Constraints on anisotropic primordial non-Gaussianity from intrinsic alignments of SDSS-III BOSS galaxies

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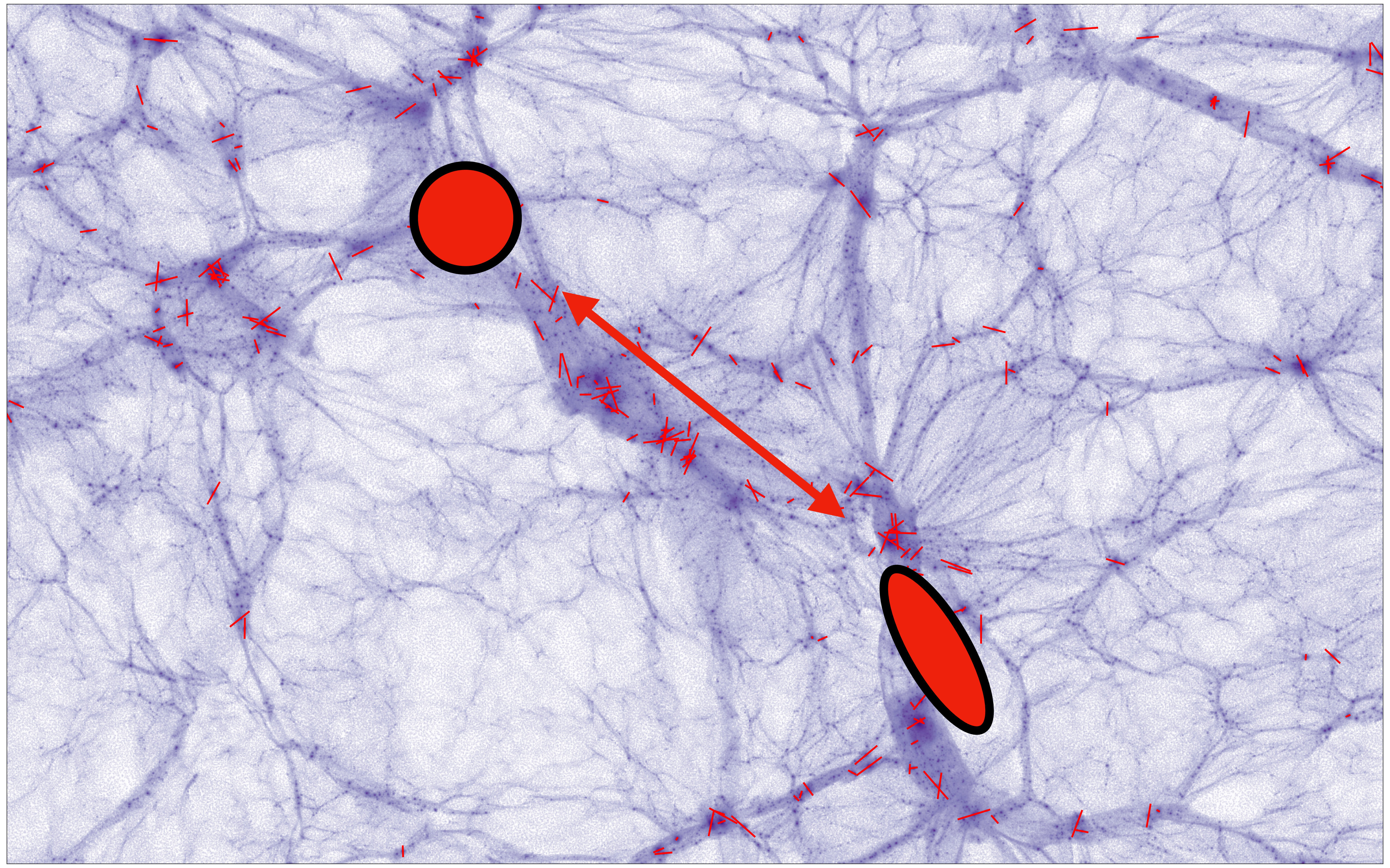
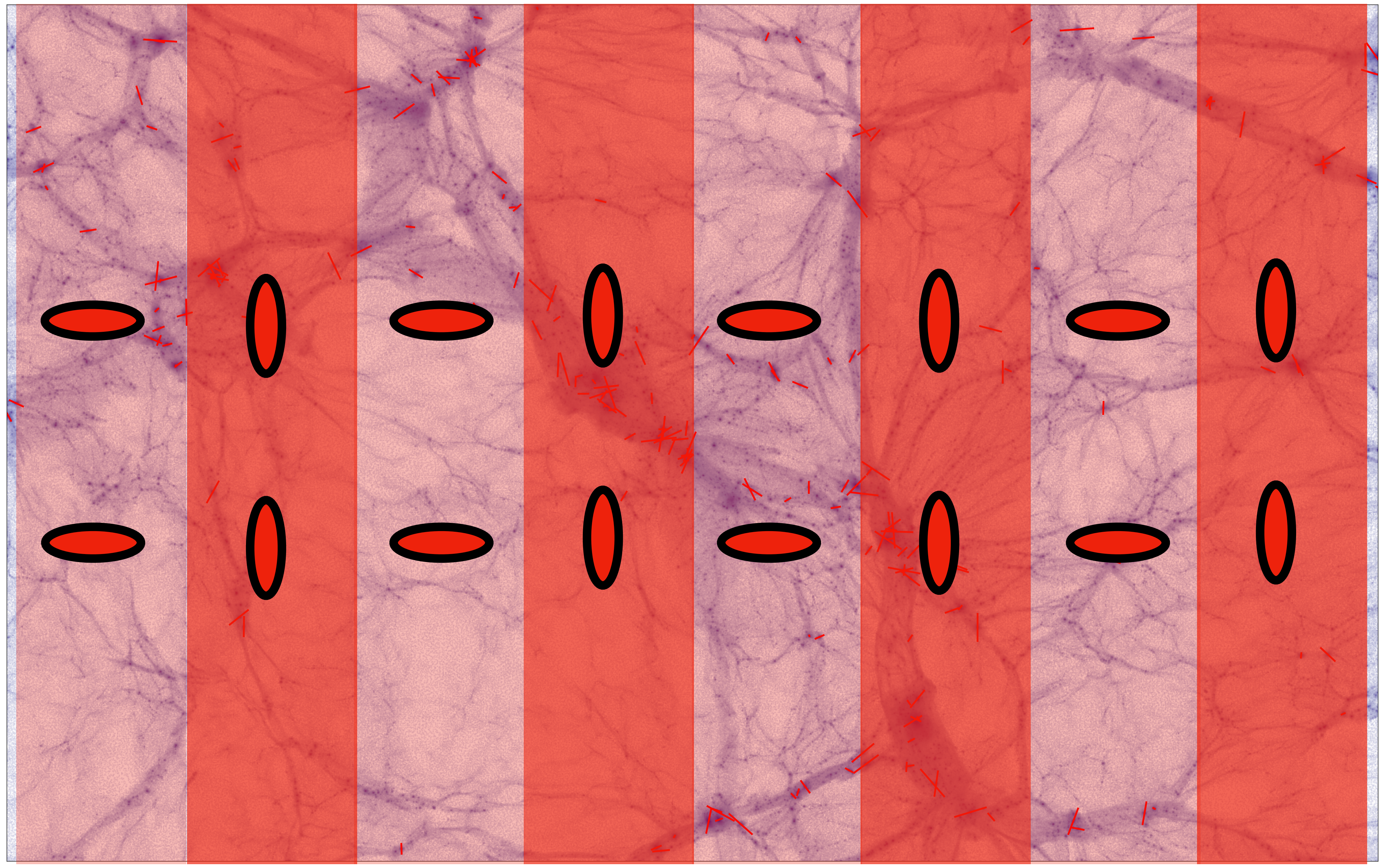
Overview



Configuration space



Fourier space
(This work)

(1) Measurements of IA power spectrum

$$-2\ln \mathcal{L}(\mathbf{d}|\mathbf{p}) \sim [\mathbf{d} - \mathbf{m}(\mathbf{p})]^{\mathrm{T}} \mathbf{C}^{-1} [\mathbf{d} - \mathbf{m}(\mathbf{p})]$$

(2) Linear theory + window convolution

(3) Analytic Covariance

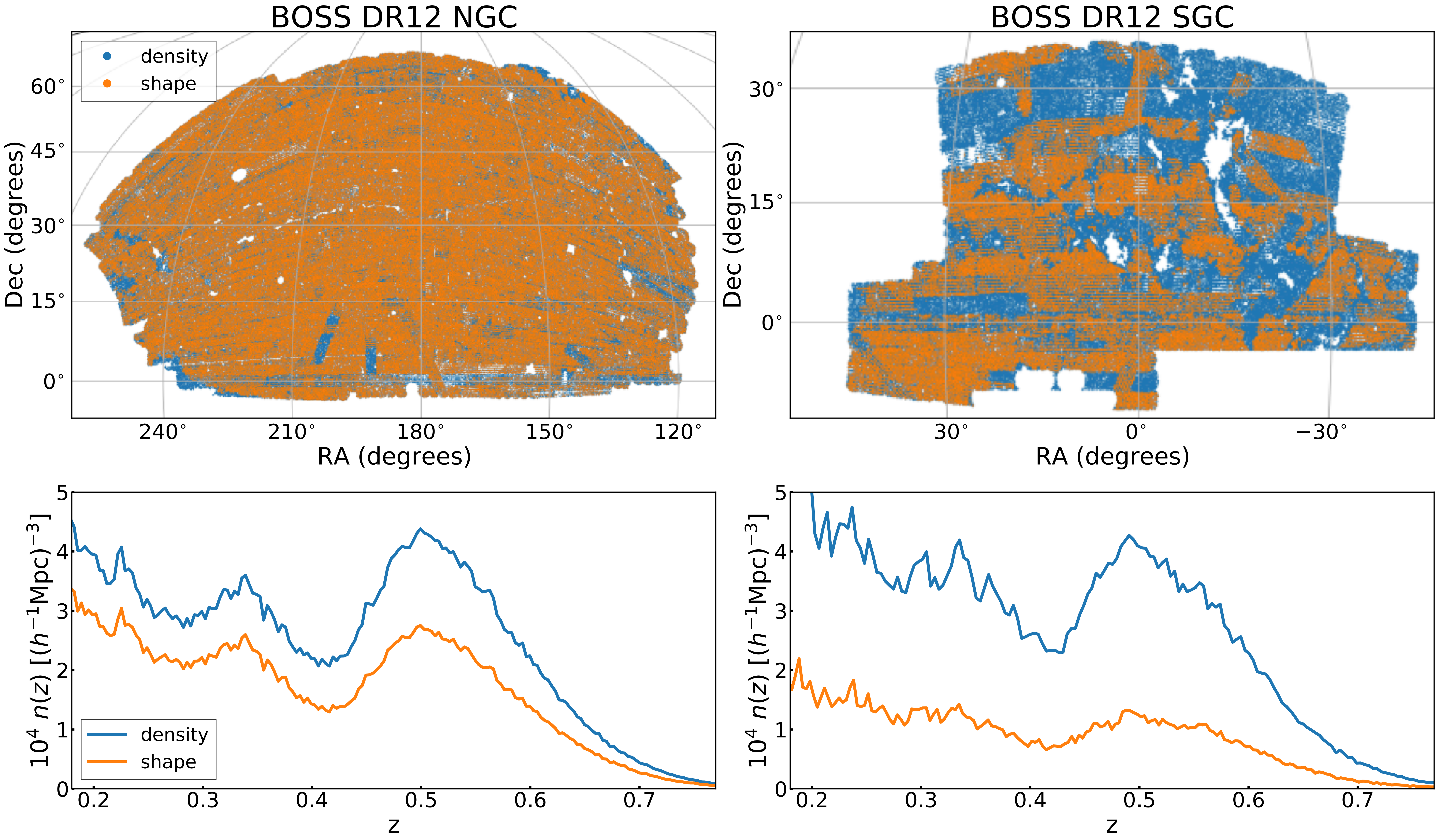
Measurements

Data

SDSS-III BOSS LOWZ+CMASS sample

- density & random catalog (Reid+2016, BOSS DR12 LSS catalog)
- shape catalog (Reyes+2012, used in gg-lens cosmological analysis, e.g. Mandelbaum+2012)

- The shape sample is generated by cross-matching the two catalogs.
  - shape sample ⊂ density sample
  - ~65% for NGC, ~31% for SGC the r-band magnitude cut due to galactic extinction (Reyes+12)
- Both angular and redshift distributions are different.
  - We generate "shape randoms" by Acceptance-Rejection sampling (with Healpix for angular part).



Estimator: Field

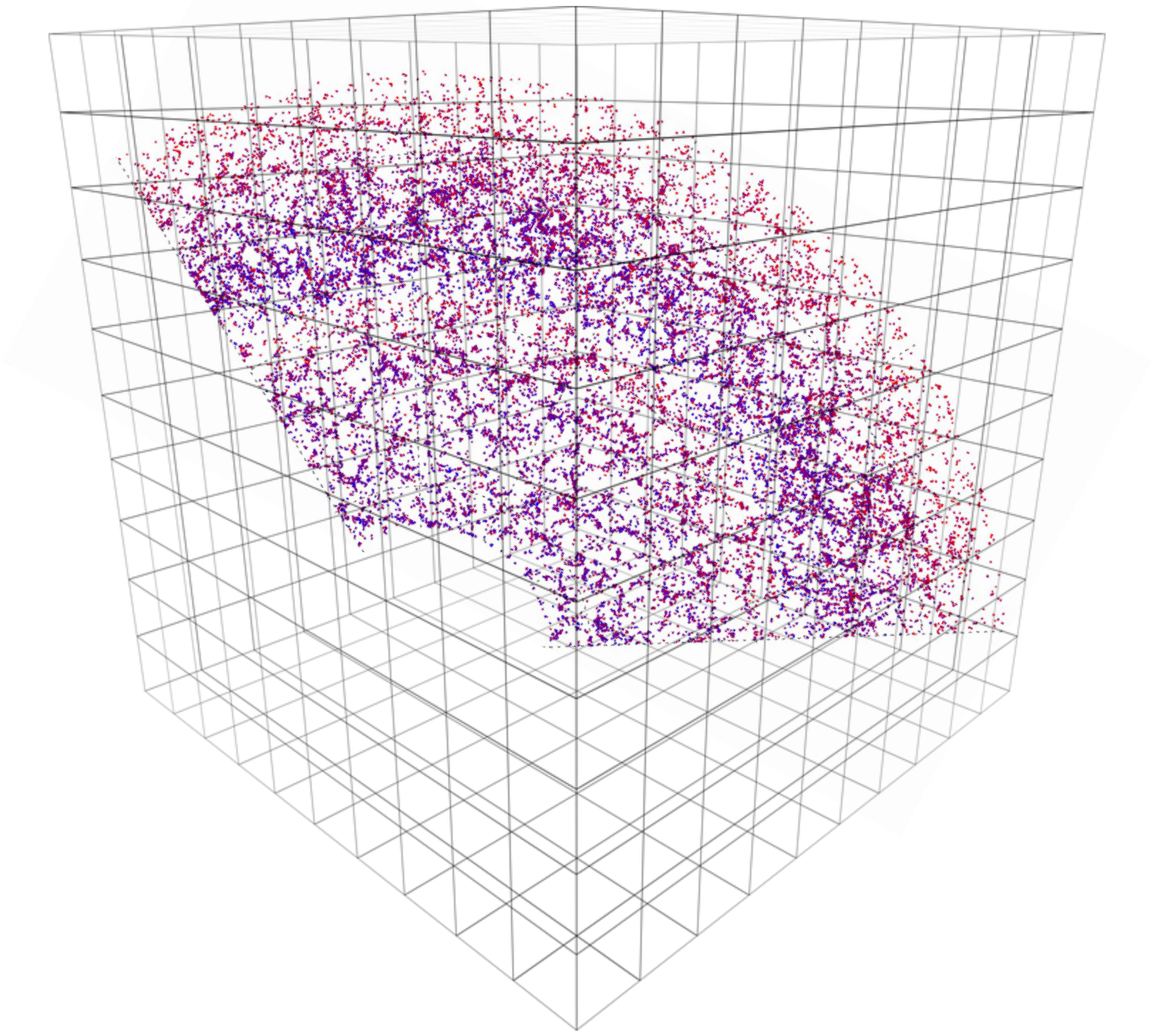
Density field (FKP 1993)

$$\hat{F}_{\mathrm{g}}(\mathbf{x}) \equiv \underbrace{w_{\mathrm{FKP,g}}(\mathbf{x})}_{\text{FKP weight}}\underbrace{[n'_{\mathrm{g}}(\mathbf{x}) - \alpha_{\mathrm{g}} n_{\mathrm{r,g}}(\mathbf{x})]}_{\text{(weighted) galaxies - randoms}},$$

FKP weight **(weighted) galaxies - randoms**

$$w_{\mathrm{FKP,g}}(z) \equiv \frac{1}{1 + \bar{n}'_{\mathrm{g}}(z) P_0},$$

- Assign galaxies and randoms to grid points and define the "density field" for FFTs.



Shape field (this work)

$$\hat{F}_{\gamma}(\mathbf{x}) \equiv w_{\mathrm{FKP},\gamma}(\mathbf{x}) n'_{\gamma}(\mathbf{x}) \gamma(\mathbf{x}),$$

"FKP" weight for IA **shear assigned for each galaxy at x**

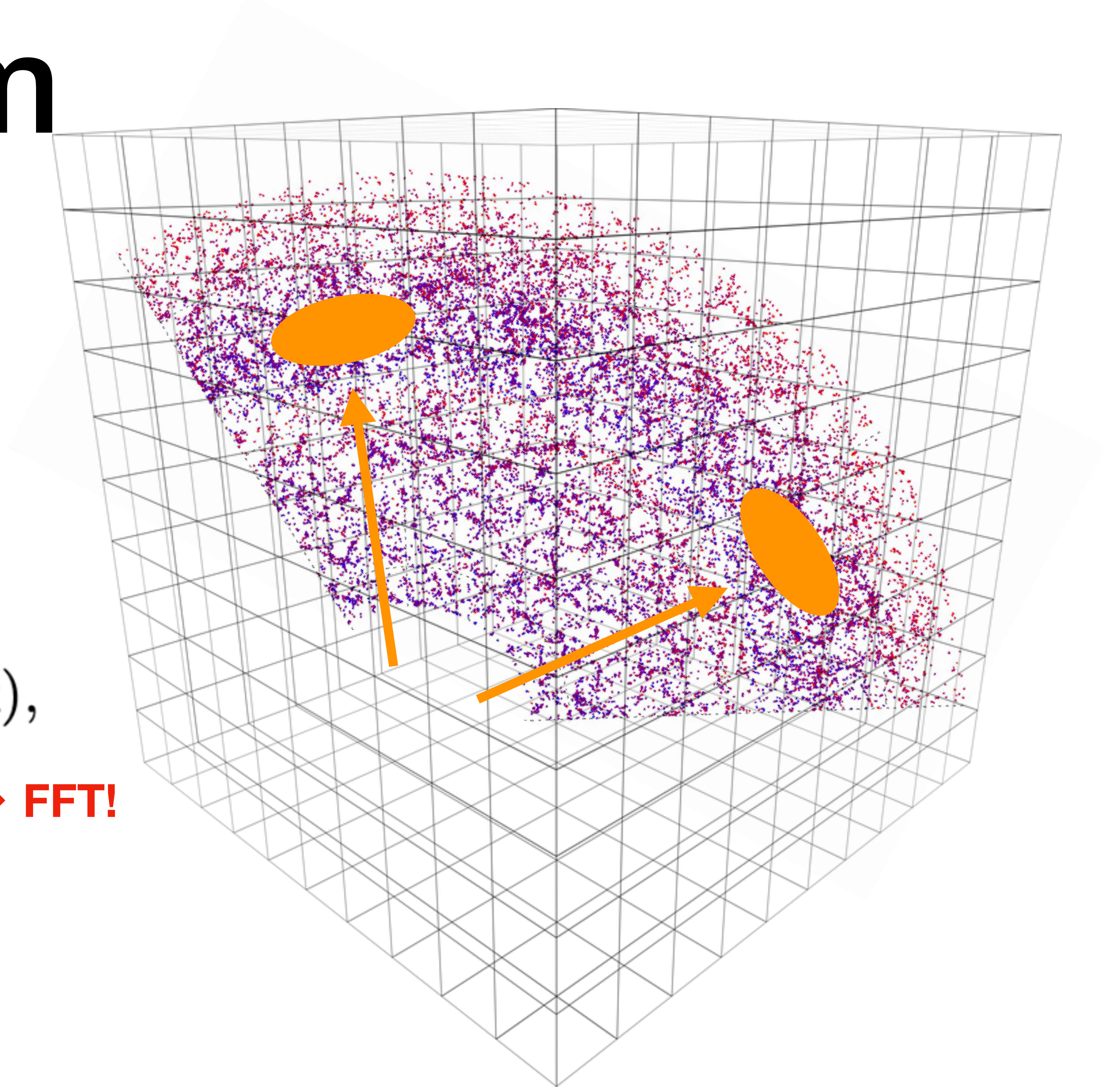
$$w_{\mathrm{FKP},\gamma}(z) \equiv \frac{1}{\sigma_{\gamma}^2 + \bar{n}'_{\gamma}(z) P_0^{\mathrm{IA}}}.$$

- Note: The shape field defined by this eq. becomes a "density weighted" field:

$$\hat{\gamma}(\mathbf{x}) = (1 + \delta_{\mathrm{g}}(\mathbf{x}))\gamma(\mathbf{x})$$

- We ignore this effect at theory side because we only use the signals in the linear regime.

Estimator: Power Spectrum



Galaxy Clustering (Yamamoto+2006, Bianchi+2015, Scoccimarro 2015)

$$\hat{P}^{(\ell)}_{\rm gg}(k_b) \equiv \frac{2\ell+1}{\mathrm{I}_{\rm gg}} \int_{\hat{\mathbf{k}}_b} \underline{\hat{F}^{(\ell)}_{\rm g}(\mathbf{k})} \hat{F}_{\rm g}(-\mathbf{k}) - S,$$

$$\hat{F}^{(\ell)}_{\rm g}(\mathbf{k}) \equiv \int_{\mathbf{x}} \hat{F}_{\rm g}(\mathbf{x}) e^{-i\mathbf{k}\cdot\mathbf{x}} \mathcal{L}_\ell(\hat{\mathbf{k}}\cdot\hat{\mathbf{x}}),$$

products of k and x → FFT!

Intrinsic Alignments (Kurita&Takada 2022)

$$\hat{P}^{(L)}_{\gamma\rm g}(k_b) = \frac{2L+1}{\mathrm{I}_{\gamma\rm g}} \frac{(L-2)!}{(L+2)!} \int_{\hat{\mathbf{k}}_b} \underline{\hat{F}^{(L)}_{\gamma}(\mathbf{k})} \hat{F}_{\rm g}(-\mathbf{k}),$$

= PEg+iPBg

Associated Legendre with m=2

$$\hat{F}^{(L)}_{\gamma}(\mathbf{k}) \equiv \int_{\mathbf{x}} \hat{F}_{\gamma}(\mathbf{x}) e^{-2i\phi_{\hat{\mathbf{k}},\hat{\mathbf{x}}}} e^{-i\mathbf{k}\cdot\mathbf{x}} \mathcal{L}^{m=2}_L(\hat{\mathbf{k}}\cdot\hat{\mathbf{x}})$$

= E(k)+iB(k)

$$\equiv \left[\int_{\mathbf{x}} \hat{F}_{\gamma}(\mathbf{x}) 2e^*_{ij}(\hat{\mathbf{x}}) e^{-i\mathbf{k}\cdot\mathbf{x}} \tilde{\mathcal{L}}^{m=2}_L(\hat{\mathbf{k}}\cdot\hat{\mathbf{x}})\right] \hat{k}_i\hat{k}_j.$$

products of k and x → FFT!

Covariance: Analytic Covariance

- We derive an analytic covariance of IA power spectrum. (extending Wadekar&Scoccimarro 2019 for clustering)
  - There is no realistic mock catalog for galaxy IA. (but for clustering, e.g. Patchy mocks)
  - Covariance = Gaussian + shot/shape noise terms including window effects.

$$\mathrm{Cov}\left[P_{\mathrm{Eg}}, P_{\mathrm{Eg}}\right] = \left\{P^2\right\} + \left\{P \times \frac{\sigma_\gamma^2}{\bar{n}}\right\} + \left\{\left(\frac{\sigma_\gamma^2}{\bar{n}}\right)^2\right\}$$

"Gaussian" "SN-related"

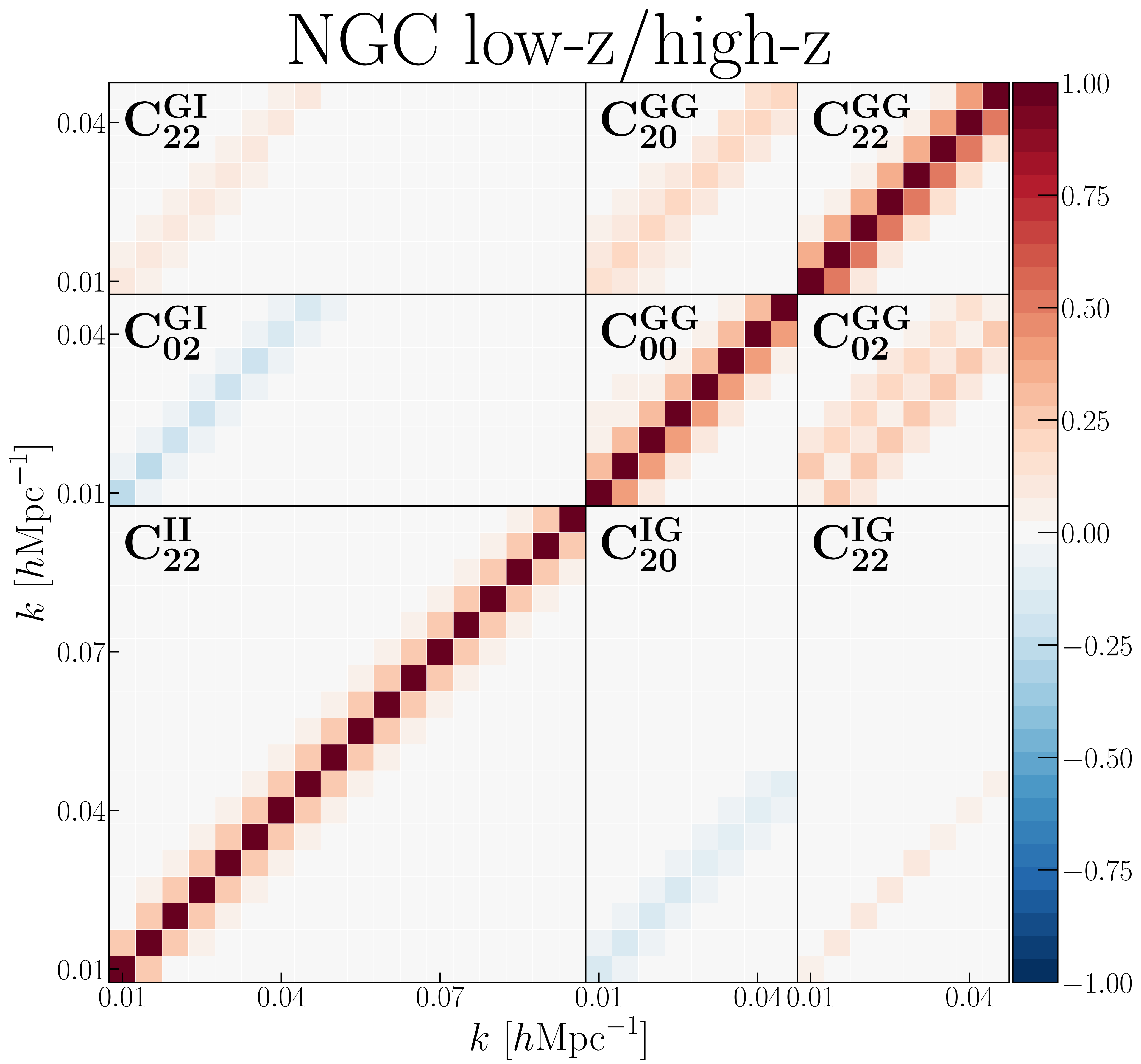
e.g. Gaussian term

$$\mathbf{C}^{\mathrm{II(cont.)}}_{L_1 L_2}(k_1, k_2) = \sum_{\ell_1', \ell_2'} P^{(\ell_1')}_{\mathrm{Eg}}(k_1) P^{(\ell_2')}_{\mathrm{Eg}}(k_2) \mathcal{W}^{\mathrm{II(1,A)}}_{L_1, L_2, \ell_1', \ell_2'}(k_1, k_2) + \sum_{\ell_1', \ell_2'} \left[P^{(\ell_1')}_{\mathrm{gg}}(k_1) P^{(\ell_2')}_{\mathrm{EE}}(k_2) \mathcal{W}^{\mathrm{II(1,B)}}_{L_1, L_2, \ell_1', \ell_2'}(k_1, k_2) + (k_1 \leftrightarrow k_2)\right]$$

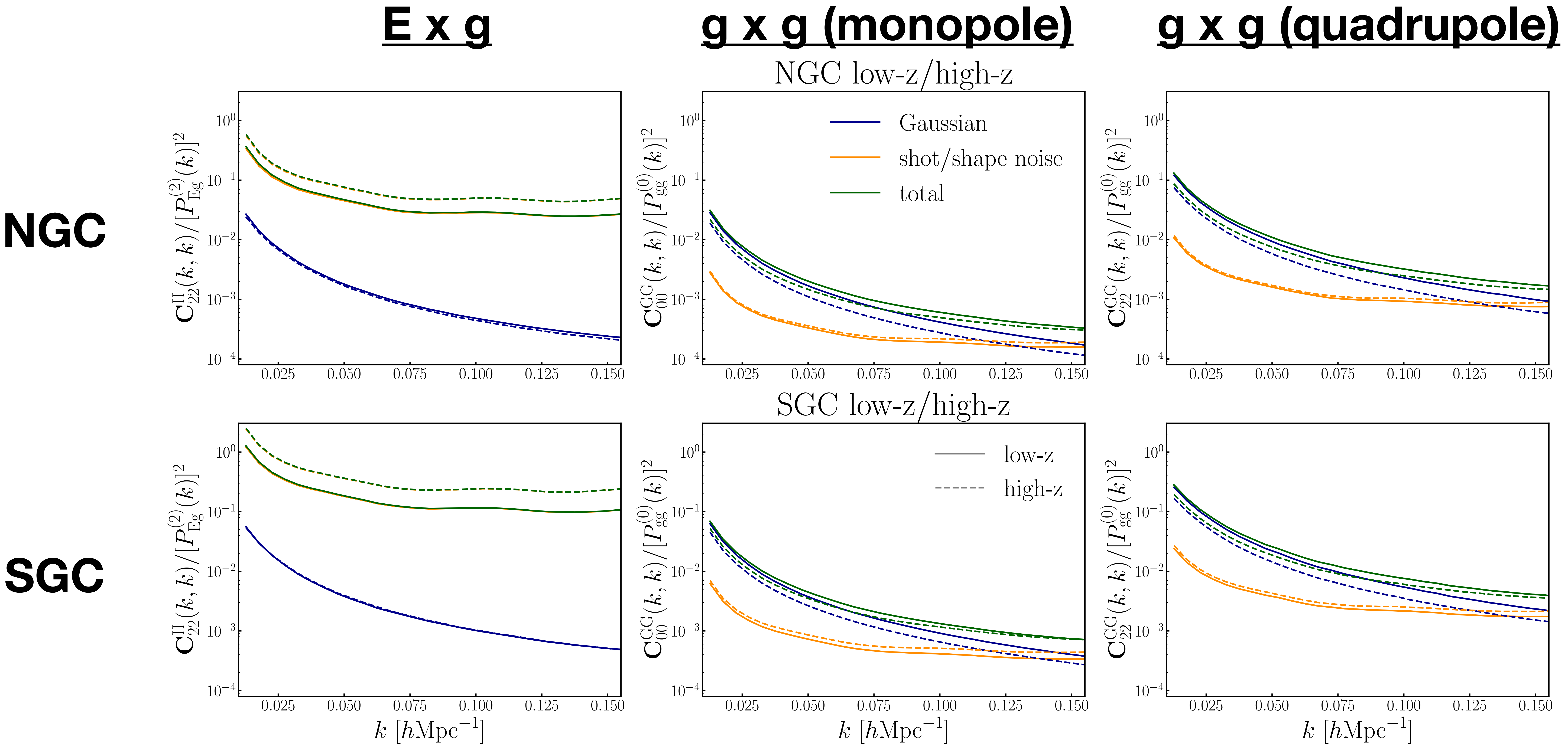
window functions computed by using randoms

- [Right Panel] Correlation matrices for the data vector: $\left\{P^{(2)}_{\mathrm{Eg}}, P^{(0)}_{\mathrm{gg}}, P^{(2)}_{\mathrm{gg}}\right\}$

$$r_{ij} \equiv \mathbf{C}_{ij} / \sqrt{\mathbf{C}_{ii} \mathbf{C}_{jj}}$$



Covariance: diagonals



- Fractional errors: Cov / P^2
- Covariance of IA is dominated by shape noise at all scales since $b_K^2 P_{\mathrm{m}}(\acute{k}) \ll \sigma_\gamma^2/\bar{n}.$

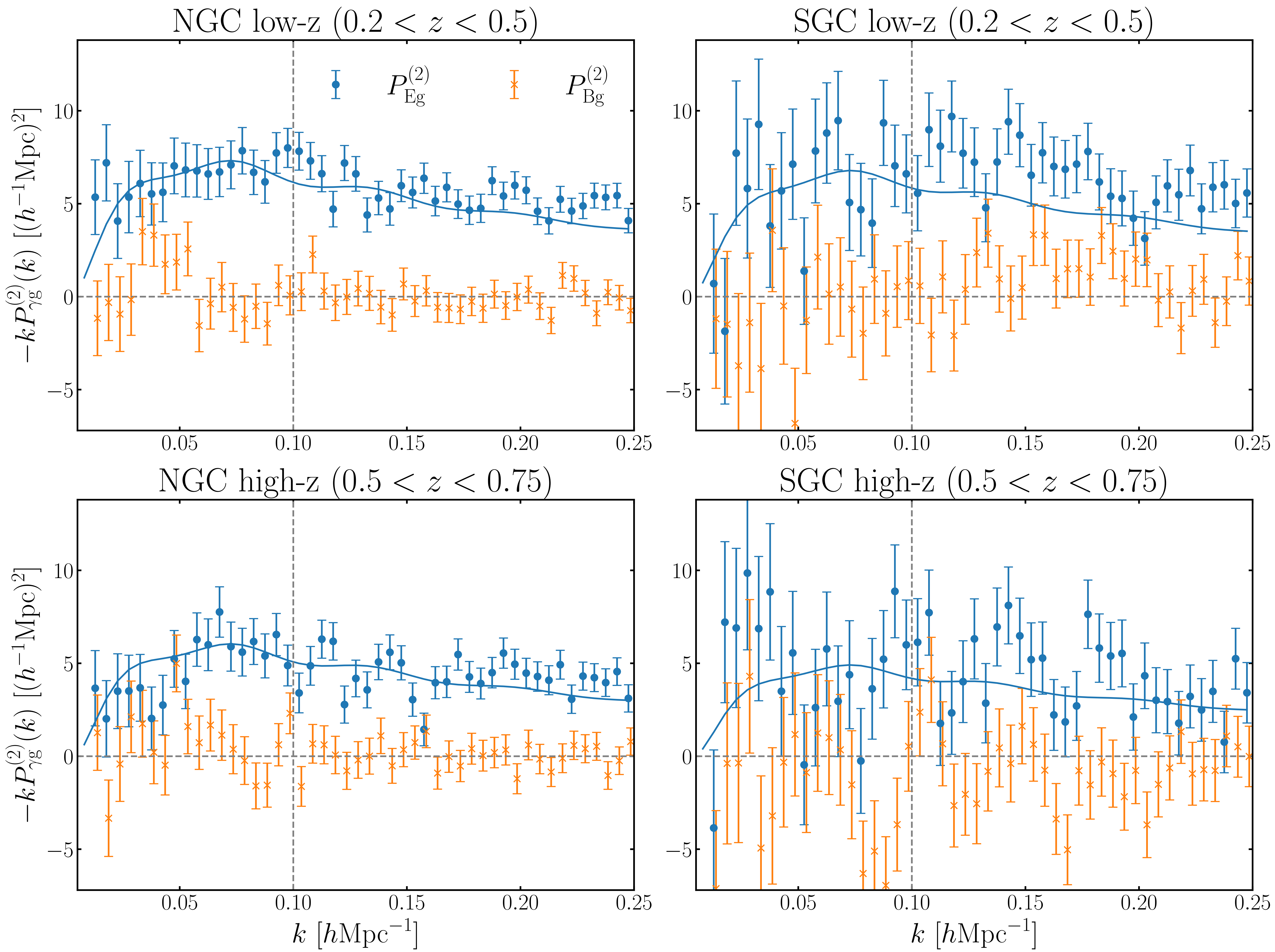
Results I: Measurements

- We divide the sample into two redshift bins for each pole:
  - low-z: 0.2 < z < 0.5 (upper panels)
  - high-z: 0.5 < z < 0.75 (lower panels)
  - kmin=0.01, kmax=0.25 dk=0.005 h/Mpc (48 bins)
- Blue: E x g
- Orange: B x g
- B-mode is null consistent.

$$41.5 < \chi_0^2 < 51.6, \text{ with } 48 \text{ bins}$$

$$0.33 < p < 0.74$$

- solid lines: linear model at MAP (later)



Results II: Signal-to-Noise Ratio

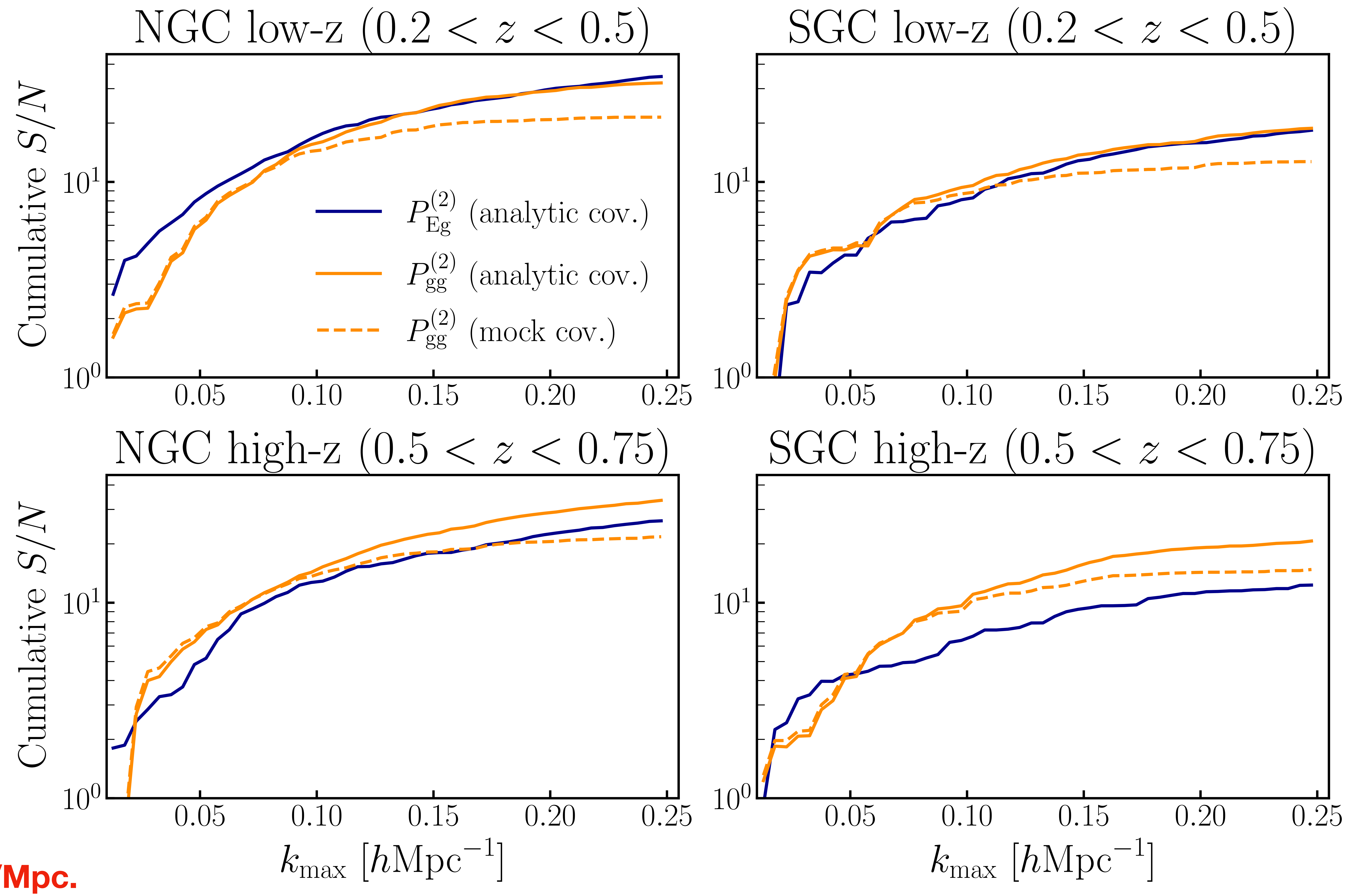
- Cumulative S/N:

$$\left(\frac{S}{N}\right)^2 = \sum_{\mathrm{b,b'}}^{k_{\max}} \hat{P}^{(\ell)}_{\alpha\beta}(k_{\mathrm{b}})\mathrm{Cov}^{-1}\left[P^{(\ell)}_{\alpha\beta}(k_{\mathrm{b}}), P^{(\ell)}_{\alpha\beta}(k_{\mathrm{b'}})\right]\hat{P}^{(\ell)}_{\alpha\beta}(k_{\mathrm{b'}})$$

- Blue: E x g
- Orange: g x g (quadrupole)
- IA is comparable with galaxy clustering quadrupole!

Sample	E-mode S/N ($k_{\max}$) 0.1 $h\mathrm{Mpc}^{-1}$	0.25 $h\mathrm{Mpc}^{-1}$
NGC low-z	16.6	34.6
SGC low-z	8.1	18.4
NGC high-z	12.7	26.2
SGC high-z	6.4	12.3
total	23.3	48.7

In our analysis, we use k up to 0.1 h/Mpc.



Analysis

Linear Model: fiducial cosmology

Galaxy Clustering

Residual shot noise

$$P_{\rm gg}(k,\mu) = \left[b_1 + f\mu^2\right]^2 P^{\rm lin}(k) + \frac{c_{\rm np}}{\bar{n}},$$

linear bias

Intrinsic Alignments

$$P_{\rm Eg}(k,\mu) = \frac{1-\mu^2}{2} b_K \left[b_1 + f\mu^2\right] P^{\rm lin}(k) + P^{\rm WL}_{\rm Eg}(k,\mu)$$

linear shape bias

weak lensing effects

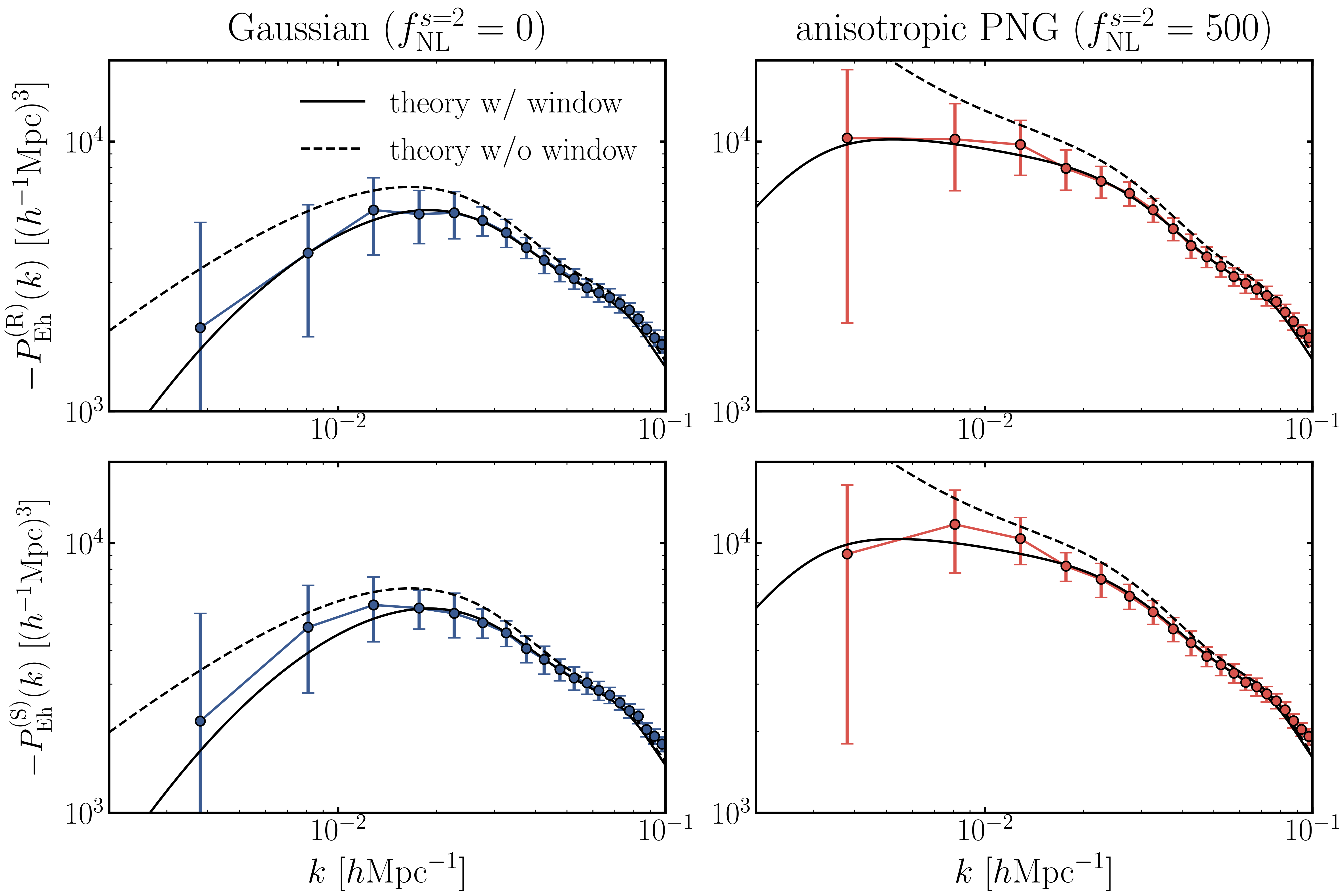
- We fix the cosmological parameters to Planck 2018.
- We estimate weak lensing effects. Non-negligible!
- For residual shot noise, we assume a gaussian prior (e.g. Kobayashi+2021) $c_{\rm np} \sim \mathcal{N}(0, 0.1)$
- We can relate our bK to A_IA $A_{\rm IA} = -\frac{\bar{D}(z)}{2C_1\rho_{\rm cri}\Omega_{\rm m}} b_K,$

Linear Model: window convolution

- We need to consider the window effects on the theory model.
- We extend the rapid convolution method for $P_{\rm gg}$ (Wilson+2015) to IA $P_{\rm Eg}$ using Hankel trs. with FFTlog. (Kurita&Takada2022)

$$P_{\gamma\delta} \xrightarrow{\text{hankel}} \xi_{\gamma\delta} \xrightarrow{\text{convolution}} \xi_{\gamma\delta} \otimes Q \xrightarrow[\text{back}]{\text{hankel}} P'_{\gamma\delta}$$

- We validate our method using N-body simulations.
  - measure halo IA PS assuming BOSS-like survey (sky cut, projection, RSD)
  - compare our measurements with our theory
- good agreement!



Results III: fiducial cosmology

- solid lines: linear model at MAP

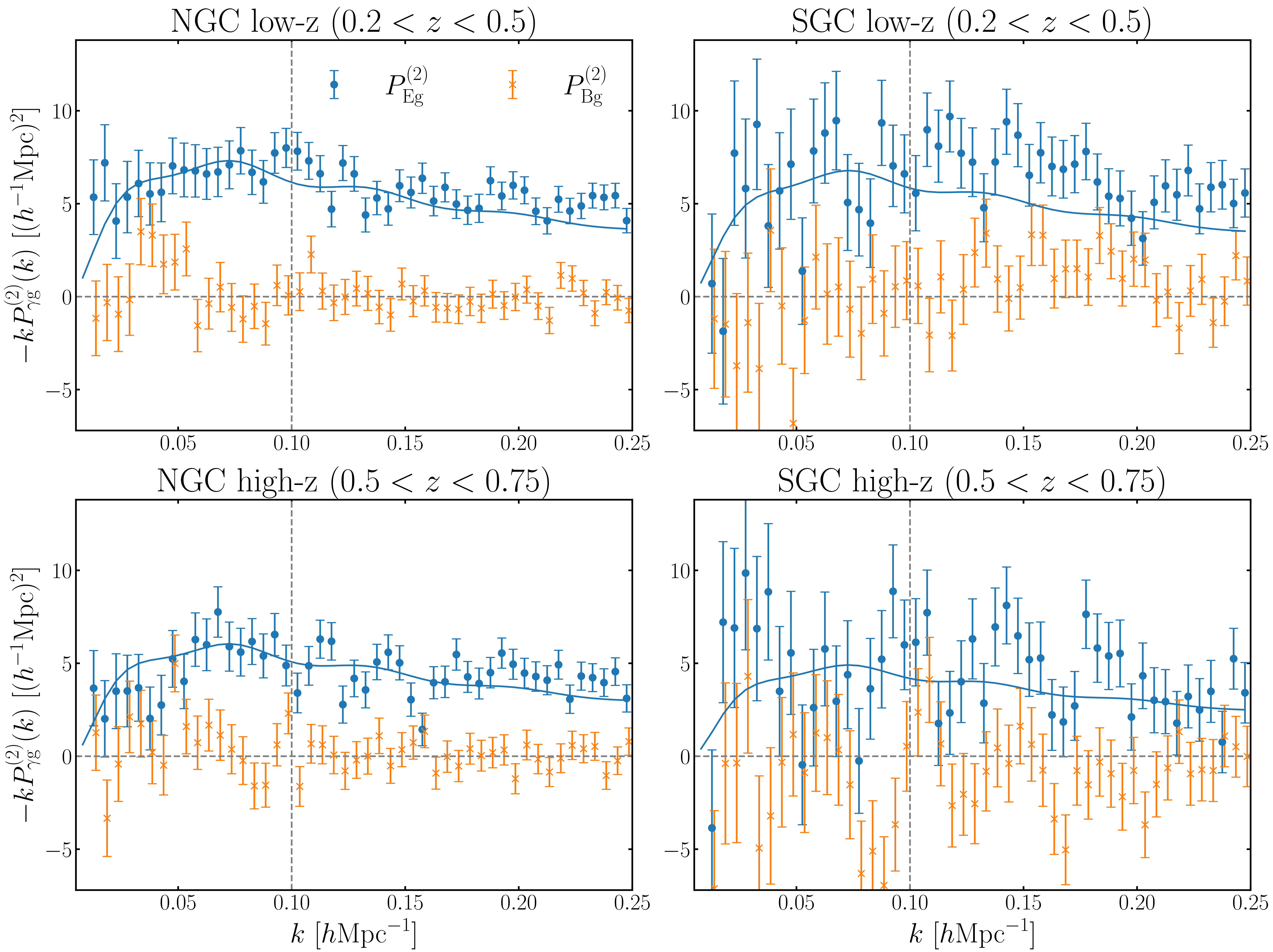
$$\chi^2/N_{\rm dof} = 125.57/(136-12) = 1.013$$
$$p = 0.444$$

- deviation from linear model due to the non-linearities at large k , but not strong -> TATT (Blazek+2017), EFT (Vlah+2020), …

- $A_{\rm IA} = 4 \sim 5$

$$A_{\rm IA} = -\frac{\bar{D}(z)}{2C_1\rho_{\rm cri}\Omega_{\rm m}} b_K,$$

Sample	$b_K \times 10^2$ 68%CI	$A_{\rm IA}$ 68%CI	b_1 68%CI
NGC low-z	$-5.14^{+0.31}_{-0.31}$	$4.97^{+0.30}_{-0.30}$	$2.03^{+0.03}_{-0.03}$
SGC low-z	$-4.90^{+0.74}_{-0.70}$	$4.74^{+0.72}_{-0.67}$	$2.08^{+0.04}_{-0.05}$
NGC high-z	$-4.67^{+0.36}_{-0.42}$	$4.02^{+0.31}_{-0.36}$	$2.17^{+0.04}_{-0.04}$
SGC high-z	$-4.26^{+1.06}_{-0.96}$	$3.66^{+0.92}_{-0.83}$	$2.17^{+0.05}_{-0.05}$

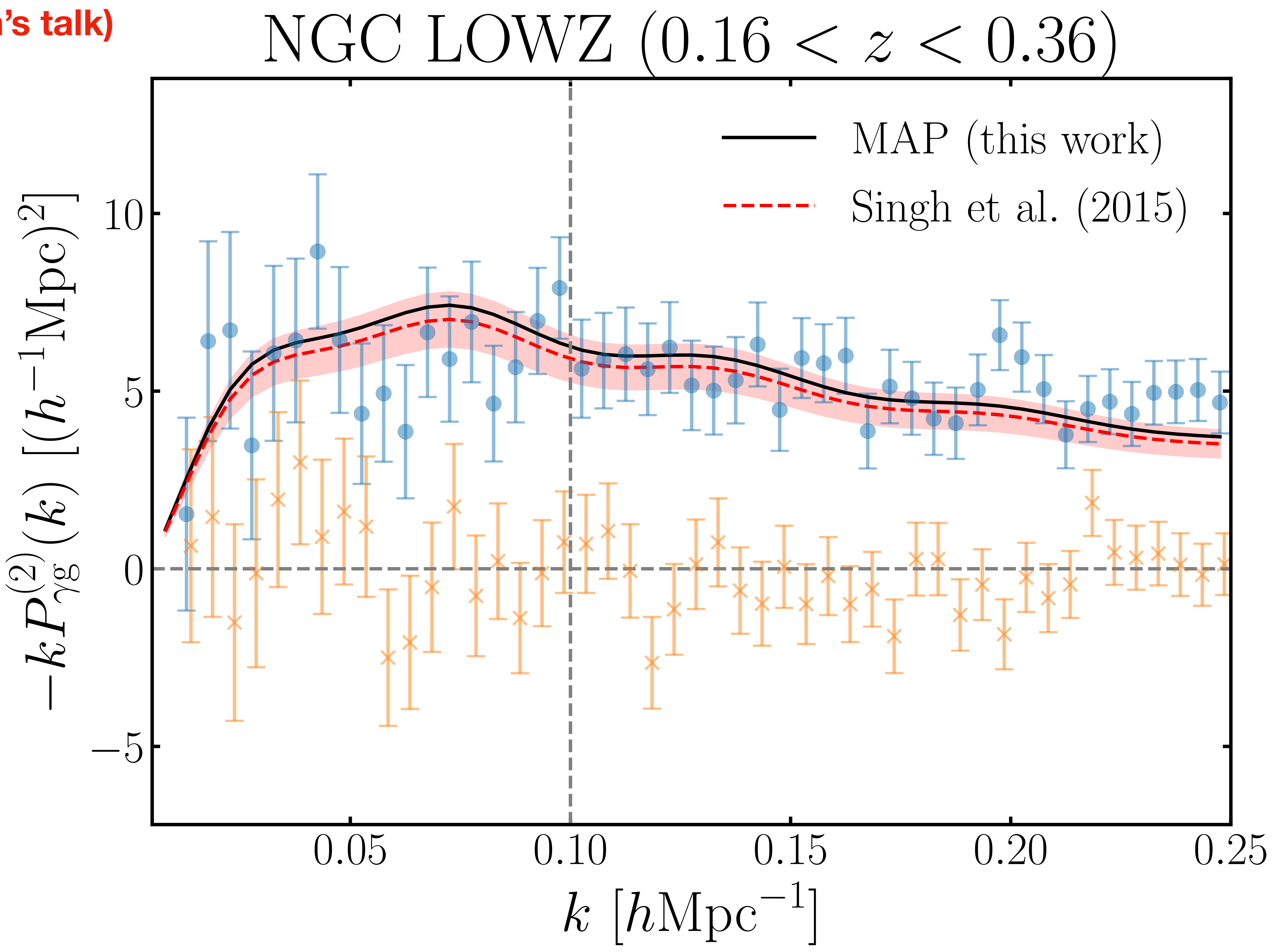


Q. Consistent with previous works?

- Singh+2015 measured the projected correlation function from BOSS LOWZ (0.16<z<0.36) and reported:

$$A_{\rm IA} = 4.6 \pm 0.5$$

Updated! (see Singh's talk)



- Our sample is CMASS+LOWZ, but galaxies at 0.16<z<0.36 are almost LOWZ galaxies.

- We did the same analysis for our "LOWZ" galaxies (0.16<z<0.36) in our sample.

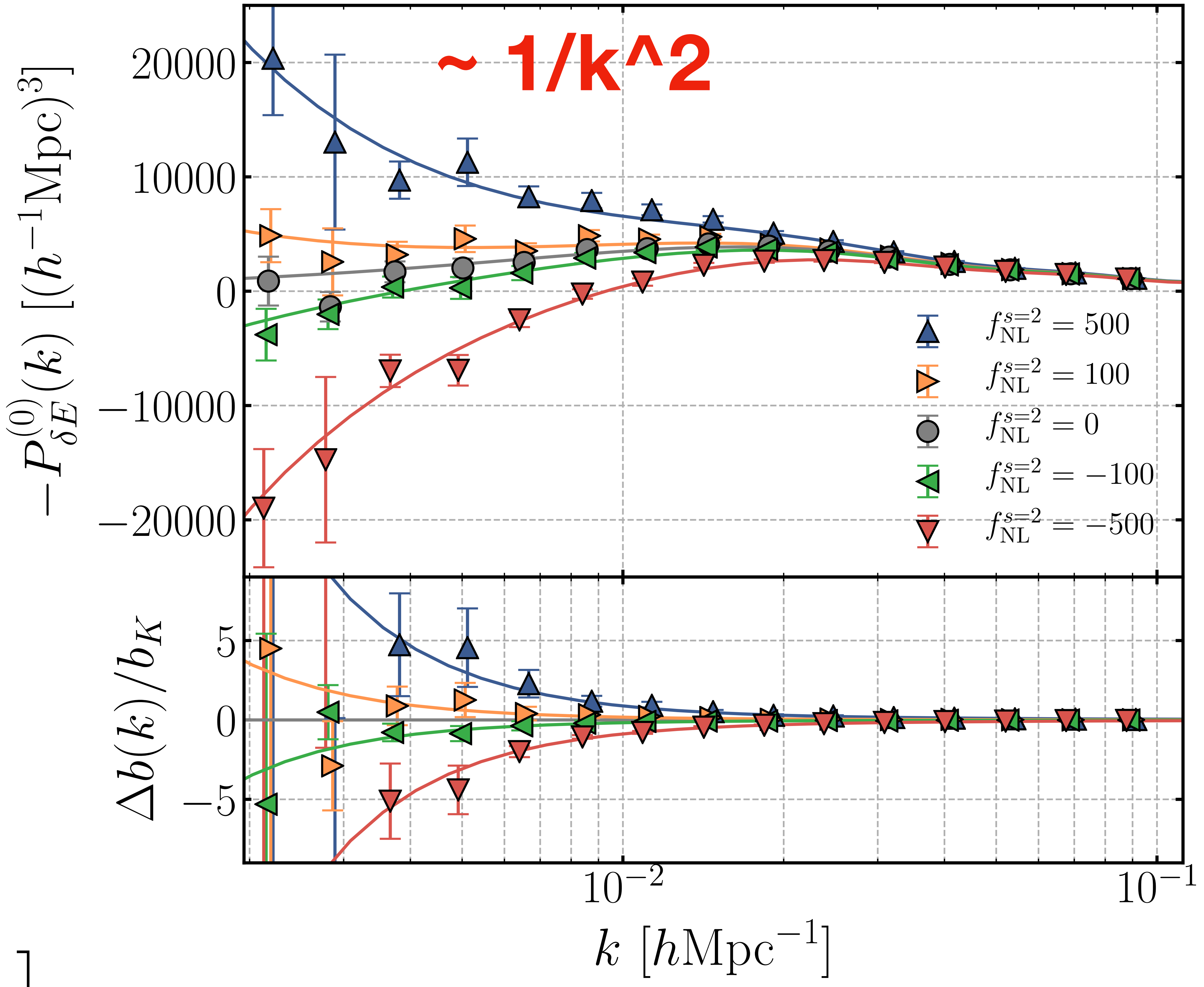
- $b_K = -0.0426^{+0.0041}_{-0.0040}$ or $A_{\rm IA} = 4.34^{+0.42}_{-0.40}$
  - Error is improved thanks to 3d! (up to $k_{\rm max} = 0.1\ h{\rm Mpc}^{-1}$.)

- There is no (overall) unknown bias for our power spectrum measurements.

Primordial Non-Gaussianity (PNG)

Linear Model: local-type PNGs

- Local-type PNG leads to the scale-dependent bias
  - tight constraints from linear-scale power spectrum



Akitsu+2021

<u>Galaxy Clustering</u>

- Isotropic local-type PNG (Dalal+2007,...)

$$B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \underline{2f_{\rm NL}^{s=0}}\left[P_\phi(k_1)P_\phi(k_2) + 2\ \text{perms.}\right]$$

$$\rightarrow\quad P_{\rm gg}(k,\mu) = \left[b_1 + f\mu^2 + \underline{\frac{b_\phi f_{\rm NL}^{s=0}}{\mathcal{M}(k)}}\right]^2 P^{\rm lin}(k) + \frac{c_{\rm np}}{\bar{n}}$$

~ 1/k^2

<u>Intrinsic Alignments</u>

- Anisotropic (quadrupolar) local-type PNG (Schmidt+2015)

$$B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \underline{2f_{\rm NL}^{s=2}}\left[\mathcal{L}_2(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)P_\phi(k_1)P_\phi(k_2) + 2\ \text{perms.}\right]$$

$$\rightarrow\quad P_{\rm Eg}(k,\mu) = \frac{1-\mu^2}{2}\left[b_K + \underline{\frac{b_\psi f_{\rm NL}^{s=2}}{\mathcal{M}(k)}}\right]\left[b_1 + f\mu^2 + \underline{\frac{b_\phi f_{\rm NL}^{s=0}}{\mathcal{M}(k)}}\right] P^{\rm lin}(k) + P^{\rm WL}_{\rm Eg}(k,\mu)$$

~ 1/k^2 ~ 1/k^2

Linear Model: assumptions for PNG bias

Without assumptions: we can constraint the parameter combinations:

$$(b_\phi f_{\rm NL}^{s=0}) \text{ and } (b_\psi f_{\rm NL}^{s=2})$$

There are several assumptions for PNG bias b_ϕ (summarized in Barreira 2022)

- Universality of halo mass function (Dalal+2007,…)
    - $b_\phi(b_1) = 2\delta_c(b_1 - 1)$

Adopted: D'Amico+2022

- Recent mergers (Slosar+2008,…)
    - $b_\phi(b_1) = 2\delta_c(b_1 - 1.6)$

Adopted: Slosar+2008, Mueller+2021, Castorina+2021

- IllustrisTNG galaxies (Barreira 2022)
    - $b_\phi(b_1) = 2\delta_c(b_1 - 0.55)$

Adopted: Cabass+2022, Barreira 2022

However, b_ψ for IA is relatively new:

- Dark matter halos (Akitsu+2021)
    - $b_\psi(b_K) = 2.04 \times b_K$
    - Note: this relation is not sensitive to mass, redshift and simulation resolution, but still aggressive.

Results IV: PNG-without bias relations

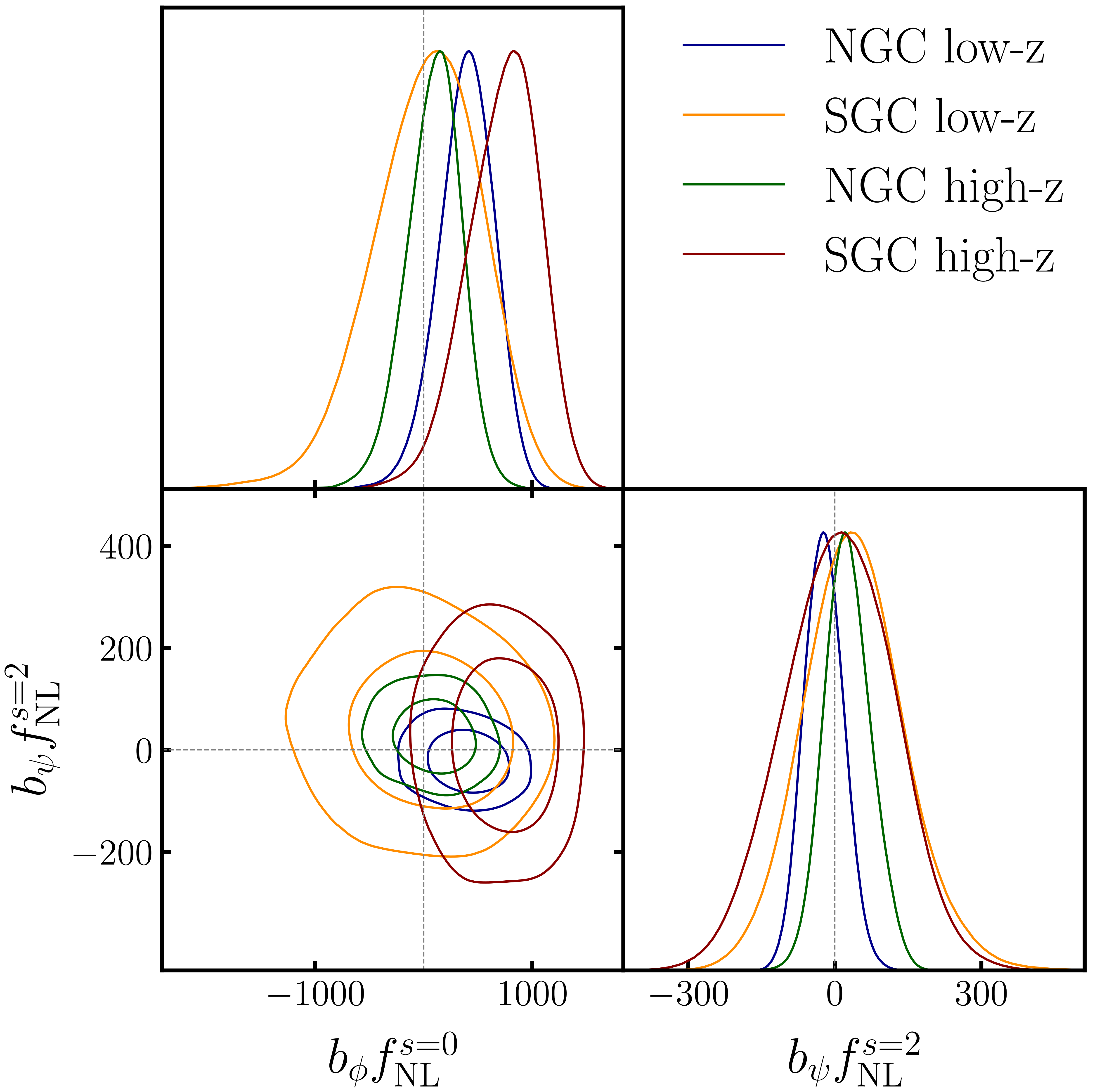
- We do not assume any additional relation between the linear bias and the PNG bias.
  - we constrain the parameter combinations:

$$(b_\phi f_{\rm NL}^{s=0}) \text{ and } (b_\psi f_{\rm NL}^{s=2})$$

  - we can learn "zero or nonzero" for PNGs

- <u>Result: zero consistent for both s=0 and s=2 PNGs for each galaxy sample.</u>

- This is the most conservative result of this work.

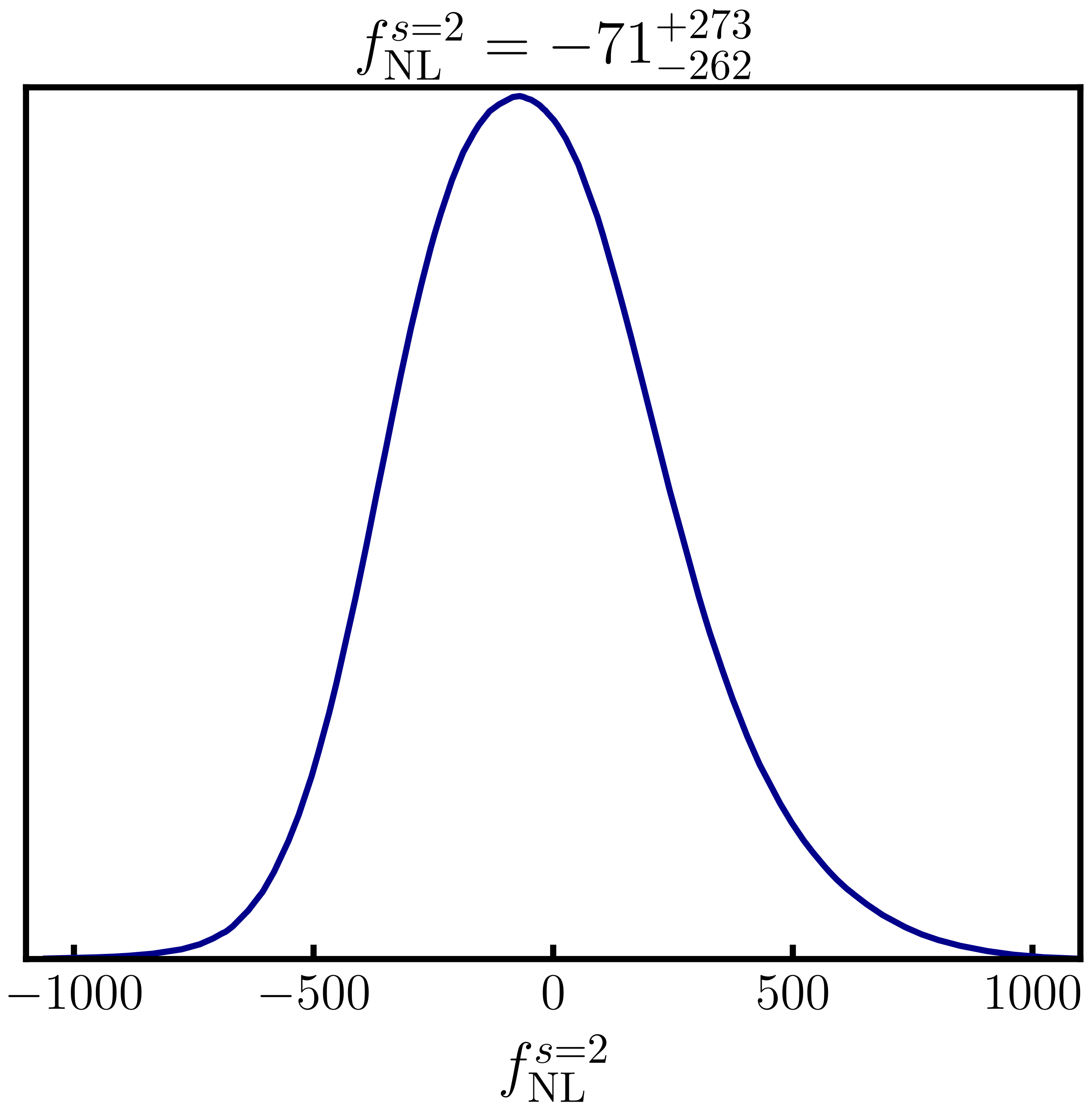


Results IV: PNG-with bias relation for IA

- We assume an additional relation between the linear shape bias and the PNG shape bias.
  - We assume the relation for dark matter halos (Akitsu+2021):

$$b'_{\psi}(b_K) = 2.04\, b_K$$

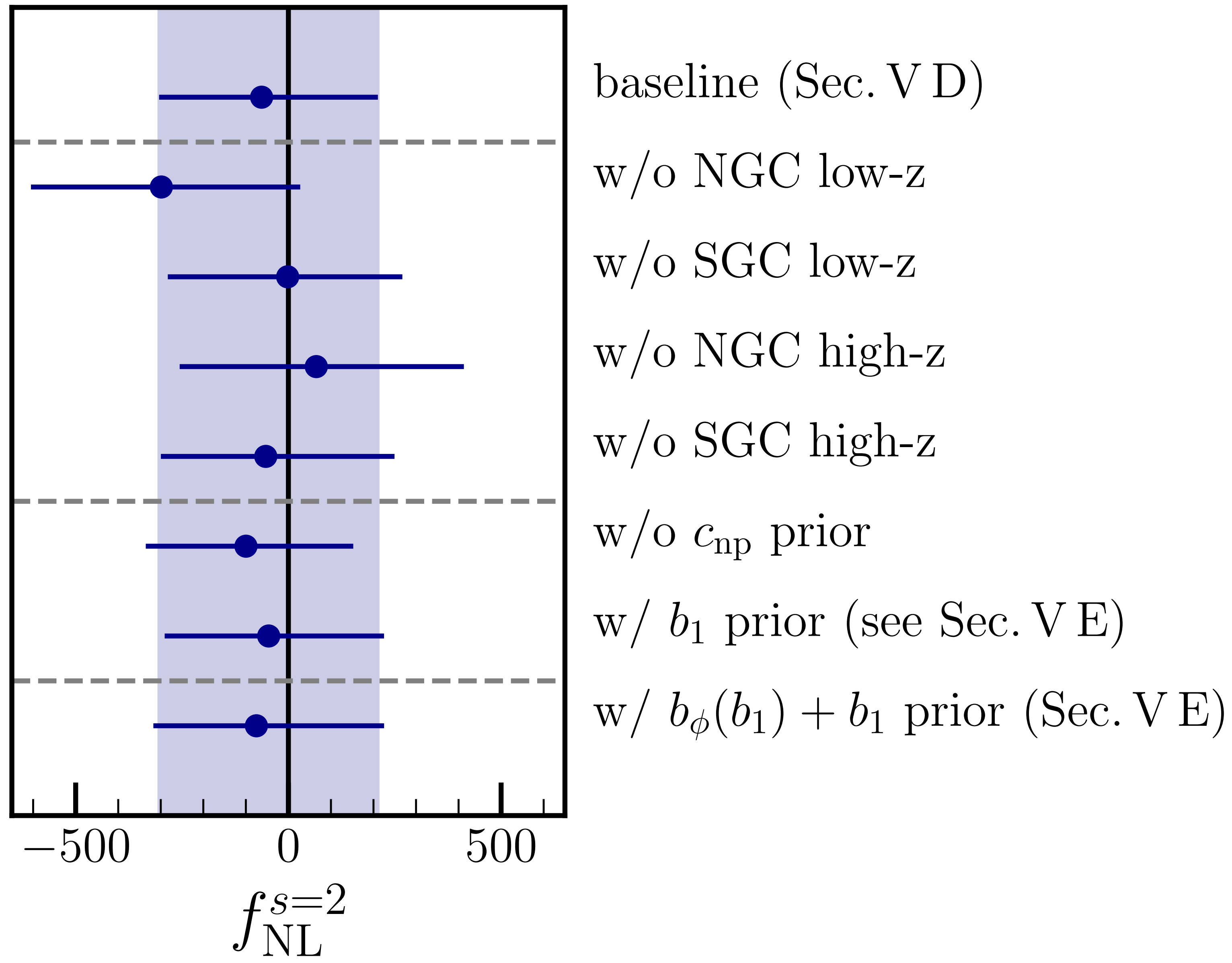
    - Note: this relation is not sensitive to mass, redshift and resolution, but aggressive.
  - We still keep the combination $(b_\phi f_{\rm NL}^{s=0})$
    - Thus this is the minimal assumption to obtain a direct constraint on $f_{\rm NL}^{s=2}$.



- Result:

$$f_{\rm NL}^{s=2} = -71^{+273}_{-262},$$

cf. Planck CMB bispectrum:
$\sigma(f_{\rm NL}^{s=2}) \sim 19$



- Constraint on $f_{\rm NL}^{s=2}$ is almost independent of prior choice of linear bias, residual shot noise, and assumption of $b_\phi f_{\rm NL}^{s=0}$ (next page)

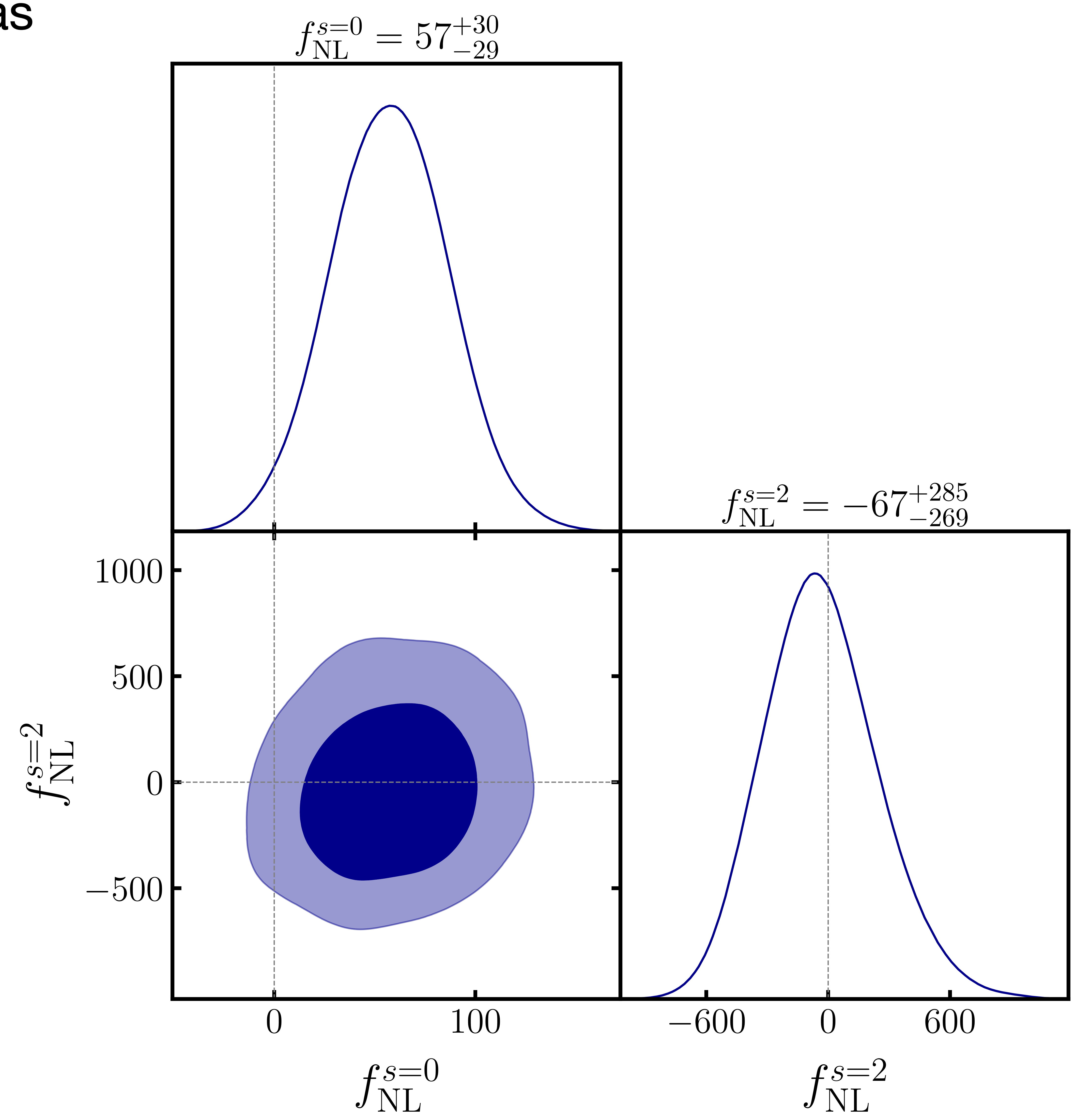
Results V: PNG-with two bias relations

- We add the relation between the linear bias and the PNG bias for the galaxy clustering part.

  - We also assume the relation for s=0 obtained by IllustrinsTNG galaxies (Barreira+2021):

$$b_\phi(b_1) = 2\delta_c(b_1 - p) \text{ with } \delta_c = 1.686 \text{ and } p = 0.55$$

  - The mode and error bar for s=0 is consistent with the previous similar analysis (Linear model constraints from clustering Barreira+2021)



Conclusion

- We analyze the intrinsic alignment signals from BOSS galaxies in Fourier space.

(1) Measurements of IA power spectrum

$$-2\ln\,\mathcal{L}(\mathbf{d}|\mathbf{p}) \sim [\mathbf{d} - \mathbf{m}(\mathbf{p})]^{\mathrm{T}} \mathbf{C}^{-1} [\mathbf{d} - \mathbf{m}(\mathbf{p})]$$

(2) Linear theory + window convolution

(3) Analytic Covariance

- S/N is comparable with the quadrupole moment of clustering power spectrum.
- Our results are consistent with the previous 2PCF results (Singh+2015).
- Constraints on the local-type PNGs are consistent with zero.