Updated Constraints on Hubble Tension solutions

With recent SPT-3G and SH0ES data

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arXiv:2312.09814

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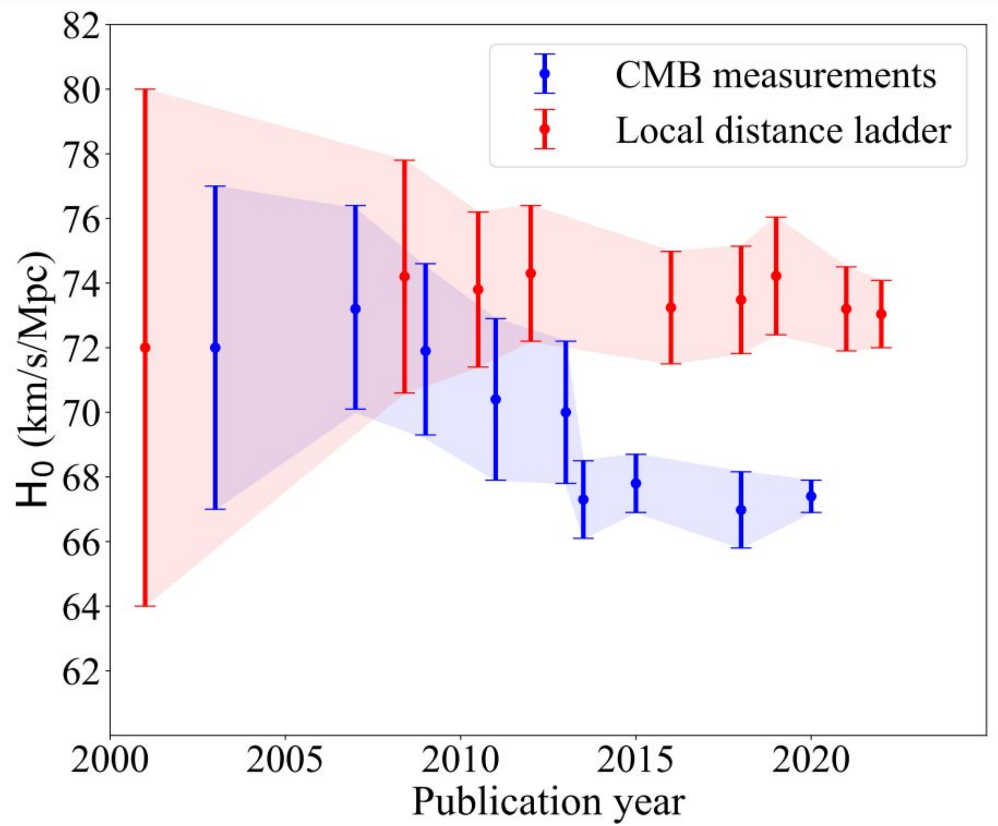
The Trouble with Hubble



Ref: Hubble Tension: The Evidence of New Physics(2302.05709)

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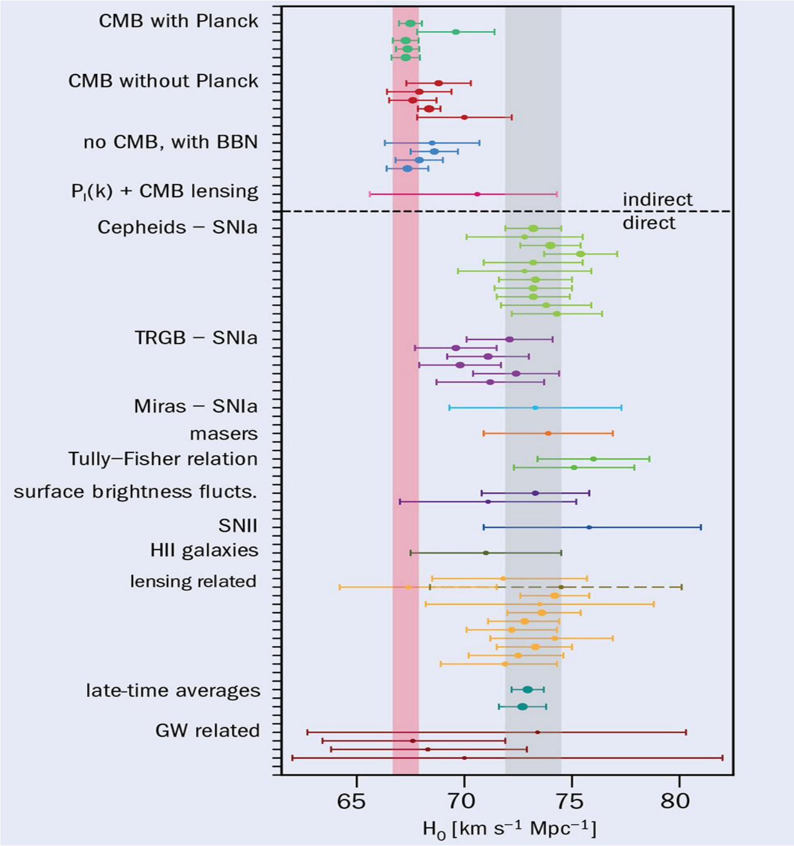

Ref: In the Realm of the Hubble Tension (2103.01183)

H_0 Olympics 2021

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	✗	✗	
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DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗	
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗	

Ref: [2107.10291]

Goal of the Project

Use the full SPT3G 2018 data, in combination with others, to evaluate the potential of

Cosmological models to solve the Hubble Tension.

Comparing with recent SH0ES analysis: **H_0= 73.29±0.90 km/s/Mpc** (2306.00070).

Study 5 classical ΛCDM extensions + 3 Elaborate Models (+extensions).

Assess these models with Tension metrics.

Update H_0 Olympics paper (2107.1029) with new metrics and with massive neutrinos.

How to Solve the Tension

- Solutions to the Hubble Tension include changing the Physics pre-recombination or in the late universe
- Note: 100xθ = 1.04075 ± 0.00028 (Balkenhol *et al.*)

Sound Speed

H(z)

$$\theta_s = \frac{r_s}{D_A} = \frac{\int_{z_*}^{\infty} \left[3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)\right]^{-1/2} \left[\frac{8\pi G}{3} \Sigma_i \rho_i\right]^{-1/2} dz}{H_0^{-1} \sin_K \left[\int_0^{z_*} \left(\Sigma_i \Omega_i(z)\right)^{-1/2} dz\right]}$$

Flat, closed or open

H(z)/H_0

The Models

ΛCDM Extensions

Extending ΛCDM with 3 degenerate massive neutrinos (Σm_ν) and:

- Chevallier-Polarski-Linder (CPL) Dark Energy ($\omega(a) = \omega_0 + \omega_a(1-a)$); a ≡ scale factor
- Free streaming Dark Radiation (N_{eff})
- Spatial Curvature (Ω_K)
- Self Interacting Dark Radiation (N_{SIDR})

$$\theta_s = \frac{r_s}{D_A} = \frac{\displaystyle\int_{z_*}^{\infty} \left[3\left(1+\frac{3\rho_b}{4\rho_\gamma}\right)\right]^{-1/2} \left[\frac{8\pi G}{3}\Sigma_i \rho_i\right]^{-1/2} dz}{H_0^{-1} \sin_K \left[\displaystyle\int_0^{z_*} \left(\Sigma_i \Omega_i(z)\right)^{-1/2} dz\right]}$$

Elaborate Models

- **Varying electron mass:**

  Compactification in higher dimensional theories results in scalar fields that alter the effective mass of elementary particles, specifically electrons.

  Recombination rate is affected → Recombination time changes

  Additional parameter: $m_{e,early}/m_{e,late}$

  More details: Hart & Chulba, 2018(1705.03925); *Planck* 2015(1406.7482)

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Elaborate Models

- **Varying electron mass (**$m_{e,early}/m_{e,late}$**)**
  - **+**$\boldsymbol{\Sigma m_\nu}$**:** Study interplay between masses of the two species

Elaborate Models

- **Varying electron mass (**$m_{e,early}/m_{e,late}$**)**
  - **+Σm_ν**
  - **+Ω_K:** Changing the time of recombination changes the distance

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More details: Sekigushi & Takahashi (2020) (2007.03381)

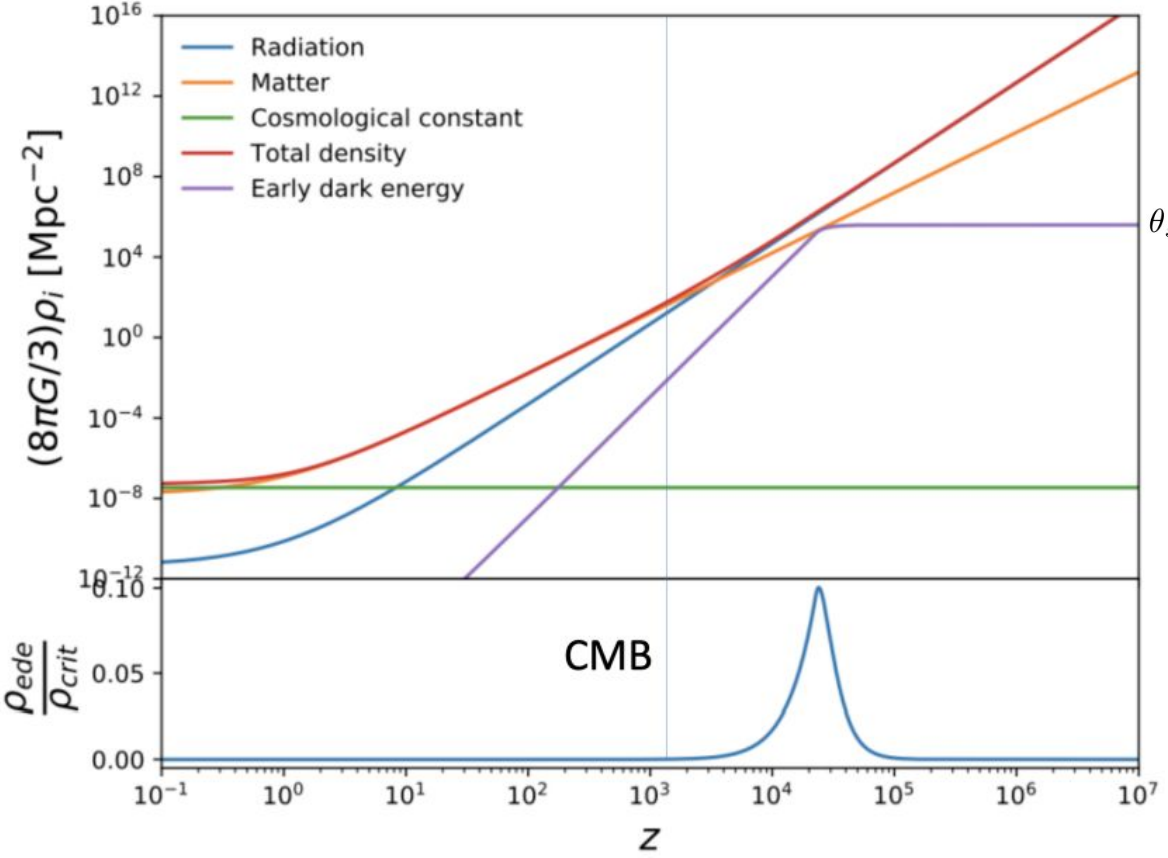
Elaborate Models

- **Varying electron mass** ($m_{e,early}/m_{e,late}$)
  - $+\Sigma m_\nu$
  - $+\Omega_K$
  - $+\Sigma m_\nu + \Omega_K$

Early Dark Energy

- Also motivated by higher dimensional theories.
- A scalar field contributes briefly to the expansion rate around matter-radiation equality.
- Decrease in sound horizon, compensated by increase in H_0.
- References: Poulin *et al.*, 2018 (1811.04083), Smith & Poulin, 2023 (2309.03265)

Early Dark Energy



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Kamionkowski & Riess,2022 (2211.04492)

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- **Early Dark Energy:**
  - Θ_i: Initial value of the scalar field
  - Z_c: Critical redshift, i.e. the field becomes dynamical
  - $f_{EDE} = \rho_{EDE}/\rho_{tot}$

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  - **$+\Sigma m_\nu + \Omega_K$**
- **Early Dark Energy (θ_i, z_c, f_{EDE})**
- **The Majoron:**

  Breaking lepton number symmetry produces a pseudo-scalar (φ) that gives neutrinos their mass (like the Higgs). A particle Physics motivated SIDR.

  Free parameters: m_φ, Γ_{eff} and N_{DR}

  More details: Escudero & Witte, 2020 (1909.04044); Escudero & Witte, 2021 (2103.03249)

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  - $f_{EDE} = \rho_{EDE}/\rho_{tot}$
- **The Majoron:**
  - m_φ: Mass of Majoron
  - Γ_{eff}: Effective Majoron to neutrinos decay rate
  - N_{ADR}: Number of additional Dark Radiation. $N_{ADR}=N_{eff}-3.044$

Tension Metrics

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*
  What's the probability of getting 0 in the distribution of the difference between SH0ES and a model's H_0 posteriors?

$$\mathcal{P}(\delta) = \mathcal{N} \int dH_0 \, \mathcal{P}_{\rm model}(H_0) \, \mathcal{P}_{\rm SH0ES}(H_0 - \delta) \simeq \mathcal{N}' \sum_i w_i \, \mathcal{P}_{\rm SH0ES}(H_{0,i} - \delta)$$

Normalisation ($\mathcal{N}$)

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Weights from chains (w_i)

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Tension in units of σ, denoted by $Q_{\rm MPCL}$

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Ref: Doux & Raveri,2021 (2105.03324); Leizerovich, Landau & Scóccola, 2023 (2312.08542)

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*

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- *Difference of the Maximum A Posteriori (DMAP):*

  $Q_{\mathrm{DMAP,\ model}} \equiv \sqrt{\chi^2_{\mathrm{min,\ model,}\ \mathcal{D}+SH0ES} - \chi^2_{\mathrm{min,\ model,}\ \mathcal{D}}}$; $\chi^2 = -2\ln\mathcal{L}$; $\mathcal{D}$ ≡ data set

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- *Akaike Information Criterion (AIC):*

$$\Delta\mathrm{AIC}_{\mathrm{model}} = \chi^2_{\mathrm{min,\ model,}\ \mathcal{D}+SH0ES} - \chi^2_{\mathrm{min,}\ \Lambda\mathrm{CDM},\mathcal{D}+SH0ES} + 2\left(N_{\mathrm{model}} - N_{\Lambda\mathrm{CDM}}\right) .$$

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- *AIC without SH0ES*

Data Sets & Numerical Tools

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- Data sets:
  - SPT-3G 2018: TT,TE,EE
  - Planck 2018: TT,TE,EE+Lensing
  - BAO: 6dFGS+SDSS MGS, DR12-16
  - ACT: DR4
  - Pantheon SN Ia
- Theory Codes: CLASS, AxiCLASS and CAMB
- Monte Carlo Sampler: COBAYA
- Minimizing χ^2: Py-BOBYQA
- New cosmological emulator (2307.01138)
- Our reference data set: SPT+Planck+BAO+Pantheon (SPBP)

Results

Main Results

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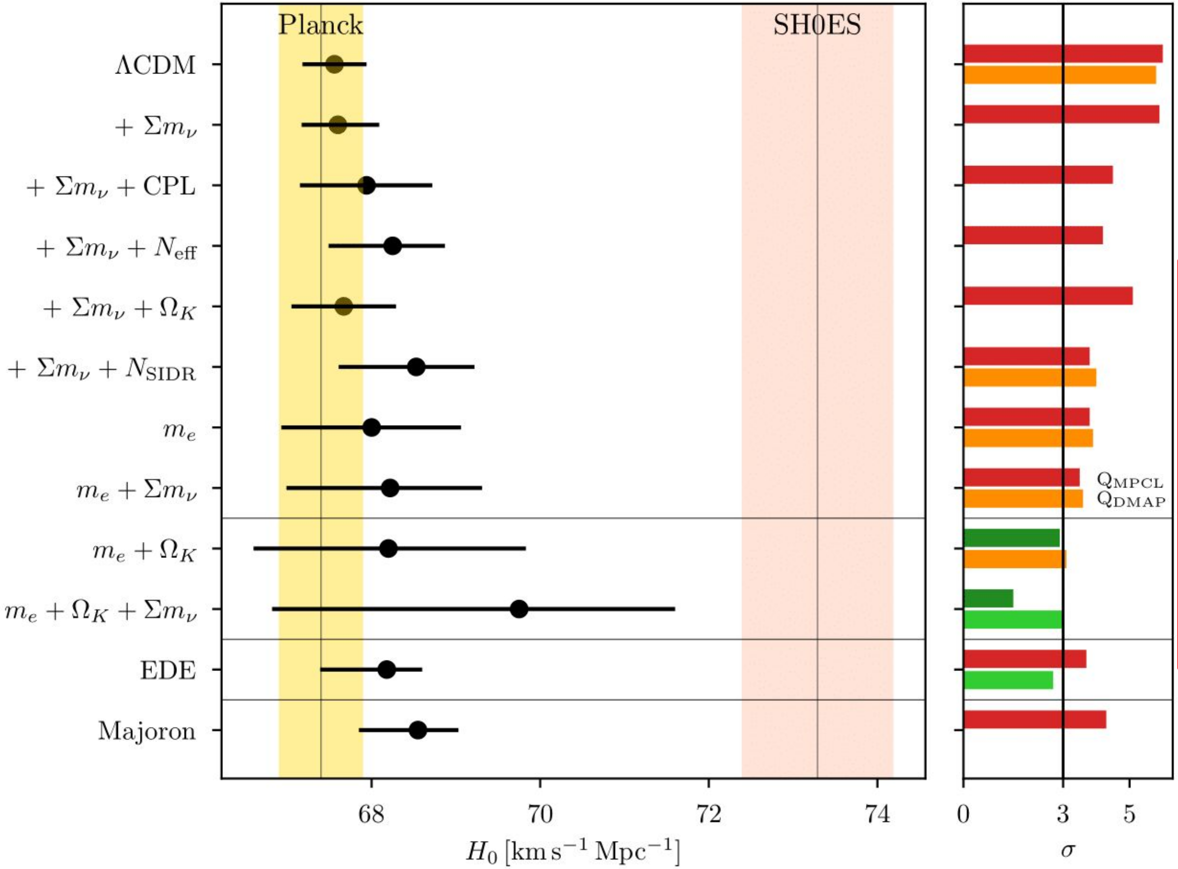

None of the models completely solve the tension.
Only $m_e+\Omega_K$, $m_e+\Omega_K+\Sigma m_\upsilon$ and EDE reduce it below 3σ

Main Results

				w/o SH0ES		w/ SH0ES	
Models	H_0(km/s/Mpc)	$Q_{\rm MPCL}(\sigma)$	$Q_{\rm DMAP}(\sigma)$	$\Delta\chi^2$	ΔAIC	$\Delta\chi^2$	ΔAIC
ΛCDM	$67.56(67.58)^{+0.38}_{-0.38}$	6.0	5.8	0	0	0	0
$+\Sigma m_\nu$	$67.60(67.01)^{+0.49}_{-0.43}$	5.9	—	—	—	—	—
$+\Sigma m_\nu$+CPL	$67.94(67.89)^{+0.78}_{-0.79}$	4.5	—	—	—	—	—
$+\Sigma m_\nu+$ N$_{\rm eff}$	$68.25(67.45)^{+0.62}_{-0.76}$	4.2	—	—	—	—	—
$+\Sigma m_\nu+\Omega_K$	$67.67(66.88)^{+0.62}_{-0.62}$	5.1	—	—	—	—	—
$+\Sigma m_\nu+$ N$_{\rm SIDR}$	$68.53(69.06)^{+0.69}_{-0.92}$	3.8	4.0	-0.1	3.9	-17.1	-13.1
m_e	$68.00(68.03)^{+1.06}_{-1.07}$	3.8	3.9	0.0	2.0	-18.0	-16.0
$m_e+\Sigma m_\nu$	$68.22(67.70)^{+1.09}_{-1.23}$	3.5	3.6	-0.9	3.1	-21.6	-17.6
$m_e+\Omega_K$	$68.20(67.42)^{+1.63}_{-1.60}$	**2.9**	3.1	-1.0	3.0	-24.7	-20.7
$m_e+\Omega_K+\Sigma m_\nu$	$69.75(67.75)^{+1.85}_{-2.93}$	**1.5**	**3.0**	-0.9	5.1	-25.8	-19.8
EDE	$68.18(68.55)^{+0.42}_{-0.79}$	3.8	**2.7**	-4.6	1.4	-31.1	-25.1
Majoron	$68.55(68.08)^{+0.48}_{-0.70}$	4.3	—	—	—	—	—

Compare with Olympics Paper

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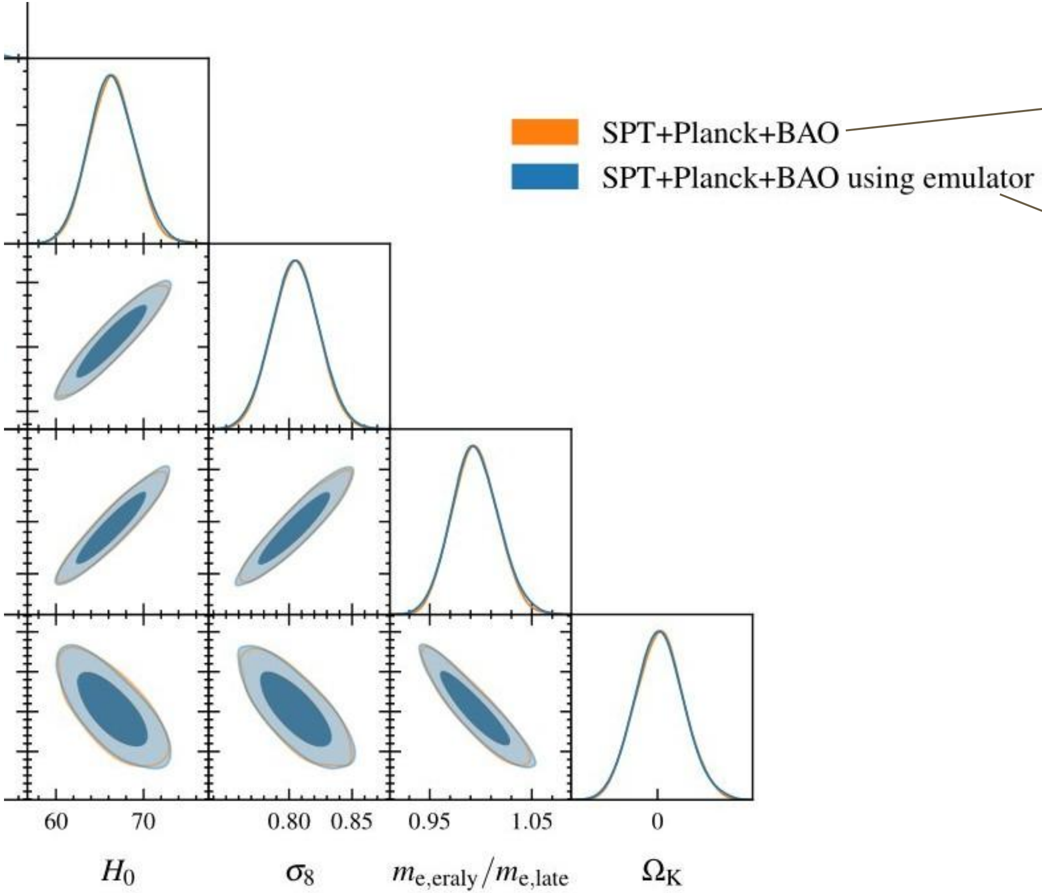
The Power of an Emulator



3 days of running time

10 hrs of running time

Conclusions & Future Works

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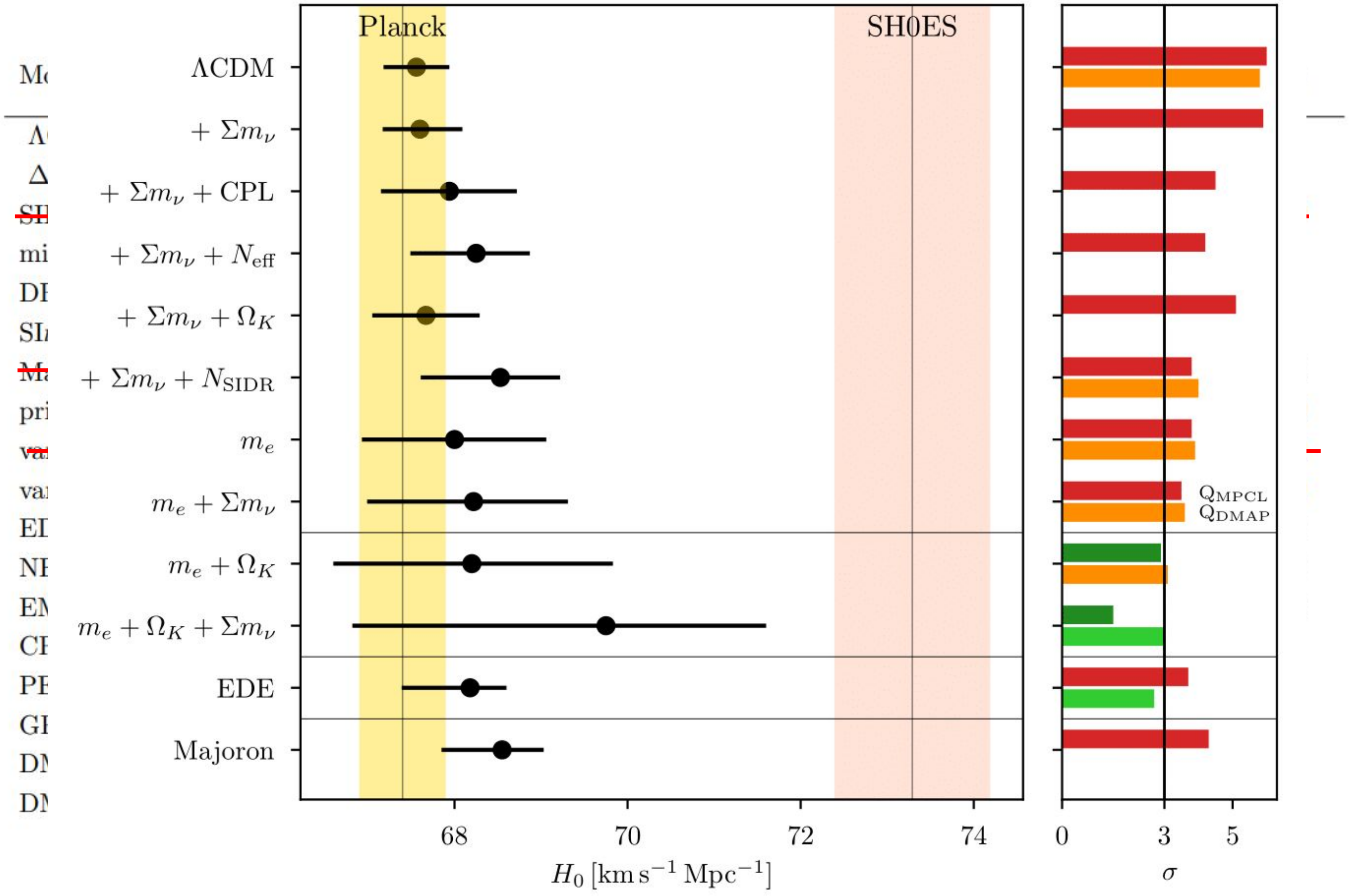
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

Conclusions & Future Works

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 $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗	
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗	

Conclusions & Future Works



Conclusions & Future Plans

- Further investigation of these models, theoretically, is needed.
- Revisit these models, along with others, with upcoming SPT-3G 2019/2020 and ACT DR6 data.

Thank you!

Questions? Comments?

Back Up

Results

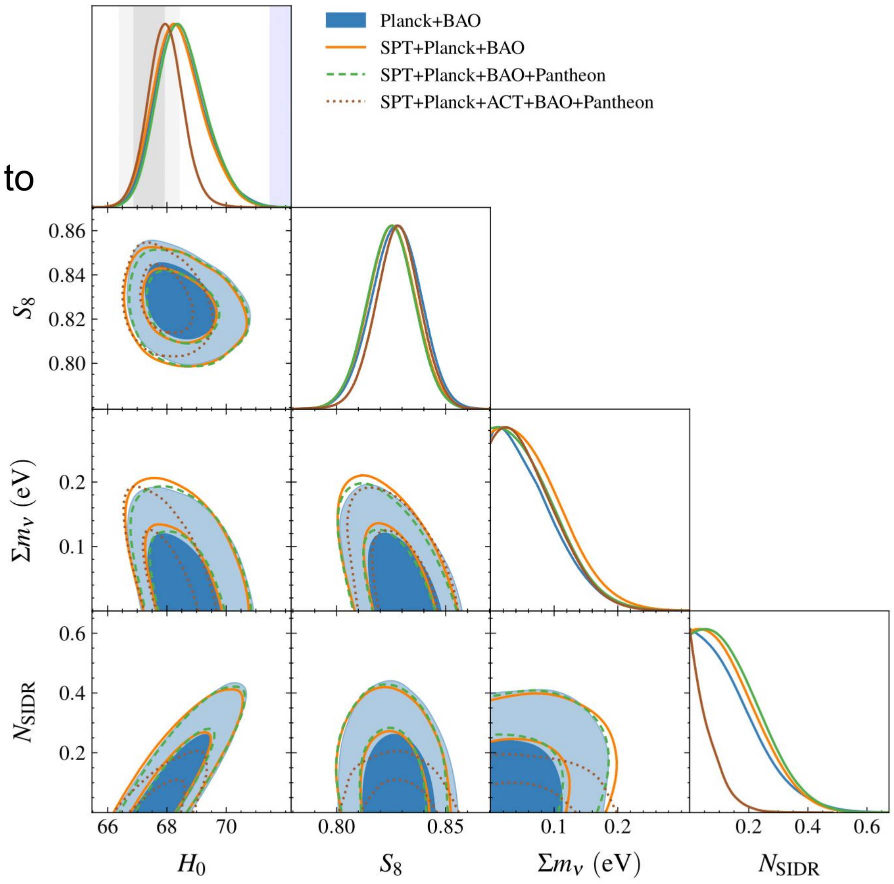
Further Results

Q_{MPCL} for Each Model and Data-set

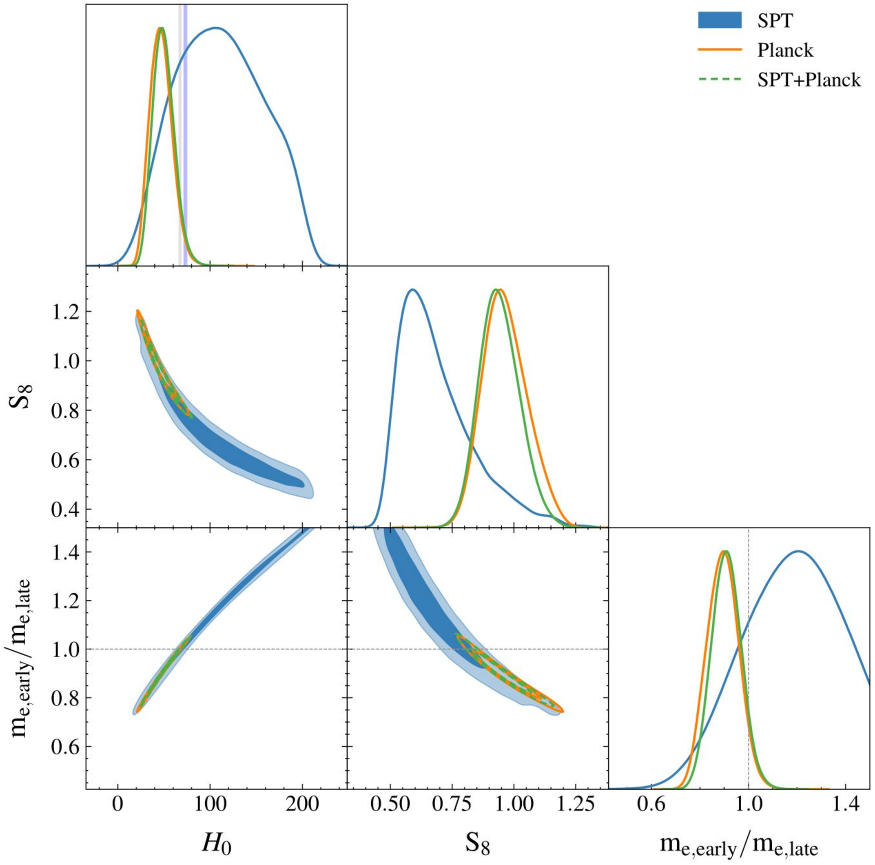
	$\mathcal{D}_{S}$	$\mathcal{D}_{SP}$	$\mathcal{D}_{SB}$	$\mathcal{D}_{PB}$	$\mathcal{D}_{SPB}$	$\mathcal{D}_{SPBP}$	$\mathcal{D}_{SPAB}$	$\mathcal{D}_{SPABP}$
ΛCDM	**2.7 σ**	6.0 σ	5.4 σ	5.9 σ	6.3 σ	6.0 σ	6.3 σ	6.1 σ
$+\ \Sigma m_\nu$	3.4 σ	5.4 σ	5.6 σ	5.7 σ	6.0 σ	5.9 σ	5.9 σ	5.9 σ
$+\ \Sigma m_\nu$ + CPL	**0.5 σ**	**0.0 σ**	3.3 σ	3.1 σ	3.2 σ	4.5 σ	4.1 σ	4.5 σ
$+\ \Sigma m_\nu + N_{\text{eff}}$	**1.4 σ**	4.0 σ	**1.3 σ**	4.0 σ	4.3 σ	4.2 σ	5.0 σ	5.1 σ
$+\ \Sigma m_\nu + \Omega_K$		4.0 σ	5.2 σ	5.2 σ	5.2 σ	5.1 σ	5.3 σ	5.3 σ
$+\ \Sigma m_\nu + N_{\text{SIDR}}$	**1.7 σ**	**3.0 σ**	**1.8 σ**	3.7 σ	3.9 σ	3.8 σ	4.8 σ	4.7 σ
m_e	**-0.1 σ**	**1.4 σ**	3.3 σ	3.8 σ	3.9 σ	3.8 σ	3.8 σ	3.8 σ
$m_e + \Sigma m_\nu$	**0.0 σ**	**1.9 σ**	**0.4 σ**	3.5 σ	3.4 σ	3.5 σ	3.7 σ	3.7 σ
$m_e + \Omega_K$	**-0.7 σ**	**1.8 σ**	3.3 σ	**1.9 σ**	**2.8 σ**	**2.9 σ**	**2.8 σ**	**2.8 σ**
$m_e + \Omega_K + \Sigma m_\nu$			**1.2 σ**	**1.0 σ**	**1.3 σ**	**1.4 σ**	**1.4 σ**	**1.4 σ**
EDE	**1.5 σ**	4.2 σ	**2.2 σ**	3.8 σ	3.7 σ	3.7 σ	3.1 σ	3.1 σ
Majoron	**-0.1 σ**	3.7 σ	**1.4 σ**	4.0 σ	4.2 σ	4.3 σ	4.0 σ	4.4 σ

ΛCDM Extensions

- Q_{MPCL} ≥3.1σ for all models with at least Planck+BAO.
- SPT & ACT marginally increase the tension compared to Planck+BAO.
- Expected degeneracies.
- ACT is slightly less compatible with larger N_{SIDR}.

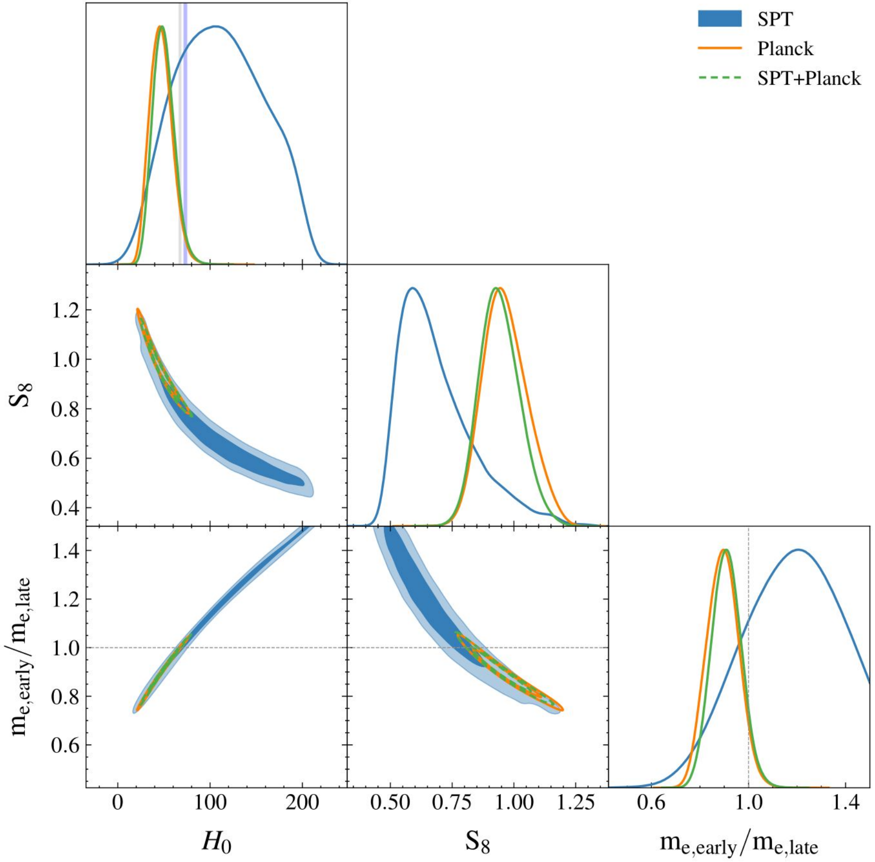


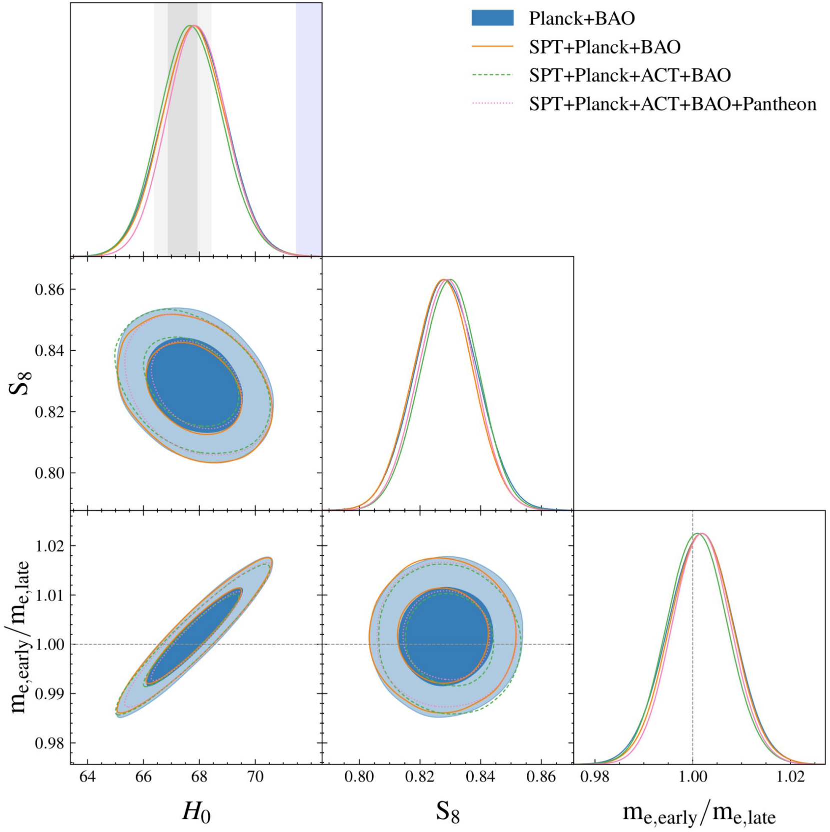
Varying Electron Mass



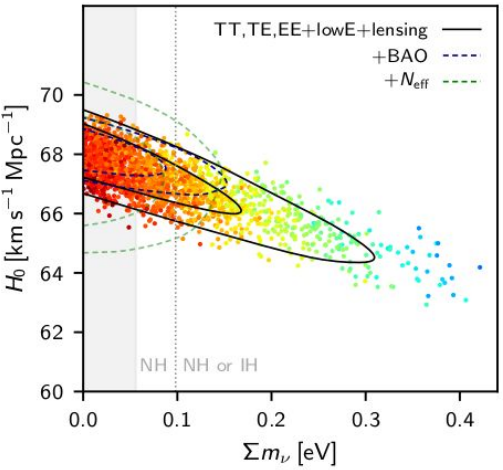
- No longer a potential solution to the tension.
- Planck is still more constraining than SPT.
- CMB alone cannot constrain this model.

Varying Electron Mass



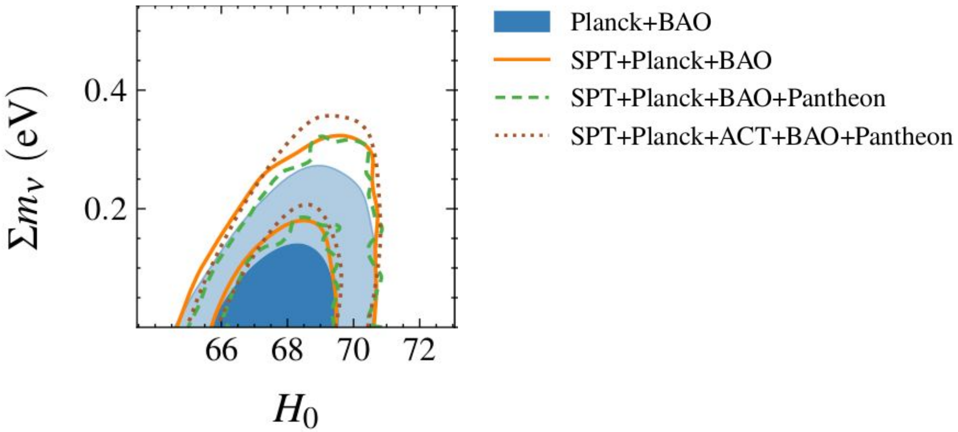


Varying Electron Mass+Σm_ν

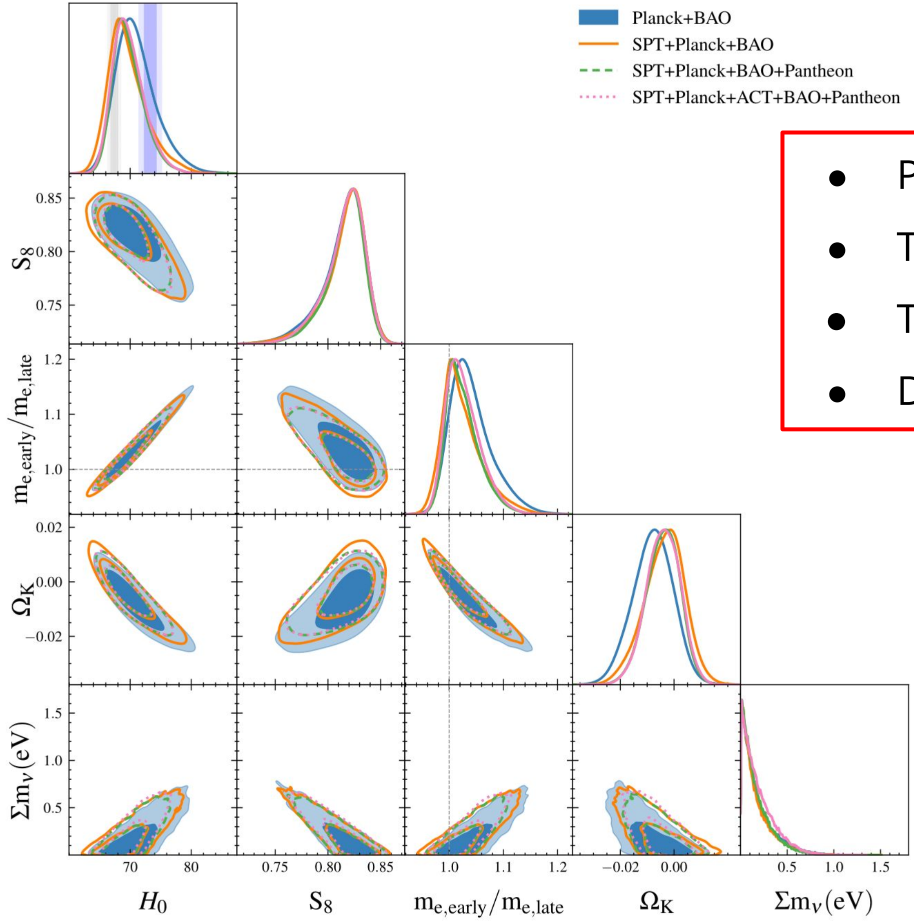


Planck 2018 (Aghanim et al.)

- Allowing Σm_ν to vary doesn't help.
- Degeneracy direction in the Σm_ν-H_0 flips.

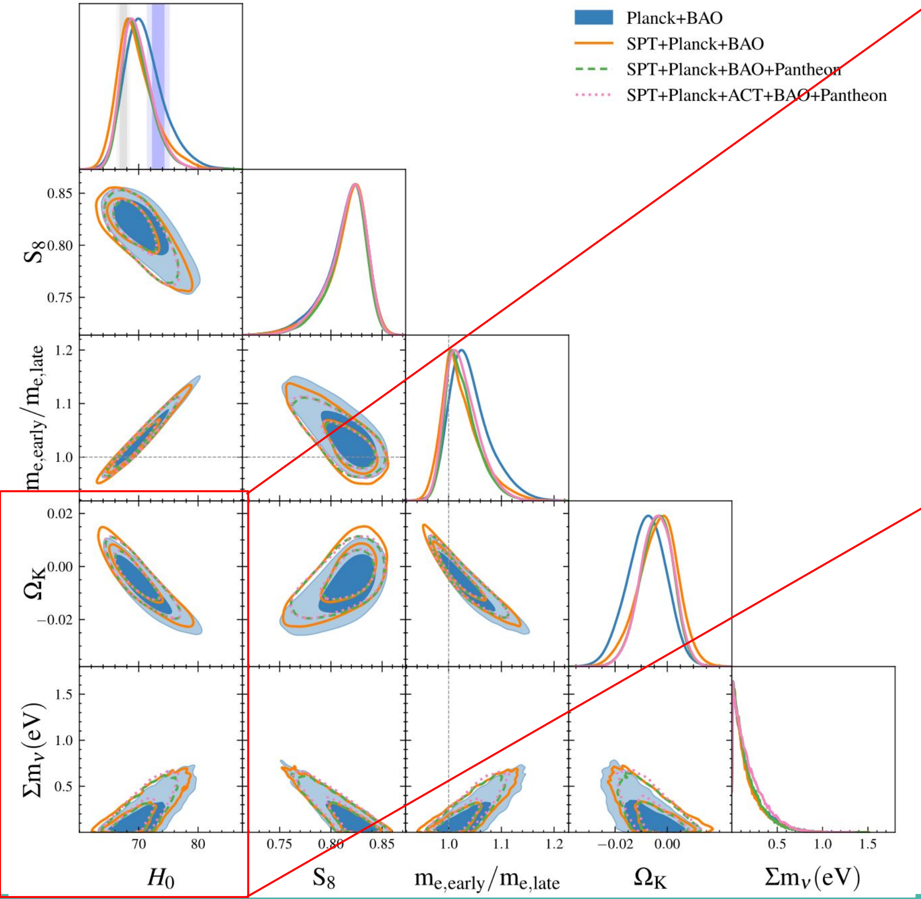


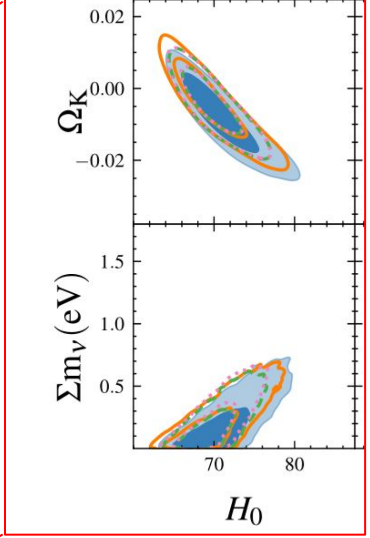
Varying Electron Mass+Σm_υ+Ω_K

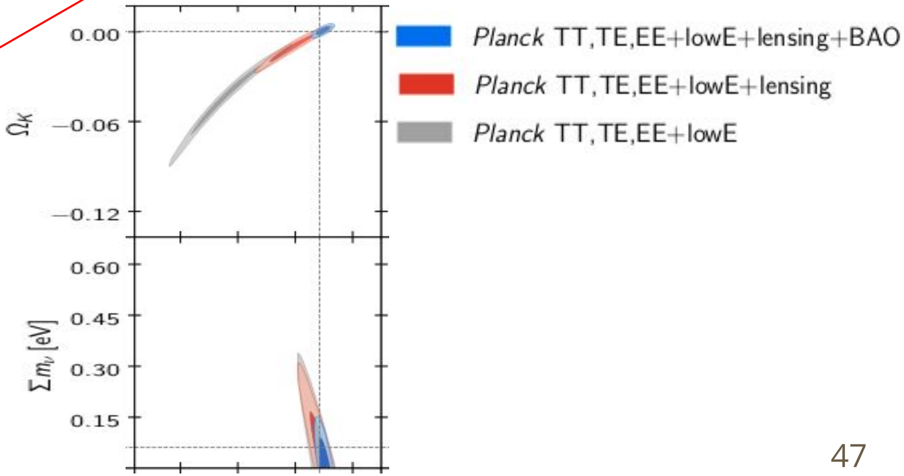


- Polarization data from SPT is particularly useful.
- The model that reduces the tension the most.
- The model with the largest error bars.
- Degeneracy direction also flips in the Ω_K-H_0 plane.

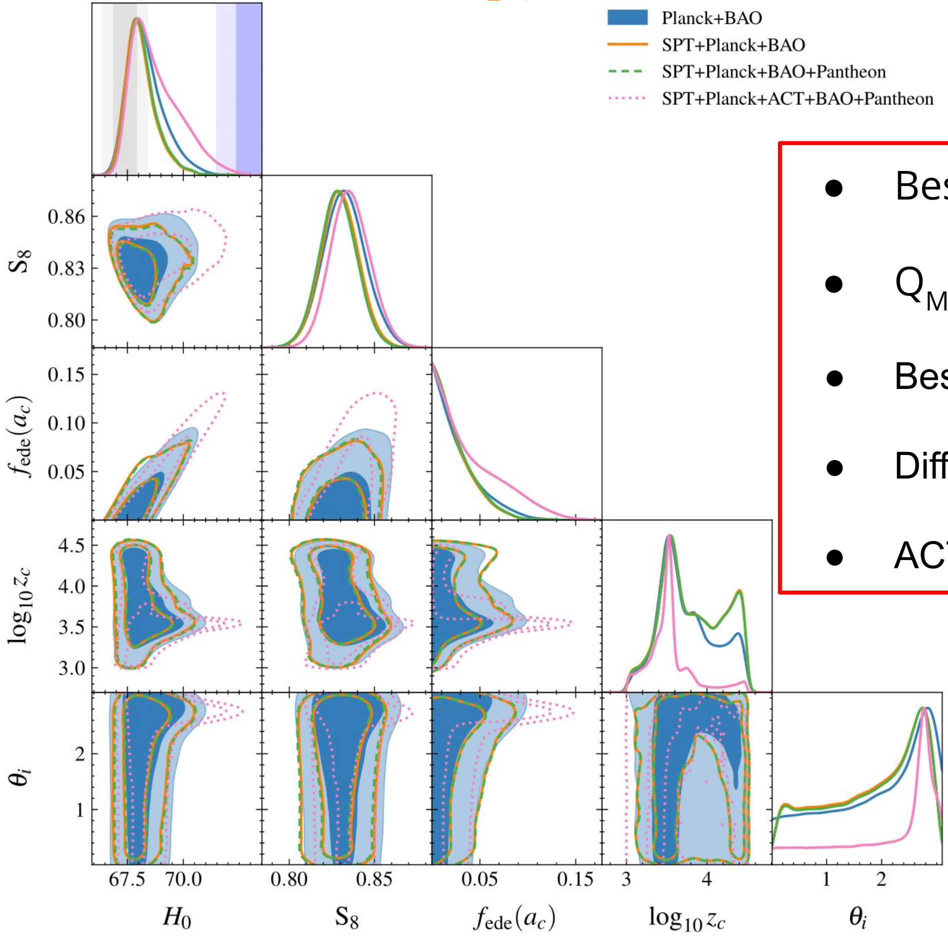
Varying Electron Mass+$\Sigma m_\nu+\Omega_K$





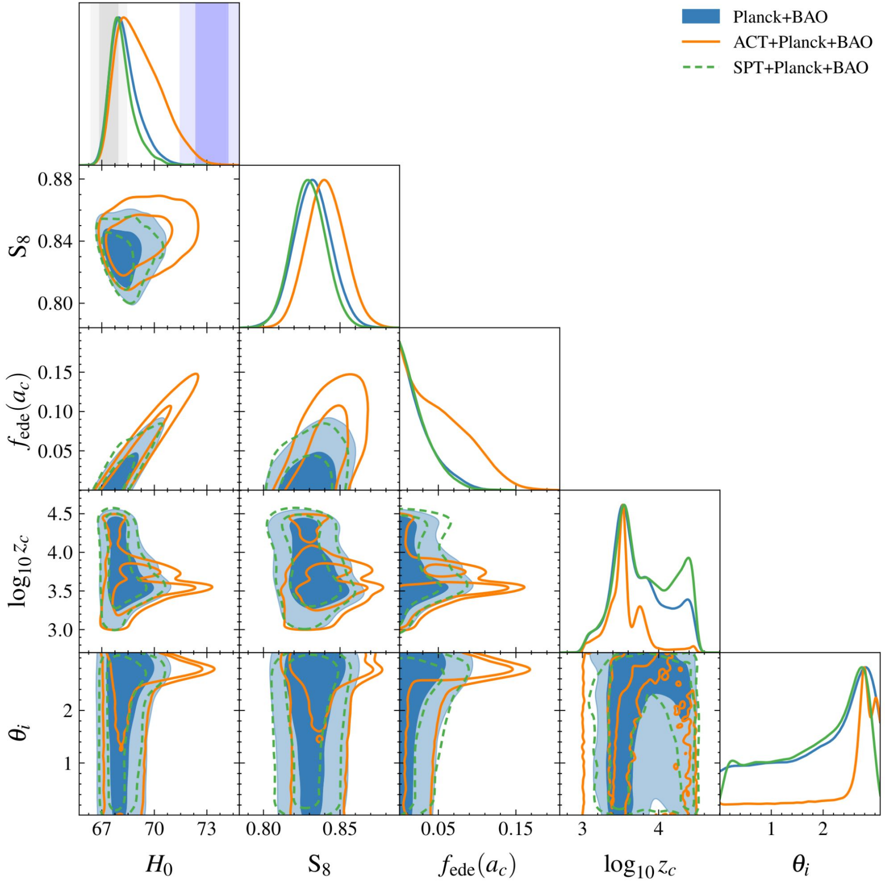


Early Dark Energy

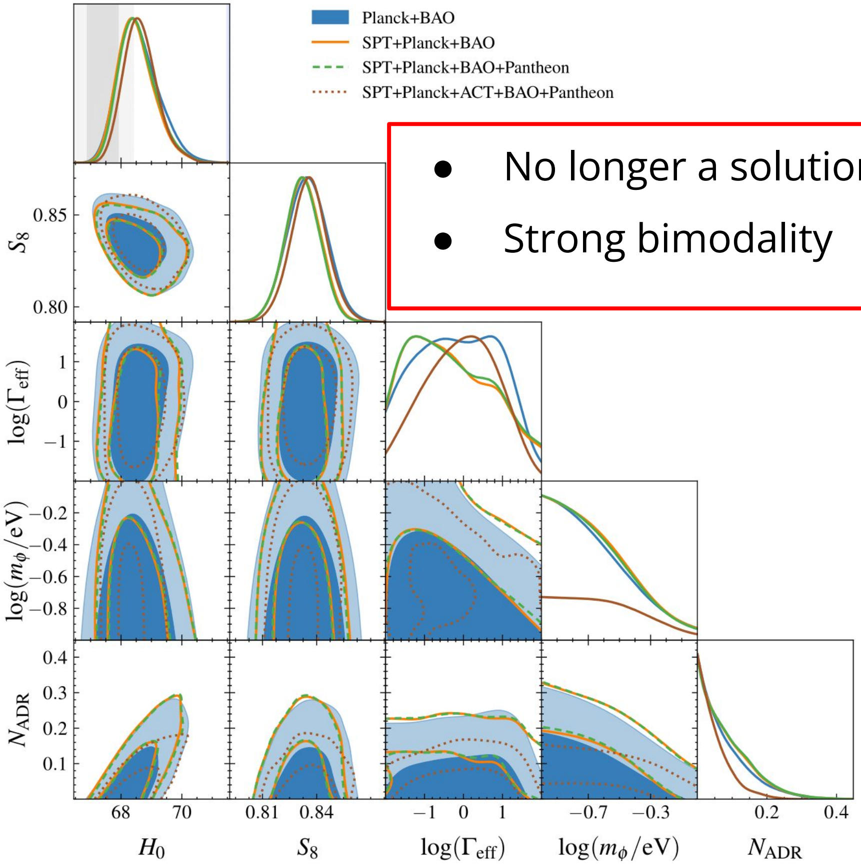


- Best constrained by CMB.
- Q_{MPCL}= 3.7σ while Q_{DMAP}=2.7σ for SPBP.
- Best-fit χ^2 compared to all models, w/ and w/o SH0ES.
- Difficult to constrain, with some bimodality.
- ACT DR4 is compatible with higher f_{EDE}.

Early Dark Energy: SPT vs ACT

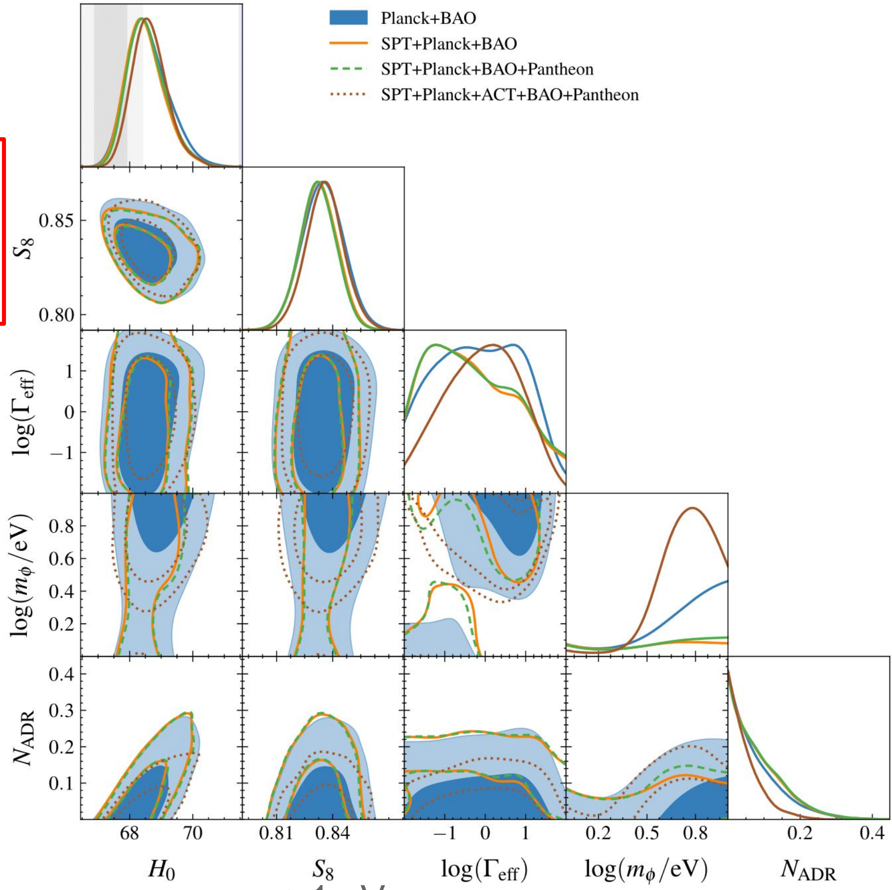


The Majoron



m_φ<1 eV

- No longer a solution
- Strong bimodality

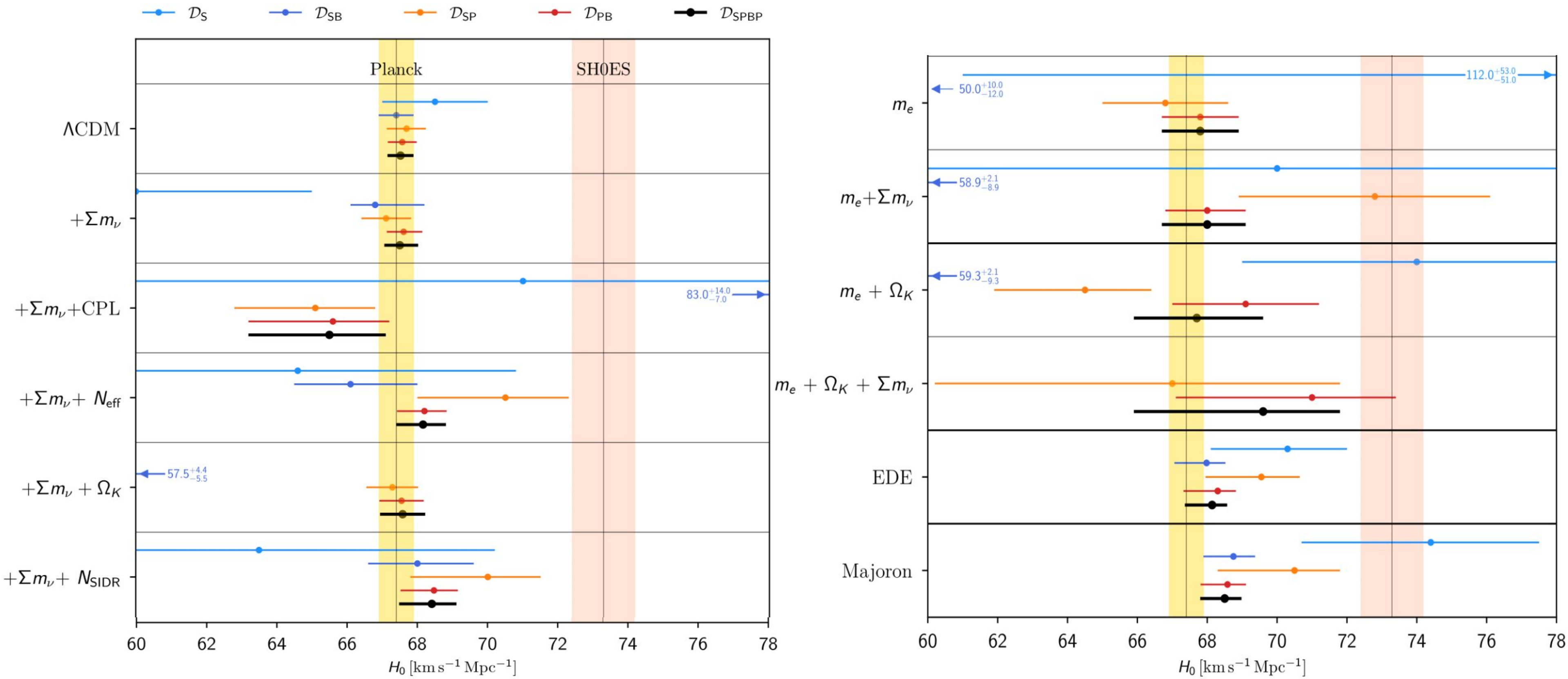


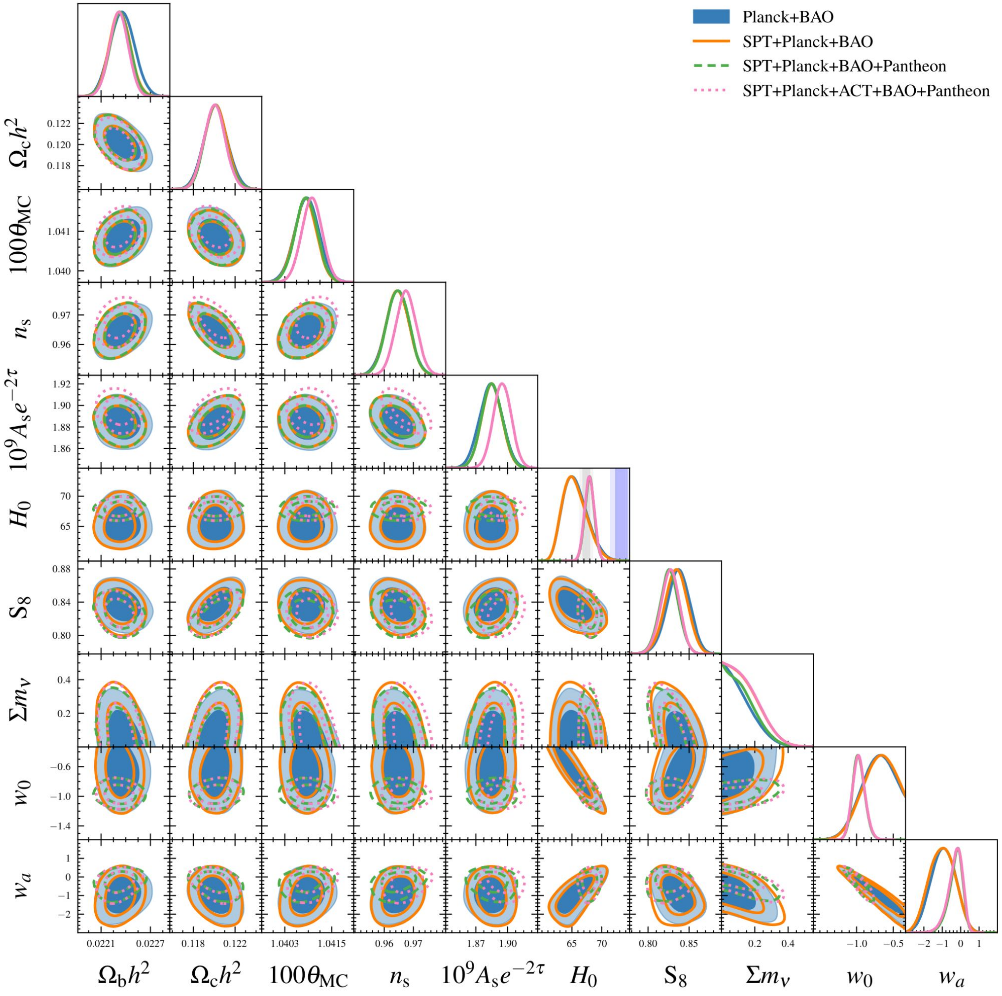
m_φ>1 eV

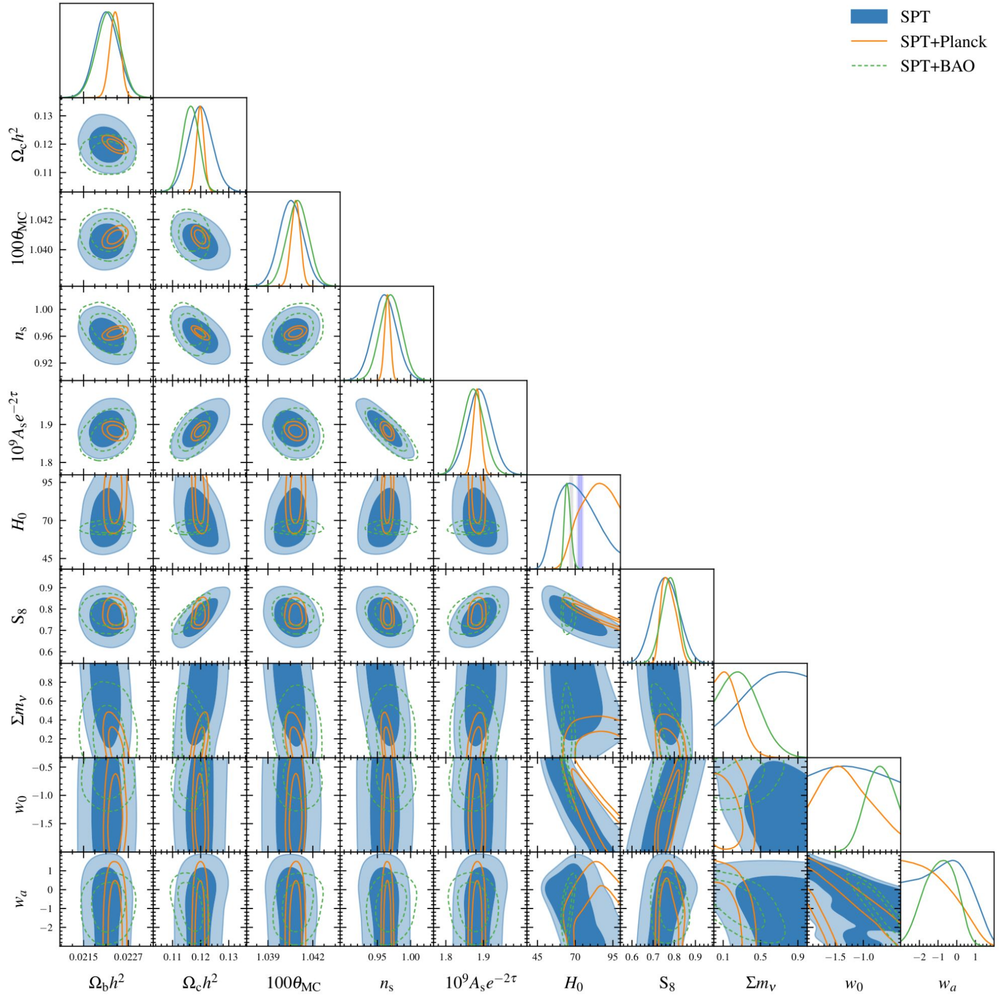
The Power of an Emulator

- Boltzmann codes are the tightest bottleneck of Bayesian analysis.
- To speed up the process, use neural-networks based emulators of Boltzmann codes.
- Classical emulators build on previously trained samples.
- The emulator we use builts its training data while running, i.e. online
- Stable results for minimizations
- Refs: arXiv:2307.01138
  https://github.com/svenguenther/cobaya

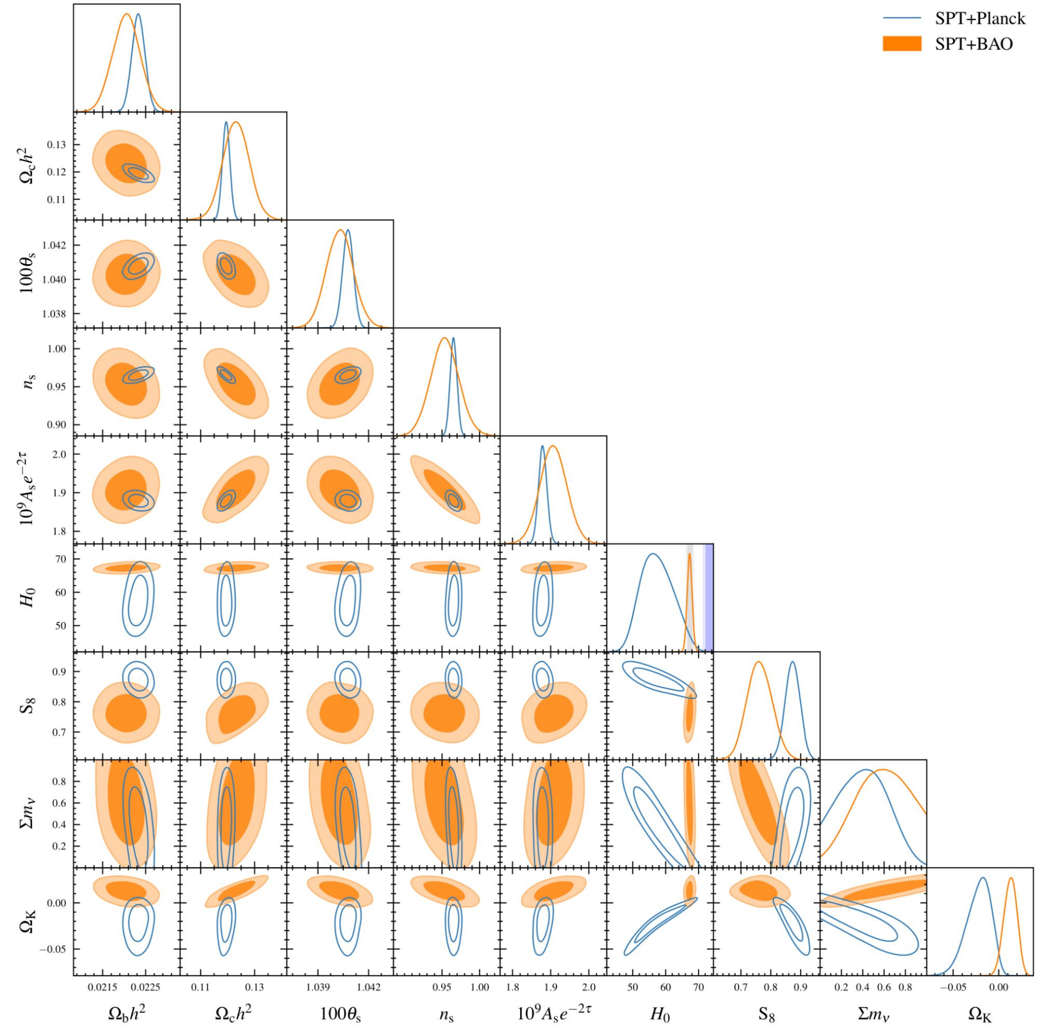
H_0 for Each Model and Data-set



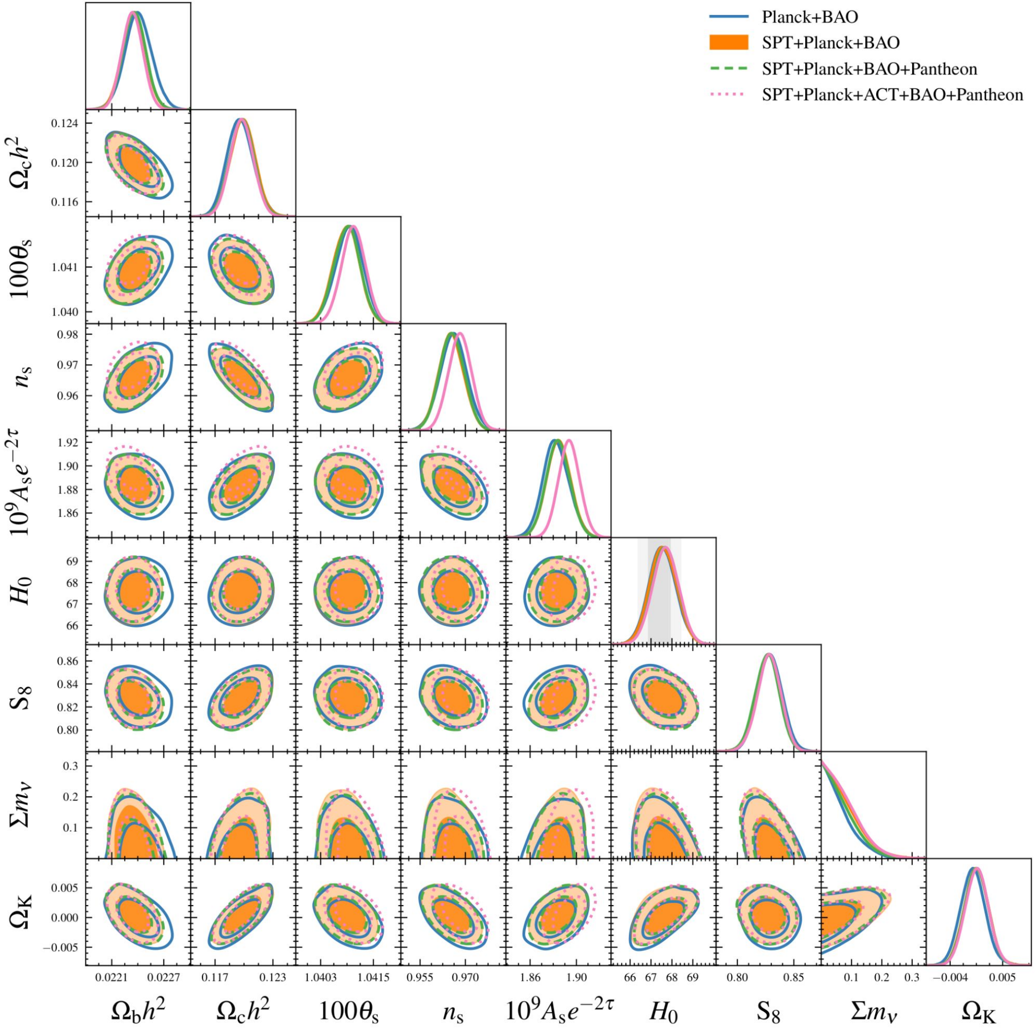

Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
w_0
w_a



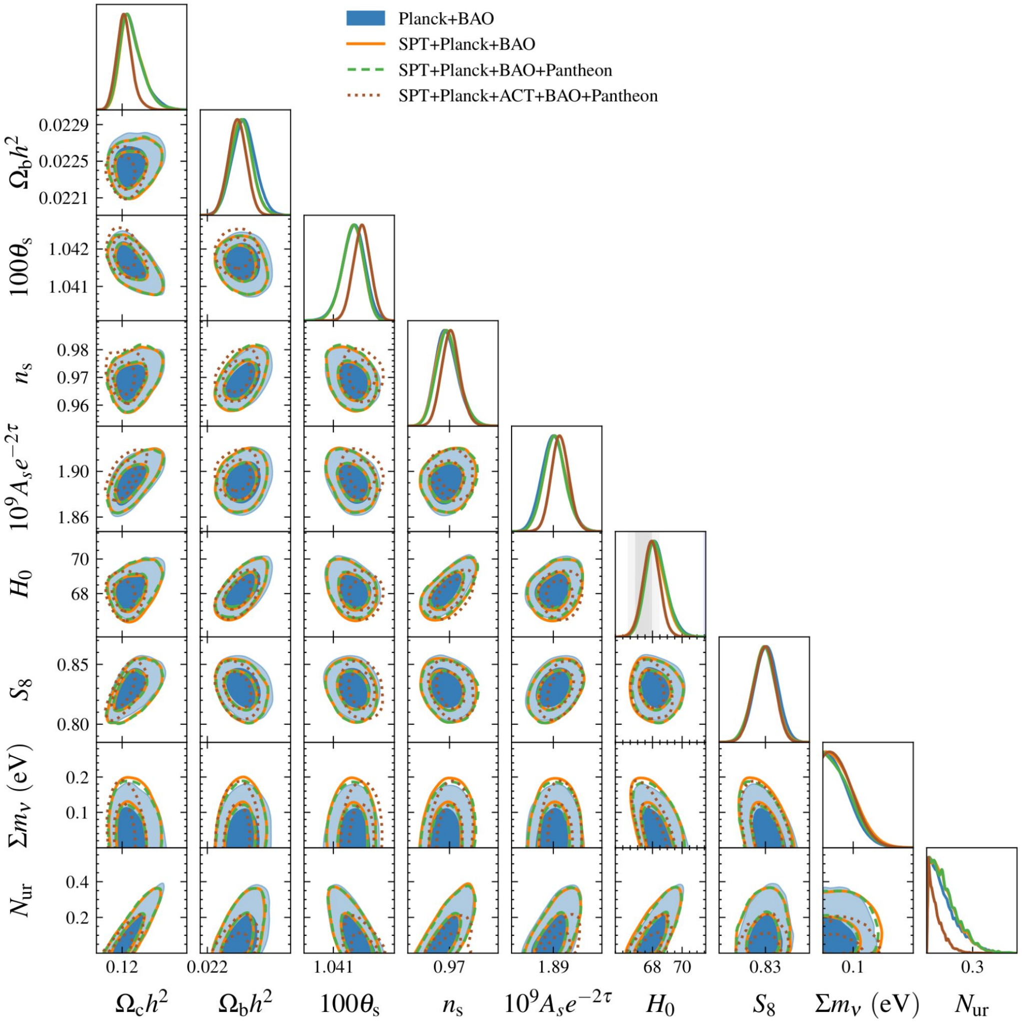
SPT
SPT+Planck
SPT+BAO
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
w_0
w_a



SPT+Planck
SPT+BAO
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_s$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
Ω_K



Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_c h^2$
$100\theta_s$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
Ω_K
$\Omega_b h^2$

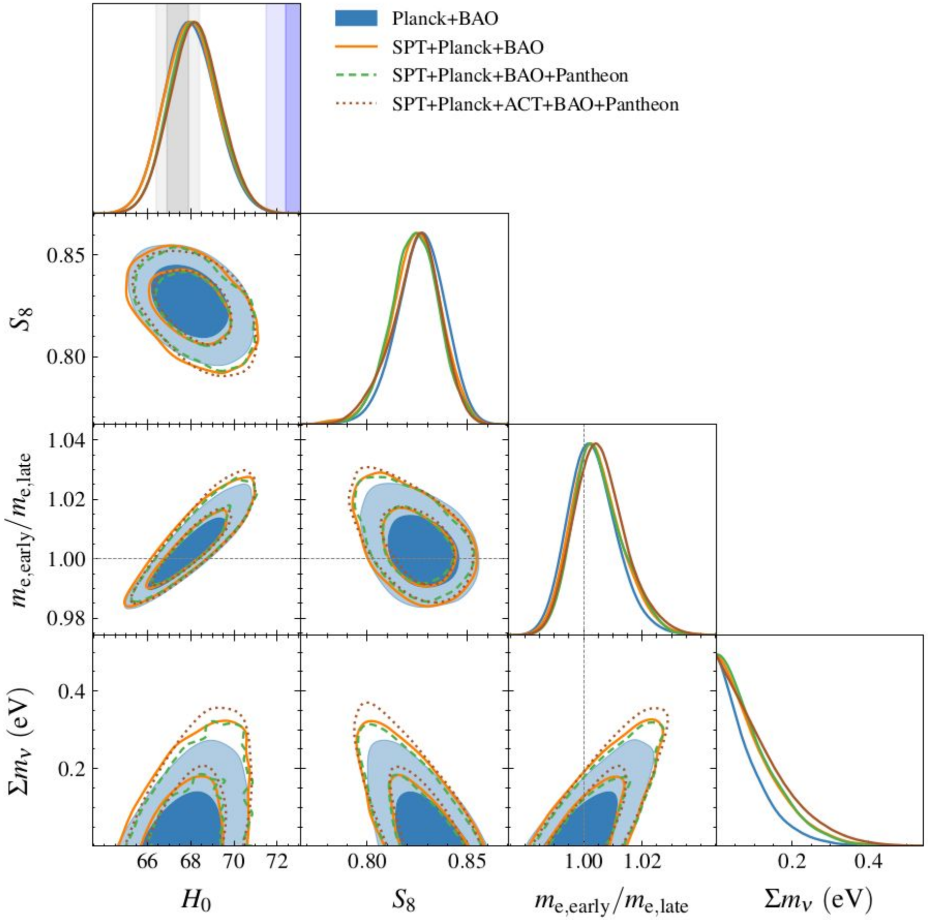


Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_b h^2$
0.0229
0.0225
0.0221
$100\theta_s$
1.042
1.041
n_s
0.98
0.97
0.96
$10^9 A_s e^{-2\tau}$
1.90
1.86
H_0
70
68
S_8
0.85
0.80
Σm_ν (eV)
0.2
0.1
N_{ur}
0.4
0.2
0.12
0.022
1.041
0.97
1.89
68
70
0.83
0.1
0.3
$\Omega_c h^2$
$\Omega_b h^2$
$100\theta_s$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν (eV)
N_{ur}

Models	$\mathcal{D}_{\mathrm{S}}$	$\mathcal{D}_{\mathrm{SP}}$	$\mathcal{D}_{\mathrm{SB}}$	$\mathcal{D}_{\mathrm{PB}}$	$\mathcal{D}_{\mathrm{SPB}}$	$\mathcal{D}_{\mathbf{SPBP}}$	$\mathcal{D}_{\mathrm{SPAB}}$	$\mathcal{D}_{\mathrm{SPABP}}$
ΛCDM	$68.5^{+1.5}_{-1.5}$	$67.40^{+0.49}_{-0.50}$	$67.69^{+0.55}_{-0.56}$	$67.57^{+0.41}_{-0.41}$	$67.52^{+0.37}_{-0.37}$	$\mathbf{67.56^{+0.35}_{-0.38}}$	$67.49^{+0.34}_{-0.39}$	$67.53^{+0.34}_{-0.37}$
$+\Sigma m_\nu$	$60.0^{+5.0}_{-5.6}$	$66.8^{+1.4}_{-0.7}$	$67.11^{+0.71}_{-0.70}$	$67.61^{+0.53}_{-0.48}$	$67.50^{+0.52}_{-0.44}$	$\mathbf{67.60^{+0.49}_{-0.43}}$	$67.50^{+0.58}_{-0.44}$	$67.59^{+0.53}_{-0.42}$
$+\Sigma m_\nu$+CPL	71^{+10}_{-15}	83^{+14}_{-7}	$65.1^{+1.7}_{-2.3}$	$65.6^{+1.6}_{-2.4}$	$65.6^{+1.6}_{-2.4}$	$\mathbf{67.94^{+0.78}_{-0.79}}$	$66.5^{+1.3}_{-1.7}$	$67.92^{+0.81}_{-0.81}$
$+\Sigma m_\nu + N_{\mathrm{eff}}$	$64.6^{+6.2}_{-7.0}$	$66.1^{+1.9}_{-1.6}$	$70.5^{+1.8}_{-2.5}$	$68.20^{+0.63}_{-0.78}$	$68.16^{+0.65}_{-0.76}$	$\mathbf{68.25^{+0.62}_{-0.76}}$	$67.83^{+0.58}_{-0.60}$	$67.93^{+0.57}_{-0.58}$
$+\Sigma m_\nu + \Omega_{\mathrm{k}}$	—	$57.4^{+4.4}_{-5.5}$	$67.29^{+0.73}_{-0.74}$	$67.55^{+0.63}_{-0.63}$	$67.58^{+0.64}_{-0.64}$	$\mathbf{67.67^{+0.62}_{-0.62}}$	$67.59^{+0.64}_{-0.64}$	$67.69^{+0.62}_{-0.62}$
$+\Sigma m_\nu + N_{\mathrm{SIDR}}$	$63.5^{+6.7}_{-6.8}$	$68.0^{+1.6}_{-1.4}$	$70.0^{+1.5}_{-2.2}$	$68.47^{+0.68}_{-0.95}$	$68.41^{+0.70}_{-0.93}$	$\mathbf{68.53^{+0.69}_{-0.92}}$	$67.86^{+0.60}_{-0.61}$	$67.96^{+0.57}_{-0.58}$
m_e	112^{+53}_{-51}	50^{+10}_{-13}	$66.8^{+1.8}_{-1.8}$	$67.8^{+1.1}_{-1.1}$	$67.8^{+1.1}_{-1.1}$	$\mathbf{68.0^{+1.1}_{-1.1}}$	$67.7^{+1.1}_{-1.1}$	$67.9^{+1.1}_{-1.1}$
$m_e + \Sigma m_\nu$	70^{+20}_{-20}	$58.9^{+2.1}_{-8.9}$	$72.8^{+3.3}_{-3.9}$	$68.0^{+1.1}_{-1.2}$	$68.0^{+1.1}_{-1.3}$	$\mathbf{68.2^{+1.1}_{-1.2}}$	$68.0^{+1.2}_{-1.2}$	$68.2^{+1.2}_{-1.2}$
$m_e + \Omega_k$	74^{+16}_{-5}	$59.3^{+2.1}_{-9.3}$	$64.5^{+1.9}_{-2.6}$	$69.1^{+2.1}_{-2.1}$	$67.7^{+1.9}_{-1.8}$	$\mathbf{68.2^{+1.6}_{-1.6}}$	$67.5^{+1.9}_{-1.9}$	$68.1^{+1.6}_{-1.6}$
$m_e + \Omega_k + \Sigma m_\nu$	—	—	$67.0^{+4.8}_{-6.8}$	$71.0^{+2.4}_{-3.9}$	$69.6^{+2.2}_{-3.7}$	$\mathbf{69.8^{+1.8}_{-2.9}}$	$69.5^{+2.3}_{-3.7}$	$69.8^{+2.0}_{-3.0}$
EDE	$70.3^{+1.7}_{-2.2}$	$67.98^{+0.54}_{-0.92}$	$69.6^{+0.9}_{-1.6}$	$68.3^{+0.52}_{-0.98}$	$68.12^{+0.43}_{-0.78}$	$\mathbf{68.18^{+0.42}_{-0.79}}$	$68.7^{+0.6}_{-1.4}$	$68.8^{+0.6}_{-1.4}$
Majoron	$74.4^{+3.1}_{-3.7}$	$68.75^{+0.62}_{-0.86}$	$70.5^{+1.3}_{-2.2}$	$68.58^{+0.53}_{-0.77}$	$68.50^{+0.48}_{-0.70}$	$\mathbf{68.55^{+0.48}_{-0.70}}$	$68.6^{+0.46}_{-0.64}$	$68.64^{+0.48}_{-0.61}$

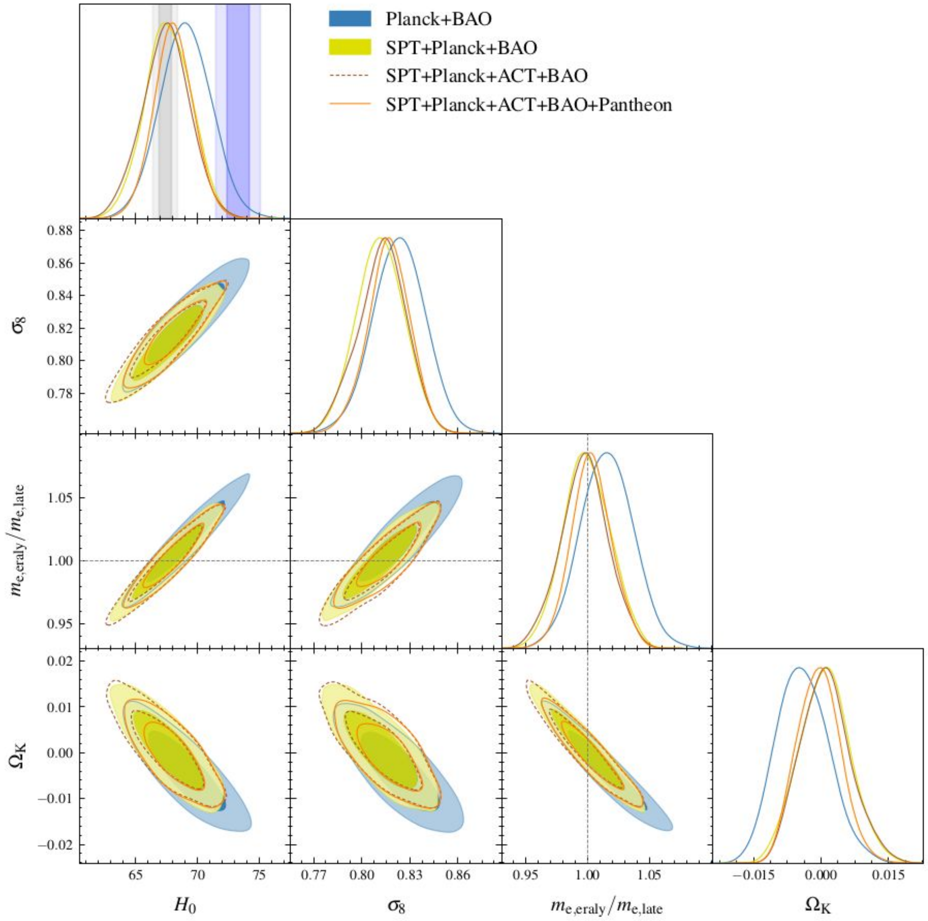
Models	Additional Parameters
ΛCDM	—
$+\Sigma m_\nu$	$\Sigma m_\nu < 0.16$ eV (95%)
$+\Sigma m_\nu$+CPL	$\Sigma m_\nu < 0.29$ eV (95%), $w_0 = -0.97 \pm 0.08$, $w_a = -0.29 \pm 0.39$
$+\Sigma m_\nu + N_{\rm eff}$	$\Sigma m_\nu < 0.15$ eV (95%) , $\mathrm{N_{eff}} < 0.17$ (95%)
$+\Sigma m_\nu + \mathrm{N_{SIDR}}$	$\Sigma m_\nu < 0.15$ eV(95%), $N_{\rm SIDR} < 0.16$ (95%)
$+\Sigma m_\nu + \Omega_K$	$\Sigma m_\nu < 0.17$ eV (95%), $\Omega_{\rm K} = -0.0005 \pm 0.0020$
m_e	$\mathrm{m_{e,early}/m_{e,late}} = 1.003 \pm 0.006$
$m_e + \Sigma m_\nu$	$\mathrm{m_{e,early}/m_{e,late}} = 1.0057 \pm 0.0090$, $\Sigma m_\nu < 0.29$ eV(95%)
$m_e + \Omega_K$	$\mathrm{m_{e,early}/m_{e,late}} = 1.0035 \pm 0.0164$, $\Omega_{\rm K} = -0.0005 \pm 0.0048$
$m_e + \Omega_K + \Sigma m_\nu$	$\mathrm{m_{e,early}/m_{e,late}} = 1.03 \pm 0.03$, $\Omega_{\rm K} = -0.004 \pm 0.006$, $\Sigma m_\nu < 0.48$ eV (95%)
EDE	$\theta_{\rm i} = 1.8 \pm 0.9$, $\log(a_{\rm c}) = -3.8 \pm 0.4$, $f_{\rm EDE}(a_{\rm c}) < 0.06$ (95%)
Majoron	$\log(m_\phi/\mathrm{eV}) = 0.2950 \pm 0.6598$, $\log(\Gamma_{\rm eff}) = 0.0556 \pm 0.8846$, $\Delta N_{\rm ADR} < 0.15$ (95%)

Me+Mnu: Results



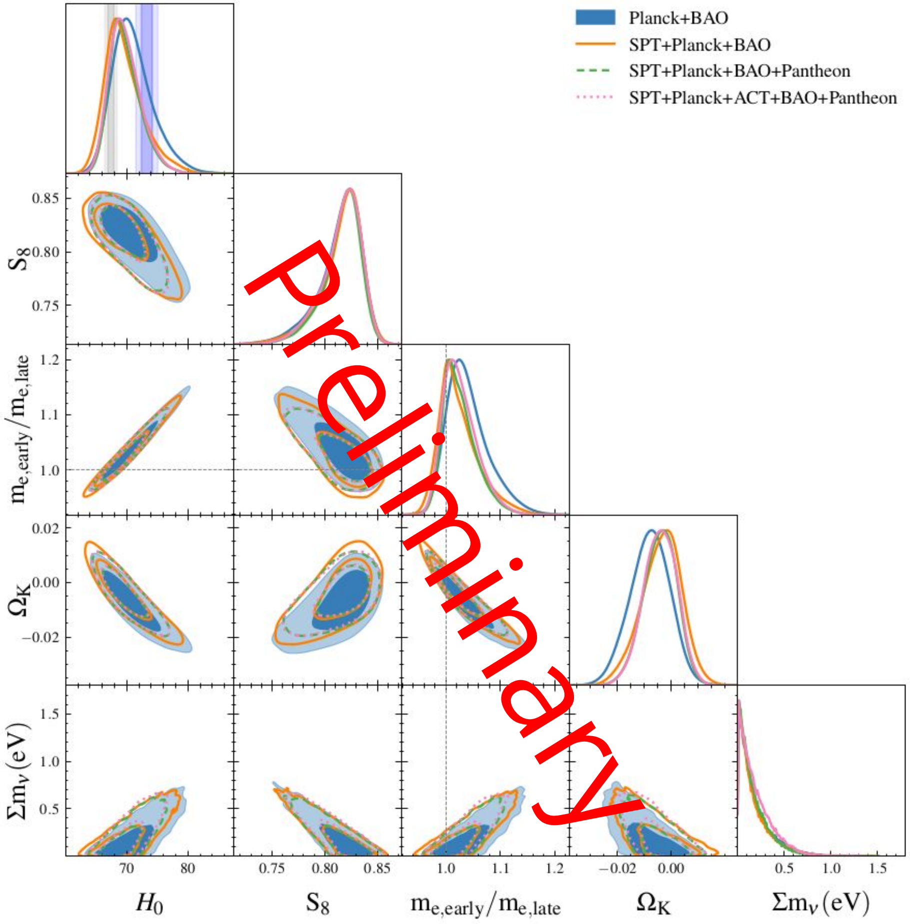
Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Me+Omk

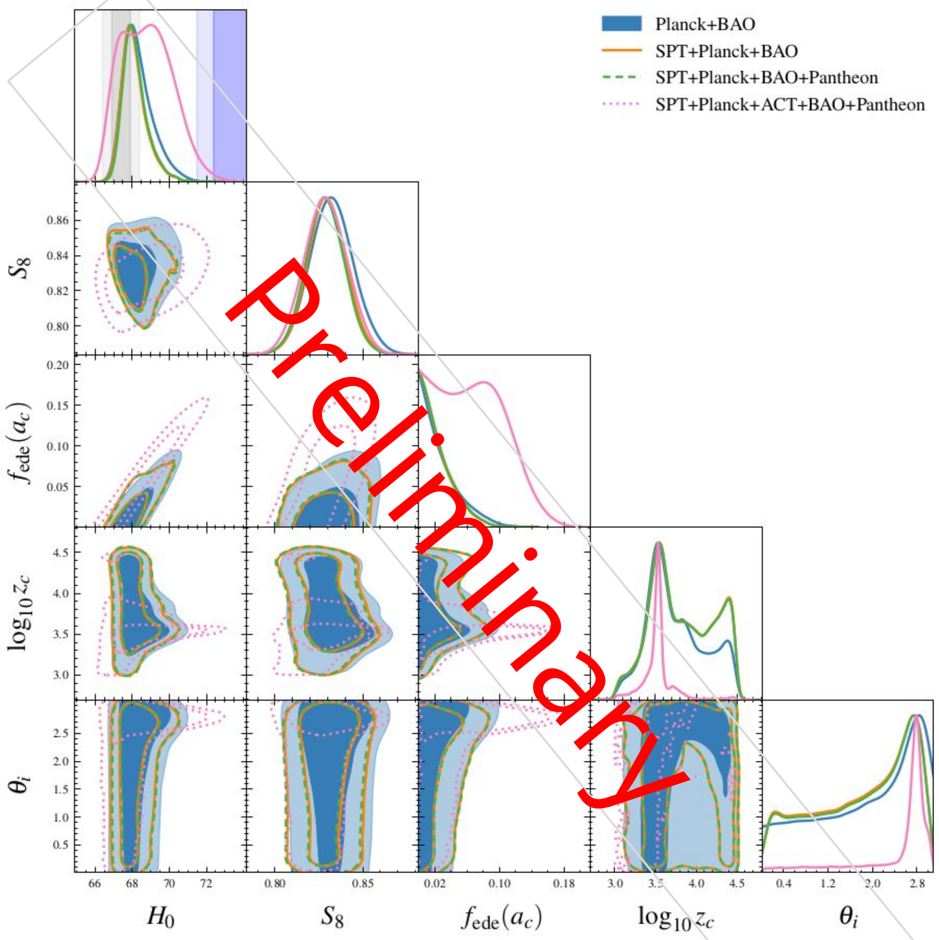


Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{e,eraly}/m_{e,late}$
Ω_K

Me+Mnu+Omk

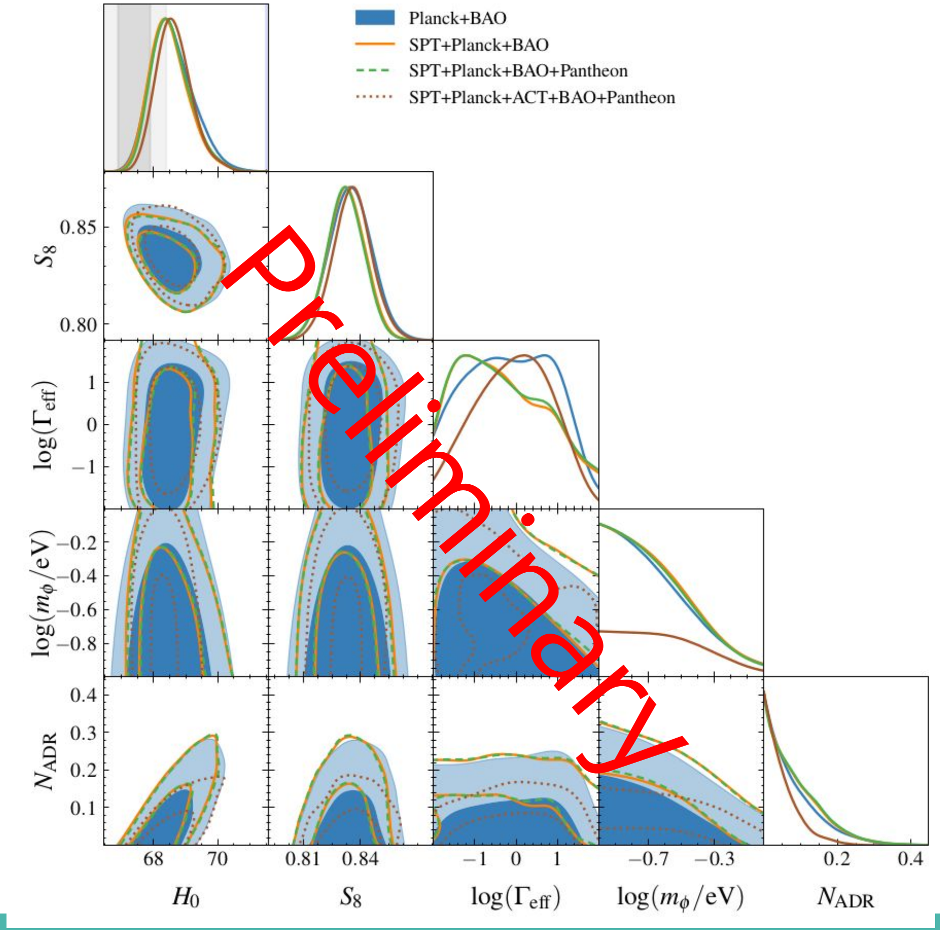

Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
H_0
S_8
$m_{e,early}/m_{e,late}$
Ω_K
Σm_ν (eV)

EDE



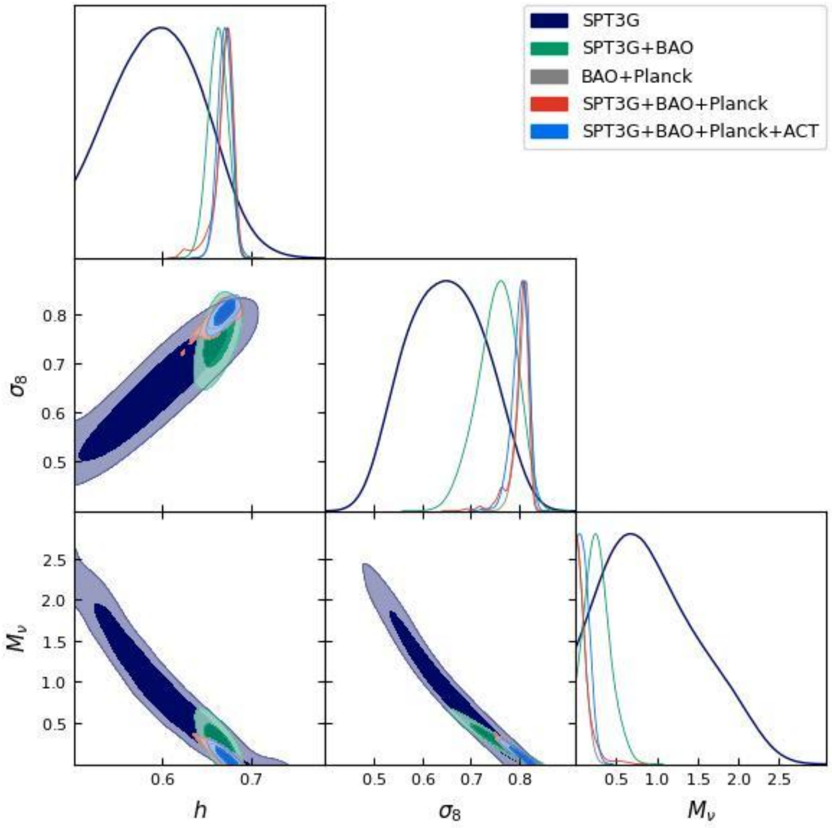
Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
S_8
$f_{\rm ede}(a_c)$
$\log_{10} z_c$
θ_i
H_0

Majoron



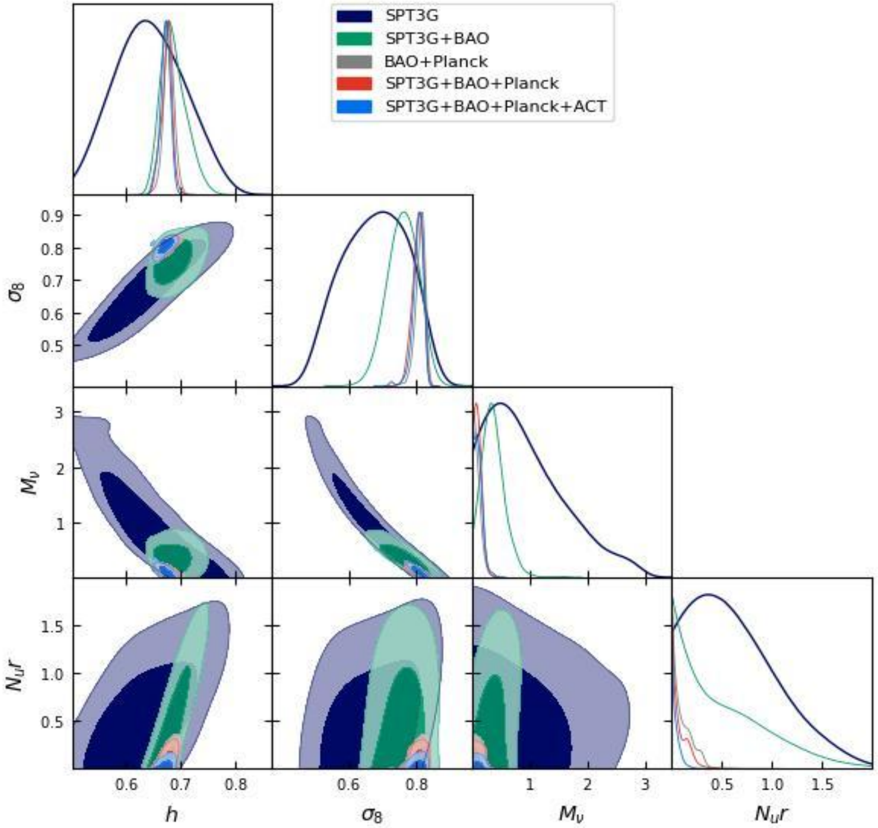
Sub eV mass

ΛCDM+Σm_ν

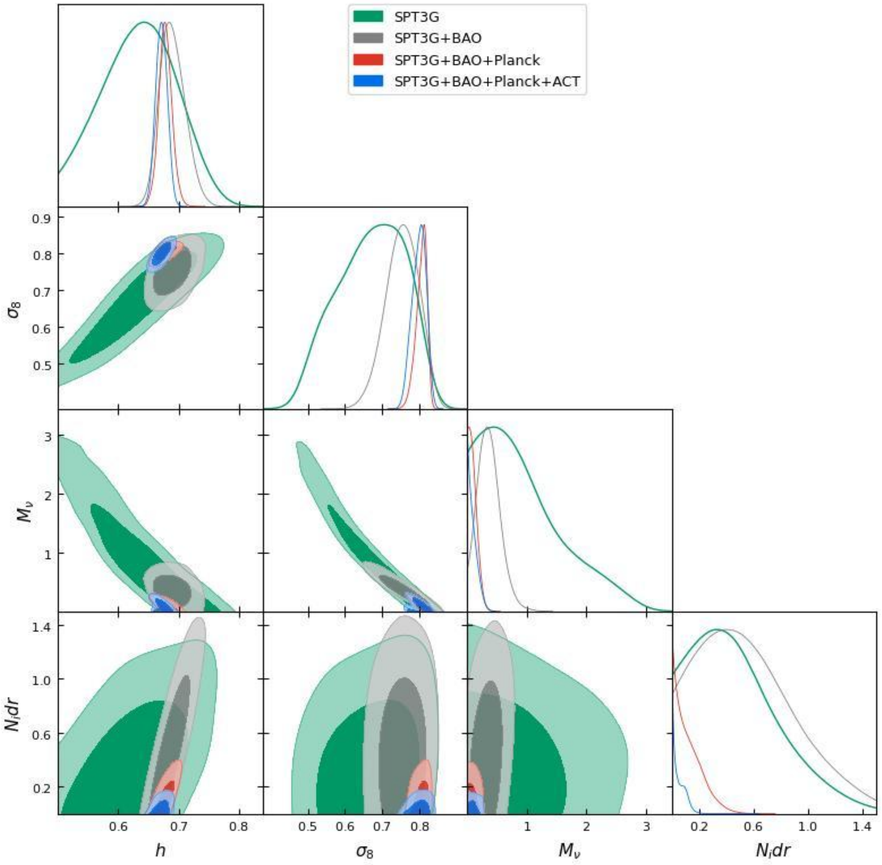


Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.00±0.82
σ_8	0.803±0.019

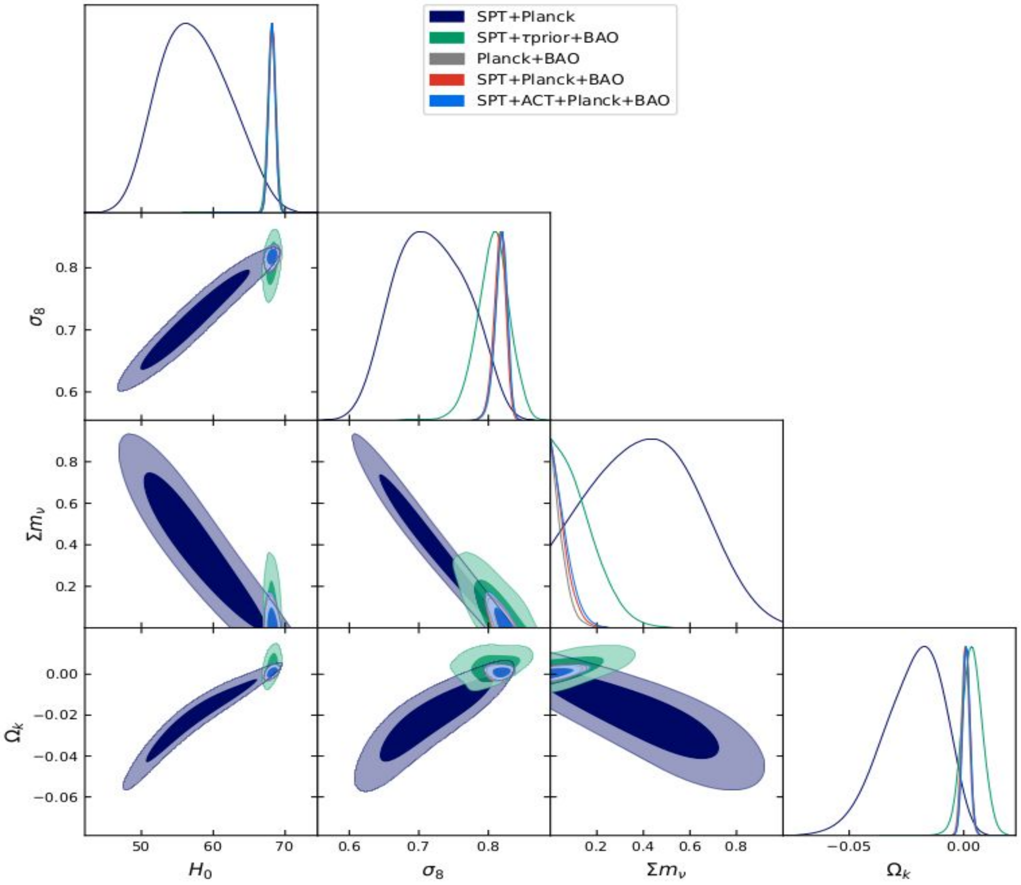
ΛCDM+Σm_ν+N_{eff}



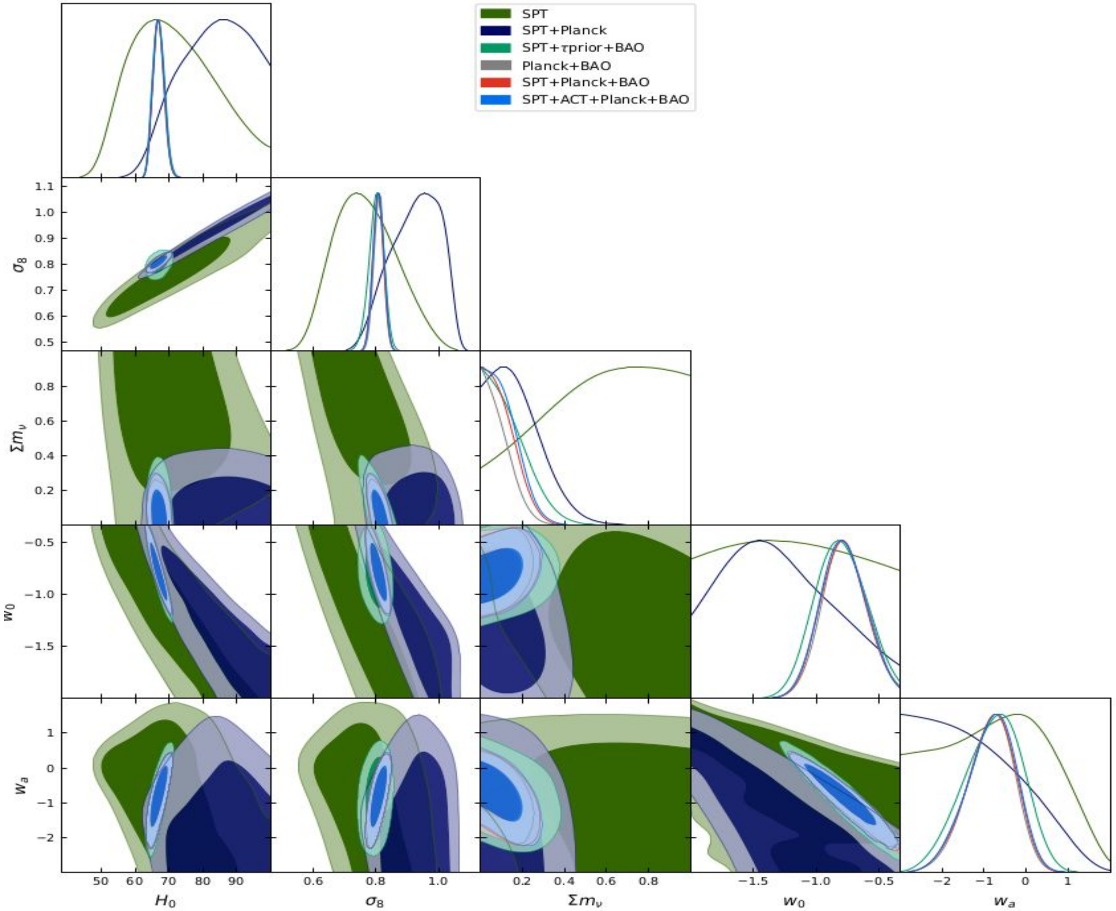
Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.10±0.85
σ_8	0.812±0.009



Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.22±0.91
σ_8	0.801±0.022



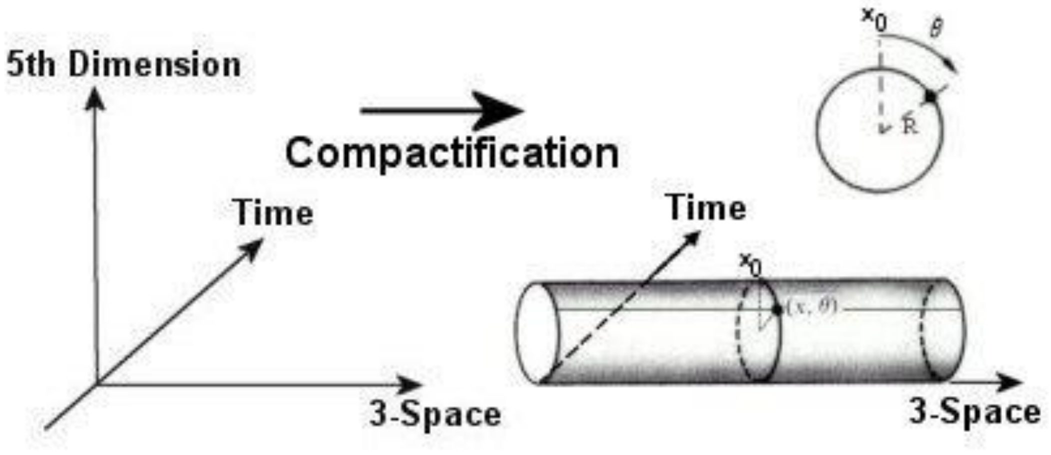
Parameter	SPT+ ACT+ Planck+ BAO
H_0	68.16±0.46
σ_8	0.818±0.009



Parameter	SPT+ ACT+ Planck+ BAO
H_0	66.89±1.62
σ_8	0.808±0.017

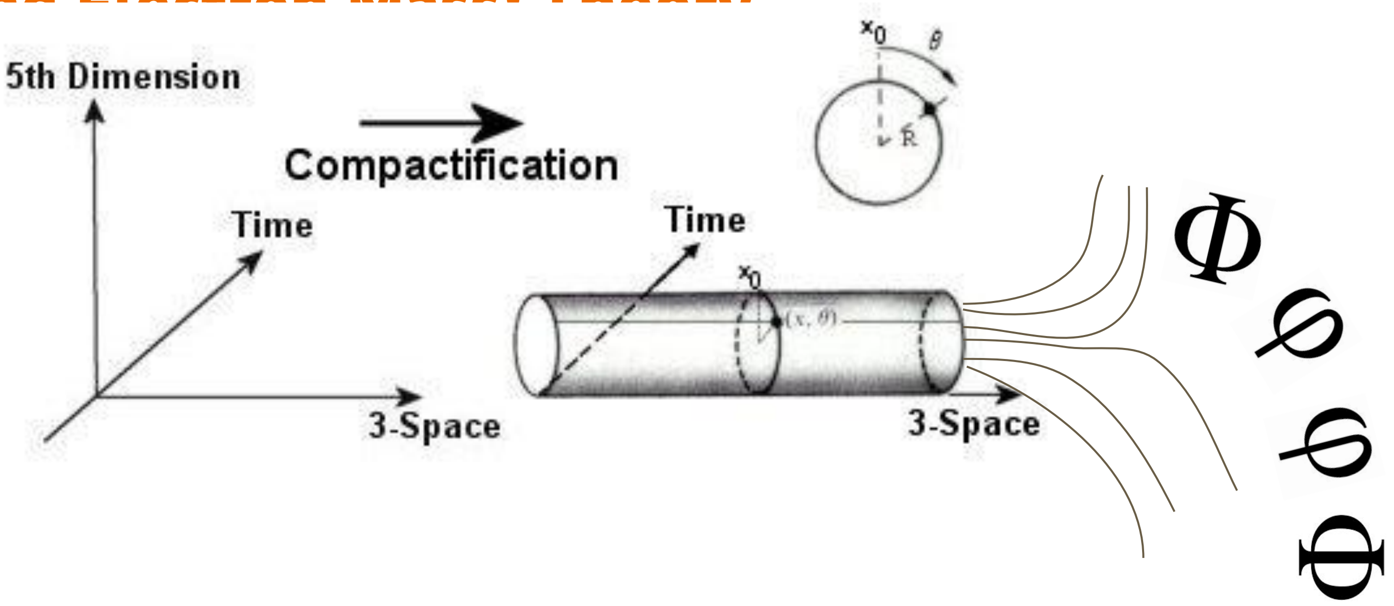
SLIDES FOR A GENERAL AUDIENCE TALK

Varyin

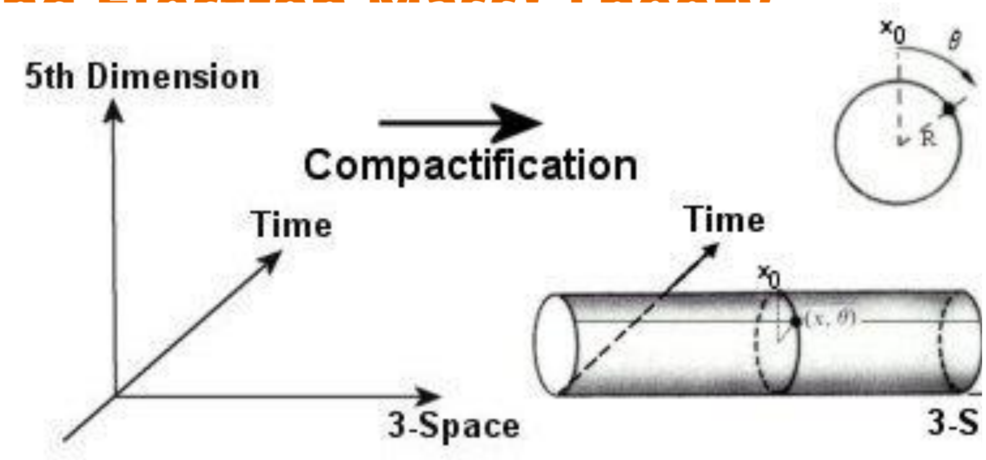


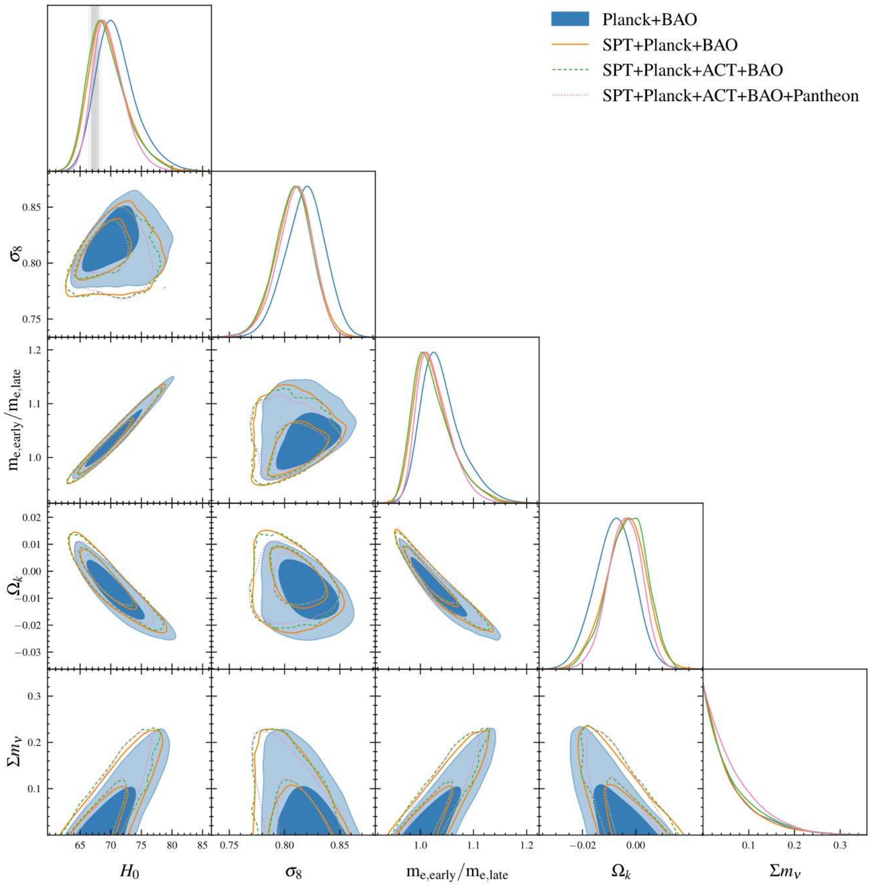
5th Dimension
Compactification
Time
3-Space
Time
x_0
(x, θ)
3-Space
x_0
θ
R

Varying Electron Mass: Theory

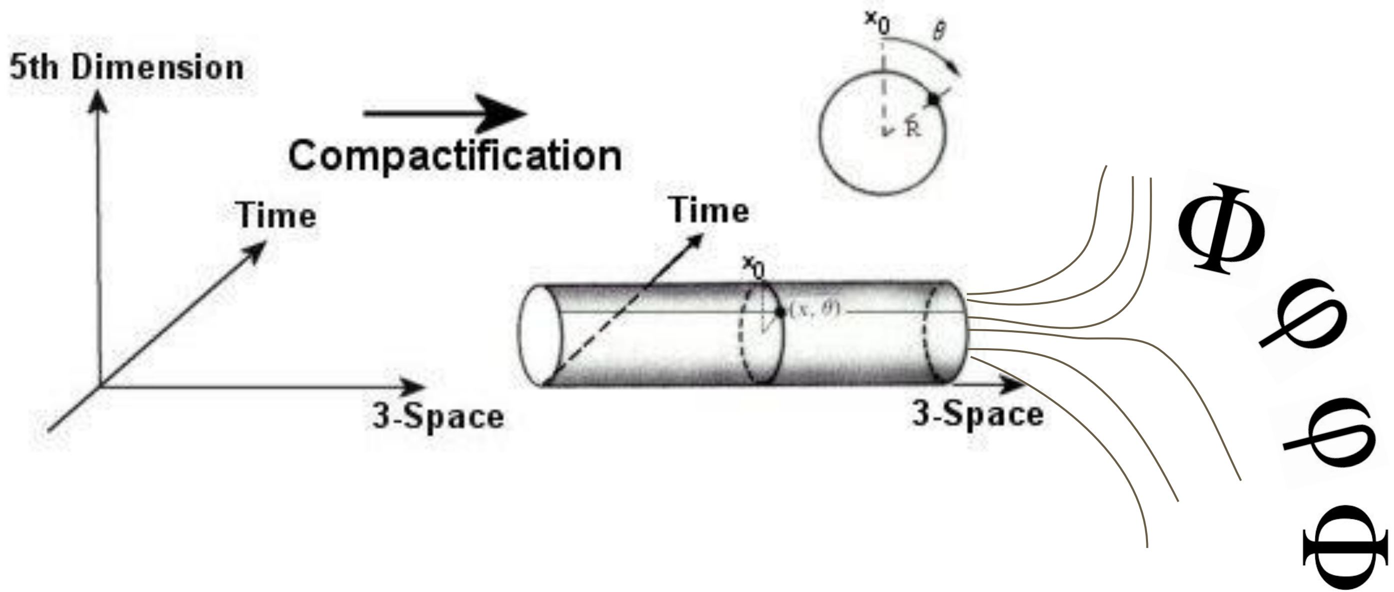


Varying Electron Mass: Theory

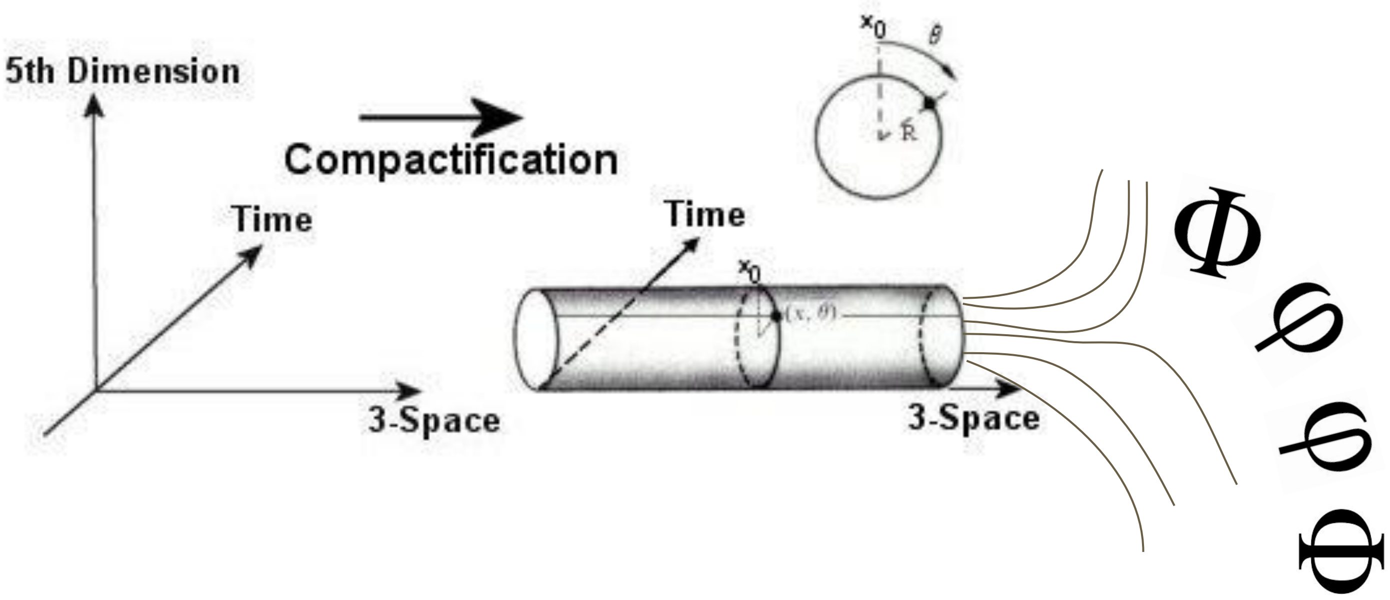



Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{e,early}/m_{e,late}$
Ω_k
Σm_ν

Early Dark Energy: Theory



Early Dark Energy: Theory



$$V(\phi) = \Lambda_{\rm ede}^4 \left[1 - \cos(\phi/f_{\rm ede})\right]^n$$

Kamionkowski & Riess(2022)