The Hubble Tension as the Signature of a New Phase Transition

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Nordita

in collaboration with:

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and

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and based on earlier work with:

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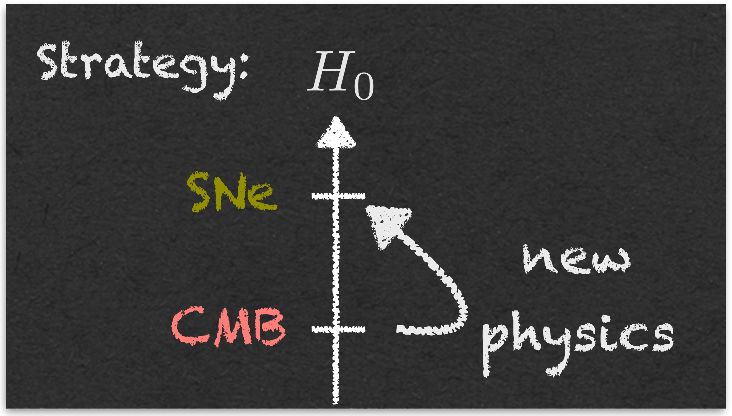

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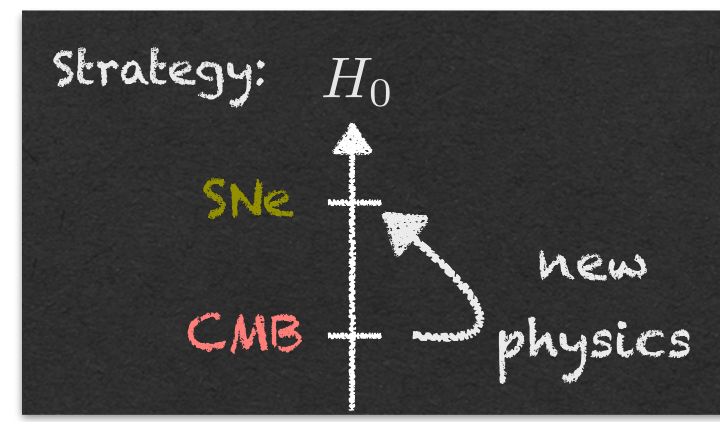

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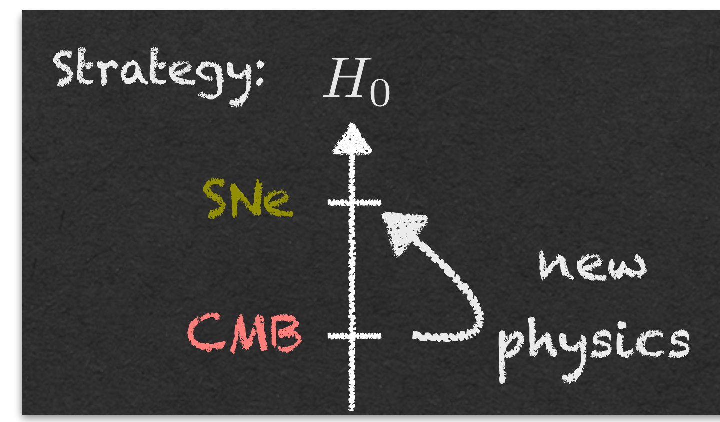

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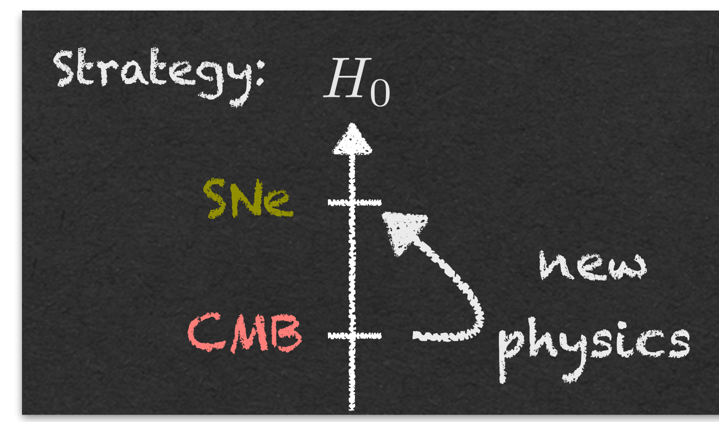

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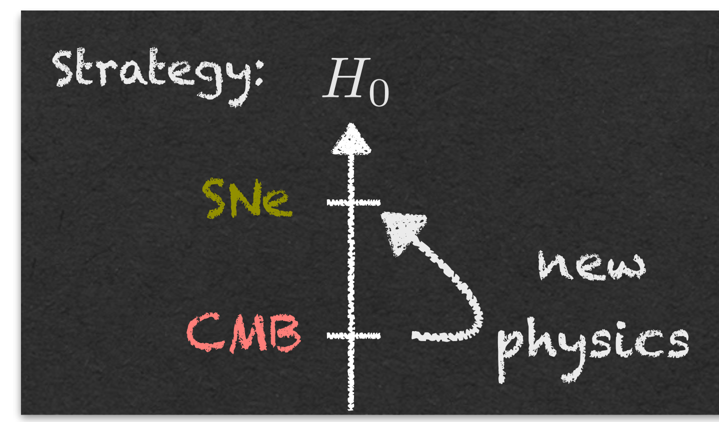

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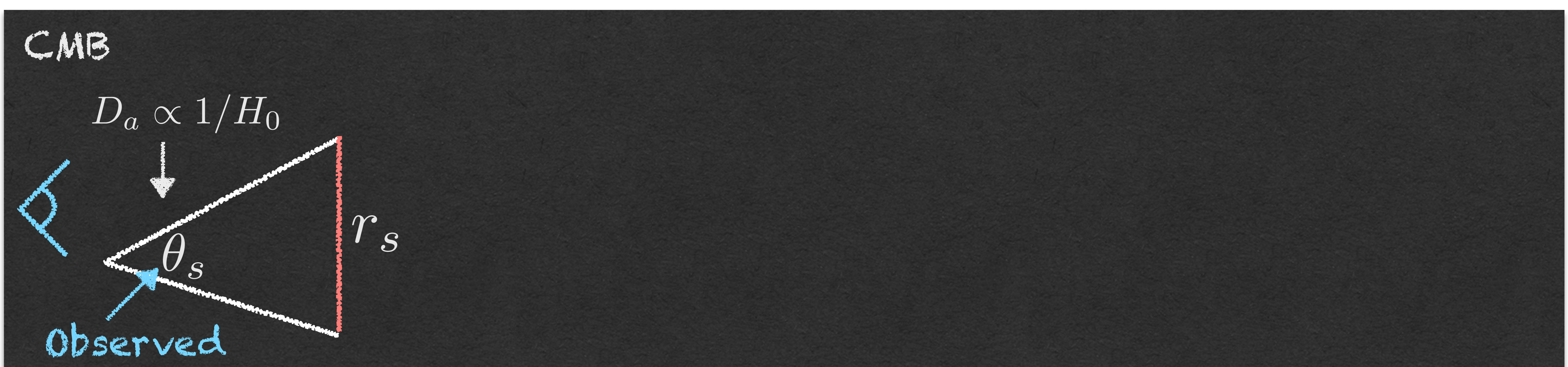

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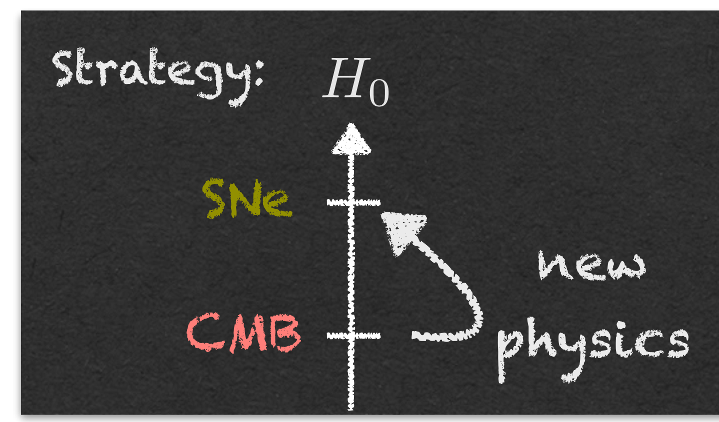

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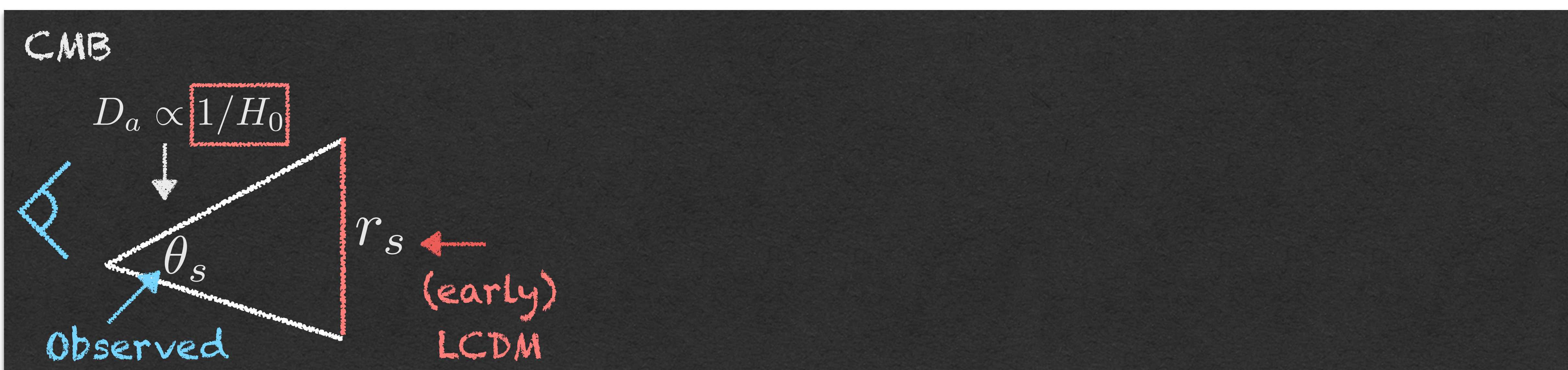

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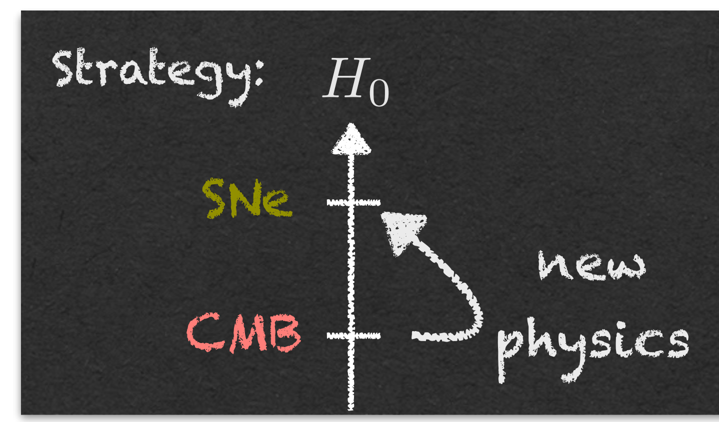

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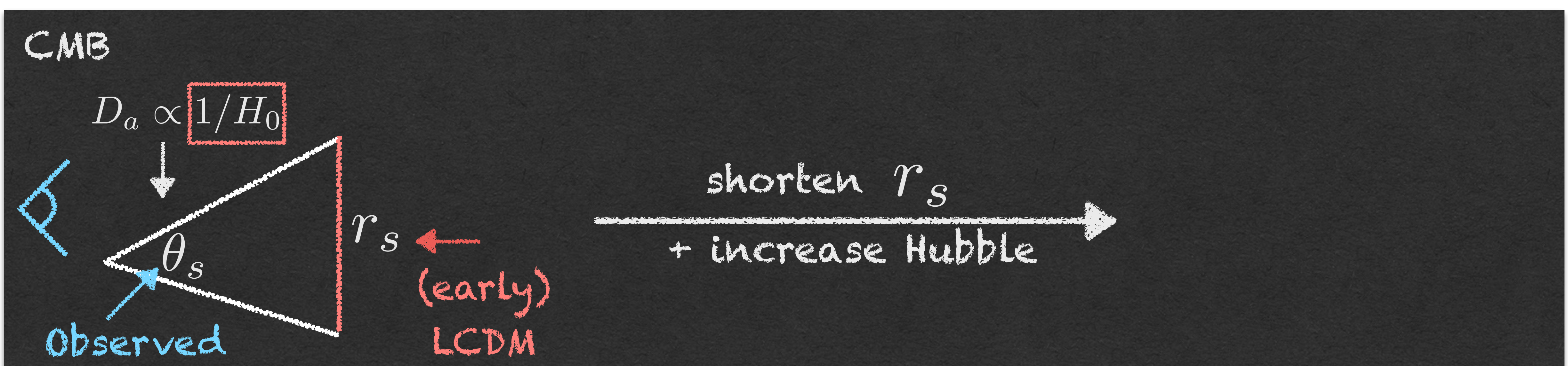

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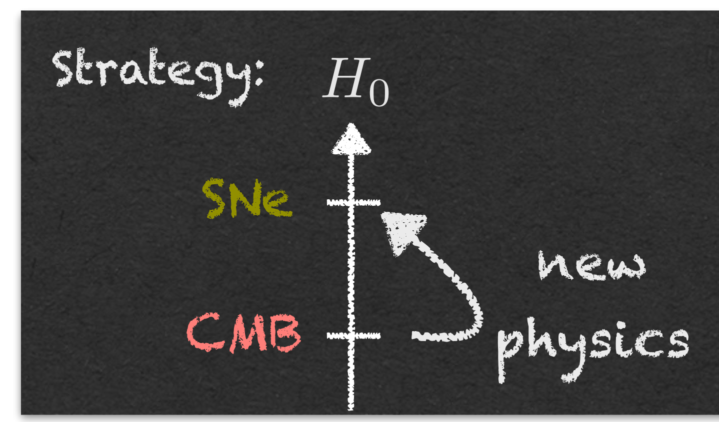

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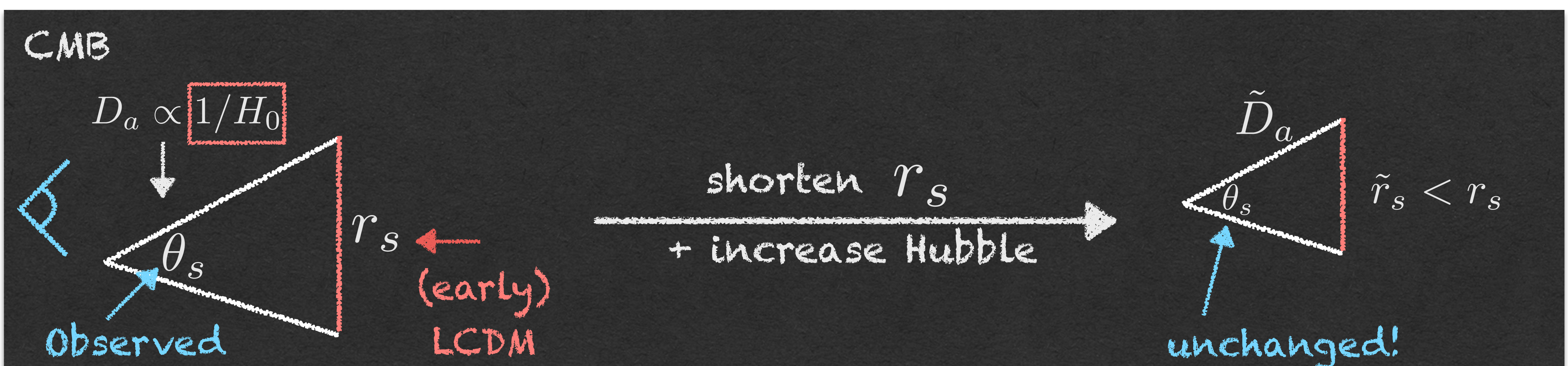

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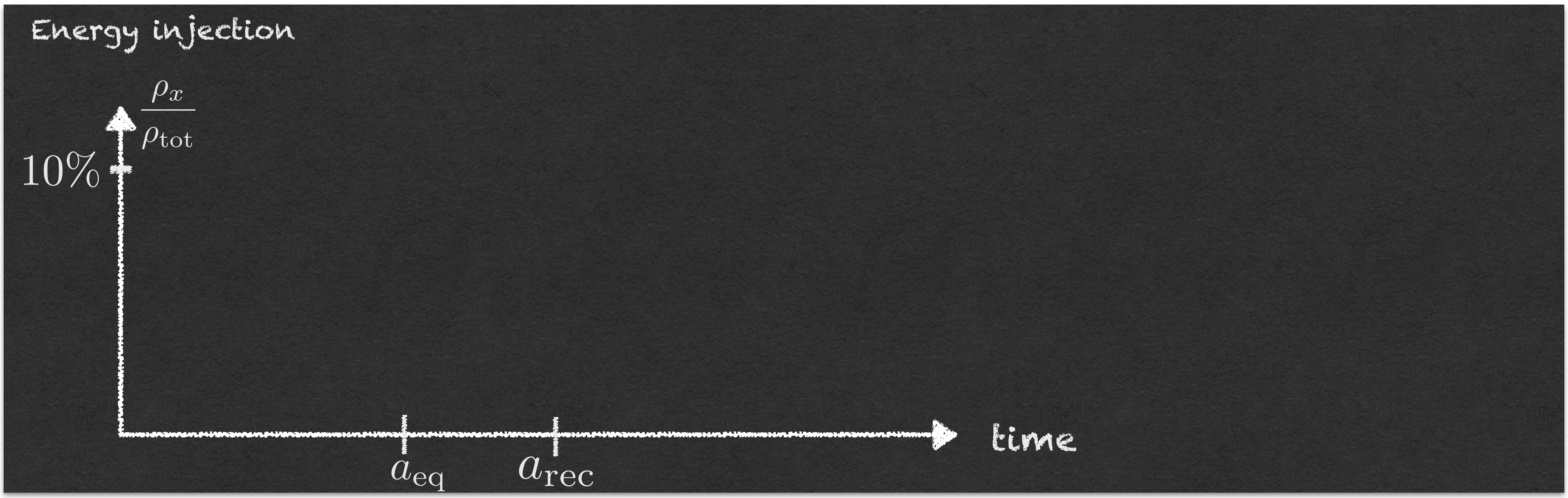

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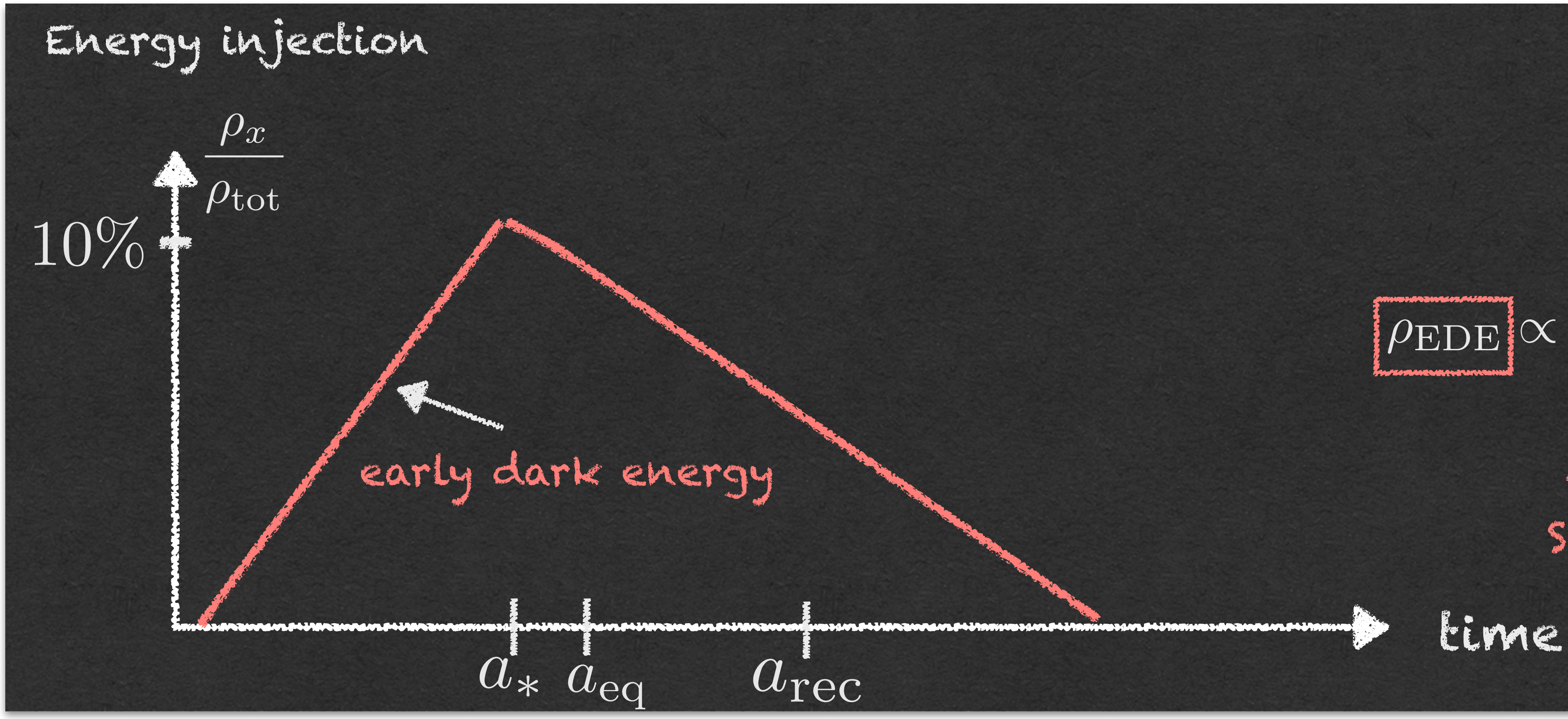

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first model: AxiEDE (Poulin, Smith, Karwal, Kamionkowski)

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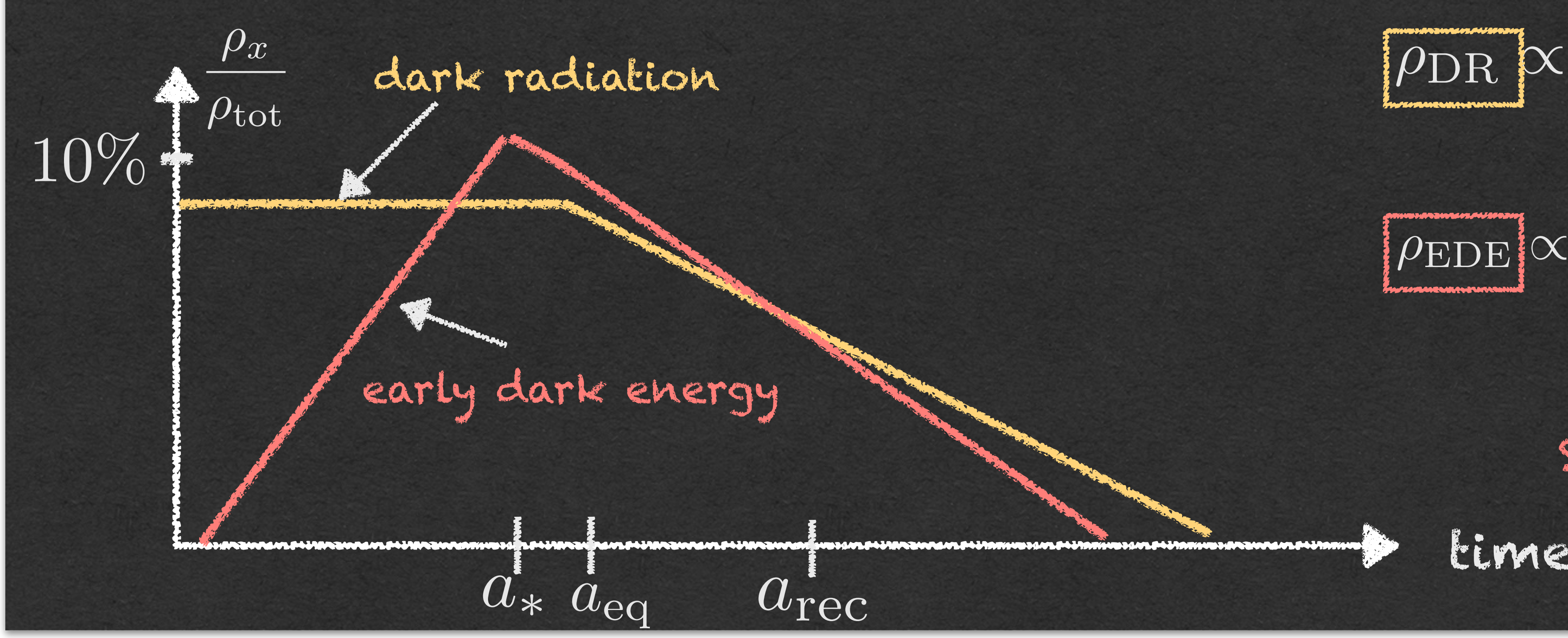

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- **DR:** Provides **continuous** injection before matter-radiation equality — Hot NEDE.

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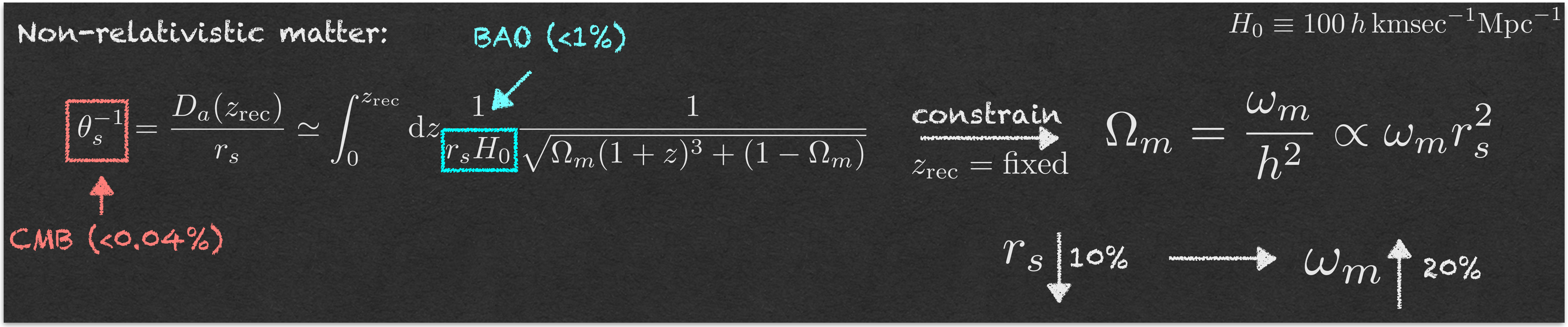

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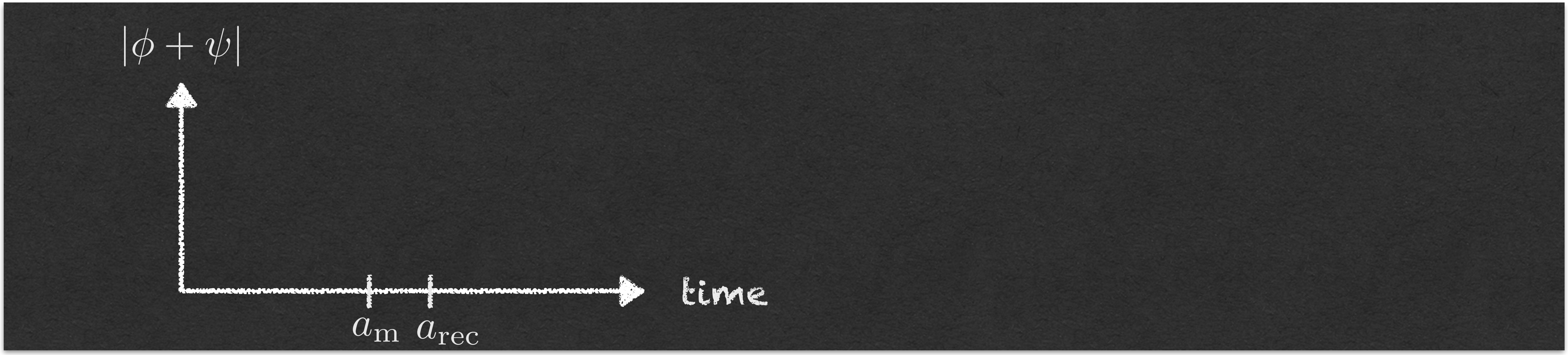

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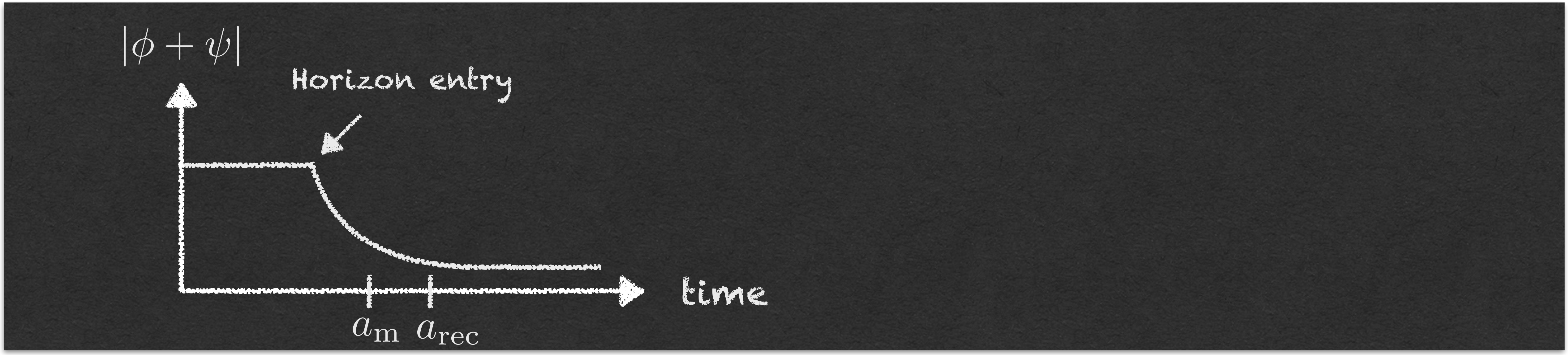

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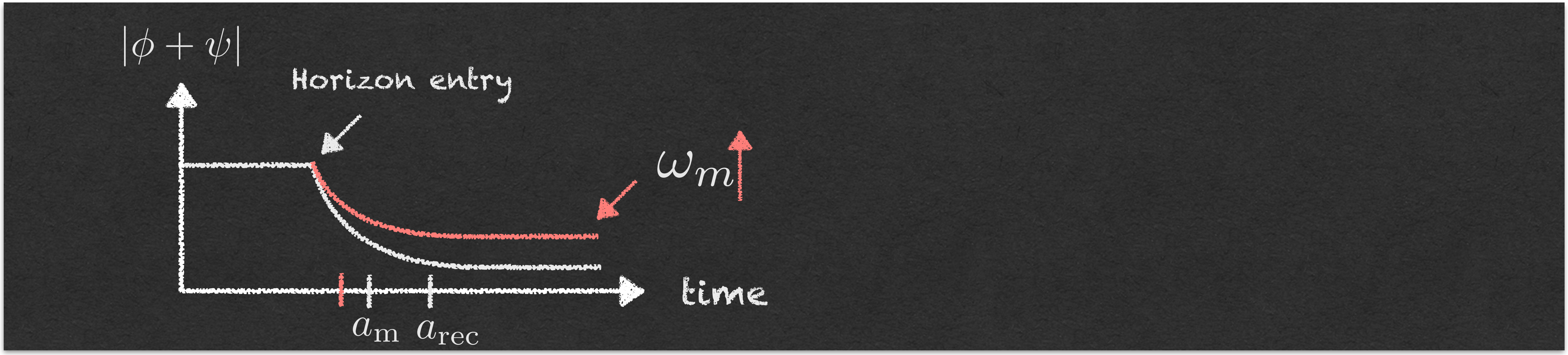

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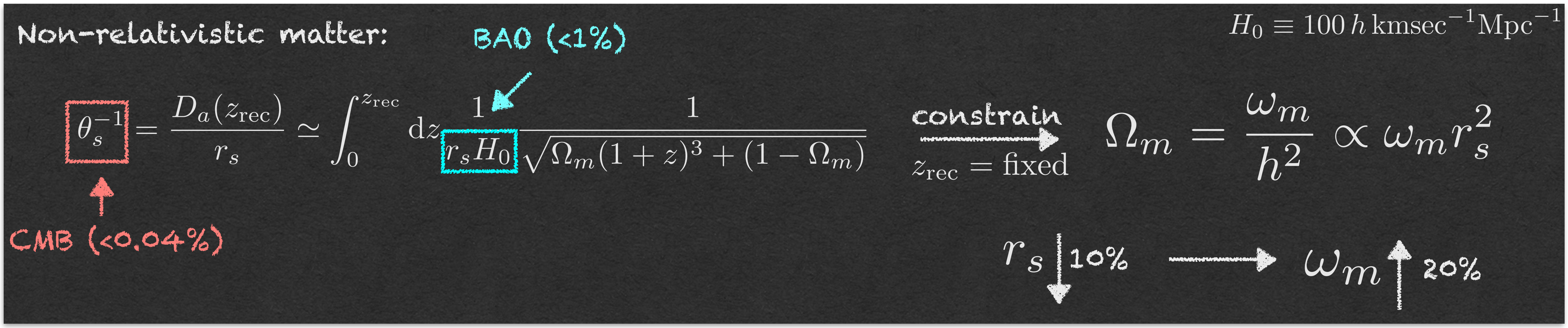

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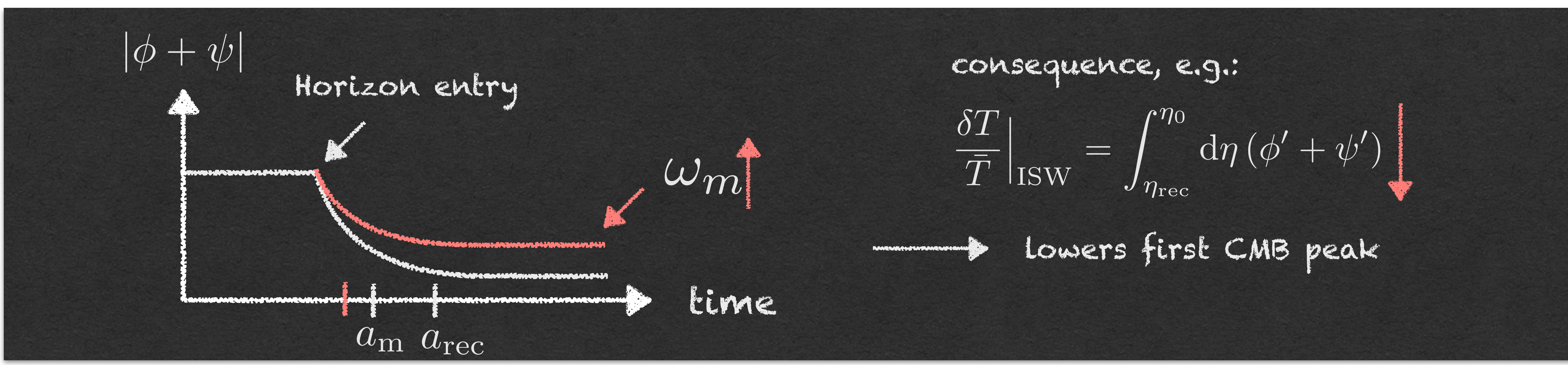

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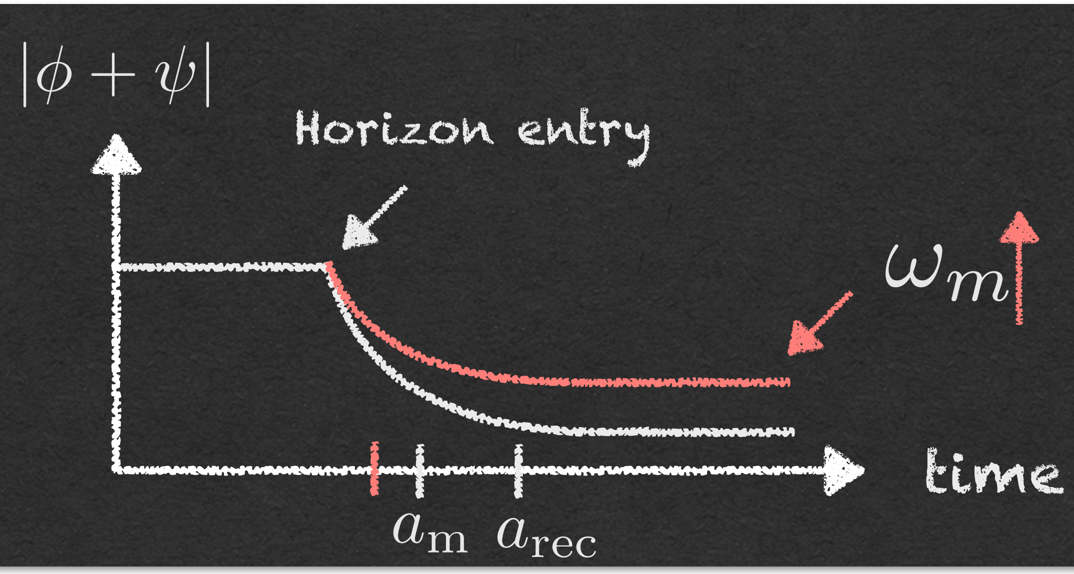

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$\longrightarrow$ lowers first CMB peak

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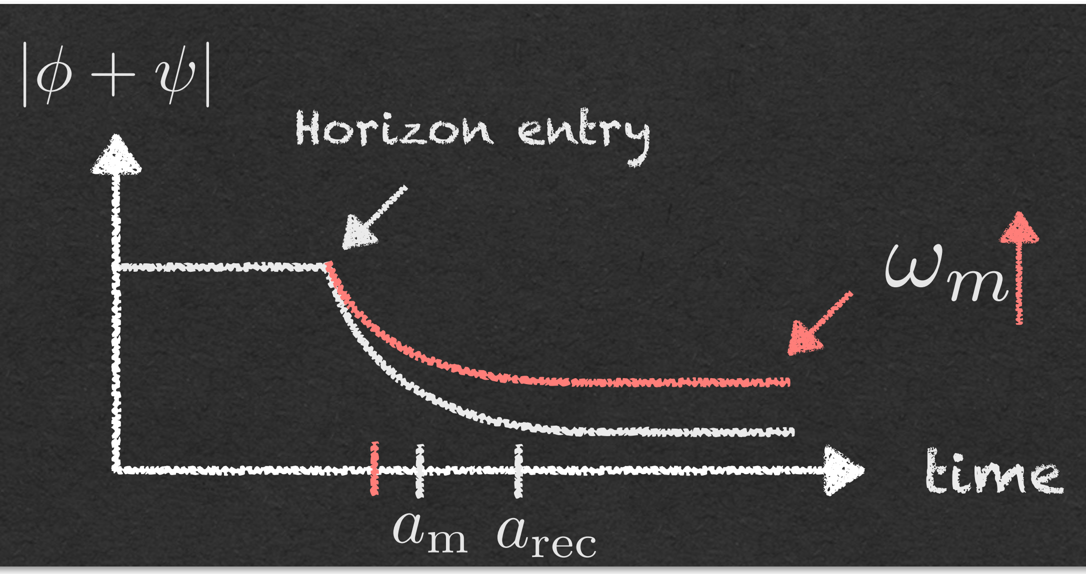

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- Any early-time model needs to come with compensation mechanism, **examples**:

  (i) delay matter domination, (ii) dark sector acoustic oscillations, (iii) fuzzy dark matter
- **Important lesson:** The detailed compensation mechanism requires a specific model!

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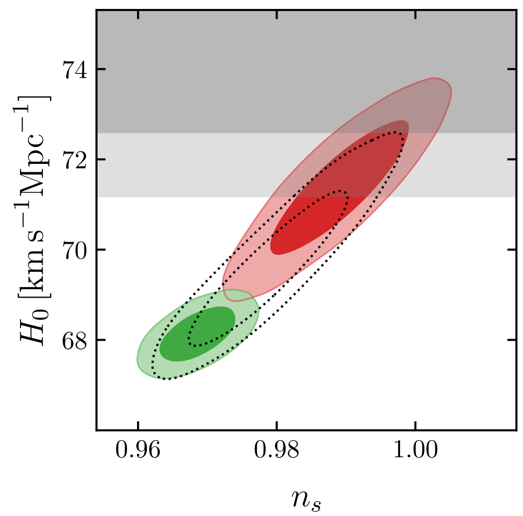

CMB damping: $$\exp\left[-2\left(\frac{r_d}{r_s}\frac{\theta_*}{2\pi}\ell\right)^2\right]$$

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

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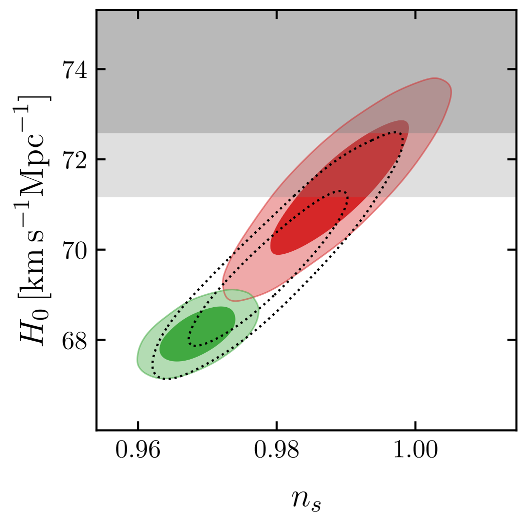
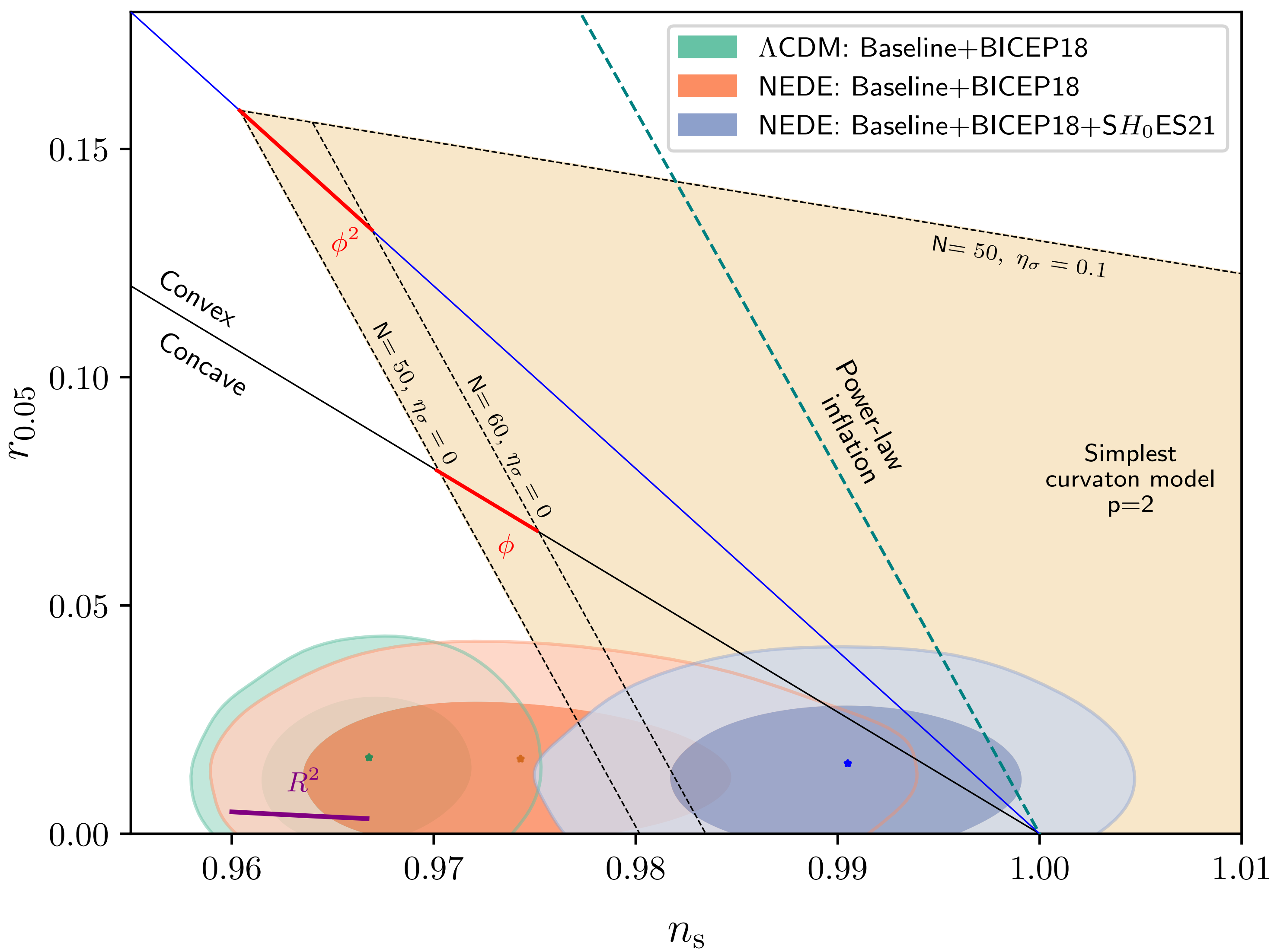


CMB damping: $\exp\left[-2\left(\frac{r_d}{r_s}\frac{\theta_*}{2\pi}\ell\right)^2\right]$

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



- 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 primordial constraints.

Part A: Early Dark Energy

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- Cosmic history:

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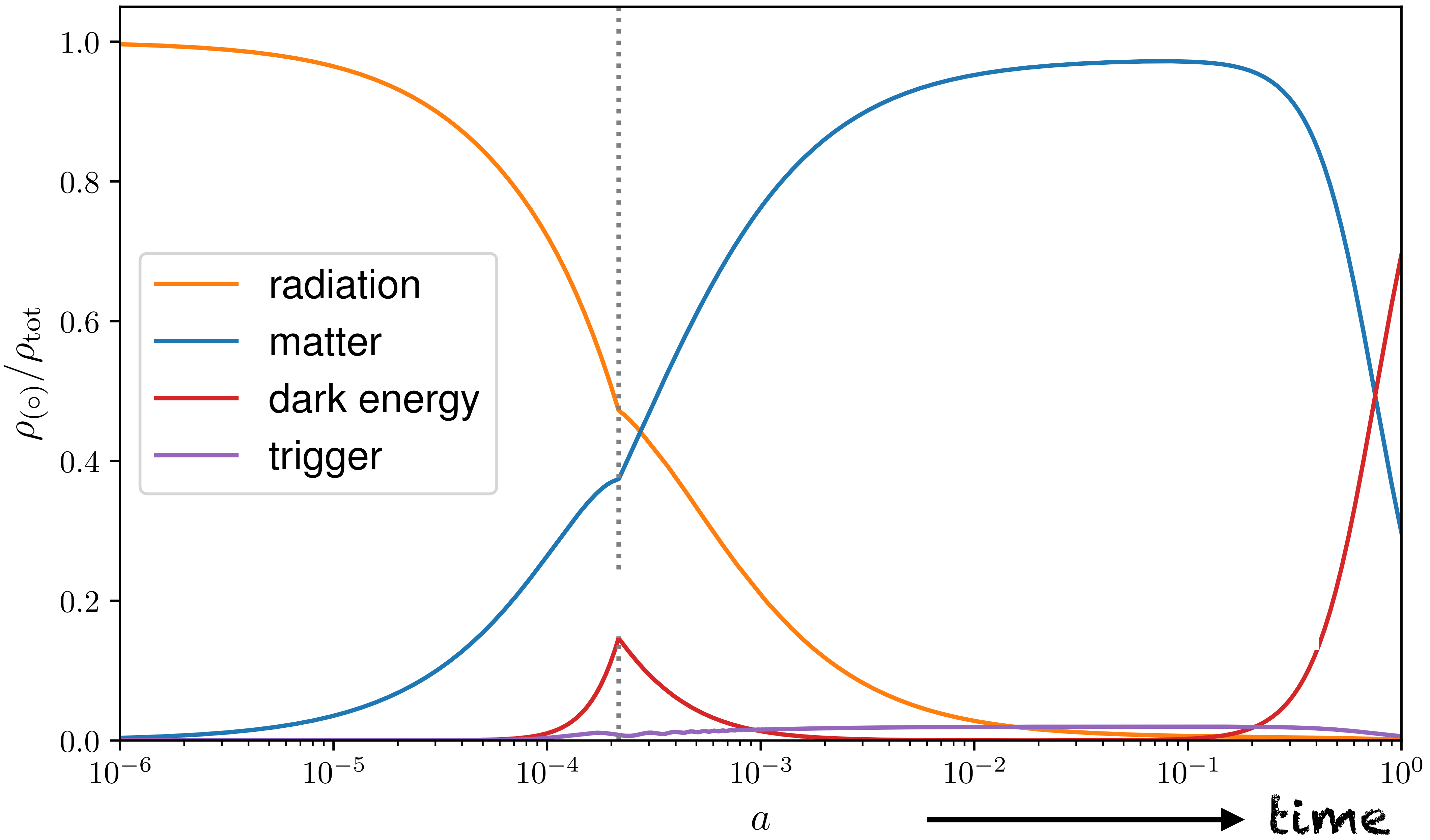

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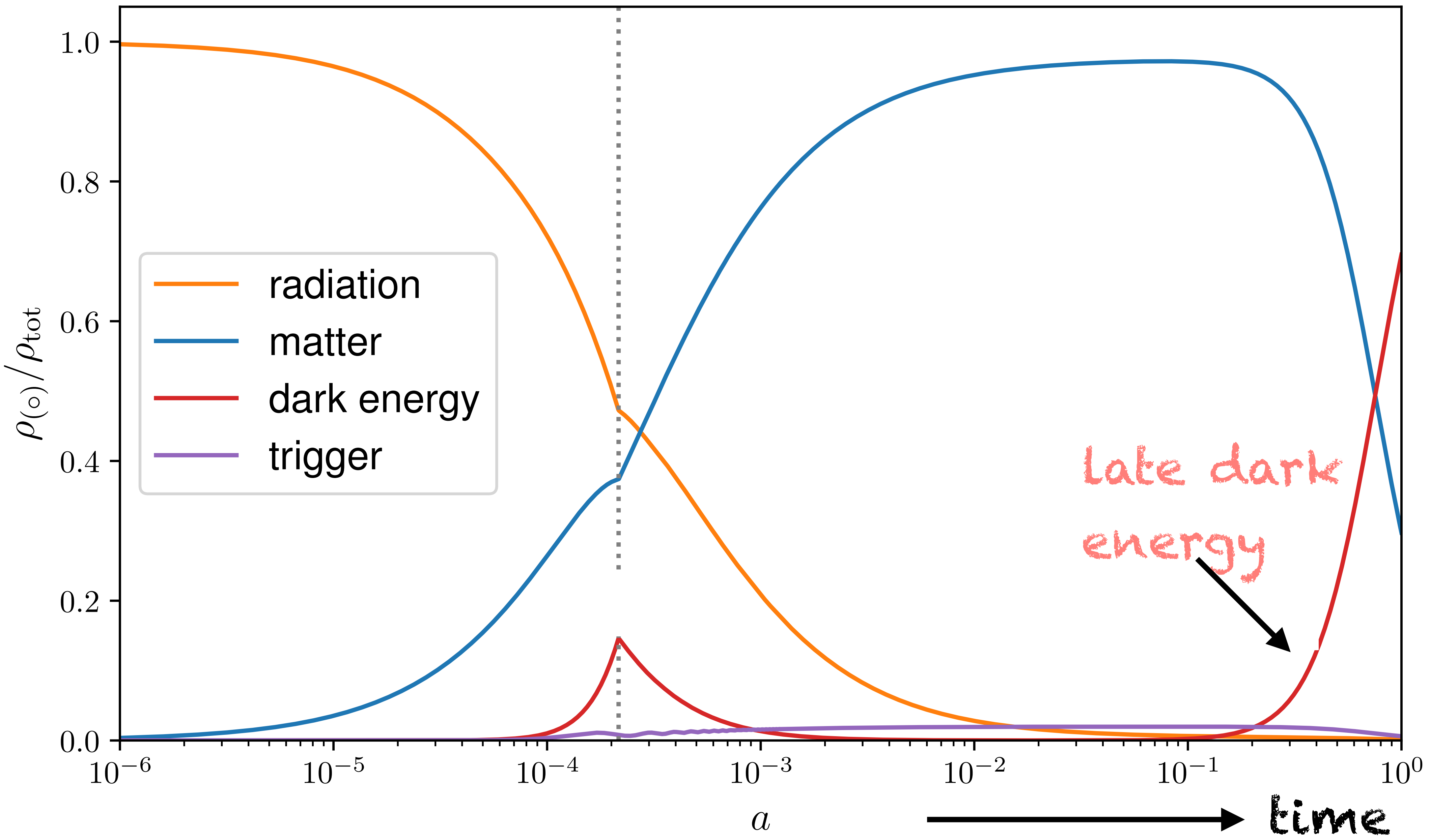

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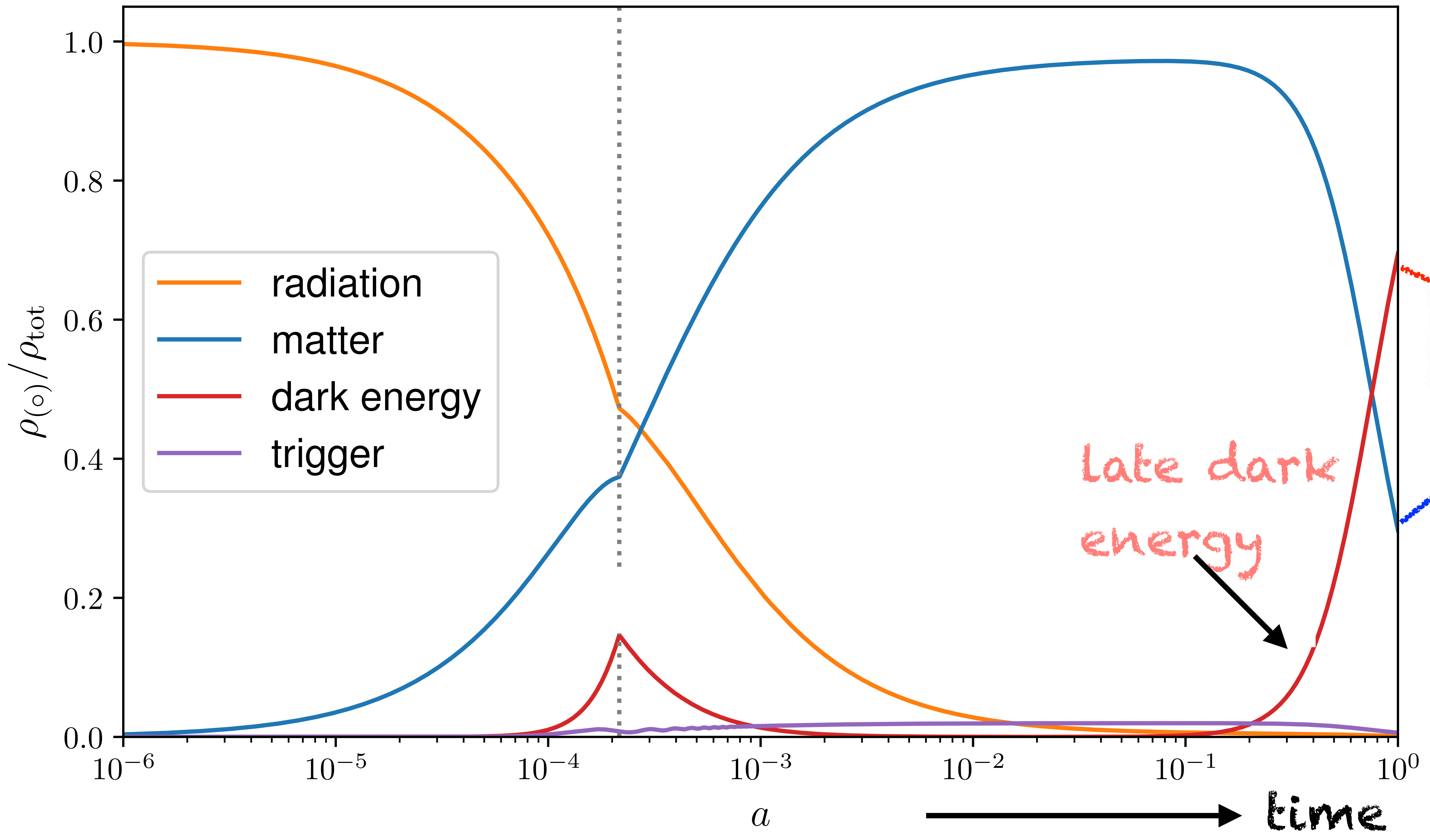

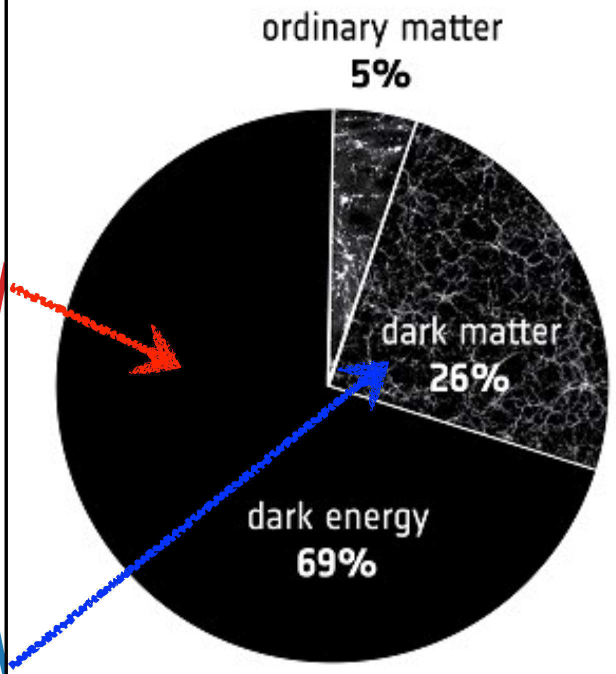

Credit: ESA

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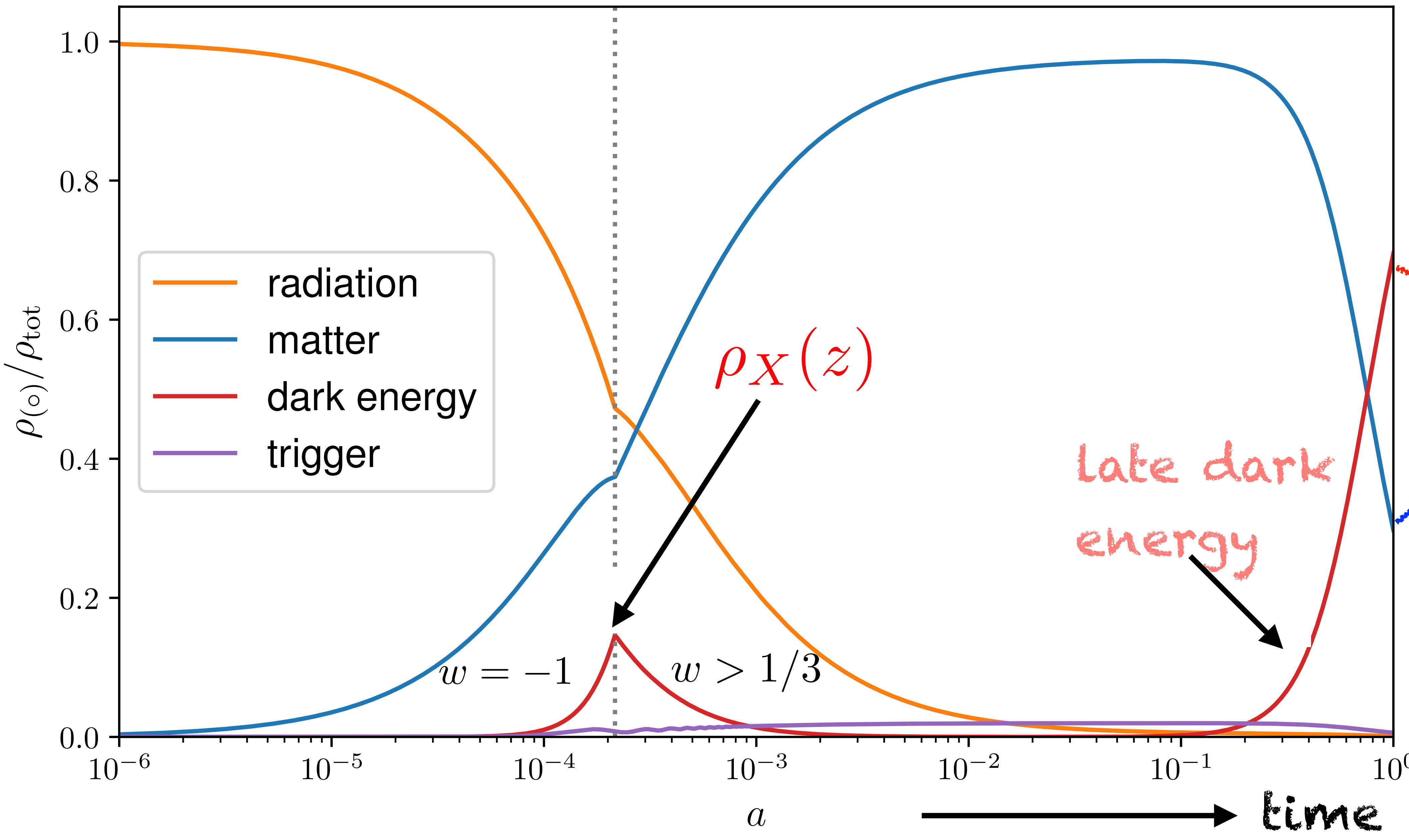

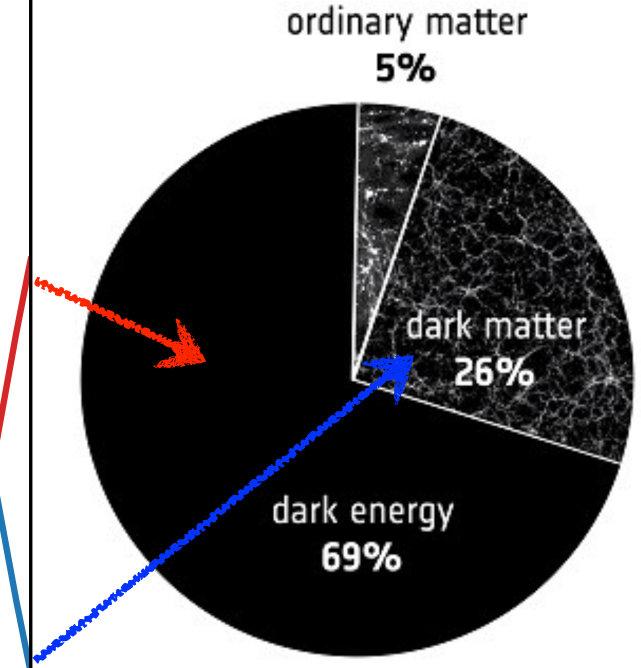

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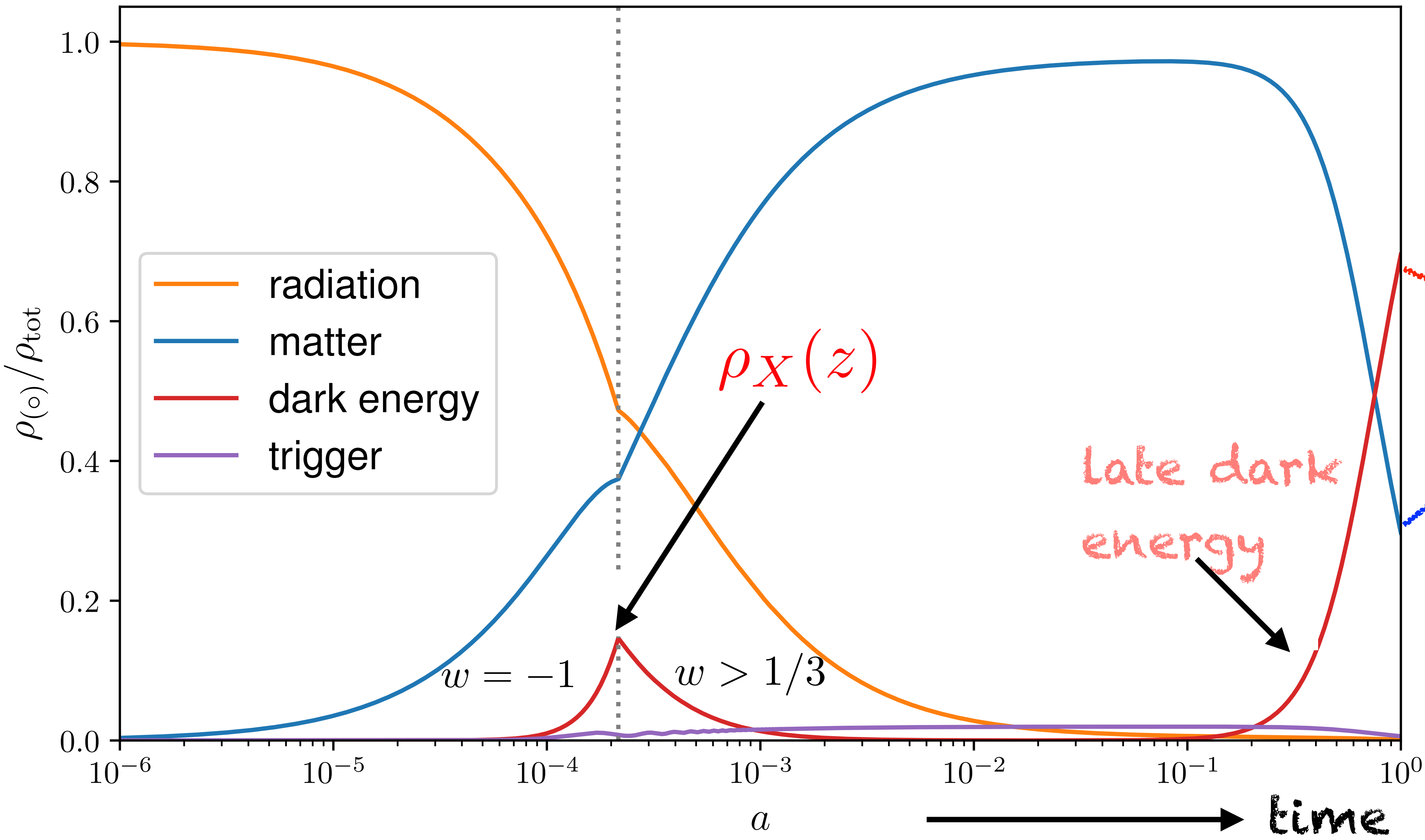

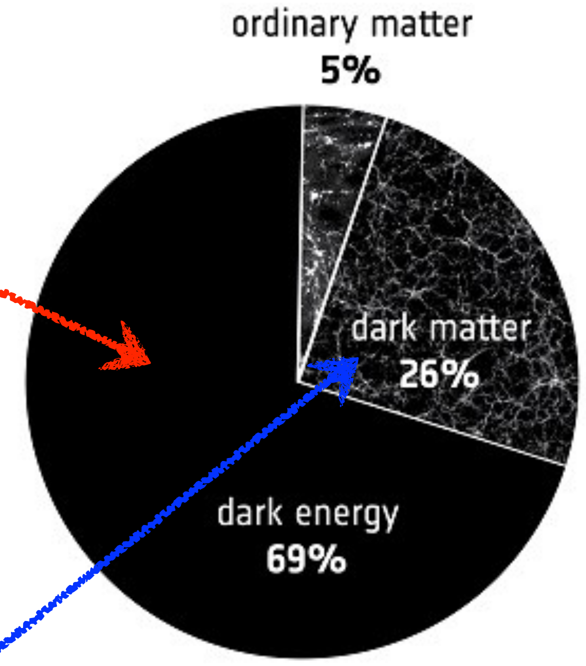

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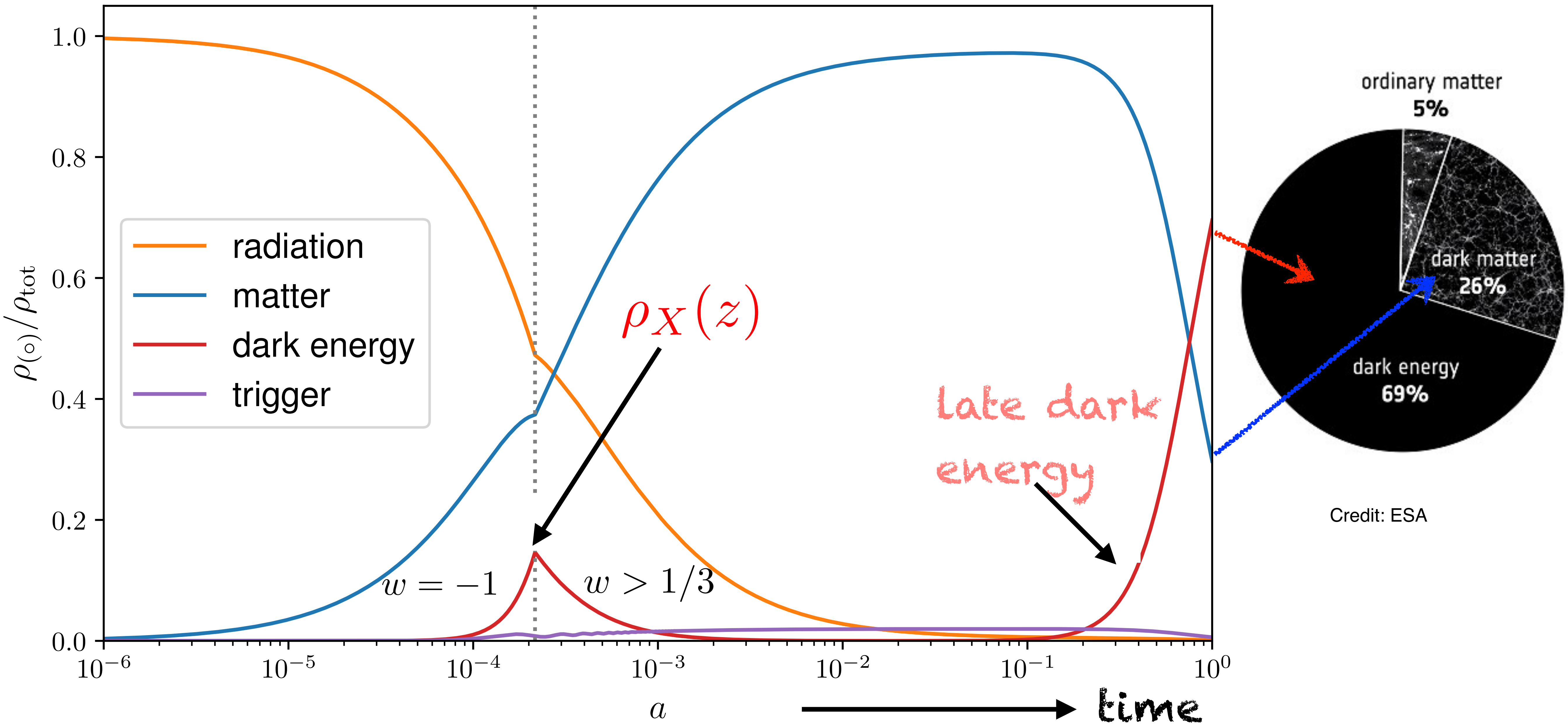
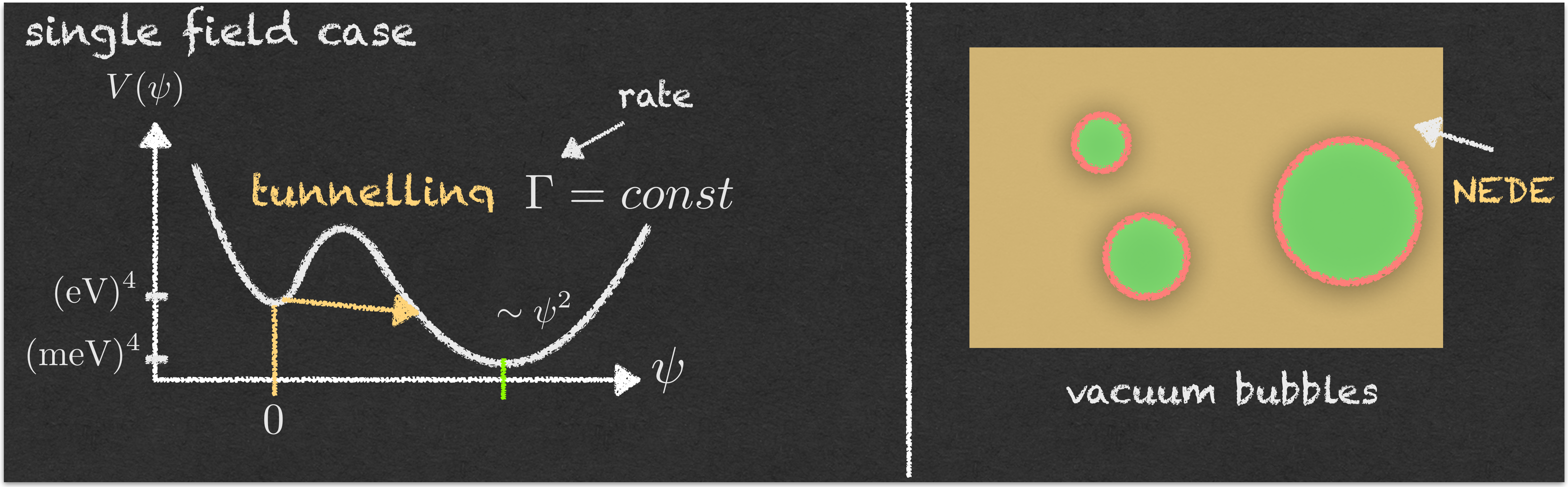


- **First model in** 2018: **AxiEDE** – Poulin, Smith, Karwal, Kamionkowski
- Insight with Martin S. Sloth 2019: Looks like a **vacuum phase transition**!

Vacuum phase transition

Vacuum phase transition



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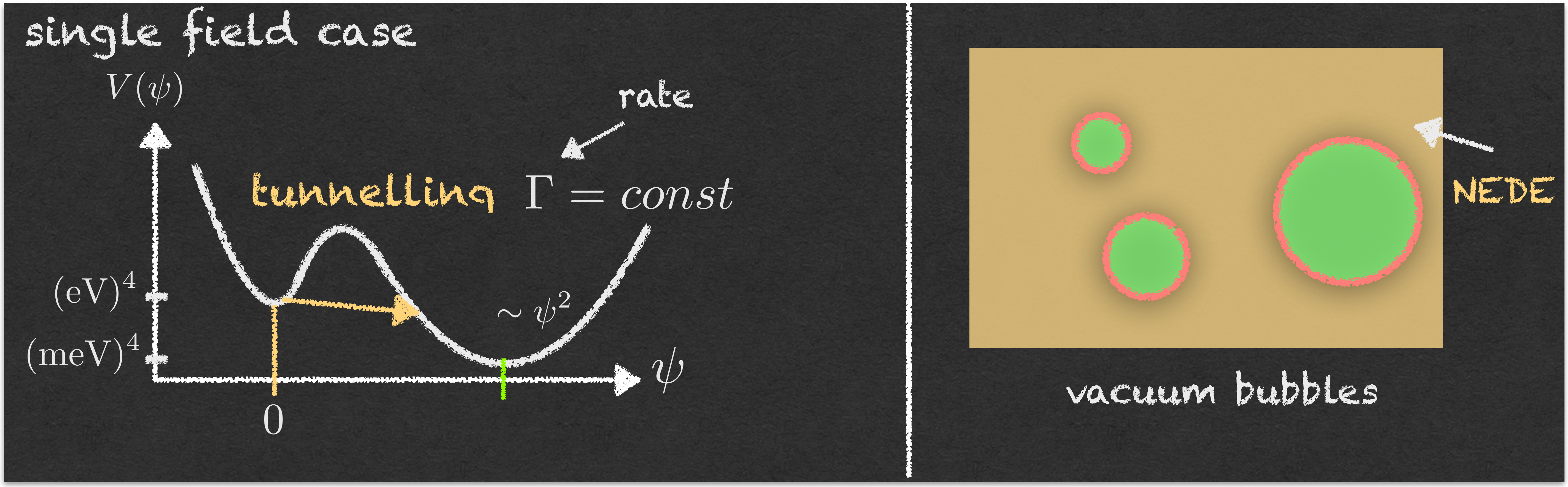

- **Hubble tension:** EDE provided by (decaying) false vacuum energy / latent heat.

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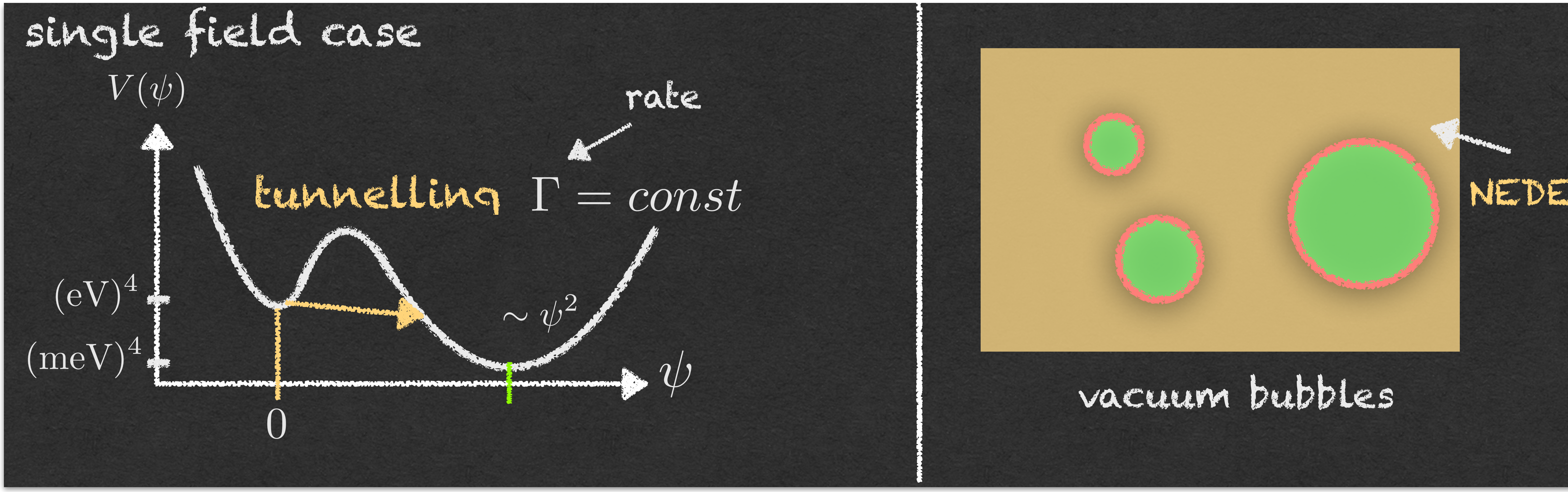

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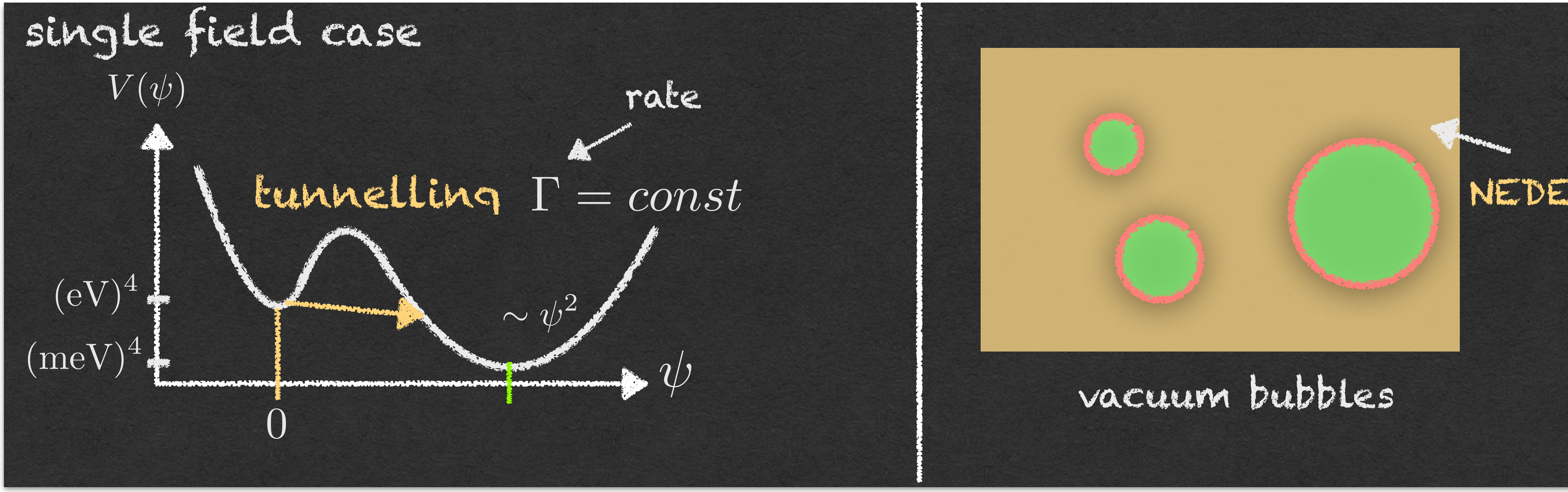
However:

Vacuum phase transition



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However:

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

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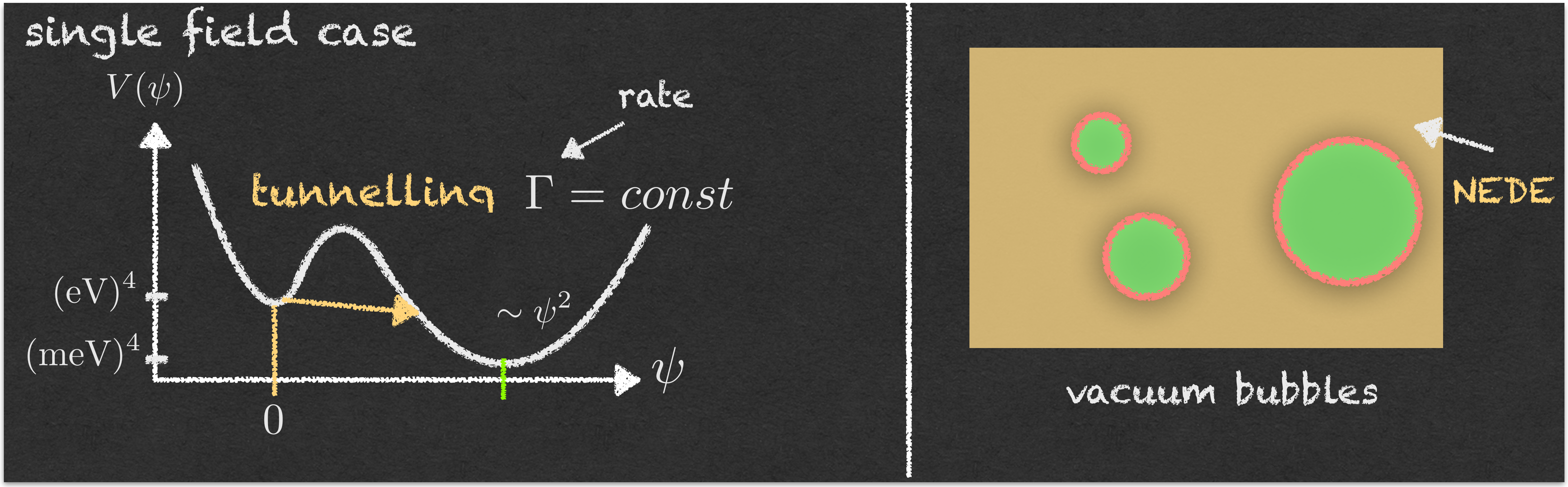

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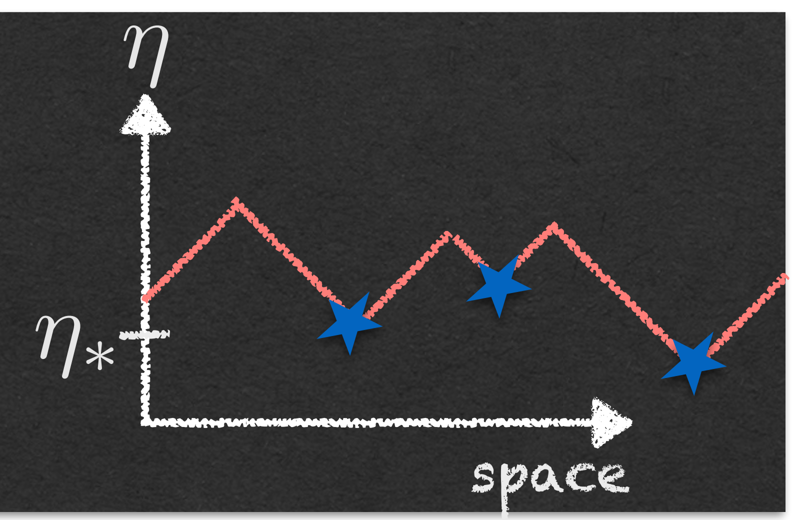

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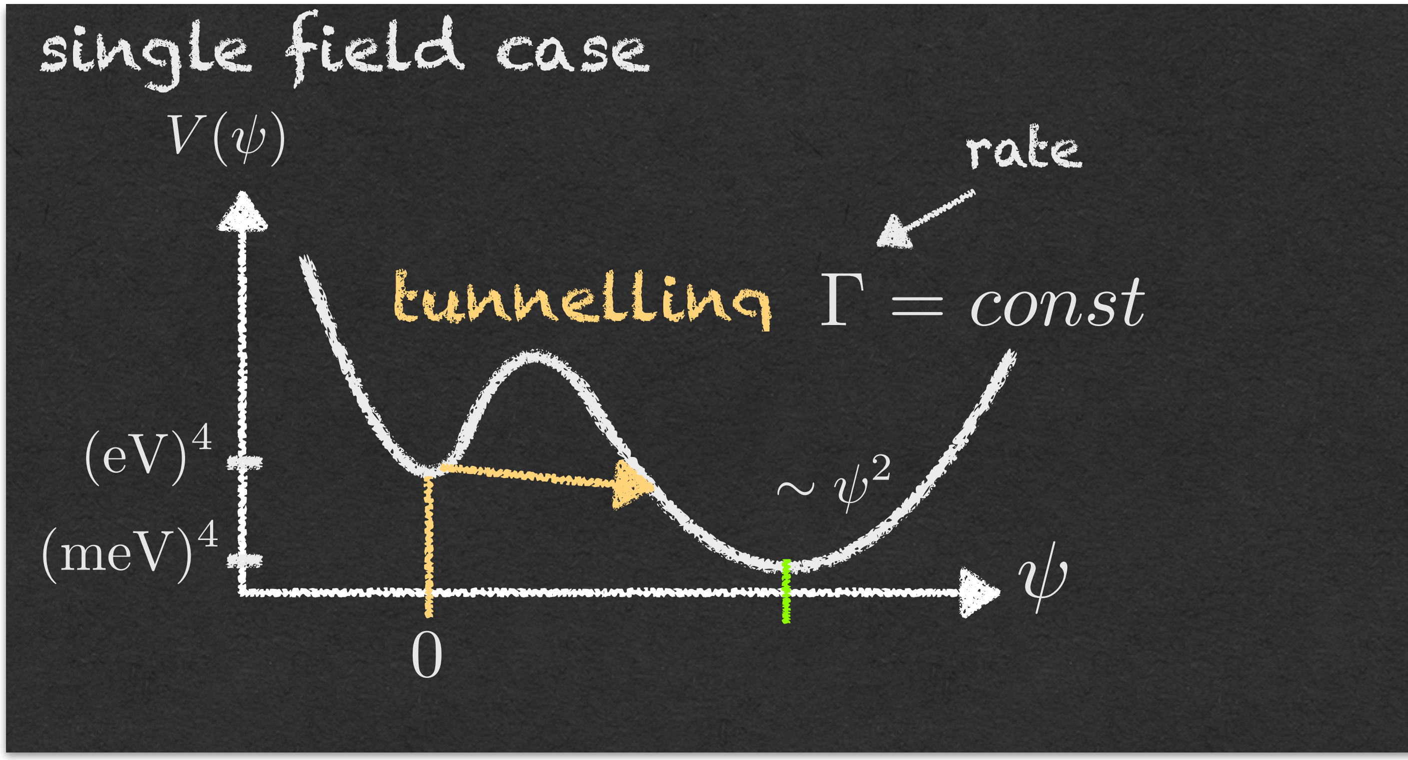

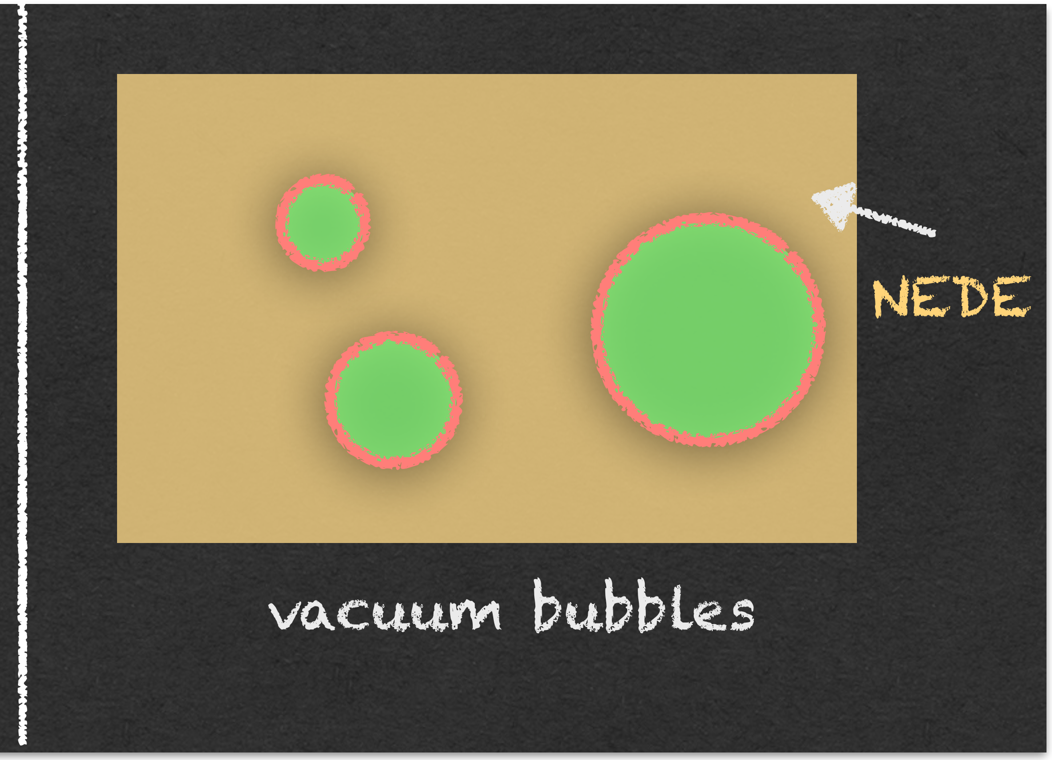

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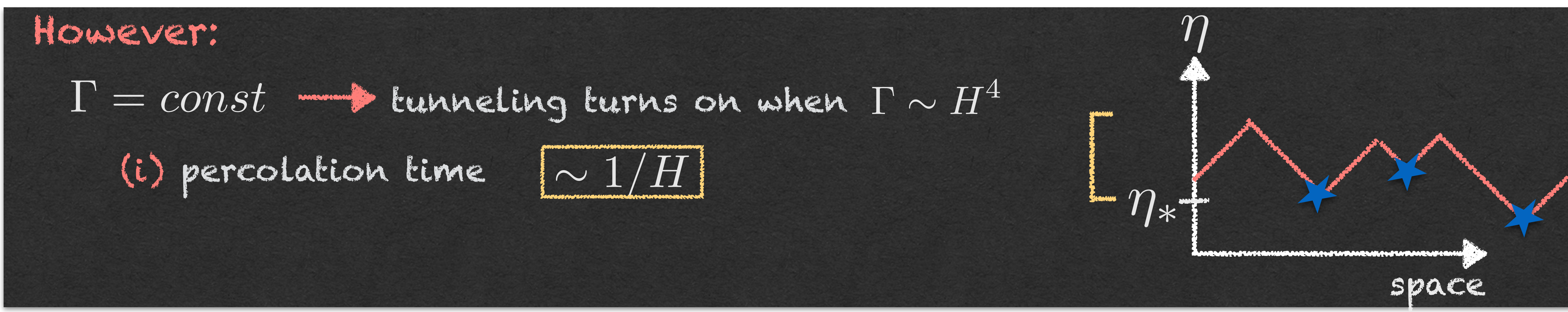

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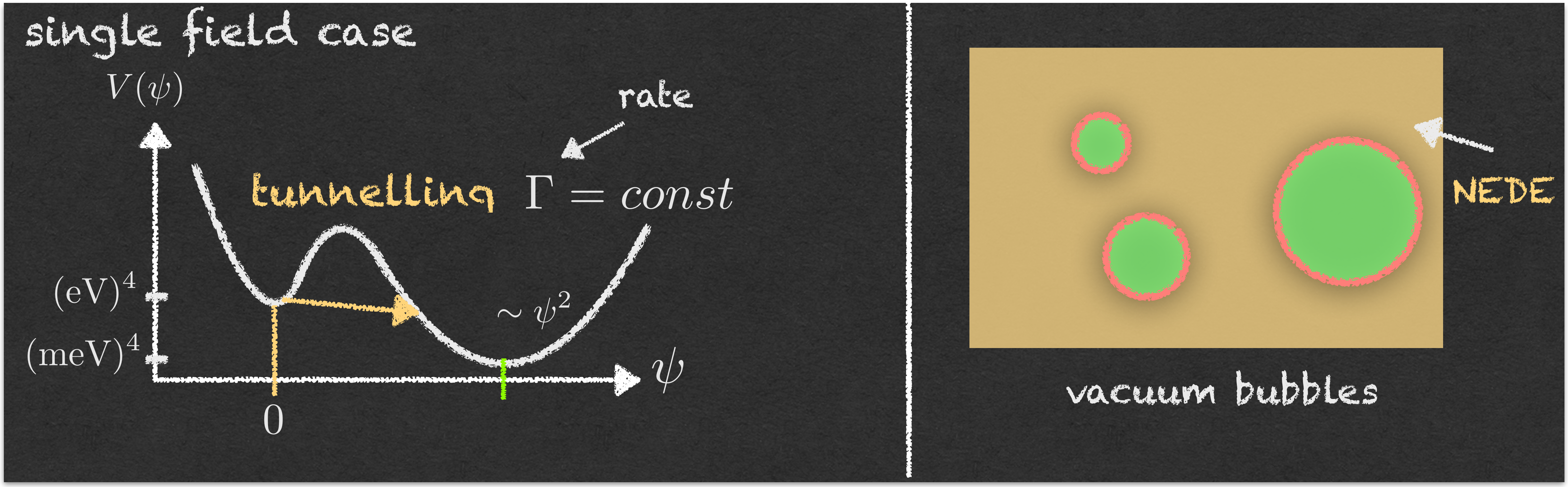

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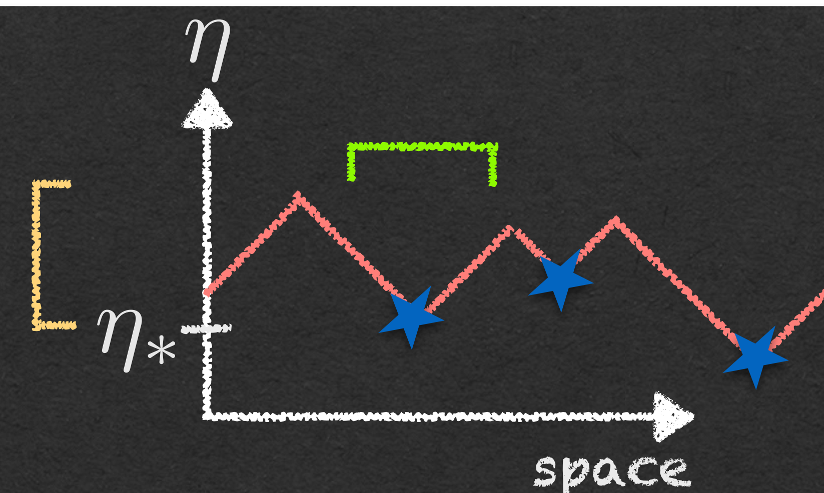
$\Gamma = const$ → tunneling turns on when $\Gamma \sim H^4$

(i) percolation time $\sim 1/H$

(ii) typical bubble size $\sim 1/H$



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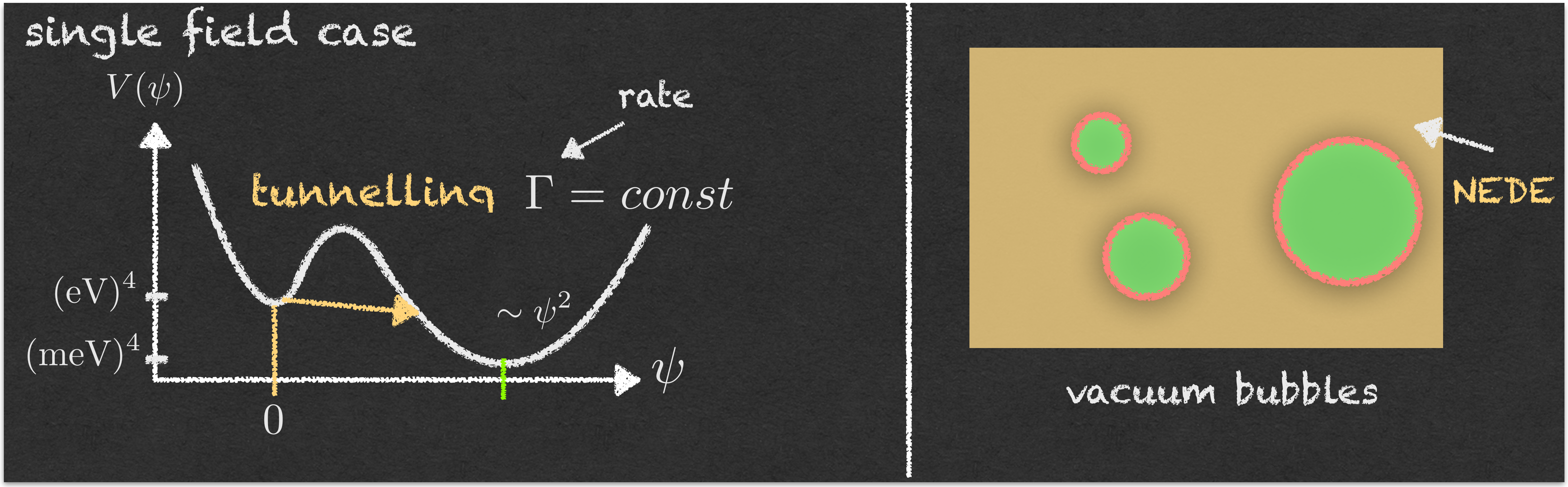

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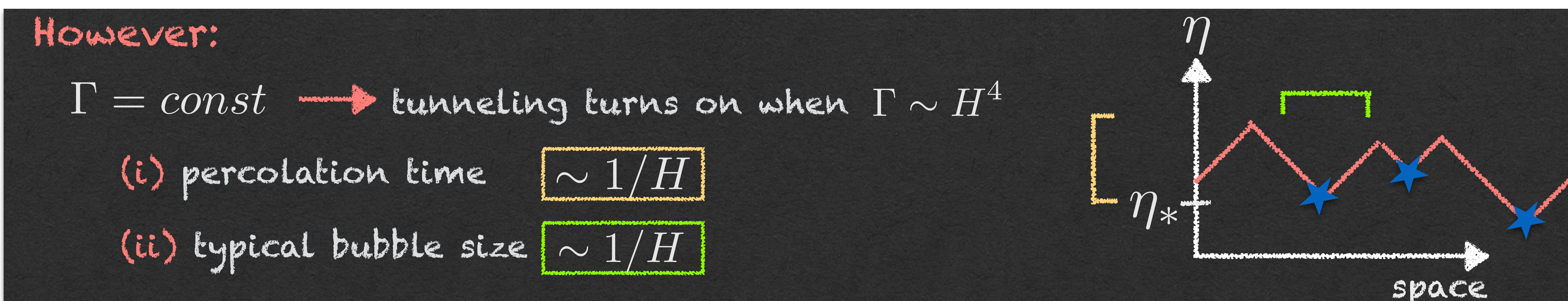
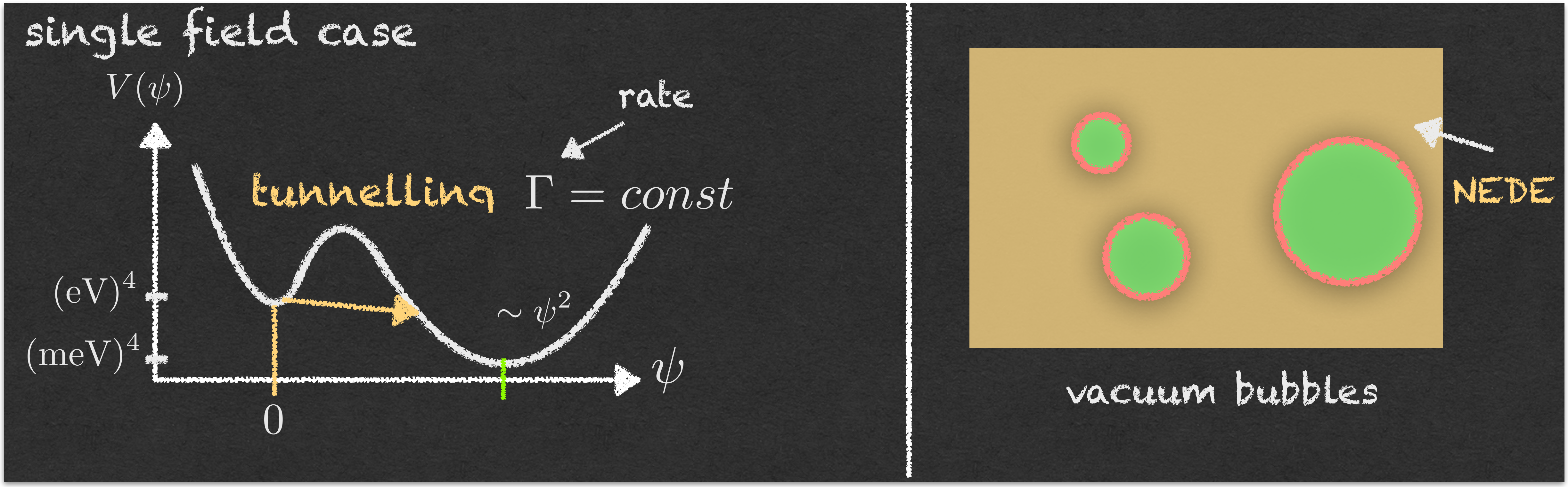


▷ **Challenge:** How to avoid anisotropies in CMB arising from large bubbles?

Vacuum phase transition



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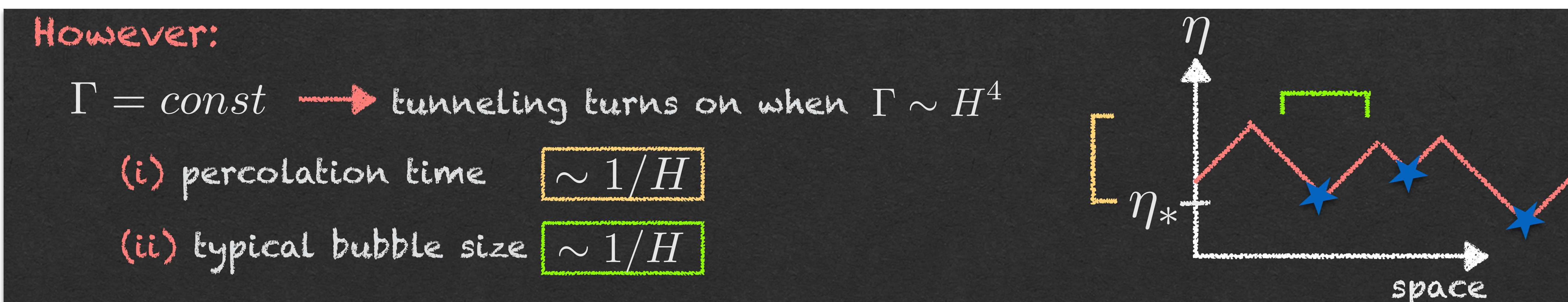

- Challenge: How to avoid anisotropies in CMB arising from large bubbles?
- Idea: Make tunneling rate time dependent: Two models **Cold and Hot NEDE.**

Cold New Early Dark Energy

Cold New Early Dark Energy

- Introduce a **trigger field** ϕ to synchronise decay.

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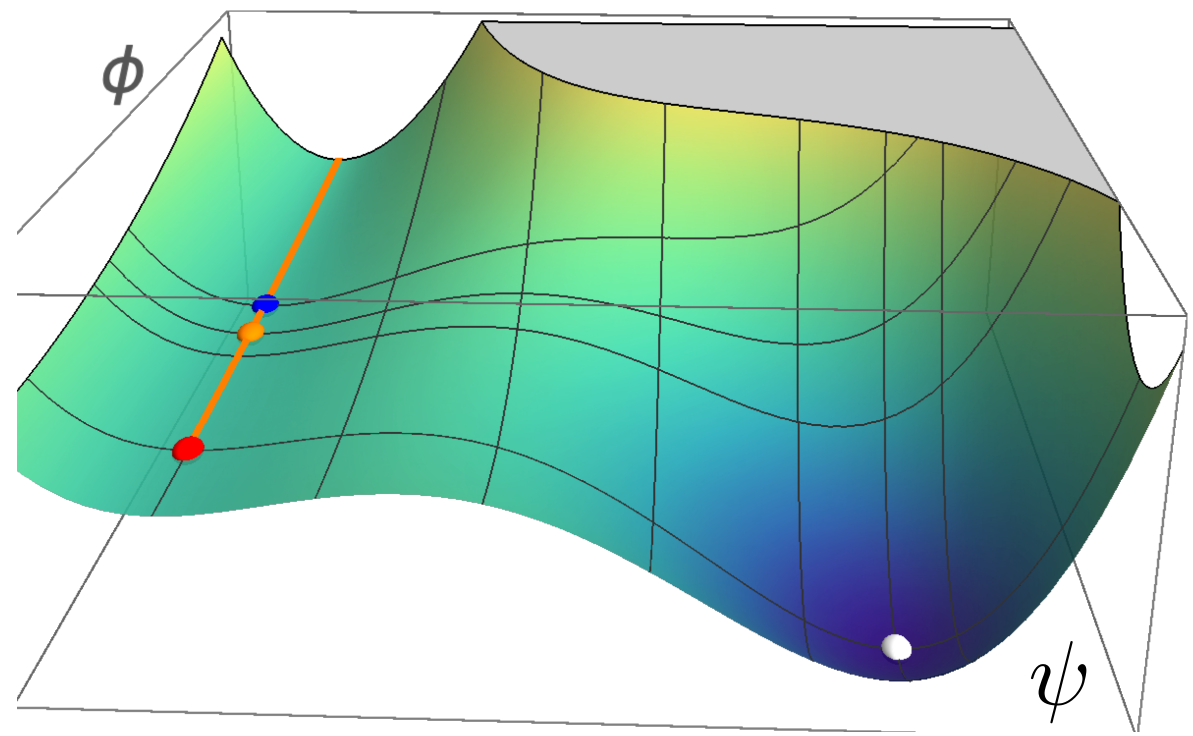

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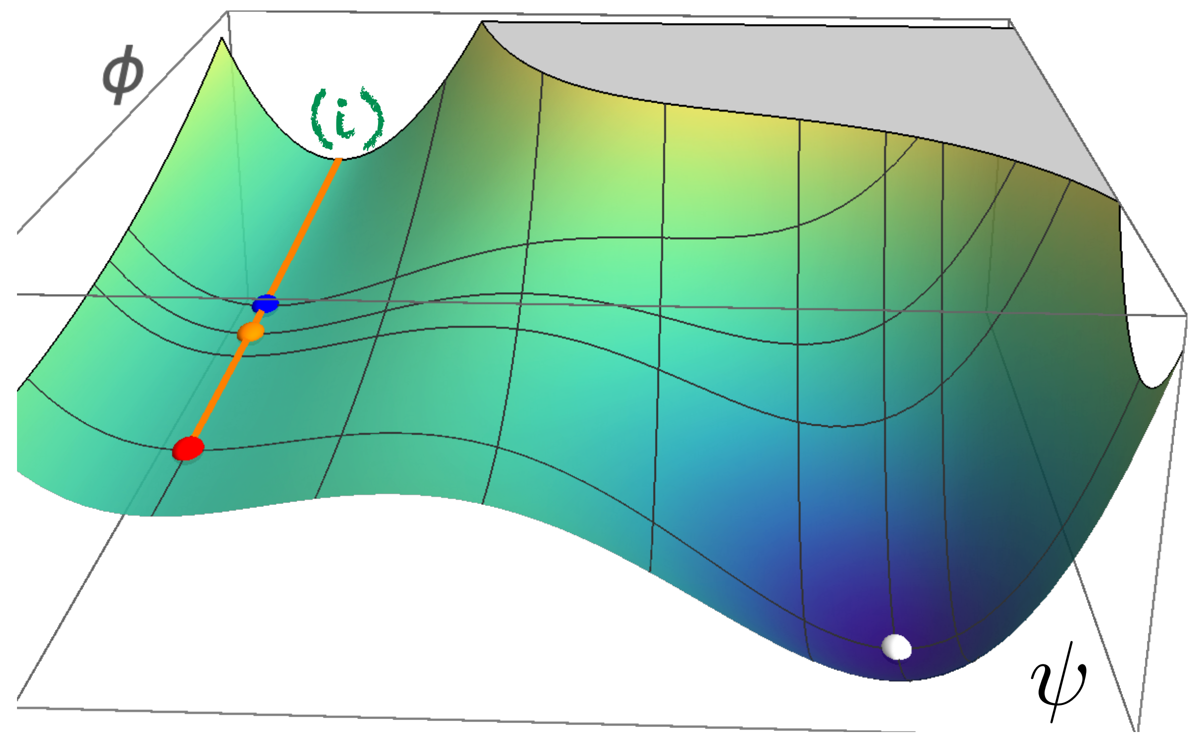

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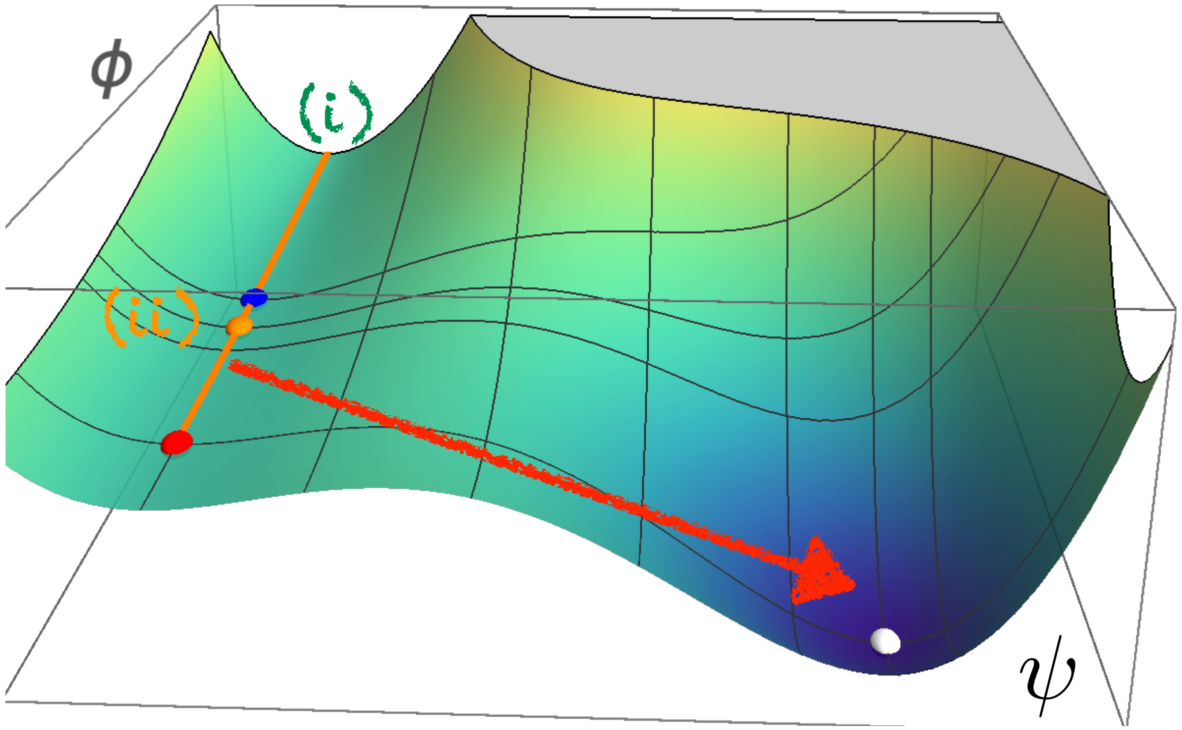

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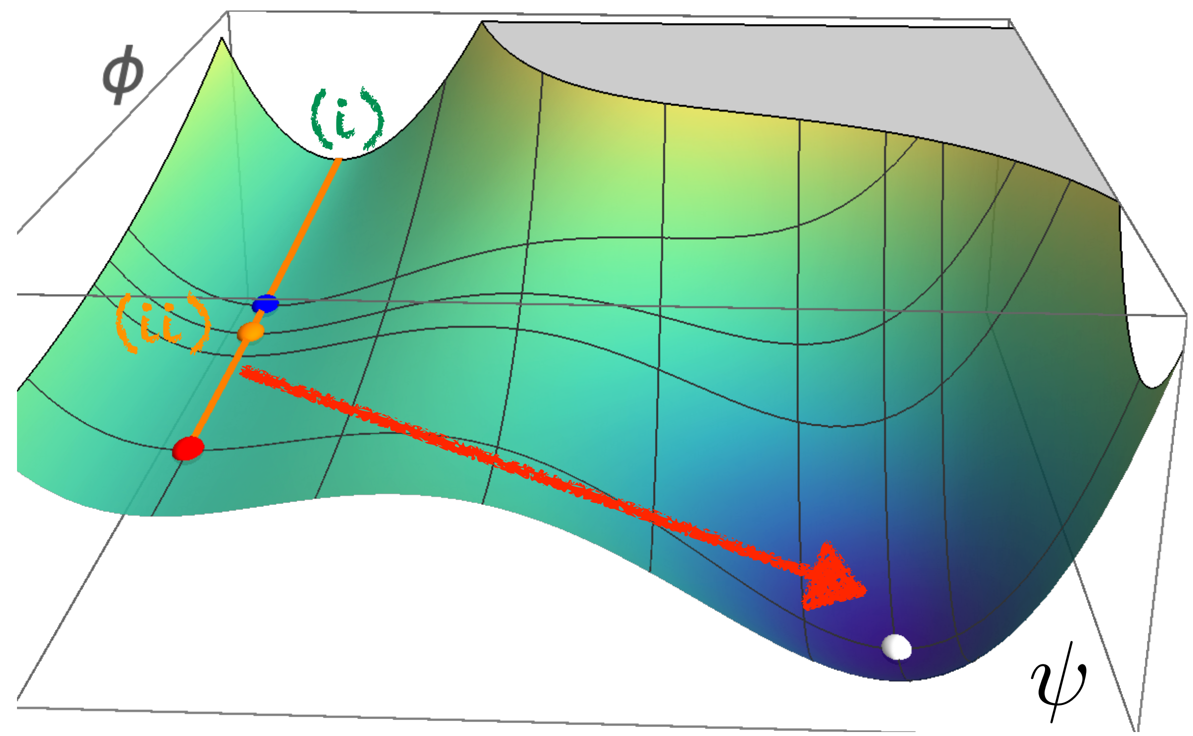

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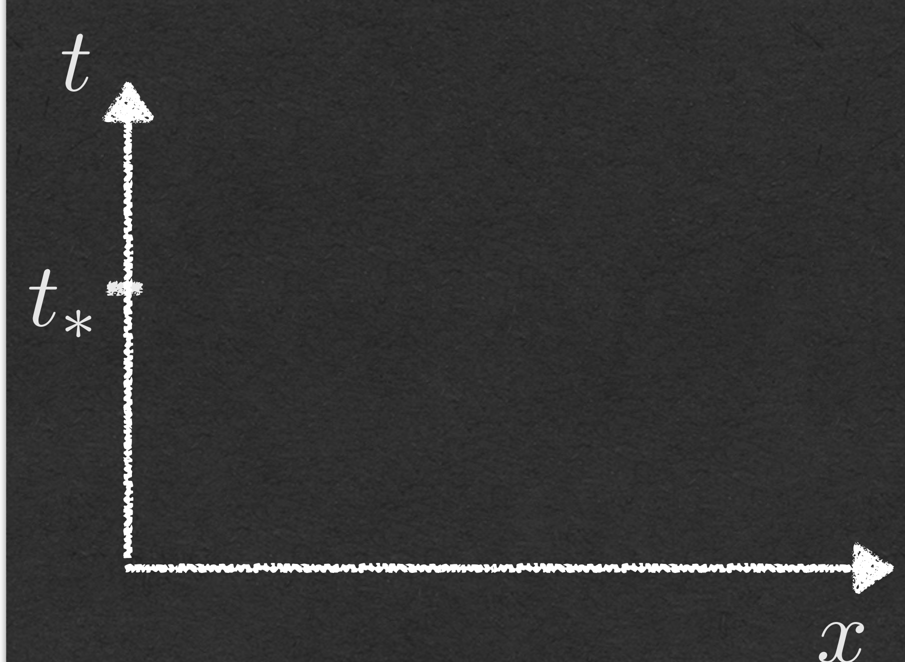

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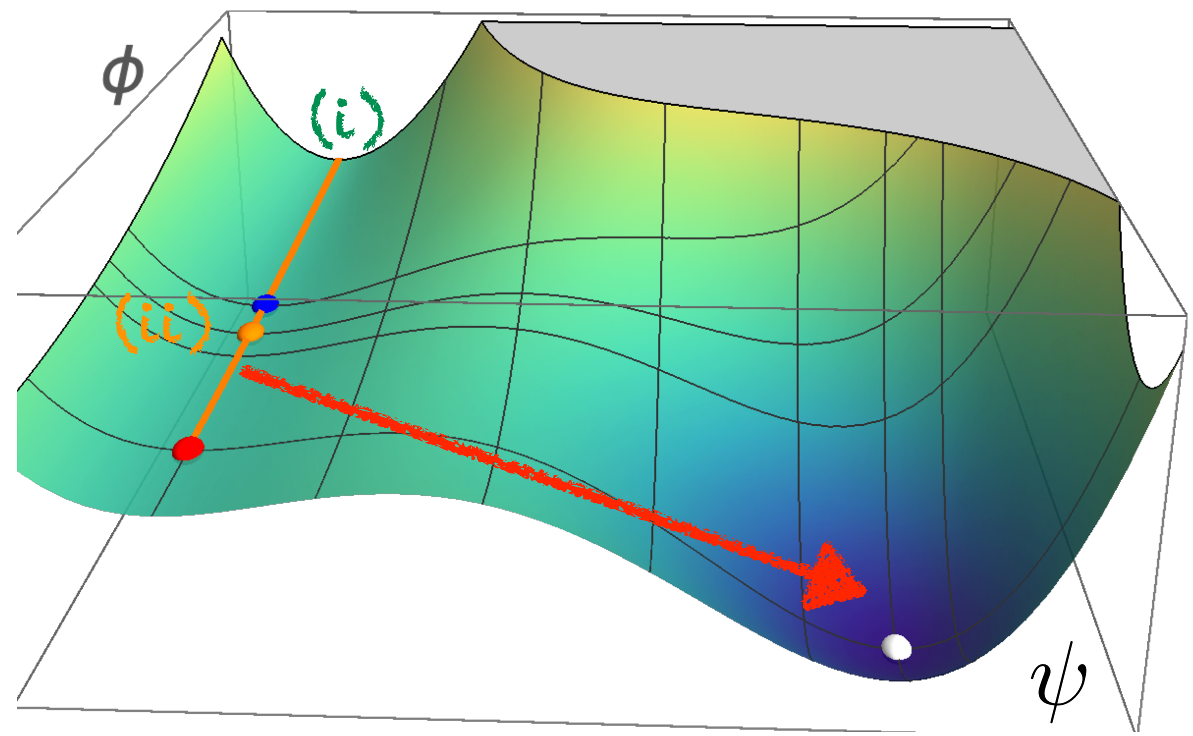

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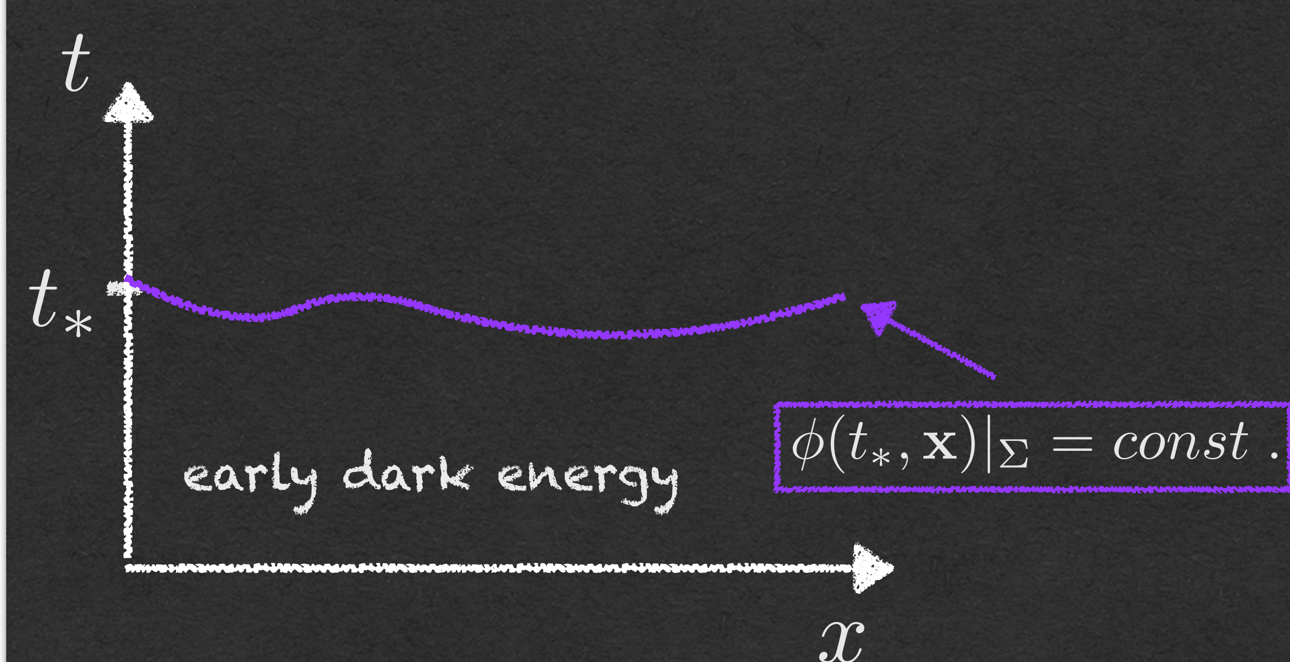

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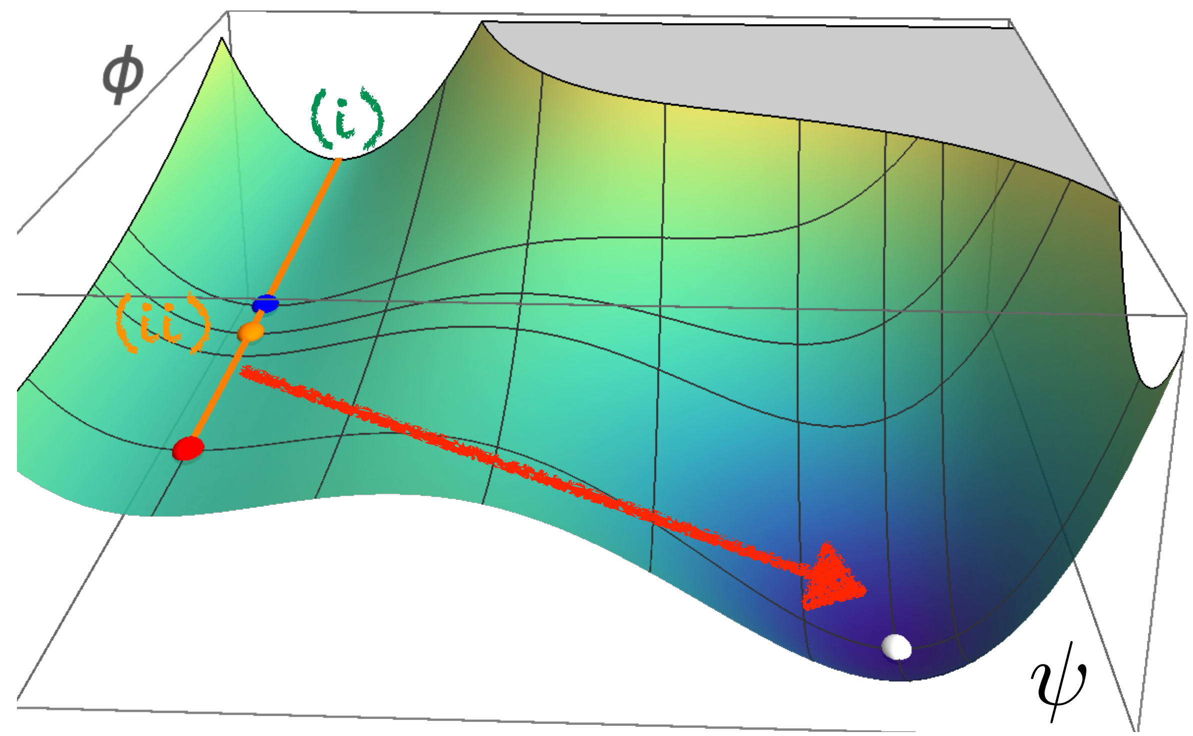

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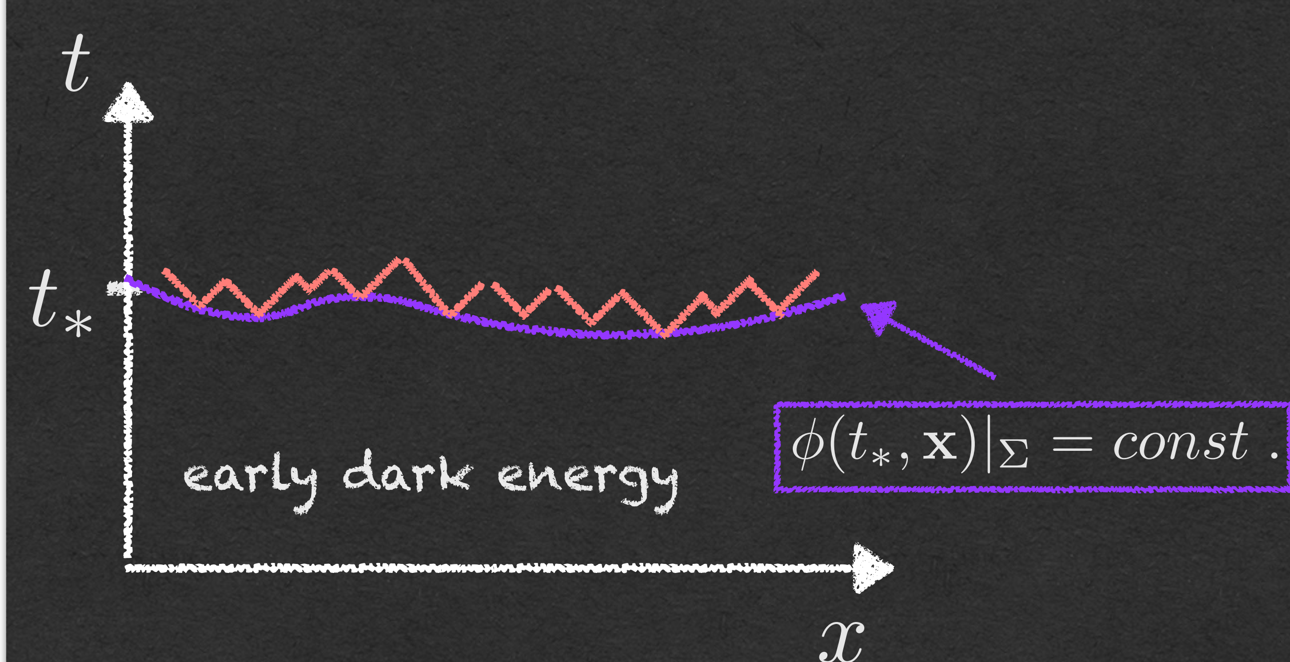

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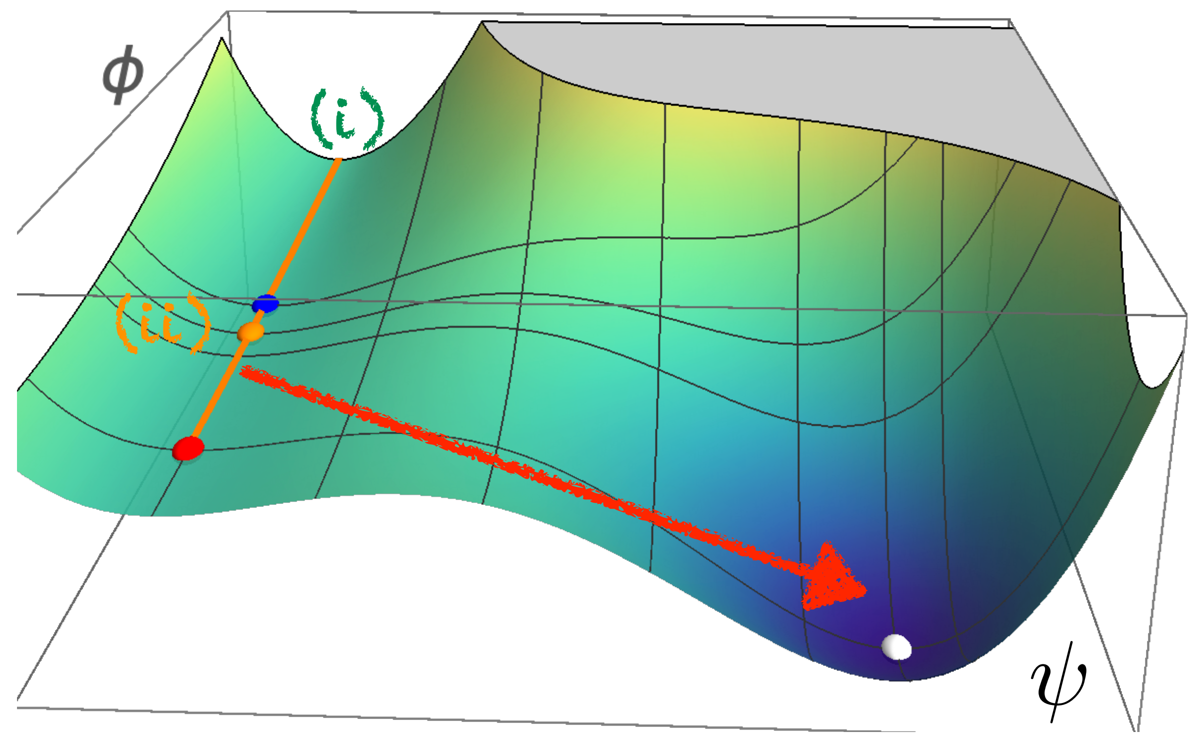

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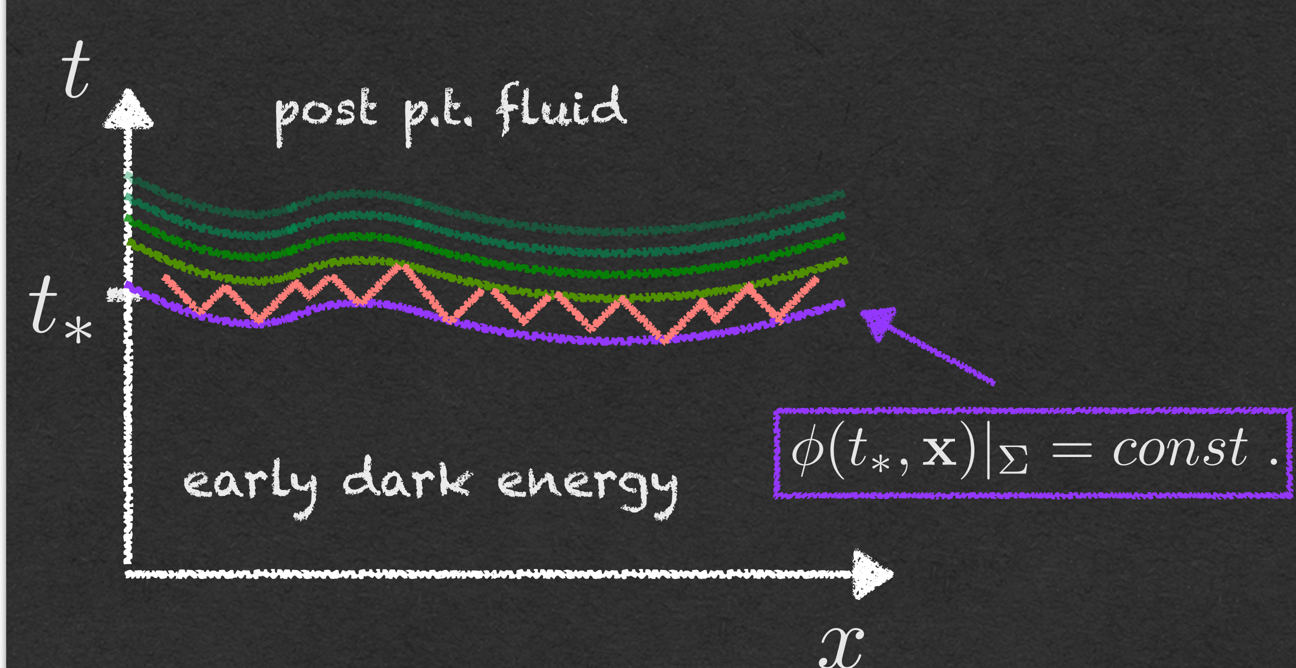

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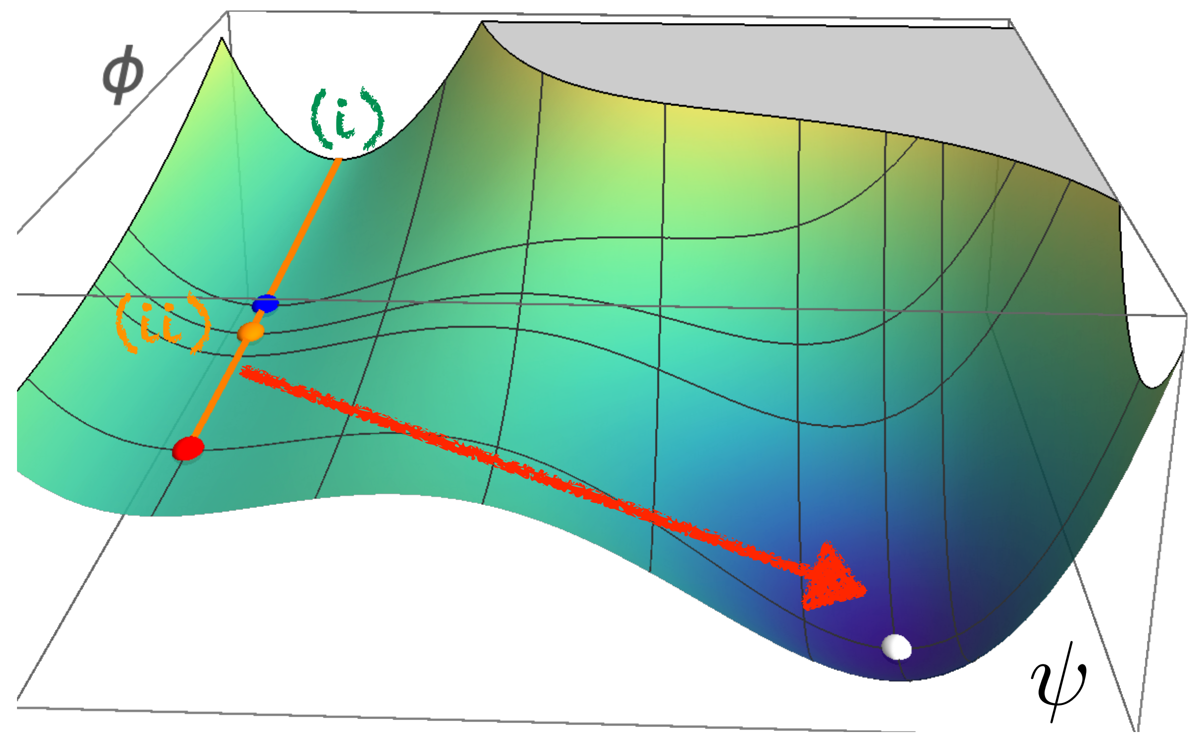

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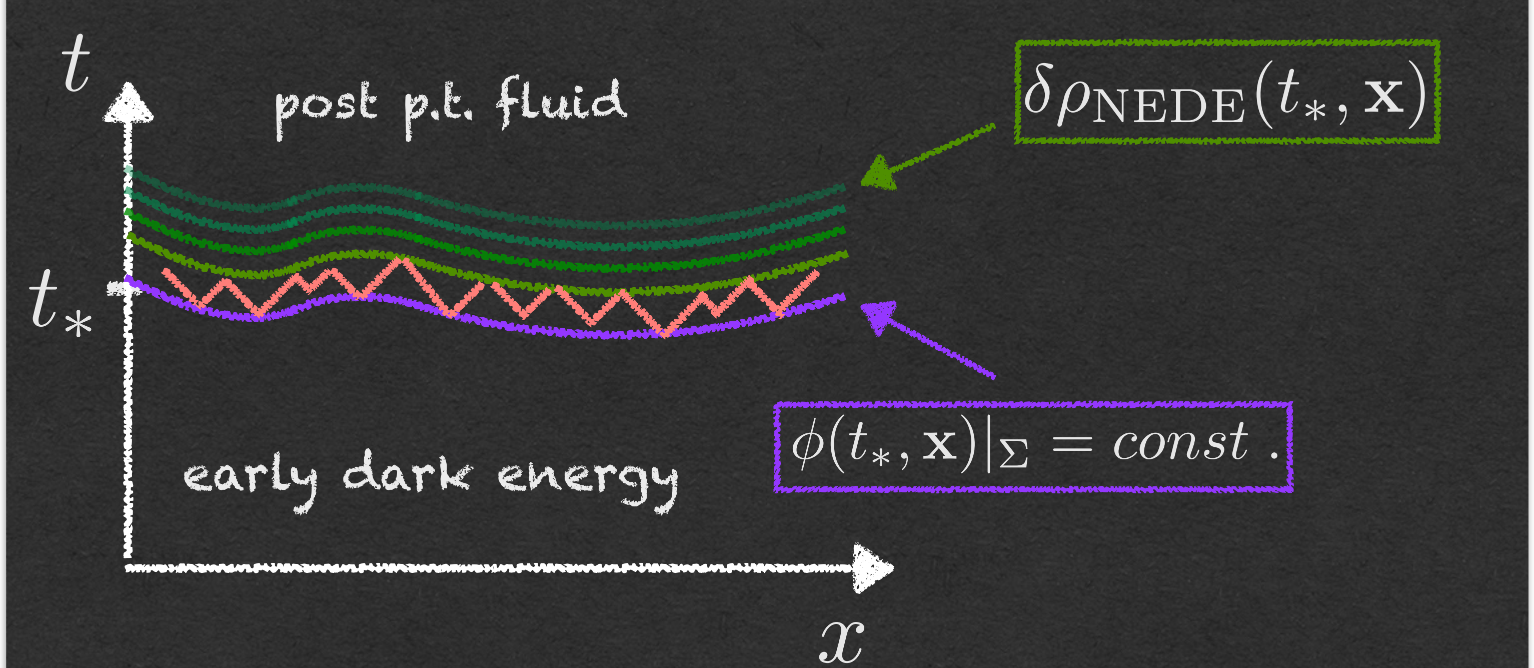

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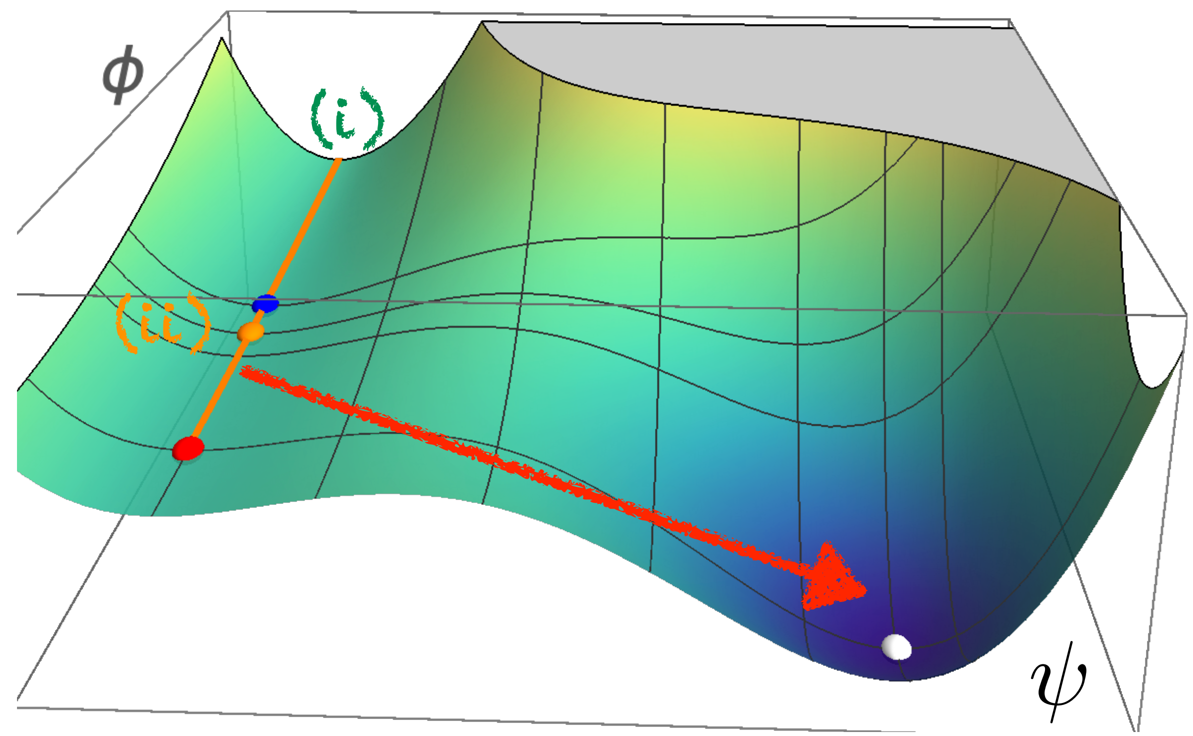

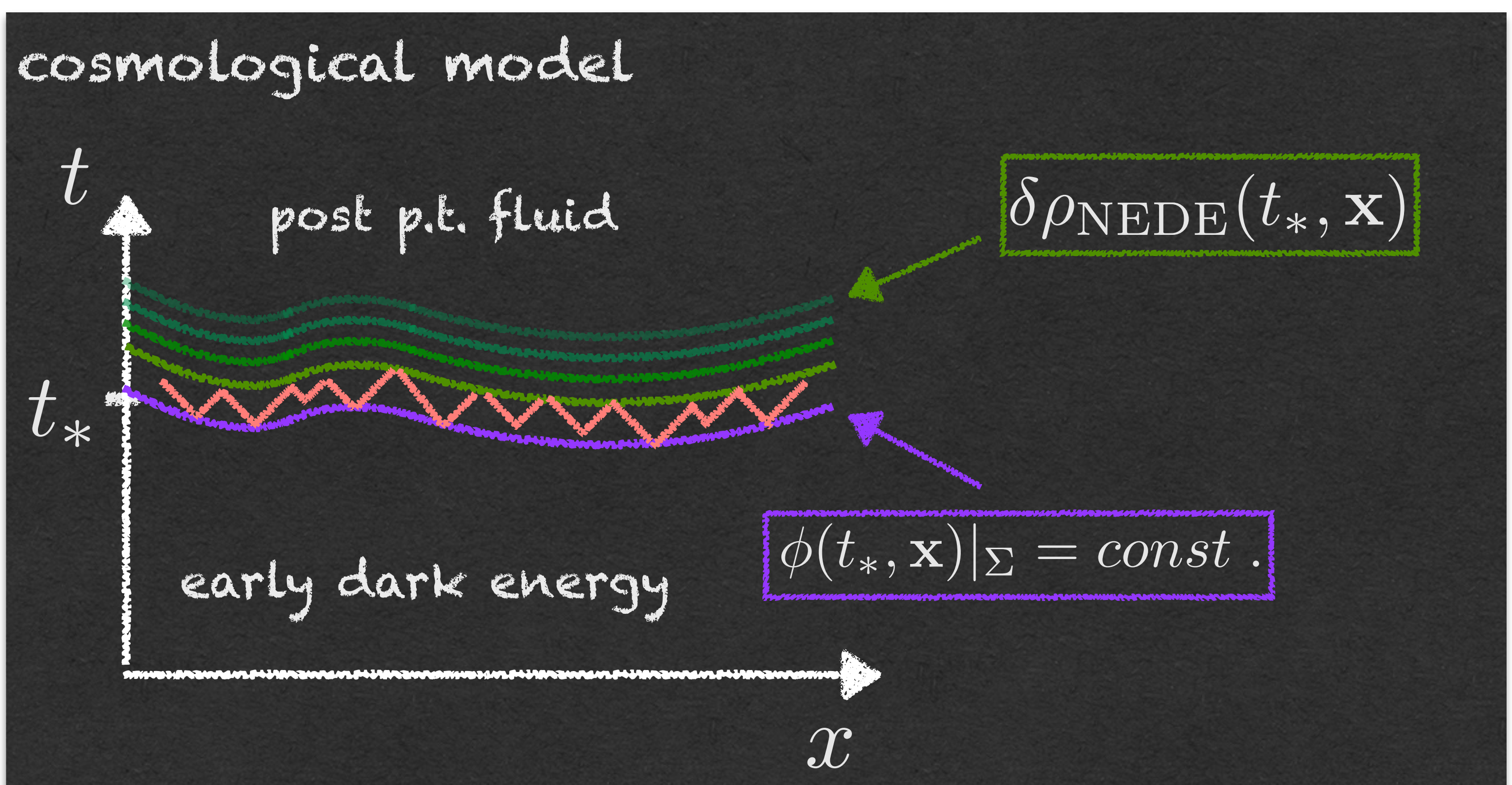

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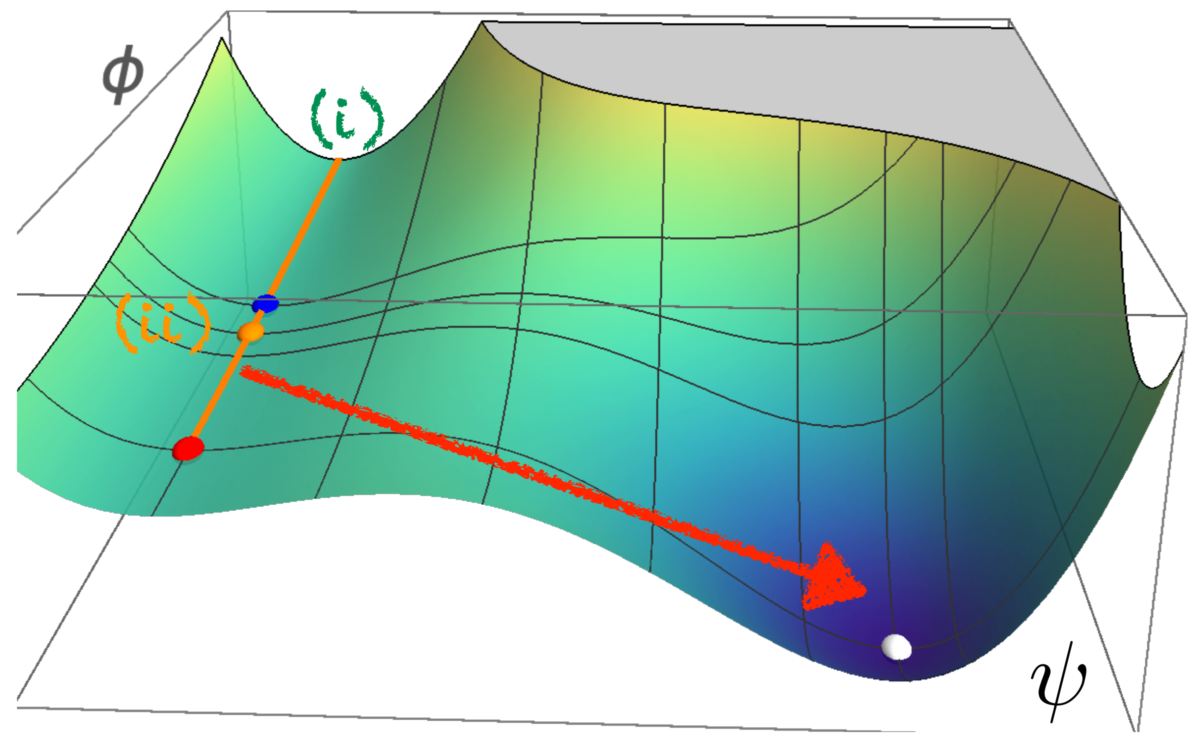

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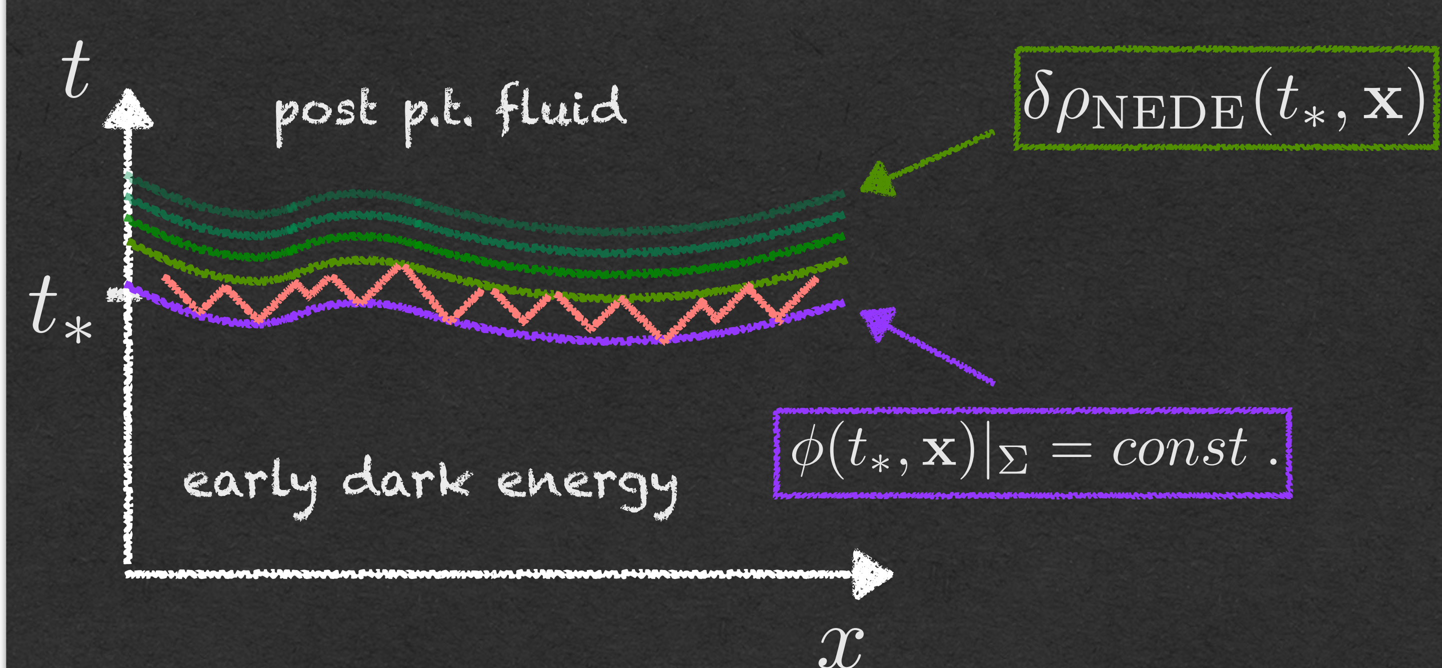

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- Implementation in Boltzmann solver CLASS -> TriggerCLASS

A testable scenario

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The H_0 Olympics: A fair ranking of proposed models

Schöneberg et al., 2022

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

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)]

- **Competition 2022:**

  EDE-type models reduce tension to ~ 2 sigma.

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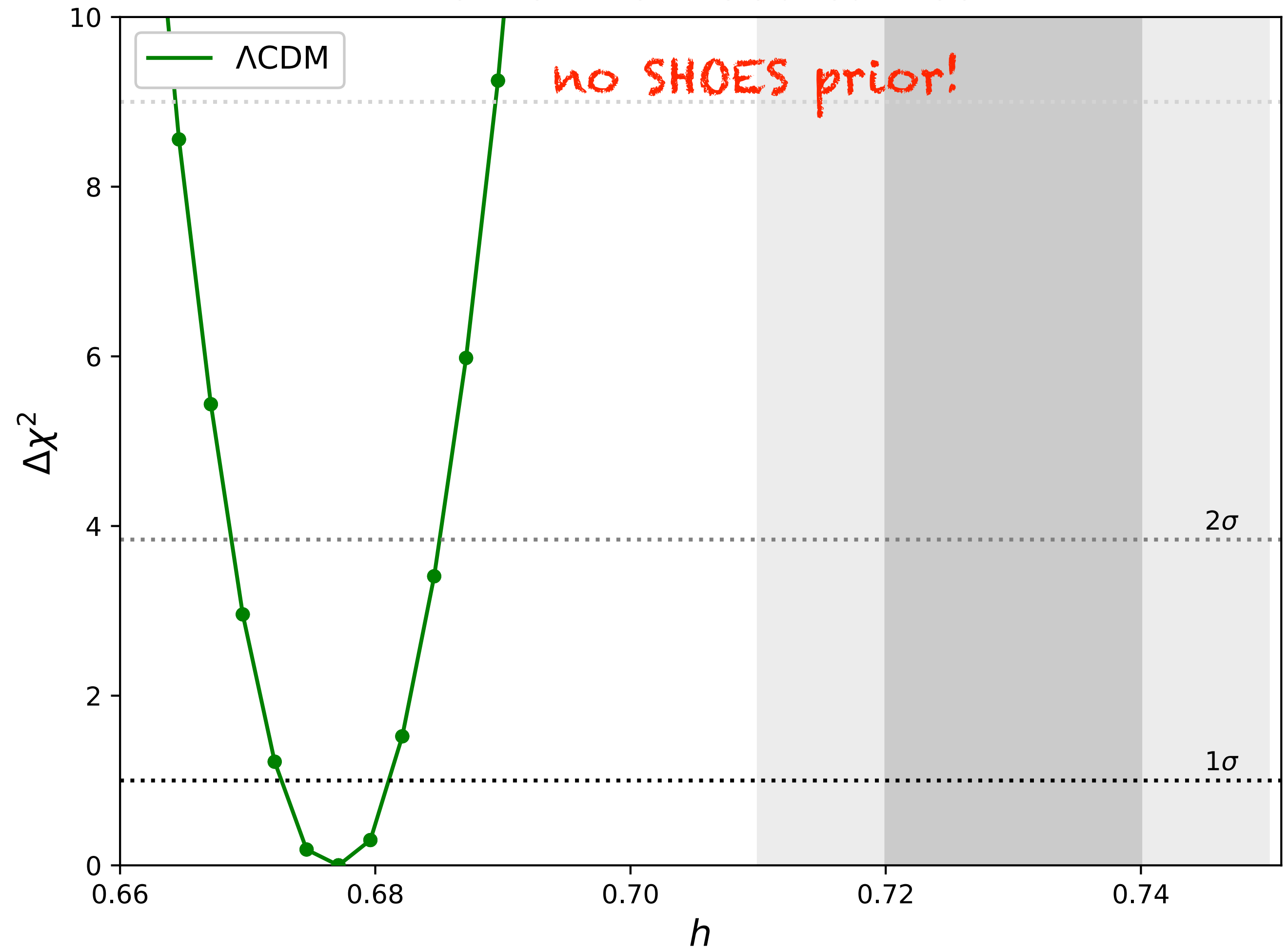

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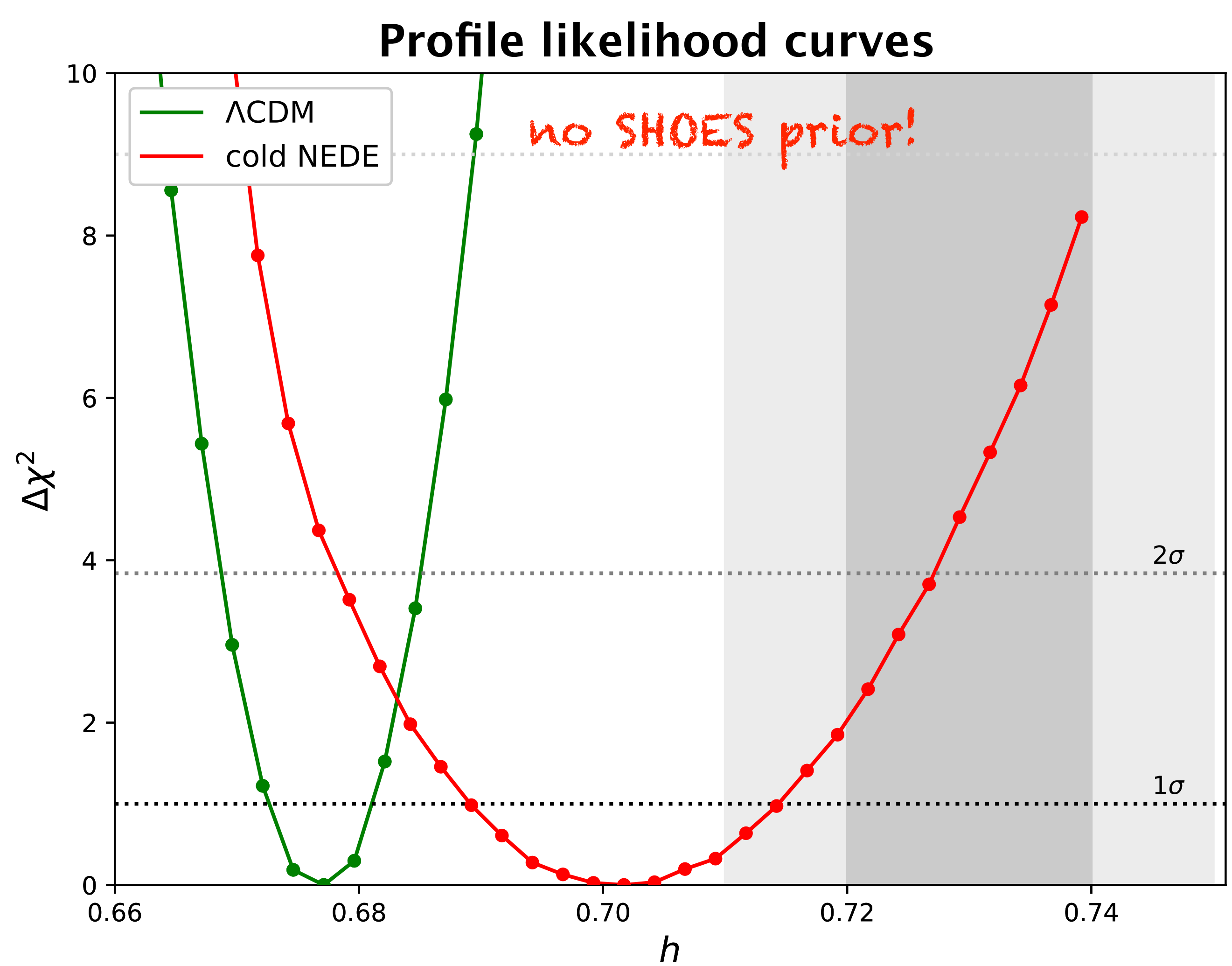

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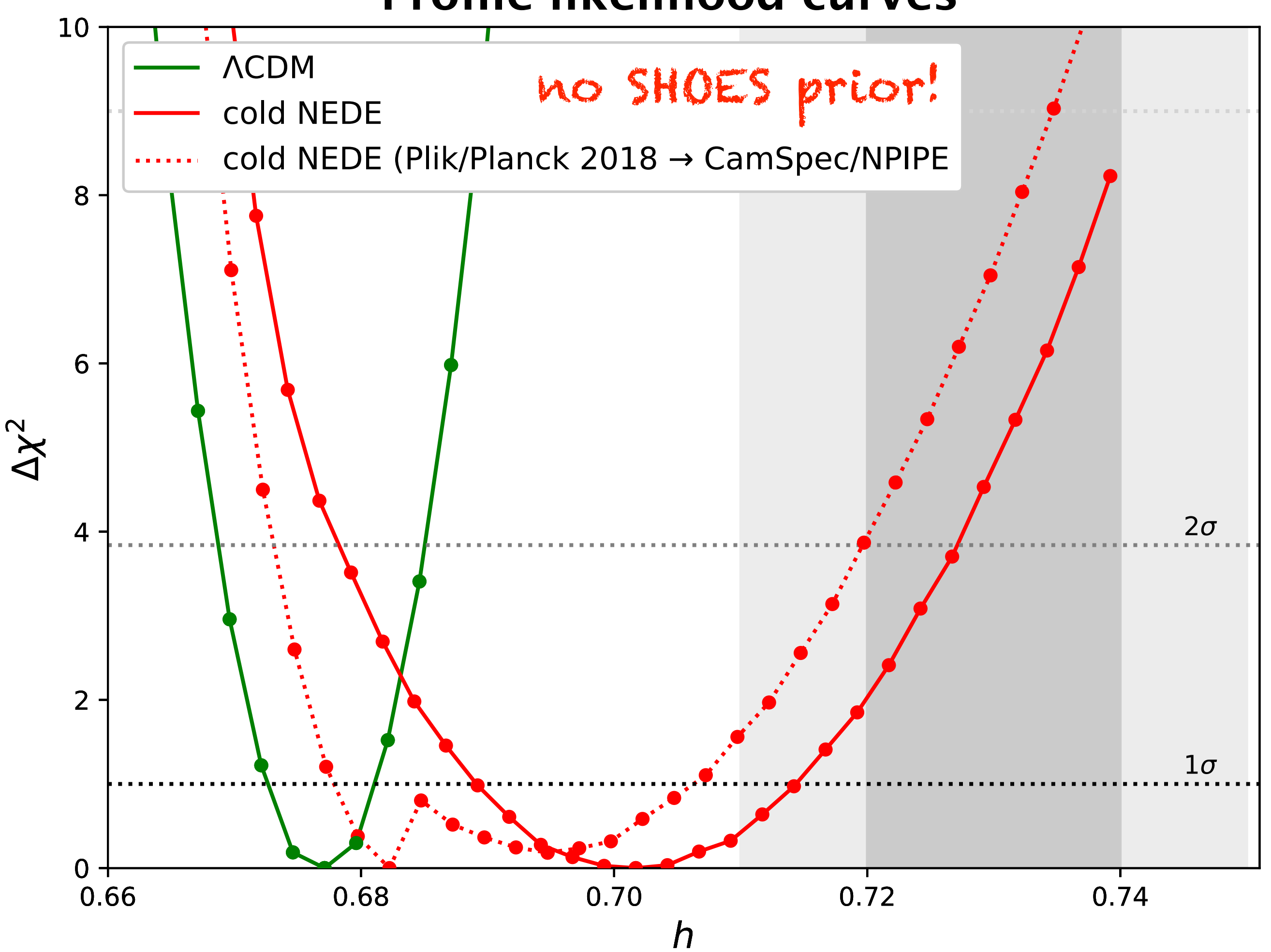

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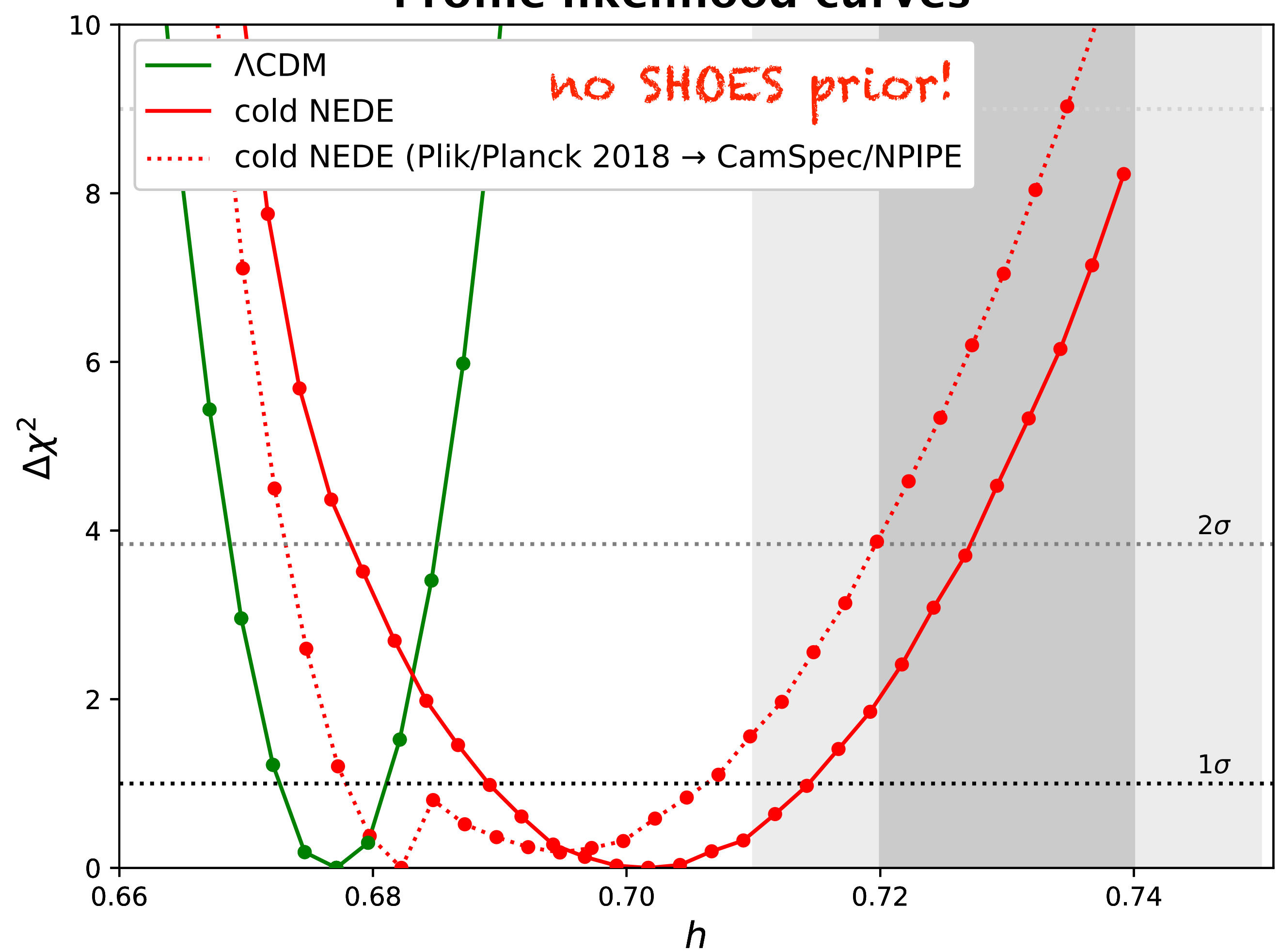

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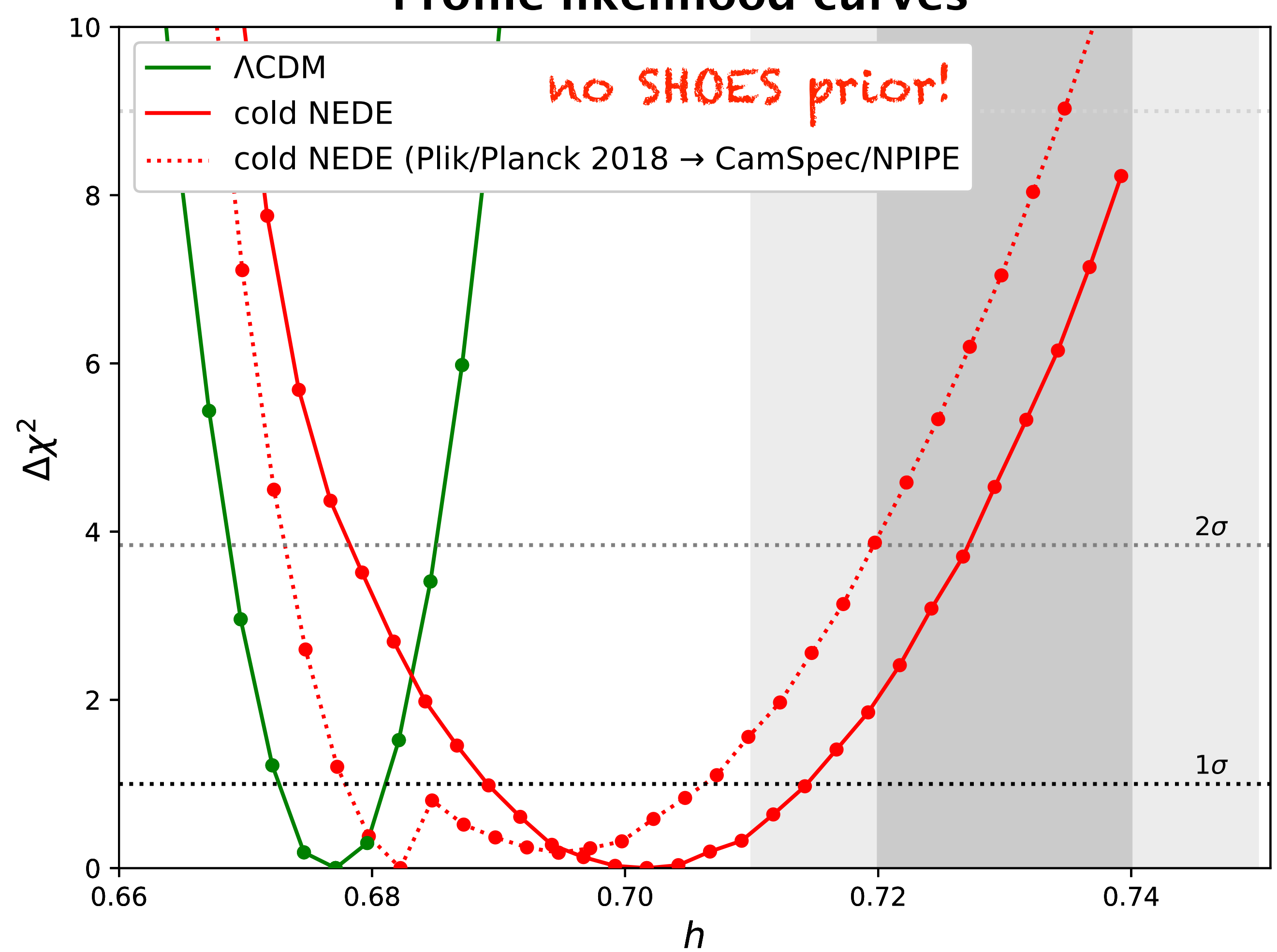

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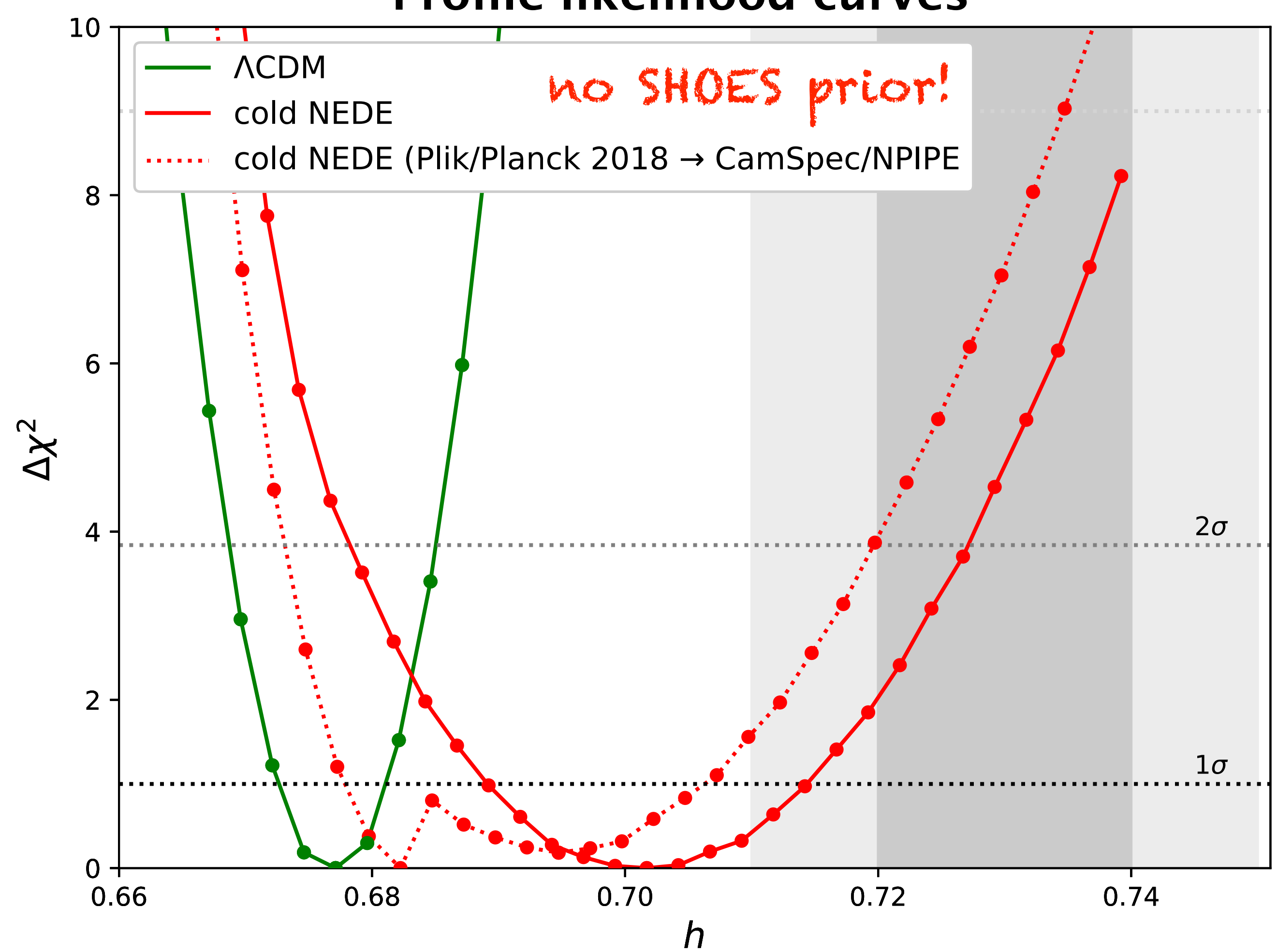

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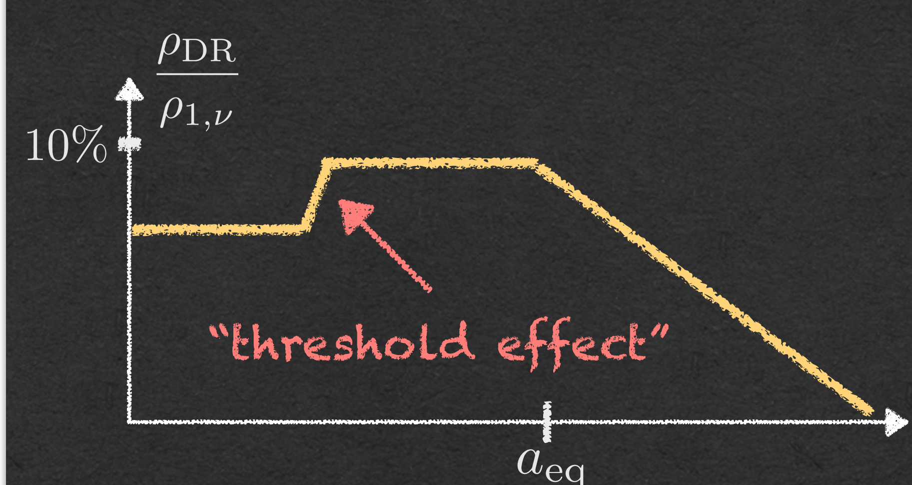

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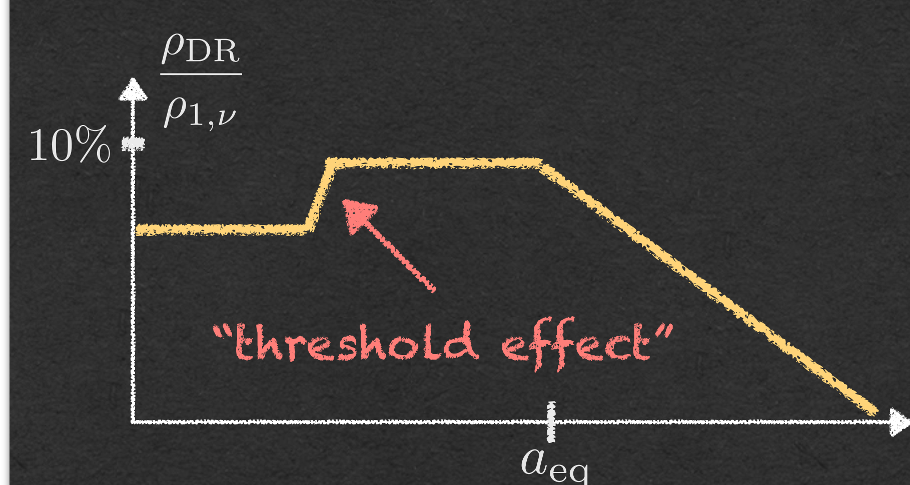

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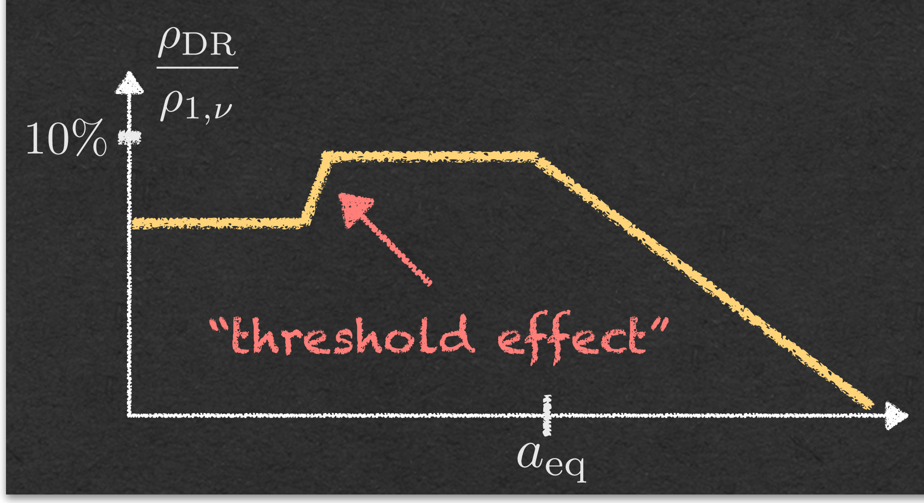

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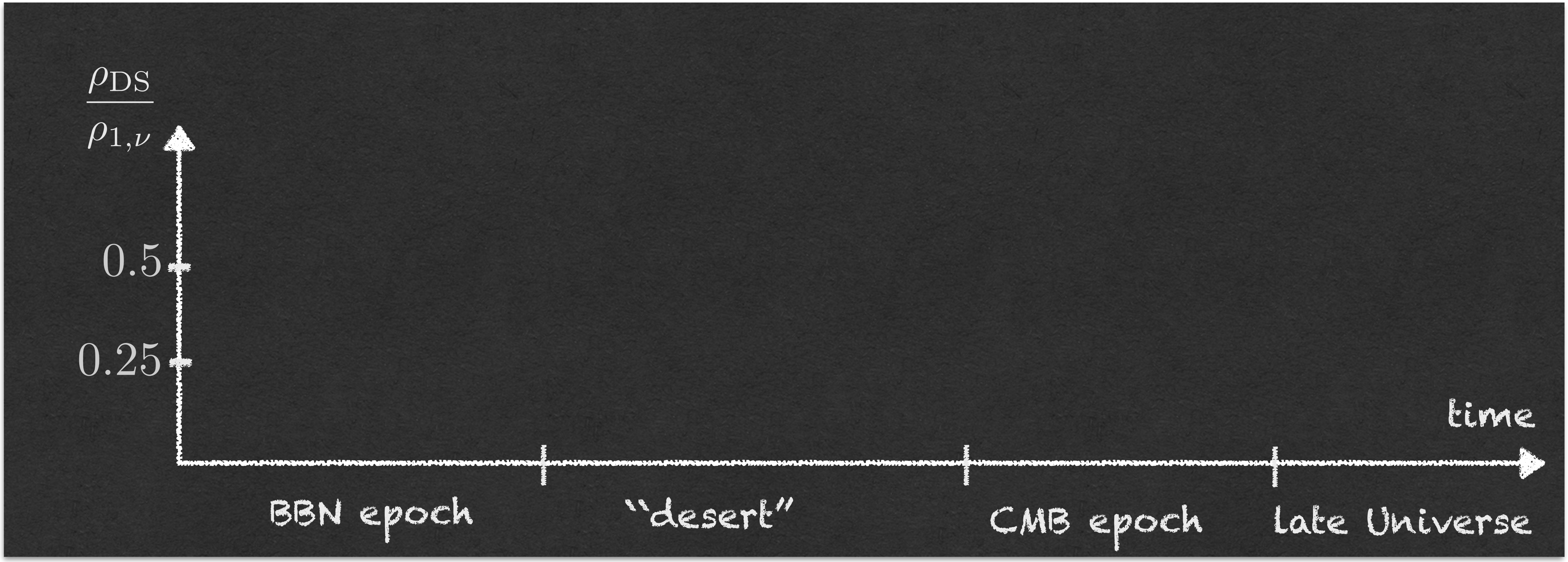
(with M.Garny, H.Rubira, M.S.Sloth)



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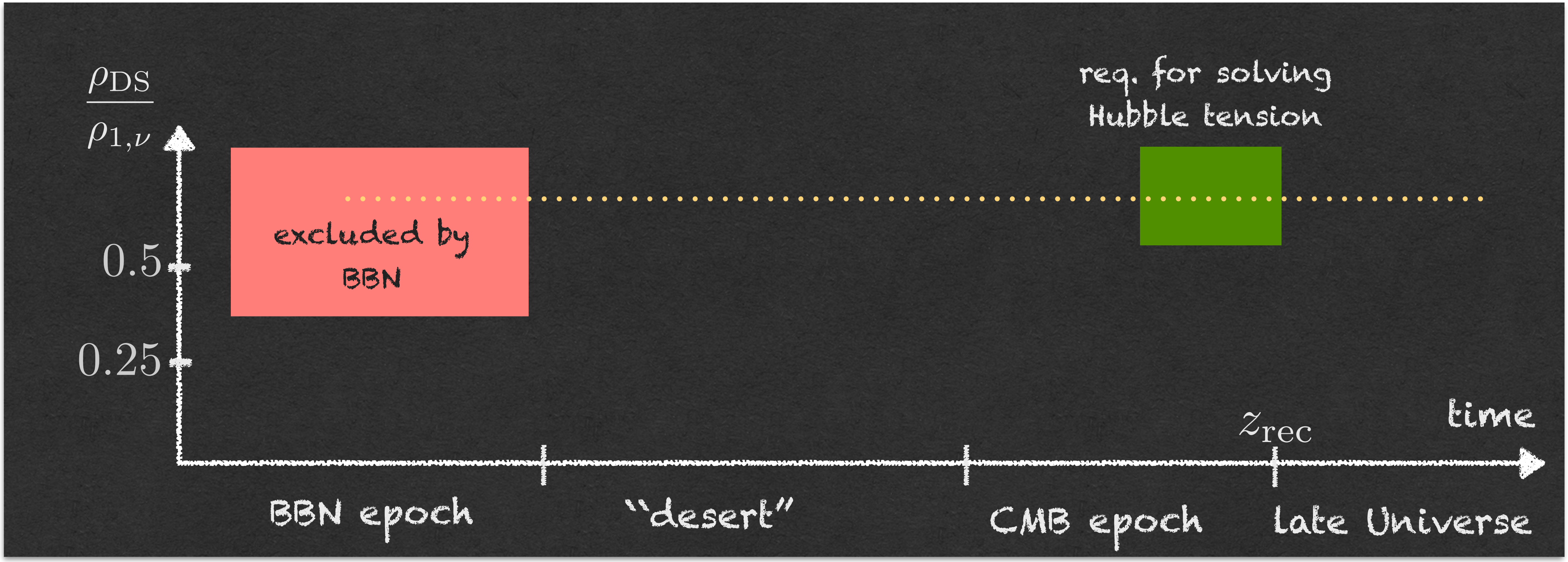

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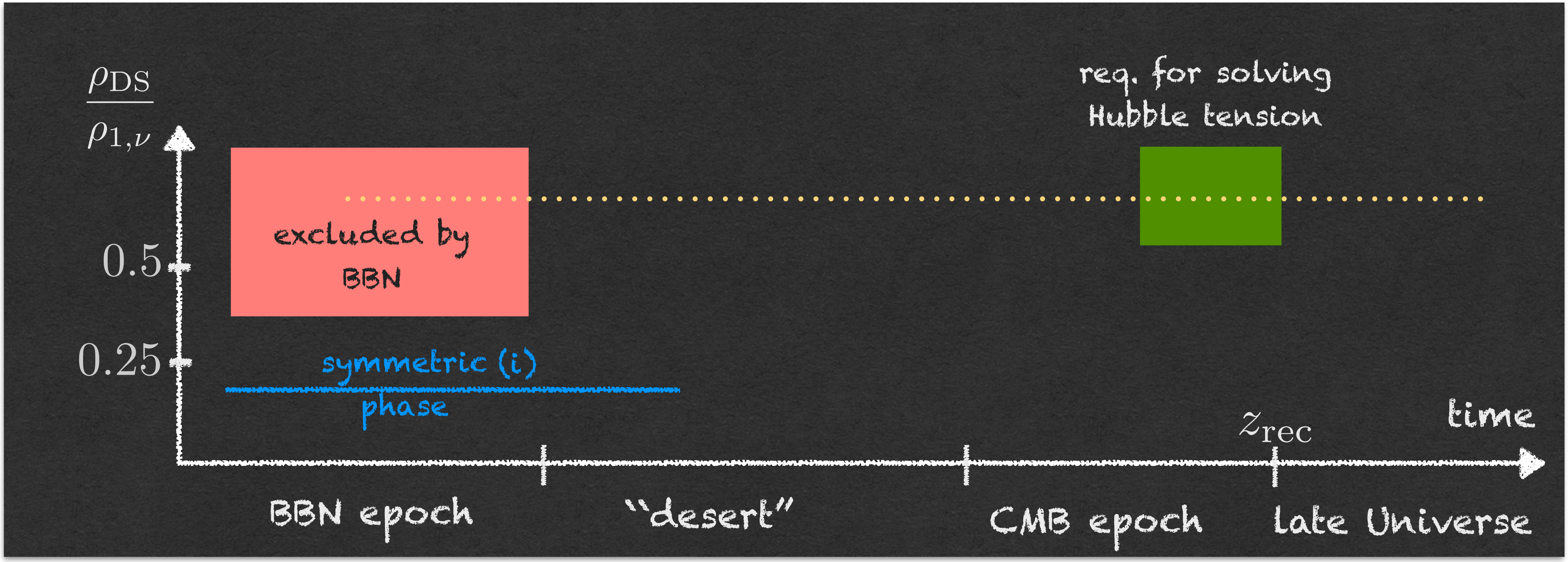

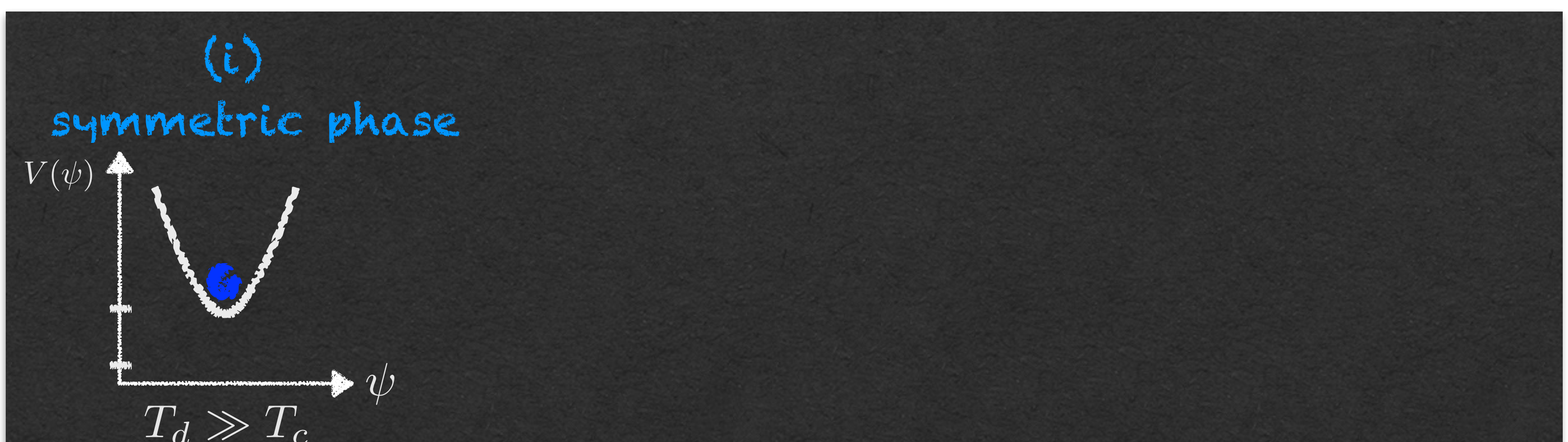

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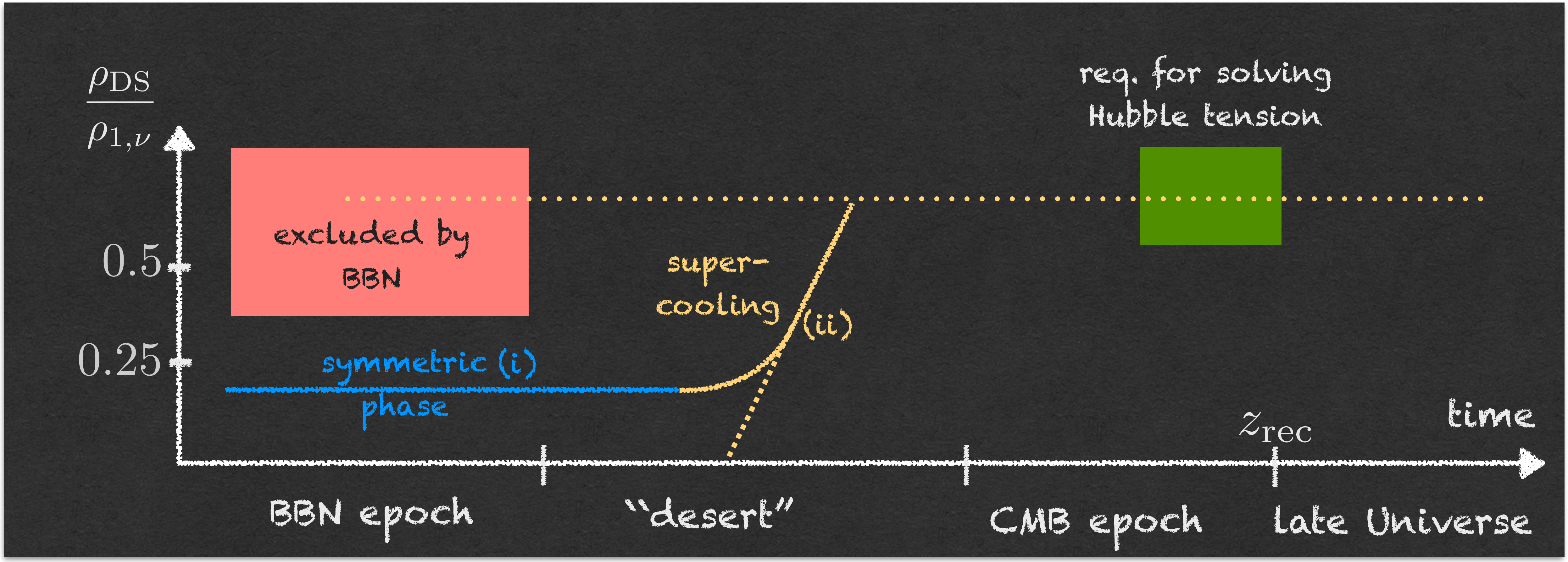

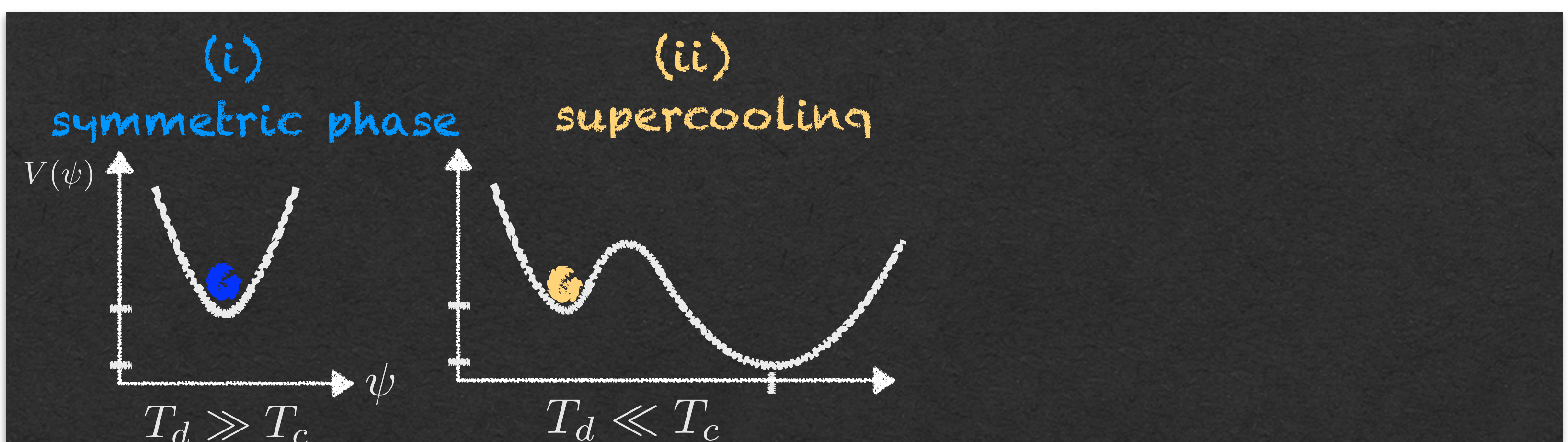

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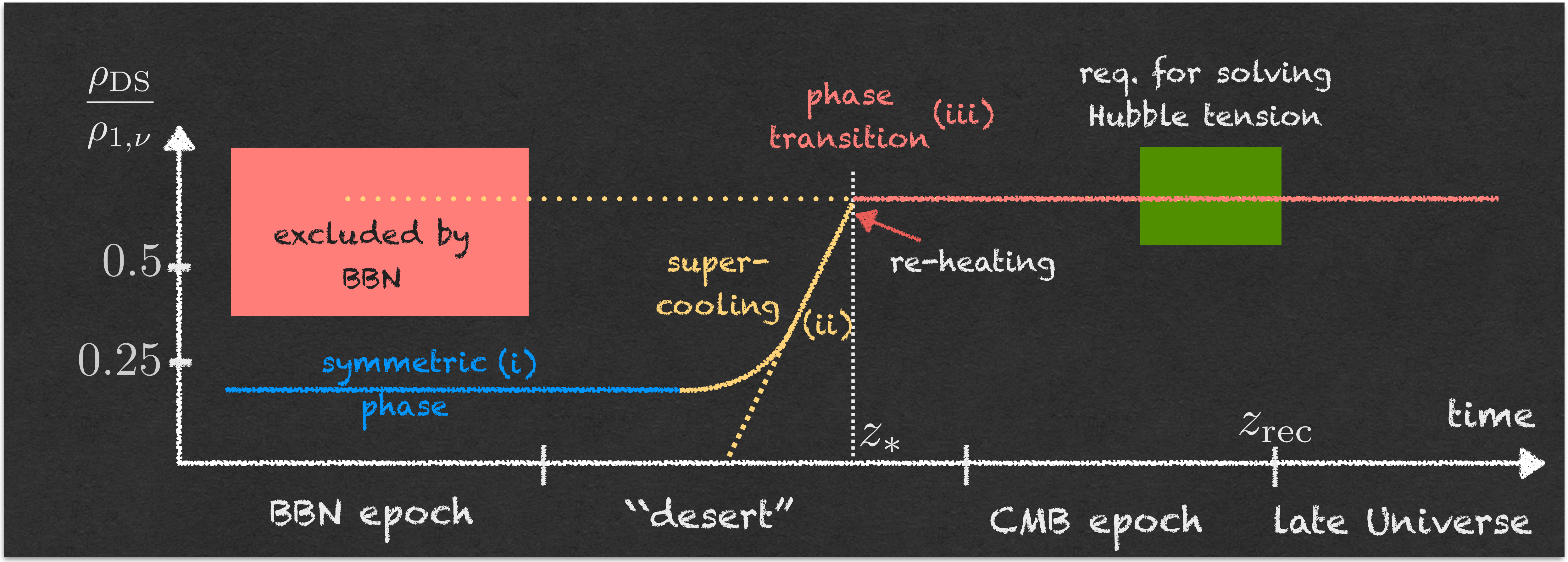

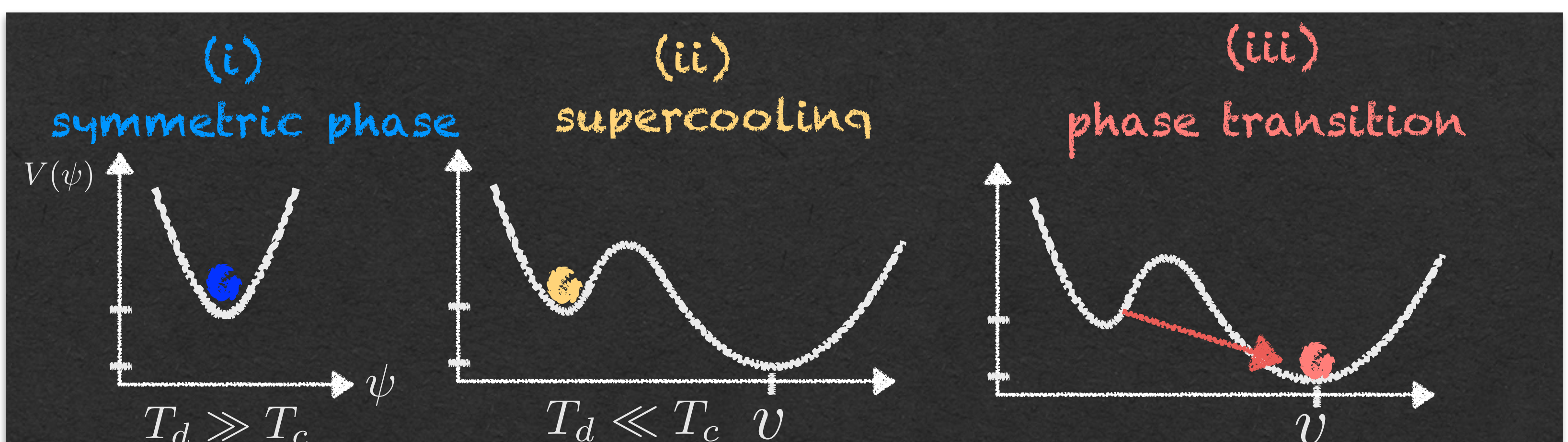

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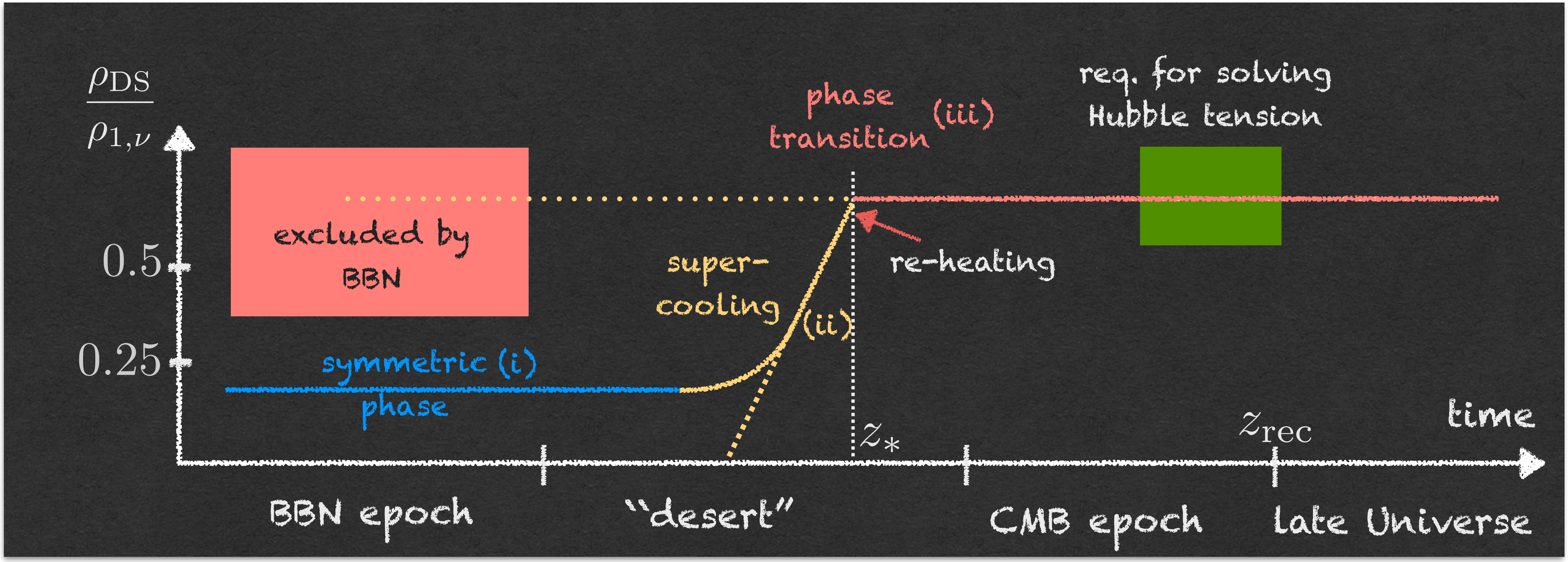

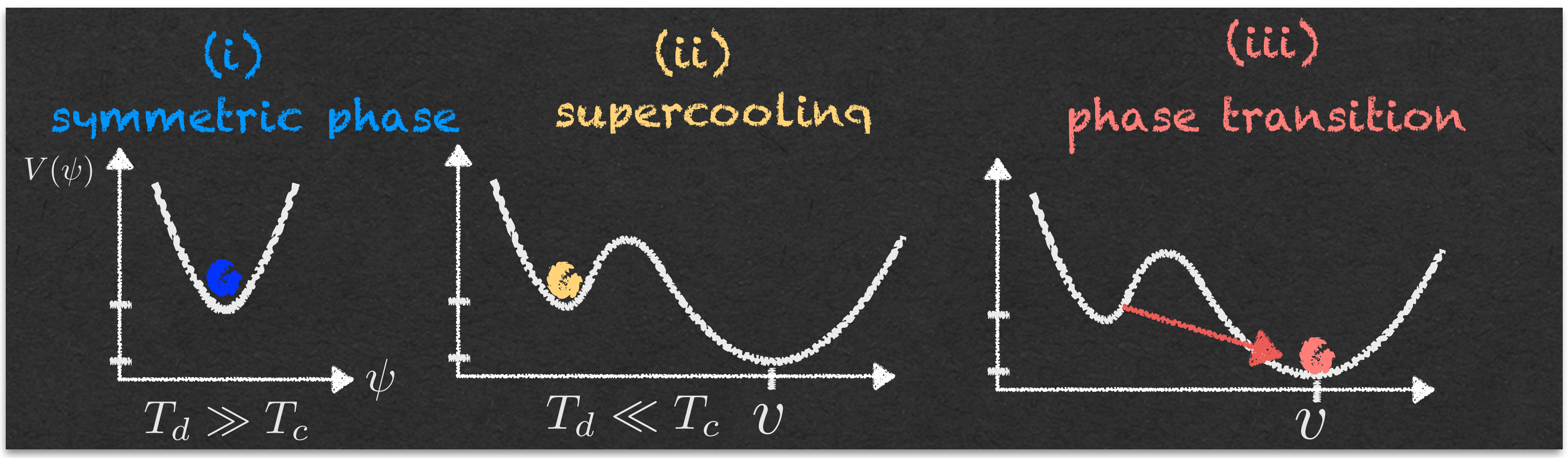

- **Supercooled** phase transition with quick re-heating of dark sector allows avoidance of BBN constraint.
- **Simple microscopic model:** SU(N) -> SU(N-1) through radiative symmetry breaking a la Coleman-Weinberg.
- **Redshift range:**

$$z_{rec} < z_* < 10^9$$

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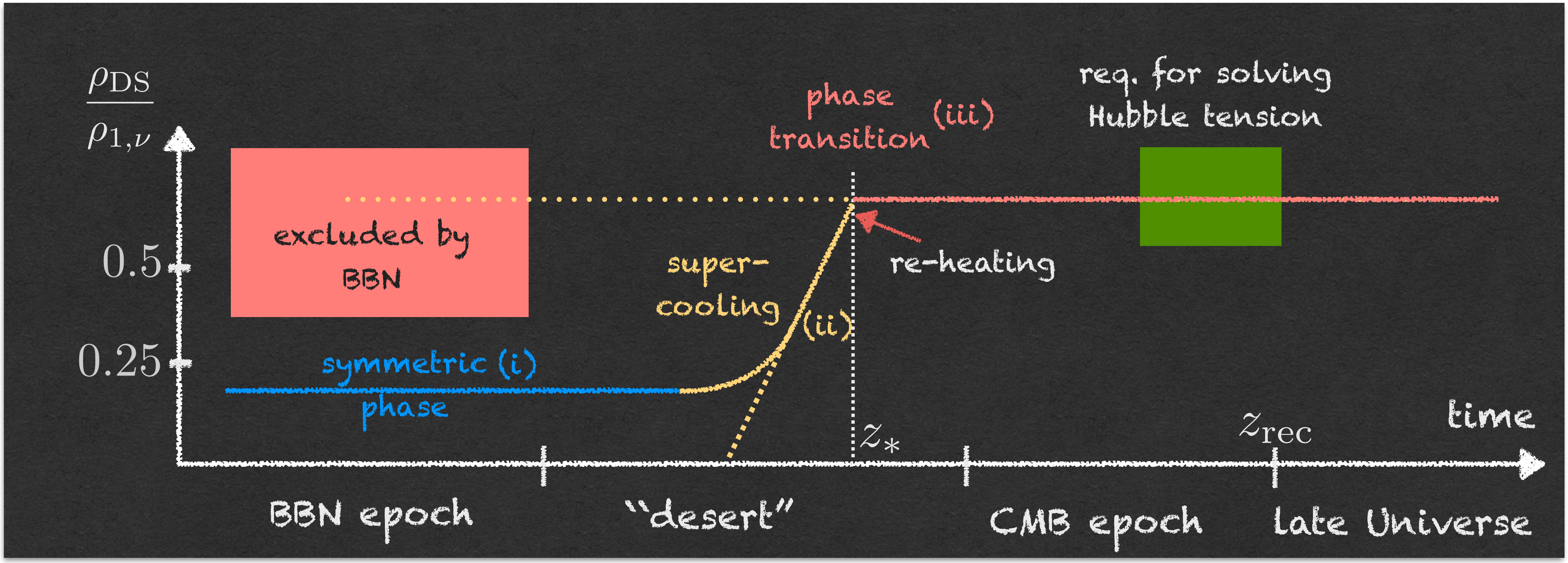

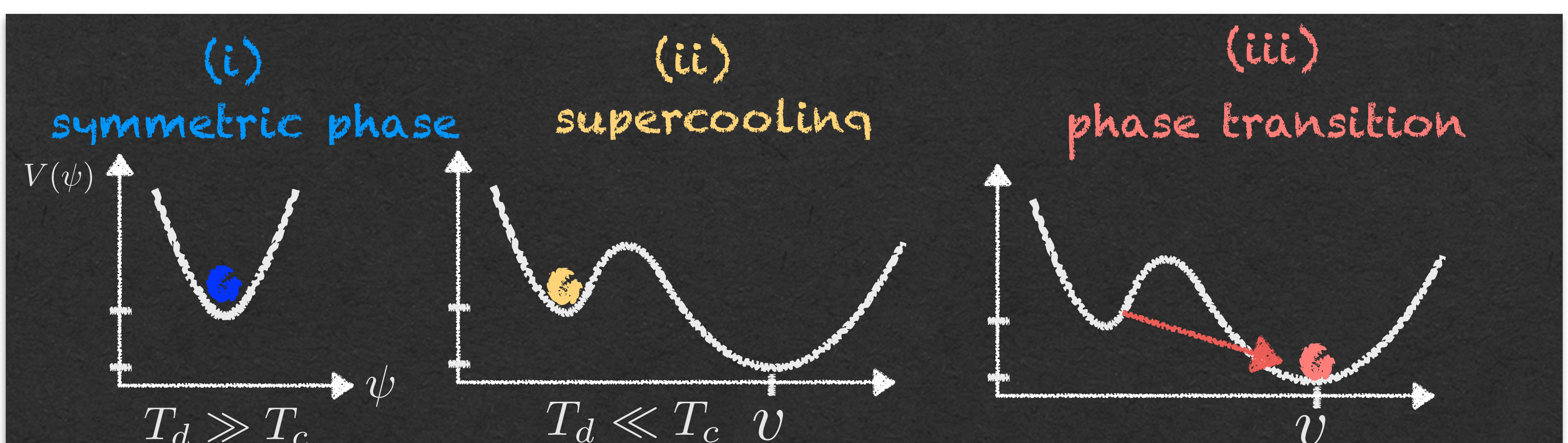

- **Central simplifying assumptions:**

(i) $p(t) \propto \exp\left(\beta(t - t_*)\right)$ with $\beta \gg H_* = 1/(2\,t_*)$ → bubbles remain small

(ii) "instantaneous" reheating

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recent bound:
$\beta > 320 H_*$
[G.Elor++,2311.16222]

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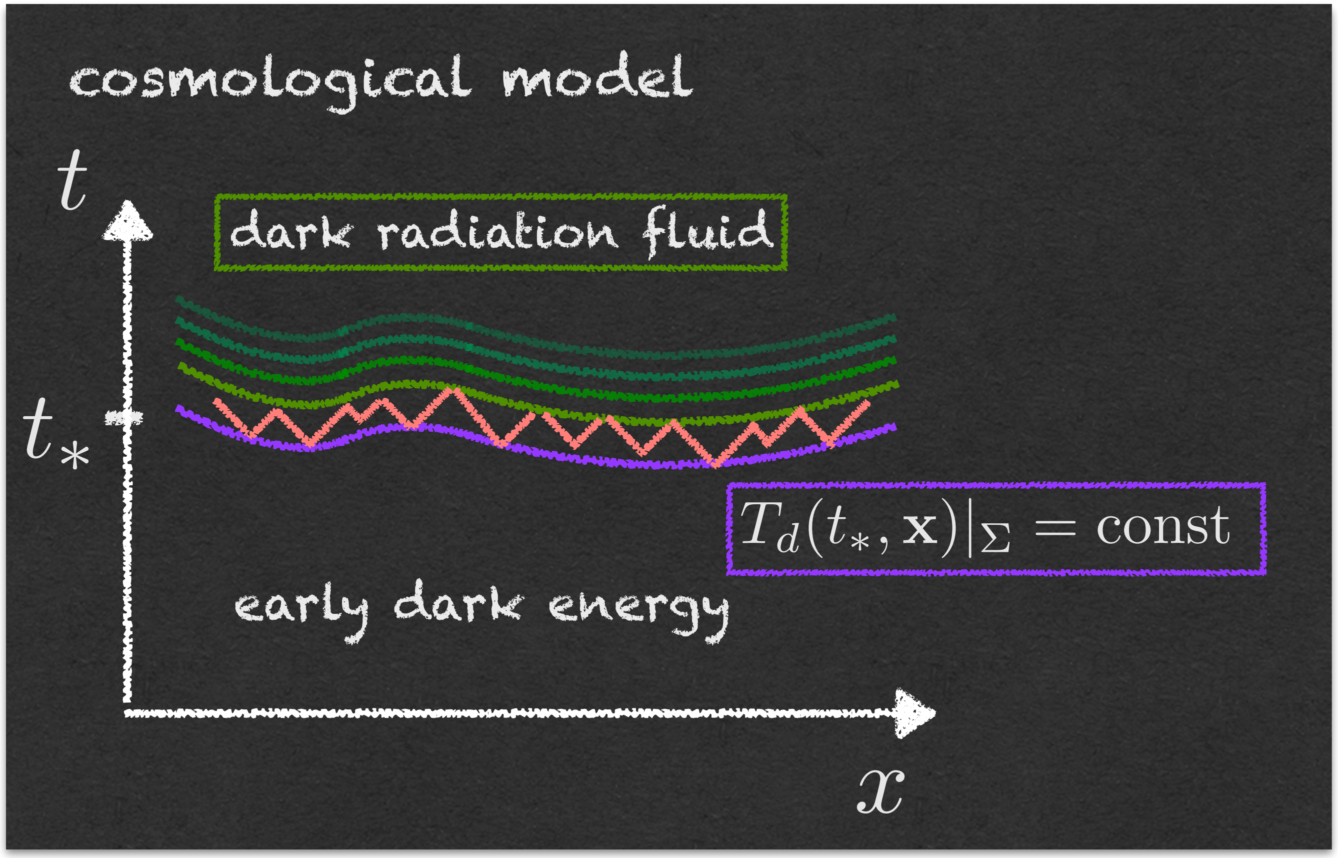
     → relevant for CMB + LSS



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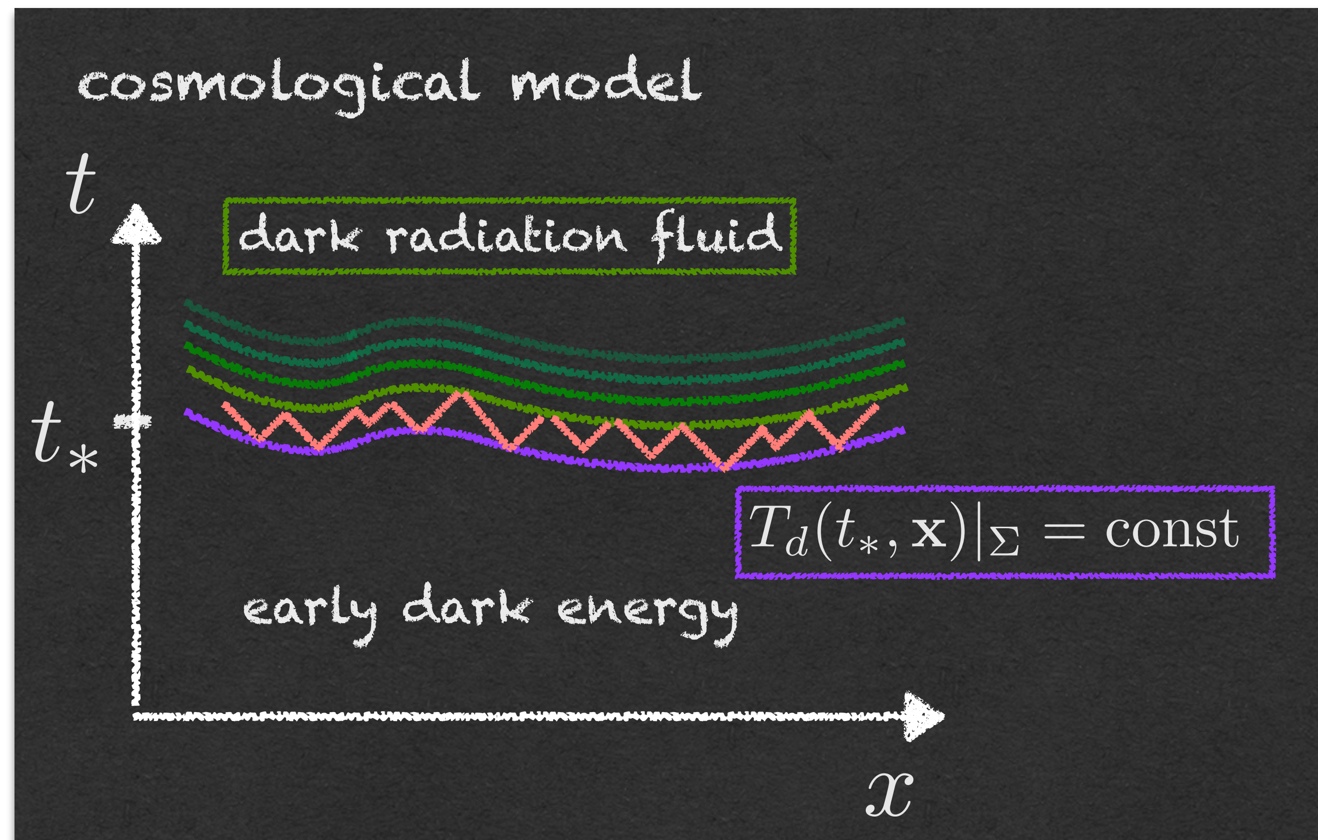

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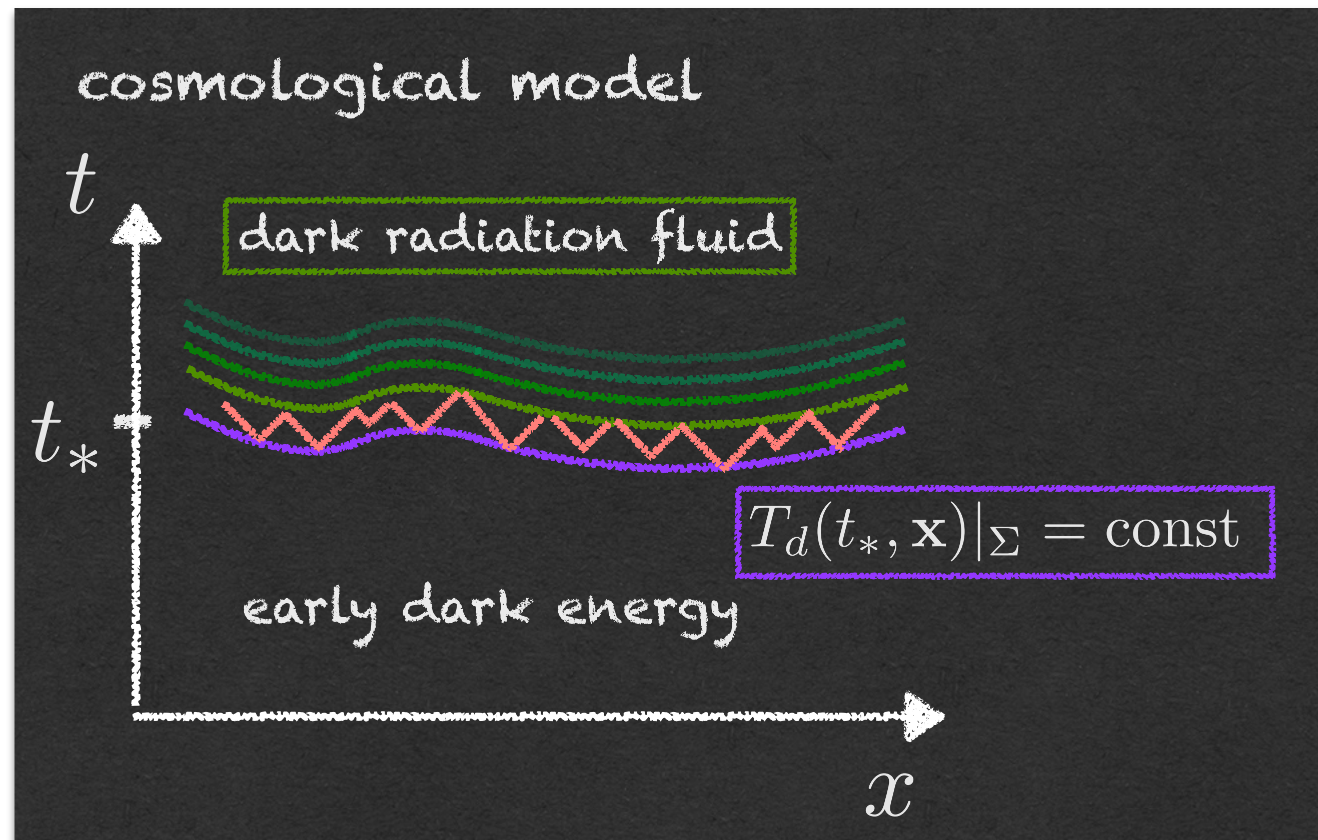

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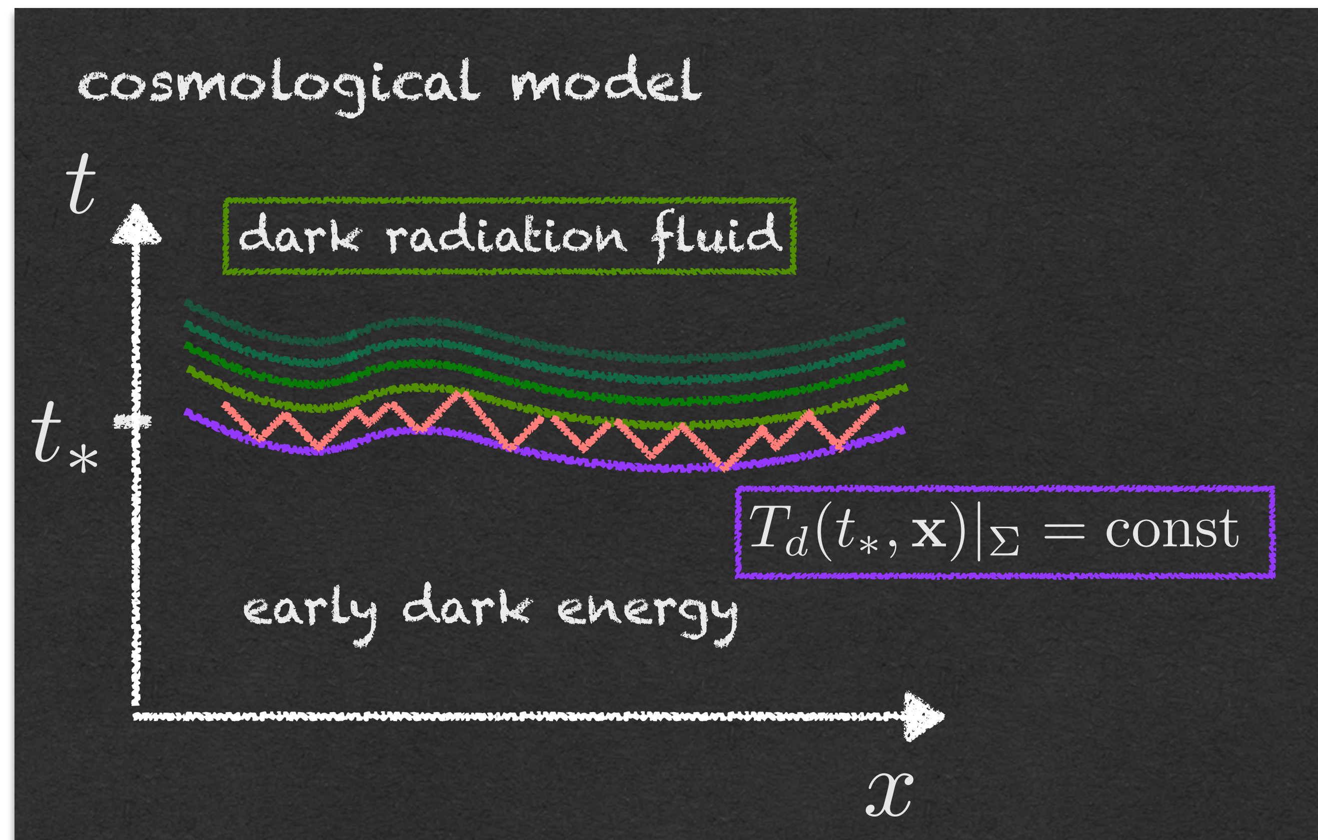

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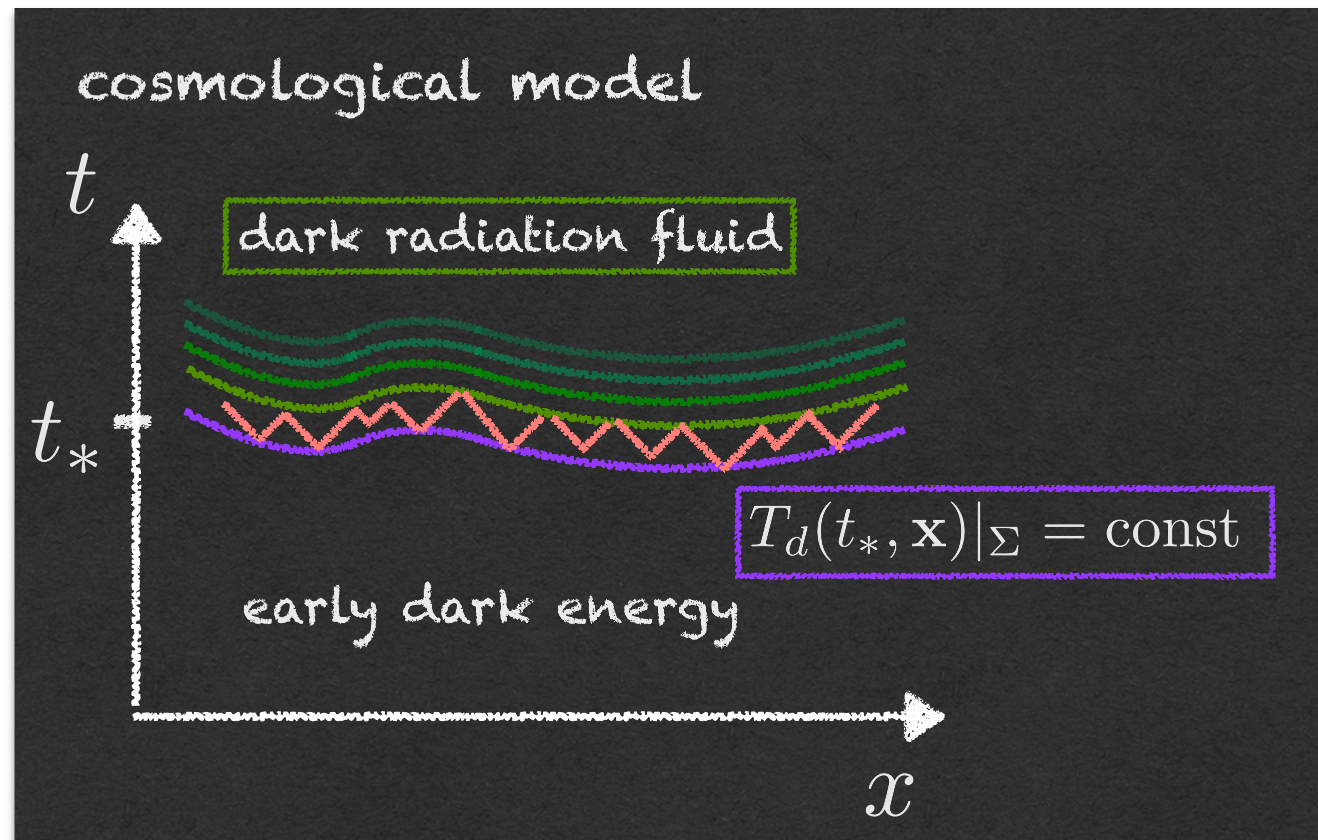
    [M.Garny++,2404.07256]



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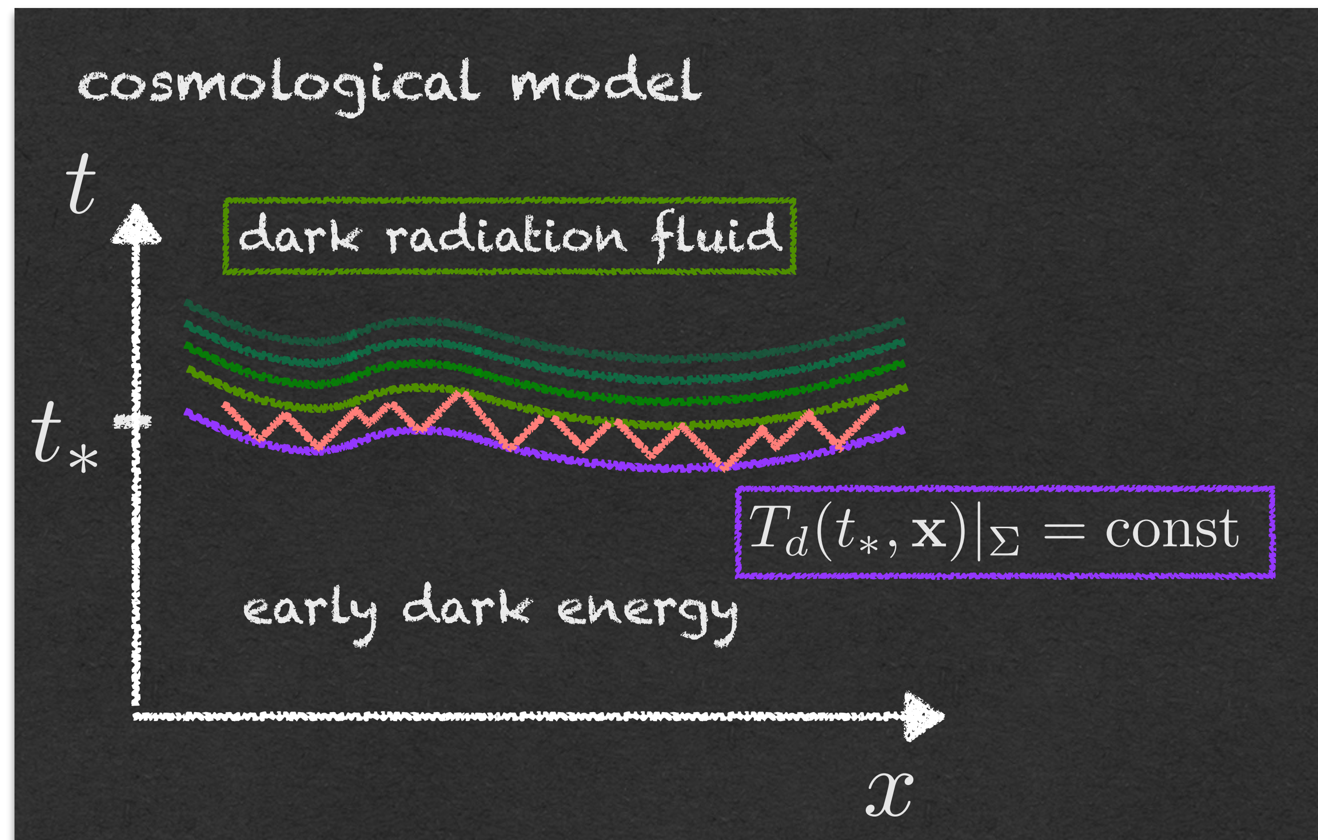

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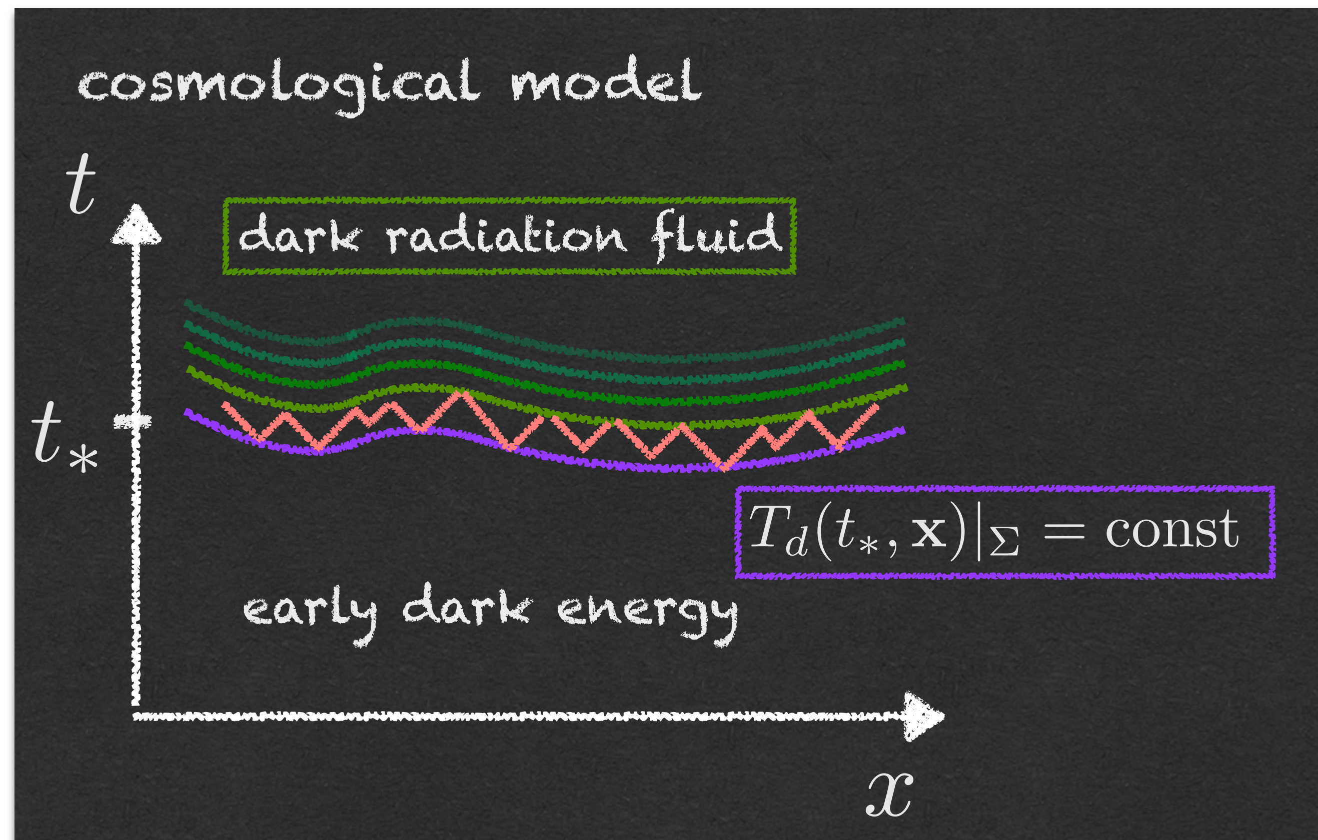

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- Work in progress […] Stay tuned!

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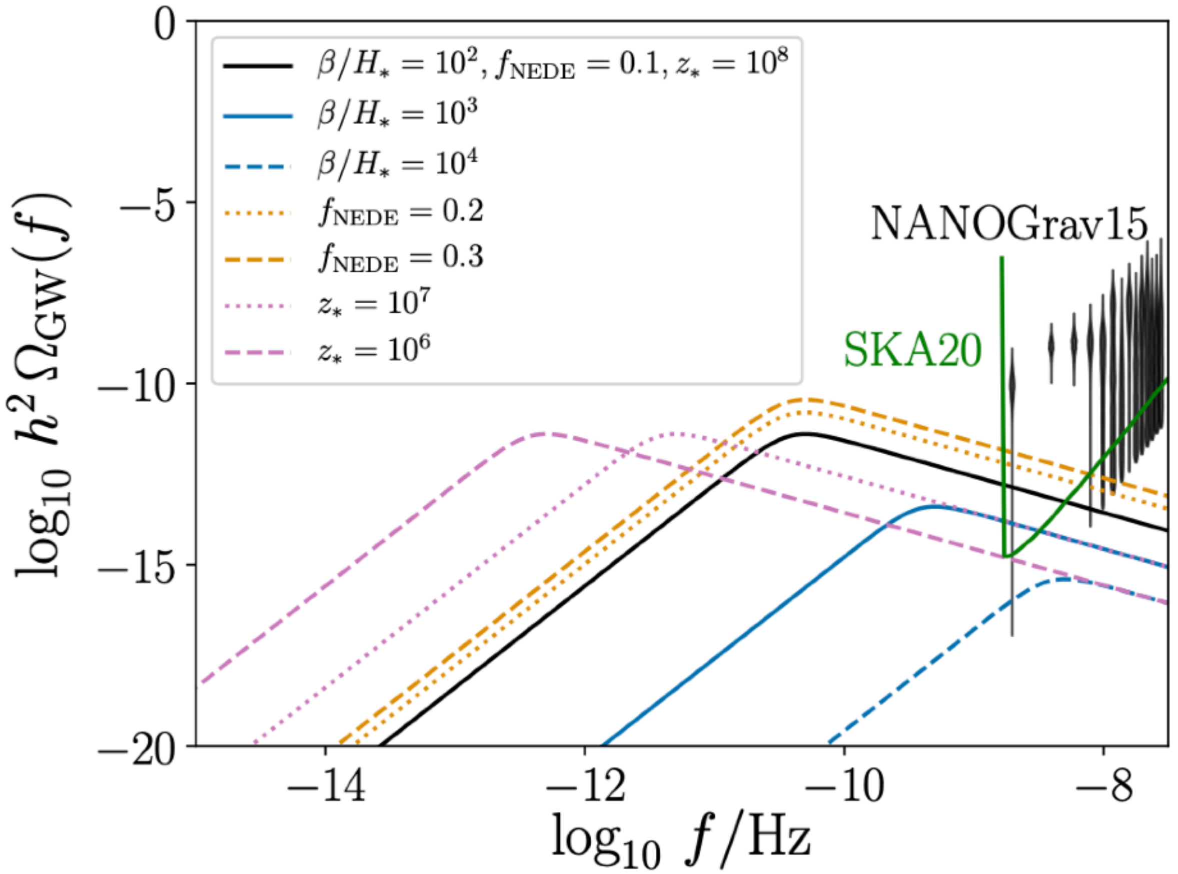
- Stochastic **gravitational wave** background
  - Overlap with PTAs for phase transitions that occur close to BBN and create large bubbles.

$$10^7 < z_* < 10^9$$

  - First estimate (envelope approximation, thin-wall, …)



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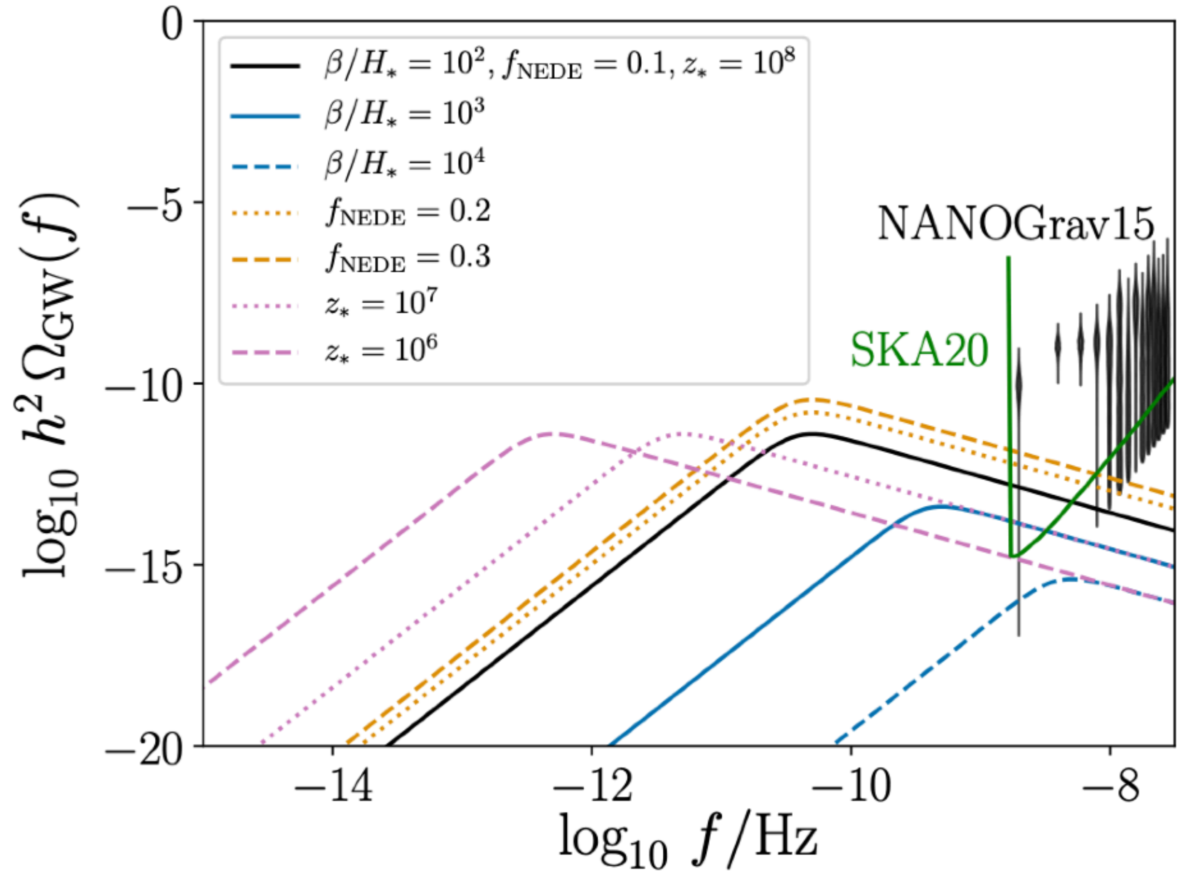
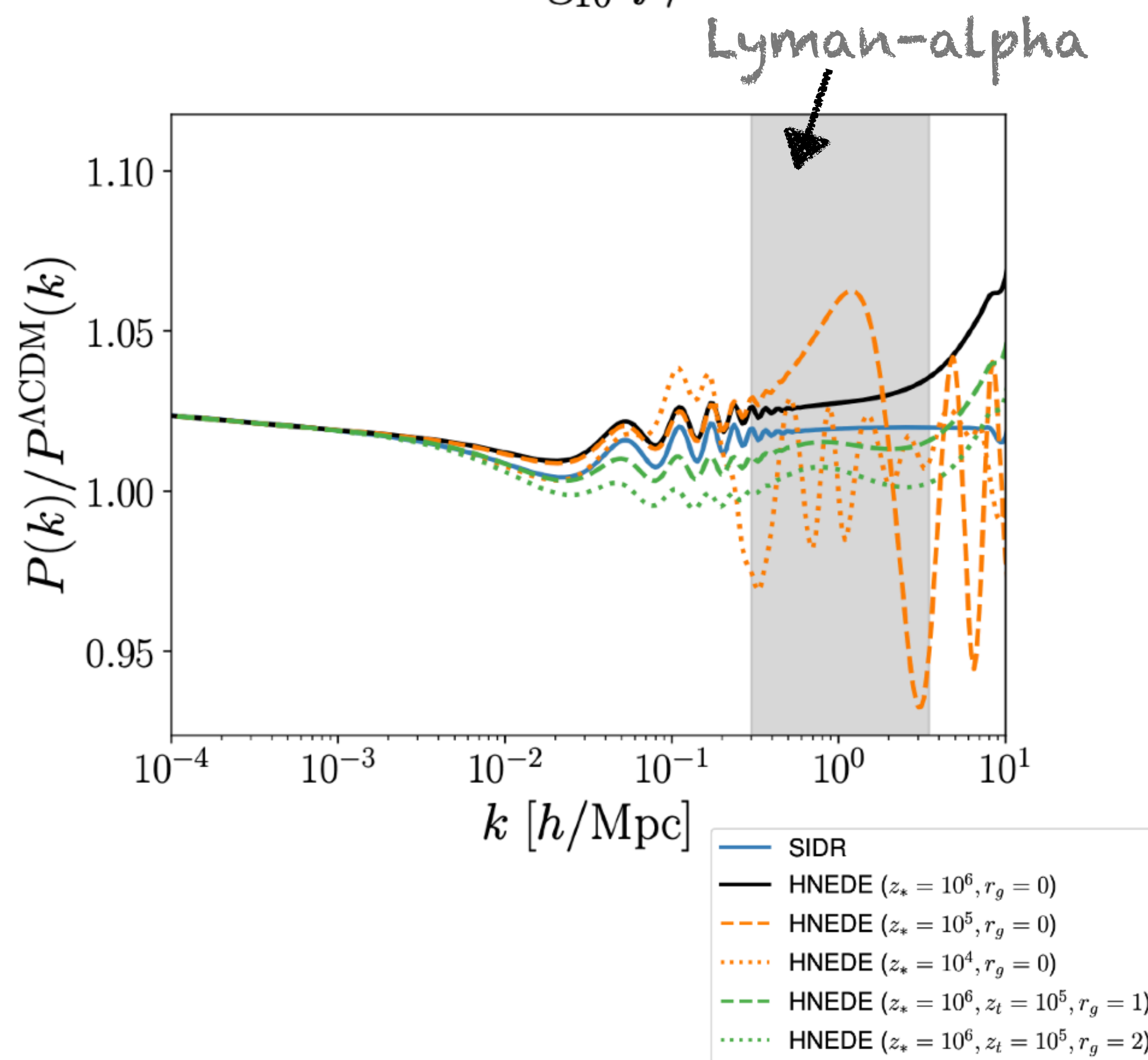
- **Acoustic oscillations** in DR fluid
  - Consequence of perturbation matching.
  - Imprinted in matter power spectrum.
  - Relevant if p.t. occurs sufficiently late:

$$10^5 < z_* < 10^6$$





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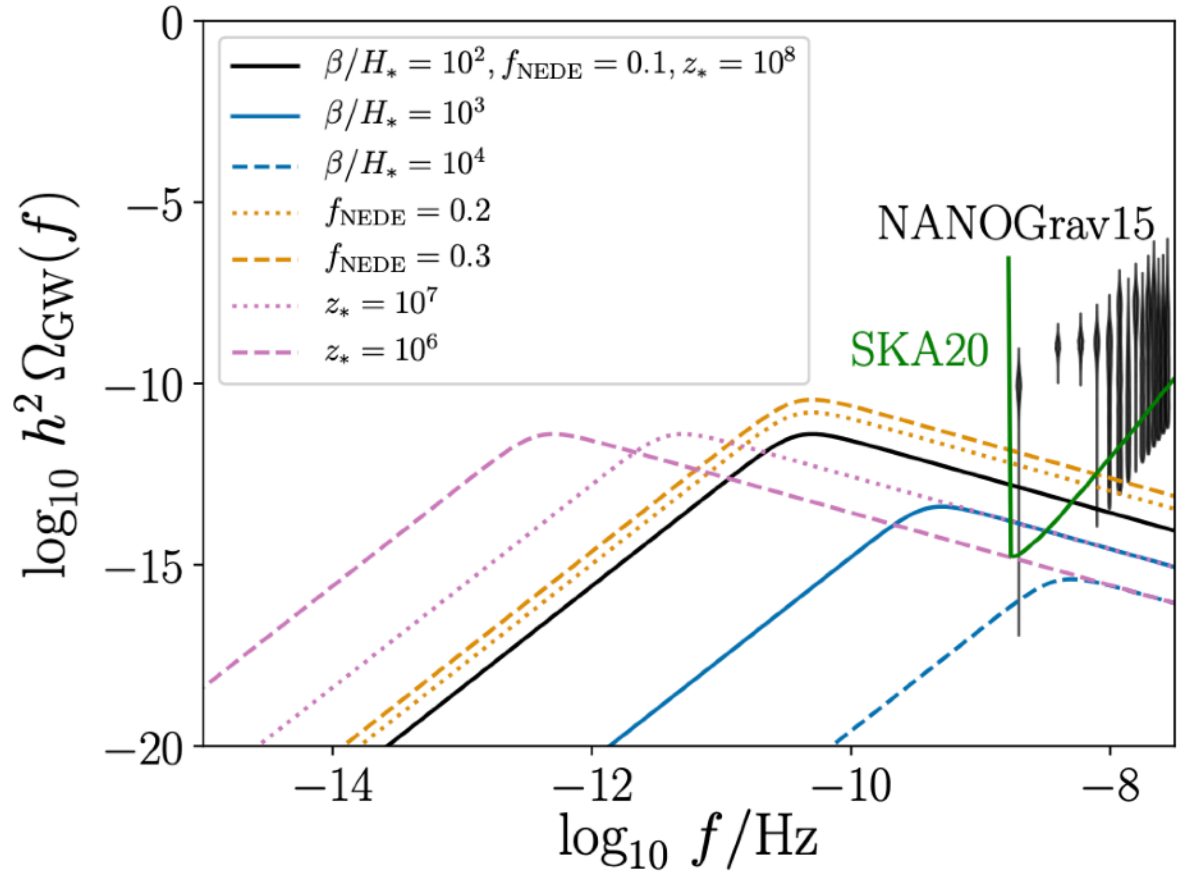

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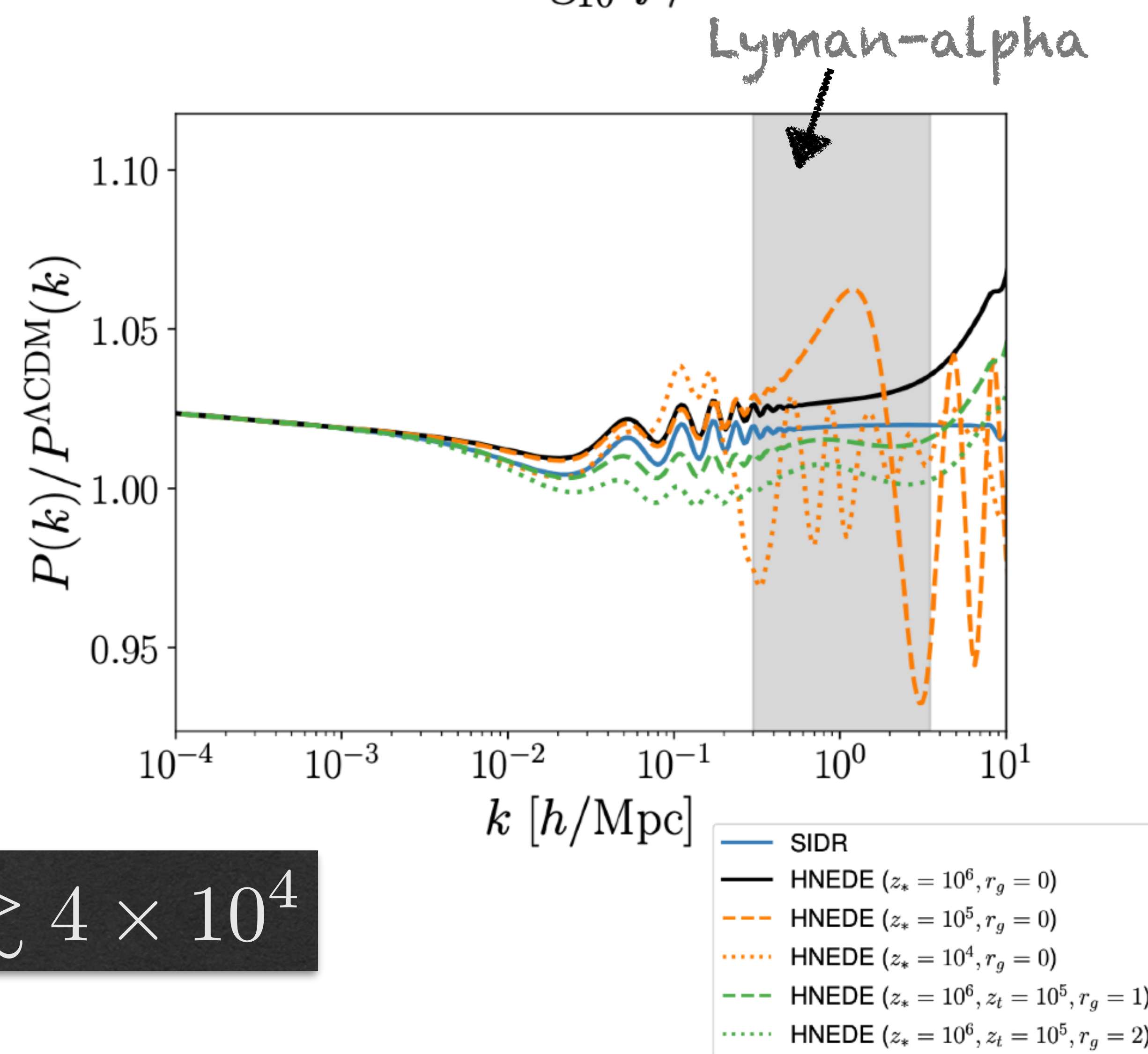


- **CMB anisotropies**
  - CMB provides lower bound on redshift
  - Difference with cold NEDE due to character of trigger field.
  - Acoustic oscillations in post p.t. fluid stronger in Hot NEDE.

$$z_* \gtrsim 4 \times 10^4$$

Summary

- The **Hubble tension** calls for new physics operative during the CMB epoch.
- Opportunity to probe new fundamental physics **above (but close to) the eV scale**!
- A strong first-order phase transition offers a simple microscopic scenario.
- **Cold New Early Dark Energy** relies on a triggered vacuum phase transition to bring the tension down to 2 sigma (challenges: describe post p.t. fluid, keep testing against new data).
- **Hot New Early Dark Energy** relies on a supercooled p.t. to produce DR **after BBN**.
- Simplest model: Brings tension below 3 sigma… → Now: Exploit benefits of having microscopic scenario.
- … with **unique signatures** in matter power spectrum (+ PTAs).
- Take home:
  - Exciting times in cosmology as constraining power of cosmological probes is increasing.
  - Phase transitions are a simple playground for (early) dark energy / dark radiation physics.
  - Time to go beyond model-independent parametrizations and use **both** theory and data constraints.
  - **Invitation:** Many ideas wait to be explored!

Hot New Early Dark Energy

- Dark non-Abelian Higgs model with radiative breaking of conformal symmetry à la Coleman-Weinberg (CW)

$$\mathcal{L} = |D\Psi|^2 - V(\Psi) - \frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu})$$

gauge coupling: $g \ll 1$

Ψ dark Higgs; transforms in fundamental

$$V(\psi; T_d) = V_0 + B\psi^4\left(\ln\frac{\psi^2}{v^2} - \frac{1}{2}\right) - \frac{\mu_{\mathrm{eff}}^2}{2}\psi^2\left(1 - \frac{\psi^2}{2v^2}\right) + \Delta V_{\mathrm{thermal}}(\psi; T_d)\ ,$$

$\psi = \sqrt{2}|\Psi|$

$B \sim g^4$

CW 1-loop result → radiative symmetry breaking due to dim. transmutation $\xrightarrow{SU(N) \to SU(N-1)}$ $\psi \to v$

(i) $\mu_{\mathrm{eff}} \to 0$: $V'(0) = V''(0) = 0$ — nucleation inhibited for $T_d > T_d^*|_{\mathrm{CW}} (\ll v)$ → strong supercooling

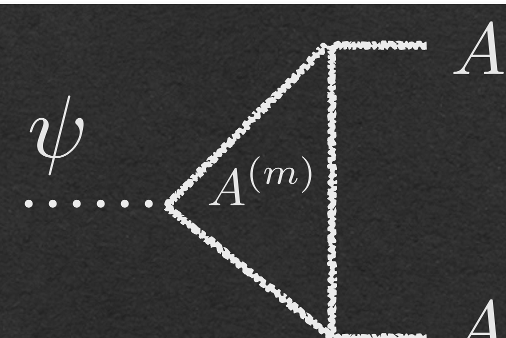
(ii) $\mu_{\mathrm{eff}} > 0$: soft breaking of conformal symmetry — nucleation possible for $T_d \gg T_d^*|_{\mathrm{CW}}$ → controlled supercooling $\mu_{\mathrm{eff}}^2 \ll v^2 g^4$

$$\frac{N_{\mathrm{eff}}^{\mathrm{after}} - N_{\mathrm{eff}}^{\mathrm{before}}}{N_{\mathrm{eff}}^{\mathrm{before}}} \propto 1/\mu_{\mathrm{eff}}^4$$ ← controls energy injection

check assumptions:

(i) $\beta/H_* \propto g^{-2}$

(ii)



efficient decay in massless gauge bosons

$$\frac{\Gamma^{(\mathrm{cm})}_{\psi\to AA}}{H_*} = \mathcal{O}(1) \times \frac{g^9 f_{\mathrm{NEDE}}^{1/4}}{1+z_*} 10^{24}$$

viable window → $0.1 \gtrsim g \gtrsim 0.01$