Forecasting CMB-S4 constraints on neutrino and cosmological parameters with emulator training

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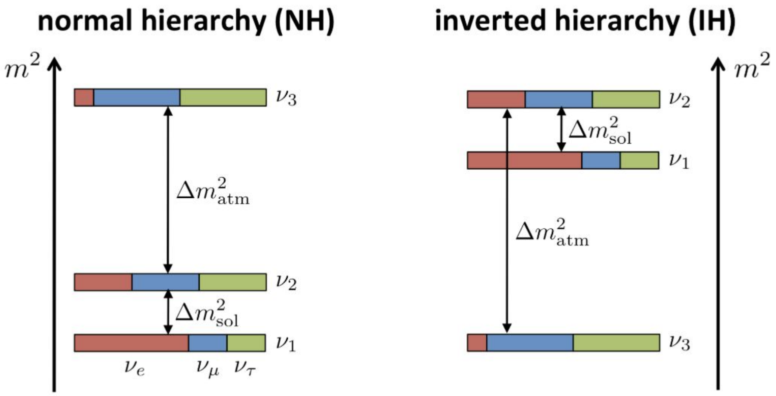
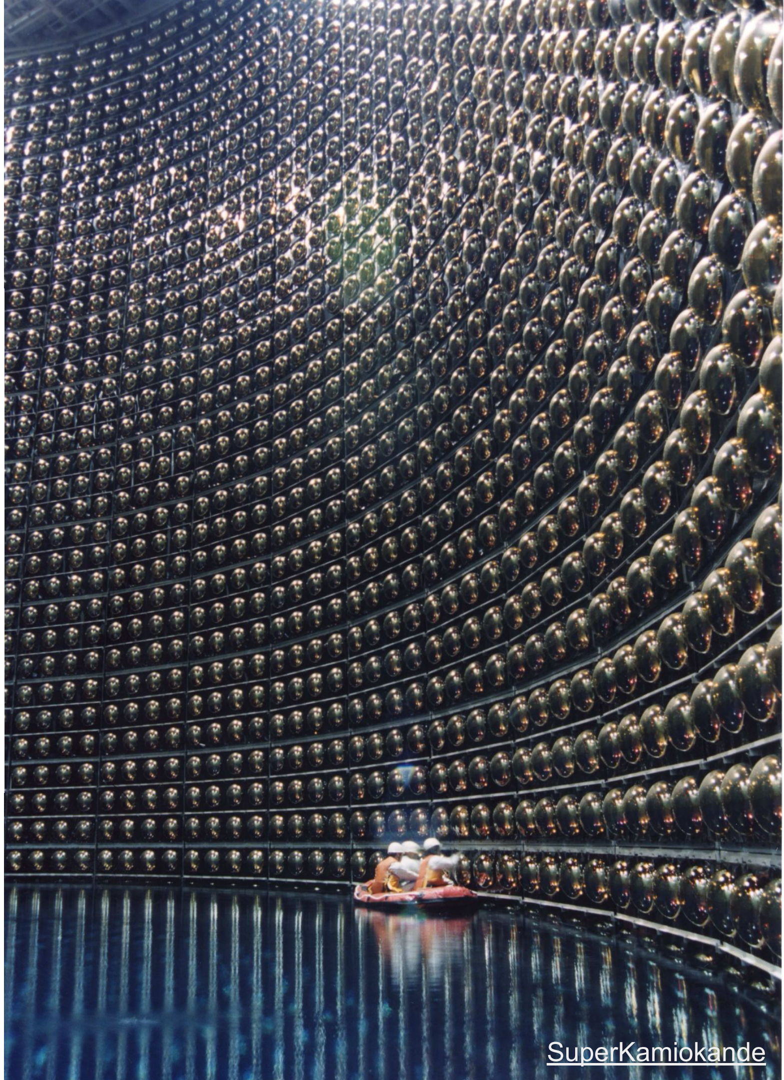
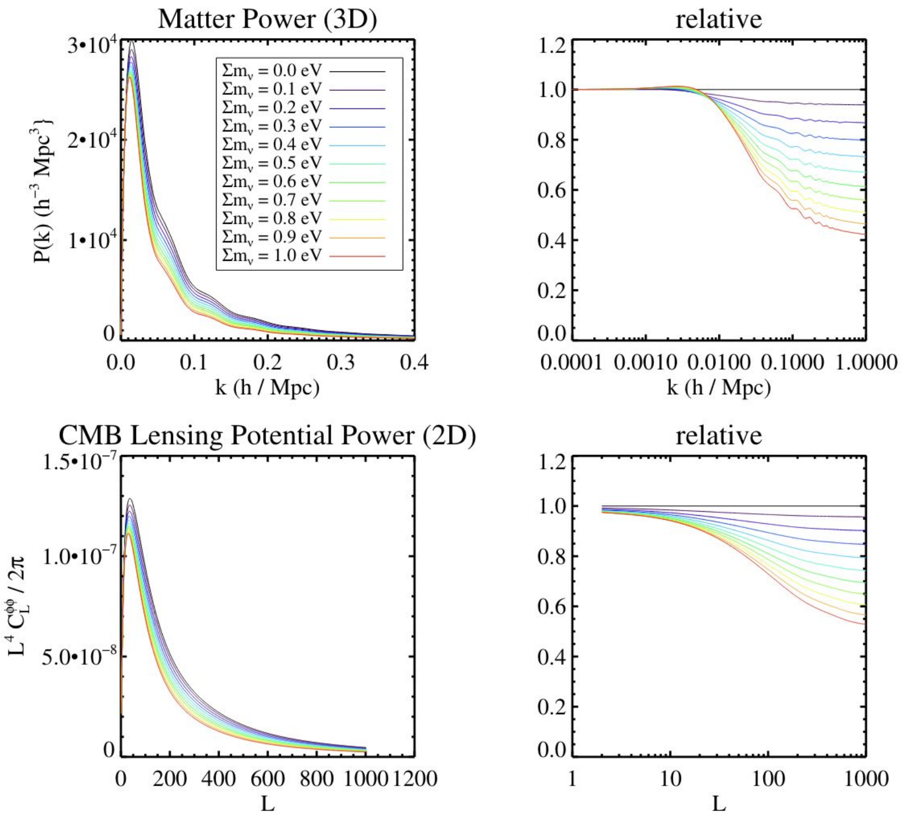


Figure 13. *Cartoon illustrating the two distinct neutrino mass hierarchies. The colors indicate the fraction of each distinct flavor contained in each mass eigenstate.*



Abazajian et al. (2016)

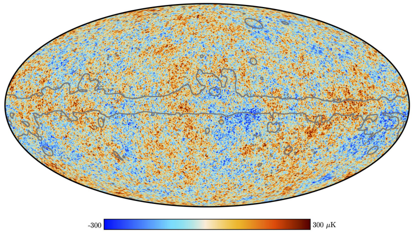
SuperKamiokande



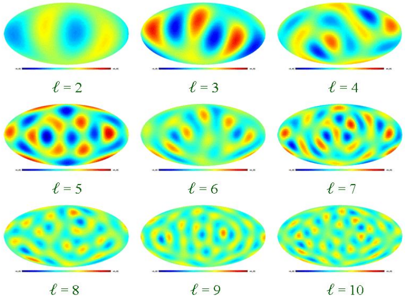
$$\sum M_\nu$$

$$\Omega_\nu^2 \simeq \frac{\sum m_\nu}{93eV} > \sim 0.0006$$

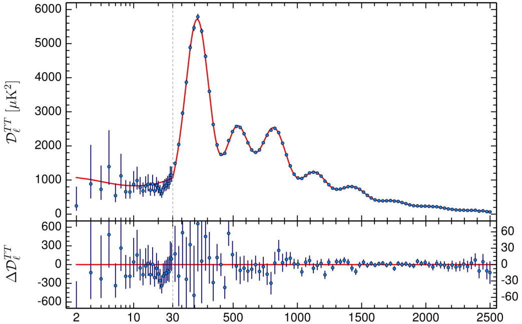
Abazajian et al. (2016)



$$\Theta(\hat{n}) = \int d^3\vec{k}\,\xi(\vec{k}) \int_0^{\tau_0} d\tau\, e^{i(\hat{k}\cdot\hat{n})(\tau_0-\tau)} S_T^{(s)}(k,\,\tau)$$



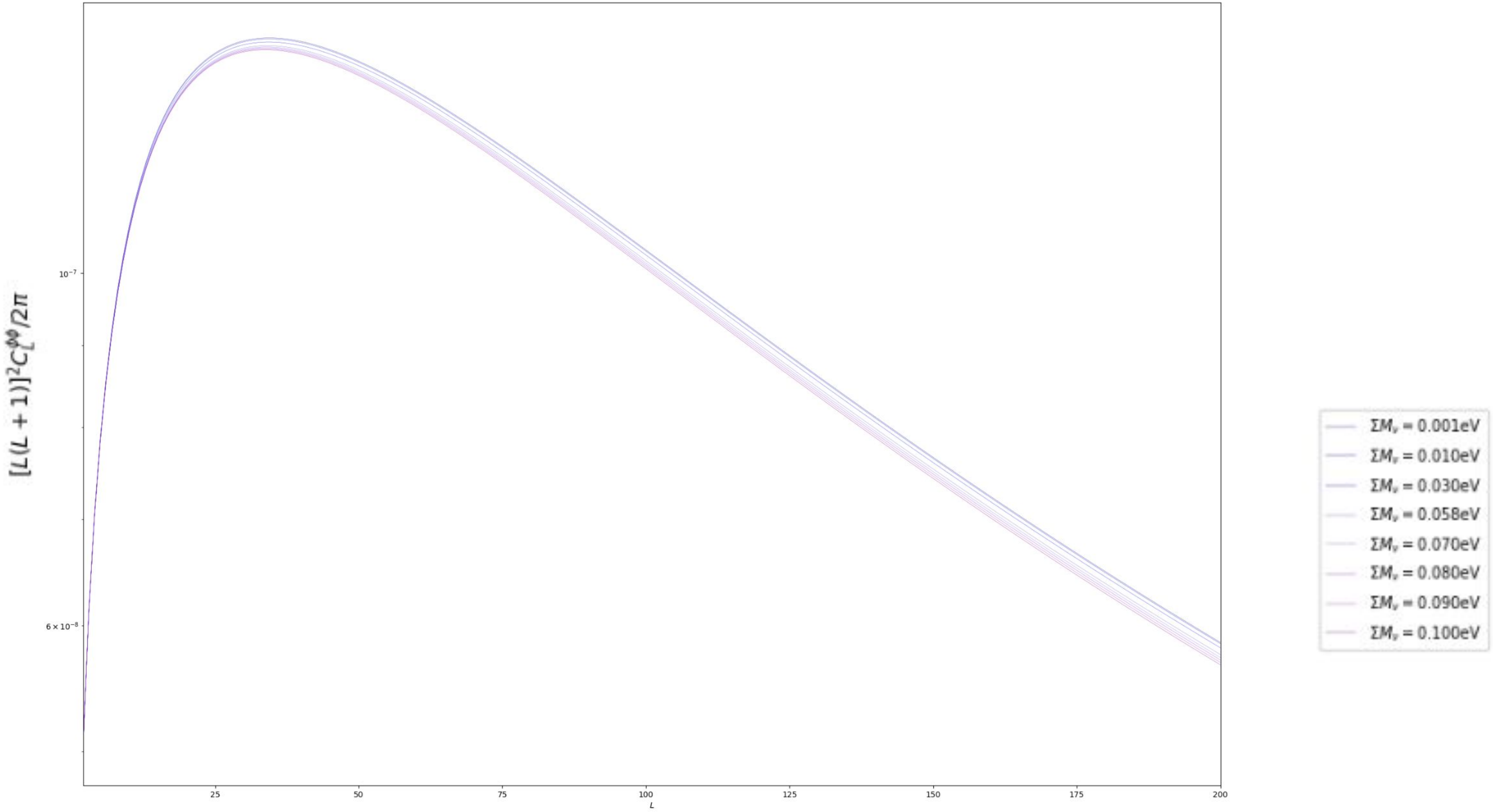
$$\Theta(\vec{x},\hat{p},\tau) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}(\vec{x},\tau) Y_{\ell m}(\hat{p})$$



$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

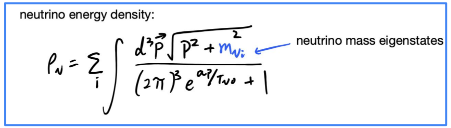
Giani (2021)
NASA / WMAP / Chiang Lung-Yih
Gerbino et al. (2020)

Lensing potential ϕϕ and neutrino mass



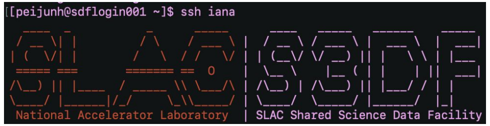
Fisher information

- Learning theory background: CMB analysis, particle physics, information theory, machine learning, CAMB...
- Python pipeline for forecasting using a noise model with CMB emulators



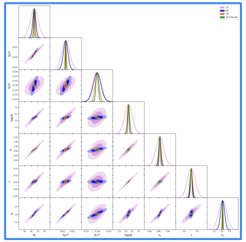
Emulator

- 5 CMB emulators
  - lensed/unlensed TT+EE
  - lensing potential
- 18 BAO emulators
  - 18 redshift bins for DESI
- Cosmopower neural network / principal component analysis



Combining

- Assessing emulator accuracy
- Differentiating CMB / BAO emulators
  - auto-diff. with JAX
  - finite difference
- Fisher information work



CAMB, S3DF

Emulator Training

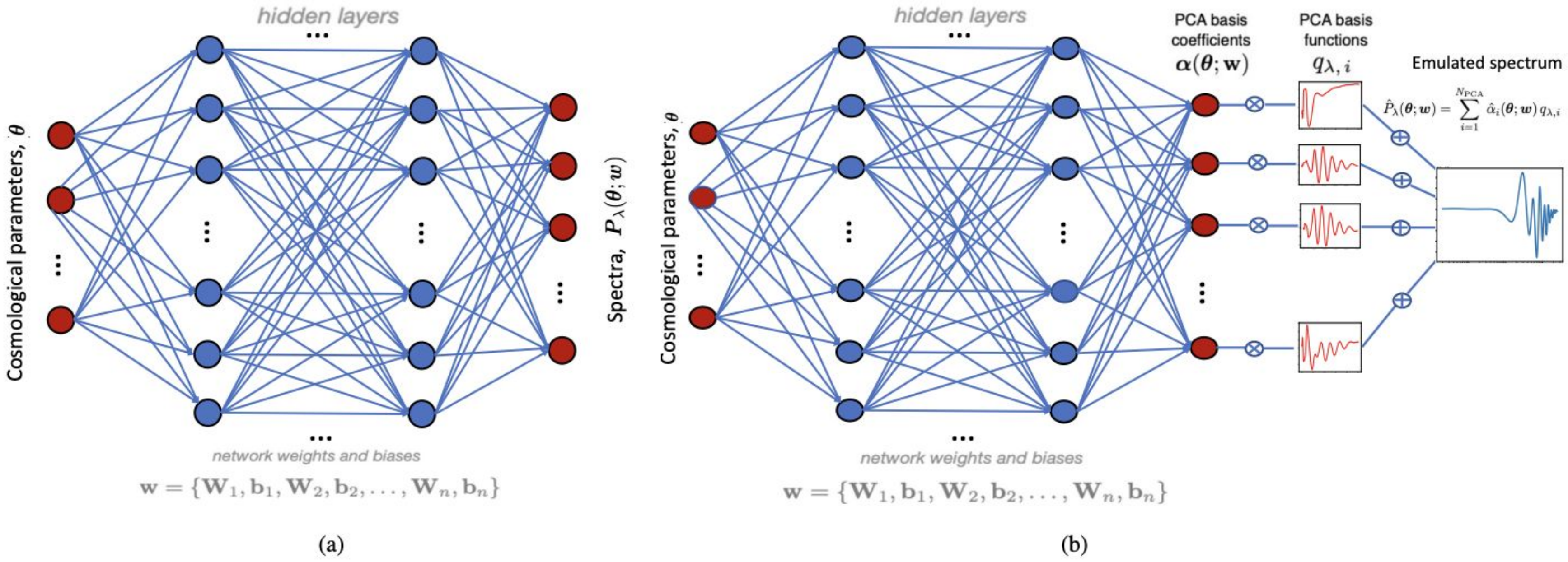
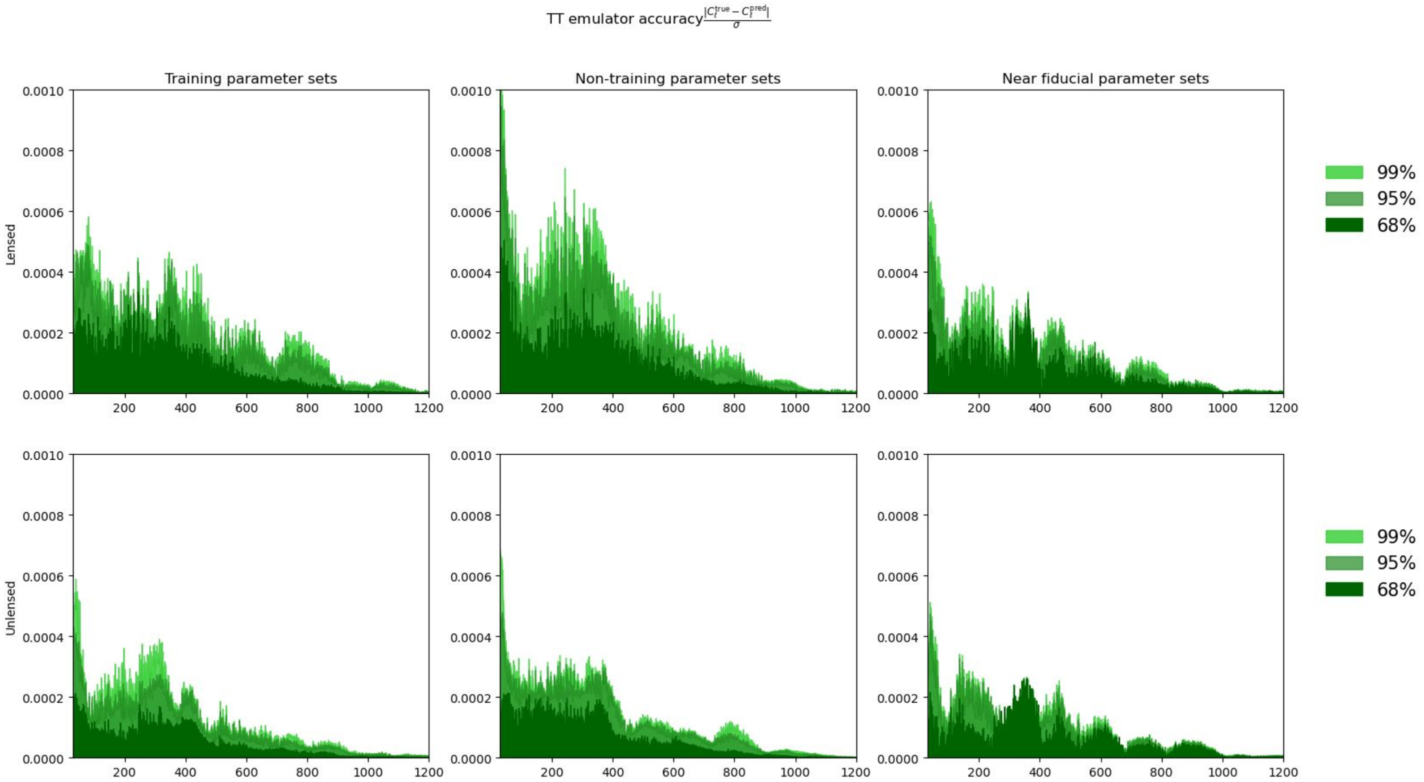


Figure 1. Schematic of the neural network emulation implemented in CosmoPower. A neural network is trained to learn the mapping between cosmological parameters and a) power spectra, b) coefficients in a Principal Component Analysis of the power spectra.

Mancini et al. (2022)

Example accuracy of emulators

$$\frac{C_{\ell,XX}^{\text{emulator}} - C_{\ell,XX}^{\text{theory}}}{\sigma_{\ell,XX}}$$



Fisher information for CMB-S4

$$\mathcal{F}_{ij} = \sum_b \frac{1}{\sigma_b^2} \frac{\partial f_b}{\partial p_i} \frac{\partial f_b}{\partial p_j}$$

$$\mathcal{F} = \begin{pmatrix} \frac{\partial C_l^{TT}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{TT}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{TE}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{TE}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{EE}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{EE}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{\phi\phi}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{\phi\phi}}{\partial \theta_i} \end{pmatrix}^T \begin{pmatrix} 2(C_l^{TT})^2 & 2(C_l^{TT} C_l^{TE}) & 2(C_l^{TE})^2 & 2(C_l^{T\phi})^2 \\ 2(C_l^{TT} C_l^{TE}) & (C_l^{TT} C_l^{EE} + (C_l^{TE})^2) & 2(C_l^{TE} C_l^{EE}) & 2(C_l^{T\phi} C_l^{E\phi}) \\ 2(C_l^{TE})^2 & 2(C_l^{TE} C_l^{EE}) & 2(C_l^{EE})^2 & 2(C_l^{E\phi})^2 \\ 2(C_l^{T\phi})^2 & 2(C_l^{T\phi} C_l^{E\phi}) & 2(C_l^{E\phi})^2 & 2(C_l^{\phi\phi})^2 \end{pmatrix}^{-1} \begin{pmatrix} \frac{\partial C_l^{TT}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{TT}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{TE}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{TE}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{EE}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{EE}}{\partial \theta_i} \\ \vdots & & \vdots \\ \frac{\partial C_l^{\phi\phi}}{\partial \theta_1} & \cdots & \frac{\partial C_l^{\phi\phi}}{\partial \theta_i} \end{pmatrix}$$

D. Wittman, Gerbino et al. (2020), JAX Autodiff

Fisher information for DESI BAO

$$\sigma_j \equiv \sigma\left(\frac{r_s}{d_V(z_j)}\right)$$
$$= \frac{1}{3}\frac{r_s}{d_V(z_j)}\sqrt{\left[\frac{\sigma(H(z_j)r_s)}{H(z_j)r_s}\right]^2 + \left[2\frac{\sigma(d_A(z_j)/r_s)}{d_A(z_j)/r_s}\right]^2}$$

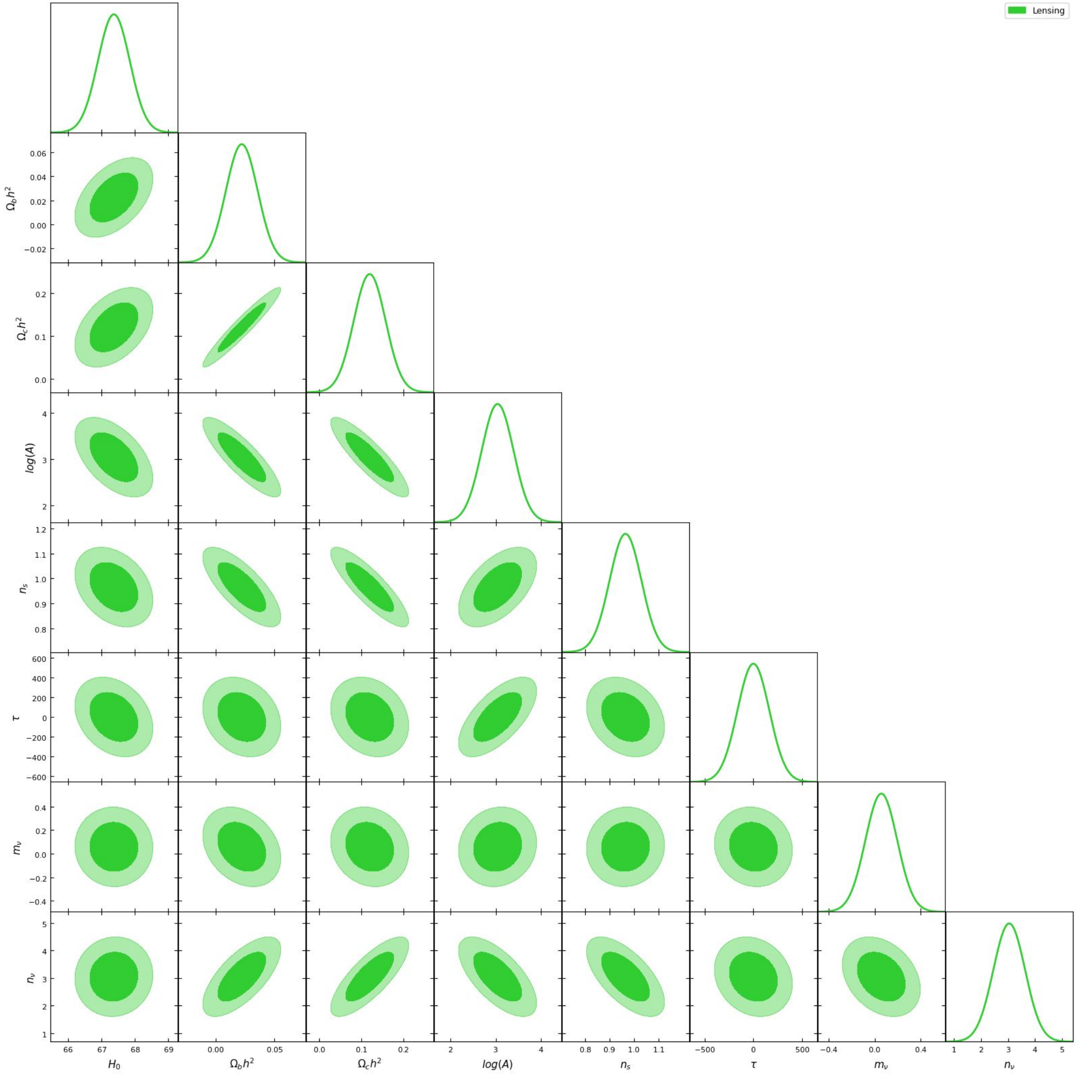
$$J = \begin{bmatrix} \frac{\partial}{\partial\theta_0}\left(\left.\frac{r_s}{d_V}\right|_{z_0}\right) & \cdots & \frac{\partial}{\partial\theta_7}\left(\left.\frac{r_s}{d_V}\right|_{z_0}\right) \\ \vdots & \ddots & \vdots \\ \frac{\partial}{\partial\theta_0}\left(\left.\frac{r_s}{d_V}\right|_{z_{18}}\right) & \cdots & \frac{\partial}{\partial\theta_7}\left(\left.\frac{r_s}{d_V}\right|_{z_{18}}\right) \end{bmatrix}$$

$$\mathcal{F} = J^T \sigma_j^{-1} J$$
$$Cov = \mathcal{F}^{-1}$$

MacInnis et al. (2024)

Preliminary constraints

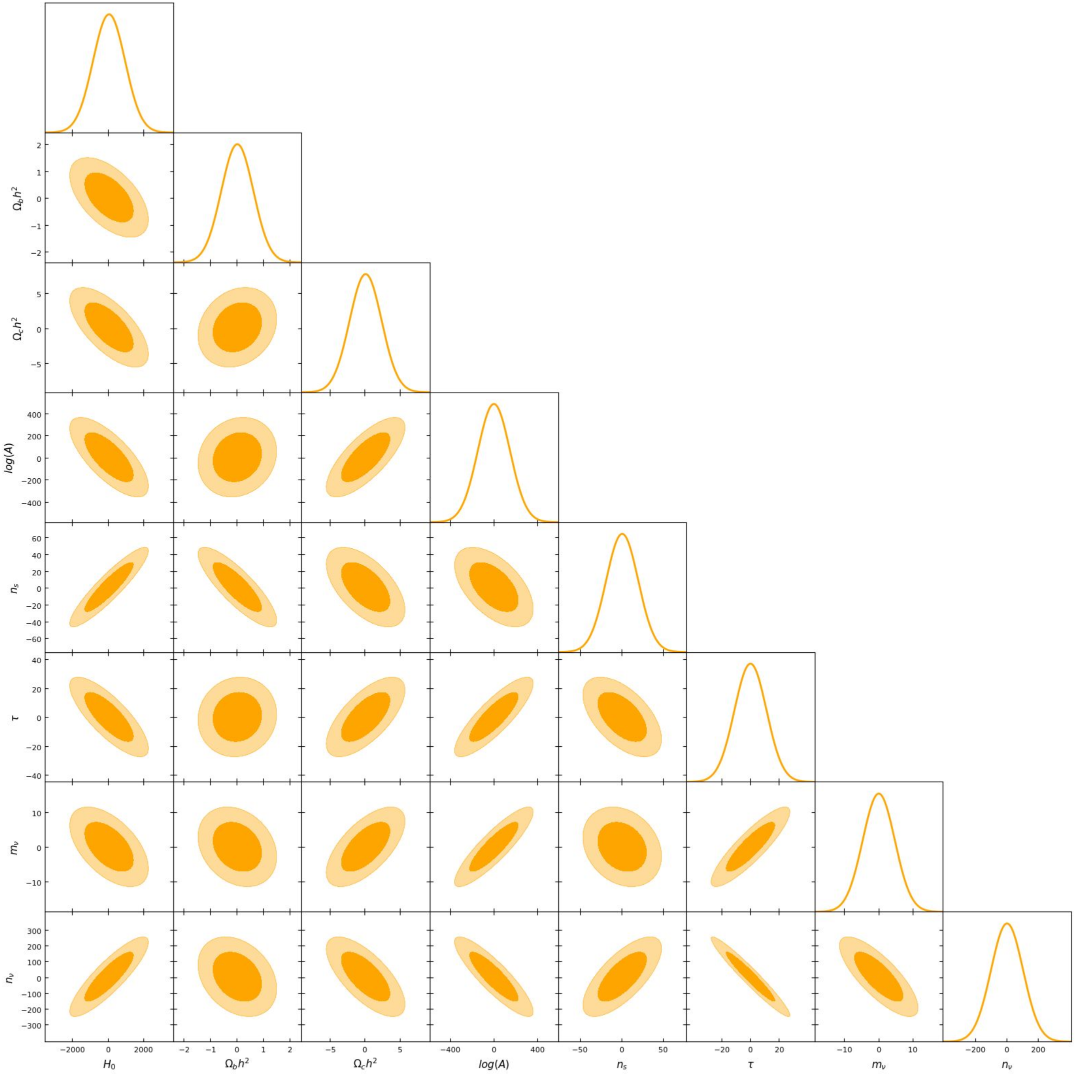
Lensing ϕϕ
from CAMB Model +
S4-Wide noise model +
finite difference



CAMB, Raghunathan & Omori (2023)

Preliminary constraints

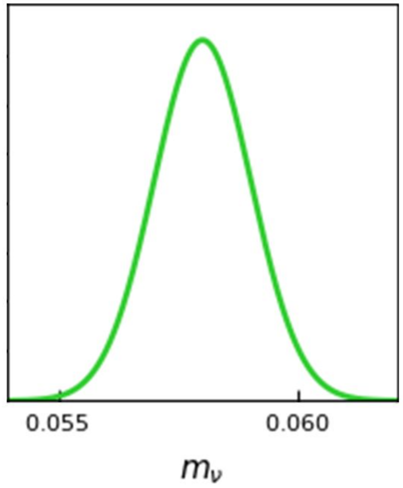
BAO
from 18 emulators +
DESI noise models +
JAX autodiff



JAX Autodiff, Raghunathan & Omori (2023)

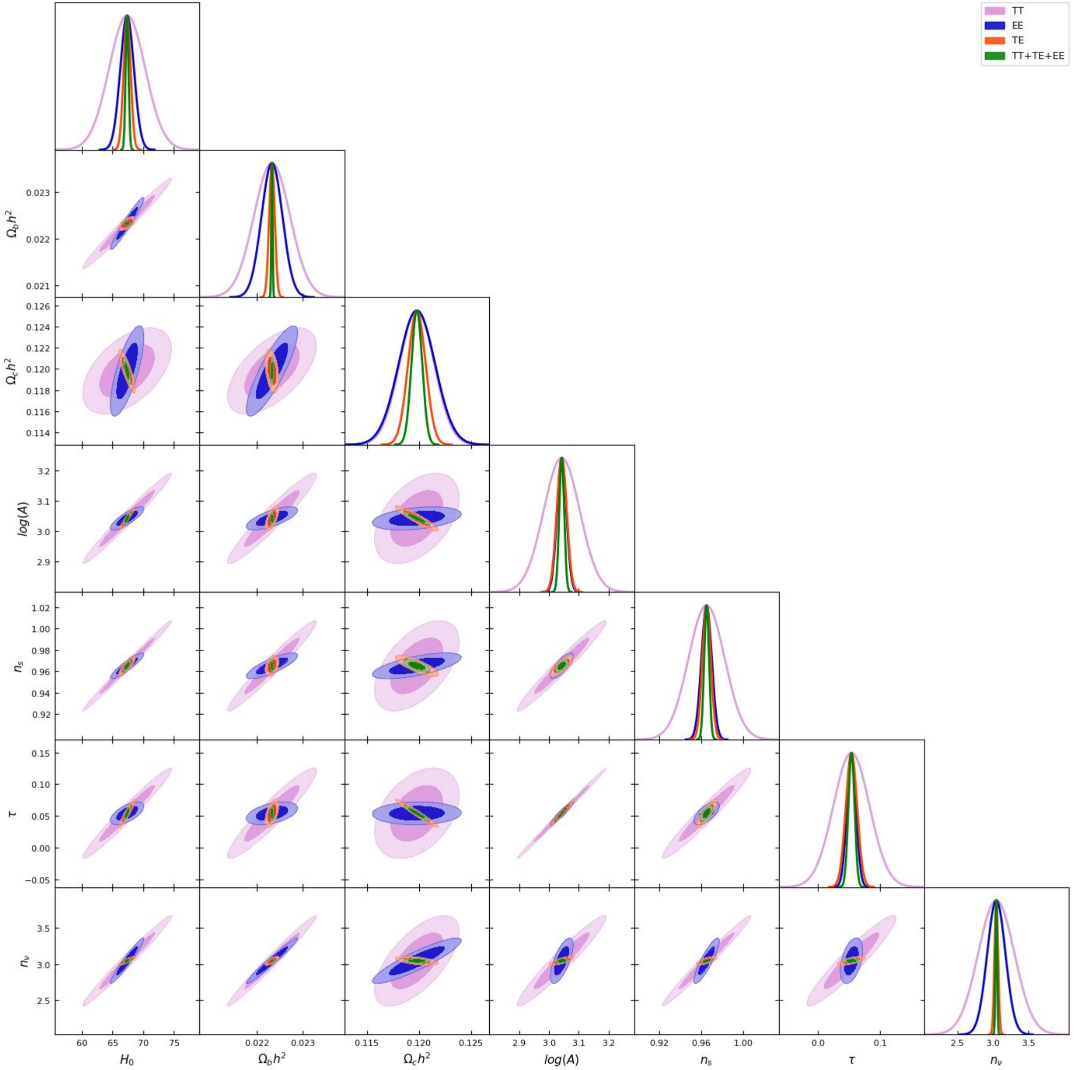
Preliminary constraints on neutrino mass

Lensing - CMB-S4



Preliminary constraints

TT+TE+EE
from SPT High-Accuracy Model +
S4 145GHz noise model +
JAX autodiff



JAX Autodiff, Balkenhol et al. (2023), Abazajian et al. (2016)

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