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

Martin S. Sloth
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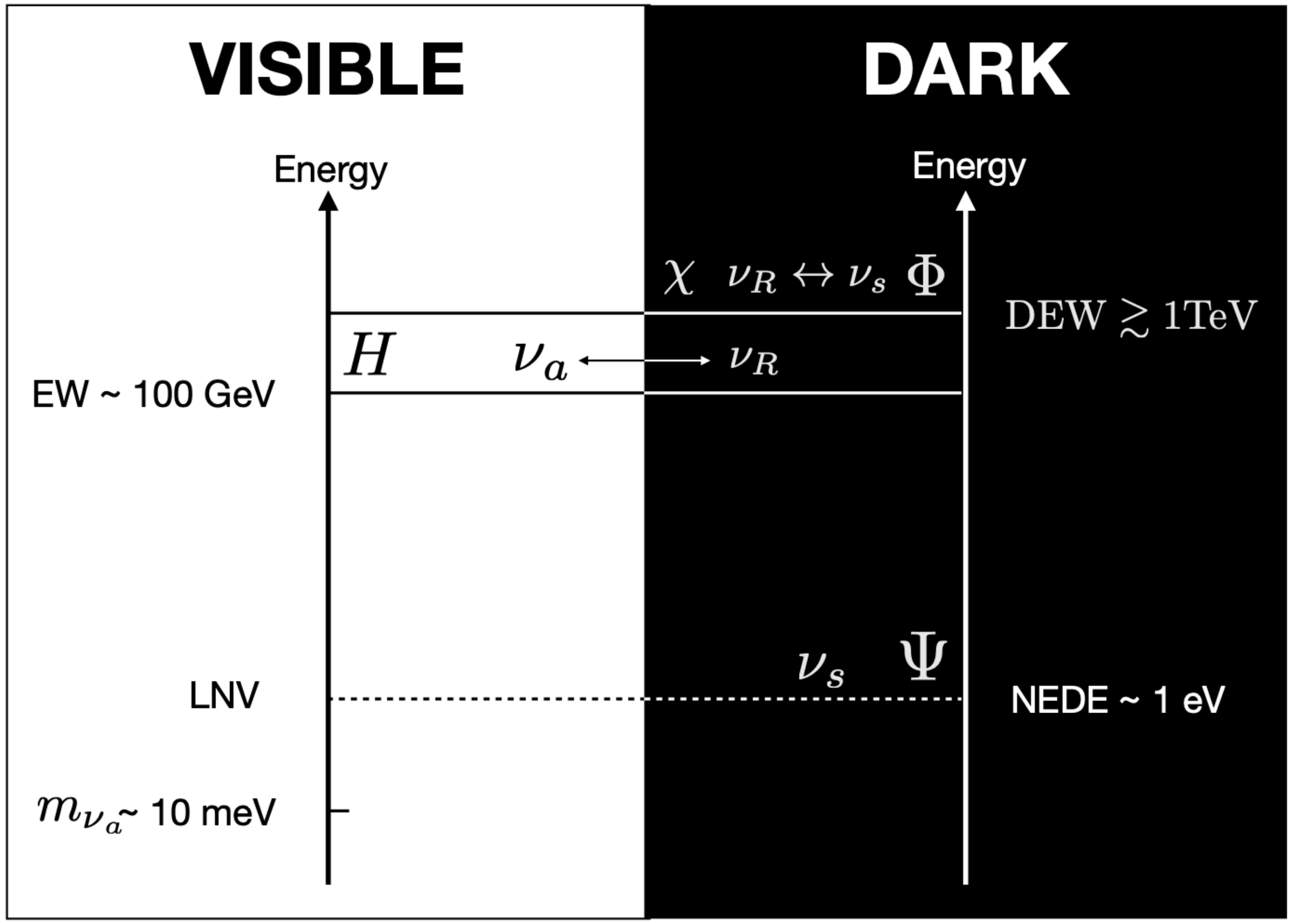
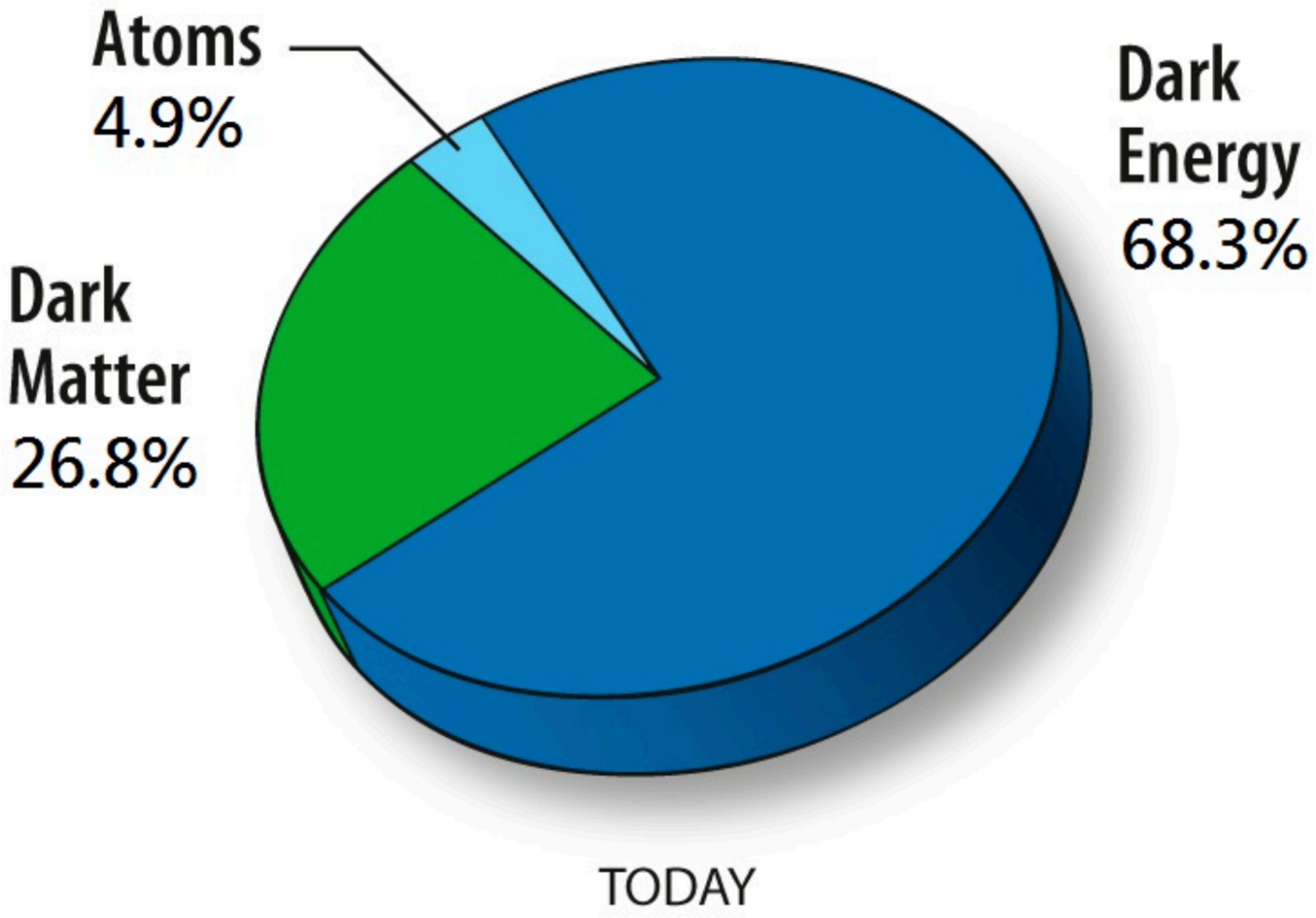


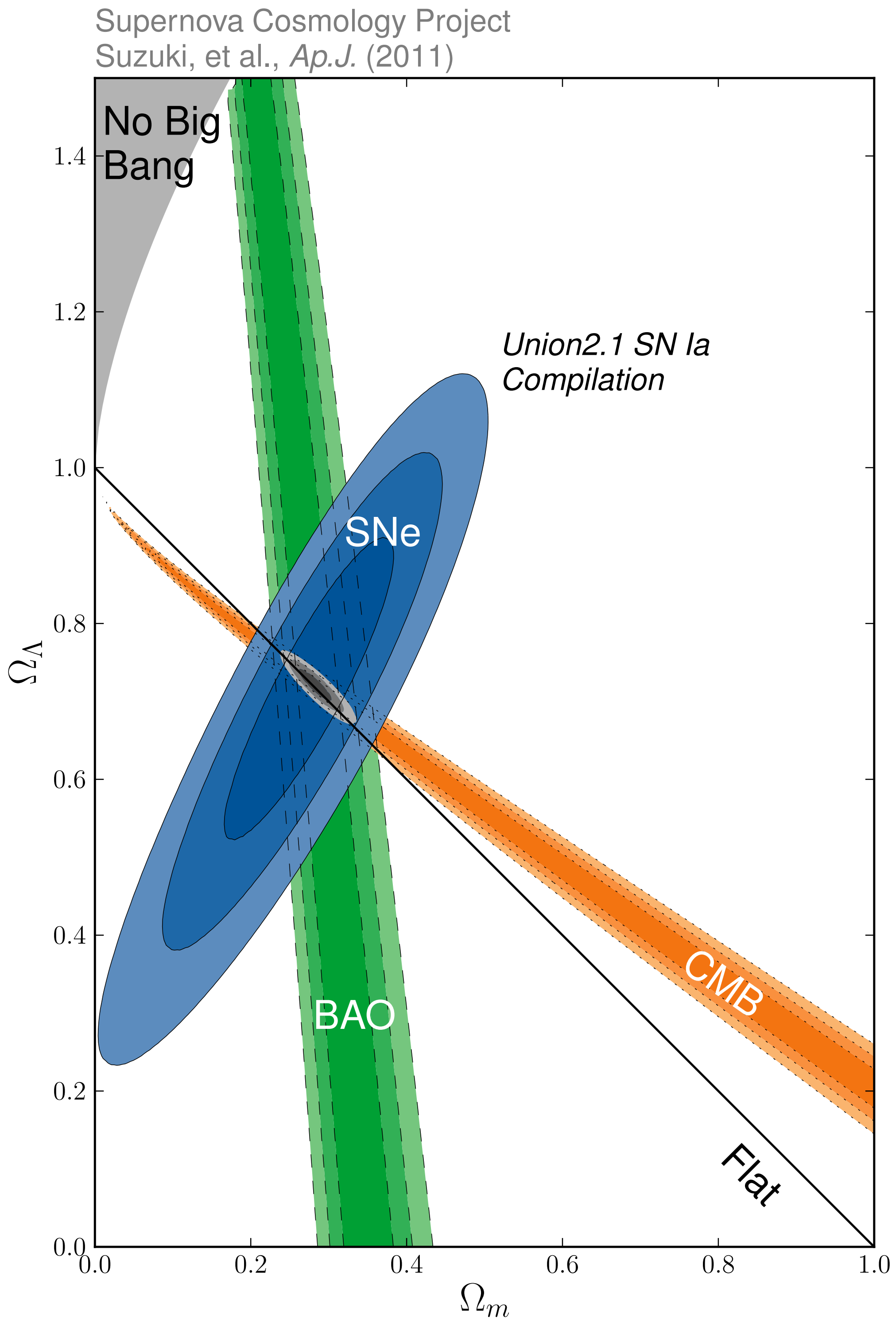
arXiv: 2112.00759, 2112.00770, 2009.00006, 2006.06686,1910.10739
w. Florian Niedermann

ΛCDM



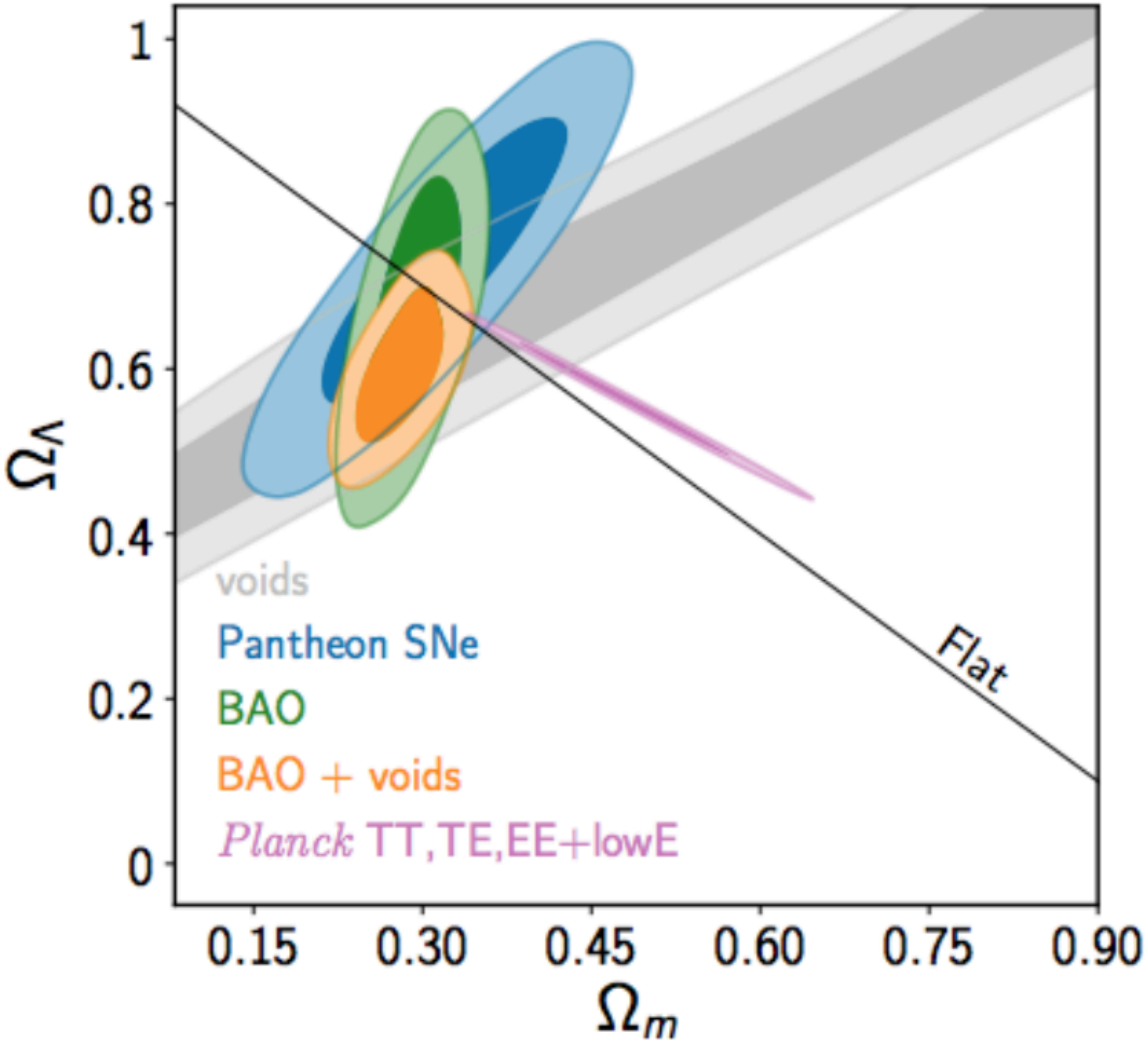
Concordance model

ΛCDM 10 years ago



Concordance model

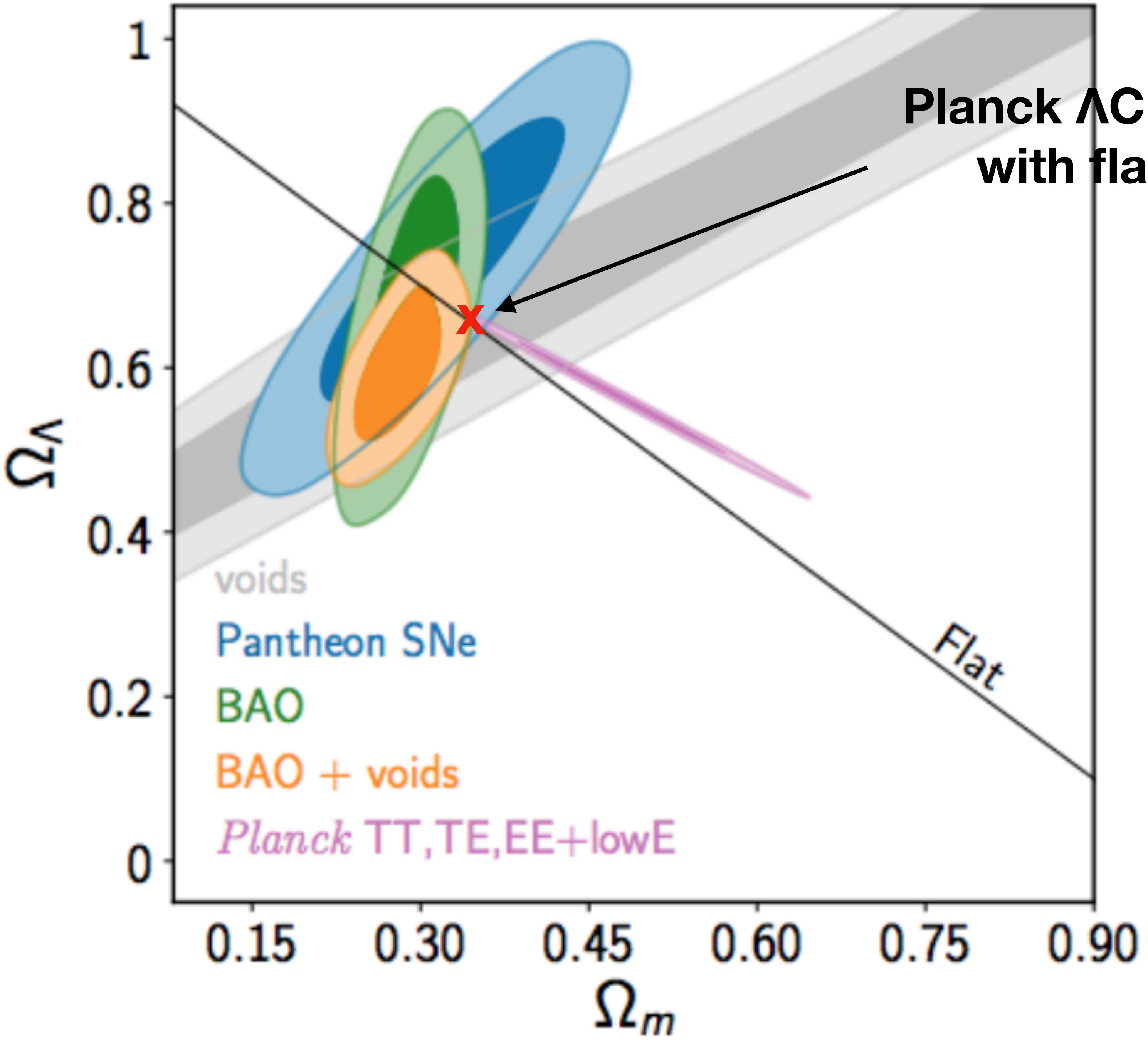
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

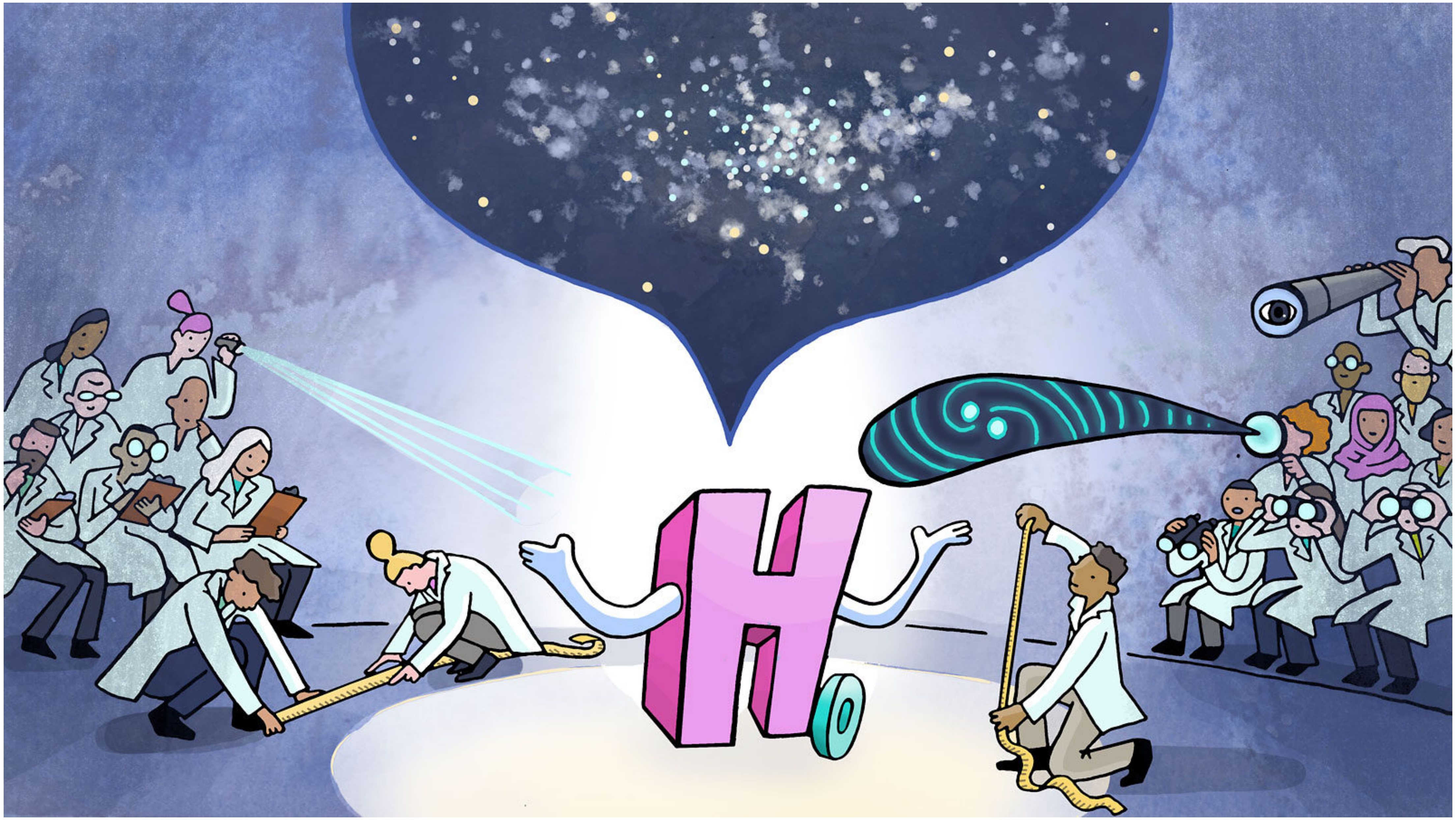
ΛCDM 2020



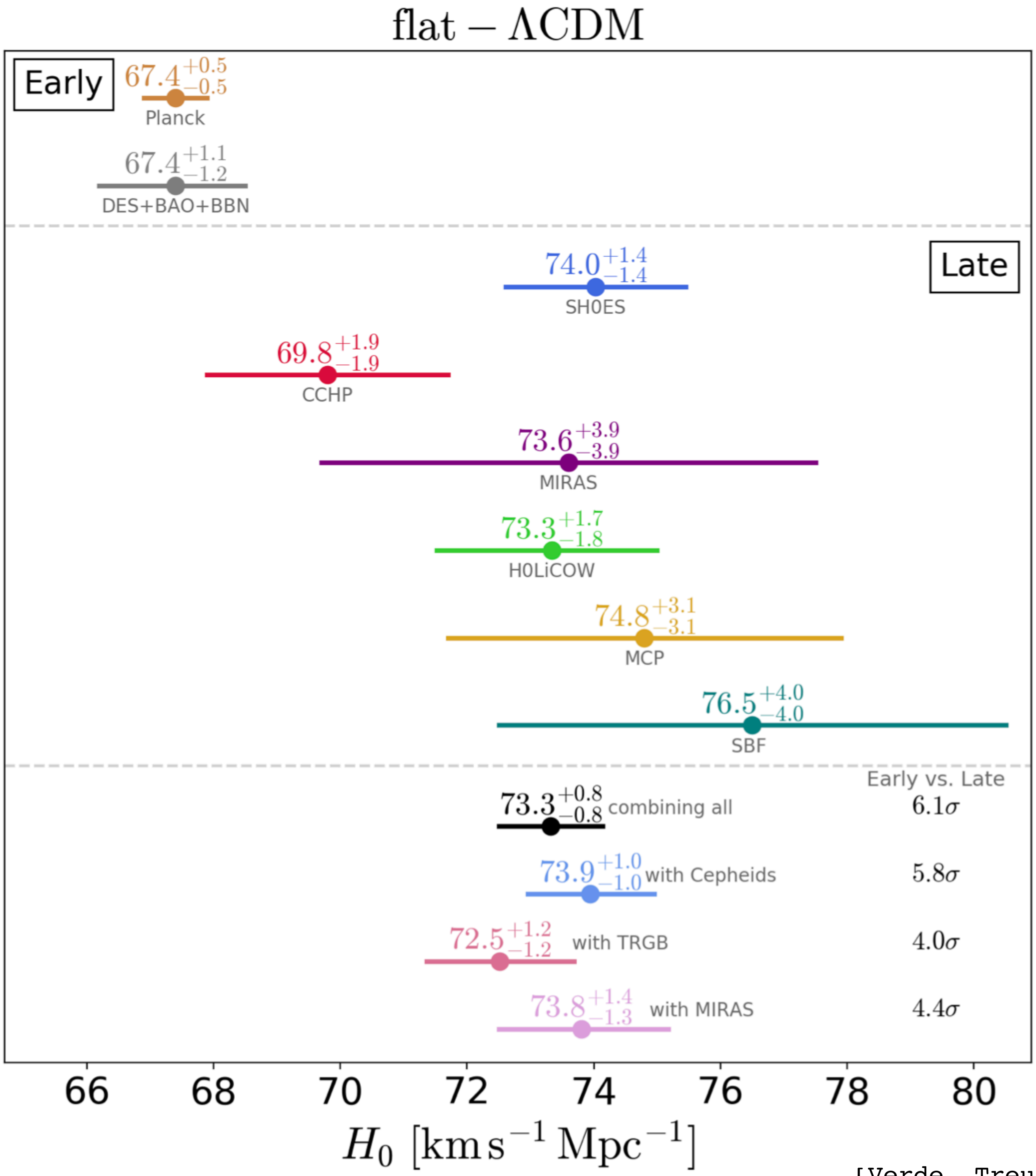
Planck ΛCDM value with flat prior

[Nadathur, Percival, Beutler, Winther; 2020]

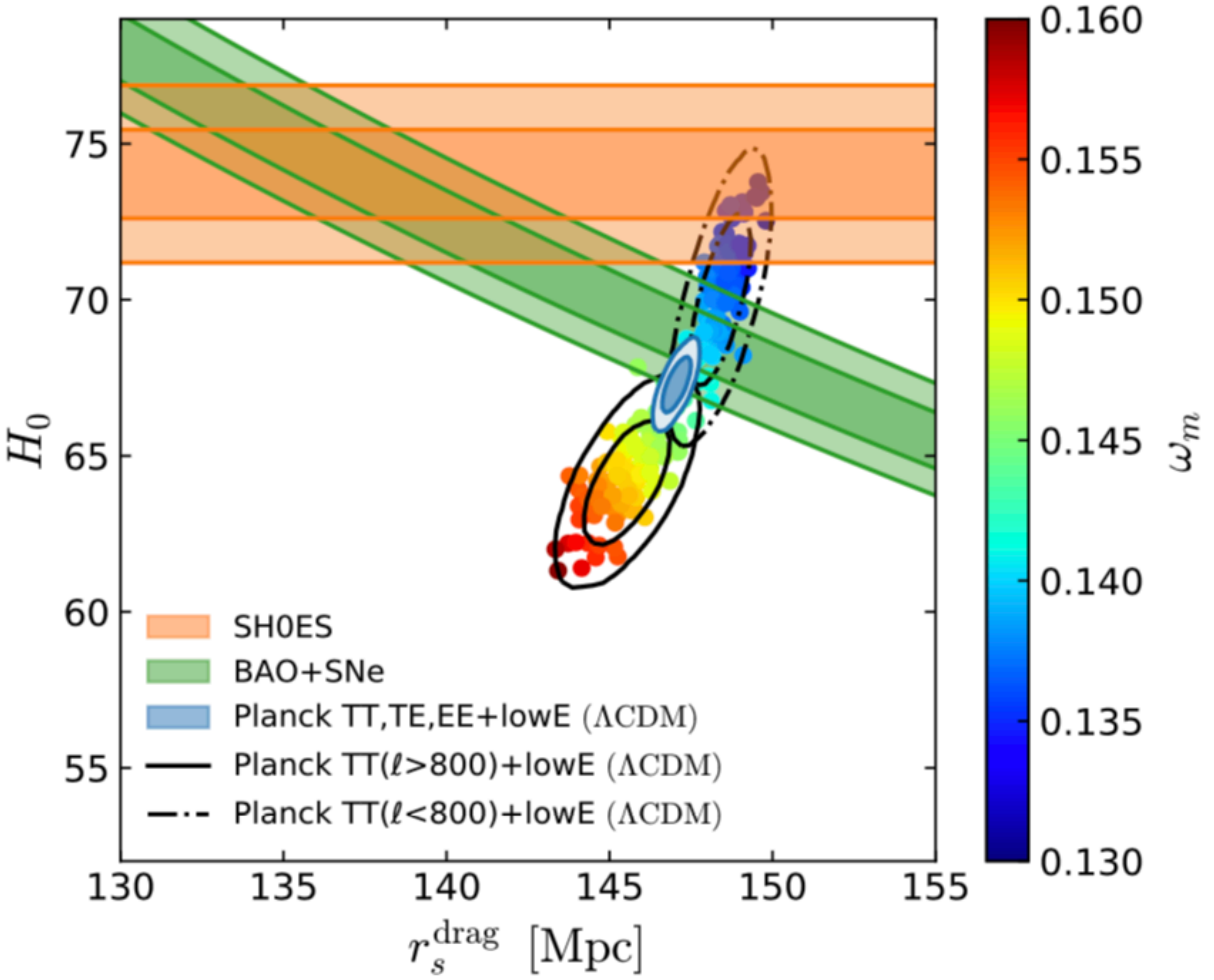
What about H_0?



[Illustration Symmetry mag. 2019]



[Verde, Treu, Riess; 2019]



[Knox, Miller; 2019]

The Hubble tension

SH$_0$ES:

[Riess et al. 2021]

$$H_0 = 73.04 \pm 1.04 \frac{\text{km}}{\text{s Mpc}}$$

Planck w. ΛCDM:

[Planck 2018]

$$H_0 = 67.4 \pm 0.5 \frac{\text{km}}{\text{s Mpc}}$$

5 σ tension

Tension is model dependent

- Redshift dependence of Hubble rate depends on the assumptions

$$\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m (1+z)^3 + \Omega_r (1+z)^4}$$

What is it telling us?

Is it systematics?

Maybe yes!

- But SH_0ES recently revisited all previously proposed sources of systematics and found their results to be robust.

- Yet, no fully independent measurement/method has confirmed the results to the same precision.

➡Independent measurement is needed to settle disputes in the community…

Could it be the end of ΛCDM?

Maybe yes!

- All local measurements of H_0 are consistently higher than Planck’s value!
- Small anomalies within CMB and a small tension between CMB and BAO (although all individually insignificant)
- The universe is likely to be more complicated than allowed for in the 6-parameter ΛCDM model!

The Hubble tension

Model-dependent statement:

- Planck and SH$_0$ES incompatible

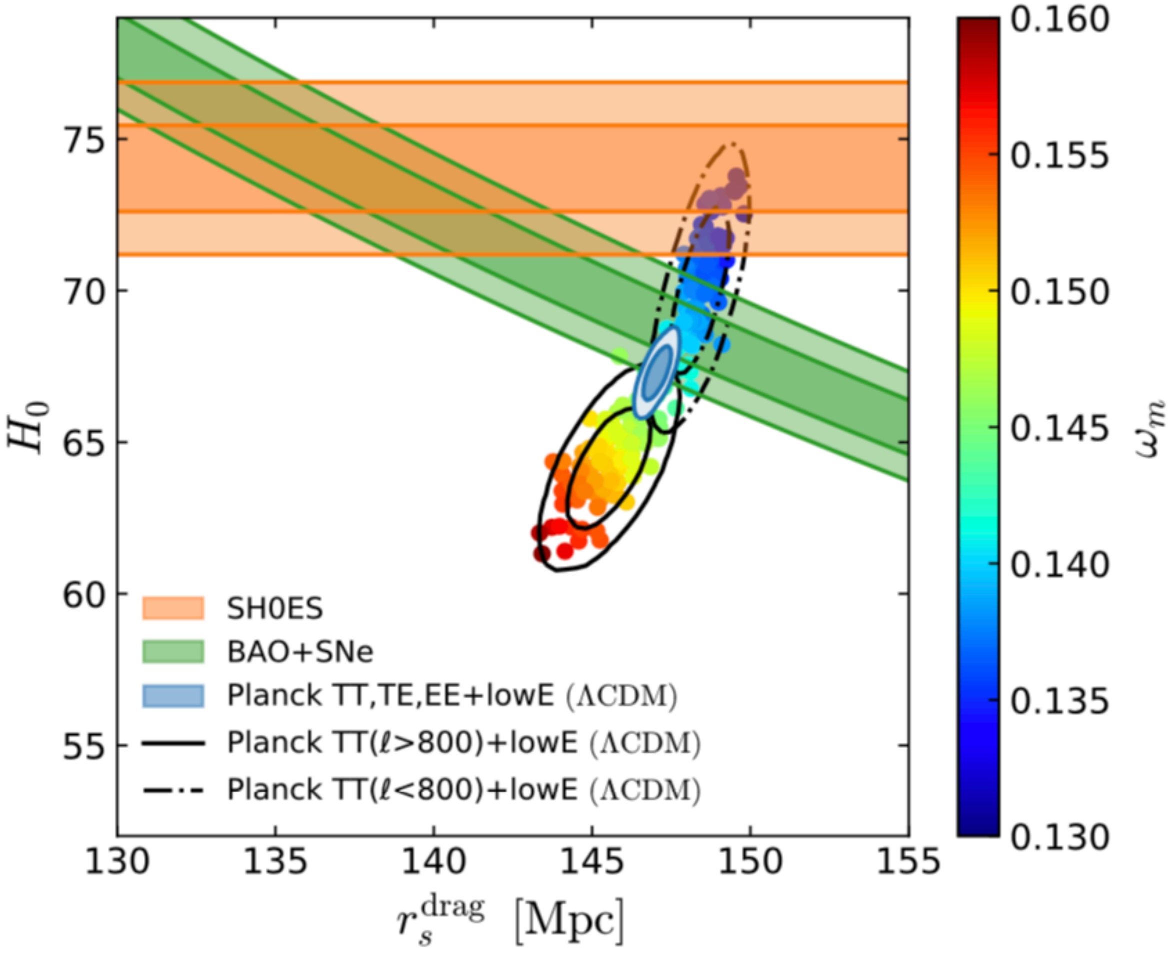
Model-independent statement:

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

Where

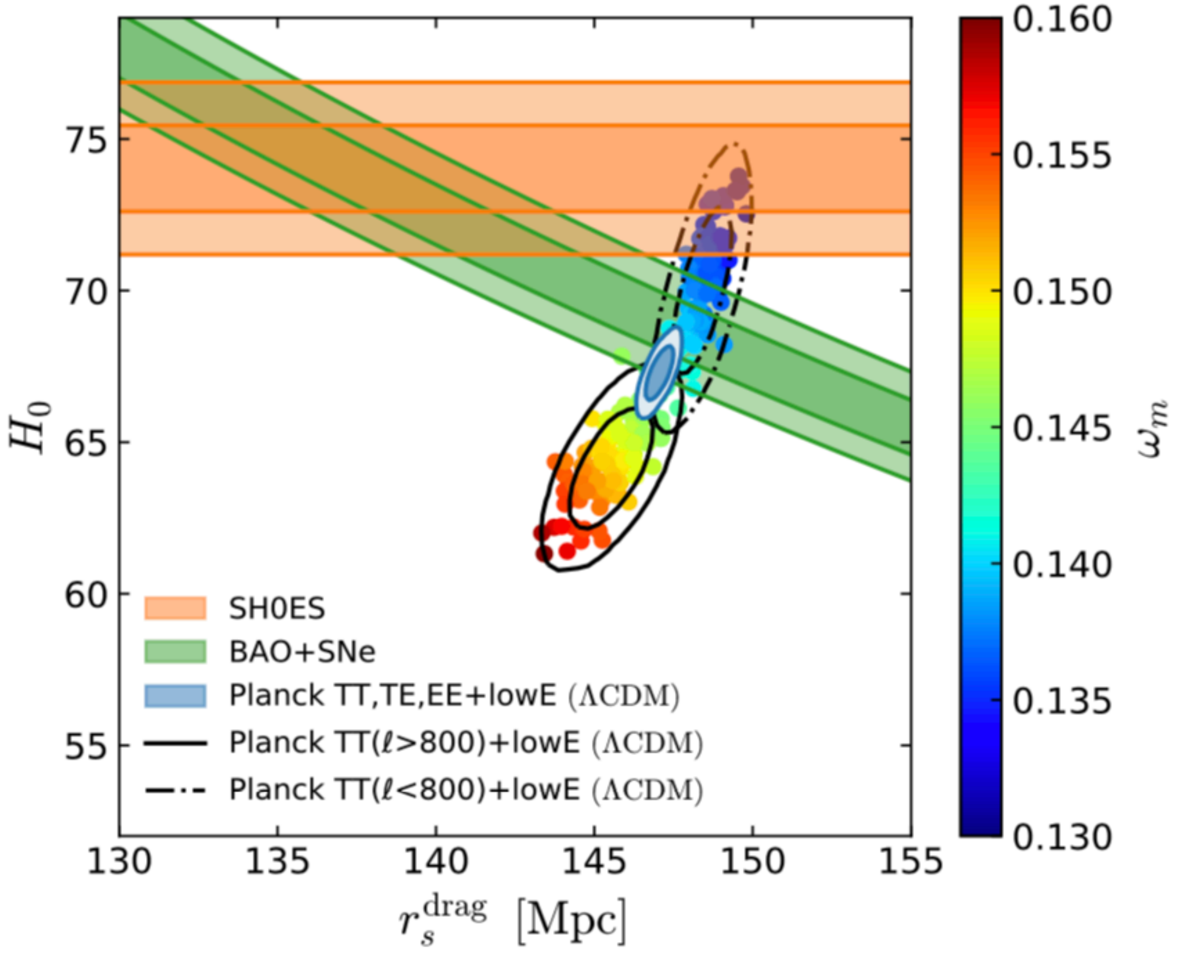
$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

depends on early time physics



[Knox, Miller; 2019]

The Hubble tension



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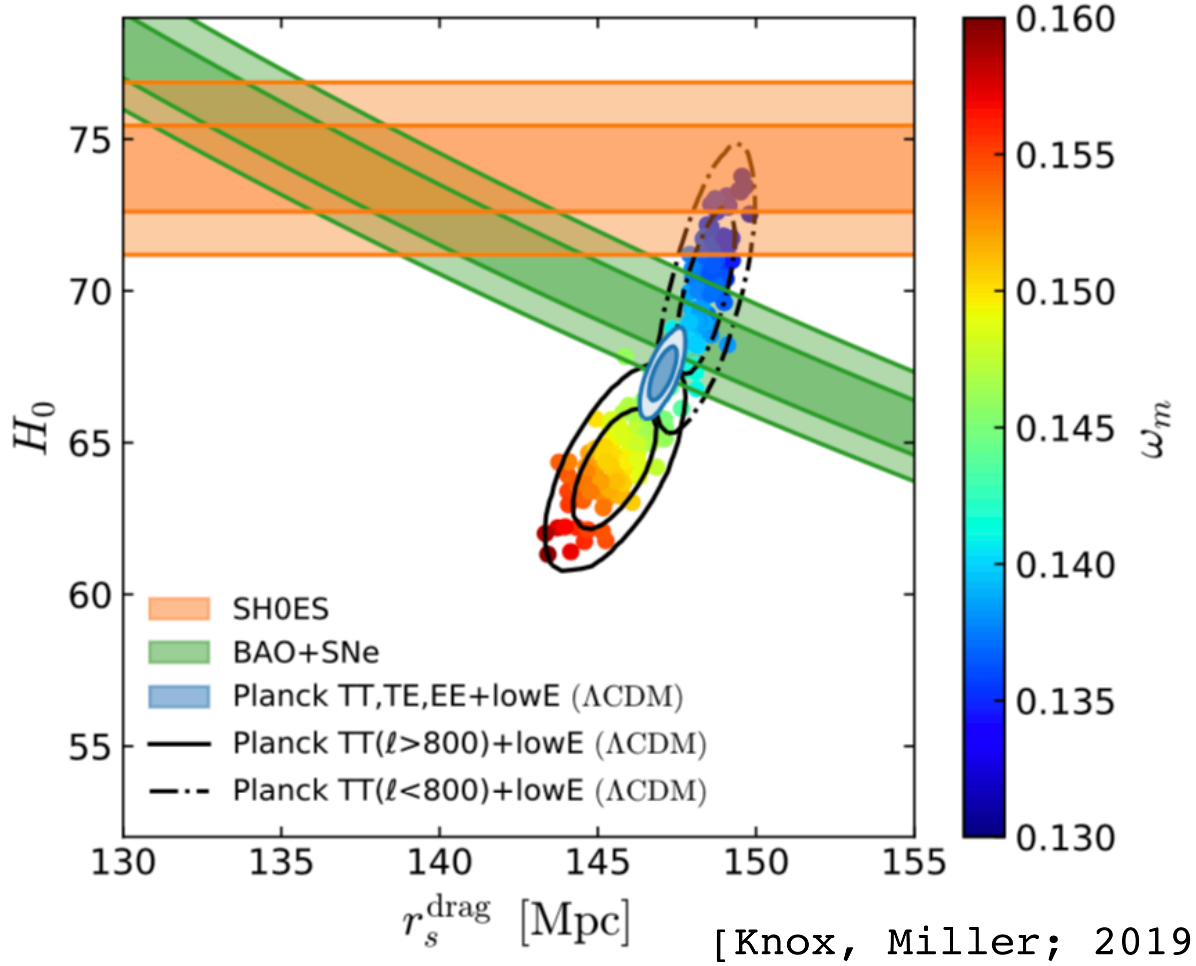
Modification of *ΛCDM* raising *H₀* while lowering *r$_s$*

The Hubble tension



[Knox, Miller; 2019]

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depends on early time physics

Modification of *ΛCDM* raising H_0 while lowering r_s

Modification of *ΛCDM* just before recombination

Late-time modifications

- Even if late-time modifications ruled out by combination of CMB, BAO and SN people still try.

➡ Almost every week a new paper to explain Hubble tension with late time effect/systematics (modified gravity, voids, phantoms…), but all “solutions” ignores one of the three; CMB, BAO, SN.

- Those who does not, does indeed find late-time solutions to be excluded:

1607.05297, 1607.05617, 1908.03663, 1811.00537, 1905.12000,
2103.08723, 2202.01202 and more…

Pre-recombination modifications

- Assume new hypothetical matter component is present before recombination

$$\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_X(z)}$$

➡ Increase in H_0 before recombination

➡ Lowering the sound horizon

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Dark radiation

- Extra relativistic degree of freedom

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

➡ Reduces the tension only slightly (~ 4 σ)

[Planck 2018+BAO +Pantheon+BBN]

$$H_0 = 66.8 \pm 1.1 \ \frac{\text{km}}{\text{s Mpc}}$$

`[Niedermann, MSS; 2020]`

Early Dark Energy

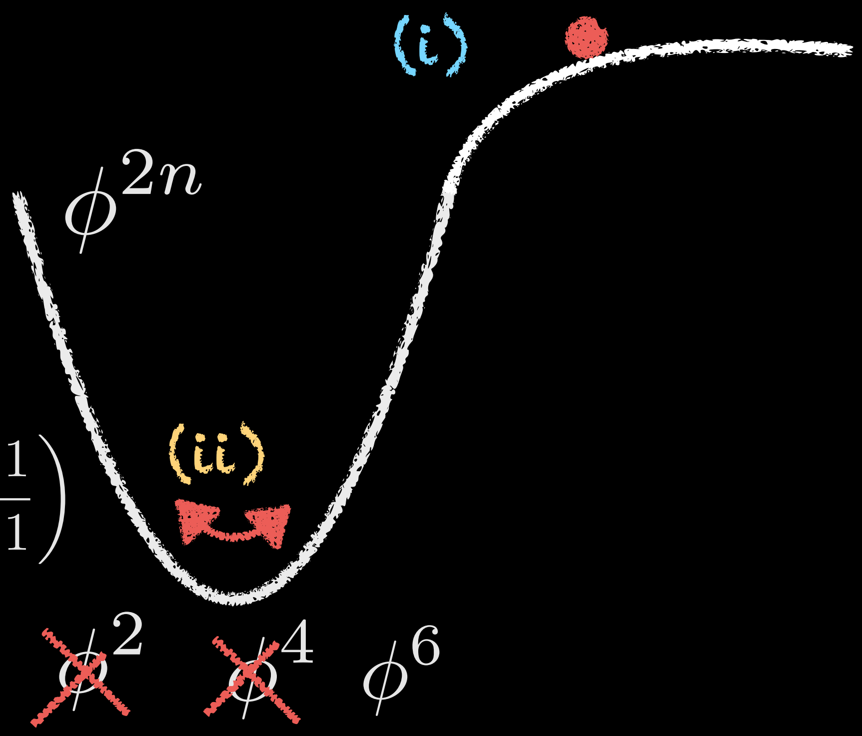
Scalar field model w. slow-roll second-order phase transition

[e.g. Karwal et al., 2016]
[Poulin et al., 2018]

$$V^{(n)}(\phi) = \Lambda_a^4 \left[1 - \cos(\phi/f_a)\right]^n$$

$$\Omega_X(z) \approx \begin{cases} \Omega_{EDE} & ;\; z \gg z_c \;\; (i) \\ \Omega_{EDE}\left(\frac{1+z}{1+z_d}\right)^{\alpha\geq 4} & ;\; z \ll z_c \;\; (ii) \end{cases}$$

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



meanvalues: $n = 3$ $z_c \approx 4000$

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

➡ How to make shallow anharmonic potentials natural…

[Kaloper, 2019]

New Early Dark Energy

NEDE is a fast triggered phase transition in the dark sector

Simple effective cosmological model:

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

arXiv: 1910.10739, 2006.06686 w. Florian Niedermann

Some microphysical examples are:

- **Cold NEDE:**
  1st order PT triggered by a second "trigger" scalar field
  arXiv: 1910.10739, 2006.06686 w. Florian Niedermann
- **Hot NEDE:**
  1st order PT triggered by a non-vanishing temperature of the dark sector
  arXiv:2112.00759, 2112.00770 w. Florian Niedermann

$\Big\}$ **Focus this talk:**
1st order
Phase Transitions

- **Hybrid NEDE:**
  2nd order PT triggered by a second "trigger" scalar field
  arXiv:2006.06686 w. Florian Niedermann

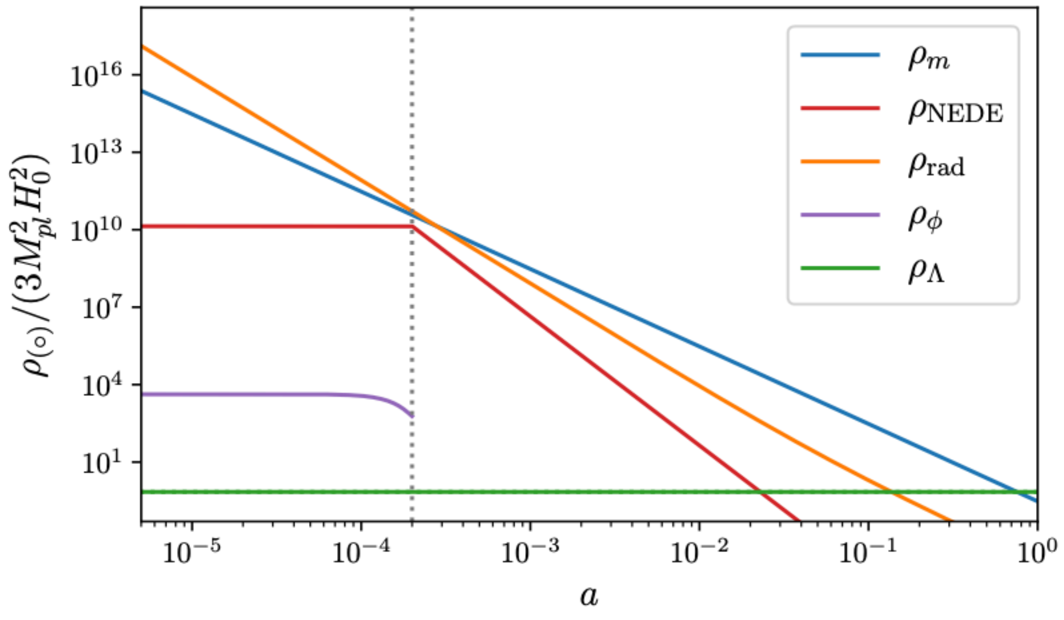
Effective cosmological model

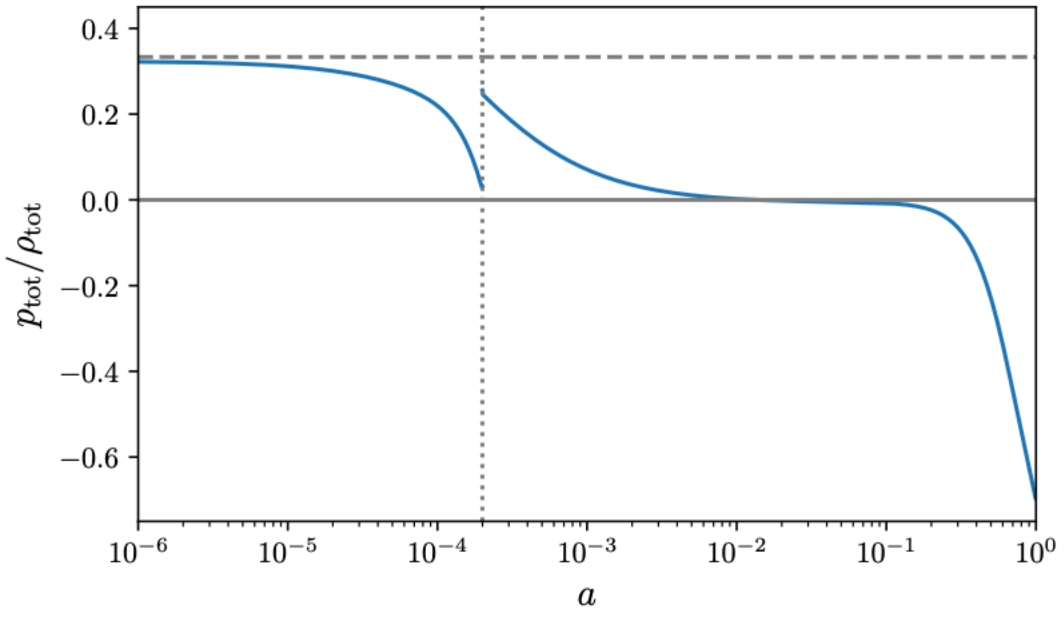
- **Background** picture: Assume that all liberated vacuum energy is converted to a fluid with fixed e.o.s.

Sudden transition at time t_*:

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

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





Cosmological perturbations

- The phase transition affects perturbations in different ways:
  - Perturbations feel the change in the effective e.o.s. → relevant for CMB
  - Transition is triggered at different places at different times due to fluctuations in trigger dynamics → relevant for CMB
- We use Israel junction conditions to match fluctuations across transition

[Deruelle, Mukhanov, 1995]

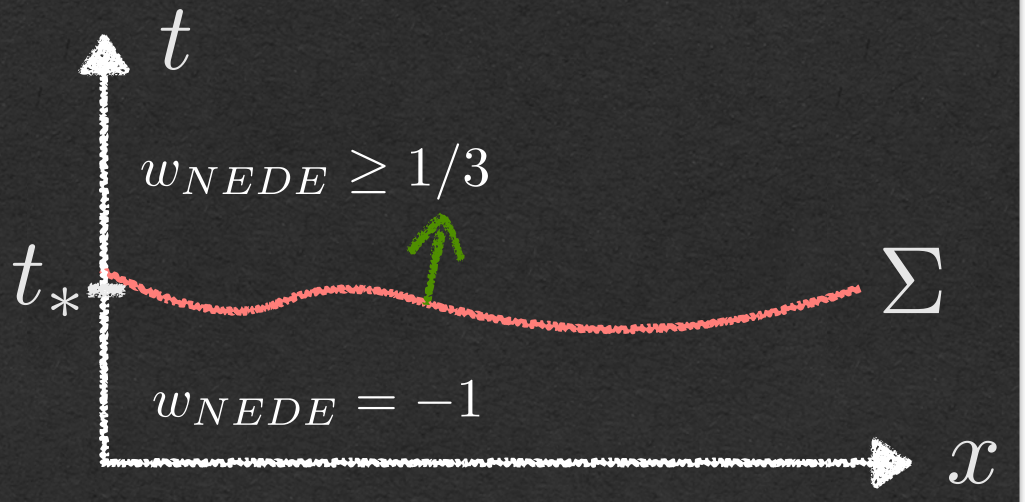
space like transition surface Σ

synchronous gauge:

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

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

has two metric perturbations



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

arXiv:2006.06686 w. Florian Niedermann

Cosmological perturbations

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

➡ The perturbations depend on the microphysical realization of NEDE

- CMB anisotropies and LSS depends on initial perturbations

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

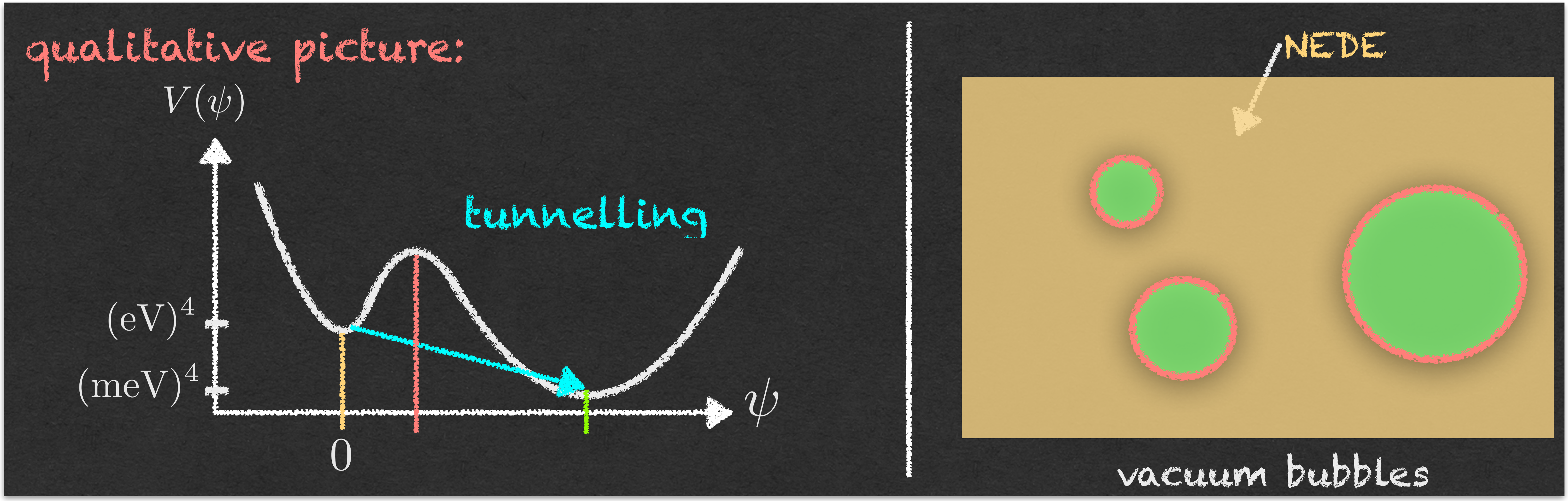
$$\text{EDE} \neq \text{Cold NEDE} \neq \text{Hot NEDE}$$

Cold New Early Dark Energy

Cold New Early Dark Energy

Scalar field model w. first order phase transition

[Niedermann, MSS; 2019, 2020]



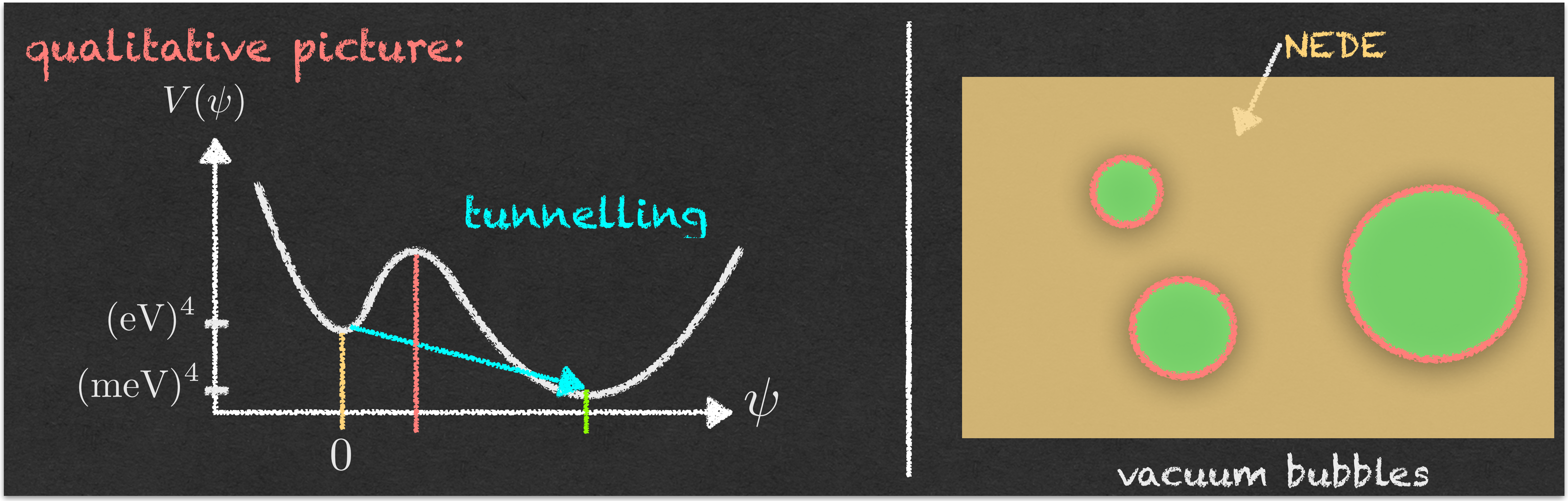
$$w = -1 \qquad \rightarrow \qquad 1/3 < w < 1$$

- Vacuum energy decays
- Free energy converted to anisotropic stress
- Anisotropic stress partially sources gravitational radiation
- Remaining anisotropic stress decays like a stiff fluid

Cold New Early Dark Energy

Scalar field model w. first order phase transition

[Niedermann, MSS; 2019, 2020]



➡ This idea faces immediate challenges:

1. Decay should happen around matter-radiation equality (lesson from EDE).
2. Bubble percolation has to be extremely efficient to avoid inhomogeneities (bubbles prevented from growing to cosmological size).
3. Imprint on super- **and** sub-horizon modes has to be tracked.
4. Stabilise ultralight physics against quantum corrections.

➡ Introduce a trigger field for the decay

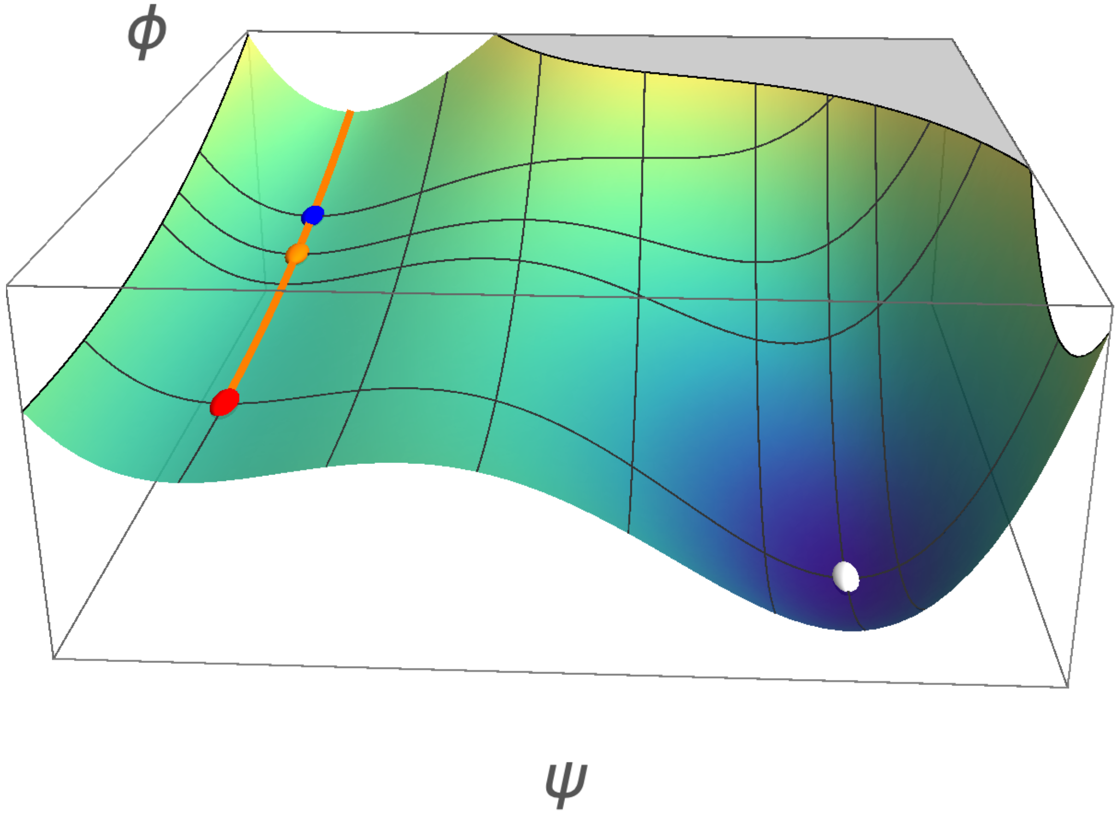
field theory model:

$\alpha, \beta, \lambda = \mathcal{O}(1)$

$$V(\psi, \phi) = \frac{1}{2}\underbrace{\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{\lambda}{4}\psi^4}_{\text{New Early Dark Energy}} + \underbrace{\frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2}_{\text{Clock}} + \underset{\substack{\uparrow \\ \text{'CC tuning'}}}{const}$$

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

initial condition: $\psi = 0$ sub-dominant trigger: $\phi_{ini} \ll M_{pl}$



(i) for $H \gg m: \ \phi \approx \phi_{ini}$

(ii) for $H \approx m: \ \phi$ starts evolving

(iii) blue dot: inflection point

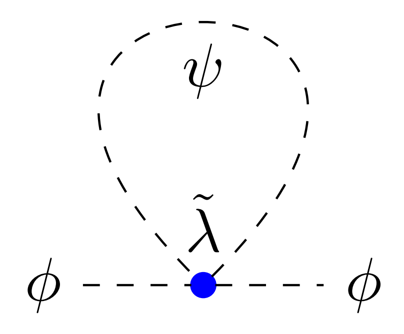
(iv) orange dot: $\Gamma = 0, \ \dot{\Gamma} > 0$

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

Technical Naturalness

- Most general renormalizable potential of two scalar fields
- Radiative stability as low energy EFT (valid up to at least scale M)

$$\delta m^2 =$$



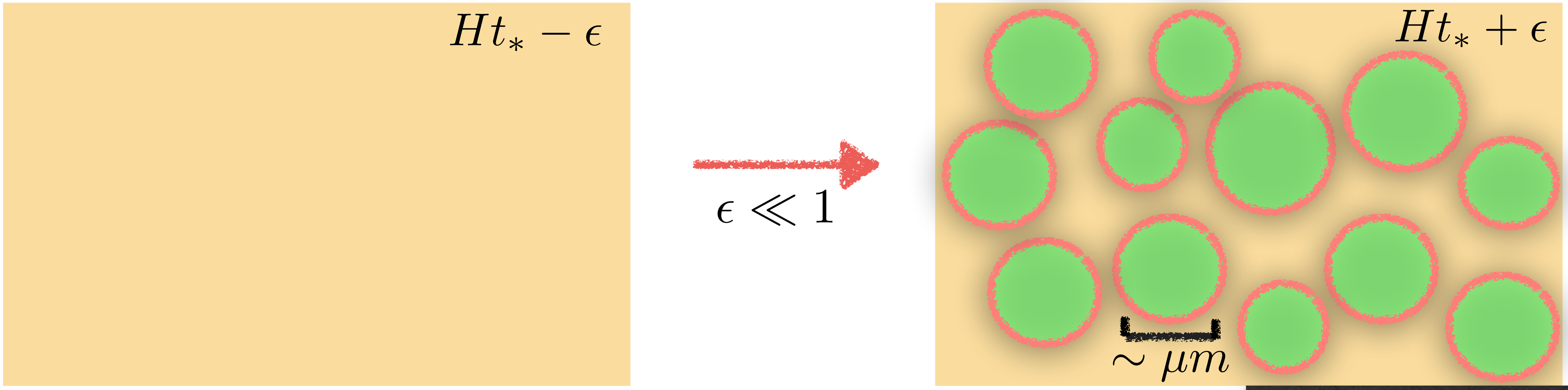
of order (suppressing logs): $\tilde{\lambda}\,\beta\, M^2/(32\pi^2)$

$$\xrightarrow[\text{stability}]{\text{radiative}} \quad \tilde{\lambda} \lesssim 10^3 \frac{m^2}{\beta M^2} \ll 1\,.$$

- May have many possible UV completions in terms of axions (monodromy, clockwork, etc.) and quantum gravity solutions to the CC problem (landscape, chain NEDE [Freese, Winkler; '21], etc.)

Bubble Coalescence

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



- Bubbles collide long before they reach cosmological size.

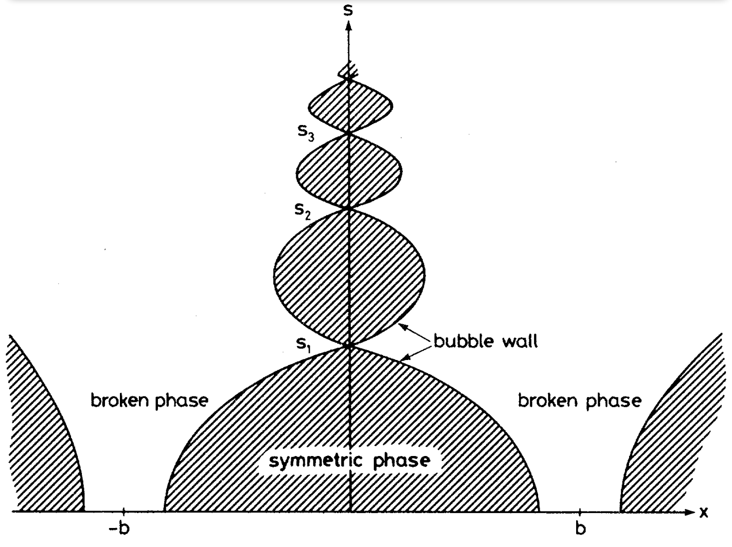
$$\ell_{bubble} < 10h^{-1}\text{Mpc}/(z_* + 1)$$

[Liddle, Wands, 1991]

- Bubble collision and dissipation is complicated.

Generally free energy converted to anisotropic stress sourcing gravitational waves.

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



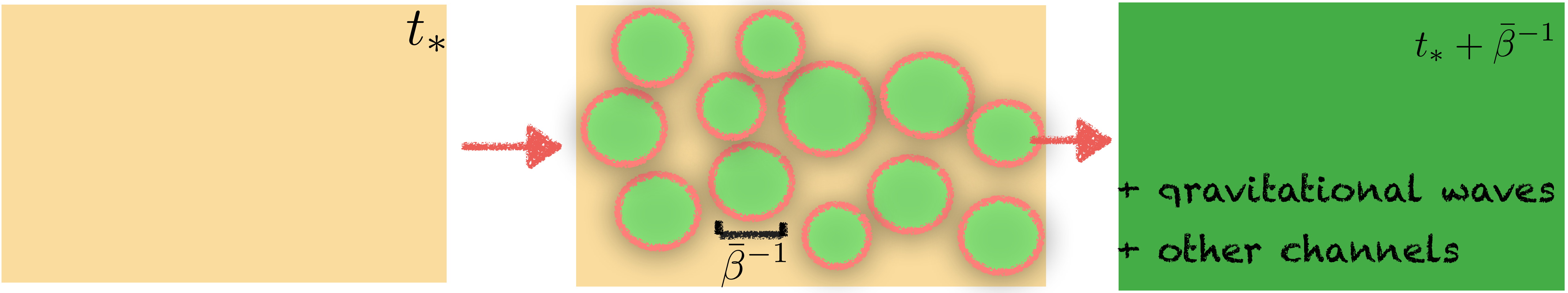
[Hawking, Moss, Stewart, 1982]

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

Effective cosmological model

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

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



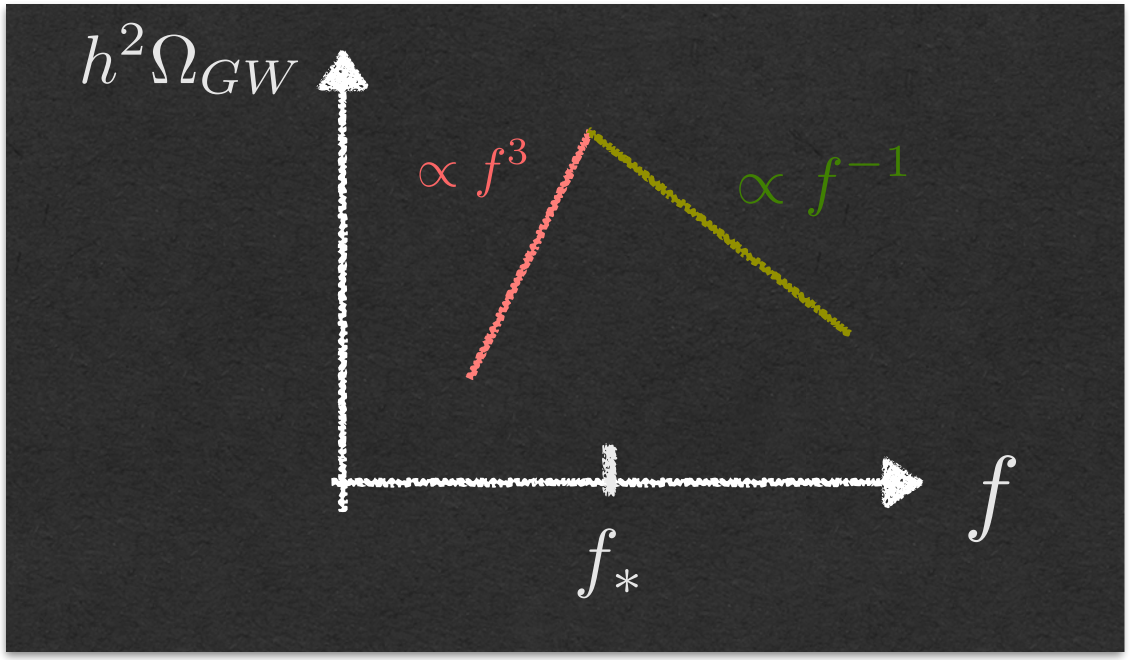
Effective model:

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

$$1/3 < w^*_{NEDE} < 1$$

Gravitational waves

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



1/f regime:

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

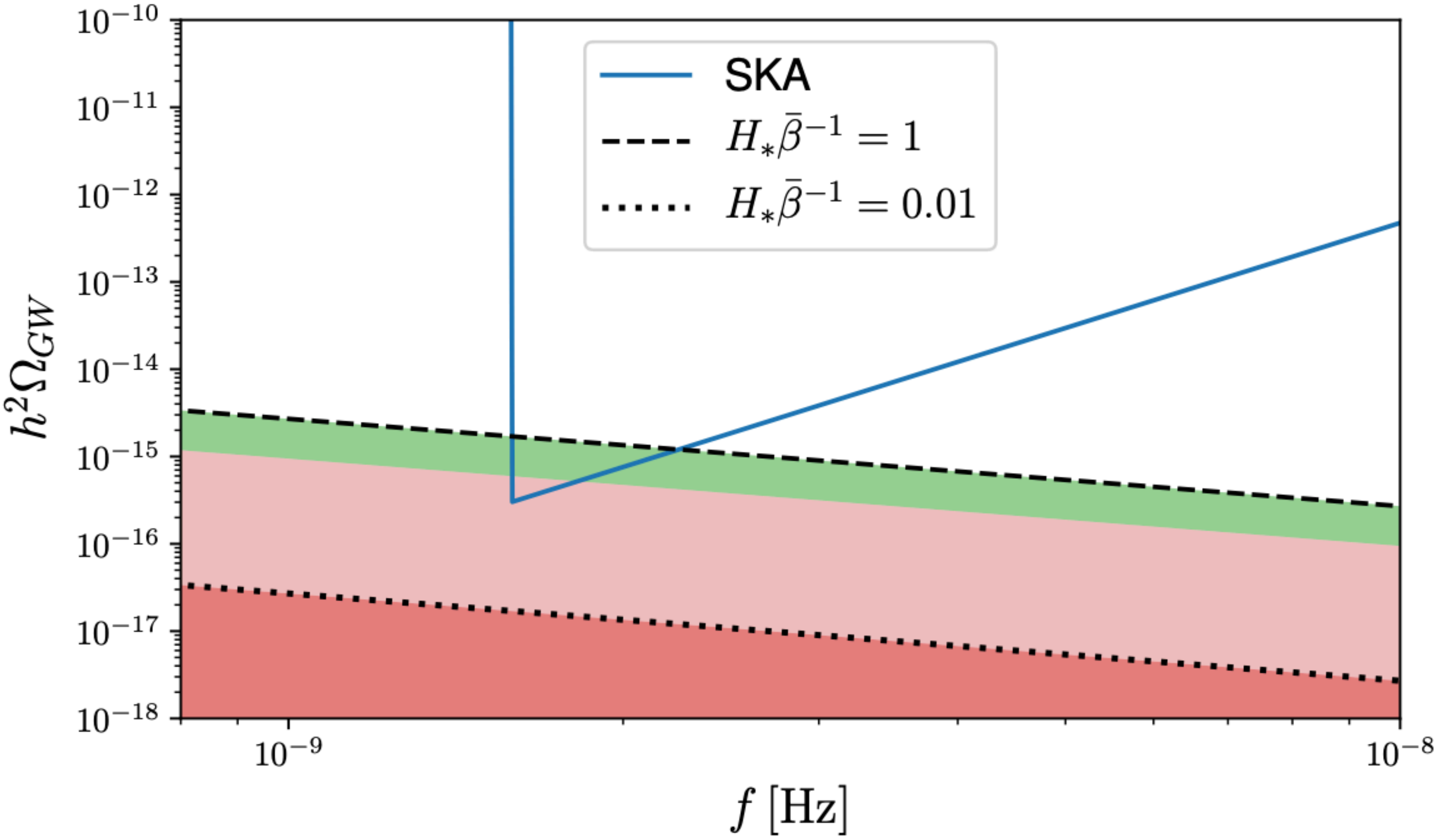
single dial

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

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

→ window for detection: $10^{-3} < H\bar{\beta}^{-1} \lesssim 1$

Gravitational waves



Cold NEDE: Cosmological perturbations

- The phase transition affects perturbations in different ways:
  - Perturbations feel the change in the effective e.o.s. → relevant for CMB
  - Transition is triggered at different places at different times due to fluctuations in trigger field phi. → relevant for CMB
  - The bubbles generate perturbations on scales comparable to their size. → irrelevant for CMB
- We use Israel junction conditions to match fluctuations across transition

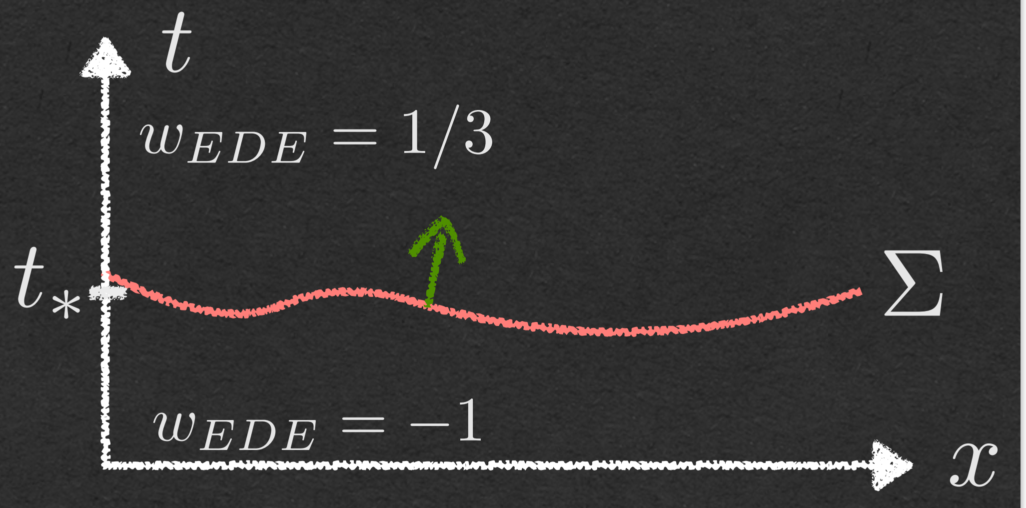
[Deruelle, Mukhanov, 1995]

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

synchronous gauge:

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

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



- Two metric perturbations: $h(t,k) \quad \& \quad \eta(t,k)$

Cold NEDE: Cosmological perturbations

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

Israel's junction conditions:

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

→ Einstein eqs.

'initial' conditions

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

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

valid for super- and sub-horizon modes

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

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

arXiv:2006.06686 w. Florian Niedermann

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

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

Two-parameter extension of LCDM

Results

datasets:

Planck 2018 TT, TE, EE

Planck 2018 Lensing

BAO + LSS

Pantheon

SH_0ES 2019

BBN

- We use simplest implementation of New EDE.
  - Phase transition described as instantaneous process.
  - All vacuum energy converted to $w^*_{NEDE} = 2/3$
  - No sizeable oscillations in trigger field after transition.

`[arXiv:1910.10739]`
`[arXiv:2006.06686]`

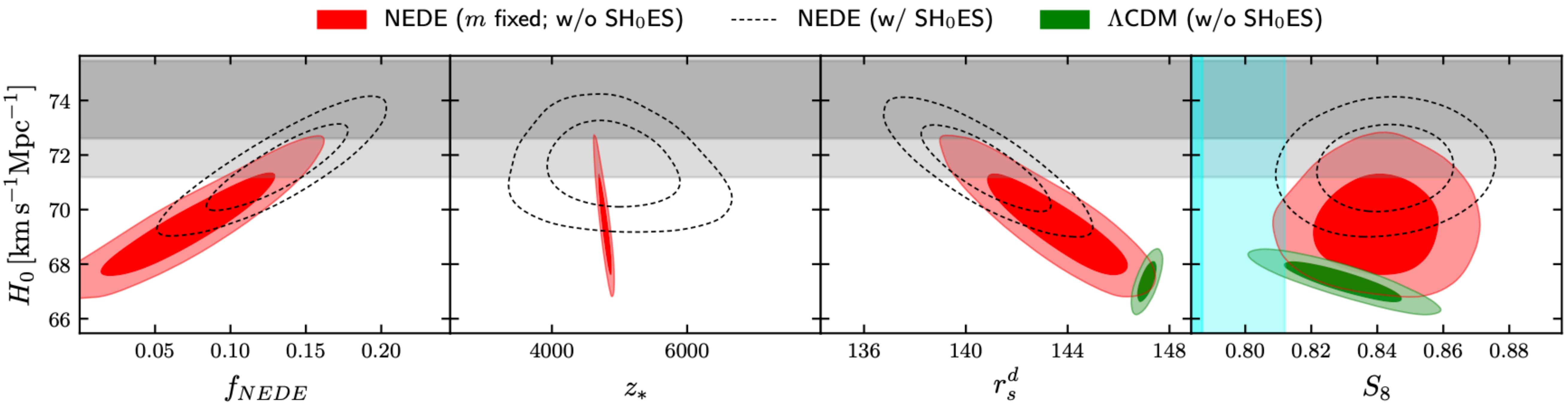
$H_0 = 71.5 \pm 1 \mathrm{km/s/Mpc}$

improvement:

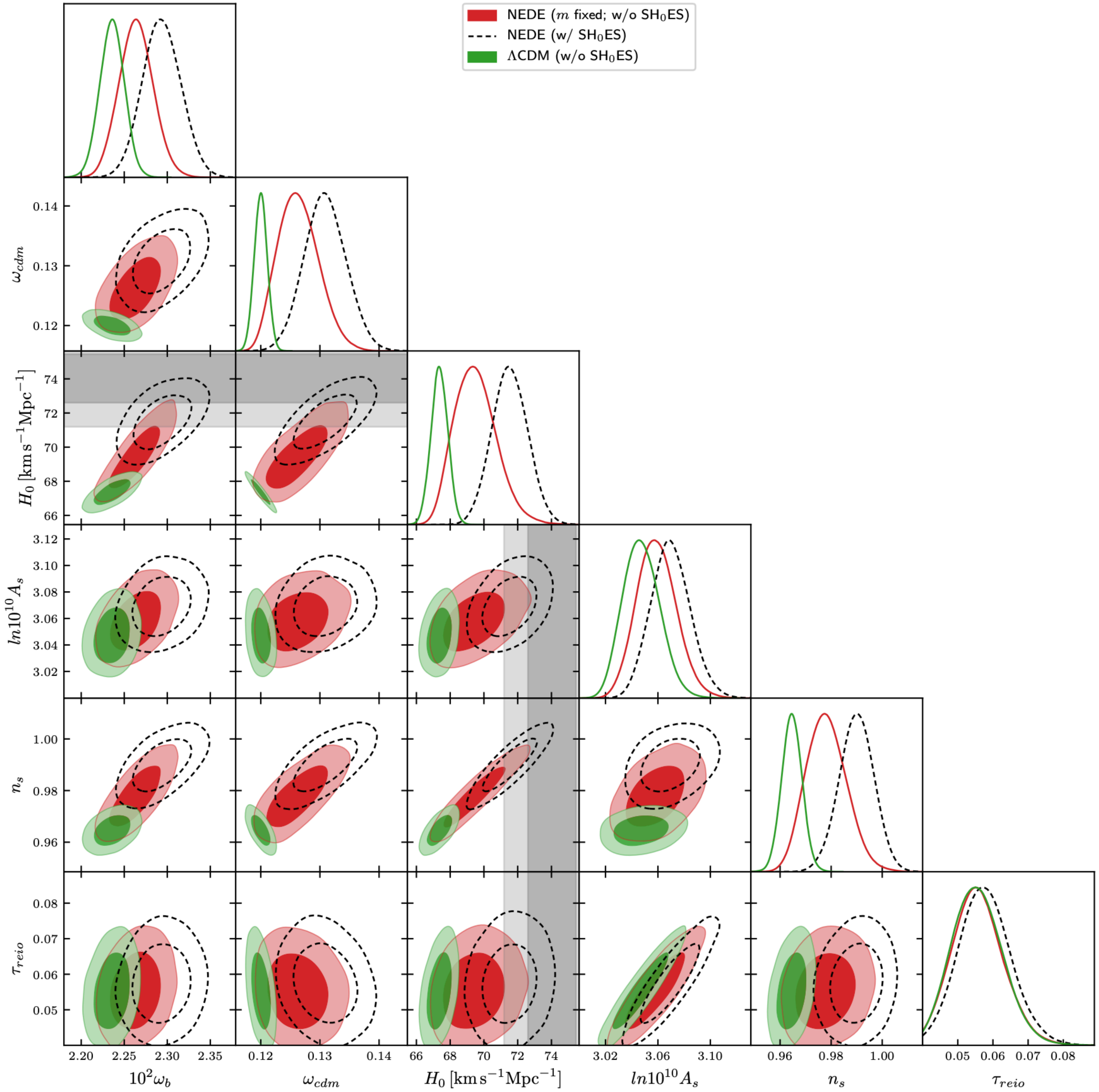
$\Delta\chi^2 \sim -16$

- Cosmological parameter extraction

4σ evidence for NEDE



Results



NEDE (m fixed; w/o SH$_0$ES)
NEDE (w/ SH$_0$ES)
ΛCDM (w/o SH$_0$ES)
ω_{cdm}
0.14
0.13
0.12
$H_0\,[\mathrm{km\,s^{-1}Mpc^{-1}}]$
74
72
70
68
66
$ln10^{10}A_s$
3.12
3.10
3.08
3.06
3.04
3.02
n_s
1.00
0.98
0.96
τ_{reio}
0.08
0.07
0.06
0.05
2.20
2.25
2.30
2.35
$10^2\omega_b$
0.12
0.13
0.14
ω_{cdm}
66
68
70
72
74
$H_0\,[\mathrm{km\,s^{-1}Mpc^{-1}}]$
3.02
3.06
3.10
$ln10^{10}A_s$
0.96
0.98
1.00
n_s
0.05
0.06
0.07
0.08
τ_{reio}

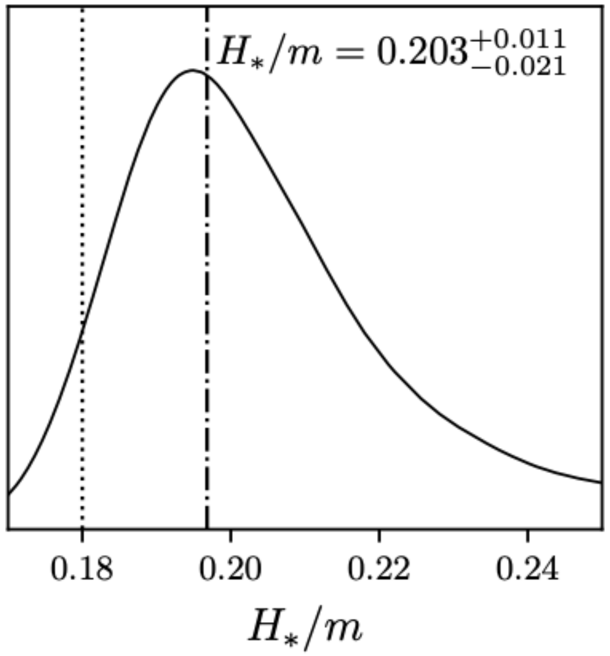
Verification of trigger mechanism

- NEDE theory predicts:

$$0.18 < H_*/m < 0.21$$

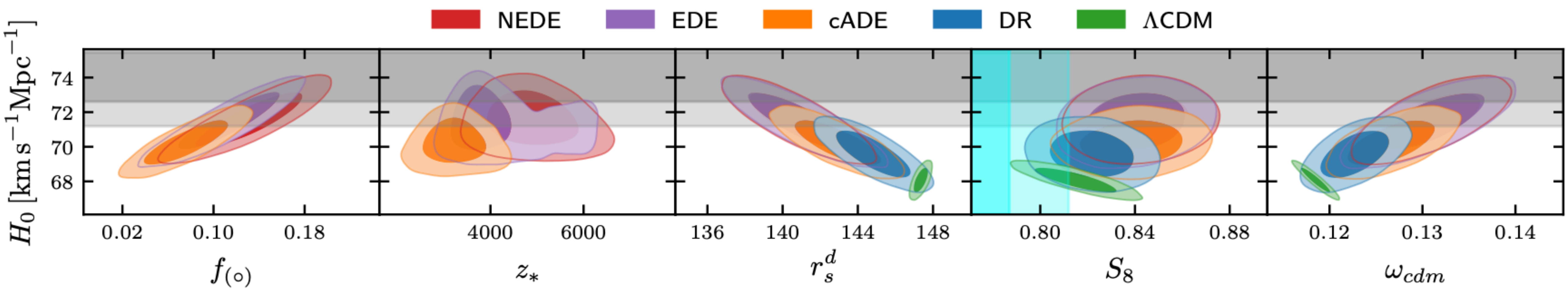
- When we fit the trigger as a free parameter, data gives

$$H_*/m = 0.203^{+0.011}_{-0.021}$$

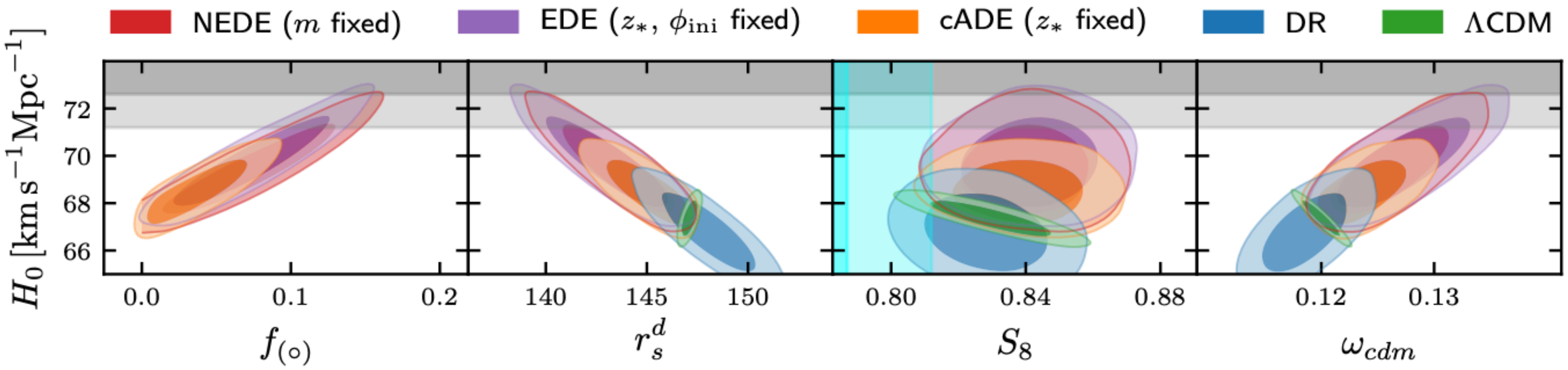


➡ Non-trivial verification of NEDE first order trigger mechanism!

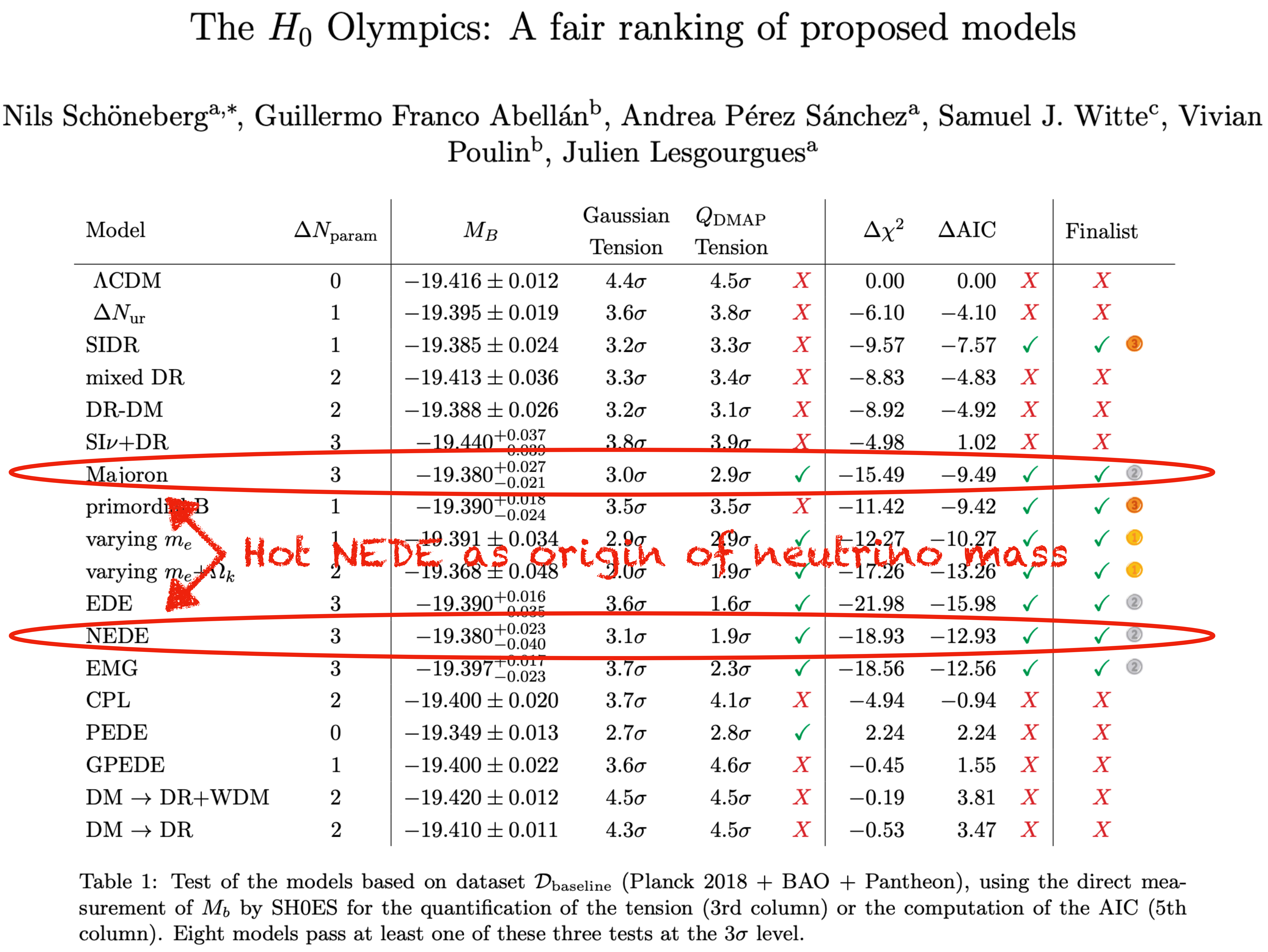
Comparison of models



(a) Combined analysis with $\mathrm{SH_0ES}$



(b) Combined analysis without $\mathrm{SH_0ES}$



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], 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	✗	✗	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	−6.10	−4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	−9.57	−7.57	✓	✓	③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	−8.83	−4.83	✗	✗	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	−8.92	−4.92	✗	✗	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	−4.98	1.02	✗	✗	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	−15.49	−9.49	✓	✓	②
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	−11.42	−9.42	✓	✓	③
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	−12.27	−10.27	✓	✓	①
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	−17.26	−13.26	✓	✓	①
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	−21.98	−15.98	✓	✓	②
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	−18.93	−12.93	✓	✓	②
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	−18.56	−12.56	✓	✓	②
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	−4.94	−0.94	✗	✗	
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗	
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	−0.45	1.55	✗	✗	
DM → DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	−0.19	3.81	✗	✗	
DM → DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	−0.53	3.47	✗	✗	

Hot NEDE as origin of neutrino mass

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

[arXiv:2107.10291]

Hot New Early Dark Energy

Hot New Early Dark Energy

- Known cosmological phase transitions (apart from end of inflation) are triggered by redshift of temperature.

➡Let us consider a thermal trigger of the NEDE phase transition.

Hot NEDE: Thermal trigger

Examples of thermal PTs:
Electroweak phase transitions
QCD phase transition
Recombination

Cold NEDE: Scalar field trigger

Example of cold PT:
End of inflation

Hot New Early Dark Energy

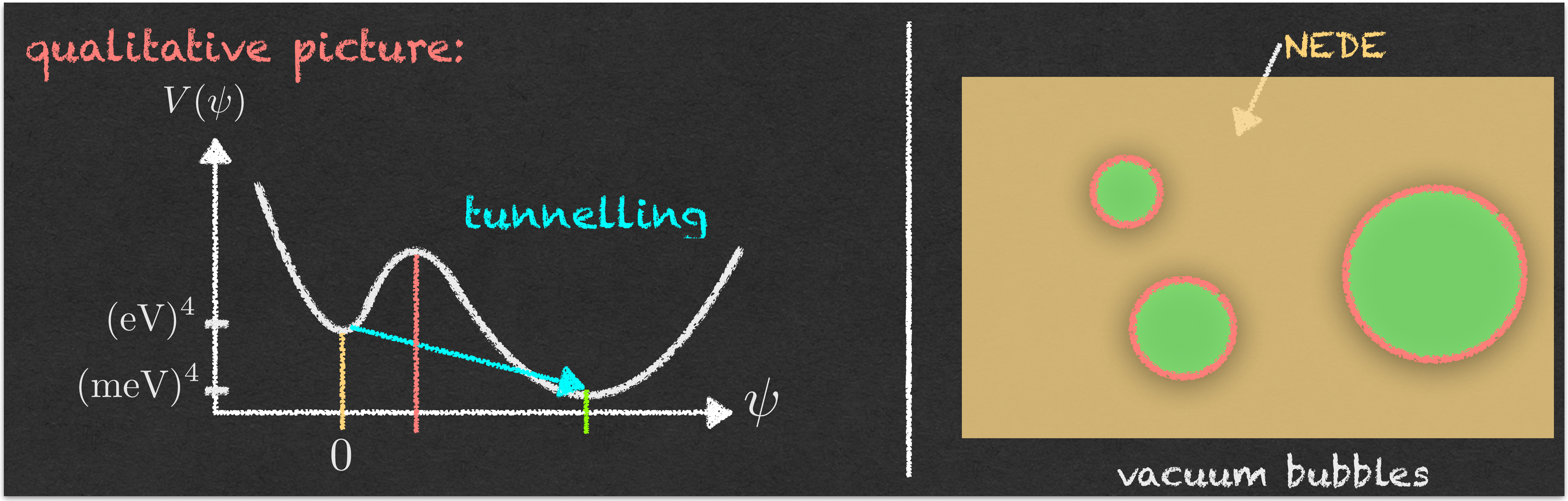
- The thermal trigger removes the need for an extra trigger mass scale.

➡Only mass scale is $\mathcal{O}$(eV) i.e. the neutrino mass scale

Is the Hubble tension a signature of how neutrinos got their mass?

Hot New Early Dark Energy

Again scalar field model w. first order phase transition



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

- Vacuum energy decays
- Free energy converted to anisotropic stress
- Anisotropic stress partially sources gravitational radiation
- Remaining anisotropic stress decays like a stiff fluid

Hot New Early Dark Energy

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

- The NEDE scalar field is charged under a dark sector gauge group

➡Potential will receive thermal corrections given by the dark sector temperature T_d

- The typical form of the effective finite temperature potential, as known also from studies of electroweak phase transition is

$$V(\psi;T_d) = D(T_d^2 - T_\circ^2)\psi^2 - ET_d\psi^3 + \frac{\lambda}{4}\psi^4 + V_0(T_d)$$

- In case of a dark *U(1)* gauge theory with gauge coupling g_{NEDE}

$$E \simeq g_{\text{NEDE}}^3/(4\pi),\, D \simeq g_{\text{NEDE}}^2/8$$

Hot New Early Dark Energy

- The usual simple form of the finite temperature potential

$$V(\psi;T_d) = D(T_d^2 - T_\circ^2)\psi^2 - ET_d\psi^3 + \frac{\lambda}{4}\psi^4 + V_0(T_d)$$

is only valid for

$$\gamma \equiv \frac{\lambda}{(4\pi E^4)^{1/3}} >> 1$$

- However, if the dark sector is dominated by vacuum energy and not radiation (low-temperature regime), this condition is not satisfied

➡ We need the more general form

$$V(\psi;T_d) = -DT_\circ^2\psi^2 + \frac{\lambda}{4}\psi^4 + 3T_d^4 K\left(\sqrt{8D}\psi/T_d\right)\mathrm{e}^{-\sqrt{8D}\psi/T_d} + V_0(T_d)$$

`[Niedermann, MSS; 2020]`

Hot New Early Dark Energy

Phenomenological d.o.f.

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

Decay time: z_*

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

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

New in Hot NEDE

Gives potential to also solve LSS tension

Microscopic d.o.f.

Parameter of dim. less potential: γ

Critical temp.: T_0

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

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

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

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

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

arXiv:2112.00759, 2112.00770 w. Florian Niedermann

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

[Buen-Abad, G. Marques-Tavares, and M. Schmaltz; 2015] [J. Lesgourgues, G. Marques-Tavares, and M. Schmaltz; 2015]

Hot NEDE and neutrino mass

- The NEDE scalar field, ψ, acquires a v.e.v. ~ $\mathcal{O}$(eV) in the P.T.

➡ May give mass to neutrinos

- Inverse seesaw can explain the observed neutrino mass and oscillation patterns and involves two new scales; a TeV and an eV scales

[A. Abada and M. Lucente; 2014]

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

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

active left-handed right-handed sterile

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

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

$n > \mathcal{O}(\text{TeV})$ **New UV scale**

$\text{eV} < m_s < \text{GeV}$ **New IR scale**

We assume dark symmetry group of form:

GD x GNEDE

Hot NEDE and neutrino mass

- We assume the dark symmetry group of the form: $G_D \times G_{NEDE}$

1. G_D is broken at new UV scale $n \geq 1$ TeV by new dark Higgs field

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

2. Subsequently, we have the EW breaking leading to

$$d = g_H v_H/\sqrt{2} \qquad v_H = 246\mathrm{GeV}$$

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

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

➡Assume charge assignments to allow for the Yukawa couplings

$$\boxed{\mathcal{L}_\mathrm{Y} = -g_\Phi \Phi \overline{\nu_R} \nu_s - \frac{g_s}{\sqrt{2}} \Psi \overline{\nu_s^c} \nu_s + g_H \overline{\nu_R} L^T \epsilon H + \mathrm{h.c.}}$$

- We can also relate sterile mass to effective NEDE parameters

$$m_s \simeq (1.0\,\mathrm{eV}) \times \frac{1}{\gamma^{1/4}} \frac{g_s}{g_\mathrm{NEDE}} \left[1 - \frac{\delta^*_\mathrm{eff}}{\pi\gamma}\right]^{1/2} \left[\frac{f_\mathrm{NEDE}/(1 - f_\mathrm{NEDE})}{0.1}\right]^{1/4} \left[\frac{1 + z_*}{5000}\right]$$

Hot NEDE and neutrino mass

Minimal example:

- As a concrete example, we take the Dark Electroweak (DEW) group broken to Dark Electromagnetism (DEM)

$$\mathrm{G_D} = \mathrm{SU(2)_D} \times \mathrm{U(1)_{Y_D}} \to \mathrm{U(1)_{DEM}}$$

- The NEDE P.T. is the breaking of lepton number

$$\mathrm{G_{NEDE}} = \mathrm{U(1)_L}$$

Majoron, η, is the massless Goldstone of the broken U(1)$_L$

Small explicit breaking gives mass – see next…

➡ We can write down the Lagrangian

Secret interaction to make eV sterile compatible with cosmology

[Hannestad, Hansen, Tram; '13]

$$\mathcal{L}_{\mathrm{Y}} = -g_\Phi \Phi \overline{\nu_R} \nu_s \boxed{- \frac{g_s}{\sqrt{2}} \Psi \overline{\nu_s^c} \nu_s} + g_H \overline{\nu_R} L^T \epsilon H + \mathrm{h.c.}$$

$$\Phi = (\Phi_+, \Phi_0)^T \qquad \Psi = \begin{pmatrix} \frac{1}{\sqrt{2}}(\Psi_0 + \Psi_{++}) \\ -\frac{\mathrm{i}}{\sqrt{2}}(\Psi_0 - \Psi_{++}) \\ \Psi_+ \end{pmatrix} \qquad S = (\nu_s, S_-)^T$$

Hot NEDE and neutrino mass

	S	ν_R	Φ	Ψ	H	χ	L
$\mathrm{SU}(2)_{\mathrm{D}}$	**2**	**1**	**2**	**3**	**1**	**2**	**1**
$\mathrm{U}(1)_{\mathrm{Y_D}}$	-1	0	1	2	0	$Y_{\mathrm{D},\chi}$	0
$\mathrm{U}(1)_{\mathrm{L}}$	1	1	0	-2	0	1	1

Small explicit lepton no. violation giving mass to majoron (Goldstone of broken $U(1)_L$

$$\Delta = \Psi \cdot \tau$$

$$V(\Psi,\Phi) = a\Phi^\dagger\Phi + c\left(\Phi^\dagger\Phi\right)^2 - \frac{\mu^2}{2}\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda}{4}\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2$$

$$+\frac{e-h}{2}\Phi^\dagger\Phi\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + h\Phi^\dagger\Delta^\dagger\Delta\Phi + \frac{f}{4}\mathrm{Tr}\left(\Delta^\dagger\Delta^\dagger\right)\mathrm{Tr}\left(\Delta\Delta\right) - \bar{\epsilon}\left(\Phi^\dagger\Delta\epsilon\Phi^* + \mathrm{h.c.}\right)$$

Vacuum condition:

$$a + cv_\Phi^2 + \frac{1}{2}\left(e-h\right)v_\Psi^2 = 0$$

$$-\mu^2 + \lambda v_\Psi^2 + \frac{1}{2}\left(e-h\right)v_\Phi^2 = 0$$

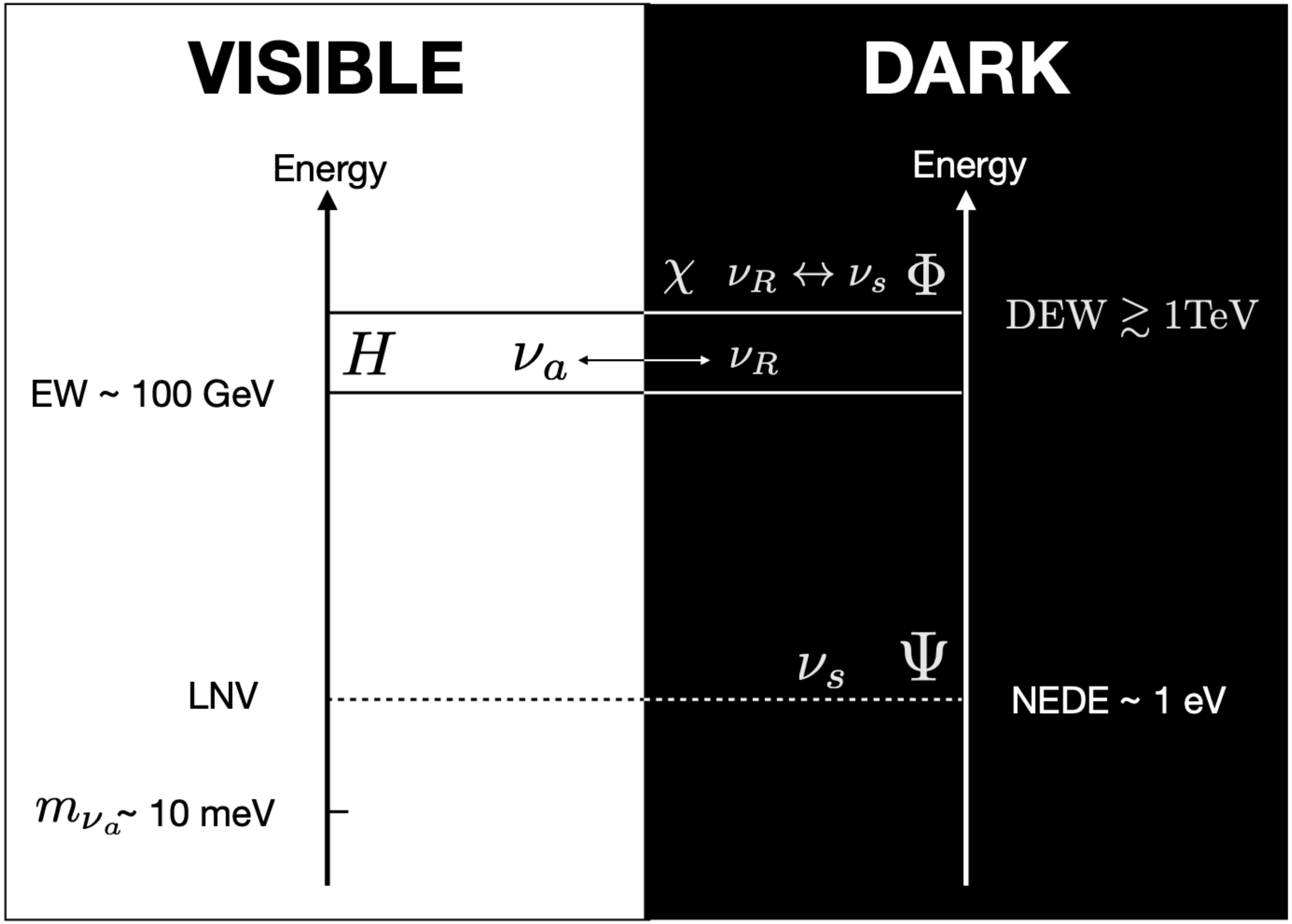
$$v_\Psi \ll v_\Phi \quad \Rightarrow \quad e, h \lesssim \lambda v_\Psi^2/v_\Phi^2 \ll 1$$

Technically natural if $g_d^2 \lesssim \mu/v_\Phi$ and $g_d^4 \lesssim \lambda$

Thermal correction driven by *f*

$\Rightarrow$ Identify g_{NEDE} with *f*

Hot NEDE and neutrino mass



Hot NEDE and neutrino mass

- DEW contains 17 boson d.o.f.

- If they are all relativistic and in thermal equilibrium at T_d, this implies

$$\Delta N_{\text{eff}} = \tfrac{4}{7}(\tfrac{11}{4})^{\bar{4}/3} 17 \xi^4$$

- Known constraints gives

$$\Delta N_{\text{eff}} < 0.1 \qquad \Rightarrow \qquad \xi \lesssim 0.2$$

and

$$f_{\text{NEDE}} = 10\% \qquad \Rightarrow \qquad \gamma \lesssim 5 \times 10^{-3}$$

Strong supercooled regime

➡<u>We expect the phenomenology to close to Cold NEDE</u>

- The heaviest active neutrino mass is related to sterile mass by

$$m_3 = \mathcal{O}(m_s)\kappa^2 \qquad \kappa = \mathcal{O}(d)/\mathcal{O}(d) \lesssim 10^{-2}$$

➡ a sterile neutrino with super-eV mass is compatible with an eV temperature phase transition

Conclusions

- Hubble tension could be explained by a fast triggered phase transition in the dark sector.

- Hubble tension could be a signature of how neutrinos got their mass.

- Cold and Hot NEDE looks theoretically and phenomenologically promising with the potential of connecting many issues!

- Verification of cold NEDE trigger mech.

- Prediction of gravitational waves.

- Many things to do — simulate Hot NEDE, more detailed modeling of the percolation phase, generalizations, etc…

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

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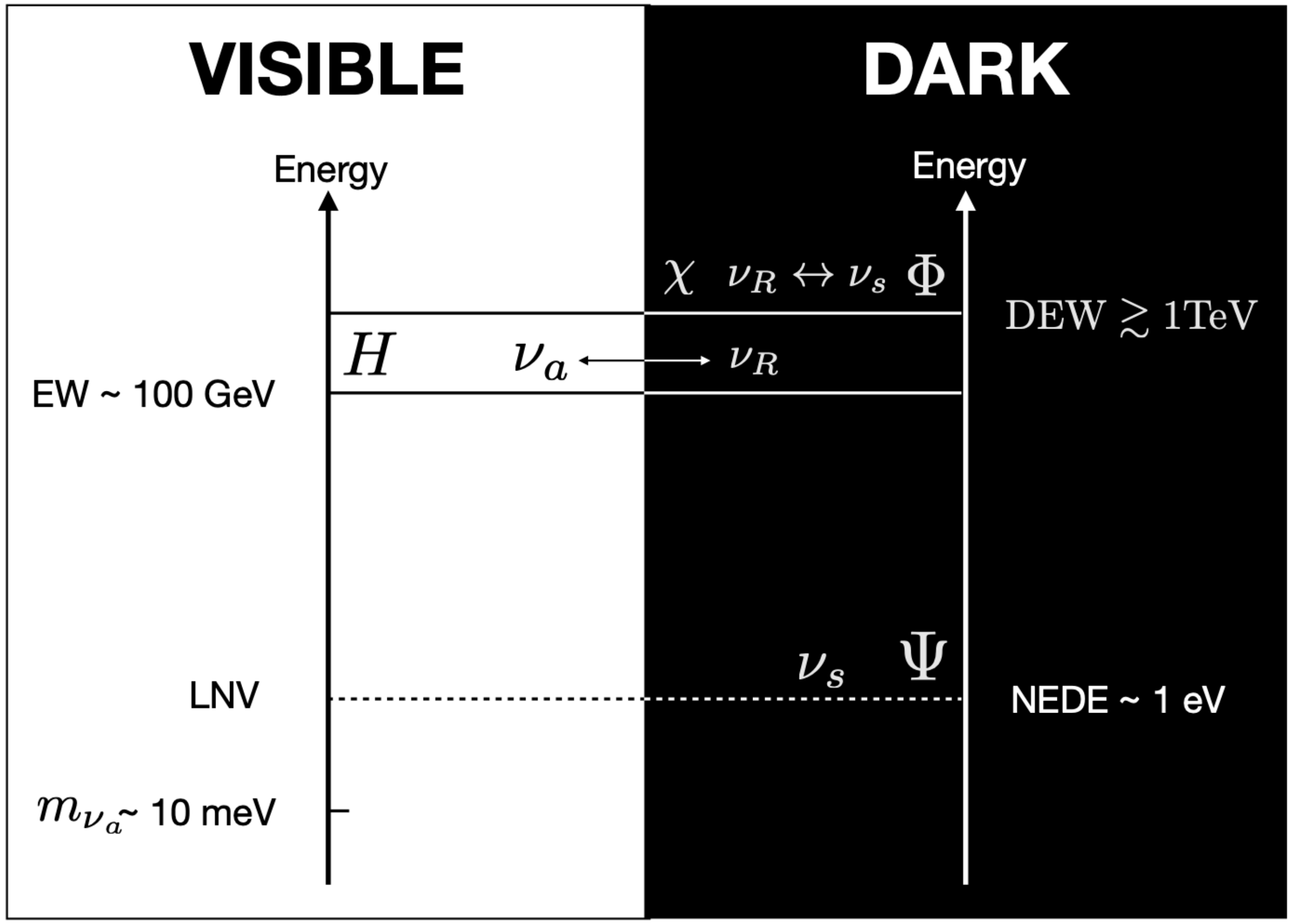

arXiv: 2112.00759, 2112.00770, 2009.00006, 2006.06686,1910.10739
w. Florian Niedermann