Updated Constraints on Hubble Tension solutions

With recent SPT-3G and SH0ES data

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(accepted in **JCAP**)

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Thanks to the great support from the IAP CMB team:
Federica Guidi, Aristide Doussot, Eric Hivon, Etienne Camphuis, Lennart Balkenhol and Aline Vitrier

Goal of the Project

- Evaluate the potential of Cosmological models to solve the Hubble Tension.
- Include primary CMB data from SPT-3G 2018, in combination with other data sets.
- Compare to recent SH0ES analysis:

  H_0= 73.29±0.90 km/s/Mpc (Murakami *et al., 2023;* 2306.00070).
- Study 5 classical ΛCDM extensions + 3 Elaborate Models (+extensions).
- Assess these models with new Tension metrics.
- Update H_0 Olympics paper (Schöneberg *et al.*, 2021; 2107.1029).

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.*,2022; 2212.05642)

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

Data Sets

CMB

<u>SPT-3G 2018:</u>

TT TE EE

- $300 \lesssim \ell \lesssim 3000$ (~3%)
- ~1.4′ resolution.
- ~15 μK-arcmin sensitivity.

(Balkenhol et al.,2022; 2212.05642
Dutcher *et al.*, 2021; 2101.01684)

<u>Planck PR3:</u>

TT TE EE ΦΦ

- $\ell \lesssim 2500$ (~full sky)
- ~7′ resolution.
- ~40 μK-arcmin sensitivity.

(Planck results I, 2018; 1807.06205)

<u>ACT DR4:</u>

TT TE EE

- $325 \lesssim \ell \lesssim 7550$ (~44%)
- ~1.3′ resolution.
- ~10 μK-arcmin sensitivity.

(Aiola *et al.*, 2020; 2007.07288
Choi *et al.* 2021; 2007.07289)

Data Sets

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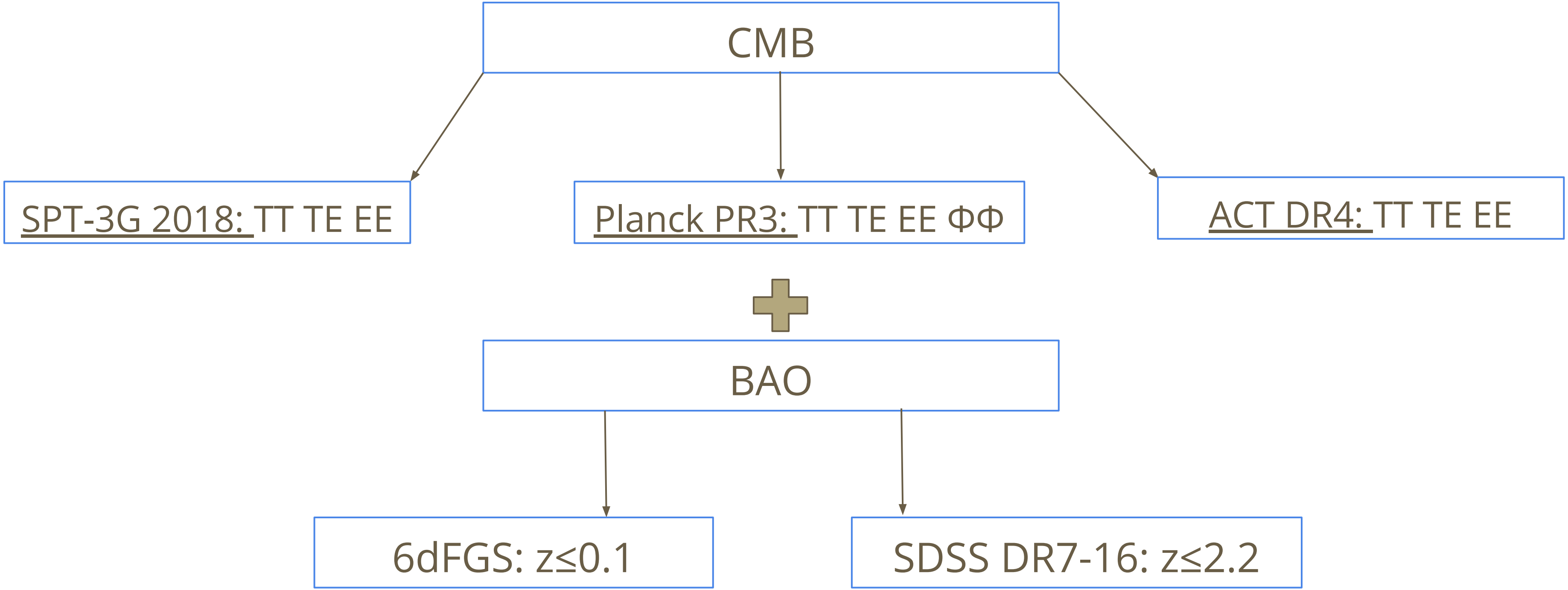
(Aiola *et al.*, 2020; 2007.07288
Choi *et al.* 2021; 2007.07289)

CMB-S4: the Best of Both Worlds

$20 \lesssim \ell \lesssim 5000$ (~60%); ~ 1′ resolution; ~1 μK-arcmin sensitivity

(CMB-S4 Science book, 1st edition; 1610.02743)

Data Sets



CMB

SPT-3G 2018: TT TE EE

Planck PR3: TT TE EE ΦΦ

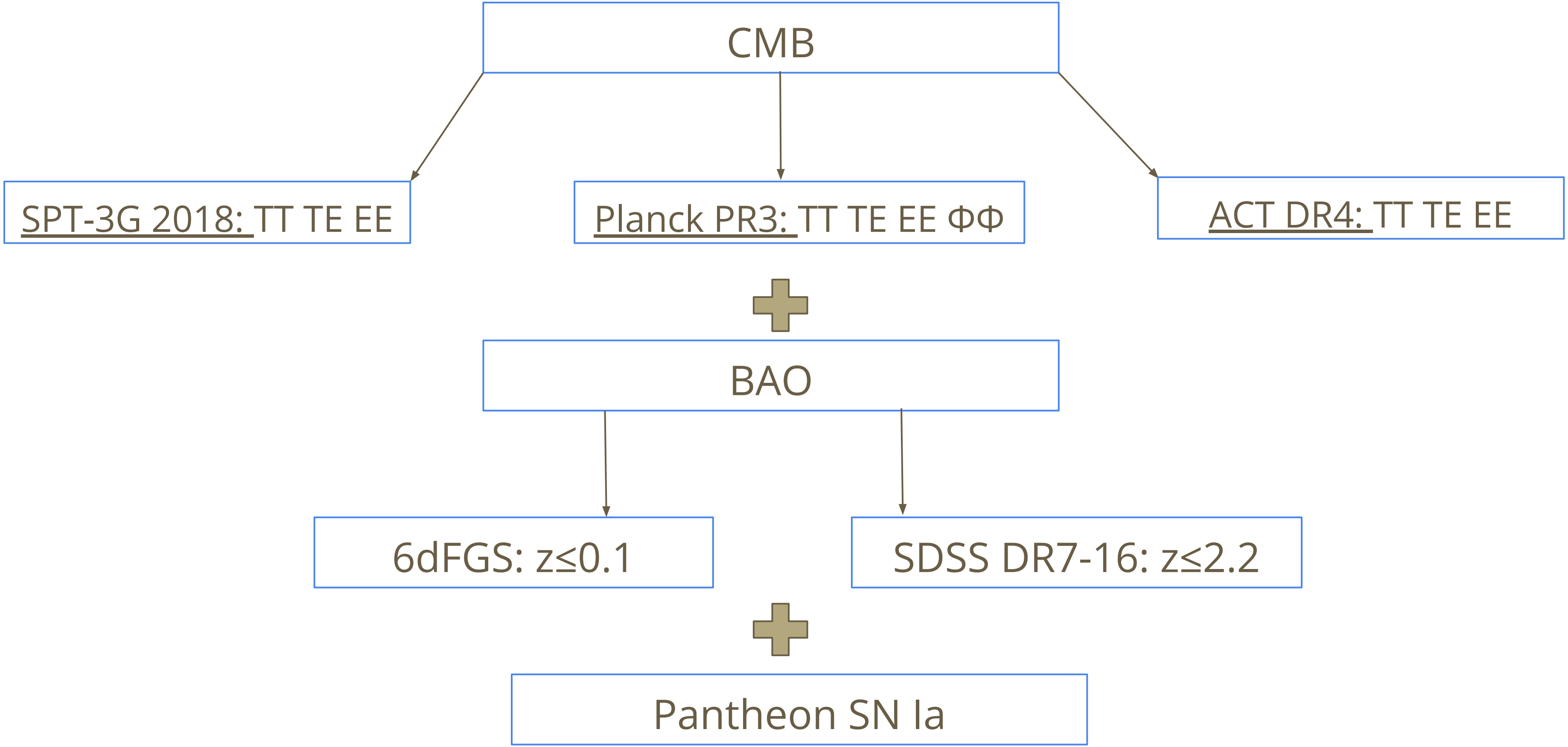
ACT DR4: TT TE EE

BAO

6dFGS: z≤0.1

SDSS DR7-16: z≤2.2

Data Sets



CMB

SPT-3G 2018: TT TE EE

Planck PR3: TT TE EE ΦΦ

ACT DR4: TT TE EE

+

BAO

6dFGS: z≤0.1

SDSS DR7-16: z≤2.2

+

Pantheon SN Ia

ΛCDM Extensions

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

Small scale CMB+BAO

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

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Large scale CMB + SN Ia

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CMB + BAO

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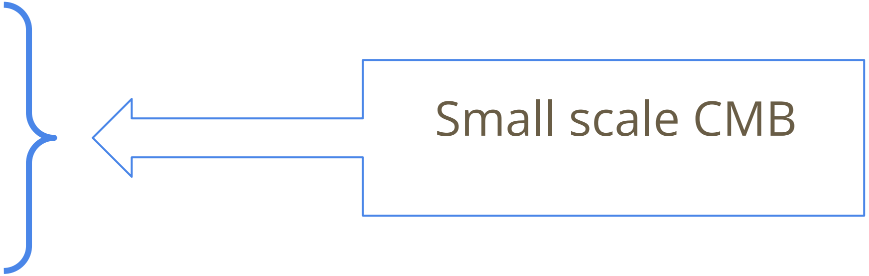

Small scale CMB

ΛCDM Extensions

Extending ΛCDM with 3 degenerate **massive neutrinos (*Σm$_\nu$*)** and:

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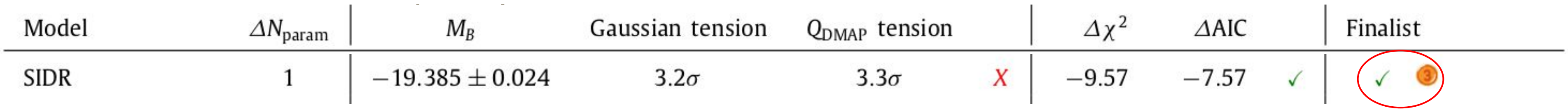
- Spatial Curvature (Ω_K)



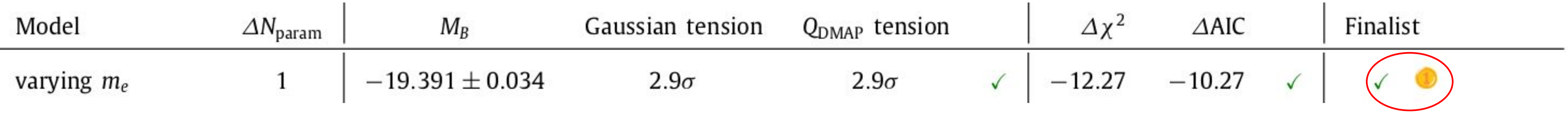
Model	ΔN_{param}	M_B	Gaussian tension	Q_{DMAP} tension		$\Delta\chi^2$	ΔAIC		Finalist
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ ③

- Self Interacting Dark Radiation (N_{SIDR})

(Schöneberg *et al.*, 2021; 2107.1029)

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
    - Changes the time (redshift) of hydrogen recombination.
    - Previously found to be an excellent reducer of the tension.
    - Must include BAO with large-scale CMB data.



Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian tension	Q_{DMAP} tension		$\Delta\chi^2$	$\Delta\mathrm{AIC}$		Finalist
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ 🥇

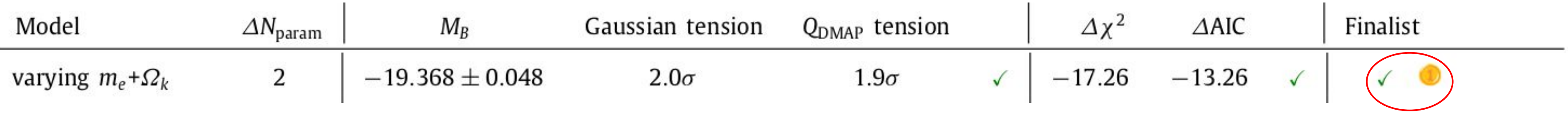
(Schöneberg *et al.*, 2021; 2107.1029)

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
    - **+Σm_ν**: First to constrain this combination.

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
  - **+Σm_ν**
  - **+Ω_K**
    - Even more promising than its ancestor.
    - Intermediate scale polarization data from SPT-3G was crucial



Model	ΔN_{param}	M_B	Gaussian tension	Q_{DMAP} tension		$\Delta\chi^2$	ΔAIC		Finalist
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ ●

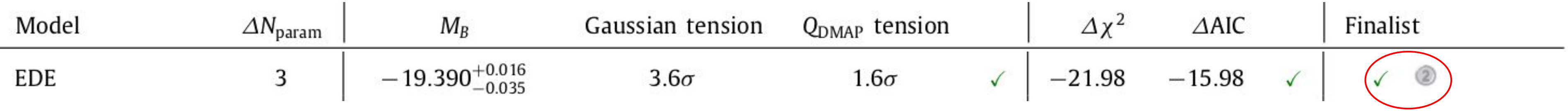
(Schöneberg *et al.*, 2021; 2107.1029)

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
  - $+\Sigma m_\nu$
  - $+\Omega_K$
  - $+\Sigma m_\nu +\Omega_K$

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
    - **$+\Sigma m_\nu$**
    - **$+\Omega_K$**
    - **$+\Sigma m_\nu +\Omega_K$**
- **Early Dark Energy: (Poulin *et al.*, 2023; 2302.09032)**
    - Scalar field reduces sound horizon around Matter-radiation equality.

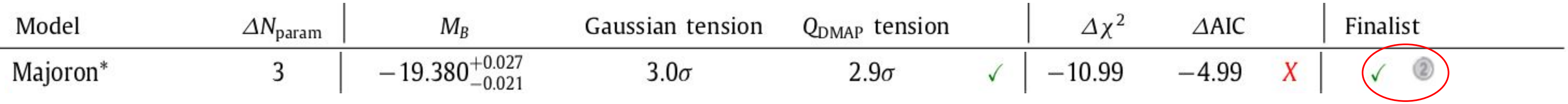


Model	$\Delta N_{\rm param}$	M_B	Gaussian tension	$Q_{\rm DMAP}$ tension		$\Delta\chi^2$	ΔAIC		Finalist
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ ②

(Schöneberg *et al.*, 2021; 2107.1029)

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
    - **$+\Sigma m_\nu$**
    - **$+\Omega_K$**
    - **$+\Sigma m_\nu +\Omega_K$**
- **Early Dark Energy: (Poulin *et al.*, 2023; 2302.09032)**
    - Scalar field reduces sound horizon around Matter-radiation equality.
- **The Majoron: (Escudero & Witte, 2021; 2103.03249)**
    - Breaking symmetry in the early Universe produces interacting Dark Radiation.



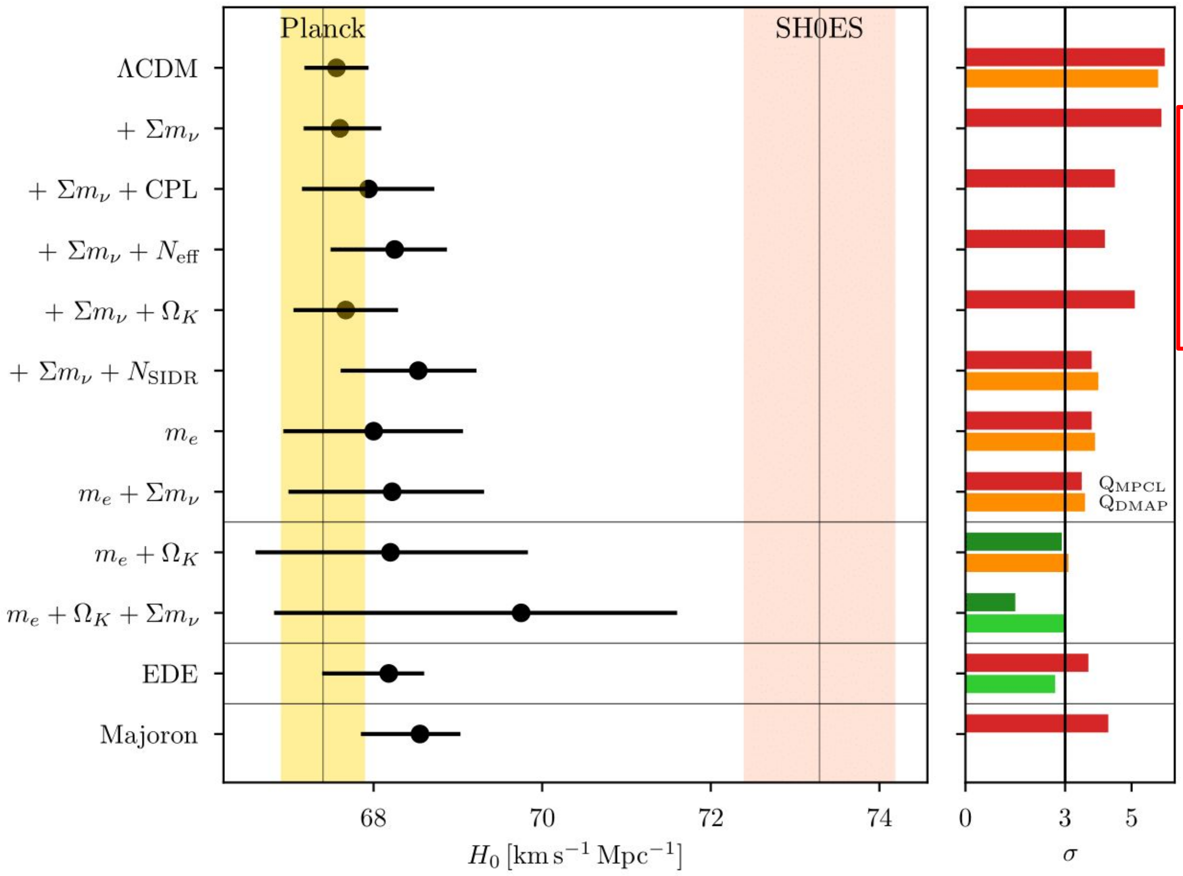
Model	ΔN_{param}	M_B	Gaussian tension	Q_{DMAP} tension		$\Delta\chi^2$	ΔAIC		Finalist
Majoron*	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-10.99	-4.99	X	✓ ②

(Schöneberg *et al.*, 2021; 2107.1029)

Tension Metrics

- *Marginalised Posterior Compatibility Level (Q_{MPCL}):*
  - Generalises Gaussian Tension metric to non-Gaussian posteriors of H_0.
  - Bayesian.
- *Difference of the Maximum A Posteriori (Q_{DMAP}):*
  - Comparison of best-fit χ^2 for a model and data set, w/ and w/o SH0ES.
  - Frequentist.
- *Akaike Information Criterion (ΔAIC):*
  - Comparison of best-fit χ^2 for a model, given a data set that includes SH0ES, with that of ΛCDM
  - Penalty for models with additional parameters.
- *ΔAIC without SH0ES*

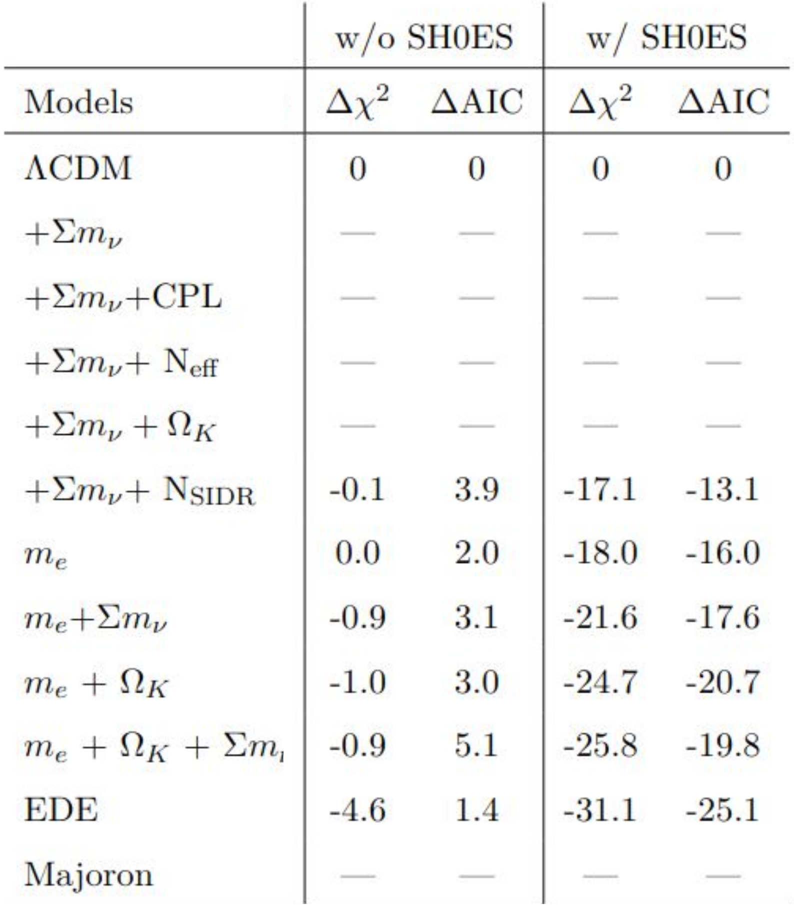
Main Results



None of the models completely solve the tension.
Only m_e+Ω_K, m_e+Ω_K+Σm_υ and EDE reduce it below 3σ.

Data: SPT+Planck+BAO+Pantheon

Main Results



	w/o SH0ES		w/ SH0ES	
Models	$\Delta\chi^2$	ΔAIC	$\Delta\chi^2$	ΔAIC
ΛCDM	0	0	0	0
$+\Sigma m_\nu$	—	—	—	—
$+\Sigma m_\nu$+CPL	—	—	—	—
$+\Sigma m_\nu+$ N$_{\mathrm{eff}}$	—	—	—	—
$+\Sigma m_\nu+\Omega_K$	—	—	—	—
$+\Sigma m_\nu+$ N$_{\mathrm{SIDR}}$	-0.1	3.9	-17.1	-13.1
m_e	0.0	2.0	-18.0	-16.0
$m_e+\Sigma m_\nu$	-0.9	3.1	-21.6	-17.6
$m_e+\Omega_K$	-1.0	3.0	-24.7	-20.7
$m_e+\Omega_K+\Sigma m$	-0.9	5.1	-25.8	-19.8
EDE	-4.6	1.4	-31.1	-25.1
Majoron	—	—	—	—

Without SH0ES, the models are not performing appreciably better than ΛCDM.

Summary

- Update previous constraints on Hubble Tension solutions with:

  SPT-3G 2018, SH0ES and SDSS DR16.

- Introduced new tension metrics that improve the assessment.
- We used a Boltzmann code emulator, making the computations faster.
- SIDR, varying m_e and the Majoron models are no longer possible solutions to the Hubble Tension.
- None of the studied models actually solve the tension.

Future Plans

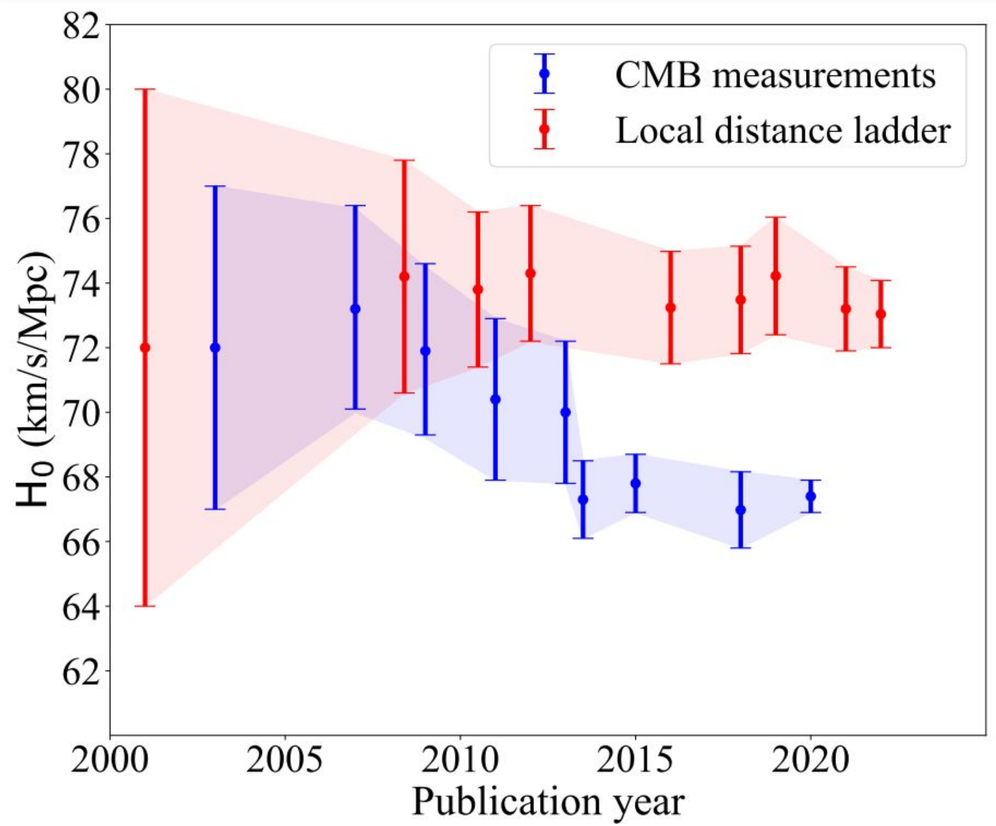
- Further investigation of the still viable models is needed.
- Revisit these models, along with others, with upcoming SPT-3G 2019/2020 and ACT DR6 data.
- CMB-S4's improved sky coverage and polarization data will be crucial.
- Perform forecasts for CMB-S4.

Thank you!

Questions? Comments?

Back Up

The Trouble with Hubble

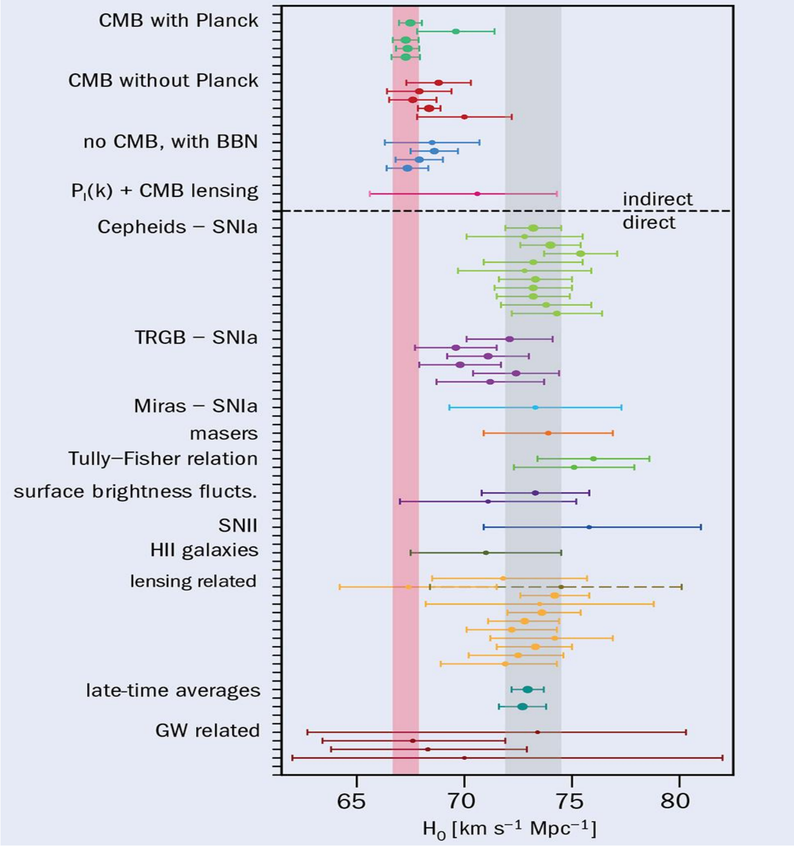


Ref: Hubble Tension: The Evidence of New Physics(2302.05709)

Data Sets and Numerical Tools

- 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)

The Trouble with Hubble



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

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)

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

Elaborate Models

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

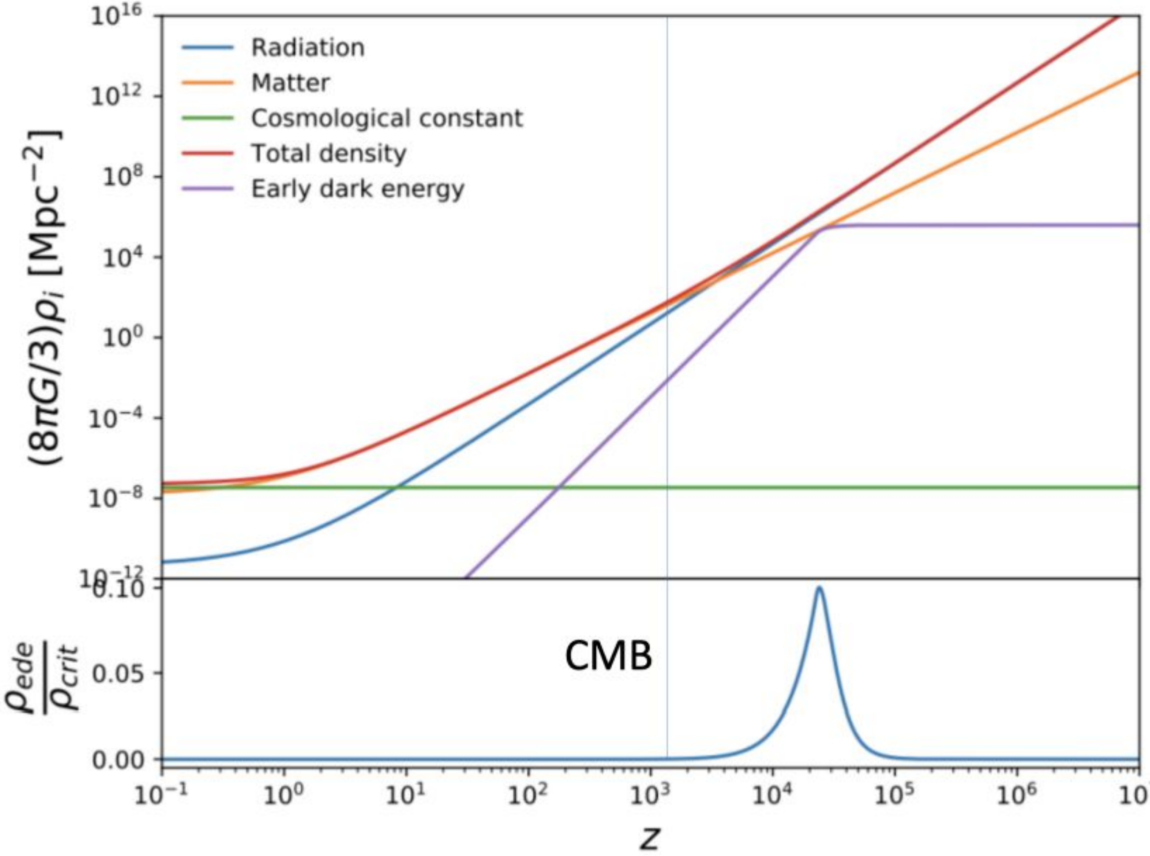
Elaborate Models

- **Varying electron mass (**$m_{e,early}/m_{e,late}$**)**
    - **+**$\boldsymbol{\Sigma m_\nu}$
    - **+**$\boldsymbol{\Omega_K}$**:** Changing the time of recombination changes the distance

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

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

Early Dark Energy



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

Kamionkowski & Riess,2022 (2211.04492)

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)

Elaborate Models

- **Varying electron mass ($m_{e,early}/m_{e,late}$)**
  - $+\Sigma m_\nu$
  - $+\Omega_K$
  - $+\Sigma m_\nu + \Omega_K$
- **Early Dark Energy:**
  - Θ_i: Initial value of the scalar field
  - Z_c: Critical redshift, i.e. the field becomes dynamical
  - $f_{EDE} = \rho_{EDE}/\rho_{tot}$

Elaborate Models

- **Varying electron mass** ($m_{e,early}/m_{e,late}$)
  - **+Σm_ν**
  - **+Ω_K**
  - **+Σm_ν +Ω_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)

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?

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

Normalisation

Normalisation

Weights from chains

Tension Metrics

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$$q = \int_0^{\delta'} d\delta \, \mathcal{P}(\delta) \ .$$

Probability of finding δ in $[0,\delta']$, such that $\mathcal{P}(\delta') = \mathcal{P}(0)$

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$$q = \int_0^{\delta'} d\delta \, \mathcal{P}(\delta) \, .$$

Probability of finding δ in [0,δ'], such that $\mathcal{P}(\delta') = \mathcal{P}(0)$

$$n = \sqrt{2}\,\mathrm{erf}^{-1}(q)$$

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

Tension Metrics

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Probability of finding δ in [0,δ'], such that $\mathcal{P}(\delta') = \mathcal{P}(0)$

$$n = \sqrt{2} \, \mathrm{erf}^{-1}(q)$$

Assuming Gaussian posteriors →

$$n = \frac{\bar{x}_2 - \bar{x}_1}{\sqrt{\sigma_{x_1}^2 + \sigma_{x_2}^2}}$$

Tension Metrics

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Probability of finding δ in [0,δ'], such that $\mathcal{P}(\delta') = \mathcal{P}(0)$

$$n = \sqrt{2}\,\mathrm{erf}^{-1}(q) \xrightarrow{\text{Assuming Gaussian posteriors}} n = \frac{\bar{x}_2 - \bar{x}_1}{\sqrt{\sigma_{x_1}^2 + \sigma_{x_2}^2}}$$

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

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*

$n = \sqrt{2}\,\mathrm{erf}^{-1}(q)$ Tension in units of σ, denoted by Q_{MPCL}

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

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

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*

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

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

- *Akaike Information Criterion (AIC):*

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

  ; N ≡ # of parameters

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*

  $n = \sqrt{2}\,\mathrm{erf}^{-1}(q)$ Tension in units of σ, denoted by $Q_{\rm MPCL}$

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

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

- *Akaike Information Criterion (AIC):*

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

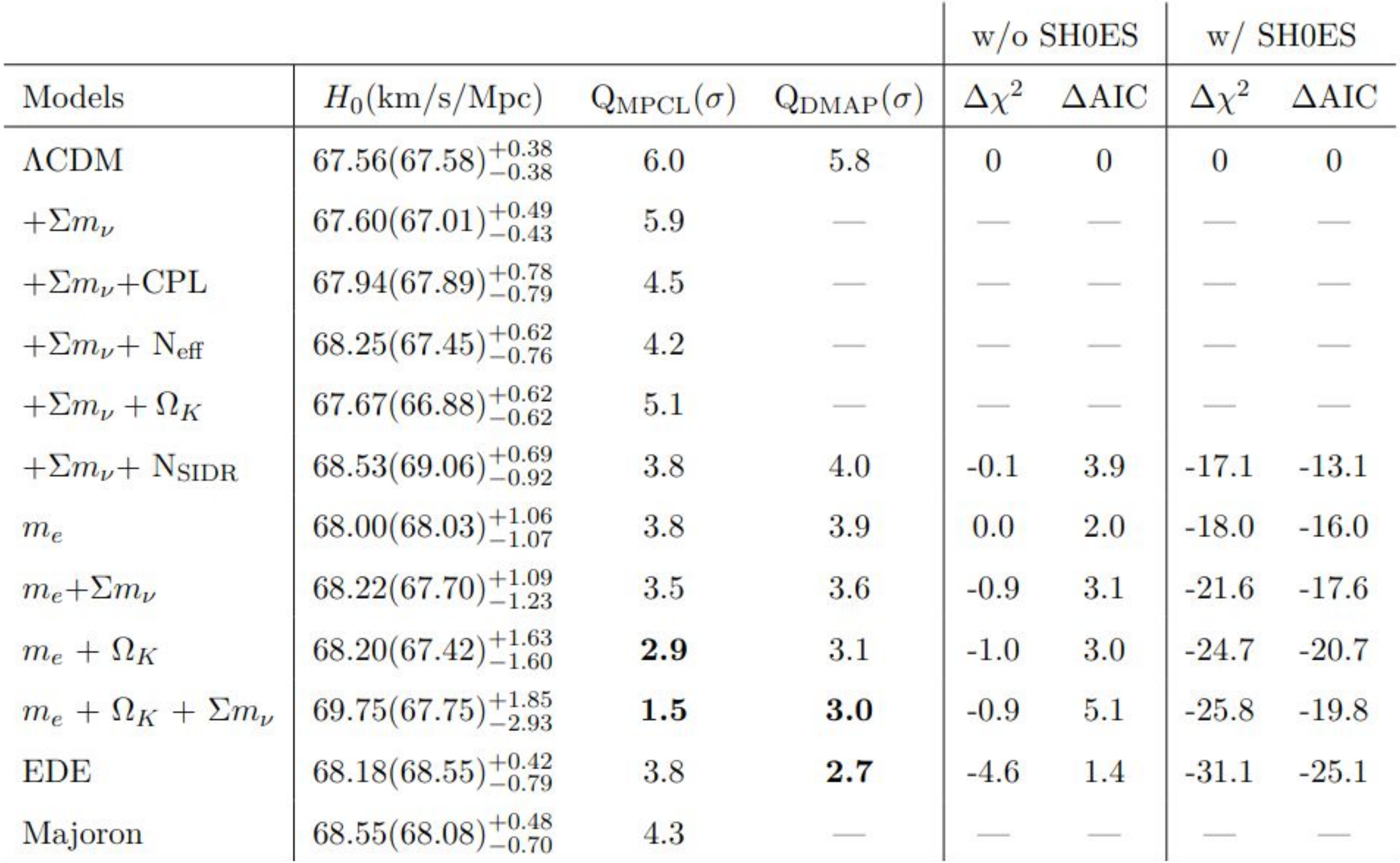
  ; *N* ≡ # of parameters

- *AIC without SH0ES*

Results

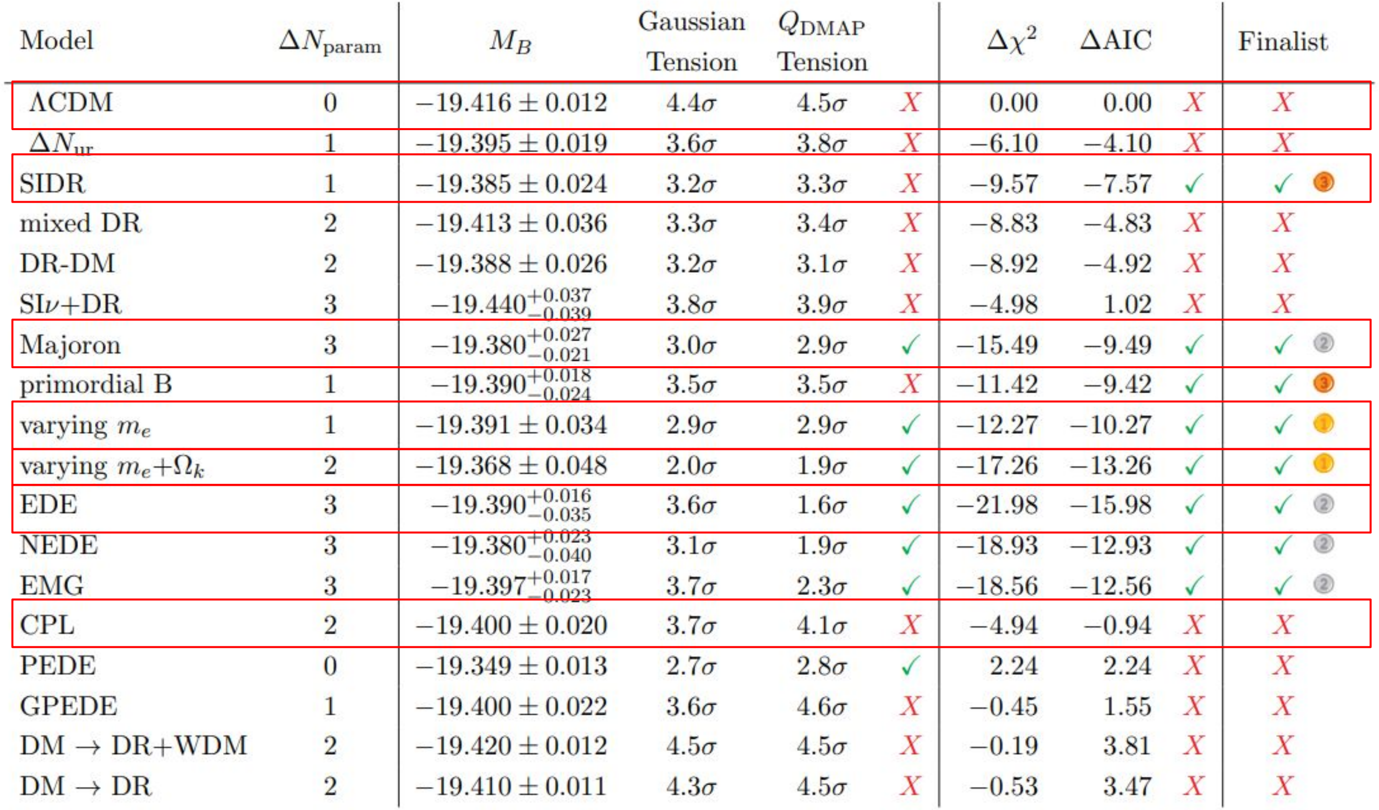
Further Results

Main Results



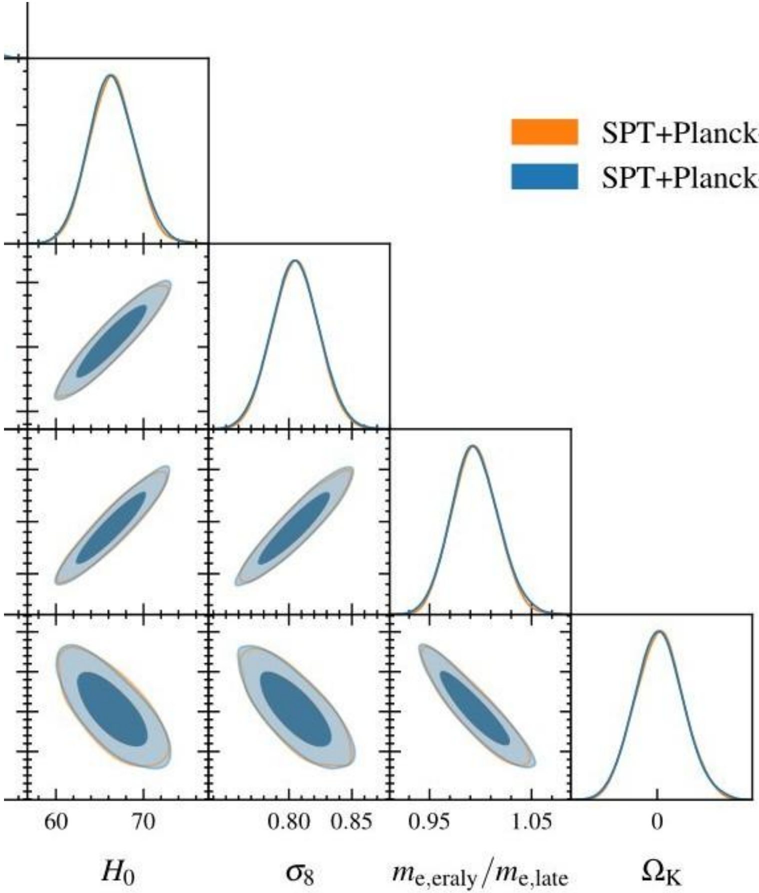
				w/o SH0ES		w/ SH0ES	
Models	H_0(km/s/Mpc)	$Q_{\rm MPCL}(\sigma)$	$Q_{\rm DMAP}(\sigma)$	$\Delta\chi^2$	ΔAIC	$\Delta\chi^2$	ΔAIC
ΛCDM	$67.56(67.58)^{+0.38}_{-0.38}$	6.0	5.8	0	0	0	0
$+\Sigma m_\nu$	$67.60(67.01)^{+0.49}_{-0.43}$	5.9	—	—	—	—	—
$+\Sigma m_\nu$+CPL	$67.94(67.89)^{+0.78}_{-0.79}$	4.5	—	—	—	—	—
$+\Sigma m_\nu+$ 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



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	X	0.00	0.00	X	X	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓	③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X	
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	X	-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	X	-4.94	-0.94	X	X	
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 → DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X	
DM → DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X	

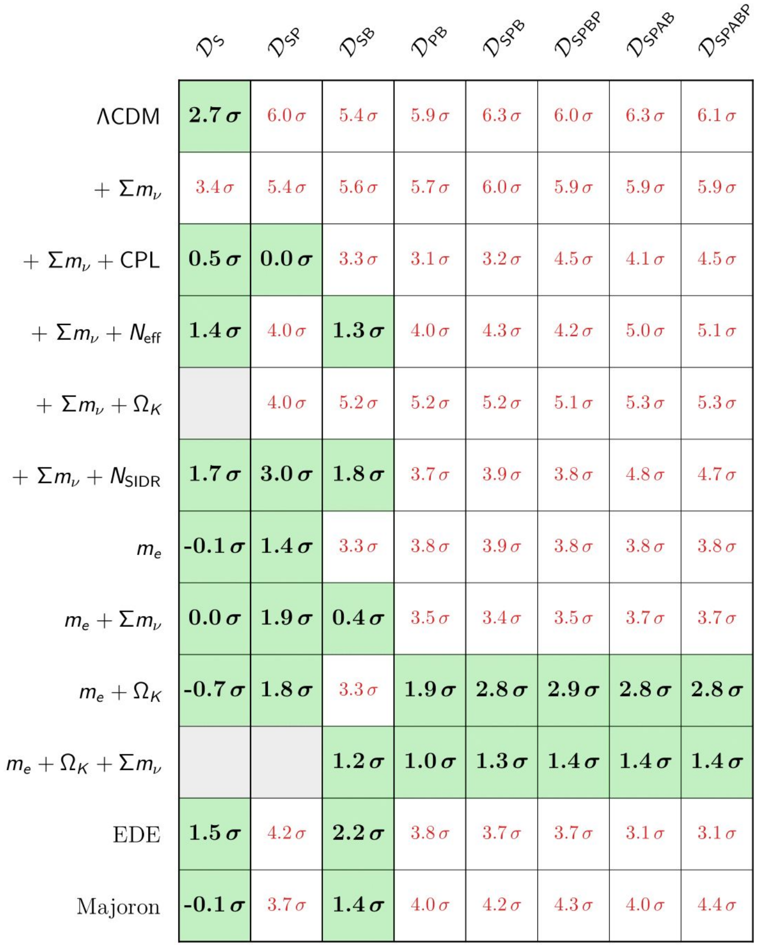
The Power of an Emulator



3 days of running time

10 hrs of running time

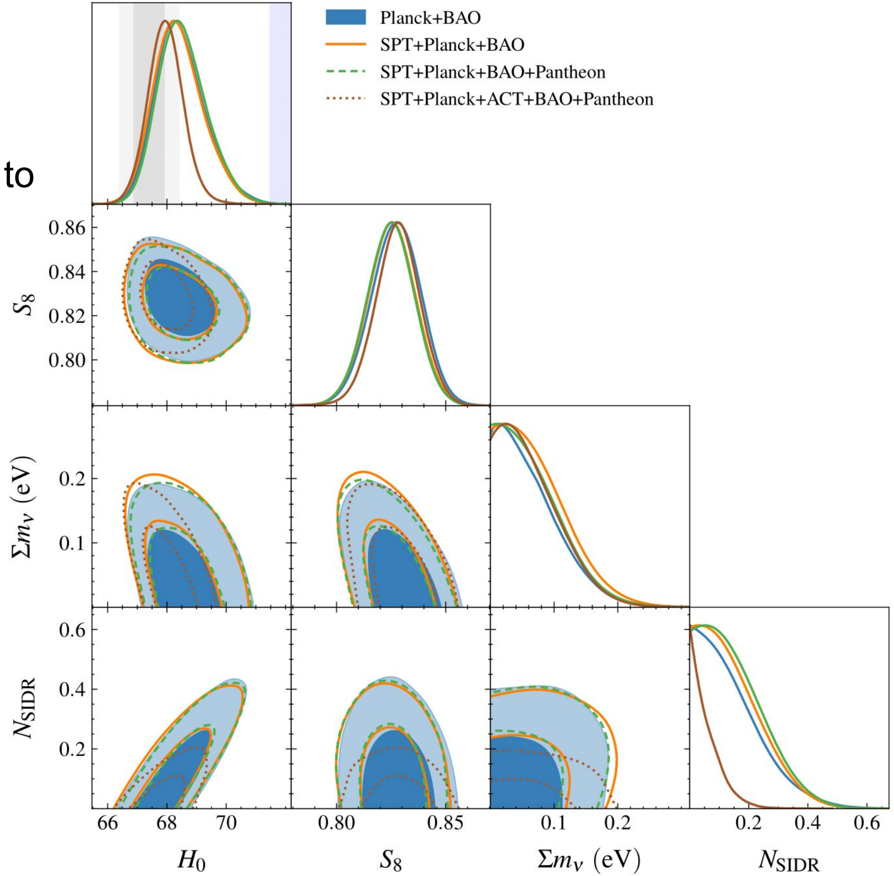
Q_{MPCL} for Each Model and Data-set



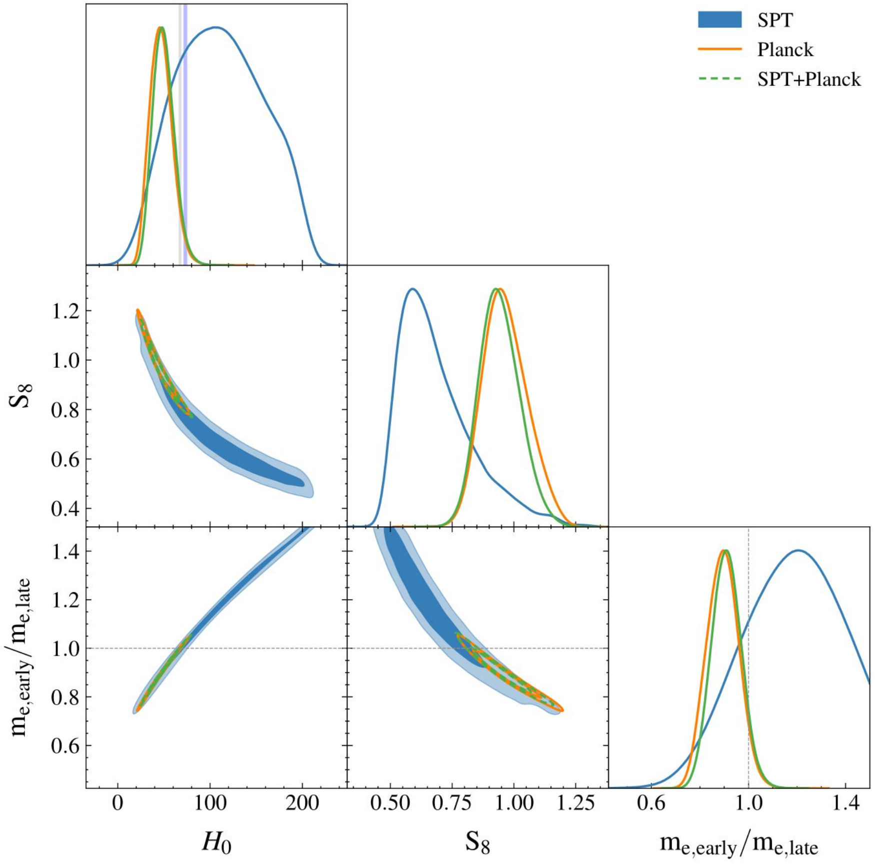
	$\mathcal{D}_{\mathrm{S}}$	$\mathcal{D}_{\mathrm{SP}}$	$\mathcal{D}_{\mathrm{SB}}$	$\mathcal{D}_{\mathrm{PB}}$	$\mathcal{D}_{\mathrm{SPB}}$	$\mathcal{D}_{\mathrm{SPBP}}$	$\mathcal{D}_{\mathrm{SPAB}}$	$\mathcal{D}_{\mathrm{SPABP}}$
ΛCDM	**$2.7\,\sigma$**	$6.0\,\sigma$	$5.4\,\sigma$	$5.9\,\sigma$	$6.3\,\sigma$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

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}.

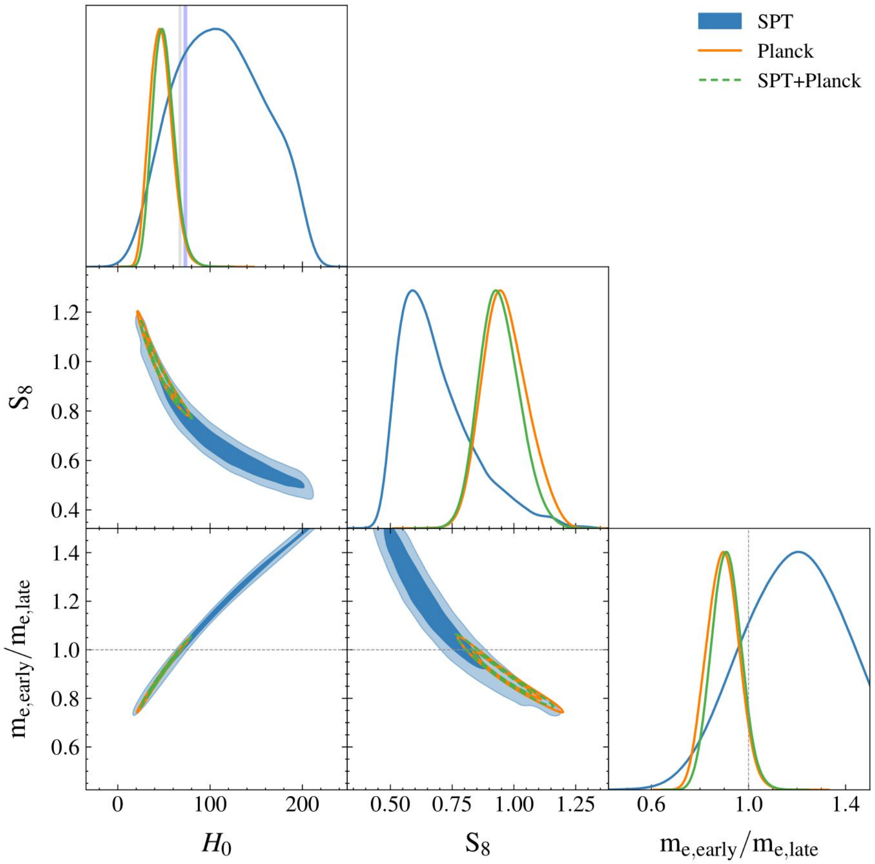


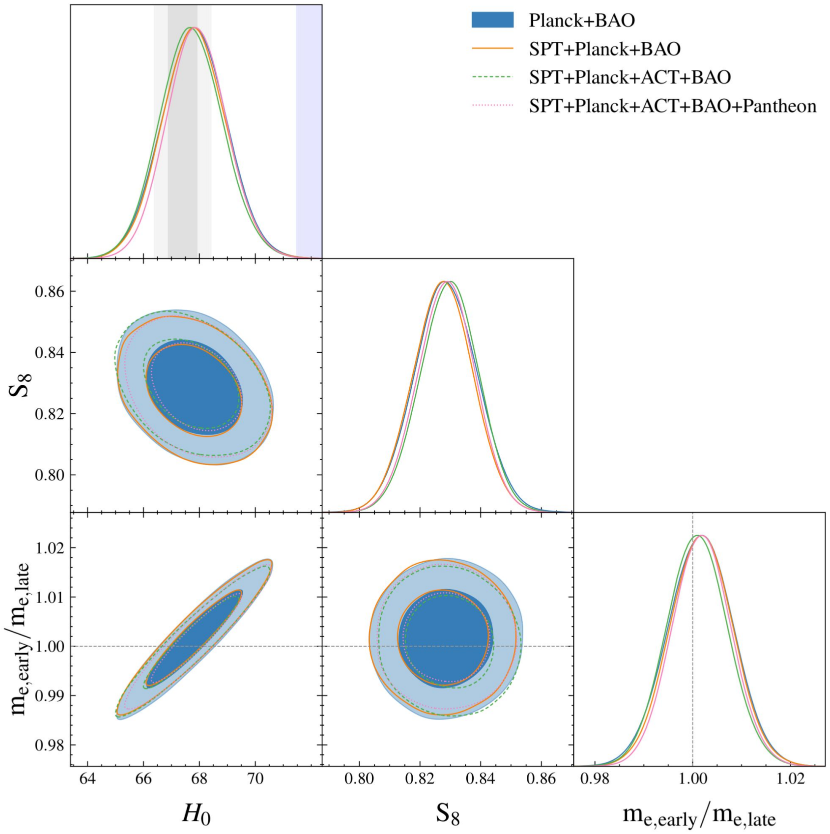
Varying Electron Mass



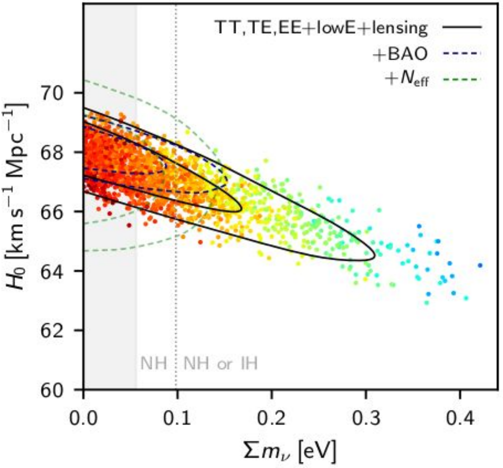
- No longer a potential solution to the tension.
- Planck is still more constraining than SPT.
- CMB alone cannot constrain this model.

Varying Electron Mass



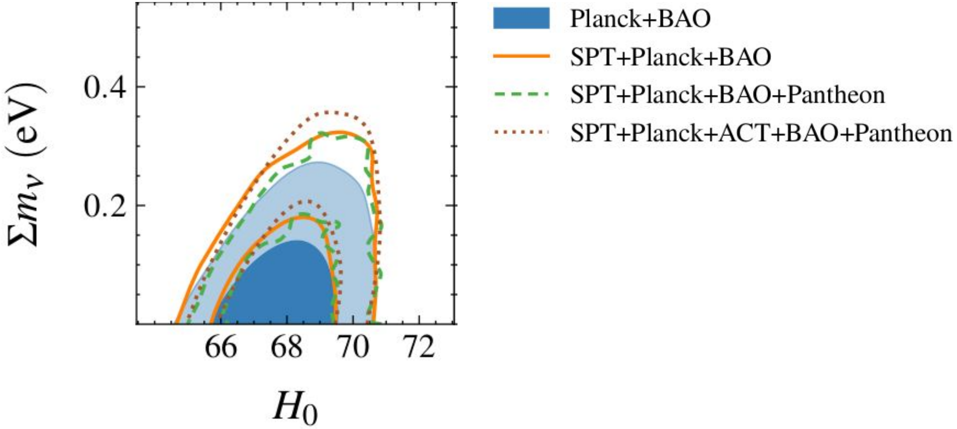


Varying Electron Mass+Σm_{υ}

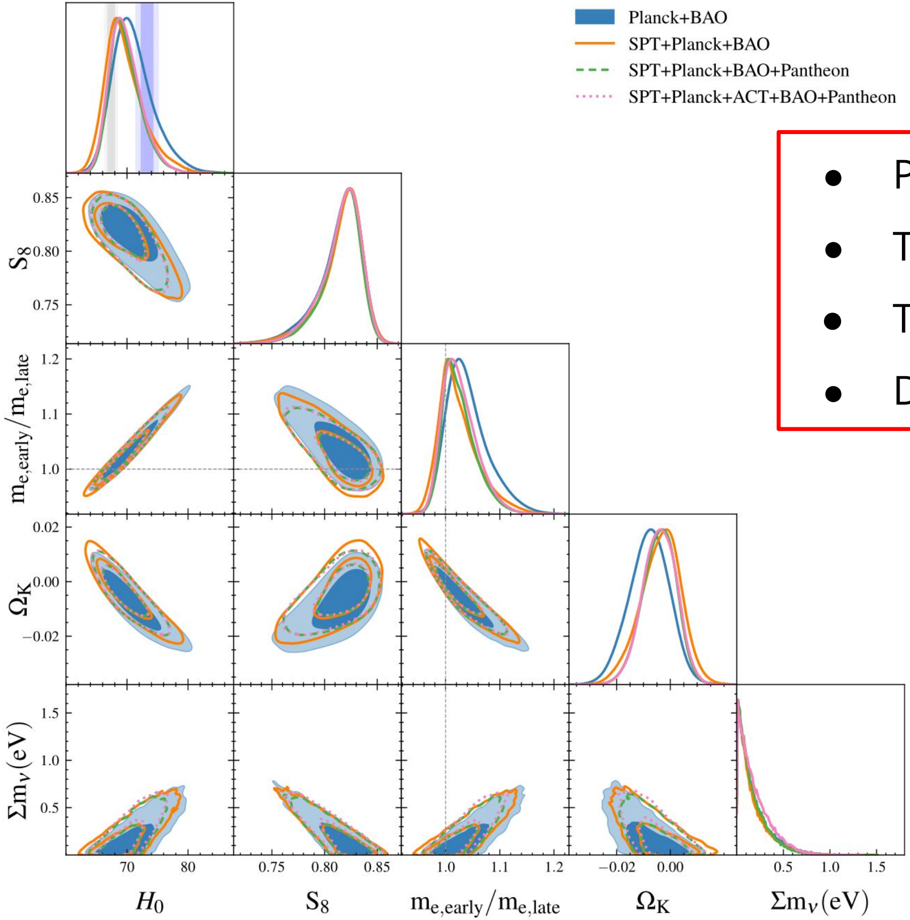


Planck 2018 (*Aghanim et al.*)

- Allowing Σm_{υ} to vary doesn't help.
- Degeneracy direction in the Σm_{υ}-H_0 flips.

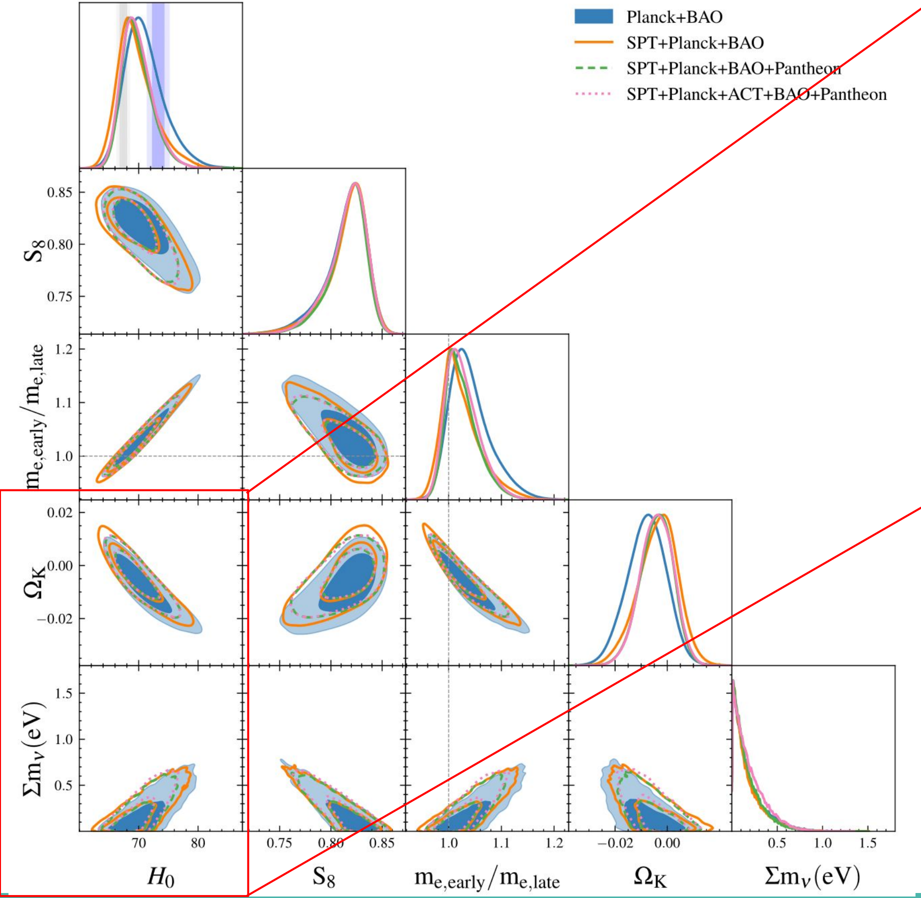


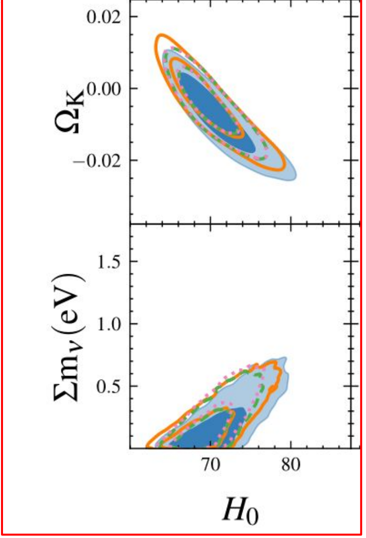
Varying Electron Mass+Σm_υ+Ω_K

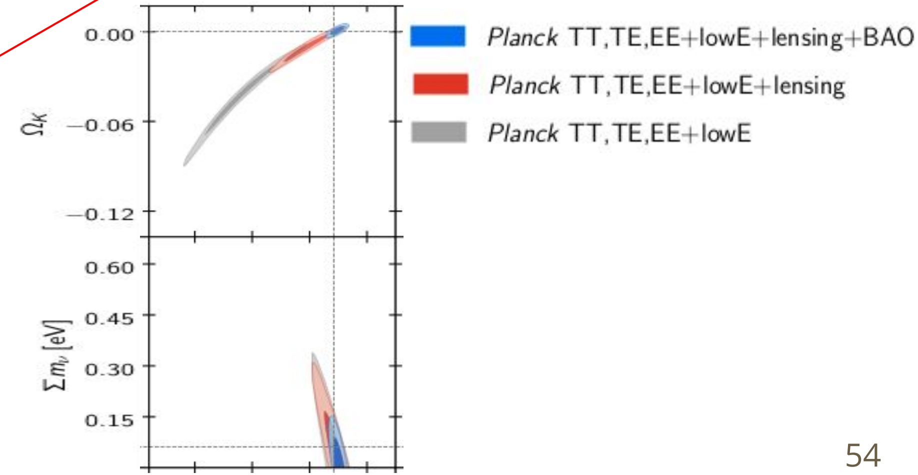


- Polarization data from SPT is particularly useful.
- The model that reduces the tension the most.
- The model with the largest error bars.
- Degeneracy direction also flips in the Ω_K-H_0 plane.

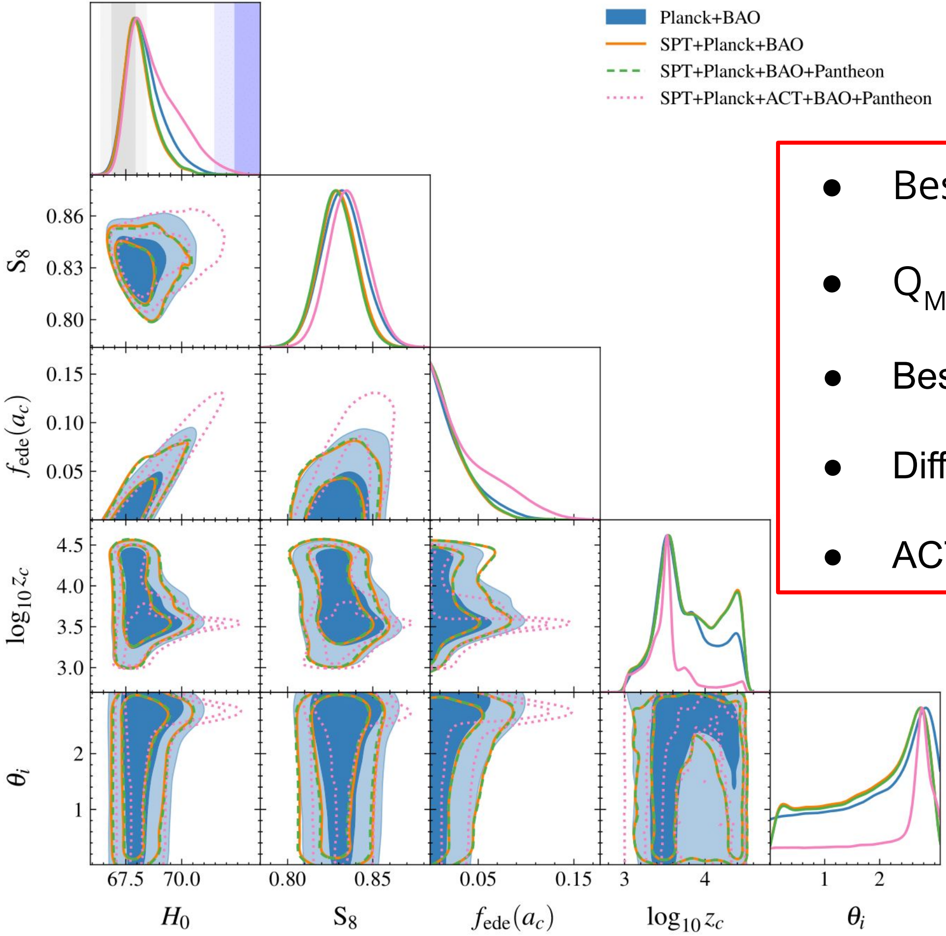
Varying Electron Mass+$\Sigma m_\nu+\Omega_K$





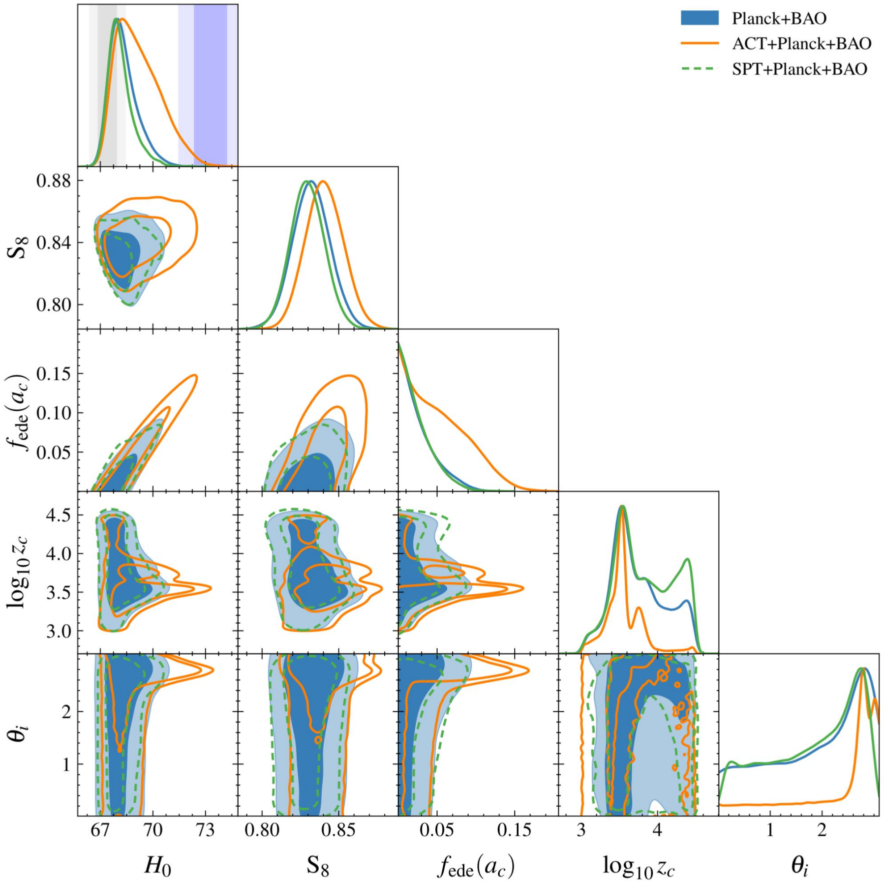


Early Dark Energy



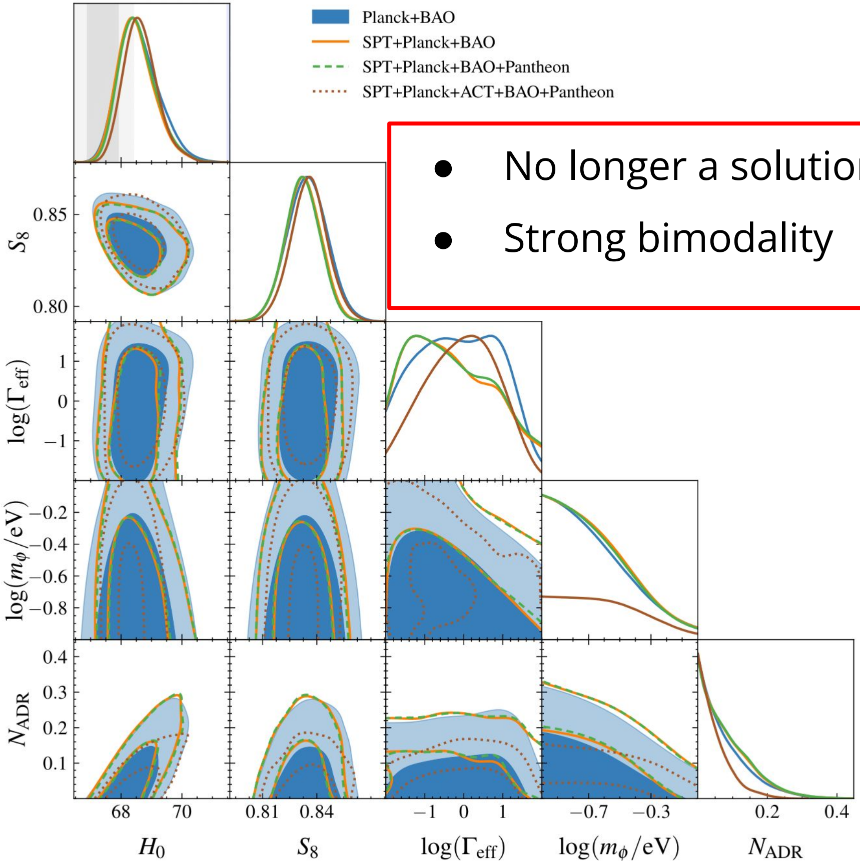
- Best constrained by CMB.
- $Q_{\rm MPCL}$= 3.7σ while $Q_{\rm DMAP}$=2.7σ for SPBP.
- Best-fit χ^2 compared to all models, w/ and w/o SH0ES.
- Difficult to constrain, with some bimodality.
- ACT DR4 is compatible with higher $f_{\rm EDE}$.

Early Dark Energy: SPT vs ACT

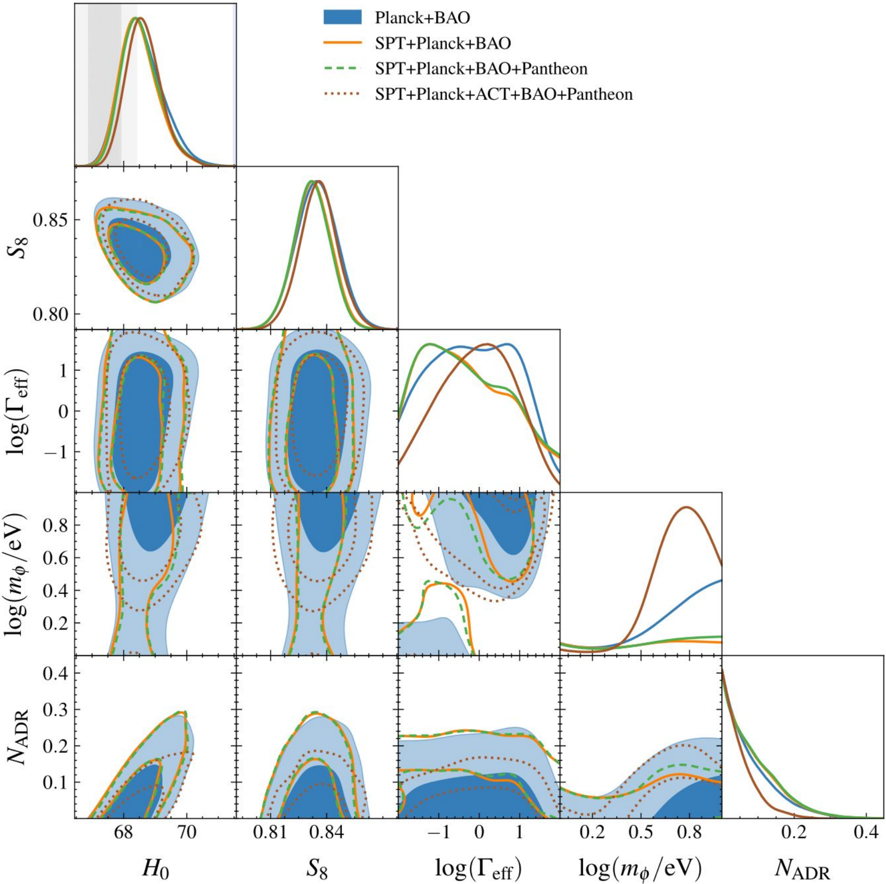


The Majoron

- No longer a solution
- Strong bimodality



m_φ<1 eV



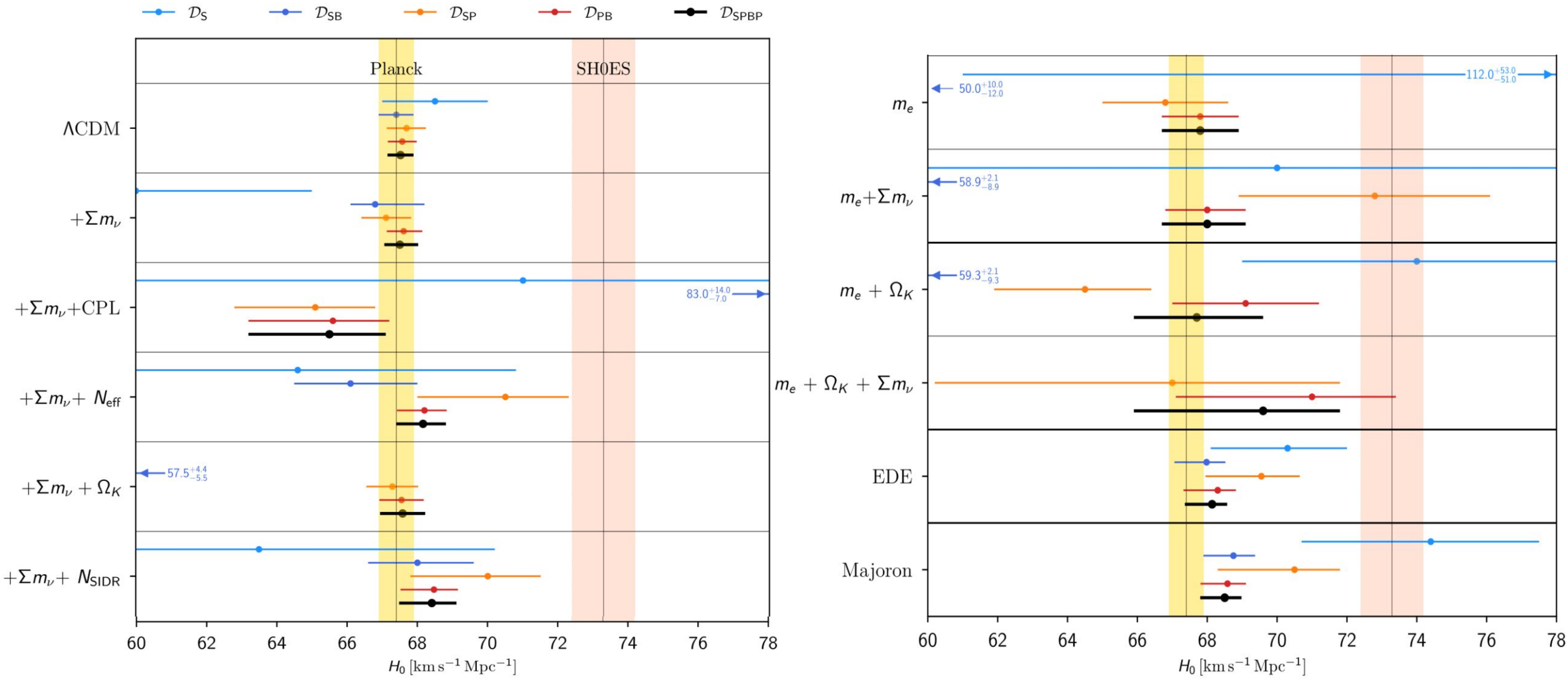
m_φ>1 eV

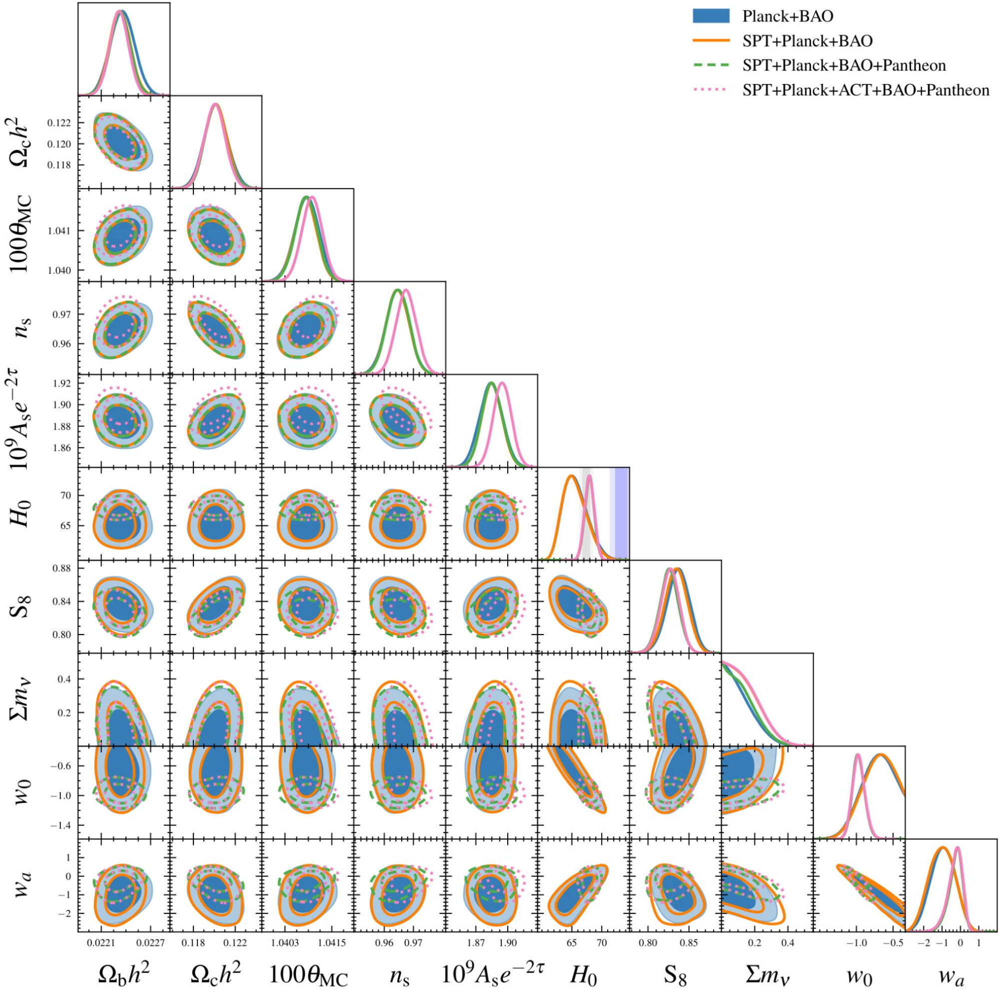
The Power of an Emulator

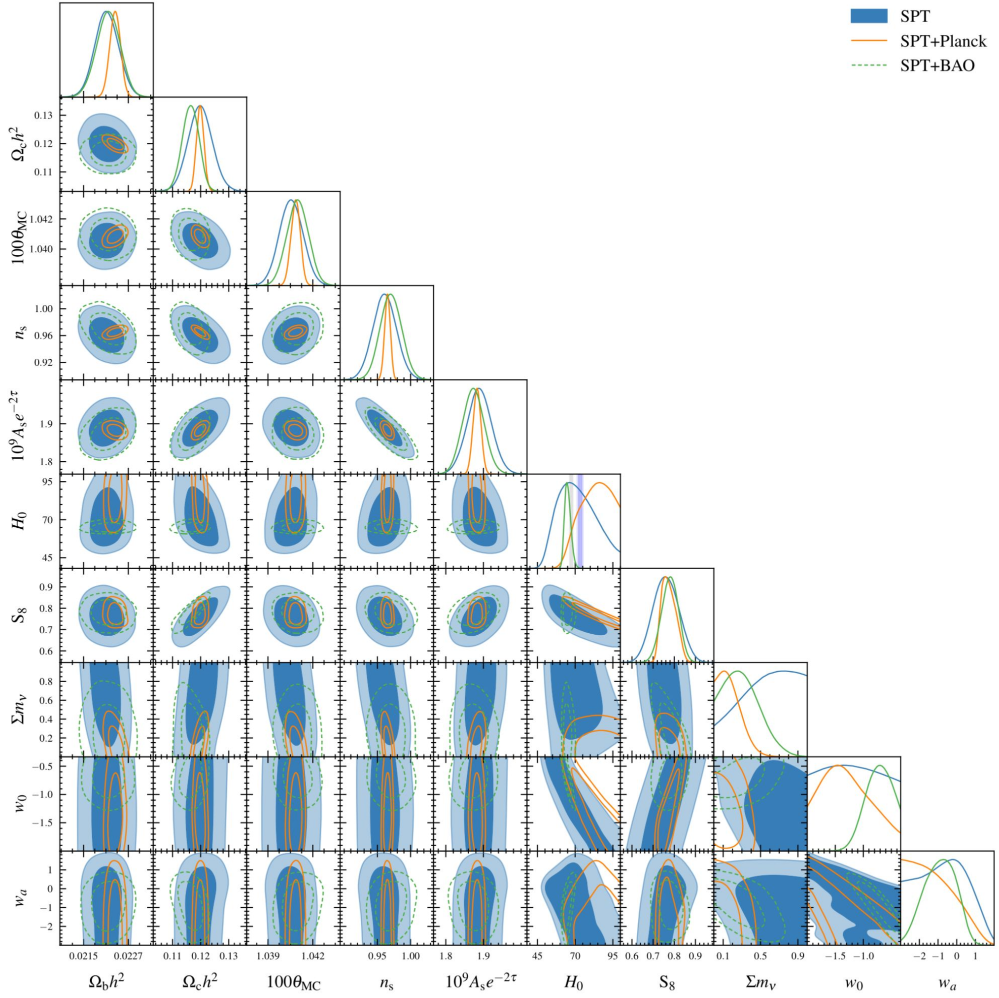
- Boltzmann codes are the tightest bottleneck of Bayesian analysis.
- To speed up the process, use neural-networks based emulators of Boltzmann codes.
- Classical emulators build on previously trained samples.
- The emulator we use builts its training data while running, i.e. online
- Stable results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

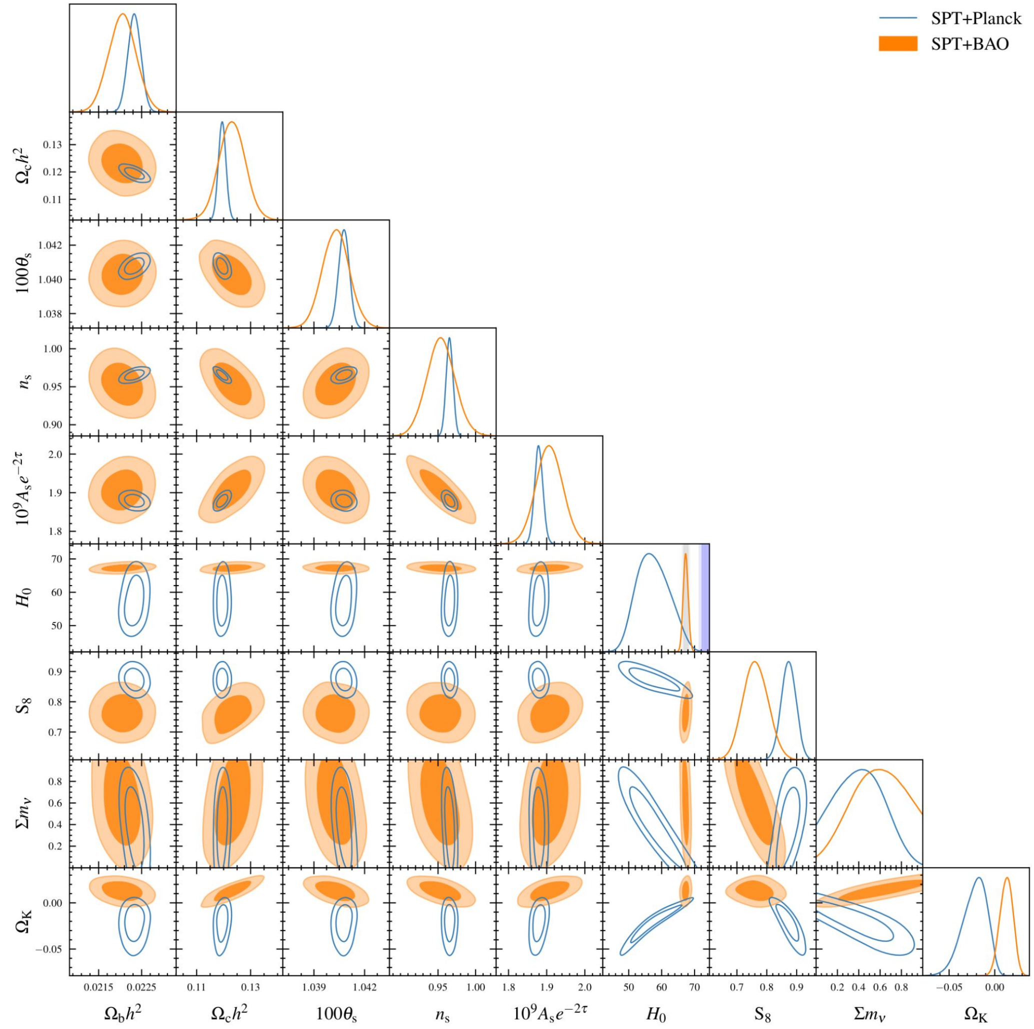
  https://github.com/svenguenther/cobaya

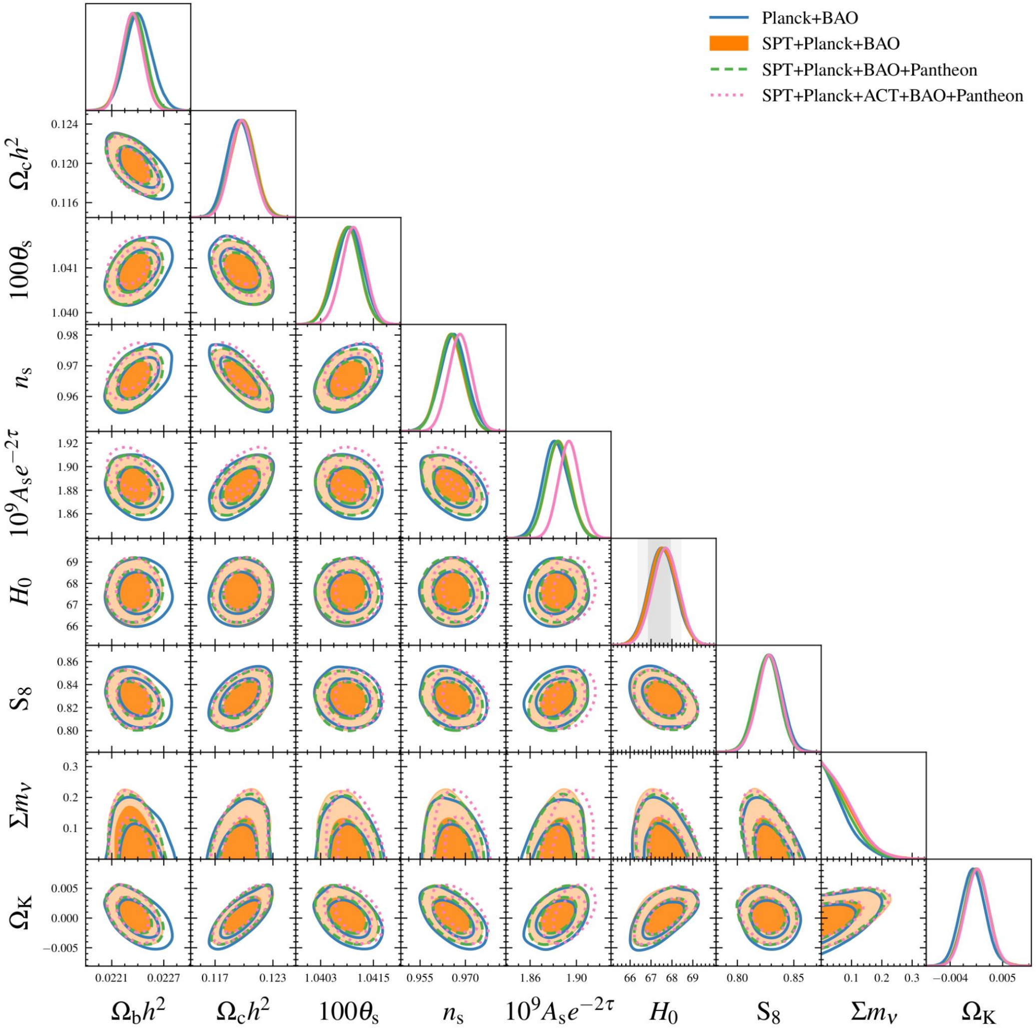
H_0 for Each Model and Data-set

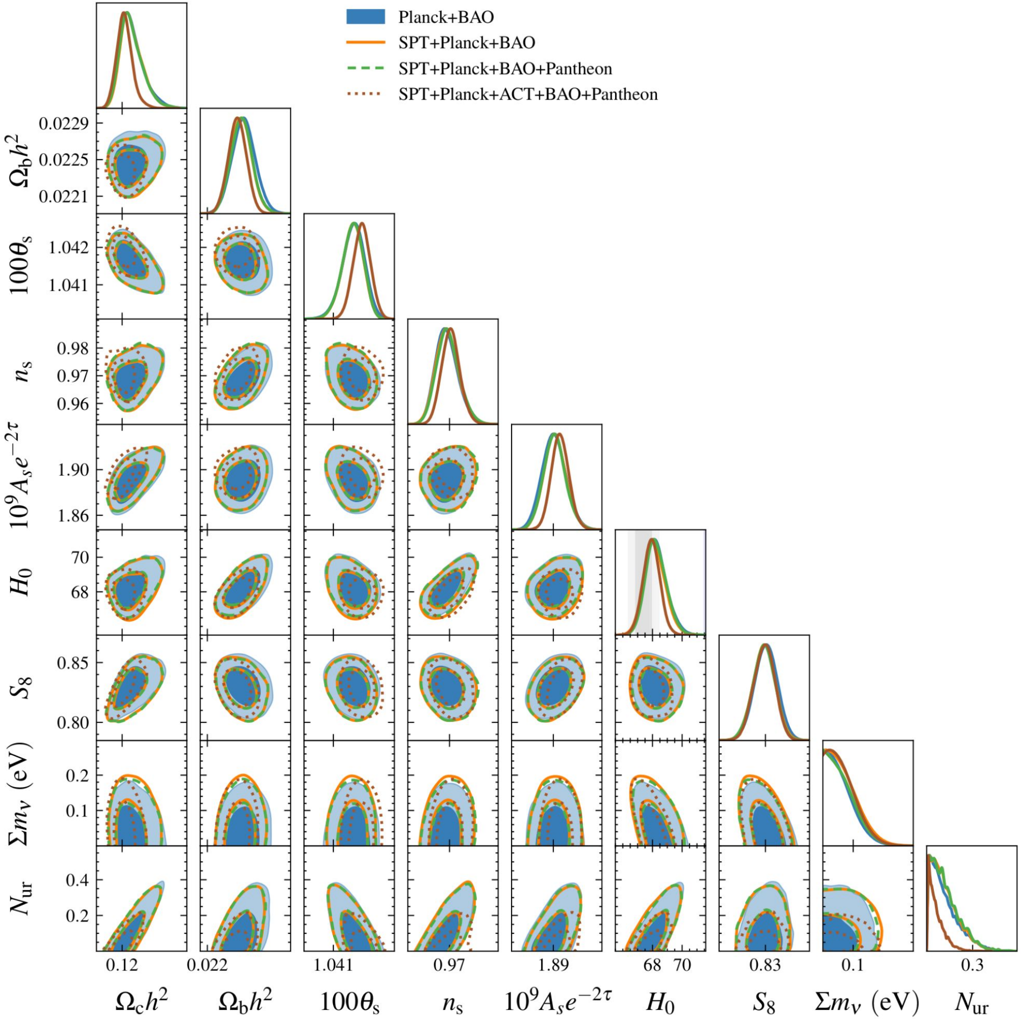


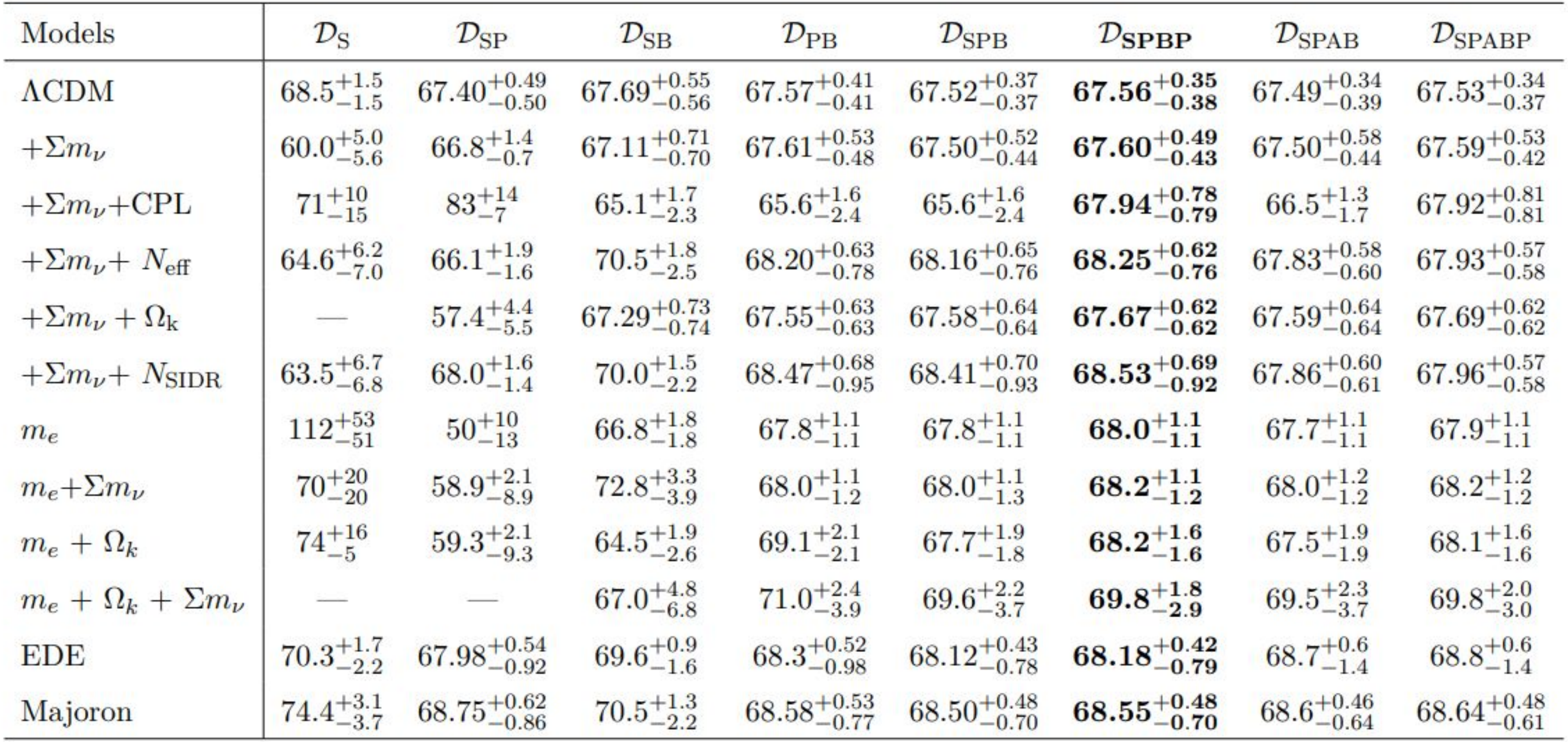

Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_c h^2$
0.122
0.120
0.118
$100\theta_{MC}$
1.041
1.040
n_s
0.97
0.96
$10^9 A_s e^{-2\tau}$
1.92
1.90
1.88
1.86
H_0
70
65
S_8
0.88
0.84
0.80
Σm_ν
0.4
0.2
w_0
−0.6
−1.0
−1.4
w_a
1
0
−1
−2
0.0221
0.0227
0.118
0.122
1.0403
1.0415
0.96
0.97
1.87
1.90
65
70
0.80
0.85
0.2
0.4
−1.0
−0.5
−2
−1
0
1
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
w_0
w_a


SPT
SPT+Planck
SPT+BAO
$\Omega_c h^2$
0.13
0.12
0.11
$100\theta_{MC}$
1.042
1.040
n_s
1.00
0.96
0.92
$10^9 A_s e^{-2\tau}$
1.9
1.8
H_0
95
70
45
S_8
0.9
0.8
0.7
0.6
Σm_ν
0.8
0.6
0.4
0.2
w_0
−0.5
−1.0
−1.5
w_a
1
0
−1
−2
0.0215
0.0227
$\Omega_b h^2$
0.11
0.12
0.13
$\Omega_c h^2$
1.039
1.042
$100\theta_{MC}$
0.95
1.00
n_s
1.8
1.9
$10^9 A_s e^{-2\tau}$
45
70
95
H_0
0.6
0.7
0.8
0.9
S_8
0.1
0.5
0.9
Σm_ν
−1.5
−1.0
w_0
−2
−1
0
1
w_a

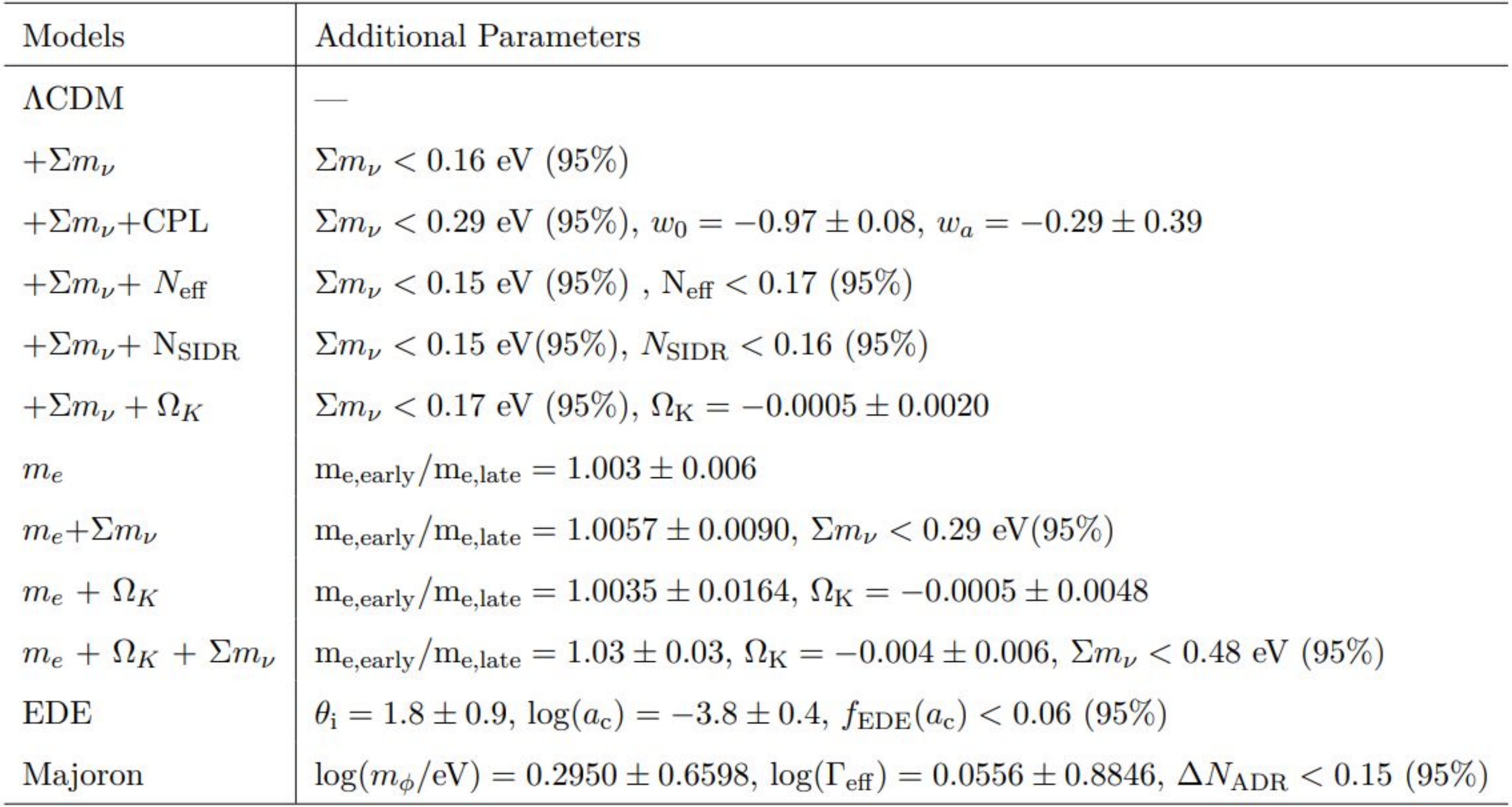

SPT+Planck
SPT+BAO
$\Omega_c h^2$
0.13
0.12
0.11
$100\theta_s$
1.042
1.040
1.038
n_s
1.00
0.95
0.90
$10^9 A_s e^{-2\tau}$
2.0
1.9
1.8
H_0
70
60
50
S_8
0.9
0.8
0.7
Σm_ν
0.8
0.6
0.4
0.2
Ω_K
0.00
−0.05
0.0215
0.0225
$\Omega_b h^2$
0.11
0.13
$\Omega_c h^2$
1.039
1.042
$100\theta_s$
0.95
1.00
n_s
1.8
1.9
2.0
$10^9 A_s e^{-2\tau}$
50
60
70
H_0
0.7
0.8
0.9
S_8
0.2
0.4
0.6
0.8
Σm_ν
−0.05
0.00
Ω_K


Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_c h^2$
0.124
0.120
0.116
$100\theta_s$
1.041
1.040
n_s
0.98
0.97
0.96
$10^9 A_s e^{-2\tau}$
1.92
1.90
1.88
1.86
H_0
69
68
67
66
S_8
0.86
0.84
0.82
0.80
Σm_ν
0.3
0.2
0.1
Ω_K
0.005
0.000
−0.005
0.0221
0.0227
0.117
0.123
1.0403
1.0415
0.955
0.970
1.86
1.90
66
67
68
69
0.80
0.85
0.1
0.2
0.3
−0.004
0.005
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_s$
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
$\Omega_b h^2$
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}

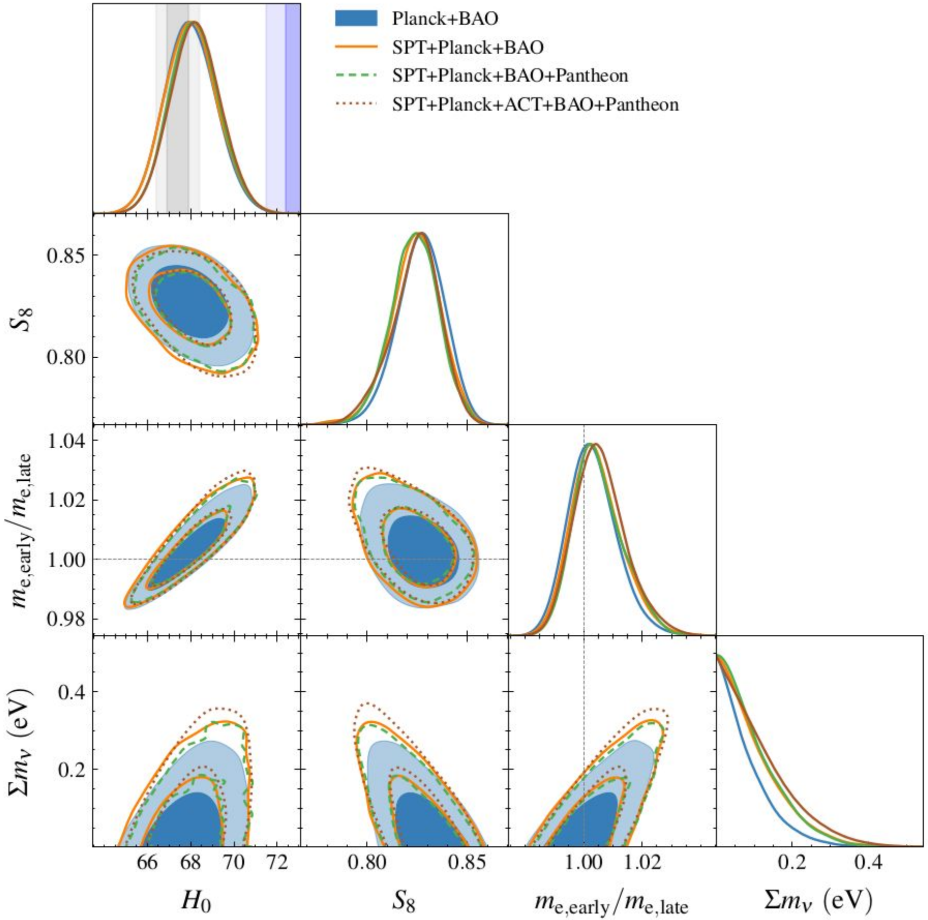


Models	$\mathcal{D}_{\rm S}$	$\mathcal{D}_{\rm SP}$	$\mathcal{D}_{\rm SB}$	$\mathcal{D}_{\rm PB}$	$\mathcal{D}_{\rm SPB}$	$\mathcal{D}_{\mathbf{SPBP}}$	$\mathcal{D}_{\rm SPAB}$	$\mathcal{D}_{\rm SPABP}$
ΛCDM	$68.5^{+1.5}_{-1.5}$	$67.40^{+0.49}_{-0.50}$	$67.69^{+0.55}_{-0.56}$	$67.57^{+0.41}_{-0.41}$	$67.52^{+0.37}_{-0.37}$	$\mathbf{67.56^{+0.35}_{-0.38}}$	$67.49^{+0.34}_{-0.39}$	$67.53^{+0.34}_{-0.37}$
$+\Sigma m_\nu$	$60.0^{+5.0}_{-5.6}$	$66.8^{+1.4}_{-0.7}$	$67.11^{+0.71}_{-0.70}$	$67.61^{+0.53}_{-0.48}$	$67.50^{+0.52}_{-0.44}$	$\mathbf{67.60^{+0.49}_{-0.43}}$	$67.50^{+0.58}_{-0.44}$	$67.59^{+0.53}_{-0.42}$
$+\Sigma m_\nu$+CPL	71^{+10}_{-15}	83^{+14}_{-7}	$65.1^{+1.7}_{-2.3}$	$65.6^{+1.6}_{-2.4}$	$65.6^{+1.6}_{-2.4}$	$\mathbf{67.94^{+0.78}_{-0.79}}$	$66.5^{+1.3}_{-1.7}$	$67.92^{+0.81}_{-0.81}$
$+\Sigma m_\nu+ N_{\rm eff}$	$64.6^{+6.2}_{-7.0}$	$66.1^{+1.9}_{-1.6}$	$70.5^{+1.8}_{-2.5}$	$68.20^{+0.63}_{-0.78}$	$68.16^{+0.65}_{-0.76}$	$\mathbf{68.25^{+0.62}_{-0.76}}$	$67.83^{+0.58}_{-0.60}$	$67.93^{+0.57}_{-0.58}$
$+\Sigma m_\nu + \Omega_{\rm k}$	—	$57.4^{+4.4}_{-5.5}$	$67.29^{+0.73}_{-0.74}$	$67.55^{+0.63}_{-0.63}$	$67.58^{+0.64}_{-0.64}$	$\mathbf{67.67^{+0.62}_{-0.62}}$	$67.59^{+0.64}_{-0.64}$	$67.69^{+0.62}_{-0.62}$
$+\Sigma m_\nu+ N_{\rm SIDR}$	$63.5^{+6.7}_{-6.8}$	$68.0^{+1.6}_{-1.4}$	$70.0^{+1.5}_{-2.2}$	$68.47^{+0.68}_{-0.95}$	$68.41^{+0.70}_{-0.93}$	$\mathbf{68.53^{+0.69}_{-0.92}}$	$67.86^{+0.60}_{-0.61}$	$67.96^{+0.57}_{-0.58}$
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+Σm_ν	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	$74.4^{+3.1}_{-3.7}$	$68.75^{+0.62}_{-0.86}$	$70.5^{+1.3}_{-2.2}$	$68.58^{+0.53}_{-0.77}$	$68.50^{+0.48}_{-0.70}$	$\mathbf{68.55^{+0.48}_{-0.70}}$	$68.6^{+0.46}_{-0.64}$	$68.64^{+0.48}_{-0.61}$



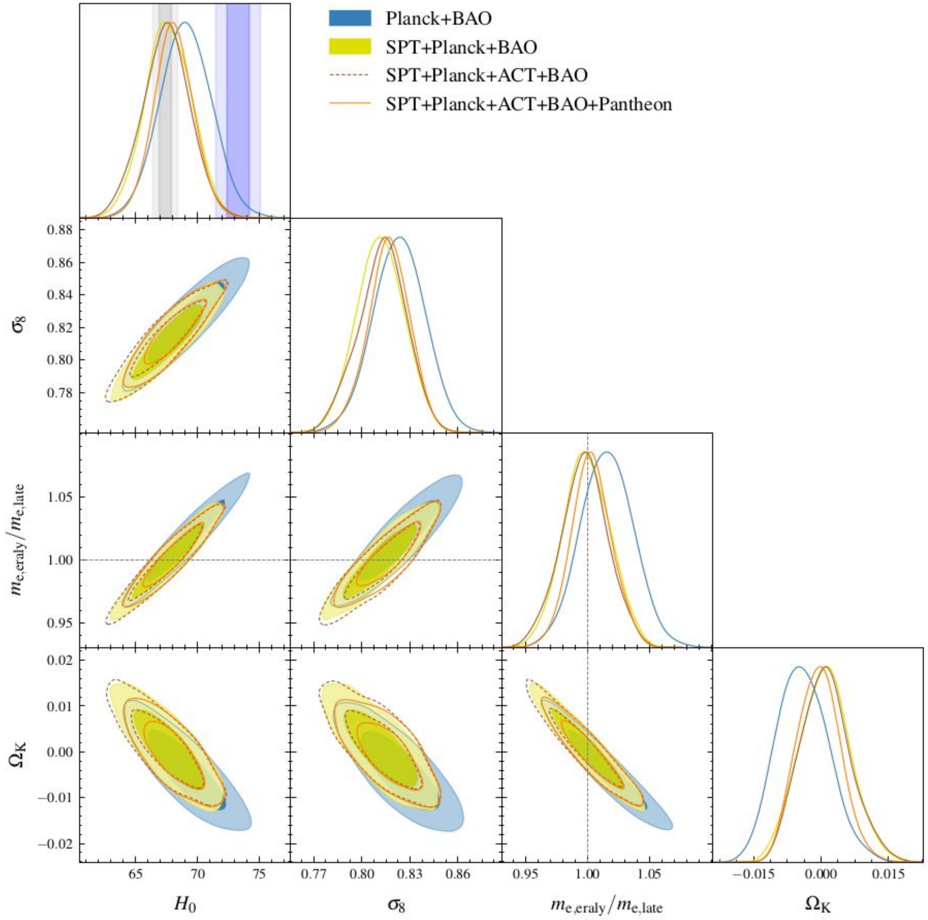
Models	Additional Parameters
ΛCDM	—
$+\Sigma m_\nu$	$\Sigma m_\nu < 0.16$ eV (95%)
$+\Sigma m_\nu$+CPL	$\Sigma m_\nu < 0.29$ eV (95%), $w_0 = -0.97 \pm 0.08$, $w_a = -0.29 \pm 0.39$
$+\Sigma m_\nu+ N_{\rm eff}$	$\Sigma m_\nu < 0.15$ eV (95%) , $\rm N_{eff} < 0.17$ (95%)
$+\Sigma m_\nu+ \rm N_{SIDR}$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

Me+Mnu: Results



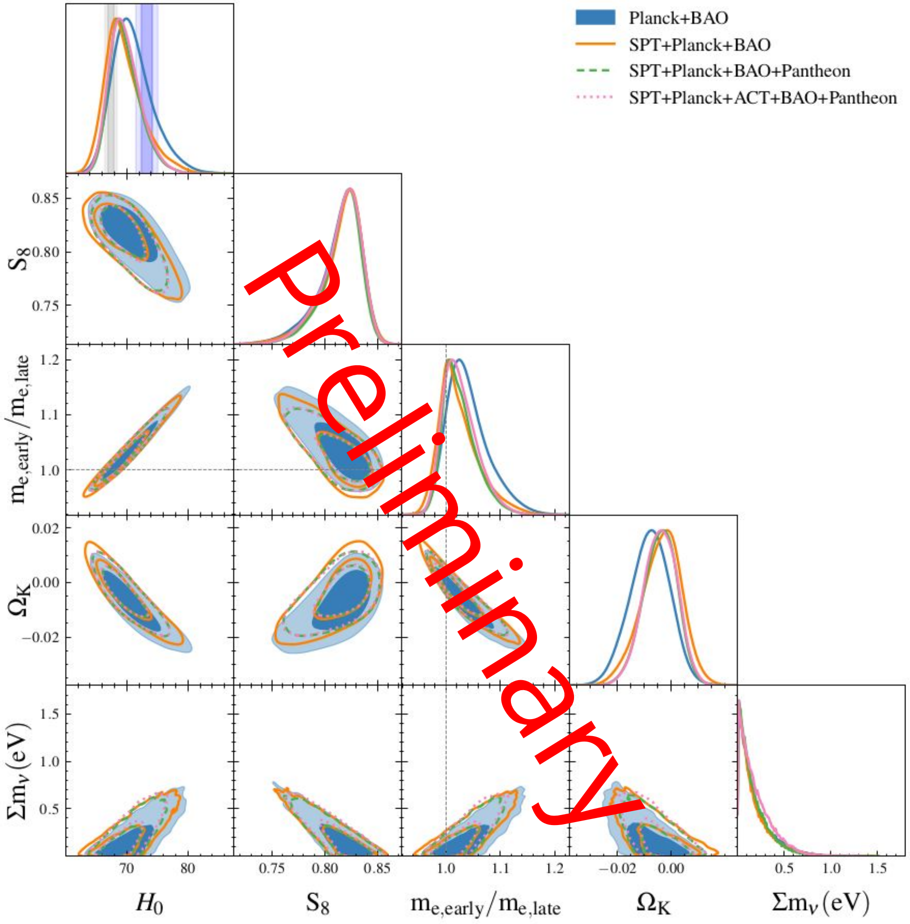
Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Me+Omk

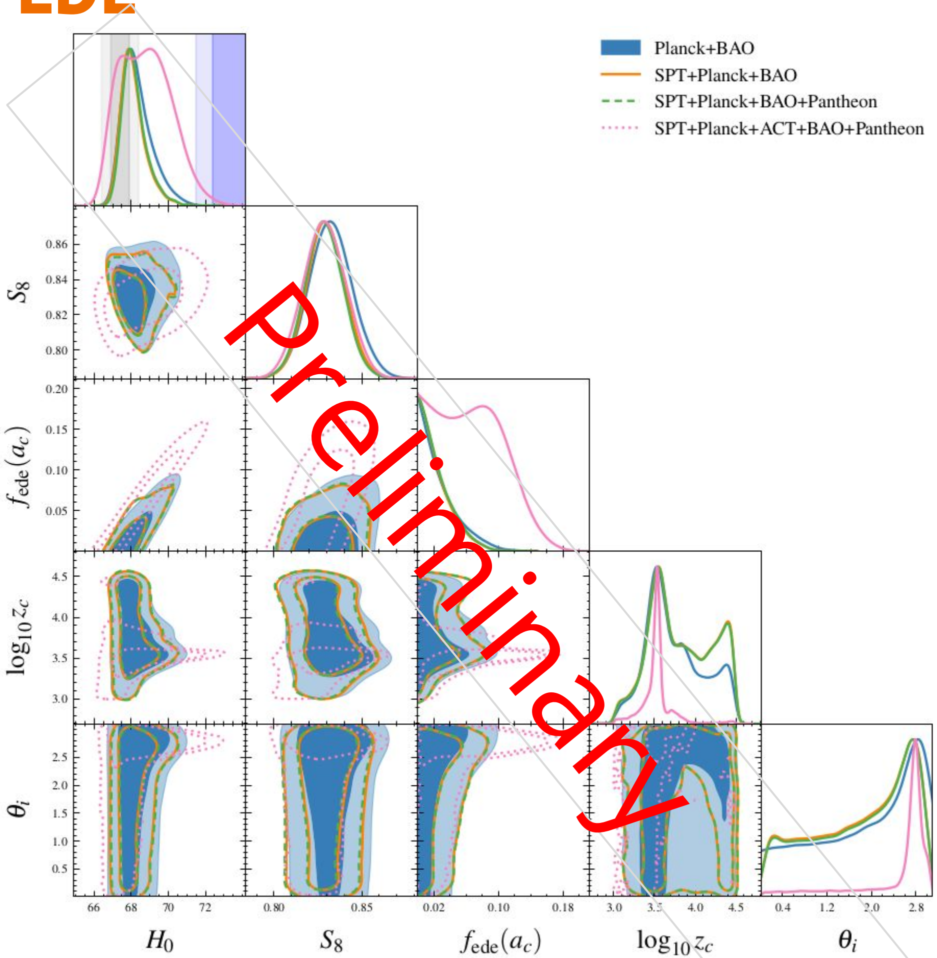


Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{\rm e,eraly}/m_{\rm e,late}$
$\Omega_{\rm K}$
65 70 75
0.77 0.80 0.83 0.86
0.95 1.00 1.05
−0.015 0.000 0.015
0.78 0.80 0.82 0.84 0.86 0.88
0.95 1.00 1.05
−0.02 −0.01 0.00 0.01 0.02

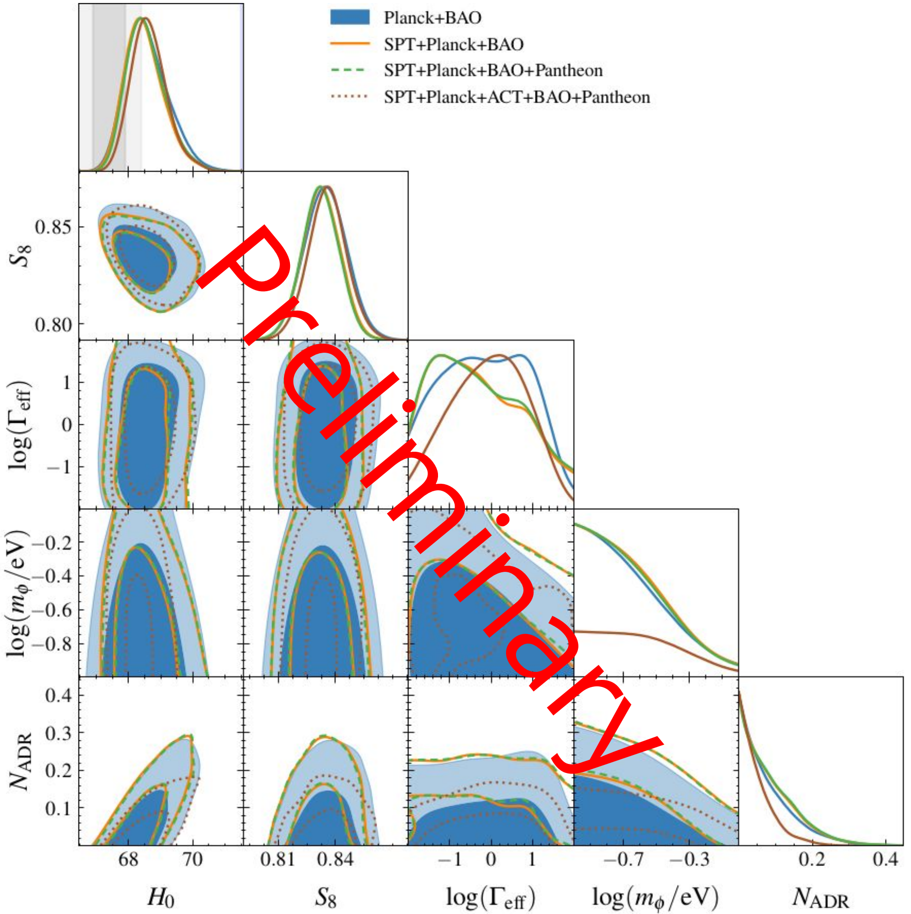
Me+Mnu+Omk


Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
S_8
0.85
0.80
0.75
$m_{e,early}/m_{e,late}$
1.2
1.1
1.0
Ω_K
0.02
0.00
−0.02
Σm_ν (eV)
1.5
1.0
0.5
70
80
0.75
0.80
0.85
1.0
1.1
1.2
−0.02
0.00
0.5
1.0
1.5
H_0
S_8
$m_{e,early}/m_{e,late}$
Ω_K
Σm_ν (eV)

EDE

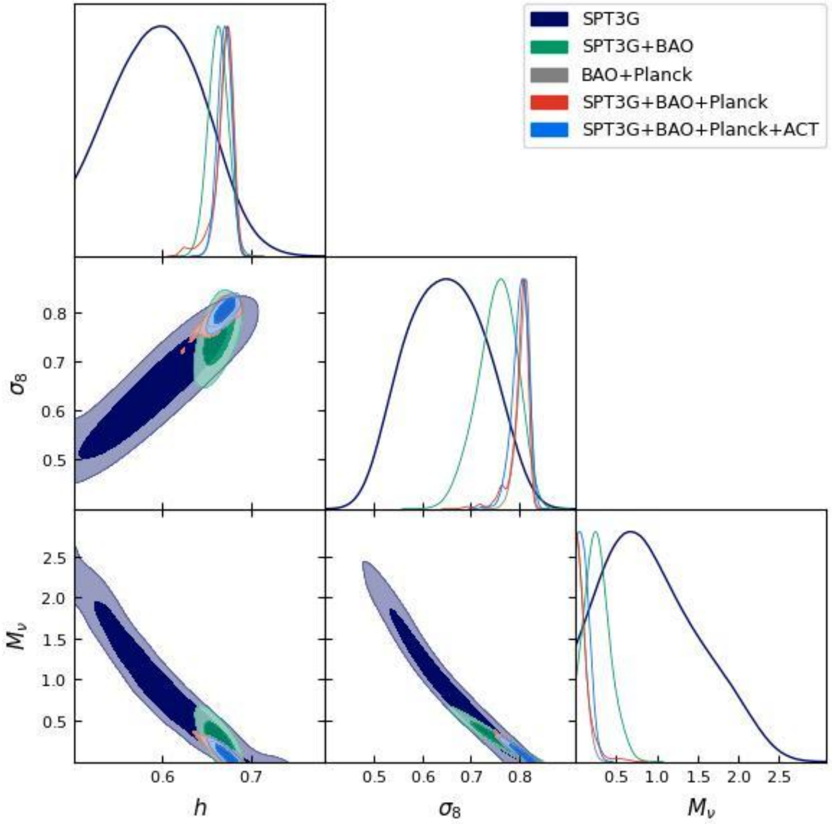

Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
S_8
0.80
0.82
0.84
0.86
$f_{\rm ede}(a_c)$
0.05
0.10
0.15
0.20
$\log_{10} z_c$
3.0
3.5
4.0
4.5
θ_i
0.5
1.0
1.5
2.0
2.5
66
68
70
72
H_0
0.80
0.85
S_8
0.02
0.10
0.18
$f_{\rm ede}(a_c)$
3.0
3.5
4.0
4.5
$\log_{10} z_c$
0.4
1.2
2.0
2.8
θ_i

Majoron



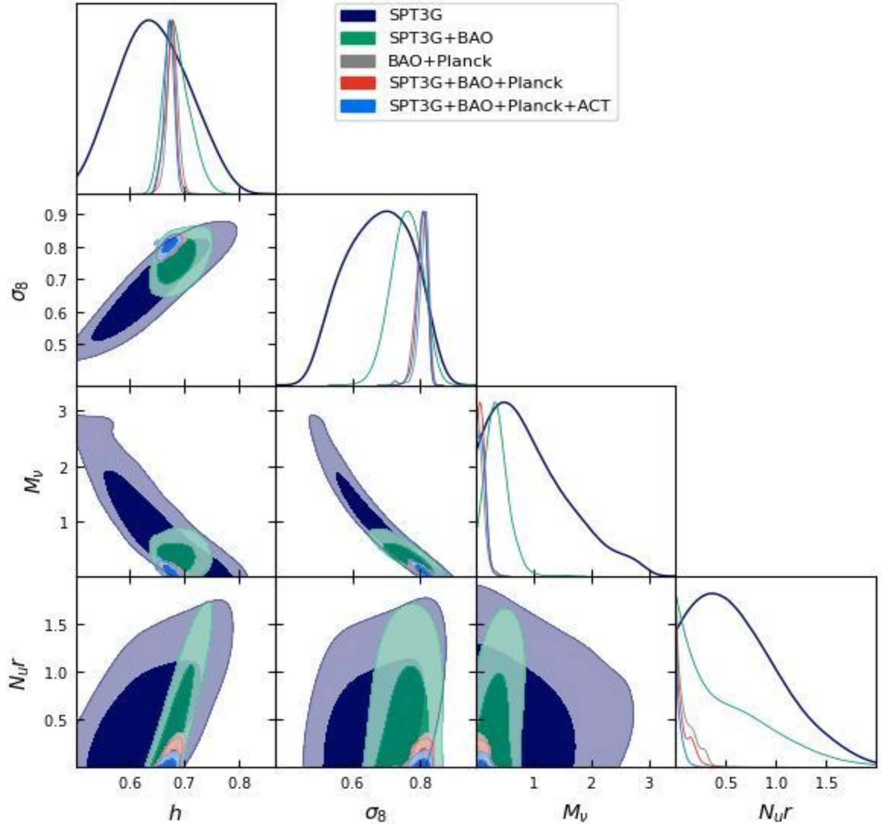
Sub eV mass

ΛCDM+Σmν

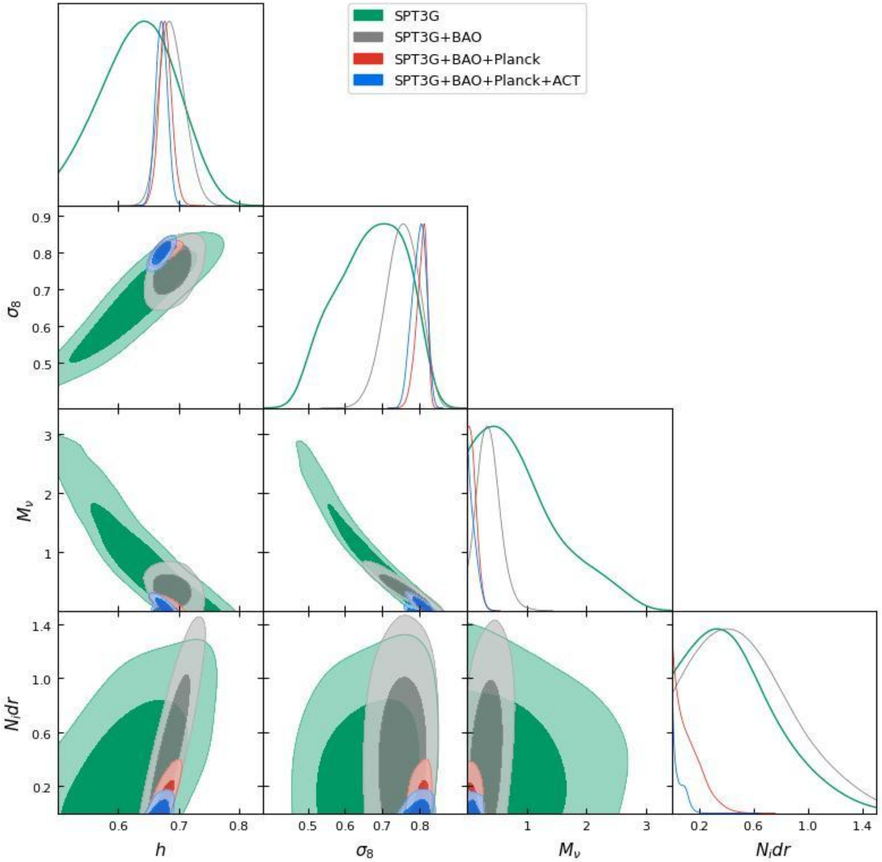


Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.00±0.82
σ_8	0.803±0.019

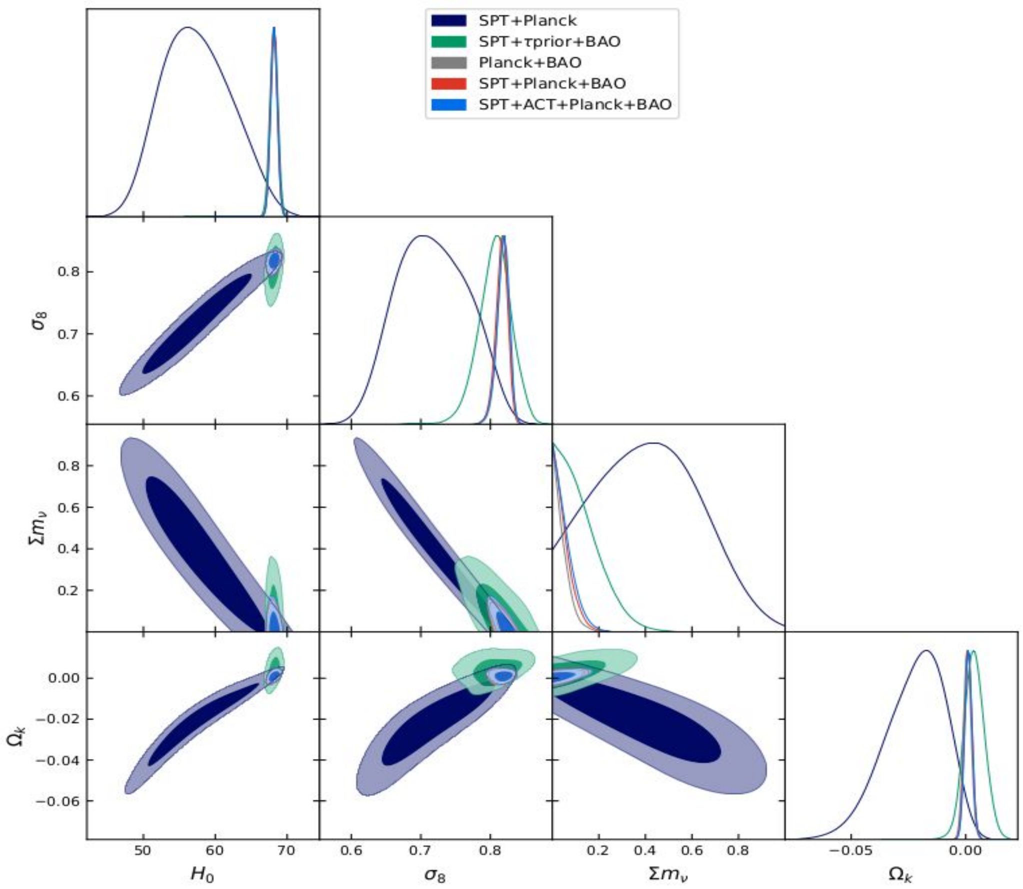
ΛCDM+Σm_ν+N_{eff}



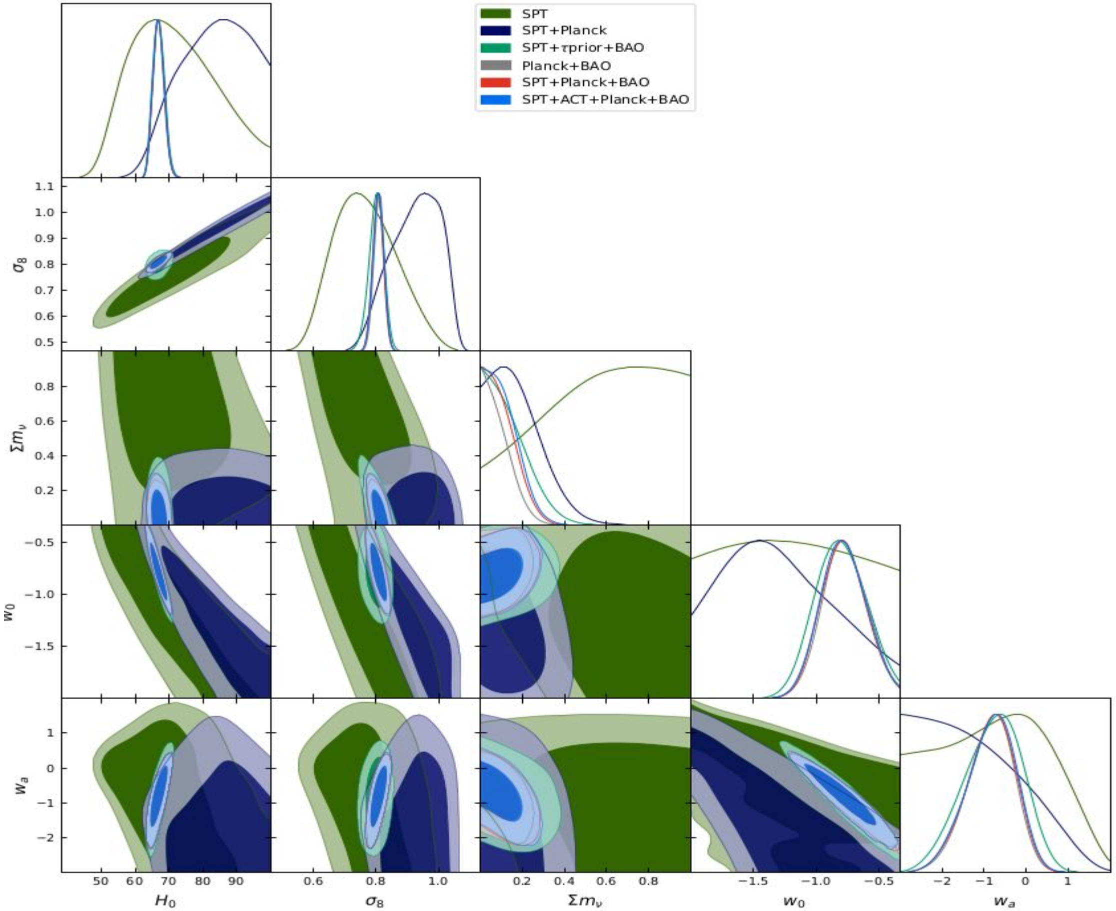
Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.10±0.85
σ_8	0.812±0.009



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



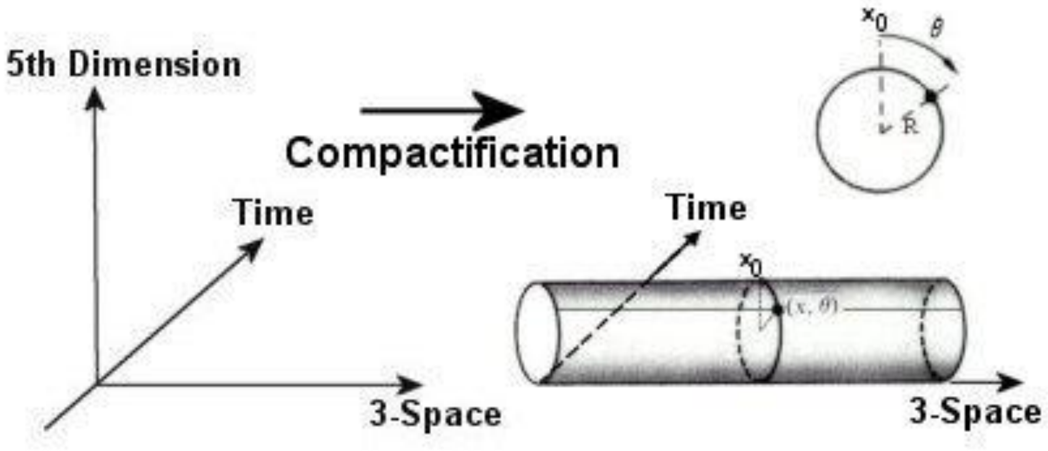
Parameter	SPT+ ACT+ Planck+ BAO
H_0	68.16±0.46
σ_8	0.818±0.009



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

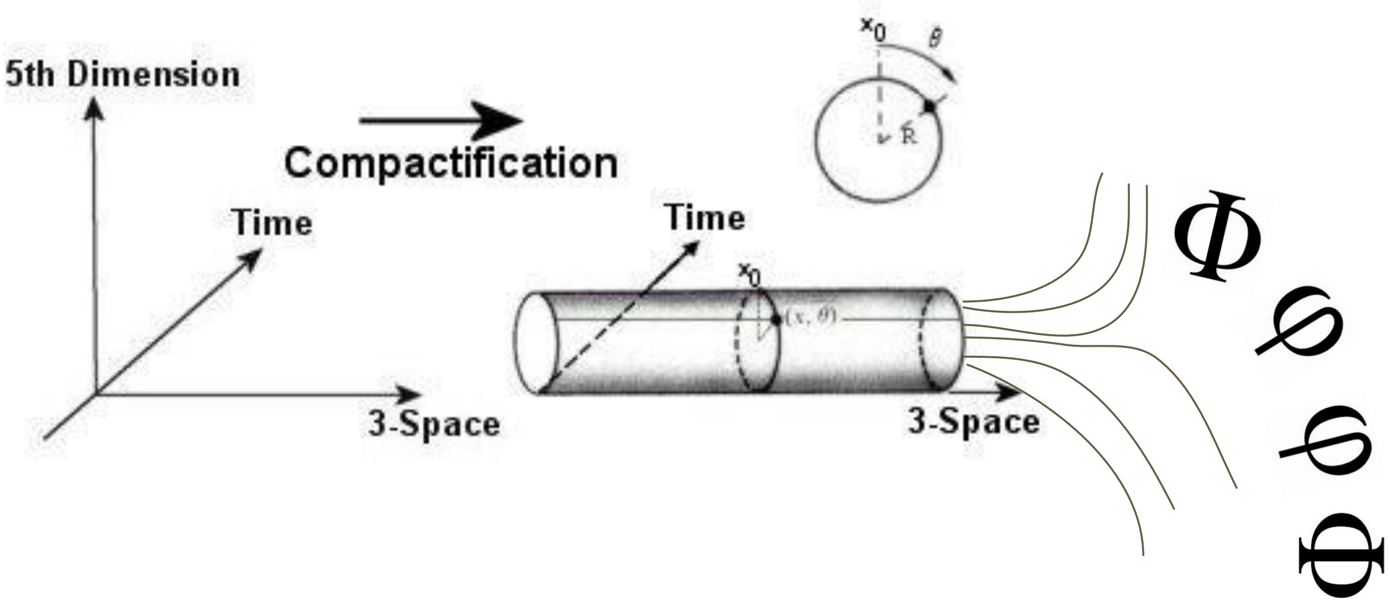
SLIDES FOR A GENERAL AUDIENCE TALK

Varyin

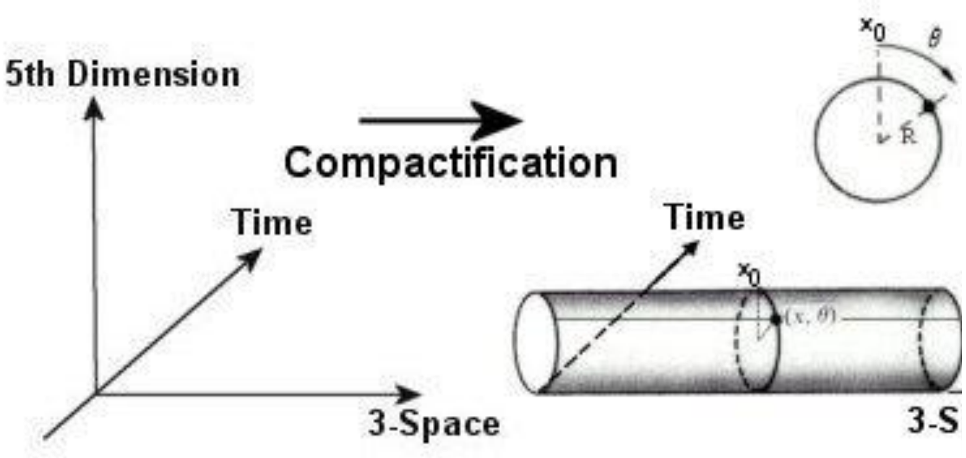


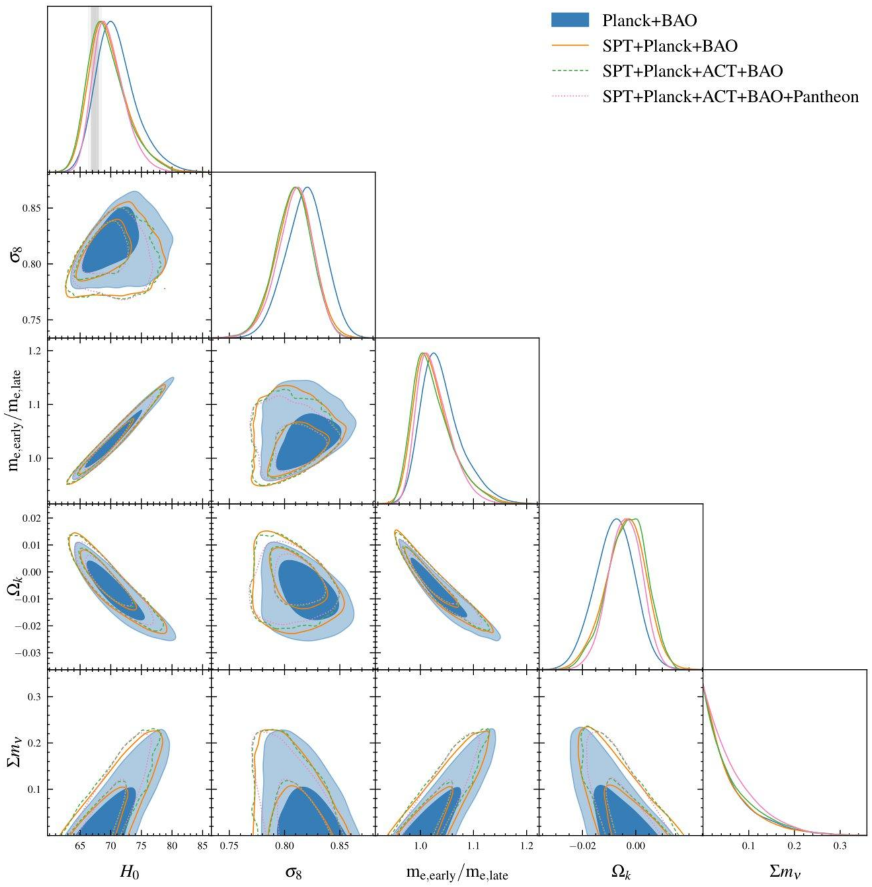
5th Dimension
Compactification
Time
3-Space
Time
x_0
(x, θ)
3-Space
x_0
θ
R

Varying Electron Mass: Theory

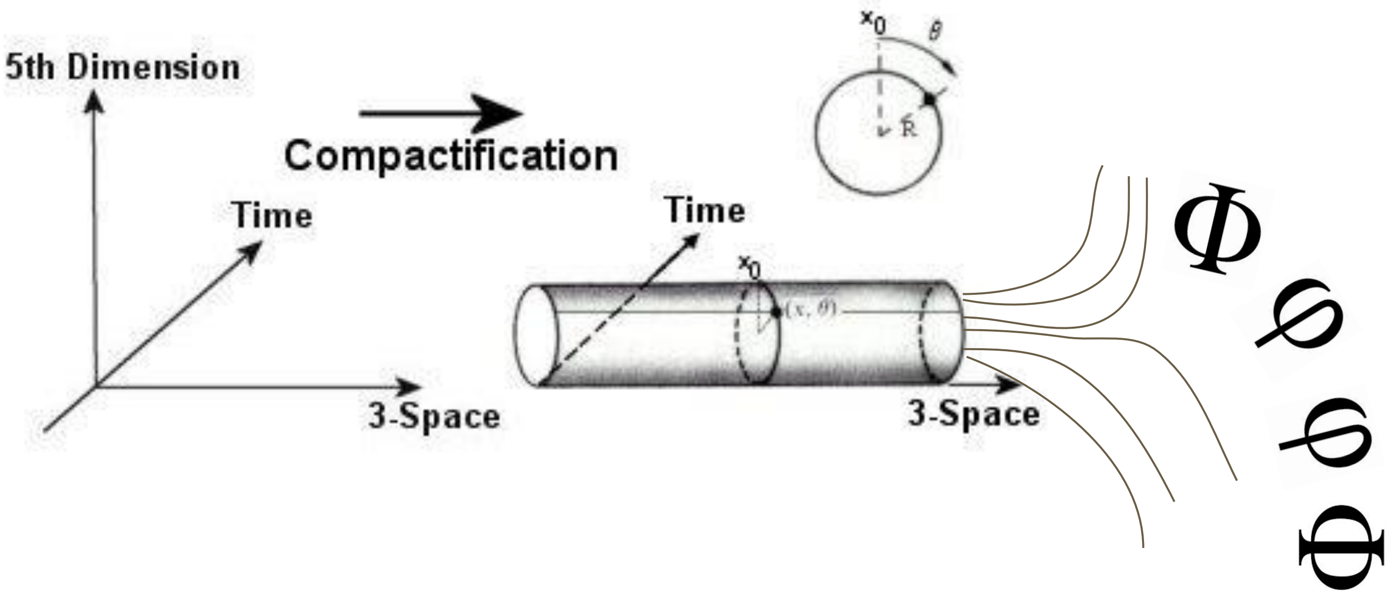


Varying Electron Mass: Theory

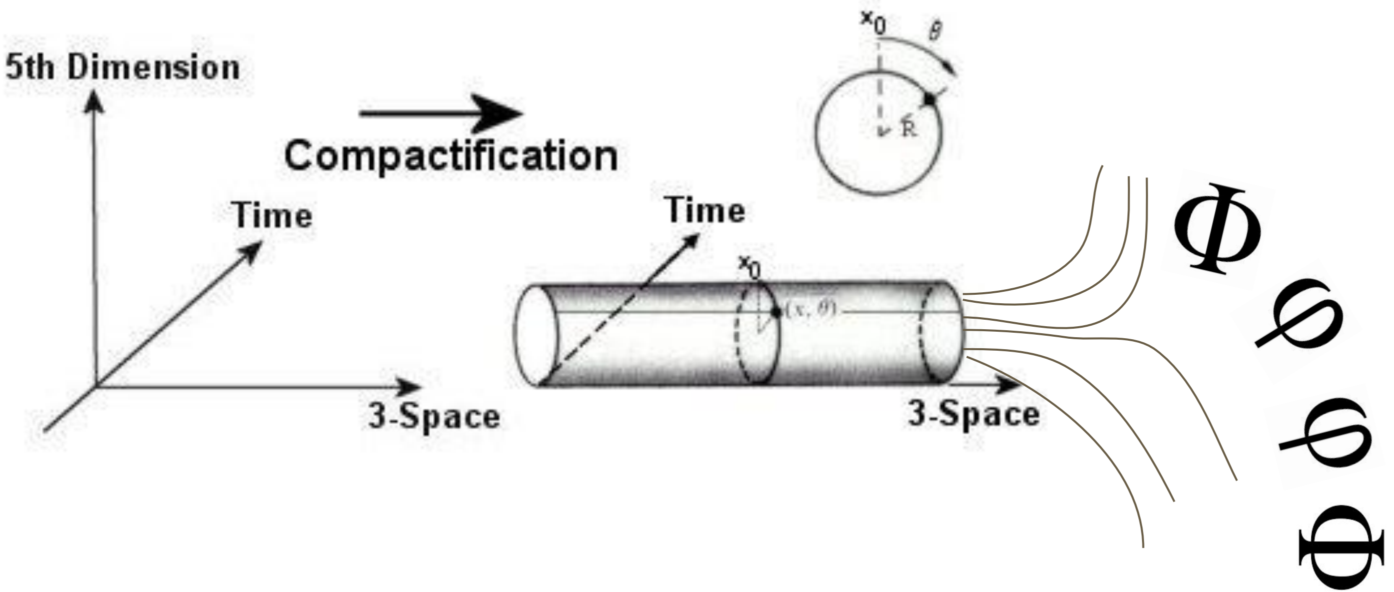


Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
σ_8
0.85
0.80
0.75
$m_{e,early}/m_{e,late}$
1.2
1.1
1.0
Ω_k
0.02
0.01
0.00
−0.01
−0.02
−0.03
Σm_ν
0.3
0.2
0.1
65
70
75
80
85
0.75
0.80
0.85
1.0
1.1
1.2
−0.02
0.00
0.1
0.2
0.3
H_0
σ_8
$m_{e,early}/m_{e,late}$
Ω_k
Σm_ν

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)