Title: Neutrino Wakes

Date: Jun 06, 2014 03:00 PM

URL: http://pirsa.org/14060041

Abstract: <span>We identify a new non-linear neutrino wake effect, due to the streaming motions of neutrinos relative to dark matter, analogous to the Tseliakhovich-Hirata effect. We compute the effect in moving background perturbation theory, compare to direct n-body simulations, and forecast its observability in current and future surveys. Depending on neutrino mass, this effect could be observable in upcoming surveys through a cross correlation dipole in lensing and galaxies. Unlike previous cosmological neutrino effects, this depends primarily on neutrino mass, making it complementary to measurements that depend on neutrino density.</span>

# Detecting Cosmic Neutrinos with Wakes

arXiv:1311.3422

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June 6, 2014

# Overview

- Neutrinos: blitz review
- Probe of neutrino masses
- Tseliakhovich-Hirata Effect: neutrino-CDM bulk flows
- Cross-correlation dipoles
- Observable consequences
- Conclusions

# Neutrino Masses

- 2002 Nobel prize: recognizes half century of experimental tests demonstrating neutrinos have mass
- 2 mass differences, 3 mixing angles measured
- $\Delta m \sim 0.05, 0.009$ eV, large mixing angles
- major experimental unknowns: mass hierarchy, mean mass
- Theoretical unknowns: Majorana vs Dirac mass

# Anti-$\nu$'s

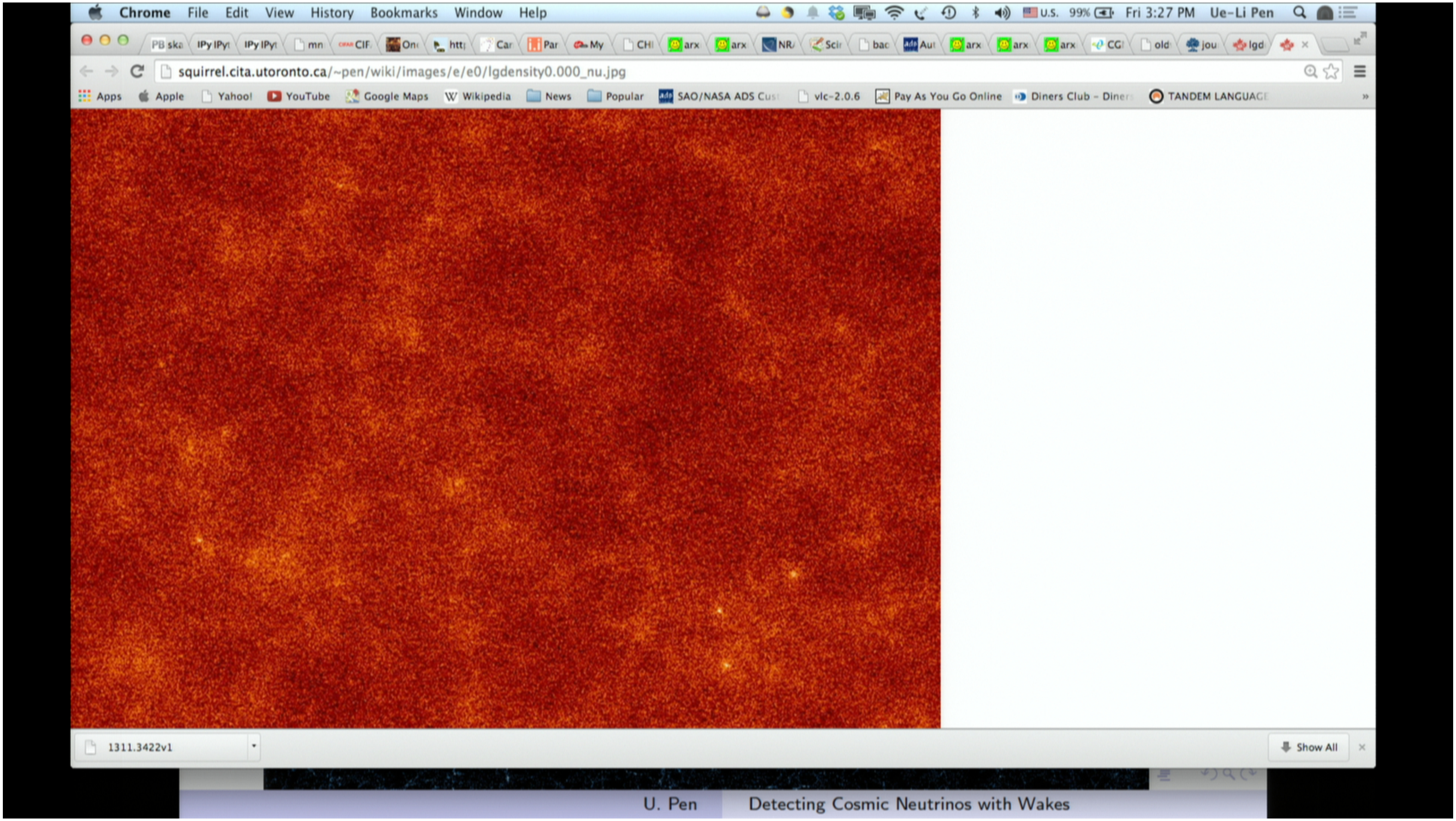
- four electron states: $-, +, \uparrow, \downarrow$
- $\uparrow, \downarrow$ can be defined in direction of motion (helicity): L, R.
- Majorana $\nu$: identify $\nu_L \equiv \bar{\nu}_R$, only two neutrino states.
- Dirac $\nu$: $\nu_L \neq \bar{\nu}_R$, two distinct particles, four neutrino states.
- in SM, only L interact. $\implies T_R \sim (11/2g_*)^{1/3} T_L \sim 0.7$ K if $\nu_R$ were in LTE before QCD ($\sim 100$ MeV, $z \sim 10^{11}$)
- any hope of detecting the cosmic $\nu_R$ background?

# Mass Hierarchy

- normal: $m_1 \sim 0, m_2 \sim 0.01, m_3 \sim 0.05$
- inverted: $m_1 \sim 0, m_2 \sim 0.05, m_3 \sim 0.06$
- degenerate: $m_1 \gg \Delta m$
- Cosmological tests: normaly sensitive to $\Sigma m_i$

# Cosmological $\nu$'s

- free streaming since $z \sim 10^{10}$
- $T_{\nu_L} \sim 2$ K, density $\sim 100/\text{cm}^3$
- possibly $T_{\nu_R} \sim 0.7$ K, density $\sim 5/\text{cm}^3$
- fourth most abundant cosmic component: $\Omega_\Lambda \sim 0.7 > \Omega_{cdm} \sim 0.2 > \Omega_b \sim 0.05 > \Omega_\nu \sim 0.01 > \Omega_\gamma \sim 0.001$
- redshifted relativistic Fermi-Dirac distribution
- computation numerically challenging: trillions of $\nu$ particles needed to accurately sample distribution function. Not well described by fluid limit.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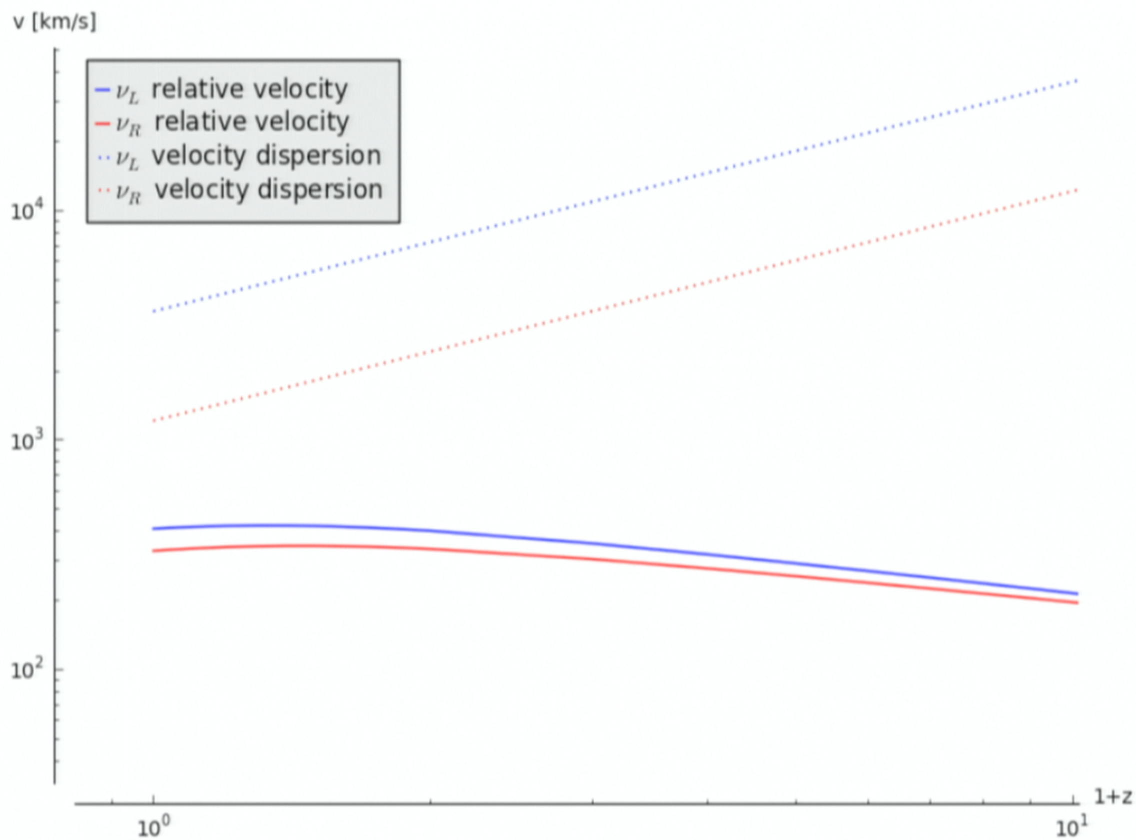
# Mach


v [km/s]
$\nu_L$ relative velocity
$\nu_R$ relative velocity
$\nu_L$ velocity dispersion
$\nu_R$ velocity dispersion
$10^4$
$10^3$
$10^2$
$10^0$
$10^1$
1+z

# LSS probes of neutrino mass

- neutrinos impact power spectrum at $\sim$ % level
- modest scale dependence
- degenerate with $\sim$ % $k$-dependent bias
- not limited by statistical noise
- lensing helps – potential challenge from non-linear baryons
- multiple techniques desirable
- mass hierarchy, R?

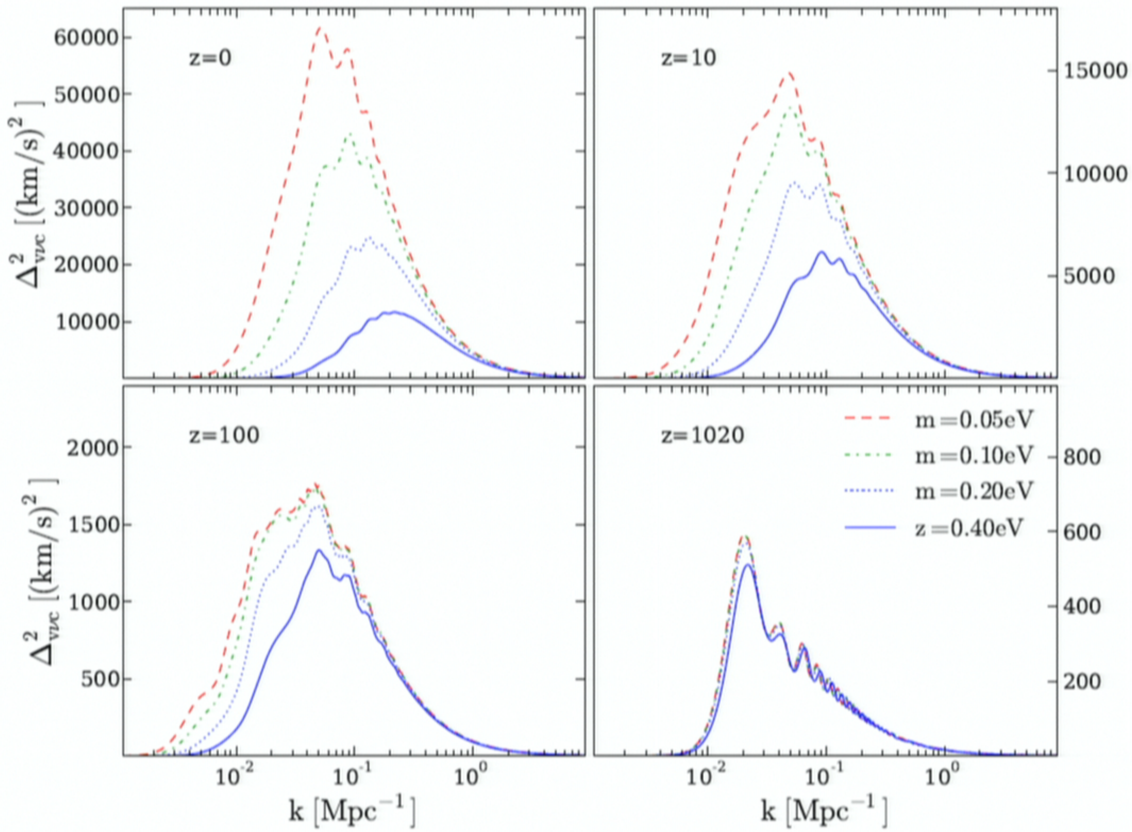
# Tseliakhovich-Hirata Effect

- Tseliakhovich and Hirata (2010) realized that baryons and dark matter develop non-perturbative relative velocity flows after recombination.
- Analogous effect for neutrino-dark matter flow

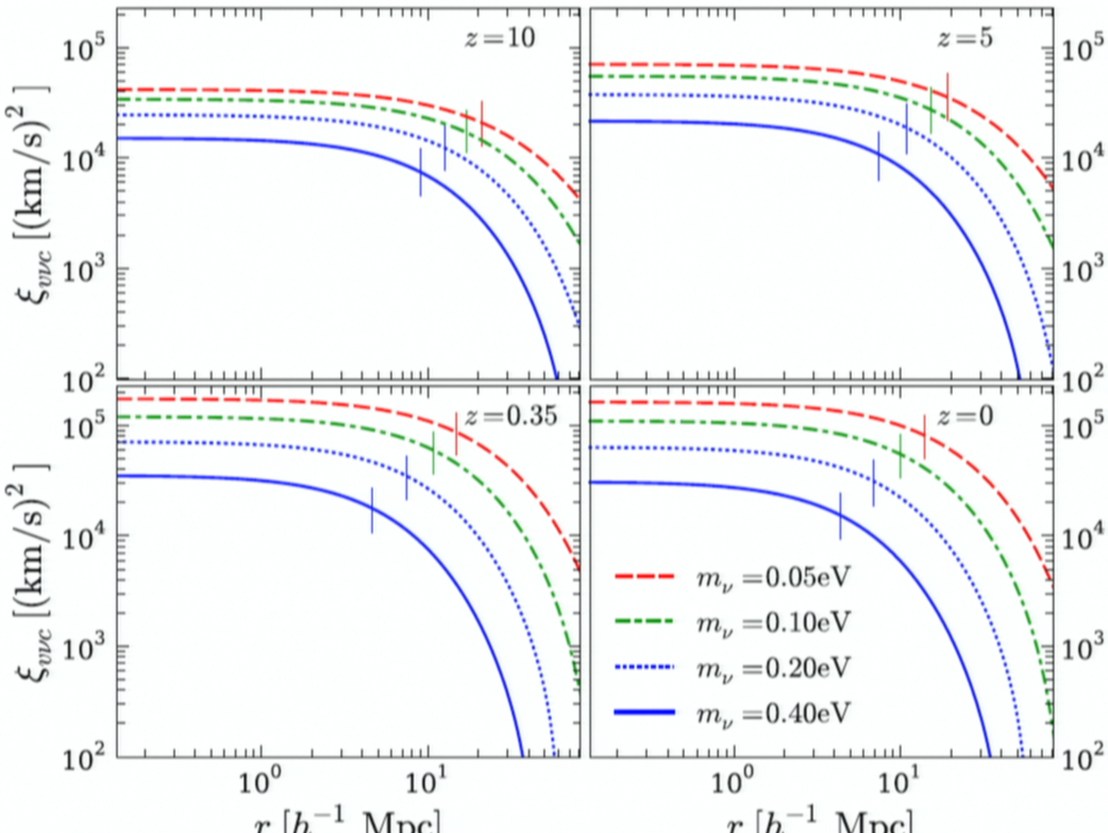
# CDM-$\nu$ flows

- linear theory predicts velocity of all fluids from density field
- neutrino density: $\delta_\nu = \delta_c \frac{T_\nu}{T_c}$
- velocity: $\vec{v}_\nu \sim \delta_\nu \dot{T}_\nu \frac{i\vec{k}}{k^2}$
- relative flow: $\vec{v}_{c\nu} \sim \delta_g \frac{\dot{T}_c - \dot{T}_\nu}{T_c} \frac{i\vec{k}}{k^2}$
- use galaxy survey (e.g. SDSS) to predict $\delta_c, \delta_\nu, v_{c\nu}$
- predictable today at high S/N.

# Flows


z=0
z=10
z=100
z=1020
m=0.05eV
m=0.10eV
m=0.20eV
z=0.40eV
$\Delta^2_{vvc}$ [(km/s)$^2$]
k [Mpc$^{-1}$]
60000
50000
40000
30000
20000
10000
15000
10000
5000
2000
1500
1000
500
800
600
400
200
$10^{-2}$
$10^{-1}$
$10^{0}$

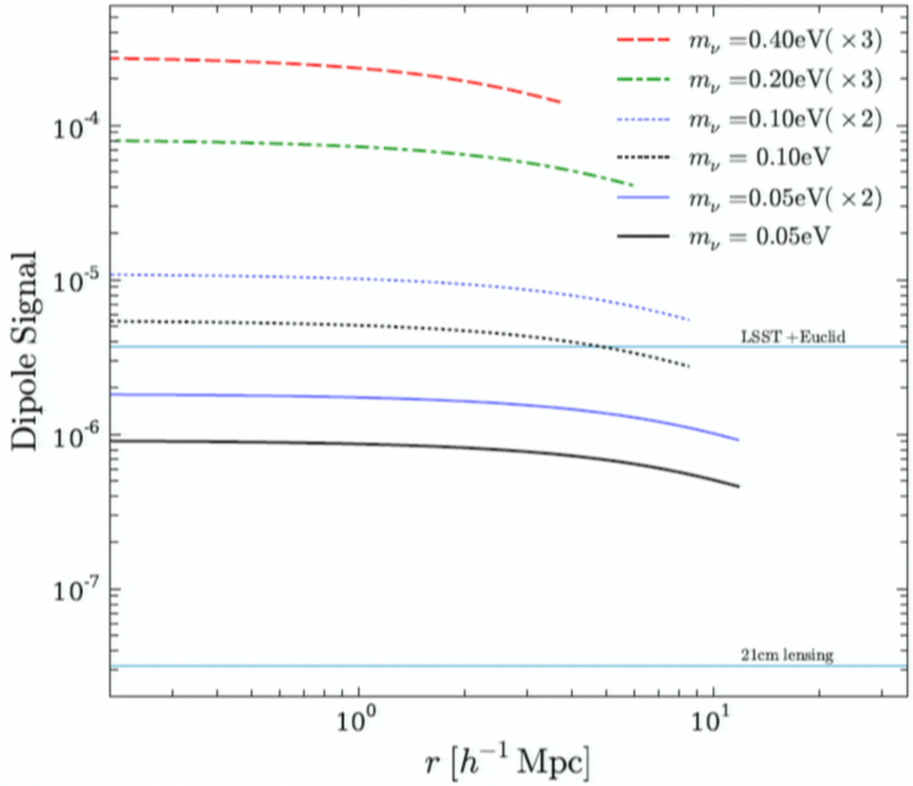
# Coherence


$z=10$
$z=5$
$z=0.35$
$z=0$
$\xi_{vvc}$ [(km/s)$^2$]
$r$ [$h^{-1}$ Mpc]
$m_\nu$ =0.05eV
$m_\nu$ =0.10eV
$m_\nu$ =0.20eV
$m_\nu$ =0.40eV

# Wakes

- each DM/galaxy halo has downwind $\nu$ wake.
- massive $\nu$'s contributes to gravitational lensing.
- potentially detectable with galaxy-galaxy lensing: search for dipole distortion
- or dipole of massive vs low mass galaxies.
- also can use 21cm intensity mapping and tides (Pen et al 2012).

# Wake lensing dipole (preliminary)



# Lensing sensitivity

Table: The forecasted error on the neutrino mass observation using a future 21cm lensing survey or with current planned galaxy surveys. The lines begin with ˜ denotes the result of inverted hierarchy.

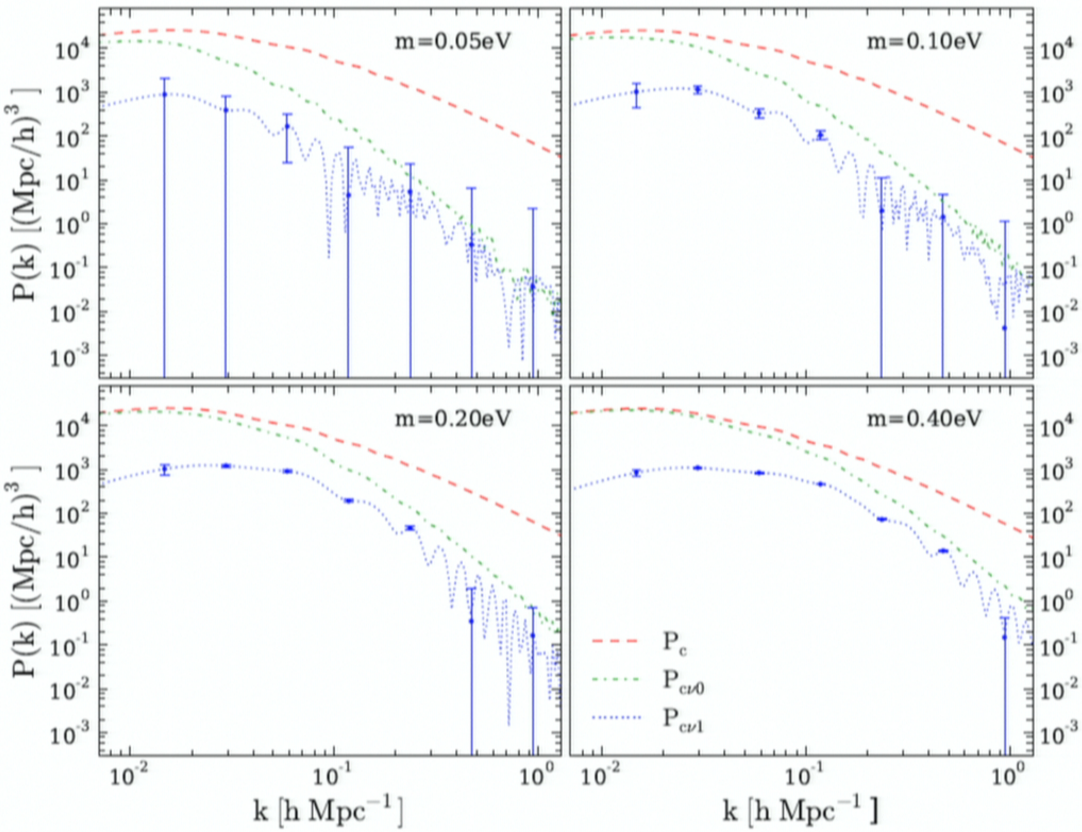
| | 21cm lensing | | LSST + Euclid | |
|---|---|---|---|---|
| $m_\nu$ (eV) | $\sigma_{m_\nu}$ | relative error | $\sigma_{m_\nu}$ | relative error |
| 0.05 | 0.00106 | 0.02115 | 0.120 | 2.410 |
| ˜0.05 | 0.00053 | 0.01058 | 0.060 | 1.205 |
| 0.10 | 0.00035 | 0.00354 | 0.040 | 0.404 |
| ˜0.10 | 0.00018 | 0.00177 | 0.020 | 0.202 |
| 0.20 | 0.00005 | 0.00024 | 0.005 | 0.027 |
| 0.40 | 0.00003 | 0.00007 | 0.003 | 0.008 |

(from Zhu et al 2014, preliminary)

# Observing Neutrinos?

- cross correlating two unobservable fields?
- cross correlate different galaxy types: $\delta_g^i = f_c^i \delta_c + f_\nu^i \delta_\nu$
- cross correlations: $\xi^{ij} = \langle \delta_g^i(x) \delta_g^j(x+r) \rangle \Big|_{r \| v_{c\nu}}$

# cross power



# Discussions

- flow direction depends on mass – use angles, not amplitudes to measure neutrino mass.
- detection may be clean and independent of bias.
- neutrino center-of-mass velocity comes from free streaming: hard to mimick by baryons.
- each neutrino mass and helicity flows in a different direction. Dipoles can be measured independently. Determine hierarchy, helicity.

# Conclusions

- neutrinos have led half a century of surprises
- DM-$\nu$ dynamics very clean problem
- Bulk relative flow: TH effect
- cross correlation dipole may be a clean observable
- potential to measure $\nu$ mass, Dirac vs Majorana