Systematic errors in weak lensing surveys and the utility of random galaxy catalogues

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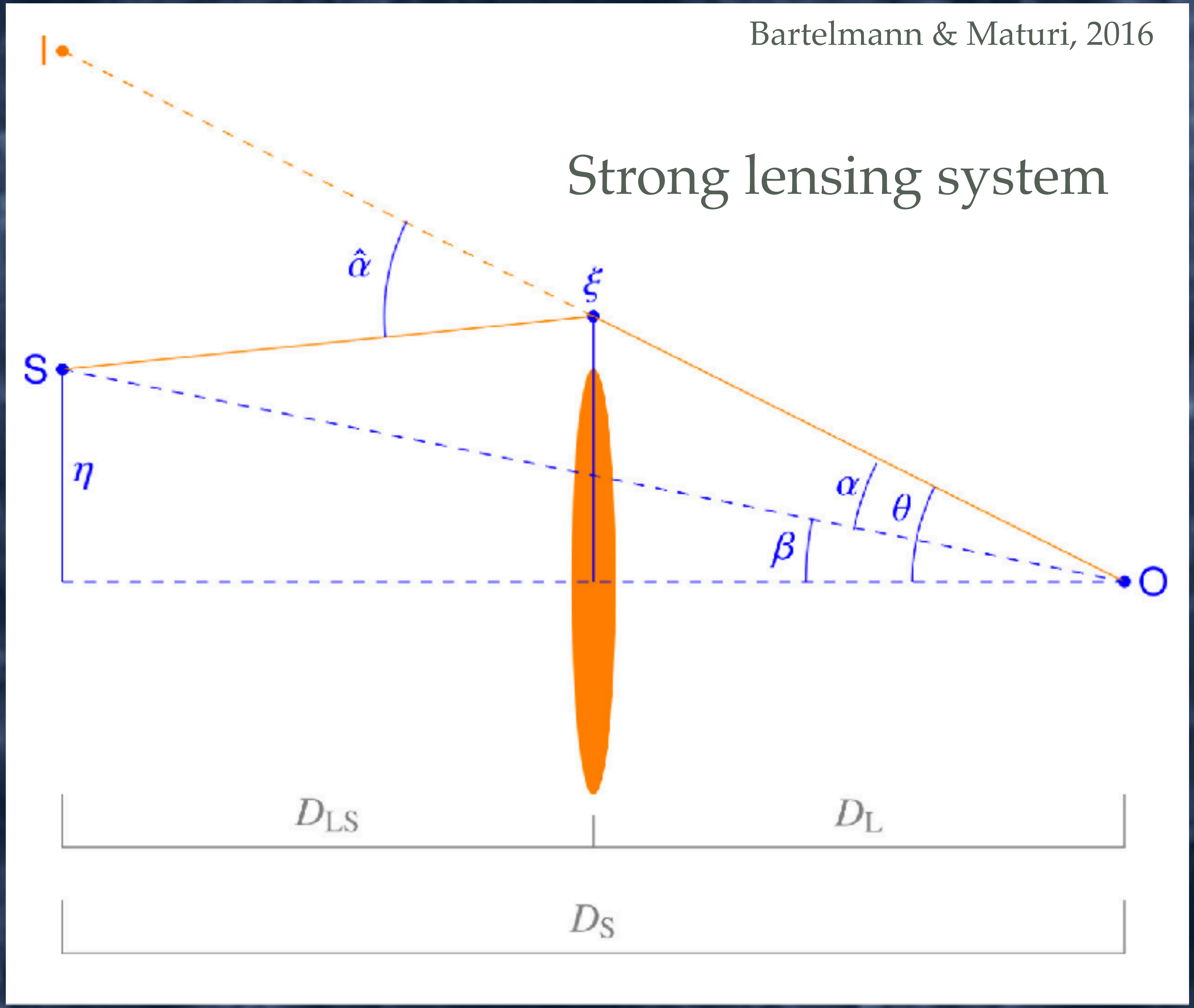
Outline

- Weak gravitational lensing
- Galaxy intrinsic alignments (IA)
- Direct measurements and modelling of IA
- Photo-z randoms
- Self-calibration with 3(+)x2-point analyses
- Correcting clustering biases with Organised Randoms

Weak Cosmological Lensing — ‘Cosmic Shear’



$$C_\kappa(\ell) = \frac{9H_0^4}{4c^4}\Omega_{m,0}^2\sigma_8^2 \int_0^{\chi_s} d\chi \left(\frac{\chi(\chi_s-\chi)}{\chi_s}\right)^2 P_\delta\left(\frac{\ell}{\chi},\chi\right)$$

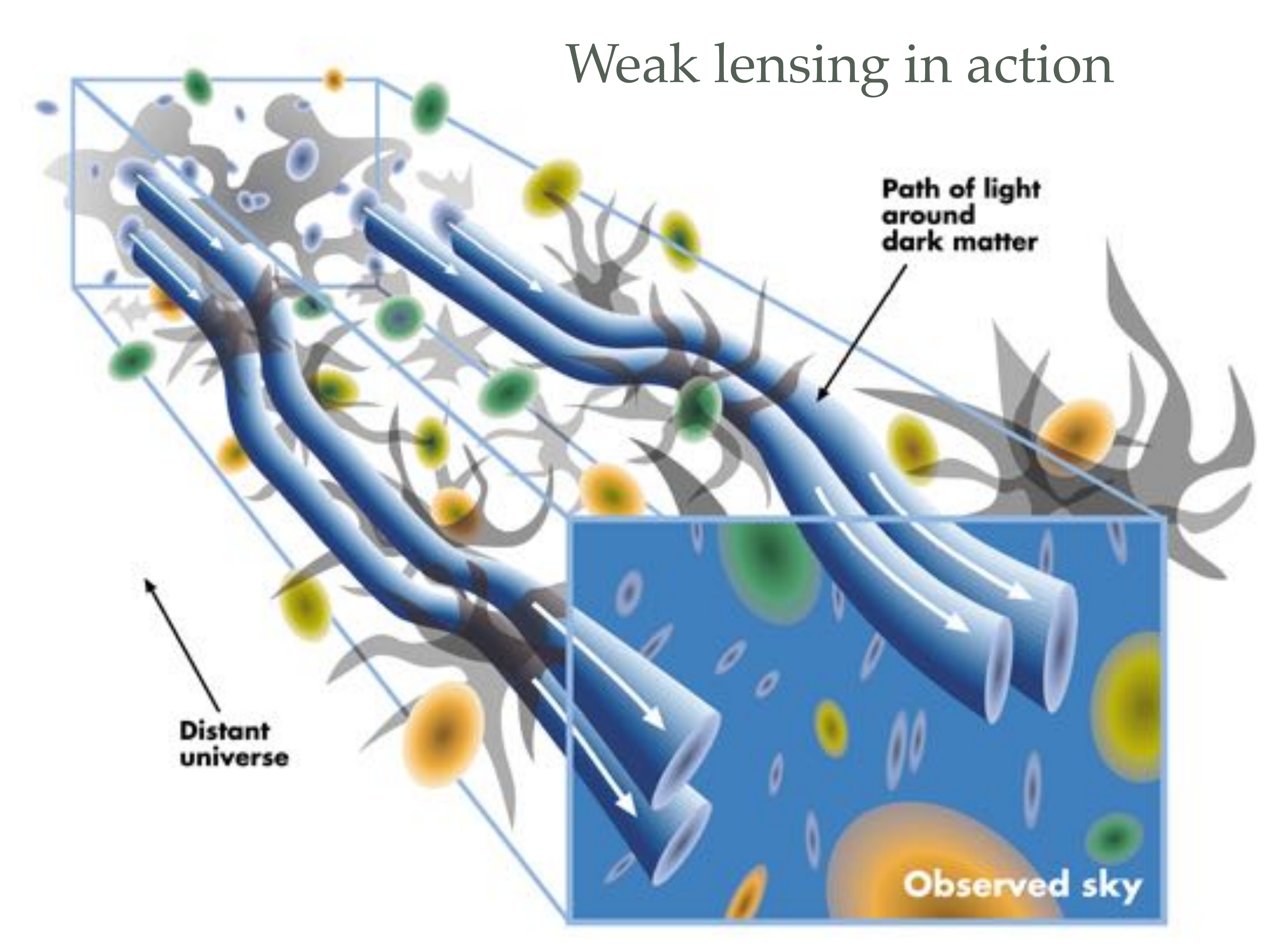
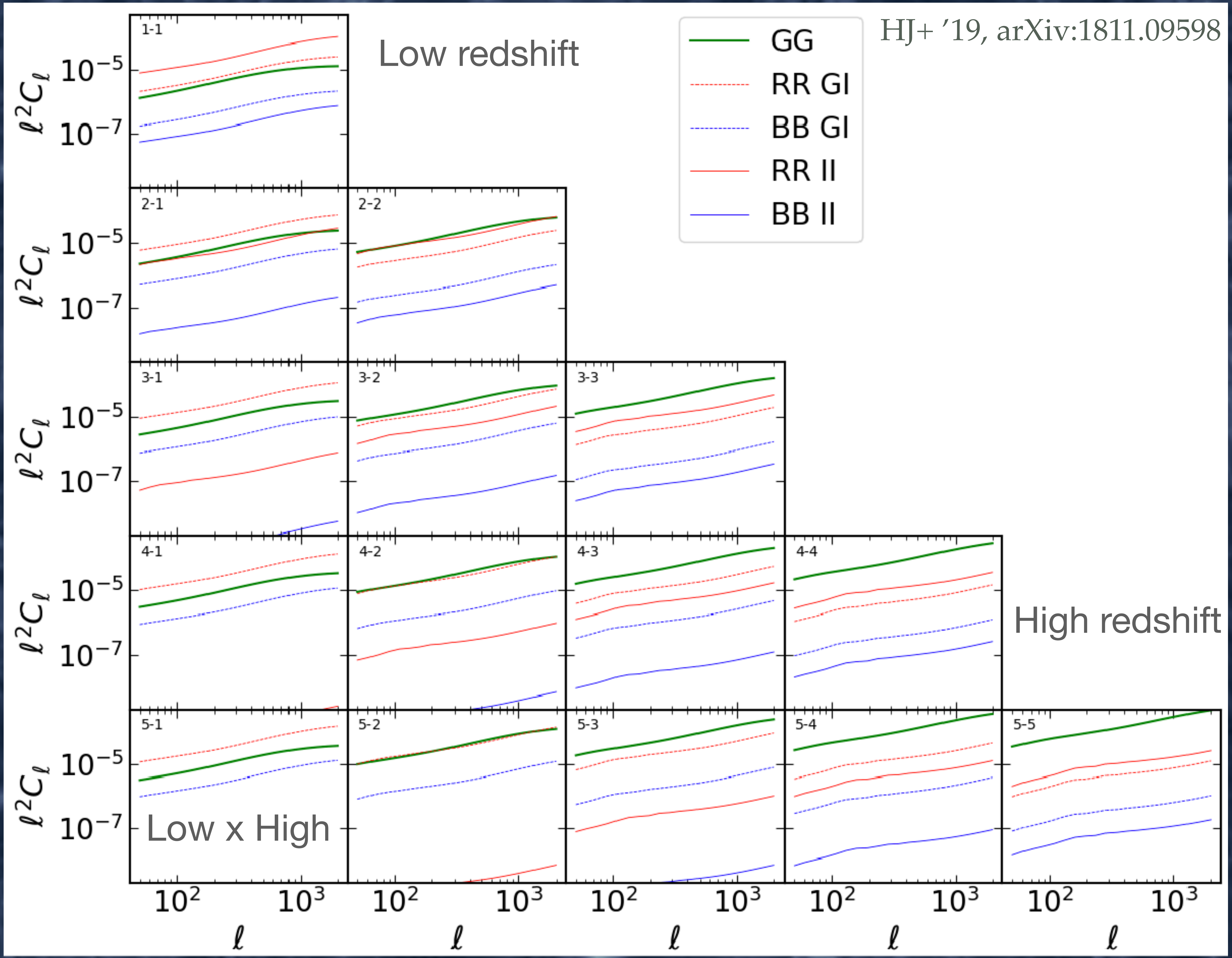


Image courtesy of Bell Labs/Lucent

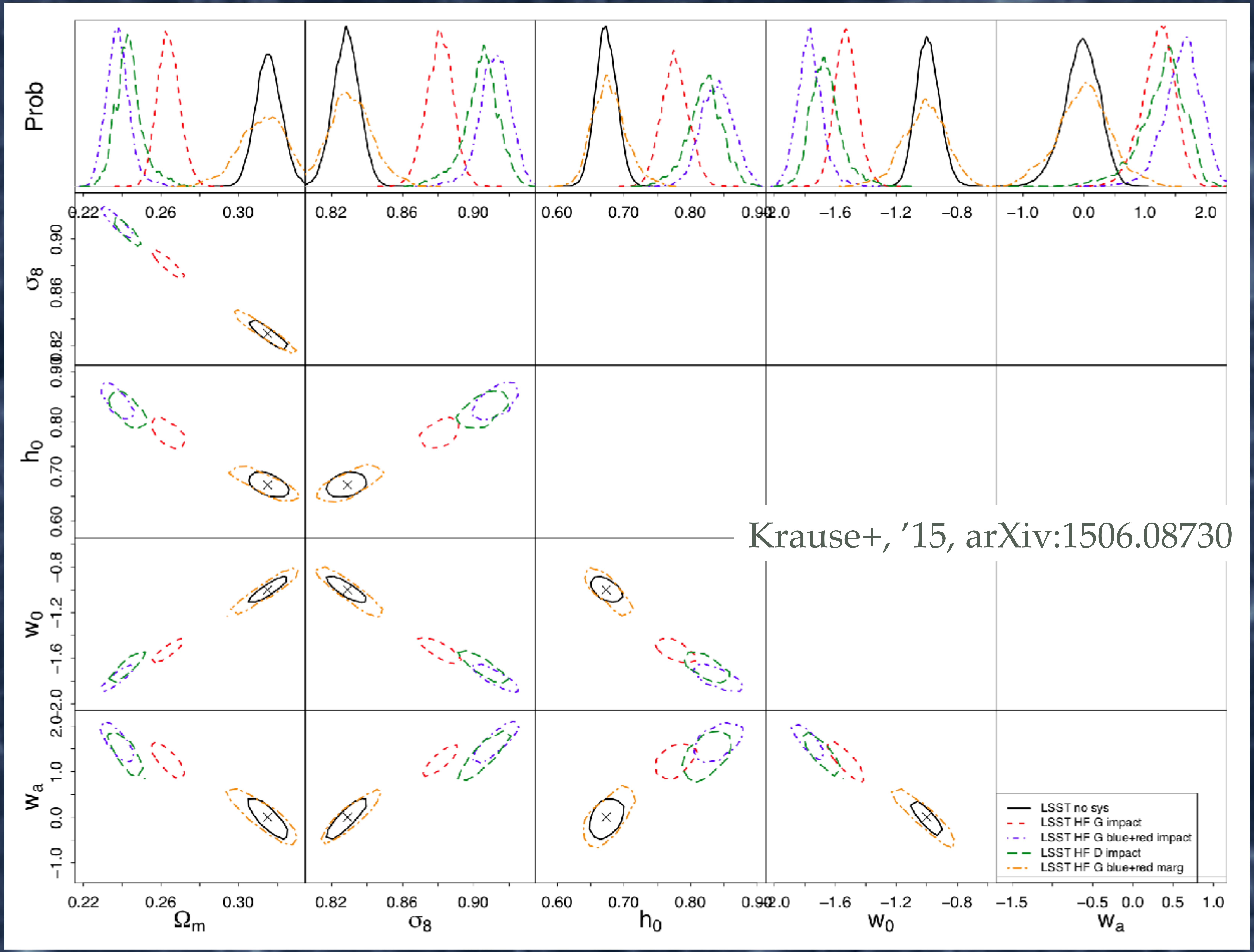
- Cosmic shear must tackle challenges wrt shape, redshift & covariance estimation, noise, systematics…

Intrinsic Alignments



- We are interested in GG
- Intrinsic alignments give other contributions: II, GI
- We know that red/blue galaxies align differently
- What we observe is some weighted linear combination of all contributions

- Ignoring IA will result in large cosmological parameter biases
- We need a descriptive model, and the data/ statistics to calibrate it
- Currently most popular is the non-linear alignments (NLA) model — issues with wide priors; lack of complexity; degradation of constraints; limited to linear scales

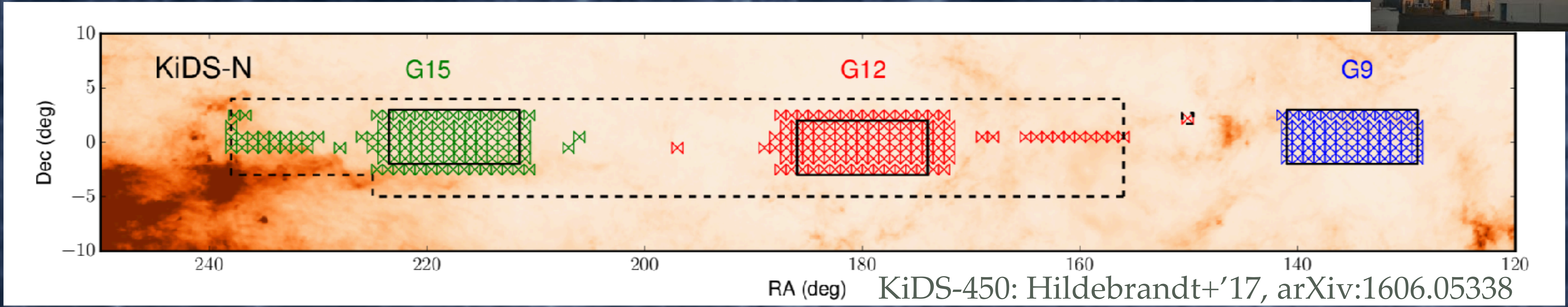


Krause+, ’15, arXiv:1506.08730


Background source
LSS
Local galaxies
GI
w_{g+}
II
II

KiDS — Kilo Degree Survey

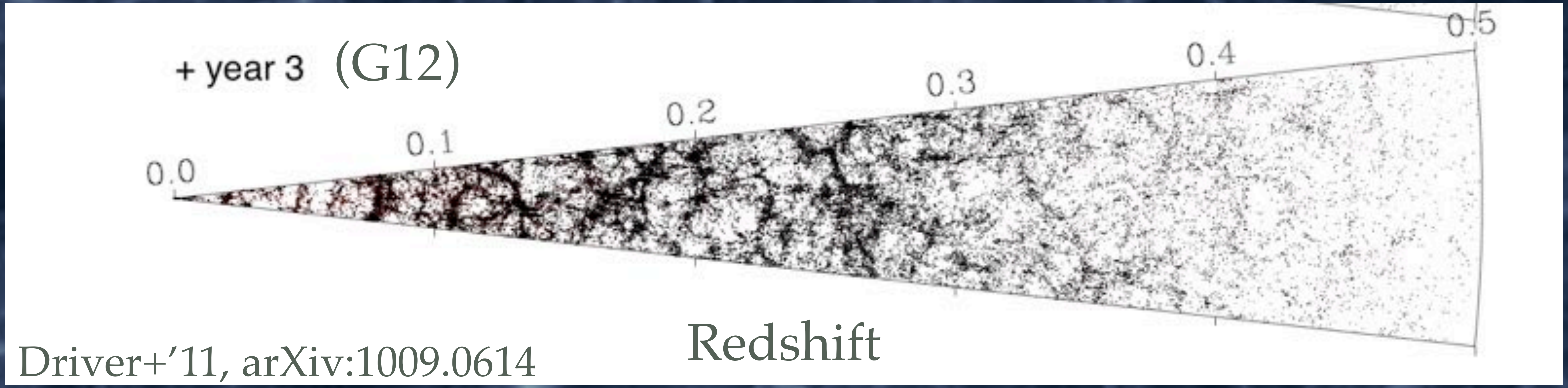
OmegaCAM @ VLT Survey Telescope (VST) — *ugri* imaging — completed 1350deg^2



KiDS-450: Hildebrandt+’17, arXiv:1606.05338

GAMA — Galaxy And Mass Assembly

AAOmega spectrograph @ Anglo-Australian Telescope (AAT) — 98% complete to r < 19.8



Driver+’11, arXiv:1009.0614

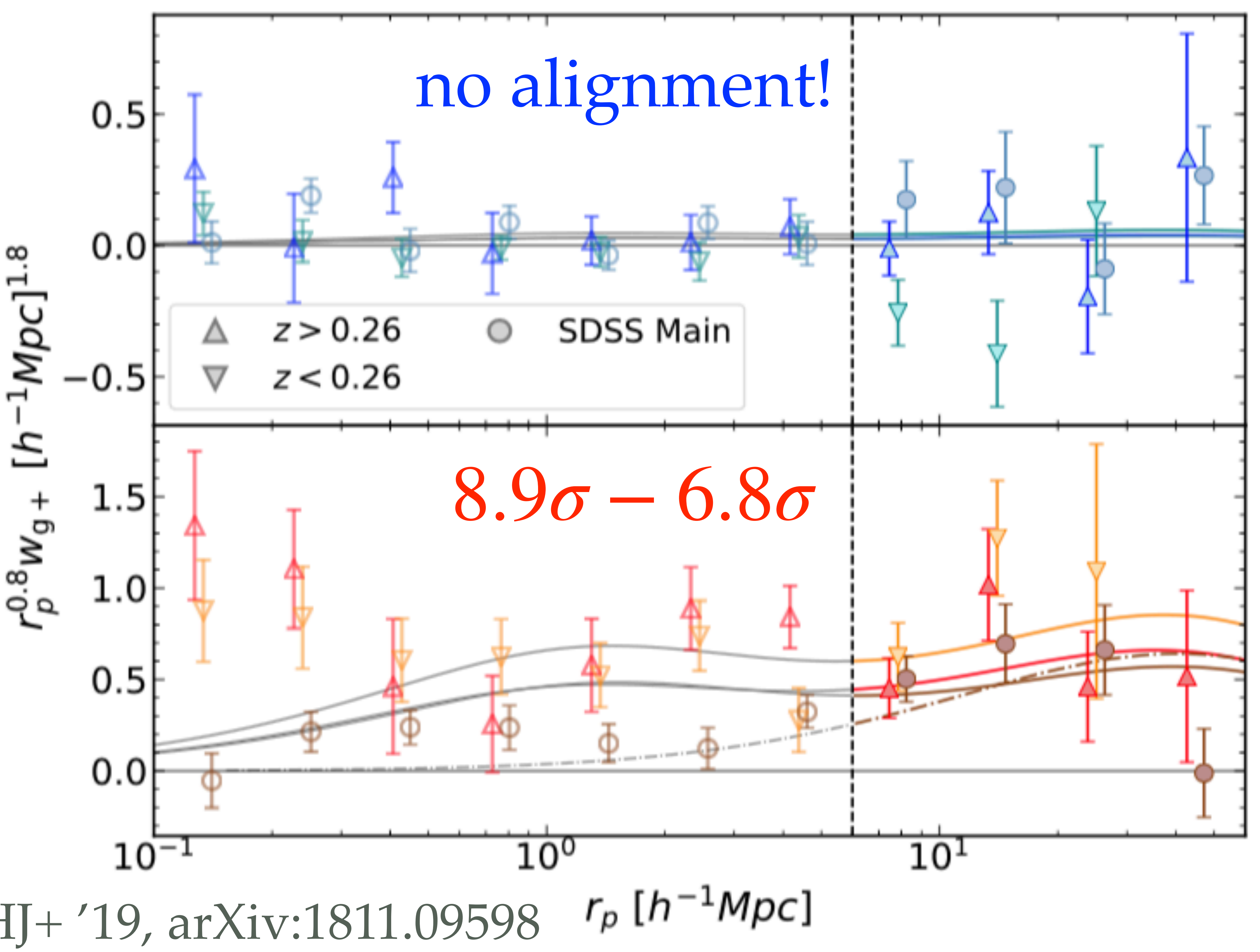
$$w_{g+} \propto b_g \int P_{\delta I}(A_{IA}, \beta)$$
$$w_{gg} \propto b_g^2 \int P_\delta$$

Fixed ΛCDM cosmology

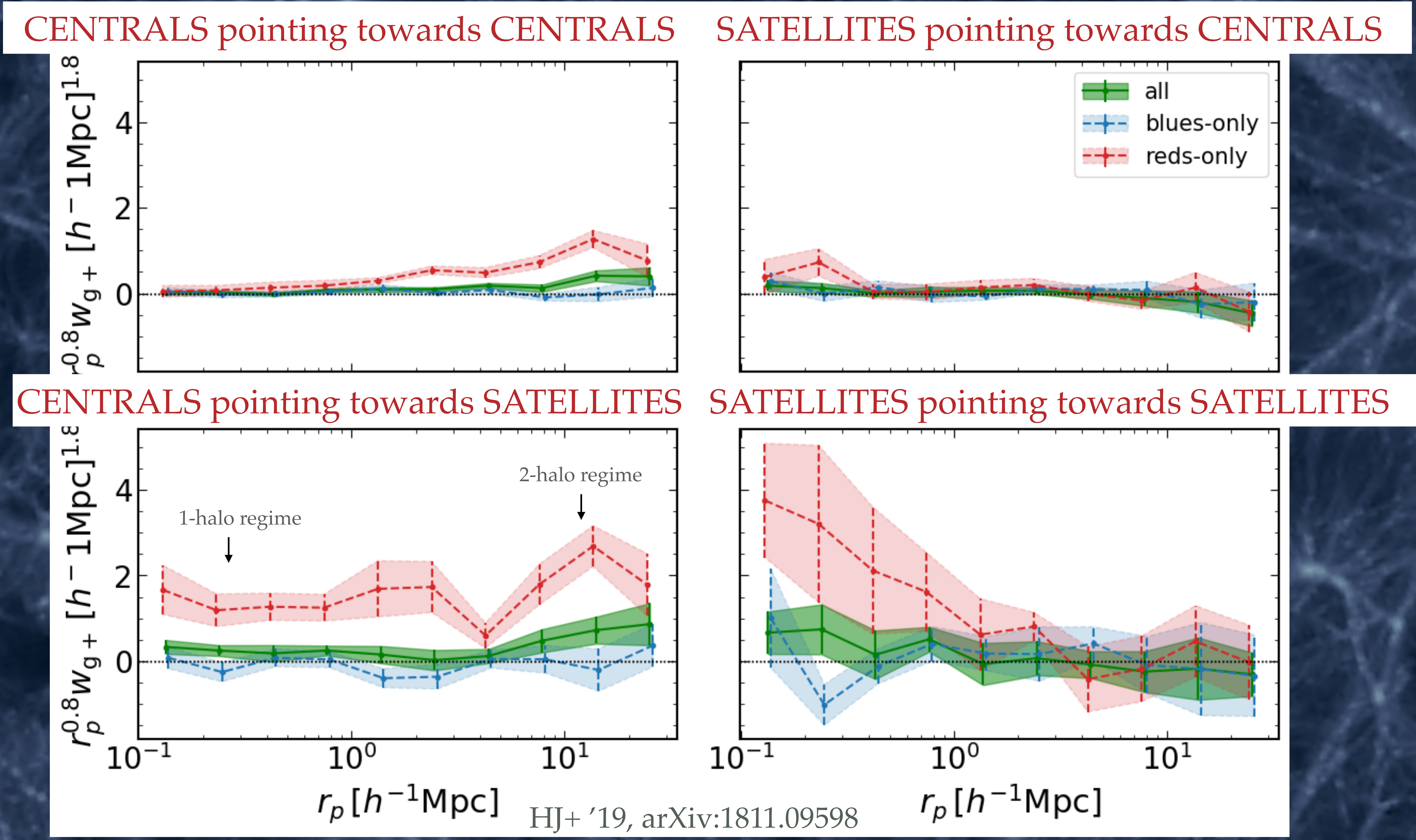
N/LA model(s)

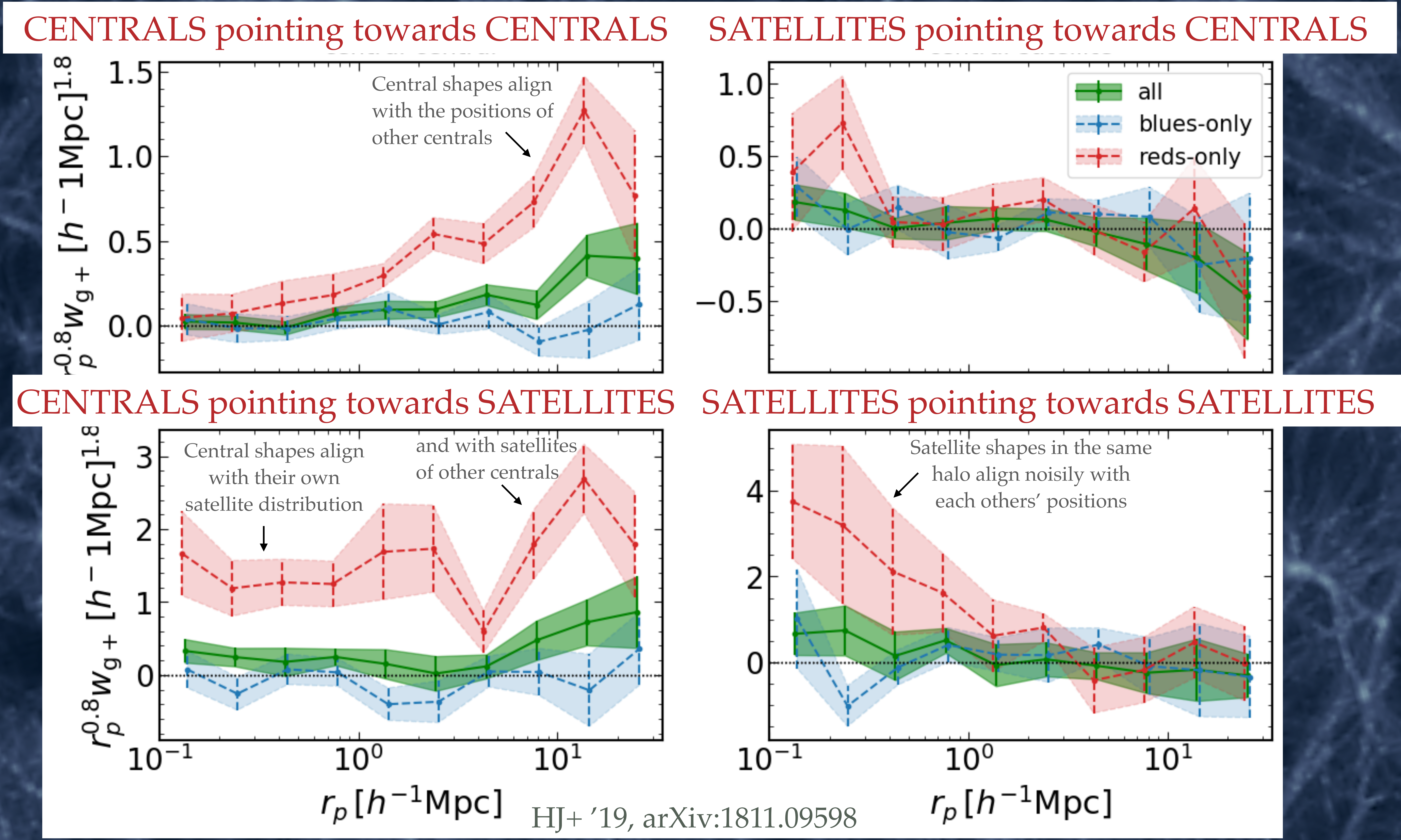
$$P_{\delta I}(k,z) = -A_{IA} \cdot \left\langle \frac{L}{L_{piv}} \right\rangle^{\beta} \cdot C_1 \frac{a^2 \bar{\rho}(z)}{D(z)} P_\delta(k,z)$$

- Blue galaxies (top) unaligned
- Red galaxies (bottom) strongly aligned with structure
- We constrain A_{IA} (and β) above 6Mpc/h
- Red signals vary greatly below ~6Mpc/h — **satellite/central galaxies align differently**



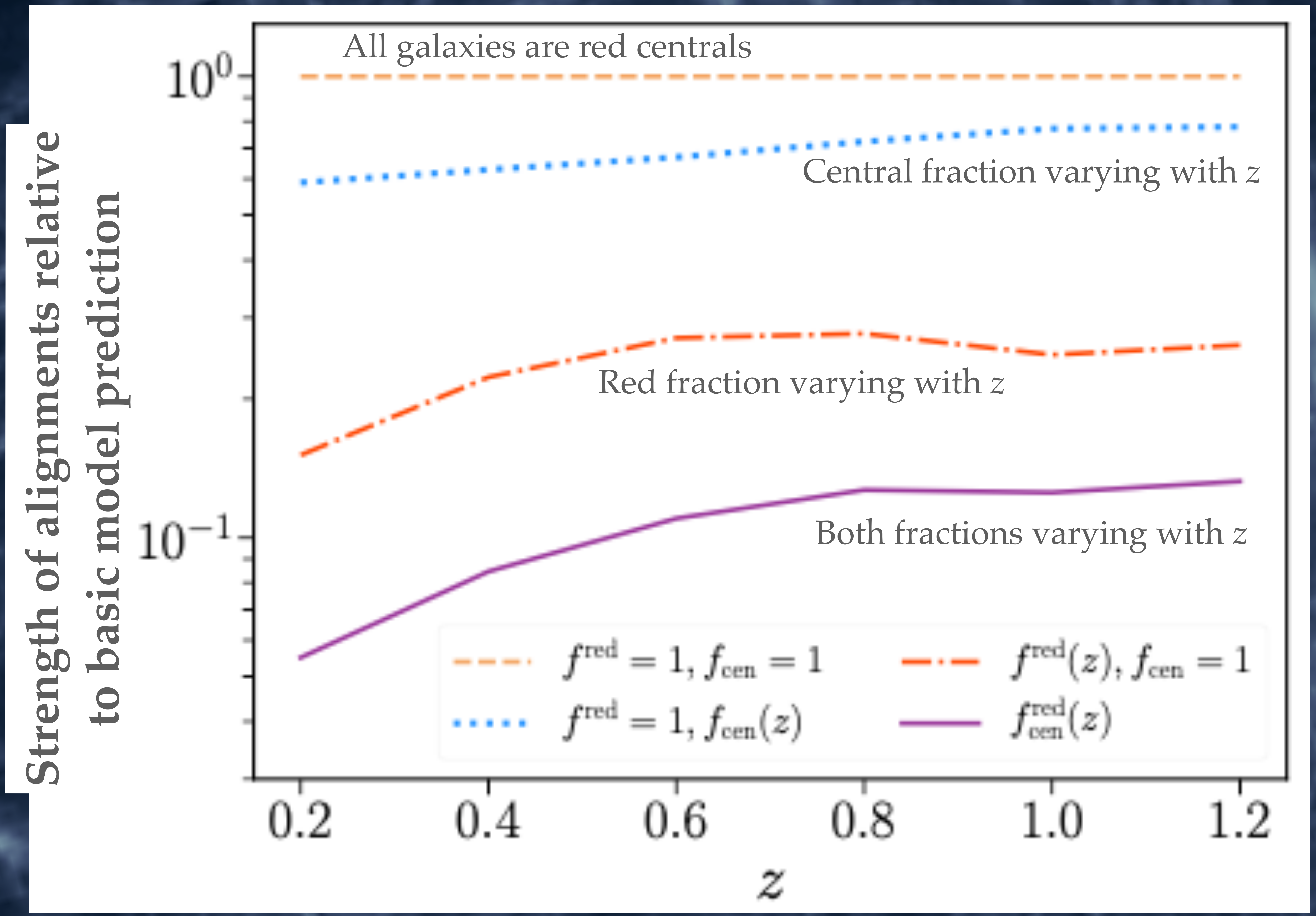
HJ+ '19, arXiv:1811.09598

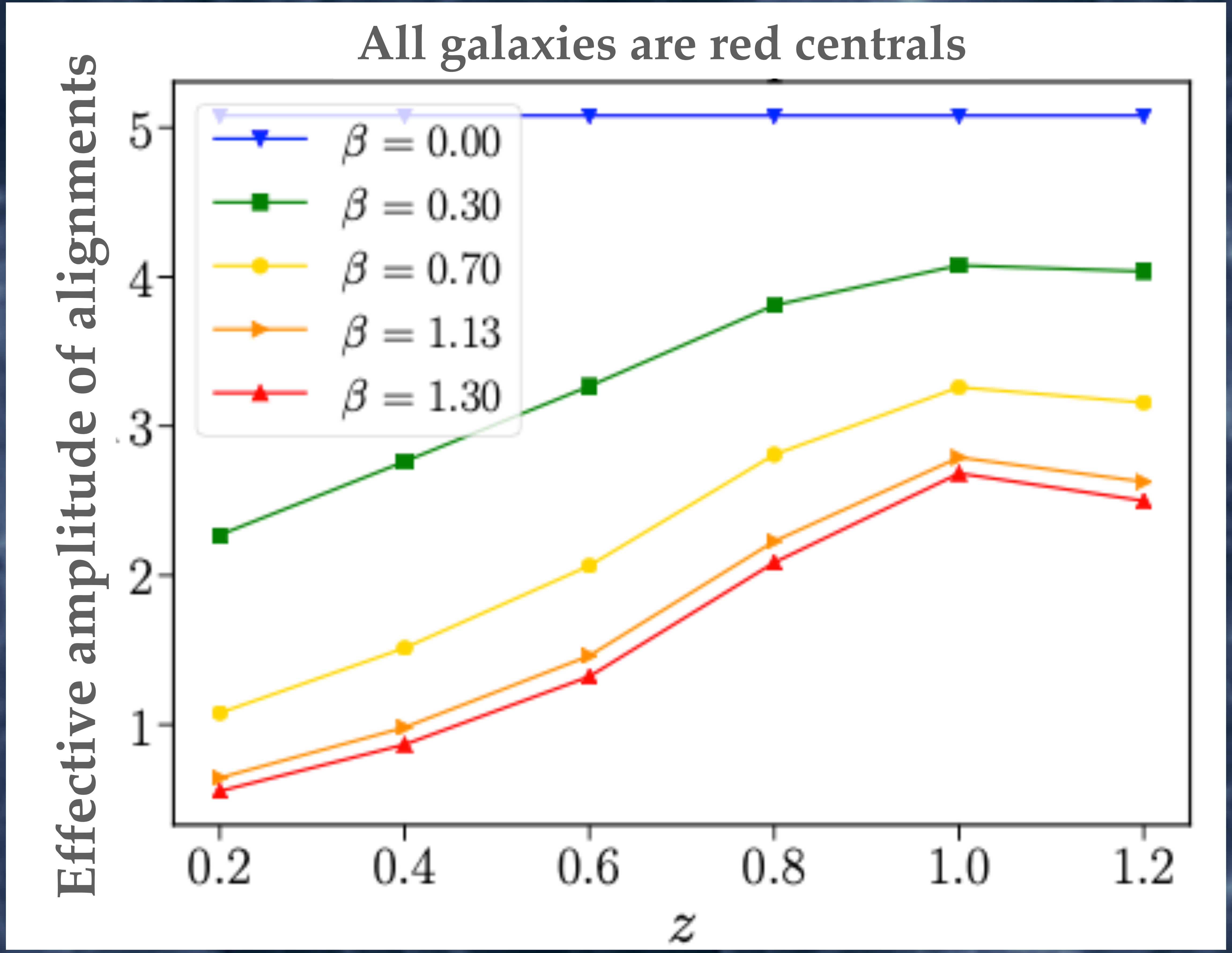

CENTRALS pointing towards CENTRALS
SATELLITES pointing towards CENTRALS
CENTRALS pointing towards SATELLITES
SATELLITES pointing towards SATELLITES
all
blues-only
reds-only
1-halo regime
2-halo regime
$r_p^{0.8} w_{g+}\,[h^{-1}\mathrm{Mpc}]^{1.8}$
$r_p\,[h^{-1}\mathrm{Mpc}]$
HJ+ '19, arXiv:1811.09598



CENTRALS pointing towards CENTRALS
SATELLITES pointing towards CENTRALS
CENTRALS pointing towards SATELLITES
SATELLITES pointing towards SATELLITES
Central shapes align with the positions of other centrals
Central shapes align with their own satellite distribution
and with satellites of other centrals
Satellite shapes in the same halo align noisily with each others' positions
all
blues-only
reds-only
$r_p^{0.8} w_{g+} [h^{-1}\mathrm{Mpc}]^{1.8}$
$r_p\,[h^{-1}\mathrm{Mpc}]$
HJ+ '19, arXiv:1811.09598

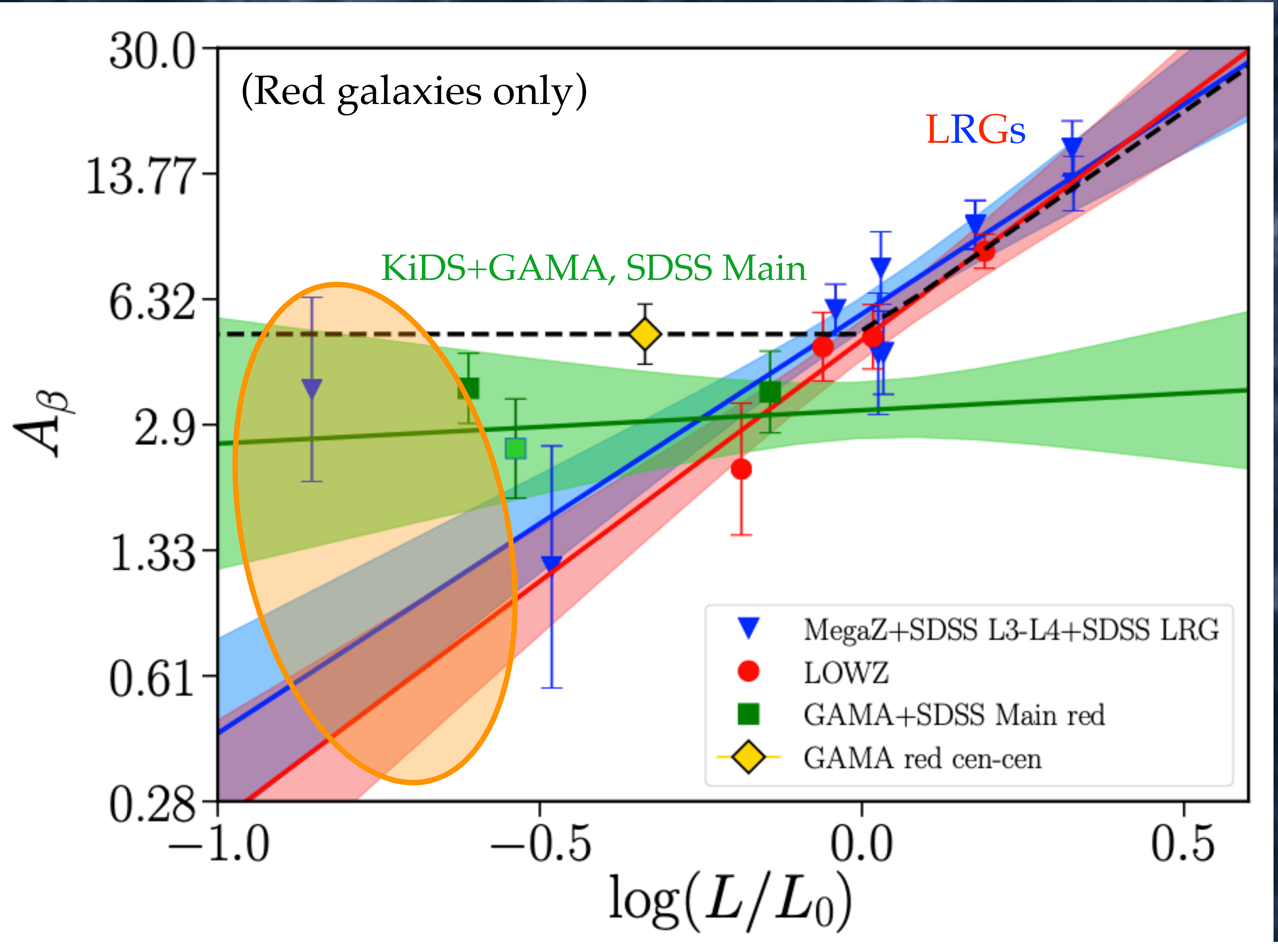
Fortuna, HJ, + ’20, arXiv:2003.02700





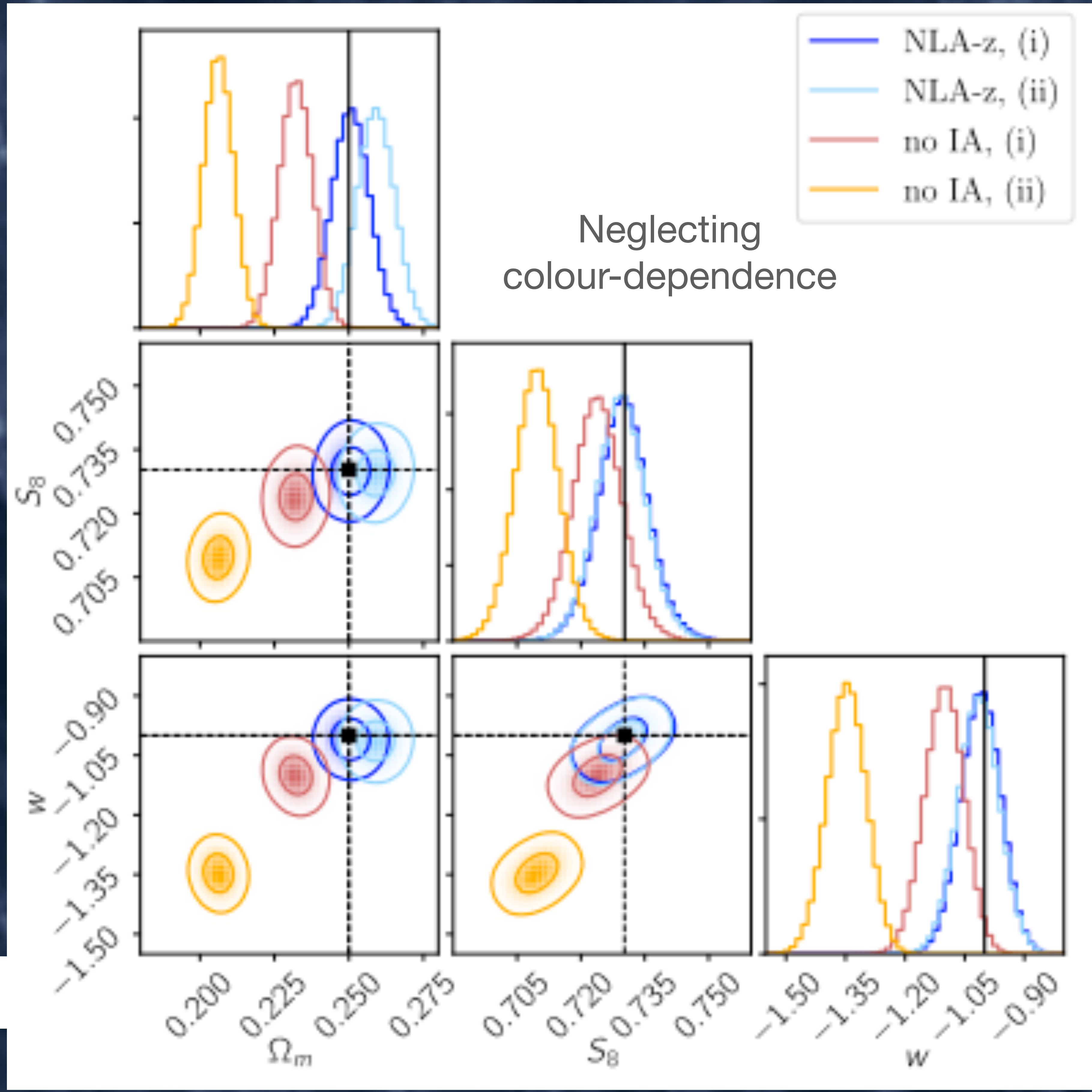
- Red galaxy fraction & central galaxy fraction determine the amplitude of linear-scale alignments in data; both of these evolve with redshift

- Galaxy colours and central/satellite status correlate with luminosity
- Do intrinsic alignments also depend on luminosity?
- (NB: Georgiou, HJ, + ’19 also found IA to differ as a function of waveband, if things were not already complicated enough)



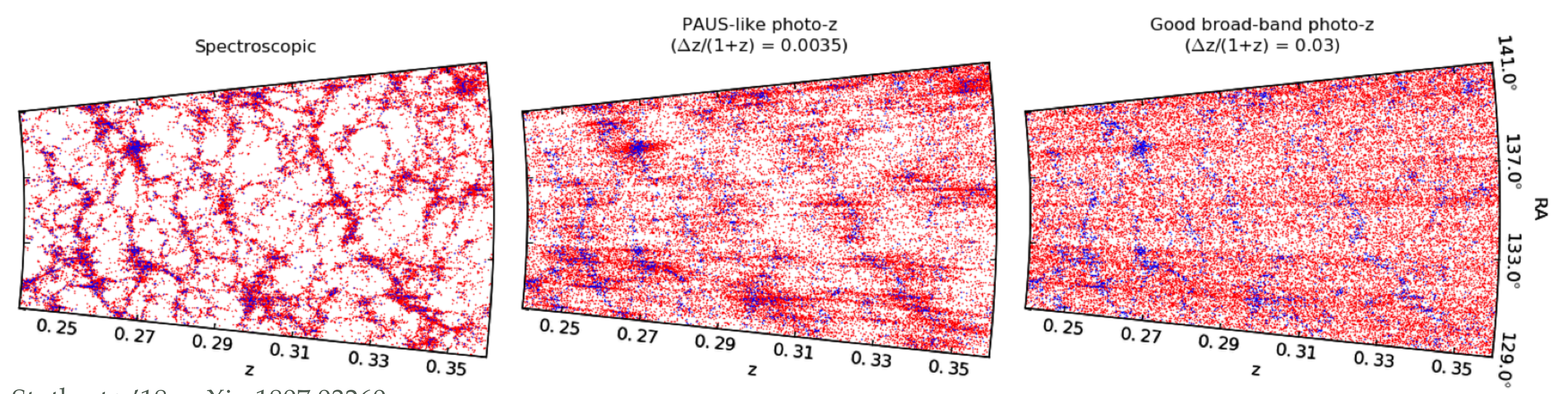
Fortuna, HJ, + '20, arXiv:2003.02700

- Bright red galaxies do seem to have luminosity-dependent alignments
- 2 regimes? Broken power-law? This would not be captured by a simple redshift dependence for IA: enter halo model
- Need additional exploration of the faint-end: enter PAUS



PAUS — Physics of the Accelerating Universe Survey

- PAUcam @ William Herschel Telescope (WHT) on La Palma
- 40 optical narrow-bands between 4500-8500Å + 6 broad-bands from CFHTLS
- Aiming for ~100 deg^2 of targeted observation over several non-contiguous fields
- Achieving photometric redshift accuracy of ~0.3%
- Recently finished a pilot study of galaxy IA + clustering in the 19 deg^2 W3 field (arXiv:2010.09696)



Stothert+ '18, arXiv:1807.03260

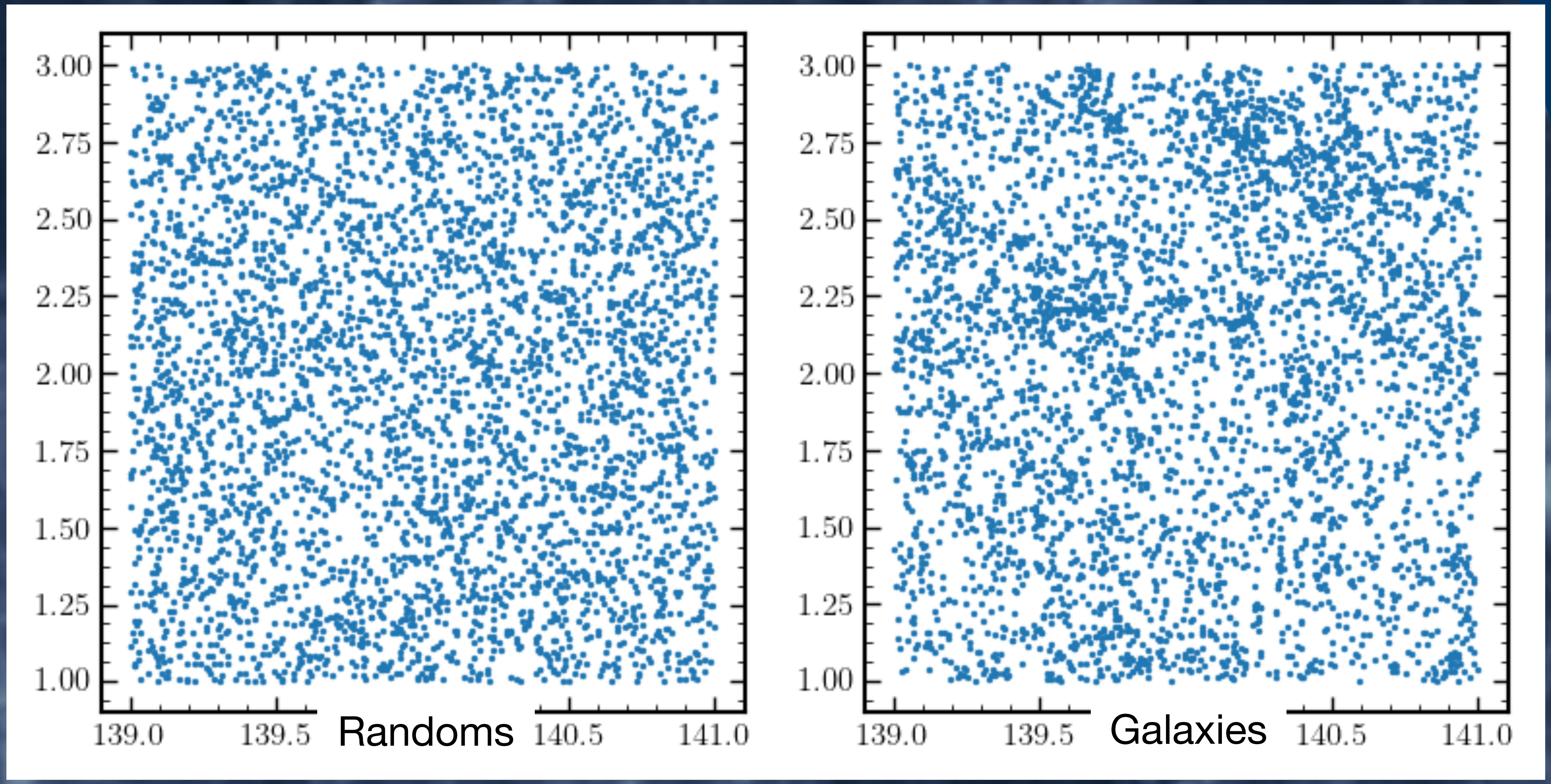
Randoms

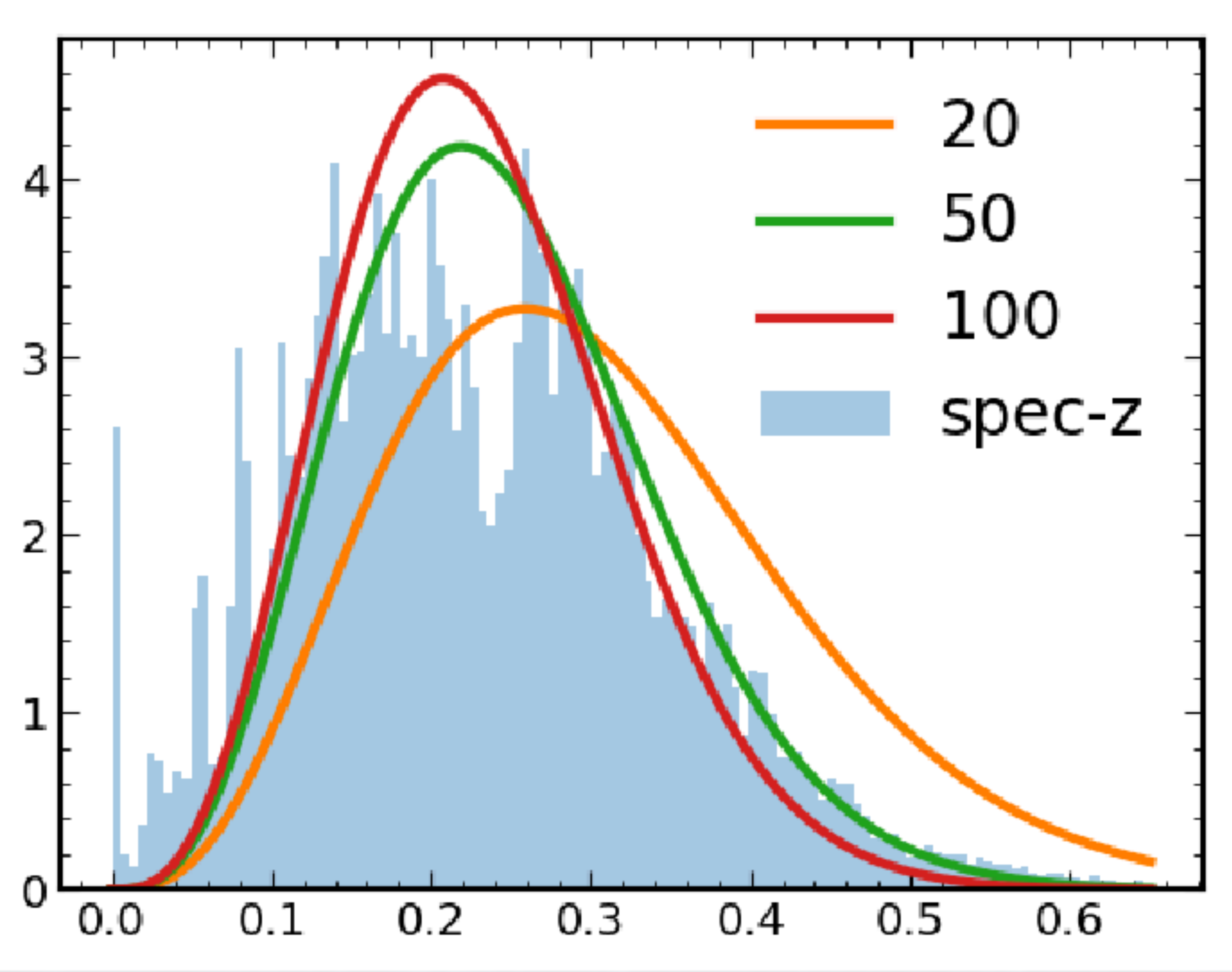
- *Random galaxy catalogues* tell us what is special about the positions of real galaxies

- Galaxies cluster together under gravity; to be quantitative, we must compare their distribution in ratio to a random, i.e. un-clustered, field

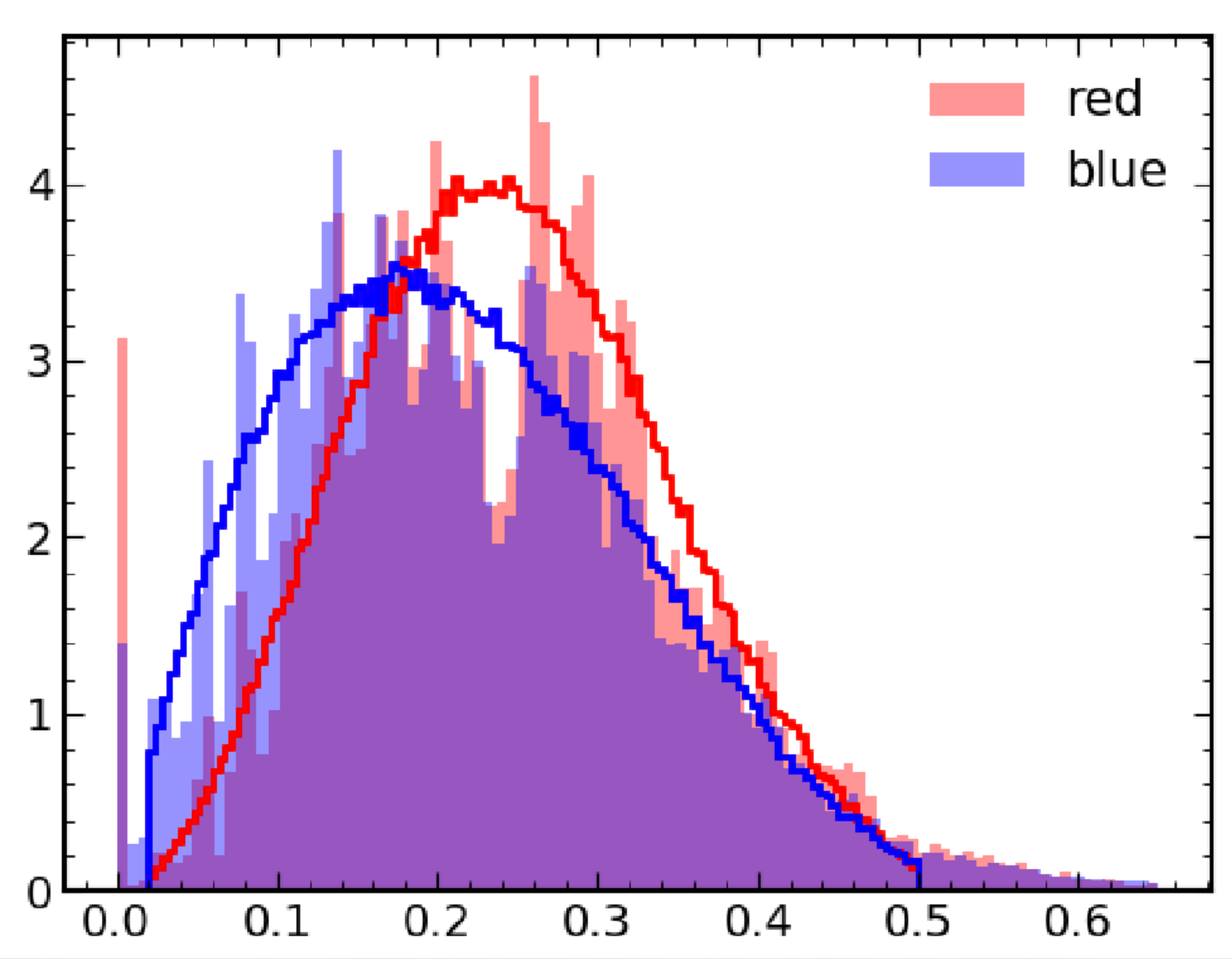
- This means we want random points over the same range in 3D as we have galaxies, but they cannot be locally clustered

- Any large-scale structure statistics interested in the positions of objects must make use of randoms





V_{max} randoms — Cole '11; Farrow, +'15



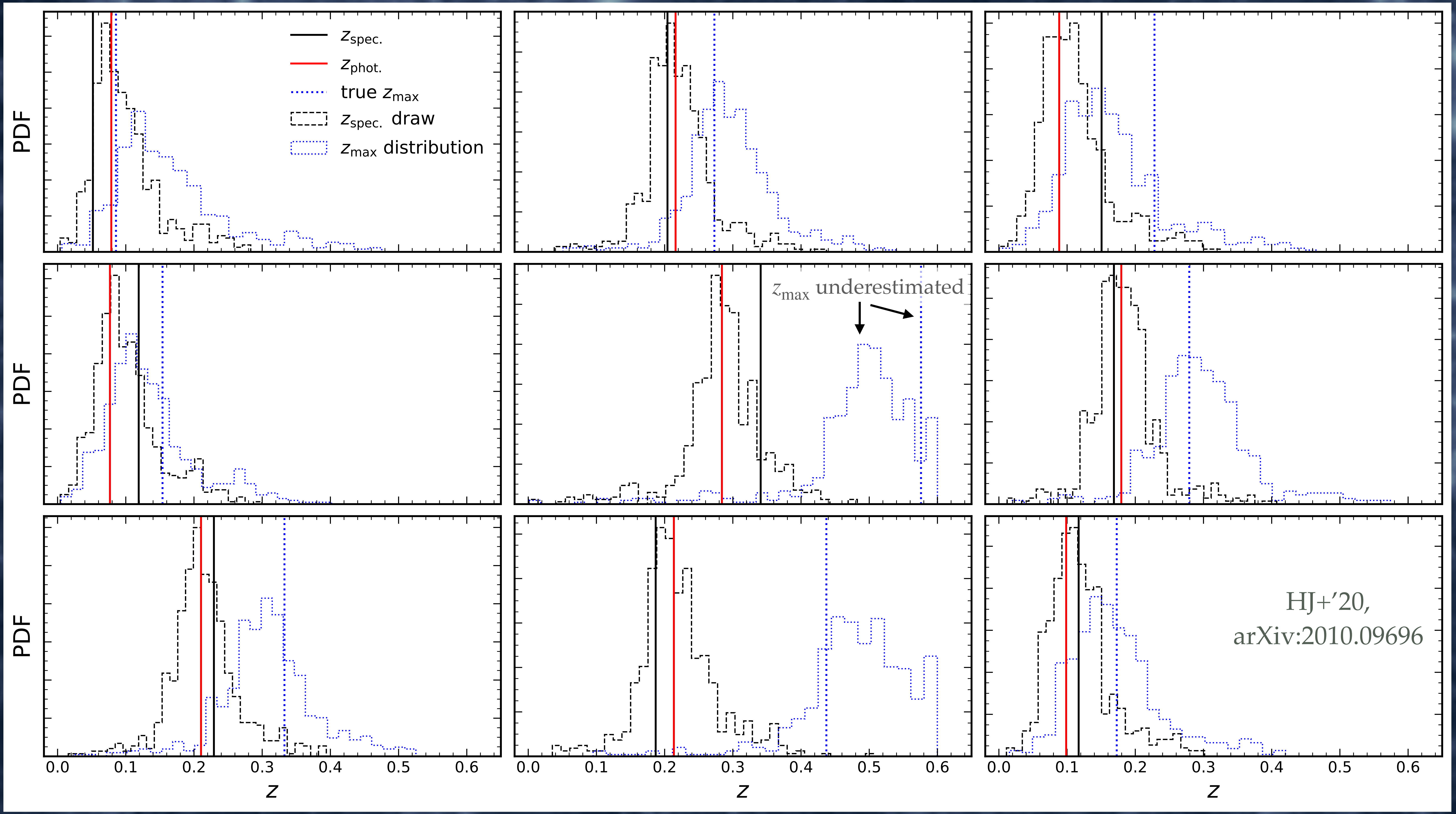
- We want the mean number density at each redshift; use the luminosity function $\phi(L) = 1/\Sigma_i V_{\max,i}(L)$
- Calculate a maximum redshift $z_{\max}$ for each object, given *k*+*e*-corrections:

$$\begin{aligned} M_{z=0} &= m_{\rm obs.} - \mu_{\rm obs.} - k_0(z_{\rm obs.}) + Q\, z_{\rm obs.} \\ &= m_{\rm limit} - \mu_{\max} - k_0(z_{\max}) + Q(z_{\rm obs.} - z_{\max}) \end{aligned}$$

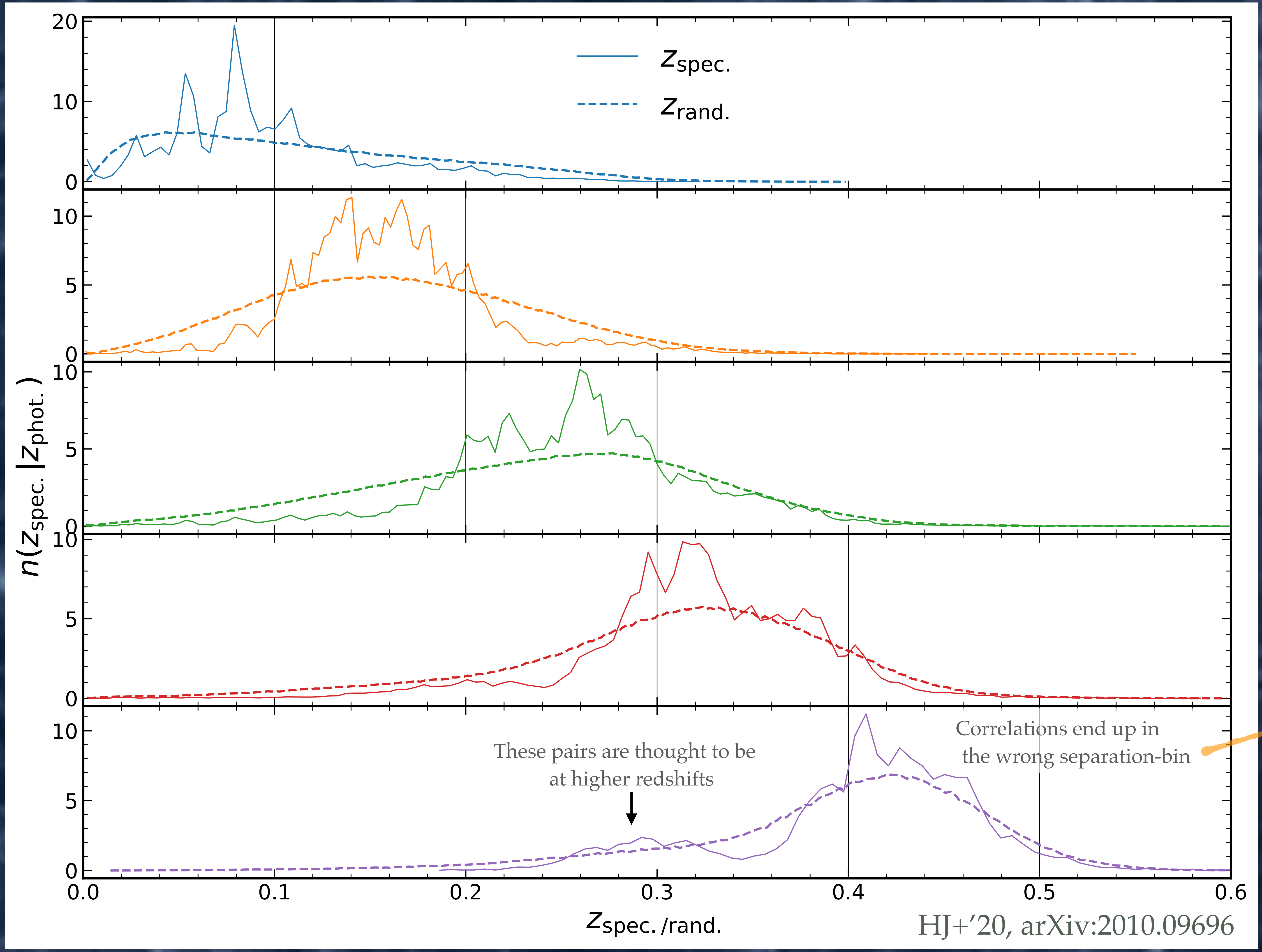
- Scatter 'clones' of each galaxy uniformly within the corresponding $V_{\max}$, or Gaussian-distribute them around the parent $z_{\rm spec}$ ('windowed' randoms)

V_{max} randoms with photo-z — HJ, + (in prep.)

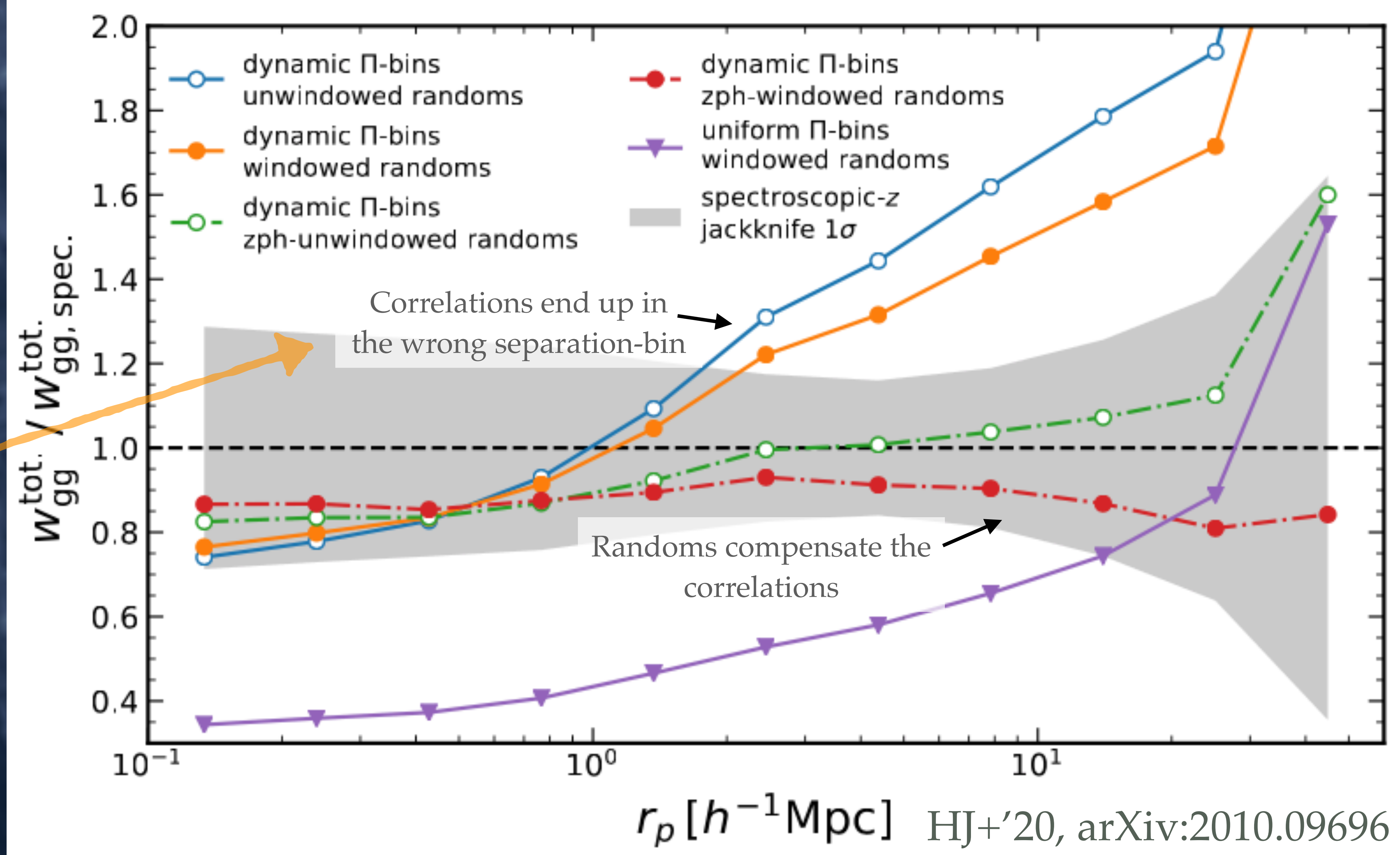
- Redshift errors → errors in z_{max}
- Given some spectroscopic objects, we can sample from $n(z_{spec} \,|\, z_{phot} \pm \delta z)$ for each galaxy
- Mitigate error in z_{max} by generating a distribution $P(V_{max})$ encoding photo-z errors

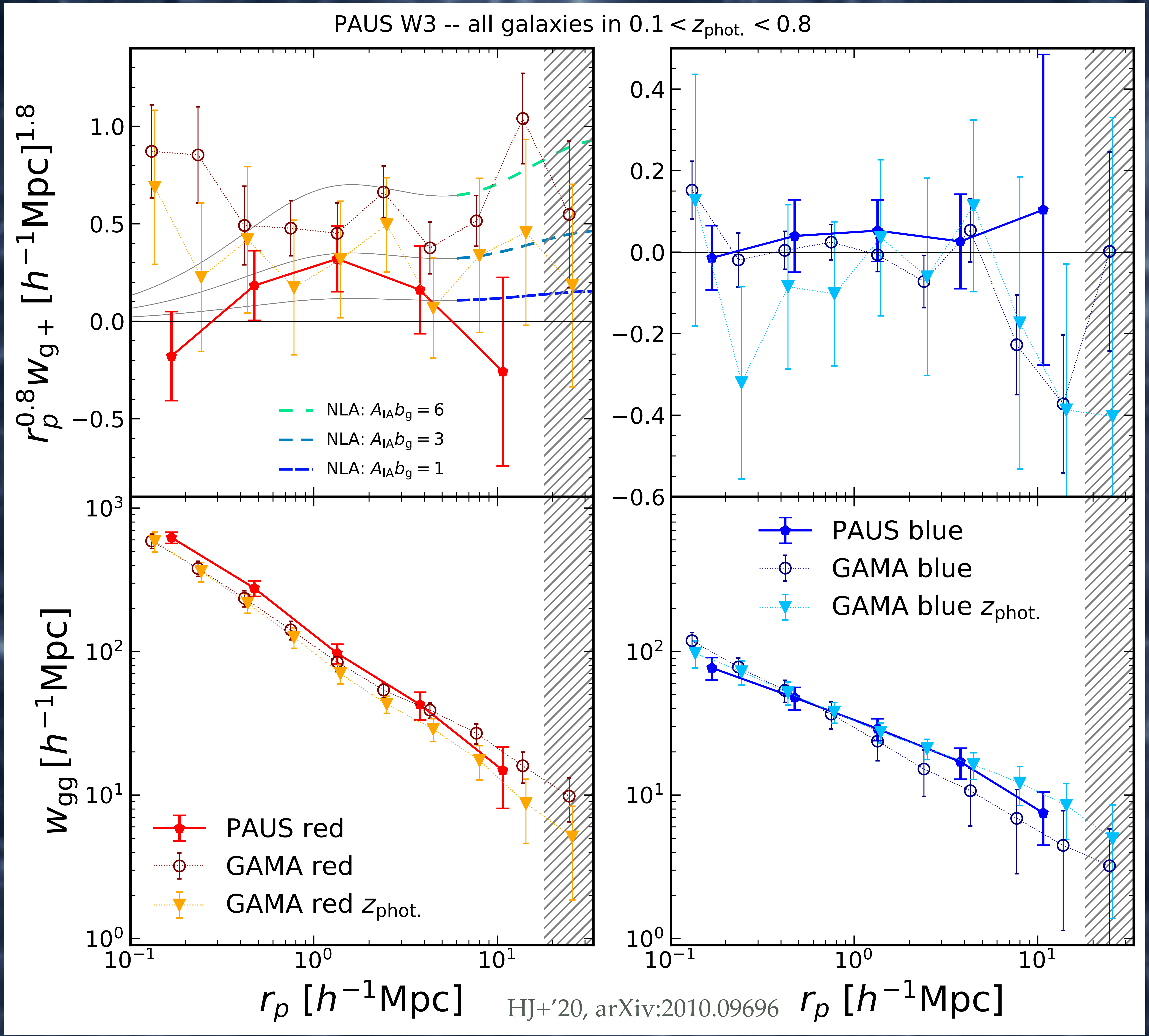


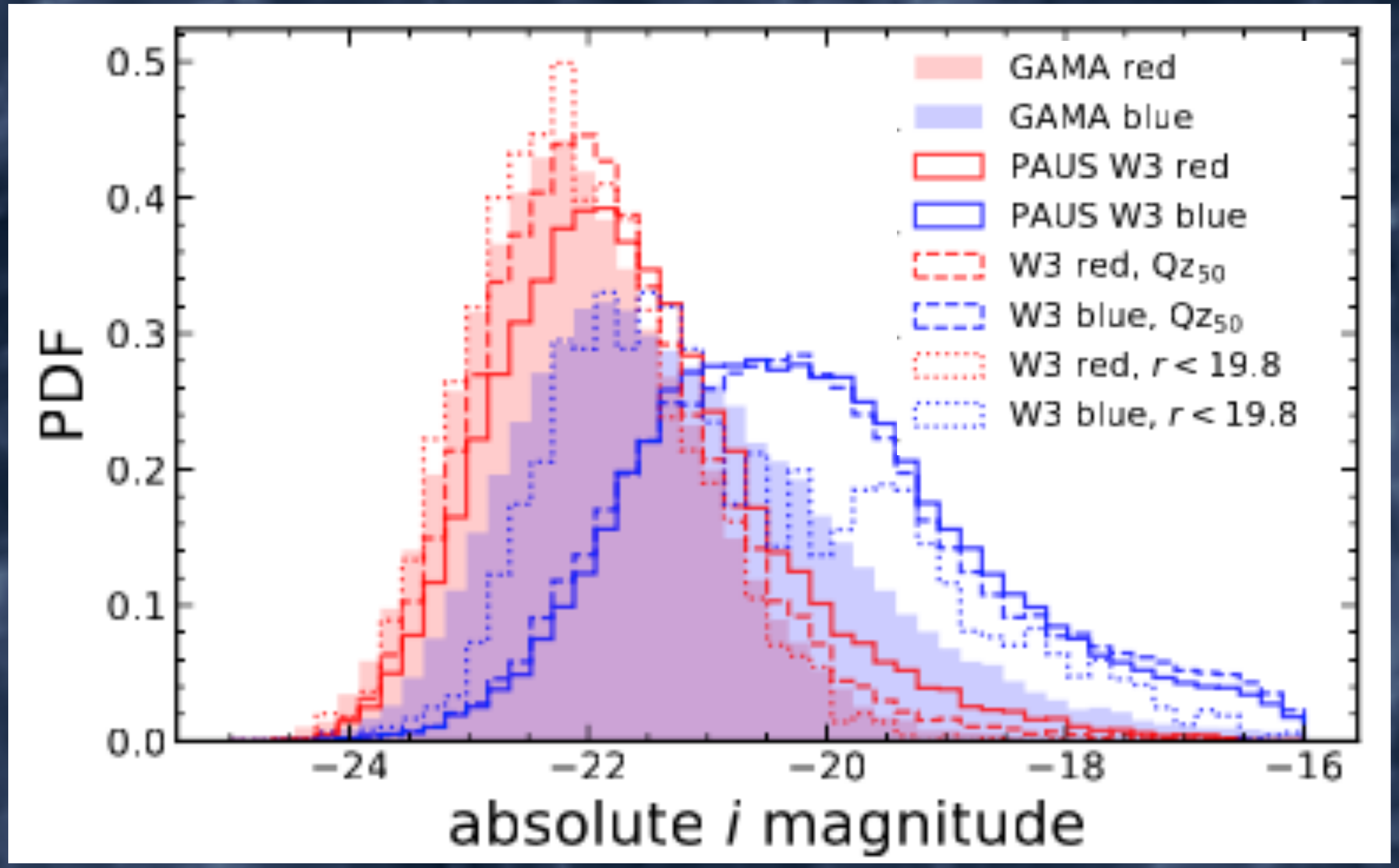
V_{max} randoms with photo-z — HJ, + (in prep.)



- Creating ensemble randoms from $P(V_{max})$ we avoid over-filling low redshifts and we compensate photo-z degeneracies
- These randoms prevent photo-z induced tilting of measured correlation function ↓



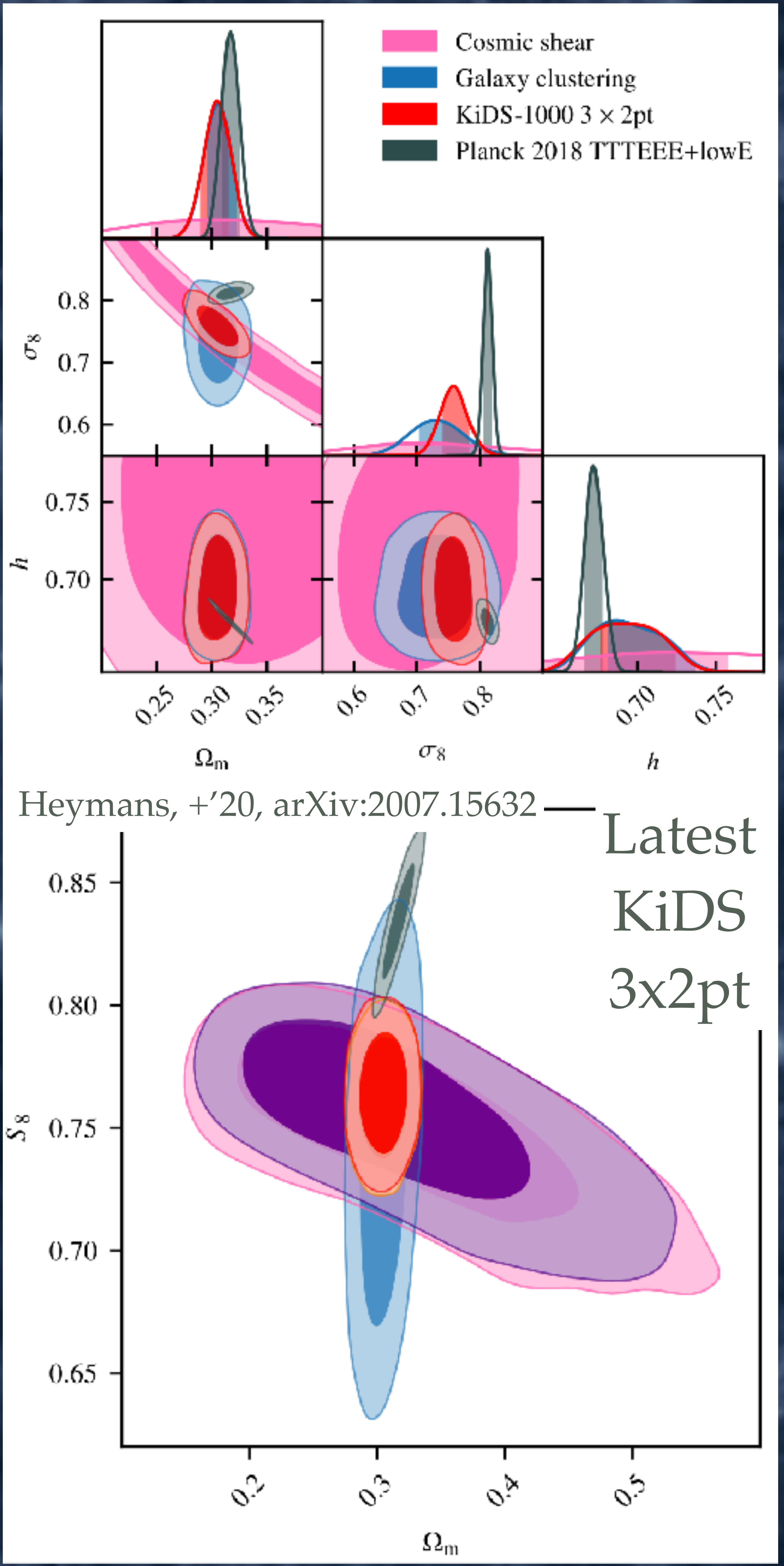




- With our fancy randoms we can measure IA + clustering in PAUS (+ mock GAMA)
- Probing fainter objects ⇌ more satellites, over a longer redshift baseline
- Red alignments lost in low S/N ($\lesssim 2\sigma$); may recover these with full PAUS area
- Blue galaxies again unaligned

3x2pt analysis

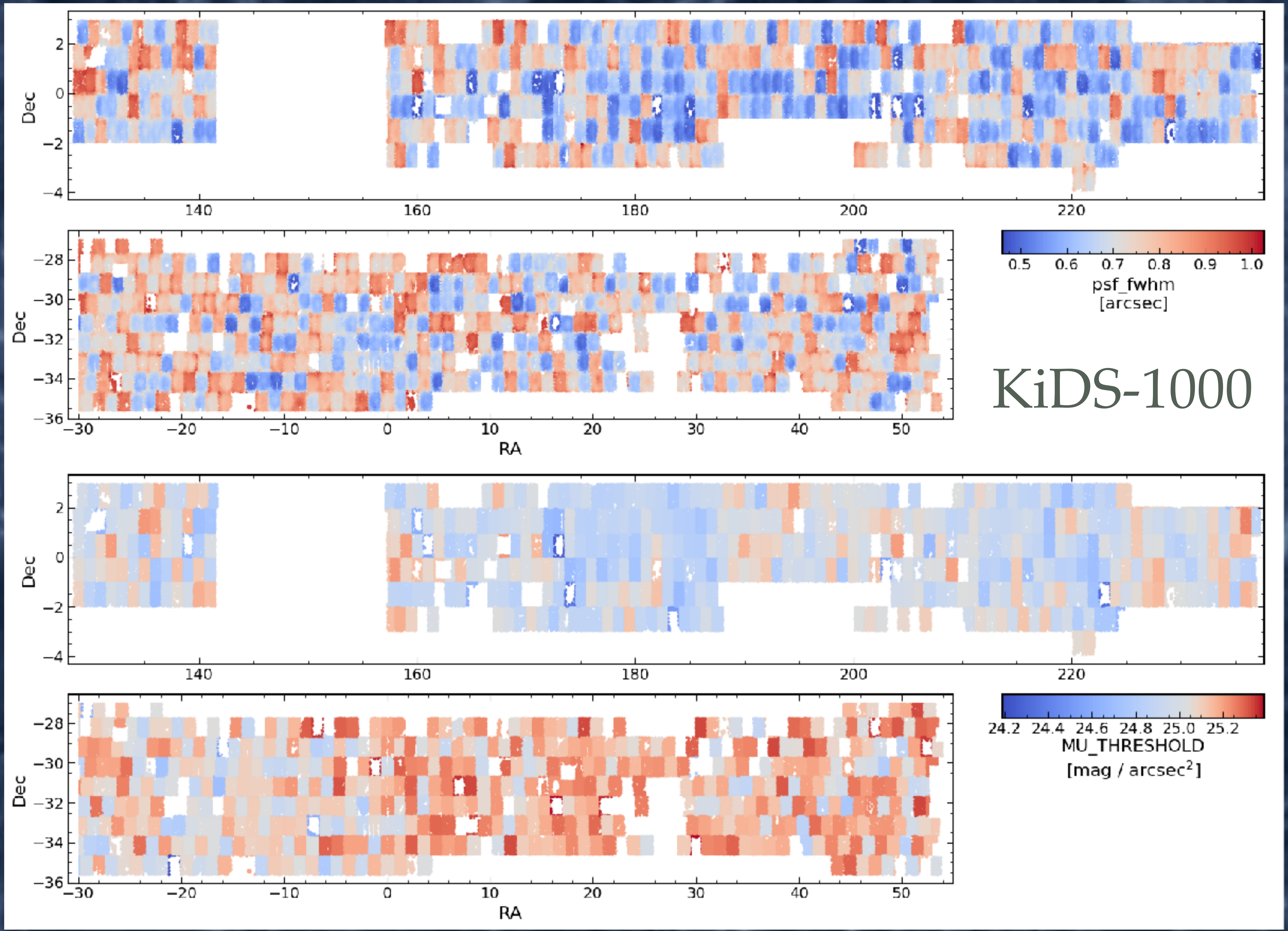
- Weak cosmological lensing — cosmic shear — is a powerful probe of the cosmic matter distribution, but is subject to a strong degeneracy between σ_8 and Ω_m
- Jointly analysing cosmic shear with galaxy clustering, and their cross-correlation: galaxy-galaxy lensing (GGL), helps to break the degeneracy and tighten parameter constrains
- The inclusion of galaxy positional statistics also helps with self-calibration of astrophysical and systematic biases, e.g. intrinsic alignments, photo-z and galaxy bias, via nuisance parameterisations



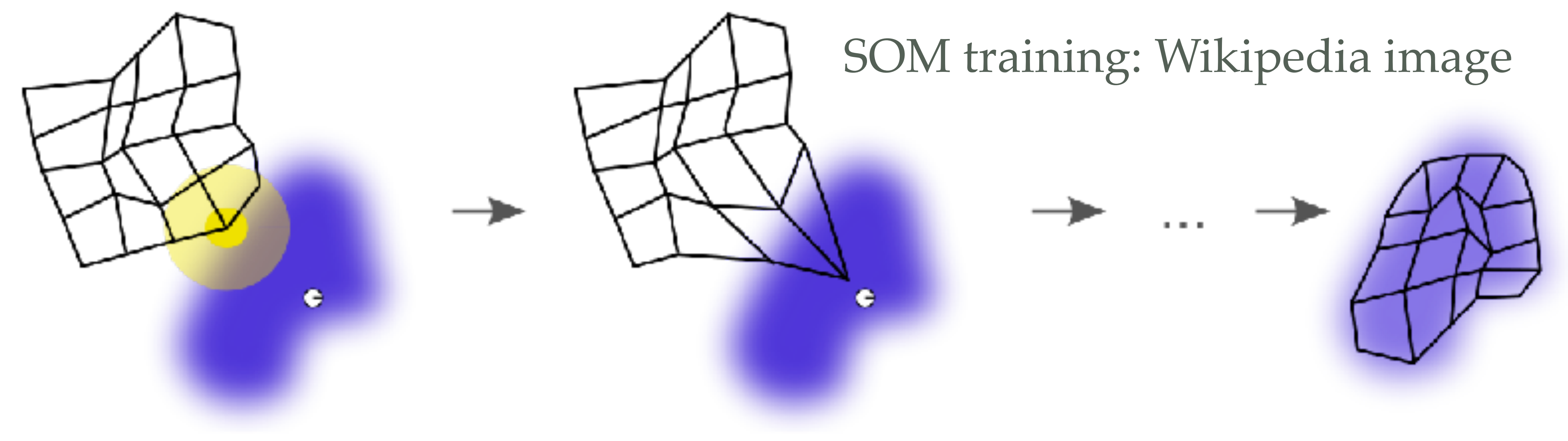
Heymans, +'20, arXiv:2007.15632

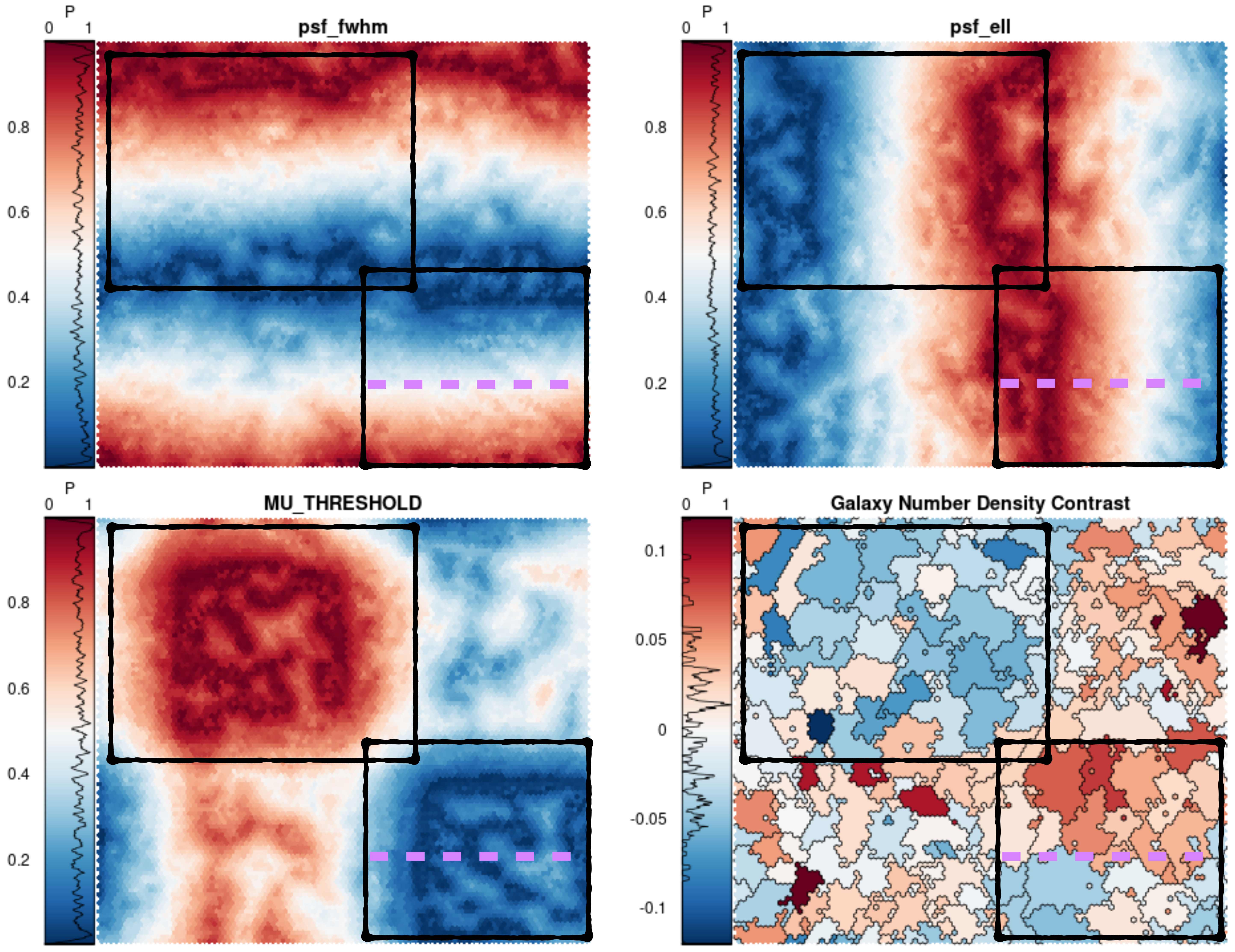
Observing conditions can mess with your positional statistics — HJ, + (in prep.)

- Variable conditions ↔ PSF, or Galactic extinction, or Milky Way stars, or…. can cause you to systematically fail to detect galaxies
- With a spatially inhomogeneous selection function, galaxy positional statistics can be biased
- We must attempt to mitigate these biases lest they contaminate our cosmological inference

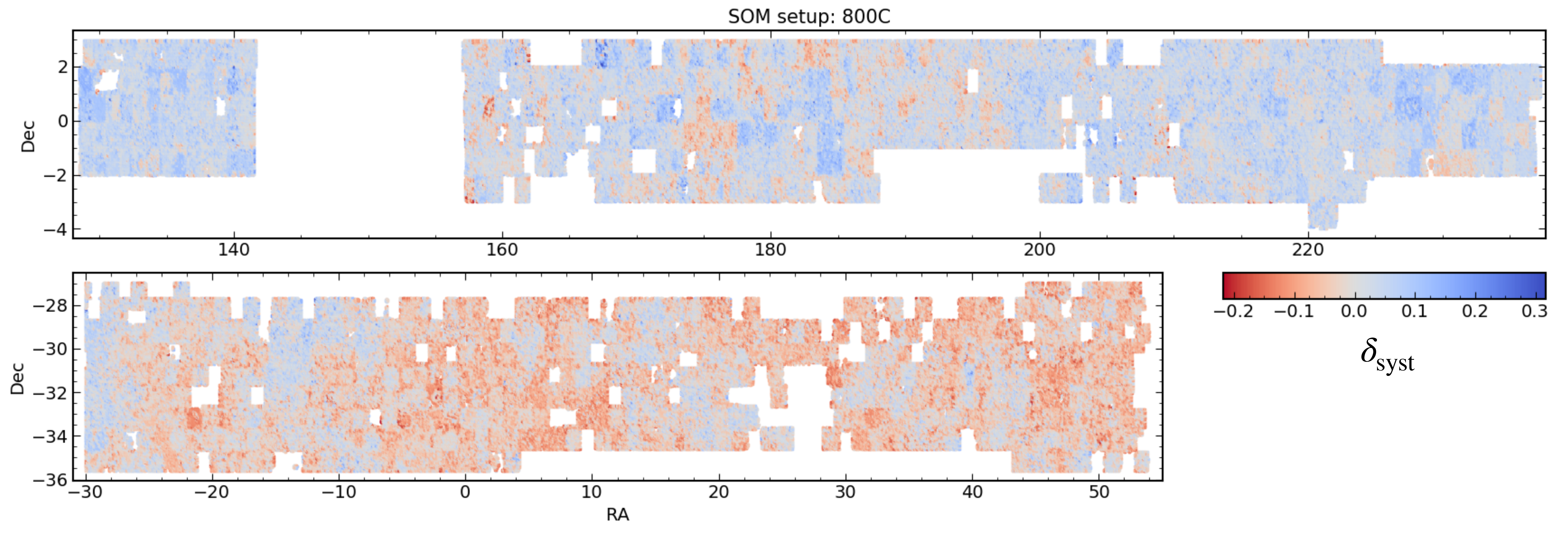


Self-organising maps (SOMs) — HJ, + (in prep.)





- SOMs: unsupervised artificial neural networks designed to project high-dimensional data onto a 2D map, preserving topological features of the space
- Useful for dimensionality reduction, classification, data visualisation…
- Training the SOM on survey systematic-tracers, we bin the map into $N_{\rm HC}$ 'hierarchical clusters'
- We can then estimate an expected galaxy density contrast for each cluster ≡ non-contiguous area of sky with correlated systematics

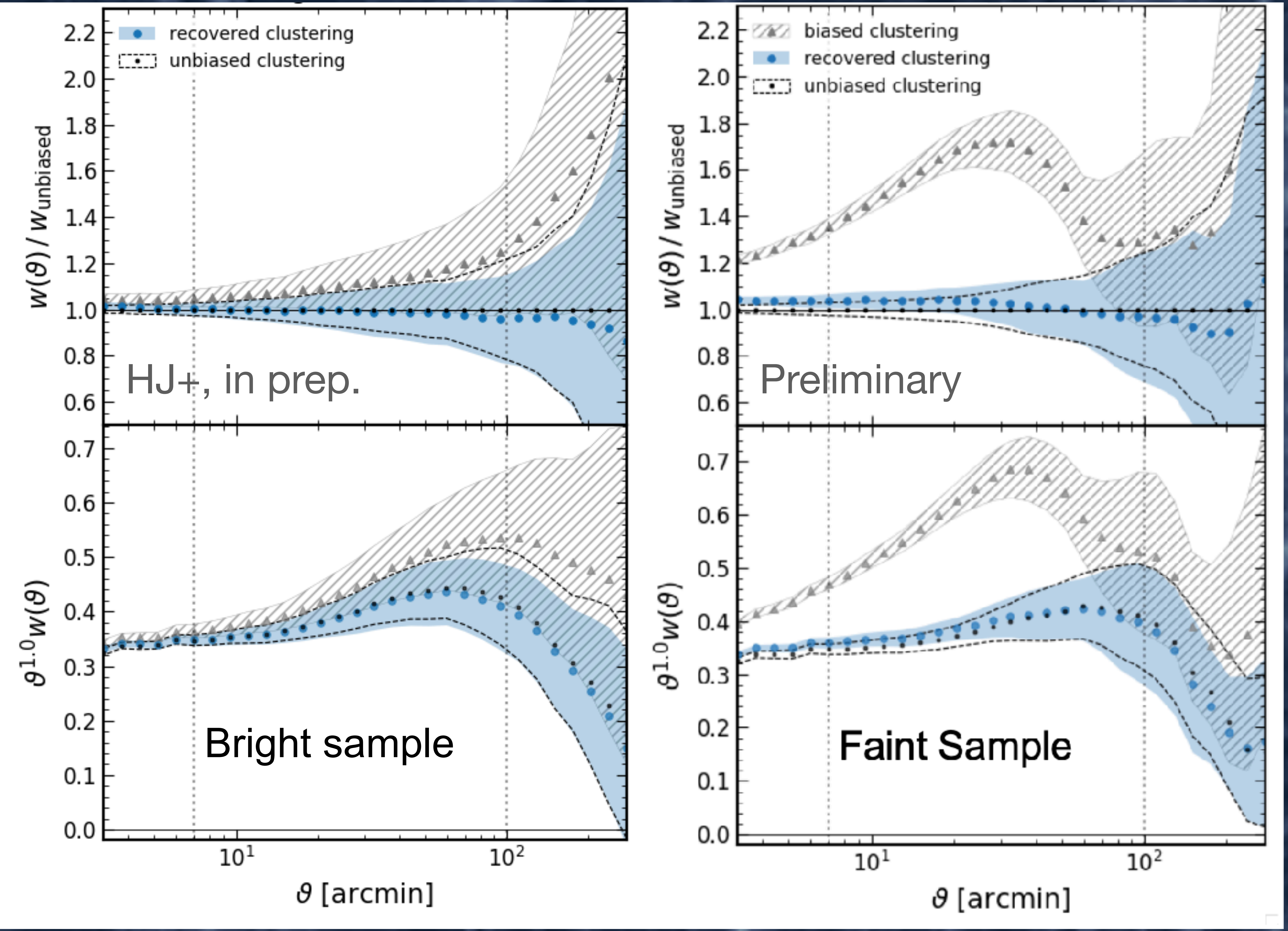


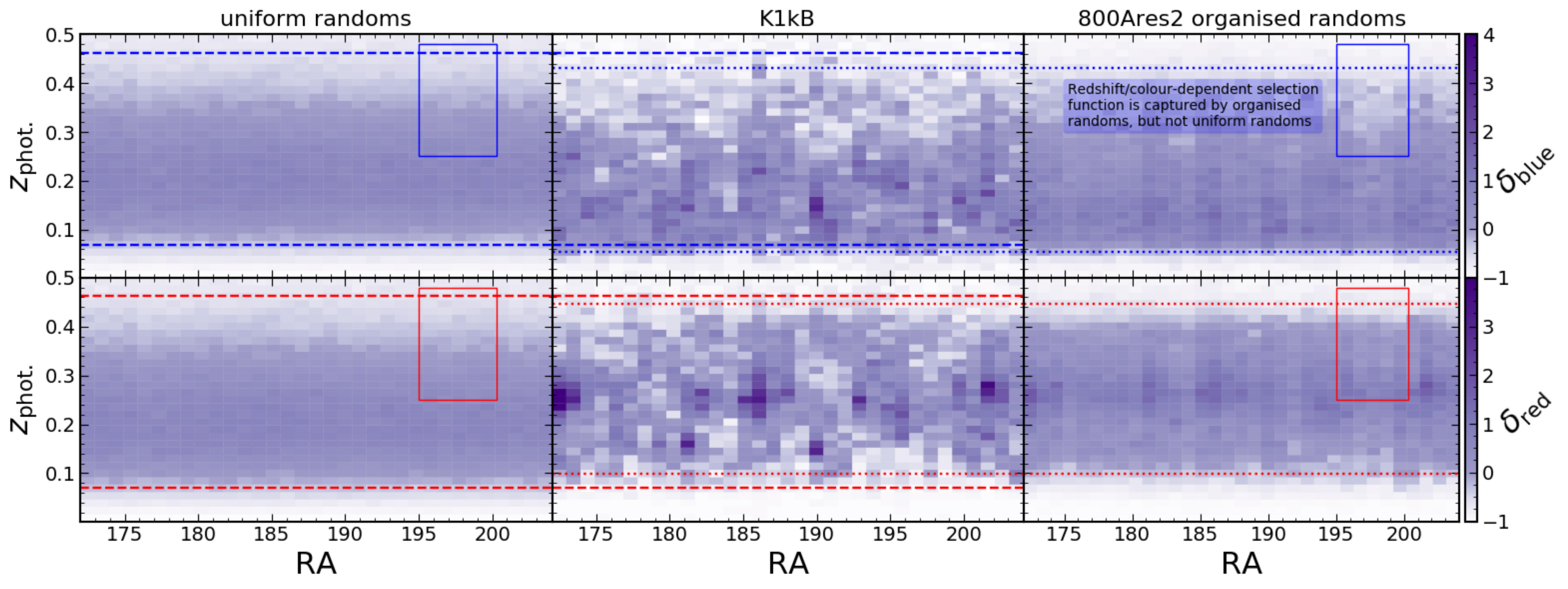
- We can now map the galaxy density contrast back onto the sky — different $N_{\rm HC}$ and systematics yield different $\delta_{\rm syst}$ — and distribute clones to reflect the systematic fluctuations: **Organised Randoms**
- Using these randoms to measure galaxy positional statistics, we should cancel the systematic fluctuations and remove density field biases
- We interpolate systematic-tracer variables from KiDS-Bright ($r \lesssim 20$) onto dozens of FLASK simulations, and probabilistically apply the systematic density fluctuations inferred from data

- We are able to reliably corrected clustering biases in KiDS-like mock samples

- Performance scales excellently with number density/systematic pathology, as we see with the faint (shear) sample

- Organised randoms are relatively robust to incomplete systematics information & non-optimal scale sensitivity, in particular for the faint sample





- Bonus: through distribution of clones, we retain the ability to mimic galaxy selection effects in the randoms
- Expanding the redshift axis and selecting on observed colours, we see underdense pointings, and variable redshift distributions, reflected in the randoms
- These benefits will be fully explored in an upcoming tomographic clustering analysis of the faint galaxy samples used for KiDS cosmic shear

Summary

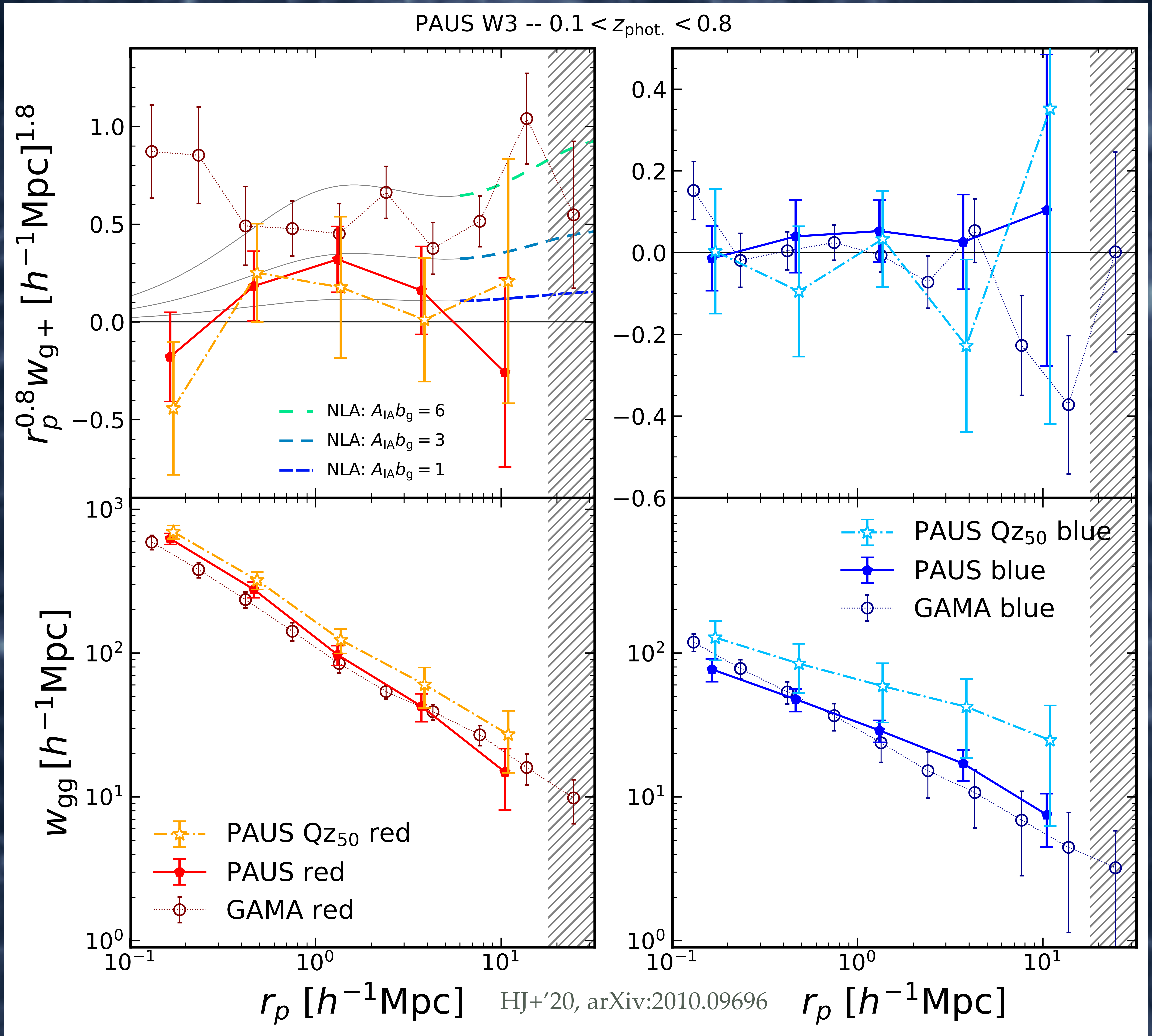
- We don’t understand intrinsic alignments very well yet

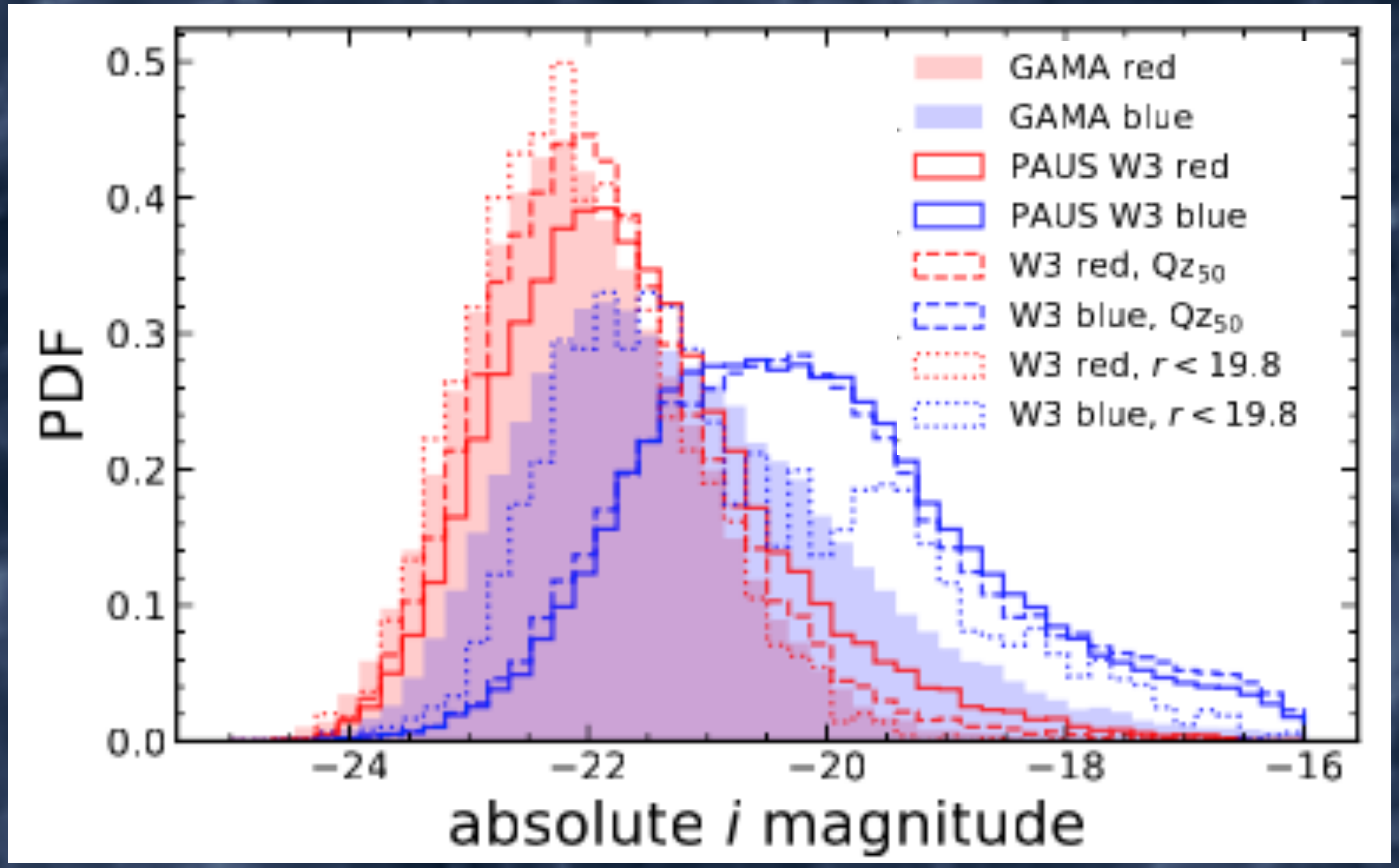
- Future analyses must focus upon the variability of alignments with respect to centrals/satellites and galaxy luminosity, with a focus on the unconstrained faint-end

- Require new models to accommodate this variability in shear analyses, e.g. perturbation theory, EFT, halo modelling

- More complex randoms can be useful for the accurate measurement of statistics

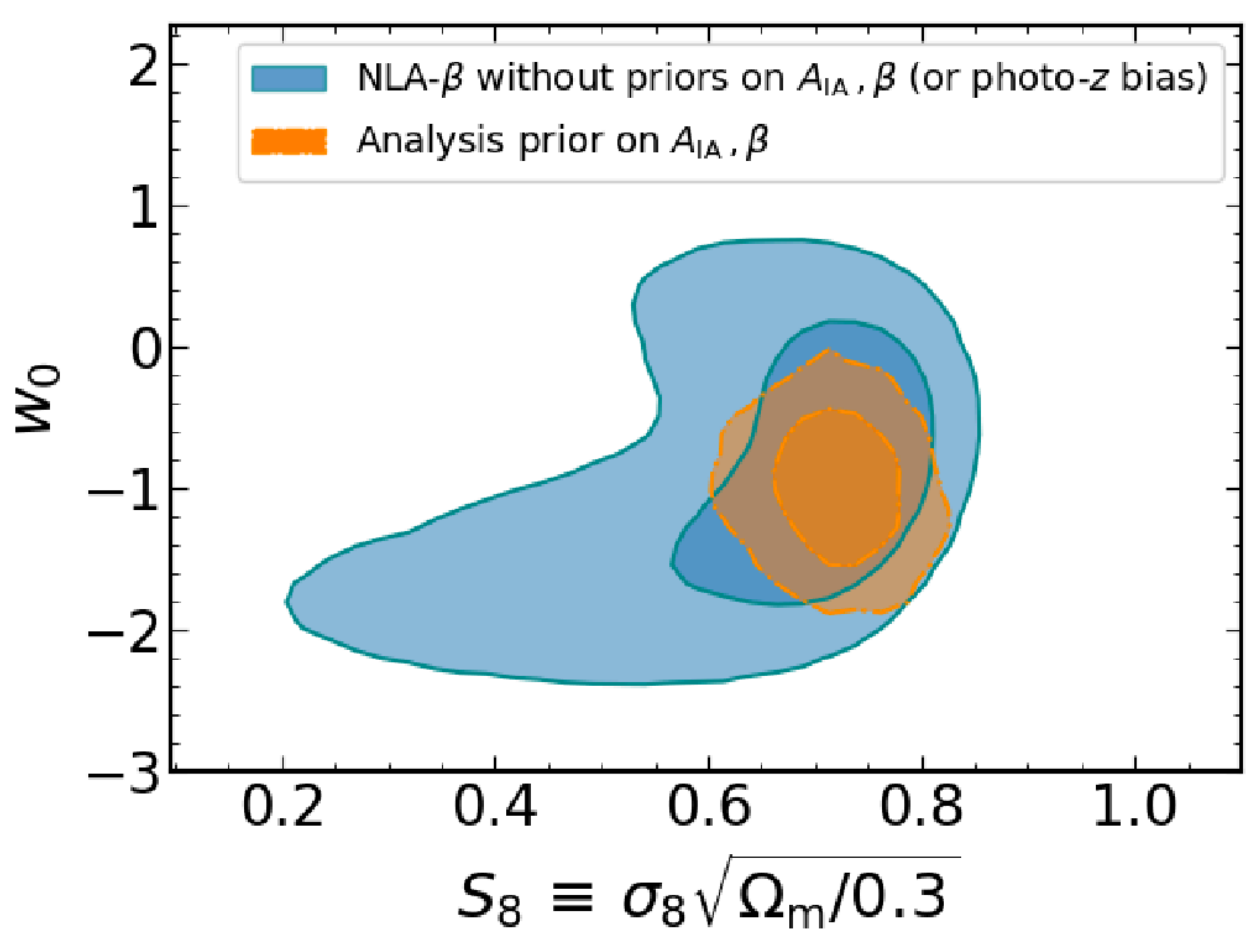
- Promising new methods for clustering bias-cancellation using “organised” randoms from self-organising maps





- Same as previous figure, but now comparing with signals from best 50% of photo-z

Completed-KiDS Forecast — demonstrating potential impact of IA priors



- colour-split cosmic shear-only
- 1350deg^2 , 9 galaxies arcmin^{-2}
- 5-bin tomography , z[0.1, 1.2]
- photo-z scatter = 0.05(1+z)

Fisher forecast cosmo parameters:

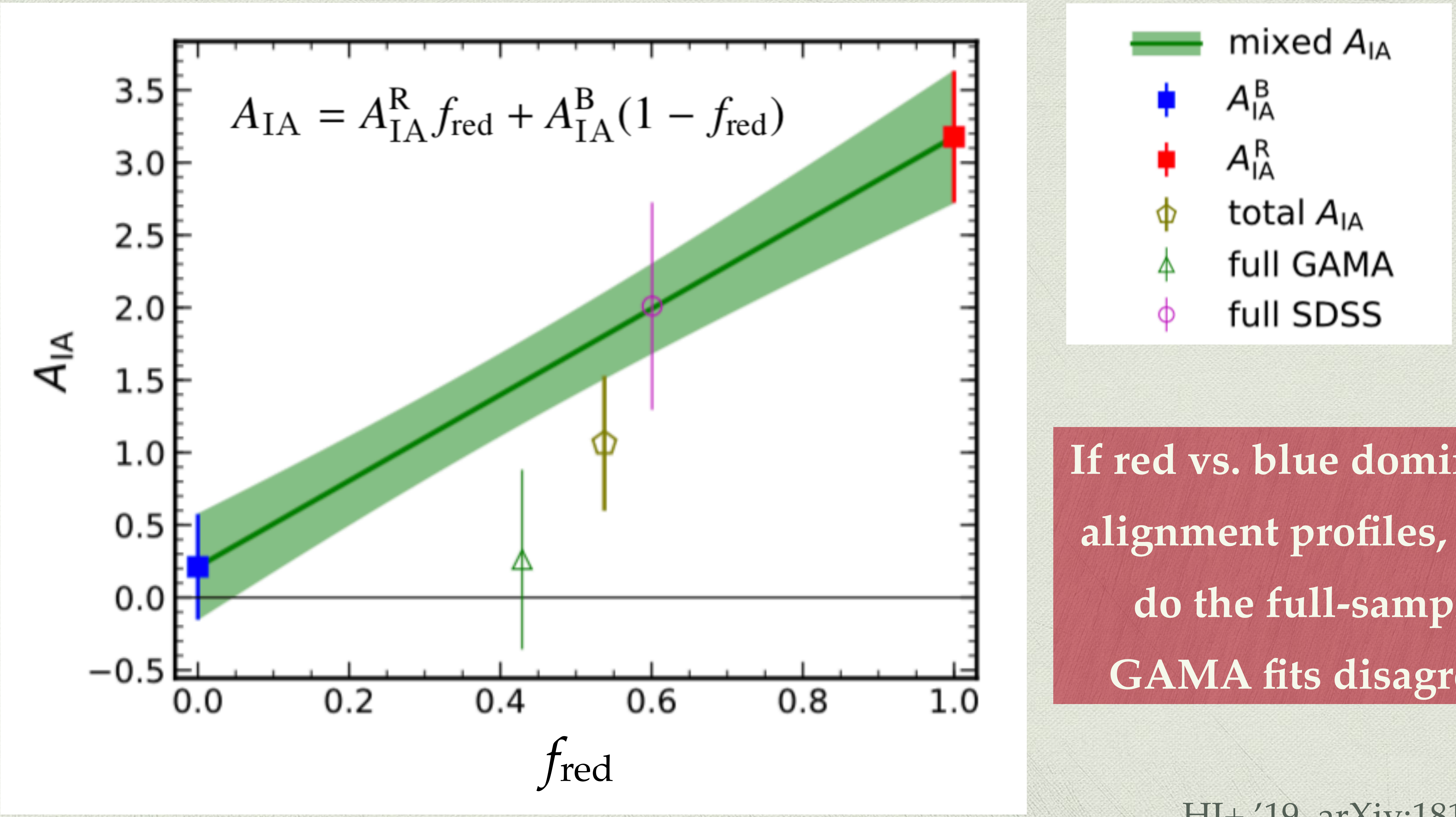
$$\Omega_{\rm m}\,,\sigma_8\,,w_0\,,\Omega_{\rm b}\,,h\,,n_{\rm s}$$

and nuisance parameters:

$$A_{\rm IA}\,,\beta\,,a_{z1}\,,\ldots a_{z5}$$

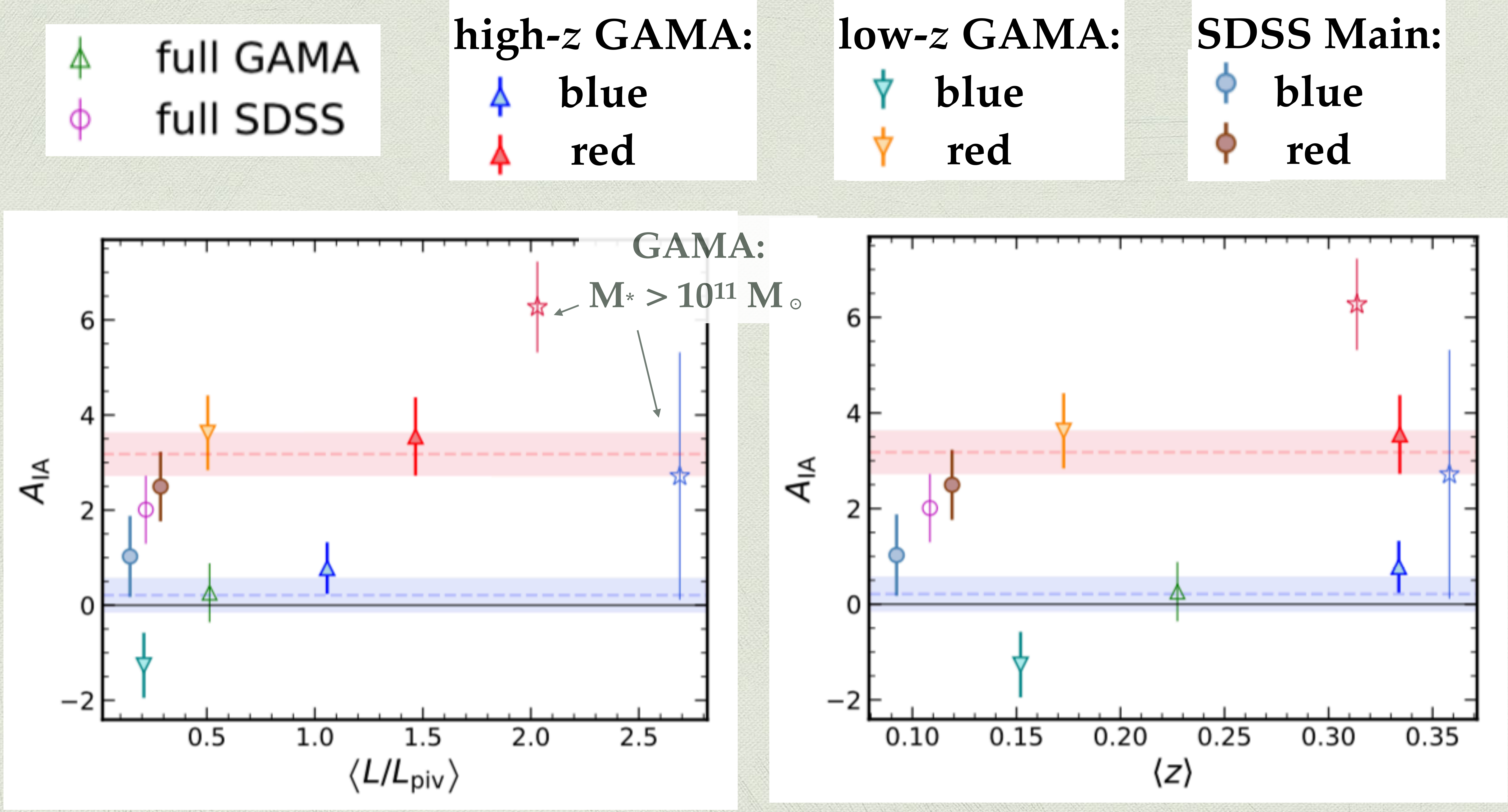
with 2 each for red / blue!

HJ+ ’19, arXiv:1811.09598 for details of forecast setup

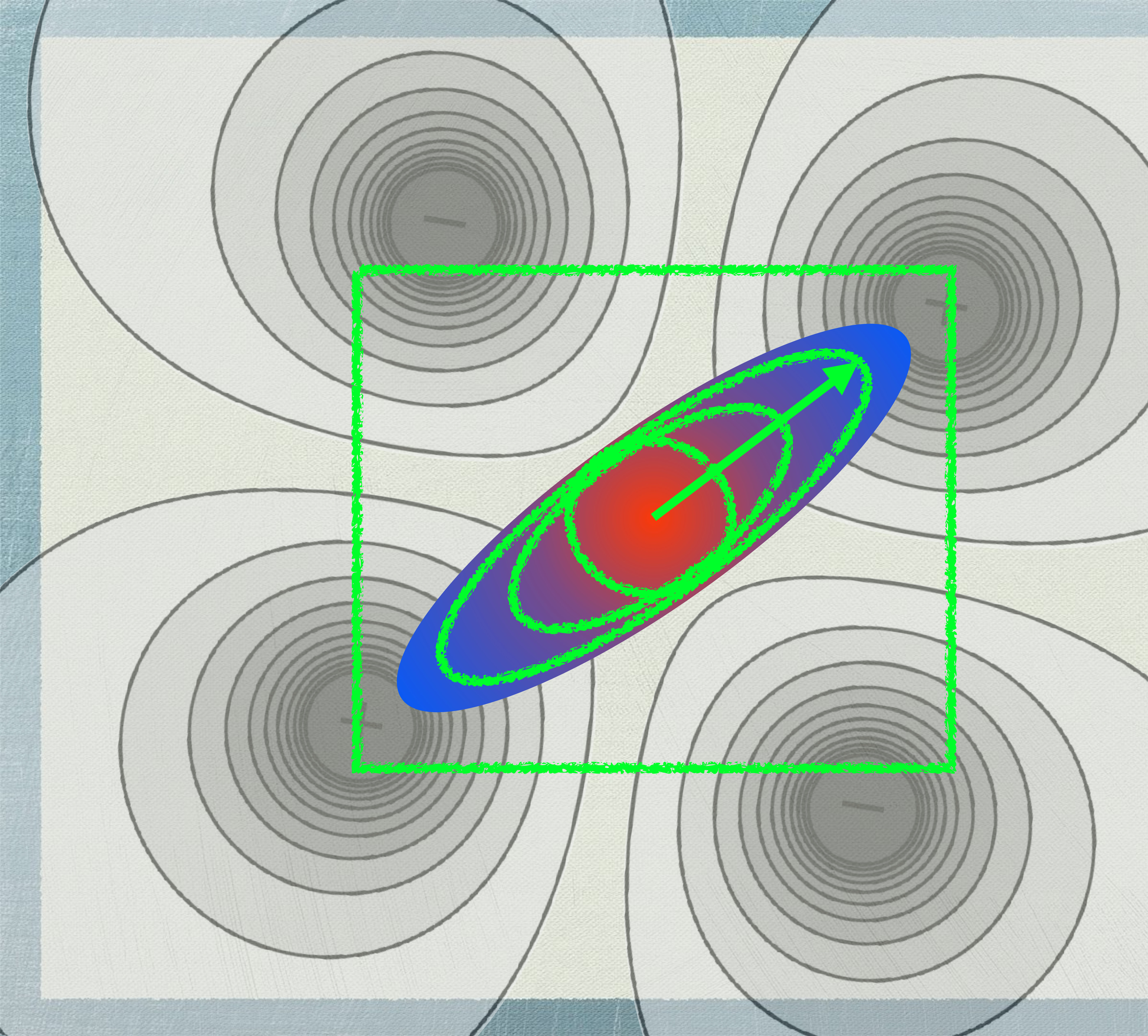


If red vs. blue dominates alignment profiles, why do the full-sample GAMA fits disagree?

HJ+ '19, arXiv:1811.09598

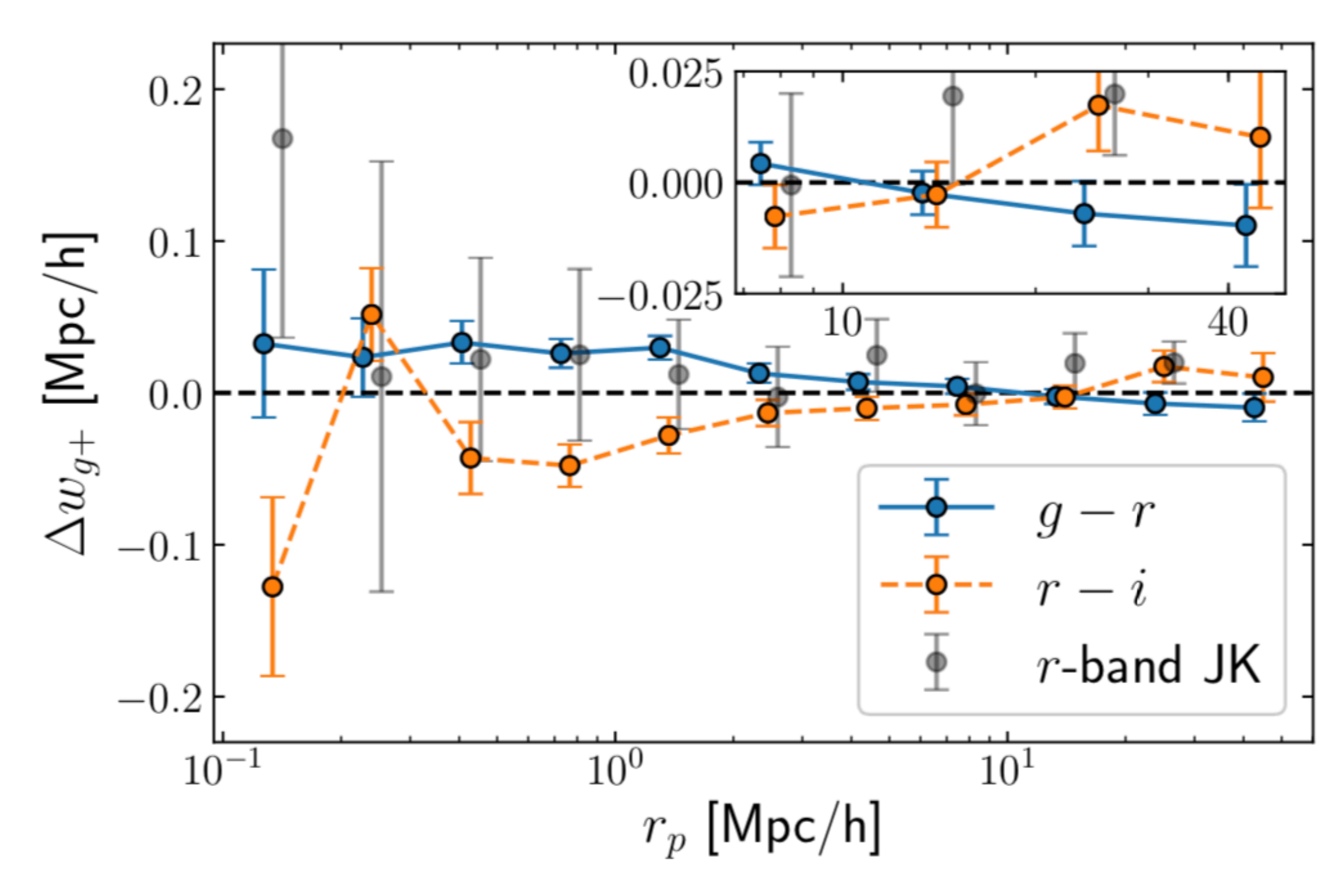


HJ+ ’19, arXiv:1811.09598



Galaxies tend to have colour gradients along the radial direction — any gravitational shielding should dissipate along the same direction

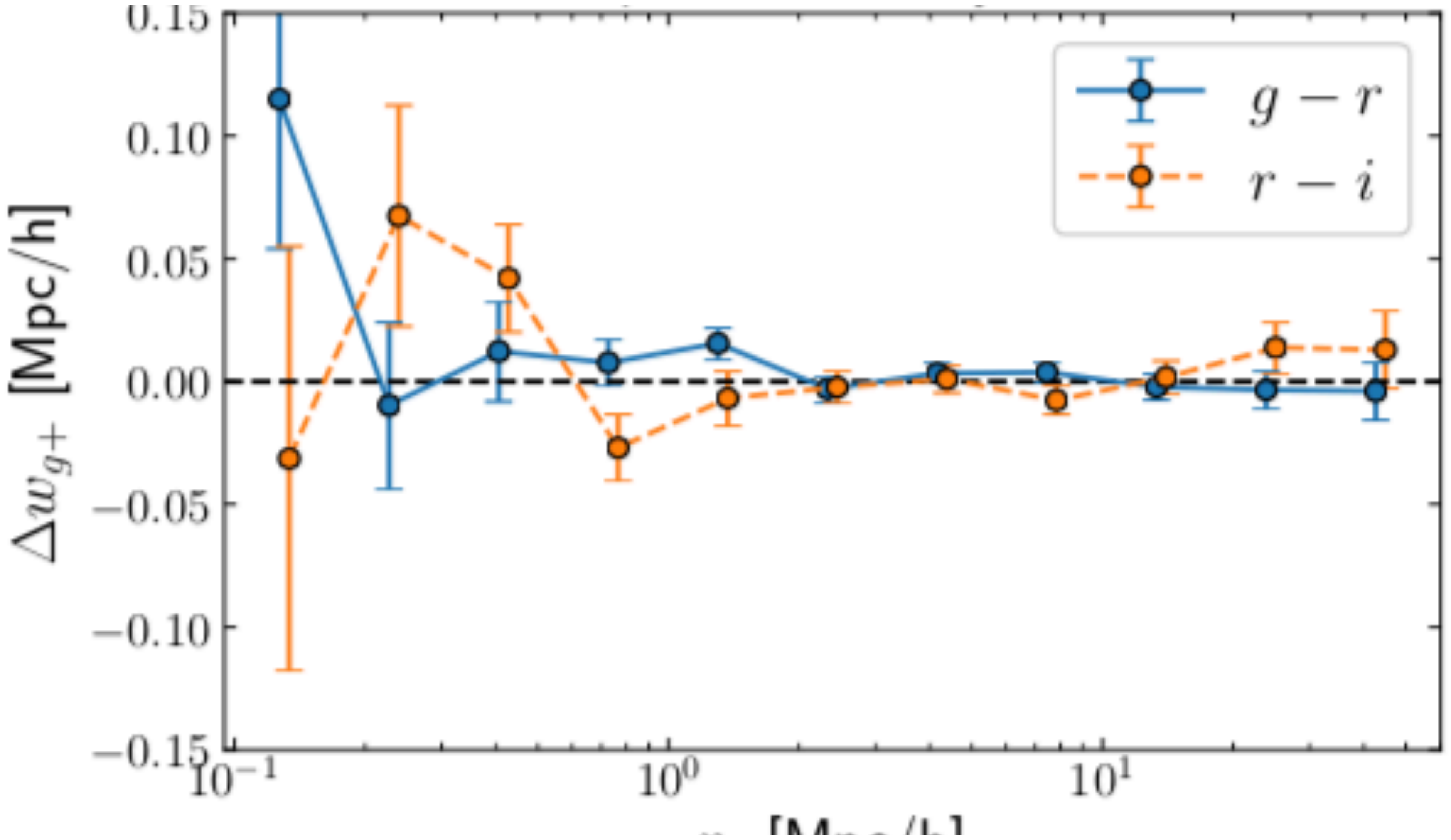
DEIMOS requires an elliptical Gaussian weight function to suppress image noise; we can fix the physical scale being measured



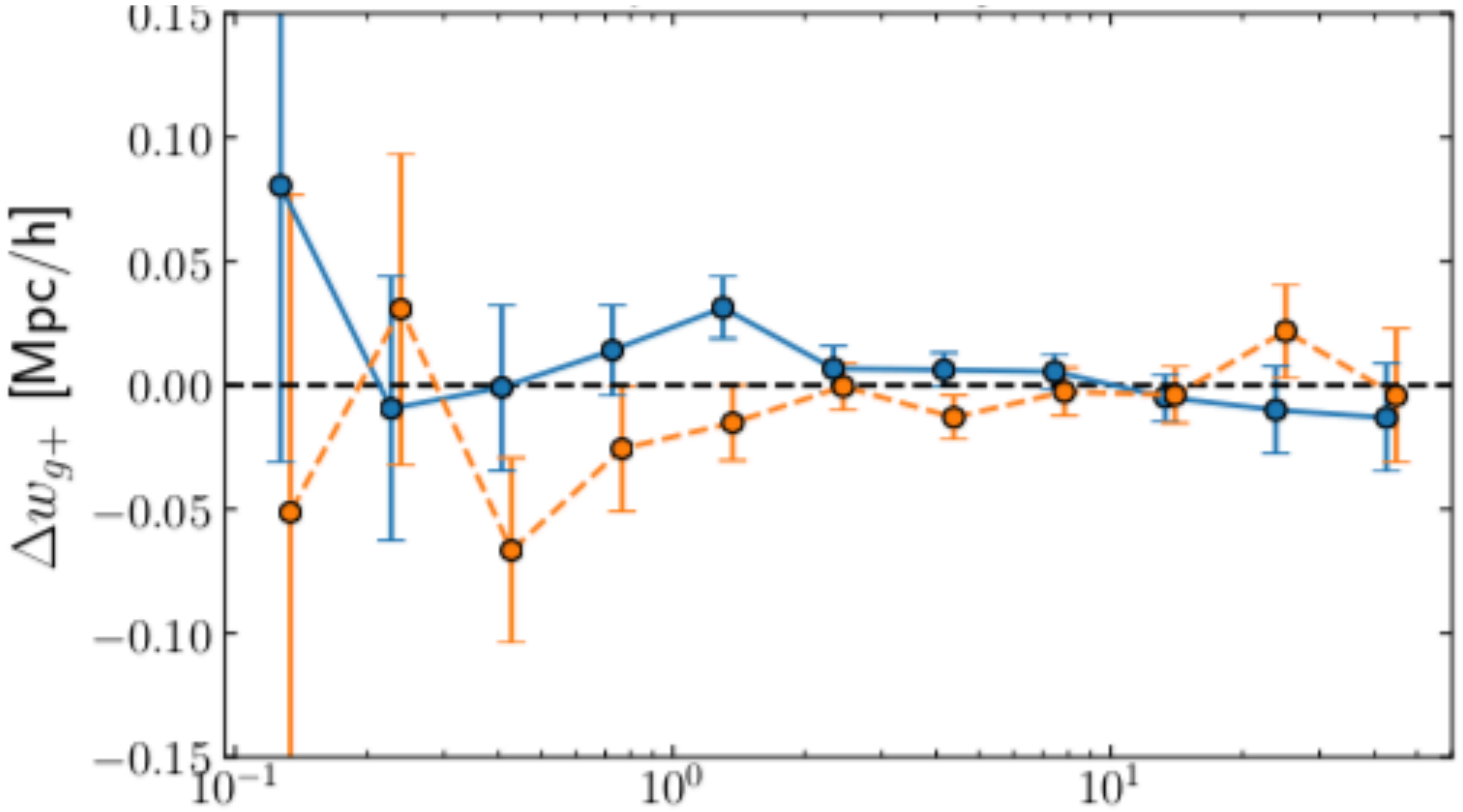
- Bluer *g*-band shapes *more* aligned than *r*-band
- Difference comparable to total *r*-band signal
- Redder *i*-band shapes also more aligned than *r*-band??

Georgiou, HJ+ '19, arXiv:1809.03602

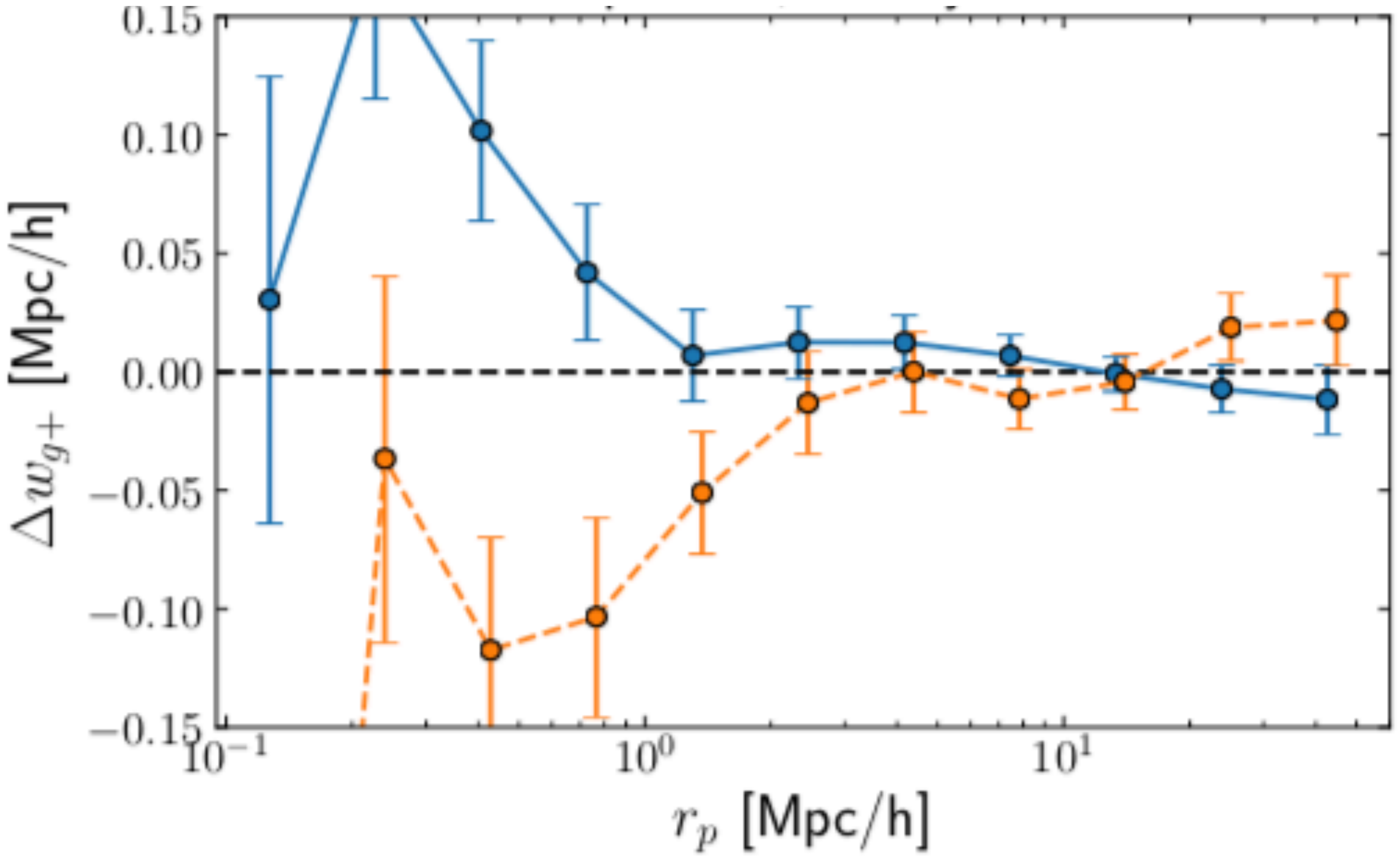
CENTRALS pointing towards CENTRALS



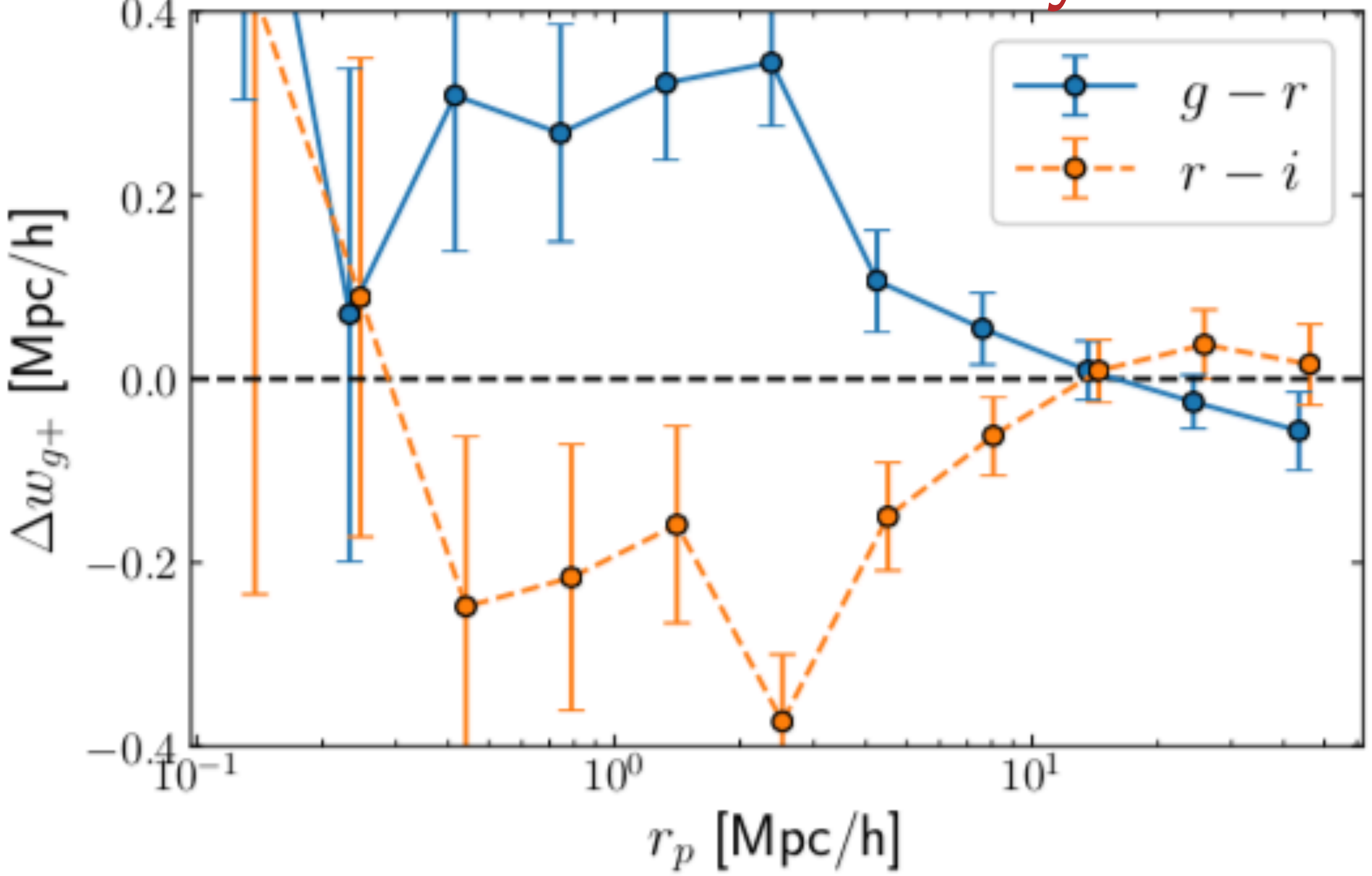
SATELLITES pointing towards CENTRALS



CENTRALS pointing towards SATELLITES



Red satellites only



Georgiou, HJ+ '19, arXiv:1809.03602

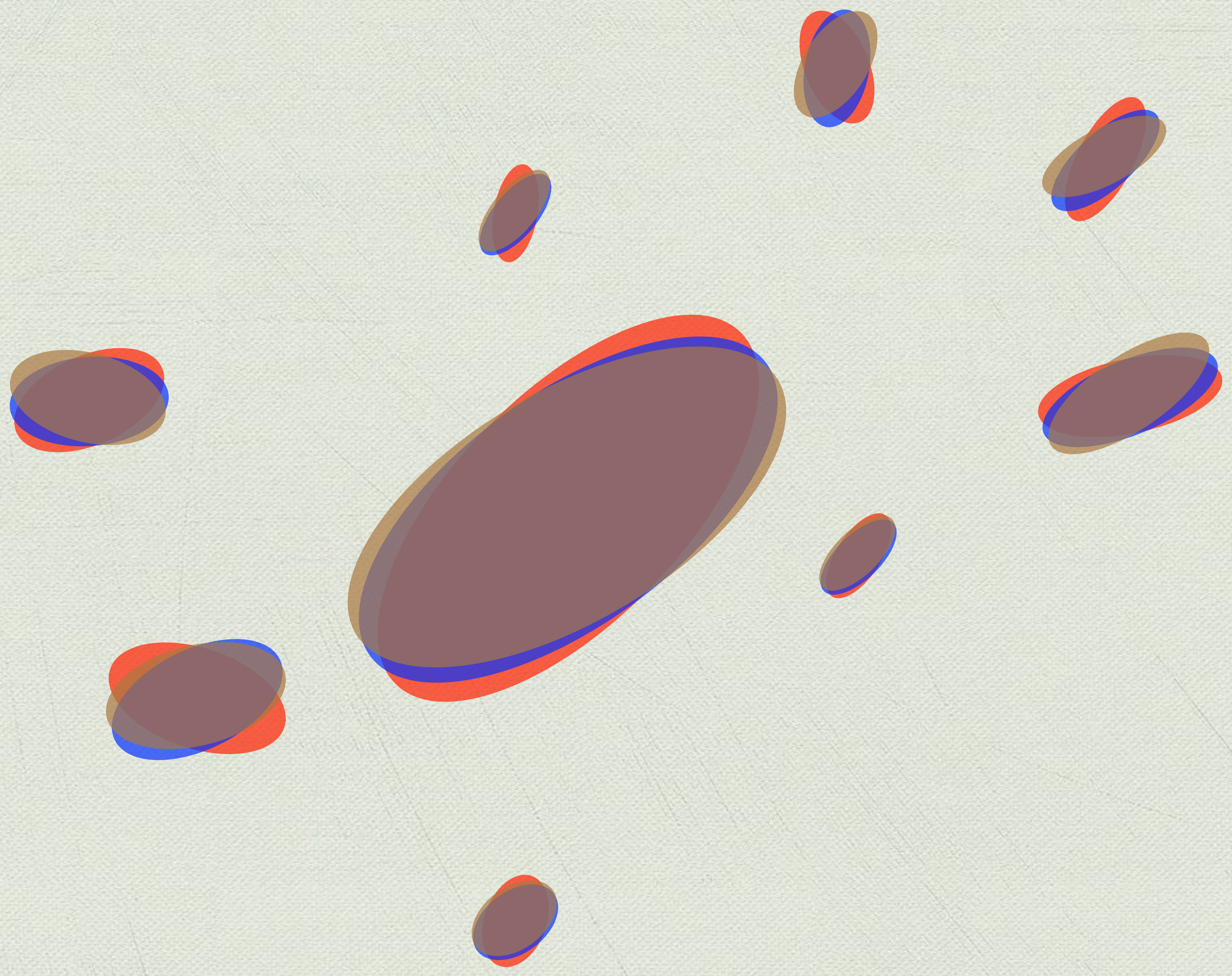
elliptical galaxies only!

r-band

old stars

g-band
r-band
i-band?

elliptical galaxies only!



star-forming
old stars
dust?