Simulating the effect of massive neutrinos on large-scale structure

A method that works for small masses

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arXiv:1209.0461

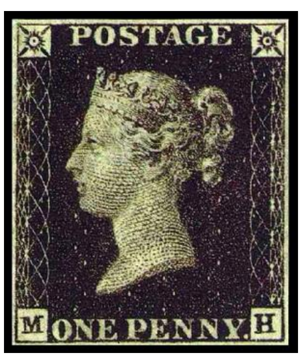
https://github.com/sbird/fs-neutrino

Massive Neutrinos

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

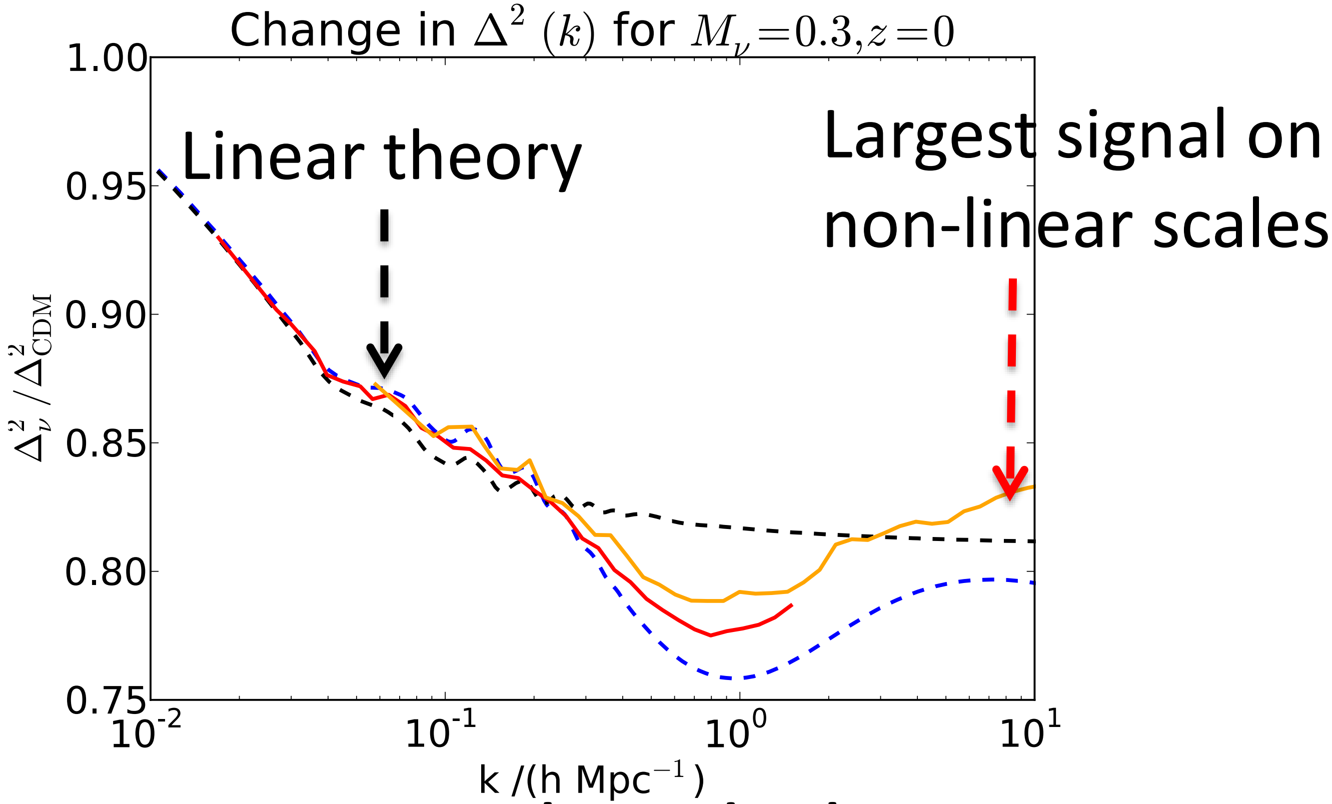
"All science is either physics or stamp collecting"
– Ernest Rutherford

The first stamp



The last stamp?

Neutrino Clustering



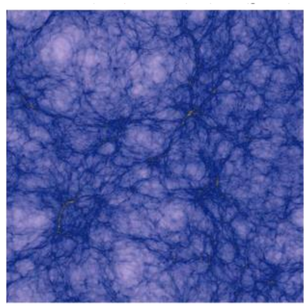
Neutrinos are hot dark matter

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

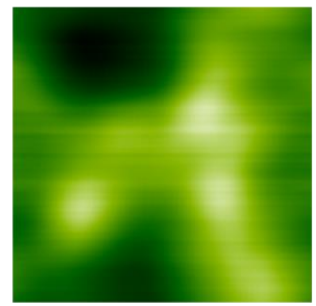
Simulating Neutrinos as Particles

Neutrinos are fast-moving dark matter:

Add an extra particle species



CDM



Neutrinos

(Viel 2010)

Works best for large neutrino masses

Simple, easy to implement

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

$$P(k) \sim 1/N_{\mathrm{part}}$$

- Dominates power at early times
- Can increase number of particles

Early-Time Relativistic Effects

Particle mass cannot change with time

$$\Omega_\nu(a) > \Omega_\nu(0)/a^3$$

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

Simulating Neutrinos as Particles

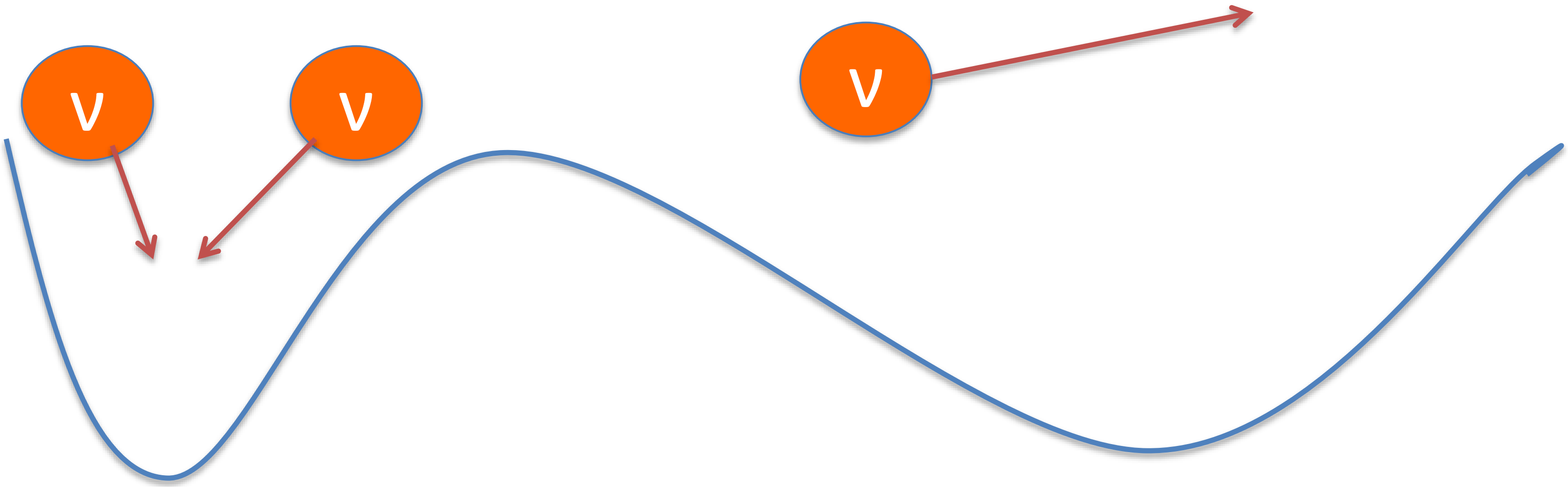
Particles work less well at small masses

- 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

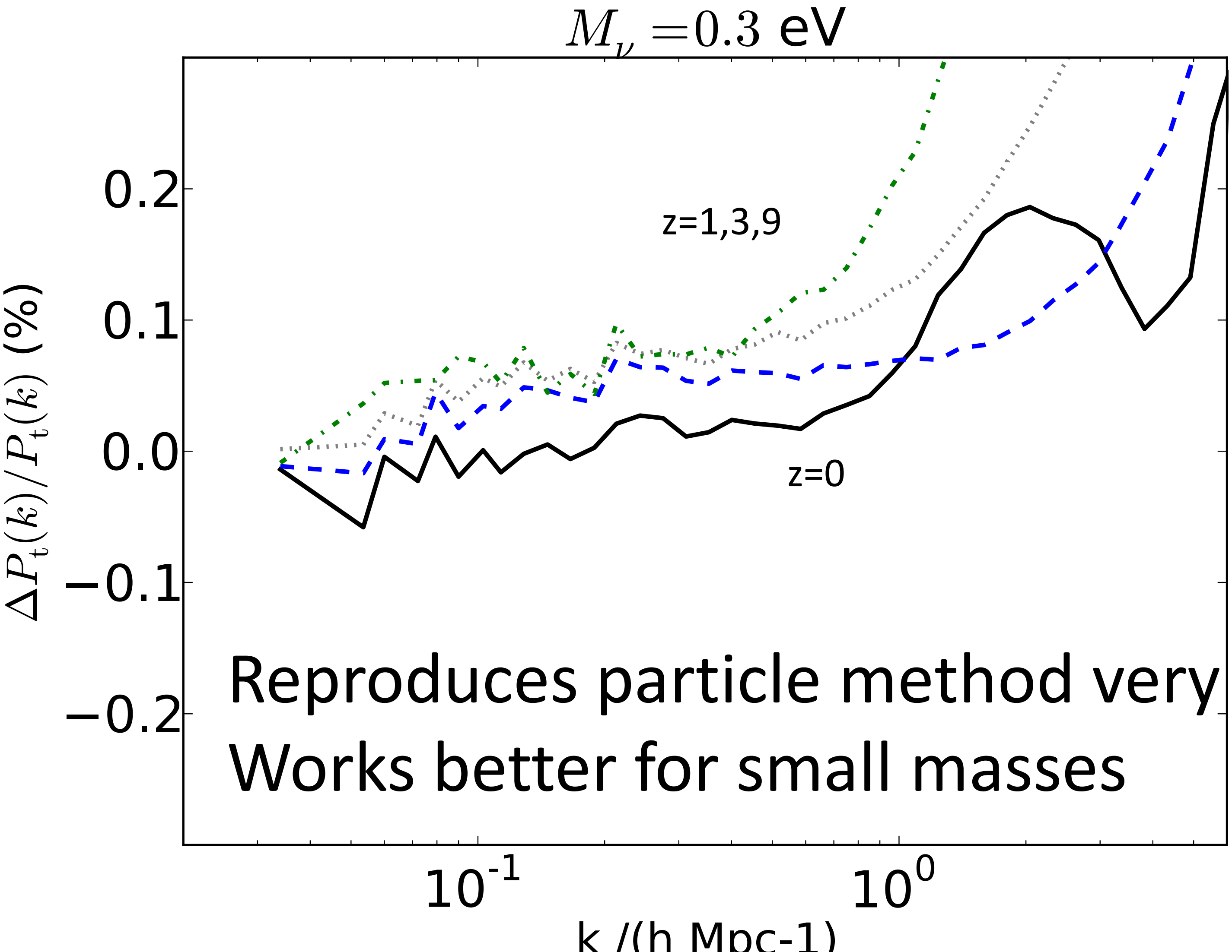
Assume neutrino power is given by perturbation theory with non-linear CDM potential

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

From N-body timestep

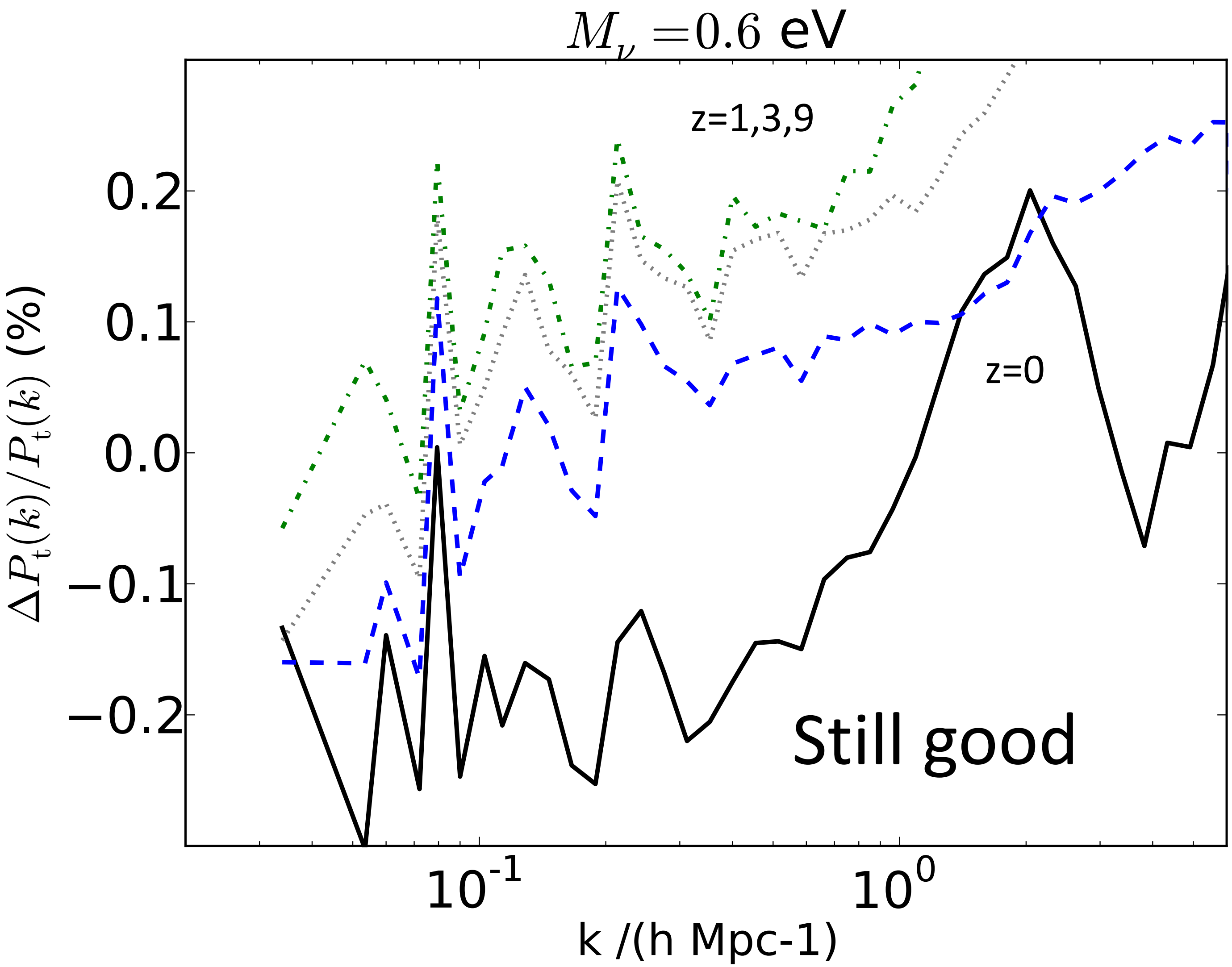
Perturbation theory sourced by N-body

A Good Method

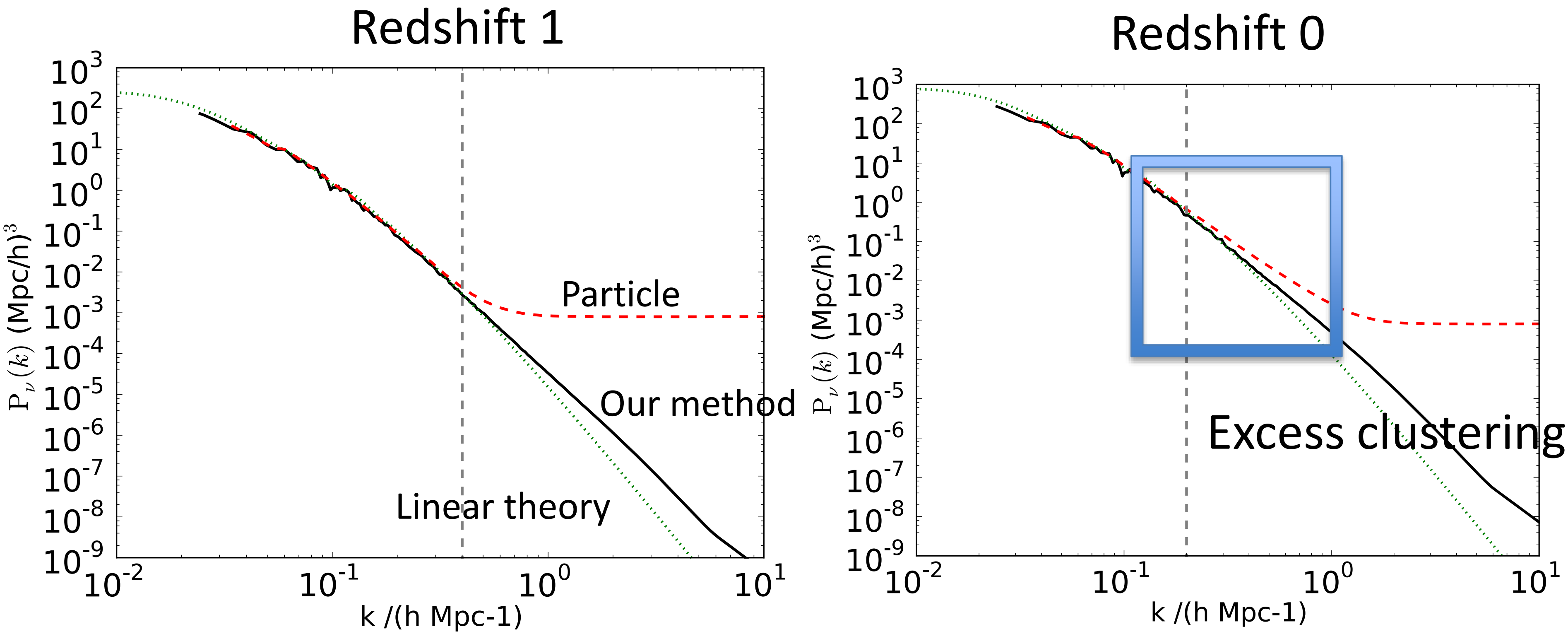


Reproduces particle method very well
Works better for small masses

Particle vs. Fourier-Space



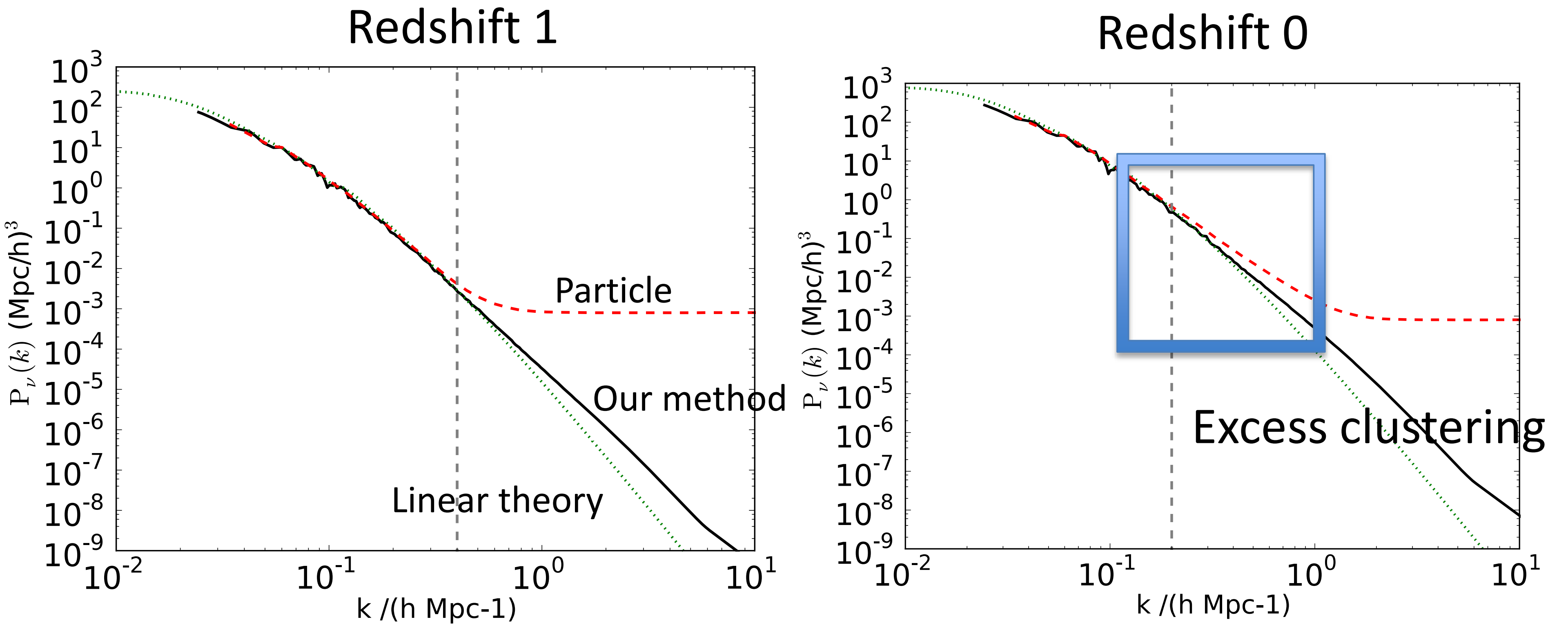
Neutrino power spectrum



Non-linear neutrino clustering: only at z < 0.5

Neutrinos in thermal energy tail – small total mass

Neutrino power spectrum

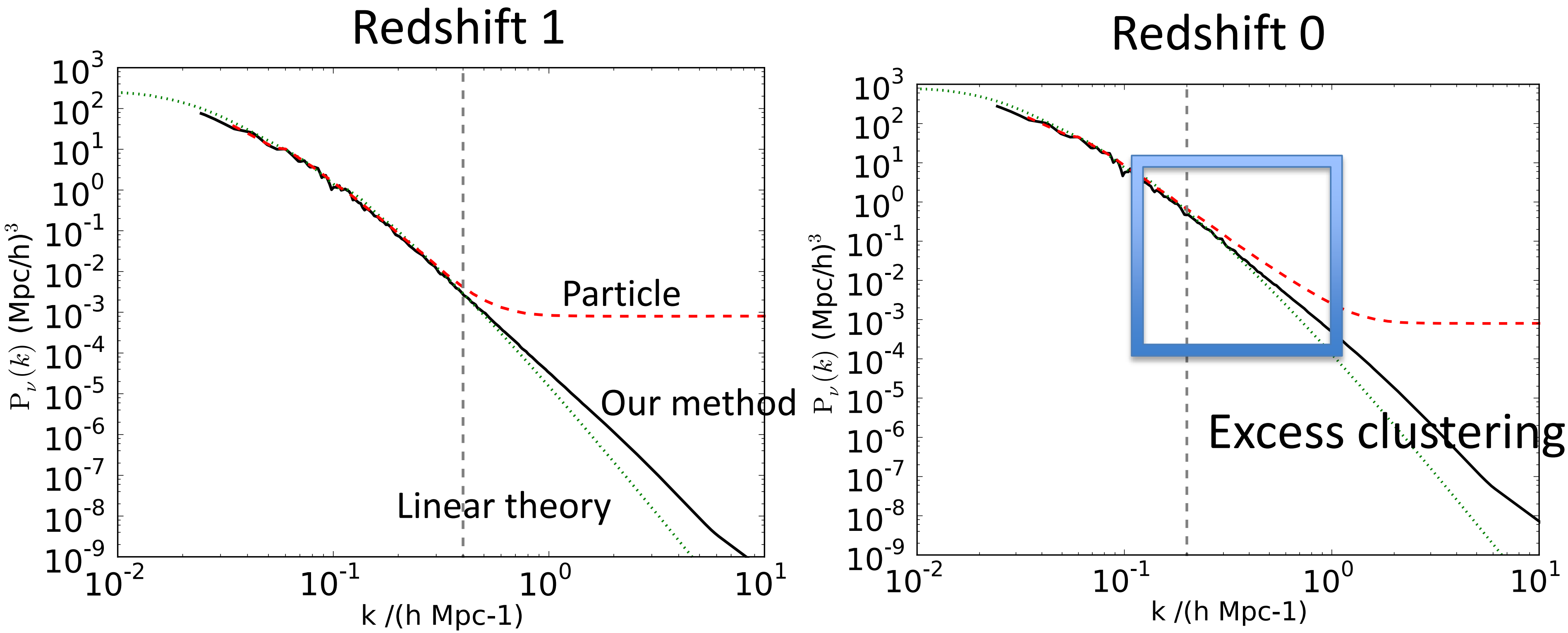


Slow neutrinos captured by large potential well

Start to cluster non-linearly

Only in regions where dark matter clusters strongly

Neutrino power spectrum



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

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