Simulating the Effect of Massive Neutrinos on Large-Scale Structure

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Massive Neutrinos

Neutrinos are last standard model particles without known mass

The last stamp in the collection!
Massive Neutrinos

• We know the mass difference between neutrino species (neutrino oscillations)
• Don’t know total mass: very hard to do with particle physics because

\[ m_\nu \sim 0.5\text{eV} \ll m_e = 511\text{keV} \]

• Solution: do cosmology on background neutrinos
Cosmic Neutrino Background

• 1 neutrino per photon produced during Big Bang Nucleosynthesis: $z = 10^9$, $T = 1$ MeV
• Relativistic at decoupling

Total density today:

$$\Omega_\nu = \frac{M_\nu}{93.14h^2}$$
Neutrinos are hot dark matter
Don’t cluster on small scales, suppress matter power spectrum
Effect on matter power spectrum

• To get to lower mass limit of 0.05 eV, need to measure power at percent level

• First step: how do you quantify effect at this precision on non-linear scales?
Effect on matter power spectrum

Change in $\Delta^2(k)$ for $M_\nu = 0.3, z = 0$

Largest signal on non-linear scales

Linear theory

$k/(h\text{ Mpc}^{-1})$
Simulating Neutrinos as Particles

Neutrinos are fast-moving dark matter:
Do N-body like CDM

Numerical problems due to discretizing neutrinos
Worse for small masses, only works for > 0.1 eV

(Viel 2010)
Particle Neutrinos

• Some problems with this method
  – Discretization noise
  – Early-time relativistic effects
  – No neutrino hierarchy

• Hard and expensive to perform
  – Large thermal velocity numerically tricky
  – Doubles memory consumption
Simulating Neutrinos

Neutrinos free-stream

Clustering sourced by (non-linear) CDM potential well
Linear Neutrinos, Non-Linear CDM

Neutrino power is given by perturbation theory with non-linear CDM potential

\[ P_{NL}^2(k) = f_{CDM} P_{NL,CDM}^2 + f_{\nu} P_{L,\nu}^2 \]

From N-body timestep

Perturbation theory sourced by N-body
Particle vs. Fourier-Space

$M_\nu = 0.6$ eV

Reproduces particle method very well
A Good Method

$M_\nu = 0.3$ eV

Works better for small masses
Works in the small mass limit
Same cost as CDM
Public code

Ali-Haimoud & Bird
arXiv:1209.0461
https://github.com/sbird/fs-neutrino
Experiments

• Cluster counts: $\sigma_8^8$
• Weak Lensing (LSST): small scales
• Lyman-alpha forest: low densities
• CMB lensing: low systematics