Controlling intrinsic alignments in weak lensing with three-point statistics

Susan Pyne

Ananth Tenneti

Benjamin Joachimi

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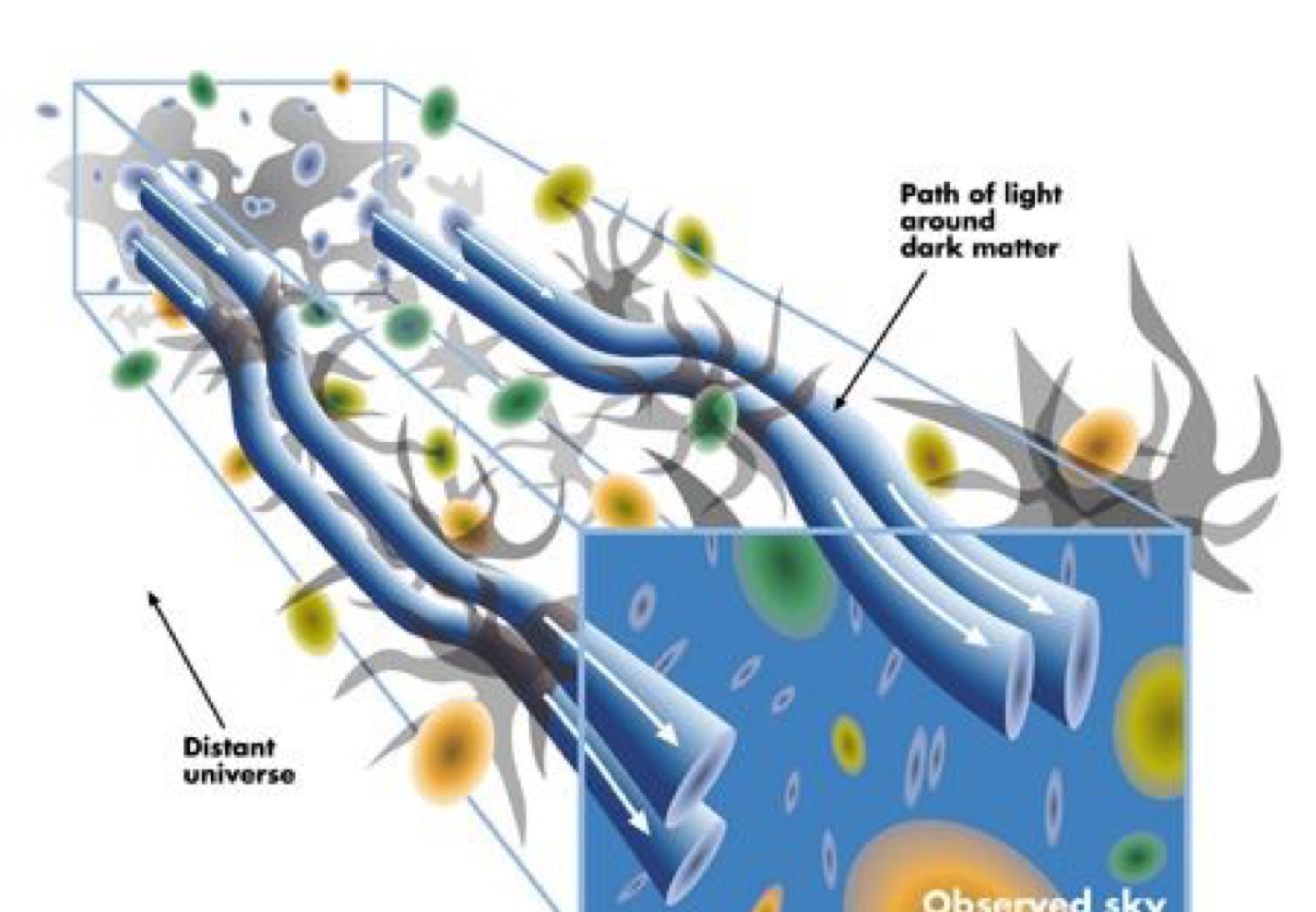
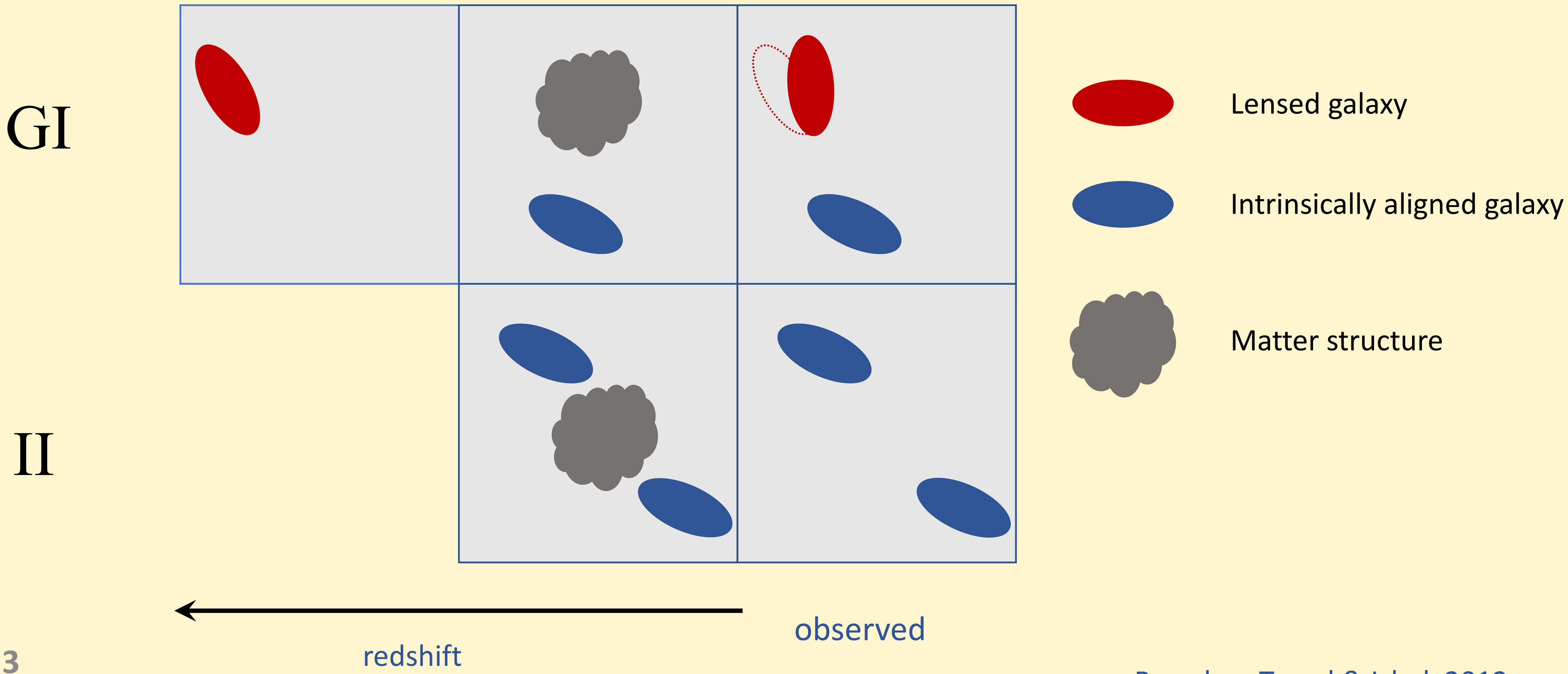
Weak gravitational lensing



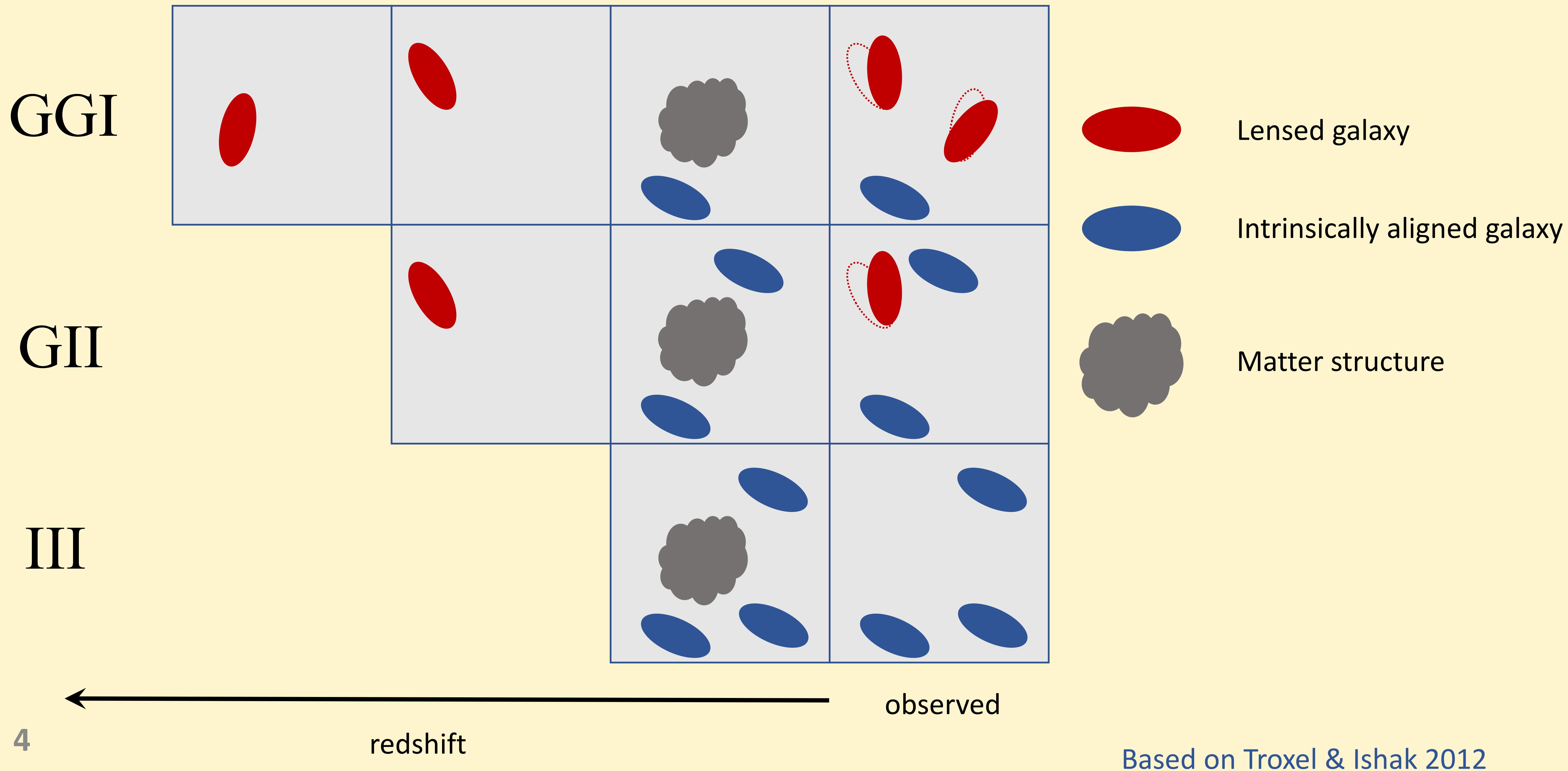
Tyson et al 2002

Intrinsic alignments can mimic the lensing signal



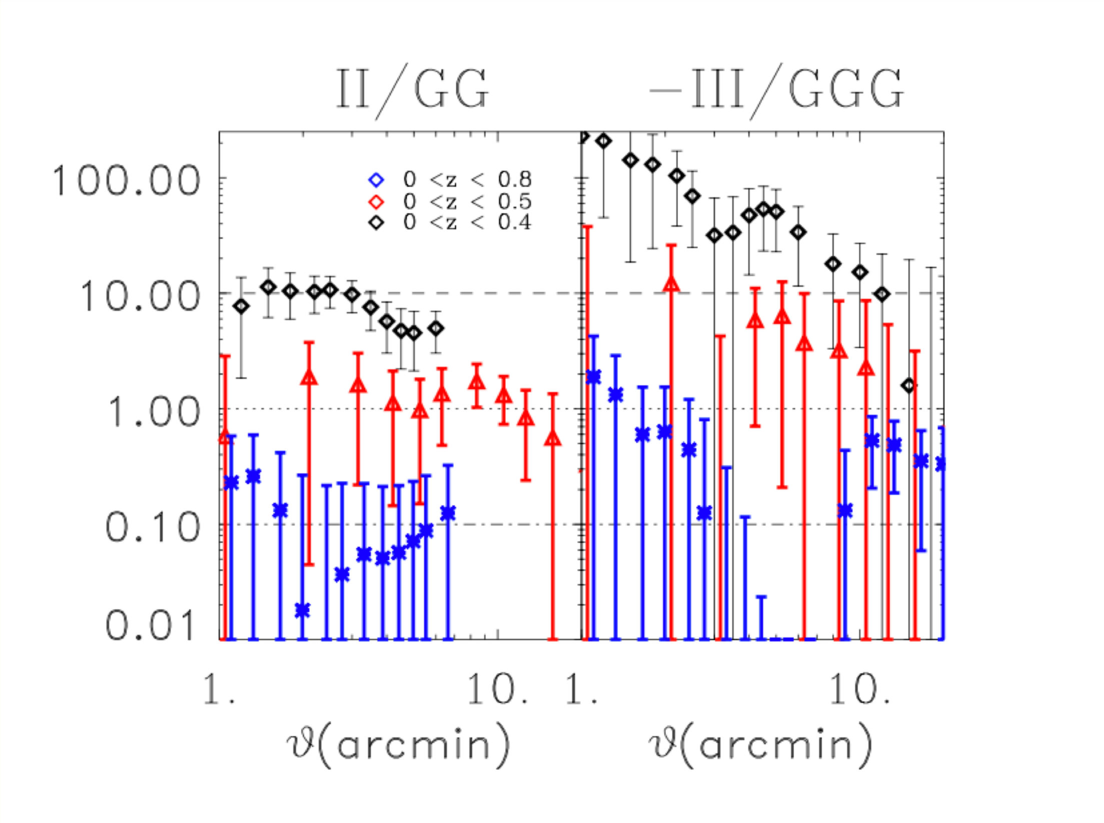
Based on Troxel & Ishak 2012

Three-point intrinsic alignment are more complex



Based on Troxel & Ishak 2012

Intrinsic alignments affect 2-point and 3-point weak lensing statistics differently



Semboloni et al 2008 – from simulations

Modelling intrinsic alignments
- the non-linear alignment model (NLA)

Fourier transform of field which produces IA → $\tilde{\delta}_{\rm I} = f_{\rm IA} \tilde{\delta}_{\rm G}$ ← matter density contrast

$$f_{\rm IA} = -A_{\rm IA} \frac{C_1 \Omega_{\rm m} \rho_{\rm cr}}{D(z)} (1+z)^{\eta_{\rm IA}}$$

2 free parameters – amplitude $A_{\rm IA}$ and redshift dependence $\eta_{\rm IA}$

This gives the intrinsic alignment power spectra

$$P_{\delta\delta_{\rm I}}(k) = f_{\rm IA} P_{\rm NL}(k) \qquad P_{\delta_{\rm I}\delta_{\rm I}}(k) = f_{\rm IA}^2 P_{\rm NL}(k)$$

Hirata & Seljak 2004, Bridle & King 2007

We also need to model intrinsic alignment bispectra

Use fitting formula from Gíl-Marin et al 2012:

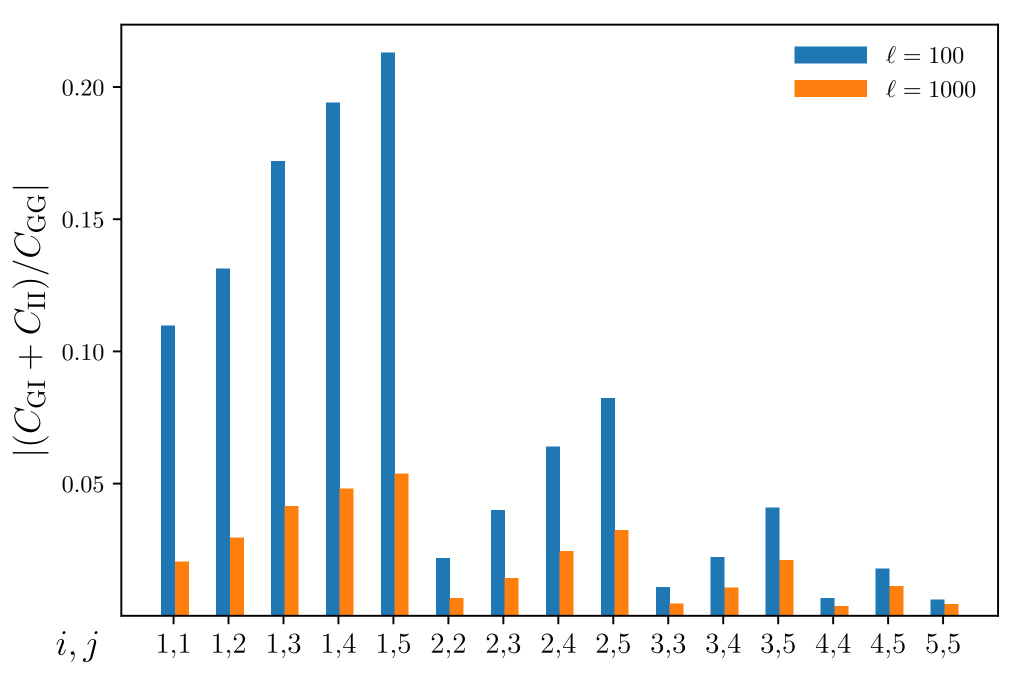
$$B_{\delta\delta\delta}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = 2F_2^{\rm eff}(\mathbf{k}_1, \mathbf{k}_2) P_{\rm NL}(k_1) P_{\rm NL}(k_2) + 2 \text{ perms.}$$

Then the IA bispectra are, for example,

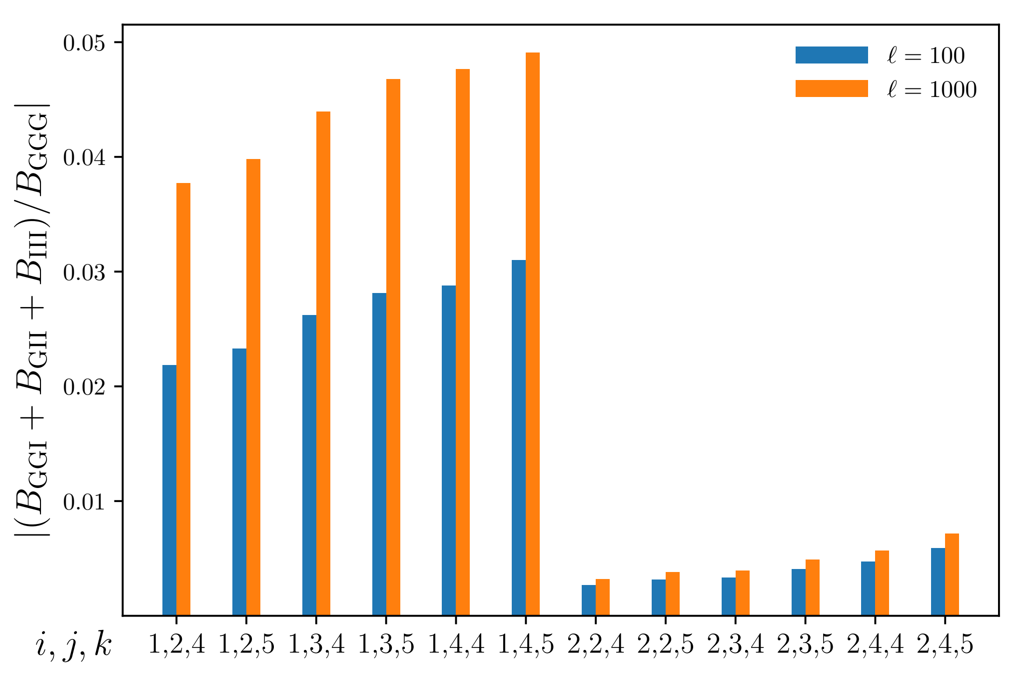
$$\begin{aligned} B_{\delta\delta_{\rm I}\delta_{\rm I}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = 2\,\big[& f_{\rm IA}^3 F_2^{\rm eff}(\mathbf{k}_1, \mathbf{k}_2) P_{\rm NL}(k_1) P_{\rm NL}(k_2) \\ & + f_{\rm IA}^2 F_2^{\rm eff}(\mathbf{k}_2, \mathbf{k}_3) P_{\rm NL}(k_2) P_{\rm NL}(k_3) \\ & + f_{\rm IA}^3 F_2^{\rm eff}(\mathbf{k}_3, \mathbf{k}_1) P_{\rm NL}(k_3) P_{\rm NL}(k_1) \big] \end{aligned}$$

The resulting IA power spectra and bispectra are differently related to the lensing signal

Power spectrum



Bispectrum



Ratio of total intrinsic alignment signal to lensing signal

We used a Fisher matrix methods and figures of merit to quantify information content

Fisher matrix

$$F_{\alpha\beta} = \frac{\partial \mathbf{D}^{\mathrm{T}}}{\partial p_\alpha} \mathrm{Cov}_{\mathrm{D}}^{-1} \frac{\partial \mathbf{D}}{\partial p_\beta}$$

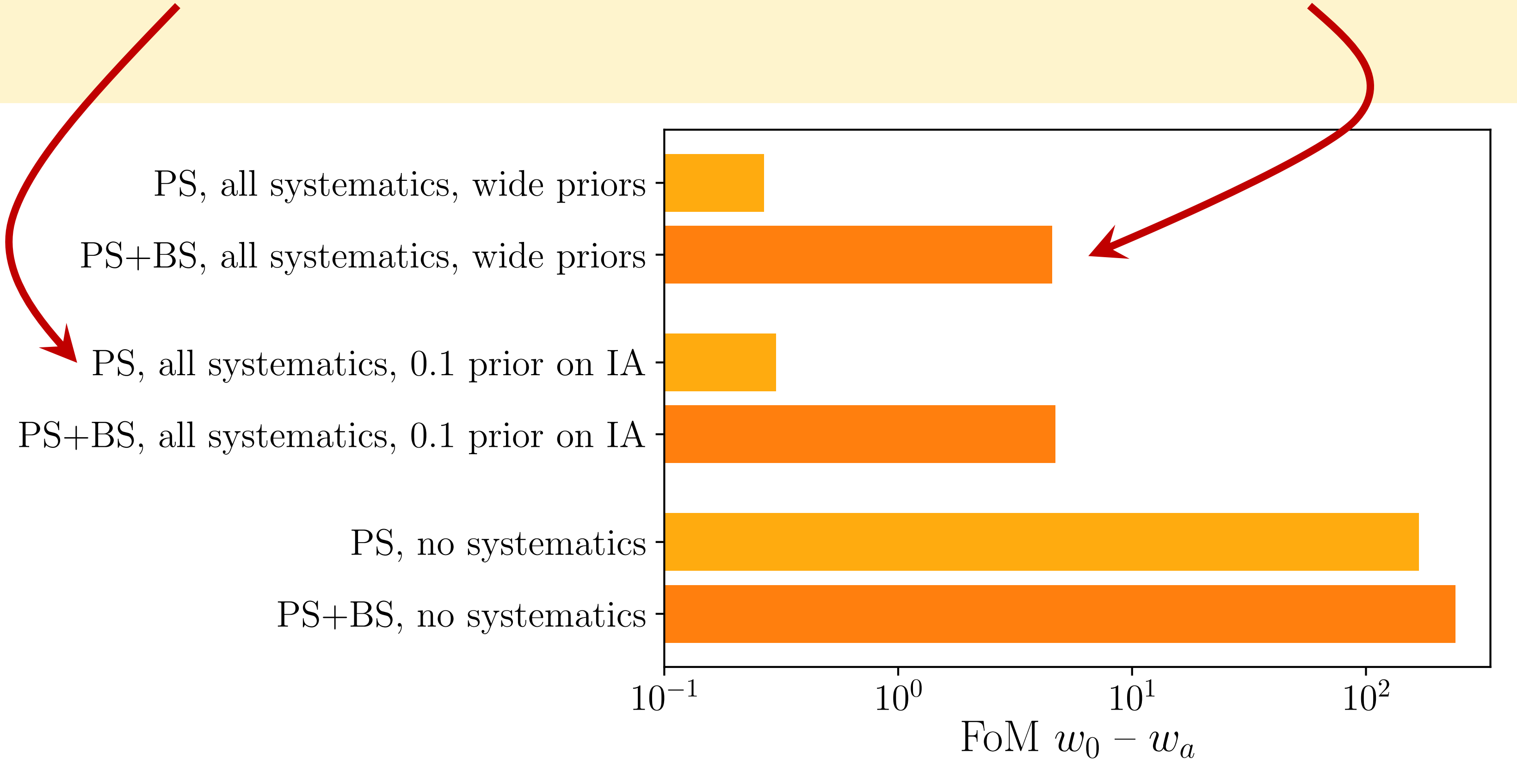
data vector – power spectrum only or power spectrum + bispectrum

Figure of merit

$$\mathrm{FoM}_{\alpha\beta} = \frac{1}{\sqrt{\det(\mathbf{F}^{-1})_{\alpha\beta}}}$$

cosmological parameters

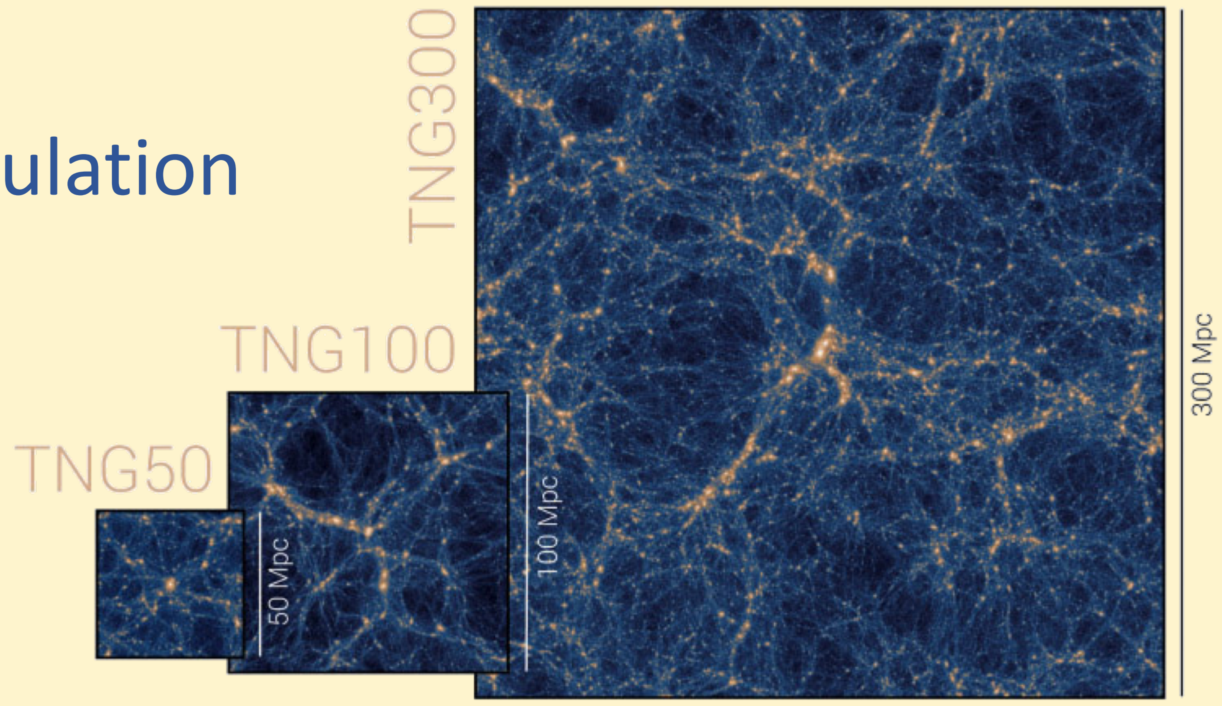
Compare PS with tight prior with self-calibration using PS+BS



Simulations

IllustrisTNG300 hydrodynamic simulation

Periodic box size 300 Mpc^3
2500^3 dark matter particles
DM particle mass $4 \times 10^7\ h^{-1}M_\odot$
Minimum halo mass ~ $4 \times 10^{10}\ h^{-1}M_\odot$



Nelson et al 2019

1. Identify halos
2. Measure their shape (ellipticity) – this gives the intrinsic shear $\tilde{\gamma}$ in Fourier space
3. Decompose into E- and B-modes and measure IA spectra

IA power spectra and bispectra

$$\langle\tilde{\delta}(\boldsymbol{k})\tilde{\gamma}_{\rm E}(\boldsymbol{k}')\rangle = (2\pi)^3\delta_{\rm D}^3(\boldsymbol{k}+\boldsymbol{k}')P_{\delta{\rm E}}(\boldsymbol{k})$$

$$\langle\tilde{\gamma}_{\rm E}(\boldsymbol{k})\tilde{\gamma}_{\rm E}(\boldsymbol{k}')\rangle = (2\pi)^3\delta_{\rm D}^3(\boldsymbol{k}+\boldsymbol{k}')P_{\rm EE}(\boldsymbol{k})$$

$$\langle\tilde{\gamma}_{\rm B}(\boldsymbol{k})\tilde{\gamma}_{\rm B}(\boldsymbol{k}')\rangle = (2\pi)^3\delta_{\rm D}^3(\boldsymbol{k}+\boldsymbol{k}')P_{\rm BB}(\boldsymbol{k})$$

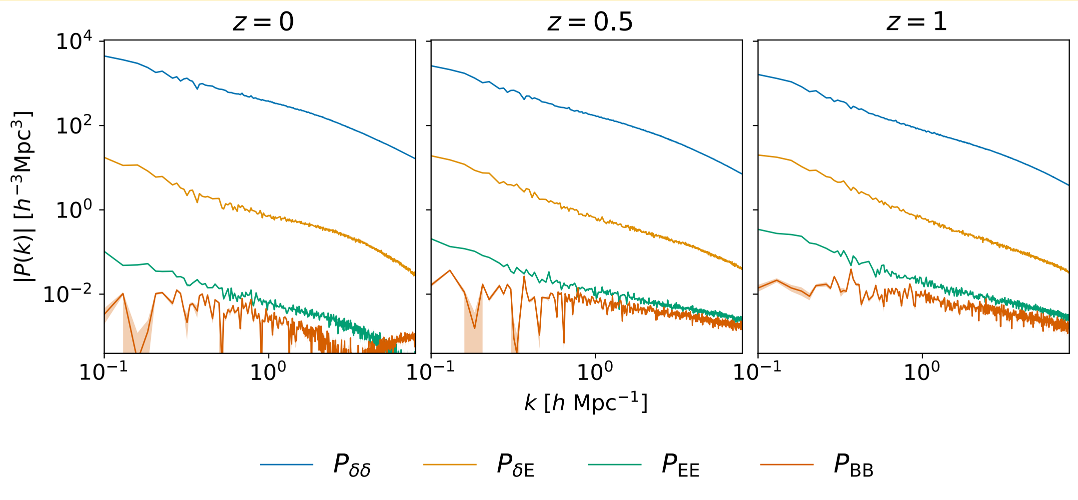
$$\langle\tilde{\delta}(\boldsymbol{k}_1)\tilde{\delta}(\boldsymbol{k}_2)\tilde{\gamma}_{\rm E}(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta_{\rm D}^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_{\delta\delta{\rm E}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$

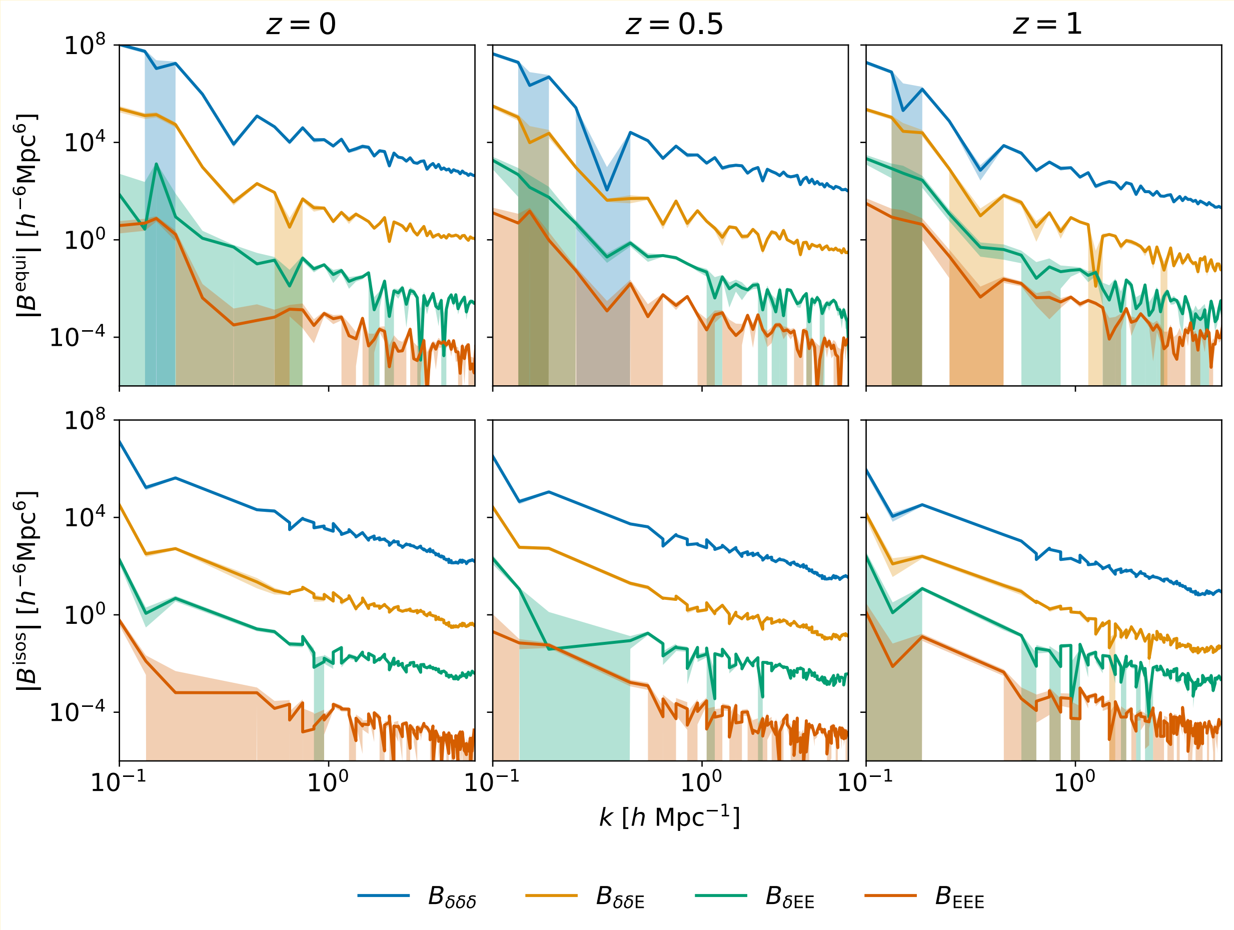
$$\langle\tilde{\delta}(\boldsymbol{k}_1)\tilde{\gamma}_{\rm E}(\boldsymbol{k}_2)\tilde{\gamma}_{\rm E}(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta_{\rm D}^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_{\delta{\rm EE}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$

etc

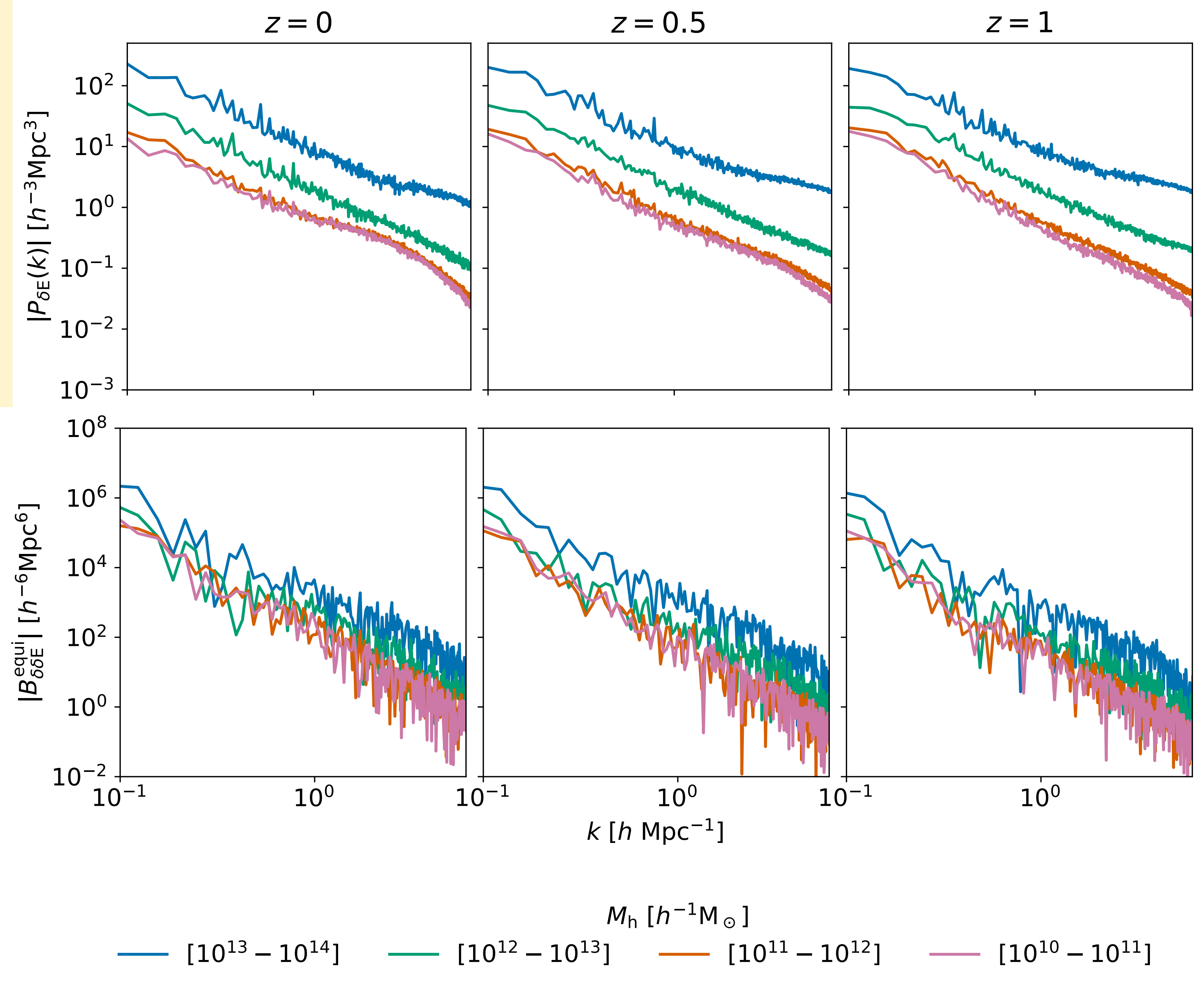
Blazek et al 2015, Kurita et al 2020

Simulation measurements



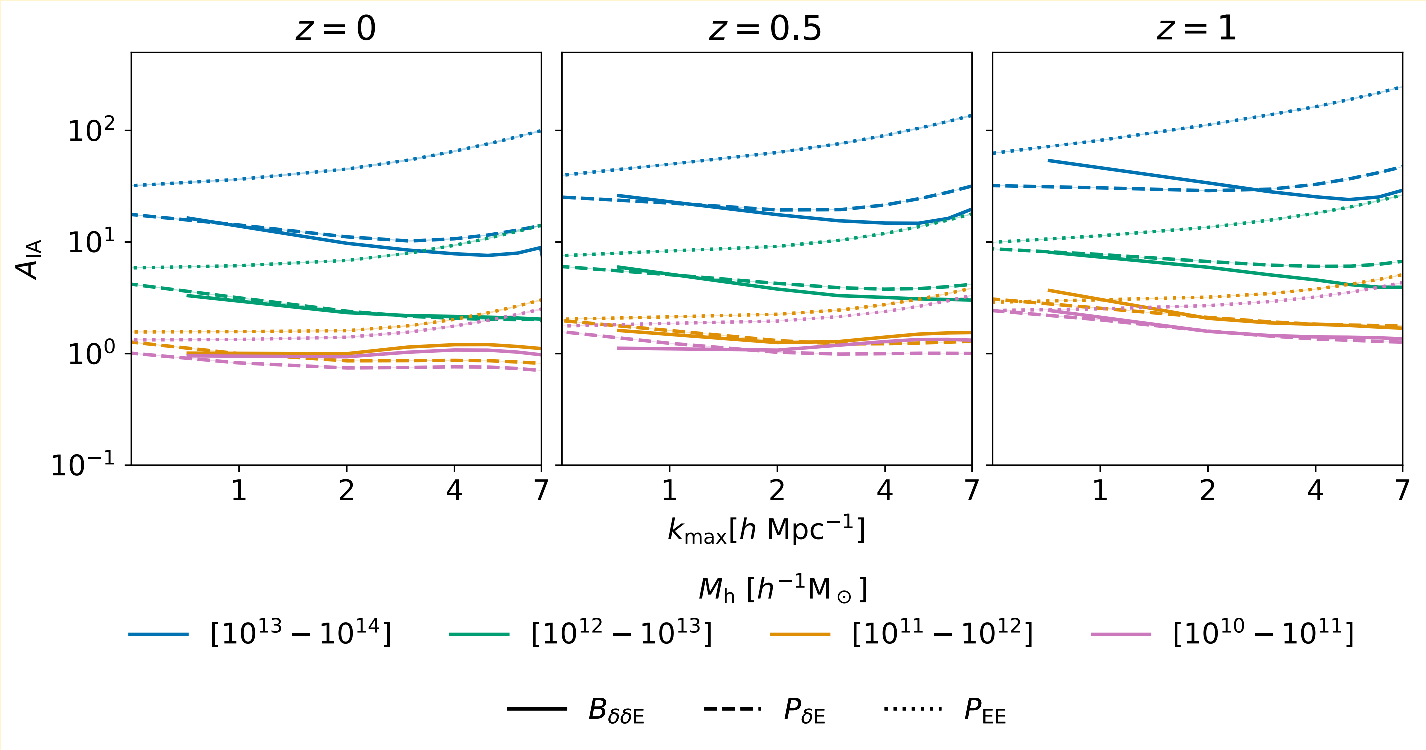


Consistent with Kurita et al 2020



IA power spectra and bispectra increase with mass, and weakly with redshift

Estimated IA amplitudes



Fitted from

$$\frac{P_{\delta E}}{P_{\delta\delta}} = f_{IA}$$

$$\frac{P_{EE}}{P_{\delta\delta}} = f_{IA}^2$$

$$\frac{B_{\delta\delta E}}{B_{\delta\delta\delta}} = \frac{1}{3}[f_{IA}^2 + 2f_{IA}]$$

equilateral triangles only

3D spectra

$$f_{IA} = -A_{IA}(1-\mu^2)\frac{C_1\Omega_m\rho_{cr}}{D(z)}$$

Summary

- Controlling intrinsic alignments is a key challenge for next-generation weak lensing surveys.
- IAs affects the power spectrum and bispectrum differently.
- Using PS and BS together mitigate IAs more effectively than using PS only with external calibration data.
- Measurements from IllustrisTNG-300 simulations show a single physically-motivated model can jointly model two-point and three-point IA statistics.
- Opens up the prospect of using three-point statistics to help separate IA from lensing signals.