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

Kavli IPMU ACP seminar
Feb. 13, 2014

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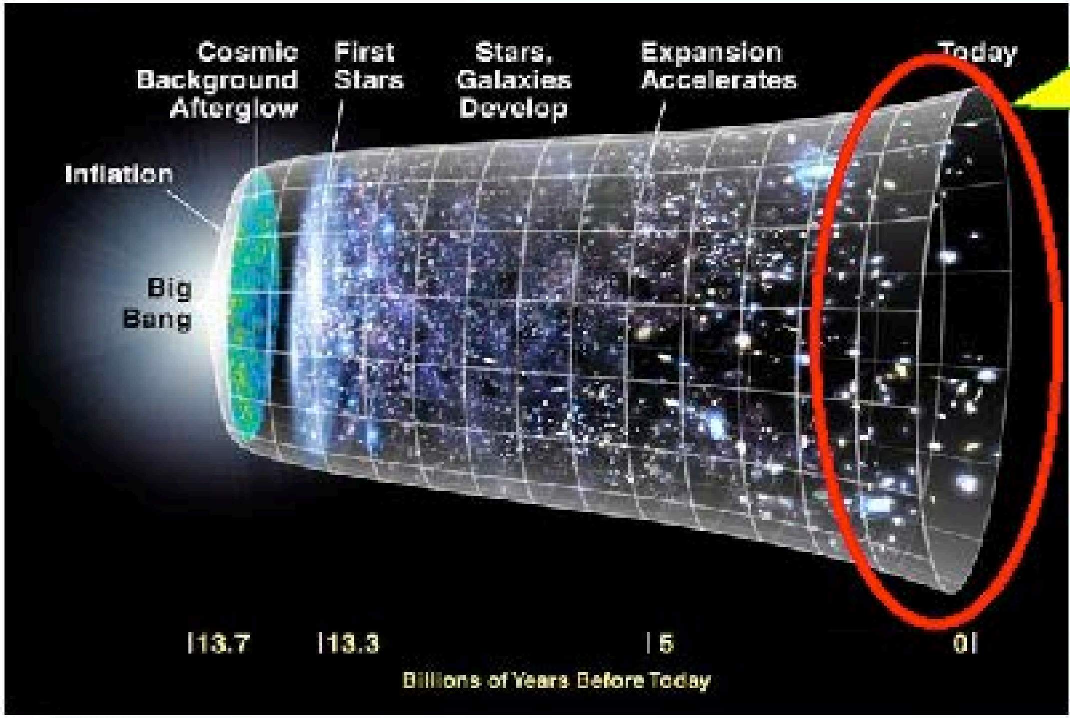
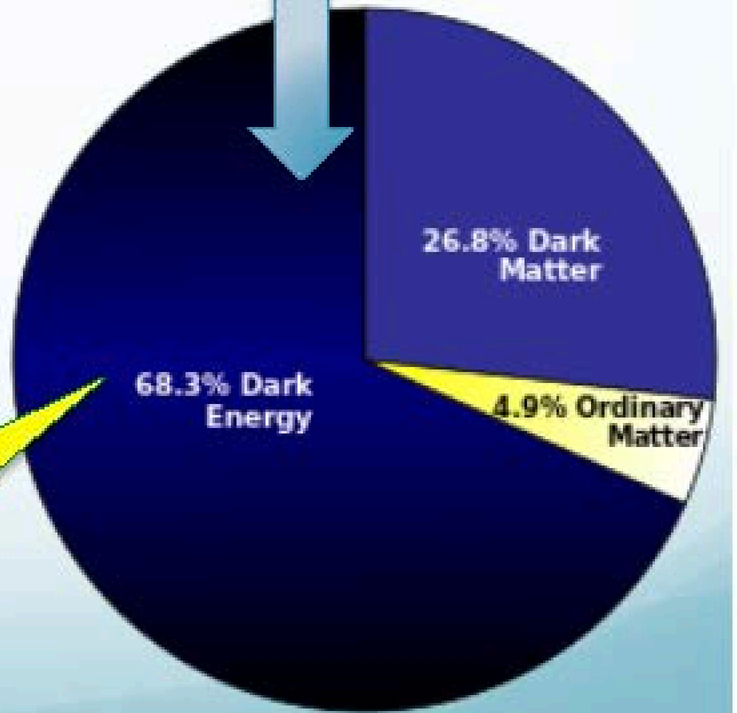
Outline of this talk

- Introduction
  - Dark energy and Galaxy redshift surveys
  - Redshift-space distortions (RSD)
  - Nonlinearity issues of galaxy clustering
- Galaxy redshift surveys
  - Theoretical modeling of nonlinear power spectrum using distribution function approach
    - Okumura, Seljak, McDonald, Desjacques (2012) JCAP
    - Okumura, Seljak, Desjacques (2013) JCAP
    - Vlah, Seljak, McDonald, Okumura, Baldauf (2013) JCAP
    - Vlah, Seljak, Okumura, Desjacques (2013) JCAP
- Peculiar velocity surveys
  - Theoretical modeling of nonlinear velocity statistics by extending the distribution function approach
    - Okumura, Seljak, Vlah, Desjacques (2013) arXiv:1312.4214

Evolution of the expanding Universe



Discovery of acceleration of the cosmic expansion in year 1998
→ 2011 Nobel prize in physics



Energy contents of the Universe today

Important not only for cosmology but also fundamental physics! But currently astronomical observation is only the way to probe it.

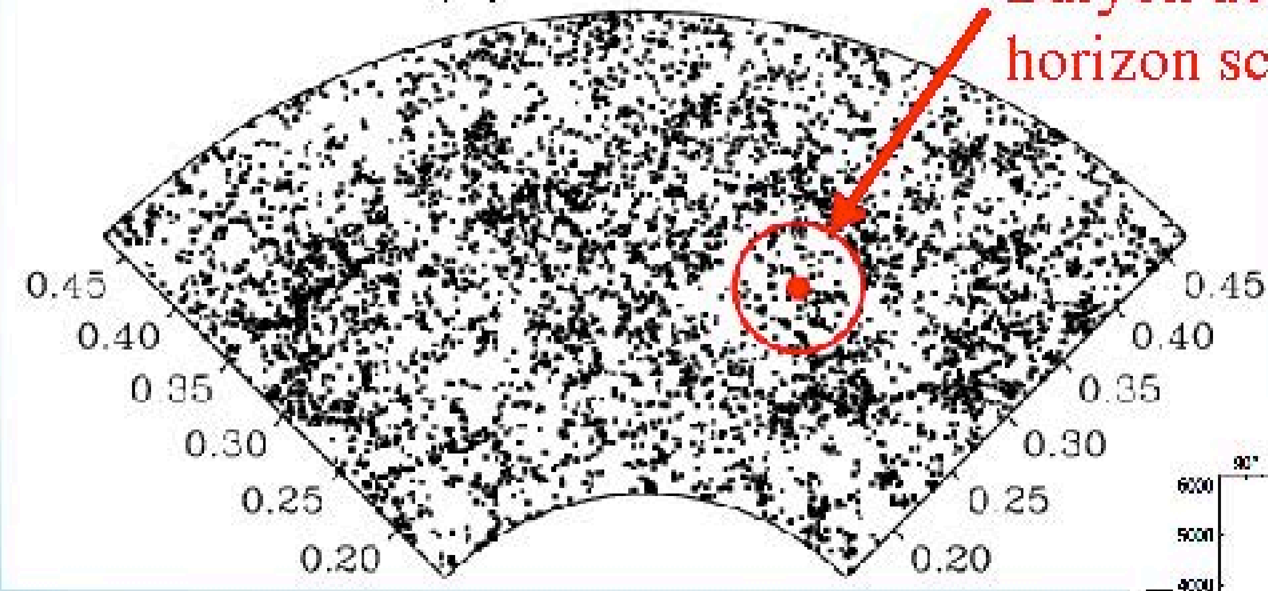
Large-scale structure of the Universe as a probe of dark energy

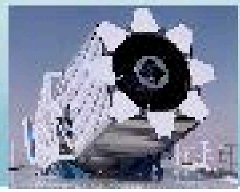
- Galaxy redshift (spectroscopic) survey

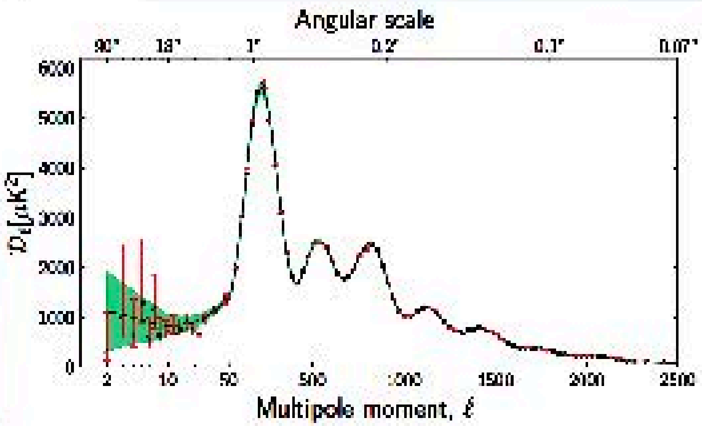
$$H(z) = H_0\sqrt{(1+z)^3\Omega_m + (1+z)^{3(1+w)}\Omega_{DE}}$$

$$D_A(z) = (1+z)^{-1}\int_0^z \frac{dz'}{H(z')}$$

Baryon acoustic scale = sound horizon scale at decoupling





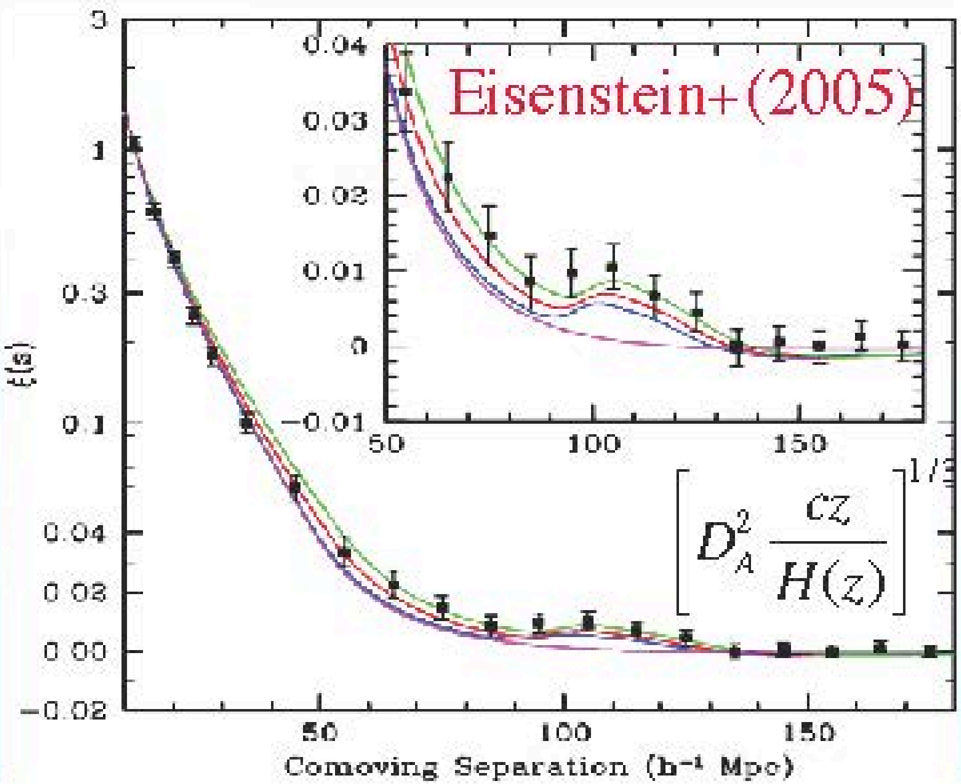


Baryon acoustic oscillations (BAO) in the Large-scale Structure

- BAO feature is imprinted at the characteristic scale in nearby galaxy distribution

Monopole correlation function

$$dP = \bar{n}^2 \left[1 + \underline{\xi(s)} \right] dV_1 dV_2$$



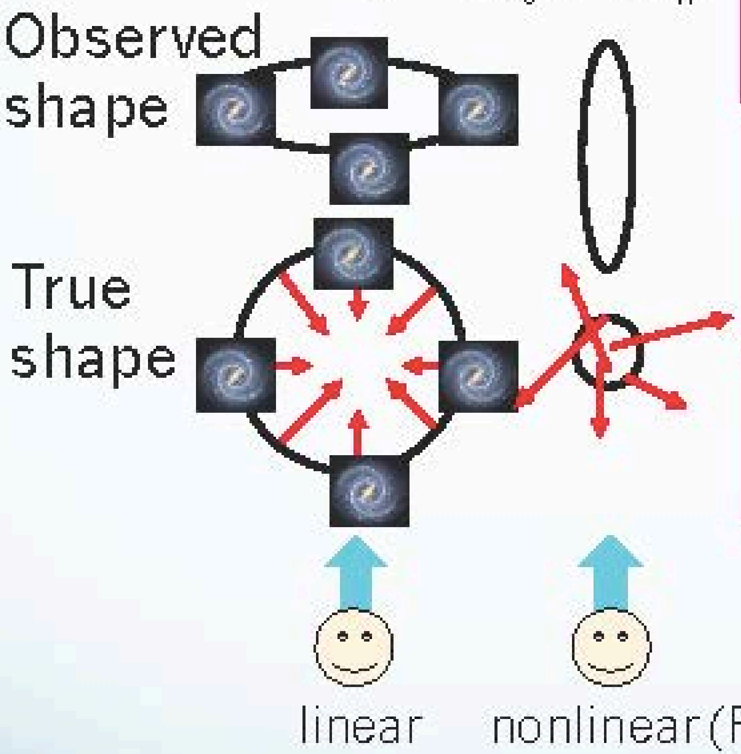
$$H(z) = H_0 \sqrt{(1+z)^3 \Omega_m + (1+z)^{3(1+w)} \Omega_{DE}}$$

$$D_A(z) = (1+z)^{-1} \int_0^z \frac{dz'}{H(z')}$$

Redshift space distortions (RSD)

- Redshift contains radial velocity information

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



Isotropic in real space $\delta_g^r(k) = b\delta_m^r(k)$

Anisotropy in redshift space $\delta_g^s(k,\mu) = (b + f\mu^2)\delta_m^r(k)$

$$f(a) = d\ln D / d\ln a = \Omega_m^{0.55}$$

Linear power spectrum (Kaiser 1987)

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

Redshift space distortions (RSD)

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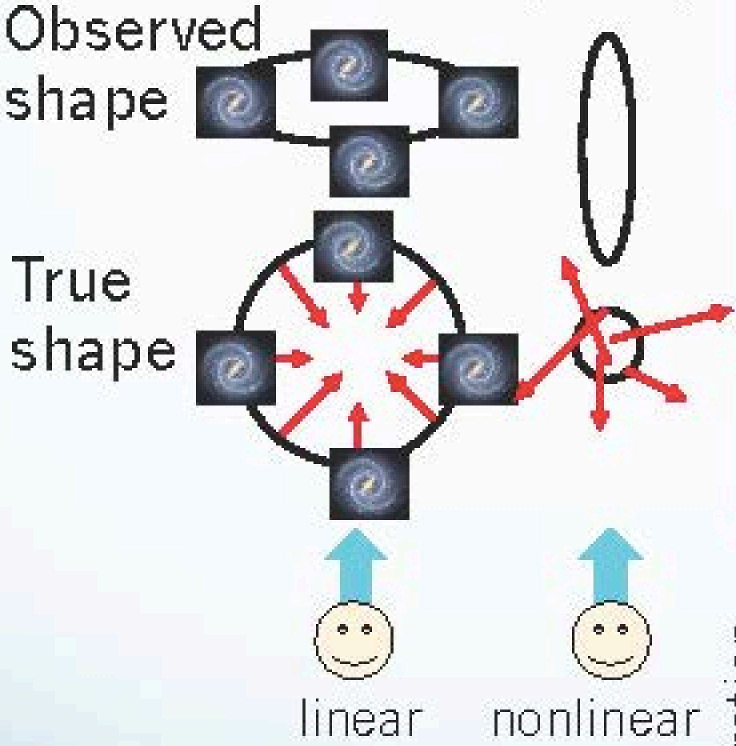

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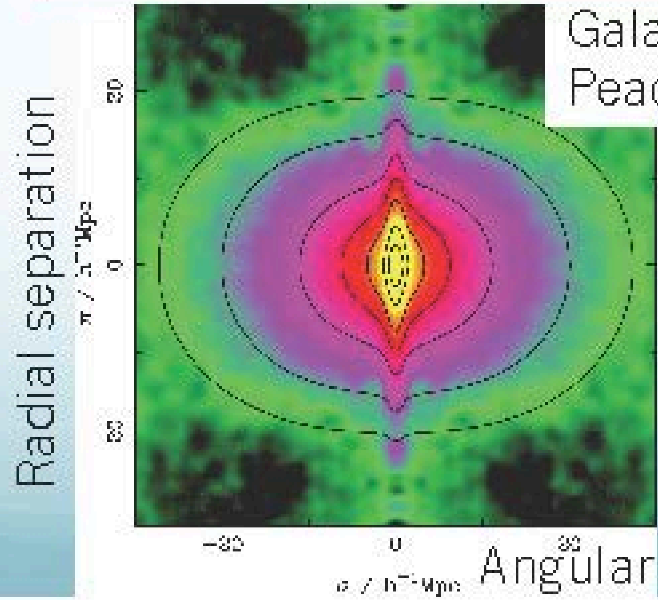
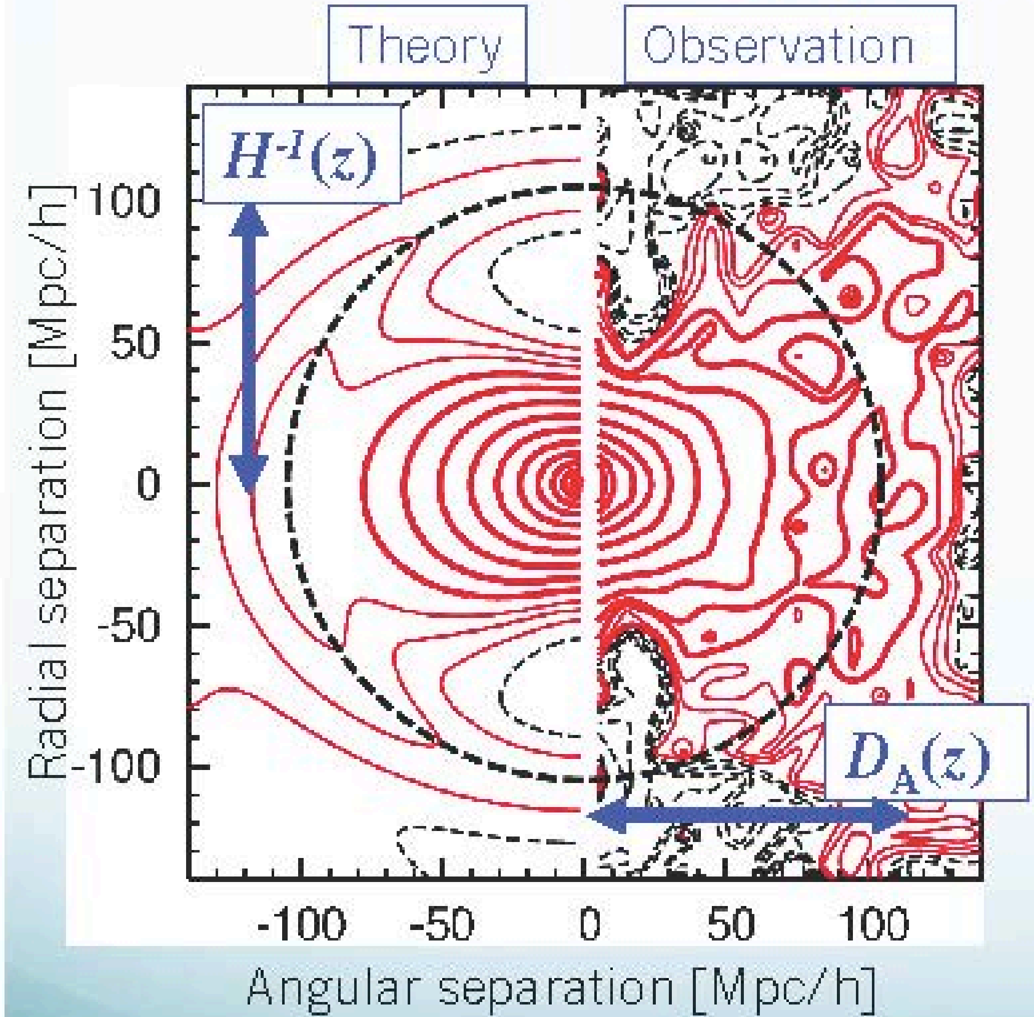


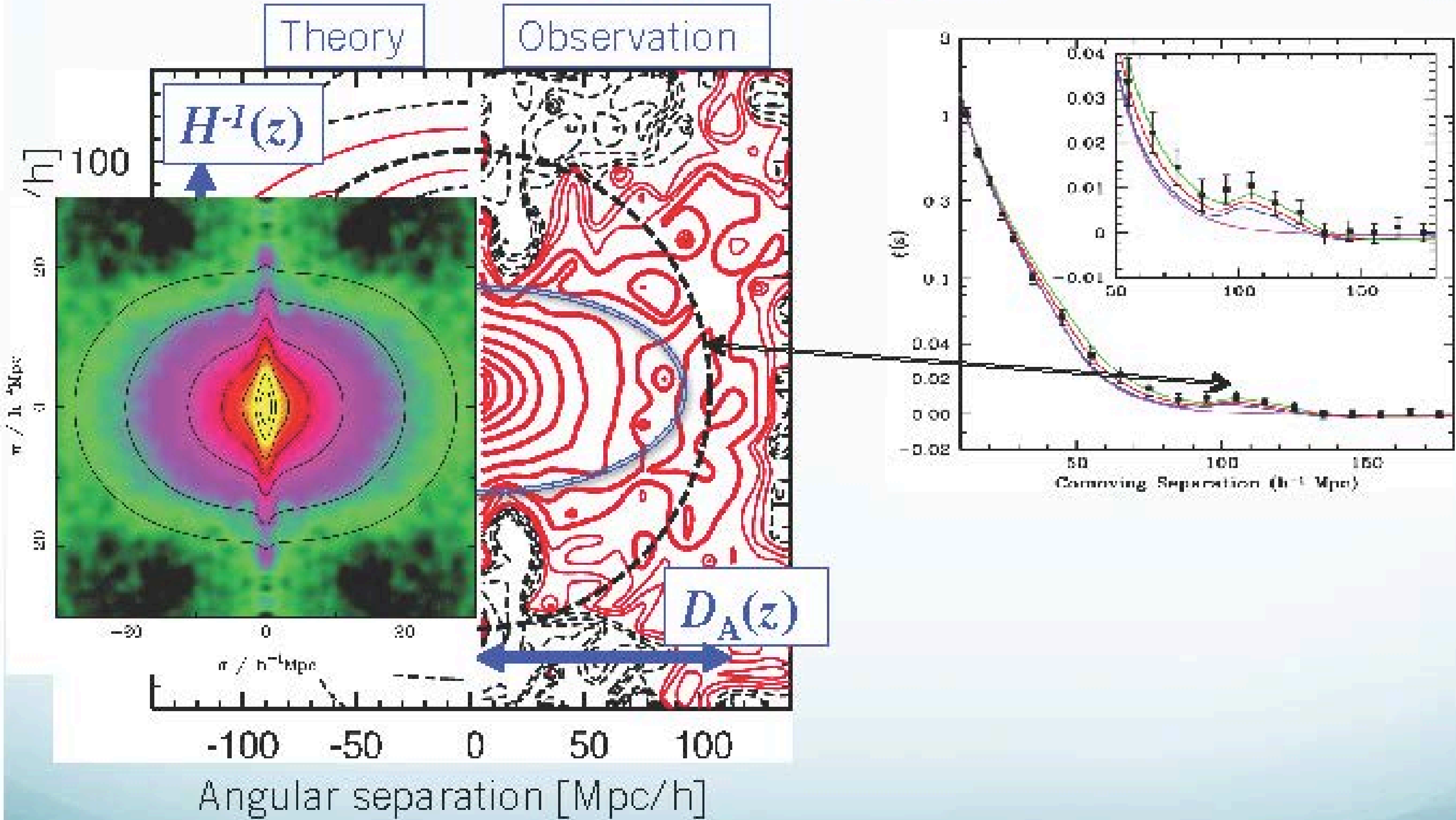
Galaxy correlation function
Peacock+(2001) Nature

Large-scale galaxy correlation function: BAO + RSD



Okumura, Matsubara, Eisenstein, Kayo, Hikage et al (2008)

Large-scale galaxy correlation function: BAO + RSD



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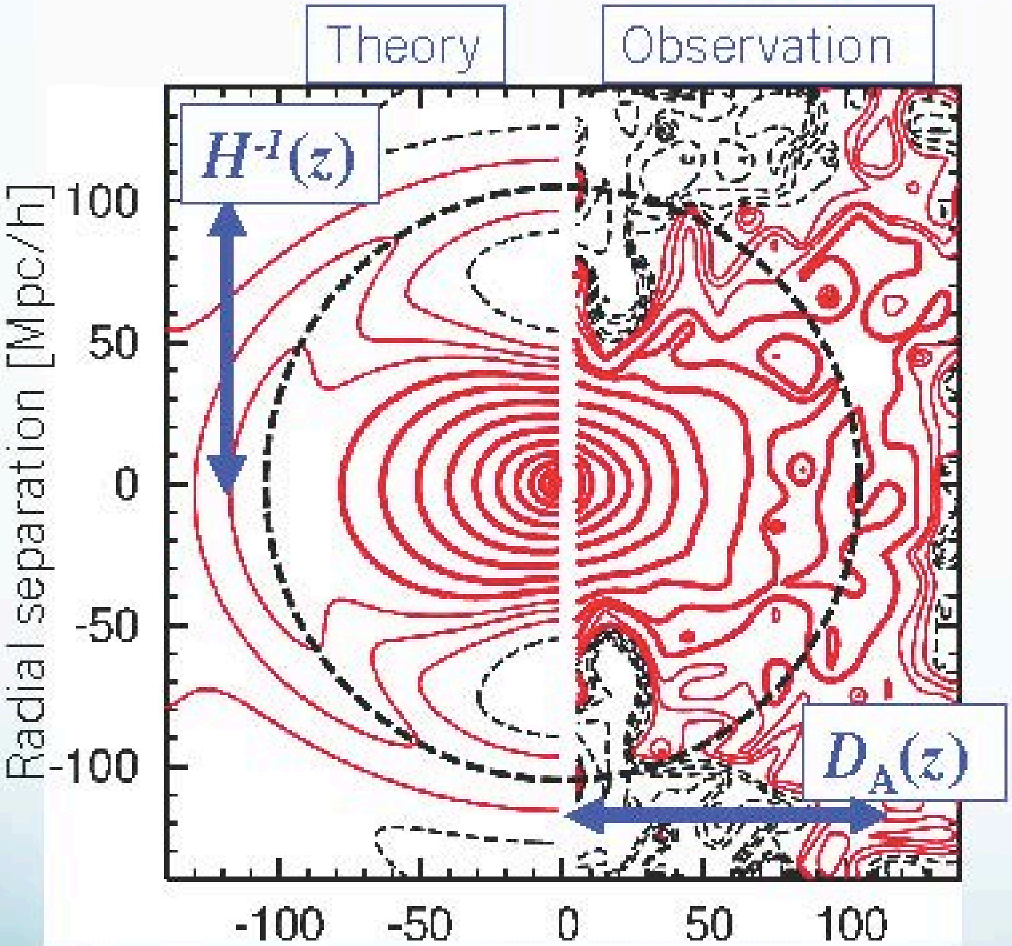
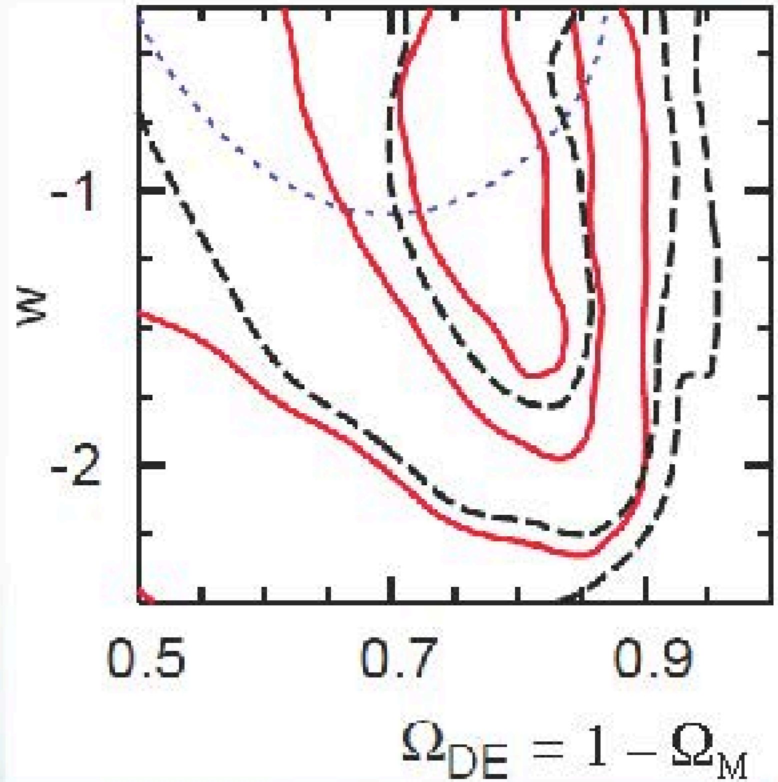
Large-scale galaxy correlation function: BAO + RSD



Dark energy constraints

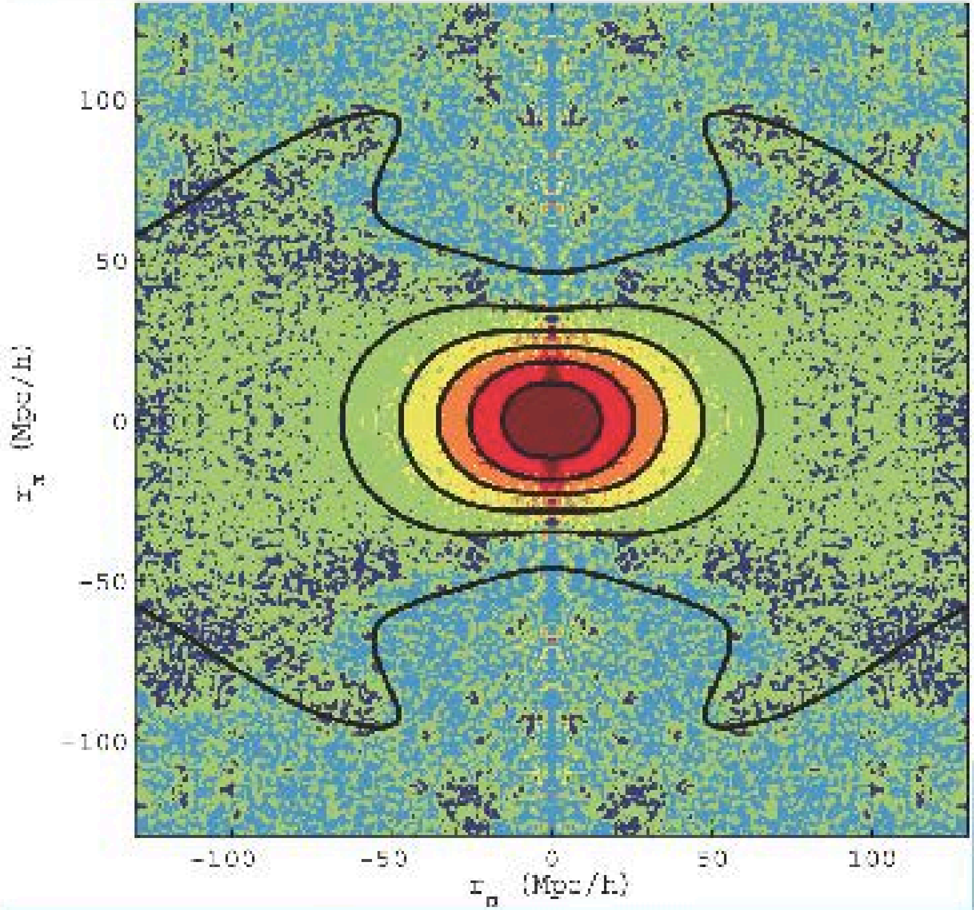


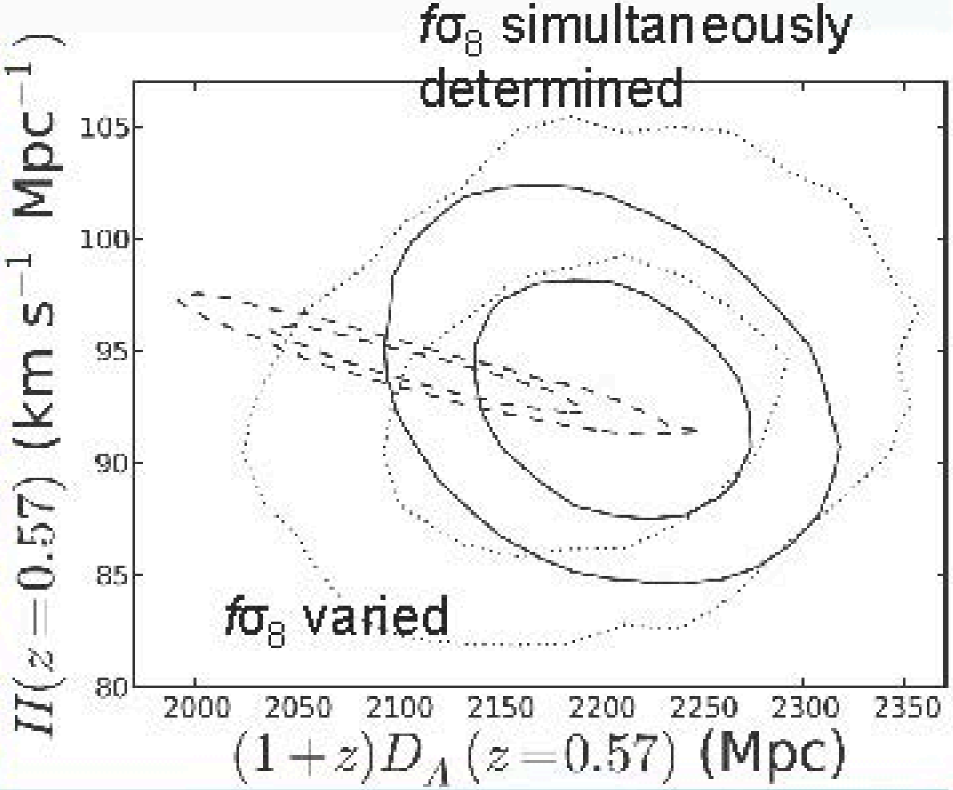
$w = -0.93 \pm 0.4$
→consistent with Einstein's cosmological constant $w = -1$

Okumura, Matsubara, Eisenstein, Kayo, Hikage et al (2008)

2D distance scales (H and D_A) well predicted

- Reid et al (2012) BOSS collaboration





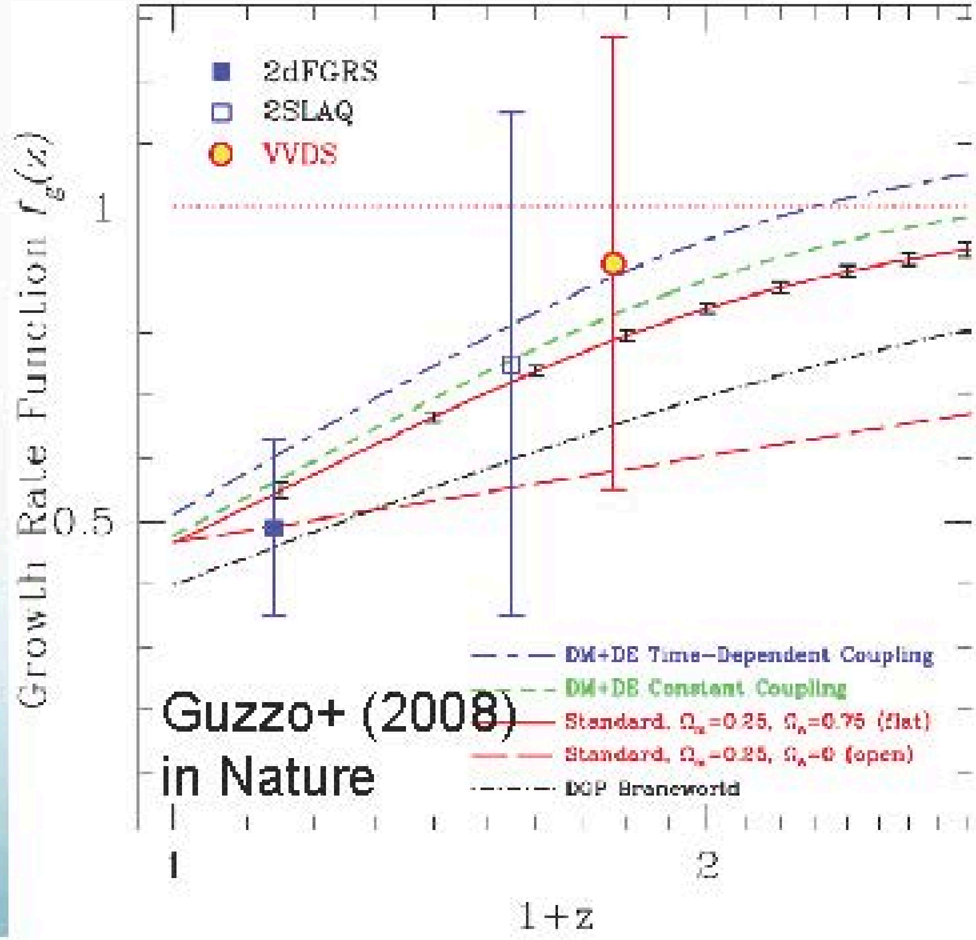
RSD for modified gravity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$P_g^s(k,\mu) = (b + f\mu^2)^2 P_m^r(k)$$
$$f(a) = d\ln D / d\ln a = \Omega_m^{0.55}$$

For GR+ΛCDM

Large error on f, but the result shows a possibility to distinguish among different gravity theories in future surveys.

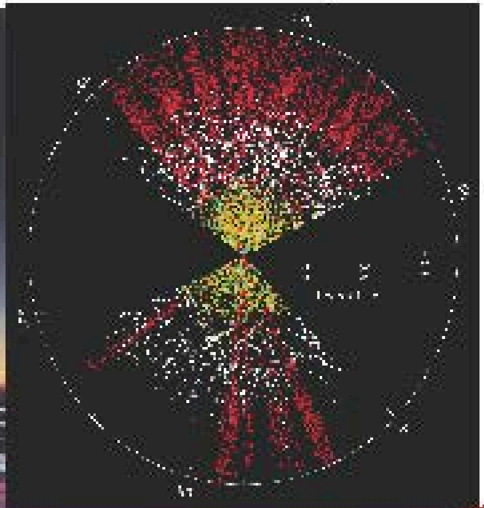


Galaxy redshift survey projects

- Galaxy surveys using shapes of the power spectrum, BAO, RSD are a promising tool to test dark energy properties.

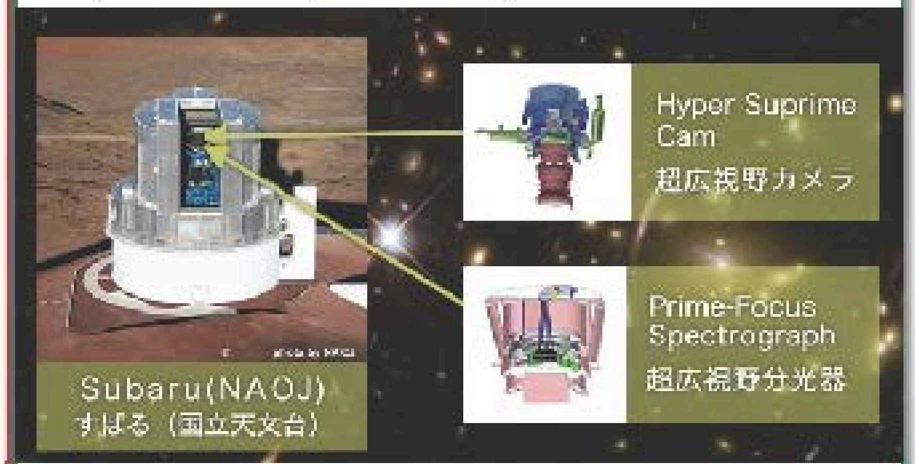
Ongoing

Sloan Digital Sky Survey III Baryon Oscillation Spectroscopic Survey (SDSS-III BOSS)



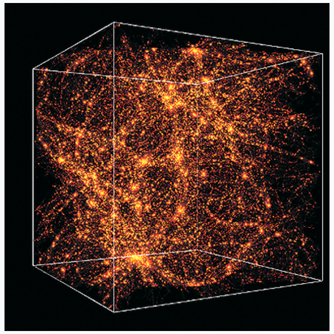
Future

Subaru Measurement of Images and Redshifts (SuMIRe) led by Kavli IPMU



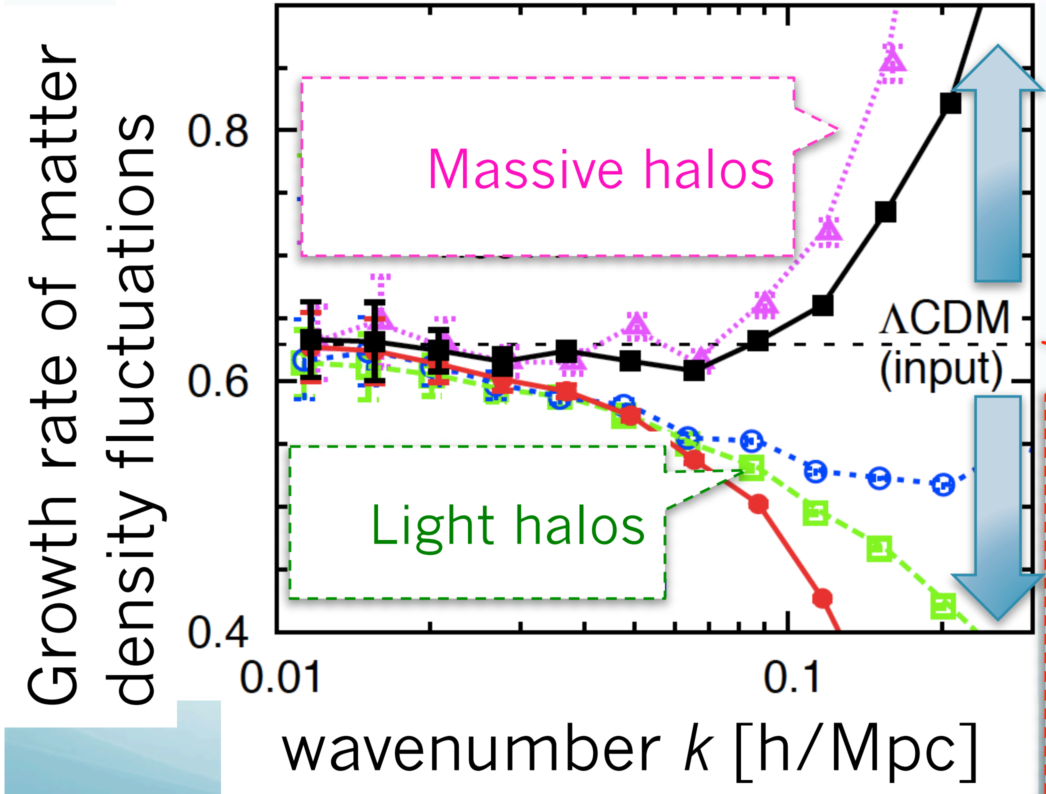
- eBOSS, HETDEX, Euclid, MS-DESI(DES+BigBOSS), and so on
- Eventually we want to constrain dark energy with 1% level

Issues on redshift-space distortions "nonlinearities"



Use computer simulations
→ true cosmology is known

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



Deviation from the true cosmology

Three important nonlinearities for precise theoretical model:
(1) Nonlinear clustering
(2) Nonlinear velocity dispersion
(3) Nonlinear bias relation between DM and galaxies

Okumura & Jing (2011)

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[redacted]

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  - Theoretical modeling of nonlinear power spectrum using distribution function approach
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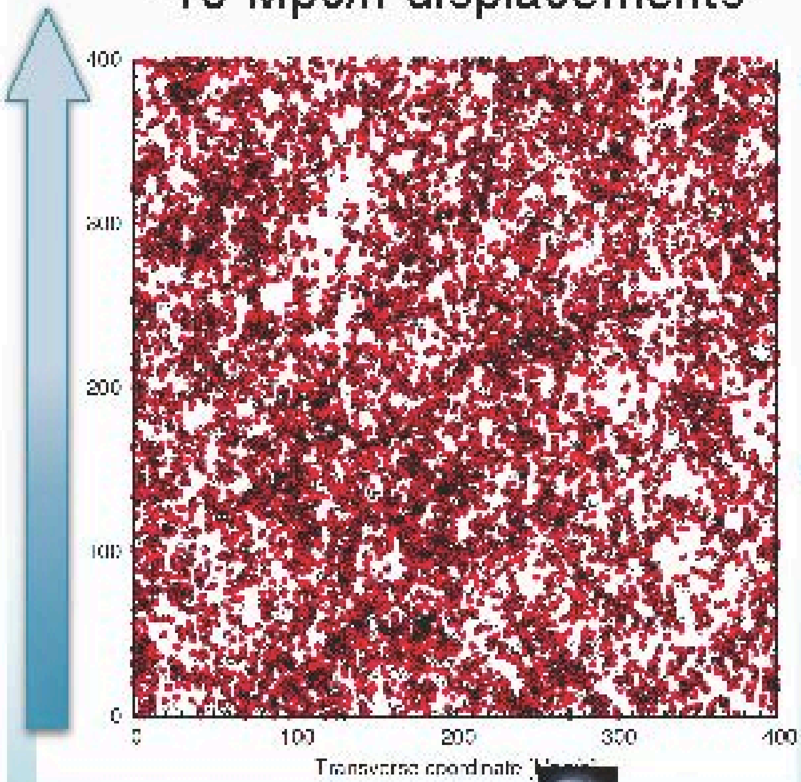
RSD from distribution function

○-Real-space (true) density
●-Redshift-space (observed) density

~10 Mpc/h displacements



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

Distortions due to radial peculiar velocities

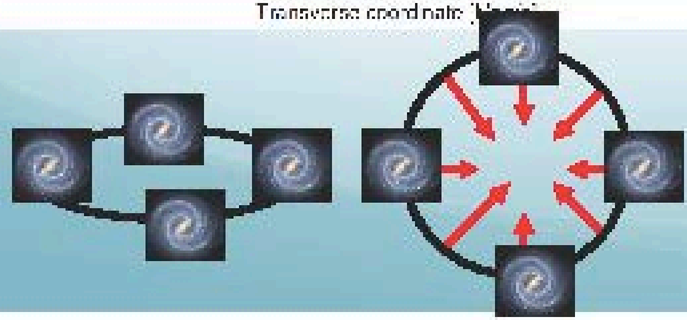
- Linear theory RSD

$$\delta_g^s(k) = \delta_g^r(k) + \mu^2 \delta_v(k)$$
$$P_{gg}^{obs}(k,\mu) = P_{gg}^r(k) + 2\mu^2 P_{gv}^r(k) + \mu^4 P_{vv}^r(k)$$
$$= P_{gg}^r(k)(1 + f\mu^2 / b)^2$$

- Distribution function approach (Seljak & McDonald 2011)

$$\delta^s(\mathbf{k}) = \delta^r(k) + \sum_{L=1} \frac{1}{L!}\left(\frac{ik_{//}}{aH}\right) T_{//}^L(\mathbf{k}) = \sum_{L=0} \frac{1}{L!}\left(\frac{ik_{//}}{aH}\right) T_{//}^L(\mathbf{k})$$

$$T_{//}^L(\mathbf{x}) = \frac{m}{\bar{\rho} a^3} \int d^3p\, f(\mathbf{x},\mathbf{p}) \left(\frac{p_{//}}{am}\right)^L = [1 + \delta(\mathbf{x})] u^L(\mathbf{x})$$



Velocity moments and redshift space power spectrum

- Redshift-space correlator: $\langle \delta_s(\mathbf{k})\delta_s^*(\mathbf{k}') \rangle \equiv (2\pi)^3 P^{ss}(\mathbf{k})\delta^D(\mathbf{k}-\mathbf{k}')$
- Redshift-space power spectrum

$$P^{ss}(\mathbf{k}) = \sum_{L=0}^{\infty} \frac{1}{L!^2}\left(\frac{k\mu}{H}\right)^{2L} P_{LL}(\mathbf{k}) + 2Re \sum_{L=0}^{\infty}\sum_{L'>L} \frac{(-1)^L}{L!\,L'!}\left(\frac{ik\mu}{H}\right)^{L+L'} P_{LL'}(\mathbf{k})$$

$$(2\pi)^3 P_{LL'}(\mathbf{k})\delta^D(\mathbf{k}-\mathbf{k}') = \left\langle T_{\parallel}^{L}(\mathbf{k}) T_{\parallel}^{*L'}(\mathbf{k}') \right\rangle$$

  - P_{00} : density-density power
  - P_{01} : density-radial momentum
  - P_{11} : radial momentum-radial momentum (scalar and vector)

Linear

$$P^{ss}(k,\mu) = (1+f\mu^2)^2 P_{lin}(k)$$

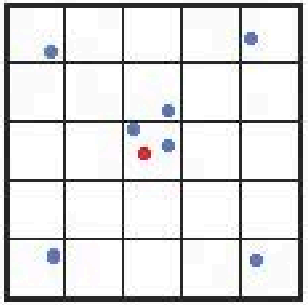
Keep nonlinear clustering

$$P^{ss}(k,\mu) = P_{00} + 2f\mu^2\left(\frac{ik}{aH\mu f}\right)P_{01} + f^2\mu^4\left(\frac{k}{aH\mu f}\right)^2 P_{11}$$

Volume-weighted and mass-weighted velocity

- **Velocity field v(x)**

$$\vec{v}(x_i) = \frac{\sum_{ith-cell}(1+\delta(x))\vec{v}(x)}{\sum_{ith-cell}(1+\delta(x))}$$



  - This quantity diverges at empty cells

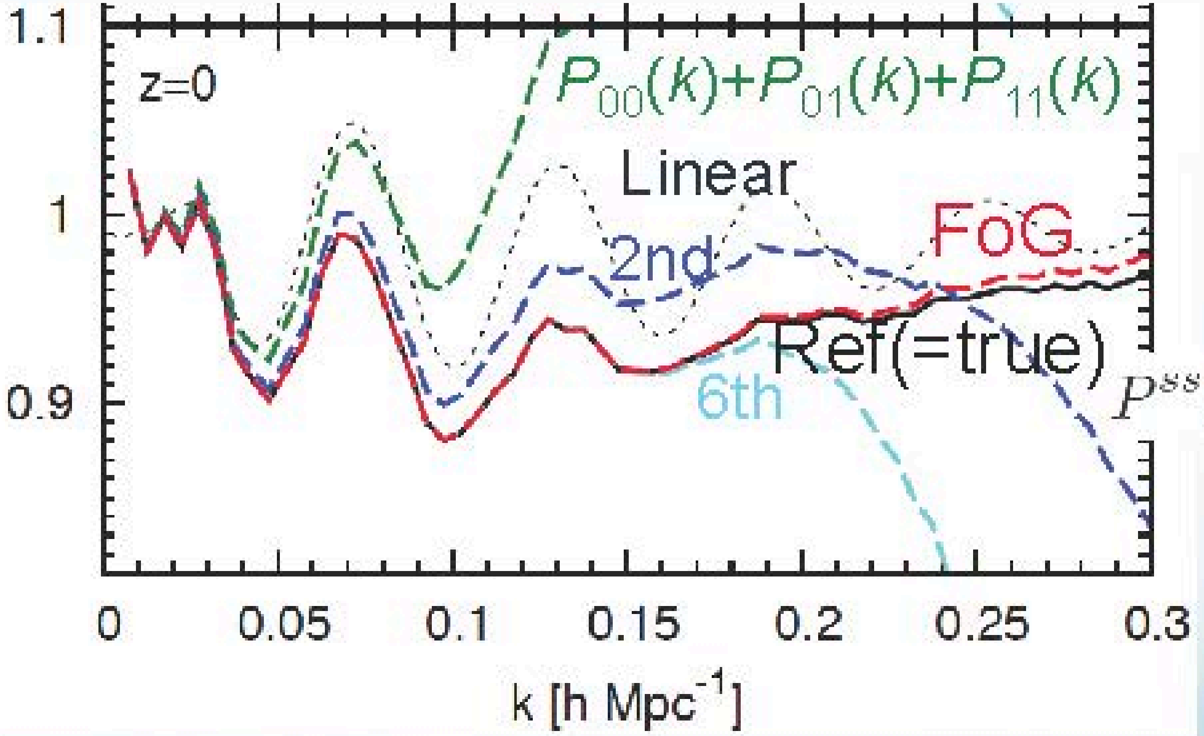
- **Momentum field: well defined everywhere**
  - Every power spectrum $P_{LL'}$ can be directly measured from *N*-body simulations!
  - (Traditional formalisms cannot do it for a sparse sample.)

Accuracy for dark matter clustering

$$P^{ss}(\mathbf{k}) = \sum_{L,L'=0}^{L+L'=n} \frac{(-1)^L}{L!L'!}\left(\frac{ik\mu}{H}\right)^{L+L'} P_{LL'}(\mathbf{k})$$

Monopole

$P^{ss}(k)/P^{ss}_{\text{no-BAO}}(k)$



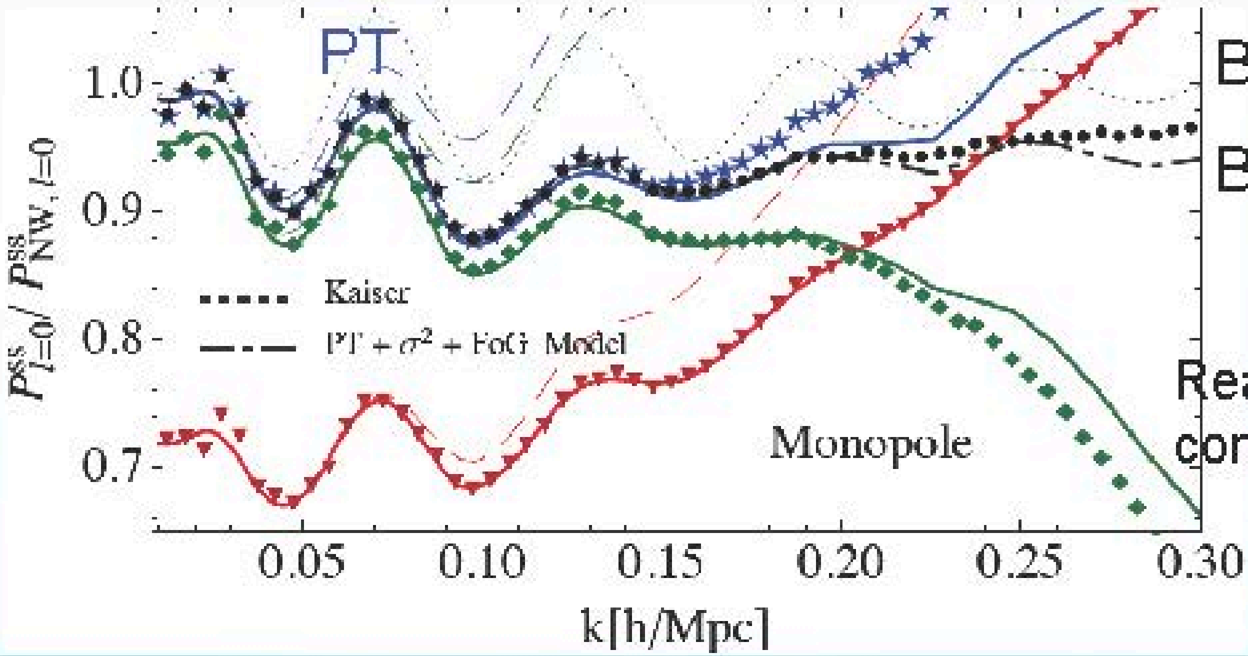
FoG resummation

$$P^{ss}(\mathbf{k}) = G_{00}\left([k\mu\sigma_{00}/H]^2\right)P_{00} + 2G_{01}\left([k\mu\sigma_{01}/H]^2\right)\frac{ik\mu}{H}P_{01} + G_{11}\left([k\mu\sigma_{11}/H]^2\right)\frac{(k\mu)^2}{H^2}P_{11}$$

Okumura, Seljak, McDonald, Desjacques (2012a)

Perturbation theory for dark matter

$$P^{ss}(\mathbf{k}) = P_{00}(\mathbf{k}) + \left(\frac{\mu k}{\mathcal{H}}\right)^2 P_{11}(\mathbf{k}) + \frac{1}{4}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P_{22}(\mathbf{k})$$
$$+2\mathrm{Re}\left[-\frac{i\mu k}{\mathcal{H}} P_{01}(\mathbf{k}) - \frac{1}{2}\left(\frac{\mu k}{\mathcal{H}}\right)^2 P_{02}(\mathbf{k}) + \frac{i}{6}\left(\frac{\mu k}{\mathcal{H}}\right)^3 P_{03}(\mathbf{k}) - \frac{i}{2}\left(\frac{\mu k}{\mathcal{H}}\right)^3 P_{12}(\mathbf{k}) - \frac{1}{6}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P_{13}(\mathbf{k}) + \frac{1}{24}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P_{04}(\mathbf{k})\right]$$



Black points : Ref(=true)

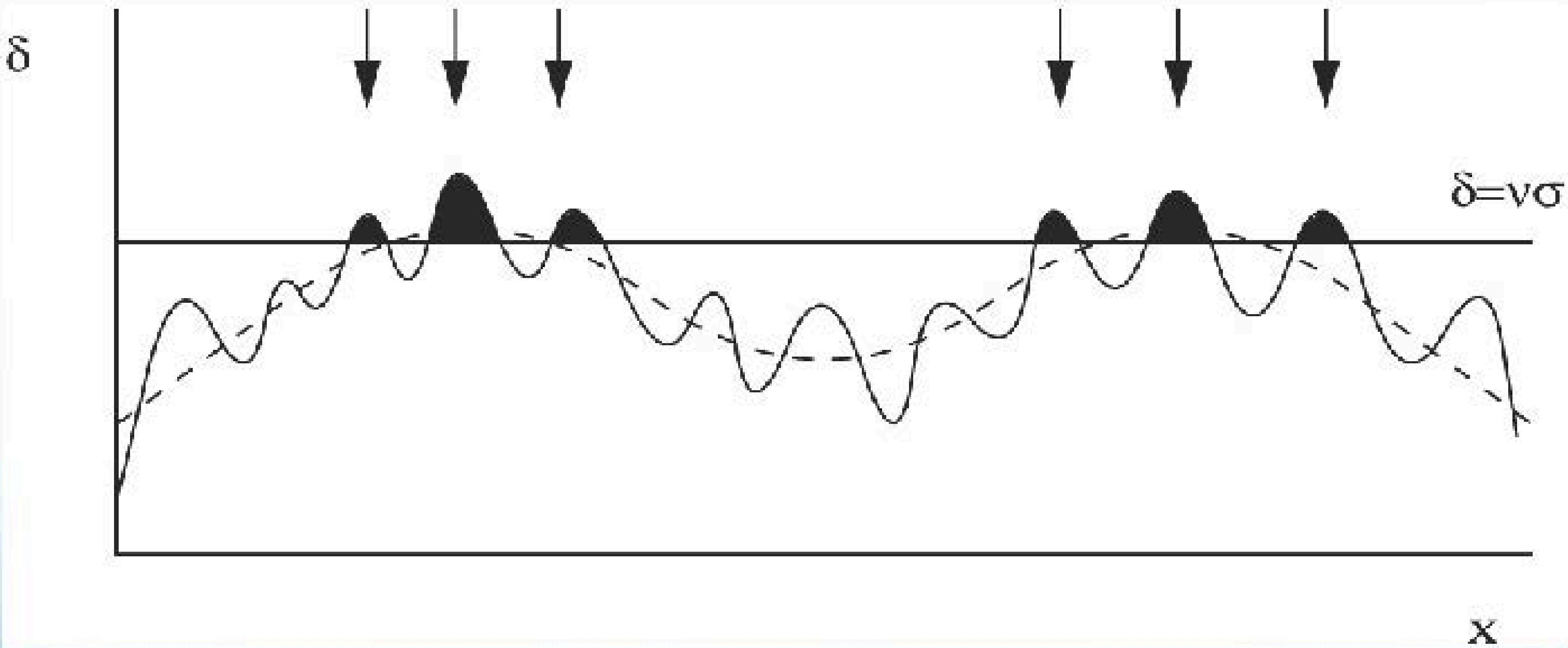
Black curve : PT+σ_v^2

Real-space power spectrum computed using simulations

Vlah, Seljak, McDonald, Okumura, Baldauf (2012)

From dark matter to dark matter halos

- A concept of bias (Kaiser 1984, Bardeen+1986)



$$b = \delta_h(k) / \delta_m(k) \quad b^2 = P_{hh}(k) / P_{mm}(k)$$

$$b = P_{mh}(k) / P_{mm}(k)$$

Halo power spectrum

Distribution function approach | Linear Kaiser

- Dark matter

$$P^s_{mm}(\mathbf{k}) = \sum_{L=0}^{\infty}\sum_{L'=0}^{\infty}\frac{(-1)^{L'}}{L!\,L'!}\left(\frac{ik\mu}{H}\right)^{L+L'} P^{mm}_{LL'}(\mathbf{k})$$

$$P^s_{mm}(\mathbf{k}) = (1+f\mu^2)^2 P^{mm}_{00}(k)$$

- Halos

$$P^s_{hh}(\mathbf{k}) = \sum_{L=0}^{\infty}\sum_{L'=0}^{\infty}\frac{(-1)^{L'}}{L!\,L'!}\left(\frac{ik\mu}{H}\right)^{L+L'} P^{hh}_{LL'}(\mathbf{k})$$

$$P^s_{hh}(\mathbf{k}) = (1+f\mu^2/b)^2 P^{hh}_{00}(k) = (b+f\mu^2)^2 P^{mm}_{00}(k)$$

- Halo biasing

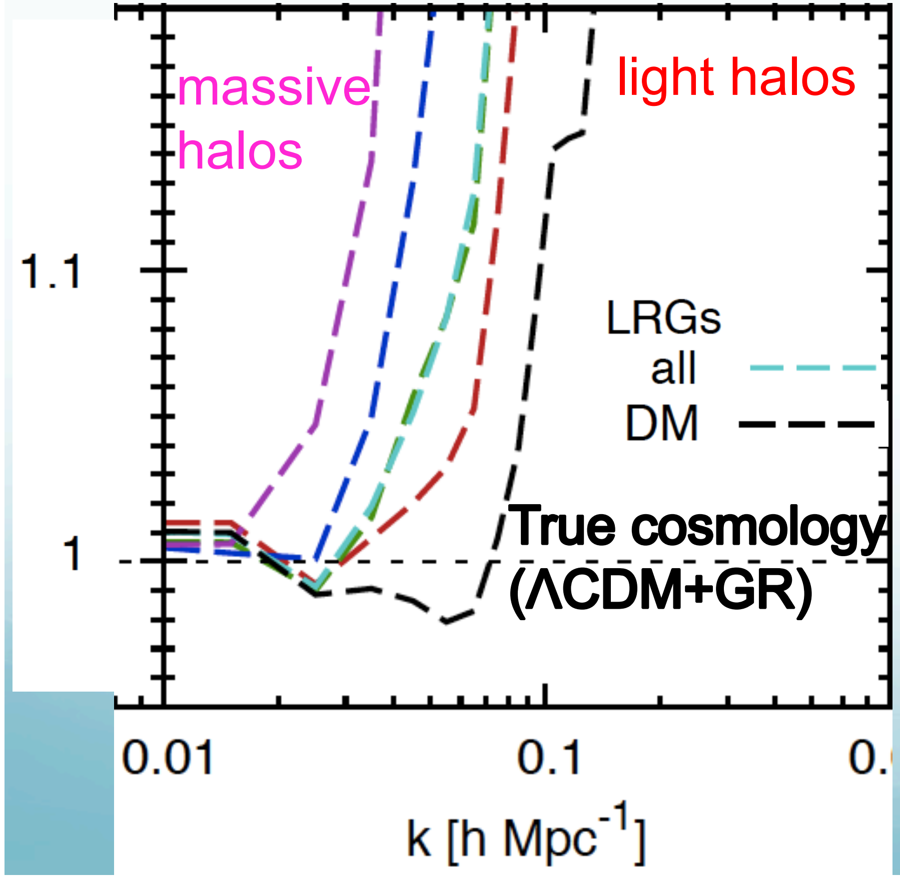
$$b^{hh}_{LL'}(\mathbf{k}) = P^{hh}_{LL'}(\mathbf{k}) \big/ P^{mm}_{LL'}(\mathbf{k}) \qquad b^2 = P^{hh}_{00}(k) \big/ P^{mm}_{00}(k)$$

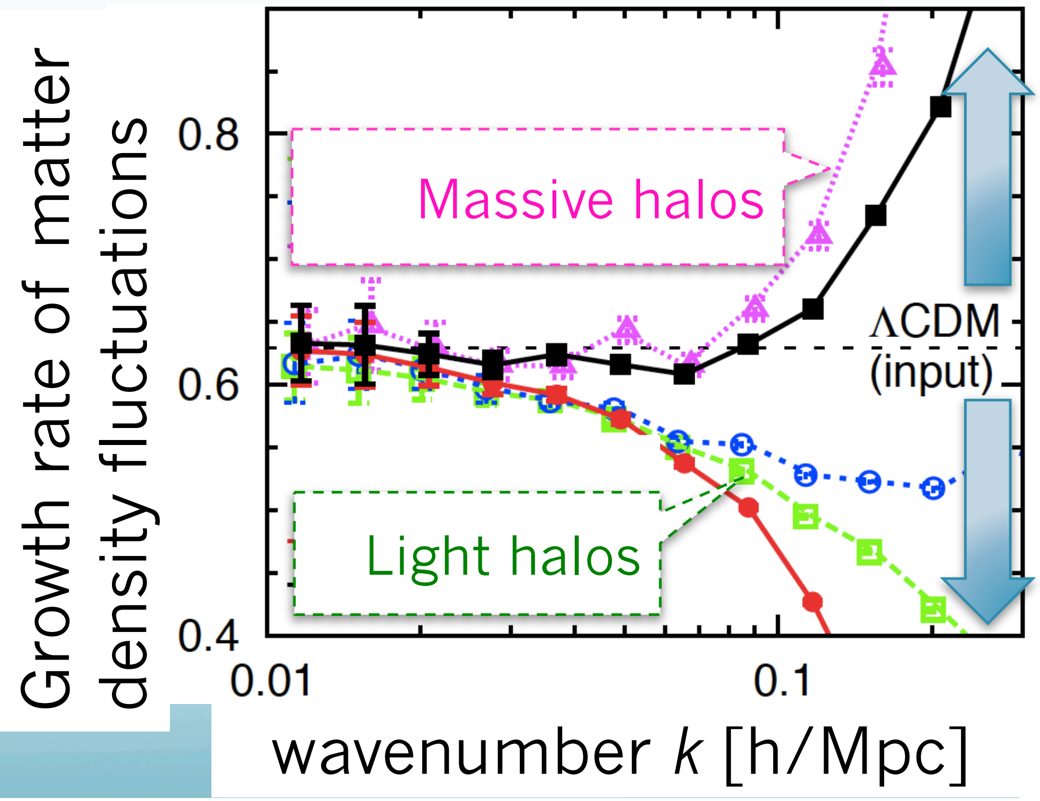
- $b^{hh}_{00} = b^2 \quad b^{hh}_{01} = b \quad b^{hh}_{11} = 1$ in linear theory

Okumura, Seljak & Desjacques (2012b)

Systematic and nonlinear effects on growth rate constraints

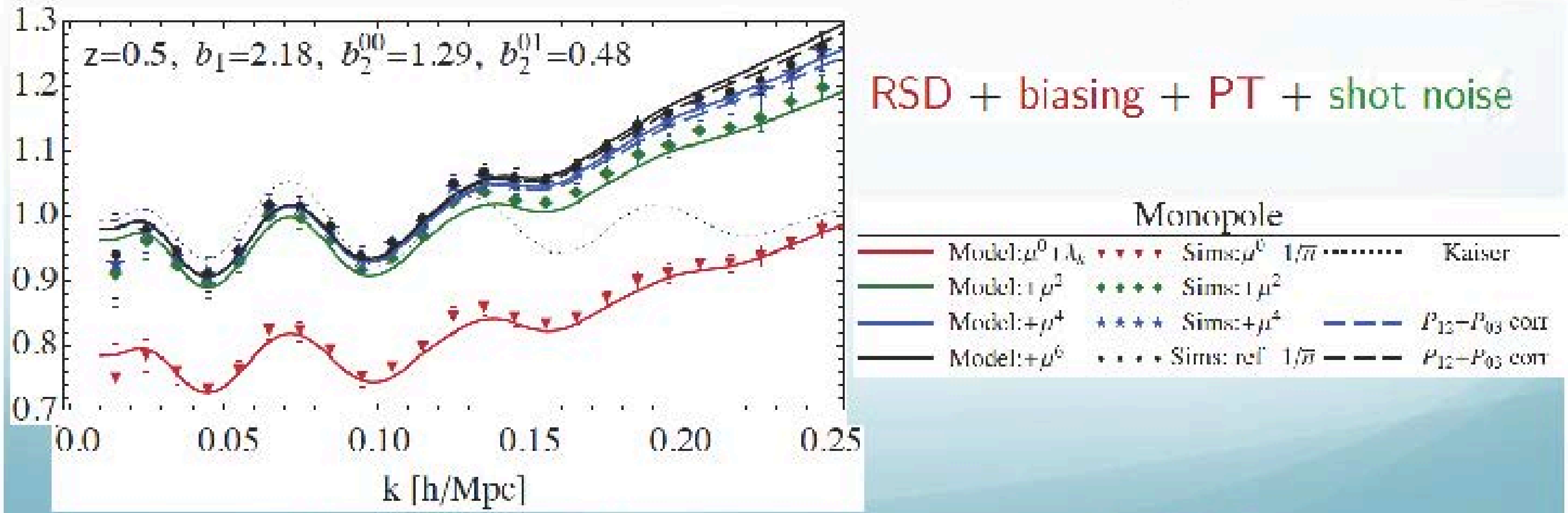
$$\frac{k^2 P_{11}^{(4)hh}(k)}{H^2 f^2 P_{00,\mathrm{lin}}^{mm}(k)}$$





Perturbation theory for halos

$$P^{ss}_{hh}(\mathbf{k}) = P^{hh}_{00}(\mathbf{k}) + \left(\frac{\mu k}{\mathcal{H}}\right)^2 P^{hh}_{11}(\mathbf{k}) + \frac{1}{4}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P^{hh}_{22}(\mathbf{k})$$
$$+2\mathrm{Re}\Big[-\frac{i\mu k}{\mathcal{H}} P^{hh}_{01}(\mathbf{k}) - \frac{1}{2}\left(\frac{\mu k}{\mathcal{H}}\right)^2 P^{hh}_{02}(\mathbf{k}) + \frac{i}{6}\left(\frac{\mu k}{\mathcal{H}}\right)^3 P^{hh}_{03}(\mathbf{k})$$
$$-\frac{i}{2}\left(\frac{\mu k}{\mathcal{H}}\right)^3 P^{hh}_{12}(\mathbf{k}) - \frac{1}{6}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P^{hh}_{13}(\mathbf{k}) + \frac{1}{24}\left(\frac{\mu k}{\mathcal{H}}\right)^4 P^{hh}_{04}(\mathbf{k})\Big]$$



RSD + biasing + PT + shot noise

Vlah, Seljak, Okumura & Desjacques (2013)

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Peculiar velocities of galaxies

- Galaxy redshift surveys
  - Redshift-space distortions

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

Radial peculiar velocity

Observed distance (redshift space)

True distance (real space)

  - Linear power spectrum (Kaiser 1987)

$$P_{gg}^{obs}(k,\mu) = (b + f\mu^2)^2 P_{mm}(k)$$

Redshift-space distortion (RSD)

- Peculiar velocity surveys
  - True distance is also measured through abs luminosity

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

  - Faber-Jackson
    - Luminosity – stellar velocity dispersion relation in elliptical galaxy
  - Tully-Fisher
    - Luminosity – rotation velocity relation in spiral galaxy
  - Type Ia supernovae
    - Luminosity – light curve relation

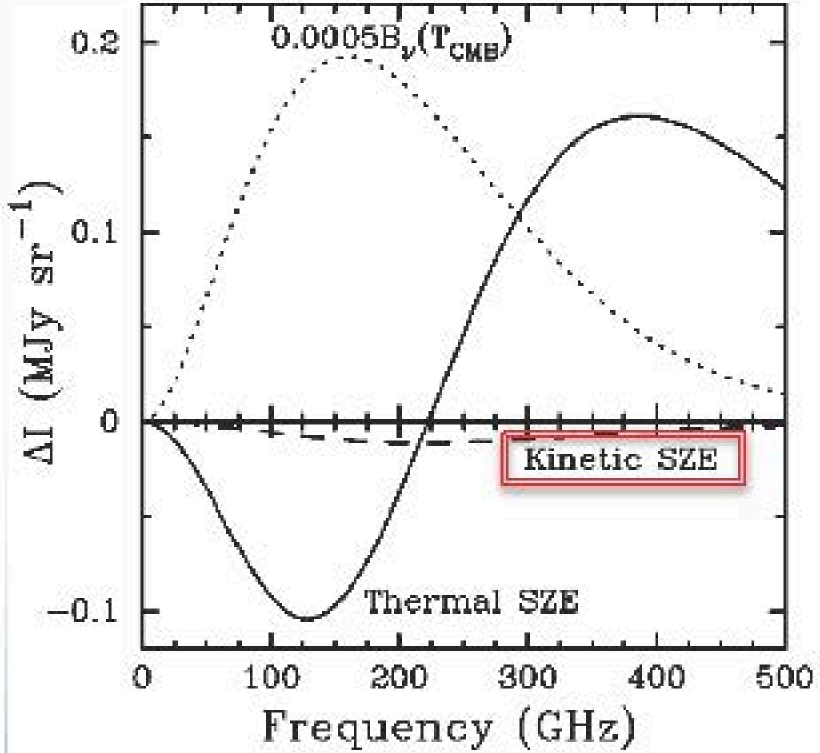
Peculiar velocity survey and galaxy redshift survey

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

- Advantages of peculiar velocity surveys
  - 3D mass distribution can be directly probed.
- Disadvantages
  - Valid for nearby universe
  - Measurement is noisy

Direct measurement of velocities: Kinetic Sunyaev-Zeld'ovich (kSZ)

- Intensity of CMB spectrum



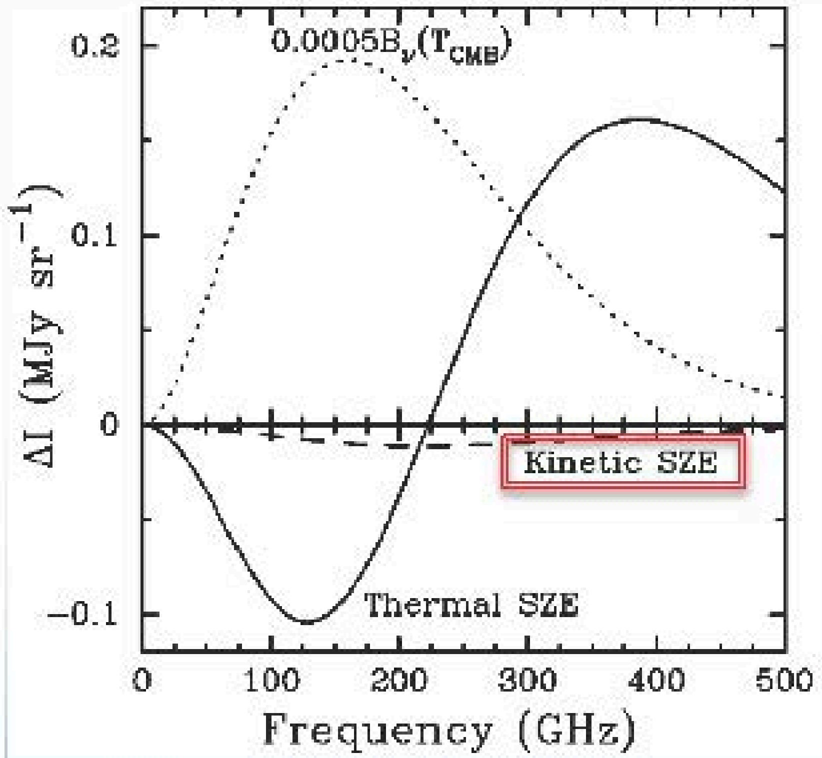
- Thermal SZ (tSZ) effect (1970)
  - Scattering of CMB photons by high energy electrons in clusters
- Kinetic SZ (kSZ) effect (1980)
  - Doppler effect of cluster bulk velocity w.r.t. CMB rest frame

$$\Delta T_{kSZ} / T_{CMB} = -\tau_e v_{//}$$

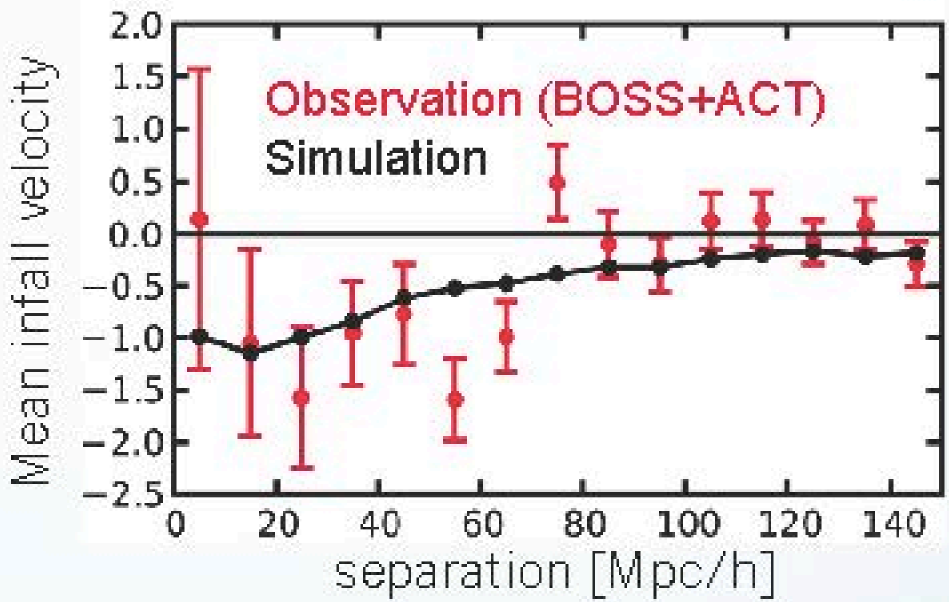
  - This effect is much smaller than tSZ

Direct measurement of velocities: Kinetic Sunyaev-Zeld'ovich (kSZ)

- Intensity of CMB spectrum



- Detection of kSZ (Hand+2012)



Positions of galaxies are measured by redshift survey, thus affected by RSD.

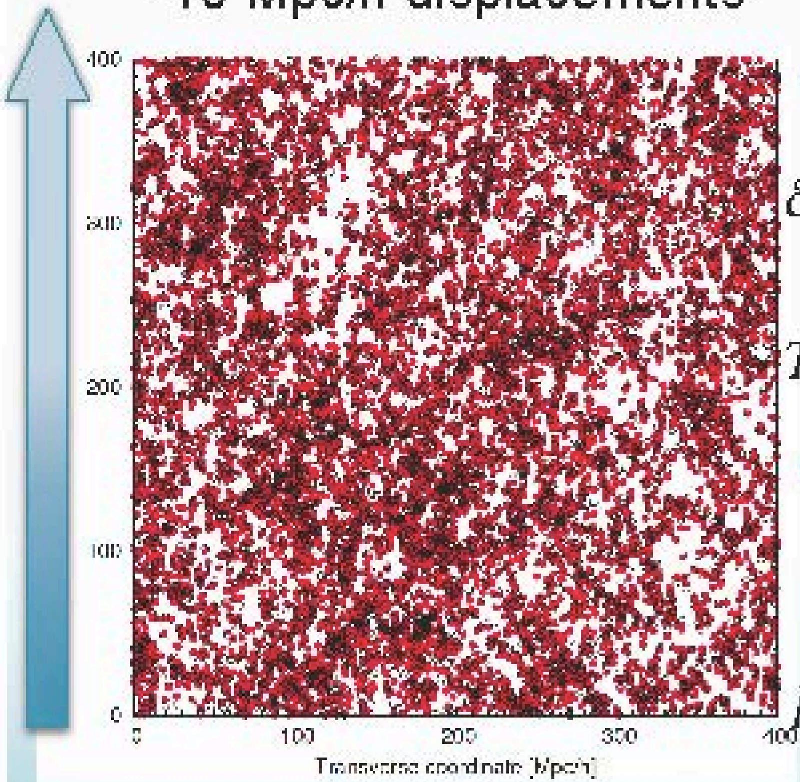
I present theoretical modeling of RSD on the velocity statistics and its test against N-body simulations.

RSD from distribution function

○-Real-space (true) density

●-Redshift-space (observed) density

~10 Mpc/h displacements



$$\vec{s} = \vec{x} + \hat{z} v_{//} / aH$$

$$= x + \hat{z} p_{//} / a^2 mH$$

Distortions due to radial peculiar velocities

- Redshift-space density field

$$\delta^s(\mathbf{k}) = \delta^r(k) + \sum_{L=1} \frac{1}{L!} \left(\frac{ik_{//}}{aH} \right) T_{//}^L(\mathbf{k}) = \sum_{L=0} \frac{1}{L!} \left(\frac{ik_{//}}{aH} \right) T_{//}^L(\mathbf{k})$$

$$T_{//}^L(\mathbf{x}) = \frac{m}{\bar{\rho} a^3} \int d^3 p \, f(\mathbf{x}, \mathbf{p}) \left(\frac{p_{//}}{am} \right)^L = [1 + \delta(\mathbf{x})] u^L(\mathbf{x})$$

- Extension to redshift-space radial momentum field

$$p_{//}^s(\mathbf{x}) = \left[1 + \delta^s(\mathbf{x}) \right] v_{//}^s(\mathbf{x})$$

$$p_{//}^s(\mathbf{k}) = p_{//}(\mathbf{k}) + \sum_{L=1} \frac{1}{L!} (ik_{//})^L T_{//}^{L+1}(\mathbf{k}) = \sum_{L=0} \frac{1}{L!} (ik_{//})^L T_{//}^{L+1}(\mathbf{k})$$

Power spectra in redshift space

$$\left\langle \delta^s(\mathbf{k})\delta^s(\mathbf{k}')\right\rangle = (2\pi)^3 P^s_{00}(\mathbf{k})\delta^D(\mathbf{k}-\mathbf{k}')$$

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

$$P^s_{00}(\mathbf{k}) = P_{00}(\mathbf{k}) - 2ik_{//}P_{01}(\mathbf{k}) + k_{//}^2 P_{11}(\mathbf{k}) - k_{//}^2 P_{02}(\mathbf{k}) + \ldots$$

Linear theory limit

$$(2\pi)^3 P_{LL'}(\mathbf{k})\delta(\mathbf{k}-\mathbf{k}') = \langle T_{\|}^{L}(\mathbf{k})(T_{\|}^{*L'}(\mathbf{k}')\rangle$$

- Density-momentum

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

$$P^s_{01}(\mathbf{k}) = P_{01}(\mathbf{k}) + ik_{//}P_{11}(\mathbf{k}) + ik_{//}^2 P_{02}(\mathbf{k}) + \ldots$$

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

Momentum-momentum

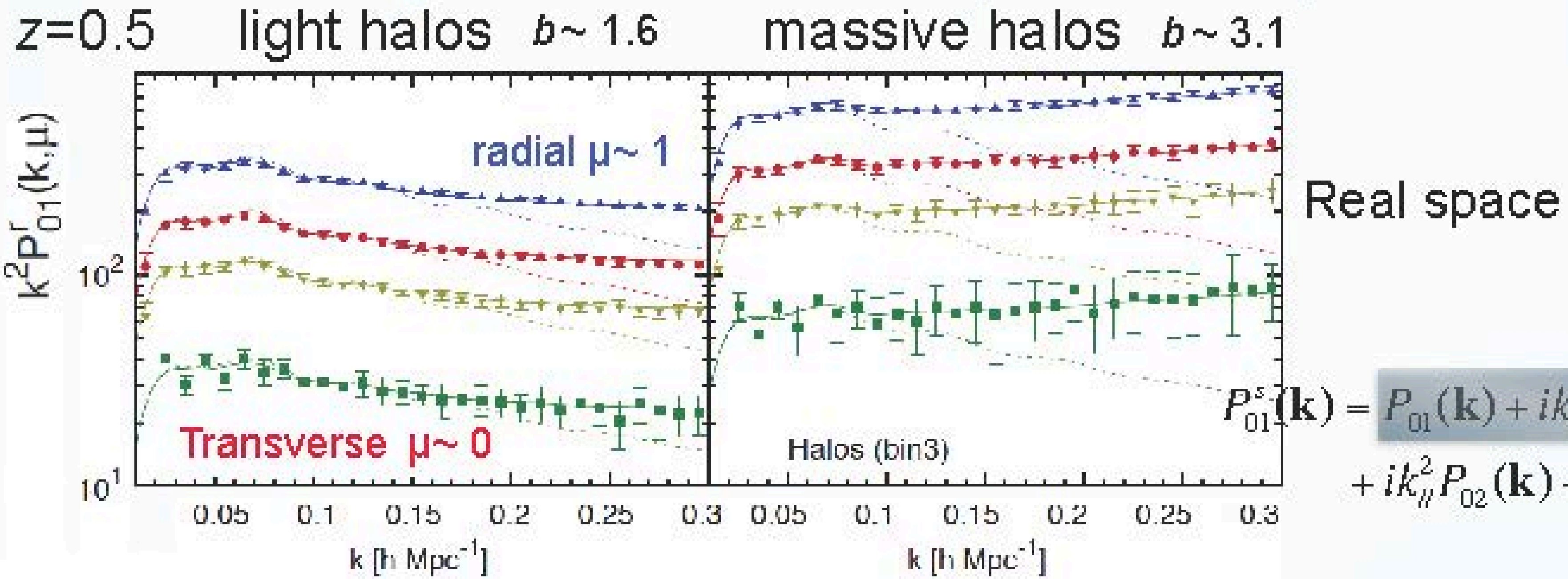
$$\left\langle p^s_{//}(\mathbf{k})p^{s*}_{//}(\mathbf{k}')\right\rangle = (2\pi)^3 P^s_{11}(\mathbf{k})\delta^D(\mathbf{k}-\mathbf{k}')$$

$$P^s_{11}(\mathbf{k}) = P_{11}(\mathbf{k}) - 2ik_{//}P_{12}(\mathbf{k}) + \ldots$$

$$P^s_{11}(k,\mu) = (f^2\mu^2/k^2)P_m(k)$$

- $P_{LL'}$'s were measured from N-body simulations (Okumura+) and modeled using nonlinear perturbation theory (Vlah+)

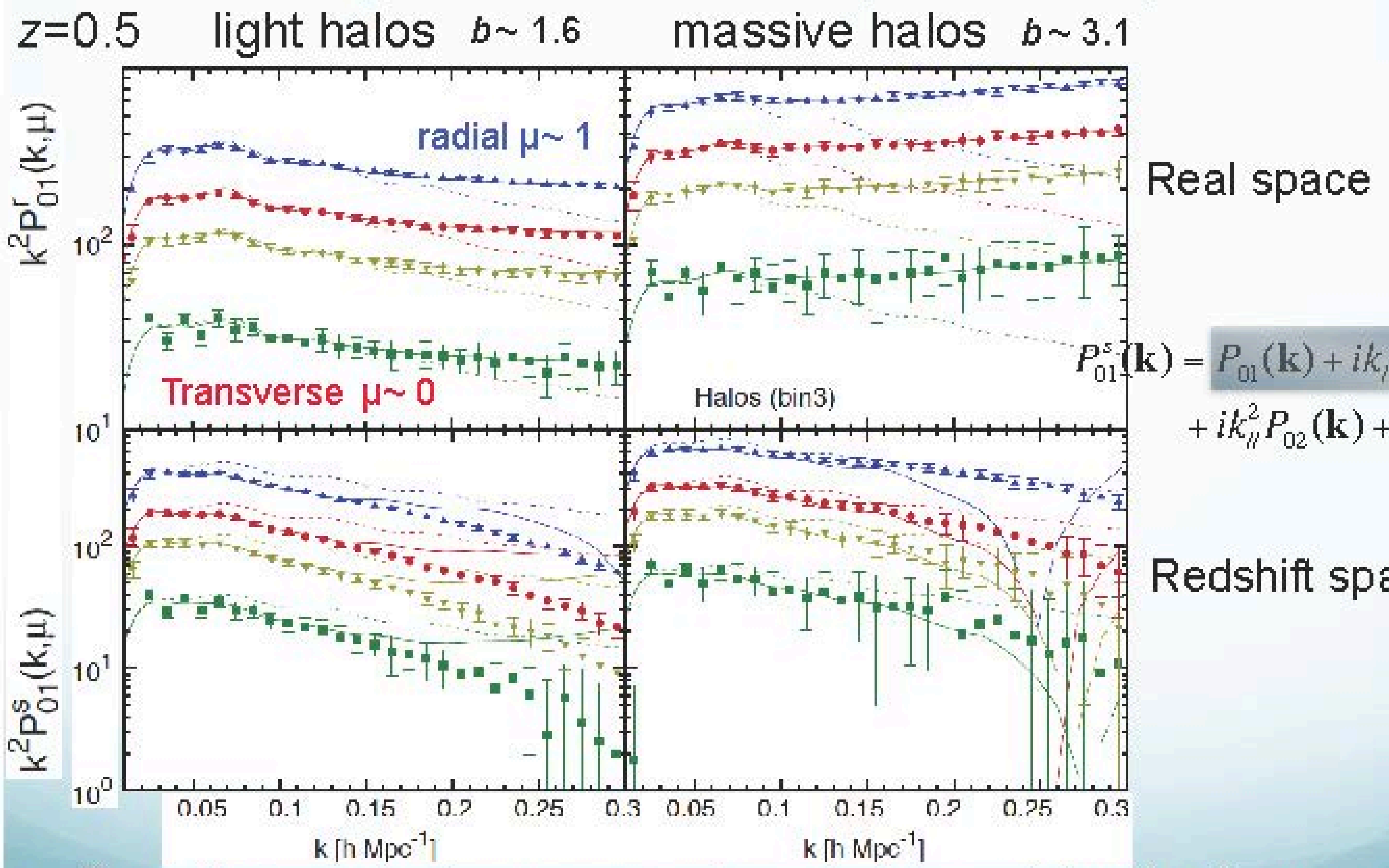
Density-momentum power spectra



$$P^s_{01}(\mathbf{k}) = P_{01}(\mathbf{k}) + ik_{//}P_{11}(\mathbf{k}) + ik^2_{//}P_{02}(\mathbf{k}) + \ldots$$

- Density-momentum power is suppressed by the large velocity dispersion as is the case for density-density power.

Density-momentum power spectra

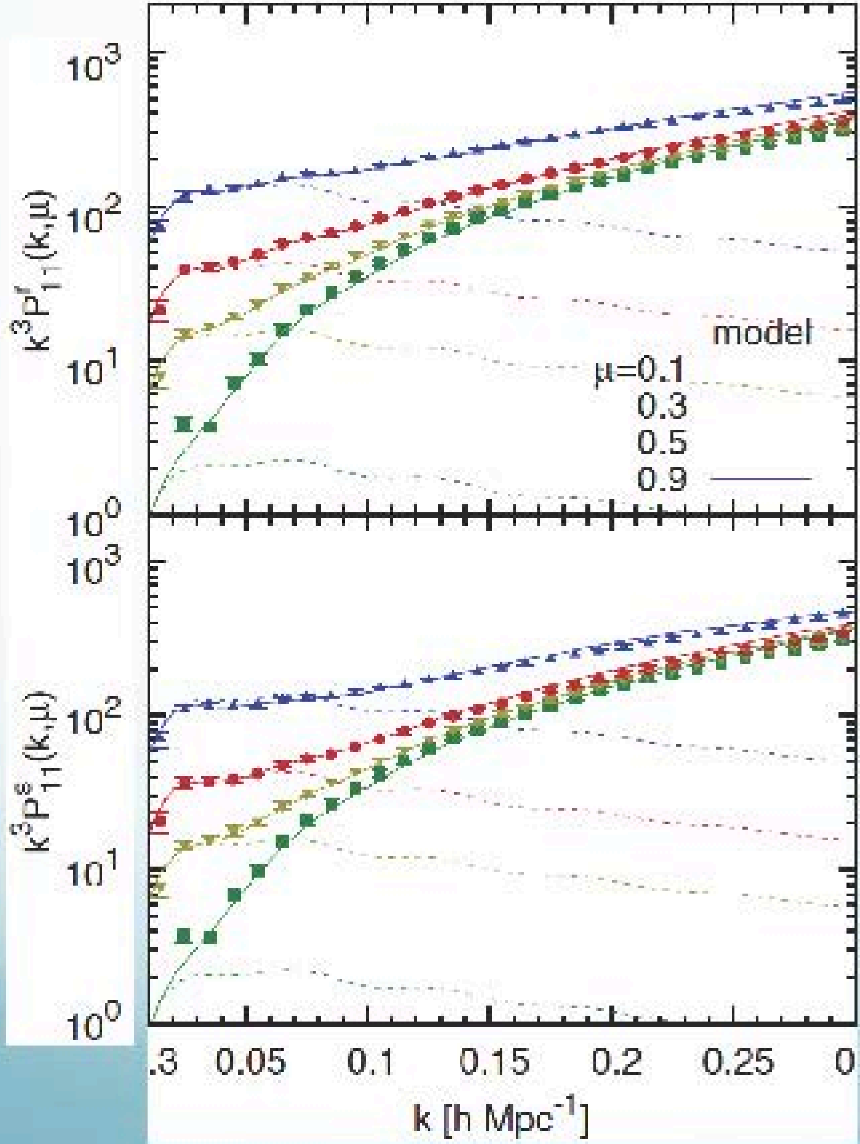


$$P^s_{01}(\mathbf{k}) = P_{01}(\mathbf{k}) + ik_{//}P_{11}(\mathbf{k}) + ik^2_{//}P_{02}(\mathbf{k}) + \ldots$$

- Density-momentum power is suppressed by the large velocity dispersion as is the case for density-density power.

Momentum-momentum power spectra

z=0.5 light halos b~ 1.6



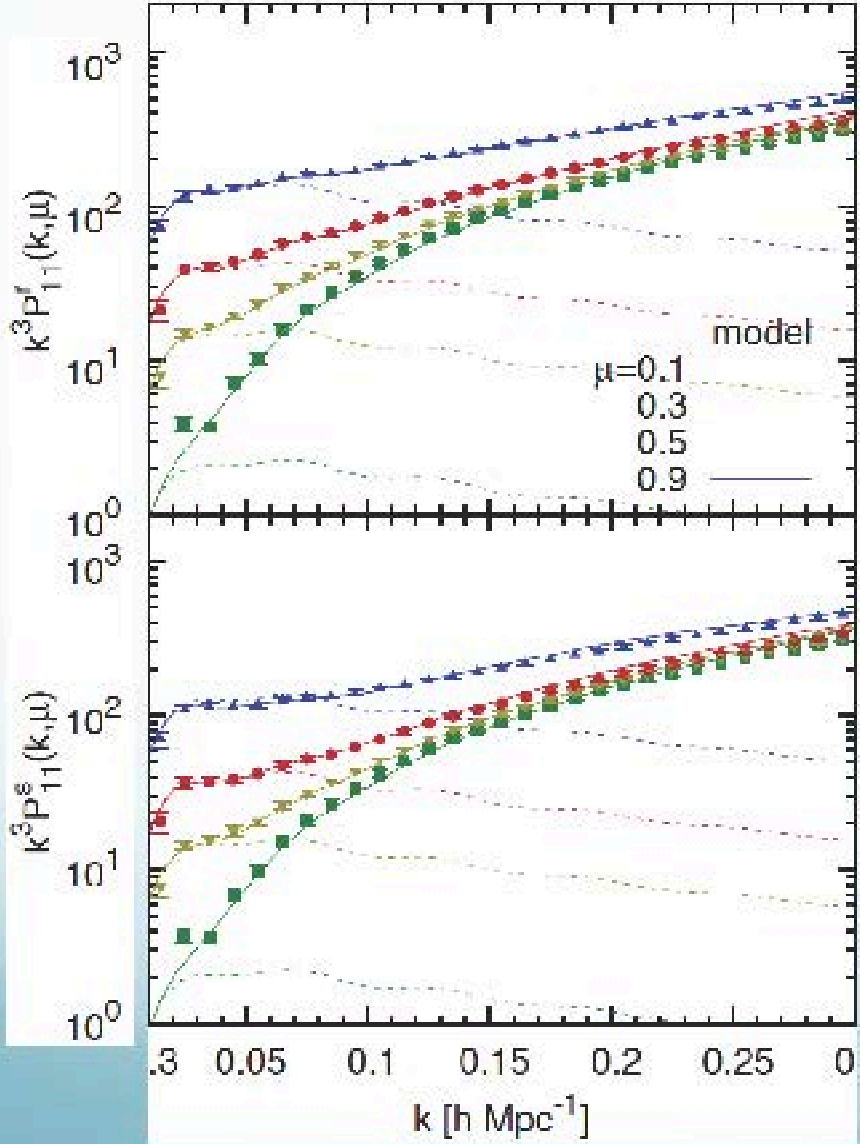
Real space

$$P^s_{11}(\mathbf{k}) = P_{11}(\mathbf{k}) - 2ik_{//}P_{12}(\mathbf{k}) + \ldots$$

Redshift space

Momentum-momentum power spectra

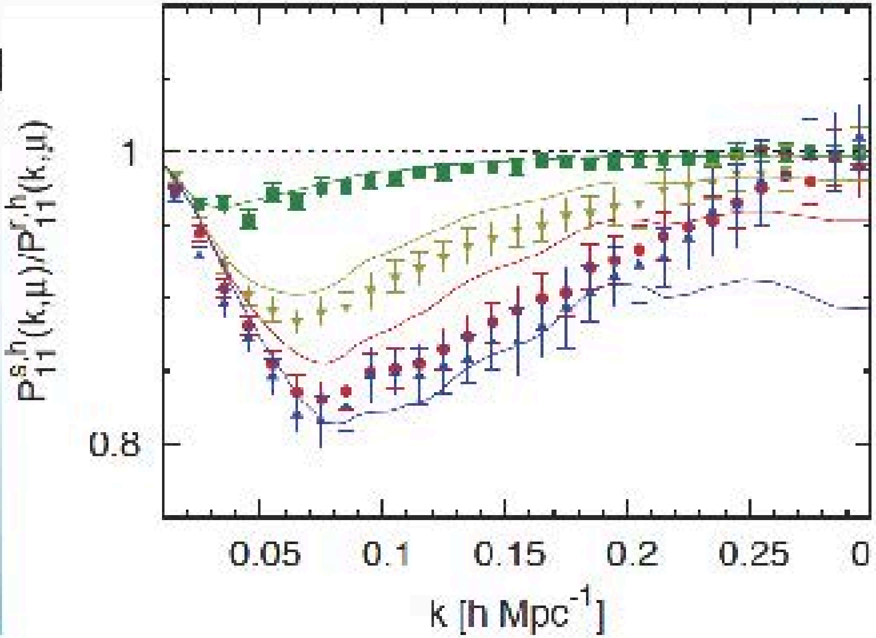
z=0.5 light halos $b \sim 1.6$



Real space

$$P^s_{11}(\mathbf{k}) = P_{11}(\mathbf{k}) - 2ik_{//}P_{12}(\mathbf{k}) + \ldots$$

Redsl



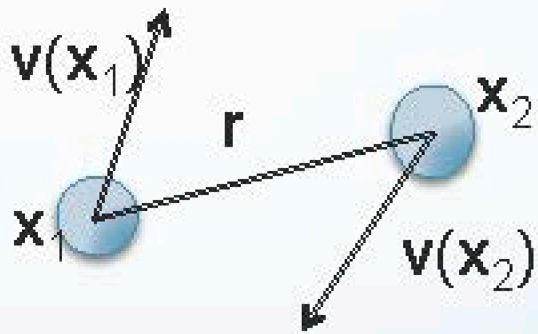
Peculiar velocity statistics (1)

- Mean pairwise infall momentum in redshift space
  - Fourier transform of $P_{01}{}^{s}$

$$v^{s}_{pair}(\mathbf{r}) = \left\langle \left[1+\delta^{s}(\mathbf{x}_1)\right]\left[1+\delta^{s}(\mathbf{x}_2)\right]\left[v^{s}_{//}(\mathbf{x}_2) - v^{s}_{//}(\mathbf{x}_1)\right]\right\rangle = -2\left\langle \delta^{s}(\mathbf{x}_2) p^{s}_{//}(\mathbf{x}_1)\right\rangle$$

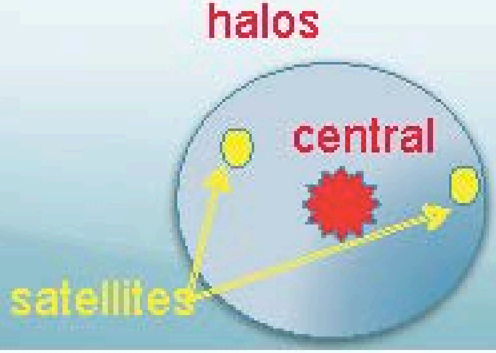
  - Linear theory

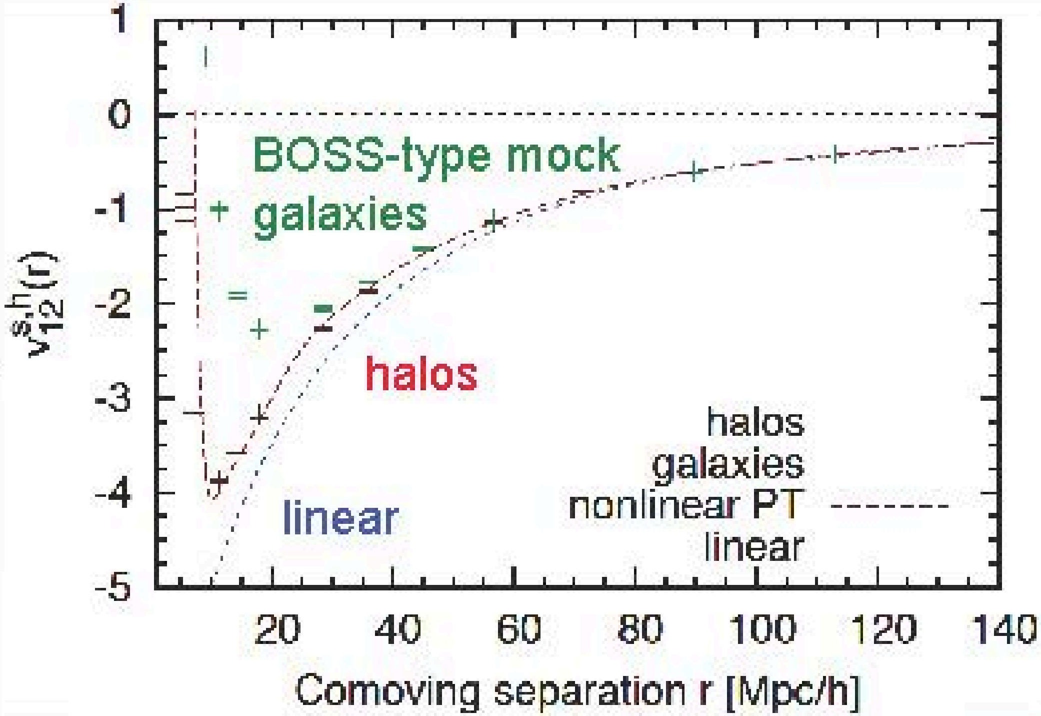
$$v^{s}_{pair}(\mathbf{r}) = v_{pair}(\mathbf{r})\left(1+3f/5b\right) - \left(3\mu/5 - \mu^{3}\right)\frac{f^{2}}{\pi^{2}}\int k\,dk\,P^{m}_{00}(k)\,j_3(kr)$$

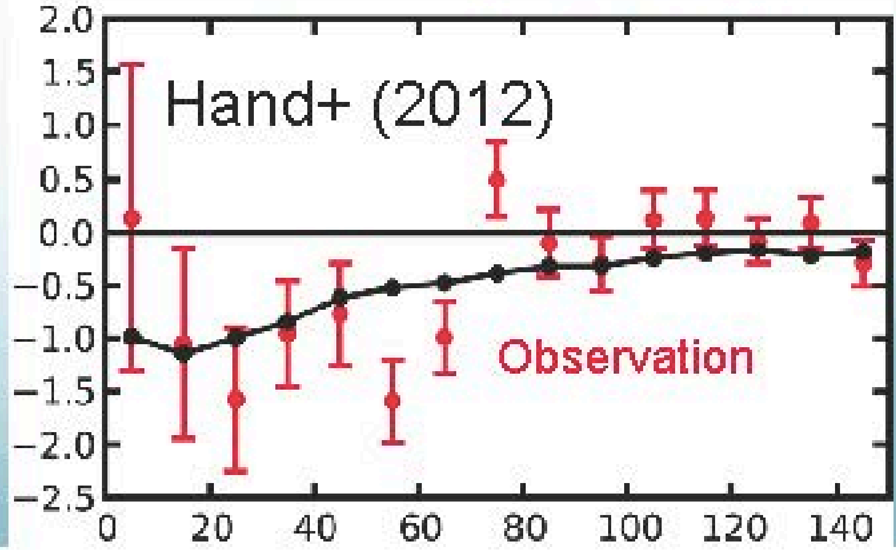


Redshift-space pairwise momentum

- Linear theory starts to deviate from simulation results at very large scales.
- Nonlinear perturbation theory can predict the mean pairwise velocity of halos in redshift space.
- We need more effort to model the statistics for galaxies that have large nonlinear velocity dispersion.







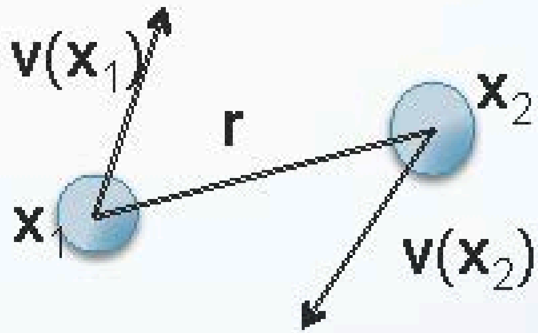
Peculiar velocity statistics (2)

- Momentum auto correlation function
  - Fourier transform of $P_{11}{}^{s}$

$$\psi^s(\mathbf{r}) = \left\langle \left[1+\delta^s(\mathbf{x}_1)\right]\left[1+\delta^s(\mathbf{x}_2)\right] v^s_{//}(\mathbf{x}_2) v^s_{//}(\mathbf{x}_1) \right\rangle = \left\langle p^s_{//}(\mathbf{x}_2) p^s_{//}(\mathbf{x}_1) \right\rangle$$

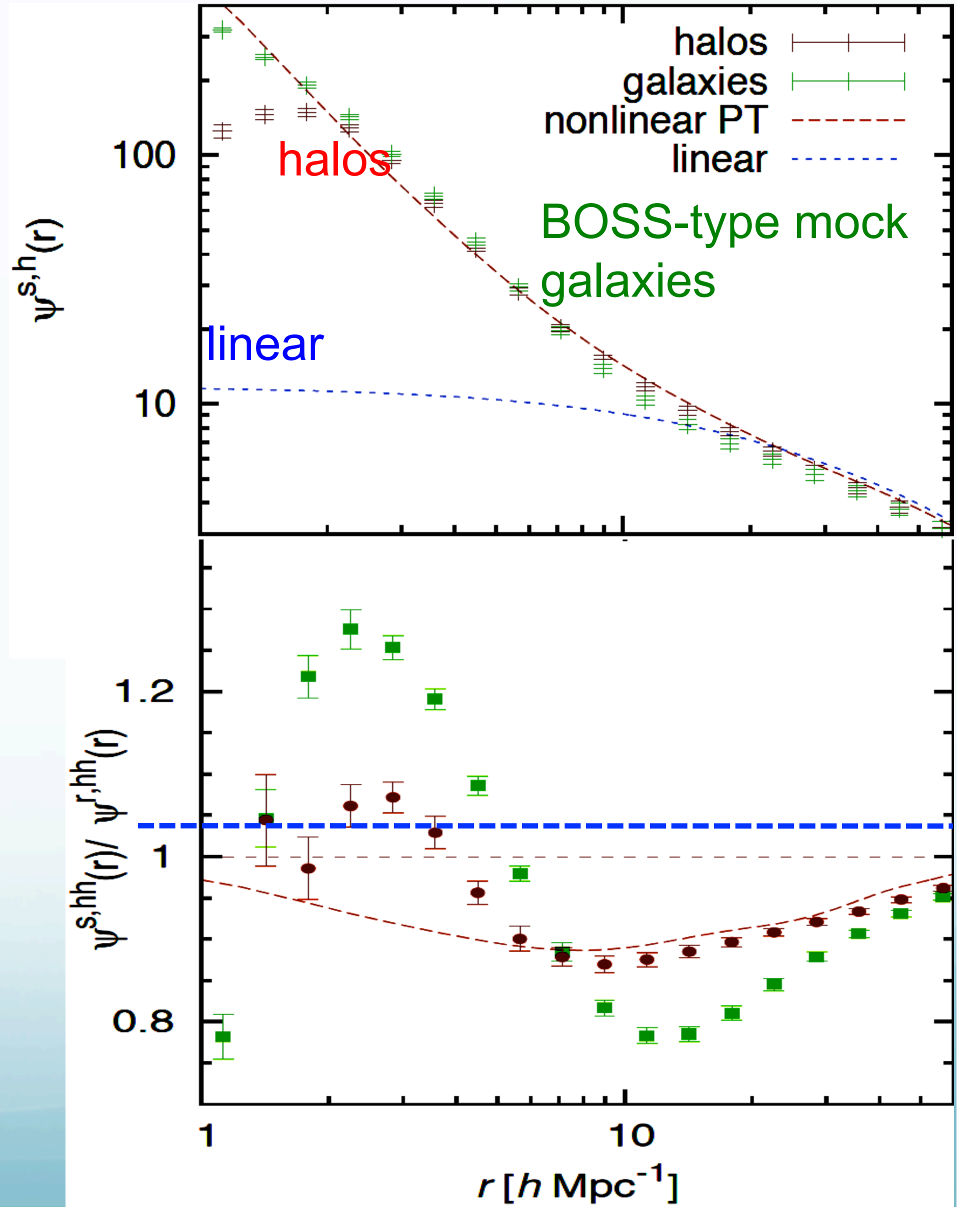
  - Linear theory

$\psi^s(\mathbf{r}) = \psi(\mathbf{r})$ (real space = redshift space)



Redshift-space momentum correlation function

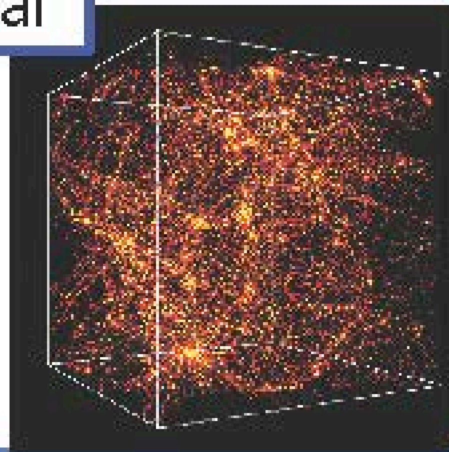
- Linear theory starts to deviate from simulation results at very large scales.
- Nonlinear perturbation theory can predict the velocity correlation of halos as well.
- We need more effort to model the statistics for galaxies that have large nonlinear velocity dispersion.



Cosmology with galaxy surveys is exciting

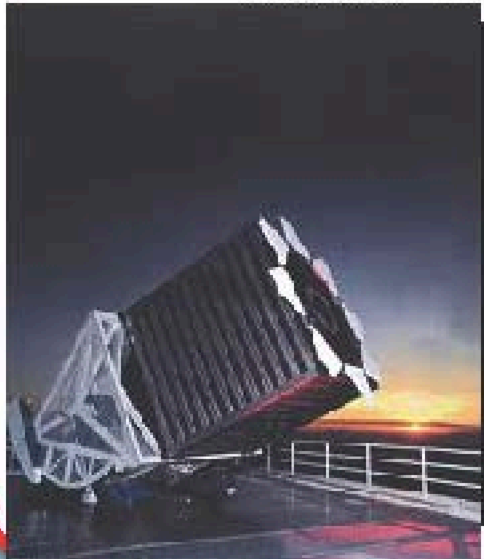
- Improvements for all the three areas are required for better understanding of dark energy.

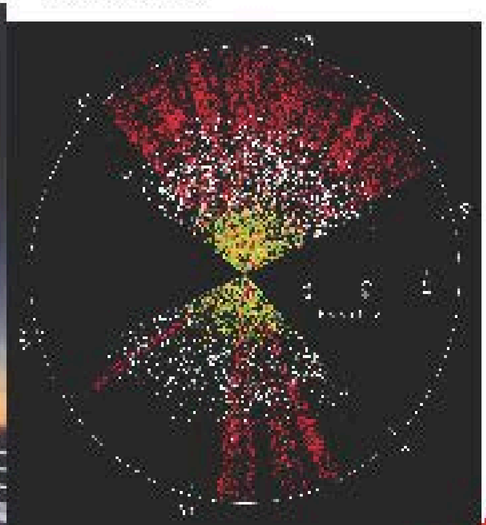
Numerical



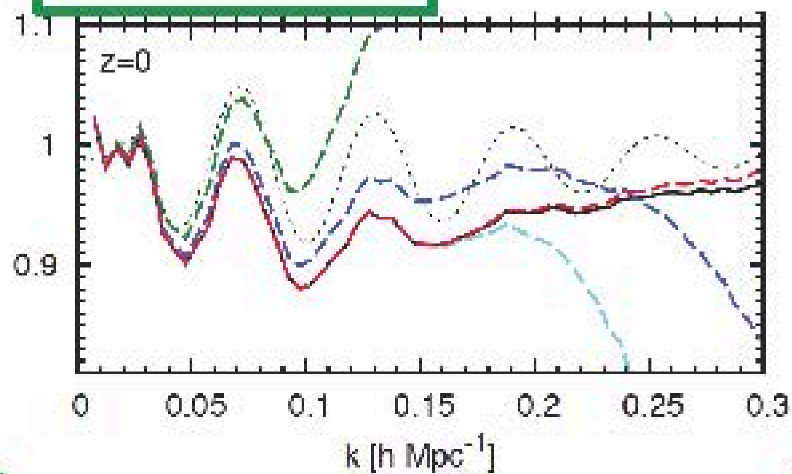
Observational

SDSS III BOSS





Theoretical



Outline of this talk

- Introduction
  - Dark energy and Galaxy redshift surveys
  - Redshift-space distortions (RSD)
  - Nonlinearity issues of galaxy clustering
- Galaxy redshift surveys
  - Theoretical modeling of nonlinear power spectrum using distribution function approach
    - Okumura, Seljak, McDonald, Desjacques (2012) JCAP
    - Okumura, Seljak, Desjacques (2013) JCAP
    - Vlah, Seljak, McDonald, Okumura, Baldauf (2013) JCAP
    - Vlah, Seljak, Okumura, Desjacques (2013) JCAP
- Peculiar velocity surveys
  - Theoretical modeling of nonlinear velocity statistics by extending the distribution function approach
    - Okumura, Seljak, Vlah, Desjacques (2013) arXiv:1312.4214