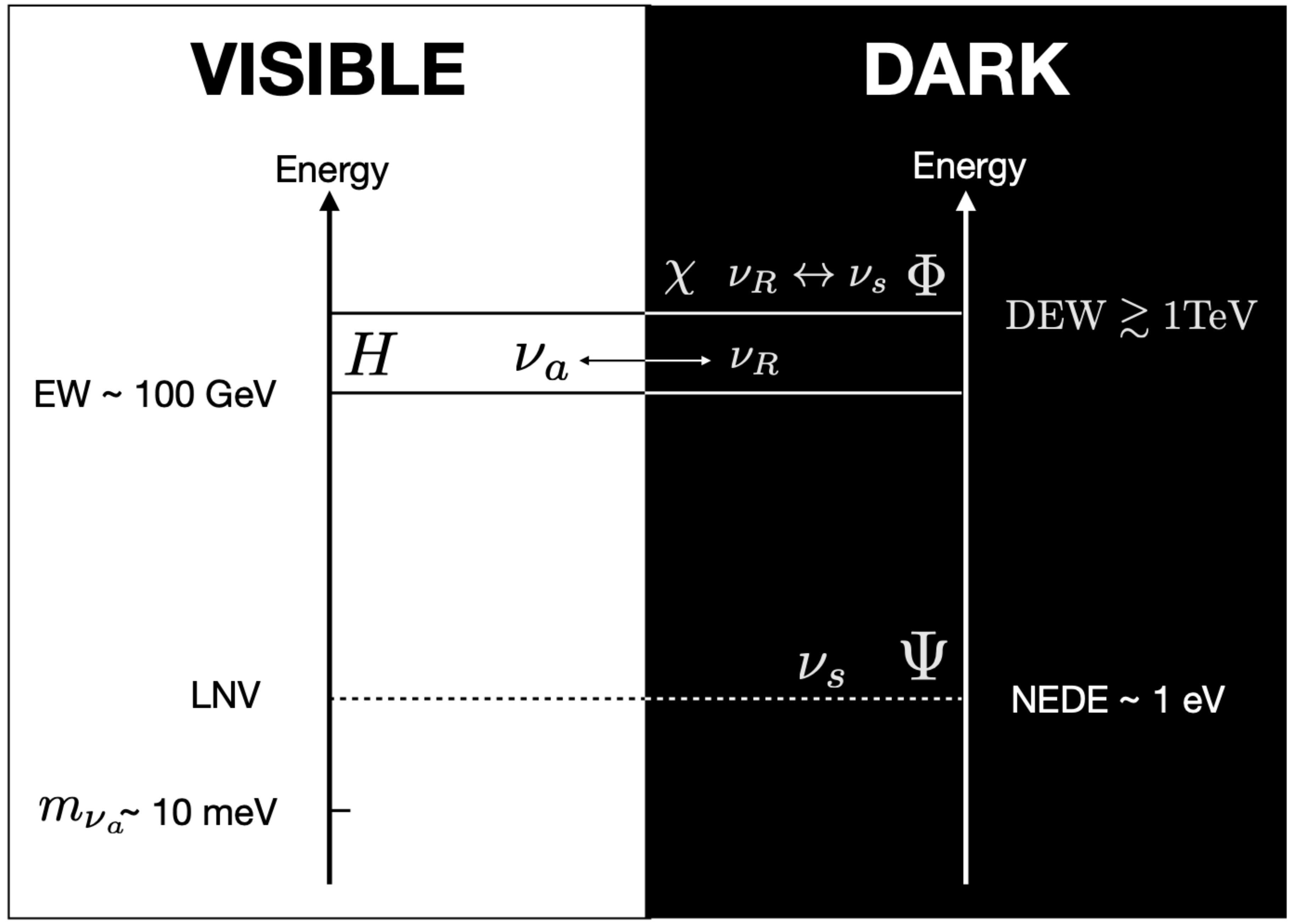
The Hubble tension and new physics at the eV scale: The path to New Early Dark Energy

Martin S. Sloth
(CP3-Origins, SDU, Denmark)



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

arXiv:2209.02708
w. Juan S. Cruz and Florian Niedermann

Why does the Hubble tension imply new physics at the eV scale?

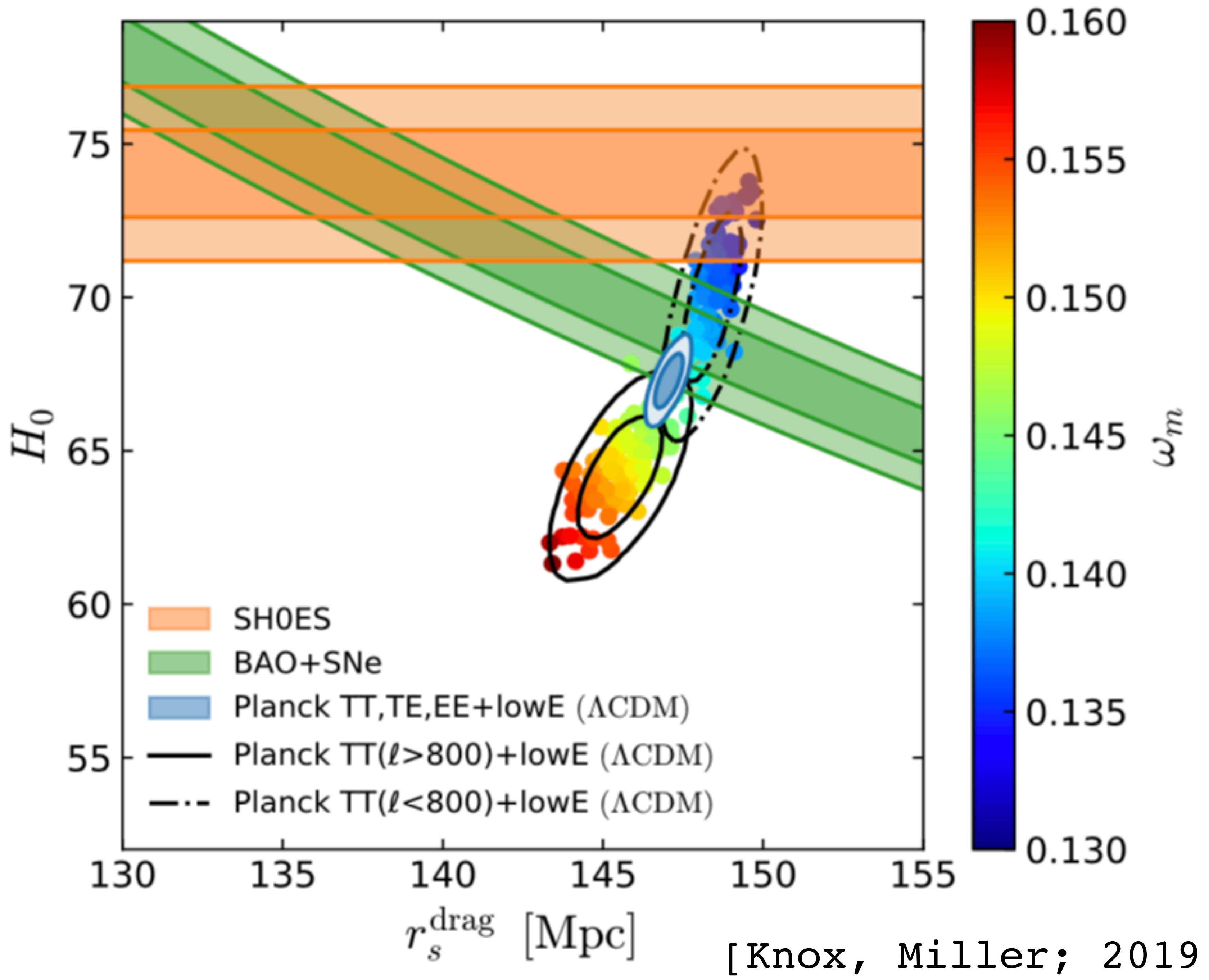
The Hubble tension

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

- Planck and SH_0ES incompatible

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

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



[Knox, Miller; 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

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

- Does not redshift away fast enough!

➡ Reduces the tension only slightly (~ 4 σ)

[Planck 2018+BAO +Pantheon+BBN]

[Niedermann, MSS; 2020]

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

Early Dark Energy

Scalar field model w. slow-roll down potential

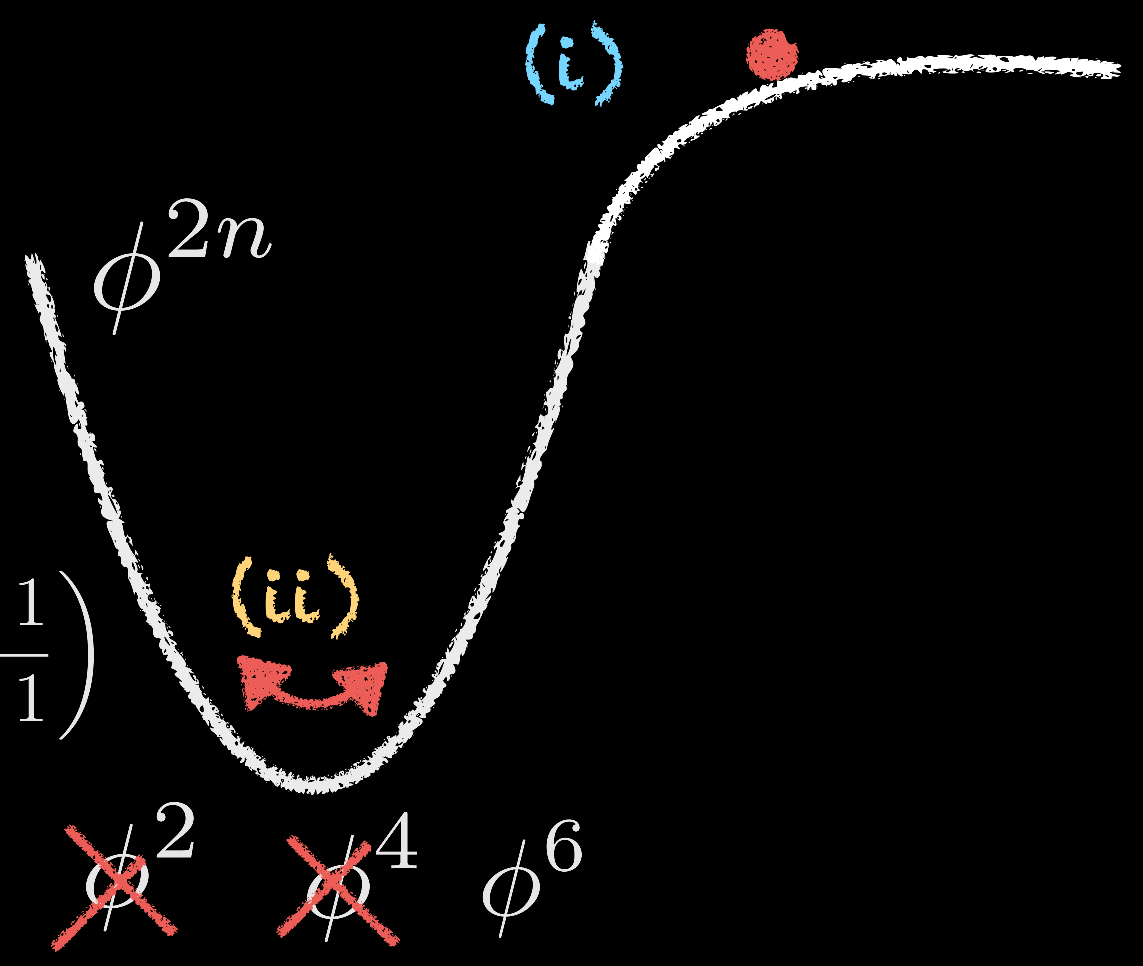
[e.g. Karwal et al., 2016]

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

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

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]

How does a NEDE Phase Transition resolve this?

New Early Dark Energy

NEDE is a fast triggered phase transition in the dark sector

<u>Simple effective cosmological model:</u>

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

arXiv: 1910.10739, 2006.06686 w. Florian Niedermann

New Early Dark Energy

<u>Some microphysical examples are:</u>

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

- **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")

Focus this talk: 1st order Phase Transitions (Cold NEDE and Hot NEDE)

What is the effective cosmological model?

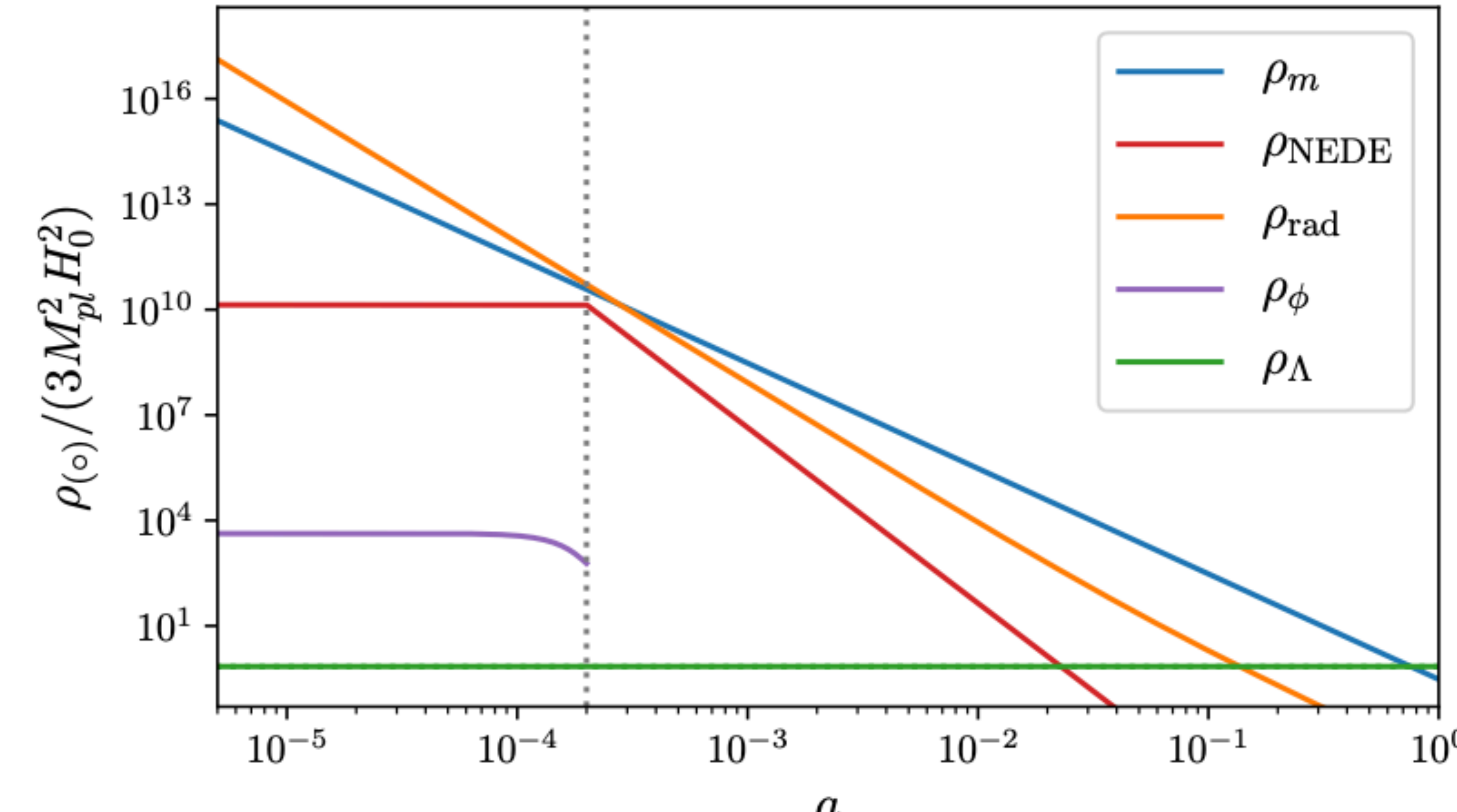
Effective cosmological model

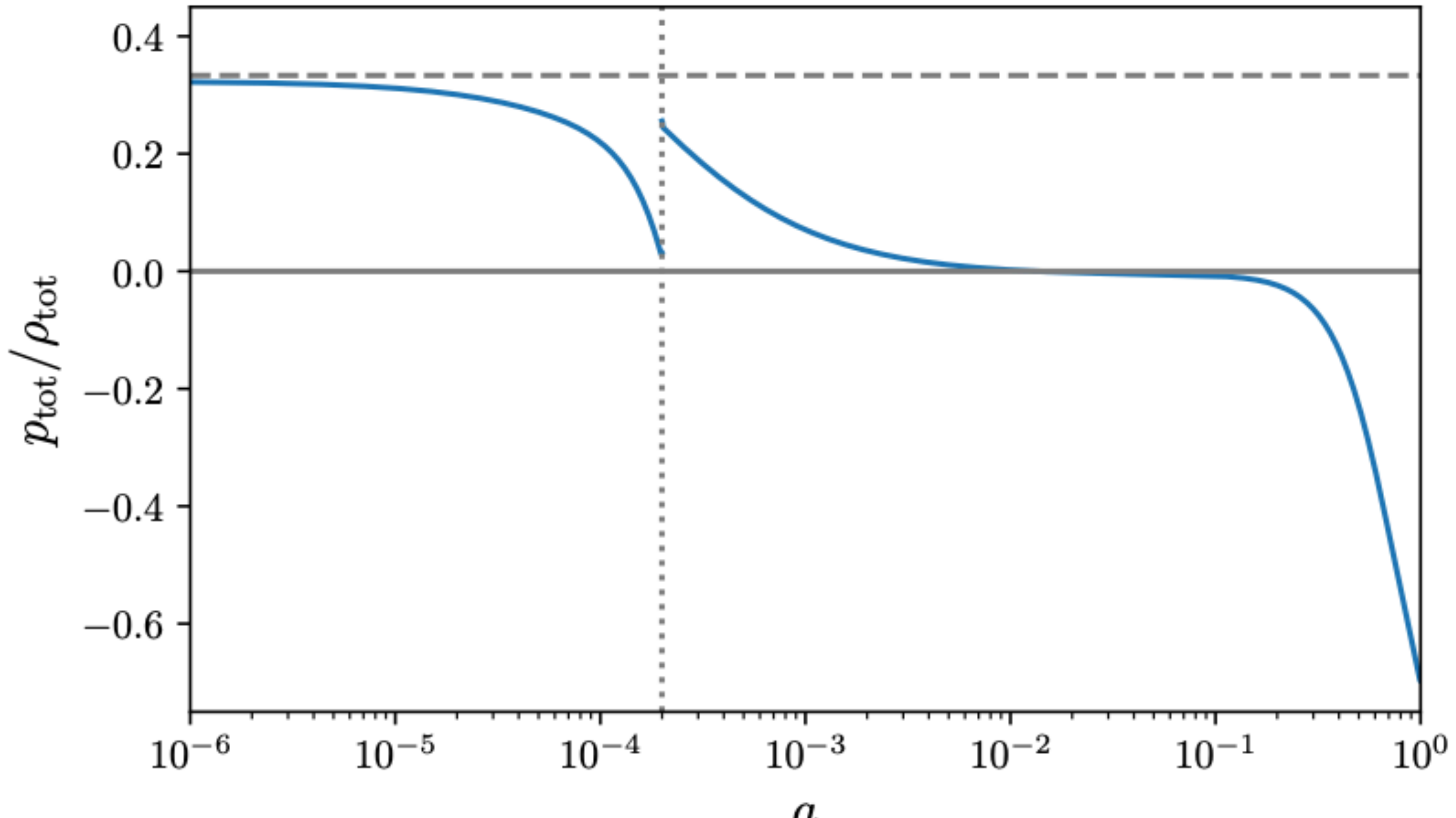
- **Background** picture: Assume that all liberated vacuum energy is converted to a fluid with fixed e.o.s.

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





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 dynamics → relevant for CMB

Cosmological perturbations

- We use Israel junction conditions to match fluctuations across transition surface.

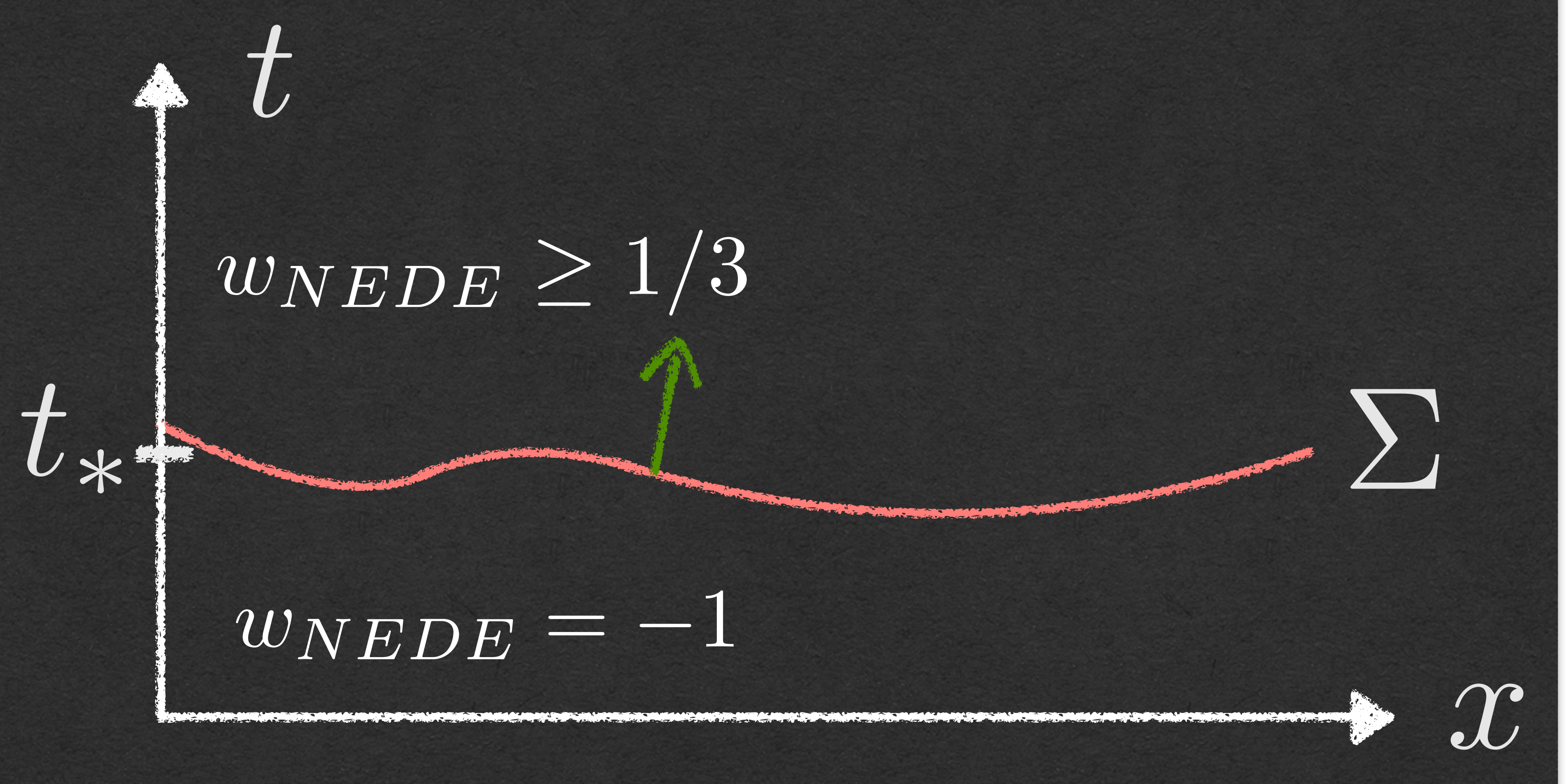
[Deruelle, Mukhanov, 1995]

space like transition surface Σ

synchronous gauge:

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

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



- This allows us to implement our model in a Boltzmann code "Trigger-CLASS".

https://github.com/flo1984/TriggerCLASS

arXiv:2006.06686 w. Florian Niedermann

Cosmological perturbations

➡The initial condition for perturbations after the phase-transition depends on the choice of the trigger

➡ The perturbations depend on the microphysical realization of NEDE

- CMB anisotropies and LSS depends on initial perturbations

➡ We can discriminate both between different EDE and between different NEDE microphysical models using CMB and LSS!

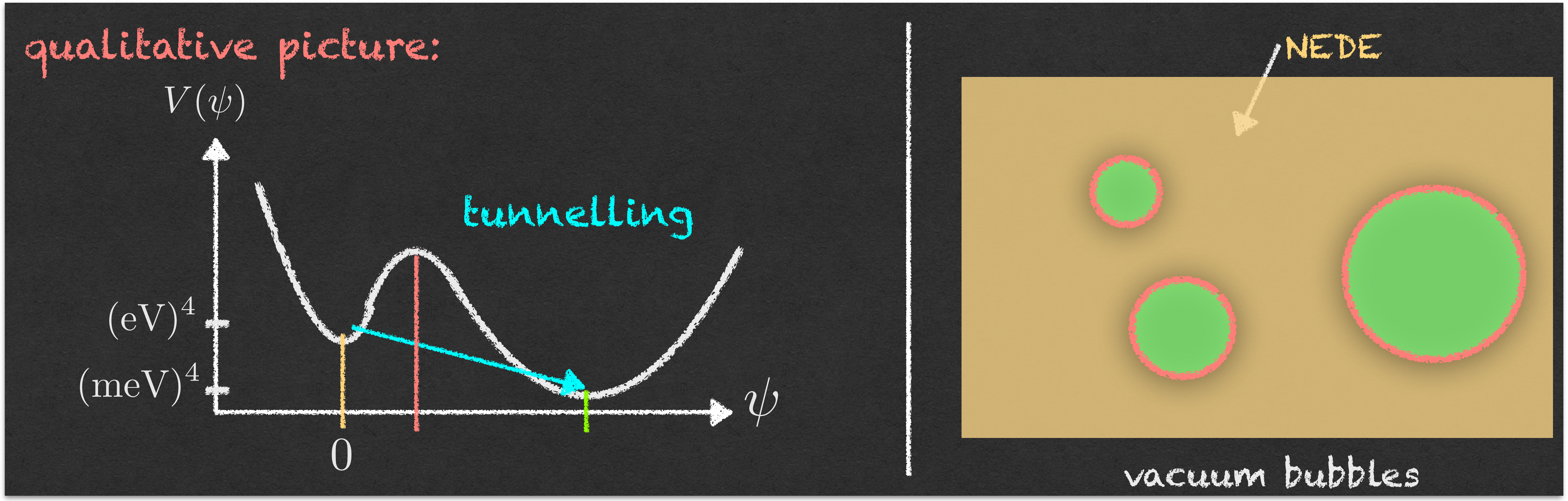
$$\text{EDE} \neq \text{Cold NEDE} \neq \text{Hot NEDE}$$

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

➡ Introduce a trigger field for the decay

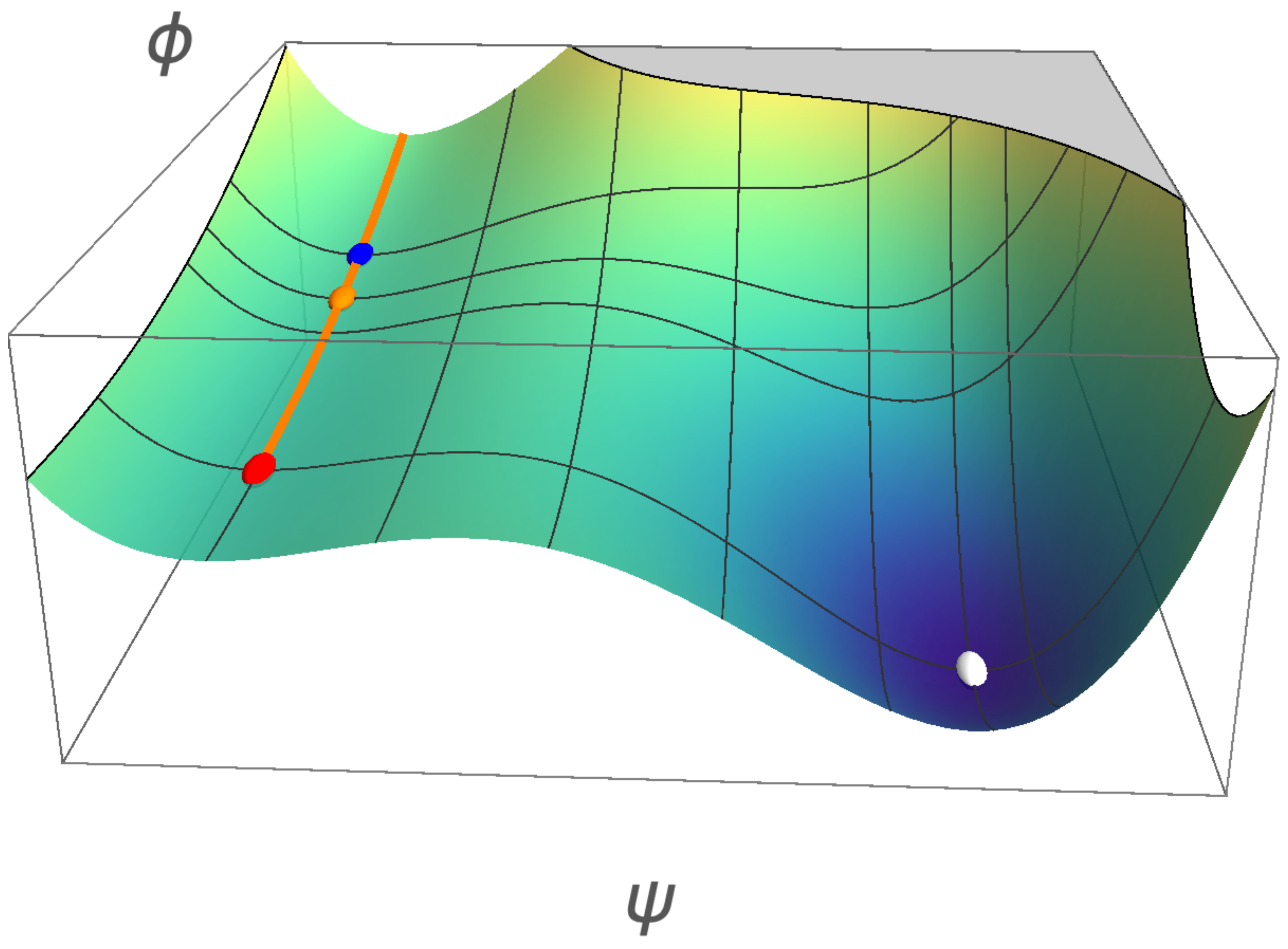
field theory model: $\alpha, \beta, \lambda = \mathcal{O}(1)$

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

New Early Dark Energy — Clock — 'CC tuning'

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

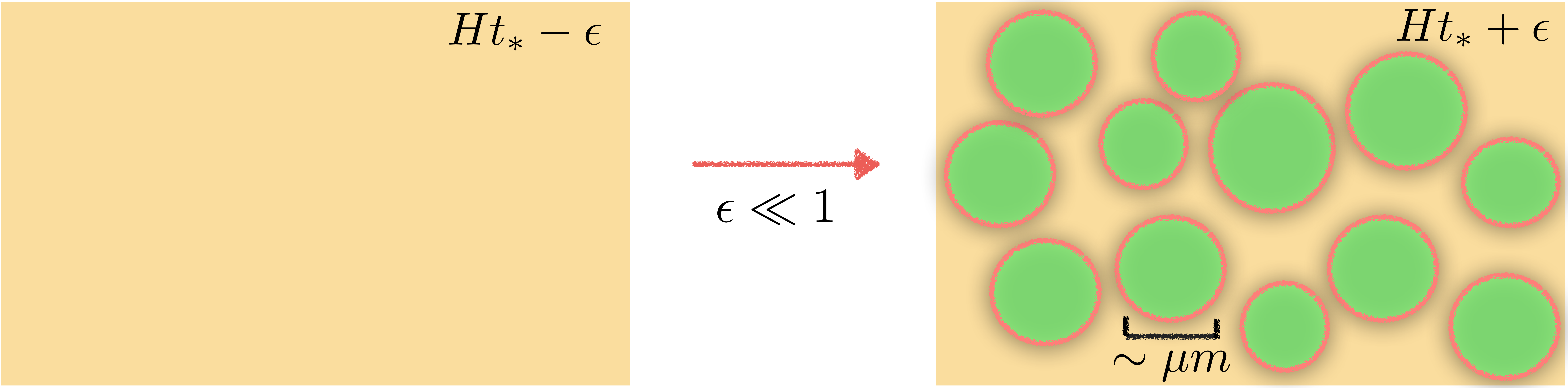
(iii) blue dot: inflection point

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

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

Bubble Coalescence

- Upshot: One burst of nucleation (when phi crosses zero) is enough to fill all of space with bubbles of true vacuum.



Bubble Coalescence

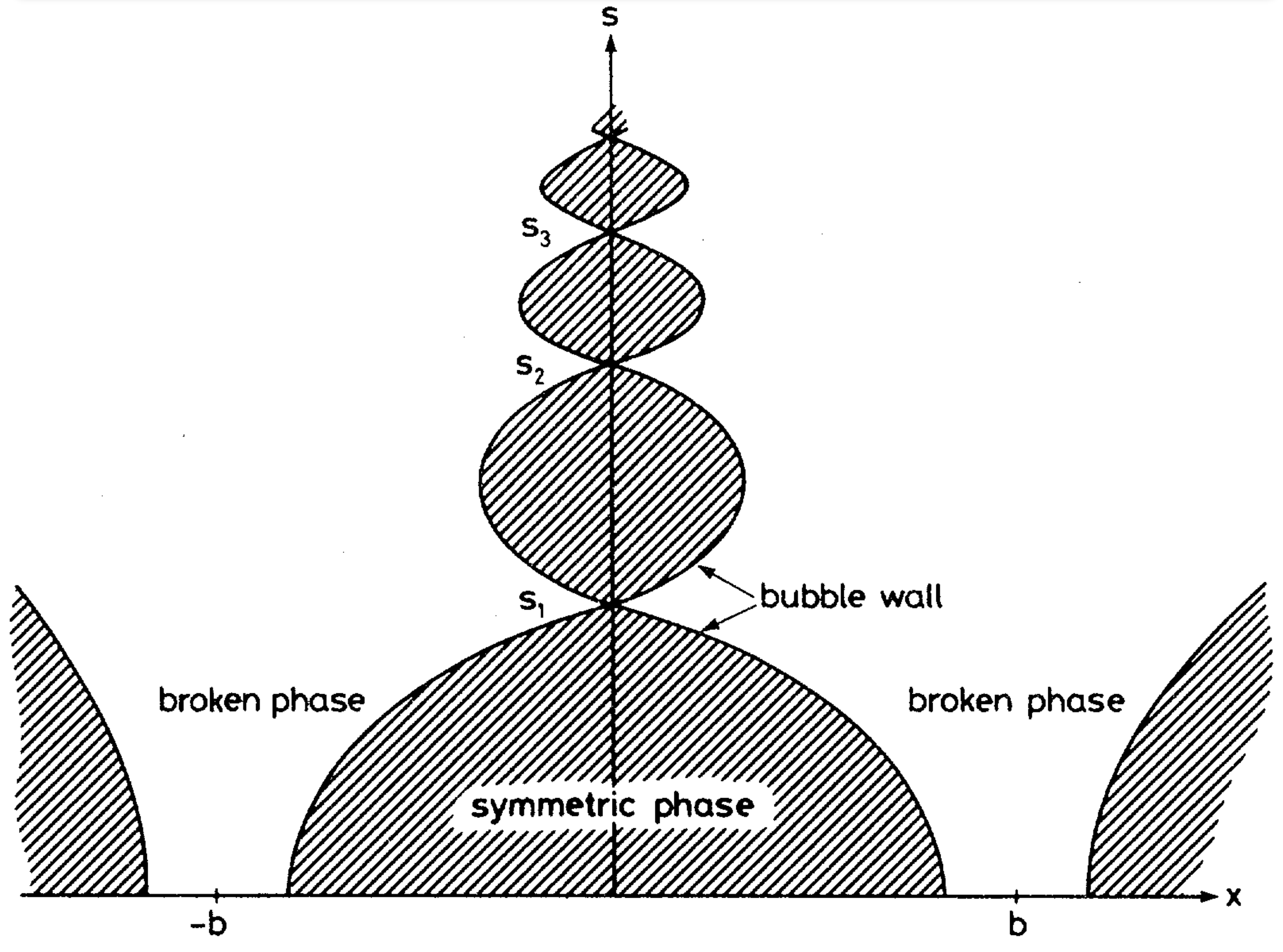
- Bubbles collide long before they reach cosmological size.

$$\ell_{bubble} < 10h^{-1}\text{Mpc}/(z_* + 1)$$

- Bubble collision and dissipation is complicated.

  Generally free energy converted to anisotropic stress sourcing gravitational waves.

  → Assume mixture of radiation and small scale anisotropic stress after transition



[Hawking, Moss, Stewart, 1982]

- **Important result**: From a cosmological perspective the phase transition can be treated as an **instantaneous** process.

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.

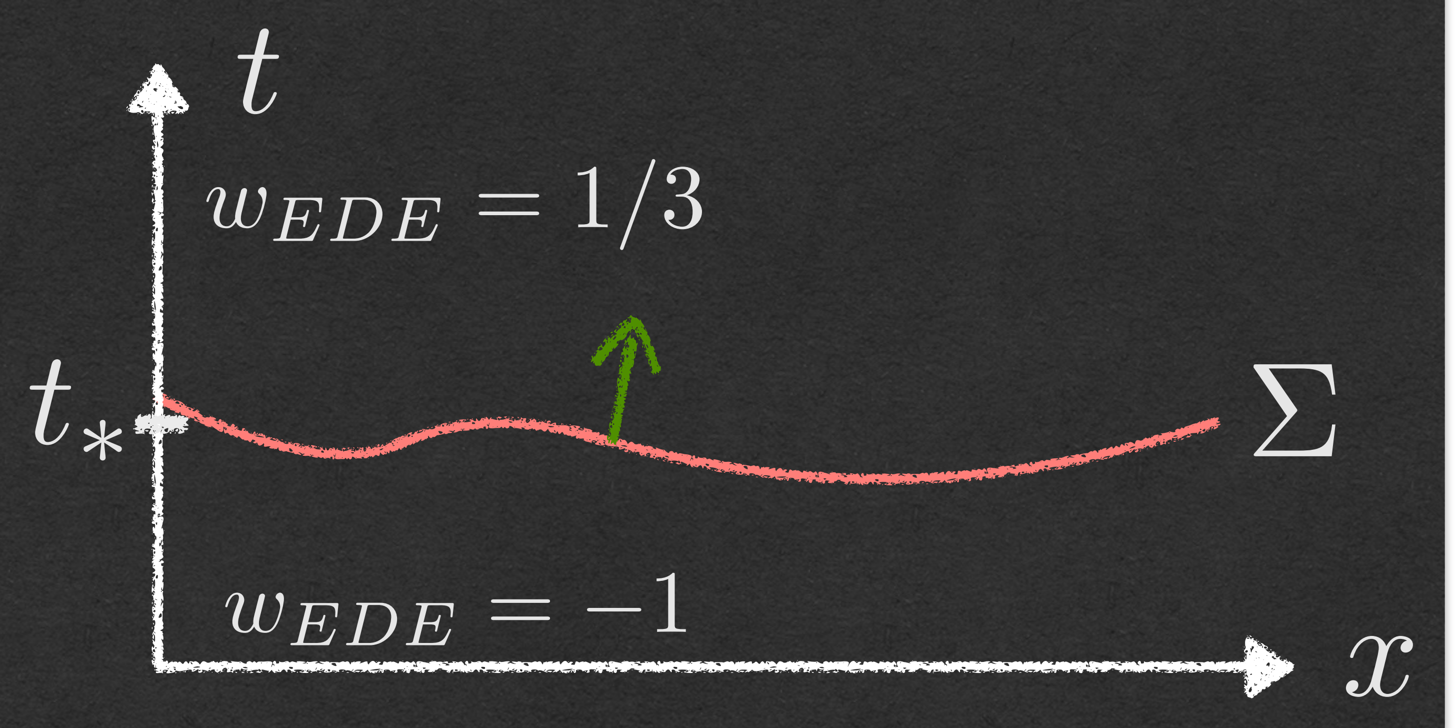
[Deruelle, Mukhanov, 1995]

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: $h(t,k)$ & $\eta(t,k)$

Does it work?

The answer is so far, yes; for details, see latest updated data analysis in arXiv:2209.02708

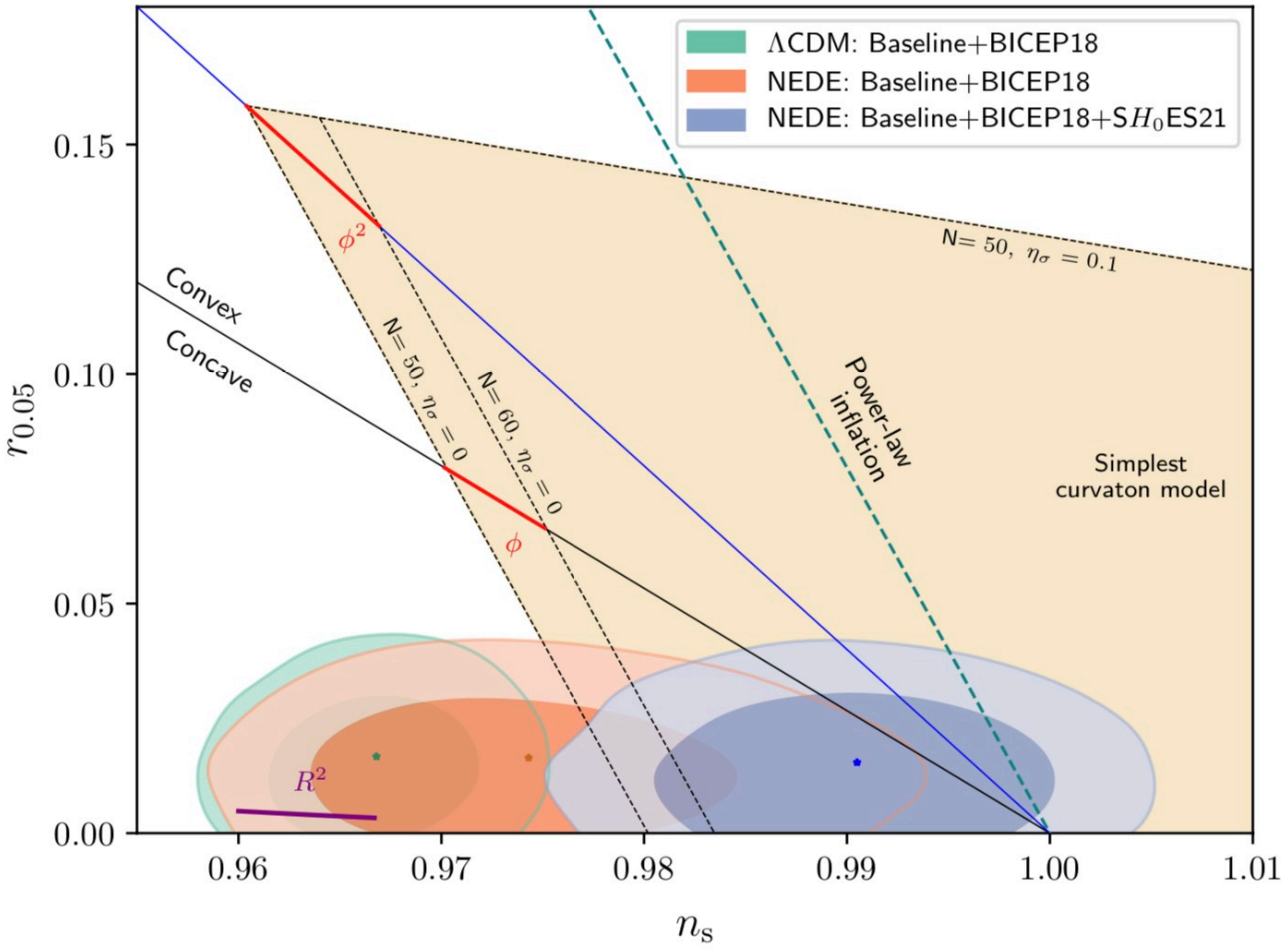
A grounded perspective on New Early Dark Energy using ACT, SPT, and BICEP/Keck

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.

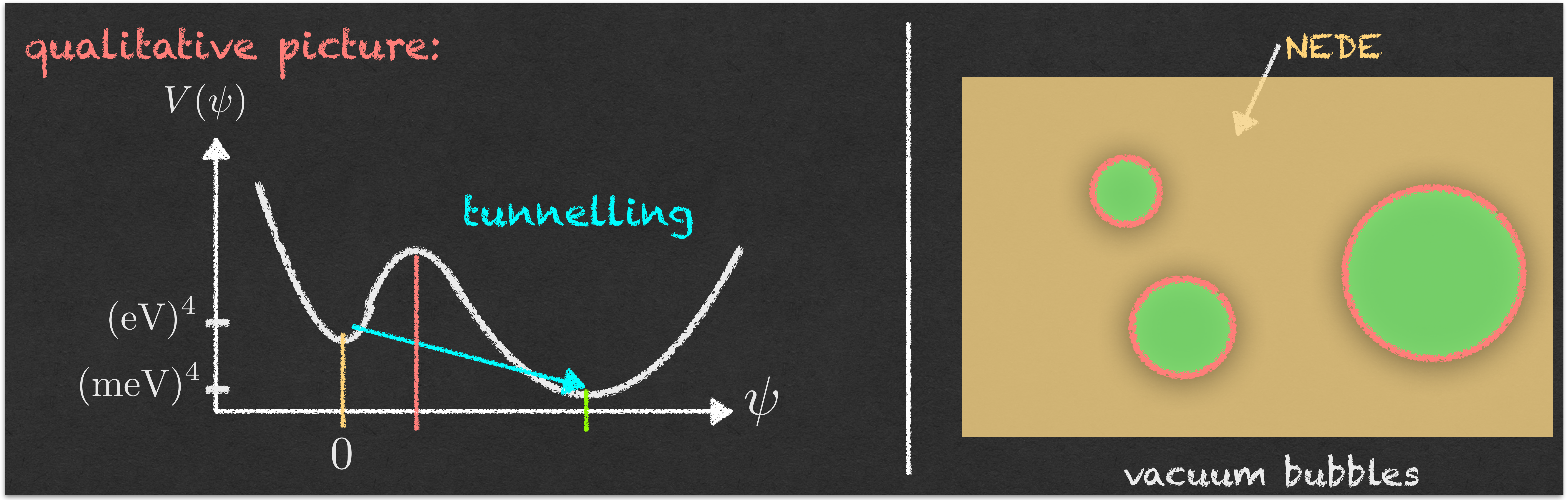


ΛCDM: Baseline+BICEP18
NEDE: Baseline+BICEP18
NEDE: Baseline+BICEP18+SH_0ES21
N= 50, $\eta_\sigma = 0.1$
ϕ^2
Convex
Concave
N= 50, $\eta_\sigma = 0$
N= 60, $\eta_\sigma = 0$
Power-law inflation
Simplest curvaton model
ϕ
R^2
$r_{0.05}$
$n_{\rm s}$
0.00
0.05
0.10
0.15
0.96
0.97
0.98
0.99
1.00
1.01

Hot NEDE

Hot New Early Dark Energy

Again we use a scalar field model w. first order phase transition



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

Hot New Early Dark Energy

- But the trigger is now given by the temperature corrections to the potential

- 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

Phenomenological d.o.f.

Fraction of NEDE: $f_{\rm NEDE}$

Decay time: z_*

Number of eff. rel. d.o.f.: $\Delta N_{\rm eff}$

Dark Matter drag force: $\Gamma^{\rm DM\text{-}DR}$

New in Hot NEDE

Gives potential to also solve LSS tension

Microscopic d.o.f.

Parameter of dim. less potential: γ

Critical temp.: T_0

Dark sector temp.: $\xi = T_d/T_{\rm vis}$

# of dark gauge bosons and coupling: $N_d \;\; \alpha_d$

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

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

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

arXiv:2112.00759, 2112.00770 w. Florian Niedermann

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

[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 x 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 a new UV scale $n \geq 1$ TeV by new dark Higgs field

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

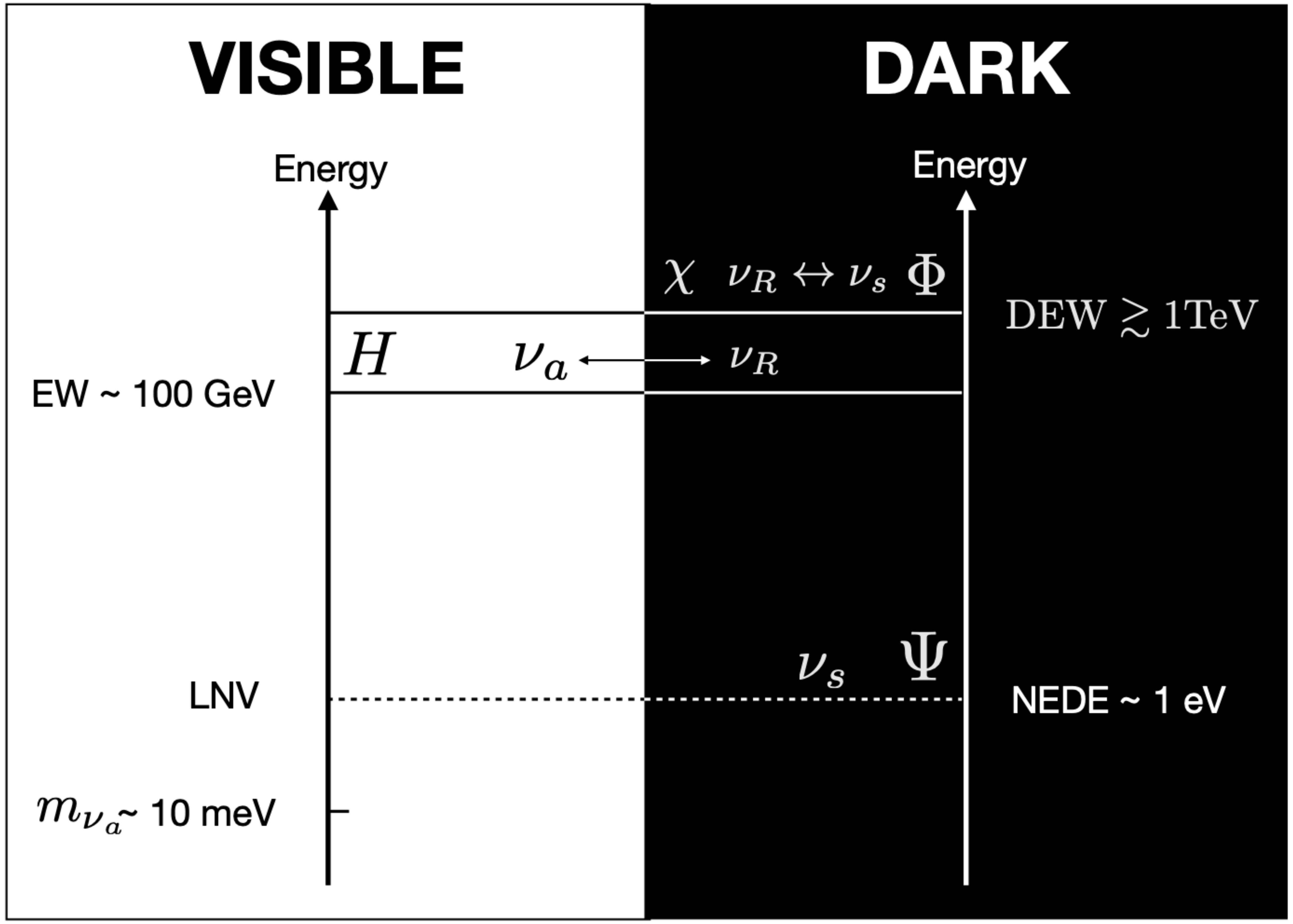
2. Subsequently, we have the EW breaking leading to

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

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

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

Hot NEDE and neutrino mass

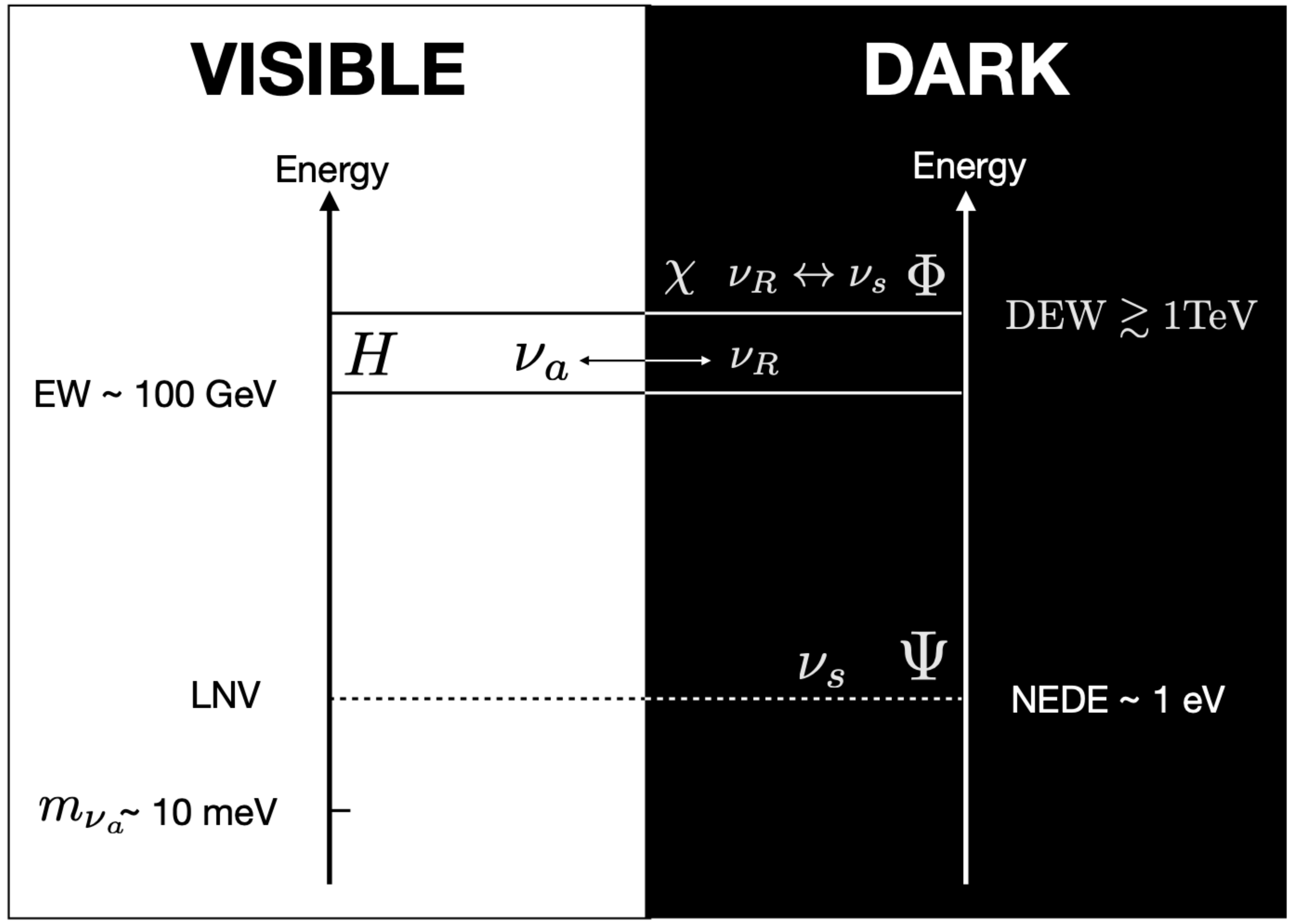


Conclusions

- NEDE offers a compelling solution for the Hubble tension
- NEDE offers a framework for a new concordance model of cosmology integrating dark and visible sectors

The Hubble tension and new physics at the eV scale:
The path to New Early Dark Energy

Martin S. Sloth
(CP3-Origins, SDU, Denmark)



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

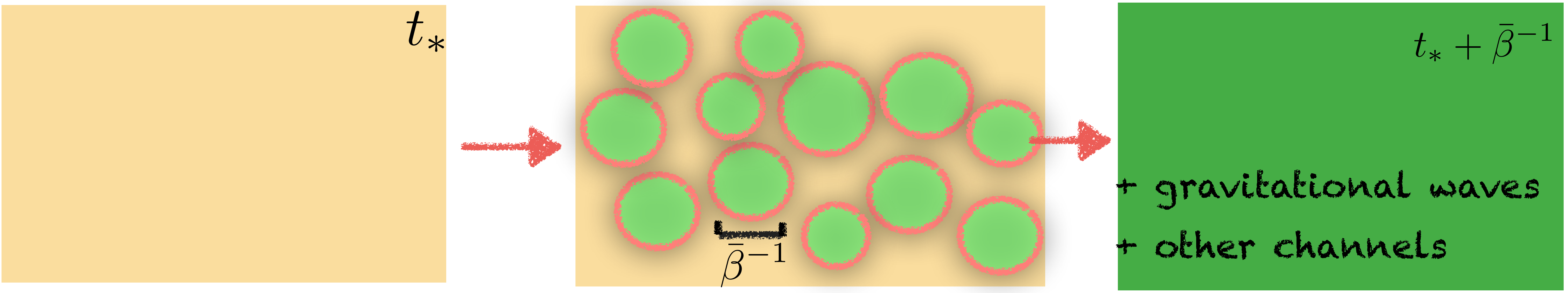
arXiv:2209.02708
w. Juan S. Cruz and Florian Niedermann

Backup slides

Effective cosmological model

- We demand phase transition to be short on cosmological time scales.

inv. duration: $\bar{\beta} = \frac{dS_E}{dt} \simeq \frac{\dot{\Gamma}}{\Gamma}$ short transition: $H\bar{\beta}^{-1} < 1$

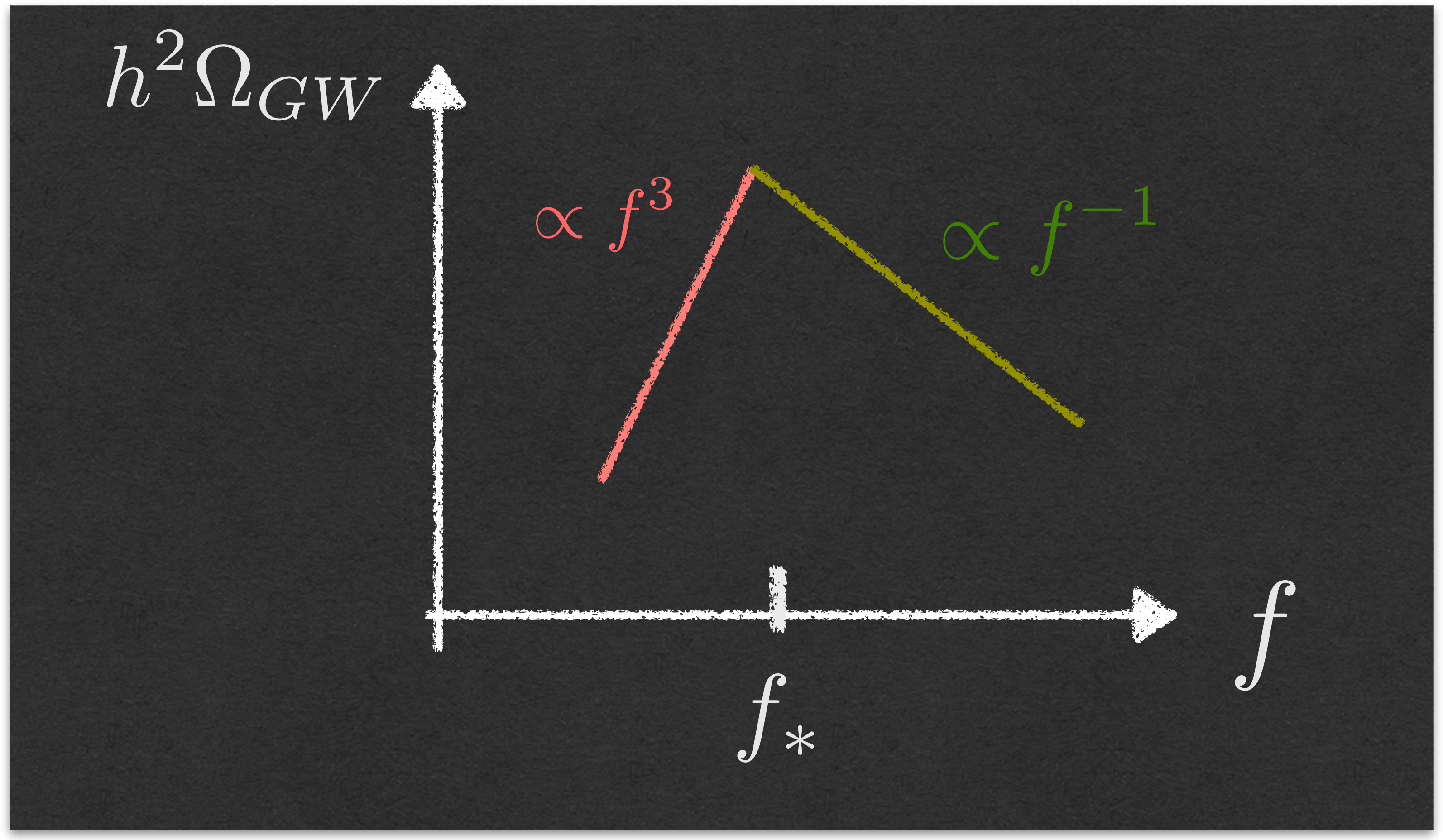


Effective model:

$$w_{\mathrm{NEDE}}(t) = \begin{cases} -1 & \text{for} \quad t < t_* \\ w^*_{\mathrm{NEDE}} & \text{for} \quad t \geq t_* \end{cases} \qquad 1/3 < w^*_{NEDE} < 1$$

Gravitational waves

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



1/f regime:

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

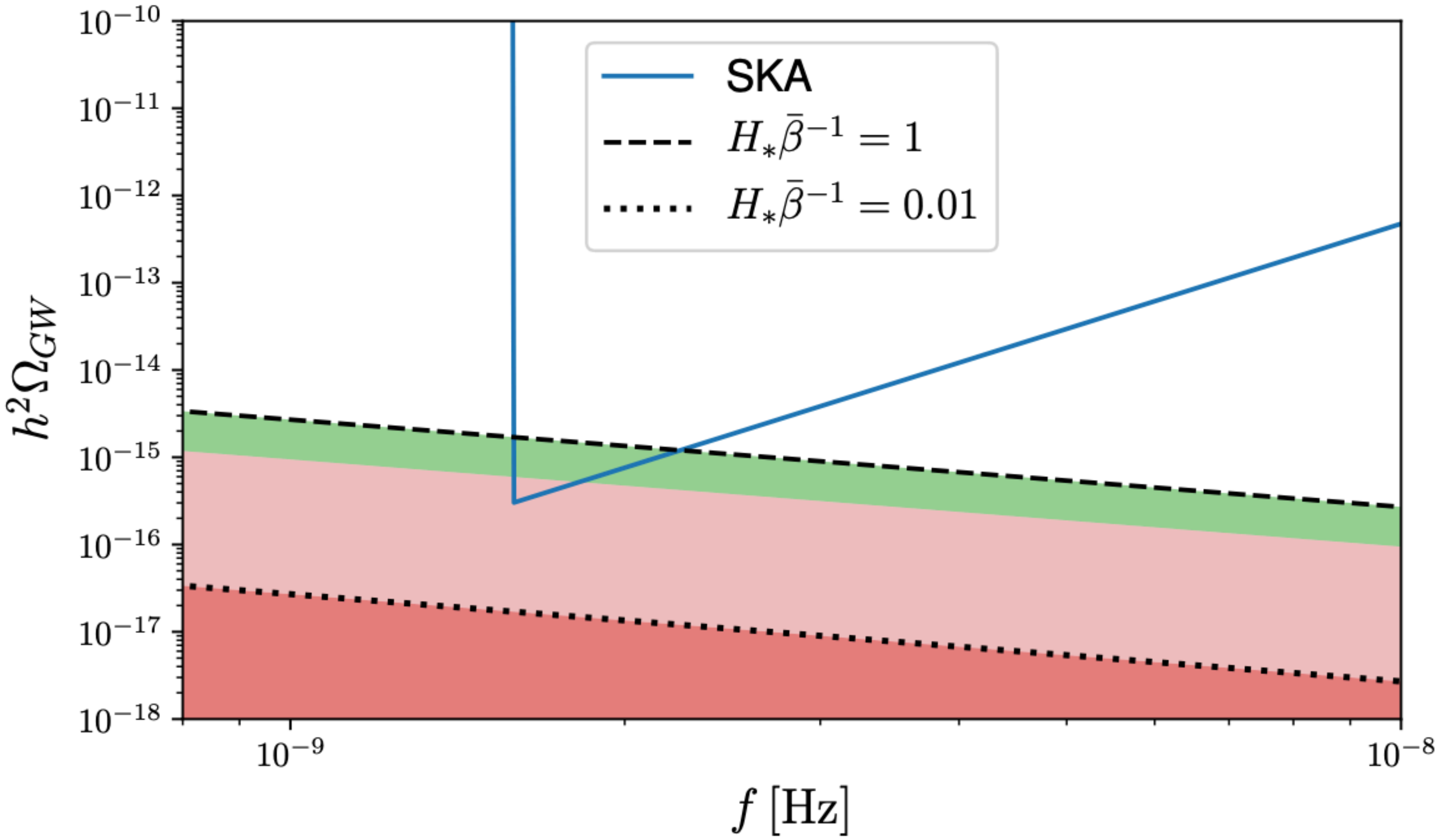
single dial

- 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



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.

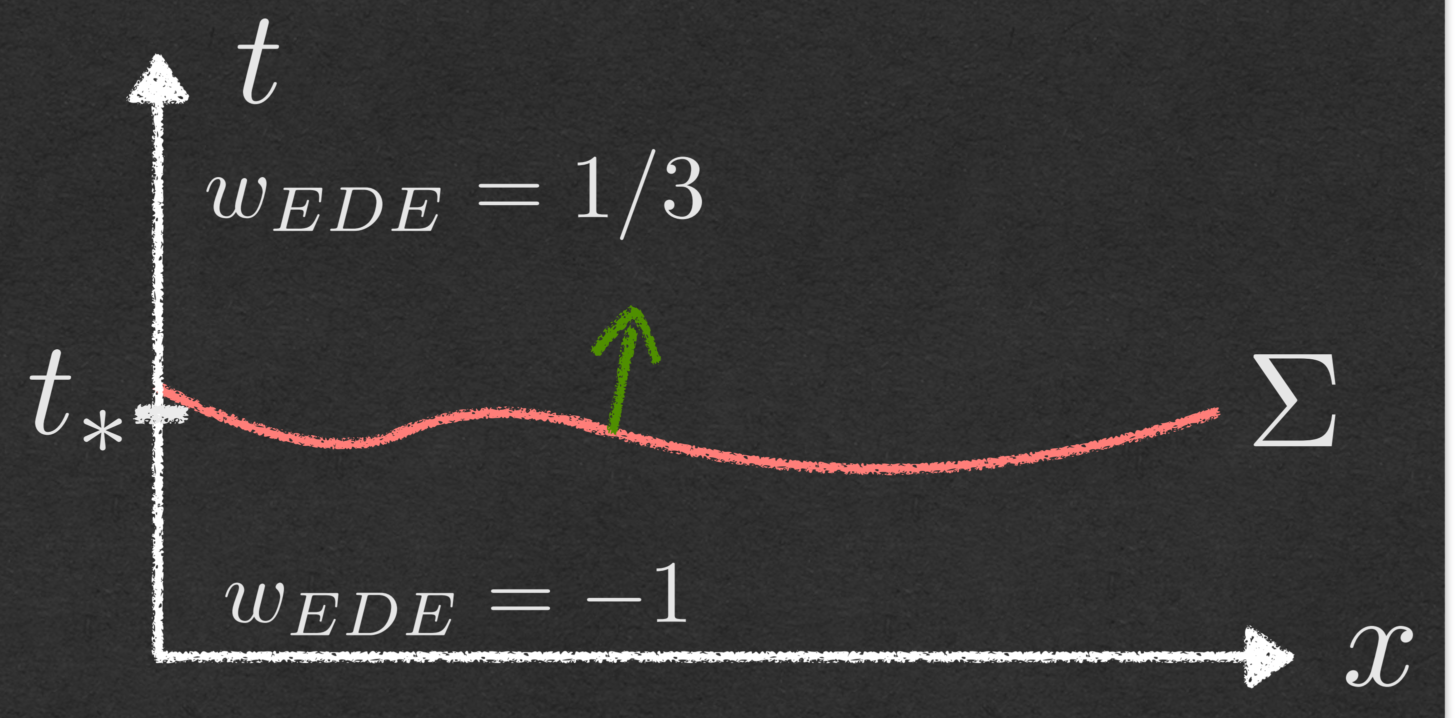
[Deruelle, Mukhanov, 1995]

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

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: $h(t,k)$ & $\eta(t,k)$

Cold NEDE: Cosmological perturbations

- Perturbations in EDE fluid:
  - **Before** transition EDE behaves as a non-fluctuating cosmological constant.
  - **After** transition perturbations in dark fluid need to be initialised.

Israel's junction conditions:

$$\left[\dot{h}\right]_\pm = -6\,[\dot{\eta}]_\pm = 6\left[\dot{H}\right]_\pm \frac{\delta\phi_*}{\dot{\phi}_*}$$

Einstein eqs. →

'initial' conditions

$$\delta^*_{EDE} = -3\,(1+w^*_{EDE})\,H_*\frac{\delta\phi_*}{\dot{\phi}_*} \quad \longleftarrow \text{density pert.}$$

$$\theta^*_{EDE} = \frac{k^2}{a_*}\frac{\delta\phi_*}{\dot{\phi}_*} \quad \longleftarrow \text{divergence fluid velocity}$$

valid for super- and sub-horizon modes

  - Fluctuations in (adiabatic) trigger field provide initial conditions for EDE perts.
  - To close differential system assume vanishing shear stress

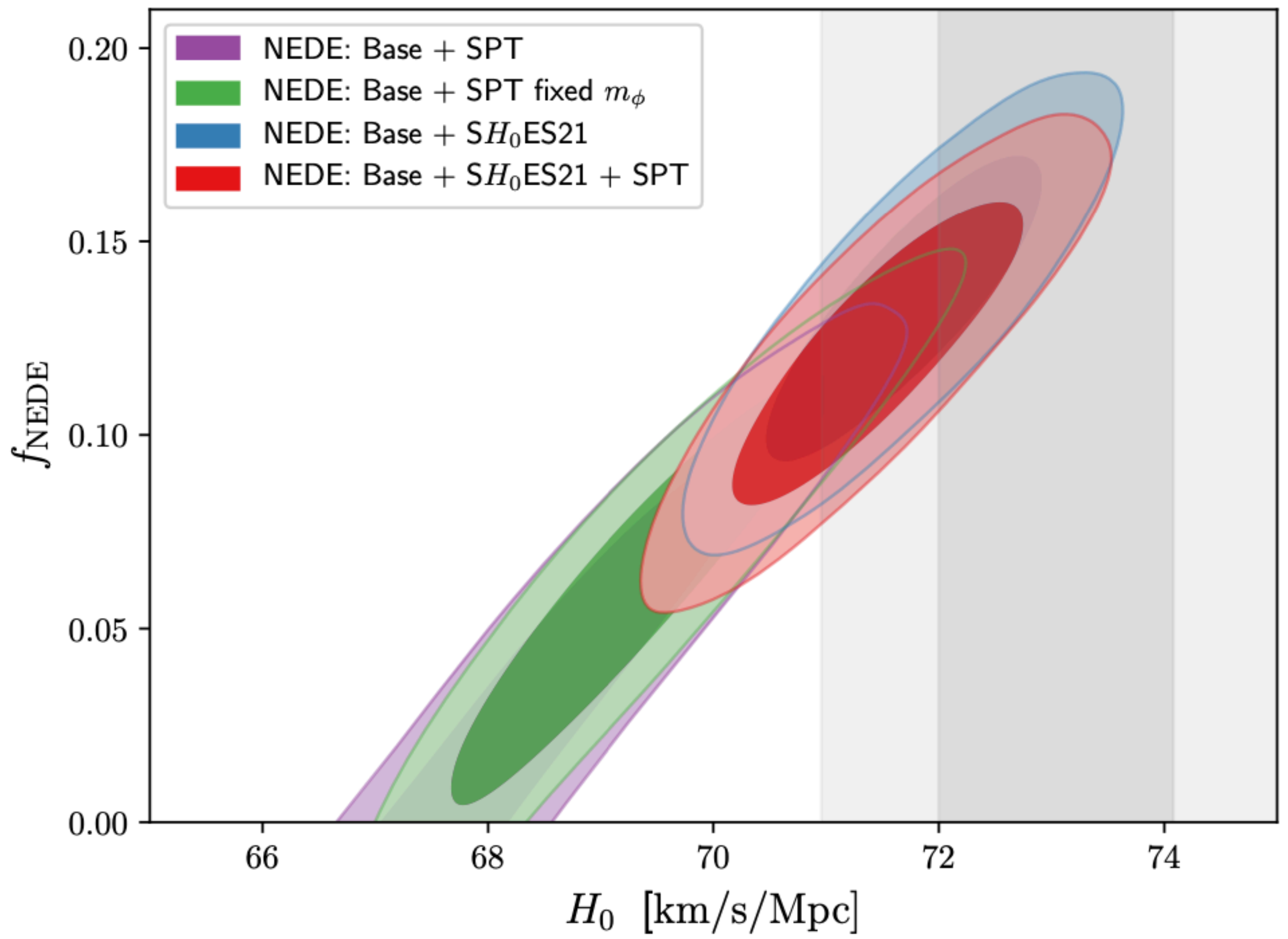
- This allows us to implement our model in a Boltzmann code: "Trigger-CLASS".

arXiv:2006.06686 w. Florian Niedermann

(i) fraction of EDE before decay: $f_{EDE} = \frac{\bar{\rho}^*_{EDE}}{\bar{\rho}^*}$

(ii) mass trigger field: m → fixes t_*

Two-parameter extension of LCDM



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.