Exploring **theoretical solutions** to the H_0 and S_8 **tensions**

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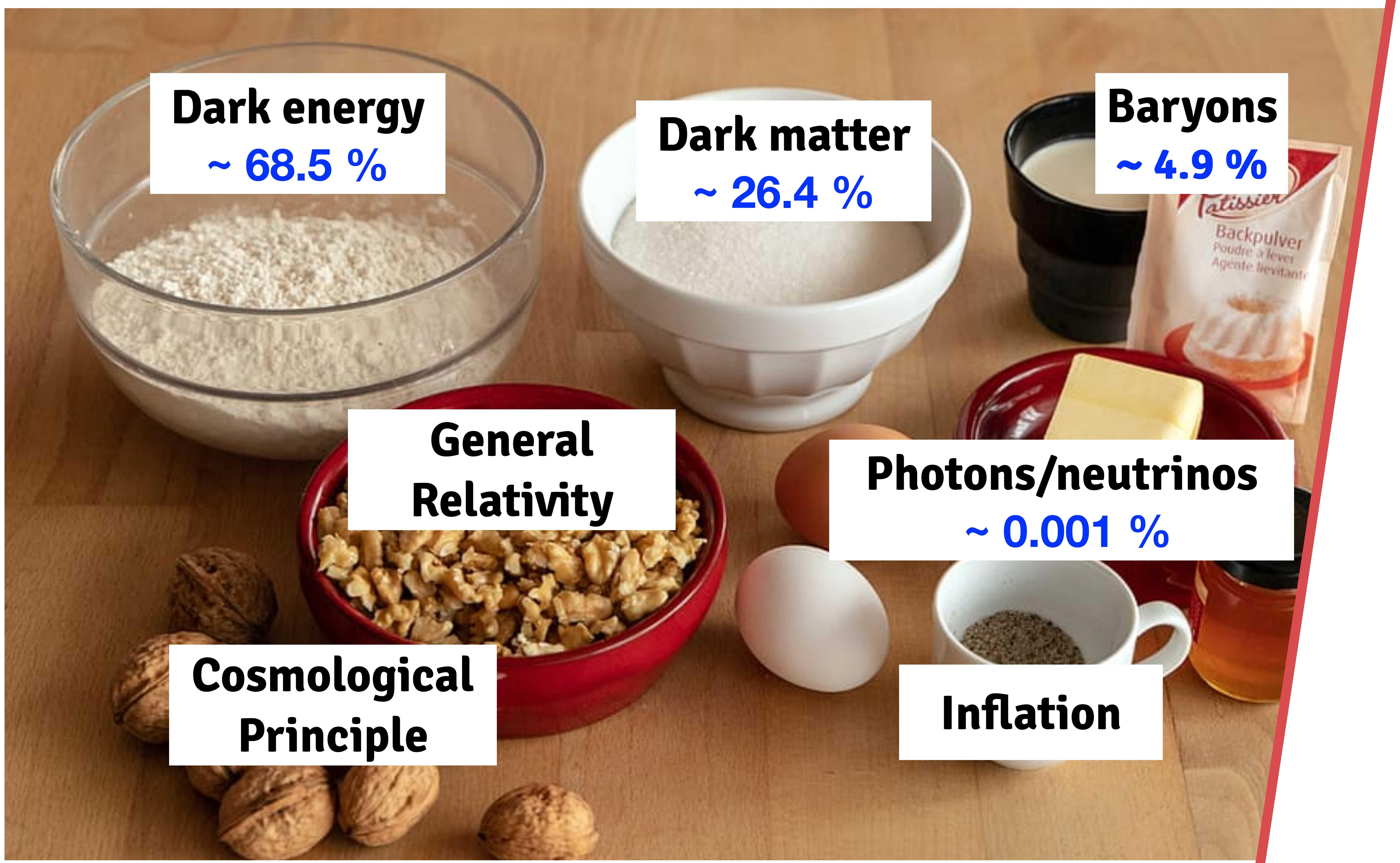
3 June 2024

Exploring the Dark Side of the Universe - Tools

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Concordance ΛCDM model of cosmology:



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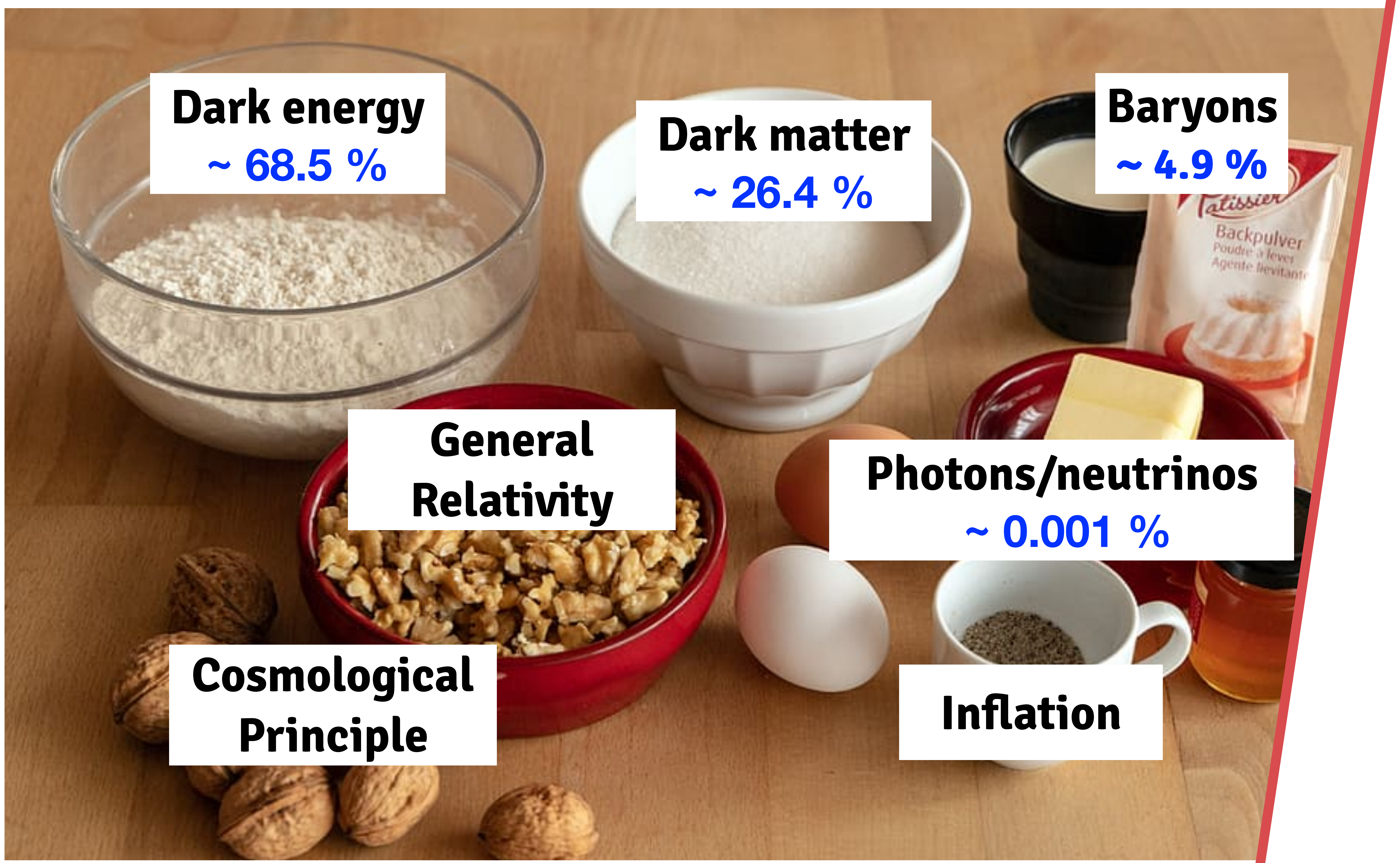
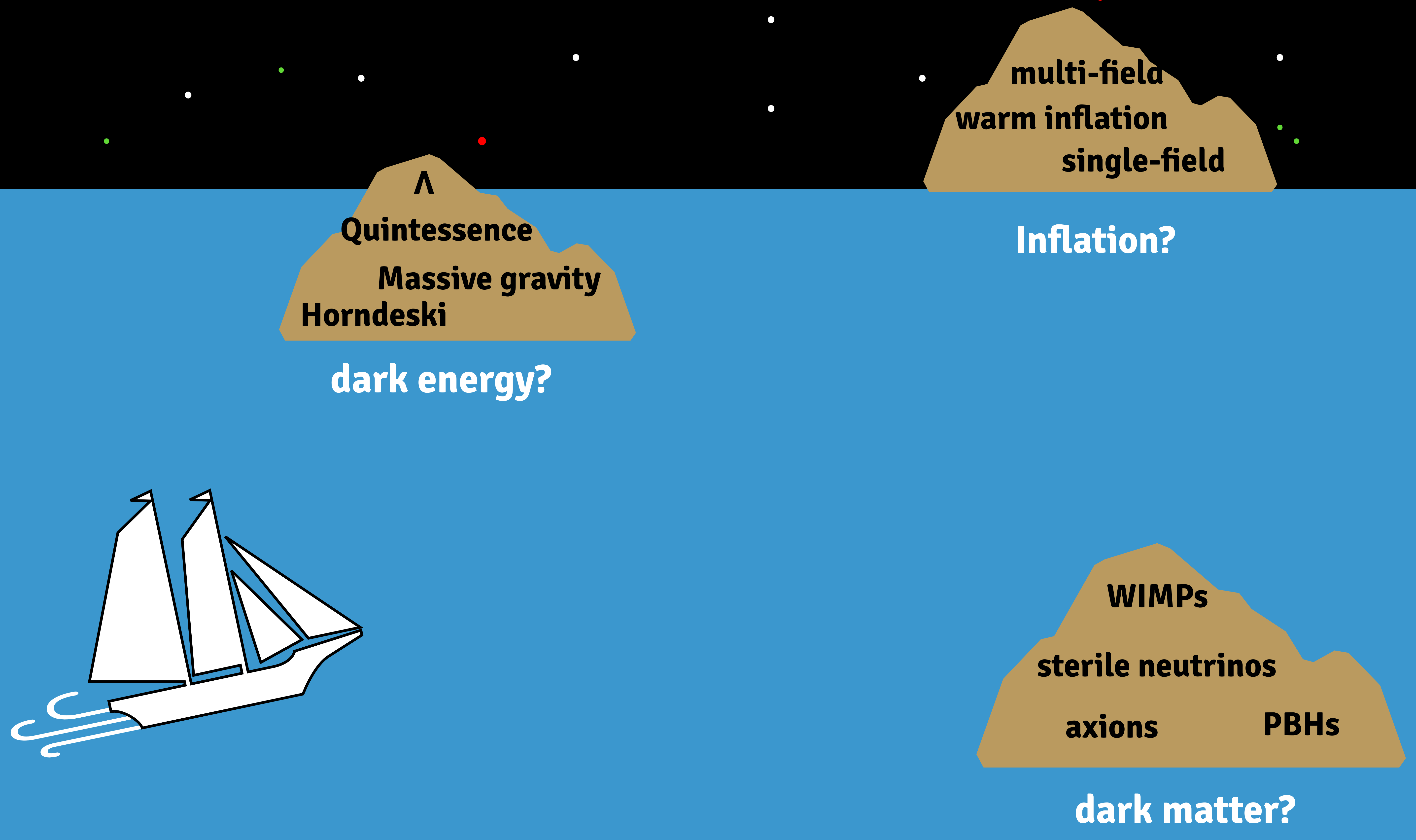


Only 6 free parameters!

Ω_c Ω_b H_0

A_s n_s τ_{reio}

However, the nature of the **dark sector** remains **unknown**



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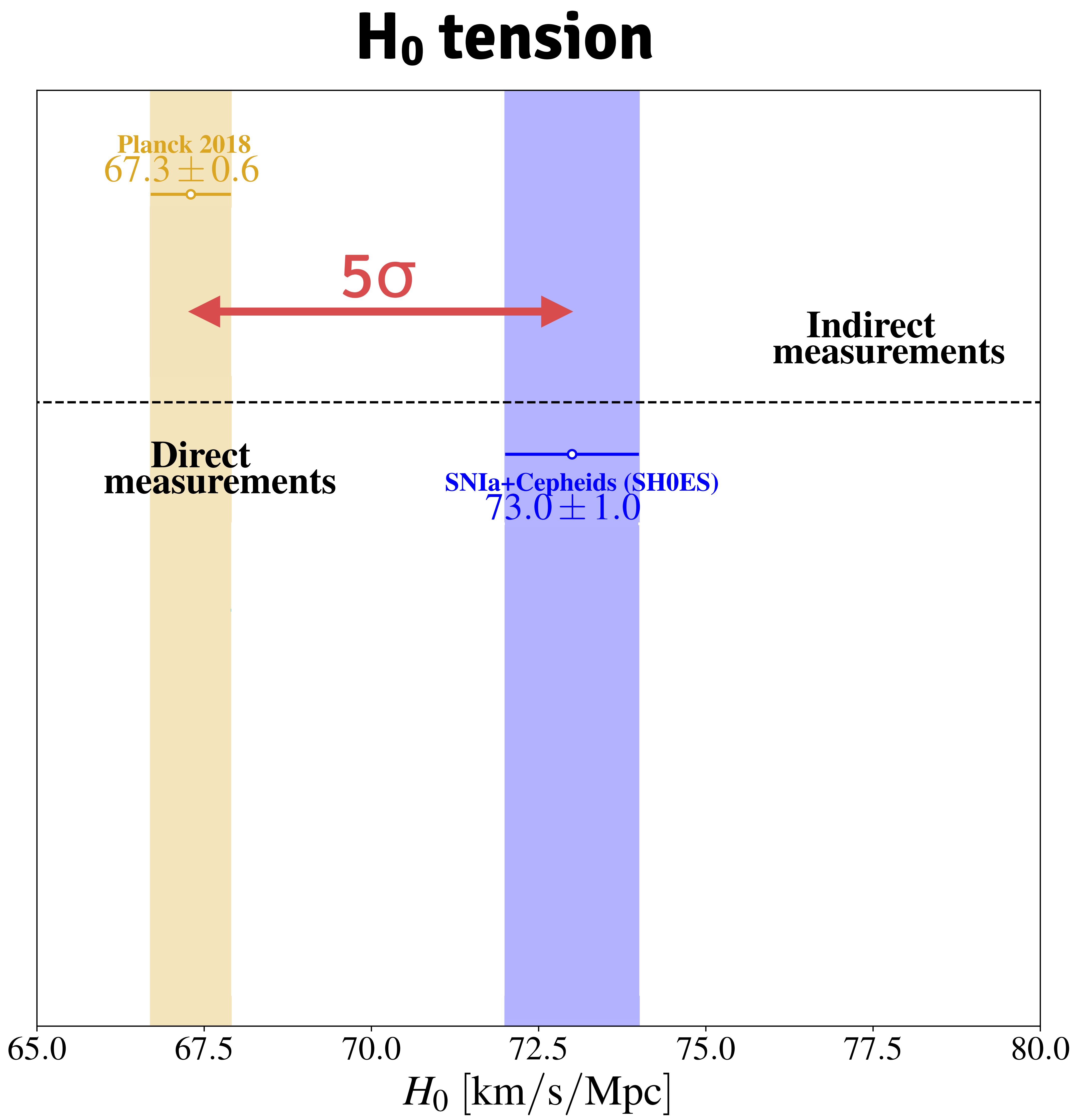

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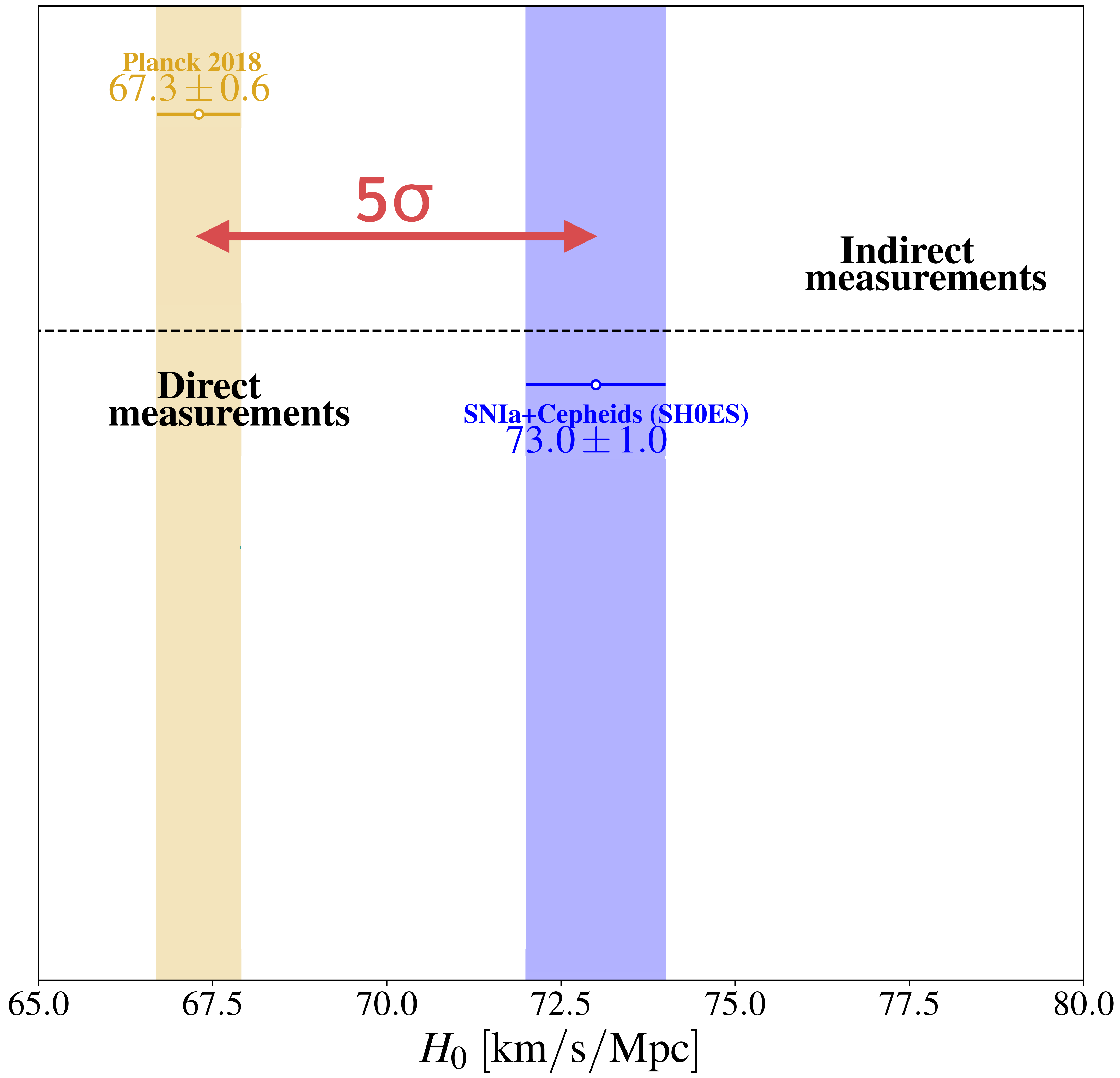
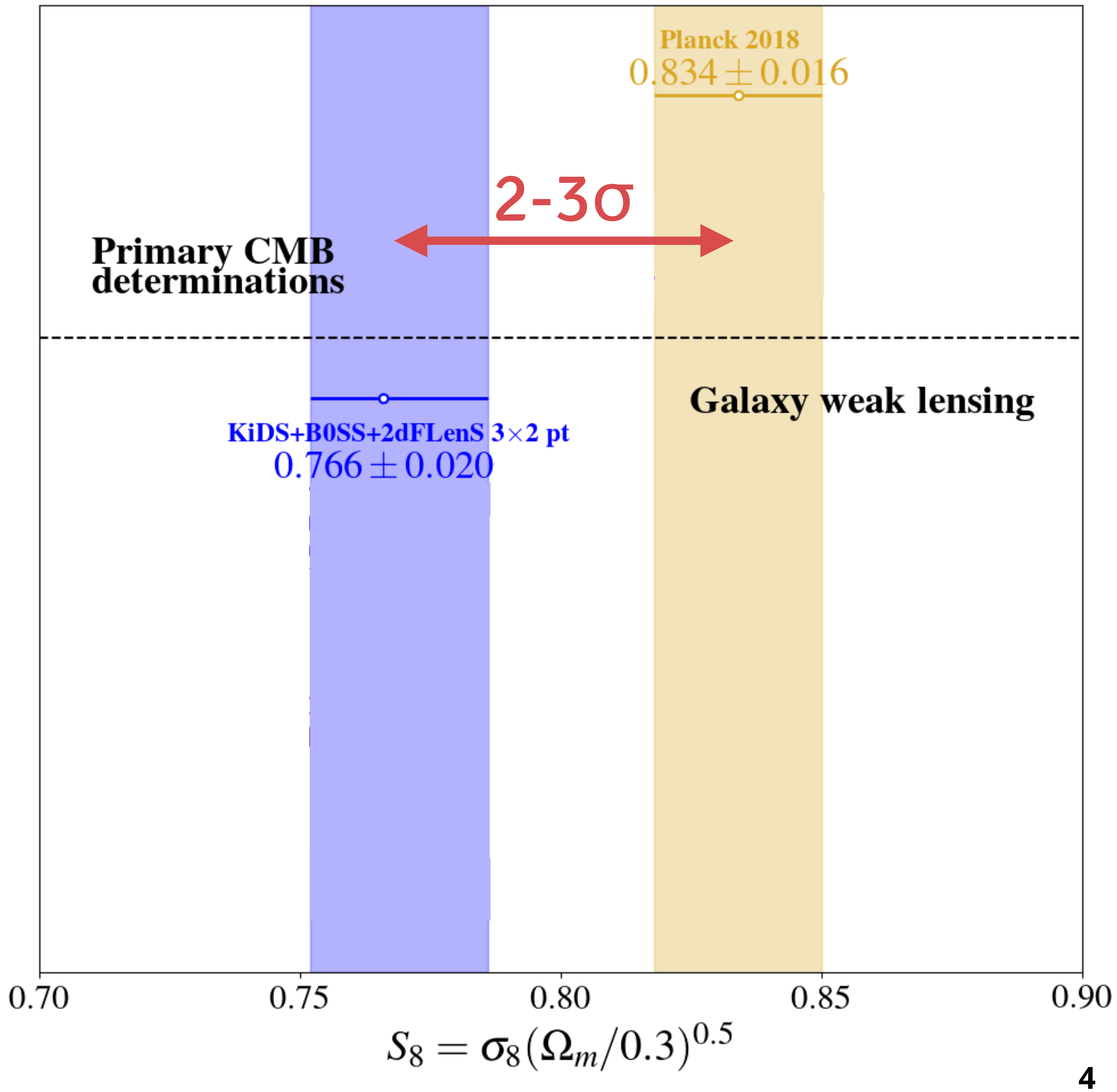
H_0 tension



S_8 tension



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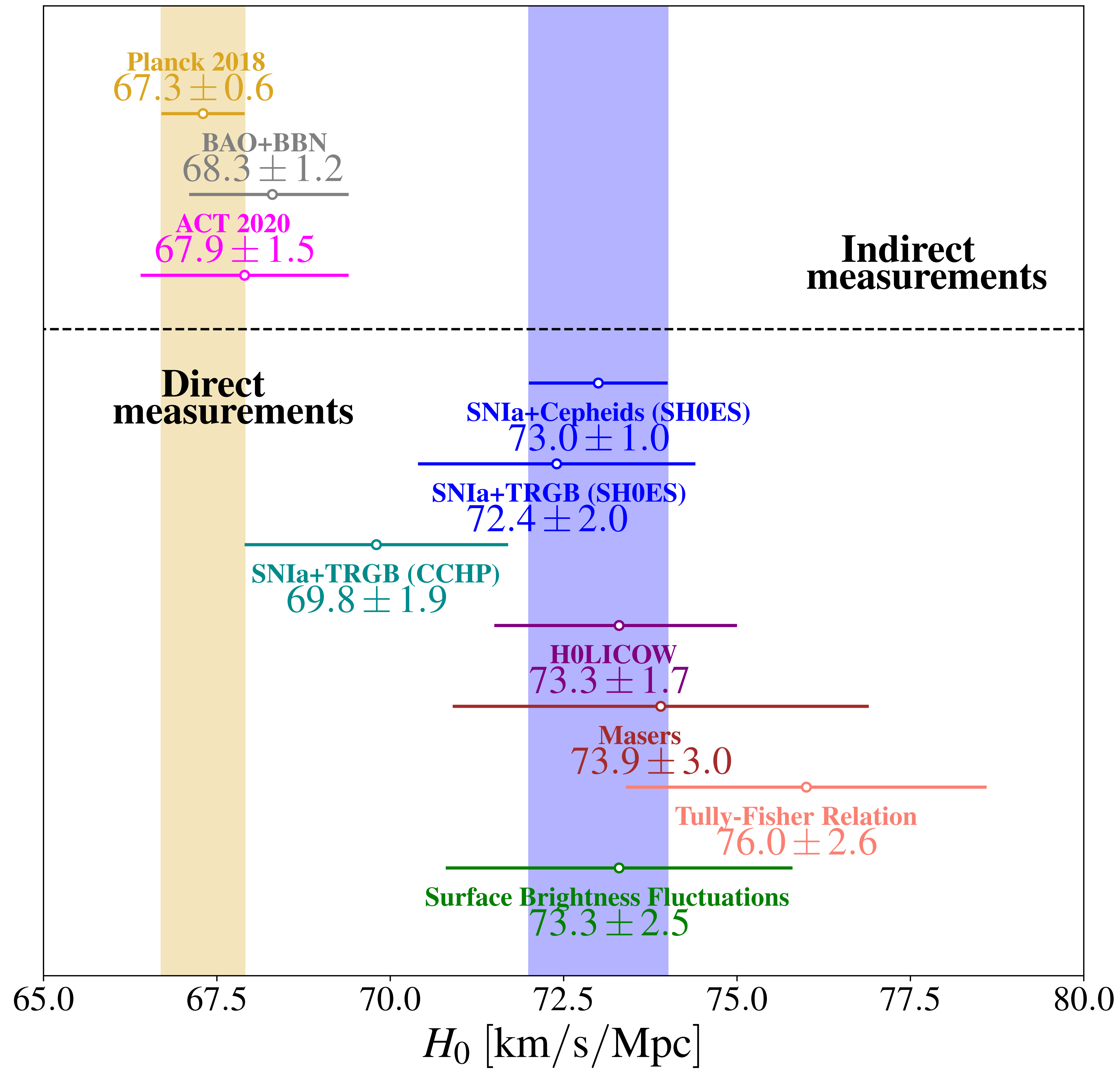

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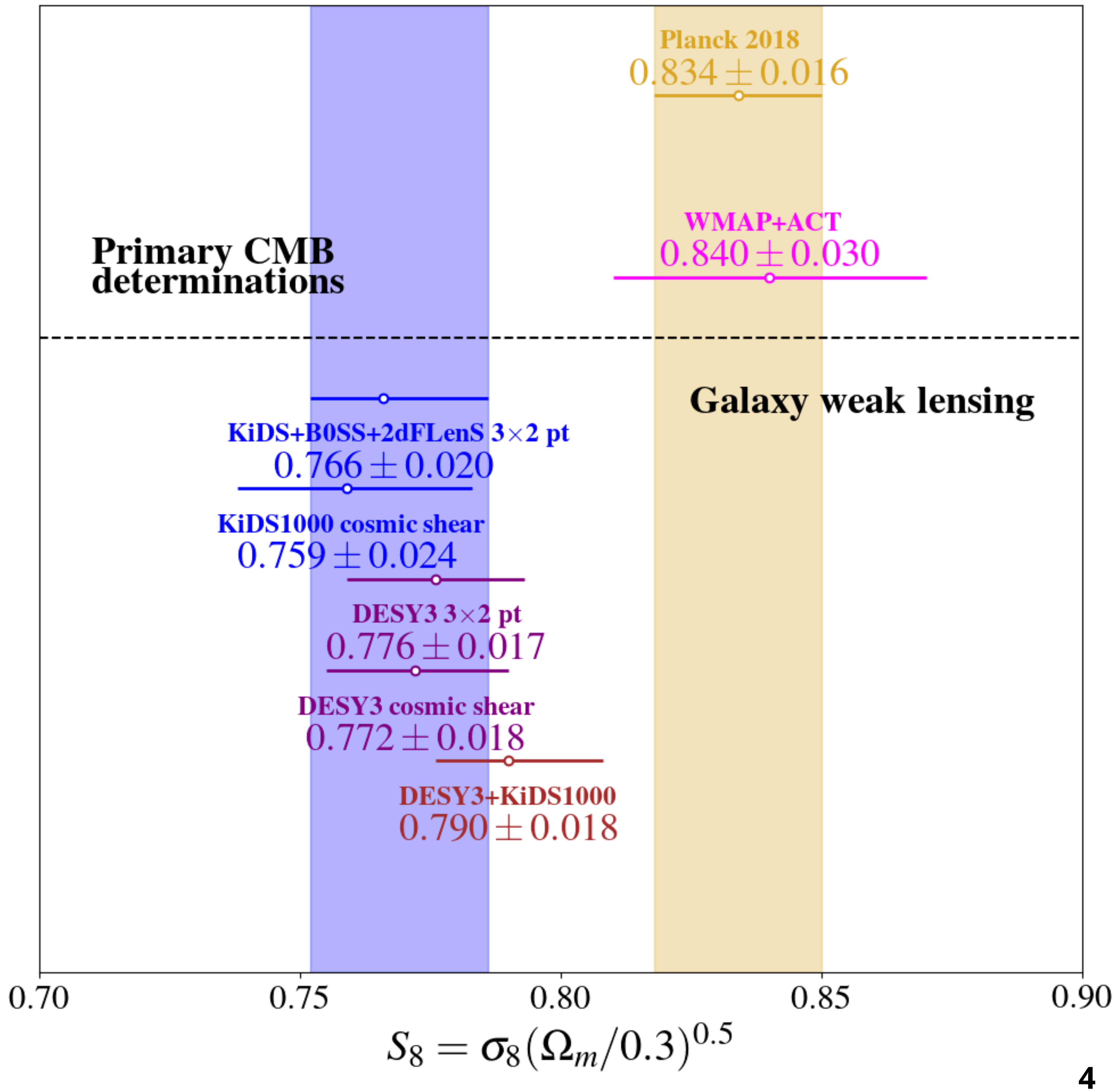
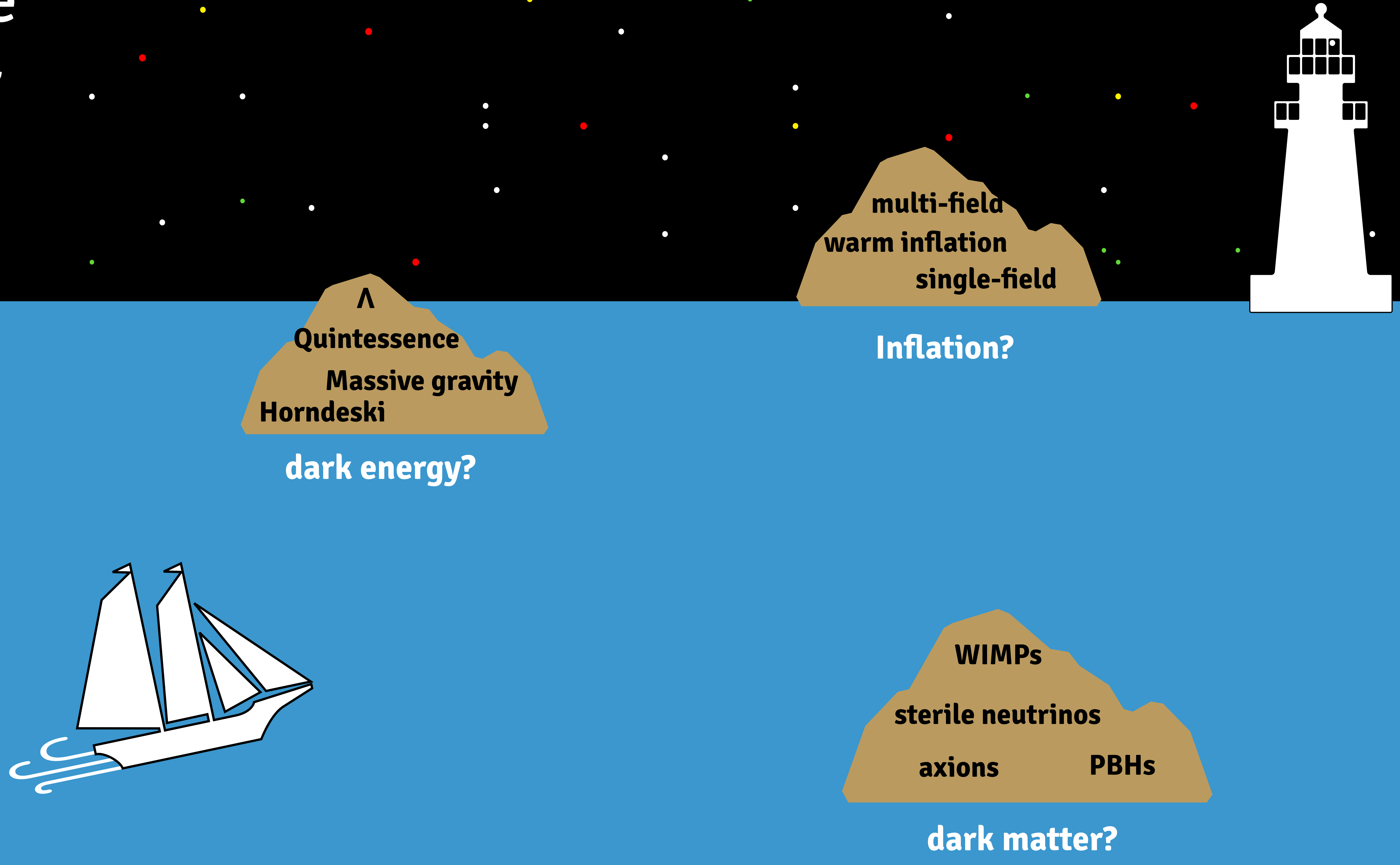


Cosmic tensions can **shed some light** on the mysterious dark sector



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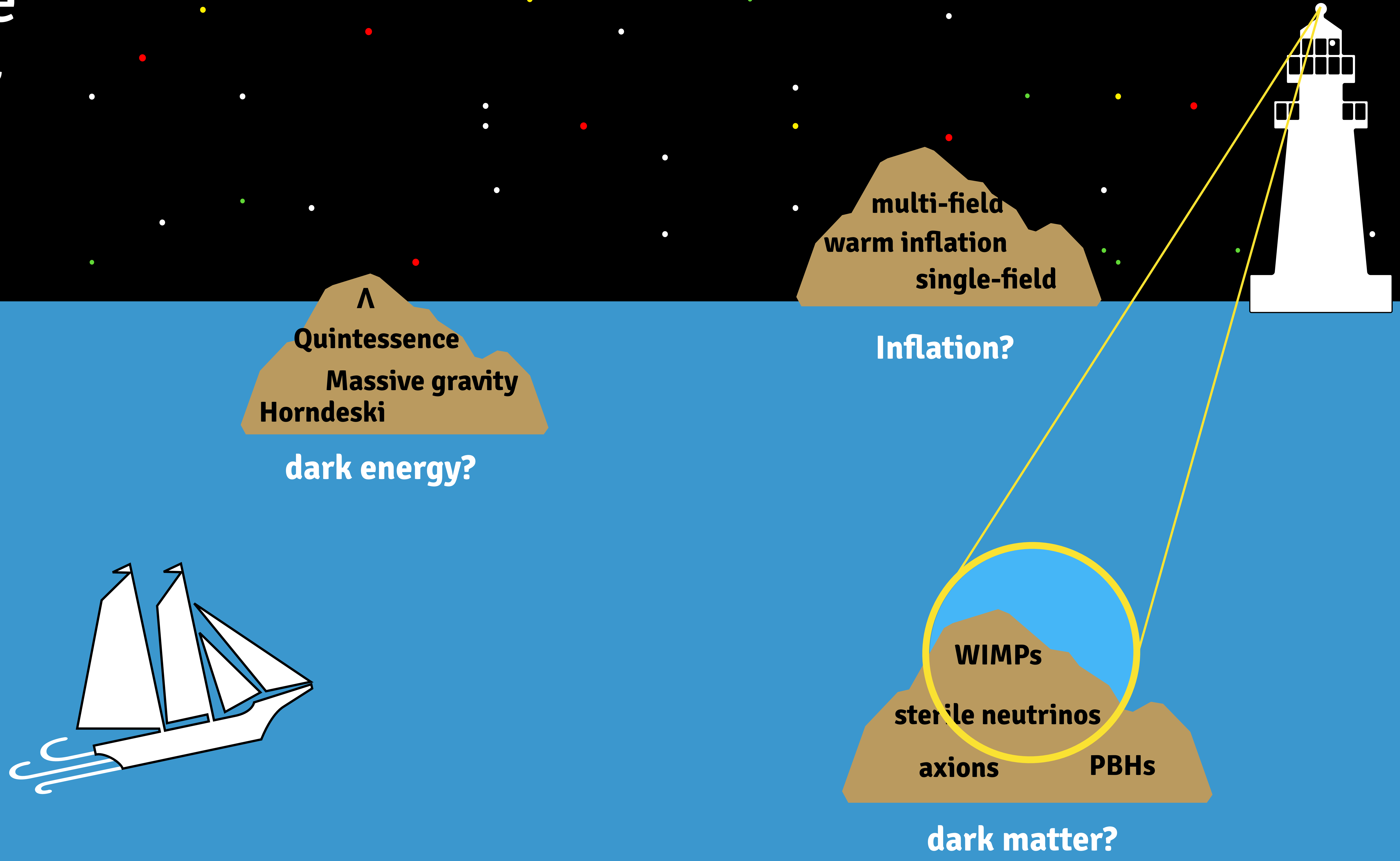

Outline

I. Decaying Dark Matter and the S_8 tension

II. Early Dark Energy and the H_0 tension

III. Easing both tensions with Interacting Dark Radiation

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What is needed to explain low S_8 values ?

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

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

with $R = 8$ Mpc$/h$

One needs to **suppress matter growth**
at scales $k \sim 0.1 - 1\ h/\mathrm{Mpc}$
while **keeping a good fit** to other data

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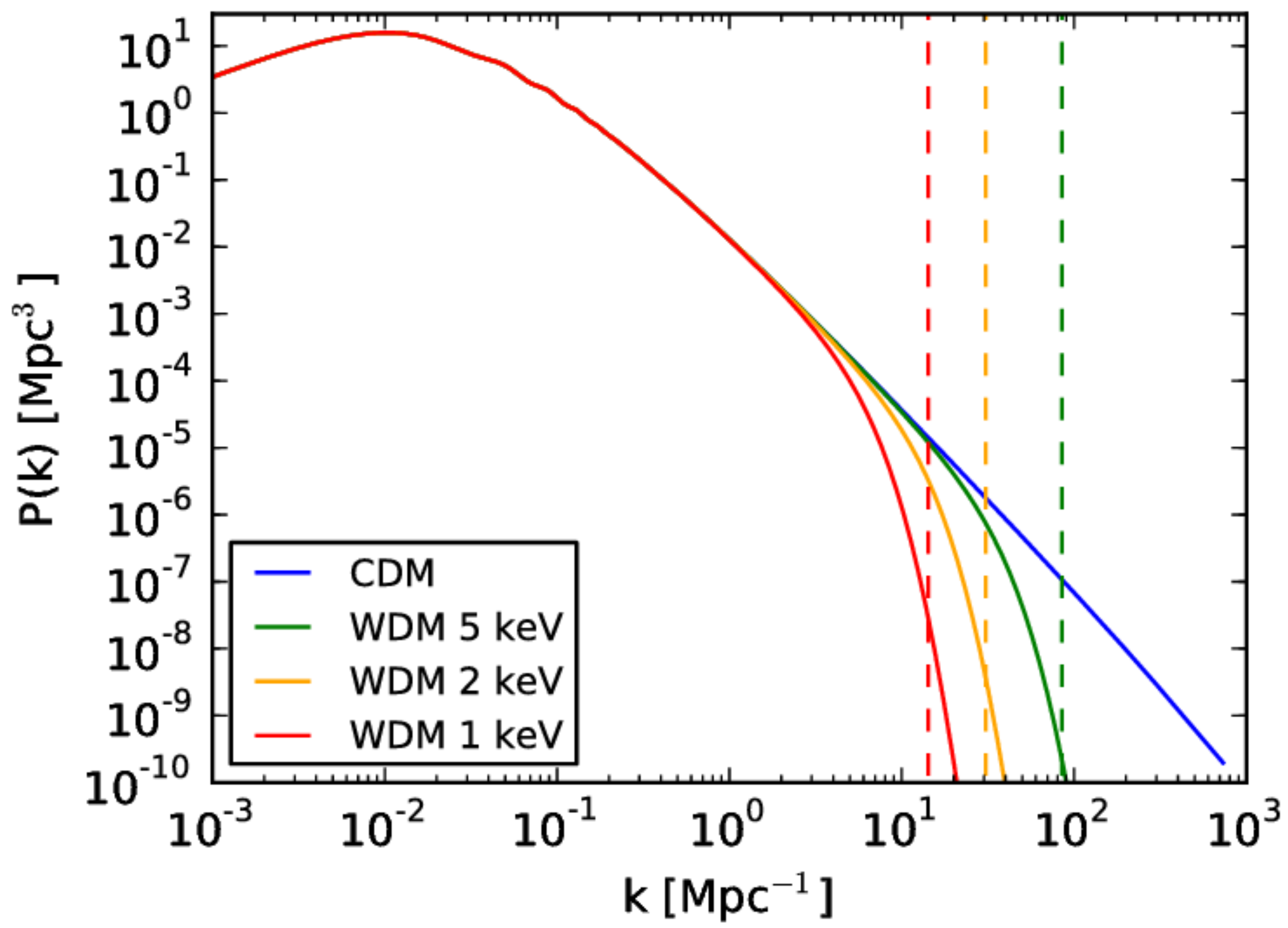
Ex: Warm dark matter

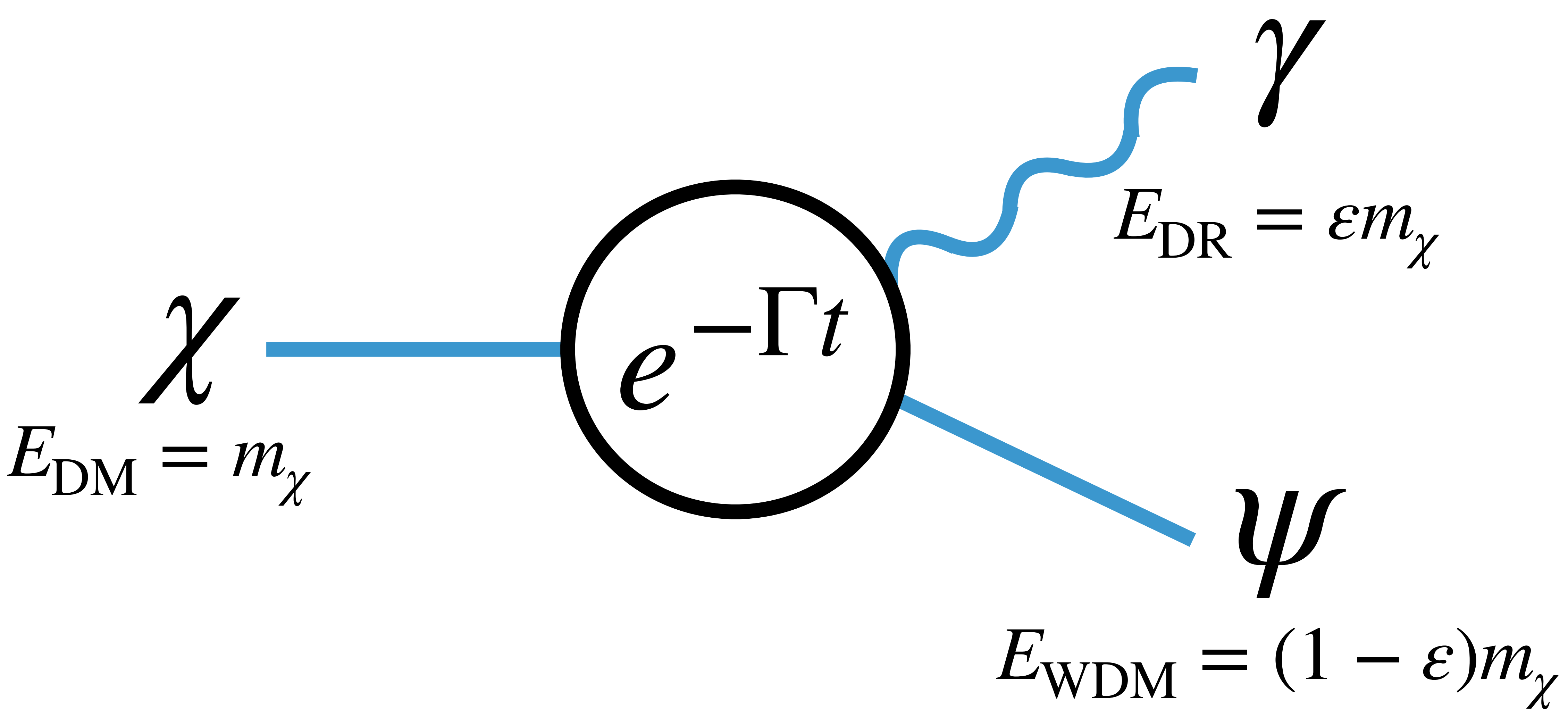


Very constrained by Ly-α !

[Iršič+ 17]

Invisible Dark Matter Decay

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



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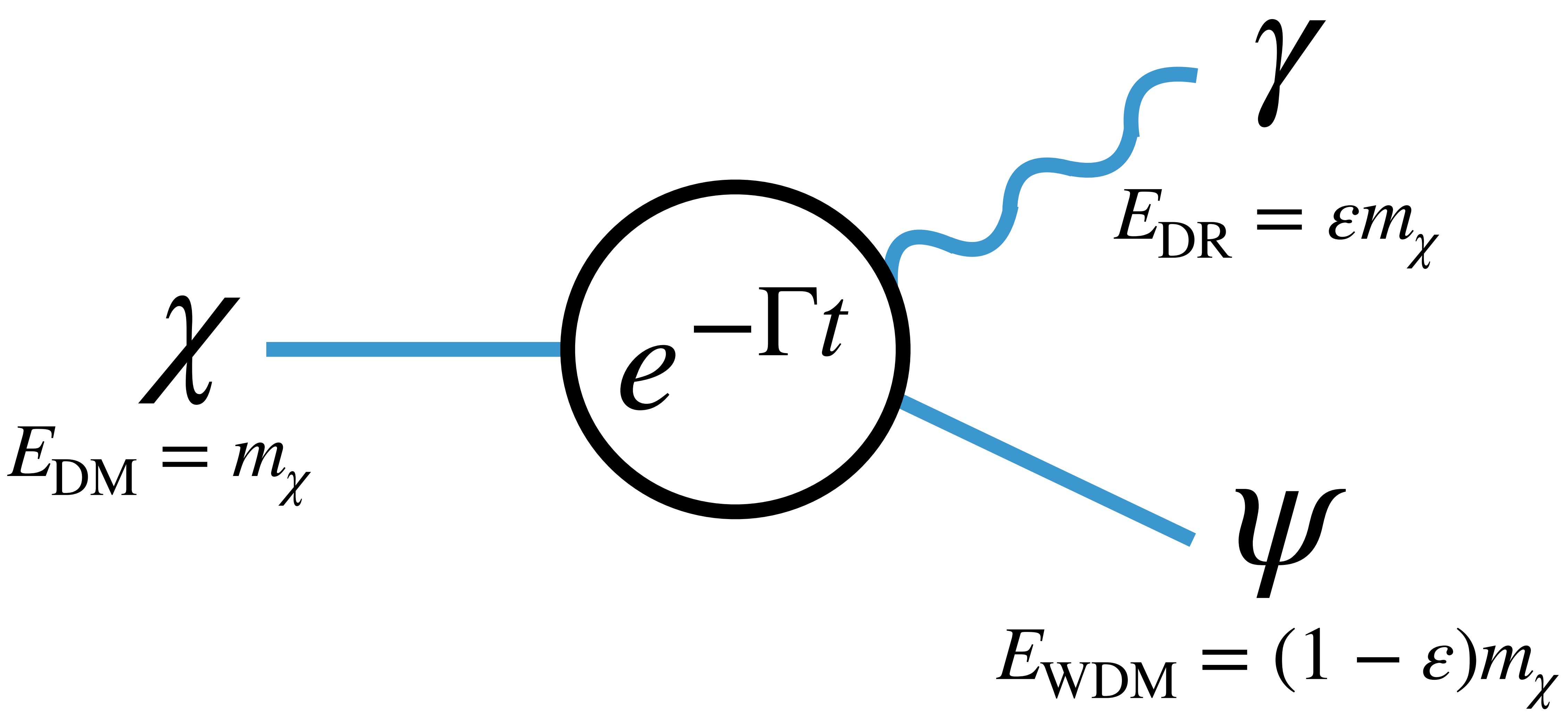


2 extra parameters:

Decay rate

$$\Gamma = 1/\tau$$

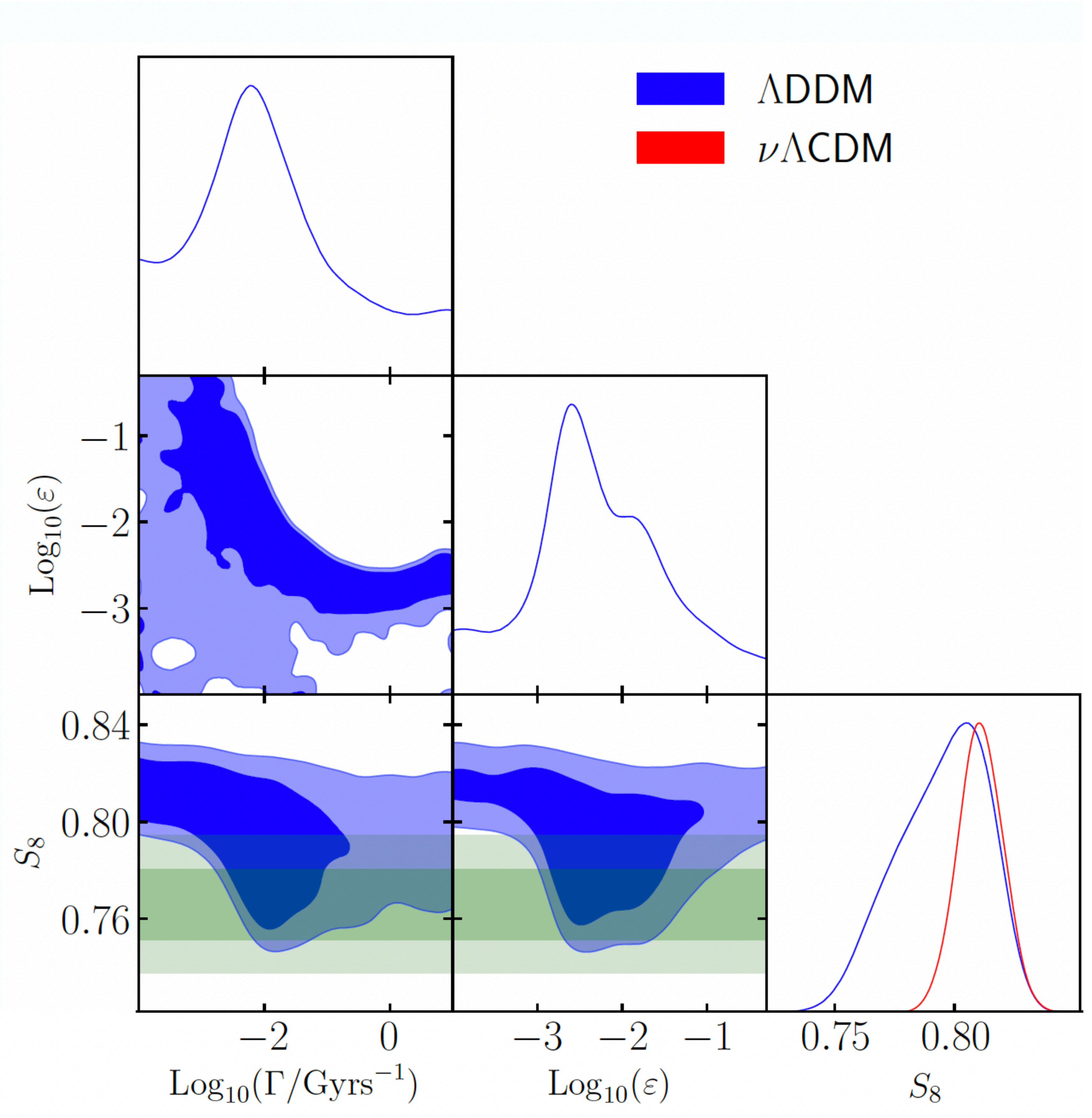
DR energy fraction

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m_\psi^2}{m_\chi^2}\right)$$

Explaining the S_8 tension

- First analysis including linear perts. showed that **DDM can explain S_8 tension** with weak-lensing data

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



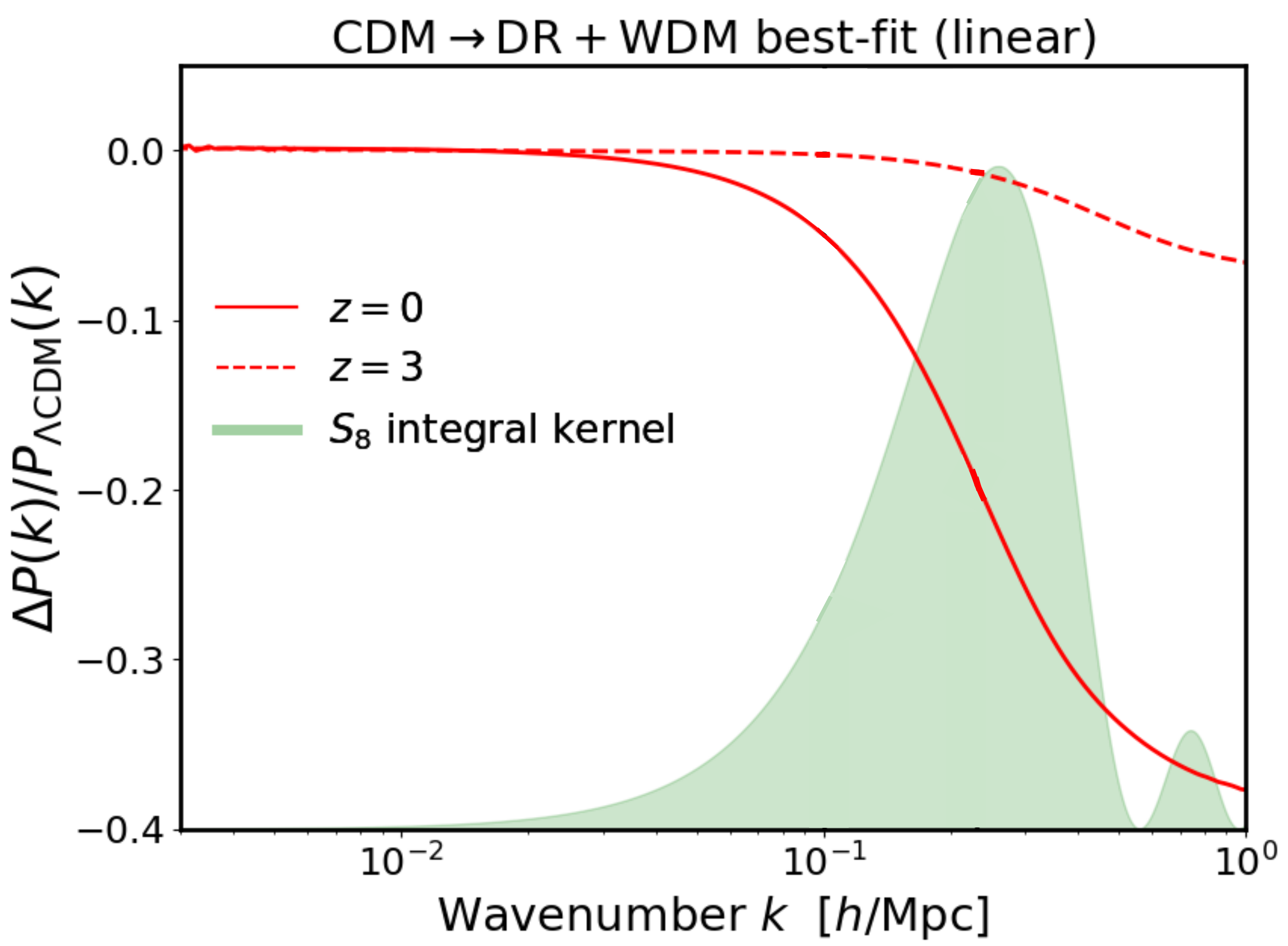
[GFA, Murgia, Poulin 21]
[GFA, Murgia++ 22]

Explaining the S_8 tension

- First analysis including linear perts. showed that **DDM can explain S_8 tension** with weak-lensing data

- The DDM provides a good fit because it yields a **lower suppression in the past***

* and it also leaves H(z) unaffected



- DDM has now been tested with various **LSS observables**, like **galaxy clustering** [Simon, GFA++ 22], the **MW satellites** [DES 22], the **Lyman-α forest** [Fuss & Garny 22], the **SZ clusters** [Tanimura++ 23], and **WL data** from KiDS-1000 [Bucko++ 24]

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- Various **particle physics models** have been proposed. **Ex:**
  - **Gravitino** decays $\tilde{G}_\mu \to \tilde{N}_1 + N_1$ [Choi & Yanagida 22]
  - **Minimal** model with SM neutrinos $N_2 \to \bar{N}_1 \nu \nu$ [Fuss++ 24]

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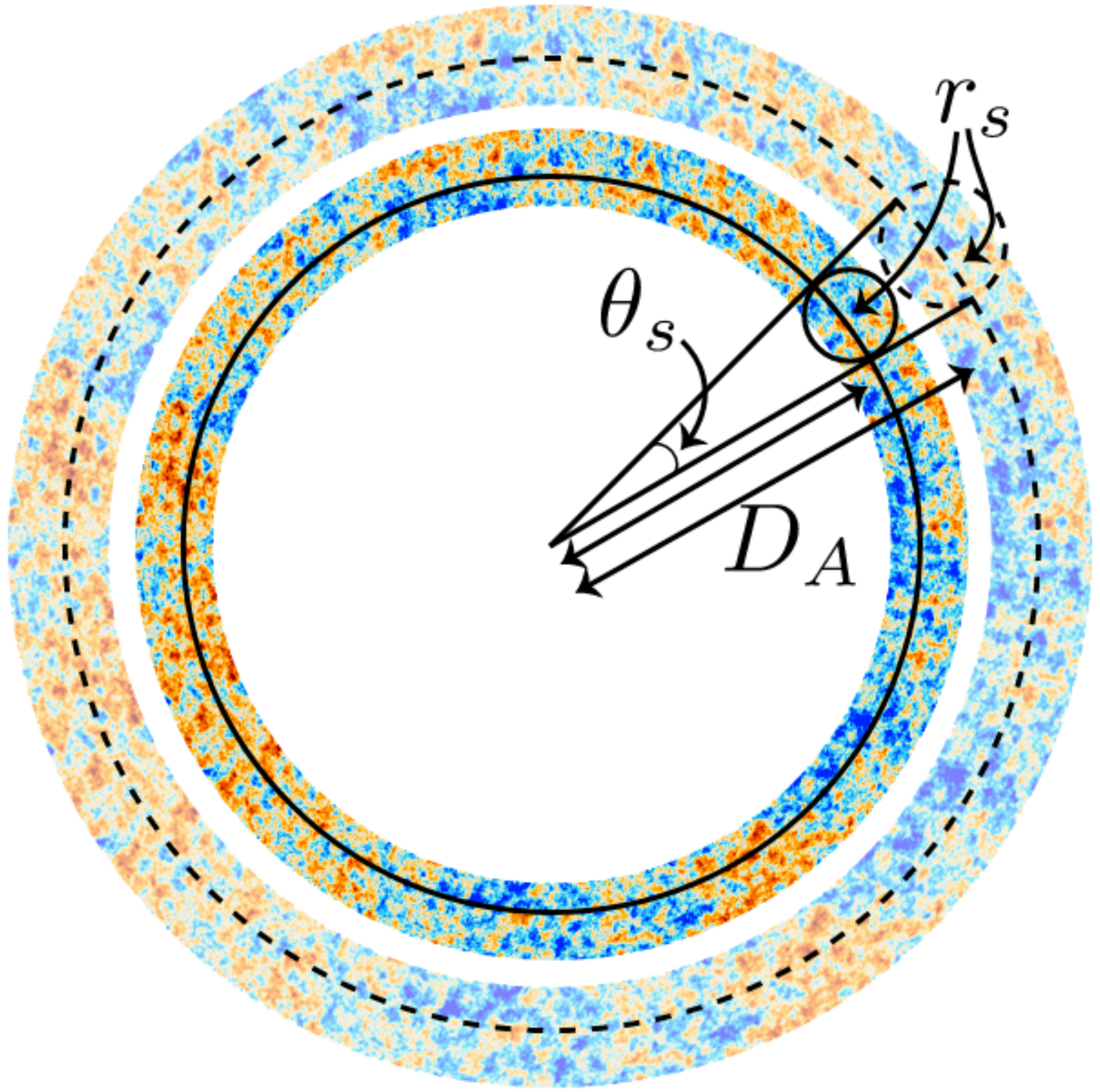
How does the **CMB** determine H_0 ?

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

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

$D_A \propto 1/H_0$



[T. Smith]

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To rise H_0 while keeping θ_s fixed:

- Decrease $r_s(z_{\rm rec})$ **(Early-time solutions)**
- Change $D_A(z < z_{\rm rec})$ **(Late-time solutions)**

…late-time solutions are disfavored by low-redshift data

[Knox & Millea 19]

[Efstathiou 21]

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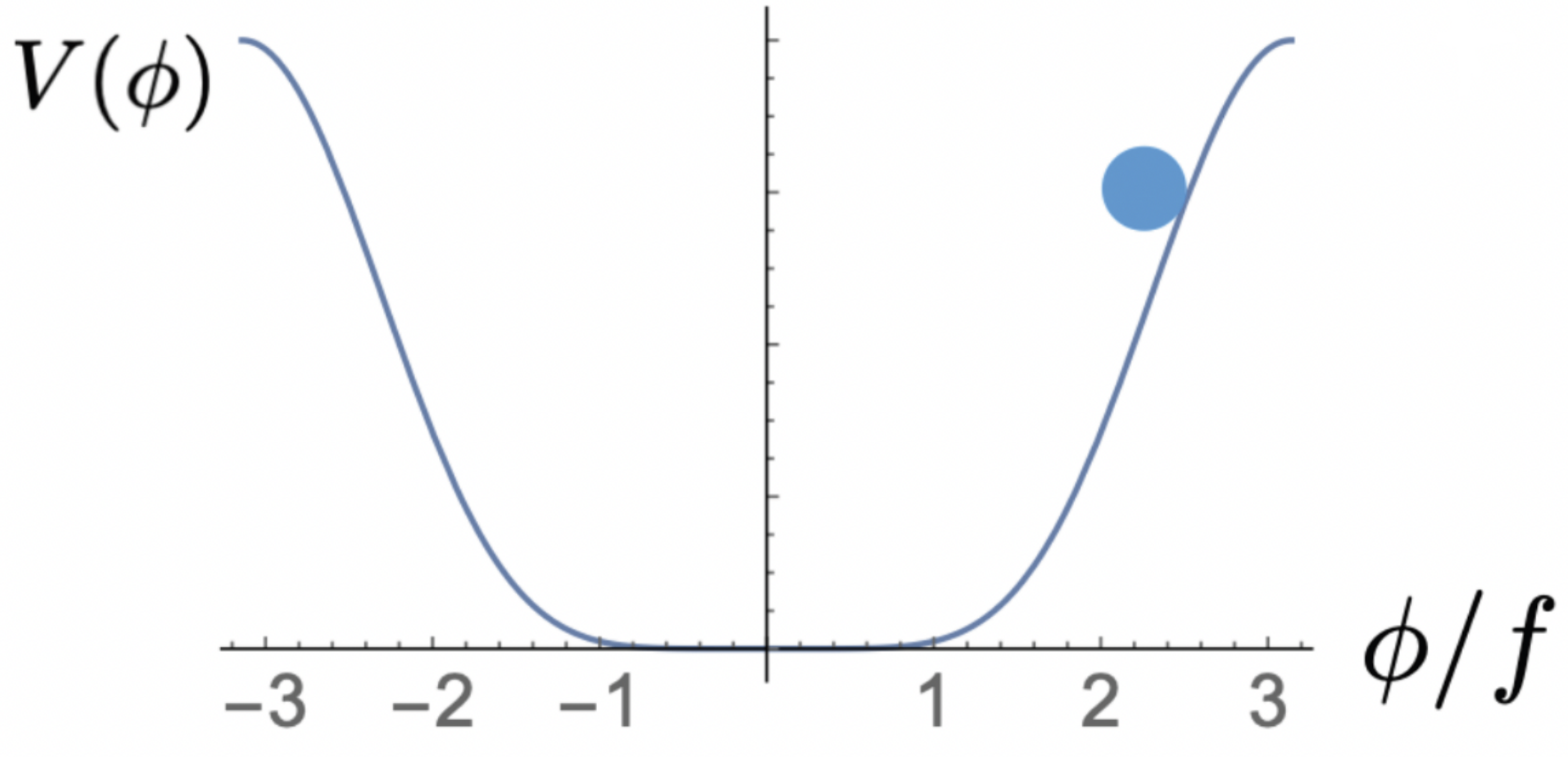
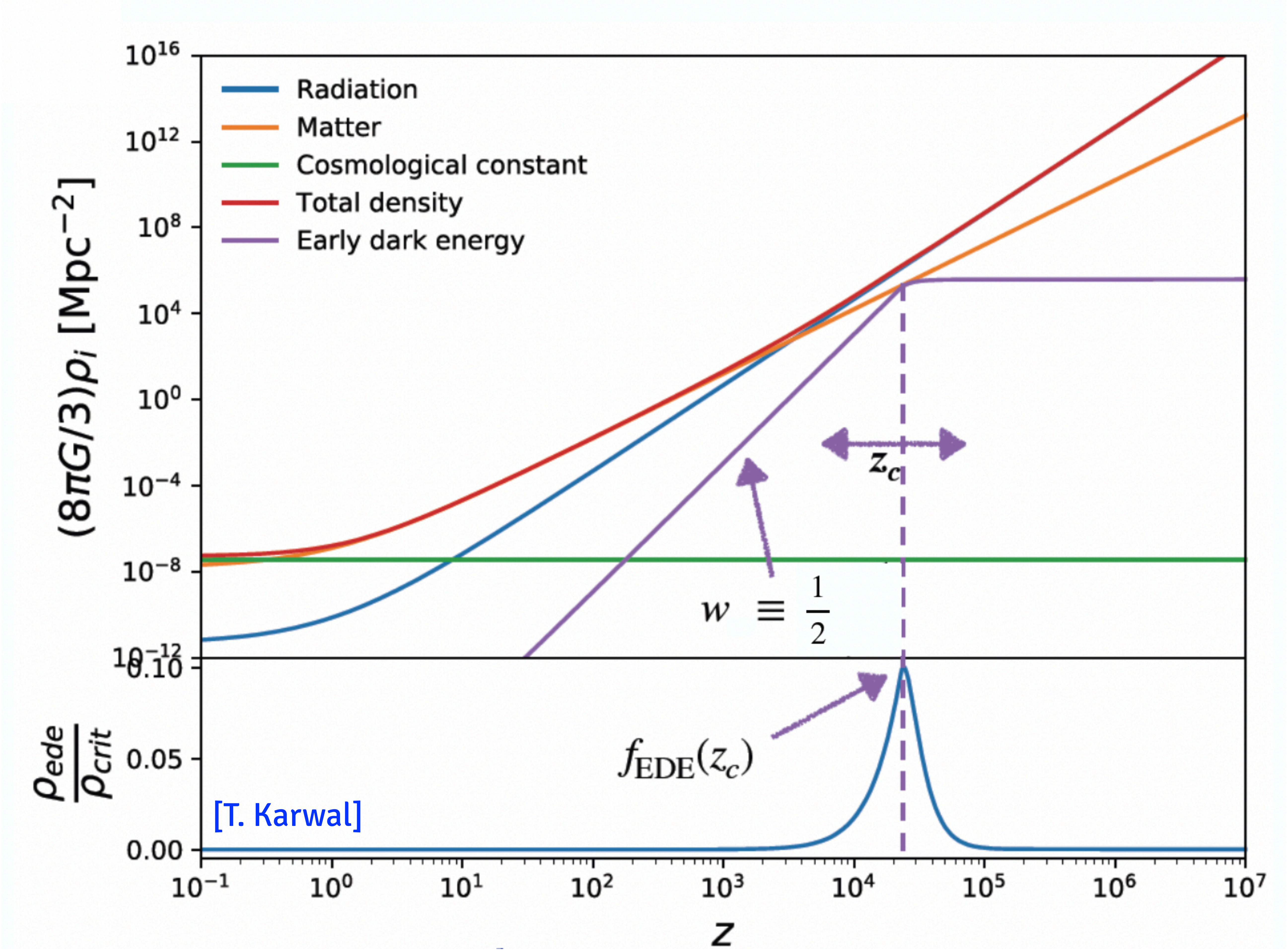
→ **need to lower r_s**



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

Early Dark Energy (EDE)

Scalar field initially frozen, dilutes faster than radiation afterwards



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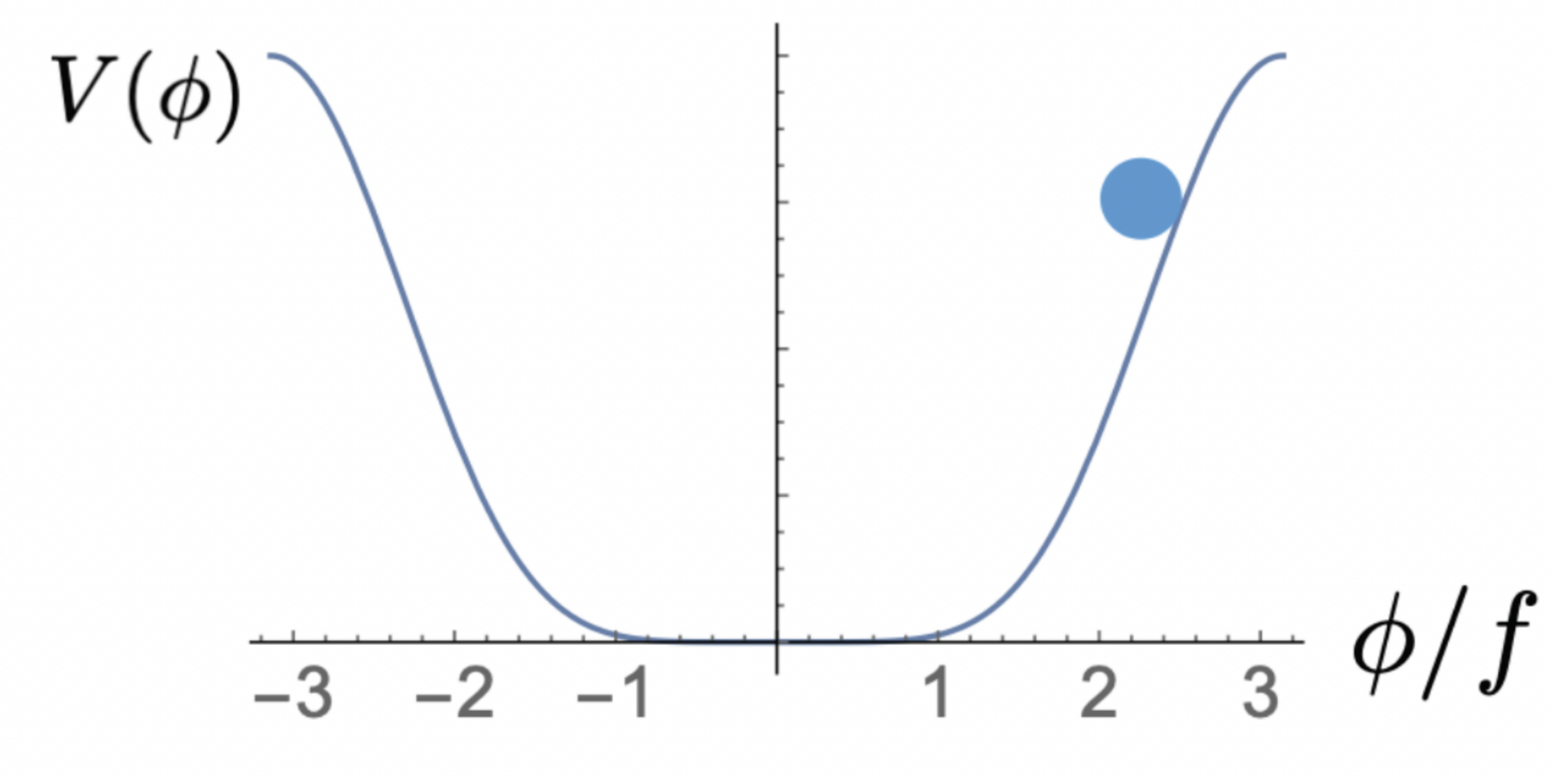

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3 extra parameters:

$f_{\mathrm{EDE}}(z_c)$ z_c ϕ_i

$V(\phi)$ params

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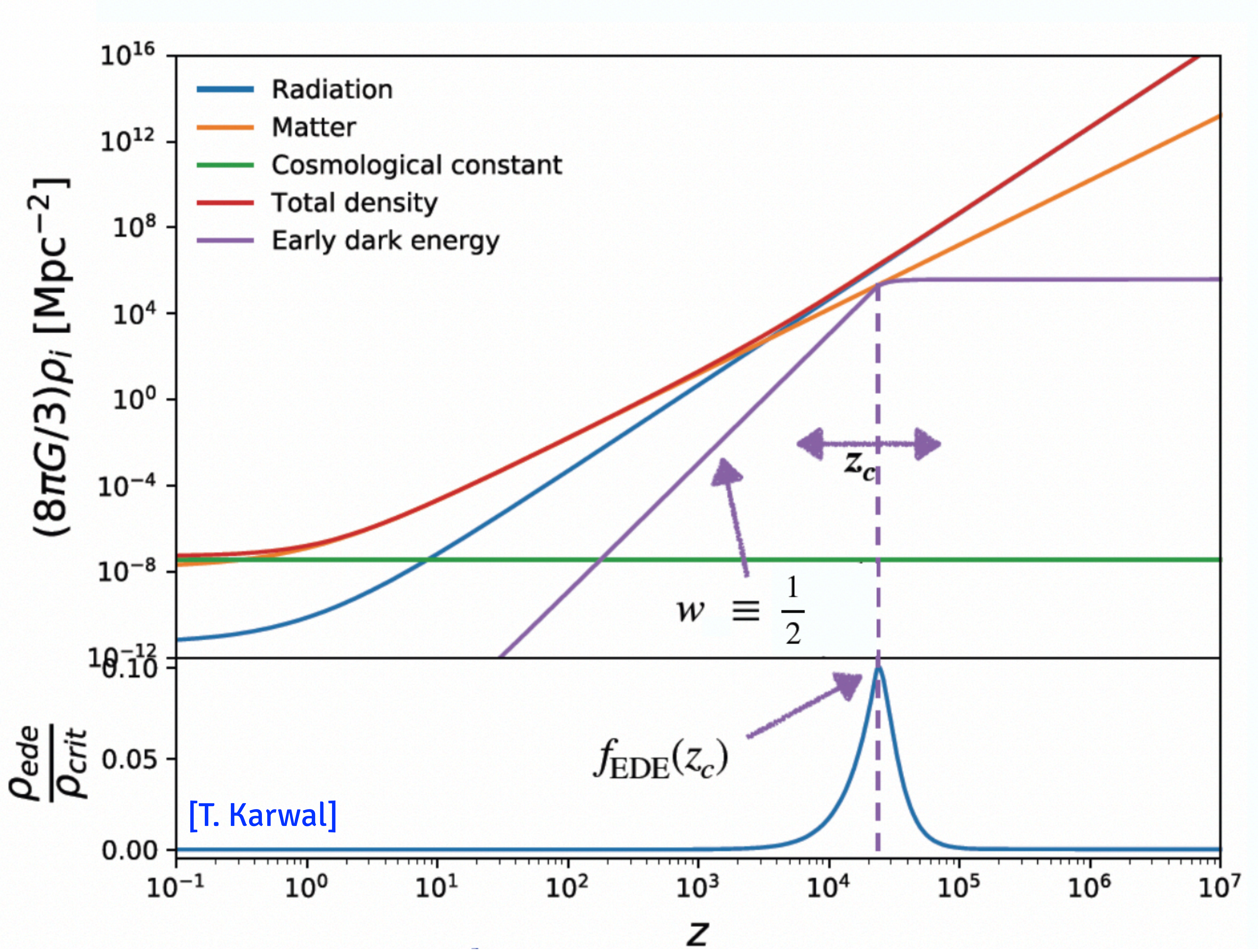

“EDE can solve the Hubble tension if it contributes $f_{\rm EDE}(z_c) \sim 10\,\%$ around $z_c \sim z_{\rm eq}$” [Poulin++ 19] [Smith++ 19]

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Axion-like potential → Canonical example, most widely studied in the literature

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

See [Poulin++ 23] for a recent review

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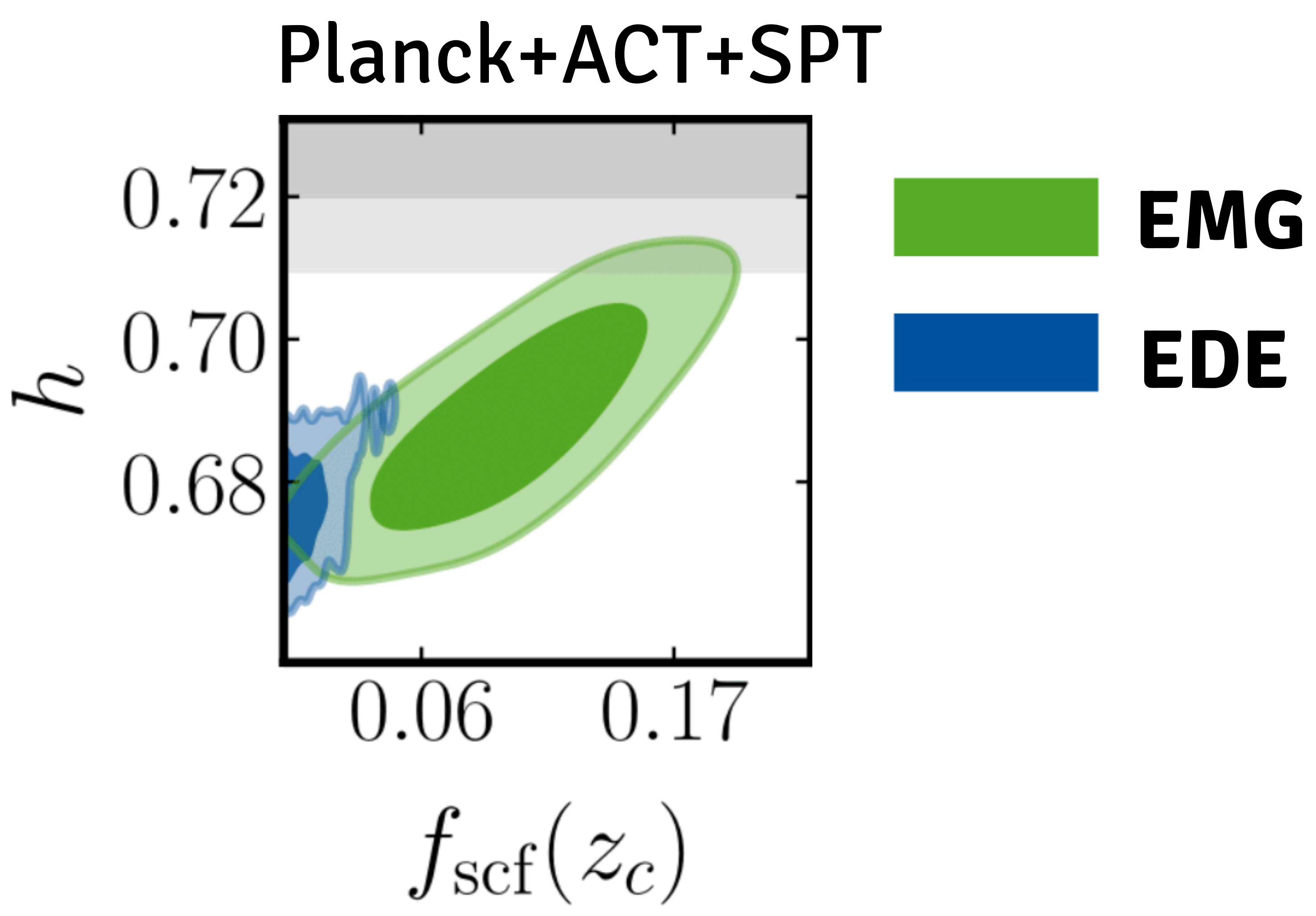
Variation: **Early Modified Gravity (EMG)**

The addition of a **non-minimal coupling to gravity** provides a much better fit to CMB data

[GFA, Braglia++ 23]



But **many other models** apart from EDE have been proposed...

Lost in the landscape of solutions

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 mag

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]

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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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Use a wide array of data

Planck 2018 + BAO + SNIa + SH0ES

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Apply different metrics

GT

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

Q_{DMAP}

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

ΔAIC

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

Results of the contest

Model	ΔN_{param}	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ (3)
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
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	✗	-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	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

[Schöneberg, GFA++ 22]

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Late-time solutions are the most **disfavored**

[Schöneberg, GFA++ 22]

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Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ ③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
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	✗	-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	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

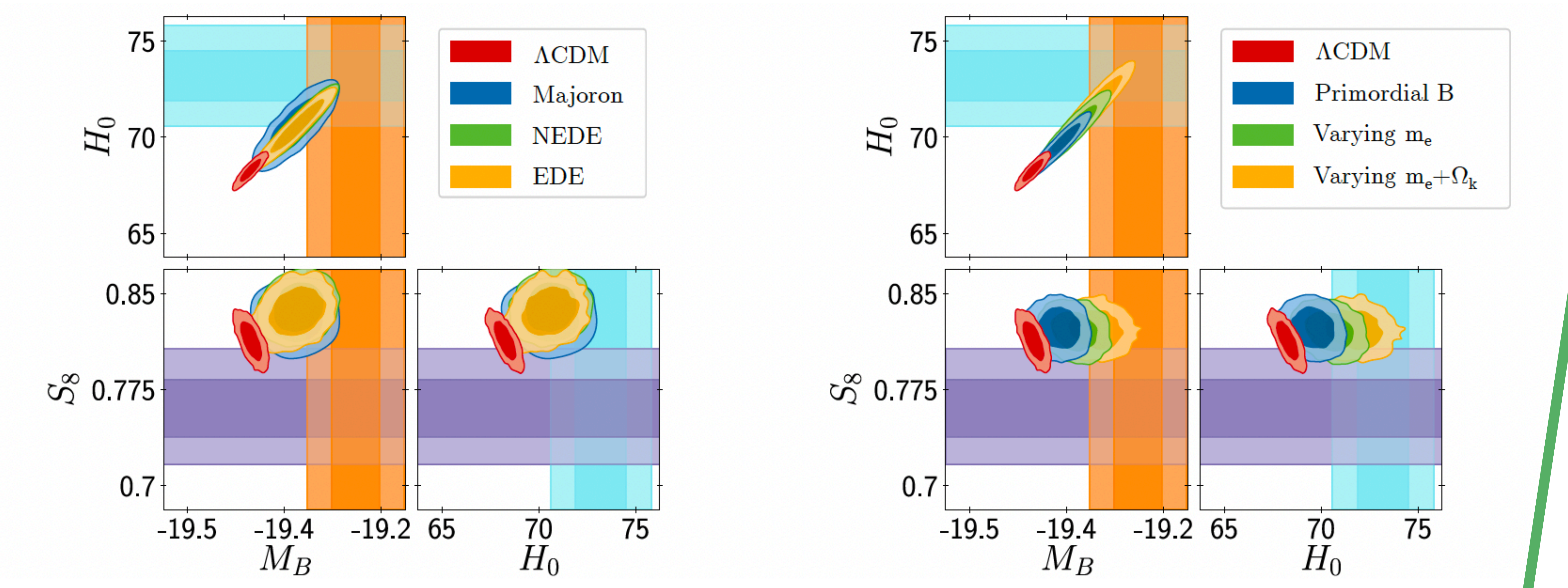
[Schöneberg, GFA++ 22]

Late-time solutions are the most **disfavored**

Early-time solutions (like EDE) appear the most **successful**

Results of the contest

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



[Schöneberg, GFA++ 22]

[Khalife++ 24] ⟶ Updated version of the contest

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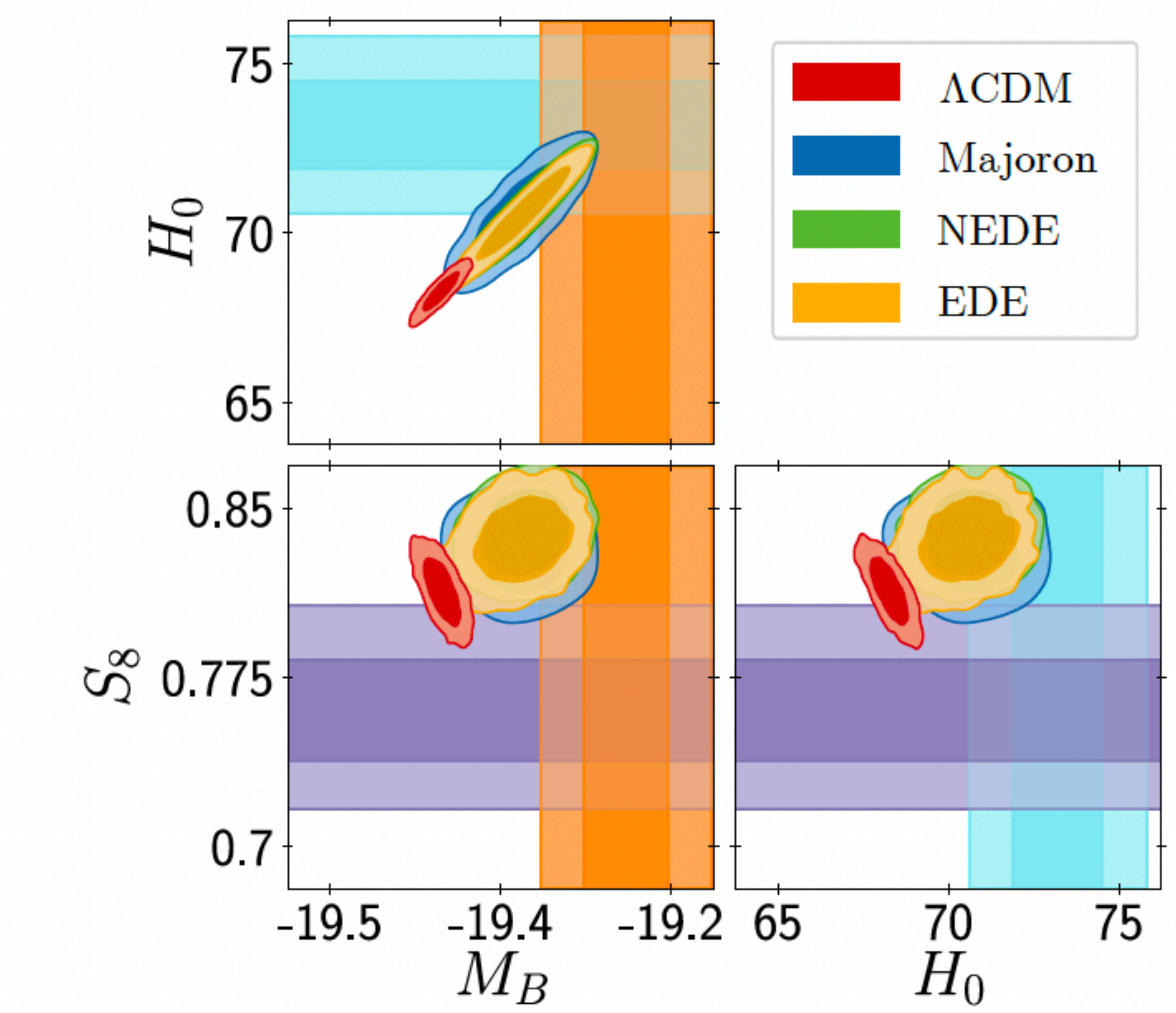
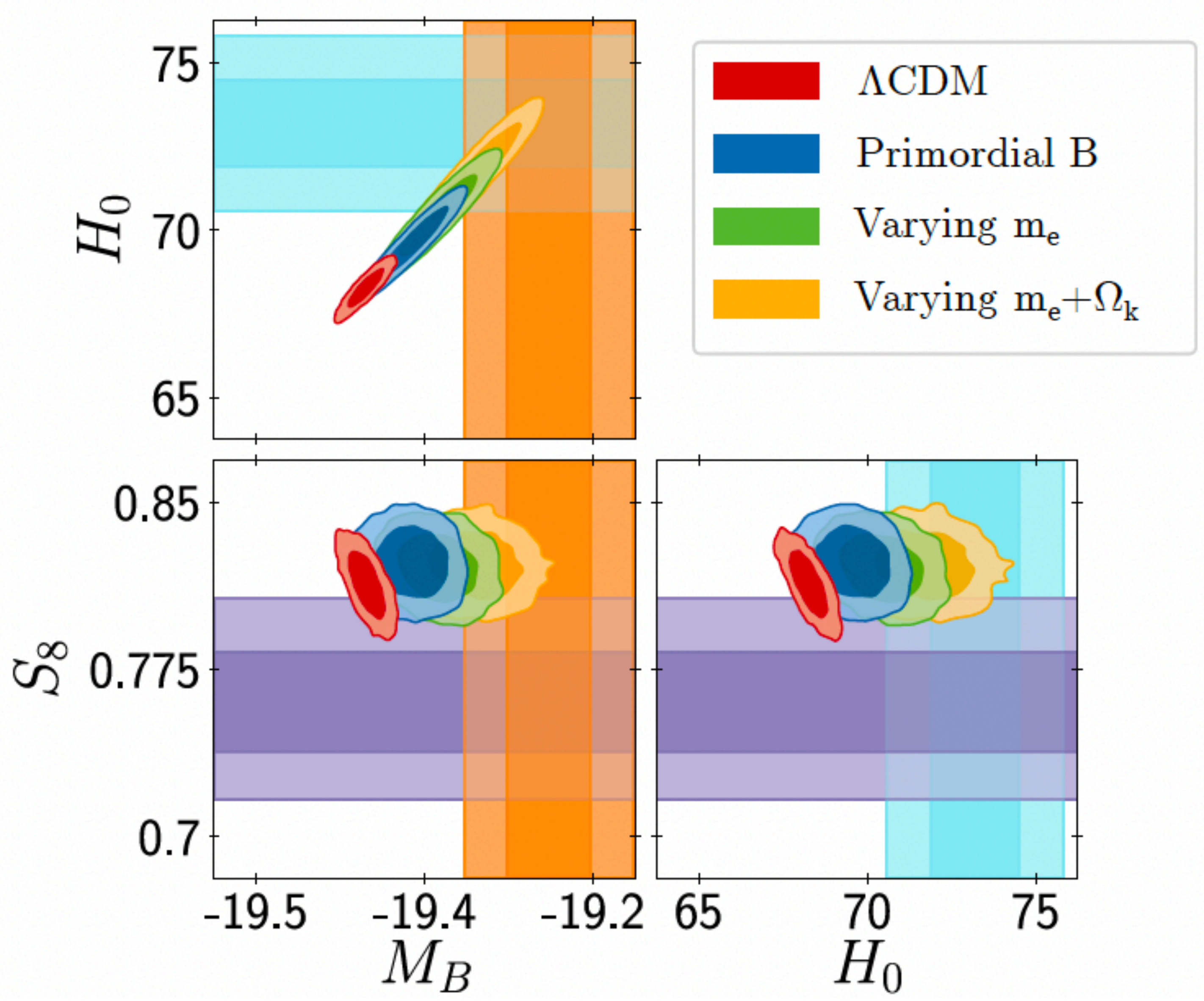




What kind of mechanism is required to **address both tensions** simultaneously?

[Schöneberg, GFA++ 22]

[Khalife++ 24] ⟶ Updated version of the contest

Outline

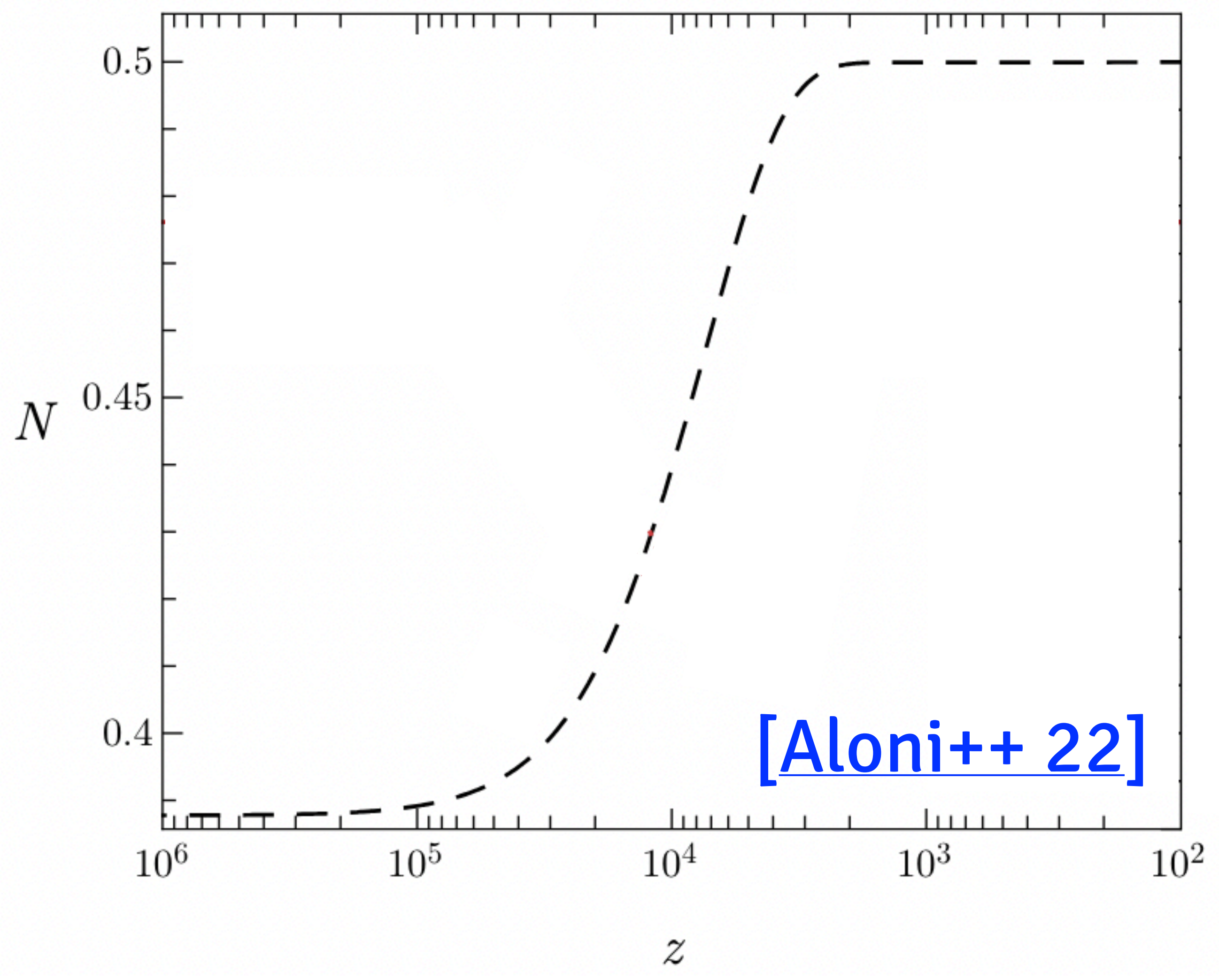
I. Decaying Dark Matter and the S_8 tension

II. Early Dark Energy and the H_0 tension

III. Easing both tensions with Interacting Dark Radiation ✓

Interacting (Stepped) Dark Radiation

Self-interacting **dark radiation fluid undergoing a "step"** in its abundance (when T<m)...



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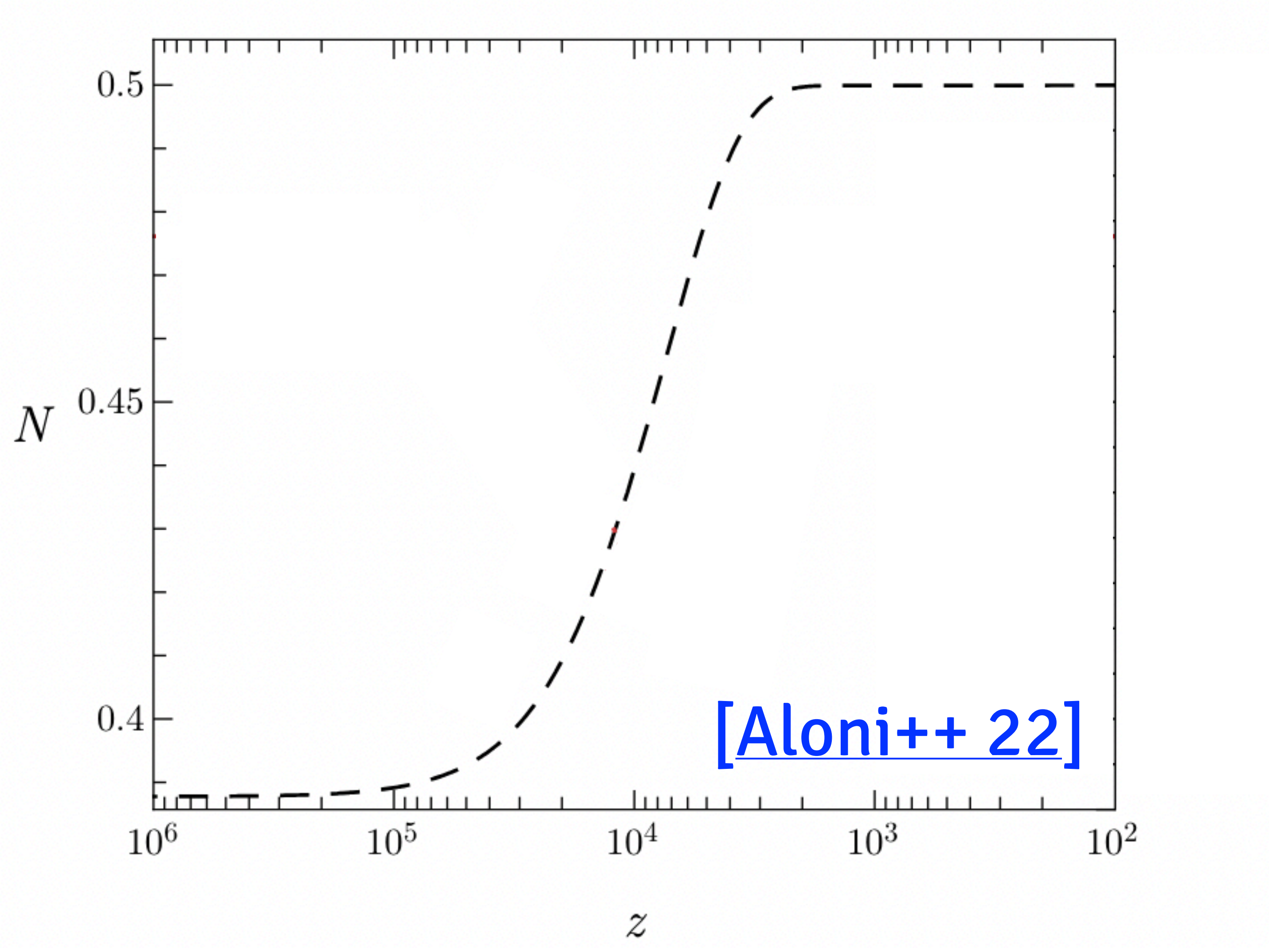
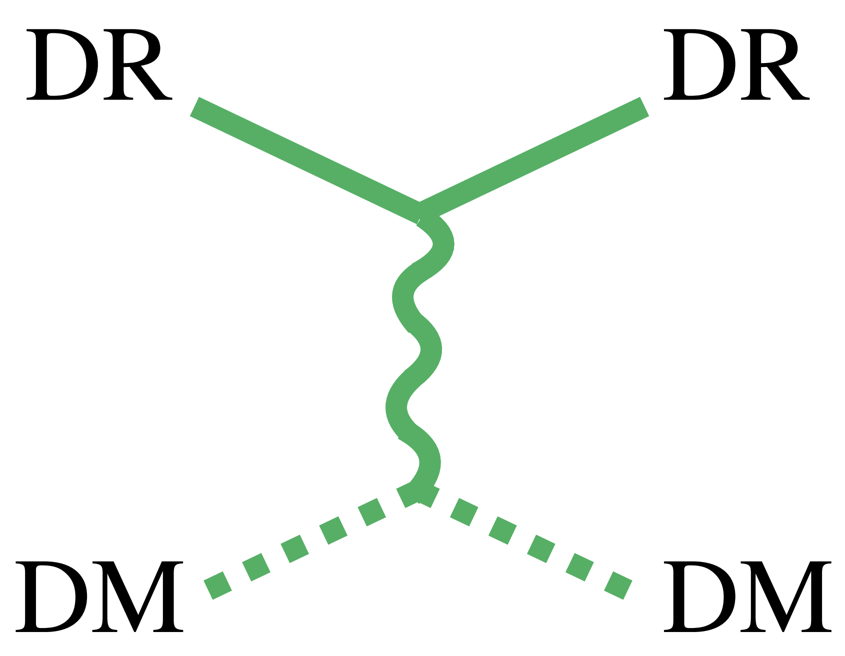


...which additionally
scatters with dark matter



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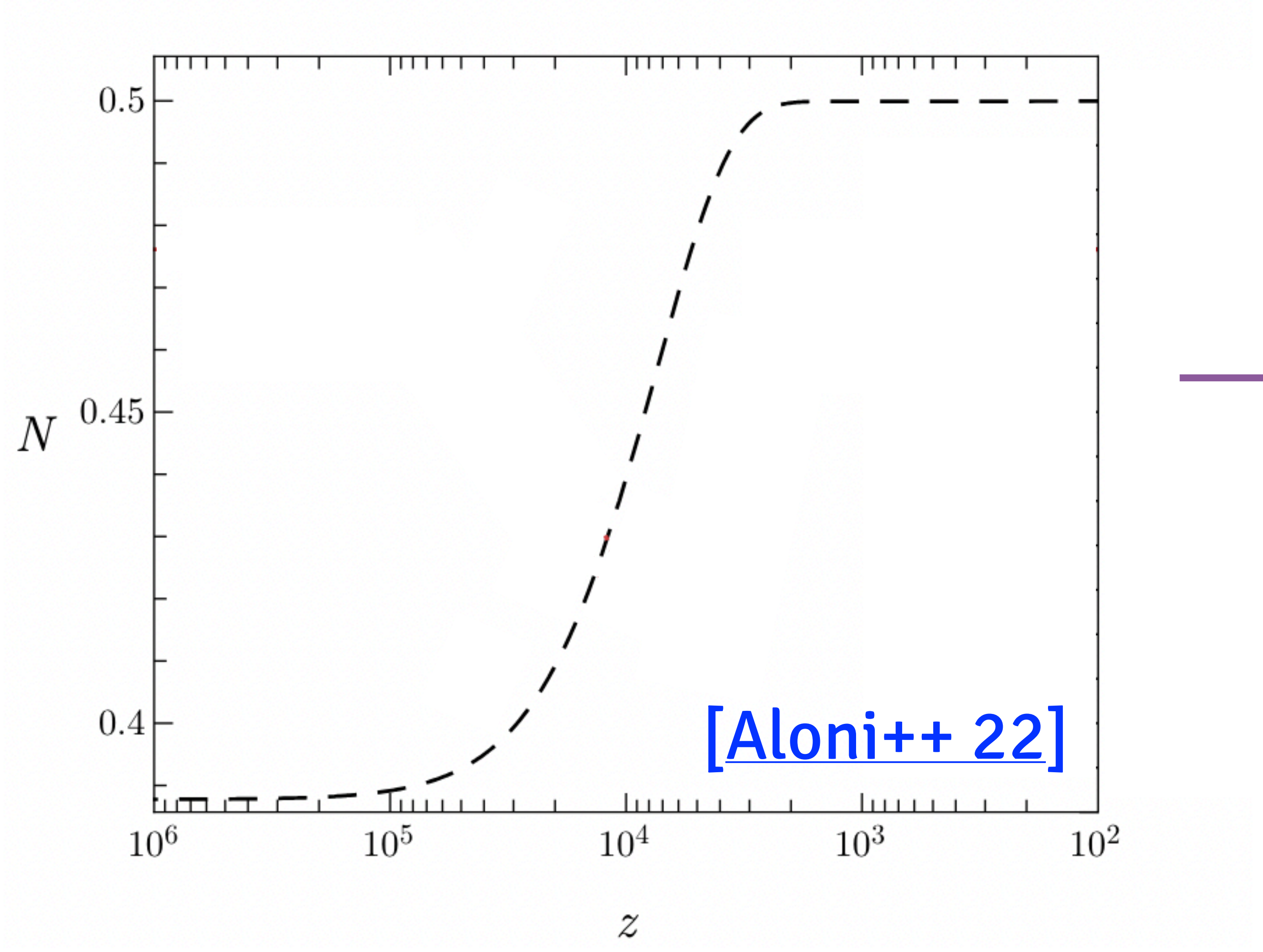

allows to lower r_s
and hence **increase H_0**

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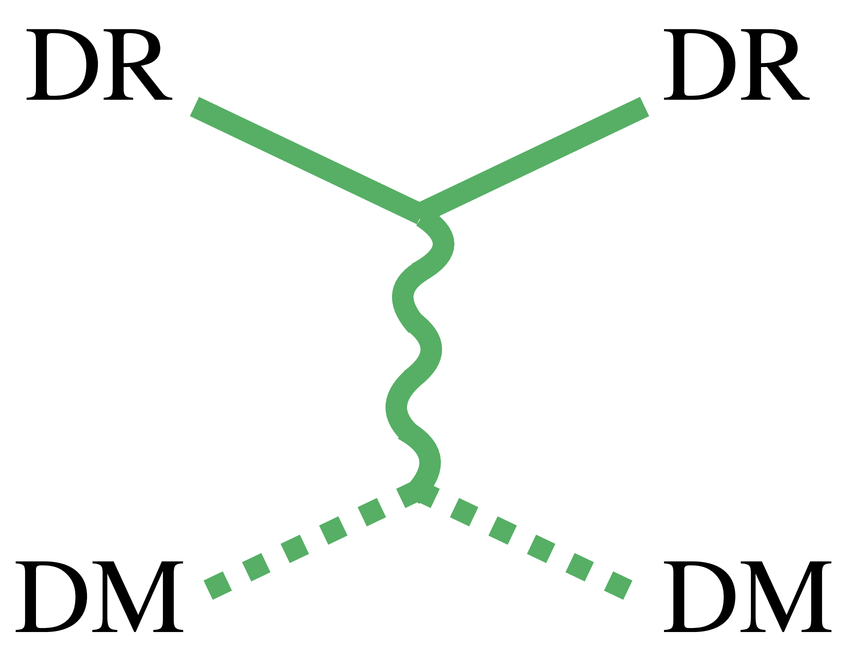

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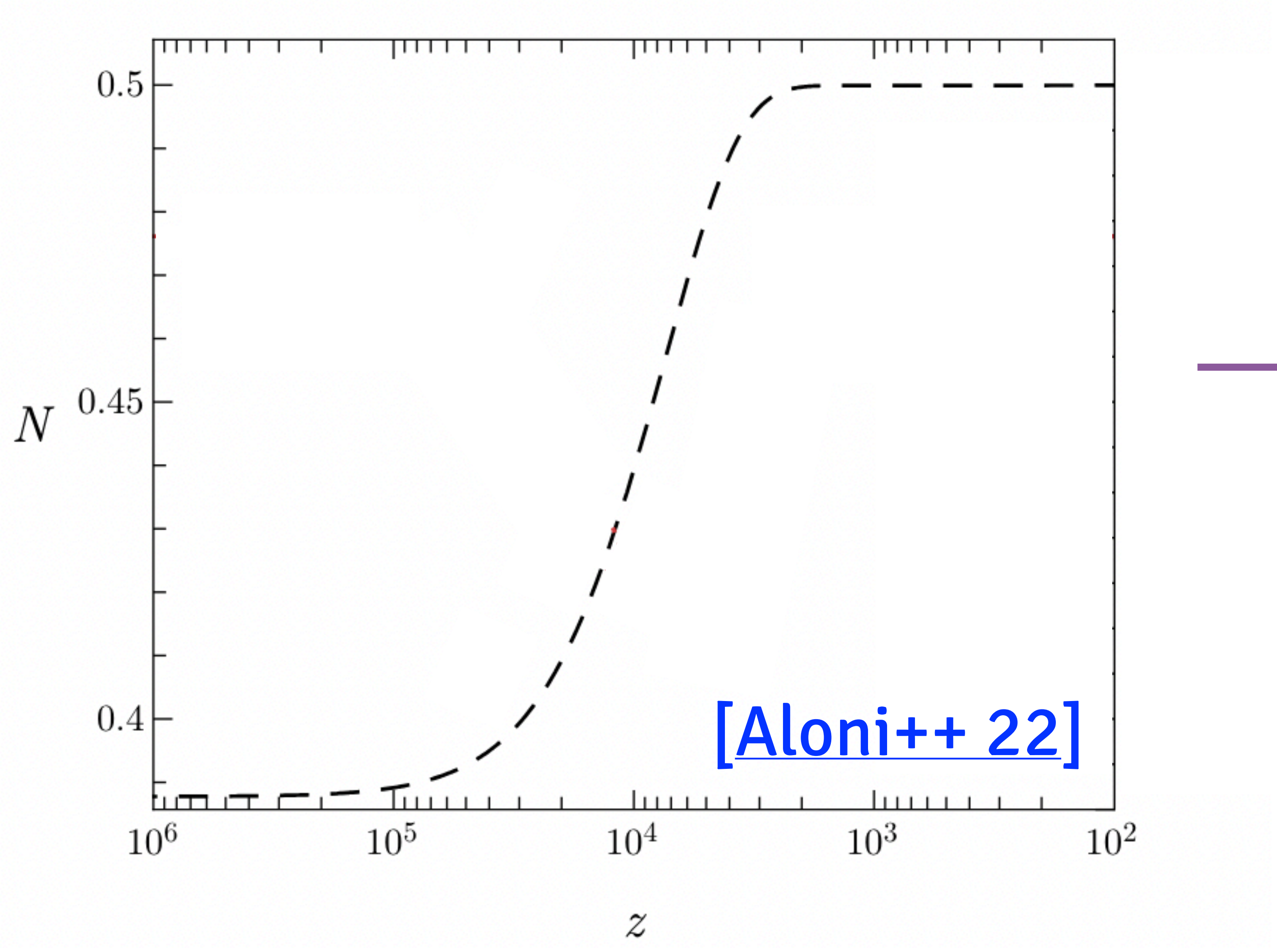

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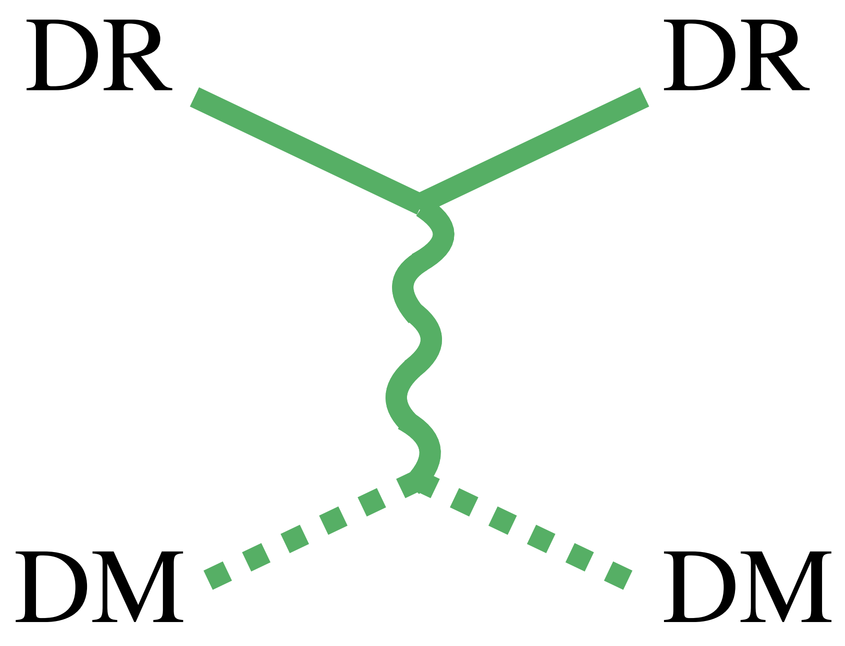

suppresses matter clustering, leading to a **smaller S_8**

Comparing different proposals

Wess-Zumino Dark Radiation (WZDR)
+ Yukawa coupling to Dark Matter

“Interaction is **weak** and with all of DM”

[Joseph++ 2023]

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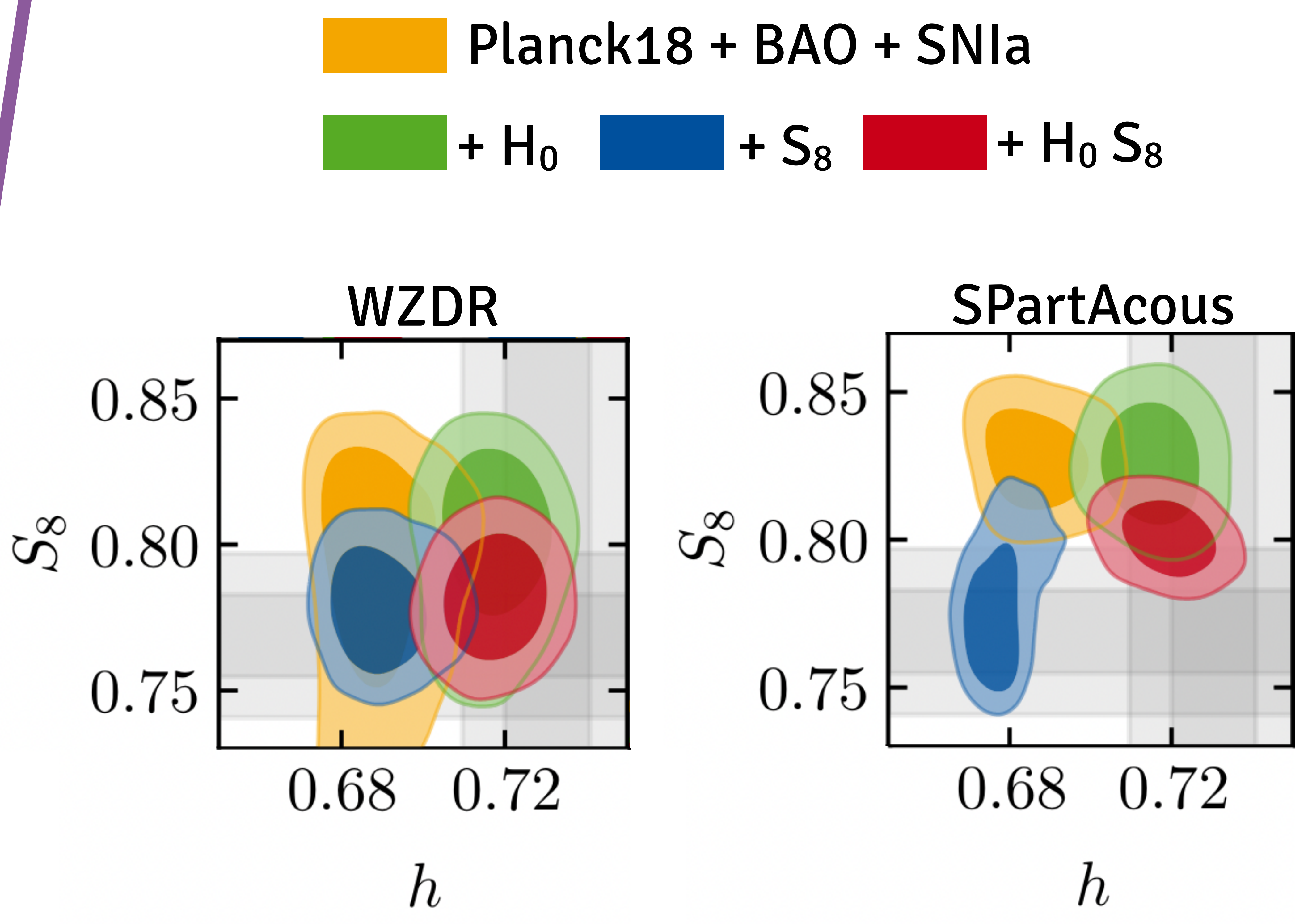

"Only the WZDR model can address both tensions simultaneously"

[Schöneberg, GFA++ 2023]

Prospects

Forthcoming cosmological surveys will provide us with unprecedented data to probe the dark sector...

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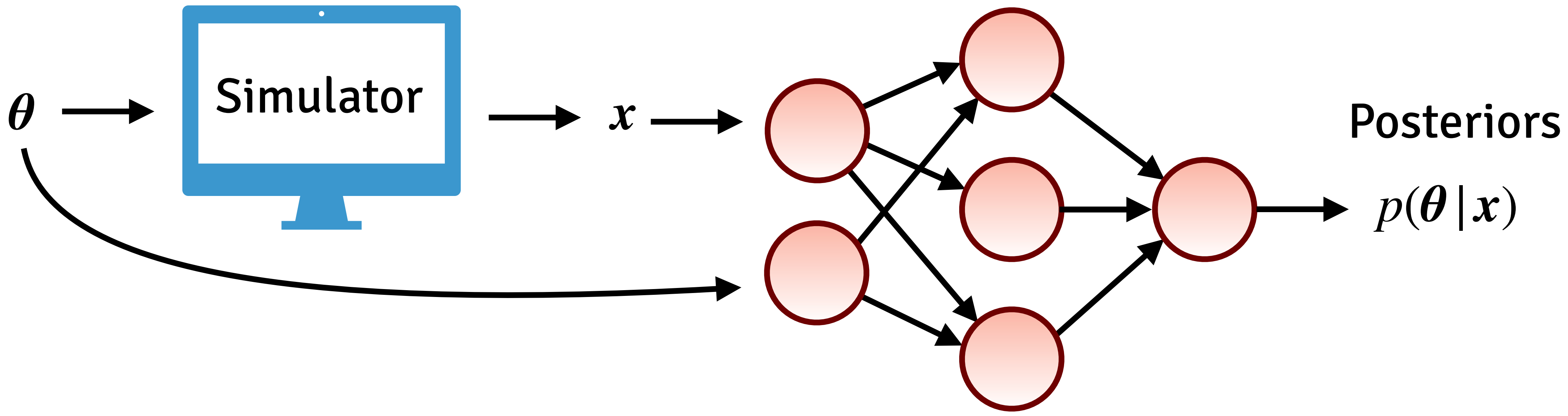
...but analysing these data will be extremely **time-consuming** with standard methods

Prospects

New techniques in **deep learning**/ simulation-based inference (SBI) will allow us to **accelerate parameter inference** in cosmology



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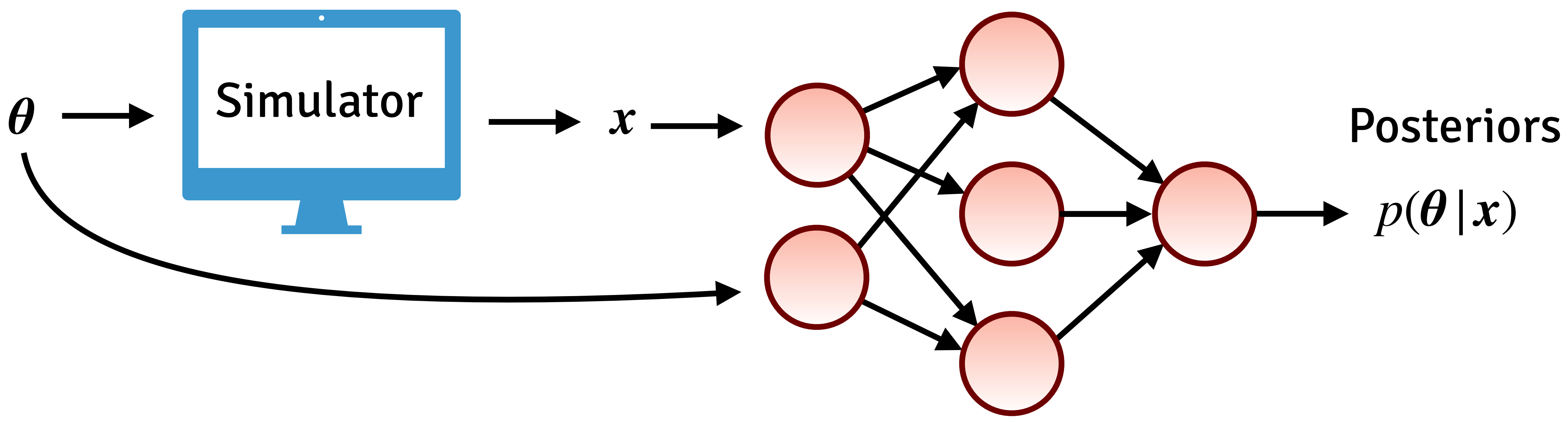
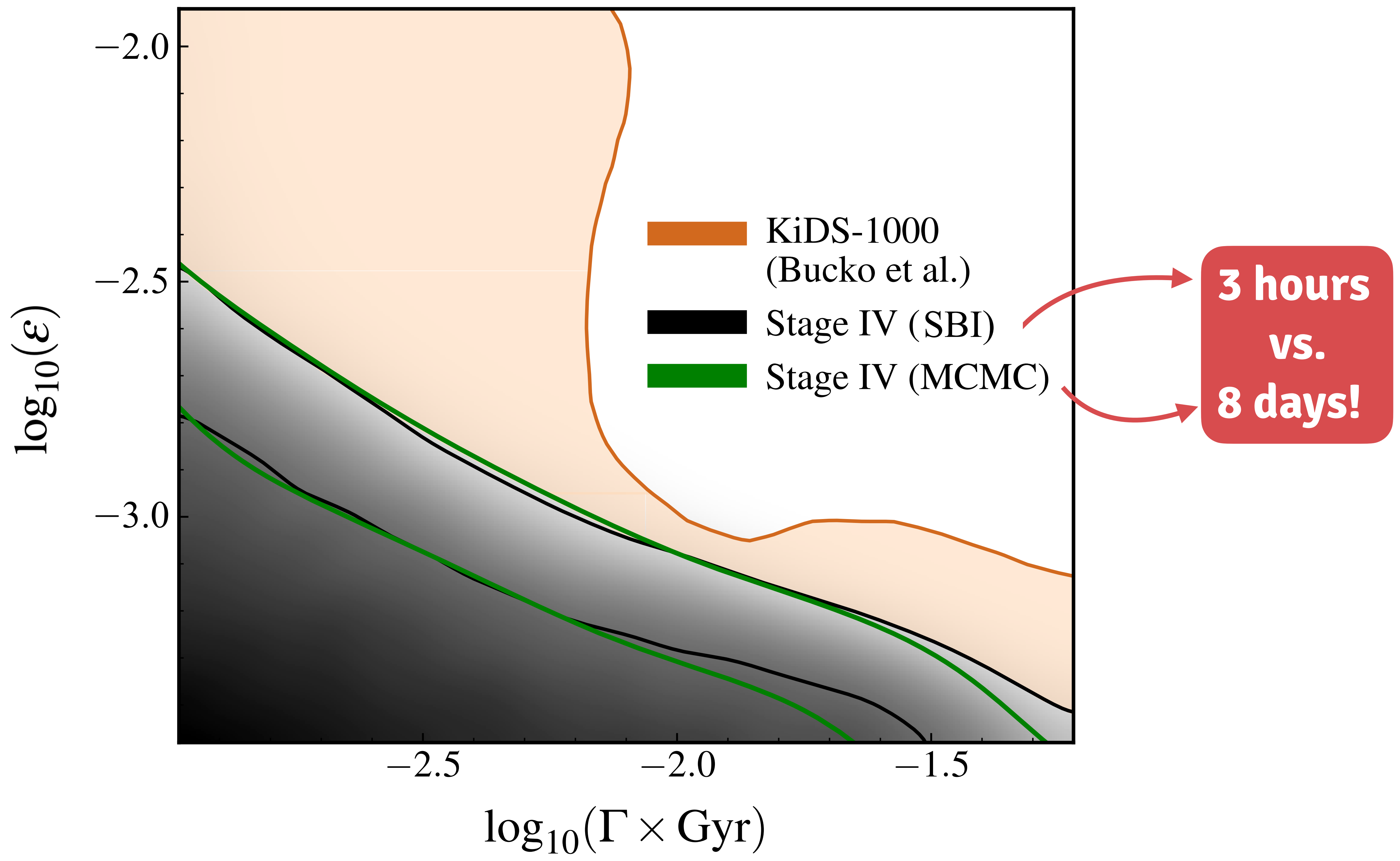


Ex: projected limits on decaying DM from Stage IV galaxy surveys

[GFA++ 2024]



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Conclusions

- Cosmic tensions might represent our best chance to **learn about the dark sector**
- **Decaying DM** and **Early Dark Energy** provide the right phenomenology to explain the S_8 and H_0 tensions, respectively. To ease both tensions, **interacting DR** models are the most successful
- **Future surveys** will allow to detect/rule out these models (new deep-learning tools will be crucial)

THANK YOU!

g.francoabellan@uva.nl

BACK UP SLIDES

Impact of decaying DM on cosmological observables

Expansion history H(z)

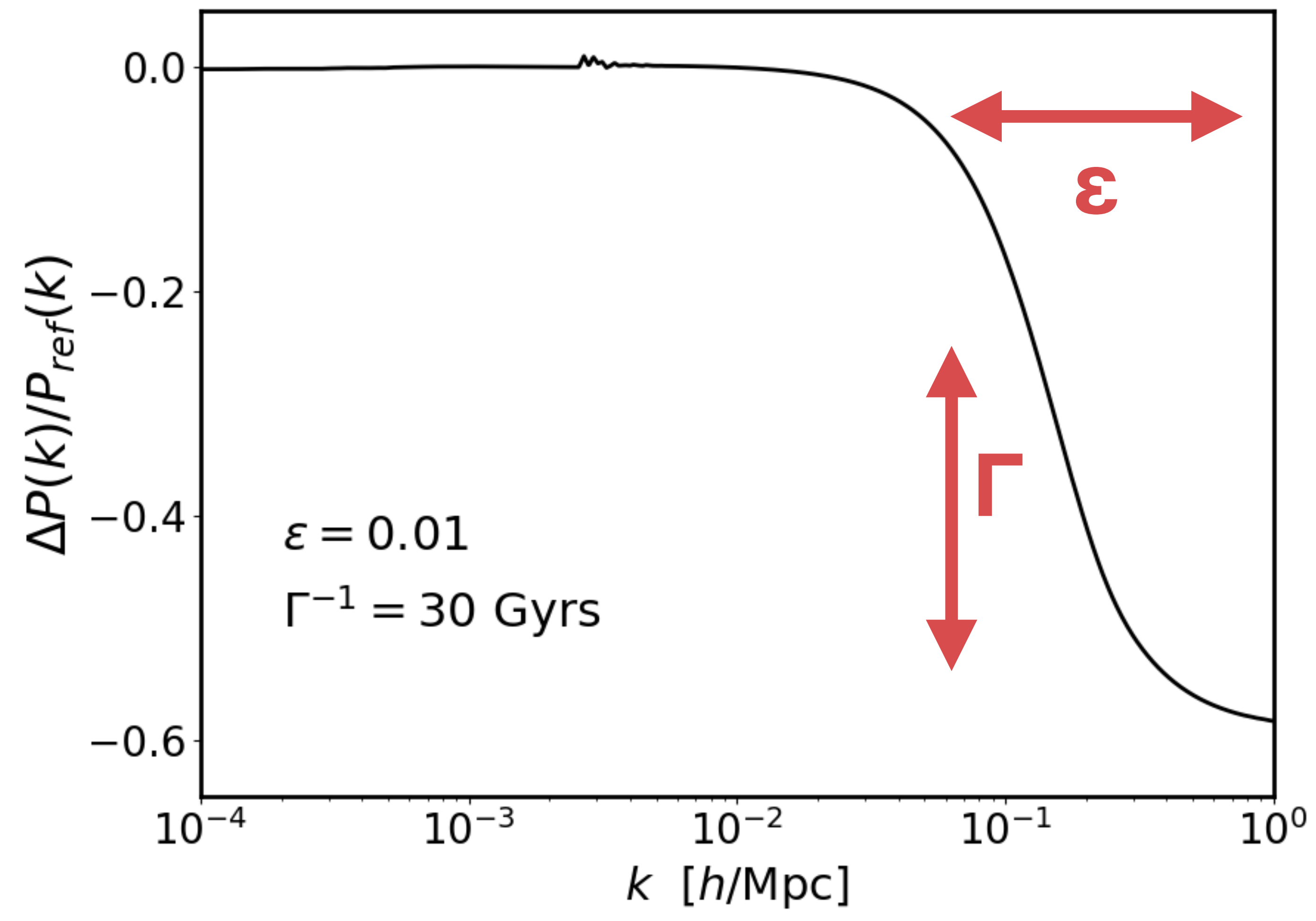
Not much impacted by
CDM → DR+WDM ($\rho_{wdm} \sim \rho_{cdm} \sim a^{-3}$)

CMB anisotropy spectra $C_\ell^{TT,EE}$

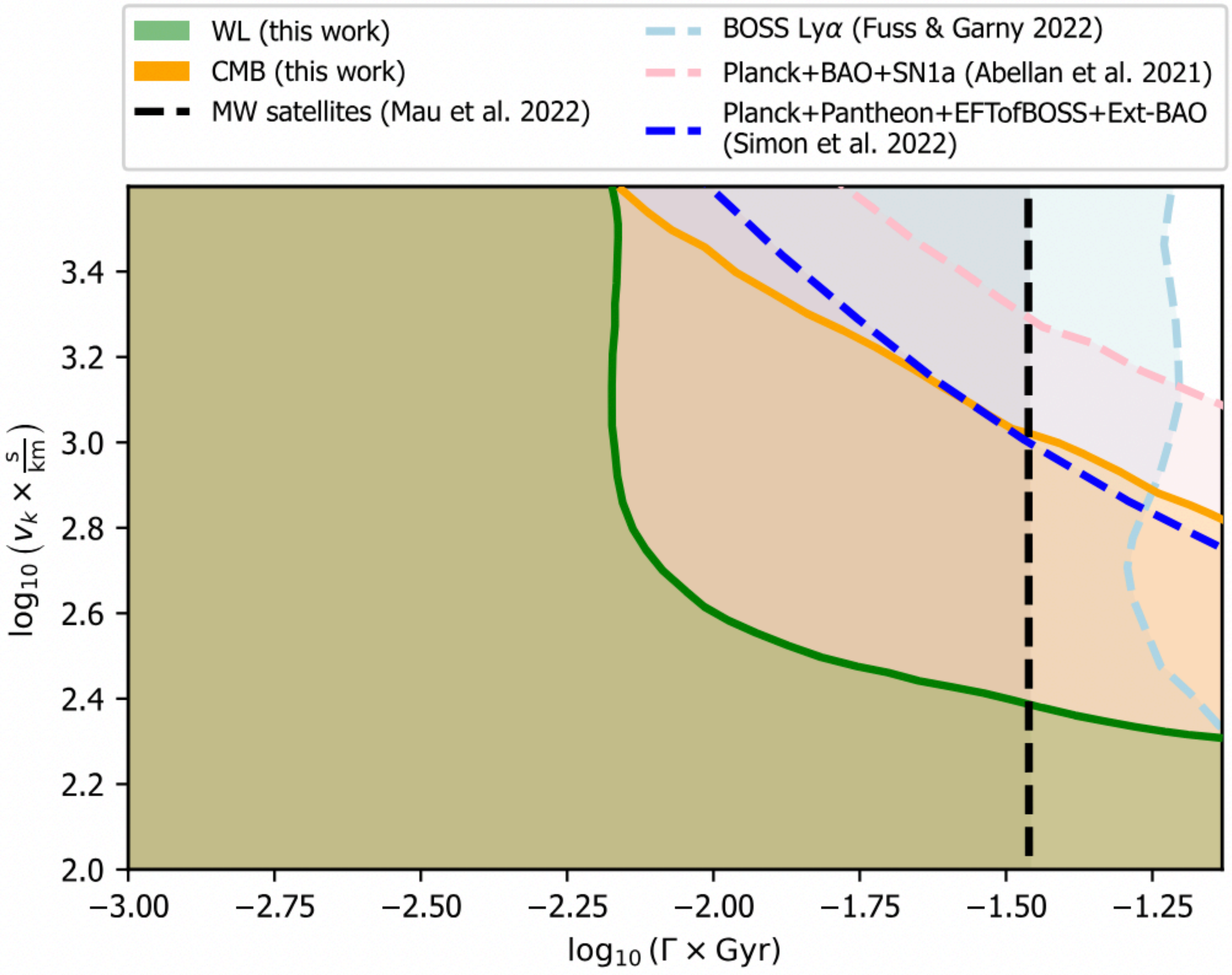
Impact even for late decays,
it affects both LISW
and CMB lensing

Linear matter power spectrum $P_m(k)$

CDM → DR+WDM suppresses power at $k > k_{fs}$



Summary of current bounds on invisible DM decay



[Bucko++ 24]

Note : $\varepsilon \simeq \frac{v_k}{c}$

Some caveats of EDE

- Fine-tuned?

  → Connexions of EDE with string theory and late DE

  [Cicoli++ 23] [Freese+ 21]

- Shift of other cosmological parameters

  $n_s \nearrow$ [Takahashi++ 21]

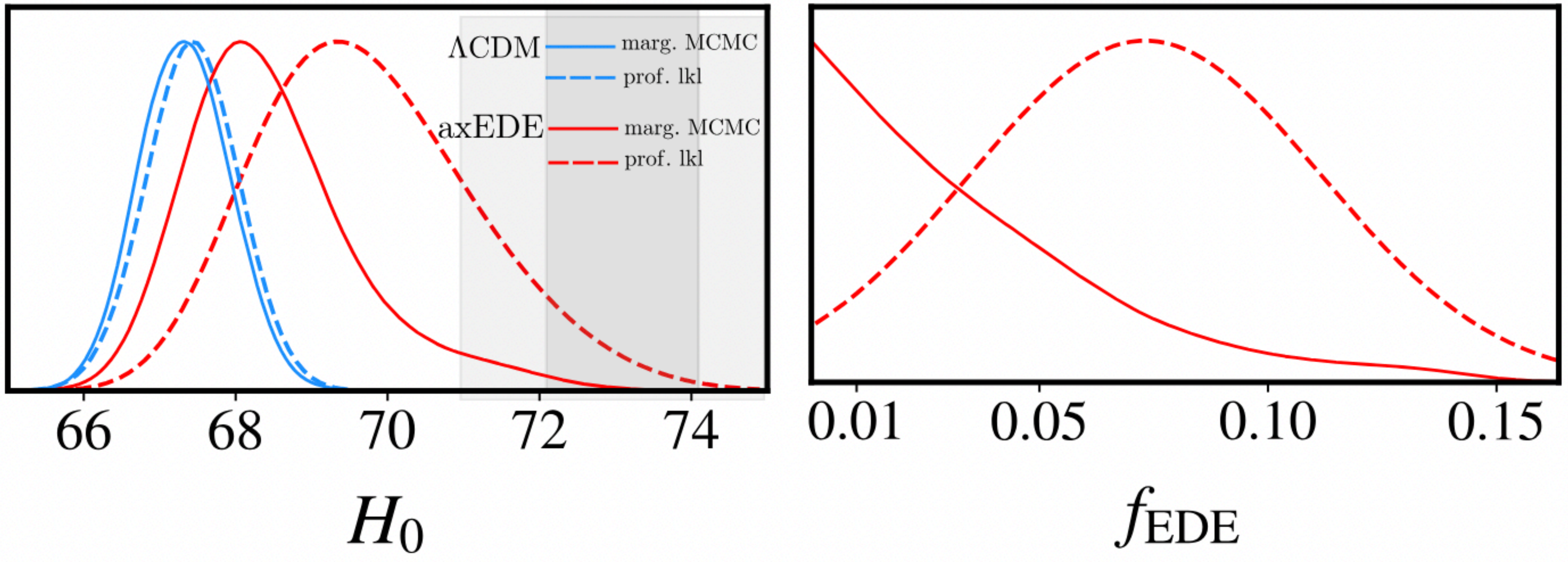
  $t_U \searrow$ [Boylan-Kolchin++ 21] [Bernal++ 21]

  $\omega_{\rm cdm} \nearrow$ [Vagnozzi++ 21] [Jedamzik++ 21]

  $S_8 \nearrow$ [Hill++ 20] [Murgia, GFA++ 20]

Prior-volume effects in EDE analyses

Results for Planck18 alone



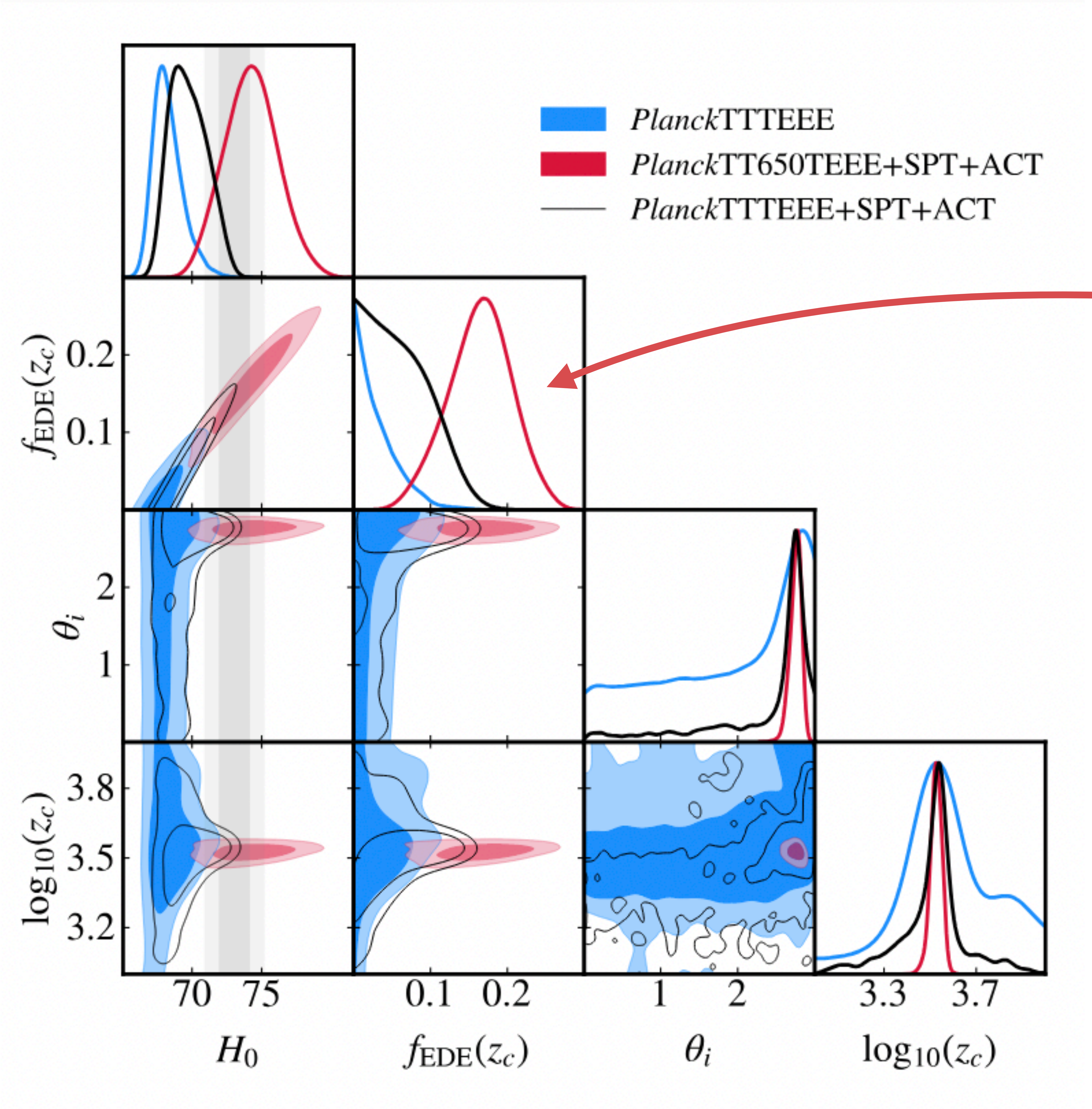
[Poulin++ 23]

For $f_{\rm EDE} \lesssim 4\,\%$, parameters z_c and ϕ_i become irrelevant, so **posteriors** are **weighted towards ΛCDM**

→

Marginalised **posteriors** and **profile likelihood** strongly **disagree**

EDE in light of CMB data from ACT and SPT



Hints coming from **ACT**, but they vanish when including **high-ℓ TT** data from **Planck**

[Smith++ 22]

[Poulin++ 23]

Comparing two simple EDE scenarios

$$S = \int d^4x\sqrt{-g}\left[\frac{F(\phi)}{2}R - \frac{g^{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi - \Lambda - V(\phi) + L_m\right]$$

Early Dark Energy

$F(\phi) = M_{\rm pl}^2$

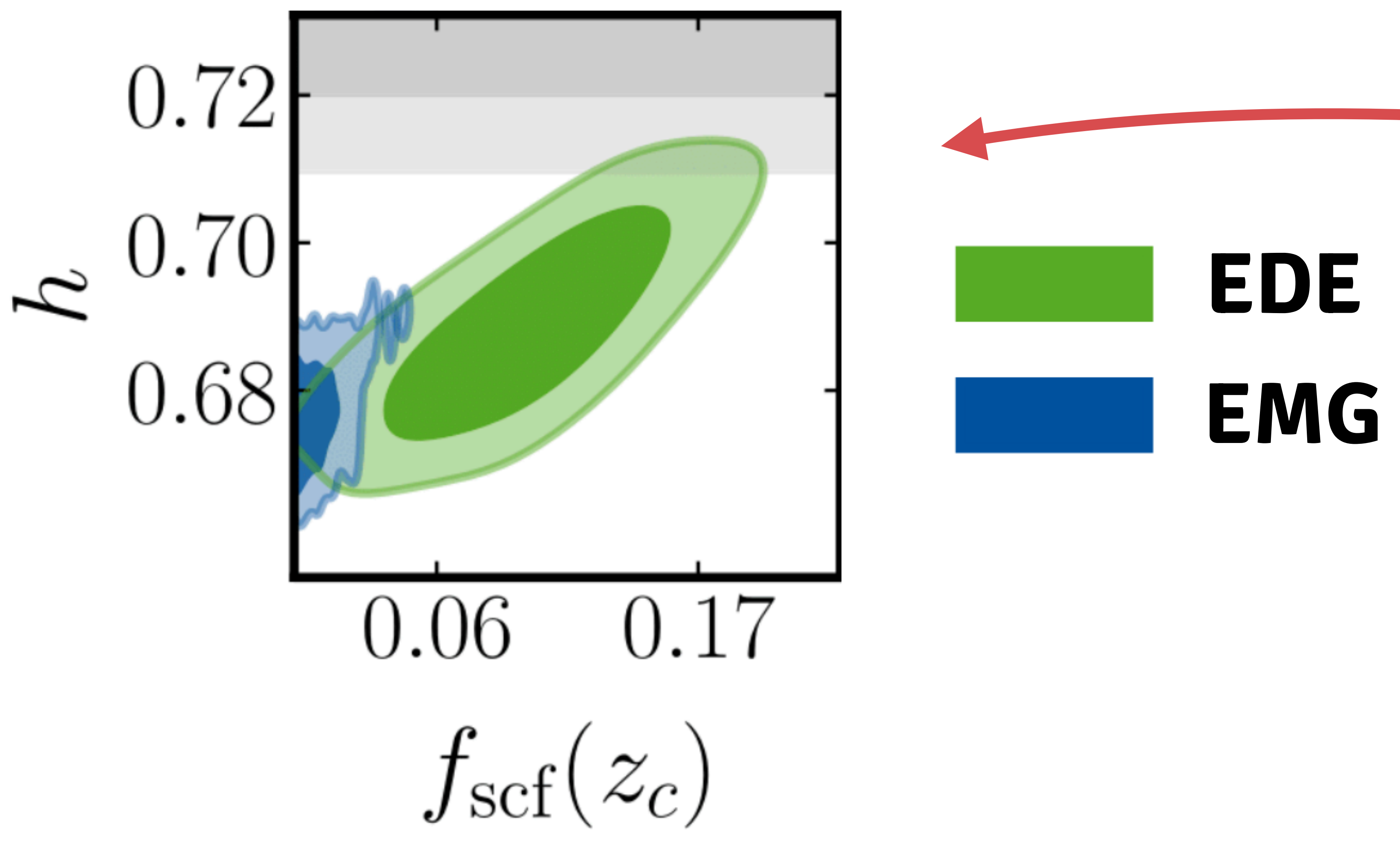
$V(\phi) = \lambda\phi^4/4$

Early Modified Gravity

$F(\phi) = M_{\rm pl}^2 + \xi\phi^2$

$V(\phi) = \lambda\phi^4/4$

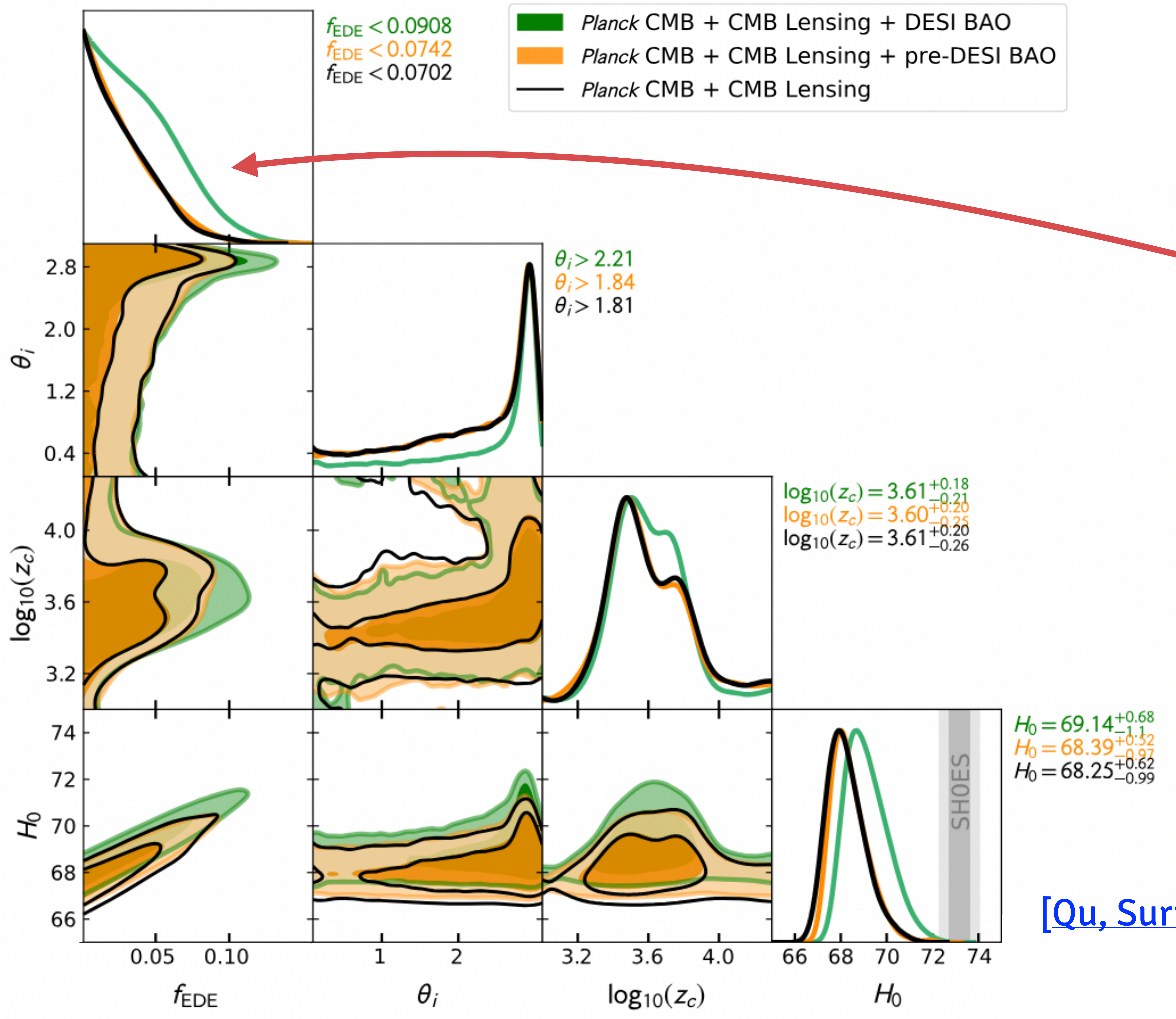
Planck+ACT+SPT



This combination of CMB data shows a **preference for a non-minimal coupling** to gravity

[GFA, Braglia++ 23]

EDE in light of DESI-Y1 BAO data

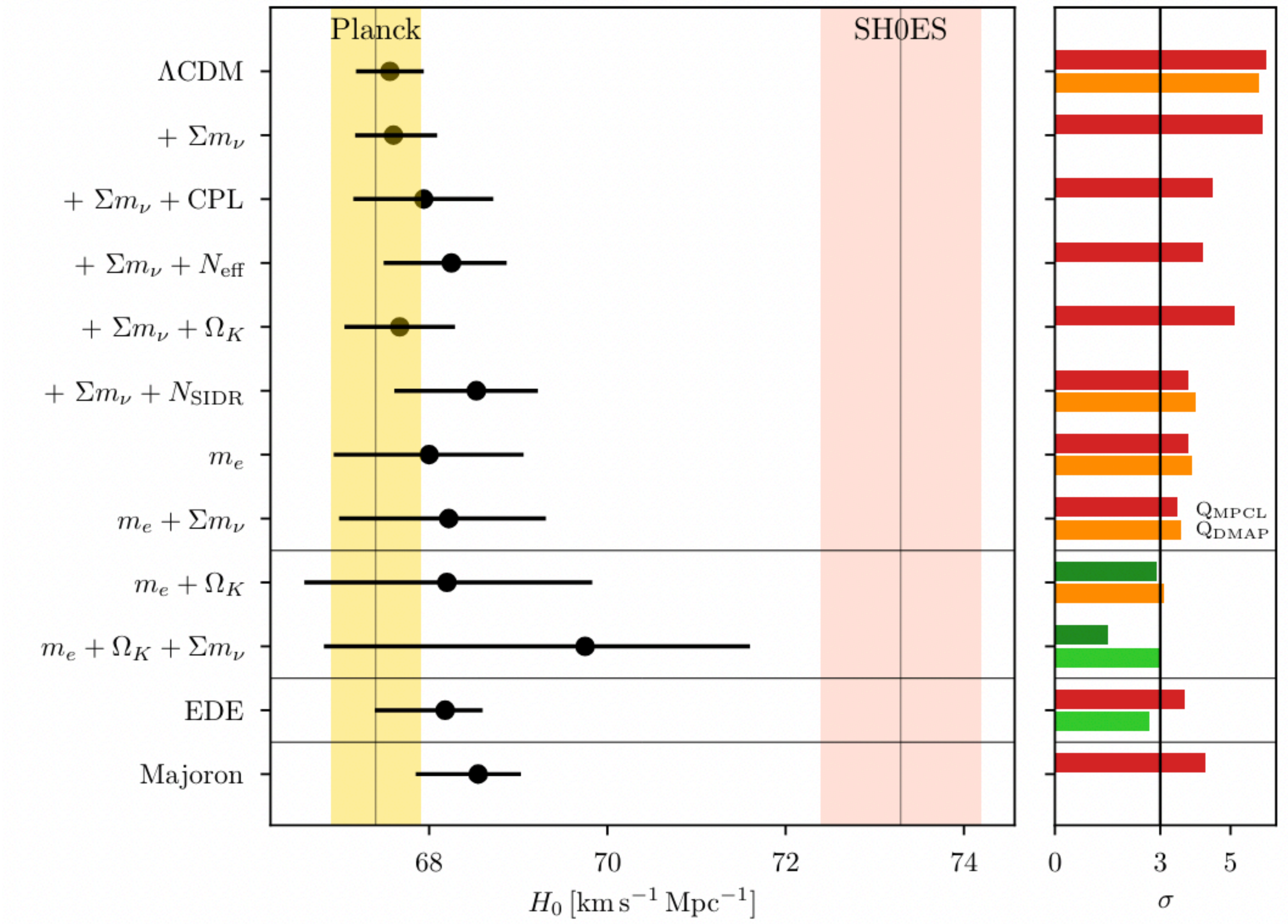


Adding DESI **weakens the bounds on EDE**, as it prefers a lower Ω_m value (negatively correlated with H_0)

[Qu, Surrao++ 24]

The H_0 Olympics with new SH0ES and SPT data

Results for Planck18 + SPT-3G + BAO + SNIa

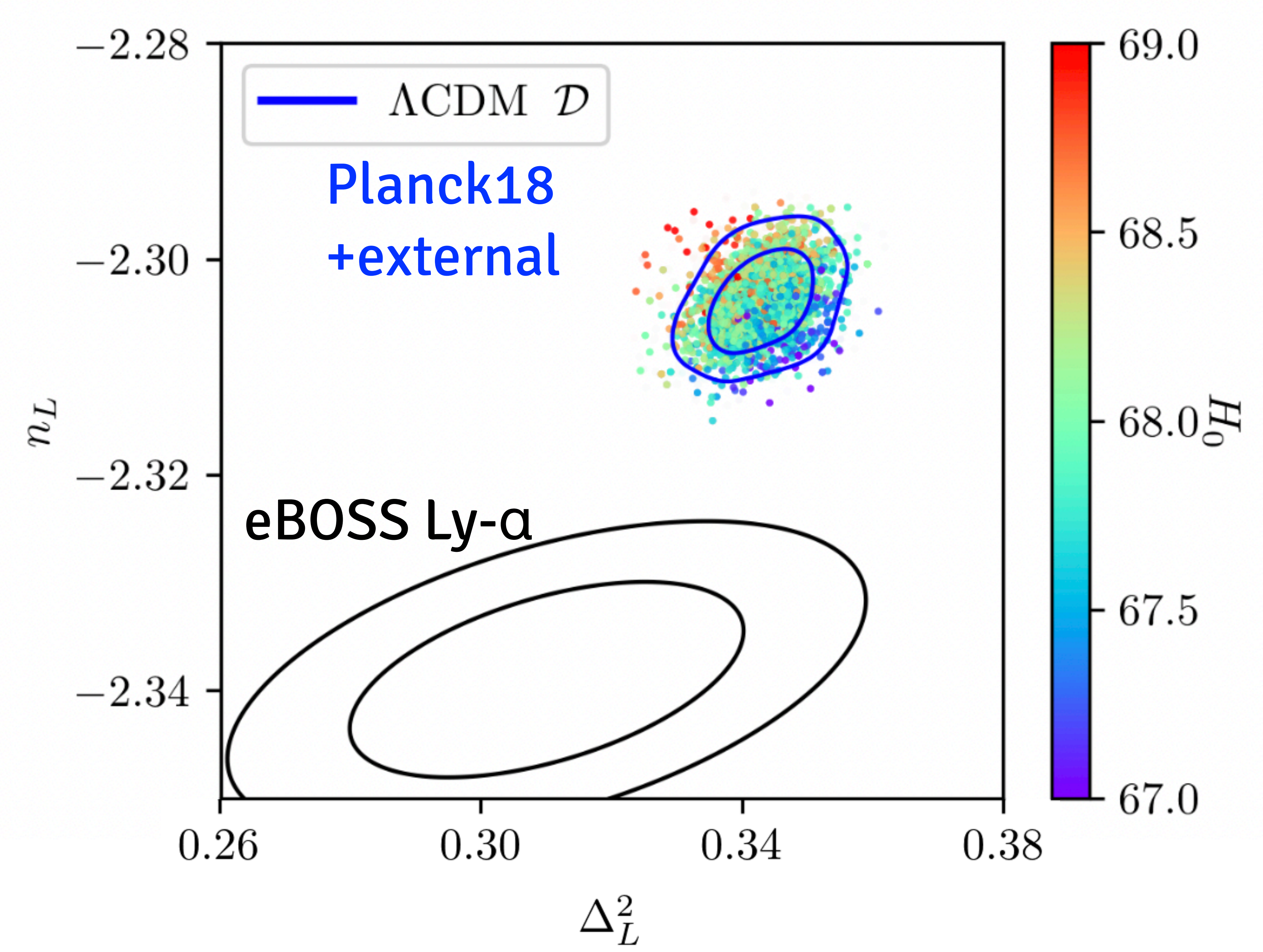


Only **EDE and varying m_e+Ω_k** can reduce the tension **below 3σ** (either in a Bayesian or in a frequentist way)

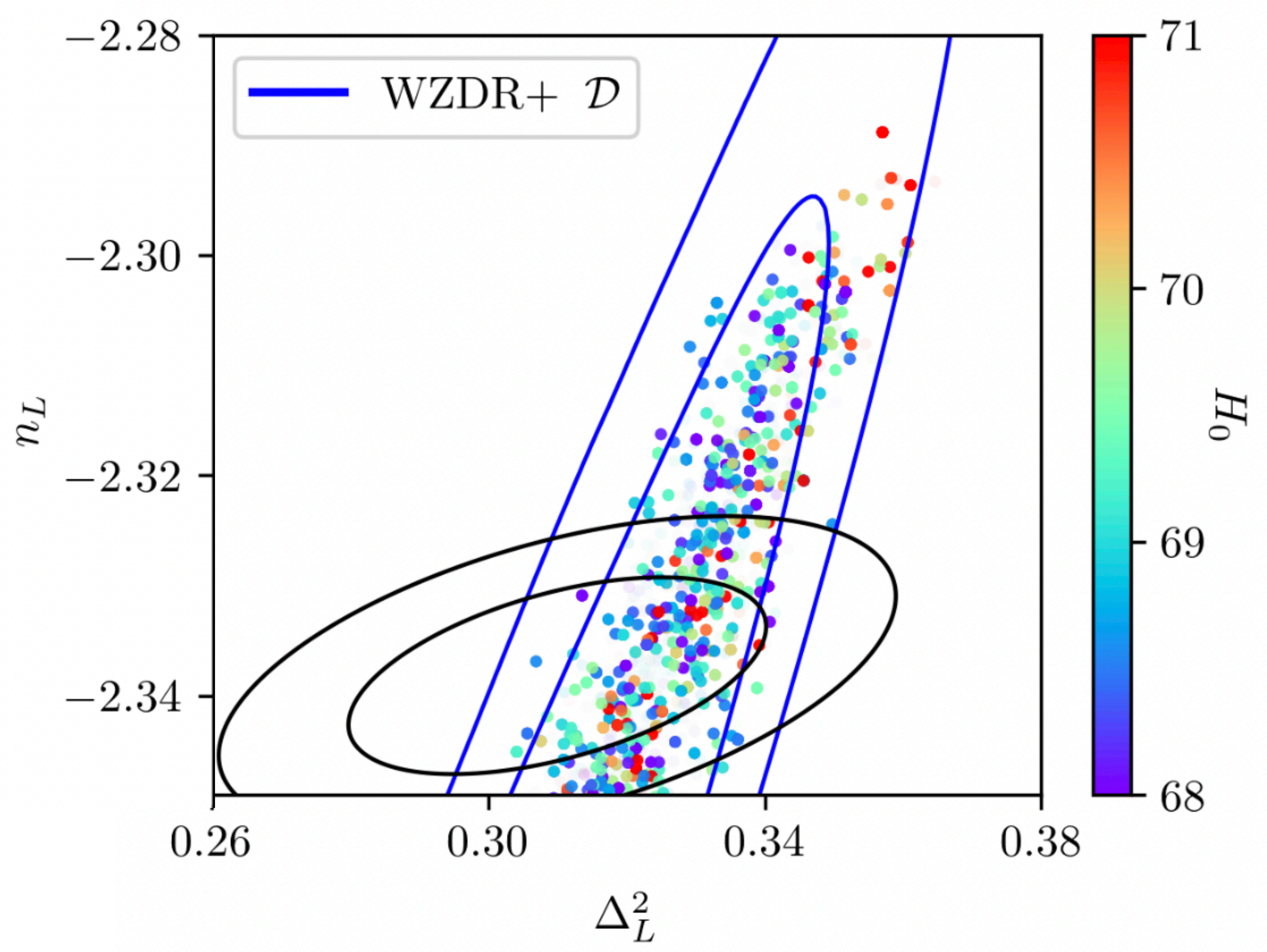
[Khalife++ 24]

What about Lyman-α data?

eBOSS Lyman-α data shows a **~5σ tension with ΛCDM** fit to CMB (preferring a **steeper slope** of P(k) at ~Mpc scales) [Rogers & Poulin, 24]



Tension worsened for EDE [Goldstein++ 23]



Wess-Zumino Dark Radiation **(WZDR) coupled to DM** can restore **concordance with Ly-α data** (while still reducing the H_0 tension)

[Bagherian++ 24]