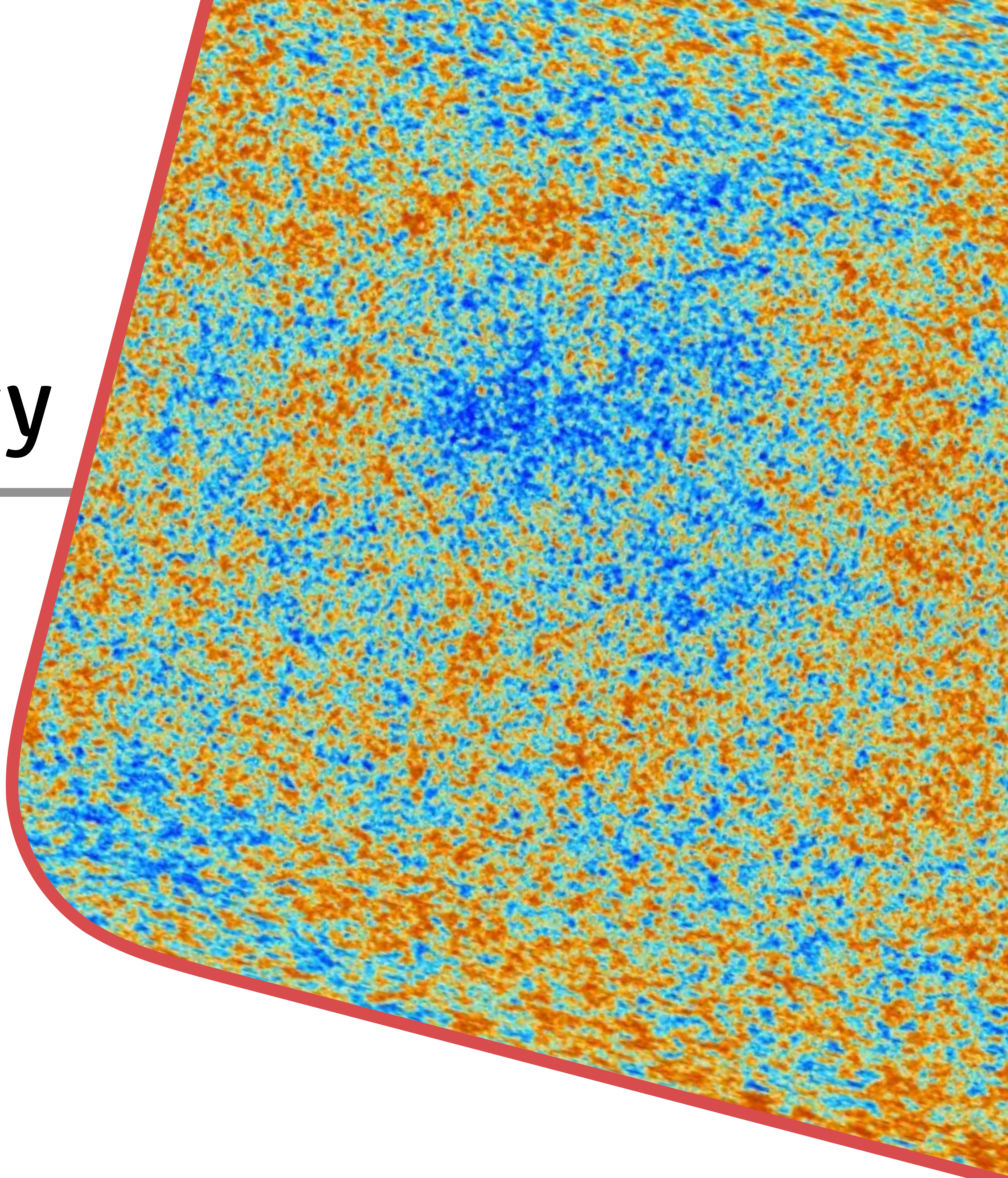
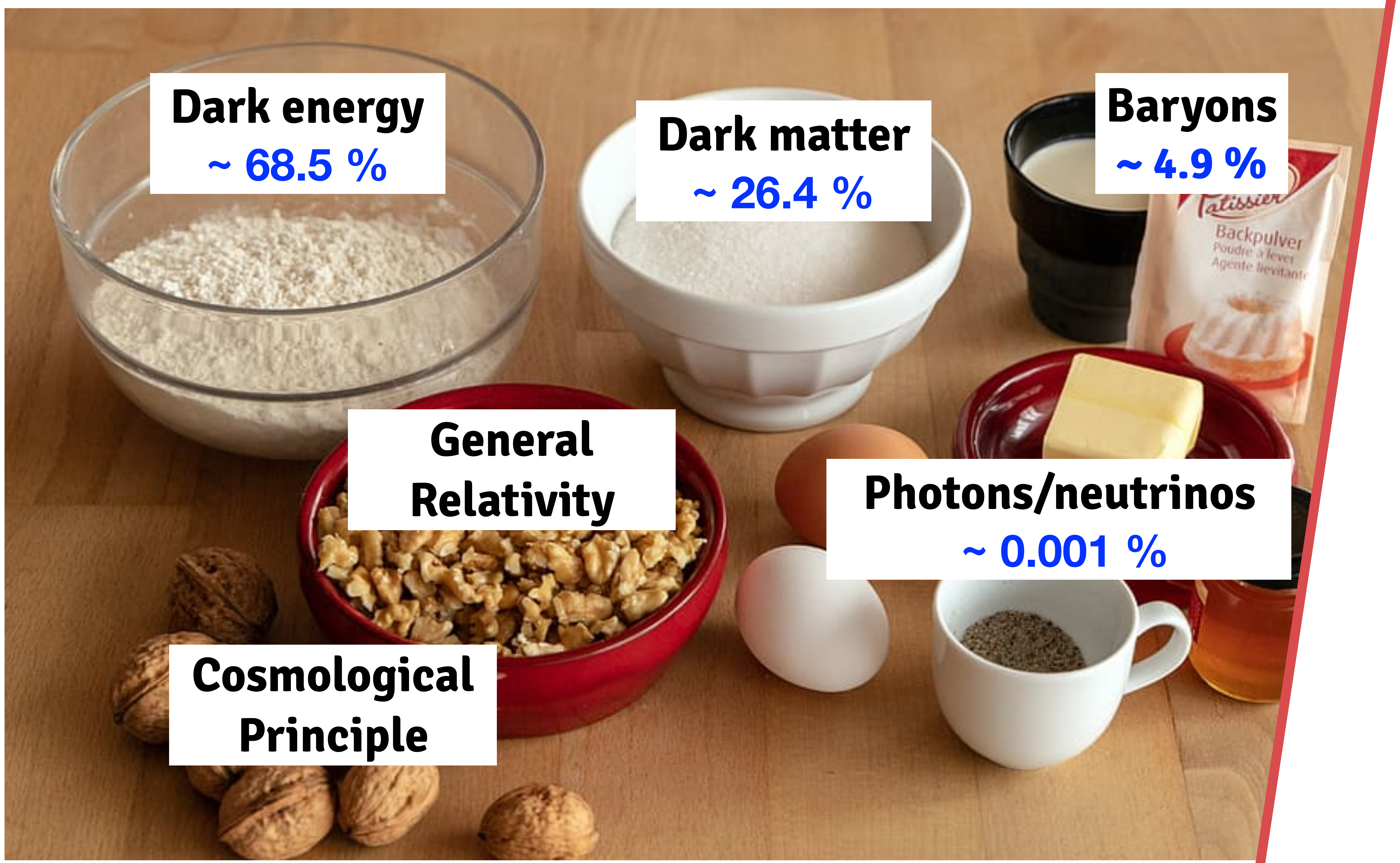
Gravitational **signatures** of **unstable** particles in cosmology

Guillermo Franco Abellán
Laboratoire Univers et Particules de Montpellier



Concordance ΛCDM model of cosmology:



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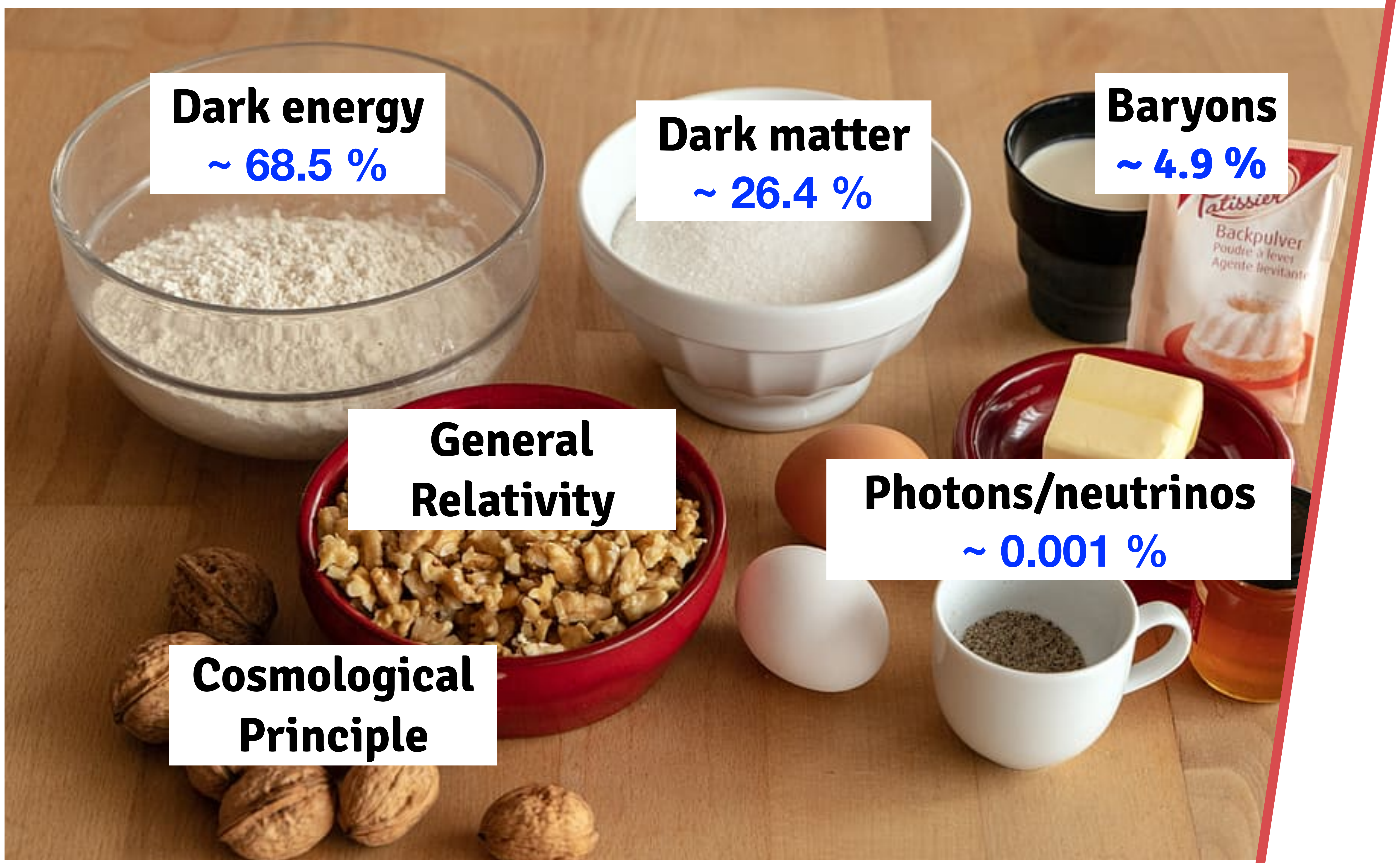
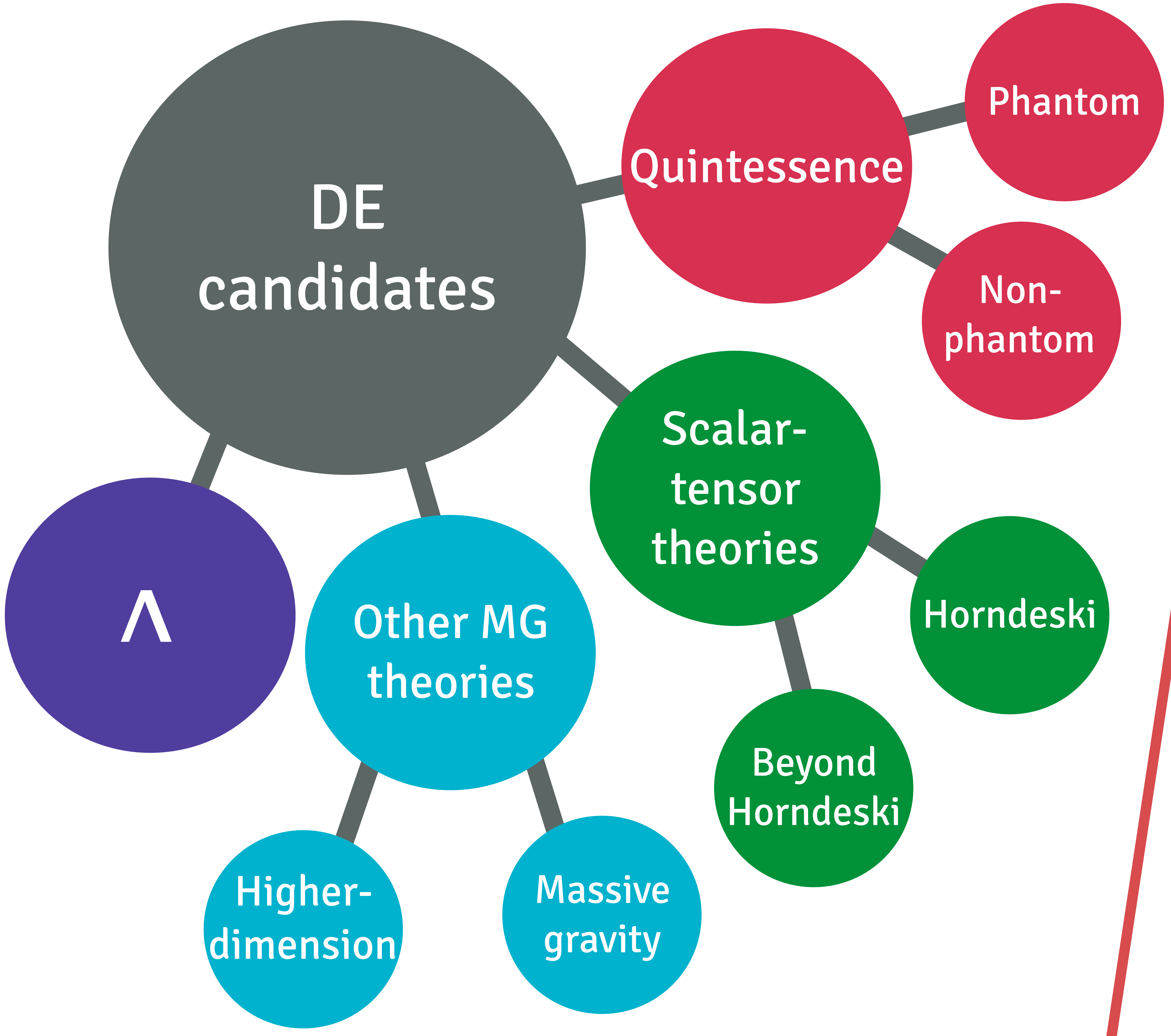


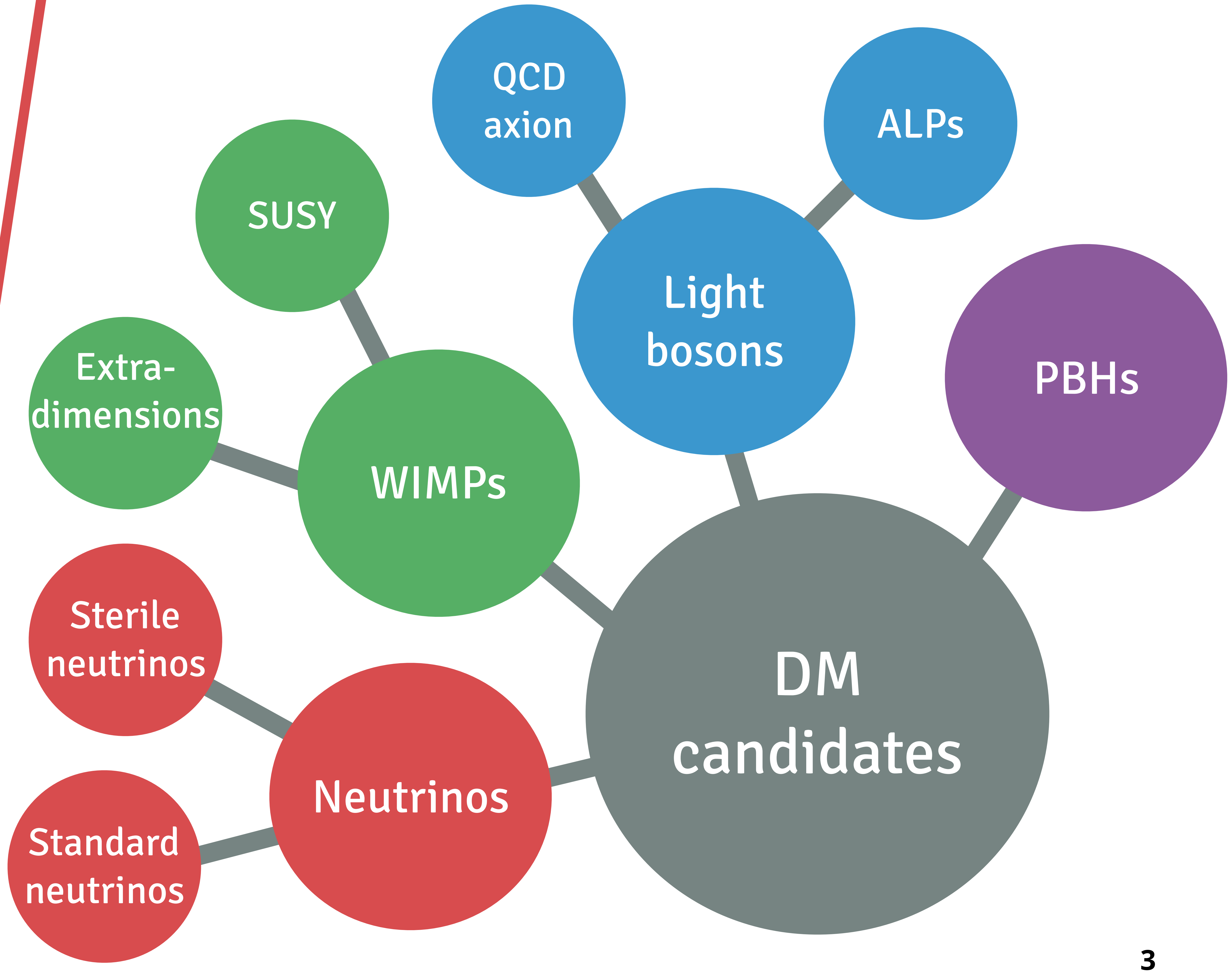
Only 6 free parameters:

ω_c ω_b H_0

A_s n_s τ_{reio}

However, the nature of the **dark sector** remains a **mystery**





In addition, several **discrepancies have emerged** in recent years

- H_0 tension (5σ)

  [Riess+ 21] [Planck 18]

- S_8 tension ($2\text{-}3\sigma$)

  [KiDS 20] [DES 21] [Planck 18]

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Systematics?

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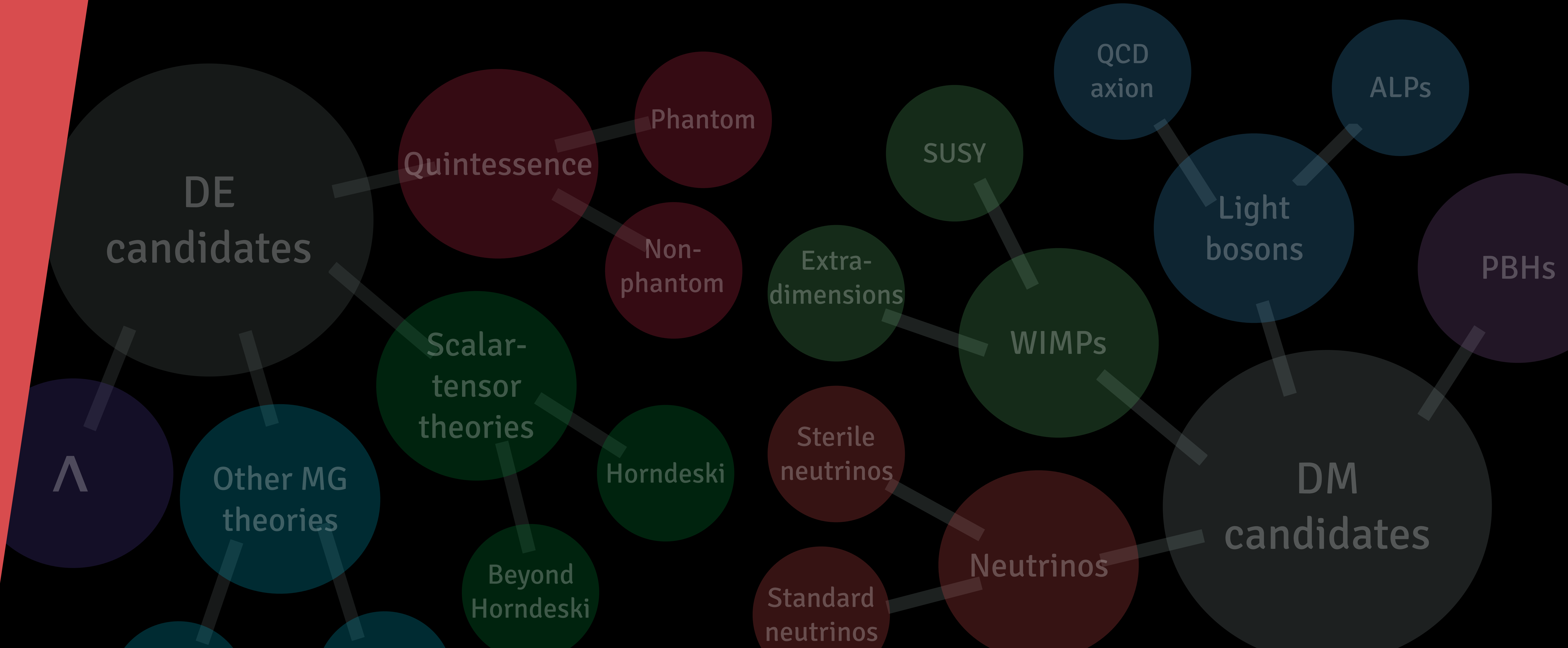
Systematics?

New physics?

Cosmic tensions could **shed some light** on the mysterious dark sector



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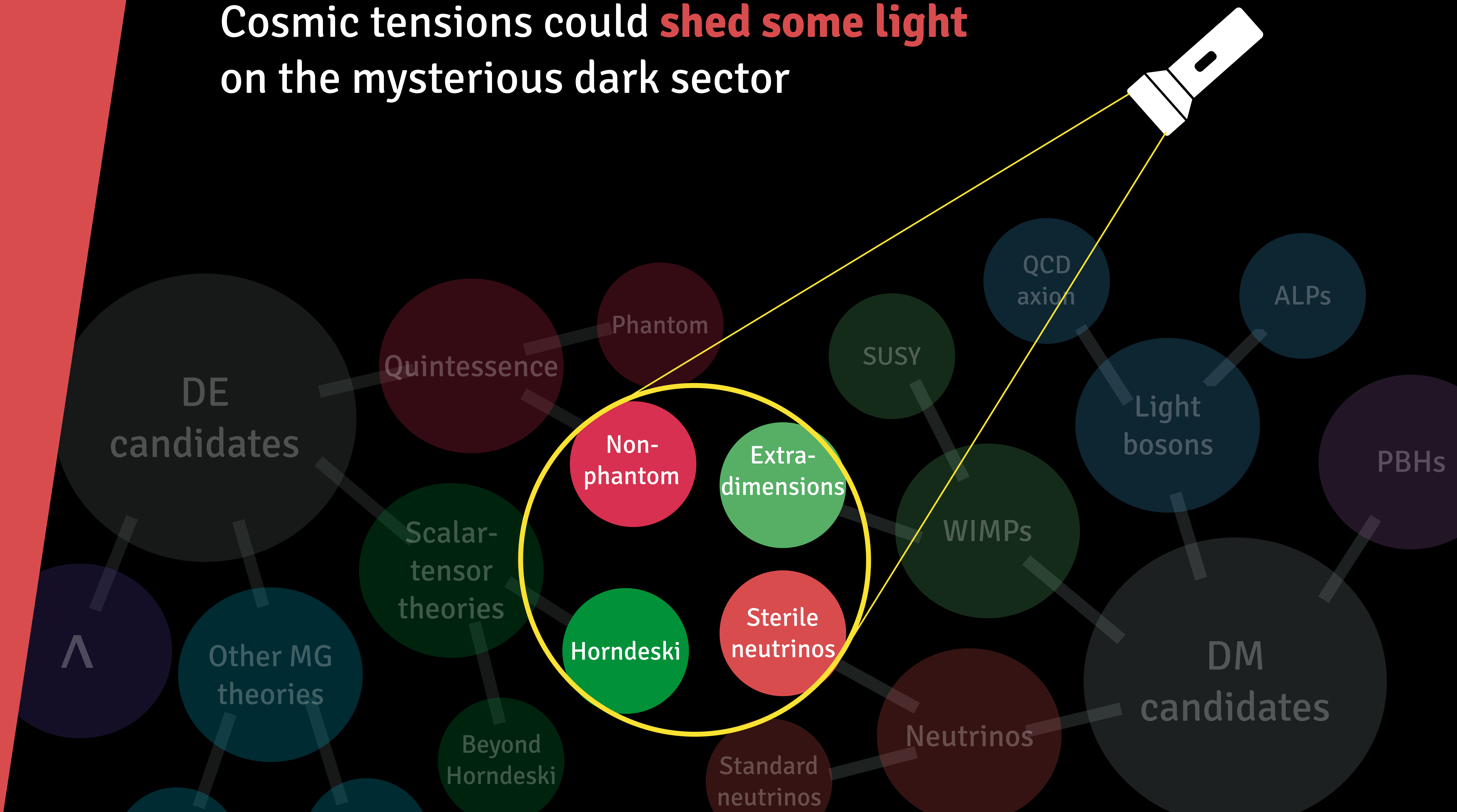
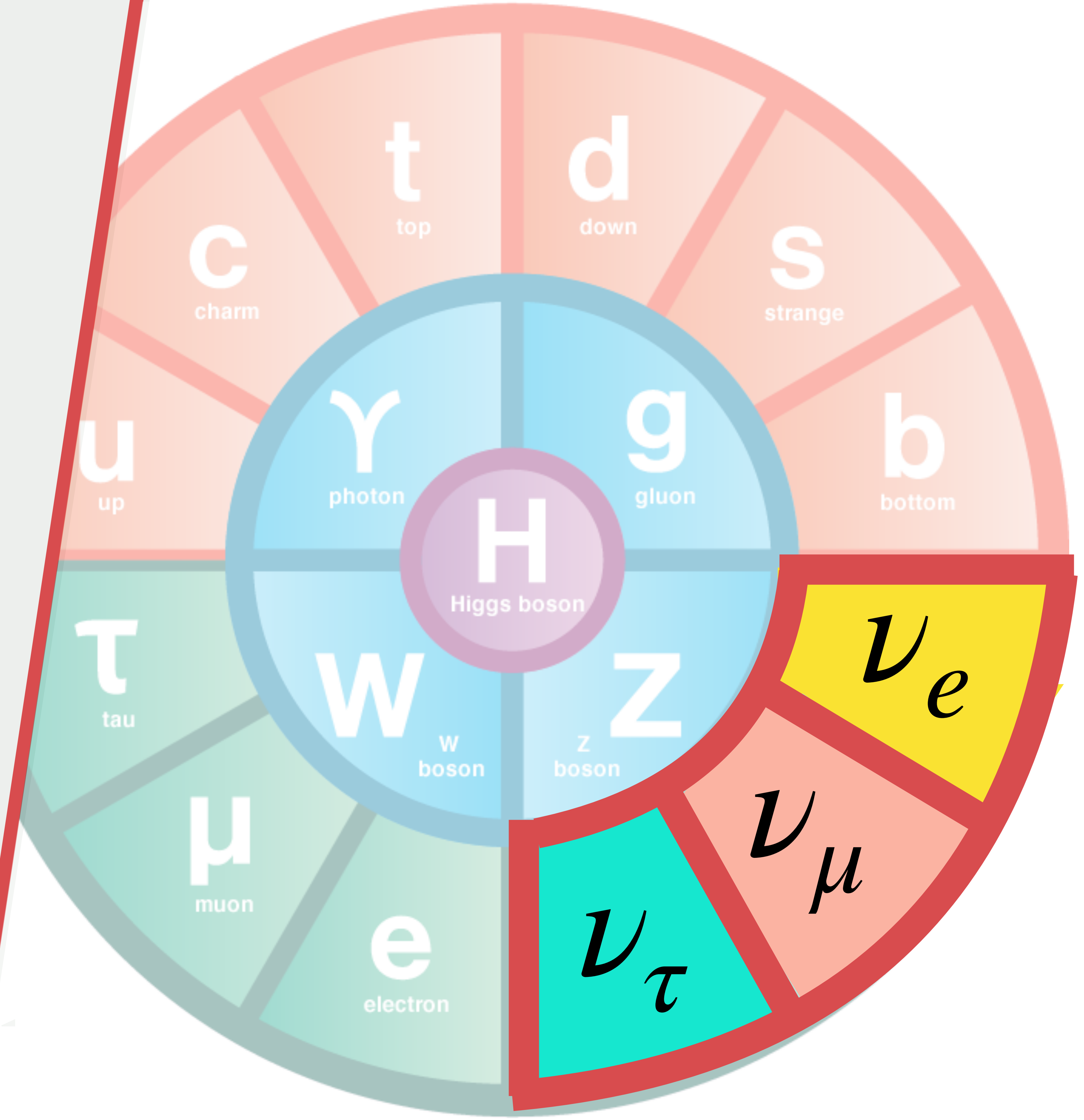


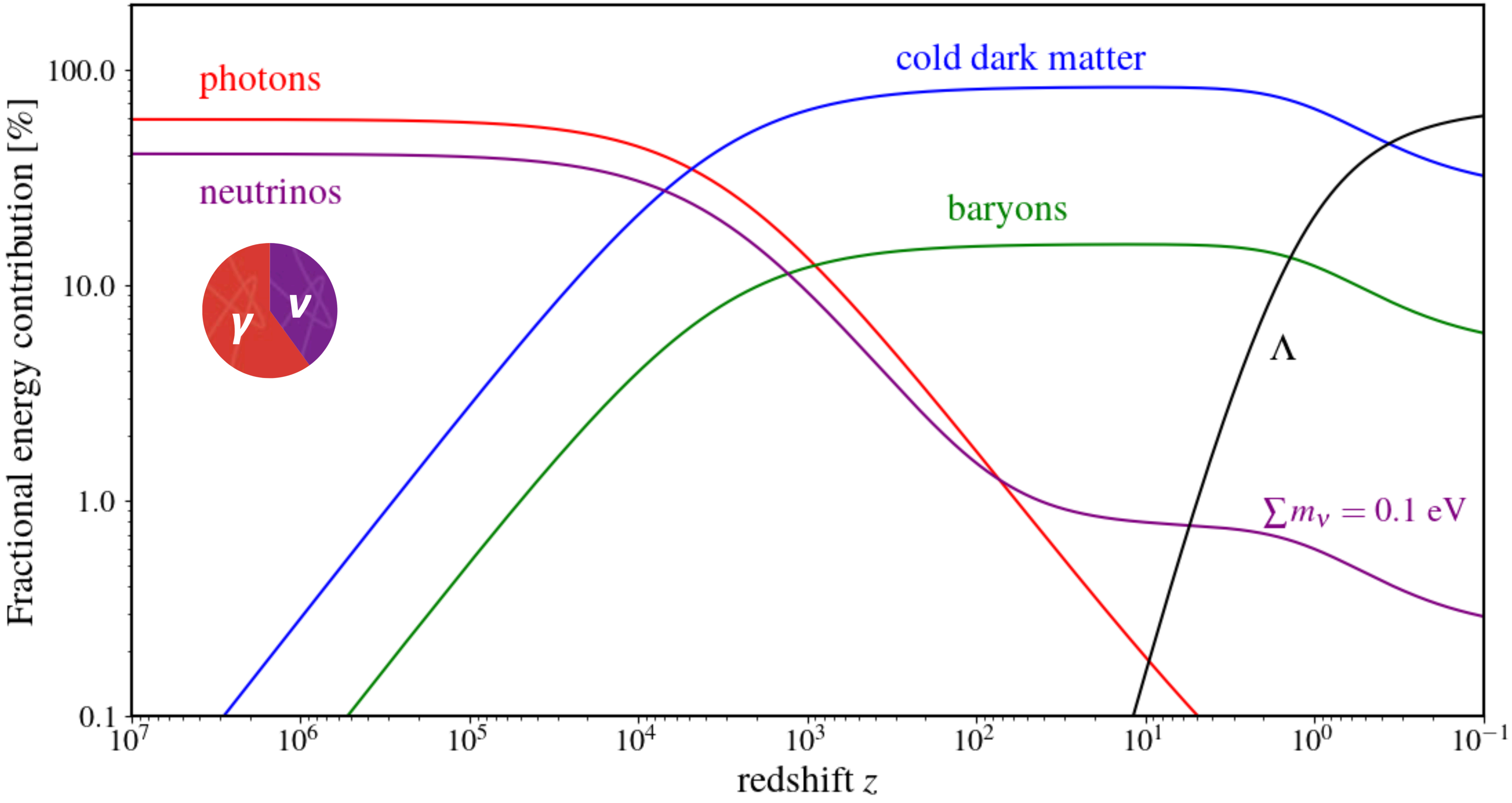
But the **visible sector** is not free of **unknowns**…

The elusive **neutrinos**

- **Lightest** fermions, very weakly-coupled
- Many properties **unknown**
- **Neutrino masses** provide the only certain evidence of physics **beyond the SM**



Neutrinos are always **relevant** for Universe's **energy budget**



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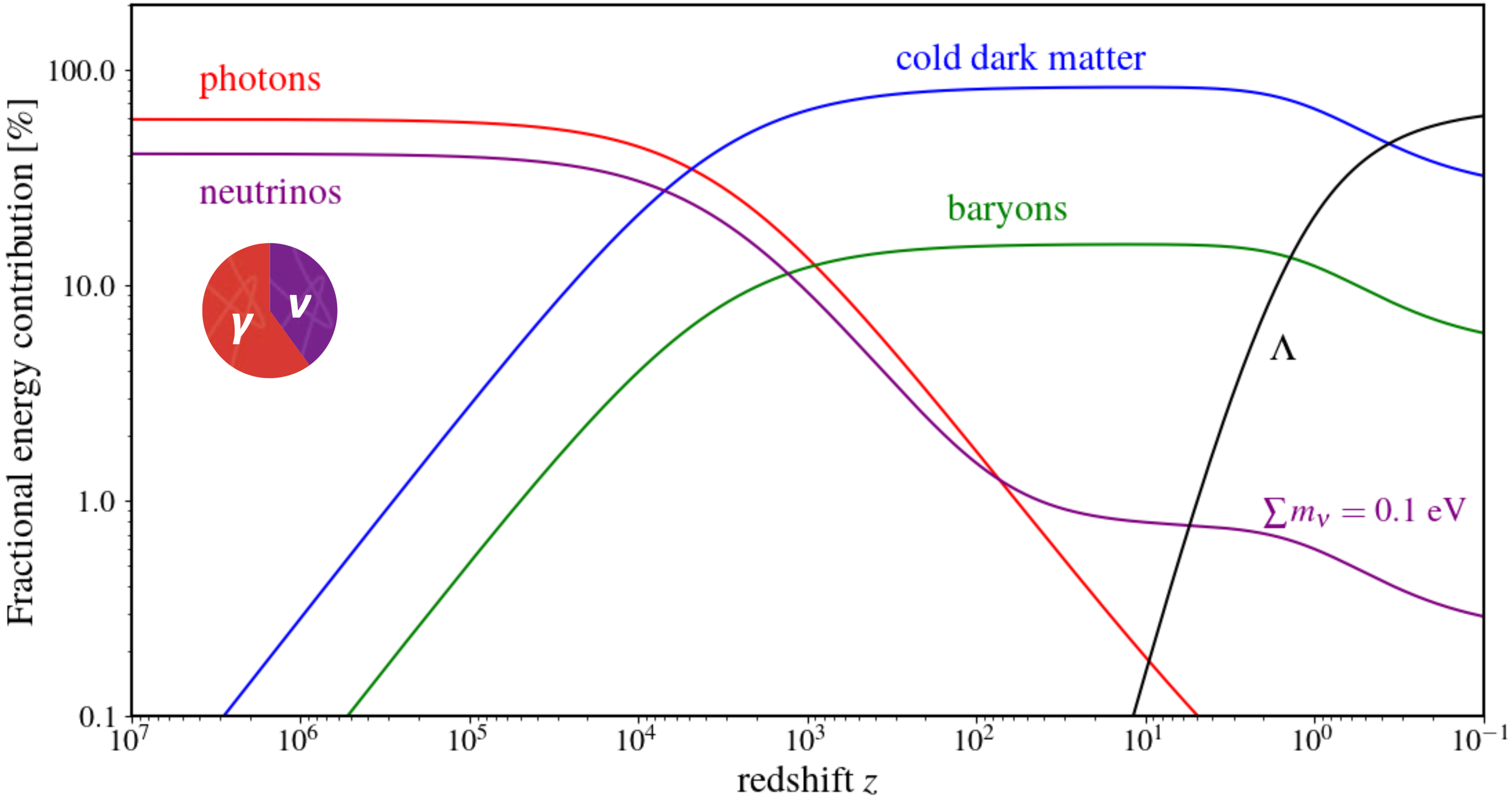


From their impact on **CMB and LSS** observables, we can learn about their **properties**

Main **GOAL** of my work:

Use the very precise **cosmological** data to **constrain new physics** (both in dark and neutrino sector), focusing on **unstable relics**

Part I:

THE H_0 OLYMPICS

A FAIR RANKING OF PROPOSED MODELS

Part II:

DECAYING DARK MATTER

& THE S_8 TENSION

Part III:

DECAYING NEUTRINOS

& THE NEUTRINO MASS BOUNDS

Part I:

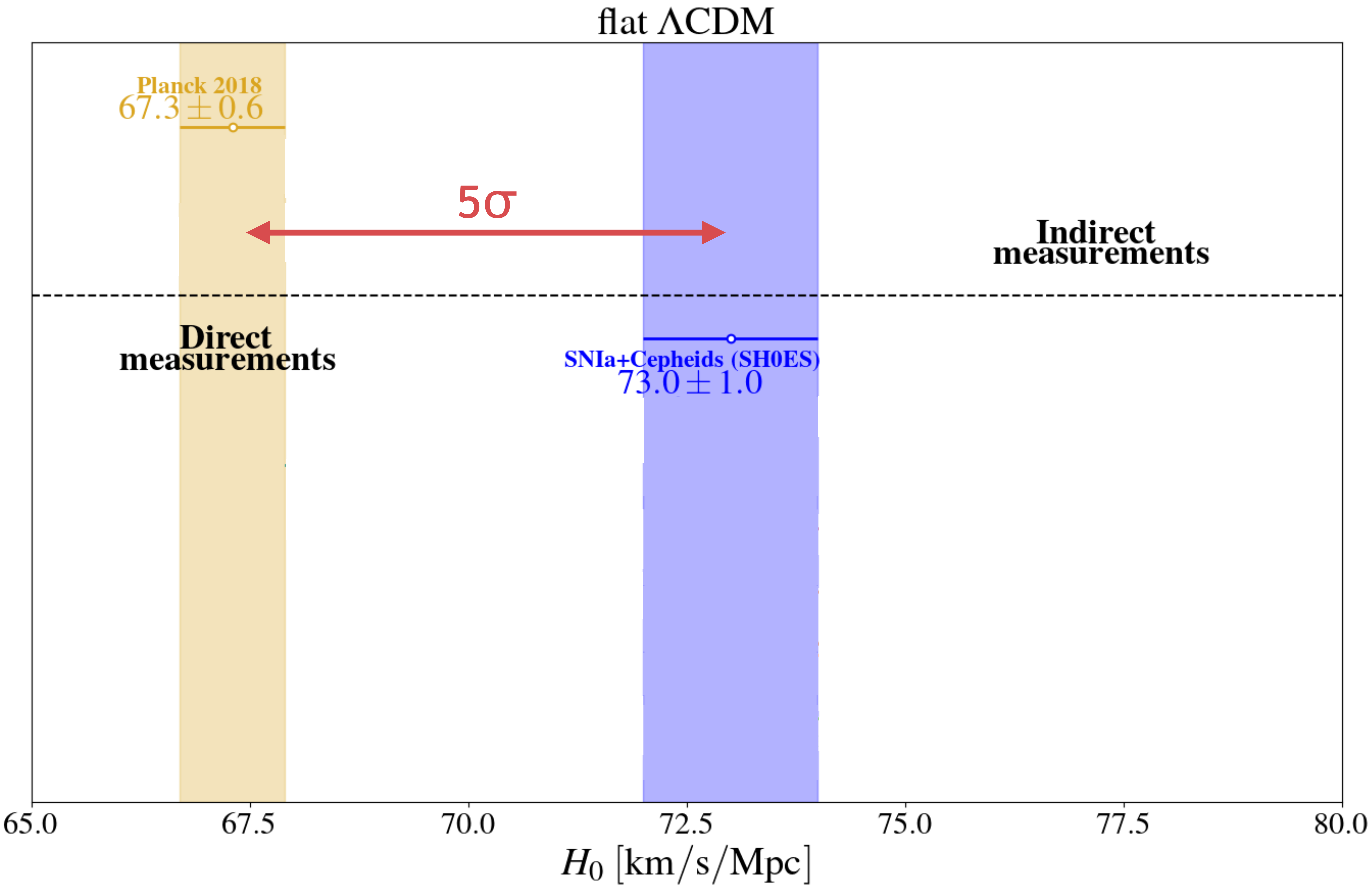
THE H_0 OLYMPICS

A FAIR RANKING OF PROPOSED MODELS

[Schöneberg, GFA, Sánchez, Witte, Poulin, Lesgourgues 2021 arXiv:2107.10291]

[Image by Sandbox studio - Symmetry]

The Hubble tension in a nutshell



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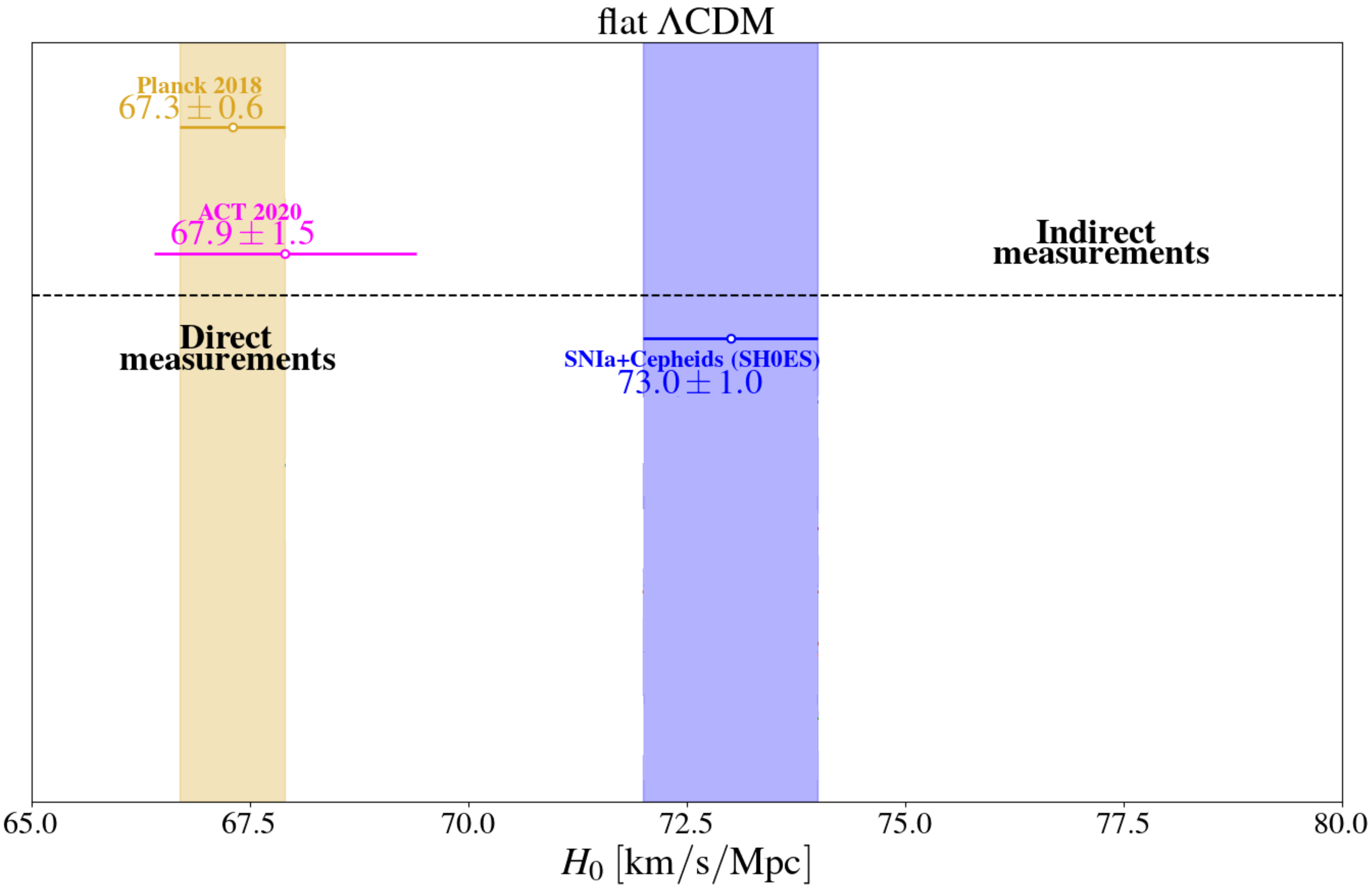

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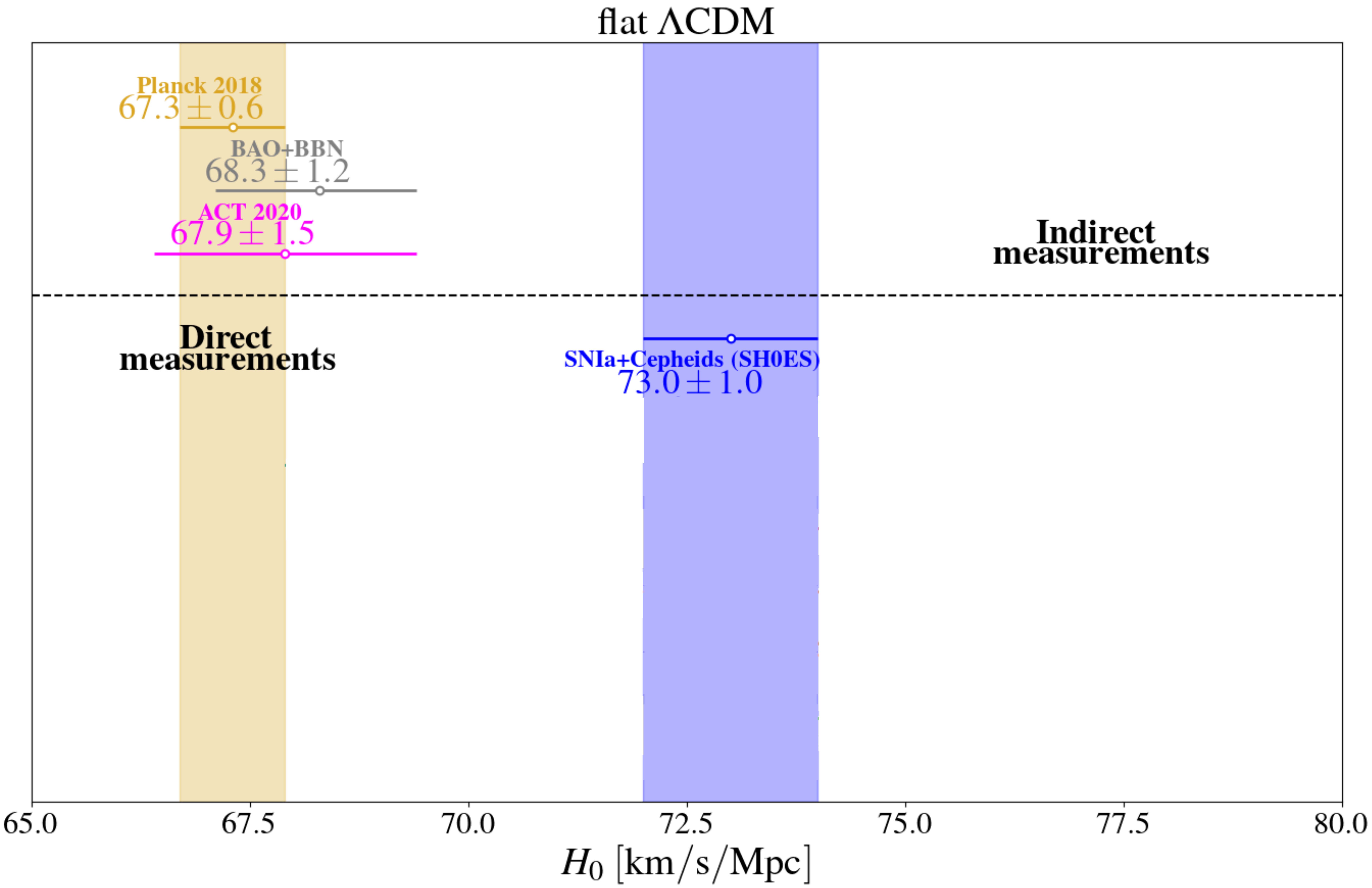

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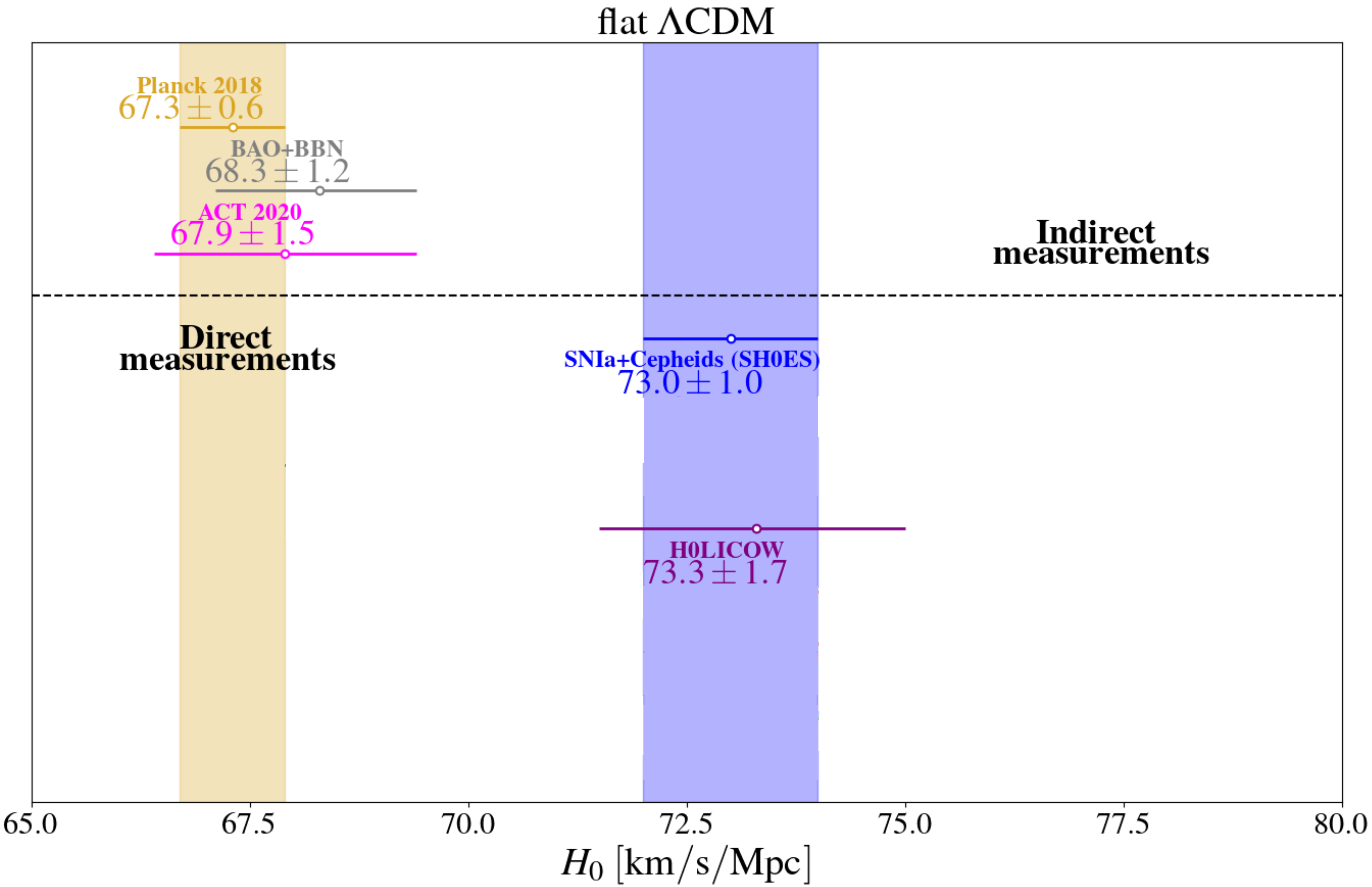

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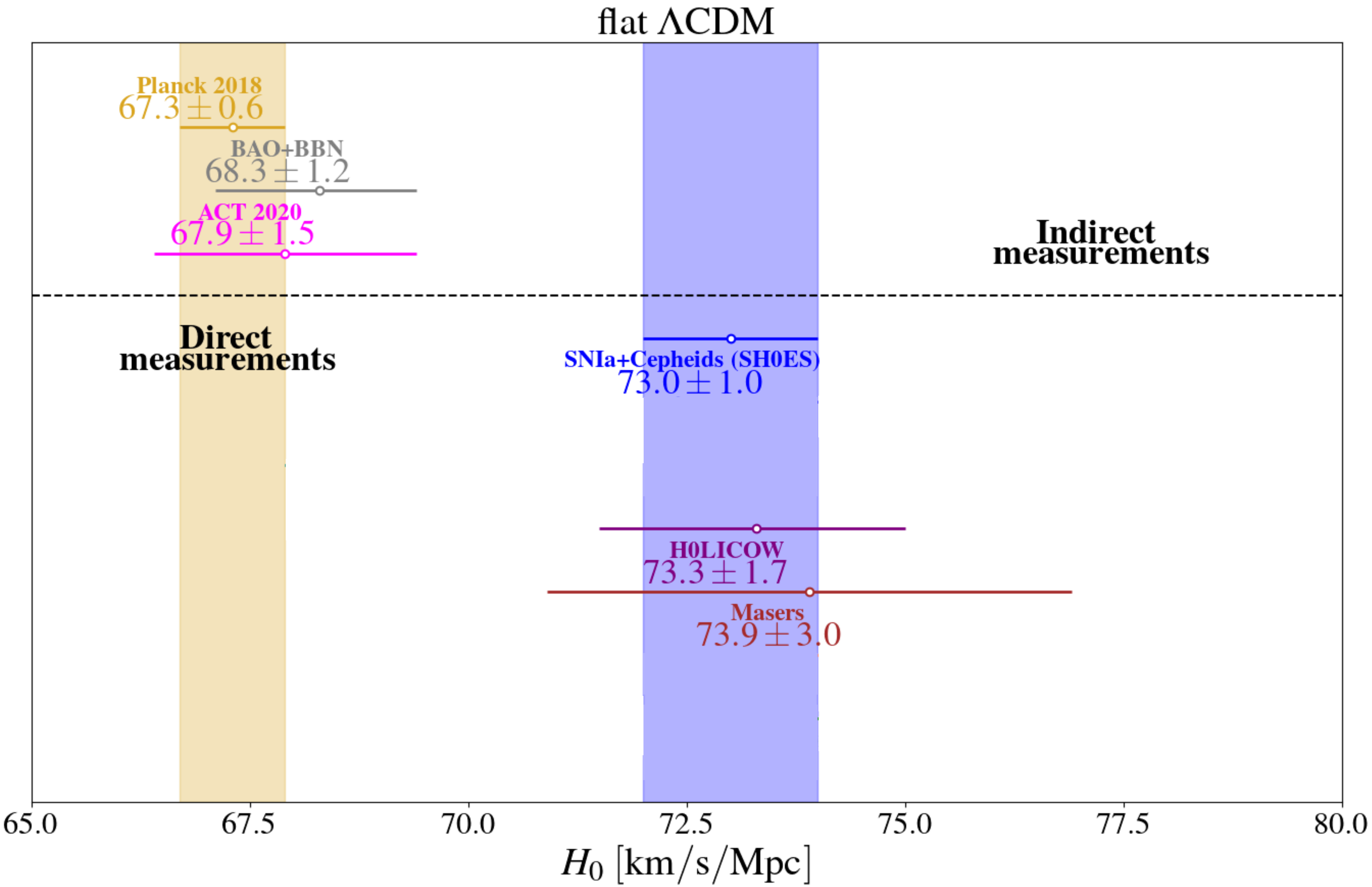

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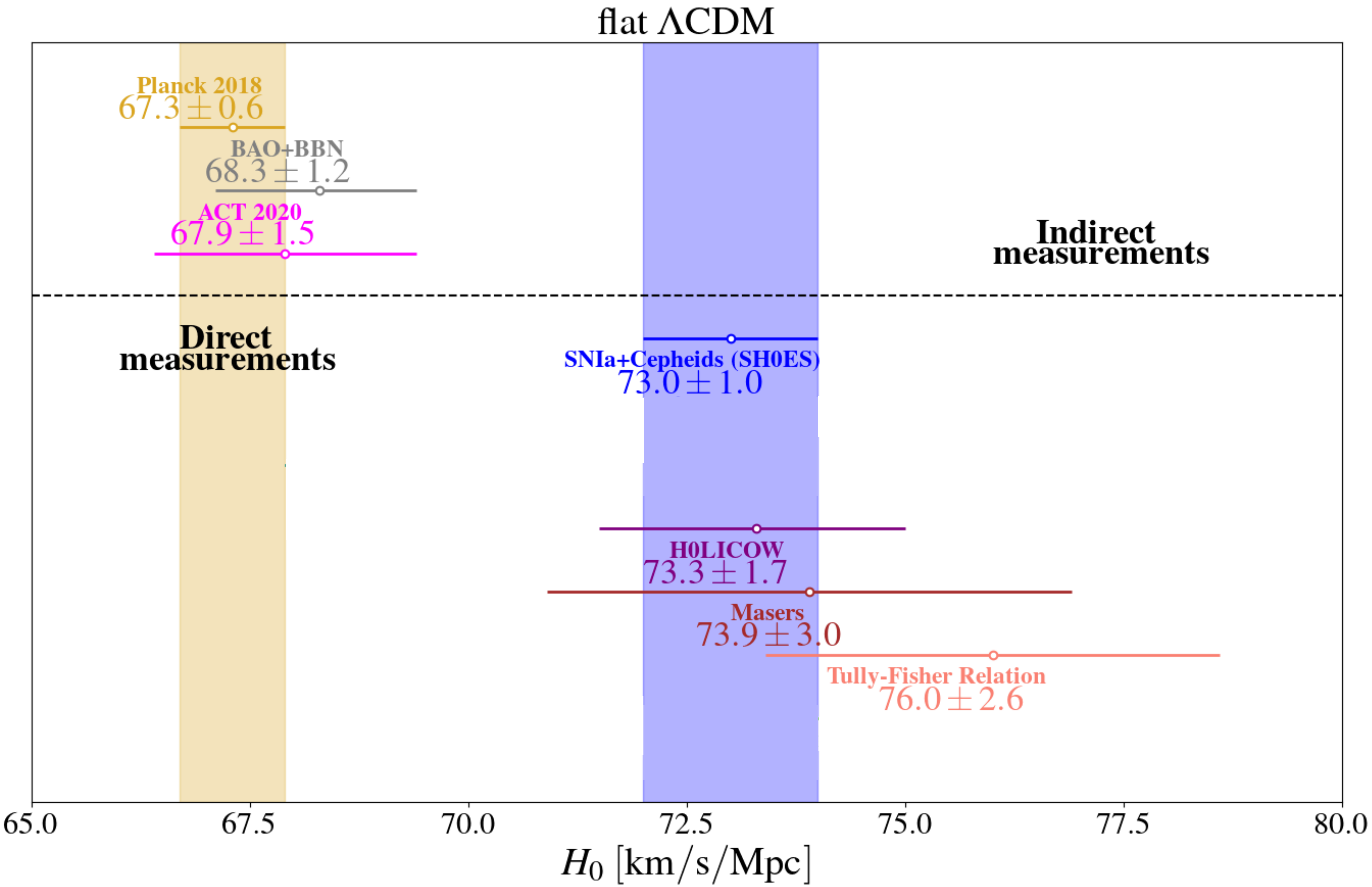

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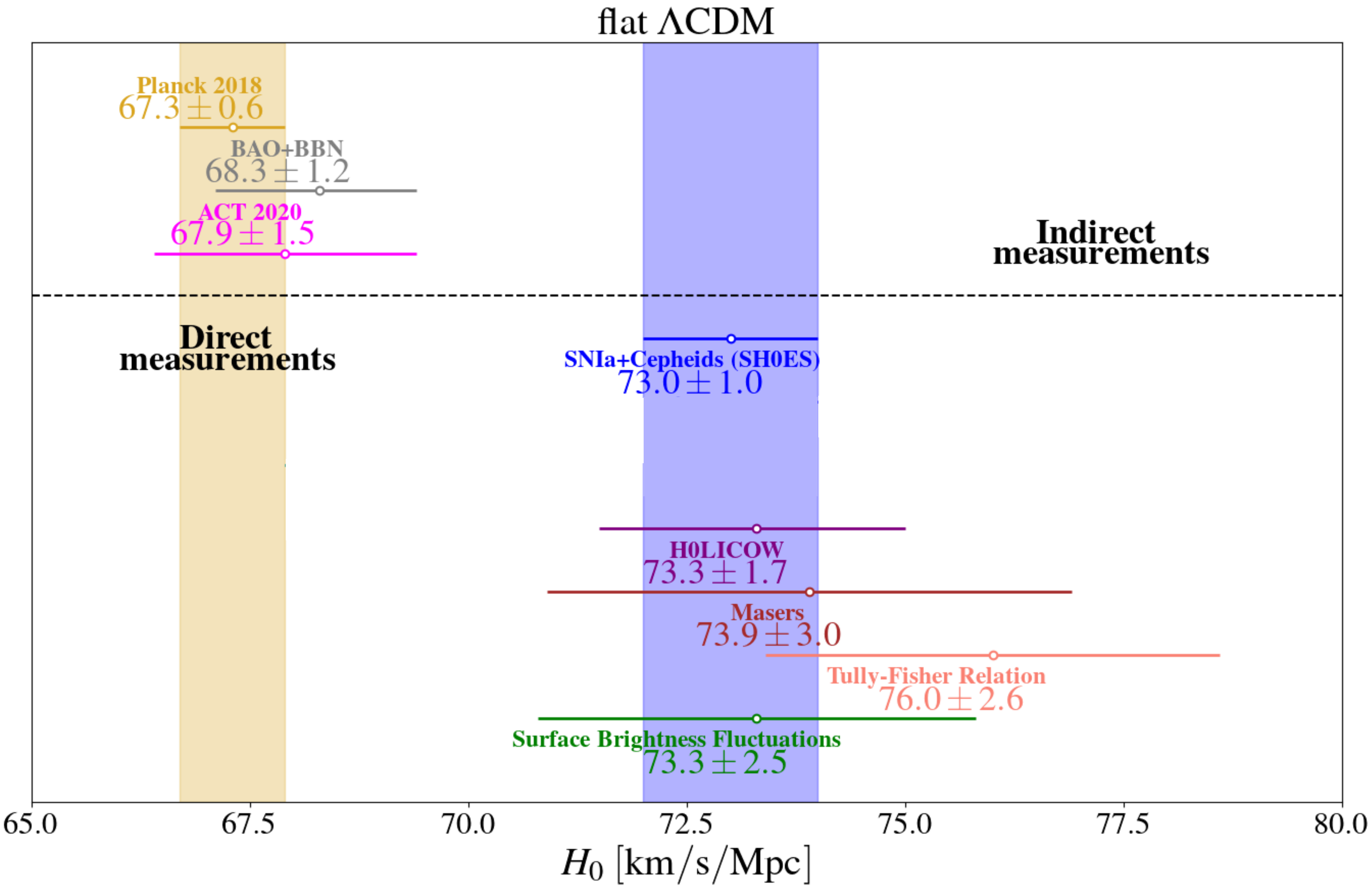

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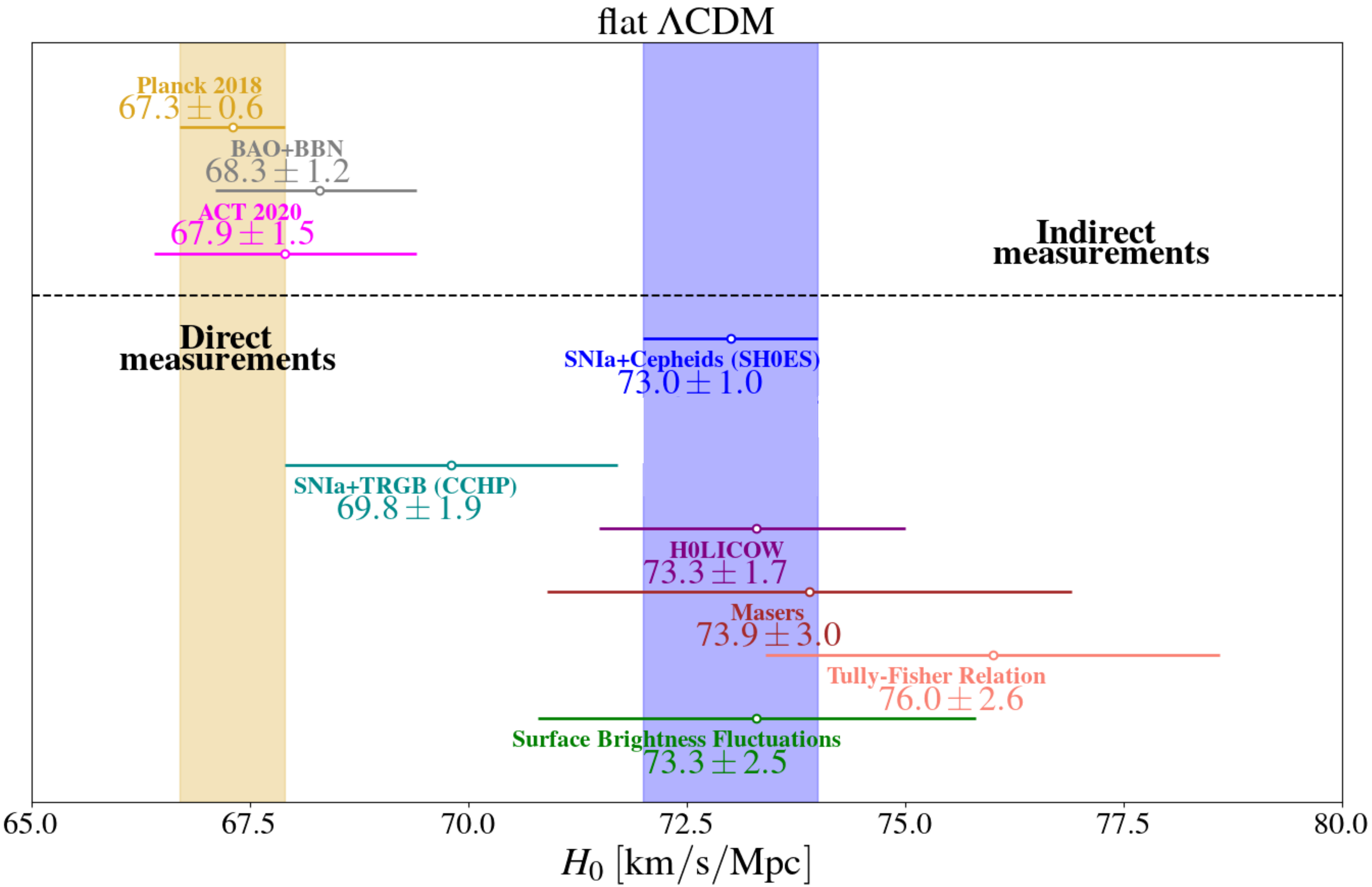

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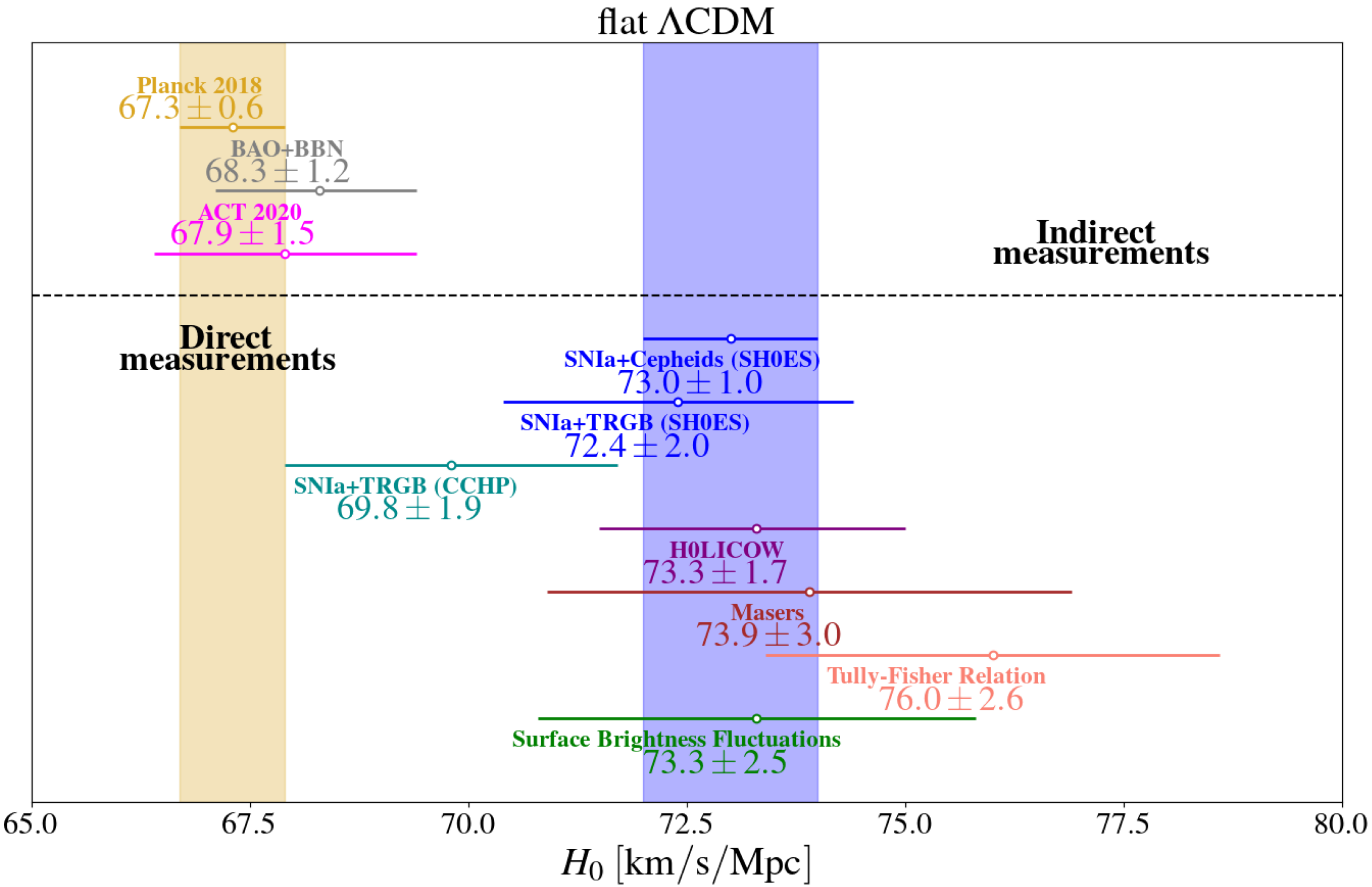
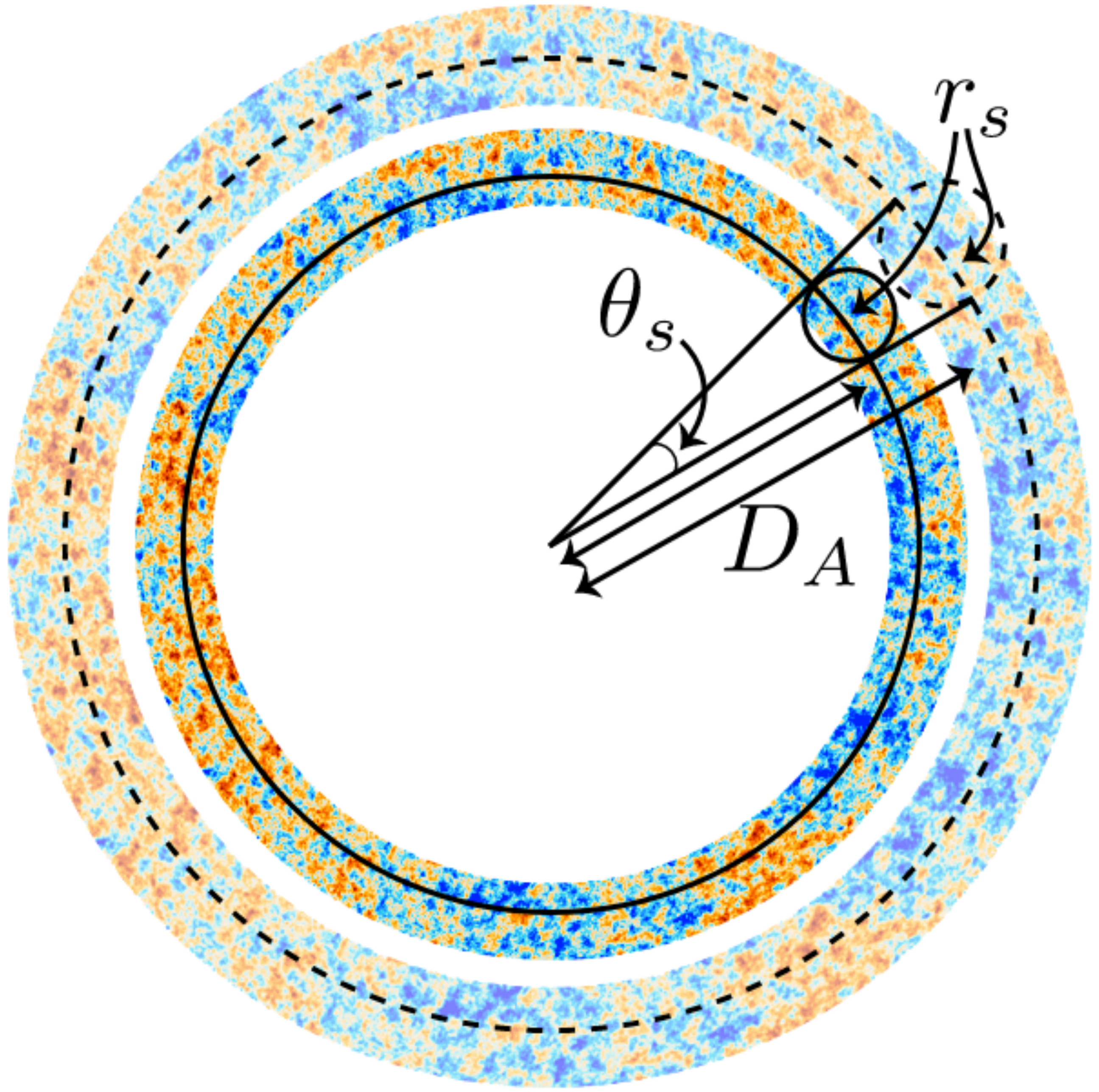


How does the CMB determine H_0 ?

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

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

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



[T. Smith]

Early-time solutions ($z > z_{rec}$)

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

Some examples:

- Free-streaming Dark Radiation
- Early Dark Energy (EDE)

[Poulin+ 18]

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Late-time solutions ($z < z_{rec}$)

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

Some examples:

- Late phantom Dark Energy
- Decaying Dark Matter

[Vattis+ 19]

Lost in the landscape of solutions

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… is it possible to **rank** the different models?

The H_0 Olympics

GOAL:
Identify which **underlying mechanisms are more likely** to be responsible for explaining the discrepancy

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Take a sample of proposed solutions

17 different models, spanning **early**- and **late**-universe solutions

Ex: EDE

Ex: DCDM → DR+ WDM

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Planck 2018 + BAO + SNIa + SH0ES

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Apply different metrics

GT

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

$Q_{\rm DMAP}$

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

ΔAIC

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

Results of the contest

Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X	
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓	3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓	3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	1
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	2
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	2
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	2
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X	
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X	
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X	
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X	
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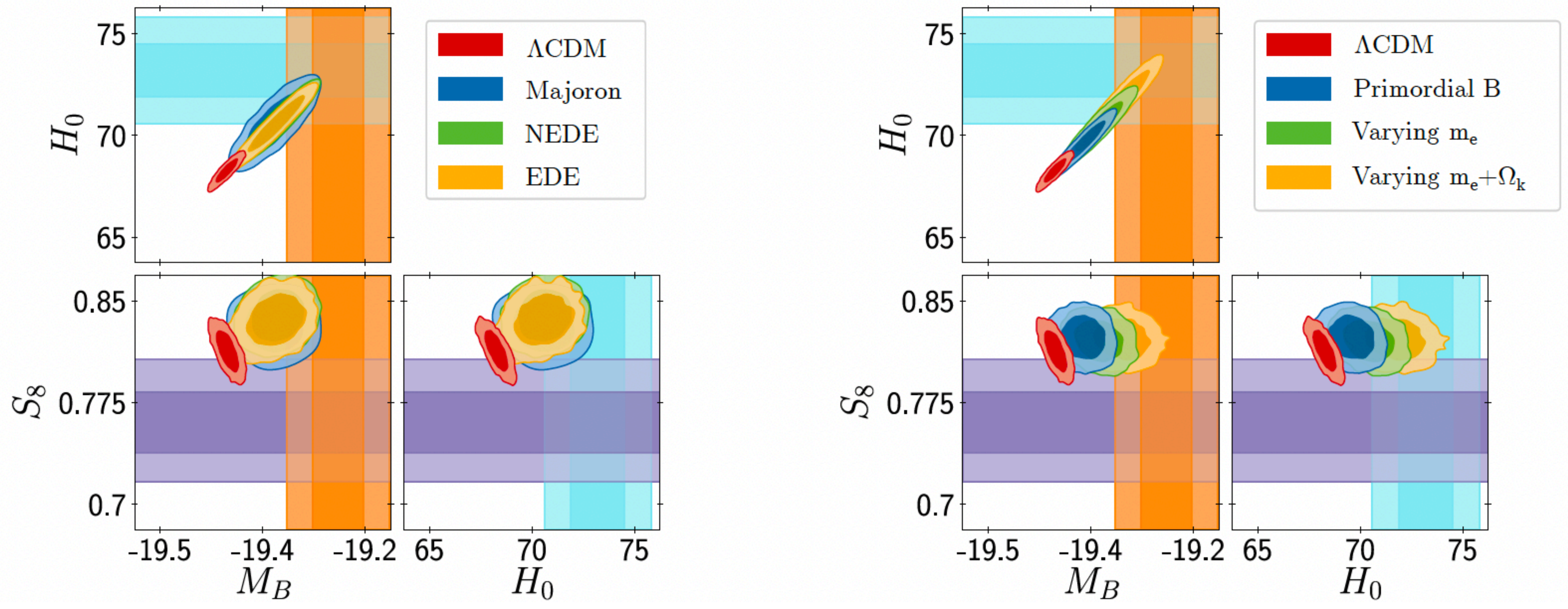
Late-time solutions (including **decay models**) are the most **disfavored** (severely constrained by SNIa+BAO)

Does this mean that **decay models** are **not worth exploring**?

The most successful models for the H_0 tension are **unable to explain the S_8 tension**



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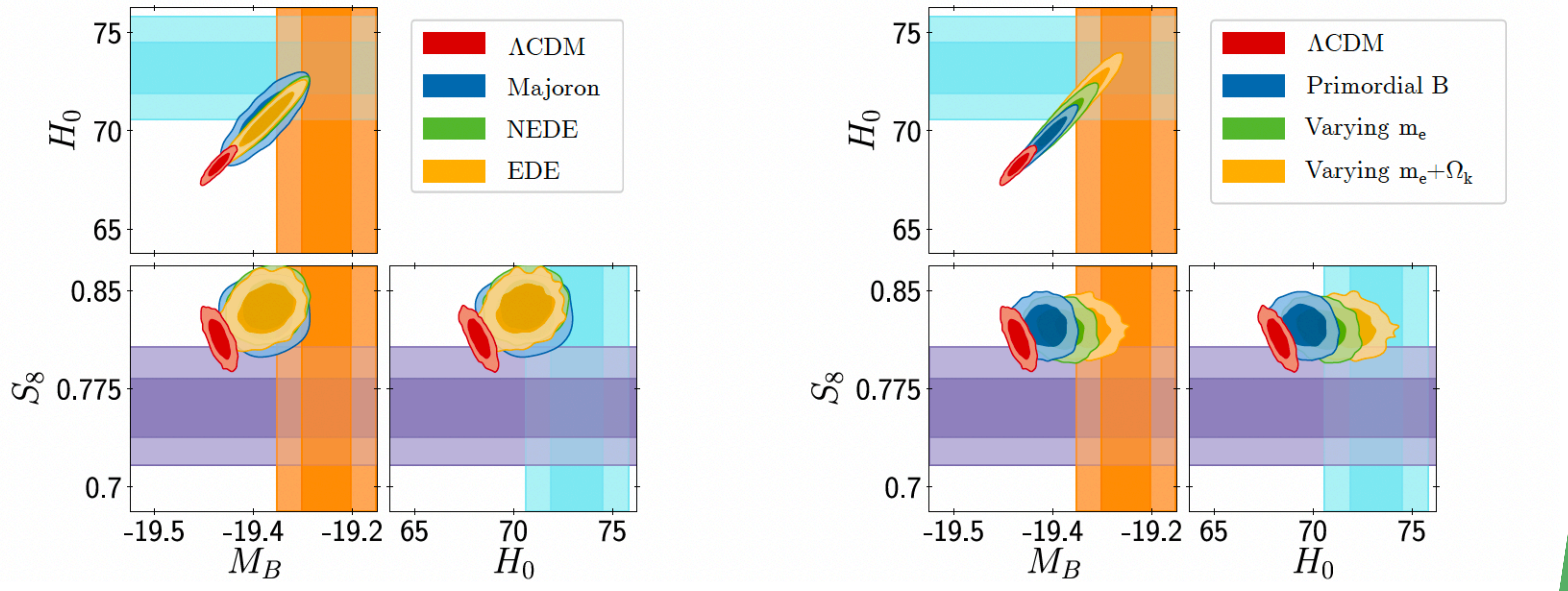

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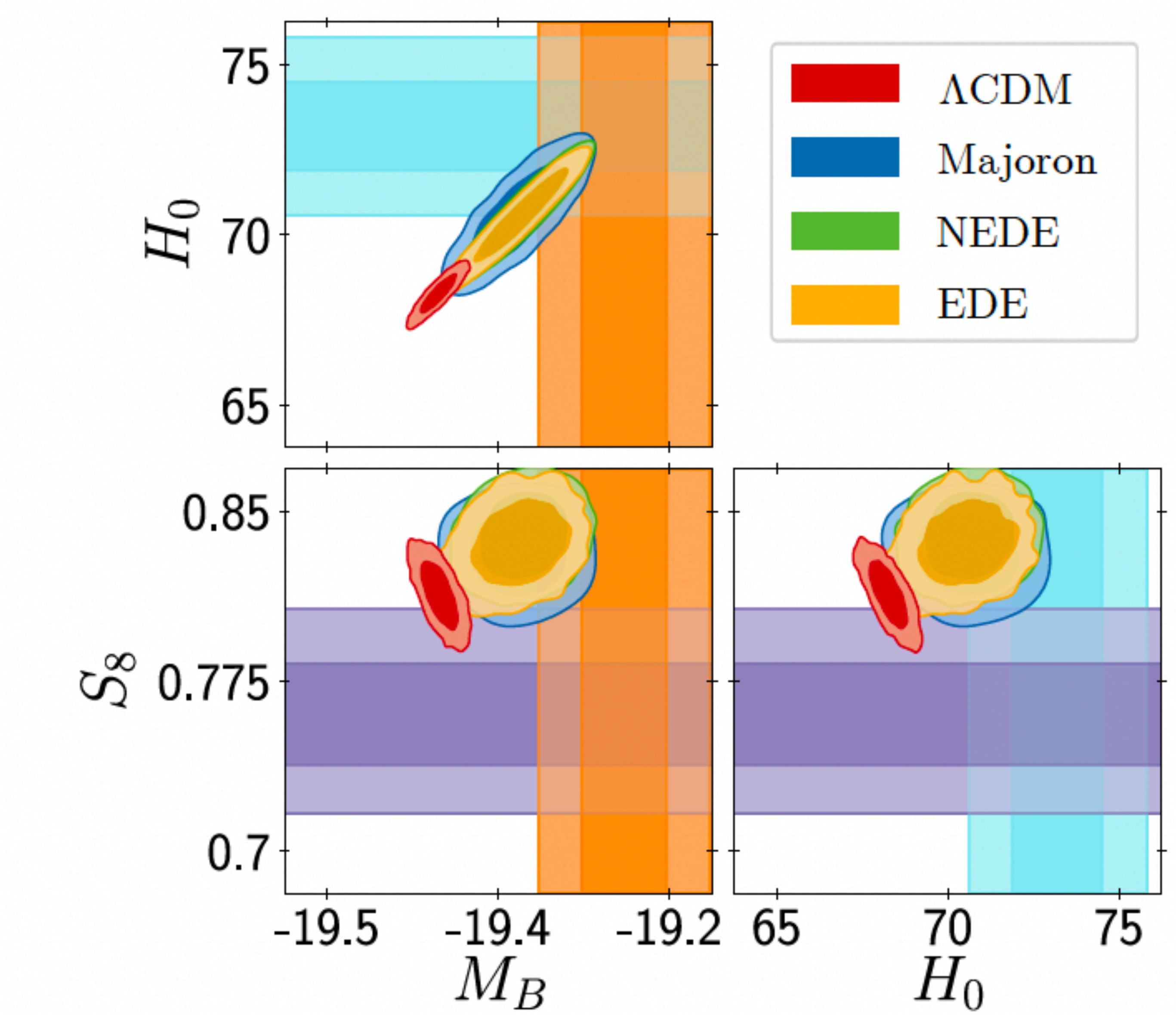
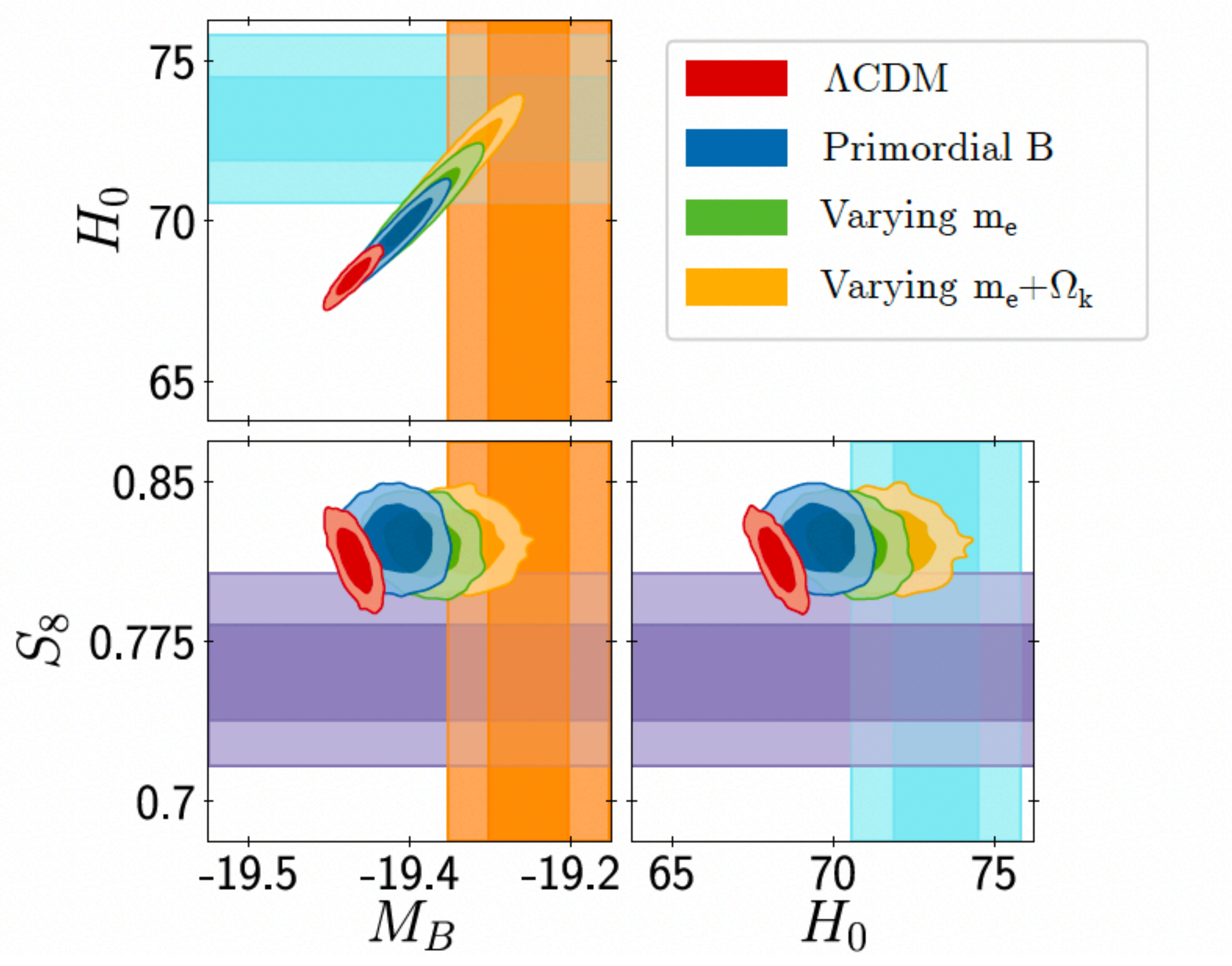




Decay models could provide a way to explain the **low** measured **S_8** values

They could also help answering other questions (like the **neutrino mass puzzle**)

Part II:

DECAYING DARK MATTER

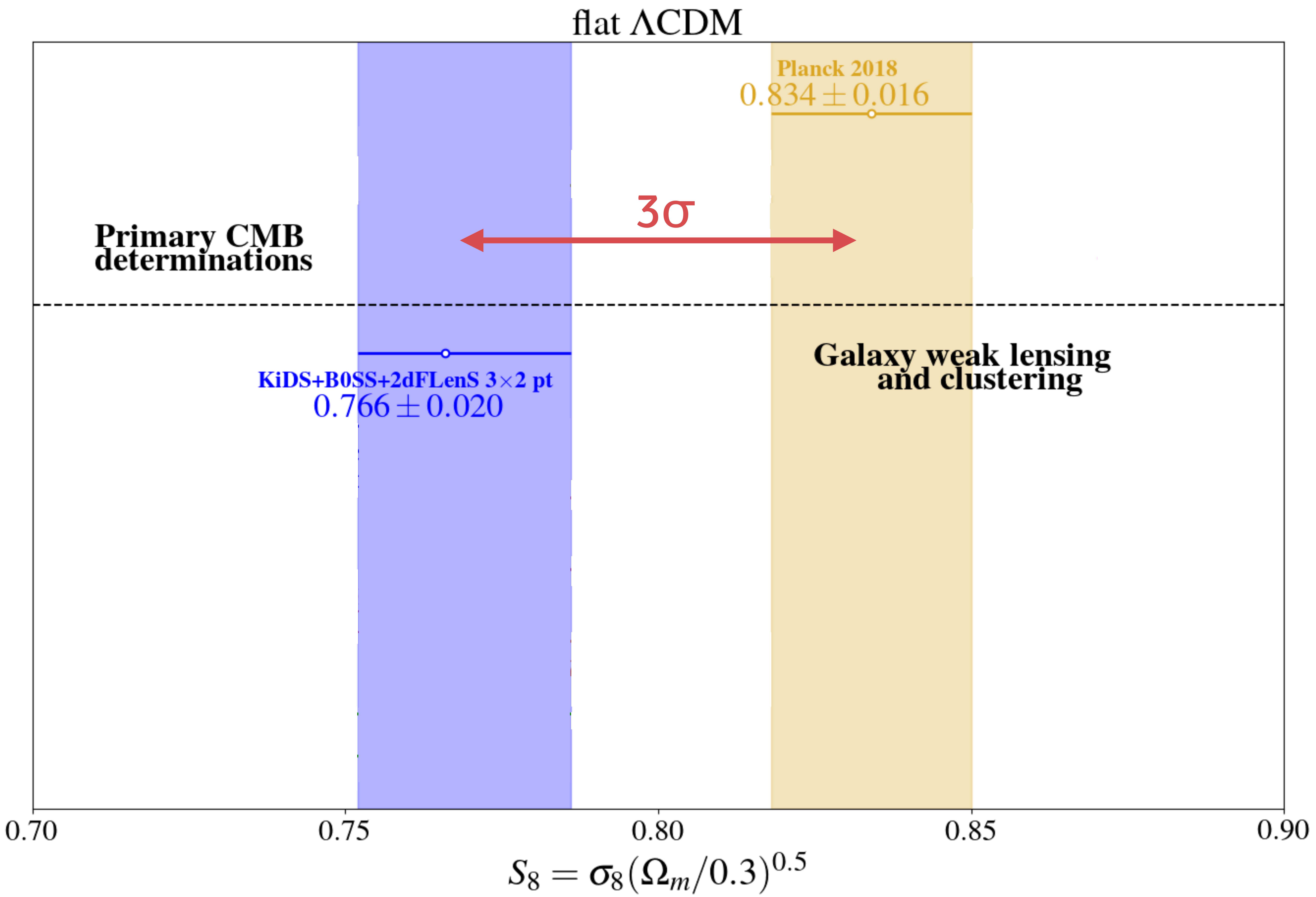
& THE S_8 TENSION

[GFA, Murgia, Poulin, Lavalle 2020 arXiv:2008.09615]

[GFA, Murgia, Poulin 2021 arXiv:2102.12498]

[Image by Sandbox studio - Symmetry]

The S_8 tension in a nutshell



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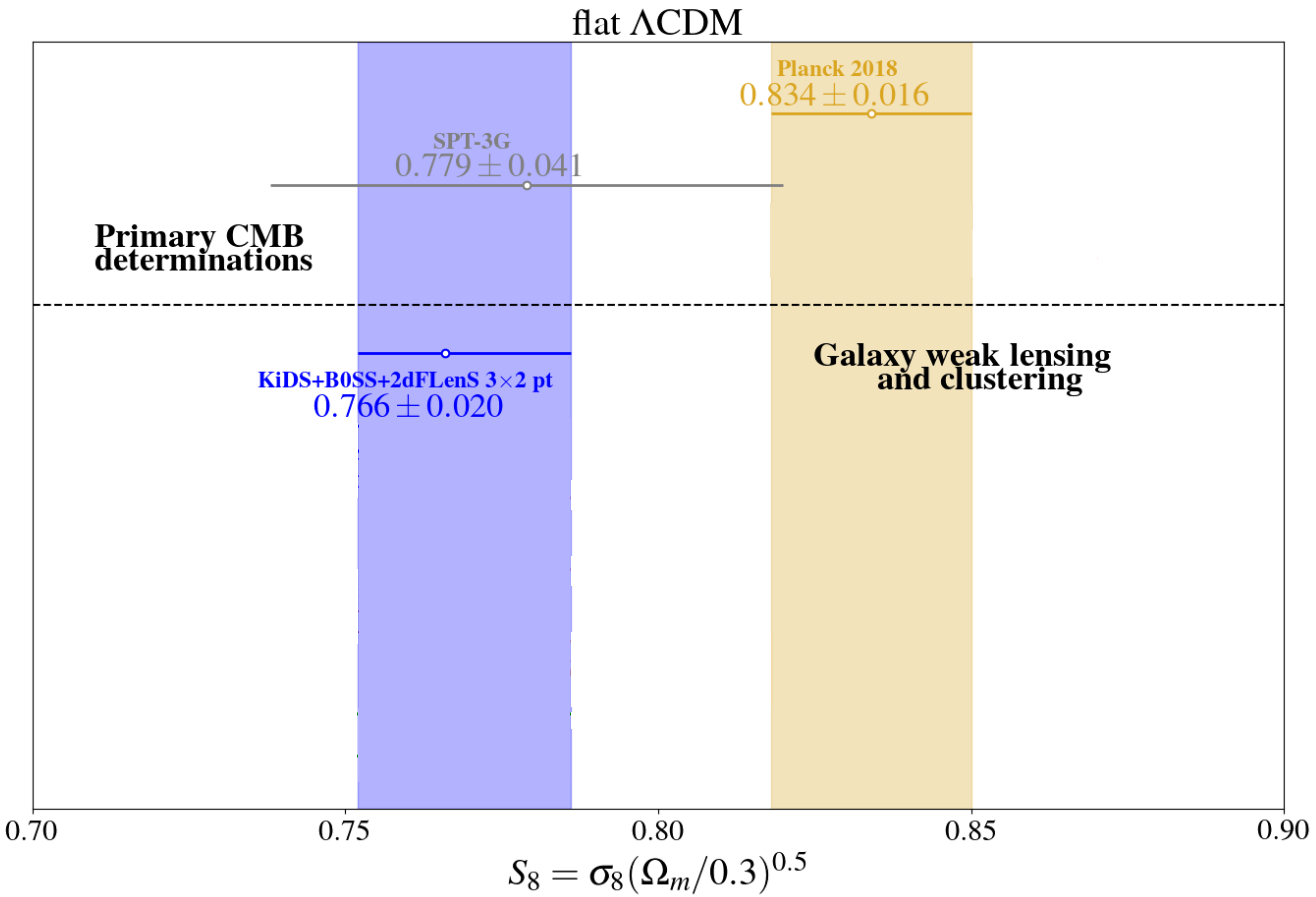

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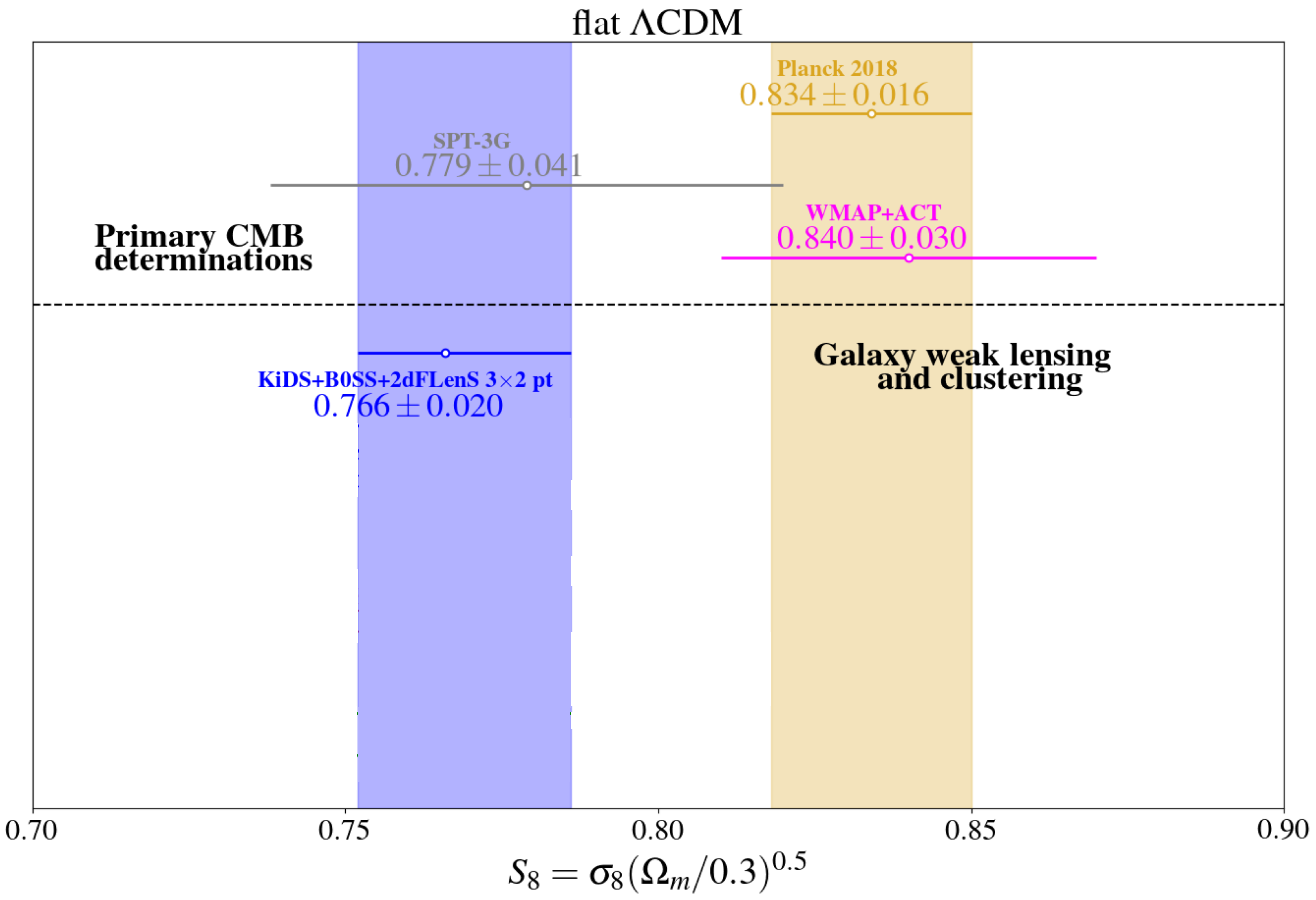

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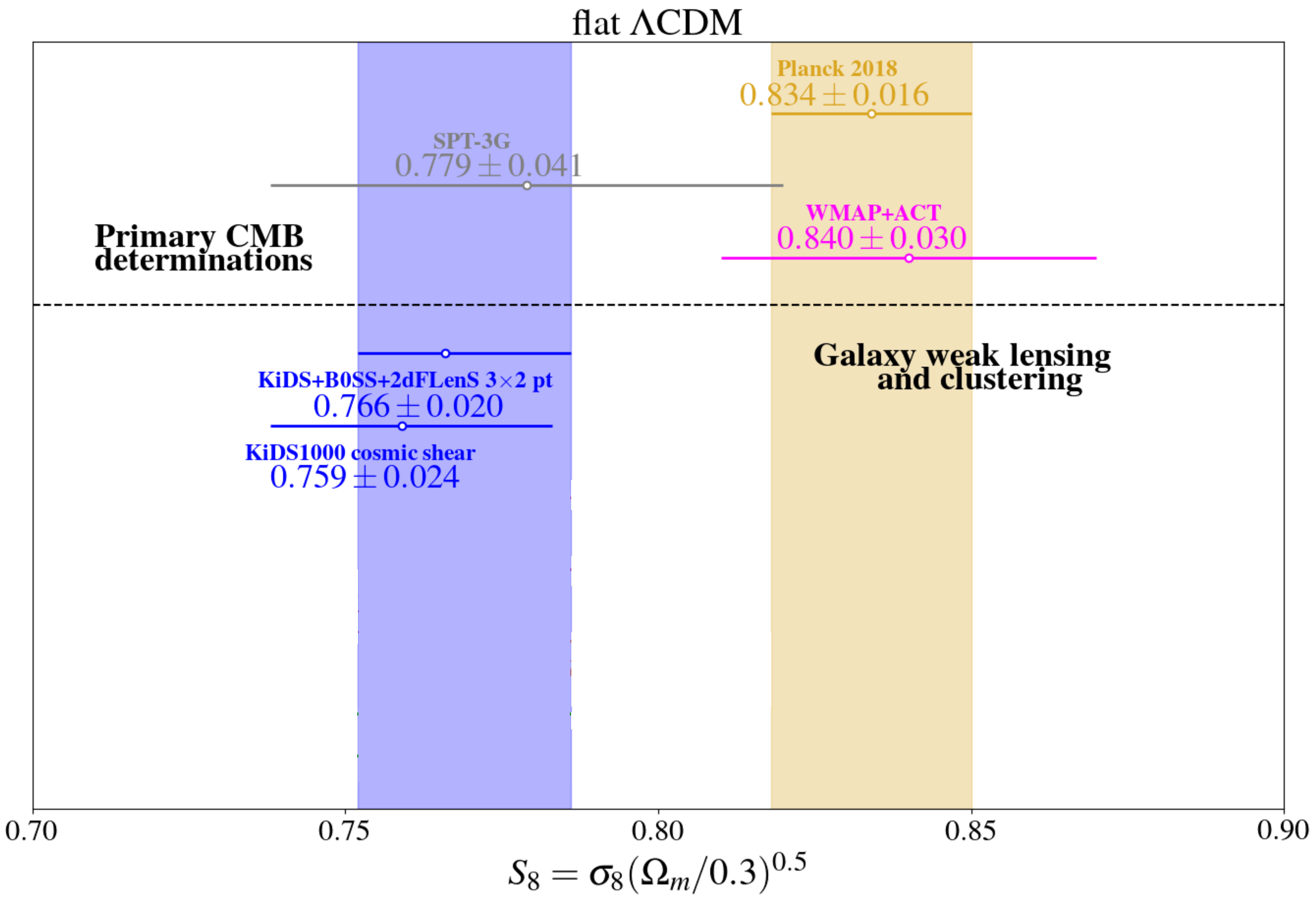

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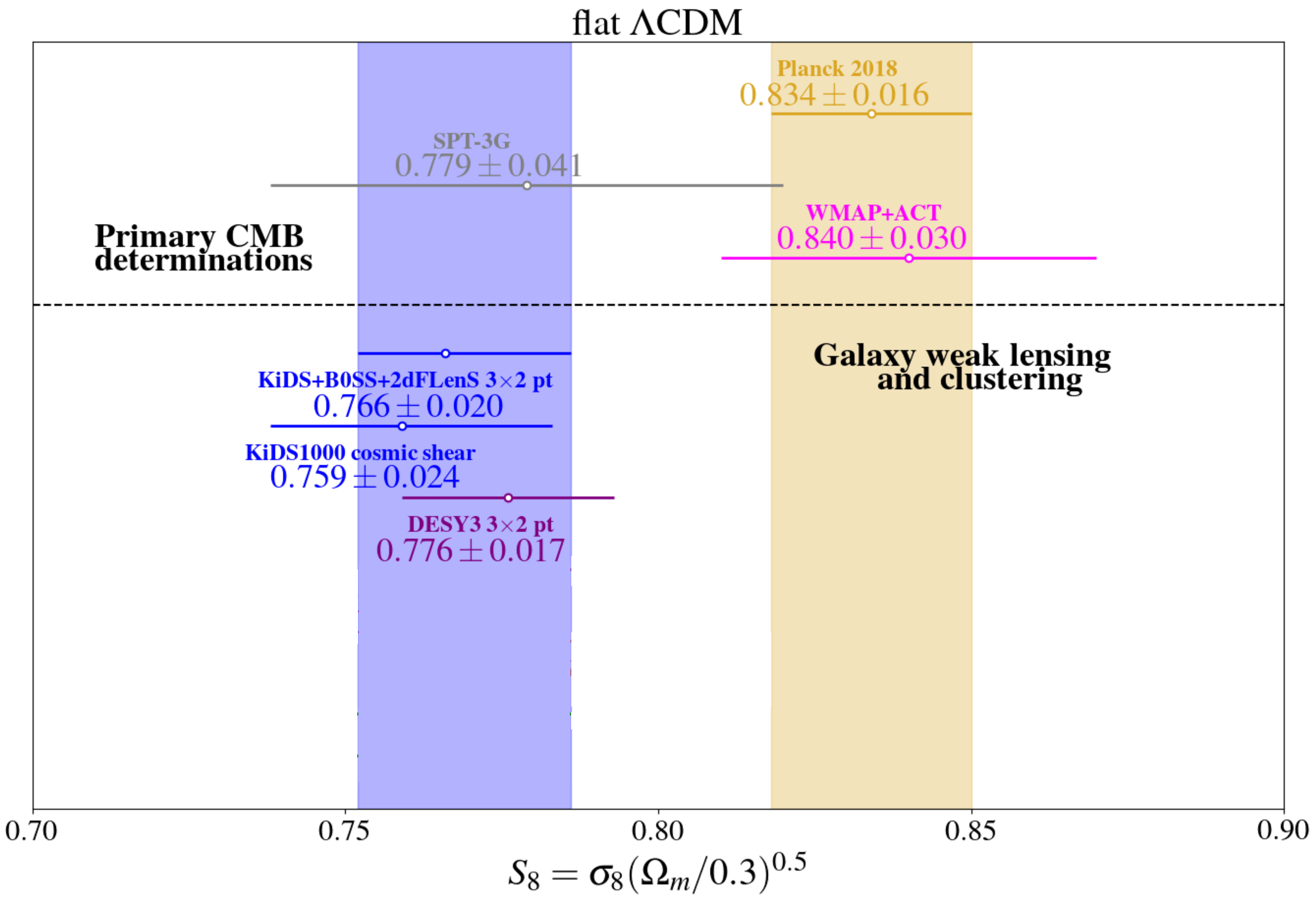

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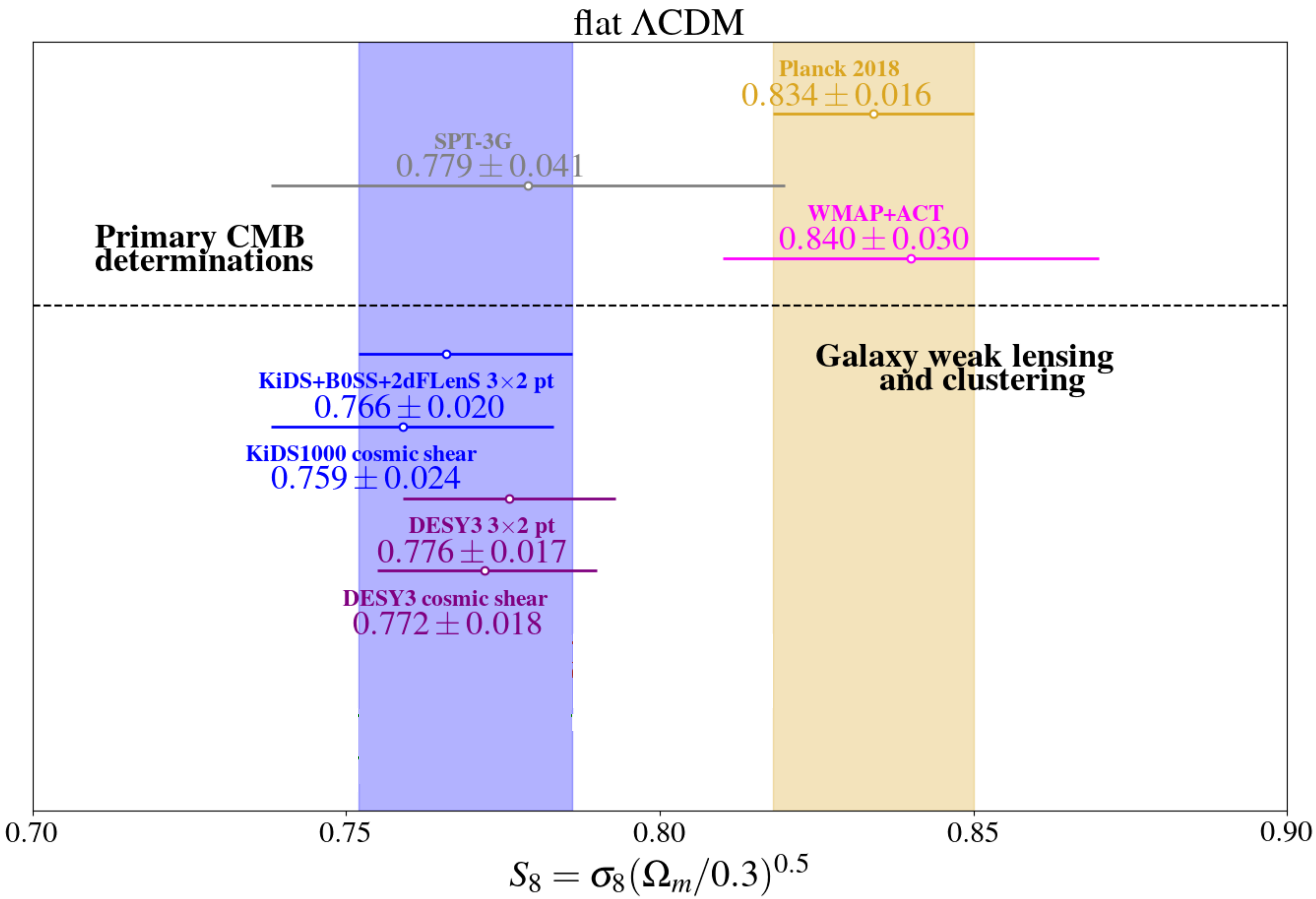

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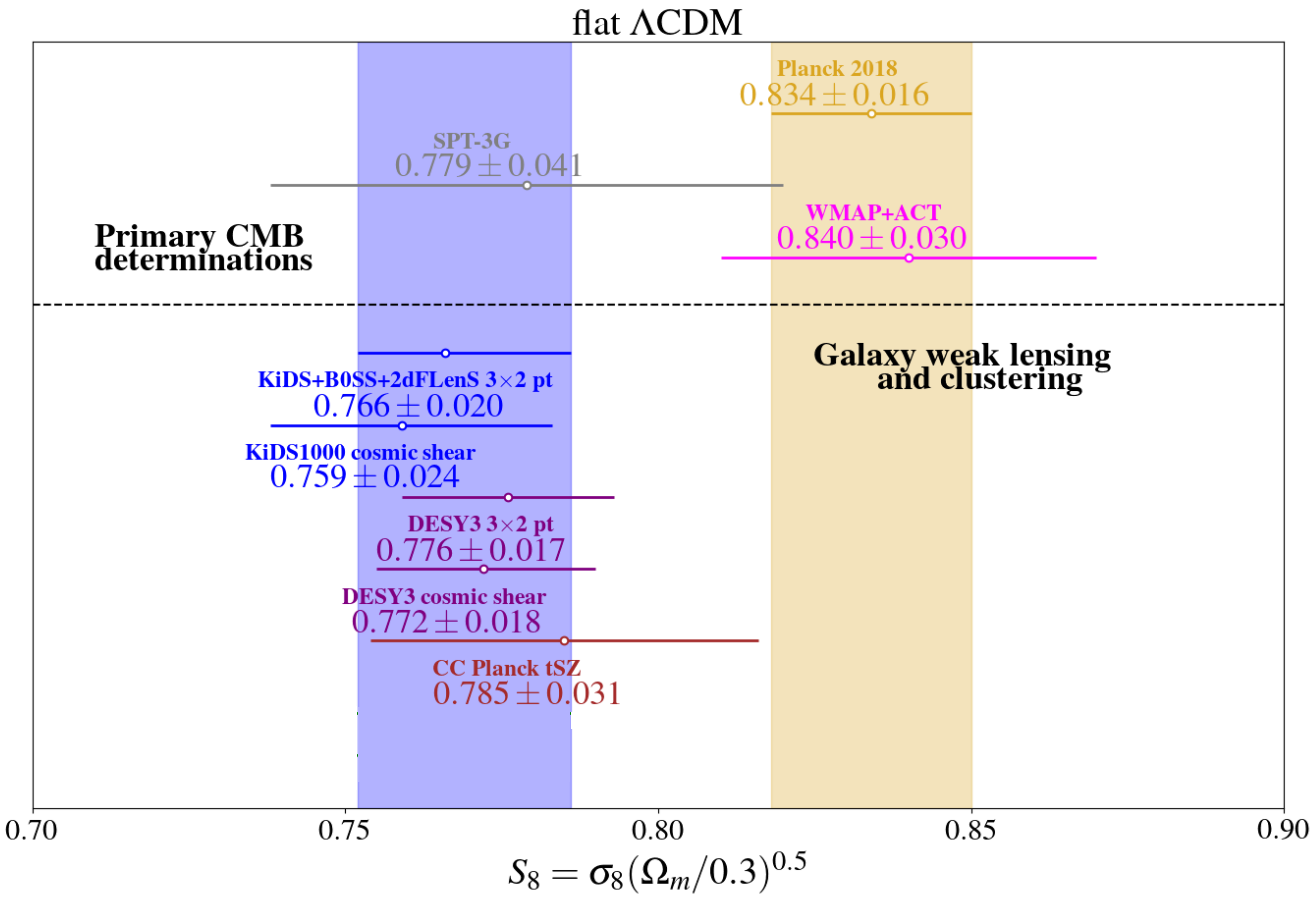

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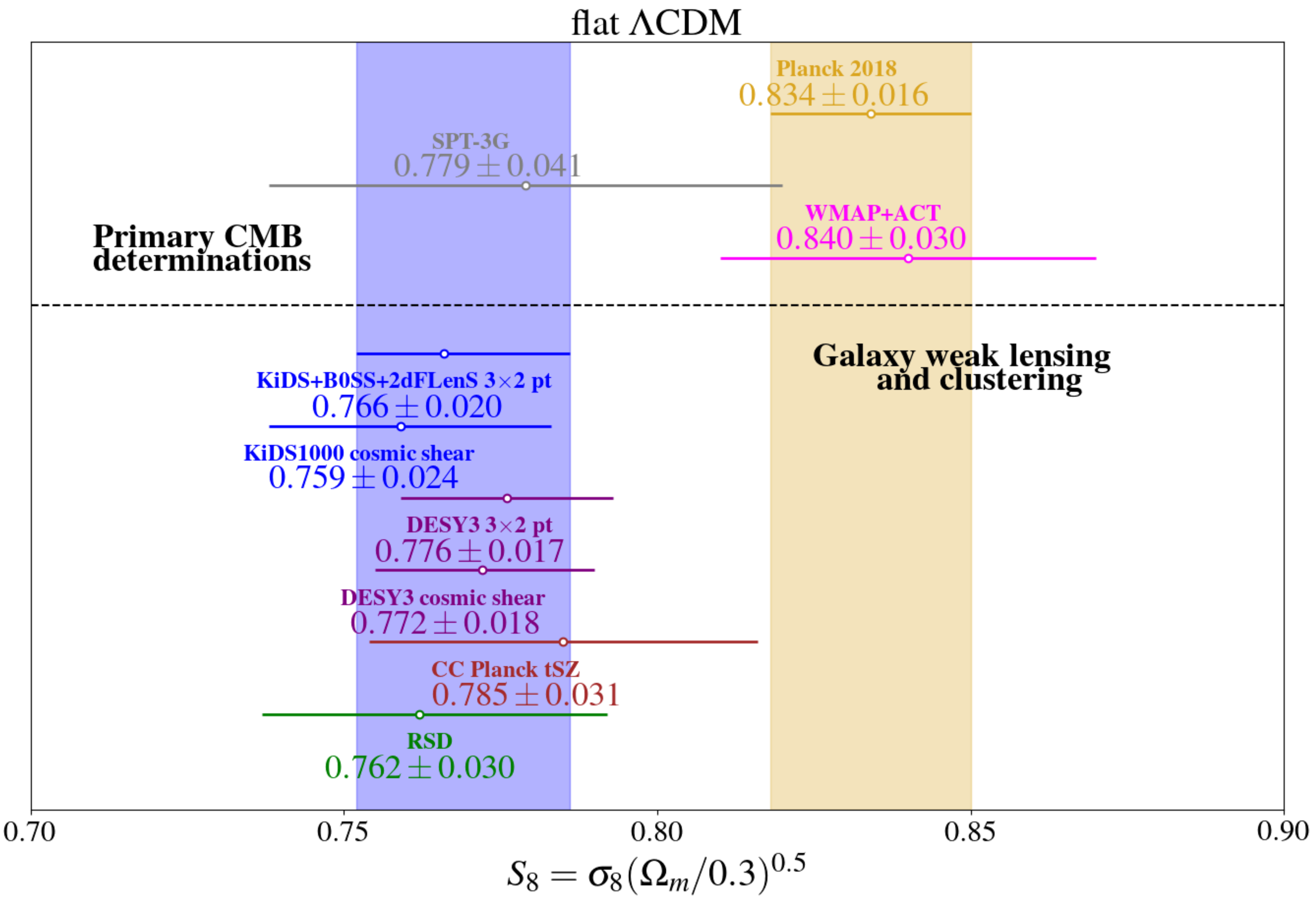

$$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$$

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

What is needed to explain low S_8 values ?

- **Ω_m should be left unchanged** (well constrained by SNIa & galaxy clustering)

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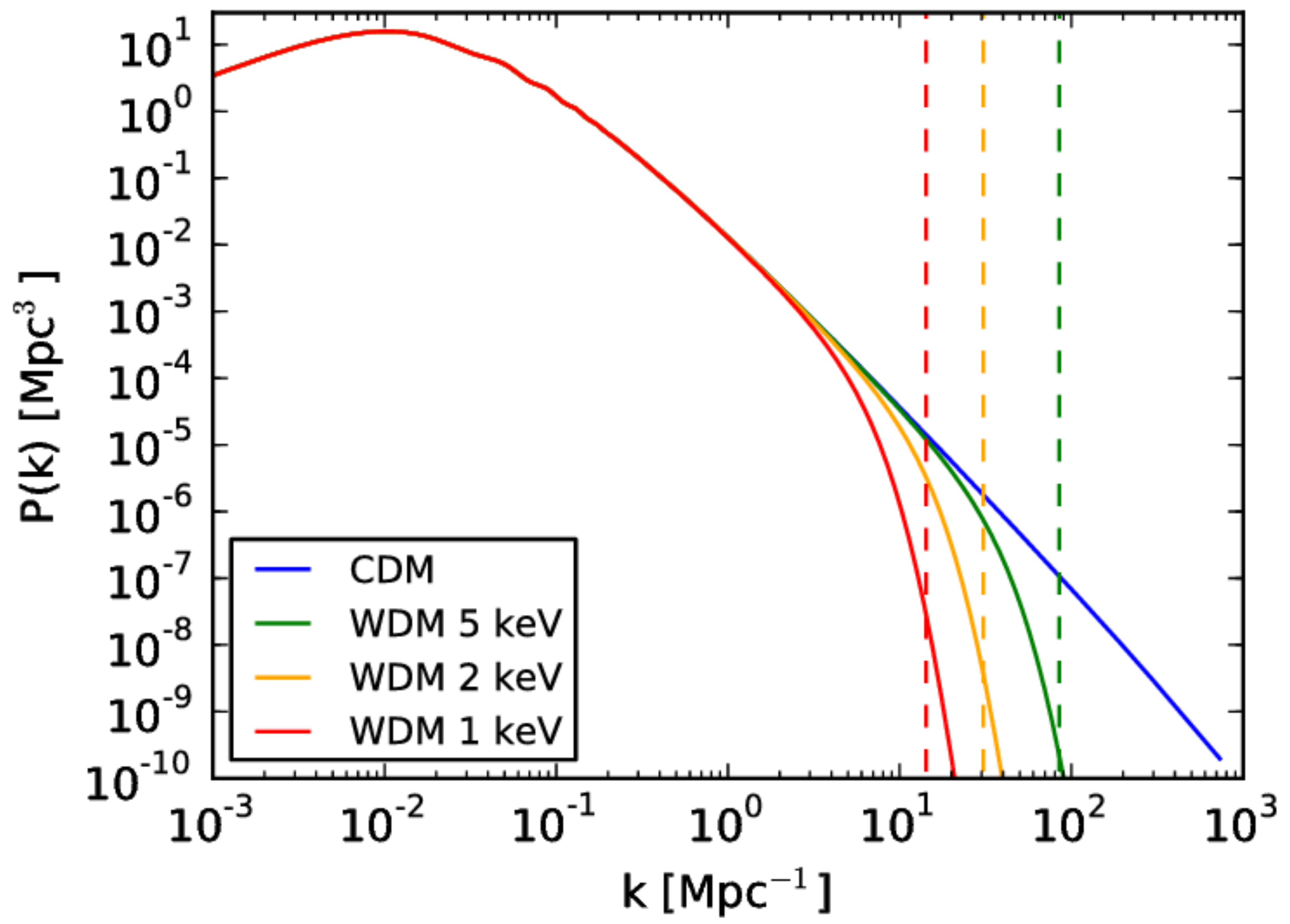
Ex: Warm dark matter



Very constrained by Ly-α !
[Iršič+ 17]

Decaying Dark Matter (DDM)

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- Decay products?

1 **To SM particles**

Model-dependent, strongly constrained $\Gamma^{-1} \gtrsim 10^7 - 10^{10}\ t_U$

[Blanco+ 18]

2 **To dark radiation**

Model-independent, less constrained $\Gamma^{-1} \gtrsim 10\ t_U$

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   Model-independent, less constrained $\Gamma^{-1} \gtrsim 10\ t_U$
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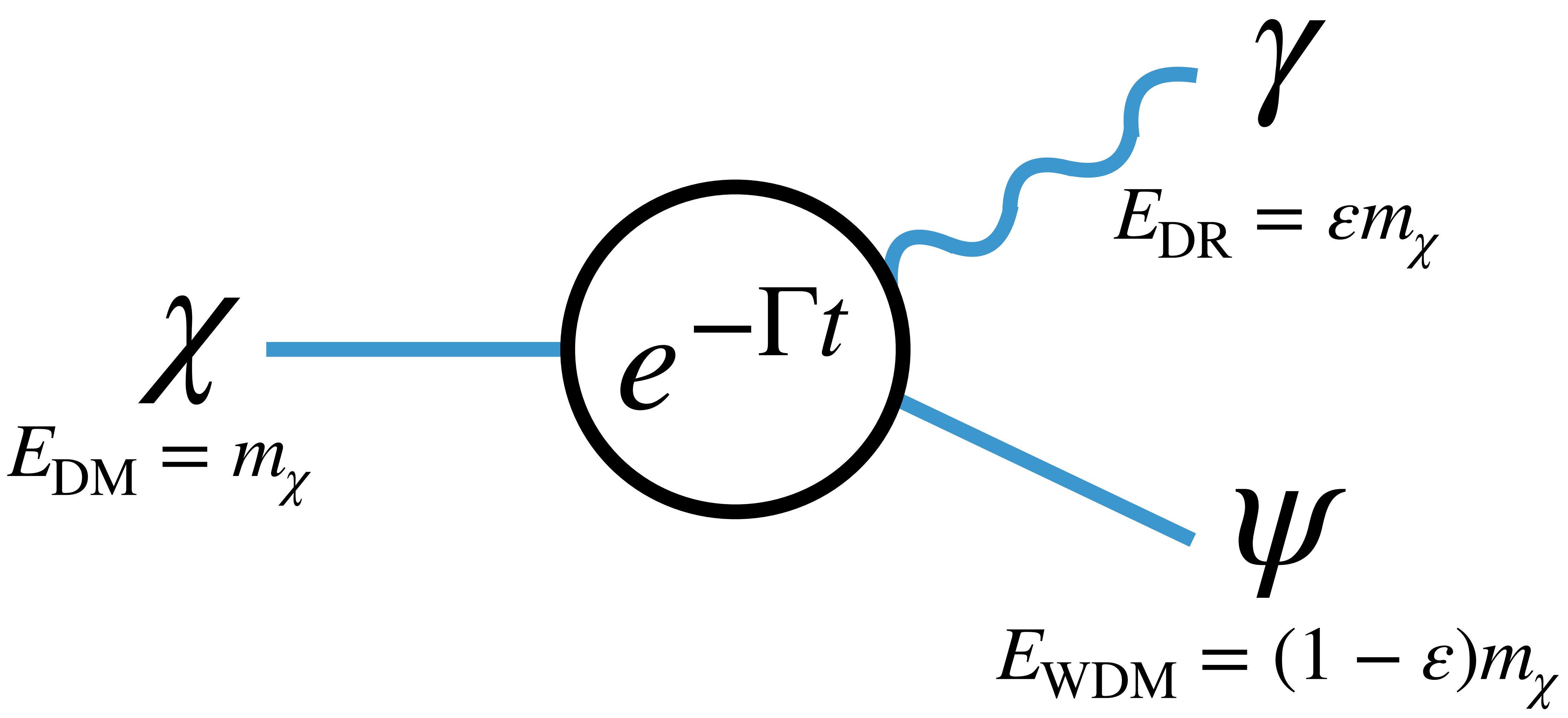
What about massive products?

DDM with massive decay products

We explore DM decays to
massless (Dark Radiation) and
massive (Warm Dark Matter) particles



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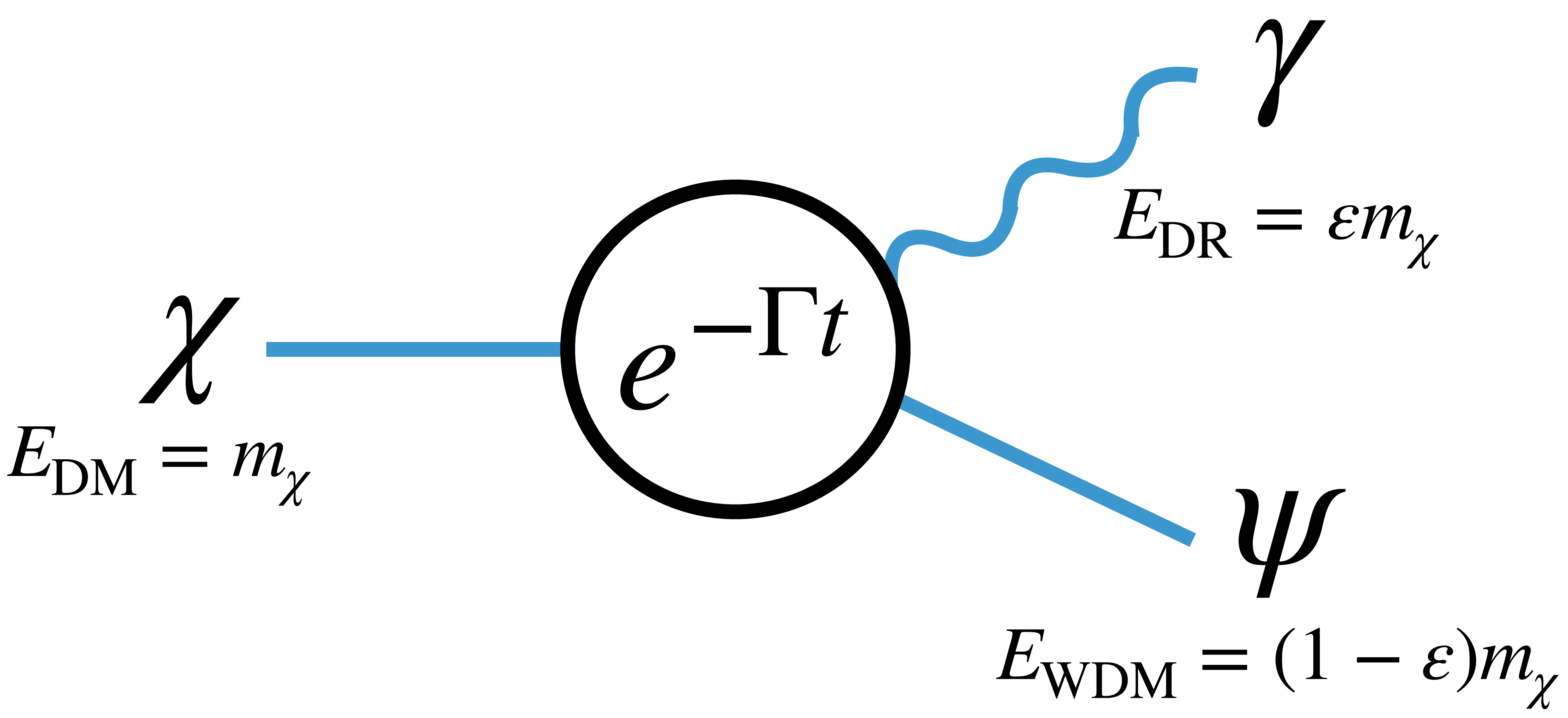

2 extra parameters:

Decay rate Γ

DR energy fraction ε

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m_\psi^2}{m_\chi^2}\right)\begin{cases} = 0 & (\Lambda\text{CDM}) \\ = 1/2 & (\text{DM} \to \text{DR}) \end{cases}$$

GOAL

Perform a parameter scan by including **full treatment of linear perts.**, in order to assess the impact on the **S_8 tension**

Evolution of DDM perturbations

- Track δ_i, θ_i and σ_i for i= dm, dr, idm
- Boltzmann hierarchy of eqs., dictate evolution of **p.s.d. multipoles $\Delta f_\ell (q, k, \tau)$**

Evolution of DDM perturbations

- Track δ_i, θ_i **and** σ_i for i= dm, dr, idm

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

  - For DM and DR, momentum d.o.f. are integrated out

  - For **WDM**, need to follow full evolution in phase space
    Computationally prohibitive, $\mathcal{O}(10^8)$ ODEs to solve!

New fluid equations for the WDM species

- **Based on previous approximation for massive neutrinos**

[Lesgourgues+ 11]

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

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

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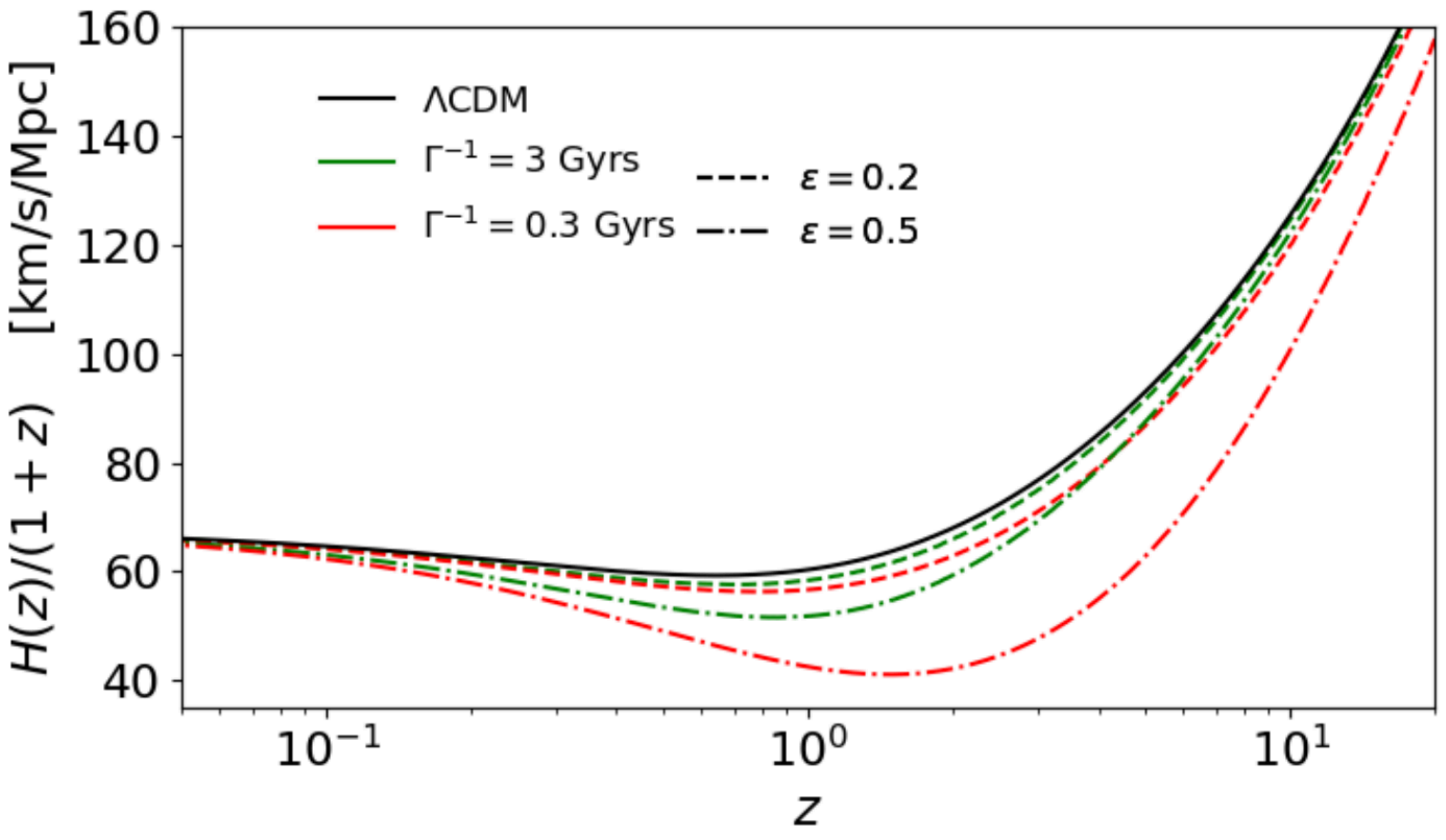
CPU time reduced from ~ 1 day to ~ 1 minute !!

H(z) more affected by the **DR**:

$\Gamma \uparrow \quad \varepsilon \uparrow$



Impact on background

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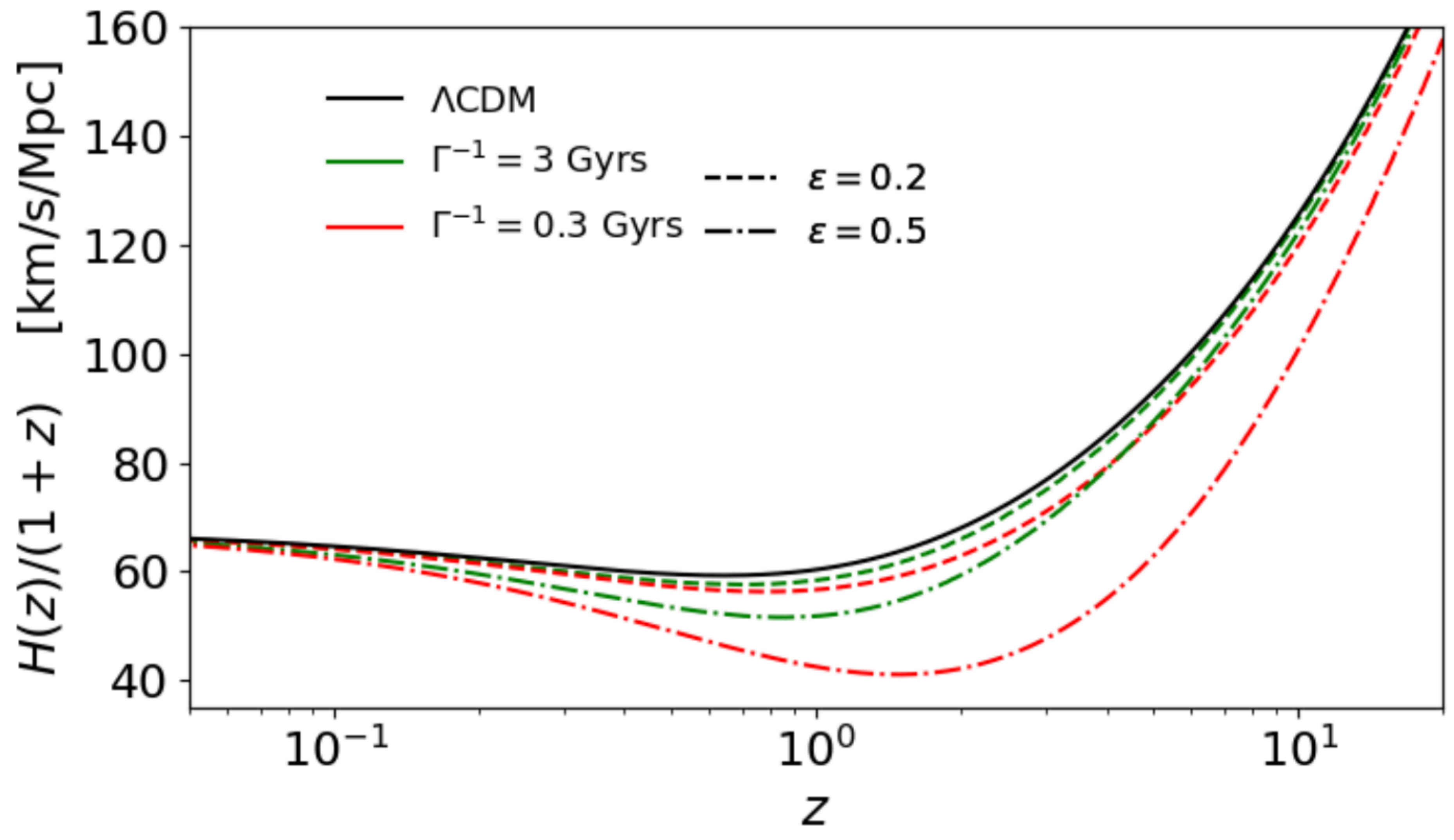

Impact on background

Impact on perturbations

P(k) more affected by the WDM (suppression at $k > k_{fs}$):

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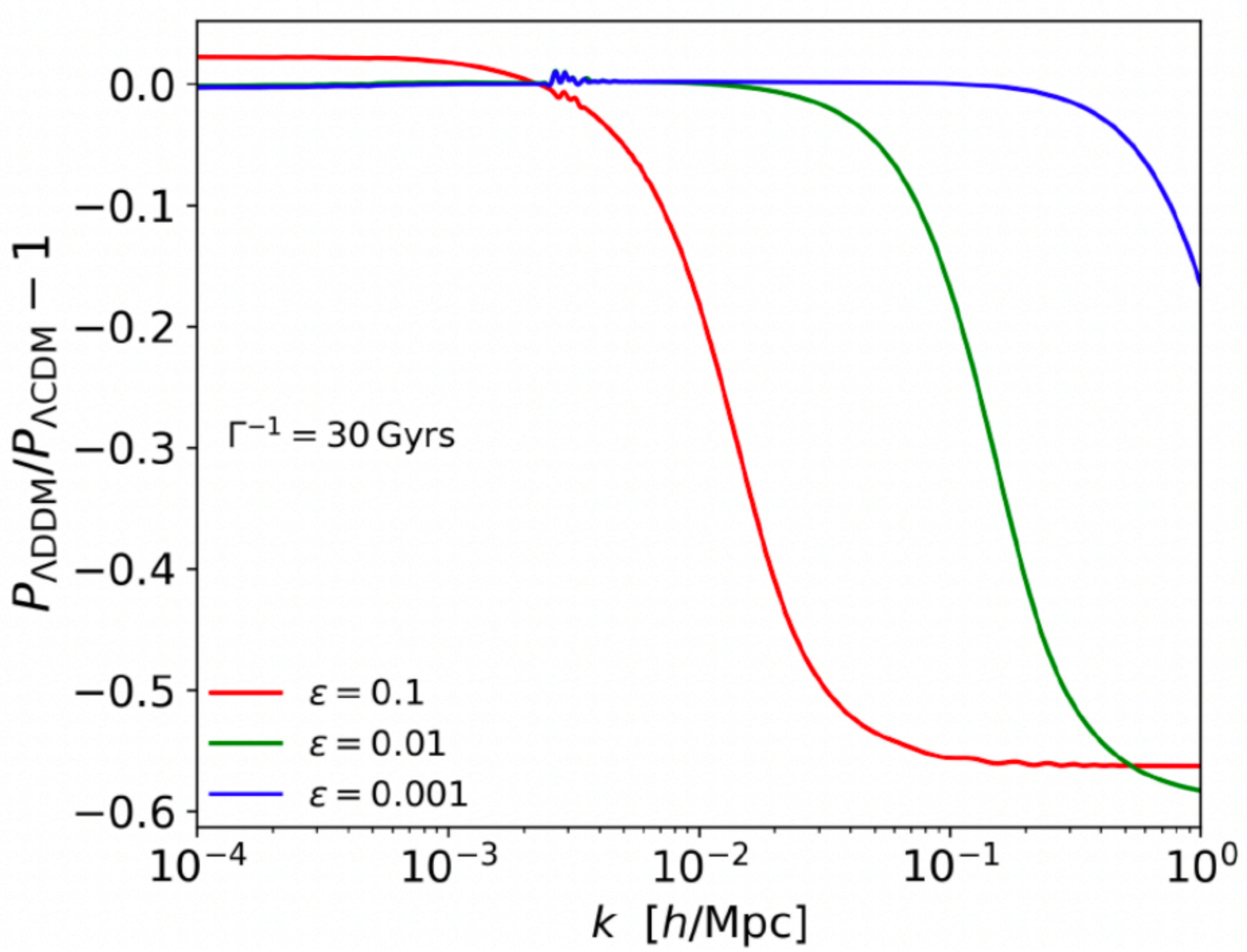

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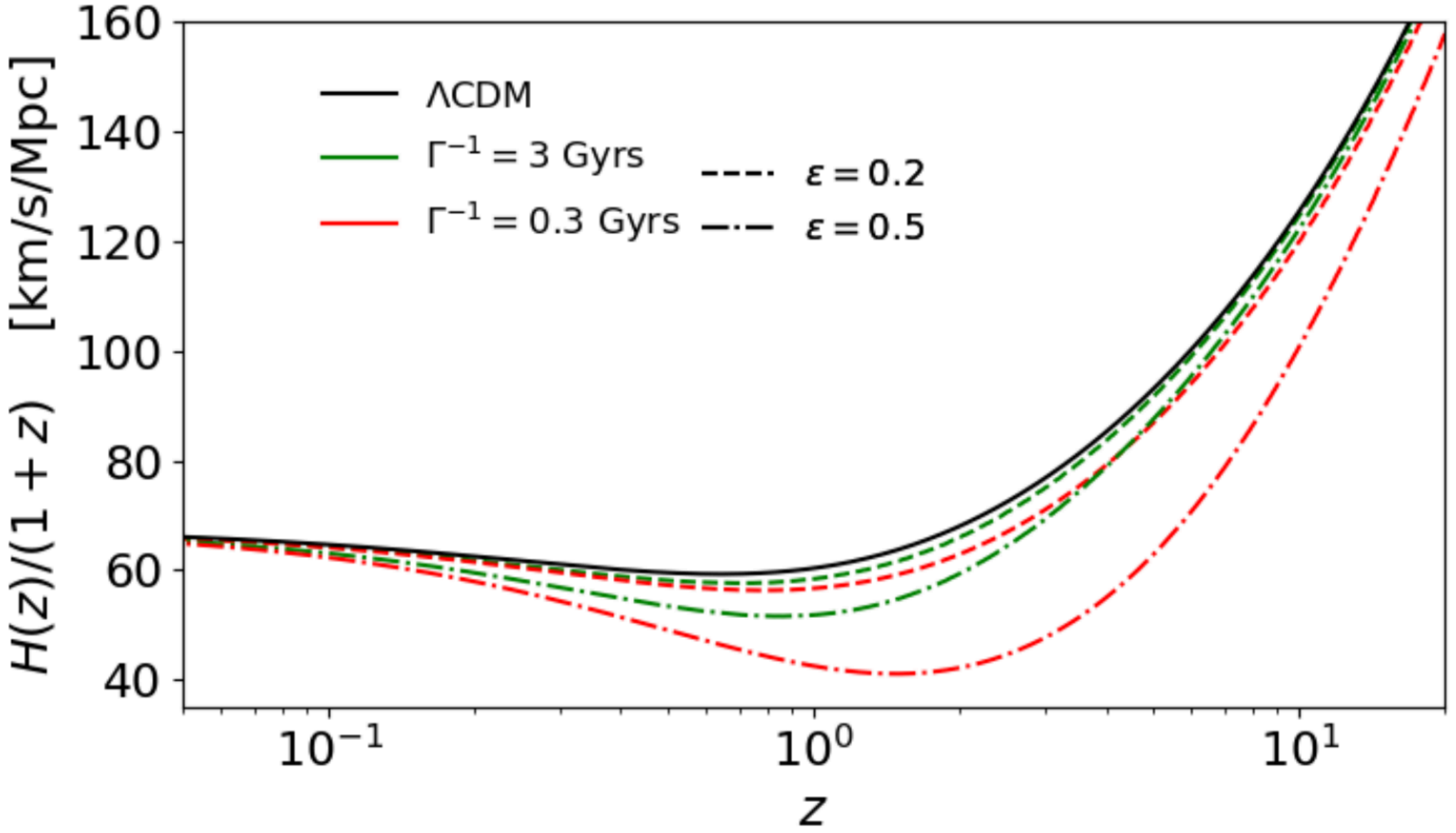

With large Γ and small ε, we can achieve a P(k) suppression while leaving H(z) unaffected

Impact on background

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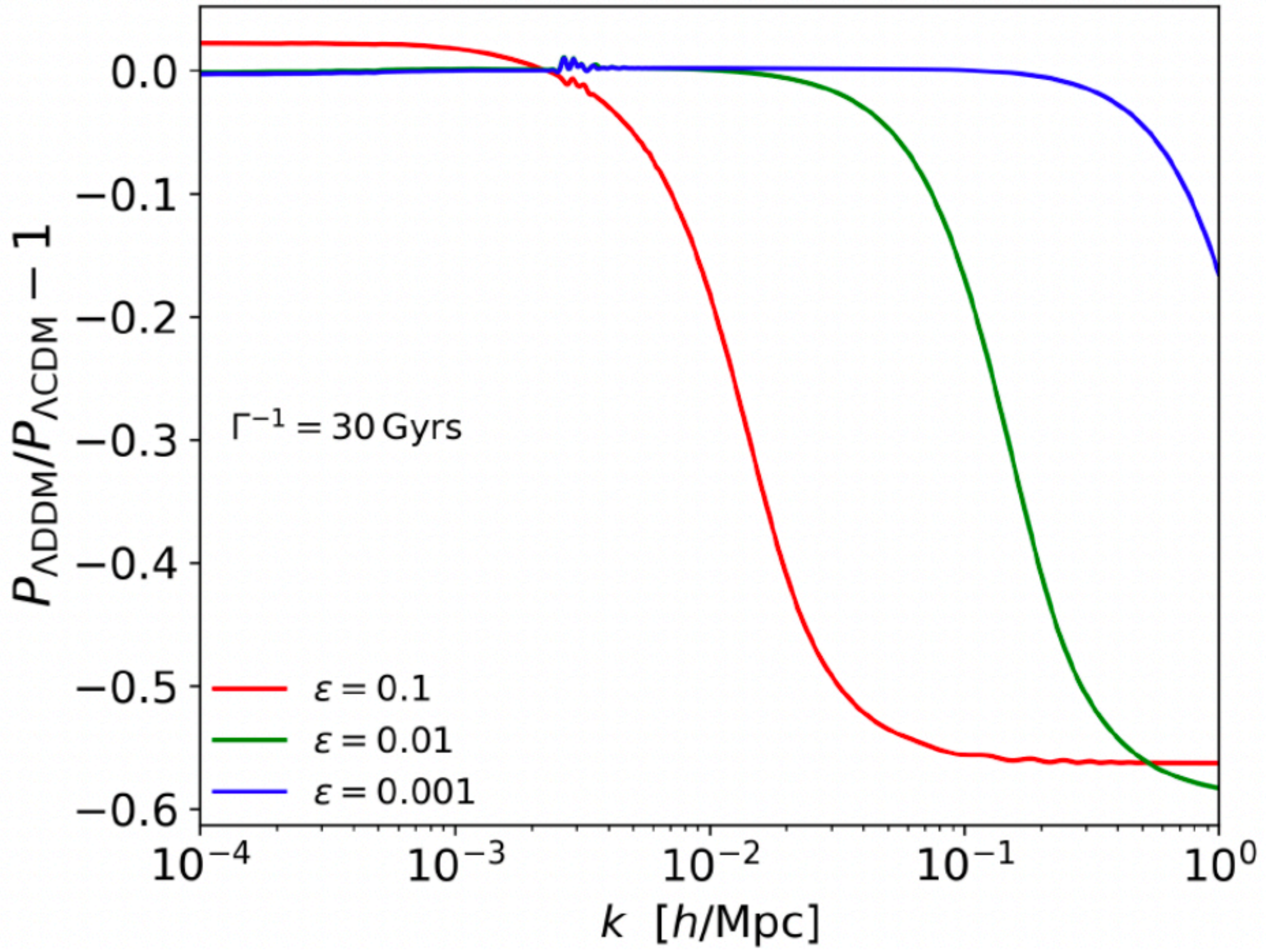

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this would require to run expensive ΛDDM simulations

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Use a **S_8 prior** instead (very simplistic, but should be seen as a **minimal test**)

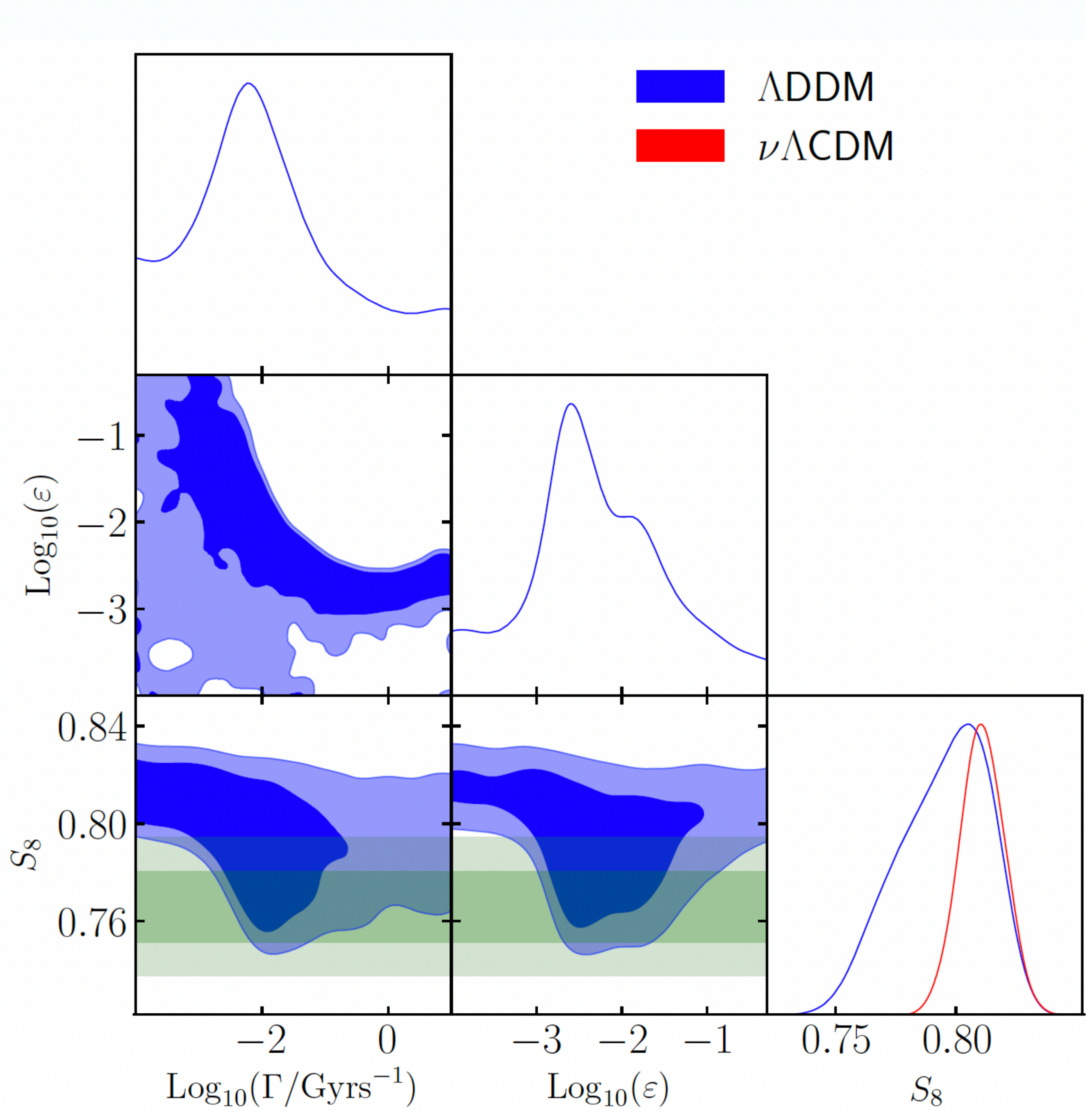
Explaining the S_8 tension

Reconstructed S_8 values are in **excellent agreement** with WL data

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

→ $\Delta\chi^2_{\rm min} = -5.5$

Planck18 + BAO + SNIa
+ S_8 (KiDS+BOSS+2dfLenS):



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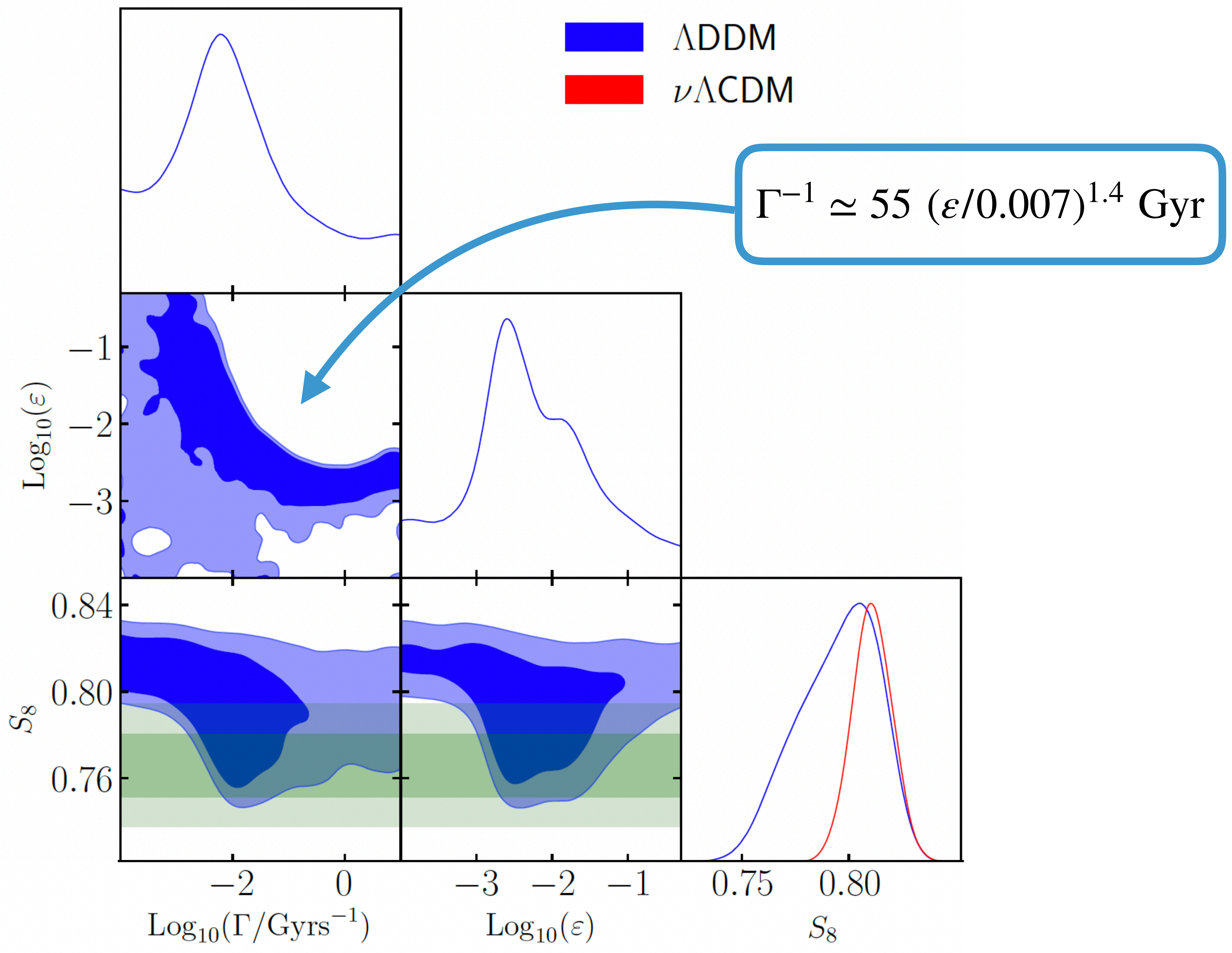
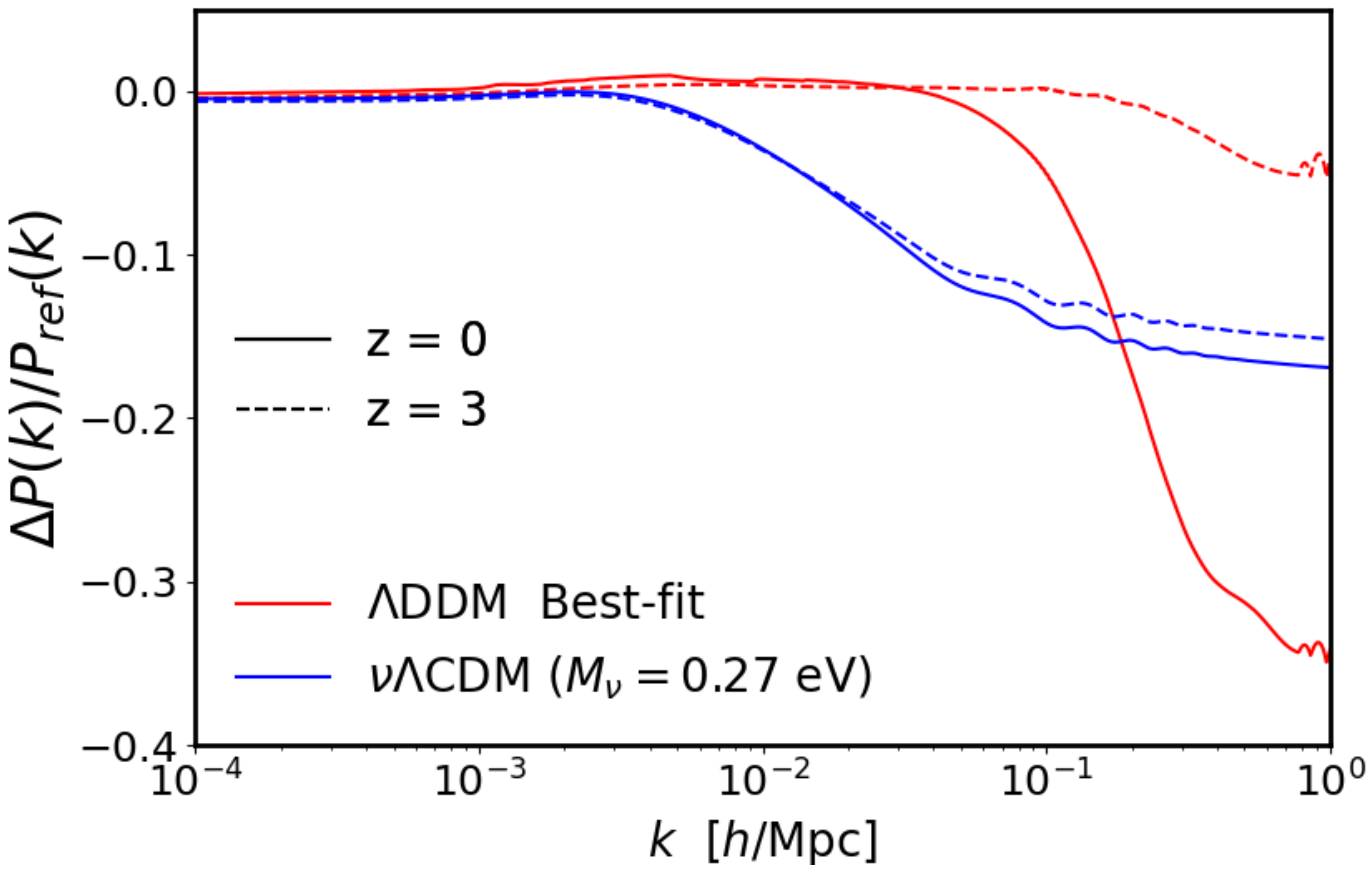


Why does the DDM model provide a better fit?



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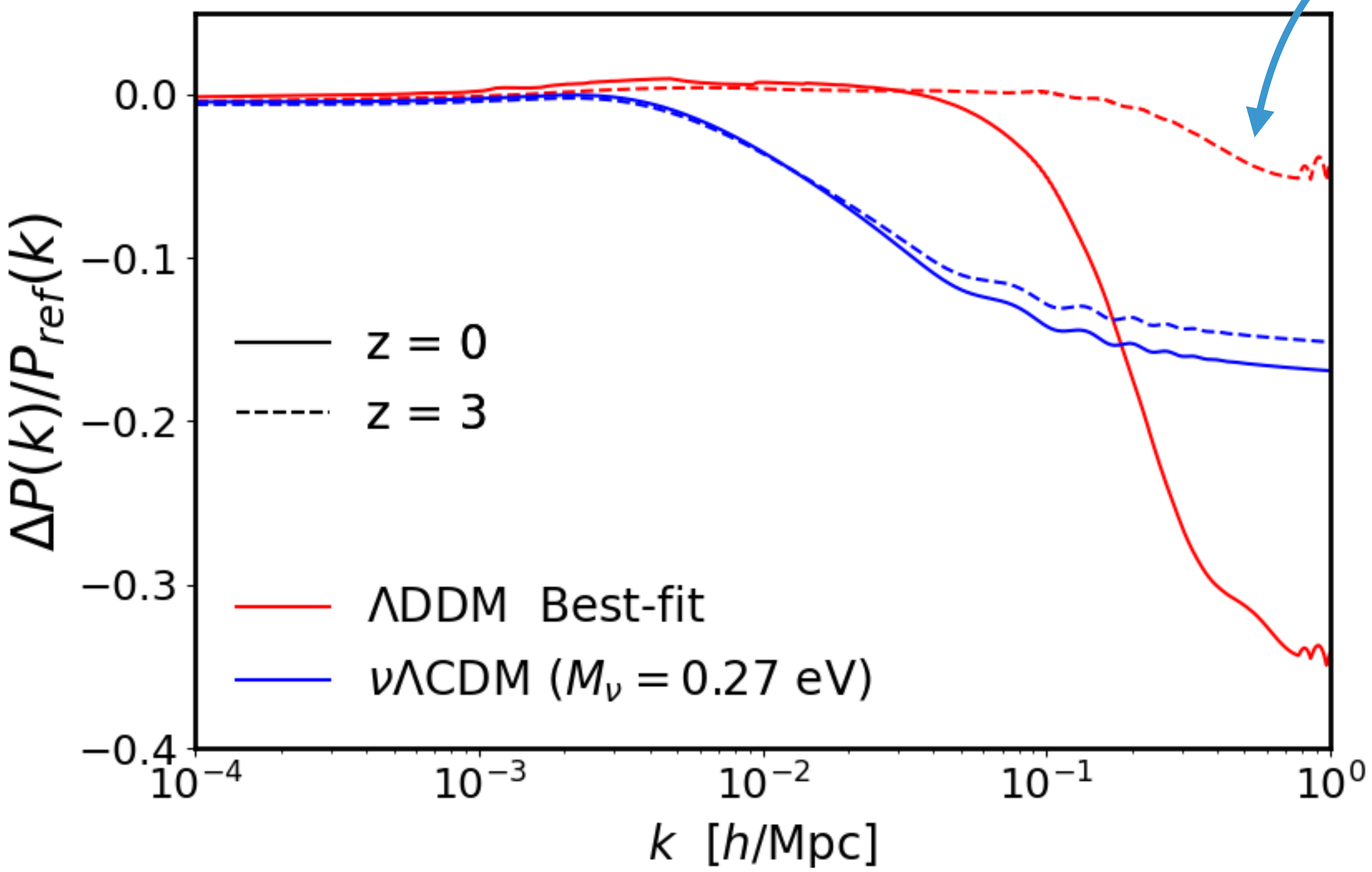

Lower suppression in the **past**

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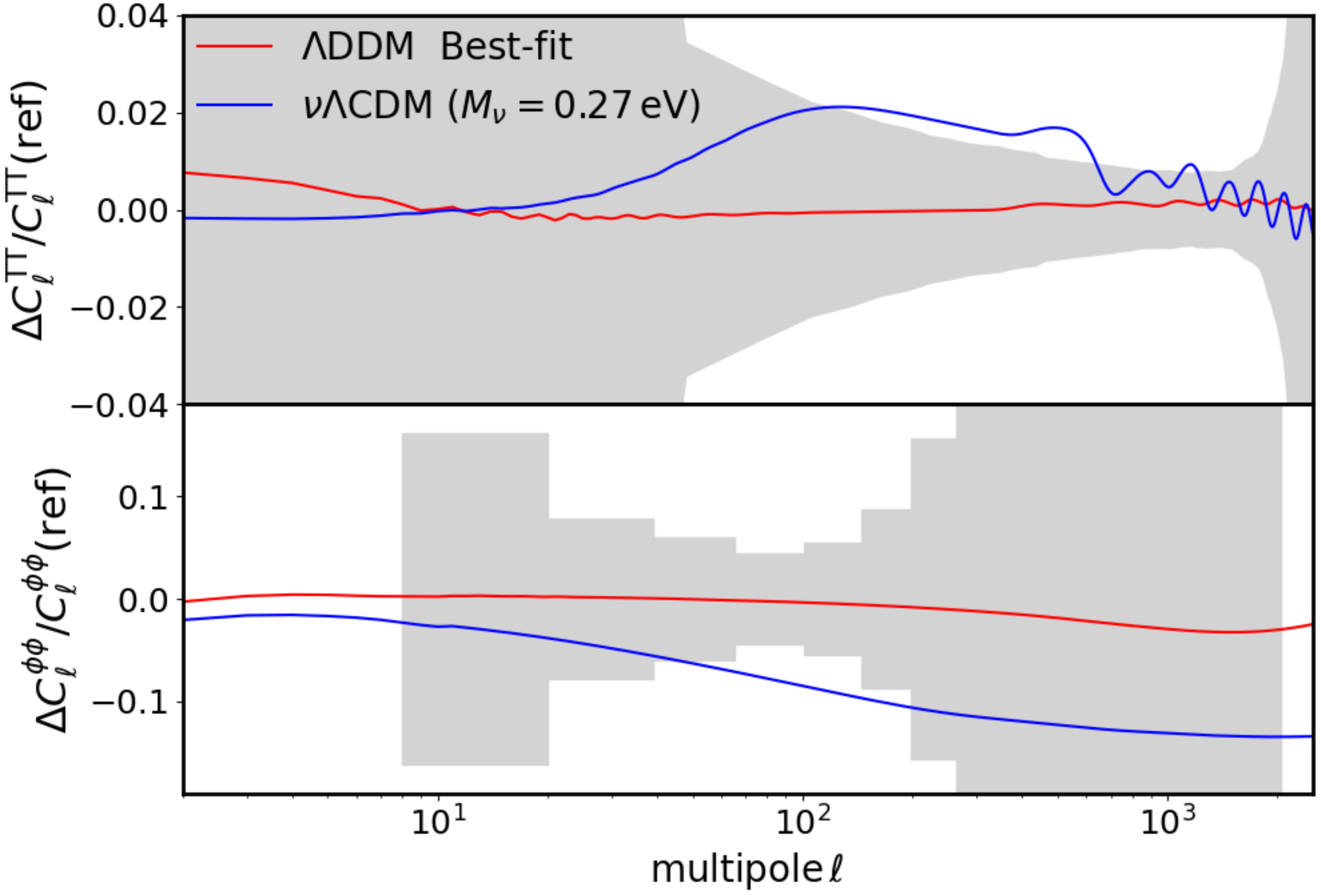

Time-dependence of DDM suppression allows for a better fit to CMB data

Prospects for DDM

- Run **DDM simulations**, to test model against **non-linear** observables like Cosmic Shear or Lyman-α forest

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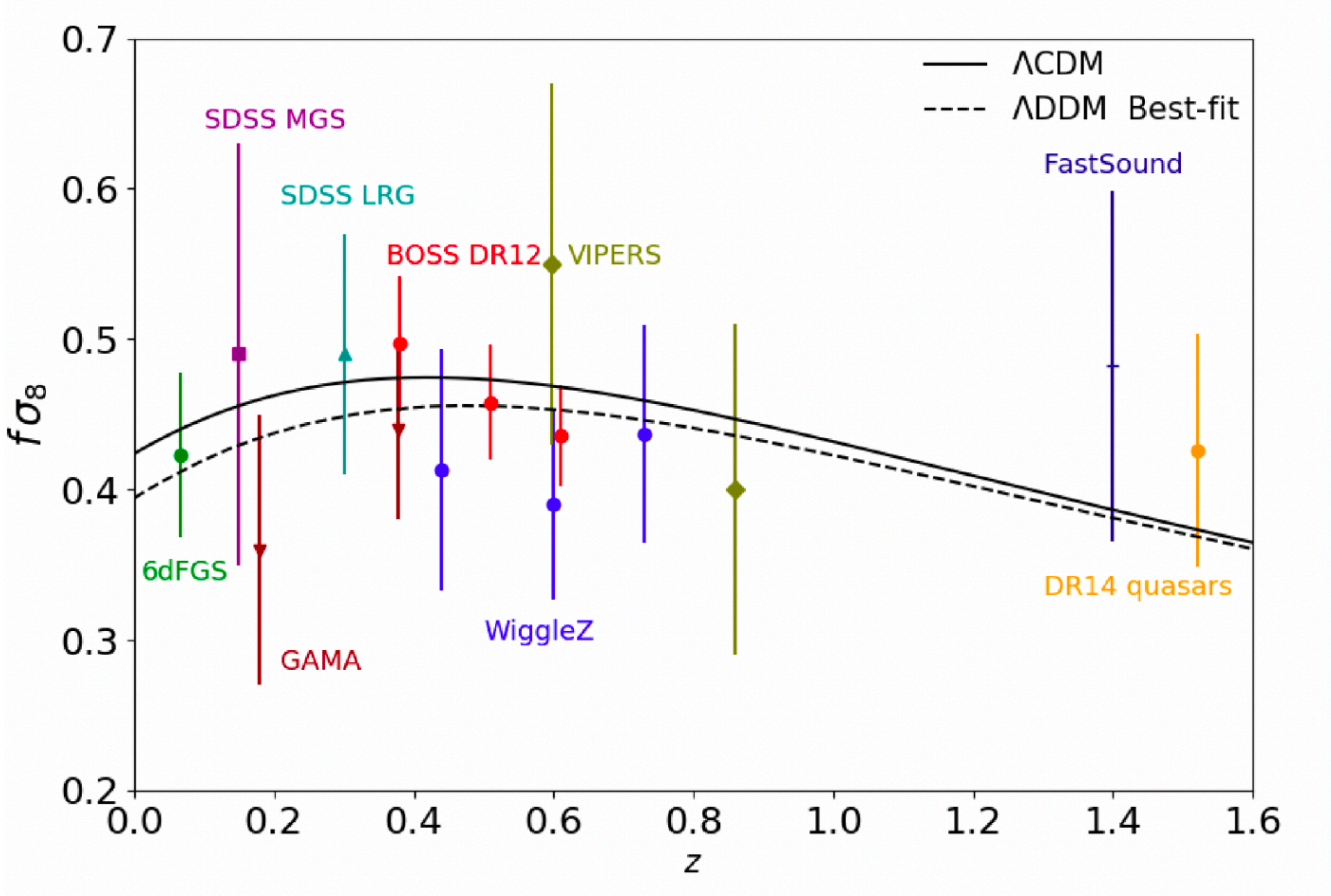
- **Future** accurate **CMB and LSS (Euclid, SKA)** data will be able to capture DDM signature

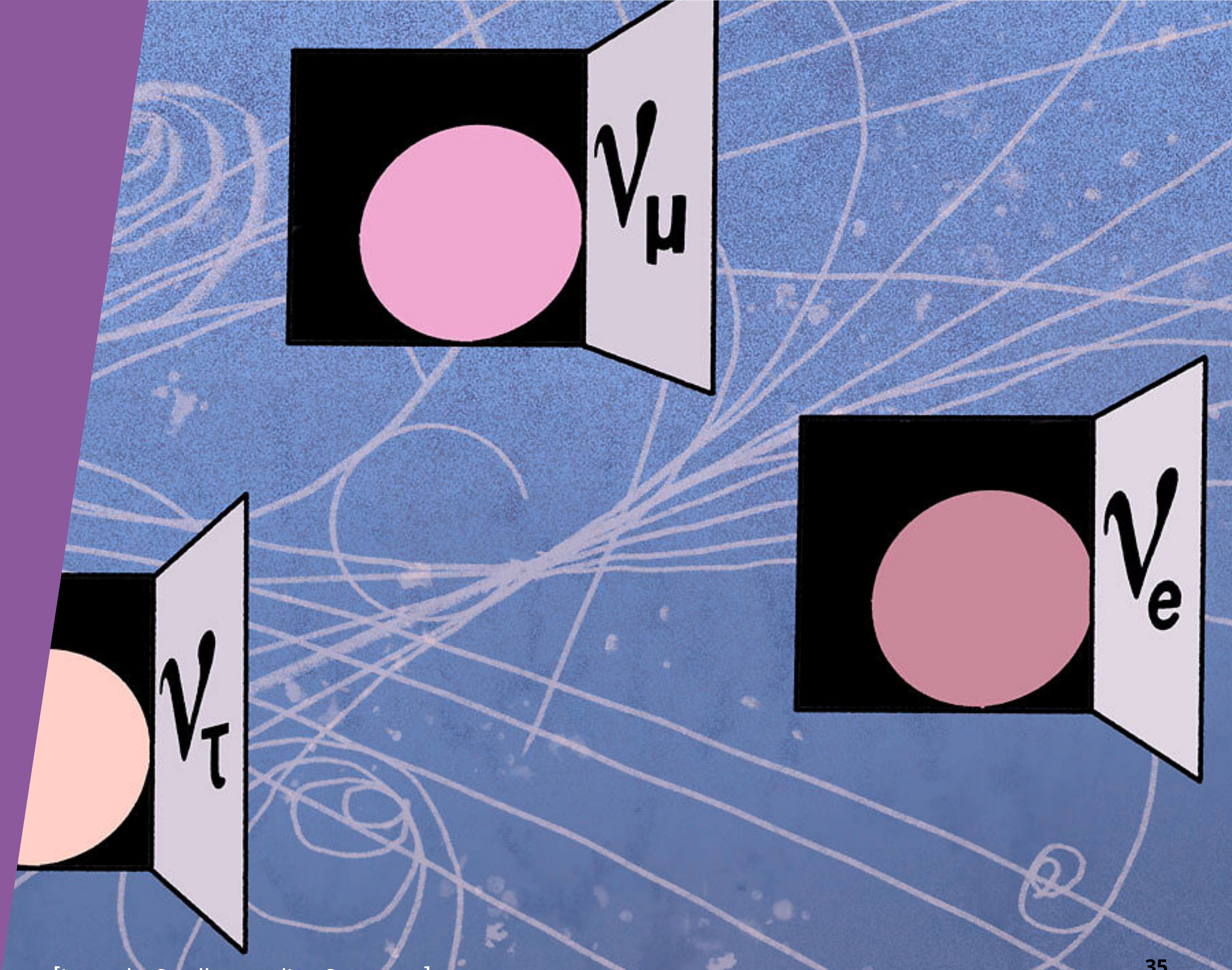


Part III:

DECAYING NEUTRINOS

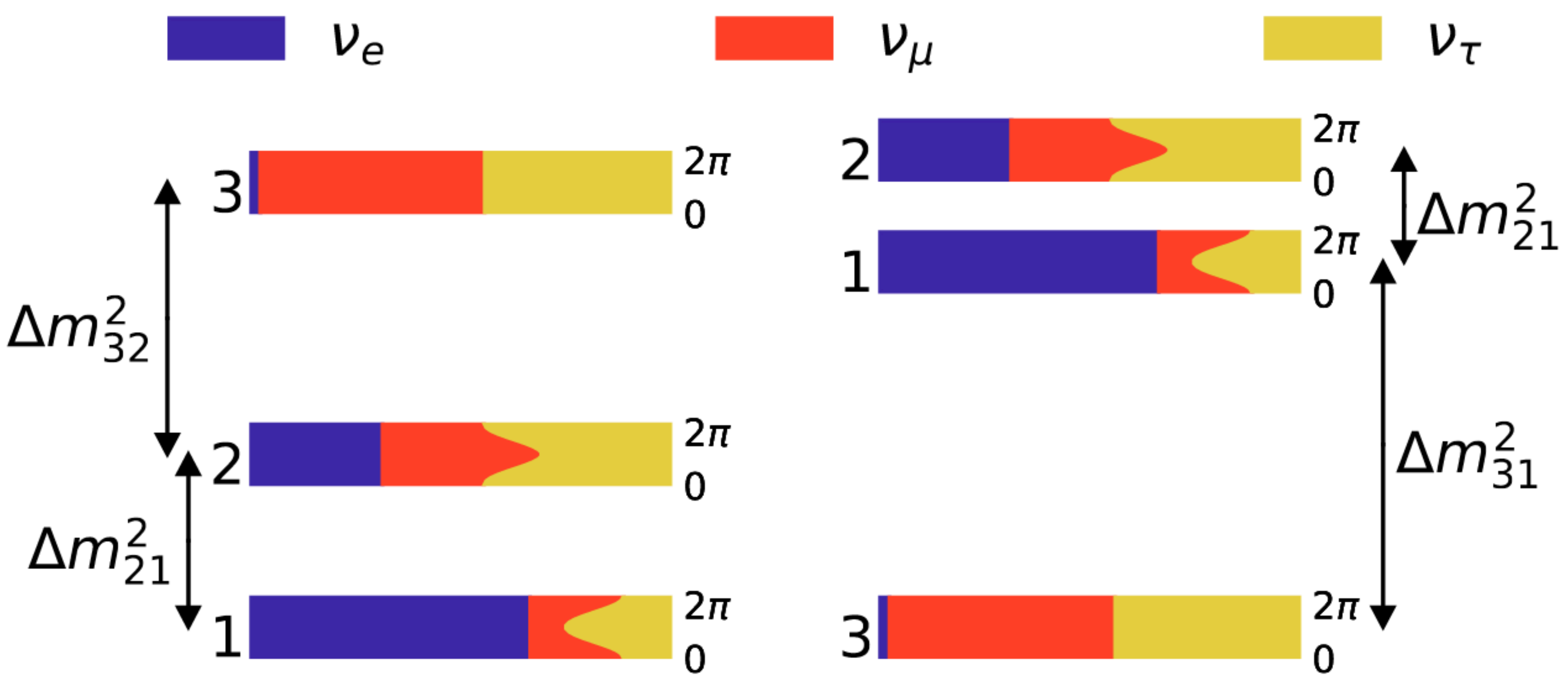
& THE NEUTRINO MASS BOUNDS

[GFA, Chacko, Dev, Du, Poulin, Tsai 2021 arXiv:2112.13862]



[Image by Sandbox studio - Symmetry]

Oscillation experiments have provided convincing evidence that **neutrinos have mass**



[Salas+ 18]

Normal

$$\sum m_\nu \gtrsim 0.06 \text{ eV}$$

Inverted

$$\sum m_\nu \gtrsim 0.10 \text{ eV}$$

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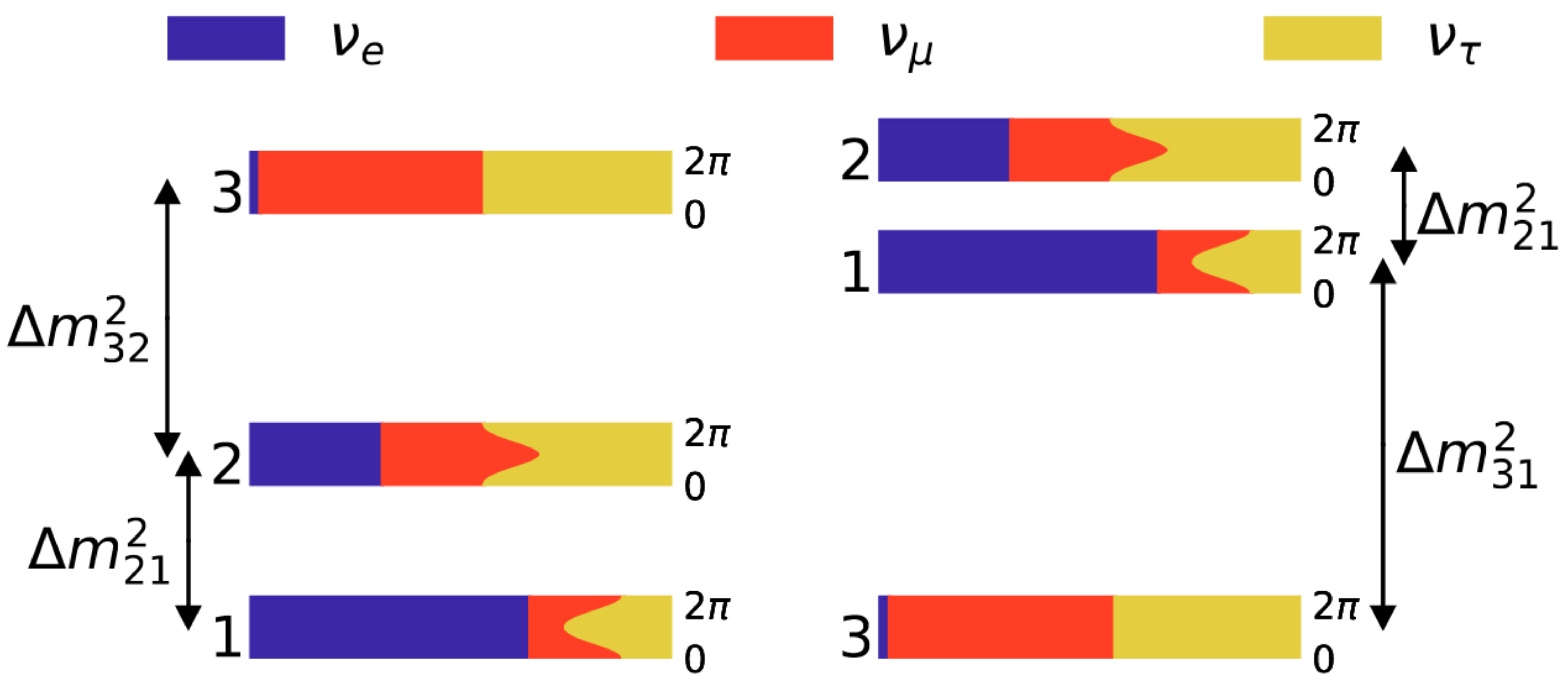

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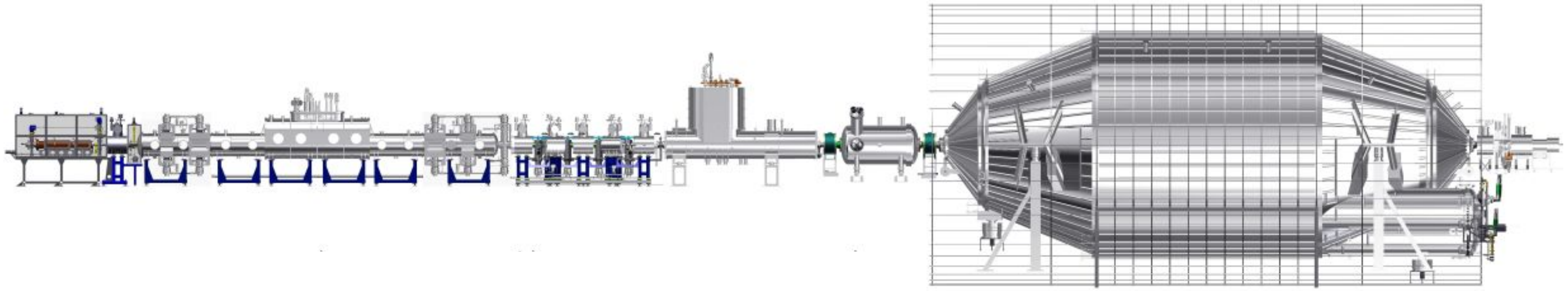
But what is the **absolute mass scale** of neutrinos ?

Laboratory bounds

KATRIN experiment

$$^3\mathrm{H} \longrightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$



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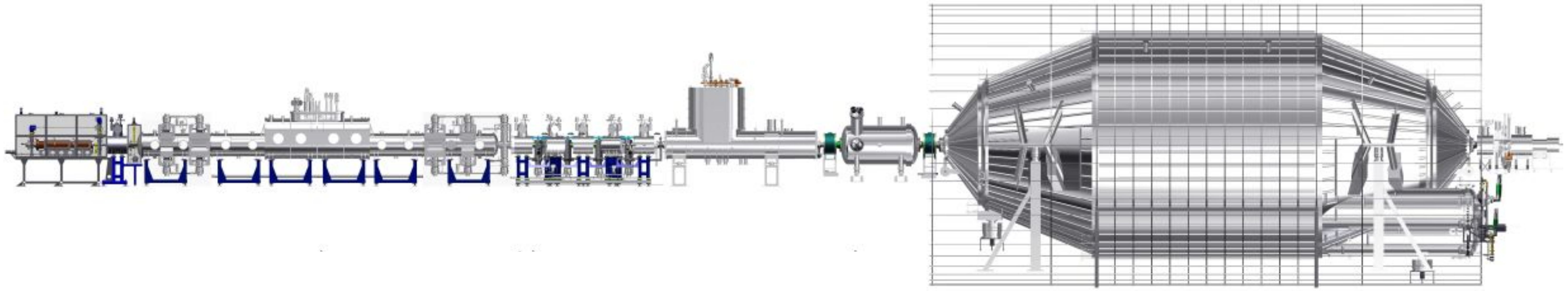

Current bounds

[KATRIN 21]

$$m_{\nu_e} < 0.8 \text{ eV}$$

$$\sum m_\nu < 2.4 \text{ eV}$$

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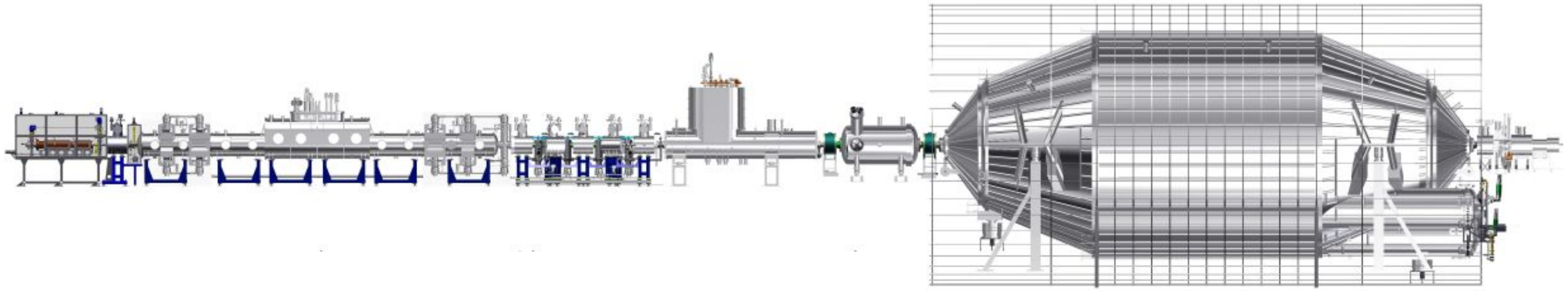

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[KATRIN 21]

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Expected KATRIN reach

(in ~3 years)

$$m_{\nu_e} < 0.2\ \mathrm{eV}$$
$$\sum m_\nu < 0.6\ \mathrm{eV}$$

Cosmological bounds

Cosmology provides the **strongest bounds** on $\sum m_\nu$

$$\boxed{\sum m_\nu < 0.12 \text{ eV}}$$

(Planck18 TTTEEE+ lensing + BAO)

…but these bounds are **model dependent**:

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CDM+m_ν+$w_0 w_a$	$\sum m_\nu < 0.25 \text{ eV}$	[Choudhury+ 19]
ΛCDM+m_ν+Ω_k	$\sum m_\nu < 0.15 \text{ eV}$	[Choudhury+ 19]
ΛCDM+m_ν+N_{eff}	$\sum m_\nu < 0.23 \text{ eV}$	[Planck 18]

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Constraints are rather **robust** upon **simple extensions**
What about changing **neutrino properties** ?

Decaying neutrinos

- 2 neutrinos decay **in the SM** but $\tau_\nu \sim (G_F^2 m_\nu^5)^{-1} \gtrsim 10^{33}$ yr $\gg t_U$

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[Aalberts+ 18]

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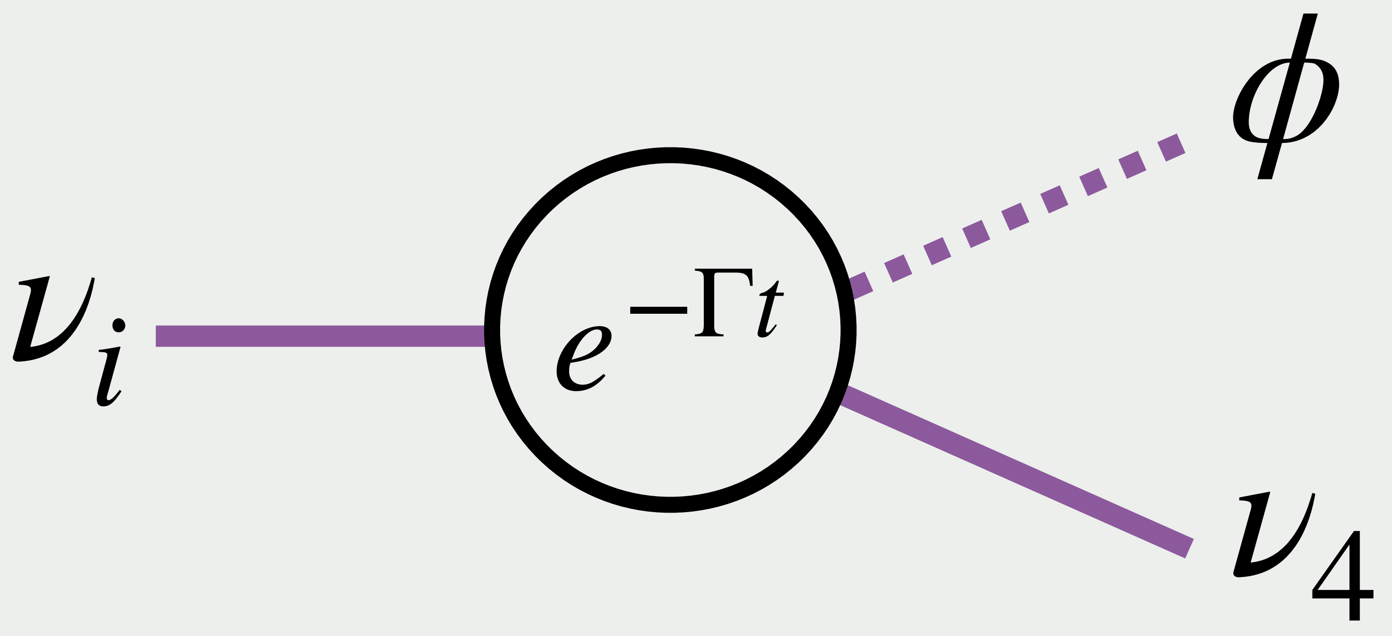
  [Aalberts+ 18]

- Decays to **dark radiation**, much less constrained



Appears naturally in many neutrino mass models

[Escudero+ 20]

Lifetime bounds on invisible neutrino decays

ν

- Long-based line exp. $\tau_\nu > 10^{-14}$ sec
- Supernovae $\tau_\nu > 10$ hrs
- CMB (neutrino free-streaming) $\tau_\nu > 10$ mths

[Barenboim+ 20]

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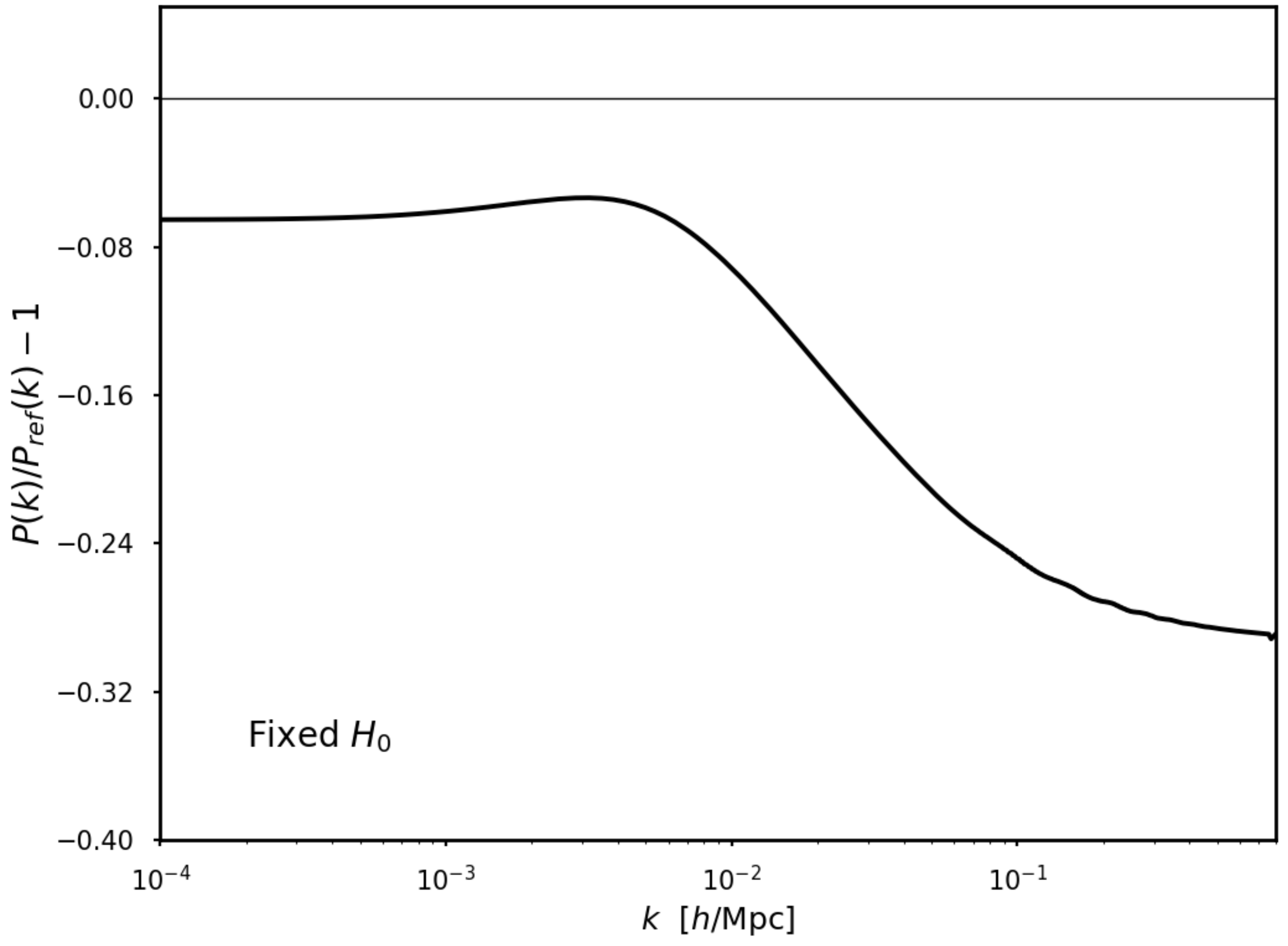
[Barenboim+ 20]

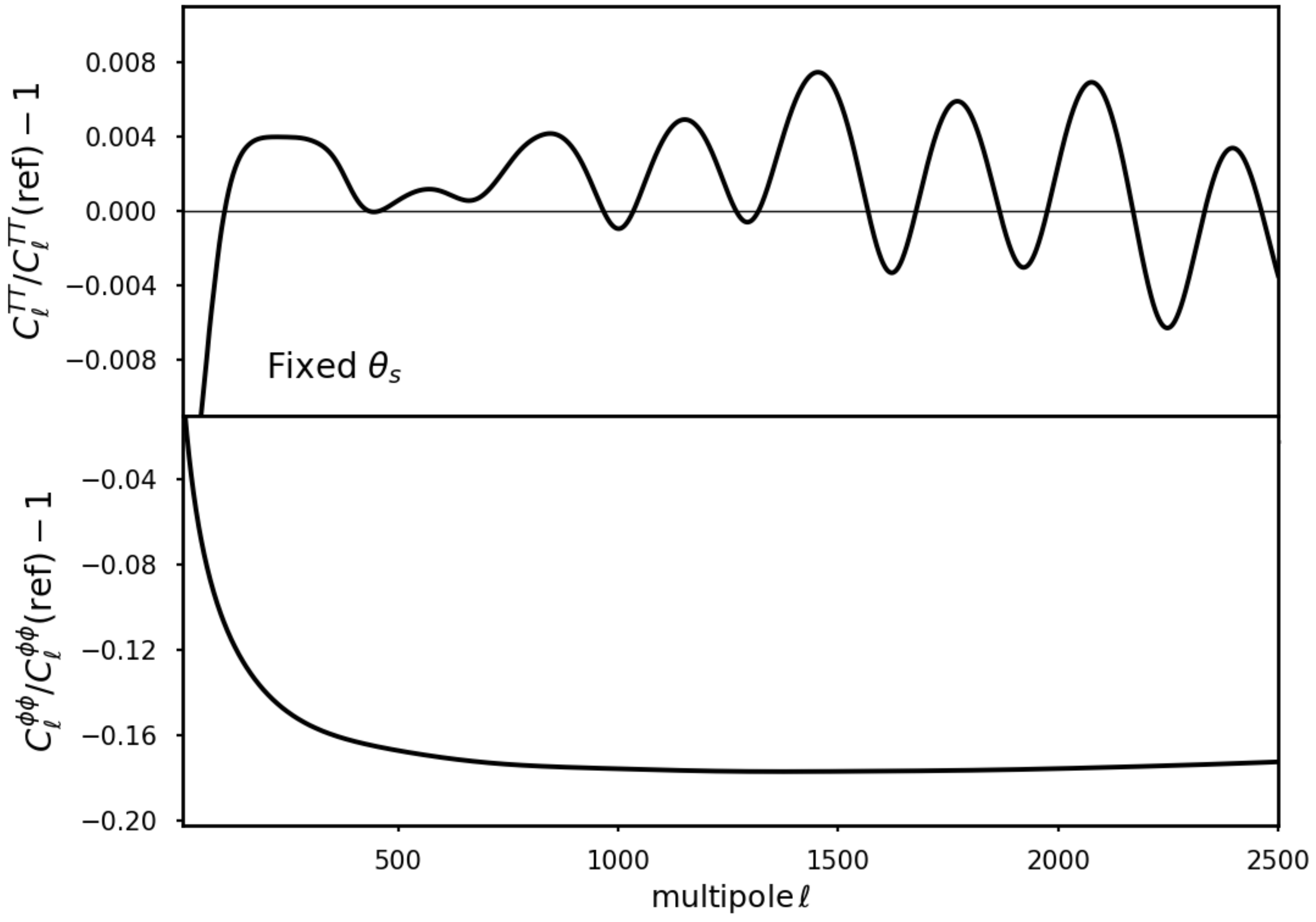
We consider neutrinos decaying much later, when already non-relativistic

Decaying neutrinos **reduce their impact** on structure formation

$\sum m_\nu = 0.6$ eV

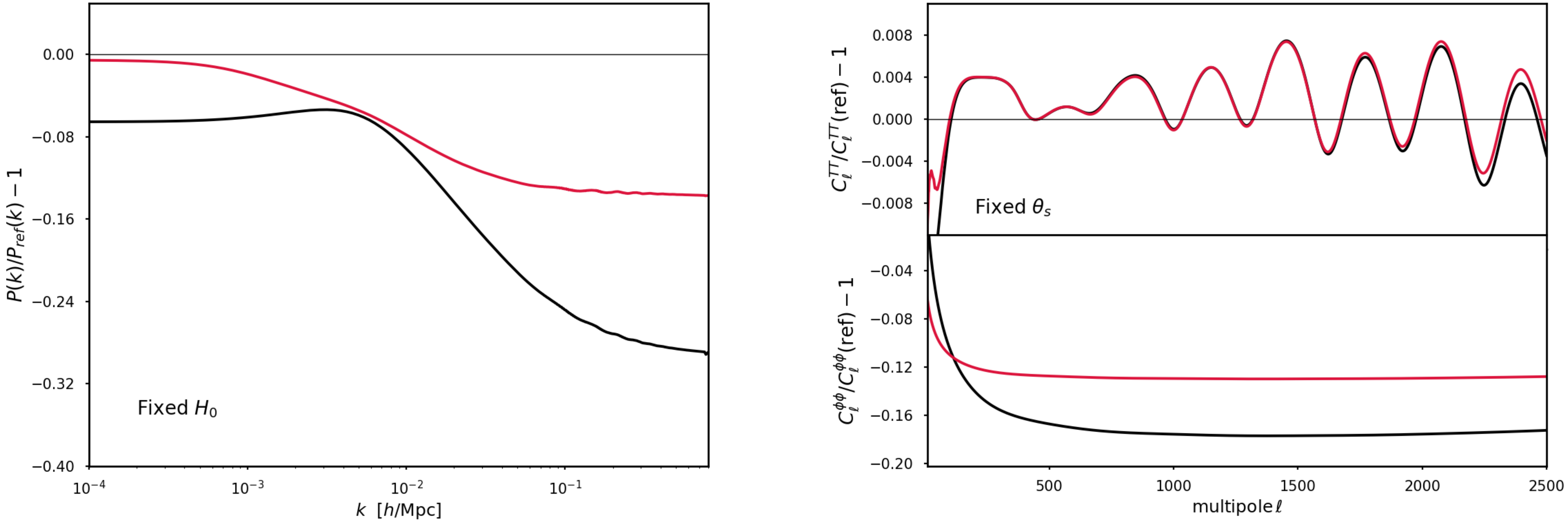
Stable



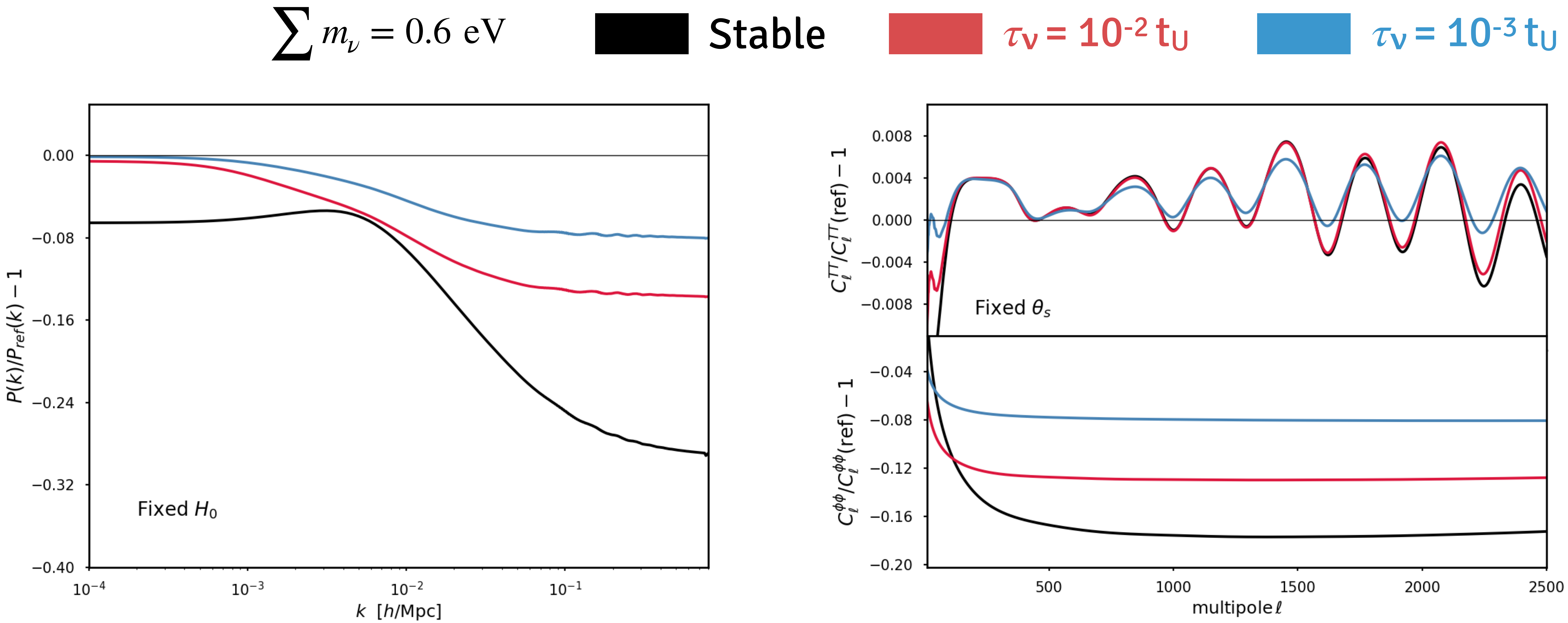


Decaying neutrinos **reduce their impact** on structure formation

$\sum m_\nu = 0.6$ eV — Stable — $\tau_\nu = 10^{-2}\, t_U$



Decaying neutrinos **reduce their impact** on structure formation



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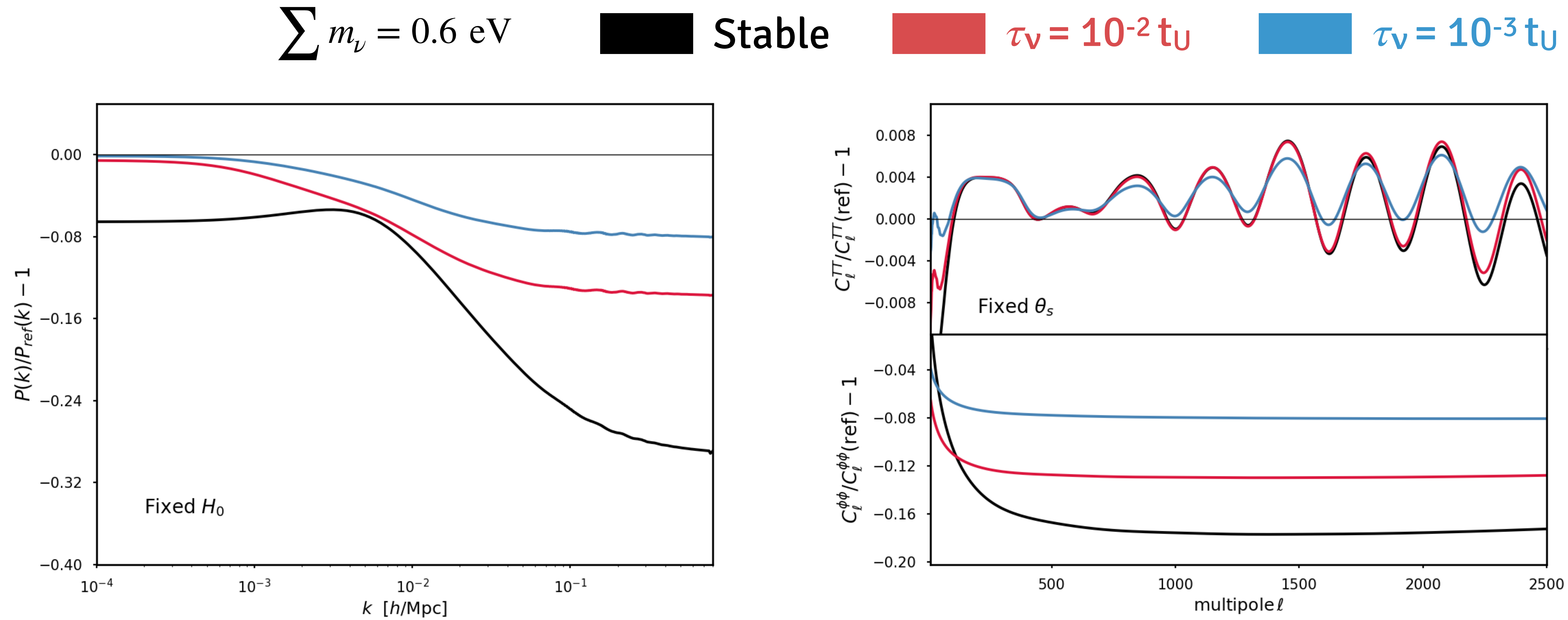
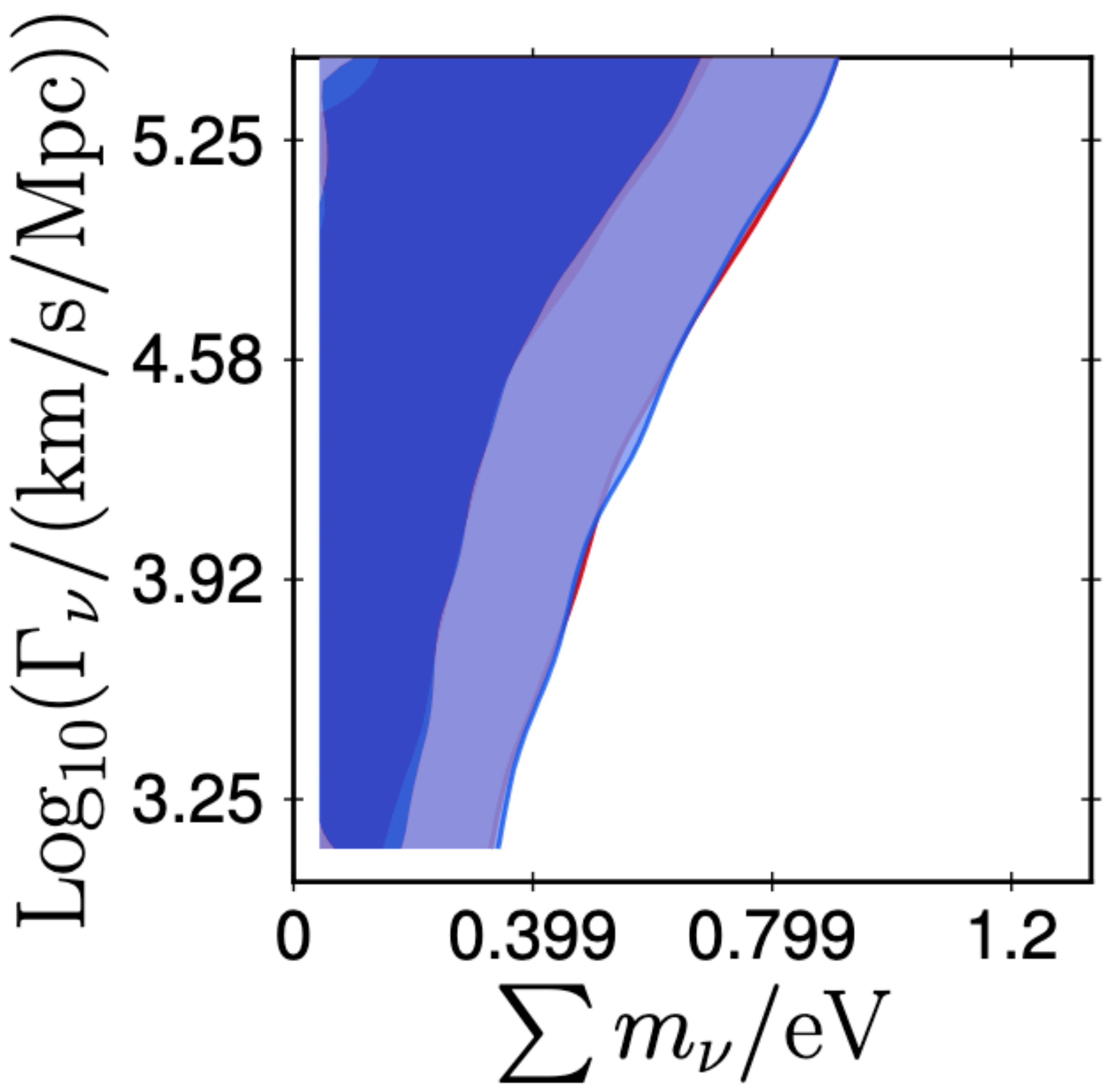


This m_ν-Γ_ν degeneracy can be exploited to relax neutrino mass bounds

Decaying neutrinos can relax mass bounds up to $\sum m_\nu < 0.9$ eV reconciling cosmic observations with a potential signal at KATRIN

Planck15 + BAO + SNIa:



[Chacko+ 19]

Improvement of the m_ν-Γ_ν bounds

- Ameliorate **Boltzmann** treatment
- **Update data** from Planck15 to Planck18

Approx. background **p.s.d.** for neutrinos

$$\bar{f}_\nu(q,\tau) \simeq \bar{f}_{\rm ini}(q) e^{-\Gamma_\nu t/\gamma}$$

Collision terms in DR hierarchy
only included at ***ℓ*=0**

$$F'_{{\rm dr},0} = \ \dots \ + \ C_0,$$

$$F'_{{\rm dr},1} = \ \dots$$

$$F'_{{\rm dr},2} = \ \dots$$

$$F'_{{\rm dr},\ell>2} = \ \dots$$

Old Boltzmann treatment

Approx. background **p.s.d.** for neutrinos

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Old Boltzmann treatment

New Boltzmann treatment

Full background **p.s.d**. for neutrinos

$$\bar{f}_\nu(q,\tau) = \bar{f}_{\rm ini}(q) e^{-\Gamma_\nu \int_{\tau_i}^{\tau} d\tau' a/\gamma(a)},$$

Collision terms in DR hierarchy included up to **ℓ=3**

$$F'_{{\rm dr},0} = \ \dots\ + \ C_0,$$
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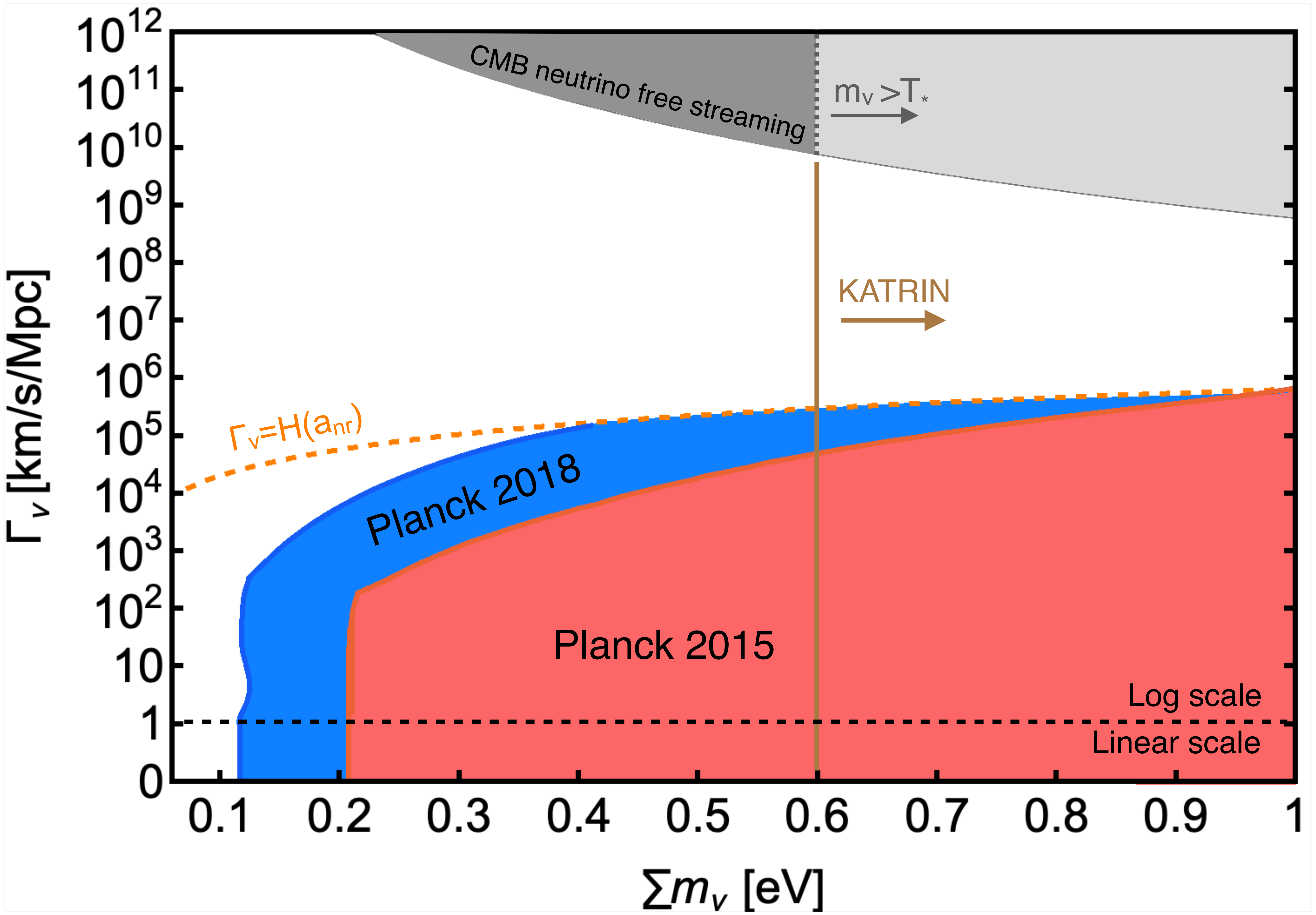
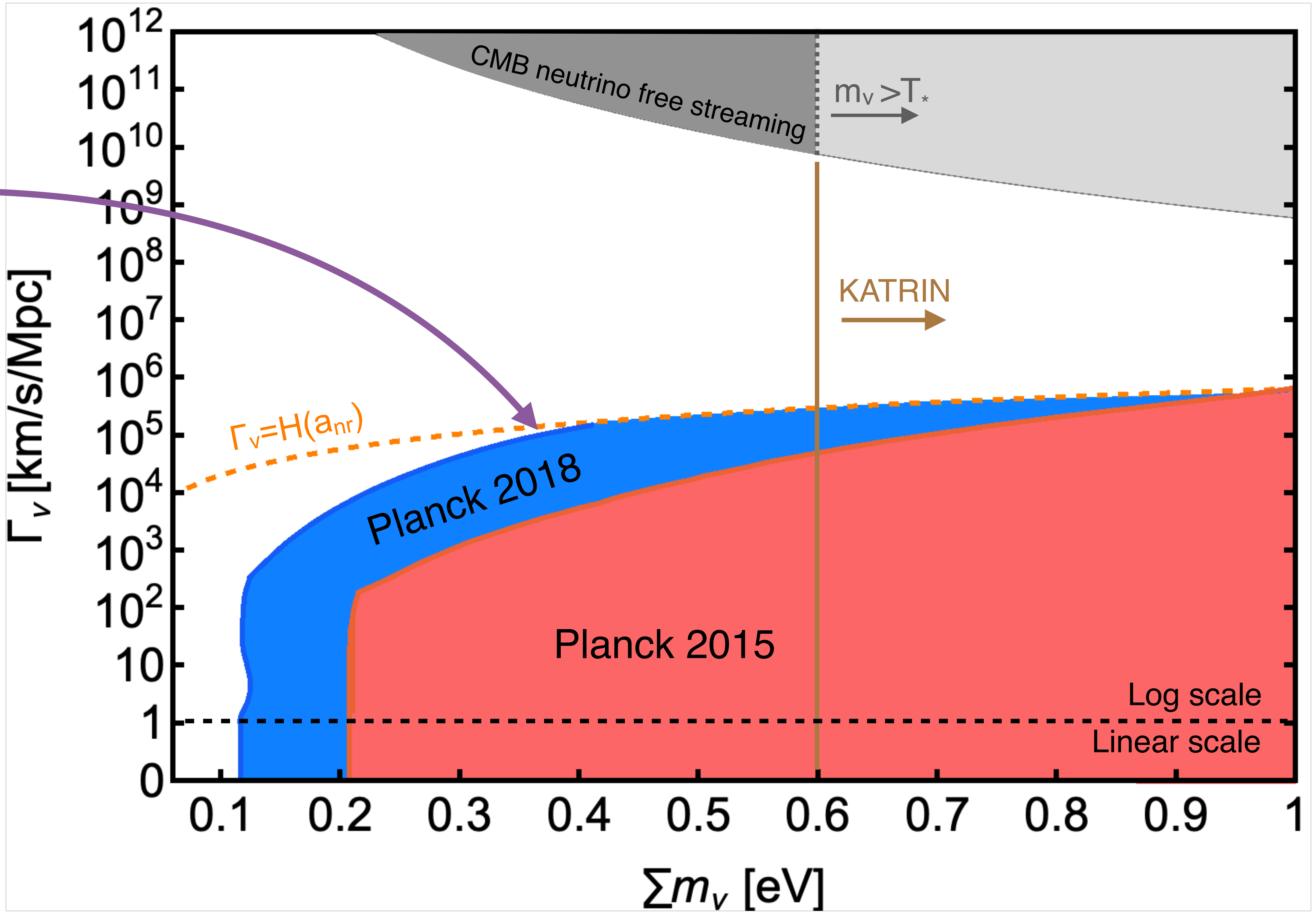
New corrections are **relevant** for **semi-relativistic decays**, and will be important for future experiments

Updated bounds with Planck18 + BAO + SNIa



Updated bounds with Planck18 + BAO + SNIa

Non-relativistic neutrino decays now **only allow masses** up to $\sum m_\nu < 0.4$ eV



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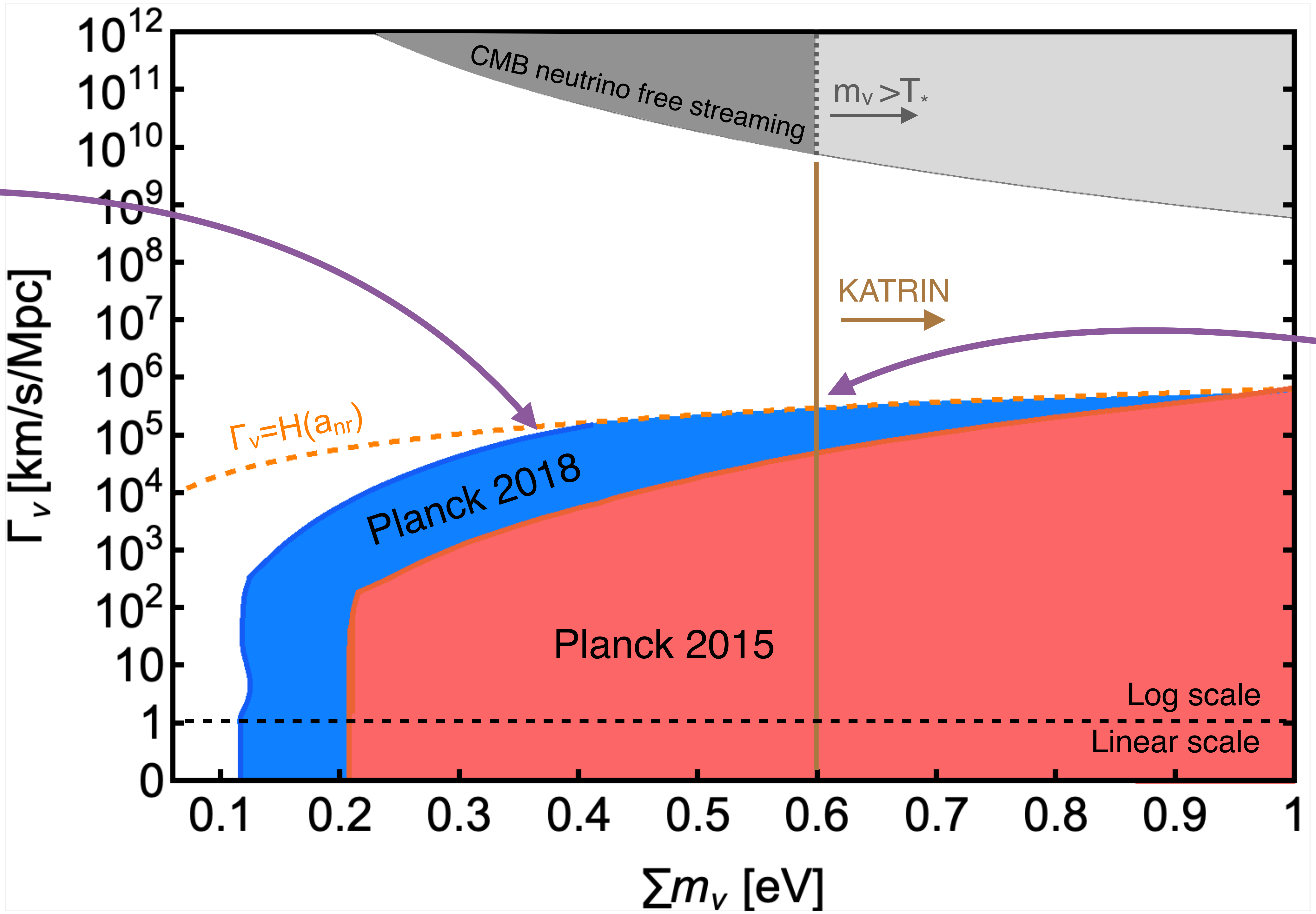
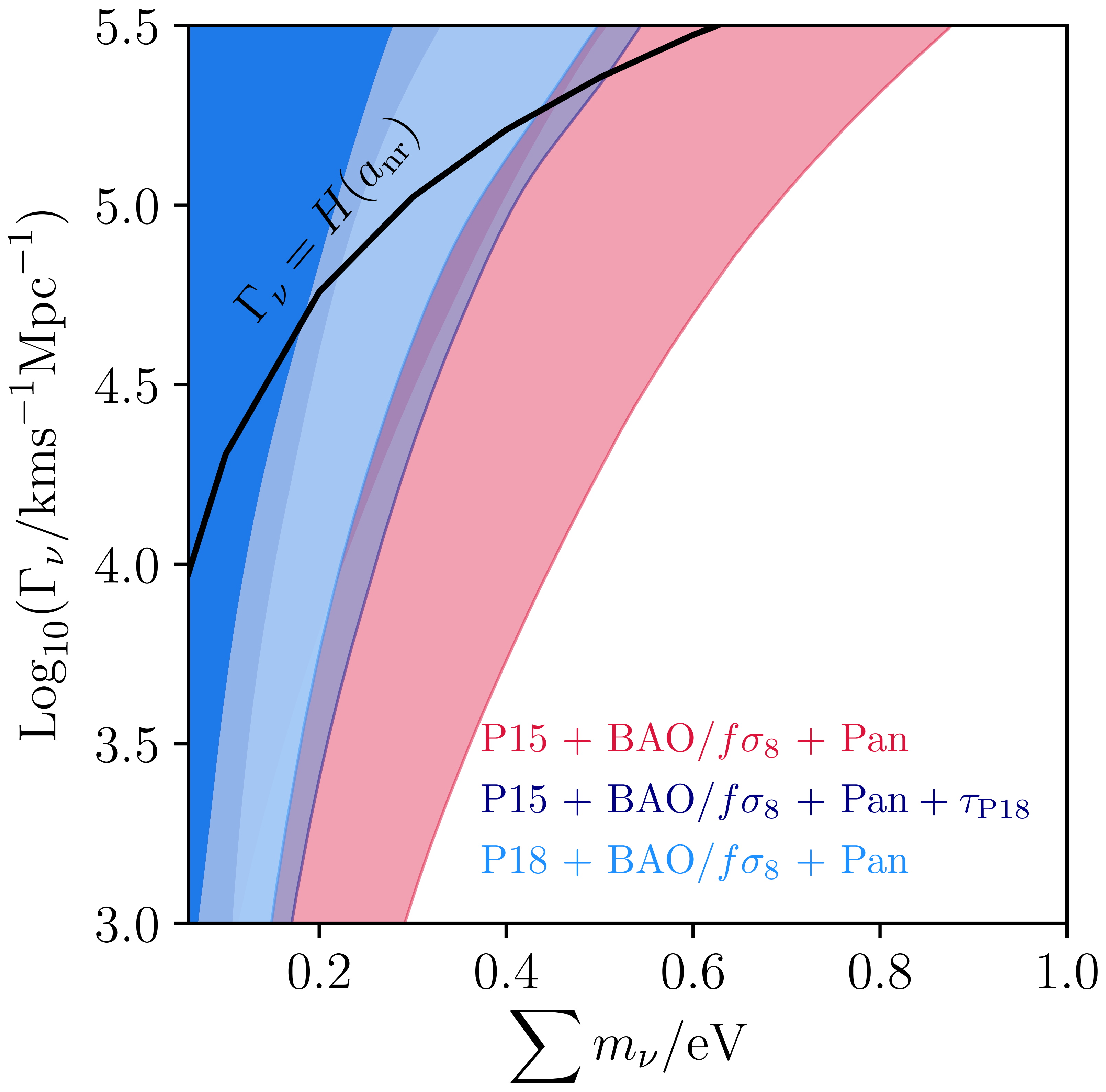


For recovering **compatibility with KATRIN**, we need to go **out** of our **regime of validity**

Why has the bound tighten so much ?

- The **more precise EE** data from Planck18 allows for a **better determination of τ_{reio}, and hence of A_s,** breaking the degeneracy arising from large m_ν on the **amplitude** of the **CMB lensing** spectrum



Prospects for neutrino decay

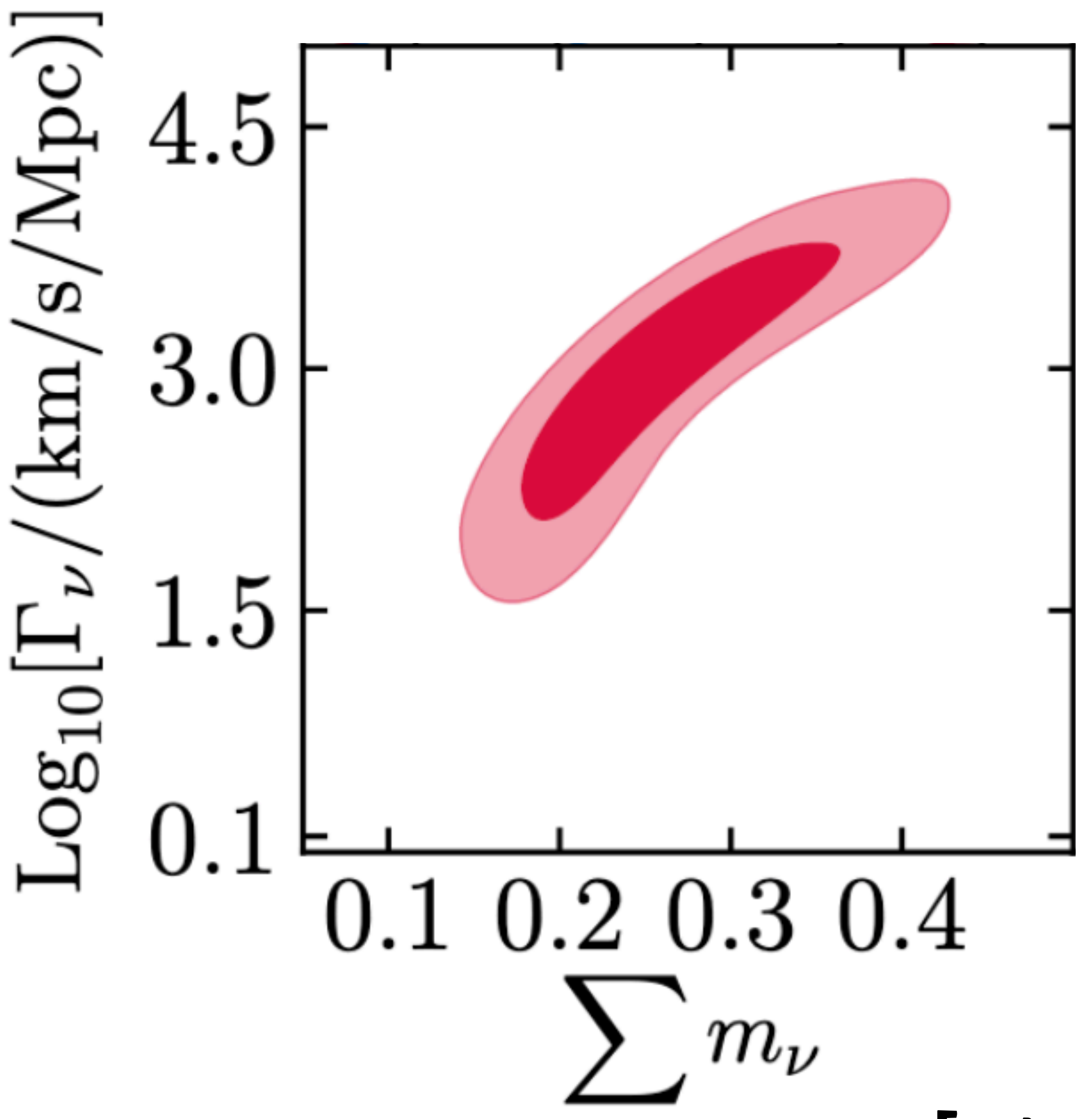
- **Extend analysis to relativistic regime,** to confirm whether decaying neutrinos can **reconcile cosmic and laboratory** measurements

Prospects for neutrino decay

- **Extend analysis to relativistic regime,** to confirm whether decaying neutrinos can **reconcile cosmic and laboratory** measurements

- **Future tomographic** measurements of P(k) by Euclid or SKA will allow an **independent determination** of the neutrino **mass and lifetime**

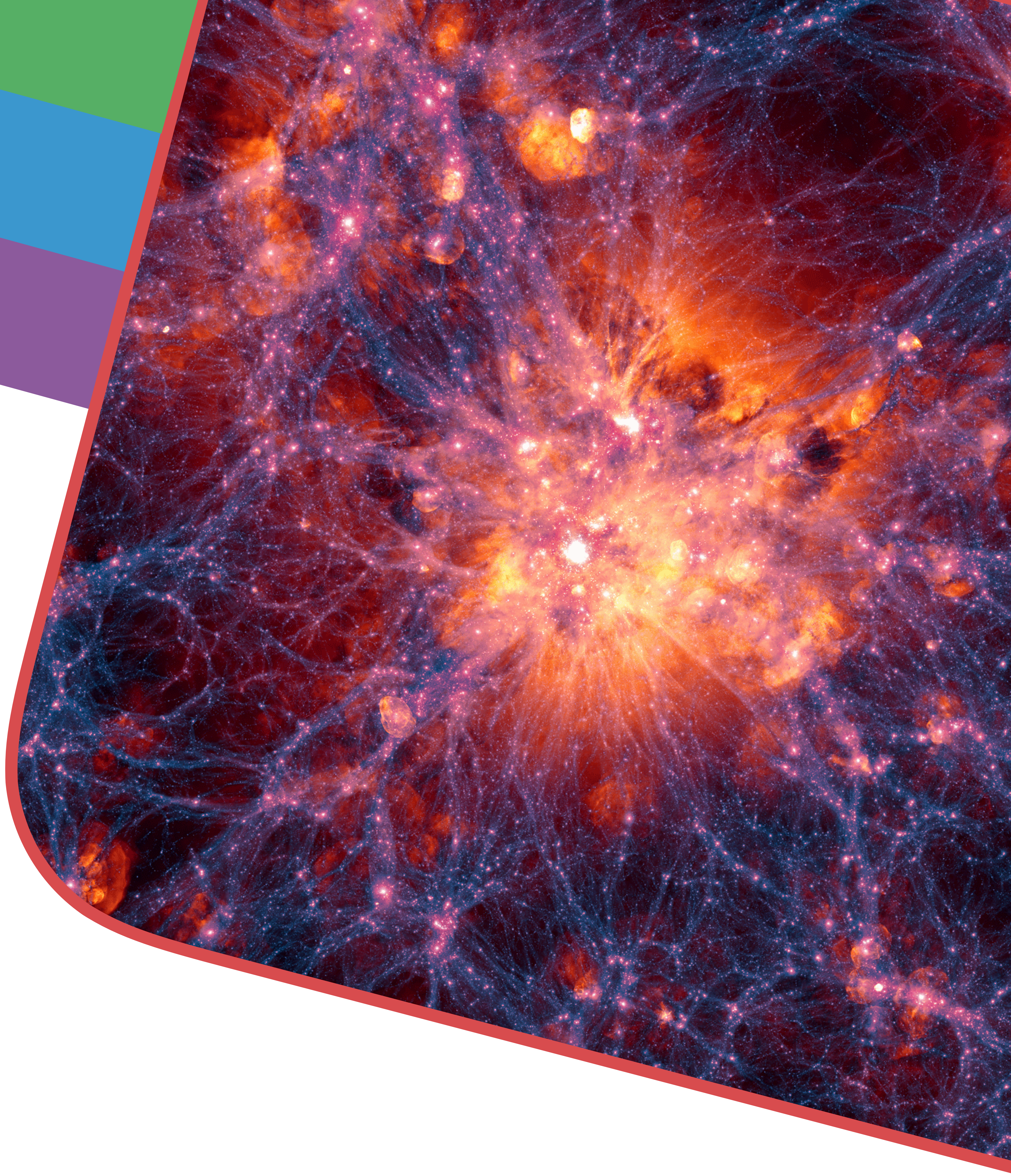
Planck + Euclid forecast



[Chacko+ 20]

Conclusions

- We have put **novel constraints** on several ΛCDM extensions, focusing on unstable relic particles



Conclusions

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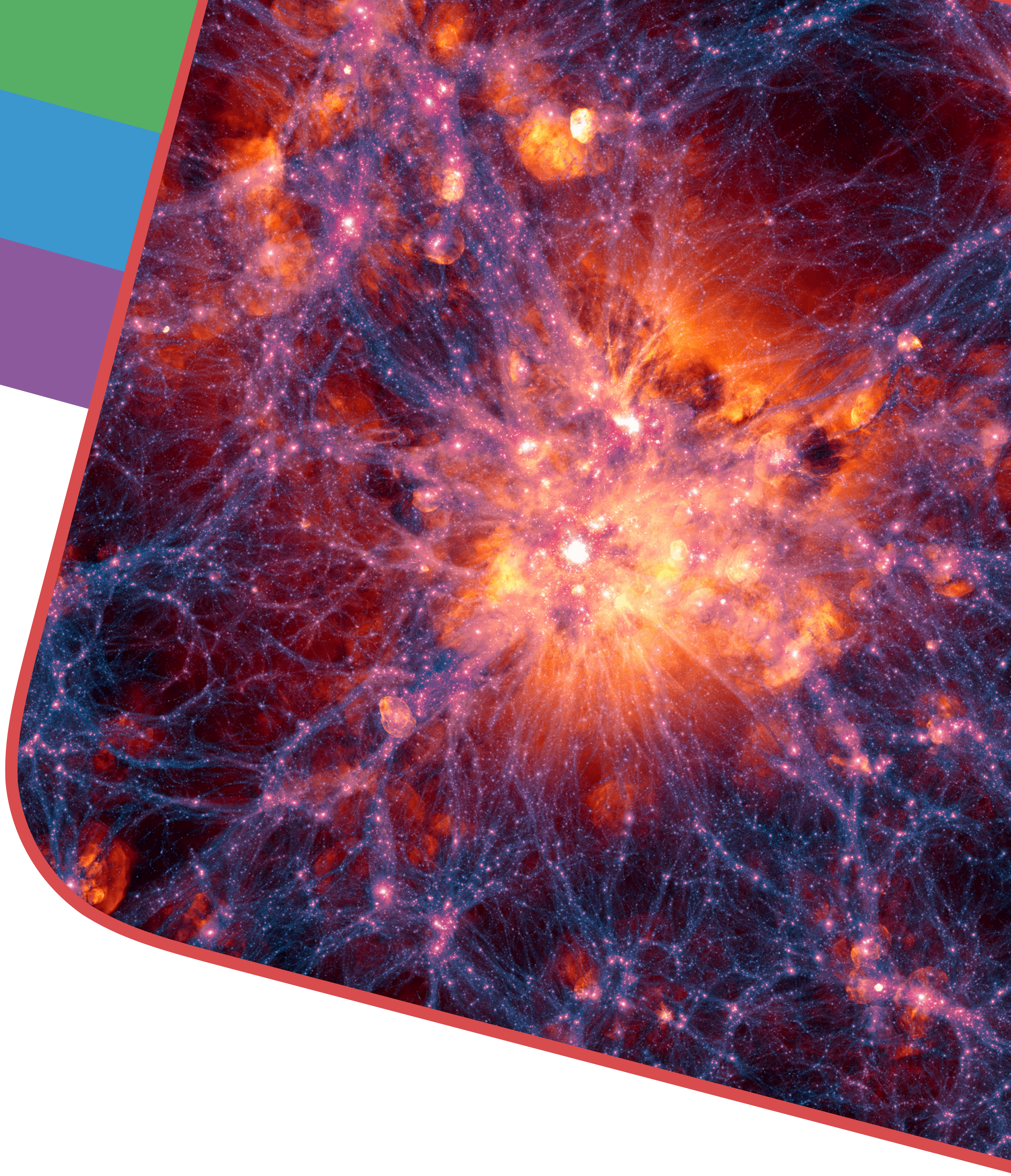
- We have shown that the most **promising solutions** to the H_0 tension **fail at** explaining the **S_8 tension.** The latter anomaly can be successfully addressed with **Decaying Dark Matter**



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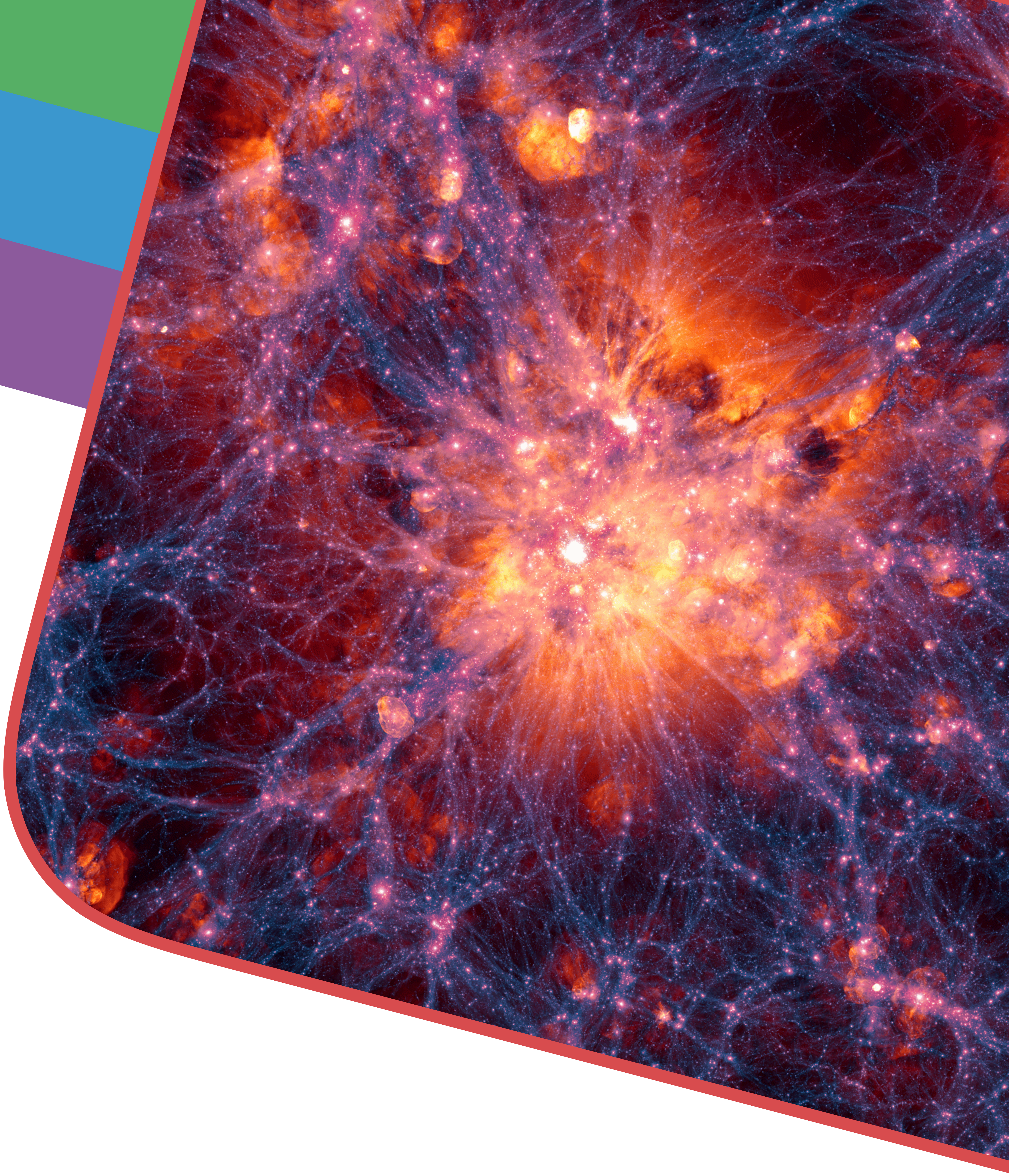
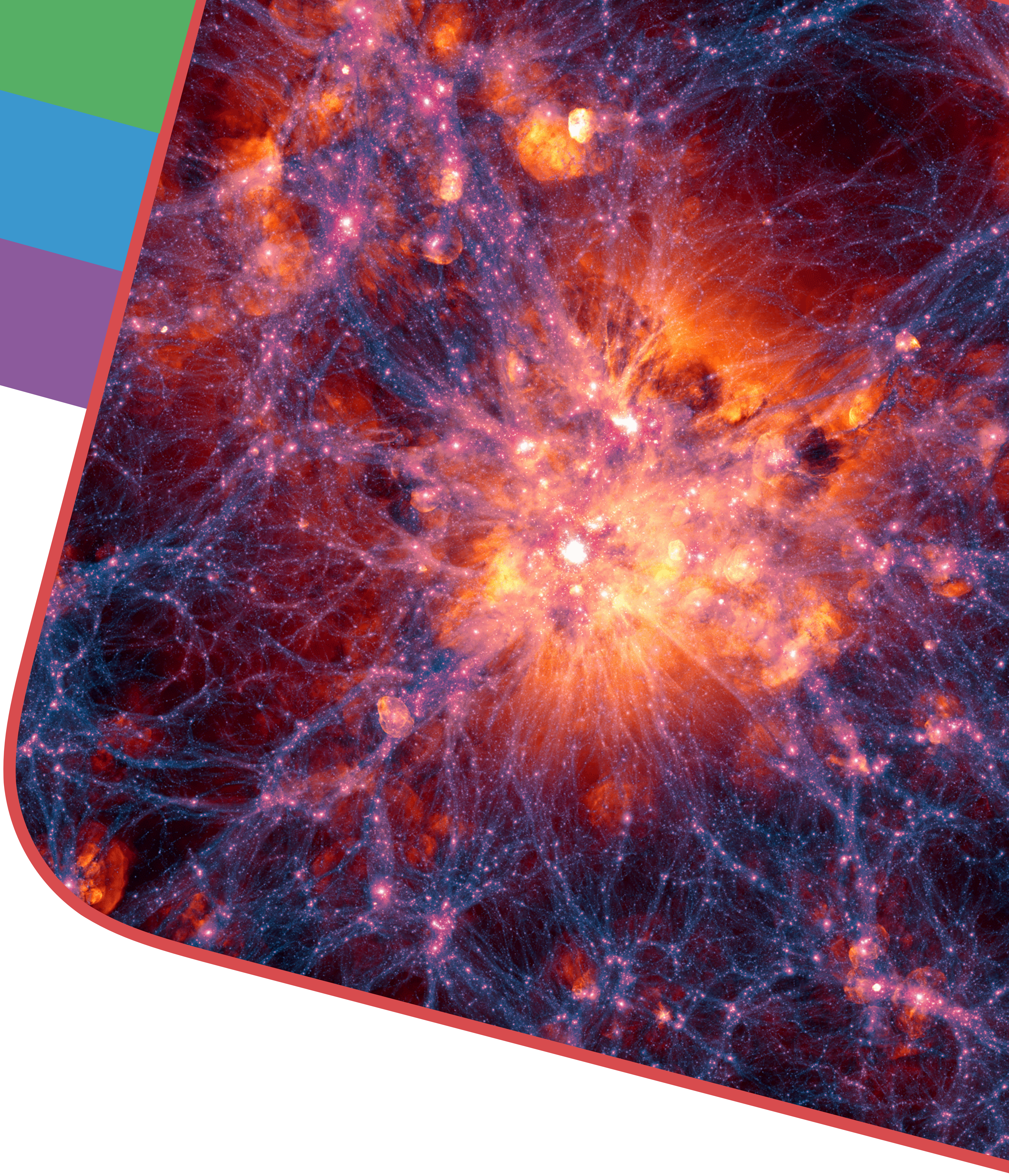


Conclusions

- We have put **novel constraints** on several ΛCDM extensions, focusing on unstable relic particles
- We have shown that the most **promising solutions** to the H_0 tension **fail at** explaining the **S_8 tension.** The latter anomaly can be successfully addressed with **Decaying Dark Matter**
- We have seen that **unstable neutrinos** can significantly **relax neutrino mass bounds**
- Future **accurate CMB and LSS** data will be able to **capture the signature** of these scenarios



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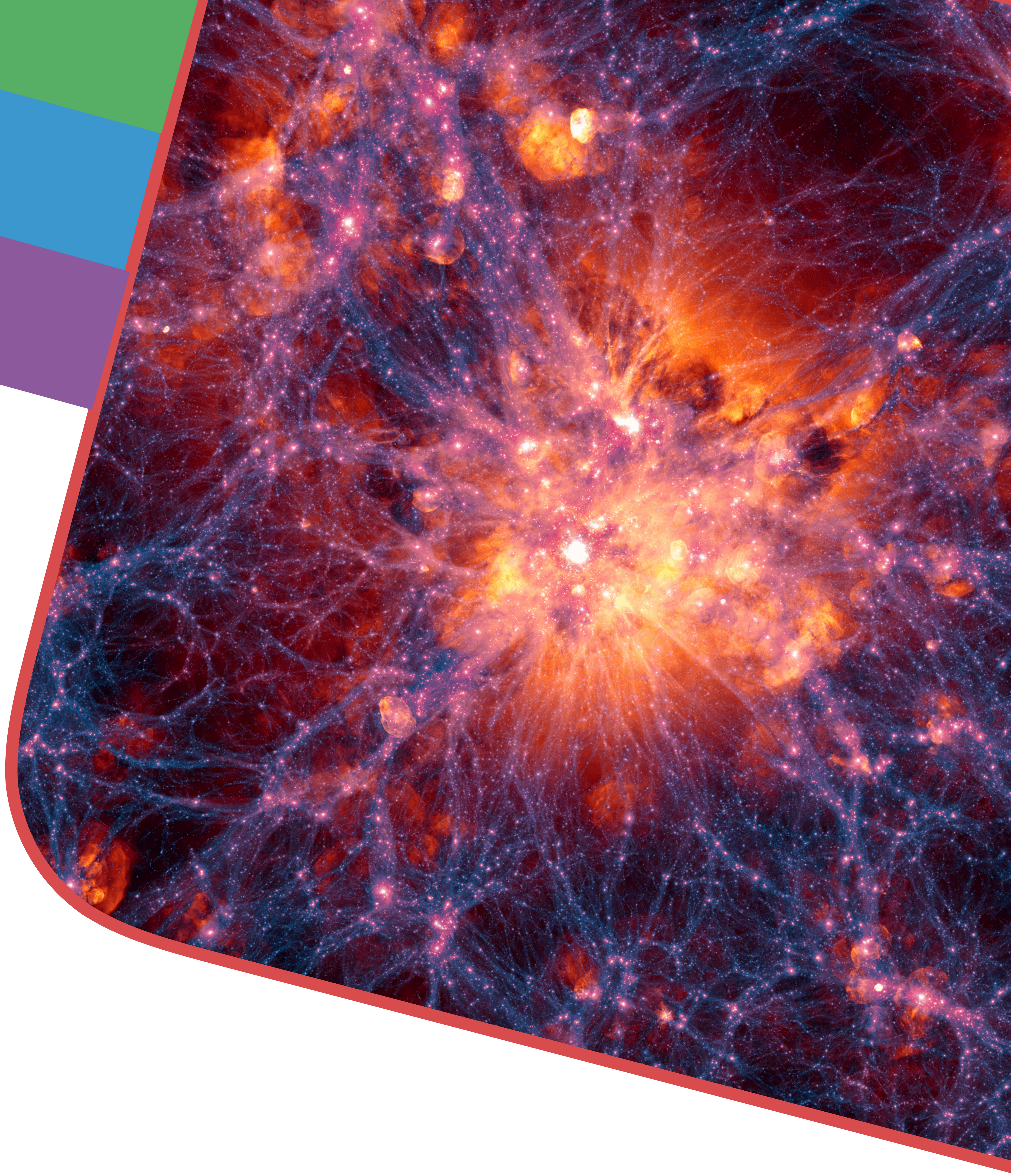

THANKS FOR YOUR ATTENTION

guillermo.franco-abellan@umontpellier.fr

BACK-UP

Late-time solutions are disfavored by low-redshift data

SNIa data

$$m_b(z) = M_b + 25 + \log_{10} D_L(z) \quad \xrightarrow[M_b]{\text{SH0ES}} \quad D_L(z)$$

BAO data

$$\theta_d(z)^{\parallel} = r_s(z_{\rm drag}) H(z), \qquad \theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)} \quad \xrightarrow[r_s(z_{drag})]{\text{Pl18-}\Lambda\text{CDM}} \quad D_A(z)$$

Late-time solutions are **disfavored** by **low-redshift data**

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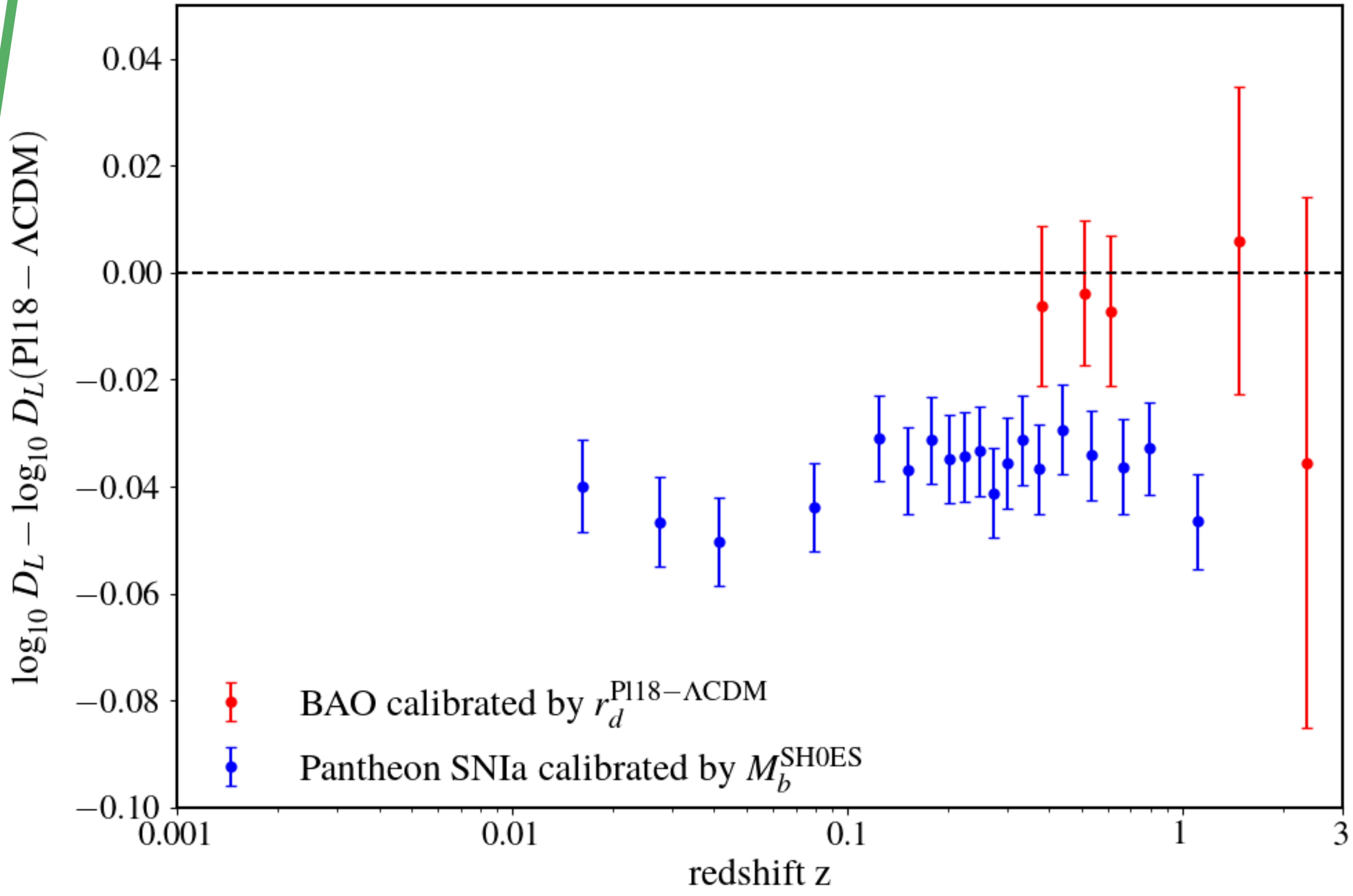
But both distances are related! $D_L(z) = (1+z)^2 D_A(z)$

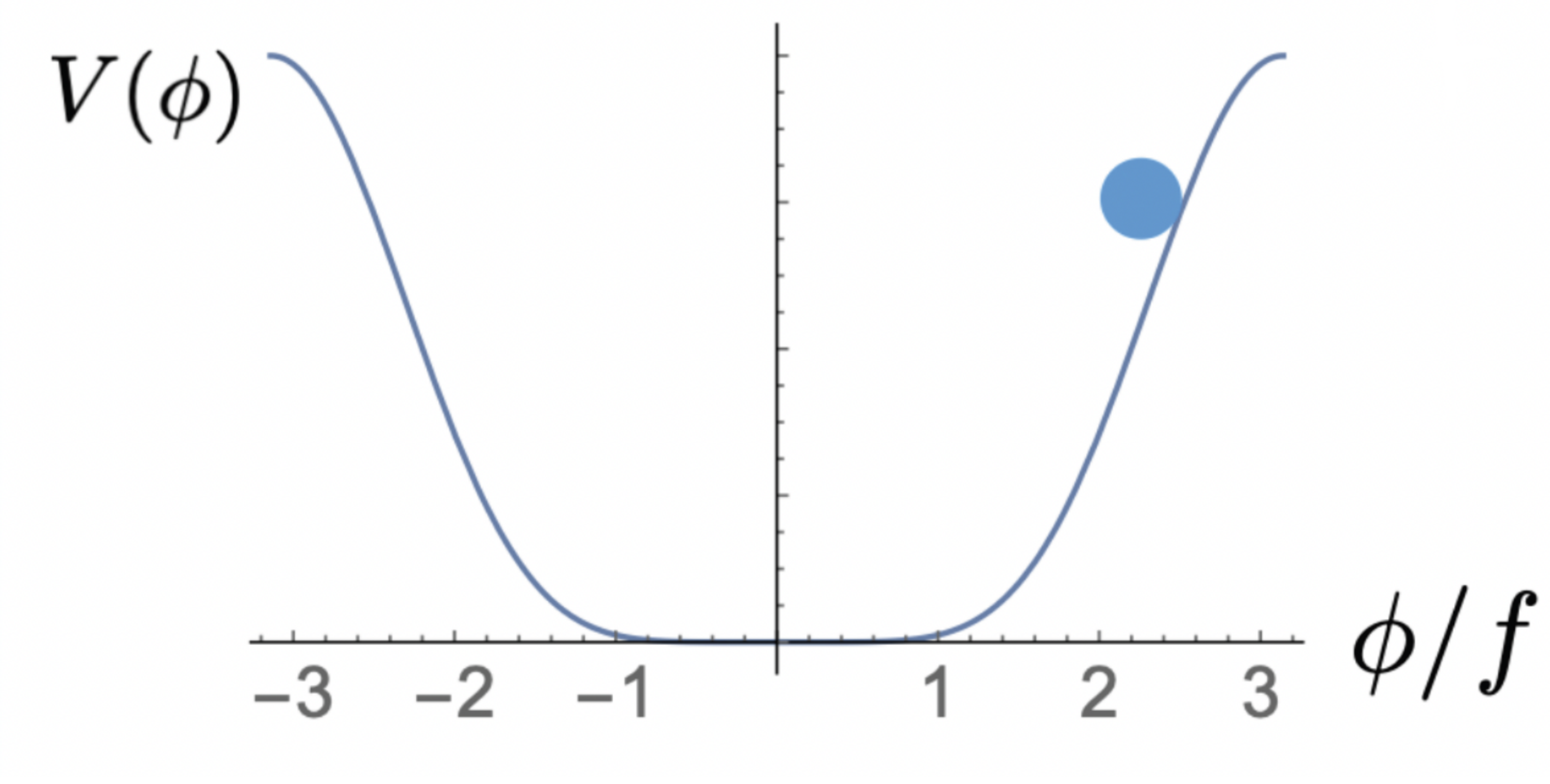
Late-time solutions are disfavored by low-redshift data



SNIa and BAO distances are in disagreement

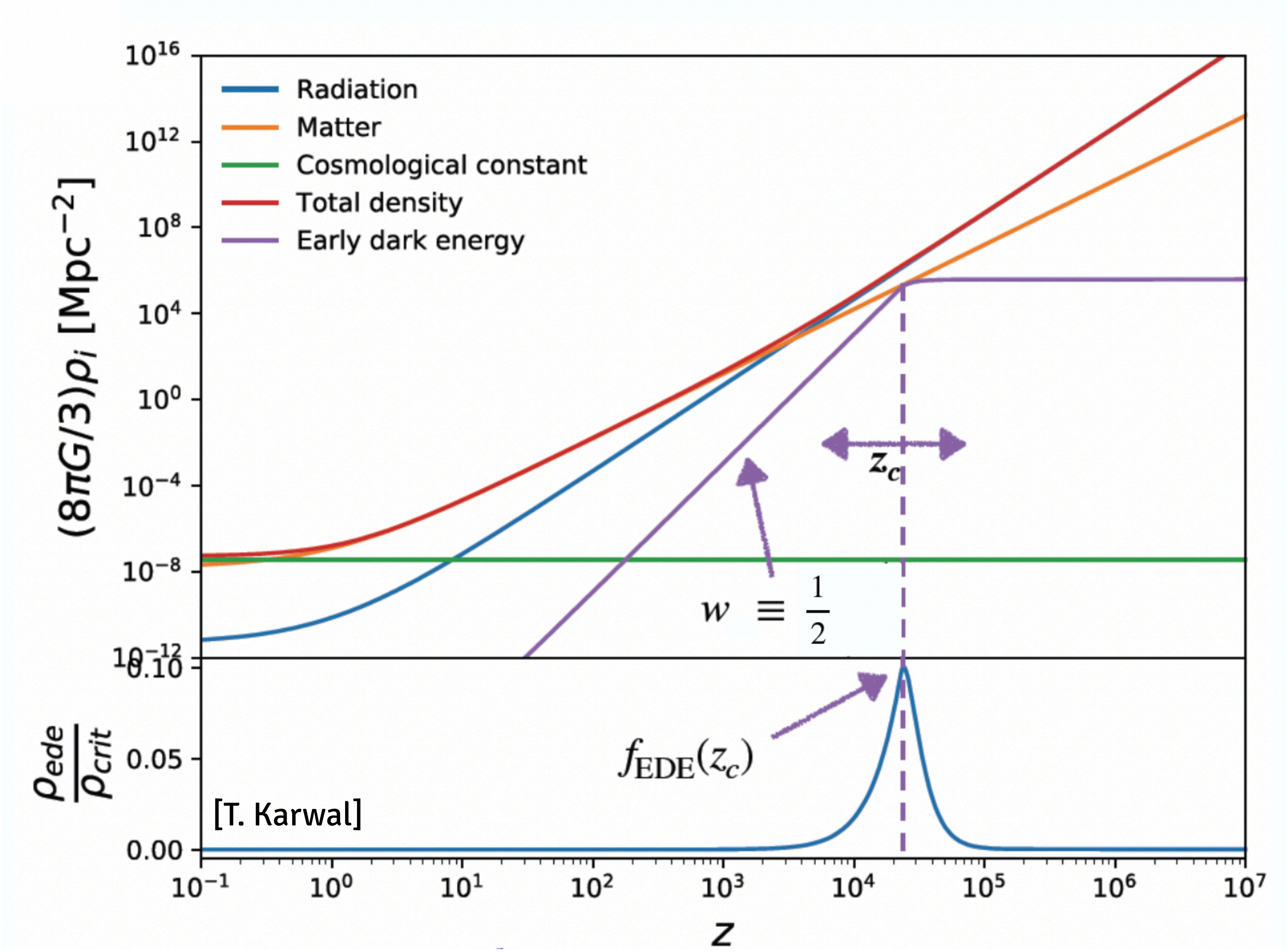
Need to lower r_d

Early Dark Energy (EDE)



$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$$

Scalar field initially frozen, dilutes faster than radiation afterwards



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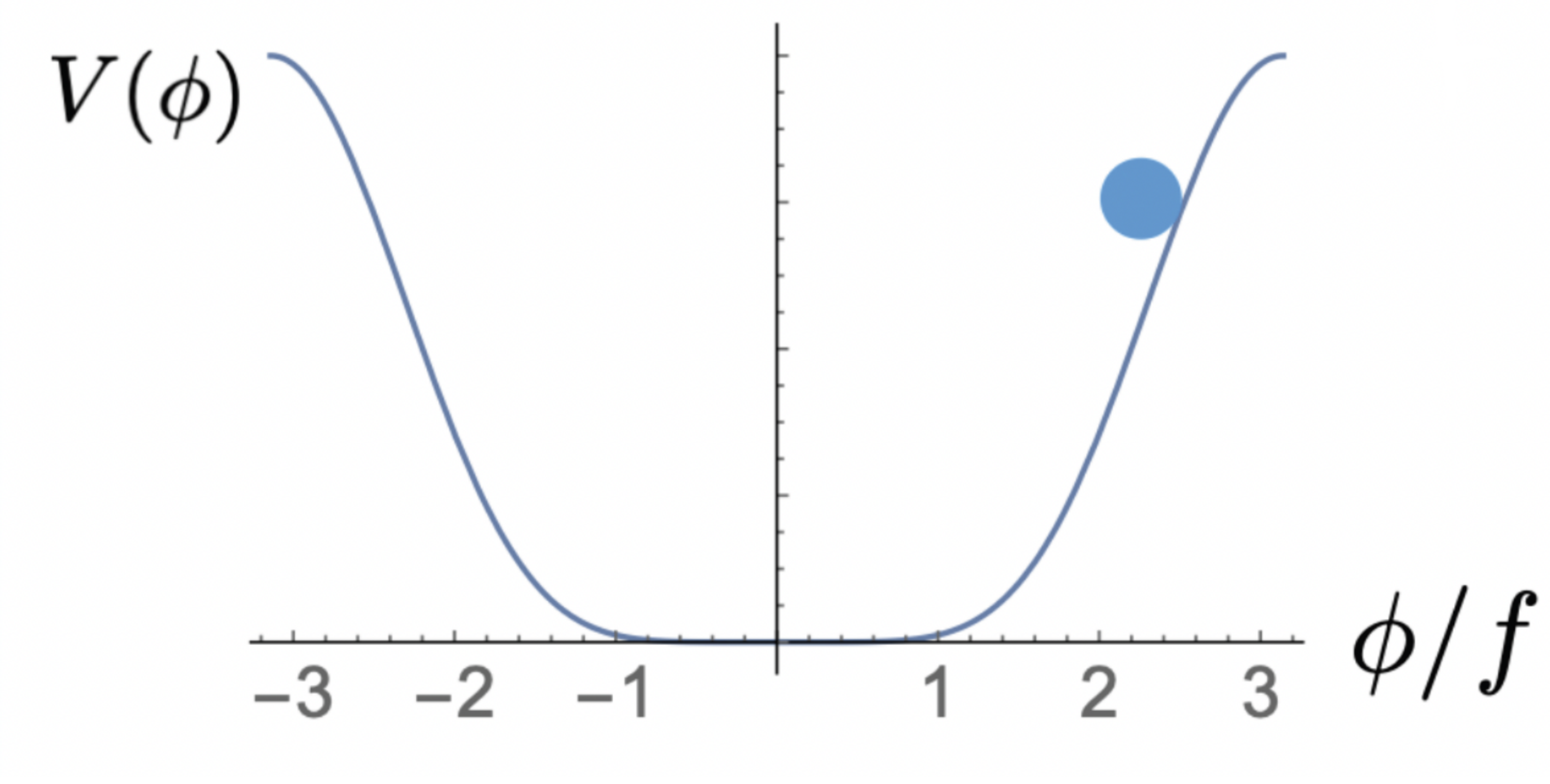
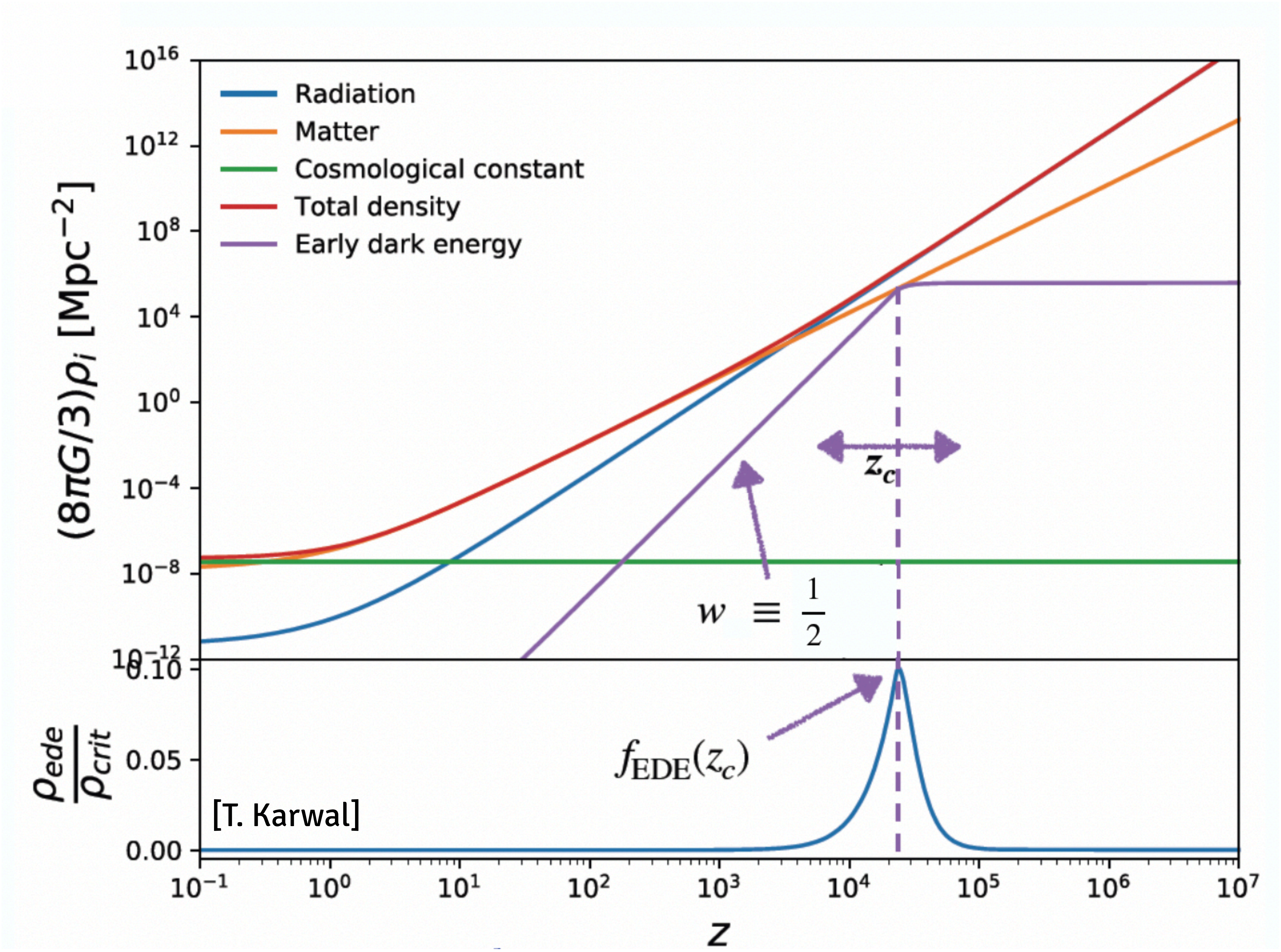


$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$$

3 extra parameters:

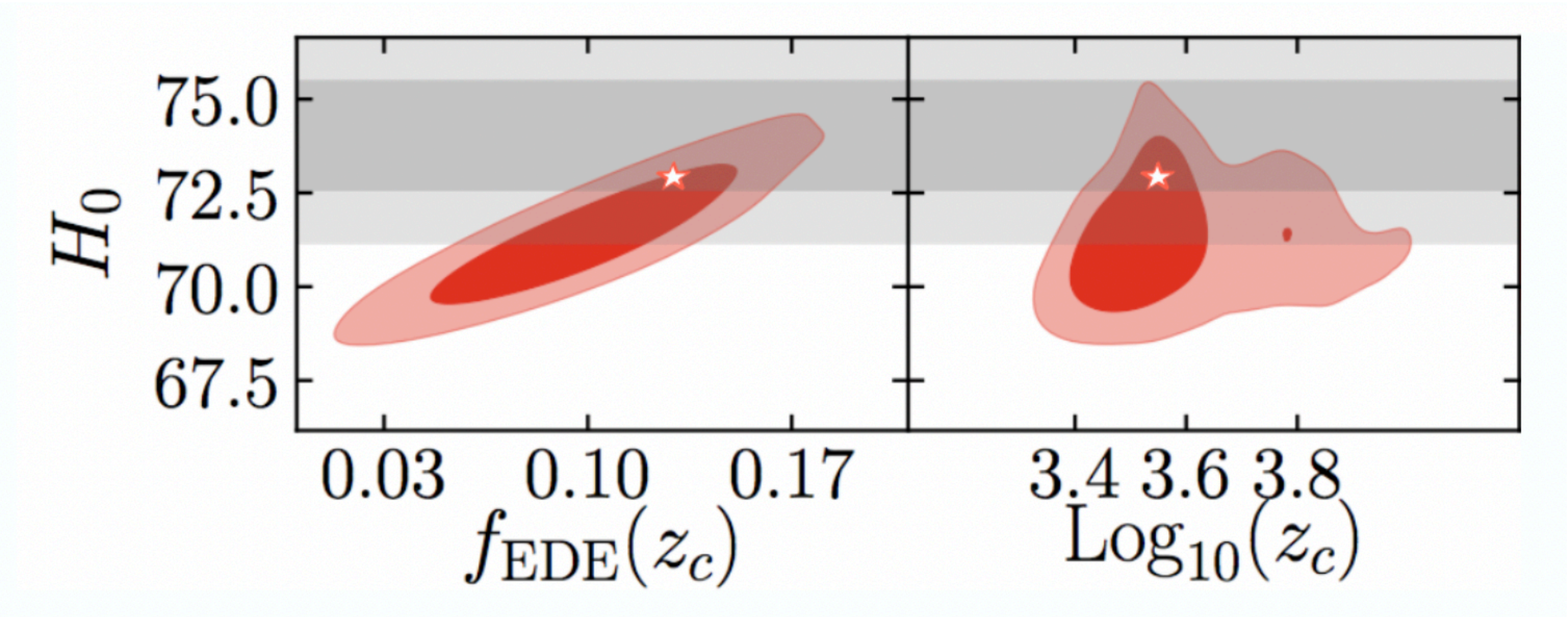
$f_{\rm EDE}(z_c)$ z_c ϕ_i

m f



Early Dark Energy can resolve the Hubble tension if it contributes $f_{\rm EDE}(z_c) \sim 10\,\%$ around $z_c \sim z_{\rm eq}$

Planck15 + BAO + SNIa + SH0ES:



[Poulin+ 18]

[Smith+ 19]

“Because of the increase in S_8, LSS data severely constrains EDE"

“EDE is not detected from Planck data alone”

[Hill+ 20]
[D'amico+ 20]
[Ivanov+ 20]

[Murgia, GFA, Poulin
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→ **Is EDE solution ruled-out?**

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→ **Is EDE solution ruled-out?**

No, EDE solution is still robust

[Murgia, GFA, Poulin 2020 arXiv:2009.10733]

Model independent treatment of SH0ES data

The cosmic distance ladder method **doesn't directly measure H_0**

It directly measures the **intrinsic magnitude of SNIa M_b** at redshifts **$0.02 < z < 0.15$**, and then obtains H_0 by comparing with the apparent SNIa magnitudes m [Efstathiou+ 21]

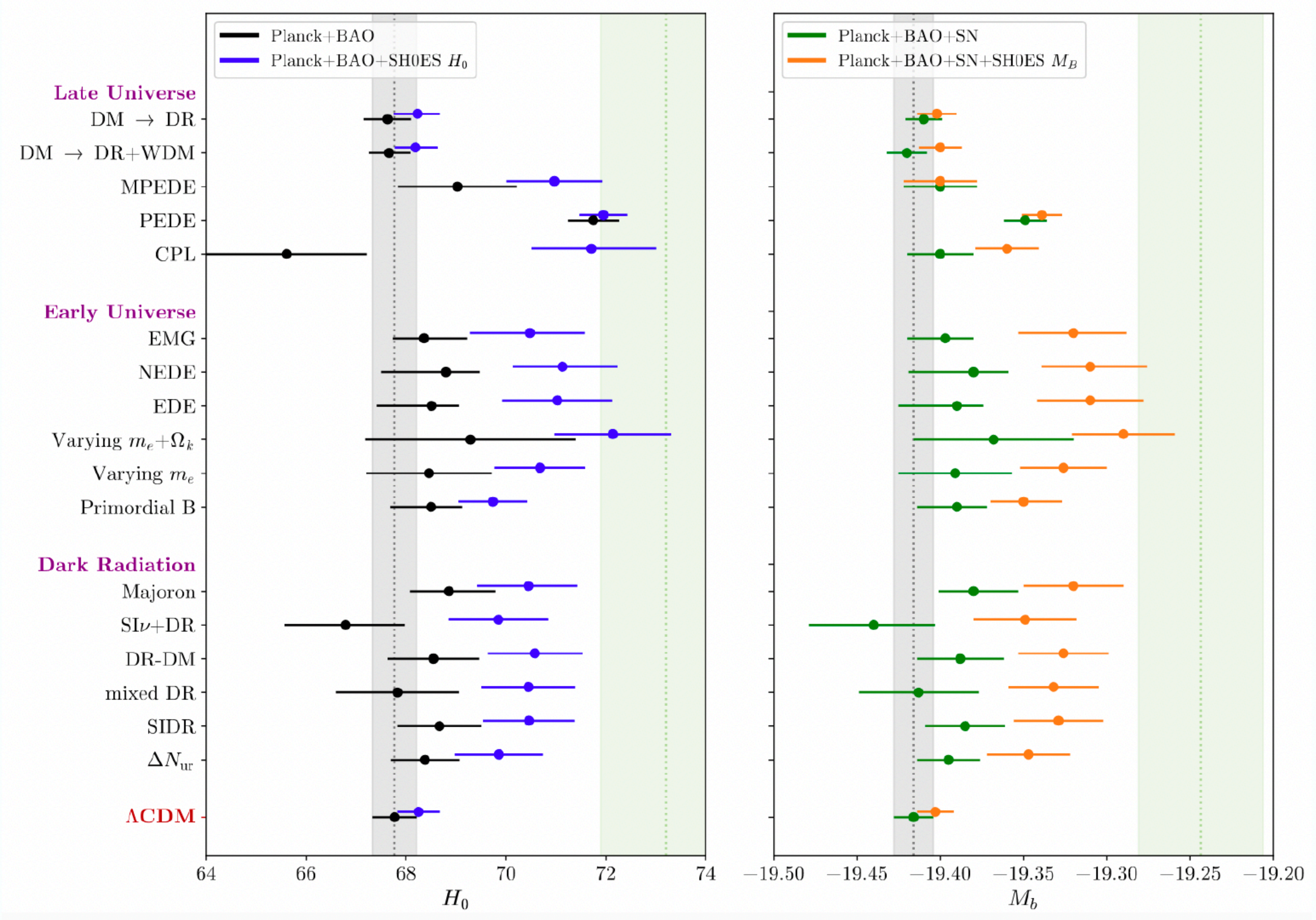
$$m(z) = M_b + 25 - 5\mathrm{Log}_{10}\mathrm{H}_0 + 5\mathrm{Log}_{10}(\hat{\mathrm{D}}_\mathrm{L}(\mathrm{z}))$$

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!

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

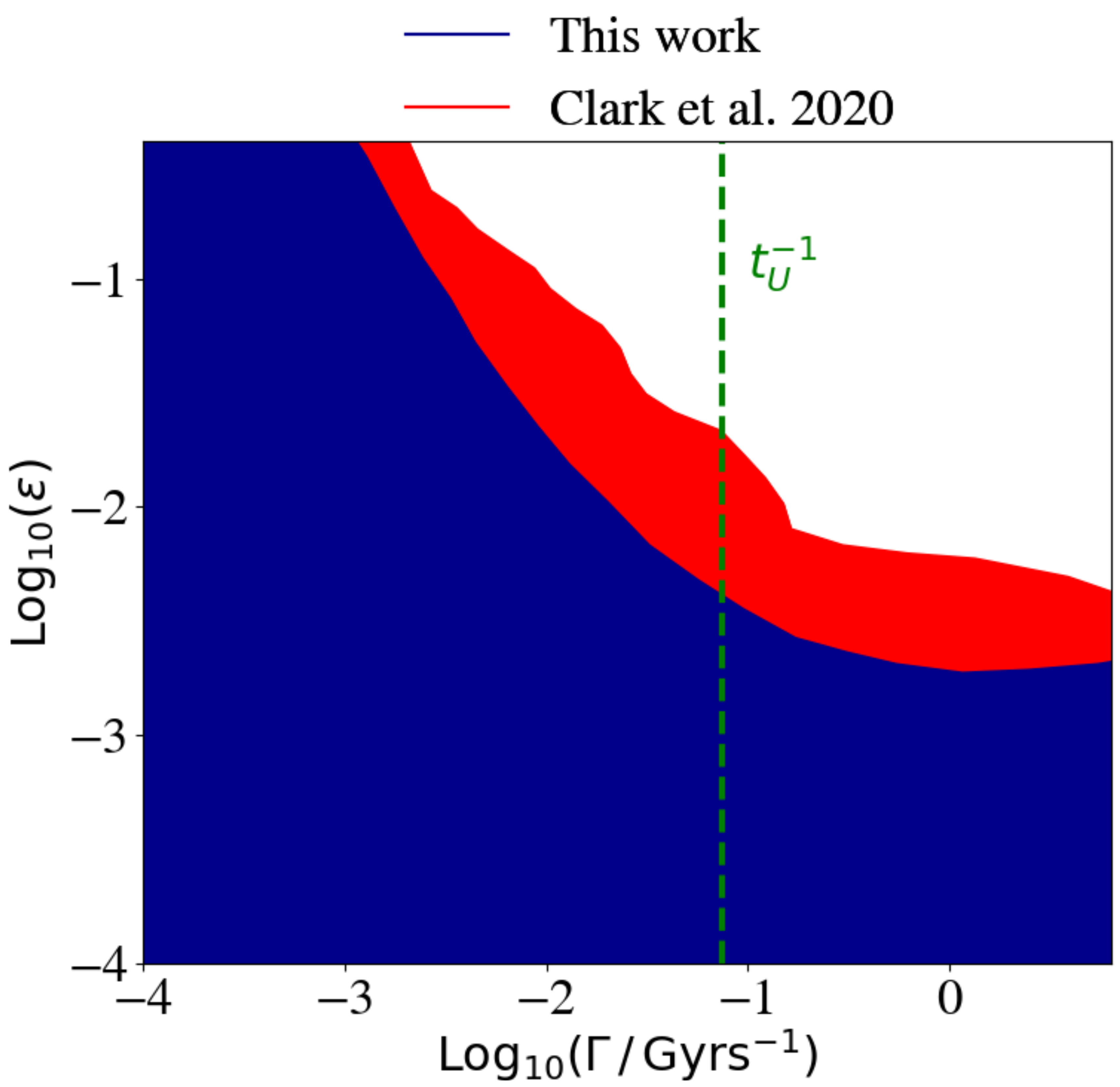
⟶ No significant changes (notable exceptions are EDE and NEDE)

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

General constraints

Planck18 + BAO + SNIa:



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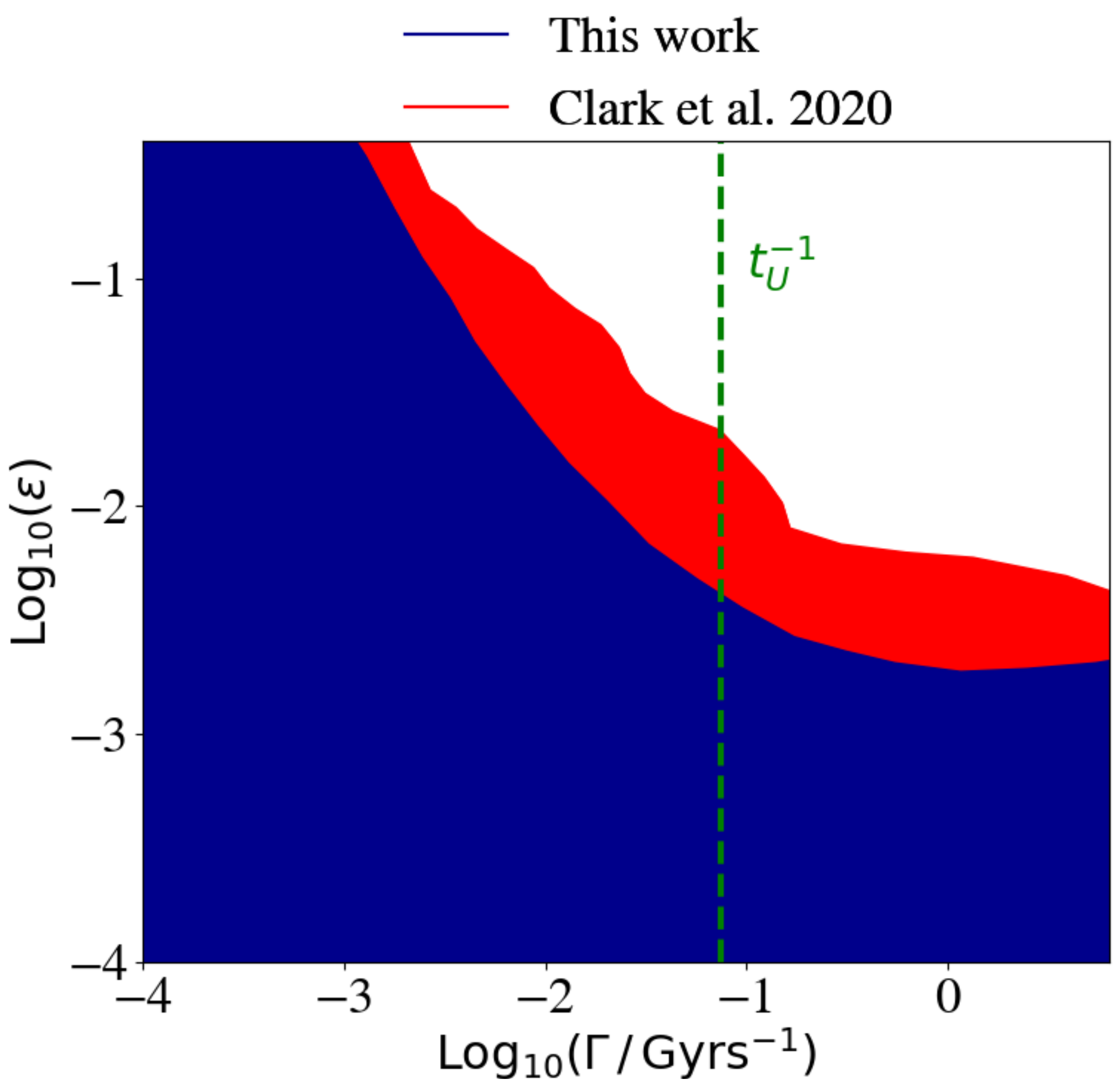
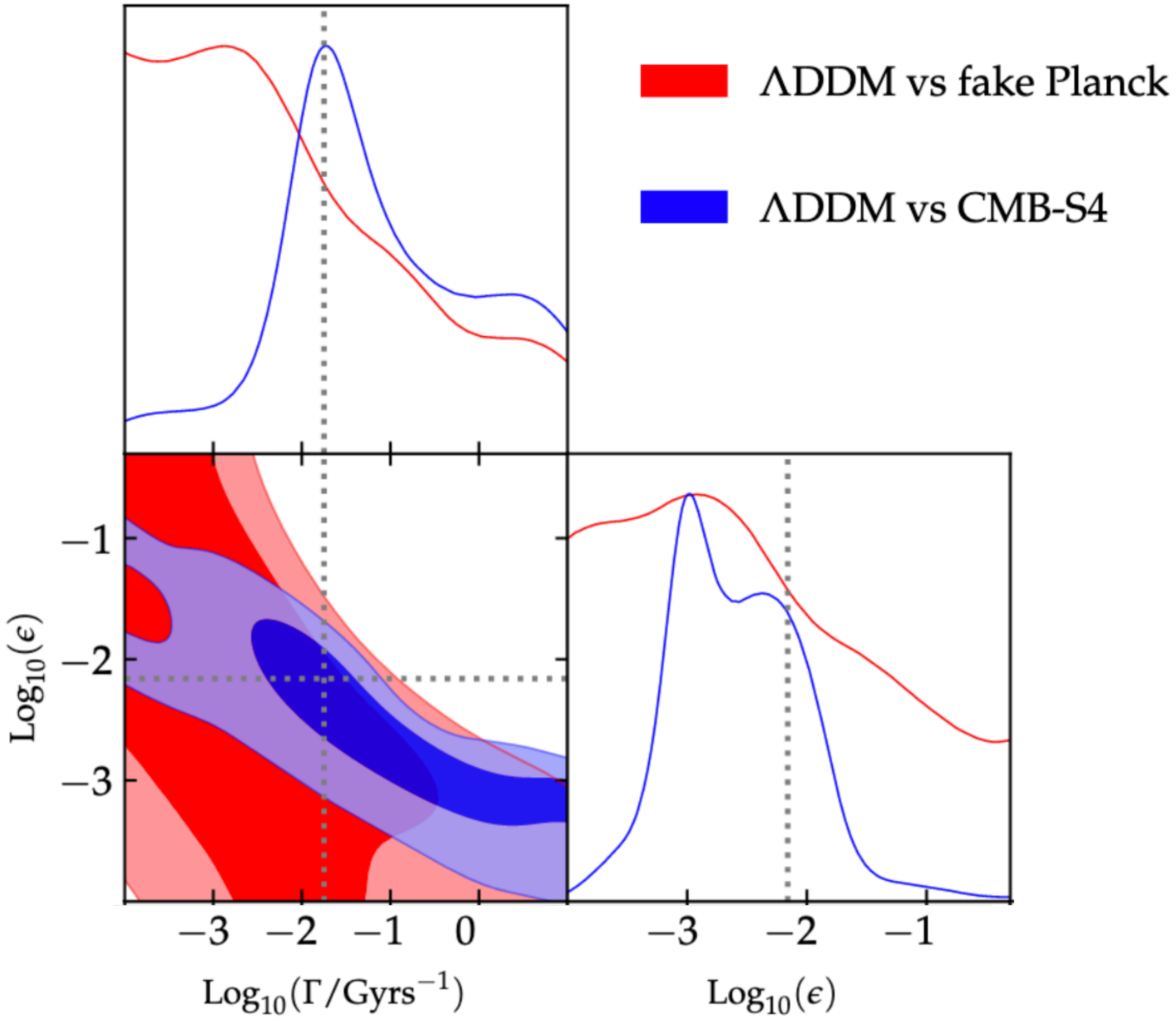
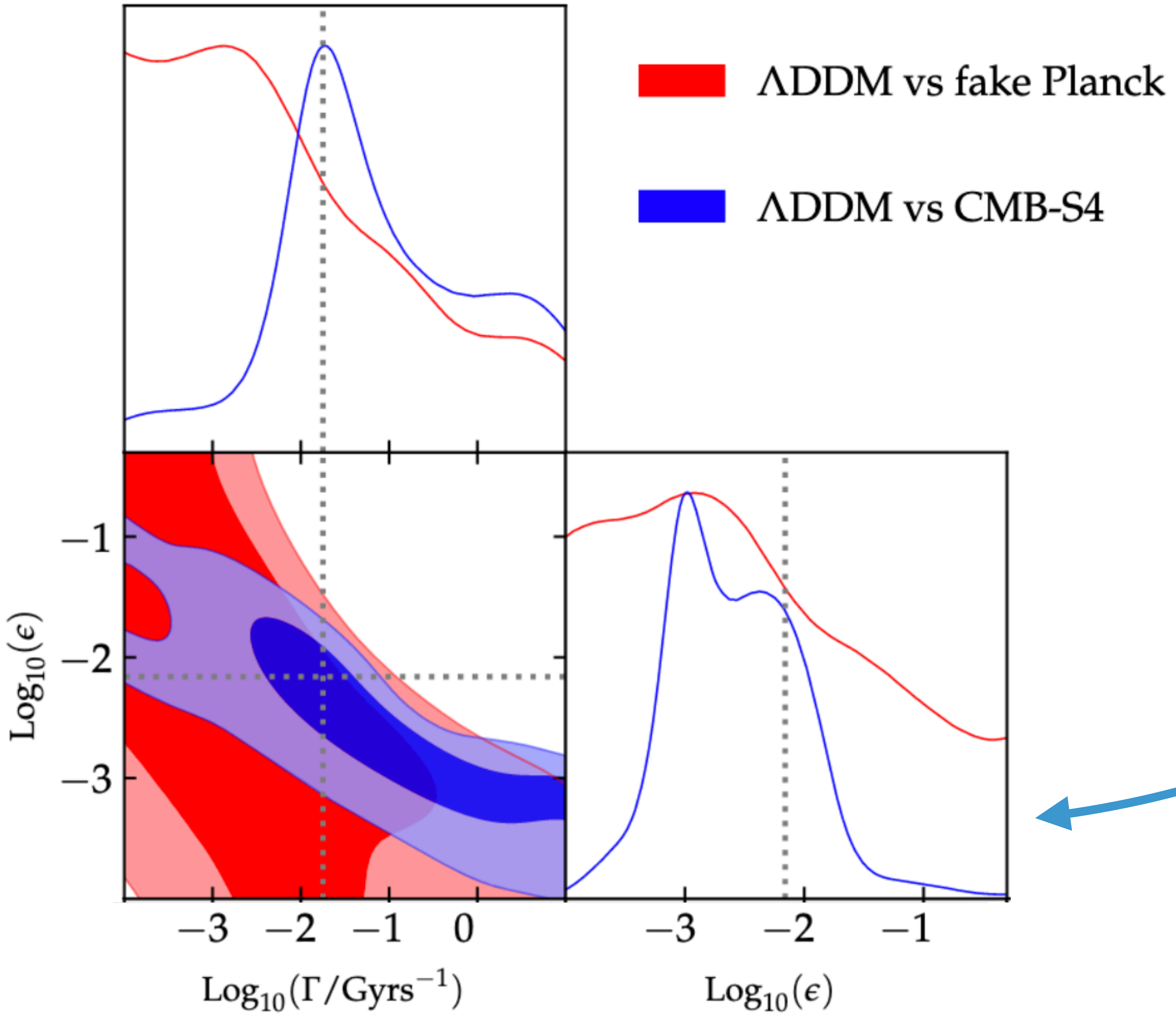


Constraints up to **1 order of magnitude stronger** than former works due to the **inclusion of WDM perts.**

CMB forecast for DDM



CMB forecast for DDM



Future accurate CMB data will be able to **capture the signature** of DDM

Interesting implications

Model building

Why ε << 1/2, i.e. $m_{wdm} \sim m_{dm}$?

Ex: Supergravity [Choi+ 21]

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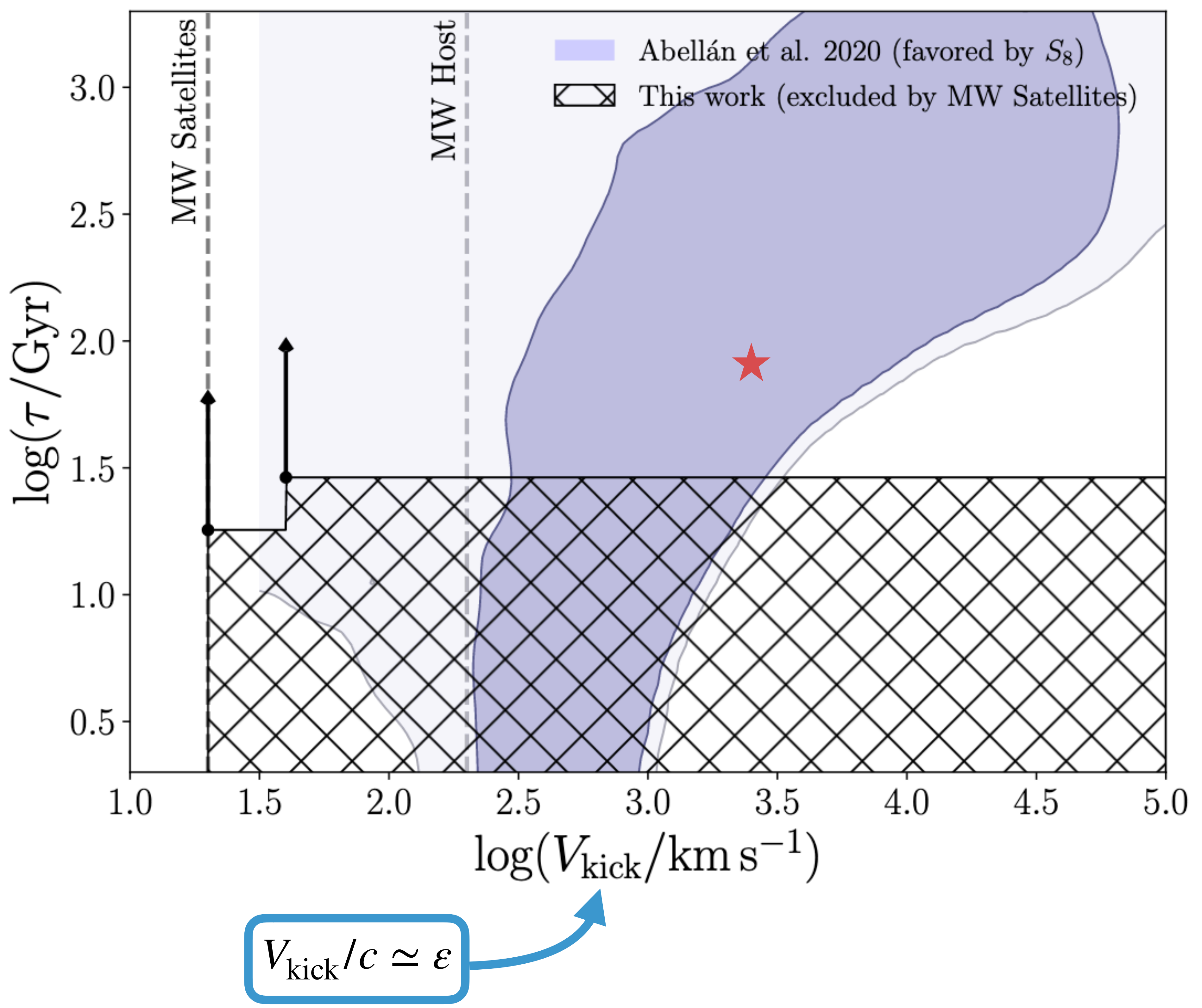
Ex: Supergravity

[Choi+ 21]

Small scales

Reduction in the abundance of **subhalos**, can be constrained by observations of **MW satellites**

[DES 22]



The full Boltzmann hierarchy

$$f(q,k,\mu,\tau) = \bar{f}(q,\tau) + \delta f(q,k,\mu,\tau)$$

Expand δf in multipoles. The Boltzmann eq. leads to the following **hierarchy** (in **synchronous** gauge comoving with the mother)

$$\frac{\partial}{\partial\tau}(\delta f_0) = -\frac{\mathbf{q}k}{\mathbf{aE}}\delta f_1 + q\frac{\partial\bar{f}}{\partial q}\frac{\dot{h}}{6} + \frac{\Gamma\bar{N}_{\rm dm}(\tau)}{4\pi q^3 H}\delta(\tau-\tau_q)\delta_{\rm dm},$$

$$\frac{\partial}{\partial\tau}(\delta f_1) = \frac{\mathbf{q}k}{3\mathbf{aE}}\left[\delta f_0 - 2\delta f_2\right],$$

$$\frac{\partial}{\partial\tau}(\delta f_2) = \frac{\mathbf{q}k}{5\mathbf{aE}}\left[2\delta f_1 - 3\delta f_3\right] - q\frac{\partial\bar{f}}{\partial q}\frac{(\dot{h}+6\dot{\eta})}{15},$$

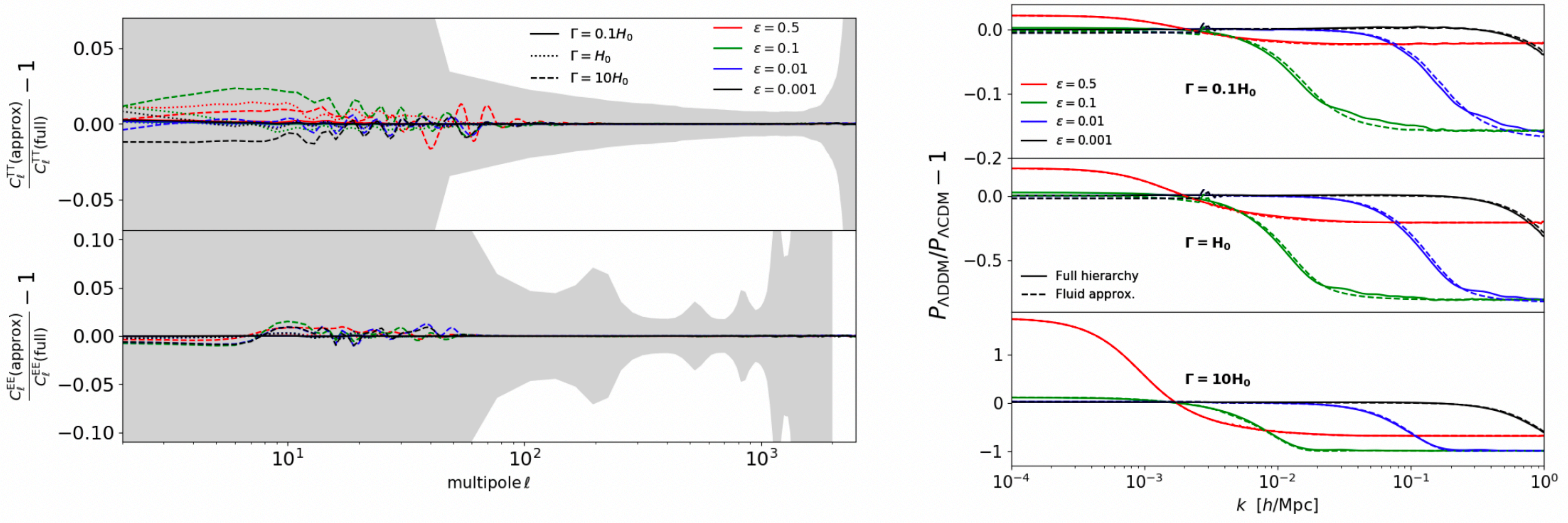
$$\frac{\partial}{\partial\tau}(\delta f_\ell) = \frac{\mathbf{q}k}{(2\ell+1)\mathbf{aE}}\left[\ell\delta f_{\ell-1} - (\ell+1)\delta f_{\ell+1}\right] \qquad (\text{for } \ell \geq 3)\,.$$

where $q = a(\tau_q)p_{\rm max}$. In the relat. limit $\mathbf{q/aE = 1}$, so one can take

$F_\ell \equiv \frac{4\pi}{\rho_c}\int dq\ q^3\delta f_\ell$ and **integrate out the dependency on q**

Checking the accuracy of the WDM fluid approx.

We compare the full Boltzmann hierarchy calculation with the WDM fluid approx.

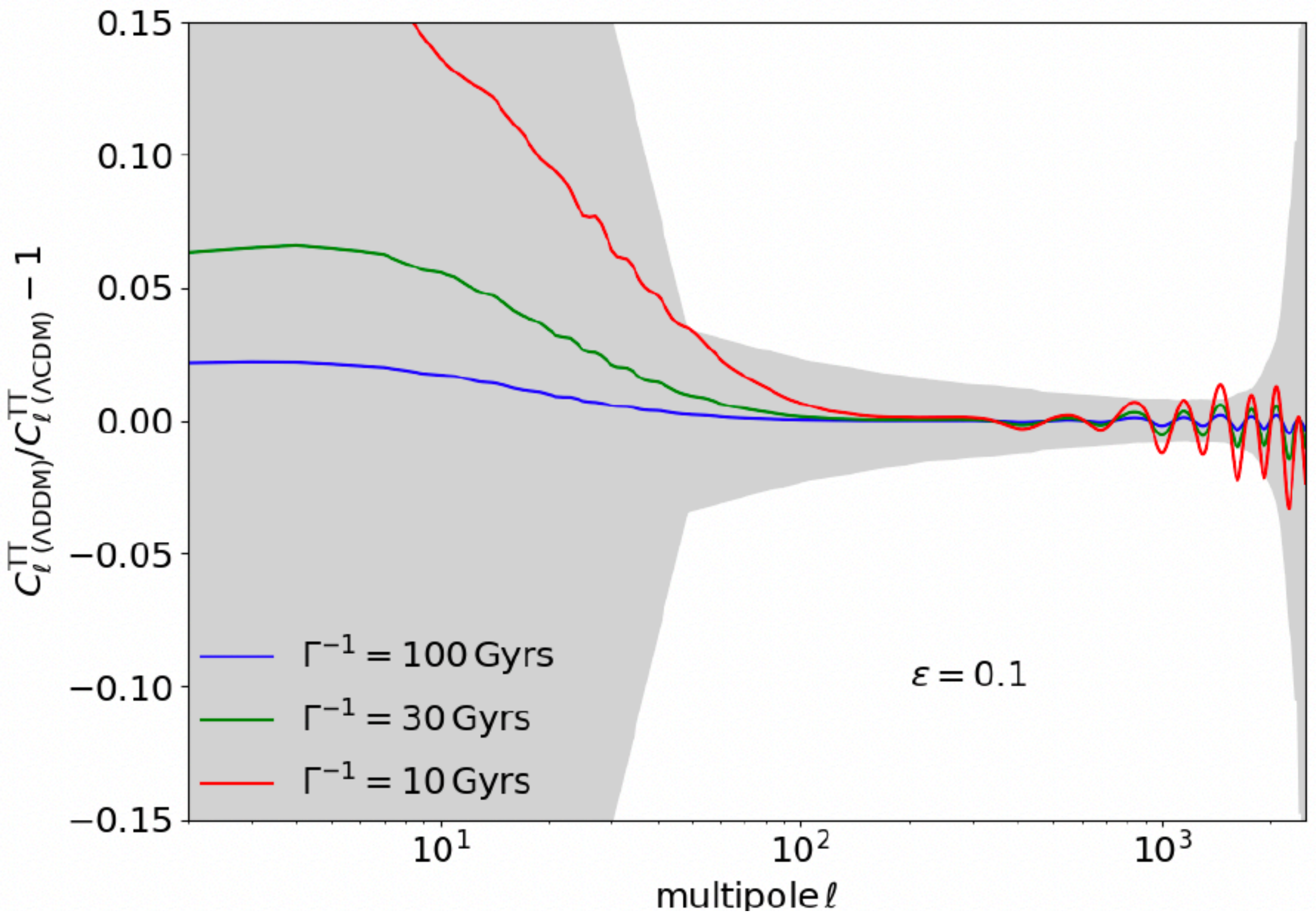


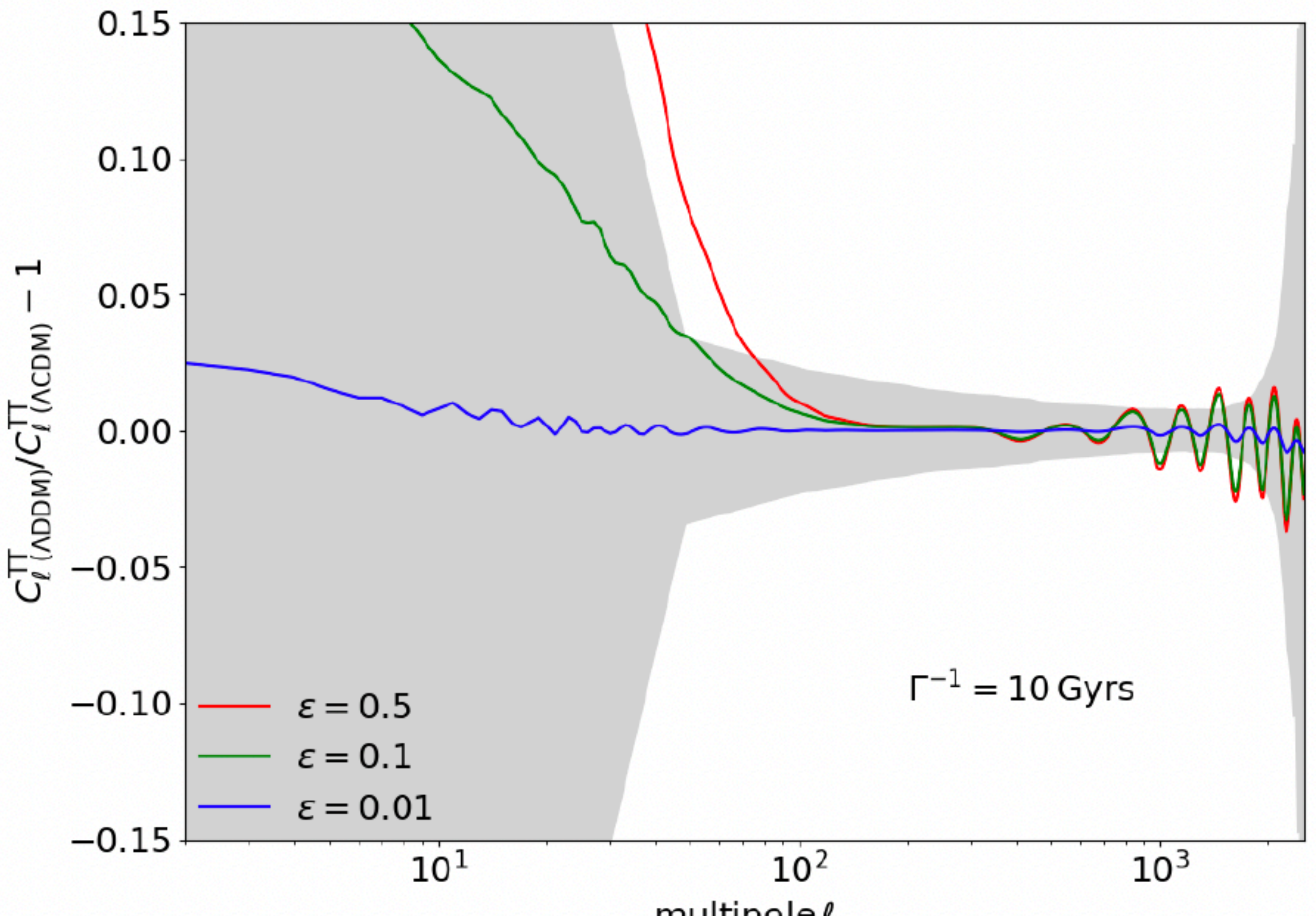
The max. error on S_8 is ~0.65 %, smaller than the ~1.8 % error of the measurement from BOSS+KiDS+2dfLenS

Impact of DDM on the CMB temperature spectrum

Low-ℓ : **enhanced** Late Integrated Sachs Wolfe (**LISW**) effect

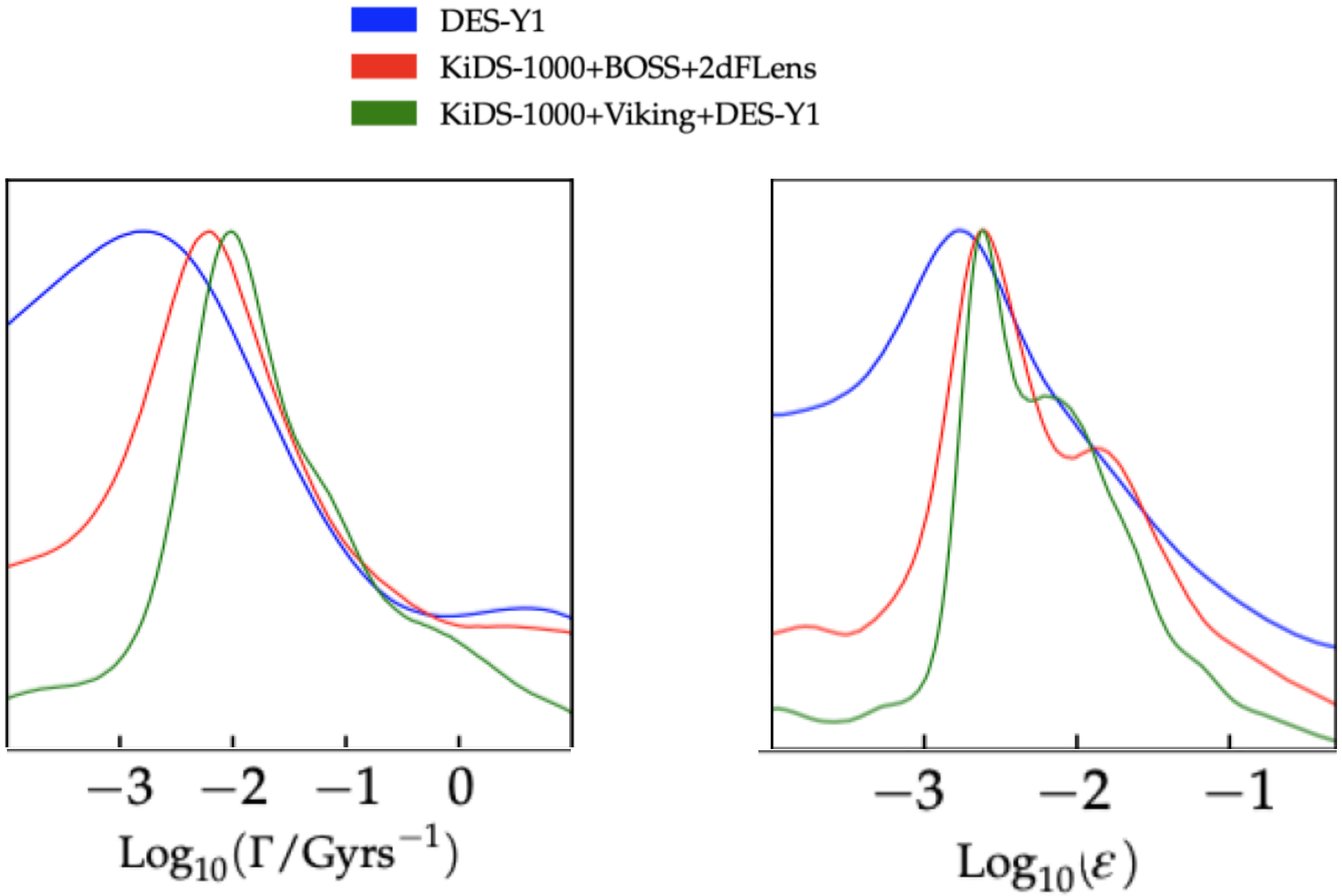
High-ℓ : **suppressed** lensing (higher contrast between peaks)



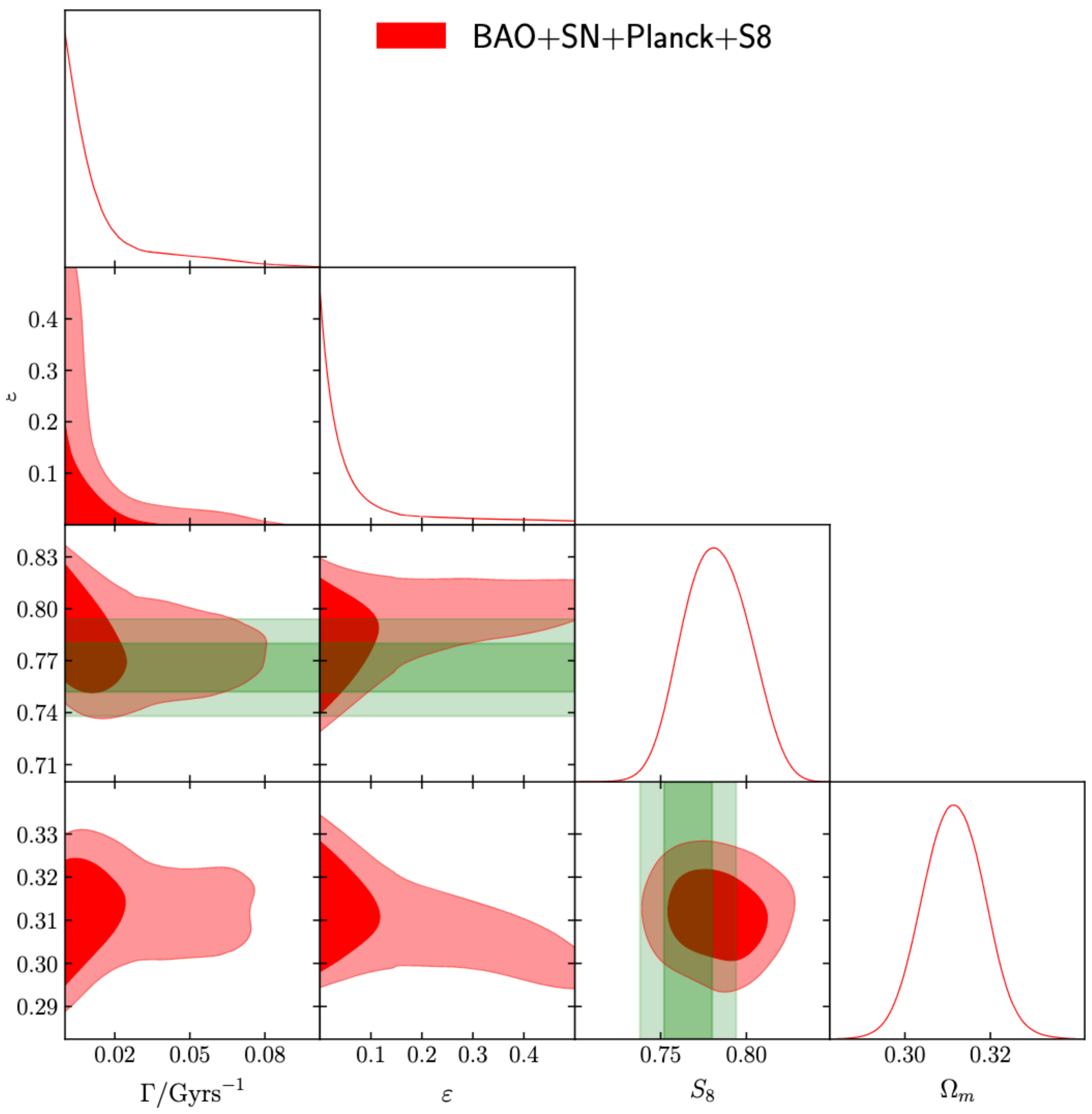


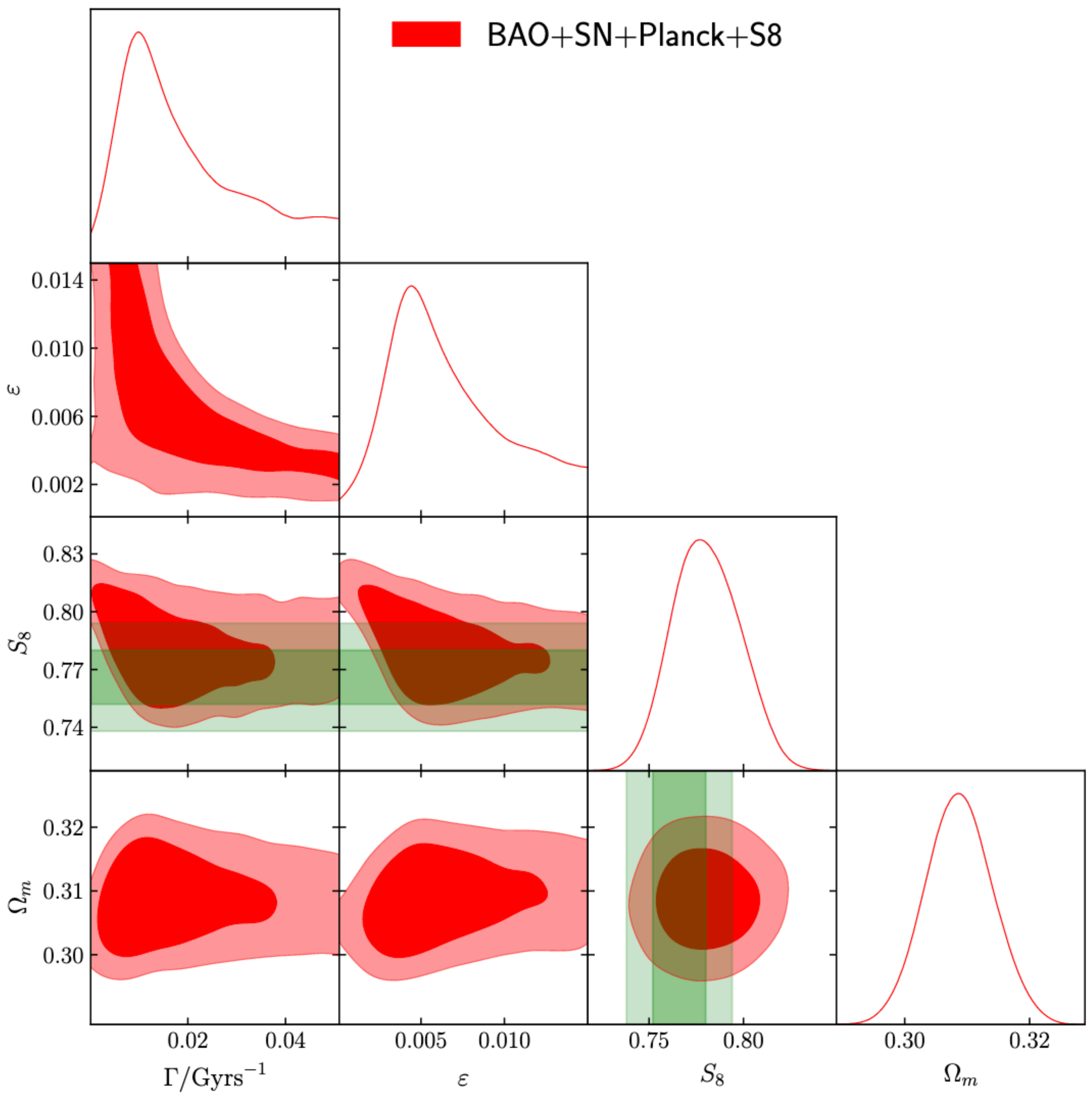
DDM resolution to the S_8 tension

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

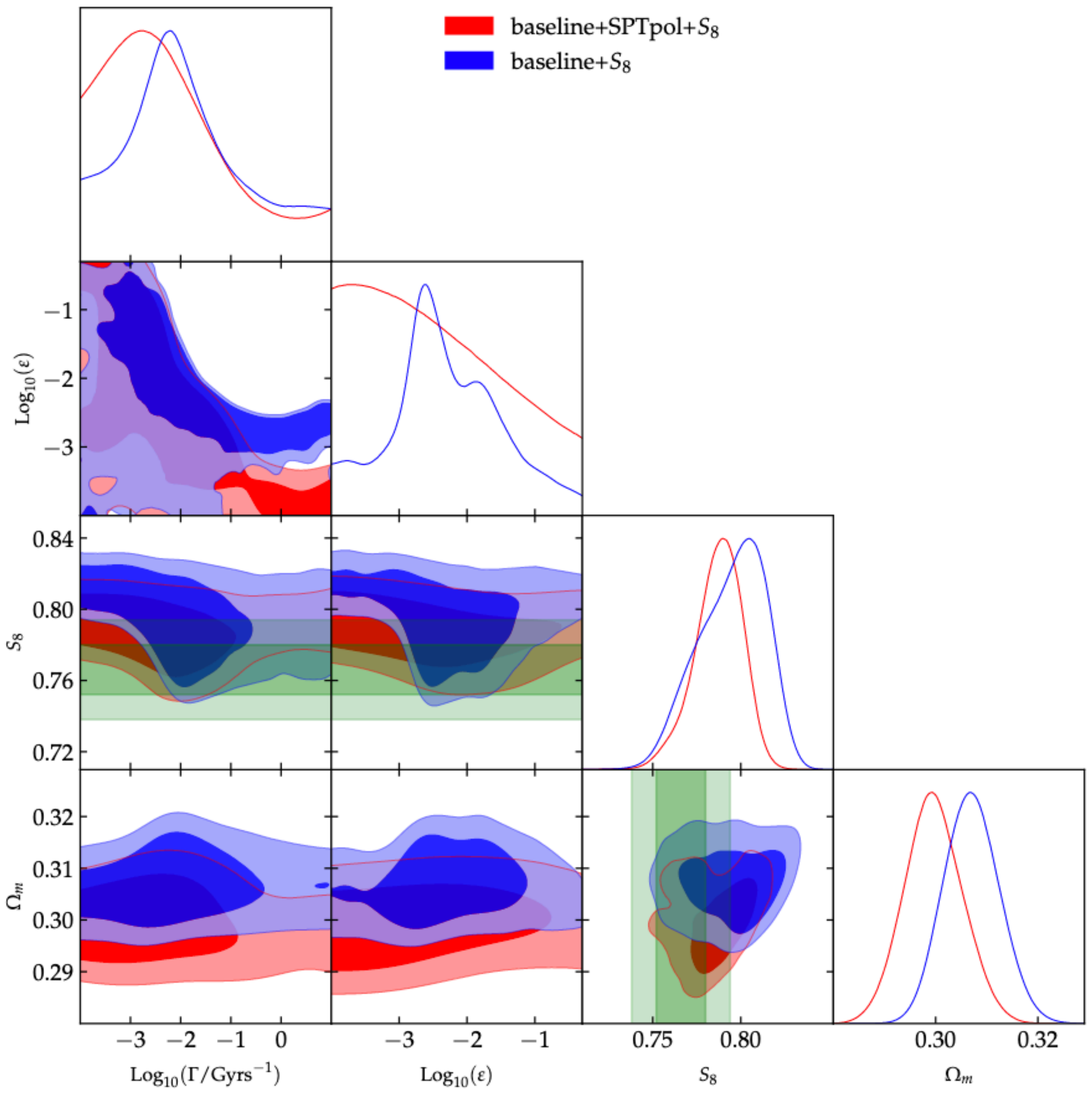


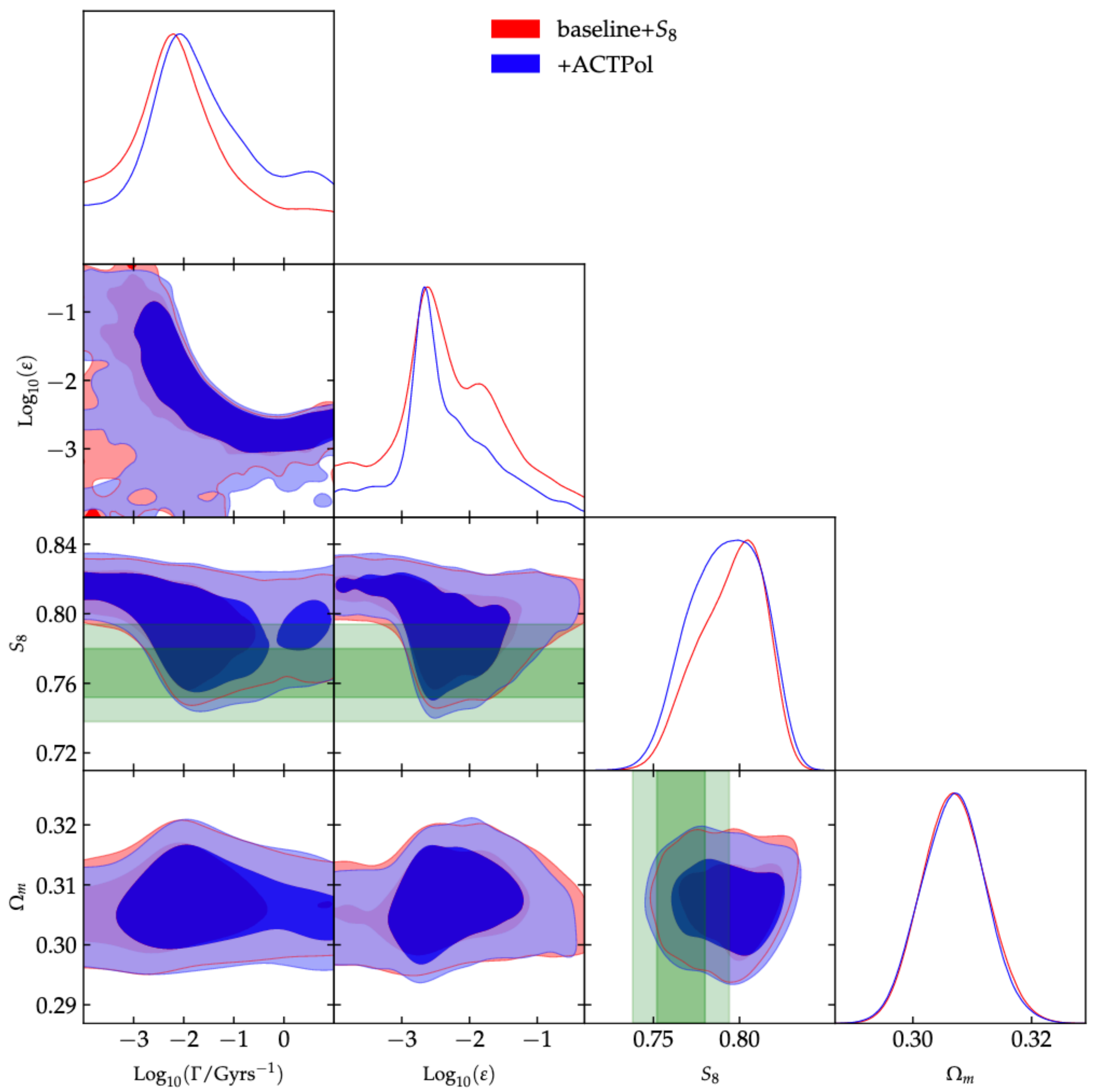
DDM results with linear priors



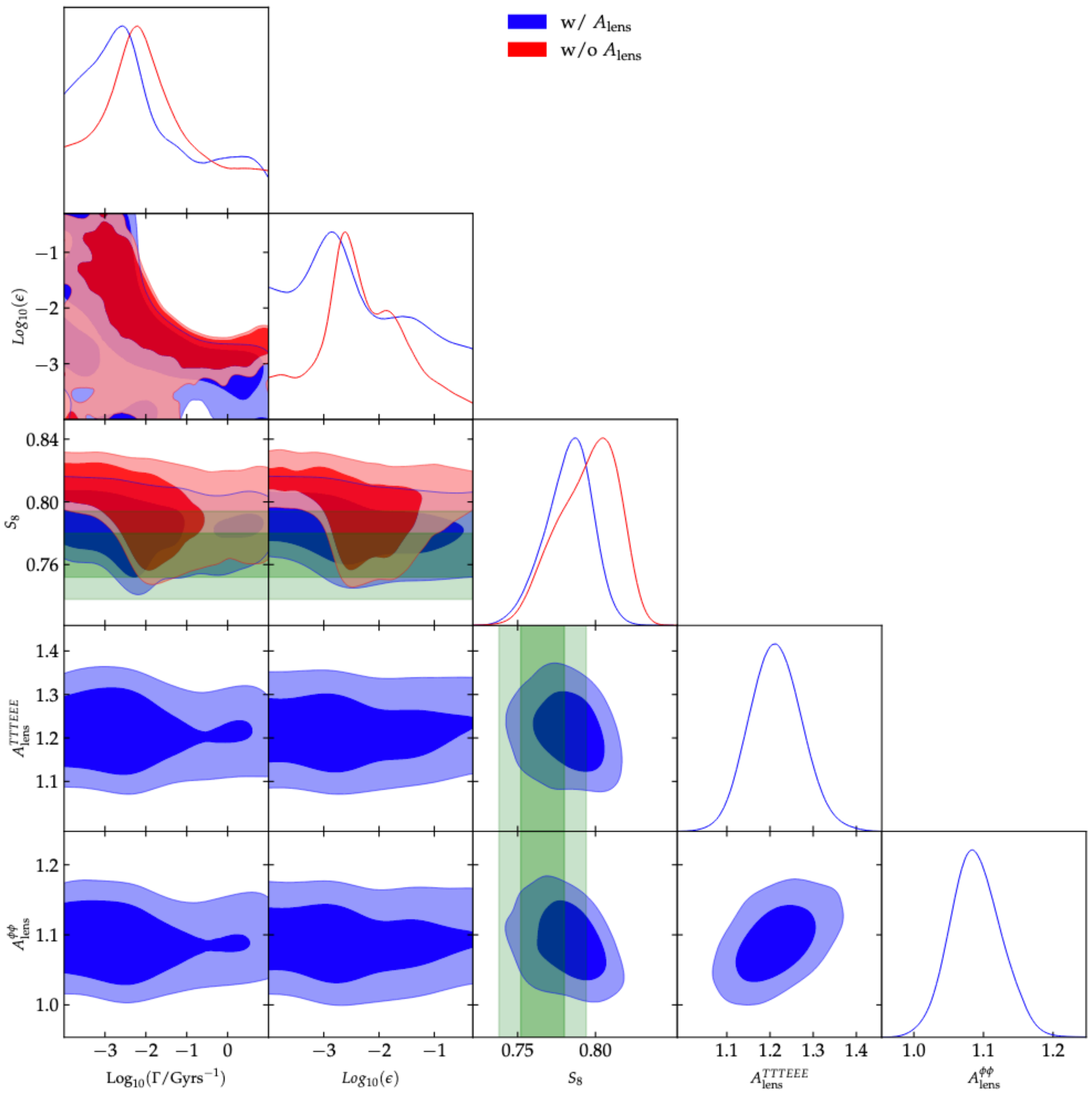


DDM results with SPTPol and ACT datasets

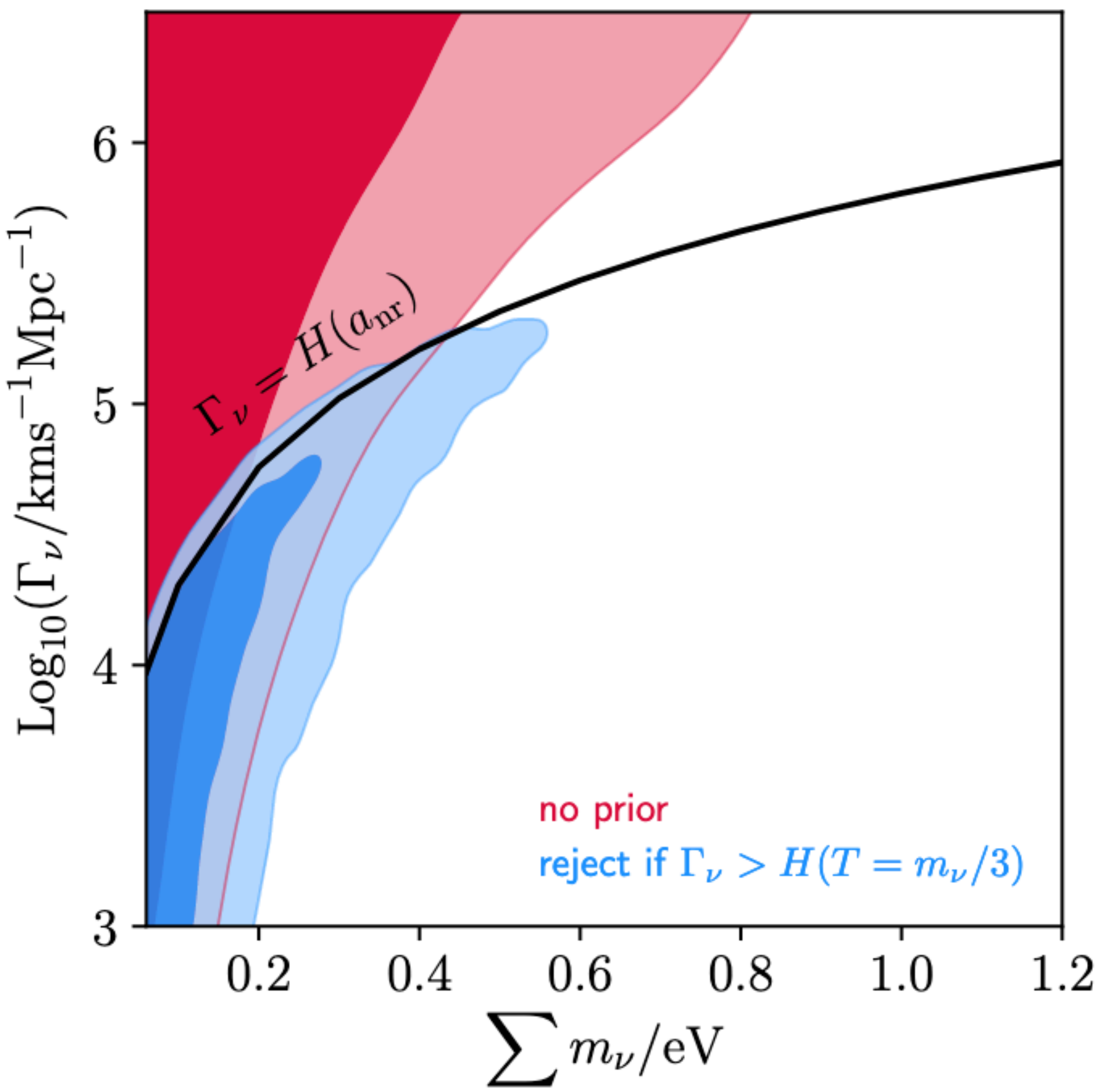




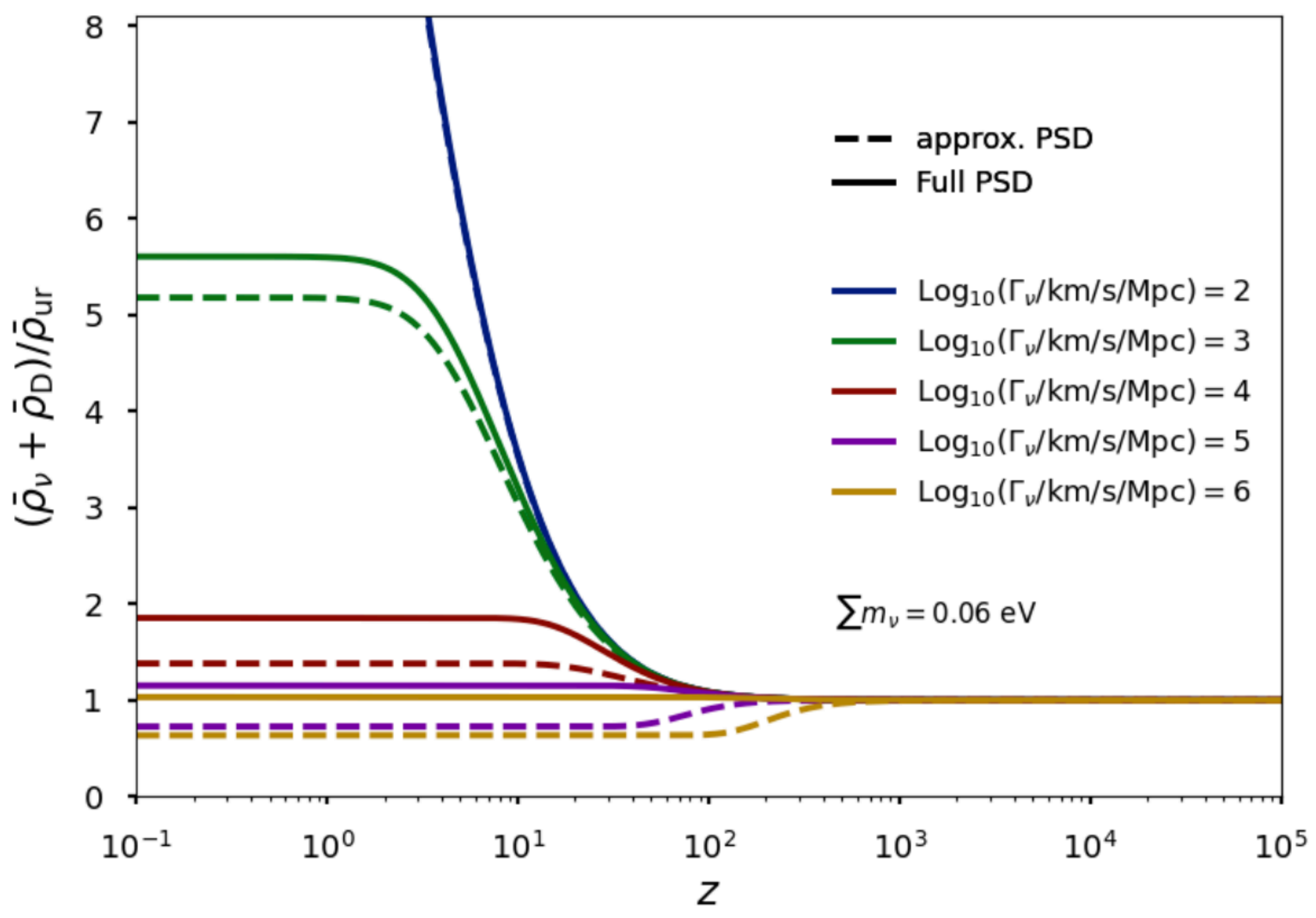
DDM results marginalizing over lensing information



Excluding relativistic regime from the MCMC



Checking consistency of Boltzman eqs.



Comparing various prescriptions