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Learning about intrinsic alignments using real galaxy surveys

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THE DARK ENERGY SURVEY

SDSS

Outline

1. Background and setup
    a. IA constraints from other sources
    b. Direct IA measurements
2. DES x eBOSS: a direct IA measurement
3. Results: What can these data tell us about IA?
4. Conclusions

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Types of IA constraints

We can (broadly) class IA studies into a few different categories:

- **Simultaneous** constraints on real data - where IAs are part of a larger model space, typically designed to constrain cosmological parameters
- **Simulation based** constraints - typically involves evaluating/fitting IA 2pt correlations using hydrodynamic simulations
- **Direct** constraints on real data - evaluating/fitting IA 2pt correlations using real galaxy data
- **Miscellaneous other** - various techniques using data including self calibration

Simultaneous IA constraints

- Recent cosmological lensing analyses have all used an IA model of some sort, although the details differ between surveys
- DES Y3 (most recent DES results) used a relatively complicated model known as TATT
- KiDS & HSC went with slightly simpler variations of the NLA model

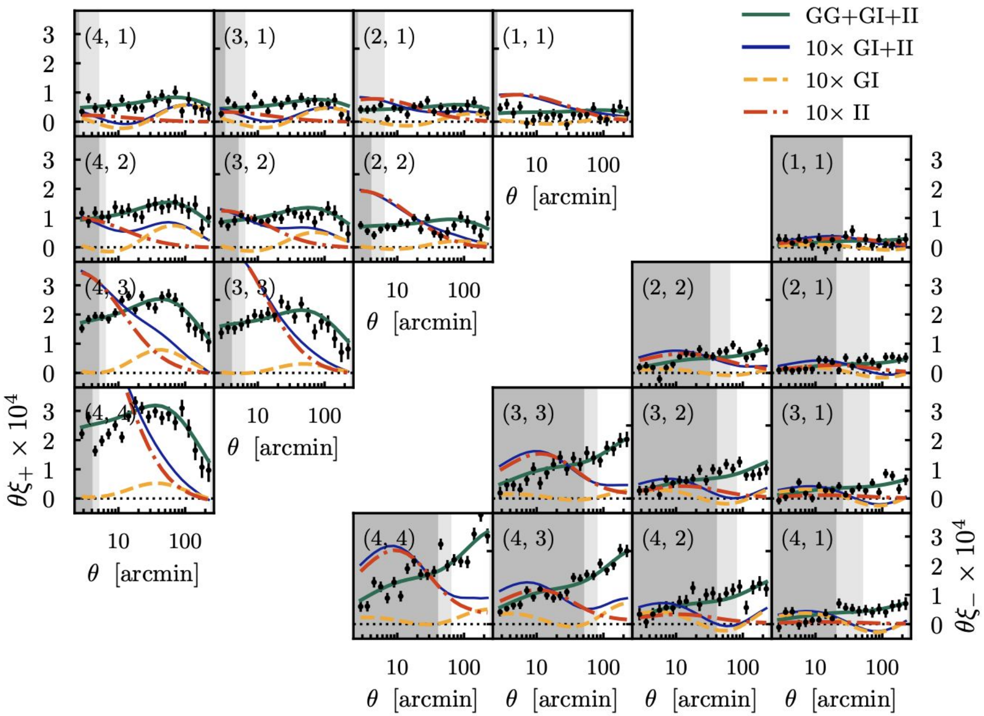


Figure from Secco & Samuroff et al 2021

Simultaneous IA constraints

- We can compare results from various surveys - all show roughly comparable IA amplitudes in the A1~0-1 range
- *However* detailed comparison is difficult as the parameter spaces differ
- Selection function, and so the composition of the samples (colour, luminosity, redshift), are potentially different
- And the shape measurement methods also differ, which further complicates things

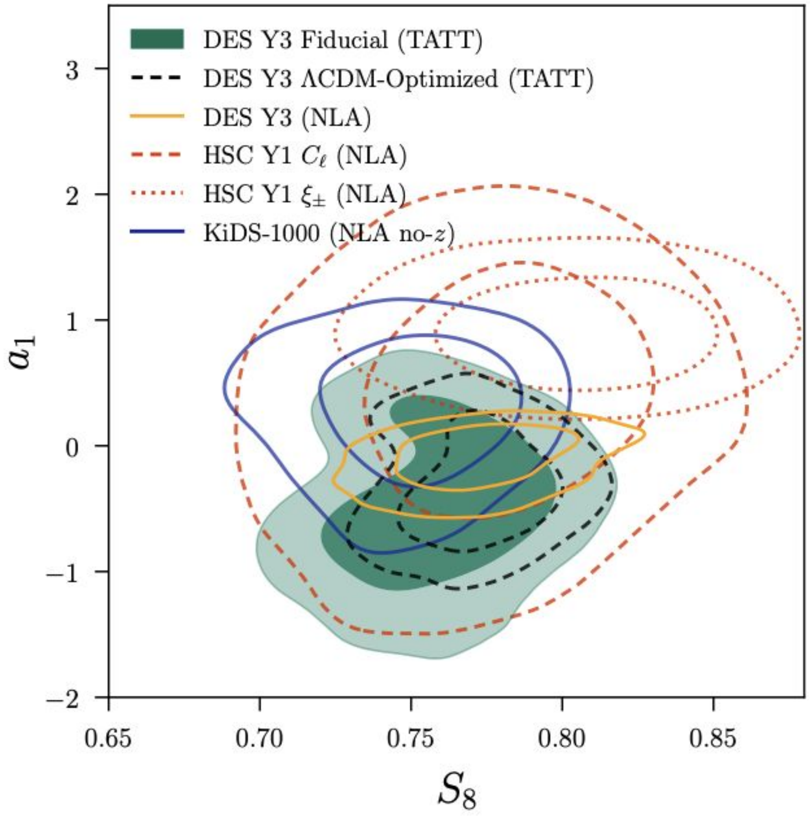


Figure from Secco & Samuroff et al 2021

Simulation based constraints

- We can infer IA parameters from hydro sims without messiness of real data
- Methodology is similar to with direct IA measurements - construct 2pt measurements, fit using models, and look at trends with galaxy properties

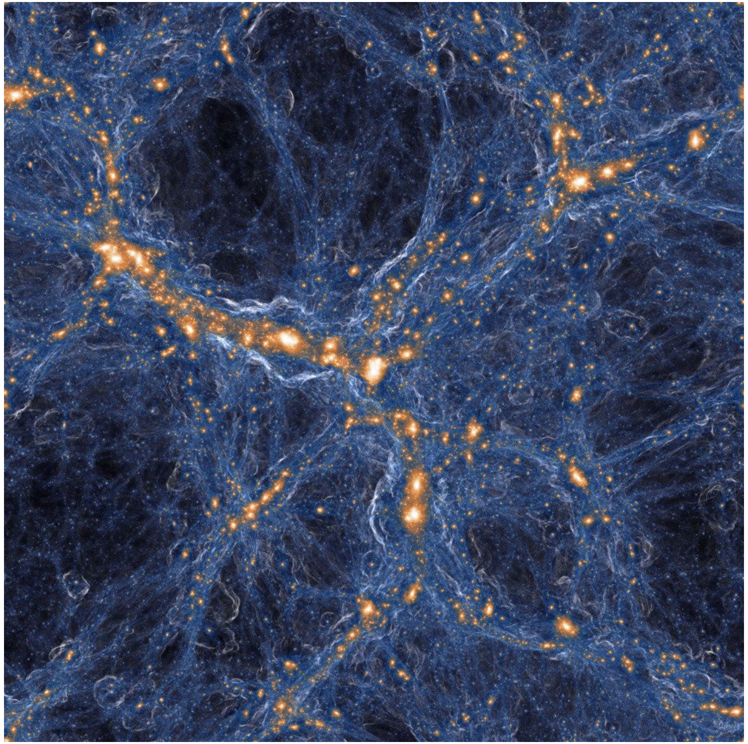
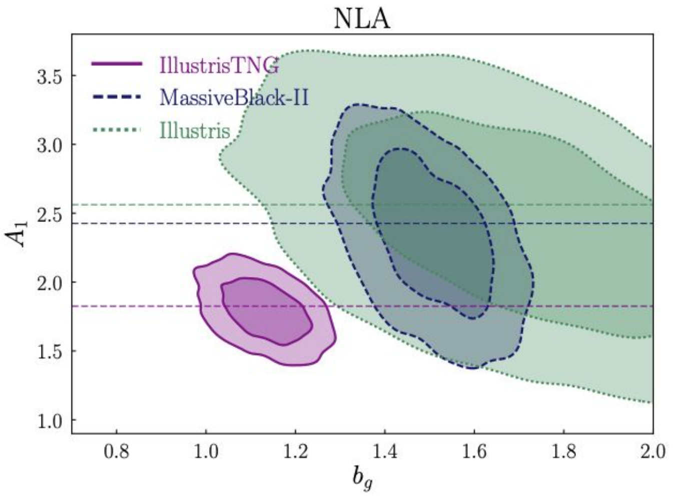
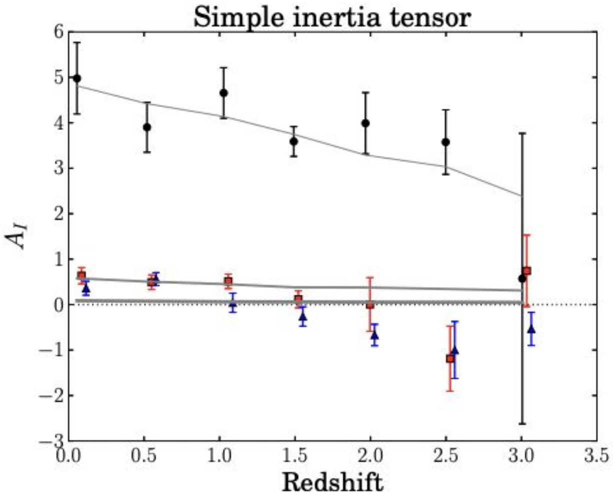


Figure credits: IllustrisTNG collaboration

Simulation based constraints

- Various studies have been carried out along these lines, using different simulations
- It is, however, quite difficult to ensure a realistic galaxy sample
- Hydro sims are also typically fairly small, meaning statistical uncertainties are large - especially on large scales
- The constraints are slightly limited by the extent to which we can trust the baryonic physics of the simulations (which is a notoriously difficult problem)





Figures from Samuroff et al 2021 and Chisari et al 2016

Simulation based constraints

- A number of other techniques using simulations exist. Typically instead of using hydro sims, these seek to imprint IAs onto DMO sims
- There are a few different ways to do this, but the key idea is to start with the properties of dark matter (tidal field, halos etc), and relate them to the properties of galaxy IAs
- See, for example: *Harnois-Deraps et al 2021*, *Hoffmann et al 2021*, *Joachimi et al 2013*, *Yagvaral et al 2022*

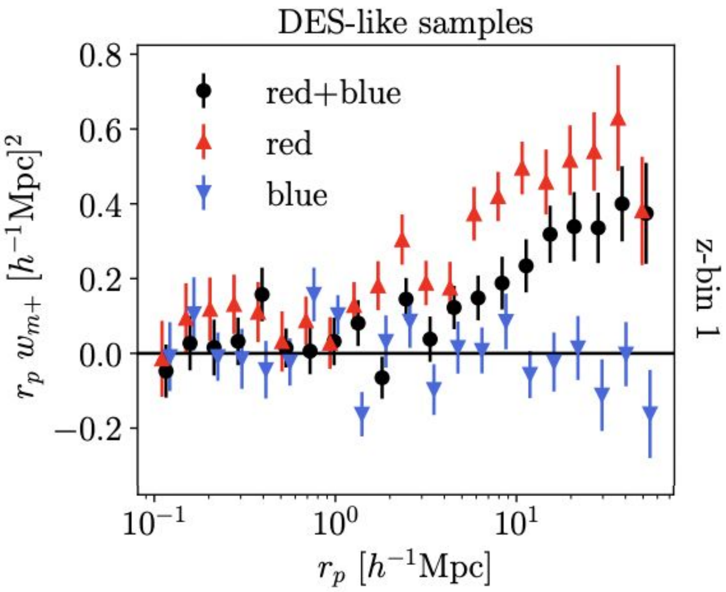


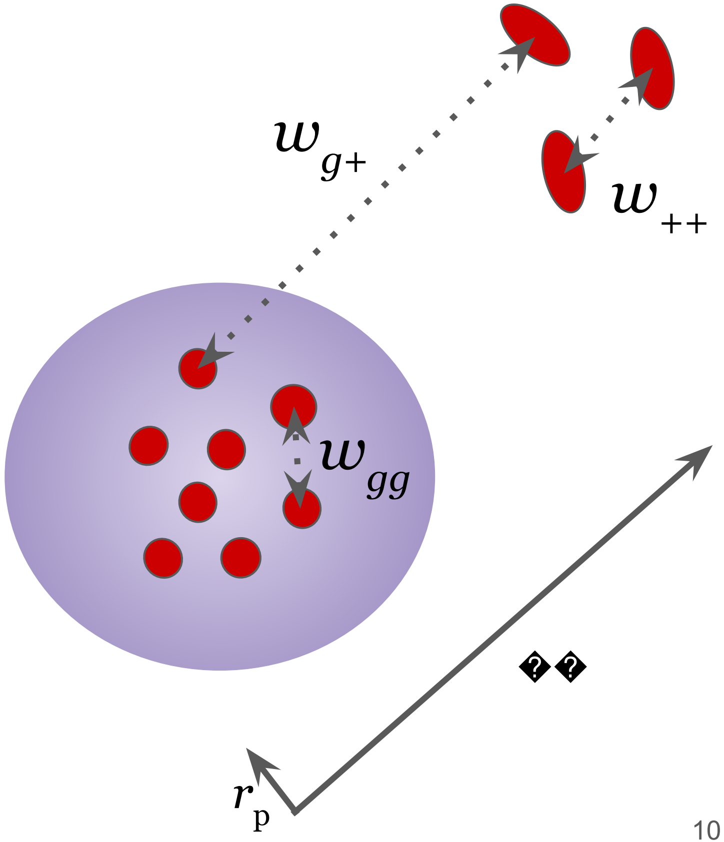
Figure from Hoffmann et al 2021

Direct IA constraints - intro

- Basic idea is to construct a measurement that is primarily sensitive to IAs
- We do this by dividing galaxies into bins of transverse and perpendicular separation r_{p} and $\mathbf{\Pi}$
- Normally we would then project in $\mathbf{\Pi}$
- This gives us three observables, roughly analogous to the standard 3x2pt probes:

$w_{gg}(r_{\mathrm{p}})$ $\quad$ $w_{g+}(r_{\mathrm{p}})$

$w_{++}(r_{\mathrm{p}})$



Direct IA constraints - intro

$w_{gg}(r_{\rm p})$

$w_{++}(r_{\rm p})$

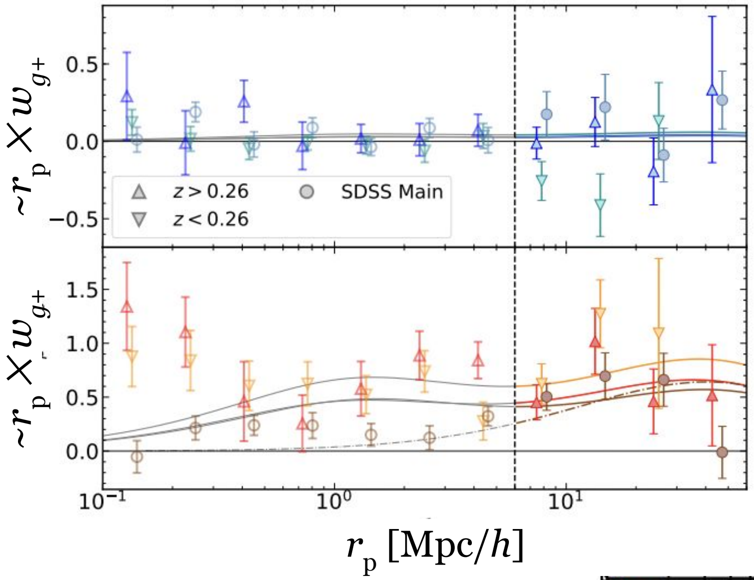
$w_{g+}(r_{\rm p})$

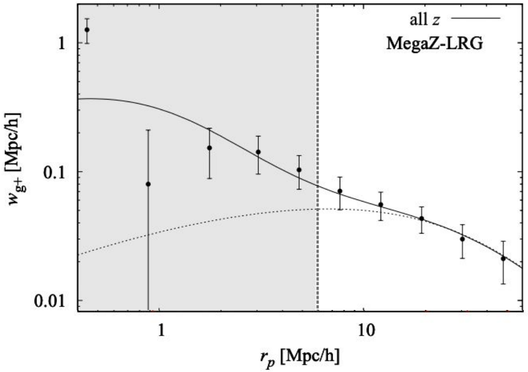
galaxy-galaxy: can't tell us anything about IAs on its own, but useful for constraining galaxy bias

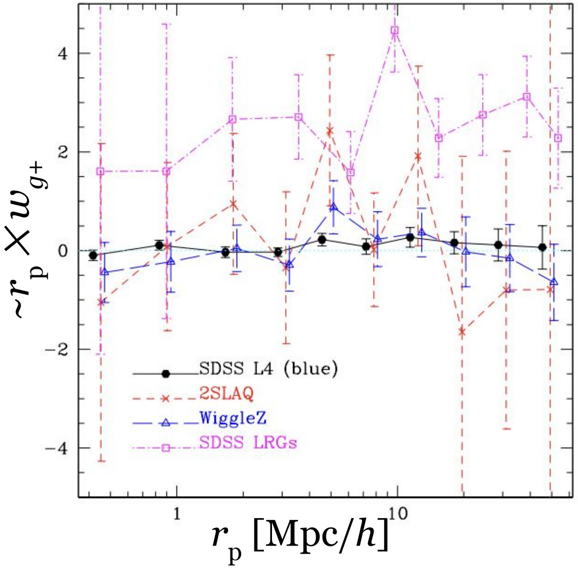
galaxy-shape: our primary probe of IAs. Sensitive to GI, but can also pick up GGL

shape-shape: in principle also sensitive to GI and II, but in practice typically much lower S/N than w_{g+} and w_{gg}

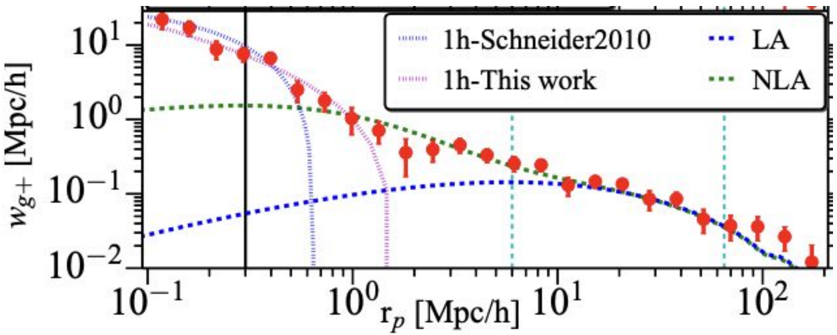
Direct IA constraints - some examples from the literature

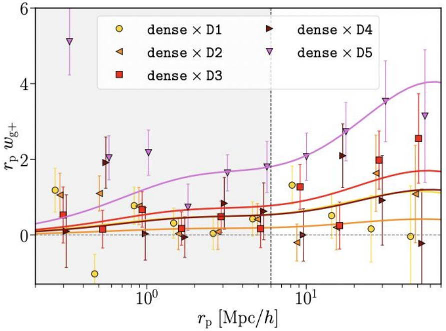






***Clockwise from top left**: Johnston et al 2019 (KiDS+GAMA), Joachimi et al 2010 (MegaZ), Mandelbaum et al 2011 (WiggleZ), Fortuna et al 2021 (KiDS-1000), Singh et al 2015 (LOWZ)*





Direct IA constraints - so why is this hard?

- We need *both* precise redshifts and shapes to construct our correlation functions - this somewhat limits the samples we can use
- This is the reason almost all of the direct IA measurements in the literature have incorporated at least some SDSS data
- It also means we are limited to certain samples - which tend to be red and bright compared with what people would typically use for lensing/cosmology
- To date we have only covered a corner of redshift/colour/luminosity space (though this is likely to change with DESI + new photometric surveys)

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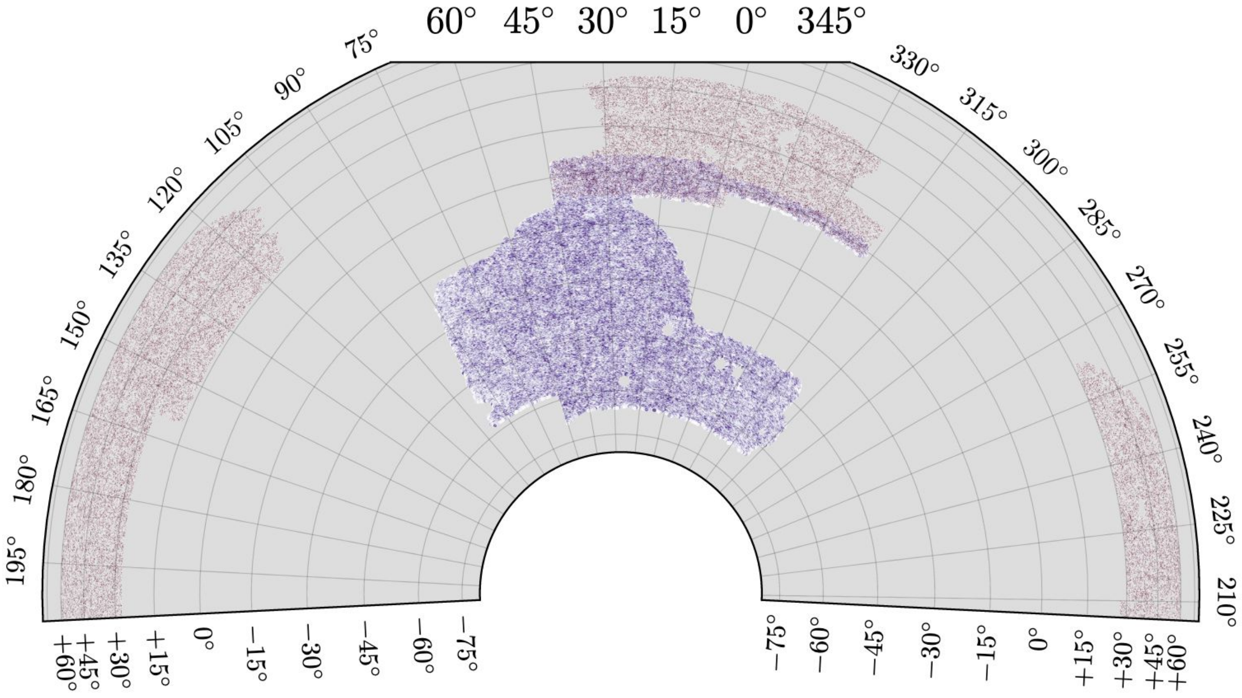
DES x eBOSS



60° 45° 30° 15° 0° 345°
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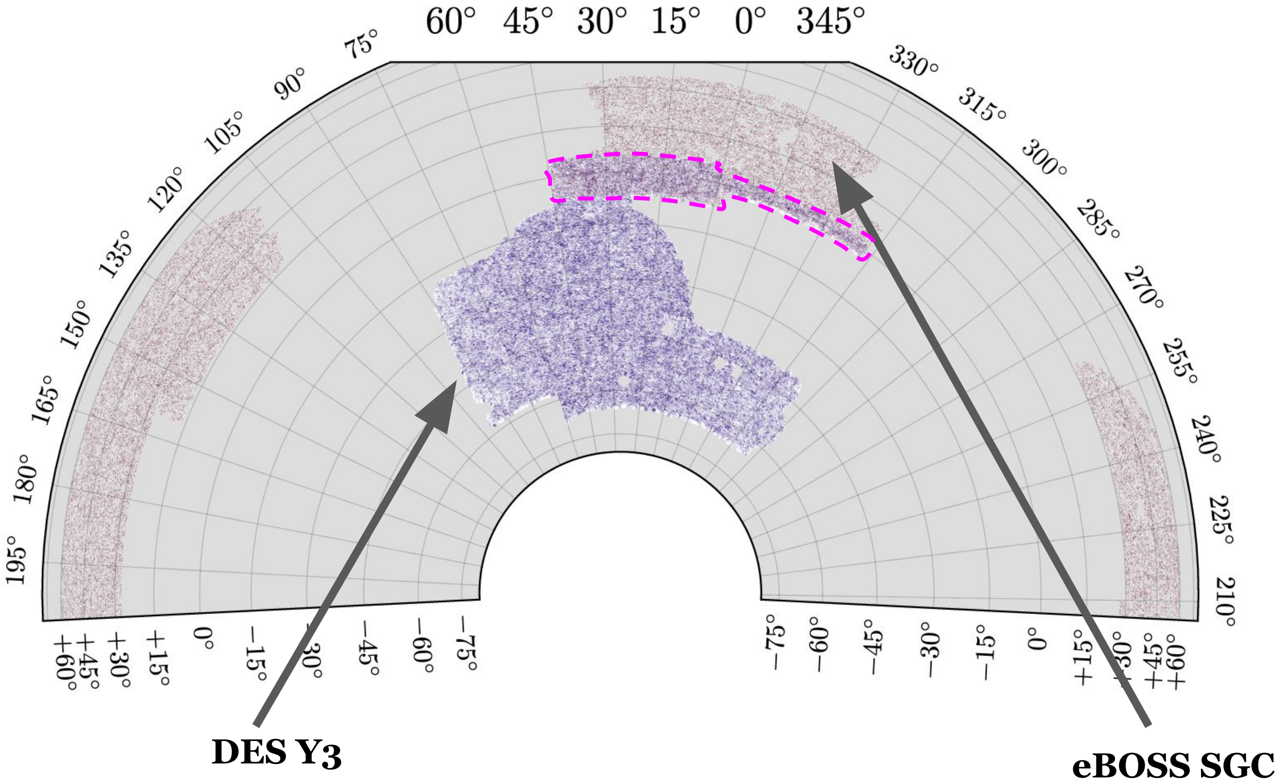
270°
255°
240°
225°
210°
+60° +45° +30° +15° 0° −15° −30° −45° −60° −75°
−75° −60° −45° −30° −15° 0° +15° +30° +45° +60°

DES x eBOSS


60° 45° 30° 15° 0° 345°
75° 90° 105° 120° 135° 150° 165° 180° 195°
330° 315° 300° 285° 270° 255° 240° 225° 210°
+60° +45° +30° +15° 0° −15° −30° −45° −60° −75°
−75° −60° −45° −30° −15° 0° +15° +30° +45° +60°
DES Y3
eBOSS SGC

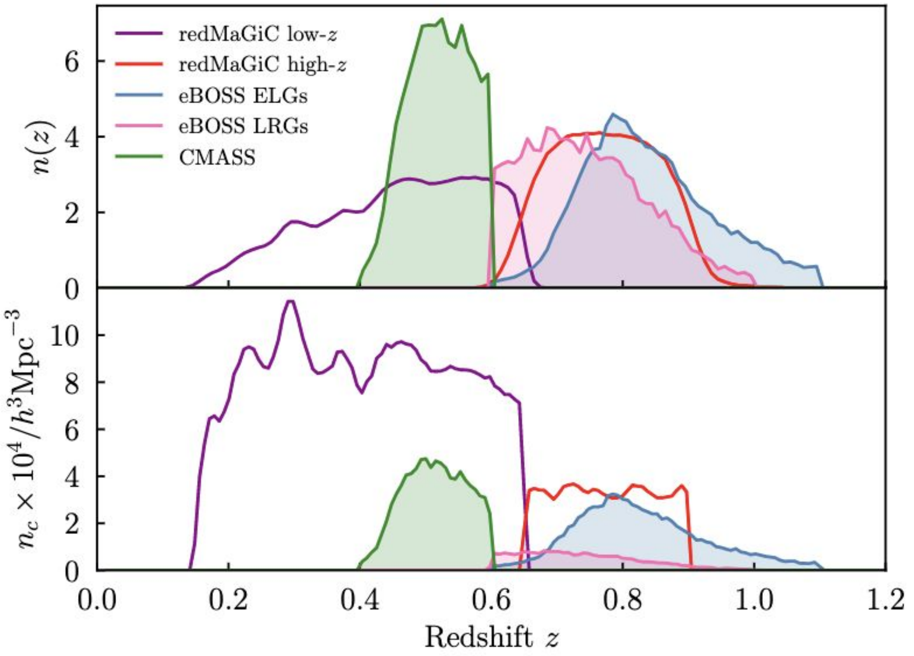
DES x eBOSS

Five samples:

- **Y3 redMaGiC high-z**
  - 4143 sq. deg., z~0.8
- **Y3 redMaGiC low-z**
  - 4143 sq. deg., z~0.45
- **CMASS**
  - 600 sq. deg., z~0.5
- **eBOSS LRGs**
  - 600 sq. deg., z~0.75
- eBOSS ELGs
  - 600 sq. deg., z~0.8

each of which are matched to DES Y3 for shapes.

For each sample, we measure the projected correlations w_{g+}, w_{++} and w_{gg}, as a fn. of r_p, and fit simultaneously



Modelling IAs

- Like most methods for learning about IAs, direct measurements are model dependent
- That is, we must choose a model with which to fit the data
- The choice of which to use depends somewhat on the scales one is fitting, and the questions one is interested in

Modelling IAs

- We fit two different IA models to our data: NLA & TATT

$$\gamma^I_{ij} = C_1 s_{ij} + C_{1\delta}\delta s_{ij} + C_2 \sum_k s_{ik}s_{kj} + \cdots$$

1 free amplitude

3 free amplitudes

See Hirata et al 2014; Blazek et al 2017

Modelling IAs - some equations

$$P_{\rm GI} = C_1 P_\delta + b_{\rm TA} C_1 P_{0|0E} + C_2 P_{0|E2},$$

$$P_{\rm II}^{\rm EE} = C_1^2 P_\delta + 2 b_{\rm TA} C_1^2 P_{0|0E} + b_{\rm TA}^2 C_1^2 P_{0E|0E} + C_2^2 P_{E2|E2} + 2 C_1 C_2 P_{0|E2} + 2 b_{\rm TA} C_1 C_2 P_{0E|E2},$$

$$P_{\rm II}^{\rm BB} = b_{\rm TA}^2 C_1^2 P_{0B|0B} + C_2^2 P_{B2|B2} + 2 b_{\rm TA} C_1 C_2 P_{0B|B2}.$$

See Hirata et al 2014; Blazek et al 2017

Direct measurements with photometric surveys

- In the cross-correlations with eBOSS, we effectively know the redshifts exactly - this makes the modelling very easy
- With the redMaGIC samples, however, the redshifts come with some uncertainty, which scatters galaxies and so alters the measured correlation functions
- Rather than try to calibrate this at the data level, we instead incorporate it into our model

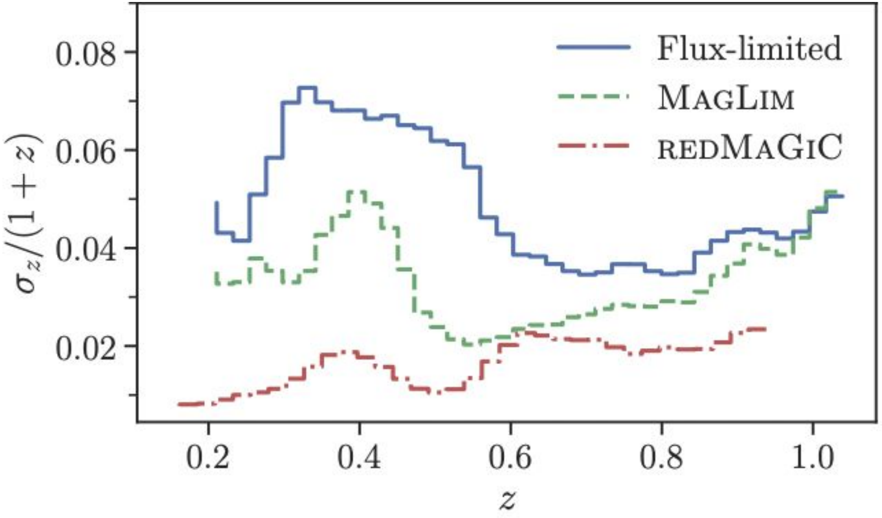
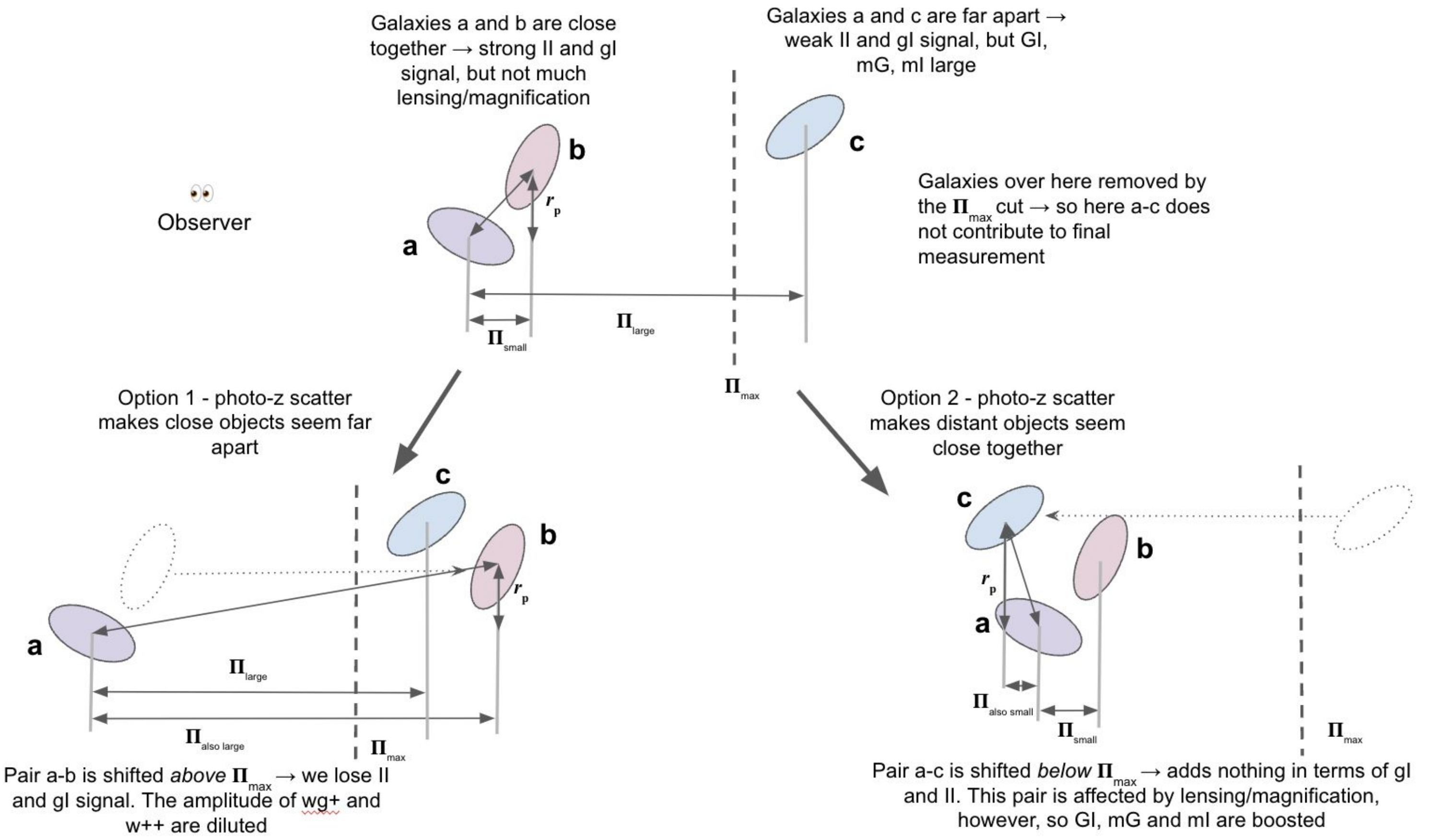


Figure from Porredon et al 2021

Direct measurements with photometric surveys



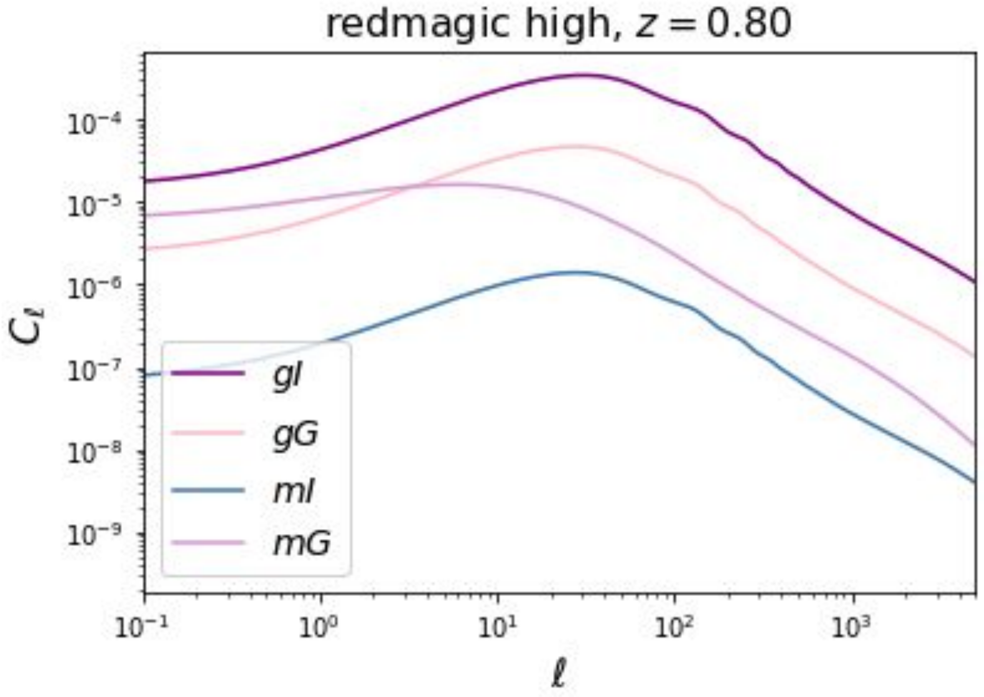
Direct measurements with photometric surveys

- Fortunately, we can model this (see *Fortuna et al* 2021 and *Joachimi et al* 2010)!
- The net effect is to suppress the dominant gI signal slightly (+ boost the lensing and magnification terms)
- Overall for our redMaGiC samples we found a ~10-15% effect (though this will depend on the redshift precision of the sample)

Modelling w_{g+}

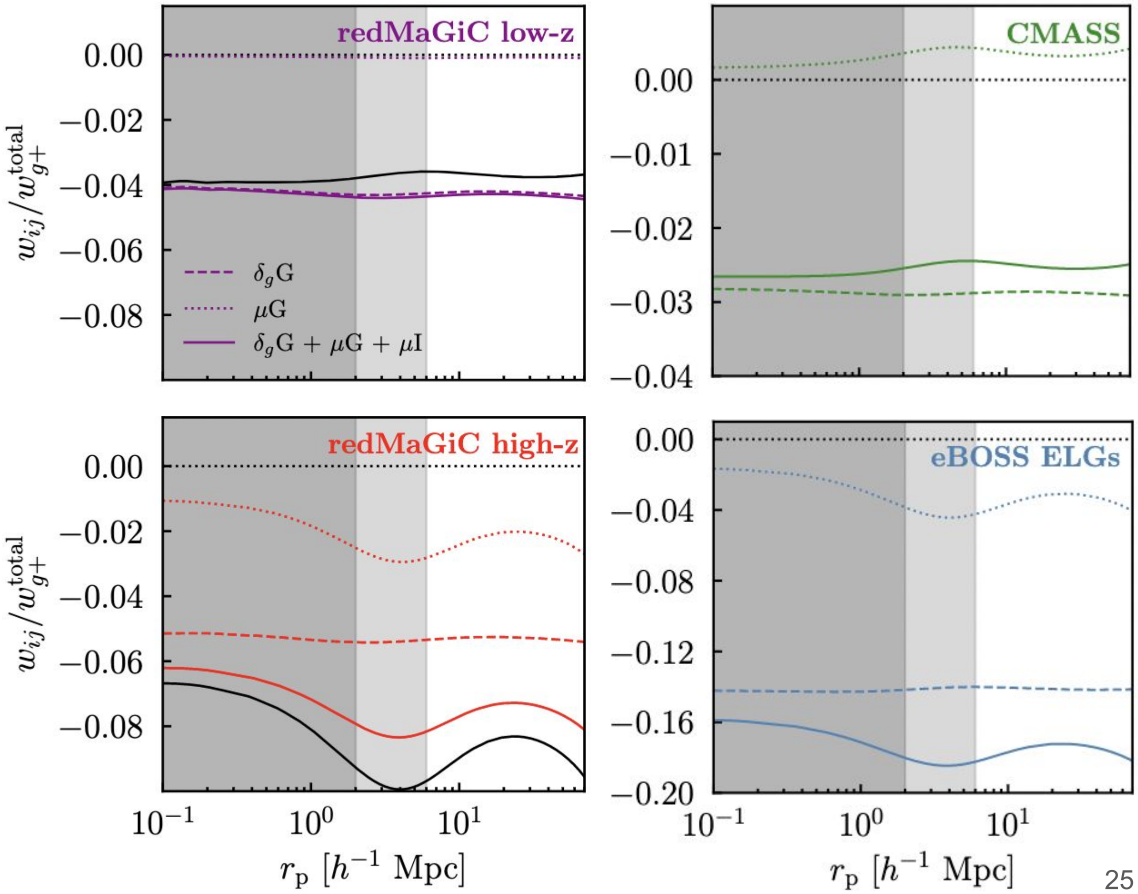
Various terms that we need to keep track of, which contribute to w_{g+}

- gI - our main IA signal, and typically dominant
- gG - galaxy-galaxy lensing. Small for spectroscopic samples, but significant for redmagic
- mI - magnification-intrinsic. Again, sensitive to the product g(z)*n(z), so should be bigger for RM
- mG - magnification-lensing. This one is a pure lensing correlation, so it will be present regardless of the quality of the redshifts and the size of the IA signal.



Modelling w_{g+}

- Lensing & magnification terms appear in our data at the level of ~ a few percent
- GGL-like contributions tend to dominate, but magnification-lensing cross term is also non-vanishing in some cases
- Significant for photometric samples (redmagic), but also potentially spectroscopic ones



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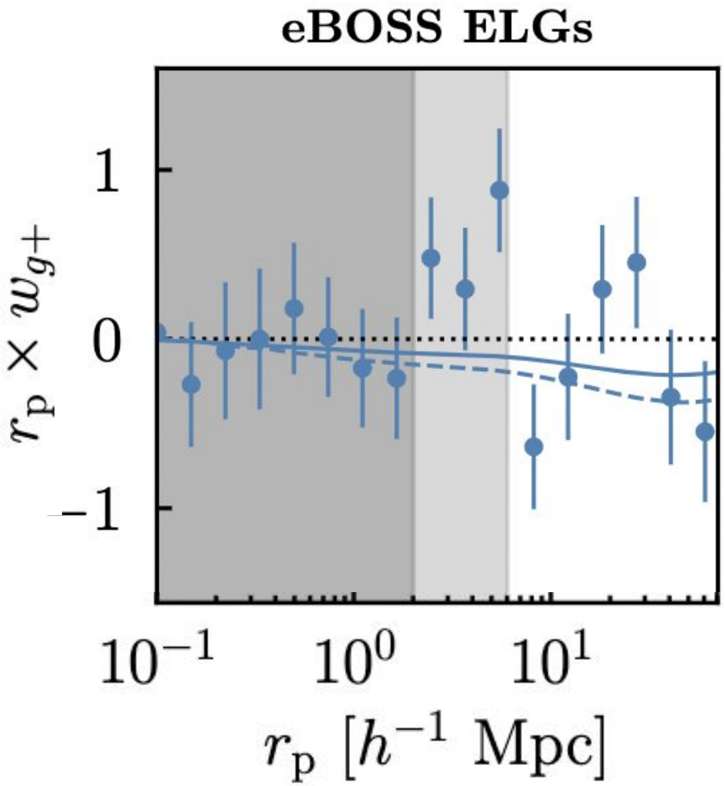
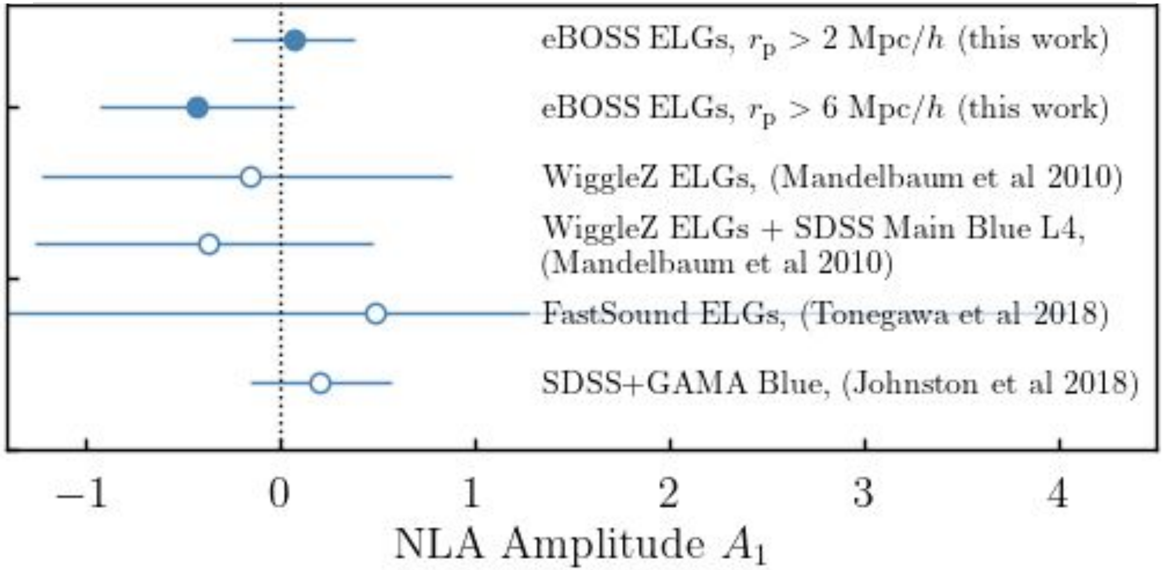
eBOSS ELGs: a null detection

- ELGs measurement is consistent with a null signal on large scales (>6 Mpc/*h*)
- This remains true at r_p>2 Mpc/*h* (and even all the way down to 0.1 Mpc/*h*) - we get a decent null χ^2 in each case
- No sign of a discernable 1-halo alignment signal above noise



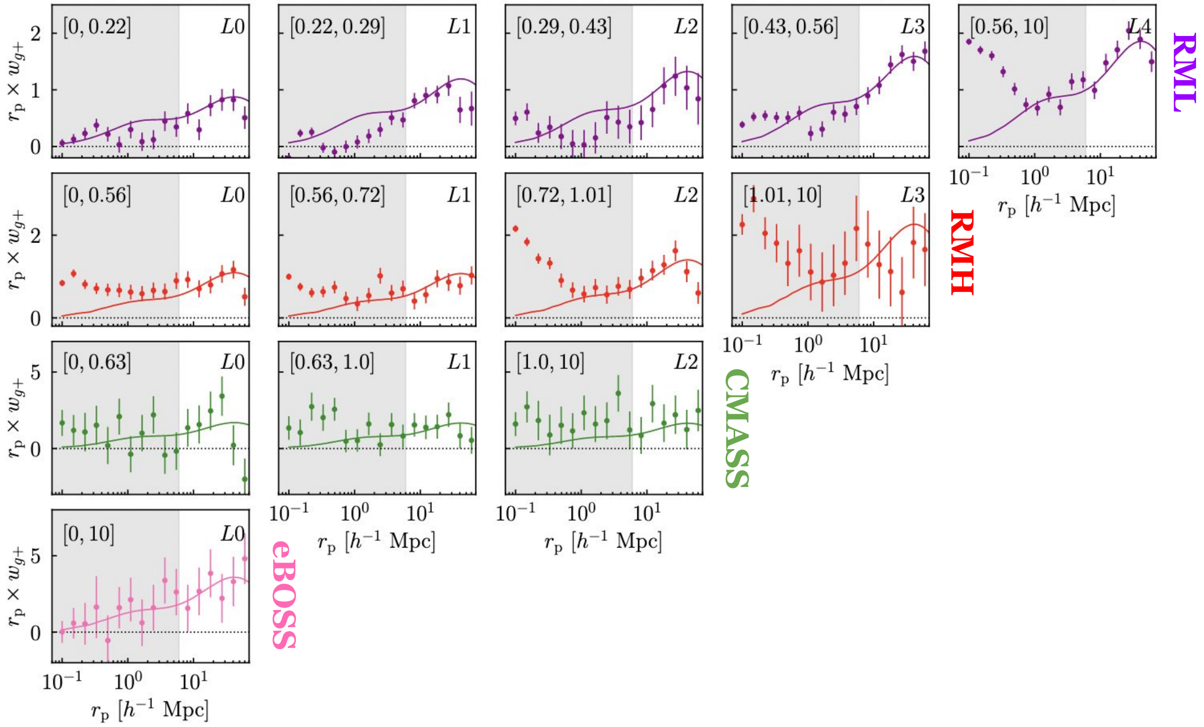
Comparing with blue galaxies in the literature

- All “blue” samples to date have been consistent with 0 alignments
- Although the selections differ quite a bit, so the comparison is not exact



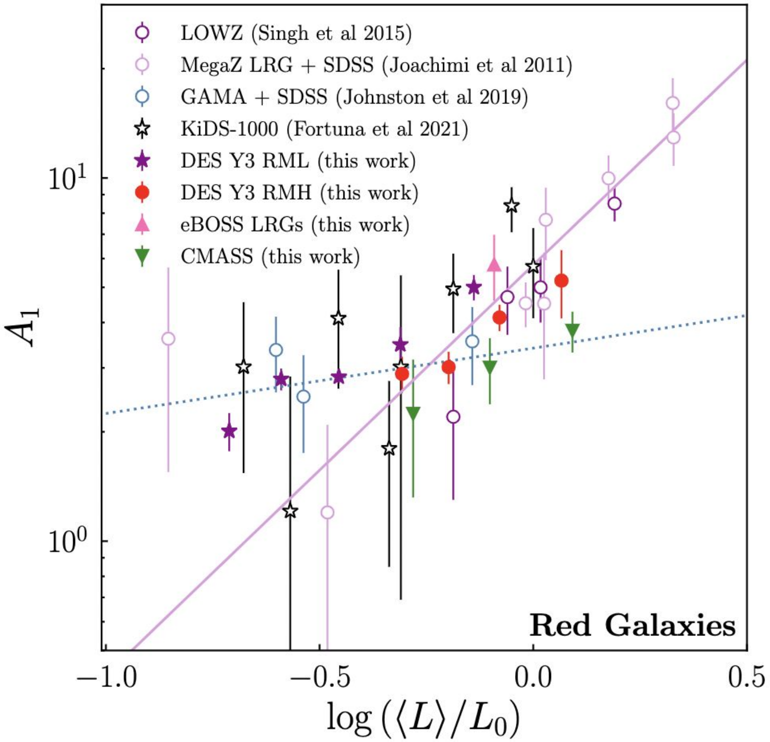
Exploring the luminosity dependence of red galaxies

- Divide our red samples into bins in r-band luminosity
- We have 13 bins in total, across 4 samples
- Fit each one independently for bias + A1 on large scales



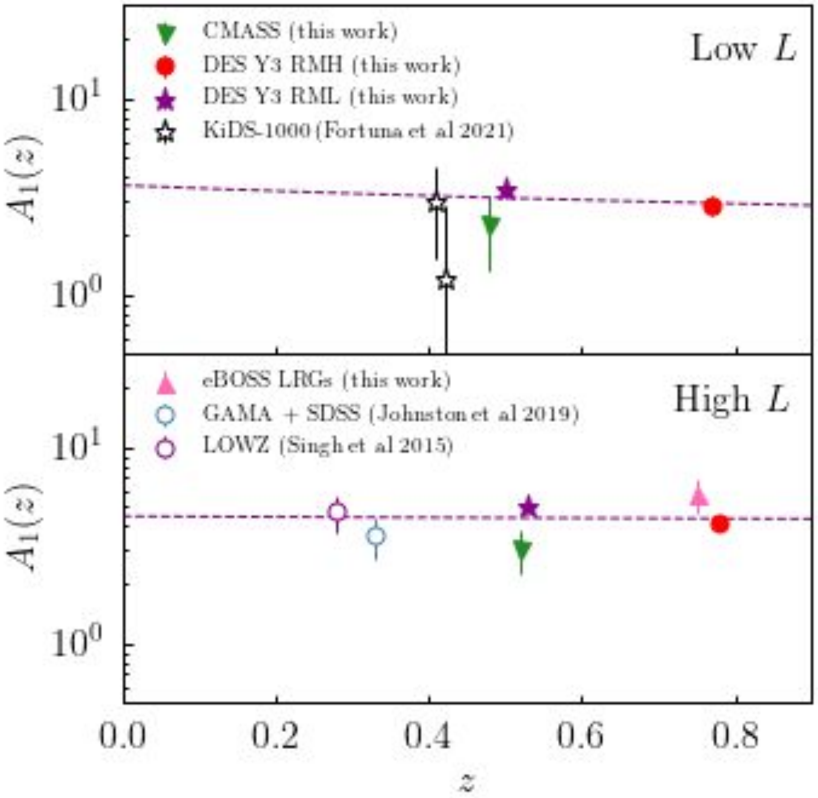
Luminosity dependence: overview

- Given these samples, we can plot best fitting A1 vs the mean luminosity in each bin (right)
- Solid points are new samples from our DES x eBOSS work
- Qualitative picture is consistent with a broken power law, although the picture is somewhat more complicated



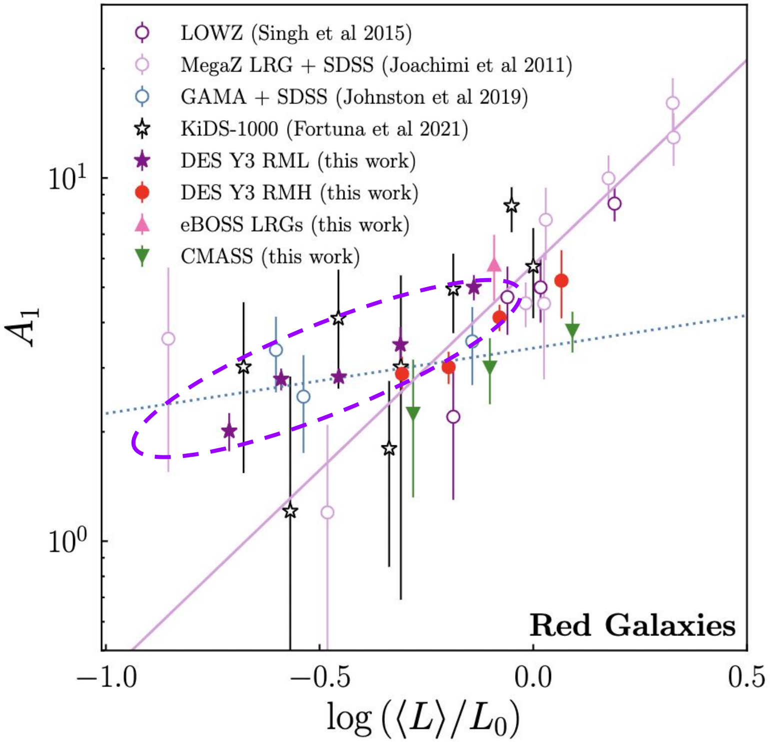
Redshift dependence

- Fit redshift dependence in red galaxies
- We split samples into two bins of luminosity (upper/lower panel in Figure) to avoid selection effects
- Consistent with no *z* evolution



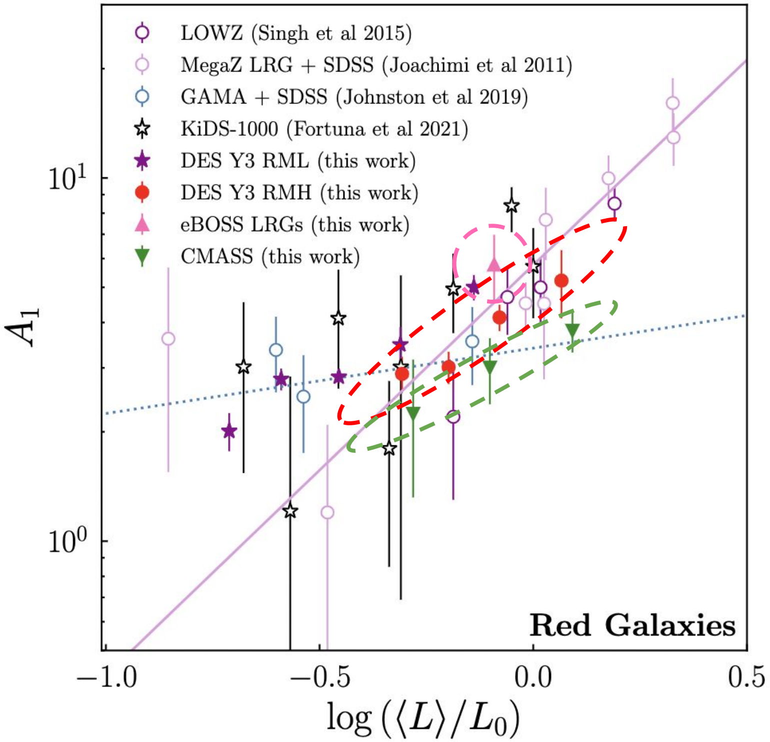
Luminosity dependence: the faint end

- Quite significant improvement in S/N of the fainter end of the A1-L relation
- Again, we see a slightly flatter trend than predicted from extrapolating the bright end slope
- → more alignment signal even in relatively faint red populations

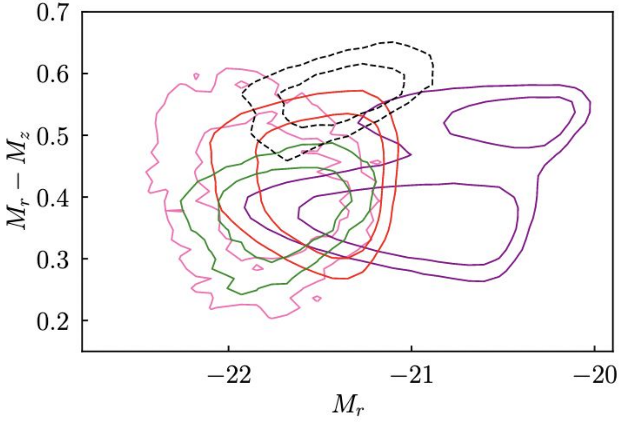


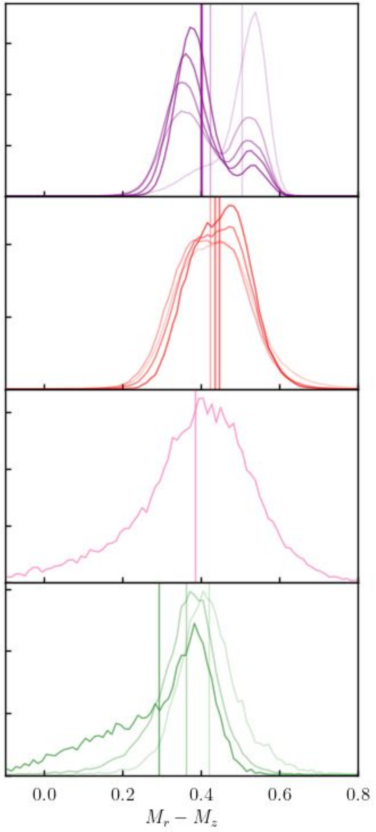
Luminosity dependence: the bright end

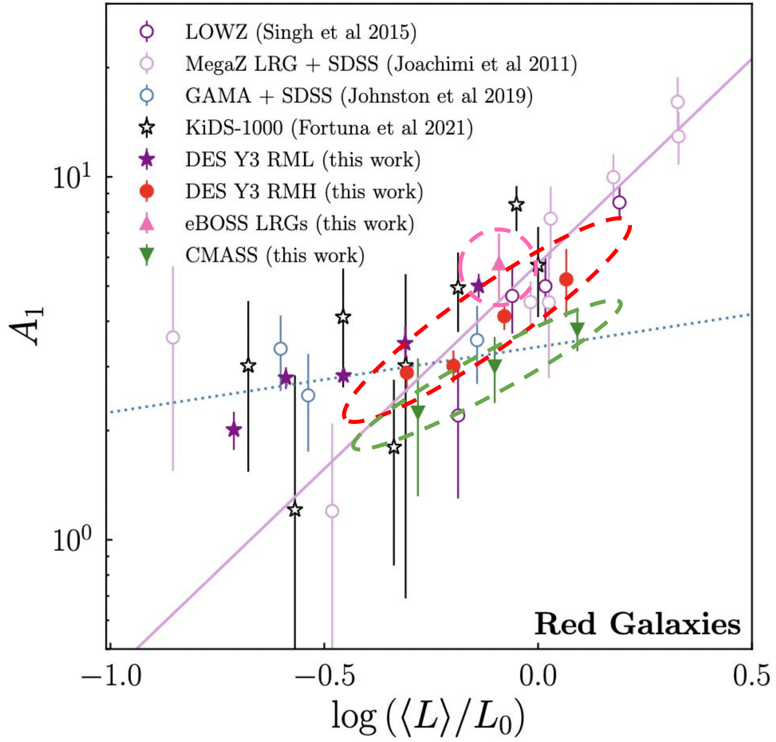
- However, things start to look more complicated as we next look at our brighter samples
- Although eBOSS and redMaGiC high-z are ~ consistent with the trend from previous surveys, CMASS is systematically lower
- It also follows a slightly shallower trend
- so… why is this?



Luminosity dependence: impact of colour differences





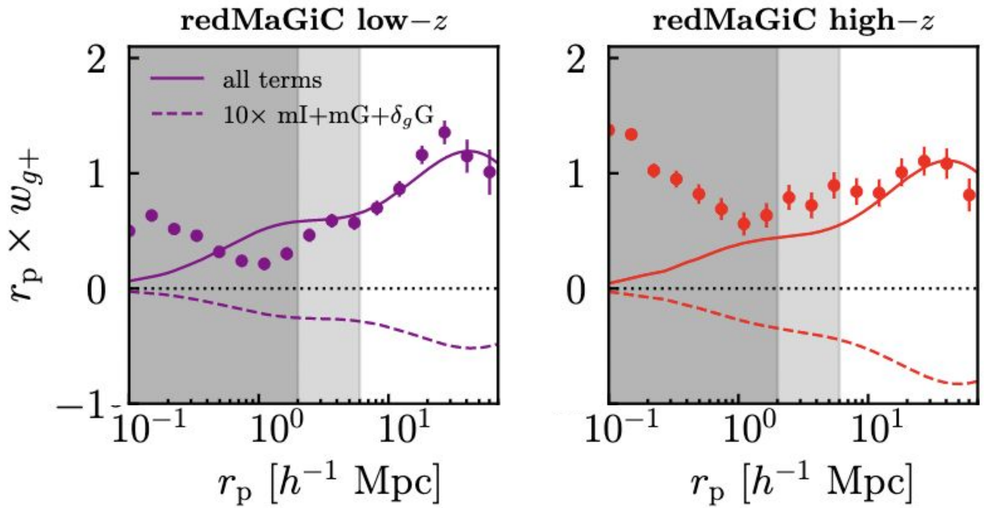


Luminosity dependence

- We see differences in the large scale IA amplitude between broadly defined "red" galaxy samples at similar luminosities
- Likely that colour differences between (and potentially *within*) samples are playing a role in this
- This points towards the need for a more sophisticated approach to modelling, which accounts for more than luminosity...
- Particularly as data sets get bigger and more constraining
- It's also true that different analyses in the literature have many different assumptions -> homogenisation is needed (echo-IA :))

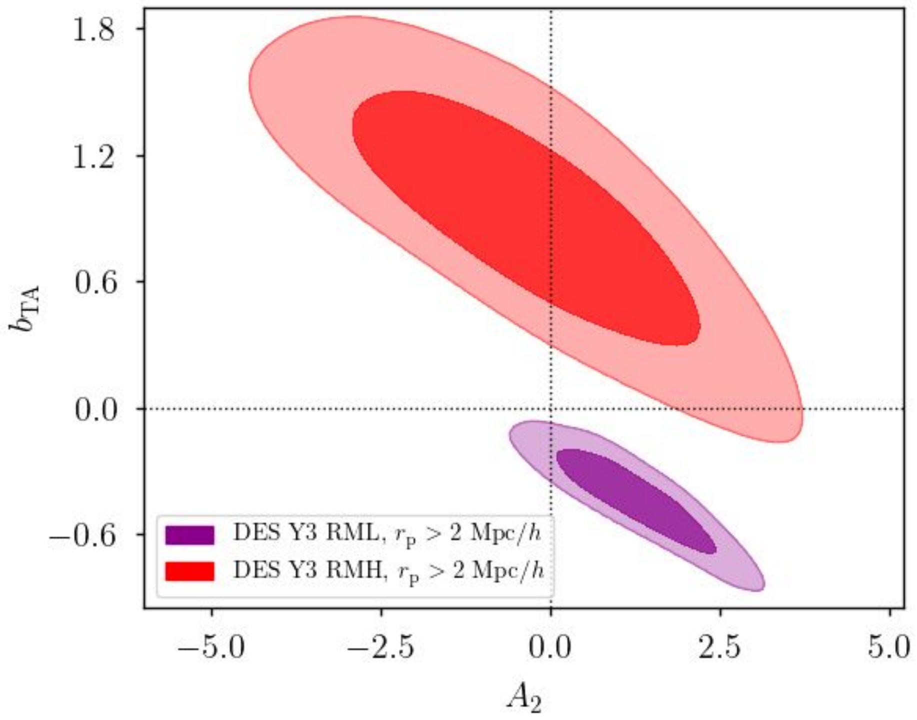
Pushing to smaller scales with TATT

- NLA does a good job describing all of our samples on large scales
- If we extrapolate the fit down <6 Mpc/h, however, we start to see deviations
- Fortunately we have a model designed to work in exactly this regime
- → analyse these data with TATT including (slightly) smaller scales



Pushing to smaller scales with TATT

- We see non-zero TATT params in both redMaGiC samples at ~ a few σ
- Mostly absorbed by the TA amplitude, but with opposite signs
- Note that these samples differ by more than their mean redshift, and so differences are not necessarily surprising



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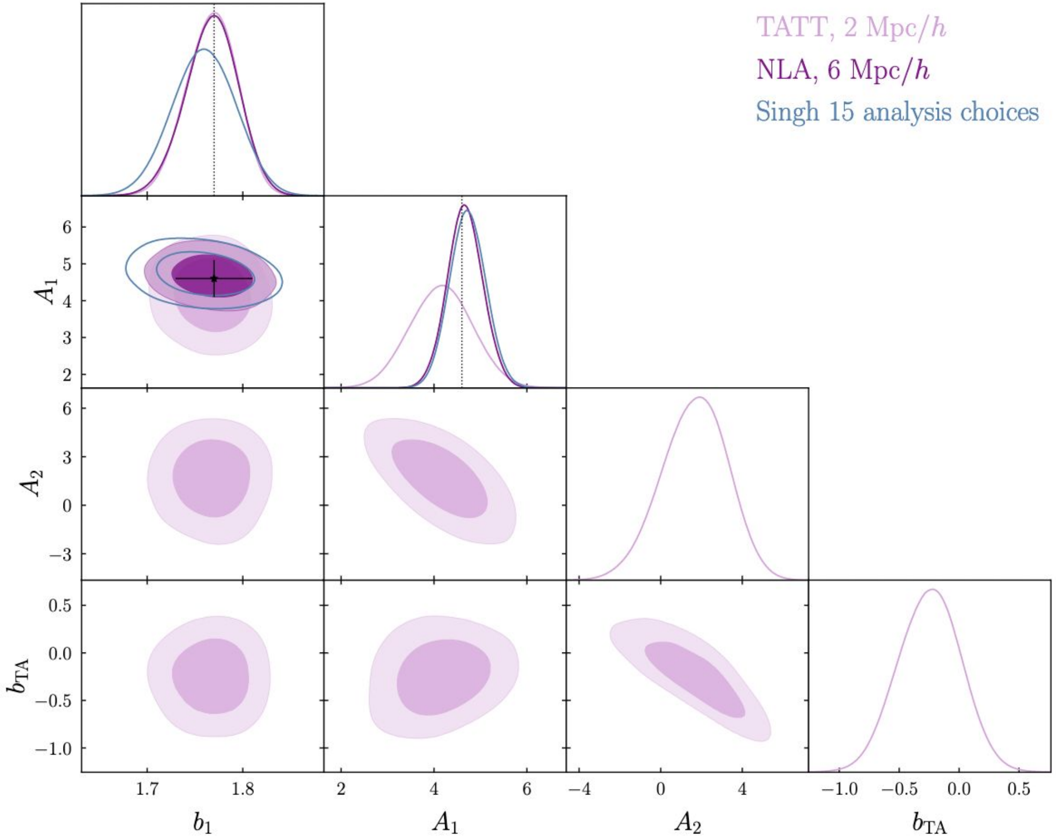
Conclusions

- Direct IA measurements on real data are one of relatively few methods available to us to learn about IAs
- We've carried out a direct measurement analysis using DES and eBOSS, which significantly improves S/N of results, particularly at high(ish)-z and in fainter galaxies
- We find no detectable IA signal in eBOSS ELGs, on any scales
- We also see no evidence for redshift dependence in the red-galaxy IA signal
- What we do see is potential colour-driven differences, beyond what a simple red/blue split can capture
- Also see some deviation from NLA on intermediate scales, which can be modelled fairly well with extra TATT parameters

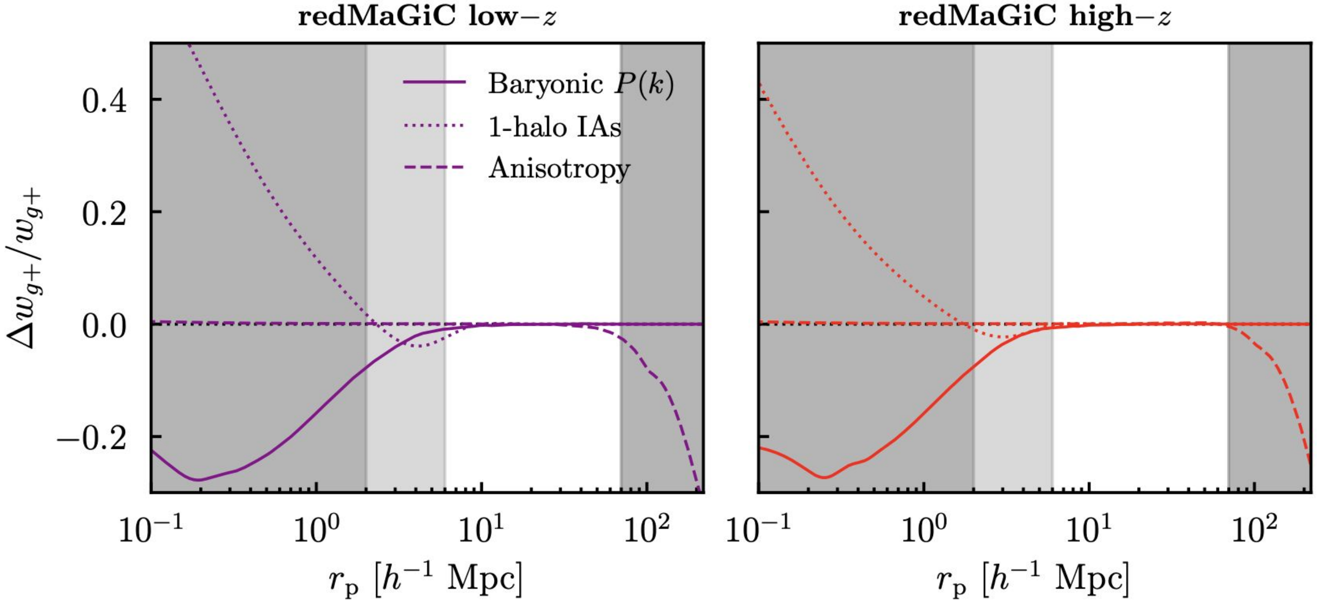

Thank you!

Validation - reanalysis of LOWZ

- BOSS LOWZ is our main benchmark for validating our measurement/analysis pipelines
- We recover the published (*Singh et al* 2015) result quite nicely
- When we fit for TATT parameters, A2 and b_{TA} are consistent with zero to ~1 sigma



Defining scale cuts - robustness to baryon feedback



Choice of bias model

- Simple linear bias is seen to fail, even on large-ish scales for several of our samples
- We thus use a 2 parameter nonlinear bias model, following *Pandey et al 2020*

4.1, one can expand the galaxy overdensity in terms of δ (McDonald 2006; Baldauf et al. 2010; Saito et al. 2014):

$$\delta_g = b_1\delta + \frac{1}{2}b_2\left(\delta^2 - \langle\delta^2\rangle\right) + \frac{1}{2}b_{s^2}\left(s^2 - \langle s^2\rangle\right) + b_{3\mathrm{nl}}\psi + \cdots \quad (12)$$