Simulating the effect of massive neutrinos on large-scale structure

A method that works for small masses

Yacine Ali-Haimoud and Simeon Bird

arXiv:1209.0461

https://github.com/sbird/fs-neutrino
Massive Neutrinos

We know neutrinos are massive but last standard model particles without known mass

“All science is either physics or stamp collecting”
– Ernest Rutherford

The first stamp

The last stamp?
Neutrino Clustering

Neutrinos are hot dark matter
Don’t cluster on small scales, suppress matter power spectrum
Simulating Neutrinos as Particles

Neutrinos are fast-moving dark matter:
Add an extra particle species

CDM

Neutrinos

Works best for large neutrino masses
Simple, easy to implement

(Viel 2010)
Particles work less well at small masses

• Neutrino mass splitting:

\[ M_{\nu(h)} \approx M_{\nu(l)} + 0.05 \]

With total mass 0.10 eV, this matters.

(But cannot distinguish between normal and inverted hierarchy with M > 0.1)
Shot noise

Minimum neutrino power due to discrete particles with random thermal velocities

\[ P(k) \sim 1/N_{\text{part}} \]

- Dominates power at early times
- Can increase number of particles
Early-Time Relativistic Effects

Particle mass cannot change with time

\[ \Omega_\nu(a) > \frac{\Omega_\nu(0)}{a^3} \]

- Neutrinos don’t cluster when this matters
- OK to just change background matter density
Simulating Neutrinos as Particles

Particles work less well at small masses

- Neutrino mass splitting
- Shot noise
- Early-time relativistic effects

Use an analytic method for neutrinos
Simulating Neutrinos

Neutrinos free-stream

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

Assume 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
A Good Method

$M_{\nu} = 0.3$ eV

Reproduces particle method very well

Works better for small masses
Particle vs. Fourier-Space

$M_{\nu} = 0.6$ eV

$z = 0, 1, 3, 9$

Still good

$\Delta P_t(k) / P_t(k)$ (%)

$k / (h \text{ Mpc}^{-1})$
Neutrino power spectrum

Non-linear neutrino clustering: only at $z < 0.5$
Neutrinos in thermal energy tail – small total mass
Neutrino power spectrum

Slow neutrinos captured by large potential well
Start to cluster non-linearly
Only in regions where dark matter clusters strongly
This does not affect dark matter because:
- Overall clustering still quite small
- Neutrino effect is over time, and at these redshifts growth has stopped
Conclusion

• Analytic method accurate in non-linear regime
• Free – same cost as simulating CDM
• Includes extra physics, eg, neutrino hierarchy.
• Good for small neutrino masses
Public Code:
you can use it easily

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