Sterile neutrinos - how bad would they be, really?

Cosmology Final Project
Julia Book Motzkin
April 18, 2024

What does cosmology have to say about neutrinos?

Neutrino Mass

The Standard Model postulates 3 massless neutrinos

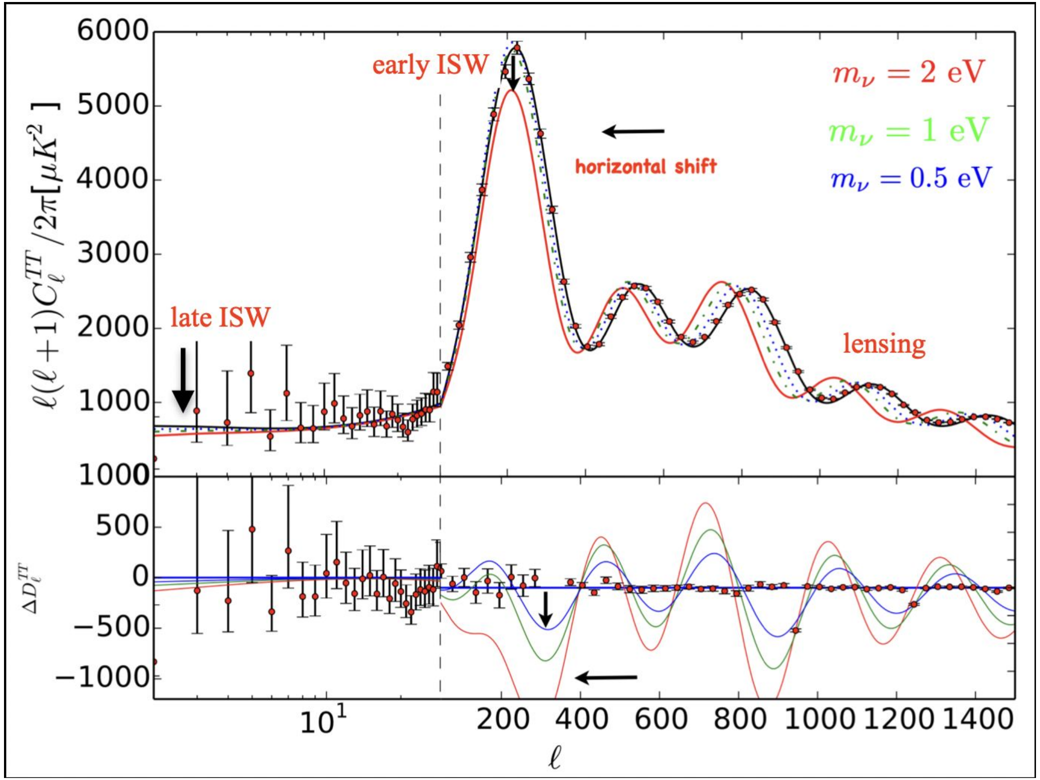
Neutrino oscillations, discovered in the last ~50 years, imply they must have mass

Large neutrino masses would be visible in the tail of the beta decay spectrum

- Current limits ~0.8 eV (KATRIN)

The CMB data place much stronger limits

Neutrino Mass - CMB Limits

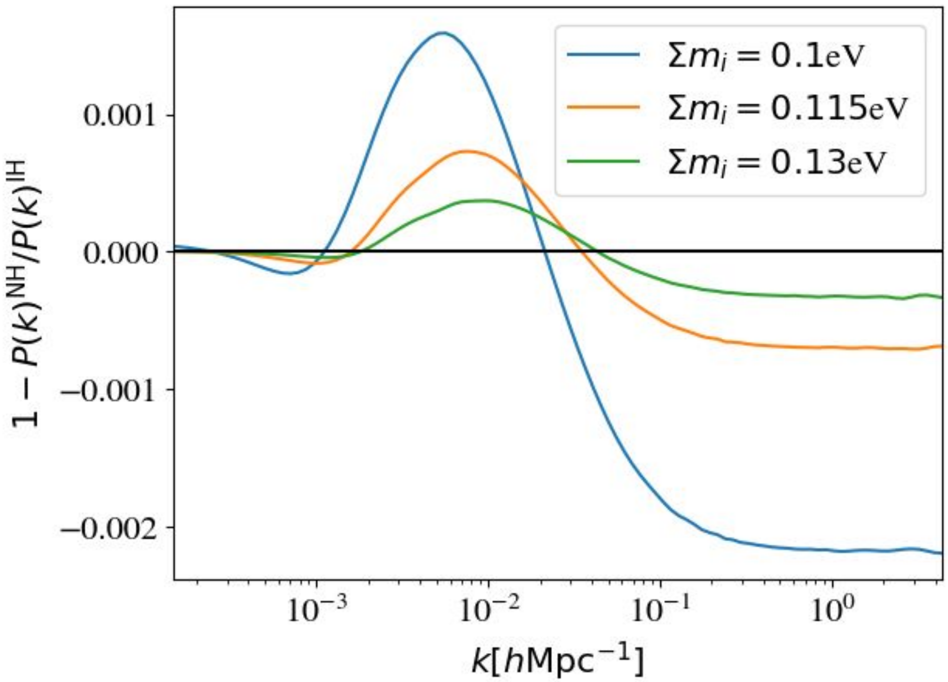


Additional neutrino mass changes the position/amplitude of these peaks, as well as damping on the tails of the spectrum.

$$\omega_m = \omega_b + \omega_{CDM} + (\Sigma m_\nu)/93.14 \text{ eV}$$

Image credit: Olga Mena via Eleanora Di Valentino (https://indico.cern.ch/event/1210319/contributions/5261524/attachments/2613873/4516975/divalentino.pdf)

Neutrino Mass - CMB Limits



Analysis of the power spectra in the CMB yield the strongest present limits.

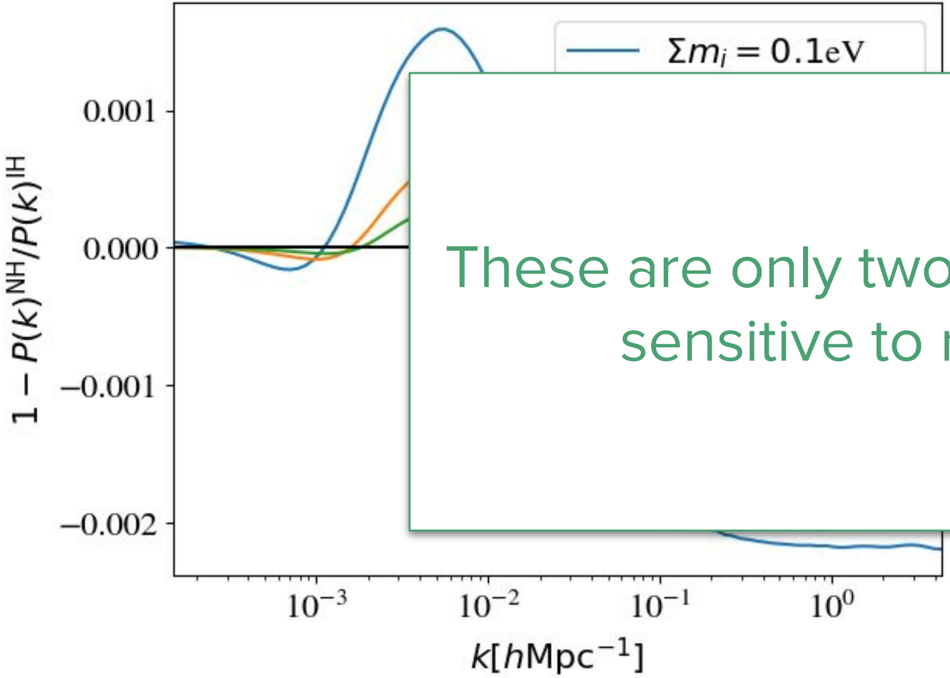
$$\sum m_\nu < 0.26\ \mathrm{eV}$$

(95 %, *Planck* TT,TE,EE+lowE).

Planck Collaboration: https://arxiv.org/pdf/1807.06209.pdf

Figure generated with CLASS (tutorial notebook, https://github.com/lesgourg/class_public/blob/ae99bcea1cd94994228acdfaec70fa8628ae24c5/notebooks/neutrinohierarchy.ipynb)

Neutrino Mass - CMB Limits



These are only two of many parameters sensitive to neutrino mass!

Analysis of the power

B yield

ent

eV

,EE+lowE).

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Number of Ultra-Relativistic Species

N effective, often referred to as the number of neutrino species, actually parameterizes the effective number of *all* ultra-relativistic species in the early universe.

$$\rho_R = \left(1 + N_{\mathrm{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right) \rho_\gamma ,$$

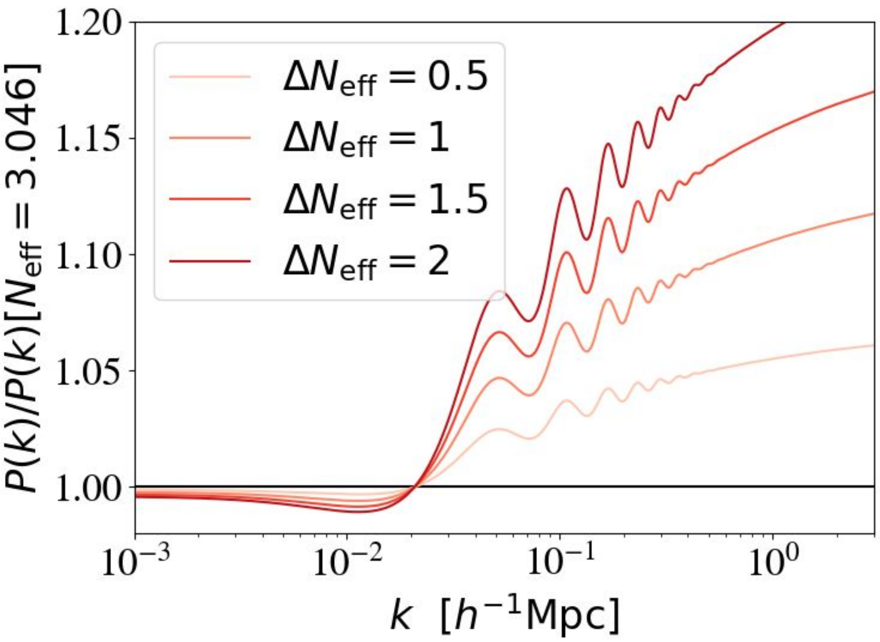
The standard 3-neutrino model anticipates $N_{eff} = 3.046$

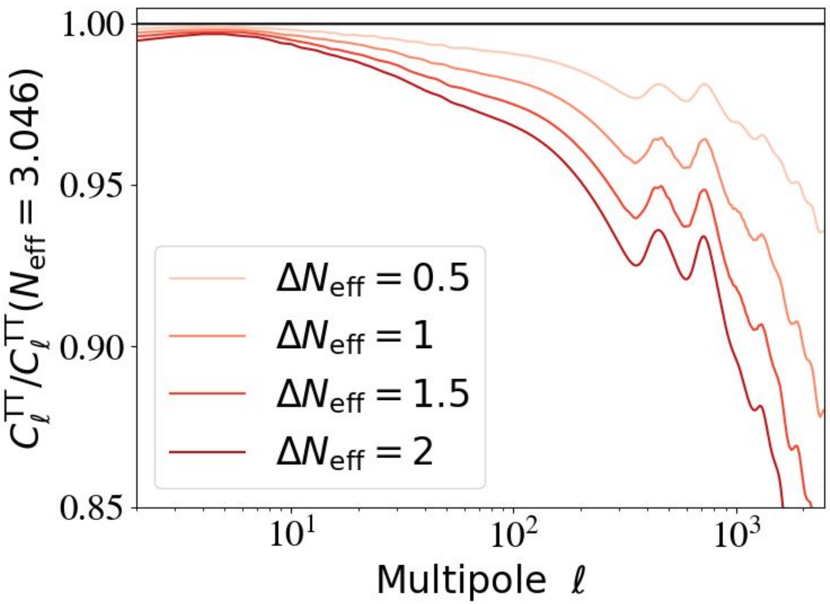
Extra 0.046 comes from non-instantaneous decoupling

Planck best-fit is currently 3.0, but the theory value is within its 1 sigma range

https://arxiv.org/pdf/1309.5383.pdf

Number of Ultra-Relativistic Species





Figures generated with CLASS (tutorial notebook, https://github.com/lesgourg/class_public/blob/ae99bcea1cd94994228acdfaec70fa8628ae24c5/notebooks/varying_neff.ipynb)

As it happens, the number and masses of the neutrino species are among the most pressing questions for neutrino physicists!

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Why? Sterile neutrinos

The Project

Let's explore an extension of ΛCDM

Suppose we have 3 active neutrino species

- Give them masses of 0, 0.00872, and 0.05 eV
- (This is the lowest possible mass combination compatible with the current best-fit values for the neutrino mass splittings; see https://www.frontiersin.org/articles/10.3389/fspas.2018.00036/full)

Add a sterile neutrino

- Give it a mass of 0.5 eV (slightly lighter than most models suggest, but within the same range)
- Give it a non-zero chemical potential of 0.1 (This paper https://arxiv.org/pdf/astro-ph/9602135.pdf) suggests that sterile neutrinos with non-zero chemical potentials may be compatible with BBN measurements. The paper is largely out of date, but I found the possibility intriguing.)

Procedure

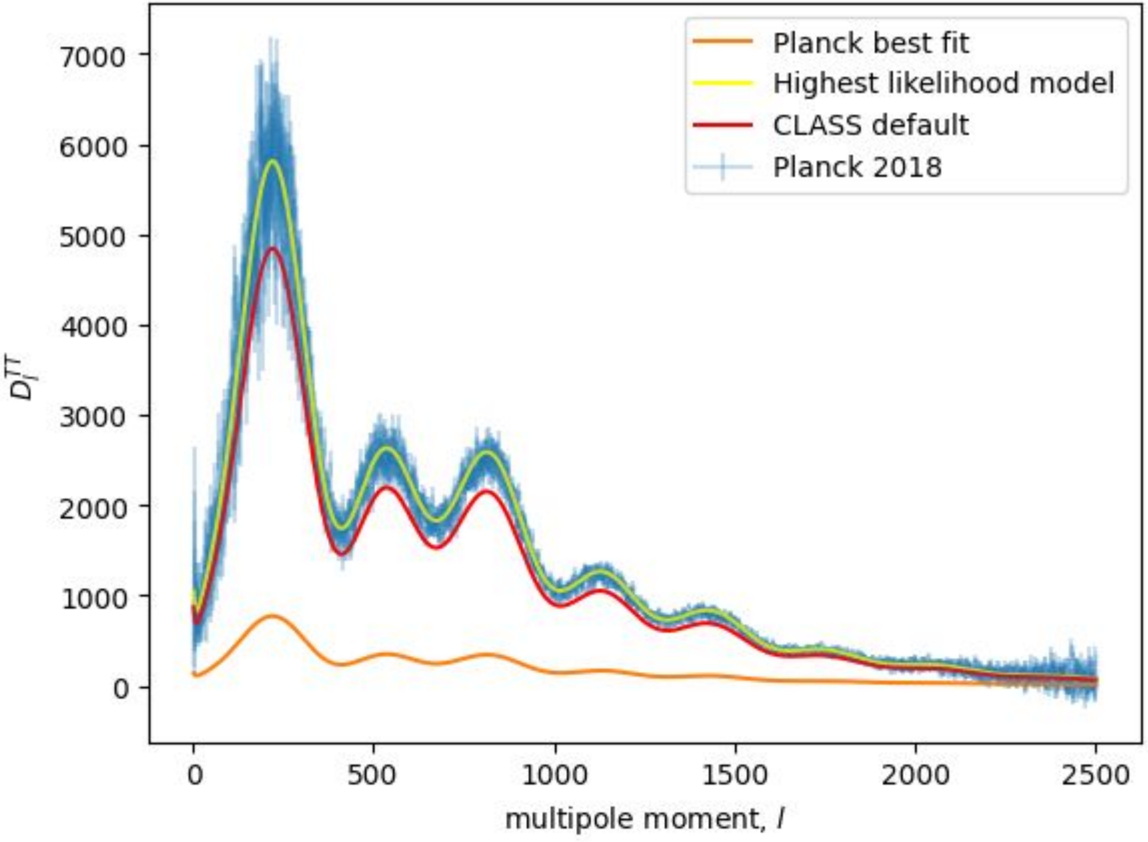
1) Set our model in CLASS - Fixing N_{eff} , neutrino masses, and the chemical potential. We'll let $\Omega_b h^2$, $\Omega_{CDM} h^2$, and h_0 vary
2) Set up an MCMC sampler
3) Profit???

Note: in CLASS, omega_x refers to $\Omega_x h^2$

Issues

The first step was to understand how CLASS works by comparing the data to the unmodified ΛCDM model

An arbitrary amplitude correction was necessary to match the data



Issues

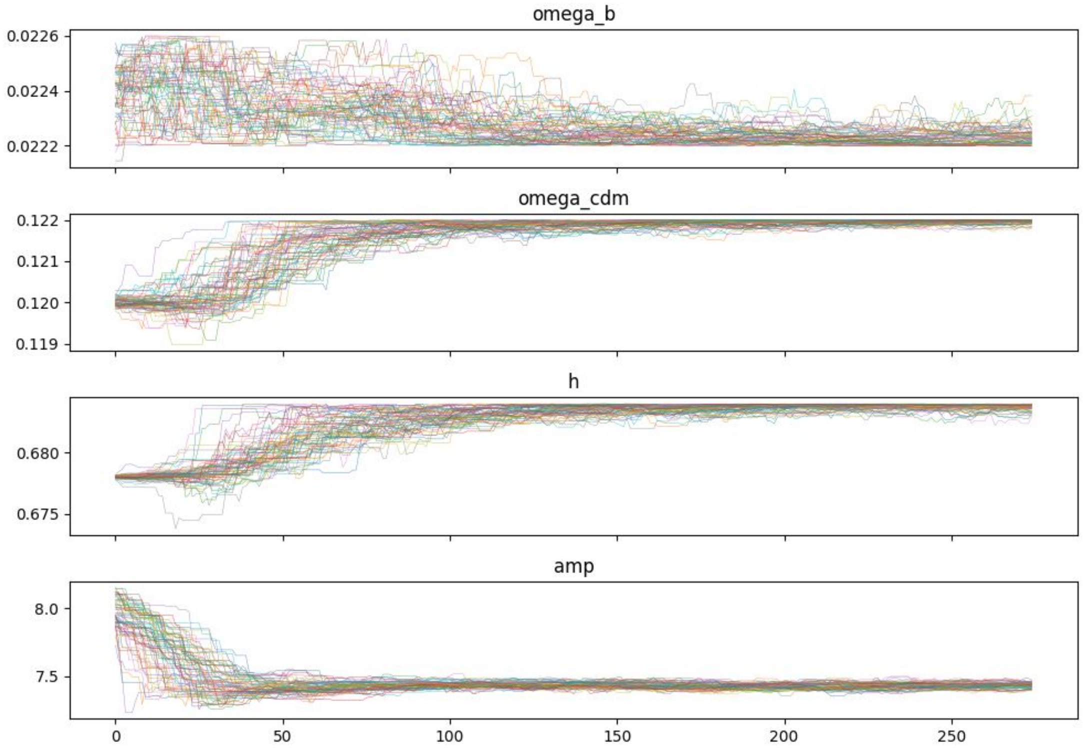
```
AutocorrError: The chain is shorter than 50 times the integrated autocorrelation time for 4
parameter(s). Use this estimate with caution and run a longer chain! N/50 = 6;

tau: [31.99536897 33.51499814 35.06662014 16.40113012]
```

The time required to diagnose and patch the fit issue cut into the available simulation time for my project, leading to too few iterations included in the final analysis

Issues

While $\Omega_b h^2$ and the amplitude converge within their allowed regions, $\Omega_{CDM} h^2$ and h_0 climb to the top of their regions, indicating the prior was too restrictive



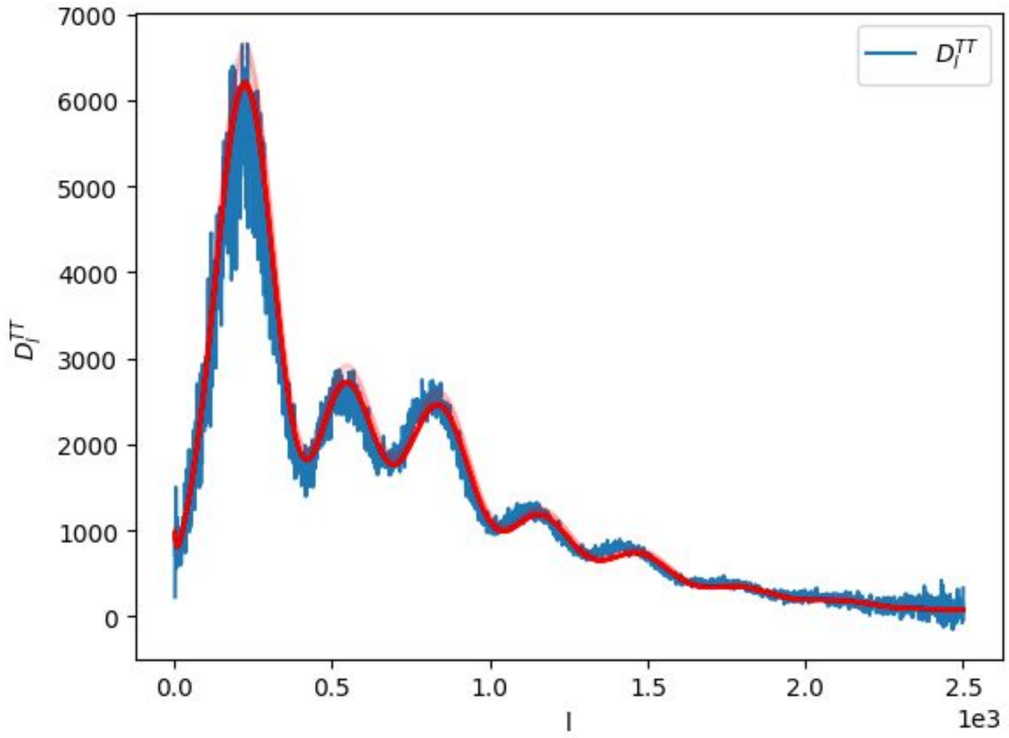
Solutions

Expand the priors

Add more iterations

- With a burn-in time of about 35 iterations, emcee suggests 1750 iterations (that’s still running)
- Run another set of a few hundred iterations to give us a ballpark of whether the expansion helped (backup slides)

Results



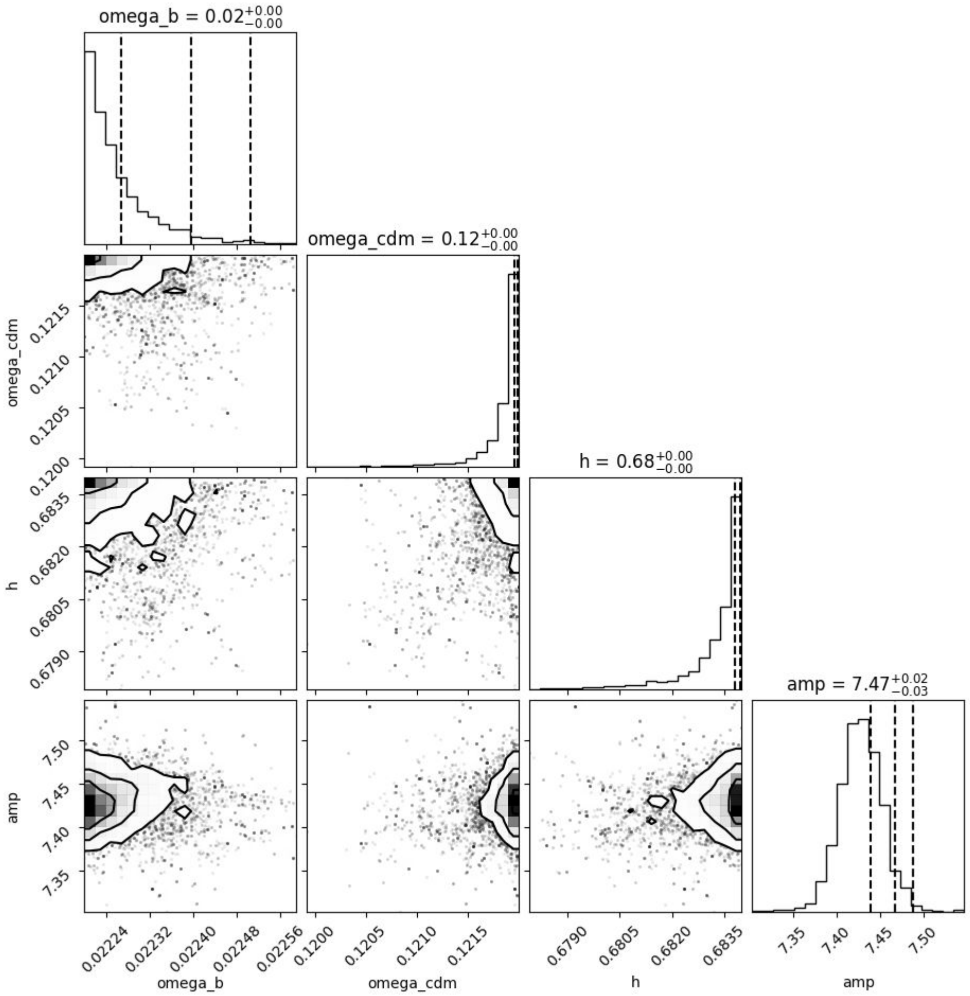
In spite of our lack of true convergence, our model has (subjectively) fit the data pretty well!

Results

Unfortunately, our posterior distributions tell another story.

We've used 64 walkers and sampled 275 times, which gives us about 17,000 samples - an order of magnitude less than we'd like

(Additionally, the first 50 steps are discarded).



What did we learn?

Data Analysis

Model comparison using the relative likelihood ratio:

$$\exp\left(\frac{\mathrm{AIC}(M_1) - \mathrm{AIC}(M_2)}{2}\right) \qquad \mathrm{AIC} = 2k - 2\ln(\hat{L})$$

The relative likelihood ratio of the default CLASS parameters to our expanded model is 0. IE, it's the default is completely preferred.

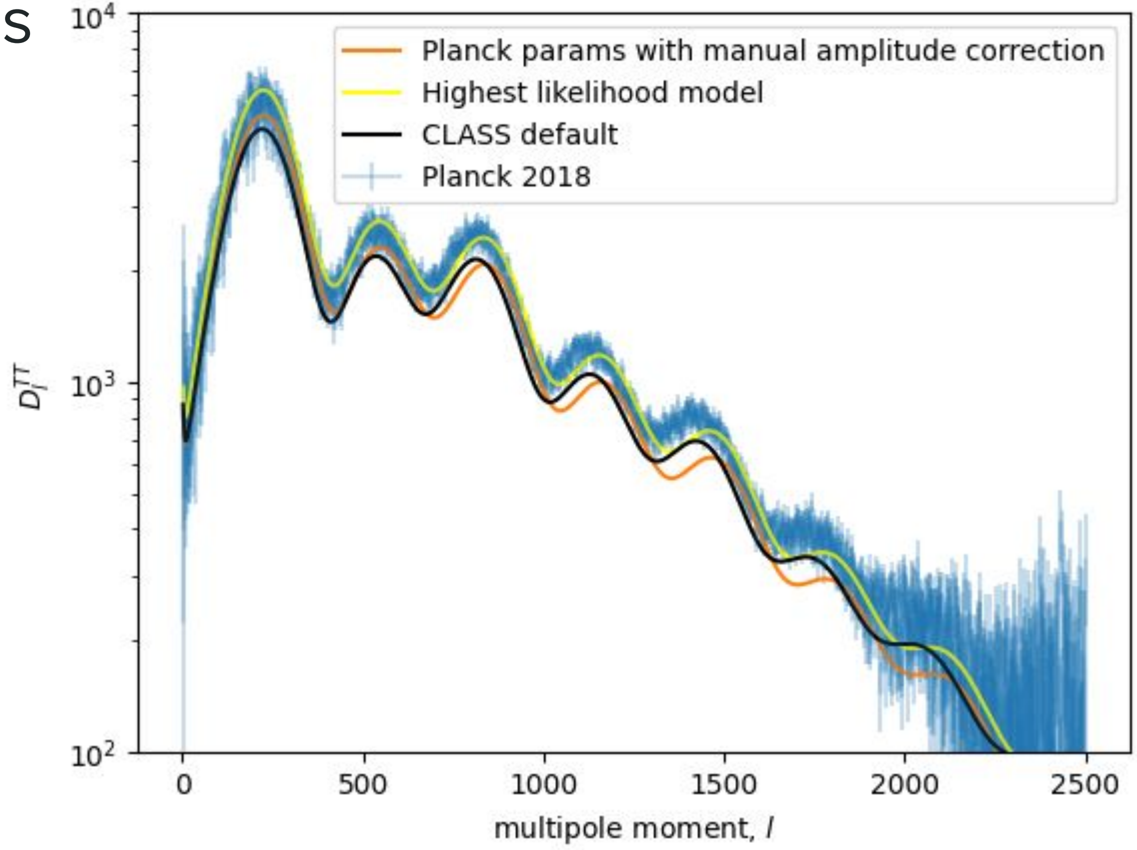
When we consider the Planck best fit values, but with our model, the relative likelihood is also zero.

This is likely to be an artifact of how low our overall likelihoods are - that being said, it looks like this model is not drastically incompatible with this particular dataset. (Though it happens to be disallowed by unrelated experiments).

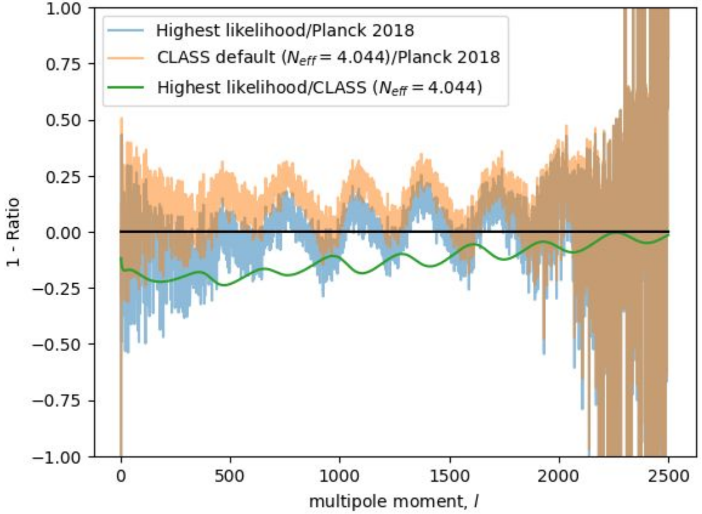
Impact of our changes

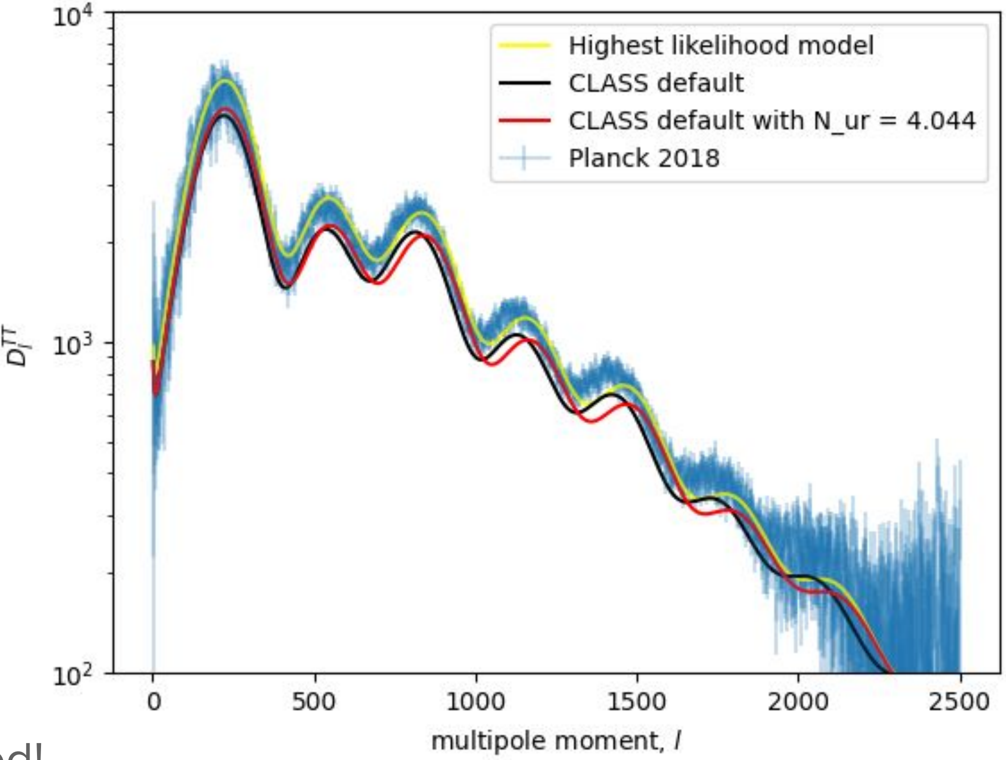
Even when fitting cosmological parameters to our new model, the additions to the neutrino sector shift our peak locations to higher multipoles

Given what we know about N_{eff}, this is as expected.



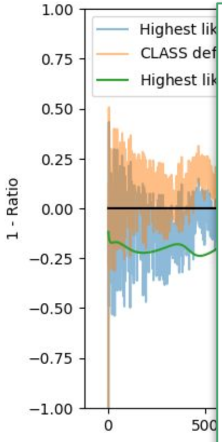
Impact of our changes

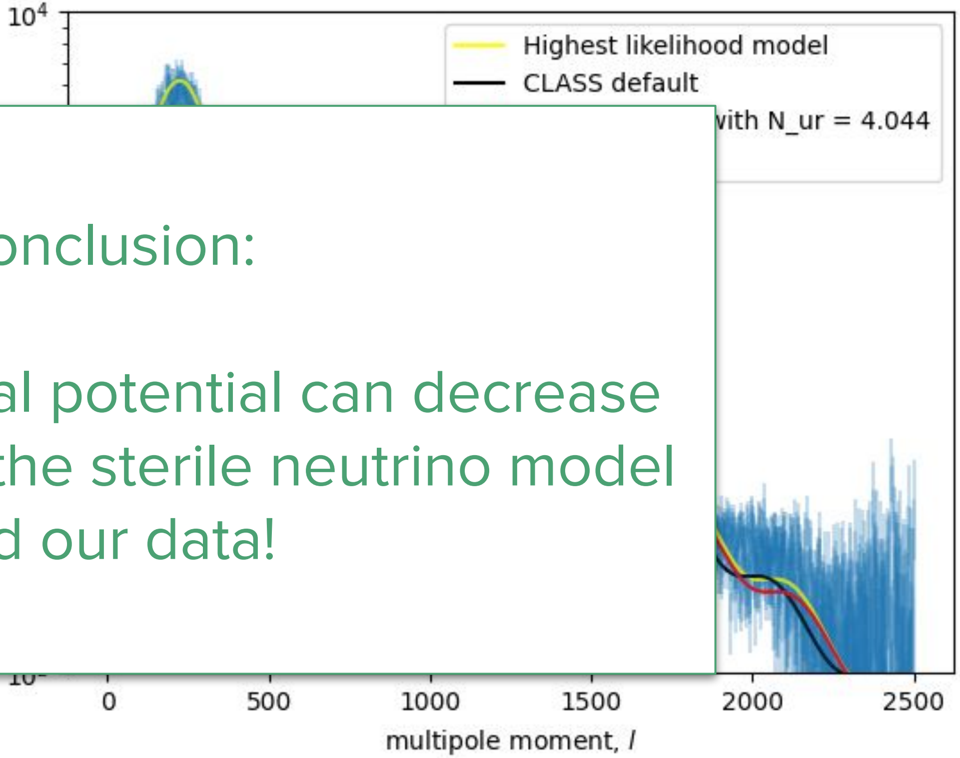




For a fixed N_{eff}, our model is preferred!

Impact of our changes





Conclusion:

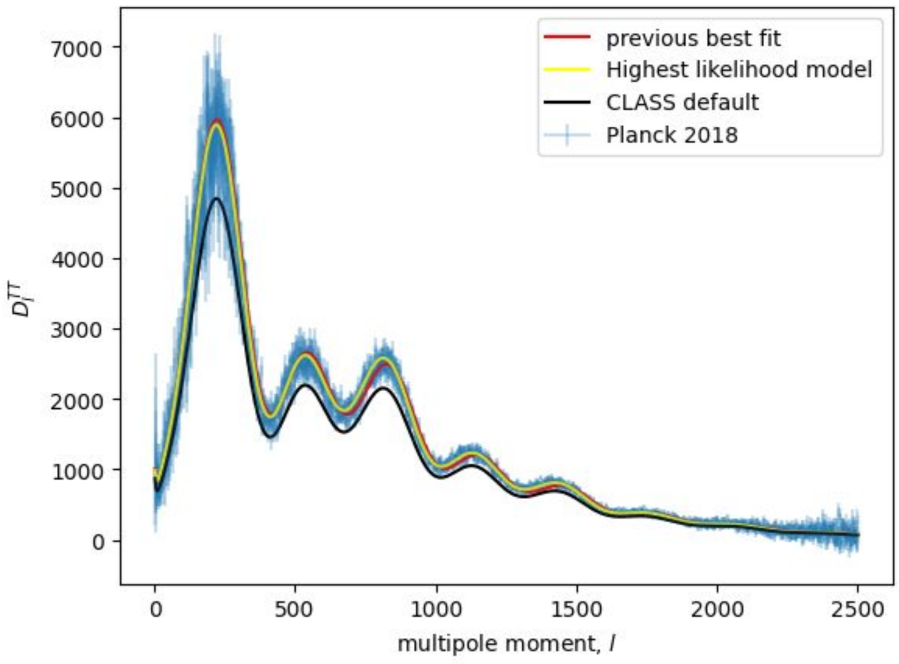
Adding a chemical potential can decrease tension between the sterile neutrino model and our data!

For a fixed
preferred!

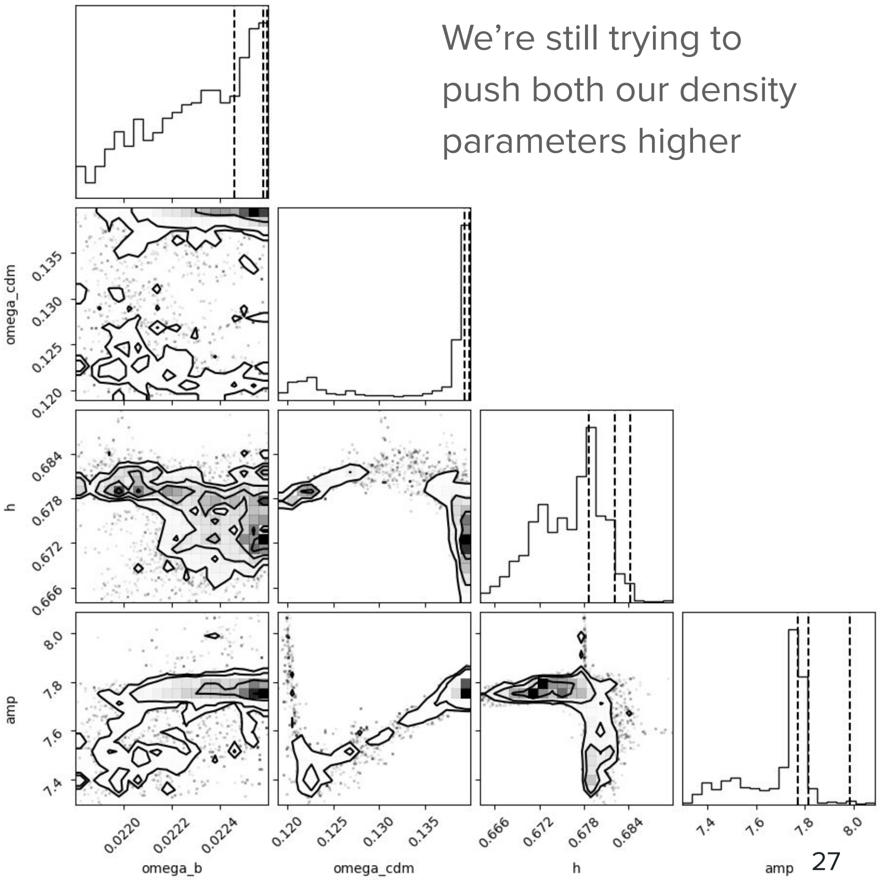
Thanks!

Backup

Small sample with broadened priors:

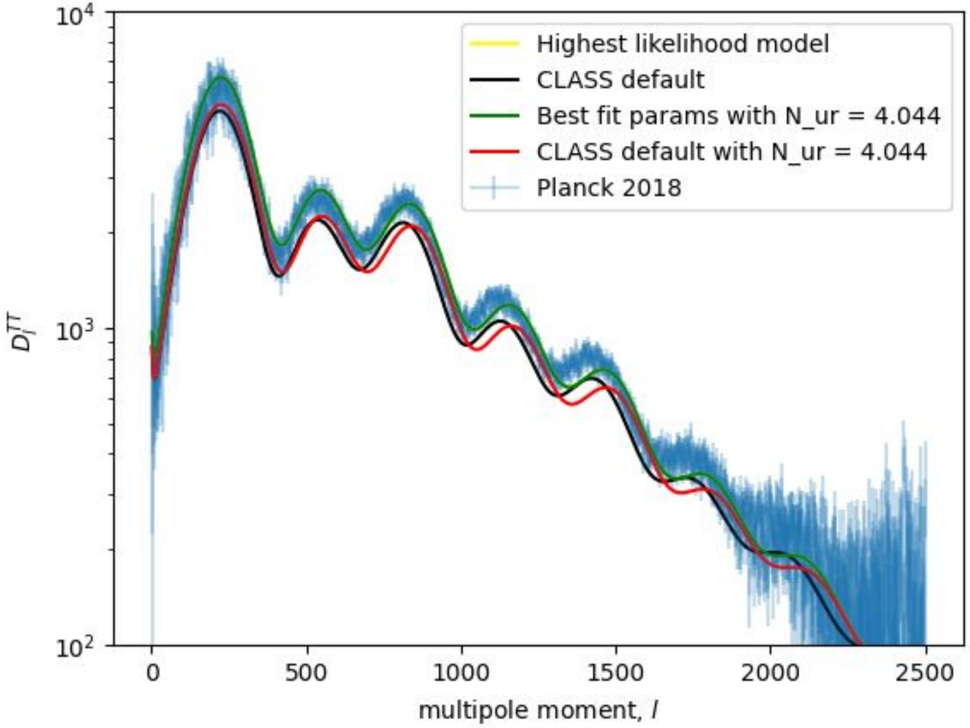


Our updated best-fit pushes the peak locations closer to the base model, and is strongly preferred compared to our original best fit



We're still trying to push both our density parameters higher

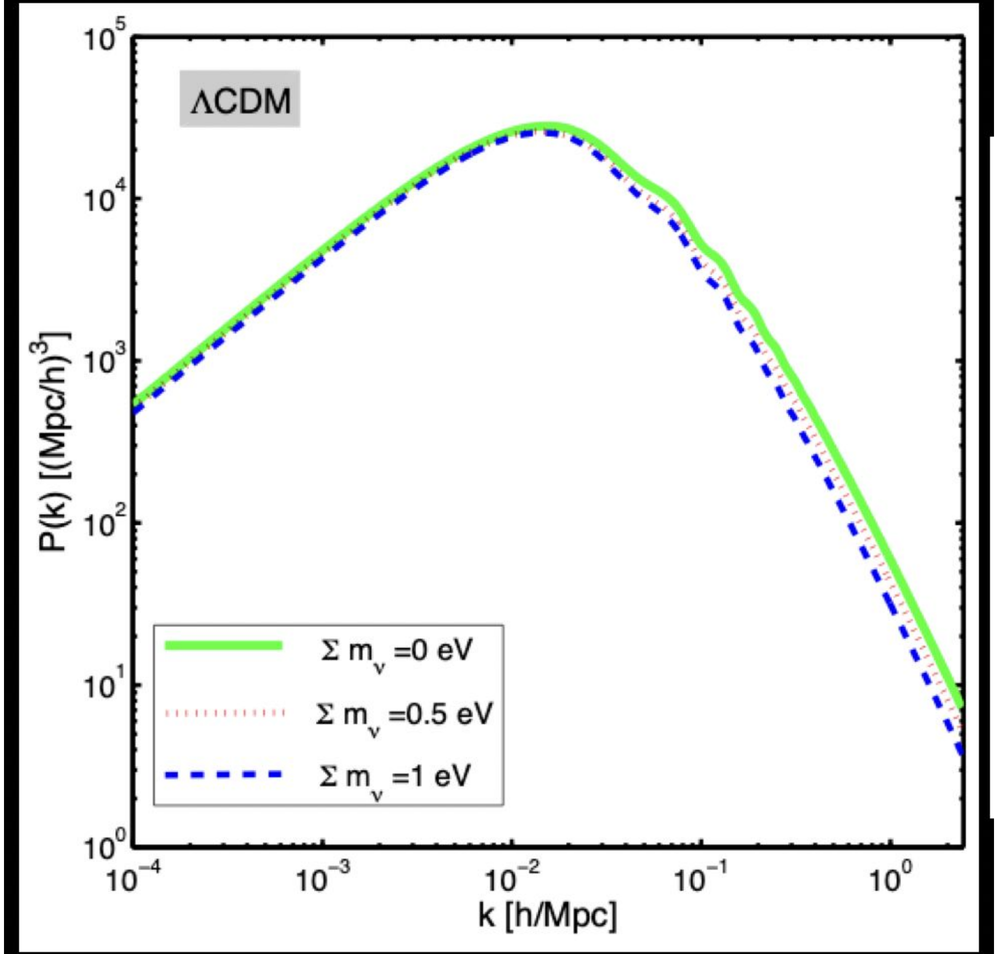
Cross check: Raising N_{eff} with no chemical potential



Though not visually distinct, our model is preferred over the 4-neutrino with no chemical potential model (at our best fit points)

This does not conclusively show a chemical potential is preferred, but rather that in some circumstances, adding a chemical potential can reduce model disagreement

Matter power spectrum and neutrino mass



Chen & Xu, Phys.Lett.B 752

(a few) Big Questions in neutrino physics

What are the neutrino masses? How are they ordered?

How many neutrino species are there?

- Z boson decay measurements limit us to 3 Weakly-interacting species
- Sterile neutrinos have been posited as an explanation for a variety of questions (what causes the miniBooNE and LSND anomalies? How do neutrinos get their mass?)
- However, many sterile neutrino models are heavily constrained by terrestrial experiments