Updated Constraints on Hubble Tension solutions

With recent SPT-3G and SH0ES data

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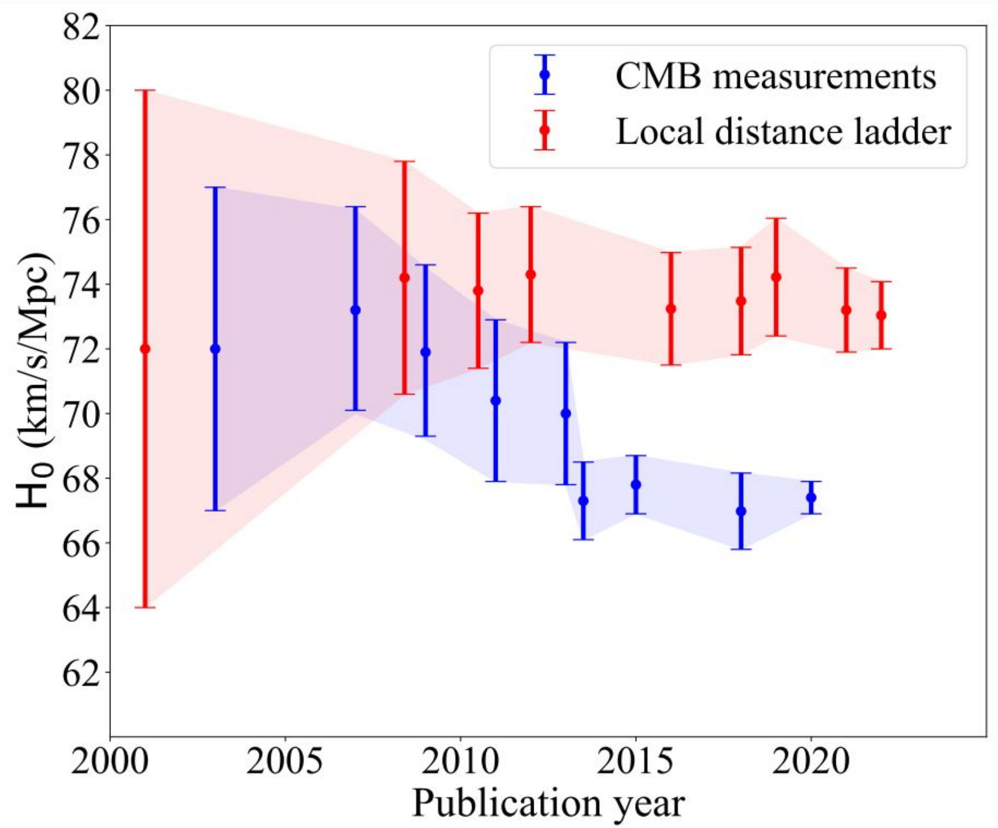
Federica Guidi, Aristide Doussot, Eric Hivon, Etienne Camphuis, Lennart Balkenhol and Aline Vitrier

04/12/2023, CMB-France

The Trouble with Hubble



Source: Hubble Tension: The Evidence of New Physics

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 it

- 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.*)

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

Sound Speed

H(z)

Flat, closed or open

H(z)/H_0

ΛCDM Extensions

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

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

Elaborate Models

- **Varying electron mass (m_e):**

  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

  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)**
  - **+Σm_ν:** Study interplay between masses of the two species

Elaborate Models

- **Varying electron mass (*m_e*)**
  - **+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)

Elaborate Models

- **Varying electron mass (m_e)**
  - **$+\Sigma m_\nu$**
  - **$+\Omega_K$**
  - **$+\Sigma m_\nu$ $+\Omega_K$**

Elaborate Models

- **Varying electron mass (m_e)**
  - **$+\Sigma m_\nu$**
  - **$+\Omega_K$**
  - **$+\Sigma m_\nu + \Omega_K$**
- **Early Dark Energy:**

  Also motivated by higher dimensional theories. A brief period of accelerated expansion around matter-radiation equality.

  Free parameters: θ_i, z_c and f_{EDE}

EDE

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

More details: Smith & Poulin, 2023 (2309.03265); Poulin *et al*, 2023 (2302.09032)

Elaborate Models

- **Varying electron mass (*m_e*)**
    - **+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

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

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

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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

- *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

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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

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  ; N ≡ # of parameters

- *AIC without SH0ES*

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 and CAMB
- Monte Carlo Sampler: COBAYA
- Minimizing χ^2: Py-BOBYQA
- New cosmological emulator (arXiv:2307.01138)
- Our reference data set: SPT+Planck+BAO+Pantheon

Main Results

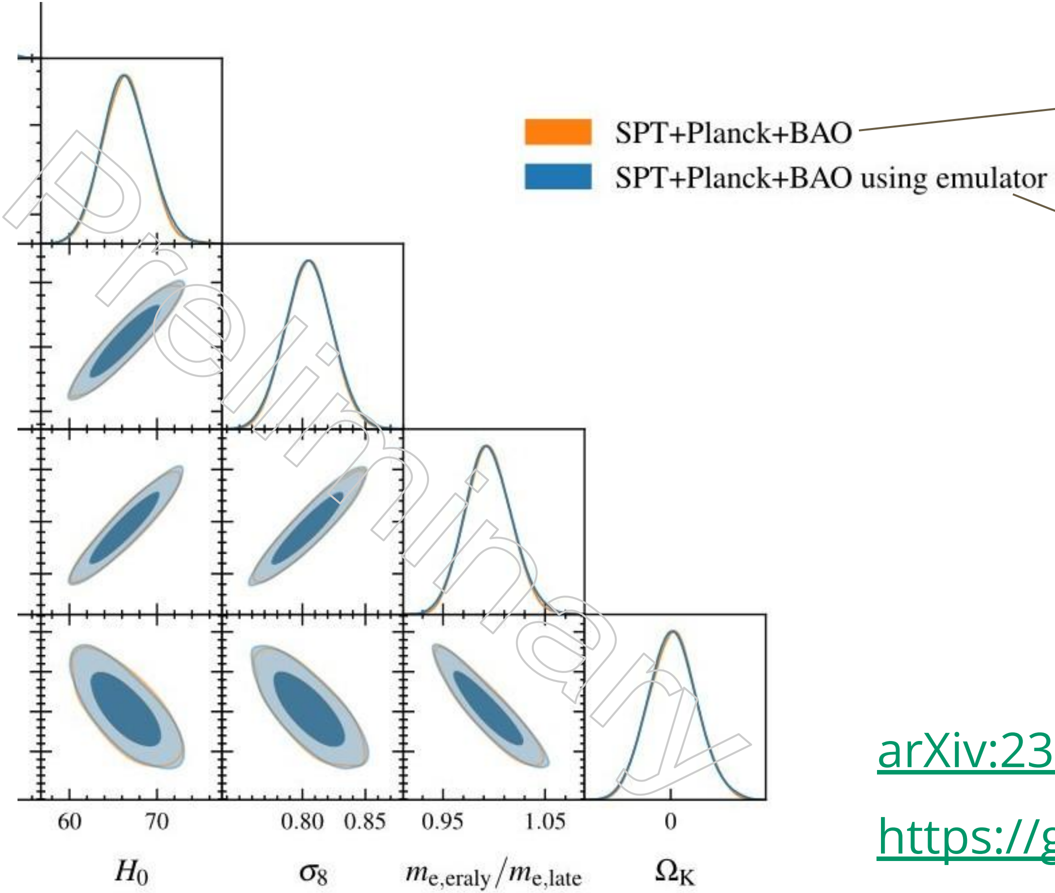
				w/o SH0ES		w/ SH0ES	
Models	H_0(km/s/Mpc)	$Q_{\mathrm{MPCL}}(\sigma)$	$Q_{\mathrm{DMAP}}(\sigma)$	$\Delta\chi^2$	ΔAIC	$\Delta\chi^2$	ΔAIC
ΛCDM	$67.56(67.58)^{+0.38}_{-0.38}$	6.0	5.8	0	0	0	0
$+\Sigma m_\nu$	$67.60(67.01)^{+0.49}_{-0.43}$	5.9	—	—	—	—	—
$+\Sigma m_\nu$+CPL	$67.94(67.89)^{+0.78}_{-0.79}$	4.5	—	—	—	—	—
$+\Sigma m_\nu + \mathrm{N_{eff}}$	$68.25(67.45)^{+0.62}_{-0.76}$	4.2	—	—	—	—	—
$+\Sigma m_\nu + \Omega_K$	$67.67(66.88)^{+0.62}_{-0.62}$	5.1	—	—	—	—	—
$+\Sigma m_\nu + \mathrm{N_{SIDR}}$	$68.53(69.06)^{+0.69}_{-0.92}$	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	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 $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	−0.19	3.81	X	X
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	−0.53	3.47	X	X

Table I of 2107.10291

The Power of an Emulator



3 days of running time

10 hrs of running time

[arXiv:2307.01138](https://arxiv.org/abs/2307.01138)

https://github.com/svenguenther/cobaya

Conclusions and Future Plans

- Classical extensions of ΛCDM are interesting, but cannot solve the HT.
- Only m_e+Ω_K (+Σm_ν) and EDE remain in the competition.
- Further investigation of these models, theoretically, is needed.
- Revisit these models, along with others, with upcoming SPT-3G 2019/2020 and ACT DR6 data.
- Stay on the lookout for the paper next week!

Back Up

Further Results

- SDSS-DR16 made the difference for the m_e model

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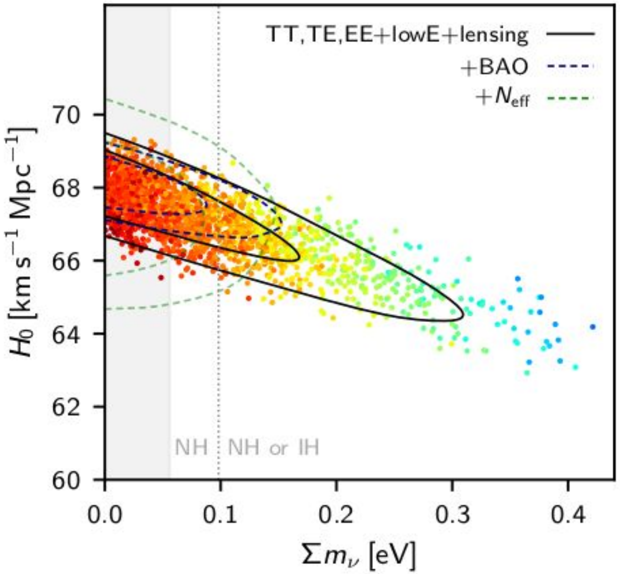
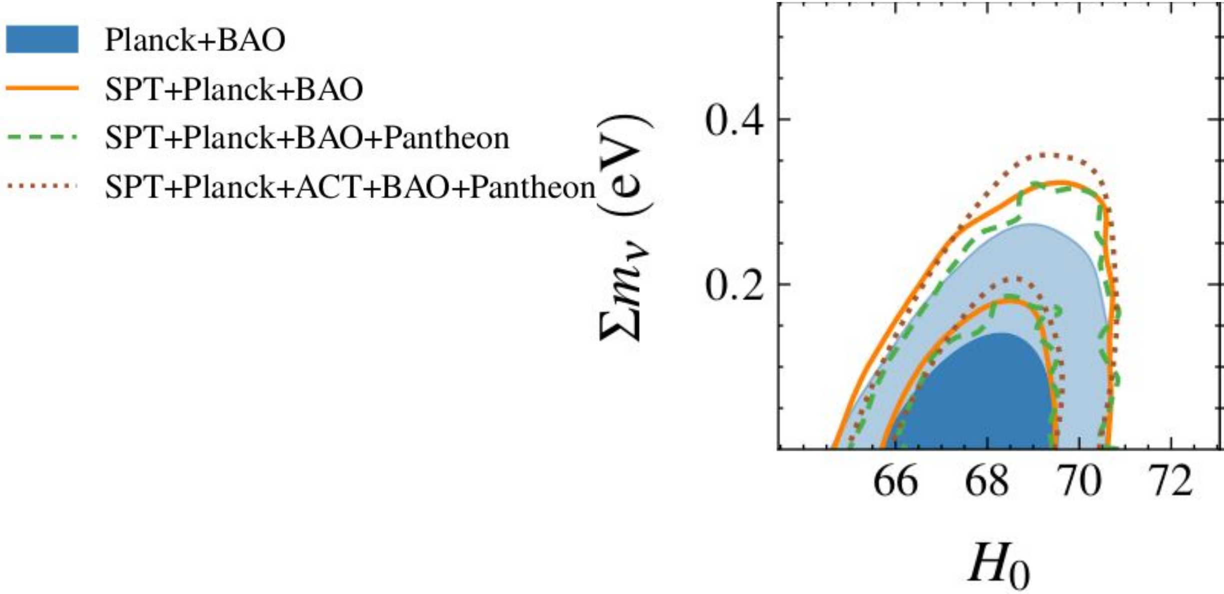
- Flip in degeneracy direction of H_0-Σm_ν when varying m_e





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

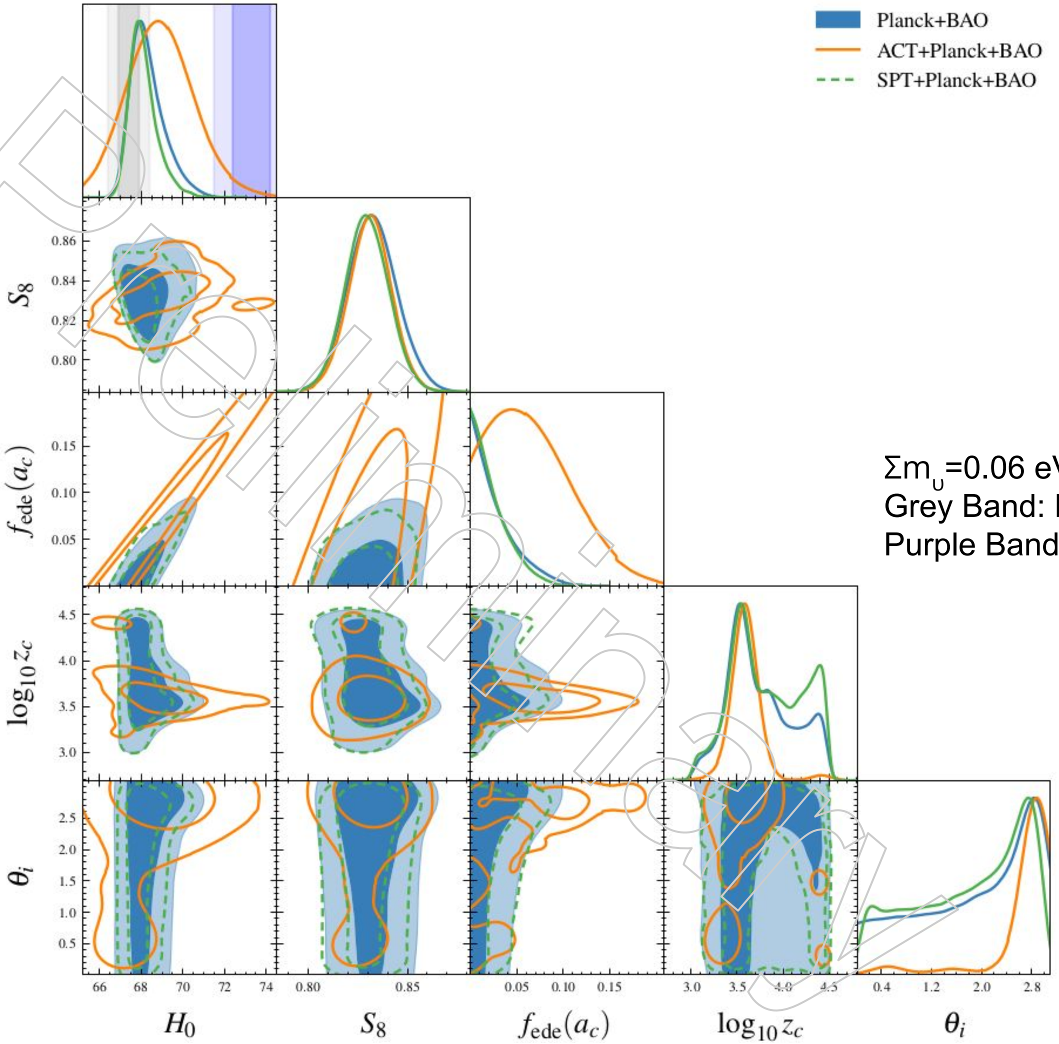
Further Results

- SDSS-DR16 made the difference for the m_e model
- Flip in degeneracy direction of H_0-Σm_ν when varying m_e
- SPT-3G improved polarization data made a difference for $m_e + \Omega_K$

H_0(Planck+BAO): $69.1^{+2.1}_{-2.1}$ H_0(SPT+Planck+BAO): $67.7^{+1.9}_{-1.8}$

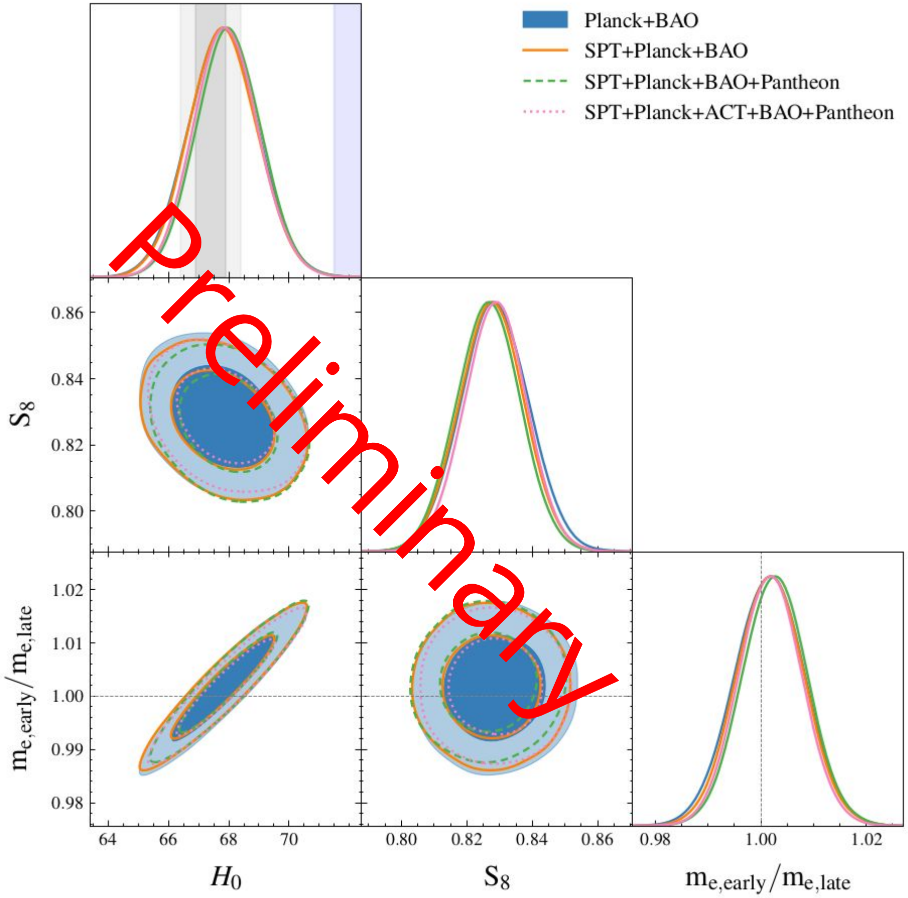
Further Results

- SDSS-DR16 made the difference for the m_e model
- Flip in degeneracy direction of H_0-Σm_υ when varying m_e
- SPT-3G improved polarization data made a difference for $m_e + \Omega_K$
- Preference for EDE from ACT-DR4 is still present



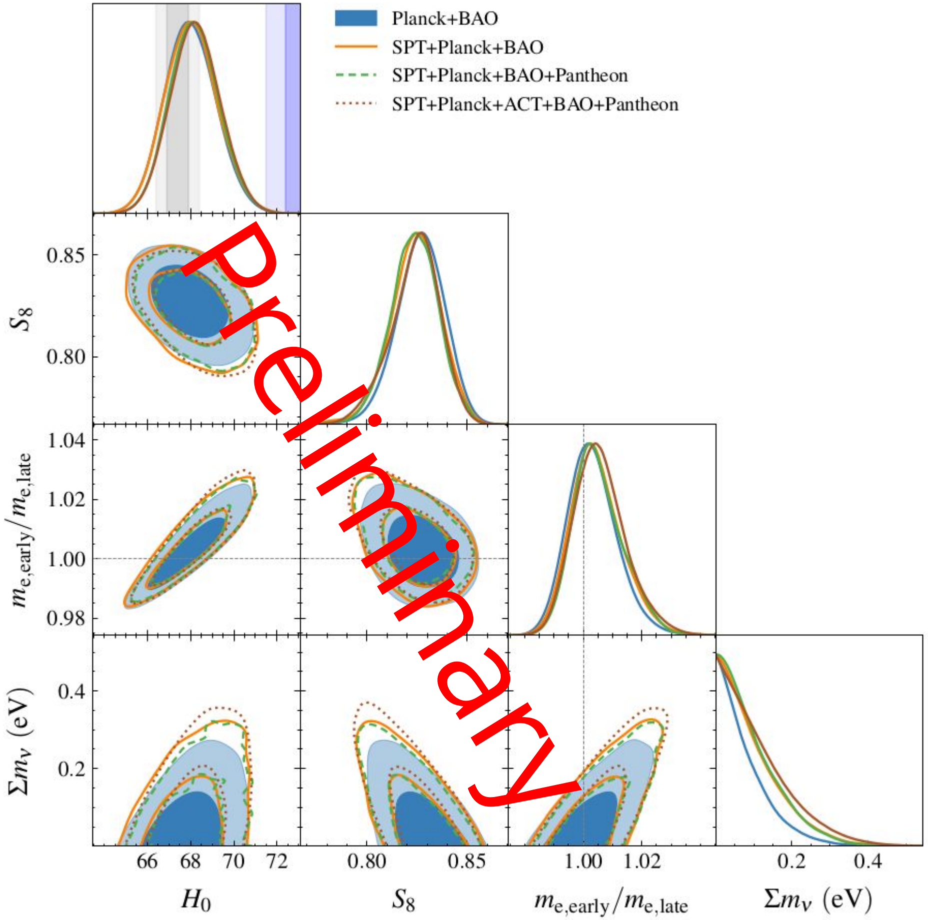
Σm_υ=0.06 eV
Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Varying Electron Mass: Results



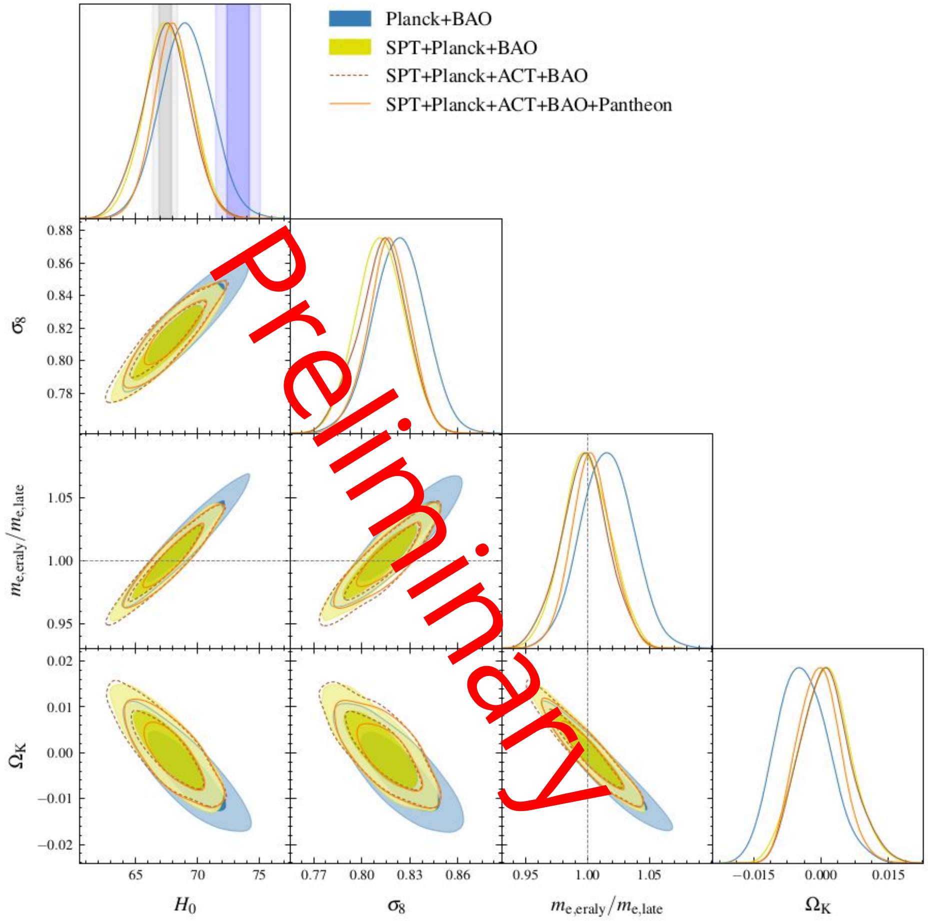
Σm_ν=0.06 eV
Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Me+Mnu: Results

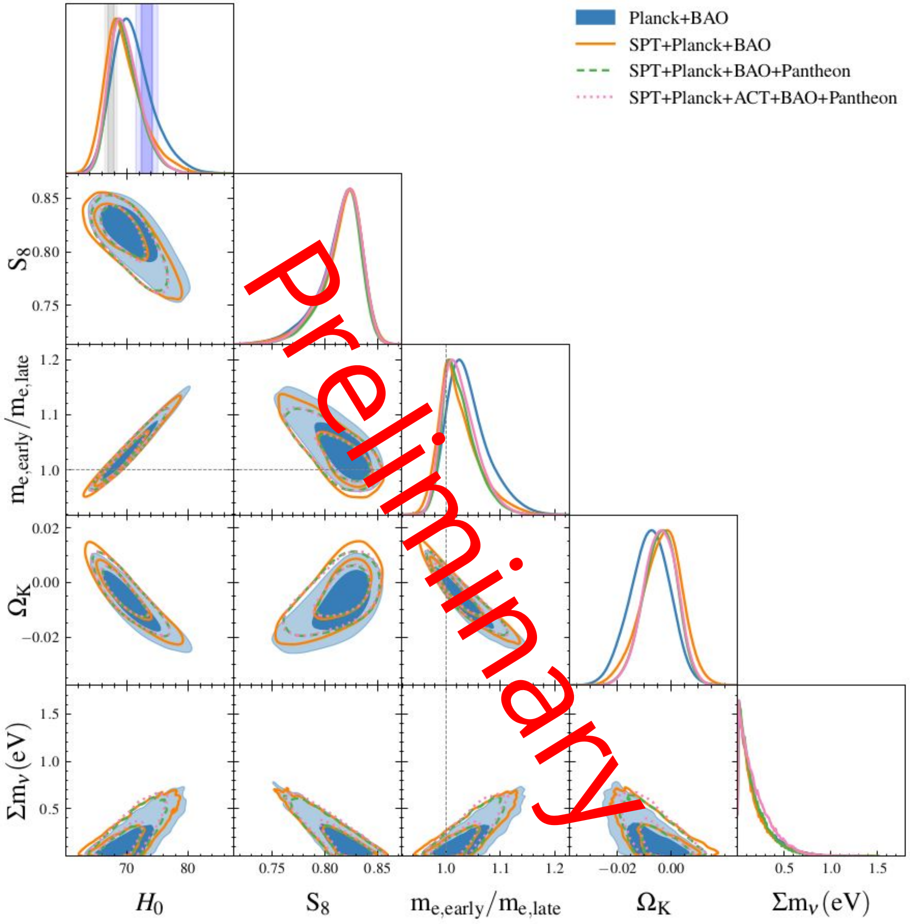


Grey Band: Planck 2018 LCDM
Purple Band: SH0ES

Me+Omk

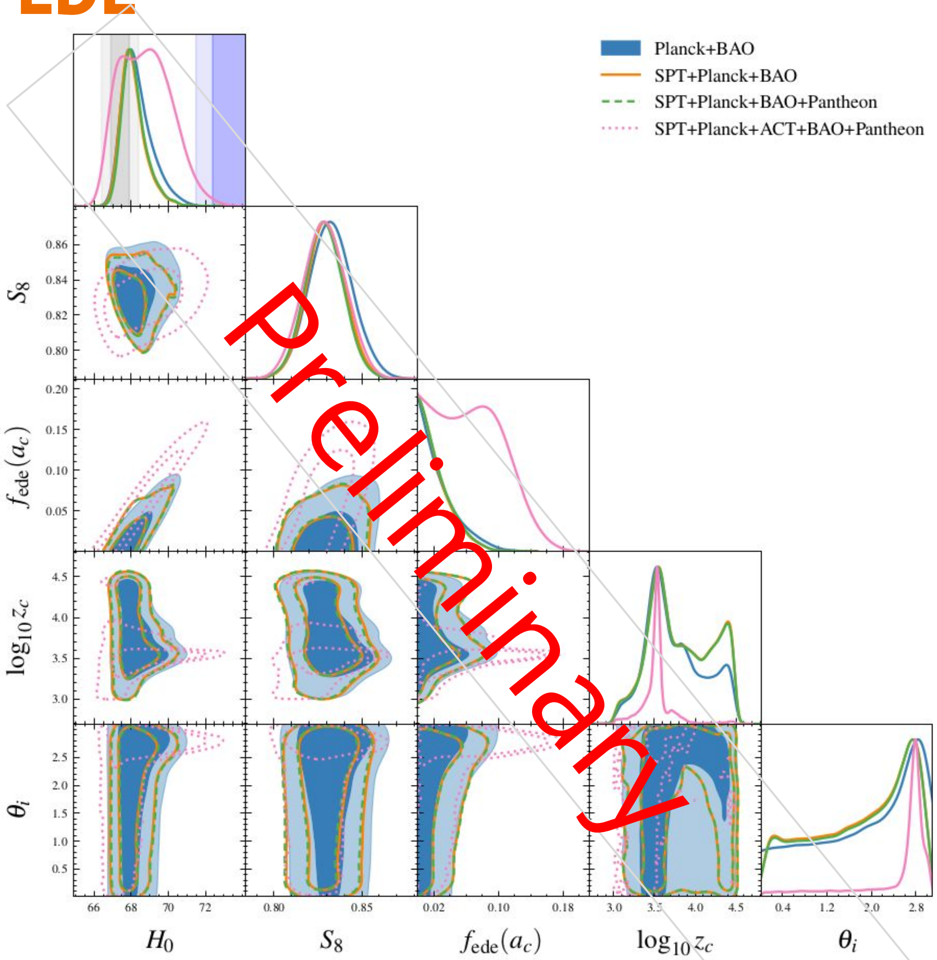

Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
Preliminary
σ_8
$m_{e,\mathrm{eraly}}/m_{e,\mathrm{late}}$
Ω_K
H_0
0.88
0.86
0.84
0.82
0.80
0.78
1.05
1.00
0.95
0.02
0.01
0.00
−0.01
−0.02
65
70
75
0.77
0.80
0.83
0.86
0.95
1.00
1.05
−0.015
0.000
0.015

Me+Mnu+Omk



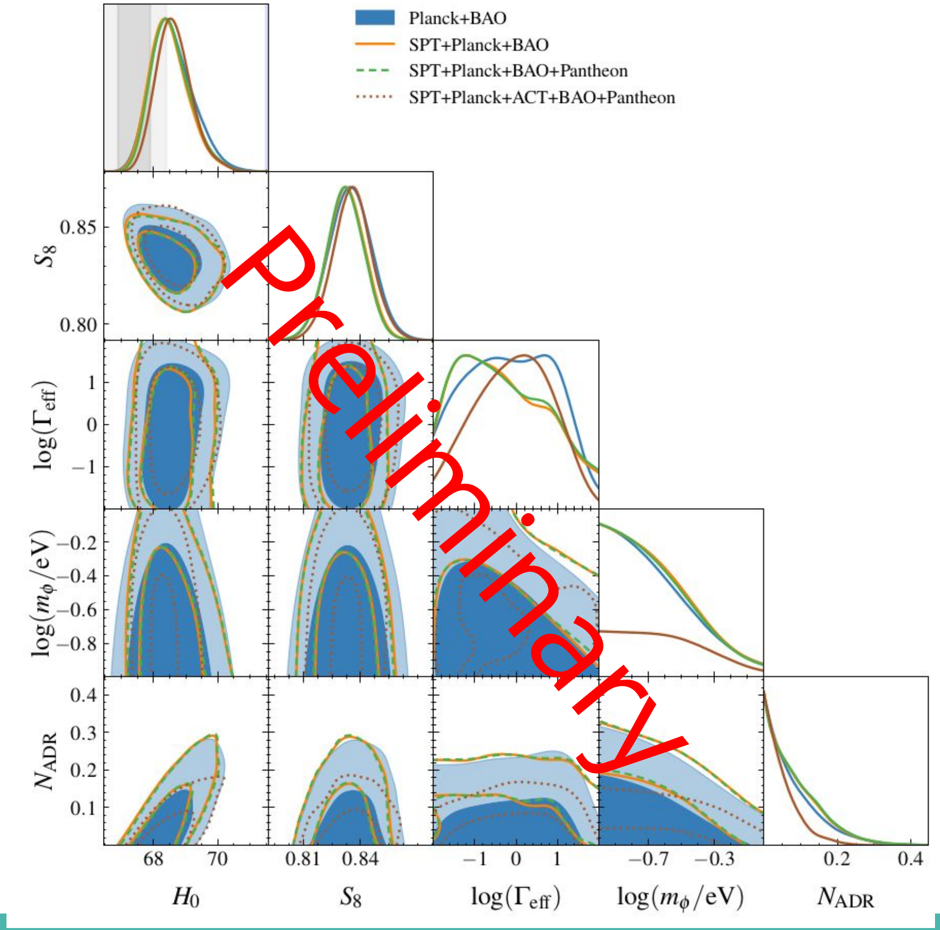
Planck+BAO
SPT+Planck+BAO
SPT+Planck+BAO+Pantheon
SPT+Planck+ACT+BAO+Pantheon
Preliminary
H_0
S_8
$m_{e,early}/m_{e,late}$
Ω_K
Σm_ν (eV)

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



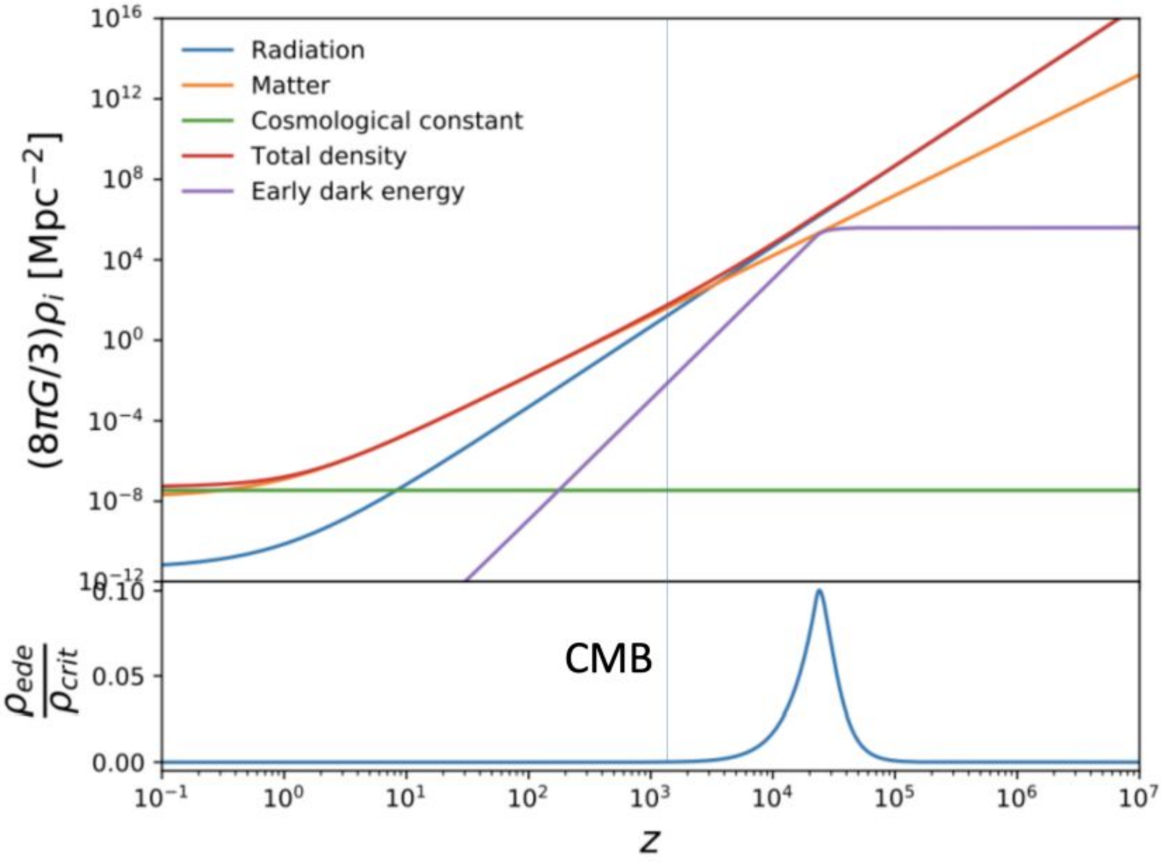
Sub eV mass

Early Dark Energy

- A short phase of accelerated expansion around matter-radiation equality.
- A scalar field around that time oscillating or slowly rolling along its potential.
- Same mechanism as Inflation, but different scalar field and time.
- Early decrease in the sound horizon is compensated by an increase in H_0.
- References: H_0 Olympics; 0205340; 2007.03381; 1912.03986; 1811.04083

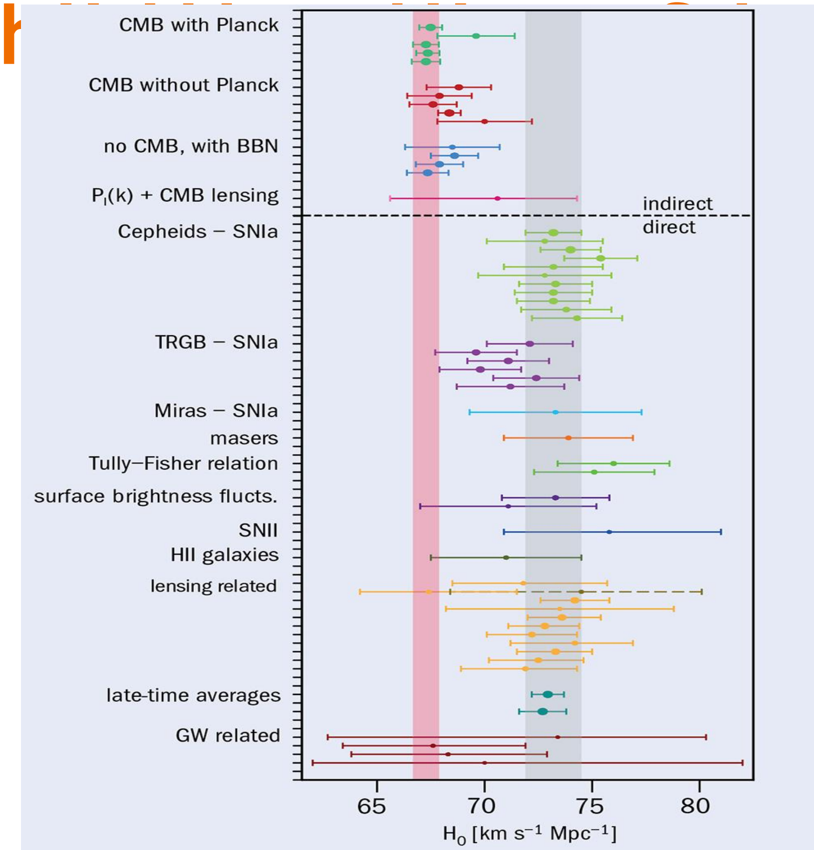
  Most recent results: arXiv:2309.03265

Early Dark Energy: Theory



Kamionkowski & Riess(2022)

The Trouble with … it



Source: [In the Realm of the Hubble Tension]

Varying Electron Mass: Theory

- In Gravity theories with higher dimensions, compactification of the latter results in scalar fields.
- These scalars are gravitationally coupled to Standard Model fields, particularly electrons
- The result is an effective electron mass that could differ from the one we measure in the lab.

Varying Electron Mass: Theory

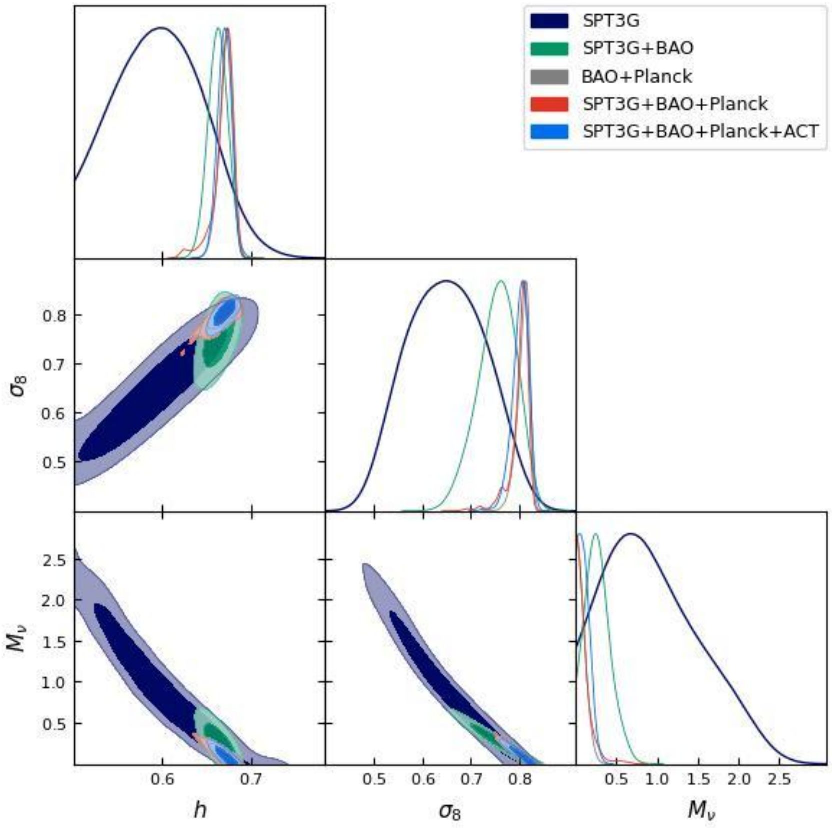
- Varying the electron mass affects Hydrogen/Helium recombination.
- Varying properties of Hydrogen/Helium formation efficiently impacts the time when recombination happens.

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

Varying Electron Mass: Theory

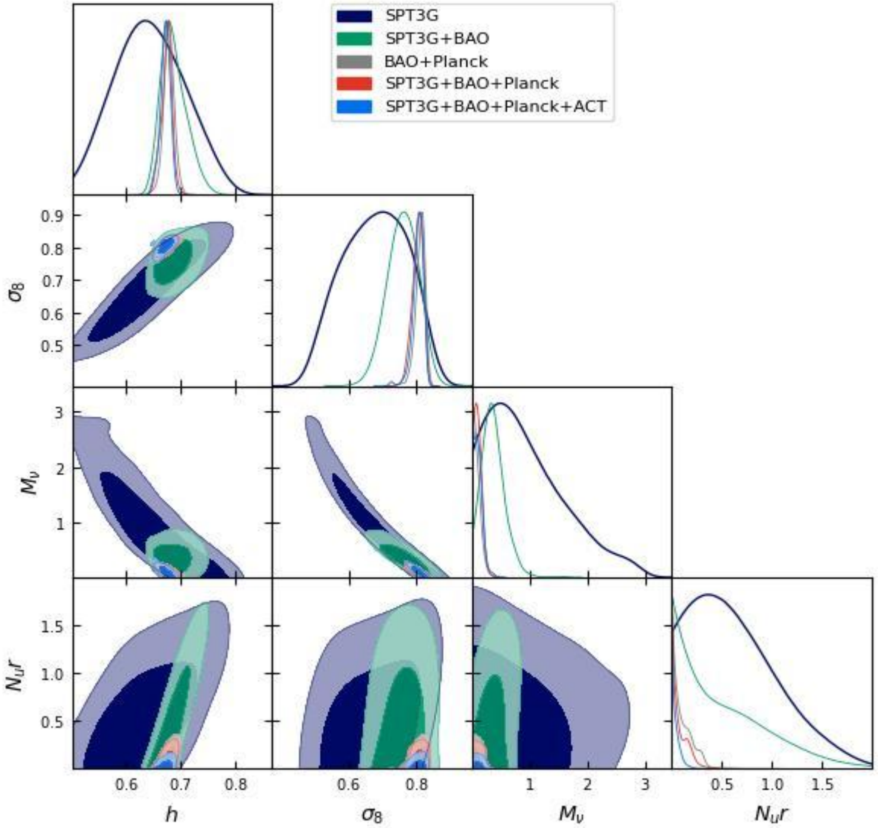
- Varying the electron mass affects Hydrogen/Helium formation rates.
- Varying properties of Hydrogen/Helium formation efficiently impacts the time when recombination happens.
- Allowing a non-zero curvature on top of that provides a better fit by adjusting the D_A to BAO and other late time probes.
- In practice, however, the model is described with a step function.

ΛCDM+Σm_ν

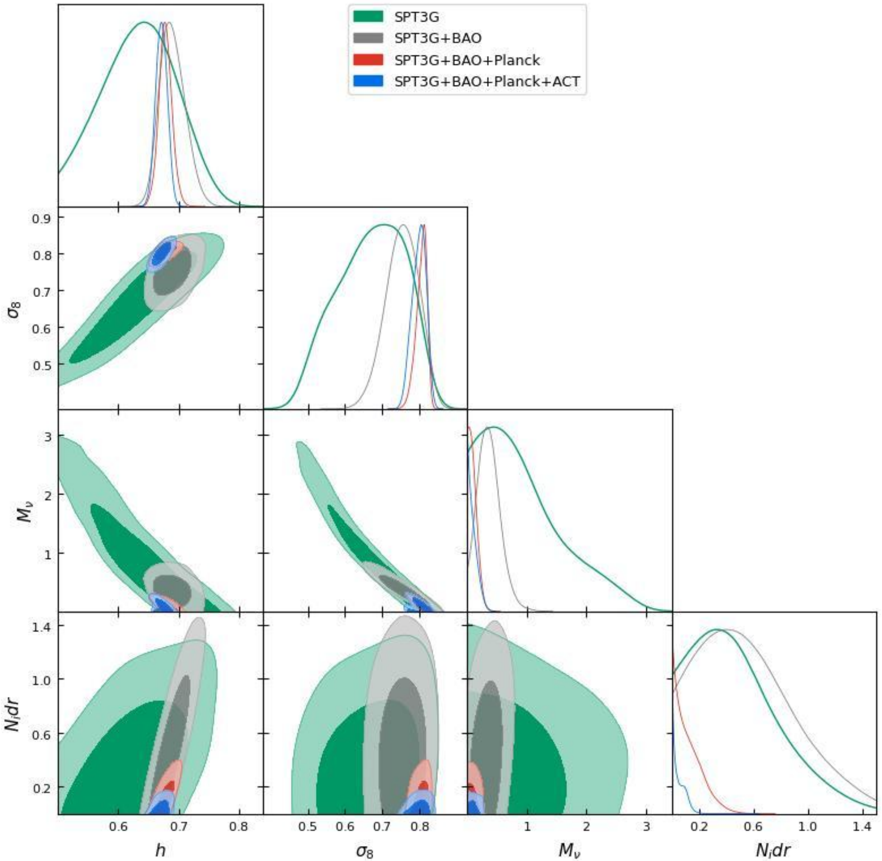


Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.00±0.82
σ_8	0.803±0.019

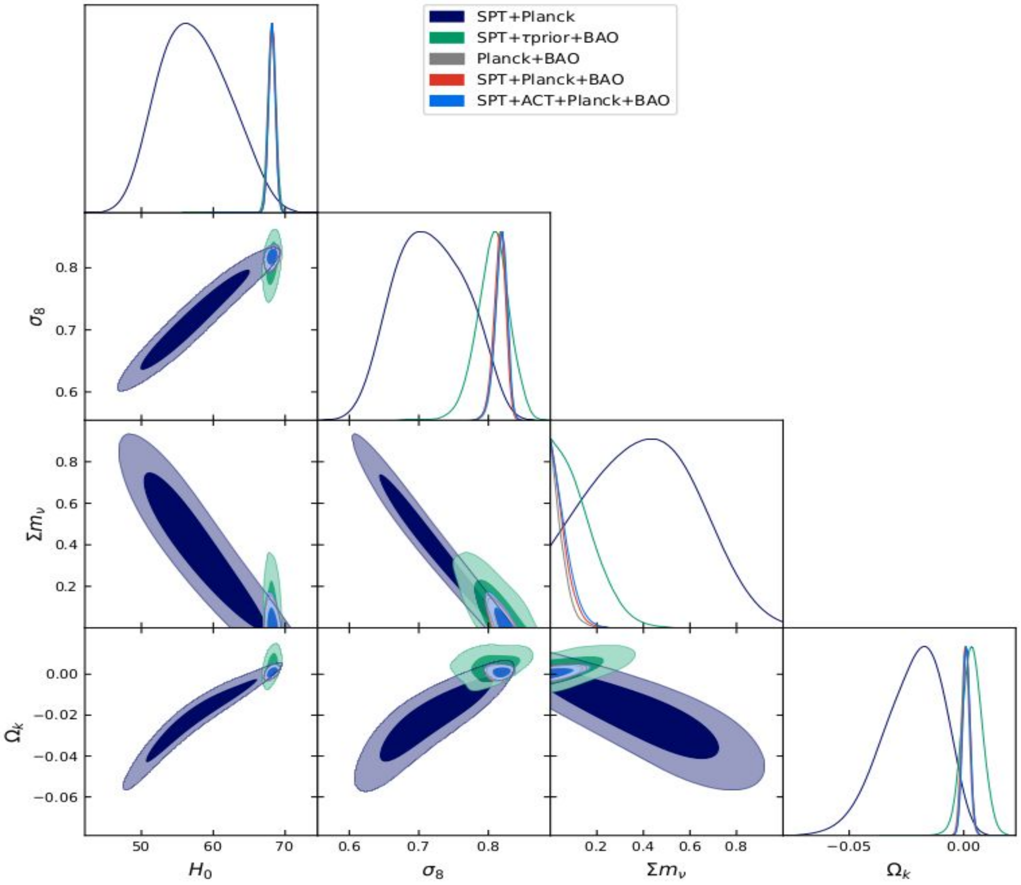
$\Lambda CDM+\Sigma m_\nu+N_{eff}$



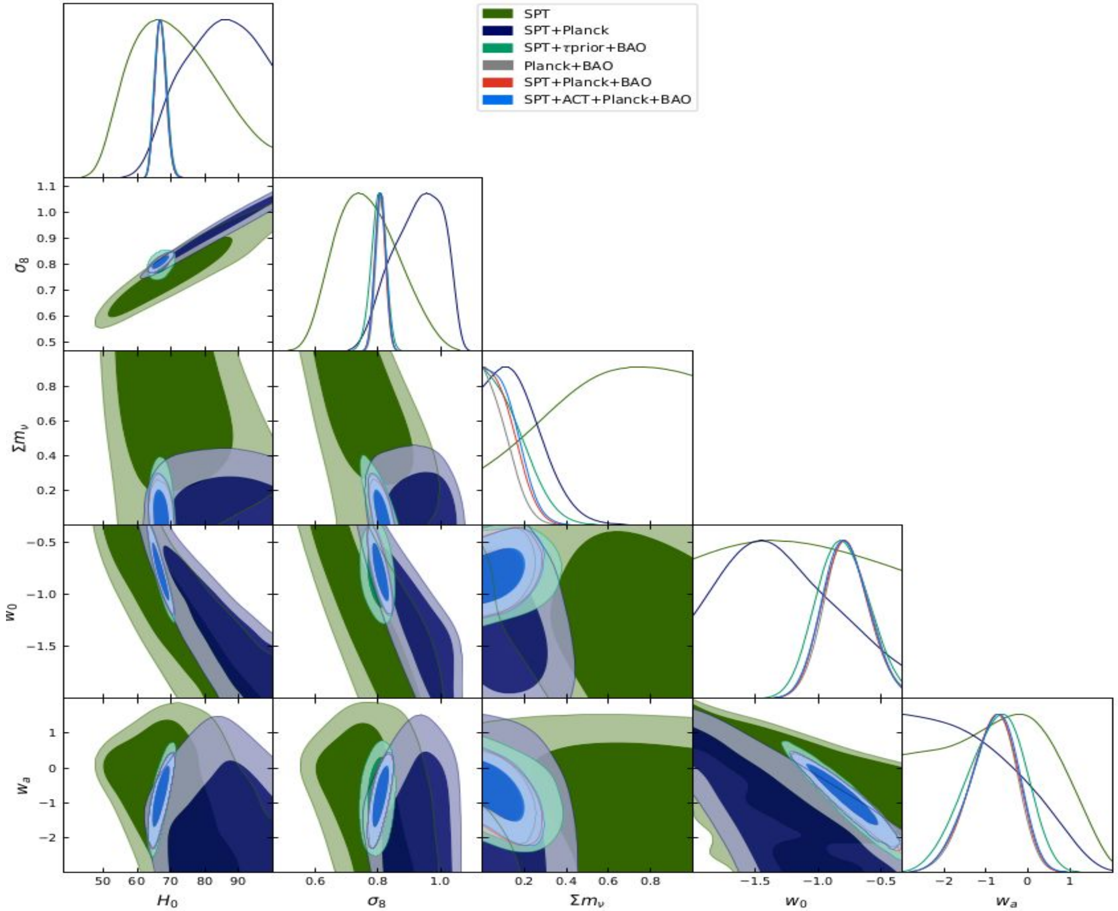
Parameter	SPT+ ACT+ Planck+ BAO
H_0	67.10±0.85
σ_8	0.812±0.009



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



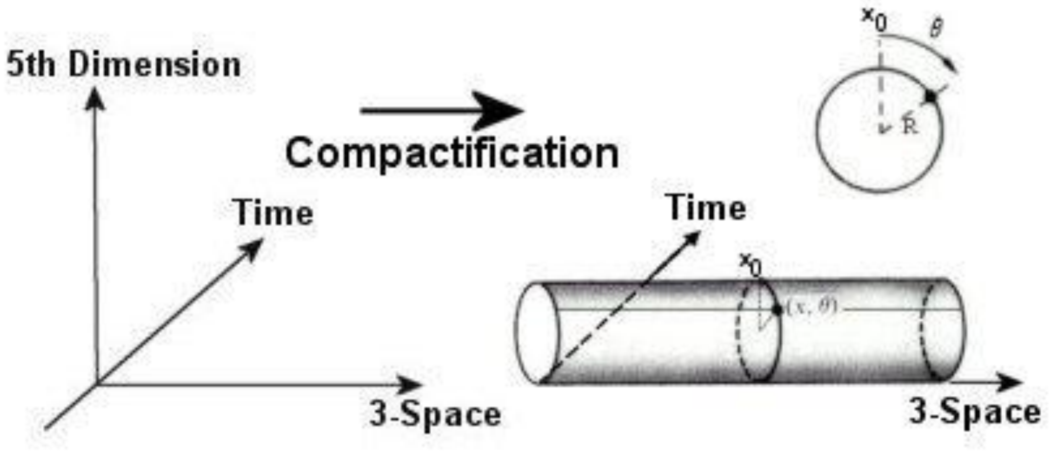
Parameter	SPT+ ACT+ Planck+ BAO
H_0	68.16±0.46
σ_8	0.818±0.009



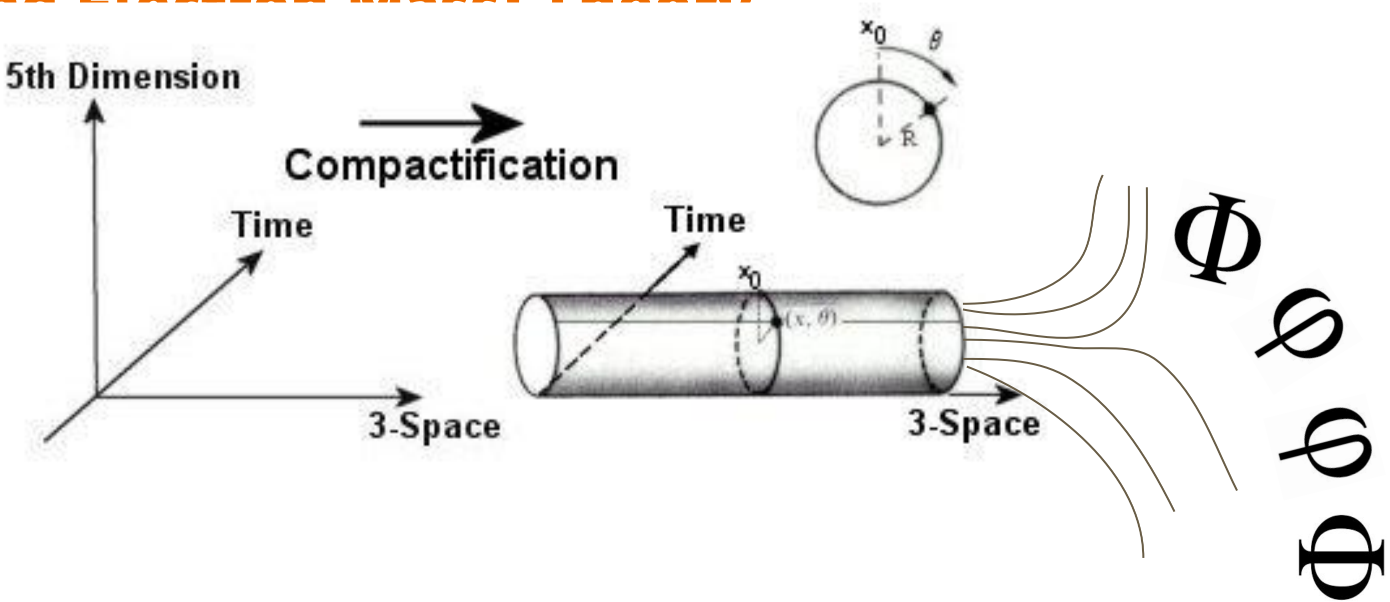
Parameter	SPT+ ACT+ Planck+ BAO
H_0	66.89±1.62
σ_8	0.808±0.017

SLIDES FOR A GENERAL AUDIENCE TALK

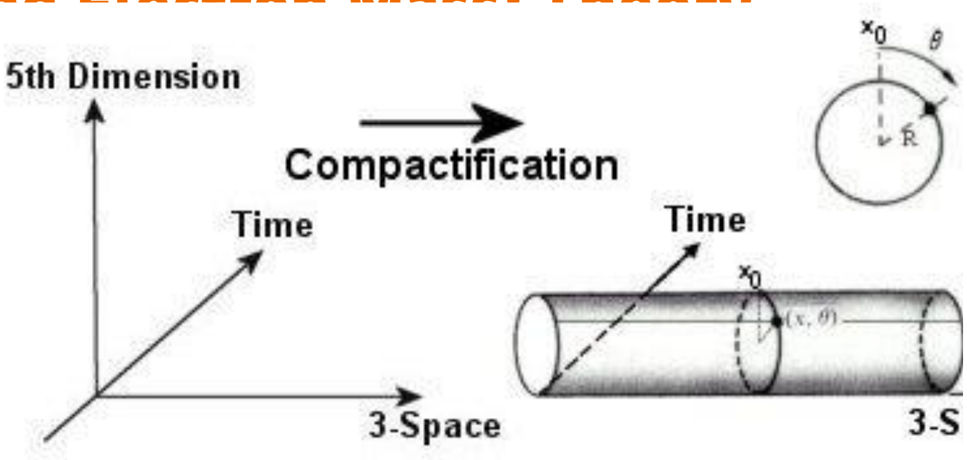
Varyin

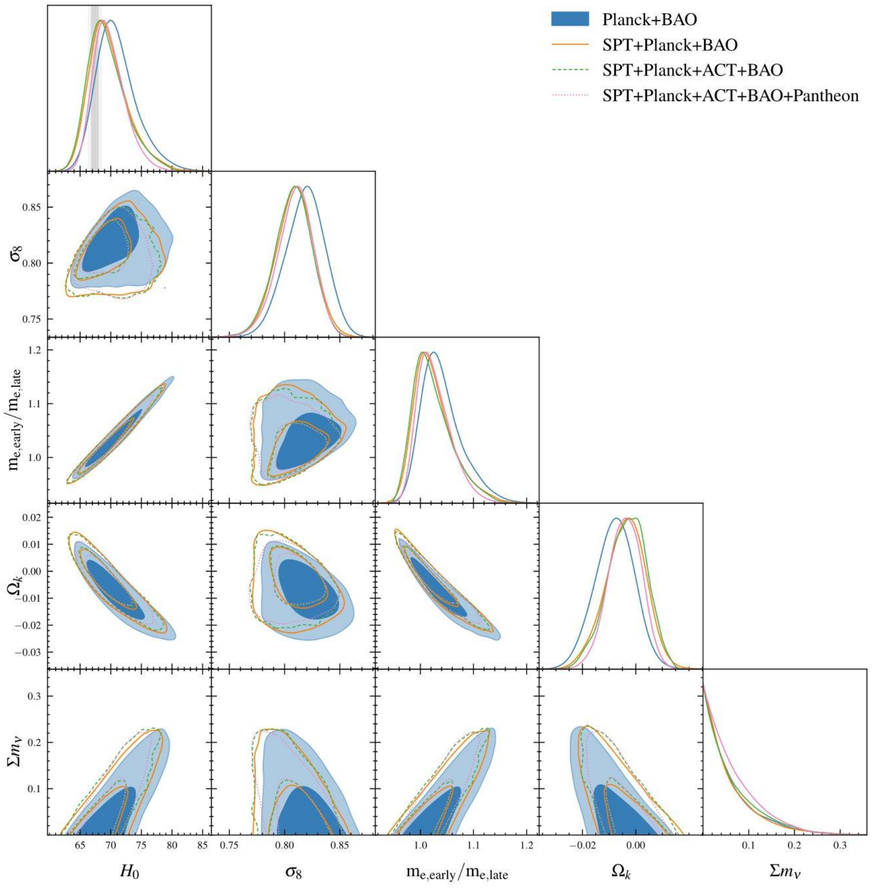

5th Dimension
Compactification
Time
3-Space
Time
x_0
θ
R
x_0
(x, θ)
3-Space

Varying Electron Mass: Theory



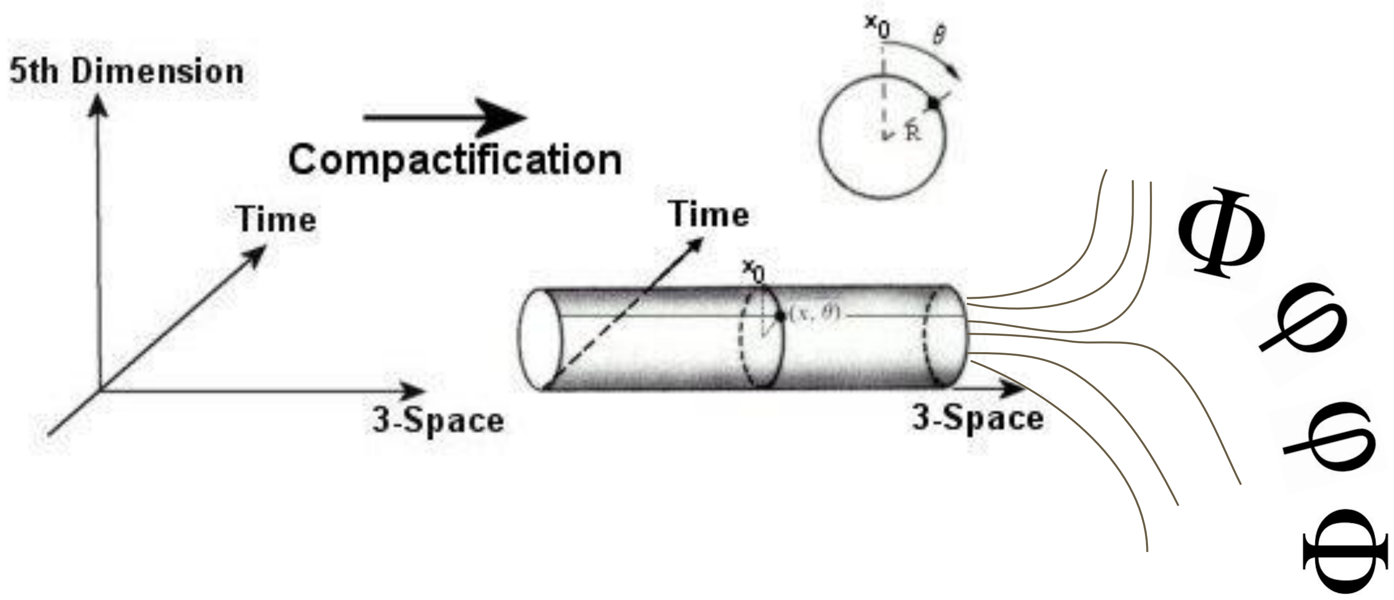
Varying Electron Mass: Theory



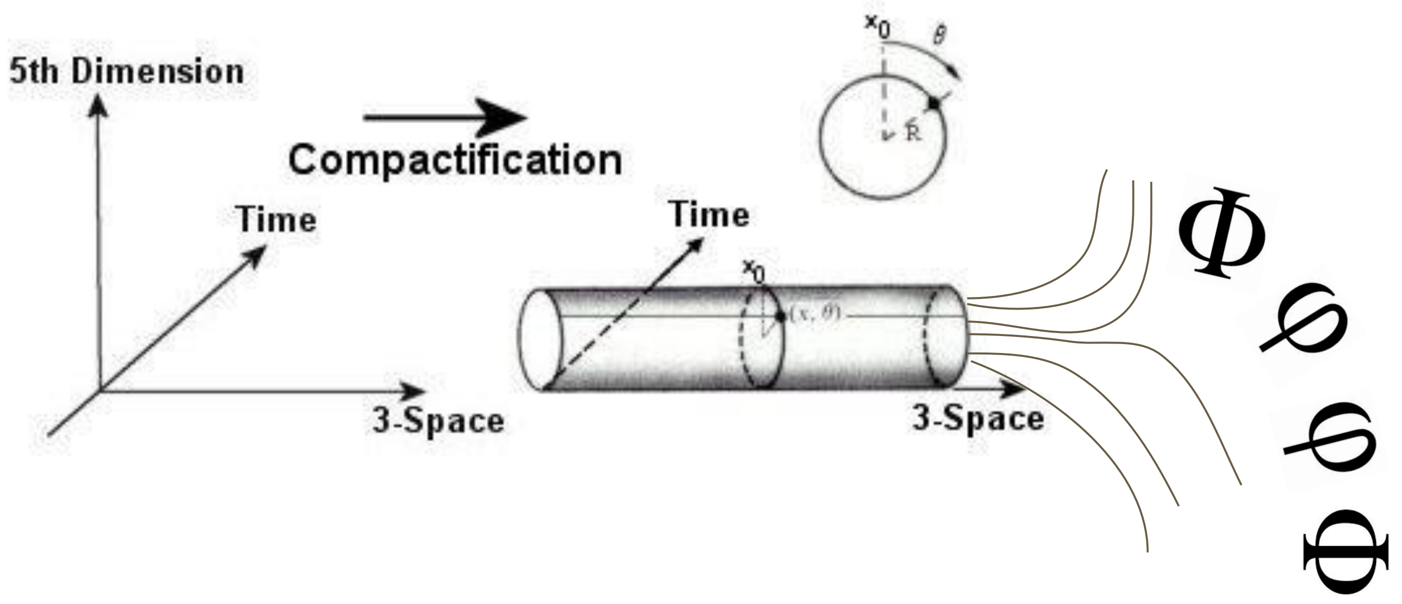


Planck+BAO
SPT+Planck+BAO
SPT+Planck+ACT+BAO
SPT+Planck+ACT+BAO+Pantheon
H_0
σ_8
$m_{e,early}/m_{e,late}$
Ω_k
Σm_ν

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)