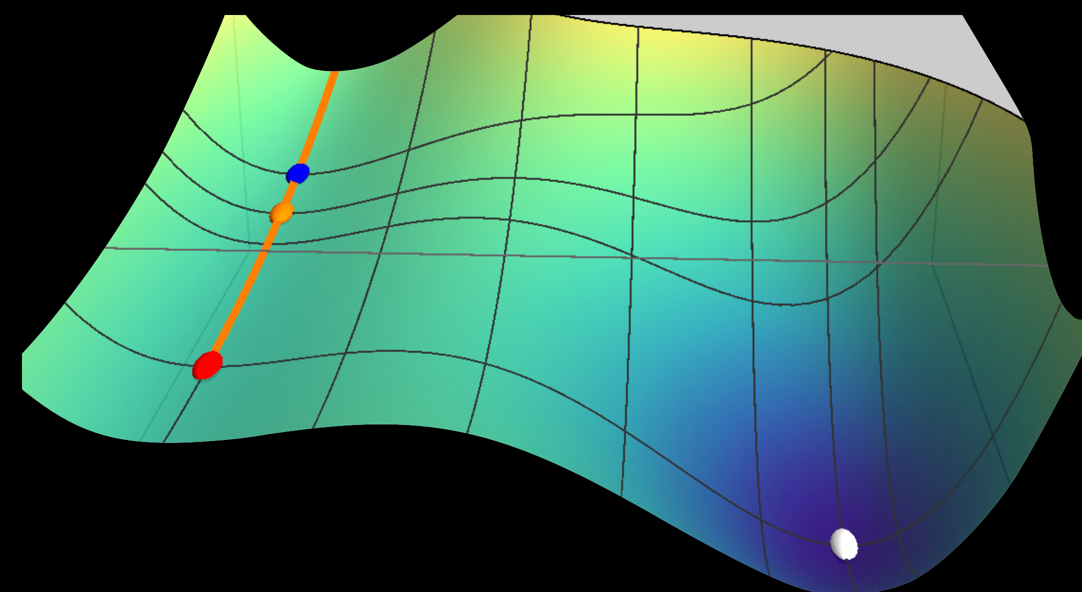
New Early Dark Energy as a resolution to the Hubble tension

Florian Niedermann
Nordita

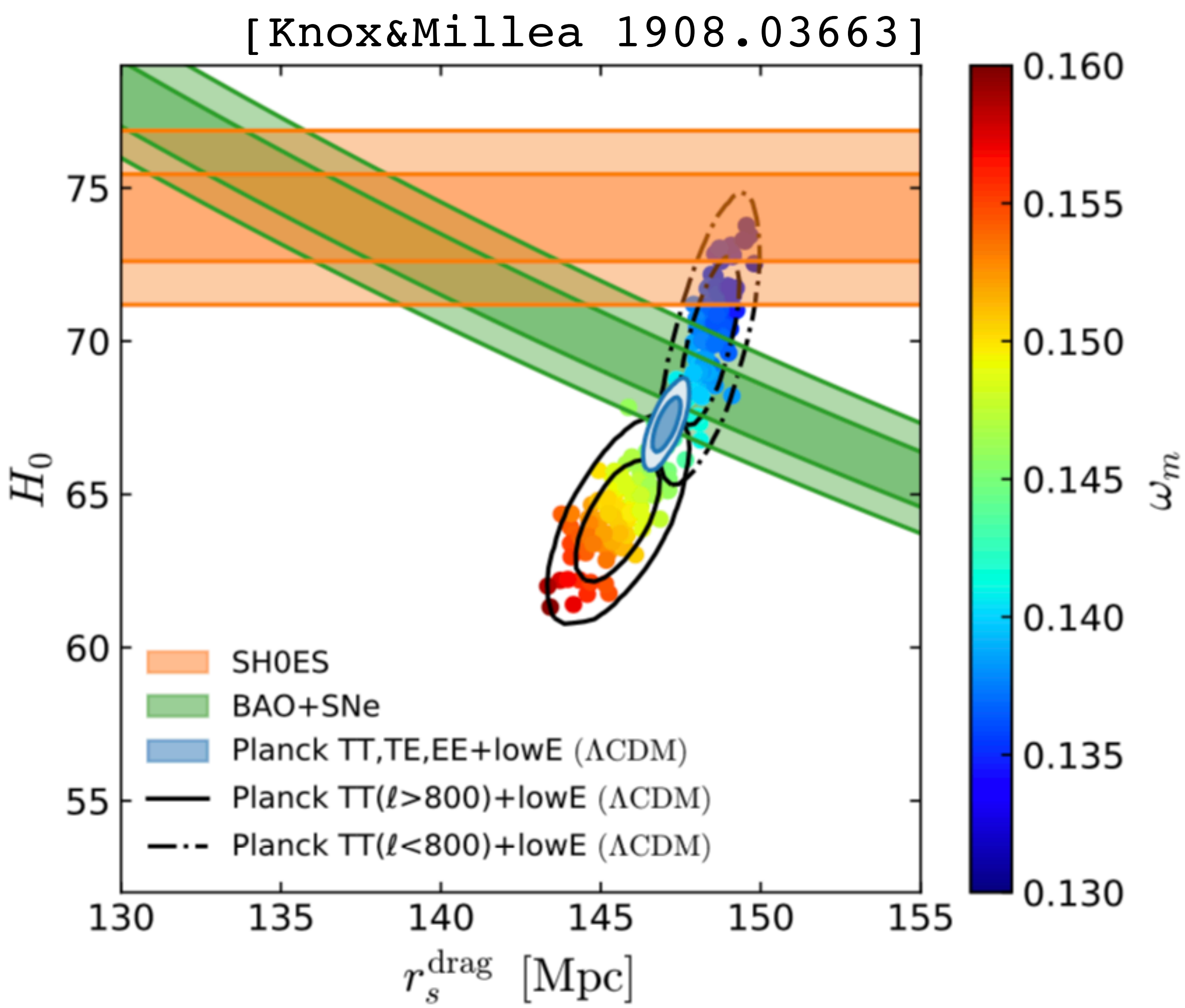
in collaboration with:
Martin S. Sloth (CP3-Origins, DK)

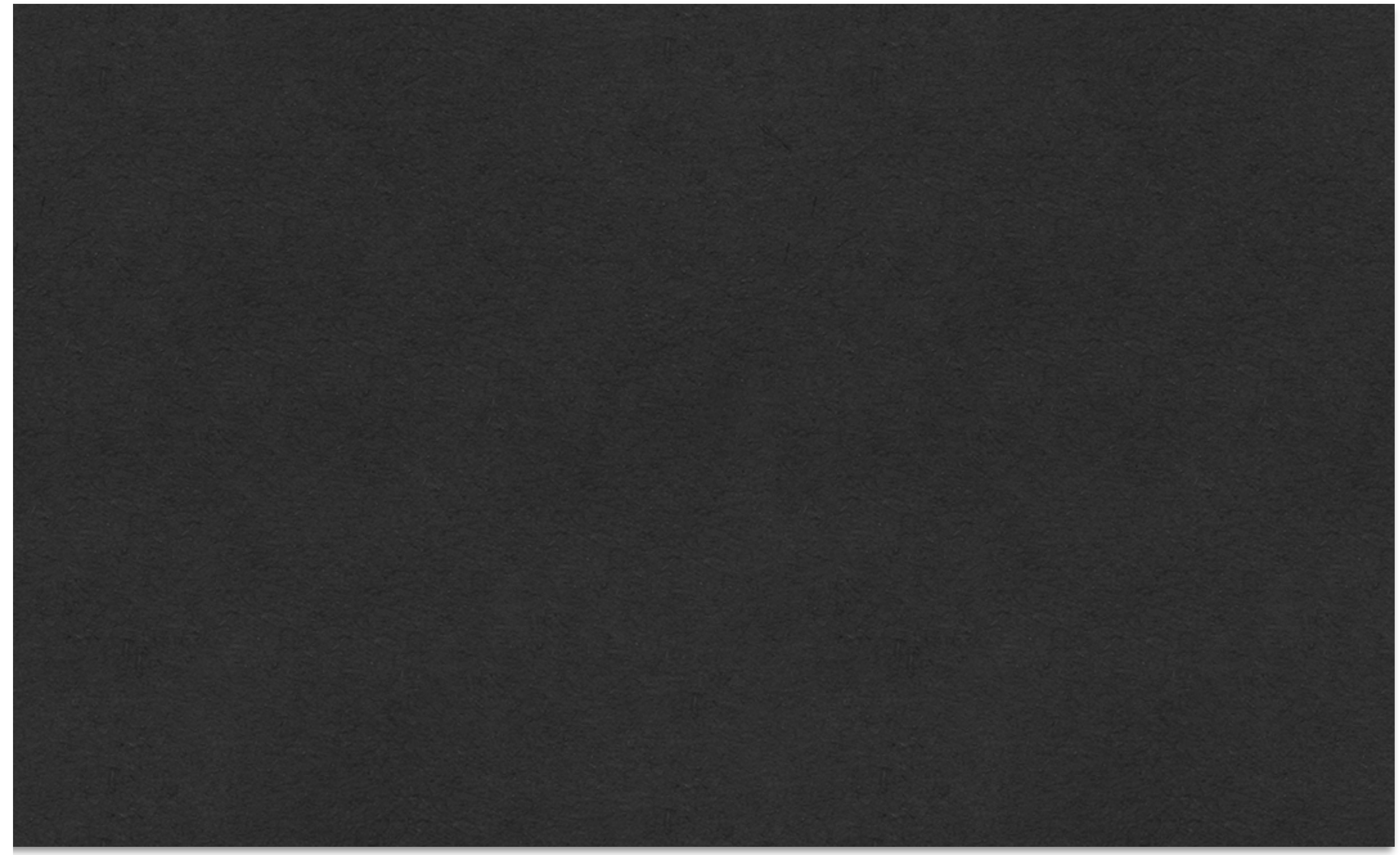


arXiv:1910.10739 (PRD letter)
arXiv:2006.06686 (PRD)
arXiv:2009.00006 (PRD)
arXiv:2112.00770 (PRD)
arXiv:2112.00759

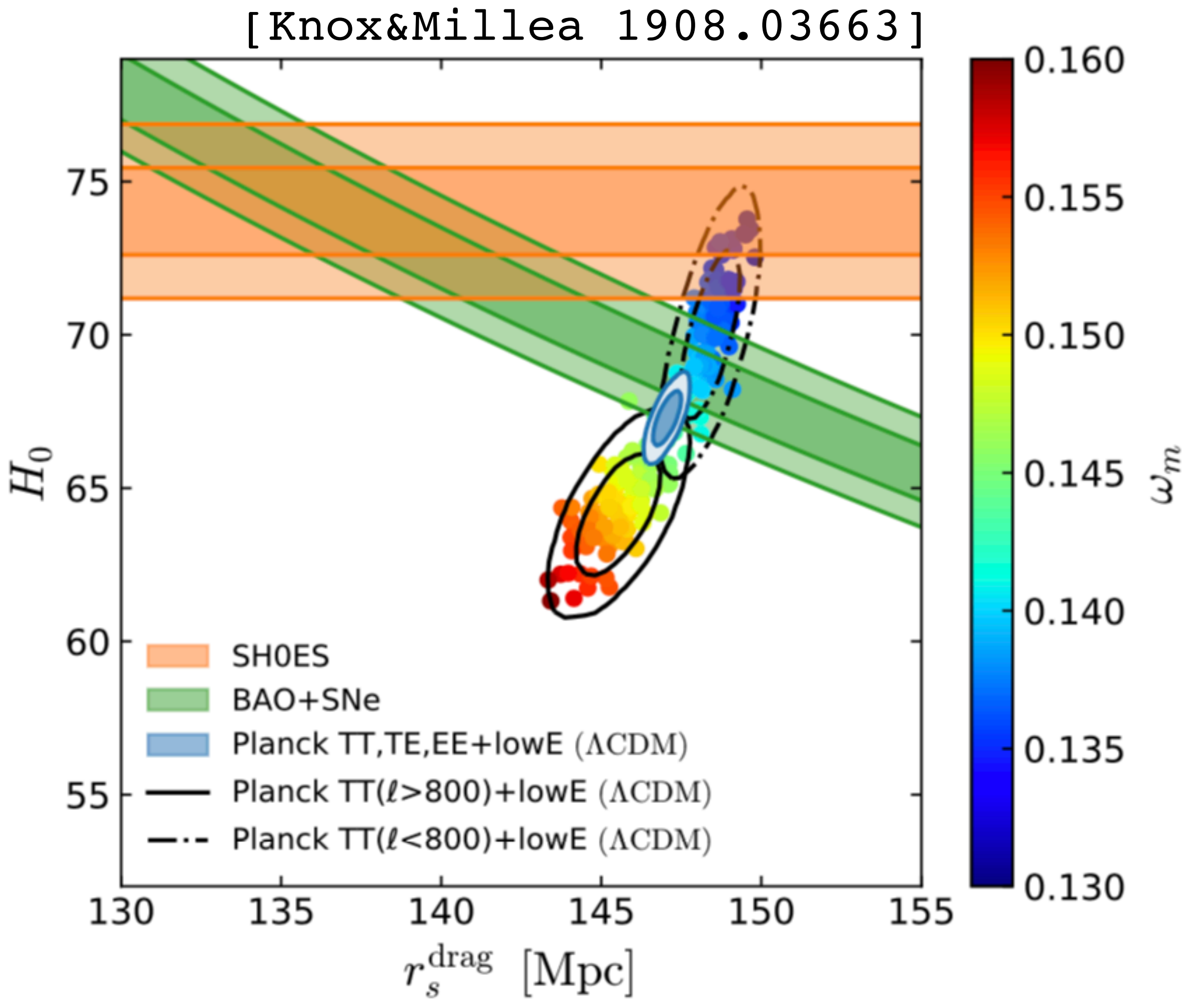
SW XIV Cargèse
8-14 May 2022

The Hubble tension





The Hubble tension

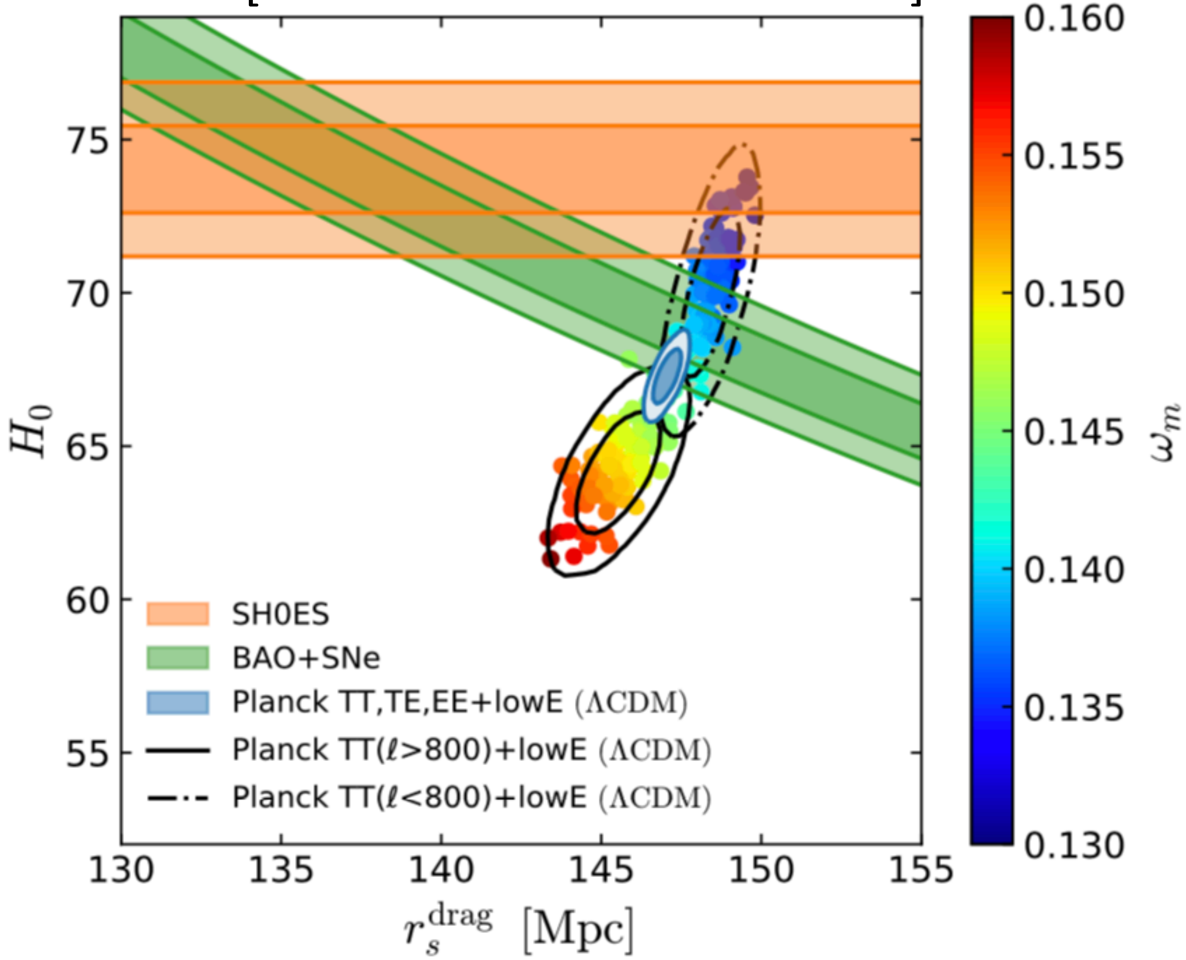


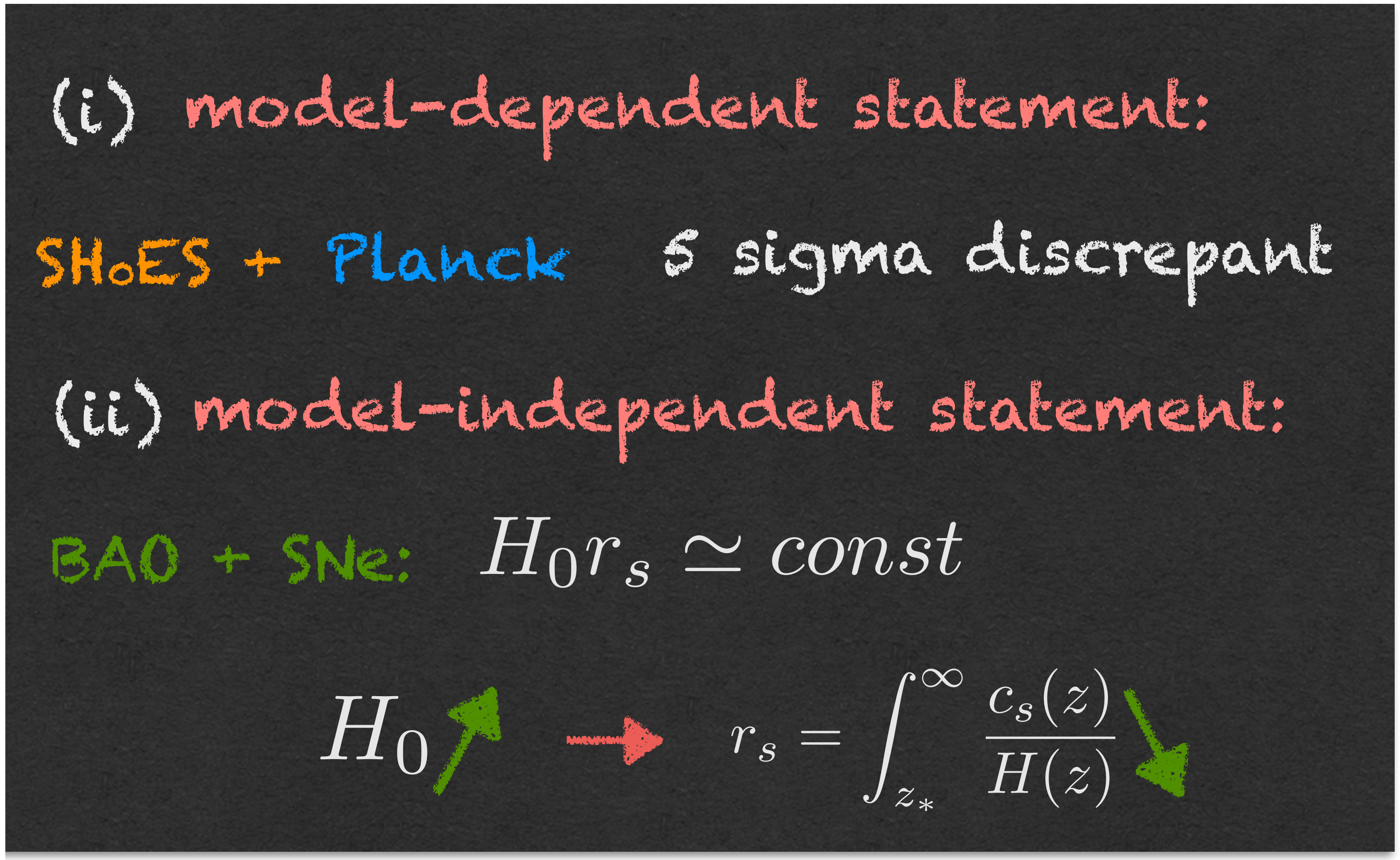
(i) model-dependent statement:

SH0ES + Planck 5 sigma discrepant

The Hubble tension

[Knox&Millea 1908.03663]

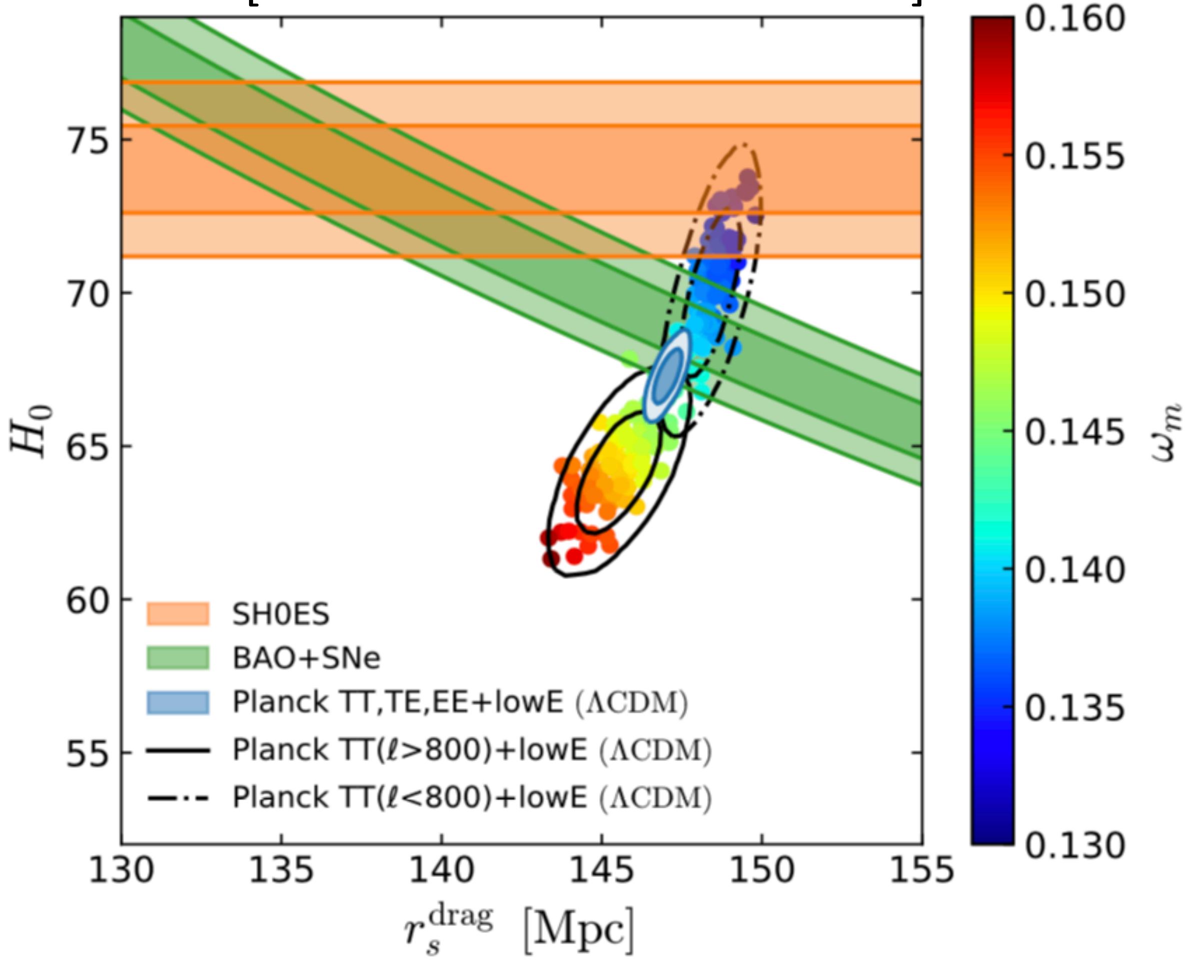


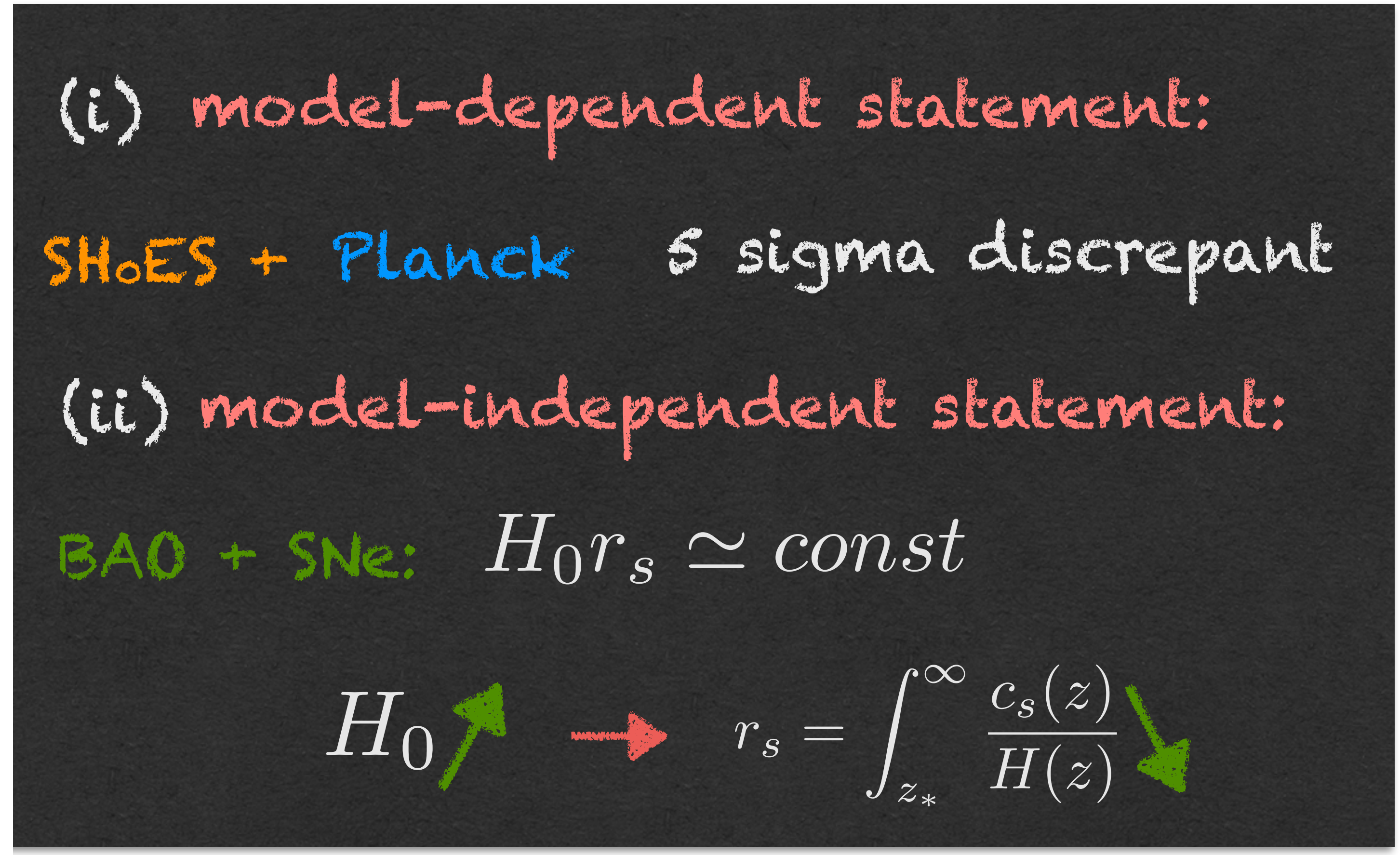


[Aylor++1811.00537] [Arendse++1909.07986]

The Hubble tension

[Knox&Millea 1908.03663]



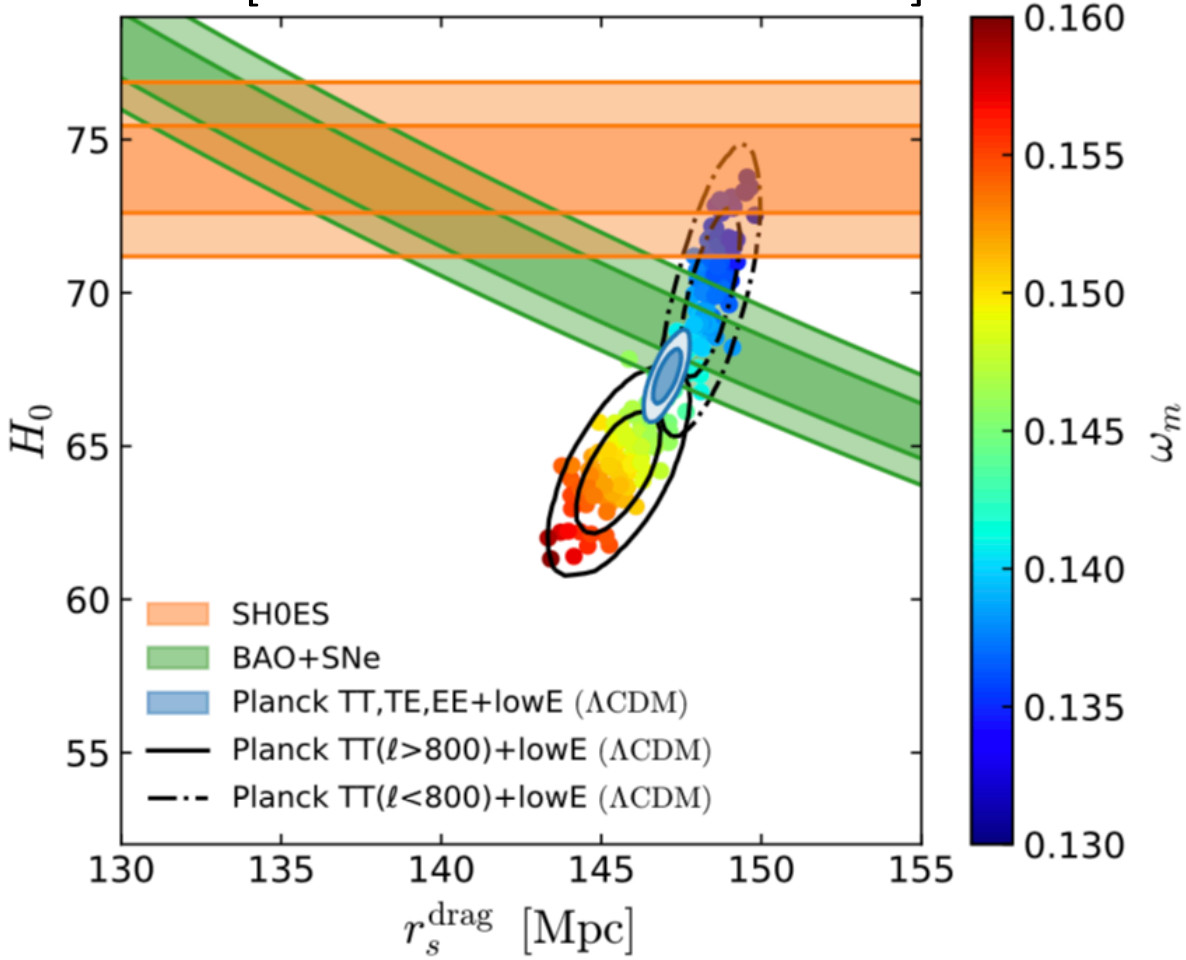


[Aylor++1811.00537] [Arendse++1909.07986]

- Resolving the tension requires lowering the sound horizon by ~ 8 Mpc.

The Hubble tension

[Knox&Millea 1908.03663]



(i) model-dependent statement:

SH0ES + Planck 5 sigma discrepant

(ii) model-independent statement:

BAO + SNe: $H_0 r_s \simeq const$

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

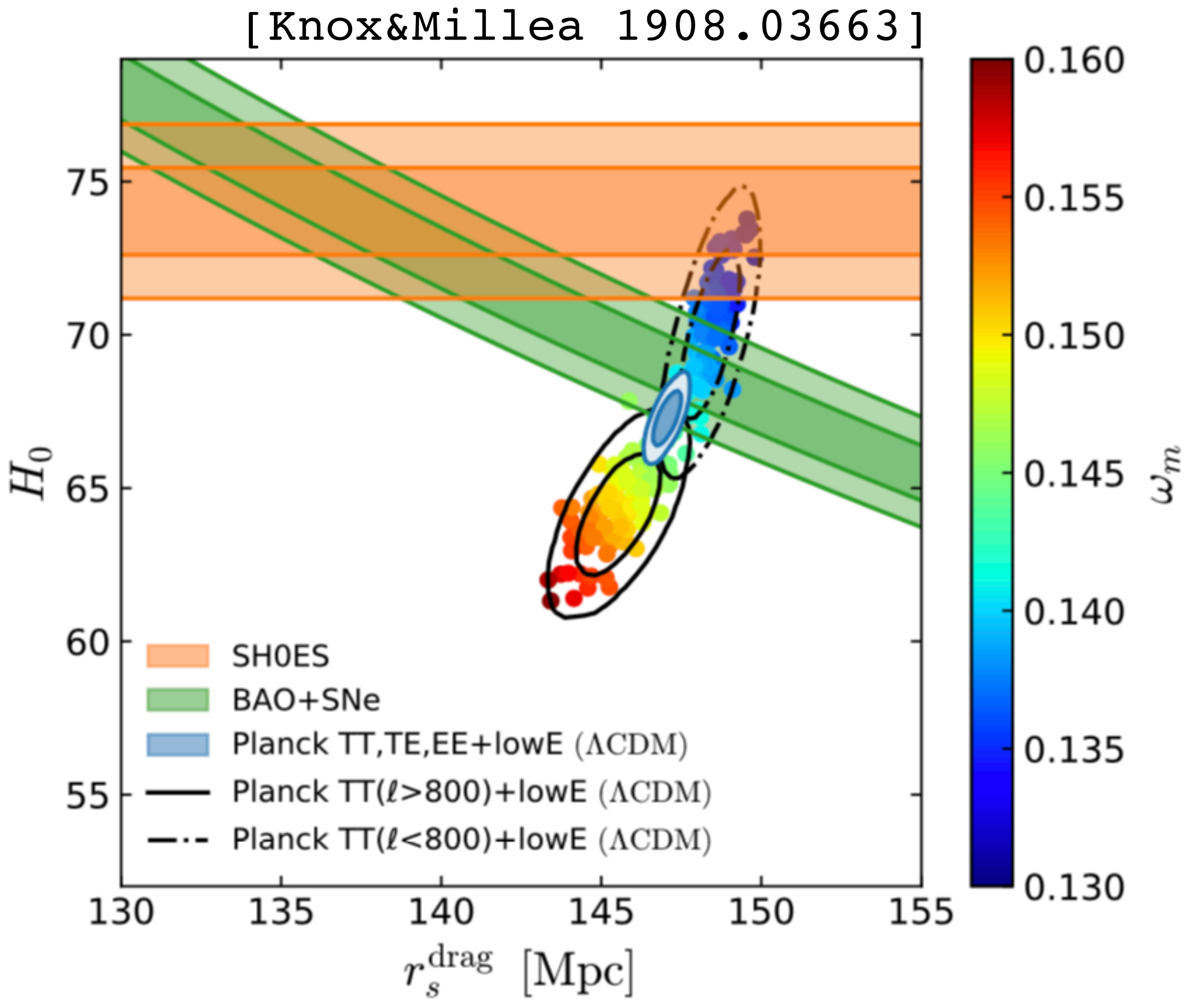
[Aylor++1811.00537] [Arendse++1909.07986]

- Resolving the tension requires lowering the sound horizon by ~ 8 Mpc.
- This clearly suggests new physics pre recombination in redshift window:

Modify history of universe when highly constrained!

$$1000 < z < 25000$$

The Hubble tension



(i) model-dependent statement:

SH0ES + Planck 5 sigma discrepant

(ii) model-independent statement:

BAO + SNe: $H_0 r_s \simeq const$

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

[Aylor++1811.00537] [Arendse++1909.07986]

- Resolving the tension requires lowering the sound horizon by ~ 8 Mpc.
- This clearly suggests new physics pre recombination in redshift window:

Modify history of universe when highly constrained!

$$1000 < z < 25000$$

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

How to shorten sound horizon?

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0
- Subsequently, the new component has to decay at least as fast as radiation.

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0
- Subsequently, the new component has to decay at least as fast as radiation.
- Canonical example: **Dark Radiation (DR)**

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0
- Subsequently, the new component has to decay at least as fast as radiation.
- Canonical example: **Dark Radiation (DR)**

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

Simplest implementation: promote $N_{\rm eff}$ to free parameter

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0
- Subsequently, the new component has to decay at least as fast as radiation.
- Canonical example: **Dark Radiation (DR)**

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

Simplest implementation: promote $N_{\rm eff}$ to free parameter

- **Result:** Tension only reduced slightly, still ~4 sigma

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

How to shorten sound horizon?

- Energy injection **before** recombination (but not too early!).

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

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

- Balanced by increasing H_0
- Subsequently, the new component has to decay at least as fast as radiation.
- Canonical example: **Dark Radiation (DR)**

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

Simplest implementation: promote $N_{\rm eff}$ to free parameter

- **Result:** Tension only reduced slightly, still ~4 sigma [Planck 2018 + BAO (+LSS) + Pantheon + BBN]
- **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).

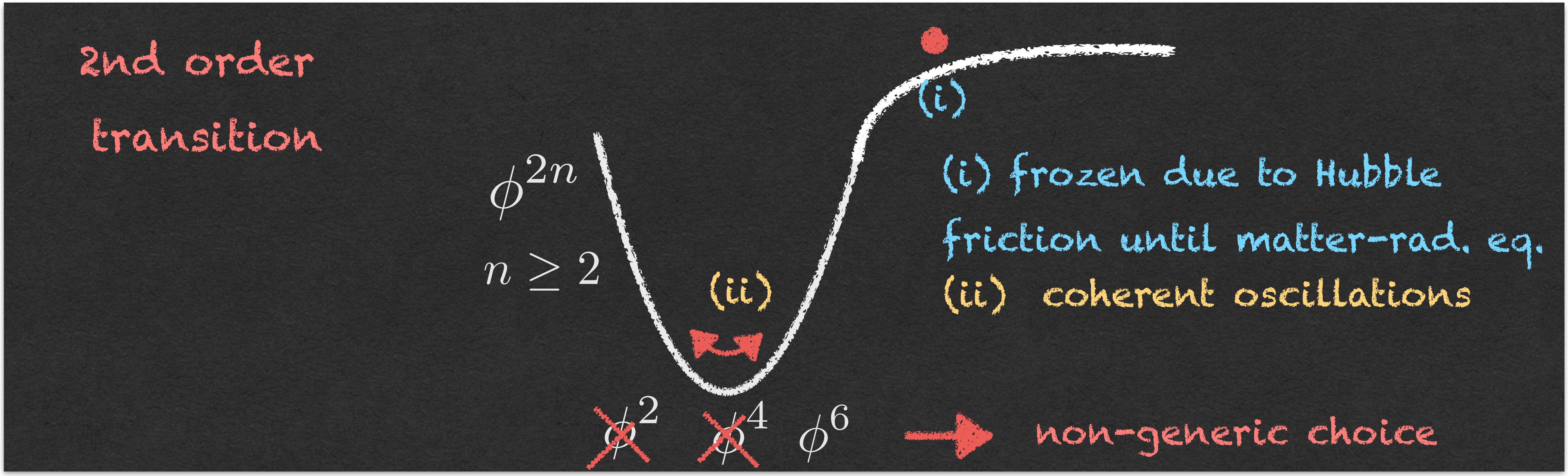
[Escudero,Witte,2004.01470] [Aloni++,2111.00014]

Early Dark Energy

[Karwal et al., 2016]
[Smith et al., 2019]

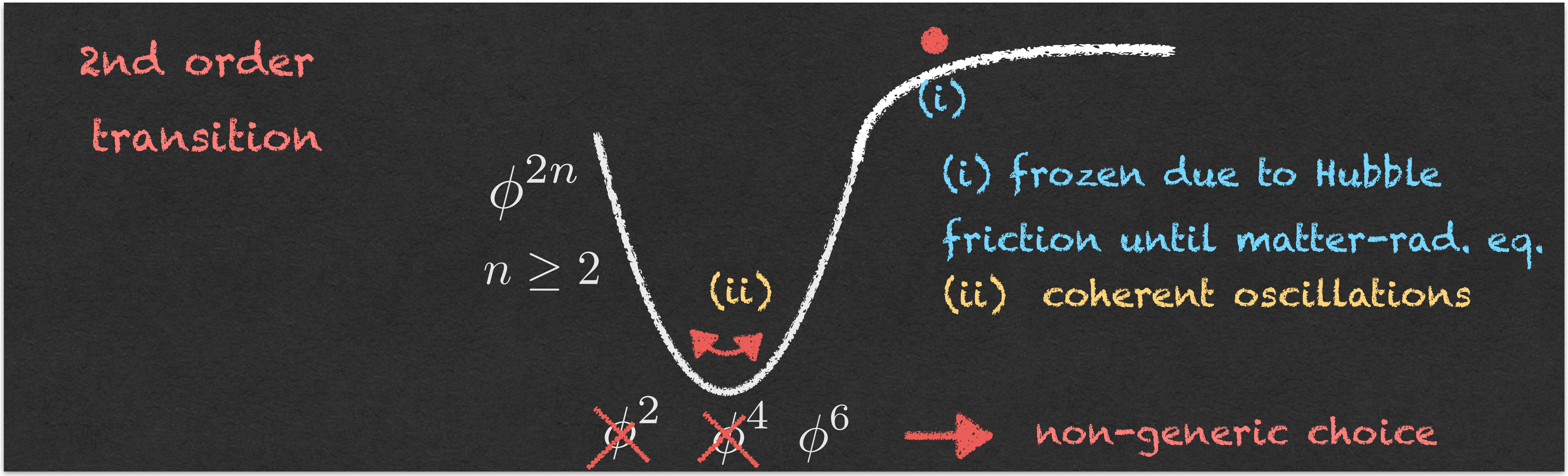
Early Dark Energy

[Karwal et al., 2016]
[Smith et al., 2019]



Early Dark Energy

[Karwal et al., 2016]
[Smith et al., 2019]



Phenomenology requires:

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

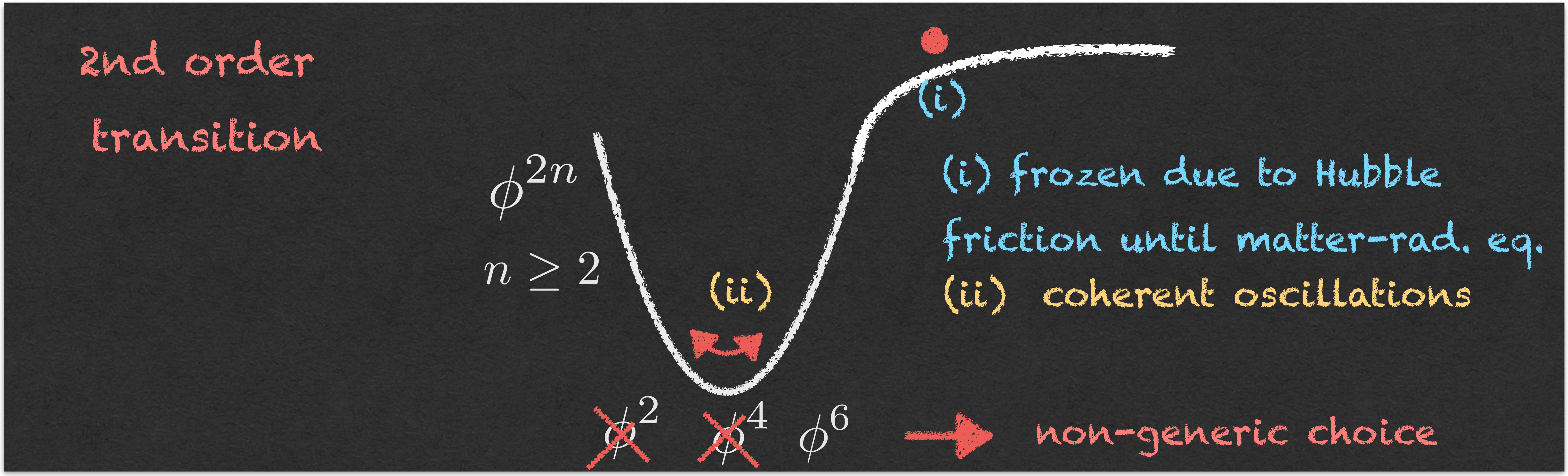
cycle-averaged:

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

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

Early Dark Energy

[Karwal et al., 2016]
[Smith et al., 2019]



- **Phenomenology requires:**
  - Flattening of potential at high field values.
  - Oscillations in anharmonic potential.
  - Ultralight effective mass : $m \sim 10^{-27}\mathrm{eV}$
- Brings tension down to ~2.5 sigma (1p-EDE).

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

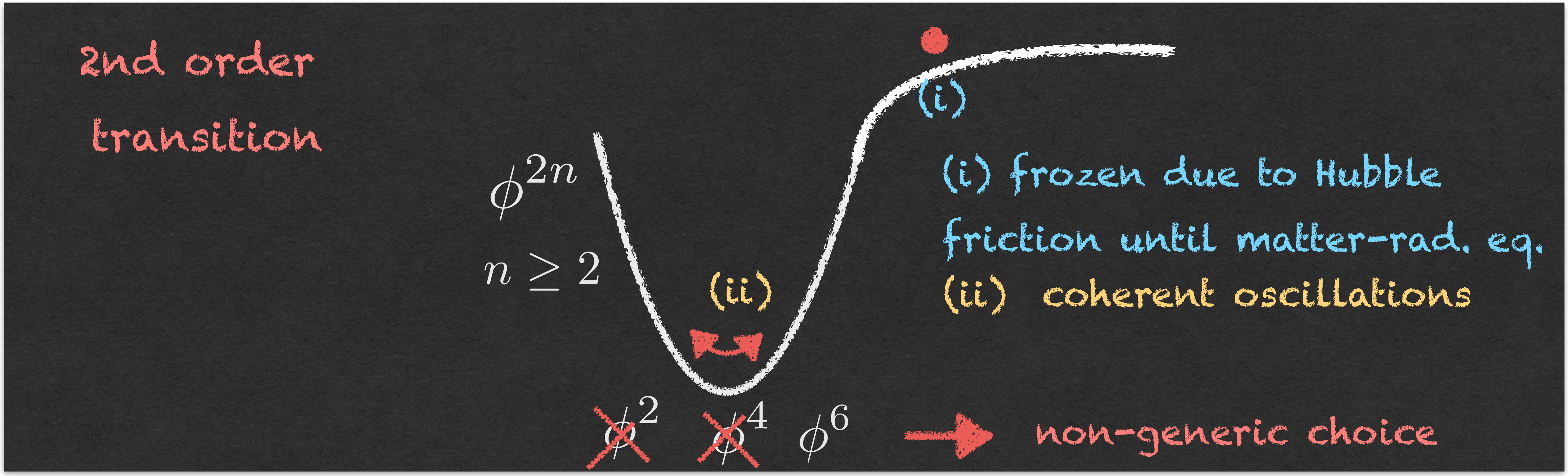
cycle-averaged:

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

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

Early Dark Energy

[Karwal et al., 2016]
[Smith et al., 2019]



- **Phenomenology requires:**
  - Flattening of potential at high field values.
  - Oscillations in anharmonic potential.
  - Ultralight effective mass : $m \sim 10^{-27}\mathrm{eV}$
- Brings tension down to ~2.5 sigma (1p-EDE).

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

cycle-averaged:

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

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

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

[Smith++,2009.10740] [Amico++,2006.12420]
[Murgia++,2009.10733] [Hill++,2003.07355]

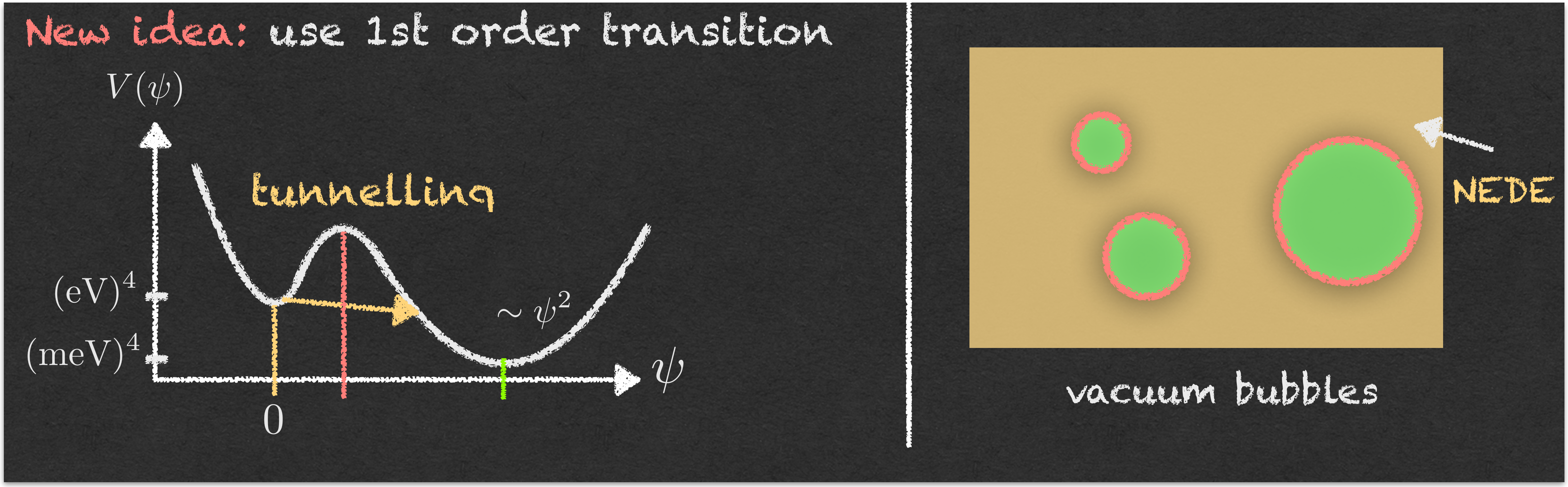
First order decay scenario

First order decay scenario

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

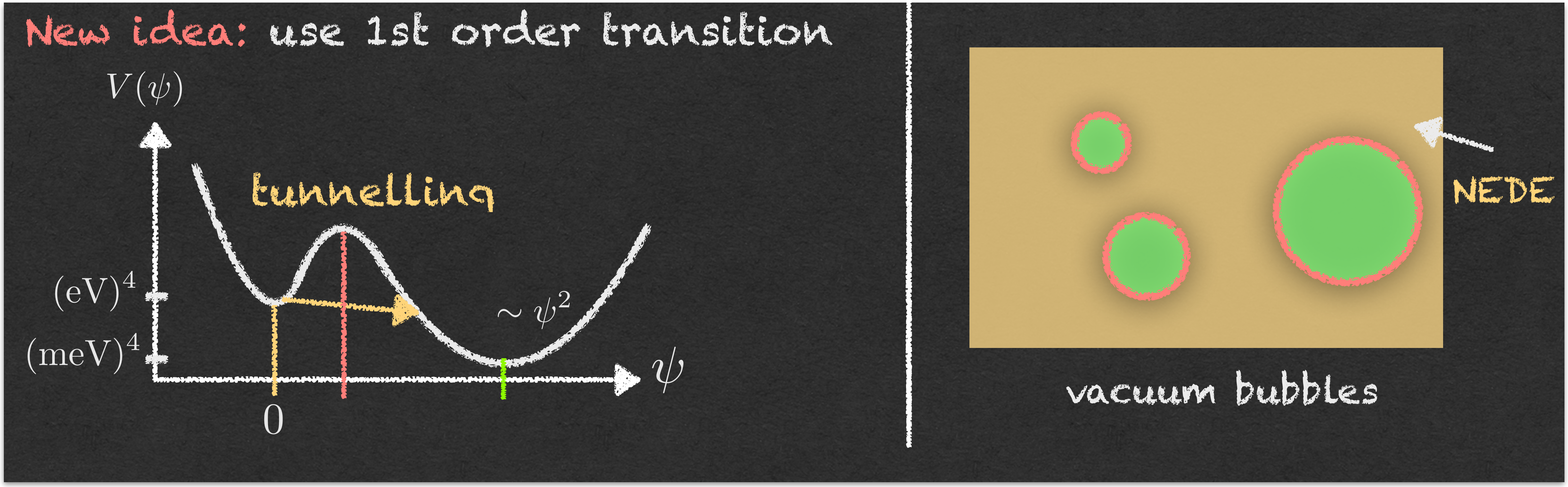
First order decay scenario

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



First order decay scenario

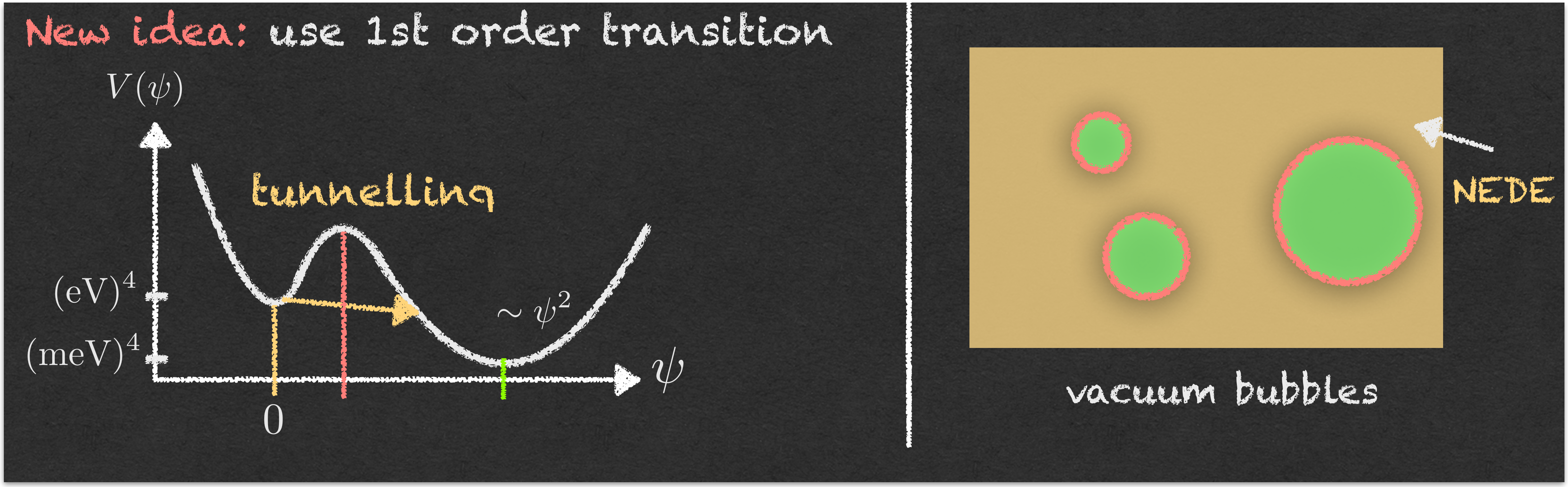
- **Question:** Can we find a model more motivated from particle physics?



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

First order decay scenario

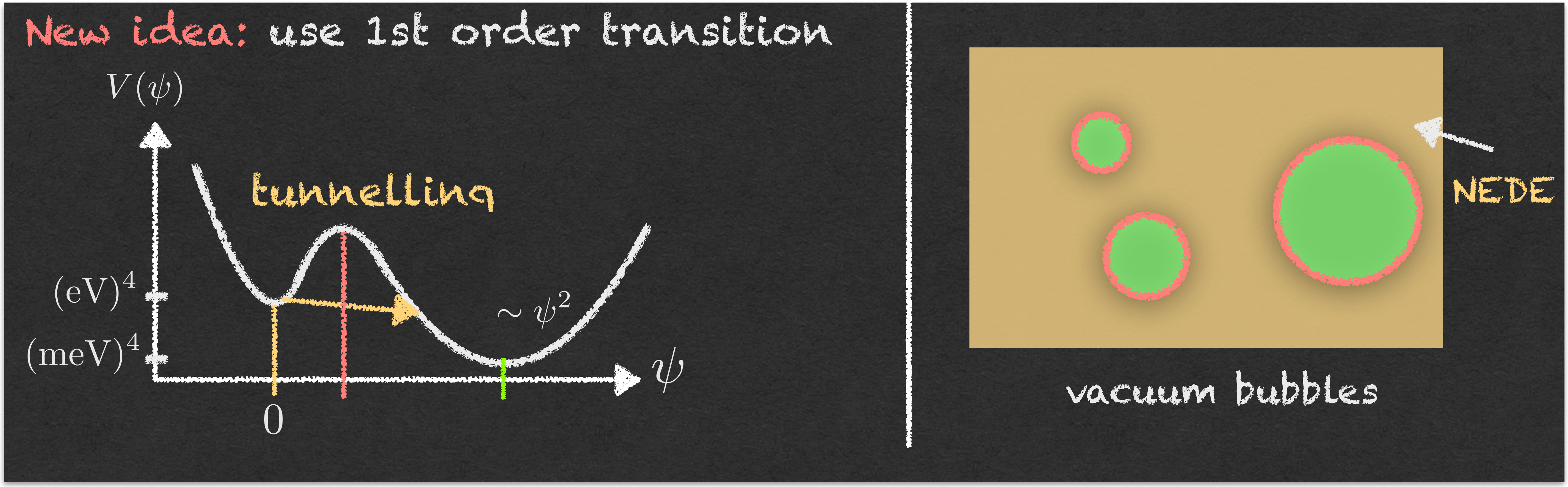
- **Question:** Can we find a model more motivated from particle physics?



- **Hubble tension:** EDE/NEDE provided by (decaying) false vacuum energy.
- This idea faces challenges:

First order decay scenario

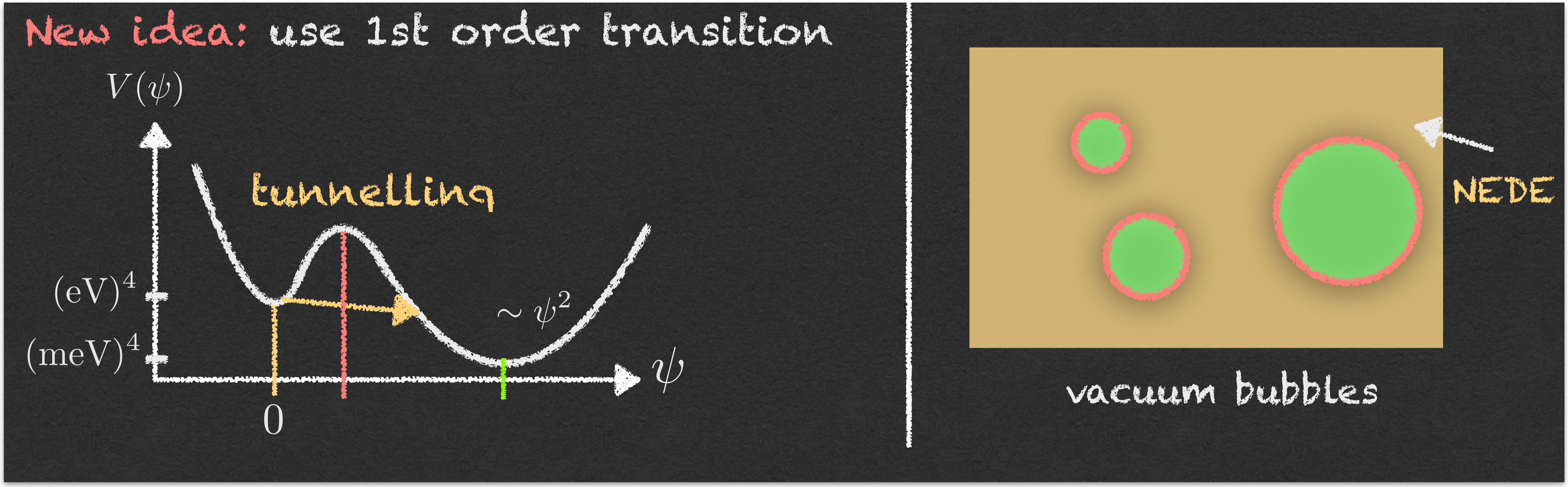
- **Question:** Can we find a model more motivated from particle physics?



- **Hubble tension:** EDE/NEDE provided by (decaying) false vacuum energy.
- This idea faces challenges:
    1. Decay should happen around matter-radiation equality (lesson from EDE).

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.
- This idea faces challenges:
    1. Decay should happen around matter-radiation equality (lesson from EDE).
    2. Bubble percolation has to be extremely efficient to avoid anisotropies.
       (prevented from growing to cosmological size).

Cold New Early Dark Energy

Cold New Early Dark Energy

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

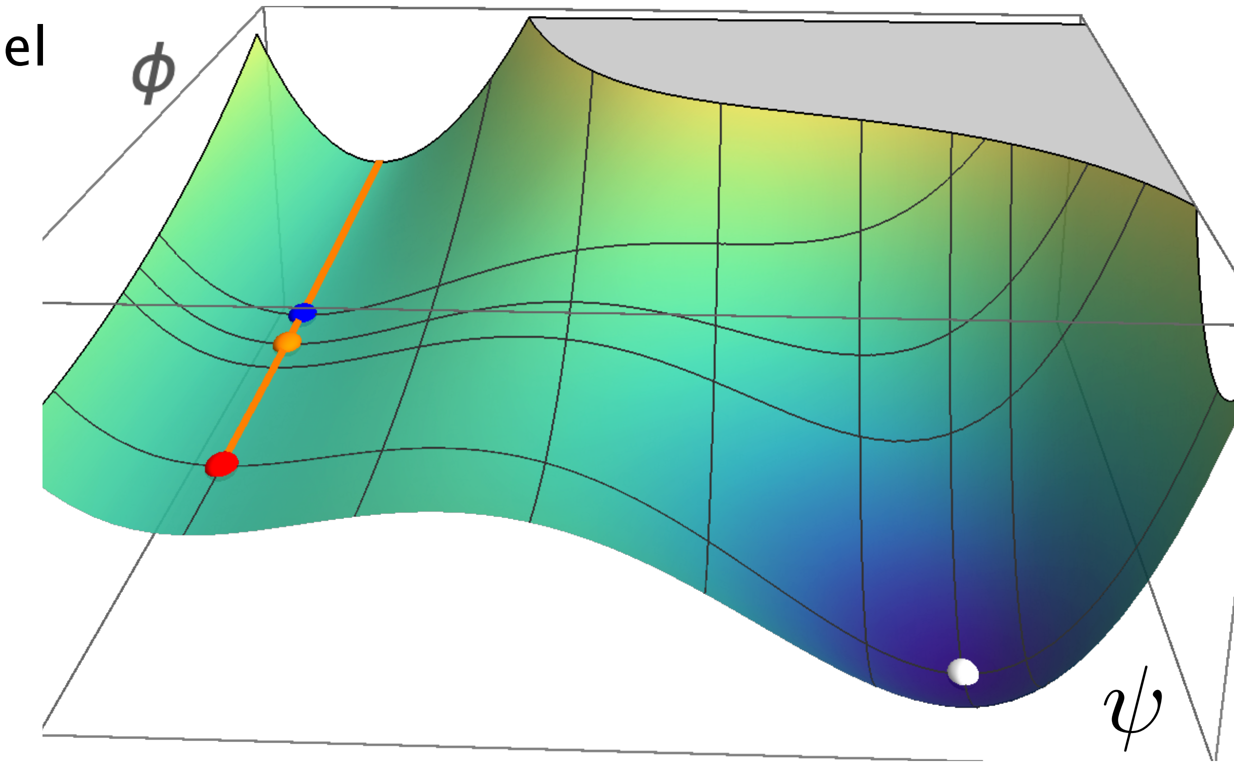
Cold New Early Dark Energy

- Introduce a **trigger field** to synchronise decay.
- eV scale adaption of first-order inflationary model
  [Linde,1990][Adams,Freese,1990]

Cold New Early Dark Energy

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

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



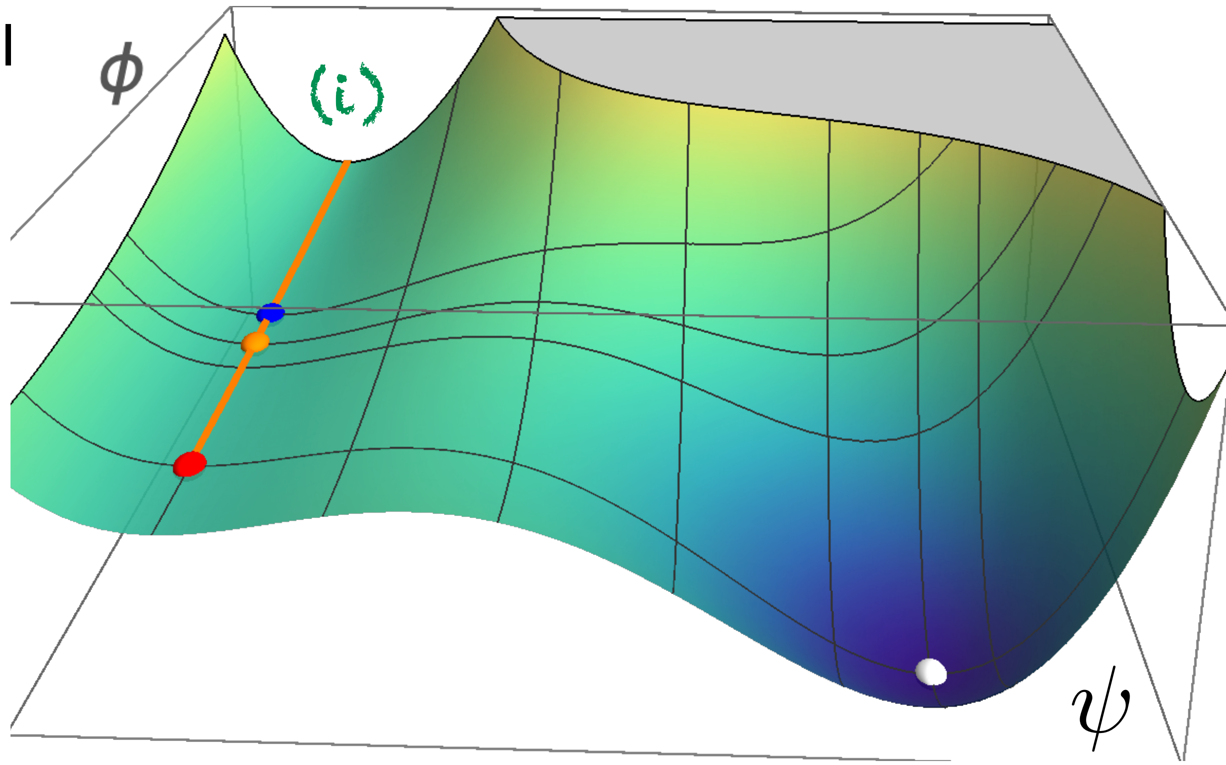
Cold New Early Dark Energy

- Introduce a **trigger field** to synchronise decay.
- eV scale adaption of first-order inflationary model
[Linde,1990][Adams,Freese,1990]

(i) $\phi \simeq \phi_{ini}$

Field stuck in false minimum

$\Gamma/H^4 \ll 1$ suppressed tunnelling rate



Cold New Early Dark Energy

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

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

(i) $\phi \simeq \phi_{ini}$

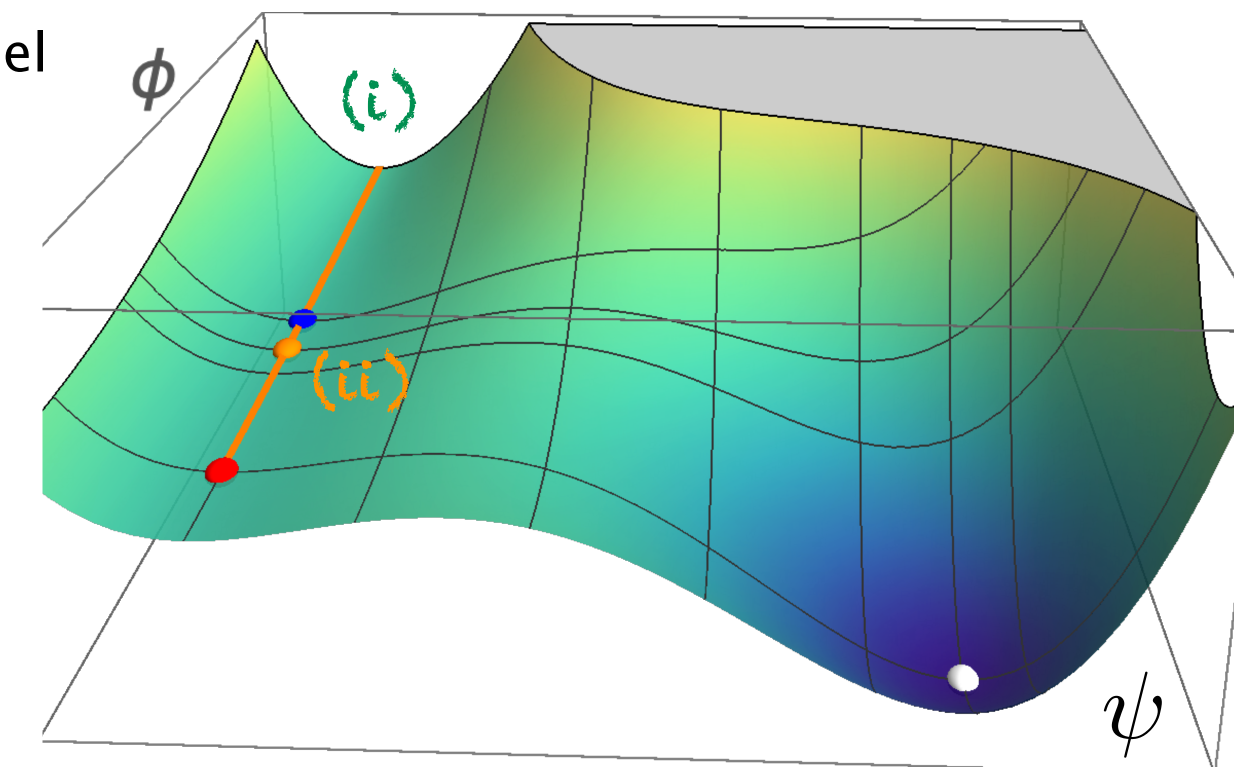
Field stuck in false minimum

$\Gamma/H^4 \ll 1$ suppressed tunnelling rate

(ii) ϕ starts evolving

after orange dot: $\Gamma/H^4 \gtrsim 1$

→ strong nucleation event



Cold New Early Dark Energy

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

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

(i) $\phi \simeq \phi_{ini}$

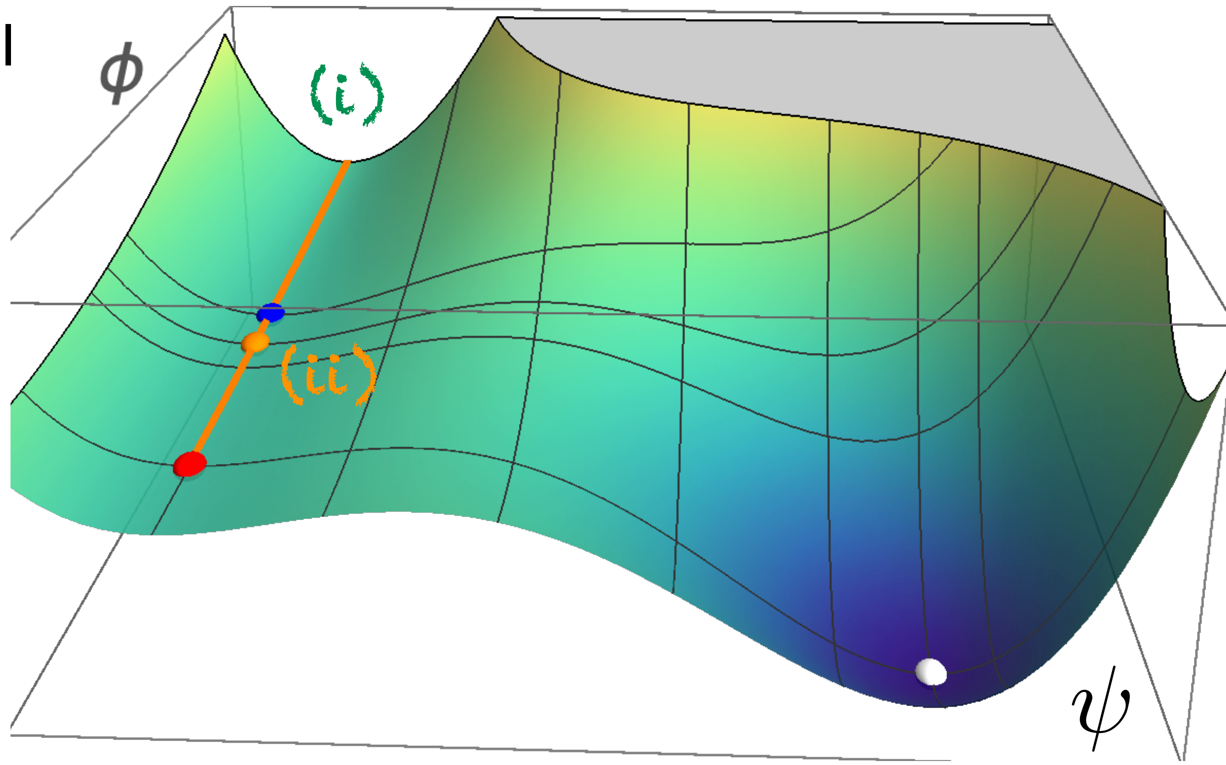
Field stuck in false minimum

$\Gamma/H^4 \ll 1$ suppressed tunnelling rate

(ii) ϕ starts evolving

after orange dot: $\Gamma/H^4 \gtrsim 1$

→ strong nucleation event



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

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

Cold New Early Dark Energy

- Introduce a **trigger field** to synchronise decay.
- eV scale adaption of first-order inflationary model [Linde,1990][Adams,Freese,1990]

(i) $\phi \simeq \phi_{ini}$

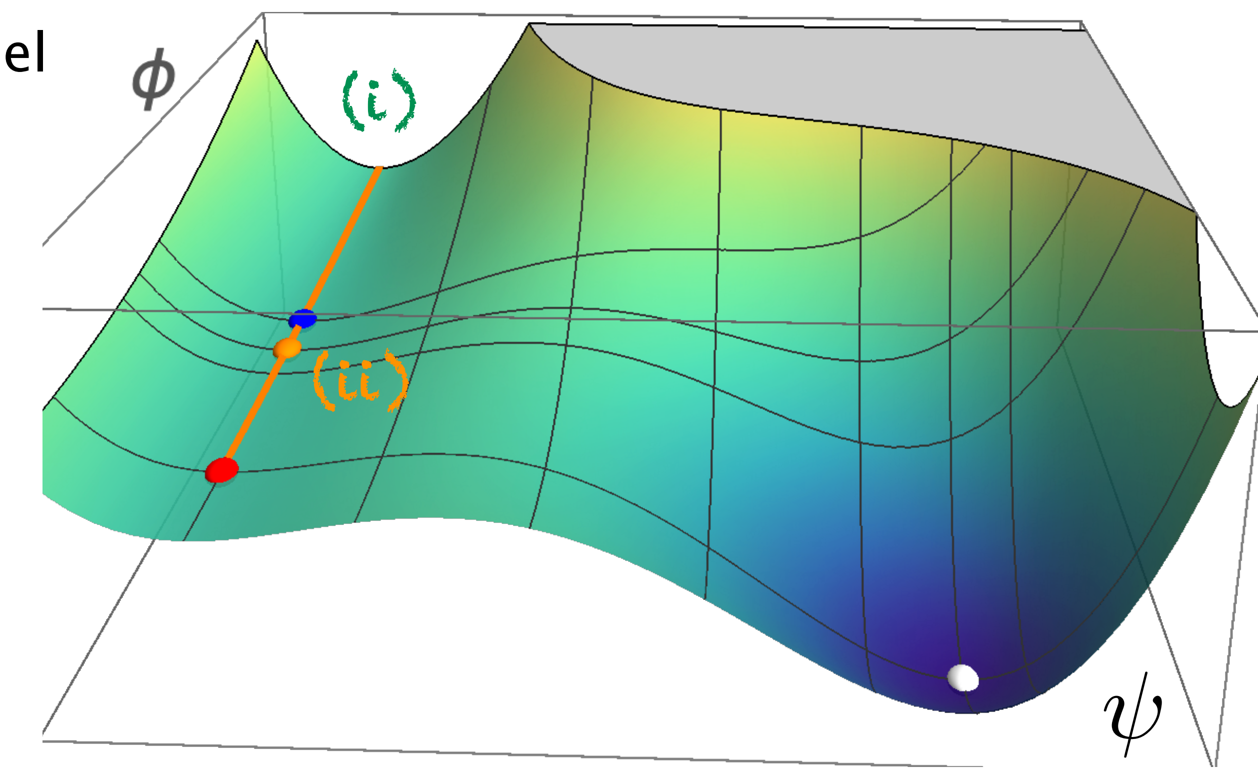
Field stuck in false minimum

$\Gamma/H^4 \ll 1$ suppressed tunnelling rate

(ii) ϕ starts evolving

after orange dot: $\Gamma/H^4 \gtrsim 1$

→ strong nucleation event



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

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

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

radiative stability: $\tilde{\lambda} \lesssim 10^3 m^2/M^2 \ll 1$ weak coupling: $\lambda < 0.1$

Cold New Early Dark Energy

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

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

(i) $\phi \simeq \phi_{ini}$

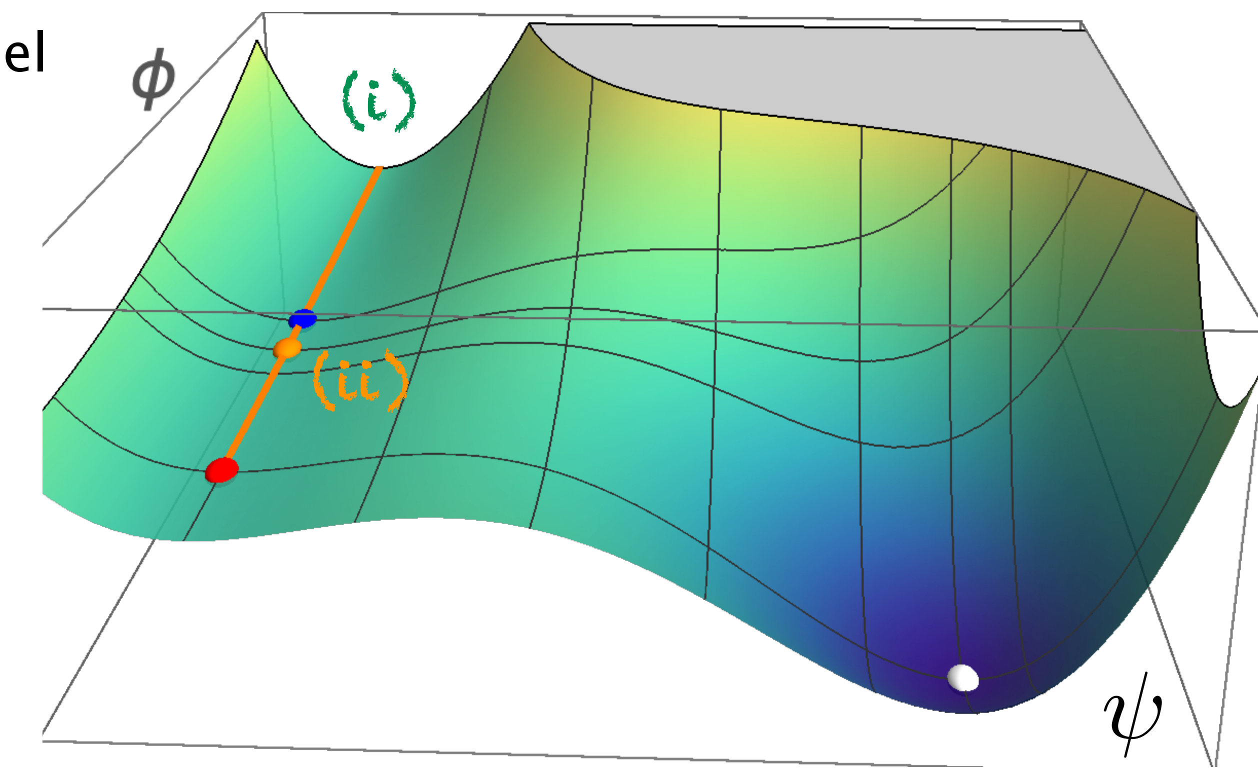
Field stuck in false minimum

$\Gamma/H^4 \ll 1$ suppressed tunnelling rate

(ii) ϕ starts evolving

after orange dot: $\Gamma/H^4 \gtrsim 1$

→ strong nucleation event



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

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

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

radiative stability: $\tilde{\lambda} \lesssim 10^3 m^2/M^2 \ll 1$ weak coupling: $\lambda < 0.1$

- Central assumption: inv. duration: $\bar{\beta} = dS_{\mathrm{E}}/dt \simeq \dot{\Gamma}/\Gamma \gg H$

NEDE Phenomenology

NEDE Phenomenology

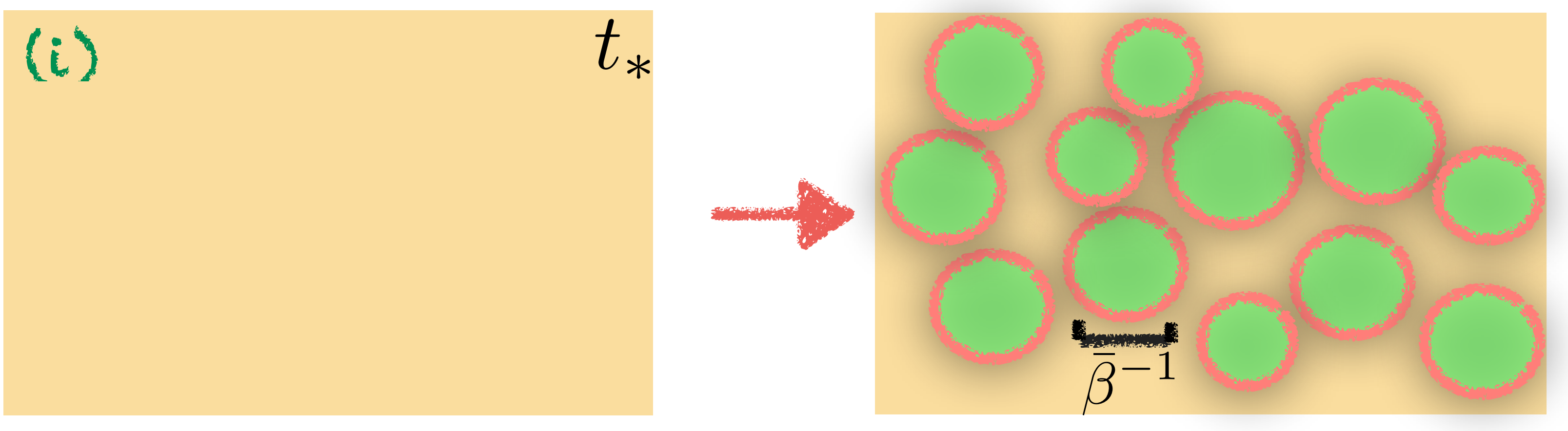
- **Important result**: Phase transition is an **instantaneous** process on cosmological scales.

NEDE Phenomenology

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

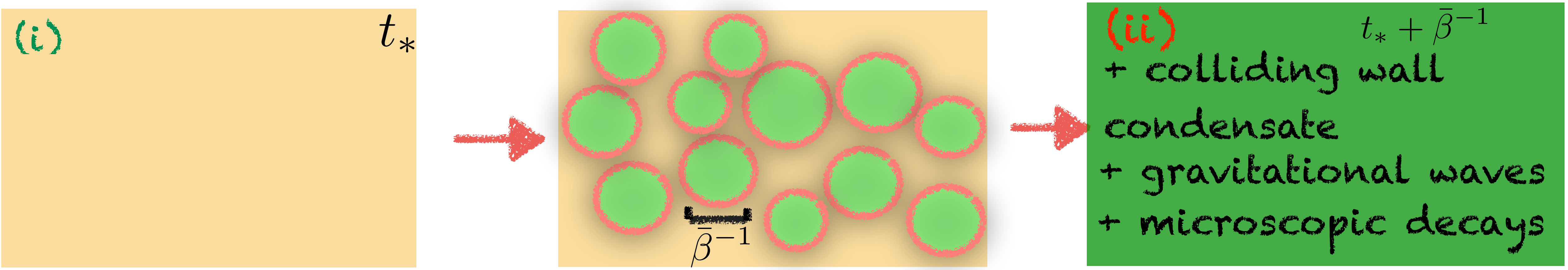
NEDE Phenomenology

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



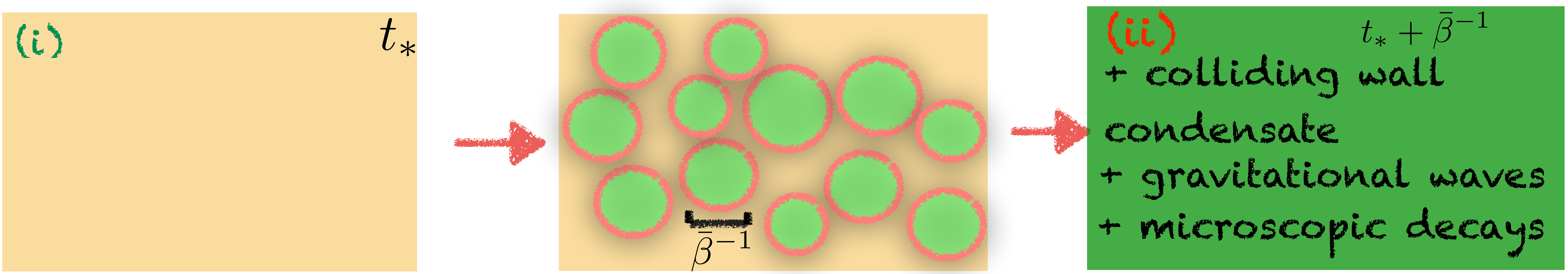
NEDE Phenomenology

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



NEDE Phenomenology

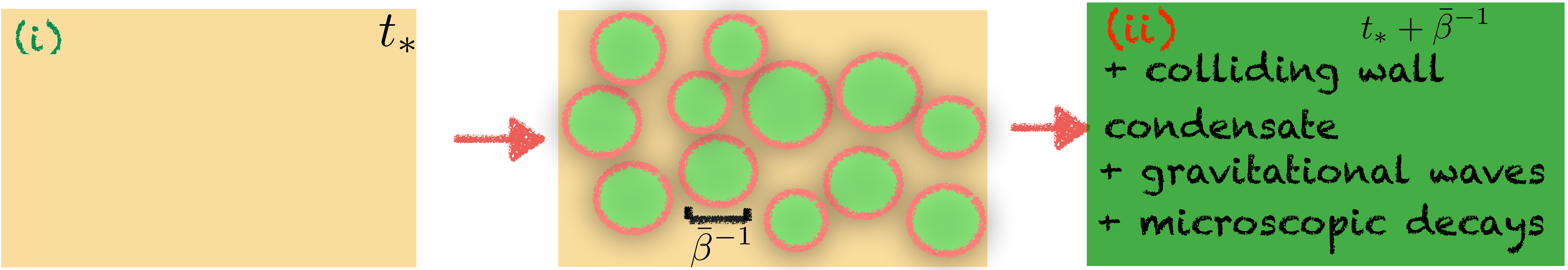
- **Important result**: Phase transition is an **instantaneous** process on cosmological scales.



- **After PT**: Mixture of **radiation** and **small scale anisotropic stress**

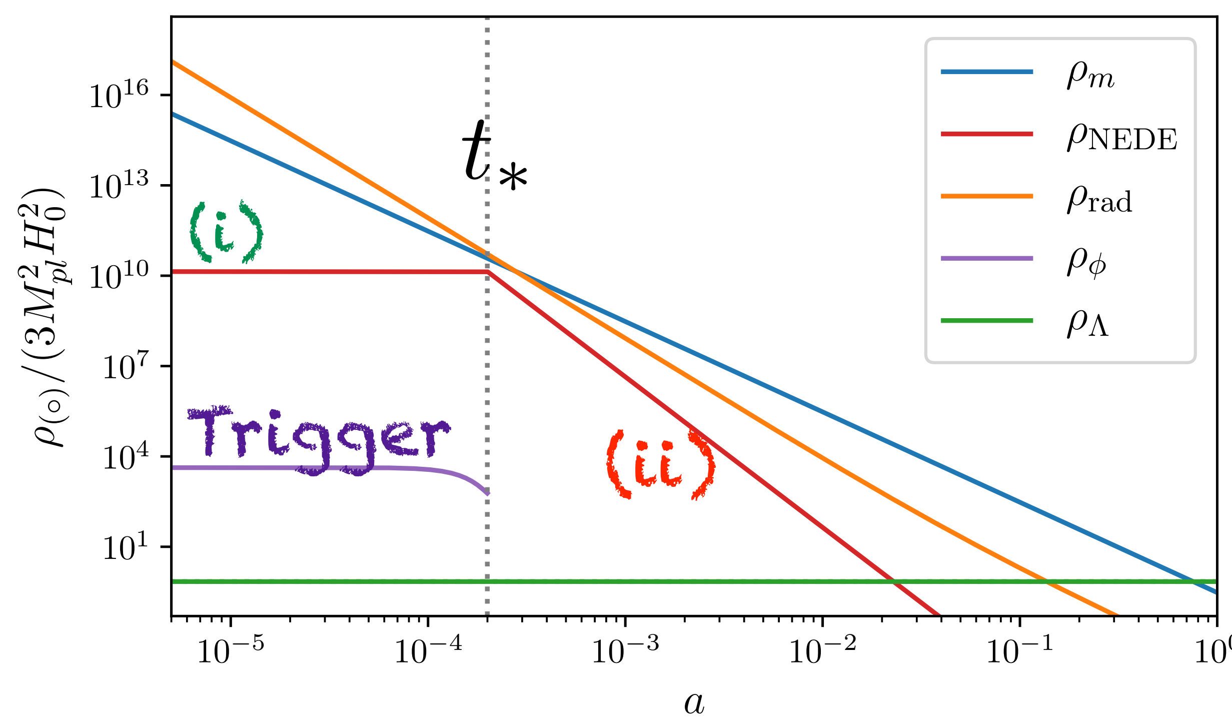
NEDE Phenomenology

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



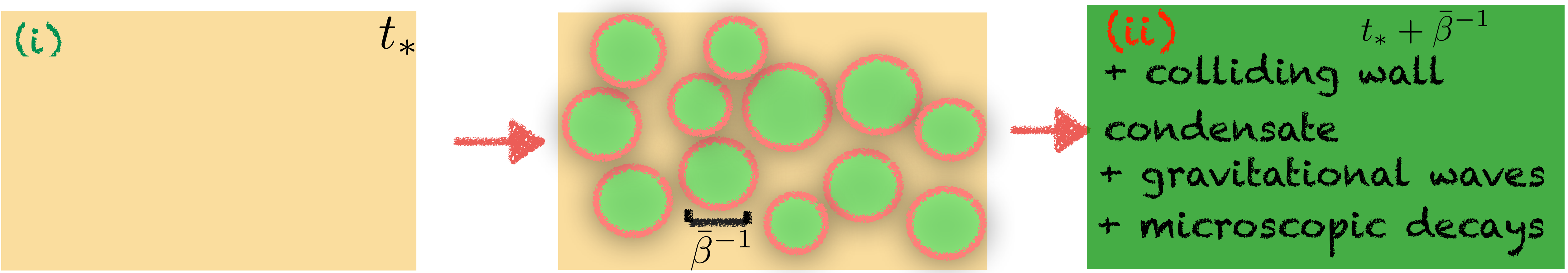
- **After PT**: Mixture of **radiation** and **small scale anisotropic stress**

- NEDE as **phenomenological model:**
  - (i) ● **Before** transition: NEDE plays role of CC.
  - ● **Sudden** triggered transition at time: t_*
  - (ii) ● **After** transition: NEDE is described by decaying dark fluid with e.o.s.p.:



NEDE Phenomenology

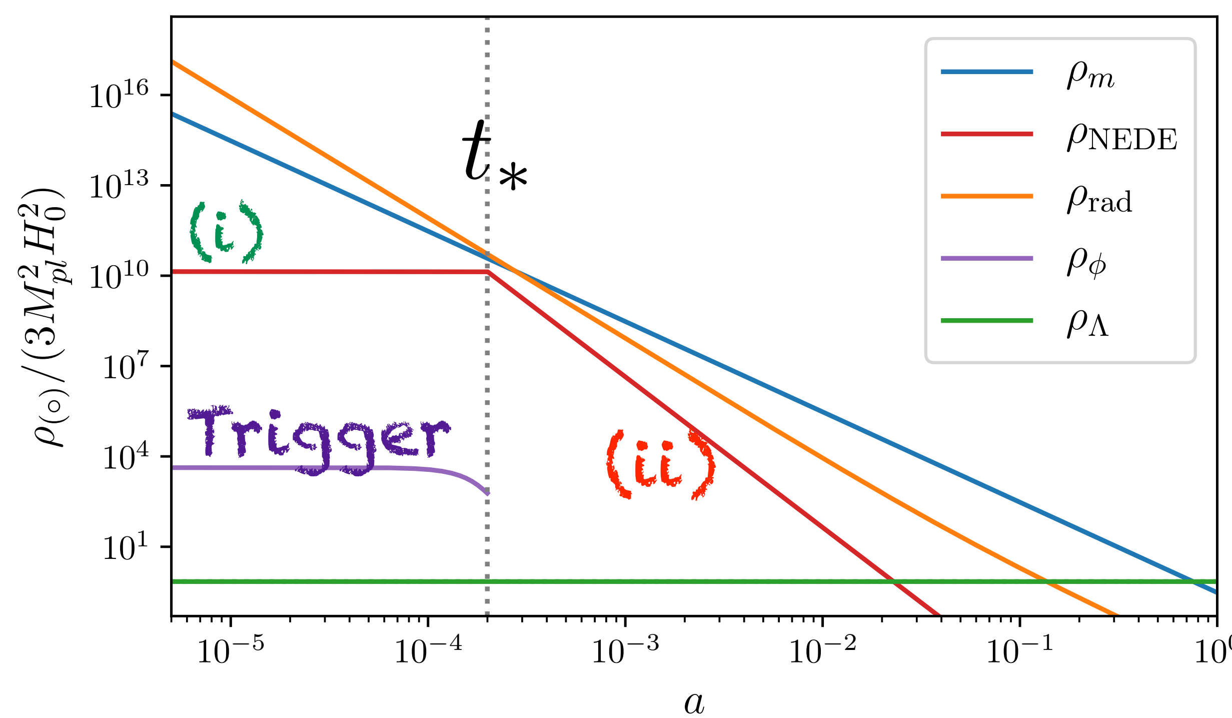
- **Important result**: Phase transition is an **instantaneous** process on cosmological scales.



- **After PT**: Mixture of **radiation** and **small scale anisotropic stress**

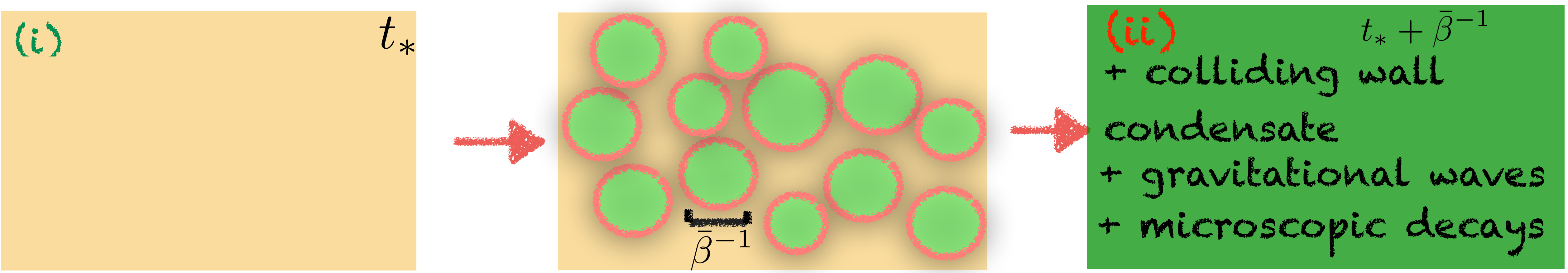
- NEDE as **phenomenological model:**
  - (i) **Before** transition: NEDE plays role of CC.
  - **Sudden** triggered transition at time: t_*
  - (ii) **After** transition: NEDE is described by decaying dark fluid with e.o.s.p.:

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



NEDE Phenomenology

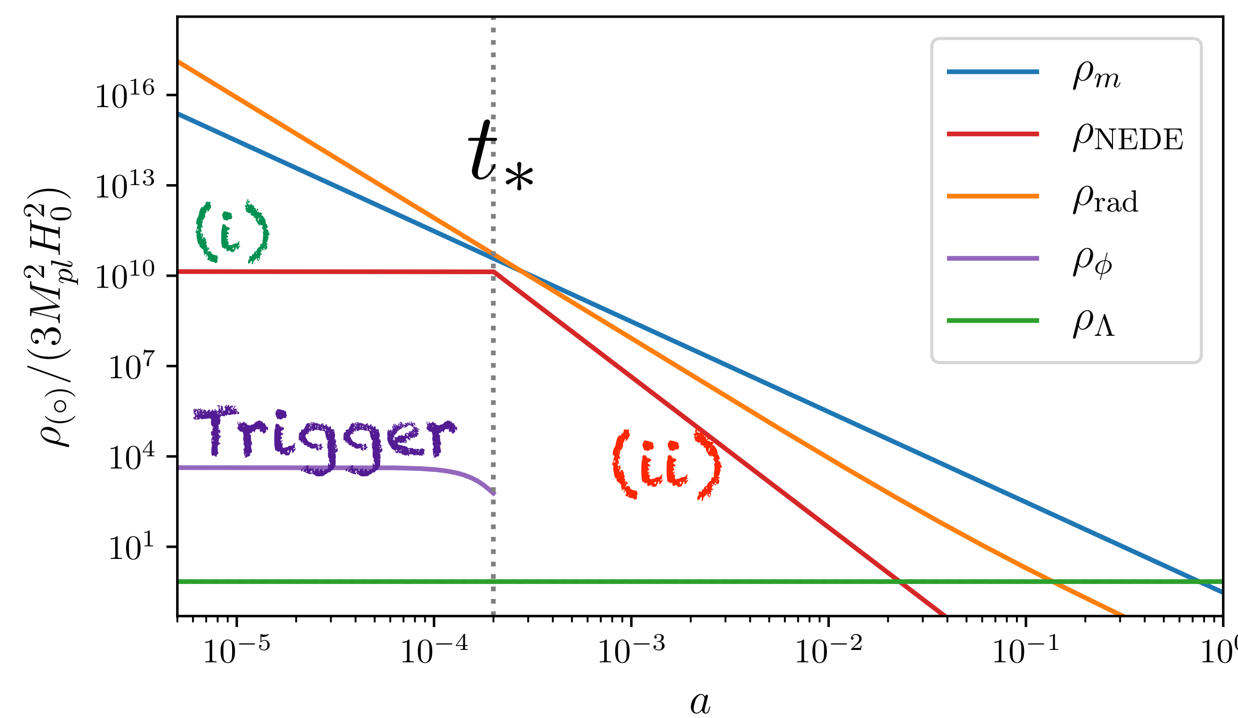
- **Important result**: Phase transition is an **instantaneous** process on cosmological scales.



- **After PT**: Mixture of **radiation** and **small scale anisotropic stress**

- NEDE as **phenomenological model:**
  - (i) ● **Before** transition: NEDE plays role of CC.
  - ● **Sudden** triggered transition at time: t_*
  - (ii) ● **After** transition: NEDE is described by decaying dark fluid with e.o.s.p.:

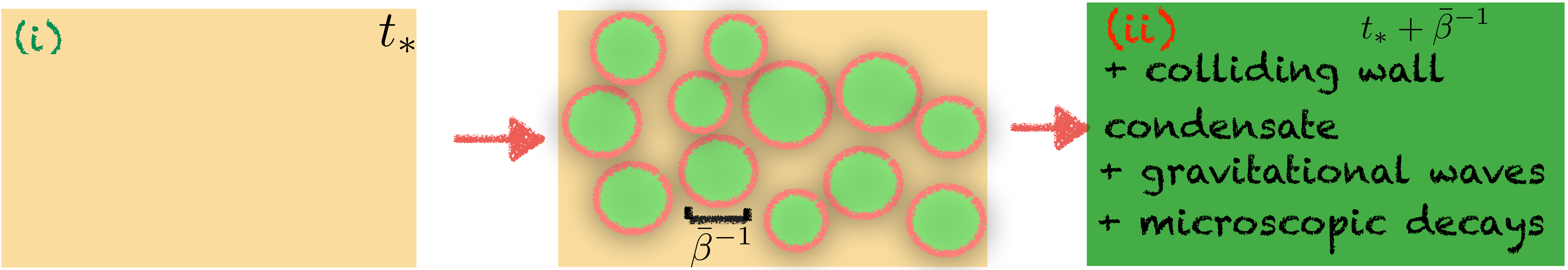
$$1/3 < w_{\mathrm{NEDE}}(t) < 1$$



- Perturbations in decaying NEDE fluid seeded by trigger field perturbations.

NEDE Phenomenology

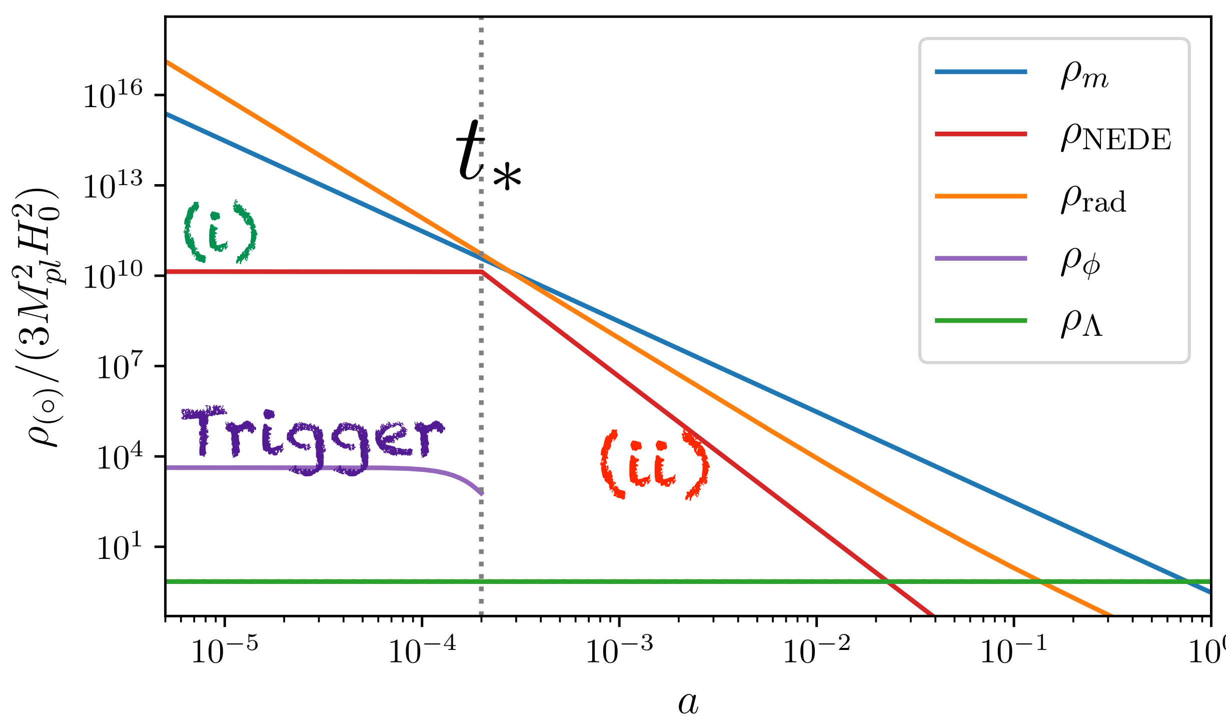
- **Important result**: Phase transition is an **instantaneous** process on cosmological scales.



- **After PT**: Mixture of **radiation** and **small scale anisotropic stress**

- NEDE as **phenomenological model:**
  - (i) ● **Before** transition: NEDE plays role of CC.
  - ● **Sudden** triggered transition at time: t_*
  - (ii) ● **After** transition: NEDE is described by decaying dark fluid with e.o.s.p.:

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



- Perturbations in decaying NEDE fluid seeded by trigger field perturbations.
- Description applies to other **triggered decay scenarios** too (e.g. hybrid NEDE).

Cosmological parameter extraction

Cosmological parameter extraction

- Consider **simplest** implementation of NEDE:
  - parameters: trigger mass & fraction NEDE $f_{\rm NEDE}$
  - fix $w_{\rm NEDE} = c_s^2 = 2/3$ (relaxed later)

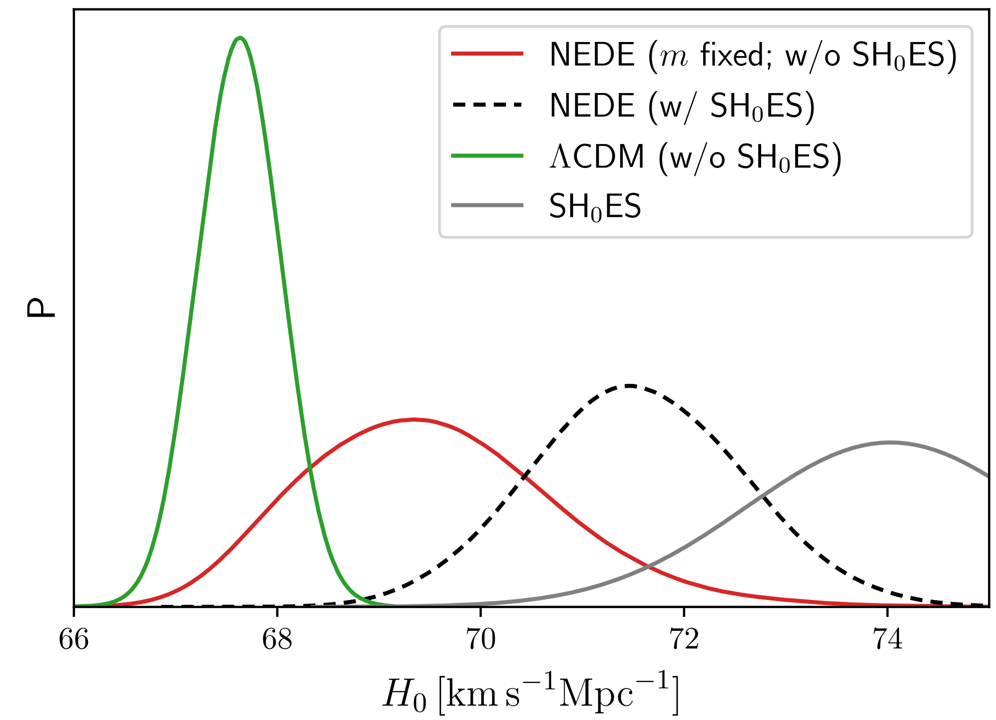
Cosmological parameter extraction

- Consider **simplest** implementation of NEDE:
  - parameters: trigger mass & fraction NEDE $f_{\rm NEDE}$
  - fix $w_{\rm NEDE} = c_s^2 = 2/3$ (relaxed later)

	w/o SH₀ES	w/ SH₀ES
Parameters	$f_{\rm NEDE}$ m(fixed)	$f_{\rm NEDE}$ m
H_0 [km/s/Mpc]	$69.6^{+1.0}_{-1.1}$	71.4 ± 1.0
Evidence $f_{\rm NEDE} \neq 0$	$\simeq 2\sigma$	$\simeq 4\,\sigma$
Hubble tension	$\simeq 2.5\sigma$	$(\simeq 1.5\,\sigma)$
S8 tension	$\simeq 2.7\sigma$	$\simeq 2.8\sigma$
$\Delta\chi^2$	-2.6	-15.6

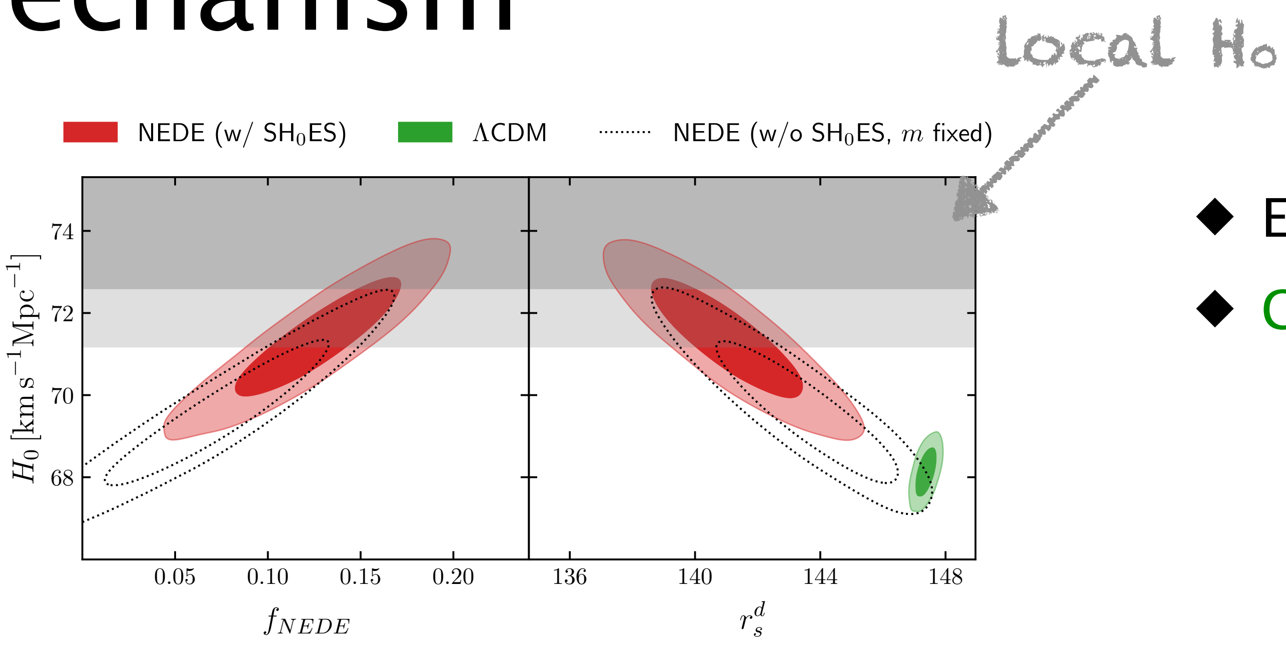
[FN&Sloth:2006.06686]

[Planck 2018, BAO, Pantheon, SH0ES 2019]



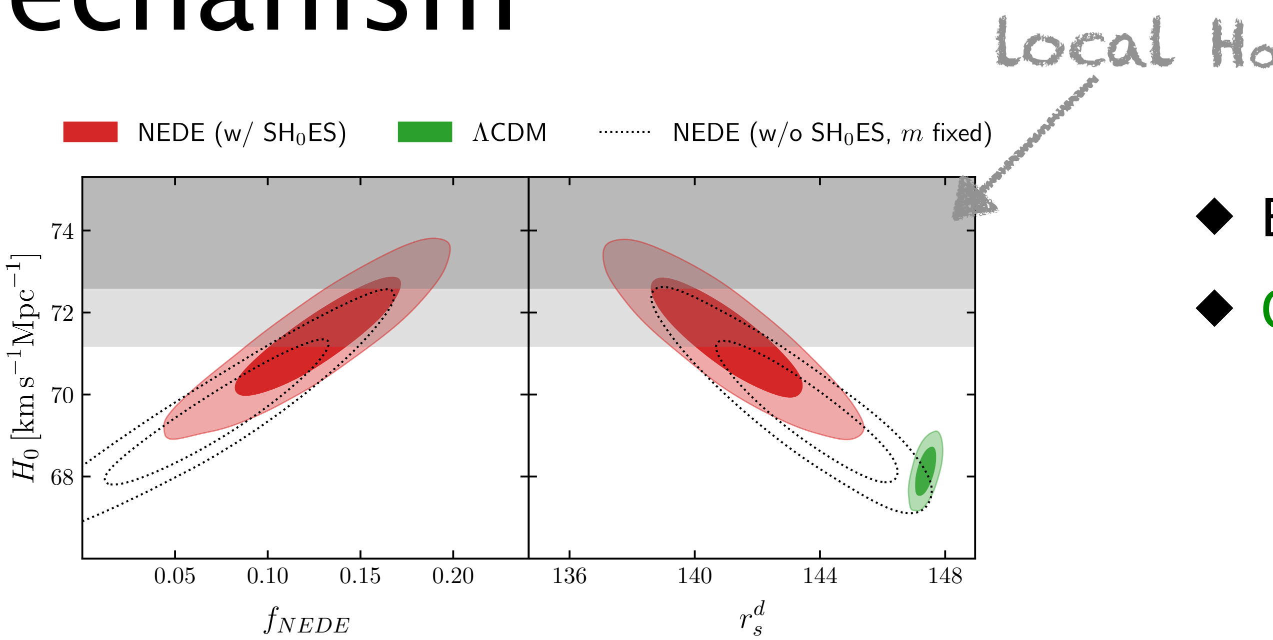
Mechanism

Mechanism

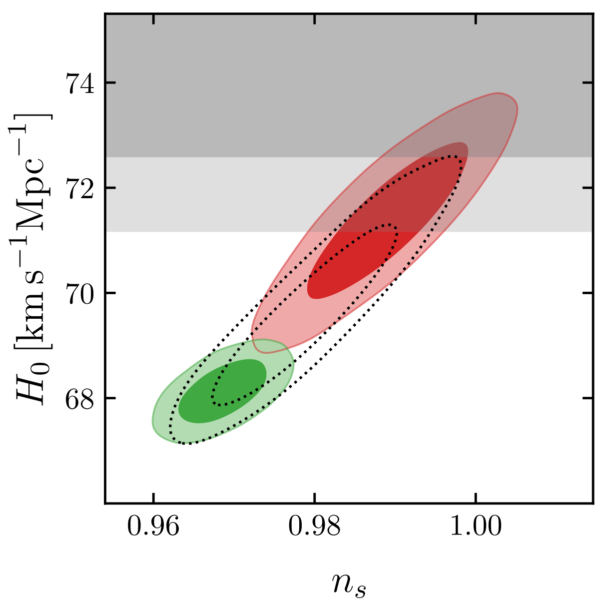


- Energy injection reduces sound horizon.
- Compensated by larger H_0

Mechanism

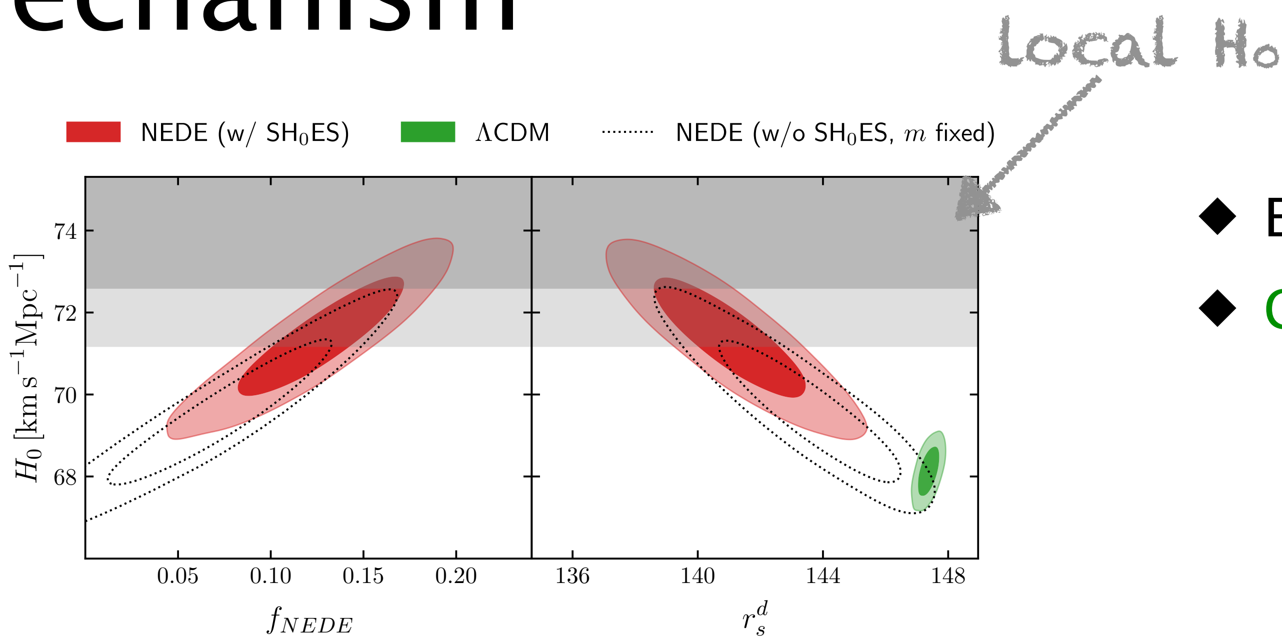


- Energy injection reduces sound horizon.
- Compensated by larger H_0

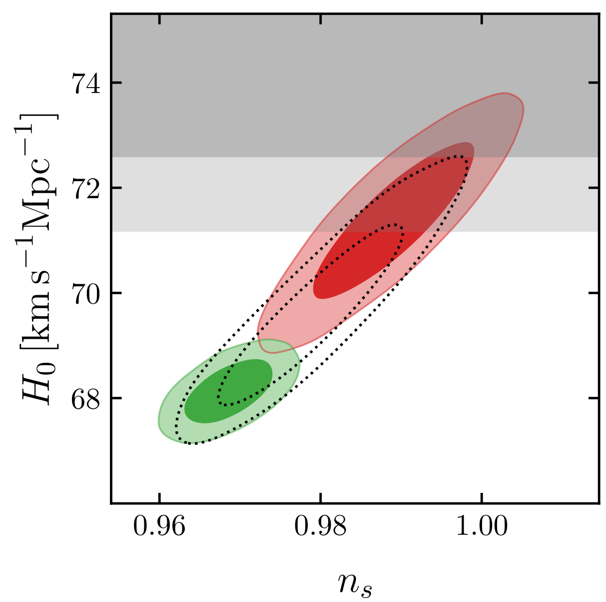


- Enhanced diffusion damping.
- Compensated by larger n_s

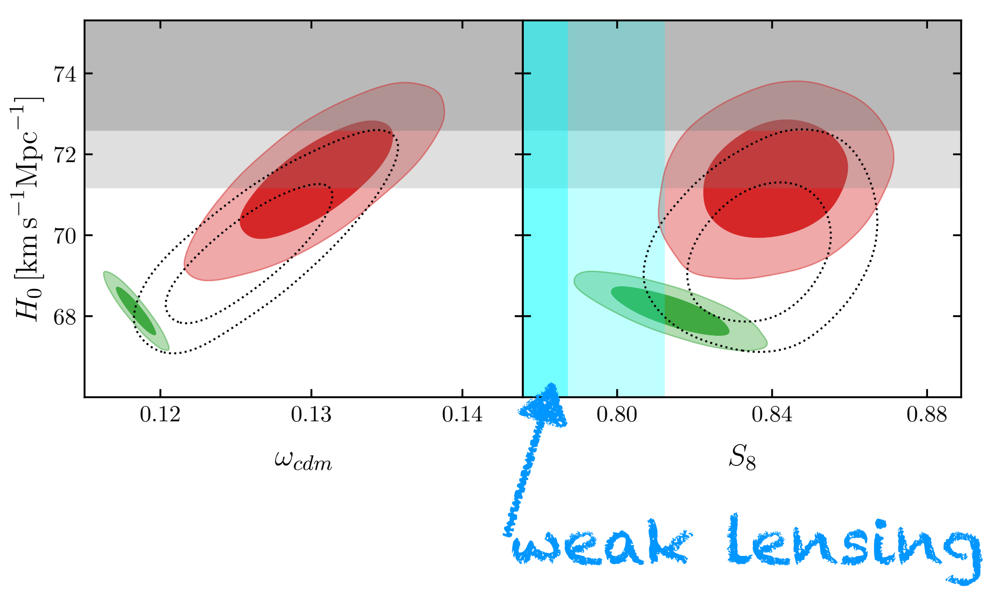
Mechanism



- Energy injection reduces sound horizon.
- Compensated by larger H_0



- Enhanced diffusion damping.
- Compensated by larger n_s



- Quicker decay of Weyl potential due to NEDE perturbations and delayed matter domination.
- Compensated by larger $\omega_{\rm cdm}$
- Small residual effect on small scales.
- Still: S8 tension comparable to LCDM (2.5 -> 2.8 sigma)

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

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

The H_0 Olympics: A fair ranking of proposed models

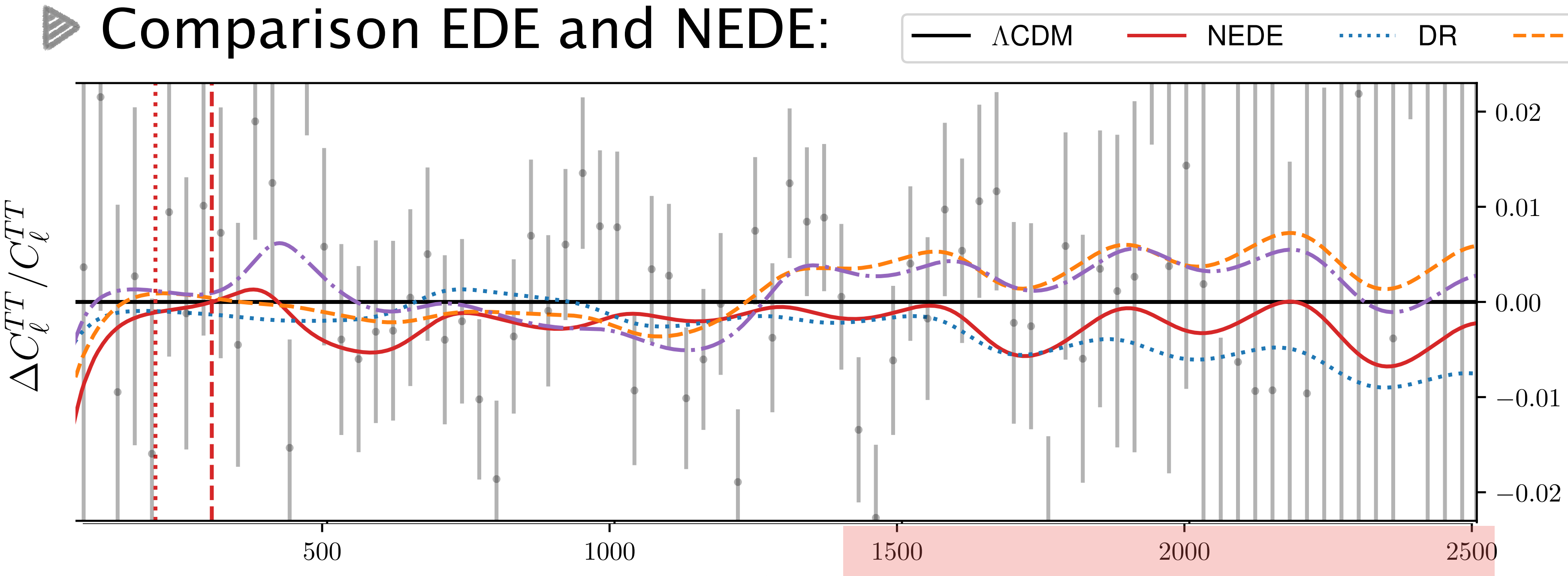
Nils Schöneberg,[a] Guillermo Franco Abellán,[b] Andrea Pérez Sánchez,[a] Samuel J. Witte,[c] Vivian Poulin,[b] and Julien Lesgourgues[a]

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)

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

Comparison EDE and NEDE:



[FN&Sloth:2006.06686]

EDE gives more power

NEDE gives less power

The H_0 Olympics: A fair ranking of proposed models

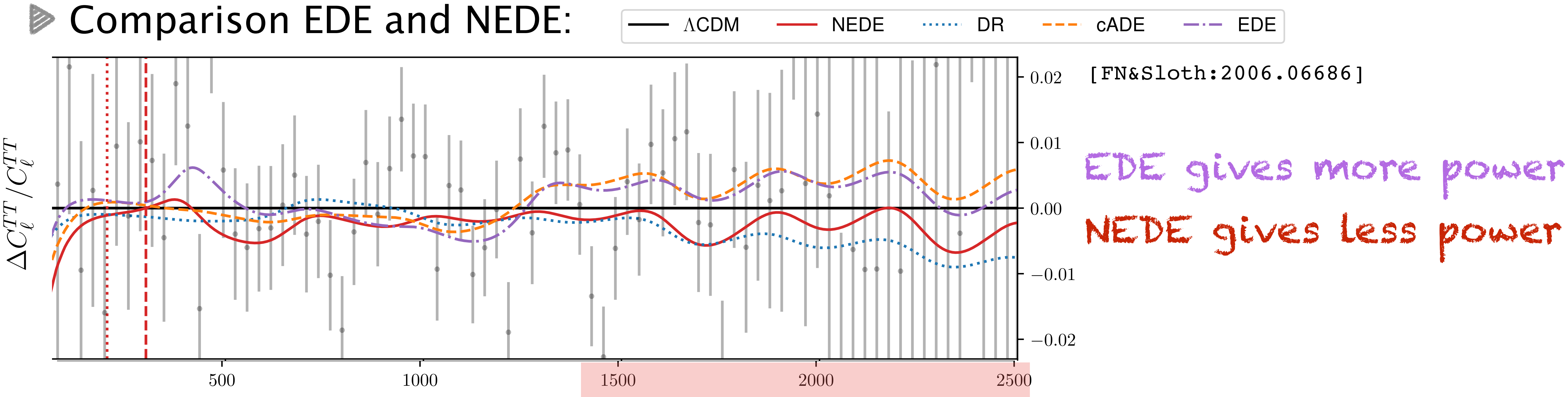
Nils Schöneberg,[a] Guillermo Franco Abellán,[b] Andrea Pérez Sánchez,[a] Samuel J. Witte,[c] Vivian Poulin,[b] and Julien Lesgourgues[a]

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)

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

- Comparison EDE and NEDE:



- More precise high-l TT (and EE) data can help distinguish EDE and NEDE.
- A special role will be played by LSS data.
- Key message: perturbation sector matters

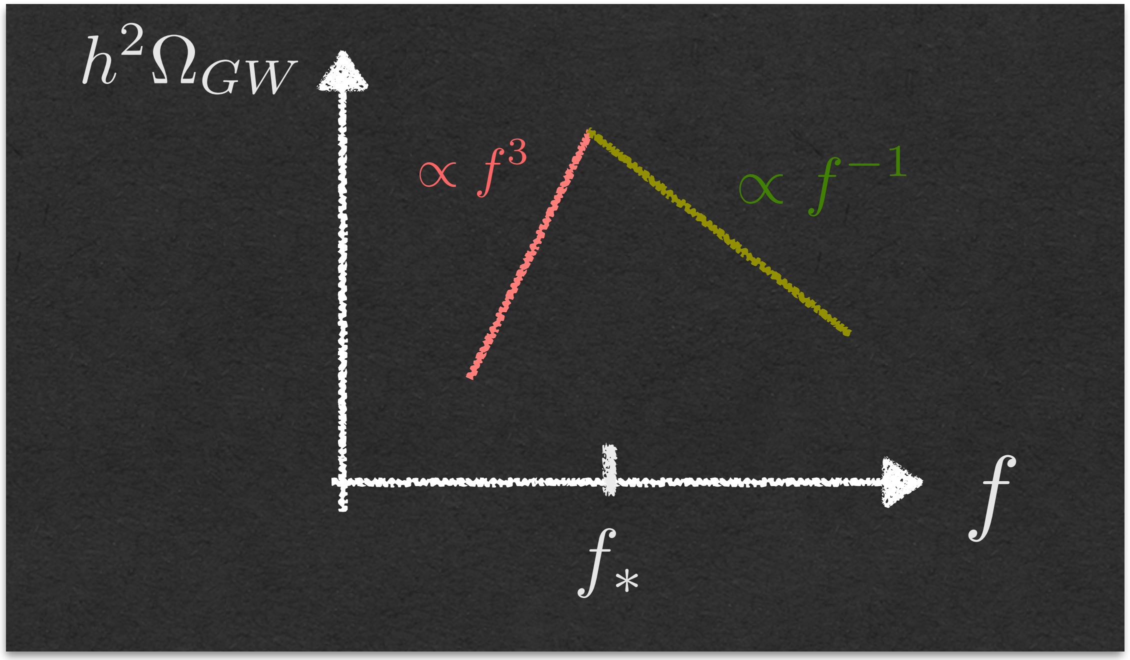
Gravitational Waves

Gravitational Waves

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

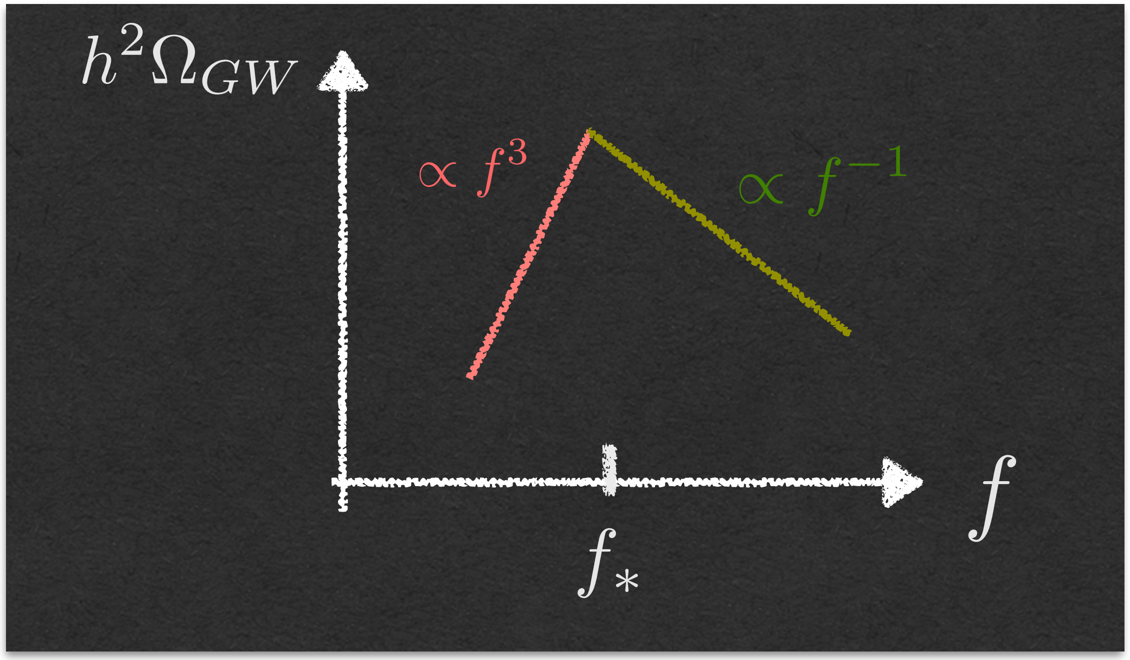
Gravitational Waves

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



Gravitational Waves

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



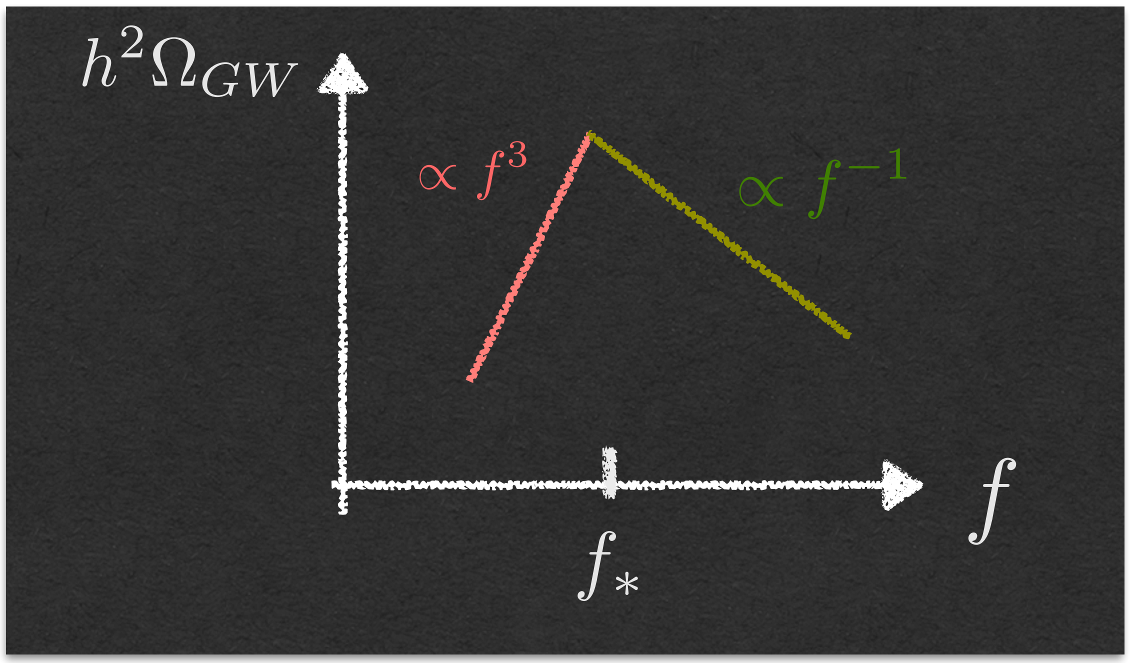
1/f regime:

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

single dial

Gravitational Waves

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



1/f regime:

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

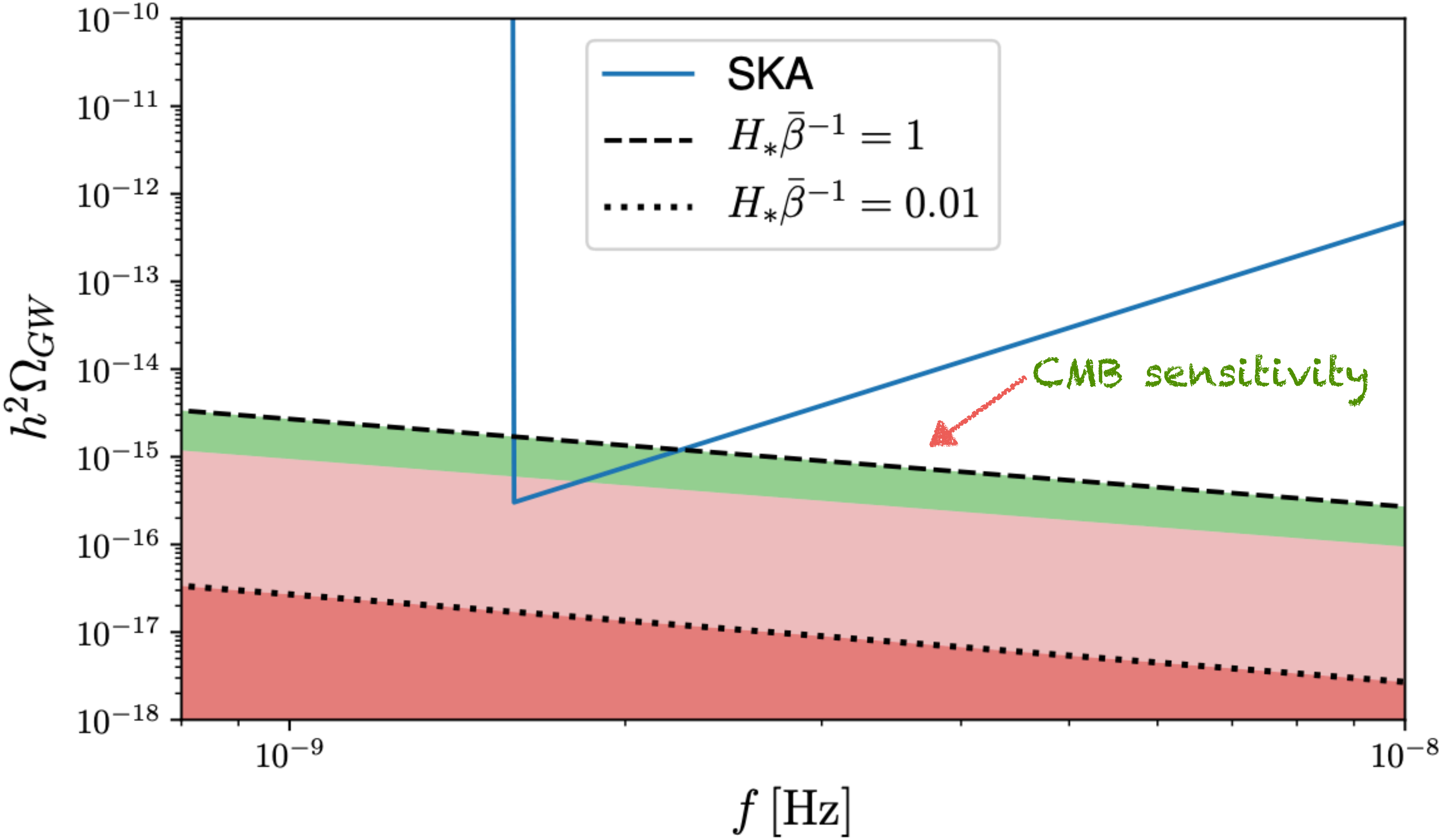
single dial

- 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.

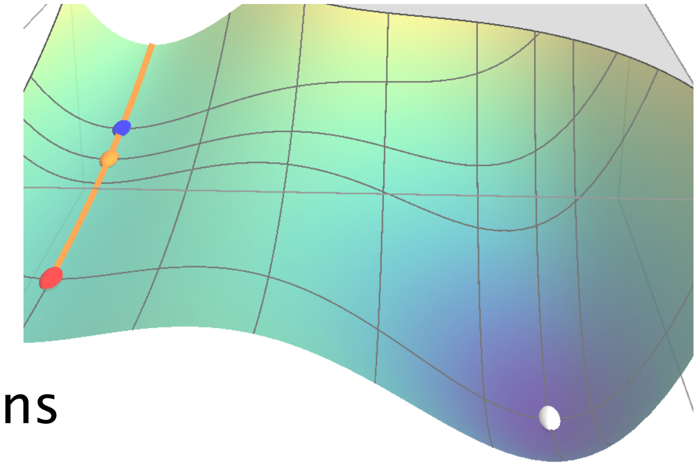


▷ Marginally compatible with Square Kilometre Array

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 brings H0 tension down to 2.5 sigma.
- **Unique** signature: gravitational waves.
- Three phenomenological challenges remain:
  - 1. **S8 tension:** → Dark sector interactions
  - 2. New **coincidence problem** → Martin's talk
  - 3. Unknown systematics → Stay open about new developments.
- Further theoretical work
  - Find new microscopic scenarios for NEDE (see Martin's talk).
  - Relate NEDE fluid to microscopic parameters.
  - Multi-axion system: small masses protected by approximately broken shift symmetry.