Updated Constraints on Hubble Tension solutions

With recent SPT-3G and SH0ES data

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arXiv:2312.09814

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Silvia Galli and Karim Benabed from **IAP**

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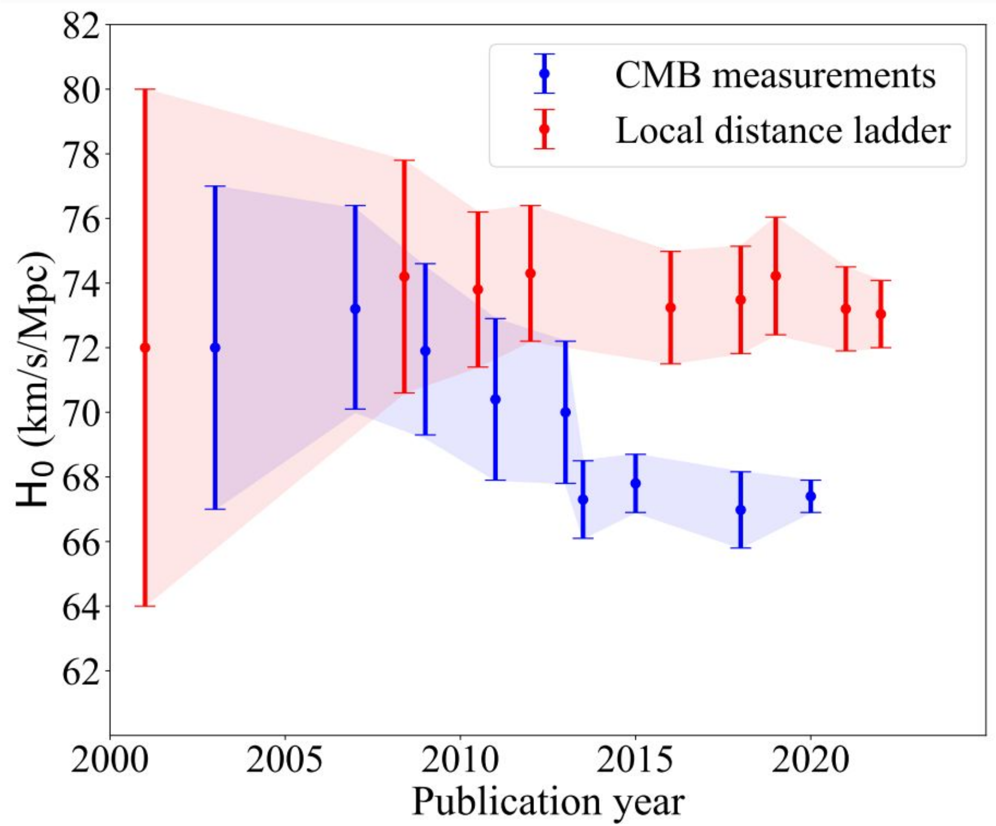
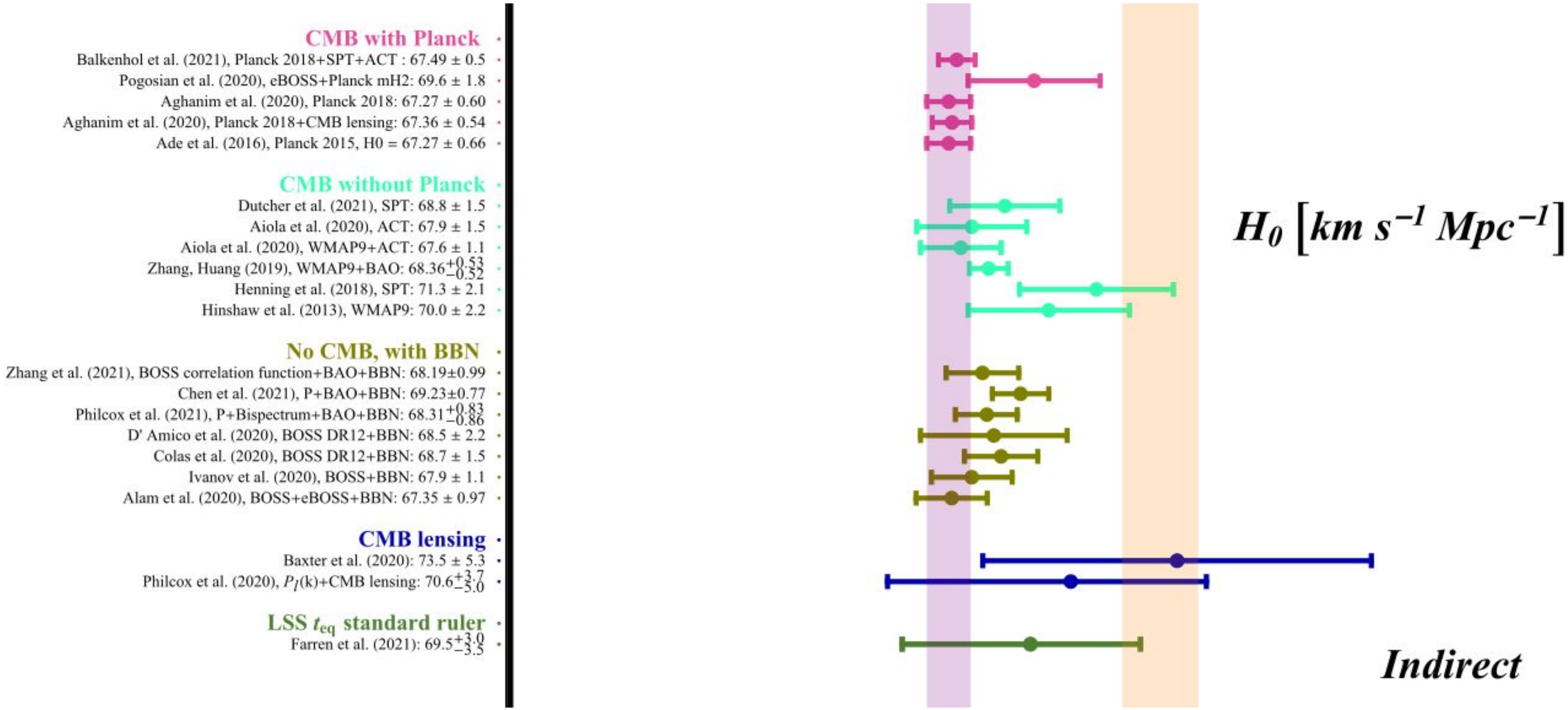
Federica Guidi, Aristide Doussot, Eric Hivon, Etienne Camphuis, Lennart Balkenhol and Aline Vitrier

The Trouble with Hubble



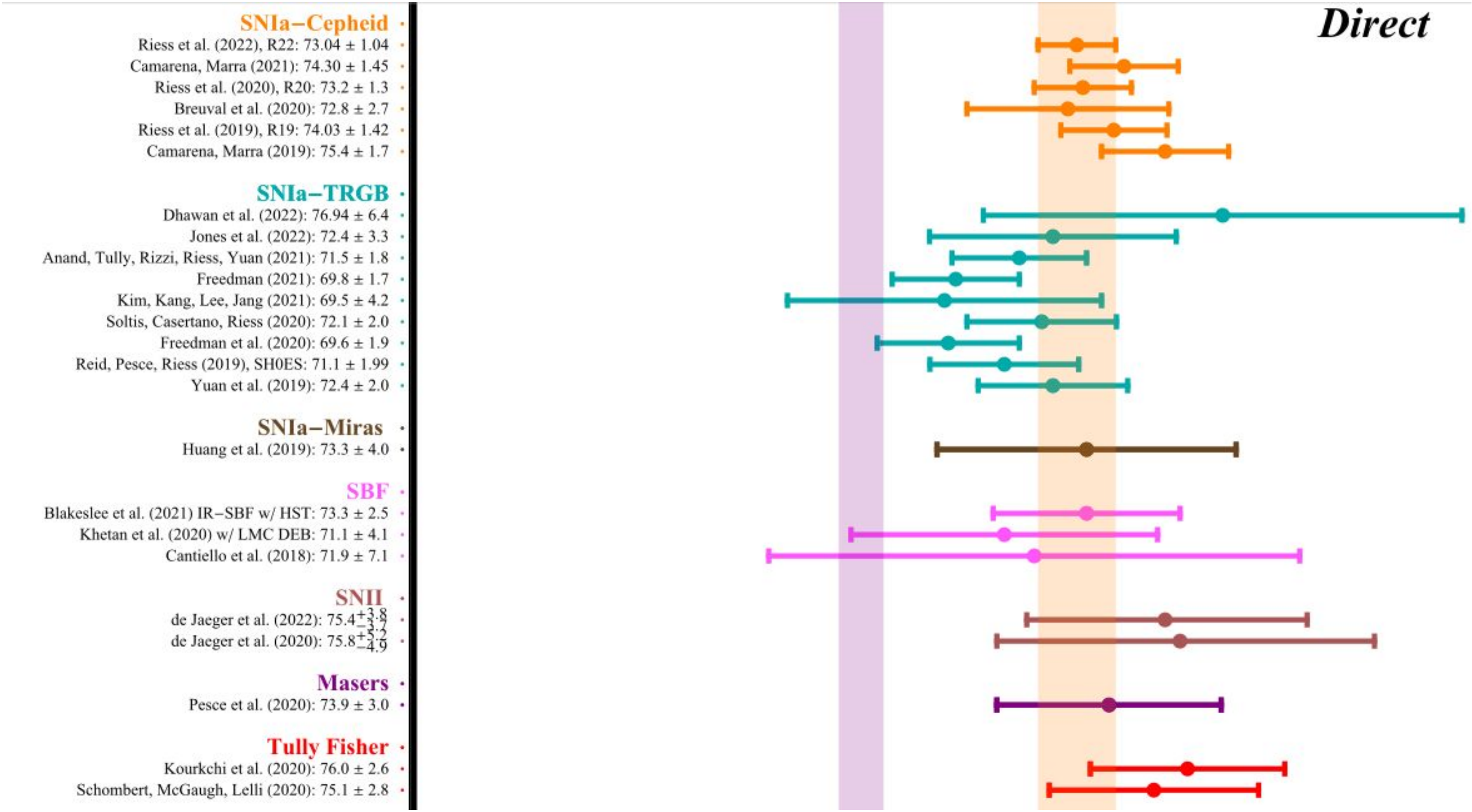
Ref: Hubble Tension: The Evidence of New Physics(2302.05709)

The Trouble with Hubble



Ref: 2203.06142

The Trouble with Hubble



Ref: [2203.06142]

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	✗	✗
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	✗	✗

Ref: 2107.10291

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

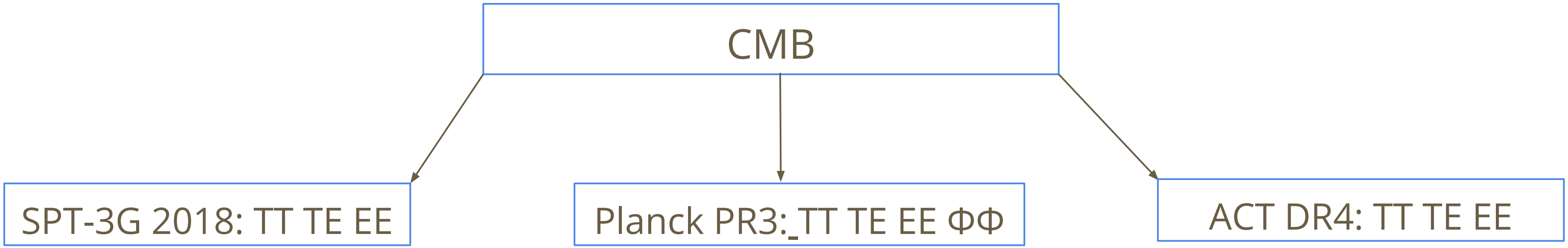
H(z)

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

Flat, closed or open

$H(z)/H_0$

Data Sets



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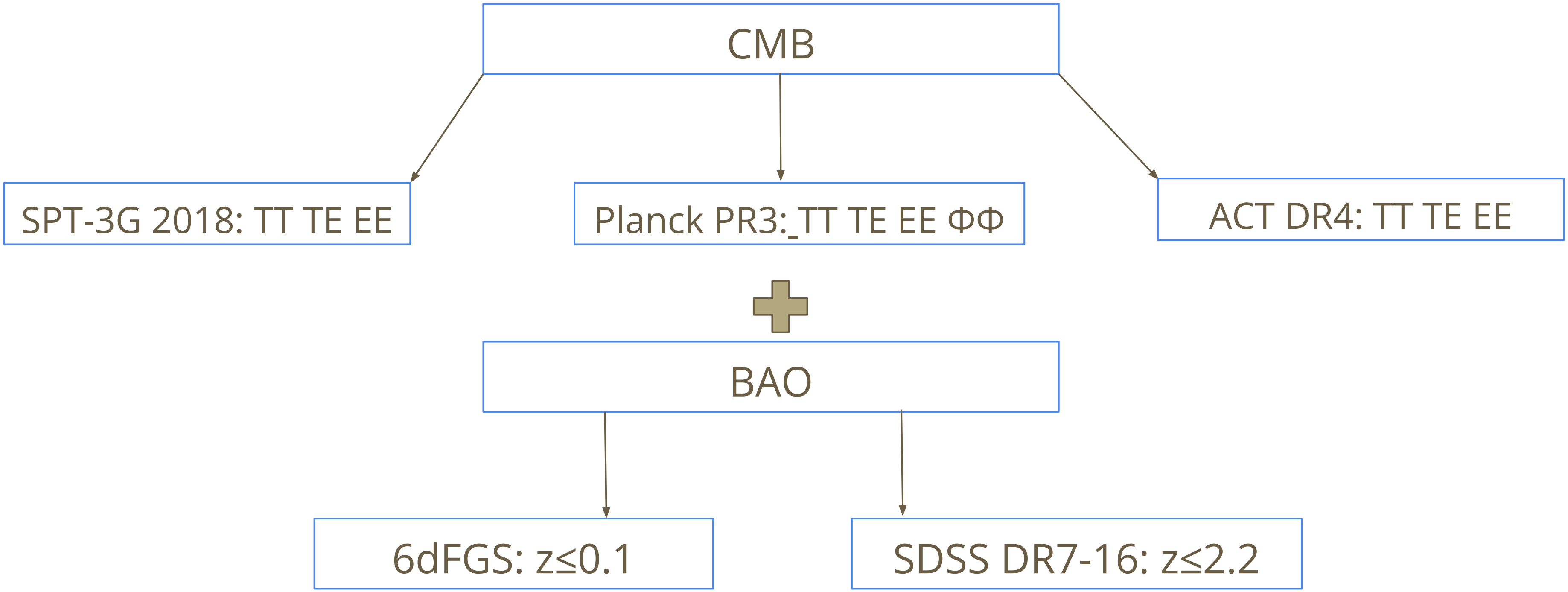
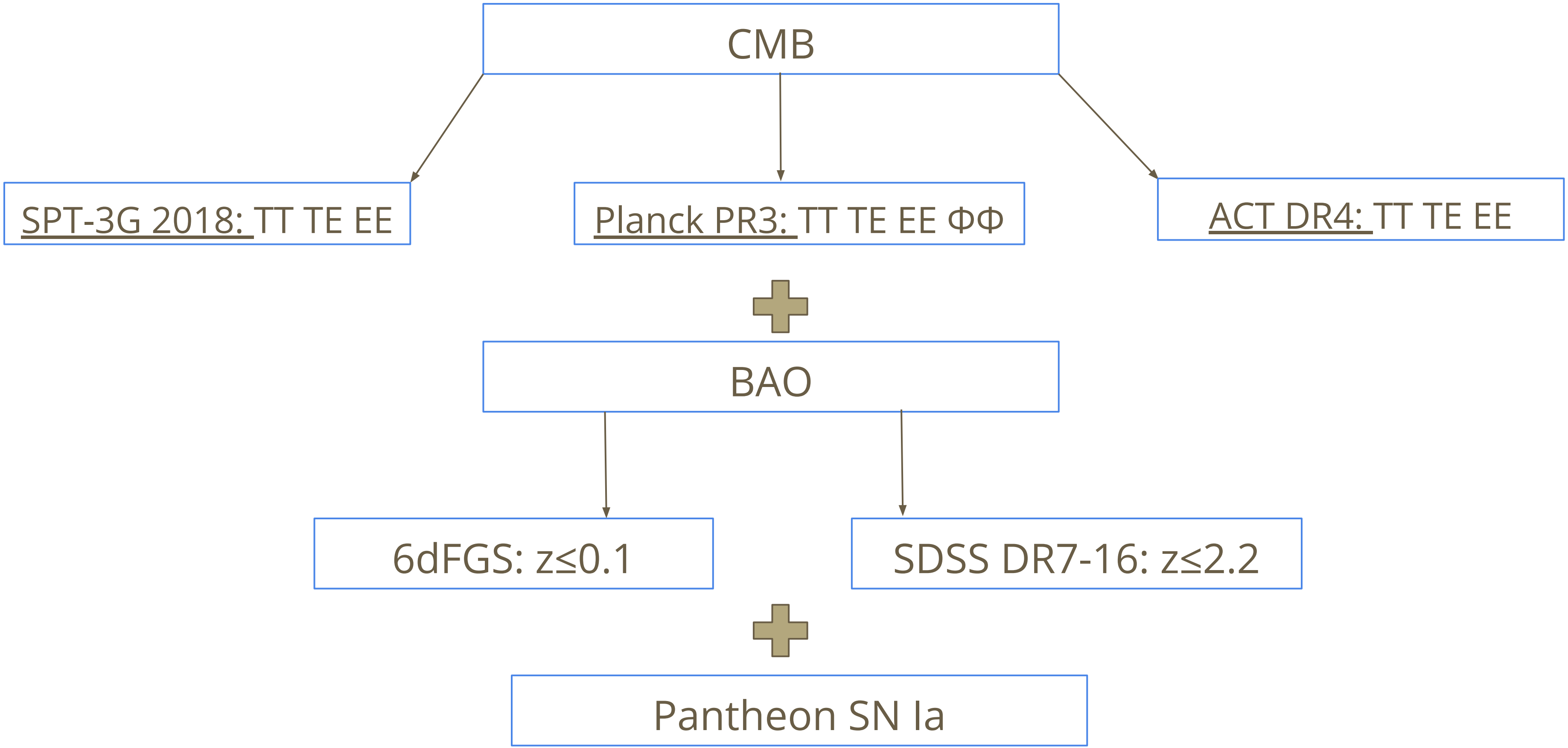

CMB
SPT-3G 2018: TT TE EE
Planck PR3: TT TE EE ΦΦ
ACT DR4: TT TE EE
BAO
6dFGS: z≤0.1
SDSS DR7-16: z≤2.2

Data Sets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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 ≡ scale factor
- Spatial Curvature (Ω_K)
- Free streaming Dark Radiation (N_{eff})
- Self Interacting Dark Radiation (N_{SIDR})

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

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Large scale CMB + SN Ia

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Small scale CMB

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- Spatial Curvature (Ω_K)

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

- Self Interacting Dark Radiation ($N_{\rm SIDR}$)

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

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
  - Motivated by higher dimensional theories, e.g. string theory
  - 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.

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Model	ΔN_{param}	M_B	Gaussian tension	Q_{DMAP} tension		$\Delta\chi^2$	ΔAIC		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$_\nu$***
    - **+Ω_K**
        - Changing z_* changes D_A. Need to compensate with late universe parameter.
        - Intermediate scale polarization data from SPT-3G was crucial.

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

Elaborate Models

- **Varying electron mass: (Hart & Chulba, 2017; 1705.03925)**
  - **$+\Sigma m_\nu$**
  - **$+\Omega_K$**
    - Intermediate scale polarization data from SPT-3G was crucial.
    - Even More promising than its ancestor.

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)**
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- **Early Dark Energy: (Poulin *et al.*, 2023; 2302.09032)**
    - Motivated by higher dimensional theories.
    - Scalar field reduces sound horizon around Matter-radiation equality.

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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

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- **The Majoron: (Escudero & Witte, 2021; 2103.03249)**
    - Breaking symmetry in the early Universe produces interacting Dark Radiation.

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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.

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

- *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.

$$Q_{\text{DMAP, model}} \equiv \sqrt{\chi^2_{\text{min, model, }\mathcal{D}+SH0ES} - \chi^2_{\text{min, model, }\mathcal{D}}}$$

- *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.

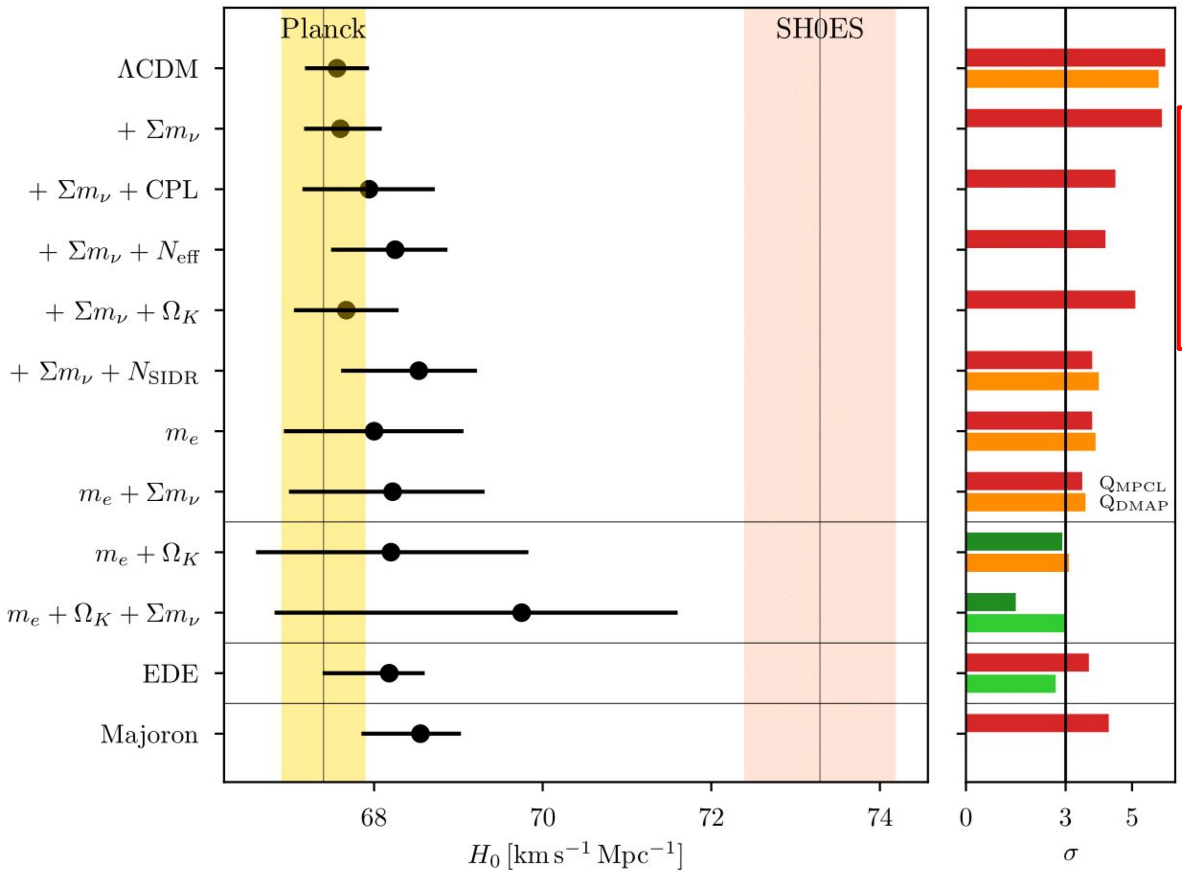
$$\Delta\text{AIC}_{\text{model}} = \chi^2_{\text{min, model, }\mathcal{D}+SH0ES} - \chi^2_{\text{min, }\Lambda\text{CDM},\mathcal{D}+SH0ES} + 2(N_{\text{model}} - N_{\Lambda\text{CDM}}) \, .$$

- *ΔAIC without SH0ES*

Numerical Tools

- Theory Codes: CLASS, AxiCLASS and CAMB
- Monte Carlo Sampler: COBAYA
- Minimizing χ^2: Py-BOBYQA
- New cosmological emulator (Günther, 2023; 2307.01138)
- Our reference data set: SPT+Planck+BAO+Pantheon (SPBP)

Main Results



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.

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	—	—	—	—
$+\Sigma m_\nu$+ $N_{\rm eff}$	—	—	—	—
$+\Sigma m_\nu + \Omega_K$	—	—	—	—
$+\Sigma m_\nu$+ $N_{\rm SIDR}$	-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
$m_e + \Omega_K + \Sigma m_\nu$	-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

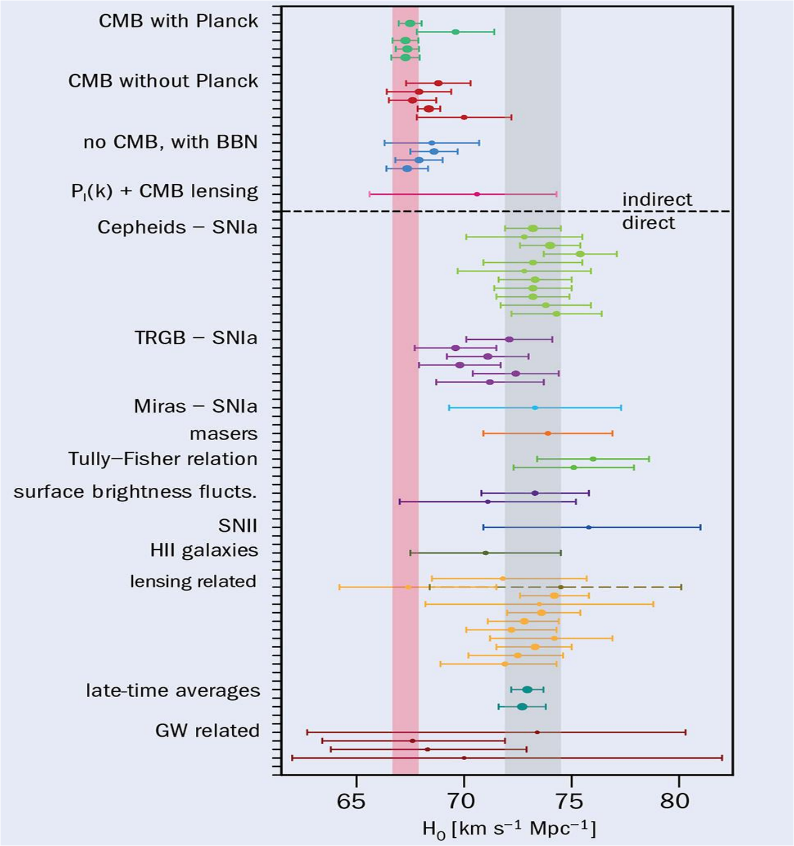
- Further investigation of the still viable models is needed.
- Revisit these models, along with others, with upcoming SPT-3G 2019/2020 and ACT DR6 data.
- Incorporate improved numerical techniques.
- Perform forecasts for SO, CMB-S4 and future SPT surveys

Thank you!

Questions? Comments?

Back Up

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

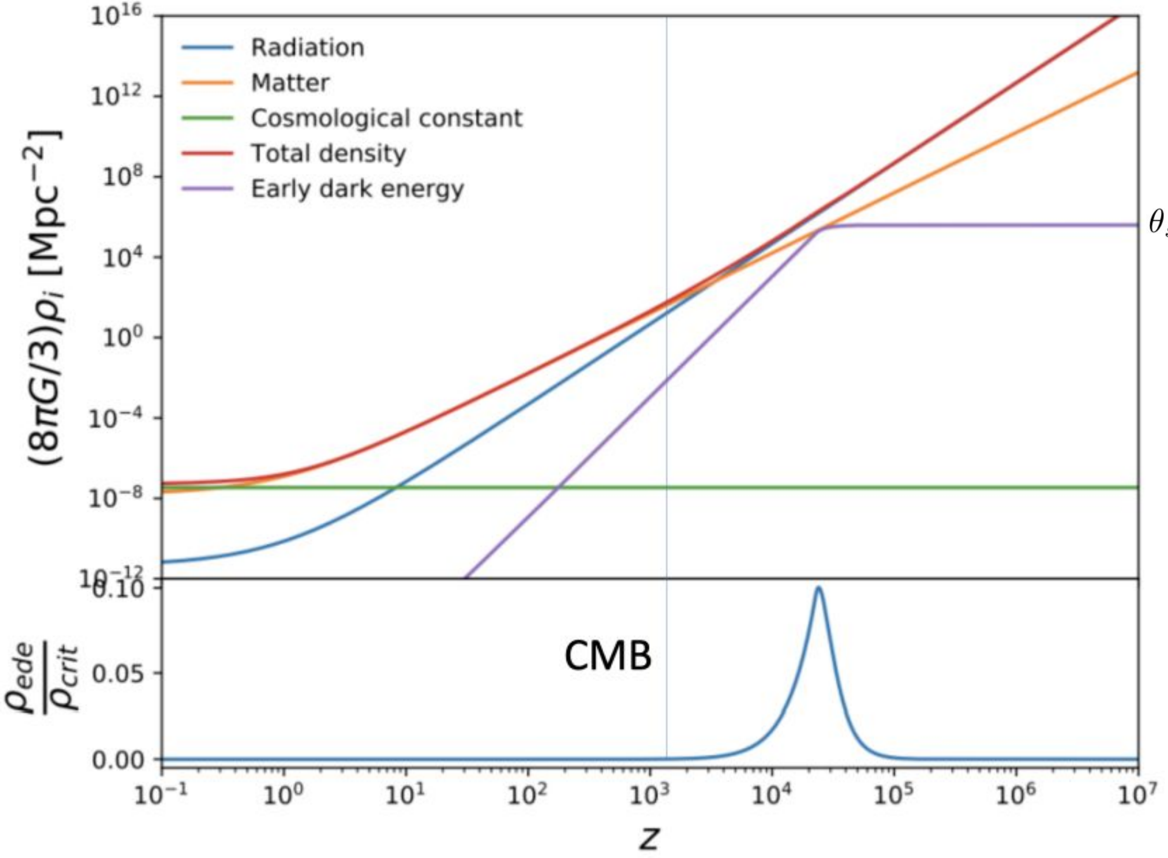
Elaborate Models

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

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

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

Early Dark Energy



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

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

Normalisation ($\mathcal{N}$)

Normalisation ($\mathcal{N}'$)

Weights from chains (w_i)

Tension Metrics

- *Marginalised Posterior Compatibility Level (MPCL):*
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$$q = \int_0^{\delta'} d\delta \, \mathcal{P}(\delta) \ .$$

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

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

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

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

Tension Metrics

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

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

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

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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  What's the probability of getting 0 in the distribution of the difference between SH0ES and a model's H_0 posteriors?

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

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

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

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

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

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- *Akaike Information Criterion (AIC):*

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

  ; N ≡ # of parameters

Tension Metrics

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

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- *Akaike Information Criterion (AIC):*

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

  ; N ≡ # of parameters

- *AIC without SH0ES*

Results

Further Results

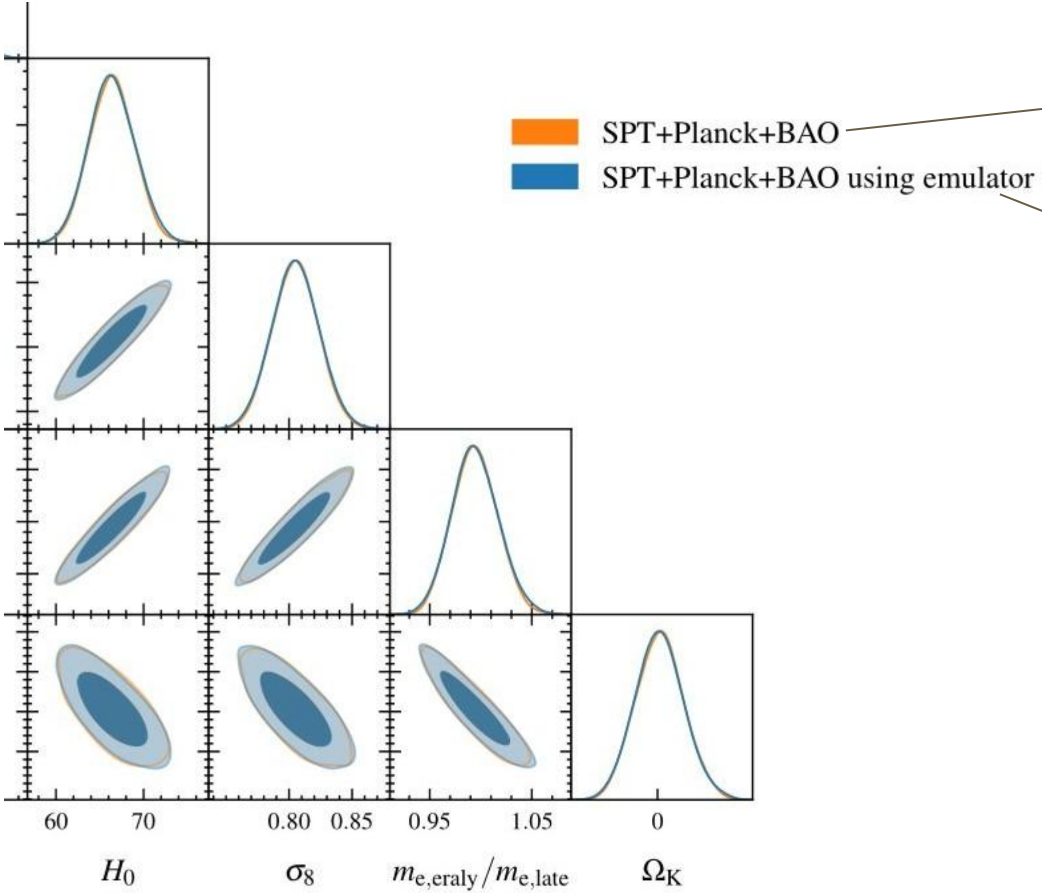
Main Results

				w/o SH0ES		w/ SH0ES	
Models	H_0(km/s/Mpc)	$Q_{MPCL}(\sigma)$	$Q_{DMAP}(\sigma)$	$\Delta\chi^2$	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_{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_{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	✗	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 $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

The Power of an Emulator



3 days of running time

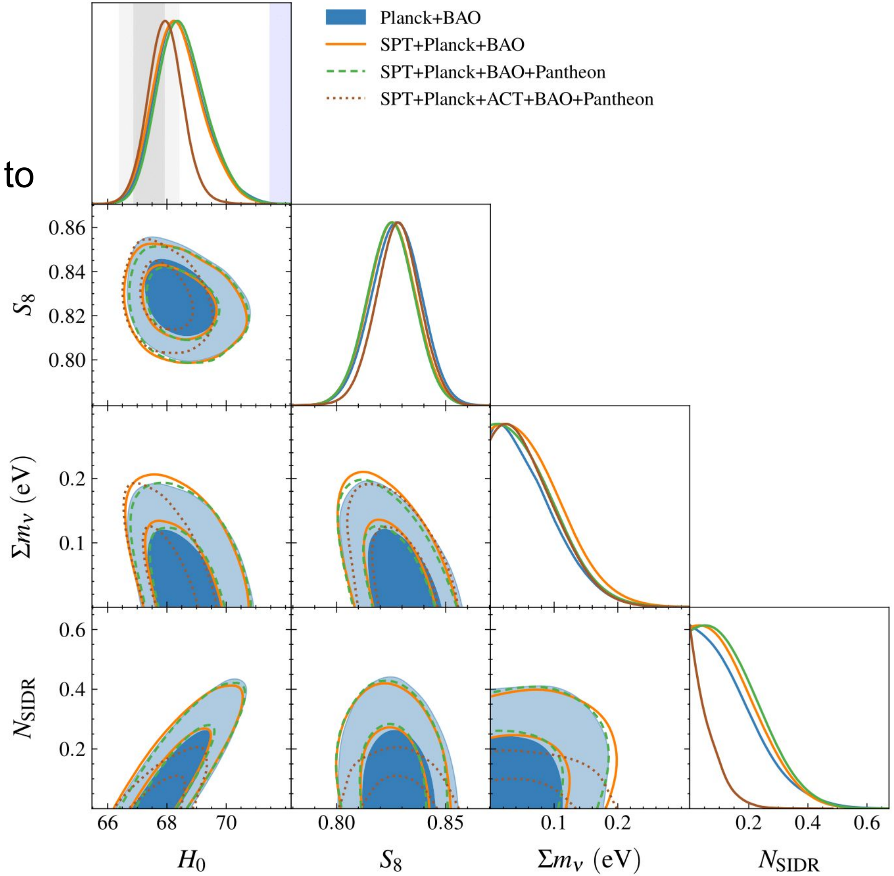
10 hrs of running time

Q_{MPCL} for Each Model and Data-set

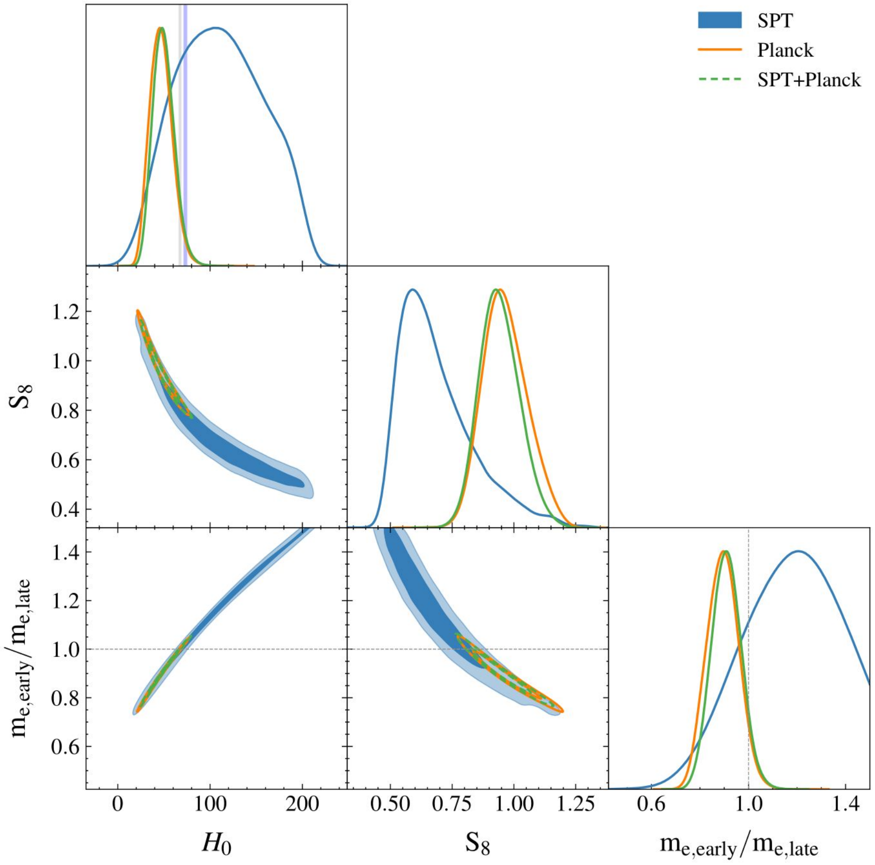
	$\mathcal{D}_S$	$\mathcal{D}_{SP}$	$\mathcal{D}_{SB}$	$\mathcal{D}_{PB}$	$\mathcal{D}_{SPB}$	$\mathcal{D}_{SPBP}$	$\mathcal{D}_{SPAB}$	$\mathcal{D}_{SPABP}$
ΛCDM	**2.7 σ**	6.0 σ	5.4 σ	5.9 σ	6.3 σ	6.0 σ	6.3 σ	6.1 σ
$+\Sigma m_\nu$	3.4 σ	5.4 σ	5.6 σ	5.7 σ	6.0 σ	5.9 σ	5.9 σ	5.9 σ
$+\Sigma m_\nu$ + CPL	**0.5 σ**	**0.0 σ**	3.3 σ	3.1 σ	3.2 σ	4.5 σ	4.1 σ	4.5 σ
$+\Sigma m_\nu + N_{\rm eff}$	**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
$+\Sigma m_\nu + N_{\rm SIDR}$	**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}.

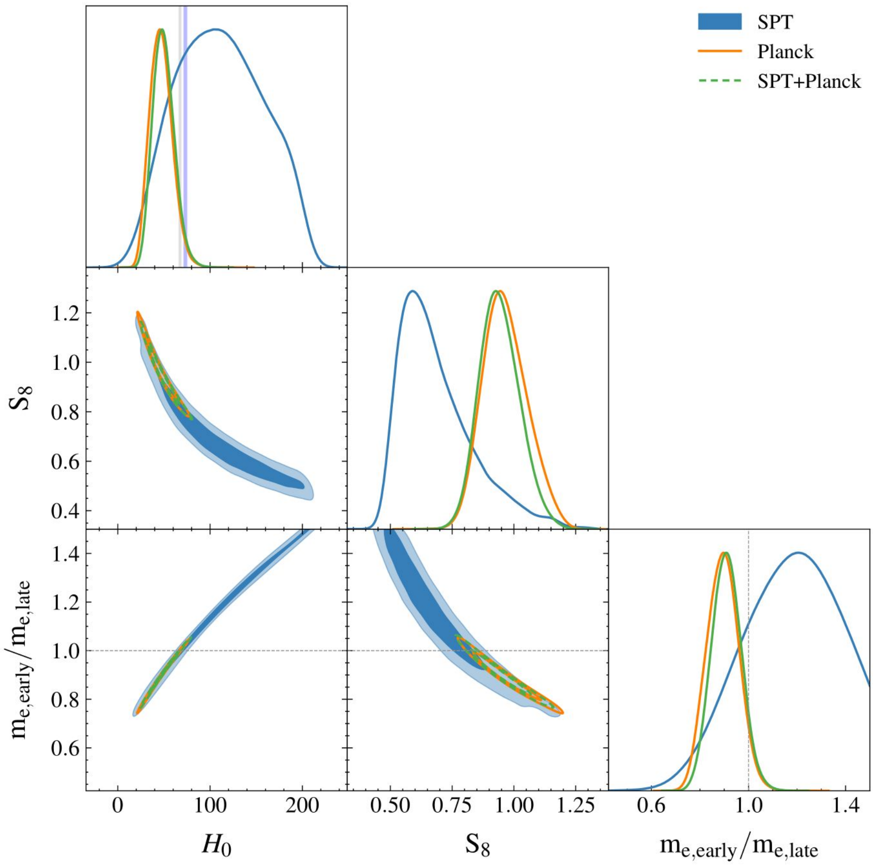


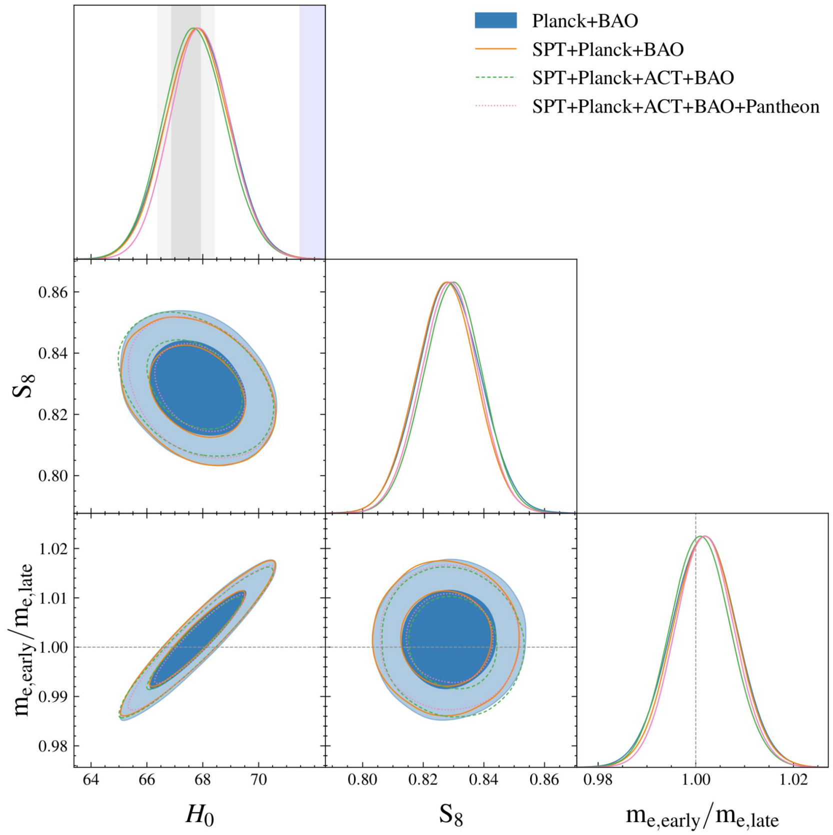
Varying Electron Mass



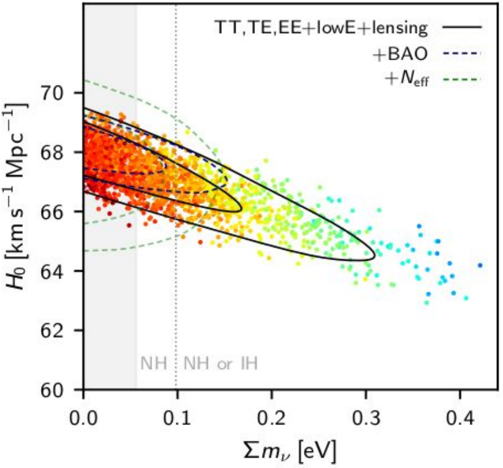
- No longer a potential solution to the tension.
- Planck is still more constraining than SPT.
- CMB alone cannot constrain this model.

Varying Electron Mass



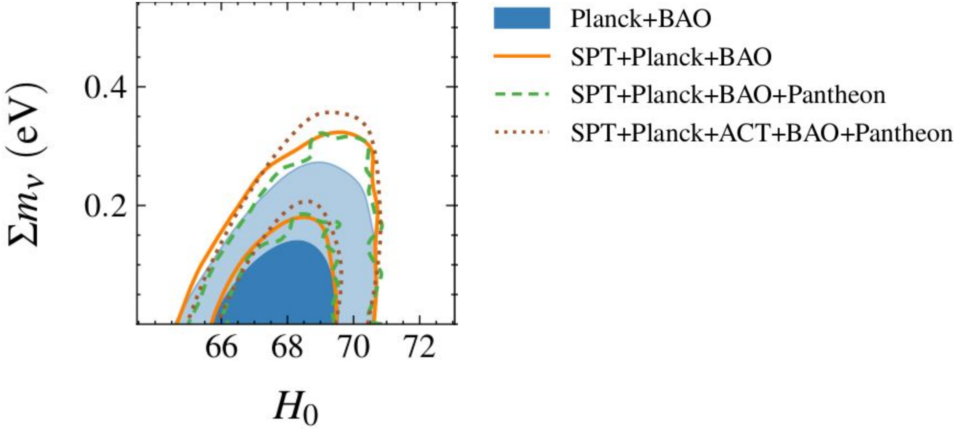


Varying Electron Mass+Σm_ν

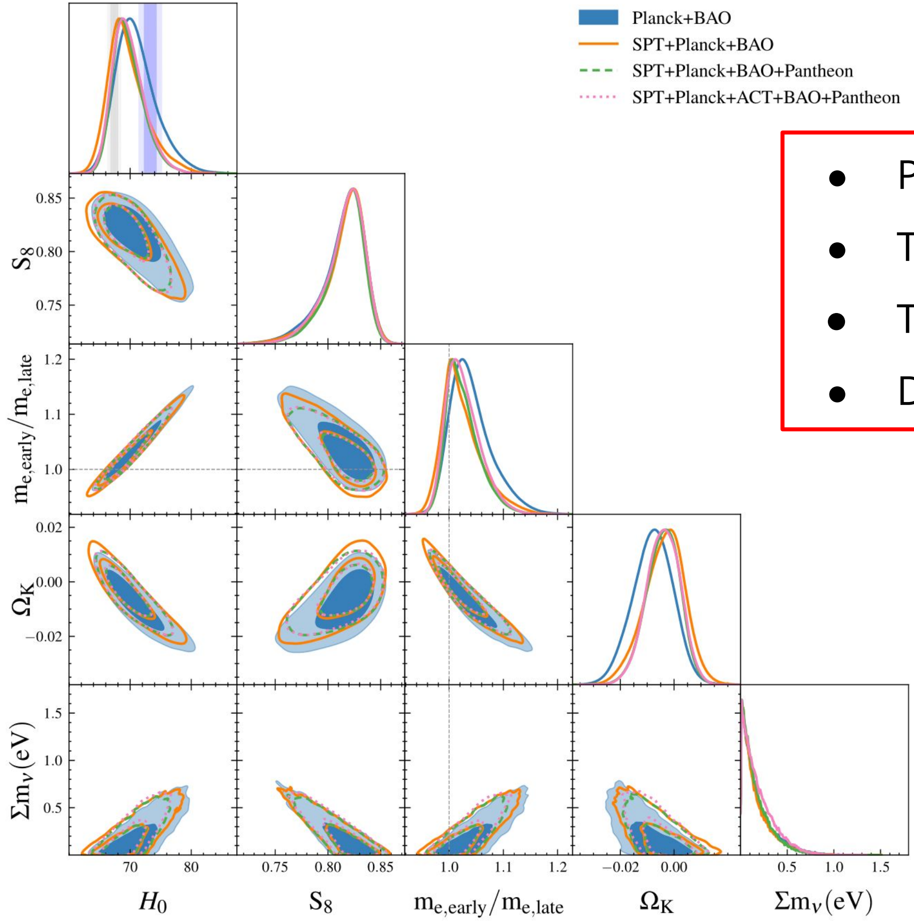


Planck 2018 ([Aghanim et al.]())

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

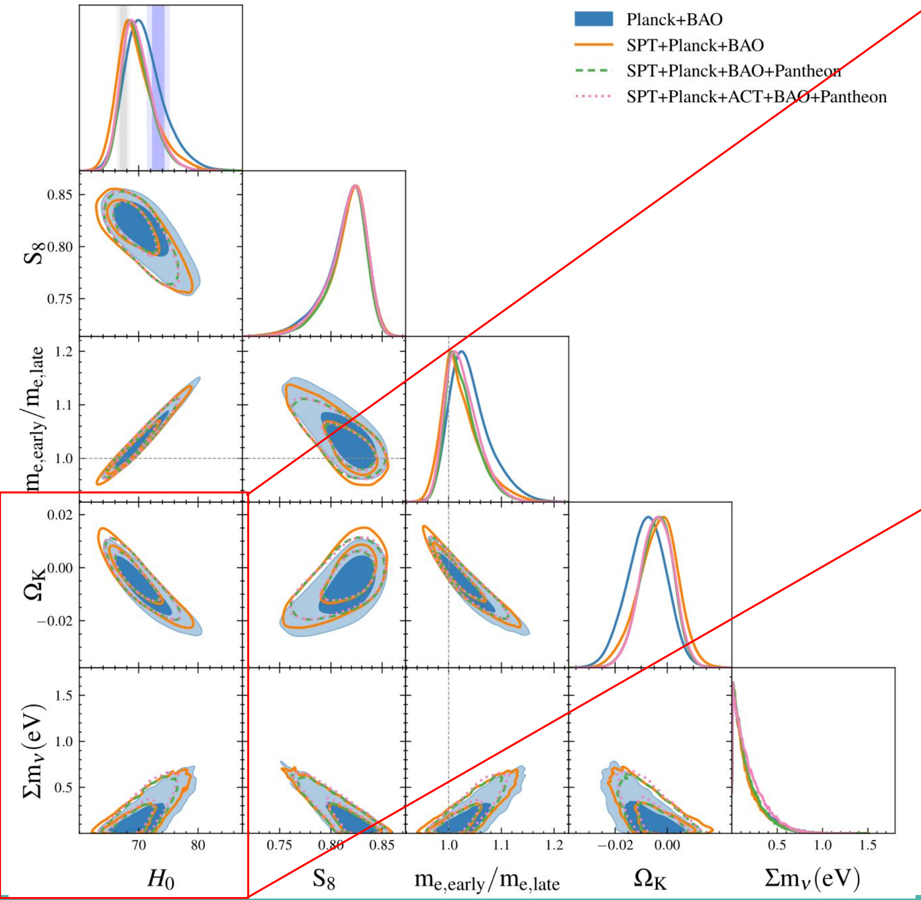


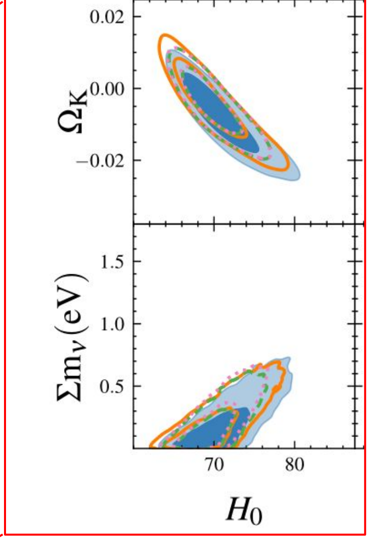
Varying Electron Mass+Σm_ν+Ω_K

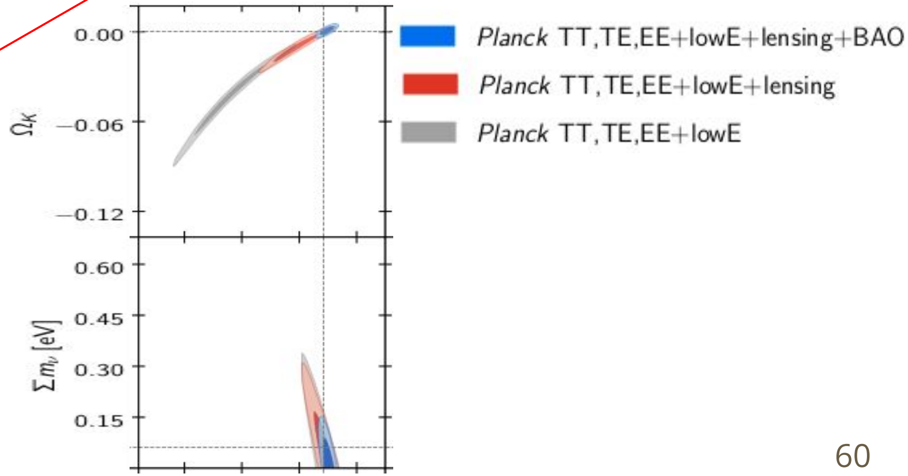


- Polarization data from SPT is particularly useful.
- The model that reduces the tension the most.
- The model with the largest error bars.
- Degeneracy direction also flips in the Ω_K-H_0 plane.

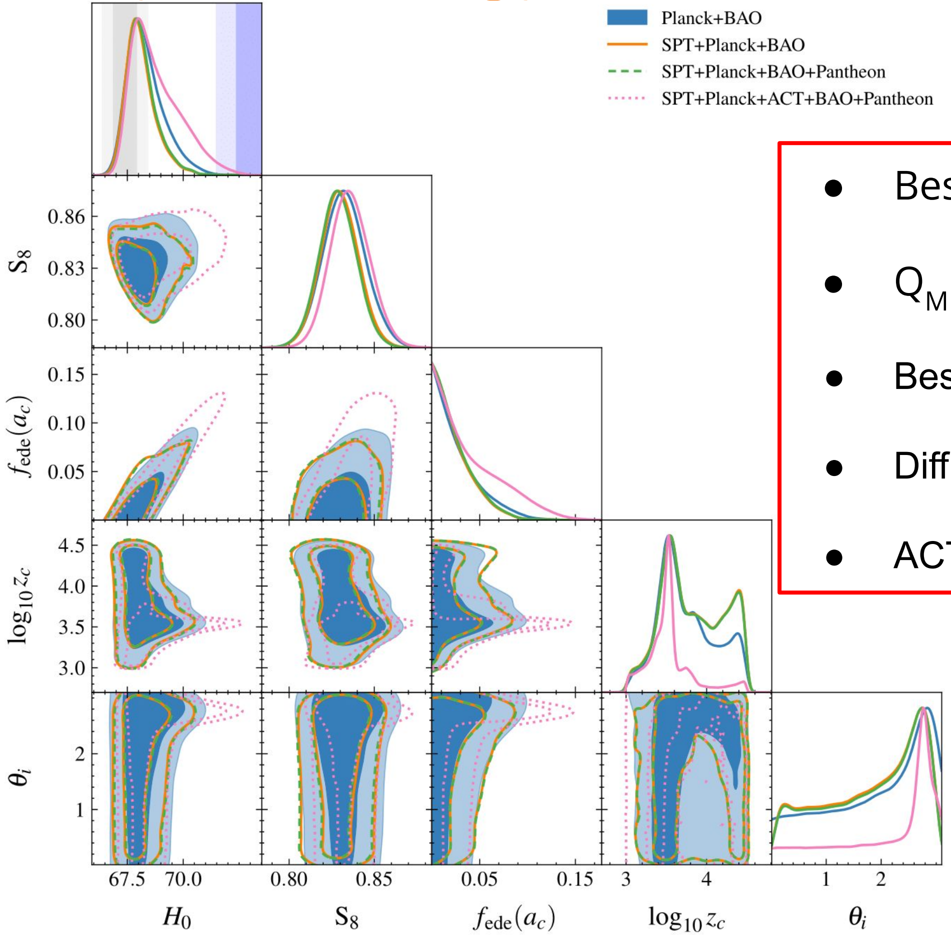
Varying Electron Mass+Σm_ν+Ω_K





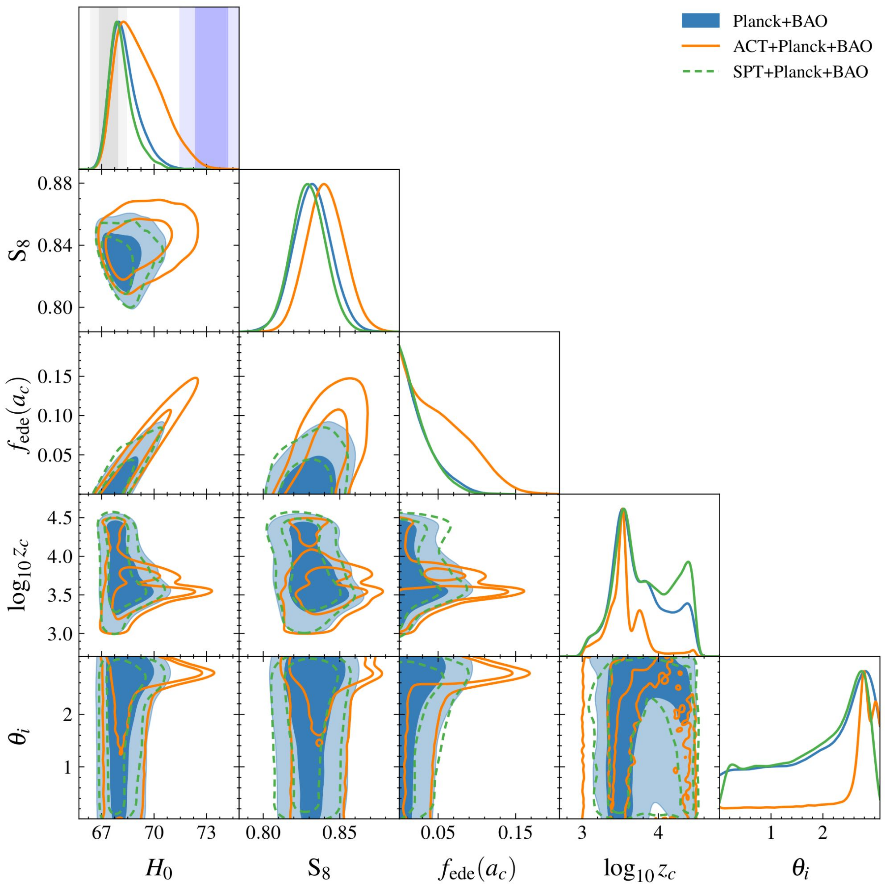


Early Dark Energy

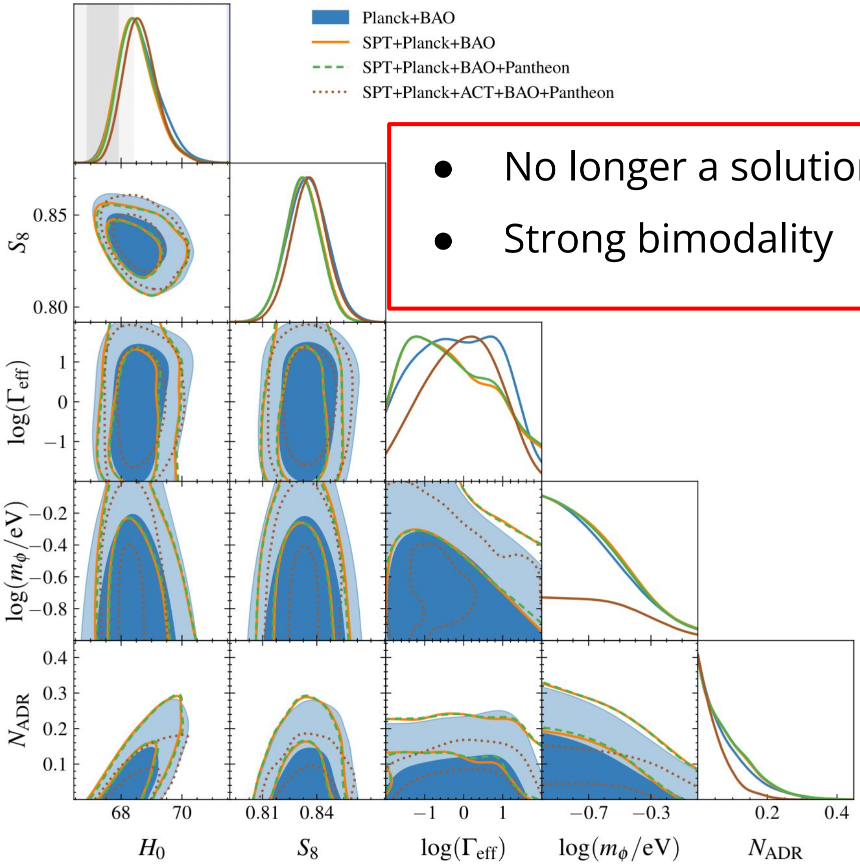


- Best constrained by CMB.
- Q_{MPCL} = 3.7σ while Q_{DMAP}=2.7σ for SPBP.
- Best-fit χ^2 compared to all models, w/ and w/o SH0ES.
- Difficult to constrain, with some bimodality.
- ACT DR4 is compatible with higher f_{EDE}.

Early Dark Energy: SPT vs ACT

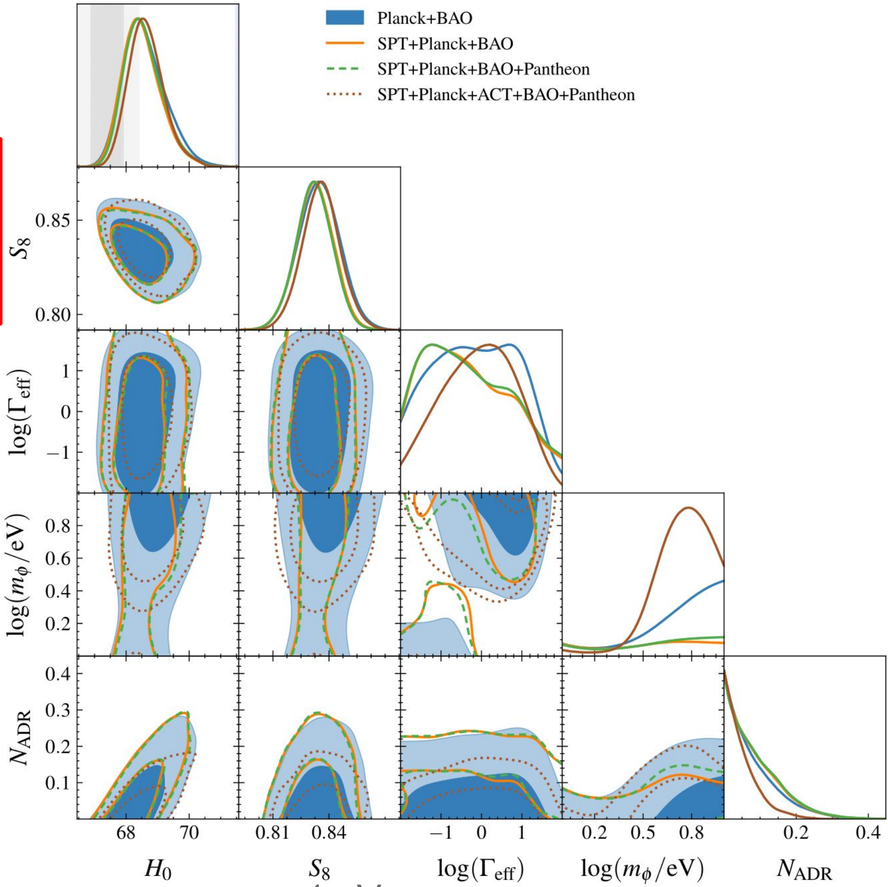


The Majoron



m_φ<1 eV

- No longer a solution
- Strong bimodality

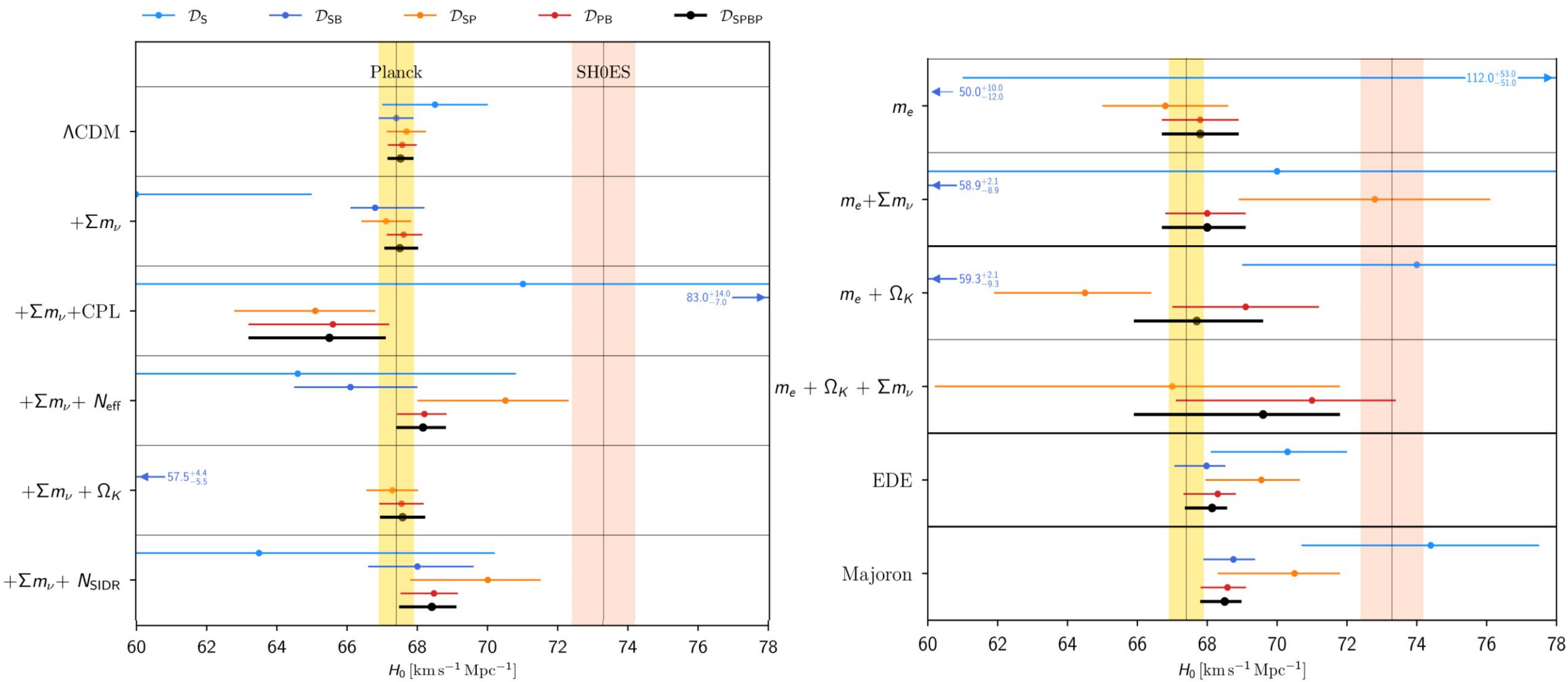


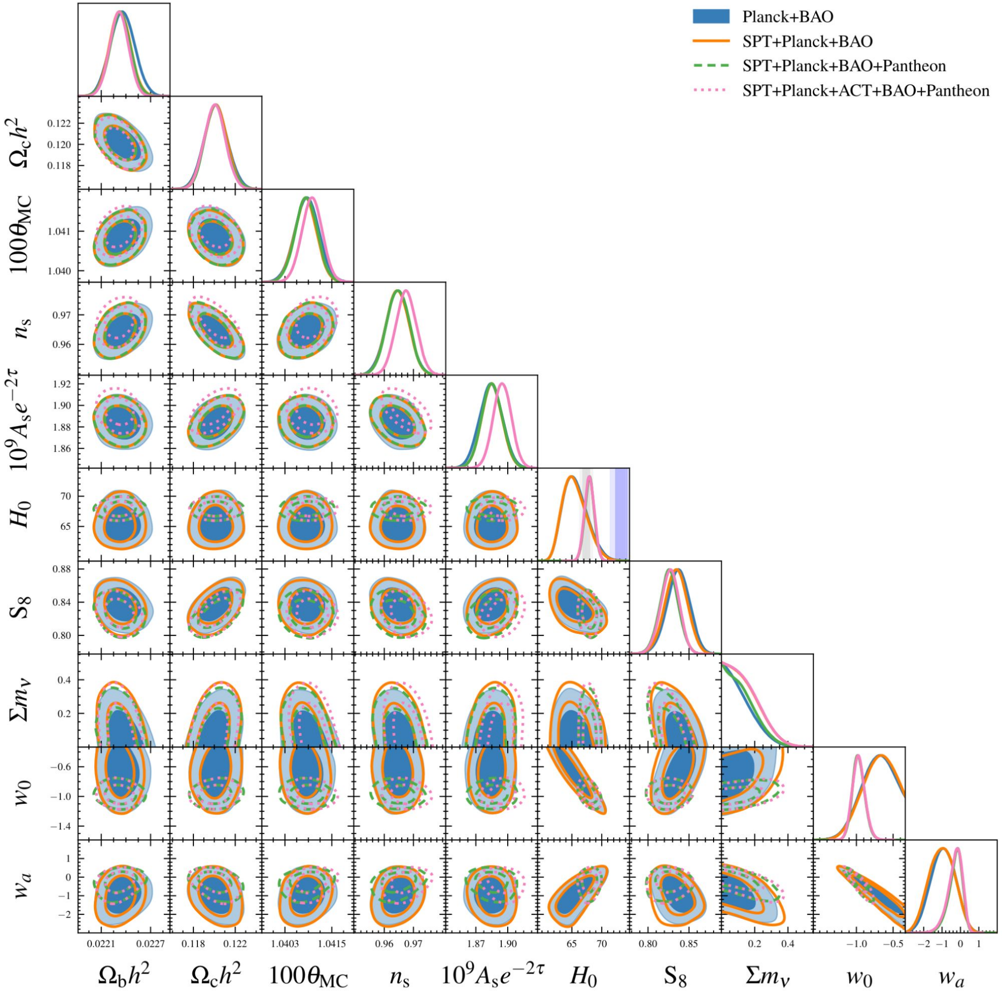
m_φ>1 eV

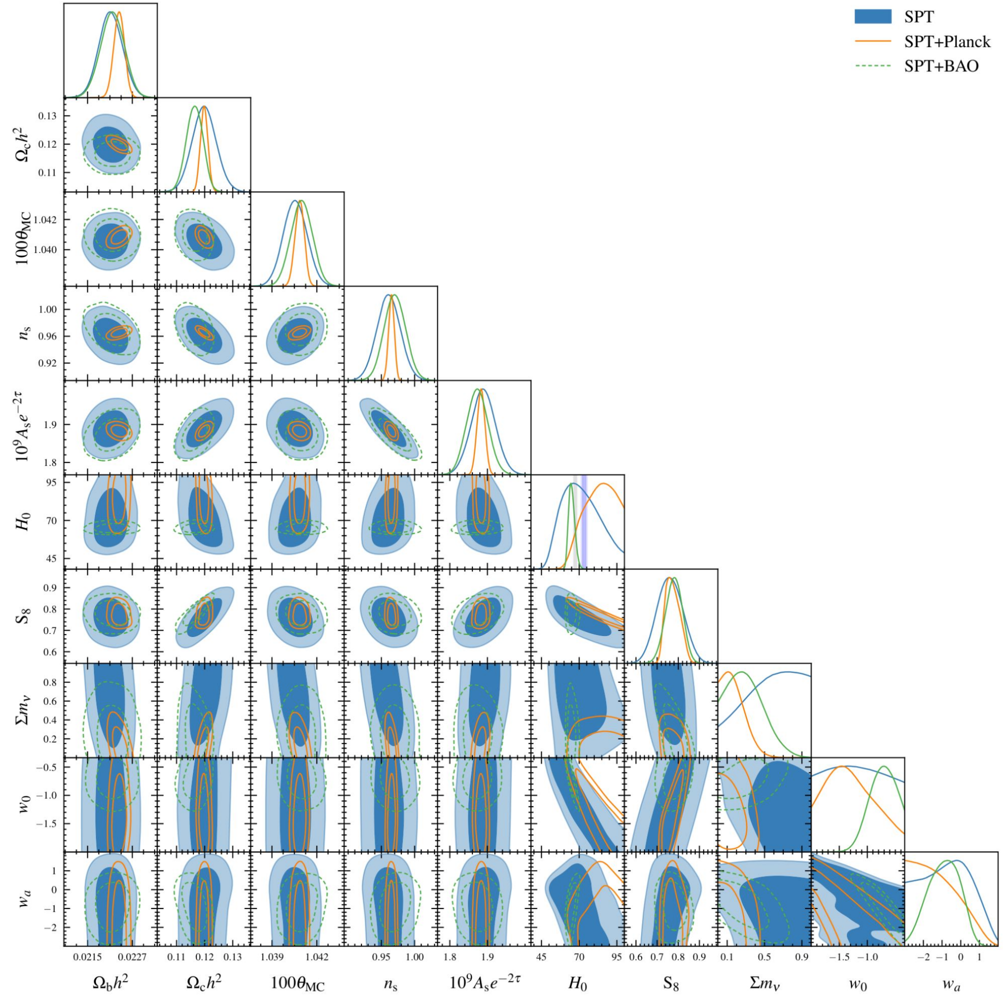
The Power of an Emulator

- 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

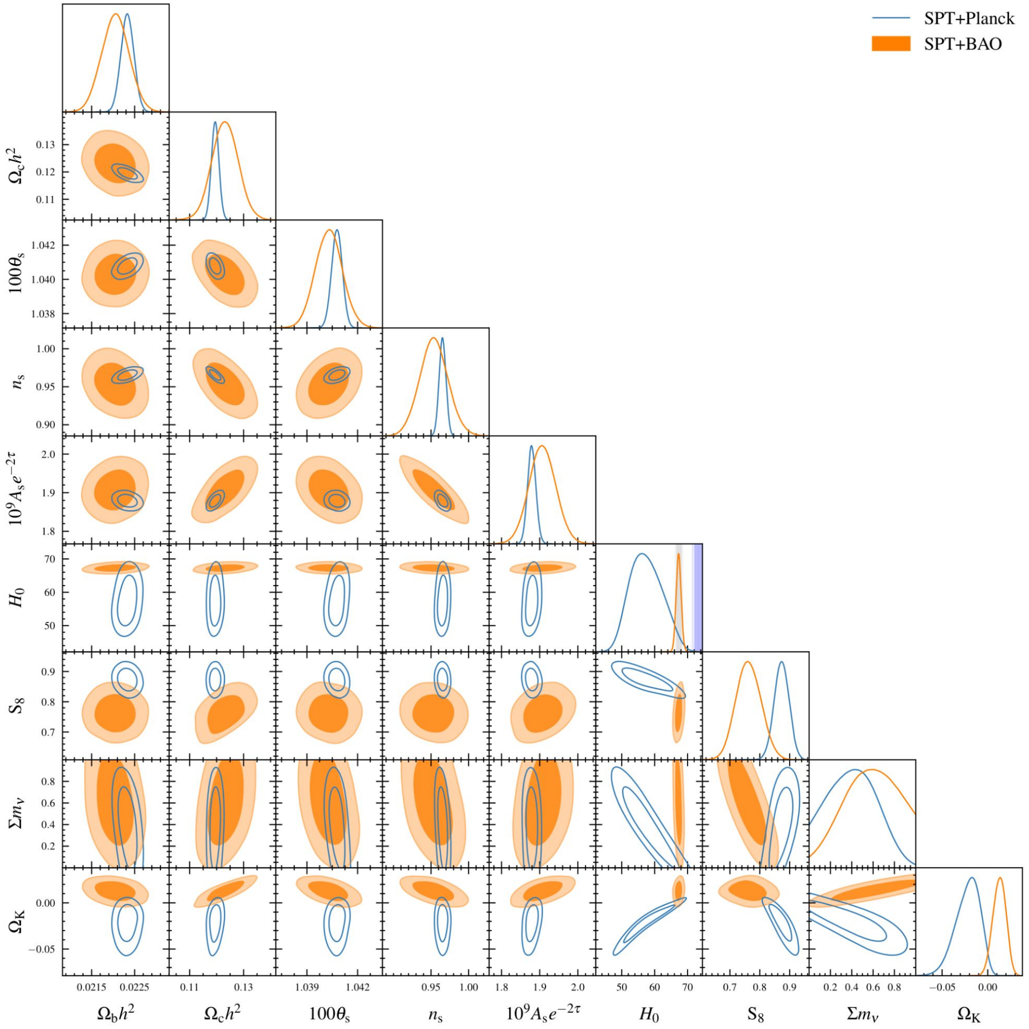
H_0 for Each Model and Data-set



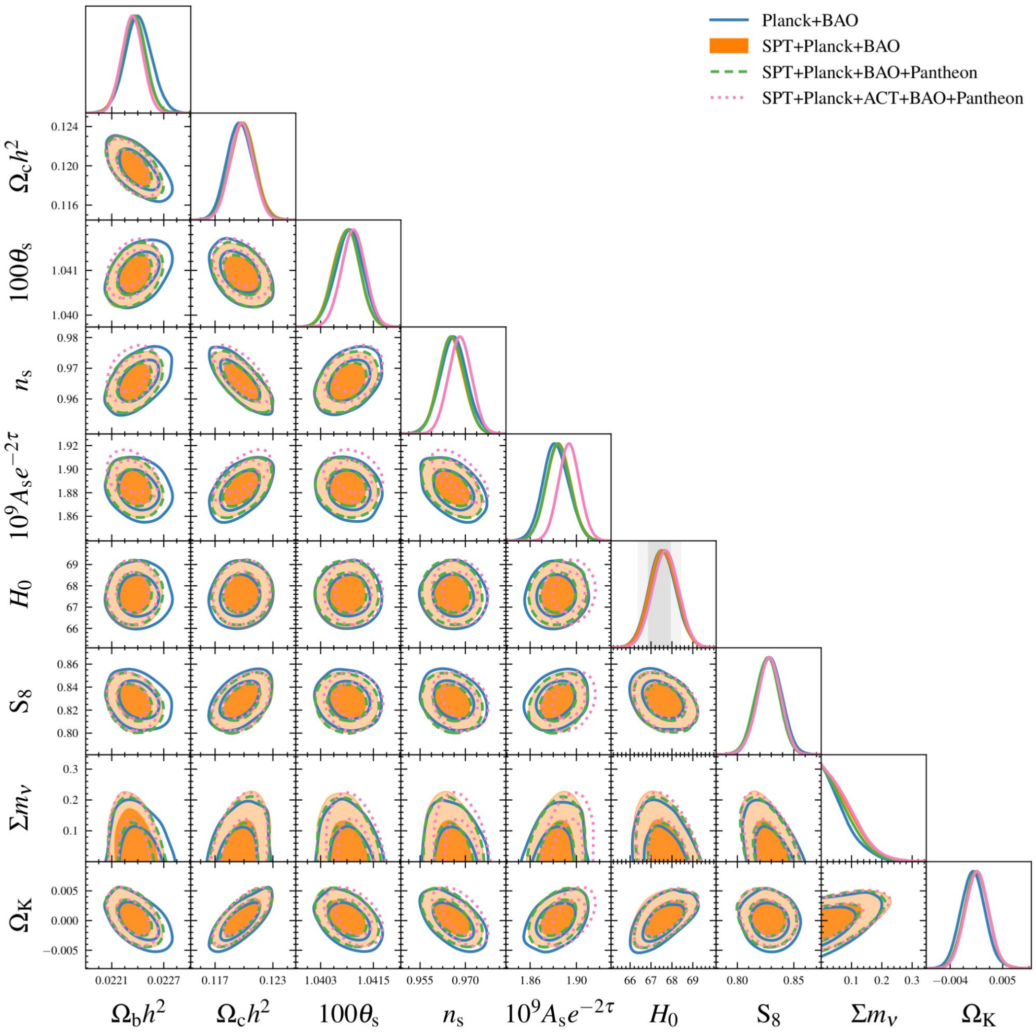

Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
w_0
w_a



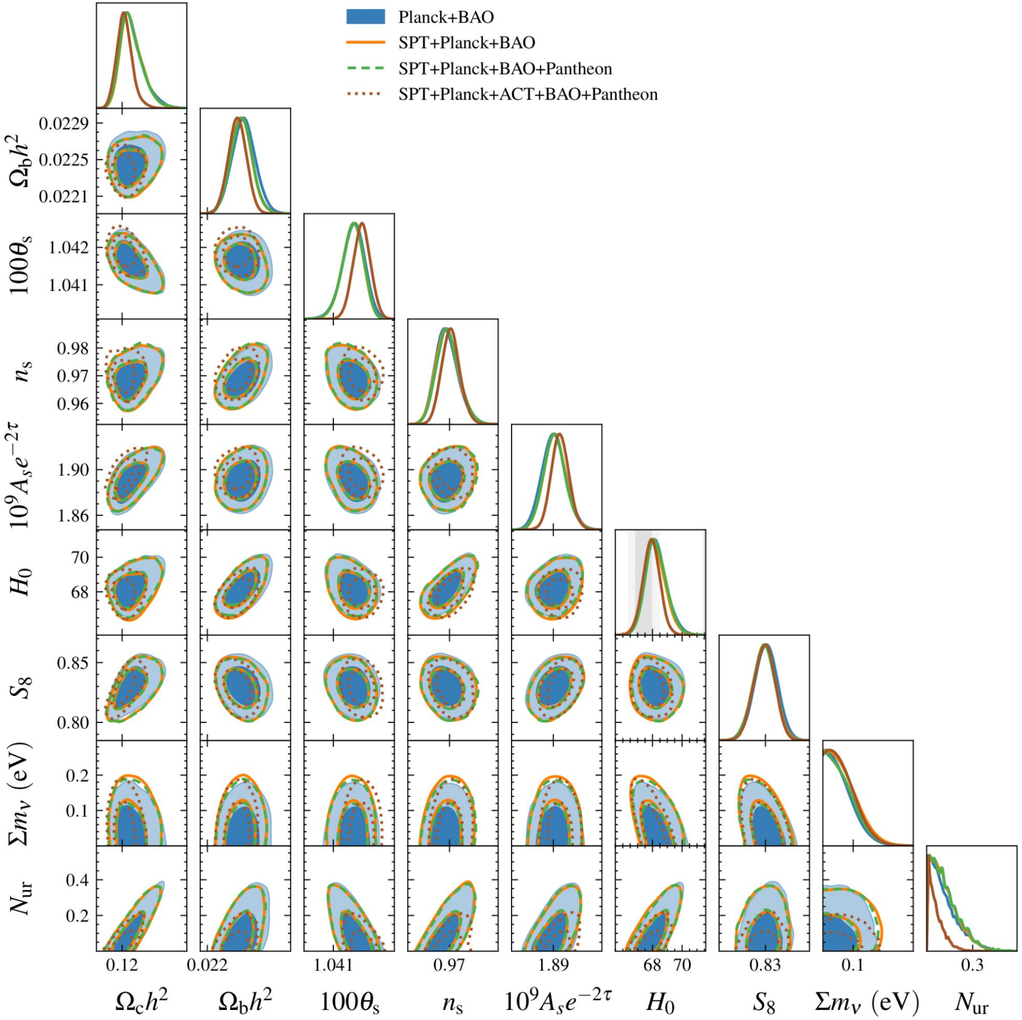
SPT
SPT+Planck
SPT+BAO
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
w_0
w_a



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



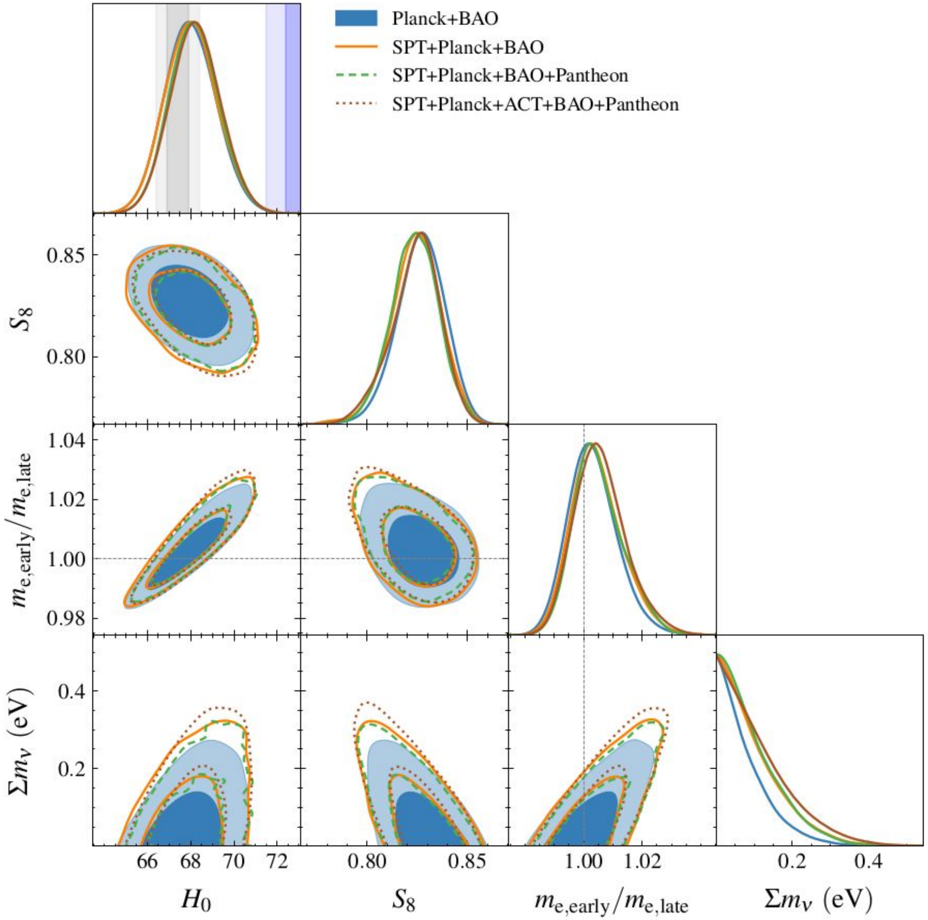
Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
$\Omega_c h^2$
$100\theta_s$
n_s
$10^9 A_s e^{-2\tau}$
H_0
S_8
Σm_ν
Ω_K
$\Omega_b h^2$


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

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	$74.4^{+3.1}_{-3.7}$	$68.75^{+0.62}_{-0.86}$	$70.5^{+1.3}_{-2.2}$	$68.58^{+0.53}_{-0.77}$	$68.50^{+0.48}_{-0.70}$	$\mathbf{68.55^{+0.48}_{-0.70}}$	$68.6^{+0.46}_{-0.64}$	$68.64^{+0.48}_{-0.61}$

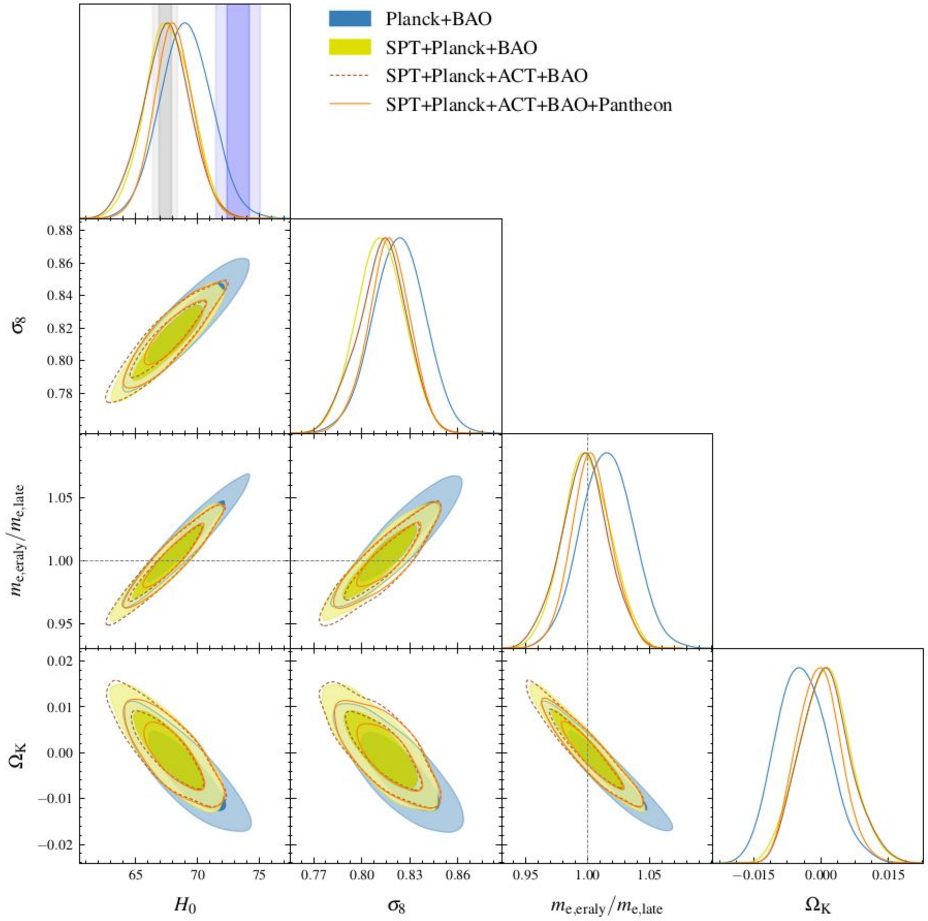
Models	Additional Parameters
ΛCDM	—
$+\Sigma m_\nu$	$\Sigma m_\nu < 0.16$ eV (95%)
$+\Sigma m_\nu$+CPL	$\Sigma m_\nu < 0.29$ eV (95%), $w_0 = -0.97 \pm 0.08$, $w_a = -0.29 \pm 0.39$
$+\Sigma m_\nu + N_{\mathrm{eff}}$	$\Sigma m_\nu < 0.15$ eV (95%) , $\mathrm{N_{eff}} < 0.17$ (95%)
$+\Sigma m_\nu + \mathrm{N_{SIDR}}$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

Me+Mnu: Results



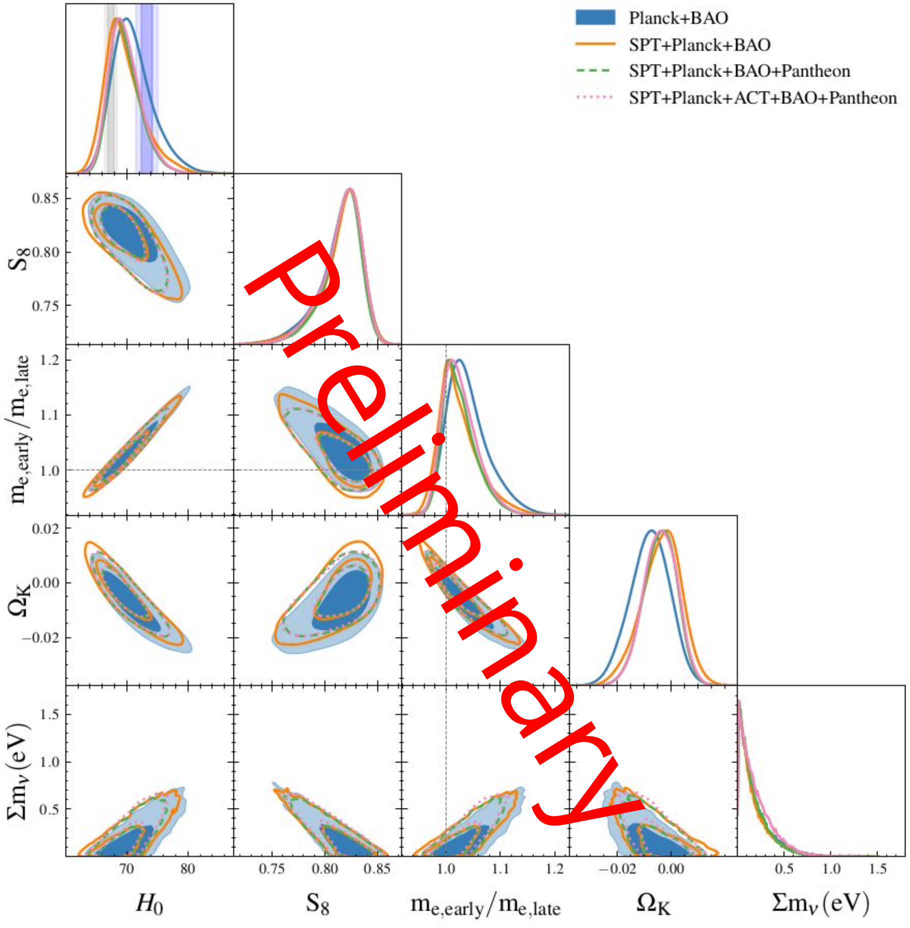
Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Me+Omk



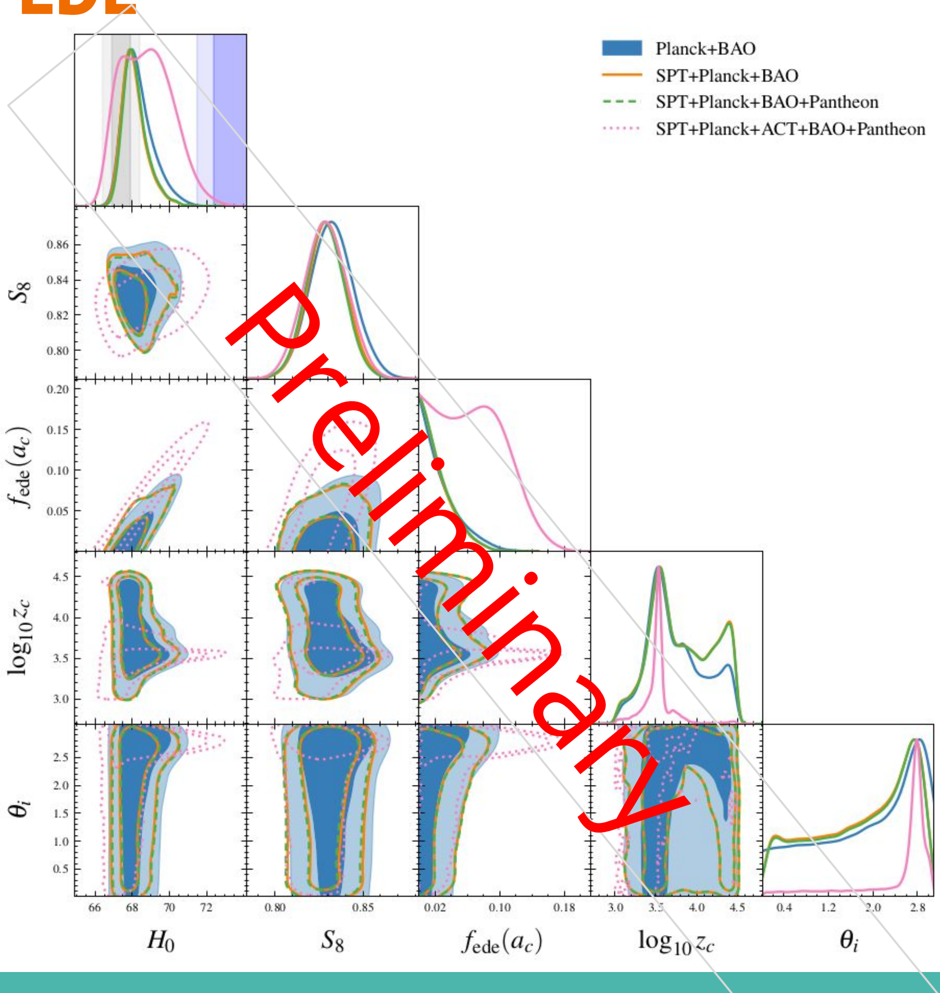
Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{e,eraly}/m_{e,late}$
Ω_K

Me+Mnu+Omk



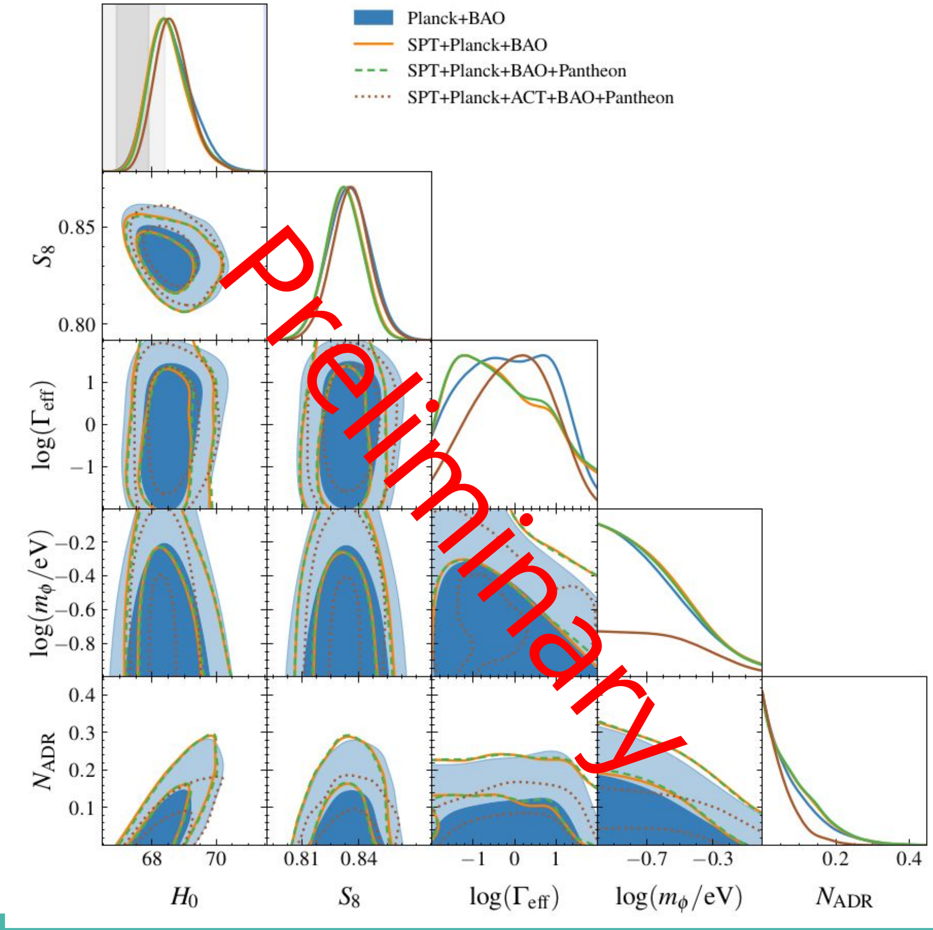
Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
H_0
S_8
$m_{e,early}/m_{e,late}$
Ω_K
Σm_ν(eV)

EDE



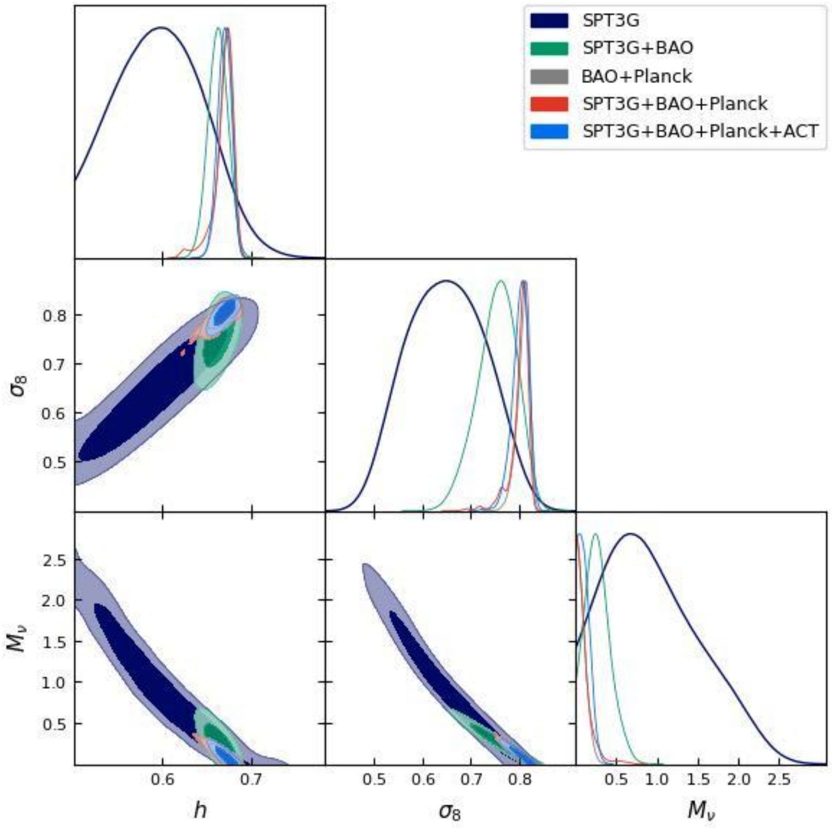
Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
S_8
$f_{\rm ede}(a_c)$
$\log_{10} z_c$
θ_i
H_0

Majoron



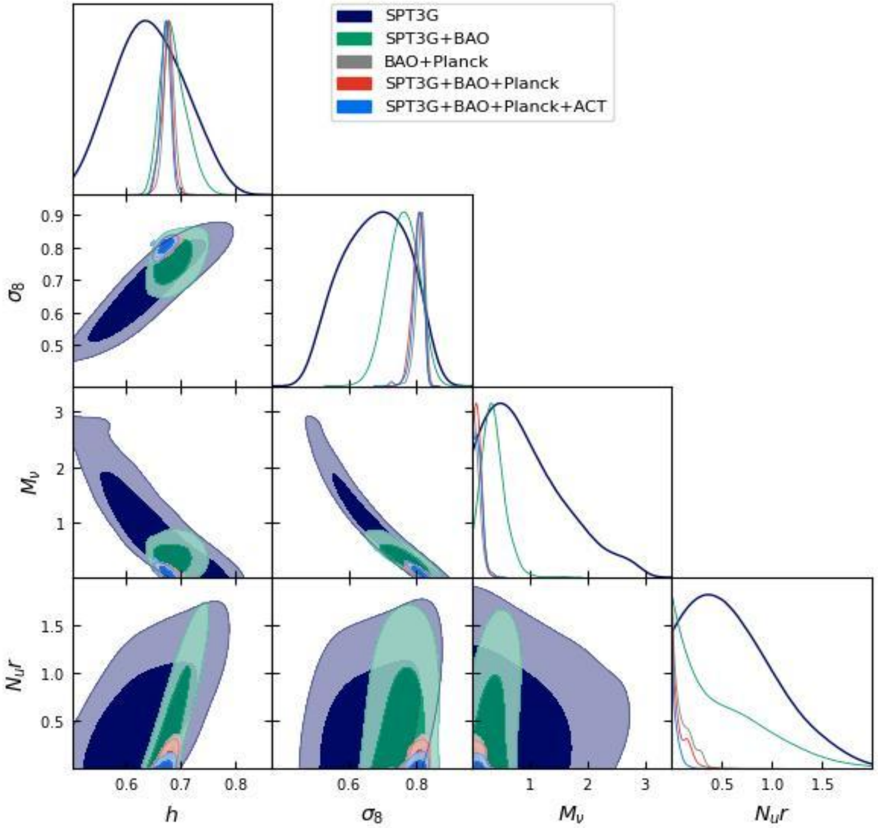
Sub eV mass

ΛCDM+Σm_ν

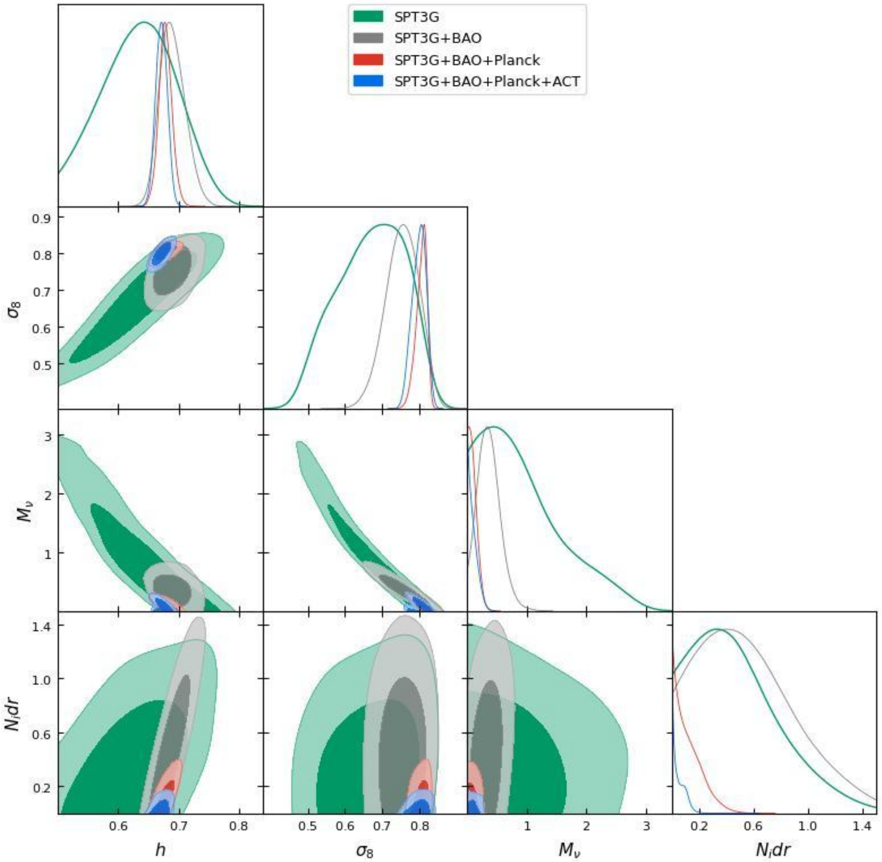


Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.00±0.82
σ_8	0.803±0.019

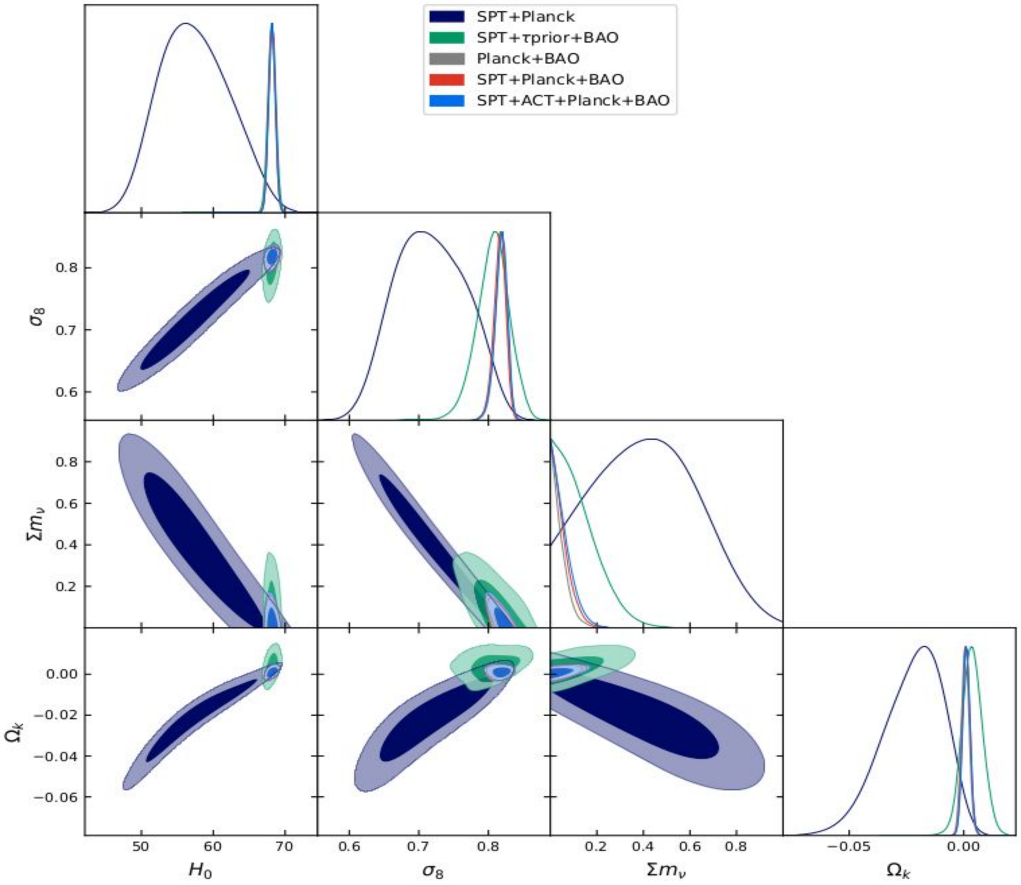
ΛCDM+Σm_ν+N_{eff}



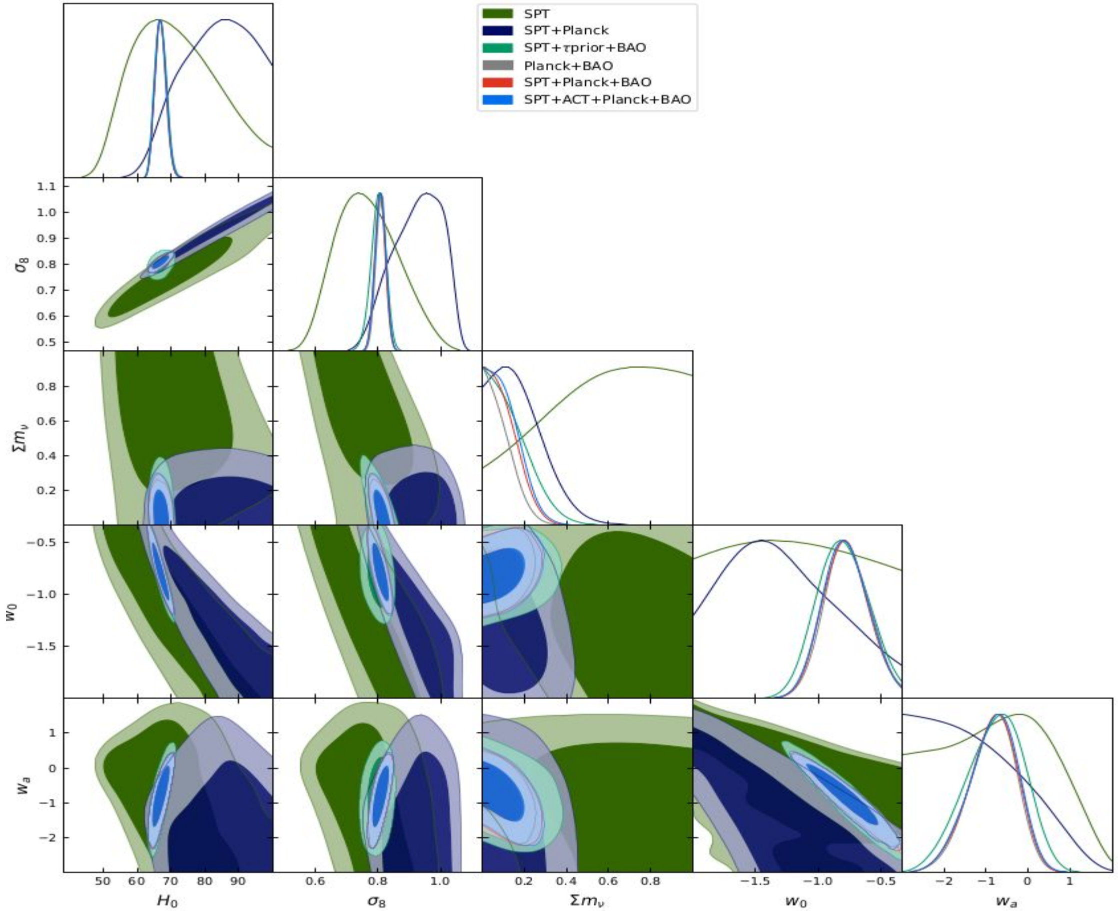
Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.10±0.85
σ_8	0.812±0.009



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



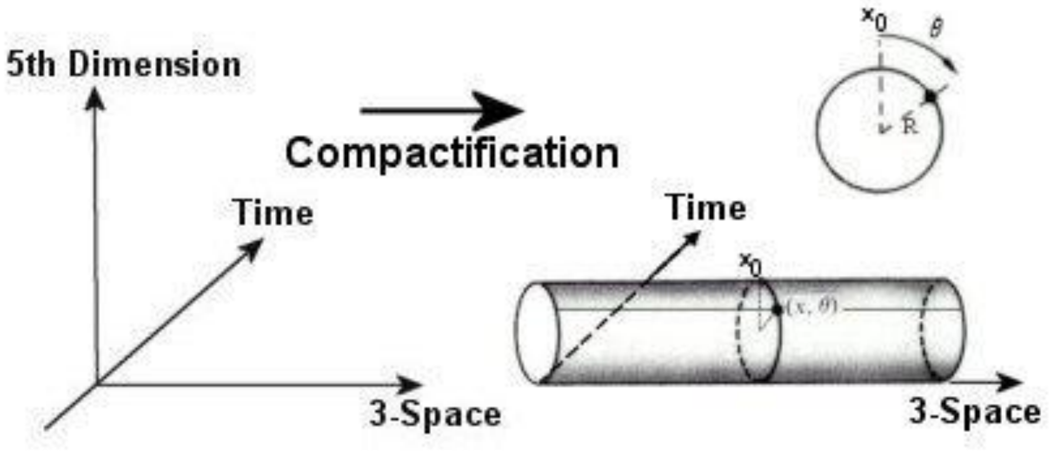
Parameter	SPT+ ACT+ Planck+ BAO
H_0	68.16±0.46
σ_8	0.818±0.009



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

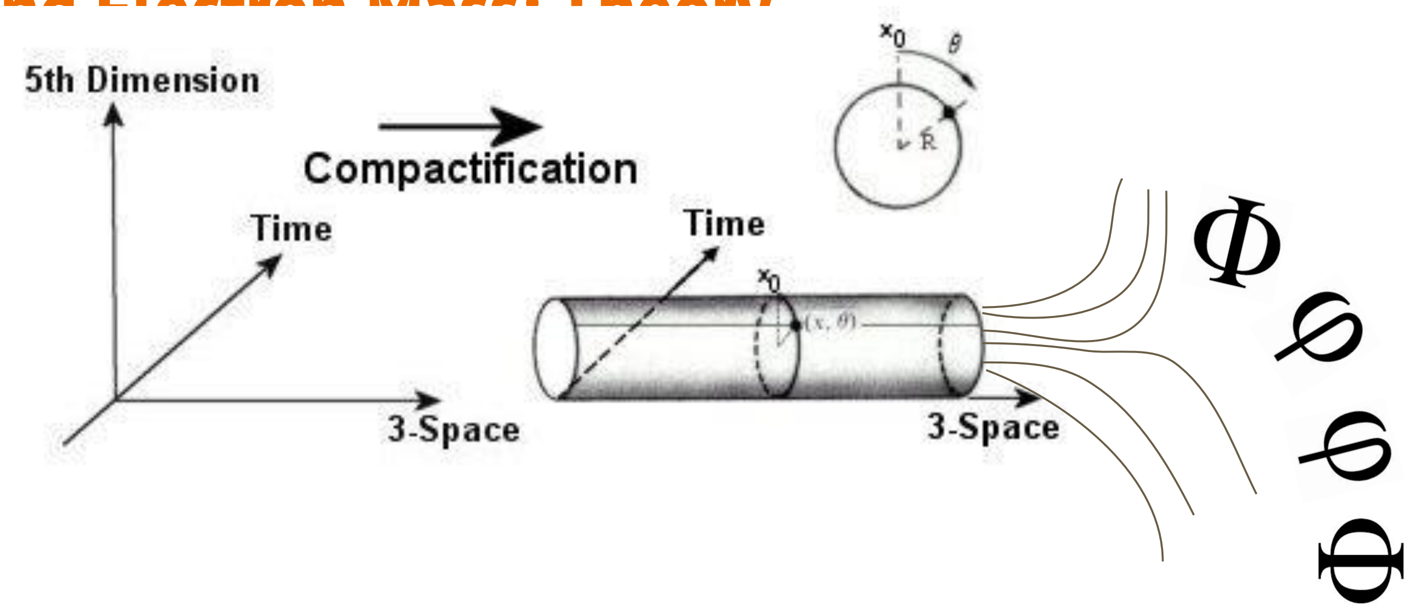
SLIDES FOR A GENERAL AUDIENCE TALK

Varyin

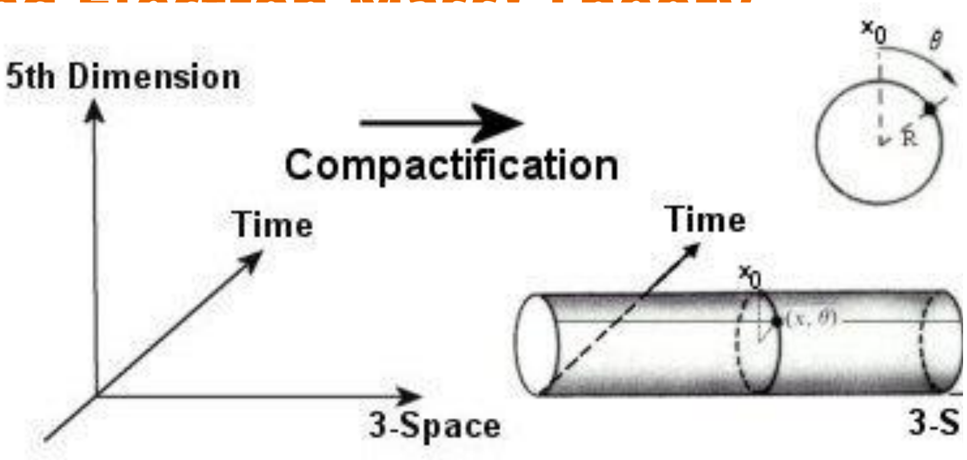


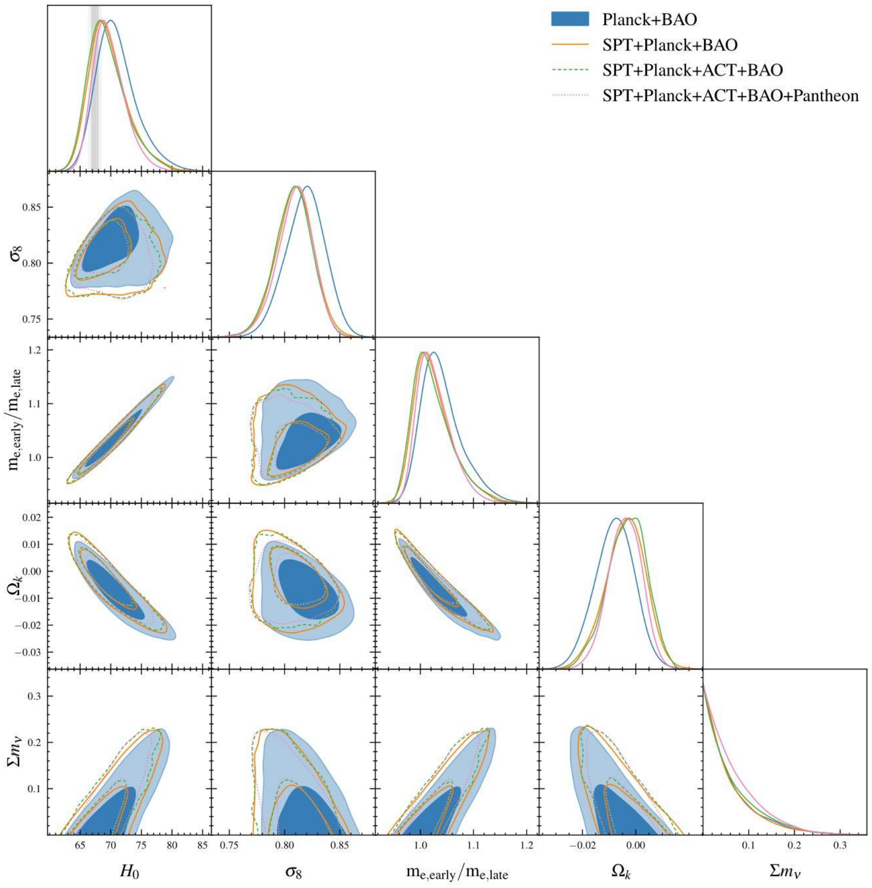
5th Dimension
Compactification
Time
3-Space
Time
3-Space
x_0
θ
R
x_0
(x, θ)

Varyi[illegible]


5th Dimension
Compactification
Time
3-Space
Time
3-Space
Φ
φ
φ
Φ

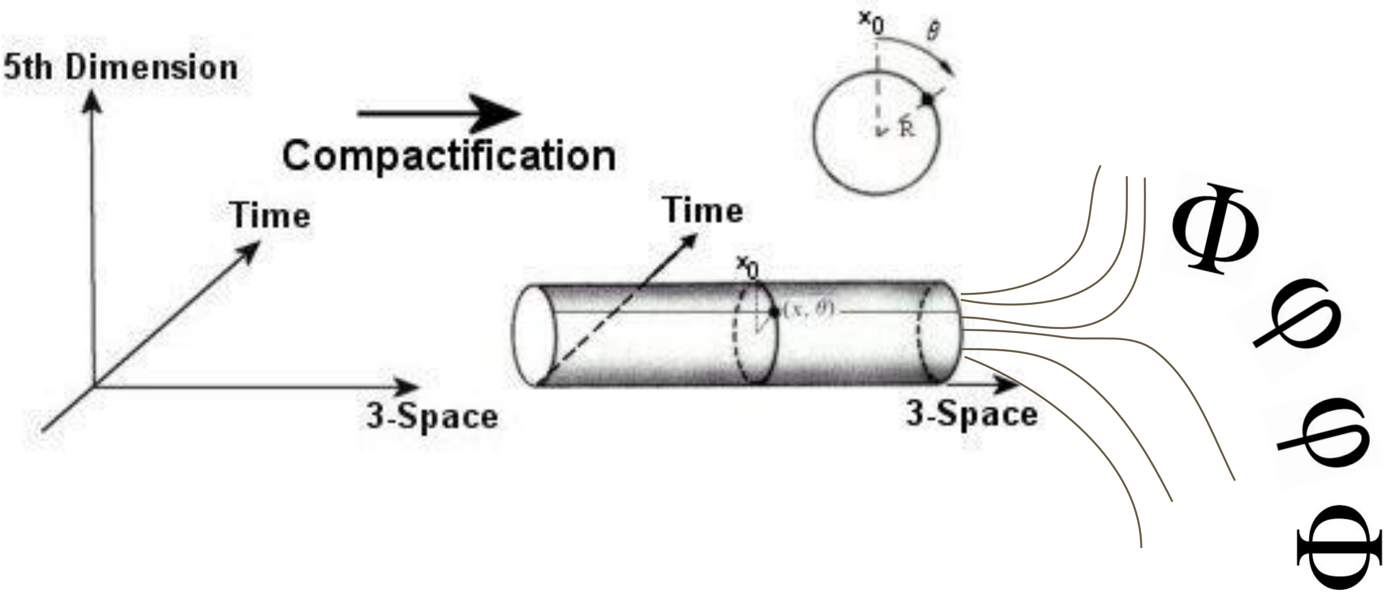
Varying Electron Mass: Theory



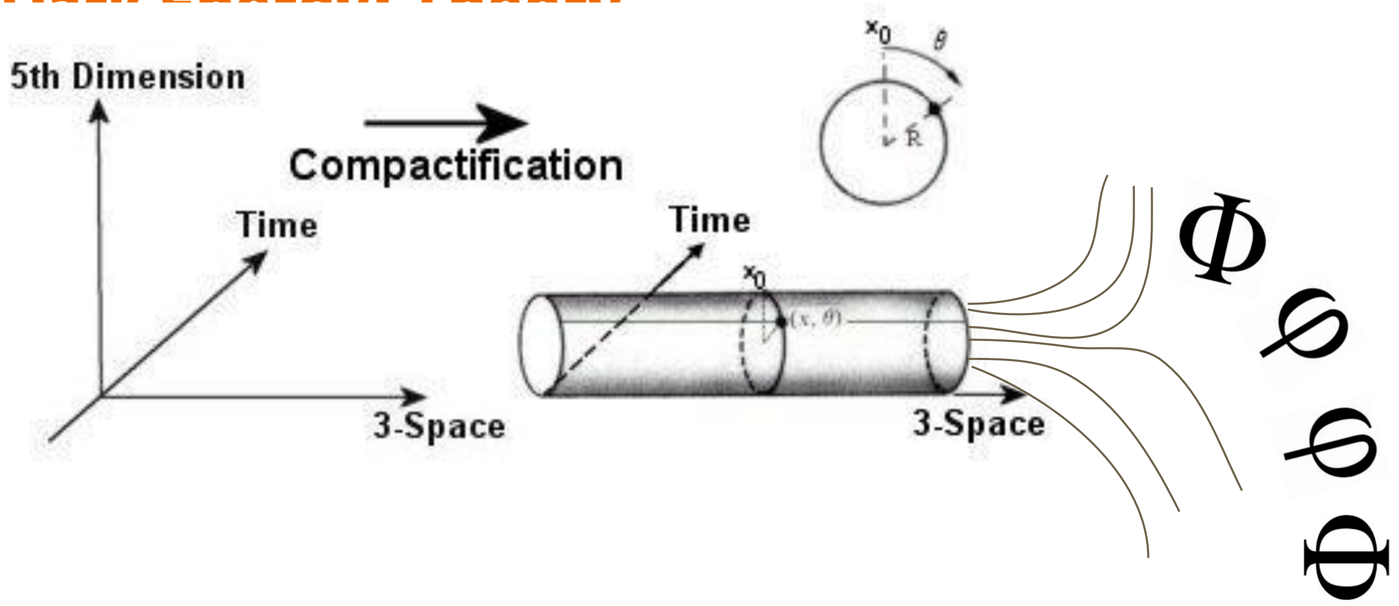


Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{e,early}/m_{e,late}$
Ω_k
Σm_ν

Early Dark Energy: Theory



Early Dark Energy: Theory



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

Kamionkowski & Riess(2022)