Constraining the Dynamics of New Early Dark Energy

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based on arXiv:2408.14537

PASCOS 2025, 21-25 July, Durham

Two paths to measuring H_0

Direct (local) measurements:

$$H_0 = \frac{z}{d}$$

- Based on cosmic distance ladder
    - Type 1a supernovae to measure distances
    - Cepheid variables to callibrate supernovae
    - Geometric methods to callibrate cepheids

- SH0ES collaboration finds

$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Riess et. al. 2022

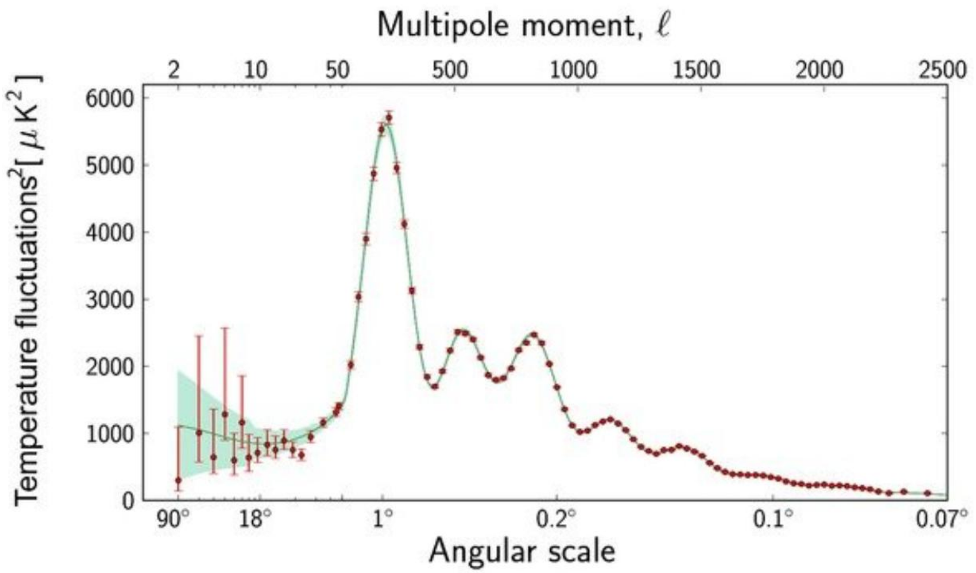
Two paths to measuring H_0

- **Indirect** measurement:
  - Based on ΛCDM model fit to CMB
  - H_0 is inferred from the angular size of the sound horizon

comoving sound horizon

$$\theta_s = \frac{r_s}{D_A(z_*)}$$

angular diameter distance, $D_A(z) = \int_0^z \frac{dz'}{H(z')}$, $\quad H(z) = H_0\sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m}$



  - Planck 2018 release

$$H_0 = 67.36 \pm 0.54\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

Aghanim et. al. 2018

Two paths to measuring H_0

Direct measurements:

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Indirect measurements:

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Roughly 5σ discrepancy between the two methods:
Hubble tension

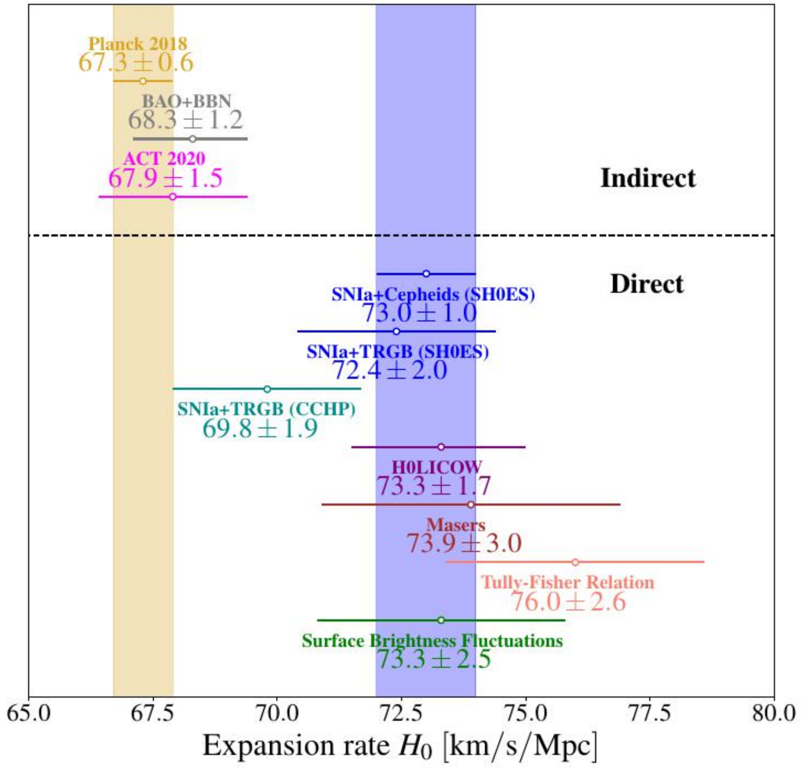

Figure taken from Poulin et. al. 2023

Smaller sound horizon to increase H_0

- Larger value of H_0 can be compensated by a smaller sound horizon r_s in the plasma

angular scale of BAO

$$r_s = \theta_s(z) D_A(z)$$

angular diameter distance, $D_A(z) \approx z H_0^{-1}$ for $z \ll 1$

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- The sound horizon can be lowered via an **energy injection** before shortly recombination

sound speed

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

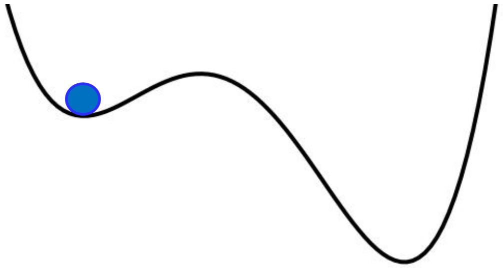
redshift of recombination

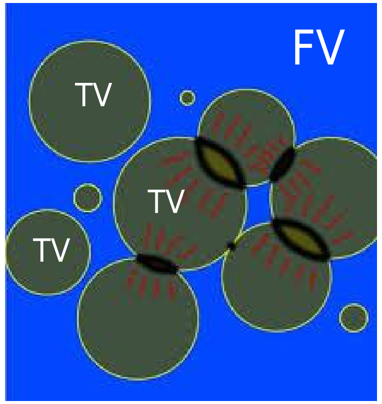
- Modify ΛCDM shortly before recombination: **energy injection**

Phase transitions

- Common in cosmology
  - Electroweak phase transition, $T \sim 100\mathrm{GeV}$
  - QCD phase transition, $T \sim 100\mathrm{MeV}$

- First-order phase transition (FOPT)
  - The field initially trapped in the false vacuum
  - Nucleation & expansion of true vacuum bubbles





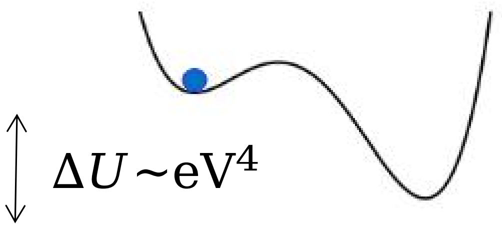
Coleman, 1977

New early dark energy

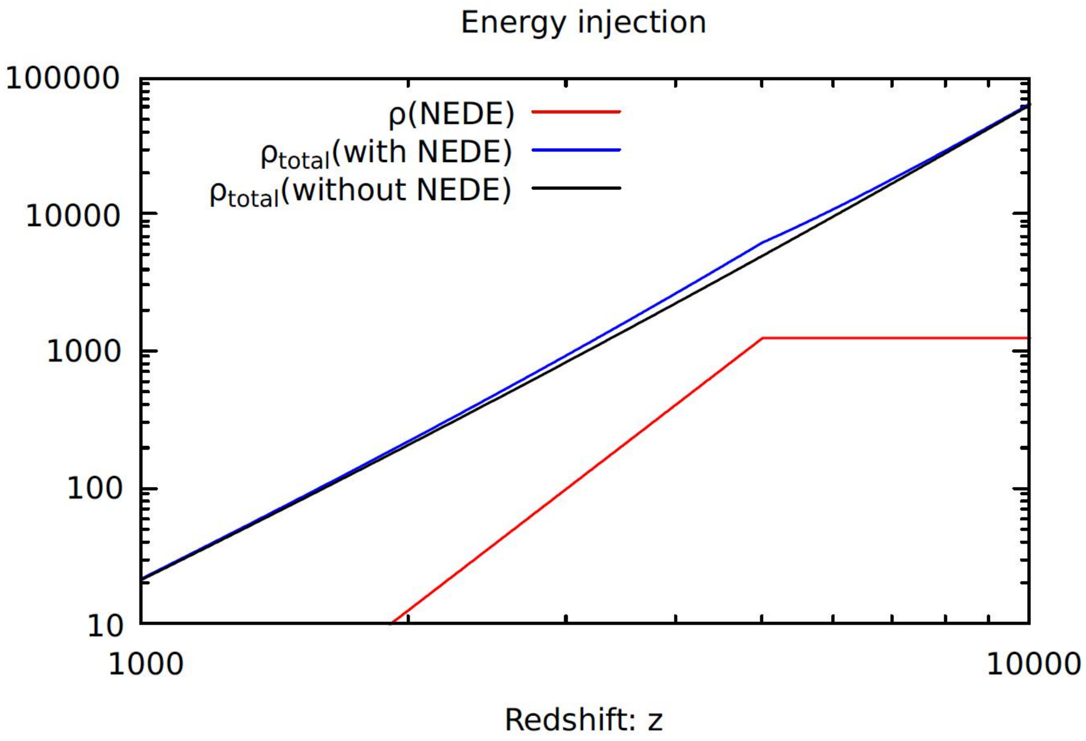
- **Energy injection** from the latent heat of the phase transition around recombination time can alleviate the **Hubble tension**
    - New early dark energy (NEDE)

Niedermann, Sloth 2021

$T \sim \mathrm{eV}$



vacuum PT: Cold NEDE
thermal PT: Hot NEDE



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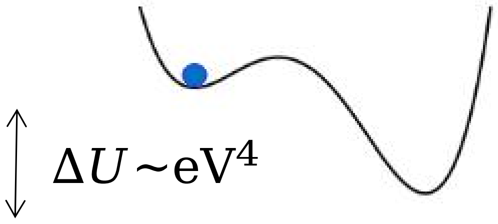

vacuum PT: Cold NEDE
thermal PT: Hot NEDE

Compare to Early Dark Energy (EDE)

Scalar field displaced from its minimum
- Initially frozen by Hubble friction
- Starts to oscillate when $H \sim m$

Poulin et. al. 2018

New early dark energy

- Fast transition, $H/\beta \ll 1$, is required to avoid large-scale CMB anisotropies from bubbles

- Can be achieved via a **triggered** phase transition in a **two-field** model
    - ψ undergoes the transition
    - ϕ triggers the transition
        - $m \sim 10^{-27}\mathrm{eV}$
        - starts rolling around $H \sim m$
        - triggers sudden nucleation of bubbles of ψ

- Can be incorporated into multi-axion models

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

Chen et al, 2109.12920,
Cicoli et al, 2407.03405

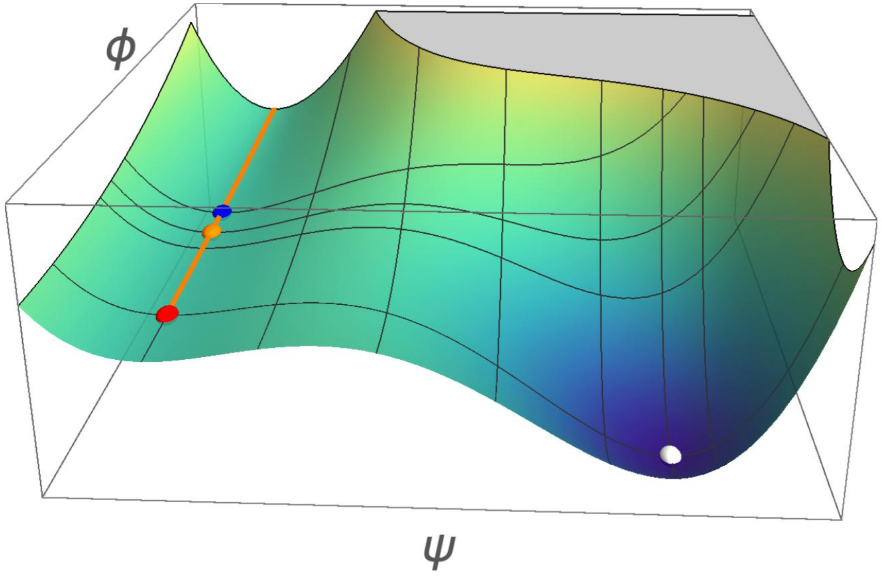

Figure taken from Niedermann et. al. 2021

Testing the model against most recent data

- NEDE is implemented in the Boltzmann code **TriggerCLASS**

The trigger field

$$\bar{\phi}'' + 2\mathcal{H}\bar{\phi}' + m^2\bar{\phi} = 0\,,$$

$$\delta\phi'' + 2H\delta\phi' + (k^2/a^2 + m^2)\delta\phi = -\frac{1}{2}h'\phi'\,,$$

The tunneling field (in terms of an ideal fluid)

$$\bar{\rho}_{\rm NEDE}(\tau) = \bar{\rho}_{\rm NEDE}(\tau_*)\exp\left[-3\int_{\tau_*}^{\tau} \mathrm{d}\tilde{\tau}\,[1 + w_{\rm NEDE}(\tilde{\tau})]\,\mathcal{H}(\tilde{\tau})\right]$$

$$\delta'_{\rm NEDE} = -(1 + w_{\rm NEDE})\left(\theta_{\rm NEDE} + \frac{h'}{2}\right) - 3(c_s^2 - w_{\rm NEDE})\mathcal{H}\delta_{\rm NEDE}\,,$$

$$\theta'_{\rm NEDE} = -(1 - 3c_s^2)\mathcal{H}\theta_{\rm NEDE} + \frac{c_s^2 k^2}{1 + w_{\rm NEDE}}\delta_{\rm NEDE}\,,$$

- Interfaced with MCMC sampler **MontePython**

$$w_{\rm NEDE} = -1 \quad \text{for} \quad \tau < \tau_*$$

$$1/3 \leq w_{\rm NEDE}(\tau) \leq 1 \quad \text{for} \quad \tau \geq \tau_*\,.$$

Testing the model against most recent data

- Included datasets:
  - **CMB** Planck data, PR4/NPIPE compared to Planck 2018 (PR3/Plik)
  - **BAO** measurements (including DESI)
  - **Pantheon+** catalogue of supernovae

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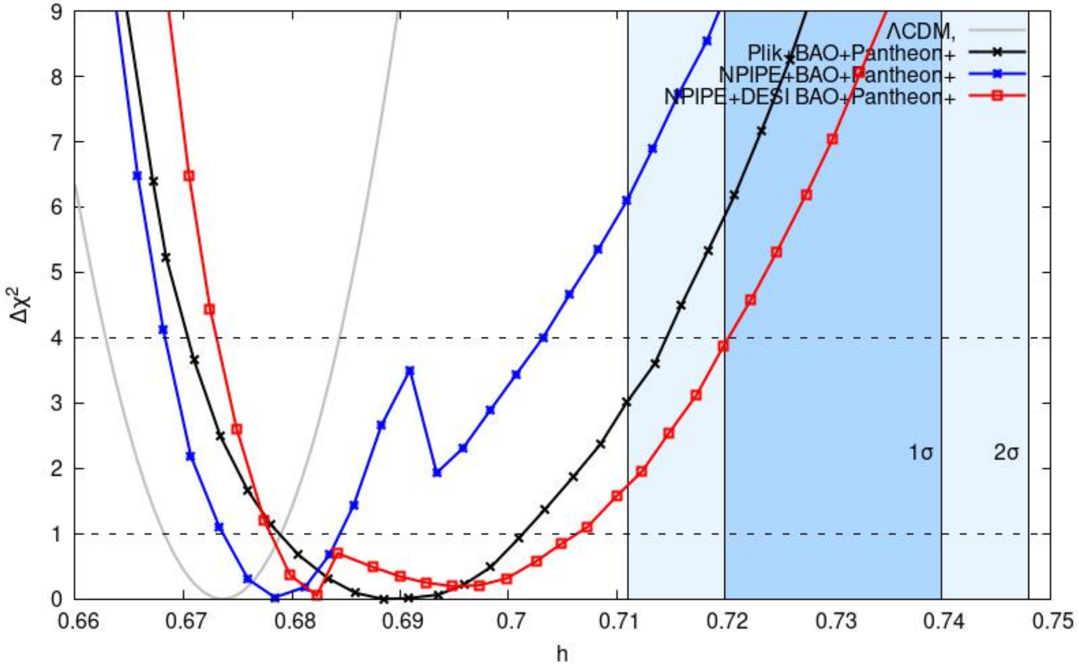
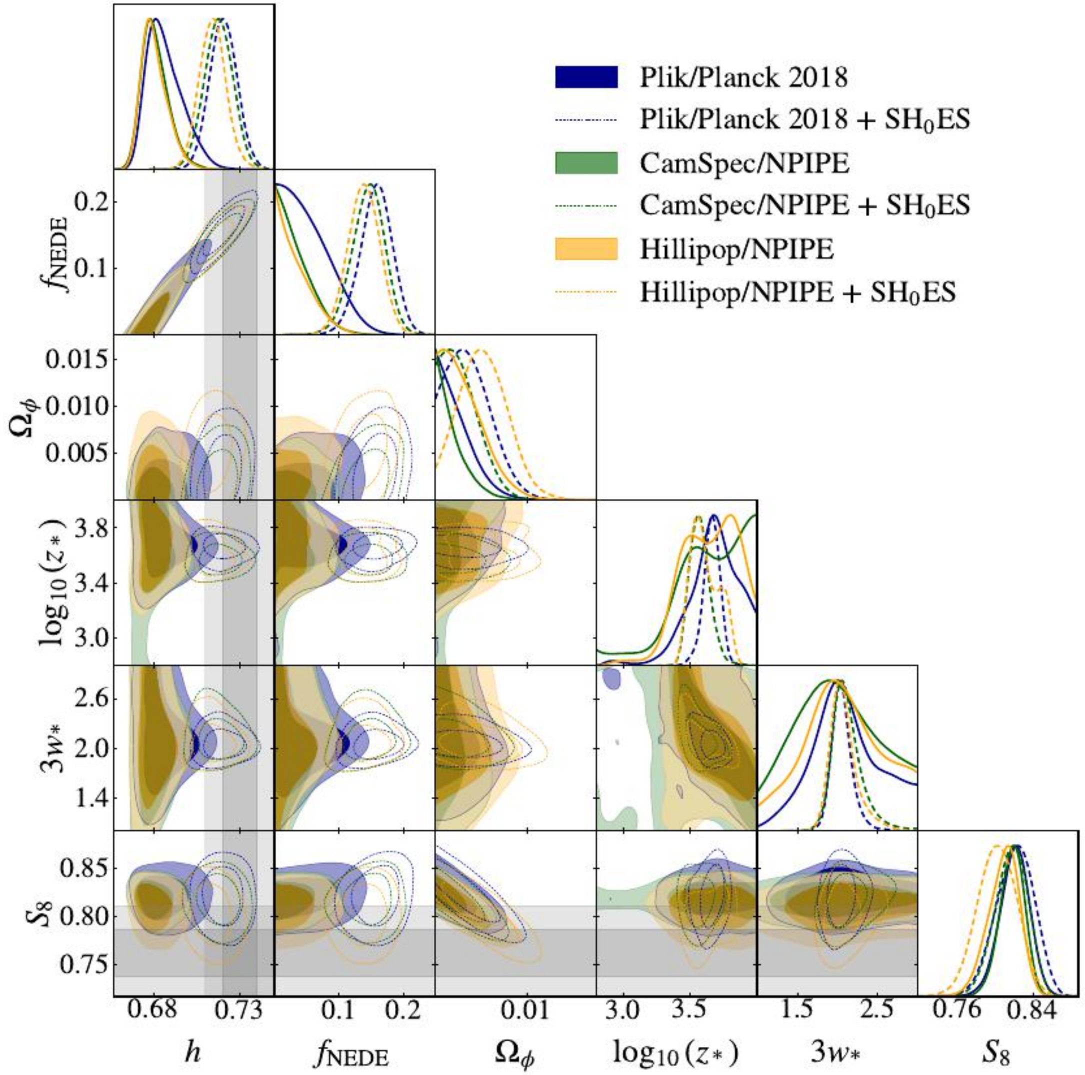
- Residual tension of 2.6σ for the most recent datasets



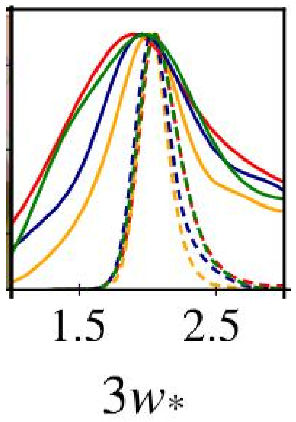
Cosmological parameter extraction

Scan four NEDE parameters
$\{f_{NEDE}, z_*, w, \Omega_\phi\}$
in addition to the six ΛCDM parameters
$\{h, \omega_b, \omega_{cdm}, A_s, n_s, \tau_{reio}\}$



Insights into the post-transition fluid

- Data prefers $w(a > a_*) > 1/3$
  - For a constant eos, $w(a) = w_* \approx 2/3$



- What contributions to the eos can we expect?
  - Expanding bubble walls: radiation, $w = 1/3$
  - Oscillations near the true minimum: depends on the potential
  - Quick decay of the tunneling field
  - Small scale shear: vector and scalar components scale as $\mathrm{w} = 1$ *Zel'dovich, 1961*

Insights into the post-transition fluid

- We parametrize the post-transition fluid with a time-dependent equation of state $w(a)$

$$w(a) = w^* + \frac{dw}{d\ln a}\Big|_{a_*} \ln\Big(\frac{a}{a_*}\Big) + \frac{1}{2}\frac{d^2 w}{d(\ln a)^2}\Big|_{a_*} \Big[\ln\Big(\frac{a}{a_*}\Big)\Big]^2 + \dots,$$

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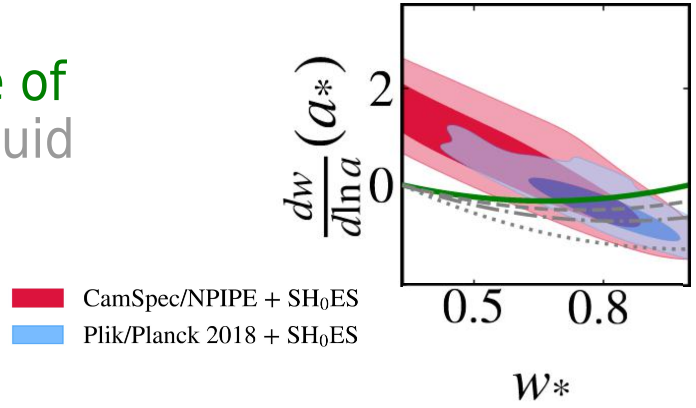
- Datasets consistent with a mixture of radiation and a stiff fluid, or a stiff fluid decaying into radiation



Summary

- NEDE offers a compelling route to alleviate the H_0 tension.

- Updated datasets provide crucial insights into the dynamics and underlying microscopic properties.

- Future work to focus on developing concrete models of the phase transition, compatible with observations.

Thank you for your attention!