Integrated 3PCFs of weak lensing cosmic shear

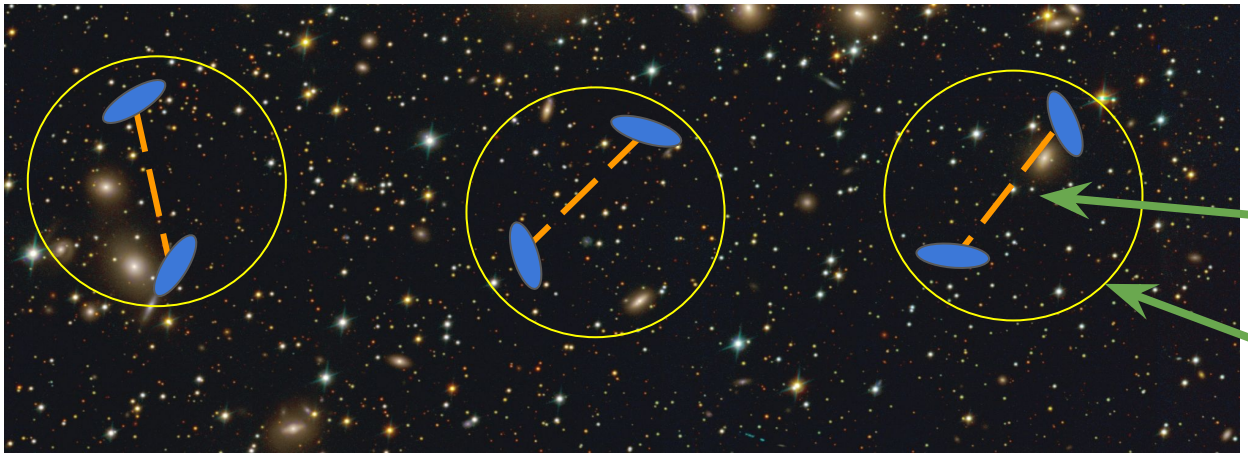
Anik Halder (IoA Cambridge)

In collaboration with: Laurence Gong, David Gebauer, Stella Seitz and DES collaboration

BIG DATA, BIG QUESTIONS: THE FUTURE OF COSMOLOGICAL SURVEYS

21st May 2025, MIAPbP, Garching

Integrated shear 3-point correlation functions



Position-dependent shear 2-pt correlation in aperture

$$\hat{\xi}_{\pm}(\theta; \boldsymbol{\theta_C})$$

1-pt aperture mass

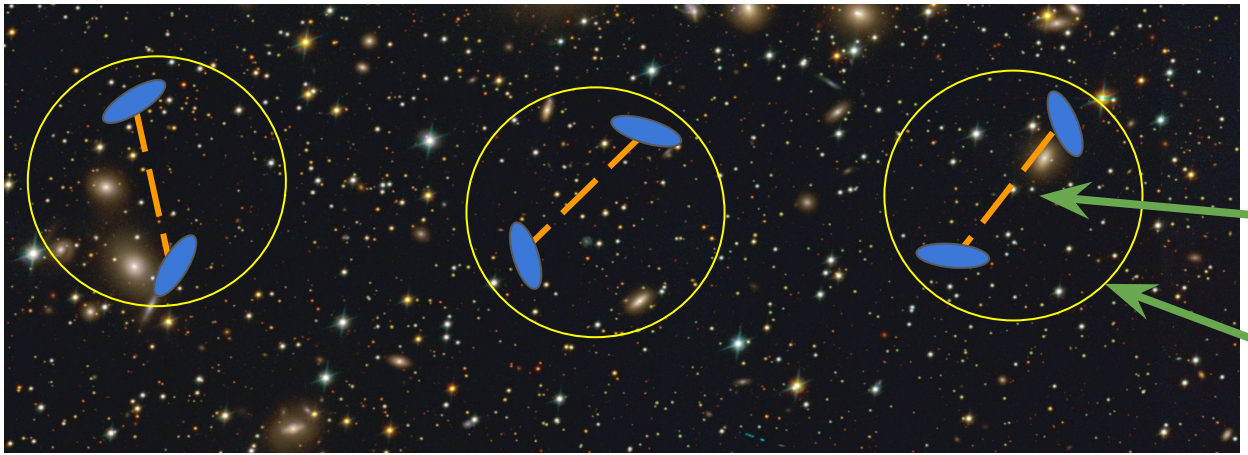
$$M_{\rm ap}(\boldsymbol{\theta_C})$$

Weighted tangential shear inside aperture

$$\zeta_{\pm}(\theta) = \left\langle M_{\rm ap}(\boldsymbol{\theta}_C)\ \hat{\xi}_{\pm}(\theta; \boldsymbol{\theta}_C) \right\rangle$$

Halder++ 2021, Halder++ 2023, Gong++ 2023

Integrated shear 3-point correlation functions



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Weighted tangential shear inside aperture

$$\zeta_{\pm}(\theta) = \left\langle M_{\rm ap}(\boldsymbol{\theta}_C)\, \hat{\xi}_{\pm}(\theta; \boldsymbol{\theta}_C) \right\rangle = \frac{1}{A(\theta)} \int \frac{{\rm d}\ell\ \ell}{2\pi} \mathcal{B}_{\pm}(\ell) J_{0/4}(\ell\theta)$$

→ Probes the line-of-sight projection of the **3D matter bispectrum** in ***'squeezed configurations'***

→ **Directly observable higher-order statistic** of the cosmic shear field! Easy to measure!

Halder++ 2021, Halder++ 2023, Gong++ 2023

Position-dependent 2PCF intuitively and modelling of integrated 3PCF

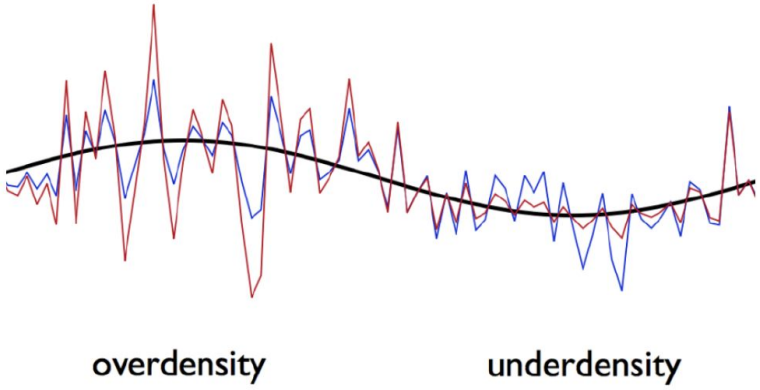
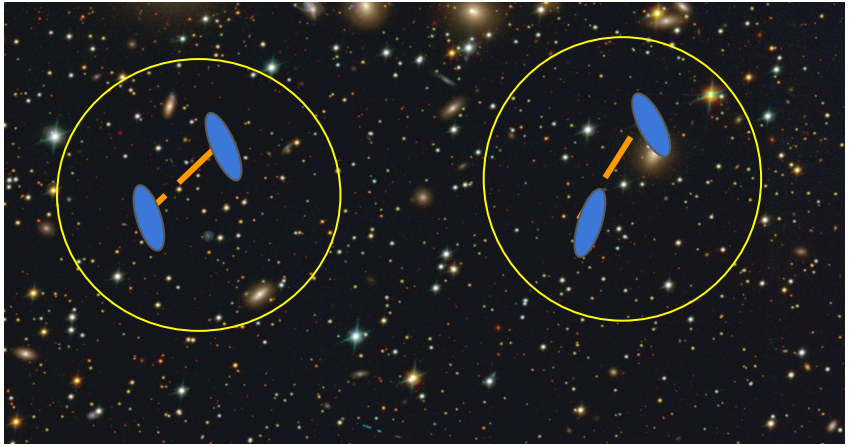
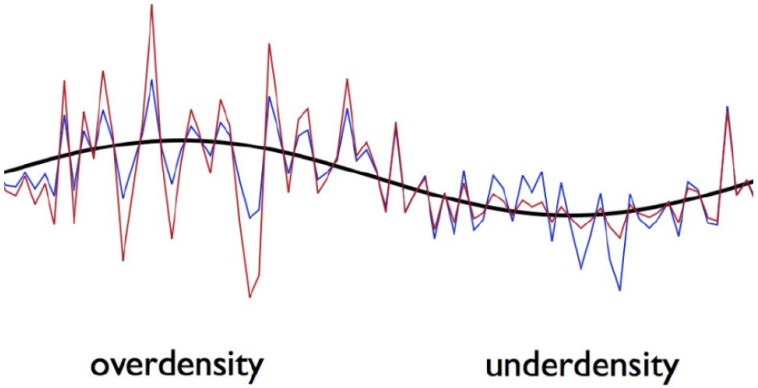


Image credit: *E. Komatsu*



Halder & Barreira 2022

Position-dependent 2PCF intuitively and modelling of integrated 3PCF



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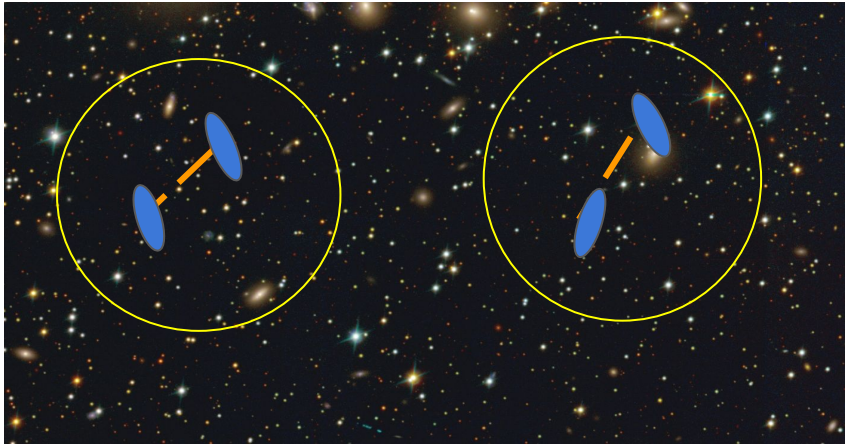
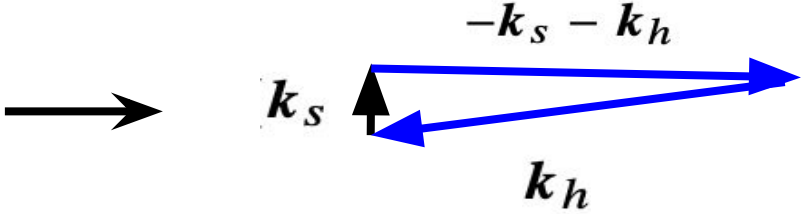




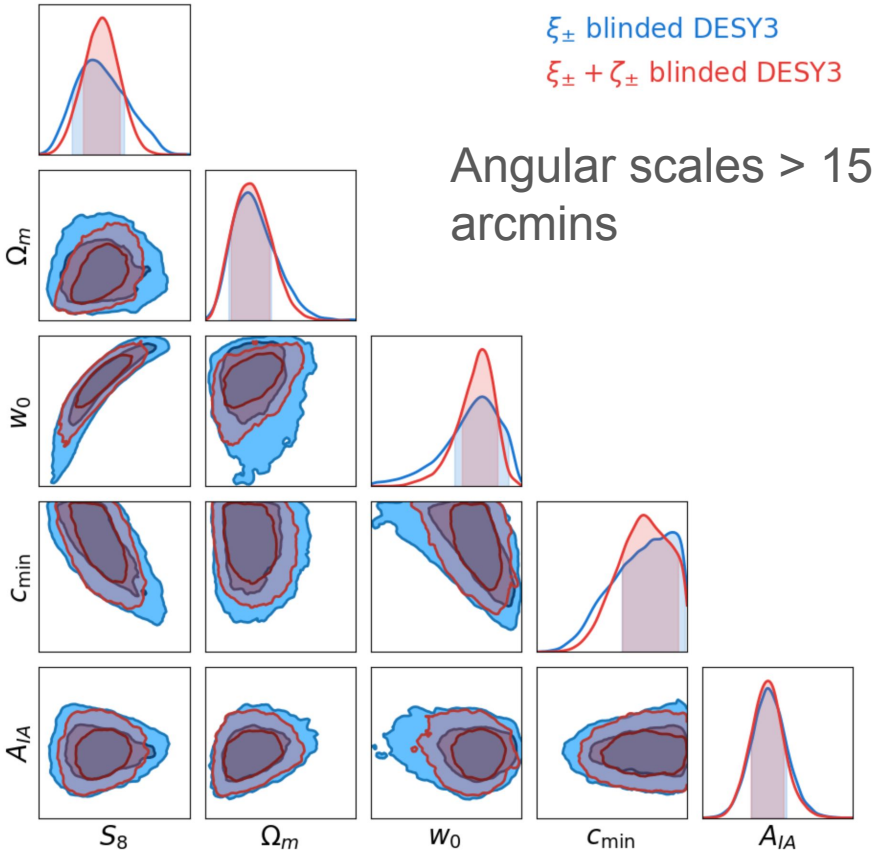
'Squeezed bispectrum' can be expressed in terms of **power spectrum** and its ***response functions***

$$B^{\rm 3D}_{\delta,\rm RF}(\boldsymbol{k}_s,\boldsymbol{k}_h,-\boldsymbol{k}_{sh},\tau) = \left[R_1(k_h,\tau) + \left(\mu^2_{\boldsymbol{k}_h,\boldsymbol{k}_s} - \frac{1}{3}\right) R_K(k_h,\tau)\right] \times P^{\rm 3D}_{\delta}(k_h,\tau) P^{\rm 3D}_{\delta,L}(k_s,\tau) + O\left[\frac{k_s^2}{k_h^2}\right]$$

→ Integrated 3PCF can be accurately modelled using the ***response approach*** to perturbation theory

Halder & Barreira 2022

Blinded DES Y3 constraints with shear 2PCF and integrated 3PCF



- Blue: shear 2PCF only
  Red: shear 2PCF & integrated shear 3PCF
- **Significant** relative improvement on S_8 and w_0 (compared to shear 2PCF alone)
- *Work in progress:*
  - Unblinding
  - Further internal consistency checks
- Also doing the same analysis with an SBI framework

***Halder, Gong, Gebauer & DES collaboration** (in prep.), **Gebauer++** (in prep.)*

How to push HOS analyses down to small scales in light of systematics?

Example of a challenge: **Intrinsic Alignment**

- HOS use NLA / TATT on small angular scales beyond their regime of validity!

$$q^i_\kappa(\chi) \longrightarrow q^i_\kappa(\chi) - A\left(z\left(\chi\right)\right) \frac{n^i_\kappa(z(\chi))}{\bar{n}^i_\kappa} \frac{dz}{d\chi} \qquad A(z) = A_{\mathrm{IA},0} \left(\frac{1+z}{1+z_0}\right)^{\alpha_{\mathrm{IA}}} \frac{C_1 \rho_{\mathrm{m},0}}{D(z)}$$

→ **Need major advances in treatment of systematics:**

- Better models for IA informed from simulations (***see Francisco's slides***)

- Cosmology with IA-clean galaxy samples (***see Jamie's talk***)

  → blue/star-forming galaxies seen to be less contaminated by IA
  (***Johnston++ 2019, McCullough++ 2024)***

  → **select** in observed colour space, or even better, **using inferred galaxy parameters**

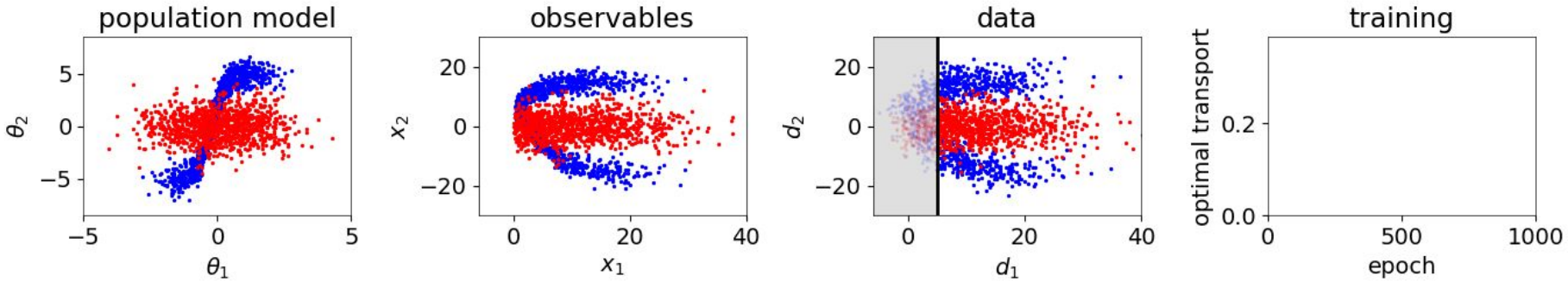
Towards galaxy-population split statistics:

Selecting galaxies based on inferred physical parameters for WL cosmology

In collaboration with: Justin Alsing, Sinan Deger, Gurjeet Jagwani, Boris Leistedt,
Joel Leja, Daniel Mortlock, Hiranya Peiris, Stephen Thorp, Madalina Tudorache

pop-cosmos: a generative model for galaxy surveys

- A generative galaxy population model calibrated with COSMOS2020 photometric data.



Physical parameters (stellar mass, SFR, redshift etc.)

Stellar population synthesis **(*see Luca's slides*)**

Noiseless fluxes

Data model

Noisy fluxes (incl. selection)

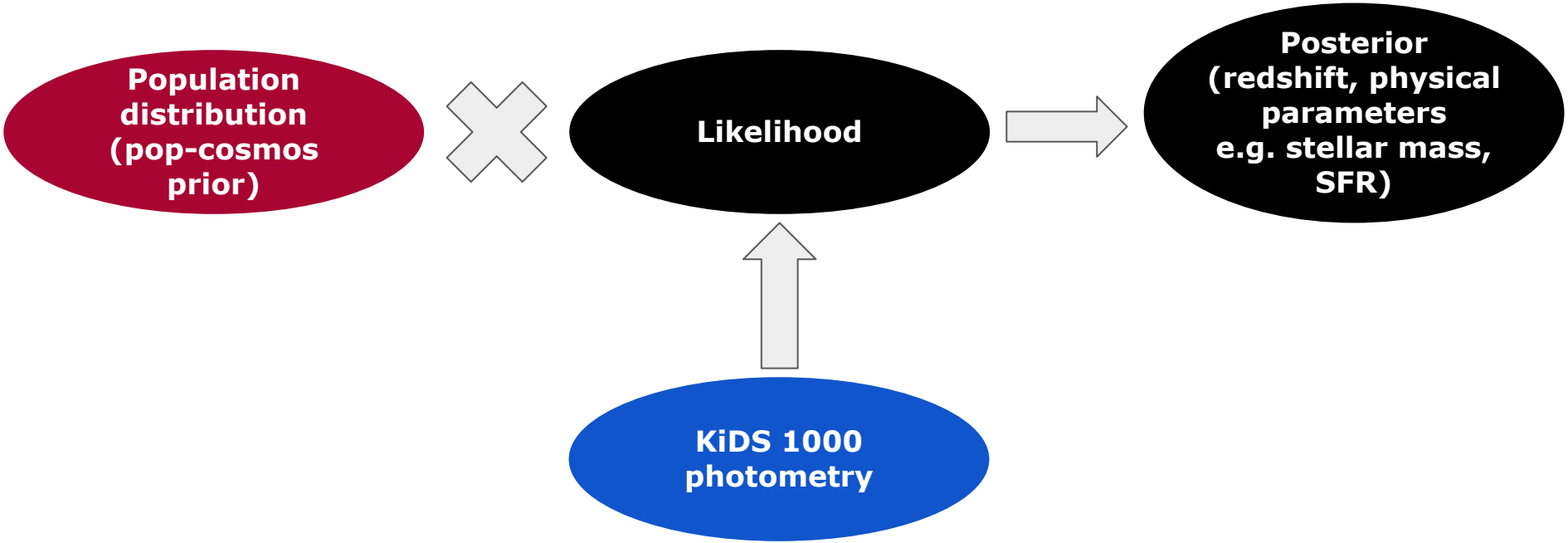
Minimize distance between red and blue clouds in data space to learn the underlying population distribution

Alsing++ 2024, Thorp++ 2024, Thorp++ (*in prep.****)***

Credit: Justin Alsing, Stephen Thorp

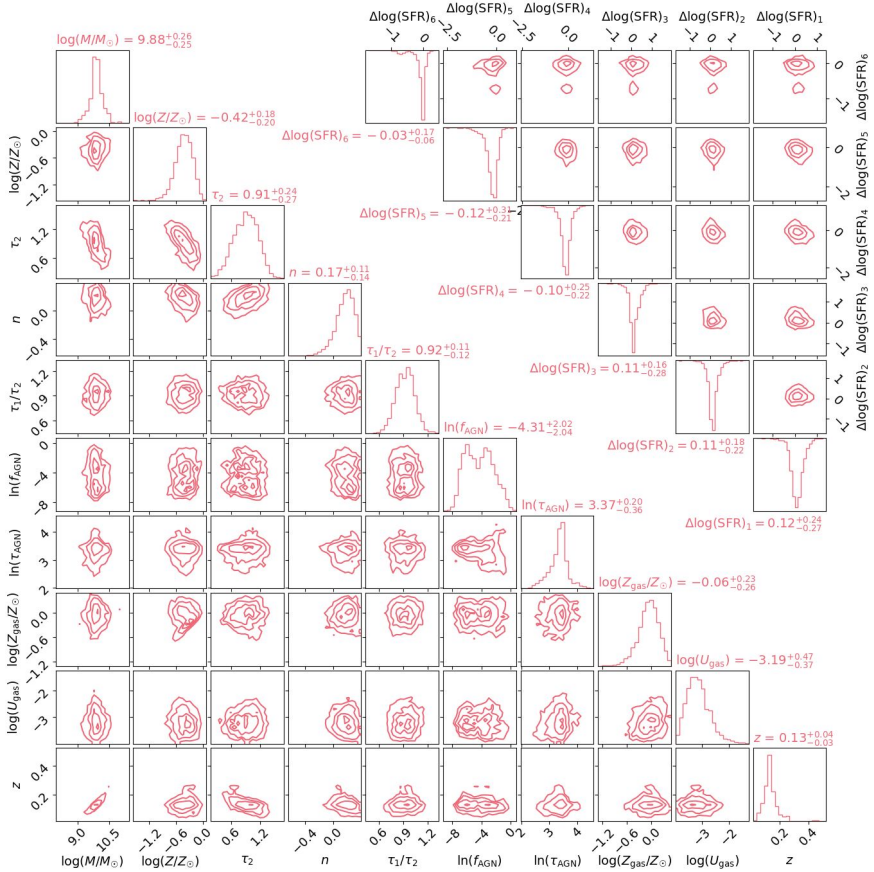
Inference of KiDS-1000 galaxy properties under **pop-cosmos** prior

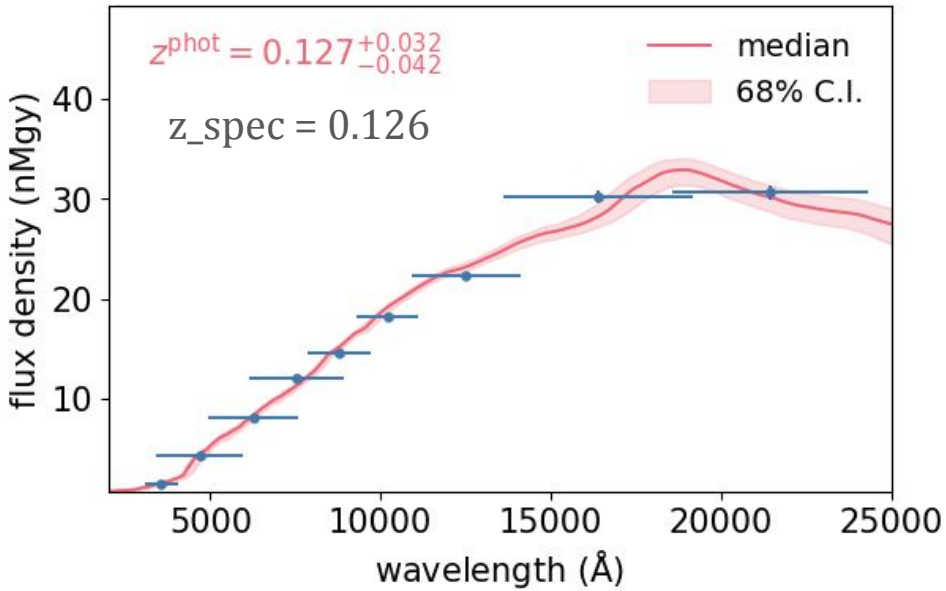
- Use the trained **pop-cosmos** model as a prior over SPS parameters when SED fitting with new photometry e.g. of KiDS-1000 galaxies



Credit: Justin Alsing, Stephen Thorp

Full Bayesian SED fitting of KiDS-1000 galaxies under **pop-cosmos** prior

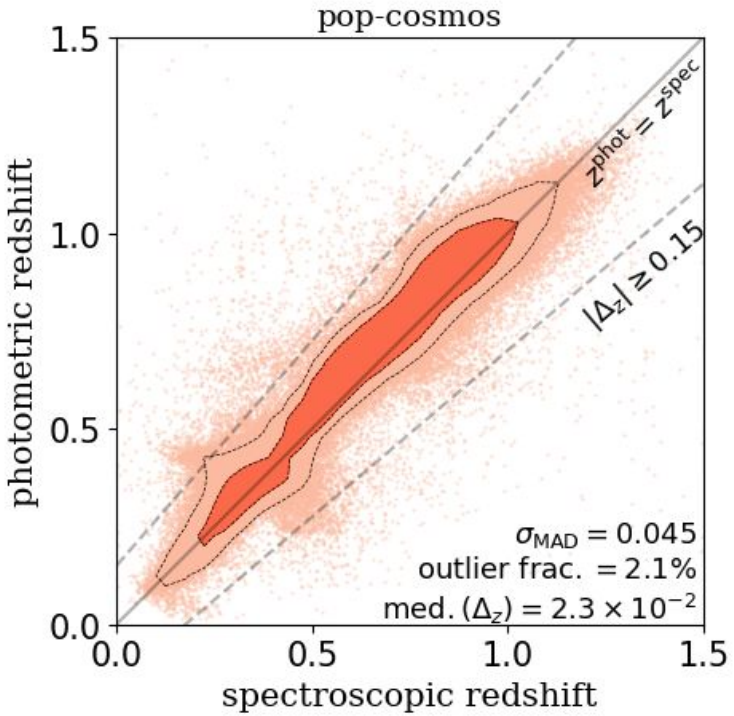




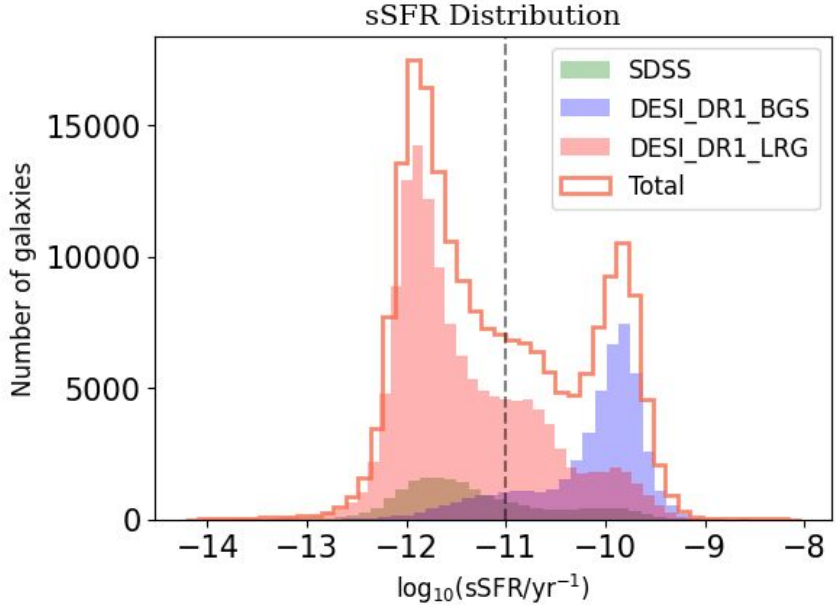
→ GPU accelerated MCMC (7 GPU-sec / galaxy) to infer joint posterior density of galaxy population parameters

Halder++ (*in prep.****)***

Inference on 200k spectroscopic cross-matched KiDS-1000 galaxies



Accurate redshift estimation!



Inference on other physical parameters e.g. star formation rate, stellar mass etc.

→ make cuts informed from simulations to extract 'IA' clean samples

Halder++ (*in prep.****)***

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How do we go forward with higher-order lensing statistics?

→ Analyse data that we really believe we can model.

Summary

- **Integrated 3PCFs** are practical and easy to measure higher-order lensing statistics!
- Can be predicted using perturbation-theory based models
- Significant improvement on parameter constraints relative to 2PCF only analyses!

  → already seen in blinded DESY3 cosmic shear data

  → ongoing works prior to unblinding
- Work in progress:

  → Extracting **clean galaxy samples** from inferred galaxy population parameters