

Title: Cosmological measurement of neutrino masses from relative velocities

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URL: <http://pirsa.org/15080010>

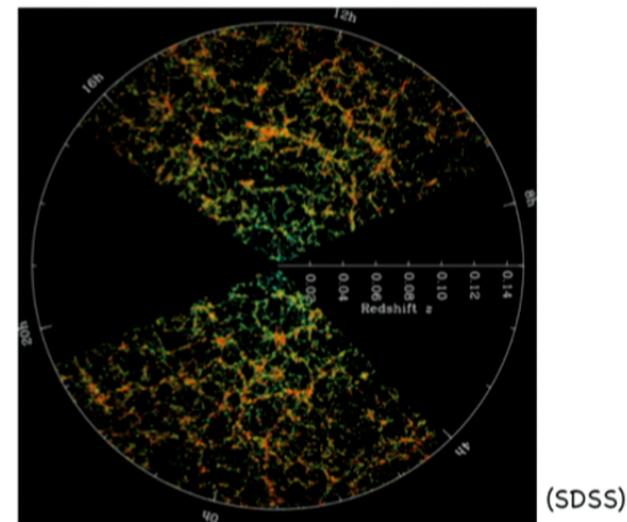
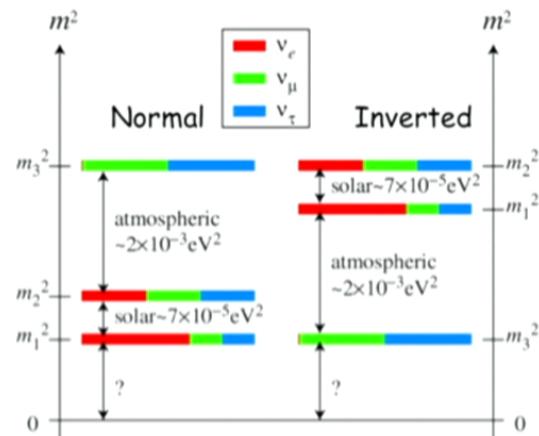
Abstract: Present day streaming motions of neutrinos relative to dark matter and baryons are several hundred km/s, comparable with their thermal velocity dispersion. This results in a unique dipole anisotropic distortion of the matter-neutrino cross power spectrum, which is observable through the dipole distortion in the cross correlation of different galaxy populations. Such a dipole vanishes if not for this relative velocity and so it is a clean signature for neutrino mass. We estimate the size of this effect and find that current and future galaxy surveys may be sensitive to these signature distortions.

Overview

- Probe of neutrino masses
- Bulk flow between neutrinos and CDM
- Cross correlation dipole (theory&simulation)
- Observable consequence
- Discussion

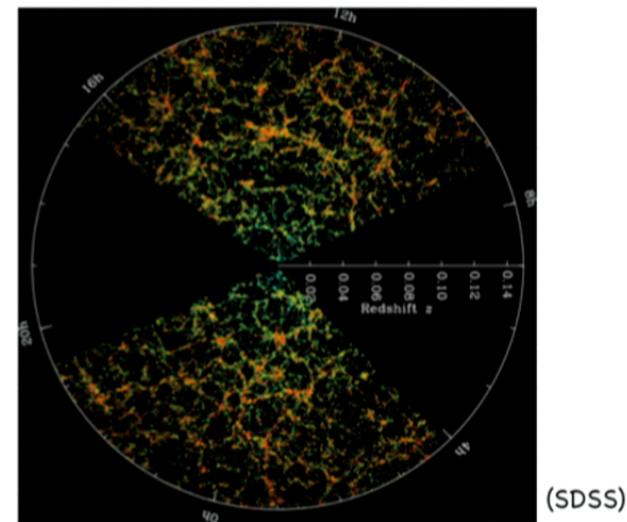
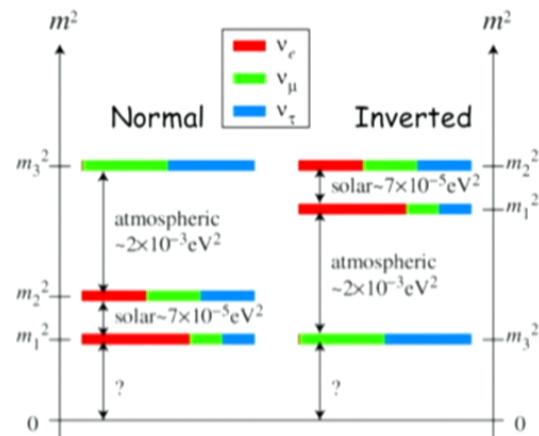
Probe of neutrino mass

- massive particles, mass difference
- absolute mass? mass hierarchy?



Probe of neutrino mass

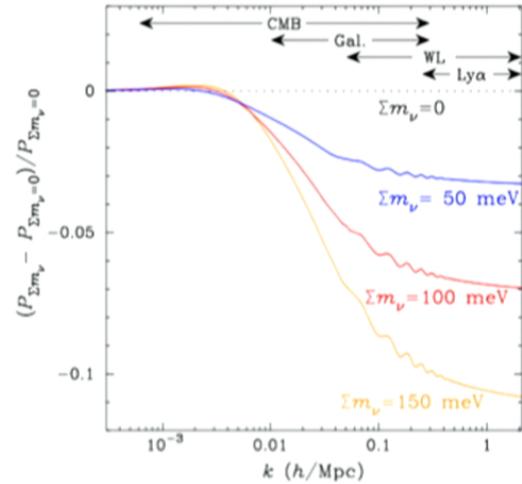
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Neutrinos in cosmology

- large velocity dispersion σ_ν
- no clustering below k_{fs}
- reduce CDM clustering below k_{fs}
- impacts power spectrum at ~% level

Neutrino mass from large scale structure



(K.N. Abazajian et al 2013)

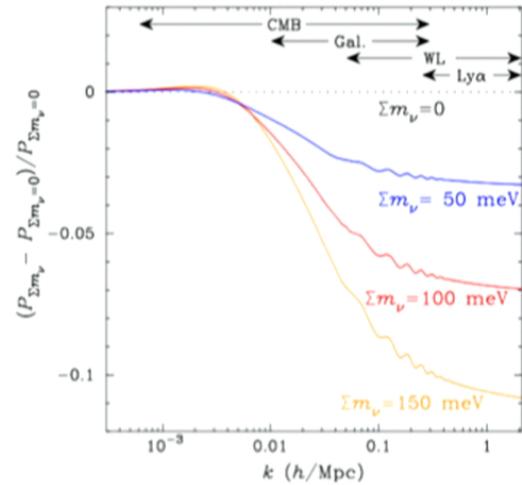
Current status

$$\sum m_\nu < 0.23 \text{ eV} (95\% \text{ C.L.})$$

(P. Ade et al 2015)

Galaxy bias? Baryon physics?

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A new method to determine neutrino mass

- new methods (Zhu et al 2013&2014)
- exploiting relative bulk flow between neutrinos and cold dark matter (similar to baryon-CDM)
- could be observed through cross correlation between different type galaxies
- pros: relative clean problem, suffer less from k-dependent bias, in principle single neutrino mass

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Neutrino bulk velocity field

- Relativistic to non-relativistic
- Neutrino clustering, bulk flow
- typical scale of neutrino bulk flow, k_{fs}

fluid approximation: accurate to 25% for
 $0.05^{\sim}0.5 \text{ eV}$ at $< 0.4 \text{ Mpc/h}$ and $z < 10$

M. Shoji & E. Komatsu (2010)

Velocity from Boltzmann code (CLASS)

- Neutrinos and CDM interact gravitationally
- Basic variable: $\delta(\mathbf{x}, t) = \rho(\mathbf{x}, t)/\bar{\rho}(t) - 1$, $\theta(\mathbf{x}, t) = \nabla \cdot \mathbf{v}(\mathbf{x}, t)$...
- from real space to Fourier space

$$\delta(\mathbf{x}, t) \longrightarrow \delta(\mathbf{k}, t)$$

Real space

$$\mathbf{v}(\mathbf{x}, t) = \nabla v(\mathbf{x}, t)$$

$$\theta(\mathbf{x}, t) = \nabla^2 v(\mathbf{x}, t)$$

Fourier space

$$\mathbf{v}(\mathbf{k}, t) = i\mathbf{k}v(k, t)$$

$$\mathbf{v}(\mathbf{k}, t) = -\frac{i\mathbf{k}}{k^2}\theta(\mathbf{k}, t)$$

Velocity field reconstruction

- adiabatic initial conditions:

$$\delta_c(k) = T_{\delta,c}(k)\zeta(k)$$

$$\delta_X(k) = \frac{T_{\delta,X}(k)}{T_{\delta,c}(k)}\delta_c(k)$$

$$\delta_b(k) = T_{\delta,b}(k)\zeta(k)$$

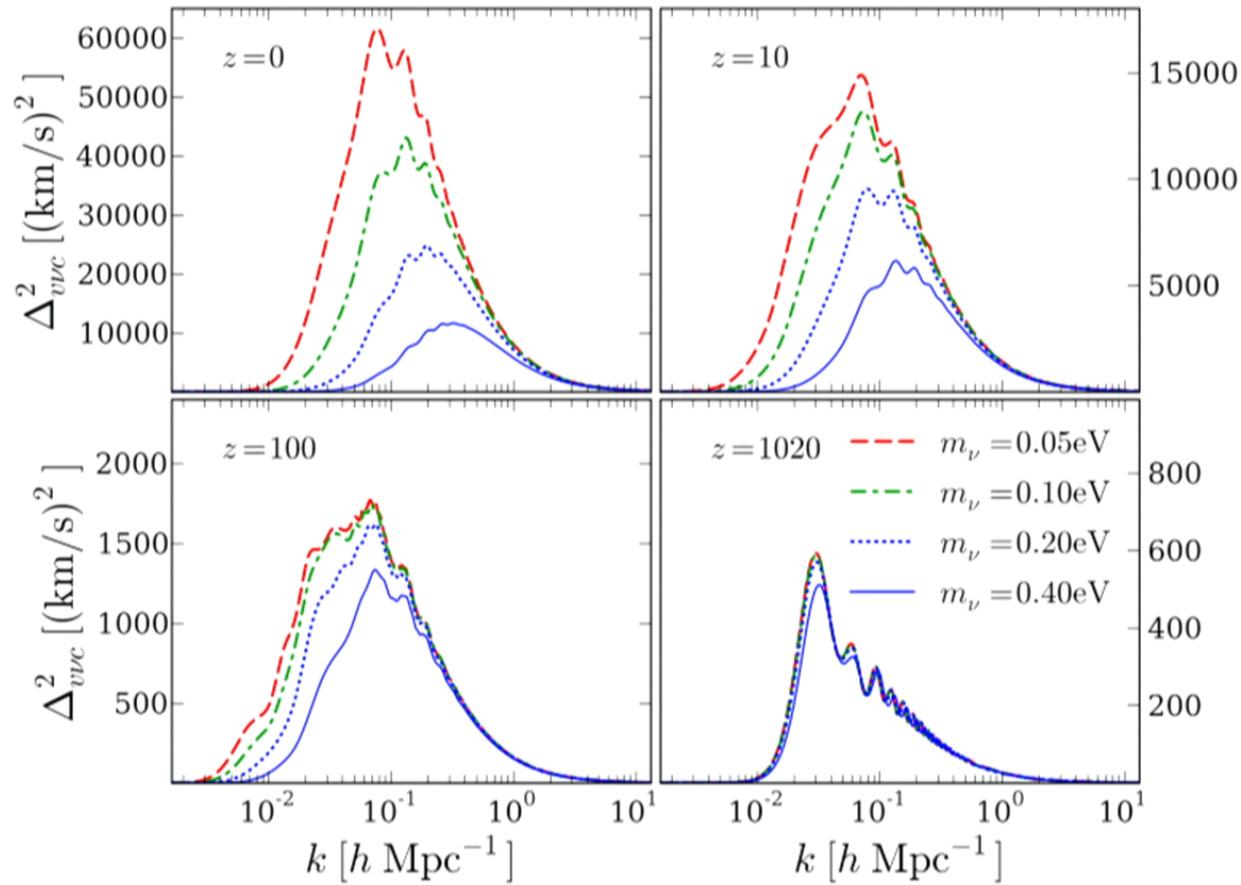
$$\theta_X(k) = \frac{T_{\theta,X}(k)}{T_{\delta,c}(k)}\delta_c(k)$$

$$\theta_\nu(k) = T_{\theta,\nu}(k)\zeta(k)...$$

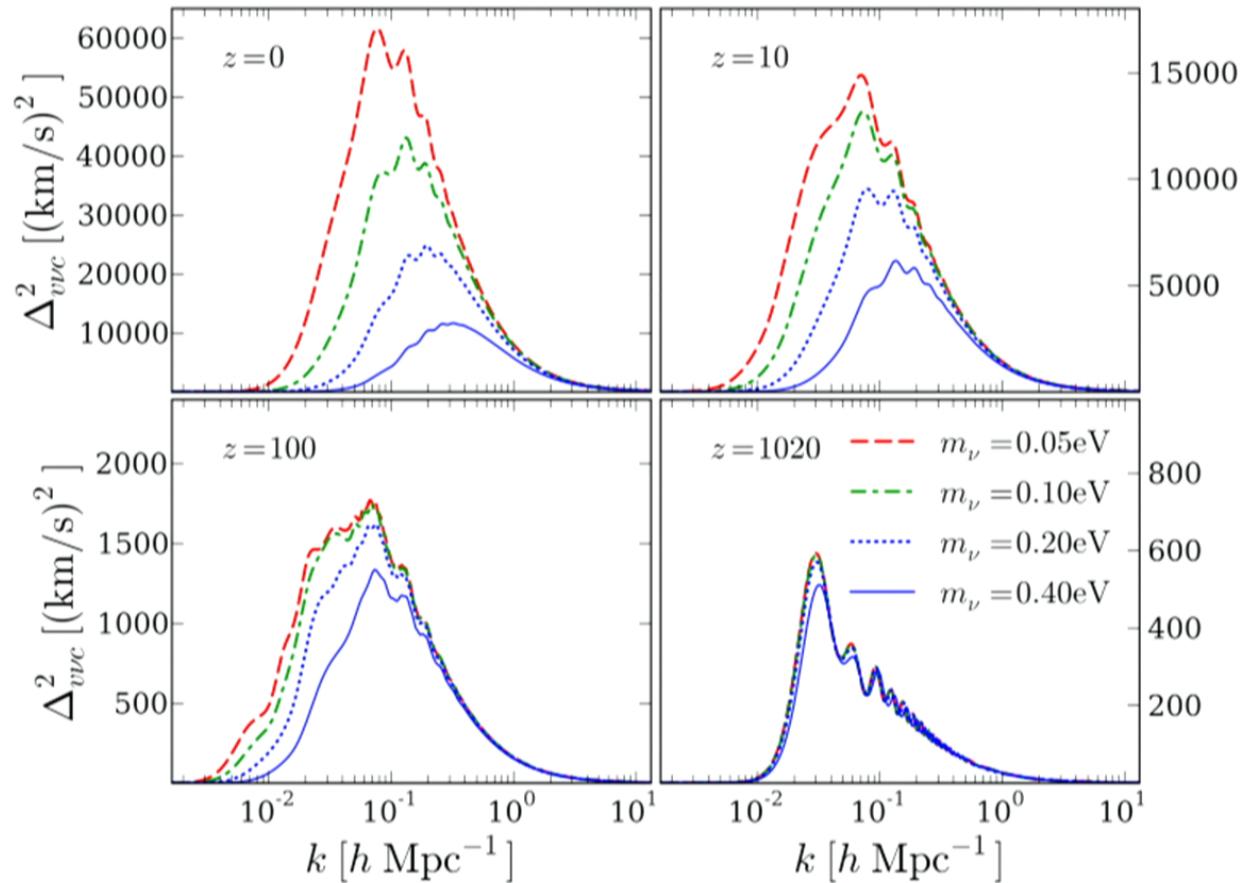
- Relative velocity field between neutrinos and CDM

$$\langle v_{\nu c}^2(z) \rangle = \int \frac{dk}{k} \Delta_\zeta^2(k) \left[\frac{\theta_\nu(k, z) - \theta_c(k, z)}{k} \right]^2$$

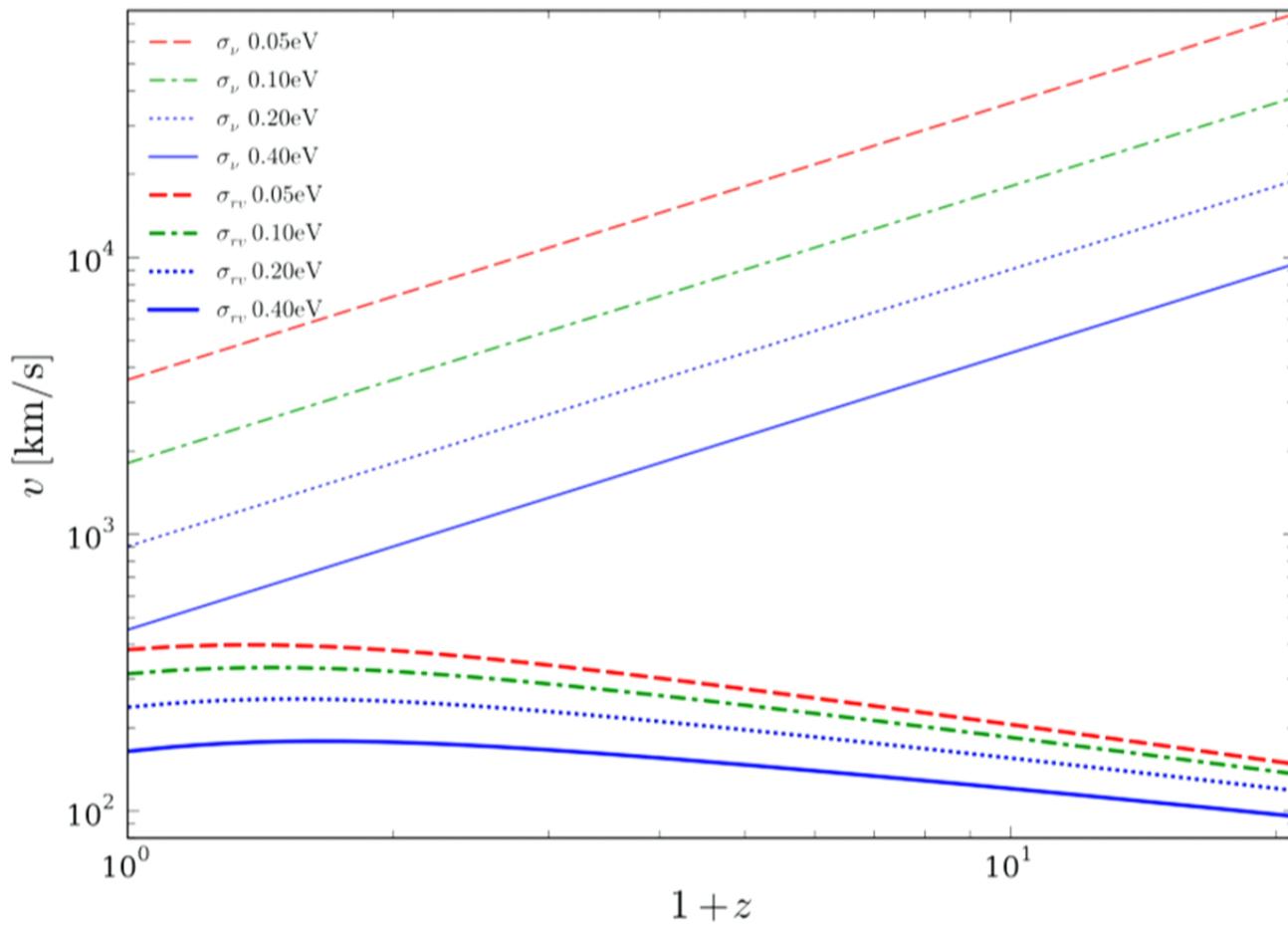
Evolution



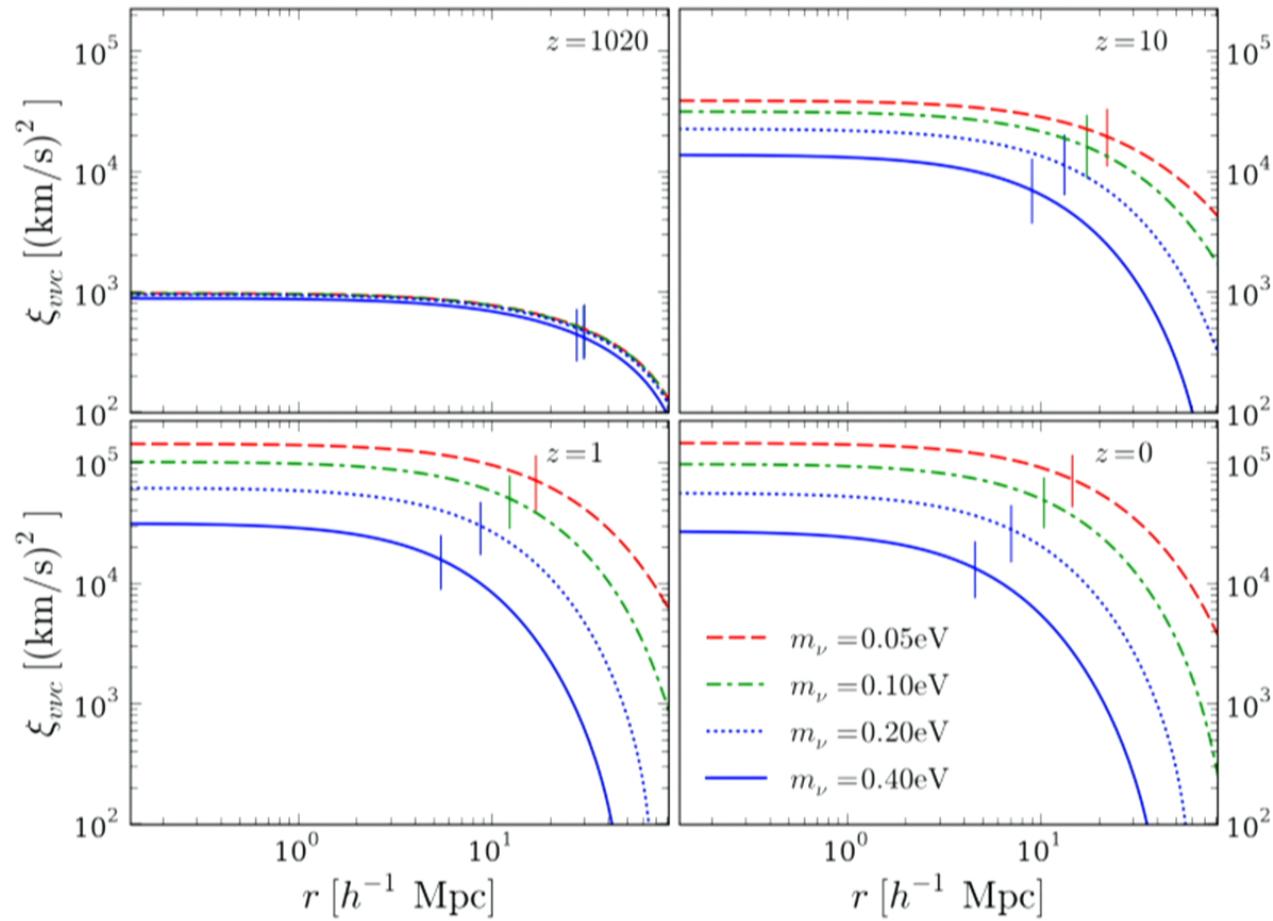
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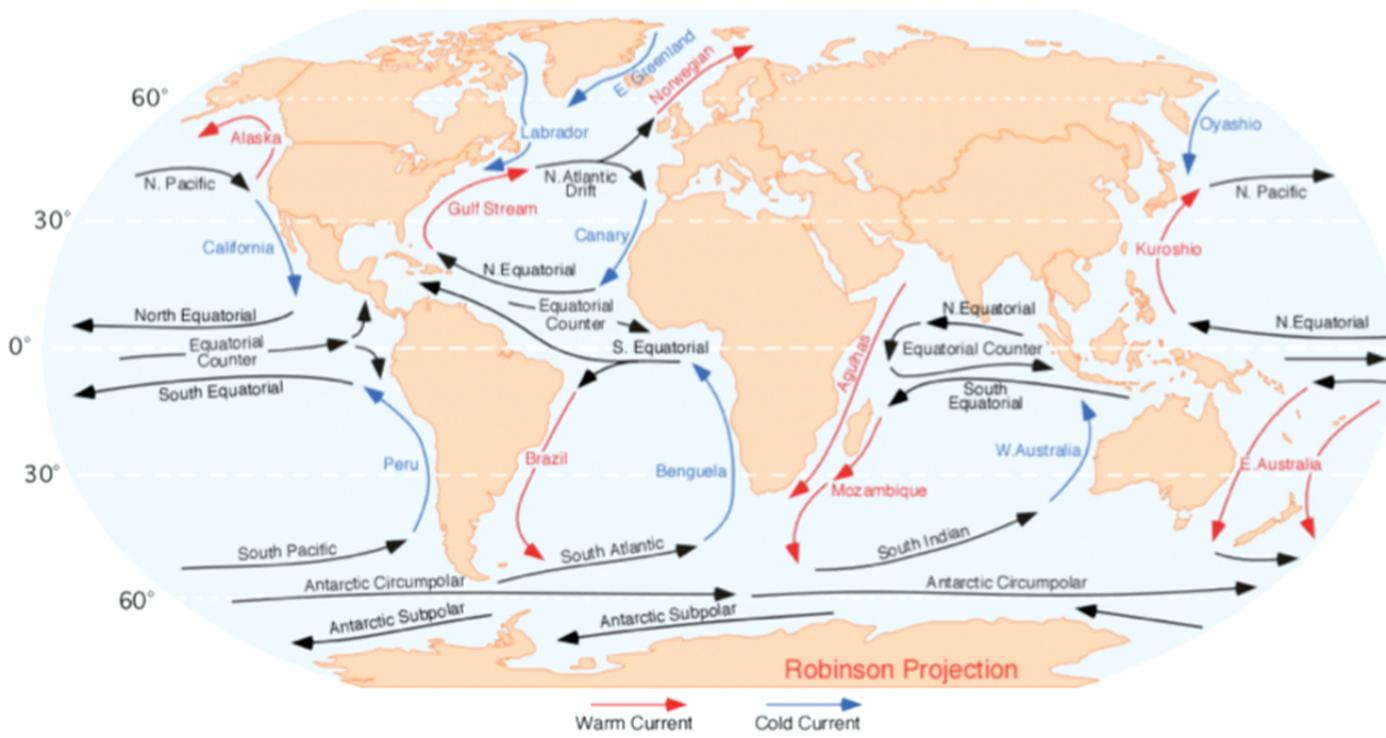


Evolution



Ocean current

- In different coherent volumes of our universe, neutrinos move relative to CDM.



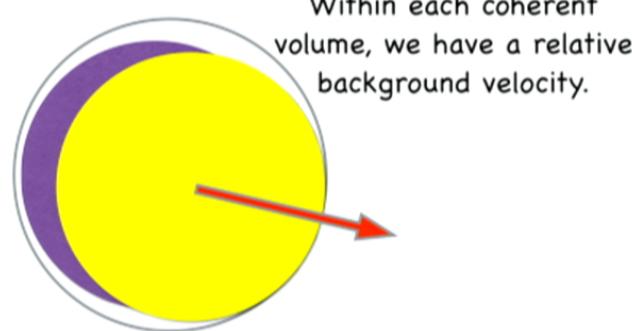
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Observable: Cross-correlation dipoles

- Modulate the evolution of cdm and neutrinos within this sub volume
- Signal: from cross correlation, depend on the direction, anti-symmetry

$$\xi_{c\nu}(\mathbf{r}, v_{\nu c}^{(bg)}) = \xi_{c\nu 0}(r, v_{\nu c}^{(bg)}) + \mu \xi_{c\nu 1}(r, v_{\nu c}^{(bg)})$$



$$\mathbf{v}(\mathbf{x}, t) = \mathbf{v}^{bg}(t) + \mathbf{u}(\mathbf{x}, t)$$

$$\mathbf{v}(k_L, t) \text{ in the } k_L \ll 1/(2R) \text{ limit}$$

Evolution equations

(MBPT from D. Tseliakhovich & C. Hirata 2010)

- Hydrodynamic equations:

$$\begin{aligned}\frac{\partial \delta_c}{\partial t} + \frac{1}{a} \mathbf{v}_c \cdot \nabla \delta_c &= -\frac{1}{a} (1 + \delta_c) \nabla \cdot \mathbf{v}_c, \\ \frac{\partial \mathbf{v}_c}{\partial t} + \frac{1}{a} (\mathbf{v}_c \cdot \nabla) \mathbf{v}_c &= -\frac{\nabla \Phi}{a} - H \mathbf{v}_c, \\ \frac{\partial \delta_\nu}{\partial t} + \frac{1}{a} \mathbf{v}_\nu \cdot \nabla \delta_\nu &= -\frac{1}{a} (1 + \delta_\nu) \nabla \cdot \mathbf{v}_\nu, \\ \frac{\partial \mathbf{v}_\nu}{\partial t} + \frac{1}{a} (\mathbf{v}_\nu \cdot \nabla) \mathbf{v}_\nu &= -\frac{\nabla \Phi}{a} - H \mathbf{v}_\nu - \frac{1}{a} c_s^2 \nabla \delta_\nu,\end{aligned}$$

and $\nabla^2 \Phi = 4\pi G a^2 \bar{\rho}_m \delta_m$.

- Perturb around background velocities:

$$\begin{aligned}\mathbf{v}_c(\mathbf{x}, t) &= \mathbf{v}_c^{(bg)}(t), \\ \mathbf{v}_\nu(\mathbf{x}, t) &= \mathbf{v}_\nu^{(bg)}(t), \\ \text{and } \Phi &= \delta_c = \delta_\nu = 0,\end{aligned}$$

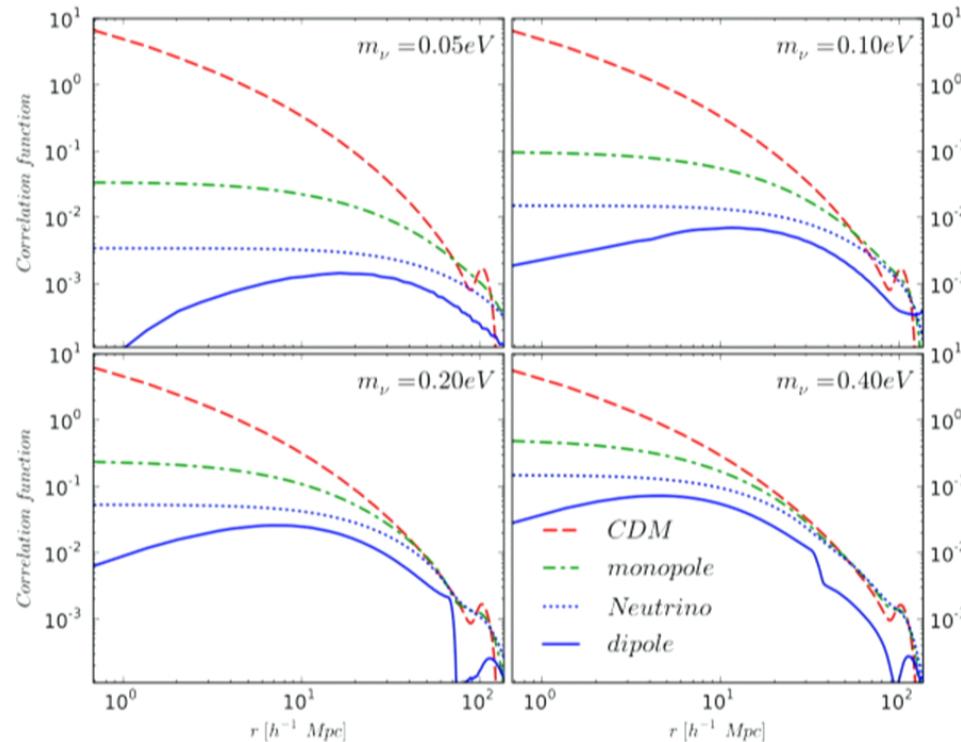
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Dipole from theory

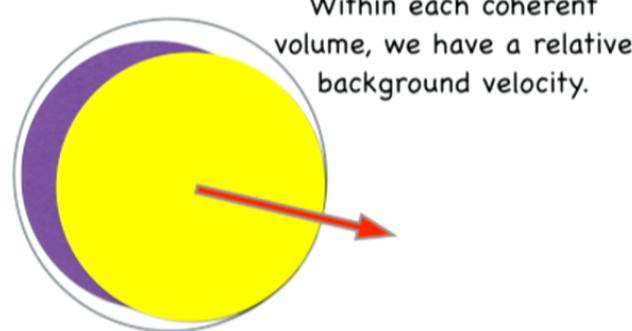
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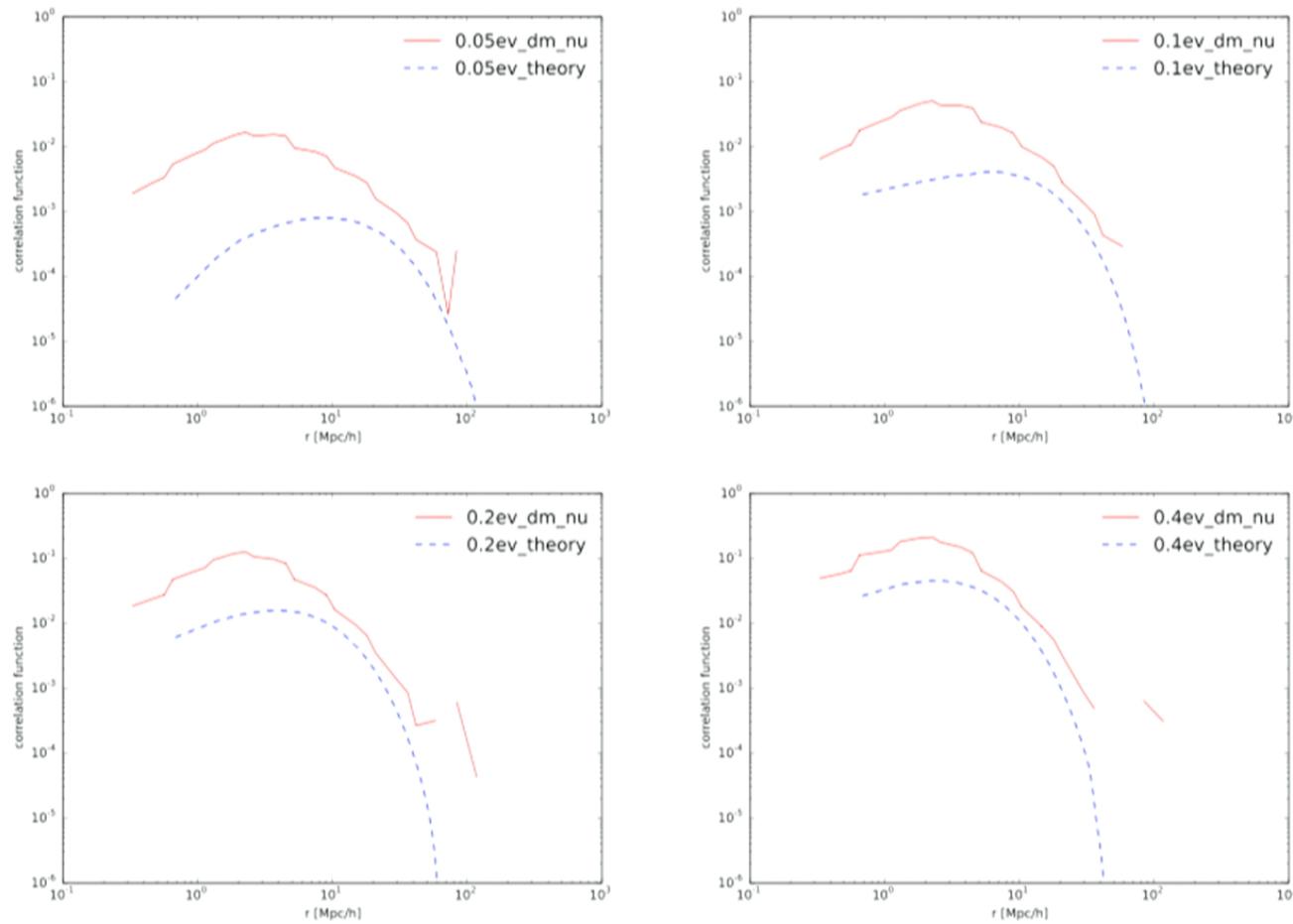
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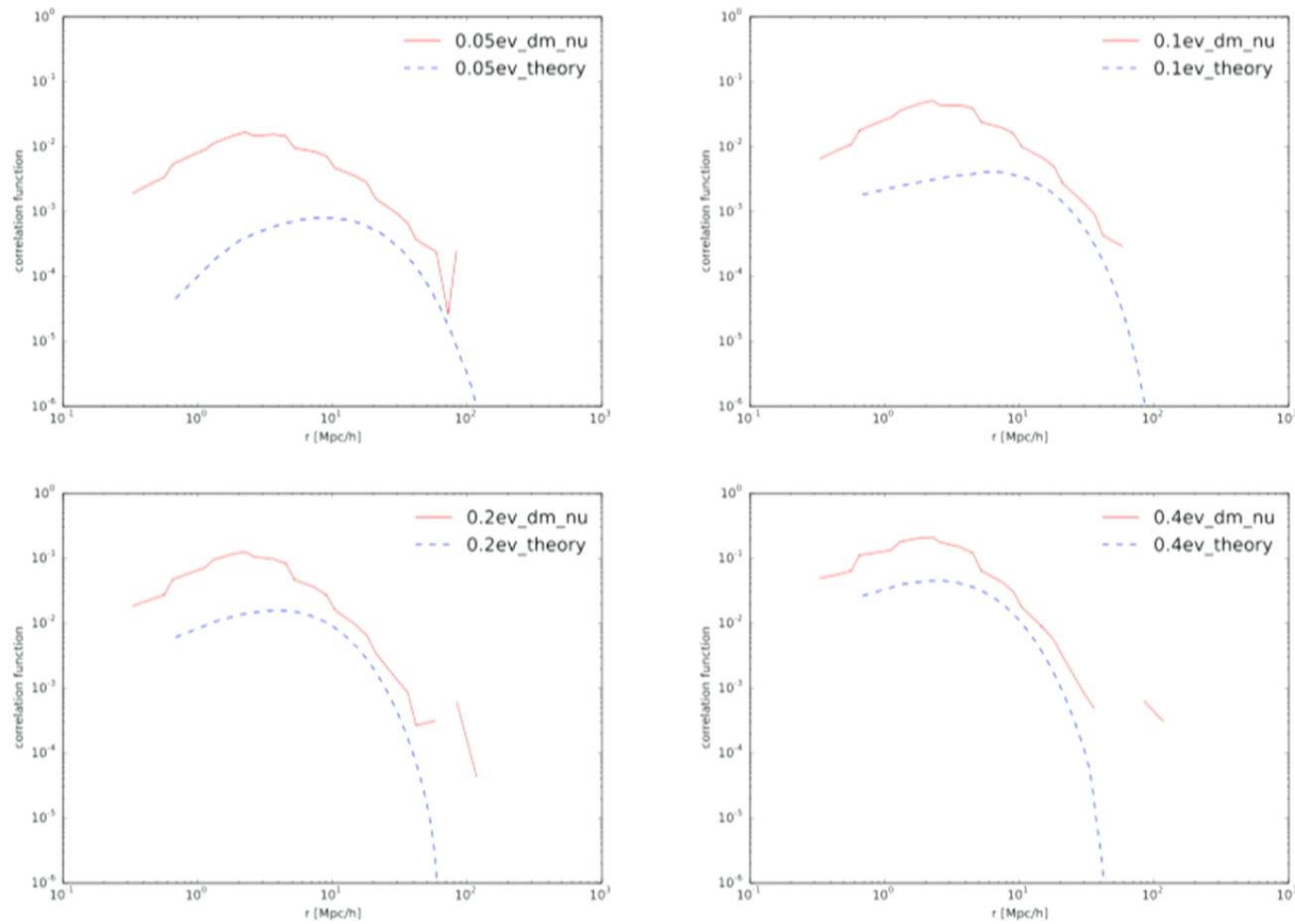
Simulation

- N-body simulations with neutrinos
- 3072^3 neutrino particles, 1536^3 CDM particles
- box size 500 Mpc/h
- neutrino mass 0.05eV, 0.10eV, 0.20eV, 0.40eV

Dipole from simulations II



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Observing neutrinos?

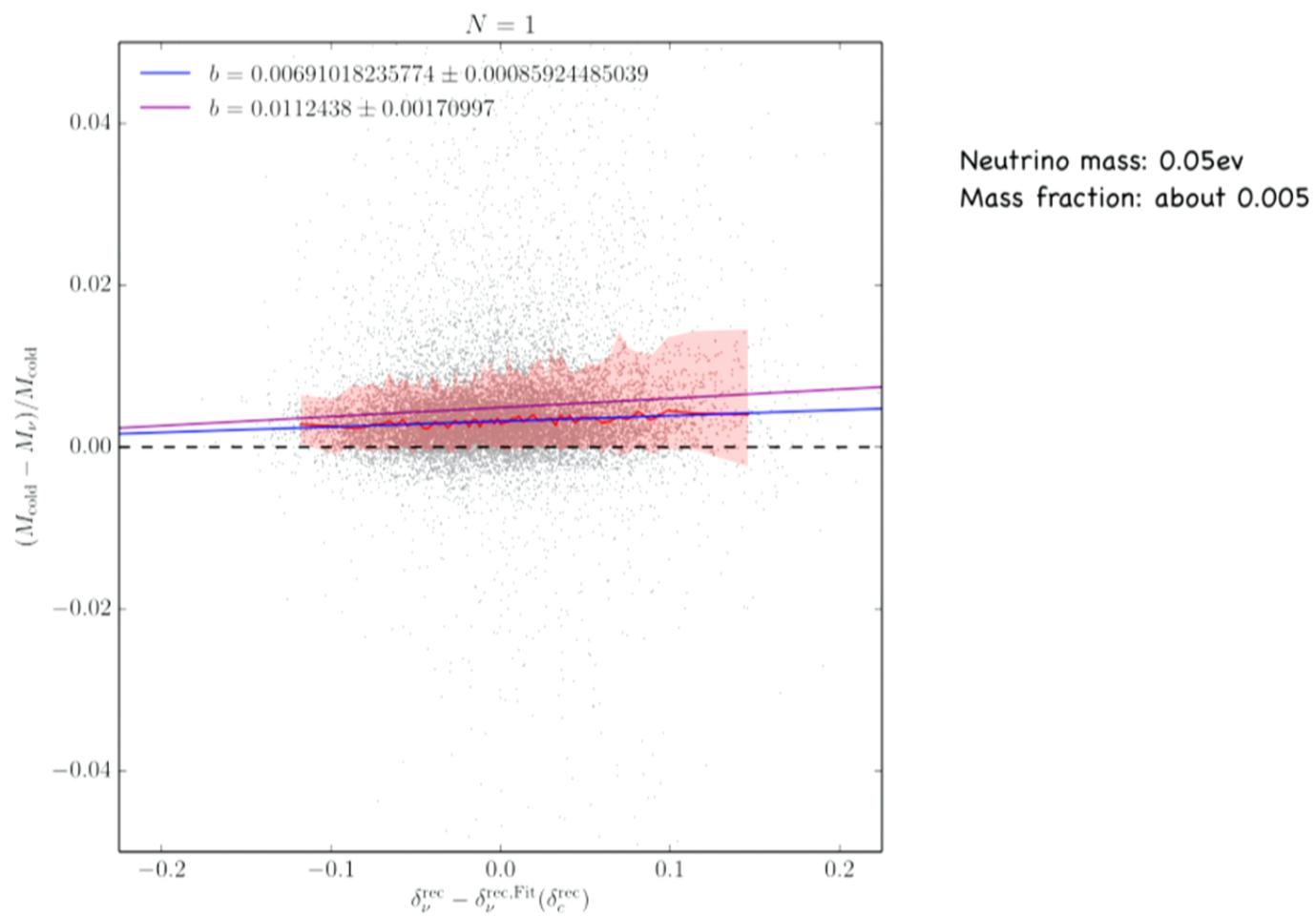
- cross correlating two unobservable fields?
- cross correlate different galaxy types:

$$\delta_{g1} = b_{c1}f_c\delta_c + b_{\nu 1}f_\nu\delta_\nu, \quad \delta_{g2} = b_{c2}f_c\delta_c + b_{\nu 2}f_\nu\delta_\nu$$

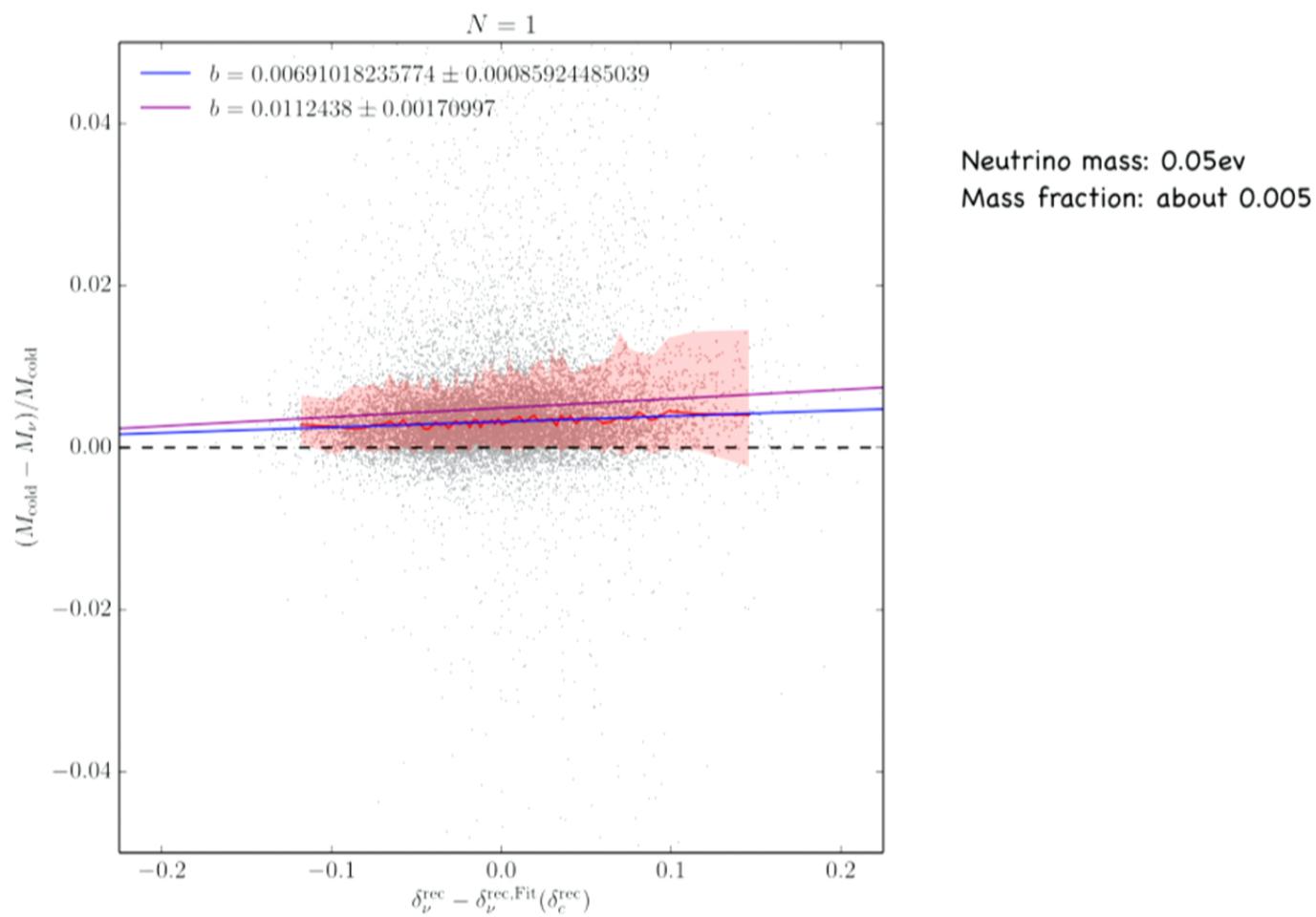
$$b_{c1} \neq b_{c2}, \quad b_{\nu 1} \simeq b_{\nu 2} \simeq b_\nu \simeq 1$$

- other tracers, 21cm? cosmic tides?

Neutrino bias from TianNu



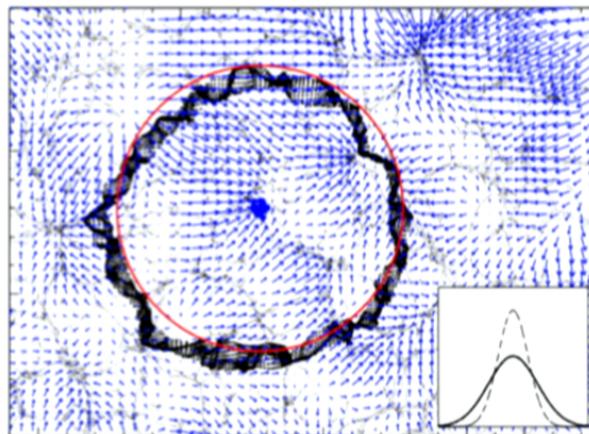
Neutrino bias from TianNu



Observing neutrinos?

- **Signal:** $\langle \delta_{g1} \delta_{g2} \rangle = b_{c1} b_{c2} f_c^2 \langle \delta_c^2 \rangle + b_\nu^2 f_\nu^2 \langle \delta_\nu^2 \rangle +$
 $(b_{c1} + b_{c2}) b_\nu f_c f_\nu \xi_{c\nu 0} +$
 $\mu(b_{c1} - b_{c2}) b_\nu f_c f_\nu \xi_{c\nu 1}$
- also needs a local direction:

$$v_{\nu c}(\mathbf{k}) = \delta_g(\mathbf{k})(T_{v,\nu}(k) - T_{v,c}(k))/T_{\delta,c}(k)$$



Adiabatic perturbations

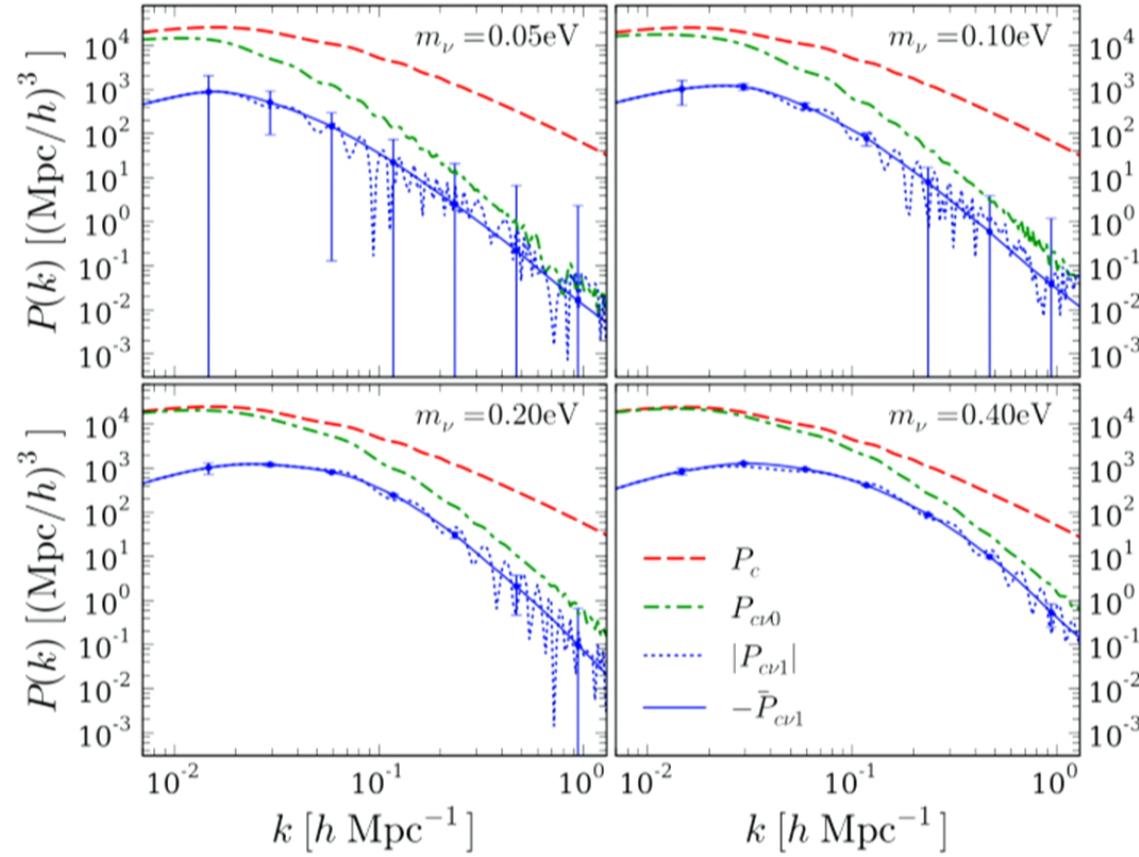
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(N. Padmanabhan et al 2012)

Cross power spectrum

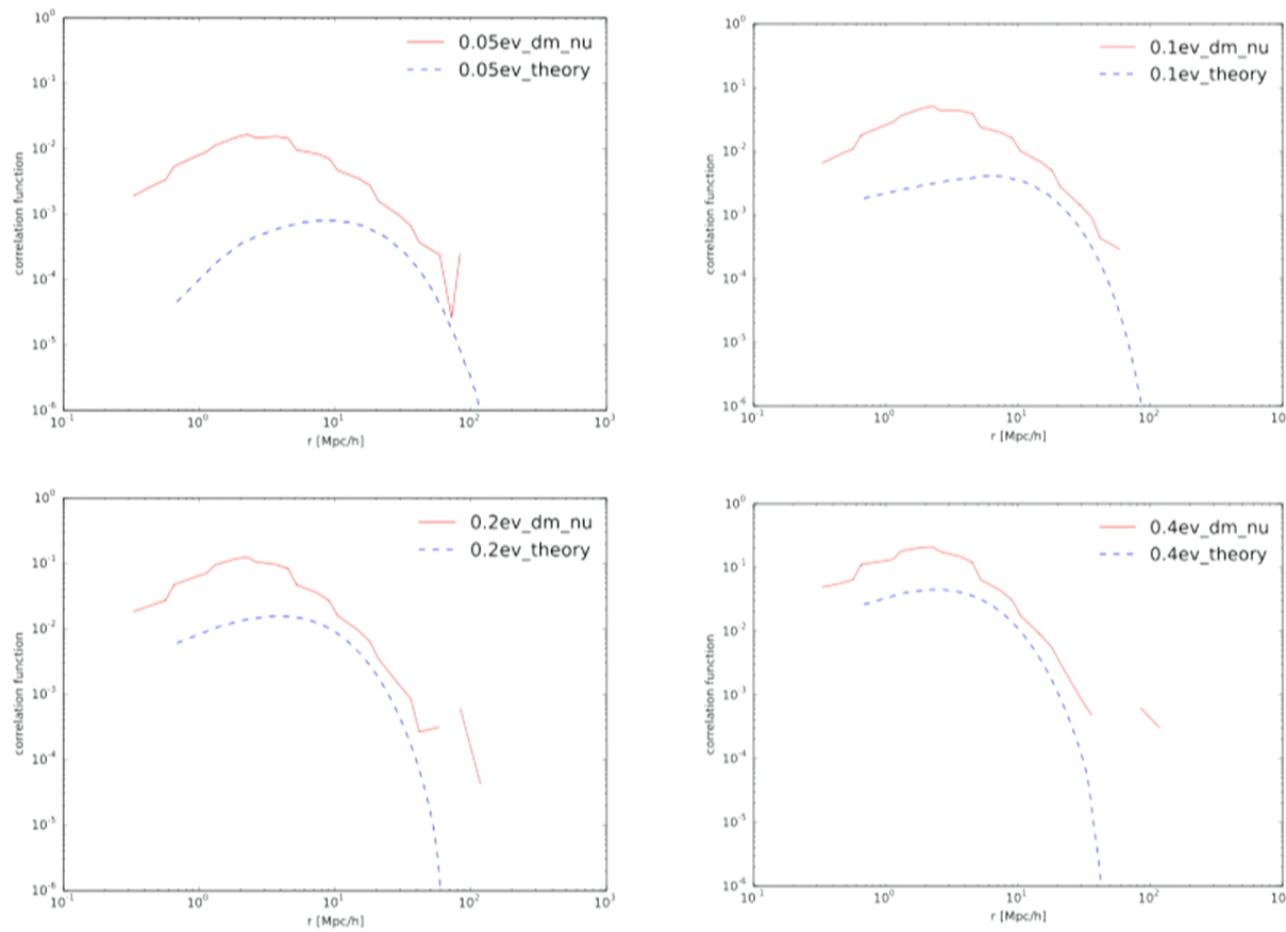


Forecasted errors

TABLE I: The forecasted error on neutrino mass with a survey of $V_s = 1.0 h^{-3} \text{Gpc}^3$, $n_g = 2.4 \times 10^{-2} h^3 \text{Mpc}^{-3}$ and with current survey data, modeled with SDSS and 2dF as $V_s = 0.2 h^{-3} \text{Gpc}^3$, $n_g V_s = 1 \times 10^6$. Note that substantial uncertainties exist due to unknown galaxy neutrino bias, which is a nuisance parameter that we marginalize over.

m_ν (eV)	future		current (SDSS)	
	σ_{m_ν}	relative error	σ_{m_ν}	relative error
0.05	0.0042	0.084	0.045	0.90
0.10	0.0041	0.041	0.044	0.44
0.20	0.0074	0.037	0.079	0.40
0.40	0.0091	0.023	0.097	0.24

Dipole from simulations II



Discussions

- neutrino-cdm dynamics relative clean problem
- no relative motion, no dipole; while other effects could generate suppression on P_k
- suffers less from k -dependent bias $\mu(b_{c1} - b_{c2})b_\nu f_c f_\nu \xi_{c\nu 1}$
- disentangle from halo-cdm dipole?
- dipole from different energy neutrinos?
- neutrino halo bias? baryon feedback?