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

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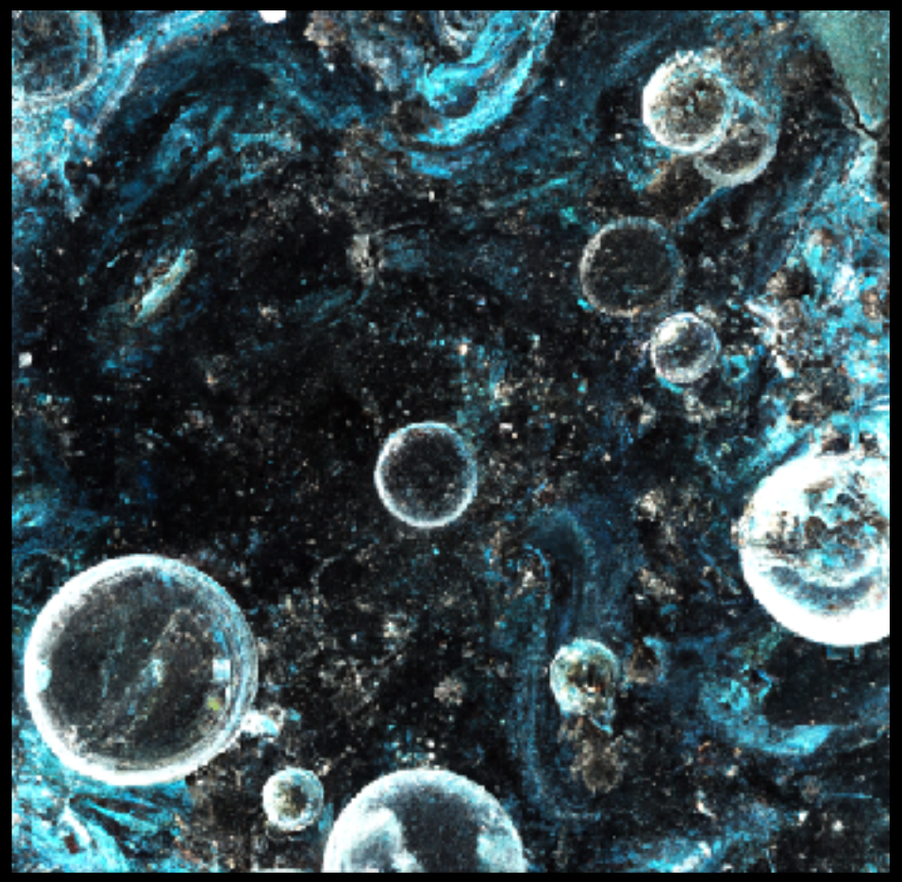

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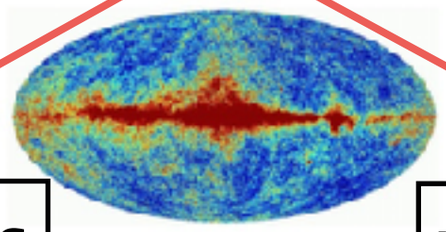
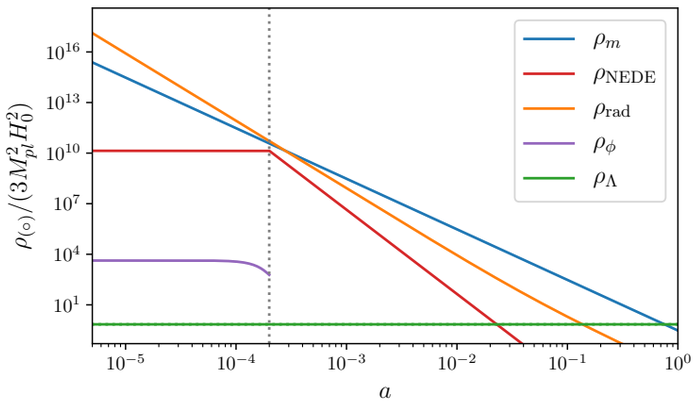
Hubble tension

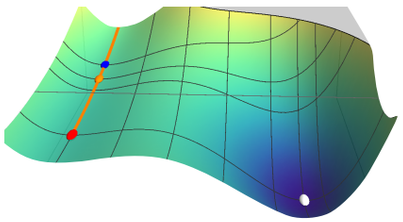
modify LCDM at early times

Early Dark Energy → New Early Dark Energy





Cold NEDE



scalar trigger
+
tunneling field

microphysics ⟷ dictionary ⟷ phenomenology

eV-phase transition

particle physics opportunities

fluid model

triggered decay of DE

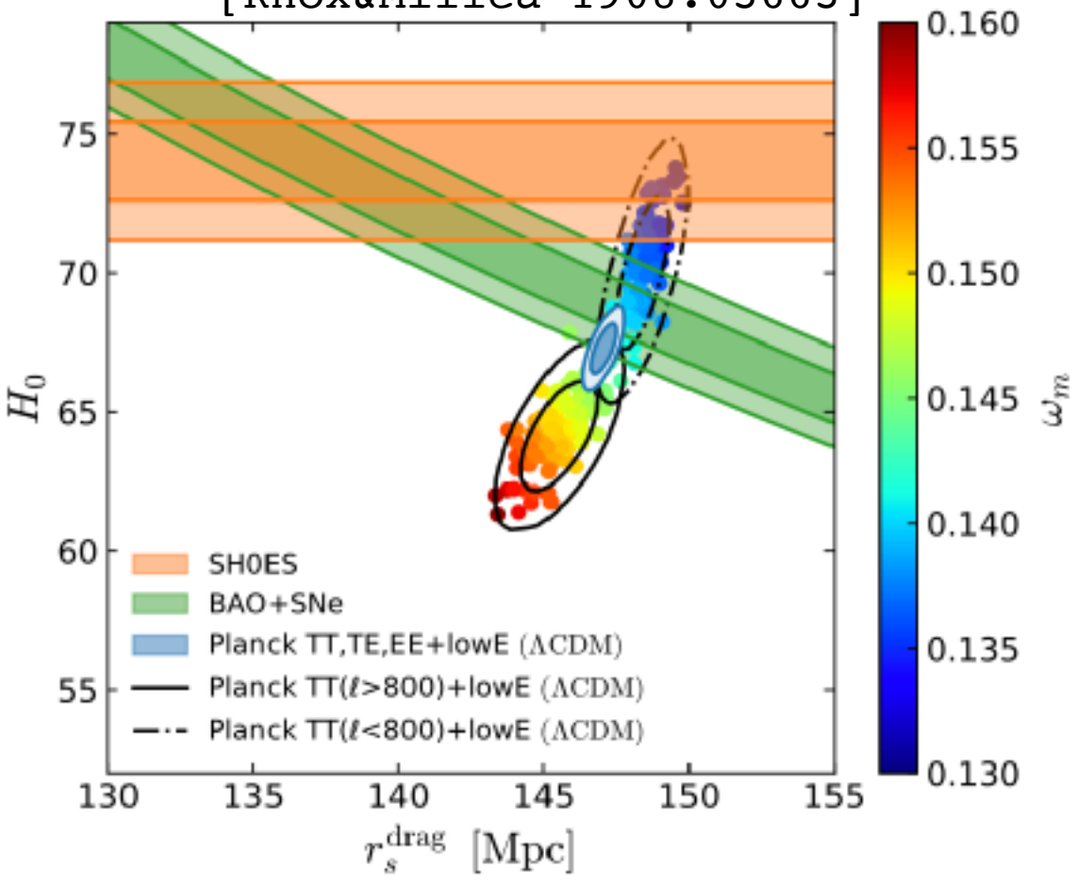
TriggerCLASS

observational challenges

LSS tension

The case for early-time physics

[Knox&Millea 1908.03663]



(i) Hubble tension (assumes LCDM!):

SH0ES + Planck >5 sigma discrepant

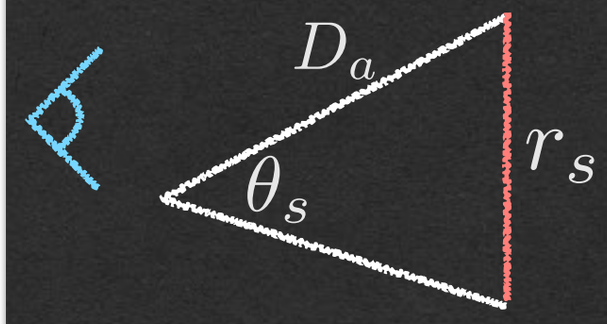
(ii) generic observation

BAO + SNe: $H_0 r_s \simeq const$

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

[Aylor++1811.00537]

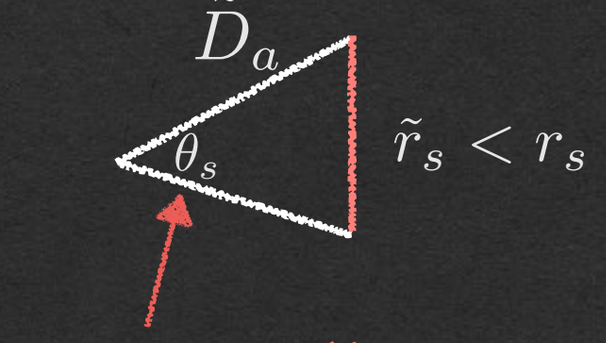
Shortening the sound horizon



increasing Hubble

$D_a \propto 1/H_0$

$(\Omega_r, \Omega_m, \Omega_\Lambda)$ fixed



A road well-travelled

- 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!

$$1100 < z < 25000$$

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

$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_X(z)}$$ ← new component (~10%)

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

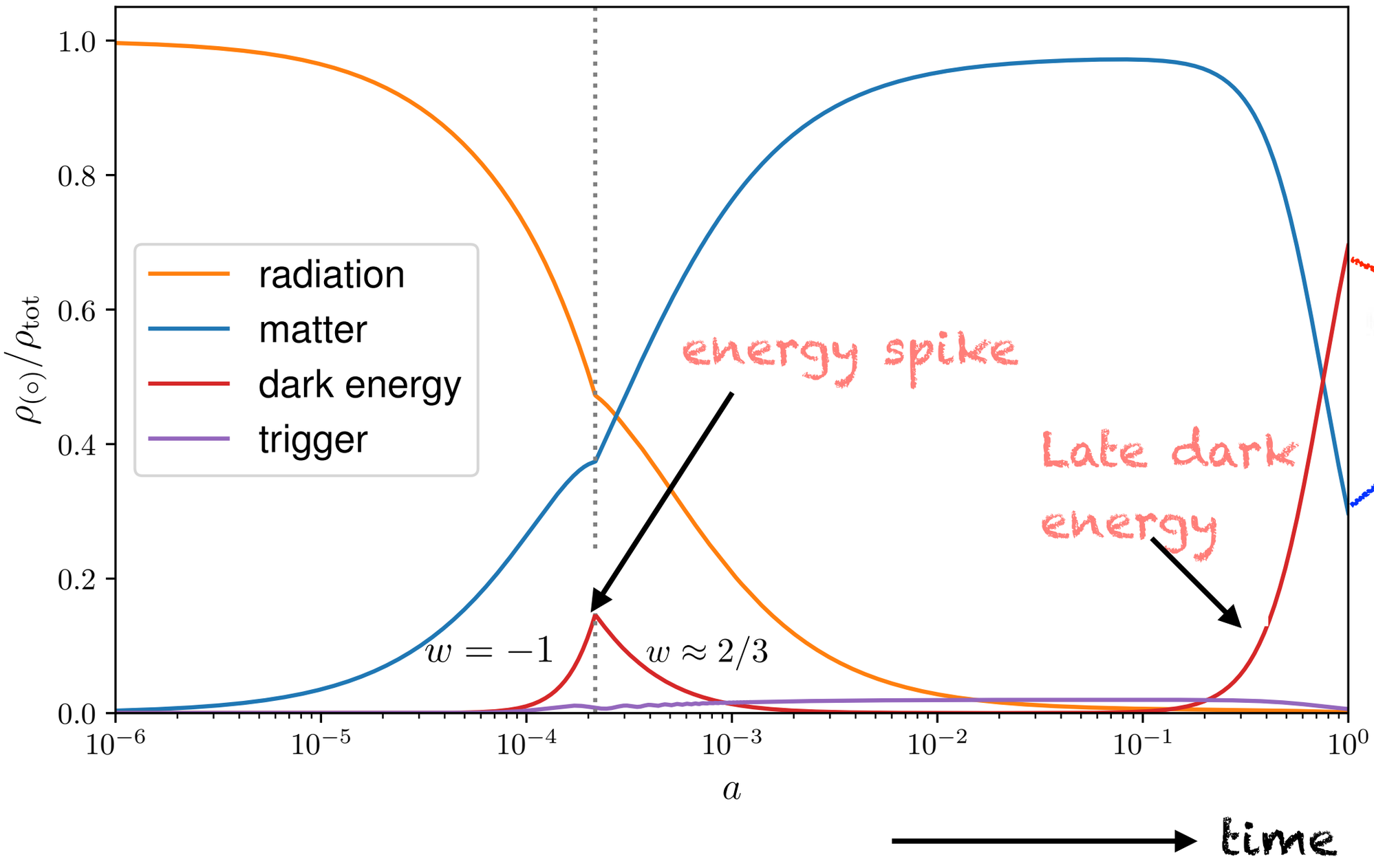
- Canonical example: **Dark Radiation (DR)**

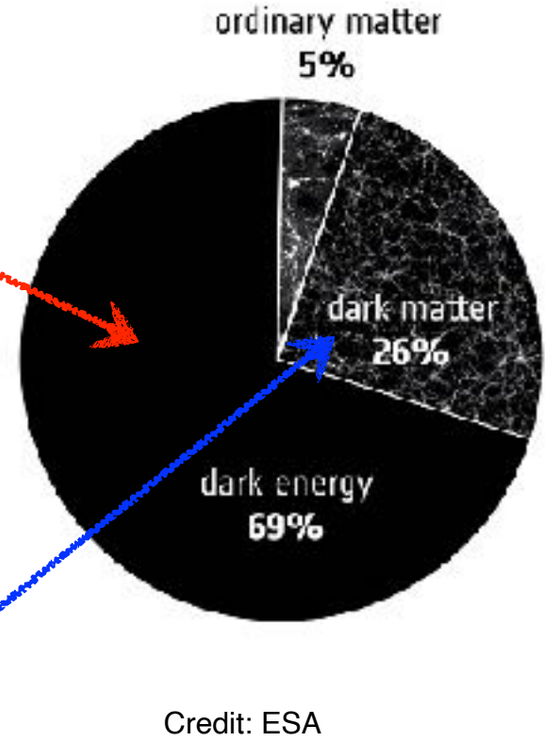
$$\Omega_X(t) = \Omega_{\rm DR}\, a(t)^{-4}$$

- **Problem:** Too much diffusion damping on small scales.
- Generalisations where DR constituents becomes non-relativistic around eV scale and annihilate are more promising (see Majoron and "step" proposal).

[Escudero++,2004.01470] [Aloni++,2111.00014]

What works phenomenologically…



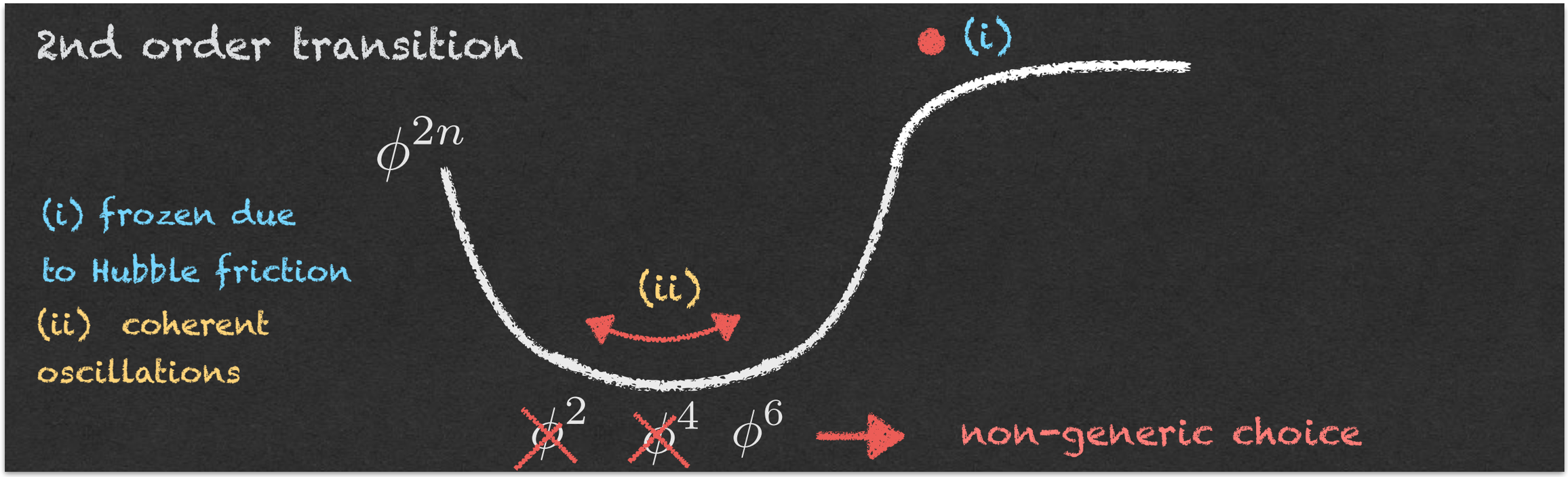


Credit: ESA

- **Question:** What is the underlying microphysics?

Early Dark Energy

[Poulin, Smith, Karwal, Kamionkowski, 2018]



- **Phenomenology requires:**
  - Flattening of potential at high field values.
  - Oscillations in anharmonic potential.
  - Ultralight effective mass : $m \sim 10^{-27}\mathrm{eV}$

cycle-averaged:

$$\Omega_X(t) \simeq \begin{cases} \Omega_{\rm EDE} \\ \Omega_{\rm EDE}\ [a(t_*)/a(t)]^\alpha \end{cases}$$

where

$$\alpha = 3(1+w_n)$$

$$w_n = \frac{n-1}{n+1}$$

- Brings tension down to ~2 sigma (1p-EDE).

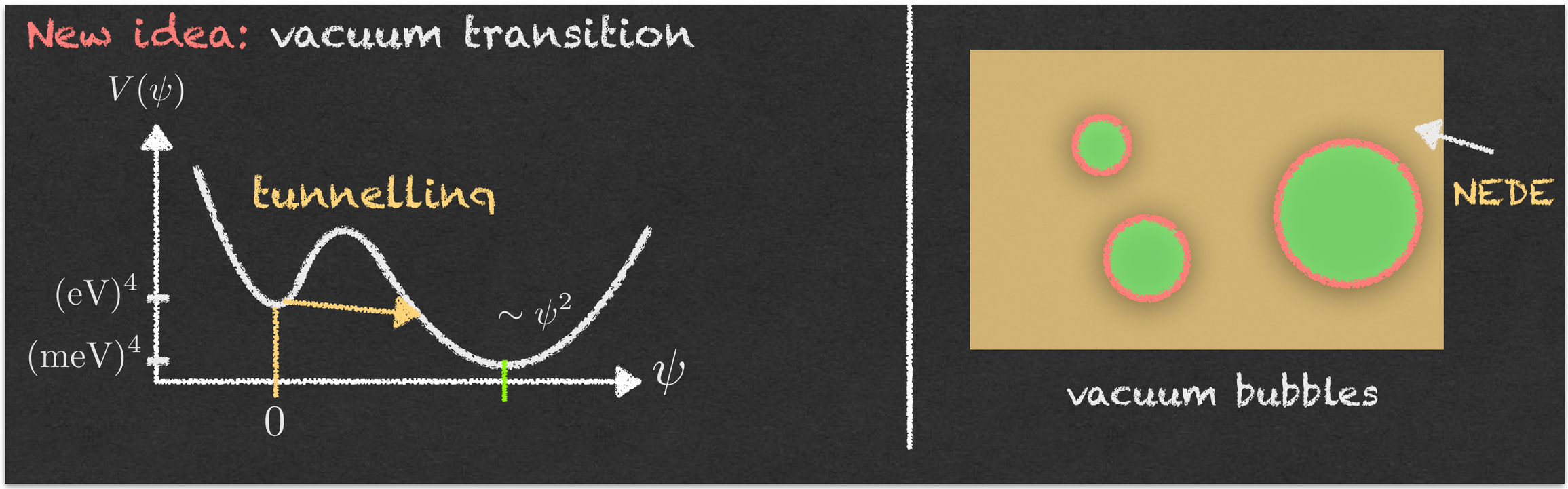
  [Planck 2018 + BAO (+LSS) + Pantheon + BBN]

- **Challenges:**
  - How to justify choice ϕ^6 ?
  - Not resolving S8 tension (does not make it much worse though).

    Poulin++,2302.09032

First order decay scenario

- **Question:** Can we find a model more motivated from particle physics?



- **Hubble tension:** EDE/NEDE 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: $\Gamma(\phi) \propto \exp\left[-S_E(\phi)\right]$

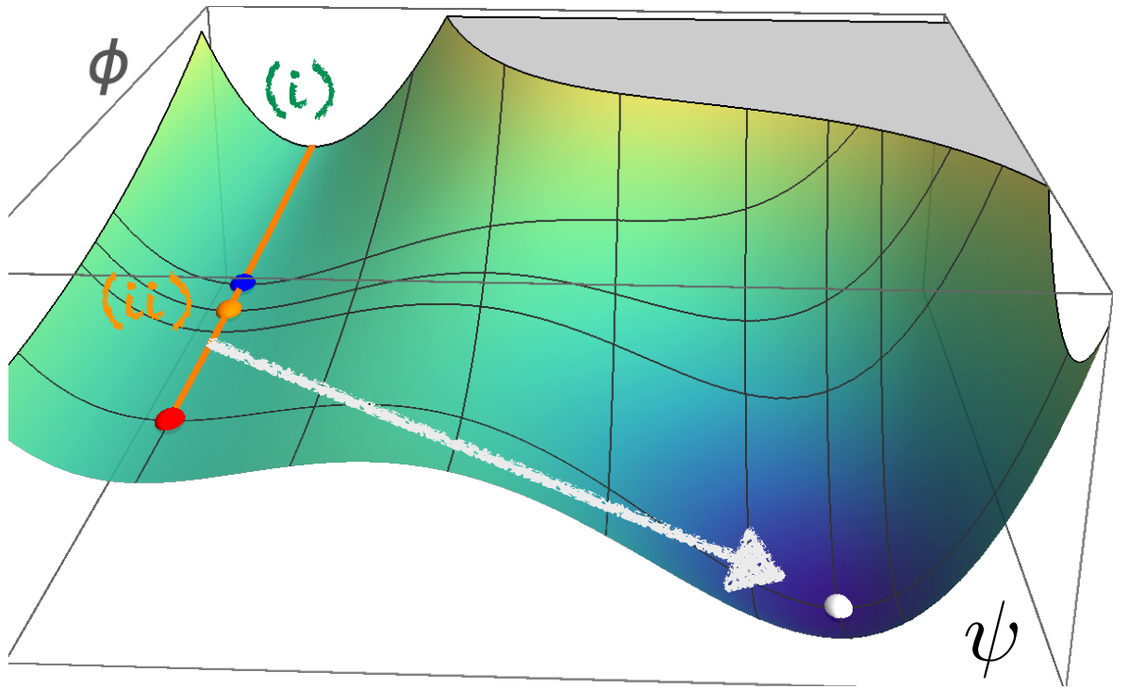
(i) field stuck initially:

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

(ii) ϕ starts evolving

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

→ bubble nucleation turns on



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

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

→ rapid nucleation event

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

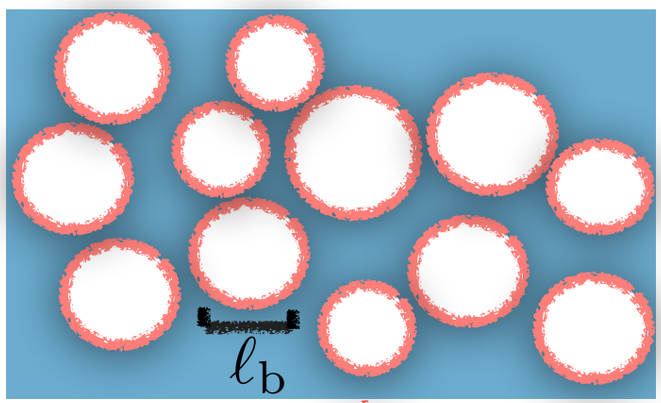
weak coupling: $\lambda < 0.1$

NEDE Phenomenology

- Central requirement:

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

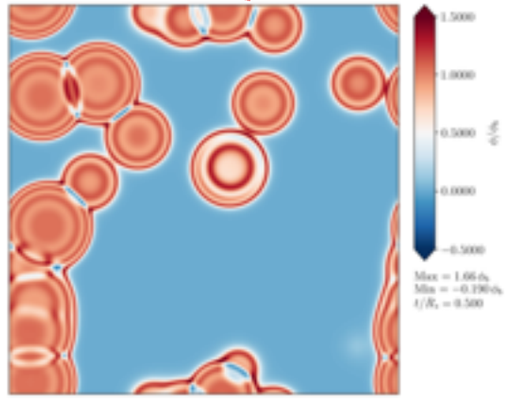
- **Consequence**: Phase transition is an **instantaneous** process on cosmological scales.

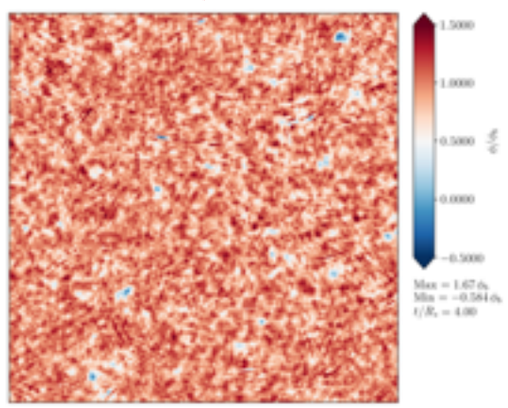


+ colliding walls
+ shear stress (e.g. GW)
+ microscopic decays

- Numerical picture (thick wall):

[Cutting++,2005.13537]



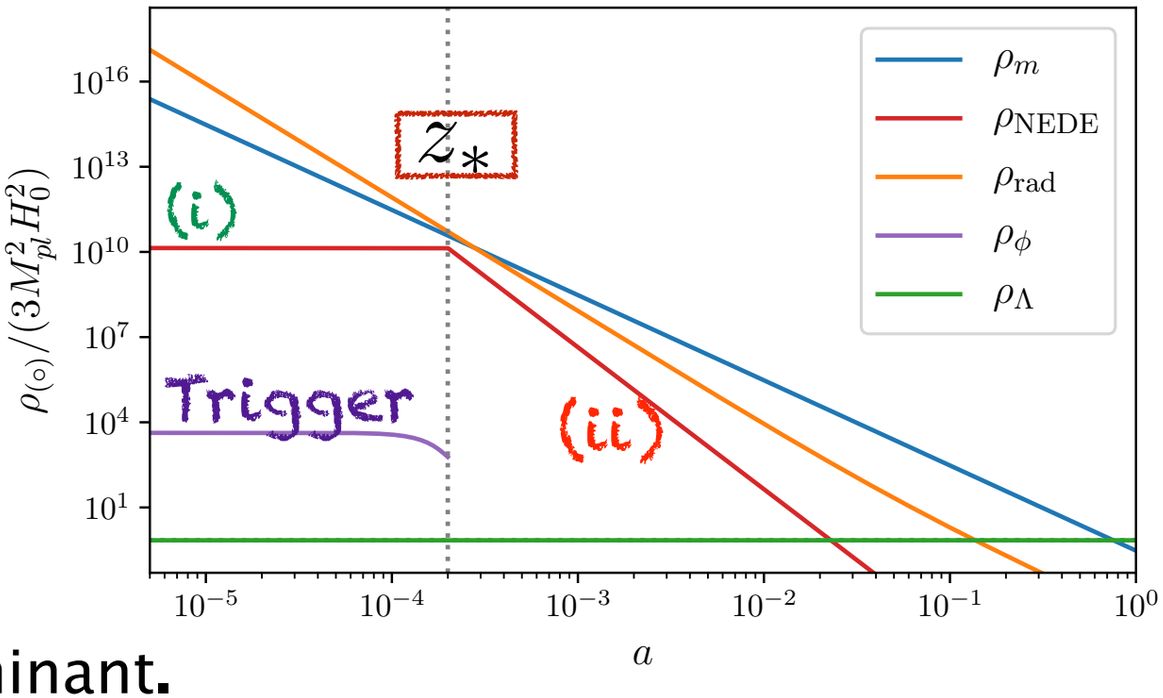


- **After phase transition**: Small-scale anisotropic stress
- Describe as **ideal fluid model** on cosmological scales (no preferred direction or position).
- Rich phenomenology: e.g. **sourcing** of tensor shear aka GWs (e.o.s.=1/3) + vector shear (e.o.s.=1) and scalar shear (e.o.s.=1/3). → **work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

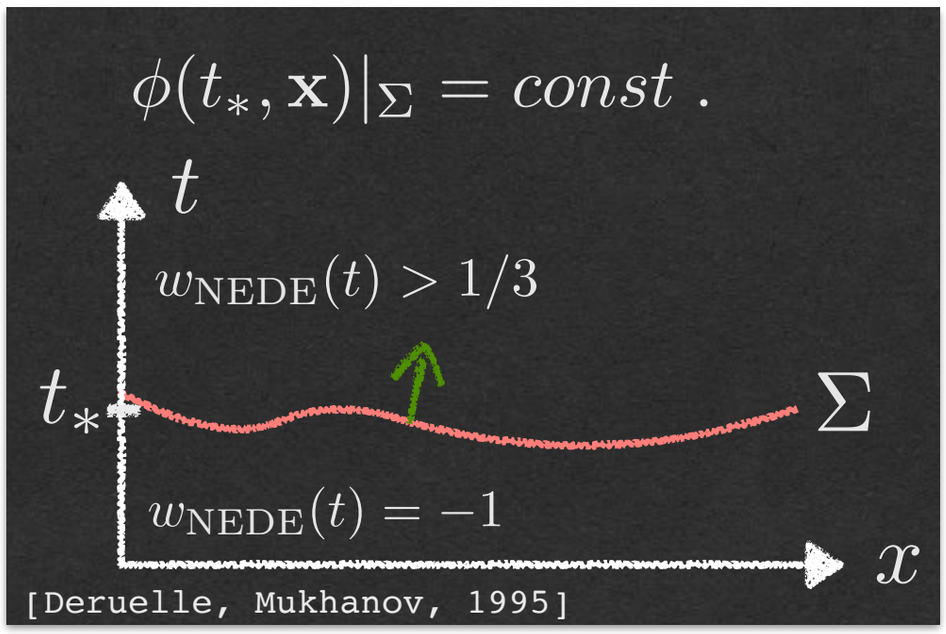
NEDE fluid model

- **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)

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



- **Trigger** field (for now) highly subdominant.
- However, trigger is still important as it seeds the NEDE fluctuations.



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

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

- Implemented in public code TriggerCLASS.

NEDE dictionary

Phenomenological parameters:

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

Microphysics:

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

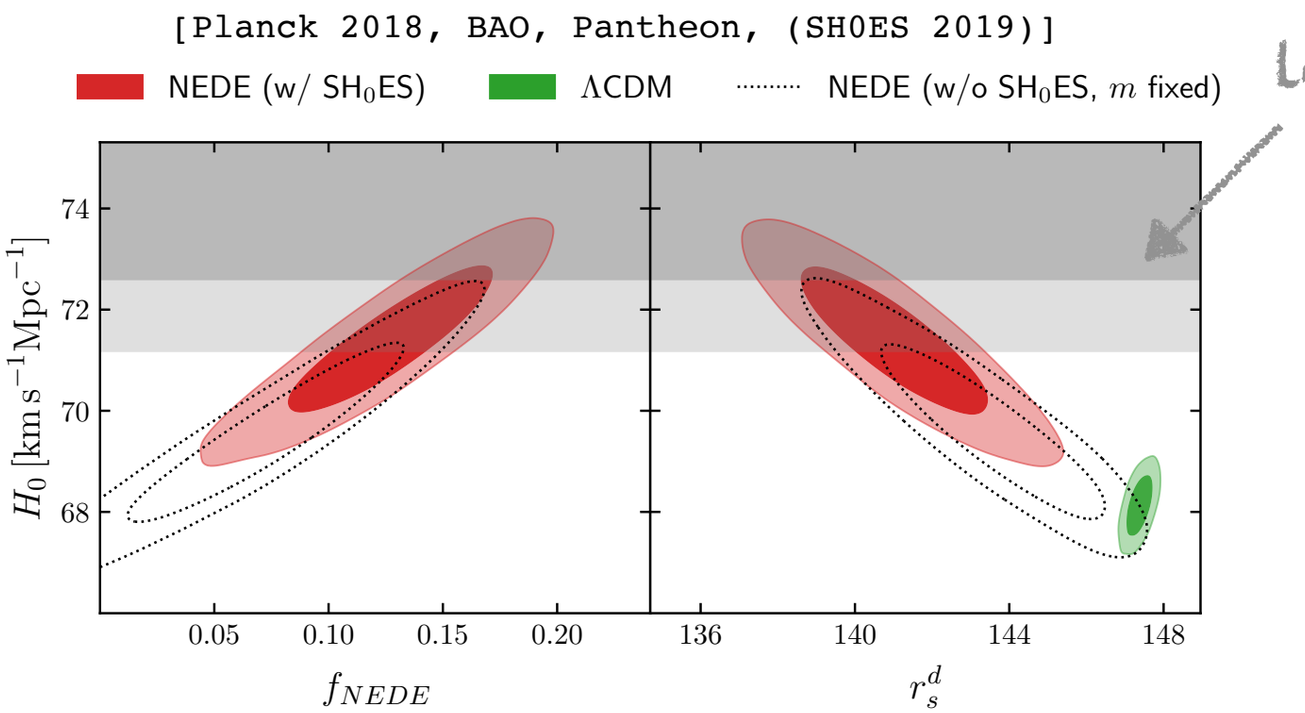
→ NEDE transition set by eV scale

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

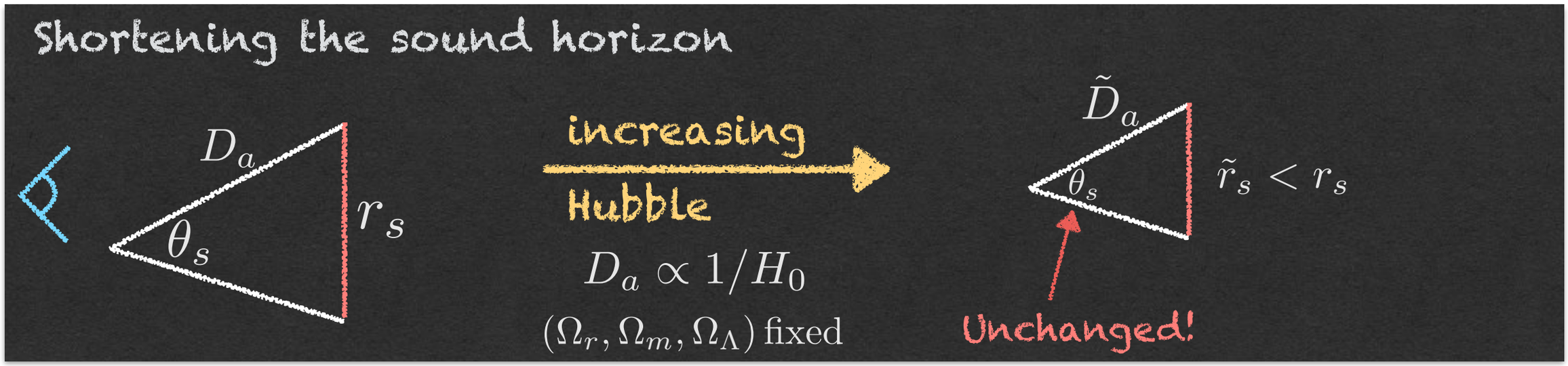
→ trigger is ultralight

- e.o.s. parameter treated phenomenologically (for now).
- Consider **simplest** implementation:
  - parameters: p.t. redshift z_* & fraction NEDE $f_{\rm NEDE}$
  - fix $w_{\rm NEDE} = c_s^2 = 2/3$ (relaxed later)
  - trigger field subdominant (relaxed later)

Background Mechanism

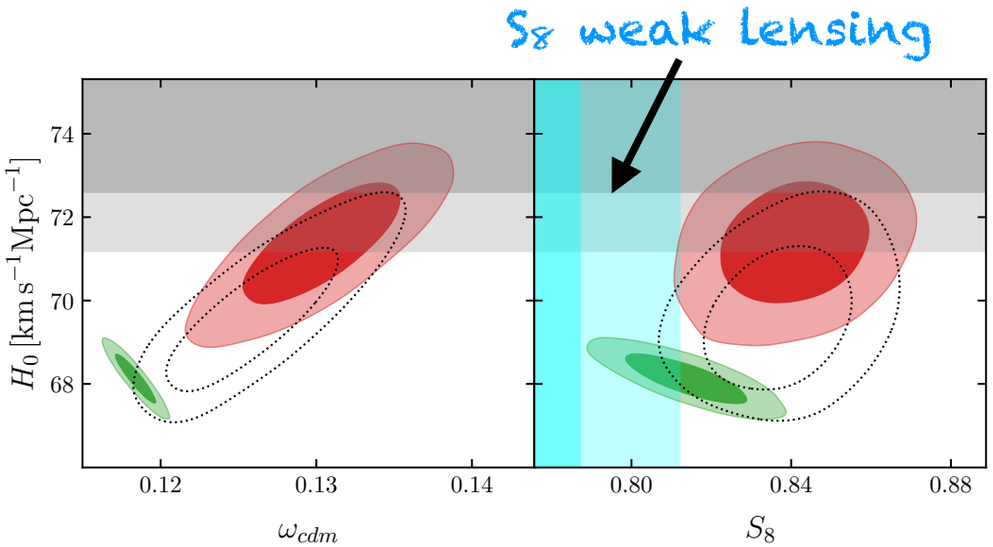


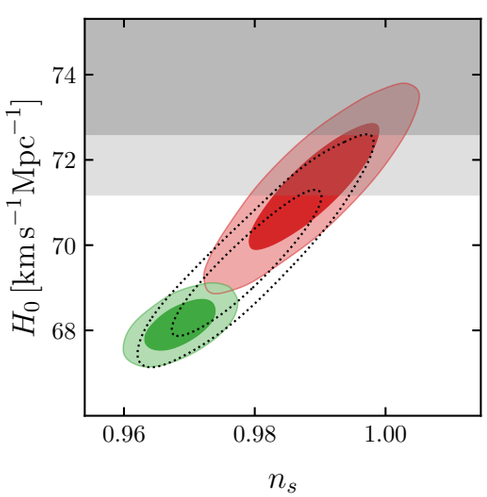
- Energy injection reduces sound horizon.
- Compensated by larger H_0
- Keeps angular scale fixed.
- Main background degeneracy (broken by including H0 prior).



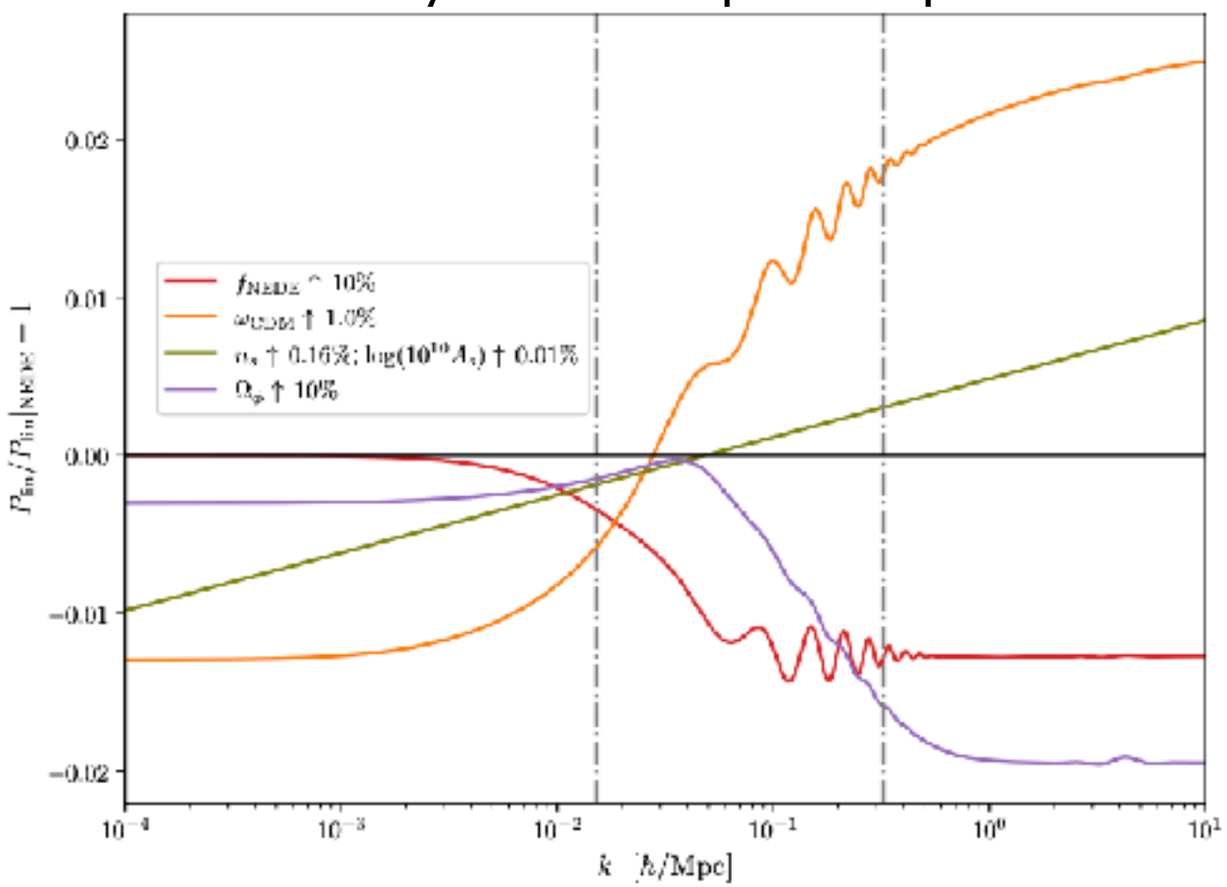
Secondary Mechanism

- 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.





sensitivity of matter power spectrum



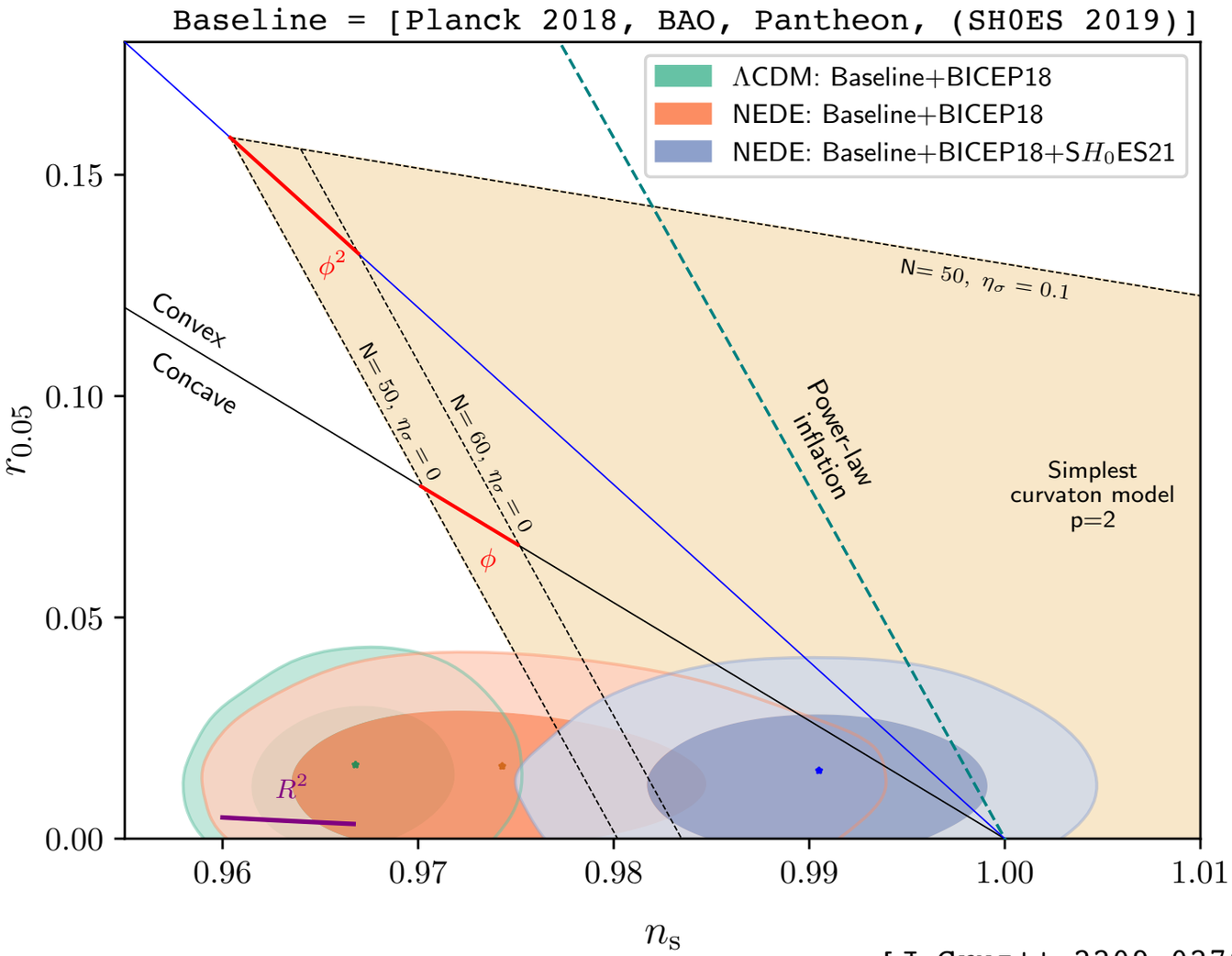
- Small residual effect on small scales.
- S8 tension: 2.5 -> 2.8 sigma

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

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

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

Interlude: 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

The H_0 Olympics: A fair ranking of proposed models

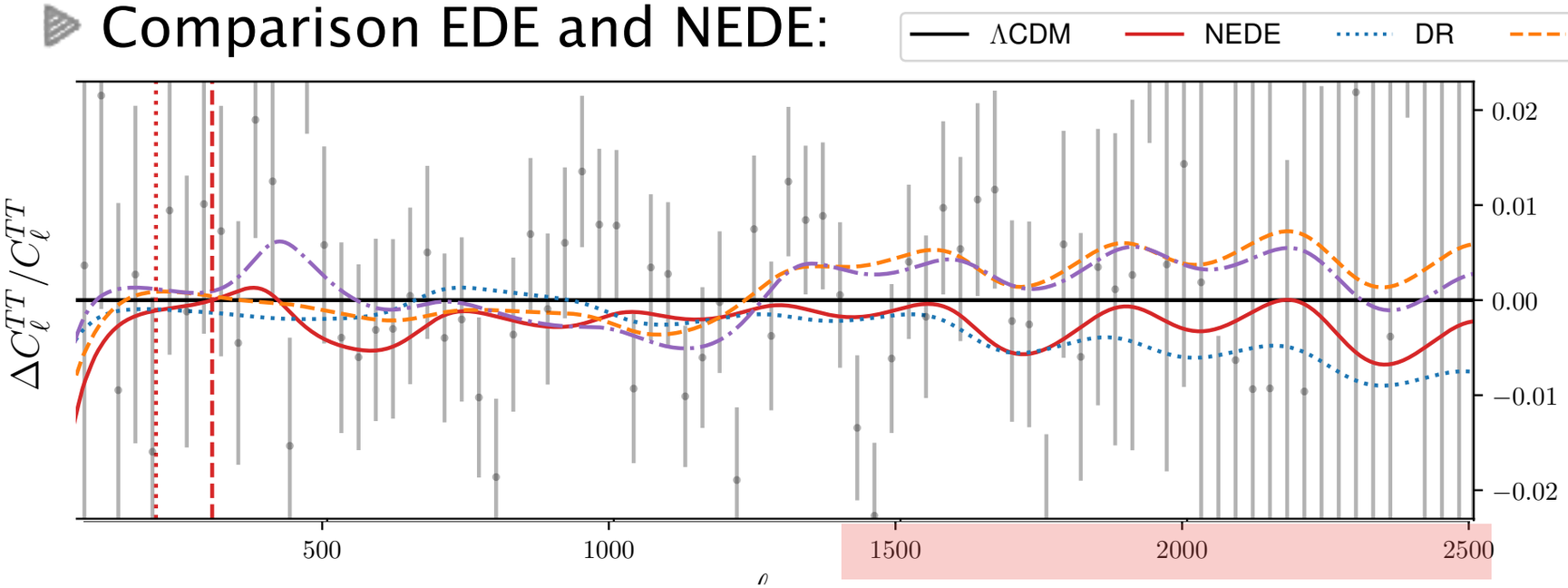
Nils Schöneberg,[a] Guillermo Franco Abellán,[b] Andrea Pérez Sánchez,[a] Samuel J. Witte,[c] Vivian Poulin,[b] and Julien Lesgourgues[a]

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	X	0.00	0.00	X	X
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	X	-10.83	-8.83	✓	✓ 3
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	X	-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

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

- Comparison EDE and NEDE:



[FN&Sloth:2006.06686]

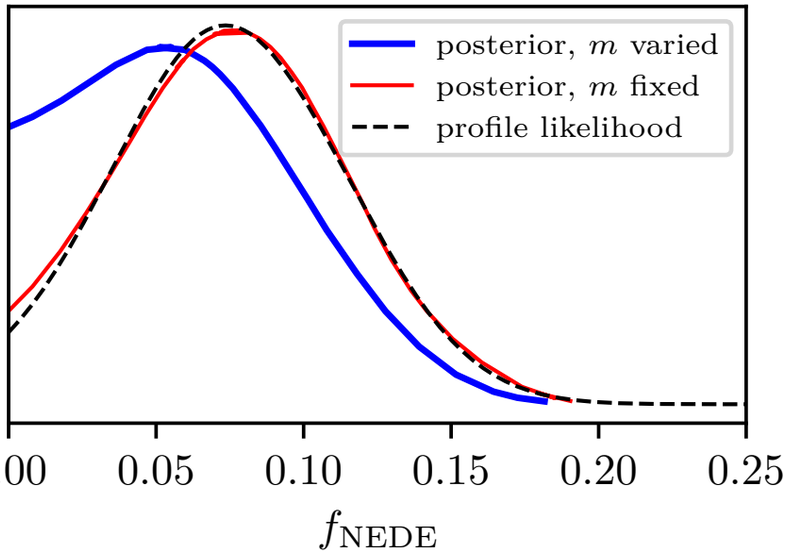
EDE gives more power

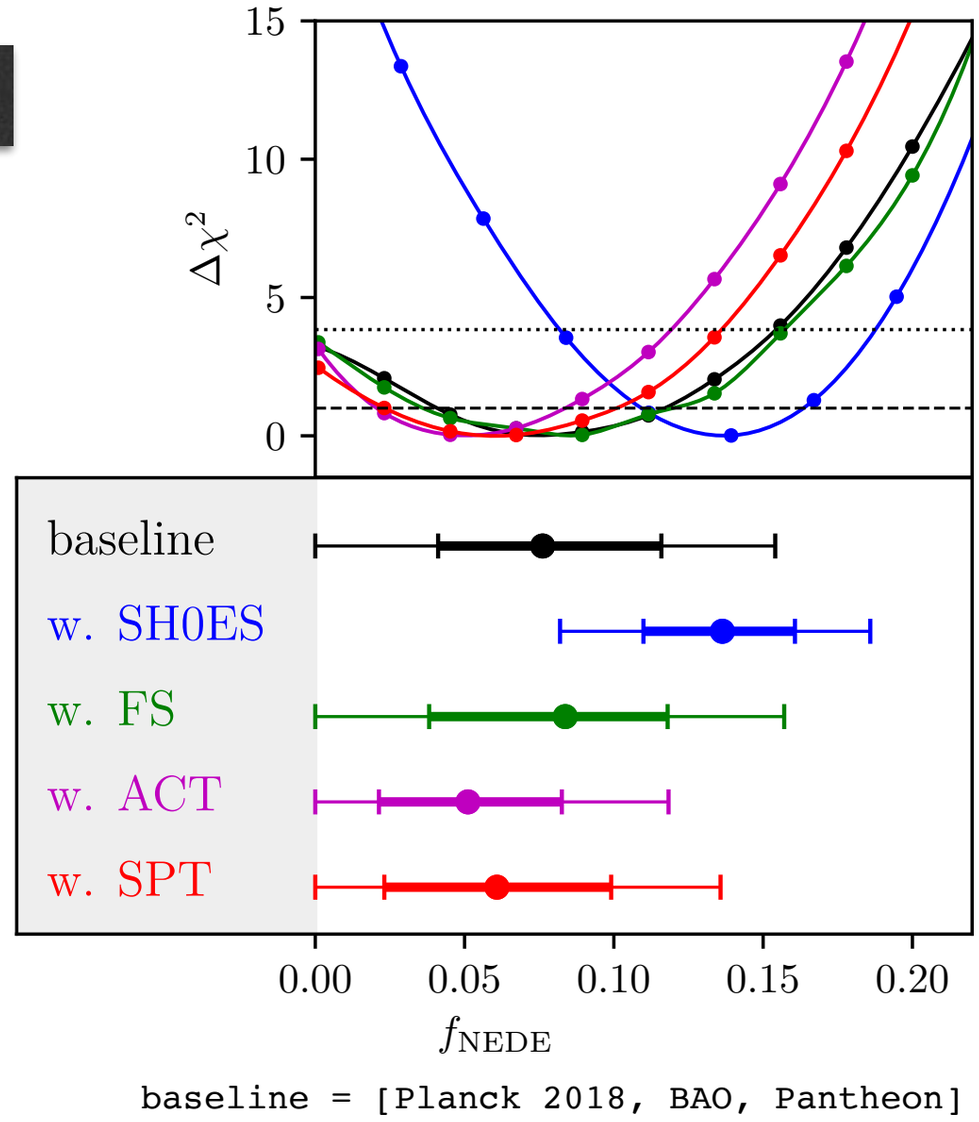
NEDE gives less power

- **Key message:** perturbation sector will help discriminate models

Profile likelihood (with J.Cruz, S. Hannestad, Emil B. Holm, M.Sloth, T. Tram)

- 3-parameter model (i) $f_{\rm NEDE}$ (ii) z_* (iii) $w_{\rm NEDE}$
- More precise high-l (TT and EE) data can help distinguish EDE and NEDE.
- A special role will be played by LSS data.
- First test with EFT of LSS, ACT and SPT data
- Profile likelihood approach avoids prior volume effects.



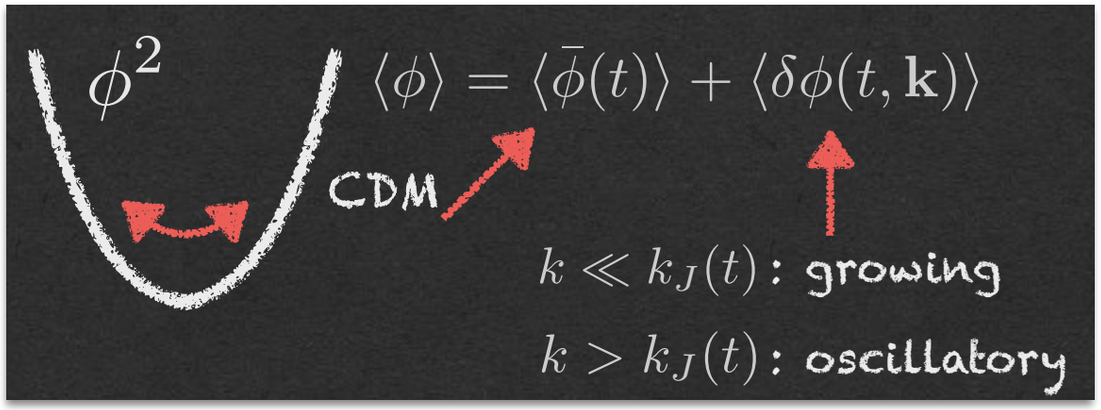


baseline = [Planck 2018, BAO, Pantheon]

- **Upshot:** Not enough constraining power (yet) to go much beyond Planck.
- Hubble tension reduced to 2.1 sigma.
- Gaussian evidence for NEDE around 2 sigma (without SH0ES) and 4.5 sigma (with SH0ES).

Trigger dark matter I

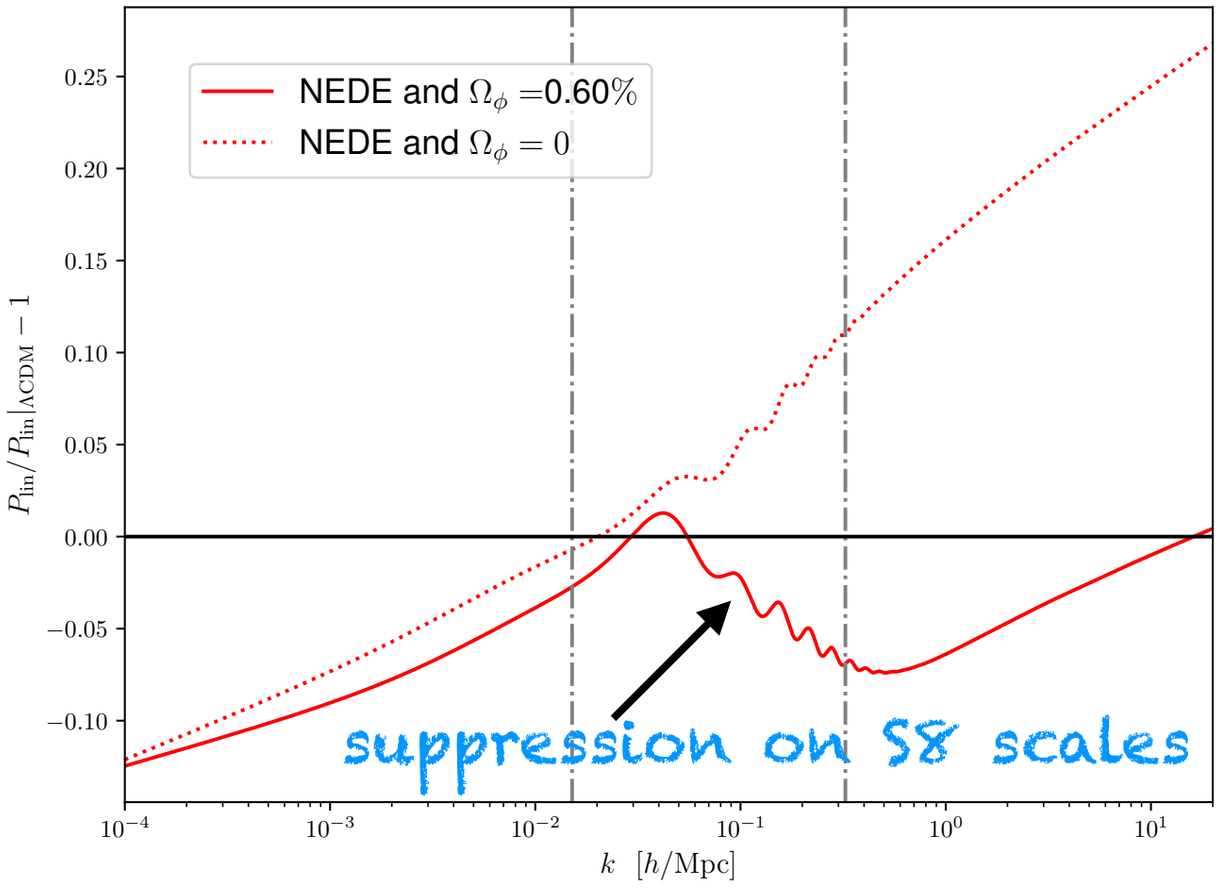
- So far we assumed the trigger to be entirely subdominant.
- However, it can naturally act as light axion-type dark matter.
- NEDE+ultralight scalar studied before by Allali, Hertzberg, and Rompineve, 2021.



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

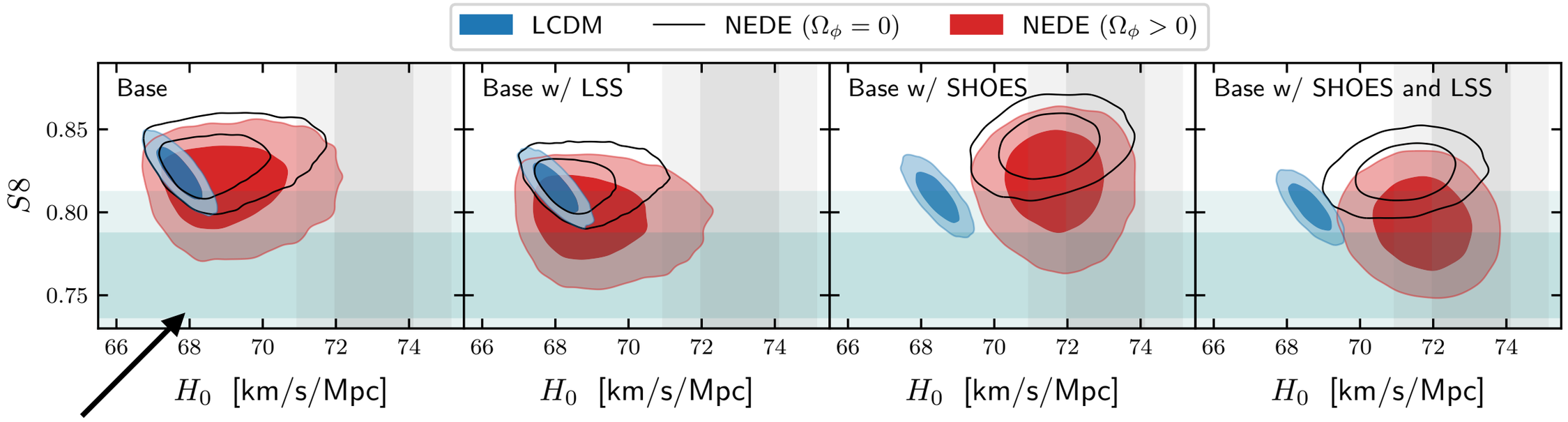


- Compared to CDM, matter power spectrum suppressed below Jeans scale:

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

- Pressure fluctuations act against gravitational collapse.
- Suppresses S8 value.

Trigger dark matter II



S_8 constraint (weak lensing, KiDs+Viking+DES [S. Joudaki et al., 2020])

`Base = [Planck 2018, BAO, Pantheon]`

- 4-parameter extensions of LCDM
- Relaxing the prior on Ω_ϕ
- Key results:
  - Both tensions reduced **below 2 sigma.**
  - Gaussian evidence for NEDE **exceeding 5 sigma.**
  - Overall chi^2 improvement **by 20 units**.
  - Fit to CMB alone improved too.
  - **No new physics** at fundamental level needed to resolve also S8 tension.

(i) $f_{\rm NEDE}$ (ii) z_* (iii) $w_{\rm NEDE}$ (iv) Ω_ϕ

Cold New Early Dark Energy pulls the trigger on the H_0 and S_8 tensions: a simultaneous solution to both tensions without new ingredients

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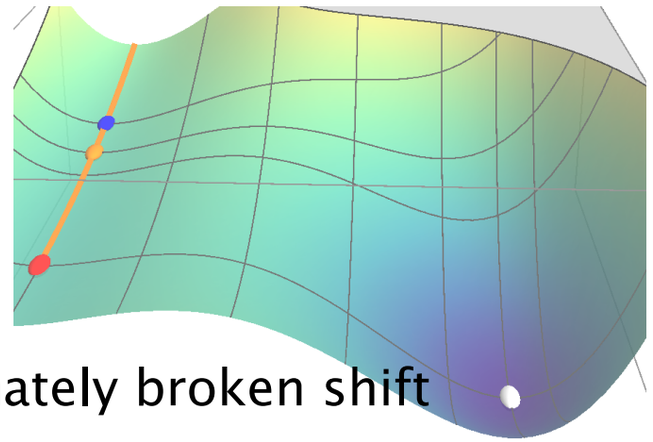
Summary

- H0 and S8 tension exciting opportunity to probe the dark sector.
- EDE looks promising, although the potential appears fine-tuned

  \+ no solution to S8 tension → look for new particle physics models!
- NEDE is a fast-triggered phase transition in dark sector.
- 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 approximately broken shift symmetry.



- Further phenomenological work:
  - Study more general fluid (background and perturbations).
  - Study other anomalies.
  - Keep testing against more LSS and CMB data.
- I did not have time to talk about:
  - Temperature trigger in **hot NEDE** (akin to electroweak phase transition).
  - **Neutrino mass** generation in hot NEDE.
  - Gravitational wave production.