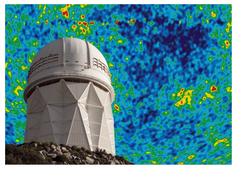

Measuring neutrino properties with BigBOSS

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Neutrino Physics

Terrestrial neutrino experiments show an indisputable evidence for neutrino oscillations. This is one of very few experimental evidences for physics beyond the standard model.

For simple models, neutrino oscillations are parametrized by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) CP violating phase ($\delta$) and three masses ($m_i$). It is important to note that indices on masses $m_{i=1,2,3}$ correspond to three mass-eigenstates, each of which is a linear combination of flavour eigenstates $\nu_{j=e,\mu,\tau}$.

Terrestrial experiments rely on flavour physics and so always depends on oscillation angles. For example, oscillation experiments measure θ_{ij} and mass square difference $m_i^2 - m_j^2$.

Absolute masses measured by

- Tritium decay experiments measure (in quasi-degenerate approximation): $m_{\nu_e}^2 \approx 0.3m_1^2 + 0.7m_2^2$.
- Cosmology measures mainly $\sum m_i$.

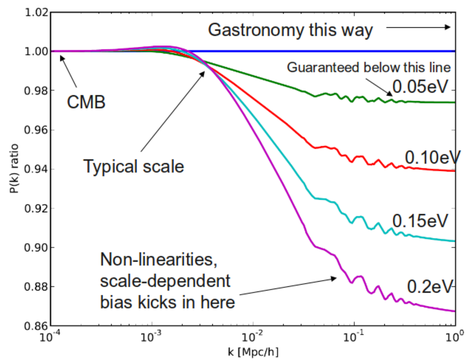
Although tritium decay experiments offers arguably the most direct path towards absolute neutrino masses, it is cosmological measurements that offer the highest precision.

Current status

Known neutrino properties:

- Two mass squared differences $\Delta m_{12}^2 = 7.6 \pm 0.2 \times 10^{-5}\mathrm{eV}^2$ and $|\Delta m_{13}^2| = 2.4 \pm 0.1 \times 10^{-3}\mathrm{eV}^2$. Note that sign of Δm_{13}^2 is unknown. This uncertainty gives two solutions for individual masses: normal and inverted hierarchy and sets the minimum sum of neutrino masses to $\sim$ 0.06 eV for normal hierarchy and $\sim$ 0.1 eV for inverted hierarchy.
- θ_{12} and θ_{23} measured, but only upper limits for θ_{13}.
- Dirac vs Majorana mass terms still unknown, exotic possibilities such as non-standard couplings, 4th sterile neutrino, etc. still only weakly constrained.

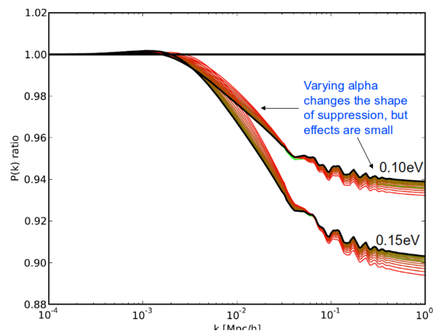
Effect on cosmology



Plot showing the suppression of the linear power spectrum as a function of the sum of neutrino masses.

For masses relevant for BigBOSS experiment, the main effect is the suppression of the linear matter power spectrum. All methods for measuring neutrino masses from cosmology depend on this suppression by measuring correlations that trace the underlying dark-matter correlations. The suppression has *a characteristic scale* that cannot be mimicked by other effects.

Measuring degeneracy



Plot showing the suppression of the linear power spectrum as a function of the degeneracy parameter α_ν.

We model the amount of non-degeneracy in neutrino masses through parameter $\alpha_\nu = m_3/\sum m_i$. This is justified by small splitting between the lowest two eigenstates ($m_1 \sim m_2$). BigBOSS will not be able to distinguish between normal and inverted hierarchy from the shape of suppression. It can, however, constrain non-degeneracies in more exotic models such as those containing a fourth sterile neutrino.

Fisher matrix projections

We made Fisher projections for the accuracy with which BigBOSS will be able to measure neutrino masses. A linear model was assumed for dark matter power spectrum, biasing and redshift-space distortions: This is not appropriate for real analysis, but good for forecasting (relative suppression the same within 10%). A fiducial ΛCDM model was used for these projections with $\sum m_i = 0.06$eV, but results do not depend strongly on the assumed model. We have also made forecasts for the ability of BigBOSS to constraint the effective number of relativistic neutrino species.

Forecasts indicate that the BigBOSS has the statistical power to measure neutrino masses at statistical significance around 3-4 sigma and has potential to exclude inverted hierarchy. BigBOSS should also measure the effective number of ultra-relativistic species in the early Universe with high accuracy and could exclude models with sterile neutrinos, even if these have significantly sub-thermal abundances.

Combination	$k_{\max} = 0.15h/\mathrm{Mpc}$	$k_{\max} = 0.3h/\mathrm{Mpc}$
Planck + H_0	0.33	
Planck + H_0 + BOSS galaxies	0.059	0.035
Planck + H_0 + BigBOSS galaxies	0.017	0.014
Planck + H_0 + BigBOSS Lyman-α	0.042	
Planck + H_0 + BigBOSS galaxies + Lyman-α	0.016	0.014

The expected 1-σ marginalized error on $\sum m_i$

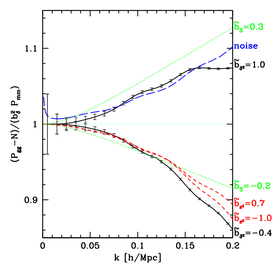
Combination	$k_{\max} = 0.15h/\mathrm{Mpc}$	$k_{\max} = 0.3h/\mathrm{Mpc}$
Planck + H_0	0.22	
Planck + H_0 + BOSS galaxies	0.14	0.12
Planck + H_0 + BigBOSS galaxies	0.071	0.059
Planck + H_0 + BigBOSS Lyman-α	0.063	
Planck + H_0 + BigBOSS galaxies + Lyman-α	0.051	0.049

The expected 1-σ marginalized error on N_ν

Control of systematics

INSTRUMENTAL SYSTEMATICS: A good understanding of selection effects is crucial for measuring power on the largest scales. Selection is affected by the effects of Milky Way (stellar crowding, reddening) and the instrument efficiency (dependence on focal plane position, seeing, focus, etc.). **BOSS experience:** Novel systematics effects were found, such as decreased observed area due to sky mask. A solid statistical framework that marginalises over systematics effects is being developed.

THEORETICAL UNCERTAINTY: We measure *non-linear* dark matter *traced by galaxies* in *redshift* space. The non-linear dark matter is a solved problem, but scale-dependence of bias and the galaxy redshift-space distortions in the mildly non-linear regime are not. These can be modelled using combination of analytical approaches using perturbation theory and N-body simulations. Our limited understanding can be marginalised over by using a sufficiently large number of bias parameters. Biasing effects produce smooth variations in Fourier space that are characteristically different from neutrino suppression.



Corrections to linear biasing from McDonald&Roy 2009. Note how shape is different from neutrino suppression.