Measuring neutrino mass imprinted on the anisotropic galaxy clustering

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   - How Massive Neutrino affect Galaxy Clustering In redshift space?

II. Theoretical Modeling & Methodology

III. Results

IV. Future work

N_{eff}

$\sum m_\nu$

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N_{eff}

Decoupling of Neutrino

$$\rho_R = \sum_{i \in R} g_i \int d^3 p f(p) E(p) = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \cdot 3 \right] \rho_\gamma$$

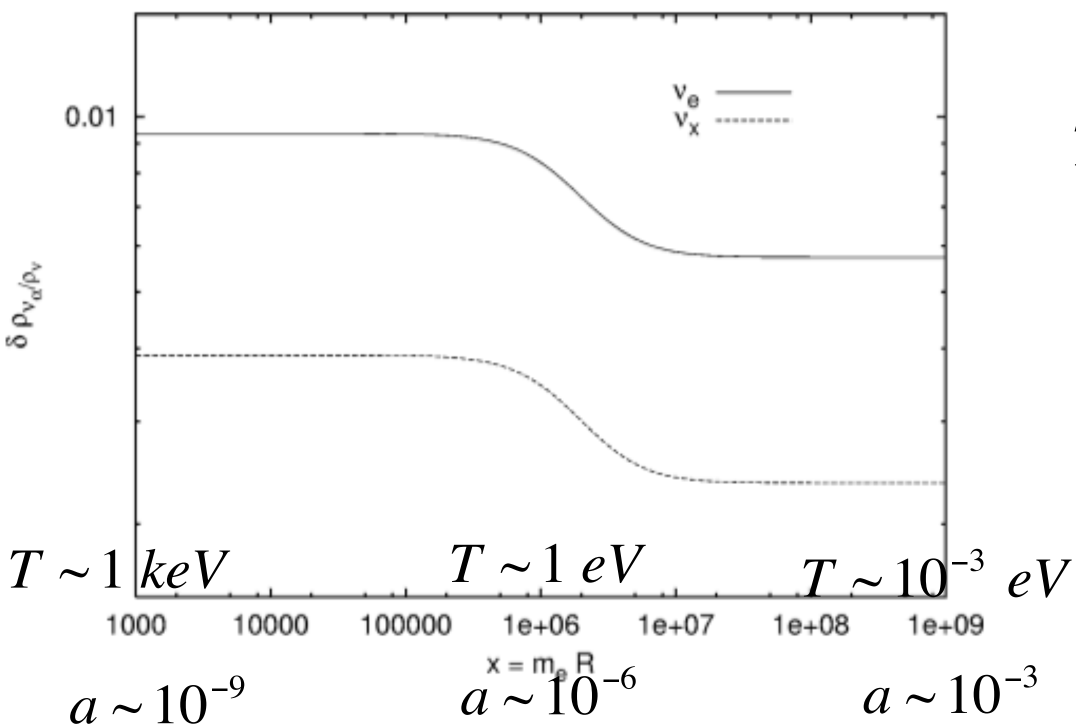
- The contribution from relativistic particles to the energy density.
- If they are in equilibrium with cosmic plasma, FD/BE distribution can be used.
- But, neutrino decoupled at around a few MeV, followed by e-e+ annihilation, which causes heating photons.
- For instantaneous decoupling approximation:

$$T_\gamma / T_\nu = (11/4)^{1/3} \cong 1.40102$$

N_{eff}

Decoupling of Neutrino

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



$$T_\gamma / T_\nu = (11/4)^{1/3} \cong 1.40102$$

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

Mangano+ (2002)

Decoupling of Neutrino

$$T_\gamma / T_\nu = (11/4)^{1/3} \cong 1.40102$$

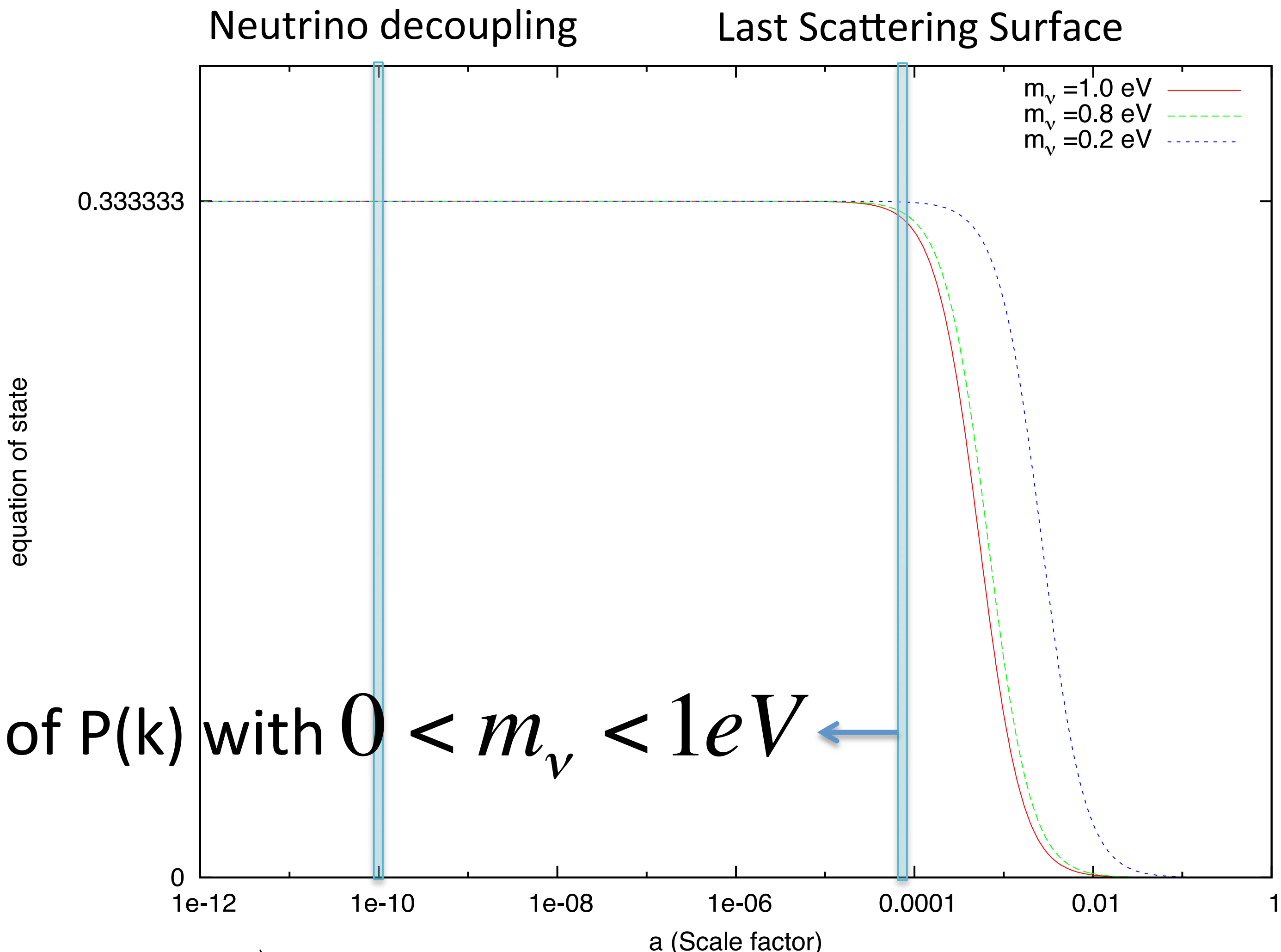
$$\rho_R = \sum_{i \in R} g_i \int d^3 p f(p) E(p) = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right] \rho_\gamma$$

- 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),

$$N_{eff} = 3.046$$

Mangano+ (2005)

After *decoupling*, starts to stream freely



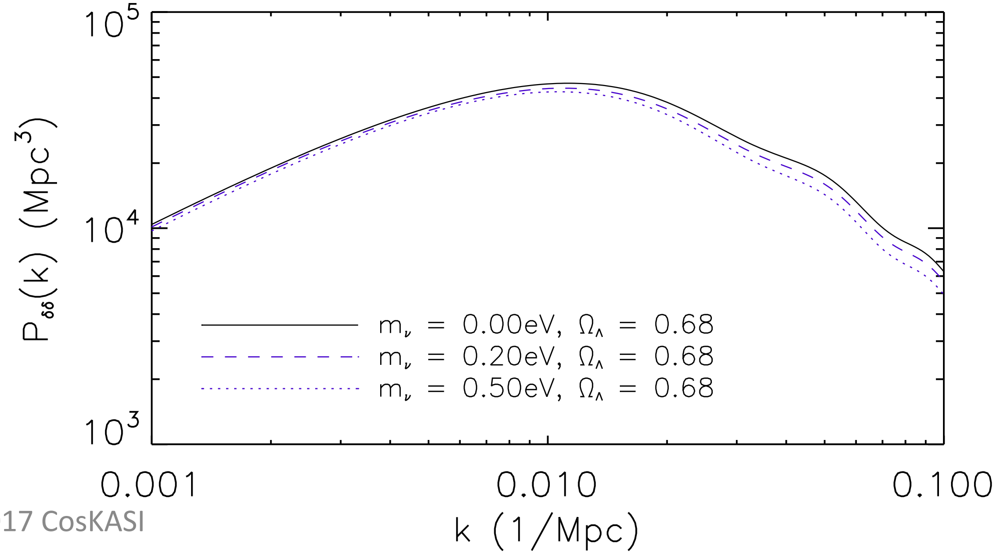
Fix the shape of P(k) with $0 < m_\nu < 1eV$

$$\sum m_\nu \rightarrow m_\nu(degenerate)$$

Effect of Massive neutrino on LSS

Yvonne Y. Y. Wong (2011)

- Free-streaming scale of massive neutrino with mass m_ν :
$$\lambda_{FS} \sim 4.2 \sqrt{\frac{1+z}{\Omega_{m,0}}} \left(\frac{eV}{m_\nu} \right) Mpc/h$$
- Structure formation smaller than this scale $k > k_{FS}$ is suppressed, *which provides the access to the neutrino mass in cosmology.*



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- How Massive Neutrino affect Galaxy Clustering In redshift space?
- we restrict out analysis to the standard case, where departure of N_{eff} from 3 is solely due to neutrino heating by e-e+ annihilation, which gives The effective number of relativistic species $N_{eff} = 3.046$.
- Neutrino 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)

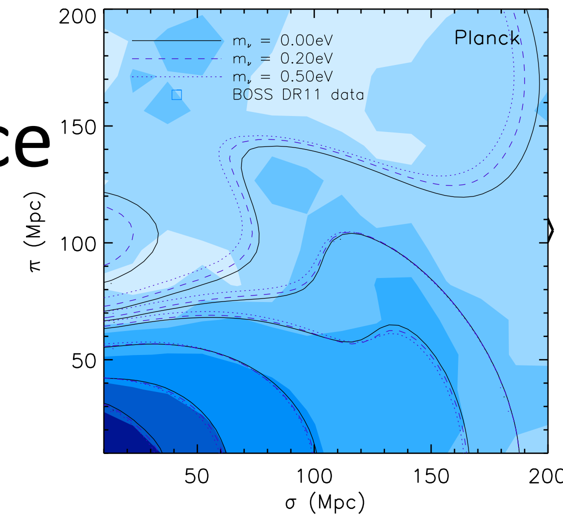
- Improvement in 2D Power spectrum in redshift space
  - Kaiser(1987)

$$P^{(s)}_{Kaiser}(k,\mu) = P^{lin}_{\delta\delta}(k) + 2\mu^2 P^{lin}_{\delta\Theta}(k) + \mu^4 P^{lin}_{\Theta\Theta}(k)$$

  - Scoccimarro(2004)

$$P^{(s)}_{scoccimarro}(k,\mu) = \left\{ P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) \right\} G^{FoG}(k\mu\sigma_p)$$

  - Taruya, Nishimichi, and Saito (Improved)(2010)



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

-> Higher order correction

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

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

Taruya, Nishimichi, and Saito (2010)

where

$$j_1 = -ik\mu$$

$$A_1 = u_z(\vec{r}) - u_z(\vec{r}')$$

$$A_2 = \delta(\vec{r}) + \nabla_z u_z(\vec{r})$$

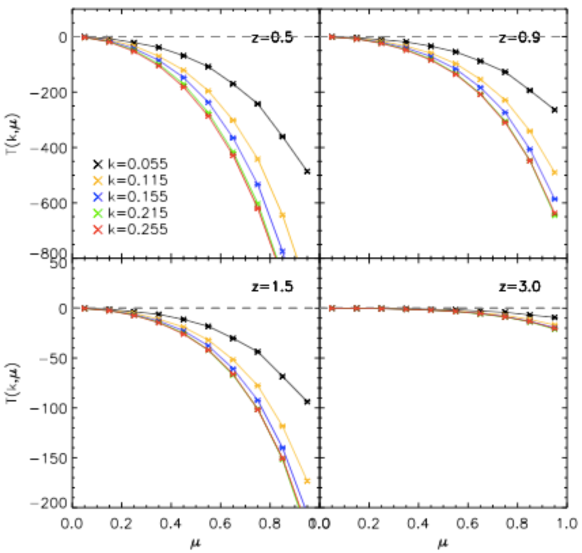
$$A_3 = \delta(\vec{r}') + \nabla_z u_z(\vec{r}')$$

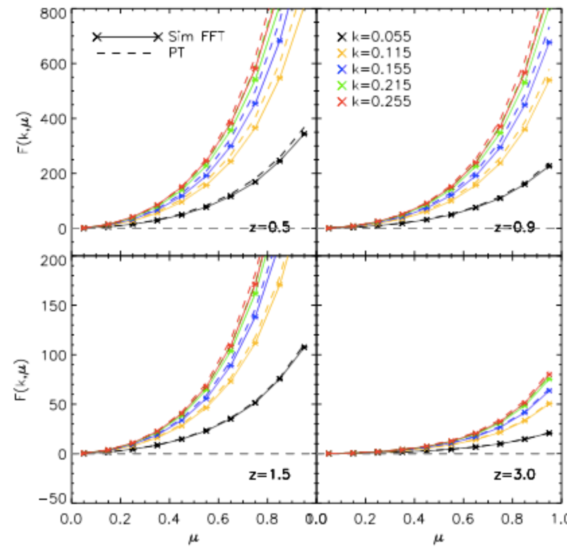
Zheng & Song (2016)

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

$$= G^{FoG}(k\mu\sigma_p) \left\{ \begin{array}{l} P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) \\ + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu) \end{array} \right\}$$

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



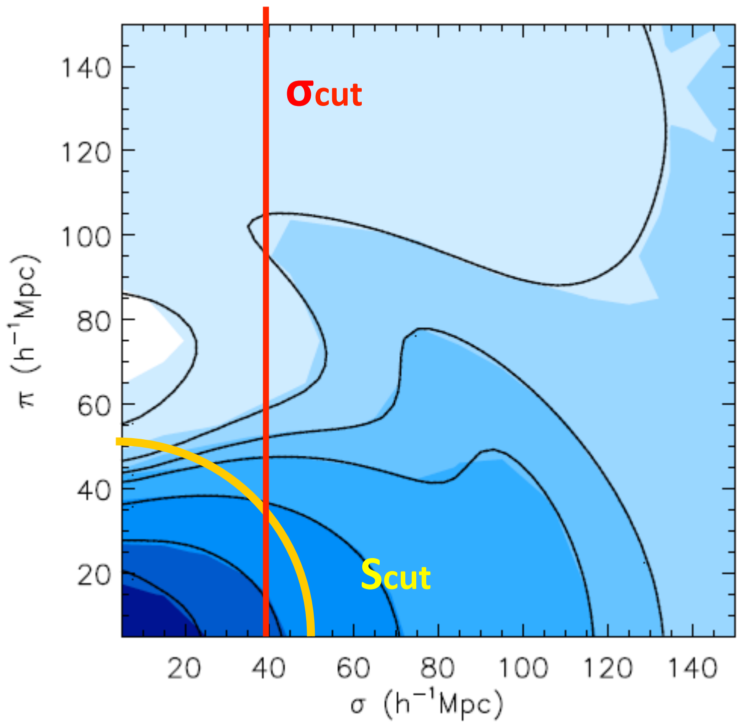


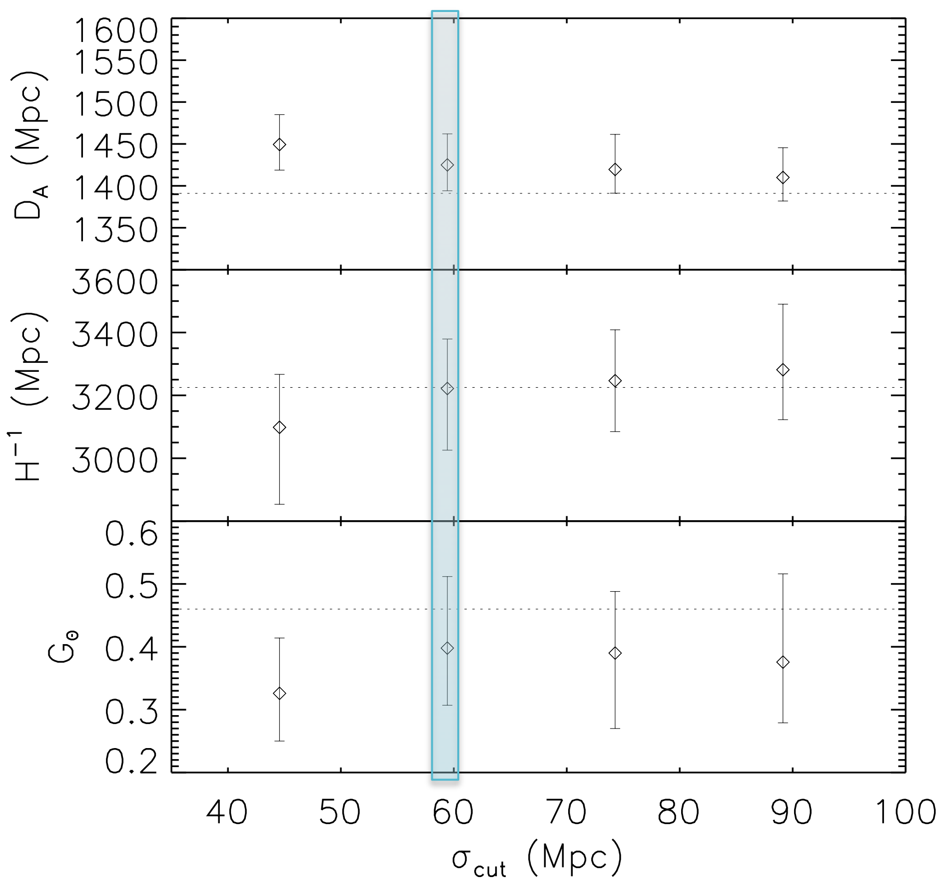
Zheng & Song (2016)

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

$$= G^{FoG}(k\mu\sigma_p) \left\{ \begin{array}{l} P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) \\ + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu) \end{array} \right\}$$

Cut-off to consider
Current status of RSD modeling





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

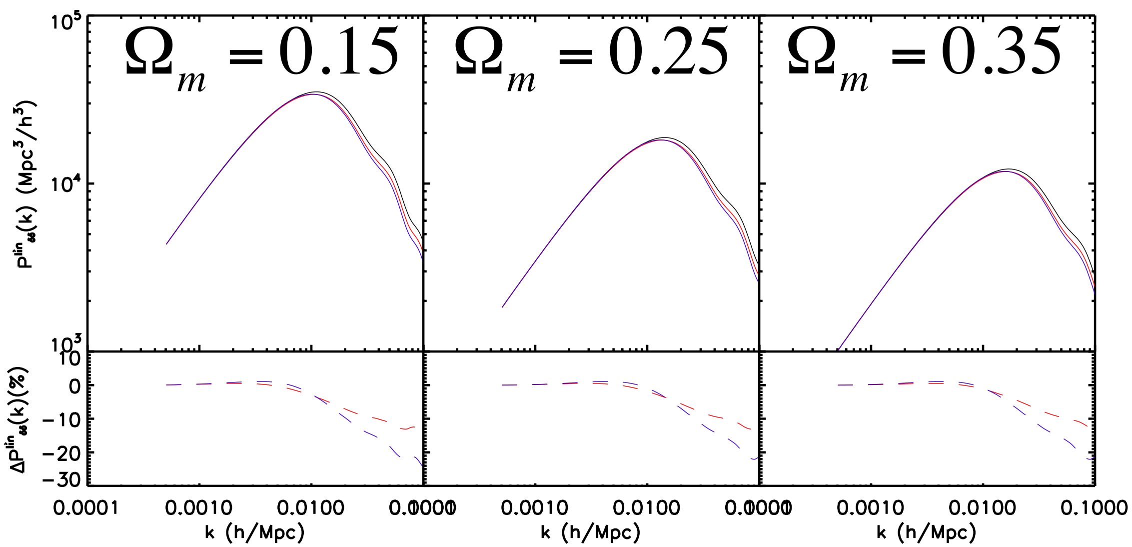
$$k_{\max} \sim 0.07h / Mpc$$

Is TNS model reliable to calculate Non-linear mapping including massive neutrino?

$$\frac{\Delta P}{P} \sim 8 \times f_\nu = 0.16 \; for \; m_\nu = 0.3 eV$$

$$where \; f_\nu \equiv \frac{\Omega_\nu}{\Omega_m} \; with \; \Omega_m = 0.31 \; and \; h = 0.68$$

Yvonne Y. Y. Wong (2011)



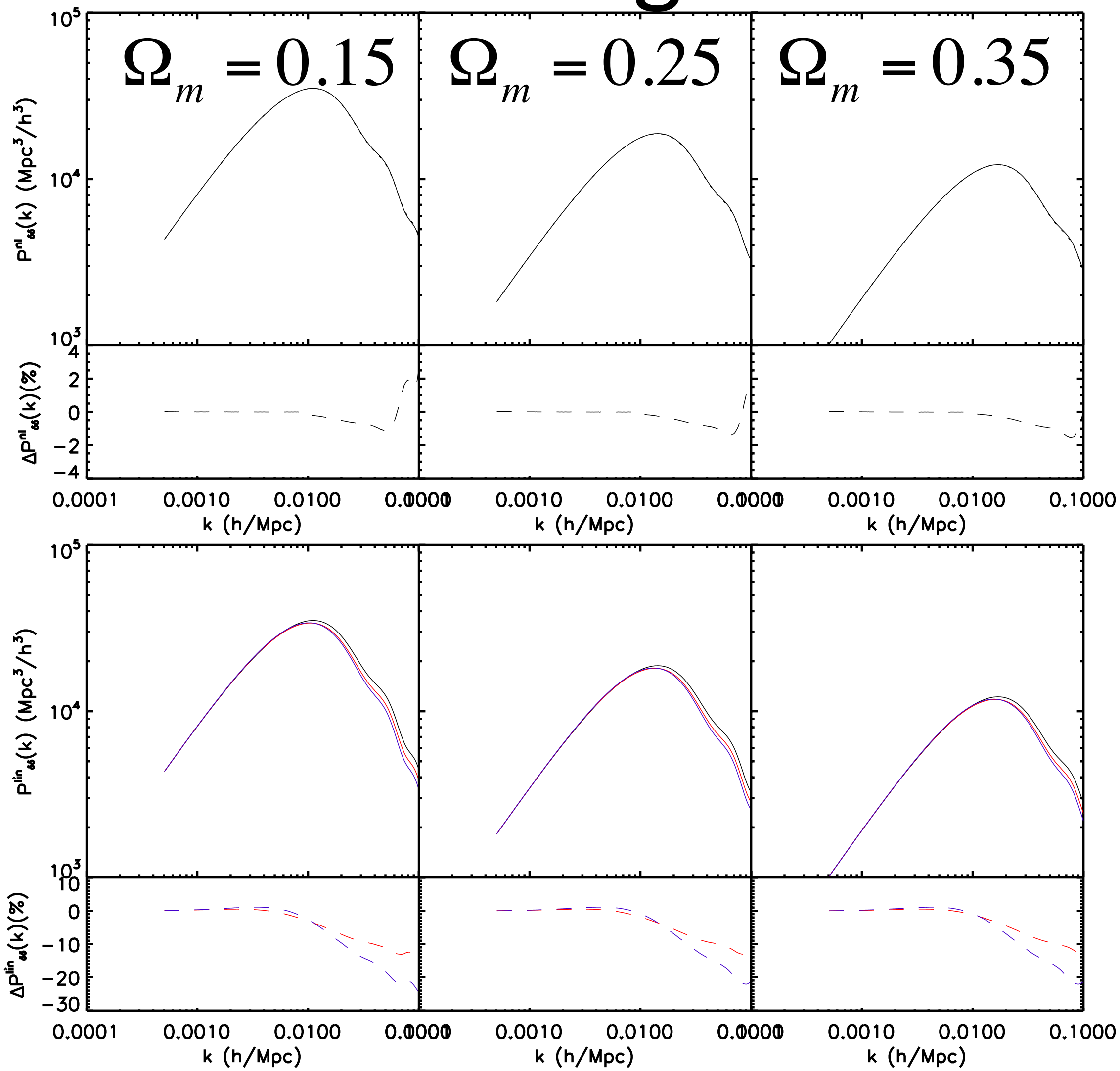
$m_\nu = 0.0$ eV

$m_\nu = 0.3$ eV

$m_\nu = 0.6$ eV

Fractional difference between linear $P_{\delta\delta}(k)$ without and with massive neutrino ~ 15%.

Is TNS model reliable to calculate Non-linear mapping including massive neutrino?



→ Yes

up to k ~ 0.1 h/Mpc

Fractional difference between linear and non-linear $P_{\delta\delta}(k)$ without massive neutrino <5%.

$m_\nu = 0.0$ eV

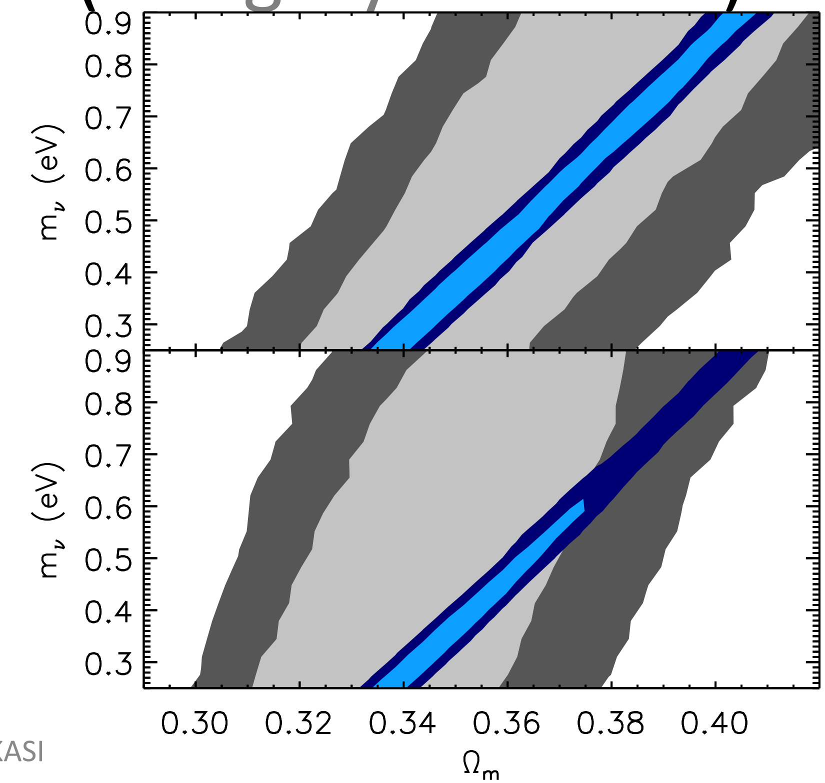
$m_\nu = 0.3$ eV

$m_\nu = 0.6$ eV

Fractional difference between linear $P_{\delta\delta}(k)$ without and with massive neutrino ~ 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).



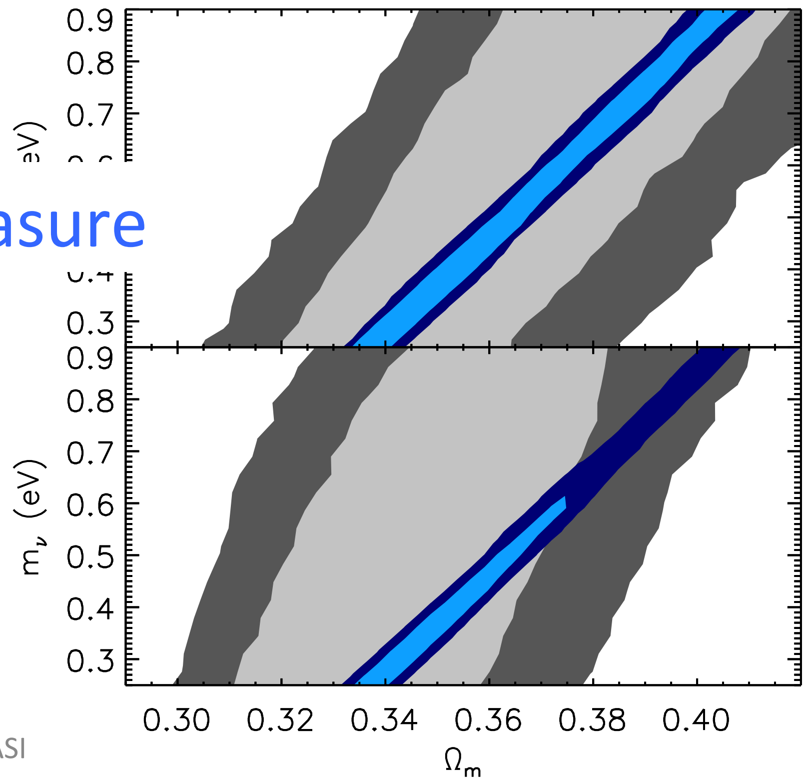
Effective growth VS Scale-dep. growth

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

$$\theta_* = \frac{r_s(z_*)}{D_A(z_*)}$$: CMB distance measure

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

$$r_s(z) = \int_0^{\eta(z)} \frac{d\eta'}{\sqrt{3(1+R)}}$$



Bias effect on neutrino mass constraint

- Beyond the linear bias, b1?

$$P_{g,\delta\delta}(k) = b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + b_2^2 P_{b22}(k)$$

b1 and b2: local bias

$$+ 2b_{s2} b_1 P_{bs2,\delta}(k) + 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k)$$
$$+ 2b_{s2} b_{3nl} \sigma_3^2(k) P^{lin}(k)$$

b_{s2}, and b_{3nl}: non-local bias

$$where\ P_{b2,\delta}(k) = \int \frac{d^3q}{(2\pi)^3} P^{lin}(q) P^{lin}(|\vec{k}-\vec{q}|) F_2^{SPT}(\vec{q},\vec{k}-\vec{q})$$

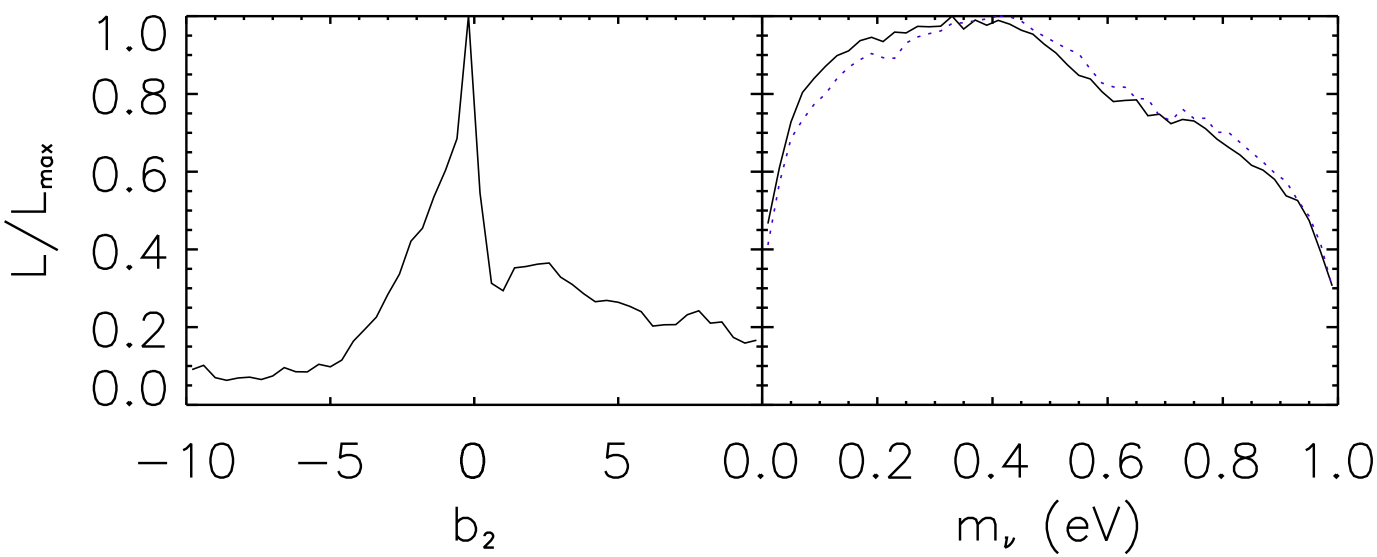
$$P_{b22}(k) = -\frac{1}{2}\int \frac{d^3q}{(2\pi)^3} P^{lin}(q)\left[P^{lin}(q) - P^{lin}(|\vec{k}-\vec{q}|)\right]$$

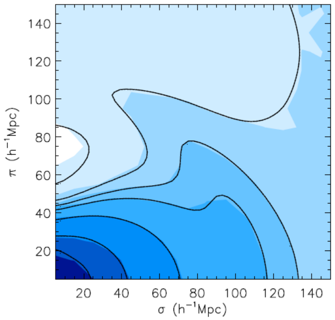
McDonald & Roy (2009)
Gill-Marin+ (2016)

Bias effect on neutrino mass constraint

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

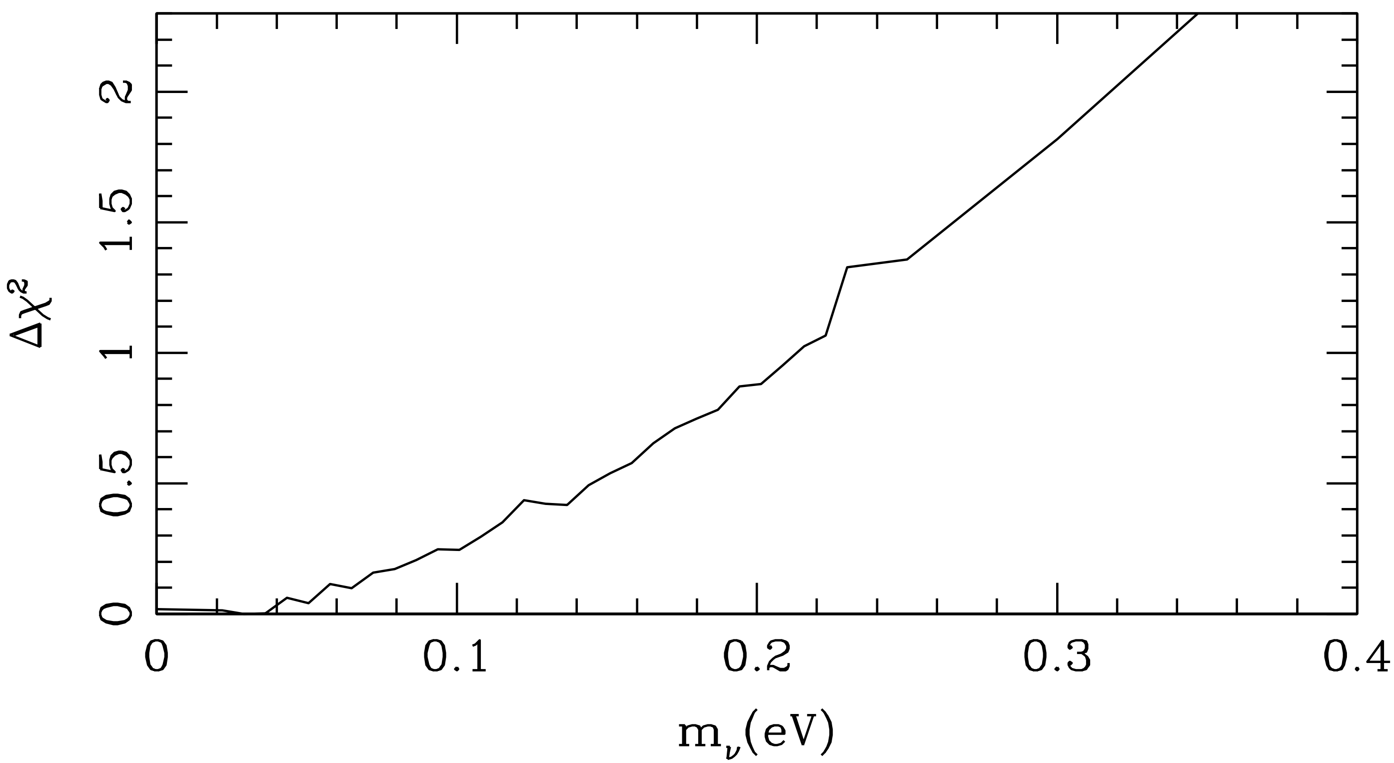
$$P_{g,\delta\delta}(k) = b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + b_2^2 P_{b22}(k)$$





Testing Methodology

- When we apply our methodology to the simulation (SDSS DR11 mock catalogue without massive neutrino), true value reproduced.



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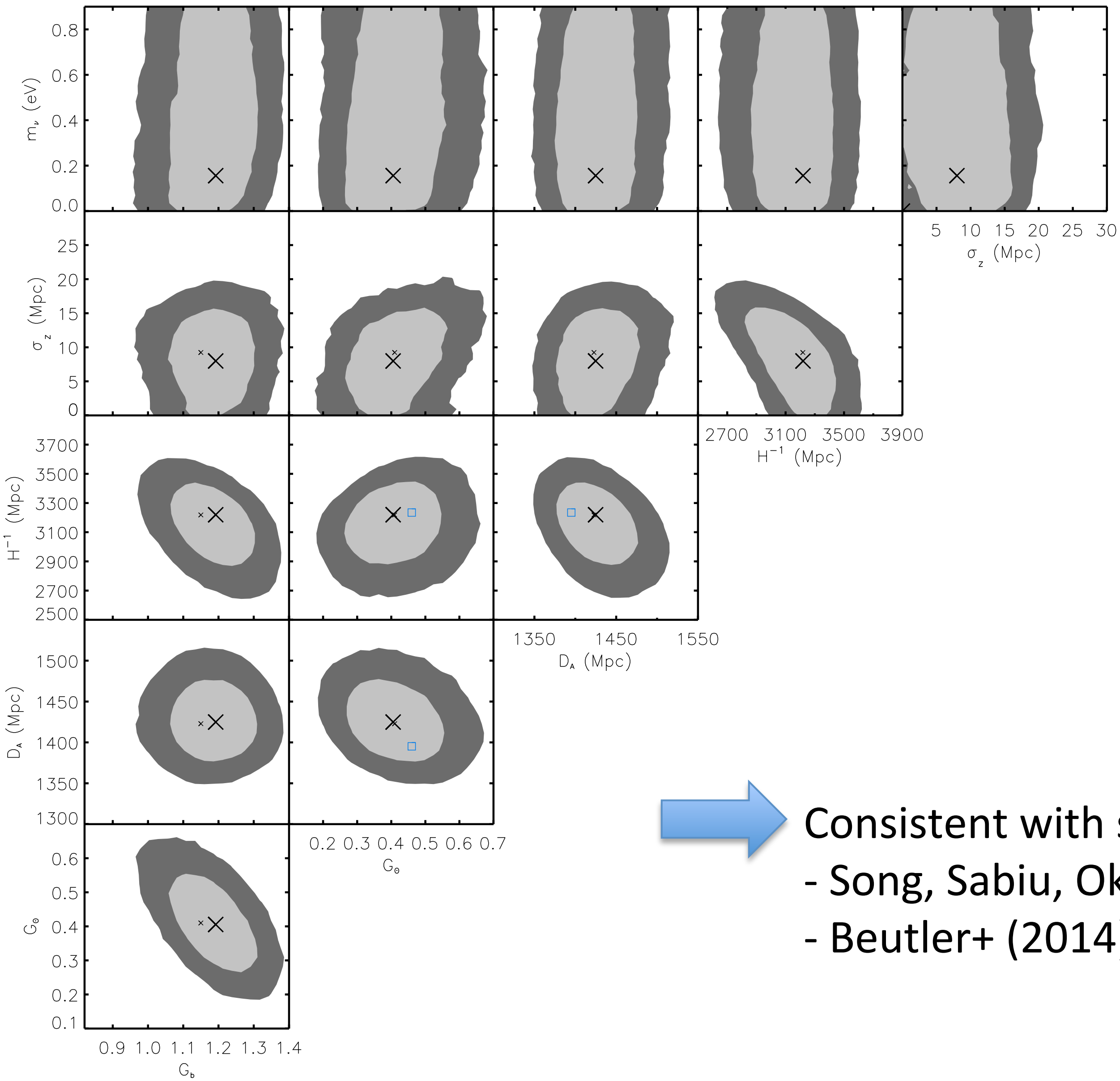
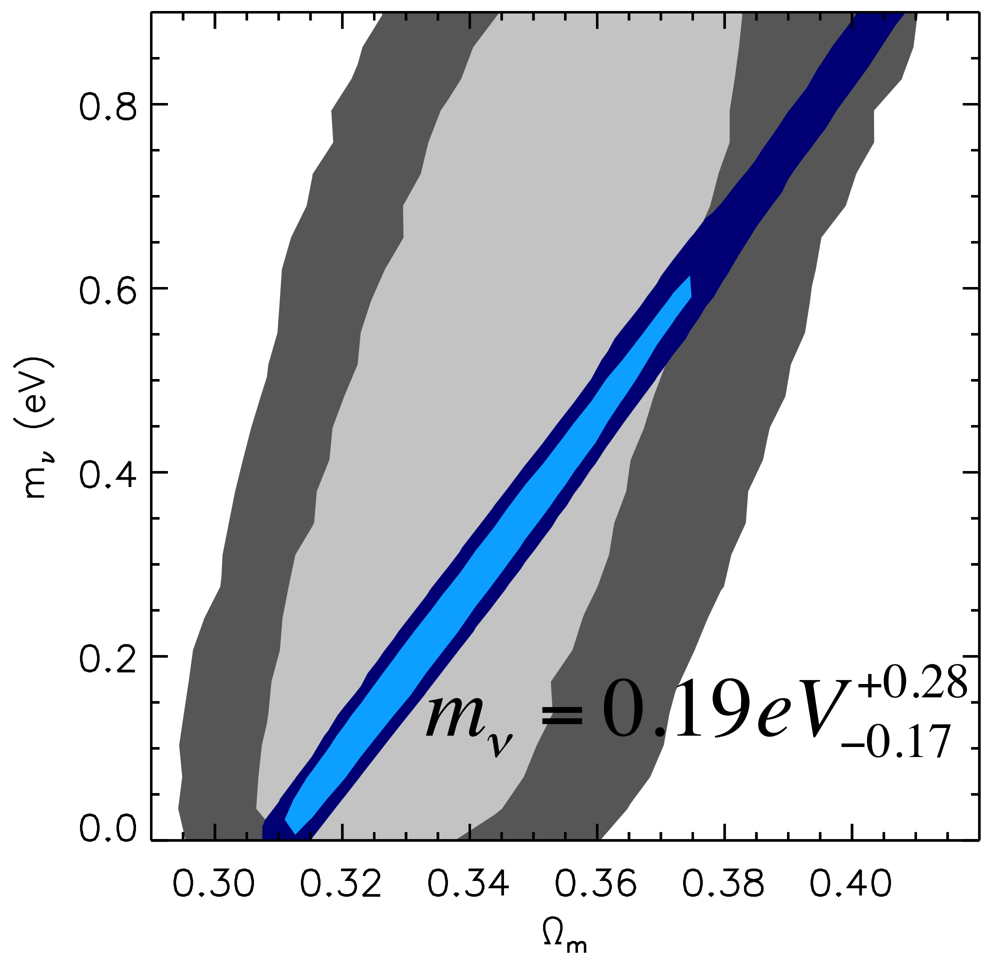
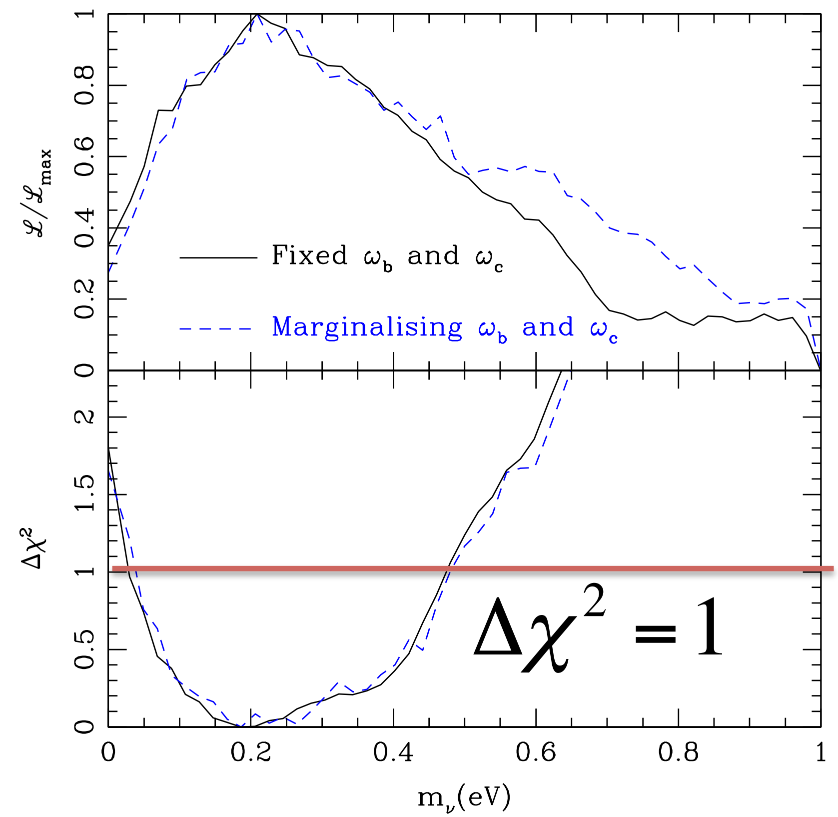
Result on $(D_A, H^{-1}, G_b, G_\theta, \sigma_p, m_\nu)$



Consistent with some previous works:
- Song, Sabiu, Okumura, Oh, Linder (2014)
- Beutler+ (2014)

Result on $(b, \Omega_m, \sigma_p, m_\nu) + \theta_*$ in 68% C. L.





$$m_\nu = 0.22eV^{+0.28}_{-0.17}\,(HPD)$$

$$m_\nu = 0.31eV^{+0.16}_{-0.26}\,(equal\text{-}tailed)$$

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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_{eff} = 0.57), which let us access neutrino mass to give $m_\nu = 0.19eV^{+0.28}_{-0.17}$ in 68% C.L.
  - TNS model is available for massive neutrino with k_{max}<0.1.
  - Our results are conservative in change 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 reporting our results.

Thank you!