Understanding Intrinsic Galaxy Alignments for Weak Lensing Cosmology

Danielle Leonard
Newcastle University

LineA Webinar
June 23, 2022

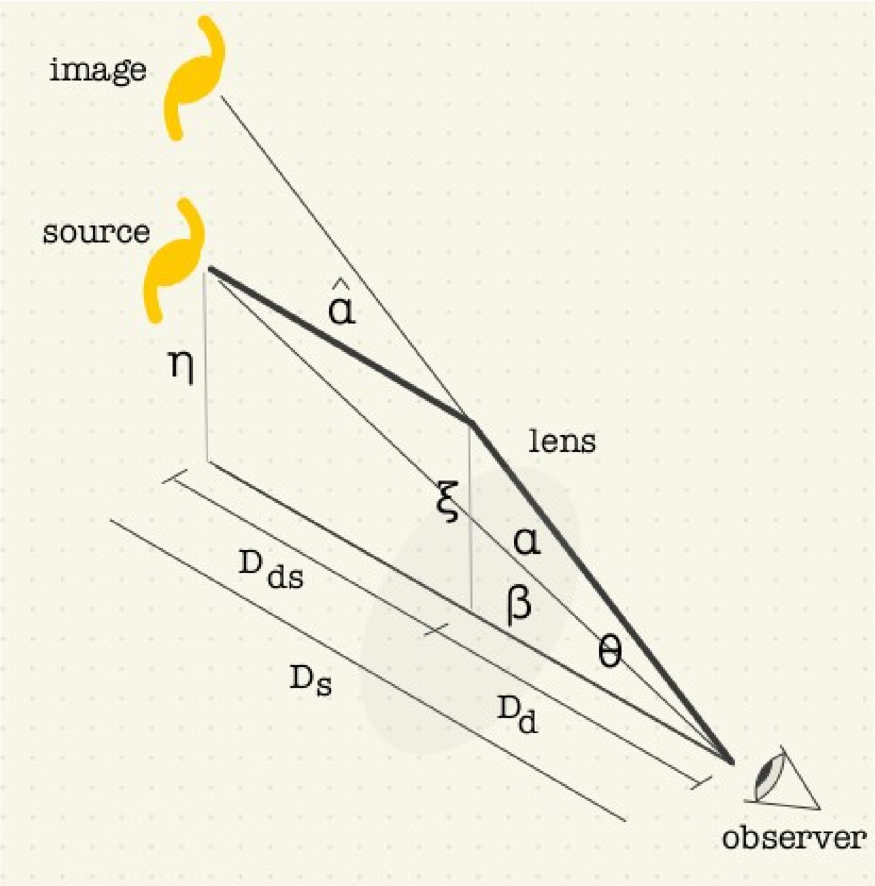
Outline

- **Introduction and motivation**
    - Weak gravitational lensing refresher
    - Intro to intrinsic alignments
    - Why this matters for cosmology

- Understanding and mitigating intrinsic alignment
    - ‘Direct’ measurements with photometric source data
    - Mock catalogues with realistic alignment
    - Modelling interplay with other systematic effects

- Summary, conclusions and outlook

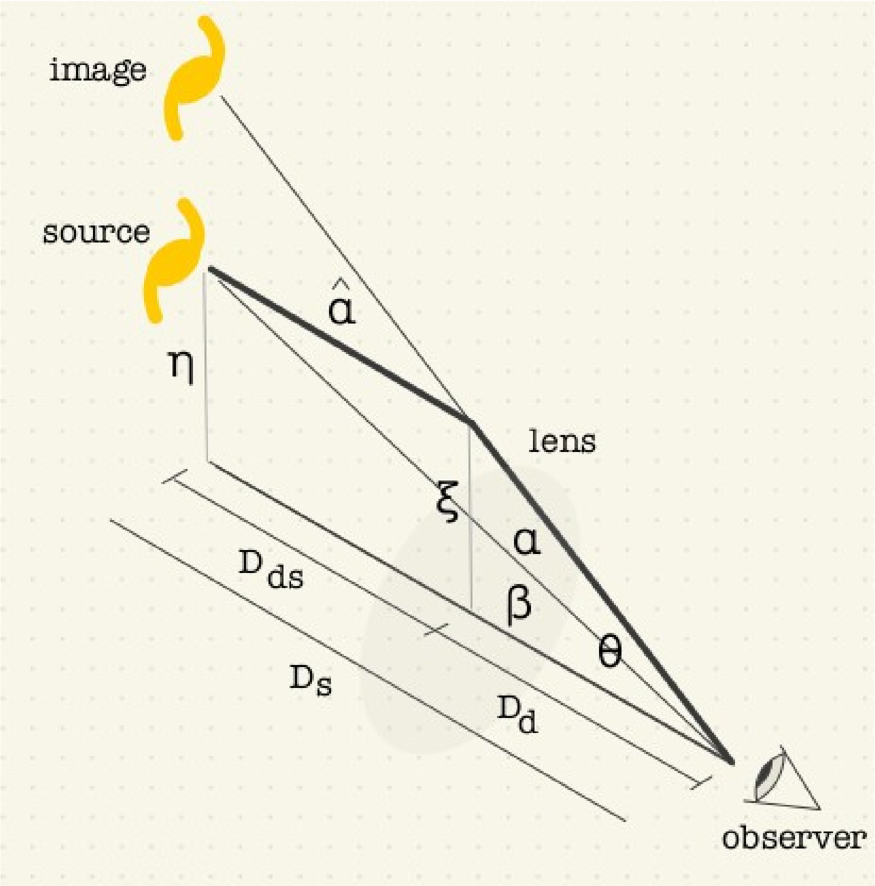
Gravitational lensing refresher

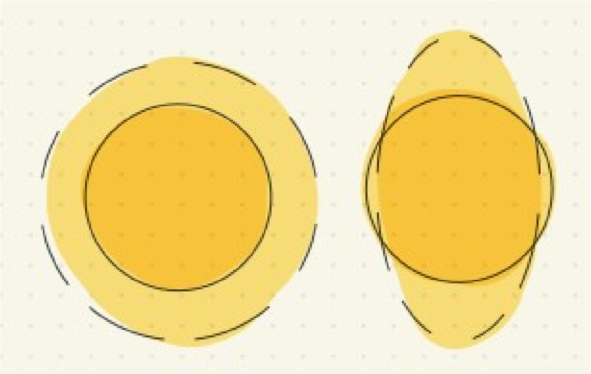


Niko Sarcevic (PhD student, Newcastle Uni)

NASA, ESA

Gravitational lensing refresher





Weak gravitational lensing must be measured statistically.

Images: Niko Sarcevic (PhD student, Newcastle Uni)

Weak lensing and galaxy clustering

Two-point correlation functions:

Cosmic shear, $\varepsilon_{\pm}(\theta)$**:** shapes of two background galaxies. Shape x Shape.

Galaxy-galaxy lensing, $\gamma_t(\theta)$**:** shape of background galaxy and position of foreground galaxy. Shape x Position.

Galaxy clustering, $w(\theta)$**:** positions of two foreground galaxies. Position x Position.

Niko Sarcevic (PhD student, Newcastle Uni)

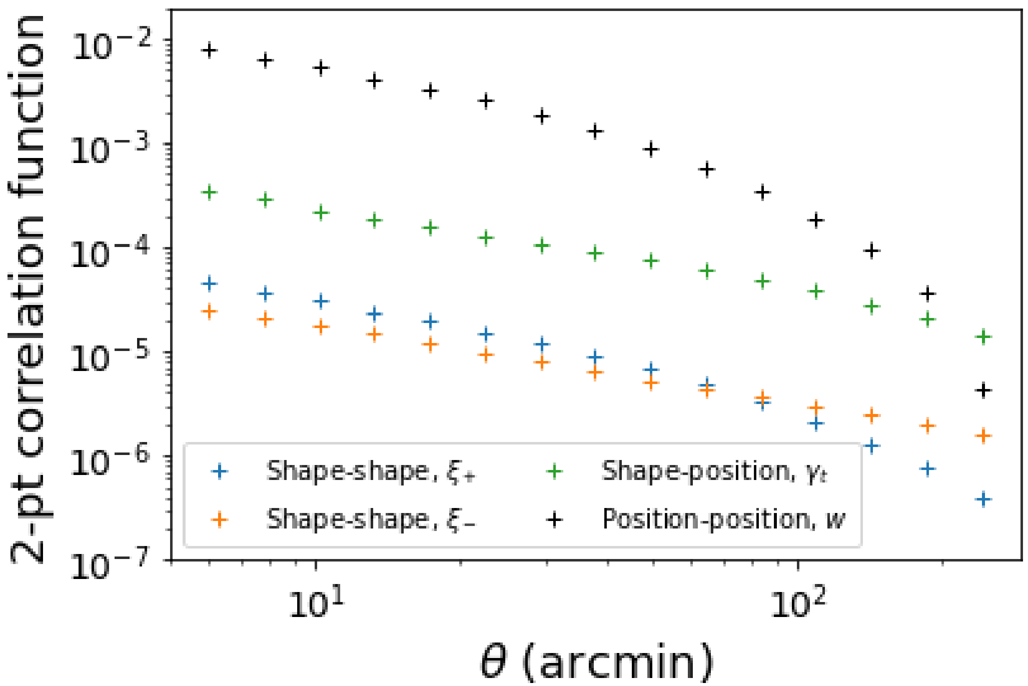
Weak lensing and galaxy clustering

Two-point correlation functions:

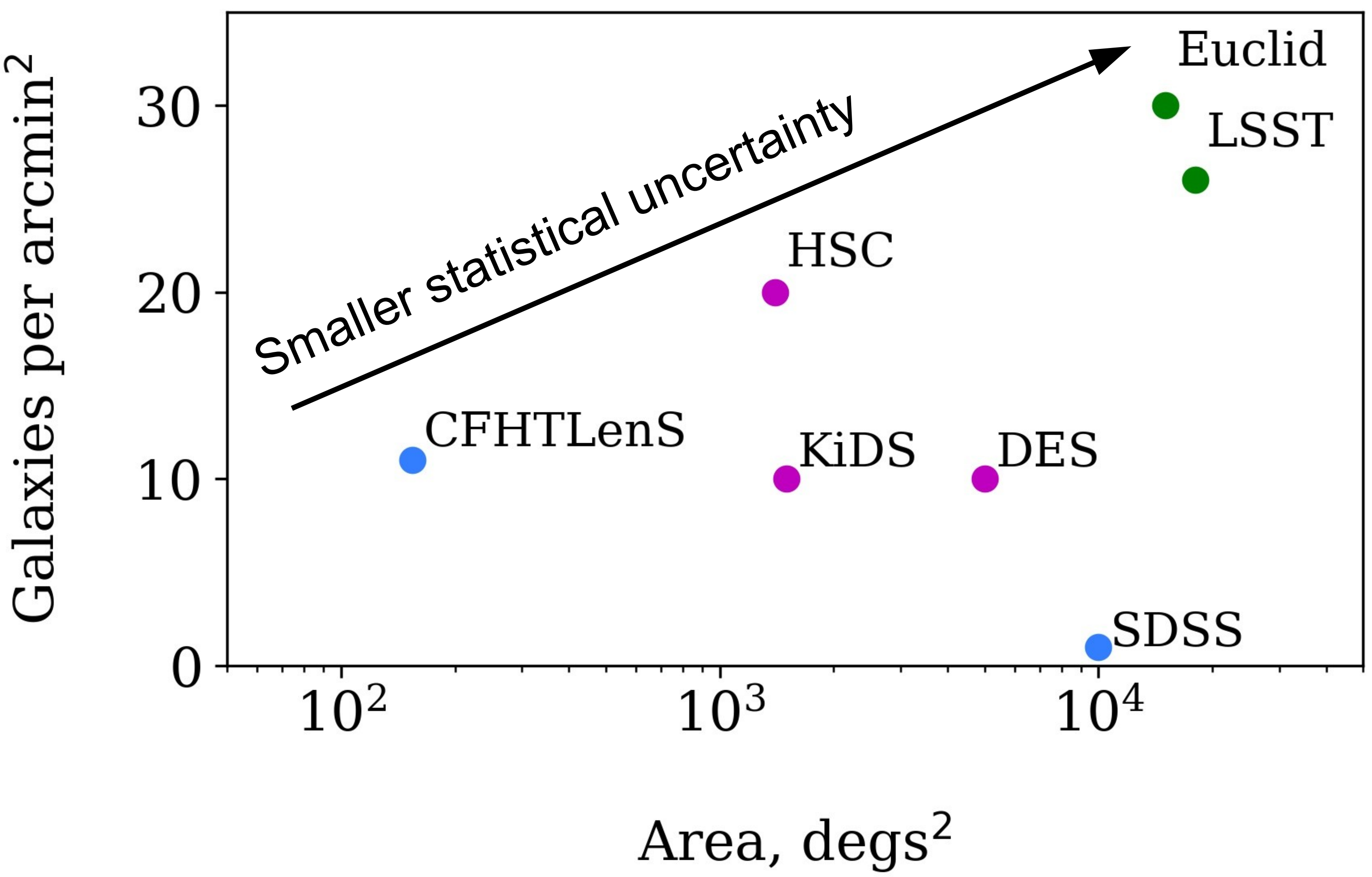
Cosmic shear, $\varepsilon_{\pm}(\theta)$**:** shapes of two background galaxies. Shape x Shape.

Galaxy-galaxy lensing, $\gamma_t(\theta)$**:** shape of background galaxy and position of foreground galaxy. Shape x Position.

Galaxy clustering, $w(\theta)$**:** positions of two foreground galaxies. Position x Position.



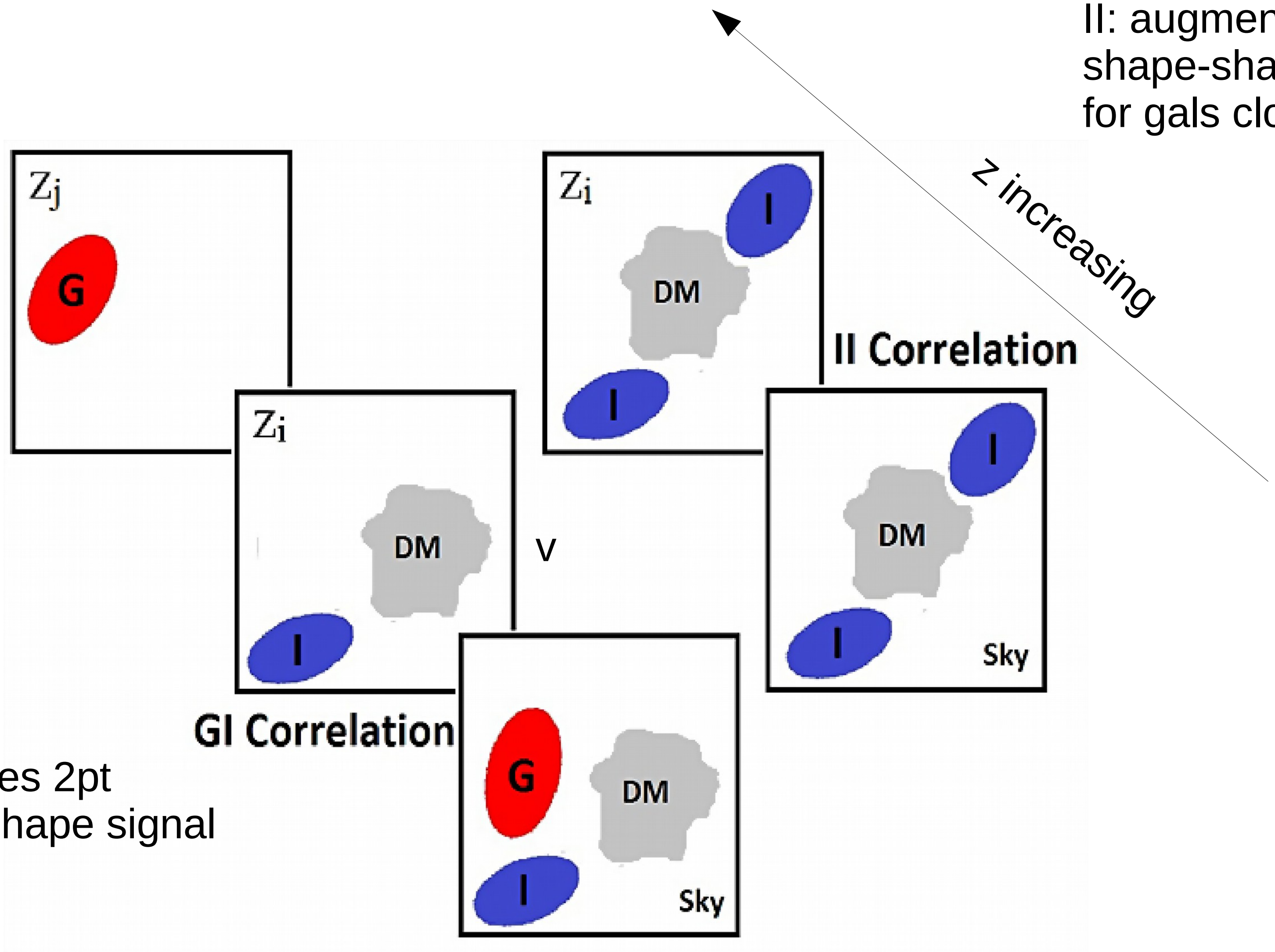
Current and upcoming lensing landscape



Complete Ongoing Upcoming

Intrinsic alignment and cosmic shear

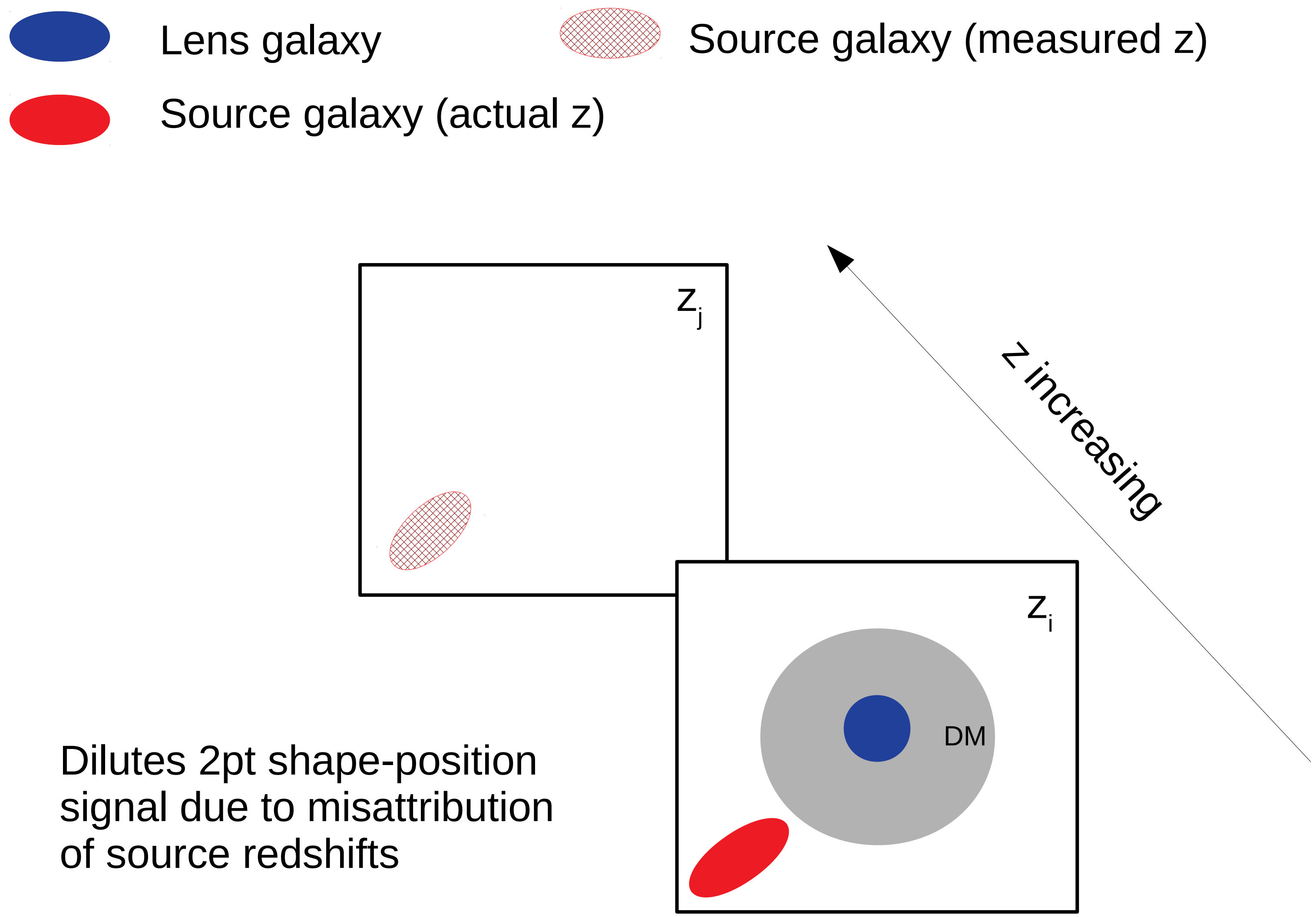
II: augments 2pt
shape-shape signal
for gals close in z



GI: dilutes 2pt
shape-shape signal

Image: Troxel & Ishak 2012

Intrinsic alignment and galaxy-galaxy lensing



Dilutes 2pt shape-position signal due to misattribution of source redshifts

Image: Inspired by Troxel & Ishak 2012

Modelling intrinsic alignments

- **Linear alignment model (LA):** alignments are ‘baked in’ at early times, so determined by the linear power spectrum at that time. (Hirata & Seljak 2004)
- **Nonlinear alignment model (NLA):** LA but with adhoc replacement of linear power spectrum with non-linear. (Bridle & King 2007)
- **Tidal alignment + tidal torquing (TATT):** standard perturbation theory approach (Blazek et al. 2015)
- **Halo model for intrinsic alignment:** unifies large scale model (e.g. NLA) with a phenomenological 1-halo term (Fortuna et al. 2020)
- **Effective field theory for intrinsic alignment:** alternative perturbation-theory approach; improves upon technical issues in TATT (Vlah et al. 2020)

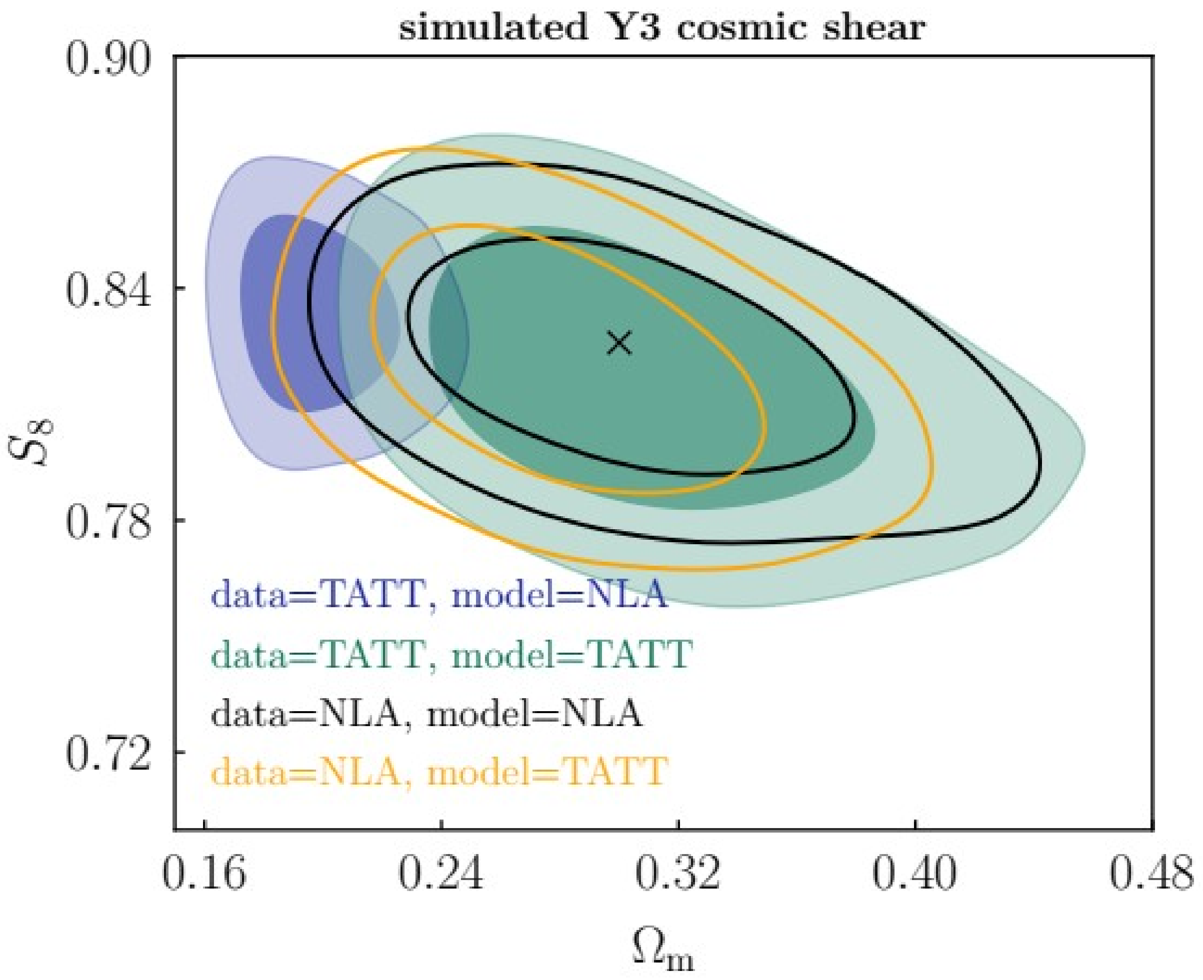
Not usually used for current data

Bread-and-butter model for past ~decade

Some analyses currently consider

Cutting edge; more development ongoing

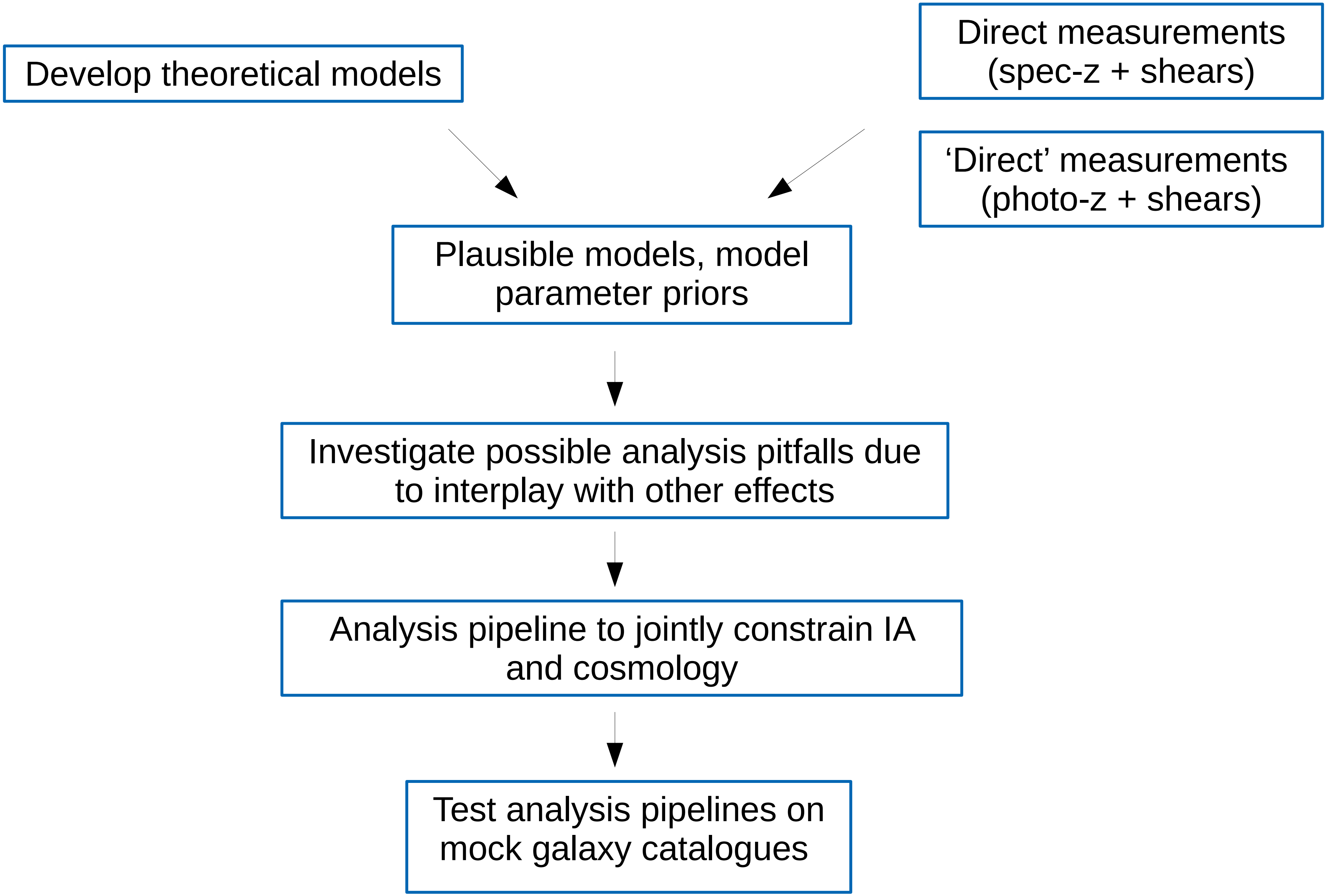
Impact on cosmological analysis



Dark Energy Survey Year 3 (pre-unblinding checks)

(*Secco & Samuroff et al. 2022*)

How to mitigate the impact on cosmology?



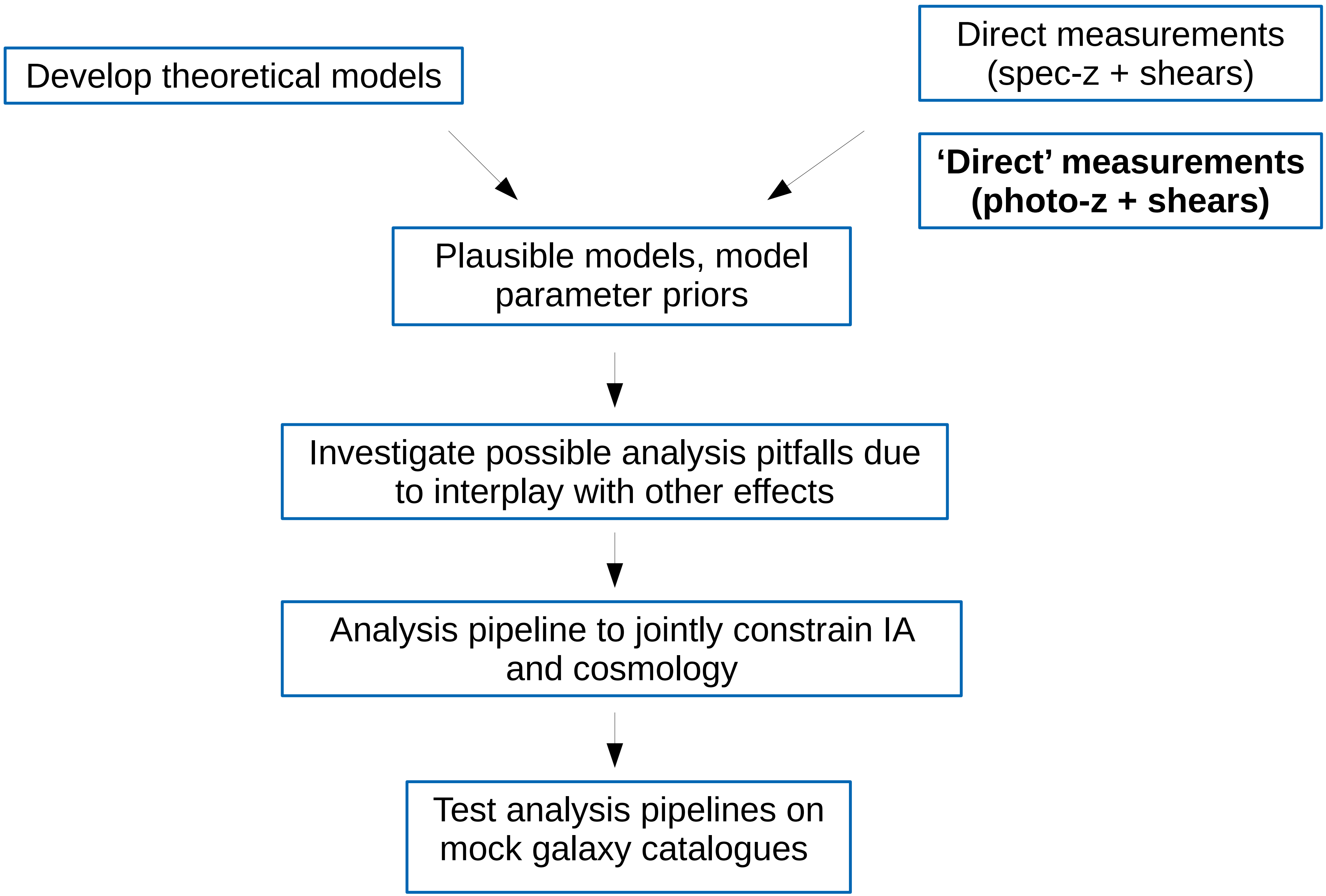
Outline

- Introduction and motivation
    - Weak gravitational lensing refresher
    - Intro to intrinsic alignments
    - Why care for cosmology?

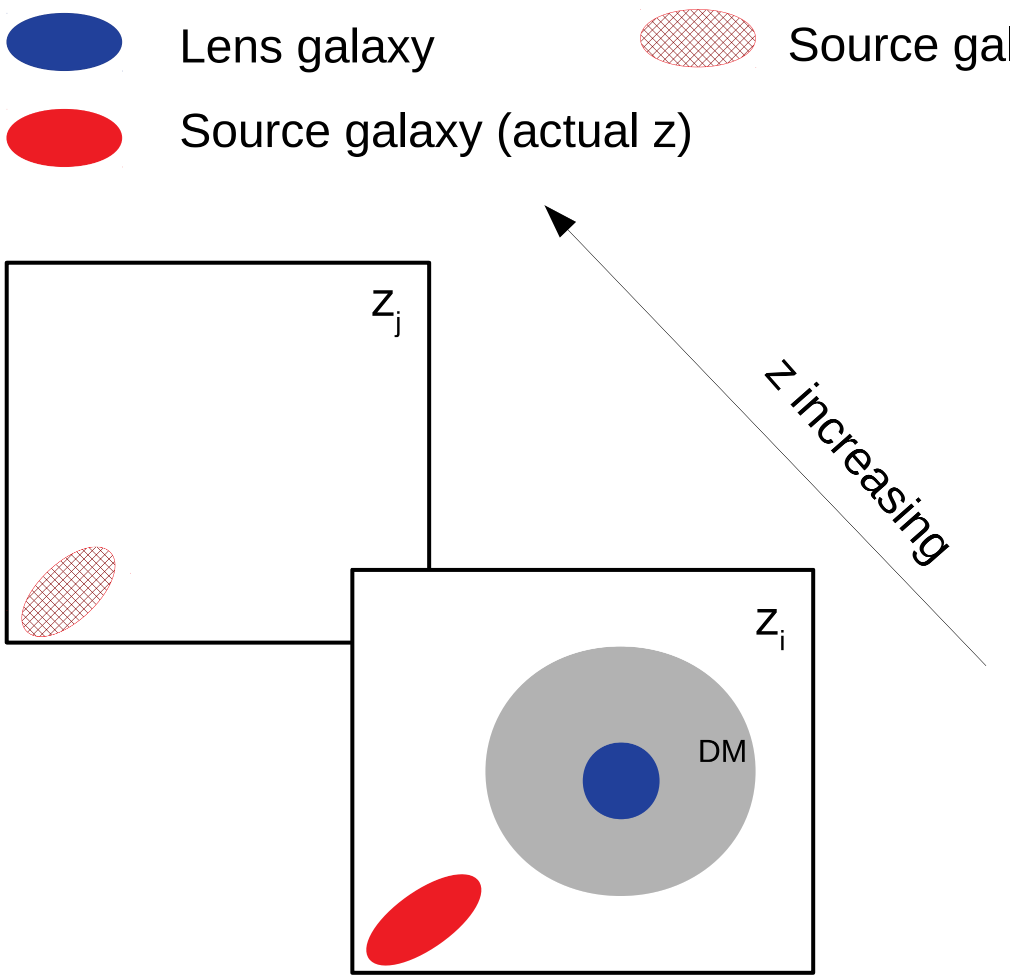
- **Understanding and mitigating intrinsic alignment**
    - ‘Direct’ measurements with photometric source data
    - Mock catalogues with realistic alignment
    - Modeling interplay with other systematic effects

- Summary, conclusions and outlook

How to mitigate the impact on cosmology?



‘Direct’ measurements with photo-z sources



If sources have spec-z: we can directly measure the IA contribution to shape-position 2pt function.

With photo-z only, we can’t.

Instead: **cancel out the lensing**.

Measure shape-position 2pt in two scenarios which should have:

- different IA
- but same lensing

(or, lensing which differs in a way we can model).

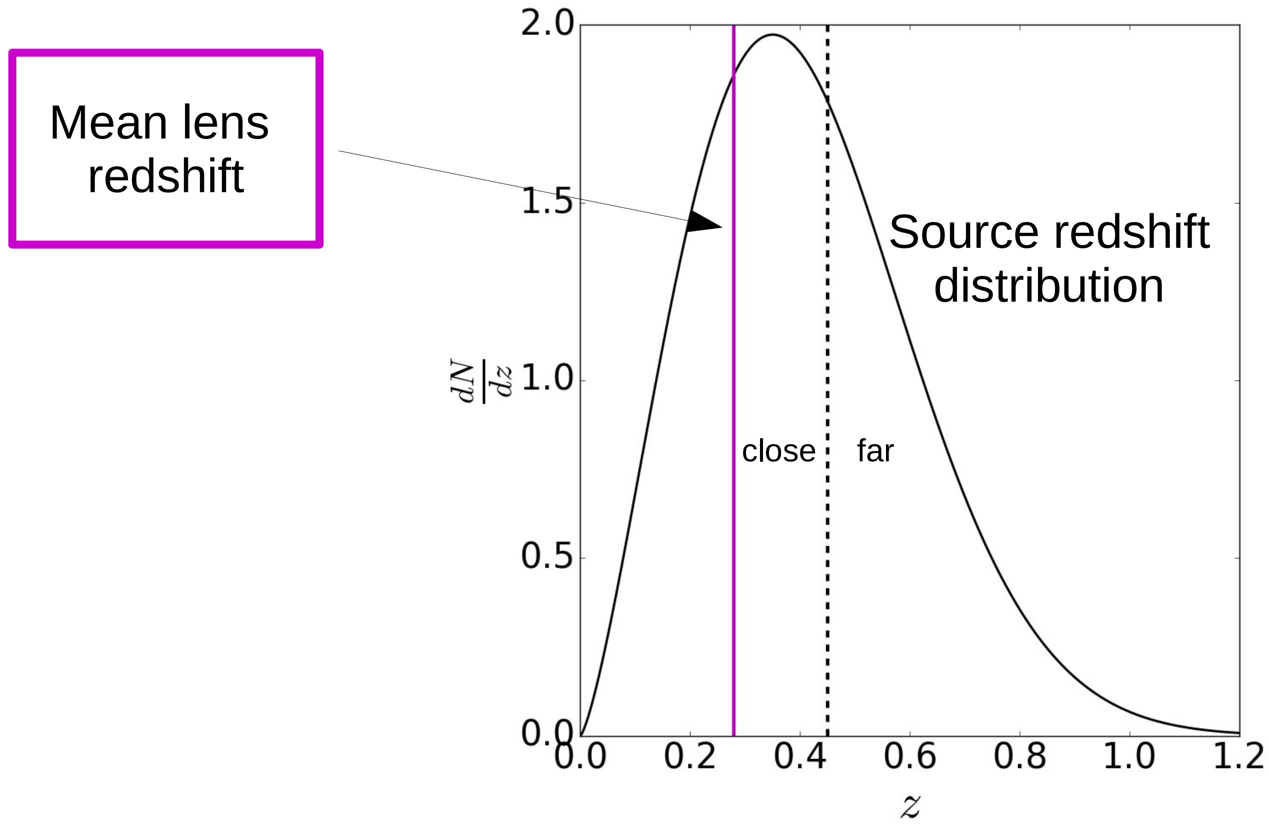
Image: Inspired by Troxel & Ishak 2012

Cancel lensing with redshift bins

Schematically:

$$\text{IA signal} = \frac{(\text{shear x positions})_{\text{close}} - (\text{shear x positions})_{\text{far}}}{\text{Galaxy pairs subject to correlated intrinsic alignment}}$$

(Blazek+2012)

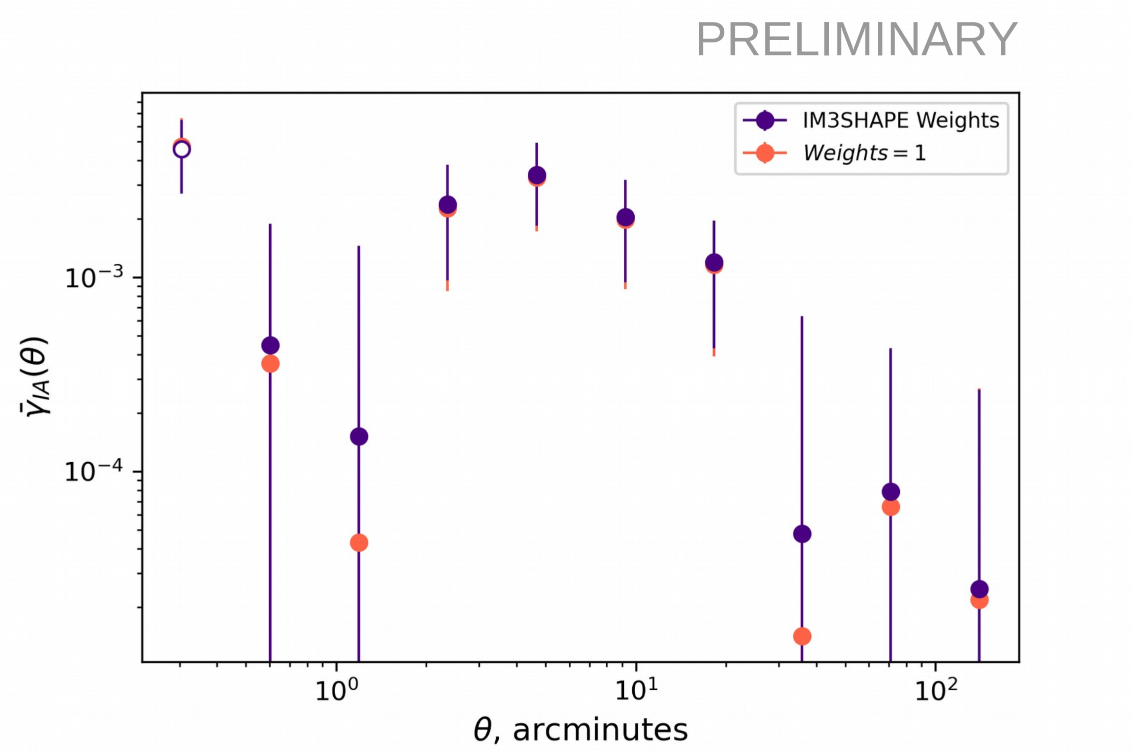


Cancel lensing with redshift bins

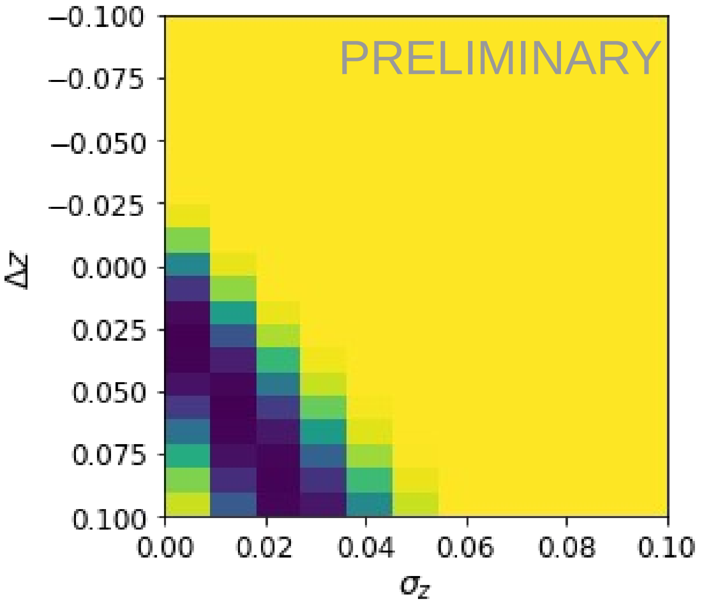
Project lead:
Sara Safari (ETH Zurich)

Application to DES Y1

Safari, Blazek, Leonard++ in prep



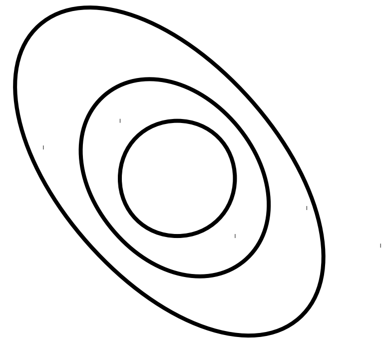
Hollow marker: negative; Filled markers: positive.
Expected IA is NEGATIVE in this convention.



Positive points may be the result of residual photo-z errors (still working to confirm this).

Cancel lensing with multiple shear estimators

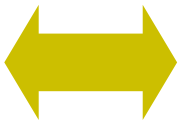
Central isophotes of galaxy images tend to be more spherical, while those further from the core are more elliptical.



Shear estimation methods which make use of further-out regions of the galaxy image will result in:

- the same correlations due to lensing
- increased amplitude of intrinsic alignment correlations

Measured Intrinsic Alignment Amplitude



Radial sensitivity of shear-estimation method

Tenneti+2014, 2015; Velliscig+2015 (Sims)
Schneider+2013; Singh+2016, Georgiou+2019 (Observations)

Cancel lensing with multiple shear estimators

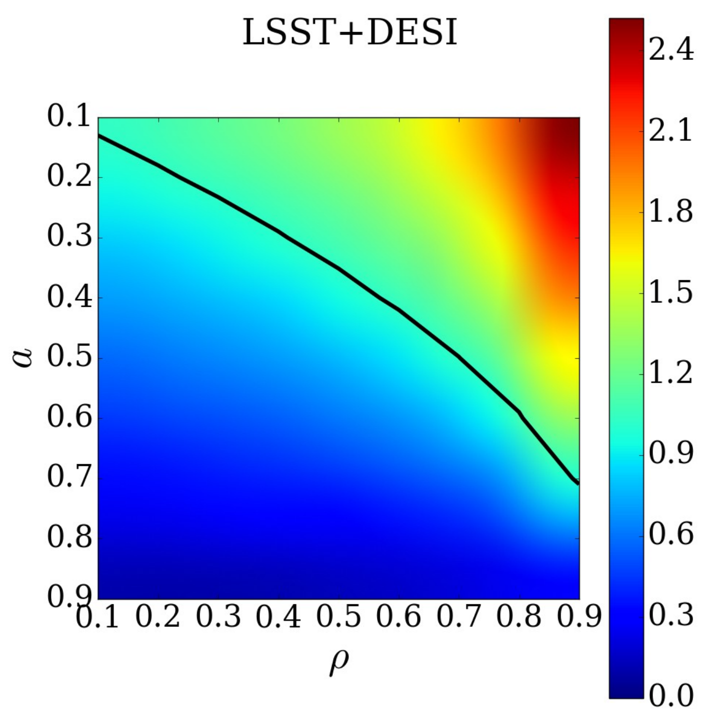
Change the radial sensitivity of shear-estimation
→ Multiply the measured IA amplitude by a constant

Singh+2016, Georgiou+2019

Schematically:

(constant a) IA = Measured shear 1 – Measured shear 2

Leonard + Mandelbaum 2018



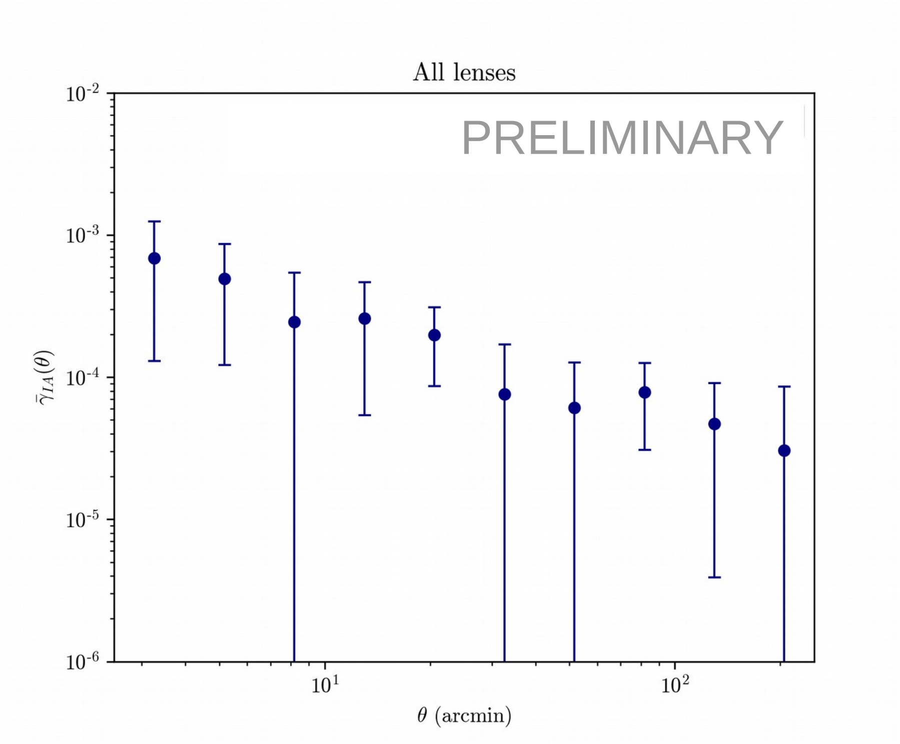
Forecast ratio of S/N's: this method vs redshift nulling method

Another key advantage: Less sensitive to systematic errors related to photo-z

ρ = correlation in shape noise of two shear-measurement methods

Cancel lensing with multiple shear estimators

Case study: naive application to DES Y1



'Signal' shown here likely spurious.

Could be due to:

- slightly different effective source galaxy redshift distributions (due to weights)

- and / or residual multiplicative biases

Currently exploring what level of:

- redshift-dependent weight discrepancy
- residual multiplicative bias discrepancy

will be tolerable for measurements with LSST.

Longer-term goal → bespoke shear estimator(s) to optimse this.

Project lead: Charlie MacMahon
(incoming PhD student, Newcastle University

How to mitigate the impact on cosmology?

Develop theoretical models

Direct measurements (spec-z + shears)

'Direct' measurements (photo-z + shears)

Plausible models, model parameter priors

Investigate possible analysis pitfalls due to interplay with other effects

Analysis pipeline to jointly constrain IA and cosmology

Test analysis pipelines on mock galaxy catalogues

Mock catalogues with realistic alignments

What is a mock catalogue?

- To validate our analysis pipelines, we would like to be able to run them on data where we know the underlying truth.
- A mock catalogue provides this at a catalogue level.
- Can include the impact of survey selection, systematic effects.

Ideally: could use hydrodynamic sims to encompass all relevant physics.

In reality: often start from n-body simulation and ‘inject’ galaxies.

We need: mock catalogues with **realistic intrinsic alignment correlations** to test our Stage IV analysis pipelines against robustness to IA.

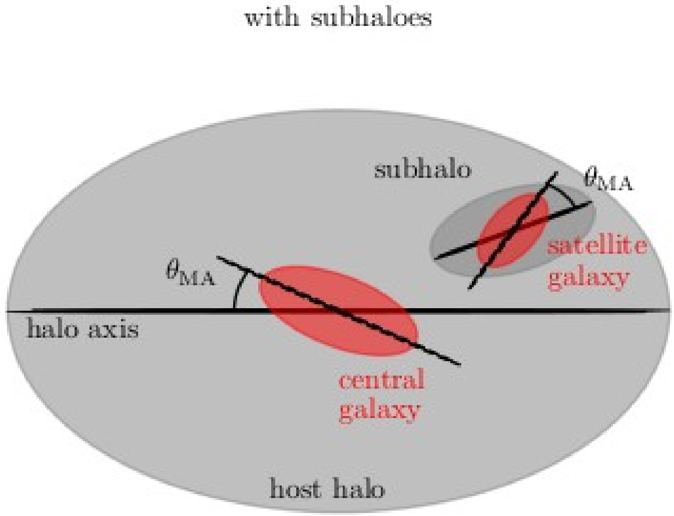
Halo-Occupation Distributions with IA

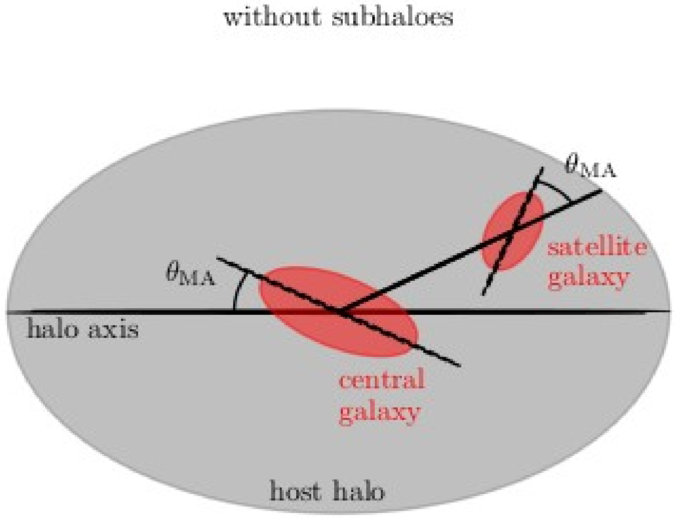
Traditional Halo Occupation Distribution (HOD) models:

- Describe the occupation of halos with central and satellite galaxies as a function of (usually just) halo mass.

Goal of this project:

- Expand this type of model to describe the orientation of satellite galaxies.
- Statistically model the misalignment angle, θ_{MA}.





Project lead:
Nick van Alfen, PhD student, Northeastern U.

van Alfen, Campbell, Blazek, Lanusse, Leonard ++ in prep

Halo-Occupation Distributions with IA

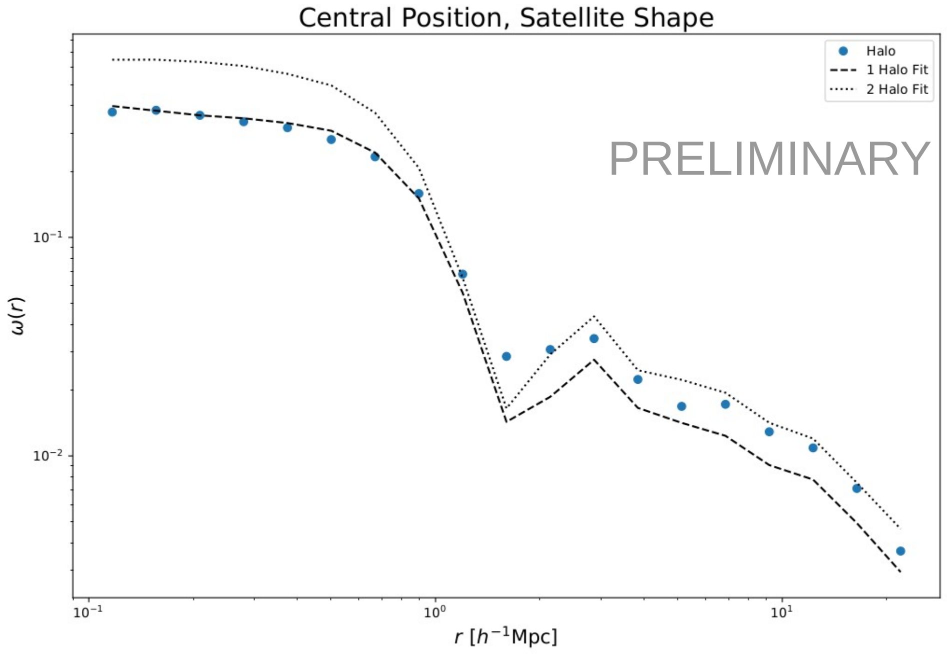
Preliminary results:

- A model with radially-dependent alignment strength and which uses subhalo information:

- models the 1-halo term adequately
- but cannot capture the 2-halo central-satellite term.

→ Satellite galaxy alignment **depends on position of external halos**.

→ Need an additional corrective factor.



Project lead:
Nick van Alfen, PhD student, Northeastern U.

van Alfen, Campbell, Blazek, Lanusse, Leonard ++ in prep

Graph neural network models for IA

Project lead: Elizabeth Ratcliffe, PhD student, Newcastle U.

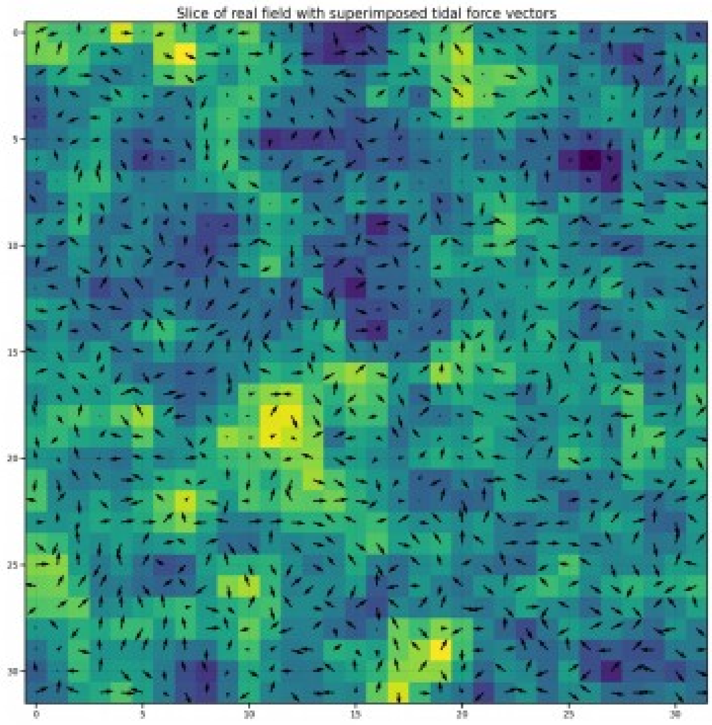
Given: dark-matter-only information paired with hydrodynamic sim

Create: mock galaxies with realistic alignments as a function of dark-matter-only info

Use: Graph neural networks

- Graph nodes: galaxy locations, mass information
- Graph vertices: imbue with connection information e.g. separation

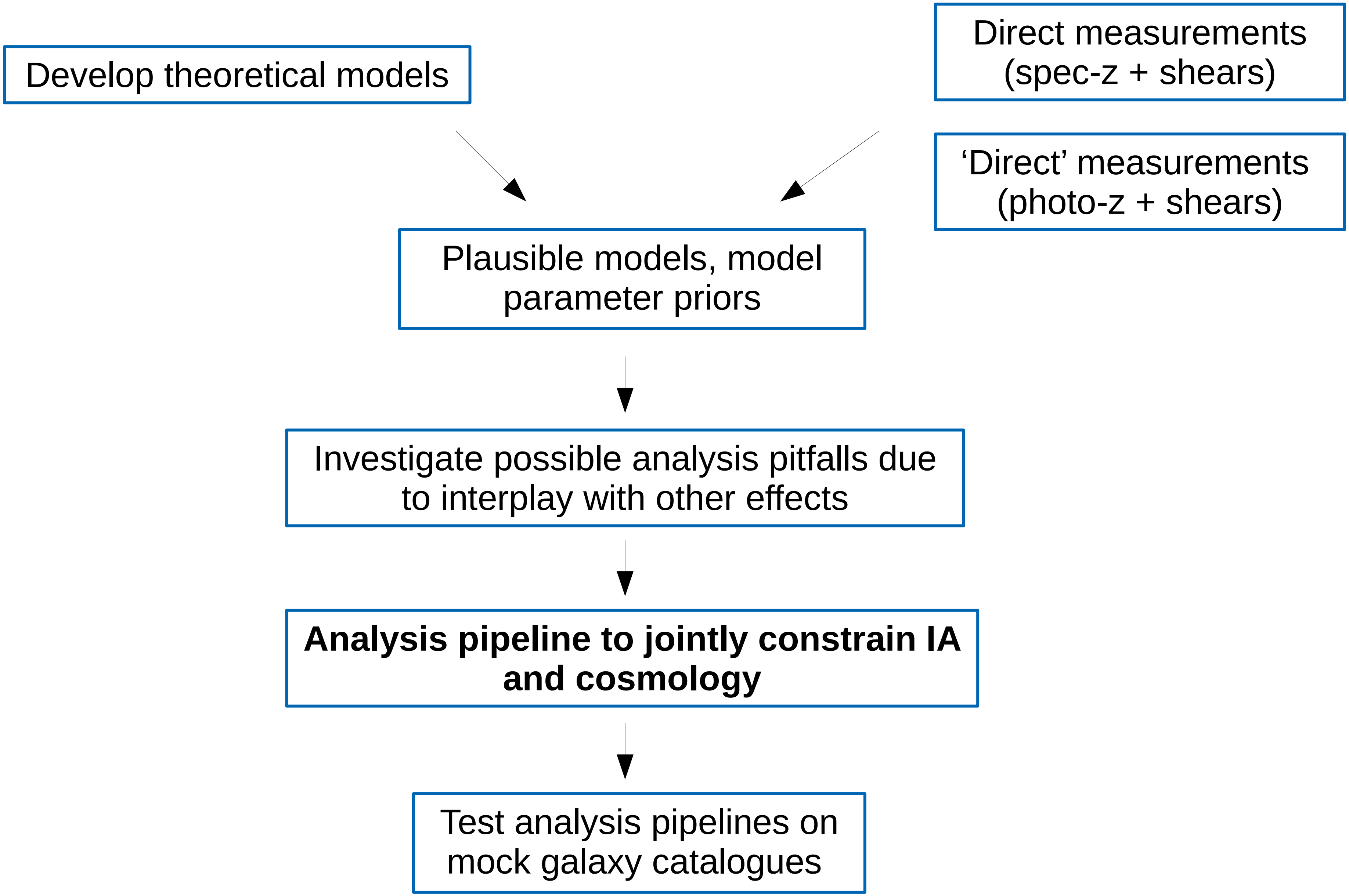
Proposal and first proof of concept: Yesukhei Jagvaral (PhD student, CMU), Lanusse ++ 2022



This project’s goal: optimise architecture for this purpose; deploy to LSST DESC sims.

(Currently working with tidal field as DM-only proxy for galaxy orientation.)

How to mitigate the impact on cosmology?



Robust and efficient analysis pipelines for IA

Understanding and taking advantage of the relationship between IA and related systematics can ensure our analysis is:

- as constraining as possible and
- unbiased

Consider links in particular with:

- photometric redshift uncertainties
- galaxy bias

Joint modelling with the luminosity function

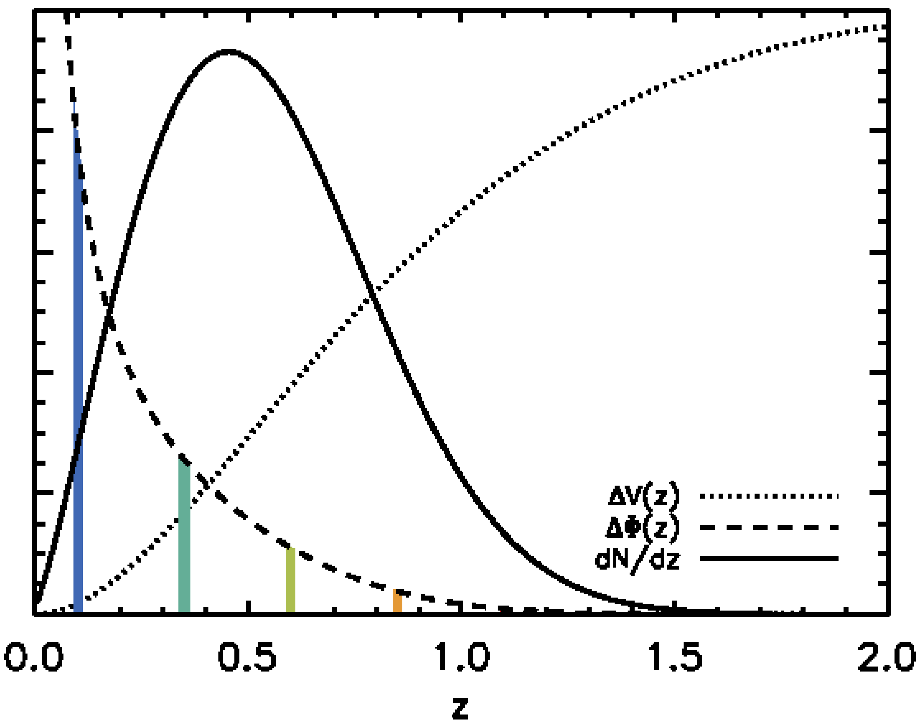
Three key ingredients for the modelling of '3x2pt' observables are:

- Intrinsic alignment
- Galaxy bias
- Redshift distributions

Typically: we model these independently.

But: all three depend on the luminosity of the galaxies in our sample.

Idea (van Daalen + White 2017): jointly model galaxy bias and redshift distribution in terms of luminosity function



Van Daalen + White 2017:
Modelling dN/dz via luminosity function Φ

Joint modelling with the luminosity function

Project lead: Niko Sarcevic
PhD student, Newcastle U.
& with Markus Rau
Postdoc, ANL/Chicago

This project: extend to include also intrinsic alignment.

Take e.g. a simple model where:

$$A_{IA} \propto \frac{L}{L_p} \qquad b_L \propto 1 + \frac{L}{L_p} \qquad \frac{dN}{dz} \approx \int \phi(z, L) V(z)$$

ϕ(z,L) is the **luminosity function**. Usually we fix parameters of ϕ(z,L) from external data.

Here: include parameters of ϕ(z,L) in cosmological analysis with priors from external data.

Status: working modelling code; currently preparing forecasts for LSST 3x2pt analysis.

Outline

- Introduction and motivation
    - Weak gravitational lensing refresher
    - Intro to intrinsic alignments
    - Why care for cosmology?

- Understanding and mitigating intrinsic alignment
    - ‘Direct’ measurements with photometric source data
    - Mock catalogues with realistic alignment
    - Modeling interplay with other systematic effects

- **Summary, conclusions and outlook**

Summary, conclusions and outlook

Stage 4 surveys like LSST and Euclid will dramatically reduce statistical errors on weak lensing measurements

→ A robust treatment of intrinsic alignments is needed.

There are many pieces to this puzzle. Today, we discussed:

- 'Direct' measurements which null the lensing signal
  - via redshift bins
  - via shear estimation methods

- Creating mock galaxy catalogs with realistic alignments
  - with a halo occupation distribution approach
  - with graph neural networks

- Understanding the interplay of IA with other systematic effects
  - via joint modelling using the luminosity function

Summary, conclusions and outlook

Some other work on intrinsic alignments in LSST DESC which didn't have time to mention:

- Implementation of the halo model for IA and the effective field theory of IA in our theory software package, the Core Cosmology Library (CCL) – Dr Christos Georgiou (postdoc, Utrecht U.)

- Self-calibration of the intrinsic alignment signal within 3x2pt analysis – Dr Eske Pedersen (postdoc, Harvard U.), Leonel Medina (PhD student, UT Dallas)

- Adding tidal field information to large-scale simulations for mock analysis - Dr Joachim Harnois-Deraps (fellow, Newcastle U.)

- Simulated analyses to determine the level of cosmological parameter biases due to incorrect modelling of IA and other systematics - Dr Supranta Sarma Boruah (postdoc, U of Arizona)

We are on the way to Stage IV cosmological analyses which are robust to IA.

Along the way, we will learn more about the physics of IA itself – also exciting!