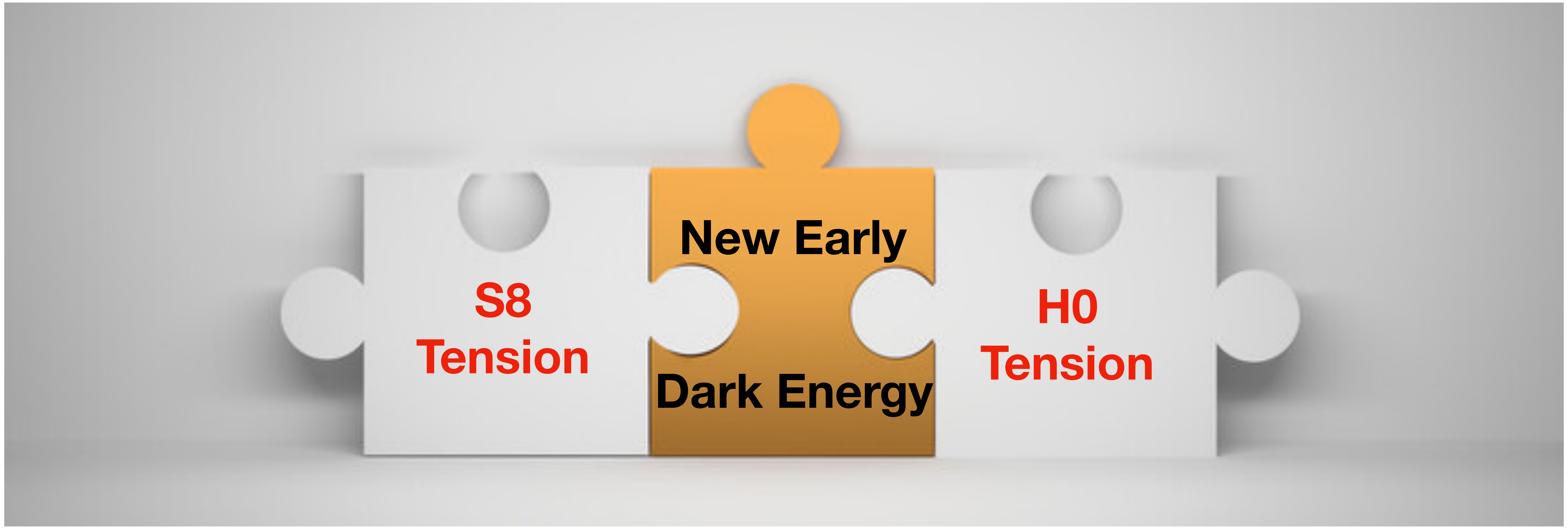
A simultaneous solution to the H0 and the S8 tensions and the implication for inflation

Martin S. Sloth

Universe-Origins, SDU, Denmark

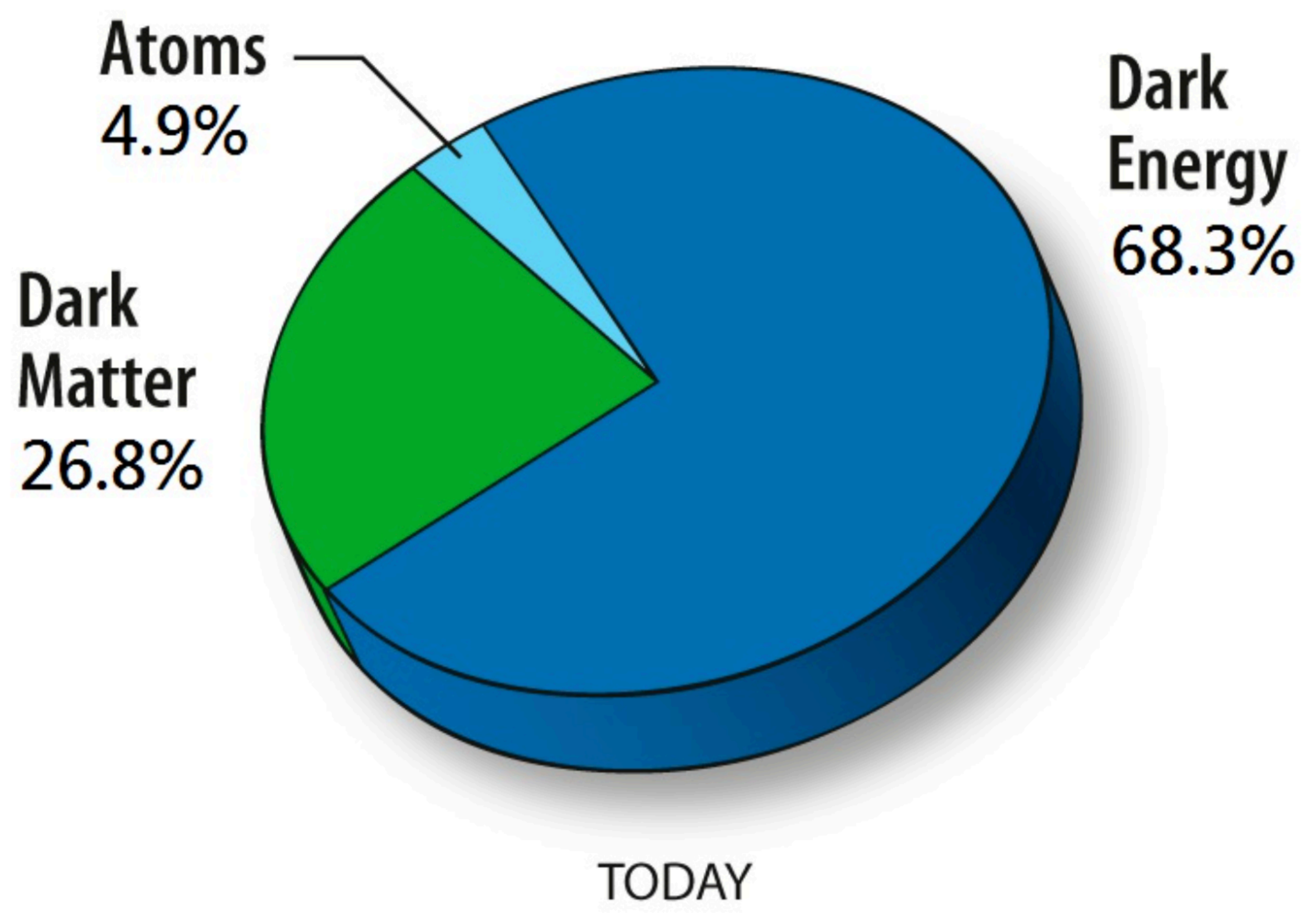


arXiv:2307.03091, 2305.08895, 2209.02708
w. Juan S. Cruz and Florian Niedermann

arXiv: 2307.03481, 2112.00759, 2112.00770, 2009.00006, 2006.06686,1910.10739
w. Florian Niedermann

arXiv:2302.07934
w. Juan S. Cruz, Steen Hannestad, Emil Brinch Holm, Thomas Tram and Florian Niedermann

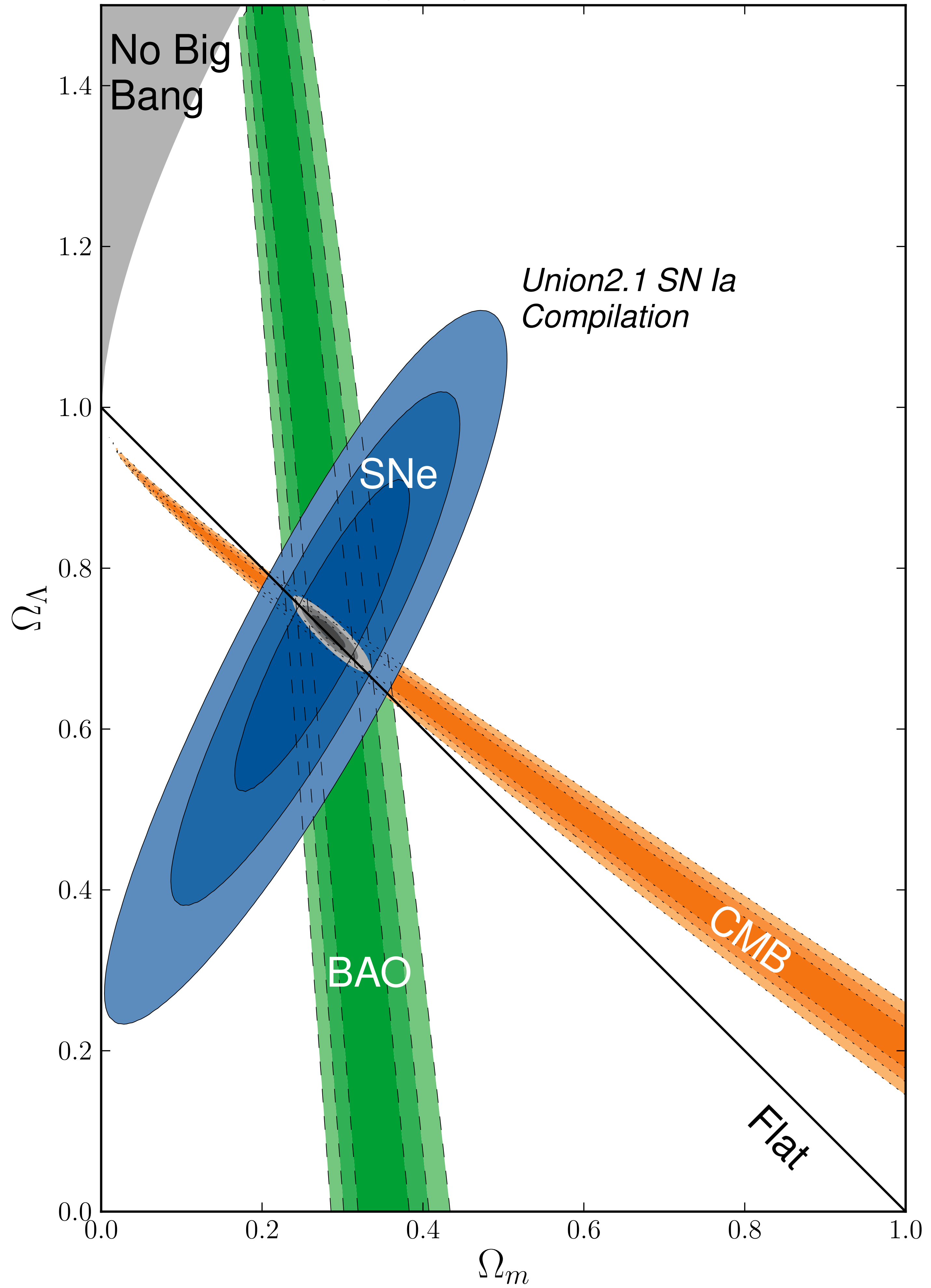
ΛCDM



Concordance model

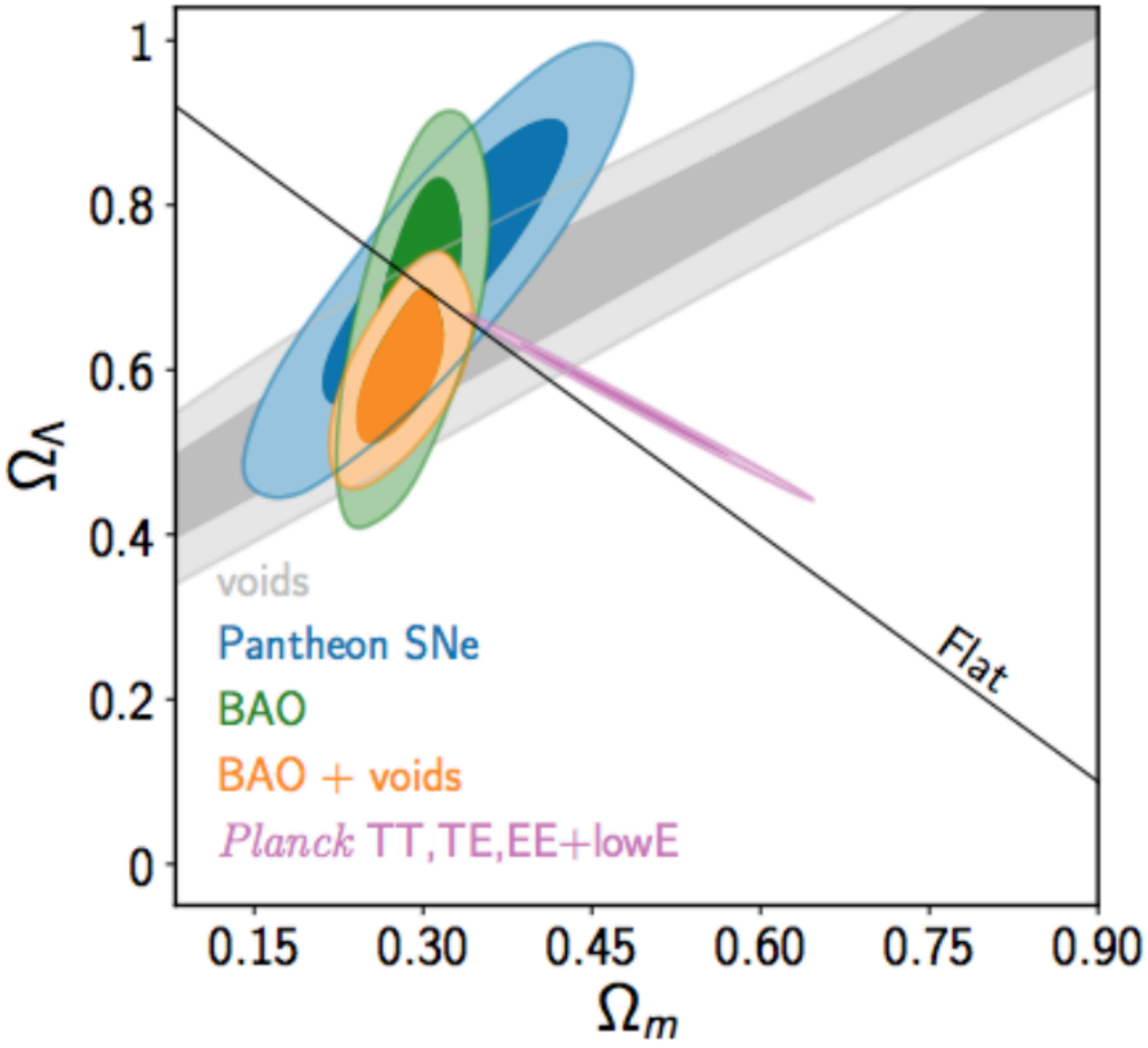
ΛCDM 10 years ago

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



Concordance model

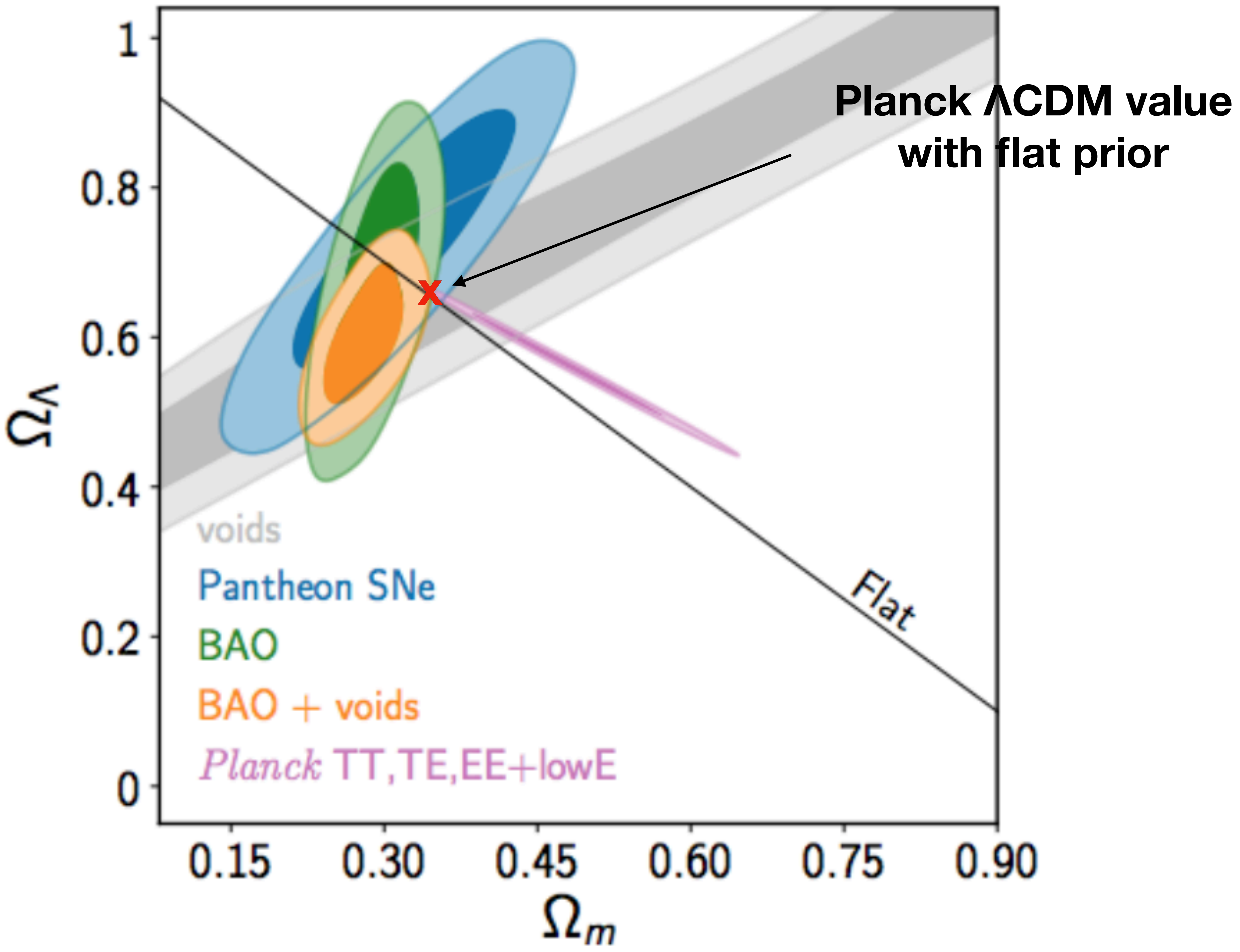
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

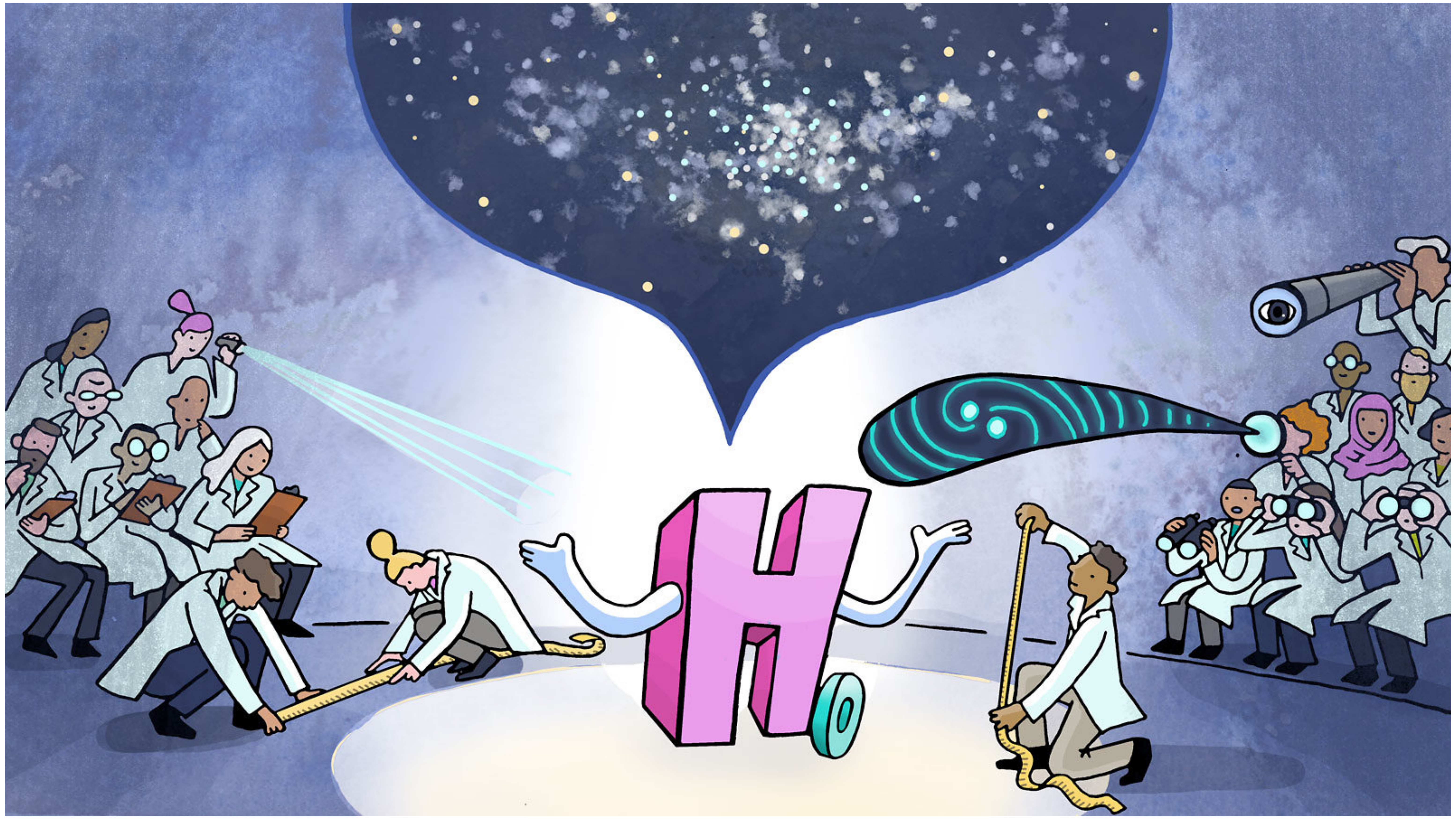
Concordance model

ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

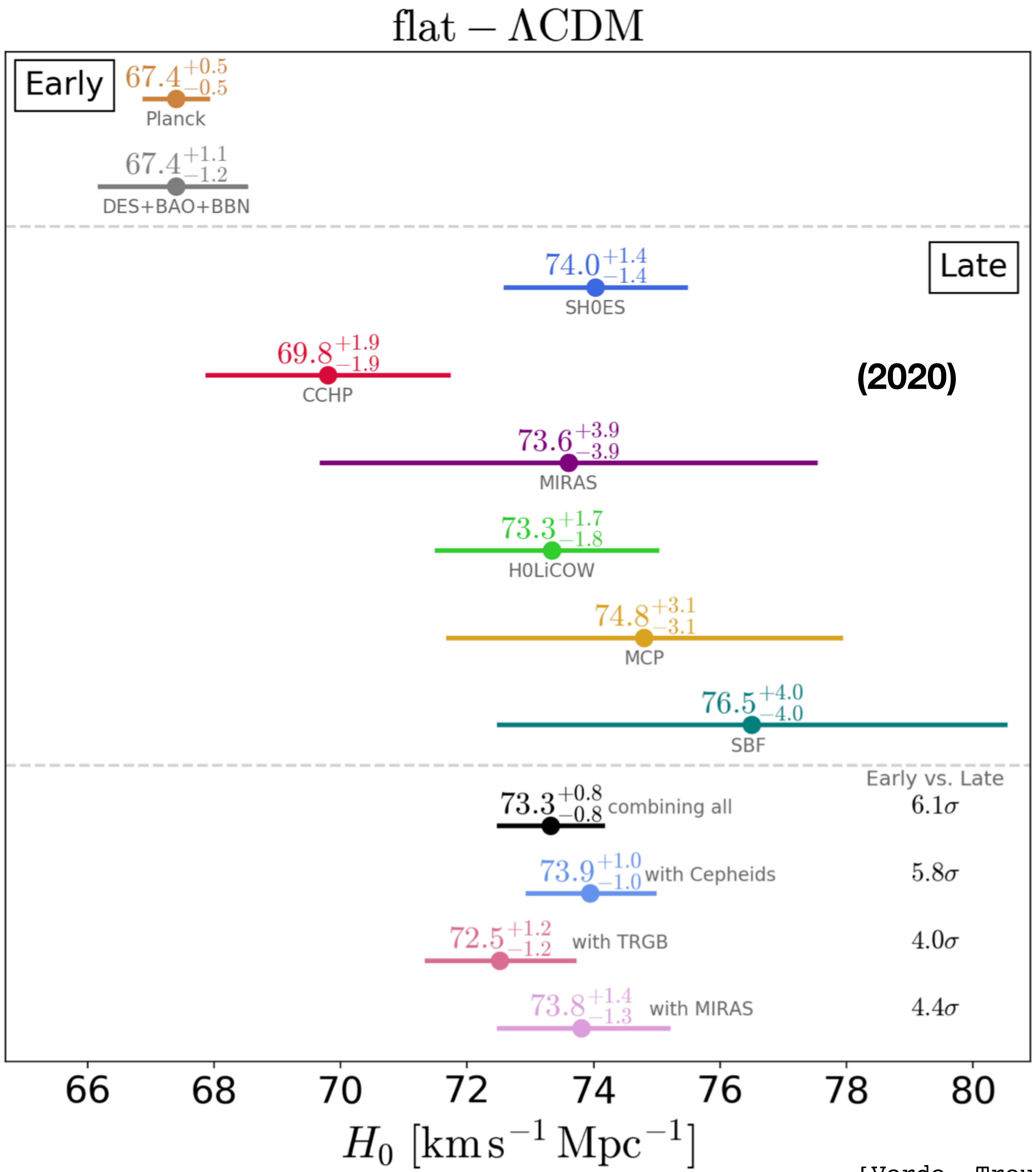
What about H_0?



[Illustration Symmetry mag. 2019]

ΛCDM

Actual Universe



[Verde, Treu, Riess; 2019]

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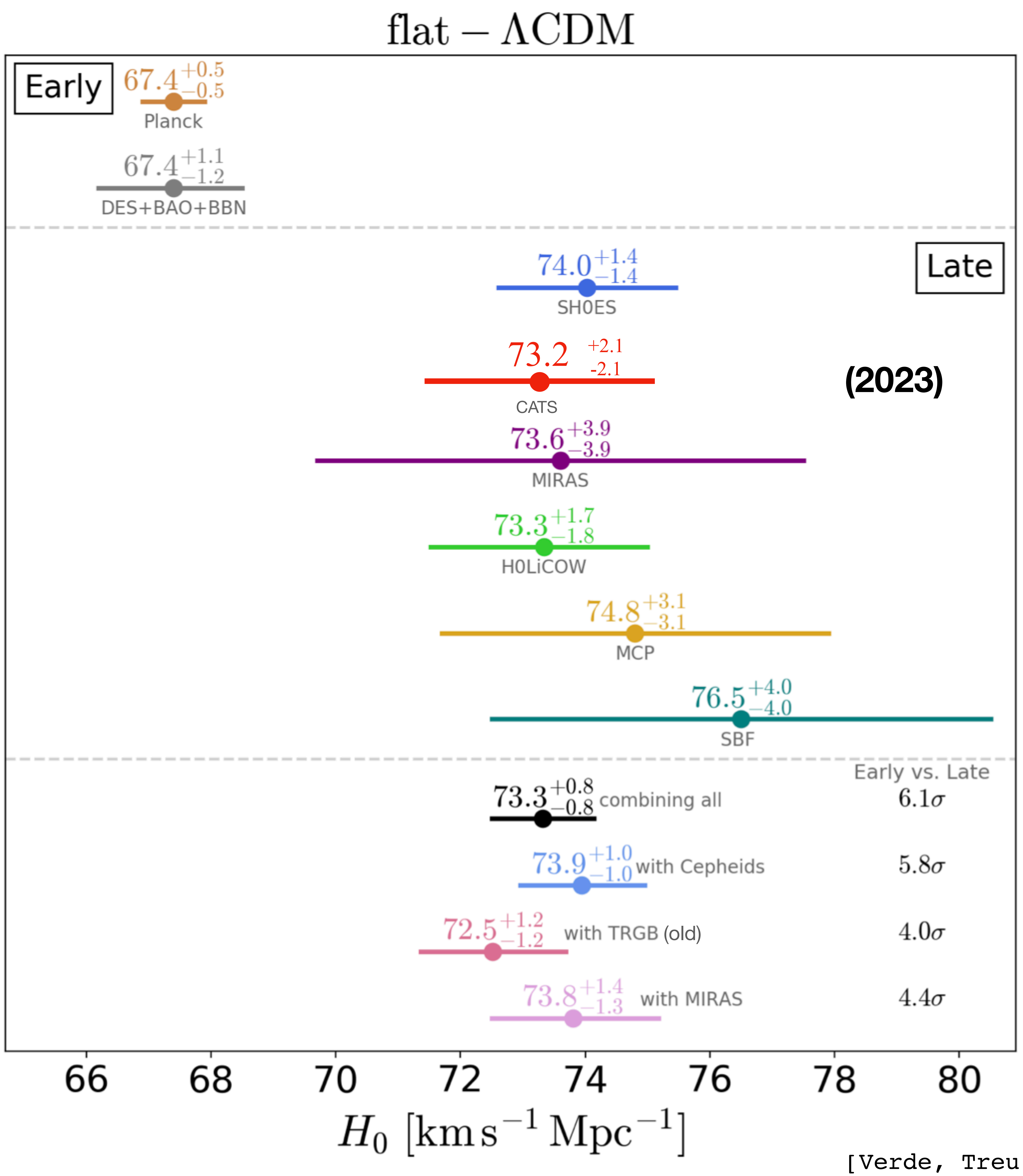
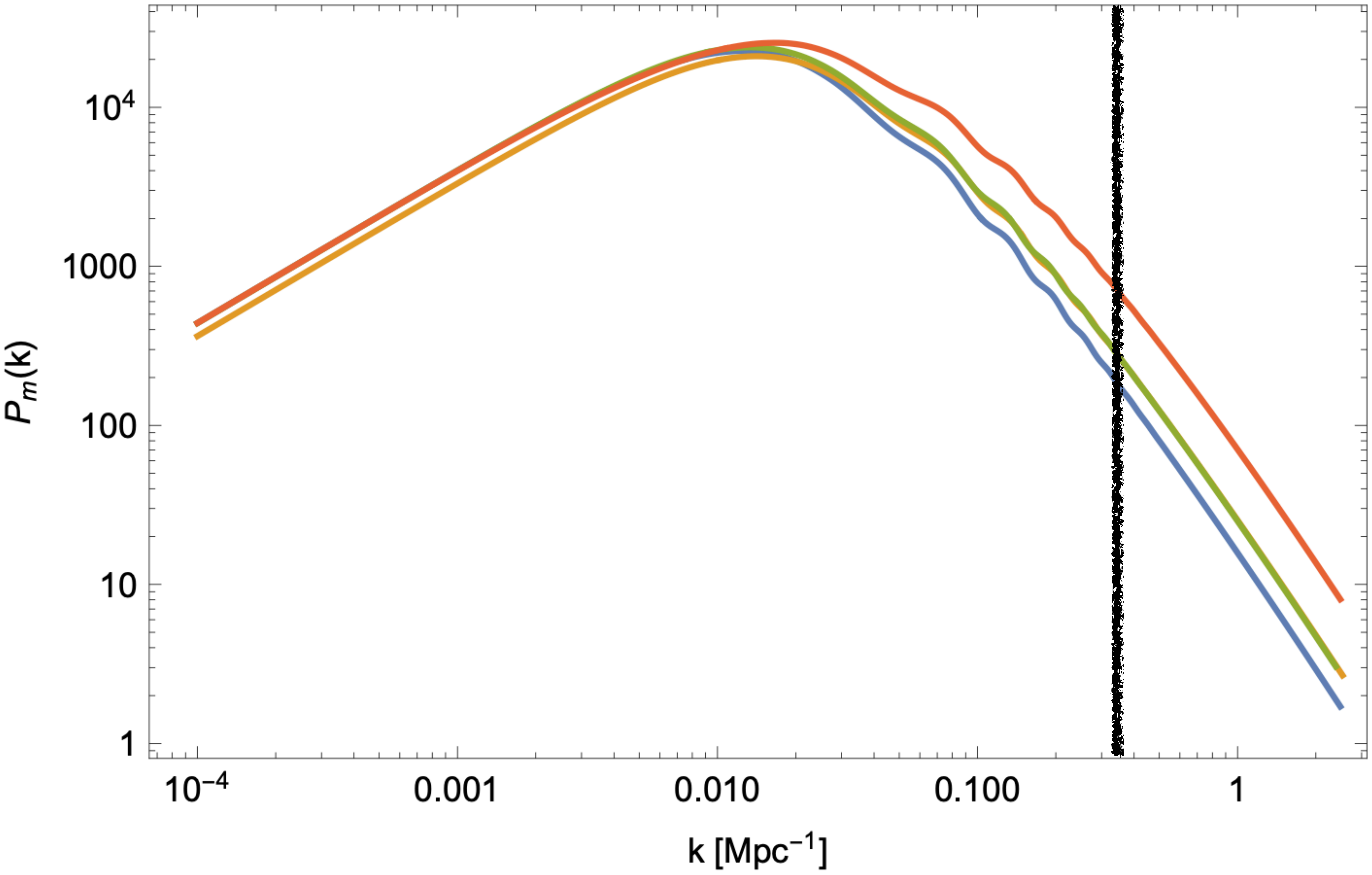


ΛCDM

[Verde, Treu, Riess; 2019]

Then what about S8?

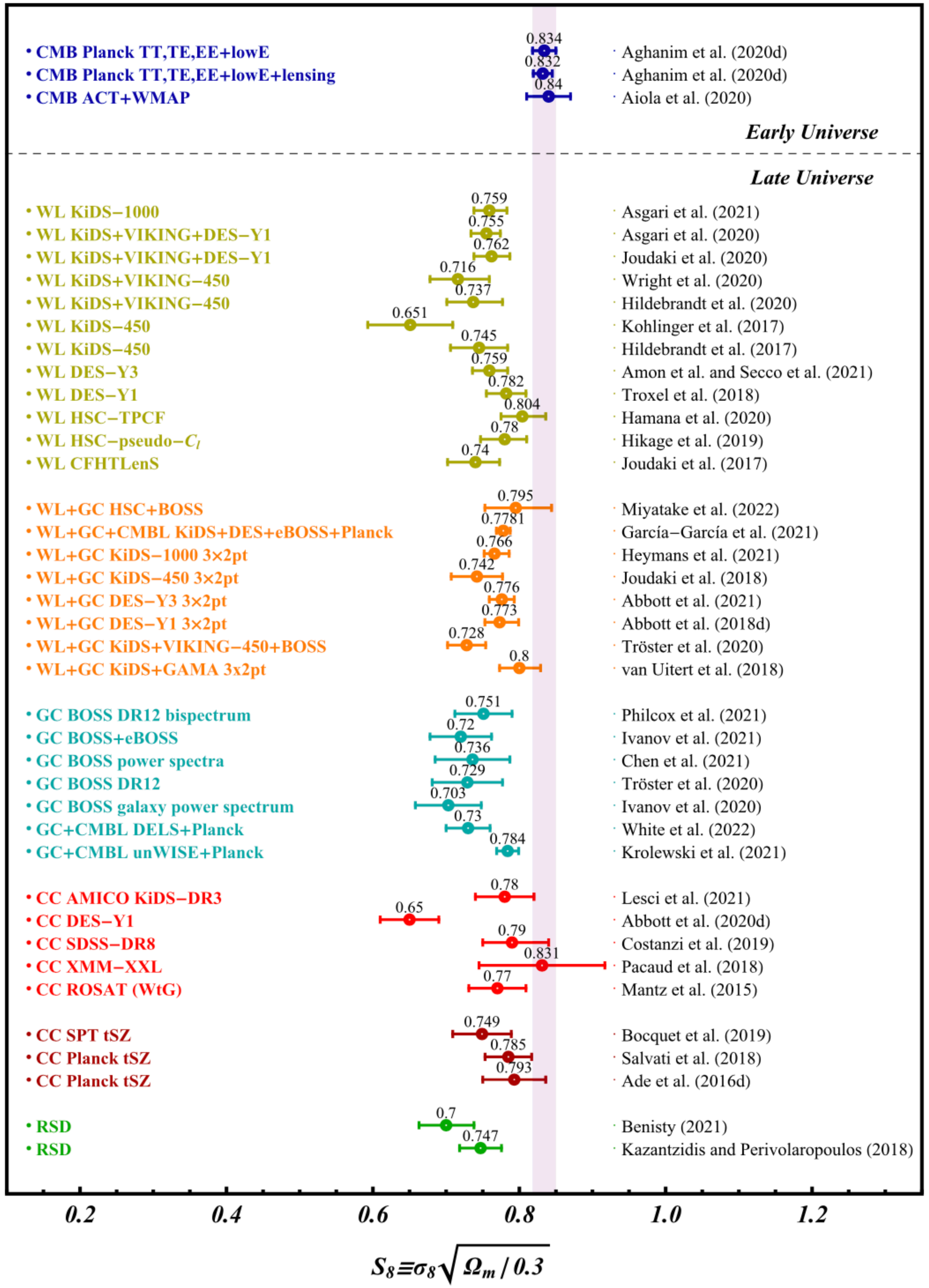
S8 scale



[1712.07109]

ΛCDM

Actual Universe



Is it systematics?

- SH0ES recently revisited all previously proposed sources of systematics and found their results to be robust.
- Many different experiments show the same trend for H0 and S8.
- Yet, no fully independent measurement/method has confirmed the results to the same precision as SH0ES

➡Independent measurement is needed to settle disputes in the community…

Is it systematics?

We can by definition never exclude “unknown systematics”…

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“Any theory that can account for all of the facts is wrong, because some of the facts are always wrong”

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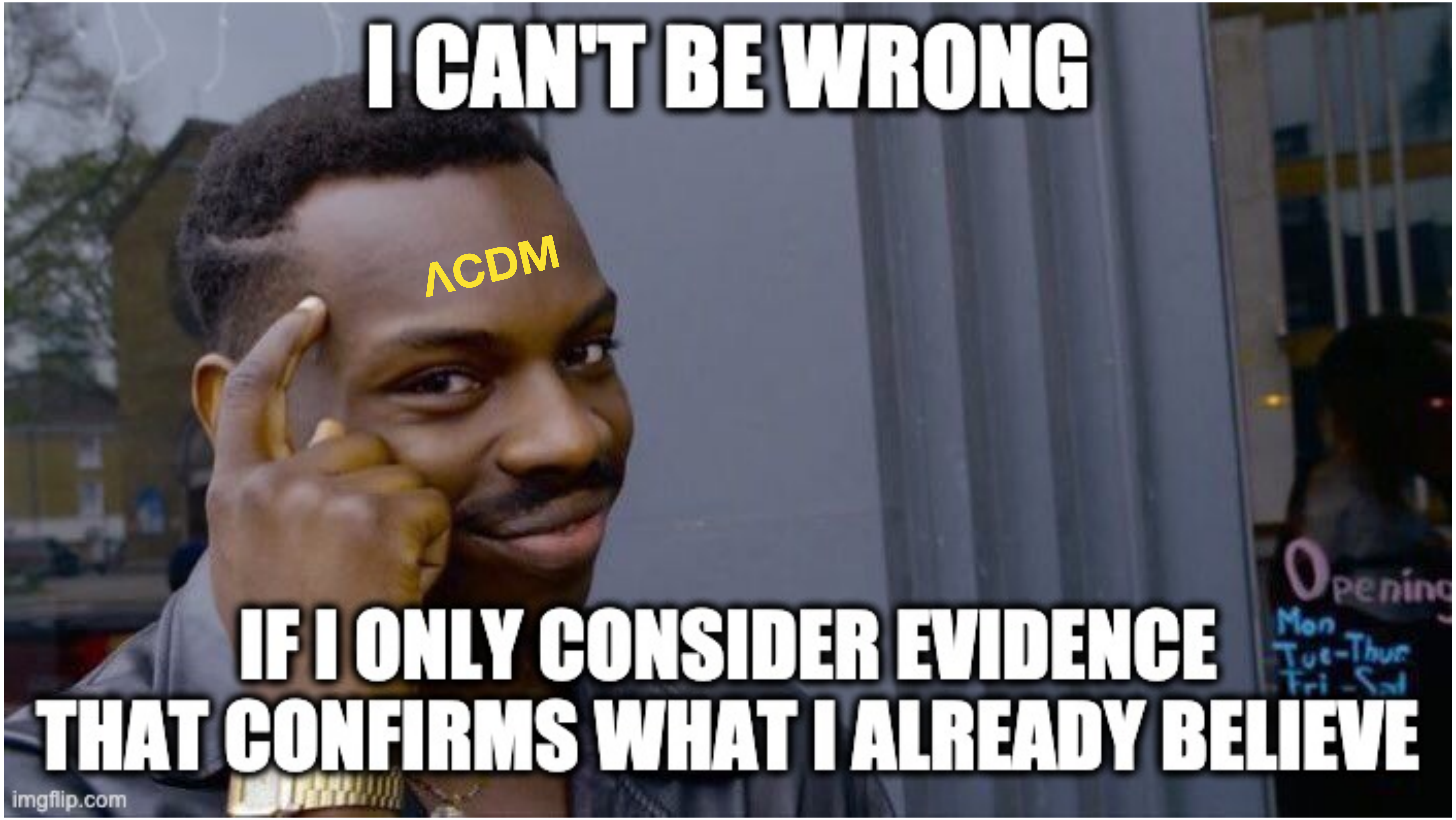
Nevertheless, cherry-picking the data is not a good scientific approach!


I CAN'T BE WRONG
ΛCDM
IF I ONLY CONSIDER EVIDENCE
THAT CONFIRMS WHAT I ALREADY BELIEVE
imgflip.com

Taken seriously,
what is the H0 tension telling us?

The Hubble tension

<u>Model-dependent statement:</u>

- Planck and SH_0ES incompatible

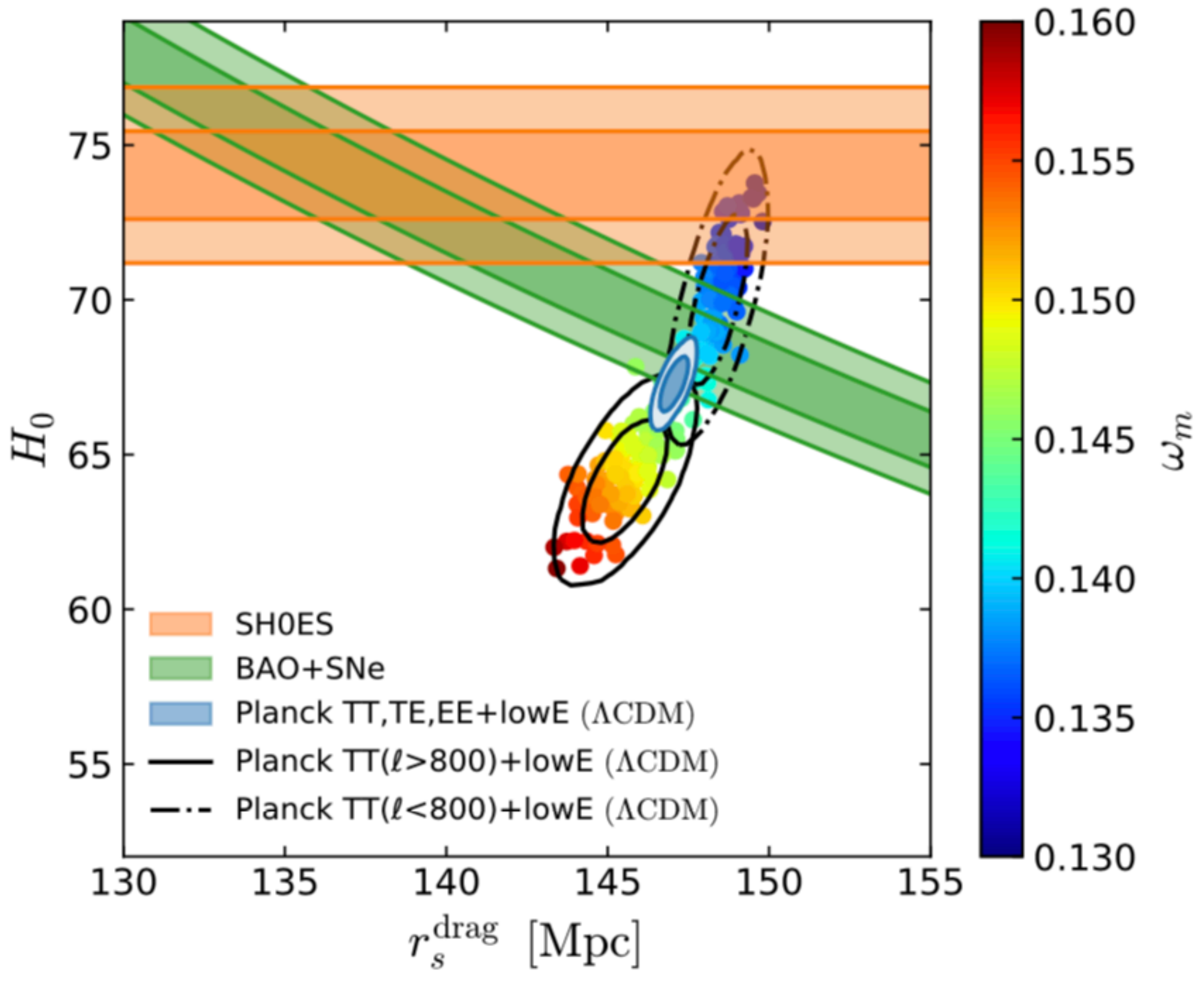
<u>Model-independent statement:</u>

- BAO+SN: $H_0 r_s \approx const$

Where

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

depends on early time physics



[Knox, Milea; 2019]

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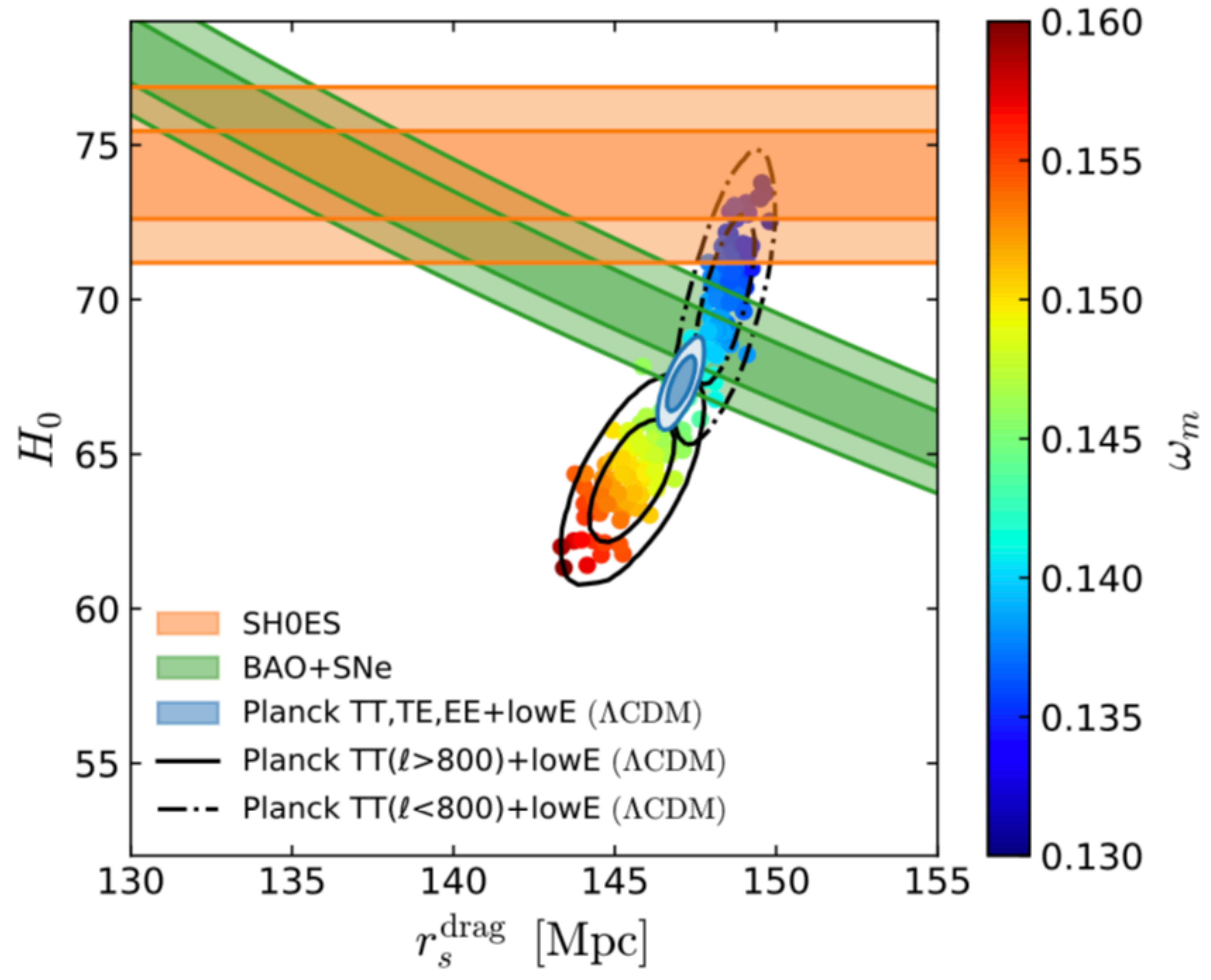

Modification of *ΛCDM* raising H_0 while lowering r_s

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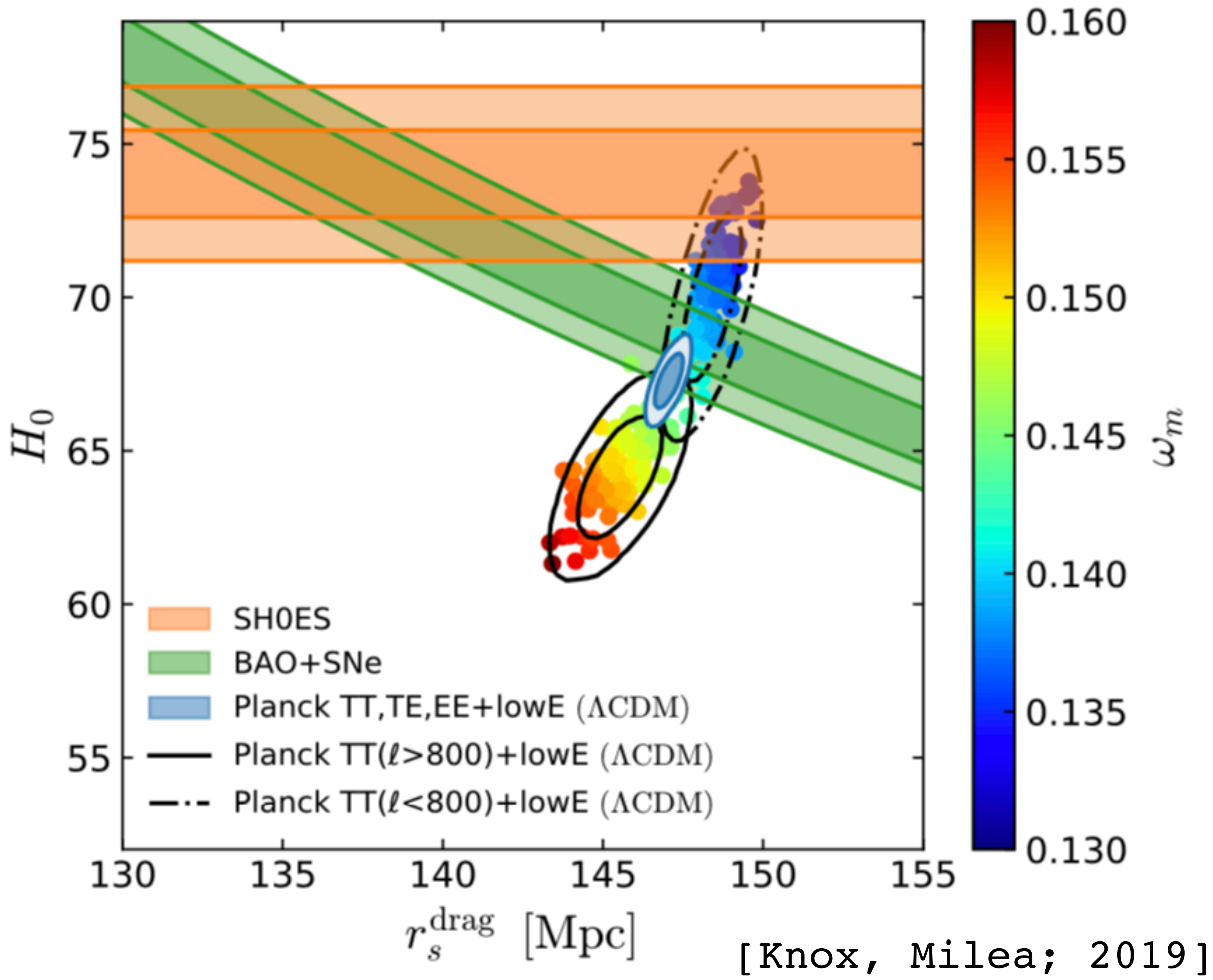


[Knox, Milea; 2019]

Where

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

depends on early time physics

➡ Modification of *ΛCDM* raising H_0 while lowering r_s

➡ Modification of *ΛCDM* just before recombination

Pre-recombination modifications

- Assume new hypothetical matter component is present before recombination

$$\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_X(z)}$$

➡ Increase in H before recombination

➡ Lowering the sound horizon

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Dark radiation

- Extra relativistic degree of freedom

$$\Omega_X(z) = \Omega_{DR}(1+z)^4$$

➡ Reduces the tension only slightly (~ 4 σ)

[Planck 2018+BAO +Pantheon+BBN]

$$H_0 = 69.49 \ \pm 0.0085 \ \frac{\text{km}}{\text{s Mpc}}$$

[Niedermann, MSS; 2020]

Early Dark Energy

Scalar field model w. slow-roll down potential

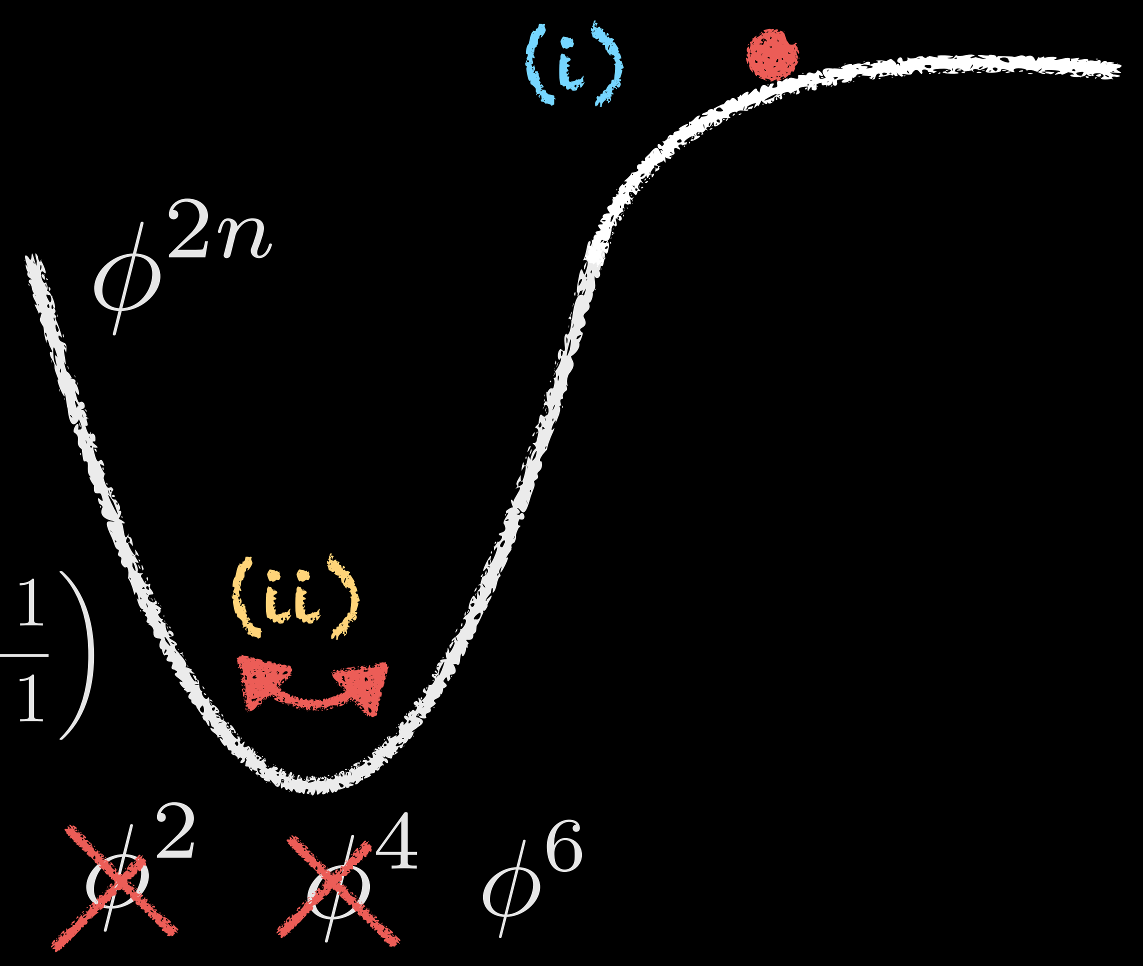
[e.g. Karwal et al., 2016]

[Poulin et al., 2018]

$$V^{(n)}(\phi) = \Lambda_a^4 \left[1 - \cos(\phi/f_a)\right]^n$$

$$\Omega_X(z) \approx \begin{cases} \Omega_{EDE} & ;\ z \gg z_c \ \text{(i)} \\ \Omega_{EDE}\left(\frac{1+z}{1+z_d}\right)^{\alpha \geq 4} & ;\ z \ll z_c \ \text{(ii)} \end{cases}$$

$$\alpha = 3\left(1 + \frac{n-1}{n+1}\right)$$



meanvalues: $n = 3$ $\quad z_c \approx 4000$

$$H_0 = 71.4 \pm 1\text{km/s/Mpc}$$

Problem: decay of EDE needs to be fast:

➡ How to make shallow anharmonic potentials natural…?

➡ Not very well motivated from a microphysical viewpoint…

[Kaloper, 2019]

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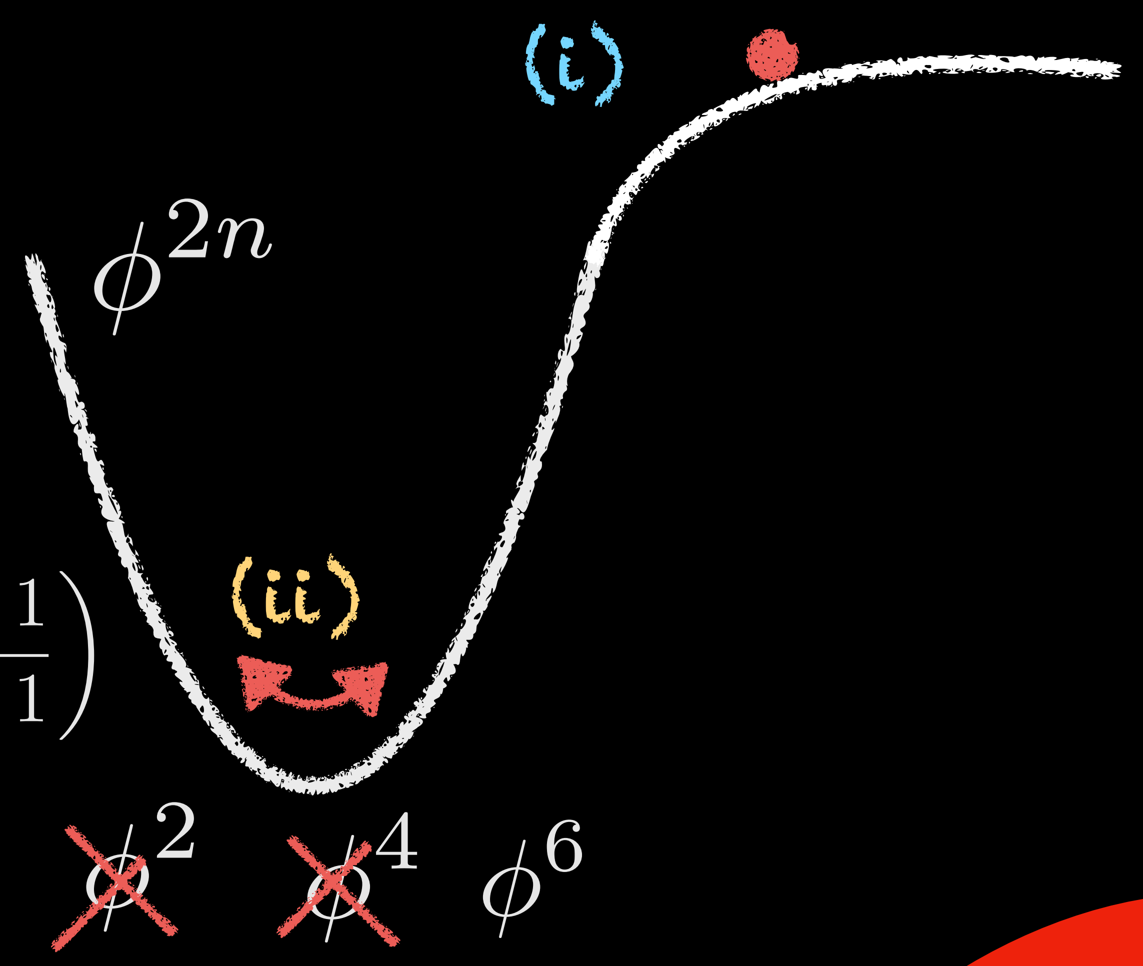

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Also cannot Resolve S8 problem

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➡ Not very well motivated from a microphysical viewpoint…

[Kaloper, 2019]

How does a NEDE Phase Transition resolve this?

New Early Dark Energy

NEDE is a fast triggered phase transition in the dark sector

Simple effective cosmological model:

- **Instant decay of New Early Dark Energy component just before recombination**

arXiv: 1910.10739, 2006.06686 w. Florian Niedermann

New Early Dark Energy

Some microphysical examples are:

- **Cold NEDE:**
  1st order PT triggered by a second "trigger" scalar field
  (Similar end of inflation)
  arXiv: 1910.10739, 2006.06686 w. Florian Niedermann

Focus of this talk

- **Hot NEDE:**
  1st order PT triggered by a non-vanishing temperature of the dark sector
  (Similar to electroweak phase transition, QCD phase transition, and recombination)
  arXiv:2112.00759, 2112.00770 w. Florian Niedermann

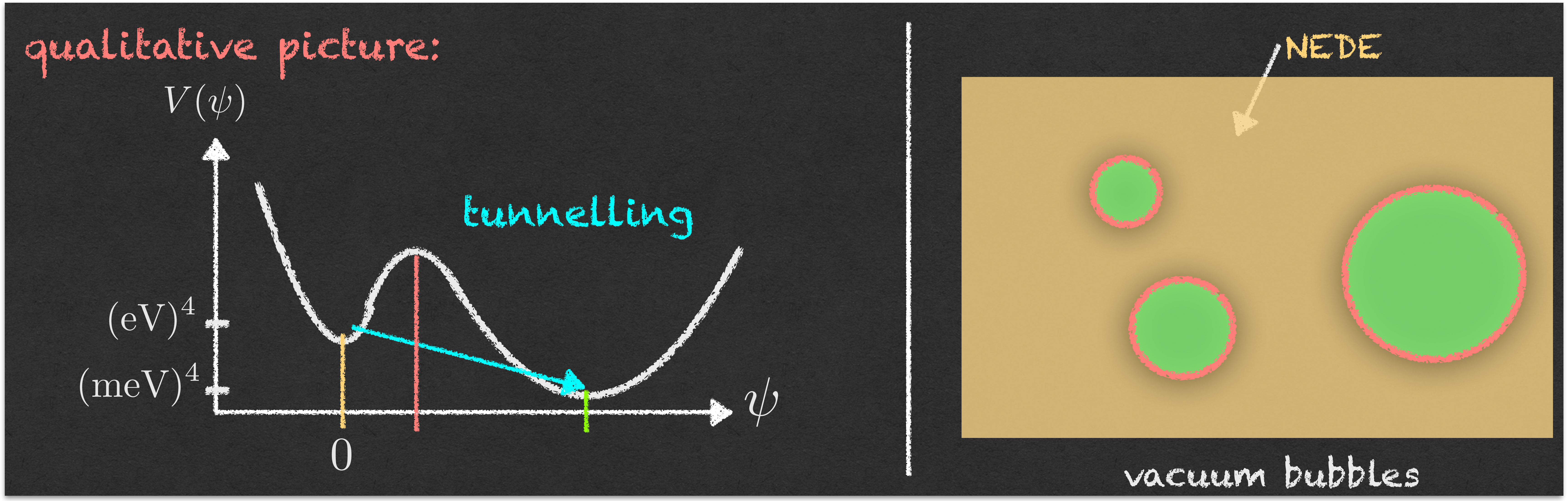
- **Hybrid NEDE:**
  2nd order PT triggered by a second "trigger" scalar field
  arXiv:2006.06686 w. Florian Niedermann
  (Similar to end of inflation in "hybrid inflation")

Cold NEDE

Cold New Early Dark Energy

Scalar field model w. first order phase transition

[Niedermann, MSS; 2019, 2020]



$$w = -1 \quad \rightarrow \quad 1/3 < w < 1$$

- Vacuum energy decays
- Free energy converted to anisotropic stress
- Anisotropic stress partially sources gravitational radiation
- Remaining anisotropic stress decays like a stiff fluid

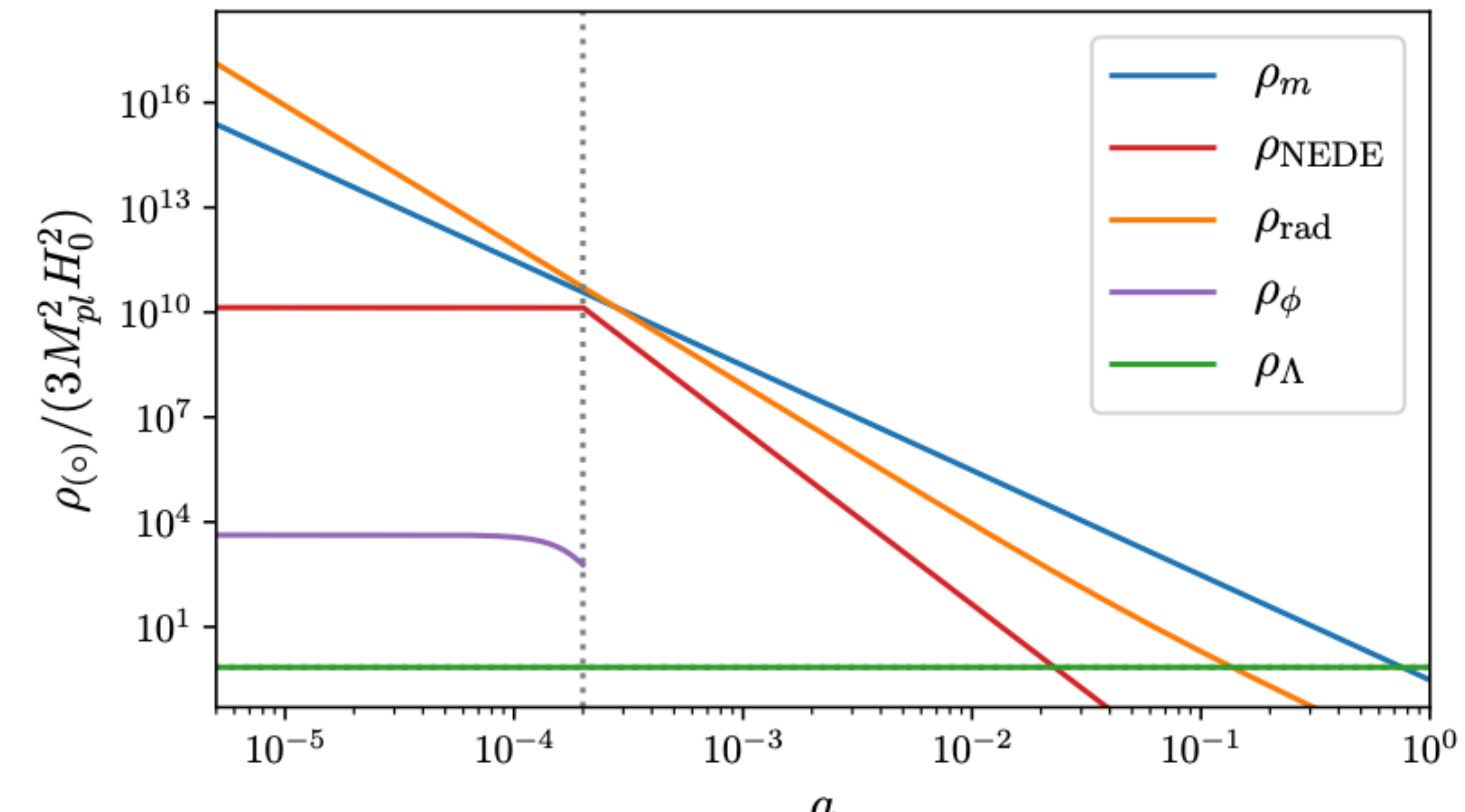
Effective cosmological model

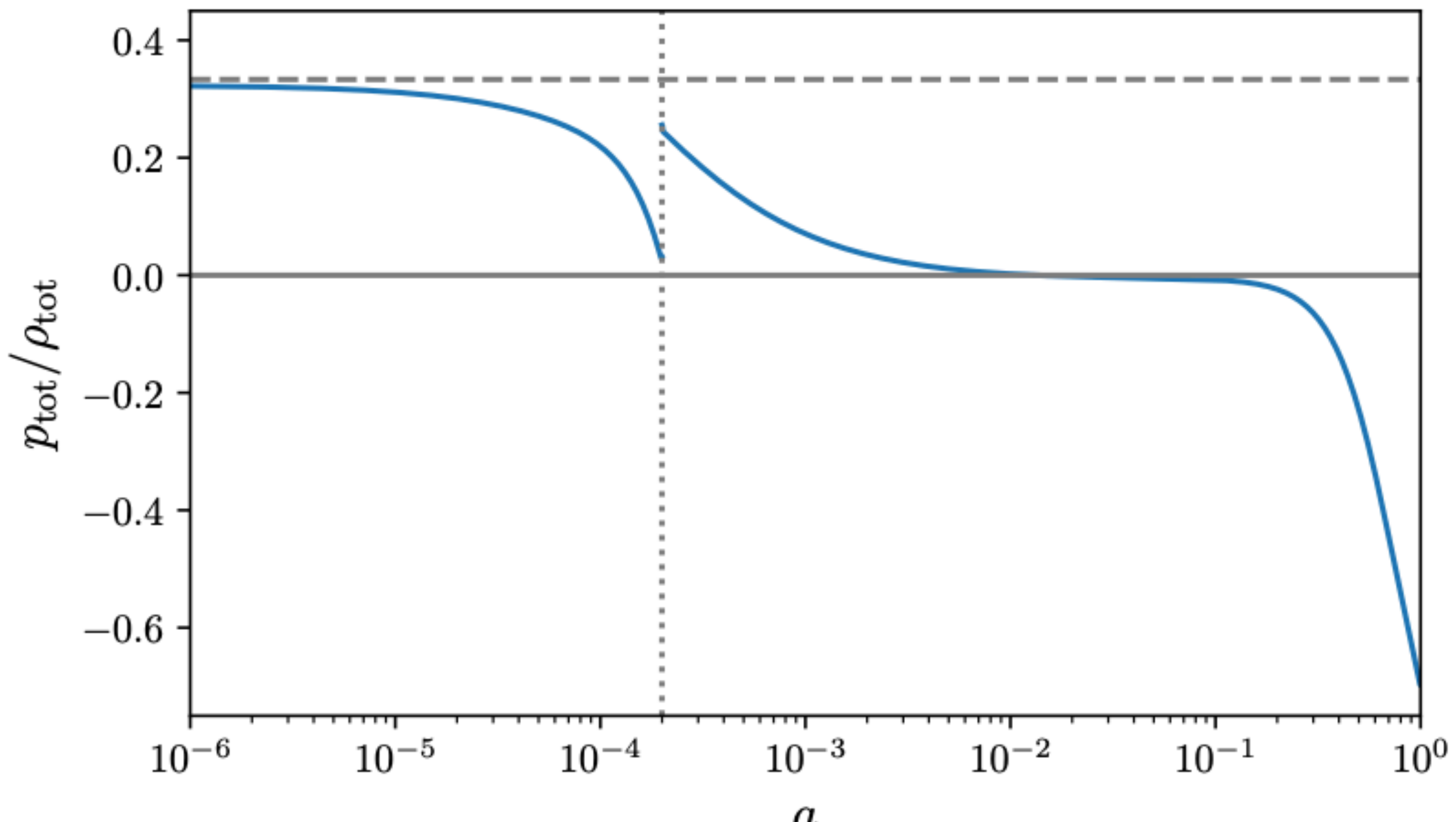
- **Background** picture: Assume that all liberated vacuum energy is converted to a fluid with fixed e.o.s.

Sudden transition at time t_* :

$$w_{\rm NEDE}(t) = \begin{cases} -1 & \text{for} \quad t < t_* \\ w^*_{\rm NEDE} & \text{for} \quad t \geq t_* \end{cases}$$

NEDE fluid: $\bar\rho_{\rm NEDE}(t) = \bar\rho^*_{\rm NEDE}\left(\frac{a_*}{a(t)}\right)^{3[1+w_{\rm NEDE}]}$





➡ Introduce a trigger field for the decay

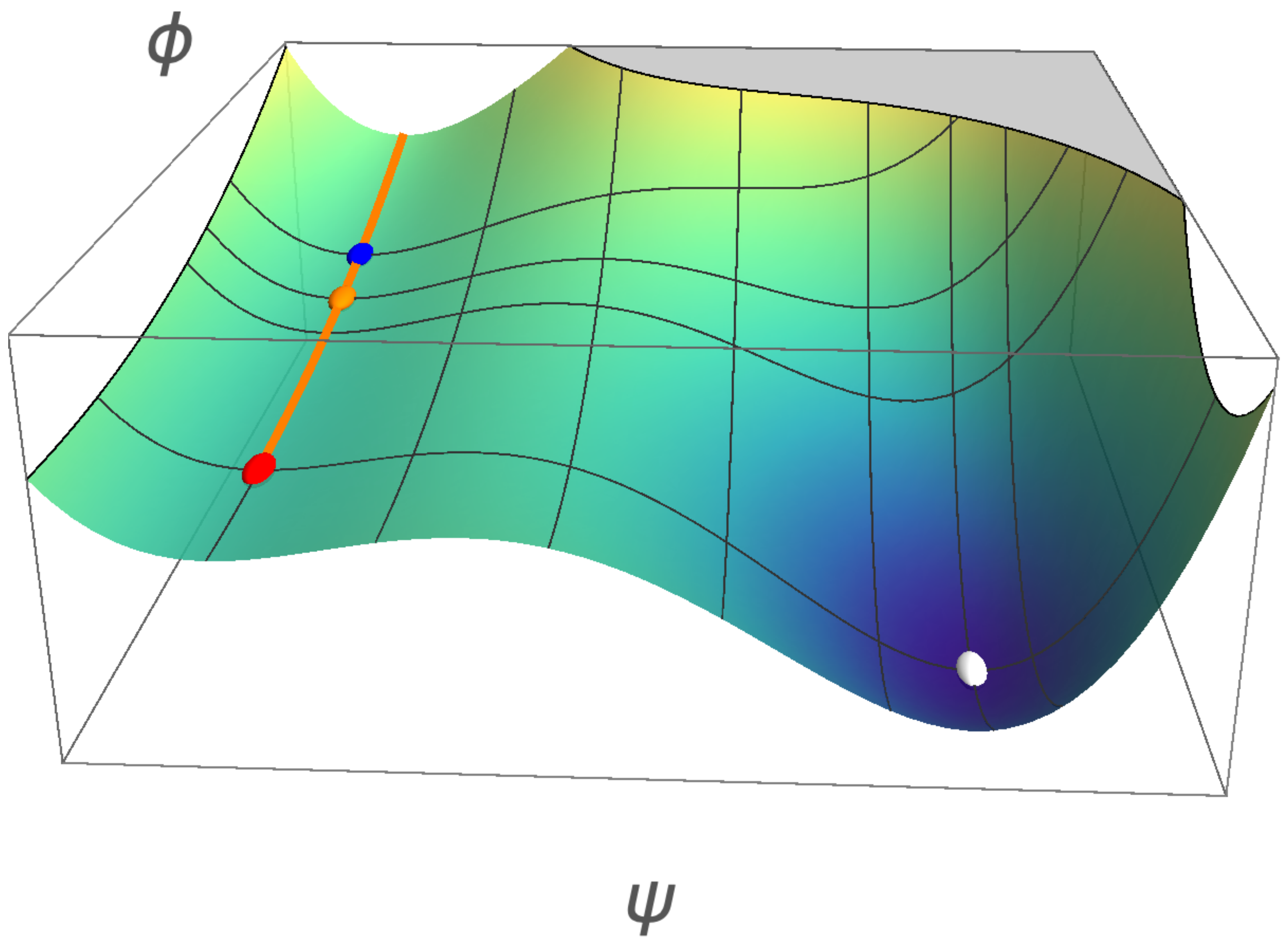
field theory model: $\alpha, \beta, \lambda = \mathcal{O}(1)$

$$V(\psi,\phi) = \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{\lambda}{4}\psi^4 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2 + const$$

New Early Dark Energy — Clock — 'CC tuning'

hierarchy: $M \sim \mathrm{eV} \quad \gg \quad m \sim 10^{-27}\mathrm{eV}$ ultra-light physics

initial condition: $\psi = 0$ sub-dominant trigger: $\phi_{ini} \ll M_{pl}$



(i) for $H \gg m : \phi \approx \phi_{ini}$

(ii) for $H \approx m :$ ϕ starts evolving

(iii) blue dot: inflection point

(iv) orange dot: $\Gamma = 0,\ \dot{\Gamma} > 0$

(v) red dot: $\Gamma = \Gamma_{max}$

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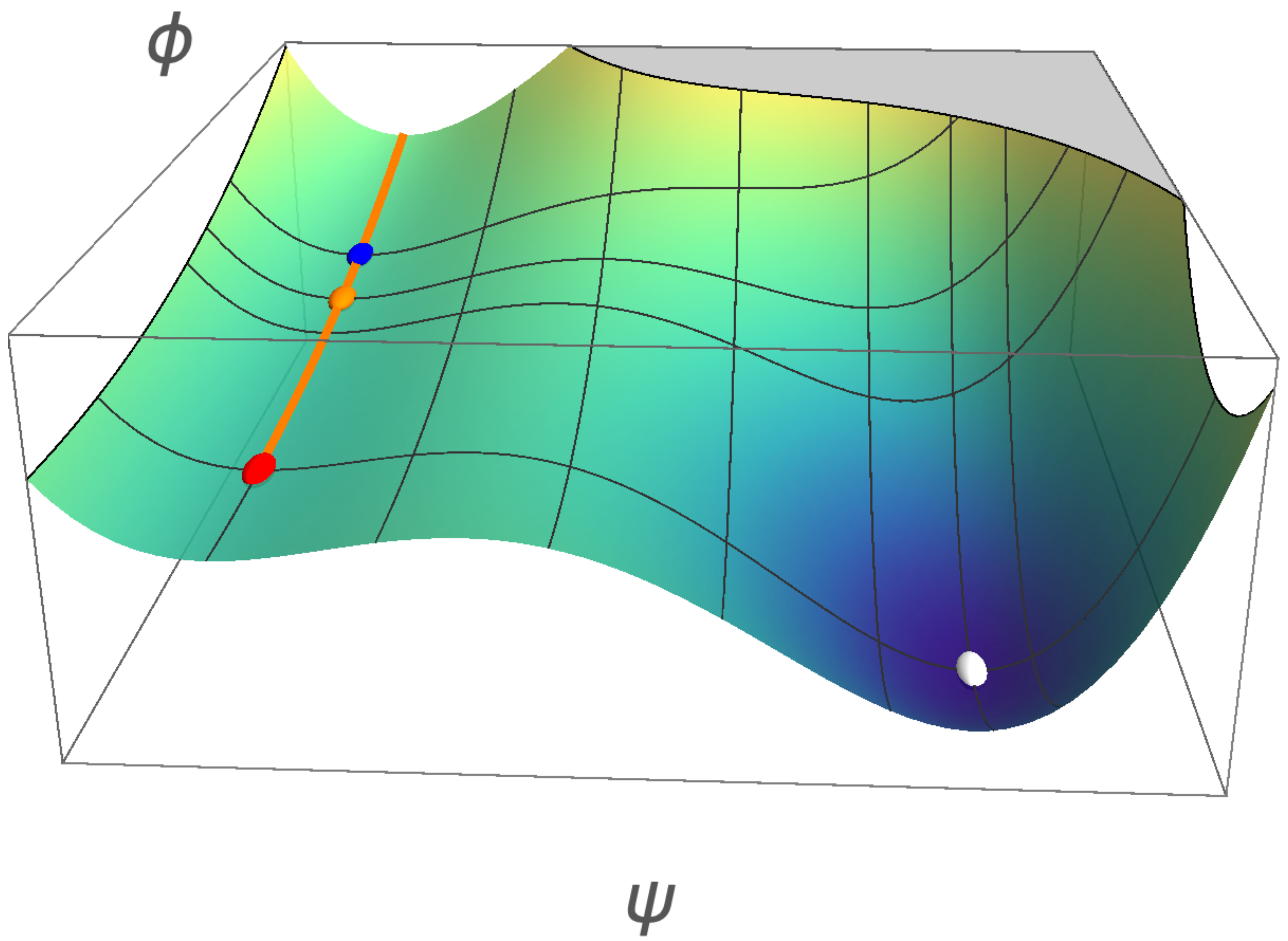

NEDE boson: tunneling field

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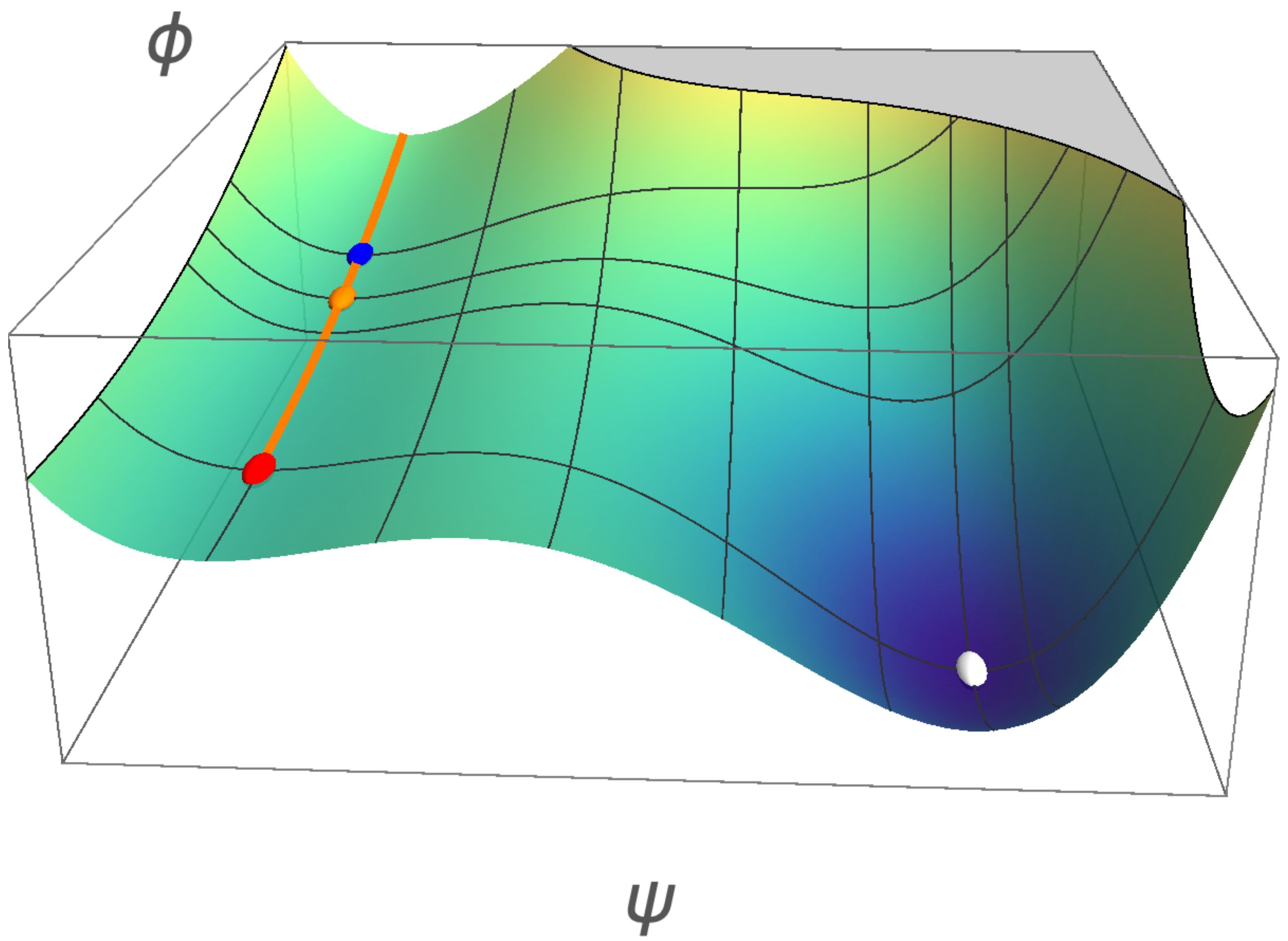
Trigger field



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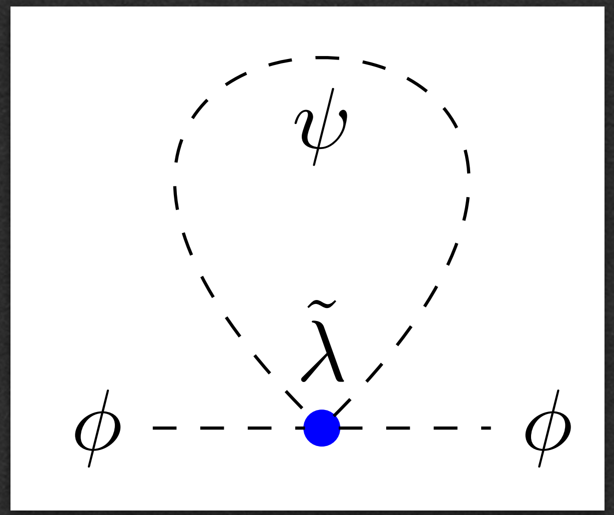
Technical Naturalness

- Most general renormalizable potential of two scalar fields

- Radiative stability as low energy EFT (valid up to at least scale M)

$\delta m^2 =$ 

of order (suppressing logs): $\tilde{\lambda}\,\beta\, M^2/(32\pi^2)$

radiative stability → $\tilde{\lambda} \lesssim 10^3 \dfrac{m^2}{\beta M^2} \ll 1\,.$

- May have many possible UV completions in terms of axions (monodromy, clockwork, etc.) and quantum gravity solutions to the CC problem (landscape, swampland conjecture, chain NEDE [Freese, Winkler; '21] , etc.)

Trigger as Ultra Light Axion

- The model can be UV completed in two axion model

➡Trigger is a ULA

- In the limit where ψ is small compared to its decay constant $\tilde{f}$

$$V(\psi,\phi) = \frac{1}{2}\lambda\psi^4 + \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 - \Lambda^4\cos\left(\frac{\phi}{f}\right) - \frac{\tilde{\Lambda}^4}{2!\tilde{f}^2}\cos\left(\frac{\phi}{f}\right)\psi^2 + \frac{\tilde{\Lambda}^4}{4!\tilde{f}^4}\cos\left(\frac{\phi}{f}\right)\psi^4 + \mathcal{O}(\psi^5)$$

where

$f \sim M_p$ and $m = \Lambda^2/f = 10^{-27}\mathrm{eV} \quad \Rightarrow \quad \Lambda \sim M \sim \mathrm{eV}$

$$\tilde{\lambda} = \tilde{\Lambda}^4/(2f^2\tilde{f}^2) \ll 1$$

➡Expanding for small ϕ, we recover the Cold NEDE potential from before!

Trigger as Ultra Light Axion

- ➡ The smallness of the trigger mass and its coupling to the NEDE boson arise from the breaking of the global continuous shift symmetry, $\phi \to \phi + const$, of an Axion-Like Particle (ALP) to a discrete shift symmetry, $\phi \to \phi + 2\pi f$.

- ➡ The theory can then be UV completed to explain also the ψ mass scale M by promoting ψ to an axion with discrete shift symmetry $\psi \to \psi + 2\pi \tilde{f}$

.

Cold NEDE: Cosmological perturbations

- The phase transition affects perturbations in different ways:
  - Perturbations feel the change in the effective e.o.s. → relevant for CMB
  - Transition is triggered at different places at different times due to fluctuations in trigger field phi. → relevant for CMB
  - The bubbles generate perturbations on scales comparable to their size. → irrelevant for CMB
- We use Israel junction conditions to match fluctuations across transition surface.

[Niedermann, MSS, 1910.10739, 2006.06686]

building on

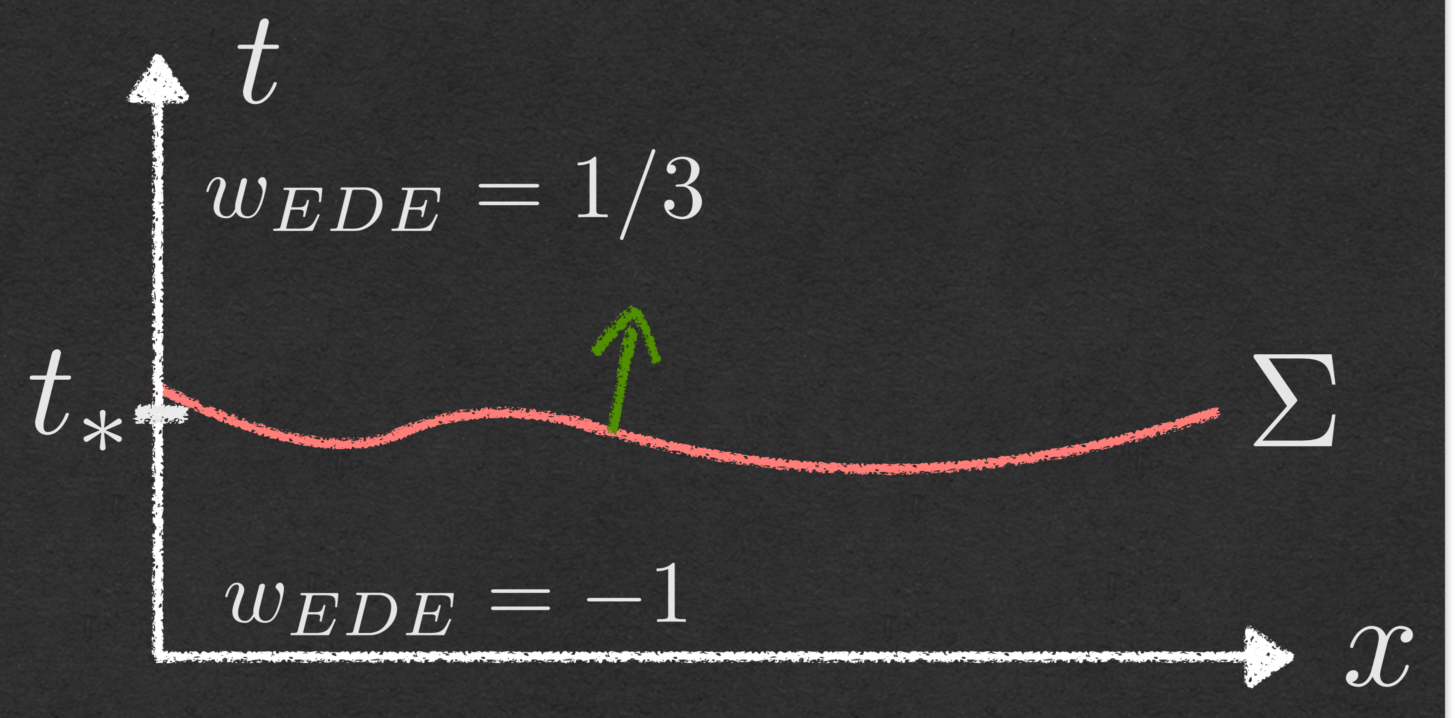
[Deruelle, Mukhanov, 1995]

space like transition surface Σ : $\phi(t_*, \mathbf{x})|_\Sigma = const$.

synchronous gauge:

$$ds^2 = -dt^2 + a(t)^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j ,$$

where $h_{ij} = \frac{k_i k_j}{k^2} h + \left(\frac{k_i k_j}{k^2} - \frac{1}{3}\delta_{ij}\right) \eta ,$



- Two metric perturbations: $h(t,k)$ & $\eta(t,k)$

Implemented in Boltzmann code: TriggerCLASS

[2006.06686, 2305.08895]

Does it work?

The answer is so far, yes; for details, see f.ex. recent data analysis in arXiv:2209.02708

A grounded perspective on New Early Dark Energy using ACT, SPT, and BICEP/Keck

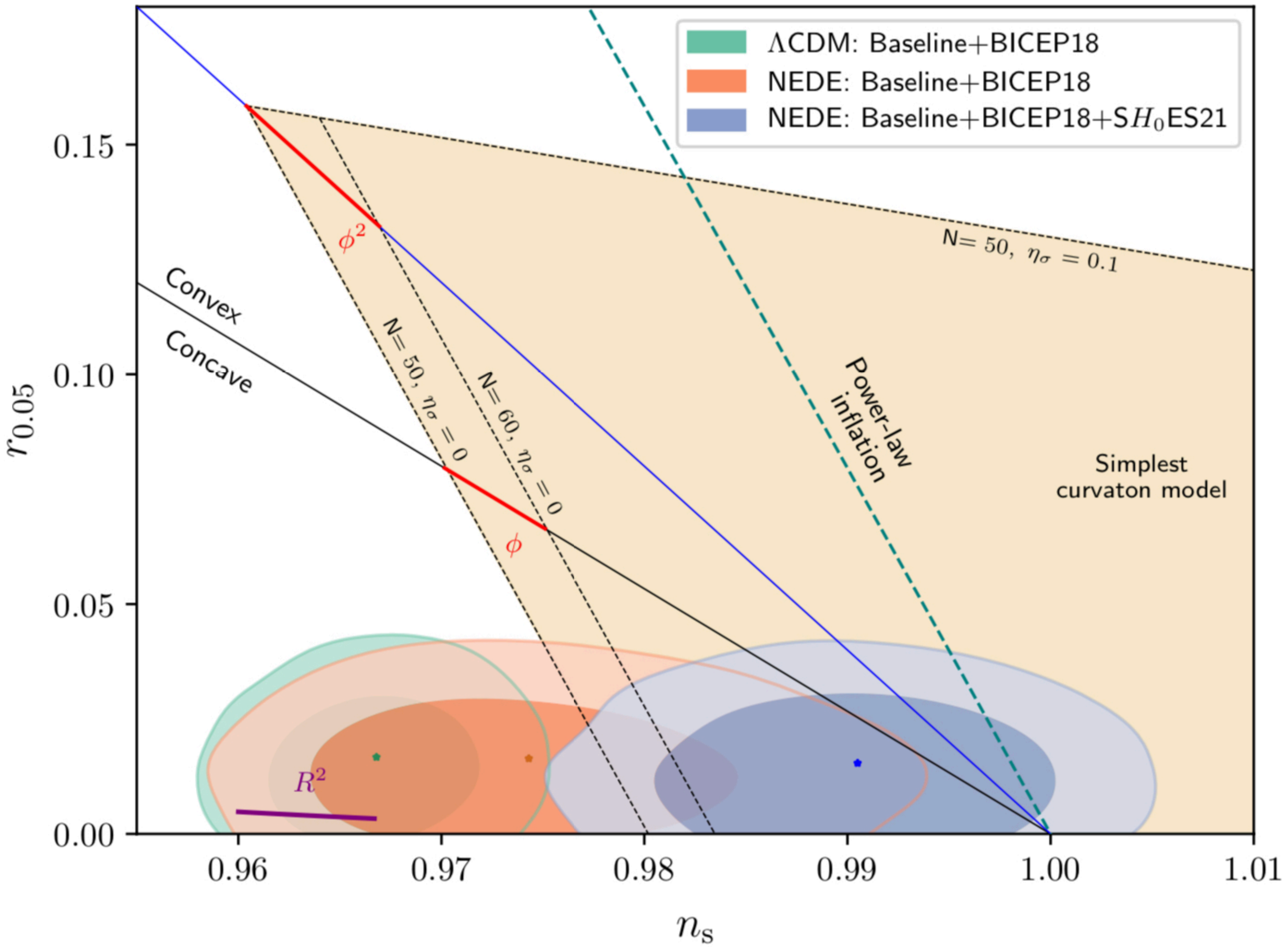
Juan S. Cruz,[1,*] Florian Niedermann,[2,†] and Martin S. Sloth[1,‡]

[1]CP3-Origins, Center for Cosmology and Particle Physics Phenomenology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

[2]Nordita, KTH Royal Institute of Technology and Stockholm University Hannes Alfvéns väg 12, SE-106 91 Stockholm, Sweden

We examine further the ability of the New Early Dark Energy model (NEDE) to resolve the current tension between the Cosmic Microwave Background (CMB) and local measurements of H_0 and the consequences for inflation. We perform new Bayesian analyses, including the current datasets from the ground-based CMB telescopes Atacama Cosmology Telescope (ACT), the South Pole Telescope (SPT), and the BICEP/Keck telescopes, employing an updated likelihood for the local measurements coming from the SH_0ES collaboration. Using the SH_0ES prior on H_0, the combined analysis with Baryonic Acoustic Oscillations (BAO), Pantheon, Planck and ACT improves the best-fit by $\Delta\chi^2 = -15.9$ with respect to ΛCDM, favors a non-zero fractional contribution of NEDE, $f_{\text{NEDE}} > 0$, by 4.8σ, and gives a best-fit value for the Hubble constant of $H_0 = 72.09$ km/s/Mpc (mean $71.48^{+0.79}_{-0.81}$ with 68% C.L.). A similar analysis using SPT instead of ACT yields consistent results with a $\Delta\chi^2 = -23.1$ over ΛCDM, a preference for non-zero f_{NEDE} of 4.7σ and a best-fit value of $H_0 = 71.77$ km/s/Mpc (mean $71.43^{+0.84}_{-0.84}$ with 68% C.L.). We also provide the constraints on the inflation parameters r and n_s coming from NEDE, including the BICEP/Keck 2018 data, and show that the allowed upper value on the tensor-scalar ratio is consistent with the ΛCDM bound, but, as also originally found, with a more blue scalar spectrum implying that the simplest curvaton model is now favored over the Starobinsky inflation model.

Consequences for Inflation



[arXiv:2209.02708]

Consequences for Inflation

- In plot on the previous slide, we used the relations for the simplest curvaton model

$$V(\phi,\sigma) = \frac{1}{2}M^2\phi^2 + \frac{1}{2}m^2\sigma^2$$

which implies

$$n_s = 1 - \frac{1}{1+R}\frac{8}{4N+2} + \frac{R}{1+R}\left[-2\epsilon + 2\eta_\sigma\right] \qquad f_{\rm NL} = \left(\frac{R}{1+R}\right)^2\left[\frac{5}{3} - \frac{5}{4r_{\rm dec}} + \frac{5}{6}r_{\rm dec}\right]$$

$$r = \frac{16\epsilon}{1+R}$$

$$R = \frac{\mathcal{P}_{\zeta_{\rm curvaton}}}{\mathcal{P}_{\zeta_{\rm inflaton}}}$$

Inflation dominates

$R \to 0$

$r \to 16\epsilon$

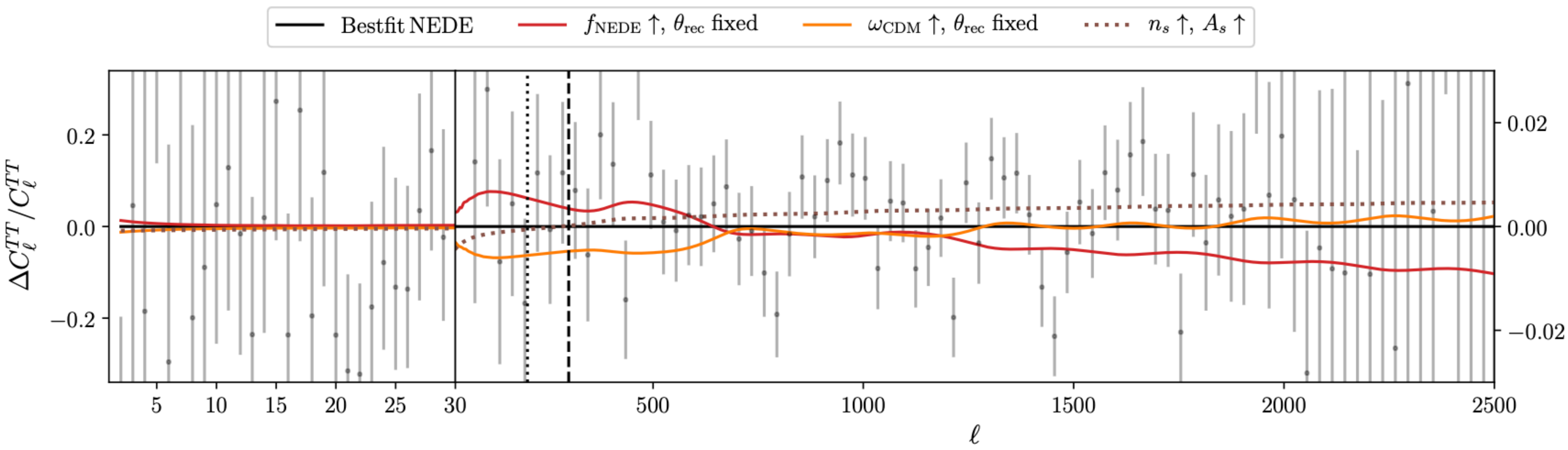
$f_{\rm NL} \to 0$

Curvaton dominates

$R \to \infty$

$r \to 0$

$|f_{\rm NL}| \to 5/4 \qquad (r_{\rm dec} = 1)$



1. $f_{NEDE} > 0$ introduces a shift in the angular peaks, which is compensated by increasing H0

2. Acoustic oscillations in the NEDE fluid lead to an excess decay of the Weyl potential, affecting the driving of acoustic CMB modes entering the sound horizon around the decay time ($l \simeq 300$). This can be counteracted by increasing w_{cdm}

3. A shortening of the CMB damping scale r_D, due to the modified expansion history, affects modes on short scales and needs to be compensated by more blue spectrum $n_s \to 1$ and increasing the amplitude A_s.

But what about the S8 tension?

But what about the S8 tension?

Surely, the right solution to the *H0* tension should also solve the *S8* tension, or at least not make it worse, right…?

The Trouble with S8

➡An increase in power on small scales is generic for other Early Dark Energy type of models

➡Other Early Dark Energy type of models have slightly higher *S8* than ΛCDM

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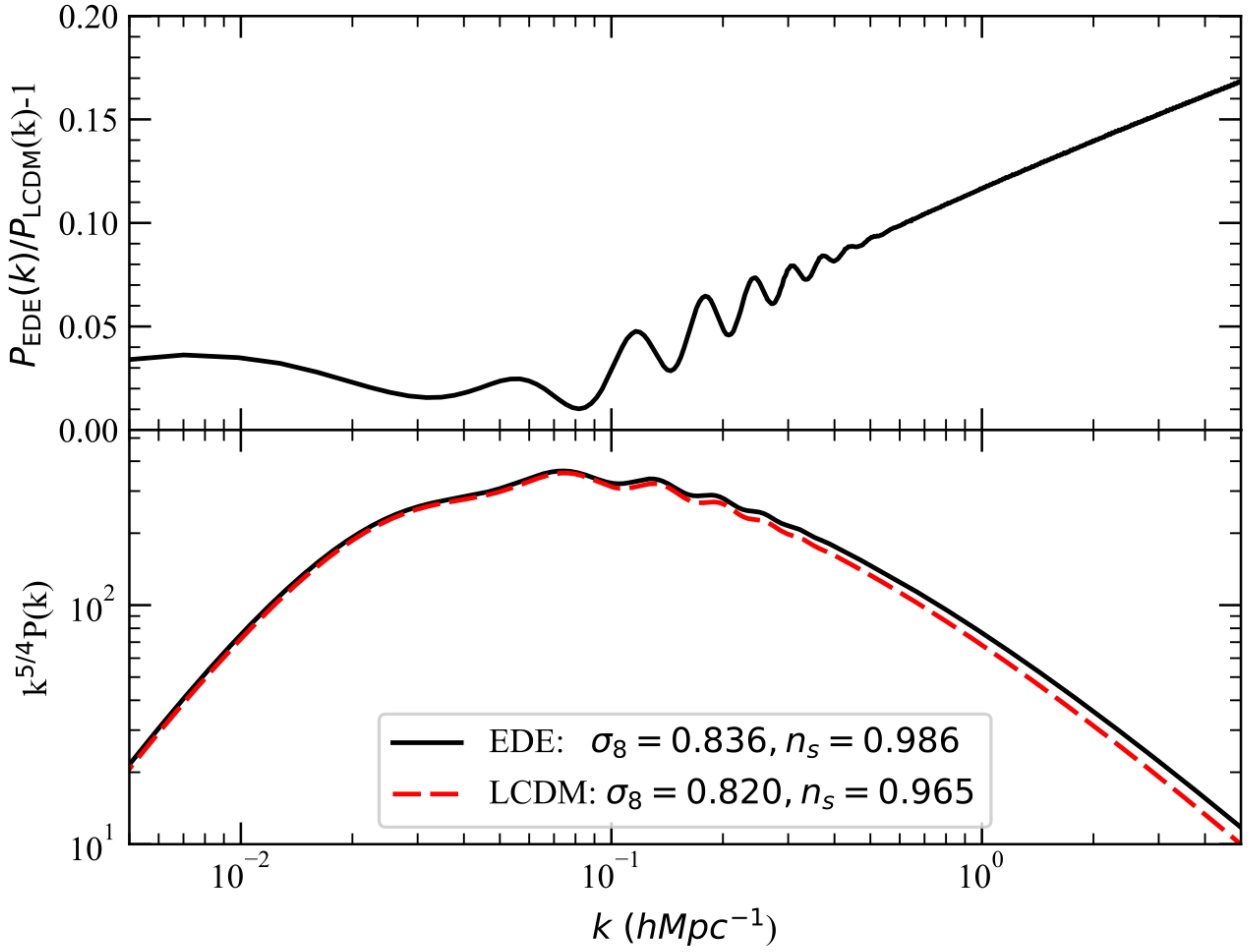
The old Early Dark Energy (EDE) model:



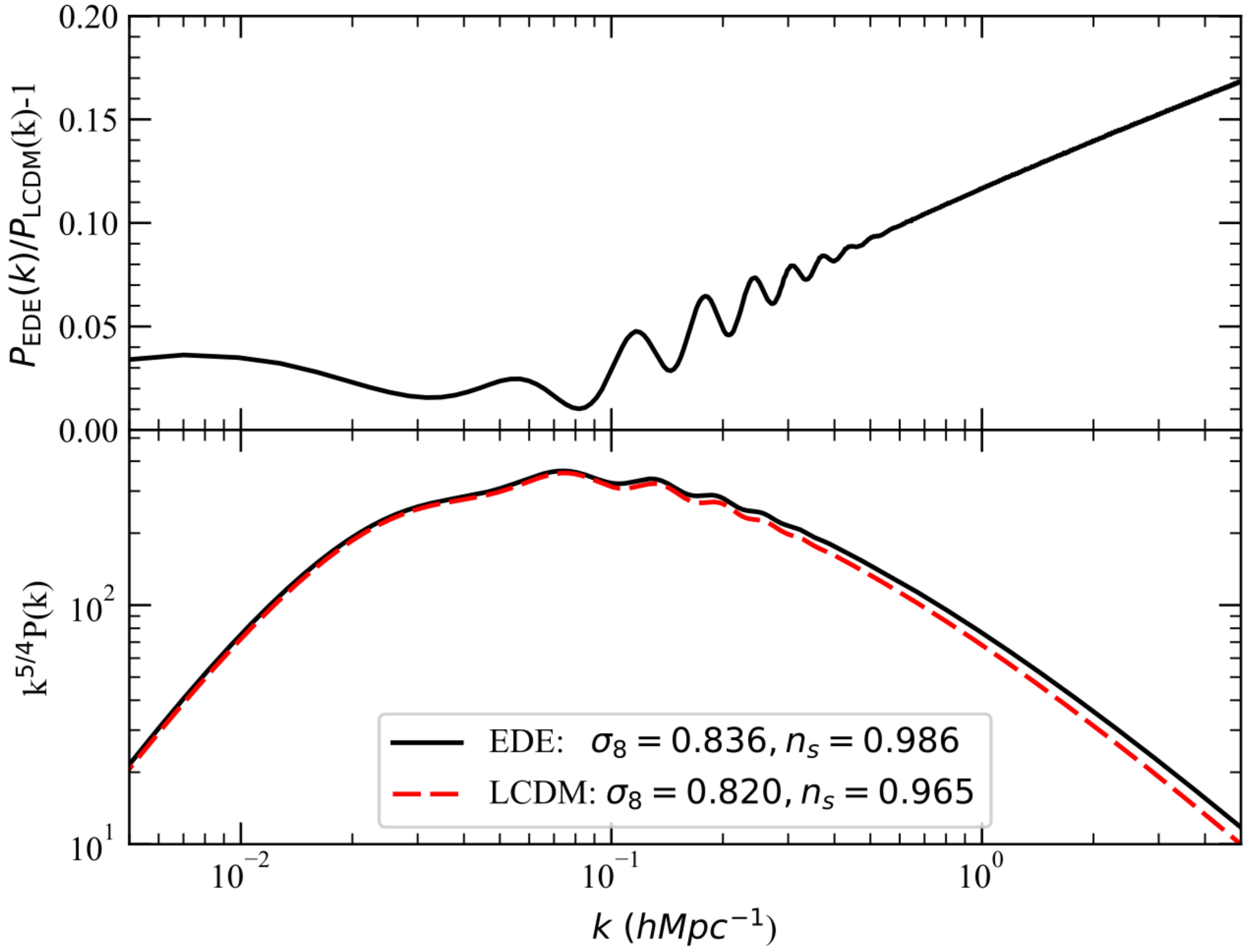
[Poulin, Schmidt, Karwal, 2023, arXiv:2302.09032]

The Trouble with S8

➡An increase in power on small scales is generic for other Early Dark Energy type of models

➡Other Early Dark Energy type of models have slightly higher *S8* than ΛCDM

The old Early Dark Energy (EDE) model:



EDE: *σ8 = 0.836*

ΛCDM: *σ8 = 0.820*

➡ **S8 tension worsened**

Note: $S_8 \approx \sigma_8$ **since** $\Omega_m \approx 0.3$

and $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$

[Poulin, Schmidt, Karwal, 2023, arXiv:2302.09032]

S8 in Cold NEDE

- In Cold NEDE the trigger is an ultra-light axion-like scalar particle $m_\phi \approx 10^{-27}$eV

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➡Smaller S8 in Cold NEDE

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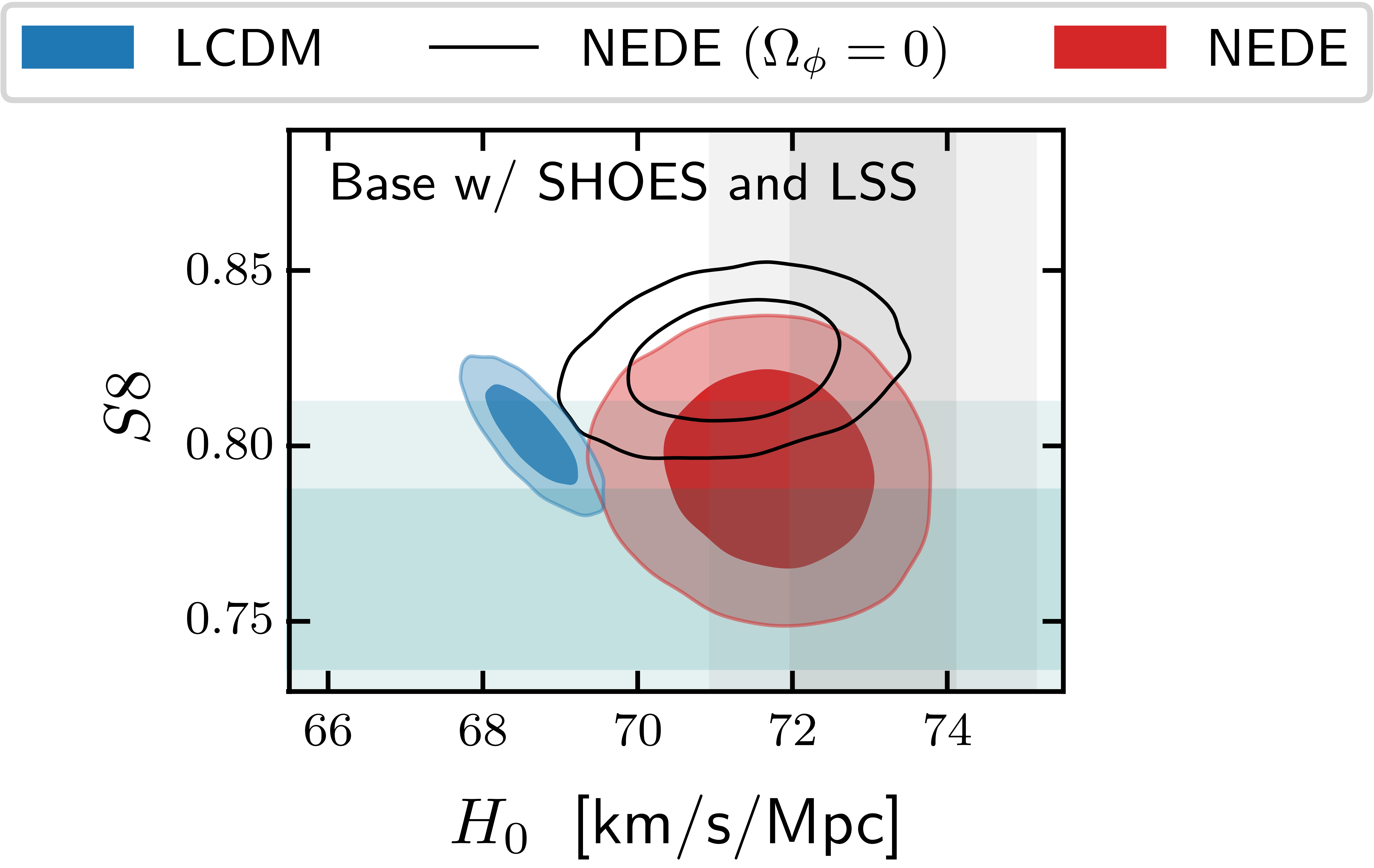
➡Smaller S8 in Cold NEDE

- On even smaller scales, the blue spectrum takes over and leads to increased structure formation on smallest scales, which might address recent JWST measurements

S8 in Cold NEDE



[Juan S. Cruz, Florian Niedermann, MSS; to appear]

Conclusions!

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- ***H0* and *S8* tension should be taken seriously**

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- **NEDE is a natural particle physics solution to the** ***H0*** **tension**

Conclusions

- ***H0* and *S8* tension should be taken seriously**
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Conclusions

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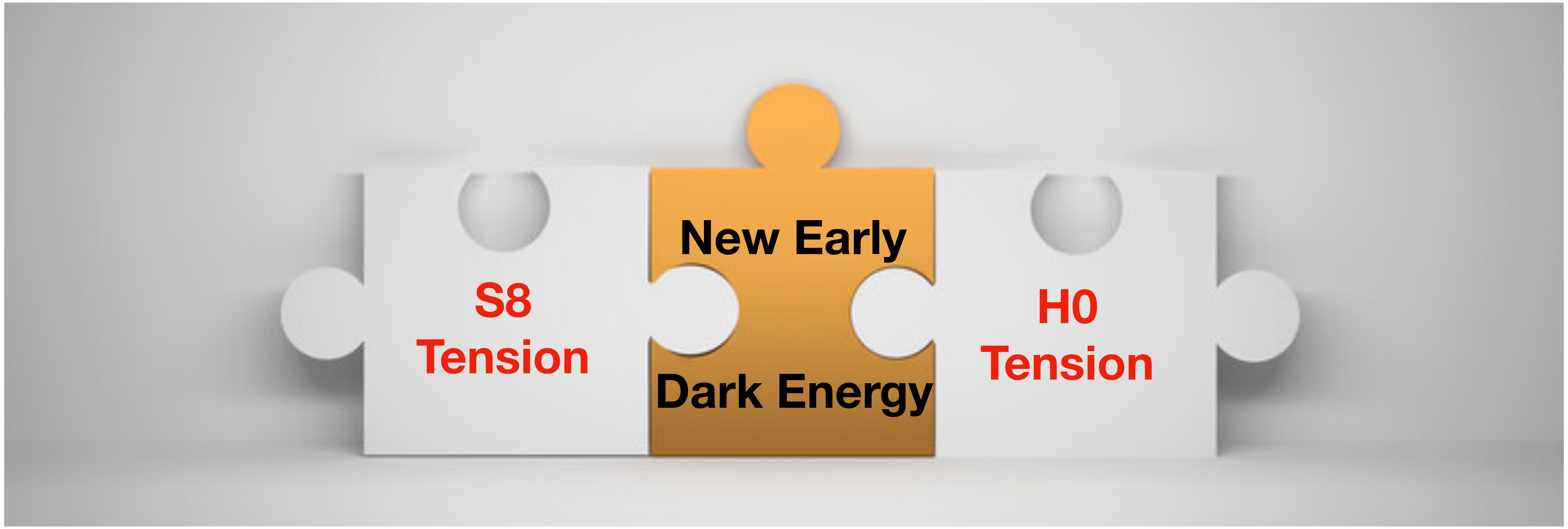
Conclusions

- *H0* and *S8* tension should be taken seriously
- *H0* tension implies new physics a la EDE before recombination
- NEDE is a natural particle physics solution to the *H0* tension
- (N)EDE rules out Starobinsky inflation and instead, the simplest curvaton model is favoured
- Other EDE-type models lead to a worsening of *S8* tension
- The ultra-light trigger field in Cold NEDE simultaneously resolve the *S8* tension

A simultaneous solution to the H0 and the S8 tensions and the implication for inflation

Martin S. Sloth

Universe-Origins, SDU, Denmark

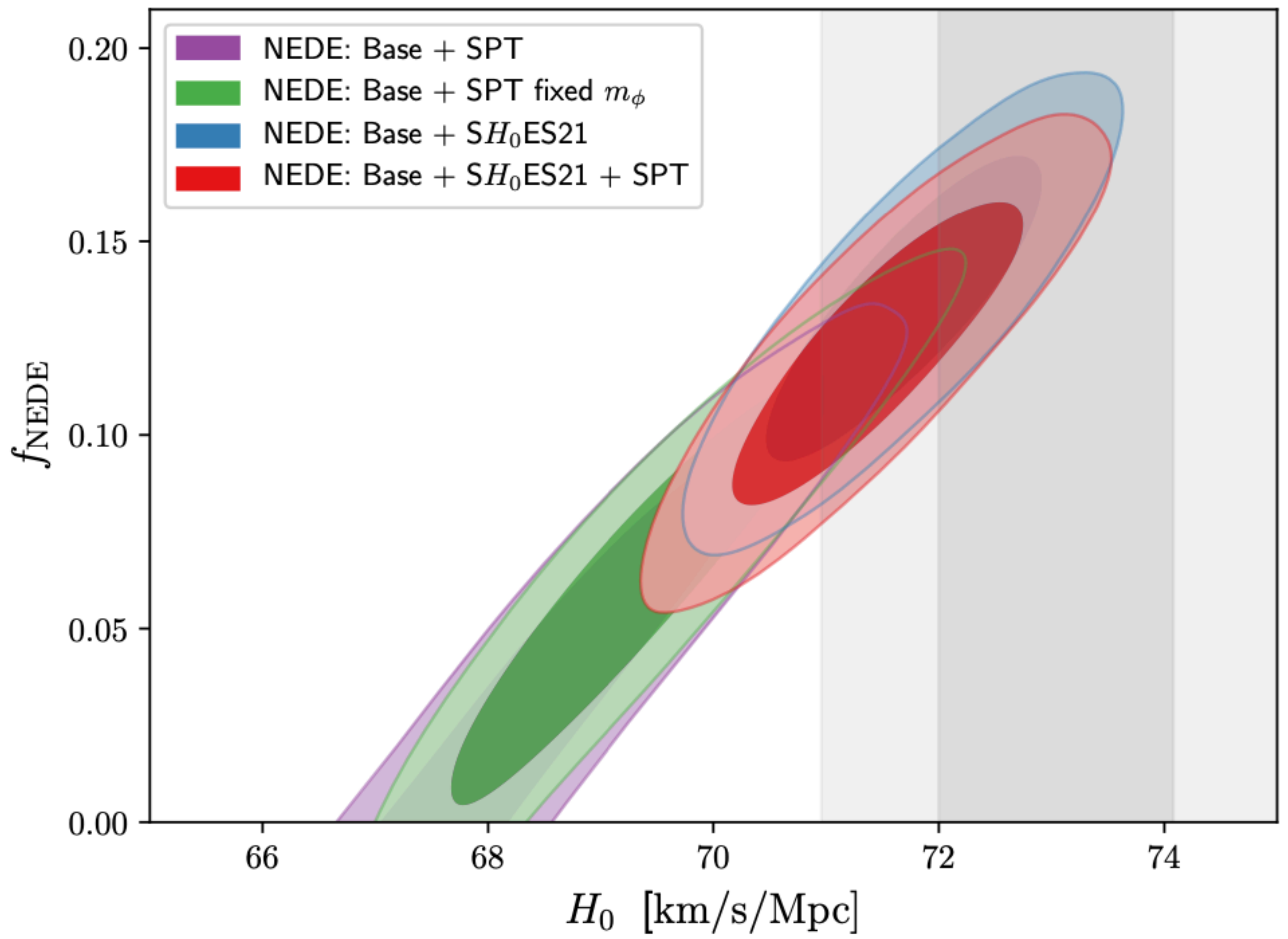


arXiv:2307.03091, 2305.08895, 2209.02708
w. Juan S. Cruz and Florian Niedermann

arXiv: 2307.03481, 2112.00759, 2112.00770, 2009.00006, 2006.06686,1910.10739
w. Florian Niedermann

arXiv:2302.07934
w. Juan S. Cruz, Steen Hannestad, Emil Brinch Holm, Thomas Tram and Florian Niedermann

Backup slides


NEDE: Base + SPT
NEDE: Base + SPT fixed m_ϕ
NEDE: Base + SH_0ES21
NEDE: Base + SH_0ES21 + SPT
0.20
0.15
0.10
0.05
0.00
$f_{\rm NEDE}$
66
68
70
72
74
H_0 [km/s/Mpc]

Dataset	NEDE fixed EOS (Base = Planck+BAO+SN)				
	Base	+SPT	+SH_0ES21	+SPT +SH_0ES21	+SPT fixed m_ϕ
Pl.18 lowl.TT	21.686	21.664	20.727	20.749	21.725
Pl.18 lowl.EE	396.087	396.166	395.918	397.283	396.445
Pl.18 lensing.clik	9.545	9.314	9.834	9.851	9.234
Pl.18 highl.TTTEEE	2336.679	2337.241	2338.514	2337.810	2337.021
bao.sdss dr7 mgs	1.465	1.409	2.045	2.331	1.526
bao.sixdf 2011 bao	0.008	0.012	0.010	0.036	0.005
bao.sdss dr12 Cons.	3.918	4.045	3.441	3.564	3.814
sn.pantheon	1034.876	1034.901	1034.735	1034.745	1034.848
SPT3G Y1.TEEE	–	1118.515	–	1118.718	1118.607
SH_0ES	–	–	1.517	1.494	–
Total chi2	3804.265	4923.266	3806.741	4926.580	4923.224
$\Delta\chi^2$	-3.19	-3.32	-23.32	-23.13	-3.37
$Q_{\rm dmap}$			1.57σ	1.82σ	

Table XIII. χ^2 values for the individual likelihoods used in the different MCMC analysis involving SPT and corresponding reference runs, together with the respective totals and $Q_{\rm dmap}$.

Parameter Name	NEDE fixed EOS				
	Base	+ACT	+SH_0ES21	+ACT +SH_0ES21	+ACT fixed m_ϕ
$\Omega_b h^2$	0.023 $0.0226^{+0.0002}_{-0.0002}$	0.022 $0.0225^{+0.0002}_{-0.0002}$	0.023 $0.0230^{+0.0002}_{-0.0002}$	0.023 $0.0227^{+0.0002}_{-0.0002}$	0.023 $0.0226^{+0.0002}_{-0.0002}$
$\Omega_c h^2$	0.125 $0.1244^{+0.0040}_{-0.0039}$	0.124 $0.1229^{+0.0033}_{-0.0031}$	0.131 $0.1308^{+0.0030}_{-0.0030}$	0.131 $0.1293^{+0.0028}_{-0.0028}$	0.129 $0.1251^{+0.0032}_{-0.0033}$
H_0	69.44 $69.3^{+1.26}_{-1.22}$	69.02 $68.9^{+1.13}_{-1.06}$	71.76 $71.70^{+0.80}_{-0.82}$	72.09 $71.48^{+0.7912}_{-0.8119}$	70.96 $69.68^{+1.10}_{-1.12}$
$\log(10^{10}A_s)$	3.047 $3.0560^{+0.0152}_{-0.0153}$	3.064 $3.0577^{+0.0141}_{-0.0139}$	3.065 $3.0688^{+0.0142}_{-0.0140}$	3.084 $3.0710^{+0.0141}_{-0.0140}$	3.078 $3.0620^{+0.0144}_{-0.0145}$
n_s	0.978 $0.9765^{+0.0084}_{-0.0081}$	0.976 $0.9756^{+0.0076}_{-0.0075}$	0.991 $0.9909^{+0.0057}_{-0.0056}$	0.995 $0.9905^{+0.0057}_{-0.0056}$	0.986 $0.9810^{+0.0069}_{-0.0070}$
$\tau_{\rm reio}$	0.055 $0.0564^{+0.0072}_{-0.0072}$	0.050 $0.0547^{+0.0068}_{-0.0068}$	0.054 $0.0575^{+0.0071}_{-0.0071}$	0.059 $0.0559^{+0.0071}_{-0.0071}$	0.053 $0.0548^{+0.0070}_{-0.0069}$
$f_{\rm NEDE}$	0.067 $0.0605^{+0.0419}_{-0.0431}$	0.053 $0.0449^{+0.0368}_{-0.0344}$	0.135 $0.1330^{+0.0257}_{-0.0257}$	0.139 $0.1191^{+0.0247}_{-0.0247}$	0.110 $0.0690^{+0.0343}_{-0.0354}$
$\log_{10}(m_\phi)$	2.543 $2.55^{+0.2238}_{-0.2044}$	2.458 $2.32^{+0.2999}_{-0.4294}$	2.583 $2.55^{+0.0981}_{-0.0981}$	2.468 $2.44^{+0.0959}_{-0.0895}$	2.458 2.4583
m_ϕ [Mpc^{-1}]	349.486 $440^{+159.7908}_{-216.3133}$	287.333 $303^{+112.5728}_{-225.6299}$	382.974 $367^{+81.1006}_{-81.8153}$	293.758 $286^{+60.8243}_{-59.8288}$	287 287
z_*	4881.454 5270^{+1350}_{-1460}	4397.410 4144^{+1260}_{-2060}	5007.738 4856^{+592}_{-596}	4306.963 4247^{+510}_{-495}	4301.678 4370^{+59}_{-57}
Total χ^2	3804.26	4040.56	3806.74	4049.05	4039.26
$\Delta\chi^2$	−3.19	−1.82	−23.32	−15.89	−3.13
H_0 Tension	2.3σ	2.7σ	–		2.2σ
$Q_{\rm dmap}$	–		1.57σ	2.9σ	–

Table II. Best-fit results of the MCMC analysis involving the ACT data and pertinent likelihood combinations for reference. Colors correspond to the contours of Fig. 2

Parameter Name	NEDE fixed EOS				
	Base	+SPT	+SH_0ES21	+SPT +SH_0ES21	+SPT fixed m_ϕ
$\Omega_b h^2$	0.023 $0.0224^{+0.0001}_{-0.0001}$	0.023 $0.0225^{+0.0002}_{-0.0002}$	0.023 $0.0230^{+0.0002}_{-0.0002}$	0.023 $0.0228^{+0.0002}_{-0.0002}$	0.023 $0.0226^{+0.0002}_{-0.0002}$
$\Omega_c h^2$	0.125 $0.1191^{+0.0009}_{-0.0009}$	0.125 $0.1233^{+0.0032}_{-0.0031}$	0.131 $0.1308^{+0.0030}_{-0.0030}$	0.129 $0.1293^{+0.0030}_{-0.0030}$	0.125 $0.1247^{+0.0033}_{-0.0033}$
H_0	69.44 $67.66^{+0.39}_{-0.39}$	69.32 $69.00^{+1.08}_{-1.04}$	71.76 $71.70^{+0.80}_{-0.82}$	71.77 $71.43^{+0.841}_{-0.843}$	69.46 $69.46^{+1.1}_{-1.11}$
$\log(10^{10} A_s)$	3.047 $3.0424^{+0.0136}_{-0.0135}$	3.055 $3.0492^{+0.0145}_{-0.0145}$	3.065 $3.0688^{+0.0142}_{-0.0140}$	3.071 $3.0617^{+0.0141}_{-0.0141}$	3.057 $3.0513^{+0.0145}_{-0.0144}$
n_s	0.978 $0.9671^{+0.0035}_{-0.0036}$	0.978 $0.9749^{+0.0072}_{-0.0071}$	0.991 $0.9909^{+0.0057}_{-0.0056}$	0.990 $0.9888^{+0.0058}_{-0.0058}$	0.978 $0.9783^{+0.0071}_{-0.0071}$
$\tau_{\rm reio}$	0.055 $0.0547^{+0.0069}_{-0.0069}$	0.055 $0.0544^{+0.0069}_{-0.0070}$	0.054 $0.0575^{+0.0071}_{-0.0071}$	0.061 $0.0555^{+0.0071}_{-0.0070}$	0.057 $0.0542^{+0.0069}_{-0.0068}$
$f_{\rm NEDE}$	0.067 —	0.066 $0.050^{+0.036}_{-0.036}$	0.135 $0.133^{+0.026}_{-0.026}$	0.126 $0.121^{+0.026}_{-0.026}$	0.066 $0.066^{+0.035}_{-0.036}$
$\log_{10}(m_\phi)$	2.543 —	2.496 $2.432^{+0.282}_{-0.221}$	2.583 $2.553^{+0.098}_{-0.098}$	2.443 $2.474^{+0.110}_{-0.108}$	2.496 2.496
m_ϕ [Mpc^{-1}]	349.486 —	313.191 $337.8^{+179.9}_{-175.2}$	382.974 $367.0^{+81.1}_{-81.8}$	277.137 $308^{+75.5}_{-75.8}$	313.191 313.191
z_*	4881.454 —	4593.696 4582^{+1519}_{-1384}	5007.738 4856^{+592}_{-596}	4190.443 4417^{+612}_{-610}	4593.468 4593^{+62}_{-61}
Total χ^2	3804.27	4923.27	3806.74	4926.58	4923.22
$\Delta\chi^2$	-3.19	-3.32	-23.32	-23.13	-3.37
H_0 Tension	2.3σ	2.7σ	–		2.4σ
$Q_{\rm dmap}$			1.57σ	1.82σ	

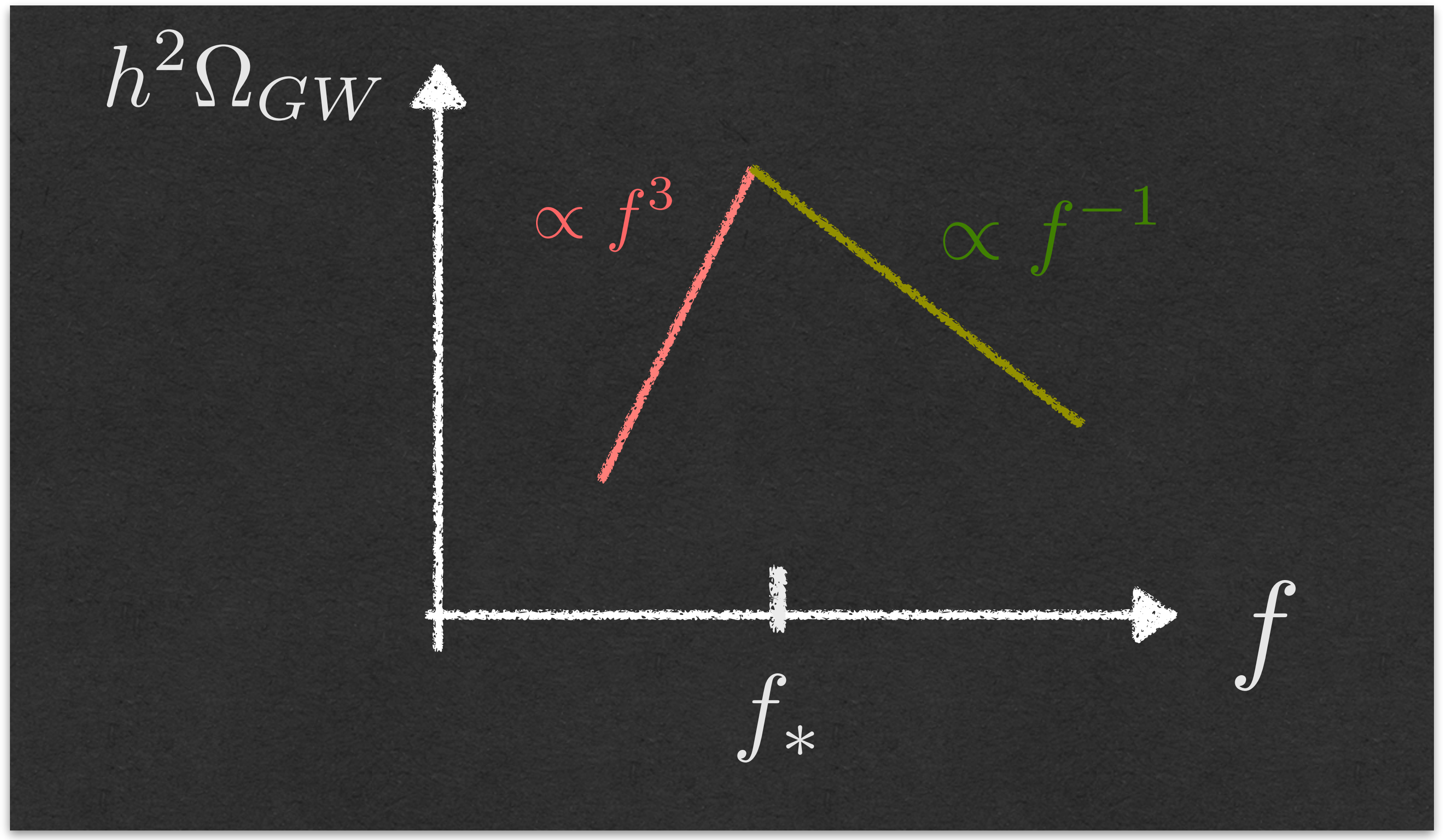
Table III. Table with the best-fit values followed by the posterior means and standard deviations of the ΛCDM and NEDE MCMC runs alternating datasets involving the baseline, SPT and SH_0ES.

Parameter Name	ΛCDM: Base + BICEP18	NEDE: Base + BICEP18	NEDE: Base + BICEP18 + SH_0ES
$\Omega_b h^2$	0.0224 $0.0224^{+0.0001}_{-0.0001}$	0.0226 $0.0226^{+0.0002}_{-0.0002}$	0.0229 $0.0230^{+0.0002}_{-0.0002}$
$\Omega_c h^2$	0.1192 $0.1193^{+0.0009}_{-0.0009}$	0.1237 $0.1232^{+0.0032}_{-0.0031}$	0.1297 $0.1300^{+0.0031}_{-0.0032}$
H_0	67.68 $67.69^{+0.4058}_{-0.4060}$	69.08 $68.92^{+1.0672}_{-1.0201}$	71.37 $71.57^{+0.8625}_{-0.8629}$
$\log(10^{10} A_s)$	3.046 $3.0487^{+0.0139}_{-0.0138}$	3.063 $3.0549^{+0.0149}_{-0.0147}$	3.062 $3.0688^{+0.0146}_{-0.0146}$
n_s	0.965 $0.9668^{+0.0037}_{-0.0036}$	0.975 $0.9743^{+0.0076}_{-0.0074}$	0.988 $0.9905^{+0.0061}_{-0.0061}$
$\tau_{\rm reio}$	0.0538 $0.0569^{+0.0070}_{-0.0070}$	0.0569 $0.0566^{+0.0071}_{-0.0071}$	0.0536 $0.0579^{+0.0073}_{-0.0072}$
$r_{0.05}$	0 $0.0167^{+0.0101}_{-0.0104}$	0 $0.0164^{+0.0100}_{-0.0102}$	0 $0.0154^{+0.0098}_{-0.0100}$
$f_{\rm NEDE}$	– –	0.054 $0.0483^{+0.0376}_{-0.0371}$	0.126 $0.1301^{+0.0278}_{-0.0281}$
$\log_{10}(m)$	– –	2.568 $2.433^{+0.3113}_{-0.2820}$	2.527 $2.519^{+0.1163}_{-0.1171}$
$3\omega_{\rm NEDE}$	– –	2.012 $2.15^{+0.4694}_{-0.3973}$	2.090 $2.12^{+0.1563}_{-0.1659}$
m_ϕ	– –	370.02 $349.02^{+205.9}_{-207.5}$	336.56 $342.78^{+88.6}_{-90.8}$
z_*	– –	5065 4637^{+1710}_{-1686}	4674 4667^{+679}_{-689}

Table IV. Best-fit values, means and 1σ confidence intervals for MCMC runs involving the BICEP18 dataset, together with their corresponding χ^2 individual and total values.

Gravitational waves

- First order phase transitions (PT) act as source of gravitational waves.



1/f regime:

$$h^2\Omega_{GW} \sim 10^{-12} H\bar{\beta}^{-1} \left(\frac{10^{-9}\mathrm{Hz}}{f}\right)$$

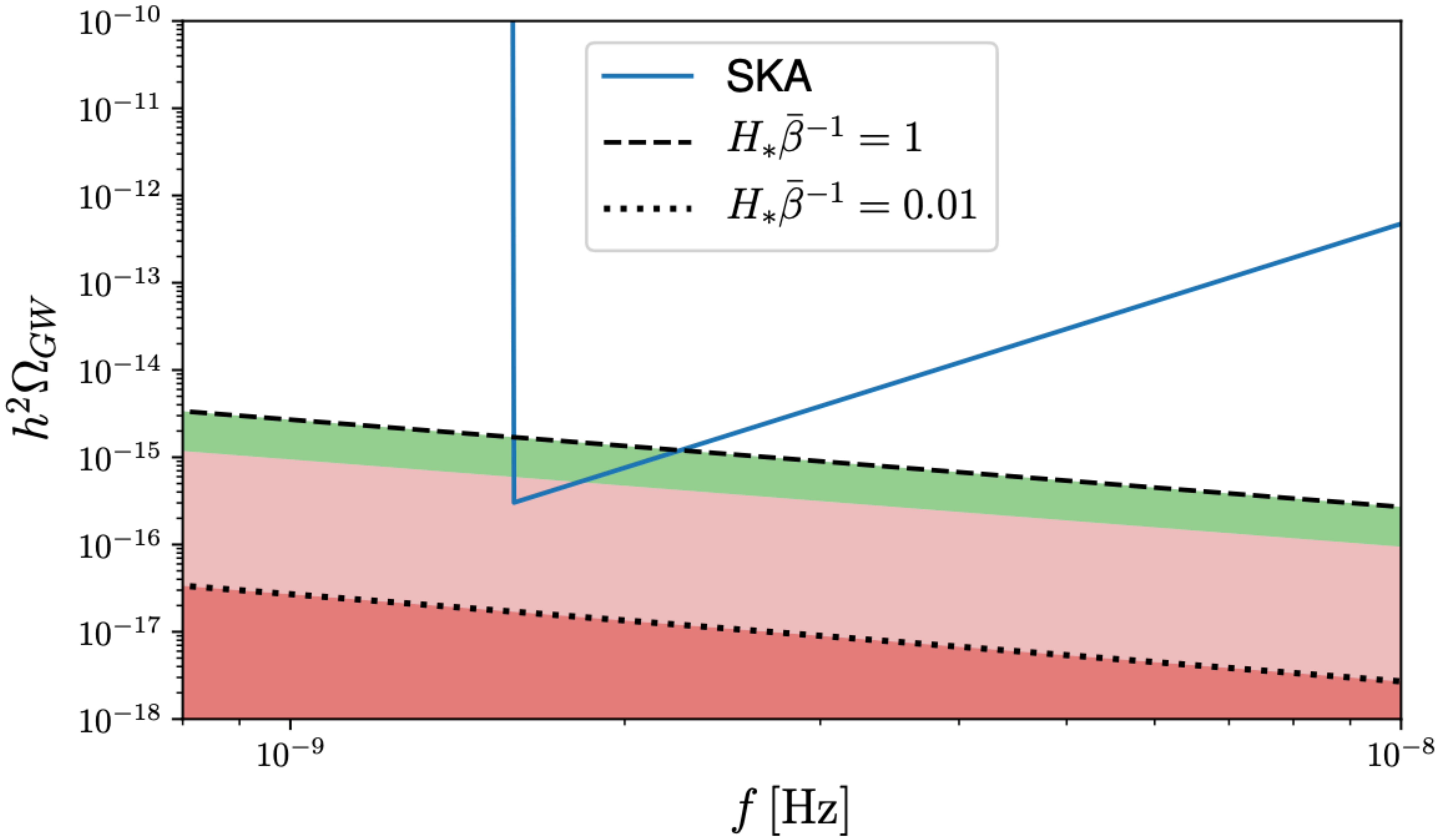
single dial

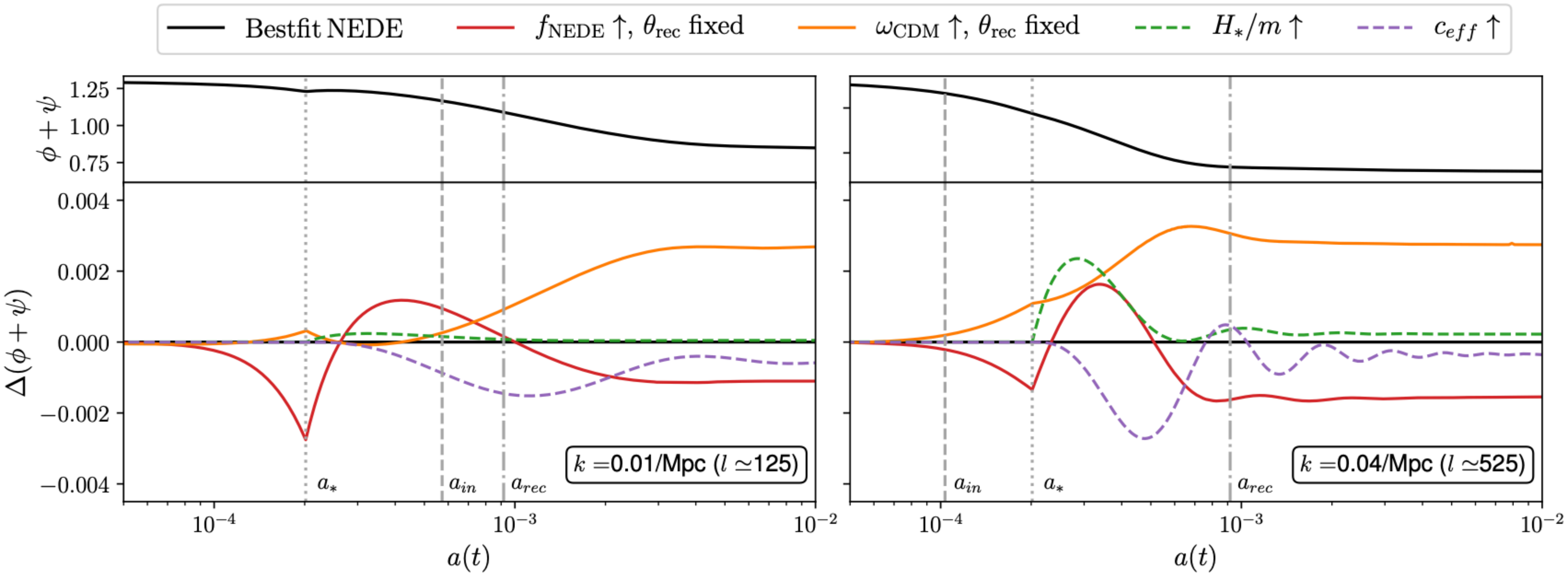
- Best prospects of detection with **pulsar timing arrays**.

Square Kilometer Array, sensitivity: $h^2\Omega_{GW} \sim 10^{-15}$

→ window for detection: $10^{-3} < H\bar{\beta}^{-1} \lesssim 1$

Gravitational waves




Bestfit NEDE
$f_{\rm NEDE}\uparrow$, $\theta_{\rm rec}$ fixed
$\omega_{\rm CDM}\uparrow$, $\theta_{\rm rec}$ fixed
$H_*/m\uparrow$
$c_{eff}\uparrow$
$\phi+\psi$
$\Delta(\phi+\psi)$
a_*
a_{in}
a_{rec}
k =0.01/Mpc ($l\simeq$125)
k =0.04/Mpc ($l\simeq$525)
$a(t)$

Hot NEDE

Hot New Early Dark Energy

- Known cosmological phase transitions (apart from end of inflation) are triggered by redshift of temperature.

➡ Let us consider a thermal trigger of the NEDE phase transition.

Hot NEDE: Thermal trigger

Examples of thermal PTs:
Electroweak phase transitions
QCD phase transition
Recombination

Cold NEDE: Scalar field trigger

Example of cold PT:
End of inflation

Hot New Early Dark Energy

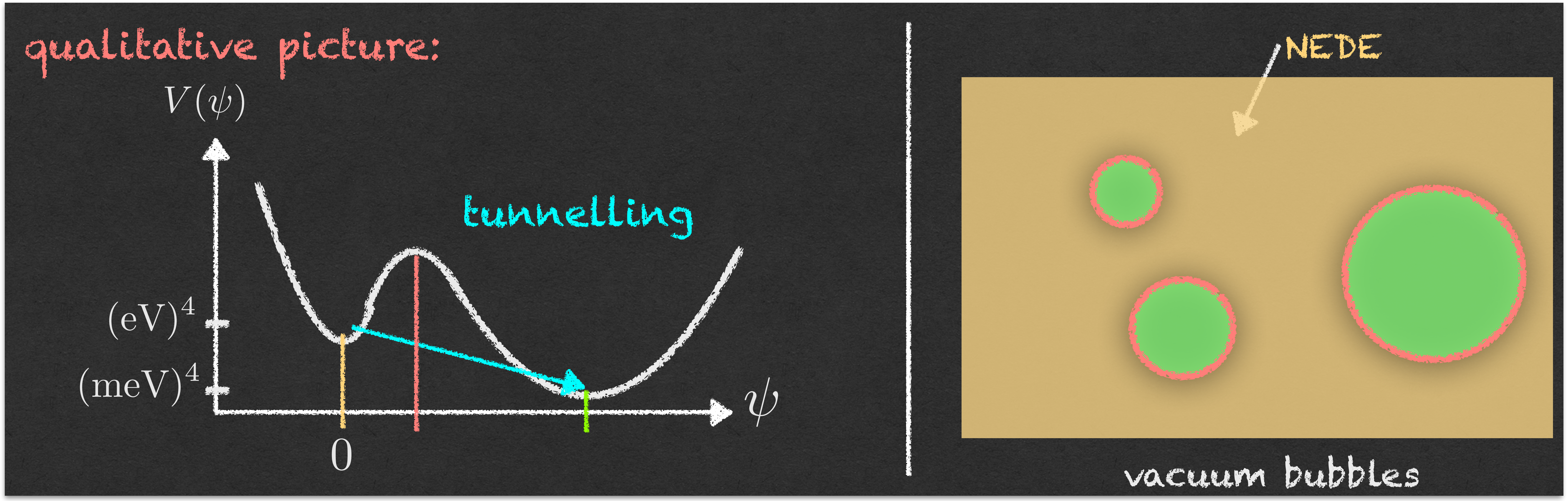
- The thermal trigger removes the need for an extra trigger mass scale.

➡Only mass scale is $\mathcal{O}$(eV) i.e. the neutrino mass scale

Is the Hubble tension a signature of how neutrinos got their mass?

Hot New Early Dark Energy

Again scalar field model w. first order phase transition



$$w = -1 \qquad \rightarrow \qquad 1/3 < w < 1$$

- Vacuum energy decays
- Free energy converted to anisotropic stress
- Anisotropic stress partially sources gravitational radiation
- Remaining anisotropic stress decays like a stiff fluid

Hot New Early Dark Energy

- But the trigger is now given by the thermal corrections to the potential
- The NEDE scalar field is charged under a dark sector gauge group

➡Potential will receive thermal corrections given by the dark sector temperature T_d

- The effective finite temperature potential is

$$V(\psi;T_d) = -DT_\circ^2\psi^2 + \frac{\lambda}{4}\psi^4 + 3T_d^4 K\left(\sqrt{8D}\psi/T_d\right) \mathrm{e}^{-\sqrt{8D}\psi/T_d} + V_0(T_d)$$

[Niedermann, MSS; 2020]

- In case of a dark *U(1)* gauge theory with gauge coupling g_{NEDE}

$$D \simeq g_{\rm NEDE}^2/8$$

Hot New Early Dark Energy

Phenomenological d.o.f.		Microscopic d.o.f.	
Fraction of NEDE:	$f_{\rm NEDE}$	Parameter of dim. less potential:	γ
Decay time:	z_*	Critical temp.:	T_0
Number of eff. rel. d.o.f.:	$\Delta N_{\rm eff}$	Dark sector temp.:	$\xi = T_d/T_{\rm vis}$
Dark Matter drag force:	$\Gamma^{\text{DM-DR}}$	# of dark gauge bosons and coupling:	$N_d \;\; \alpha_d$

New in Hot NEDE

Gives potential to also solve LSS tension

$$f_{\rm NEDE} = \frac{\pi}{16\gamma}\left(1-\frac{\delta^*_{\rm eff}}{\pi\gamma}\right)^2 \frac{T_d^{*4}}{\rho_{\rm tot}(t_*)} \,. \quad \text{with} \quad \delta_{\rm eff}(T_d) = \pi\gamma\left(1-\frac{T_\circ^2}{T_d^2}\right)$$

$$T_d^{*4} \simeq (0.7\text{eV})^4\gamma\left[\frac{f_{\rm NEDE}/(1-f_{\rm NEDE})}{0.1}\right]\left[\frac{1+z_*}{5000}\right]^4$$

$$\Delta N_{\rm eff} = N_d \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\xi^4 \simeq 0.06 N_d$$

arXiv:2112.00759, 2112.00770 w. Florian Niedermann

$$\Gamma^{\rm DM-DR} = N_d \Gamma_0^{\rm DM-DR}\frac{T_{\rm vis}^2}{T_{\rm vis,0}^2}\left[\frac{g_{{\rm rel},d}(T_{\rm vis})}{g_{{\rm rel},d}(T_{\rm vis,0})}\right]^{2/3} \quad \text{with} \quad \Gamma_0^{\rm DM-DR} = \frac{\pi}{9}\alpha_d^2 \log\alpha_d^{-1}\frac{T_d^2}{M_X}\Big|_{\rm today}$$

[Buen-Abad, G. Marques-Tavares, and M. Schmaltz; 2015] [J. Lesgourgues, G. Marques-Tavares, and M. Schmaltz; 2015]

How does Hot NEDE explain neutrino masses?

Hot NEDE and neutrino mass

- The NEDE scalar field, ψ, acquires a v.e.v. ~ $\mathcal{O}$(eV) in the P.T.

➡ May give mass to neutrinos

- Inverse seesaw can explain the observed neutrino mass and oscillation patterns and involves two new scales; a TeV and an eV scales

[A. Abada and M. Lucente; 2014]

$$\mathcal{L}_\nu = -\frac{1}{2} N^T C M N + \text{h.c.}$$

$$N \equiv (\nu_L, \nu_R^c, \nu_s)^T$$

active left-handed — right-handed — sterile

$$M = \begin{pmatrix} 0 & d & 0 \\ d & 0 & n \\ 0 & n & m_s \end{pmatrix}$$

$d = \mathcal{O}(100\,\text{GeV})$ **EW scale**

$n > \mathcal{O}(\text{TeV})$ **New UV scale**

$\text{eV} < m_s < \text{GeV}$ **New IR scale**

We assume dark symmetry group of form:

$G_D \times G_{NEDE}$

Hot NEDE and neutrino mass

- We assume the dark symmetry group of the form: $G_D \times G_{NEDE}$

1. G_D is broken at new UV scale $n \geq 1$ TeV by new dark Higgs field

$$n = g_\Phi v_\Phi/\sqrt{2} \text{ as } \Phi \to v_\Phi/\sqrt{2}.$$

2. Subsequently, we have the EW breaking leading to

$$d = g_H v_H/\sqrt{2} \qquad v_H = 246\text{GeV}$$

3. Finally G_{NEDE} is broken at the new IR scale ~ eV by NEDE P.T.

$$\Psi \to v_\Psi/\sqrt{2} \qquad m_s = g_s v_\Psi$$

➡Assume charge assignments to allow for the Yukawa couplings

$$\mathcal{L}_Y = -g_\Phi \Phi \overline{\nu_R} \nu_s - \frac{g_s}{\sqrt{2}} \Psi \overline{\nu_s^c} \nu_s + g_H \overline{\nu_R} L^T \epsilon H + \text{h.c.}$$

- We can also relate sterile mass to effective NEDE parameters

$$m_s \simeq (1.0\,\text{eV}) \times \frac{1}{\gamma^{1/4}} \frac{g_s}{g_{\text{NEDE}}} \left[1 - \frac{\delta^*_{\text{eff}}}{\pi\gamma}\right]^{1/2} \left[\frac{f_{\text{NEDE}}/(1-f_{\text{NEDE}})}{0.1}\right]^{1/4} \left[\frac{1+z_*}{5000}\right]$$

Hot NEDE and neutrino mass

Minimal example:

- As a concrete example, we take the Dark Electroweak (DEW) group broken to Dark Electromagnetism (DEM)

$$G_D = SU(2)_D \times U(1)_{Y_D} \to U(1)_{DEM}$$

- The NEDE P.T. is the breaking of lepton number

$$G_{NEDE} = U(1)_L$$

➡ We can write down the Lagrangian

$$\mathcal{L}_Y = -g_\Phi \Phi \overline{\nu_R} \nu_s - \frac{g_s}{\sqrt{2}} \Psi \overline{\nu_s^c} \nu_s + g_H \overline{\nu_R} L^T \epsilon H + \text{h.c.}$$

$$\Phi = (\Phi_+, \Phi_0)^T \qquad \Psi = \begin{pmatrix} \frac{1}{\sqrt{2}}(\Psi_0 + \Psi_{++}) \\ -\frac{i}{\sqrt{2}}(\Psi_0 - \Psi_{++}) \\ \Psi_+ \end{pmatrix} \qquad S = (\nu_s, S_-)^T$$

Secret interaction to make eV sterile compatible with cosmology

[Hannestad, Hansen, Tram; '13]

Majoron, η, is the massless Goldstone of the broken U(1)$_L$

Small explicit breaking gives mass – see next…

Hot NEDE and neutrino mass

	S	ν_R	Φ	Ψ	H	χ	L
$SU(2)_D$	**2**	**1**	**2**	**3**	**1**	**2**	**1**
$U(1)_{Y_D}$	-1	0	1	2	0	$Y_{D,\chi}$	0
$U(1)_L$	1	1	0	-2	0	1	1

Small explicit lepton no. violation giving mass to majoron (Goldstone of broken $U(1)_L$

$$\Delta = \Psi \cdot \tau$$

$$V(\Psi,\Phi) = a\Phi^\dagger\Phi + c\left(\Phi^\dagger\Phi\right)^2 - \frac{\mu^2}{2}\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda}{4}\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + \frac{e-h}{2}\Phi^\dagger\Phi\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + h\Phi^\dagger\Delta^\dagger\Delta\Phi + \frac{f}{4}\mathrm{Tr}\left(\Delta^\dagger\Delta^\dagger\right)\mathrm{Tr}\left(\Delta\Delta\right) - \bar{\epsilon}\left(\Phi^\dagger\Delta\epsilon\Phi^* + \mathrm{h.c.}\right)$$

Vacuum condition:

$$a + cv_\Phi^2 + \frac{1}{2}(e-h)v_\Psi^2 = 0$$

$$-\mu^2 + \lambda v_\Psi^2 + \frac{1}{2}(e-h)v_\Phi^2 = 0$$

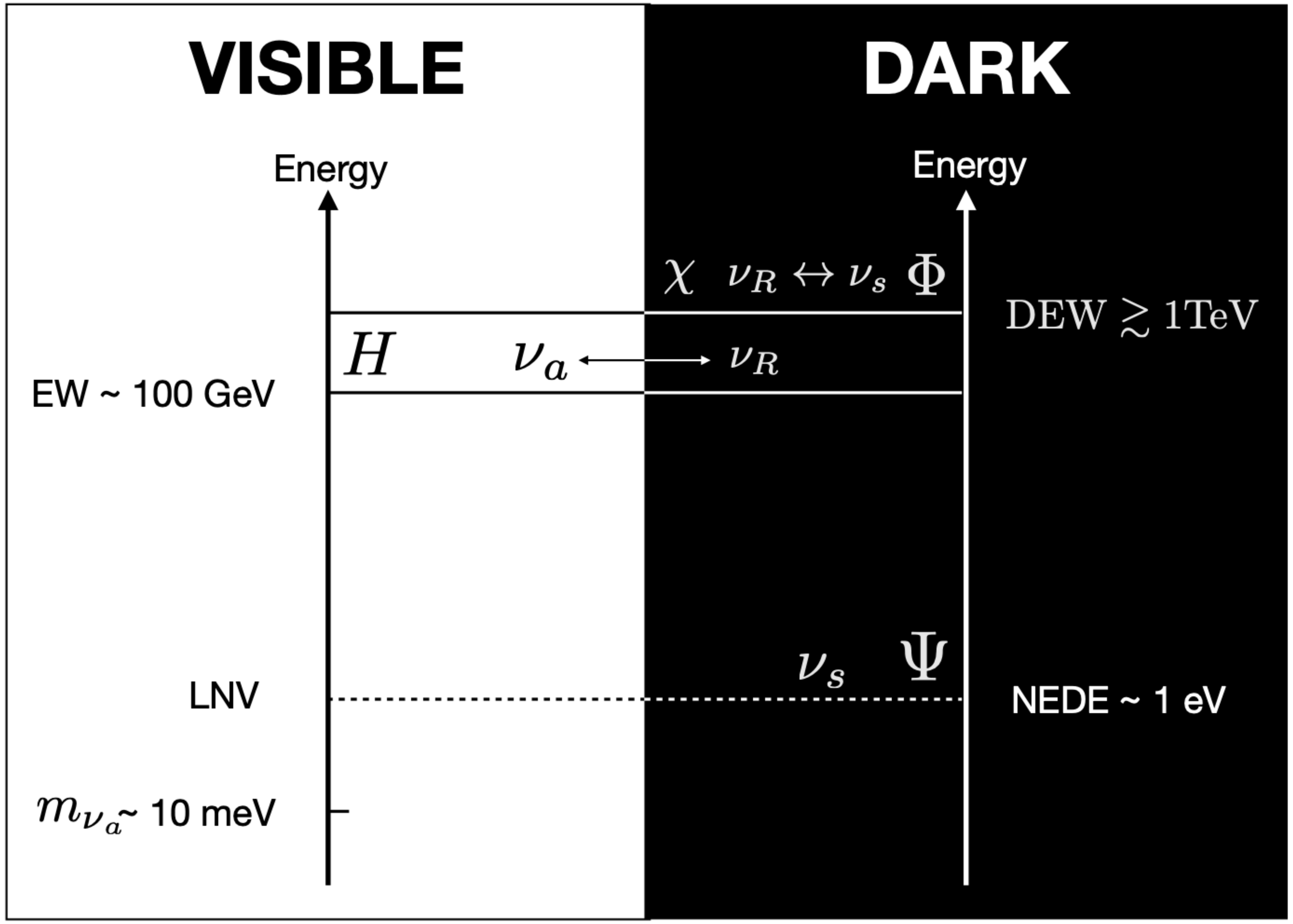
$v_\Psi \ll v_\Phi \quad \Rightarrow \quad e, h \lesssim \lambda v_\Psi^2/v_\Phi^2 \ll 1$

Technically natural if $g_d^2 \lesssim \mu/v_\Phi$ and $g_d^4 \lesssim \lambda$

Thermal correction driven by *f*

$\Rightarrow$ Identify g_{NEDE} with *f*

Hot NEDE and neutrino mass



Hot NEDE and neutrino mass

- DEW contains 17 boson d.o.f.
- If they are all relativistic and in thermal equilibrium at T_d, this implies

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} 17\xi^4$$

- Known constraints gives

$$\Delta N_{\rm eff} < 0.1 \quad \Rightarrow \quad \xi \lesssim 0.2$$

and

$$f_{\rm NEDE} = 10\% \quad \Rightarrow \quad \gamma \lesssim 5\times 10^{-3}$$

Strong supercooled regime

➡ <u>We expect the phenomenology to close to Cold NEDE</u>

- The heaviest active neutrino mass is related to sterile mass by

$$m_3 = \mathcal{O}(m_s)\kappa^2 \qquad \kappa = \mathcal{O}(d)/\mathcal{O}(n) \lesssim 10^{-2}$$

➡ a sterile neutrino with super-eV mass is compatible with an eV temperature phase transition

Conclusions

- Hubble tension could be explained by a fast triggered phase transition in the dark sector.
- Hubble tension could be a signature of how neutrinos got their mass.
- Cold and Hot NEDE looks theoretically and phenomenologically promising with the potential of connecting many issues!
- Verification of cold NEDE trigger mech.
- Prediction of gravitational waves.
- Many things to do — simulate Hot NEDE, more detailed modeling of the percolation phase, generalizations, etc…