Addressing Cosmic Tensions with a New Phase Transition in the Early Universe

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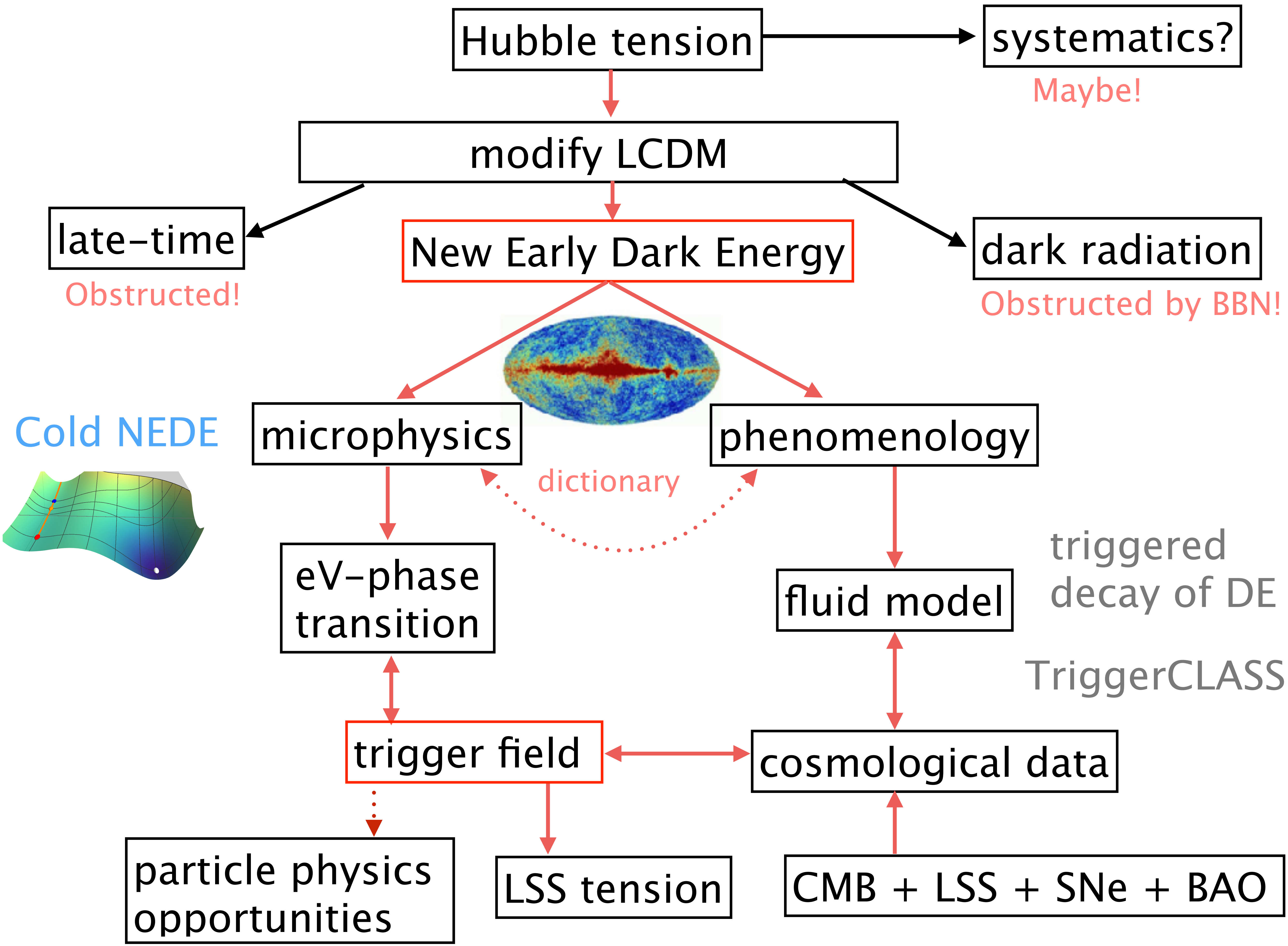
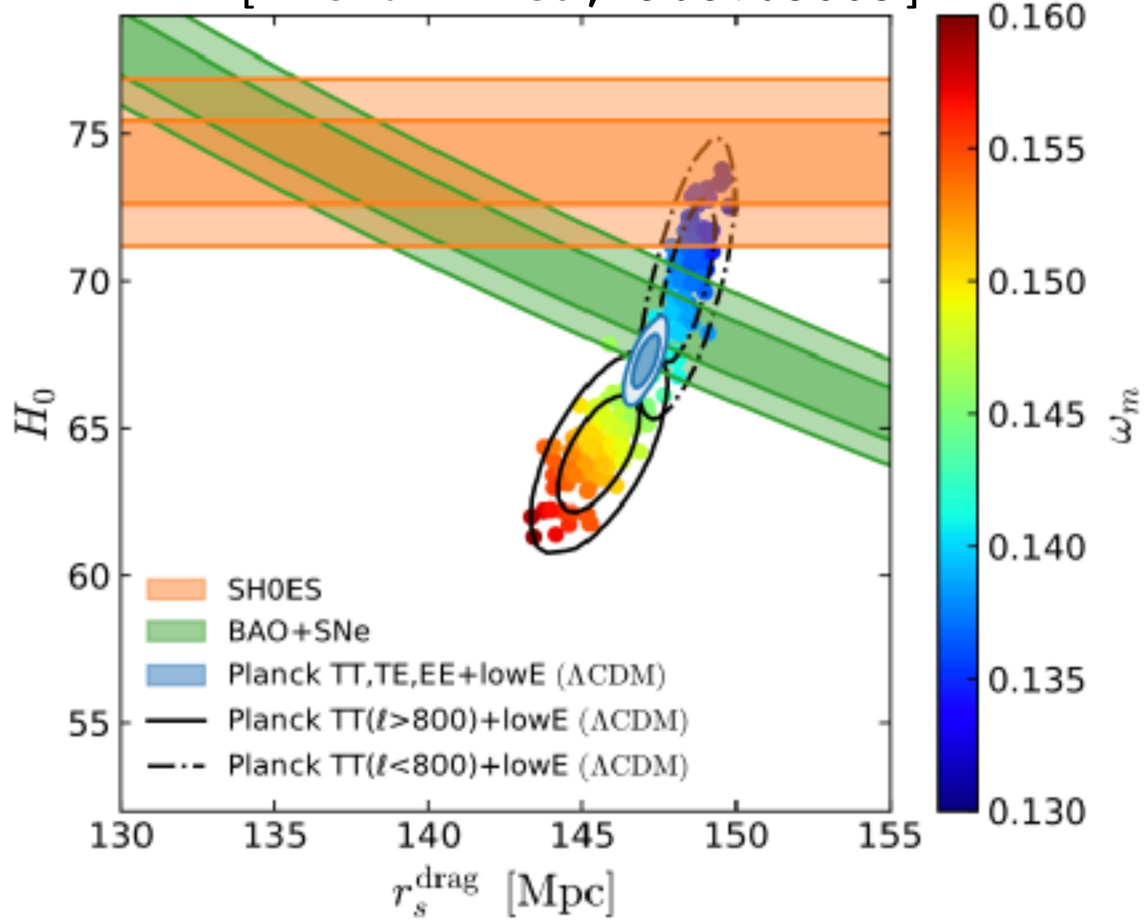
University of Oslo
Theory Seminar
10 April 2024


Hubble tension
systematics?
Maybe!
modify LCDM
late−time
Obstructed!
New Early Dark Energy
dark radiation
Obstructed by BBN!
Cold NEDE
microphysics
phenomenology
dictionary
eV−phase transition
fluid model
triggered decay of DE
TriggerCLASS
trigger field
cosmological data
particle physics opportunities
LSS tension
CMB + LSS + SNe + BAO

The case for early-time physics

[Knox&Millea,1908.03663]



(i) Hubble tension (assumes LCDM!):

SH0ES + Planck >5 sigma discrepant

(ii) generic observation

BAO + SNe: $H_0 r_s \simeq const$

$H_0 \nearrow \rightarrow r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} \searrow$

- Resolving the tension requires lowering the sound horizon by ~ 5-6 %.
- This clearly suggests new physics pre recombination in redshift window:

Modify history of universe when highly constrained!

$1100 < z < 25000$

A road well-travelled

$$H^2(z) = \frac{1}{3M_{\rm pl}^2}\left[\rho_\Lambda + \rho_{\rm matter}(z) + \rho_r(z) + \rho_X(z)\right]$$ ← new component (>10%)

→ increases $H(z)$ prior to recombination → $r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}$ ↘

- **Challenge:** The new physics should preserve good fit to CMB observables.

- Canonical example: **Dark Radiation (DR)**
- **Parametrization:** Effective number of relativistic degrees of freedom

$$\rho_X(z) = \rho_{\rm DR}^{(0)}(1+z)^4$$

$$\Delta N_{\rm eff} = \rho_X / \rho_{1,\nu}$$

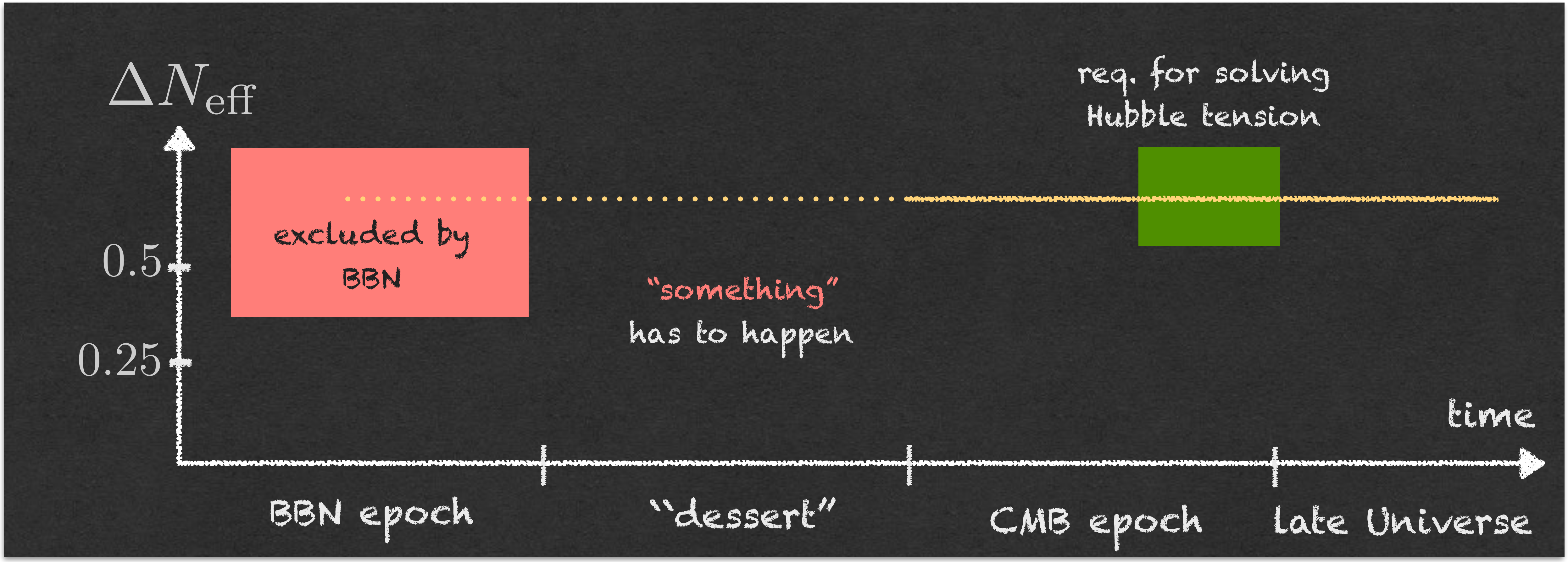
- **Free streaming DR:** too much diffusion damping on small scales.
- Strongly interacting dark radiation (**SIDR**) is more promising.
- **Different sophistications**: stepped SIDR (mass threshold), coupled DM-DR, …

[Aloni++,2111.00014]

- Depending on detailed model: brings tension down to ~**3 sigma** level.

[2206.11276,2306.12469, 2305.14166]

BBN challenge



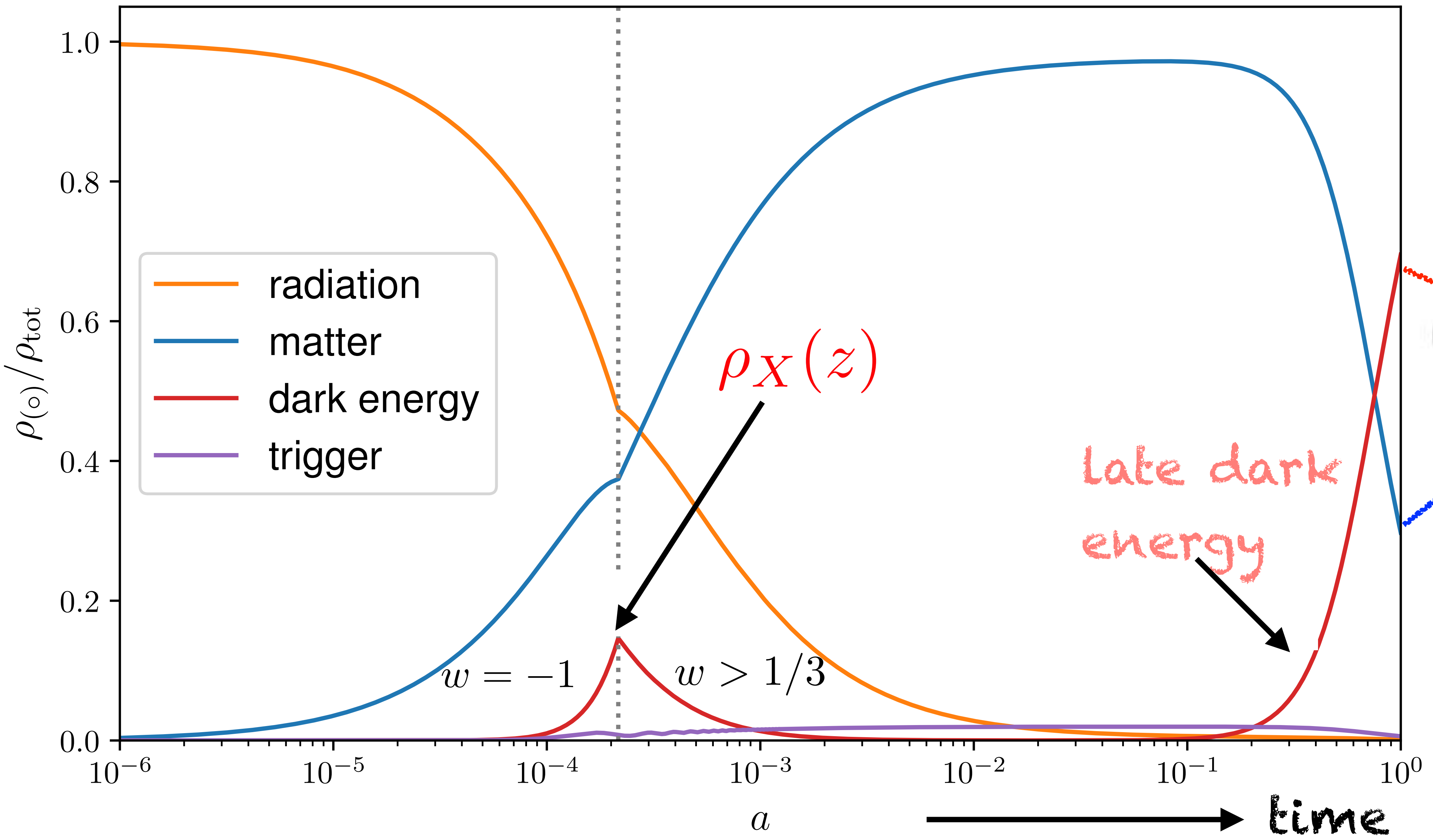
e.g. [Schöneberg++,2206.11276]

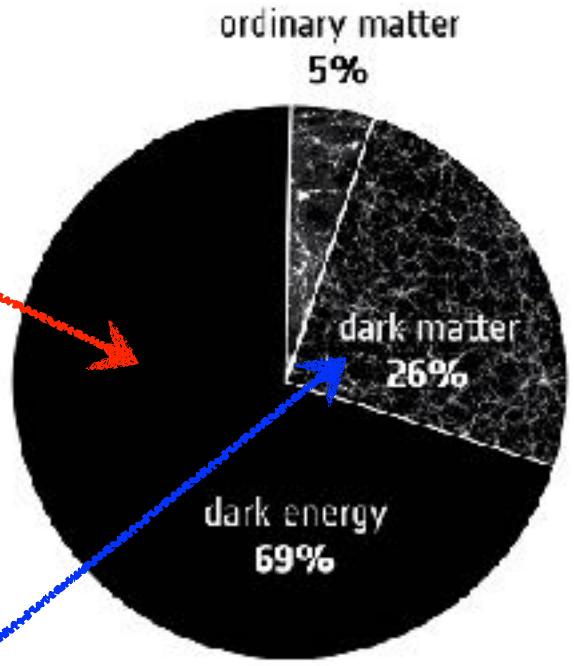
- **Advertisement:** In our upcoming publication, we will reveal "something" .

(with M.Garny, H.Rubira, M.S.Sloth)

What works instead...

- **Early Dark Energy (EDE): 2018** – Poulin, Smith, Karwal, Kamionkowski

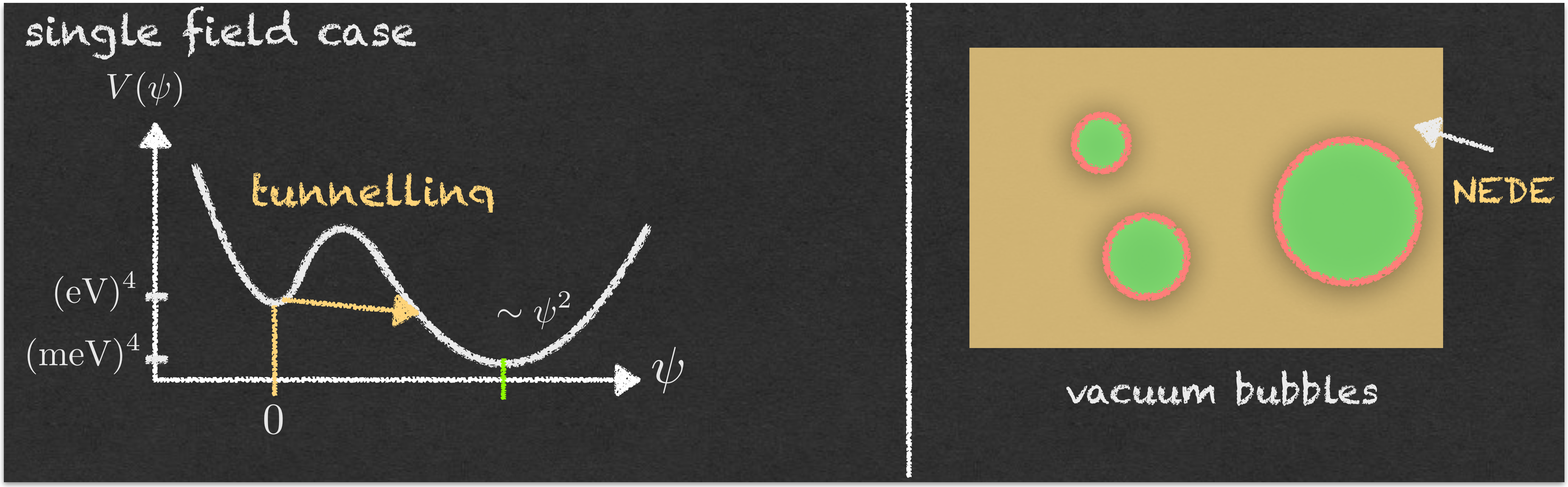




Credit: ESA

- **Explanation:** Energy injection shortens sound horizon observed in CMB.
- Insight with Martin S. Sloth: Looks like a **vacuum phase transition**!

Vacuum phase transition



- **Hubble tension:** EDE provided by (decaying) false vacuum energy.

However:

$\Gamma = const$ → tunneling turns on when $\Gamma \sim H^4$

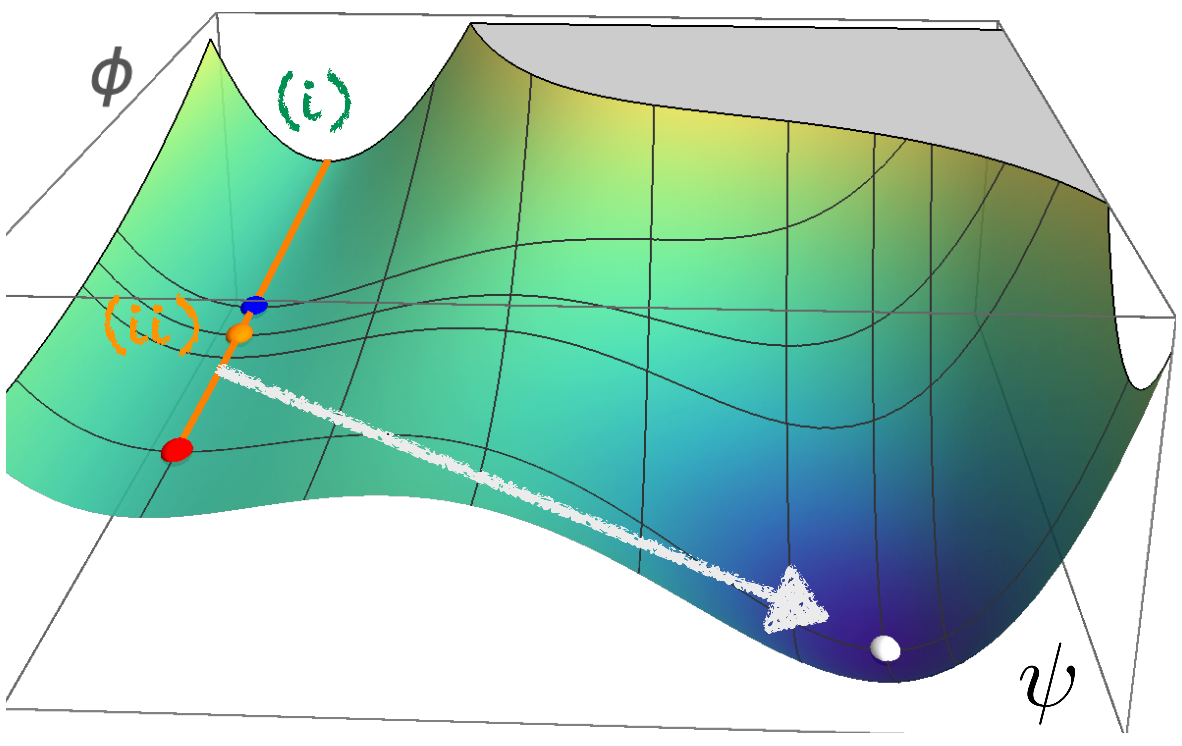
→ (i) percolation time $\sim 1/H$ (ii) typical bubble size $\sim 1/H$

- Challenge: How to avoid anisotropies in CMB arising from large bubbles?
- Idea: Make tunneling rate time dependent.

Cold New Early Dark Energy

- Introduce a **trigger field** ϕ to synchronise decay.
- eV scale adaption of first-order inflationary model

[Linde,1990][Adams,Freese,1990]



tunnelling rate: $\Gamma(\phi) \propto \exp\left[-S_E(\phi)\right]$

(i) field stuck initially:

$\phi \simeq \phi_{ini}$ and $\Gamma/H^4 \ll 1$

(ii) ϕ starts evolving

eventually: $\Gamma/H^4 \gtrsim 1$

→ bubble nucleation turns on

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

$\alpha = \mathcal{O}(1)$

hierarchy: $M \sim \mathrm{eV} \gg m \sim 10^{-27}\mathrm{eV}$ → $\Gamma_{\max} \gg H^4$

→ rapid nucleation event

radiative stability: $\tilde{\lambda} \lesssim 10^3 m^2/M^2 \ll 1$

weak coupling: $\lambda < 0.1$

NEDE Phenomenology

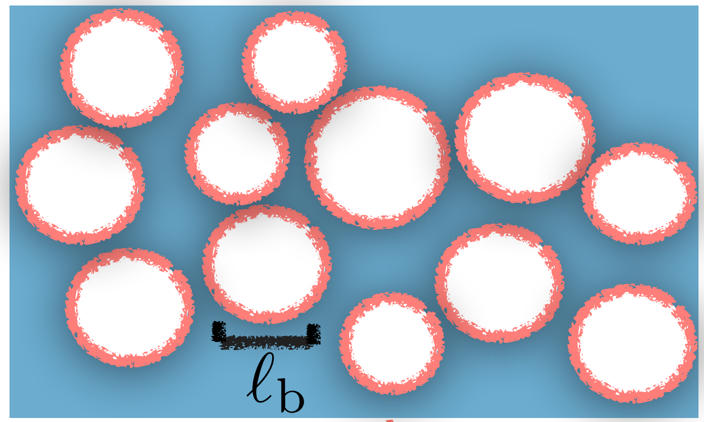
- Central requirement:

percolation time: $T_\mathrm{b} = \ell_\mathrm{b}/c \ll 1/H$

recent bound: $T_\mathrm{b} < 0.003/H$

[G.Elor++,2311.16222]

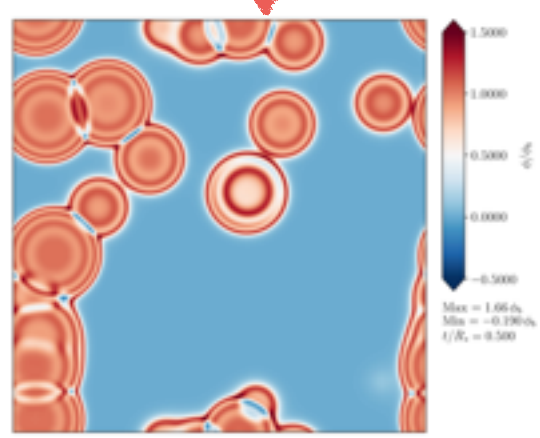
- **Consequence**: Phase transition is an **instantaneous** process on cosmological scales.

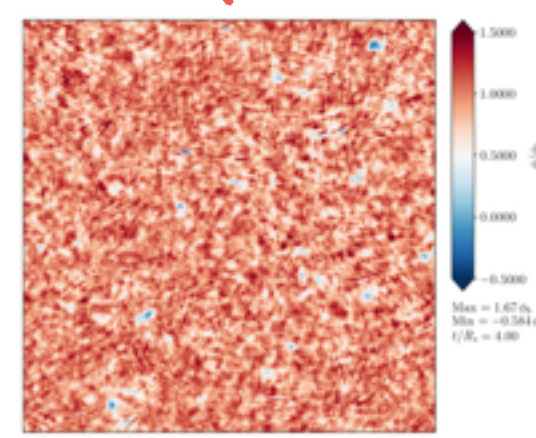


+ colliding walls
+ shear stress (e.g. GW)
+ microscopic decays

- Numerical picture (thick wall):

  [Cutting++,2005.13537]

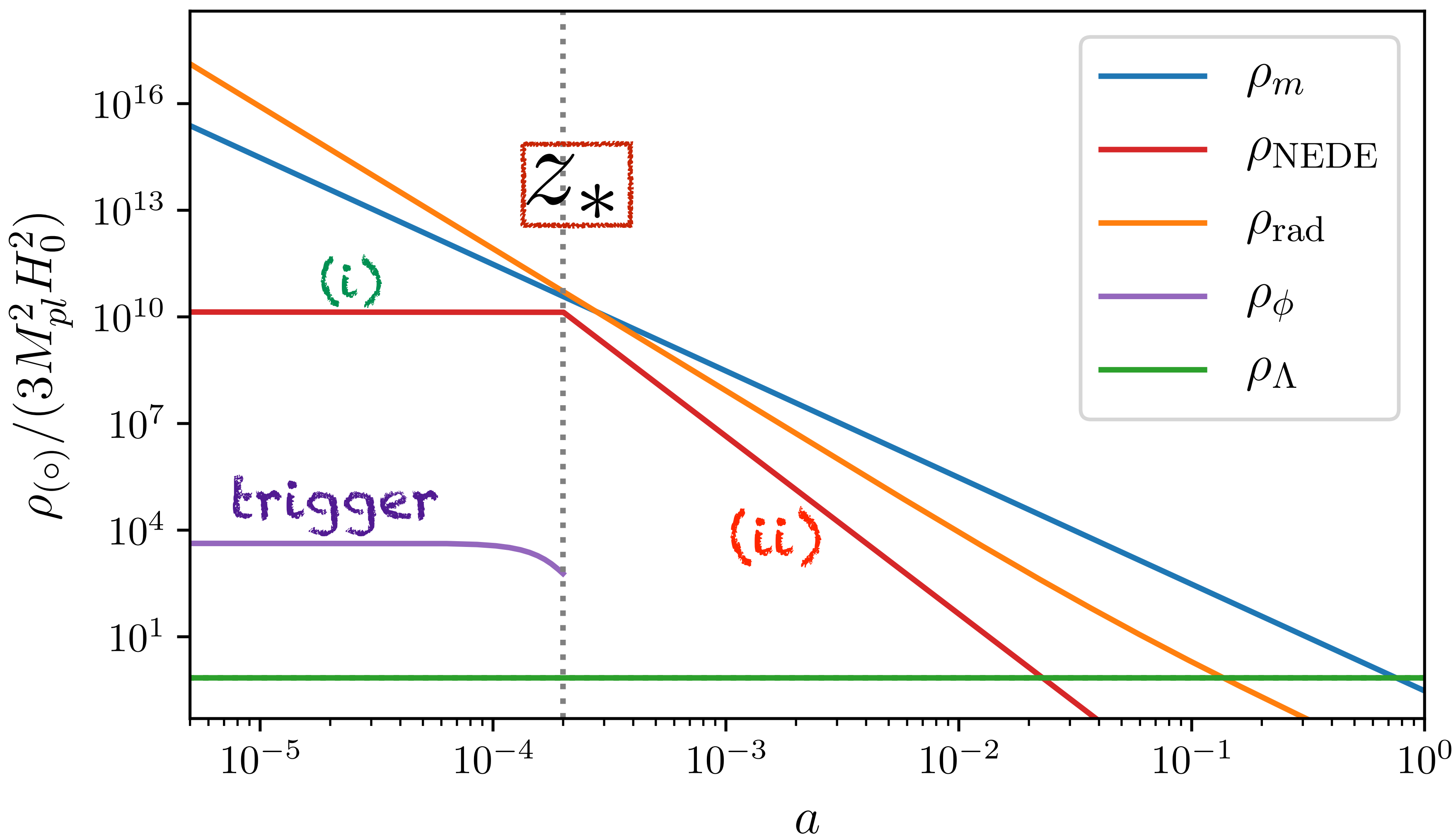




- **After phase transition**: Small-scale anisotropic stress
- Describe as **ideal fluid** on cosmological scales (no preferred direction or position).
- Rich phenomenology: e.g. **sourcing** of tensor shear aka GWs (e.o.s.=1/3) + vector shear (e.o.s.=1) and scalar shear (e.o.s.=1/3). → **work in progress**

[Xue,Steinhardt++,1106.1416]

Phenomenological Model

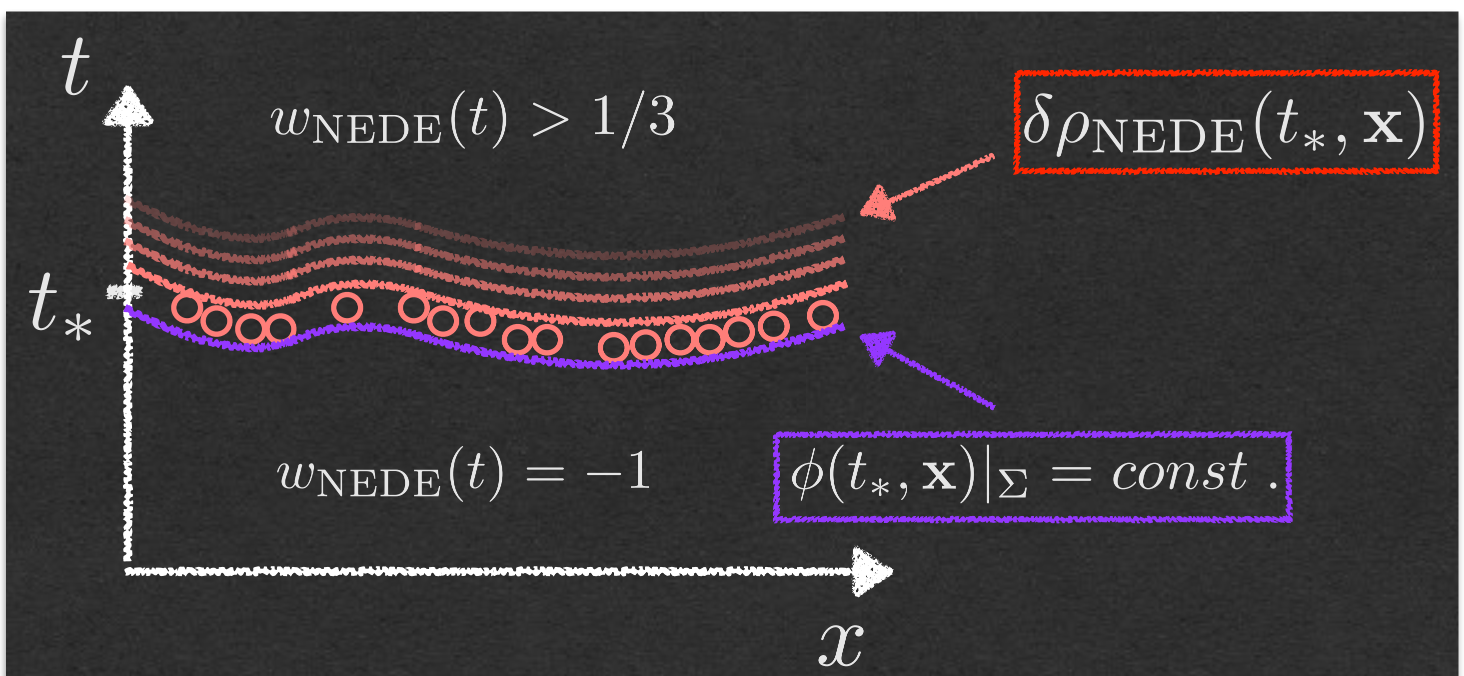


- At background level, NEDE is described as an ideal fluid:
  - **Before** transition: NEDE plays role of CC. (i)
  - **Sudden** triggered transition at time: z_*
  - **After** transition: NEDE is described by decaying dark fluid with e.o.s.p.: (ii)
- **Trigger** field (for now) highly subdominant.

$$1/3 < w_{\rm NEDE}(t) < 1$$

Cosmological Perturbation Theory

- The phase transition affects perturbations in different ways:
  - The bubbles generate perturbations on scales comparable to their size.
    → irrelevant for CMB if bubbles remain small
  - 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, seeding perturbations in decaying NEDE fluid. → relevant for CMB



Israel matching:

$$\frac{\delta\rho^*_{\rm NEDE}}{\rho^*_{\rm NEDE}} = -3\left(1 + w^*_{\rm NEDE}\right) H_* \frac{\delta\phi_*}{\dot\phi_*}$$

$$\theta^*_{\rm NEDE} = \frac{k^2}{a_*}\frac{\delta\phi_*}{\dot\phi_*}$$

[Deruelle, Mukhanov, 1995]

- Covariant perturbation matching implemented in public code TriggerCLASS.
- Rather universal, e.g. for temp. trigger as in **Hot NEDE**:

$$\frac{\delta\phi_*}{\dot\phi_*} \to \frac{1}{H(t_*)}\frac{\delta T^*_d}{T^*_d}$$

NEDE dictionary and results

Phenomenological parameters:

(i) fraction of NEDE $f_{\rm NEDE}$ (ii) decay time z_* (iii) e.os. for decay $w_{\rm NEDE}$

Microphysics:

$$M^4 \simeq (0.4\,\mathrm{eV})^4 \left(\frac{\lambda^3\alpha^{-4}}{0.01}\right)\left(\frac{f_{\rm NEDE}/(1-f_{\rm NEDE})}{0.1}\right)\left(\frac{z_*}{5000}\right)^4$$

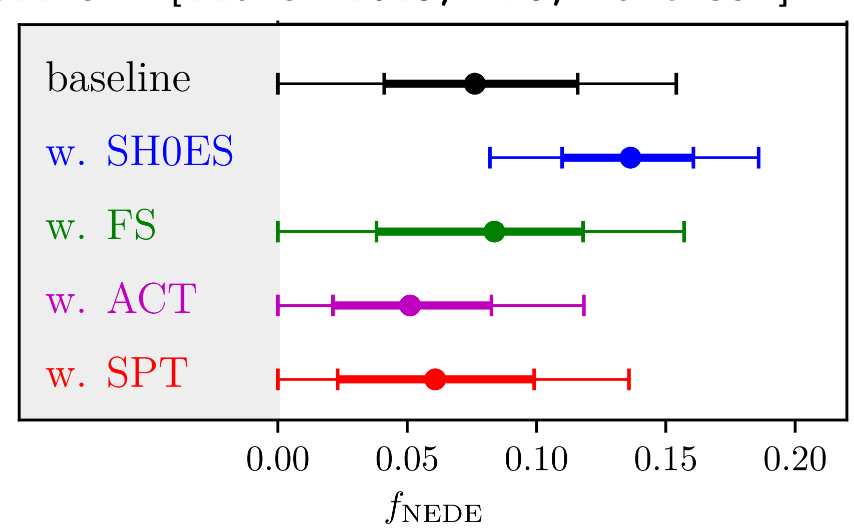
→ NEDE transition set by eV scale

$$m = 1.7\times 10^{-27}\,\mathrm{eV}\,(1-f_{\rm NEDE})^{-1/2}\left(\frac{z_*}{5000}\right)^2\left(\frac{0.2}{H_*/m}\right)$$

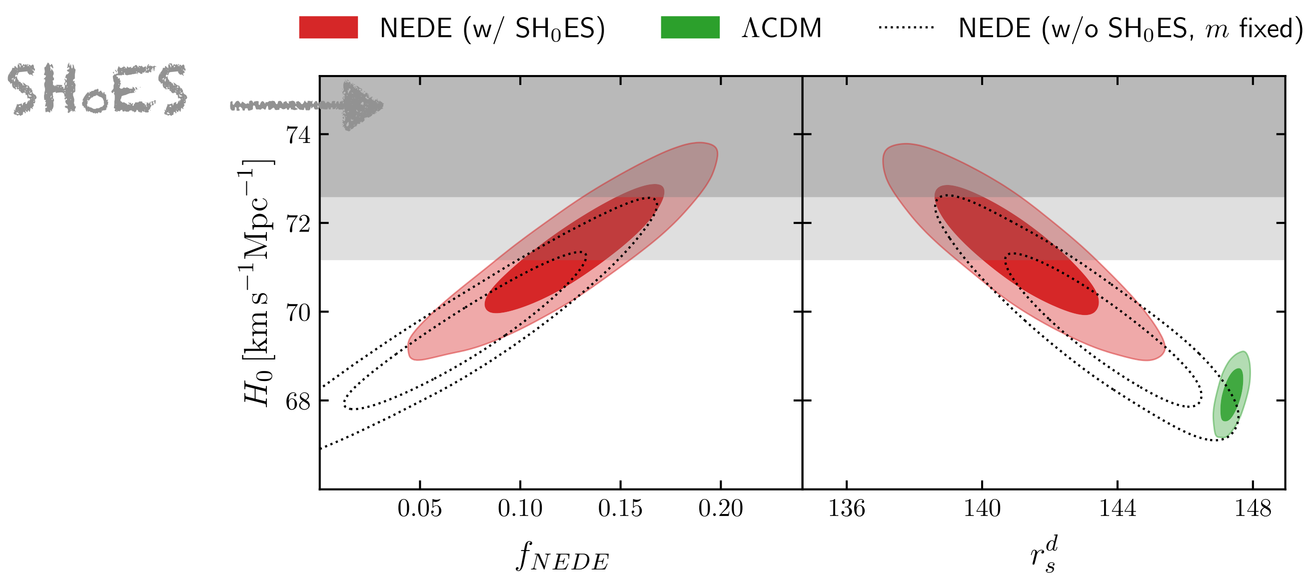
→ trigger is ultralight

- e.o.s. parameter treated phenomenologically (as a constant).
- Test of 3-parameter model: (with J.Cruz, S. Hannestad, Emil B. Holm, M. Sloth, T. Tram, arXiv: 2302.07934)
  - Hubble tension reduced to 2.1 sigma.
  - Gaussian evidence for NEDE around 2 sigma (without SH0ES) and 4.5 sigma (with SH0ES).
  - Profile likelihood approach avoids prior volume effects.
  - E.O.S roughly 2/3

baseline = [Planck 2018, BAO, Pantheon]

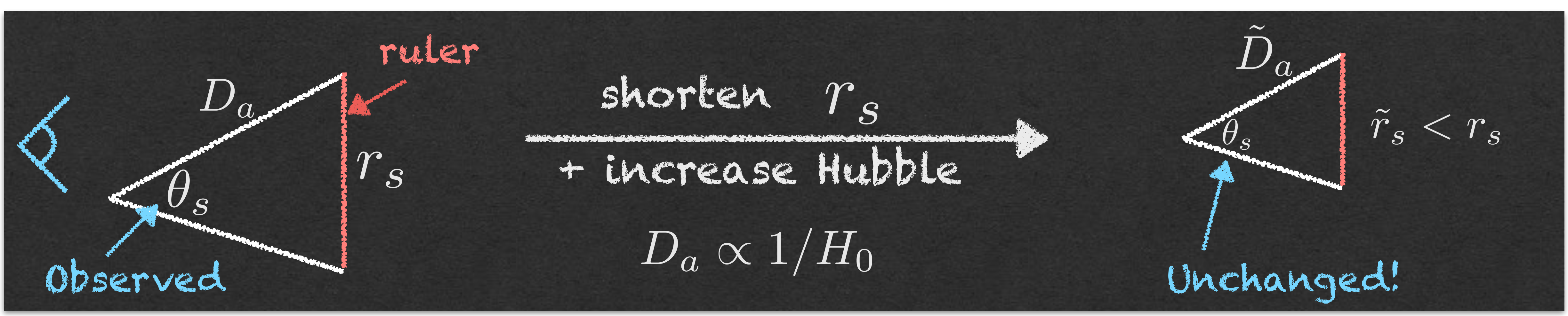


Primary Mechanism



[Planck 2018, BAO, Pantheon, (SH0ES 2019)]

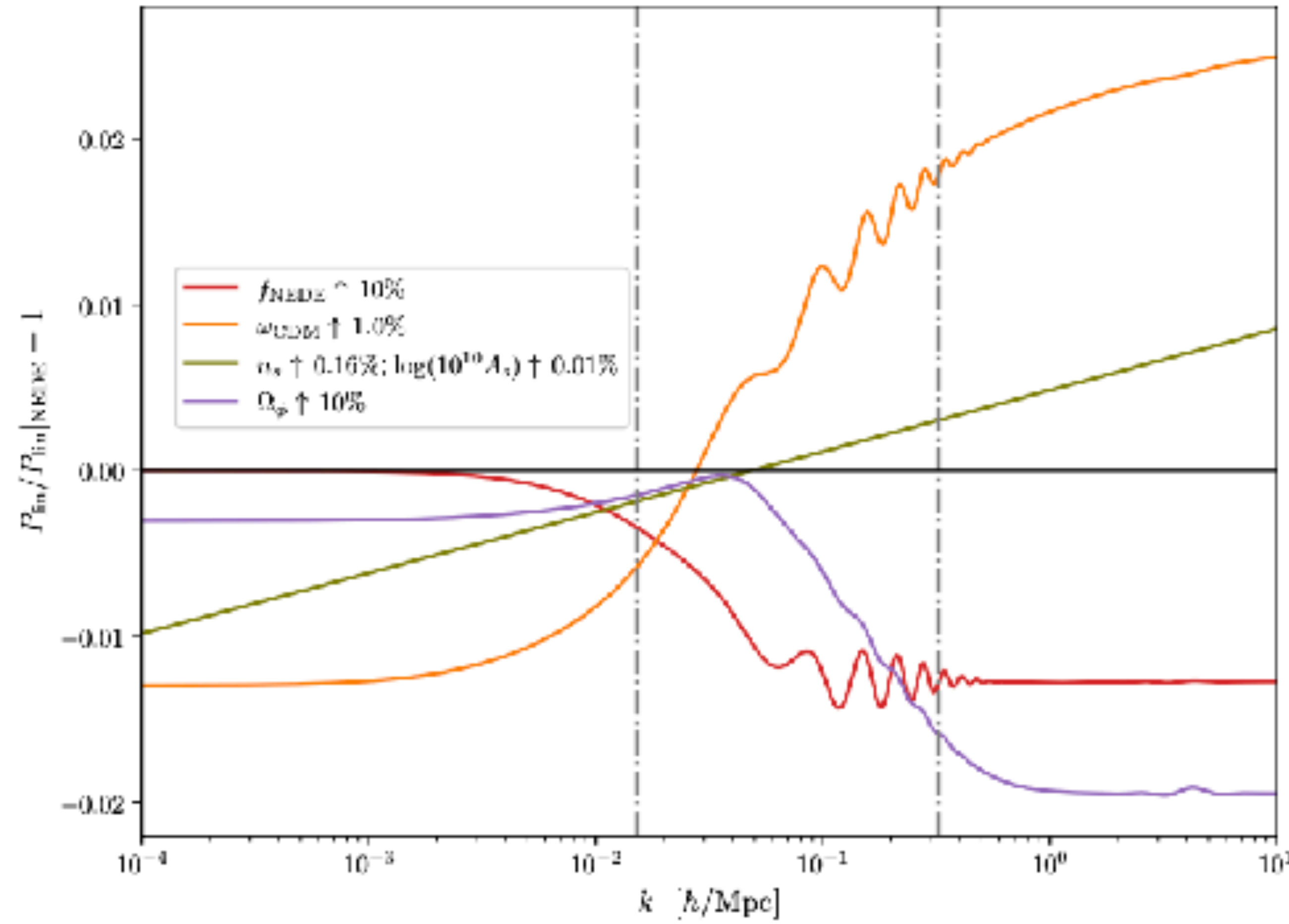
- Energy injection reduces sound horizon.
- Compensated by larger H_0
- Keeps angular scale fixed.
- Main background degeneracy (broken by including H0 prior).



Mechanism: Shorten sound horizon and compensate by raising Hubble today!

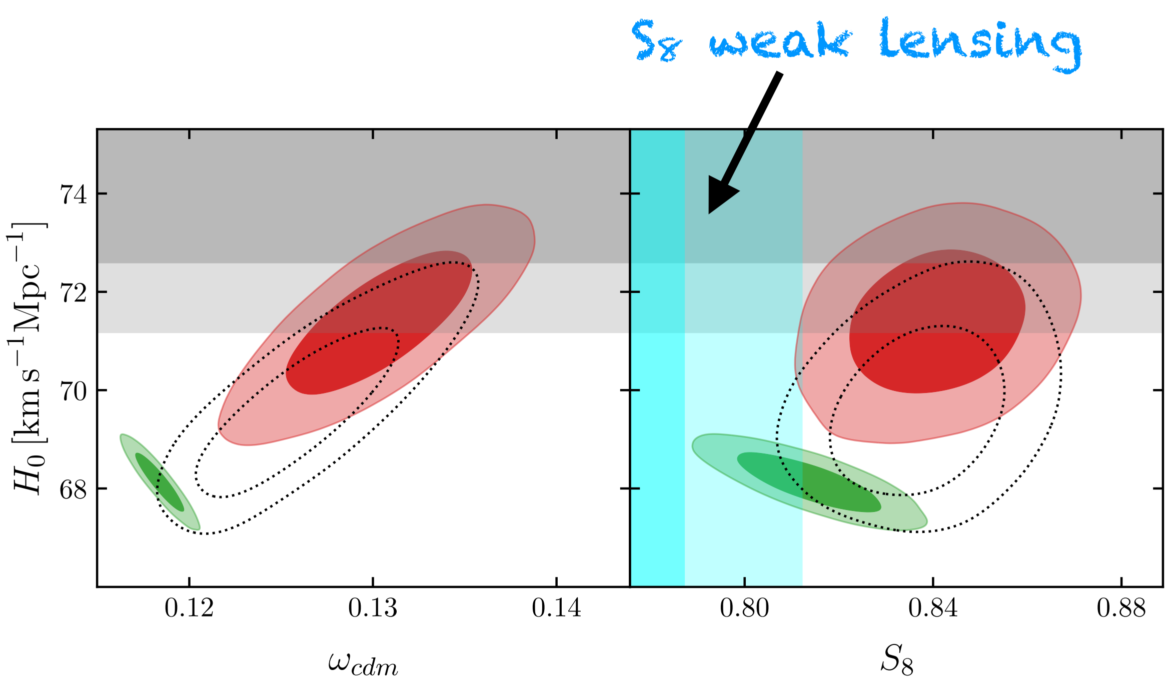
Secondary Mechanisms

sensitivity of matter power spectrum



- Increased DM density $\omega_{\rm cdm} = \Omega_{\rm cdm} h^2$
- Compensated by enhanced decay of Weyl potential due to NEDE acoustic oscillations and delayed matter domination.

[Lin,Benevento,Hu,2009.08974]

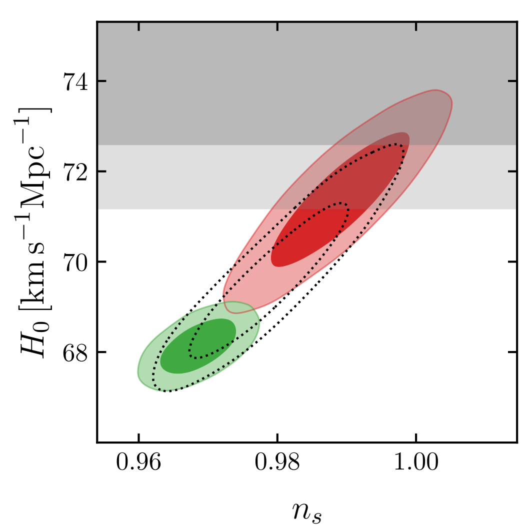


- Small residual effect on small scales.
- S8 tension: 2.5 -> 2.8 sigma

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

$$\sigma_8^2 = \frac{1}{2\pi^2} \int \mathrm{d}k k^2 P_{\rm lin}(k) W^2(k \times 8{\rm Mpc}/h),$$

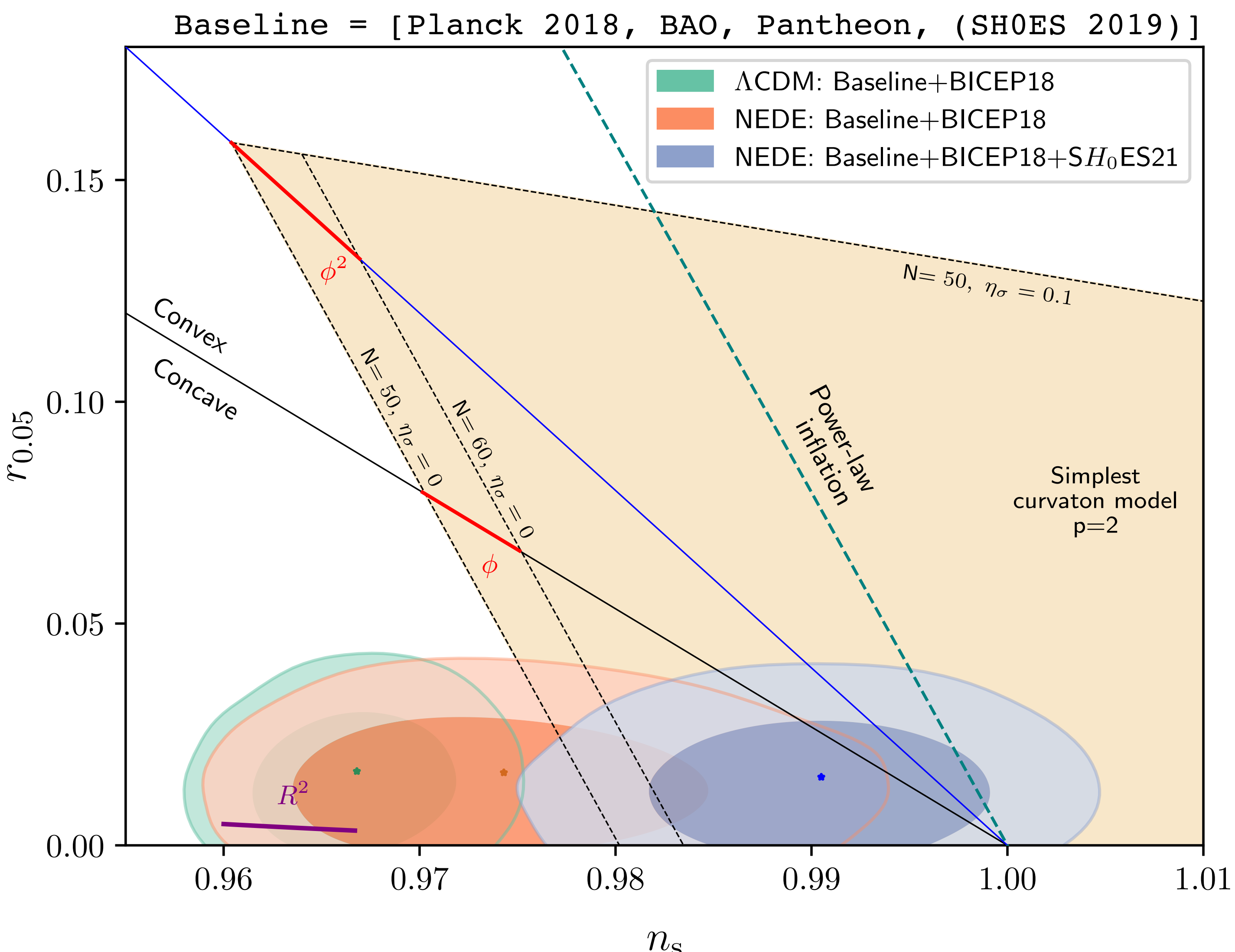
- Increased n_s (to compensate enhanced diffusion damping in CMB)
- Primordial spectrum one-sigma compatible with scale invariance.



CMB damping: $\exp\left[-2\left(\frac{r_d}{r_s}\frac{\theta_*}{2\pi}\ell\right)^2\right]$

$$\Delta\left(\frac{r_d}{r_s}\right) \simeq -\frac{r_d}{r_s}\frac{1}{2}\frac{\Delta r_s}{r_s} > 0$$

Comments on Inflation



[J.Cruz++,2209.02708]

- Could bring back to life simple models of inflation, e.g.:
  - quadratic potential + curvaton
  - power-law inflation (exp. potentials)
- **For now:** Keep in mind LCDM dependence of usual constraints.

Competition (2 years ago)

The H_0 Olympics: A fair ranking of proposed models

Nils Schöneberg,[a] Guillermo Franco Abellán,[b] Andrea Pérez Sánchez,[a] Samuel J. Witte,[c] Vivian Poulin,[b] and Julien Lesgourgues[a]

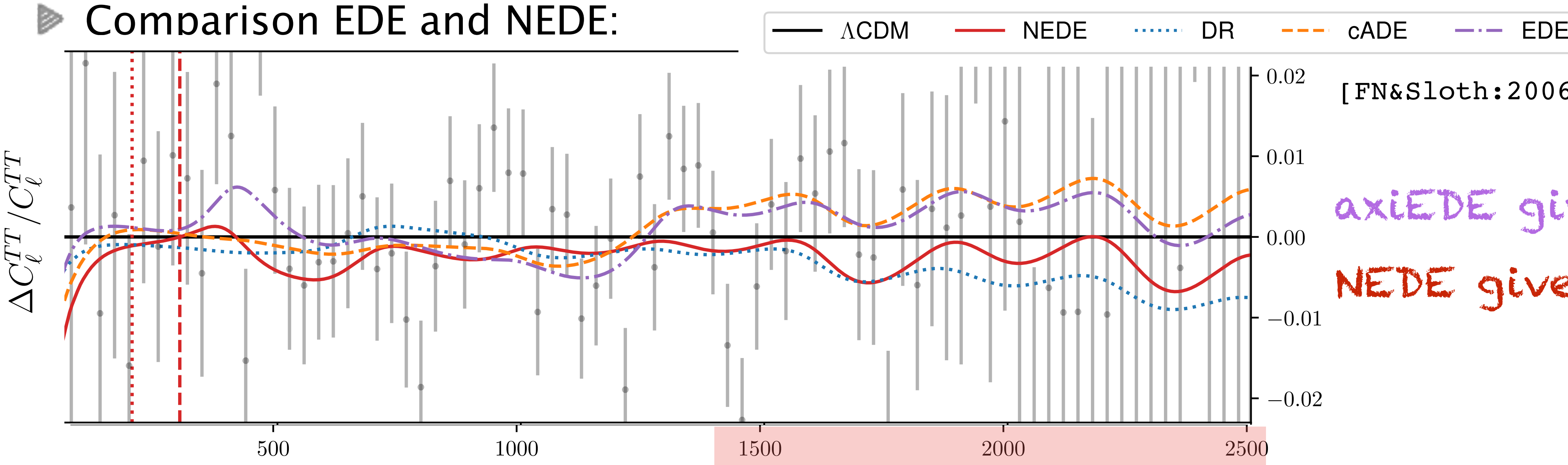
deals with non-Gaussian posteriors

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	✗	✗	
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓	2
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	✗	-10.83	-8.83	✓	✓	3
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	✗	-9.87	-7.87	✓	✓	3
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.7σ	✓	-16.11	-12.11	✓	✓	1
EDE	3	-19.390 ± 0.016	3.6σ	1.6σ	✓	-20.80	-14.80	✓	✓	2
NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓	2

← axiEDE
← NEDE

[Planck 2018 + BAO + Pantheon (+ SH0ES)]

- Comparison EDE and NEDE:



[FN&Sloth:2006.06686]

axiEDE gives more power

NEDE gives less power

- **Upshot 2022:** High-ell data will help discriminate EDE models.

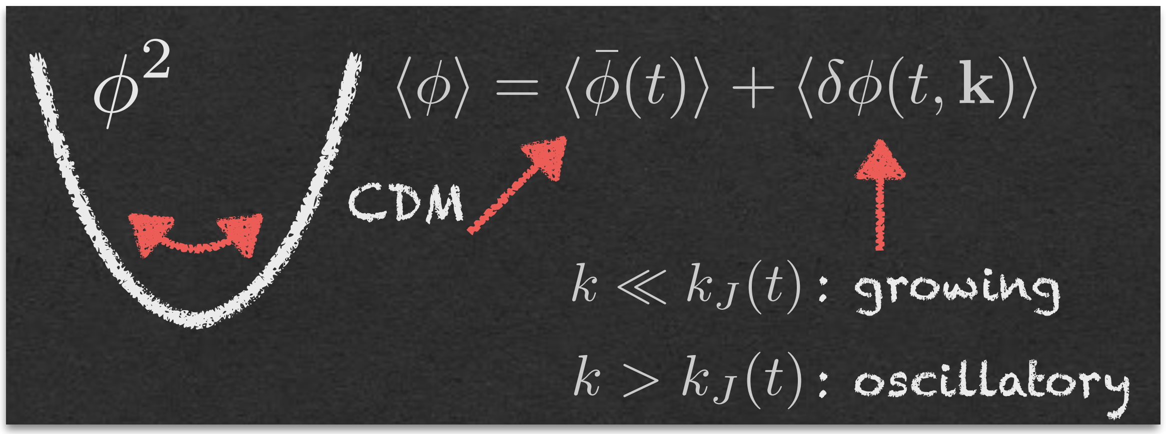
[G.Efstathiou++,2311.00524]

- **Late 2023:** axiEDE obstructed by new Planck NPIPE data (residual Hubble tension: 3.7 sigma).

→ We are currently testing cold NEDE with NPIPE and Panth+ data!

Trigger dark matter

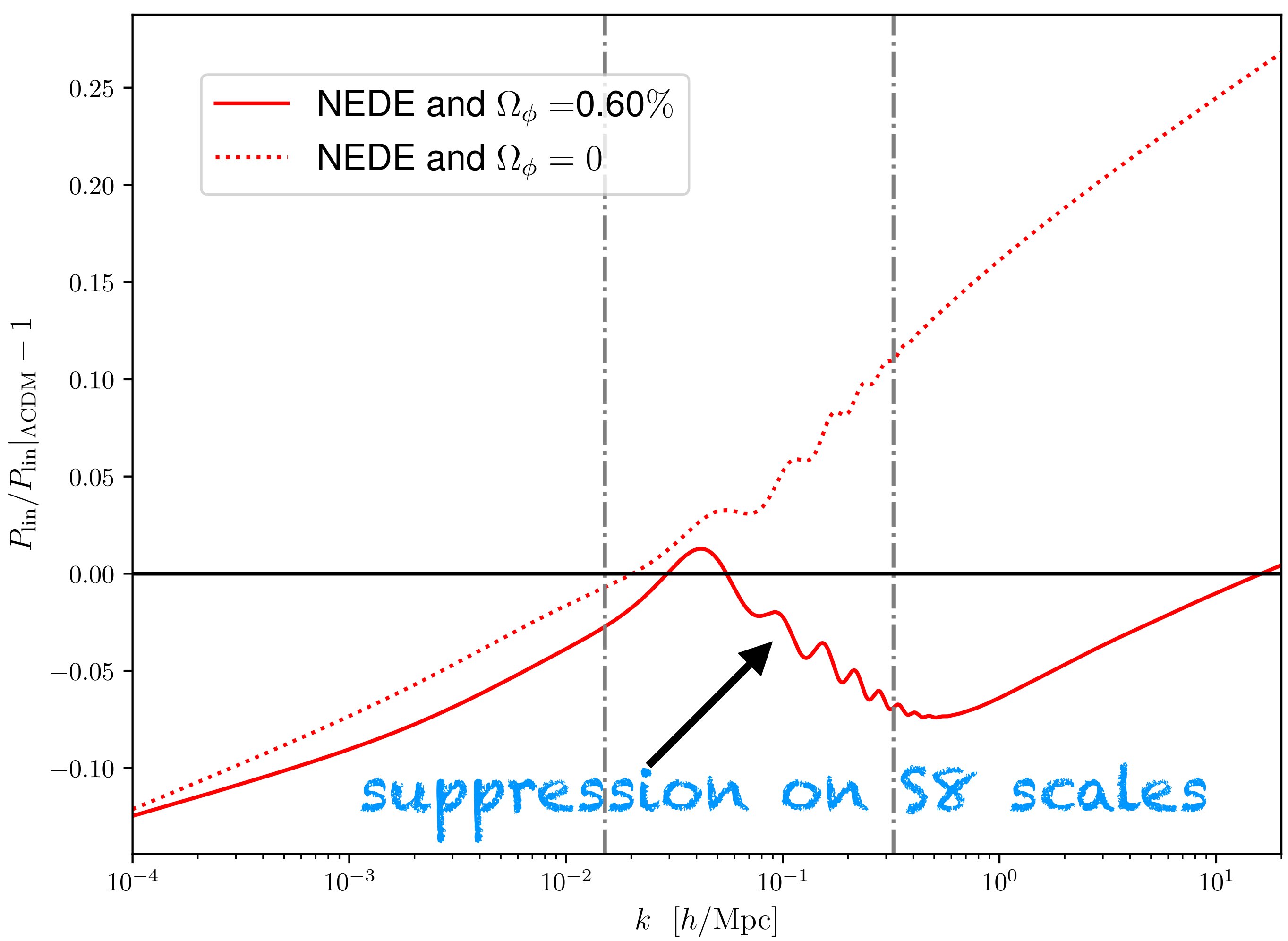
- So far we assumed the trigger to be entirely subdominant.
- However, it can naturally act as light axion-type dark matter.
- NEDE+ultralight scalar studied before by Allali, Hertzberg, and Rompineve, 2021.



Trigger abundance:

$$\Omega_\phi \approx 0.4 \times \left(\frac{1+z_*}{5000}\right)\left(\frac{\phi_{\rm ini}}{M_{\rm Pl}}\right)^2 (1 - f_{\rm NEDE}) \,.$$

Controlled by initial field value



- Compared to CDM, matter power spectrum suppressed below Jeans scale:

$$k_{\rm J,eq} \simeq 0.16 \ {\rm Mpc}^{-1} \left(\frac{m}{10^{-27}\ {\rm eV}}\right)^{1/2}$$

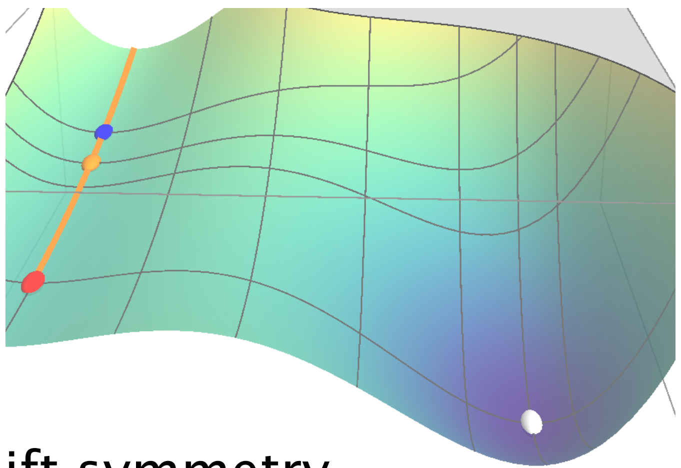
- Pressure fluctuations act against gravitational collapse.
- Suppresses S8 value.
- 4-parameter extensions of LCDM
- Key result: Both tensions < **2 sigma.**

Summary

- H0 and S8 tension exciting opportunity to probe the dark sector.
- Early dark energy models look promising.

  → Search for new particle physics models!

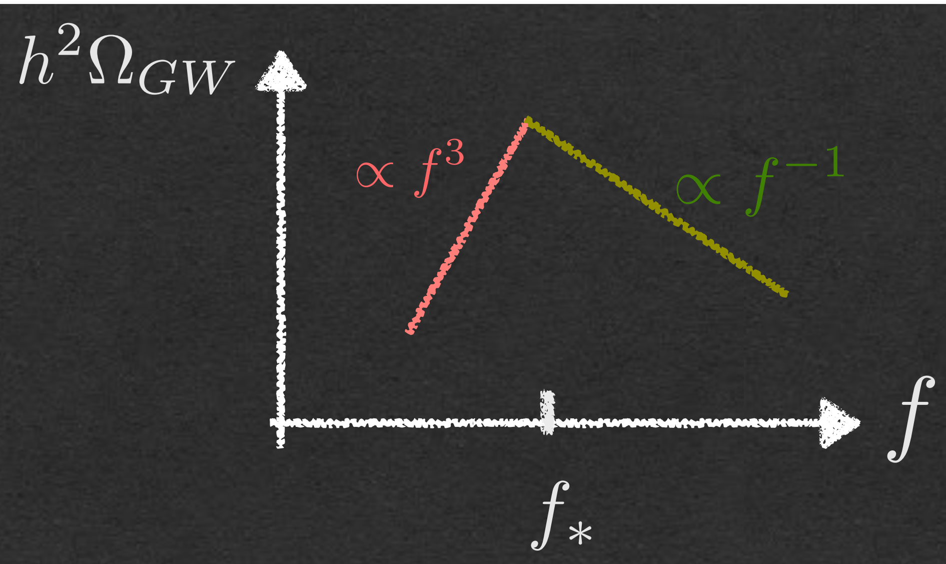
- NEDE is a fast-triggered phase transition in dark sector.
- NEDE is a theory playground (similar to inflation).
- Cold NEDE brings H0 and S8 tension down to 2 sigma.
- Further theoretical work:
  - Relate cold NEDE fluid to microscopic parameters (on-going).
  - Embed in multi-axion system: small masses protected by broken shift symmetry.



- Further phenomenological work:
  - Study more general fluid (background and perturbations).
  - Study other anomalies.
  - Keep testing against more LSS, SNe, and CMB data.
- I did not have time to talk about:
  - Temperature trigger in **hot NEDE** (akin to electroweak phase transition).
  - Address coincidence problem with n**eutrino mass** generation in hot NEDE.

Gravitational Waves

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



$$f_* \simeq 2.6 \times 10^{-17}\,\mathrm{Hz}\,\frac{1}{(H_*\bar{\beta}^{-1})}\left(\frac{1+z_*}{5000}\right)\left(\frac{g_*(T_*)}{3.9}\right)^{1/6}$$

1/f regime:

$$h^2\Omega_{GW} \sim 10^{-15}\,H\bar{\beta}^{-1}\left(\frac{10^{-9}\mathrm{Hz}}{f}\right)$$

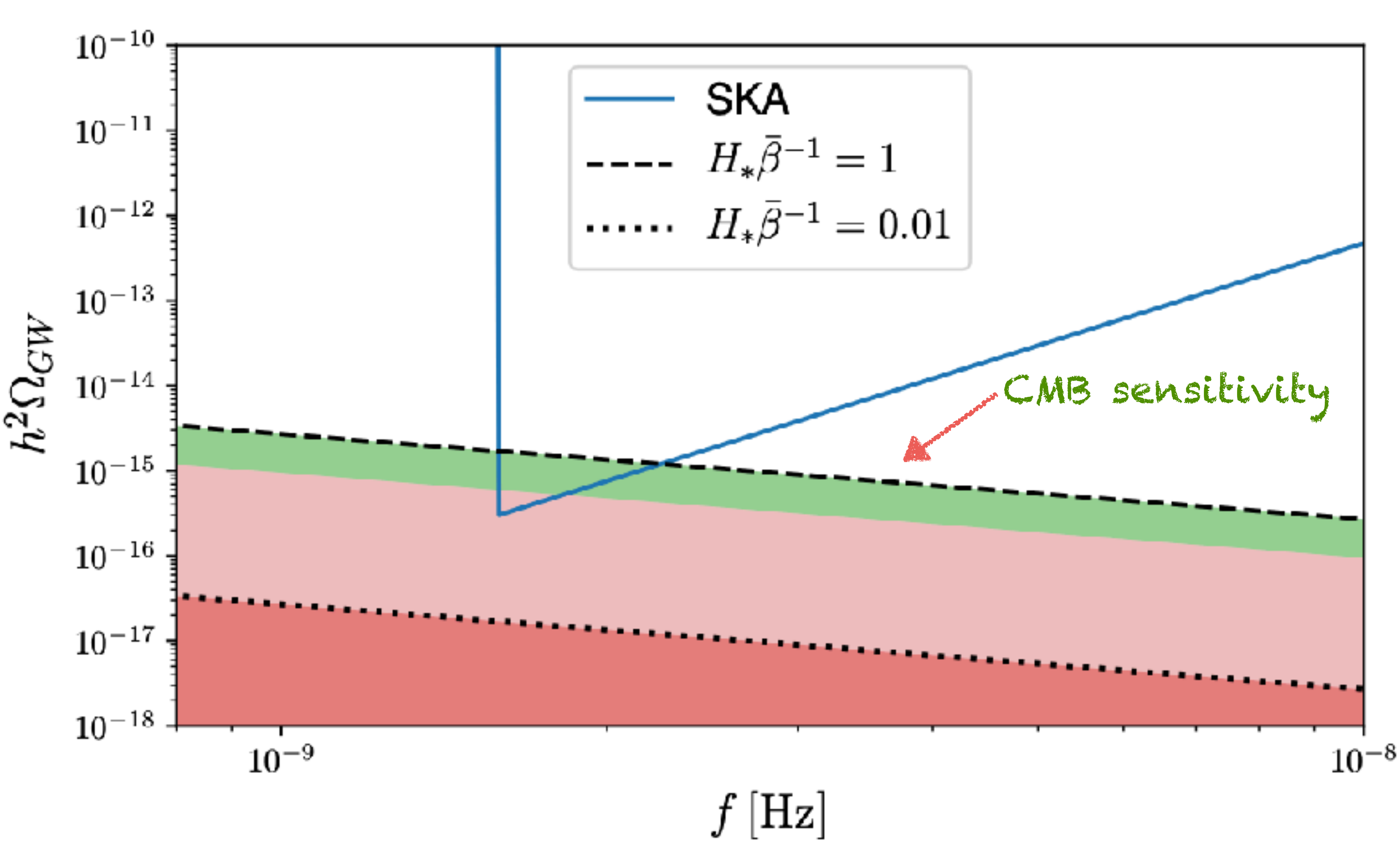
single dial

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

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

→ window for detection: $0.1 < H\bar{\beta}^{-1} \lesssim 1$

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



▶ Marginally compatible with Square Kilometre Array

Neutrino masses I

- Can the NEDE phase transition create the neutrino masses via a low-scale seesaw mechanism? Consider the inverse-seesaw: e.g. [Abada, Lucente, 2014]

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

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

NEDE

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

active right-handed sterile

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

$$n > \mathcal{O}(\text{TeV})$$

$$m_s \gtrsim \text{eV}$$

- Upon diagonalization this yields a sub-eV active mass eigenstate

$$m_3 \simeq \mathcal{O}(m_s)\kappa^2/(1+\kappa^2) \qquad \kappa = d/n$$

- Generalized to three generations, this can explain the observed mass spectrum and mixing pattern.

Neutrino masses II

- Consider Yukawa:

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \sum_{ij} (g_s)_{ij} \Psi \overline{(\nu_s)_i}^c (\nu_s)_j + \text{h.c.}$$

Coupling matrix

NEDE scalar

Global lepton symmetry
(makes mass t'Hooft natural)

spont. broken as $\Psi \to v_\Psi/\sqrt{2}$

- Dictionary to NEDE phenomenology:

$$m_s \approx (1.0\,\text{eV}) \times \frac{g_s}{\lambda^{1/4}} \times \left[\frac{f_{\text{NEDE}}/(1-f_{\text{NEDE}})}{0.1}\right]^{1/4} \left[\frac{1+z_*}{5000}\right].$$

- NEDE scalar couples to active mass eigenstates due to mixing.

Phenomenological bound: $g_s < 10^{-7}/\kappa^2$,

→ It works if $\lambda < 10^{-20} \left(\frac{10^{-2}\text{eV}}{m_3}\right)^4$ ← heaviest neutrino mass