Neutrinos in Large-scale structure

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(Fall 2015 → Yang Institute for Theoretical Physics, Stony Brook University)
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Outline

- Neutrinos in Cosmology
- Scale-dependent structure growth from massive neutrinos
- Scale-dependent halo bias from massive neutrinos
- Observational Consequences
Neutrinos
Neutrinos!

flavor eigenstates

$\nu_{\text{electron}}$  $\nu_{\text{tau}}$  $\nu_{\text{muon}}$

mass eigenstates

$\nu_1$  $\nu_2$  $\nu_3$

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962
Neutrinos!

flavor eigenstates

\( \nu_{\text{electron}} \)
\( \nu_{\text{muon}} \)
\( \nu_{\text{tau}} \)

mass eigenstates

\( \nu_1 \)
\( \nu_2 \)
\( \nu_3 \)

oscillation data gives mass splittings

\[ m_2^2 - m_1^2 = (7.5 \pm 0.2) \times 10^{-5} \text{ eV}^2 \]  
(solar neutrino oscillations)

\[ |m_3^2 - m_2^2| = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2 \]  
(atmospheric neutrino oscillations)

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962
Neutrinos!

Flavor eigenstates:

- $\nu_{\text{electron}}$
- $\nu_{\text{tau}}$
- $\nu_{\text{muon}}$

Mass eigenstates:

$\nu_1 \approx 0.047\text{eV}$
$\nu_2 \approx 0.049\text{eV}$
$\nu_3 \approx 0\text{eV}$

but the absolute masses are unknown!

``Normal'' $\rightarrow$ "Inverted'' $\rightarrow$ "Degenerate''

Pontecorvo 1957, 1958, 1967; Maki, Nakagawa, Sakata 1962
Neutrinos in Cosmology
Neutrinos in cosmology

neutrinos in equilibrium with photons $e^+$, $e^-$

$T_\gamma = T_\nu \propto 1/a$

neutrinos decoupled

$T_\nu \propto 1/a$
Neutrinos in cosmology

relativistic, in thermal equilibrium at early times

\[ n_{\nu} \sim T_{\nu}^3 \]

\[ T_{\gamma} \approx \left( \frac{11}{4} \right)^{1/3} T_{\nu} \]
Neutrinos in cosmology

\[ T_{\gamma} = T_\nu \propto 1/a \]

relativistic, in thermal equilibrium at early times

\[ n_{1\nu} \sim T_\nu^3 \]

\[ T_{\gamma} \approx \left( \frac{11}{4} \right)^{1/3} T_\nu \]

neutrinos in equilibrium with photons e+, e-

neutrinos decoupled

\[ T_\nu \propto 1/a \]

energy density dominated by mass at late times

\[ \rho_\nu \sim \sum_i m_{\nu_i} n_{1\nu} \]
Neutrinos in cosmology

\[ T_\gamma = T_\nu \propto 1/a \]

neutrinos in equilibrium with photons e\(^+\), e\(^-\)

\[ n_{1\nu} \sim T_\nu^3 \]

relativistic, in thermal equilibrium at early times

energy density dominated by mass at late times

\[ \rho_\nu \sim \sum_i m_{\nu i} n_{1\nu} \]

\[ T_\gamma \approx \left(\frac{11}{4}\right)^{1/3} T_\nu \]

\[ n_{1\nu} \text{ is known, so a measurement of } \rho_\nu \text{ gives } \sum m_\nu \]
Neutrinos in Large-scale structure

(Kravtsov)
Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for **fast** and **slow** moving particles.
Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for **fast** and **slow** moving particles.

(clump easily)  (don’t clump easily)
Massive neutrinos and linear structure growth

The gravitational evolution of large-scale structure is different for **fast** and **slow** moving particles

- baryons and cold dark matter (clump easily)
- neutrinos (or other exotic light dark matter) (don’t clump easily)
Massive neutrinos and linear structure growth

Small-scale density perturbations don't retain neutrinos

cold dark matter and baryons density perturbation growing

Neutrino density perturbation decaying
Massive neutrinos and linear structure growth

small-scale density perturbations don't retain neutrinos

cold dark matter, baryons and neutrinos growing together

large-scale density perturbations do retain neutrinos

\[ \frac{\delta \rho_\nu}{\rho_\nu} \frac{\delta \rho_c}{\rho_c} \]
Massive neutrinos and linear structure growth

- Small-scale density perturbations don't retain neutrinos.
- Large-scale density perturbations do retain neutrinos.

Growth of matter perturbations is scale-dependent.

time
Massive neutrinos and linear structure growth

small-scale density perturbations don't retain neutrinos

large-scale density perturbations do retain neutrinos

Growth of matter perturbations is scale-dependent

Relevant scale:

Typical distance a neutrino can travel in a Hubble time

\[ \lambda_{fs} \sim u \nu / H \]
Massive neutrinos and linear structure growth

Small-scale density perturbations don't retain neutrinos.

Large-scale density perturbations do retain neutrinos.

Growth of matter perturbations is scale-dependent.

Relevant scale:

Typical distance a neutrino can travel in a Hubble time

$\lambda_{fs} \sim \frac{u\nu}{H}$

“Free-streaming scale”
Scale-dependent growth

\[ \Delta \frac{P_{\text{mm}}(k)}{P_{\text{mm}}(k)} = \text{change in typical amplitude of } \delta_m(k) \text{ from } m \neq 0 \]

![Graph showing change in typical amplitude of \( \delta_m(k) \) from \( m \neq 0 \)]

- one \( \nu, m_\nu = 0.05\,\text{eV} \)
- one \( \nu, m_\nu = 0.10\,\text{eV} \)
- one \( \nu, m_\nu = 0.30\,\text{eV} \)
- three \( \nu, m_\nu = 0.10\,\text{eV} \)

large compared to \( \lambda \text{ free streaming} \)

Planck Data

Ade et al 2013

![Graph showing cosmological constraints!]

Bond, Efstathiou, Silk 1980

Hu, Eisenstein, Tegmark 1998
The scale-dependent growth of density perturbations causes halo bias to be scale dependent.
Scale-dependent bias:

halos are biased tracers of the matter density field
Scale-dependent bias:

**halos** are biased tracers of the matter density field.

The number density of halos is modulated by long-wavelength fluctuations in the matter density field.
Scale-dependent bias:

Halos are biased tracers of the matter density field.

The number density of halos is modulated by long-wavelength fluctuations in the matter density field.

\[ \frac{\delta n}{n} \equiv b \frac{\delta \rho}{\rho} \]

\( b \) is the **halo bias**.
Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength.

\[ \frac{\delta \rho}{\rho}(k, z_{\text{final}}) \propto D(z_{\text{final}}) \frac{\delta \rho}{\rho}(k, z_{\text{initial}}) \]
Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength.

\[
\frac{\delta \rho}{\rho} (k, z_{\text{final}}) \propto D(z_{\text{final}}) \frac{\delta \rho}{\rho}(k, z_{\text{initial}})
\]

Halos can't tell the wavelength of the background matter density perturbation.
Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength.

Halos can't tell the wavelength of the background matter density perturbation.

The effect of $\frac{\delta \rho}{\rho}$ on the halo field (the linear bias) is independent of $k$. 
Scale-dependent bias:

In a universe with CDM only, the linear evolution of matter fluctuations is independent of their wavelength.

Halos can't tell the wavelength of the background matter density perturbation.

The effect of $\frac{\delta \rho}{\rho}$ on the halo field (the linear bias) is independent of $k$.

Massive neutrinos break this:

Halo bias can depend on $k$. 
Scale-dependent bias:

neutrinos
cold dark matter
Scale-dependent bias:

WANT: estimate of k-dependence of the halo bias caused by massive neutrinos.
WANT: estimate of $k$-dependence of the halo bias caused by massive neutrinos

Scale-dependent bias:

(see also Hui & Parfrey 2008; Parfrey, Hui, Sheth 2011;)

neutrinos
cold dark matter
Prescription for calculating the halo bias in a universe with massive neutrinos
Prescription for calculating the halo bias

\[ \frac{\delta n}{n} \equiv b \frac{\delta \rho}{\rho} \]

initial density field \quad \text{long-wavelength}

initial proto-halo distribution

late time halo distribution

Gunn & Gott 1972
Press & Schechter 1974
Prescription for calculating the halo bias

initial density field $\frac{\delta n}{n} \equiv b \frac{\delta \rho}{\rho}$

initial proto-halo distribution

long-wavelength

late time halo distribution

want this!
Numerical estimates for scale-dependent halo bias
Numerical results for halo bias

scale-dependent change to final bias

\[ \frac{\delta n(k)}{n} = b(k) \delta_{\text{matter}}(k) \]

\[ b(k) = \sqrt{\frac{P_{hh}(k)}{P_{mm}(k)}} \]

(Use Bhattacharya et al 2011 for \( n(M|\delta_{\text{crit}}) \))
Numerical results for halo bias

scale-dependent change to final bias \[ \frac{\delta n(k)}{n} = b(k) \delta_{\text{matter}}(k) \]

(Use Bhattacharya et al 2011 for \( n(M|\delta_{\text{crit}}) \) )
Observational consequences of scale-dependent bias?
Observational consequences of scale dependent bias?

(incorrectly) assuming constant bias

suppression in galaxy power spectrum less than in matter power spectrum

\[ M = 10^{13}, \, z = 0.50 \]

\[ \text{suppression in } P_{\text{gal}}(k/m_\text{b}) \text{ for fixed fixed } \Omega_\text{m} \]

\[ k \text{ (wave number) } \]

(ML 2014)
But the scale-dependent halo bias is itself an observable!
The scale-dependent halo bias is an observable!

\[ \sigma_{b1/b2} \sim \frac{1}{\sqrt{n_1 P_{g2g2}}} \]
The scale-dependent halo bias is an observable!

\[ \sigma_{b1/b2} \sim \frac{1}{\sqrt{N_\ell n_1 C_{g2g2}}} \]

(ML in prep.)
Accuracy of these predictions?

N-body simulations are the community standard for cold dark matter structure.

Simulations with massive neutrinos?

(i) Tricky. very few exist, very new
(ii) Want a model that provides insight into the physical processes responsible for new effects
(iii) Don’t want to rerun for every possible neutrino mass hierarchy scenario
(iv) It will be great to make comparisons in the future!
Scale-dependent bias from massive neutrinos

comparison with sims looks reasonable!

my calculations

simulations from Castorina et al 2013

(ML 2014)
Conclusions

- Cosmology provides interesting information about neutrino physics!

- Scale-dependent halo bias is a new signal of massive neutrinos in large-scale structure.

- Scale-dependent halo bias is a new systematic for massive neutrinos in large-scale structure.