Formulation and measurement of the galaxy bias based on the renormalized Standard Perturbation Theory

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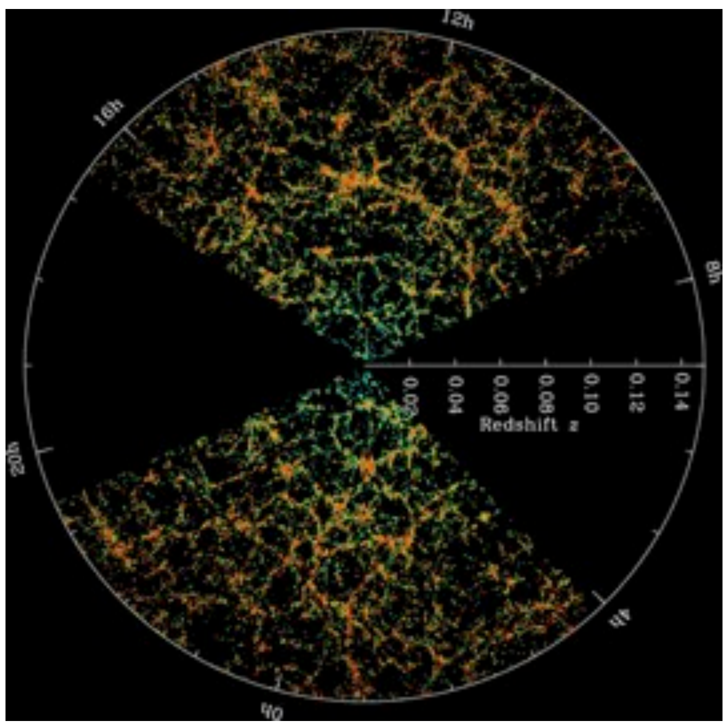
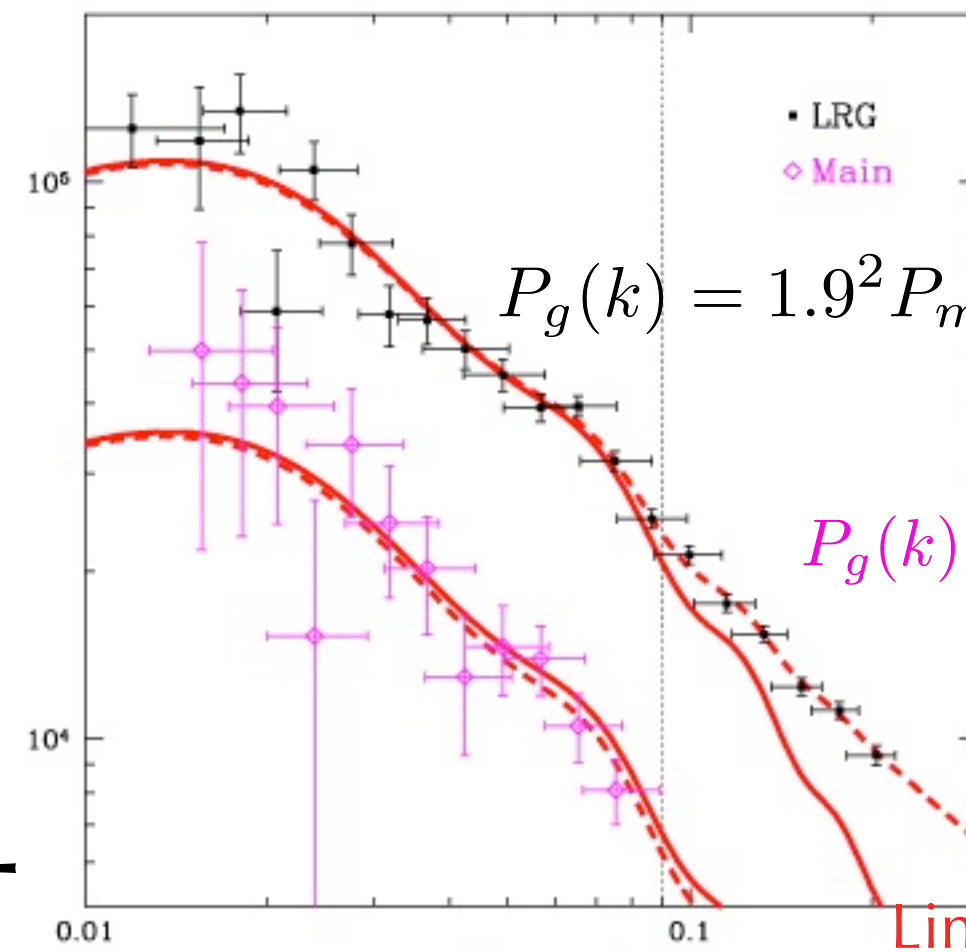
Background

What we observe is luminous object fluctuation that is different from underlying dark matter distribution.

http://www.SDSS.org



Tegmark+ 2006



Amplitude of fluctuation

$$P_g(k) = 1.9^2 P_m(k) \frac{1+Q_{\rm nl}k^2}{1+1.4k}$$

$$P_g(k) = 1.1^2 P_m(k) \frac{1+Q_{\rm nl}k^2}{1+1.4k}$$

unphysical model

Linear theory

fluctuation scale[h/Mpc]

1min. lesson ~ 95% is in this slide ~

Theory to predict the scale dependent bias

Standard Perturbation Theory for DM

+

Peak Background splitting

+

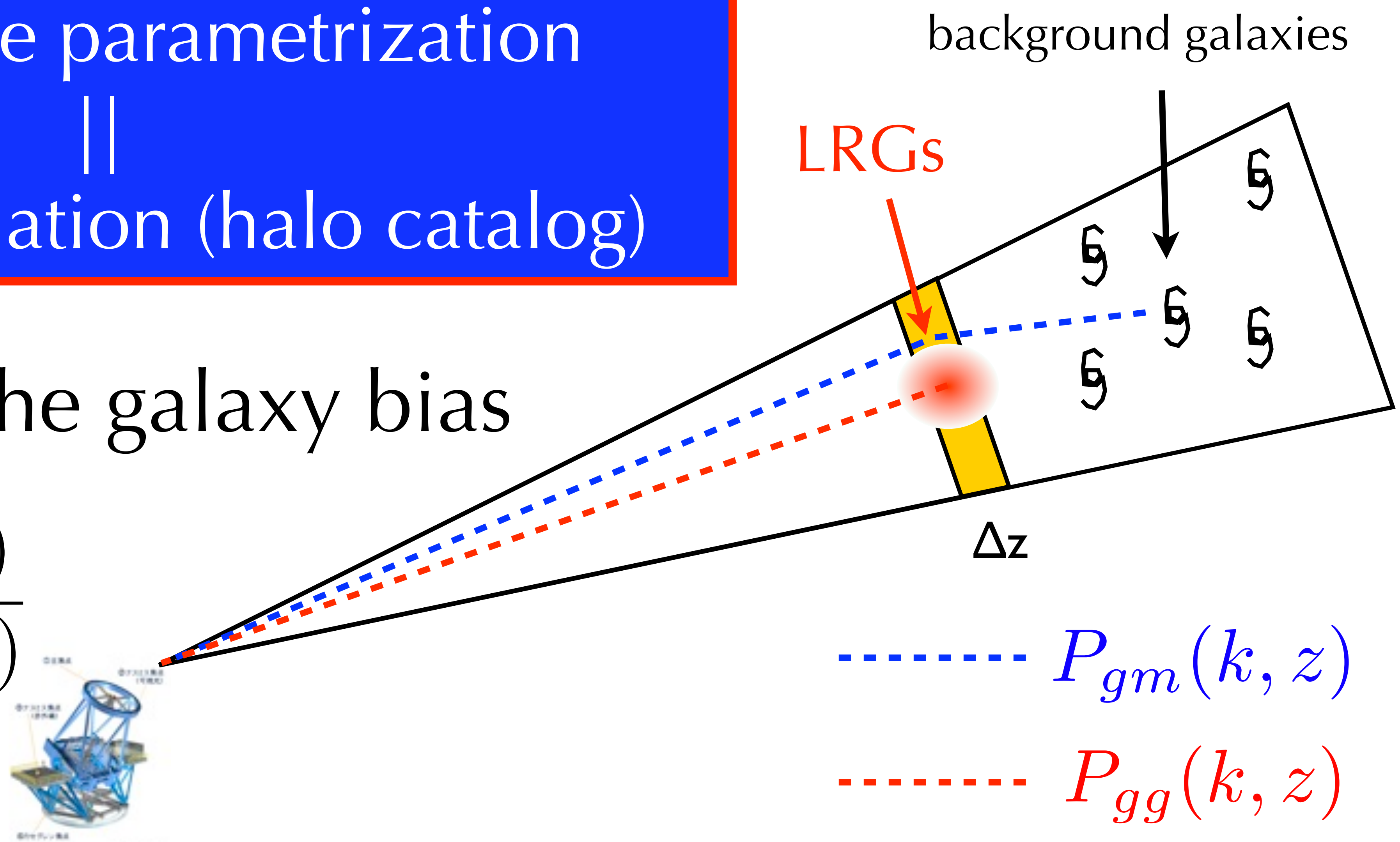
Renormalize parametrization

||

N-body simulation (halo catalog)

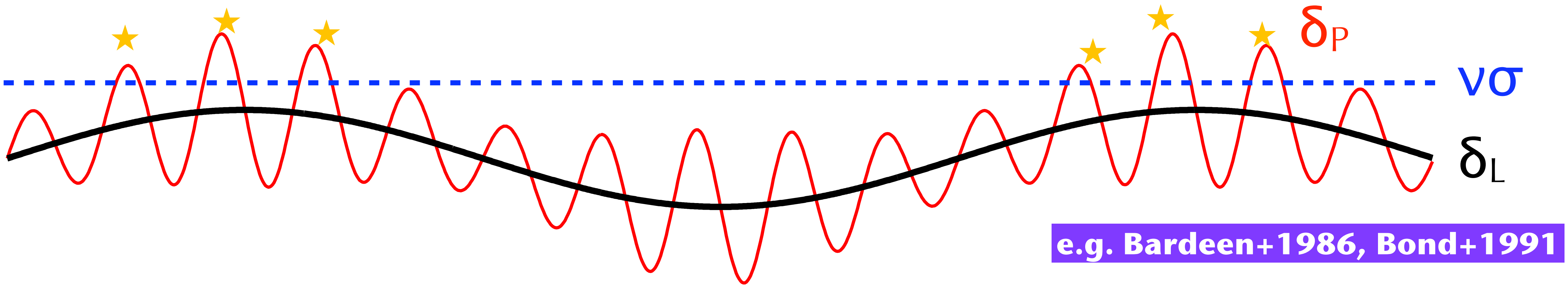
Measurement of the galaxy bias

$$b(k,z) = \frac{P_{gg}(k,z)}{P_{gm}(k,z)}$$



Peak Background Splitting

matter at dense region in Large-mode(δ_L) likely forms object



$\delta = \delta_P + \delta_L$

Suppose the density perturbation is decomposed into background and peak fluctuations.

$$P(>\nu, x) = P(>\nu, x)\left[1 - \frac{d\ln P(>\nu, x)}{d\nu}\frac{\delta_L(x)}{\sigma}\right]$$

$$\delta_g(x) = -\frac{d\ln P(>\nu, x)}{d\nu}\frac{\delta_L(x)}{\sigma} = b\delta_L(x)$$

Then the probability to find the object can be Taylor expanded in terms of the background fluctuation, δ_L

$$n(M)dM = \frac{\bar{\rho}_{m0}}{M} f(\nu)d\nu$$
$$= \frac{\bar{\rho}_{m0}}{M} A\left[1 + (a\nu)^{-p}\right]\sqrt{a\nu}\exp\left[-\frac{a\nu}{2}\right]\frac{d\nu}{\nu}$$

mass function for Bounded object (ST)

Sheth Tormen 1999

Standard Perturbation Theory

Regard DM as a perfect fluid (not compressive, no pressure), the continuity and Euler equations in the Fourier space are given as

e.g. Makino+ 1992, Jain+1994

$$\begin{cases} \dfrac{\partial\delta(\boldsymbol{k})}{\partial\tau} + \theta(\boldsymbol{k}) = -\displaystyle\int d^3k_1 \int d^3k_2 \delta_D(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}) \frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{k_1^2}\theta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2) \\ \dfrac{\partial\theta(\boldsymbol{k})}{\partial\tau} + \dfrac{\dot{a}}{a}\theta(\boldsymbol{k}) + \dfrac{6}{\tau^2}\delta(\boldsymbol{k}) = -\displaystyle\int d^3k_1 \int d^3k_2 \delta_D(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}) \frac{k^2(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)}{2k_1^2k_2^2}\theta(\boldsymbol{k}_1)\theta(\boldsymbol{k}_2) \end{cases}$$

Solving the equations above order by order together with Poisson equation, we obtain the power spectrum; $\langle\delta(k)\delta^*(k')\rangle = P(k)\delta_D(k-k')$

$$P_m(k) = P_m^L(k) + P_{m(13)} + P_{m(22)}$$

$$P_{m(13)} \equiv \frac{k^3 P^L(k;z)}{252(2\pi)^2}\int_0^\infty dr P^L(kr;z)\left[\frac{12}{r^2} - 158 + 100r^2 - 42r^4 + \frac{3}{r^2}(r^2-1)^3(7r^2+2)\ln\left|\frac{1+r}{1-r}\right|\right],$$

$$P_{m(22)} \equiv \frac{k^3}{98(2\pi)^2}\int_0^\infty dr P^L(kr;z) \times \int_{-1}^1 d\mu P^L(k\sqrt{1+r^2-2r\mu};z)\frac{(3r+7\mu-10r\mu^2)^2}{(1+r^2-2r\mu)^2}$$

Combine PBS with SPT

Now the DM halo can be expanded in terms of DM density as,

$$\delta_h(x, M) = \sum_n \frac{1}{n!} b_n(M)(\delta_m^n(x) - \langle \delta_m^n \rangle)$$

$$\delta_h(k, M) = \sum_n \frac{1}{n!} b_n(M) \int d^3q_1 \cdots d^3q_n \delta_D \left(\sum_i^n \boldsymbol{q}_i - \boldsymbol{k} \right) \prod_i^n \delta_m(\boldsymbol{q}_i)$$

Then the power spectrum of halo-DM correlation is...

$$P_{\rm hm}(k; M, z) = \left[b_1 + \frac{\sigma^2}{2} \left(b_3 + \frac{68}{21} b_2 \right) \right] P^{\rm L}(k) + b_1 [P_{m(13)} + P_{m(22)}]$$
$$+ b_2 \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} P_m^{\rm L}(q) P_m^{\rm L}(|\boldsymbol{k} - \boldsymbol{q}|) F_2(\boldsymbol{q}, \boldsymbol{k} - \boldsymbol{q})$$

Similar formula for hh auto correlation is derived by **McDonald 2006**

δb_1 δP_m

$$\left[b_1 + \frac{\sigma^2}{2} \left(b_3 + \frac{68}{21} b_2 \right) \right] P_m^{\rm L}(k) + b_1 [P_{m(13)} + P_{m(22)}]$$
$$\simeq [b_1 + \delta b_1] P_m^{\rm NL} + \mathcal{O}(\delta b_1 \delta P_m)$$

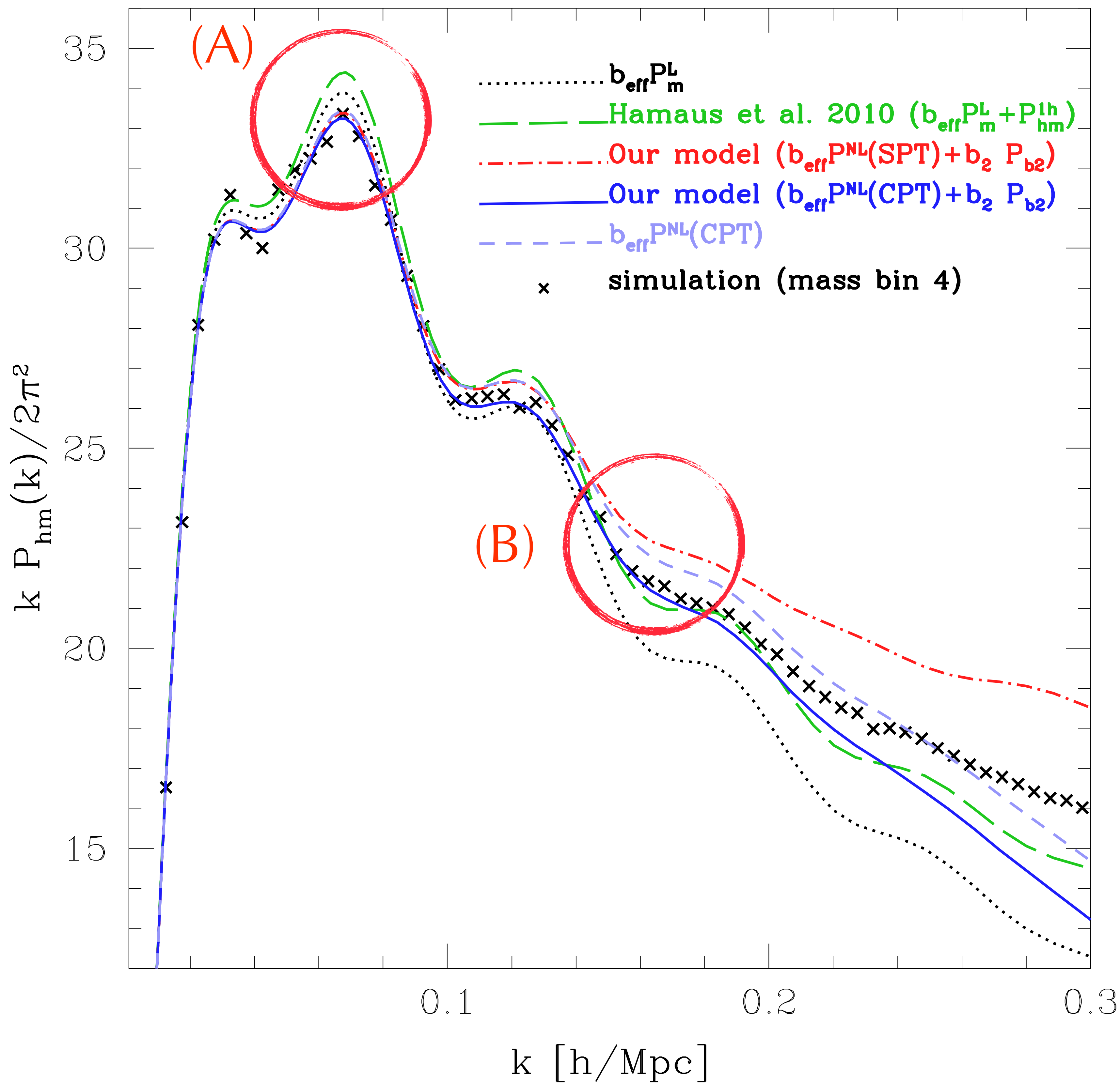
Renormalize σ up to O(δ^6)

$$\delta b_1 \sim \sigma^2 = \mathcal{O}(P_m^{\rm L}(k)) = \mathcal{O}(\delta_m^2)$$
$$\delta P_m = \mathcal{O}([P_m^{\rm L}(k)]^2) = \mathcal{O}(\delta_m^4)$$

$$P_{\rm hm}(k; M, z) \equiv b_1^{\rm eff} P_m^{\rm NL}(k) + b_2(M) \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} P_m^{\rm L}(q) P_m^{\rm L}(|\boldsymbol{k} - \boldsymbol{q}|) F_2(\boldsymbol{q}, \boldsymbol{k} - \boldsymbol{q})$$

Nishizawa+ in prep.

Halo-Matter power spectrum

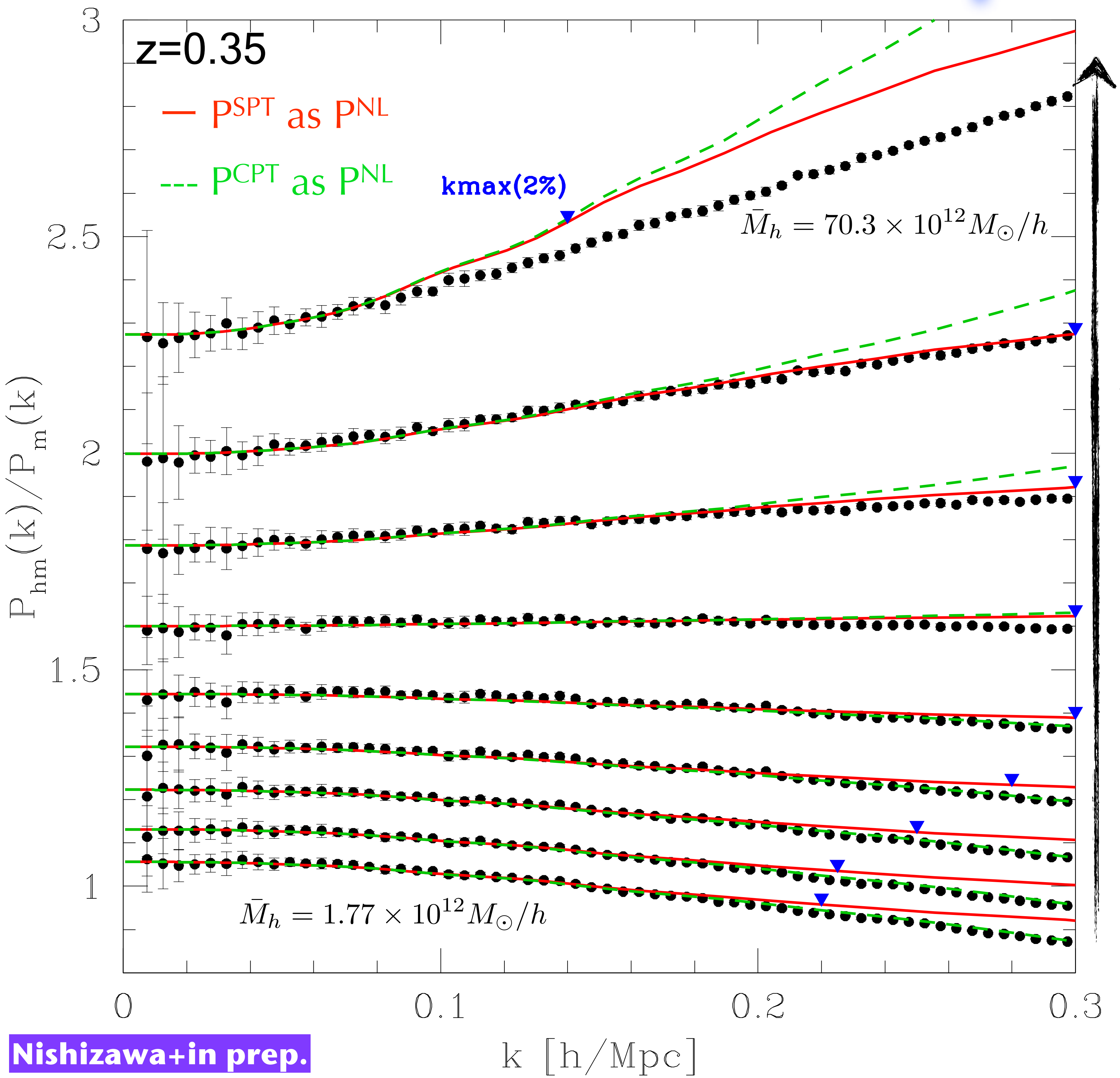


Our model has only one fitting parameter, "b_{eff}" which can be well determined at the linear scale.

(A) On quasilinear scales, P^{NL} contribute to suppress the power.

(B) On nonlinear scale, $b_{eff}P^{NL}$ overestimates the power but b_2P_{b2} term contributes to suppress it to agree the N-body simulation.

mass and scale dependent bias



$$b(k,z) \equiv \frac{P_{gm}(k,z)}{P_{mm}(k,z)}$$

$$P_{\rm hm}(k,z) = \int dM \frac{dn}{dM} N_{\rm HOD}(M) P_{\rm hm}(k;M,z)$$

$$N_{\rm HOD} = \begin{cases} 1, & M_{\rm min} < M < M_{\rm max}, \\ 0, & \text{otherwise} \end{cases}$$

Our model can predict b(k,M) very accurately up to k~0.2 h/Mpc.(*)

(*) The range that CPT is valid is k<0.13 h/Mpc (@z=0.35)

Nishizawa+in prep.

Nishimichi+2009

Halo-Halo correlation

In the same manner, $P_{hh}(k)$ can be computed, but it contains the nasty residual problem (ε_k)

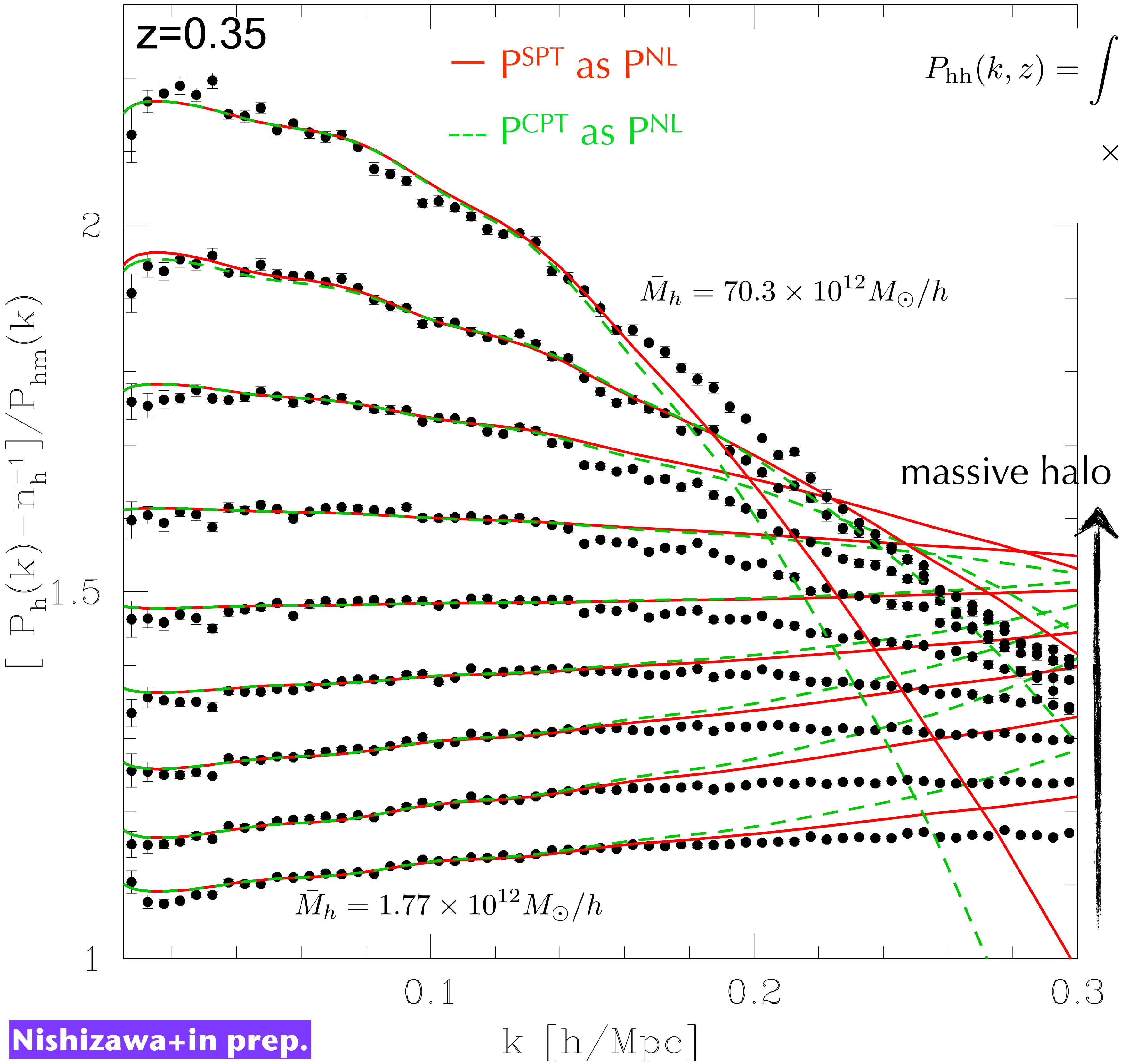
$$P_{\mathrm{hh}'}(k, M, M', z) = b_1^{\mathrm{eff}} b_1'^{\mathrm{eff}} P_m^{\mathrm{NL}}(k) + \frac{1}{2} b_2 b_2' \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left[P_m^{\mathrm{L}}(q) P_m^{\mathrm{L}}(|\boldsymbol{k}-\boldsymbol{q}|) - P_m^{\mathrm{L}}(q)\right]$$
$$+ (b_1 b_2' + b_1' b_2) \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} P_m^{\mathrm{L}}(q) P_m^{\mathrm{L}}(|\boldsymbol{k}-\boldsymbol{q}|) F_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) + \delta N$$

Halo sample	bin 1	bin 2	bin 3	bin 4	bin 5	bin 6	bin 7	bin 8	bin 9
$M_{\mathrm{min}}/10^{12}\ [M_\odot/h]$	1.77	2.49	3.54	4.98	7.09	10.0	14.2	20.1	28.4
$M_{\mathrm{max}}/10^{12}\ [M_\odot/h]$	5.54	10.2	17.4	26.6	40.4	67.6	119.0	208.0	–
$\bar{M}_h/10^{12}\ [M_\odot/h]$	2.96	4.65	7.08	9.37	14.7	21.8	32.1	46.3	70.3
$\bar{n}_h/10^{-4}\ [h^3\mathrm{Mpc}^{-3}]$	15.7	12.6	9.46	6.87	4.87	3.47	2.43	1.64	1.09
$\bar{n}_h P_{hh}(k=0.1\ h/\mathrm{Mpc})$	7.35	6.78	5.90	4.97	4.16	3.57	3.06	2.52	2.12
$\bar{n}_h P_{hh}(k=0.2\ h/\mathrm{Mpc})$	2.71	2.54	2.22	1.88	1.58	1.34	1.14	0.93	0.76
b_1^{eff} (from P_{hm}/P_m)	1.06	1.13	1.22	1.33	1.45	1.61	1.79	2.00	2.26
b_1^{eff} (from P_h/P_{hm})	1.07	1.16	1.25	1.35	1.48	1.63	1.81	1.99	2.19
C^{PT} (from P_h/P_{hm})	0.64	0.52	0.35	0.19	0.03	-0.09	-0.19	-0.21	-0.13
$\bar{b}_1(M_h)$	1.18	1.28	1.38	1.49	1.63	1.82	2.02	2.23	2.60
$\bar{b}_2(M_h)$	-0.47	-0.44	-0.40	-0.32	-0.19	0.078	0.47	0.96	2.43
$k_{\mathrm{max}}(2\%)\ [h/\mathrm{Mpc}]$	0.22	0.23	0.25	0.28	0.30	0.30	0.30	0.30	0.14

$$\delta N = (1 + C)\frac{1}{\bar{n}_h}$$

Poissonian shot-noise does not account for the residuals

mass and scale dependent bias



Nishizawa+in prep.

$$P_{hh}(k,z) = \int dM \frac{dn}{dM} N_{HOD}(M) \times \int dM' \frac{dn}{dM'} N_{HOD}(M') P_{hh}(k, M, M', z)$$

$$b(k,z) = \frac{P_{gg}(k,z)}{P_{gm}(k,z)}$$

b(k,M) defined by Phh/Phm is also accurately predicted by our model up to k~0.15 h/Mpc.(*)

(*) The range that CPT is valid is k<0.13 h/Mpc (@z=0.35)

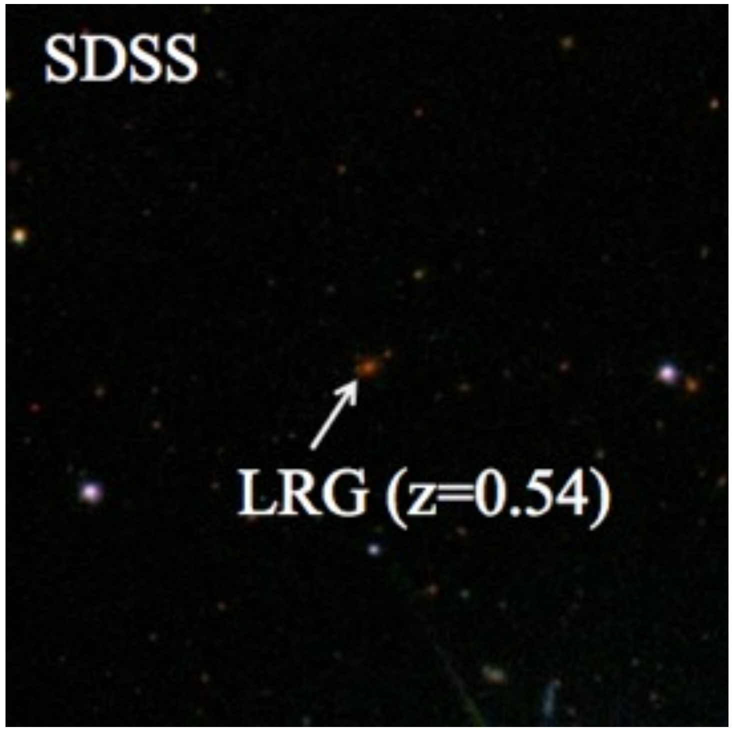
Nishimichi+2009

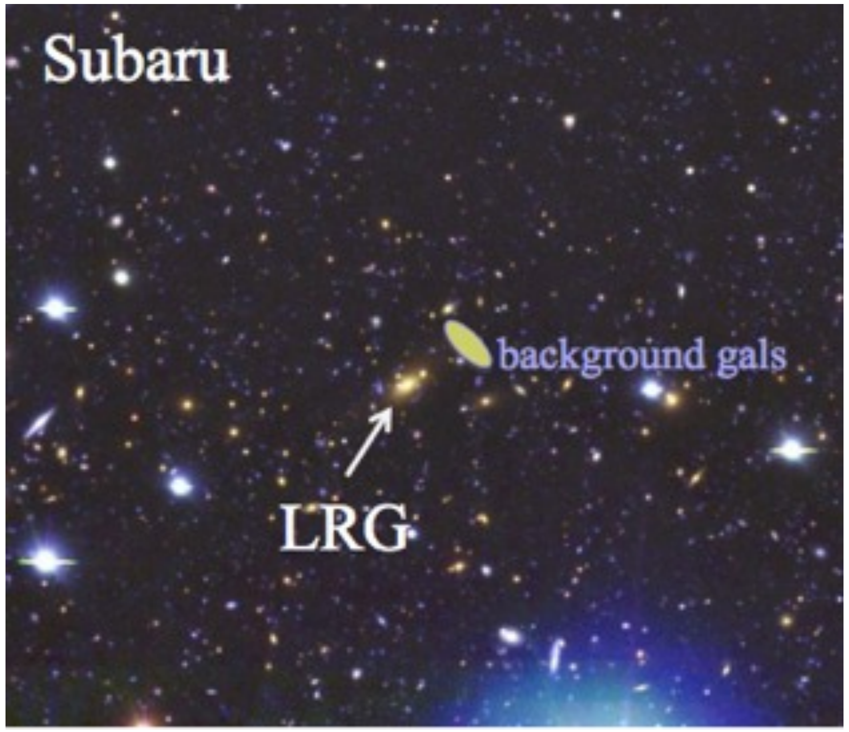
How do we measure it?

We need both **spectroscopic galaxy survey** and **imaging survey!!**

Image Credit: M. Tanaka(IPMU)

Slide Credit: M. Takada(IPMU)





- spec-z survey (BOSS, PFS, EUCLID,...)
  → measure the redshift of LRGs
- imaging survey(HSC, DES, LSST,...)
  → measure the shape of background galaxies of LRGs

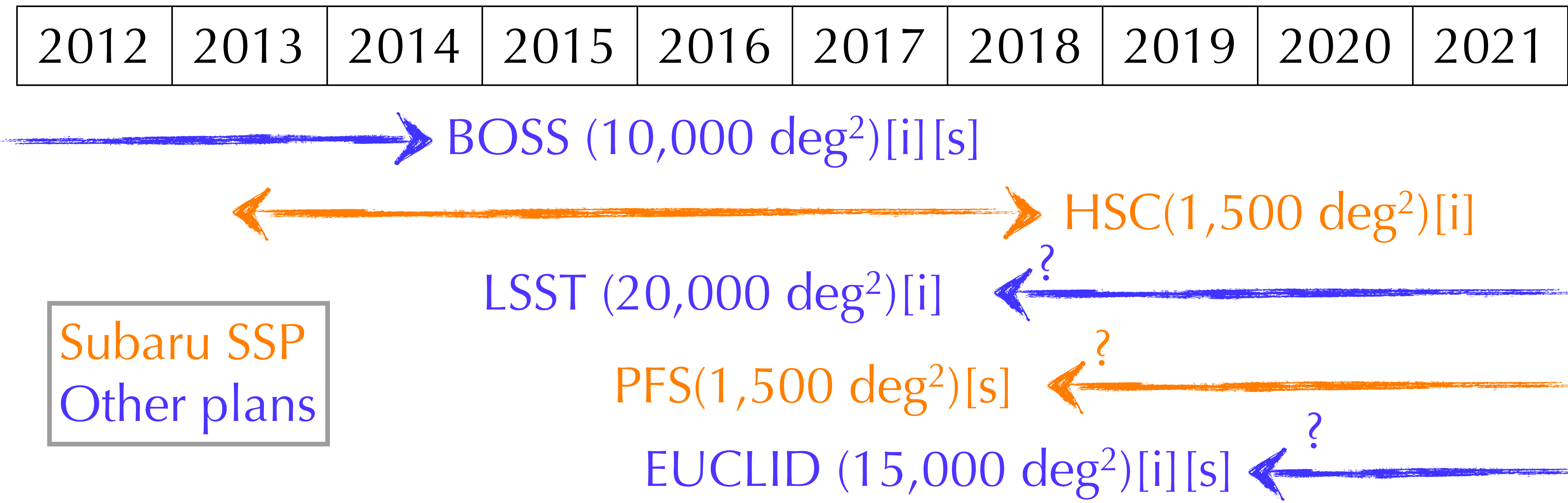
measure the angular power spectra

$$C_\ell^{gg} = \frac{1}{\bar{n}_g^2} \int d\chi \, W_g^2(\chi)\chi^{-2} P_{\rm m}(\ell/\chi, z)$$

$$C_\ell^{g\kappa} = \frac{1}{\bar{n}_g} \int d\chi \, W_g(\chi) W_\kappa(\chi)\chi^{-2} P_{\rm gm}(\ell/\chi, z)$$

$$b_{\rm est}(k, z_i) = \frac{P_{gg}(k, z_i)}{P_{gm}(k, z_i)} \simeq W_\kappa(\chi_i)\Delta\chi_i \frac{C_\ell^{gg}}{C_\ell^{g\kappa}}$$

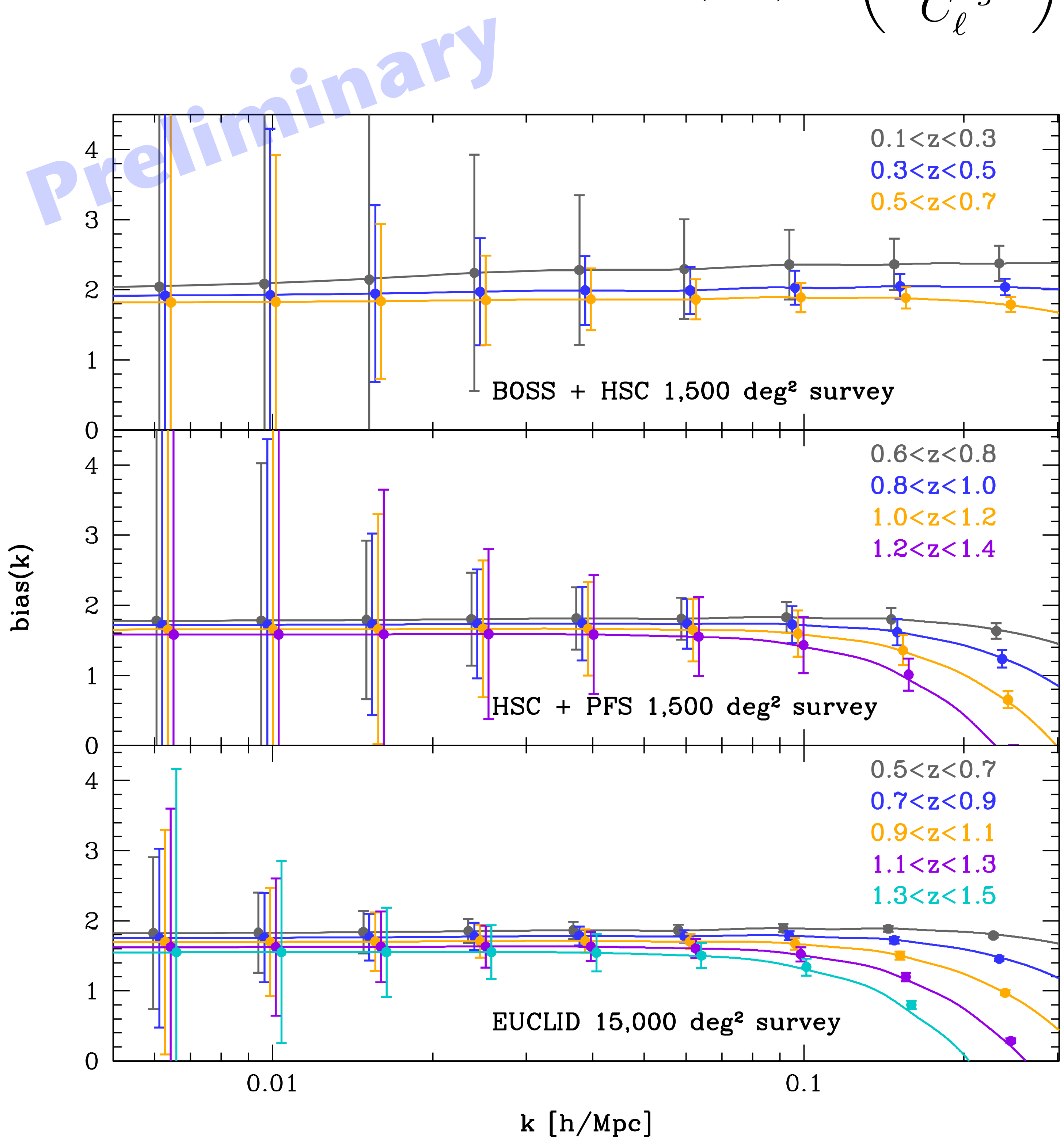
Future survey plans



spec-z	imaging	sky coverage	redshift	begin	complete
BOSS	HSC	1,500	$0.1 < z < 0.7$	2013	2018
PFS	HSC	1,500	$0.6 < z < 1.4$	2018(?)	2023(?)
EUCLID	EUCLID	15,000	$0.5 < z < 1.5$	2020(?)	2026(?)

significance of b(k) detection

$$\sigma^2(b_{\rm est}) = \left(\frac{W_\kappa \Delta\chi}{C_\ell^{\kappa g}}\right)^2 \left[\boldsymbol{C}_\ell^{gg,gg} - 2\frac{C_\ell^{gg}}{C_\ell^{\kappa g}} \boldsymbol{C}_\ell^{gg,\kappa g} + \left(\frac{C_\ell^{gg}}{C_\ell^{\kappa g}}\right)^2 \boldsymbol{C}_\ell^{\kappa g,\kappa g} \right]$$



$$\mathrm{Cov}[C_\ell^{gg}, C_{\ell'}^{gg}] = \frac{2\delta_{\ell\ell'}^K}{(2\ell+1)f_{sky}}(\hat{C}_\ell^{gg})^2,$$

$$\mathrm{Cov}[C_\ell^{\kappa g}, C_{\ell'}^{\kappa g}] = \frac{\delta_{\ell\ell'}^K}{(2\ell+1)f_{sky}}[\hat{C}_\ell^{gg}\hat{C}_\ell^{\kappa\kappa} + (C_\ell^{\kappa g})^2],$$

$$\mathrm{Cov}[C_\ell^{gg}, C_{\ell'}^{\kappa g}] = \frac{2\delta_{\ell\ell'}^K}{(2\ell+1)f_{sky}}C_\ell^{\kappa g}\hat{C}_\ell^{gg},$$

BOSS_01	:S/N= 13.0935
BOSS_02	:S/N= 23.8122
BOSS_03	:S/N= 24.4225
HSC_01	:S/N= 21.7679
HSC_02	:S/N= 16.054
HSC_03	:S/N= 10.8162
HSC_04	:S/N= 6.8333
EUCLID_01	:S/N= 89.1785
EUCLID_02	:S/N= 68.6688
EUCLID_03	:S/N= 48.7576
EUCLID_04	:S/N= 30.2891
EUCLID_05	:S/N= 23.2495

summary

❋ We developed a physically motivated model to predict the halo (galaxy) bias based on the Standard Perturbation Theory combined with the Peak Background Splitting.

❋ Our model well predicts both scale and mass dependence of the halo bias up to k ~ 0.2 h/Mpc scale.

❋ Halo clustering needs alternative models to predict the residuals which might be related with stochasticity of the halo bias.

❋ The scale dependent bias can be measured with the combination of spec-z and imaging surveys, and the significant detection of the scale dependent bias can be expected for up-coming Subaru SSP(HSC and PFS)

❋ In the future, we'll explore how the bias determination will improve the cosmological constraints and also extension of this formula to the RSD.