The H_0 Olympics: a fair ranking of proposed models

Guillermo Franco Abellán
Laboratoire Univers et Particules de Montpellier

Based on:

arXiv:2102.12498 (PRD in press)

arXiv:2008.09615 (PRD in press)

arXiv:2009.10733 PRD 103 (2020)

arXiv:2107.10291, submitted to Physics Reports

UNIVERSITÉ MONTPELLIER

LUPM LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

Index

I. Cosmic concordance and discordance

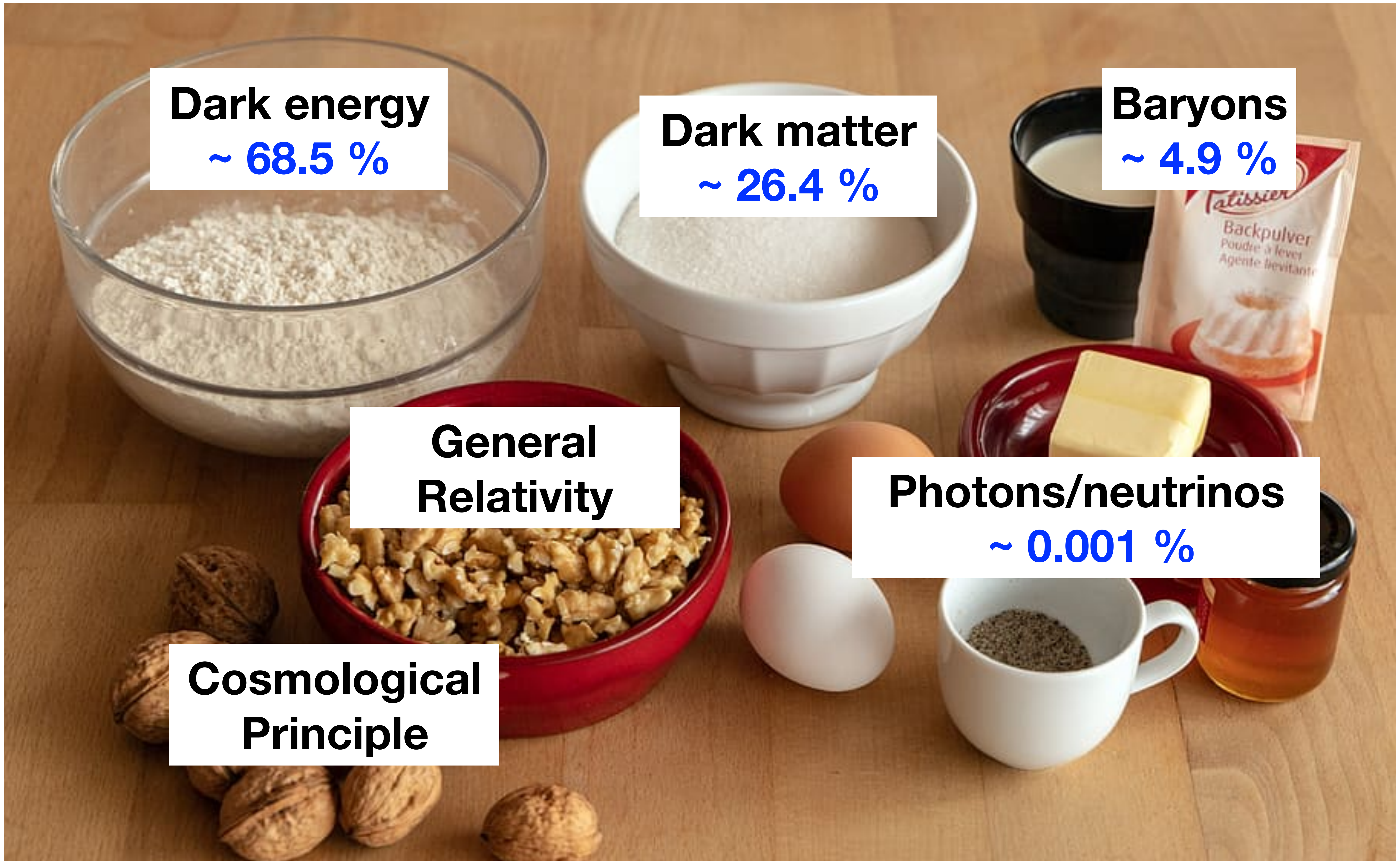
II. The H_0 Olympics: quantifying the success of a resolution

III. Explaining the S_8 tension with Decaying Dark matter

IV. Conclusions

I. Cosmic concordance and discordance

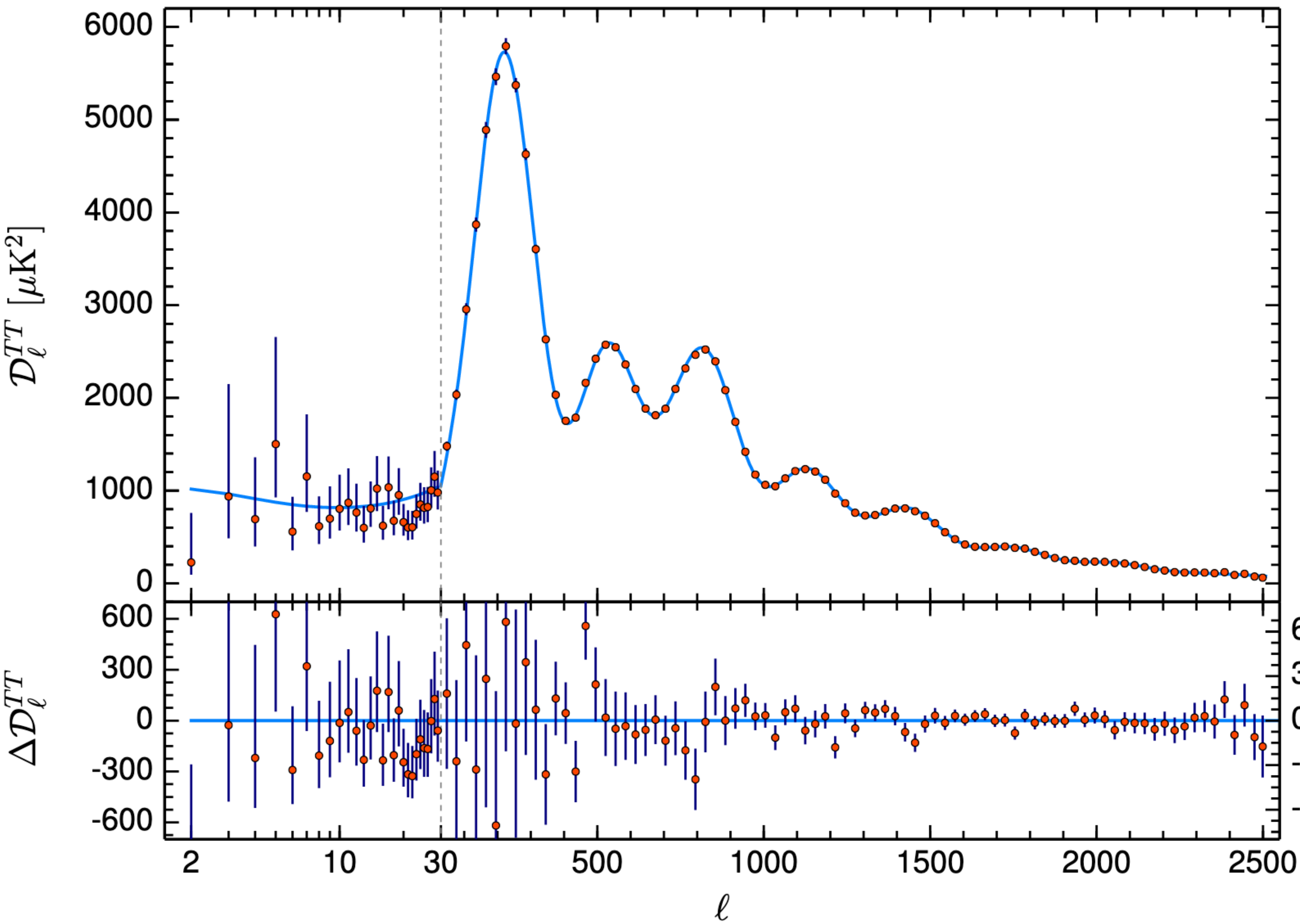
Cosmic recipe



ΛCDM model fully specified by $\{\Omega_c, \Omega_b, H_0, A_s, n_s, \tau_{reio}\}$

The era of precision cosmology

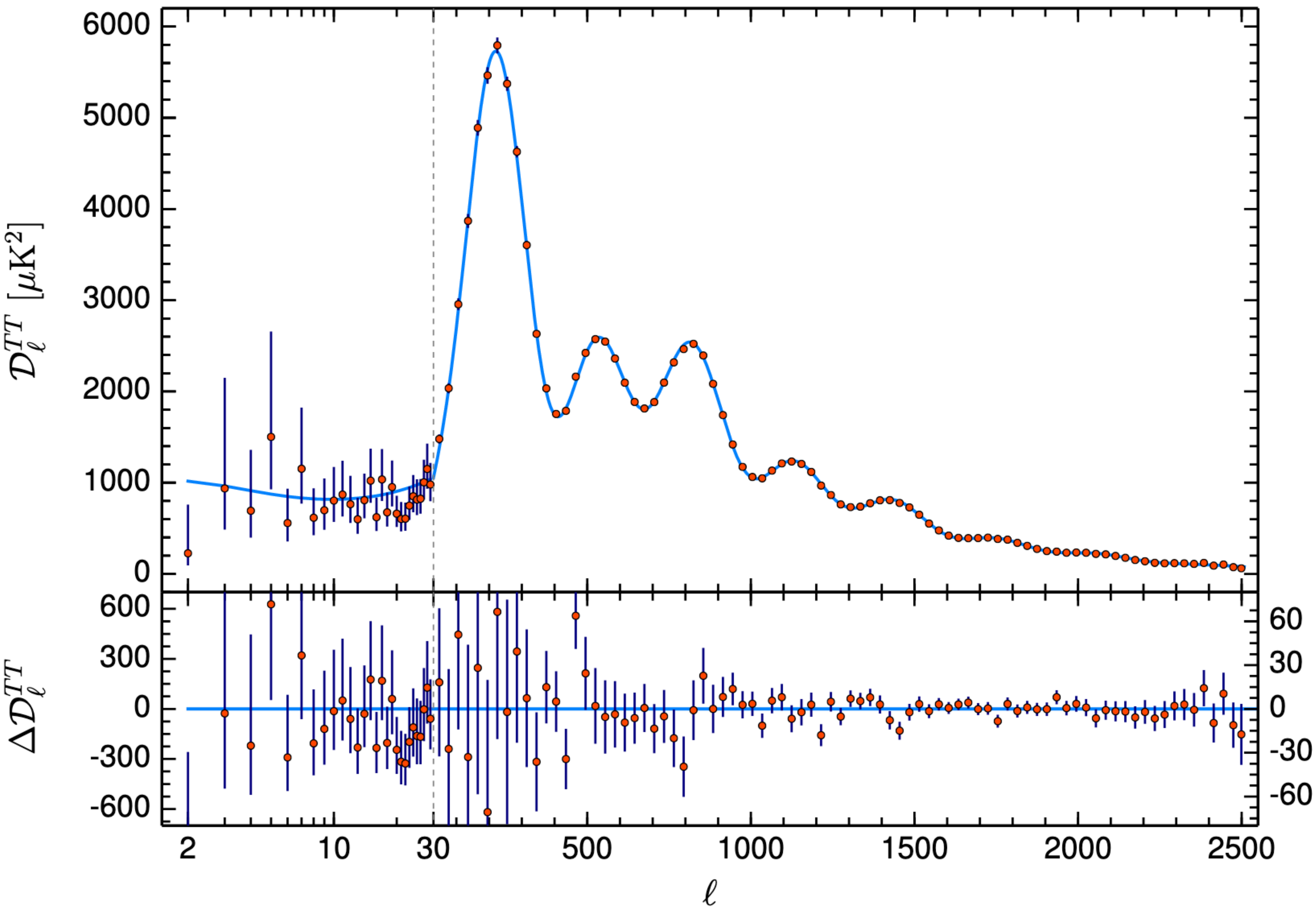
ΛCDM gives excellent fit to CMB anisotropy spectra



Planck 2018, 1807.06209

The era of precision cosmology

ΛCDM gives excellent fit to CMB anisotropy spectra



Planck 2018, 1807.06209

Also explains:

- Baryon acoustic oscillations,
- Supernovae Ia,
- Light element abundances,
- Large Scale Structure, etc

Challenges to the ΛCDM paradigm

1. What is dark matter? And dark energy?

- Are they made of **particles**?
- Are they made of **single species**?
- How are they **produced**?
- What is their **lifetime**?
- And their **mass**?

Challenges to the ΛCDM paradigm

2. Several discrepancies emerged in recent years

- S_8 with weak-lensing data
  KiDS-1000 2007.15632

- H_0 with local measurements
  Riess++ 2012.08534

Challenges to the ΛCDM paradigm

2. Several discrepancies emerged in recent years

- S_8 with weak-lensing data
  KiDS-1000 2007.15632

- H_0 with local measurements
  Riess++ 2012.08534

Unaccounted systematics?

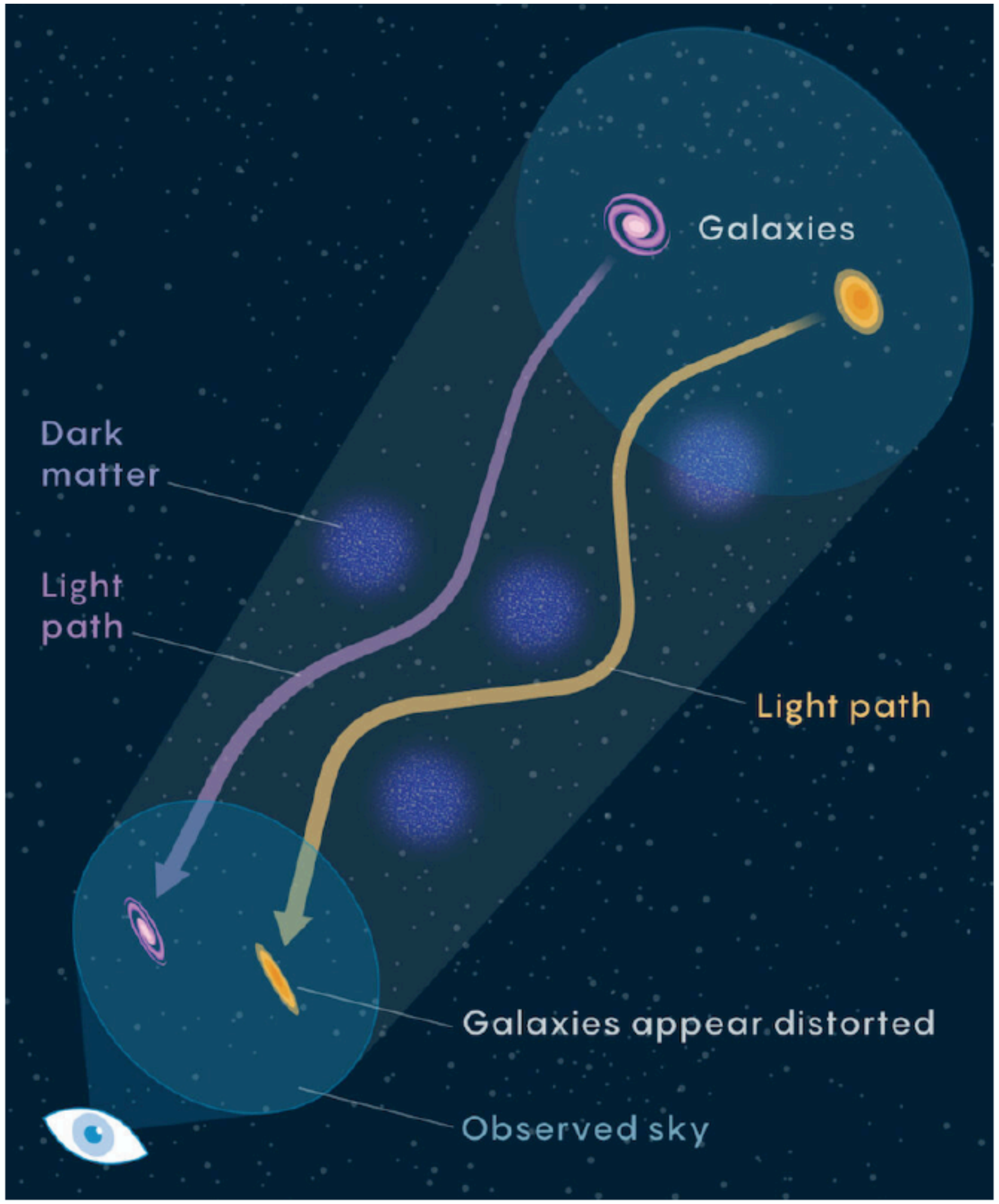
- Less exotic explanation ✅
- Difficult to account for all discrepancies ❌

Physics beyond ΛCDM?

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

The 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*):

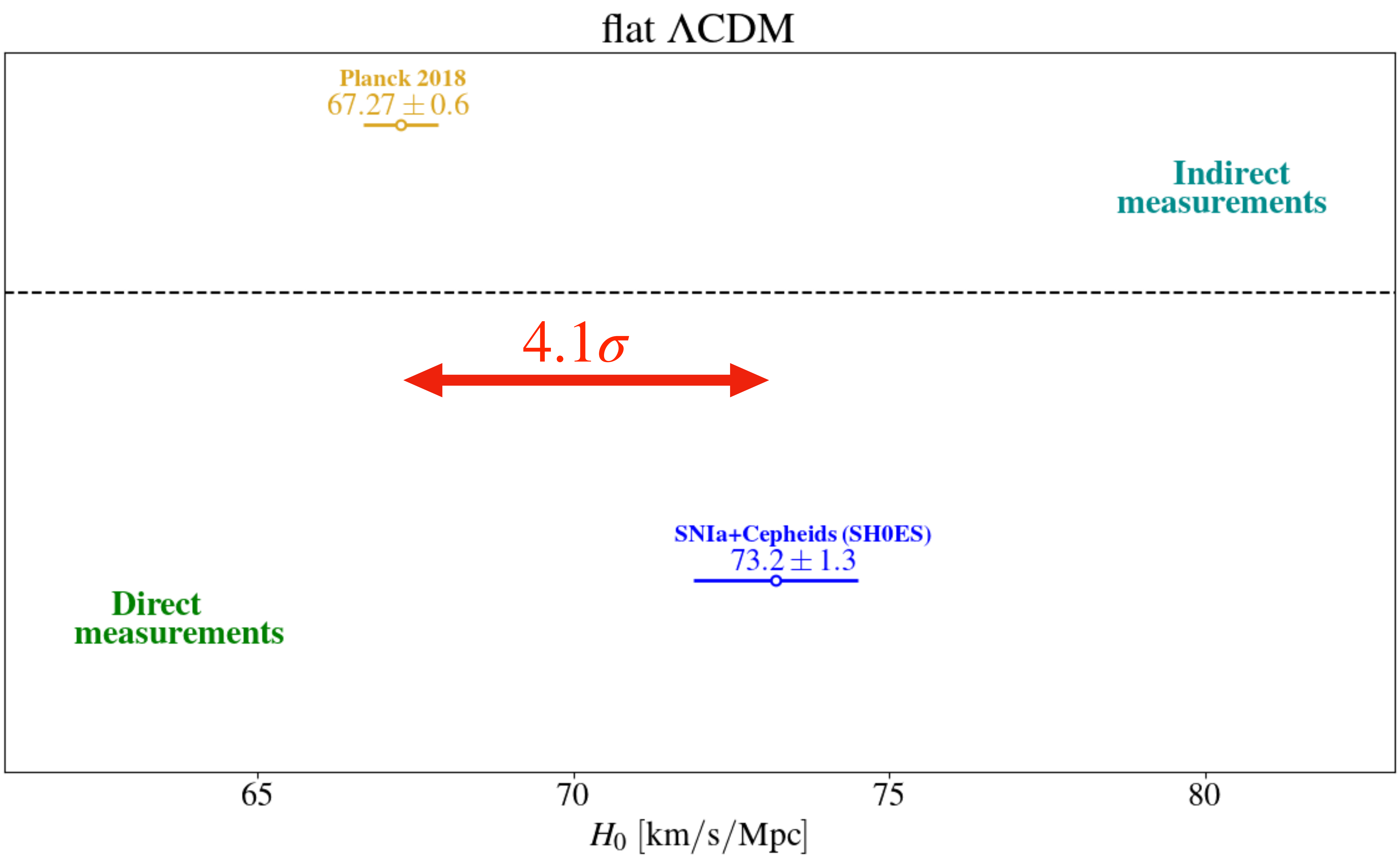
$$S_8 = 0.830 \pm 0.013$$

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

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

The H_0 tension

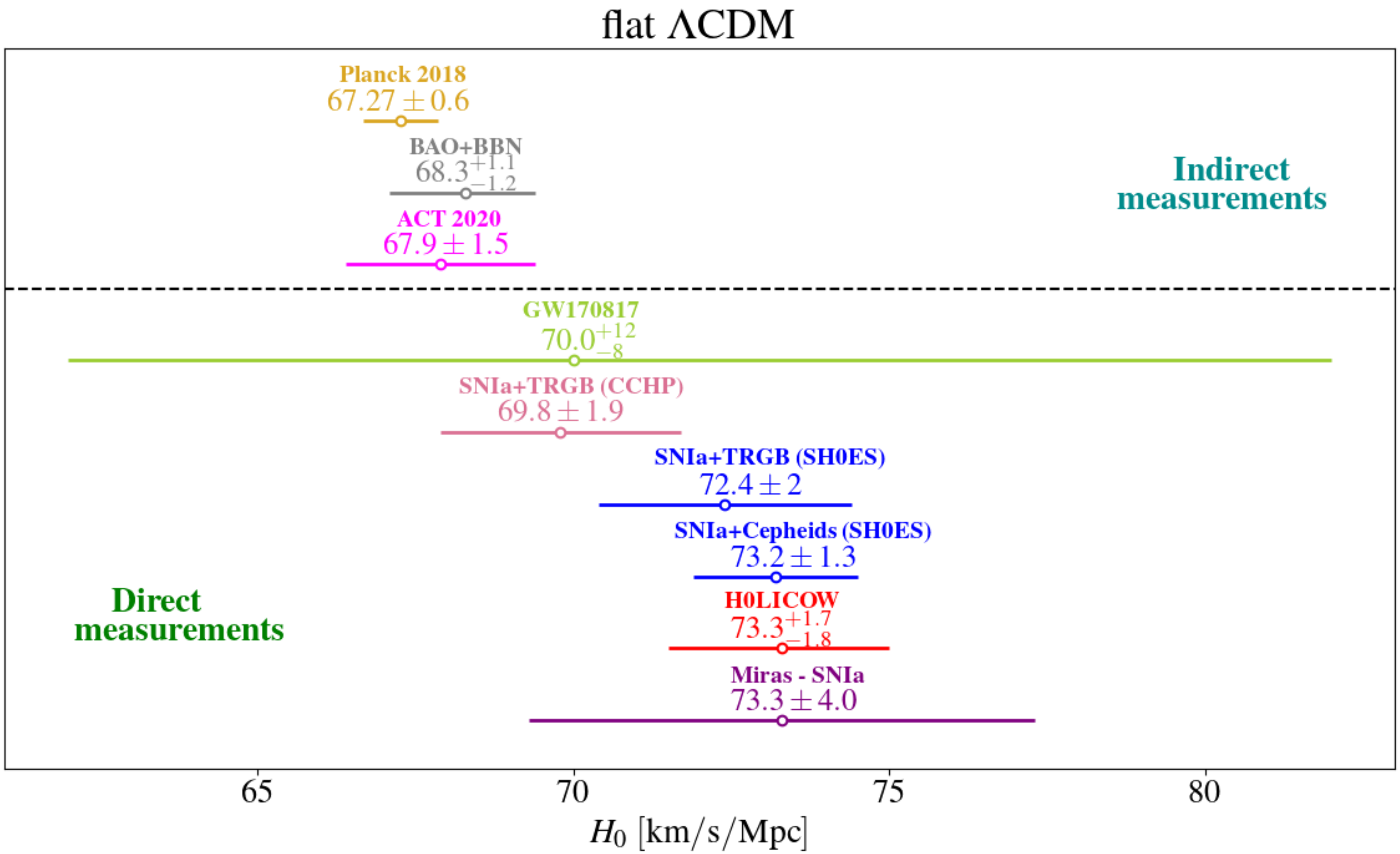
Planck (*under ΛCDM*) and SH0ES measurements are in **4.1σ tension**



The H_0 tension

Planck (*under ΛCDM*) and SH0ES measurements are in **4.1σ tension**

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

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

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

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

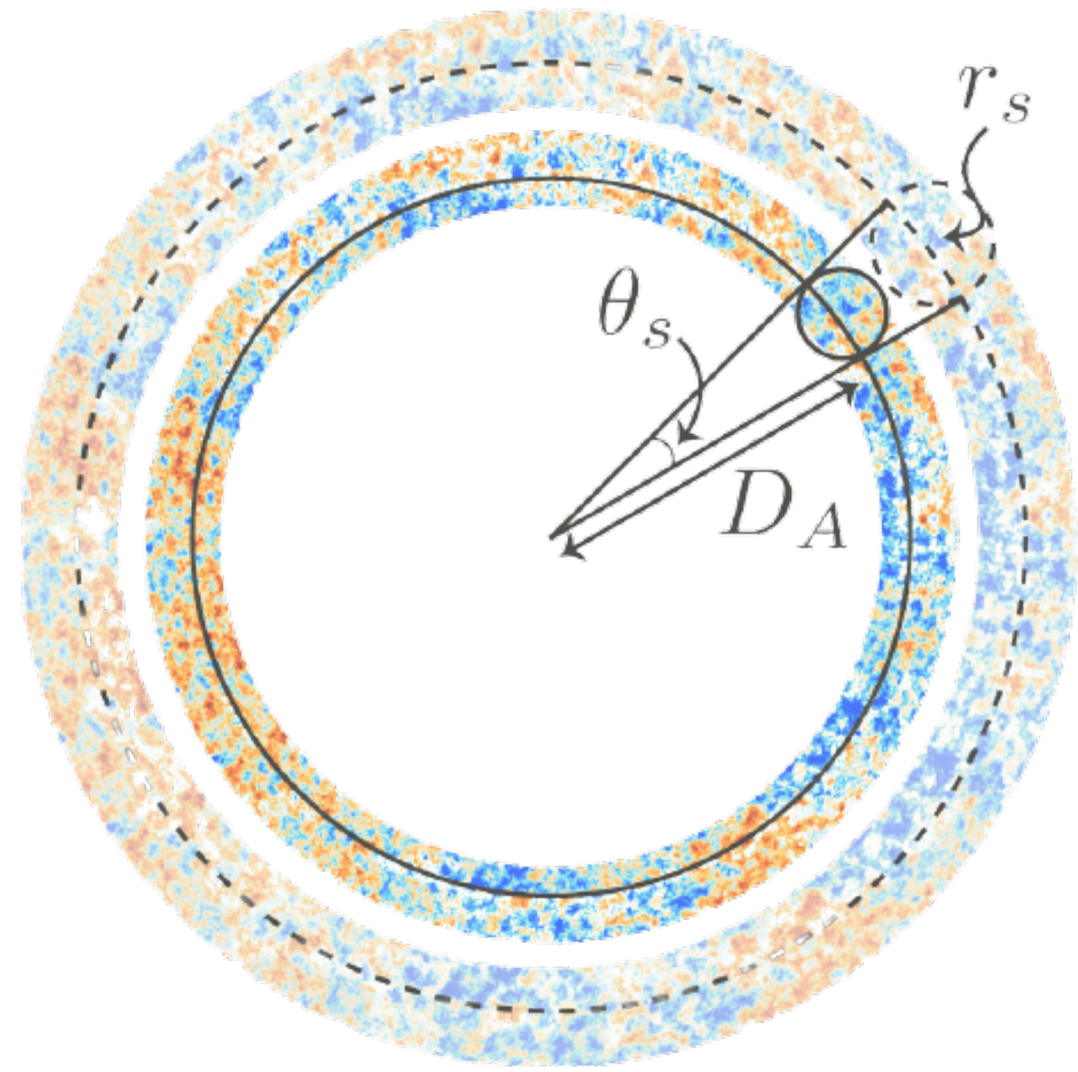
$$\text{where } \mathrm{H}^2(\mathrm{z}) = \frac{8\pi \mathrm{G}}{3}\sum_\mathrm{i} \rho_\mathrm{i}(\mathrm{z})$$

*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

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



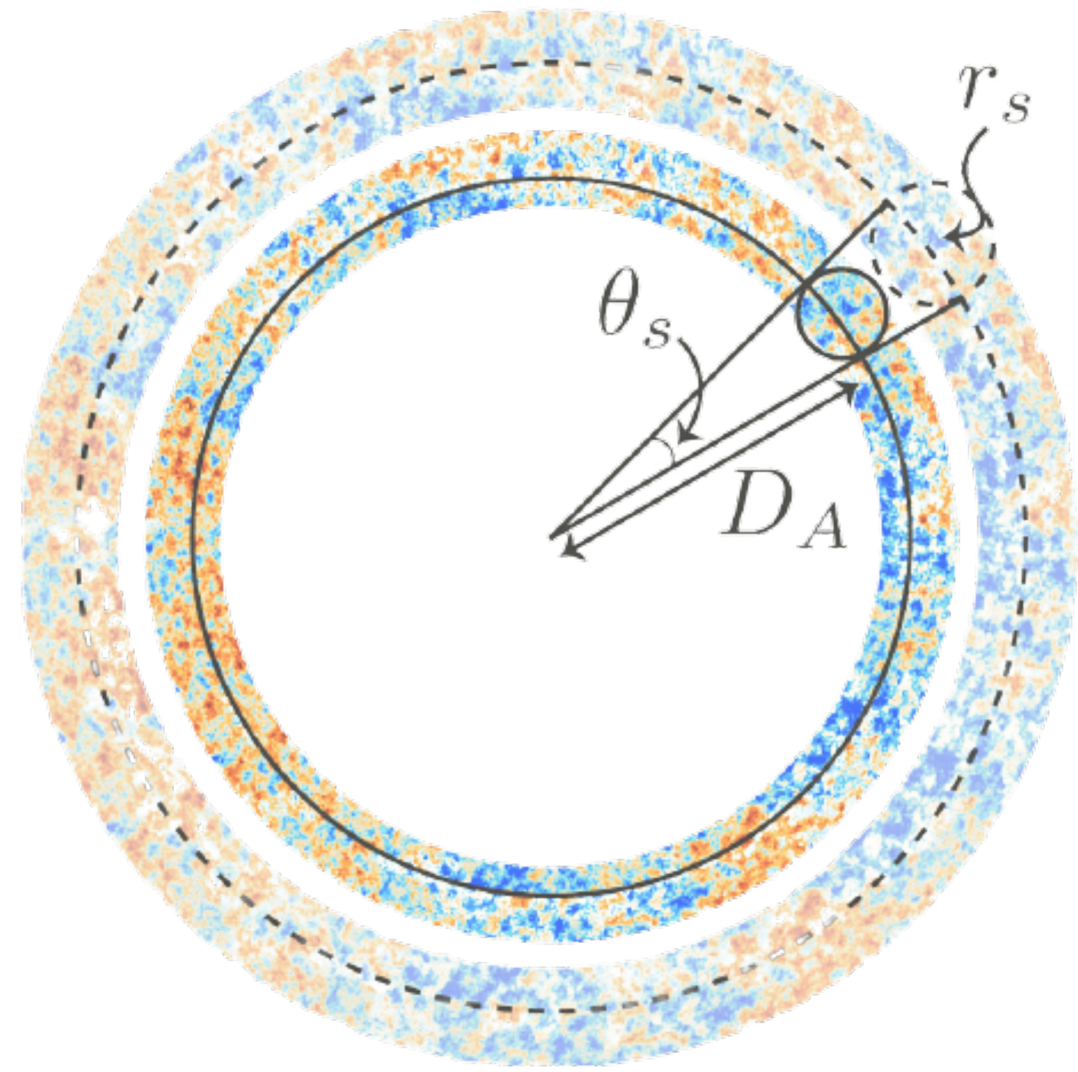
T. Smith

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

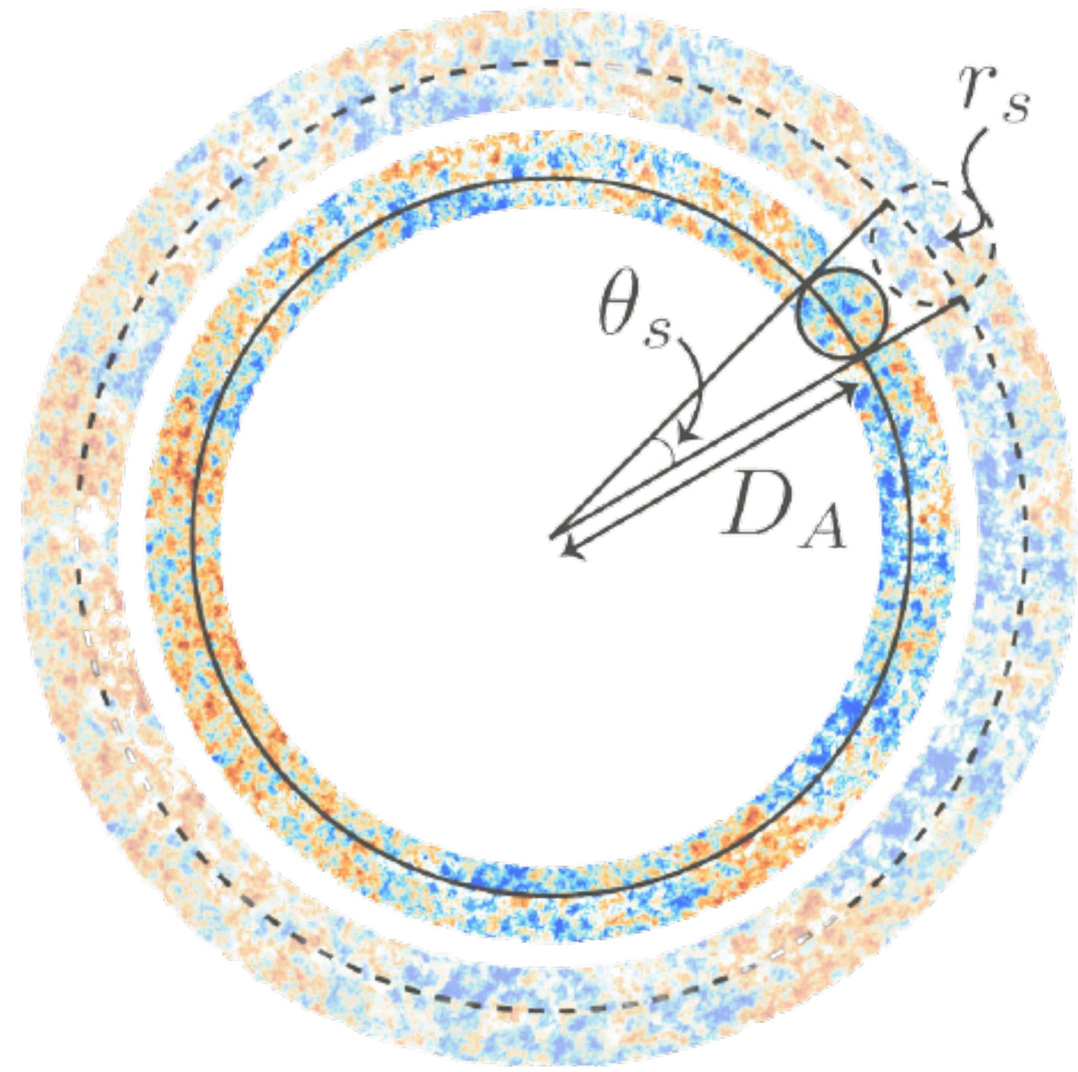
T. Smith

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

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 : $w < -1$

II. The H_0 Olympics: quantifying the success of a resolution

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

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?

leonora 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

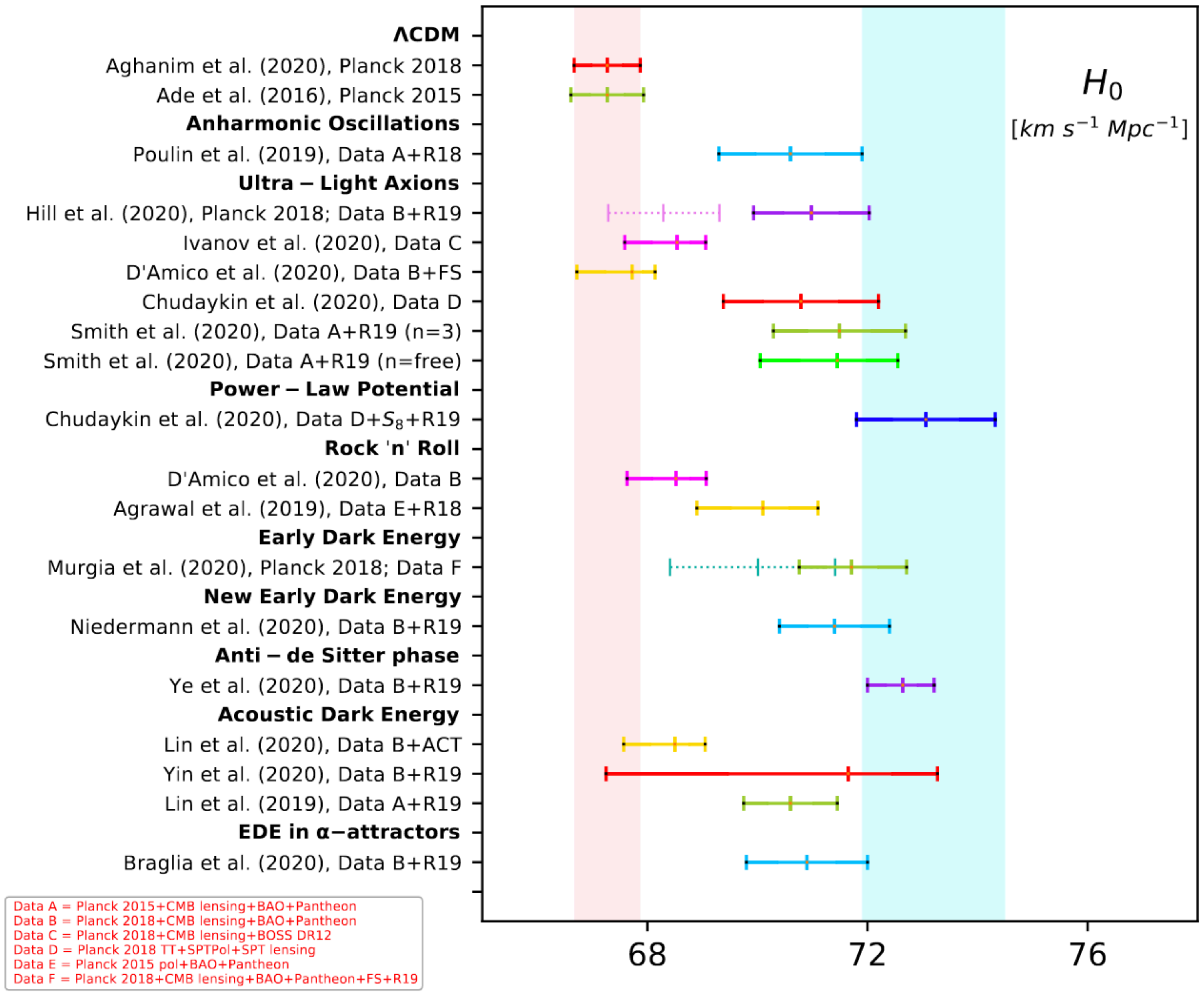
Toyokazu Sekiguchi[1,*] and Tomo Takahashi[2,†]

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

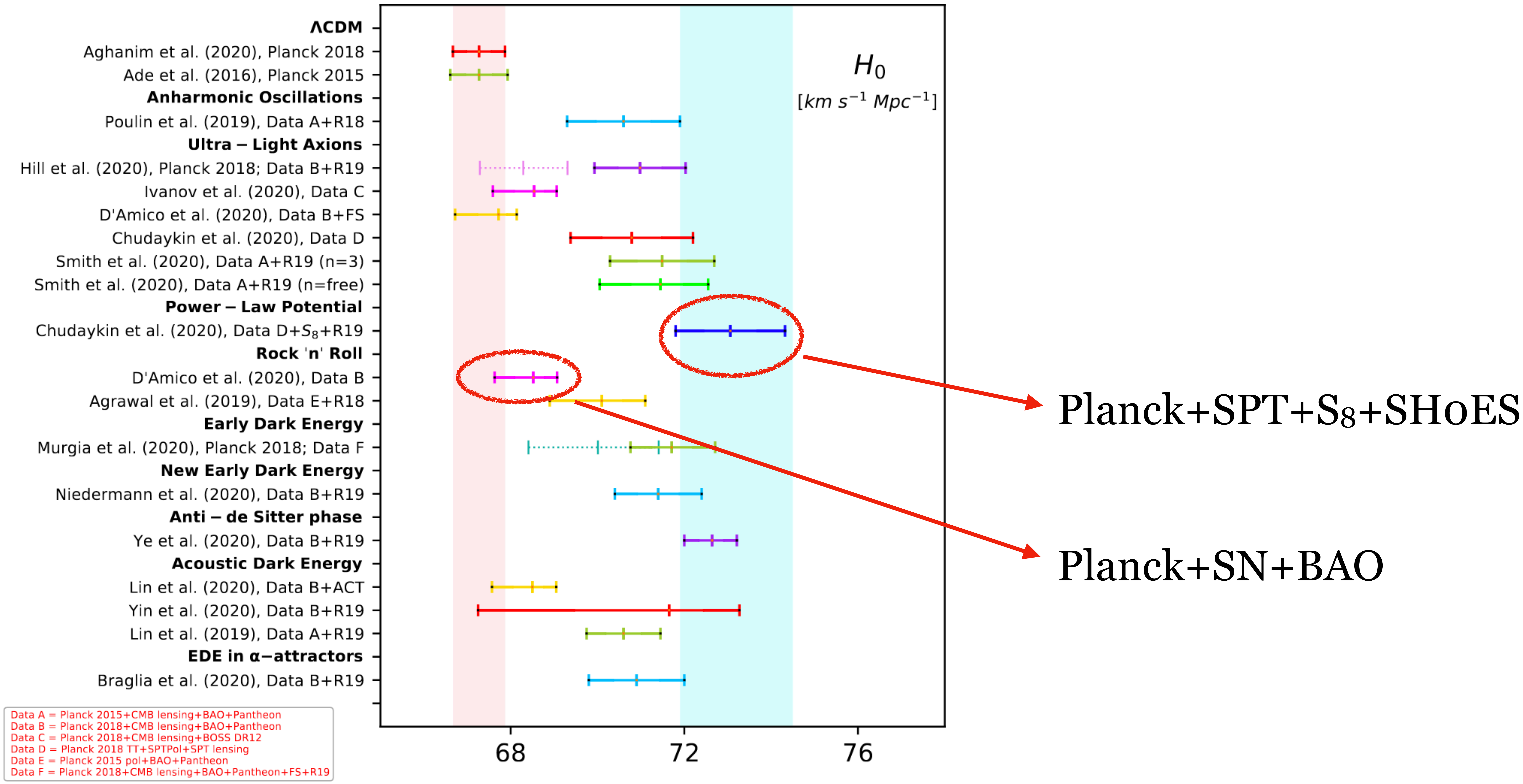
It proves difficult to compare success of the different proposed solutions, since authors typically use differing and incomplete combinations of data



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

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 obtains 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

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

$$q_0 = -0.53, \quad j_0 = 1 \qquad (\Lambda\mathrm{CDM\ assumed!})$$

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 obtains 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

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

$$q_0 = -0.53, \quad j_0 = 1 \qquad (\Lambda\text{CDM assumed!})$$

Quantifying model success

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

Gaussian tension GT

$$\frac{\bar{x}_D - \bar{x}_{SH0ES}}{\sqrt{\sigma_D^2 + \sigma_{\mathrm{SH0ES}}^2}} \text{ for } \mathrm{x} = \mathrm{H}_0 \text{ or } \mathrm{M}_\mathrm{b}$$

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

Quantifying model success

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

Gaussian tension GT

$$\frac{\bar{x}_D - \bar{x}_{SH0ES}}{\sqrt{\sigma_D^2 + \sigma_{\mathrm{SH0ES}}^2}} \text{ for } \mathrm{x} = \mathrm{H}_0 \text{ or } \mathrm{M}_\mathrm{b}$$

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

Caveats:

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

Example: ΛCDM with fixed $\Omega_{\mathrm{cdm}}h^2 = 0.11$ yields $H_0 = 71.84 \pm 0.16$ km/s/Mpc but has $\Delta\chi^2 \simeq 106$

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?

$Q_{\rm DMAP}$ tension

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

Raveri&Hu 1806.04649

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

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 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

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

Compare all models against
- Planck 18 TTTEEE+lensing
- BAO (BOSS DR12+MGS+6dFGS)
- Pantheon SNIa catalog
- SH0ES

Steps of the contest

Compare all models against
- Planck 18 TTTEEE+lensing
- BAO (BOSS DR12+MGS+6dFGS)
- Pantheon SNIa catalog
- SH0ES

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

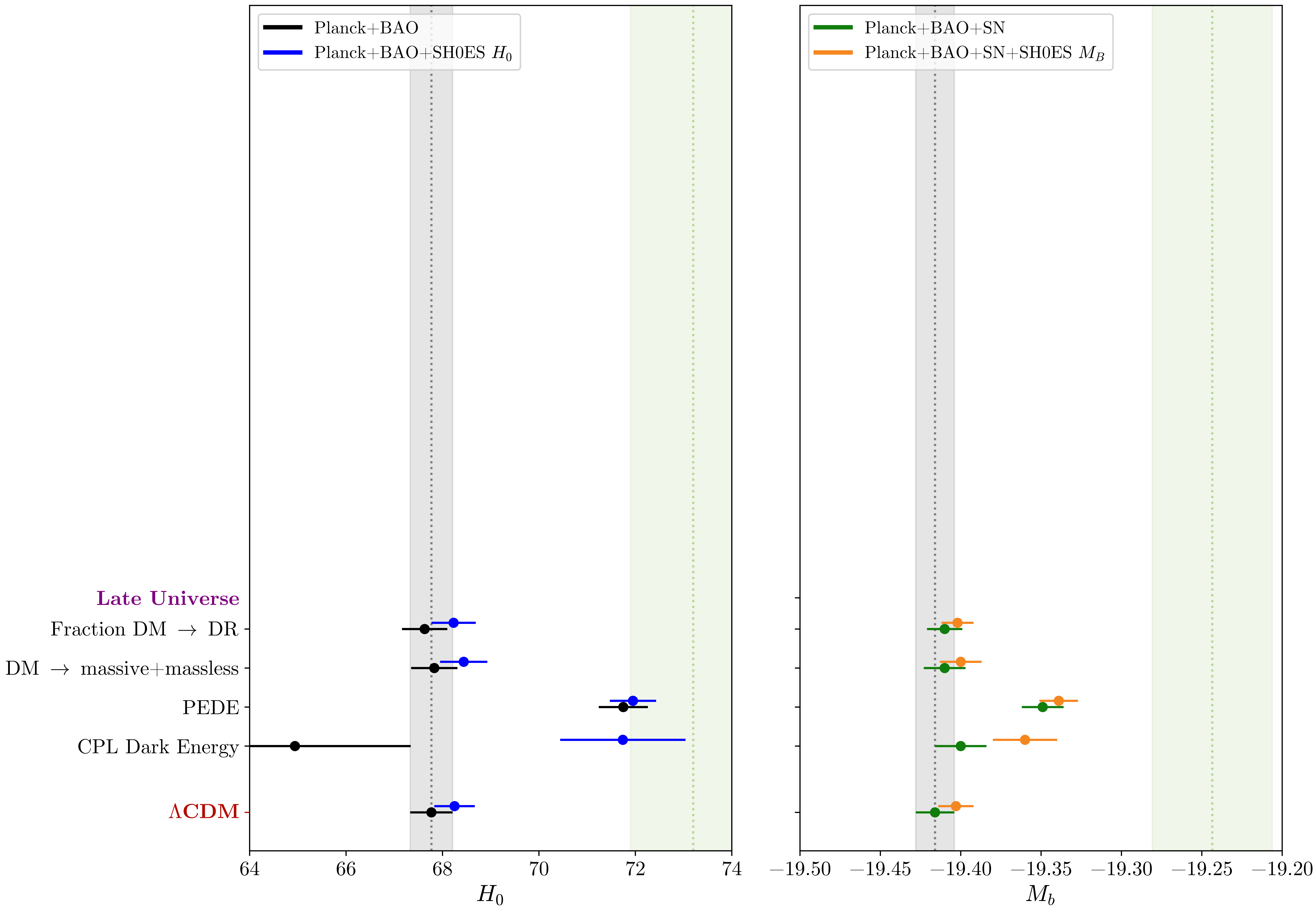
Steps of the contest

Compare all models against
- Planck 18 TTTEEE+lensing
- BAO (BOSS DR12+MGS+6dFGS)
- Pantheon SNIa catalog
- SH0ES

As long as ΔAIC < 0, models go into finalist if criterium 2 or 3 are satisfied

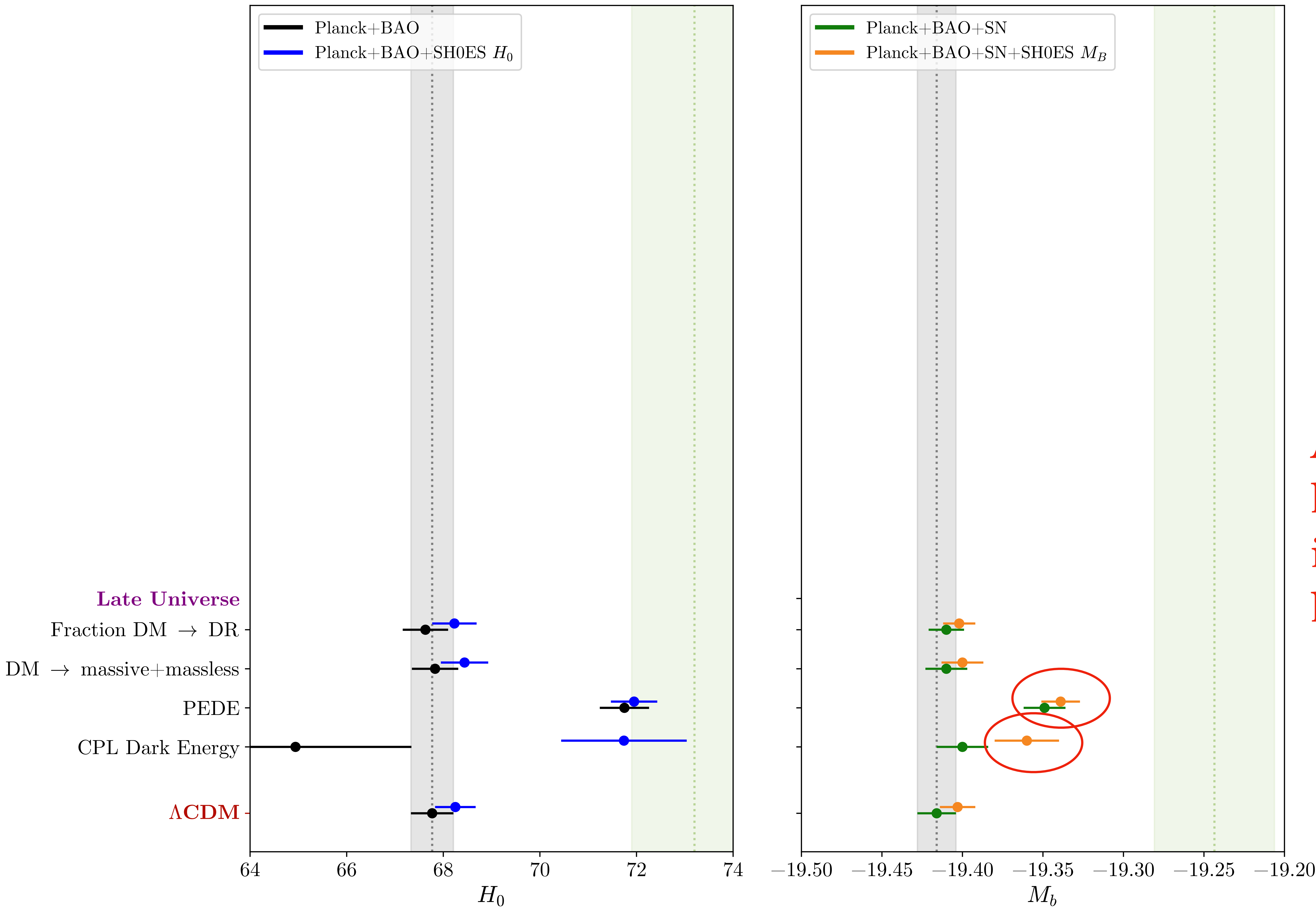
Finalists receive bronze, silver or golden medals if they satisfy one, two or three criteria, respectively

Results of the contest



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

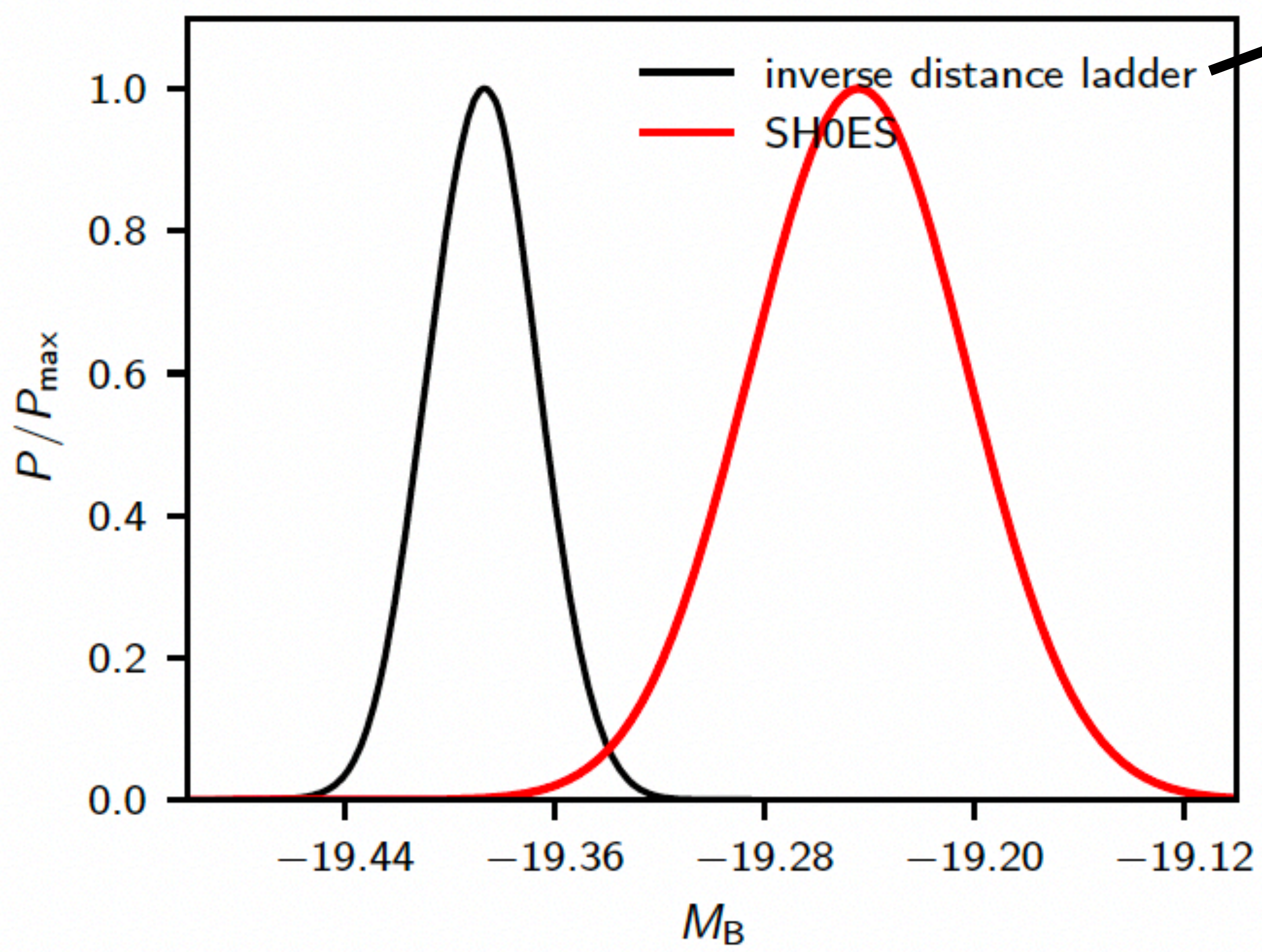
Results of the contest



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

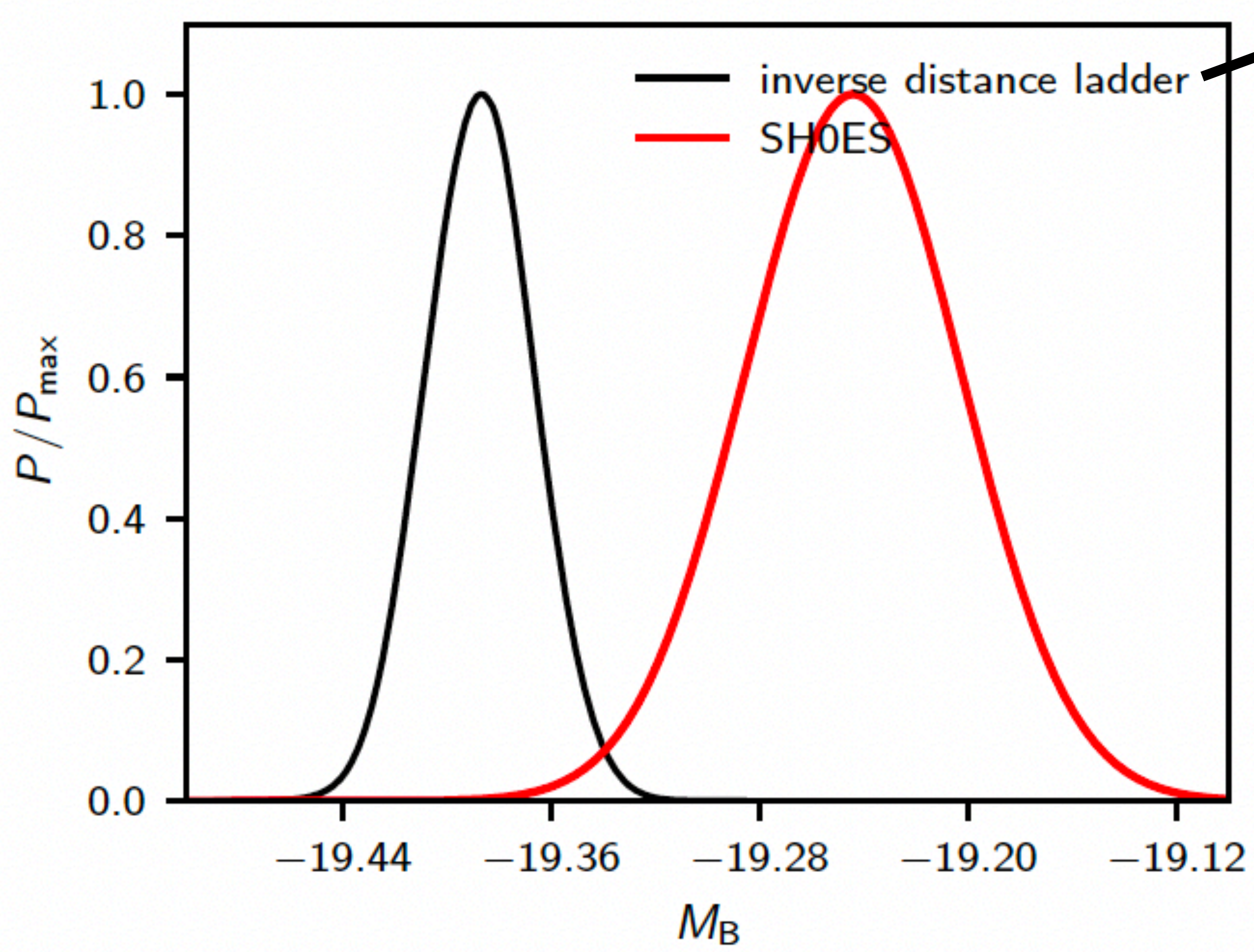
$$\theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)}, \quad \theta_d(z)^{\parallel} = r_s(z_{\rm drag})H(z)$$

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

Obtain M_b from calibration const. of SNIa

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

Late-time solutions are disfavoured by BAO+SNIa



Efstathiou 2103.08723

Given r_s, obtain D_A using BAO data

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

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

Obtain M_b from calibration const. of SNIa

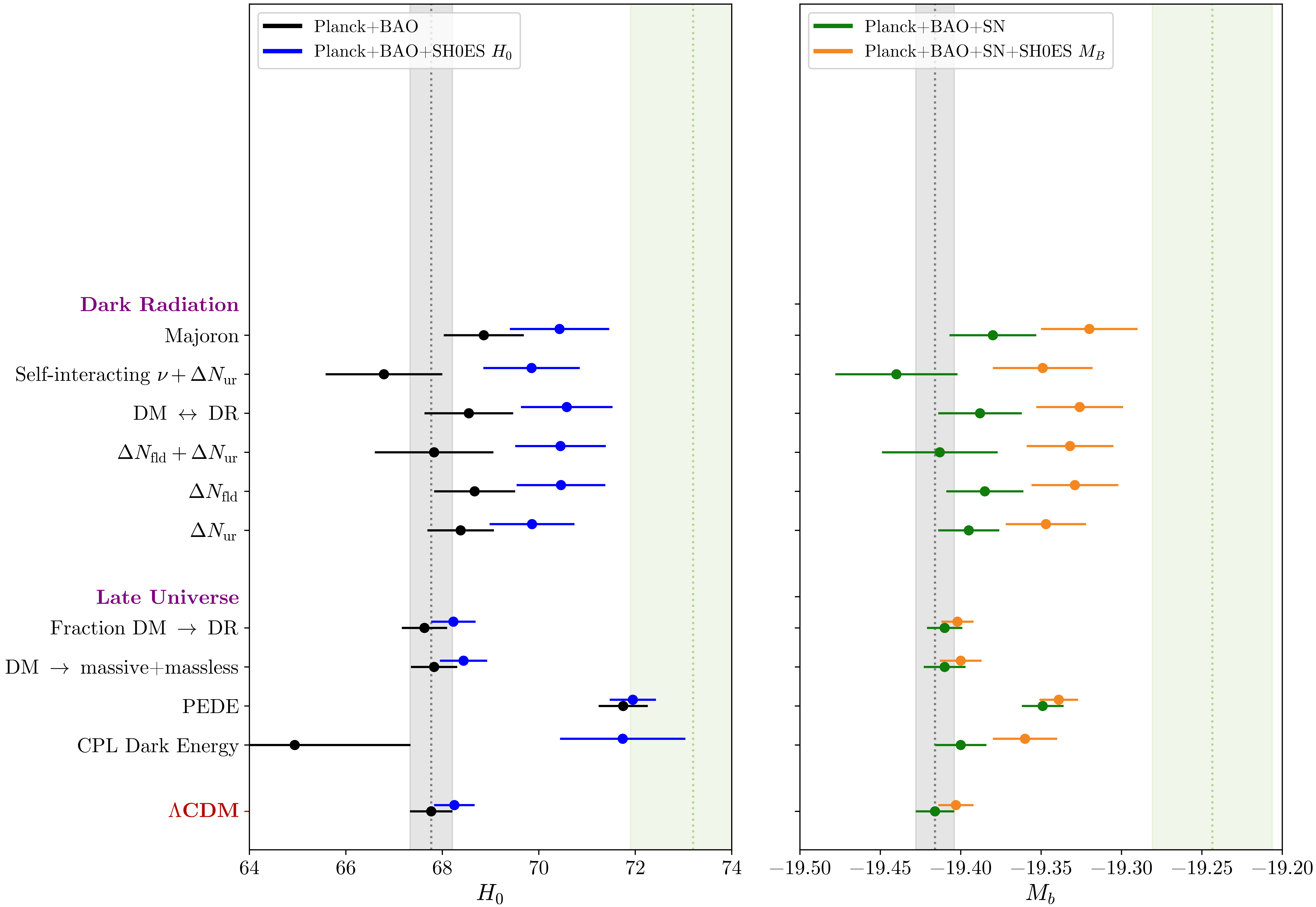
$$m(z) = 5\mathrm{Log}_{10}\mathrm{D_L}(z) + \mathrm{const}$$

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

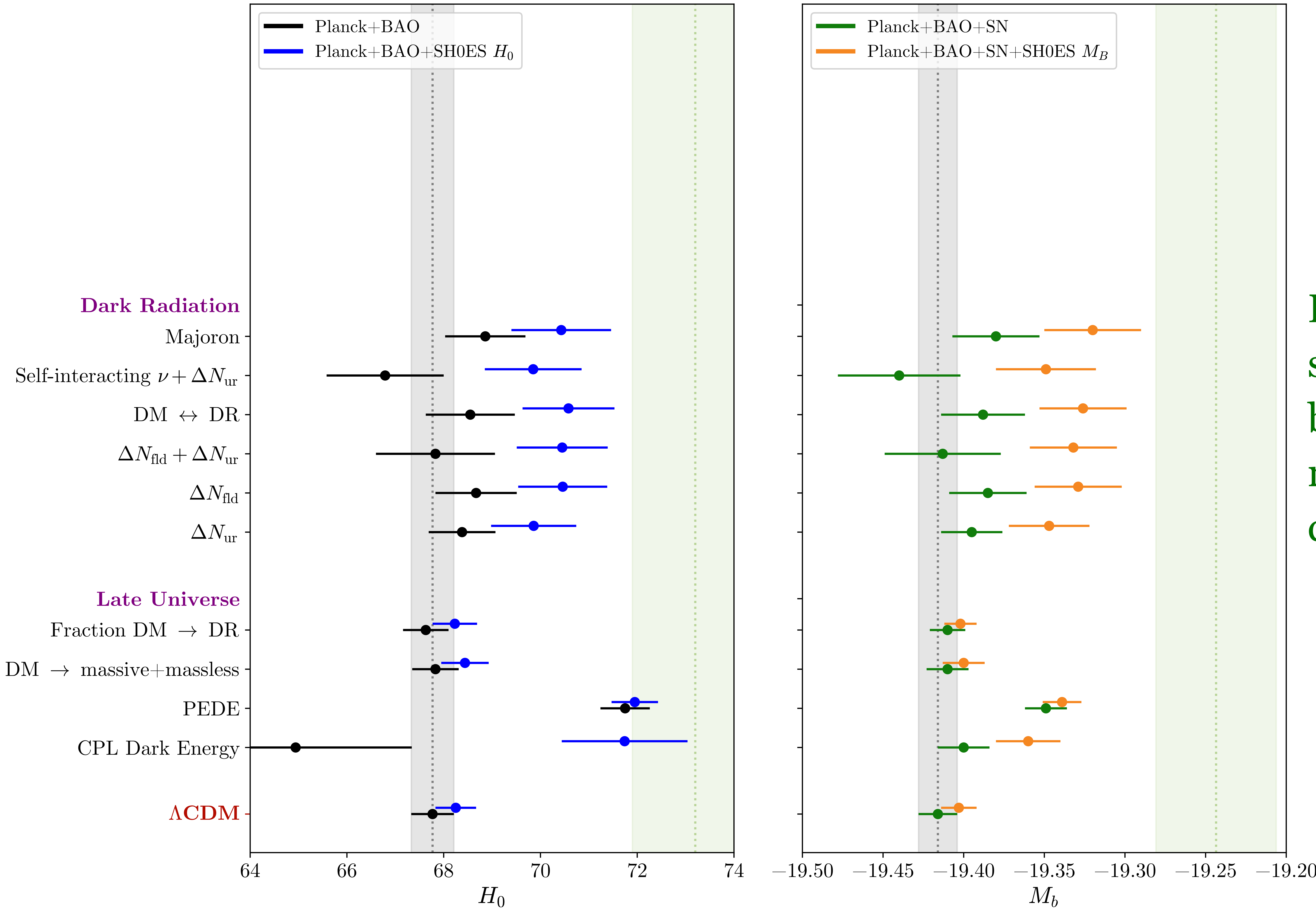
Ex: *Early Dark Energy or exotic neutrino interactions*

Results of the contest



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

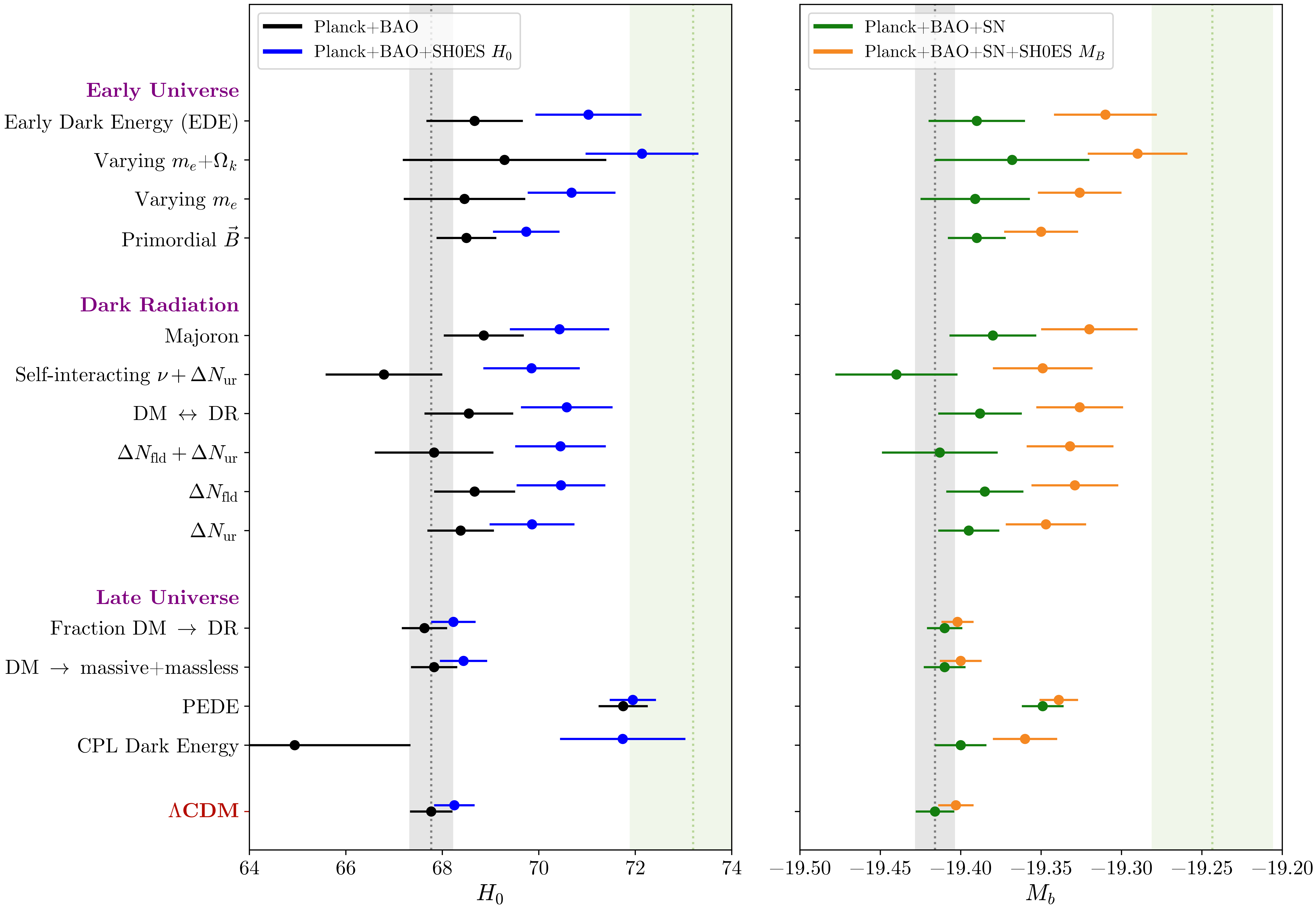
Results of the contest



Dark radiation solutions work better, but remain very constrained

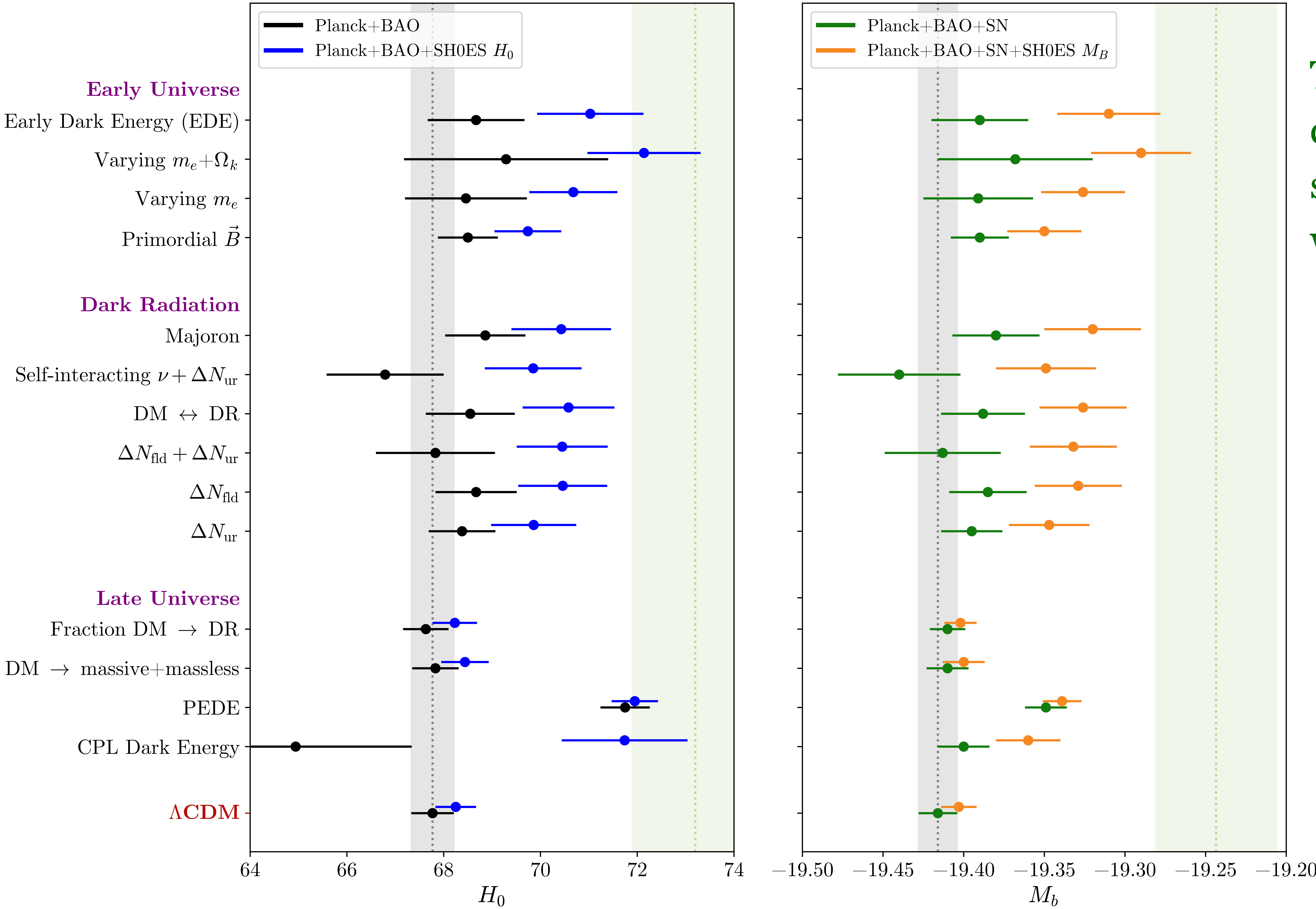
Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

Results of the contest



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

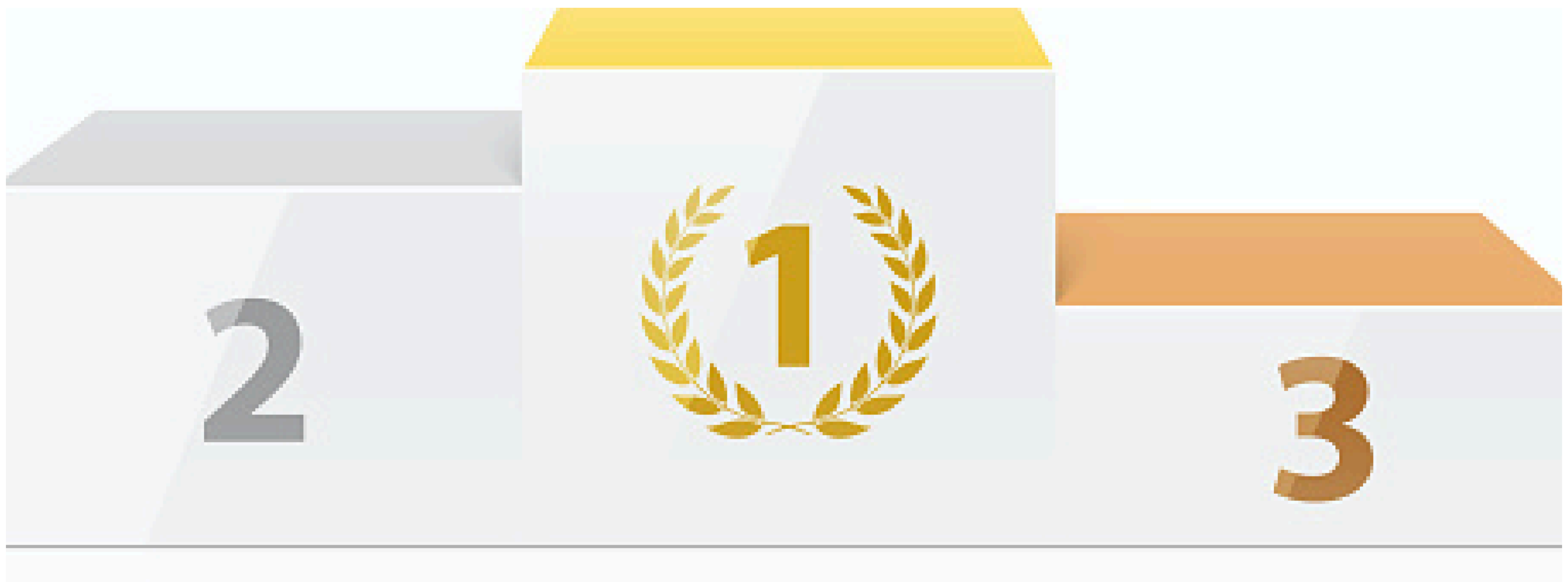
Results of the contest



This is the category of solutions that work the best

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

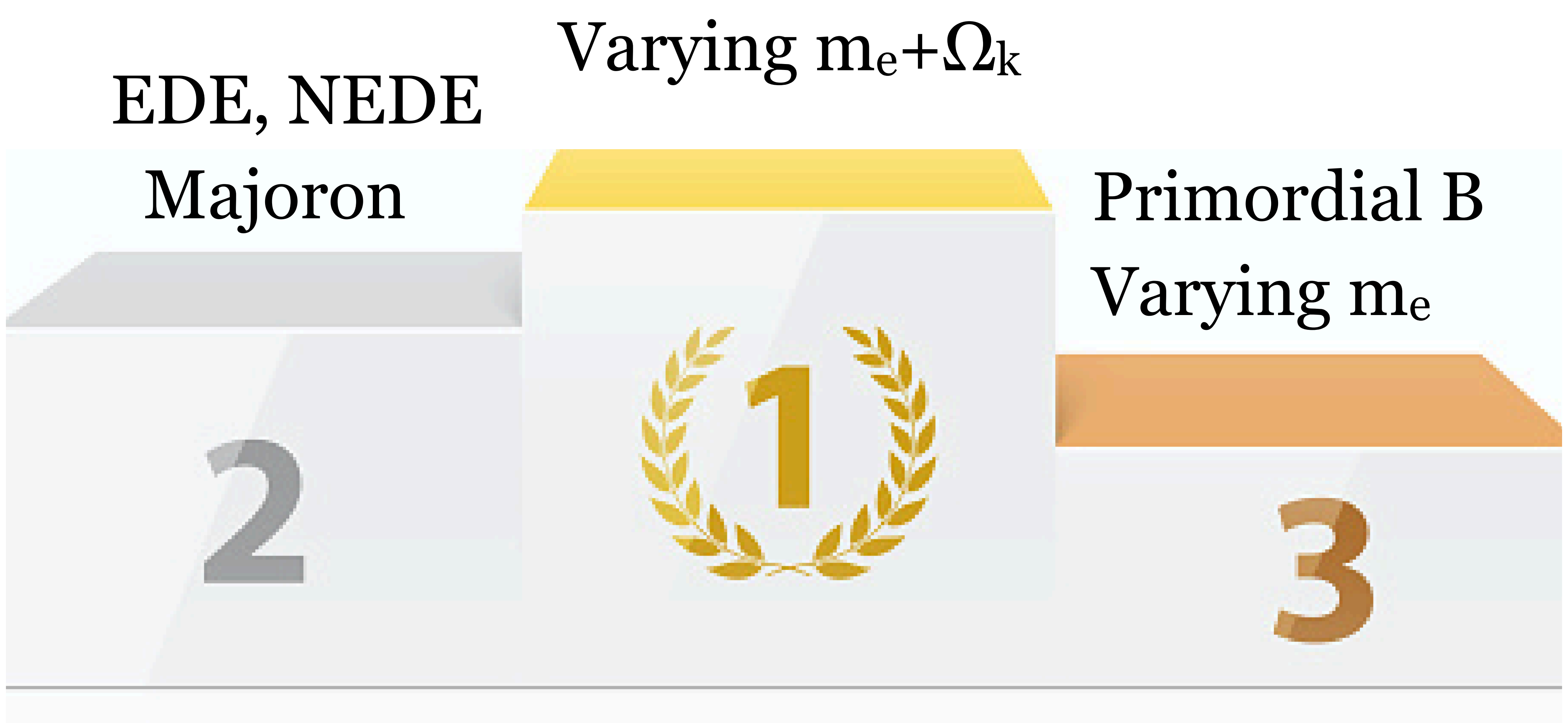
Results of the contest



Results of the contest

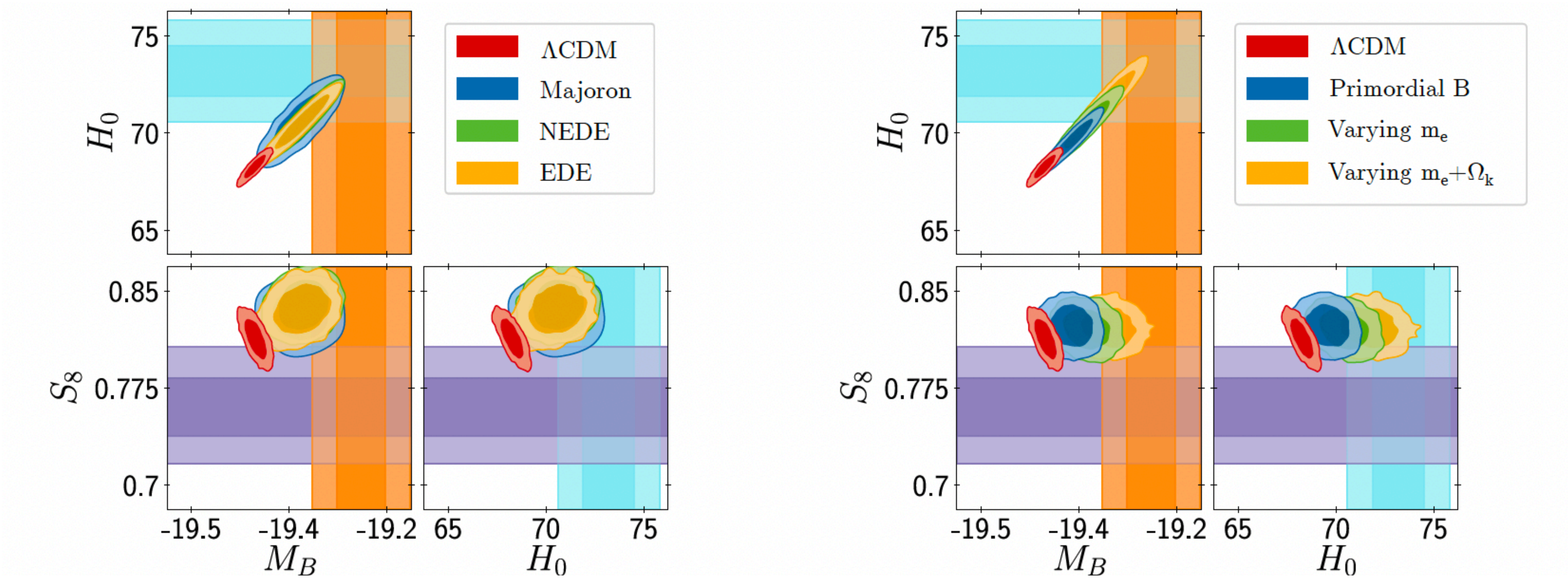
Results of the contest

Results of the contest



Results of the contest

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

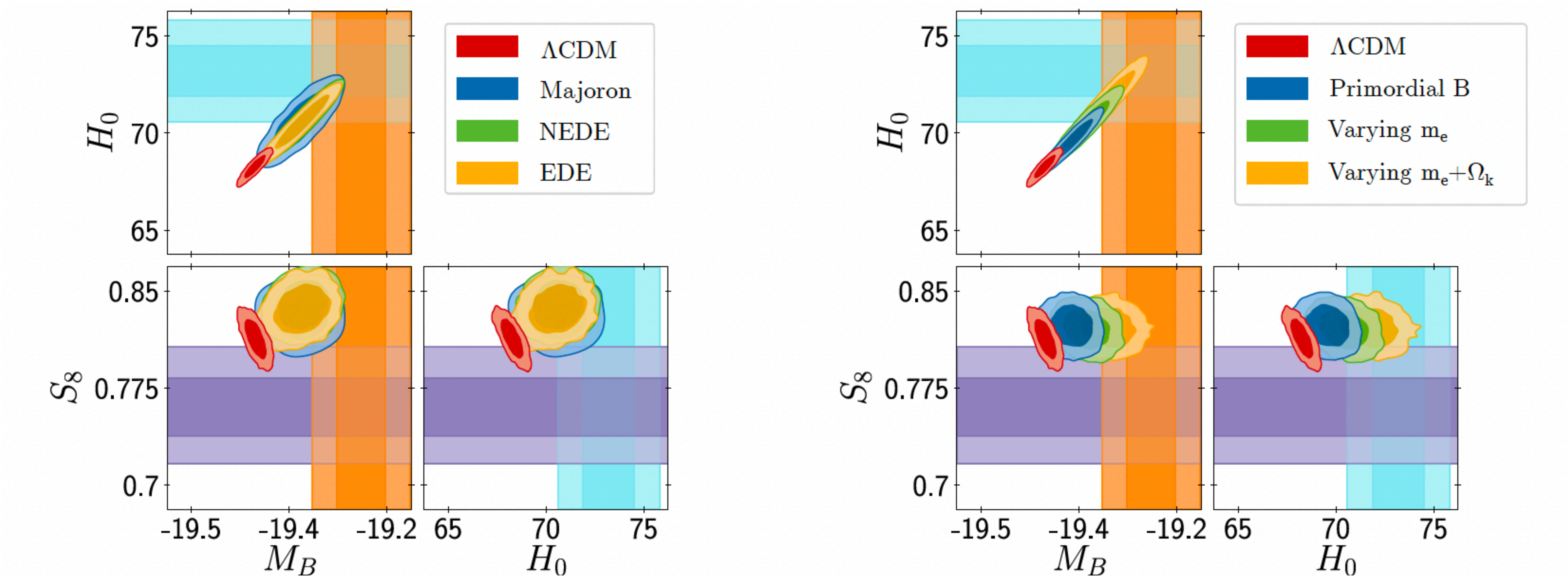


Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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

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



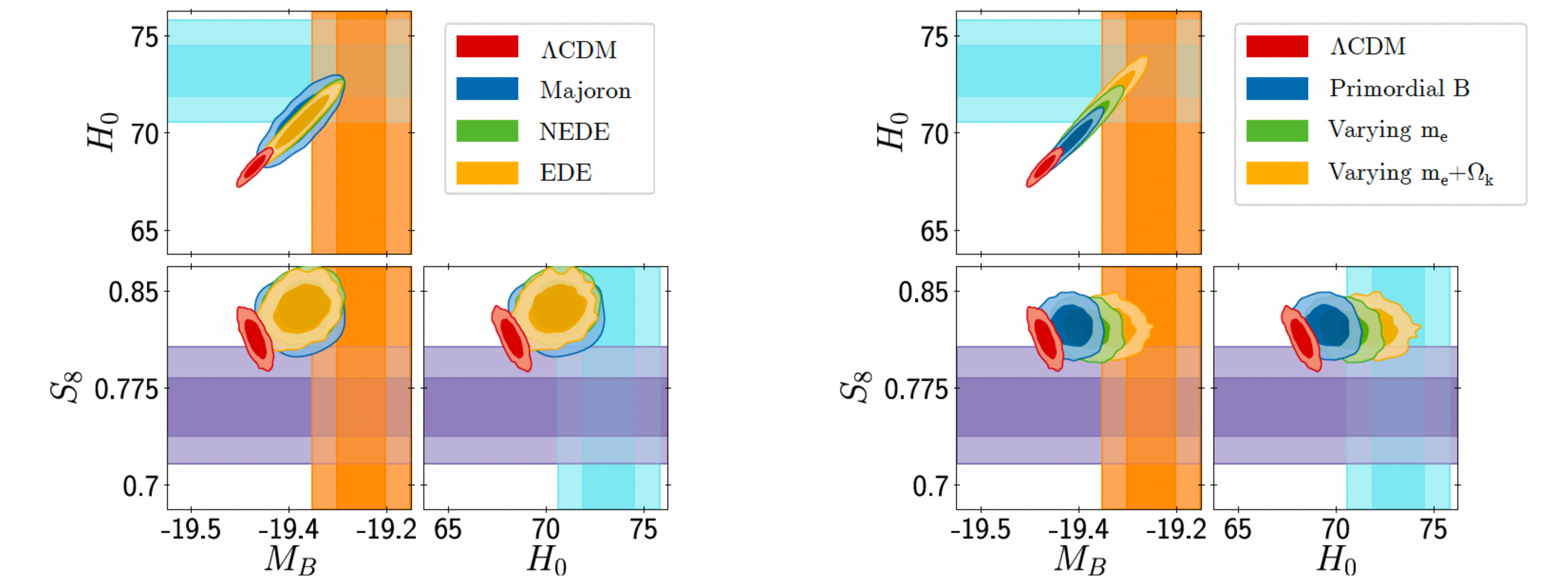
Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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

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



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

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?

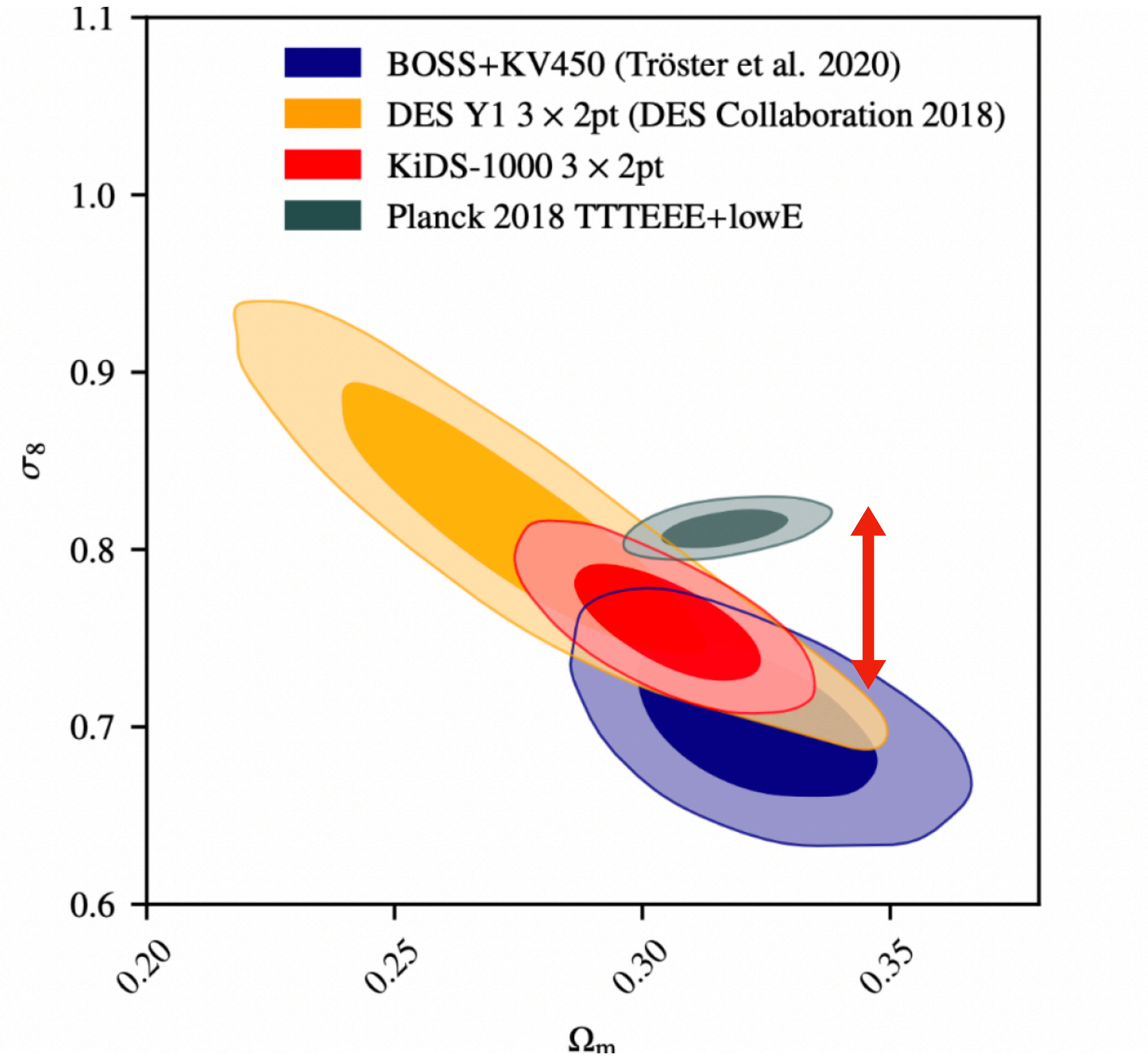
III. Explaining the S_8 tension with Decaying Dark Matter

In collaboration with Riccardo Murgia, Vivian Poulin and Julien Lavalle

What is needed to resolve the S_8 tension?

Di Valentino++ 2008.11285

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



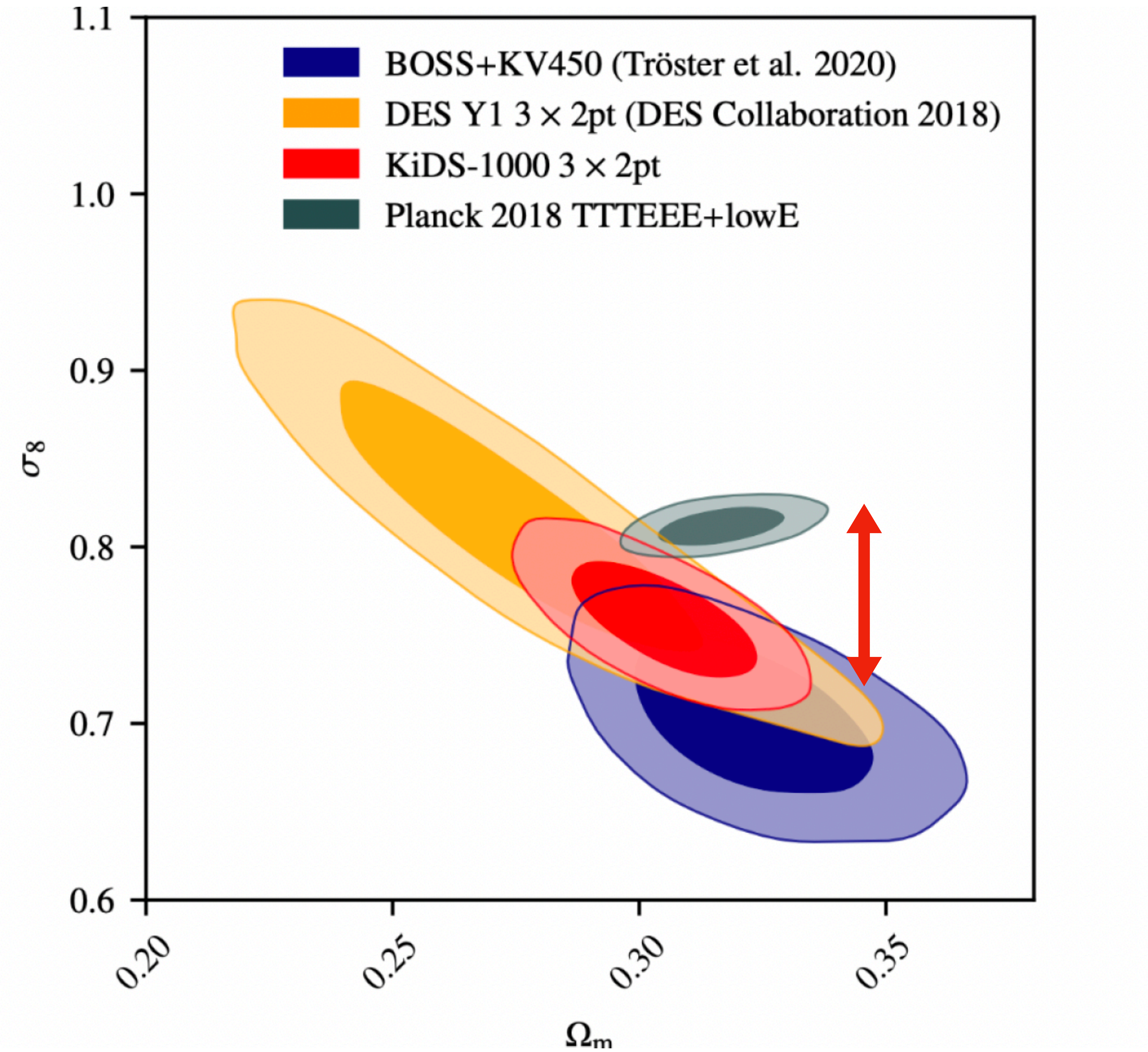
Ω_m should be left unchanged

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

What is needed to resolve the S_8 tension?

Di Valentino++ 2008.11285

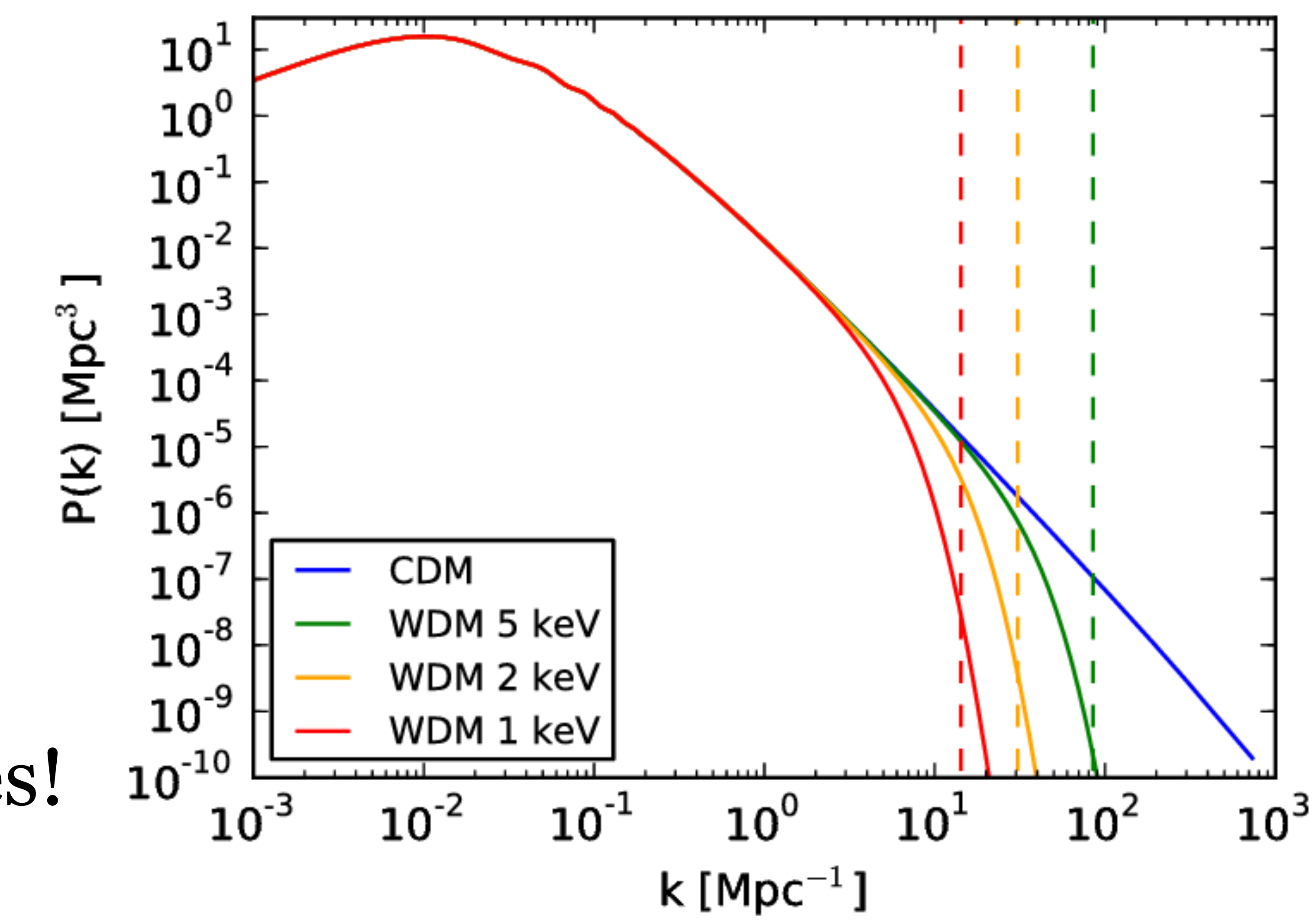
$$S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$$



Ω_m should be left unchanged

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

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

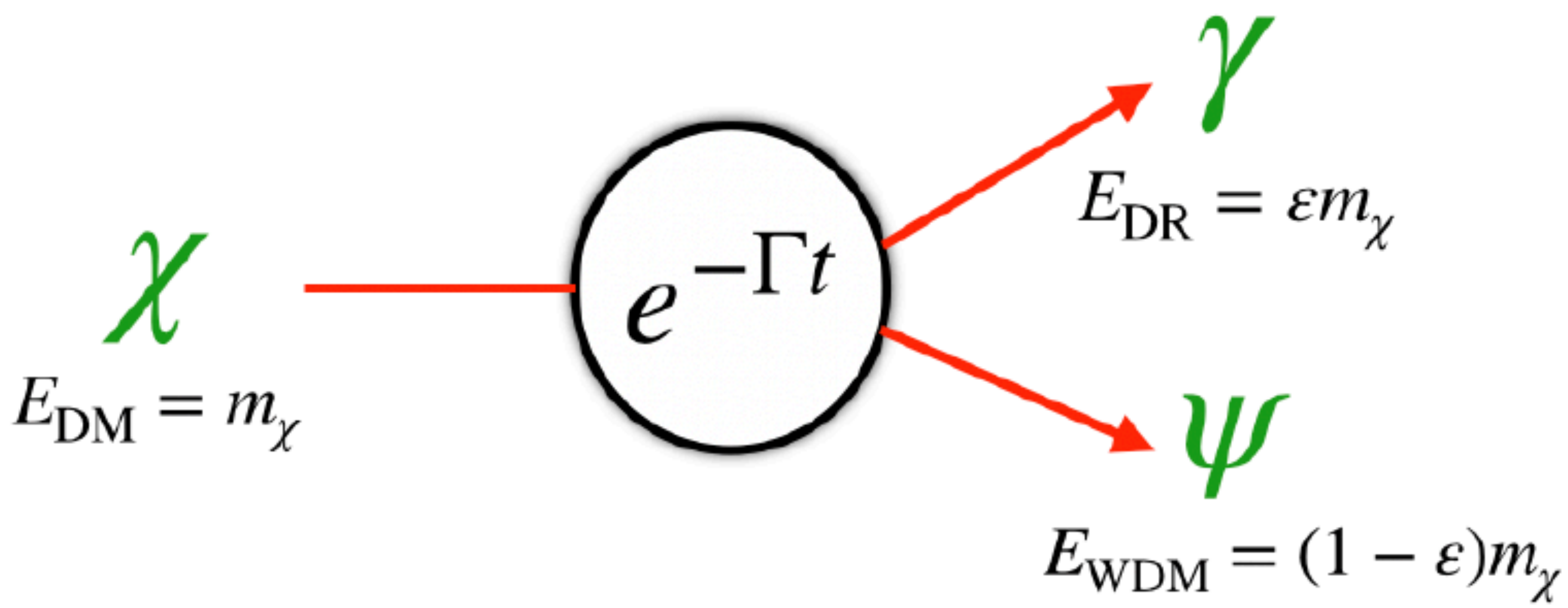


Ex: Warm Dark Matter

Very constrained by many probes!

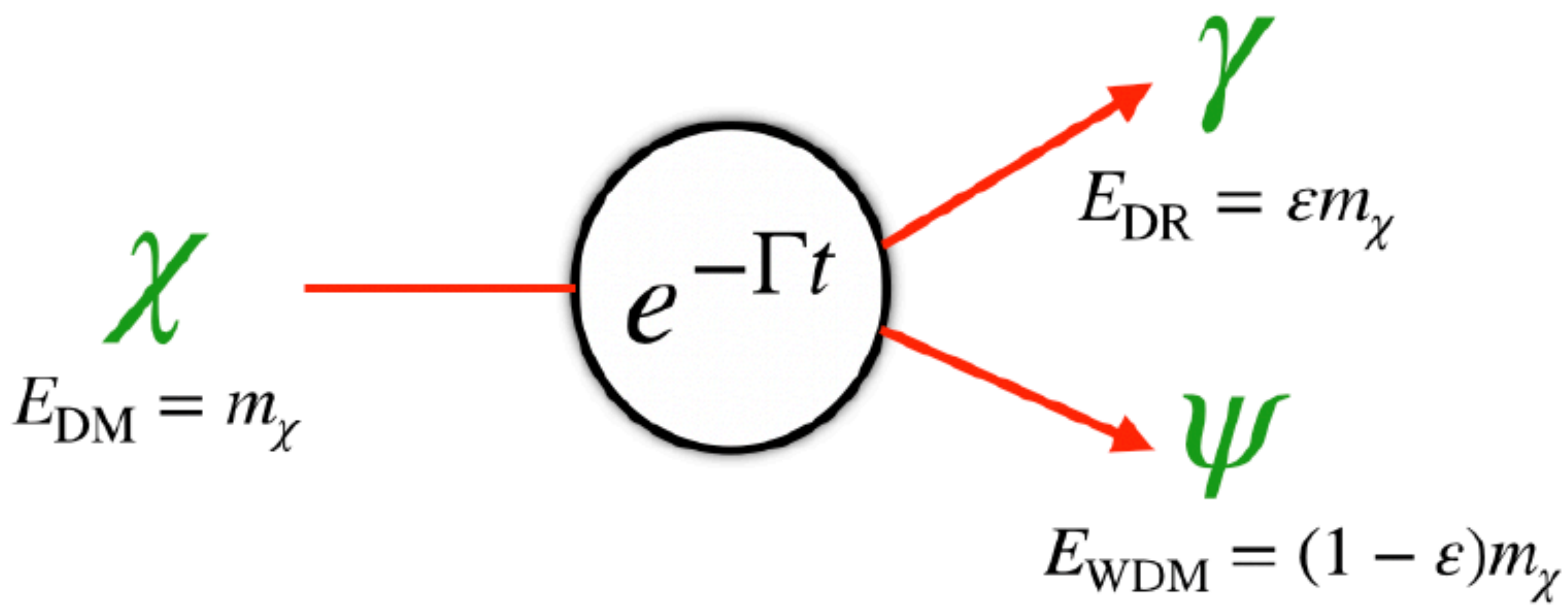
2-body Dark Matter decay

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



2-body Dark Matter decay

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



The model is fully specified by:

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

2-body Dark Matter decay

Aoyama++ 1402.2972	→	Full treatment of perts.	No parameter scan
Vattis++ 1903.06220	→	Resolution to H_0 tension ?	No perturbations
Haridasu&Viel 2004.07709	→	SNIa+BAO rule out solution	
Clark++ 2006.03678	→	CMB rule out solution	

2-body Dark Matter decay

Aoyama++ 1402.2972 ⟶ Full treatment of perts. — No parameter scan

Vattis++ 1903.06220 ⟶ Resolution to H_0 tension ?

Haridasu&Viel 2004.07709 ⟶ SNIa+BAO rule out solution

Clark++ 2006.03678 ⟶ CMB rule out solution

(Vattis++, Haridasu&Viel, Clark++): No perturbations

Our goal: Perform parameter scan by including full treatment of linear perts, in order to assess the impact on the S_8 tension

⟶ Track δ_i, θ_i and σ_i for $\mathrm{i} = \mathrm{dm}, \mathrm{dr}, \mathrm{wdm}$

Evolution of perturbations: fluid equations

New fluid eqs.*, based on previous approximation for massive neutrinos

Lesgourgues & Tram, 1104.2935

$$\dot{\delta}_{\rm wdm} = -3aH(c_{\rm syn}^2 - w)\delta_{\rm wdm} - (1+w)\left(\theta_{\rm wdm} + \frac{\dot{h}}{2}\right) + a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dm} - \delta_{\rm wdm})$$

$$\dot{\theta}_{\rm wdm} = -aH(1-3c_a^2)\theta_{\rm wdm} + \frac{c_{\rm syn}^2}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{1+c_a^2}{1+w}\theta_{\rm wdm}$$

*Implemented in modified version of public Boltzmann solver CLASS

Evolution of perturbations: fluid equations

New fluid eqs.*, based on previous approximation for massive neutrinos

Lesgourgues & Tram, 1104.2935

$$\dot{\delta}_{\rm wdm} = -3aH(c_{\rm syn}^2 - w)\delta_{\rm wdm} - (1+w)\left(\theta_{\rm wdm} + \frac{\dot{h}}{2}\right) + a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dm} - \delta_{\rm wdm})$$

$$\dot{\theta}_{\rm wdm} = -aH(1-3c_a^2)\theta_{\rm wdm} + \frac{c_{\rm syn}^2}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{1+c_a^2}{1+w}\theta_{\rm wdm}$$

where

$$c_a^2(\tau) = w\left(5 - \frac{\mathfrak{p}_{\rm wdm}}{\bar{P}_{\rm wdm}} - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{3wH}\frac{\varepsilon^2}{1-\varepsilon}\right)\left[3(1+w) - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{H}(1-\varepsilon)\right]^{-1}$$

and

$$c_{\rm syn}^2(k,\tau) = c_a^2(\tau)\left[1 + (1-2\varepsilon)T(k/k_{\rm fs})\right]$$

*Implemented in modified version of public Boltzmann solver CLASS

Evolution of perturbations: fluid equations

New fluid eqs.*, based on previous approximation for massive neutrinos

Lesgourgues & Tram, 1104.2935

$$\dot{\delta}_{\rm wdm} = -3aH(c_{\rm syn}^2 - w)\delta_{\rm wdm} - (1+w)\left(\theta_{\rm wdm} + \frac{\dot{h}}{2}\right) + a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dm} - \delta_{\rm wdm})$$

$$\dot{\theta}_{\rm wdm} = -aH(1-3c_a^2)\theta_{\rm wdm} + \frac{c_{\rm syn}^2}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{1+c_a^2}{1+w}\theta_{\rm wdm}$$

where

$$c_a^2(\tau) = w\left(5 - \frac{\mathfrak{p}_{\rm wdm}}{\bar{P}_{\rm wdm}} - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{3wH}\frac{\varepsilon^2}{1-\varepsilon}\right)\left[3(1+w) - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{H}(1-\varepsilon)\right]^{-1}$$

and

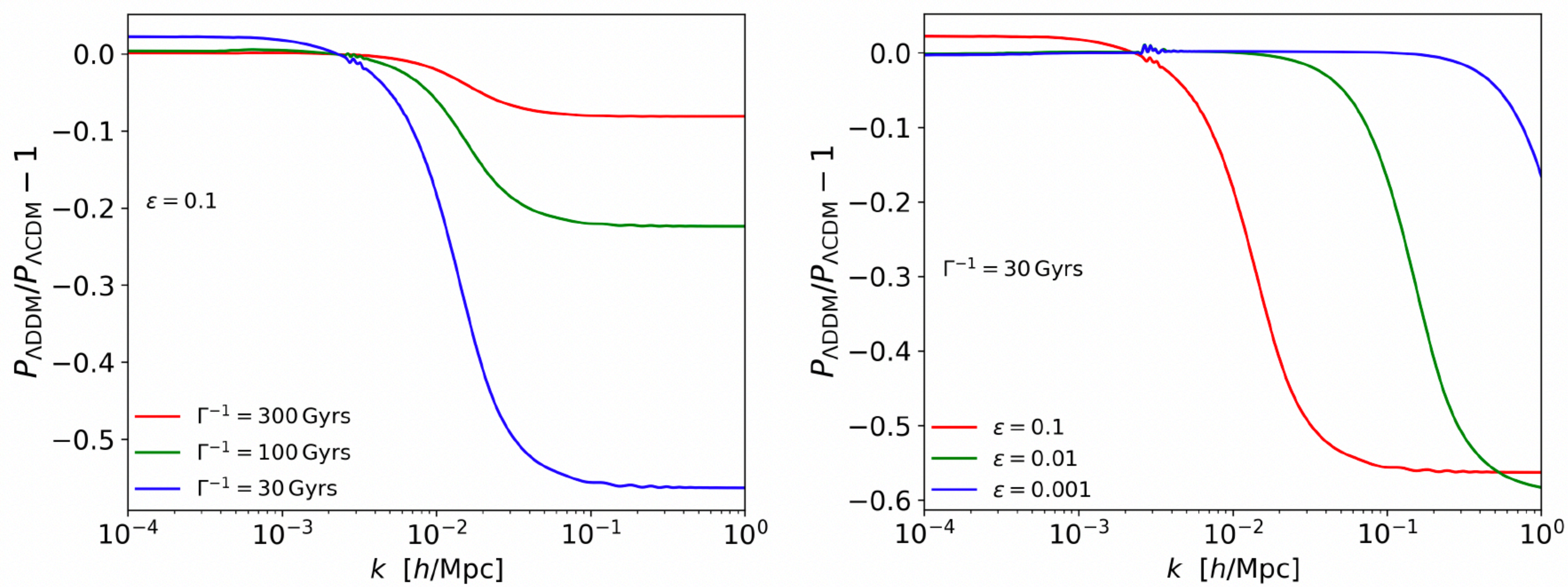
$$c_{\rm syn}^2(k,\tau) = c_a^2(\tau)\left[1 + (1-2\varepsilon)T(k/k_{\rm fs})\right]$$

CPU time reduced from ~ 1 day to ~ 1 minute!

*Implemented in modified version of public Boltzmann solver CLASS

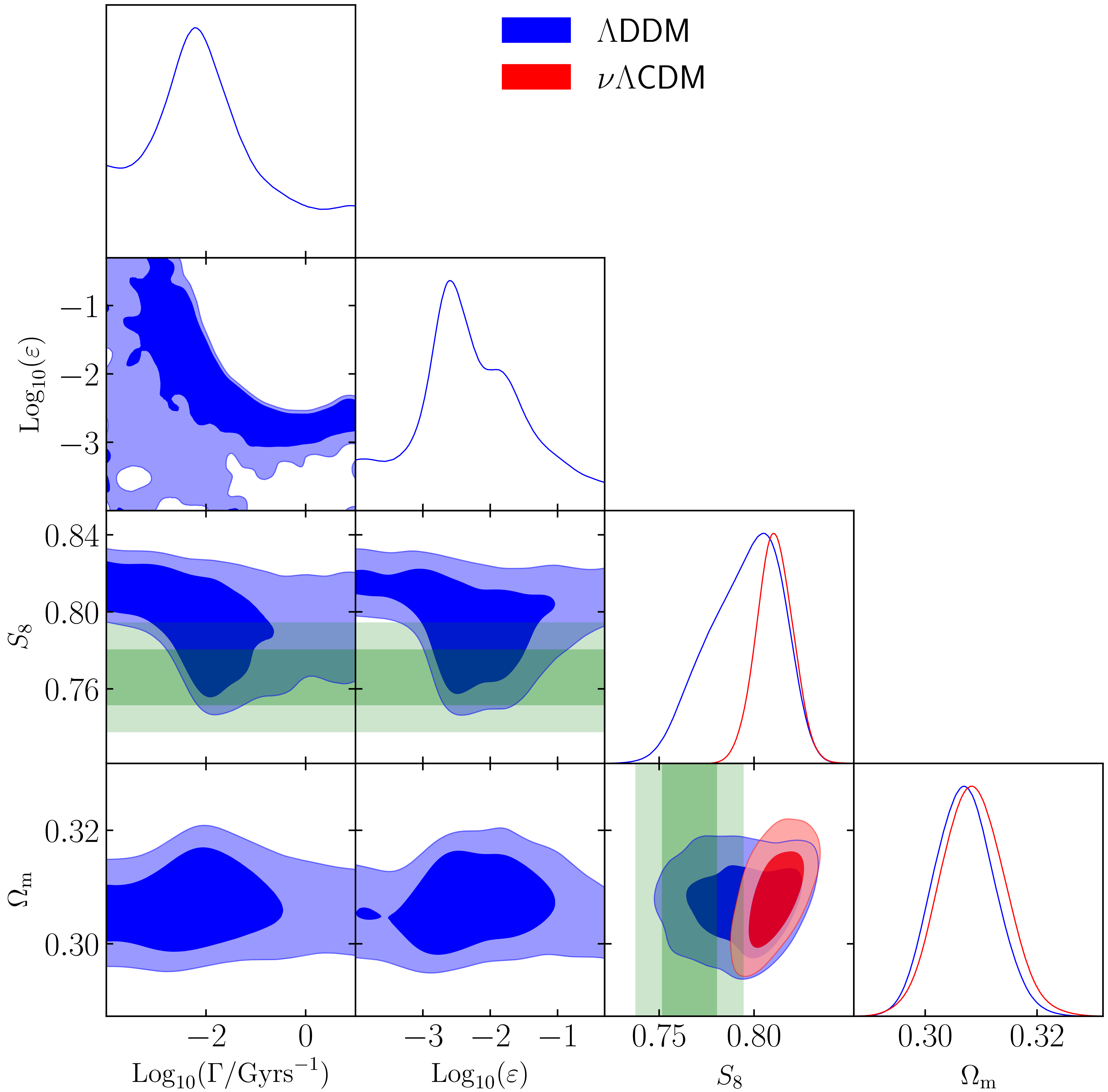
Impact of decaying DM on the matter spectrum

The WDM daughter leads to a power suppression in $P_m(k)$ at small scales $k > k_{\rm fs}$, where $\mathrm{k_{fs}} \sim \mathrm{aH/c_a}$



GFA, Murgia, Poulin 2008.09615

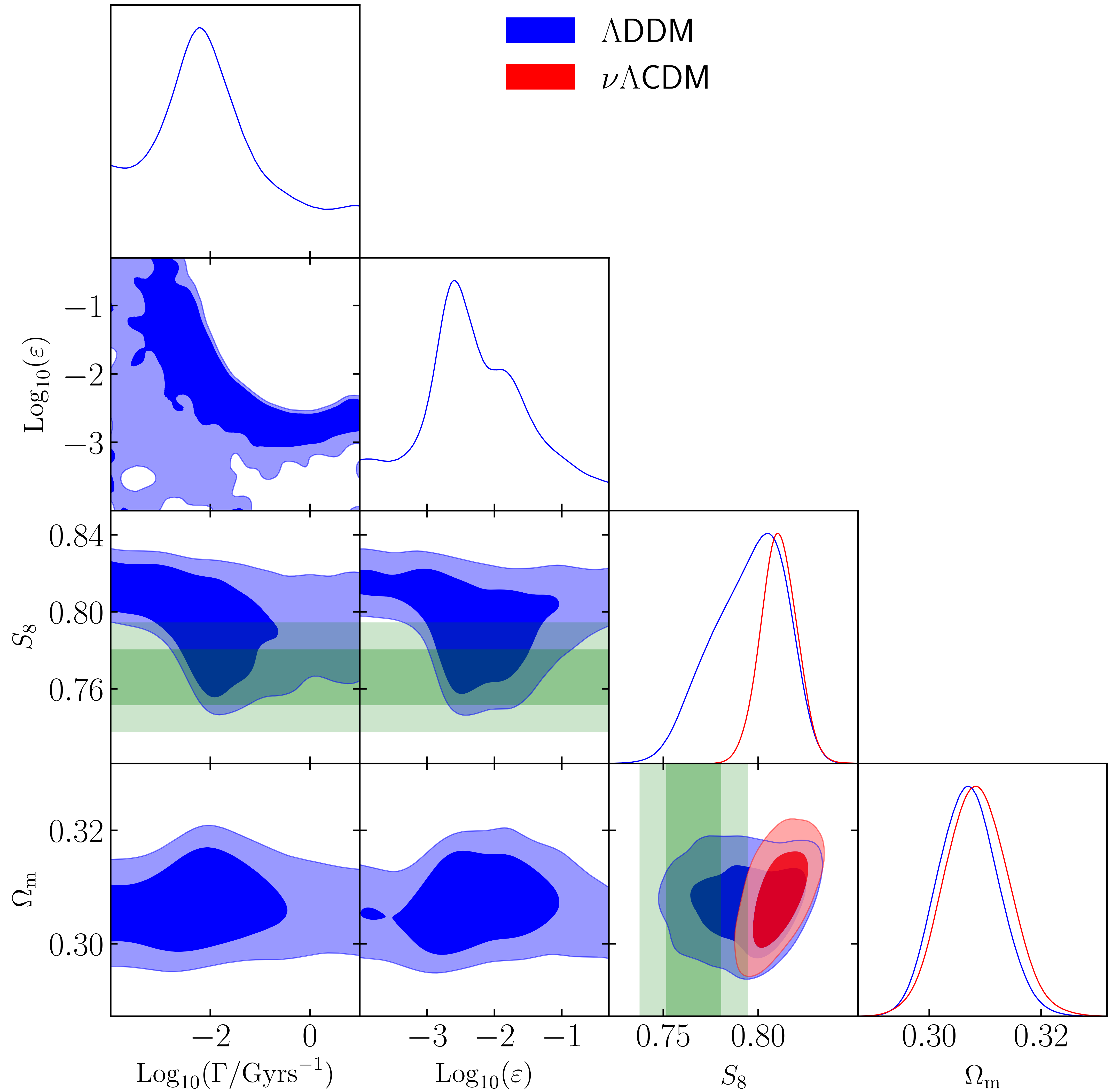
Resolution to the S_8 tension



GFA, Murgia, Poulin 2102.12498

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

Resolution to the S_8 tension



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!

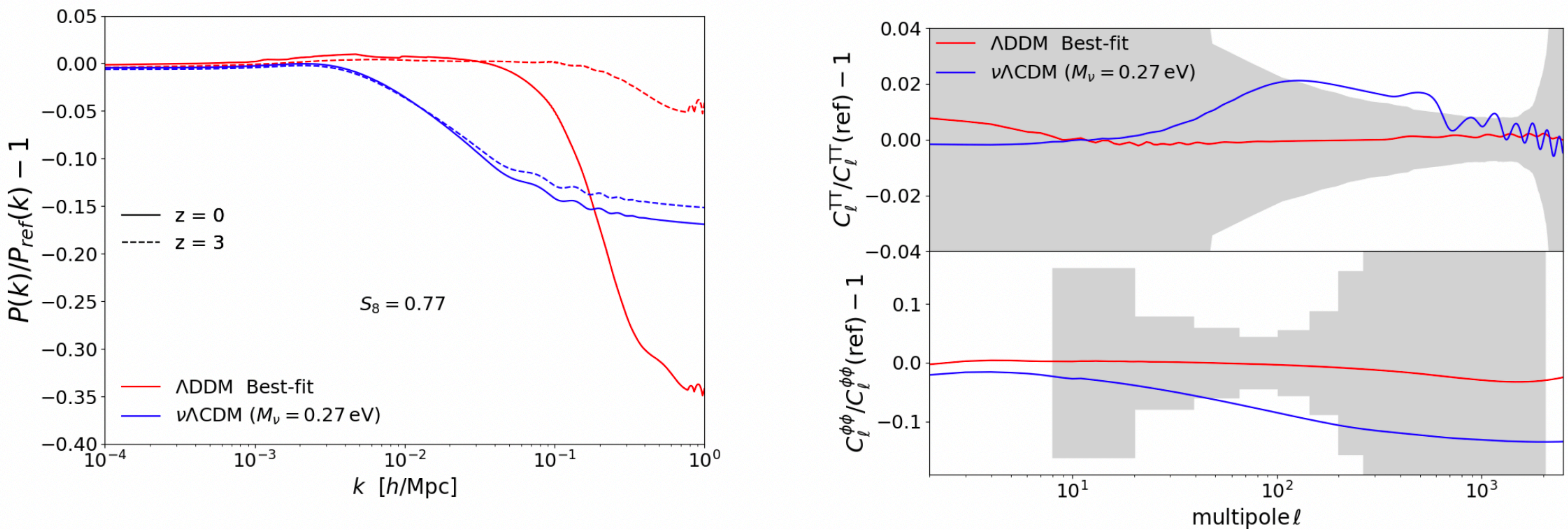
	$\nu\Lambda$CDM	ΛDDM
$\chi^2_{\rm CMB}$	1015.9	1015.2
$\chi^2_{S_8}$	5.64	0.002

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

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

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



GFA, Murgia, Poulin 2102.12498

Interesting implications

- Model building: Why $\varepsilon \ll 1/2$, i.e. $m_{\rm wdm} \sim m_{\rm dm}$?
  Ex : Supergravity Choi&Yanagida 2104.02958

Interesting implications

- Model building: Why $\varepsilon \ll 1/2$, i.e. $m_{wdm} \sim m_{dm}$?
  Ex : Supergravity Choi&Yanagida 2104.02958

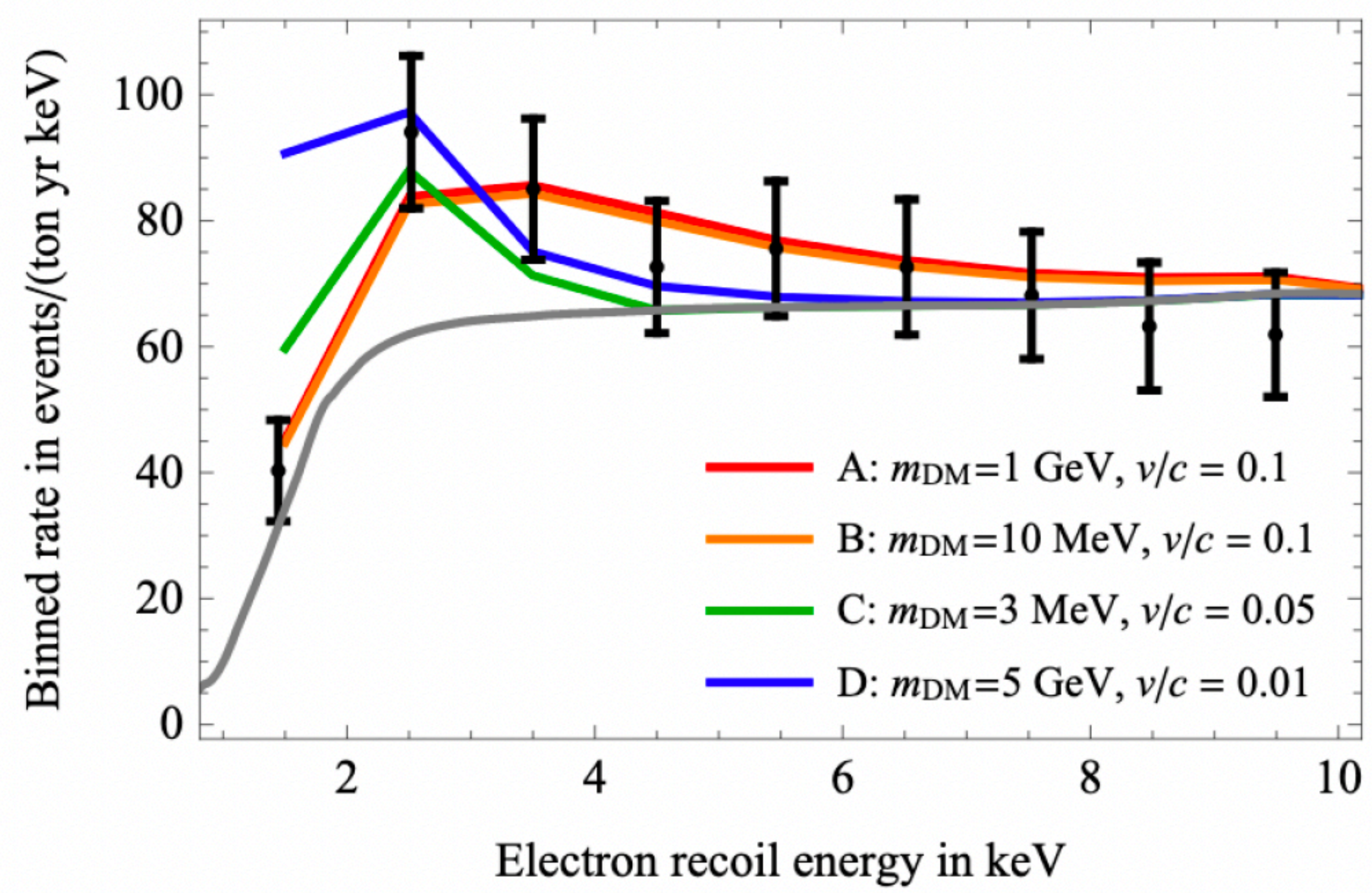
- Small-scale crisis of ΛCDM: Reduction in the abundance of subhalos and their concentrations Wang++ 1406.0527

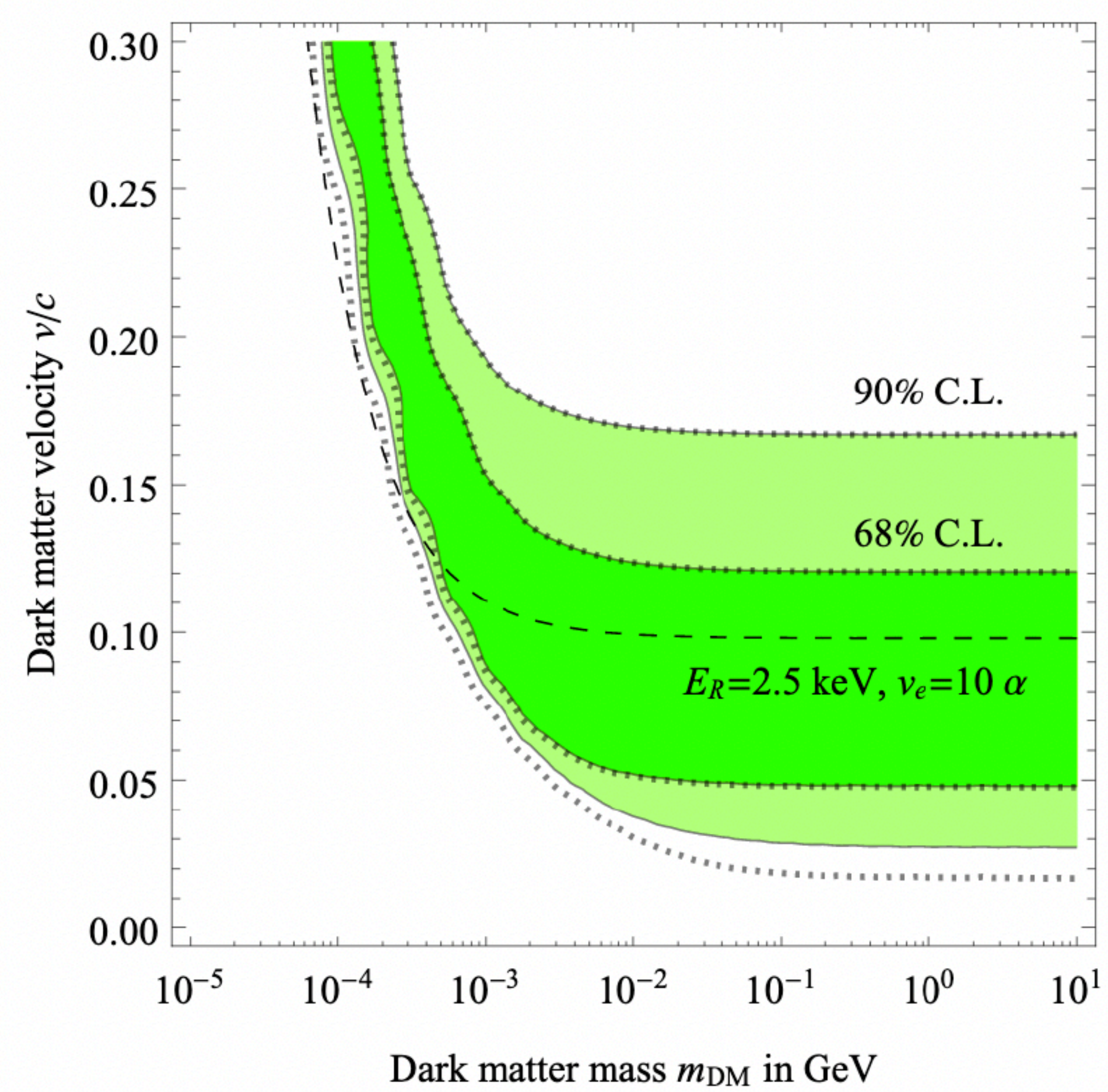
Interesting implications

- Model building: Why $\varepsilon \ll 1/2$, i.e. $m_{wdm} \sim m_{dm}$?
  Ex : Supergravity Choi&Yanagida 2104.02958

- Small-scale crisis of ΛCDM: Reduction in the abundance of subhalos and their concentrations Wang++ 1406.0527

- Xenon-1T excess: It could be explained by a fast DM component, such as the WDM, with $v/c \simeq \varepsilon$ Kannike++ 2006.10735





Conclusions

- ΛCDM provides a remarkable fit to many observations, but there exists a 4-5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

Conclusions

- ΛCDM provides a remarkable fit to many observations, but there exists a 4-5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

- Thanks to a systematic study, 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 provides a remarkable fit to many observations, but there exists a 4-5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

- Thanks to a systematic study, 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 provides a remarkable fit to many observations, but there exists a 4-5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

- Thanks to a systematic study, 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).

- The S_8 anomaly can be explained by a 2-body Decaying Dark Matter (DDM) , which has many interesting implications for model building, the Xenon-1T excess, etc.

Conclusions

- ΛCDM provides a remarkable fit to many observations, but there exists a 4-5σ H_0 tension and a 2-3σ S_8 tension. These tensions offer an interesting window to the yet unknown dark sector.

- Thanks to a systematic study, 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.

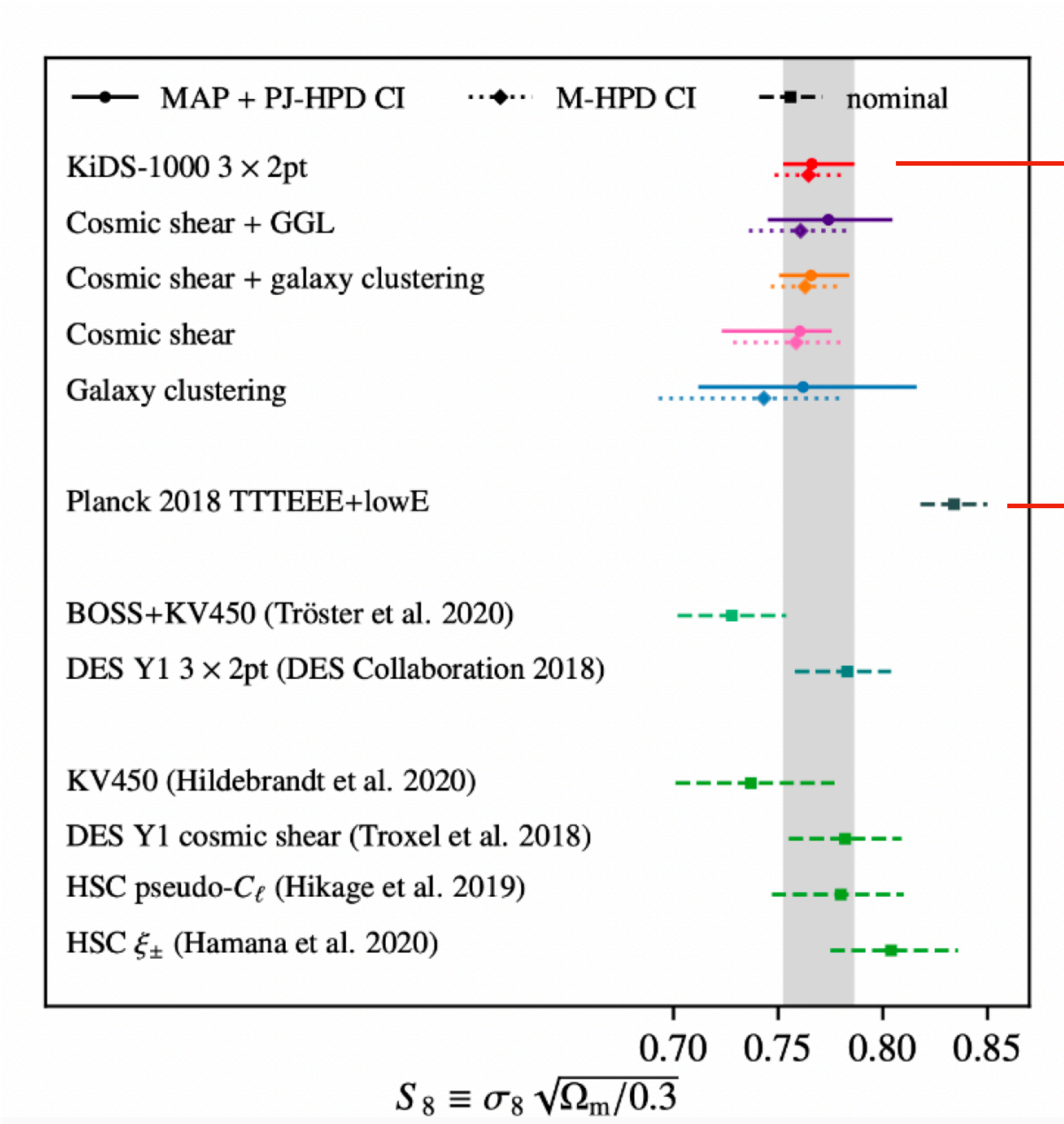
- None of these successful models is able to relieve the S_8 tension. However, resolutions of these tensions might lie in different sectors ($H_0 \longleftrightarrow$ new background contribution, $S_8 \longleftrightarrow$new perturbation properties).

- The S_8 anomaly can be explained by a 2-body Decaying Dark Matter (DDM) , which has many interesting implications for model building, the Xenon-1T excess, etc.

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

BACK-UP SLIDES

The S_8 tension



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

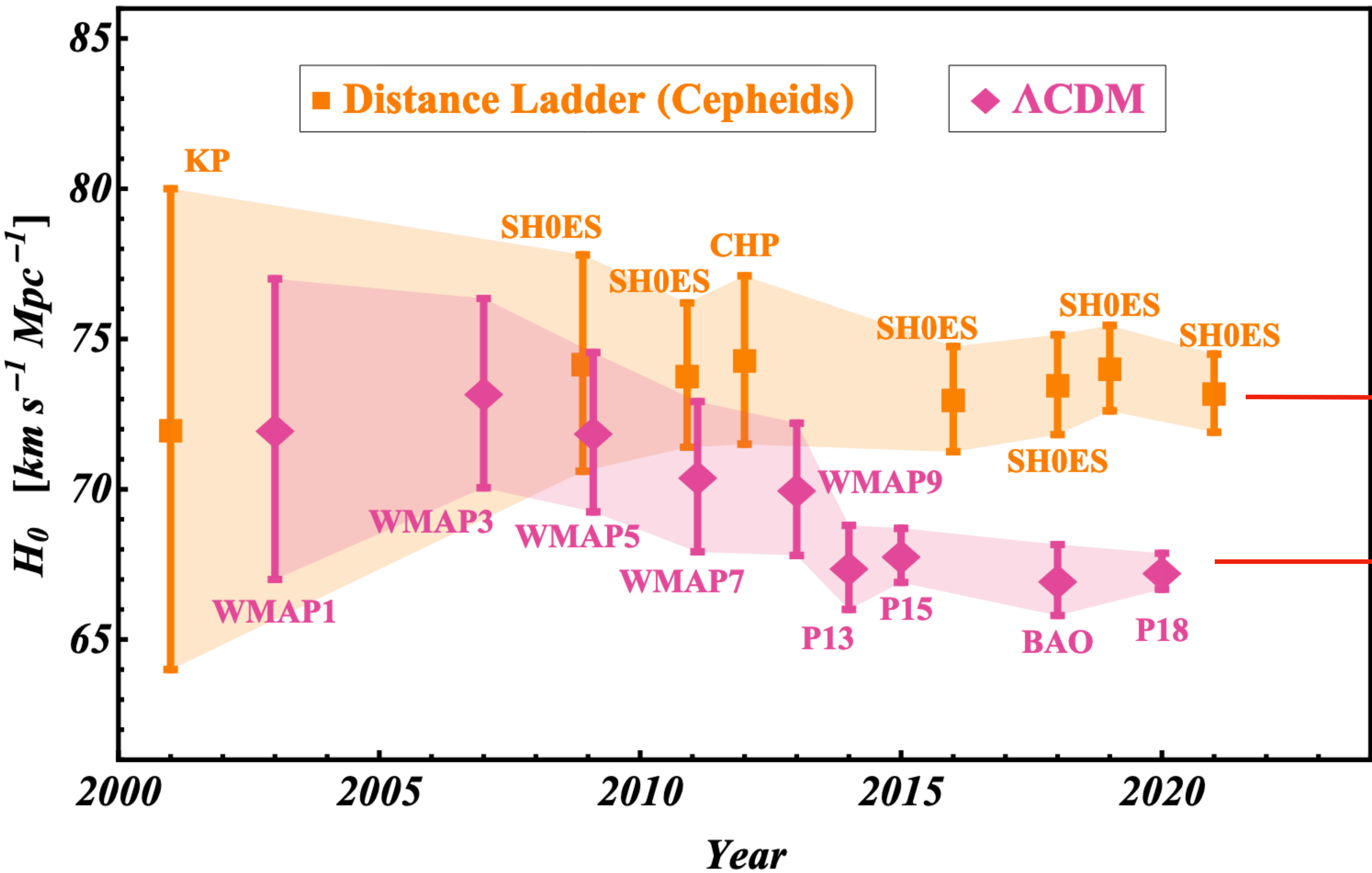
$$S_8 = 0.830 \pm 0.013$$

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

Di Valentino++ 2008.11285

The H_0 tension

Predominantly driven by the Planck and SH0ES collaborations



$H_0 = 73.2 \pm 1.3$*

$H_0 = 67.27 \pm 0.6$

$\Longrightarrow$ 4.1σ tension

Perivolaropoulos&Skara 2105.05208

*Units of km/s/Mpc are always assumed

H_0 Olympics: testing against other datasets

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

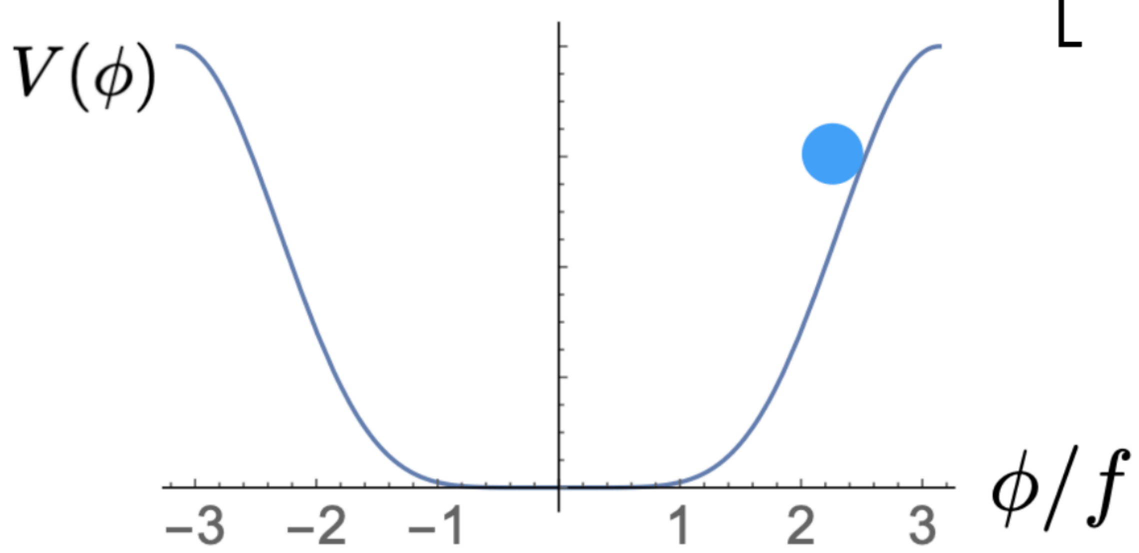
⟶ No significant changes (*notable exceptions are EDE and NEDE*)

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

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



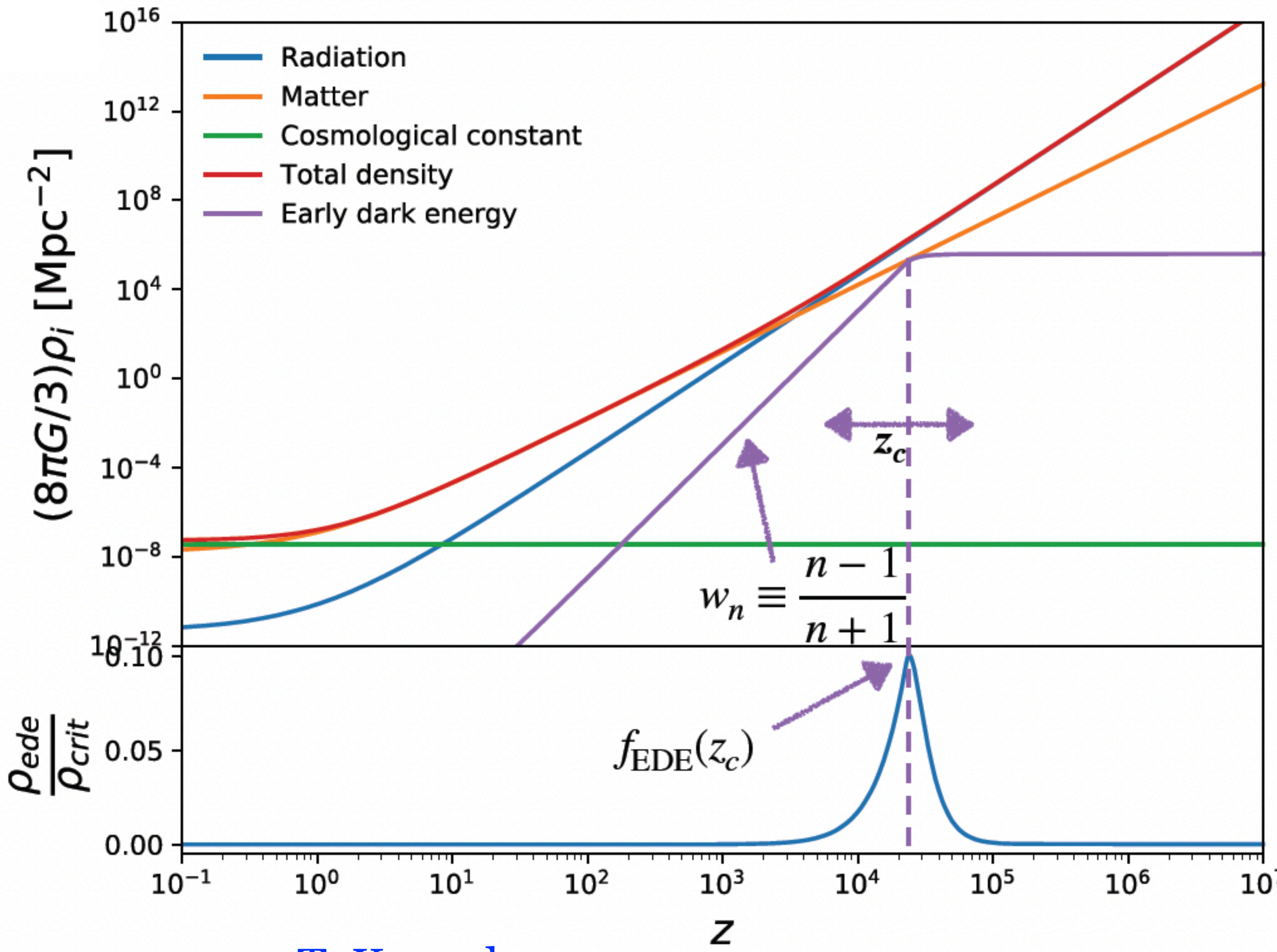
Scalar field initially frozen, then dilutes away equal or faster than radiation

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

+ perturbed linear eqs.

The model is fully specified by

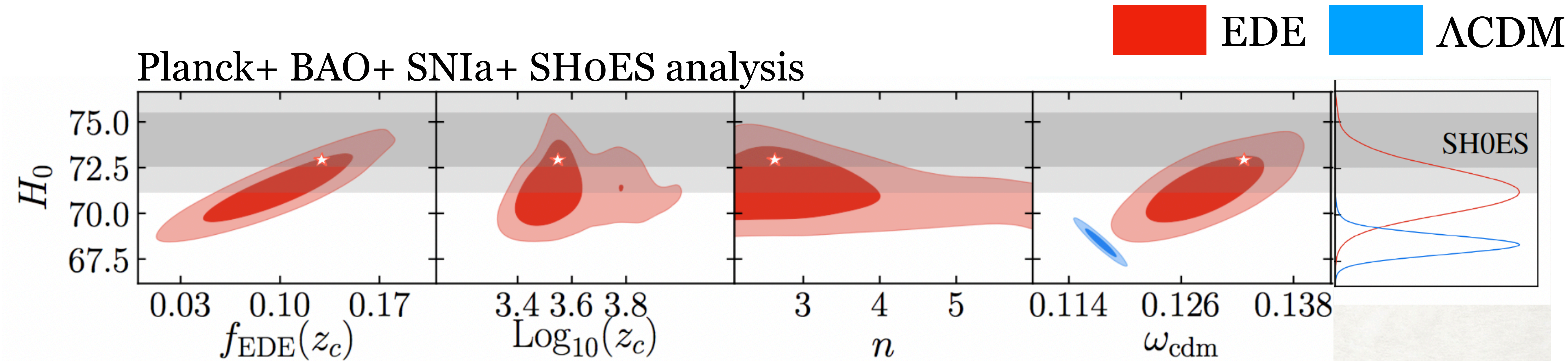
$$\{f_{\rm EDE}(z_c),\ z_c,\ n,\ \phi_i\}$$



T. Karwal

Early Dark Energy

Early Dark Energy can resolve the H_0 tension if $f_{\rm EDE}(z_c) \sim 10\,\%$ 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 $\omega_{\rm cdm} = \Omega_{\rm cdm} h^2$, *exacerbates S_8 tension*

   Jedamzik++ 2010.04158.

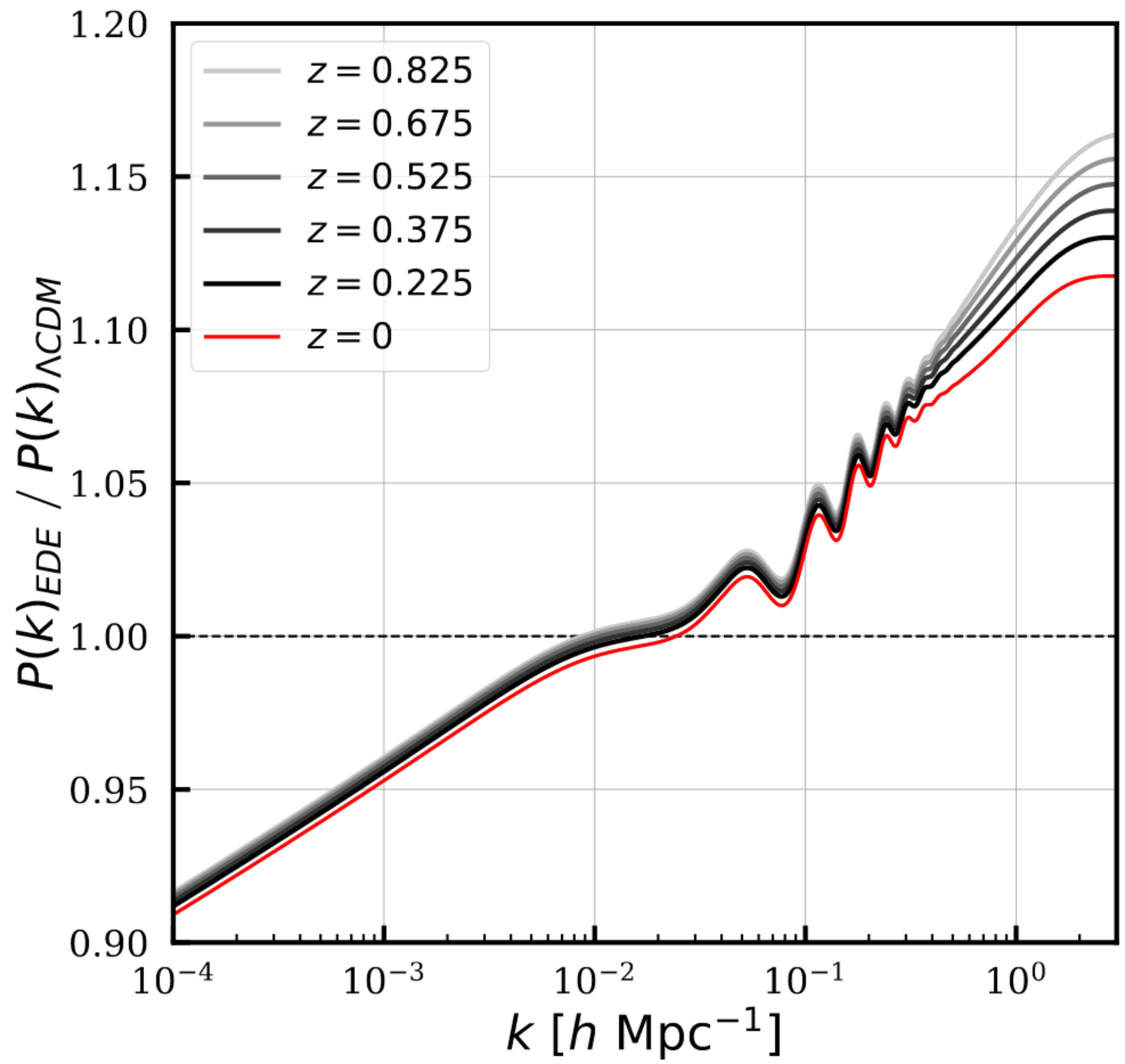
Is EDE solution ruled out?

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

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



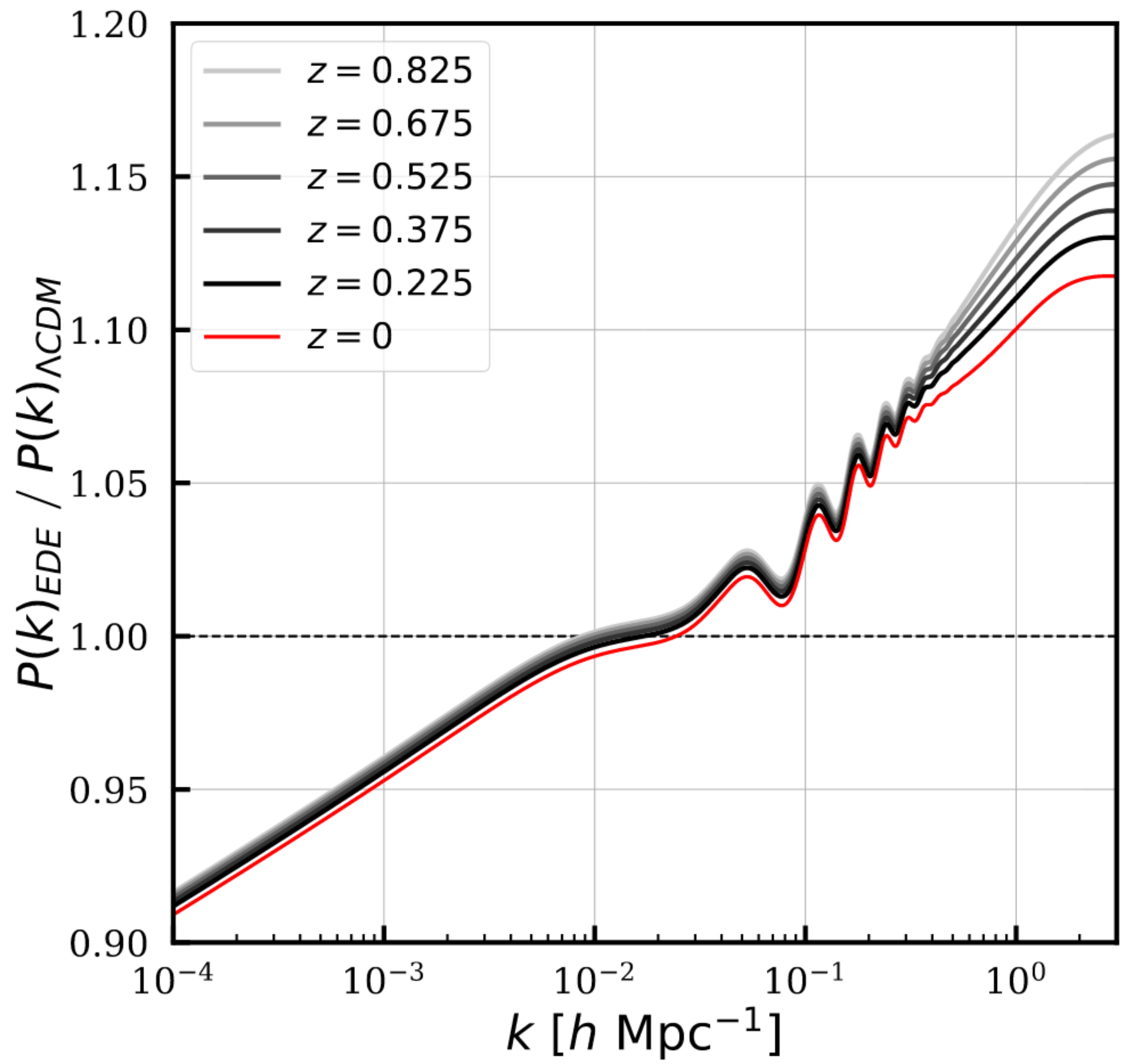
Hill++ 2003.07355

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

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?

Strong χ^2 degeneracy in Planck between ΛCDM and EDE :
Once $f_{\rm EDE} \to 0$, parameters z_c and $\phi_{\rm i}$ become irrelevant, so posteriors are naturally weighted towards ΛCDM

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

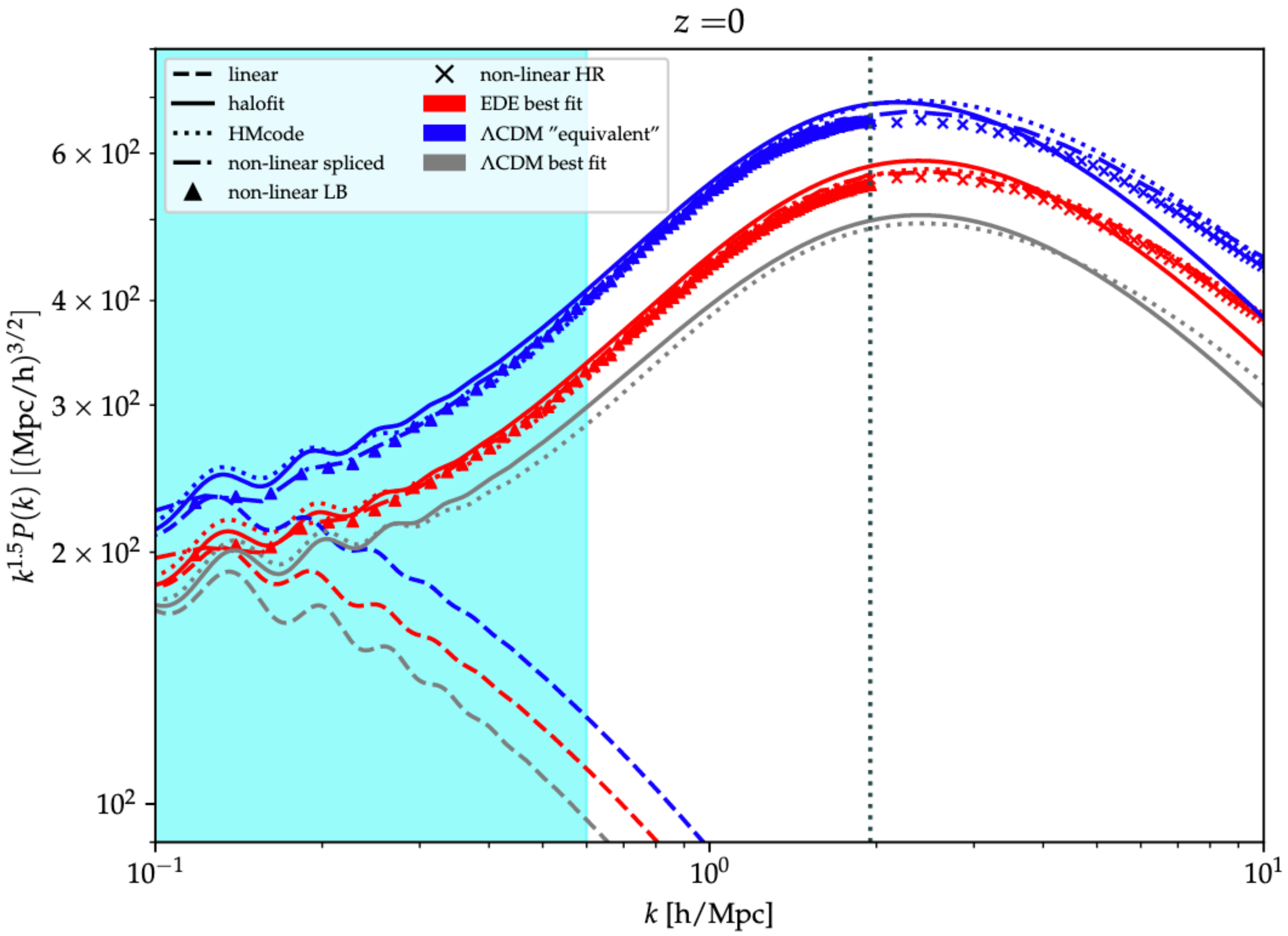
Within 1pEDE, we get a 2σ detection of EDE from *Planck data alone*

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

Murgia, GFA, Poulin 2107.10291

Answer: no, EDE solution is still robust

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



Important cross-check:

EDE non-linear P(k) from standard semi-analytical algorithms agrees well with results from N-body simulations

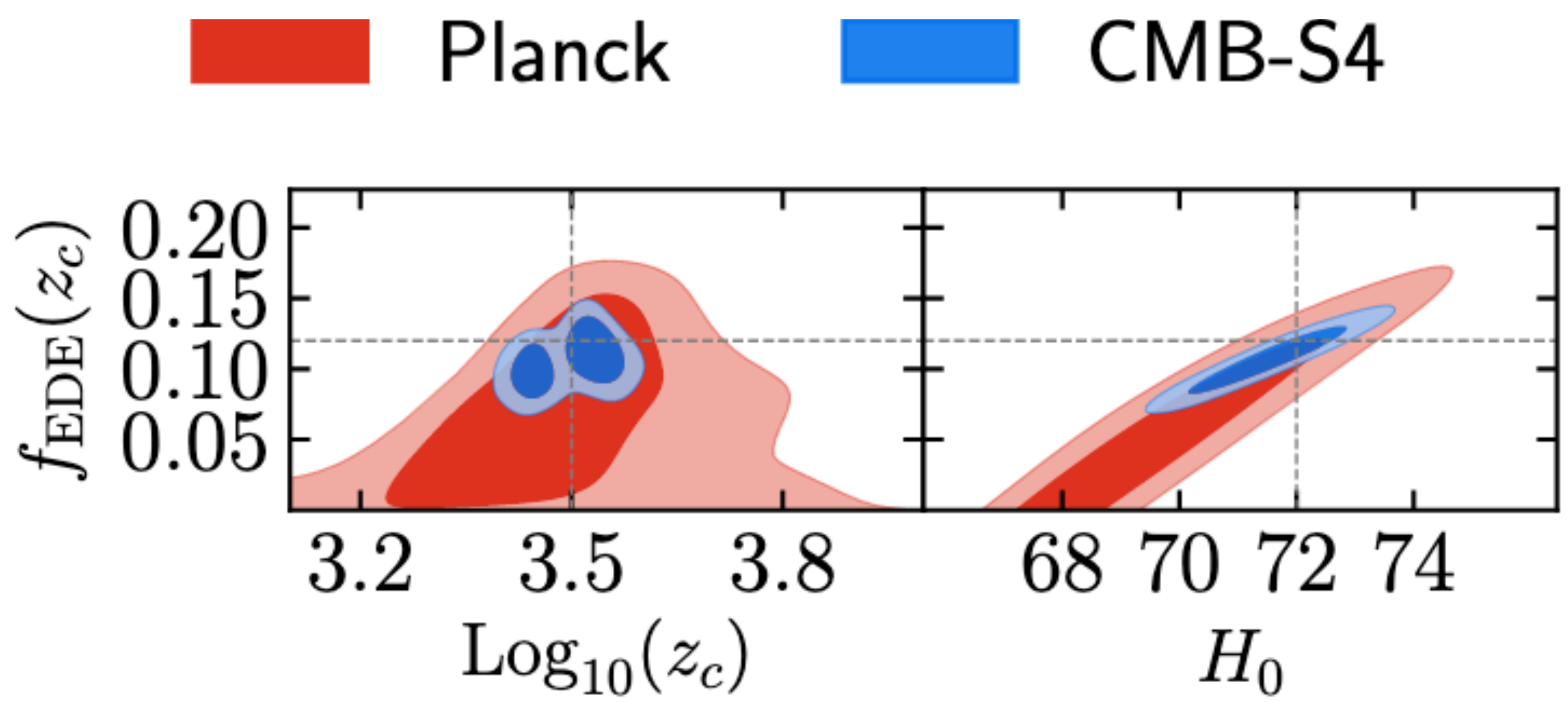
1pEDE tested against Planck+BAO+SNIa+SH0Es and WL data from KiDS/Viking+DES: S_8 tension persists, but fit is not significantly degraded wrt ΛCDM, and solution to the H_0 tension survives

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

Murgia, GFA, Poulin 2107.10291

Prospects for Early Dark Energy

Future CMB experiments (i.e. CMB-S4) will be able to unambiguously detect EDE



Smith++ 1908.06995

Other current CMB experiments like ACT are already showing a 3σ detection of EDE!

Hill++ 2109.04451

Poulin++ 2109.06229

Decaying dark matter

- Dark matter (DM) is assumed to be perfectly stable in ΛCDM

Can we test this hypothesis?

- DM Decays to SM particles ⟶ very constrained

From $\mathbf{e.m.\ impact}$ on CMB : $\Gamma^{-1} \gtrsim 10^8$ Gyr Poulin++ 1610.10051

- DM decays to **massless** Dark Radiation ⟶ less constrained, but more model-independent

From $\mathbf{grav.\ impact}$ on CMB : $\Gamma^{-1} \gtrsim 10^2$ Gyr Audren++ 1407.2418
Poulin++ 1606.02073

- What about massive products?

Evolution of perturbations: full treatment

- Effects on $P_m(k)$ and C_ℓ ? Track linear perts. for the particles species involved in the decay: δ_i, θ_i and σ_i for $\mathrm{i} = \mathrm{dm}, \mathrm{dr}, \mathrm{wdm}$

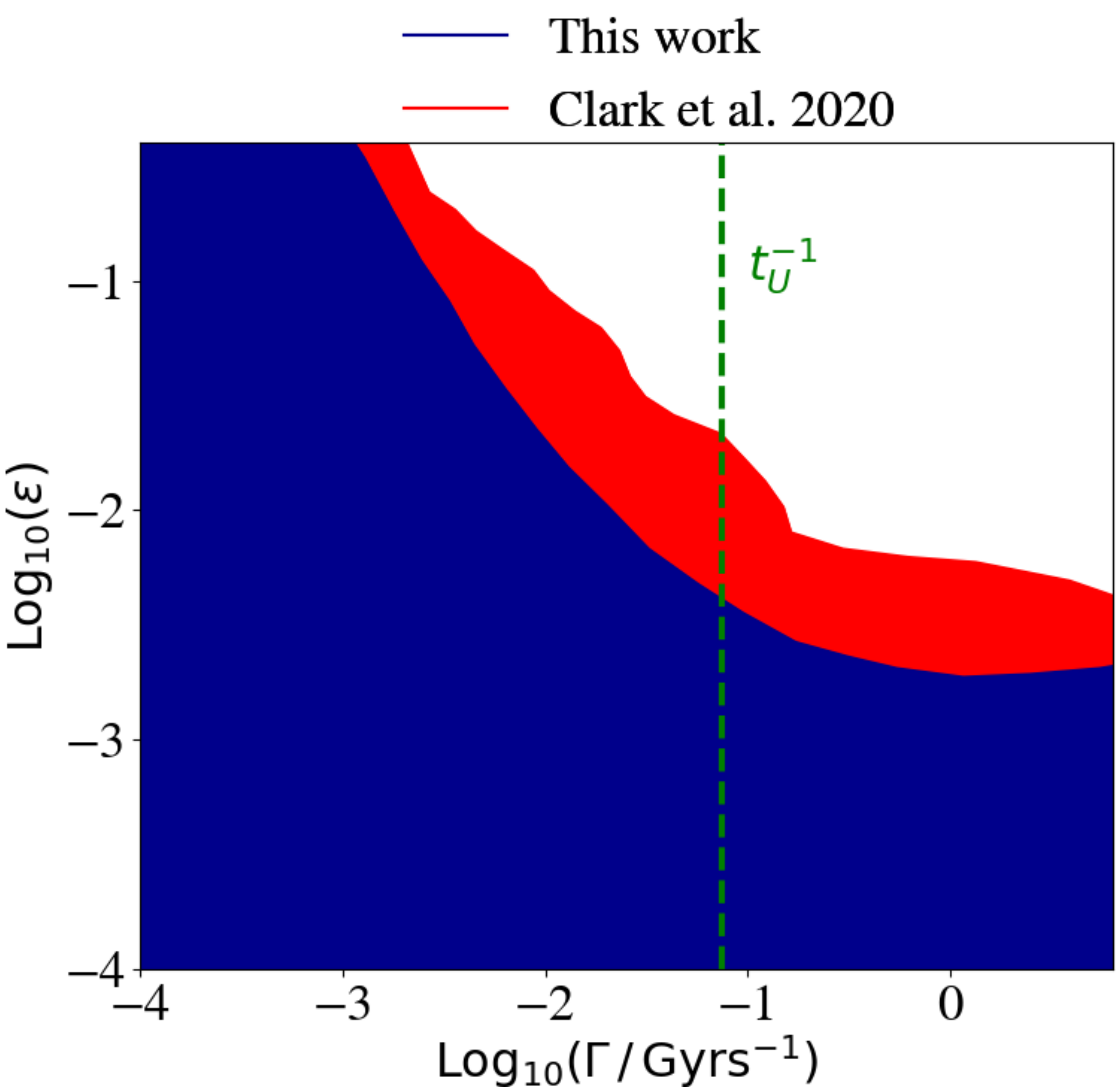
- Boltzmann hierarchy of eqs. Dictate the evolution of the p.s.d. multipoles $\Delta f_\ell(q, k, \tau)$

  ✦ DM and DR treatments are easy, momentum d.o.f. are integrated out

  ✦ For WDM, one needs to follow the evolution of the full p.s.d.
  Computationally expensive ⟶ $\mathcal{O}(10^8)$ ODEs to solve!

General constraints on the 2-body DM decay

Planck+BAO+SNIa analysis



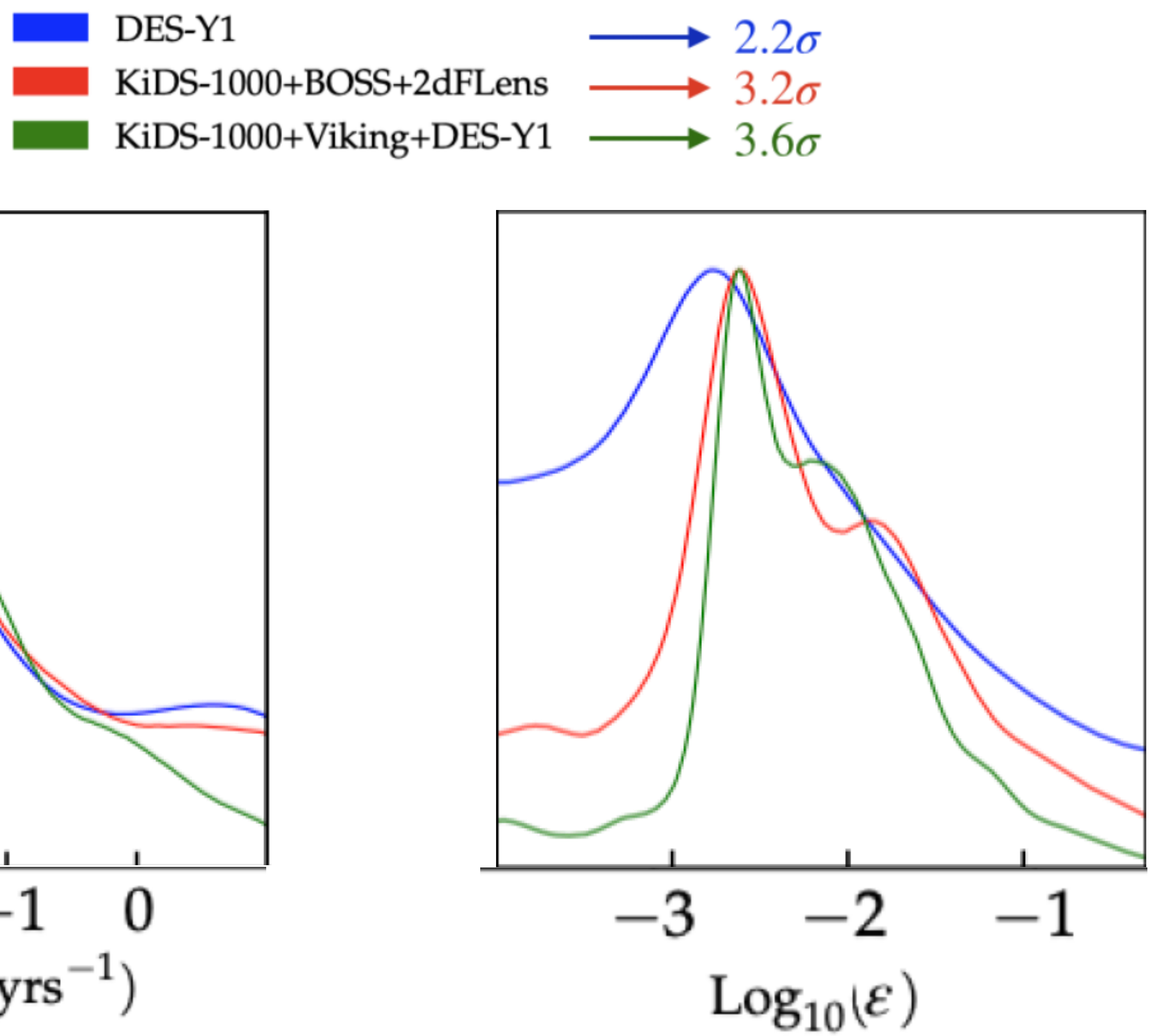
Strong negative correlation between ε and Γ

Constraints up to 1 order of magnitude stronger than previous literature

GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension

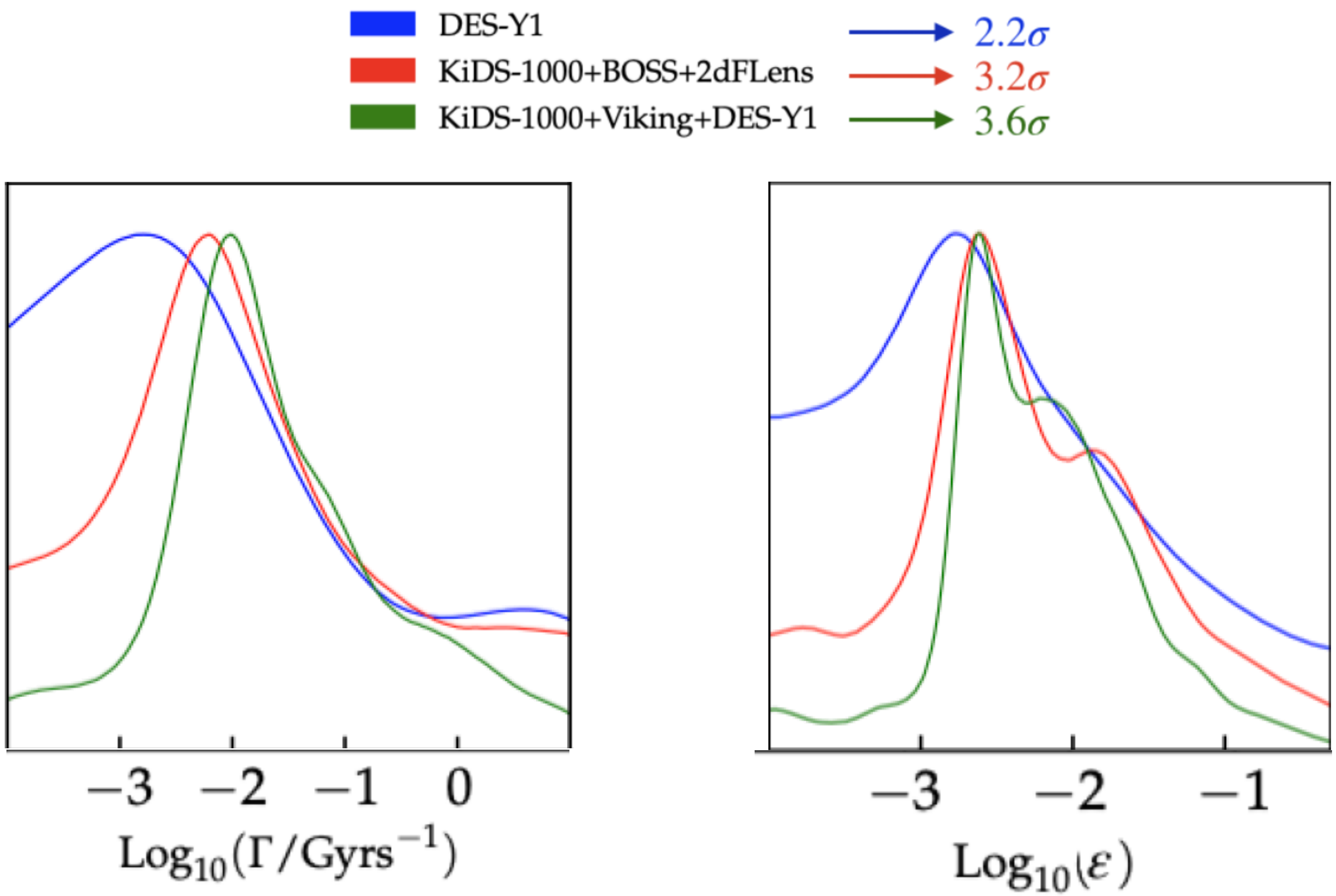
The level of detection depends on the level of tension with ΛCDM



GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension

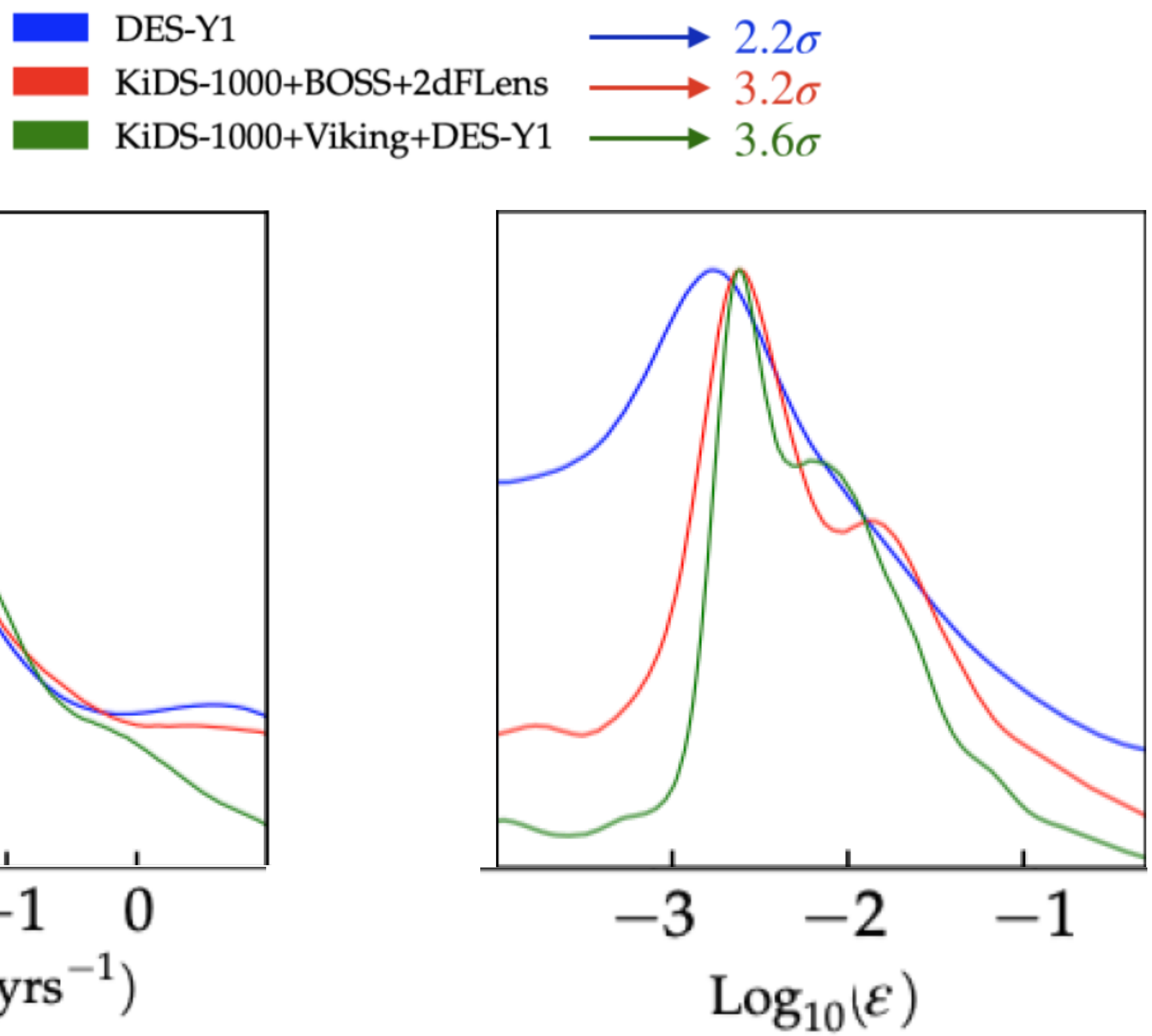
The level of detection depends on the level of tension with ΛCDM



GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension

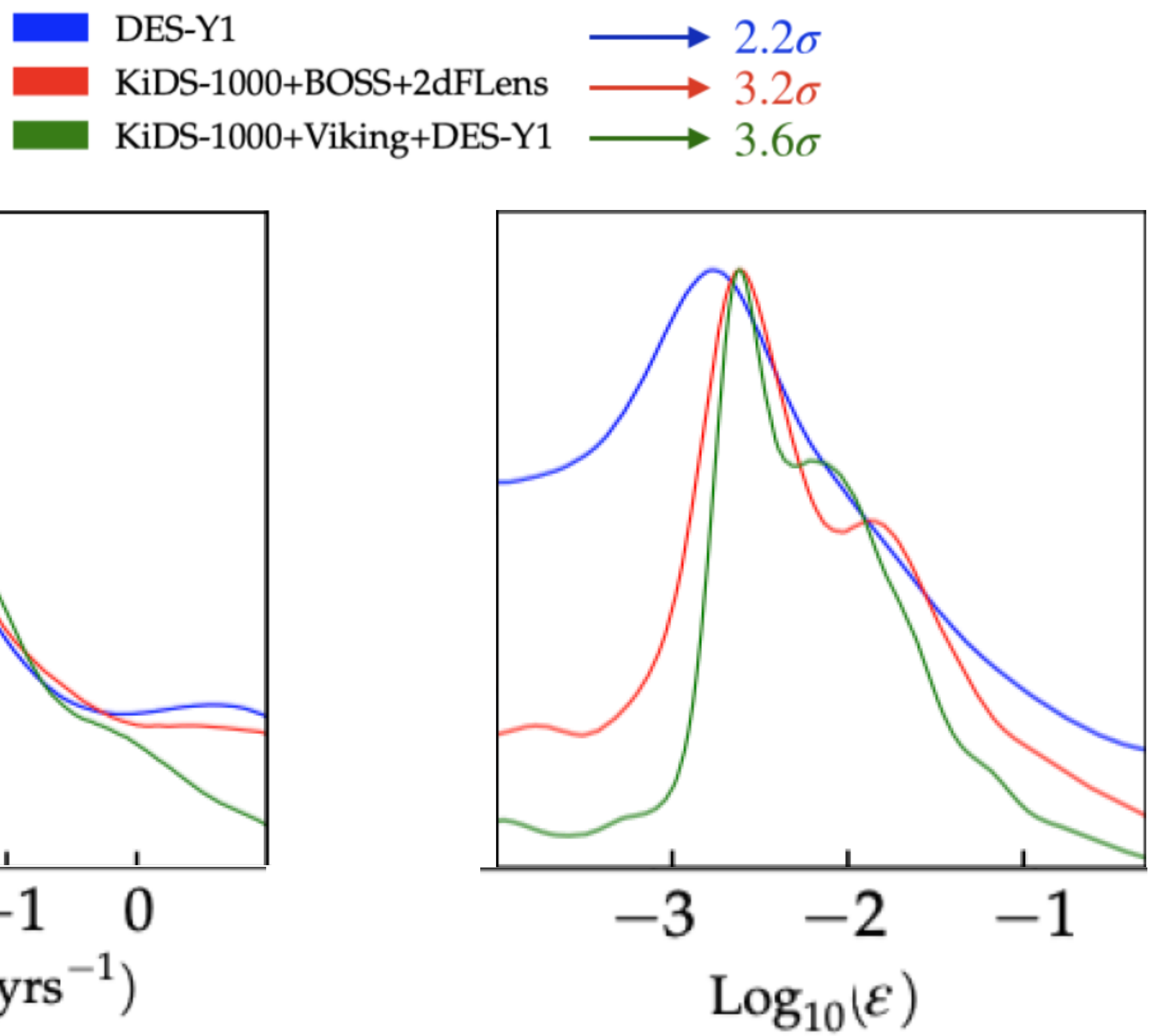
The level of detection depends on the level of tension with ΛCDM



GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension

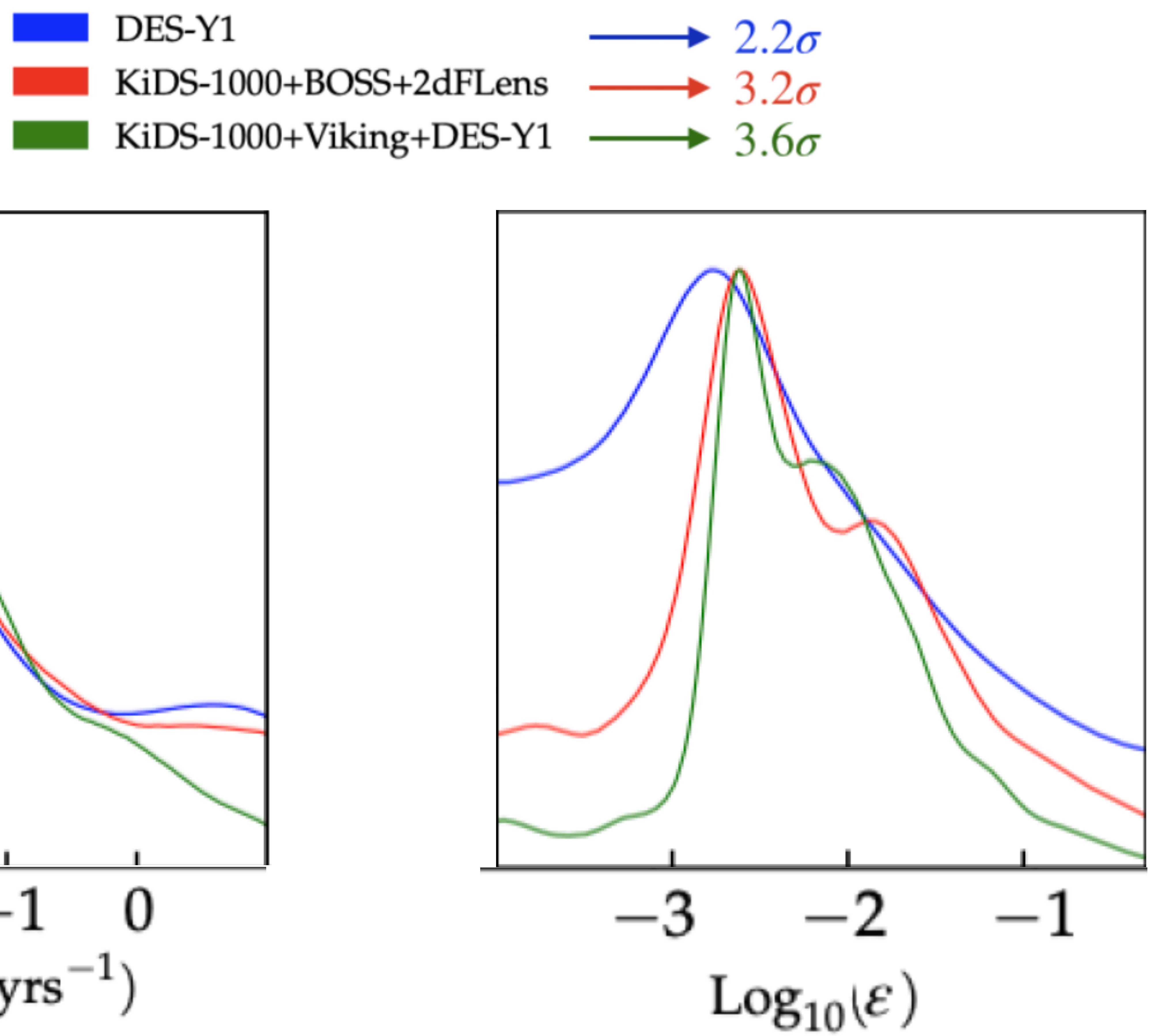
The level of detection depends on the level of tension with ΛCDM



GFA, Murgia, Poulin 2008.09615

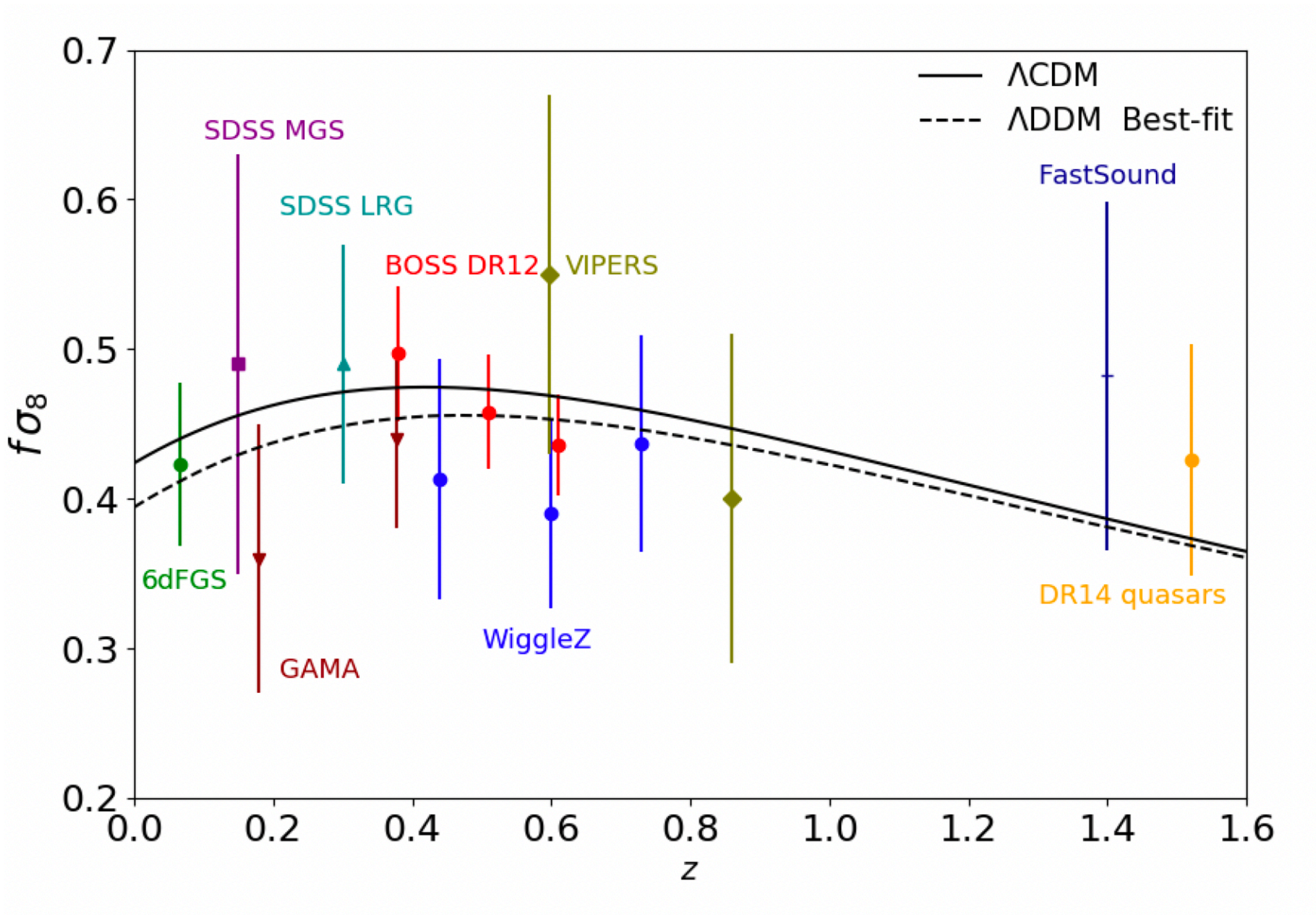
Resolution to the S_8 tension

The level of detection depends on the level of tension with ΛCDM



GFA, Murgia, Poulin 2008.09615

Prospects for the 2-body DM decay



Accurate measurements of $f\sigma_8$ at $0 \lesssim z \lesssim 1$ will further test the 2-body decay

Next goal: Predict non-linear matter power spectrum (using either N-body simulations or EFT of LSS)