銀河の赤方偏移変形効果のモデリング

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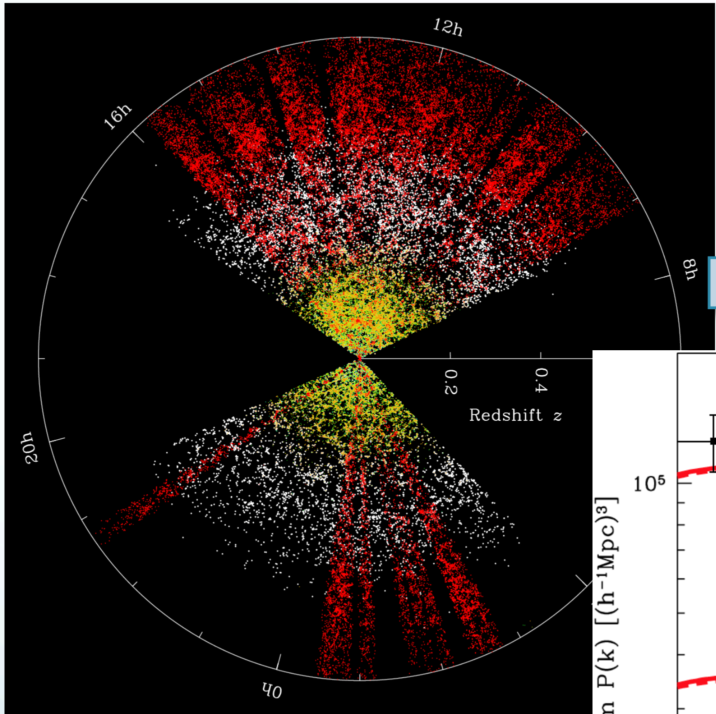
References:
TO, Hand, Seljak, Vlah & Desjacques (2015) PRD in press, 1506.05814
TO, Takada, More & Masaki, in prep.

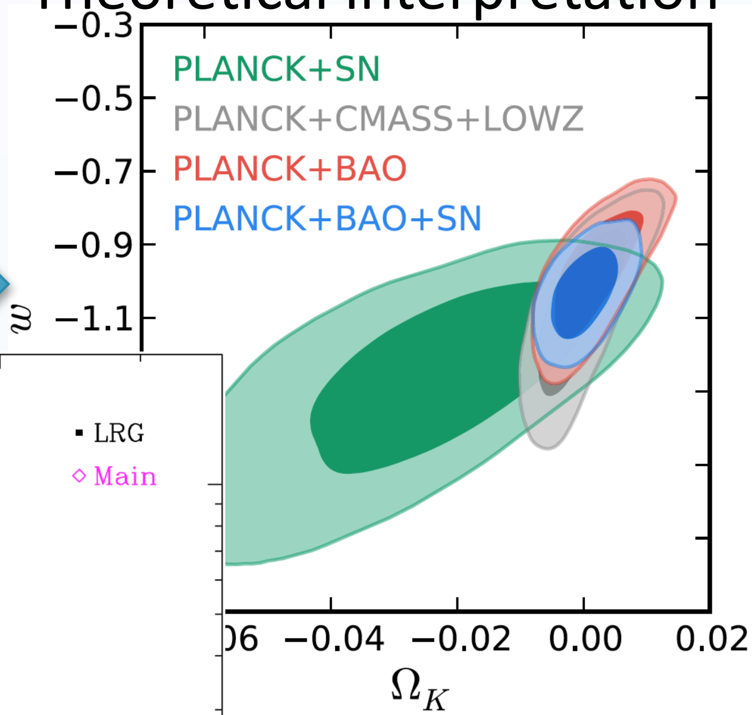
観測的宇宙論研究会@京大基研, May 18-20, 2015

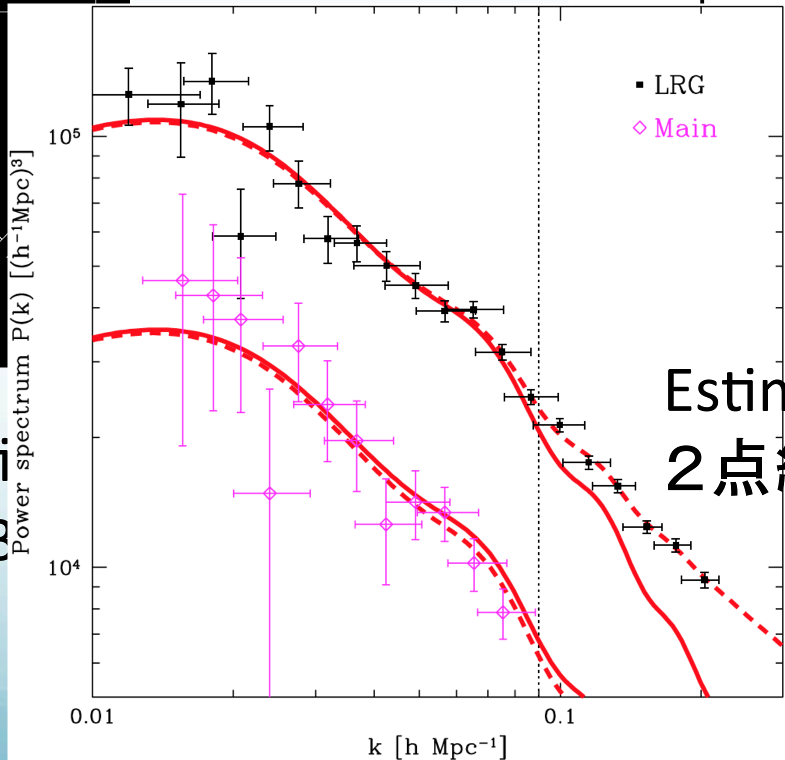
Galaxy redshift surveys: galaxies as tracers of large-scale structure

Observation



Theoretical interpretation

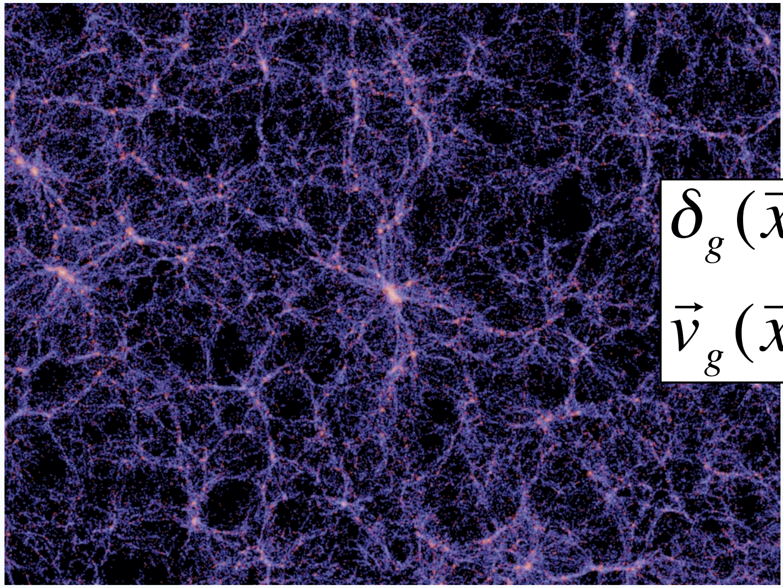




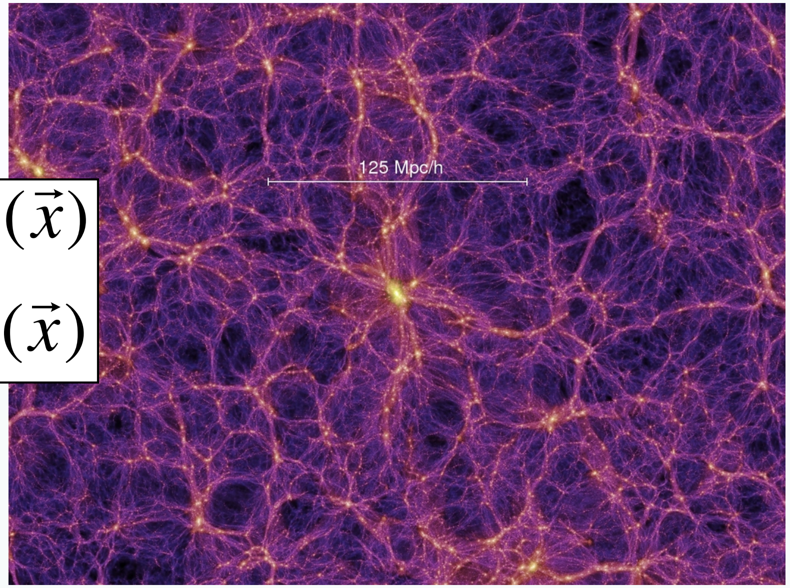
SDSS-III Baryon Oscillati
Spectroscopic Survey (B

Estimator:
2点統計量

Dark matter, halos and galaxies



$$\delta_g(\vec{x}) \neq \delta_m(\vec{x})$$
$$\vec{v}_g(\vec{x}) \neq \vec{v}_m(\vec{x})$$



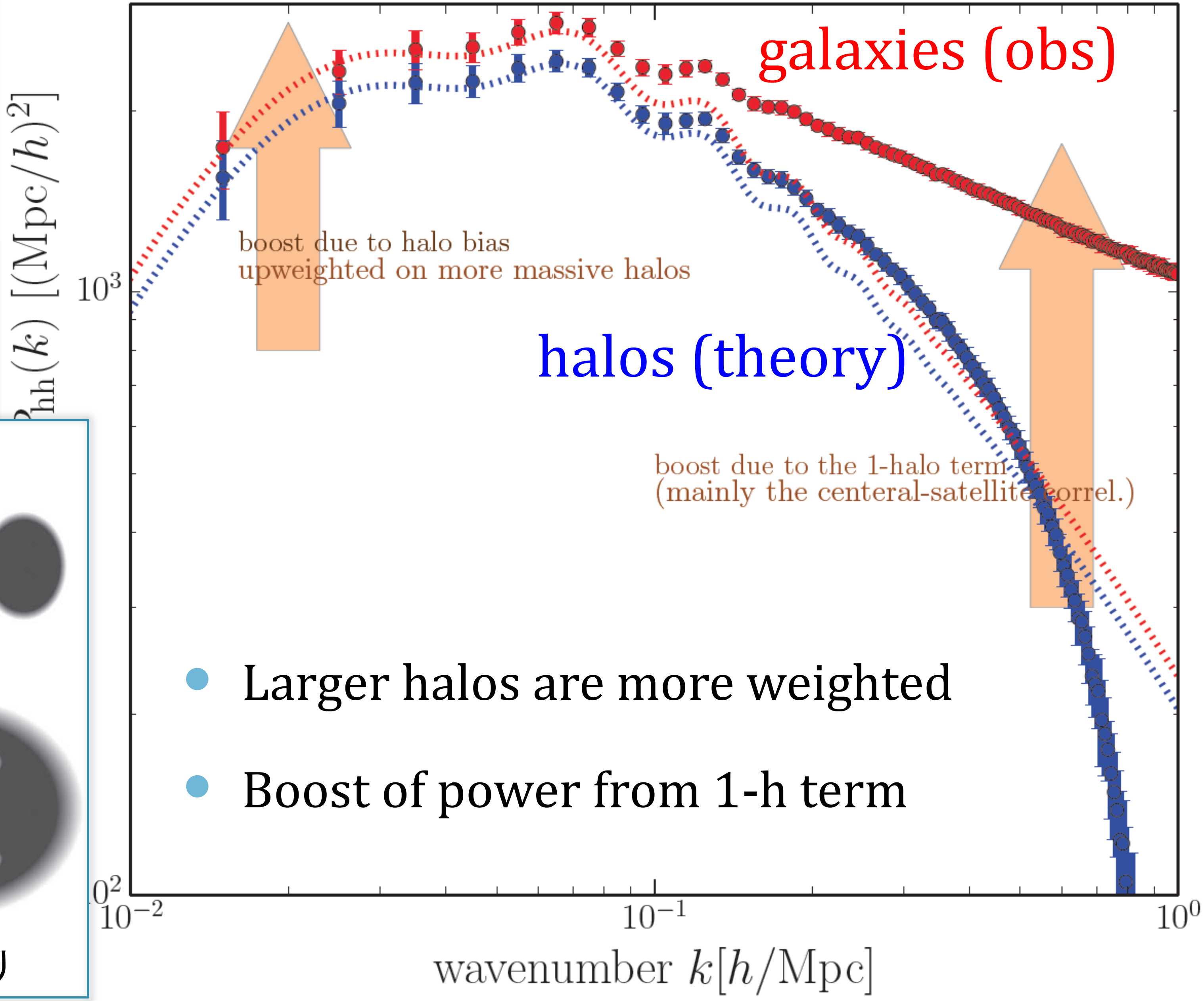
Observable: Galaxies

Predictable: Dark matter (halos)

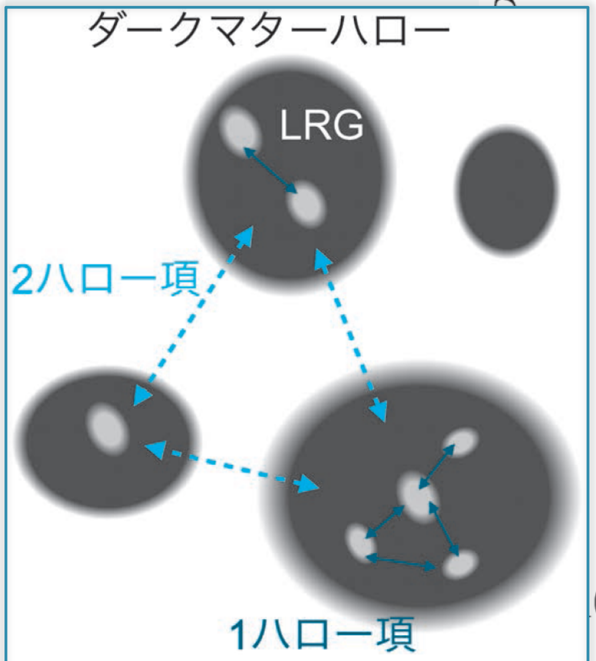
- Dark matter halos are formed at high−density regions of dark matter, and galaxies are formed inside halos
- What one can predict is clustering of dark matter, while what one can observe is galaxies.

Millennium simulations (Springel+)

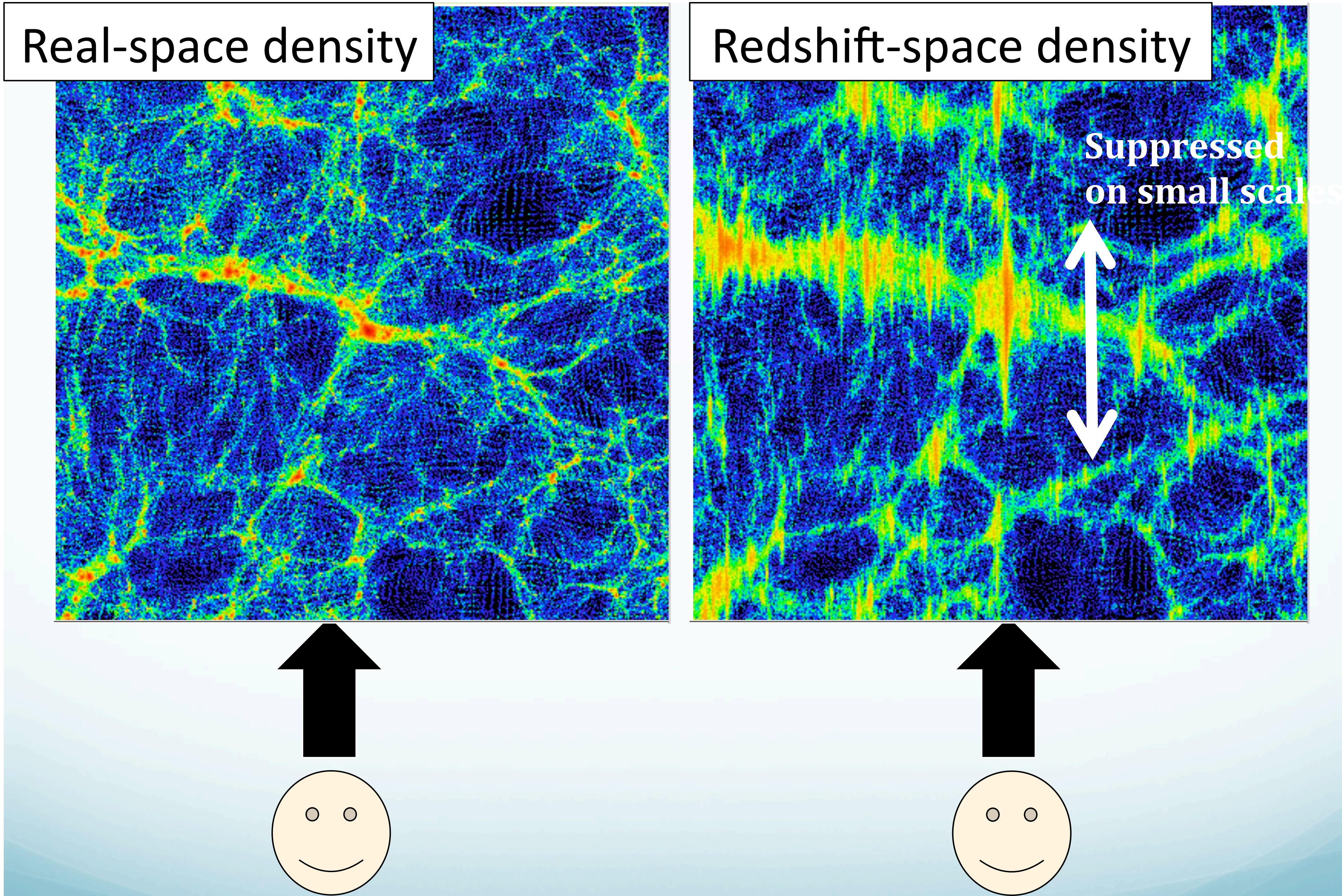
Halo *vs* galaxy: real-space clustering



- Larger halos are more weighted
- Boost of power from 1-h term



日影さん月報記事より



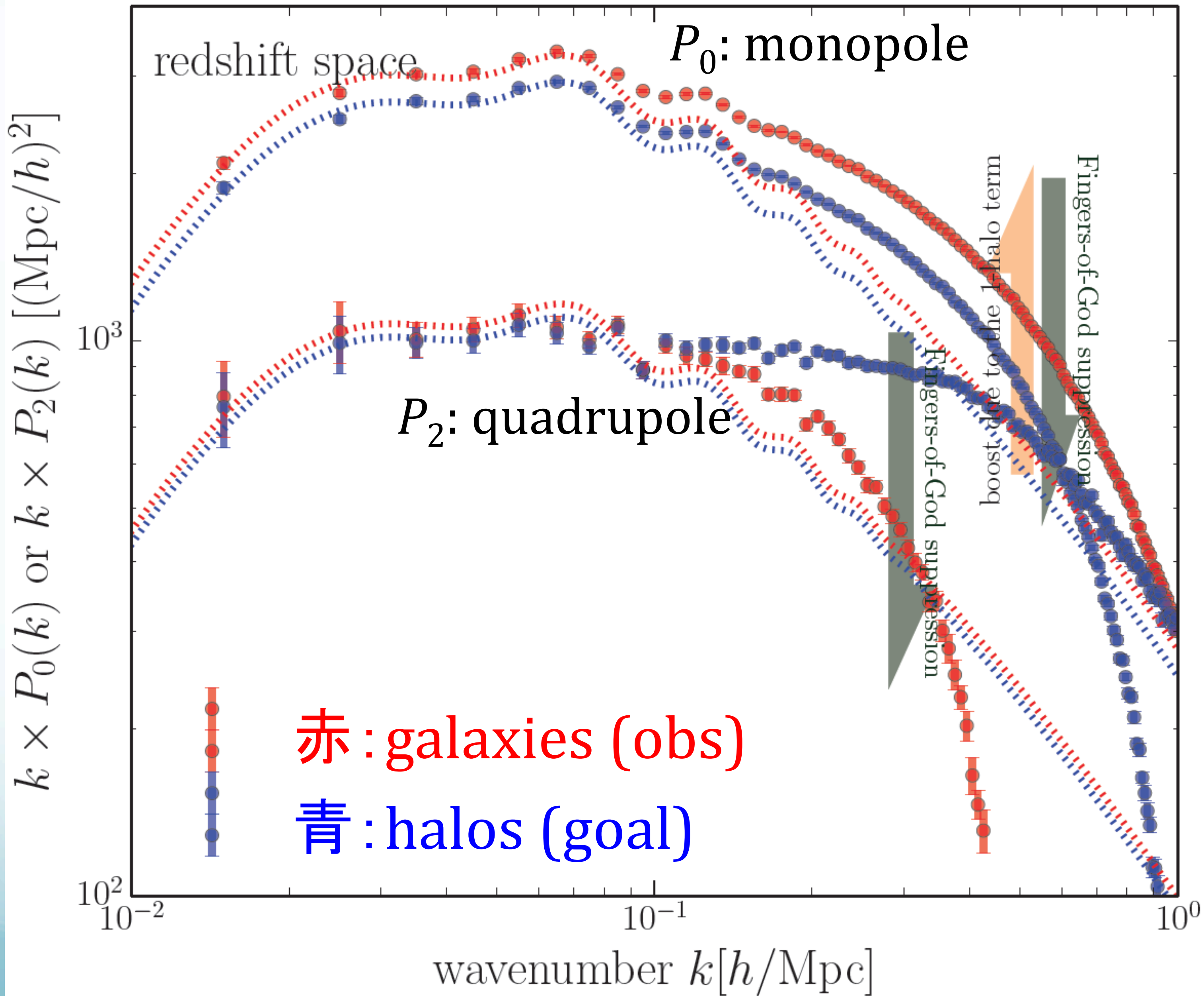
Redshift z = expansion + peculiar velocity

distance

The visualization made by T. Nishimichi

Halo *vs* galaxy: redshift-space clustering

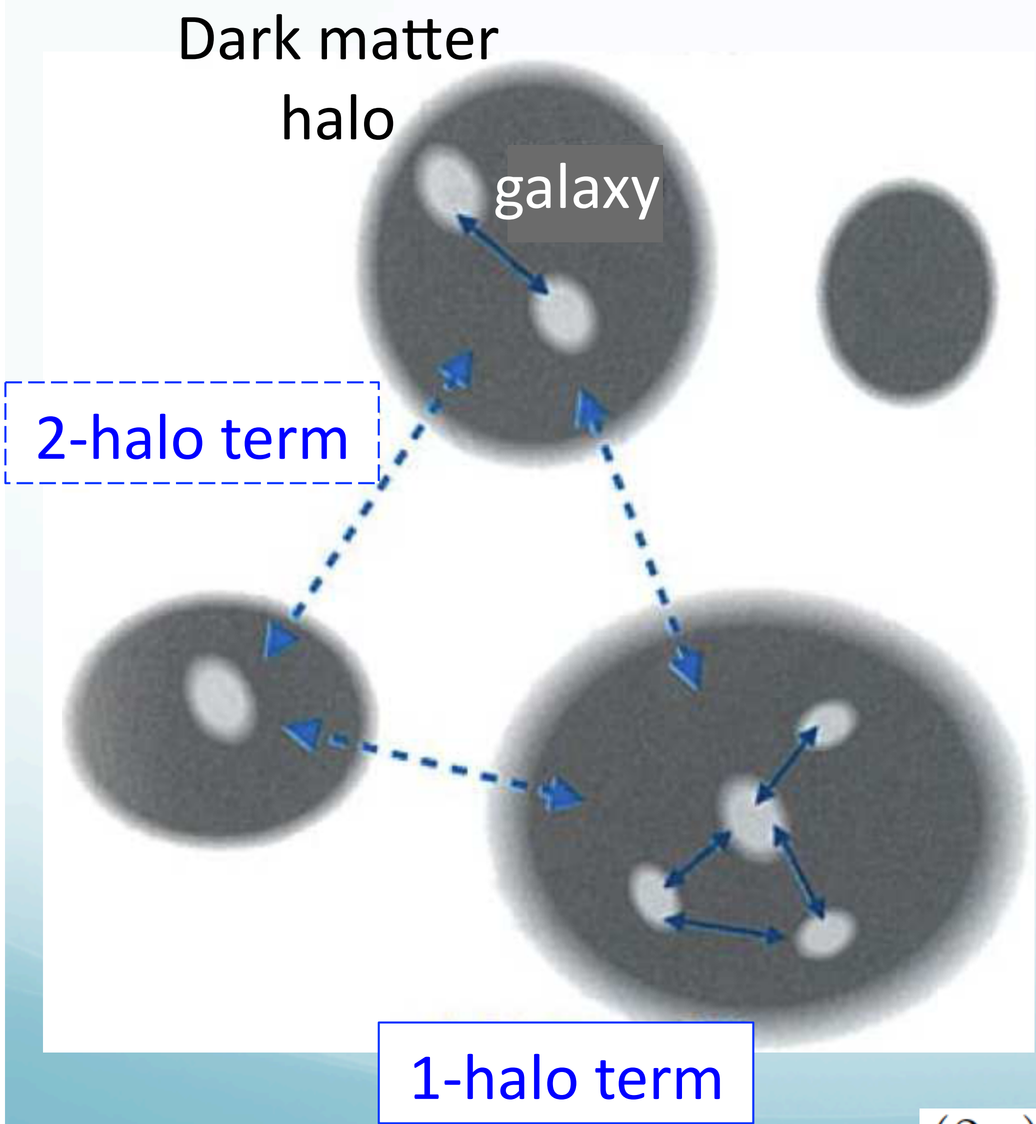
- Larger halos are more weighted
- Boost of power from 1-h term
- Suppression of power for both 1-h and 2-h term



Purpose and results of this work

- 目的：銀河サーベイで精密宇宙論をやるために、銀河(観測)とハロー(理論) の間のdistribution & kinetics のギャップを埋めたい
- 理論をハローから銀河：***TO***, Hand, Seljak, Vlah & Desjacques 2015
  - 摂動論／N体でハロークラスタリングを計算し、ハローモデルで銀河クラスタリングをモデルする。
- 観測を銀河からハロー：***TO***, Takada, More & Masaki, in prep.
  - RSD 入りの銀河分布からハローパワースペクトルをreconstruct する。
- 結論：N体でSDSS-III BOSS 型の銀河モックを作ってテストした結果、どちらの方法もhigh-k までうまくいくことがわかった。

Halo model description



- Theory
  - Galaxies = 1h + 2h

$$P_{gg}^{S}(\mathbf{k}) = \underbrace{P_{gg}^{S1h}(\mathbf{k})}_{\text{1-halo}} + \underbrace{P_{gg}^{S2h}(\mathbf{k})}_{\text{2-halo}}$$

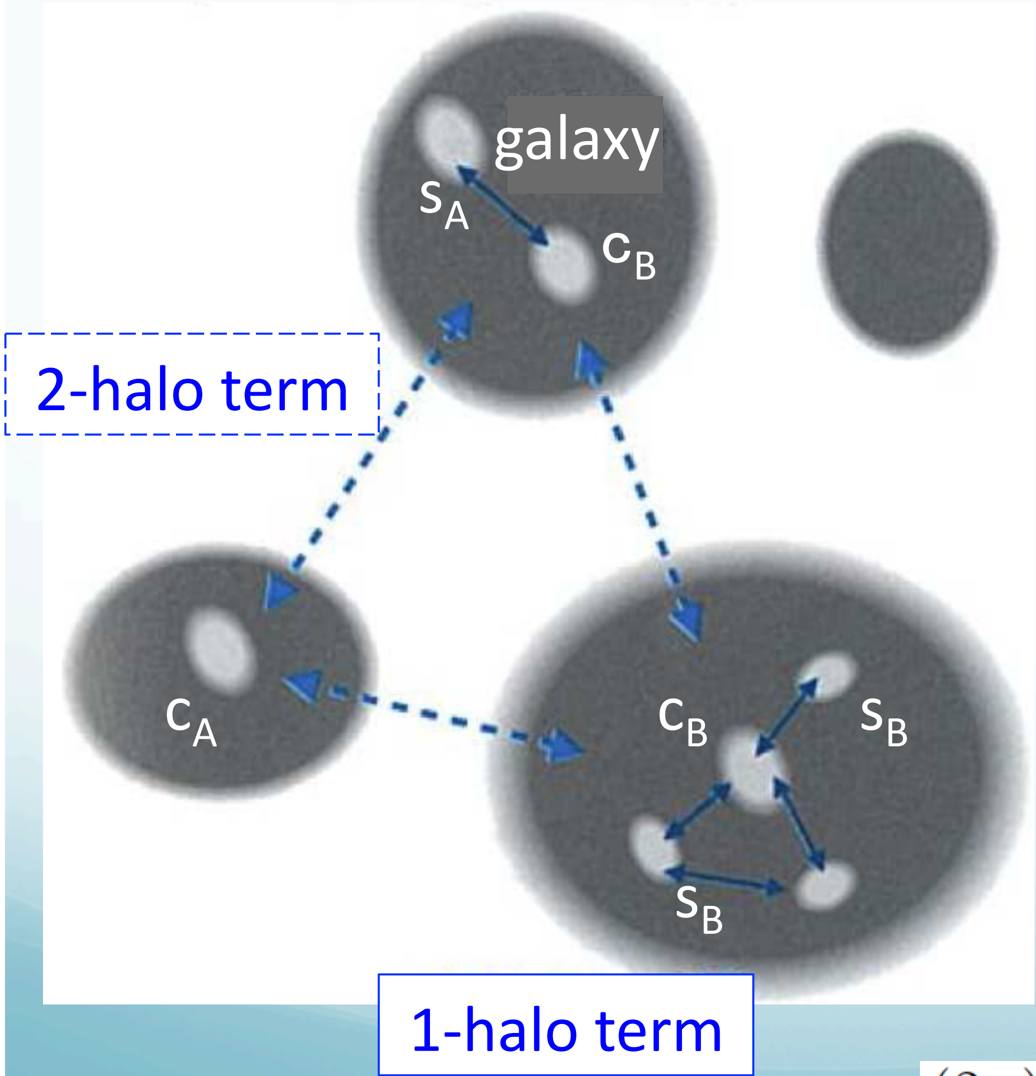
- Observation
  - Galaxies
  - = centrals + satellites

$$\delta_g^S(\mathbf{k}) = (1-f_s)\delta_c^S(\mathbf{k}) + f_s\delta_s^S(\mathbf{k})$$

$$\begin{aligned} P_{gg}^S(\mathbf{k}) &= (1-f_s)^2 P_{cc}^S(\mathbf{k}) \\ &+ 2f_s(1-f_s)P_{cs}^S(\mathbf{k}) + f_s^2 P_{ss}^S(\mathbf{k}) \end{aligned}$$

$$(2\pi)^3 P_{gg}^S(\mathbf{k})\delta(\mathbf{k}-\mathbf{k}') \equiv \left\langle \delta_g^S(\mathbf{k})\delta_g^{S*}(\mathbf{k}') \right\rangle$$

Decomposing galaxy field in redshift survey (density field + velocity field)



- Galaxies
  - = centrals (c)+ satellites (s)
- Centrals
  - = with no satellite (c_A)
  - + with satellite (c_B)
- Satellites
  - = with no other satellite (s_A)
  - + with other satellites (s_B)

$$(2\pi)^3 P_{gg}^S(\mathbf{k})\delta(\mathbf{k}-\mathbf{k}') \equiv \langle \delta_g^S(\mathbf{k})\delta_g^{S*}(\mathbf{k}')\rangle$$

Power spectra of decomposed fields

Decomposed power

$$P^S_{gg}(\mathbf{k}) = \boxed{P^{S1h}_{gg}(\mathbf{k})} + \boxed{P^{S2h}_{gg}(\mathbf{k})}, \tag{5}$$

where the 2-halo and 1-halo terms are given by

$$\begin{aligned}\boxed{P^{S2h}_{gg}(\mathbf{k})} &= (1-f_s)^2 \boxed{P^S_{cc}(\mathbf{k})} + 2f_s(1-f_s) \\ &\quad \times \left(\frac{N_{c_A}}{N_c} \boxed{P^S_{c_A s}(\mathbf{k})} + \frac{N_{c_B}}{N_c} \boxed{P^{S2h}_{c_B s}(\mathbf{k})} \right) \\ &\quad + f_s^2 \left(\frac{N^2_{s_A}}{N^2_s} \boxed{P^S_{s_A s_A}(\mathbf{k})} + \frac{2N_{s_A}N_{s_B}}{N^2_s} \boxed{P^S_{s_A s_B}(\mathbf{k})} \right. \\ &\quad \left. + \frac{N^2_{s_B}}{N^2_s} \boxed{P^{S2h}_{s_B s_B}(\mathbf{k})} \right), \end{aligned} \tag{6}$$

$$\begin{aligned}\boxed{P^{S1h}_{gg}(\mathbf{k})} &= 2f_s(1-f_s)\frac{N_{c_B}}{N_c} \boxed{P^{S1h}_{c_B s}(\mathbf{k})} \\ &\quad + f_s^2 \frac{N^2_{s_B}}{N^2_s} \boxed{P^{S1h}_{s_B s_B}(\mathbf{k})}. \end{aligned} \tag{7}$$

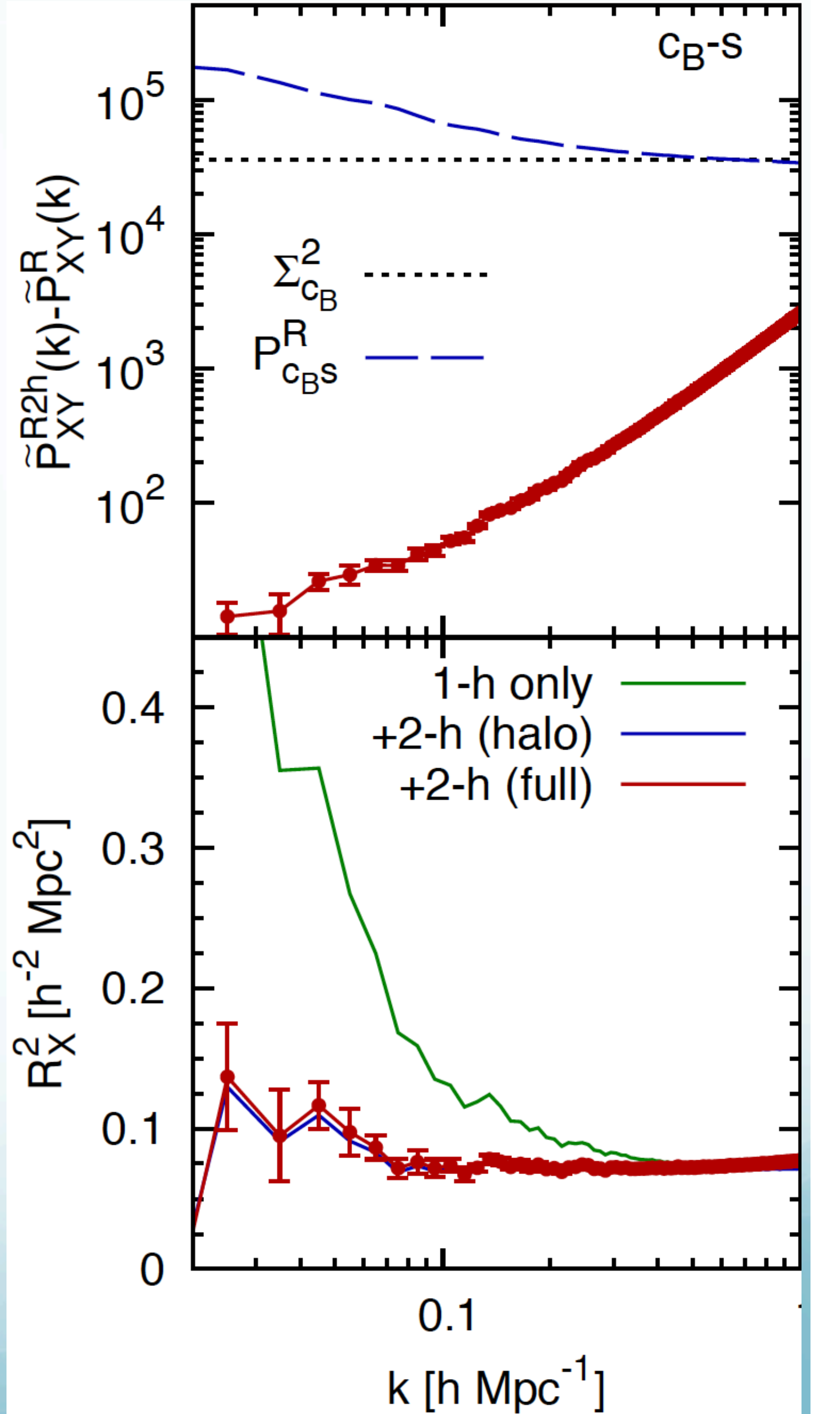
Effect of halo satellite radius

- In real-space power spectrum
  - Satellite clustering = host halo clustering?
  - Expanding halo profile with halo radius R_s

$$P^{1h}_{c_B s} = A_0 k^0 - A_2 k^2 R_s^2 + \cdots$$

$$P^{2h}_{c_B s} = P_{lin}(k^0 - B_2 k^2 R_s^2 + \cdots)$$

  - ~3% effect at k~0.5h/Mpc
  - → for BOSS-type galaxies, < 1%
- Even more smeared out in redshift space



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$$\begin{aligned} P^{S2h}_{gg}(\mathbf{k}) = {} & (1-f_s)^2 P^S_{cc}(\mathbf{k}) + 2f_s(1-f_s) \\ & \times \left(\frac{N_{c_A}}{N_c} P^S_{c_A s}(\mathbf{k}) + \frac{N_{c_B}}{N_c} P^{S2h}_{c_B s}(\mathbf{k}) \right) \\ & + f_s^2 \left(\frac{N^2_{s_A}}{N^2_s} P^S_{s_A s_A}(\mathbf{k}) + \frac{2N_{s_A}N_{s_B}}{N^2_s} P^S_{s_A s_B}(\mathbf{k}) \right. \\ & \left. + \frac{N^2_{s_B}}{N^2_s} P^{S2h}_{s_B s_B}(\mathbf{k}) \right), \quad (6) \end{aligned}$$

$$\begin{aligned} P^{S1h}_{gg}(\mathbf{k}) = {} & 2f_s(1-f_s)\frac{N_{c_B}}{N_c} P^{S1h}_{c_B s}(\mathbf{k}) \\ & + f_s^2 \frac{N^2_{s_B}}{N^2_s} P^{S1h}_{s_B s_B}(\mathbf{k}). \quad (7) \end{aligned}$$

2-halo terms

$$\begin{aligned} P^S_{cc}(k,\mu) &= P^S_{cc,h}(k,\mu) && (27) \\ P^S_{c_A s}(k,\mu) &= G(k\mu;\sigma_{v,s}) P^S_{c_A s,h}(k,\mu), && (28) \\ P^S_{s_A s_A}(k,\mu) &= G^2(k\mu;\sigma_{v,s_A}) P^S_{s_A s_A,h}(k,\mu), && (29) \\ P^S_{s_A s_B}(k,\mu) &= G(k\mu;\sigma_{v,s_A}) G(k\mu;\sigma_{v,s_B}) \\ & \quad \times P^S_{s_A s_B,h}(k,\mu), && (30) \end{aligned}$$

1 and 2-halo terms

$$\begin{aligned} P^S_{c_B s}(k,\mu) &= G(k\mu;\sigma_{v,s}) \left[\widetilde{P}^S_{c_B s,h}(k,\mu) - \Sigma^2_{c_B} \right] \\ & \quad + G(k\mu;\sigma_{v,s}) \Sigma^2_{c_B} \\ &= G(k\mu;\sigma_{v,s}) \widetilde{P}^S_{c_B s,h}(k,\mu) && (31) \end{aligned}$$

$$P^S_{s_B s_B}(k,\mu) = G^2(k\mu;\sigma_{v,s_B}) \left[\widetilde{P}^S_{s_B s_B,h}(k,\mu) - \sigma^2_{n,s_B} \right]. \quad (33)$$

$$G(k\mu;\sigma_v) = \begin{cases} e^{-k^2\mu^2\sigma_v^2/2} & \text{Gaussian,} \\ (1+k^2\mu^2\sigma_v^2/2)^{-2} & \text{Lorentzian.} \end{cases} \quad (34)$$

$$\sigma_v^2(M) = \sigma^2_{v,0} \left(\frac{M}{10^{13} M_\odot/h} \right)^{2/3}$$

- $P_{XY,h}$: power spectrum of halos hosting galaxies X and Y

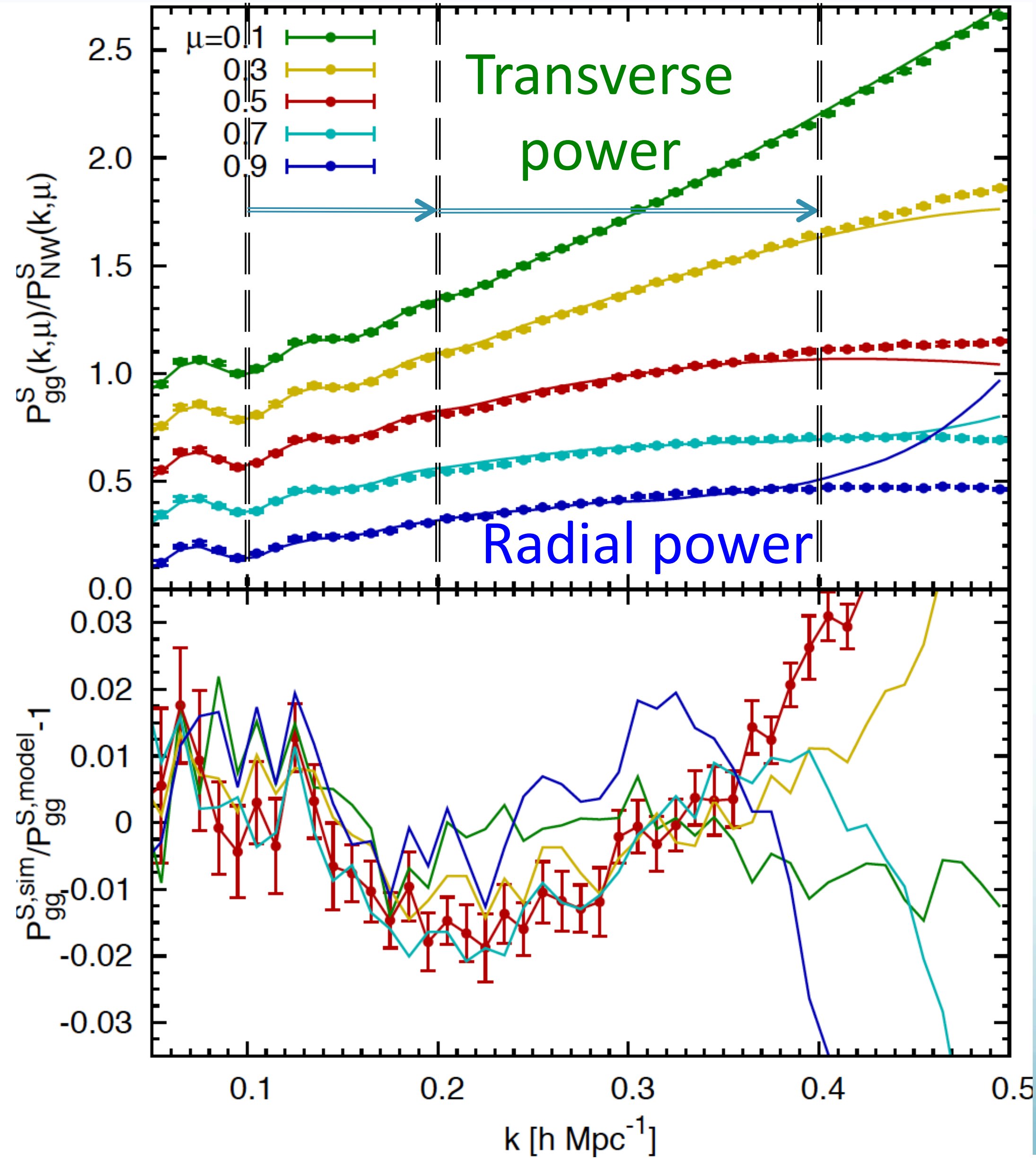
Perturbation theory for redshift-space halo clustering

- Distribution function approach
  - Paper I. Seljak & McDonald (2011) JCAP
  - Paper II. ***Okumura***, Seljak, McDonald, Desjacques (2012a) JCAP
  - Paper III. ***Okumura***, Seljak, Desjacques (2012b) JCAP
  - Paper IV. Vlah, Seljak, McDonald, ***Okumura***, Baldauf (2012) JCAP
  - Paper V. Vlah, Seljak, ***Okumura***, Desjacqeus (2013) JCAP
  - Paper VI. Blazek, Seljak, Vlah, ***Okumura*** (2014) JCAP

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

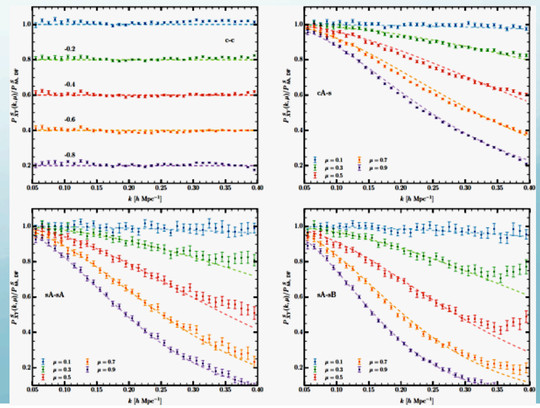
$$P^{XY,h}_{LL'}(\mathbf{k})(2\pi)^3\delta_D(\mathbf{k}-\mathbf{k}') = \left\langle T^{X,L}_{\parallel}(\mathbf{k})T^{Y,L'*}_{\parallel}(\mathbf{k}')\right\rangle$$

Testing theoretical model with BOSS-like simulation result at z=0.5



- Points:
  - Simulation results
- Lines:
  - Theoretical (PT) model

  - 3% at k=0.4h/Mpc for PT-based model
  - 1.5% at k=0.5h/Mpc for sim-based model



Summary for the first half

- Galaxy density field can be decomposed to subsamples and be separated into 1-halo and 2-halo terms.
- We found the power spectrum of galaxies can be well modeled by that of their host halos with only one (or at most two) additional parameter, the velocity dispersion damping $\sigma_v(M)$
- Percent accuracy up to k~0.4h/Mpc (4^3=64 times more modes compared to k~0.1h/Mpc case) for SDSS-III BOSS mock galaxies.
- We can apply this technique to the real BOSS surveys, and also eBOSS, Subaru PFS, DESI, etc.

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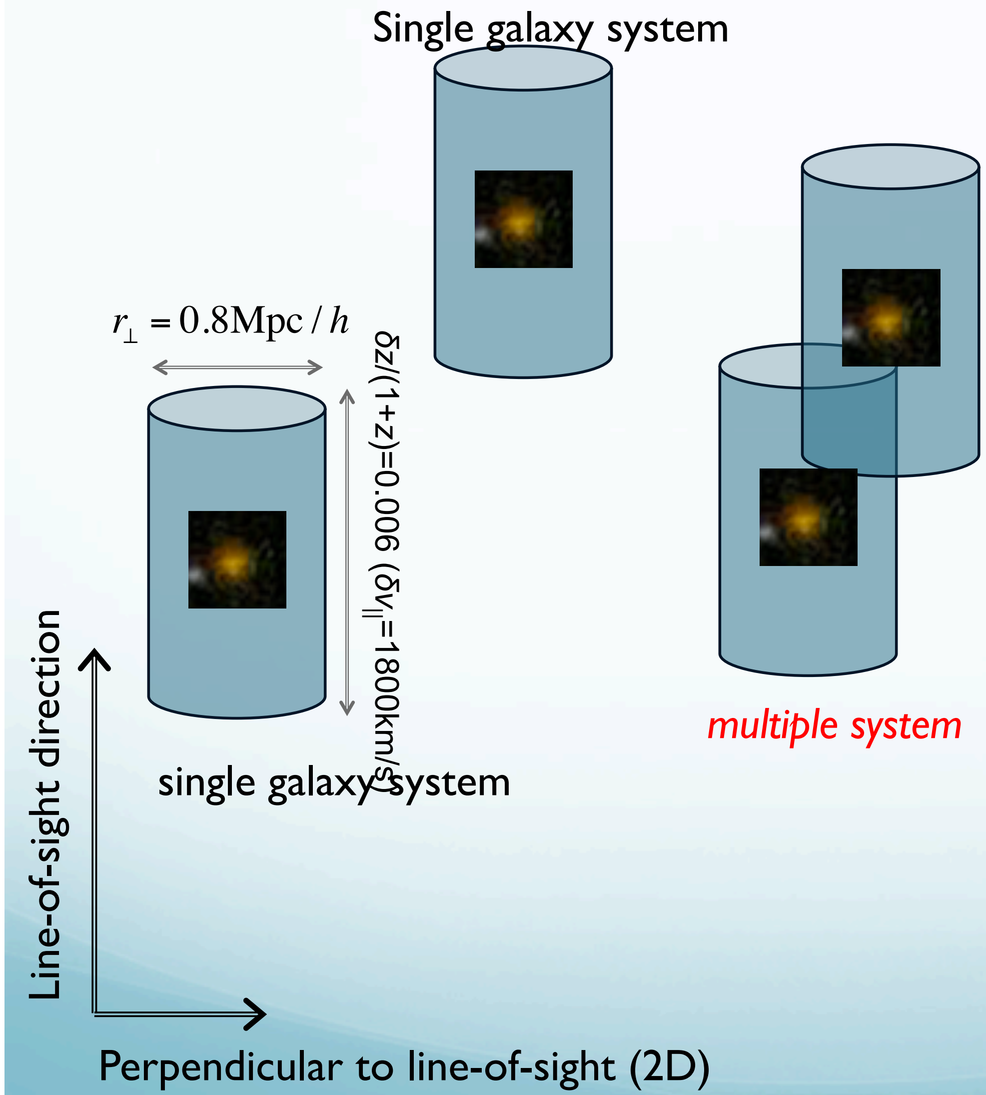
- 結論:N体でSDSS-III BOSS 型の銀河モックを作ってテストした結果、どちらの方法もhigh-k までうまくいくことがわかった。

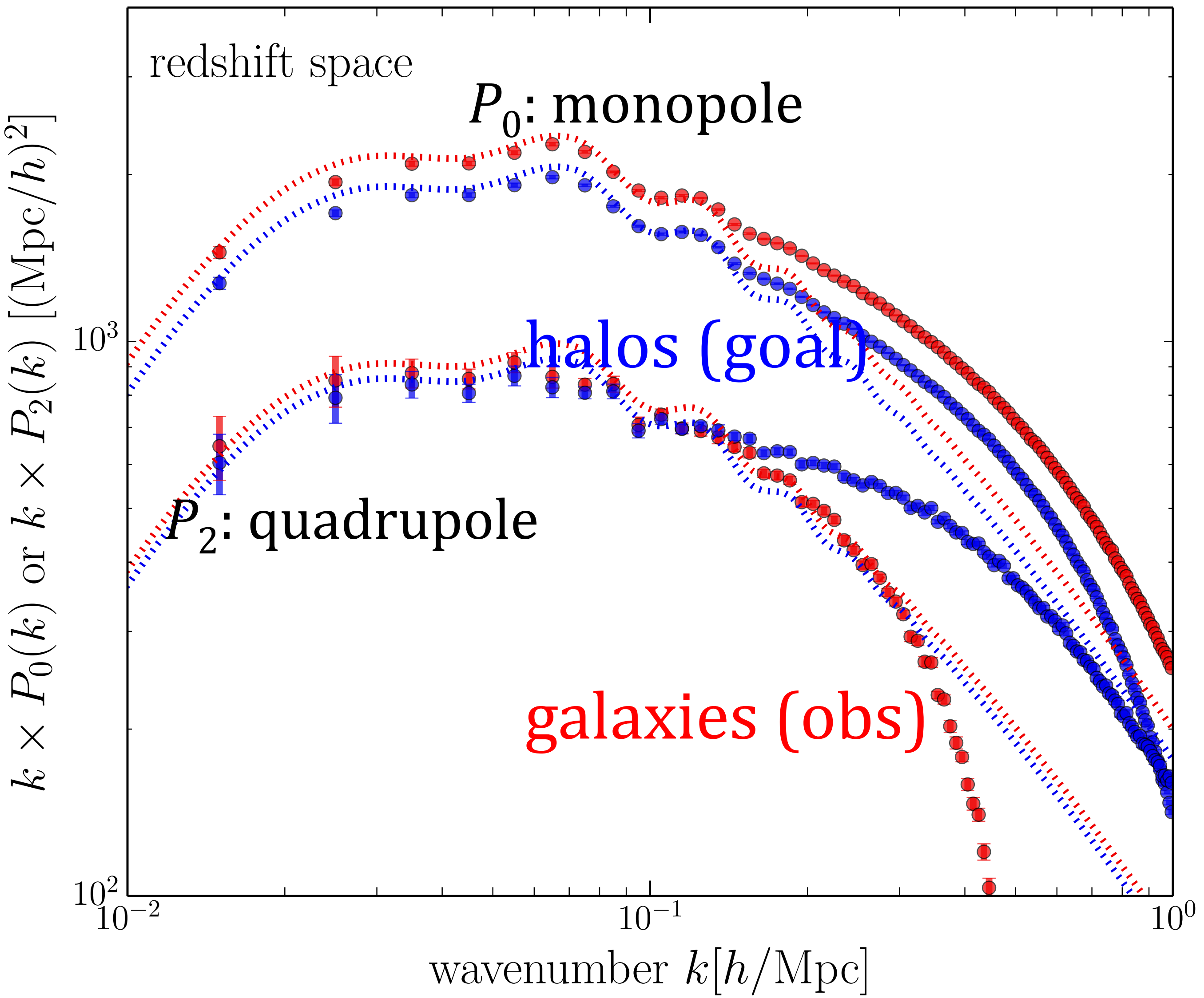
From galaxies to halos: Counts-in-Cylinders technique

Reid & Spergel 2009



- Apply a cylinder-shape region around each galaxy (taking into account RSD)
- Overlapped cylinders are considered to be in the same halo.
- RS09 found multiple SDSS LRG systems are about 5-6% of all LRGs
- *Question: can we apply this technique for high-density samples with higher satellite fraction, such as BOSS CMASS?*

Applying CiC to mock galaxies at z=0.5



- Galaxy dist.

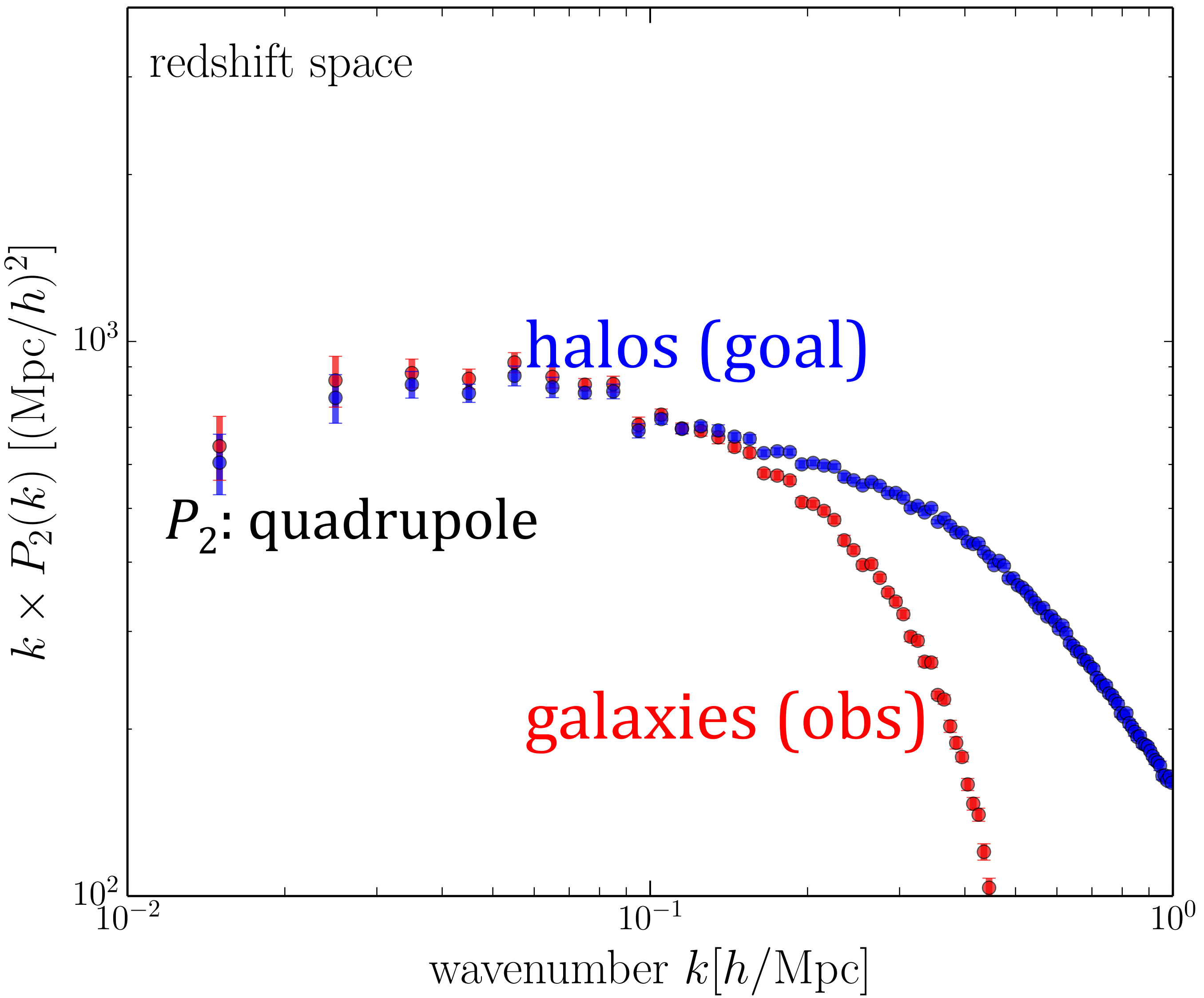
  Identify halos using CiC and compute their power spectrum

- Halo clustering?

- $n_g \sim 3.5\times10^{-4}\,(h/\mathrm{Mpc})^3$

  $\sim n_{\mathrm{BOSS}}$

Applying CiC to mock galaxies at z=0.5



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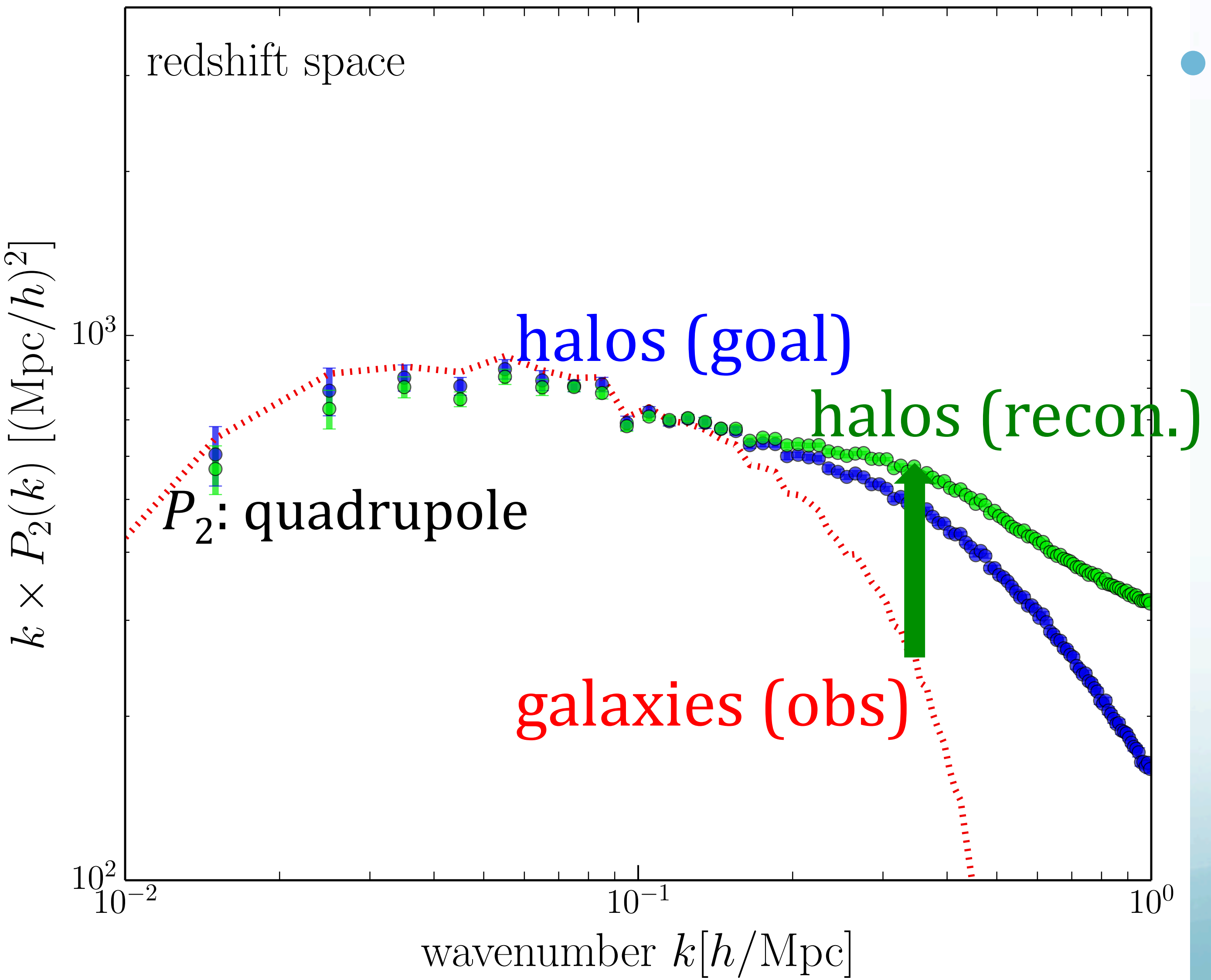
Applying CiC to mock galaxies at *z*=0.5



- The cylinder itself has an anisotropic shape, thus produces the artificial quadrupole.

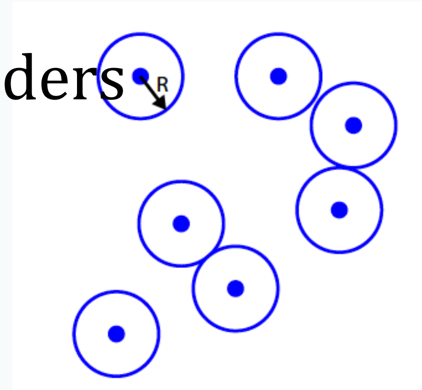
Correcting for the cylinder anisotropies

- Decomposed power spectrum (Okumura et al 2015)

$$P^S_{\rm gg}(\mathbf{k}) = f_{\rm c}^2 P^S_{\rm cc}(\mathbf{k}) + 2 f_{\rm c} f_{\rm s} P^S_{\rm cs}(\mathbf{k}) + f_{\rm s}^2 P^S_{\rm ss}(\mathbf{k})$$

?

- Holds for the spectra decomposed based on cylinders



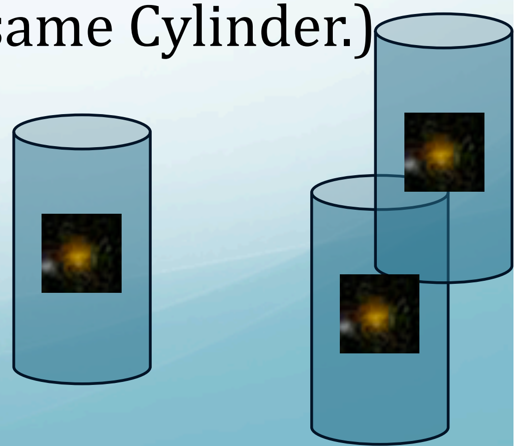
$$P^S_{gg}(\mathbf{k}) = \boxed{\tilde{f}_c^2 \tilde{P}^S_{cc}(\mathbf{k})} + 2\tilde{f}_c f_s \tilde{P}^S_{cs}(\mathbf{k}) + \tilde{f}_s^2 \tilde{P}^S_{ss}(\mathbf{k})$$

- Power spectrum with exclusion   Baldauf et al (2013)

$$P^S_{hh}(\mathbf{k}) = \tilde{f}_c^2 \tilde{P}^S_{cc}(\mathbf{k}) - \tilde{f}_c^2 \boxed{\left\{ W(\mathbf{k}) + \left[W * \tilde{P}^S_{cc} \right](\mathbf{k}) \right\}} + \boxed{\alpha(\mu)} P^S_{lin}(\mathbf{k})$$

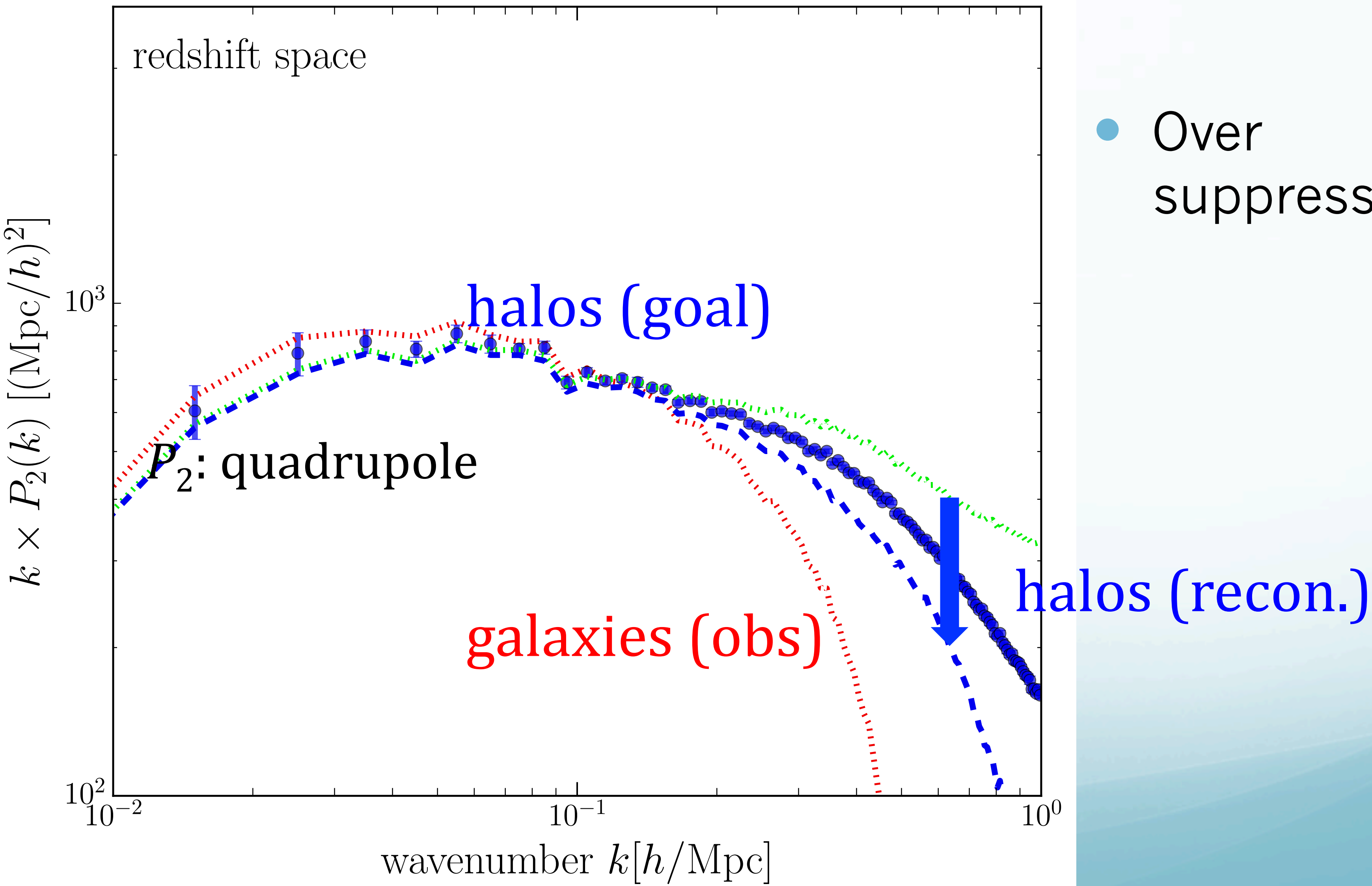
  - *W*(**k**) : window (Two galaxies cannot be in the same Cylinder.)

$$|W(\mathbf{k})| = 2\frac{J_1(k_\perp r)}{k_\perp r}\frac{\sin(k_\parallel l)}{k_\parallel l} V_W$$



  - $\alpha(\mu)$: Large-scale clustering amplitude
  is determined using the real−space multipole.

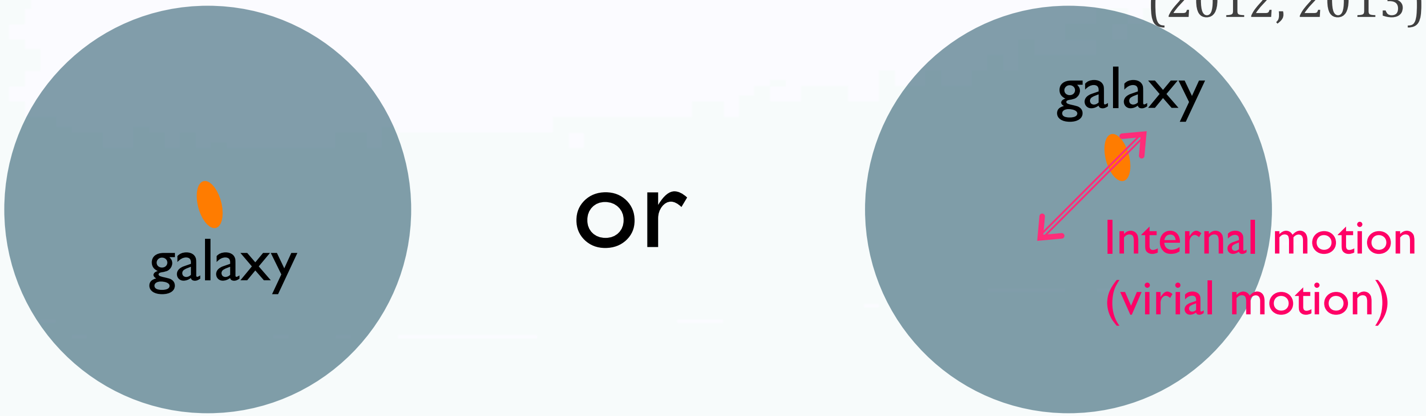
Applying CiC to mock galaxies at z=0.5



- Over suppression

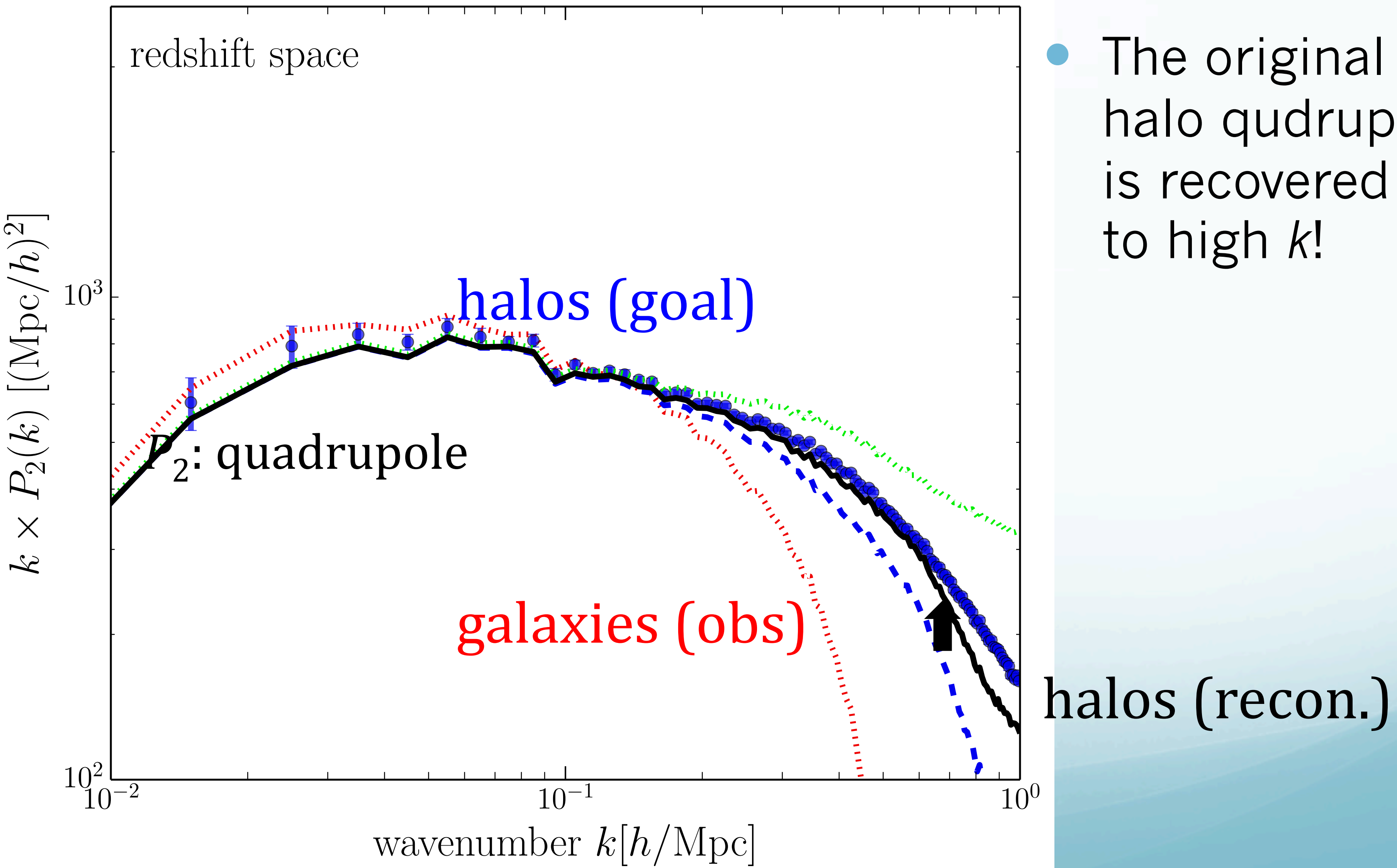
Off-centering effect even for single galaxy systems

Hikage, Takada et al (2012, 2013)



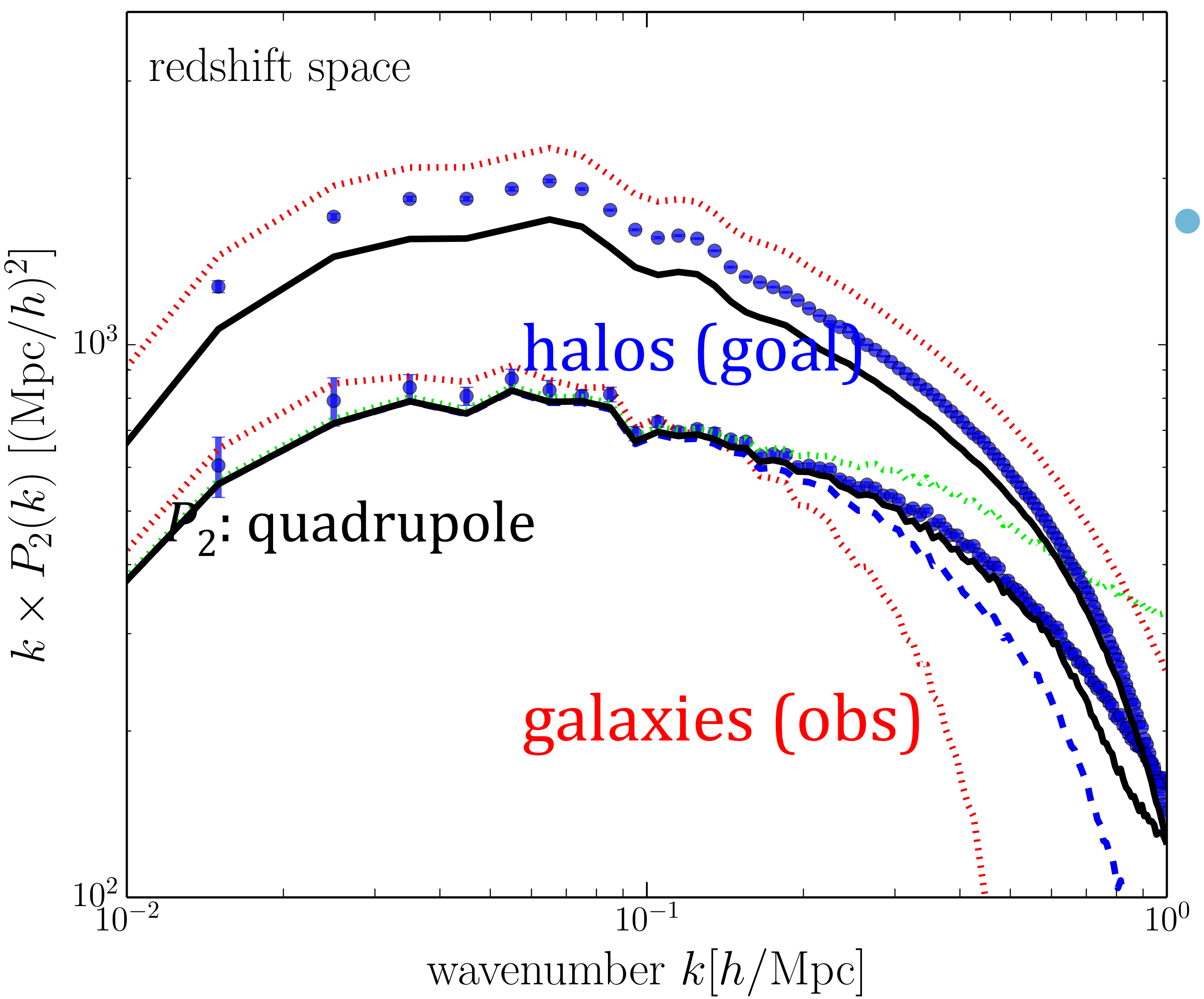
- ~20% of SDSS central LRGs are actually off-centered.
- It causes the residual FoG damping.
- Assuming we can correct for the effect (we could if galaxy-galaxy lensing is used), the galaxy velocity is replaced by the halo center.

Applying CiC to mock galaxies at *z*=0.5



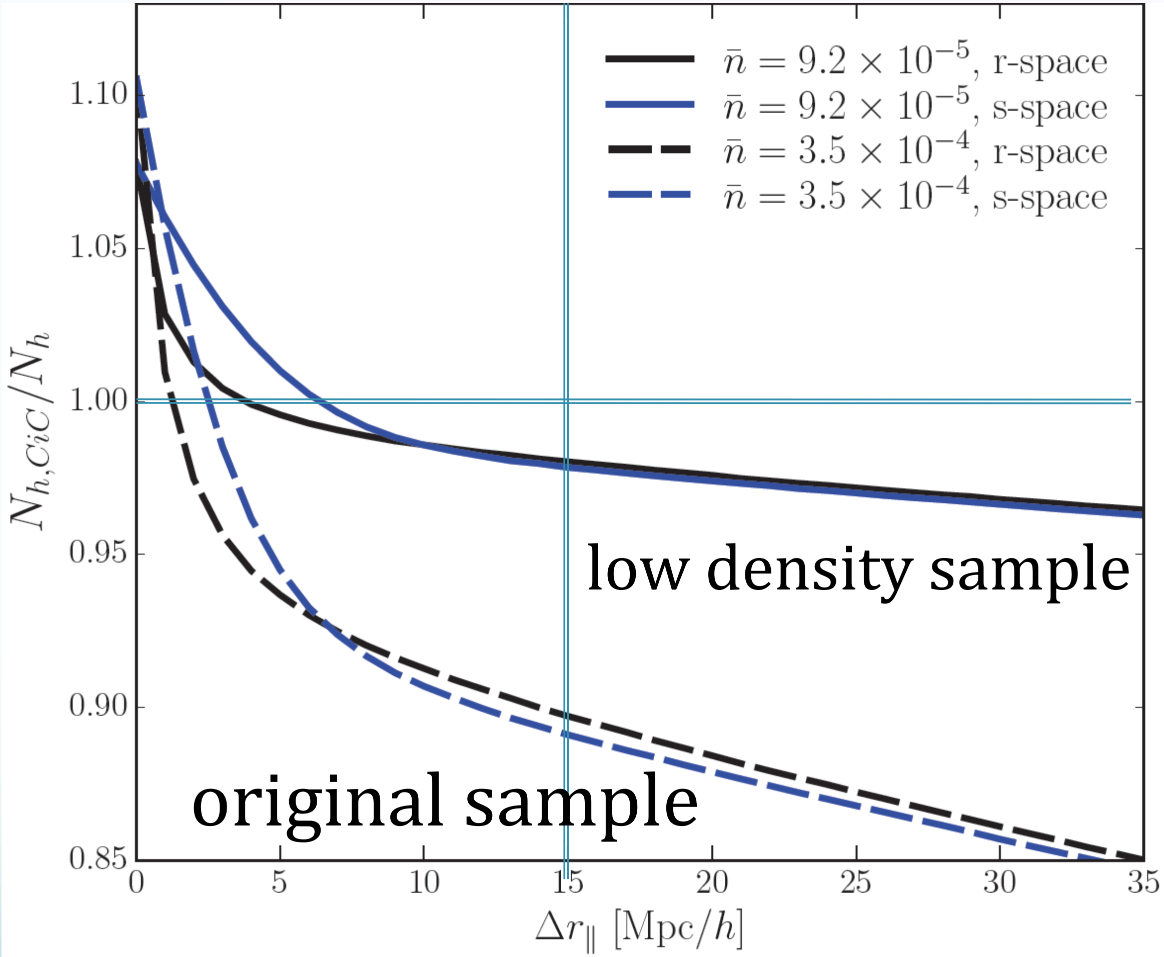
- The original halo qudrupole is recovered up to high *k*!

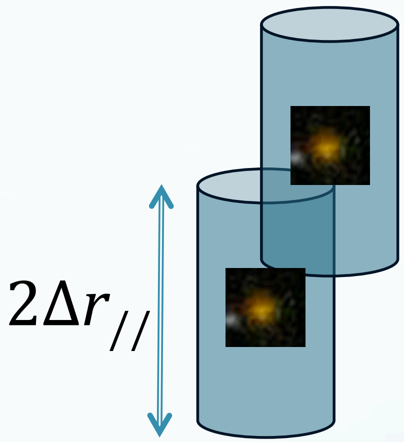
Applying CiC to mock galaxies at *z*=0.5



- However, note that the clustering loss due to window is corrected using the real-space quadrupole (coming only from cylinder anisotropy).

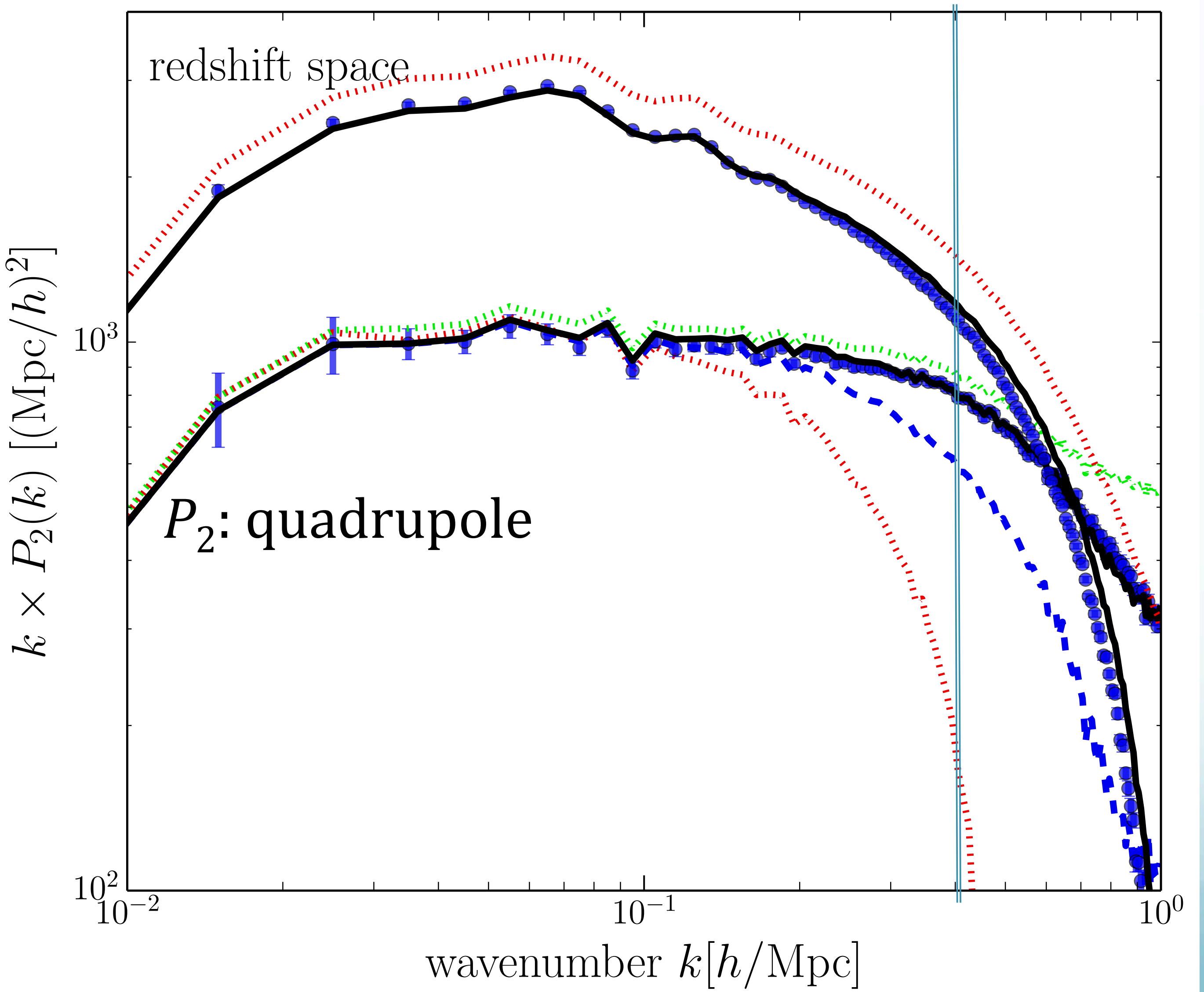
CiCハロー数と真のハロー数の比





$$P^S_{hh}(\mathbf{k}) = \widetilde{f}_c^2 \widetilde{P}^S_{cc}(\mathbf{k}) - \widetilde{f}_c^2 \left\{ W(\mathbf{k}) + \left[W * \widetilde{P}^S_{cc} \right](\mathbf{k}) \right\} + \boxed{\alpha(\mu) P^S_{lin}(\mathbf{k})}$$

Applying CiC to mock galaxies at z=0.5

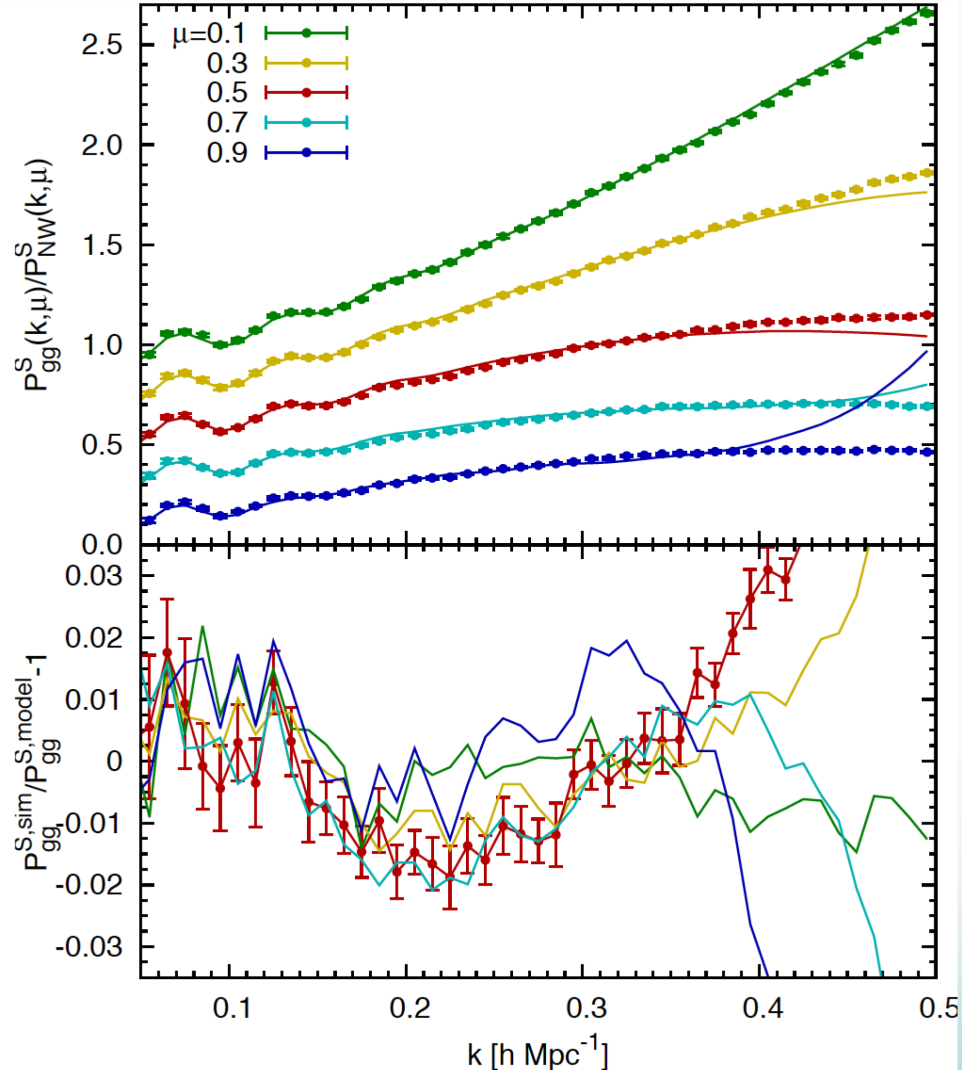


- Reduce number density to
- $n_g \sim 1.0\times10^{-4}$ (h/Mpc)^3
- Monopole + quadrupole with galaxy-halo lensing work up to $k\sim0.3$h/Mpc for BOSS sample.

Summary for the second half

- We have developed a method to reconstruct halo power spectrum from observed redshift-space galaxy distribution using CiC and halo exclusion correction.
- It works pretty well for BOSS-type galaxy sample, particularly when we reduce the number density by a factor of 3 close to SDSS LRG.
- Up to $k \sim 0.3$ h/Mpc for both Monopoles and quadrupoles, if galaxy off-centering effect is corrected for using galaxy-galaxy lensing.
- We can extract cosmological information from the BOSS survey using theoretical model for halos.
- Can be extended to eBOSS, HETEX, PFS, DESI,…

- 理論：ハローから銀河



- 観測：銀河からハロー