Imprints of massive neutrinos on Large Scale Structure

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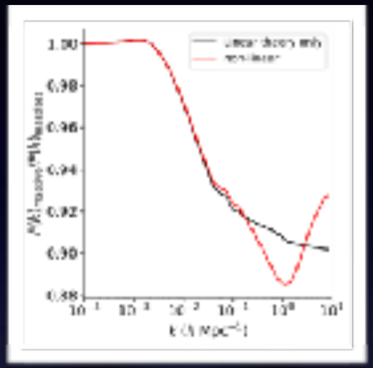
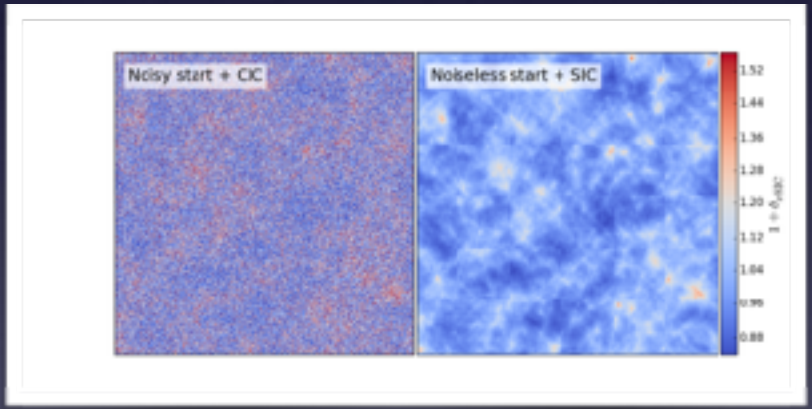
Outline

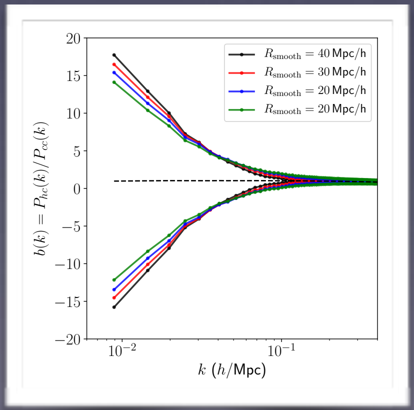
- Introduction



- Simulating structure formation in the massive neutrino cosmologies

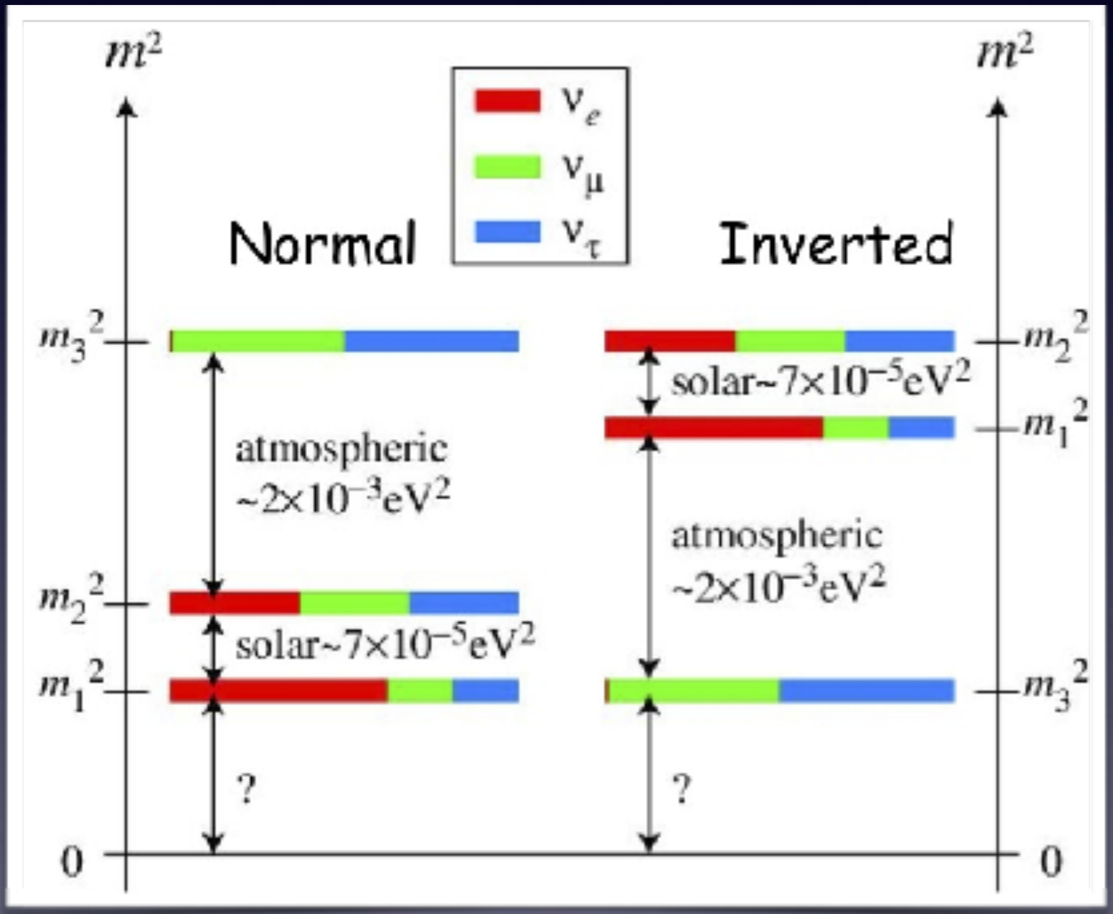


- Scale dependent bias in massive neutrino cosmologies



Massive neutrinos

- Measurements of neutrino oscillations have shown that neutrinos have mass.
- Neutrino masses are much smaller than all other Standard Model particles.
- Mass generation mechanism could be different, and offer insights into physics beyond SM.
- Ongoing terrestrial experiments such as KATRIN are looking to pin down the exact mass scale of neutrinos.
- Can cosmological observables help measure the neutrino mass?



Neutrinos at high redshifts

- Analogous to the Cosmic Microwave Background (CMB), there is a Cosmic Neutrino Background relic.
- In the CMB epoch, neutrinos are almost completely relativistic, and act like extra radiation. The effect of the neutrino background is expressed in terms of N_{eff}.
- Imprints of their mass appear only at lower redshifts once neutrinos become non-relativistic.
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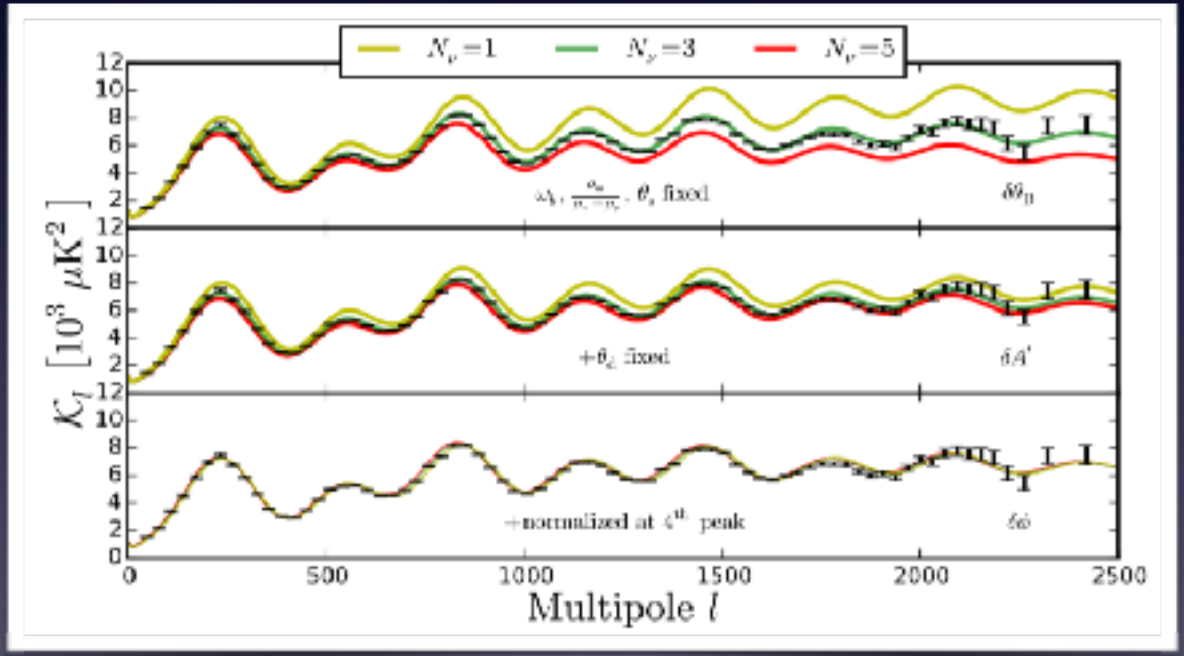

Follin et al 2015

Energy density of massive neutrinos

- If neutrinos were massless, the energy density in neutrinos today would be comparable to that of radiation i.e. negligible.

- However, for massive neutrinos, the energy density is given by

$$\Omega_\nu = \frac{\sum m_\nu}{94h^2} \quad , \quad f_\nu = \frac{\Omega_\nu}{\Omega_{C+b} + \Omega_\nu}$$

- For a fixed Ω_Λ, increasing the energy density of neutrinos implies decreasing the energy density in CDM.

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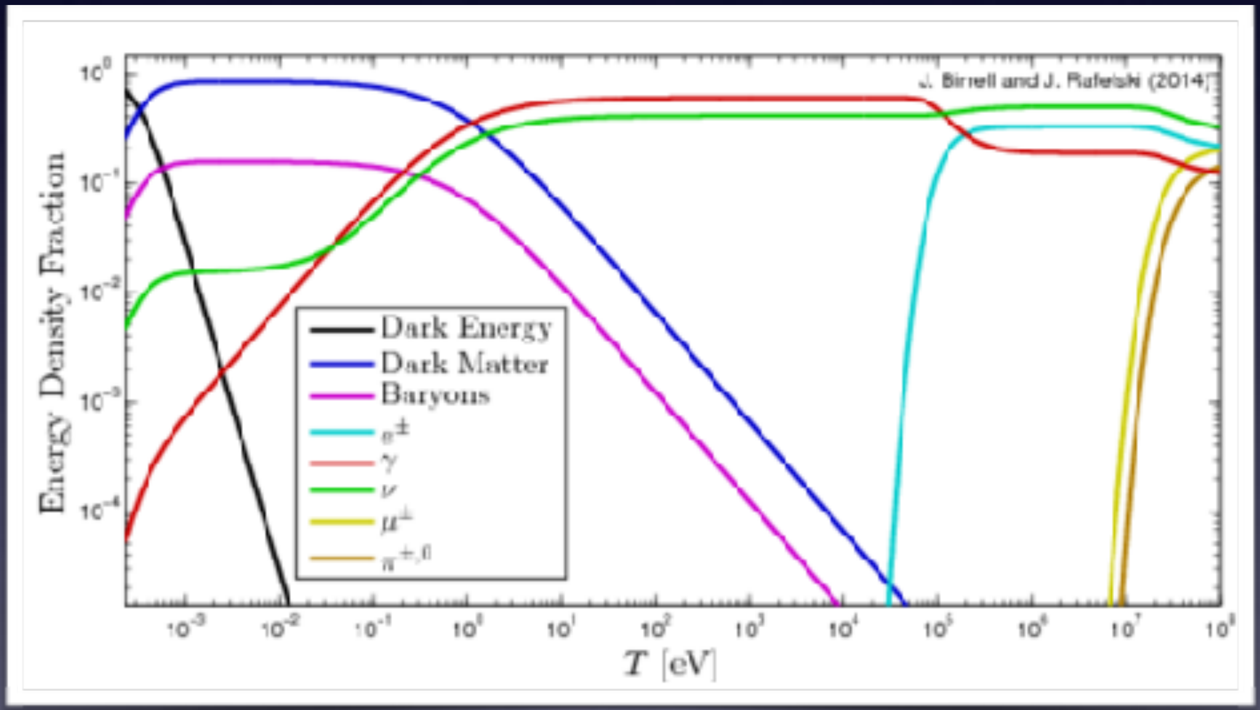

Birrell & Jeremiah, 2014

Neutrino free streaming

- Even when non-relativistic, neutrinos have large thermal velocities.
- Their motion is not affected by small scale perturbations (smaller than the free streaming scale).
- On large scales, the evolution is affected by gravity.
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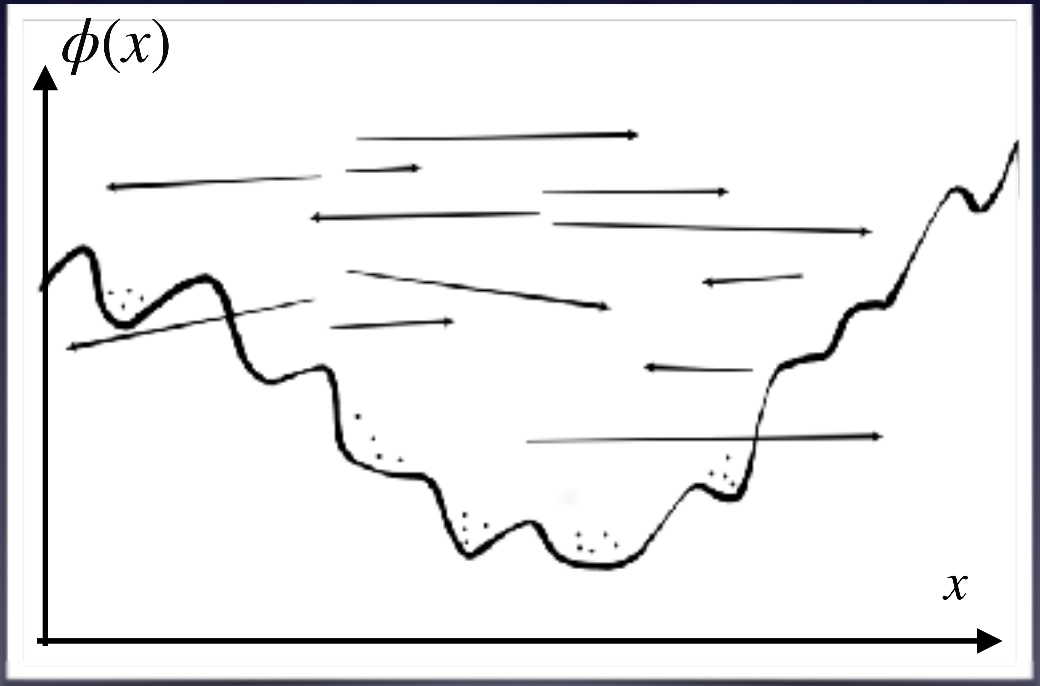
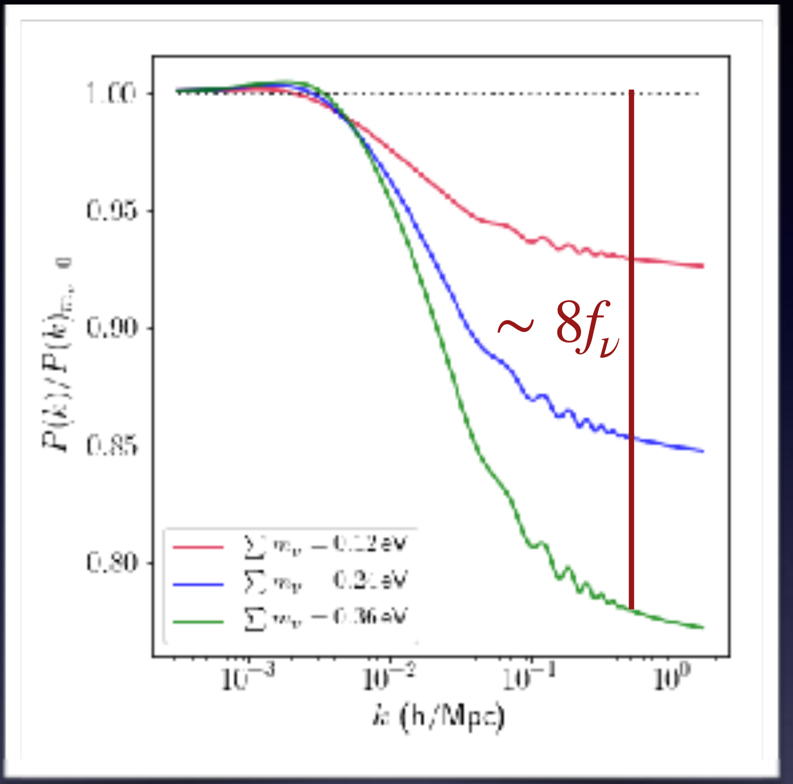


Effect on power spectrum

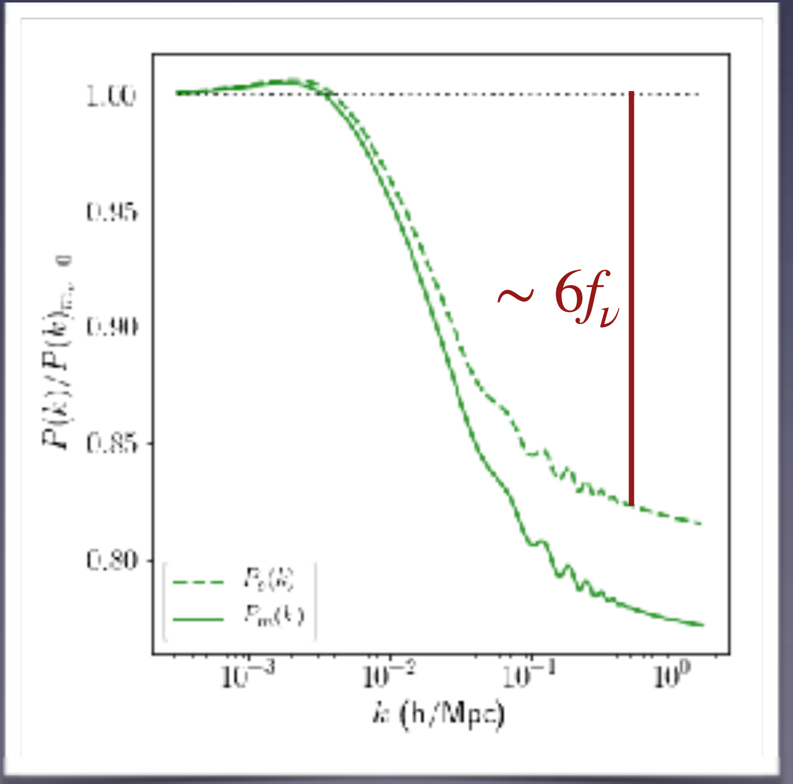


- Changes the growth of perturbations in both δ_c as well $\delta_m = f_c\,\delta_c + f_\nu\,\delta_\nu$.

- The peculiar gravitational potential which sources the growth is altered on small scales:

$$\nabla^2\phi \propto (f_c\delta_c + f_\nu\delta_\nu)$$

- At a fixed redshift the power spectrum of perturbations is damped.



Measuring neutrino mass in cosmological surveys

- Just using scales at which linear theory is valid, the neutrino mass will be well constrained in upcoming surveys like DESI, CMB S4 and LSST.
- 3-d clustering of galaxies is related to the underlying Cold Dark Matter field.
- Galaxy-galaxy lensing and cosmic shear measurements depend on the projected total matter field (including neutrinos).

LSST 3X2 pt + Planck

	$\sigma(\sum m_\nu)$ (eV)	$\sigma(w)$
$N_S = 1$, $N_L = 1$	0.093	0.069
$N_S = 4$, $N_L = 4$	0.052	0.028
$N_S = 6$, $N_L = 6$	0.041	0.020
$N_S = 6$, $N_L = 6$ (+ DESI[52])	0.032	0.017
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Banerjee et al 2017

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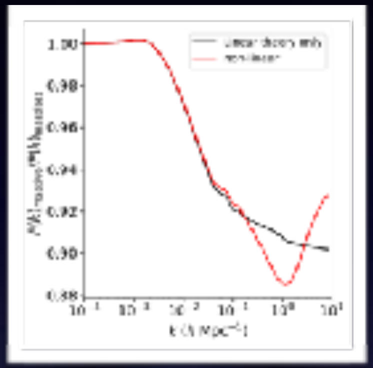

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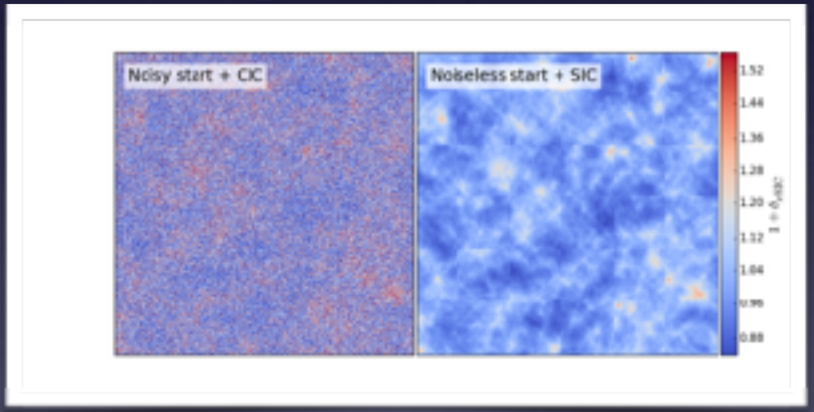

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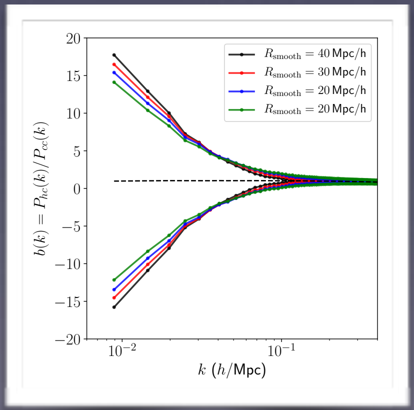
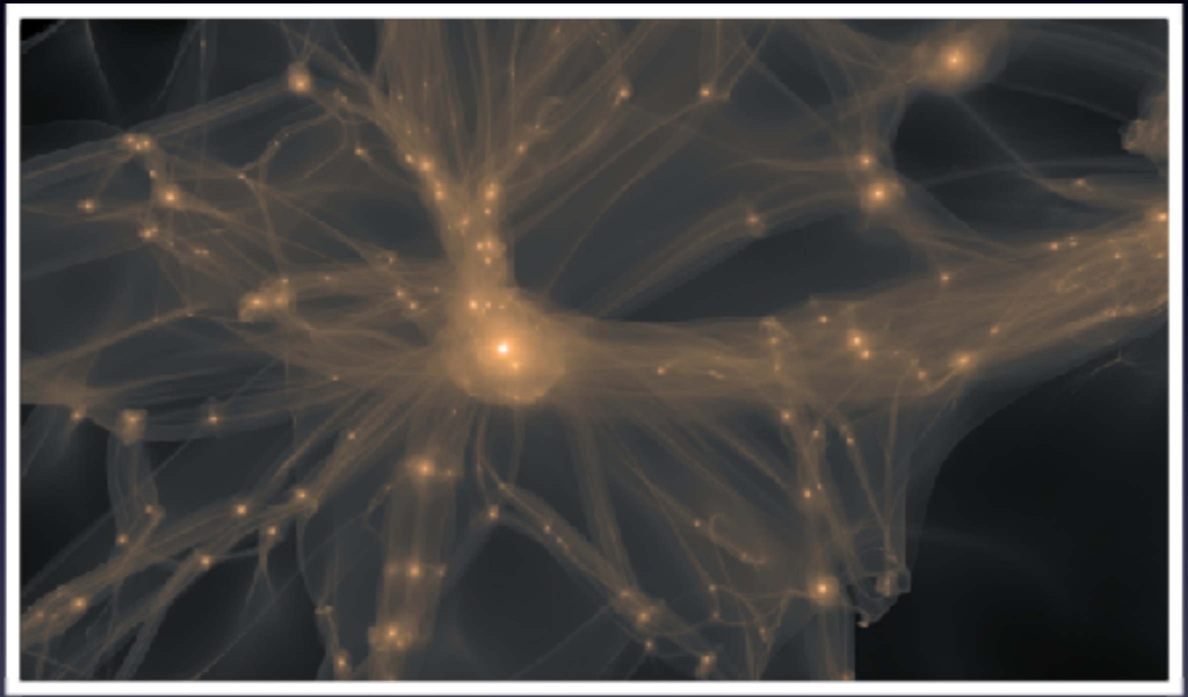
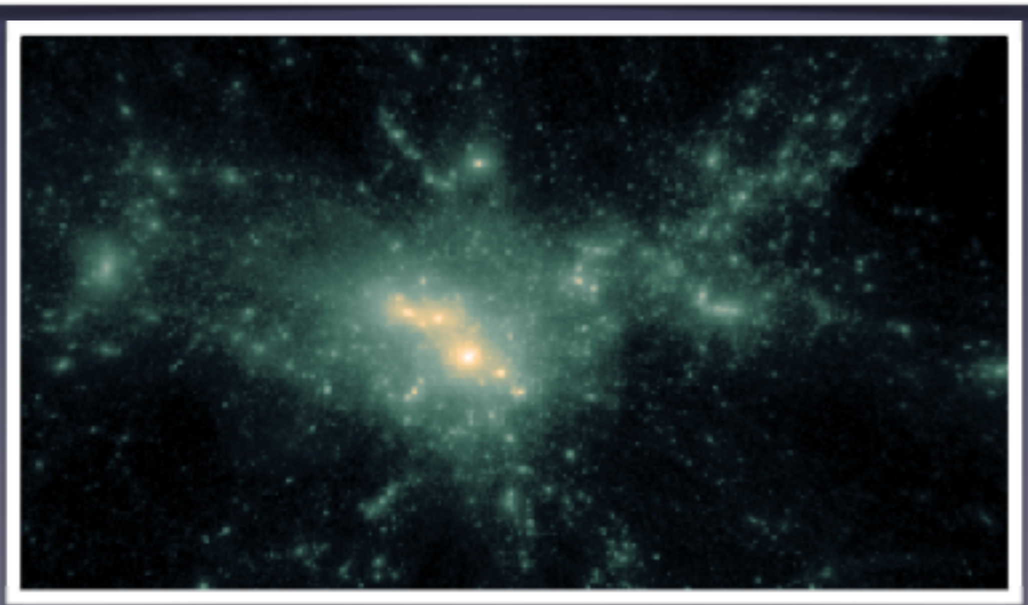


N-body simulations in Λ-CDM cosmologies

- N-body simulations have been the tool of choice for studying non-linear structure formation for cosmologies where CDM is the only clustering component.
- Start at high redshifts when perturbations are linear and follow the gravitational evolution of particles.
- Relies on the assumption that the number of simulation particles in a given region is a good representation of the physical density.

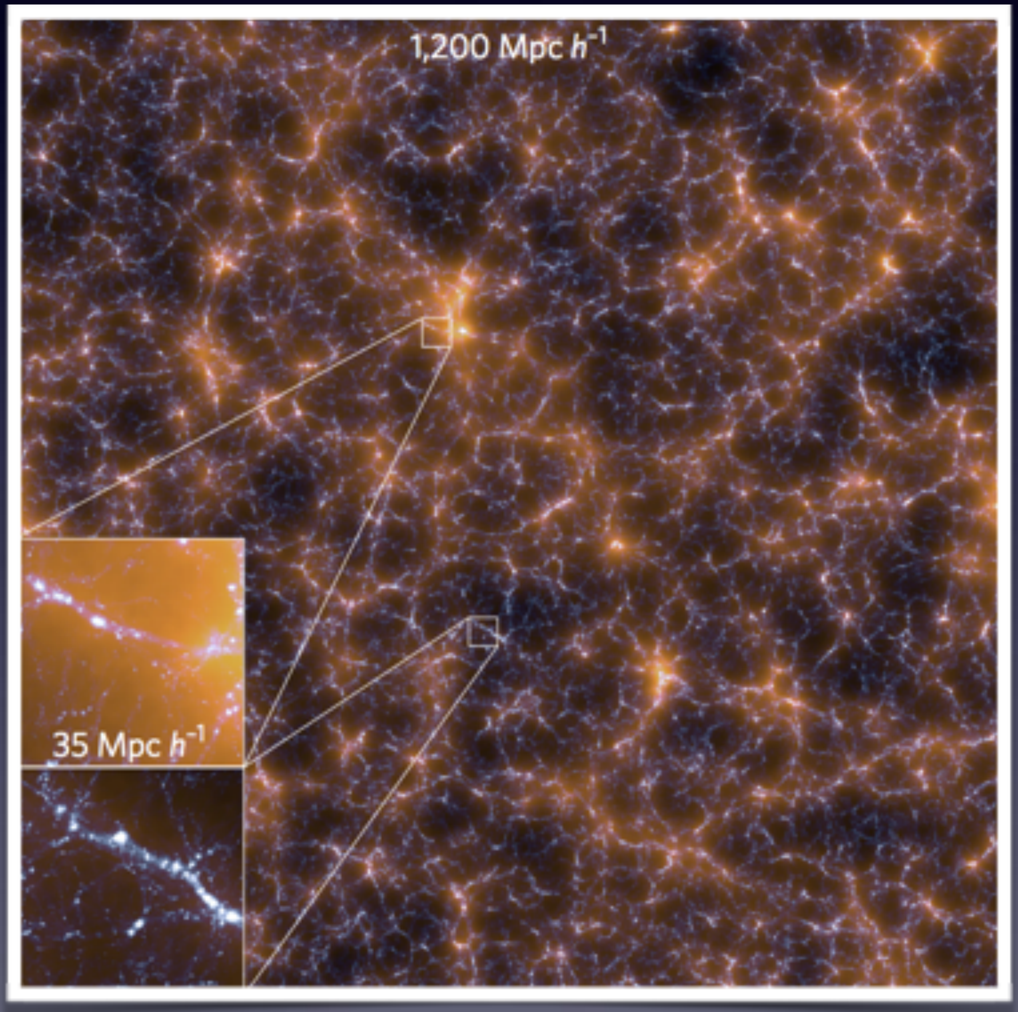




Credit: Ralf Kaehler (SLAC)

Including neutrinos in N-body simulations

- Neutrinos are treated as a fluid on a grid with linearized fluid equations coupled to the full non-linear gravitational potential.
- Neutrinos as an extra set of N-body particles.
- Hybrid methods combining particle and fluid features.



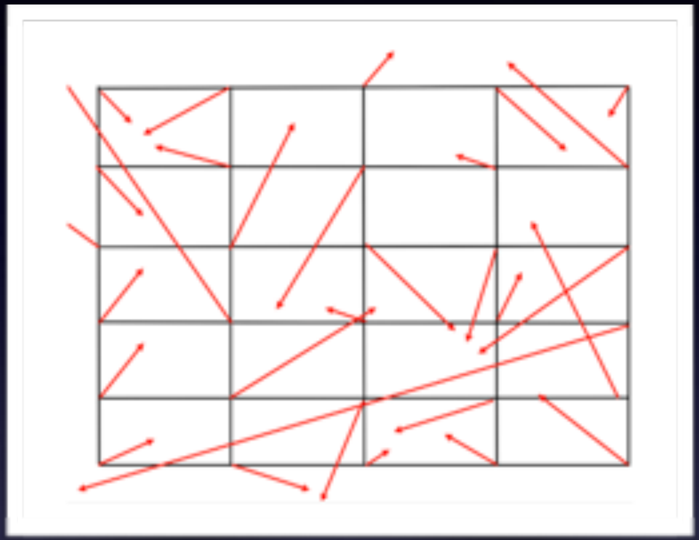
Yu et al 2017

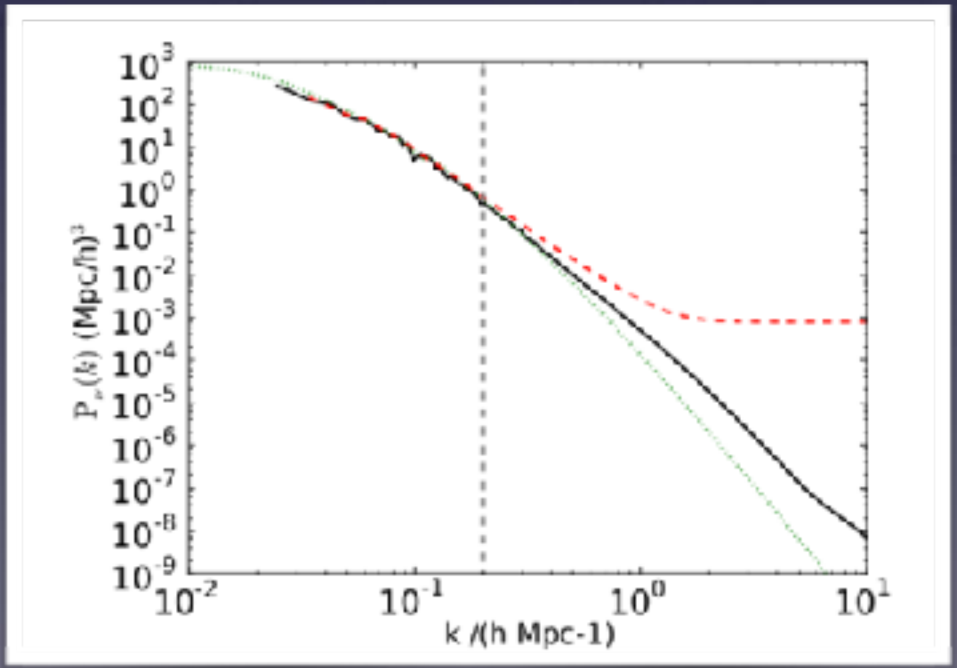
Neutrinos as extra N-body particles

- Neutrinos have large thermal velocities (drawn from an underlying redshifting FD distribution), which have to be accounted for in the simulations.

- Standard approach: Sample this distribution in a random manner to get the magnitude of velocity, and then choose a random direction.

- Density field of neutrinos gets swamped by shot noise. Goes as 1/N.

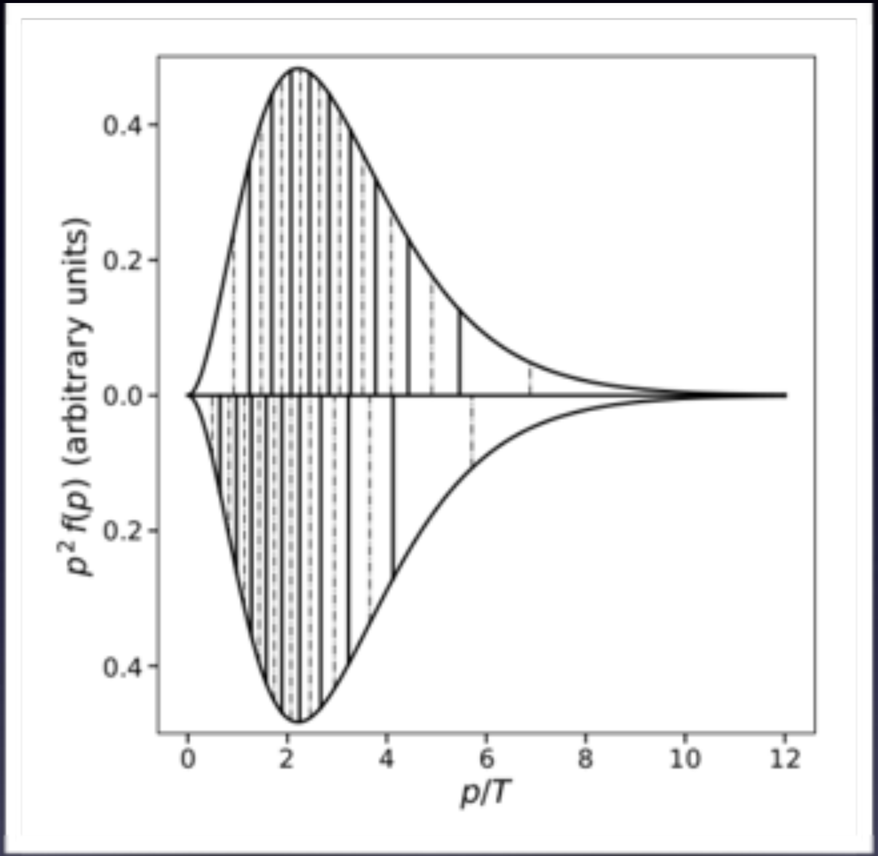




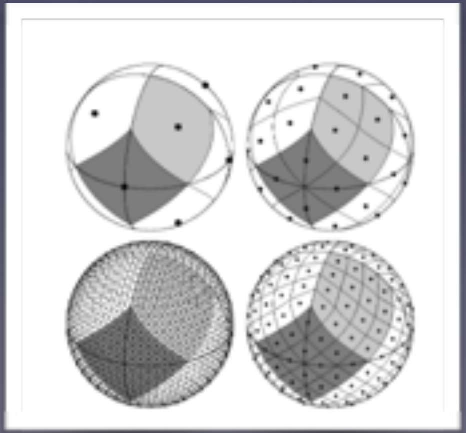
Ali Haimoud and Bird, 2013

Changing the initial conditions

- Instead of sampling randomly, we can sample the distribution the same way at every point on the IC grid.
- At every point, fixed number of velocity magnitude sample points. For every velocity magnitude, use HEALPIX algorithm to fix directions.
- Number of neutrino particles moving into and out of different regions is the same.



Banerjee et al, 2018



Gorski et al 2005

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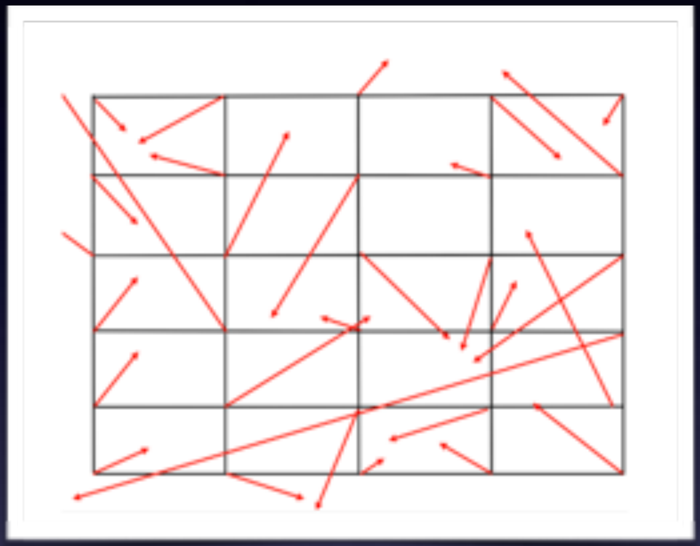
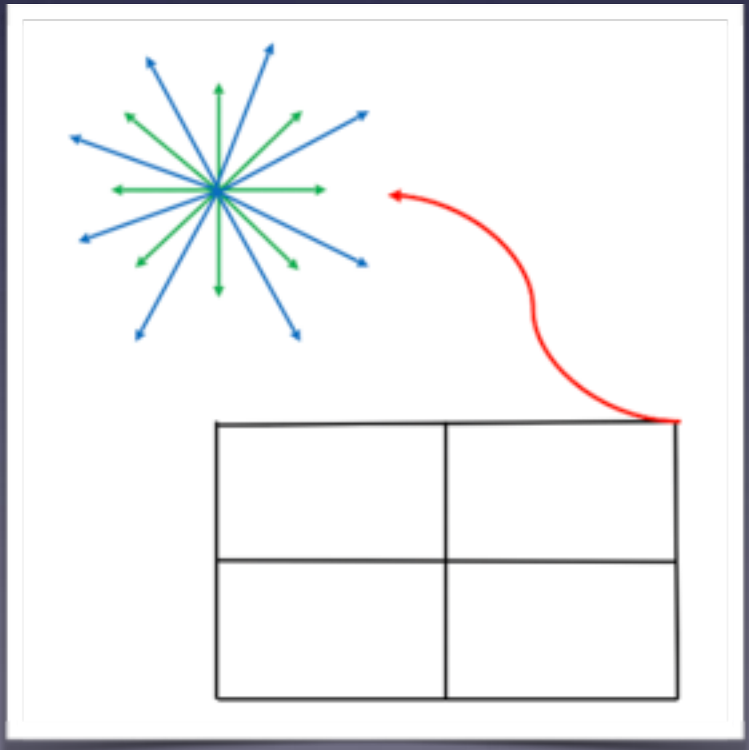
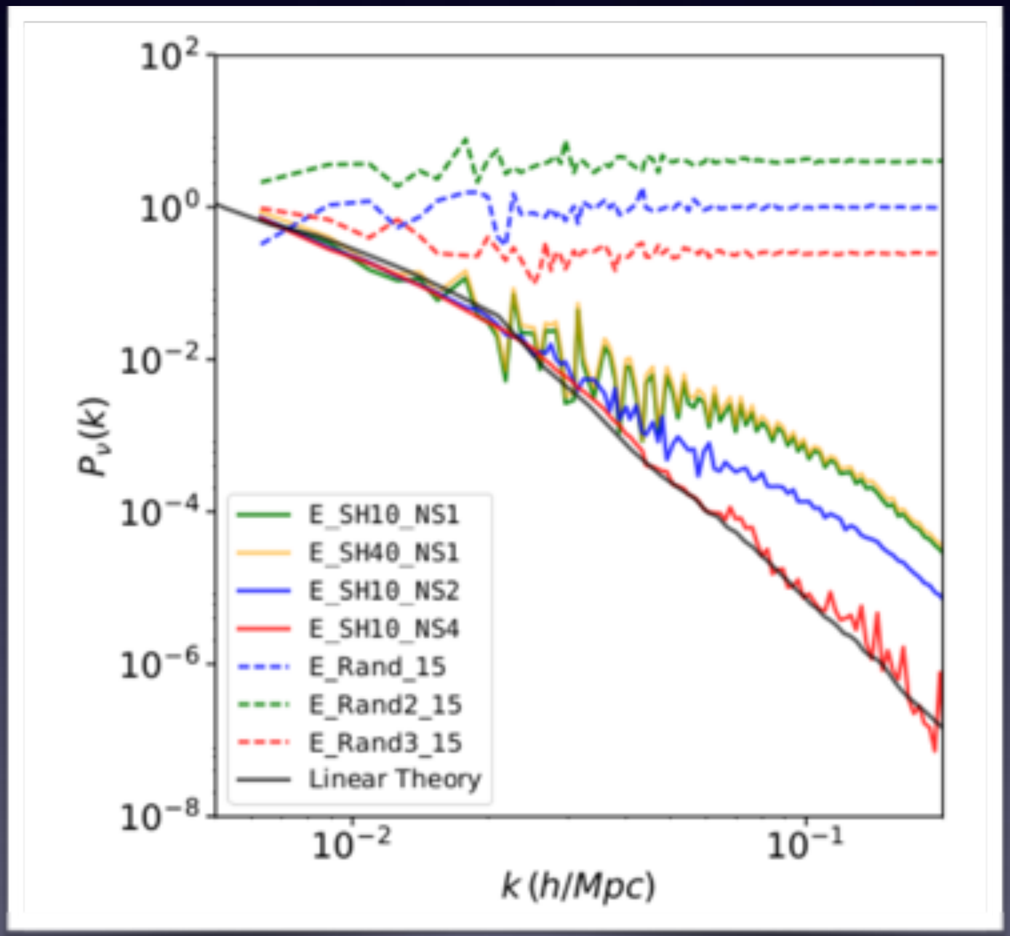




High redshift power spectrum

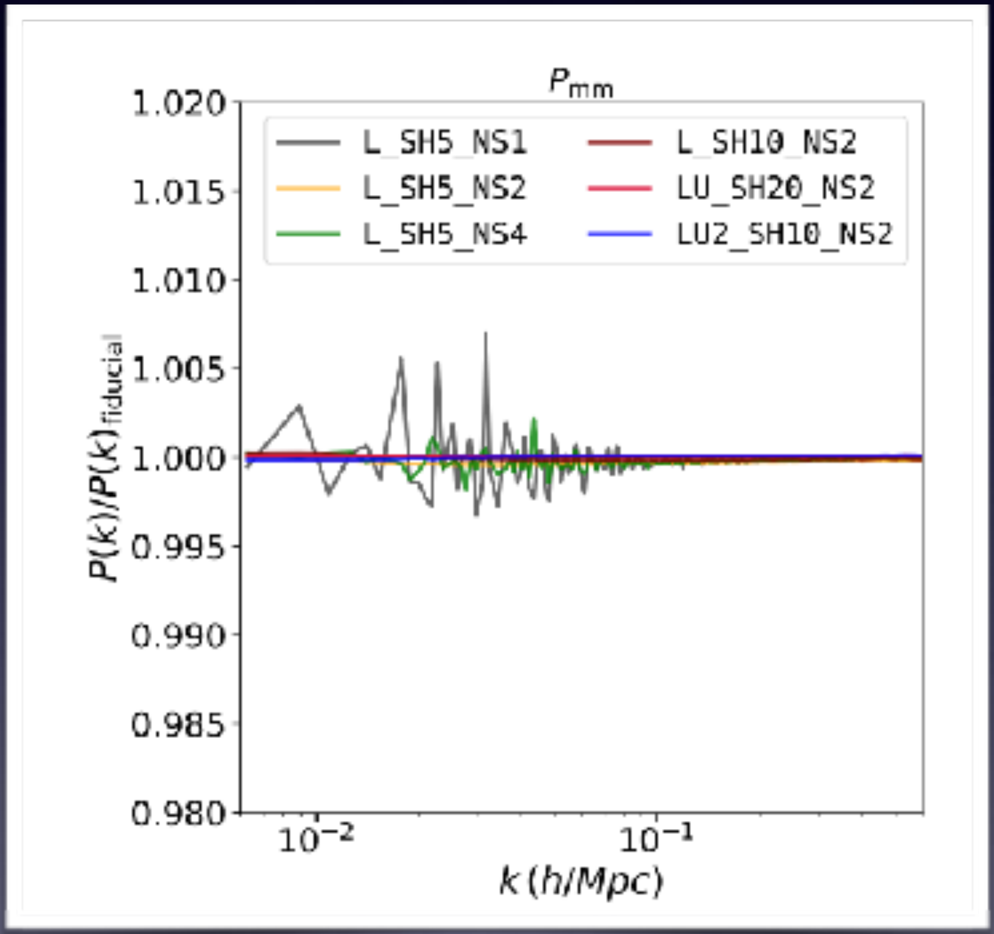
- Start at z=99. Look at results at z=49. Equal mass subdivisions of the FD distribution.
- Shot noise in neutrino power spectrum goes away.
- Results at high redshift not very sensitive to number of sample points from the F-D distribution.
- Is sensitive to the isotropy of the distribution. Controlled by N_{shell} in HEALPIX.



Banerjee et al, 2018

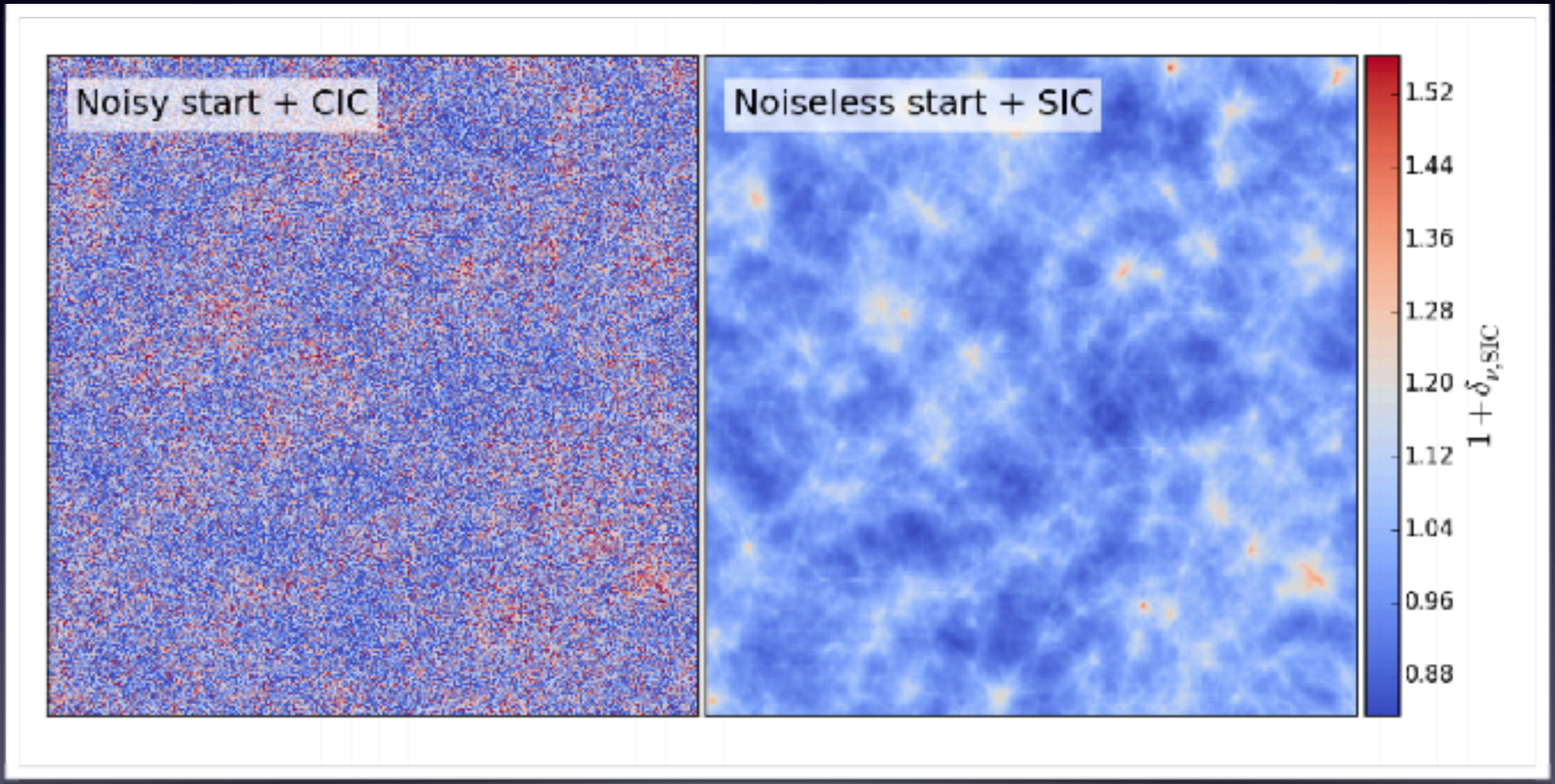
Matter power spectrum at z=0

- Use finer grid to generate CDM IC's. Neutrinos are generated off a coarser grid.
- We focus on the convergence of the total matter power spectrum.
- Grid size of neutrinos is not very important.
- $N_{shell} = 1$ is somewhat noisy on large scales.
- Not very sensitive to the number of radial velocity shells.



Banerjee et al, 2018

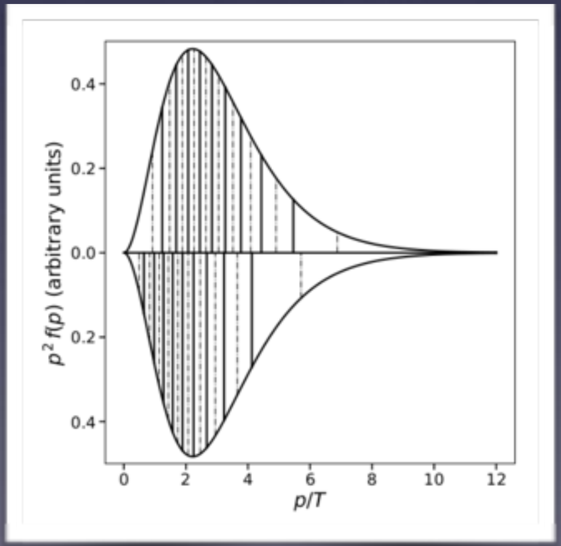
Neutrino density field at low redshift

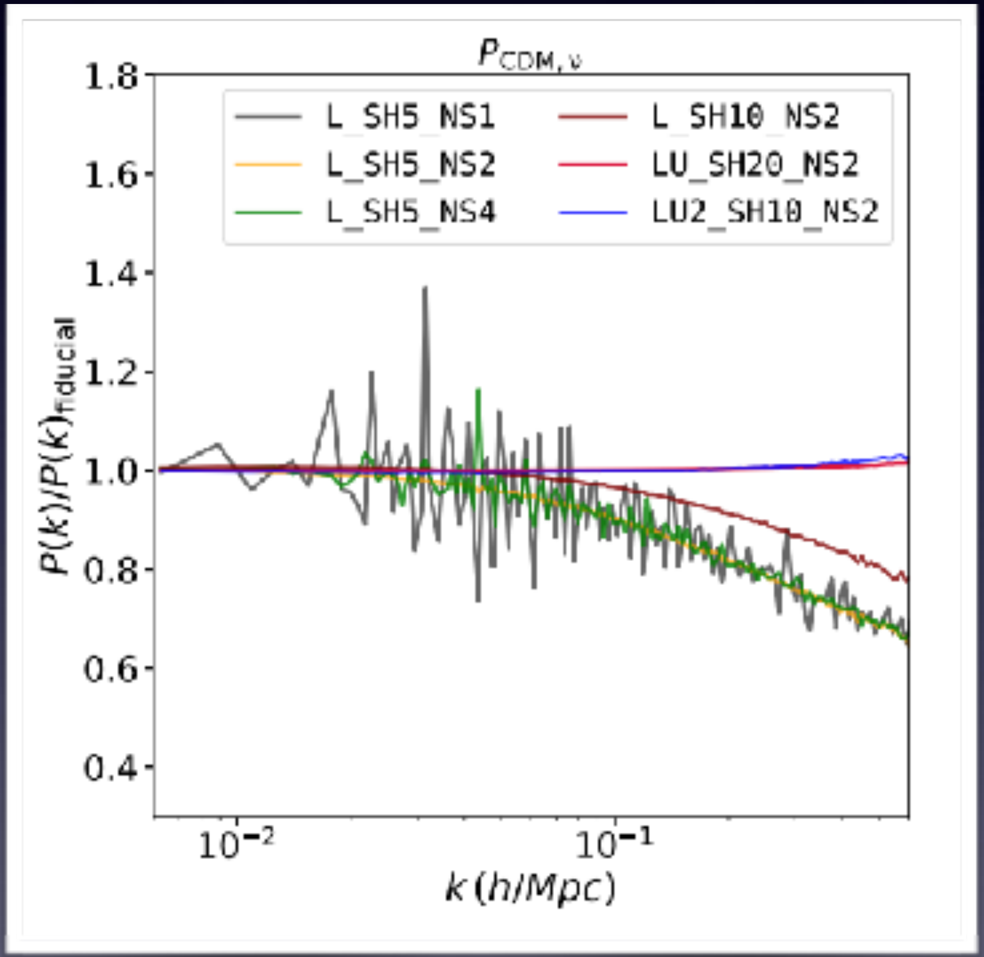


Banerjee et al,
2018

CDM-neutrino cross power spectrum at z=0

The CDM-neutrino cross power spectrum can tell us about how neutrinos cluster around the CDM cosmic web.

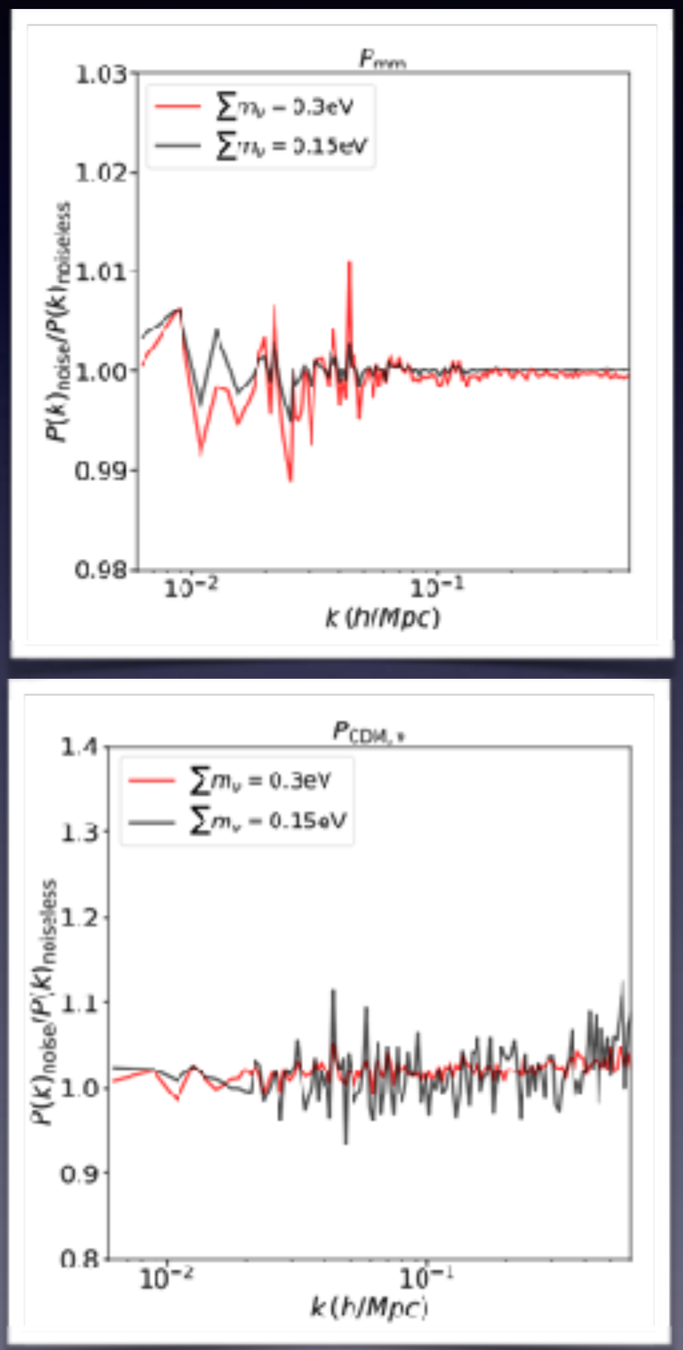




Banerjee et al, 2018

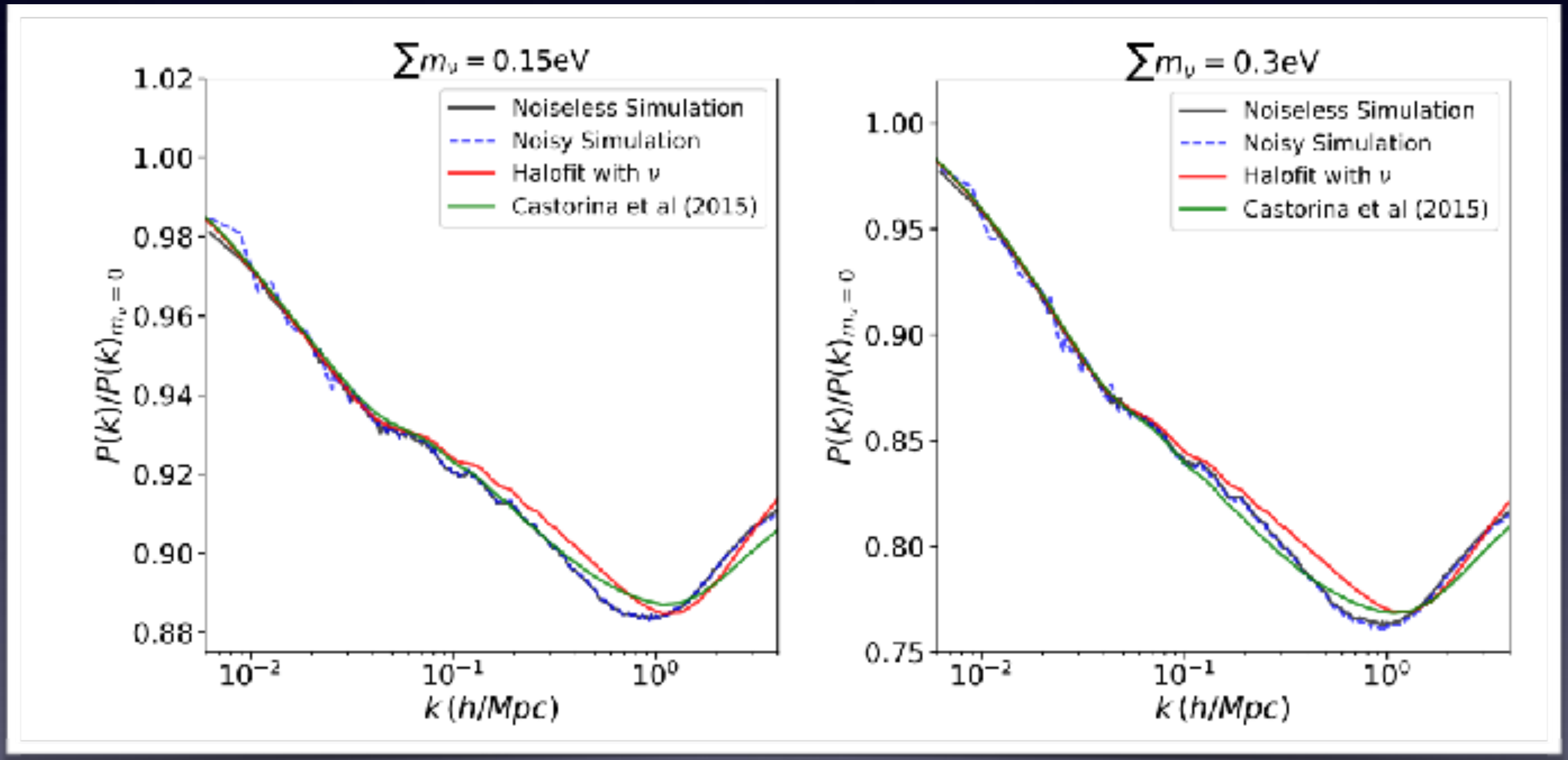
Comparison to previous simulations

- On small scales, agree remarkably well with each other in spite of very different discreteness effects. We can trust these scales from N-body simulations.
- New method reduces noise on large scales - for the noisy simulations even large scales are affected by shot noise - this imprints itself in the density field even at late times.
- New method can help reduce sample variance on large scales.



Banerjee et al, 2018

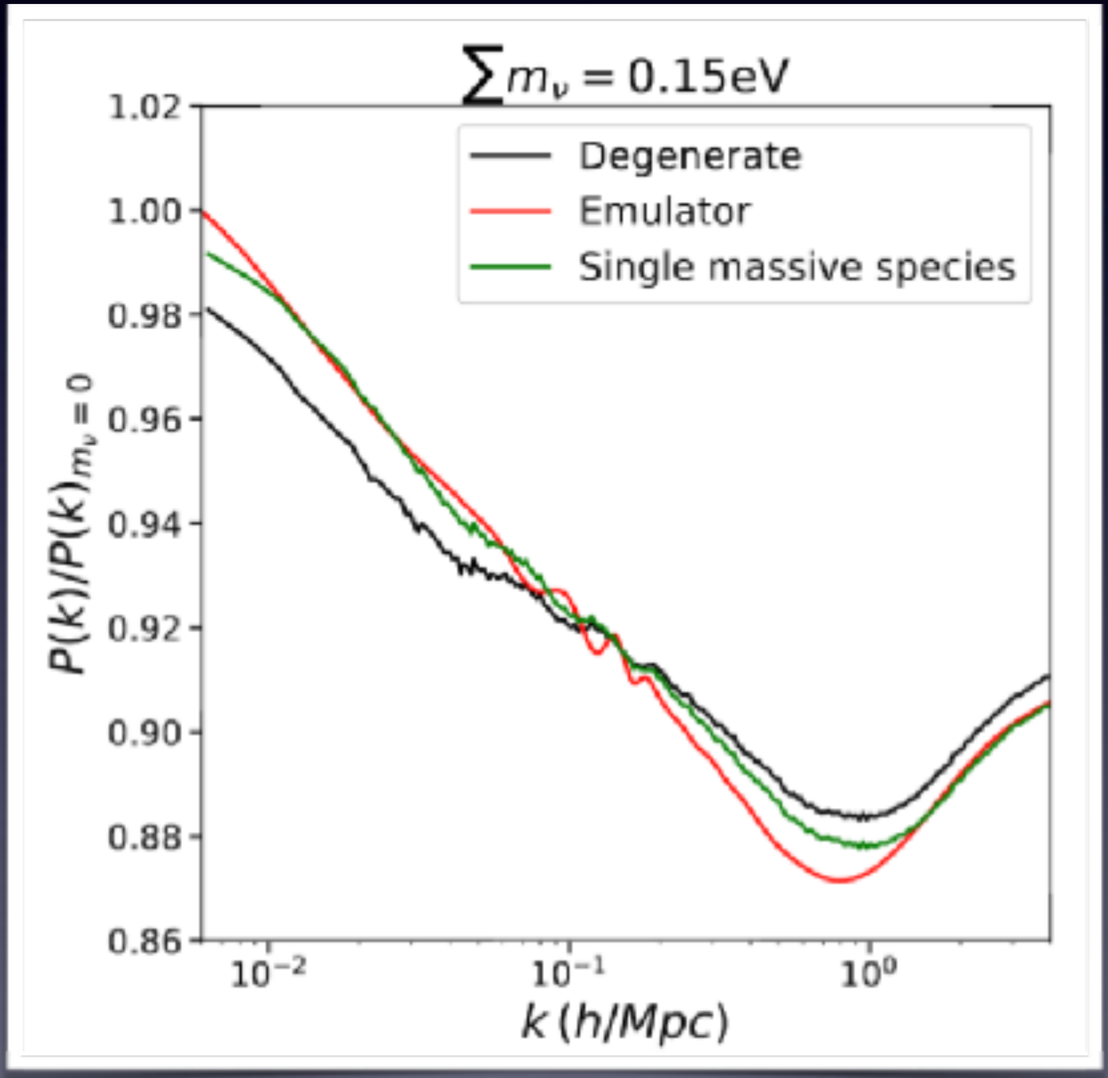
Comparison to existing fitting formulas



Banerjee et al,
2018

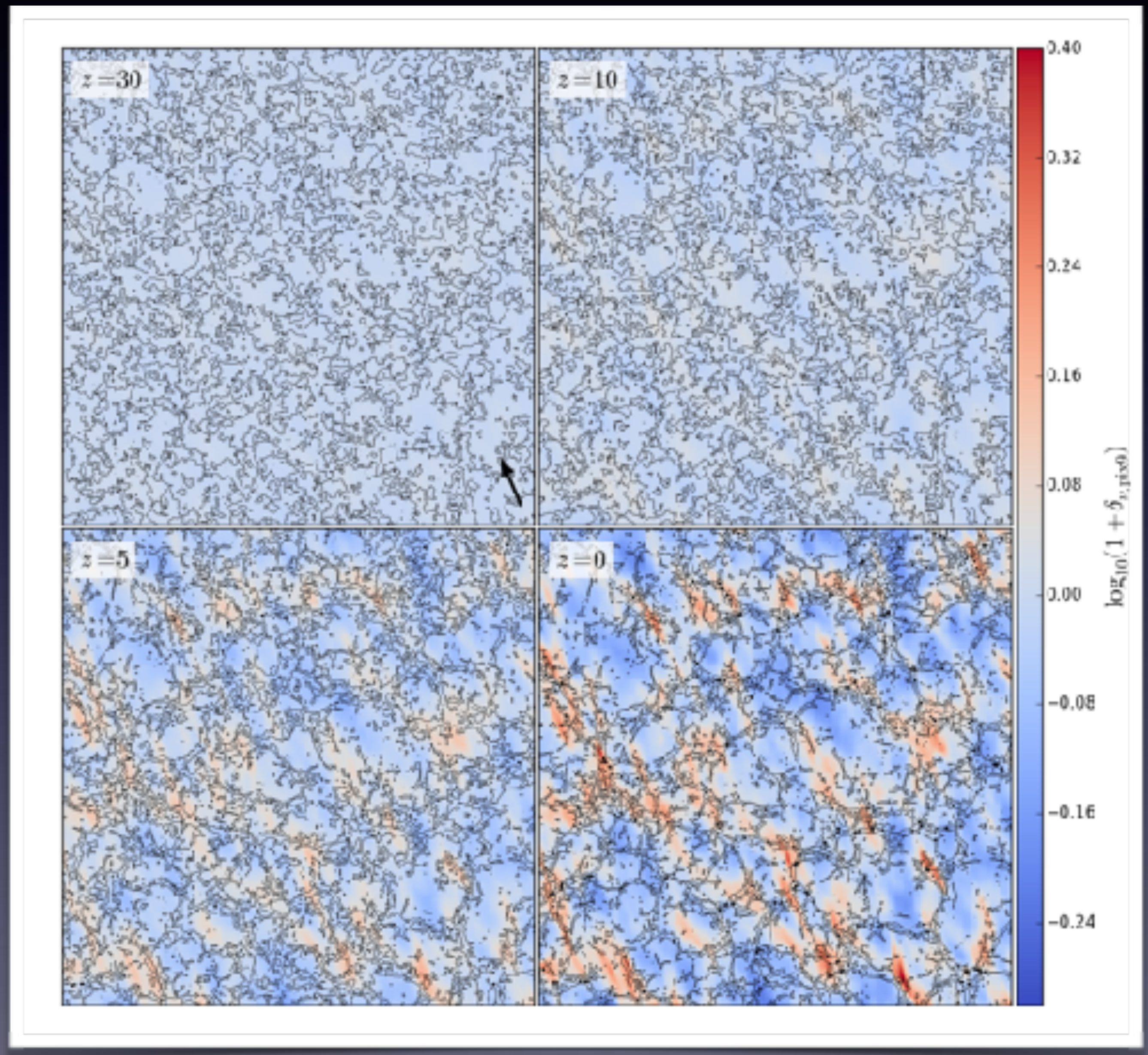
Mass ordering

- Using only a single parameter - i.e. total mass - fails to capture the shape of the damping.
- Shows up most when comparing a single massive species to three degenerate massive species for a fixed mass.
- Even for a mass as low as 0.15eV, the effect on large scales is as much as 2% for the matter power spectrum.



Banerjee et al, 2018

Directional clustering



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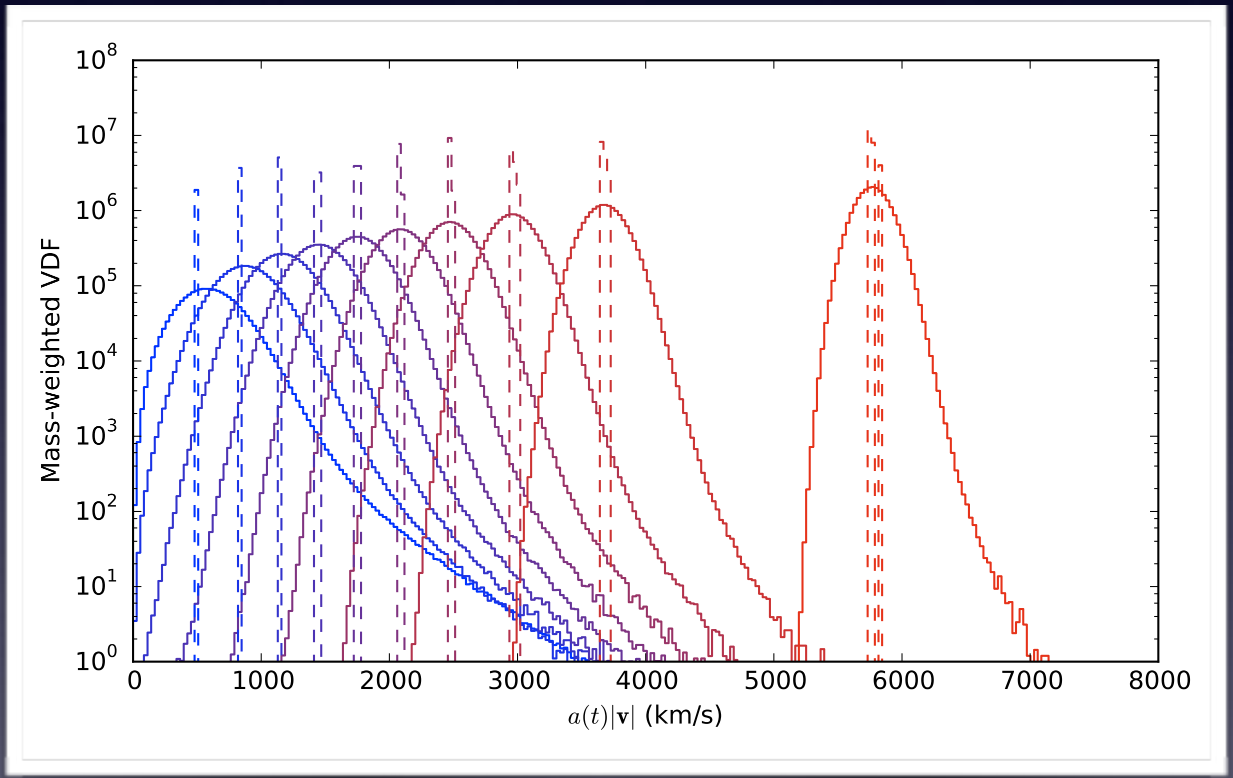
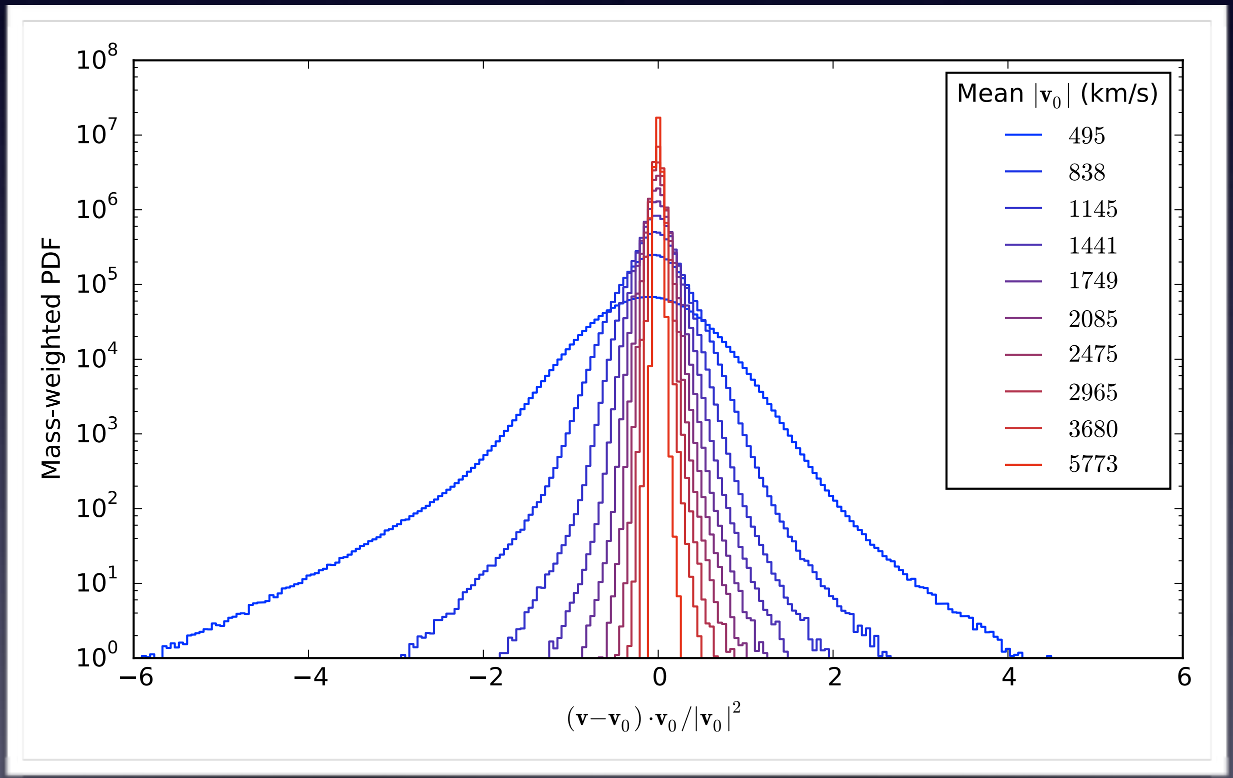
2018

Evolution of the velocity distribution function

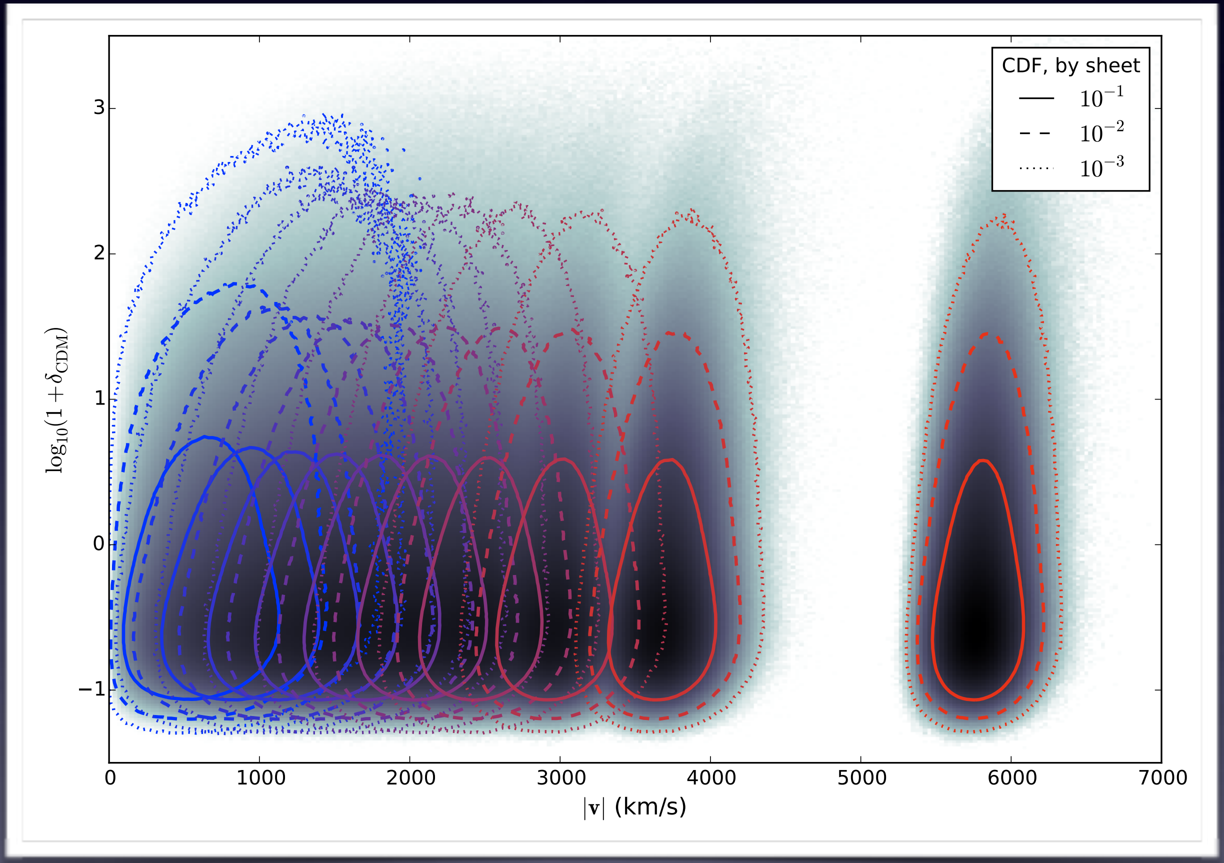




Banerjee et al,
2018

Environment dependence of acceleration

- For the slowest initial shell, the fastest particles correlate with regions where the CDM density is high.
- Weaker effect for faster shells.



Banerjee et al, 2018

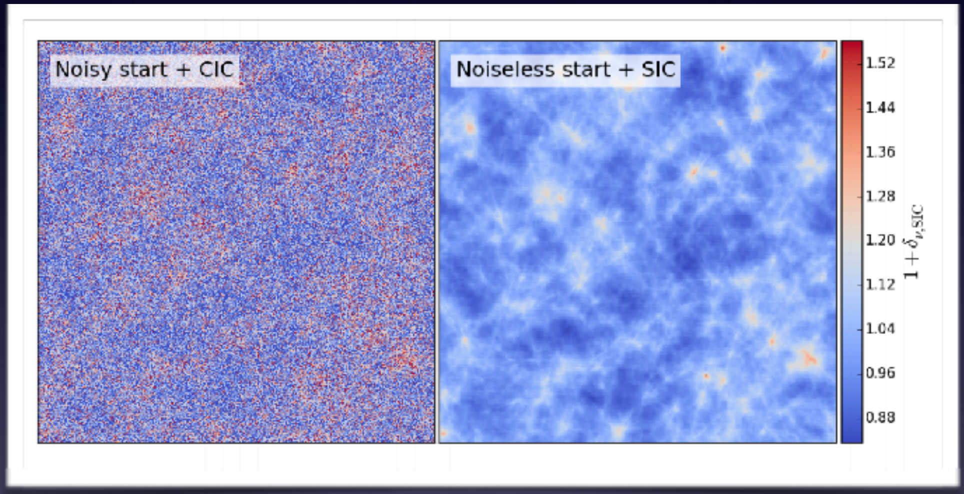
Summary

- Shot noise in N-body simulations with massive neutrinos can be eliminated by just changing the initial conditions - in particular, the way thermal velocities are assigned to neutrino particles. Produces accurate results at all scales and redshifts.

- The new method helps reduce noise on large scales. Extremely useful validation of the results from previous “noisy” N-body simulations on small scales.

- We can systematically study the change in the neutrino distribution function with redshift and environment.

- Study cosmic neutrino background around Milky Way sized objects.



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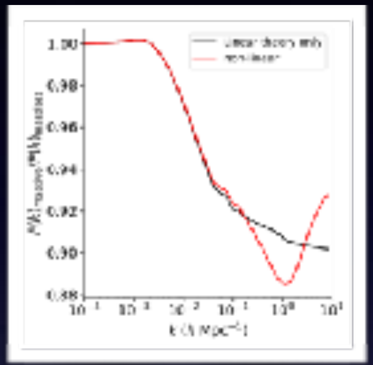

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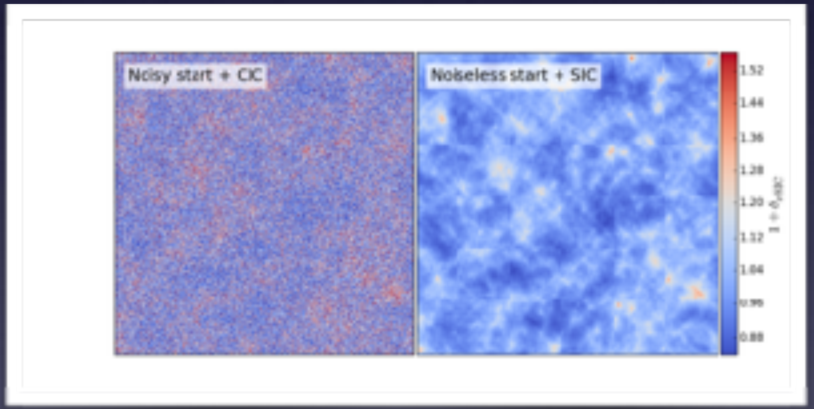

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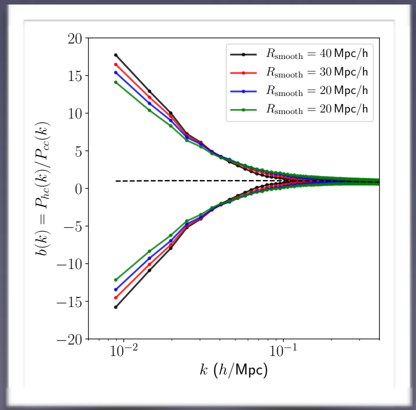


Bias of halos and voids

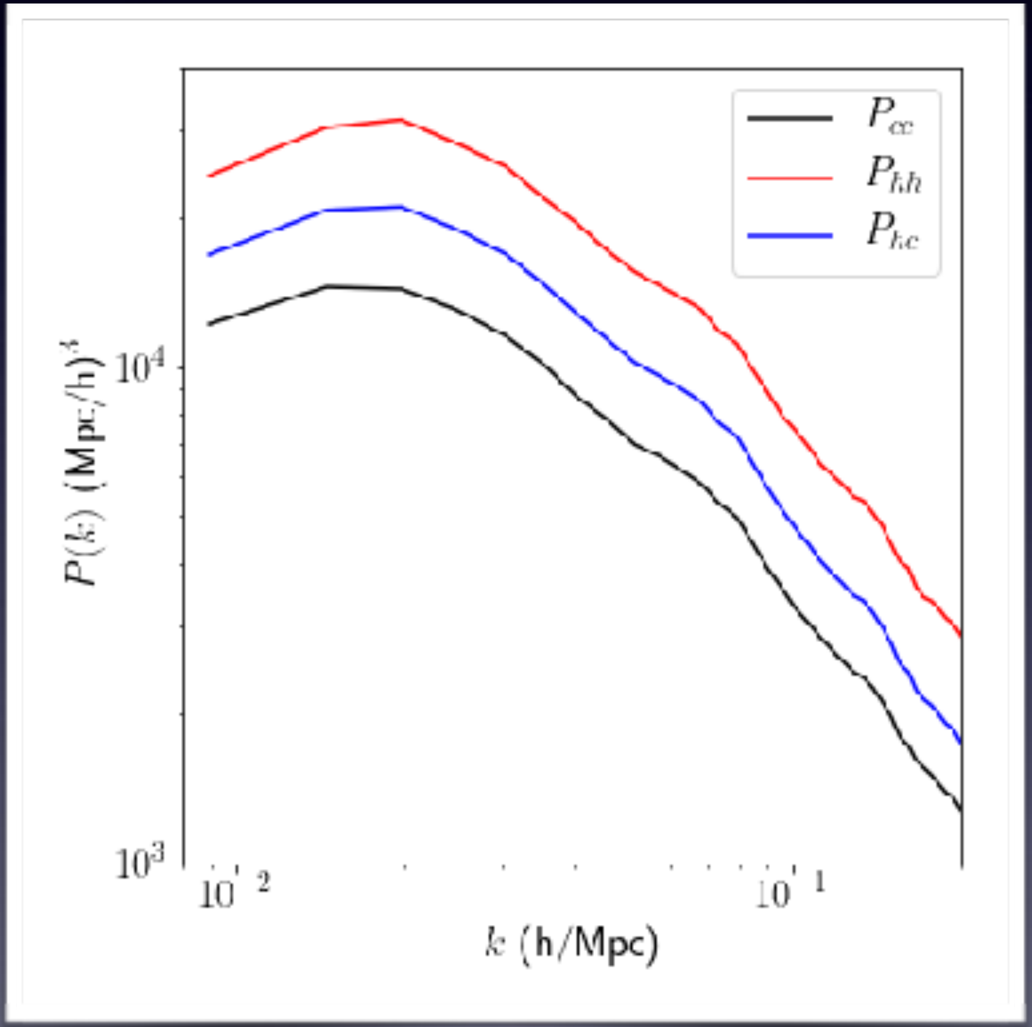
- Nonlinear objects are biased tracers of the underlying matter distribution.

$$\delta_h(k) = b(k)\delta_m(k)\ ,\ b(k) = \frac{P_{hc}(k)}{P_{cc}(k)}\ ,\ b(k) = \sqrt{\frac{P_{hh}(k)}{P_{cc}(k)}}$$

- For ΛCDM cosmologies, b(k) is the same for all k at low k (very large scales).

- In the presence of multiple species, bias can be defined in two ways:

$$b(k) = \frac{P_{hm}(k)}{P_{mm}(k)}\ ,\ b(k) = \frac{P_{hc}(k)}{P_{cc}(k)}$$



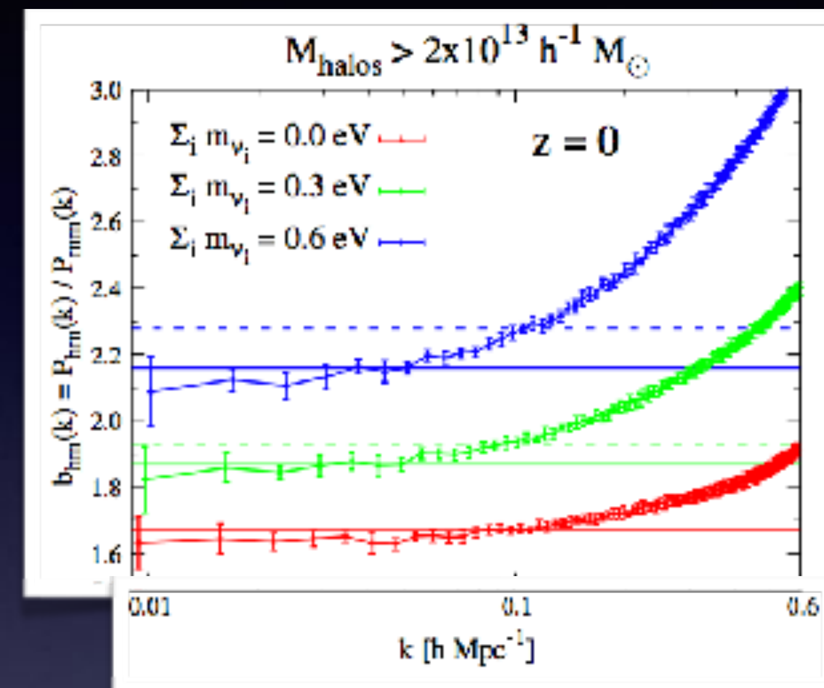
Scale dependent bias in halos and voids

- CDM halos show scale dependent bias on large scales wrt the total matter field (Villaescusa-Navarro et al 2014).

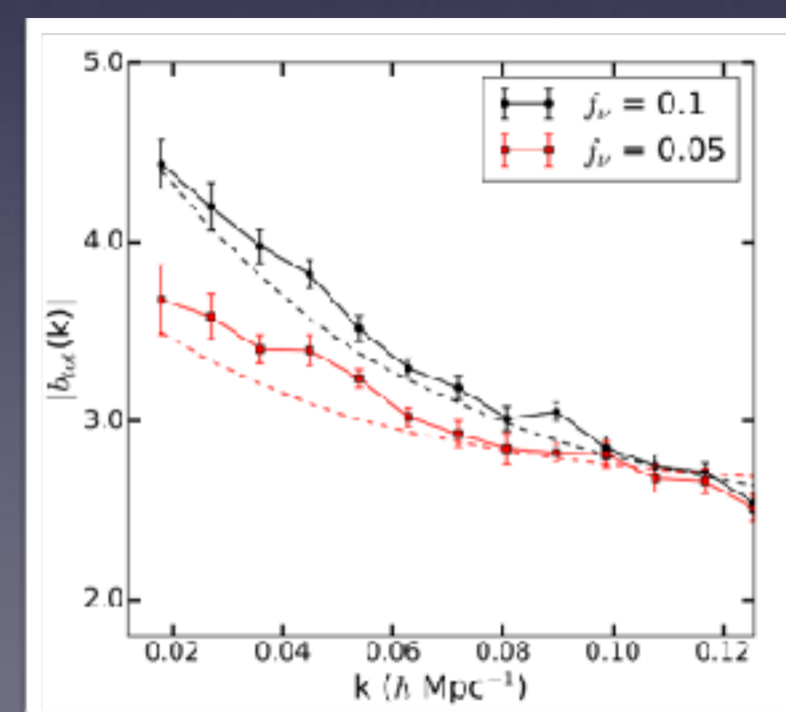
- Voids defined in the CDM field show similar scale dependence, but voids defined in total matter fields show stronger scale dependence (Banerjee & Dalal, 2016).

- The scale dependent piece is fit very well by the ratio of the transfer functions of the two species: $\dfrac{T_\nu(k)}{T_{\mathrm{CDM}}(k)}$

- Characteristic feature in neutrino cosmology - absent in standard ΛCDM cosmology.



Villaescusa-Navarro et al, 2014



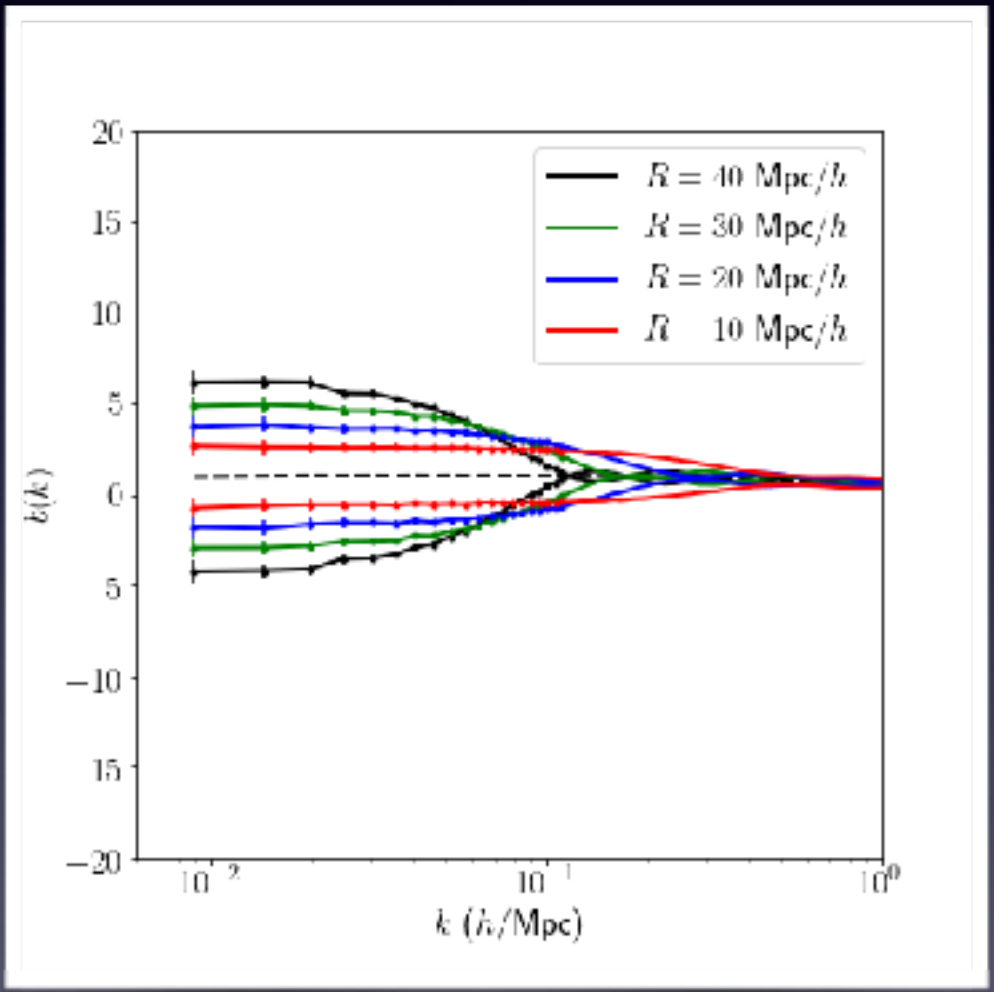
Banerjee & Dalal, 2016

Enhancing scale dependence using the environment

- Can the large scale environment of the halo be used to enhance the scale dependent bias of a selected subsample of halos?
- Simulation details: $(1\ \mathrm{Gpc}/h)^3$ box, with 1600^3 CDM particles and 1600^3 neutrino particles.
- Different neutrino masses and σ_8.
- Simulations available at https://franciscovillaescusa.github.io/hades.html

Splitting on different environments

Use the large scale δ_{CDM} to split



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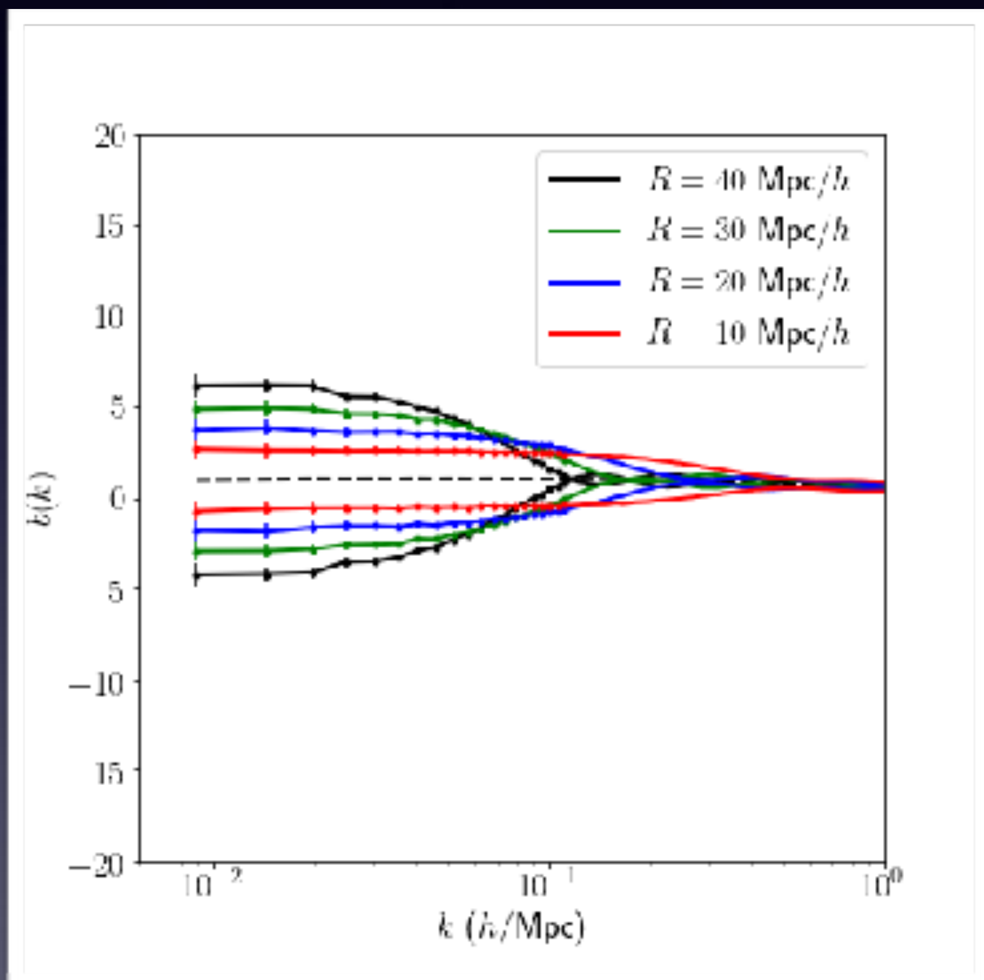

Use the large scale δ_v to split

Splitting on different environments

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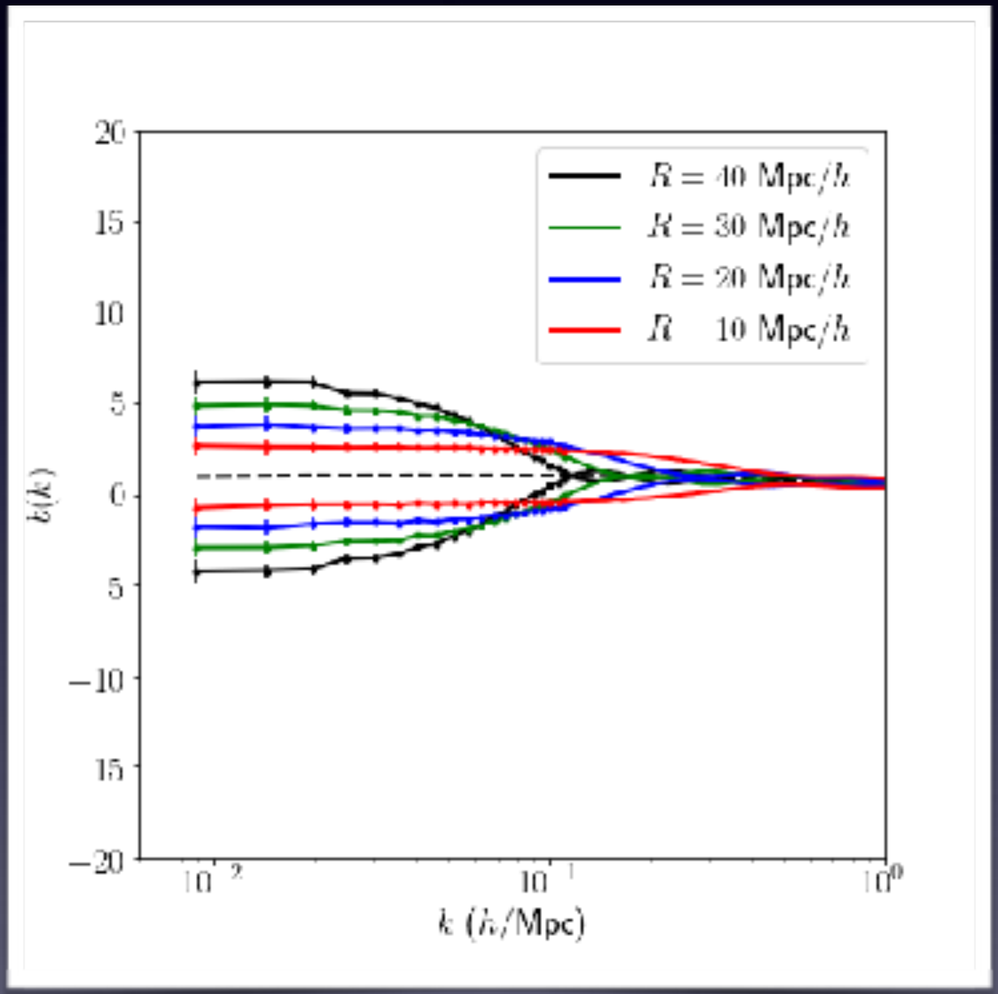
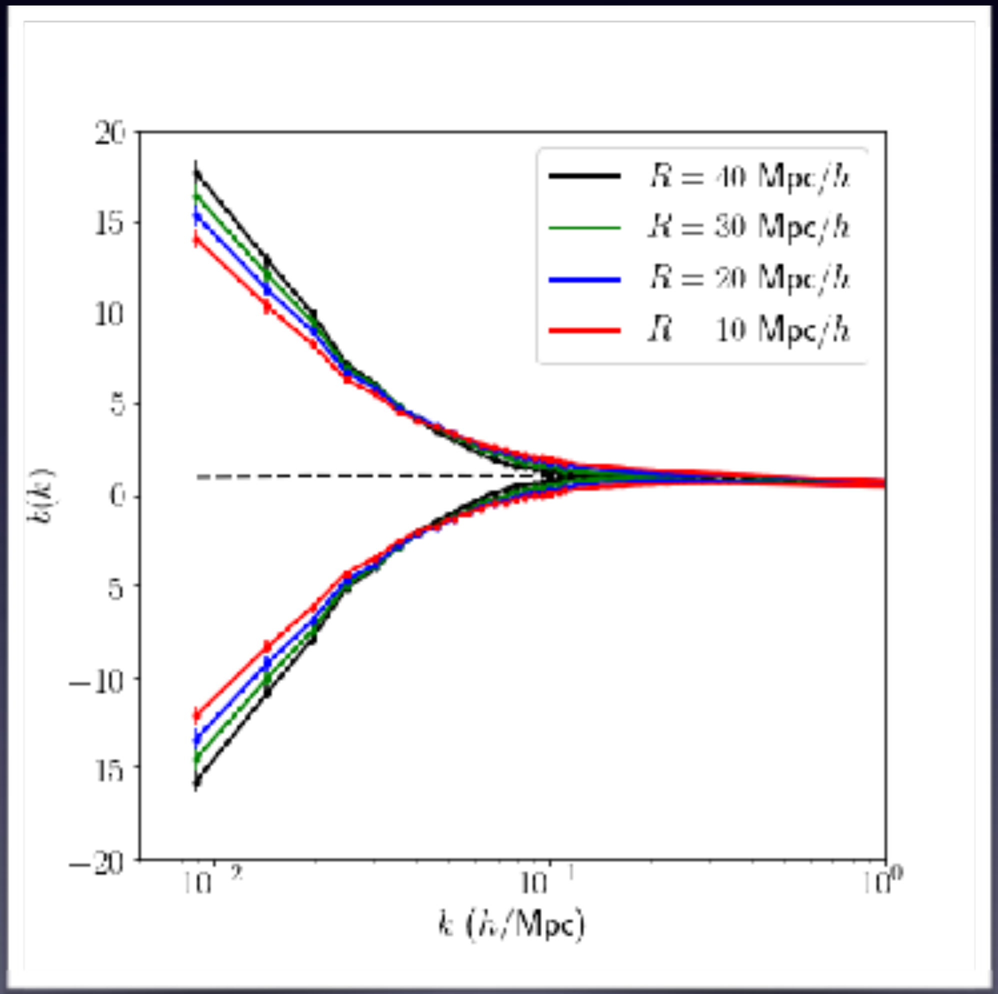


Use the large scale δ_v to split



Understanding the shape of the bias

- We expect the shape to be set by the ratio of transfer functions. For each smoothing scale we fit the bias with

$$b(k) = A + B\frac{P_{c\nu}(k)}{P_{cc}(k)}$$

- A and B are independent of scale.

- This effect is independent of f_ν - the shape of the effect is the same if for e.g.

$$m_\nu^i = 0.05\mathrm{eV}\,,\ \sum_i m_\nu = 0.15\mathrm{eV}$$

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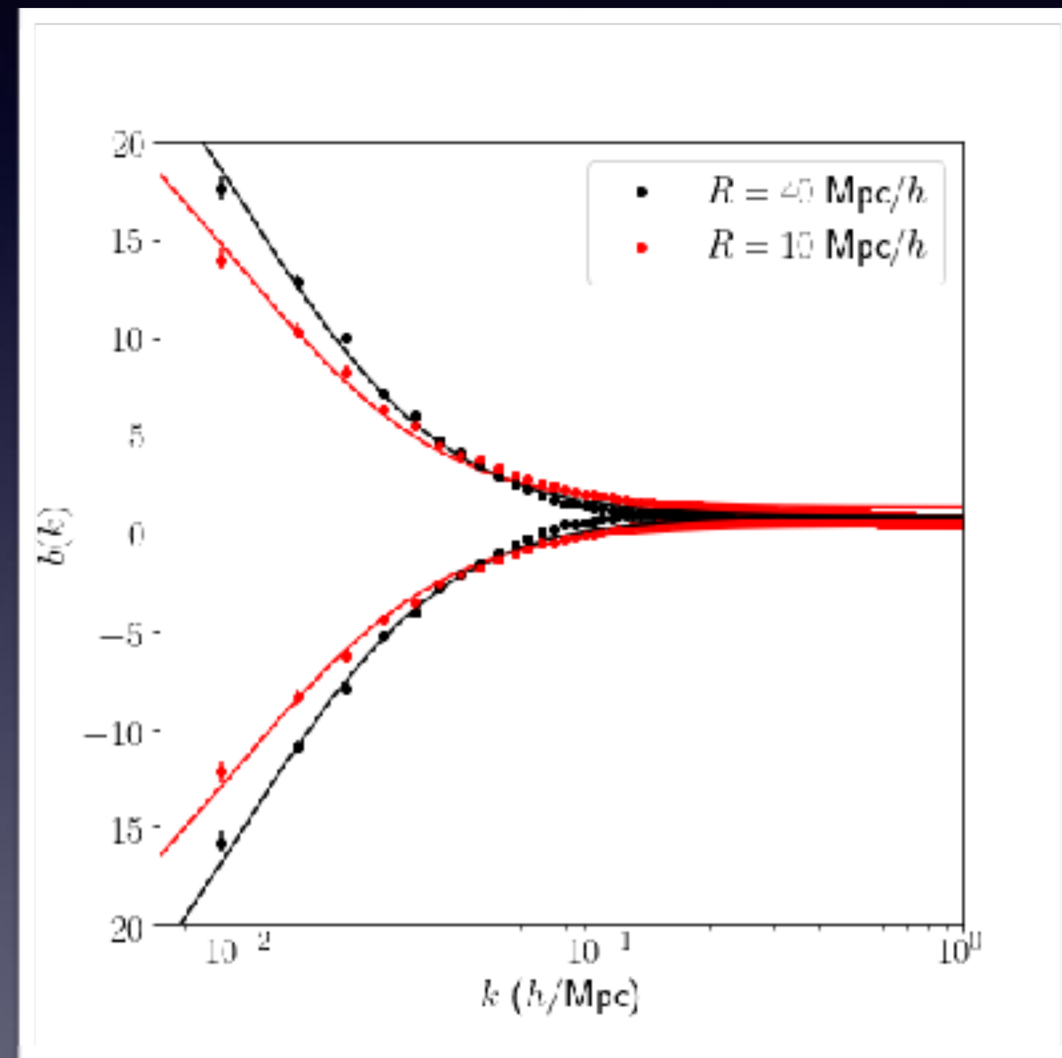
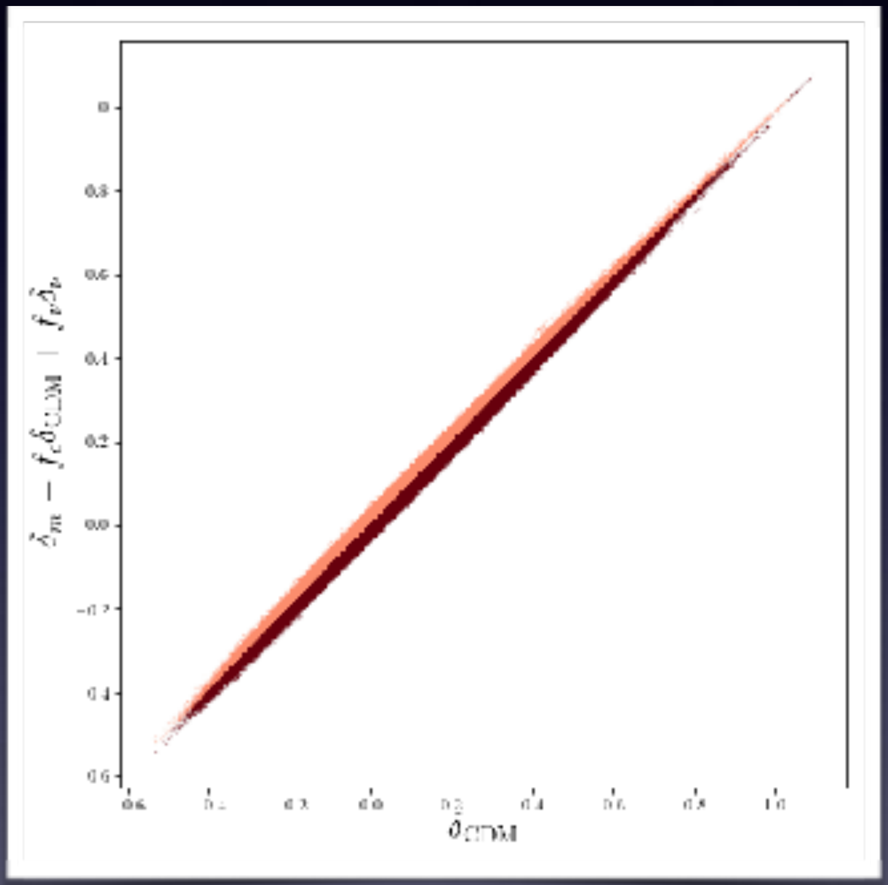


Is there an equivalent split using “observables”?



Find the large scale δ_{CDM} and δ_{matter} and use the following quantity to split:

$$\delta = \delta_m - \langle \delta_m | \delta_{\mathrm{CDM}} \rangle$$

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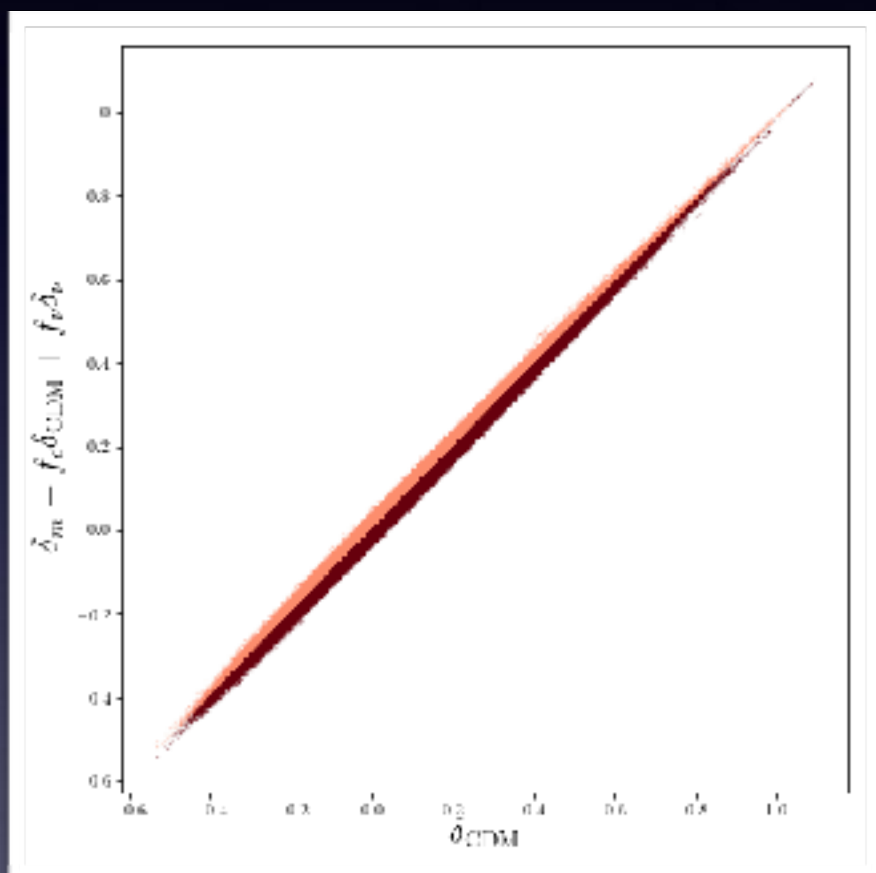

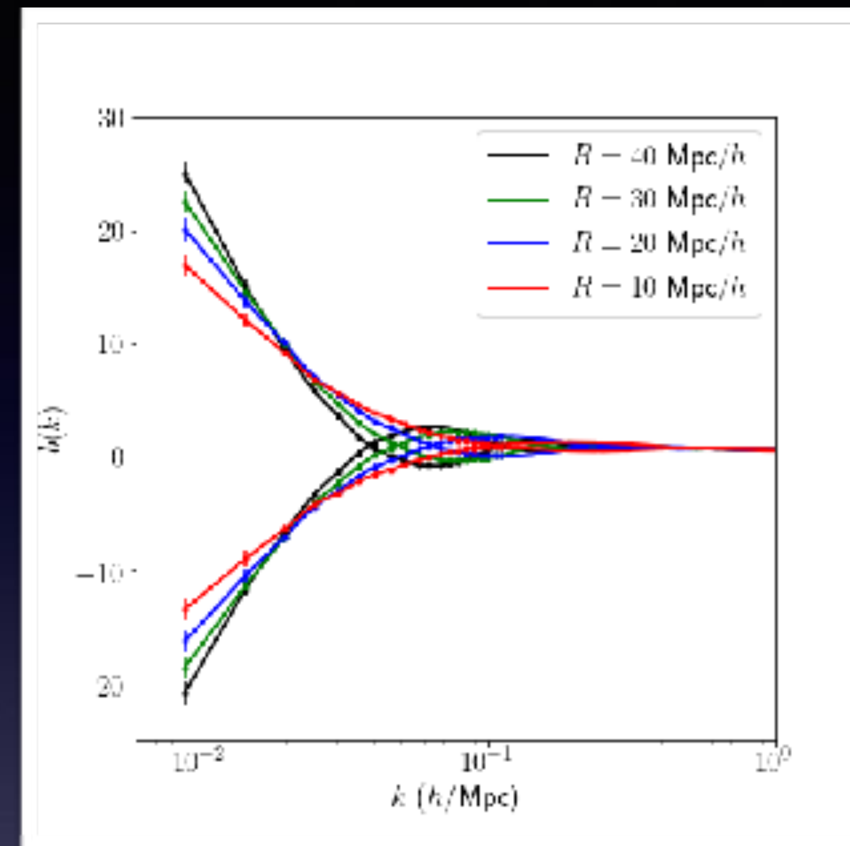

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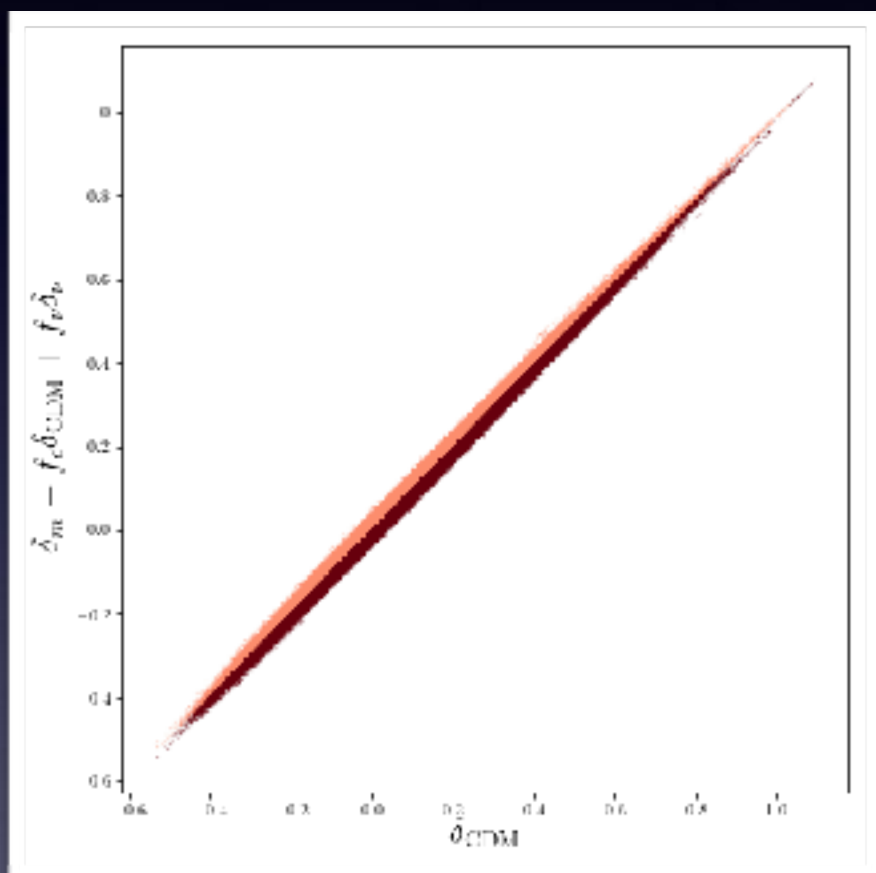

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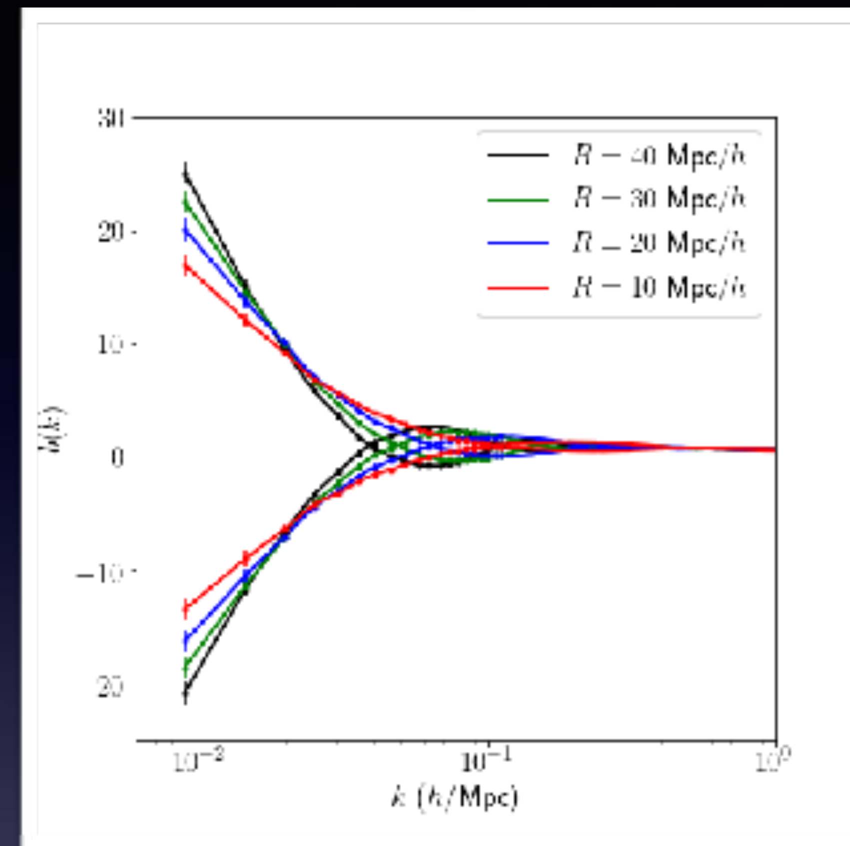
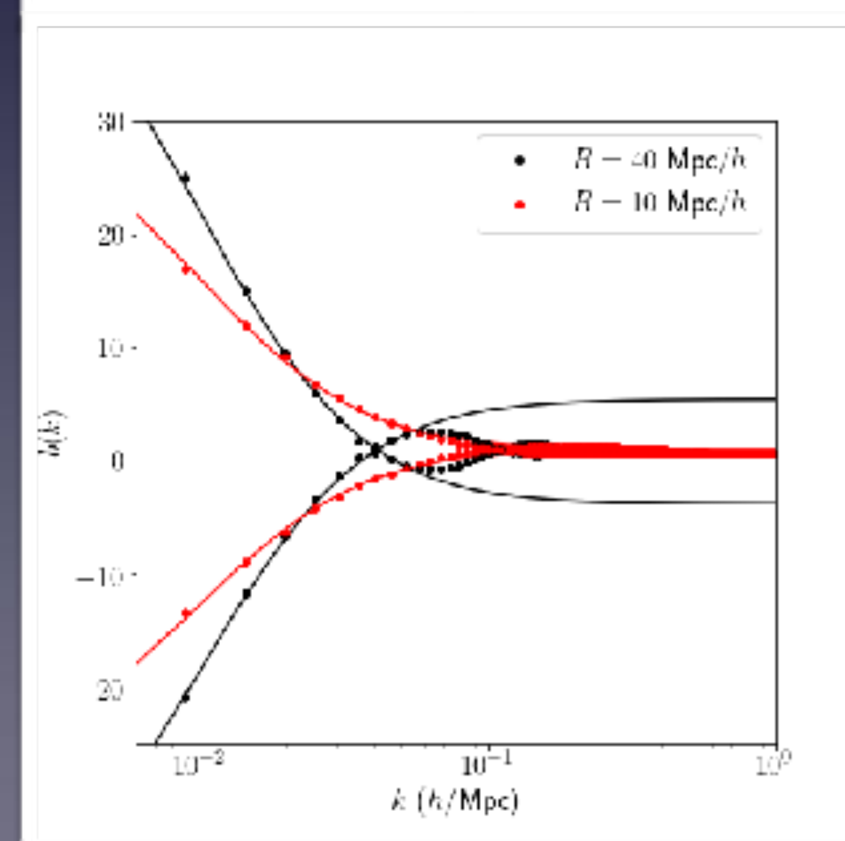
$$\delta = \delta_m - \langle \delta_m \,|\, \delta_{\rm CDM} \rangle$$

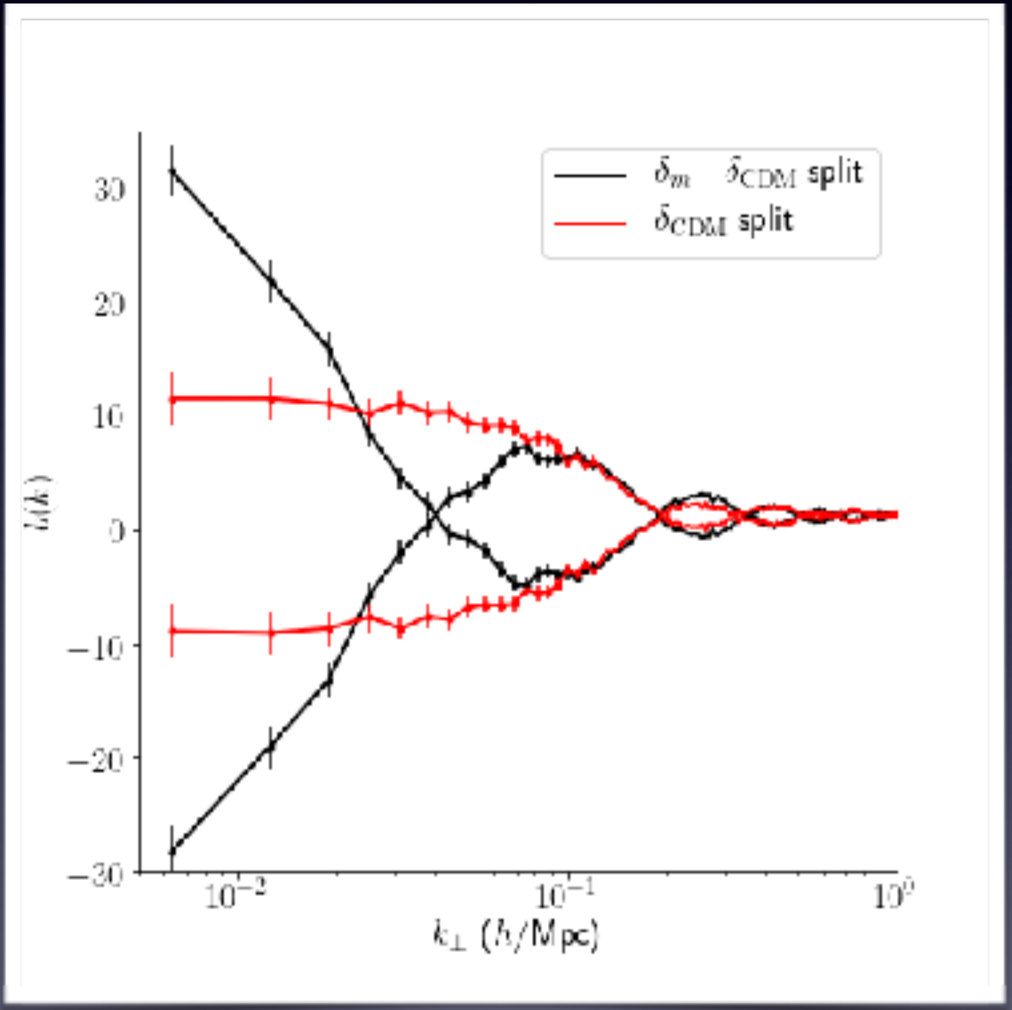




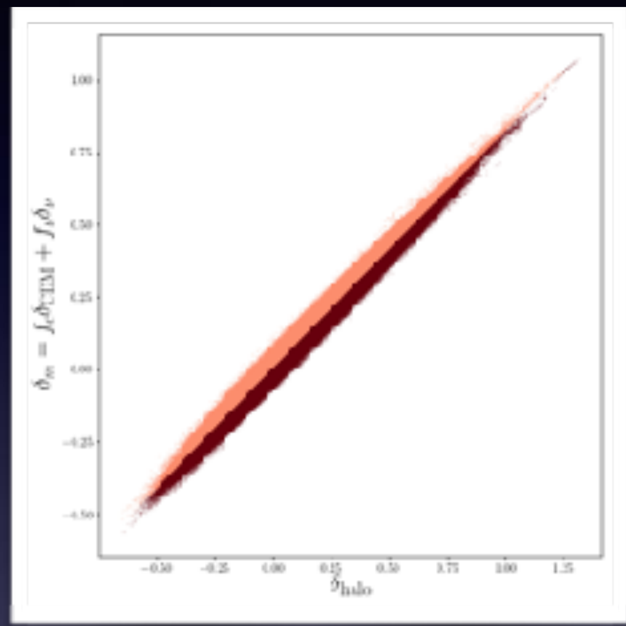
What happens when we project?

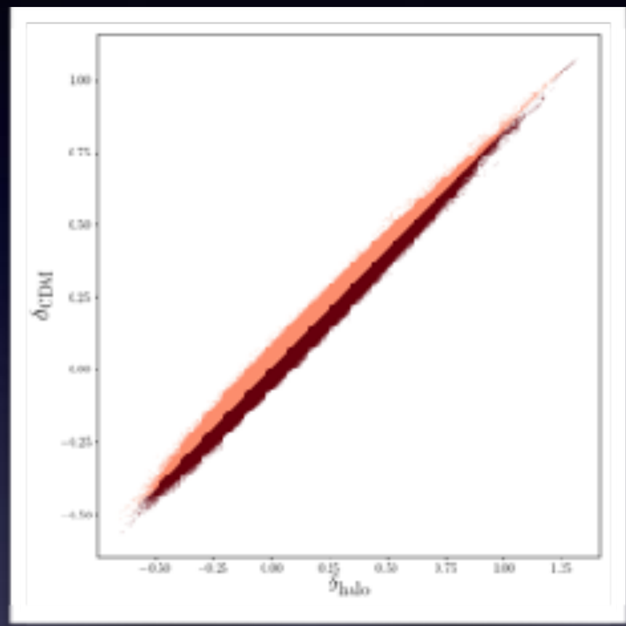
- Project all quantities along one of the simulation axis. Repeat the splitting procedure with

$$\delta_{2D} = \delta_{m,2D} - \langle \delta_{m,2D} | \delta_{\mathrm{CDM,2D}} \rangle$$



Using halos to approximate the CDM field





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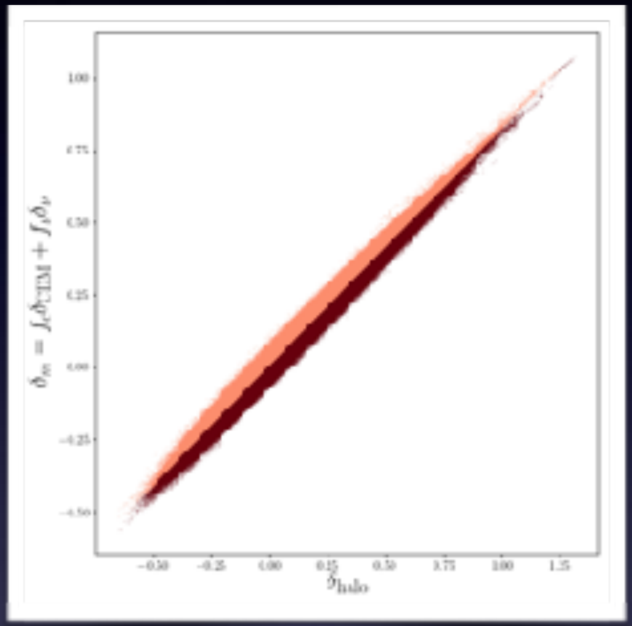

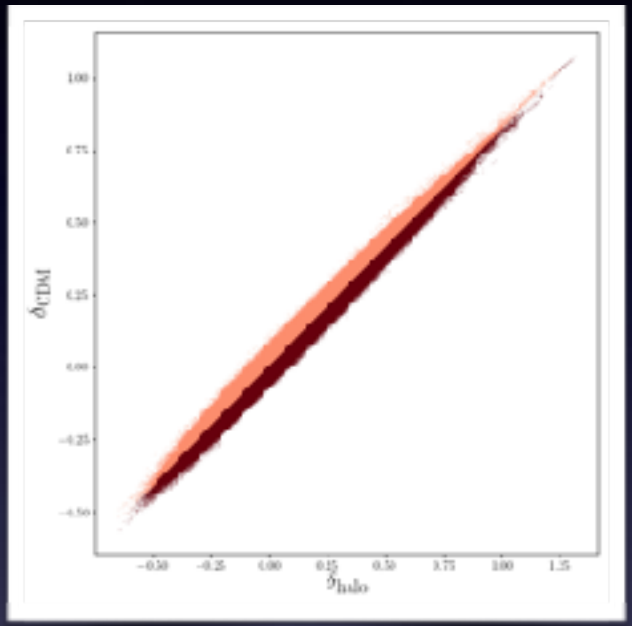

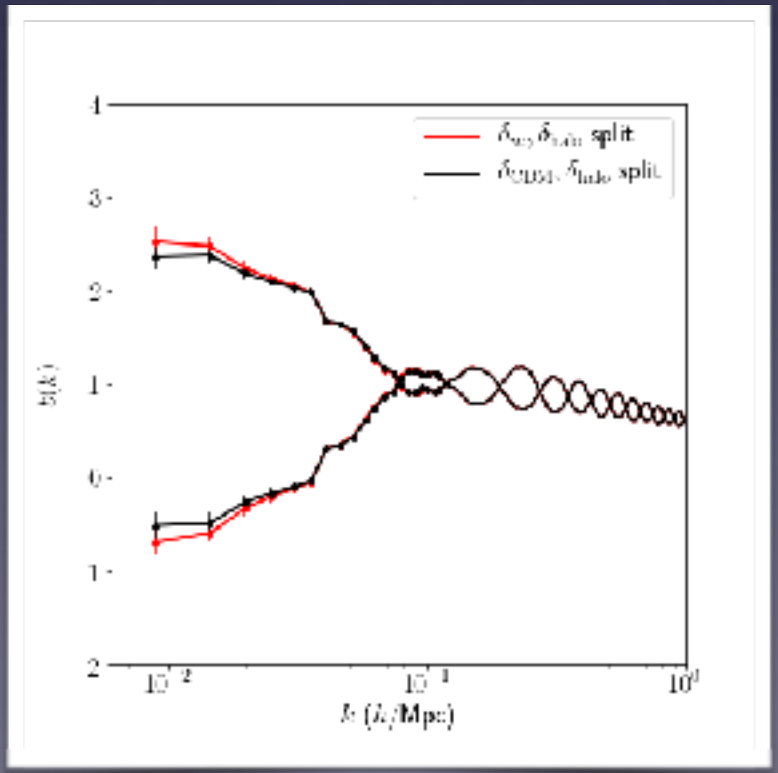

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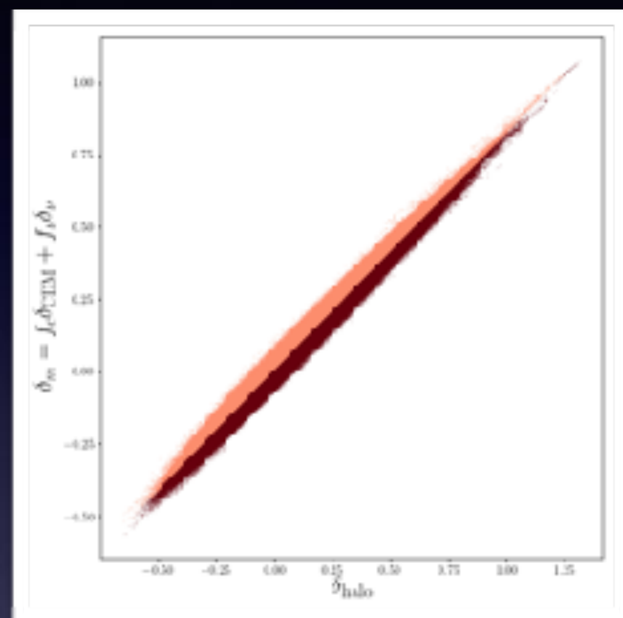
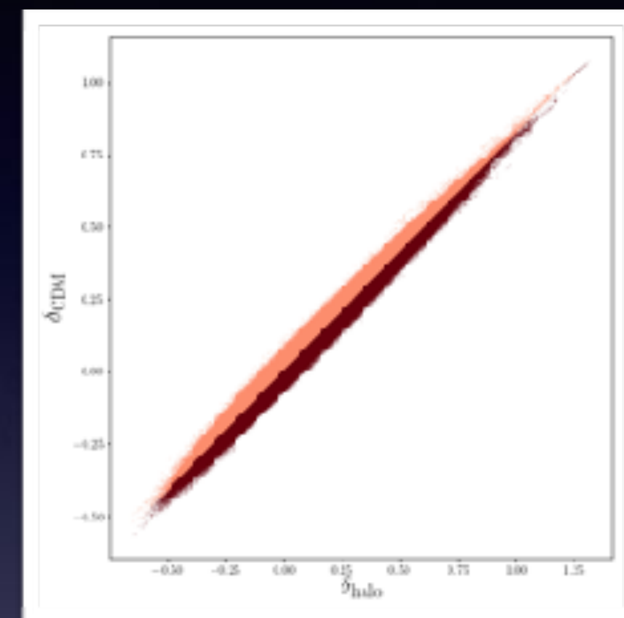
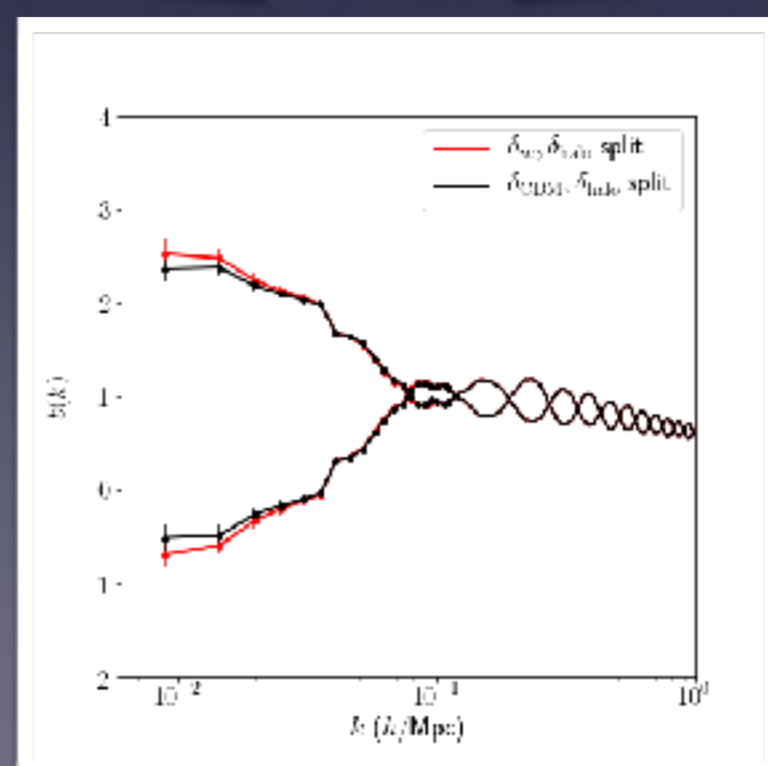




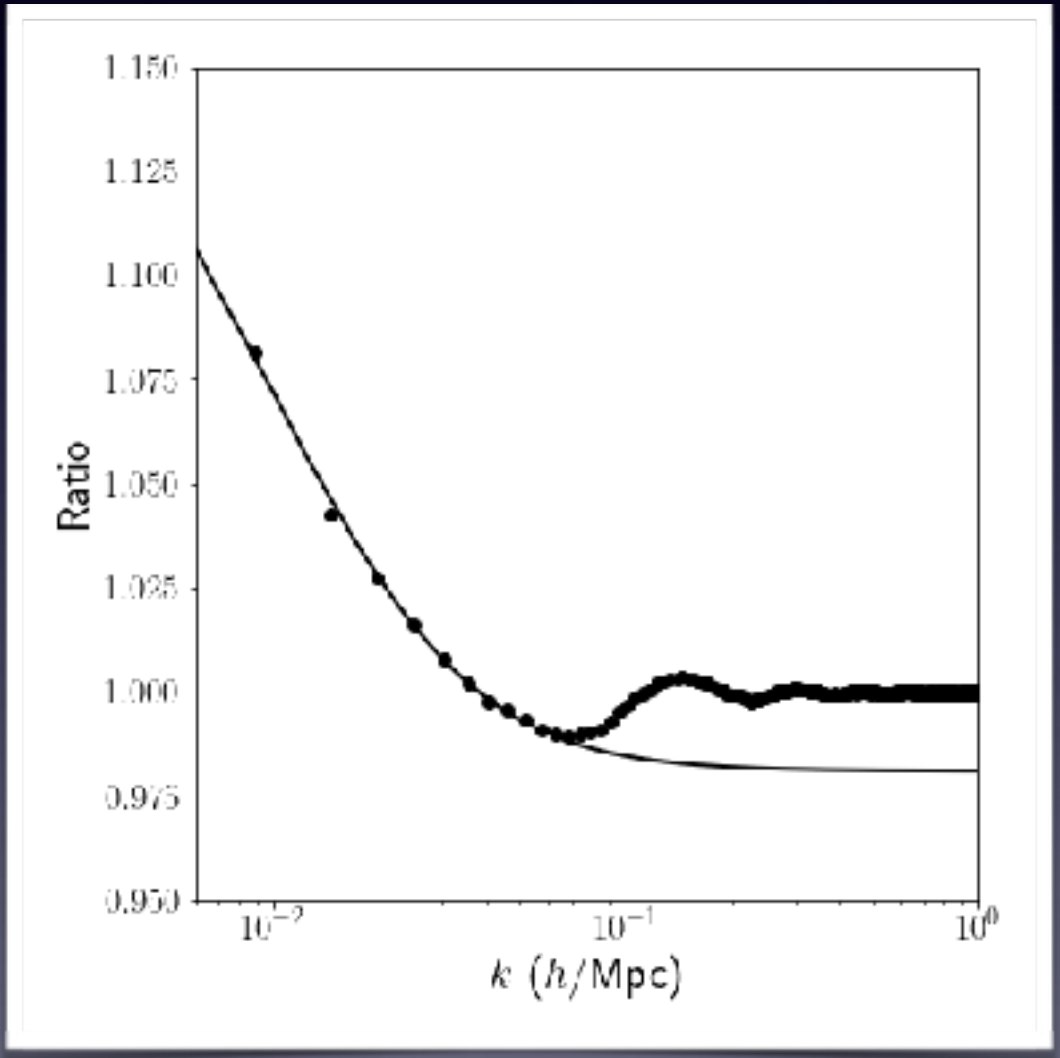


The obvious scale dependence is no longer visible when we use δ_{halo} to approximate δ_{CDM}, even when we use mass weighting of the halo field.

Using halos to approximate the CDM field

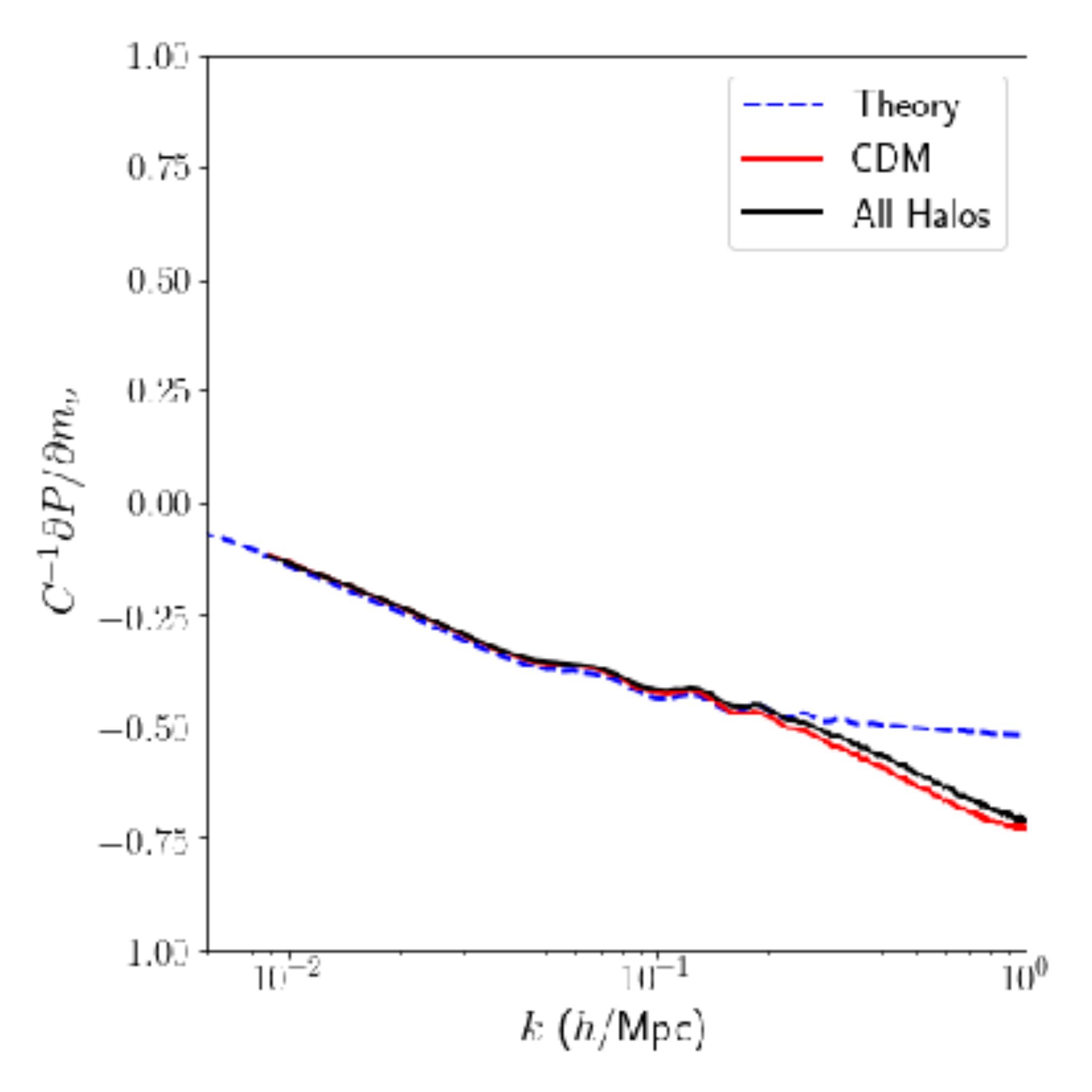
- Clearly the stochasticity in the halo fields will wipe out a large part of the signal. But size of the effect is still larger than f_ν.

- The ratio still behaves as expected, i.e., the shape is described by $P_{c\nu}/P_{cc}$.



Response to change in neutrino mass

- This time the derivative for the split sample is, in general much larger on large scales, i.e., it is more sensitive to a change in neutrino mass than only the CDM and halo power spectra.
- Whether this scale dependence can be detected will depend on noise levels from different surveys.



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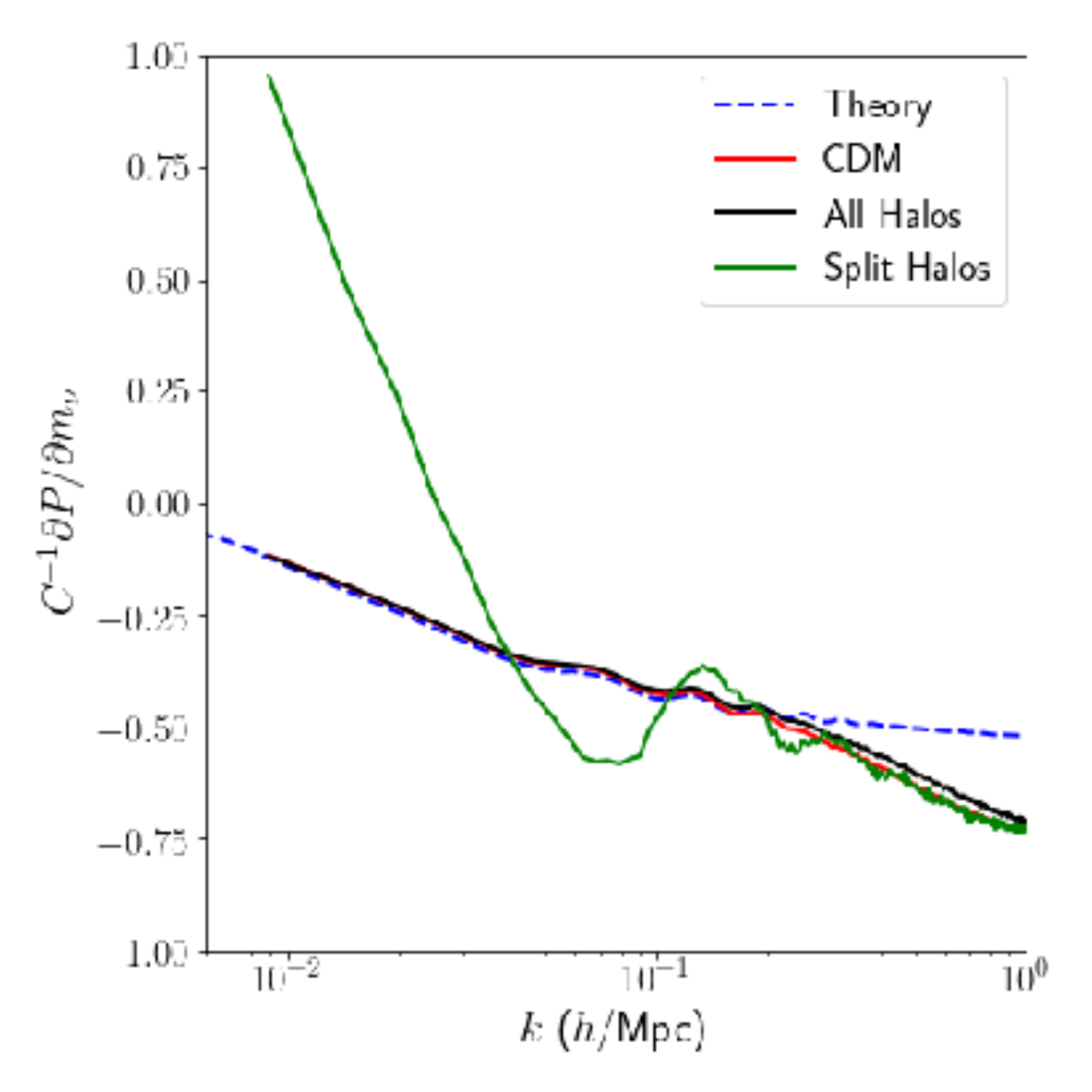

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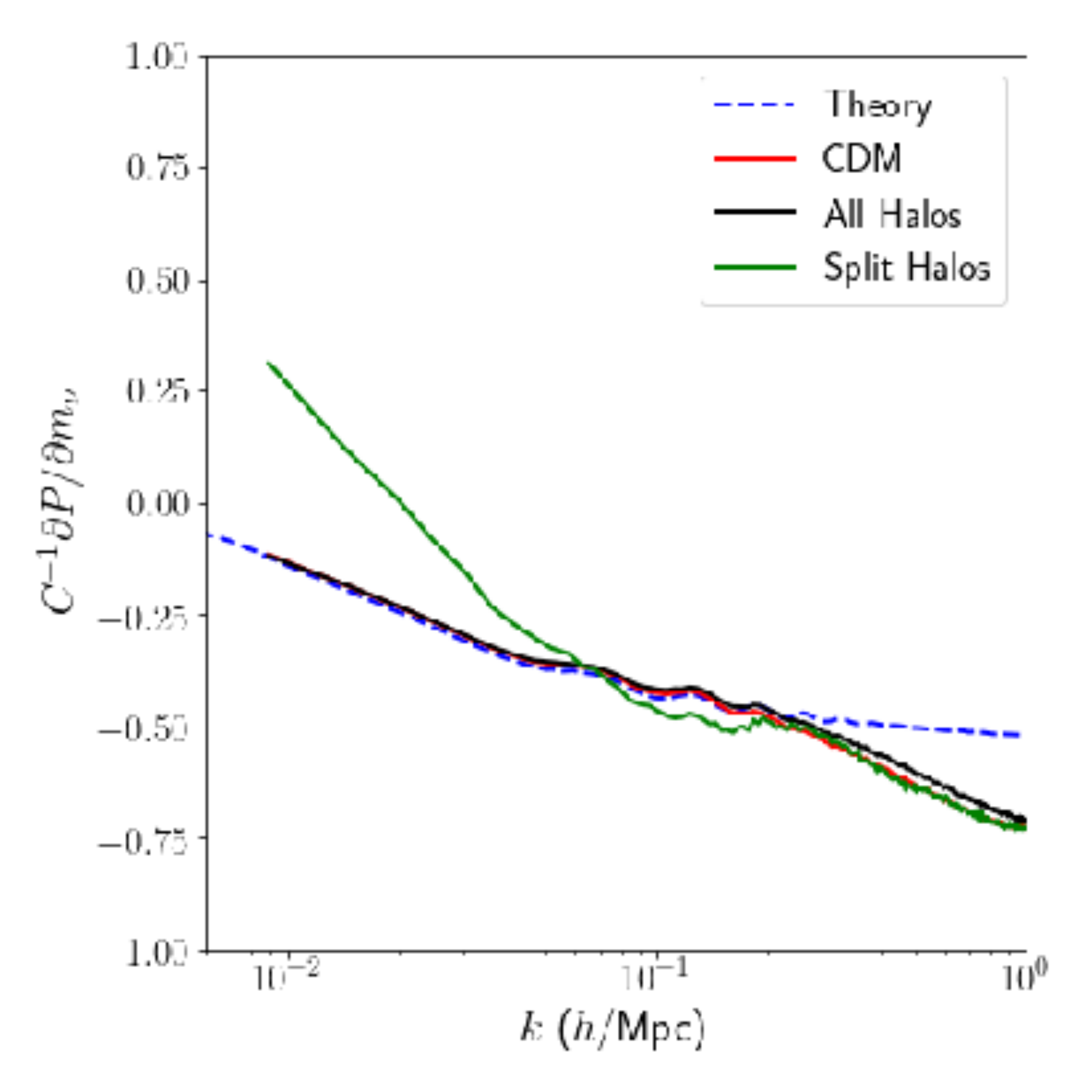

Summary

- Scale dependent bias in cosmologies with massive neutrinos.
- Halos show strong scale dependent bias when split on the large scale neutrino environment. Similar effect can be recovered by using a combination of the CDM and matter environment.
- Size of the effect becomes smaller with noise, e.g., using the halo overdensity field as a proxy for the CDM overdensity field.
- Effect persists when looking a projected quantities in 2-d.
- Will be interesting to look for the size of this effect for various survey specifications which will set the noise levels.