Nonlinear velocity statistics and redshift-space distortions in peculiar velocity surveys

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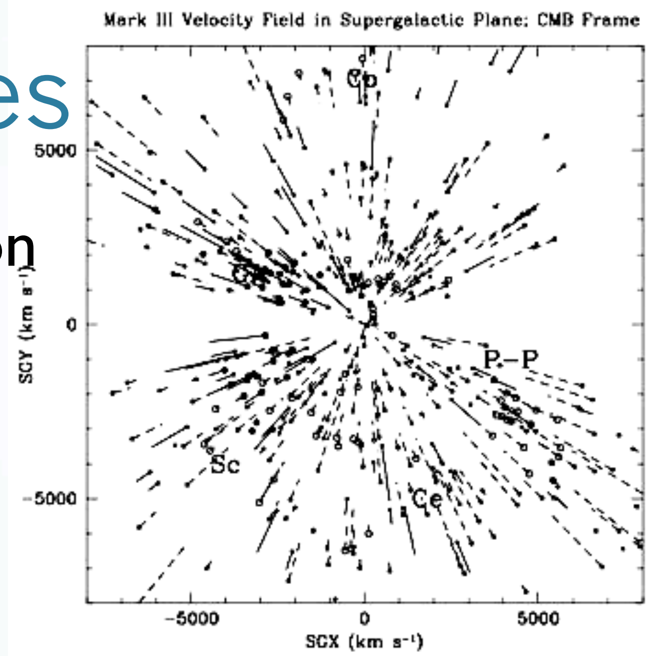
Okumura, Seljak, Vlah, Desjacques, (2014) JCAP accepted (arXiv:1312.4214)

Peculiar velocities of galaxies



- Contains information of 3D mass distribution

Distance to galaxies through spectroscopy

$$z = H_0 x + v_{//}$$

Radial peculiar velocity

Redshift (redshift space)

True distance (real space)

- It's hard to measure peculiar velocities themselves, but by measuring power spectrum in galaxy surveys the effect of peculiar velocities shows up as anisotropy (Redshift-sapce distortions)

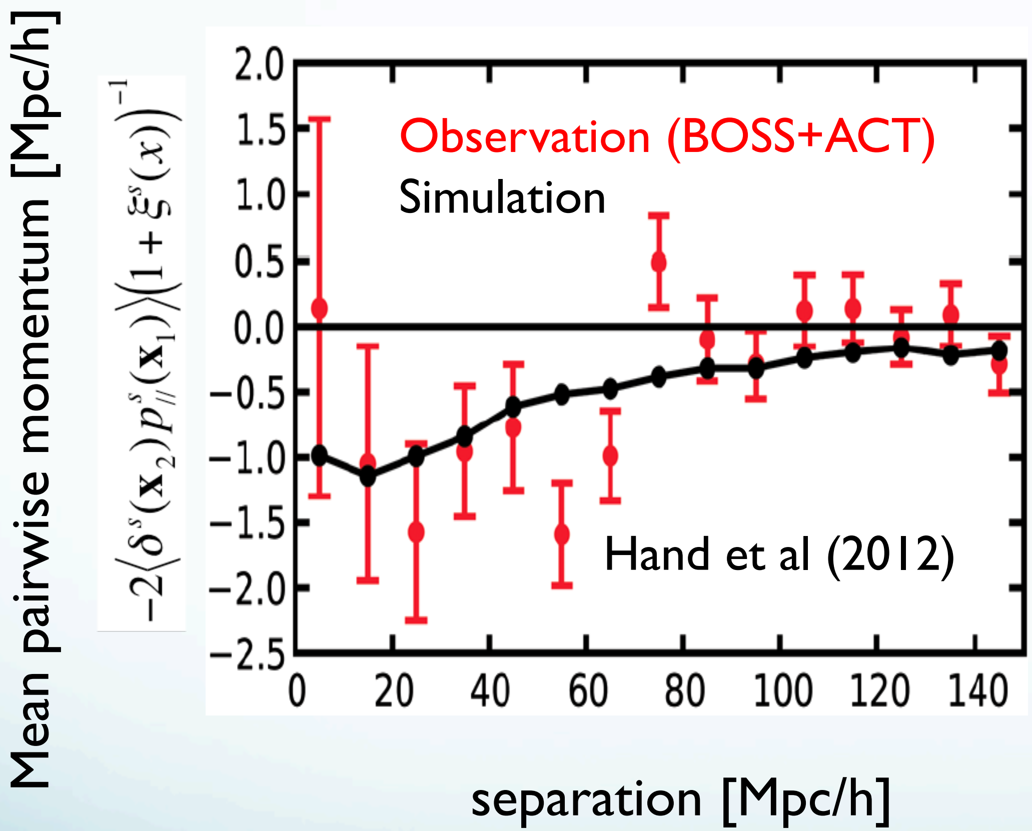
Formula of galaxy power spectrum in linear thoery (Kaiser)

$$P_g^s(k,\mu) = (b + f\mu^2)^2 P_m^r(k)$$

Anisotropy due to RSD (μ: direction cosine between wavevector and LoS)

- Theoretical modeling of redshift-space density power spectrum has been extensively studies as an observable.

Direct measurement of peculiar velocities: kinetic Sunyaev-Zeld'vich (kSZ)

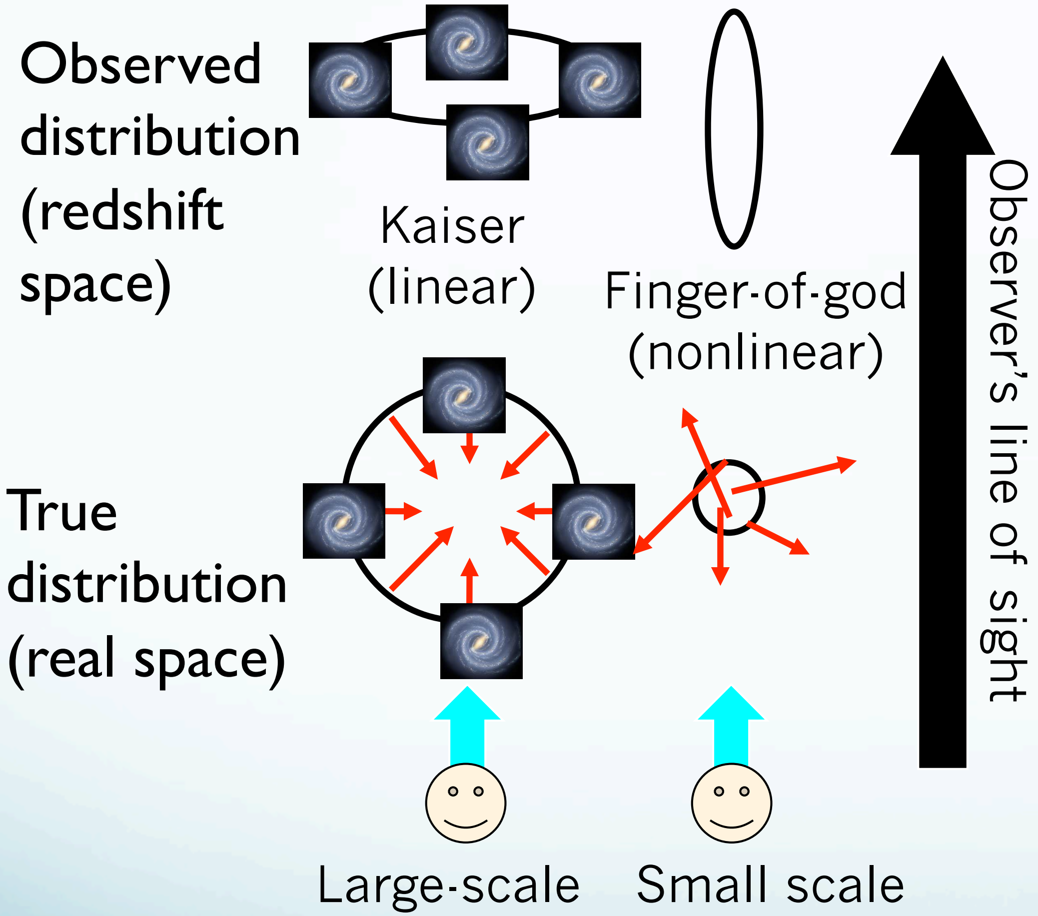


- By combining a galaxy survey (BOSS) and a CMB map (ACT), measured the distortion of the CMB spectrum along the line of observed clusters of galaxies (kSZ effect) and determined peculiar velociteis
- Observables are momentum field sampled in redshift-space positions of galaxies, thus affected by (nonlinear) RSD.
- However, such a formulation has been made so far only by linear theory in Fourier space (thus simply Kaiser).

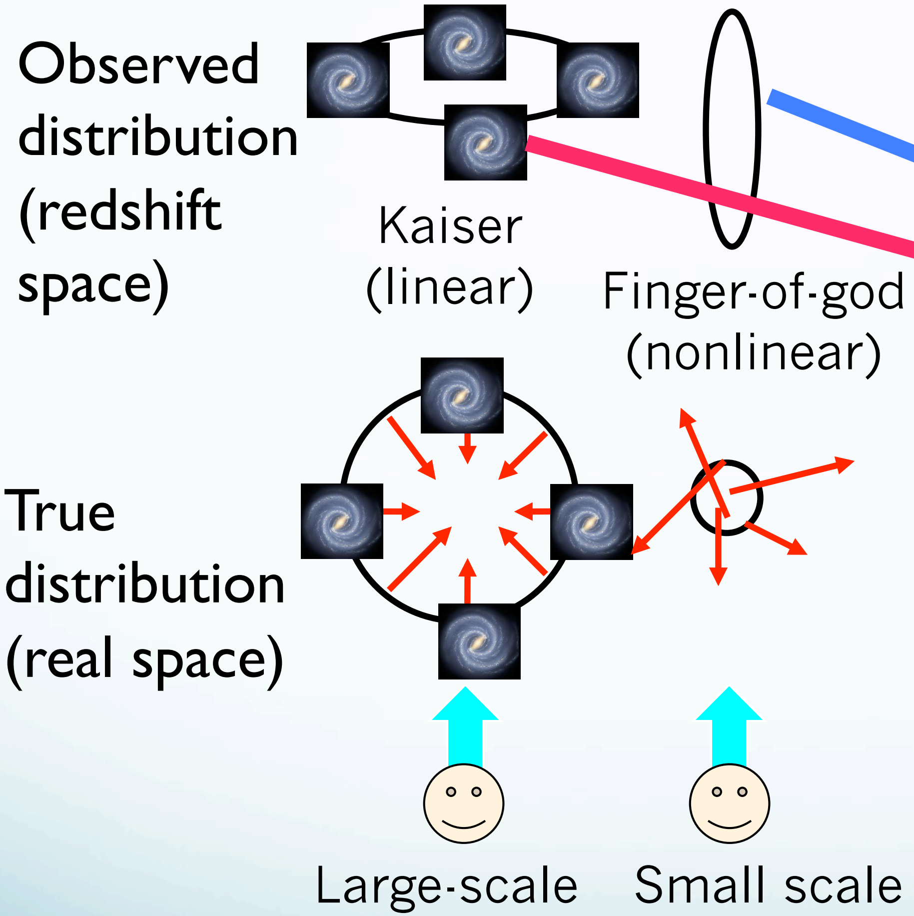
Purpose and conclusion of this study

- We define the momentum field in redshift space, and derive formulae for peculiar velocity statistics that include nonlinear RSD.
- We compute the statistics using Eulerinan 1-loop perturbation theory and linear theory.
- We compare them to the numerical results measured from N-body simulations.
- We find that N-body results cannot be explained by linear theory even in very large scales, while our nonlinear PT improves the accuracy.
  - reference :
  - *Okumura, Seljak, Vlah, Desjacques, (2014) JCAP (arXiv:1312.4214)*

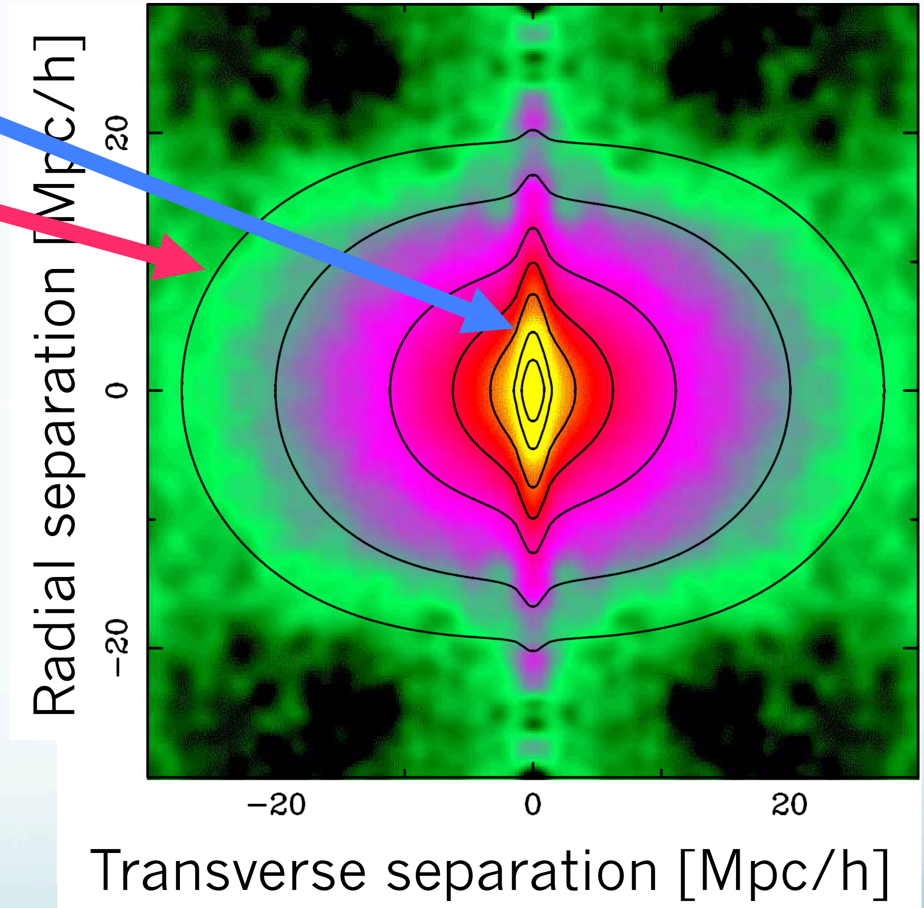
Redshift-space distortions (RSD)



Redshift-space distortions (RSD)



2-pt correlation function of galaxies from survey (Peacock et al., 2001 Nature)



Linear power spectrum + FOG damping

$$P_g^s(k,\mu) = (b + f\mu^2)^2 P_m^r(k) \times \exp(-k^2\mu^2\sigma_v^2)$$

Redshift-space power spectrum using phase-space distribution function

- RSD is defined in phase space *f*(**x**,**p**) starting from Vlasov equation

$$\vec{s} = \vec{x} + \hat{z}v_{//}/aH = \vec{x} + \hat{z}\,p_{//}/a^2 mH$$

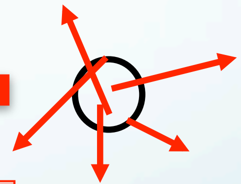
Distortions due to radial momentum (~10Mpc/h)

- Redshfit-space density field is described by real-space one + infinite sum of moments of mass-weighted velocities

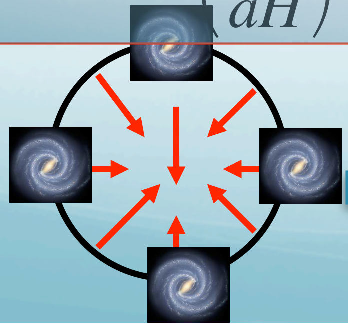
$$\delta^s(\mathbf{k}) = \delta^r(k) + \sum_{L=1} \frac{1}{L!}\left(\frac{ik_{//}}{aH}\right) T^L_{//}(\mathbf{k})$$ where $$T^L_{//}(\mathbf{x}) = \frac{m}{\bar{\rho}a^3}\int d^3p\, f(\mathbf{x},\mathbf{p})\left(\frac{p_{//}}{am}\right)^L = [1+\delta(\mathbf{x})]u^L(\mathbf{x})$$

- Power spectrum becomes an infinite sum as well.

$$\langle \delta^s(\mathbf{k})\delta^s(\mathbf{k}')\rangle = (2\pi)^3 P^s(\mathbf{k})\delta^D(\mathbf{k}-\mathbf{k}')$$



$$P^s(\mathbf{k}) = P_{00}(\mathbf{k}) - 2i\left(\frac{k\mu}{aH}\right)P_{01}(\mathbf{k}) + \left(\frac{k\mu}{aH}\right)^2 P_{11}(\mathbf{k}) - \left(\frac{k\mu}{aH}\right)^2 P_{02}(\mathbf{k}) + \ldots$$



Seljak & McDonald (2011) JCAP (paper I)
***Okumura**, Seljak, McDonald, Desjacques (2012a) JCAP (II)*
***Okumura**, Seljak, Desjacques (2012,b) JCAP (III)*
*Vlah, Seljak, McDonald, **Okumura**, Baldauf (2012) JCAP (IV)*
*Vlah, Seljak, **Okumura**, Desjacques (2013) JCAP (V)*

Extension to redshift-space momentum

$$\vec{s} = \vec{x} + \hat{z} v_{//}/aH = \vec{x} + \hat{z}\, p_{//}/a^2 mH$$

Distortions due to radial peculiar velocities (~10Mpc/h)

- Derivation for density field can be applied to momentum

$$\delta^s(\mathbf{k}) = \delta^r(k) + \sum_{L=1} \frac{1}{L!}\left(\frac{ik\mu}{aH}\right) T^L_{//}(\mathbf{k})$$

where

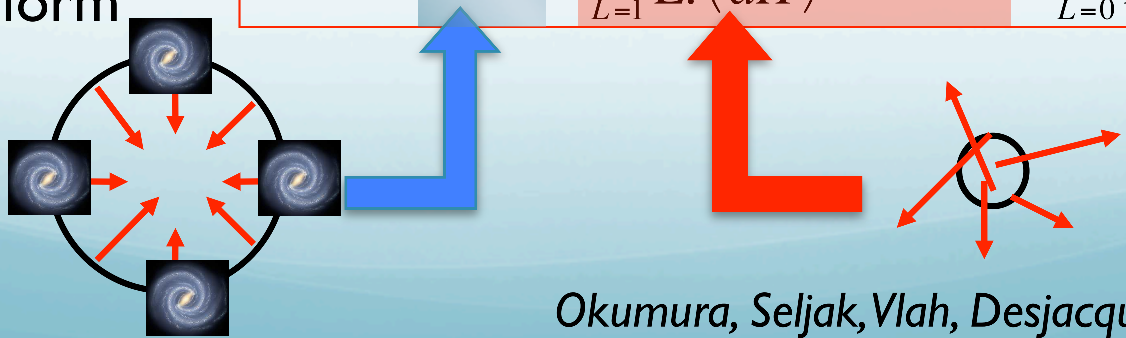
$$T^L_{//}(\mathbf{x}) = \left[1 + \delta(\mathbf{x})\right] u^L(\mathbf{x})$$

- Redshift-space momentum field can also be described by a sum over real-space velocity moments.

$$p^s_{//}(\mathbf{x}) = \left[1 + \delta^s(\mathbf{x})\right] v^s_{//}(\mathbf{x})$$

→ Fourier transform

$$p^s_{//}(\mathbf{k}) = p_{//}(\mathbf{k}) + \sum_{L=1} \frac{1}{L!}\left(\frac{ik\mu}{aH}\right)^L T^{L+1}_{//}(\mathbf{k}) = \sum_{L=0} \frac{1}{L!}\left(\frac{ik\mu}{aH}\right)^L T^{L+1}_{//}(\mathbf{k})$$



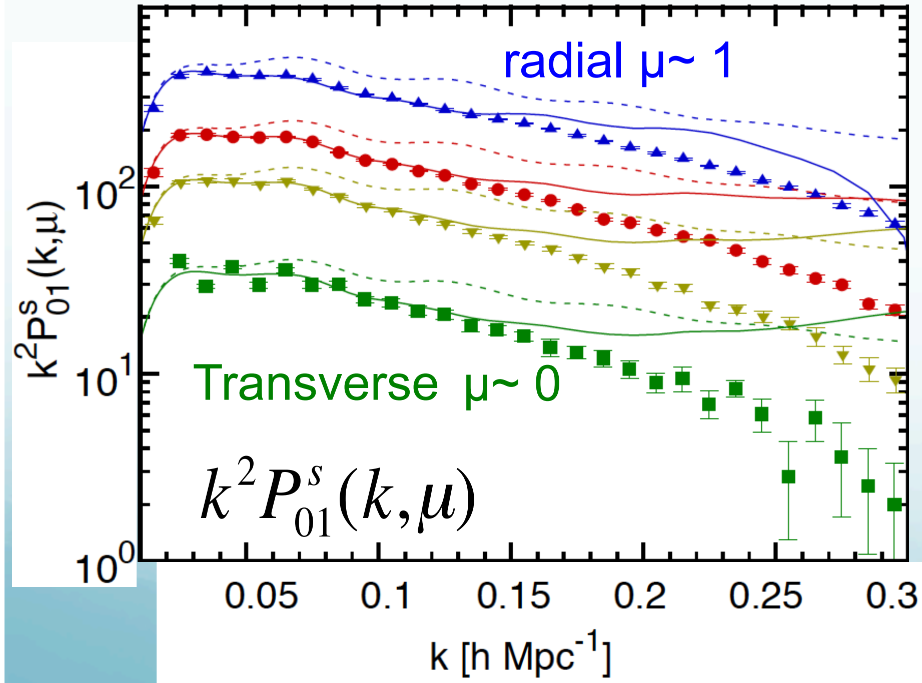
Okumura, Seljak, Vlah, Desjacques (arXiv:1312.4214)

Expression for density-momentum power

$$\left\langle \delta^s(\mathbf{k}) p_{//}^{s*}(\mathbf{k}') \right\rangle = (2\pi)^3 P_{01}^s(\mathbf{k}) \delta^D(\mathbf{k}-\mathbf{k}')$$

$$-i\frac{k\mu}{\mathcal{H}}P_{01}^s(\mathbf{k}) = -i\frac{k\mu}{\mathcal{H}}P_{01}^r(\mathbf{k}) + \left(\frac{k\mu}{\mathcal{H}}\right)^2 P_{11}^r(\mathbf{k}) - \left(\frac{k\mu}{\mathcal{H}}\right)^2 P_{02}^r(\mathbf{k}) + \frac{i}{2}\left(\frac{k\mu}{\mathcal{H}}\right)^3 P_{03}^r(\mathbf{k})$$
$$-2i\left(\frac{k\mu}{\mathcal{H}}\right)^3 P_{12}^r(\mathbf{k}) + \frac{1}{6}\left(\frac{k\mu}{\mathcal{H}}\right)^4 P_{04}^r(\mathbf{k}) - \left(\frac{k\mu}{\mathcal{H}}\right)^4 P_{13}^r(\mathbf{k}) + \frac{1}{2}\left(\frac{k\mu}{\mathcal{H}}\right)^4 P_{22}^r(\mathbf{k})$$

Halos at z=0.5 (*b* ~ 1.6)

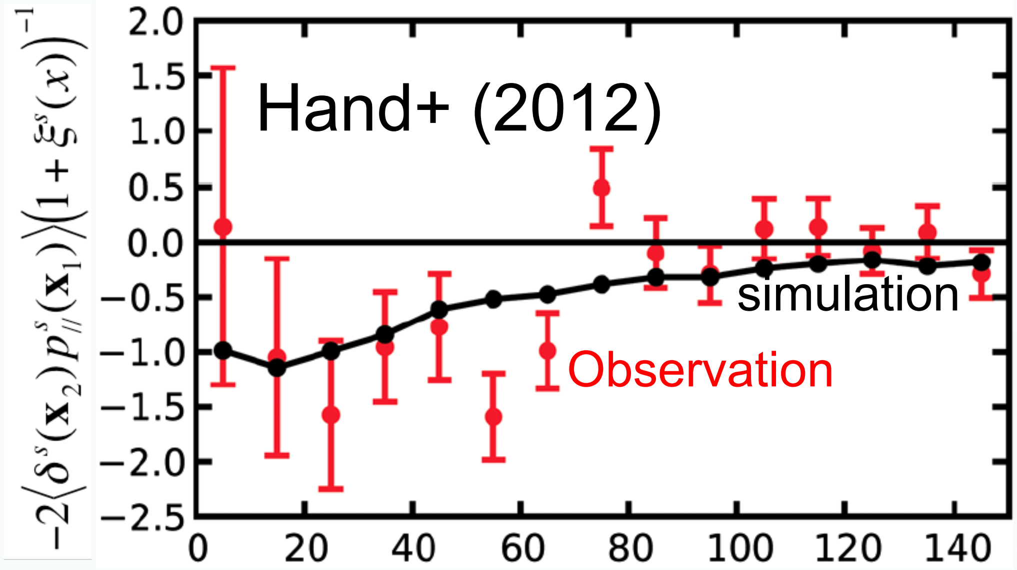


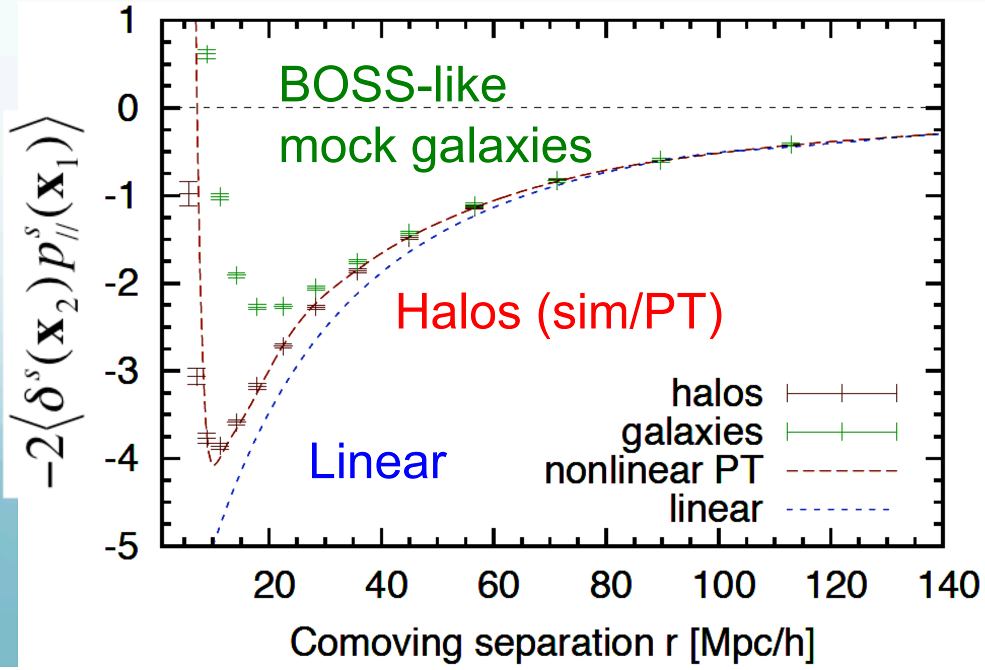
- Data points are simulation results
- Dotted lines are linear theory (Kaiser)

$$P_{01}^s(k,\mu) = (if\mu/k)(b + f\mu^2)P_m(k)$$

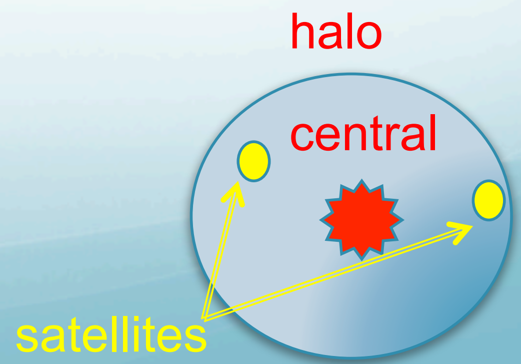
- Solid lines are 1-loop PT + non-local bias + DM spectrum from sim
- Suppression starting at large scales is nonlinear velocity dispersion (RSD)
- No free parameter for RSD

Redshift-space pairwise infall momentum





- $-2\langle \delta^s(\mathbf{x}_2) p^s_{//}(\mathbf{x}_1) \rangle$: Fourier tr of P_{01}
- Transition of sign seen in observed data on small scales is caused by nonlinear RSD.
- PT well explains the halo results.
- Finger-of-god for satellites needs to be taken into account.

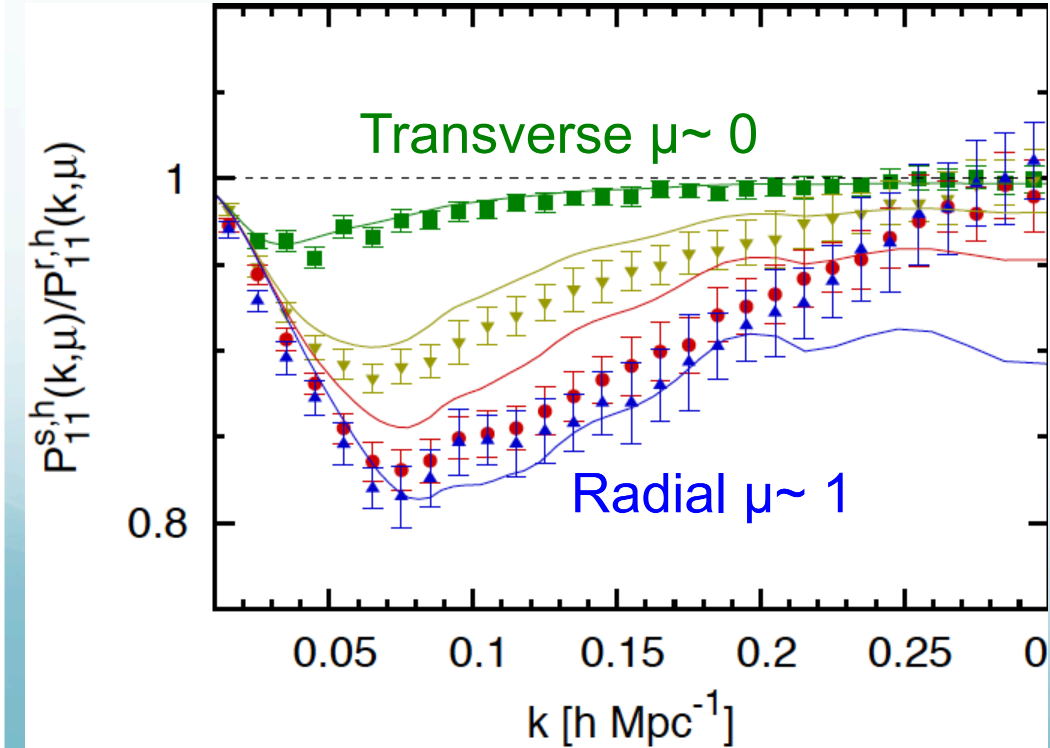


Momentum-momentum power spectrum

$$\left\langle p_{//}^{s}(\mathbf{k}) p_{//}^{s*}(\mathbf{k}') \right\rangle = (2\pi)^3 P_{11}^{s}(\mathbf{k}) \delta^{D}(\mathbf{k}-\mathbf{k}')$$

$$\left(\frac{k\mu}{\mathcal{H}}\right)^2 P_{11}^s(\mathbf{k}) = \left(\frac{k\mu}{\mathcal{H}}\right)^2 P_{11}^r(\mathbf{k}) - 2i\left(\frac{k\mu}{\mathcal{H}}\right)^3 P_{12}^r(\mathbf{k}) - \left(\frac{k\mu}{\mathcal{H}}\right)^4 P_{13}^r(\mathbf{k}) + \left(\frac{k\mu}{\mathcal{H}}\right)^4 P_{22}^r(\mathbf{k})$$

Ratio of redshift space and real space for halos P_{11}^s/P_{11}^r



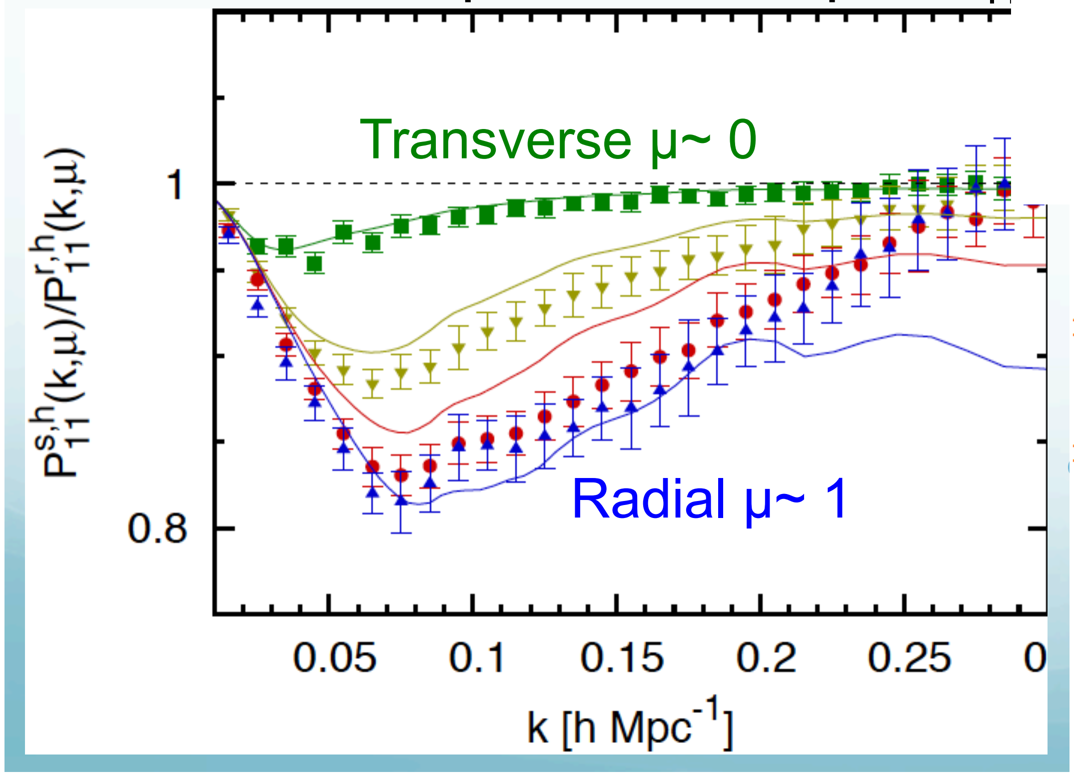
- Unity in linear theory
- Deviation from unity is entirely due to nonlienar RSD (~20%)
- Affected by shot noise

Momentum-momentum power spectrum

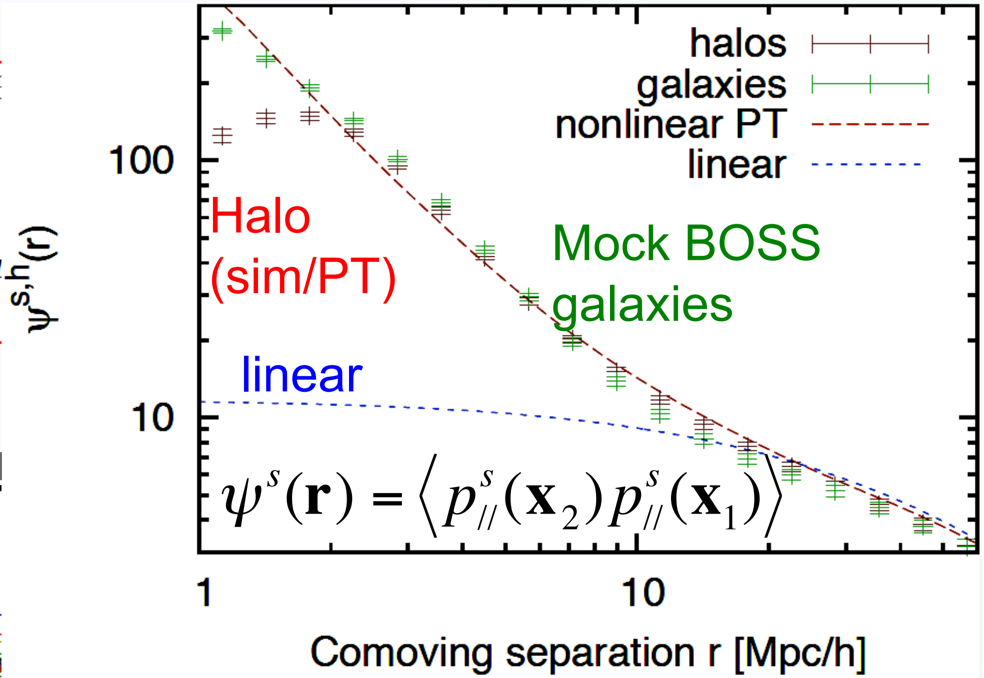
$$\left\langle p^s_{//}(\mathbf{k})\, p^{s*}_{//}(\mathbf{k}')\right\rangle = (2\pi)^3 P^s_{11}(\mathbf{k})\,\delta^D(\mathbf{k}-\mathbf{k}')$$

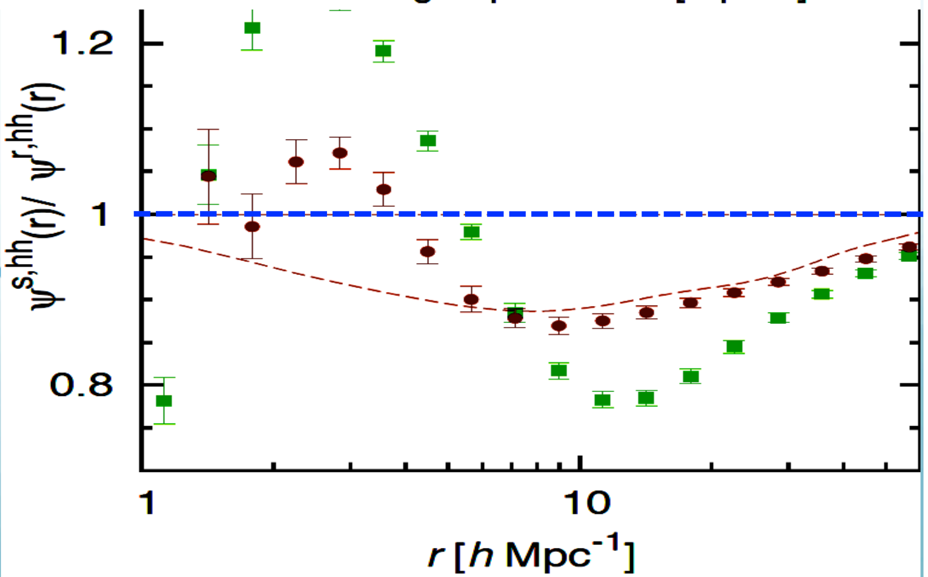
$$\left(\frac{k\mu}{\mathcal{H}}\right)^2 P^s_{11}(\mathbf{k}) = \left(\frac{k\mu}{\mathcal{H}}\right)^2 P^r_{11}(\mathbf{k}) - 2i\left(\frac{k\mu}{\mathcal{H}}\right)^3 \ldots - \left(\frac{k\mu}{\mathcal{H}}\right)^4 P^r_{13}(\mathbf{k}) + \left(\frac{k\mu}{\mathcal{H}}\right)^4 P \ldots$$

Ratio of redshift space and real space P_{11}



Momentum correlation function





Conclusions

- Observables from kSZ survey is momentum field (not velocity field) in redshift-space.
- Expressions for velocity statistics in redshift space were derived.
- Power spectra were computed based on 1-loop nonlinear PT and compared to N-body results for halos/dark matter.
- Linear theory does not work even at very large scales.
- See *Okumura, Seljak, Vlah & Desjacques, (arXiv:1312.4214)* for the detail

To improve precision

- Better understanding for shot noise is required for momentum auto power spectrum P_{11}
- We have a good model for halos, but not yet for galaxies (1halo term, Finger-of-God, halo models, etc).