Beyond Planck: Neutrino Mass Limits from a Cosmological Dataset

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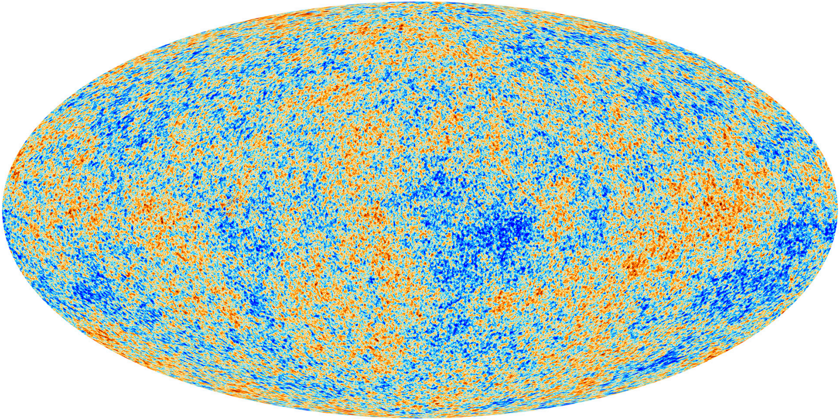
The $\sum m_\nu$ Problem

- Numerous ground-based experiments support the existence of neutrino flavour oscillations, generally requiring neutrinos to be massive
- Oscillation experiments allow us to put lower limits on the sum of neutrino mass state eigenvalues ($\sum m_\nu > 0.06$ eV for normal hierarchy / 0.10 eV for inverse mass hierarchy, assuming the lightest state is massless)
- Conversely, setting an upper limit is difficult due to the weakness of neutrino-nucleon interactions
- $m_{\nu_e}^{eff} < 0.8$ eV (KATRIN)

Looking Up



Cosmology with Massive Neutrinos

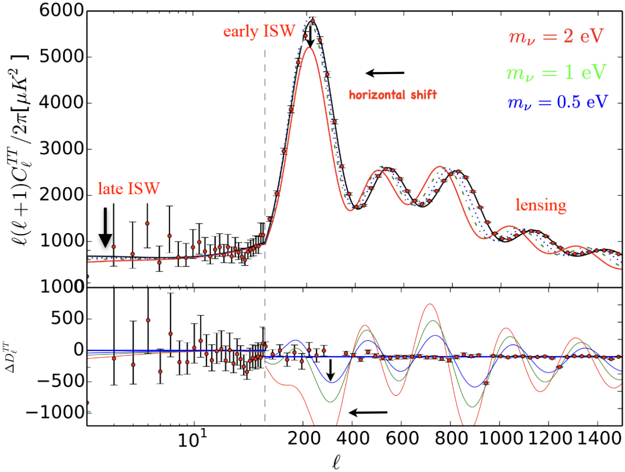


Figure: credit: Eleonora di Valentino

Constructing a Dataset

1. The only currently available full-sky CMB maps come from Planck, but they exhibit certain anomalies, such as enhanced lensing at large ℓ which suppresses $\sum m_\nu$
2. We have chosen a combination of CMB data from Planck (TT, $\ell_{max} = 1000$) and SPT-3G (TE, EE, lensing)

Removing Degeneracies with Large-Scale Structure

- $H^2 = H_0^2(\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_{DE})$
- The CMB acoustic scale $\theta^* \propto 1/\int_0^{z_{rec}} \frac{dz}{H(z)}$
- In the CMB data $\sum m_\nu$ is degenerate with several other parameters, most notably with the present-day expansion rate H_0
- Measuring the large-scale structure (LSS) of the Universe via proxies such as galaxies and clusters provides information about the Baryon Acoustic Oscillation (BAO) scale and constrains the expansion history, breaking the degeneracy

Constructing a Dataset II

1. Spatial distribution of galaxies is complex, containing not only the BAO signal but a lot of additional information about the matter distribution
2. Usually the data is greatly simplified down to one or two main components
3. We are instead using an Effective Field Theory treatment of the full BOSS DR12 set which allows us to make use of the full spectrum (up to hexadecopole) in constraining the cosmology
4. $+$ additional observations (matter density fluctuation amplitude S_8, type Ia supernova-based distance measurements) consistent with the CMB+LSS result

Results

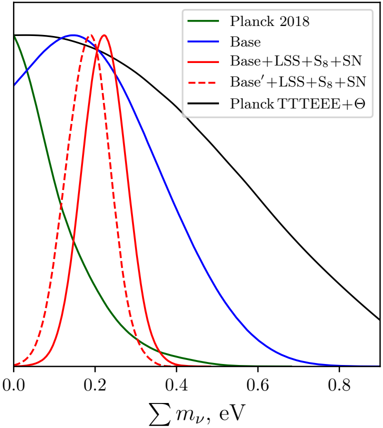
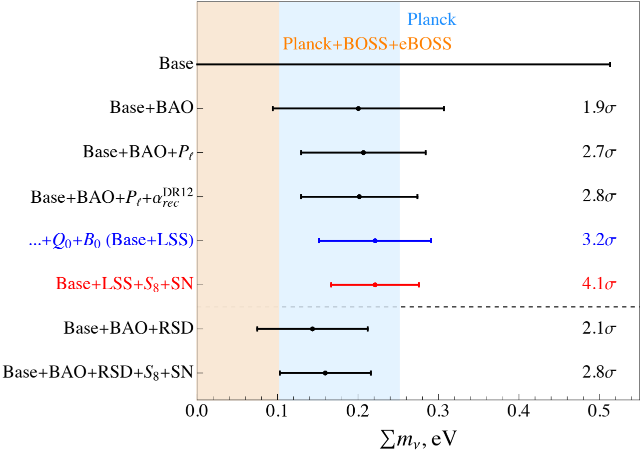


Figure: Evidence for $\sum m_\nu > 0$ at the 4σ level (0.221 ± 0.055 eV)

Results



Planck
Planck+BOSS+eBOSS
Base
Base+BAO
1.9σ
Base+BAO+P_ℓ
2.7σ
Base+BAO+P_ℓ+α_{rec}^{DR12}
2.8σ
...+Q_0+B_0 (Base+LSS)
3.2σ
Base+LSS+S_8+SN
4.1σ
Base+BAO+RSD
2.1σ
Base+BAO+RSD+S_8+SN
2.8σ
0.0
0.1
0.2
0.3
0.4
0.5
$\sum m_\nu$, eV

The τ Question

1. τ_{reion} is the optical depth to reionization, a measure of line-of-sight free-electron opacity of the Universe
2. It is degenerate with the acoustic peak amplitude and therefore in a CMB-only analysis it is also degenerate with $\sum m_\nu$
3. Polarization measurements by Planck give $\tau_{reion} = 0.0581 \pm 0.0055$
4. Curiously, recent observations of early galaxies, most notably by JWST, indicate an earlier reionization and a significantly higher τ_{reion}

The τ Question

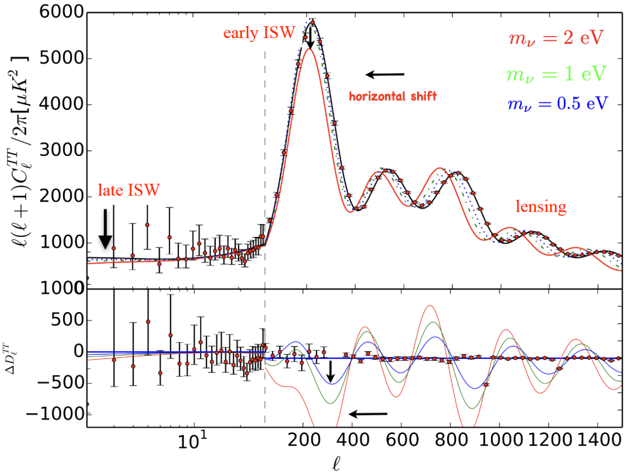
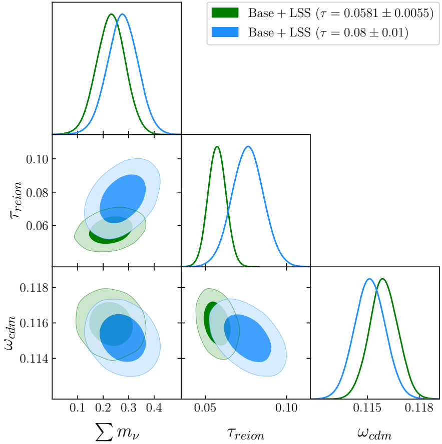


Figure: credit: Eleonora di Valentino

Accomodating higher τ_{reion}



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