Title: Data-driven solutions to the Hubble tension - VIRTUAL

Speakers: Nanoom Lee

Series: Cosmology & Gravitation

Date: January 30, 2024 - 11:00 AM

URL: https://pirsa.org/24010095

Abstract: While the standard ΛCDM model provides an astonishing fit to cosmological data, there is a 4-6 σ tension in the Hubble constant, H_0, between the value inferred from early-Universe observables, Planck CMB anisotropy spectra, and the value determined by local measurements from SH0ES collaboration using Type 1a supernovae calibrated with Cepheid variables. As an effort to solve this tension, we develop a method of searching for data-driven solutions to the Hubble tension given cosmological dataset, based on the standard Fisher bias formalism. Taking as proof of principle the case of a time-varying electron mass, and focusing first on Planck CMB data, we demonstrate a modified recombination can solve the Hubble tension and lower S_8 to better match weak lensing measurements. Once baryonic acoustic oscillation and uncalibrated supernovae data are included, it is not possible to fully solve the tension with perturbative modifications to recombination. The method we develop in this work can be a useful tool to search for many other possible extensions to the ΛCDM model, and is expected to inspire a model-building effort from the cosmology and particle physics community.

Zoom link

Data-driven Solutions to the Hubble Tension

Nanoom Lee (NYU)

with Yacine Ali-Haïmoud (NYU), Nils Schöneberg (Barcelona U.), and Vivian Poulin (CNRS & U.Montpellier)

Based on "What it takes to solve the Hubble tension through modifications of cosmological recombination"
Phys.Rev.Lett. 130 (2023) 16, 161003 [arXiv:2212.04494]

Perimeter Institute - 01/30/24

Nanoom Lee (NYU, Ph.D expected in 2024)

Cosmological Recombination / CMB

A new recombination code, HYREC-2 (2007.14114)

Probing small-scale isocurvature perturbations with CMB anisotropies (2108.07798)

Probing cosmic birefringence with pSZ tomography (2207.05687)

The Hubble Tension

Data-driven solutions to the Hubble tension (2212.04494)

21-cm from Cosmic Dawn

Probing light relics through cosmic dawn (2309.15119)

Ongoing/Future Plans

Redshift-space distortion, modifying primordial power spectrum for the Hubble tension, DM-baryon scattering, 21cm/CMB cross-bispectrum, magnetic field from Biermann-battery mechanism.

Nanoom Lee (NYU, Ph.D expected in 2024)

Cosmological Recombination / CMB

A new recombination code, HYREC-2 (2007.14114)

Probing small-scale isocurvature perturbations with CMB anisotropies (2108.07798)

Probing cosmic birefringence with pSZ tomography (2207.05687)

The Hubble Tension

Data-driven solutions to the Hubble tension (2212.04494)

21-cm from Cosmic Dawn

Probing light relics through cosmic dawn (2309.15119)

Ongoing/Future Plans

Redshift-space distortion, modifying primordial power spectrum for the Hubble tension, DM-baryon scattering, 21cm/CMB cross-bispectrum, magnetic field from Biermann-battery mechanism.

Data-driven Solutions to the Hubble Tension

Nanoom Lee (NYU)

with Yacine Ali-Haïmoud (NYU), Nils Schöneberg (Barcelona U.), and Vivian Poulin (CNRS & U.Montpellier)

Based on "What it takes to solve the Hubble tension through modifications of cosmological recombination"
Phys.Rev.Lett. 130 (2023) 16, 161003 [arXiv:2212.04494]

Perimeter Institute - 01/30/24

OUTLINE

01 MOTIBATION

What is the Hubble tension?

Non-standard physics keeping the goodness of fit to the Planck CMB data?

02 METHOD

Built on Fisher bias formalism / some approximations

Non-standard physics resulting in shifts in best-fit cosmological parameters (e.g., H0)

Requiring no increase in chi-squared

03 APPLICATION

Time-varying electron mass

With Planck CMB / BOSS BAO / PantheonPlus data

OUTLINE

01 MOTIBATION

What is the Hubble tension?

Non-standard physics keeping the goodness of fit to the Planck CMB data?

02 METHOD

Built on Fisher bias formalism / some approximations

Non-standard physics resulting in shifts in best-fit cosmological parameters (e.g., H0)

Requiring no increase in chi-squared

03 APPLICATION

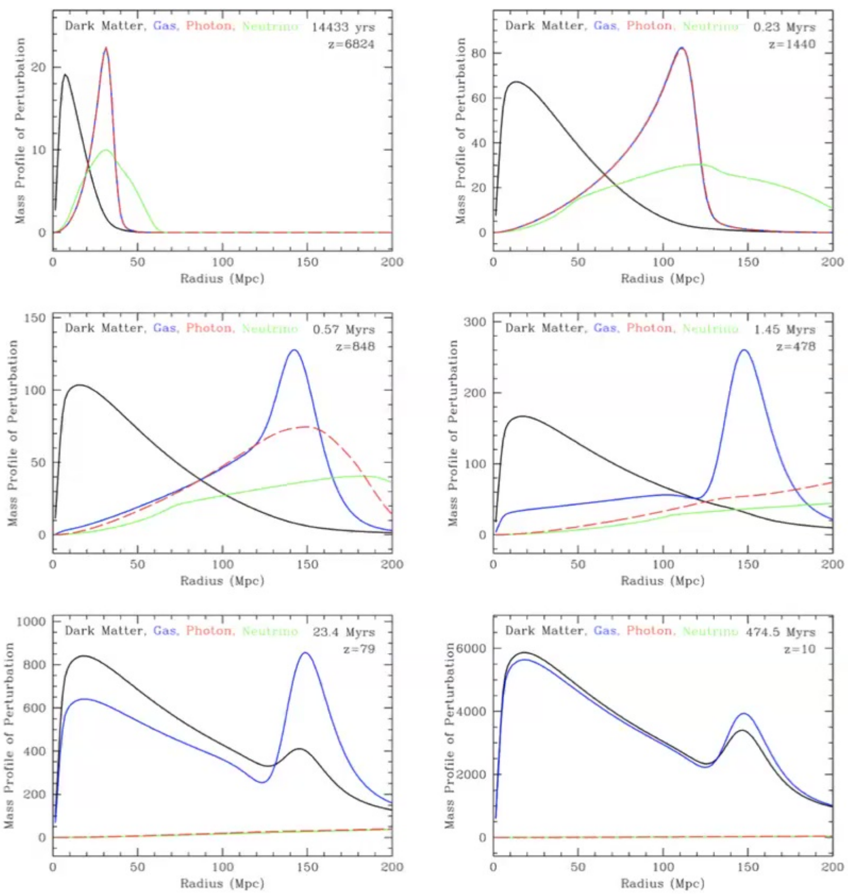
Time-varying electron mass

With Planck CMB / BOSS BAO / PantheonPlus data

MOTIVATION - Hubble Tension

- Standard LCDM model with six cosmological parameters $\{\omega_c, \omega_b, H_0, \tau, \ln(10^{10}A_s), n_s\}$
- 4-6 sigma tension in the Hubble constant H0 (the present-time expansion rate)
- Early-universe measurements from Planck CMB: $H_0 = 67.36 \pm 0.54\ \mathrm{km/s/Mpc}$
- Local measurements by SH0ES type 1a SN: $H_0 = 73.04 \pm 1.04\ \mathrm{km/s/Mpc}$
- A various new physics (extensions to LCDM model) have been proposed / studied

MOTIVATION - How to resolve the Hubble Tension

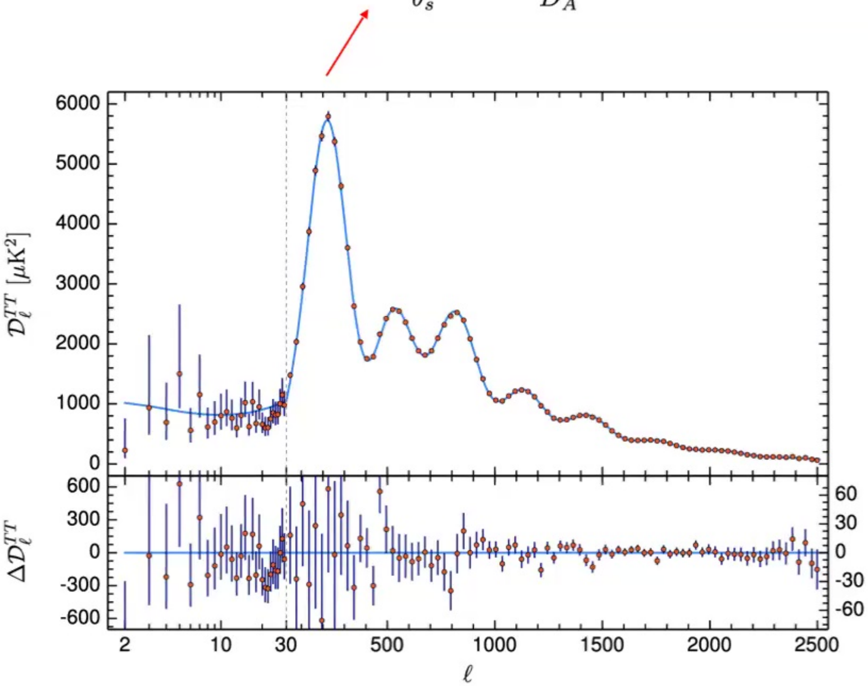


- Early-time universe was hot and dense
- Baryons and photons formed a fluid
- At overdense region, pressure induces a sound wave
- The wave traveled until decoupling
- A signature at sound horizon scale ~ 150Mpc

(Eisenstein et al. (2007))

MOTIVATION - How to resolve the Hubble Tension

$$\ell_s \approx \frac{\pi}{\theta_s}, \quad \theta_s = \frac{r_s}{D_A}$$



(Planck 2018)

$$r_s = \int_{z_{1s}}^{\infty} dz\, \frac{c_s(z)}{H(z)}, \quad c_s(z) = \frac{c}{\sqrt{3[1+R(z)]}}, \quad R(z) = \frac{3\rho_b(z)}{4\rho_\gamma(z)}$$

$$D_A = \frac{c}{H_0}\int_0^{z_{1s}} \frac{dz}{H(z)/H_0} = \frac{c}{H_0}\int_0^{z_{1s}} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda}}$$

- We have very precise measurements of theta_s from Planck, which should be kept when modifying LCDM.
- Late-time solutions modify H(z)/H_0 in D_A.
- Early-time solutions modify r_s.

MOTIVATION - Search for new physics as a solution to the tension

10

MOTIVATION - Search for new physics as a solution to the tension

- Given observations / theory, can obtained best-fit parameters by minimizing $\chi^2[\boldsymbol{X}(\vec{\Omega}); \boldsymbol{X}^{\rm obs}]$
- The best-fit parameters and best-fit chi-squared both depend on underlying theory: $\vec{\Omega}_{\rm BF},\ \chi^2_{\rm BF} \equiv \chi^2[\boldsymbol{X}(\vec{\Omega}_{\rm BF}); \boldsymbol{X}^{\rm obs}]$

- A model differs from standard model would results in shifts in best-fit parameters and best-fit chi-squared
- Consider changes in model from perturbations of a smooth function f(z)

$$\text{minimize}(||\Delta f||^2) \quad \text{with} \begin{cases} \vec{\Omega}_{\rm BF}[\Delta f(z)] = \vec{\Omega}_{\rm target}, \\ \Delta\chi^2_{\rm BF}[\Delta f(z)] \leq 0 \end{cases}$$

-> Smallest possible extensions to LCDM model resulting in desired shifts in cosmological parameters, while not increasing chi-squared given dataset

METHOD - Fisher bias formalism

- Given data / theory, one can estimate best-fit parameters by Taylor expanding chi-squared around a fiducial cosmology, and minimizing it

$$\chi^2(\vec{\Omega}) \equiv [\boldsymbol{X}(\vec{\Omega}) - \boldsymbol{X}^{\rm obs}] \cdot \boldsymbol{M}(\vec{\Omega}) \cdot [\boldsymbol{X}(\vec{\Omega}) - \boldsymbol{X}^{\rm obs}]$$

$$\Omega^i_{\rm BF} = \Omega^i_{\rm fid} - \frac{1}{2}(F^{-1})_{ij} \frac{\partial \chi^2}{\partial \Omega^j}\bigg|_{\rm fid}$$

To achieve desired shifts in best-fits, what modifications in the model needed?

- Used to study "biases" in the estimated parameters
- Due to, for example, an incorrect modeling / systematic errors
- Also used to constrain arbitrary functions (e.g., PCAs)

METHOD

- Can estimate best-fit parameters starting from fiducial cosmology

$$\chi^2(\vec{\Omega}) \approx \chi^2(\vec{\Omega}_{\rm fid}) + \frac{\partial \chi^2}{\partial \Omega^i}\bigg|_{\rm fid}(\Omega^i - \Omega^i_{\rm fid}) + \frac{1}{2}\frac{\partial^2 \chi^2}{\partial \Omega^i \partial \Omega^j}\bigg|_{\rm fid}(\Omega^i - \Omega^i_{\rm fid})(\Omega^j - \Omega^j_{\rm fid})$$

$$0 = \frac{\partial \chi^2}{\partial \Omega^i}\bigg|_{\rm BF} = \frac{\partial \chi^2}{\partial \Omega^i}\bigg|_{\rm fid} + 2F_{ij}(\Omega^j_{\rm BF} - \Omega^j_{\rm fid}), \quad F_{ij} \equiv \frac{1}{2}\frac{\partial^2 \chi^2}{\partial \Omega^i \partial \Omega^j}\bigg|_{\rm fid} \approx \left(\frac{\partial \boldsymbol{X}}{\partial \Omega^i} \cdot \boldsymbol{M} \cdot \frac{\partial \boldsymbol{X}}{\partial \Omega^j}\right)\bigg|_{\rm fid}$$

$$\Omega^i_{\rm BF} = \Omega^i_{\rm fid} - \frac{1}{2}(F^{-1})_{ij}\frac{\partial \chi^2}{\partial \Omega^j}\bigg|_{\rm fid} \approx \Omega^i_{\rm fid} - (F^{-1})_{ij}\frac{\partial \boldsymbol{X}}{\partial \Omega^j}\bigg|_{\rm fid} \cdot \boldsymbol{M}(\vec{\Omega}_{\rm fid}) \cdot [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]$$

- Can estimate best-fit chi-squared using $\Omega^i_{\rm BF}$

$$\chi^2(\vec{\Omega}_{\rm BF}) \approx \chi^2(\vec{\Omega}_{\rm fid}) + \frac{\partial \chi^2}{\partial \Omega^i}\bigg|_{\rm fid}(\Omega^i_{\rm BF} - \Omega^i_{\rm fid}) + \frac{1}{2}\frac{\partial^2 \chi^2}{\partial \Omega^i \partial \Omega^j}\bigg|_{\rm fid}(\Omega^i_{\rm BF} - \Omega^i_{\rm fid})(\Omega^j_{\rm BF} - \Omega^j_{\rm fid})$$

$$= [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}] \cdot \widetilde{\boldsymbol{M}} \cdot [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]$$

$$\widetilde{M}_{\alpha\beta} \equiv M_{\alpha\beta} - M_{\alpha\gamma}\frac{\partial X^\gamma}{\partial \Omega^i}(F^{-1})_{ij}\frac{\partial X^\sigma}{\partial \Omega^j}M_{\sigma\beta}$$

(A side note: A new matrix can be understood as the inverse covariance matrix after marginalizing over parameters.)

METHOD

- The best-fit and chi-squared estimated by Fisher formalism:

$$\Omega^i_{\rm BF} \approx \Omega^i_{\rm fid} - (F^{-1})_{ij} \frac{\partial \boldsymbol{X}}{\partial \Omega^j}\Big|_{\rm fid} \cdot \boldsymbol{M}(\vec{\Omega}_{\rm fid}) \cdot [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]$$
$$\chi^2(\vec{\Omega}_{\rm BF}) \approx [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}] \cdot \widetilde{\boldsymbol{M}} \cdot [\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]$$

- Now, we consider a model which differs from the standard model of which changes are resulting from a smooth function f(z).

$$\boldsymbol{X}'(\vec{\Omega}) = \boldsymbol{X}(\vec{\Omega}) + \Delta \boldsymbol{X}(\vec{\Omega}), \quad \Delta \boldsymbol{X} = \int dz \, \frac{\delta \boldsymbol{X}}{\delta f(z)} \Delta f(z)$$

Approximation 2:
Linearity of X in f(z)

- To estimate how new theory affects best-fit parameters and best-fit chi-squared, we replace the standard theory with new theory in above expressions.

METHOD

The shift of best-fits and the change in chi-squared are given by

$$\Delta\Omega^i_{\rm BF} = \int dz\, \frac{\delta\Omega^i_{\rm BF}}{\delta f(z)}\Delta f(z)$$

$$\Delta\chi^2_{\rm BF} = \int dz\, \frac{\delta\chi^2_{\rm BF}}{\delta f(z)}\Delta f(z) + \frac{1}{2}\iint dz\, dz'\, \frac{\delta^2\chi^2_{\rm BF}}{\delta f(z)\delta f(z')}\Delta f(z)\Delta f(z')$$

where

$$\frac{\delta\Omega^i_{\rm BF}}{\delta f(z)} = -(F^{-1})_{ij}\frac{\partial \boldsymbol{X}}{\partial\Omega^j}\cdot\boldsymbol{M}\cdot\frac{\delta\boldsymbol{X}}{\delta f(z)}$$

$$\frac{\delta\chi^2_{\rm BF}}{\partial f(z)} = 2[\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]\cdot\widetilde{\boldsymbol{M}}\cdot\frac{\delta\boldsymbol{X}}{\delta f(z)}$$

$$\frac{\delta^2\chi^2_{\rm BF}}{\delta f(z)\delta f(z')} = 2\frac{\delta\boldsymbol{X}}{\delta f(z)}\cdot\widetilde{\boldsymbol{M}}\cdot\frac{\delta\boldsymbol{X}}{\delta f(z')}$$

Now we can solve our minimization problem:

$$\text{minimize}(||\Delta f||^2) \quad \text{with} \quad \begin{cases} \vec{\Omega}_{\rm BF}[\Delta f(z)] = \vec{\Omega}_{\rm target}, \\ \Delta\chi^2_{\rm BF}[\Delta f(z)] \leq 0 \end{cases}$$

APPLICATION - Dataset considered

- Planck 2018 high-ell lite-likelihood (TT, TE, EE)
- Low-ell (<30) TT, EE compressed likelihood (Prince and Dunkley 2022)
- BOSS DR12 anisotropic BAO measurements: $\left\{\frac{D_M(z_{\rm eff})r_d^{\rm fid}}{r_d}, \frac{H(z_{\rm eff})r_d}{r_d^{\rm fid}}\right\}$
- PantheonPlus uncalibrated SN: $\Omega_m = (\omega_c + \omega_b)/h^2 = 0.334 \pm 0.018$

Data set 1: Planck CMB data only

Data set 2: Planck CMB + BOSS BAO

Data set 3: Planck CMB + BOSS BAO + PantheonPlus

APPLICATION - Time-varying electron mass

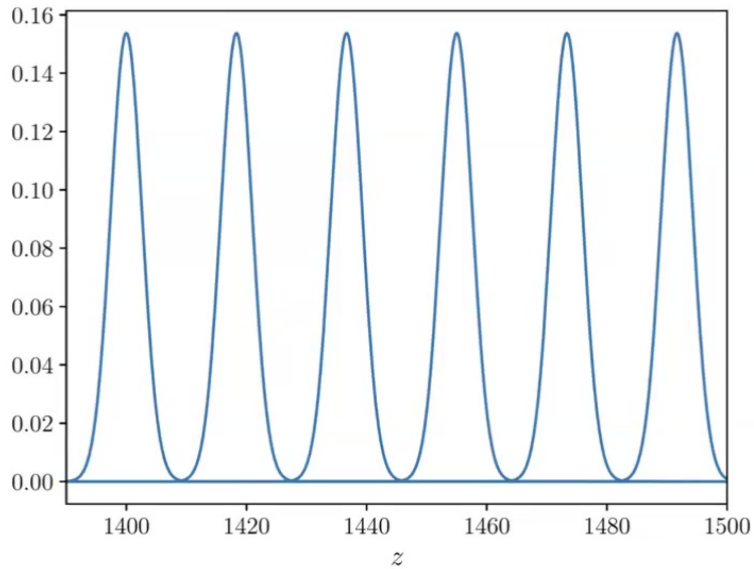
- Cosmological recombination depends on the values of electron mass / fine structure constant.
- We make use of the dependencies of the energy levels of hydrogen and helium, atomic transition rates, photo-ionization / recombination rates.

$$
\begin{aligned}
\mathcal{A}_{2s},\ \mathcal{A}_{2p} &\propto \alpha^2 m_e^{-2} \\
\mathcal{B}_{2s},\ \mathcal{B}_{2p},\ \mathcal{R}_{2p2s},\ \mathcal{R}_{2s2p} &\propto \alpha^5 m_e \\
\Lambda_{2s,1s} &\propto \alpha^8 m_e \\
\sigma_T &\propto \alpha^2 m_e^{-2} \\
T_{\rm eff} &\propto \alpha^{-2} m_e^{-1}
\end{aligned}
$$

APPLICATIONS - Time-varying electron mass

- Define N perturbations in electron mass in 300 < z < 2500 (N=120), and numerically calculate all the functional derivatives with respect to f(z).

$$\Delta f(z) \equiv \frac{\Delta m_e}{m_e}(z), \quad \Delta f(z, z_i) \equiv \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(z-z_i)^2}{2\sigma^2}\right]$$



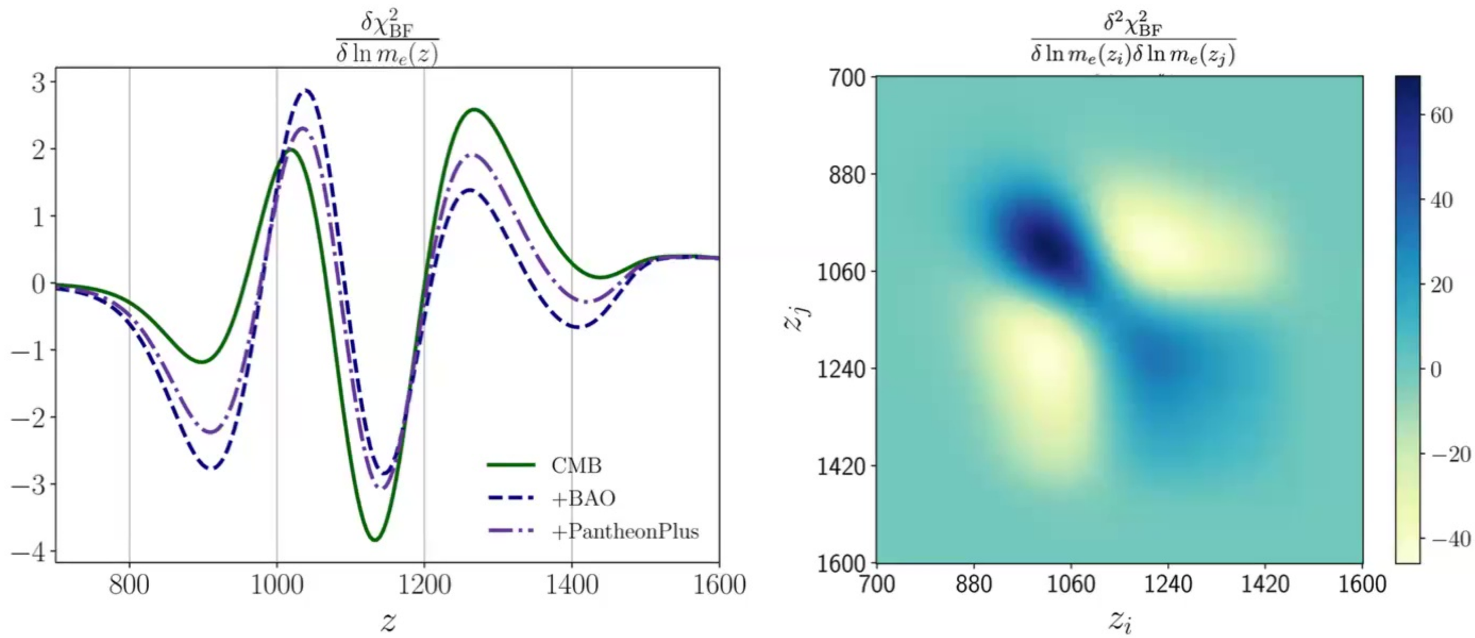
- Two-side numerical derivative:

$$\frac{\delta \boldsymbol{X}}{\delta f(z_i)} = \frac{\boldsymbol{X}[\Omega_{\rm fid}, \epsilon\Delta f(z,z_i)] - \boldsymbol{X}[\Omega_{\rm fid}, -\epsilon\Delta f(z,z_i)]}{2\epsilon}$$

- To modify electron mass as a function of redshift, we modify CLASS code and recombination code HyRec-2.

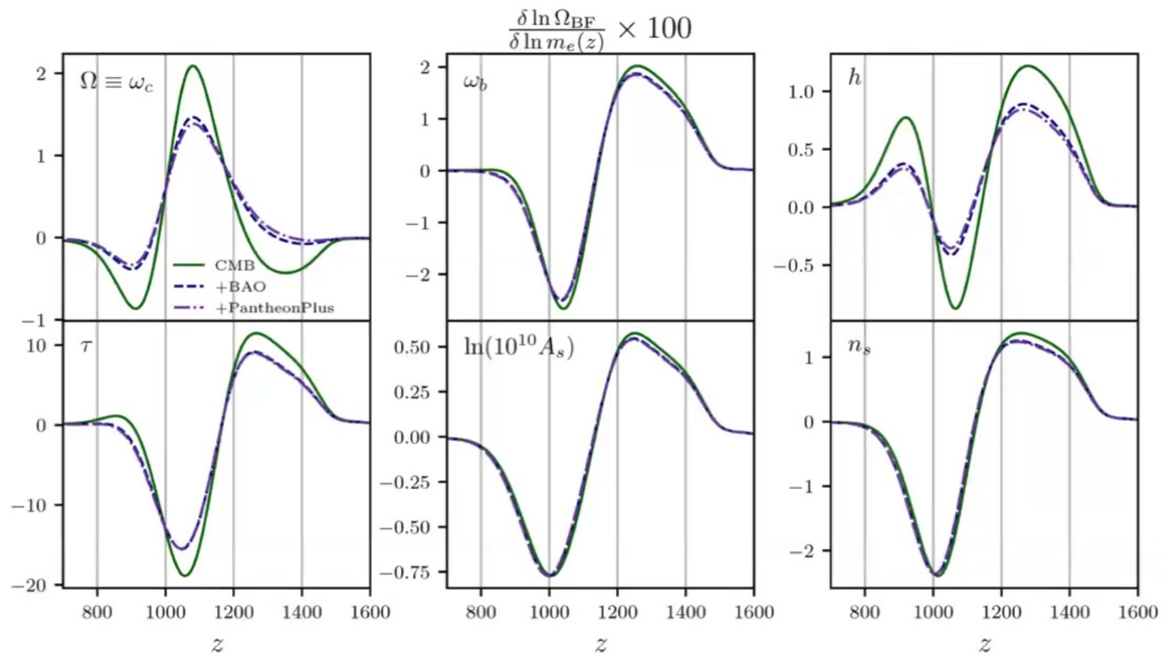
APPLICATIONS - Time-varying electron mass

- Linear and quadratic responses in best-fit chi-squared per unit logarithmic changes in electron mass

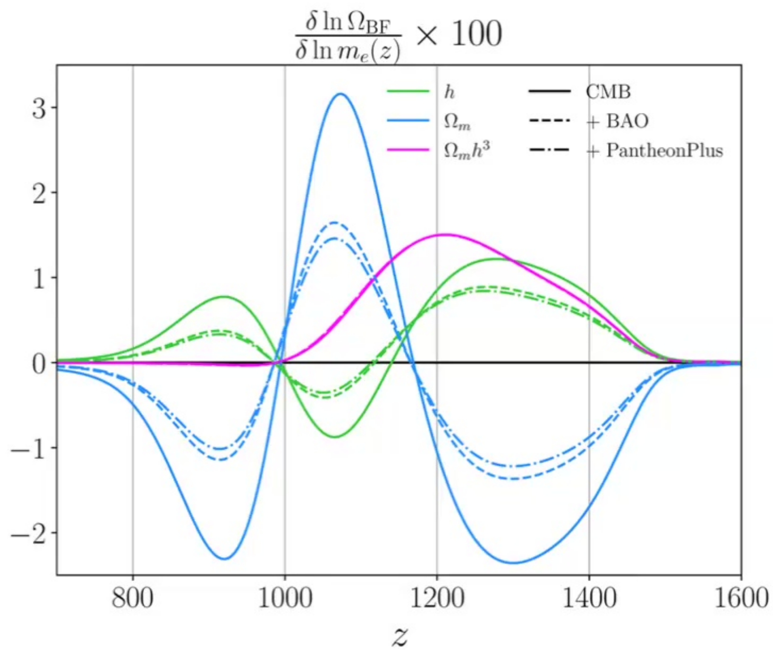


APPLICATIONS - Time-varying electron mass

- Logarithmic changes in best-fit parameters per unit logarithmic changes in electron mass



APPLICATIONS - Time-varying electron mass



- Almost opposite behavior of h and Omega_m
- Impact of adding BAO / PantheonPlus data
- Dependency of $\theta_s \propto (\Omega_m h^3 z_*^{-3.88})^{0.17}$
- The increase in m_e accelerates recombination, hence decrease z_*.

APPLICATIONS - Time-varying electron mass

We calculated functional derivatives

$$\frac{\delta \Omega^i_{\rm BF}}{\delta \ln m_e(z)} = -(F^{-1})_{ij} \frac{\partial \boldsymbol{X}}{\partial \Omega^j} \cdot \boldsymbol{M} \cdot \frac{\delta \boldsymbol{X}}{\delta \ln m_e(z)}$$

$$\frac{\delta \chi^2_{\rm BF}}{\partial \ln m_e(z)} = 2[\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}] \cdot \widetilde{\boldsymbol{M}} \cdot \frac{\delta \boldsymbol{X}}{\delta \ln m_e(z)}$$

$$\frac{\delta^2 \chi^2_{\rm BF}}{\delta \ln m_e(z) \delta \ln m_e(z')} = 2 \frac{\delta \boldsymbol{X}}{\delta \ln m_e(z)} \cdot \widetilde{\boldsymbol{M}} \cdot \frac{\delta \boldsymbol{X}}{\delta \ln m_e(z')}$$

APPLICATIONS - Time-varying electron mass

We calculated functional derivatives

$$\frac{\delta\Omega^i_{\rm BF}}{\delta\ln m_e(z)} = -(F^{-1})_{ij}\frac{\partial \boldsymbol{X}}{\partial\Omega^j}\cdot\boldsymbol{M}\cdot\frac{\delta\boldsymbol{X}}{\delta\ln m_e(z)}$$

$$\frac{\delta\chi^2_{\rm BF}}{\partial\ln m_e(z)} = 2[\boldsymbol{X}(\vec{\Omega}_{\rm fid}) - \boldsymbol{X}^{\rm obs}]\cdot\widetilde{\boldsymbol{M}}\cdot\frac{\delta\boldsymbol{X}}{\delta\ln m_e(z)}$$

$$\frac{\delta^2\chi^2_{\rm BF}}{\delta\ln m_e(z)\delta\ln m_e(z')} = 2\frac{\delta\boldsymbol{X}}{\delta\ln m_e(z)}\cdot\widetilde{\boldsymbol{M}}\cdot\frac{\delta\boldsymbol{X}}{\delta\ln m_e(z')}$$

from which we can estimate, given arbitrary modification in m_e(z)

$$\Delta\Omega^i_{\rm BF} = \int dz\,\frac{\delta\Omega^i_{\rm BF}}{\delta\ln m_e(z)}\Delta\ln m_e(z)$$

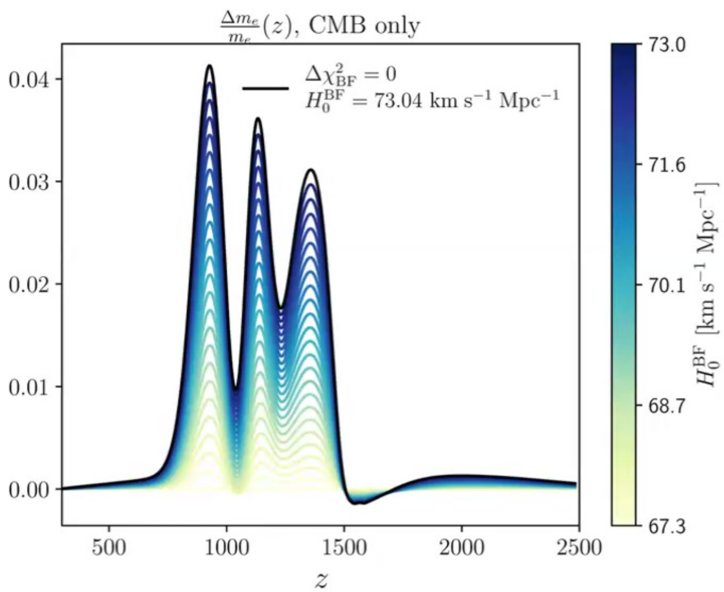
$$\Delta\chi^2_{\rm BF} = \int dz\,\frac{\delta\chi^2_{\rm BF}}{\delta\ln m_e(z)}\Delta\ln m_e(z) + \frac{1}{2}\iint dz\,dz'\,\frac{\delta^2\chi^2_{\rm BF}}{\delta\ln m_e(z)\delta\ln m_e(z')}\Delta\ln m_e(z)\Delta\ln m_e(z')$$

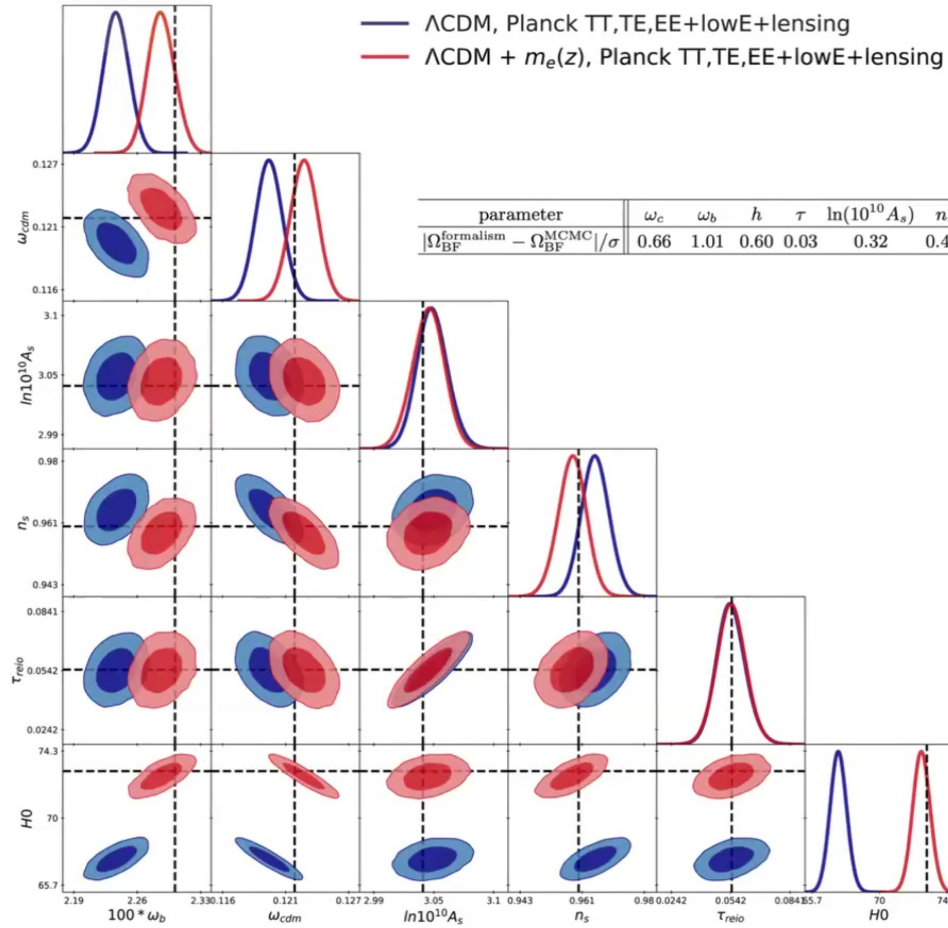
hence, now we can solve

$$\text{minimize}(||\Delta\ln m_e(z)||^2)\quad\text{with}\quad\begin{cases}\vec{\Omega}_{\rm BF}[\Delta\ln m_e(z)] = \vec{\Omega}_{\rm target},\\ \Delta\chi^2_{\rm BF}[\Delta\ln m_e(z)] \le 0.\end{cases}$$

APPLICATIONS - Time-varying electron mass

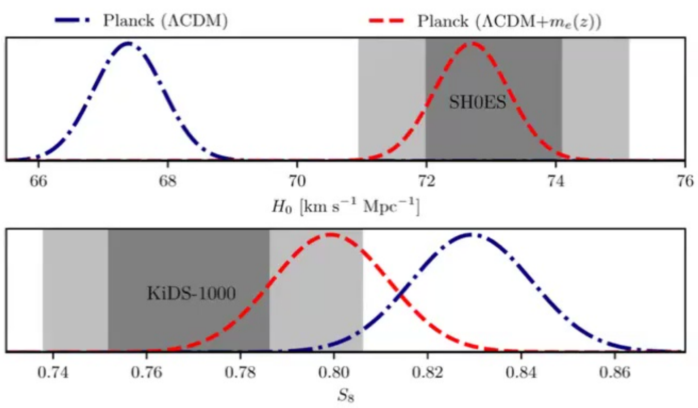
- Solutions we found for each target value of H0





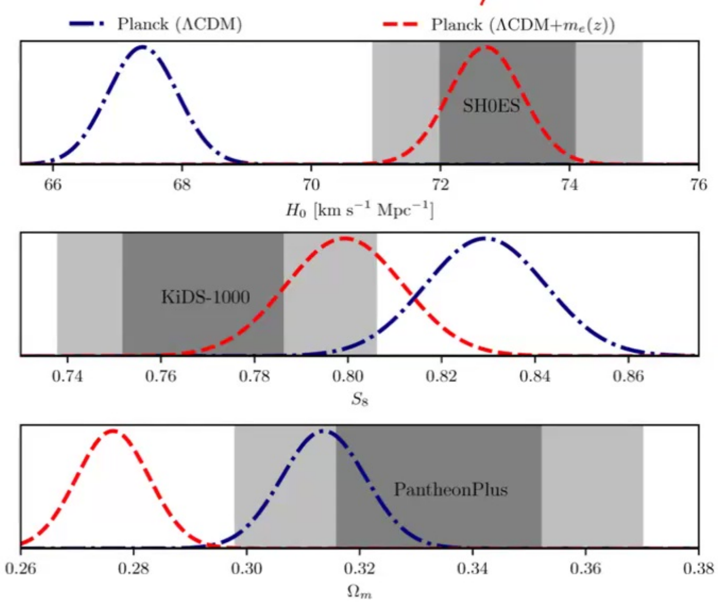
parameter	ω_c	ω_b	h	τ	$\ln(10^{10}A_s)$	n_s
$\lvert\Omega_{\rm BF}^{\rm formalism} - \Omega_{\rm BF}^{\rm MCMC}\rvert/\sigma$	0.66	1.01	0.60	0.03	0.32	0.46

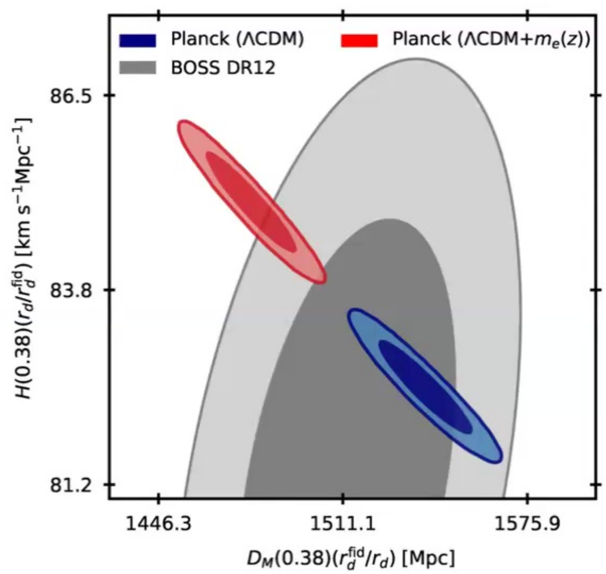
APPLICATIONS - Time-varying electron mass



APPLICATIONS - Time-varying electron mass

$H_0 = 72.70 \pm 0.57$ km/s/Mpc, $\Delta\chi^2 = -1.15$

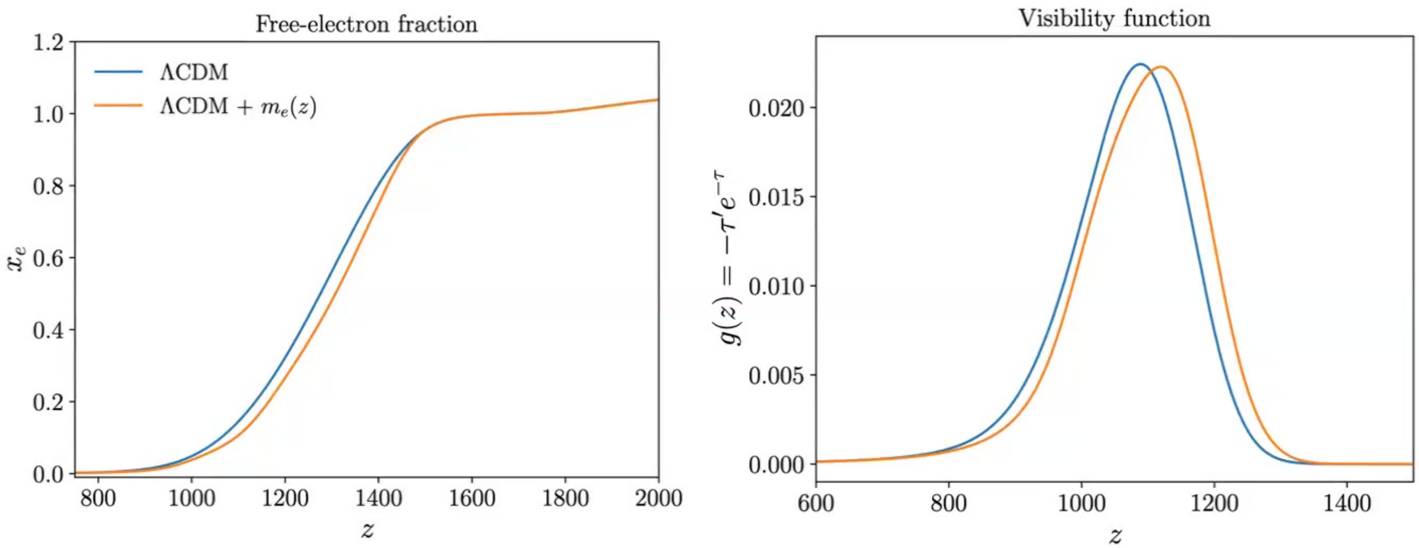




- While the solution resolves the tension between Planck CMB and SH0ES, this solution becomes much less consistent with PantheonPlus and BAO data.
- 3sigma tension with PantheonPlus and $\Delta\chi^2_{\rm BAO} = +5.37$

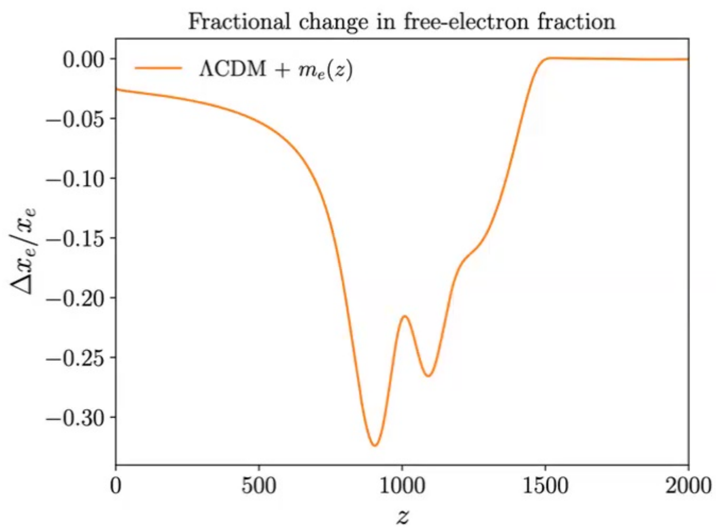
APPLICATIONS - Time-varying electron mass

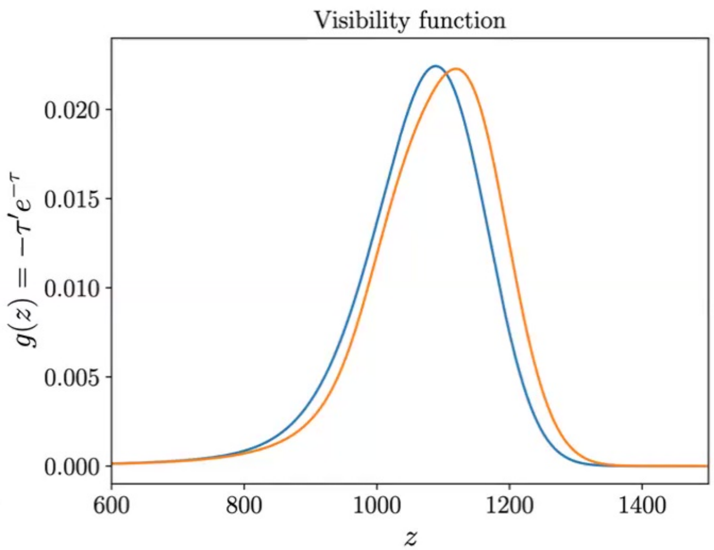
- How the time-varying electron mass solution impacts the recombination history?



APPLICATIONS - Time-varying electron mass

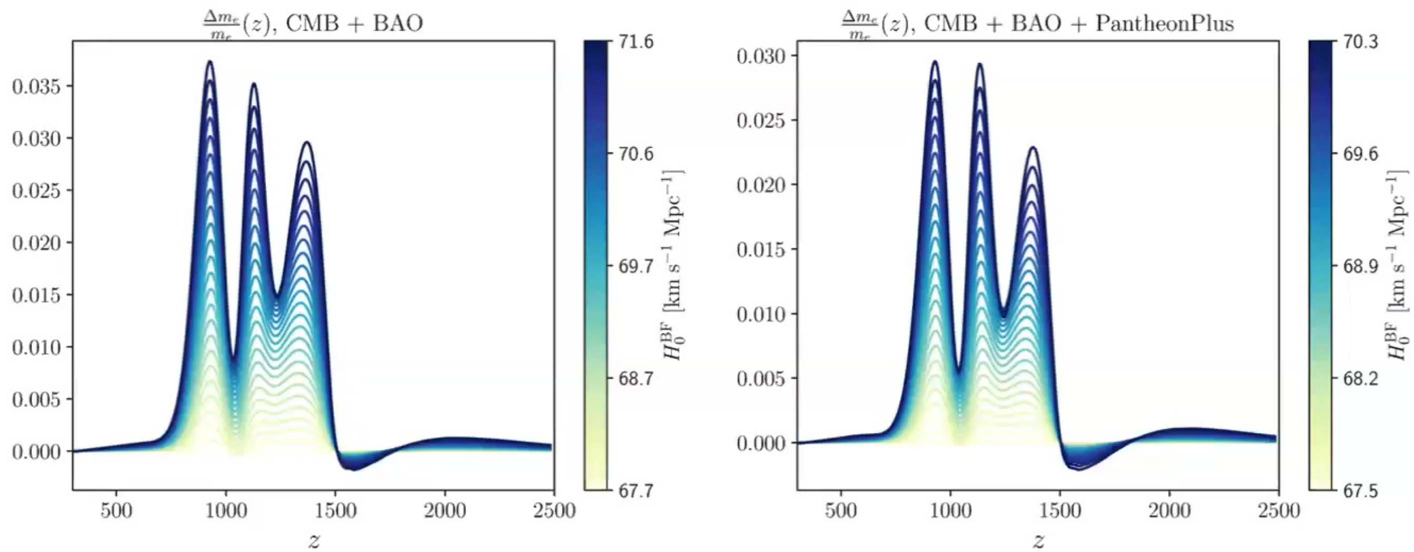
- How the time-varying electron mass solution impacts the recombination history?





- Today, we have very accurate recombination calculations, ~ O(0.1%).
- While CMB spectra are sensitive to the recombination, an order of 10% change in recombination history still gives us the same good fit to Planck data!

APPLICATIONS - Time-varying electron mass



- Including BAO / PantheonPlus data makes it more difficult to obtain solutions to the tension.
- Partially due to break-down of our assumptions
- We only show solutions which passed our consistency test: $\Delta\chi^2 < 1$ and $|\Omega_{\rm BF}^{\rm formalism} - \Omega_{\rm BF}^{\rm MCMC}|/\sigma < 1$

SUMMARY

- Built on Fisher bias formalism to search for possible new physics as a solution to the Hubble tension
- Applied to time-varying electron mass:
  1. Found a solution entirely resolving the tension with Planck CMB data
  2. As more data added (BAO/PantheonPlus), was able to partially ease the tension
- Our method can be used to search for various extensions to LCDM model

  [e.g., expansion rate H(z), primordial power spectrum P(k)]

SUMMARY

- Built on Fisher bias formalism to search for possible new physics as a solution to the Hubble tension
- Applied to time-varying electron mass:
  1. Found a solution entirely resolving the tension with Planck CMB data
  2. As more data added (BAO/PantheonPlus), was able to partially ease the tension
- Our method can be used to search for various extensions to LCDM model
  [e.g., expansion rate H(z), primordial power spectrum P(k)]

(Limitations)

- No model building for new physics?
- Additional degree of freedom?