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Is new physics hidden in our expansion history?
an Update

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24th International Conference - Planck 2022 - Paris - 1st of June 2022

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We need to describe the contents too!

Many models out there...

best so far ΛCDM

2. ΛCDM in Brief

Parameter	Bestfit value
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_*$	1.04108 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042

From the CMB [Planck Collaboration, 2020]

with $h = H_0/100$ km s^{-1} Mpc^{-1}.

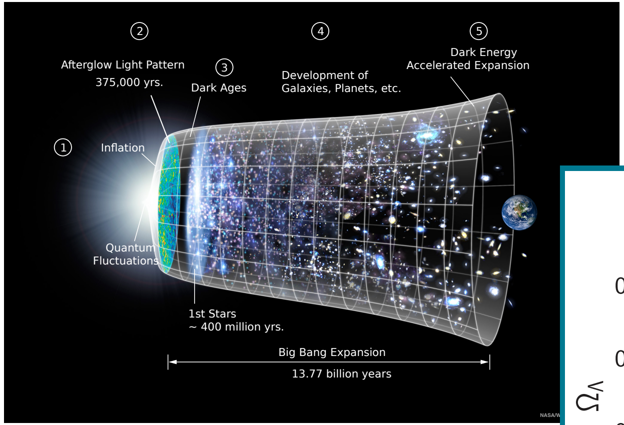
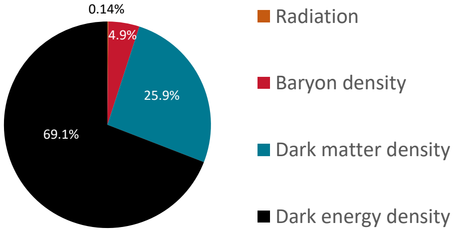
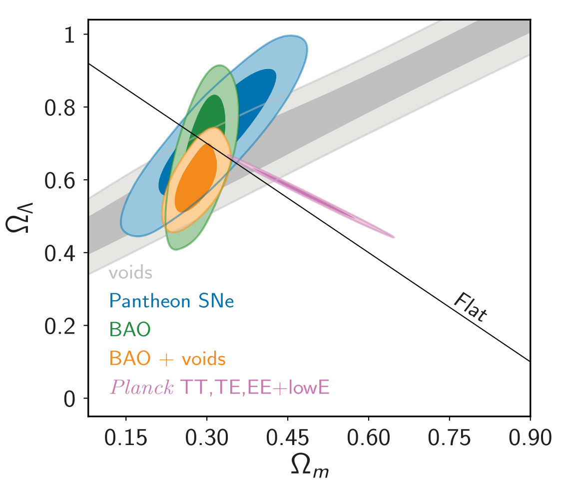


Image credit: NASA/ LAMBDA Archive / WMAP Science Team



But precision cosmology is starting to have a say:



[Nadathur et al., 2020]

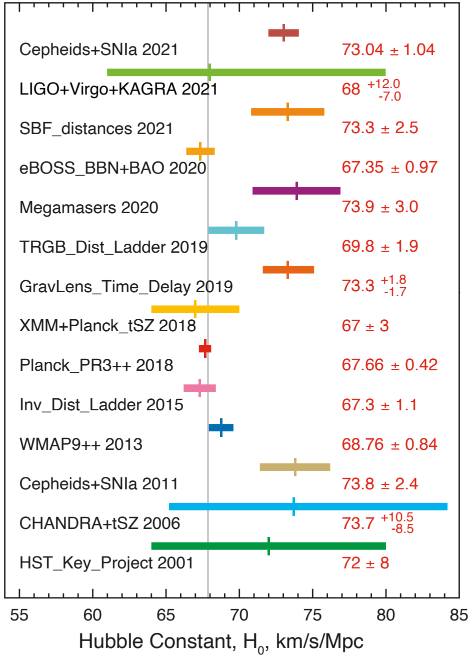
3. Measuring H_0 and the tension

Early time

Most recent and precise uses CMB power spectrum Planck-2018 [Planck Collaboration, 2020]

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

+ Extremely precise
– Depends on the ΛCDM model



Credit: NASA / LAMBDA Archive Team

Late time

Most recent and precise uses Cepheids+SNIa from SH_0ES-2021 [Riess et al., 2021]

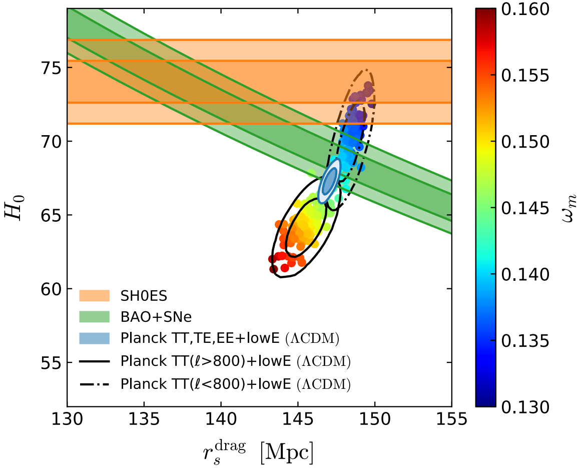
$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

+ Independent of the expansion history.
– Most of them have still big uncertainties.

For a more details on observations for H_0 in flat ΛCDM see [Di Valentino et al., 2021]

4. Possible solutions

Let us assume there are no systematic errors in the above.



[Knox and Millea, 2020]

⟸ Modifications of ΛCDM at late times do not seem to be favored by data [Mörtsell and Dhawan, 2018] [Arendse et al., 2020]

Theorists have produced models with early and late time modifications of ΛCDM, (see [Di Valentino et al., 2021] for a review)

Watch the Olympics [Schöneberg et al., 2021] for the standings in the market, including:

- Local underdensities
- Pre-recombination mods: $N_{\rm eff}$, EDE, NEDE, $m_e(z)$,...
- Post-recombination mods: ωCDM, PEDE,...

5. The idea behind (New) Early Dark Energy models

How is H_0 obtained (given the content)?

$$H(z) = H_0\sqrt{(\Omega_c + \Omega_b)a^{-3} + \Omega_{\text{rad}}a^{-4} + \Omega_\Lambda}$$

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Model-independent measured by Planck $\Longrightarrow \theta^* = \dfrac{r_s^*}{D_A^*}$

D_A^*: angular diameter distance to recombination, $\Longrightarrow D_A^* = \displaystyle\int_0^{z_*} \frac{\mathrm{d}z}{H(z)}$

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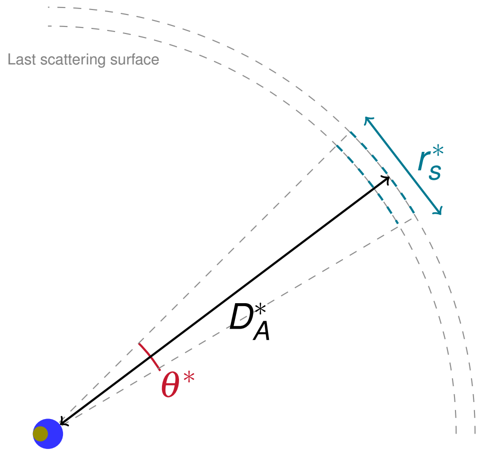

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How is H_0 obtained (given the content)?

$$H(z) = H_0\sqrt{(\Omega_c+\Omega_b)a^{-3}+\Omega_{\rm rad}a^{-4}+\Omega_\Lambda+\Omega_{\rm NEDE}a^{-3(1+\omega_{\rm NEDE})}}$$

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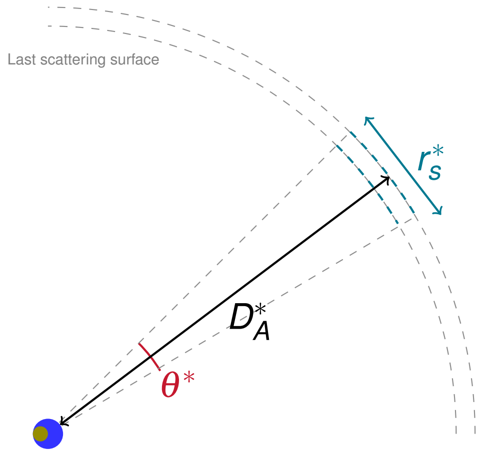
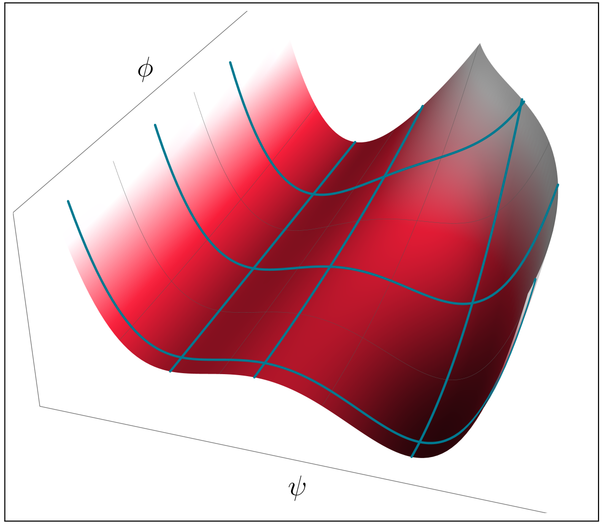


$H(z)$ can be increased in a specific z-range while keeping θ^* fixed.

6. NEDE's Microperspective



- Introducing a new dark-energy component near recombination **(EDE)** seems to decrease the tension [Karwal and Kamionkowski, 2016] [Poulin et al., 2018]
- Introduce two-field triggered-FOPT (First order phase transition) [Niedermann and Sloth, 2020]
  - Ultra-light trigger field ϕ with $m \sim 10^{-26}$eV
  - New **EDE** field ψ with $M \sim$ eV
- Dimensionless potential:

$$\bar{V}(\bar{\phi}, \bar{\psi}) = \frac{1}{4}\bar{\psi}^4 - \bar{\psi}^3 + \frac{1}{2} \underbrace{\delta_{\text{eff}}(\bar{\phi})}_{\text{Trigger mechanism}} \bar{\psi}^2 + \frac{1}{2}\kappa^2\bar{\phi}^2.$$

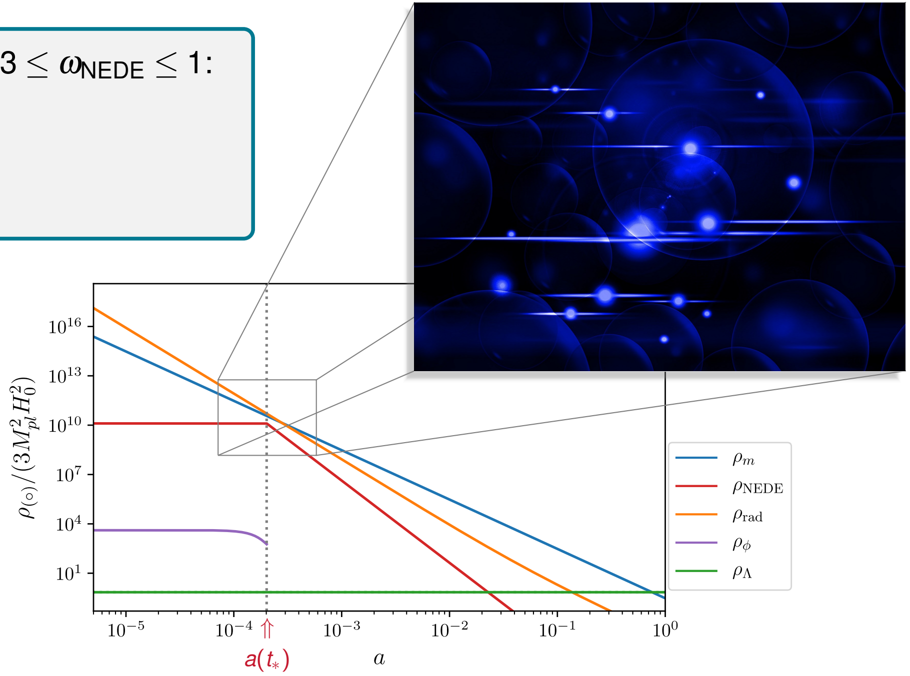
- NEDE predicts that $0.18 < \frac{H_*}{m} < 0.21$.

7. NEDE's Macroperspective

Effective description of the transition as a stiff fluid with $1/3 \leq \omega_{\text{NEDE}} \leq 1$:
[Baumann et al., 2012]

$$\omega_{\text{NEDE}} = \begin{cases} -1 & \text{for} \quad t < t_* \\ \omega^*_{\text{NEDE}} & \text{for} \quad t \geq t_* \end{cases}$$

- The transition happens extremely quickly compared to the scale factor evolution.
- Energy stored in the NEDE field is dissipated in bubble collisions which produce NEDE fluid and GWs and possibly other channels.
- Impose the percolation of small enough bubbles to be consistent with CMB.



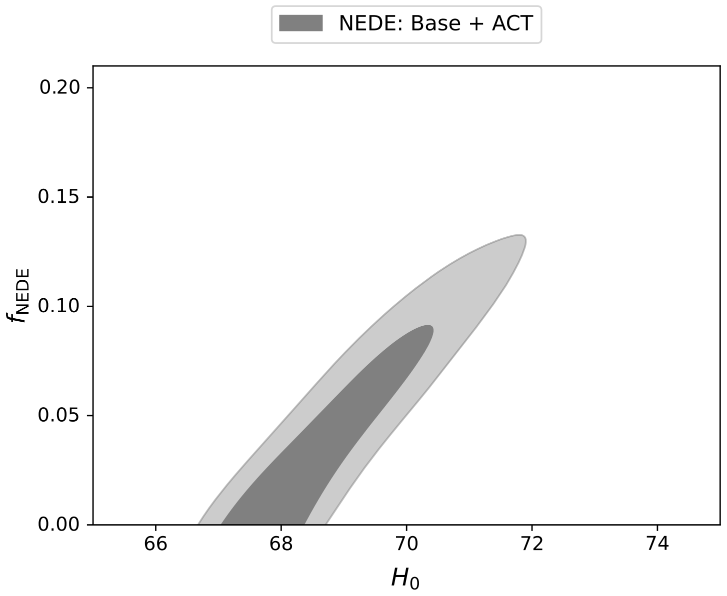
8. MCMC Analysis

New – we focus on the impact of the **ACT** lkhd. on the model's fits.
[Aiola et al., 2020]

- We fix the equation of state to $\omega_{\text{NEDE}} = 2/3$.
- **Base** (likelihoods):
  - Planck 2018 TT,TE,EE+lowE,lensing [Planck Collaboration et al., 2020],
  - BAO: 6dF 2011 + SDSS DR7&12 [Beutler et al., 2011, Ross et al., 2015, Alam et al., 2017]
  - SN: Pantheon [Scolnic et al., 2018]
  - BBN: PArthENoPE [Pisanti et al., 2008]

Mean w/o SH_0ES $\Rightarrow$ $H_0 = 69.68^{+0.94}_{-1.2}$ lowers the Hubble tension to 2.25σ.

			+ ACT		ΛCDM + ACT	
Data ▶	Base	+ SH_0ES	Base	+ SH_0ES	Base	+ SH_0ES
f_{NEDE}	0.067	0.135	0.053	0.139	-	-
m_ϕ[1/Mpc]	349.5	383.0	287.3	293.8	-	-
χ^2	3886.4	3909.9	4130.3	4133.0	4147.9	4186.7
Q_{dmap}	4.8σ		1.6σ			



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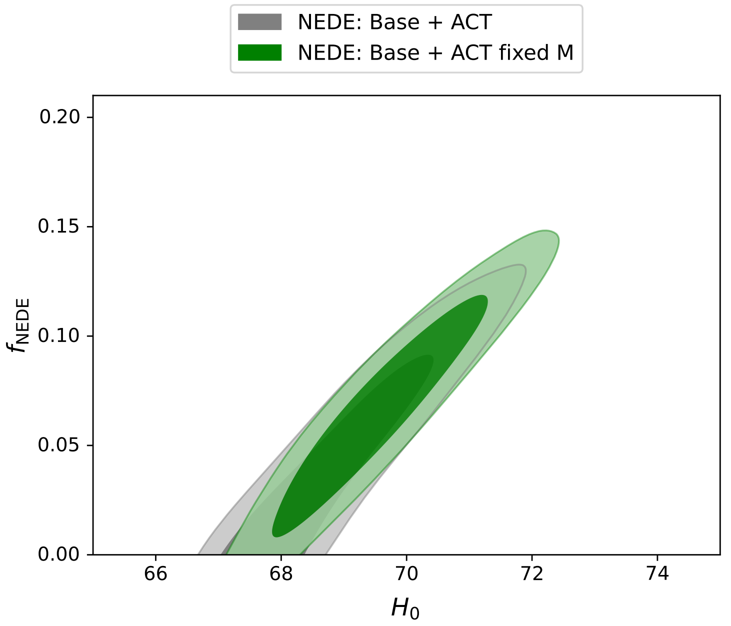

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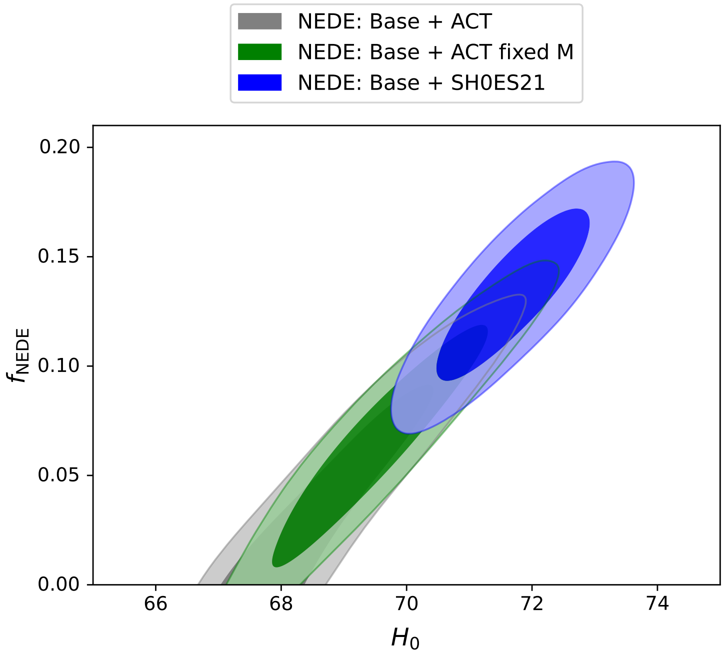

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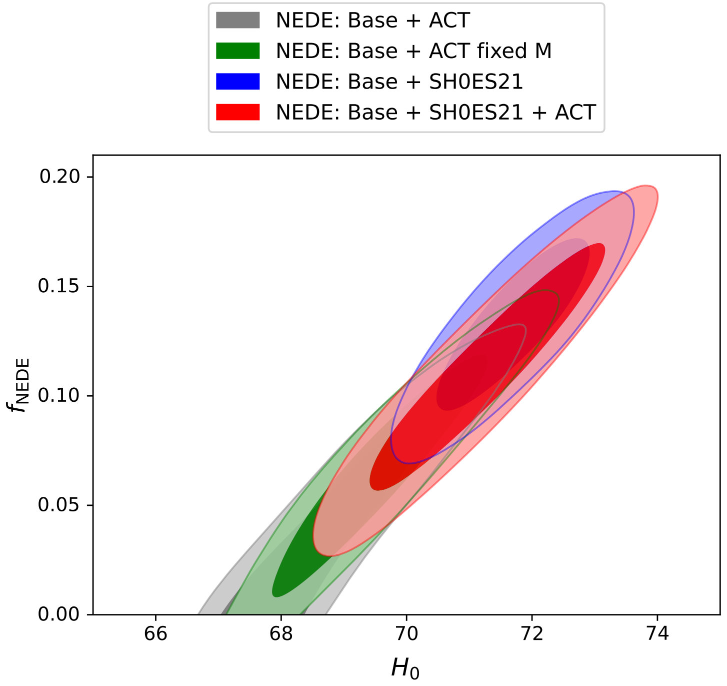
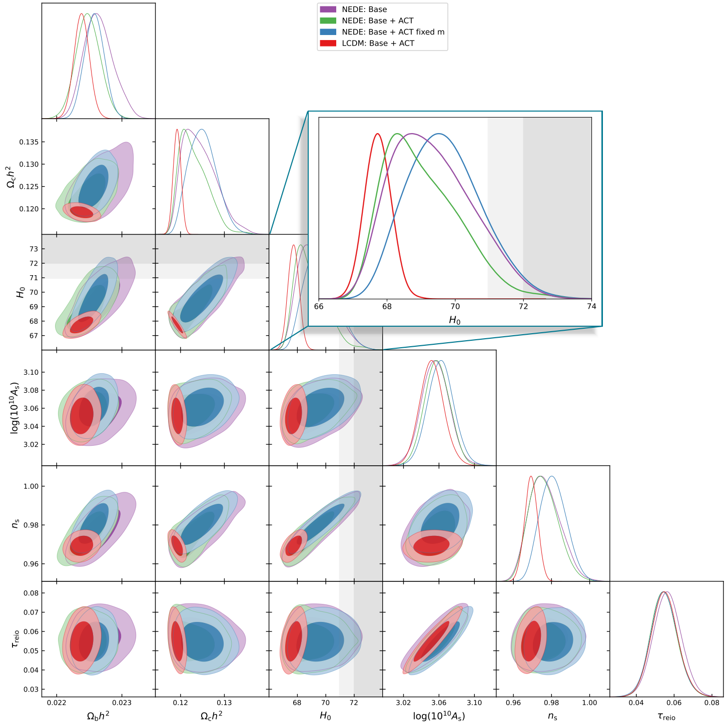


9. Summary and perspectives



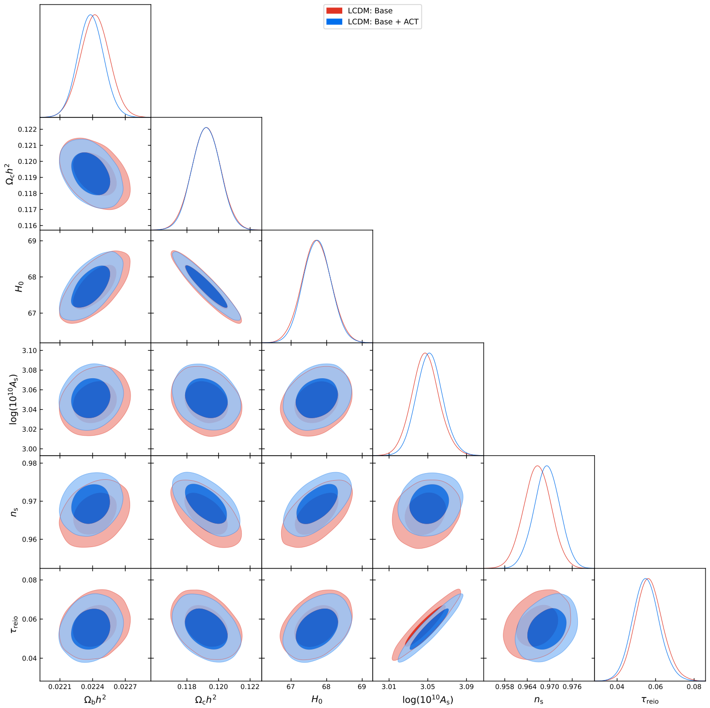
- Performed MCMC analysis with an new setup compared the previous studies using Cobaya sampler and latest `clik`.
- ACT decreases slightly the fraction of NEDE but improves the χ^2 of the bestfit.
- Non-zero $f_{\rm NEDE}$ remains favored reducing the Hubble tension.
- In the fixed mass runs, the bestfit is $H_0 = 70.96$ km/s/Mpc without including local measurements.

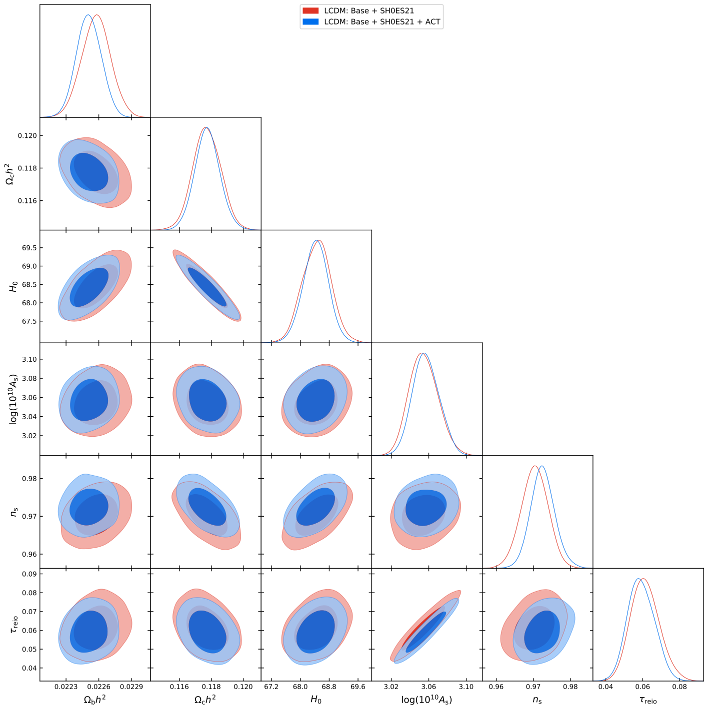
Ongoing

- Including SPT data in the analysis.
- Improving sampling issues for low $f_{\rm NEDE}$.
- Studying possible multi-modality of the model.
- Analysis Hot-NEDE, using a thermal trigger [Niedermann and Sloth, 2021].
- A richer dark sector in the NEDE model may address other issues like the σ_8-discrepancy.

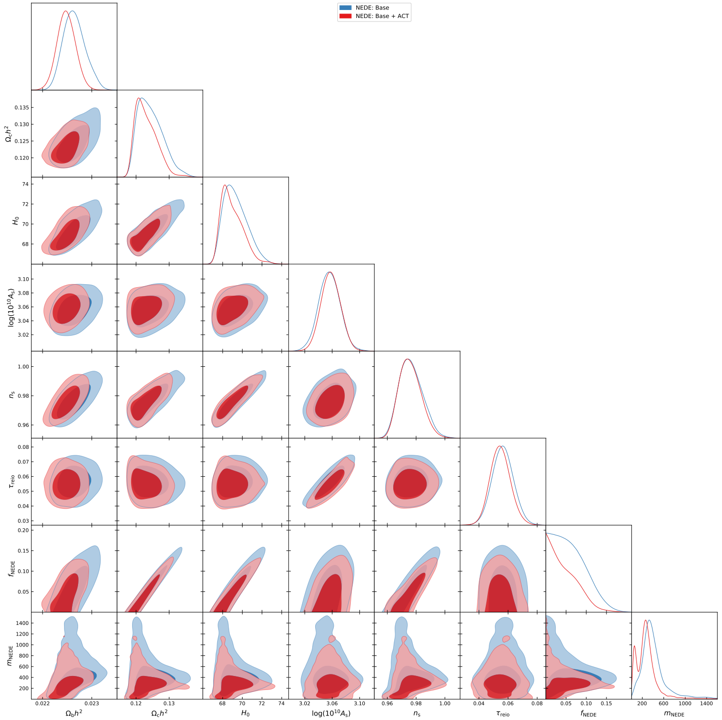
∗∗ Backup slides ∗∗

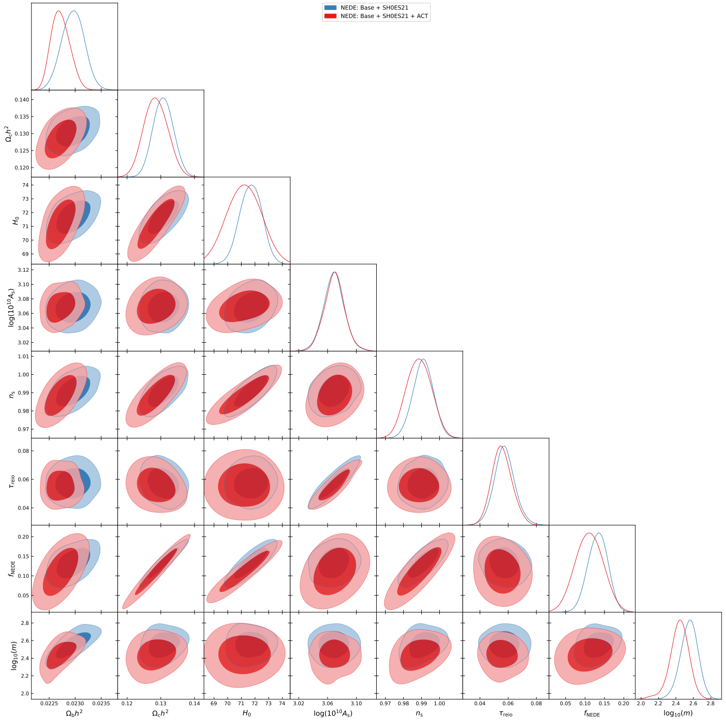
10. Effects of ACT on ΛCDM





11. Effects of ACT on the NEDE model





12. Bestfit table for NEDE runs

	LCDM (Base = Planck+BAO+SN)				*NEDE fixed EOS*				*NEDE fixed EOS and fixed Mass*
Parameter Name	***Base***	***Base + ACT***	***BASE + SH0ES***	***Base + ACT + SH0ES21***	***NEDE: Base***	***NEDE: Base + ACT***	***NEDE: Base + SH0ES21***	***NEDE: Base + ACT + SH0ES21***	***NEDE: Base + ACT***
omega_b	0.022	0.022	0.023	0.022	0.023	0.022	0.023	0.023	0.023
omega_cdm	0.119	0.119	0.117	0.118	0.125	0.124	0.131	0.131	0.129
H0	67.643	67.817	68.630	68.242	69.444	69.015	71.759	72.086	70.955
logA	3.052	3.067	3.061	3.073	3.047	3.064	3.065	3.084	3.078
n_s	0.966	0.968	0.971	0.971	0.978	0.976	0.991	0.995	0.986
tau_reio	0.058	0.057	0.062	0.060	0.055	0.050	0.054	0.059	0.053
f_NEDE	NA	NA	NA	NA	0.067	0.053	0.135	0.139	0.110
logNEDE_trigger_mass	NA	NA	NA	NA	2.543	2.458	2.583	2.468	2.458
three_eos_NEDE	NA	NA	NA	NA	2.000	2.000	2.000	2.000	2.000
NEDE_trigger_mass	NA	NA	NA	NA	349.486	287.333	382.974	293.758	287.276
z_decay	NA	NA	NA	NA	4881.454	4397.410	5007.738	4306.963	4301.678

13. Chi^2 table for NEDE runs

	LCDM (Base = Planck+BAO+SN)				NEDE fixed EOS				NEDE fixed EOS and fixed Mass
Parameter Name	***Base***	***Base + ACT***	***BASE + SH0ES***	***Base + ACT + SH0ES21***	***NEDE: Base***	***NEDE: Base + ACT***	***NEDE: Base + SH0ES21***	***NEDE: Base + ACT + SH0ES21***	***NEDE: Base + ACT***
ChiSq									
BAO	5.756	5.338	5.730	5.250	5.392	5.413	5.497	5.822	5.324
CMB	2766.652	2766.796	2771.616	2767.842	2763.997	2765.011	2764.993	2768.683	2764.070
SN	1035.046	1034.920	1034.734	1034.769	1034.876	1034.919	1034.735	1034.739	1034.752
planck_2018_lowl.TT	23.129	22.634	22.481	22.253	21.686	21.885	20.727	20.507	21.030
planck_2018_lowl.EE	396.815	396.556	397.687	397.215	396.087	395.709	395.918	396.836	395.866
planck_2018_lensing.clik	8.738	8.733	9.178	8.616	9.545	9.305	9.834	10.394	9.942
planck_2018_highl.TTTEEE	2337.971	2338.872	2342.270	2339.759	2336.679	2338.113	2338.514	2340.946	2337.233
bao.sdss_dr7_mgs	1.211	1.436	2.240	1.865	1.465	1.409	2.045	2.279	1.907
bao.sixdf_2011_bao	0.034	0.010	0.026	0.002	0.008	0.012	0.010	0.030	0.003
bao.sdss_dr12_consensus	4.511	3.892	3.464	3.383	3.918	3.992	3.441	3.513	3.414
sn.pantheon	1035.046	1034.920	1034.734	1034.769	1034.876	1034.919	1034.735	1034.739	1034.752
ACTPol_lite_DR4	NA	235.329	NA	235.793	NA	235.214	NA	238.969	235.112

14. Posterior means for NEDE run w/o SHOES fixed m