How well can LSST measure neutrino masses?

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Neutrino masses:

1. Solar neutrinos: SNO
2. Atmospheric neutrinos: SuperK

\[
\Delta m^2_{21} \approx 7.6 \times 10^{-5} \\
\Delta m^2_{31} \approx 2.4 \times 10^{-3} \text{ eV}^2
\]

mass \(> 0.06\) eV
Neutrino masses:

Upper limits from cosmology - Excludes neutrinos from being all the DM!
Neutrino masses:

Cosmology:

\[ \text{CMB + BAO (Planck)} \quad m < 0.23 \text{ eV (95\%)} \]
\[ \text{with Lyman Alpha} \quad m < 0.17 \text{ eV} \]
Neutrino masses:

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Signs of neutrino mass in current cosmological datasets

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Mass = 0.36 eV !!!
The Large Synoptic Sky Telescope

1. 3200 Megapixel camera.
2. 20 Terabytes per night!
3. Photometric data only.

LSST will measure neutrino masses very precisely!
Weak lensing -

Galaxies randomly distributed

Slight alignment
Weak lensing -

\[ m = 0.05 \text{ eV} \]

\[ m = 0.1 \text{ eV} \]
But the matter power spectrum is not well known!

Baryons cause:

- a damping on intermediate scales.
- a boost on very small scales.

We need high res numerical simulations to study the baryon power spectrum on small scales.
But the matter power spectrum is not well known!

FIG. 1: The square of the baryon bias, \( \frac{P_{\text{full}}(k)}{P_{\text{DM}}(k)} \), for feedback models #1, #2, and #3 at redshift zero. The damping in the power spectrum is especially large for feedback model #1, while feedback model #3 shows the largest effect of baryonic feedback on the matter power spectrum.
Distinguishing these models through weak lensing-

\[ C_\ell \propto \ell (\ell + 1) C^{\text{gal}}_\ell / 2\pi \]

\[ C^{\text{gal}}_\ell = \frac{1}{\sigma^2} \int_{\alpha_{\text{gal}}}^{\alpha_{\text{gal}}} \frac{\cos^2 \xi}{\Delta \alpha^2} d\alpha \]

\[ \sigma^2 = \frac{4}{3} \pi \rho_0 \Delta^2 \]

Feedback model #1
Feedback model #2
Feedback model #3
What is the error on the measured neutrino mass?

Fisher matrix analysis:

\[
\tilde{\theta} = \{ \Omega_b h^2, \Omega_c h^2, h, 10^9 A_s, n_s, m_\nu \}
\]

\[
F = C_{\text{prior}}^{-1} + \sum_\ell \frac{\partial P}{\partial \tilde{\theta}} \text{Cov}^{-1} \frac{\partial P^T}{\partial \tilde{\theta}}
\]

\[
\sigma(\theta_i) = \sqrt{[F^{-1}]}_{ii}
\]
What is the error on the measured neutrino mass?

Fisher matrix analysis:

![Graph showing statistical error in neutrino mass as a function of $\ell_{\text{max}}$. The graph includes three curves for different numbers of bins: 1 bin, 3 bins, and 5 bins. The x-axis represents $\ell_{\text{max}}$ ranging from 500 to 3000, and the y-axis represents the statistical error in $m_\nu$ (eV). The curves decrease as $\ell_{\text{max}}$ increases, indicating reduced error with higher $\ell_{\text{max}}$. The 1-bin curve is the lowest, followed by the 3-bin and 5-bin curves, each showing a slight increase in error with fewer bins.](image-url)
But Fisher matrix analysis also gives us systematic errors:

\[ \Delta \vec{\theta} = F^{-1} \sum_{\ell} \frac{\partial C_{\ell}}{\partial \theta} \text{Cov}^{-1} \Delta C_{\ell} \]
Let us now consider the bias introduced in our measurement of parameter $\nu$. Using the Fisher matrix formalism, one may obtain an estimate of the statistical error on each cosmological parameter to be constrained. The Fisher matrix is then a 15 matrix. Let the inferred cosmological parameters be $\theta$, and define the covariance matrix

$$\text{Cov}(\theta) = \text{Fisher matrix}. \quad (1)$$

The Fisher matrix formalism is used to construct 15 power spectra, and 1 cross-power spectrum. The covariance matrix is $\text{Cov}(\theta)$. Thus, when the data consists of only 1 redshift bin, the errors can be measured. The redshift range is divided into 1 bin (black, solid), 3 bins (red, dashed), and 5 bins (blue dotted). There is one power spectrum with 1 bin, six power spectra with 3 bins, and fifteen power spectra with 5 bins. Note that the errors on neutrino masses with the LSST considering source galaxies in the redshift range 0.01, 0.02, 0.04, 0.06, 0.07, and 0.08 are shown.

Shown are results for Feedback model#1, Feedback model#2, and Feedback model#3. Note that the Fisher matrix formalism is not reliable when $|\nu| > m$. With 2 bins, one can construct $\text{Cov}(\theta)$, and similarly for $\text{Cov}(\theta)$. With 5 bins, one can distinguish between feedback models. Conversely, if the true model is unknown, there will substantial errors in the measurement of parameter $\nu$. The lensing covariance matrix is $\text{Cov}(\theta)$. If multipoles up to $\ell = 5$, approximately equal to 20,000 square arcminutes, with 500 galaxies per square arcminute, with the LSST considering source galaxies in the redshift range 0.01, 0.02, 0.04, 0.06, 0.07, and 0.08 are shown.

IV. RESULTS

Let us now estimate the errors in the neutrino mass parameter $\nu$. The lensing covariance matrix is $\text{Cov}(\theta)$. The shot noise term is chosen to be the set of cosmological parameters to be constrained. The Fisher matrix is then a 15 matrix. Let the inferred cosmological parameters be $\theta$, and define the covariance matrix $\text{Cov}(\theta)$.

For the shot noise term, we choose redshift errors, beam errors, etc. In order to map the power spectrum indices, we use the lensing covariance matrix $\text{Cov}(\theta)$.

<table>
<thead>
<tr>
<th>$\ell_{\text{max}}$</th>
<th>$\Delta \nu/\nu$</th>
<th>$\Delta \nu/\nu$</th>
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<tbody>
<tr>
<td>500</td>
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(a) $\nu = 0.30 \text{ eV}$
(b) $\nu = 0.20 \text{ eV}$
(c) $\nu = 0.10 \text{ eV}$
(d) $\nu = 0.05 \text{ eV}$
CMB lensing can also probe neutrino masses –

![Graph showing expected errors in the neutrino mass from CMB lensing.](image)

The graph shows the errors that may be expected from a cosmic variance limited CMB lensing experiment assuming a sky fraction of 0.5 and cosmic variance error bars. The true neutrino mass was set to 0.1 eV. For all models, the systematic error due to feedback models #1, #2, and #3 are shown. The black (solid), red (dashed), and blue (dotted) curves show the effect of feedback processes on CMB lensing, assuming feedback while analyzing data from future weak lensing surveys such as the LSST. Feedback model #3 ignored supernova feedback as well as cooling by heavy elements. Feedback model #2 considered a top heavy stellar IMF which yields more supernova energy compared to the Chabrier IMF. Feedback model #1 included AGN feedback from gas accretion on to black holes, with 15% of the radiated energy coupling to the gas. Feedback processes on the shear power spectrum. It was found that weak lensing is sensitive to the small scale non-linear matter power spectrum and is a powerful tool to probe neutrino masses. We then investigated the effect of including various baryonic feedback models, the bias introduced in the neutrino mass estimate even in the case of the minimal normal hierarchy. Feedback model #1 in particular shows a substantial damping of the power spectrum on small and intermediate scales due to thermal gas pressure, while the AGN feedback results in realistic models of large scale physics, photometric errors, beam errors, etc, weak lensing results are particularly in the case of AGN feedback. Feedback models #1, #2, and #3 respectively. Due to this high sensitivity, the weak lensing results are of the power spectrum (nearly a 30% e\textsuperscript{-1} correction) seen by other authors such as [20].

In conclusion, we discussed how future weak lensing observations can measure neutrino masses at high significance even in the case of the minimal normal hierarchy. With upcoming surveys such as LSST, a bound which may be reduced further by including future galaxy surveys. The black (solid), red (dashed), and blue (dotted) curves show the statistical error in neutrino mass. The magenta curve shows a statistical error in neutrino mass. The true neutrino mass was set to 0.1 eV. For all models, the systematic error due to feedback models #1, #2, and #3 are shown. The black (solid), red (dashed), and blue (dotted) curves show the effect of feedback processes on CMB lensing, assuming feedback while analyzing data from future weak lensing surveys such as the LSST. Feedback model #3 ignored supernova feedback as well as cooling by heavy elements. Feedback model #2 considered a top heavy stellar IMF which yields more supernova energy compared to the Chabrier IMF. Feedback model #1 included AGN feedback from gas accretion on to black holes, with 15% of the radiated energy coupling to the gas. Feedback processes on the shear power spectrum. It was found that weak lensing is sensitive to the small scale non-linear matter power spectrum and is a powerful tool to probe neutrino masses. We then investigated the effect of including various baryonic feedback models, the bias introduced in the neutrino mass estimate even in the case of the minimal normal hierarchy. Feedback model #1 in particular shows a substantial damping of the power spectrum on small and intermediate scales due to thermal gas pressure, while the AGN feedback results in realistic models of large scale physics, photometric errors, beam errors, etc, weak lensing results are particularly in the case of AGN feedback. Feedback models #1, #2, and #3 respectively. Due to this high sensitivity, the weak lensing results are of the power spectrum (nearly a 30% e\textsuperscript{-1} correction) seen by other authors such as [20].

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Conclusions –

1. Weak Lensing is a very good probe of neutrino masses. However, it is extremely sensitive to baryonic effects!

2. The bias introduced in the neutrino mass is of order (or greater than) the neutrino mass itself. The mass inferred from weak lensing can be larger or smaller than the true mass.

3. CMB lensing is less sensitive to neutrino masses, but also less sensitive to baryonic effects.