Measuring neutrino mass imprinted on the anisotropic galaxy clustering

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I. Background Physics
   – How Massive Neutrino affect Galaxy Clustering In redshift space?
Decoupling of Neutrino

\[ R = \sum_{iR} g_i d^3 p f(p) E(p) \]

- The contribution from relativistic particles to the energy density.
Decoupling of Neutrino

\[ R = \sum_{i \in R} g_i \int d^3 p f(p) E(p) = 1 + \frac{7}{8} \cdot 3 \]

- The contribution from relativistic particles to the energy density.
- If they are in equilibrium with cosmic plasma, FD/BE distribution can be used.
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Decoupling of Neutrino

- The contribution from relativistic particles to the energy density.
- If they are in equilibrium with cosmic plasma, FD/BE distribution can be used.
- But, neutrino decoupled at around a few MeV, followed by $e^{-}e^{+}$ annihilation, which causes heating photons.
- For instantaneous decoupling approximation:

$$T / T = (11/4)^{1/3} \approx 1.40102$$
Decoupling of Neutrino

\[ R = \sum_{i \in R} g_i \int d^3 p f(p) E(p) = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right] N_{\text{eff}} \]

\[ T / T = (11/4)^{1/3} \approx 1.40102 \]

Fig. 1. Evolution of \( \delta \rho_{\nu\alpha}(m_\alpha)/\rho_{\nu\alpha}^0(m_\alpha) \), for a neutrino mass \( m_\alpha = 1 \text{ eV} \) (see text for further details).

Mangano+ (2002)
Decoupling of Neutrino

\[ R = \sum_{i \in R} g_i \int d^3 p f(p) E(p) = \left[ \frac{T}{T} = \left( \frac{11}{4} \right)^{1/3} \right] \begin{bmatrix} 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \left( N_{\text{eff}} \right) \end{bmatrix} \]

• The contribution from relativistic particles to the energy density.

• If they are in equilibrium with cosmic plasma, FD/BE distribution can be used.

• But, neutrino decoupled at around a few MeV, followed by e-e+ annihilation, which causes heating photons.

• Instead of instantaneous decoupling approximation,

• In reality, there is some distortion in f(p),

\[ N_{\text{eff}} = 3.046 \]

Mangano+ (2005)
Decoupling of Neutrino

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\[ N_{\text{eff}} = 3.046 \]

Mangano+ (2005)
After *decoupling*, starts to stream freely.

Equation of state

$\text{Last Scattering Surface}$

After decoupling, starts to stream freely.

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After *decoupling*, starts to stream freely

Fix the shape of $P(k)$ with $0 < m < 1 \text{eV}$

$$\sum m \rightarrow m \text{ (degenerate)}$$
Effect of Massive neutrino on LSS

- Free-streaming scale of massive neutrino with mass $m$:
  \[ FS \sim 4.2 \sqrt{\frac{1+z}{m_{\nu,0}}} \left( \frac{eV}{m} \right) Mpc / h \]

- Structure formation smaller than this scale $k > k_{FS}$ is suppressed, which provides the access to the neutrino mass in cosmology.
I. Background Physics

– How **Massive Neutrino** affect **Galaxy Clustering In redshift space**?

– we restrict our analysis to the standard case, where departure of $N_{\text{eff}}$ from 3 is solely due to neutrino heating by $e^-e^+$ annihilation, which gives The effective number of relativistic species $N_{\text{eff}} = 3.046$.

– Neutrino of mass < 1 eV was relativistic before LSS. Therefore, we can fix the clustering feature (=shape of power spectrum) at LSS using Planck experiment result.

– Distortion (scale-dependent damping) from the fixed clustering feature by massive neutrino with m <1 eV provides the access to the neutrino mass in cosmology.
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Theoretical model on $P(k)$ in Redshift Space Distortion (RSD)

- Improvement in 2D Power spectrum in redshift space
  - Kaiser (1987)
    \[
    P^{(s)}_{Kaiser}(k,\mu) = P^{\text{lin}}(k) + 2^2 P^{\text{lin}}(k) + 4^4 P^{\text{lin}}(k)
    \]
  - Scoccimarro (2004)
    \[
    P^{(s)}_{\text{scoccimarro}}(k,\mu) = \left\{ P(k) + 2^2 P^2(k) + 4^4 P^4(k) \right\} G^{FoG}(k_p)
    \]
  - Taruya, Nishimichi, and Saito (Improved) (2010)
    \[
    P^{(s)}_{\text{TNS}}(k,\mu) = \left\{ P(k) + 2^2 P^2(k) + 4^4 P^4(k) + A(k,\mu) + B(k,\mu) \right\} G^{FoG}(k_p)
    \]
    \[
    \text{-> Higher order correction}
    \]

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Theoretical model on \( P(k) \) in Redshift Space Distortion (RSD)

\[
P^{(s)}(k, \mu) = \int d^3 x e^{i \vec{k} \cdot \vec{x}} \left\langle e^{j_1 A_1} A_2 A_3 \right\rangle
\]

where

\[
 j_1 = -i k \mu \\
 A_1 = u_z(\vec{r}) - u_z(\vec{r}') \\
 A_2 = \delta(\vec{r}) + \nabla_z u_z(\vec{r}) \\
 A_3 = \delta(\vec{r}') + \nabla_z u_z(\vec{r}')
\]

\[
P^{(s)}(k, \mu) = \int d^3 x \exp\left\{ e^{i \vec{k} \cdot \vec{x}} \left\langle e^{j_1 A_1} \right\rangle \right\} \times \left[ \left\langle e^{j_1 A_1} A_2 A_3 \right\rangle + \left\langle e^{j_1 A_1} A_2 \right\rangle \left\langle e^{j_1 A_1} A_3 \right\rangle \right]
\]

\[
= G^{\text{FoG}}(k \mu \sigma_p) \left\{ P_\delta(k) + 2 \mu^2 P_\Theta(k) + \mu^4 P_{\Theta \Theta}(k) + A(k, \mu) + B(k, \mu) + T(k, \mu) + F(k, \mu) \right\}
\]

Taruya, Nishimichi, and Saito (2010)

Zheng & Song (2016)
Theoretical model on P(k) in Redshift Space Distortion (RSD)

\[ P^{(s)}(k, \mu) = \int d^3 x \exp \left\{ e^{i \mathbf{k} \cdot \mathbf{x}} \left\langle e^{i \mathbf{j}_1 A_1} \right\rangle_c \right\} \times \left[ \left\langle e^{i \mathbf{j}_1 A_1} A_2 A_3 \right\rangle_c + \left\langle e^{i \mathbf{j}_1 A_1} A_2 \right\rangle_c \left\langle e^{i \mathbf{j}_1 A_1} A_3 \right\rangle_c \right] \]

\[ = G^{FoG} (k \mu \sigma_p) \left\{ P_{\delta \delta}(k) + 2 \mu^2 P_{\delta \Theta}(k) + \mu^4 P_{\Theta \Theta}(k) + A(k, \mu) + B(k, \mu) + T(k, \mu) + F(k, \mu) \right\} \]

Zheng & Song (2016)
Cut-off to consider
Current status of RSD modeling

\[ s = \left( \sigma^2 + \pi^2 \right)^{1/2} \]

\[ k_{\text{max}} \sim 0.07h / \text{Mpc} \]
Is TNS model reliable to calculate Non-linear mapping including massive neutrino?

\[
\frac{P}{p} \sim 8 \times f = 0.16 \text{ for } m = 0.3 \text{eV}
\]

where \( f \equiv \frac{P}{p} \) with \( m = 0.31 \) and \( h = 0.68 \)

Yvonne Y. Y. Wong (2011)

Fractional difference between linear \( P(k) \) without and with massive neutrino ~ 15%.
Is TNS model reliable to calculate Non-linear mapping including massive neutrino?

\[ W_m = 0.15 \]

\[ W_m = 0.25 \]

\[ W_m = 0.35 \]

→ Yes
up to \( k \sim 0.1 \, \text{h/Mpc} \)

Fractional difference between linear and non-linear \( P(k) \) without massive neutrino <5%.

- \( m = 0.0 \, \text{eV} \)
- \( m = 0.3 \, \text{eV} \)
- \( m = 0.6 \, \text{eV} \)

Fractional difference between linear \( P(k) \) without and with massive neutrino \( \sim 15\% \).
Effective growth VS Scale-dep. growth

- Depending on how the effect from massive neutrino is parameterized, the constraint on neutrino mass is affected (See grey contours).
Effective growth VS Scale-dep. growth

- Depending on how the effect from massive neutrino is parameterized, the constraint on neutrino mass is affected.

\[ q^* = \frac{r_s(z^*)}{D_A(z^*)} \]  : CMB distance measure

\[ D_A(a) = a \int_a^1 \frac{da'}{a'H(a')} \]

\[ r_s(z) = \int_0^{(z)} \frac{d'}{\sqrt{3(1+R)}} \]
Bias effect on neutrino mass constraint

• Beyond the linear bias, $b_1$?

\[ P_{g,\delta\delta}(k) = b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b_2,\delta}(k) + b_2^2 P_{b_22}(k) \]

\[ + 2b_{s_2} b_1 P_{b_{s_2},\delta}(k) + 2b_2 b_{s_2} P_{b_{2s_2}}(k) + b_{s_2}^2 P_{b_{s_22}}(k) \]

\[ + 2b_{s_2} b_{3nl} \sigma_3^2(k) P^{\text{lin}}(k) \]

where \[ P_{b_2,\delta}(k) = \int \frac{d^3q}{(2\pi)^3} P^{\text{lin}}(q) P^{\text{lin}}(|\vec{k} - \vec{q}|) F_2^{\text{SPT}}(\vec{q}, \vec{k} - \vec{q}) \]

\[ P_{b_22}(k) = -\frac{1}{2} \int \frac{d^3q}{(2\pi)^3} P^{\text{lin}}(q) \left[ P^{\text{lin}}(q) - P^{\text{lin}}(|\vec{k} - \vec{q}|) \right] \]

McDonald & Roy (2009)
Gill-Marin+ (2016)
Bias effect on neutrino mass constraint

- Scale-dependency of bias $b(k)$ doesn’t affect neutrino mass constraint in scales of interest.

$$P_{g, d}(k) = b_1^2 P_{dd}(k) + 2b_2 b_1 P_{b2, d}(k) + b_2^2 P_{b22}(k)$$
Testing Methodology

- When we apply our methodology to the simulation (SDSS DR11 mock catalogue without massive neutrino), true value reproduced.
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Result on \((D_A, H^1, G_b, G, p, m)\)

Consistent with some previous works:
- Song, Sabiu, Okumura, Oh, Linder (2014)
- Beutler+ (2014)
Result on \((b, m, p, m)\) * in 68% C. L.

\[
\begin{align*}
\langle m \rangle &= 0.19 \text{eV}^{+0.28}_{-0.17} \\
\langle m \rangle &= 0.22 \text{eV}^{+0.28}_{-0.17} \text{(HPD)} \\
\langle m \rangle &= 0.31 \text{eV}^{+0.16}_{-0.26} \text{(equal-tailed)}
\end{align*}
\]
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Future Work

• Precision in Theoretical prediction
  – To prepare forthcoming DESI data with higher precision, theoretical prediction for nonlinearity in redshift space should be more elaborated up to higher k where the effect of massive neutrino comes in.
  – Alternatively, templates could be supplied by neutrino simulations. (similar manner to Zheng & Song 2016)
Future Work

• Precision in Theoretical prediction
• with full-scale information from CMB instead of one distance scale.
• using SDSS DR12.
Summary

• The effect of massive neutrino with mass < 1 eV, which decoupled when it was relativistic & became non-relativistic after LSS, affect anisotropic galaxy clustering (SDSS DR11 CMASS at \( z_{\text{eff}} = 0.57 \)), which let us access neutrino mass to give \( m = 0.19eV^{0.28}_{0.17} \) in 68% C.L.
  – TNS model is available for massive neutrino with \( k_{\text{max}} < 0.1 \).
  – Our results are conservative in the existence of local bias.
  – Free form of Dark energy doesn’t help us to constrain neutrino mass, but consistent with the previous works.
  – Cosmological constant with CMB distance measure can help us for neutrino mass.
  – Type of credible/confidence Interval doesn’t change much our results.
Thank you!