Simulating the Effect of Massive Neutrinos on Large-Scale Structure

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arXiv:1209.0461

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

$$m_\nu \sim 0.5\mathrm{eV} \ll m_\mathrm{e} = 511\mathrm{keV}$$

- Solution: do cosmology on background neutrinos

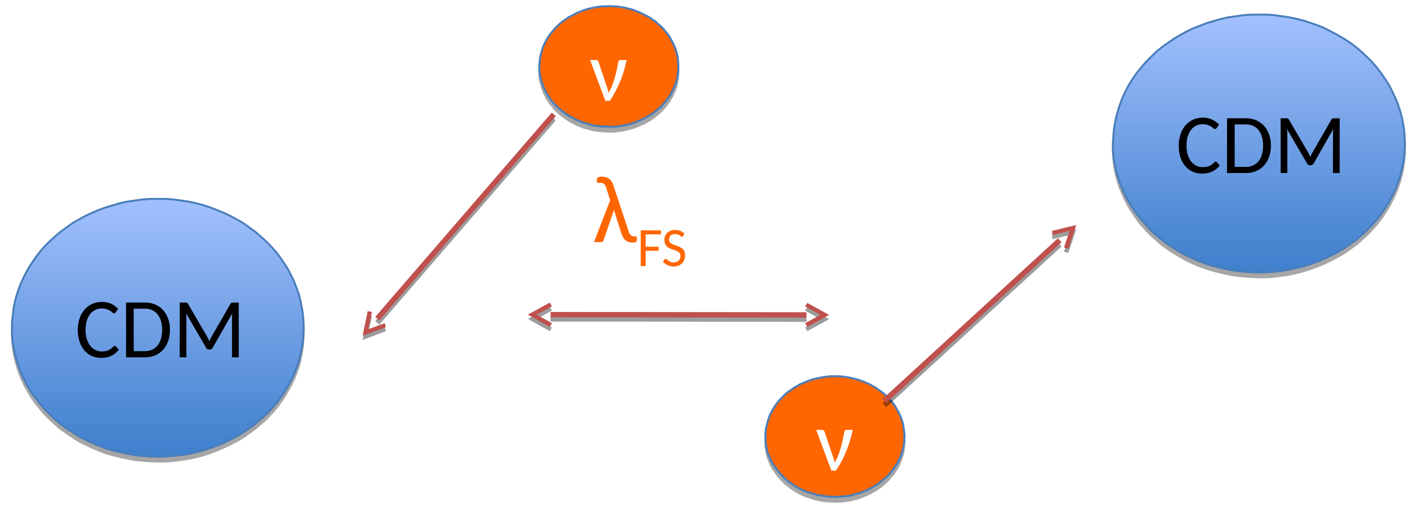
Cosmic Neutrino Background

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

Total density today:

$$\Omega_\nu = \frac{M_\nu}{93.14 h^2}$$

Neutrinos



Neutrinos are hot dark matter

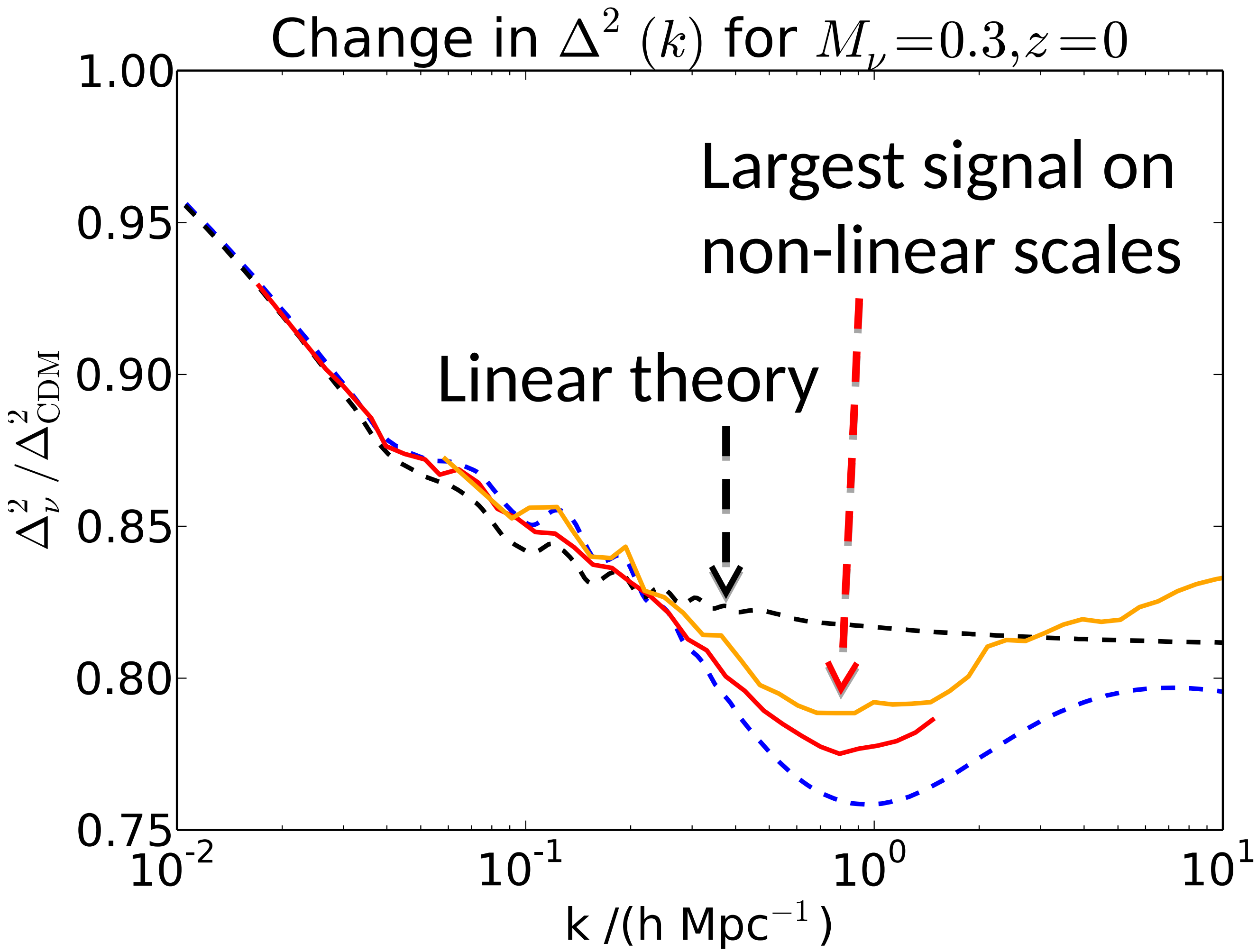
Don't cluster on small scales, suppress matter power spectrum

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?

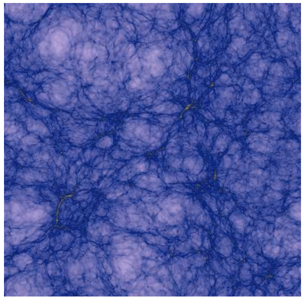
Effect on matter power spectrum

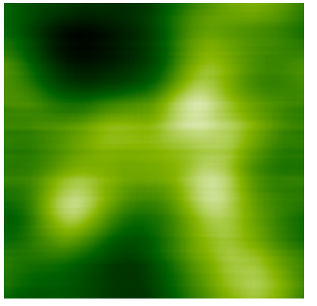


Simulating Neutrinos as Particles

Neutrinos are fast-moving dark matter:

Do N-body like CDM





(Viel 2010)

CDM

Neutrinos

Numerical problems due to discretizing neutrinos

Worse for small masses, only works for > 0.1 eV

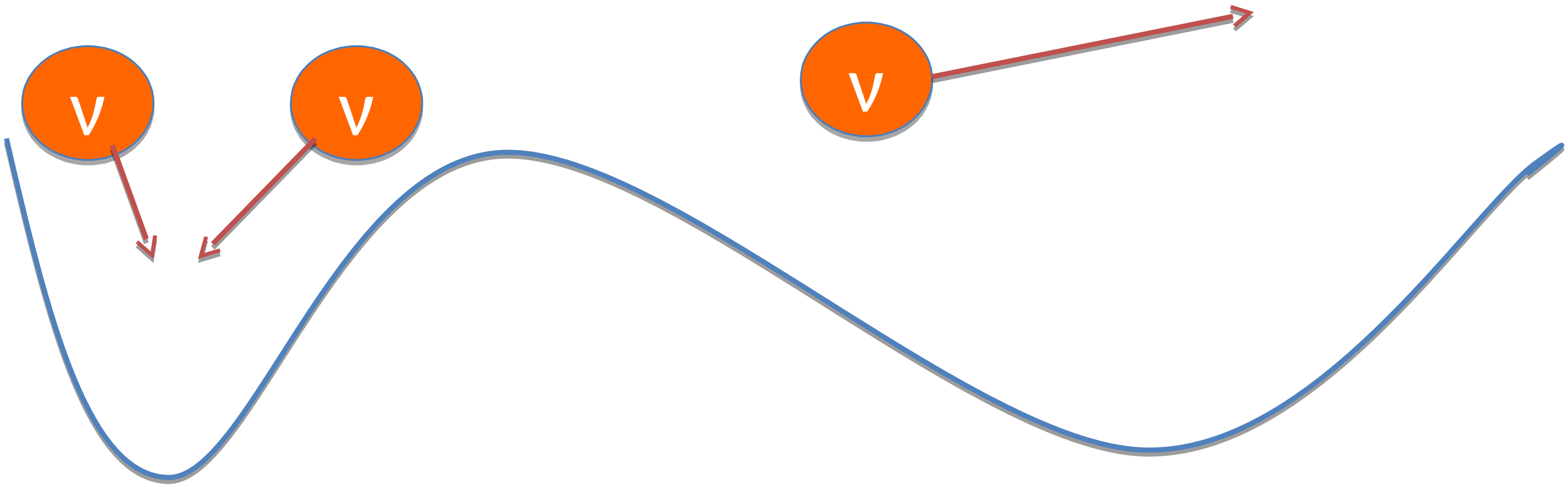
Particle Neutrinos

- 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

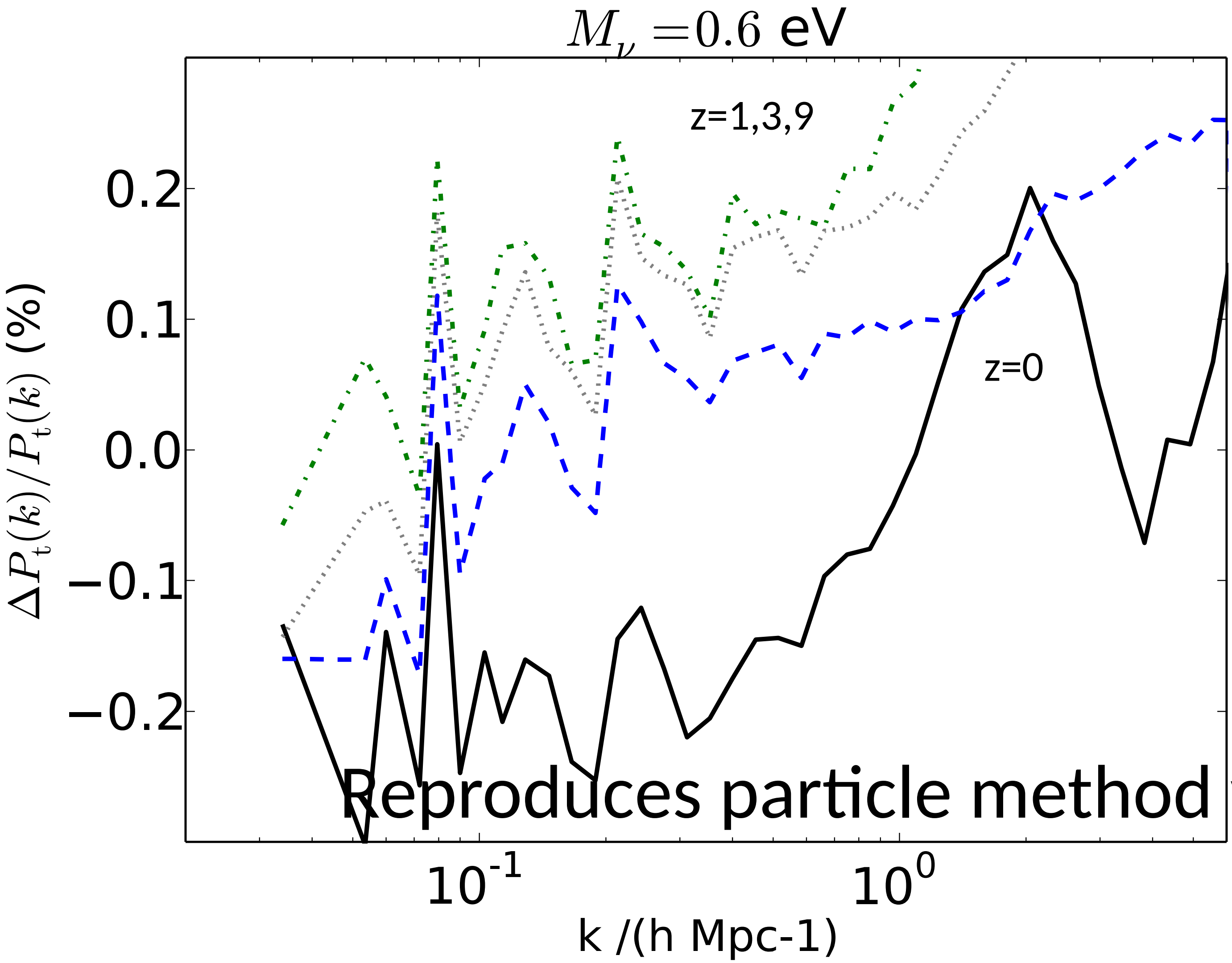
Neutrino power is given by perturbation theory with non-linear CDM potential

$$P^2_{NL}(k) = f_{CDM} P^2_{NL,CDM} + f_\nu P^2_{L,\nu}$$

From N-body timestep

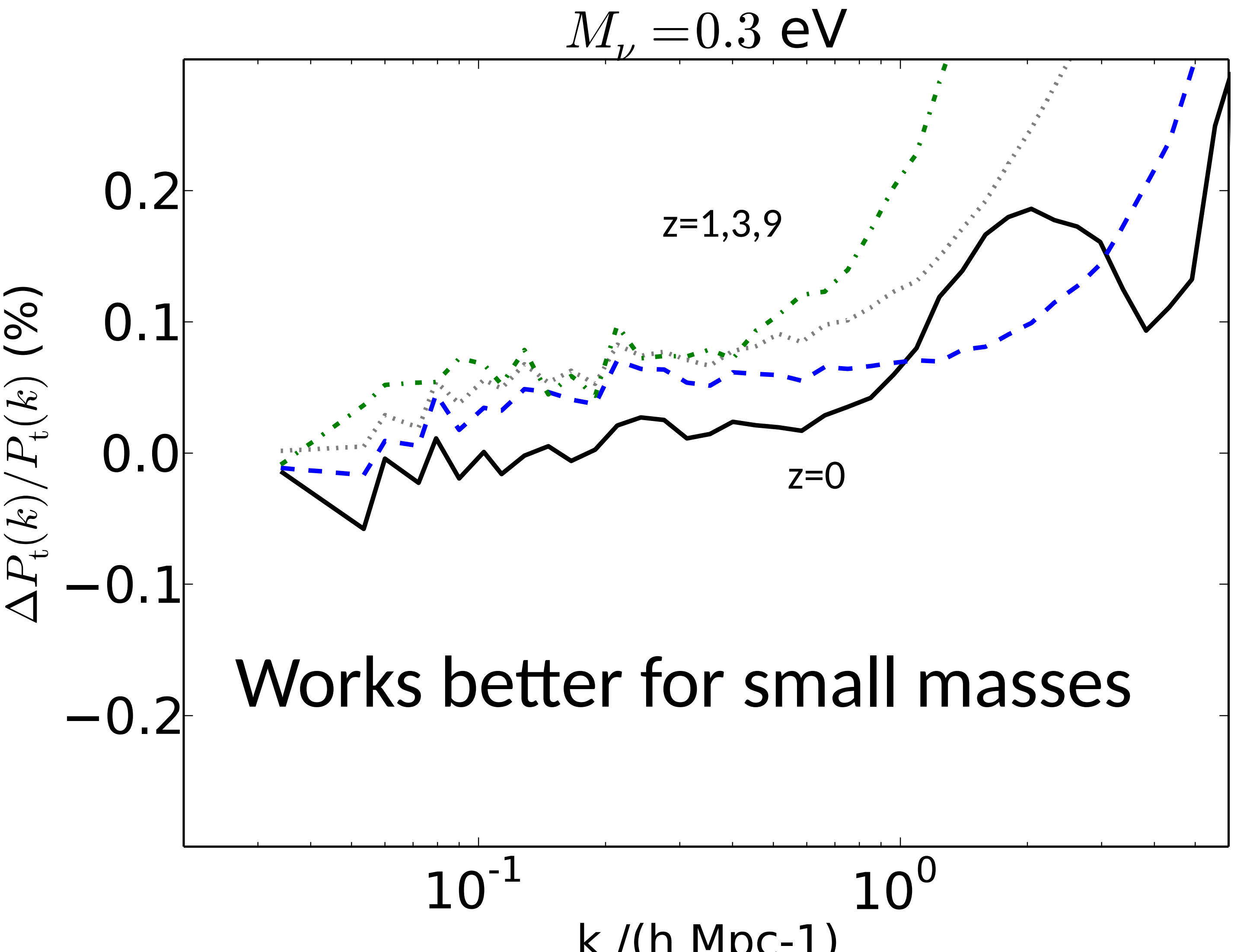
Perturbation theory sourced by N-body

Particle vs. Fourier-Space



Reproduces particle method very well

A Good Method



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: σ_8^8
- Weak Lensing (LSST): small scales
- Lyman-alpha forest: low densities
- CMB lensing: low systematics