Analysis of Anisotropic Galaxy Clustering with Massive Neutrino Using BOSS DR11

(w/ Y. -S. Song)

CosKASI

(Cosmology group at Korea Astronomy and Space Science Institute)

Minji Oh
The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which shows that neutrinos have mass”
Previously on our work (RSD Analysis)

**Redshift Space Distortion (RSD)**

: Anisotropic features in the clustering pattern of galaxies in redshift space

- **Main features**
  - At linear regimes,
    - Kaiser effect- squeezes clustering pattern along line of sight
  - At non-linear regimes,
    - Finger of God effect- elongates clustering along line of sight
    - caused by the random virial motions of galaxies residing at halos
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\[ \xi^s(\sigma, \pi) \quad \tilde{P}(k, \mu) \]
Previously on our work (RSD Analysis)
Measurement: fitting method

• Fitting by rescaling the transverse and radial distances

\[ \sigma_{\text{fid}} = \frac{D_A^{\text{fid}}}{D_A^{\text{true}}} \sigma_{\text{true}}, \quad \pi_{\text{fid}} = \frac{H^{-1\text{fid}}}{H^{-1\text{true}}} \pi_{\text{true}} \]

\[ \xi_{\text{fid}}(\sigma_{\text{fid}}, \pi_{\text{fid}}) \leftarrow \text{fitted by rescaling} \quad \xi_{\text{true}}(\sigma_{\text{true}}, \pi_{\text{true}}) \]

The observed anisotropy Correlation Function ↑
using ‘LCDM caaaahhhhoncordance mode

The theoretical C.F. ↑

• The other fitting parameters: \( G_b, G_{\theta}, \) and \( \sigma_p \) (model-independent)
  – \( \sigma_p \) representing non-linear contamination to the power spectra of the density and velocity fields (FoG/ Gaussian)
Previously on our work (RSD Analysis)

**Measurement: cut-off**

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

• In SM of particle physics on $\Sigma m_\nu$,
  – Three species with non-negligible mass
  – Current Experimental constraints on $\Delta m^2$
    
    $\Delta m^2_{\text{sun}} \equiv \Delta m^2_{12} = m^2_2 - m^2_1 = 7.58 \times 10^{-5}$
    
    $\left|\Delta m^2_{\text{atm}}\right| \equiv \left|\Delta m^2_{13}\right| = m^2_3 - m^2_1 = 2.35 \times 10^{-3}$

    gives two types of mass hierarchy. (negligible at the level of sensitivity of Planck)

• The effective number of species, $N^\text{eff}_\nu = 3.046$
  – includes an effect of neutrino decoupling
    (partial heating of neutrinos during the $e^\pm$ annihilations)

Particle Data Group (2014)

Mangano, Miele, Pastor, Peloso (2002)
Neutrino from Planck

• Constraint on the summed neutrino mass
  \[ \Sigma m_\nu < 0.66eV (95\%; \text{Planck} + \text{WP} + \text{high}L) \]
  assuming that three species of degenerate massive neutrinos in standard cosmology.

  \[ \text{Planck Collaboration (2013)} \]

• Background physics on a way of constraining with CMB \( \Sigma m_\nu \)
  – lensing effect (at high \( l \))
  – the ISW effect (at low \( l \))
  – ...

  \[ \text{Kaplinghat, Knox, Song (2003)} \]
Neutrino mass range

- Neutrino starts to contribute to clustering of matter when it becomes a non-relativistic particle, $m_\nu < T_{\text{background}}$.
- Neutrino with $0.0\,\text{eV} \leq m_\nu \leq 1.0\,\text{eV}$ becomes non-relativistic after LSS.
Neutrino mass range

• Neutrino starts to contribute to clustering of matter when it becomes a non-relativistic particle, $m_{\nu} < T_{\text{background}}$.

• Neutrino with $0.0eV \leq m_{\nu} \leq 1.0eV$ becomes non-relativistic after LSS.

• With this range, using the ‘Planck 2013 prior’ to fix the shape of $P(k)$ at LSS and treat $P(k)$ as broad band after LSS ($\omega_c = 0.12038$, $\omega_b = 0.022032$ at LSS) is reasonable.
Parameterization of Neutrino effect

\[ \lambda_{FS} \sim 4.2 \sqrt{\frac{1+z}{\Omega_{m,0}}} \left( \frac{eV}{m_\nu} \right) Mpc / h \]

\[ k > k_{FS} = \frac{2\pi}{\lambda_{FS}} : \text{suppression} \]

Variation of \( m_\nu \) with fixed \( h=0.6711 \)

\[ \Omega_m = \Omega_b + \Omega_c + \Omega_\nu \]
where \( \Omega_\nu = m_\nu / 94h^2 eV \)

\[ P(k)/h^3 [\text{Mpc}^3] \]

- LCDM + one \( \nu \) with \( m_\nu=0.00eV \)
- LCDM + one \( \nu \) with \( m_\nu=0.32eV \)
- LCDM + one \( \nu \) with \( m_\nu=0.70eV \)
Parameters under consideration

\[ P(k)/h \text{ [Mpc}^3\text{]} \]

- \( m_\nu, H^{-1}, D_A, G_g, G_\theta, \sigma_p \)

- \( \text{-> Control scale-dependent variation} \)
- \( \text{-> Control scale-independent overall amplitude} \)

2015 CosPA
Parameters under consideration

\[ P(k)/h^3 \]

\[ kh \text{ [1/Mpc]} \]

**Variation of** \( m_\nu \) **with fixed** \( h=0.6711 \text{ LCDM} + \text{ one} \)

- \( m_\nu = 0.00\text{eV} \)
- \( m_\nu = 0.32\text{eV} \)
- \( m_\nu = 0.70\text{eV} \)

**-> Control**

- scale-independent overall amplitude
- scale-dependent damping
Theoretical model on $P(k)$ in Redshift Space Distortion (RSD)

- Improvement in 2D Power spectrum in redshift space
  - Kaiser (1987)
    $$ P_{Kaiser}(k, \mu) = P_{\delta\delta}^{lin}(k) + 2\mu^2 P_{\Theta}^{lin}(k) + \mu^4 P_{\Theta\Theta}^{lin}(k) $$
  
  - Scoccimarro (2004)
    $$ \tilde{P}_{scoccimarro}(k, \mu) = \left\{ P_{\delta\delta}(k) + 2\mu^2 P_{\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) \right\} G^{FoG}(k\mu\sigma_p) $$
  
  - Taruya, Nishimichi, and Saito (Improved) (2010)
    $$ \tilde{P}_{TNS}(k, \mu) = \left\{ P_{\delta\delta}(k) + 2\mu^2 P_{\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k, \mu) + B(k, \mu) \right\} G^{FoG}(k\mu\sigma_p) $$

$\rightarrow$ Higher order correction
Theoretical model on $P(k)$ in Redshift Space Distortion (RSD)

- Improvement in 2D Power spectrum in redshift space
  - Taruya, Nishimichi, and Saito (Improved) (2010)

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\tilde{P}_{\text{TNS}}(k, \mu) = \left\{ P_{\delta \delta}(k) + 2\mu^2 P_{\Theta}(k) + \mu^4 P_{\Theta \Theta}(k) + A(k, \mu) + B(k, \mu) \right\} G^{FoG}(k\mu\sigma_p)
\]

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

- Higher order correction
  - (tree-level used to make overall 1-loop correction)
Redshift Space Distortion (RSD)

- Decomposition

\[
\tilde{P}(k, \mu) = \{[P_{\delta\delta}^{\text{lin}}(k) + \delta P_{\delta\delta}(k)] \\
+ \mu^2[P_{\delta\delta}^{\text{lin}}(k) + \delta P_{\delta\delta}]
+ \mu^4[P_{\Theta\Theta}^{\text{lin}}(k) + \delta P_{\Theta\Theta}]
+ A(k, \mu) + B(k, \mu) \} \times G^ \text{FoG} (k\mu; \sigma_p)
\]

- Virialized random motion of galaxies (Gaussian form): non-perturvtative

Song, Nishimichi, Taruya and Kayo (2013)
Redshift Space Distortion (RSD)

- From $\tilde{P}(k, \mu)$ to $\xi^s(\sigma, \pi)$
  - By Fourier transformation

$$\xi^s(\sigma, \pi) = \int \frac{d^3k}{(2\pi)^3} \tilde{P}(k, \mu)e^{ik \cdot \tilde{s}}$$

$$v = \pi / s, \quad s = (\sigma^2 + \pi^2)^{1/2}$$

$$= \sum_{\text{even } l} \xi_l(s) P_l(v)$$

where $P_l$ is the Legendre polynomials

$$\xi_l(s) = i^l \int k^2 dk P_l(k) j_l(ks)$$

$$P_0(k) = p_0(k)$$

$$P_2(k) = 5 / 2 [3p_1(k) - p_0(k)]$$

$$P_4(k) = 9 / 8 [35p_2(k) - 30p_1(k) + 3p_0(k)]$$

$$P_6(k) = 13 / 16 [231p_3(k) - 315p_2(k) - 105p_1(k) + 5p_0(k)]$$

$$p_n(k) = 1 / 2 [\gamma(n + 1 / 2, \kappa) / \kappa^{n+1/2} Q_0(k) + \gamma(n + 3 / 2, \kappa) / \kappa^{n+3/2} Q_2(k) + \gamma(n + 5 / 2, \kappa) / \kappa^{n+5/2} Q_4(k) + \gamma(n + 7 / 2, \kappa) / \kappa^{n+7/2} Q_6(k)]$$

$$\kappa = k^2 \sigma_p^2$$

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2-point correlation function, $\xi(\sigma, \pi)$

$$\xi^e(\sigma, \pi) = \int \frac{d^3 k}{(2\pi)^3} \tilde{P}(k, \mu) e^{ik\cdot x}$$

$$= \sum_{\text{even } l} \xi_l(s) P_l(\nu)$$

where $P_l$ is the Legendre polynomials.
Result: constraint on $m_\nu$

$\Sigma m_\nu < 0.66 eV (95\%; Planck + WP + highL)$

$0.341^{+0.36}_{-0.34} eV$
Result: $m_\nu$ vs $G_\Theta$
Conclusion

• Using anisotropic RSD analysis with BOSS DR11 data, neutrino mass is constrained to $0.341^{+0.36}_{-0.34}\,eV$, consistent with Planck2013.

• 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.
Thank you 😊
Neutrino from Planck

• Constraint on the summed neutrino mass
  \[ \Sigma m_\nu < 0.66eV (95\%; Planck + WP + highL) \]
  assuming that three species of degenerate massive neutrinos in standard cosmology.

Planck Collaboration (2013)

• Background physics on a way of constraining
  \[ \Sigma m_\nu \] with CMB: through the ISW effect
  \[ \Sigma m_\nu \uparrow \rightarrow \text{expansion rate} \uparrow \rightarrow \text{scale-dependent gravitational potential decay} \]
  (Jeans length)

Parameters under consideration

- Six parameter estimation:
  \( m_\nu, H^{-1}, D_A, G_g, G_\theta, \sigma_p \)

- Fix \( \omega_c = 0.12038 \), \( \omega_b = 0.022032 \) with the Planck 2013 prior.