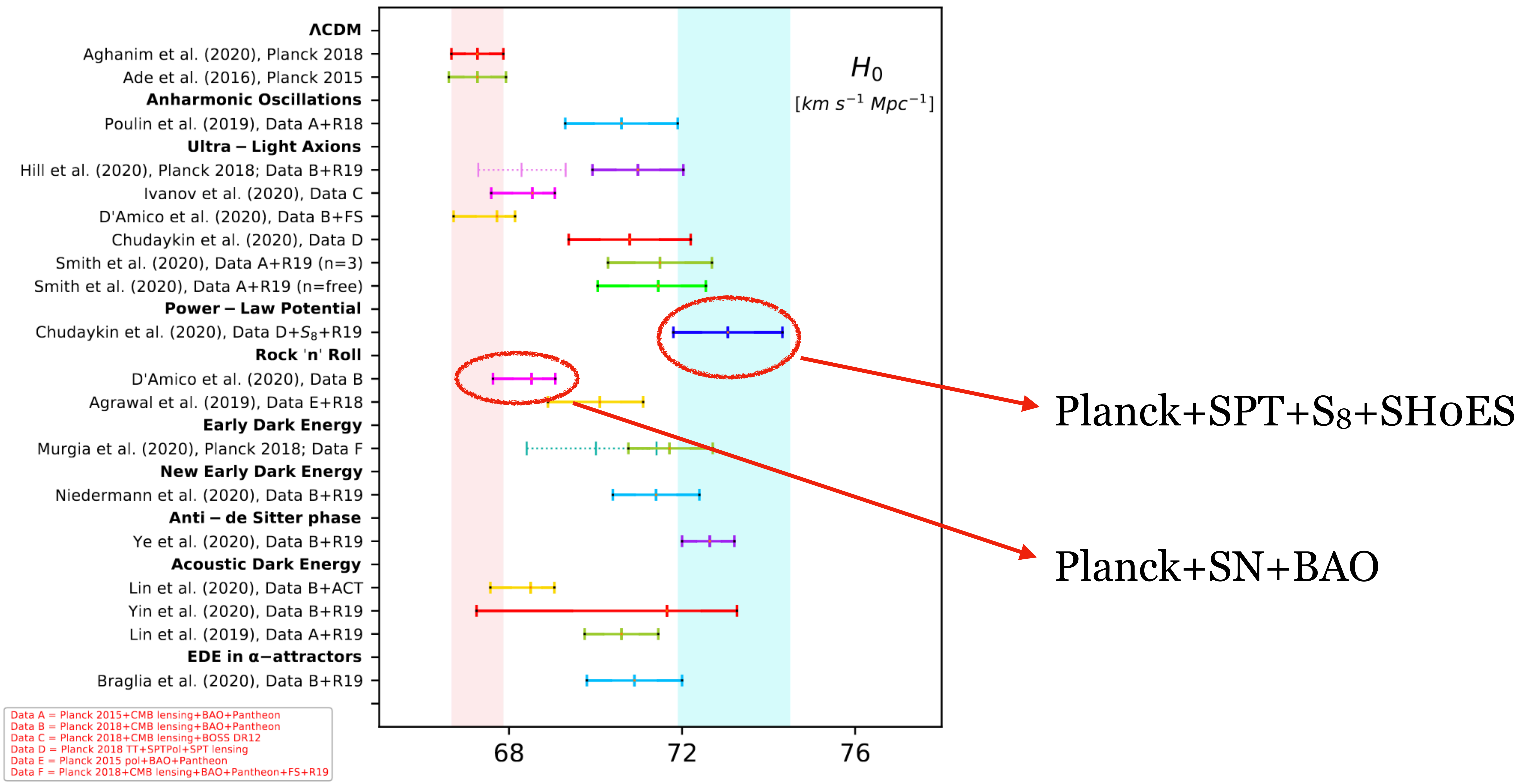
It proves difficult to compare success of the different proposed solutions, since authors typically use differing and incomplete combinations of data



Di Valentino++ 2103.01183

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



Di Valentino++ 2103.01183

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

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

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
- Majoron-ν_s interactions

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

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
- Majoron-ν_s interactions

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)

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

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
- Majoron-ν_s interactions

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)

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!

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!

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

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

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

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

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

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

We demand $Q_{\mathrm{DMAP}} < 3\sigma$

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

We demand $Q_{\mathrm{DMAP}} < 3\sigma$

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

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

Caveats:

- Simple to use and prior-independent ✅

*Corresponds to weak preference according to Jeffrey's scale

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

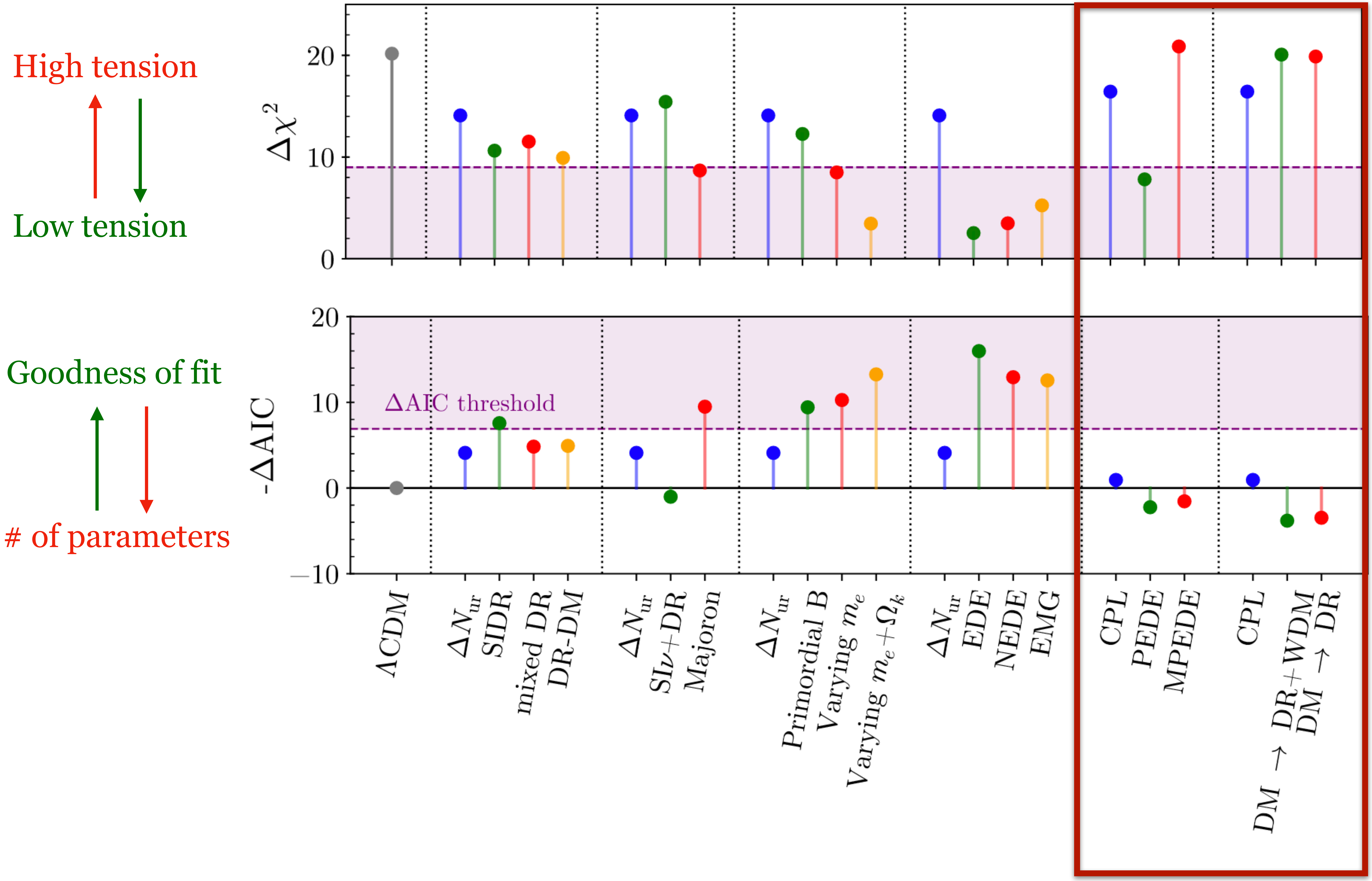
As long as $\Delta AIC < 0$, models go into **finalist** if criterium 2 or 3 are satisfied

Steps of the contest

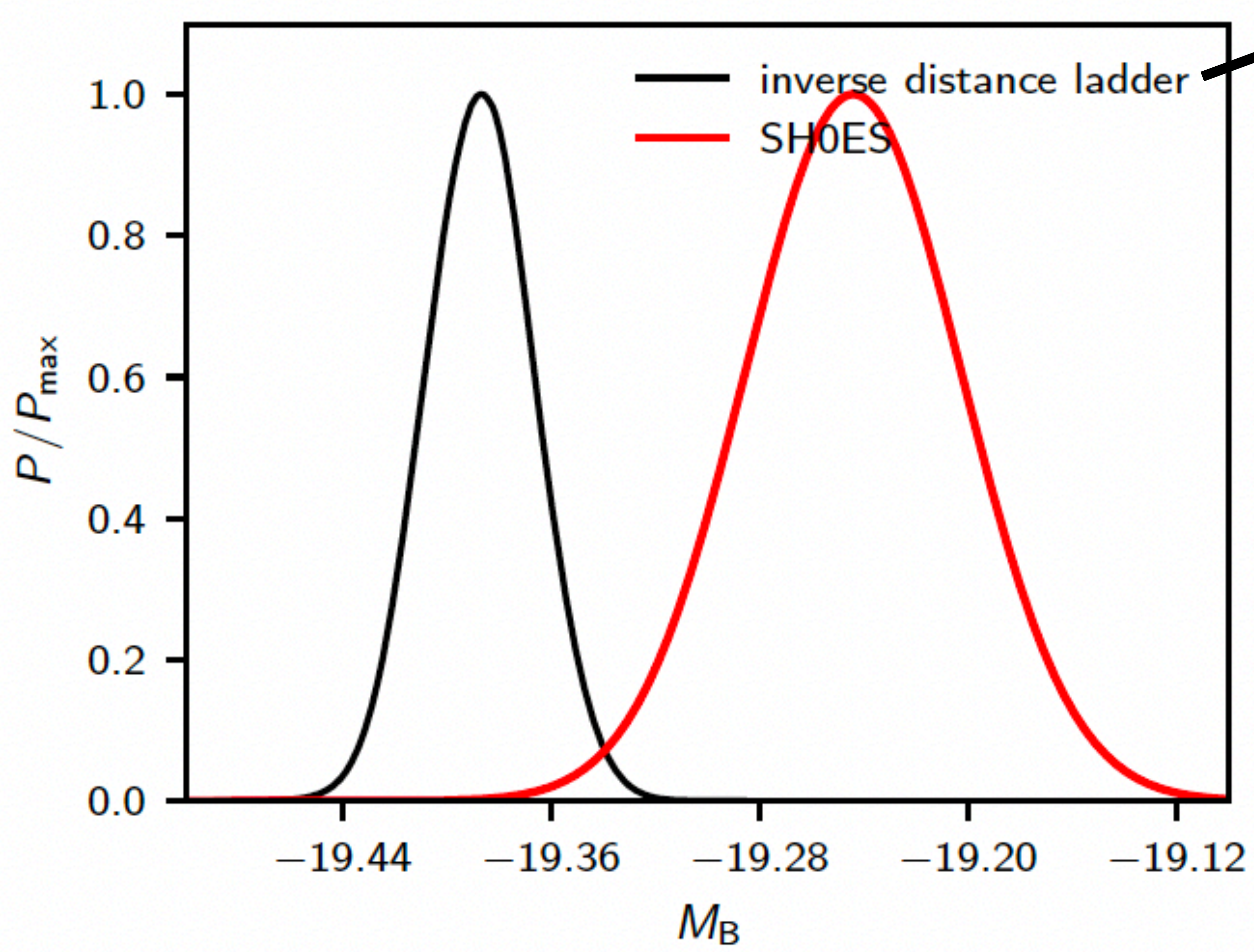
3

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

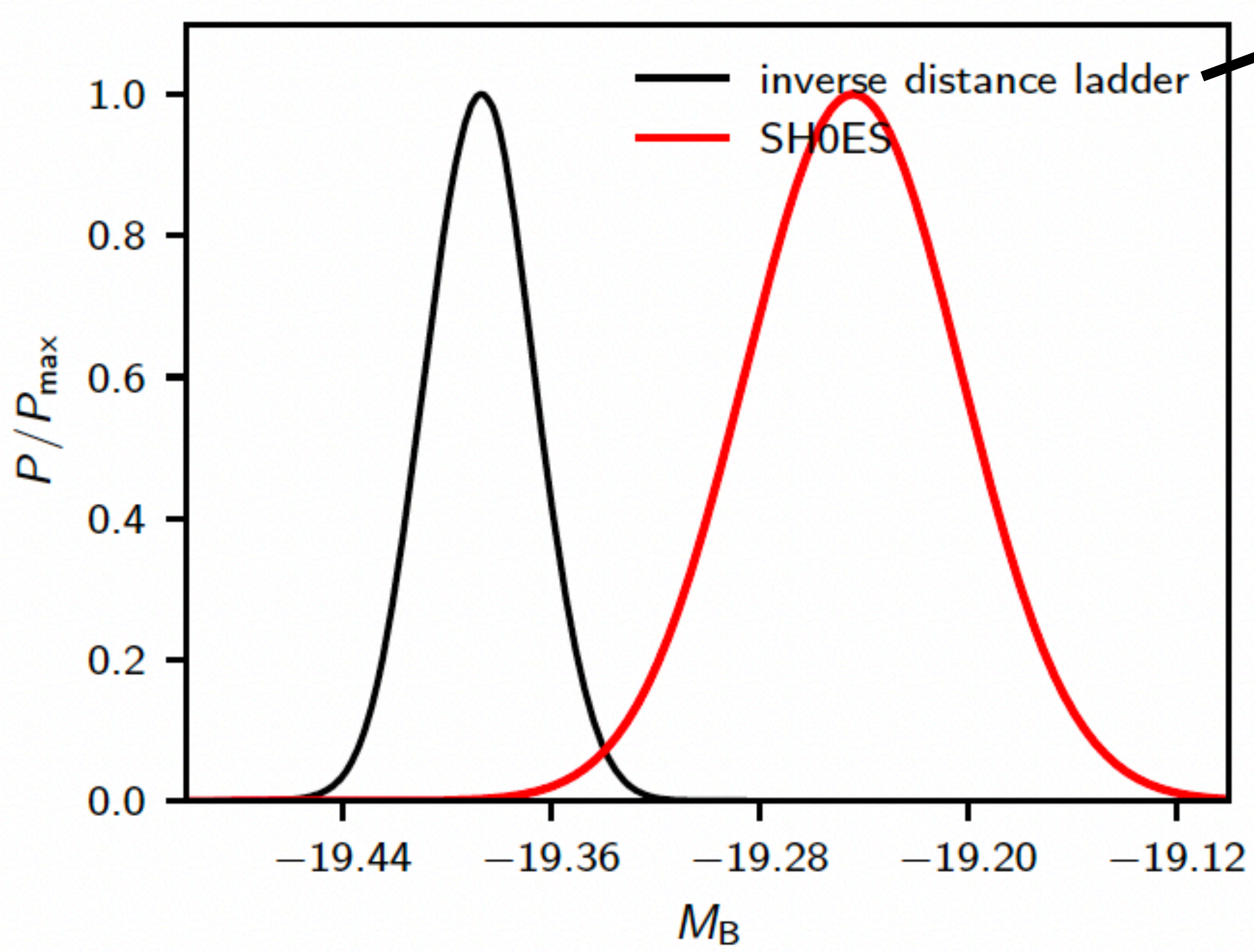
$$\theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)}, \quad \theta_d(z)^{\parallel} = r_s(z_{\rm drag})H(z)$$

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

Obtain M_b from calibration const. of SNIa

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

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

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

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*

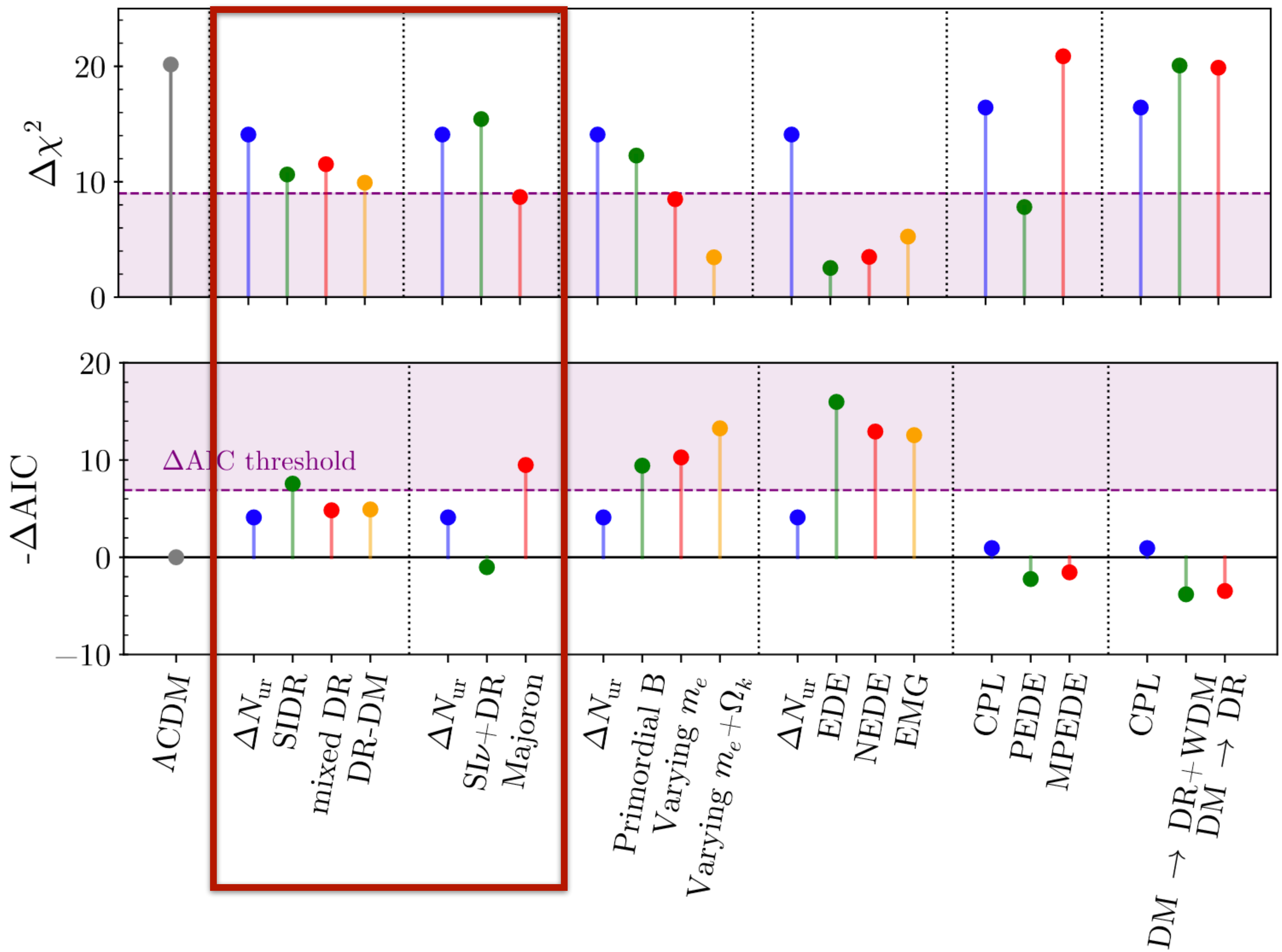
Results: early-time solutions with Dark Radiation

High tension

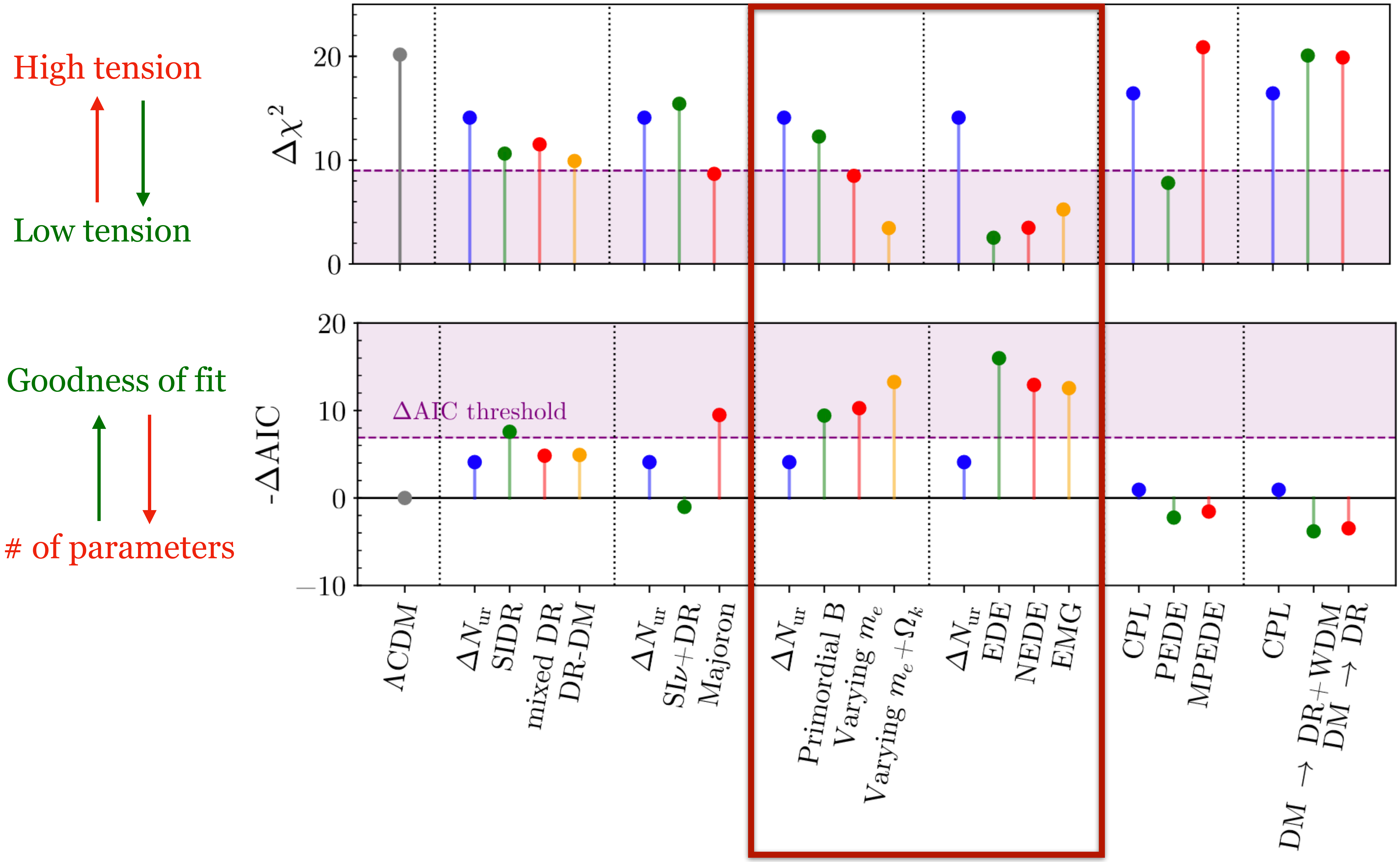
Low tension

Goodness of fit

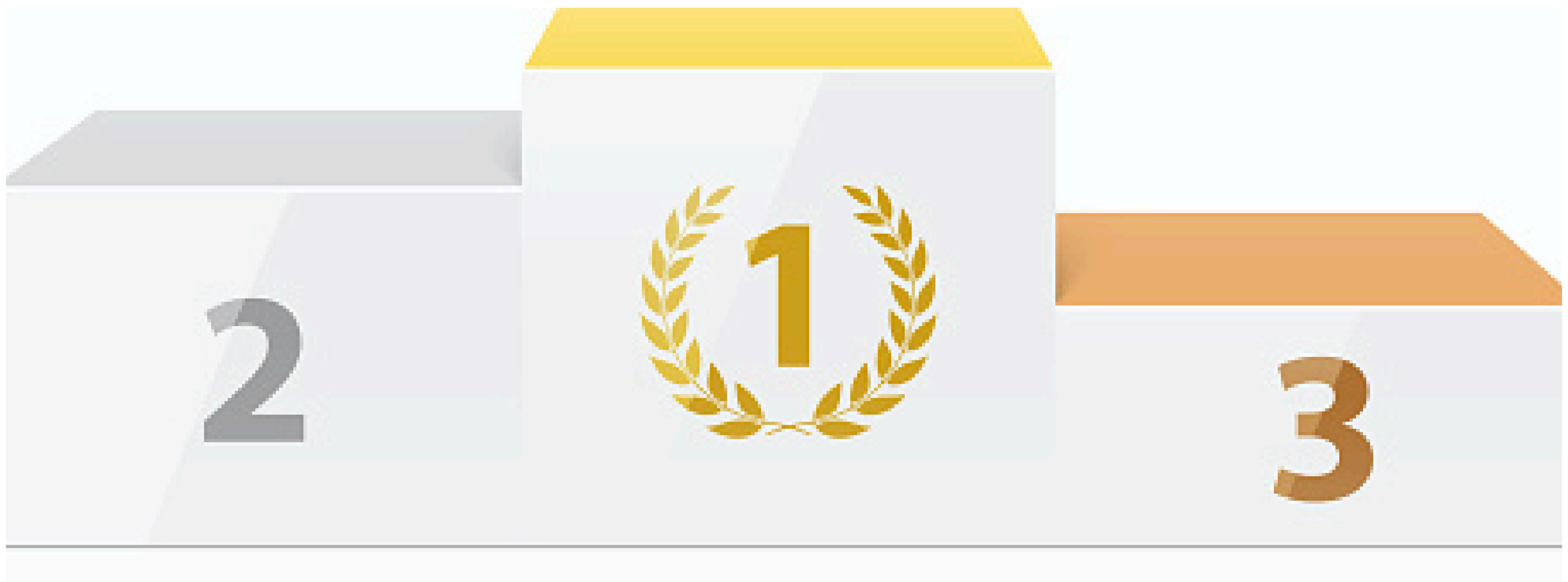
# of parameters



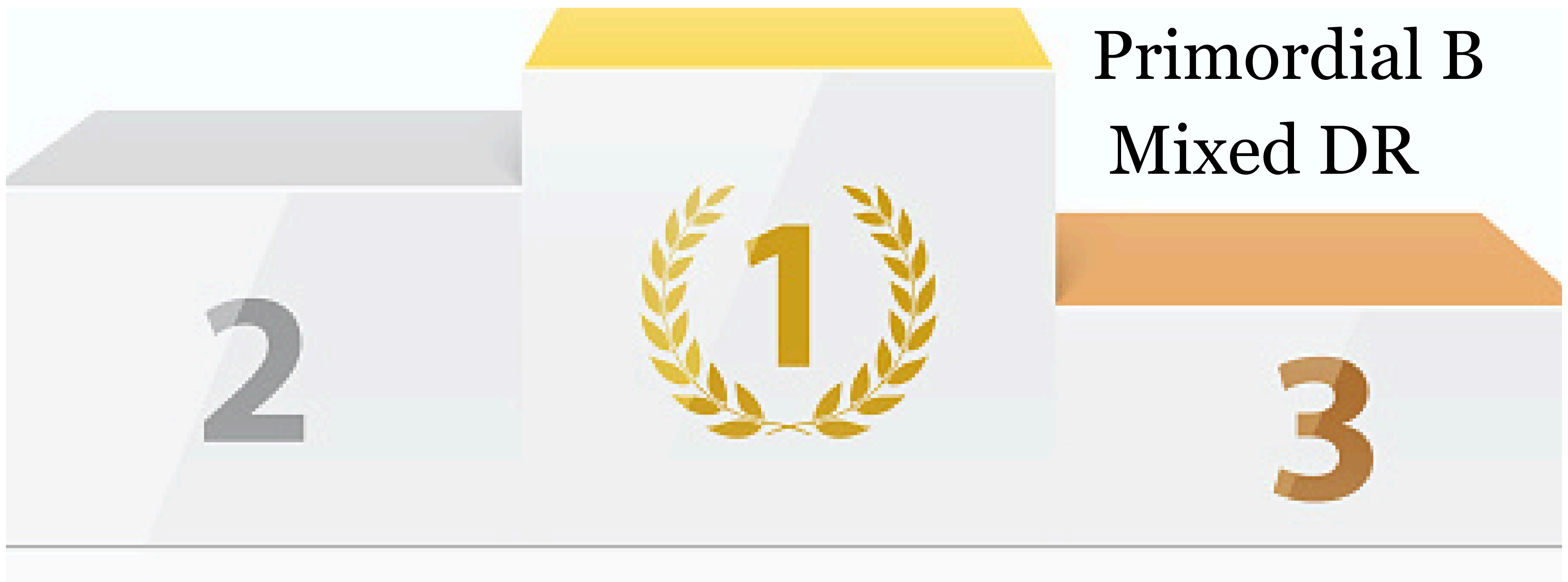
Results: early-time solutions without Dark Radiation



Results of the contest



Results of the contest

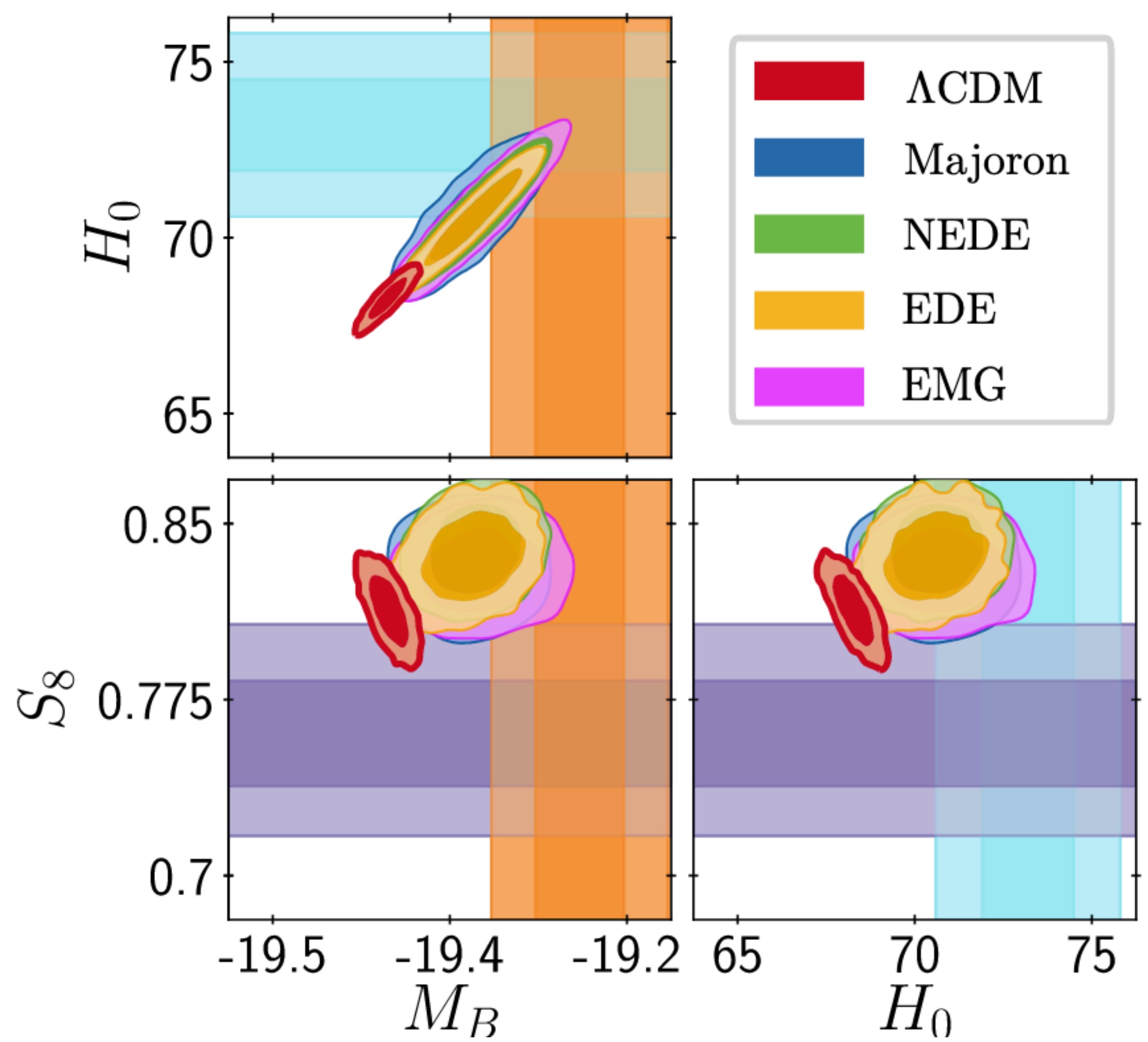


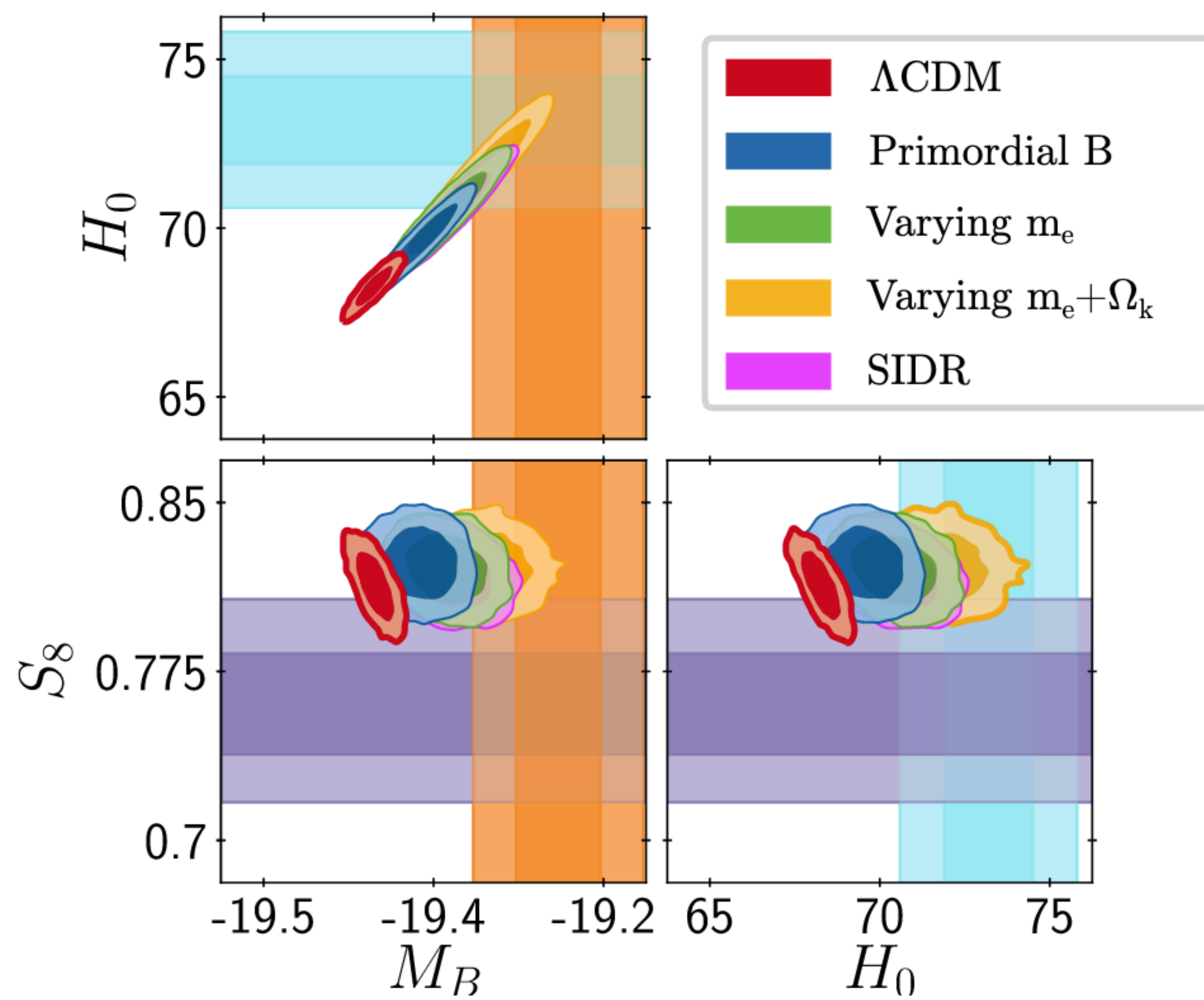
Results of the contest

Results of the contest

Results of the contest

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





Results of the contest

Does this mean that adding Large Scale Structure data rules out the resolution of some of the winners (e.g. Early Dark Energy)?

Results of the contest

Does this mean that adding Large Scale Structure data rules out the resolution of some of the winners (e.g. Early Dark Energy)?

⟶ The answer is no! Murgia, GFA, Poulin 2107.10291

Results of the contest

Does this mean that adding Large Scale Structure data rules out the resolution of some of the winners (e.g. Early Dark Energy)?

→ The answer is no! Murgia, GFA, Poulin 2107.10291

Is there any model that could explain the S_8 anomaly?

Results of the contest

Does this mean that adding Large Scale Structure data rules out the resolution of some of the winners (e.g. Early Dark Energy)?

⟶ The answer is no! Murgia, GFA, Poulin 2107.10291

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 currently shows a 5σ H_0 tension and a 2-3σ S_8 tension, which could offer an interesting window to the yet unknown dark sector.

Conclusions

- ΛCDM currently shows a 5σ H_0 tension and a 2-3σ S_8 tension, which could offer an interesting window to the yet unknown dark sector.

- Thanks to a meaningful set of benchmarks, we have concluded that late-time solutions to the H_0 tension are the most disfavoured, while solutions changing the sound horizon without dark radiation are the most successful.

Conclusions

- ΛCDM currently shows a 5σ H_0 tension and a 2-3σ S_8 tension, which could offer an interesting window to the yet unknown dark sector.

- Thanks to a meaningful set of benchmarks, we have concluded that late-time solutions to the H_0 tension are the most disfavoured, while solutions changing the sound horizon without dark radiation are the most successful.

- None of these successful models is able to relieve the S_8 tension. However, resolutions of these tensions might lie in different sectors ($H_0 \longleftrightarrow$ new background contribution, $S_8 \longleftrightarrow$ new perturbation properties).

Conclusions

- ΛCDM currently shows a 5σ H_0 tension and a 2-3σ S_8 tension, which could offer an interesting window to the yet unknown dark sector.

- Thanks to a meaningful set of benchmarks, we have concluded that late-time solutions to the H_0 tension are the most disfavoured, while solutions changing the sound horizon without dark radiation are the most successful.

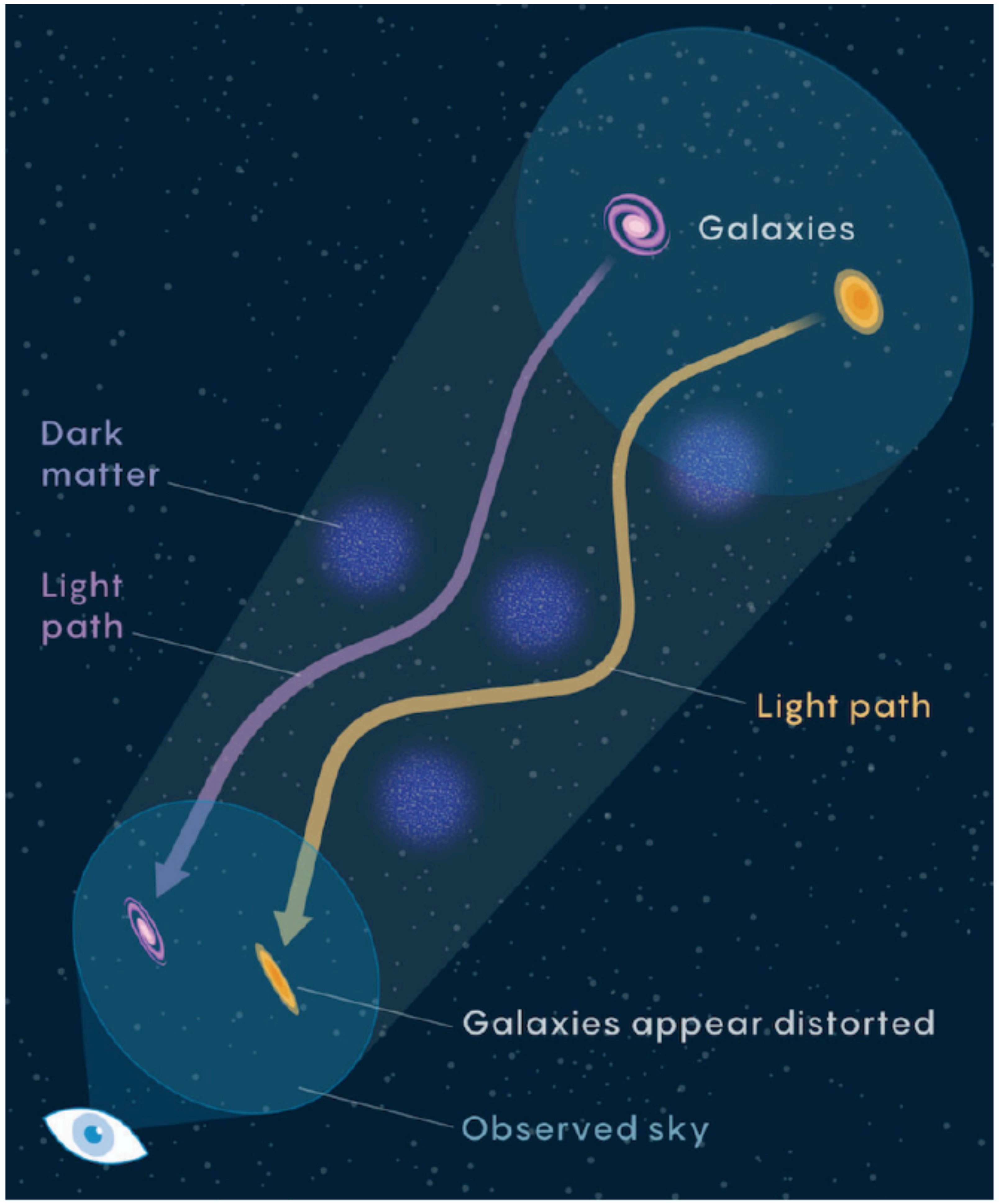
- None of these successful models is able to relieve the S_8 tension. However, resolutions of these tensions might lie in different sectors ($H_0 \longleftrightarrow$ new background contribution, $S_8 \longleftrightarrow$ new perturbation properties).

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

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

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

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

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

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

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

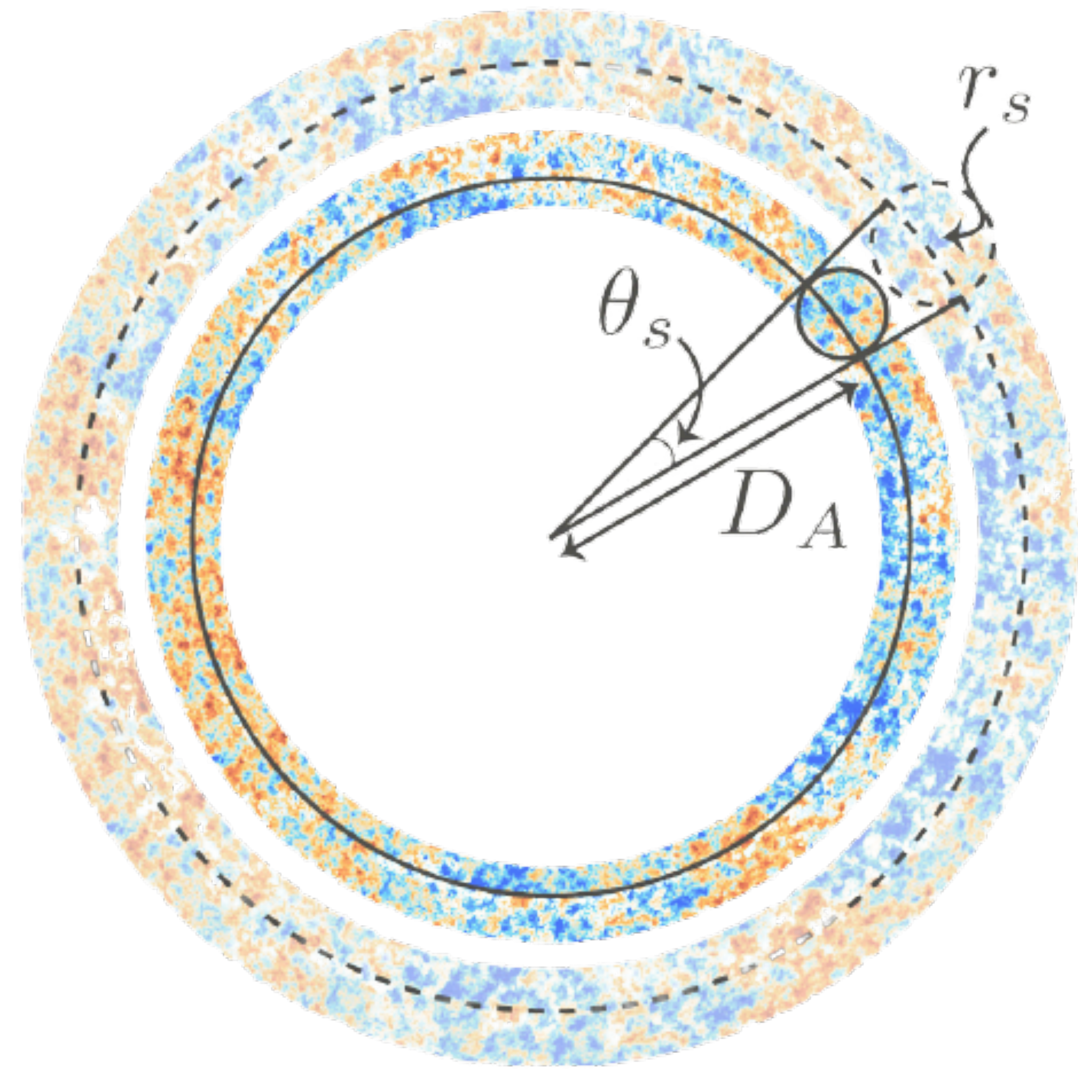
$$\text{where } \mathrm{H}^2(\mathrm{z}) = \frac{8\pi \mathrm{G}}{3}\sum_\mathrm{i} \rho_\mathrm{i}(\mathrm{z})$$

*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

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



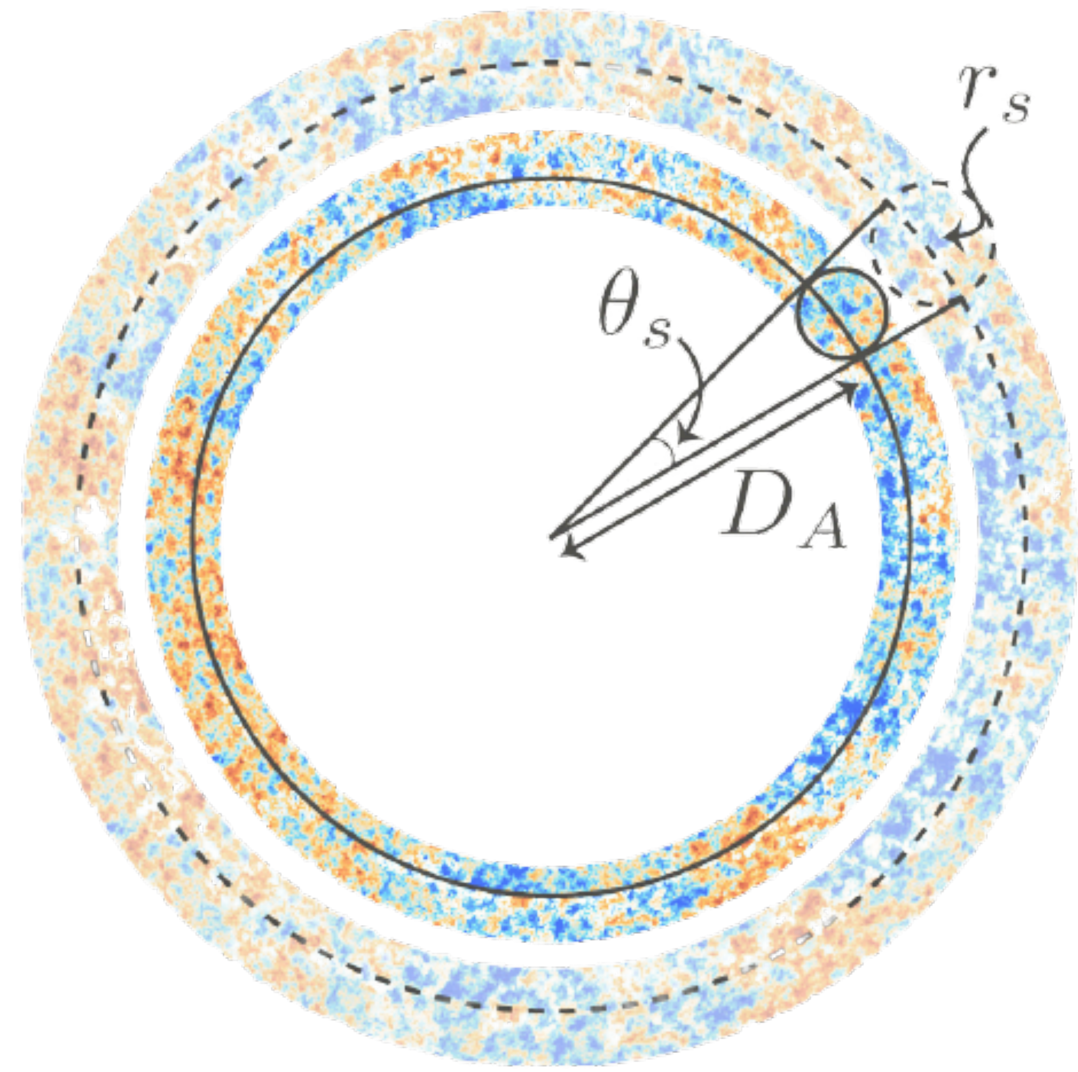
T. Smith

How does Planck determine H_0?

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

$$\theta_s = \frac{r_s(z_{\rm rec})}{D_A(z_{\rm rec})} = \frac{\int_0^{\tau_{\rm rec}} c_s(\tau)d\tau}{\int_{\tau_{\rm rec}}^{\tau_0} c\,d\tau} = \frac{\int_\infty^{z_{\rm rec}} c_s(z)dz/\sqrt{\rho_{\rm tot}(z)}}{\int_0^{z_{\rm rec}} c\,dz/\sqrt{\rho_{\rm tot}(z)}}$$

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



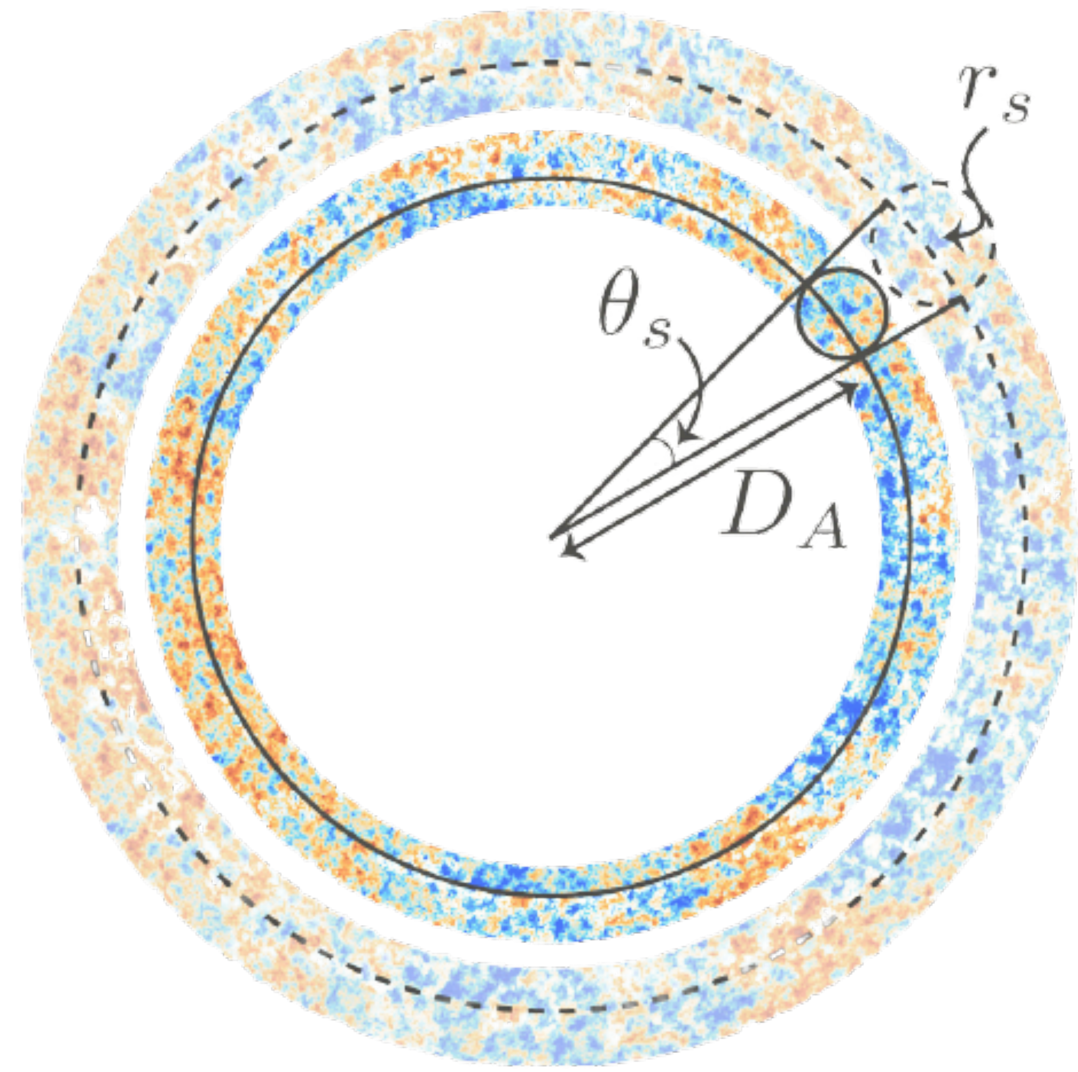
model prediction of r_s + measurement of θ_s $\longrightarrow$ H_0

T. Smith

How does Planck determine H_0?

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

$$\theta_s = \frac{r_s(z_{rec})}{D_A(z_{rec})} = \frac{\int_0^{\tau_{rec}} c_s(\tau)d\tau}{\int_{\tau_{rec}}^{\tau_0} c\,d\tau} = \frac{\int_\infty^{z_{rec}} c_s(z)dz/\sqrt{\rho_{tot}(z)}}{\int_0^{z_{rec}} c\,dz/\sqrt{\rho_{tot}(z)}}$$



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

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

T. Smith

Early-time solutions

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

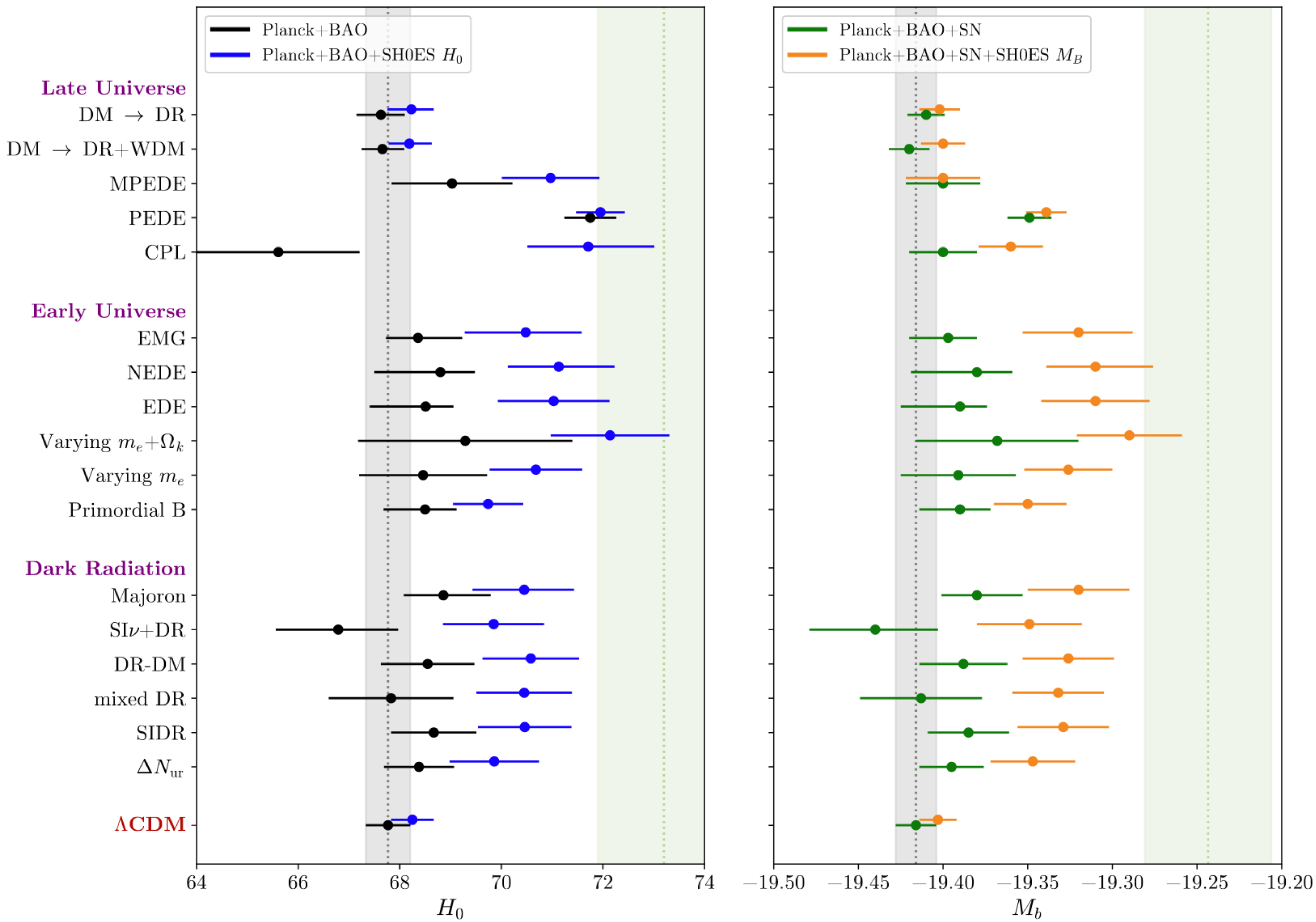
$$\mathbf{Ex: \Delta N_{eff} > 0}$$

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

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

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

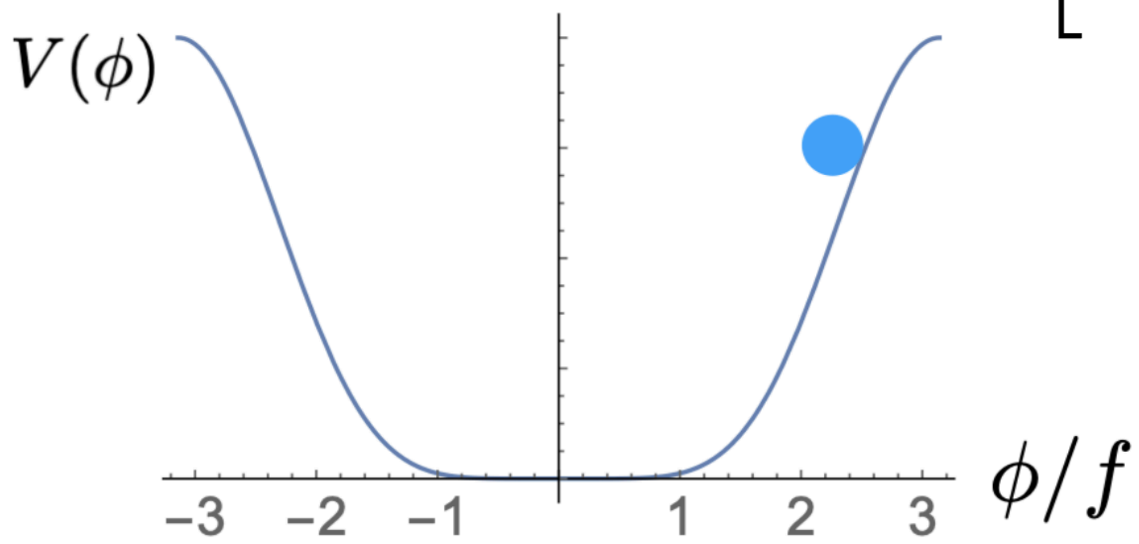
⟶ No significant changes (*notable exceptions are EDE and NEDE*)

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

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



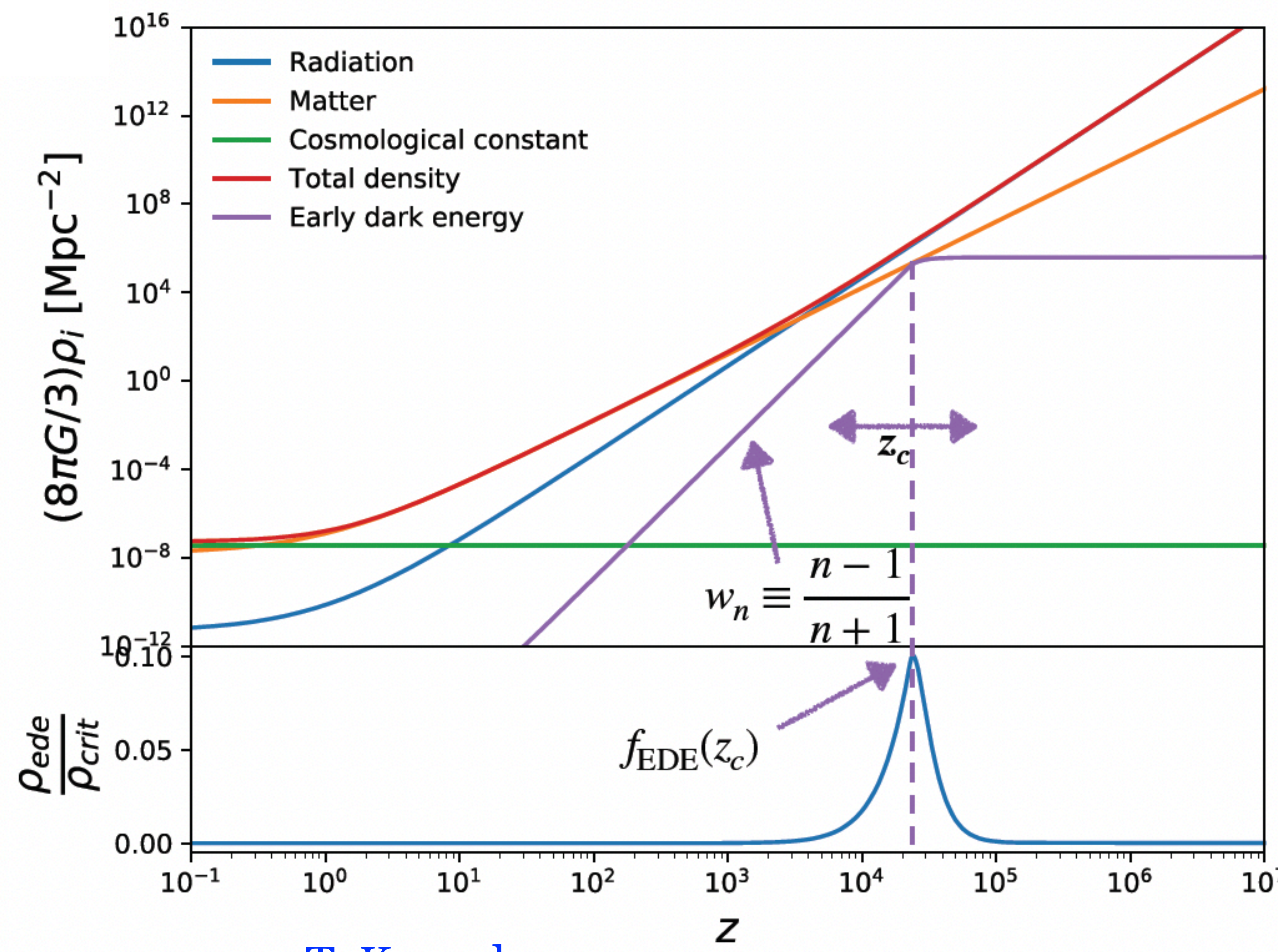
Scalar field initially frozen, then dilutes away equal or faster than radiation

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

+ perturbed linear eqs.

The model is fully specified by

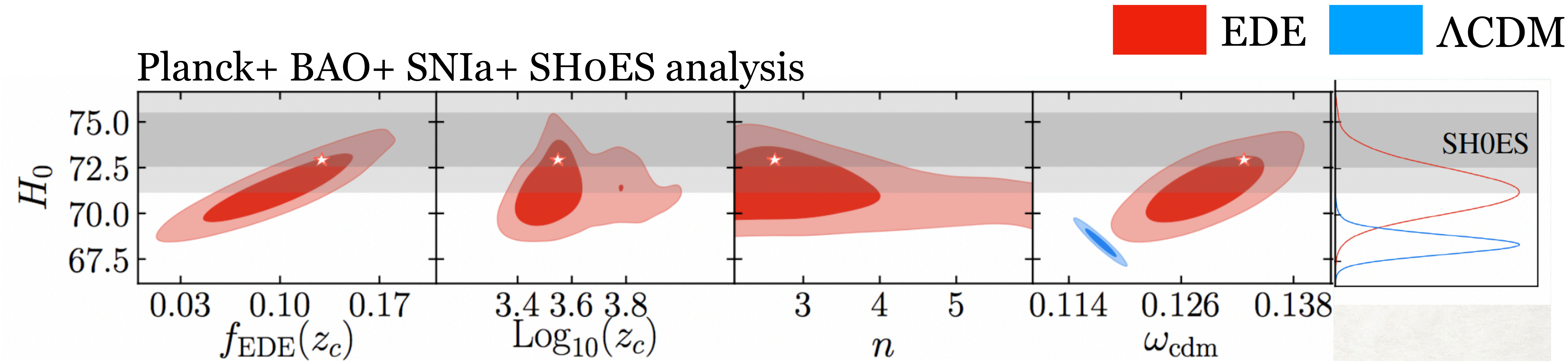
$$\{f_{\mathrm{EDE}}(z_c),\ z_c,\ n,\ \phi_i\}$$



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.