Massive neutrinos and environmental scale dependence of halo bias

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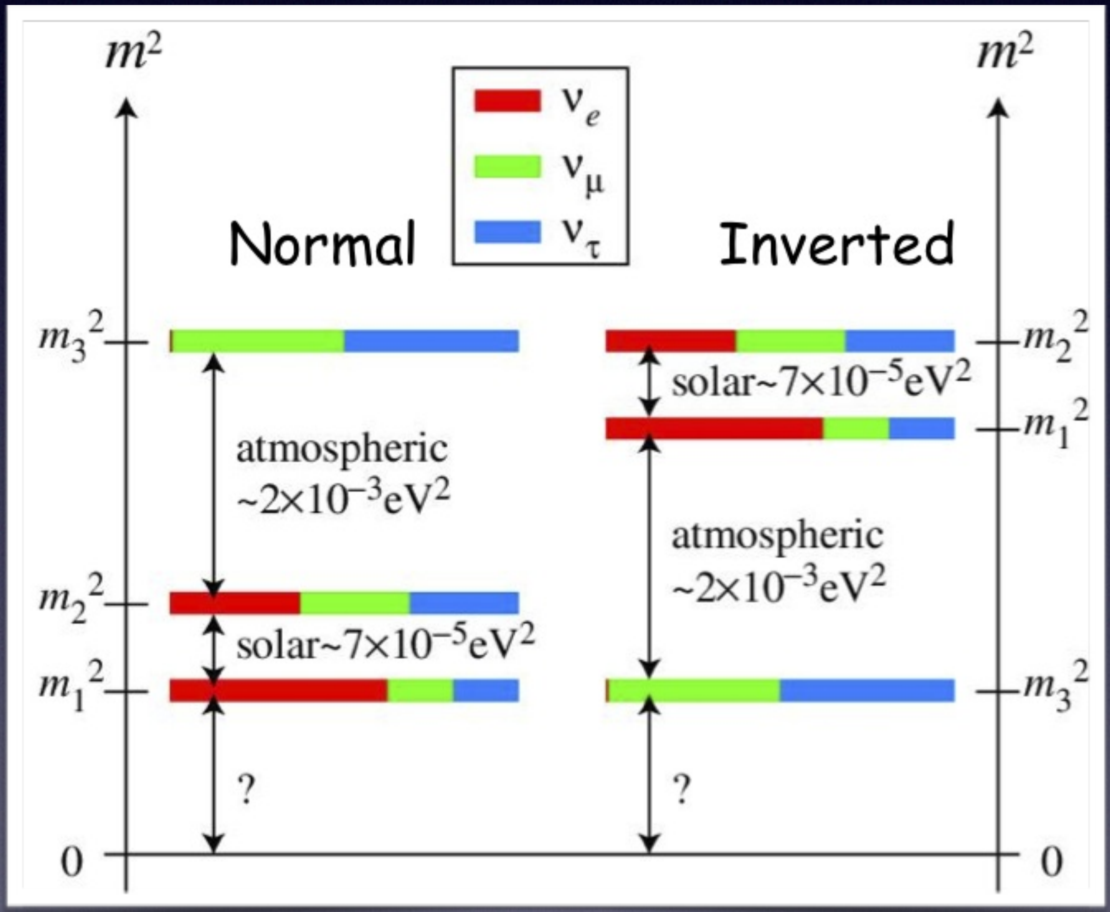
Massive neutrinos

- 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?



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.
- 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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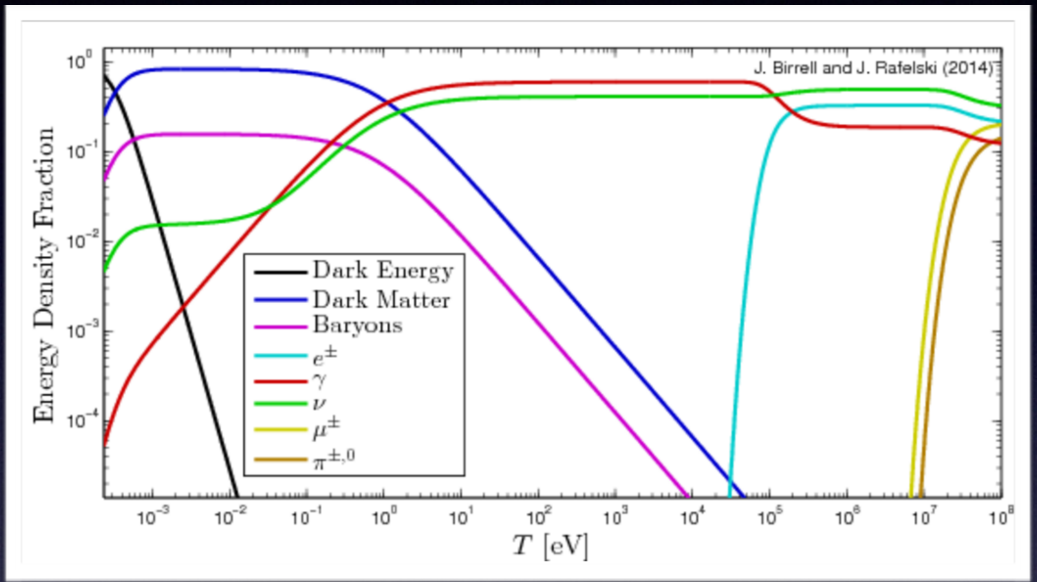
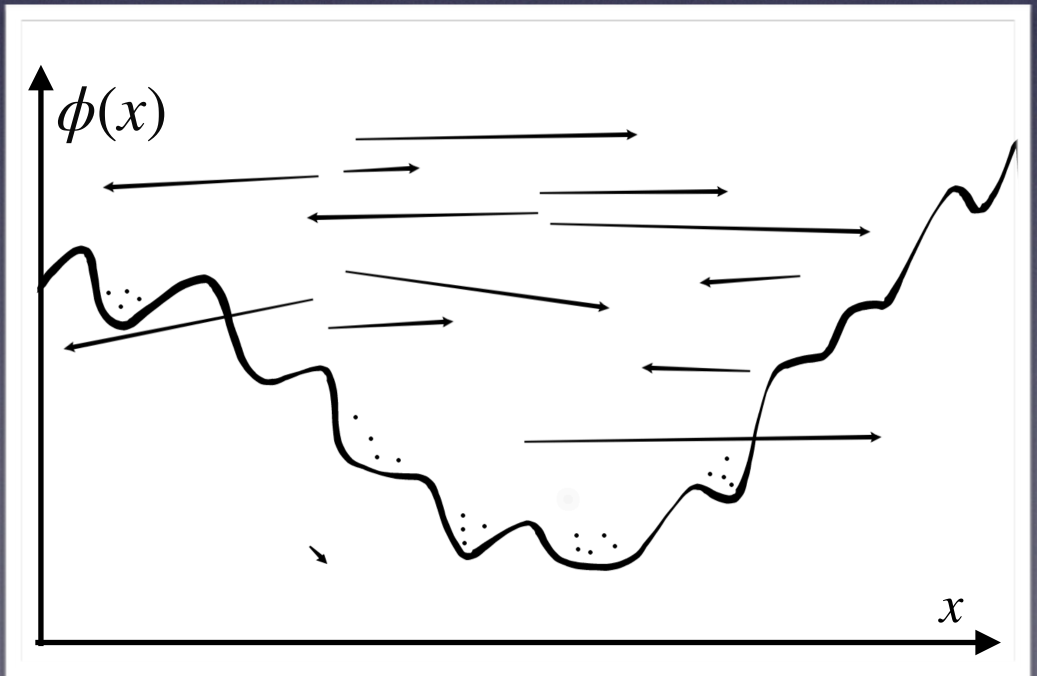


Birrell et al, 2014



Effect of massive neutrinos on P(k)

- Once non-relativistic, massive neutrinos contribute to the energy budget proportional to the sum of the masses:

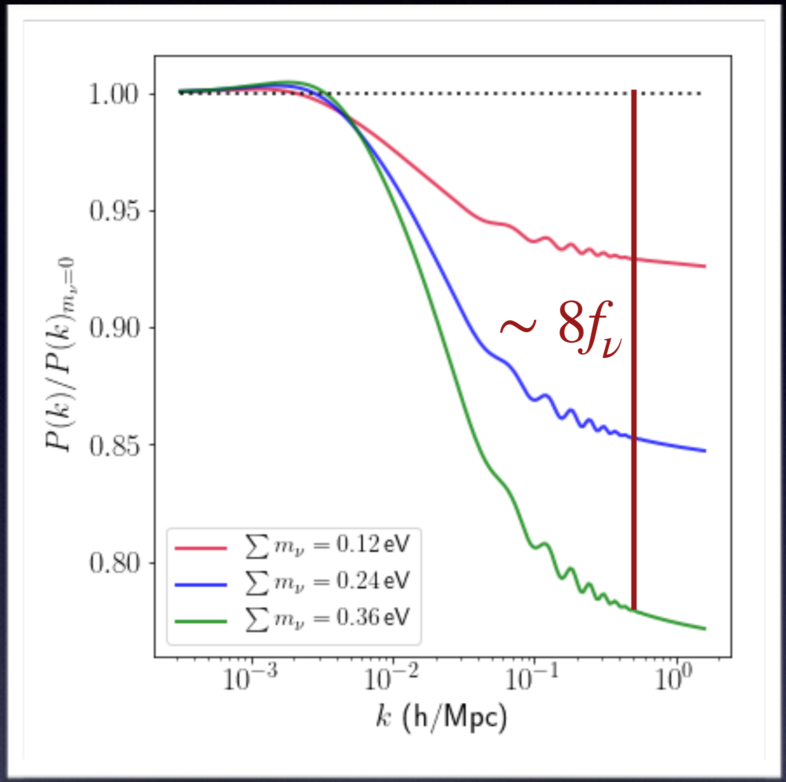
$$\Omega_\nu = \frac{\sum m_\nu}{94h^2} \quad , \quad f_\nu = \frac{\Omega_\nu}{\Omega_{C+b} + \Omega_\nu}$$

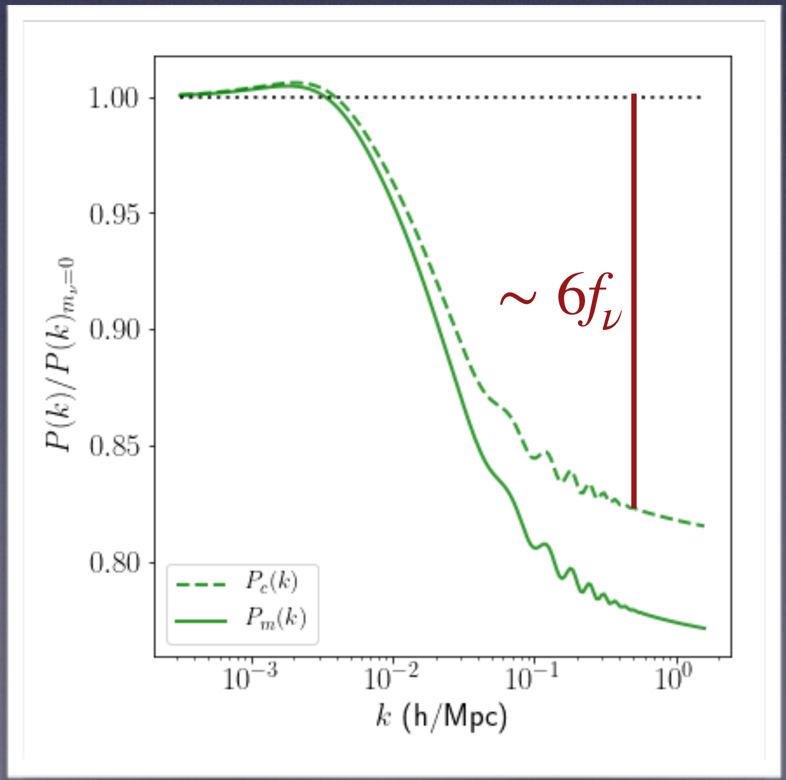
- Due to their large thermal velocities, do not cluster strongly on small scales.

- Leads to the damping of the power spectrum on small scales, which is the most obvious way of looking for signatures of massive neutrinos

$$\boxed{\delta_{\rm tot} = f_{\rm CDM}\delta_{\rm CDM} + f_\nu \delta_\nu}$$

$$\begin{cases} 8f_\nu & \text{Matter P(k)} \\ 6f_\nu & \text{CDM P(k)} \end{cases}$$





Neutrino mass constraints from linear scales

Using information only from scales which are linear, we use the Fisher matrix formalism to convert survey specifications into parameter constraints.

$$F^{\rm LSST}_{\alpha\beta} = f_{\rm sky} \sum_l (2l+1) \sum_{ijkl} \frac{\partial C_l^{x_i x_j}}{\partial p_\alpha} [\mathcal{C}_l]^{-1}_{ij,kl} \frac{\partial C_l^{x_k x_l}}{\partial p_\beta}$$

$$F = F^{\rm LSST} + F^{Planck}$$

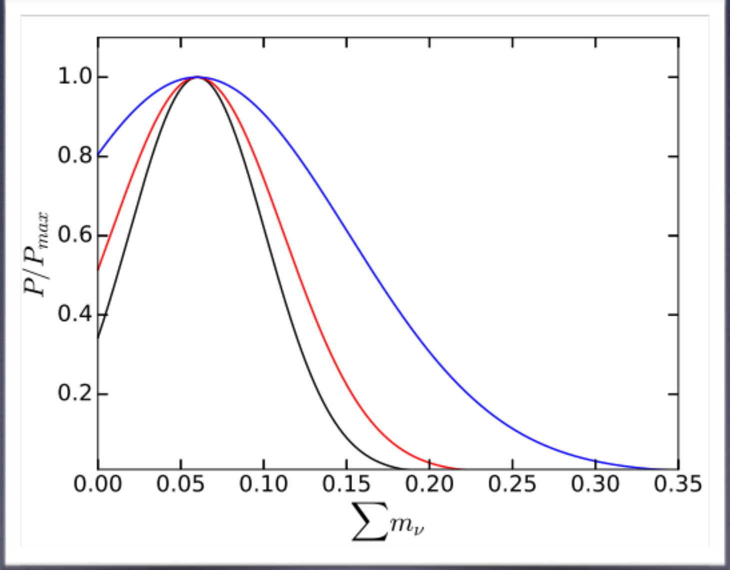
$$\sigma(p_\alpha) = \sqrt{(F^{-1})_{\alpha\alpha}}$$

LSST 3X2 pt + Planck

	$\sigma\left(\sum m_\nu\right)$ (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
$N_S = 6$, $N_L = 6$ (+ DESI[52] + $N_{\rm eff}$ prior))	0.028	0.016

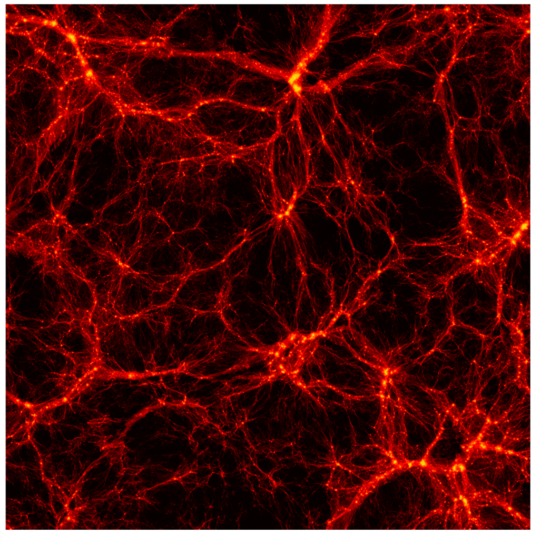
Banerjee et al 2017

LSST



Banerjee et al 2017

HADES About Team Data Publications



Welcome to the HADES simulations!

The HADES simulations are a set of more than 1000 publicly available N-body and hydrodynamic simulations with massless and massive neutrinos.

The HADES simulations are meant to be a powerful tool to understand the impact of neutrino masses on cosmological observables on the fully non-linear regime.

The HADES simulations is the result of many years of development and research by the team members. The about page provides a detailed description of the simulations.

The simulations are stored in a server at the Center for Computational Astrophysics in New York, and can be downloaded here.

For comments, problems, technical support...etc you can reach us here.

N-body / Hydro

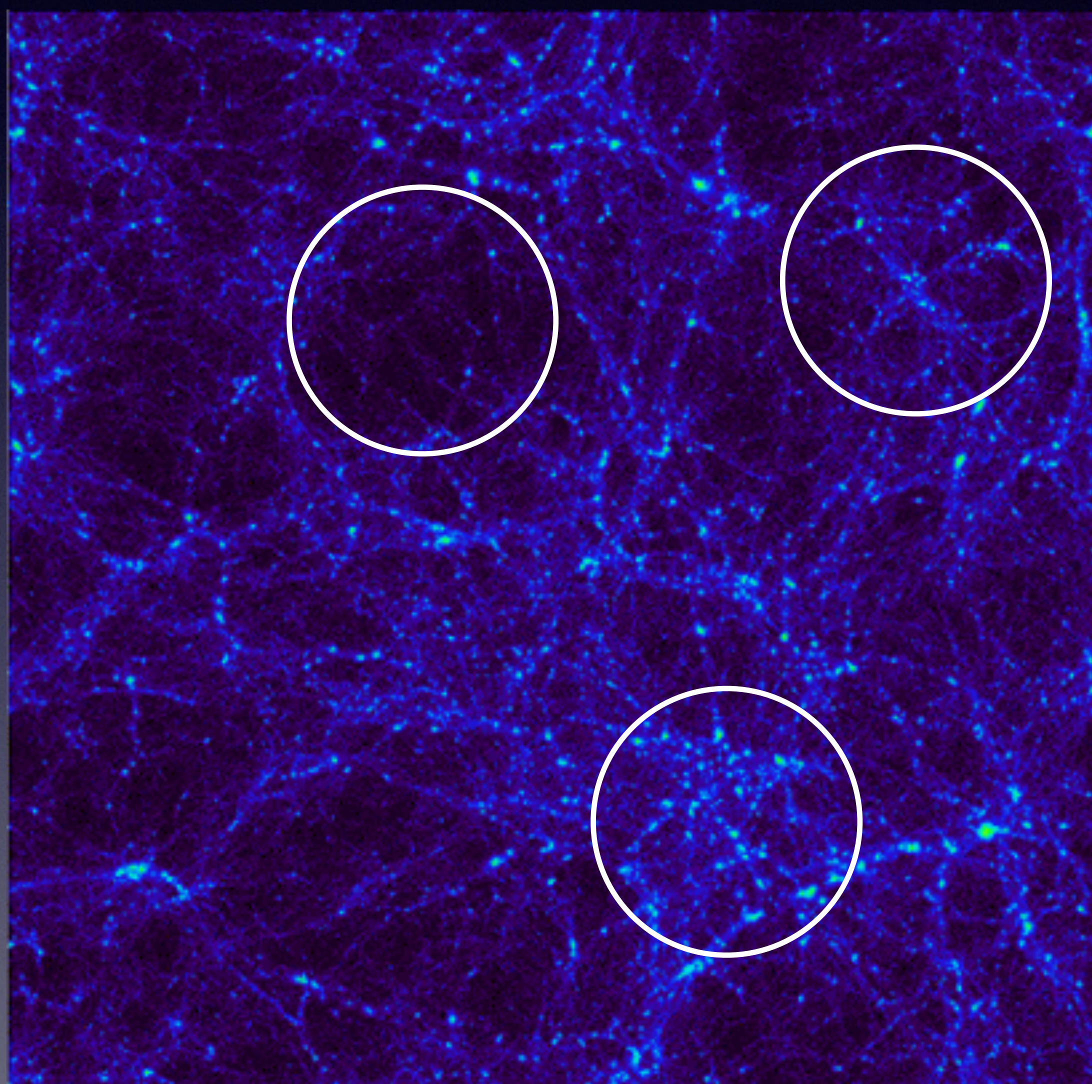
Boxes in green contain both N-body and hydrodynamic simulations, while boxes in blue only contain N-body simulations. We provide both full snapshots and halo catalogues. A description of the simulations can be found here.

0.0eV 0.10eV 0.15eV 0.6eV

0.0eV_0.822 0.0eV_0.818 0.0eV_0.807 0.0eV_0.798

0.0eV_0.717 0.0eV_0.693

Bias of non-linear objects



ESA

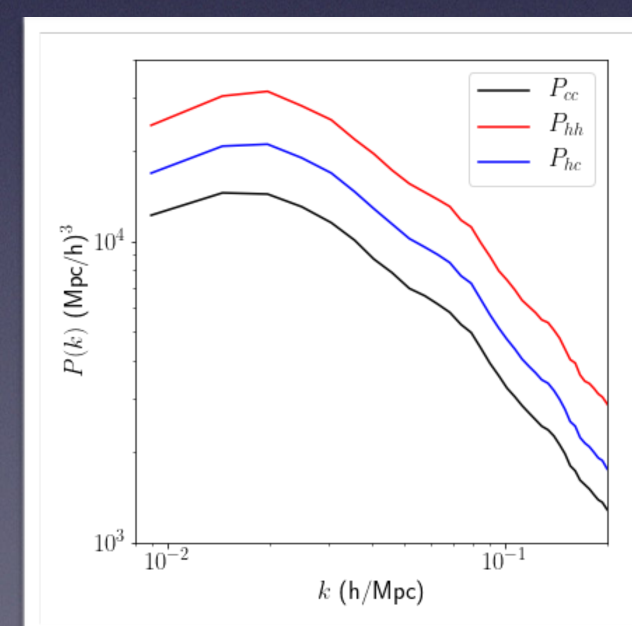
$$\delta_m^i = \frac{\rho_m^i - \bar{\rho}_m}{\bar{\rho}_m}$$

$$\delta_h^i = \frac{n_h^i - \bar{n}_h}{\bar{n}_h}$$

$$\delta_h^i = b^i \delta_m^i$$

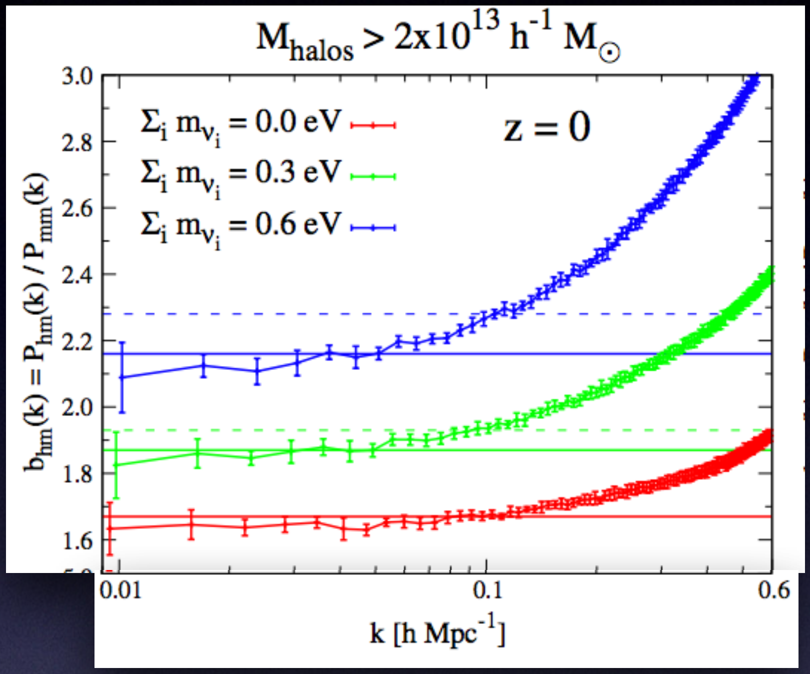
In Fourier space

$$\delta_h(\vec{k}) = b(\vec{k})\delta_m(\vec{k})$$

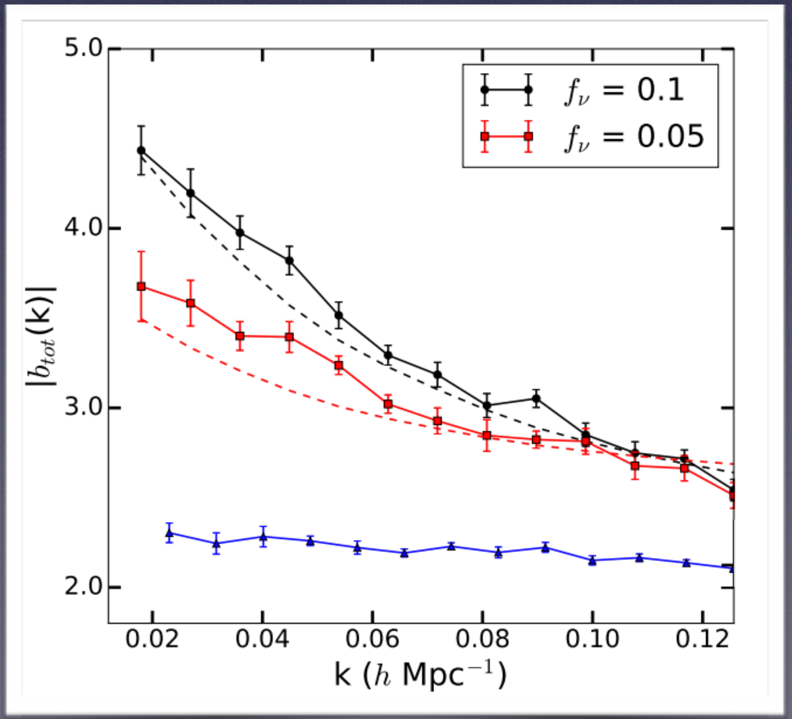


Scale dependent bias in halos and voids

- 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 dependence 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.

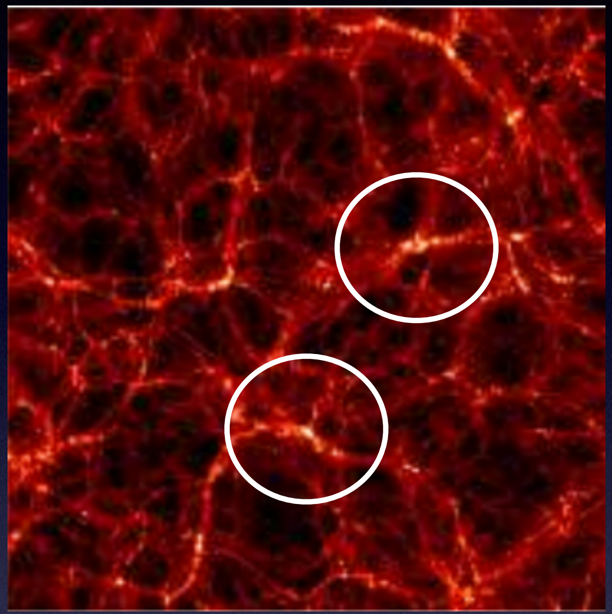


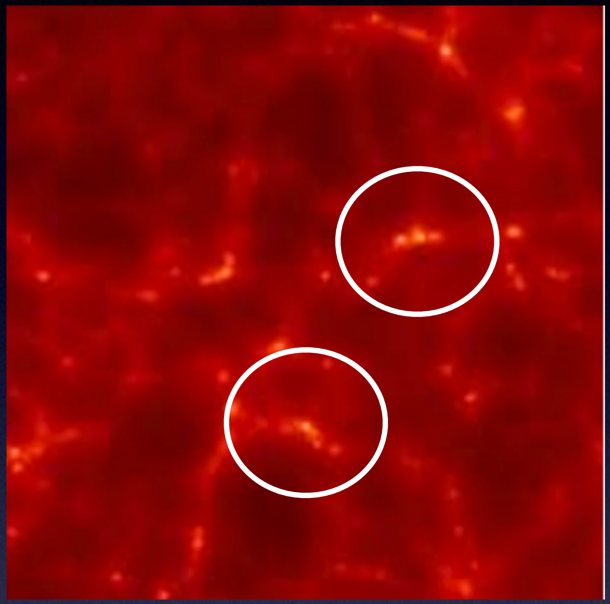
Villaescusa-Navarro et al 2014

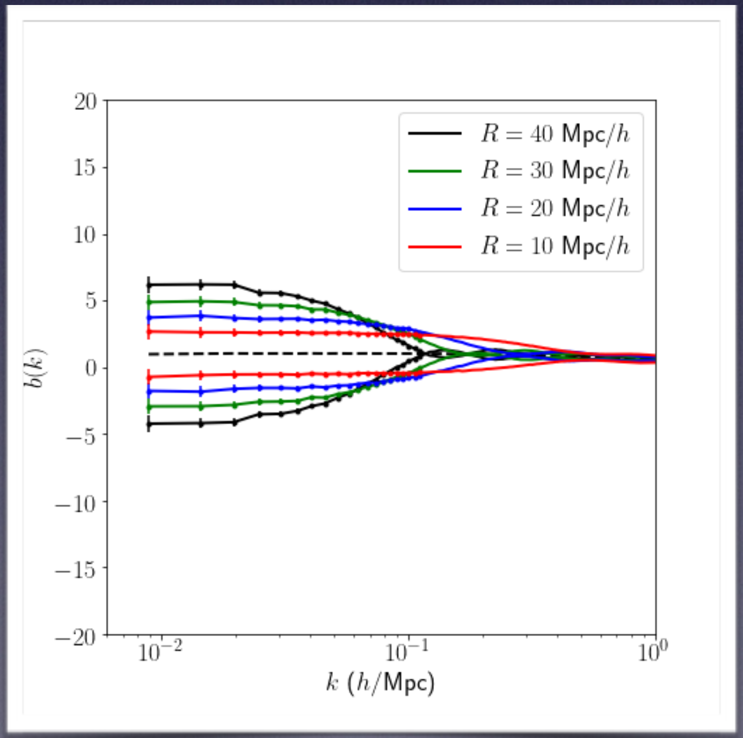


Banerjee & Dalal, 2016

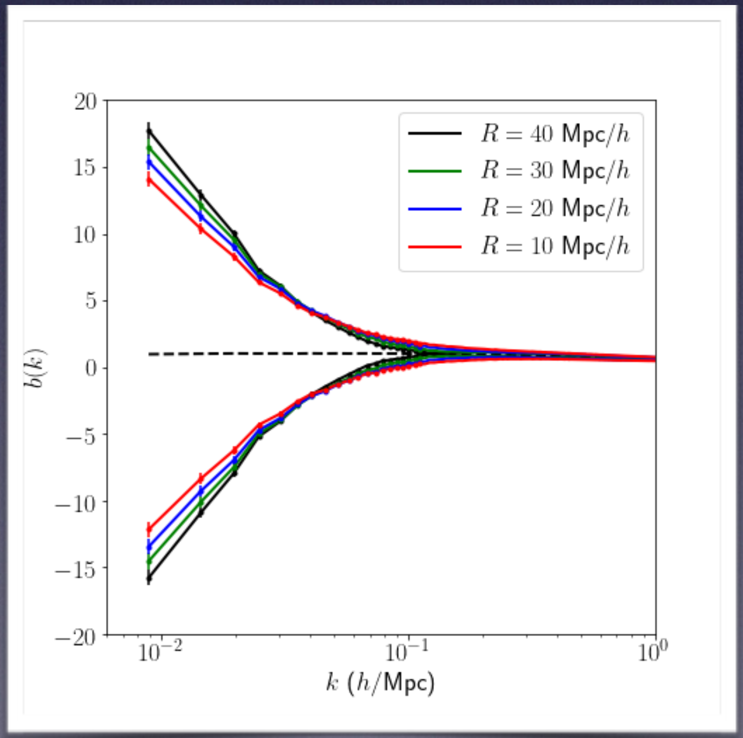
Using the environment to enhance the signal







Banerjee et al 2019 (in prep.)



Banerjee et al 2019 (in prep.)

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

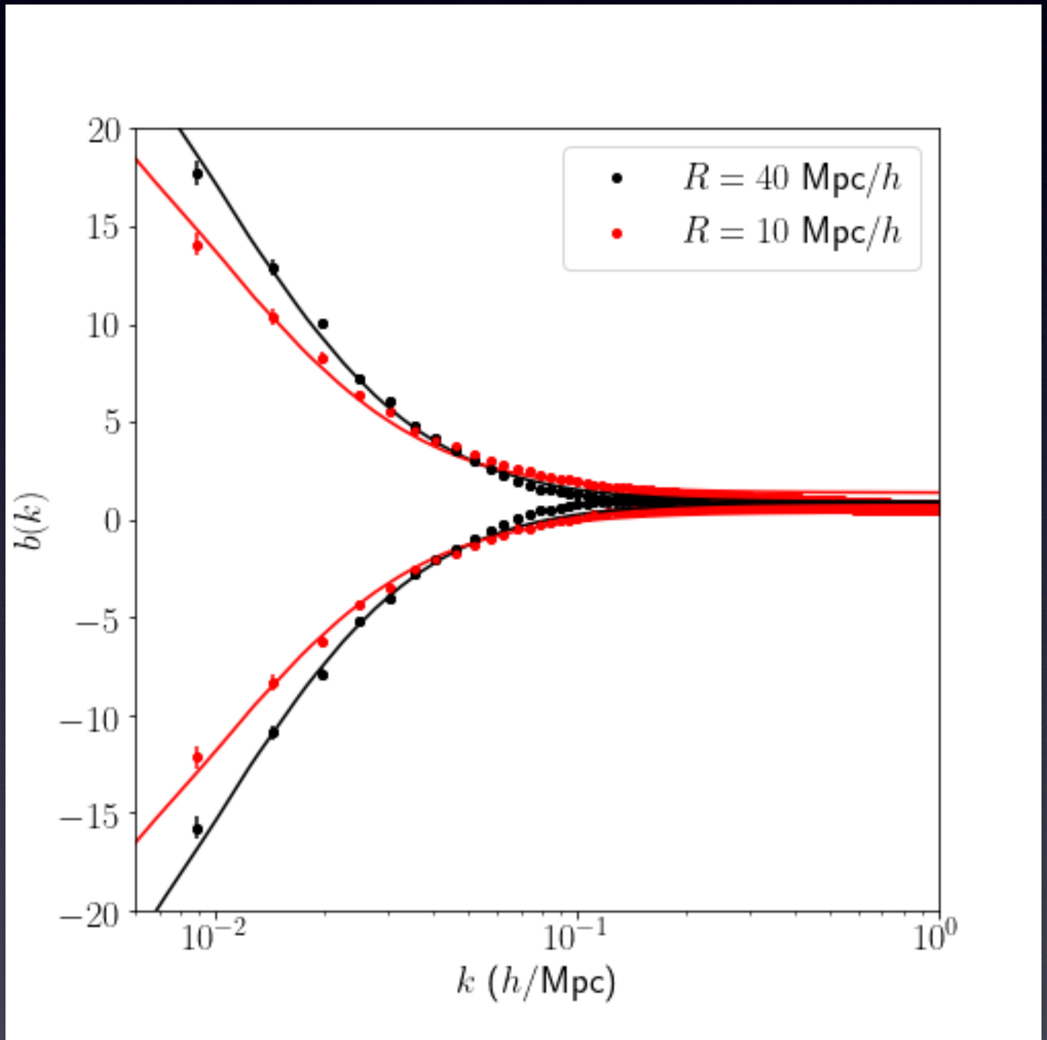
$$b(k) = A + B\frac{P_{c\nu}(k)}{P_{cc}(k)}$$

- 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.

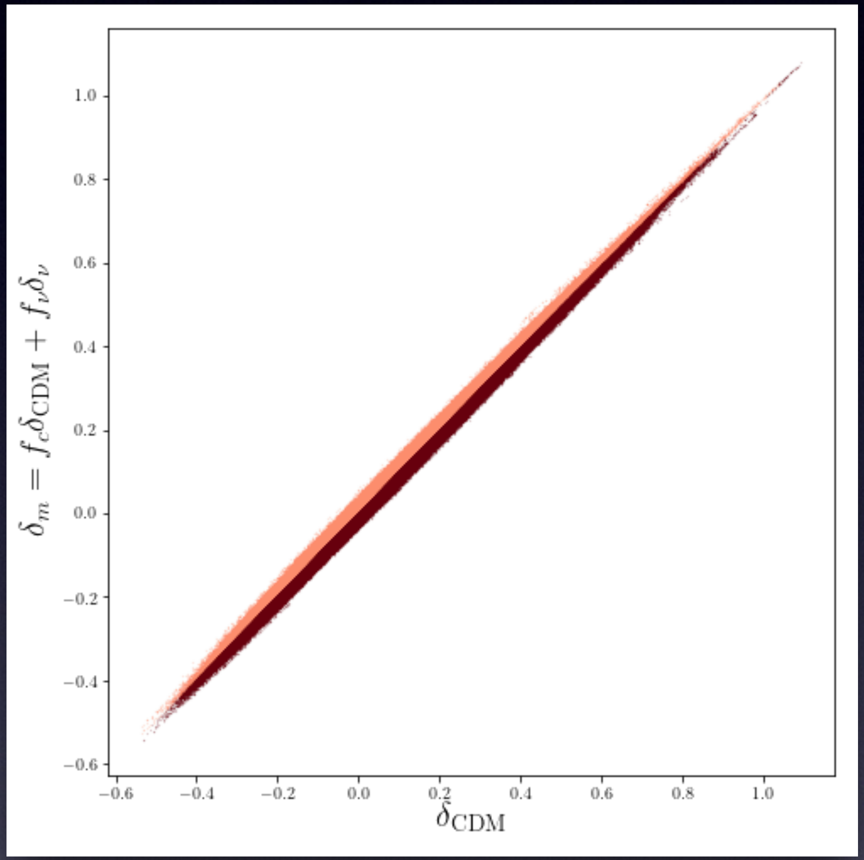
$$m_\nu^i = 0.05\text{eV}\,,\ \sum_i m_\nu = 0.15\text{eV}$$

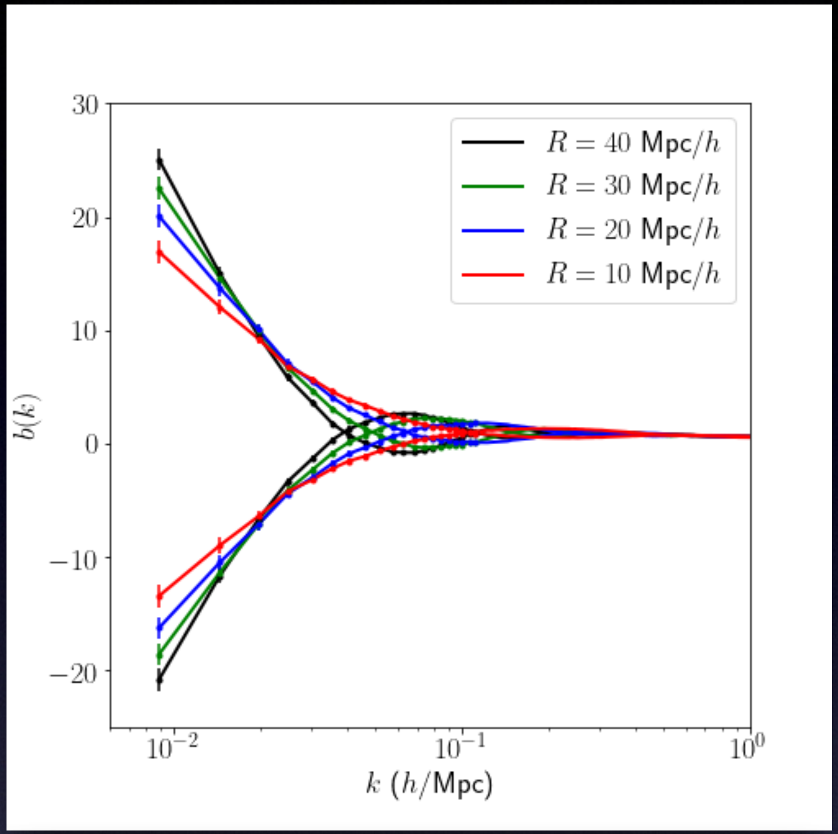
$$m_\nu^i = 0.05\text{eV}\,,\ \sum_i m_\nu = 0.10\text{eV}$$

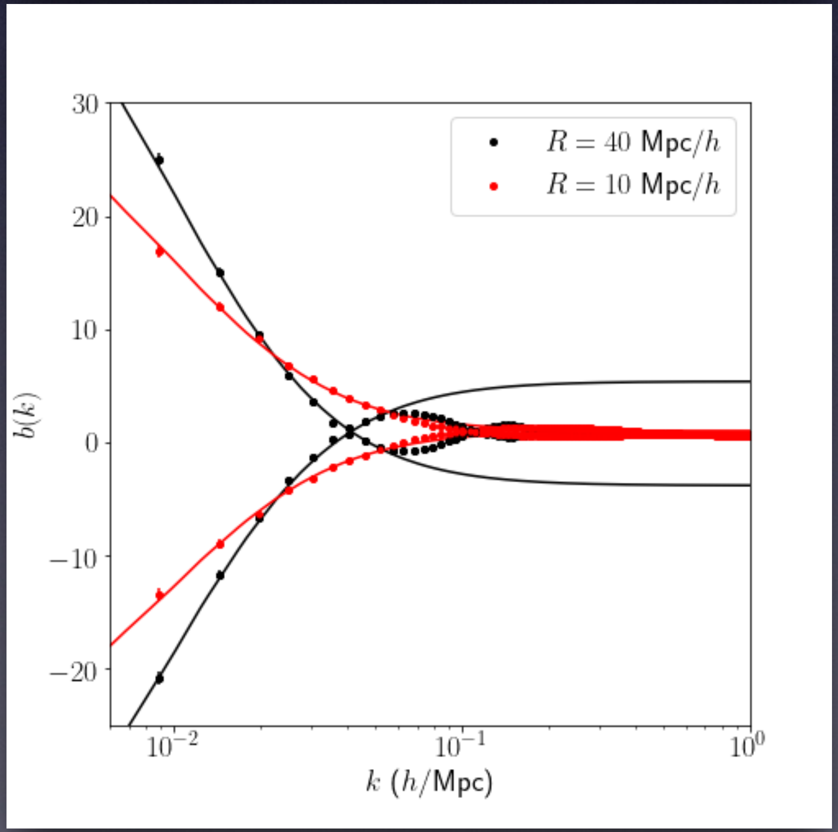


Banerjee et al 2019 (in prep.)

Is there an equivalent split using “observables”?







Find the large scale $\delta_{\rm CDM}$ and $\delta_{\rm matter}$ and use the following quantity to split:

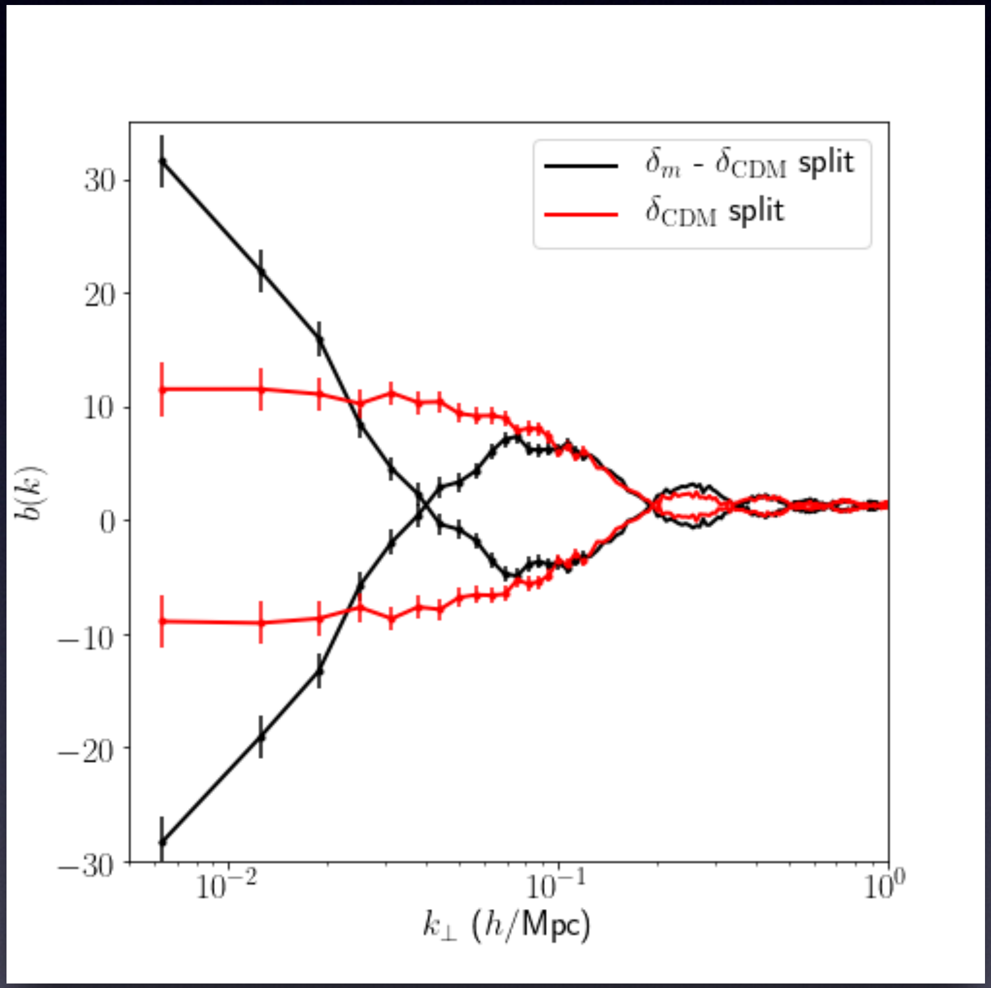
$$\delta = \delta_m - \langle \delta_m | \delta_{\rm CDM} \rangle$$

Banerjee et al 2019 (in prep.)

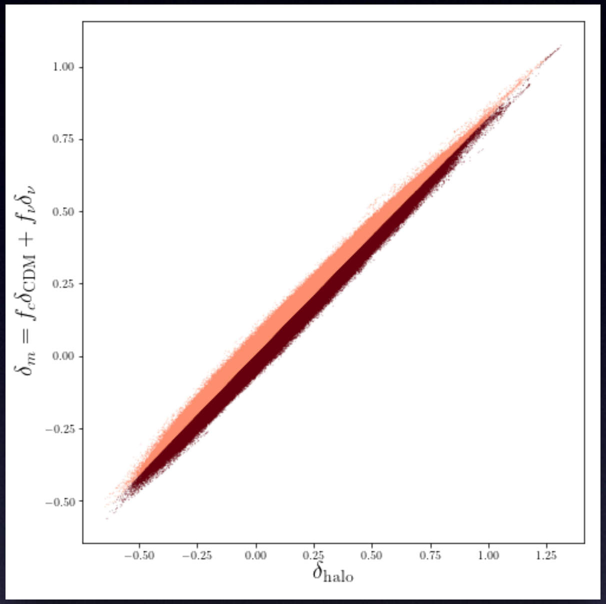
What happens when we project?

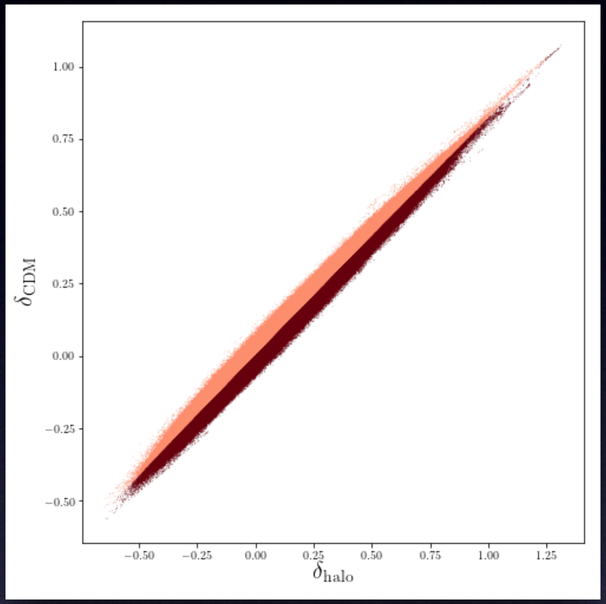
- Project all quantities along one of the simulation axis. Repeat the splitting procedure with

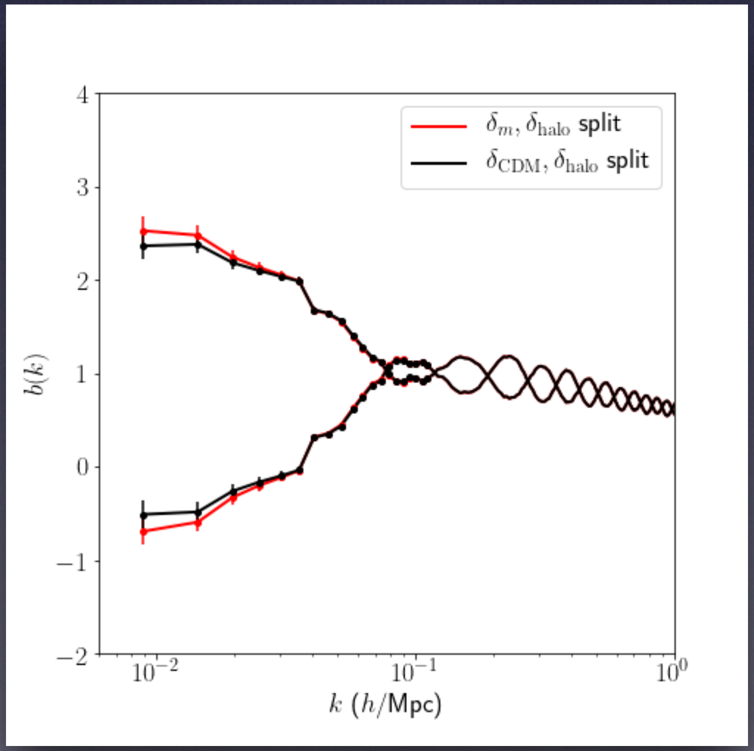
$$\delta_{2D} = \delta_{m,2D} - \langle \delta_{m,2D} | \delta_{\mathrm{CDM,2D}} \rangle$$



Using halos to approximate the CDM field





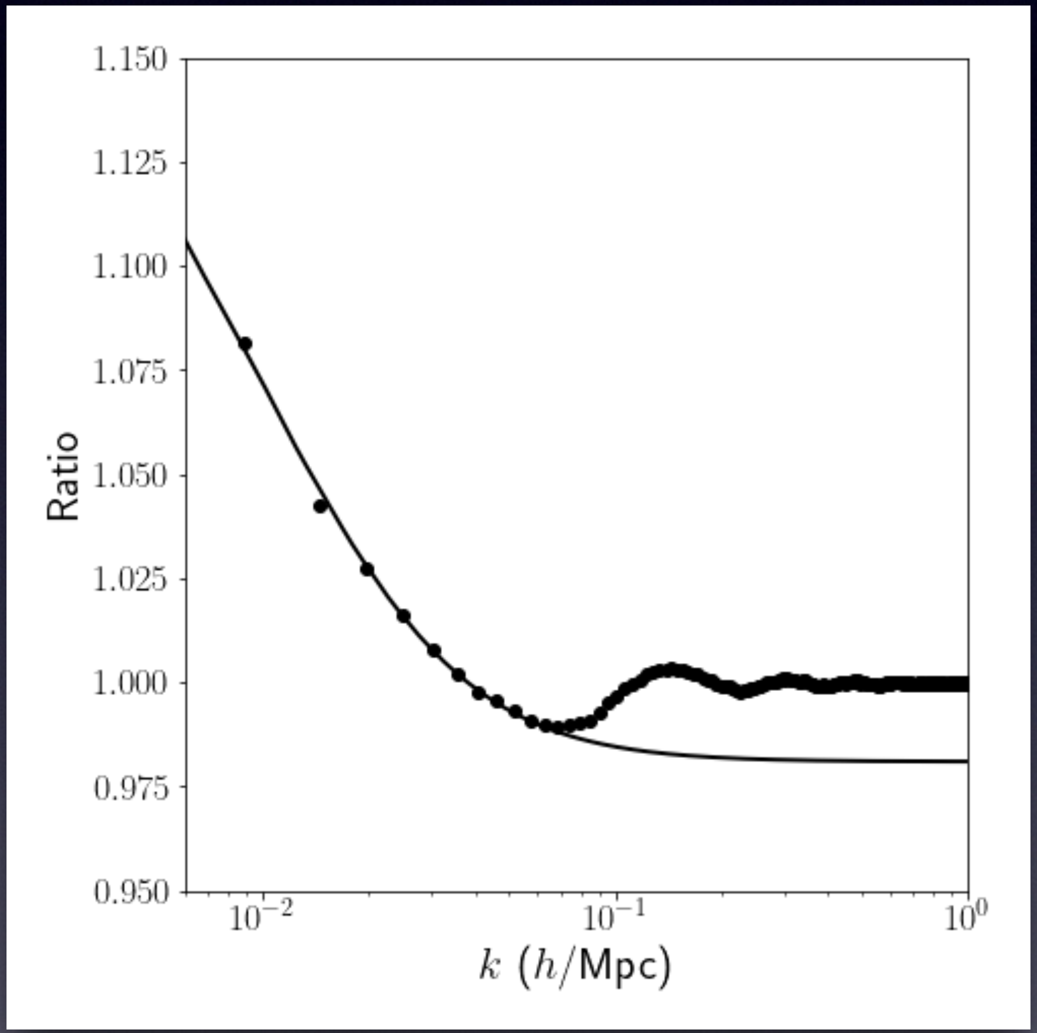


The obvious scale dependence is no longer visible when we use $\delta_{\rm halo}$ to approximate $\delta_{\rm CDM}$, even when we use mass weighting of the halo field.

Banerjee et al 2019 (in prep.)

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 $P_{c\nu}/P_{cc}$.
- Next step: convert to concrete mass bounds for LSST (+DESI).



Banerjee et al 2019 (in prep.)

Conclusions

- Scale dependent bias of halos on large scales is a unique feature of massive neutrino cosmology (modulo PNG).

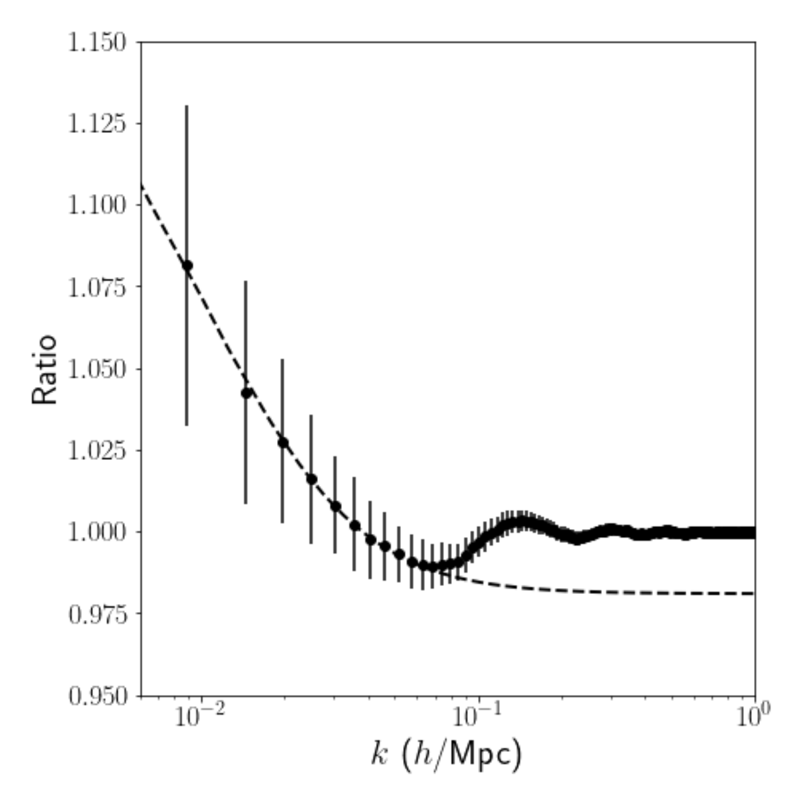
- Halos show strong scale dependent bias when split on the large scale neutrino environment.

- Similar effect can be recovered by using a combination of the CDM and matter environment. The shape is of the scale dependence is set exactly by the neutrino transfer function. Hence this can be used to constrain the neutrino mass.

- 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.



1.150
1.125
1.100
1.075
1.050
1.025
1.000
0.975
0.950
Ratio
10^{-2}
10^{-1}
10^{0}
k (h/Mpc)