Scale-dependent bias and bispectrum in neutrino separate universe simulations

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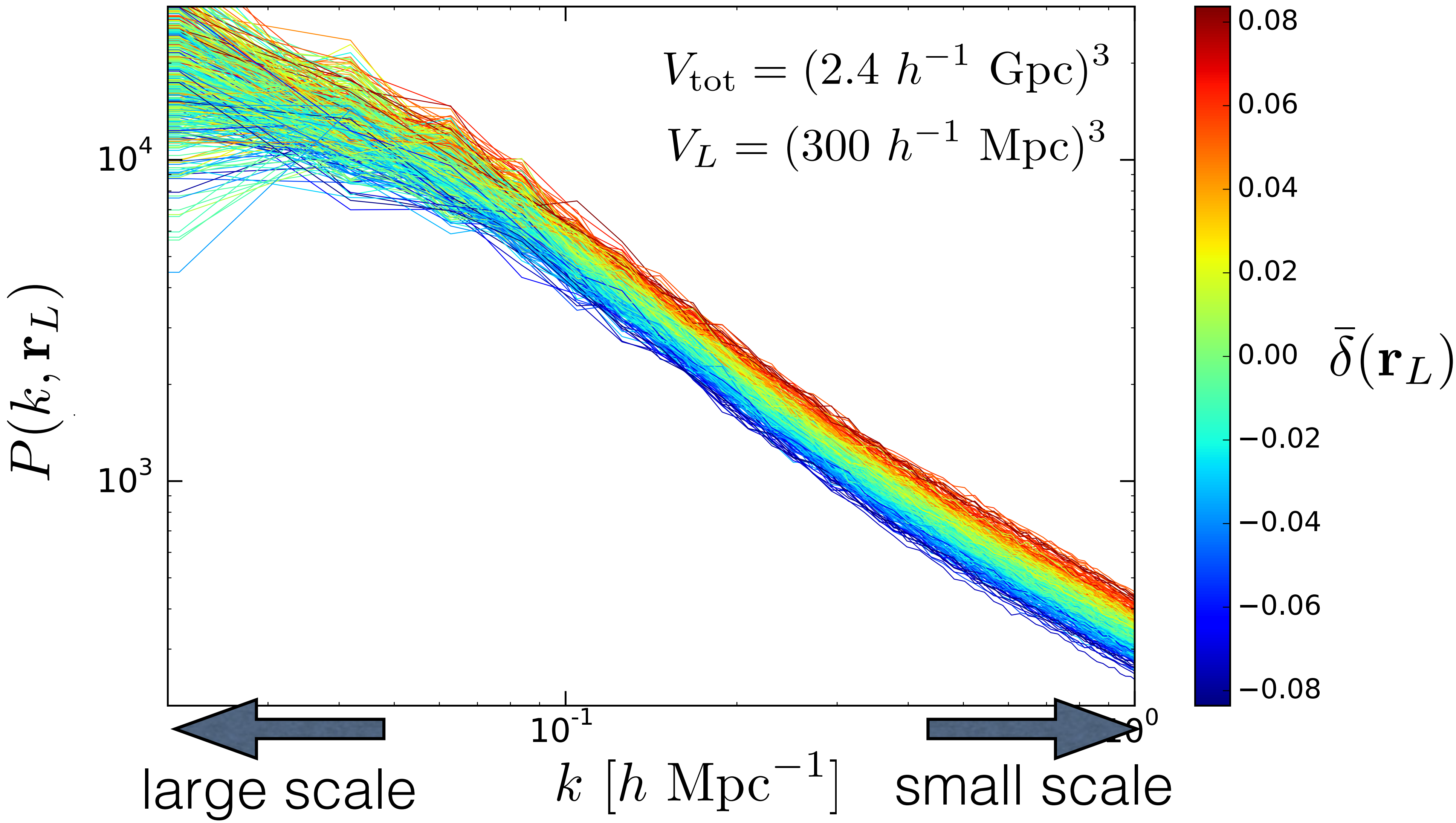
Motivation

- Simulating neutrinos is difficult due to their large thermal motion, and so one in general needs many more particles than CDM to sample the phase-space distribution well.
- Separate universe approach provides a way to simulate neutrino effect without directly simulating neutrinos.
- Separate universe simulations have been successful in calibrating the squeezed-limit bispectrum and halo bias.

Philosophy of separate universe approach

- Consider being a local observer in a region (~few hundred Mpc) with uniform density.
- The density can be larger, equal, or less than the background density.
- Is the structure formation in this region affected by the uniform density?

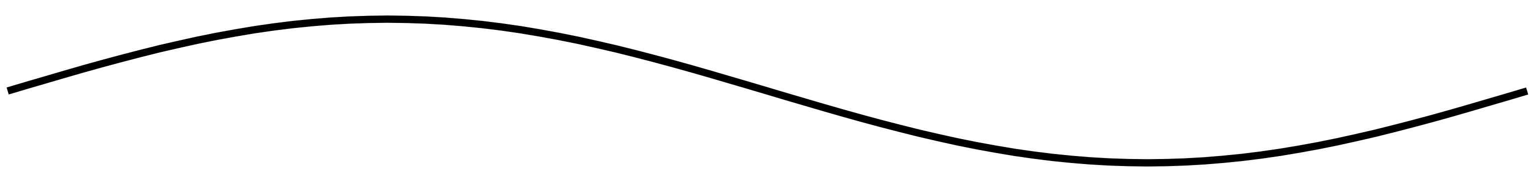
Small-scale power spectra depend on large-scale densities



CTC, Wagner, Schmidt, Komatsu, 2014

How is the power spectrum affected by the environment?

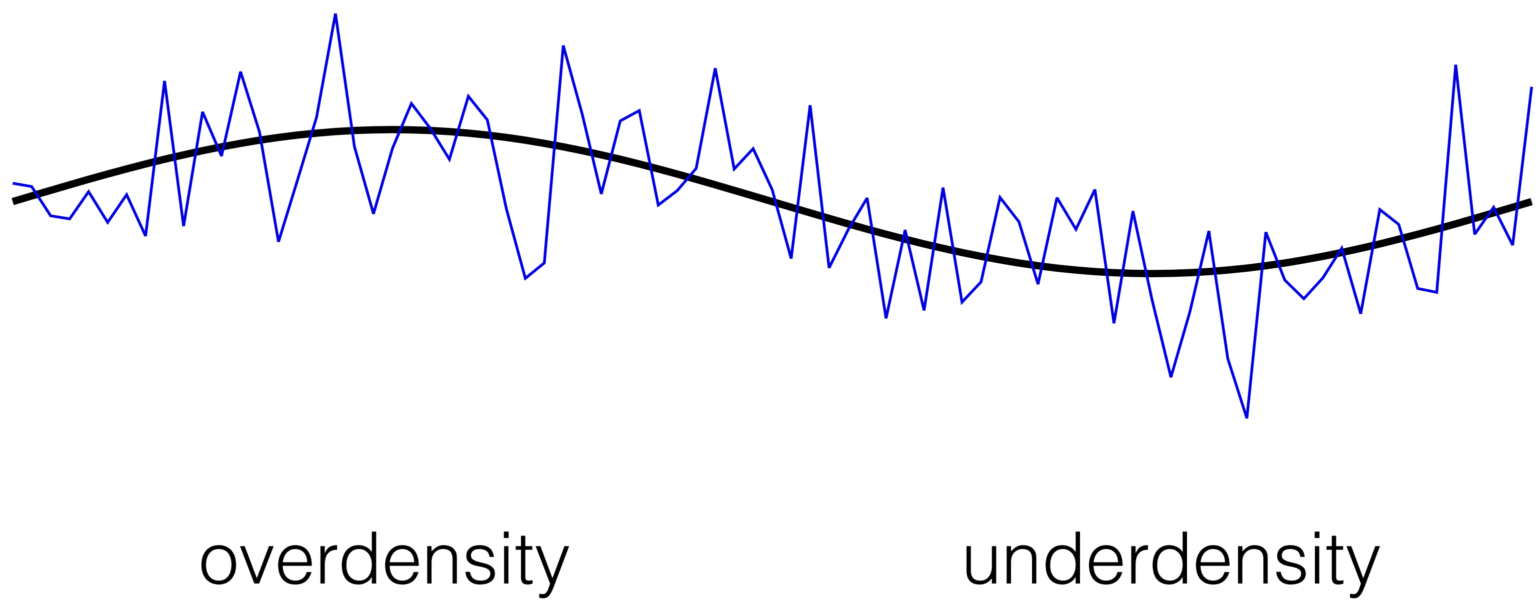
consider a long-wavelength density fluctuation



overdensity underdensity

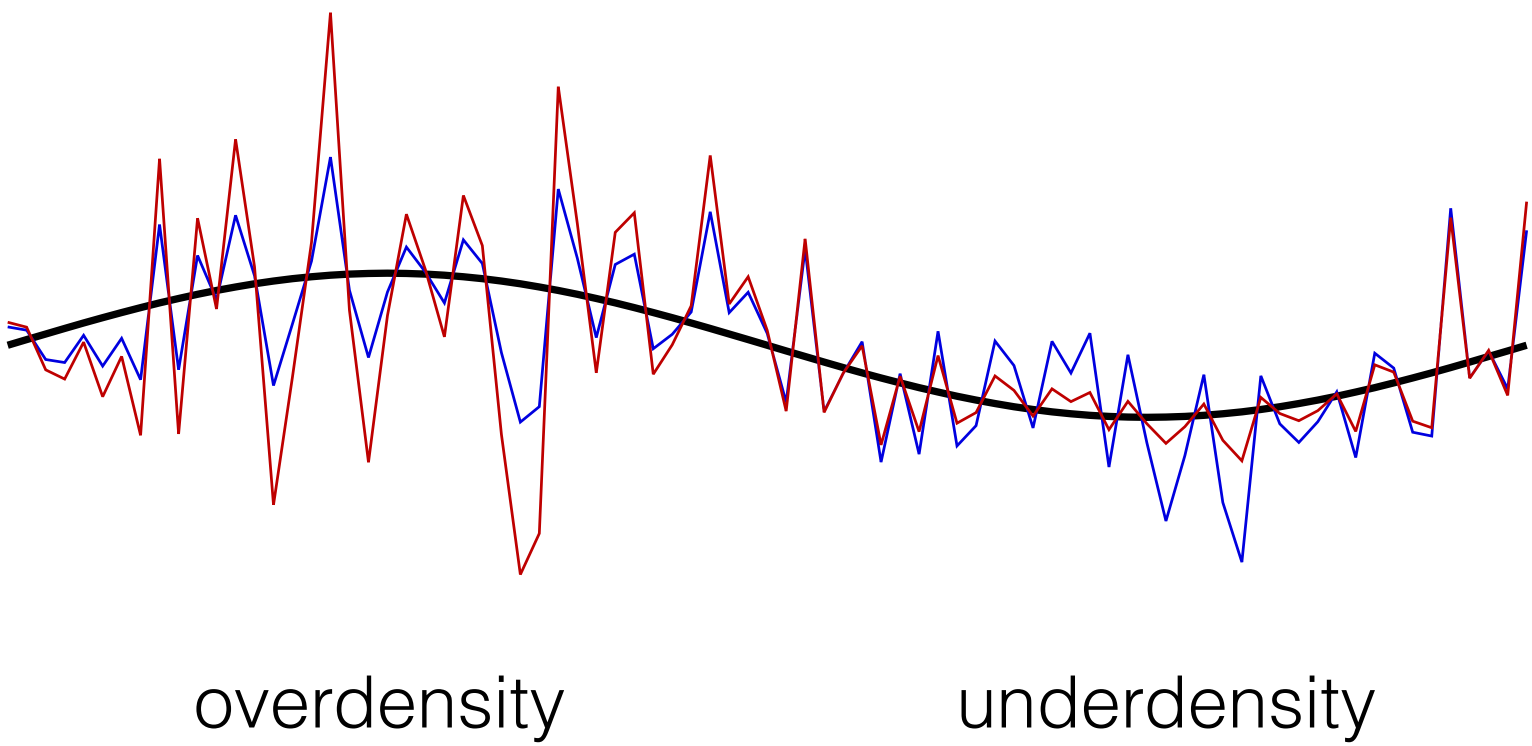
How is the power spectrum affected by the environment?

no correlation between power spectra and environments



How is the power spectrum affected by the environment?

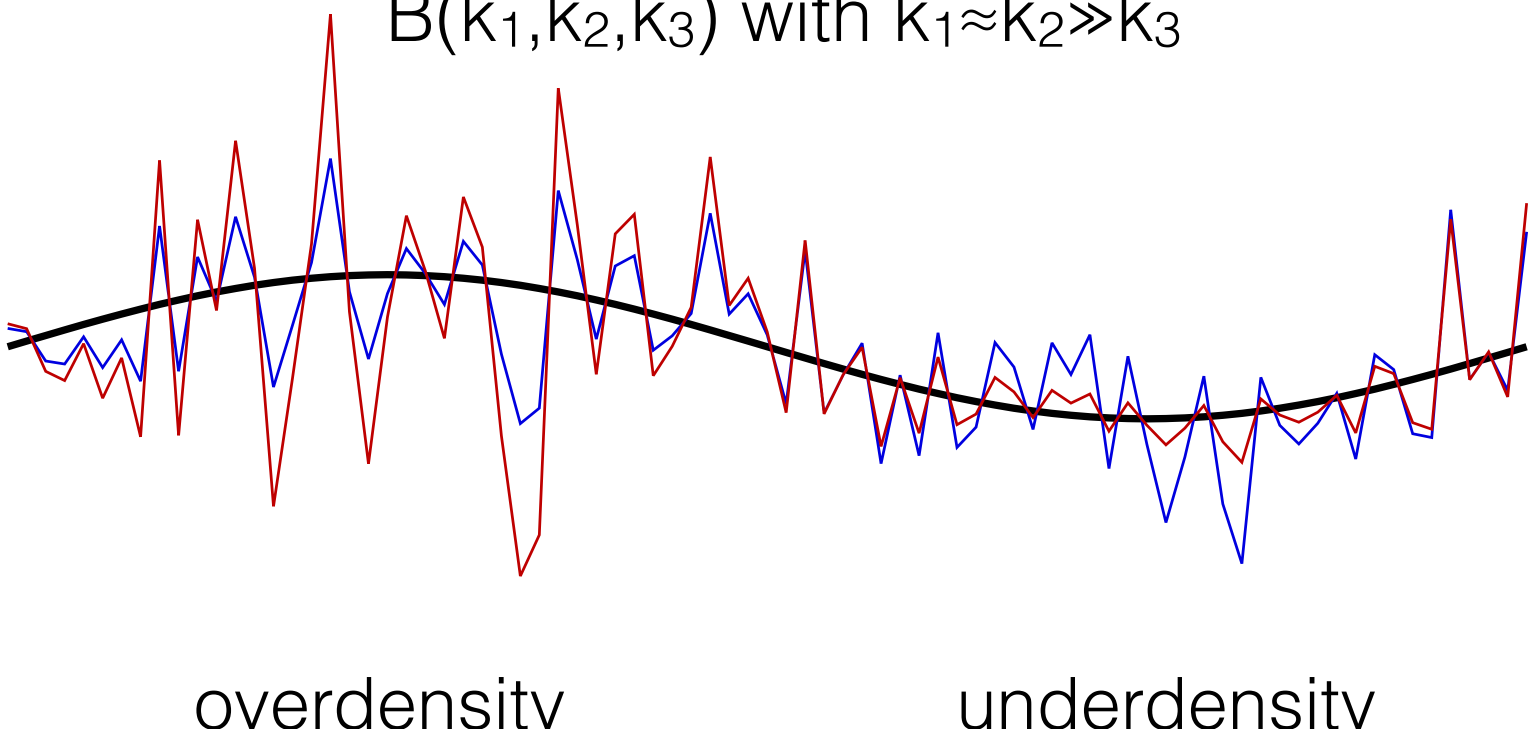
positive correlation between power spectra and environments

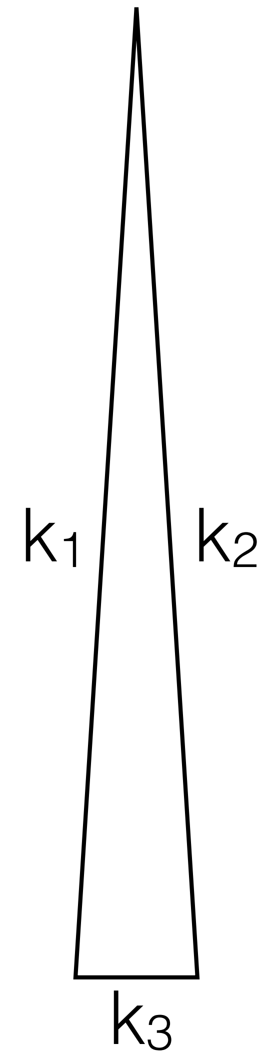


How is the power spectrum affected by the environment?

positive correlation between power spectra and environments

non-zero squeezed-limit bispectrum
$B(k_1,k_2,k_3)$ with $k_1 \approx k_2 \gg k_3$





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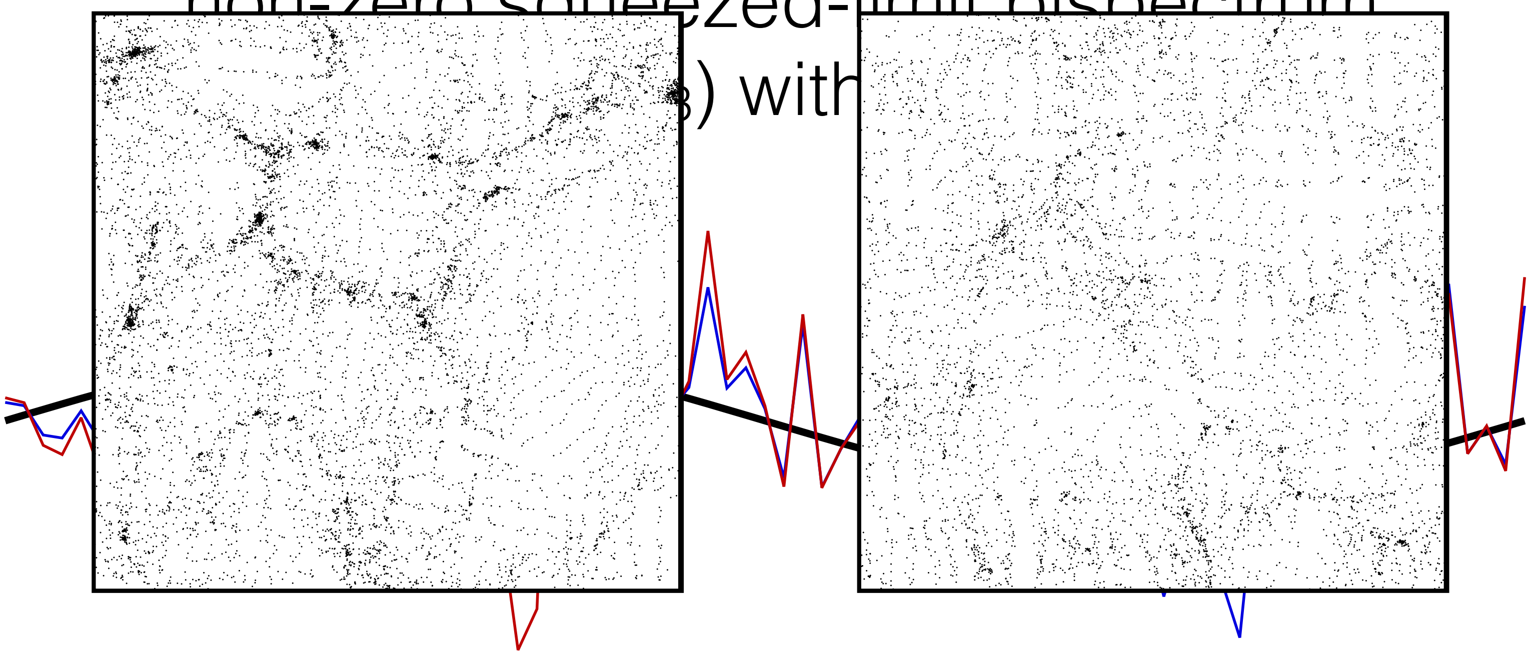
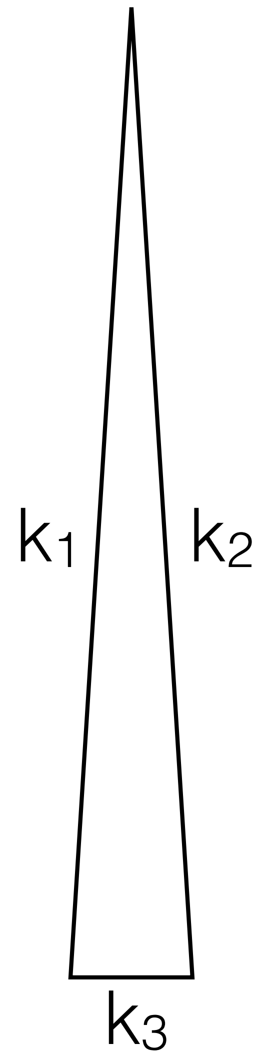
) with



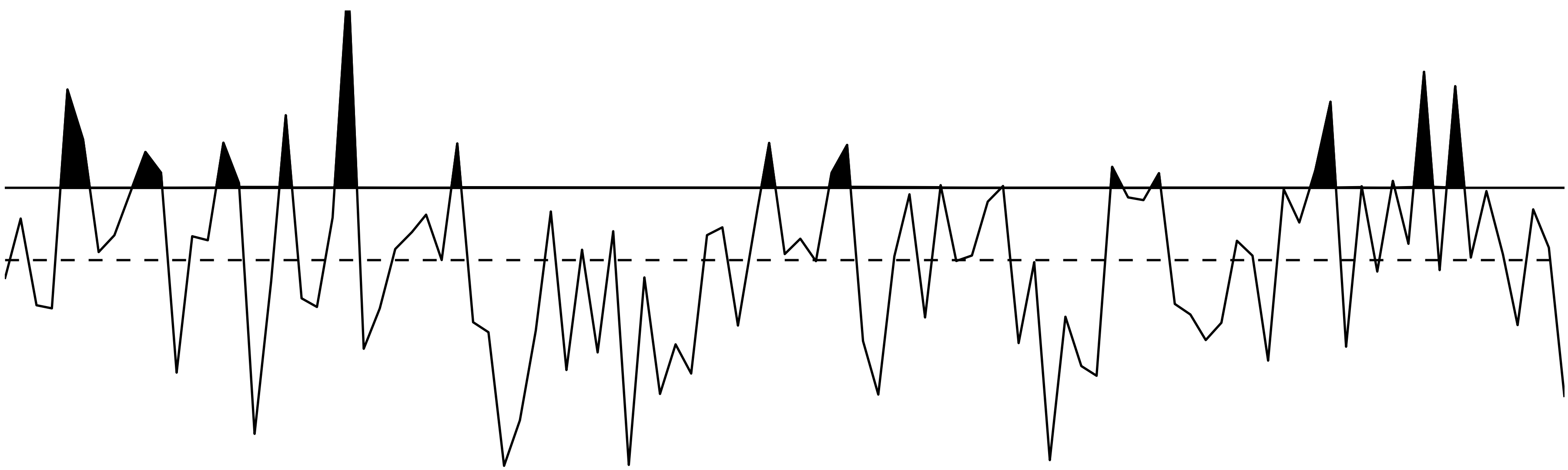
overdensity

underdensity



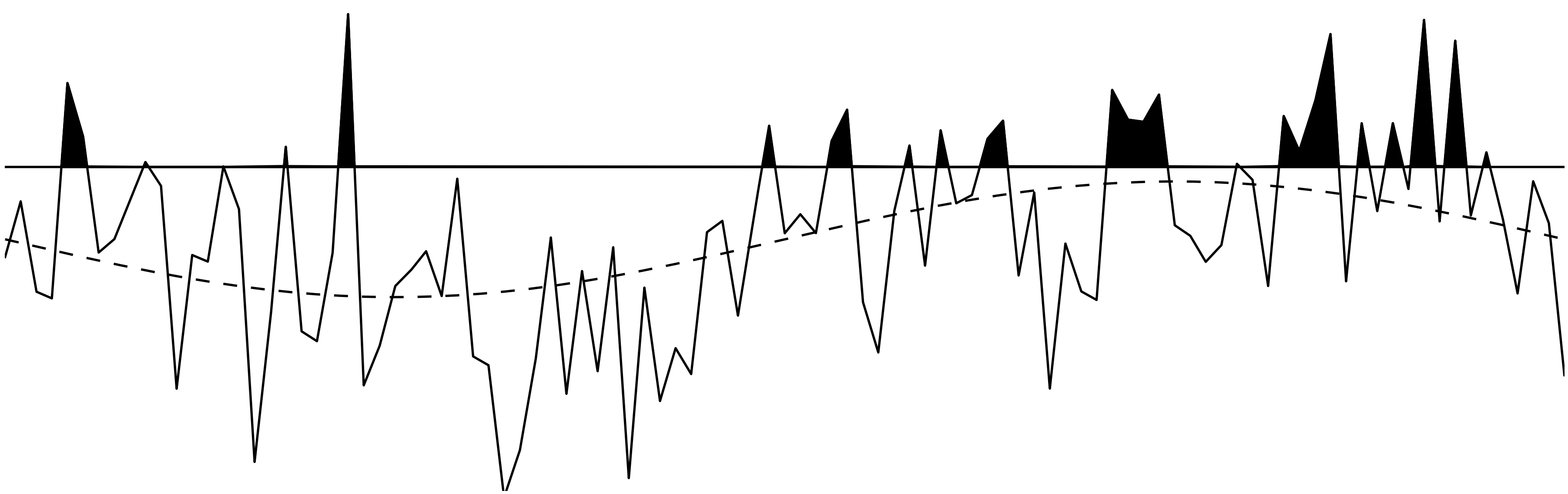
How is the halo formation affected by the environment?

When the density fluctuation exceeds the threshold, “halos” would form, as the shaded areas.



How is the halo formation affected by the environment?

In overdense (underdense) regions, more (less) halos would form, and so the halo number density depends on the environment.



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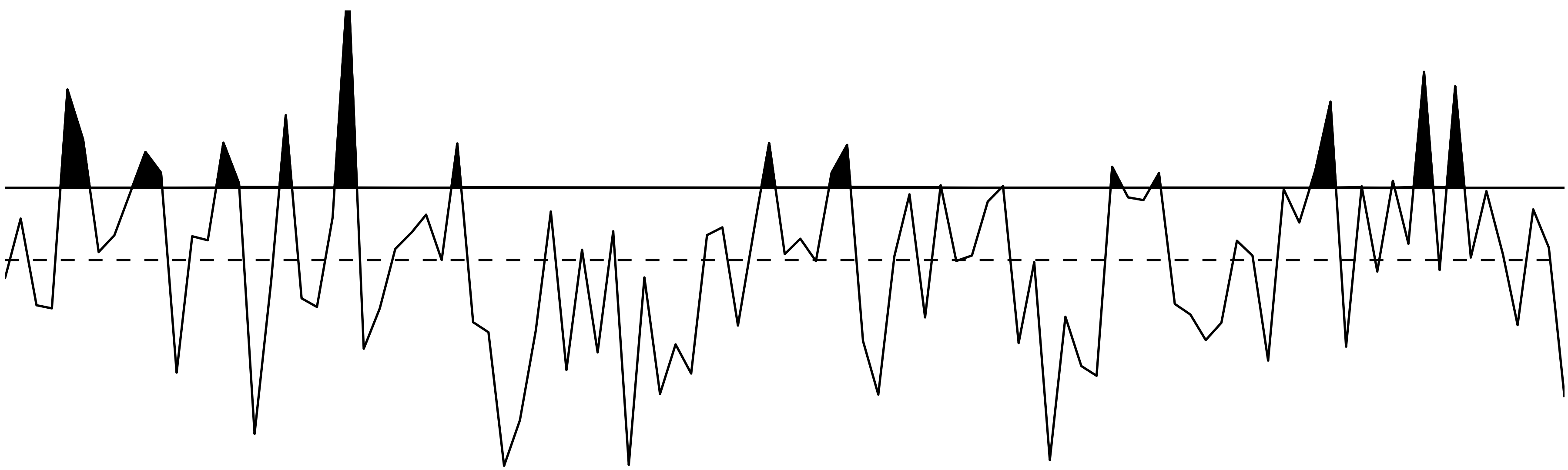

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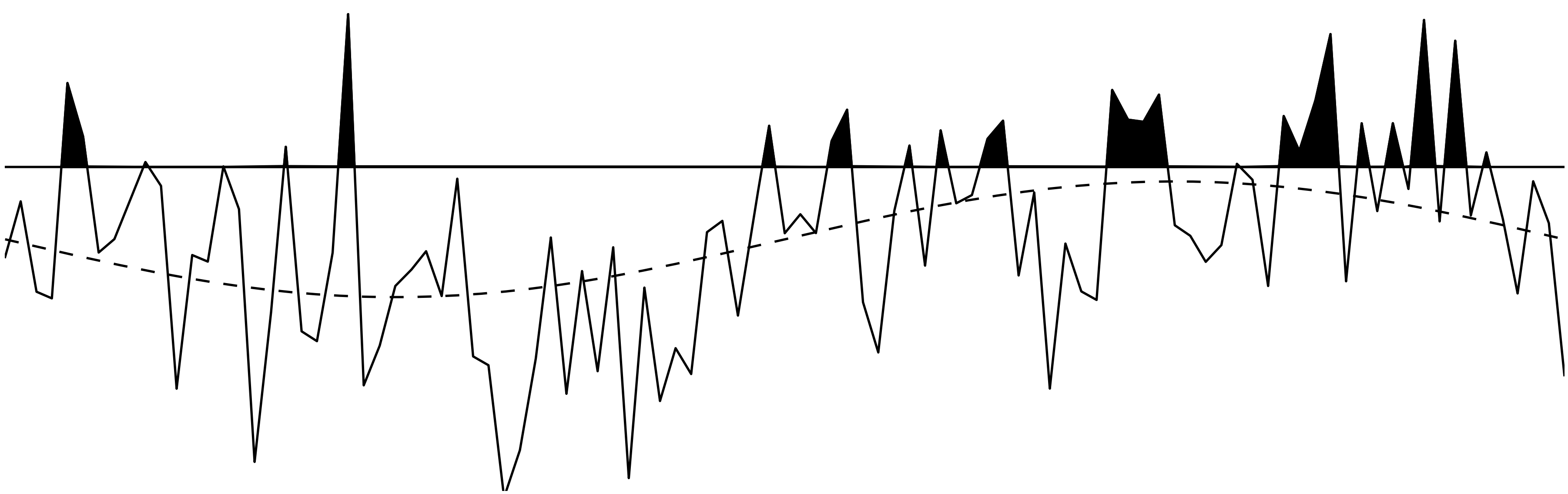
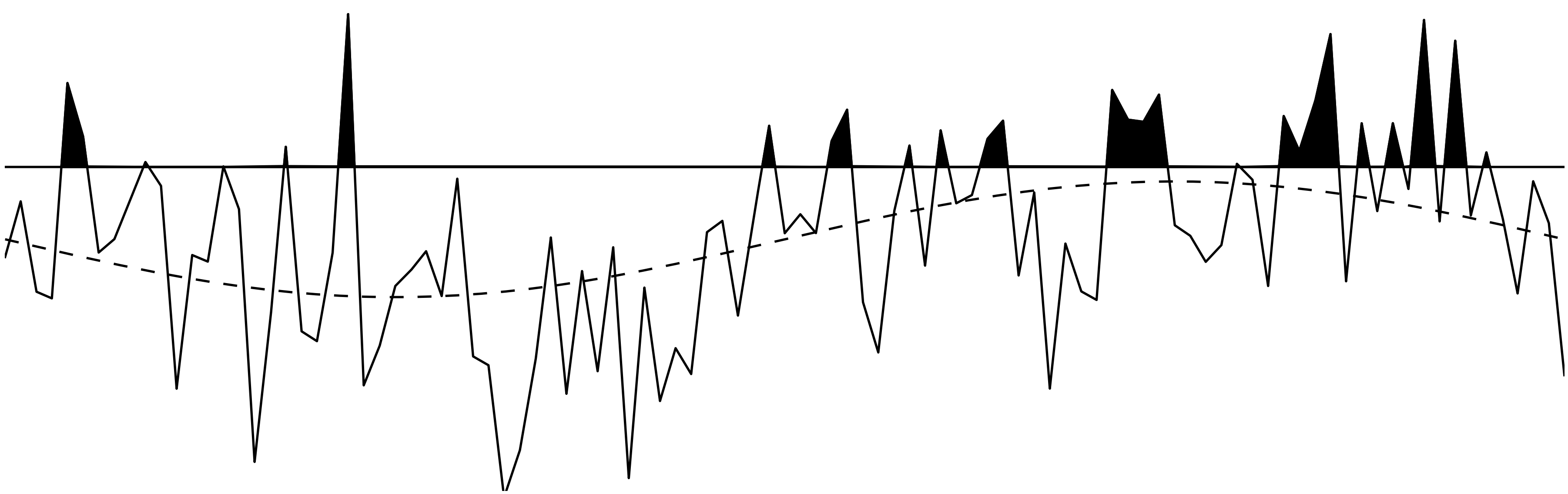


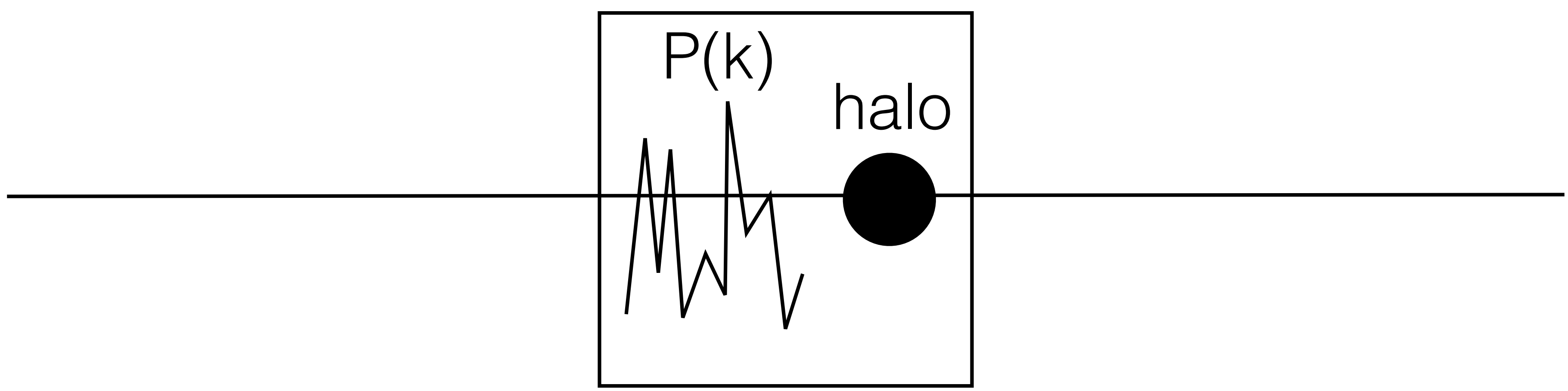
How is the halo formation affected by the environment?

Halo number density perturbation is biasedly tracing the underlying matter perturbation, so on large scale they are related by $\delta_h = b\delta_c$ where b is the halo bias.



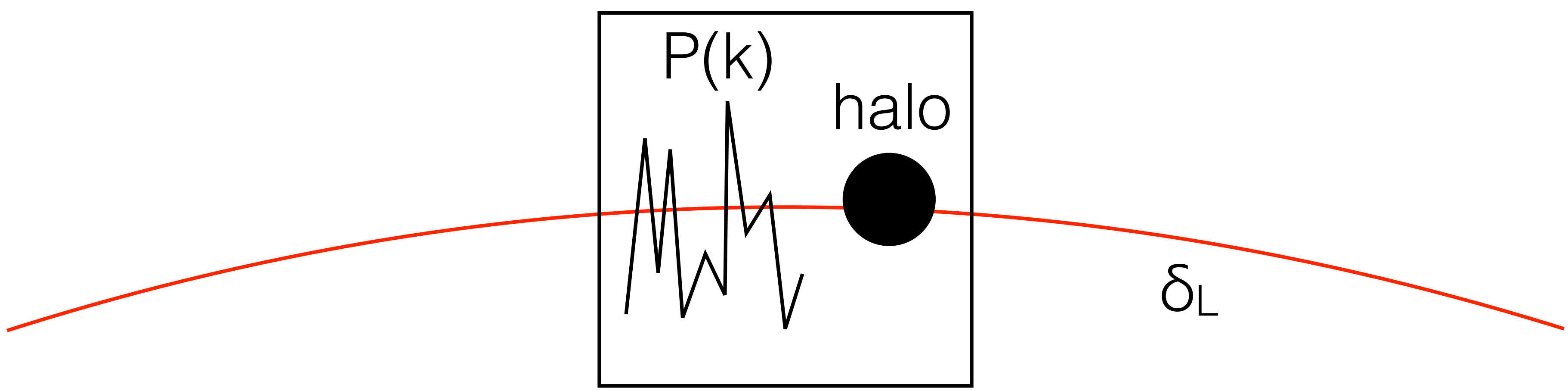
What is separate universe simulation?

consider simulating structure formation
in a box of ~ few hundred Mpc



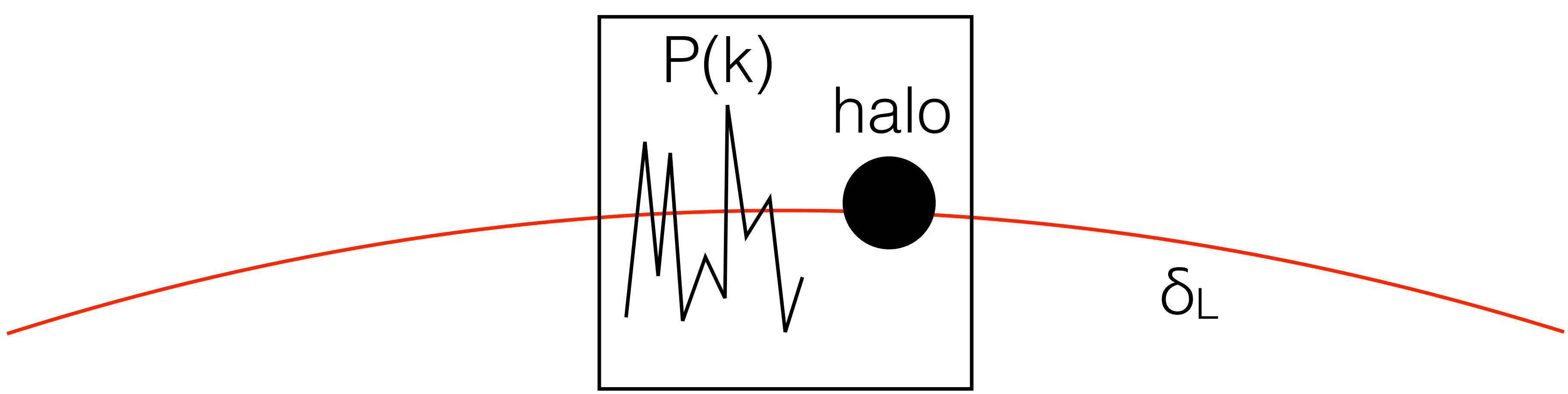
What is separate universe simulation?

We put in by hand a density perturbation δ_L with wavelength longer than the box, and so the local observer would feel δ_L to be uniform in the box.



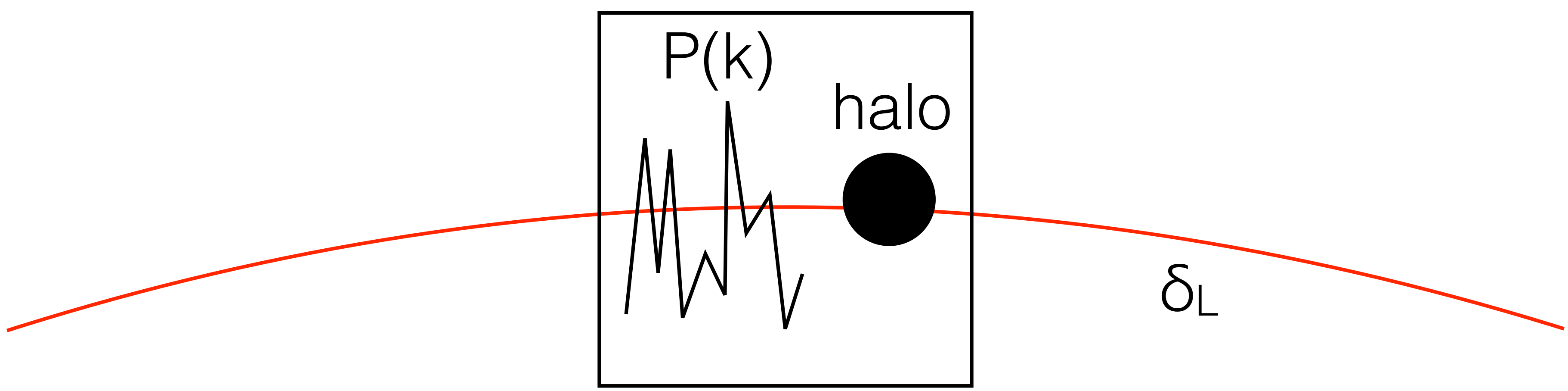
What is separate universe simulation?

δ_L would change the expansion history of the box from that without the long-wavelength perturbation, and so as the structure formation.



What is separate universe simulation?

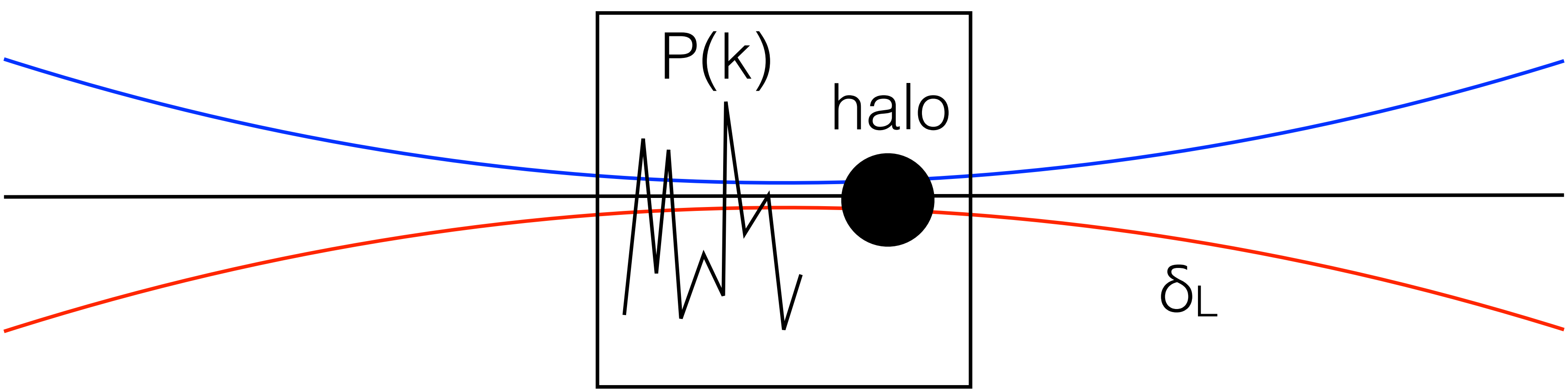
If we know how δ_L changes the expansion history, then we can directly perform simulations in different density environment without the need of running gigantic simulations and identify various environments.



What is separate universe simulation?

Running separate universe simulations in overdense and underdense environments, we can directly calibrate the response of observable A to δ_L as

$$R_A = (A_{\delta_L^+} - A_{\delta_L^-})/(2\delta_L A_{\delta_L^0})$$



What if there are neutrinos?

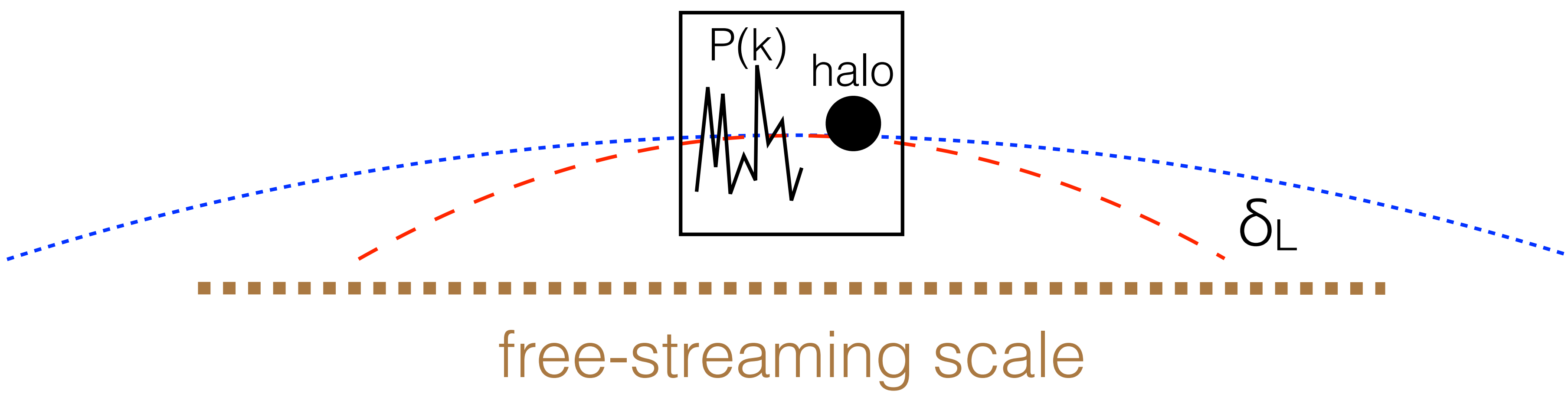
- Due to the large thermal motion, neutrinos only cluster with CDM beyond the free-streaming scale, and within the free-streaming scale their fluctuations are washed out.

- The growth of CDM density perturbation becomes scale dependent, and the scale dependence appears across the free-streaming scale.

- The corresponding separate universes also depend on the wavelengths of the long modes.

Separate universe with neutrinos

The long and short modes evolve differently, and so they will influence the expansion history and structure formation of the small box differently. This implies that the response of small-scale observables to δ_L would depend on its wavelength. We thus expect to find new scale-dependent feature due to massive neutrinos.



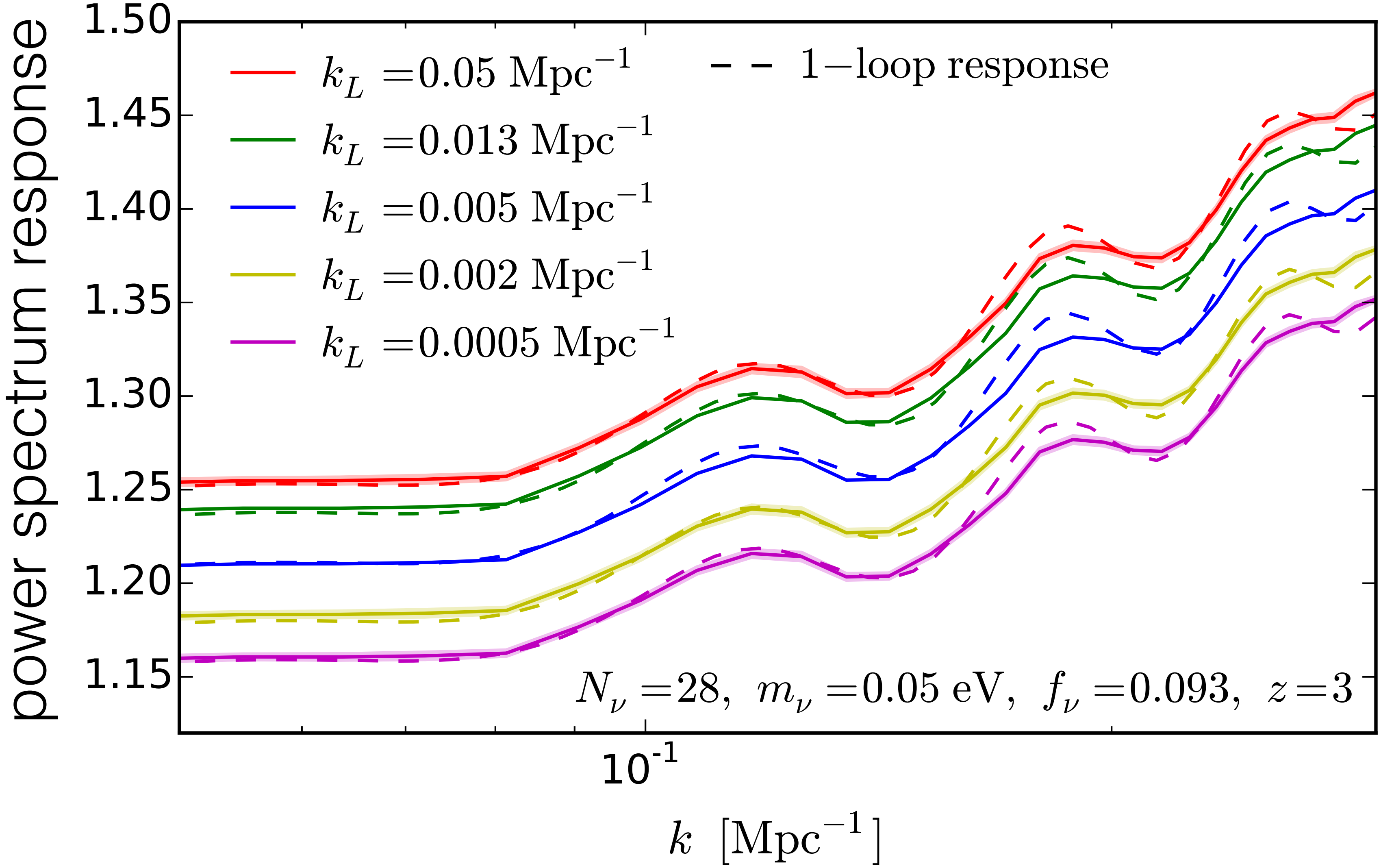
Neutrino separate universe simulations

- Perform separate universe N-body simulations with $\delta_L = \pm 0.01$ for different large-scale wavenumbers k_L.

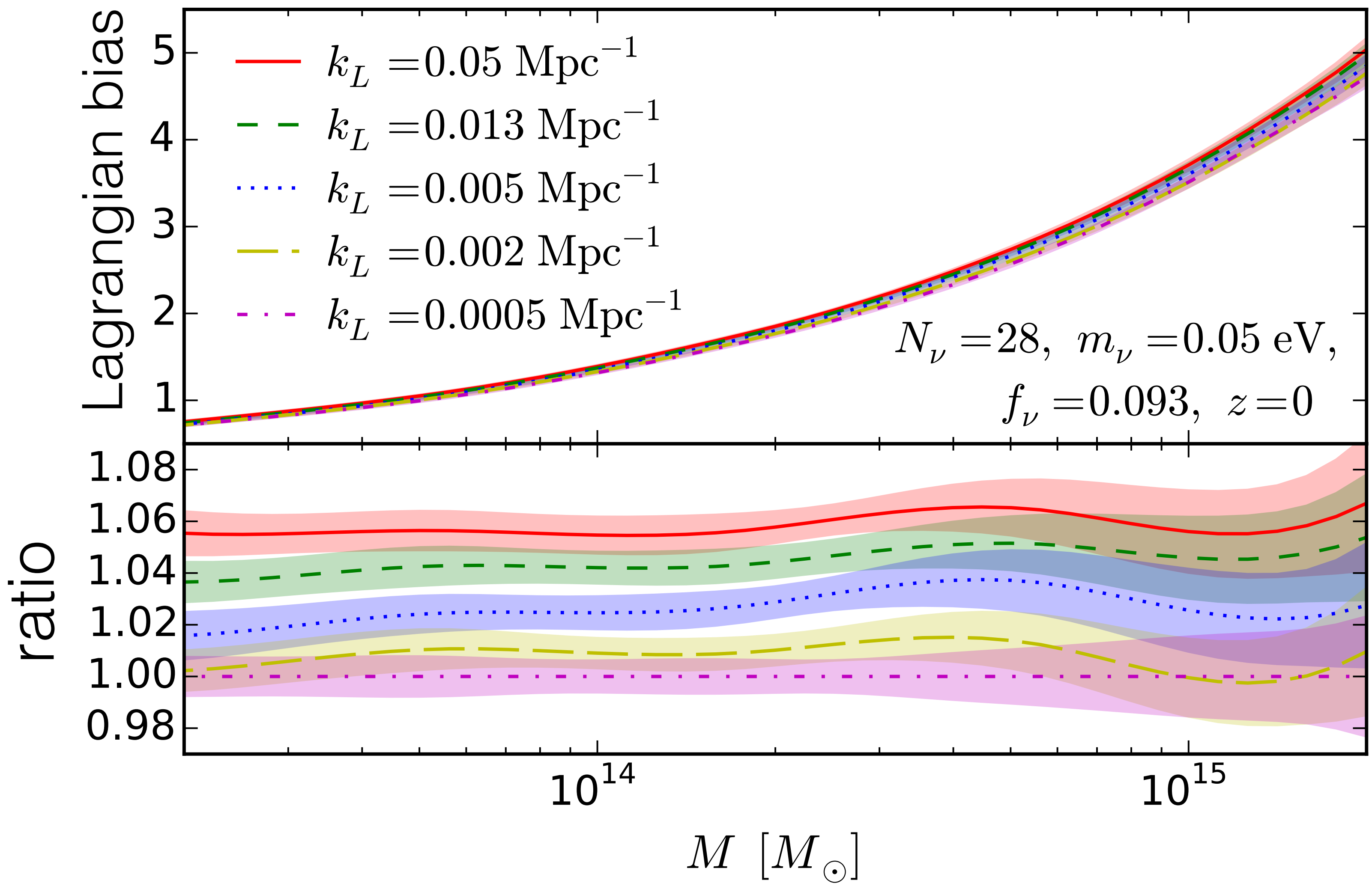
- Define the response of the observable A to δ_L to be $R_A(k_L)=[A(k_L, \delta_L^+)-A(k_L, \delta_L^-)]/[2\delta_L A(k_L, \delta_L^0)]$

- Consider A to be the small-scale power spectrum and halo mass function. The resulting responses are equivalent to the squeezed-limit bispectrum and response halo bias.

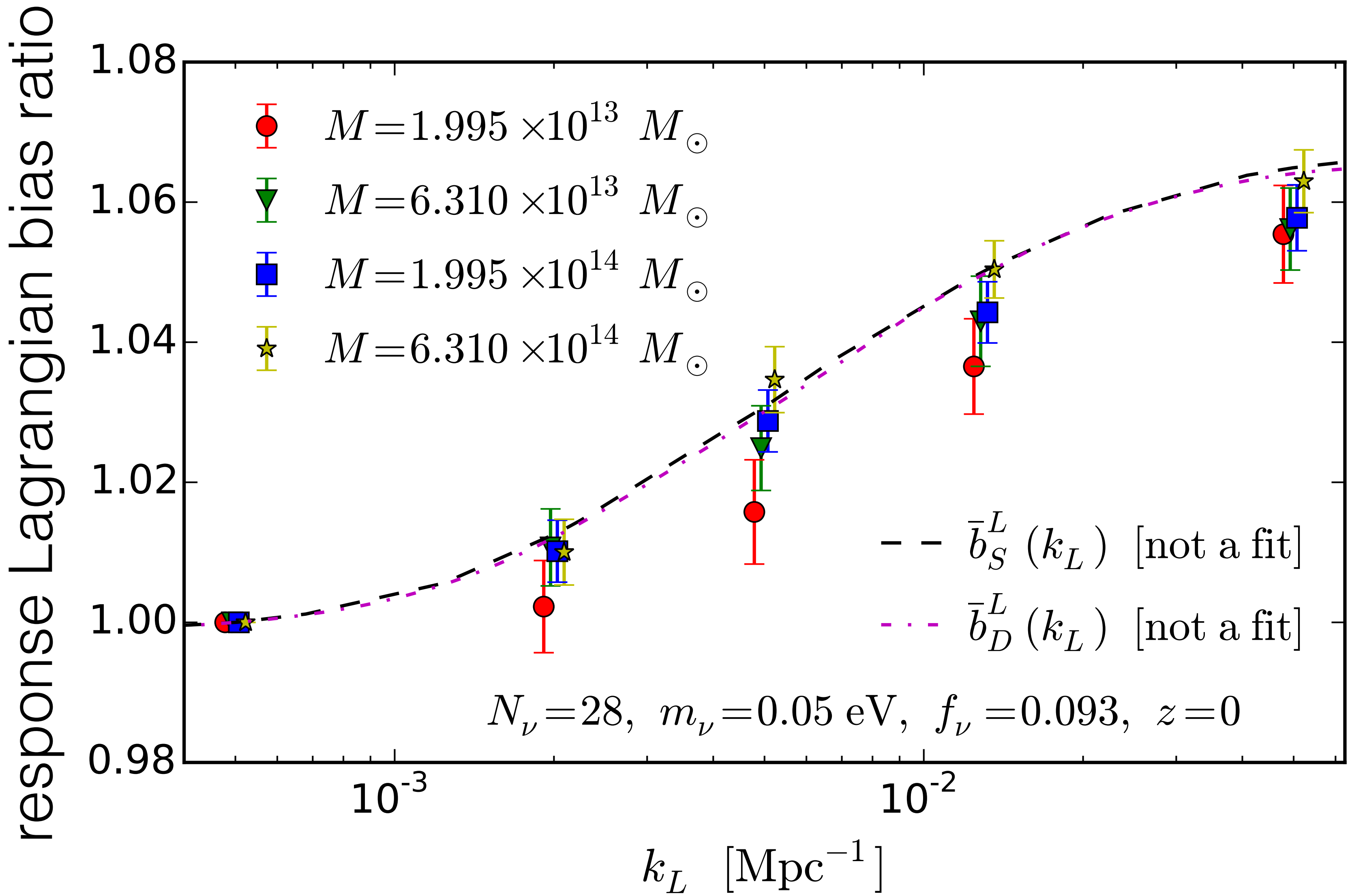
Power spectrum response [squeezed-limit B(k,k,k$_L$)]



Halo mass function response [Lagrangian halo bias]



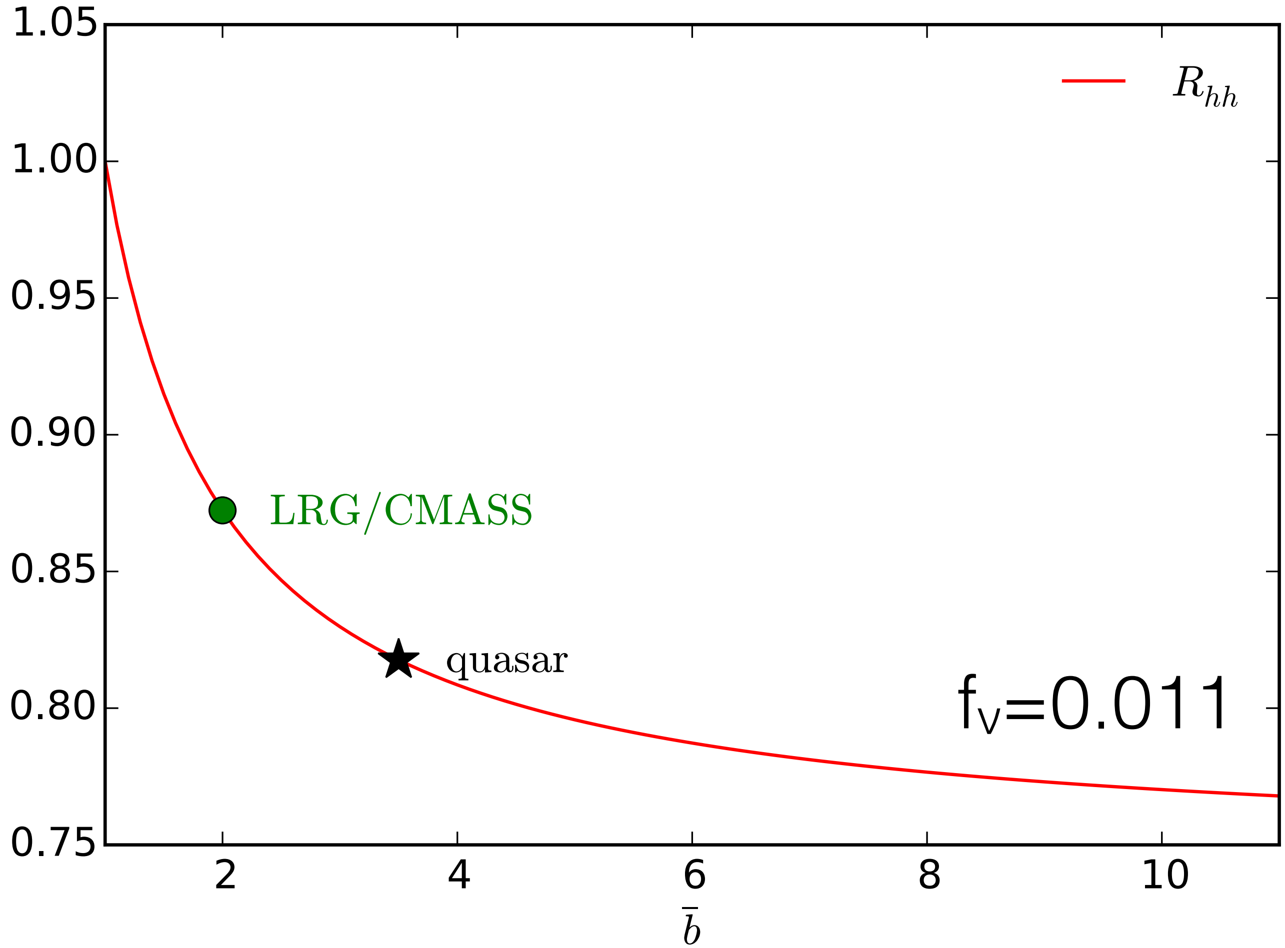
Scale-dependent halo bias



Effect on halo power spectrum

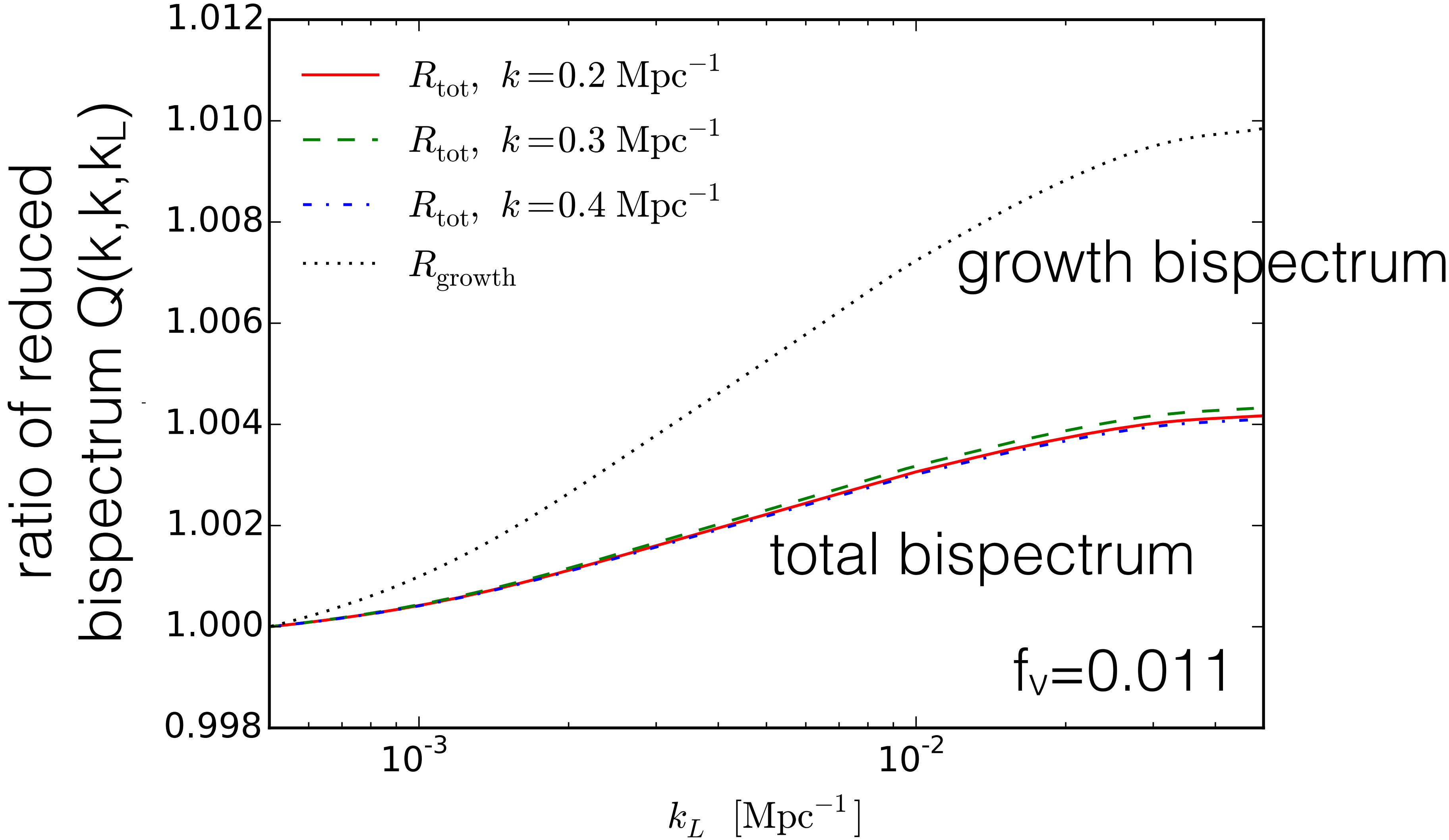
Massive neutrinos suppress the small-scale power spectrum due to the lack of clustering, but the new scale-dependent bias would reduce the suppression.

decrease of halo power spectrum suppression due to neutrino induced scale-dependent bias



Effect on the bispectrum

Without massive neutrinos, the reduced bispectrum is independent of k_L.



Conclusions

- We find scale-dependent response of power spectrum and halo mass function from neutrino separate universe simulations.
- This scale dependence will affect the halo power spectrum and squeezed-limit bispectrum, and these new features can be used to probe massive neutrinos.
- Confirm this with other neutrino simulation techniques!

Response example 1: power spectrum

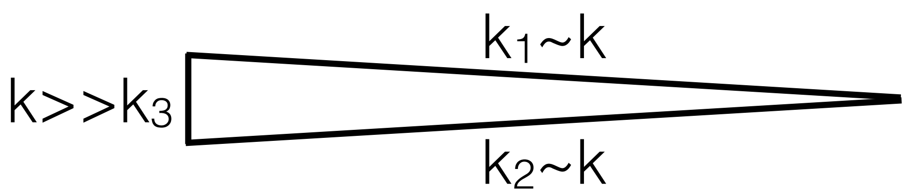
- Assume that the power spectrum depends on its density environment, and then Taylor expand it in series of the environment:

$$P(k|\delta_L) = P(k)|_{\delta_L=0} + P(k) \left. \frac{d \ln P(k)}{d\delta_L} \right|_{\delta_L=0} \delta_L + \mathcal{O}(\delta_L^2)$$

- Correlate the power spectrum with its environment:

$$\langle P(k|\delta_L)\delta_L \rangle = P(k) \frac{d \ln P(k)}{d\delta_L} \langle \delta_L^2 \rangle + \mathcal{O}(\delta_L^3)$$

- This is equivalent to the squeezed-limit bispectrum



Response example 2: halo mass function

- Expand the halo mass function in series of the large-scale density environment:

$$n_h(M_h|\delta_L) = n_h(M_h)|_{\delta_L=0} + \left.\frac{dn_h(M_h)}{d\delta_L}\right|_{\delta_L=0} \delta_L + \mathcal{O}(\delta_L^2)$$

- Rewrite the derivatives as the “bias” parameters for the halo number density fluctuation:

$$\delta_h(M_h|\delta_L) = \frac{n_h(M_h|\delta_L)}{n_h(M_h)} - 1 = \frac{d\ln n_h(M_h)}{d\delta_L}\delta_L + \mathcal{O}(\delta_L^2)$$
$$= b_1(M_h)\delta_L + \mathcal{O}(\delta_L^2)$$

- Large-scale halo and halo-matter power spectra:

$$P_{hh} = b_1^2 P_{mm} \qquad P_{hm} = b_1 P_{mm}$$

Separate universe mapping

- In the fiducial ΛCDM universe:

$$H^2 = H_0^2 \left[\Omega_m a^{-3} + \Omega_\Lambda\right] \qquad \frac{\ddot{a}}{a} = -\frac{H_0^2}{2}\left[\Omega_m a^{-3} - 2\Omega_\Lambda\right]$$

- In the universe with long-wavelength fluctuation:

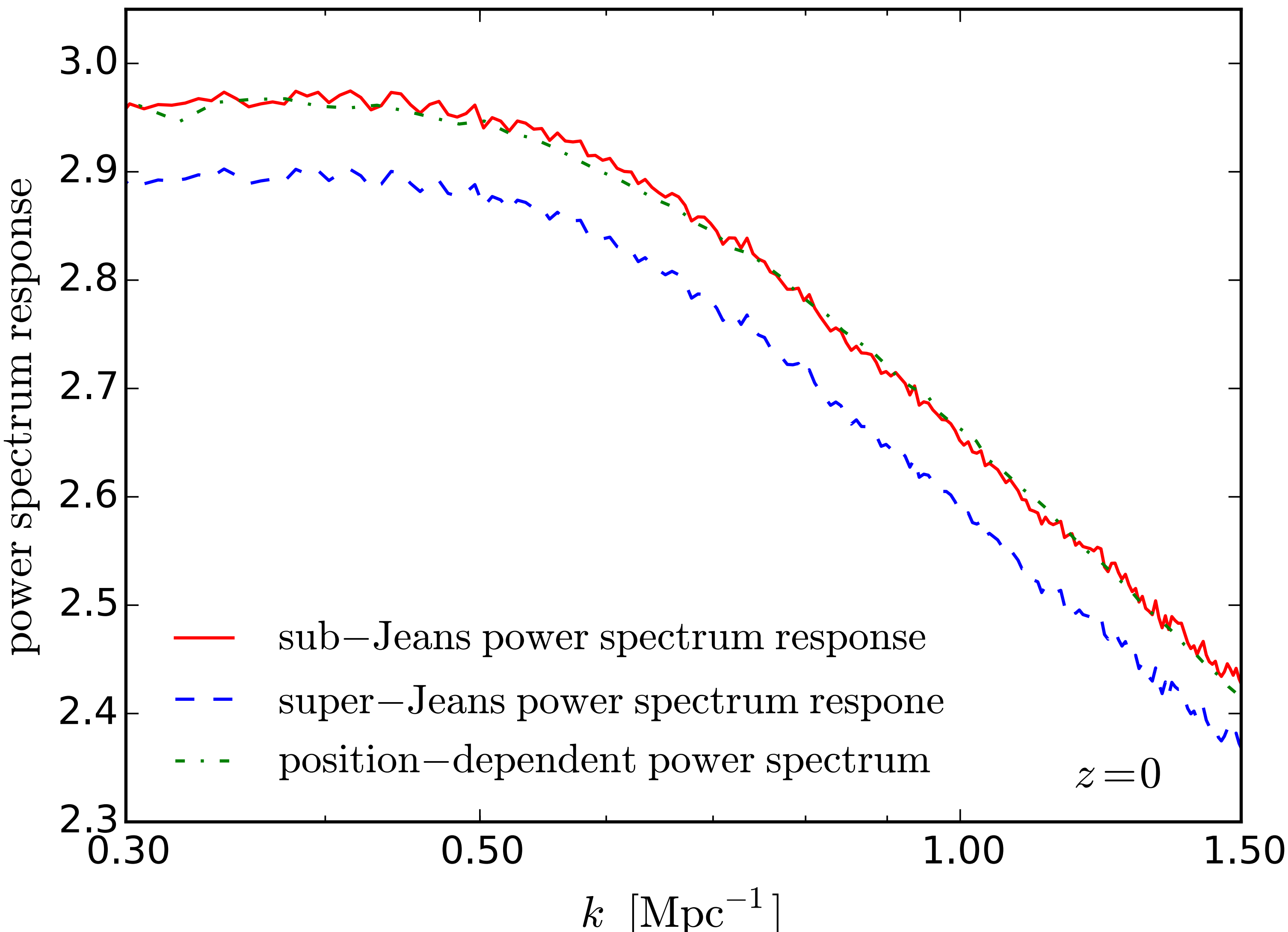
$$\tilde{H}^2 = \tilde{H}_0^2 \left[\tilde{\Omega}_m \tilde{a}^{-3} + \tilde{\Omega}_\Lambda + \tilde{\Omega}_X \tilde{a}^{-3(1+w_X)}\right]$$

$$\frac{\ddot{\tilde{a}}}{\tilde{a}} = -\frac{\tilde{H}_0^2}{2}\left[\tilde{\Omega}_m \tilde{a}^{-3} - 2\tilde{\Omega}_m + \tilde{\Omega}_X \tilde{a}^{-3(1+w_X)}(1+3w_X)\right]$$

- For ΛCDM (fiducial) universe, the long-wavelength density fluctuation behaves as curvature. Namely, in the overdense (underdense) universe, the separate universe is positively (negatively) curved.

Wagner, Schmidt, ***CTC***, Komatsu, 2014

Validation from quintessence separate universe simulation



CTC, Li, Hu, LoVerde, 2016

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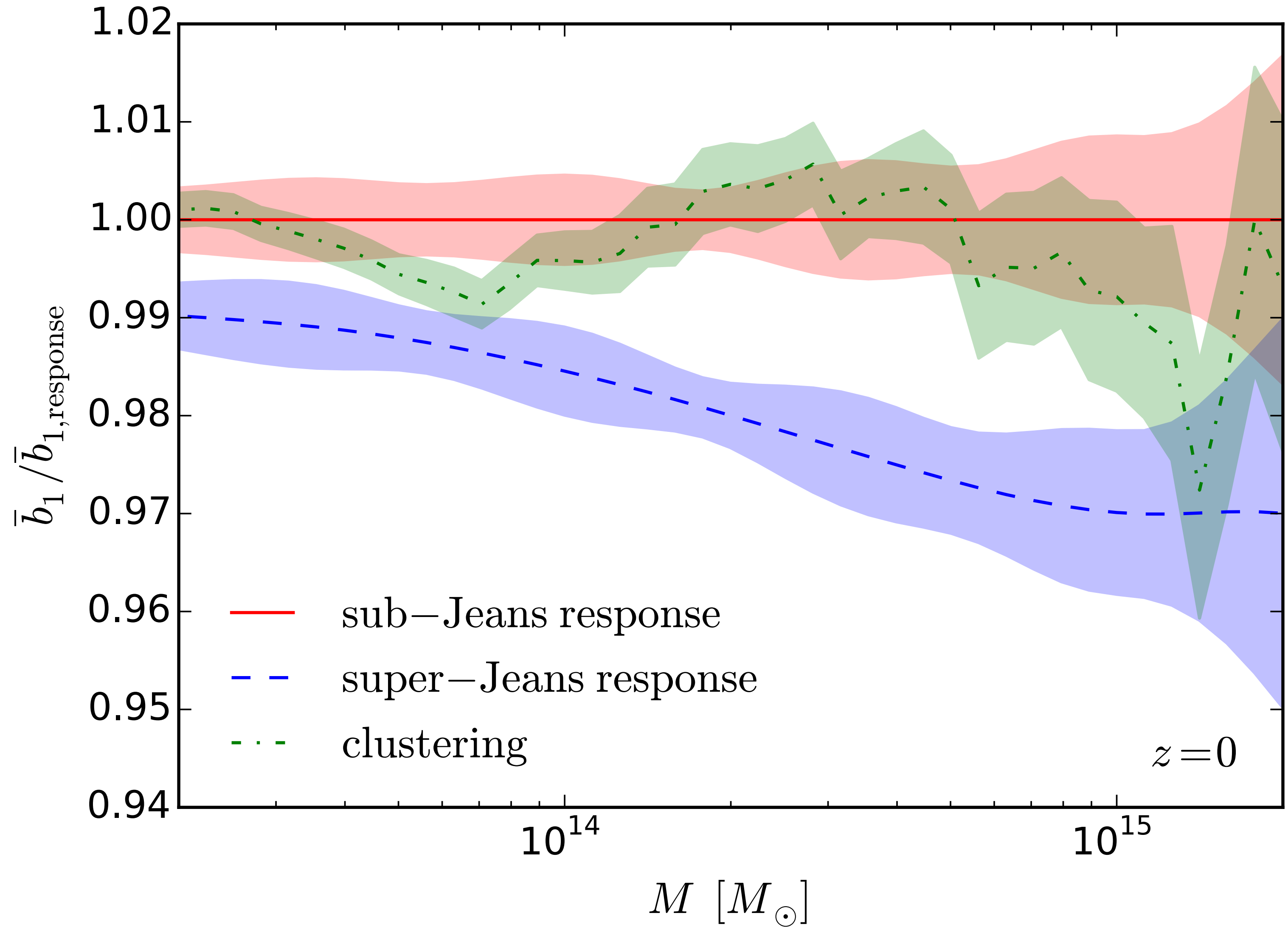

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Comparison to the transfer function bias