Resolving the Hubble Tension with New Early Dark Energy

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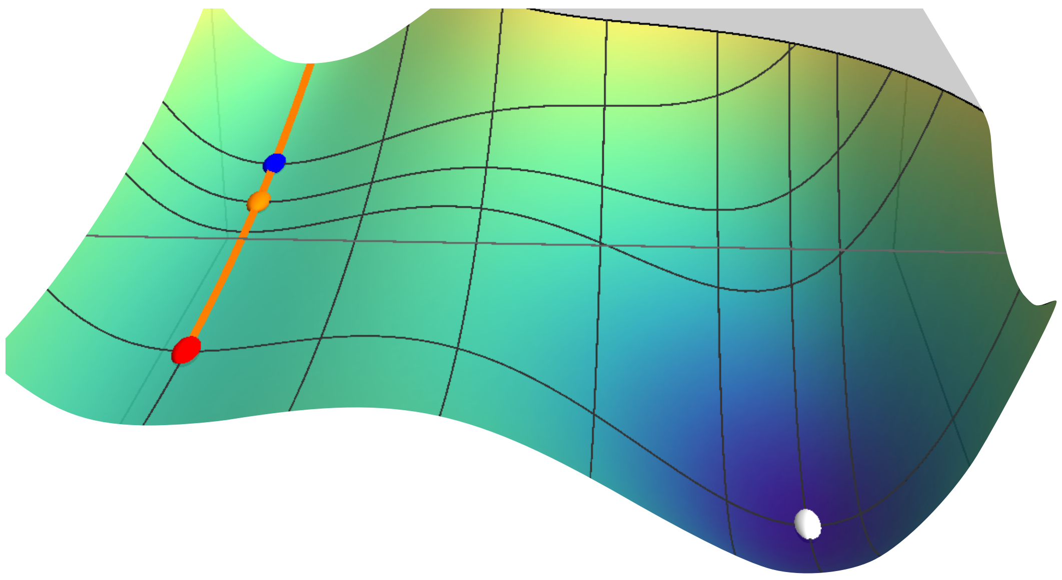
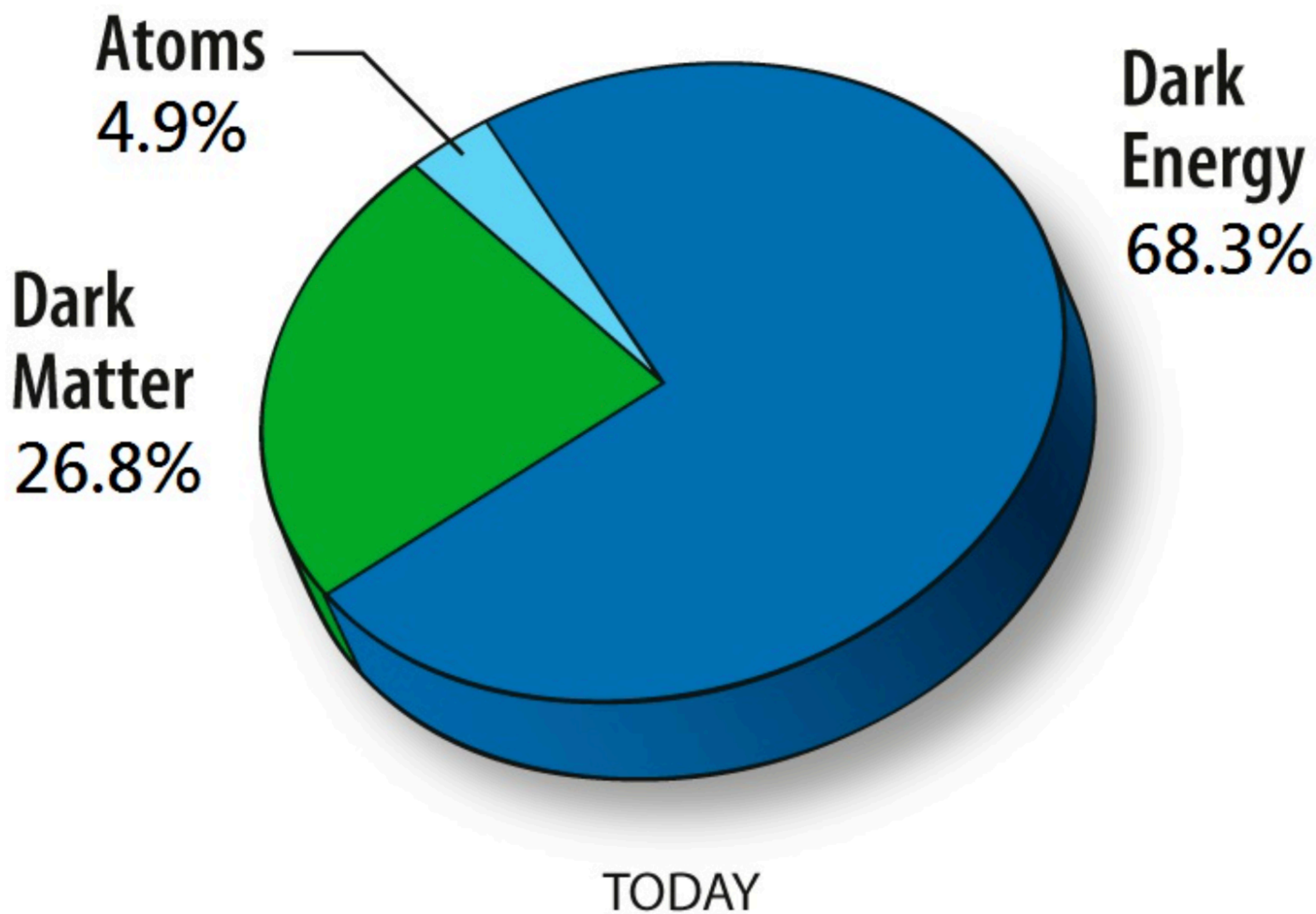


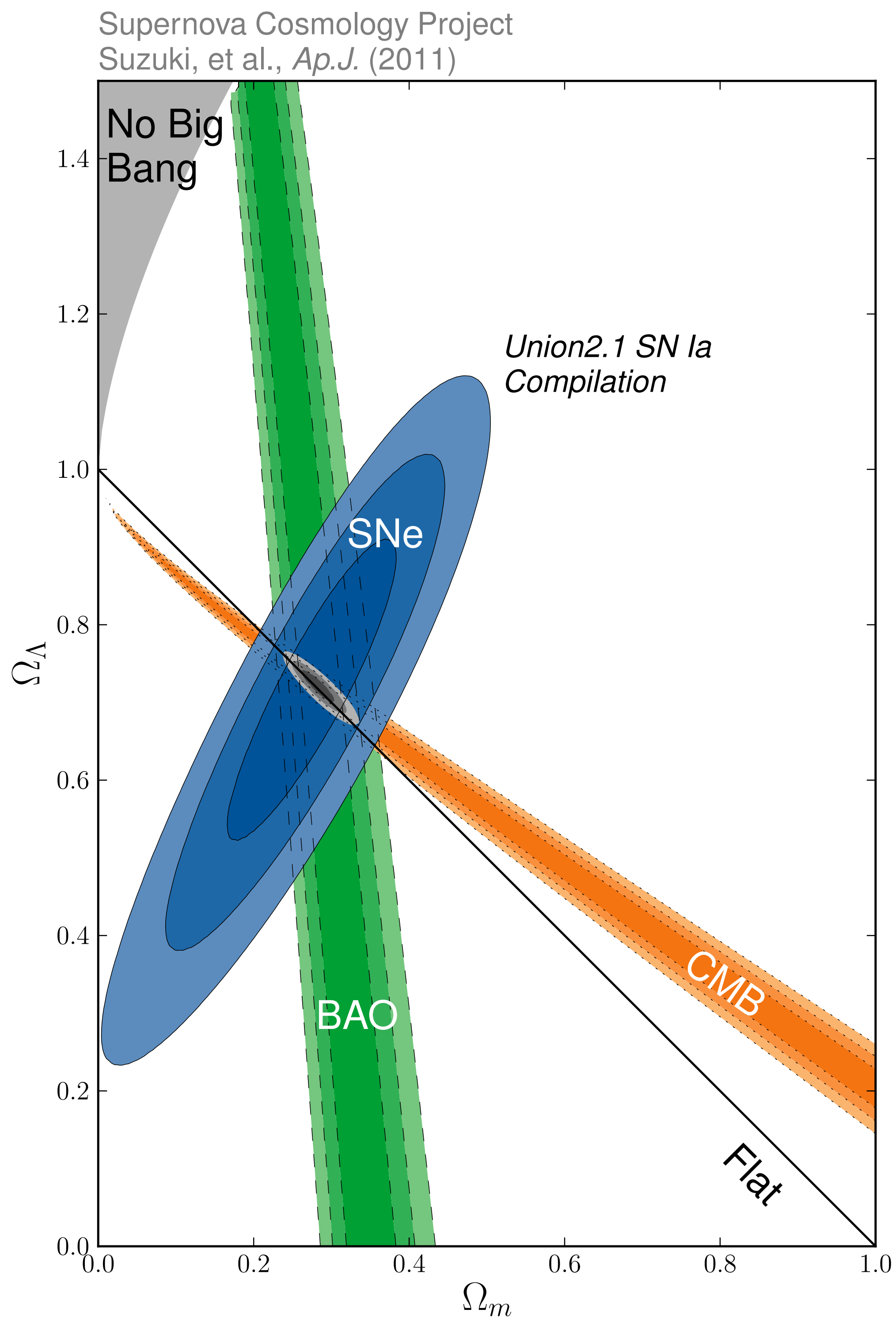
arXiv:1910.10739 w. Florian Niedermann
arXiv: 2006.06686 w. Florian Niedermann

ΛCDM



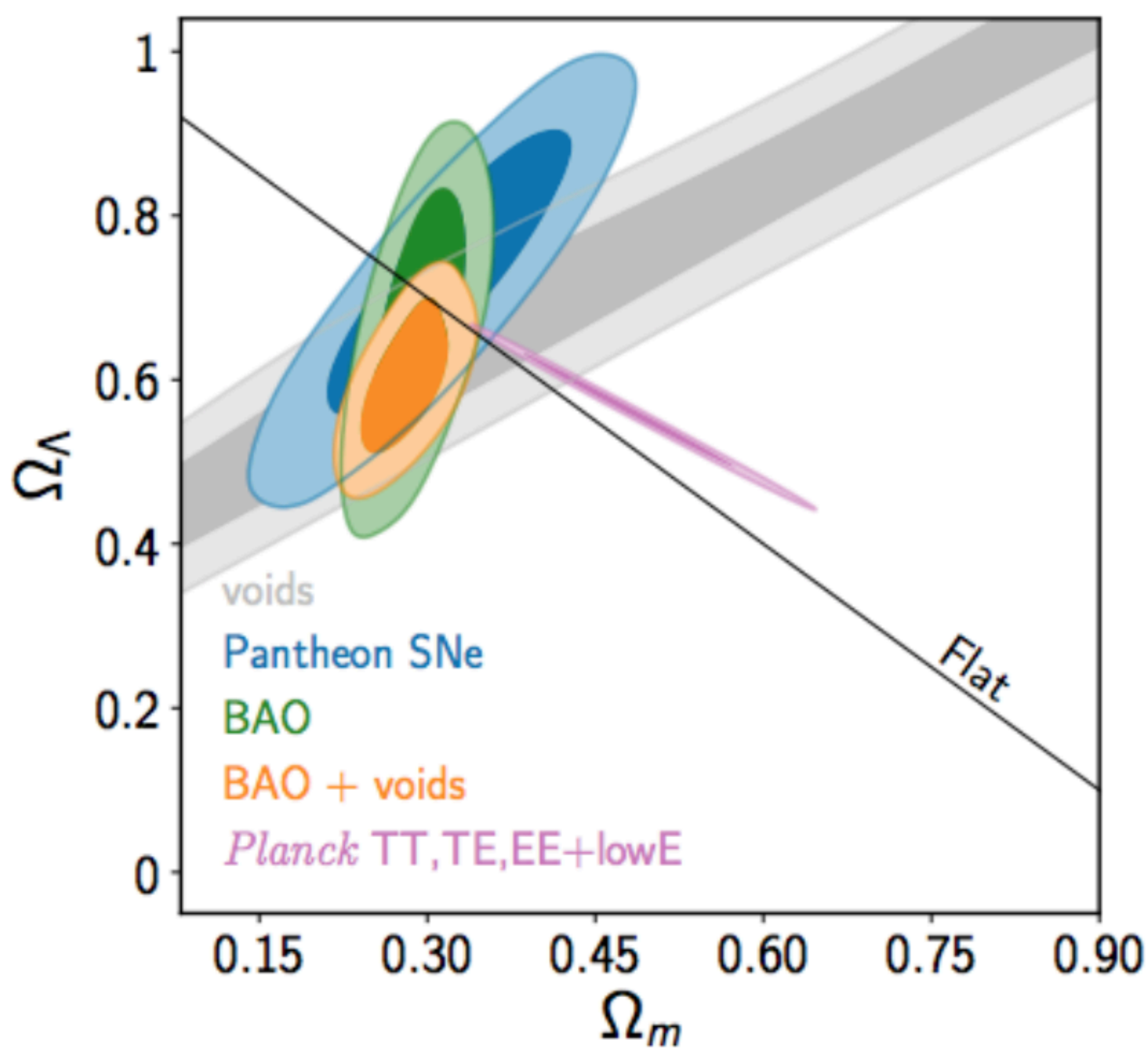
Concordance model

ΛCDM 10 years ago



Concordance model

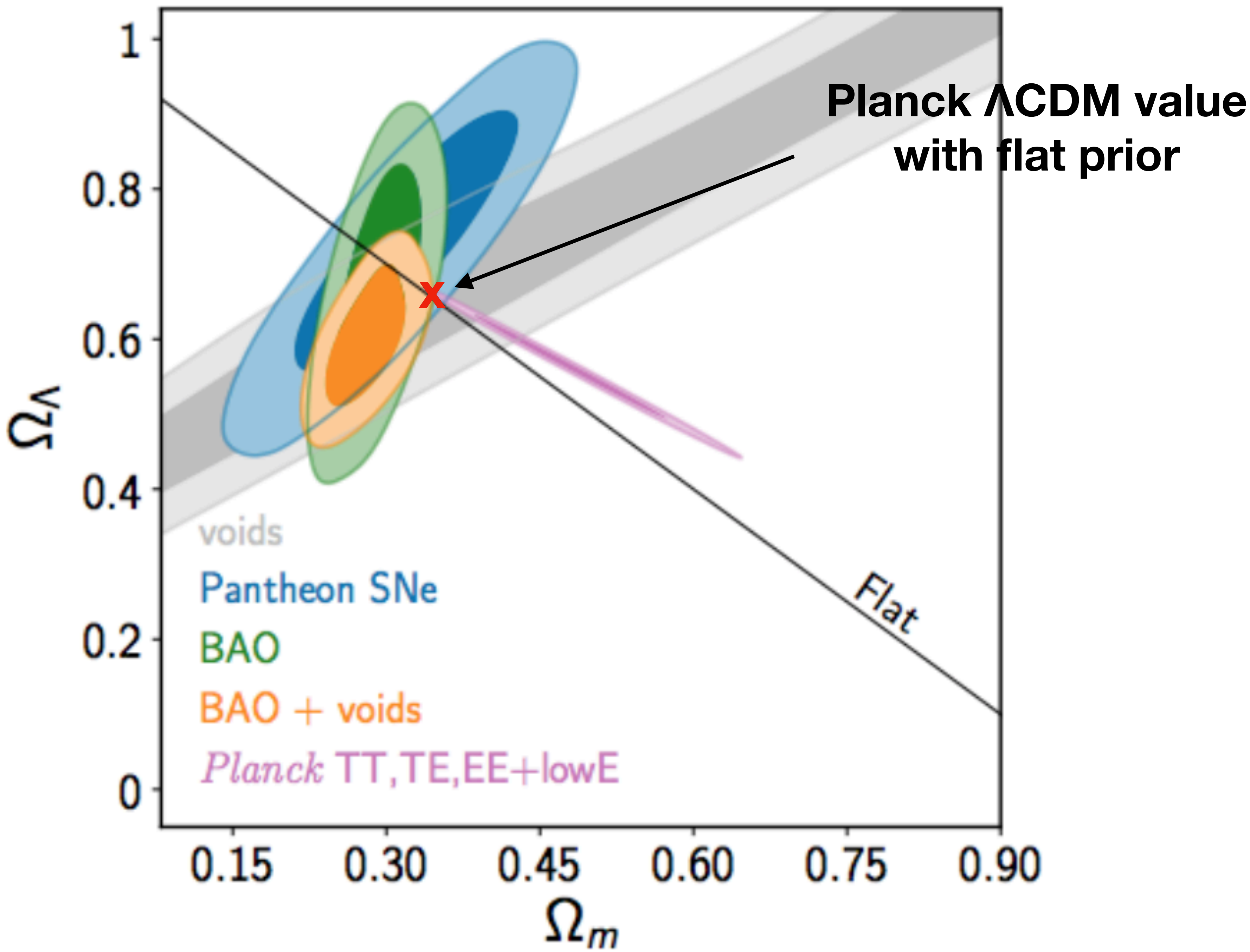
<u>ΛCDM 2020</u>



[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

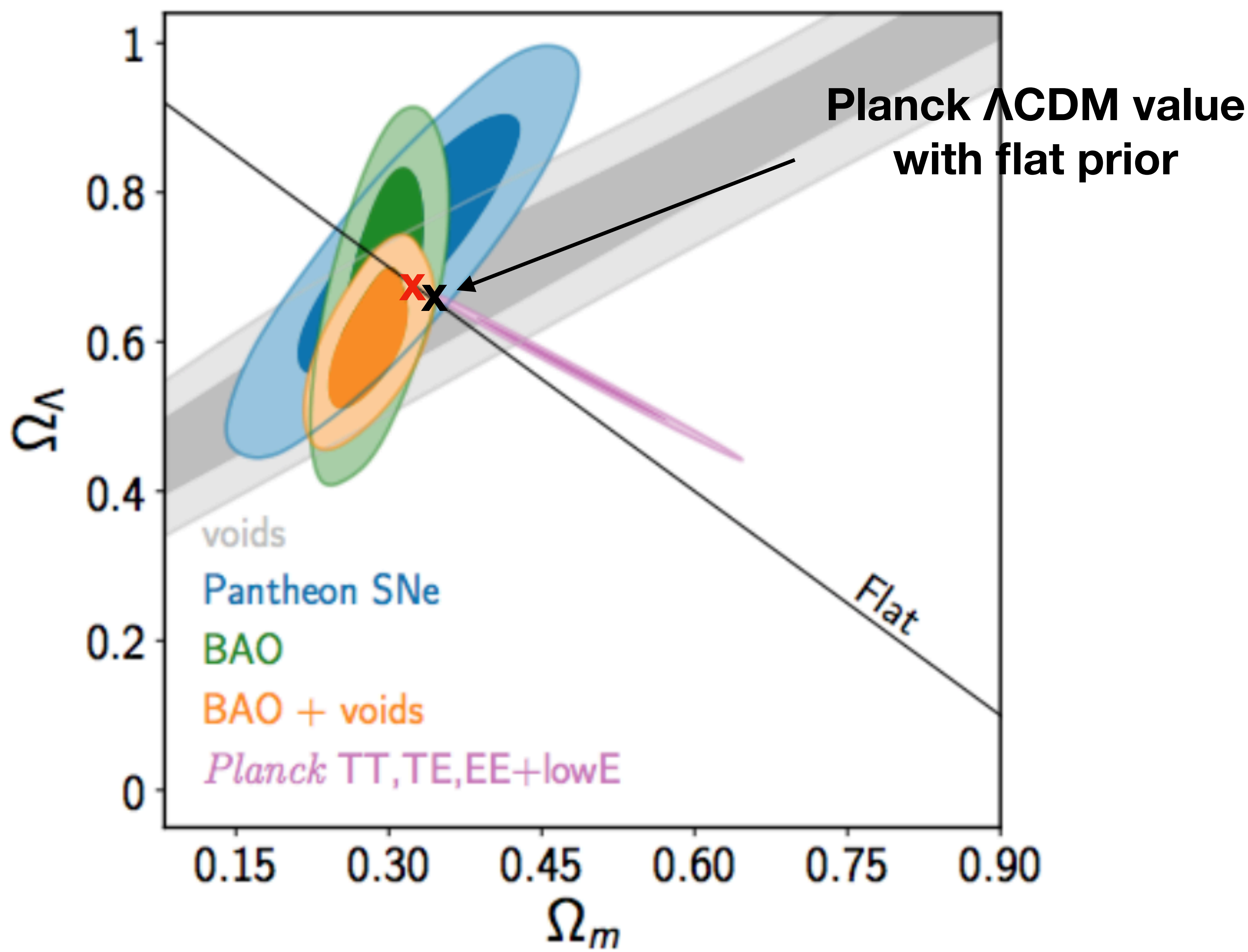
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

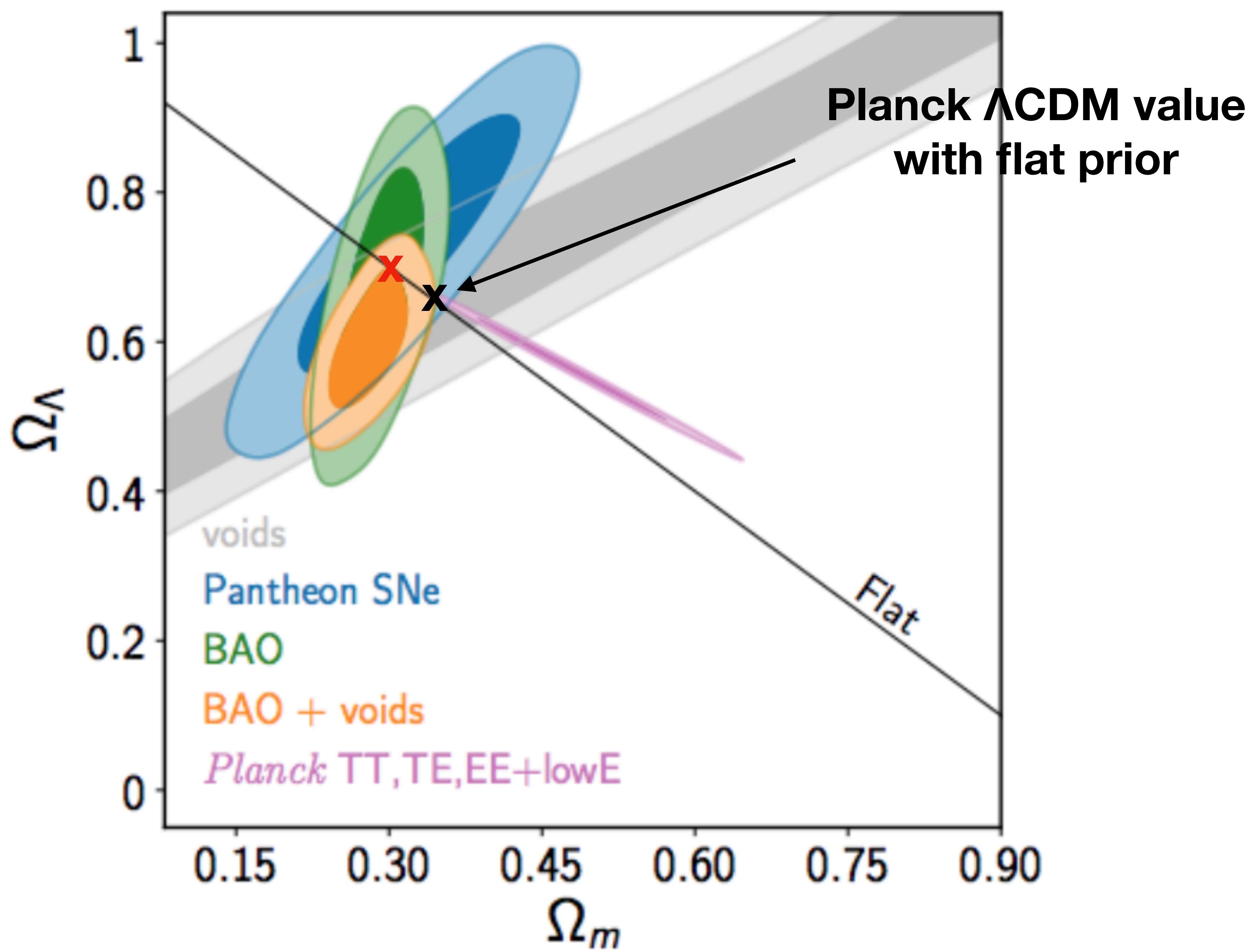
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

ΛCDM 2020

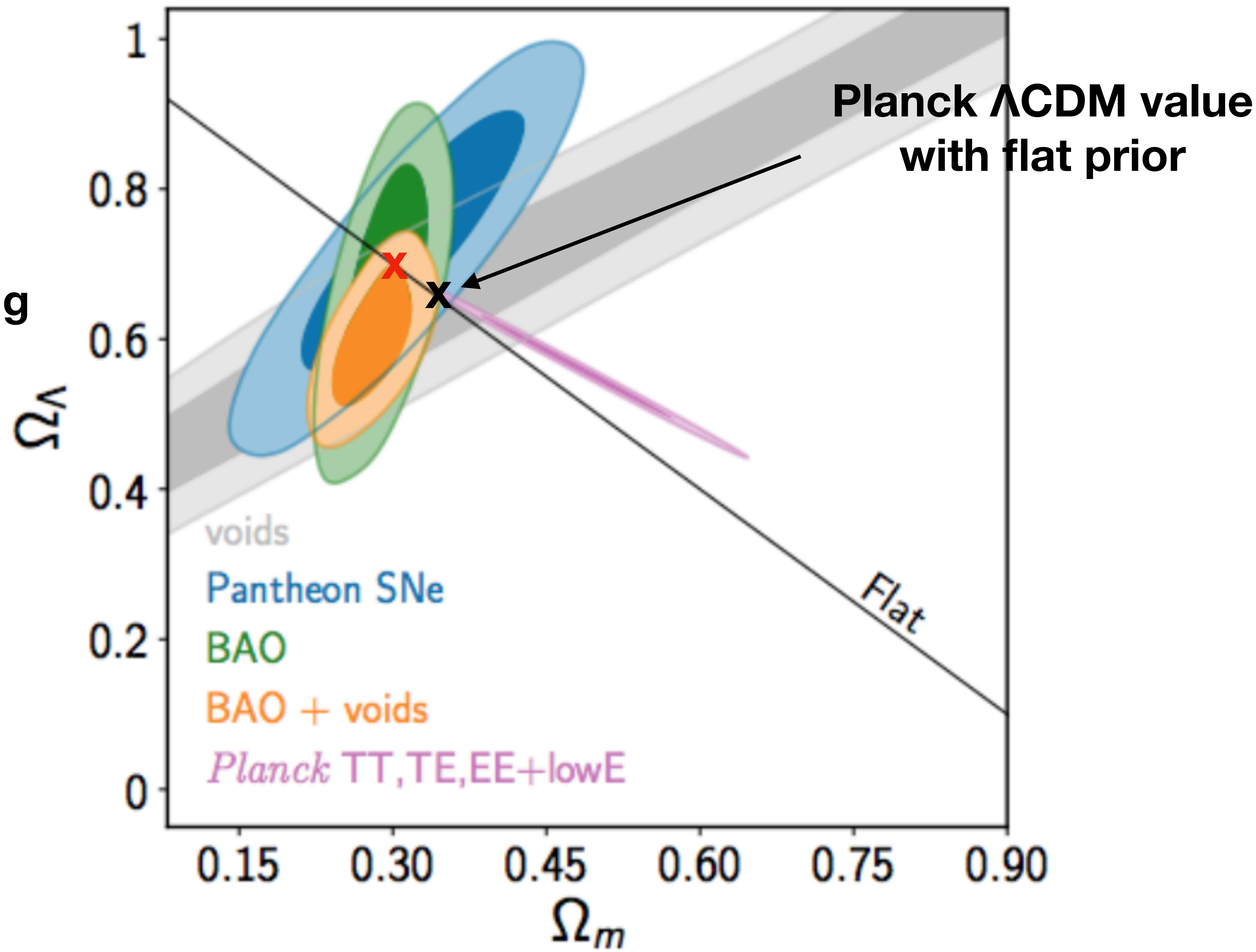


[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

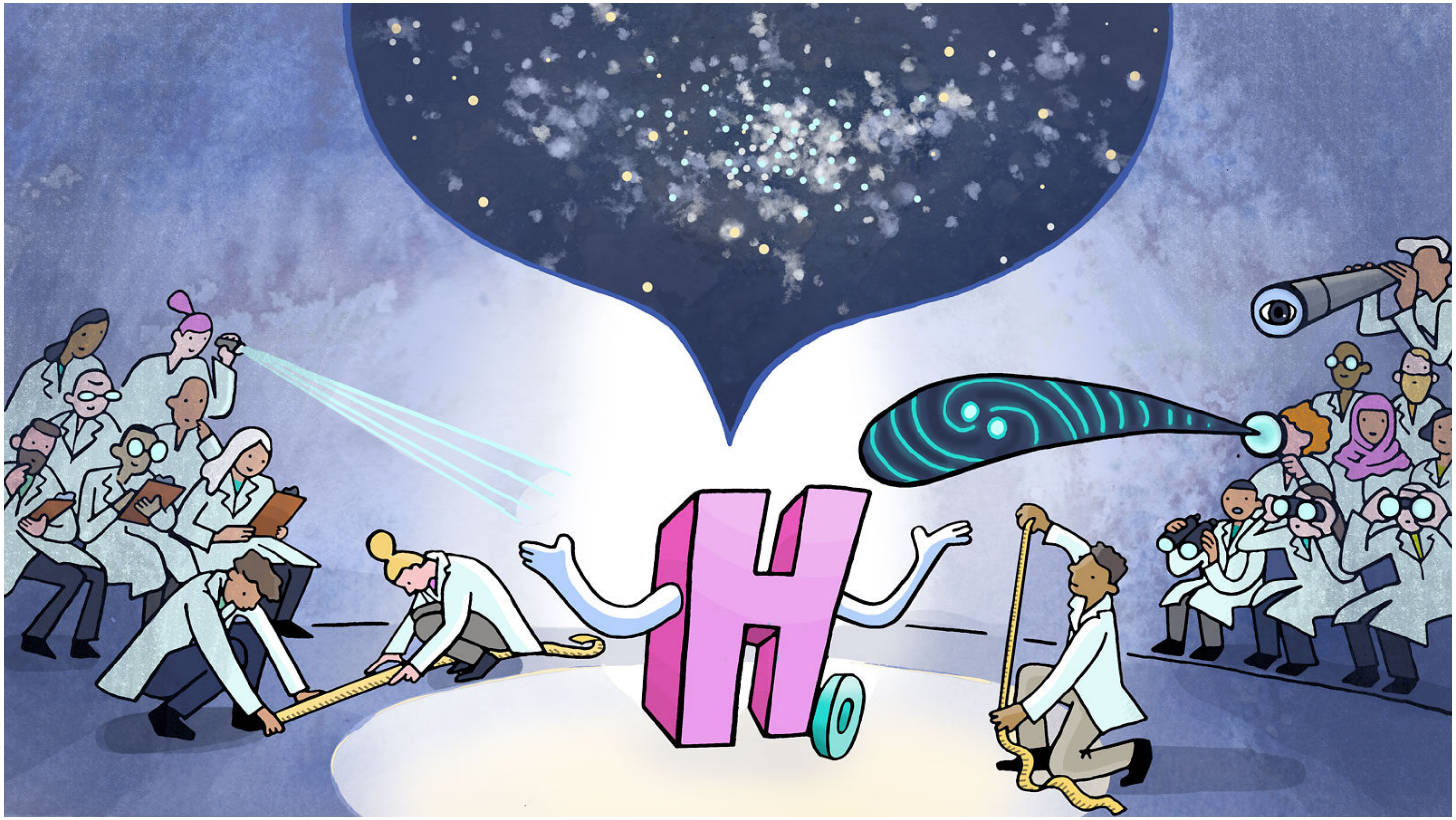
ΛCDM 2020

Resolving 2σ tension is not achieved by adding curvature but in models raising H_0 In CMB fits

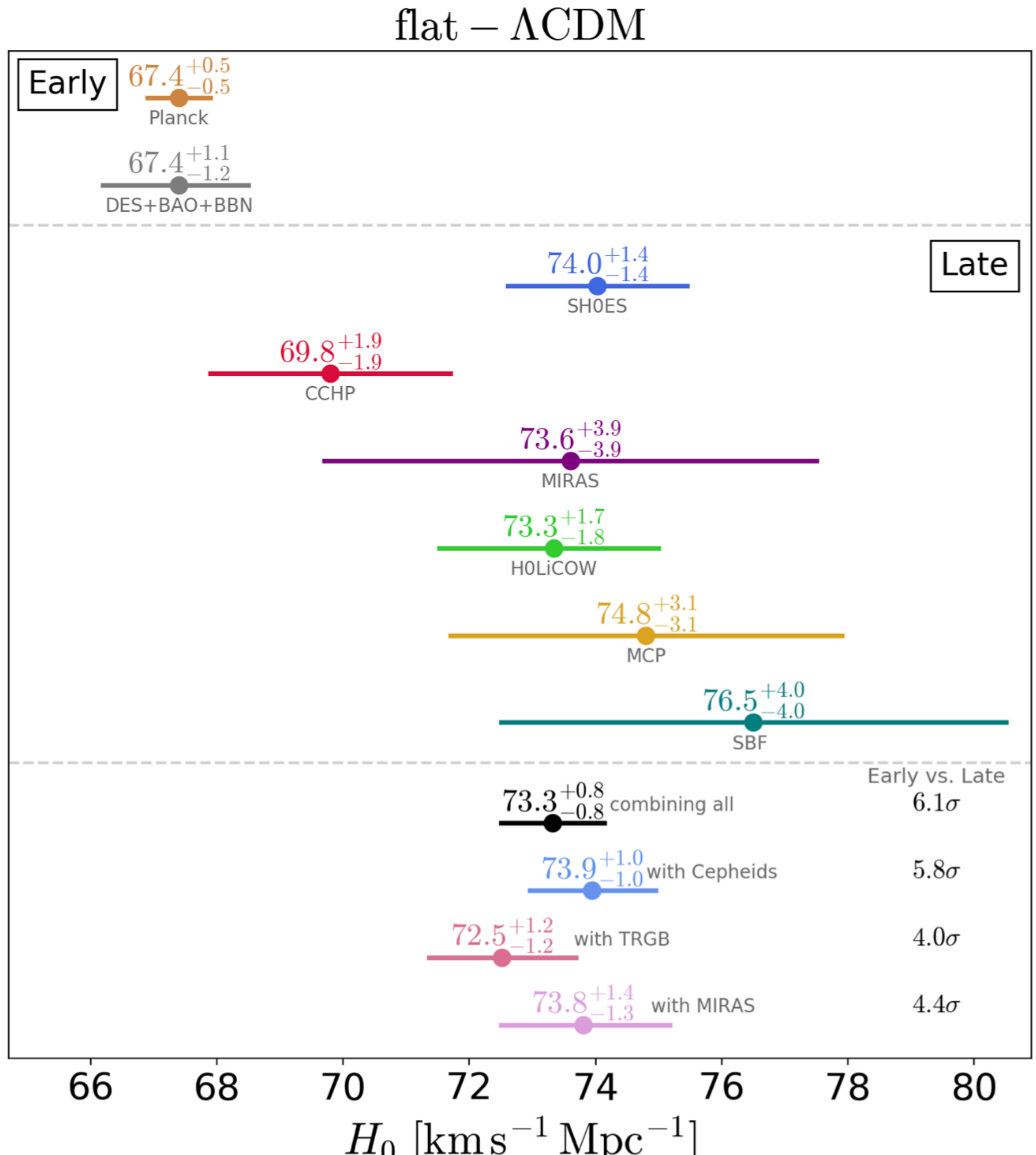


[Nadathur, Percival, Beutler, Winther; 2020]

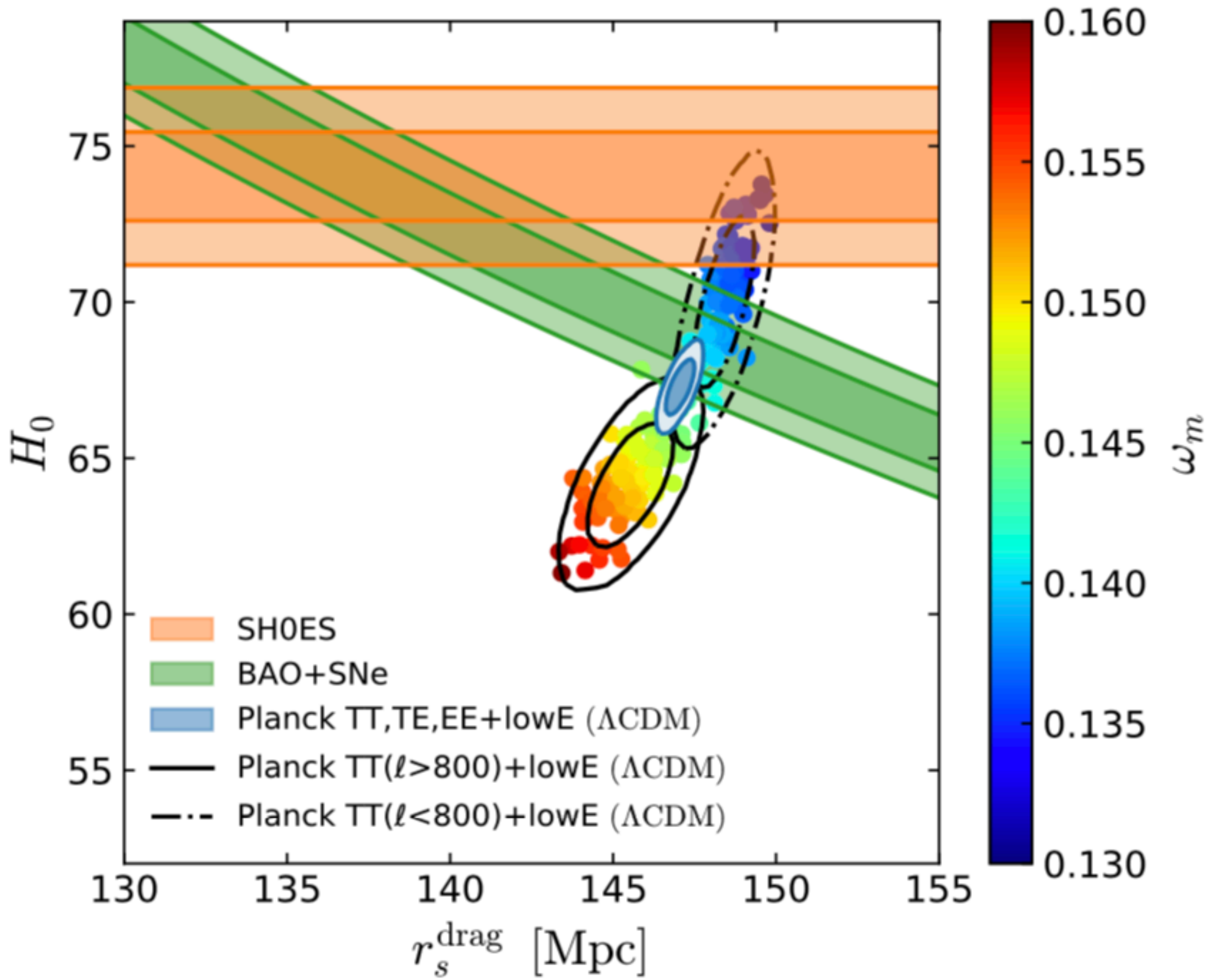
What about H_0?



[Illustration Symmetry mag. 2019]



[Verde, Treu, Riess; 2019]



[Knox, Miller; 2019]

The Hubble tension

SH$_0$ES:

[Riess et al. 2019]

$$H_0 = 74.03 \pm 1.42 \frac{\text{km}}{\text{s Mpc}}$$

Planck w. ΛCDM:

[Planck 2018]

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

4.4 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!

- Distance ladder applied by SH_0ES involves many assumptions and extrapolations
- H_0LiCoW makes disputed assumptions about the galaxy density profiles

➡ More data 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!

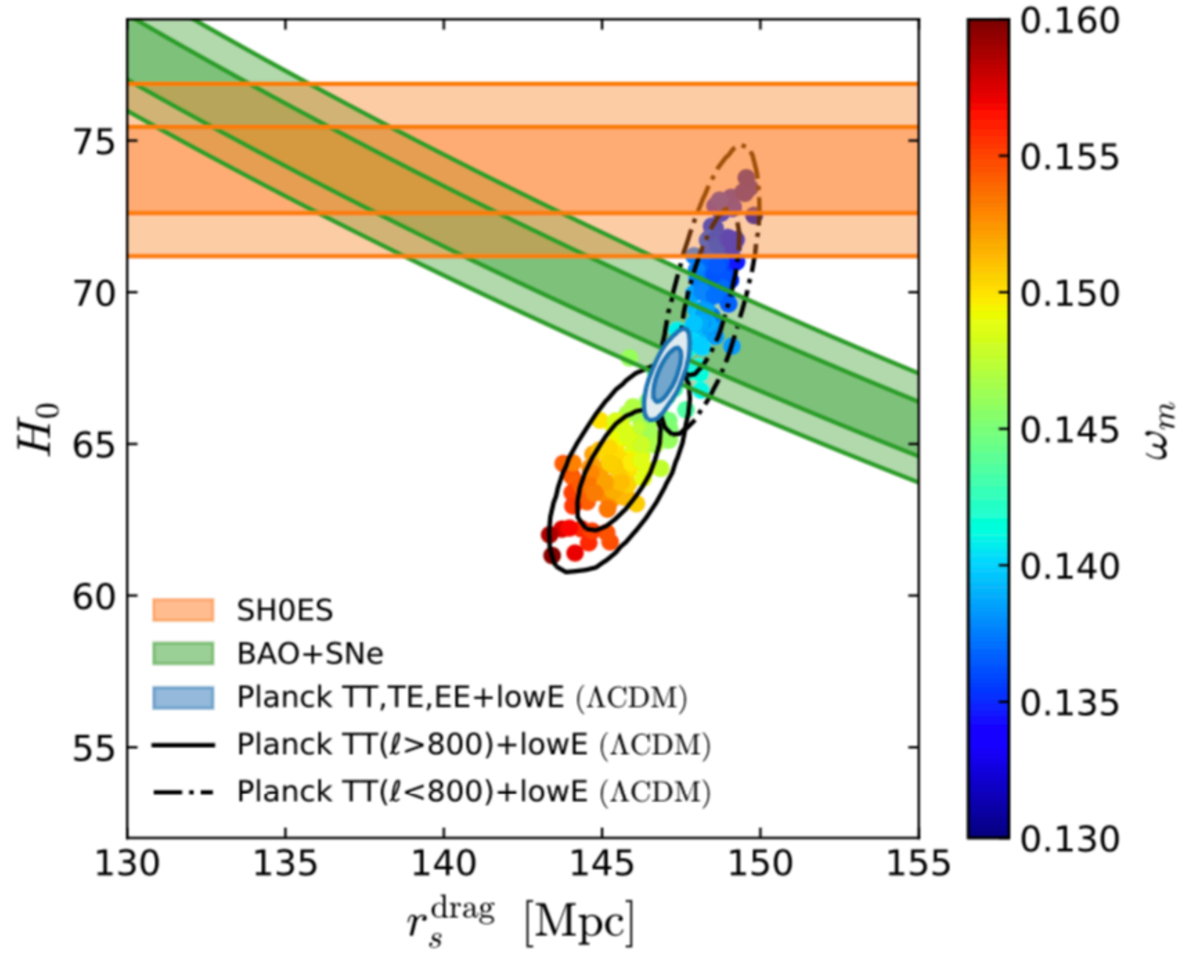
The Hubble tension

<u>Model-dependent statement:</u>

- Planck and SH_0ES incompatible

<u>Model-independent statement:</u>

- 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

The Hubble tension

<u>Model-dependent statement:</u>

- Planck and SH_0ES incompatible

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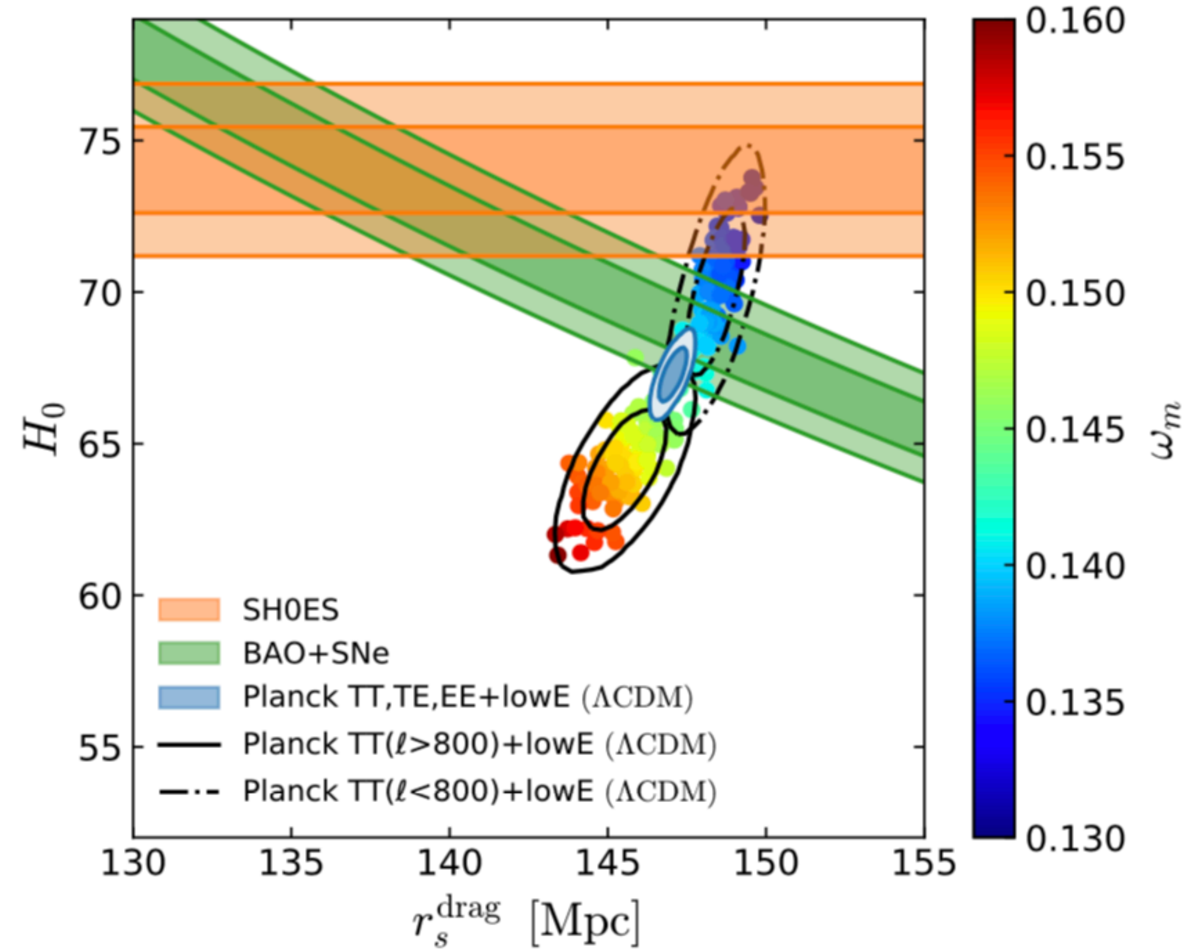

Where

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

depends on early time physics

Modification of *ΛCDM* raising H_0 while lowering r_s

The Hubble tension

<u>Model-dependent statement:</u>

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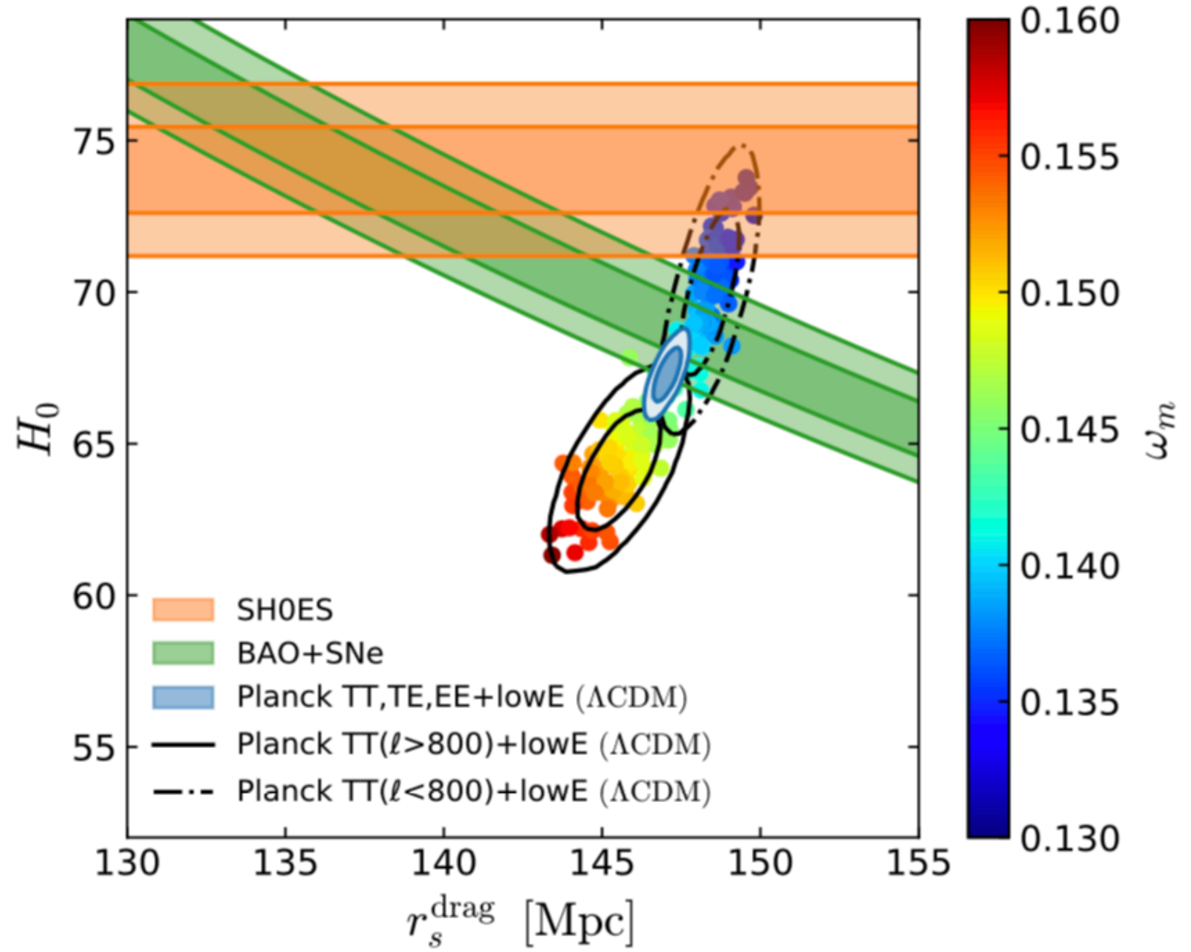


Where

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

depends on early time physics

→ Modification of *ΛCDM* raising H_0 while lowering r_s

→ Modification of *ΛCDM* just before recombination

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

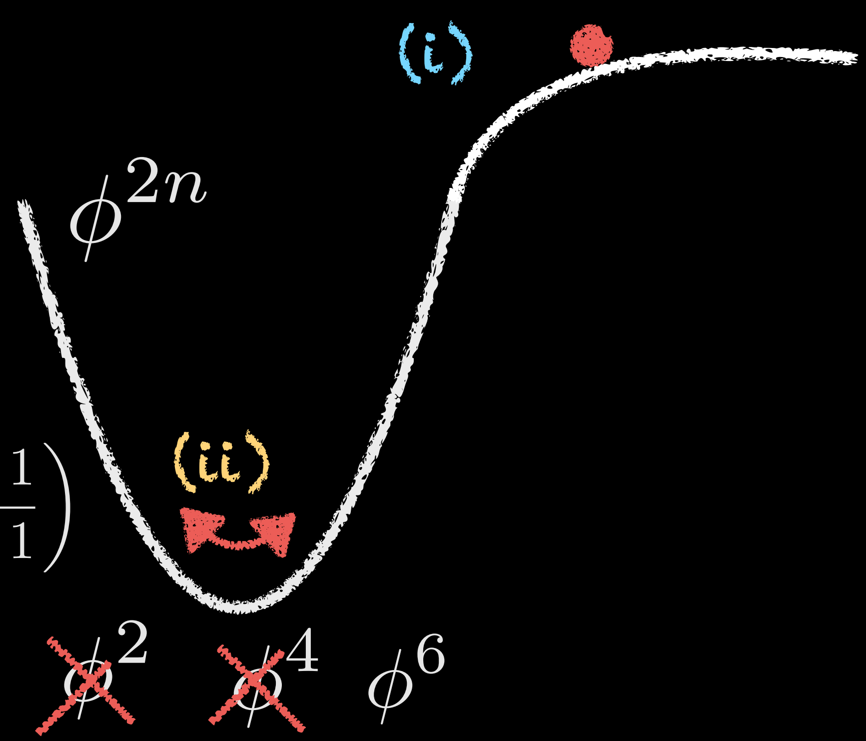
Scalar field model w. second order phase transition

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

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

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

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



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

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

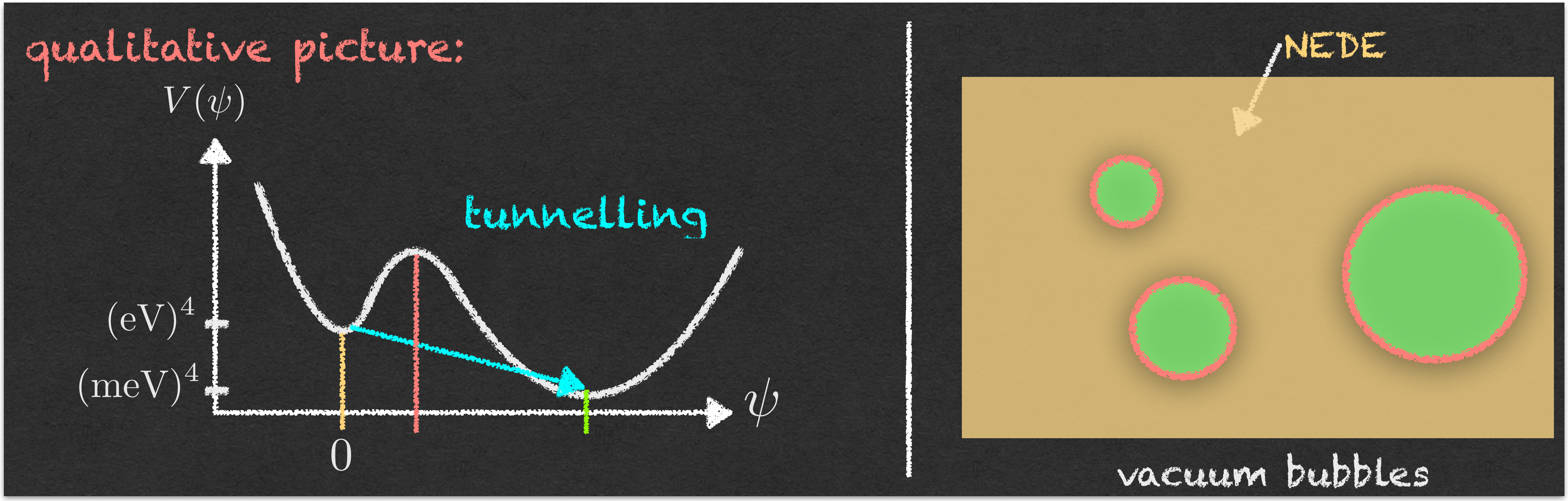
➡ How to make shallow anharmonic potentials natural…

[Kaloper, 2019]

New Early Dark Energy

Scalar field model w. first order phase transition

[Niedermann, MSS; 2019, 2020]



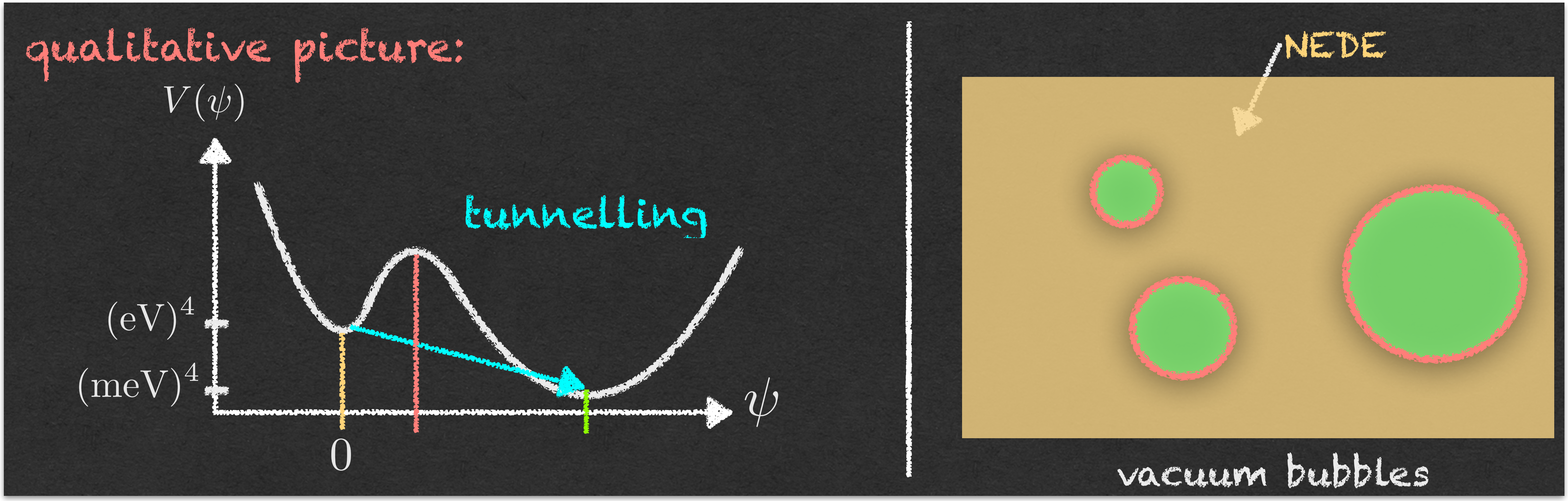
$$w = -1 \qquad \rightarrow \qquad 1/3 < w < 1$$

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

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.

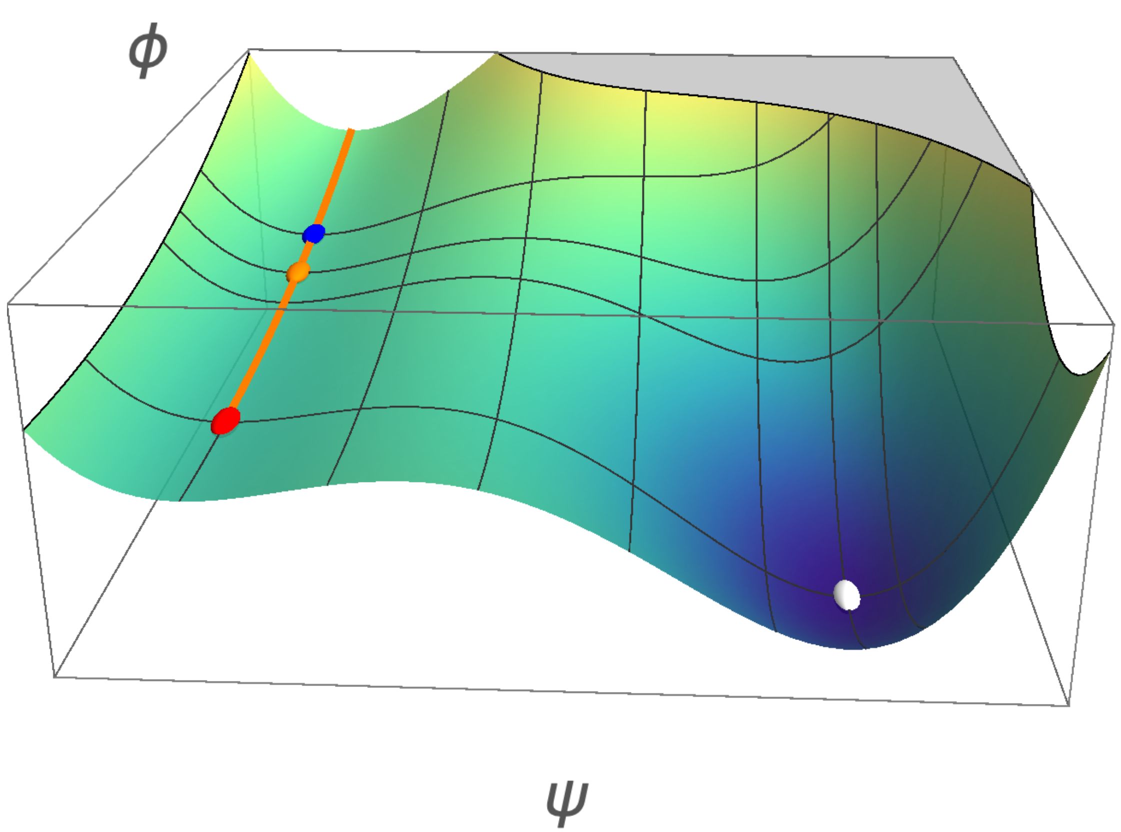
➡ Introduce a trigger field for the decay

field theory model: $\alpha, \beta, \lambda = \mathcal{O}(1)$

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

hierarchy: $M \sim \text{eV} \gg m \sim 10^{-27}\text{eV}$ 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

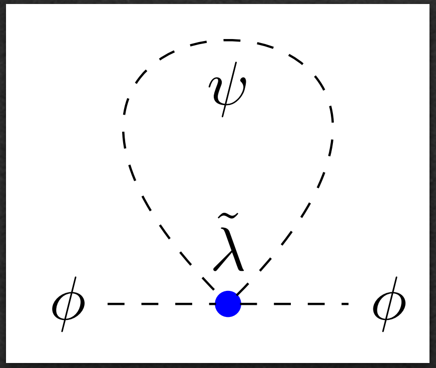
(iv) orange dot: $\Gamma = 0, \ \dot{\Gamma} > 0$

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

Technical Naturalness

- Radiative stability as low energy EFT (valid up to scale M)

$\delta m^2 =$



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

radiative stability → $\tilde{\lambda} \lesssim 10^3 \dfrac{m^2}{\beta M^2} \ll 1\,.$

Bubble Percolation

- The tunneling rate is given by

$$\Gamma = M^4 \exp(-S_E)$$

- To compute Euclidian action, we introduce a dimensionless potential

$$\bar{V}(\bar{\psi},\bar{\phi}) = \frac{1}{4}\bar{\psi}^4 - \bar{\psi}^3 + \frac{\delta_{eff}(\bar{\phi})}{2}\,\bar{\psi}^2 + \frac{1}{2}\kappa^2\bar{\phi}^2$$

in terms of dimensionless variables

$$\bar{V} = \frac{81\lambda^3}{\alpha^4 M^4} V\,, \qquad \bar{\psi} = \frac{3\lambda}{\alpha M}\psi\,, \qquad \bar{\phi} = \frac{3\sqrt{\lambda\tilde{\lambda}}}{\alpha M}\phi$$

and

$$\delta_{eff}(\bar{\phi}) = \delta + \bar{\phi}^2\,, \qquad \delta = 9\,\frac{\lambda\beta}{\alpha^2} \qquad \kappa = \frac{3\lambda}{\alpha\sqrt{\tilde{\lambda}}}\frac{m}{M}\,.$$

Bubble Percolation

- To have analytical solutions we assume $\kappa << 1$

➡ The Lorentz-inv. vacuum solution becomes

$$\bar{\psi} = 0 \text{ and } \bar{\phi} \approx const.$$

➡The Euclidian action for *O*(4)-symmetric configurations becomes

$$S_E = \frac{2\pi^2}{\lambda} \int_0^\infty d\bar{r}\, \bar{r}^3 \left[\frac{1}{2} \left(\frac{d\bar{\psi}}{d\bar{r}} \right)^2 + \frac{1}{2} \frac{\lambda}{\tilde{\lambda}} \left(\frac{d\bar{\phi}}{d\bar{r}} \right)^2 + \bar{V}(\bar{\psi}) \right]$$

With e.o.m.

$$\bar{\psi}'' + \frac{3}{\bar{r}} \bar{\psi}' = \bar{\psi}^3 - 3\bar{\psi}^2 + \delta_{eff}(\bar{\phi})\bar{\psi} \,,$$

$$\bar{\phi}'' + \frac{3}{\bar{r}} \bar{\phi}' = \frac{\tilde{\lambda}}{\lambda} \left[\bar{\psi}^2 \bar{\phi} + \mathcal{O}\left(\kappa^2\right) \right] \,.$$

- The e.o.m.

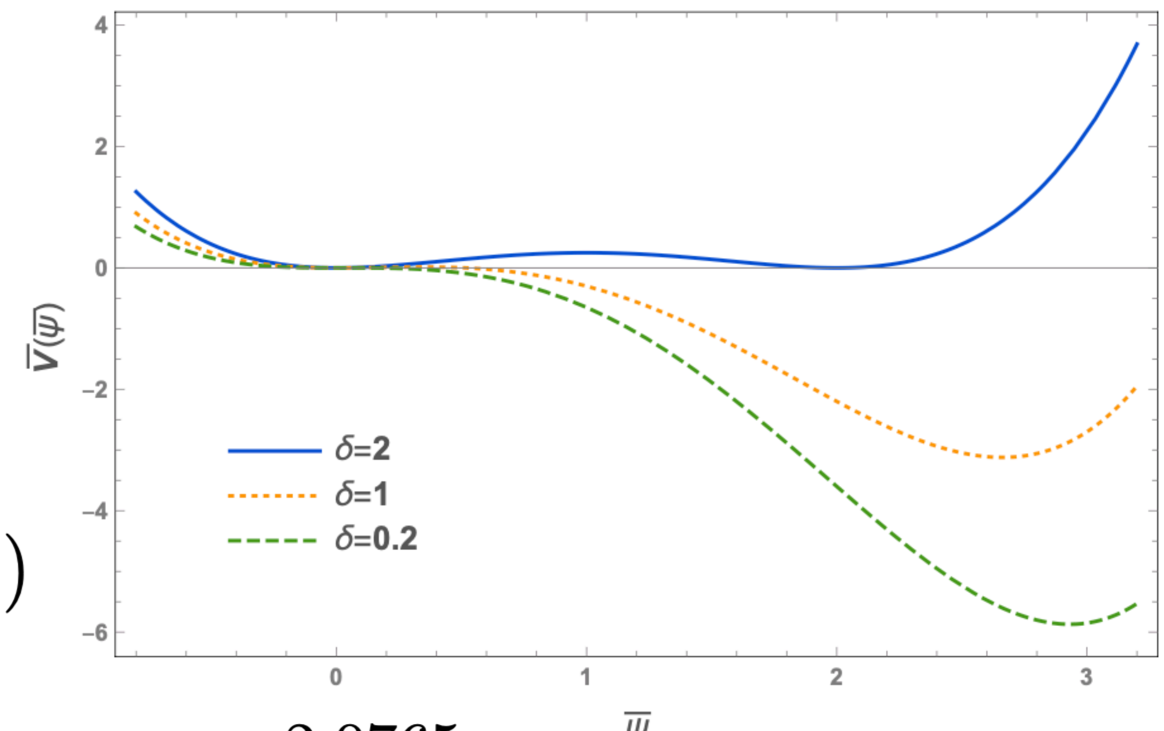
$$\bar{\psi}'' + \frac{3}{\bar{r}}\bar{\psi}' = \bar{\psi}^3 - 3\bar{\psi}^2 + \delta_{eff}(\bar{\phi})\bar{\psi}\,,$$

$$\bar{\phi}'' + \frac{3}{\bar{r}}\bar{\phi}' = \frac{\tilde{\lambda}}{\lambda}\left[\bar{\psi}^2\bar{\phi} + \mathcal{O}\left(\kappa^2\right)\right]\,.$$

decouple for $\tilde{\lambda}/\lambda << 1$ and the second equation can trivially be solved by $\bar{\phi}(\bar{r}) = \bar{\phi}(t_*) = const.$ (t_* time of tunneling)

➡Euclidian action given by effective single-field potential

$$\bar{V}(\bar{\psi}) = \frac{1}{4}\bar{\psi}^4 - \bar{\psi}^3 + \frac{\delta_{eff}}{2}\bar{\psi}^2$$

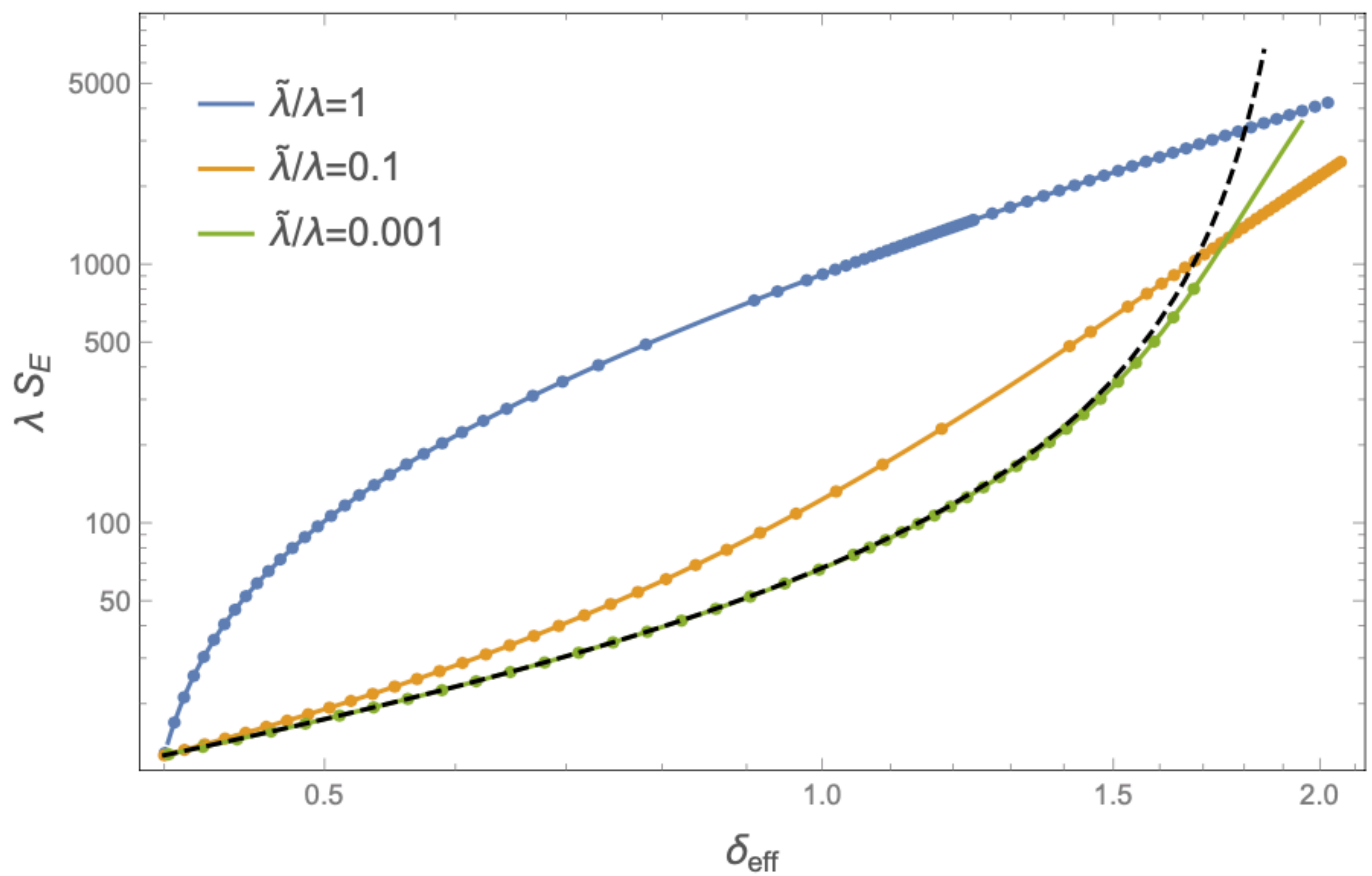


giving to good approximation

$$S_E \simeq \frac{4\,\pi^2}{3\lambda}\,(2-\delta_{eff})^{-3}\left(\alpha_1\,\delta_{eff} + \alpha_2\,\delta_{eff}^2 + \alpha_3\,\delta_{eff}^3\right)$$

$\alpha_1 = 13.832\,,$ $\alpha_2 = -10.819\,,$ $\alpha_3 = 2.0765$

$\delta_{eff}(\bar{\phi}) = \delta + \bar{\phi}^2\,,$ $\delta = 9\,\frac{\lambda\beta}{\alpha^2}$



(b) Euclidian action as a function of δ_{eff} for $\delta = 0.4$. The dashed line plots the semi-analytic result (9) derived in the one-field case. We find that it is approached as $\tilde{\lambda}/\lambda \to 0$.

Bubble percolation summary

Percolation parameter $p \equiv \Gamma / H^4$

<u>Quasi-stable phase</u> (p<<1):

$H > > m$ and ϕ is frozen to $\phi_{init} \Rightarrow S_E > S_E^* \simeq 250$

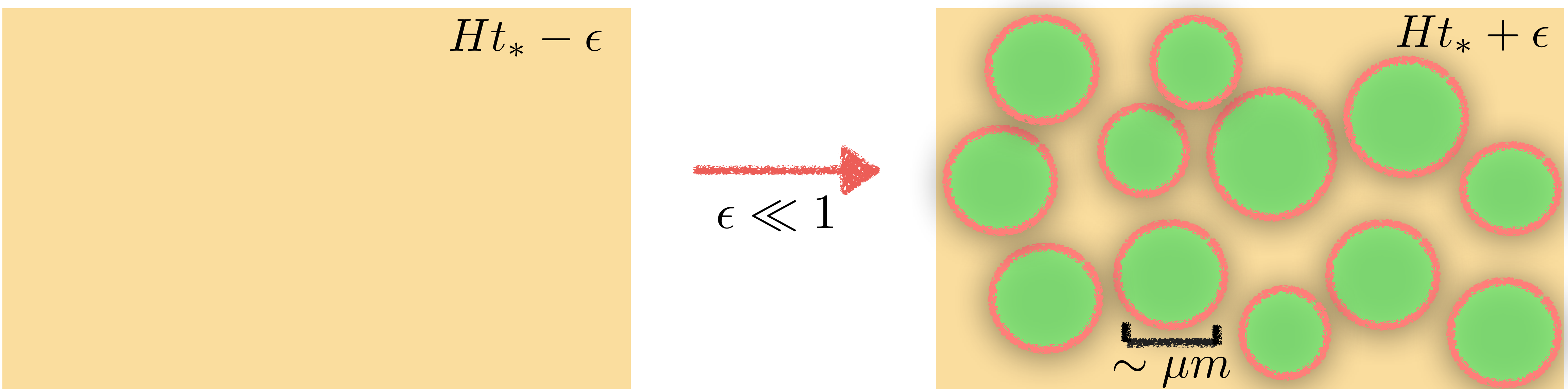
<u>Percolation phase</u> (p>>1):

$$m > > H \Rightarrow \phi \to 0 \Rightarrow S_E \to 10 \Rightarrow p \to 10^{104}$$

➡Strong burst of nucleation filling each Hubble volume out with bubbles in a tiny fraction of a Hubble time

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.

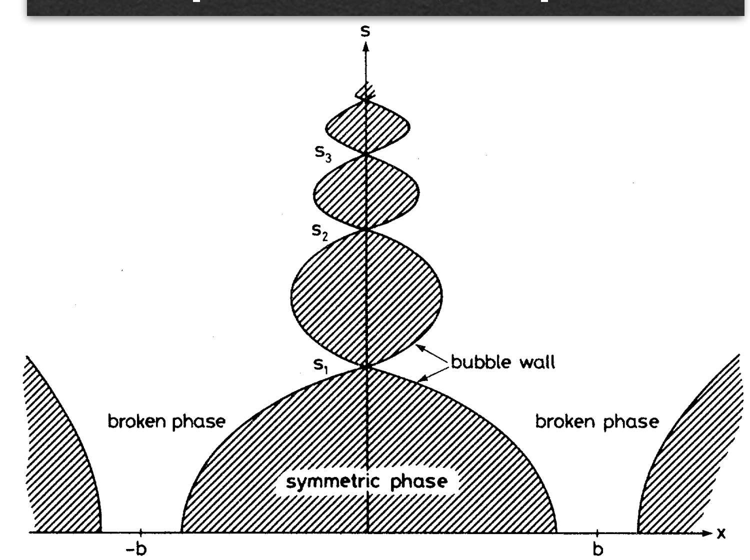
$$\ell_{bubble} < 10h^{-1}\mathrm{Mpc}/(z_* + 1)$$

[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

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



[Hawking, Moss, Stewart,

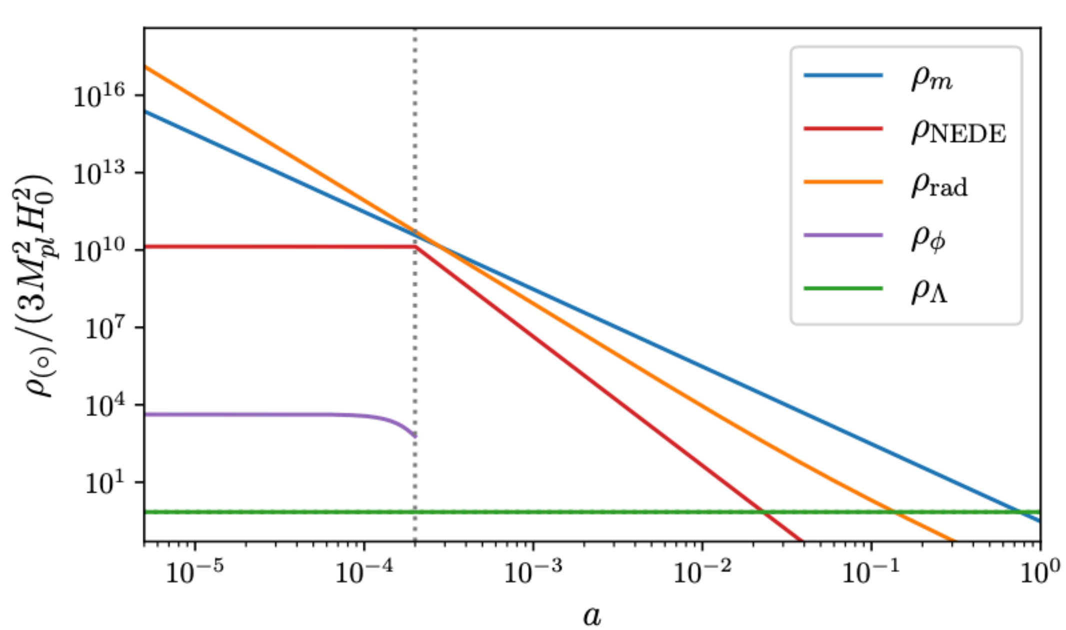
Effective cosmological model

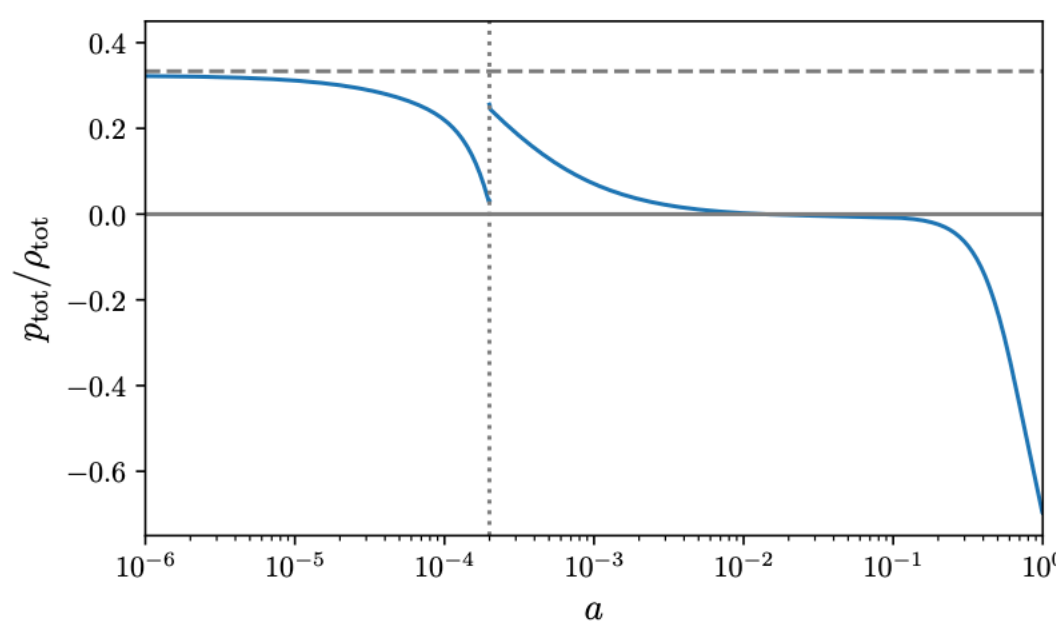
- **Background** picture: Assume that all liberated vacuum energy in psi is converted to a fluid with fixed e.o.s.

Sudden transition at time t_*:

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

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

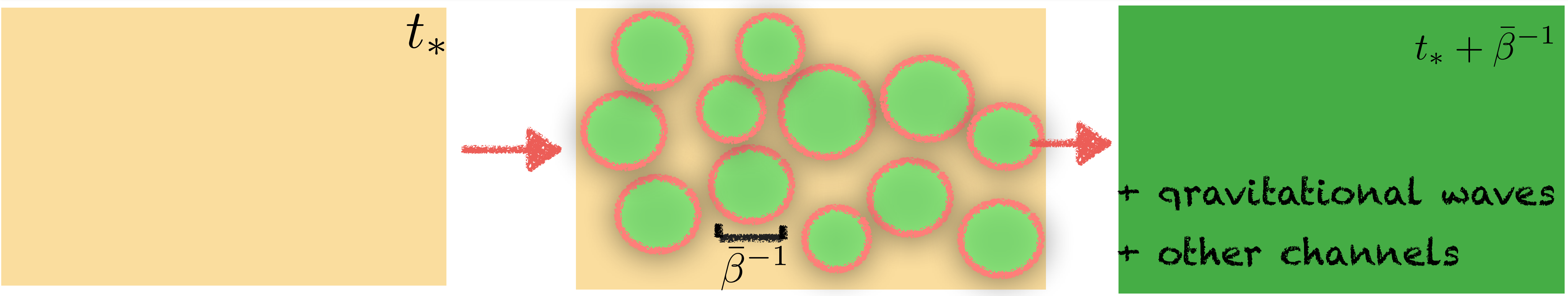




Effective cosmological model

- 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: $H\bar{\beta}^{-1} < 1$

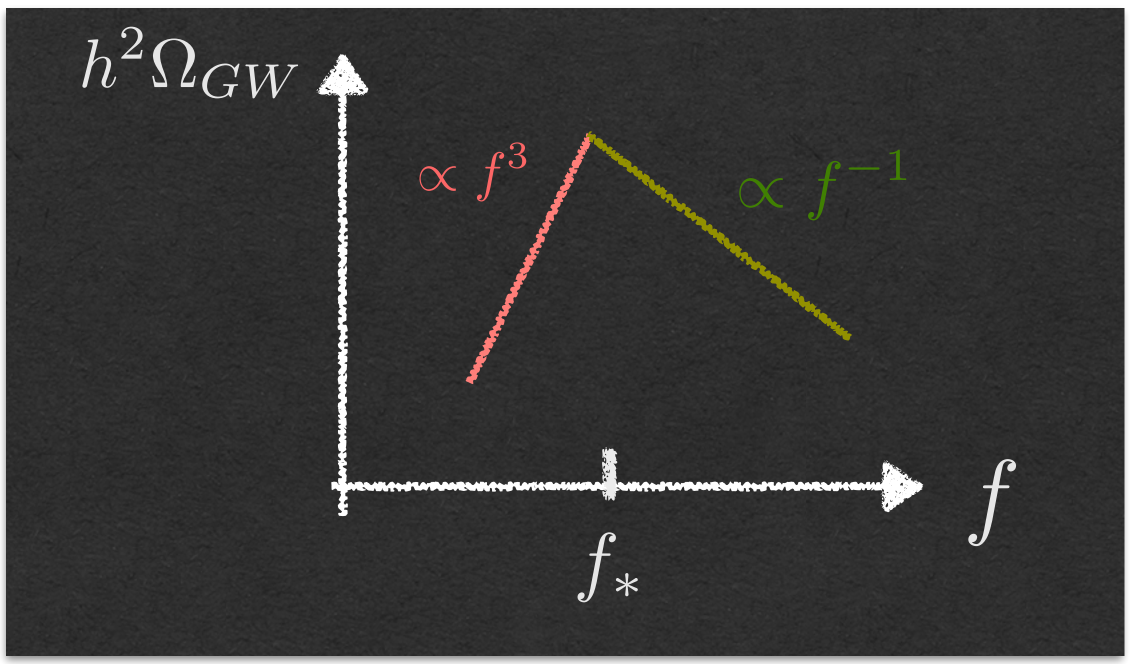


Effective model:

$$w_{\rm NEDE}(t) = \begin{cases} -1 & \text{for} \quad t < t_* \\ w^*_{\rm NEDE} & \text{for} \quad t \geq t_* \end{cases} \qquad 1/3 < w^*_{NEDE} < 1$$

Gravitational waves

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



1/f regime:

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

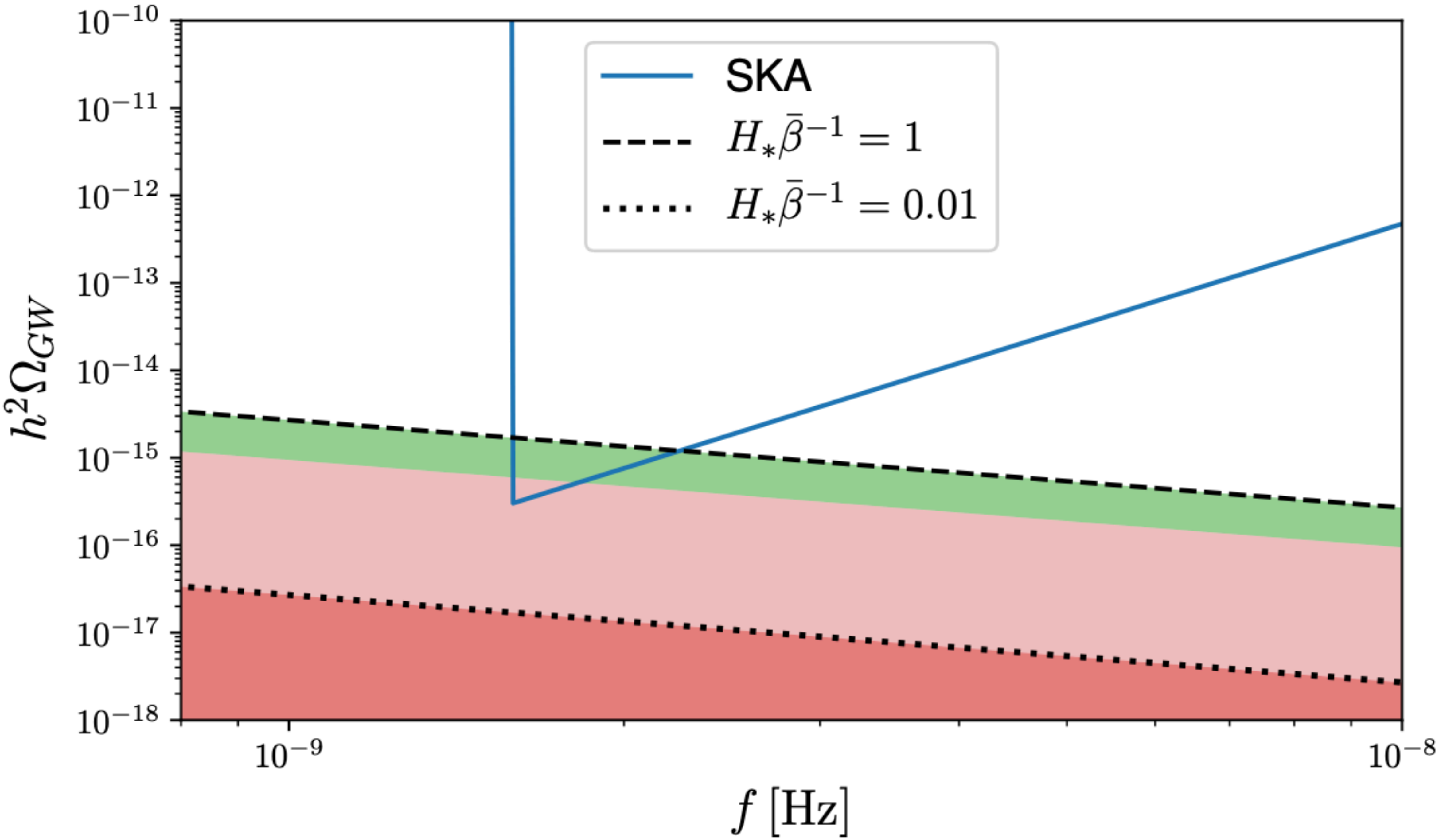
single dial

- 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



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

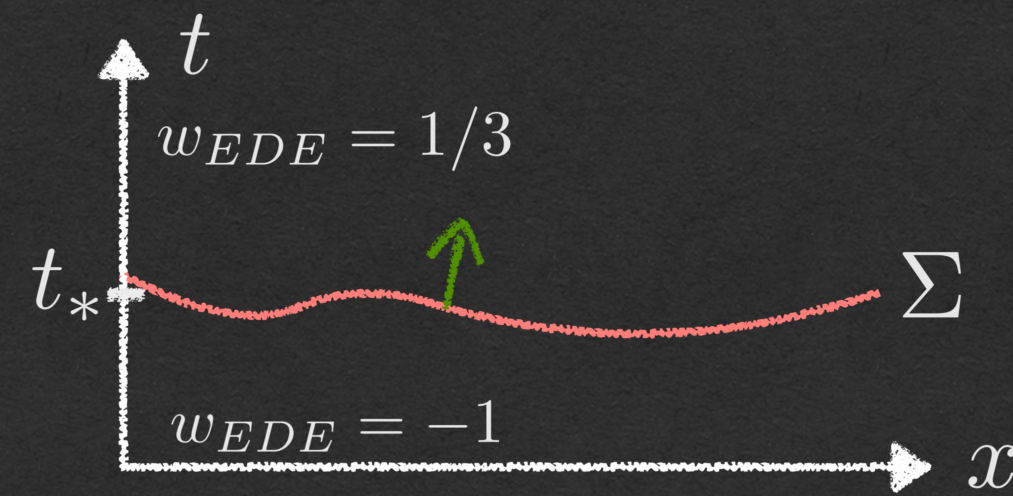
[Deruelle, Mukhanov, 1995]

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

synchronous gauge:

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

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



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

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

$$\delta^*_{EDE} = -3\left(1 + w^*_{EDE}\right) H_* \frac{\delta\phi_*}{\dot{\phi}_*} \quad \longleftarrow \text{density pert.}$$

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

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 like CLASS.

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

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

Two-parameter extension of LCDM

Results

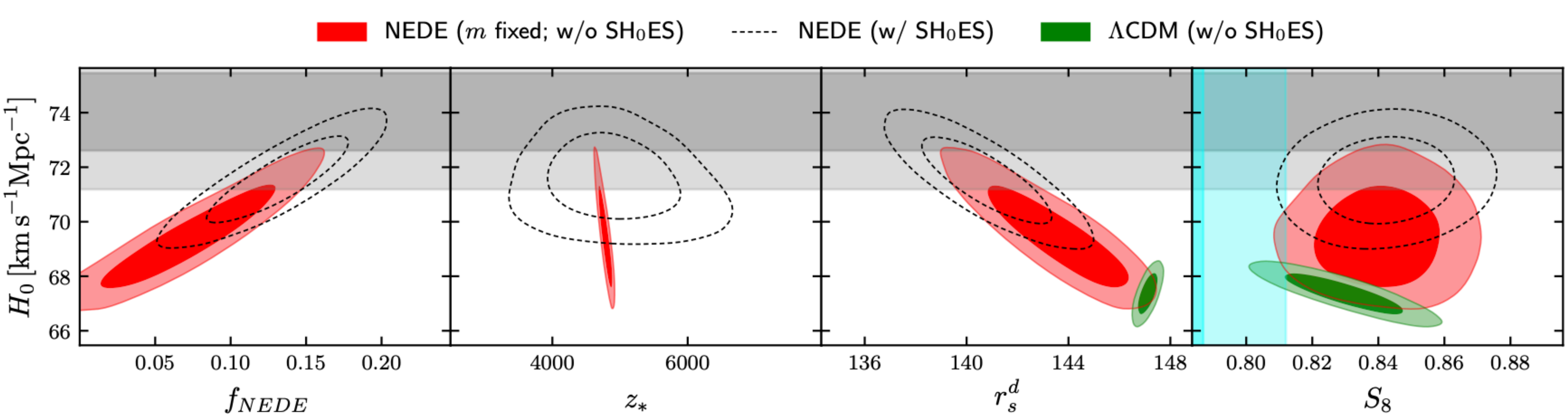
- We use simplest implementation of New EDE.
  - Phase transition described as instantaneous process.
  - All vacuum energy converted to $w^*_{NEDE} = 2/3$
  - No sizeable oscillations in trigger field after transition.

[arXiv:1910.10739]
[arXiv:2006.06686]

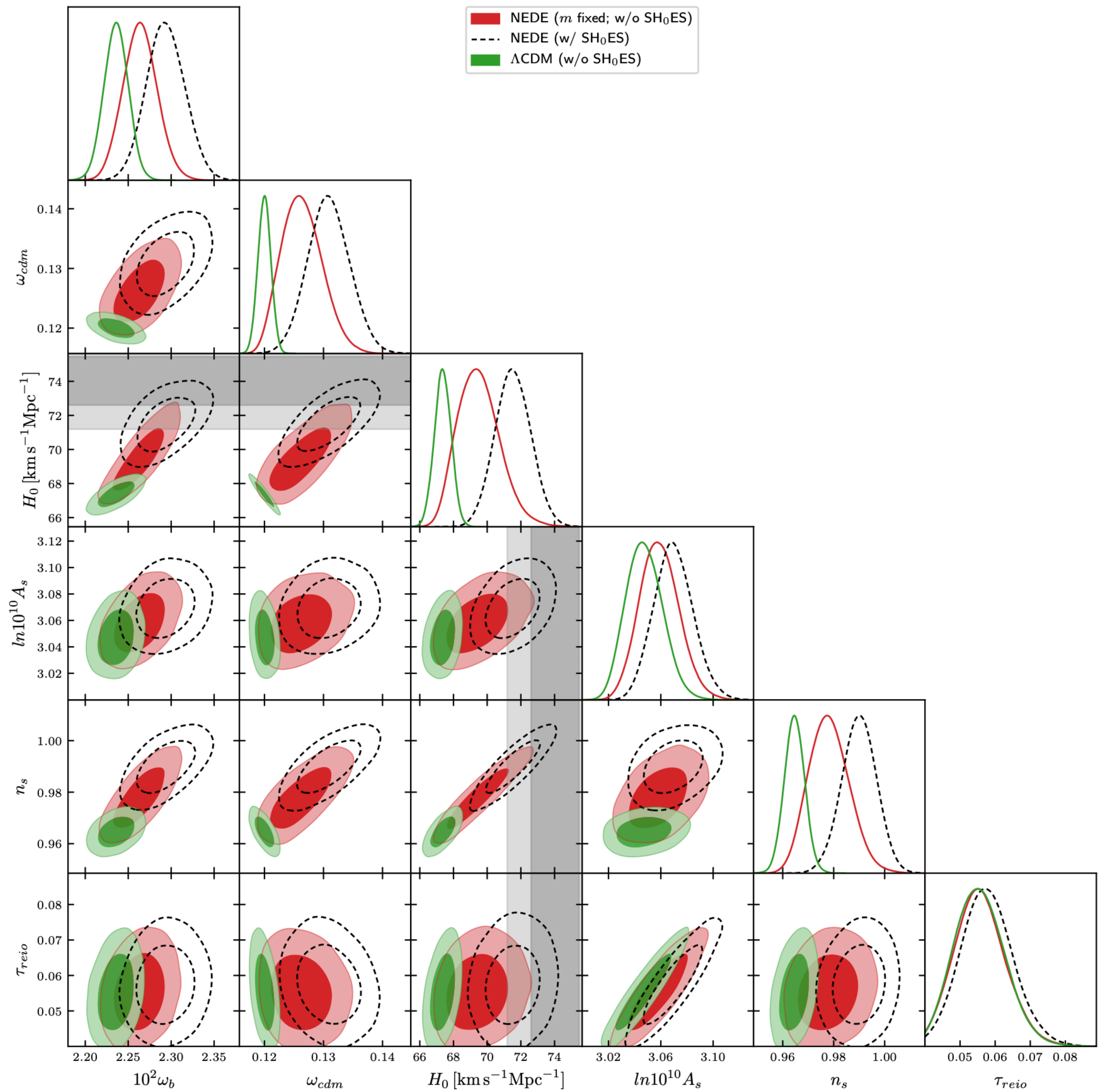
- Cosmological parameter extraction

datasets:
Planck 2018 TT, TE, EE
Planck 2018 Lensing
BAO + LSS
Pantheon
SH_0ES 2019
BBN

$H_0 = 71.5 \pm 1 \mathrm{km/s/Mpc}$
improvement:
$\Delta\chi^2 \sim -16$



Results



NEDE (m fixed; w/o SH_0ES)
NEDE (w/ SH_0ES)
ΛCDM (w/o SH_0ES)
$10^2\omega_b$
ω_{cdm}
$H_0\,[\mathrm{km\,s^{-1}Mpc^{-1}}]$
$ln10^{10}A_s$
n_s
τ_{reio}

Verification of trigger mechanism

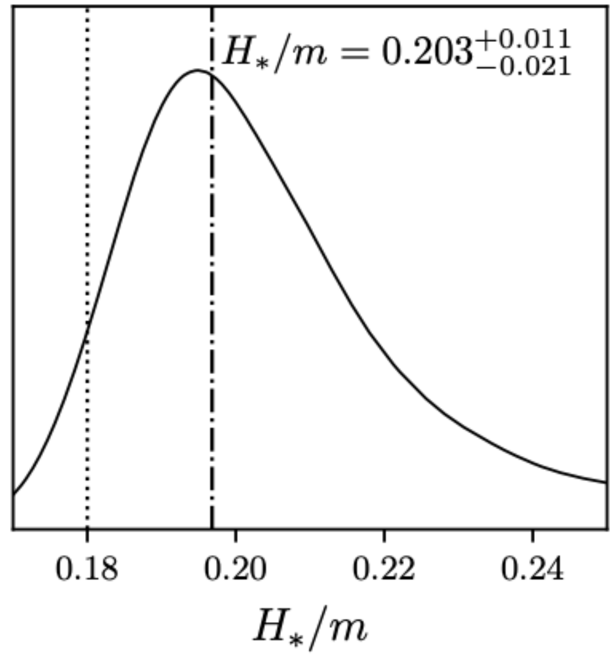
- NEDE theory predicts:

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

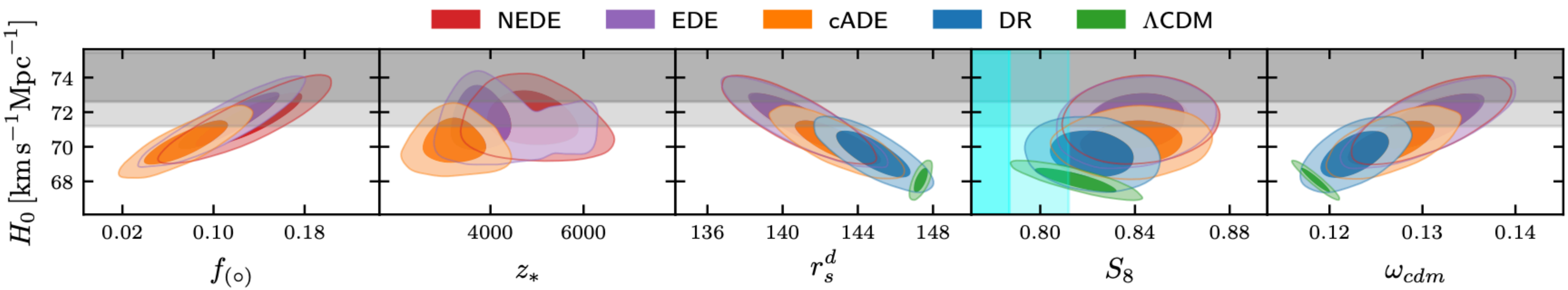
- When we fit the trigger as a free parameter, data gives

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

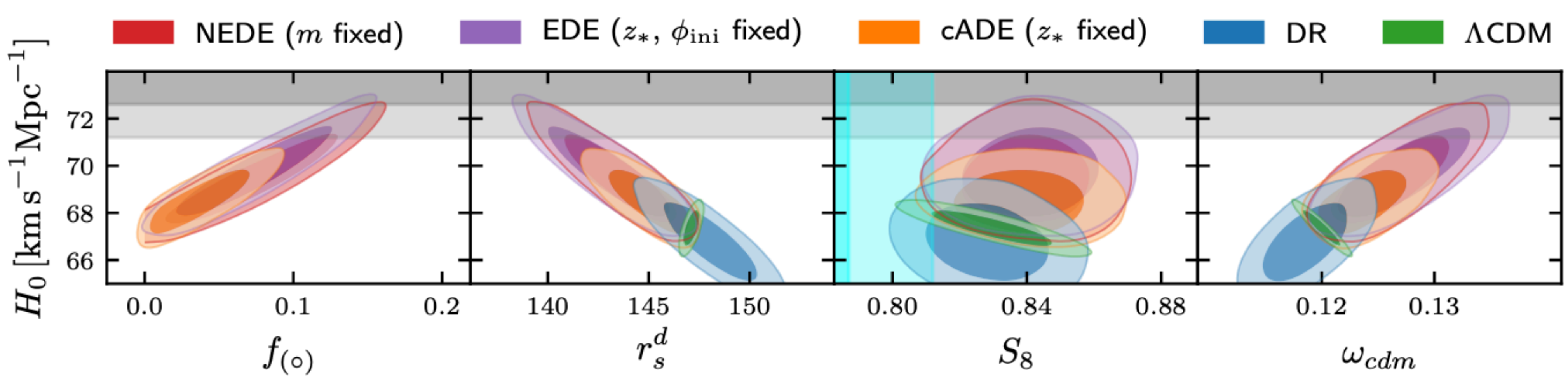
➡ Non-trivial verification of NEDE first order trigger mechanism!



Comparison of models



(a) Combined analysis with SH_0ES



(b) Combined analysis without SH_0ES

Conclusions

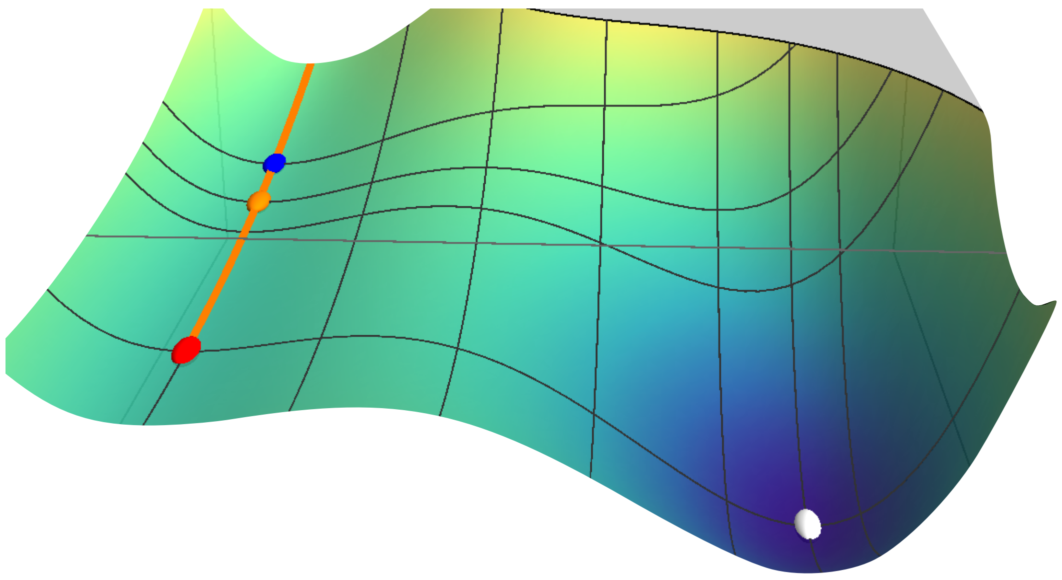
- Hubble tension could yet be systematics
- If not — exciting opportunity to probe the dark sector
- EDE looks promising, although old EDE appears fine-tuned

➡ Look for new EDE models!

- New EDE look theoretically and phenomenologically promising!
- Verification of NEDE trigger mech.
- Prediction of gravitational waves.
- Lots of things to do — more detailed modelling of percolation phase, generalisations, etc…

Resolving the Hubble Tension with New Early Dark Energy

Martin S. Sloth
(CP3-Origins, SDU, Denmark)



arXiv:1910.10739 w. Florian Niedermann
arXiv: 2006.06686 w. Florian Niedermann