UNIONS:

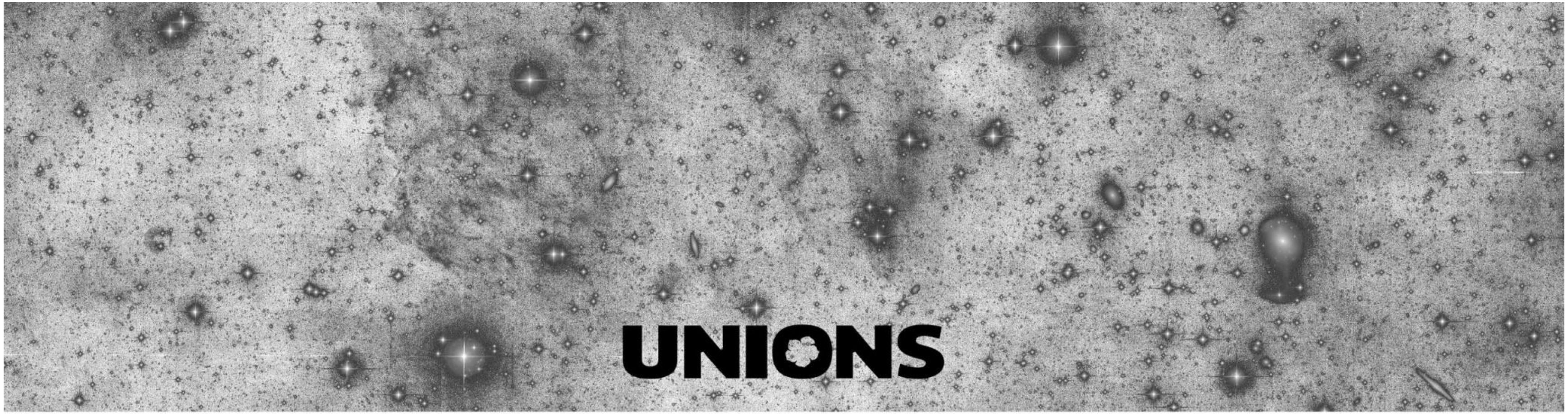
First Cosmic Shear Constraints from 3000 deg² of Northern Sky

Cail Daley & Martin Kilbinger
on behalf of the UNIONS Weak Lensing Team

Talk overview

- The UNIONS survey
- Weak lensing with UNIONS
- ShapePipe & the UNIONS shape catalog
- First shear cosmology with UNIONS:
  - 2-point correlation functions
  - systematics: PSF leakage & B-modes
  - photometric redshift estimation & blinding
  - inference & covariance

UNIONS: A combination of 3 Hawai'ian telescopes

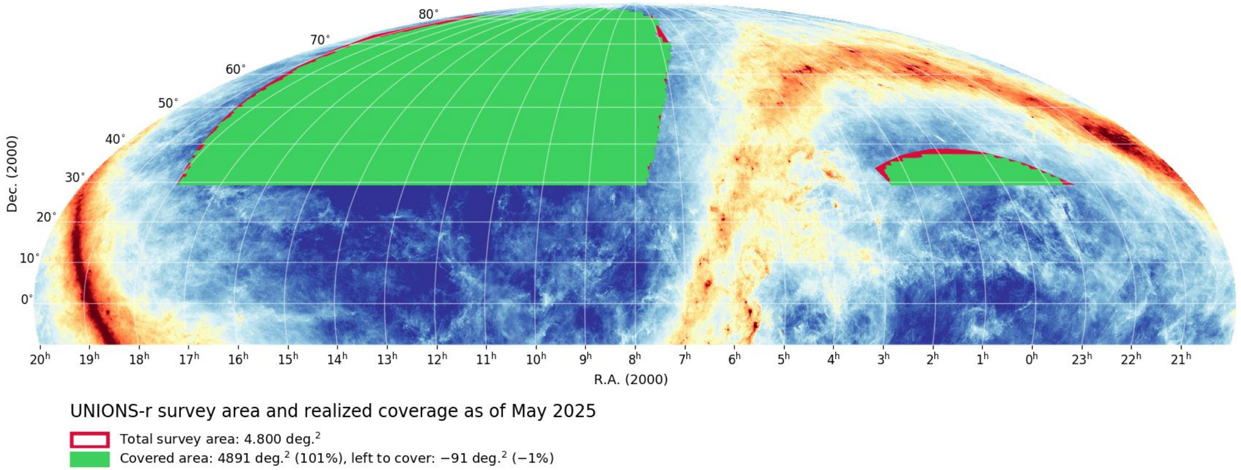


UNIONS: Ultra-violet Near-Infrared Optical Northern Survey

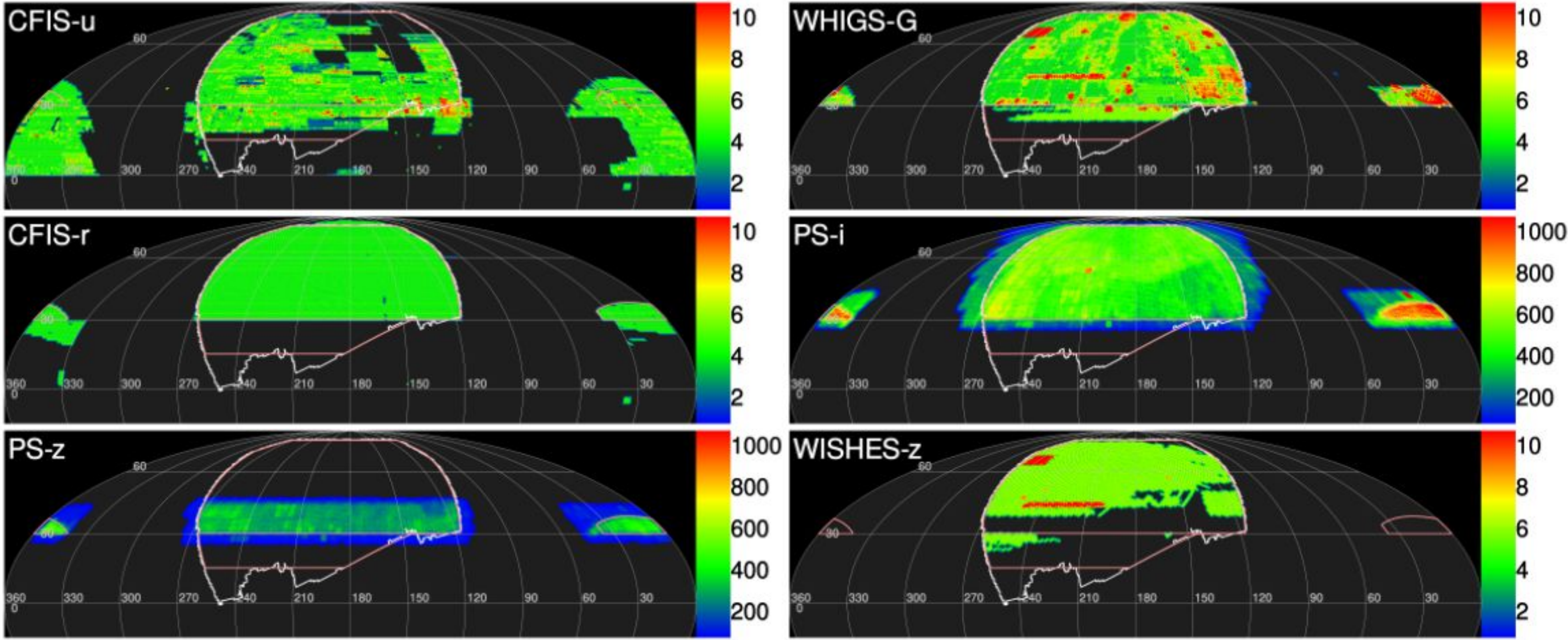
6,200 deg^2 with bands:
u, *r* (CFIS: Canada-France Imaging Survey)
i, *z* (Pan-STARRS)
g, *z* (HSC).

P.I.: Jean-Charles Cuillandre (CEA Paris-Saclay) & Alain McConnachie (Victoria/Canada)

- **Optical bands for Euclid for photometric redshifts**
- **Weak lensing**
- Milky Way dynamics
- Large-scale structure
- Galaxy evolution



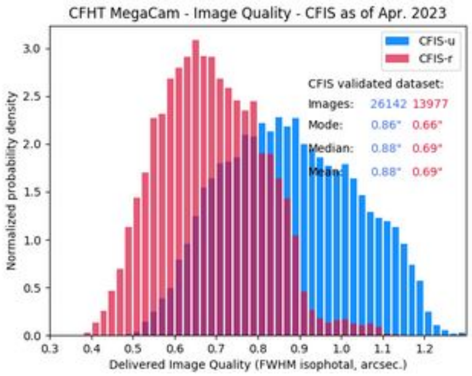
UNIONS multi-band data sky coverage

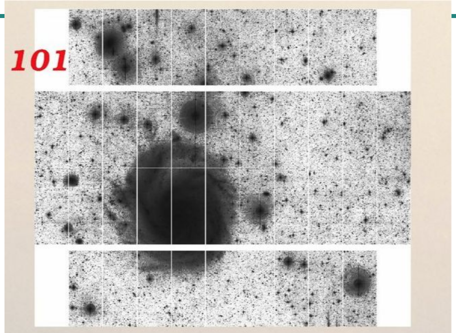


UNIONS image quality

Best wide-field imager on CFHT ever.

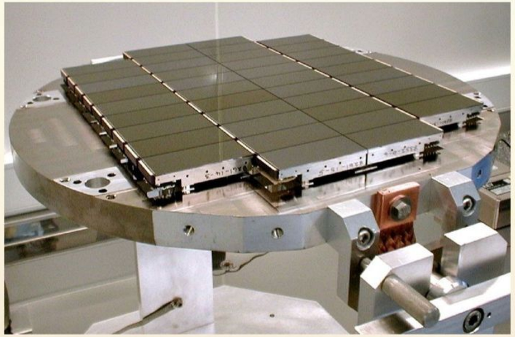
Improvements (2011 - 2014)



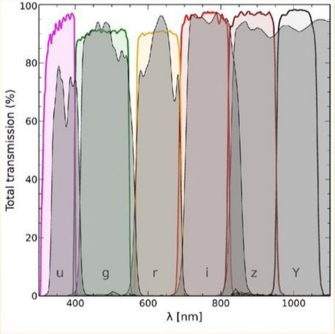


Elixir–LSB

Dome venting



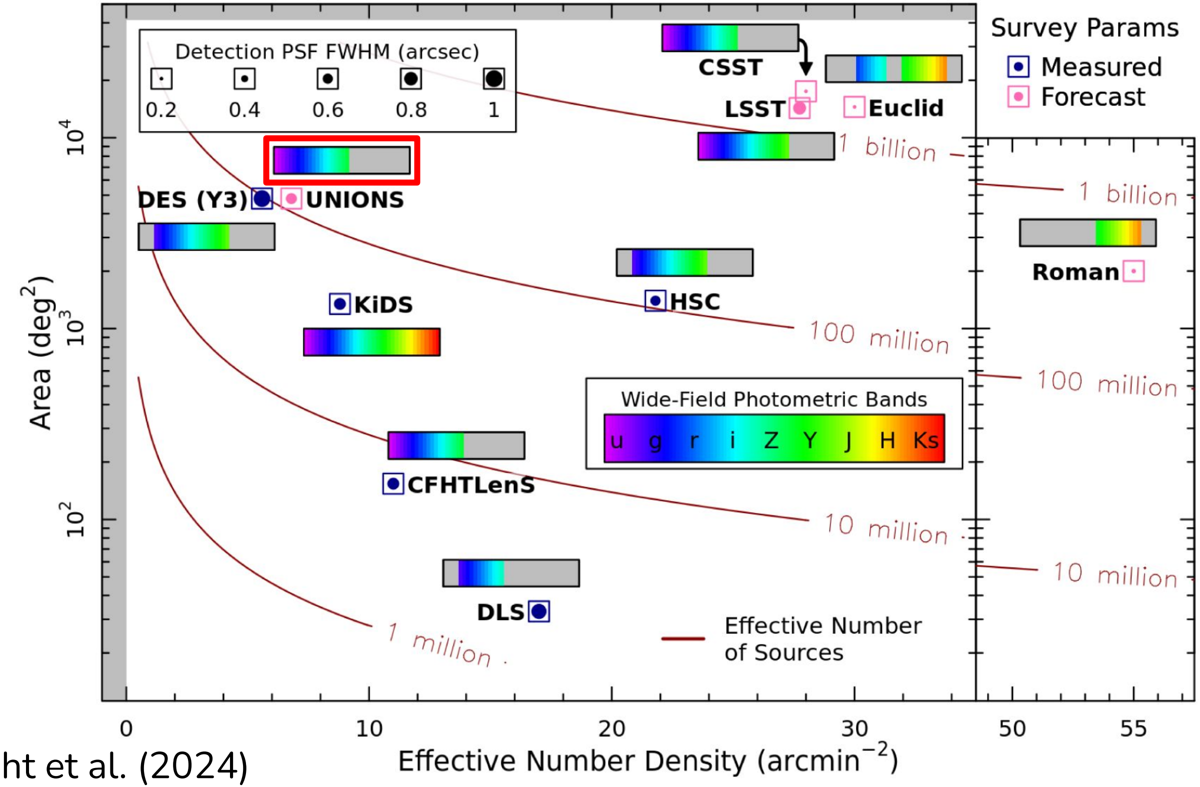
40 CCDs + Fast readout



New "square" filters

UNIONS in the broader survey landscape

Final UNIONS will be a "Stage 3.5" survey—roughly equivalent in depth & area to LSST Y1.



Wright et al. (2024)

ShapePipe & the UNIONS shape catalog

https://github.com/cosmostat/shapepipe

Farrens et al., 2022, A&A, 664, 141

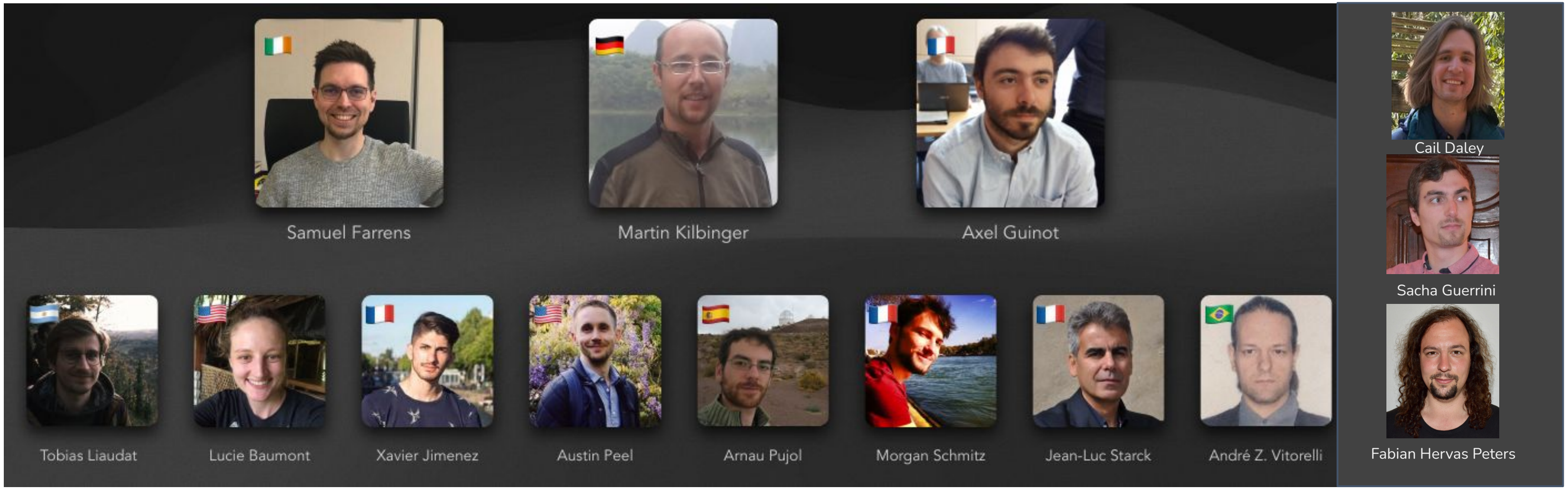

ShapePipe

CI passing | pages-build-deployment passing | python 3.9 | release v1.0.1

ShapePipe is a galaxy shape measurement pipeline developed within the CosmoStat lab at CEA Paris-Saclay.

See the documentation for details on how to install and run ShapePipe.

https://github.com/cosmostat/sp_validation/ for post-processing



ShapePipe philosophy

Goals

- Modular
- Easy
- Fast (enough)
- Robust

Code installation

- Conda
- Docker [allows for cloud computing]
- CD/CI

Three components

Pipeline

- Arguments & config
- I/O
- Job handling (MPI, SMP)
- Errors & logging

Modules

- WL data processing
- Book-keeping
- Post-processing

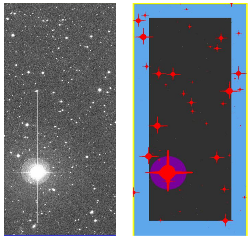
Utilities

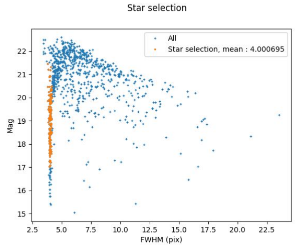
- Scripts
- Tools
- Survey-specific content

Can process 10k+ images, create catalogues with ~ 500 million objects, 150 Tb.

ShapePipe WL image processing

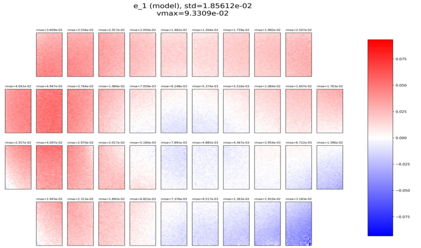
Input images are pre-processed (calibrated for astrometry and photometry)





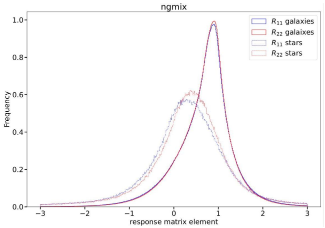
Main processing

- Mask
- Detect objects
- Star candidates on single exposures
- Galaxy candidates on stacks
- Select stars
- Create PSF model (PSFEx, Bertin et al. 2011; MCCD, Liaudat et al. 2021)
- Interpolate PSF model to galaxy positions
- Validate PSF model
- Measure galaxy shapes including calibration information [ngmix + metacalibration]



Post-processing

- Galaxy selection
- Apply calibration
- Systematic checks and validation



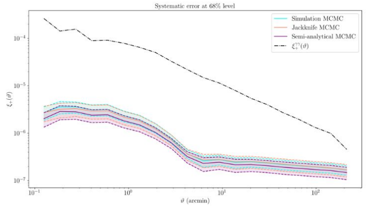
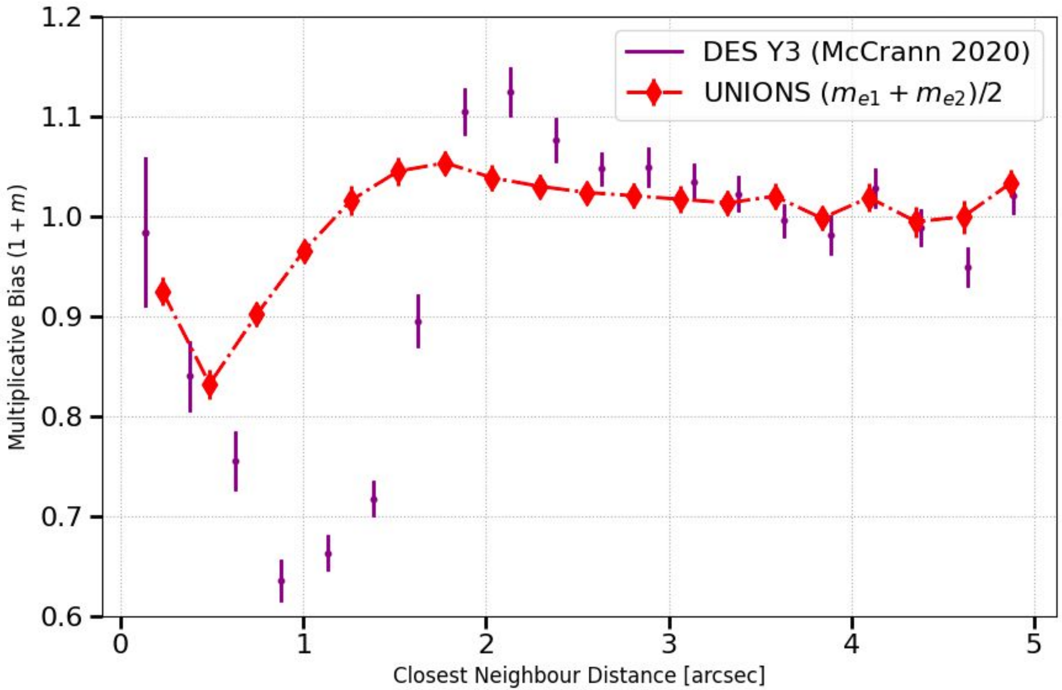


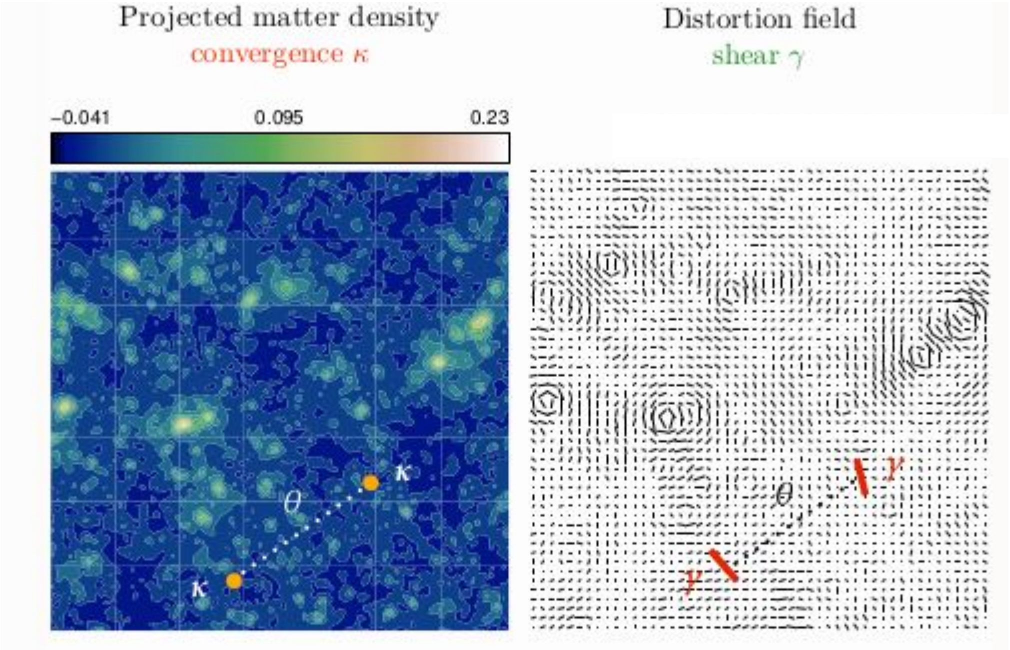
Image simulations & shear calibration

UNIONS vs. DES:

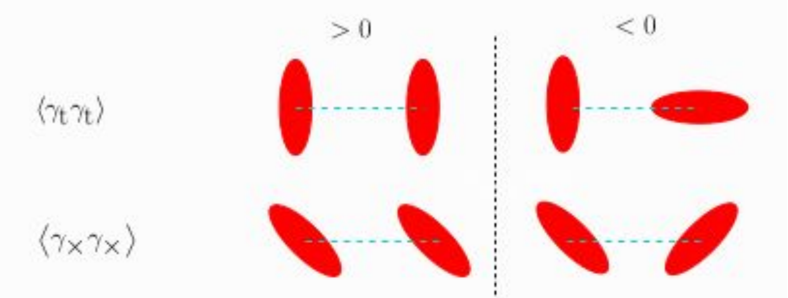
- Seeing 0.69” vs. 0.95”
- Less sensitive to blends
  - 2x smaller shear bias amplitude
  - At 2x smaller distance between galaxies



2-point correlation functions



2-point shear correlation function
$\leftrightarrow$variance of convergence σ^2_κ
$\leftrightarrow$ κ power spectrum
= projection(δ power spectrum)



Linear combinations

$$\xi_+(\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) + \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$
$$\xi_-(\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) - \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$

First shear cosmology with UNIONS

- Traditional cosmic shear analysis à la KiDS, DES, HSC.
- 2D: single redshift bin since more time is required to estimate & validate tomographic redshifts.
- Blinded analysis; blinding performed on the redshift distribution.
- 2-point correlation function (2PCF) used as data vector for cosmological inference.

The 2D cosmic shear team

Core members in alphabetical order (many others have contributed as well):

Cail Daley
(B-mode systematics)

Lisa Goh
(inference / covariance)

Sacha Guerrini
(inference / PSF systematics)

Fabian Hervas-Peters
(image simulations)

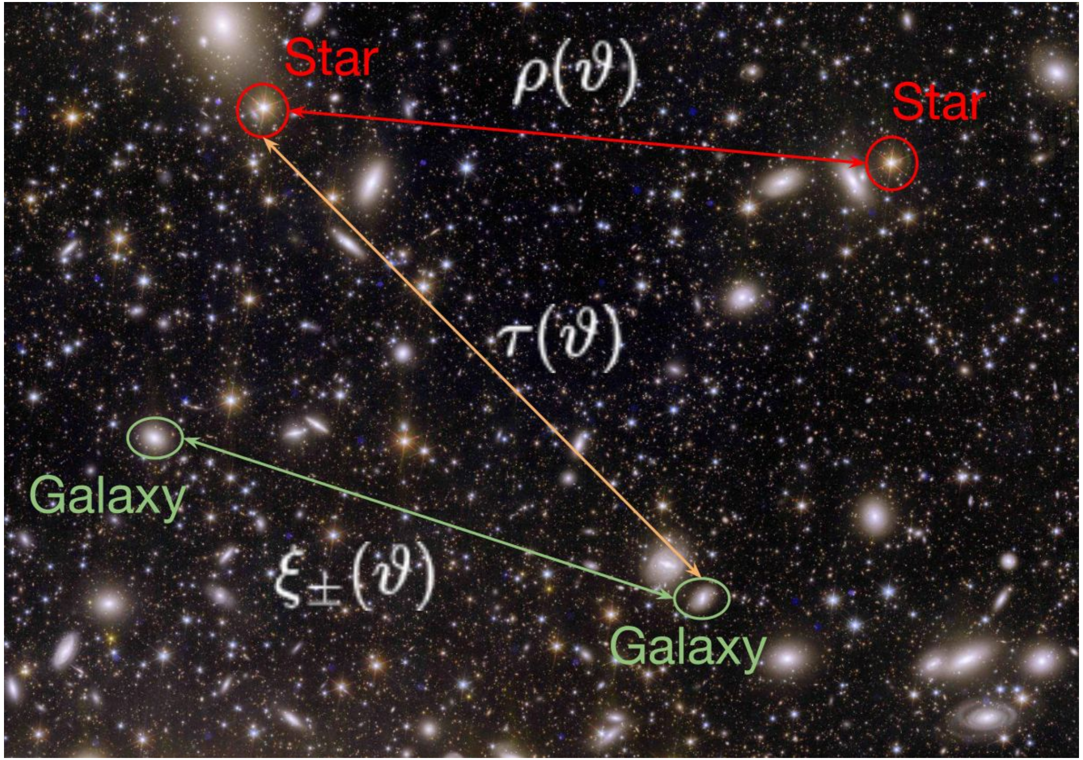
Martin Kilbinger
(shape catalog & wisdom)

Anna Wittje
(redshift estimation)

PSF Modeling & Systematics

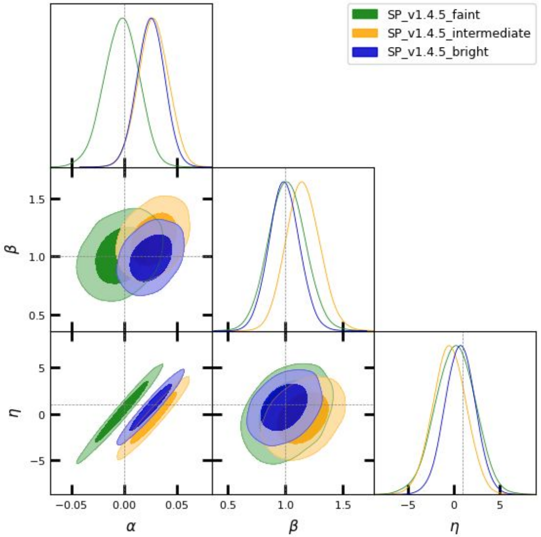
Stars are used to quantify the PSF size & shape.

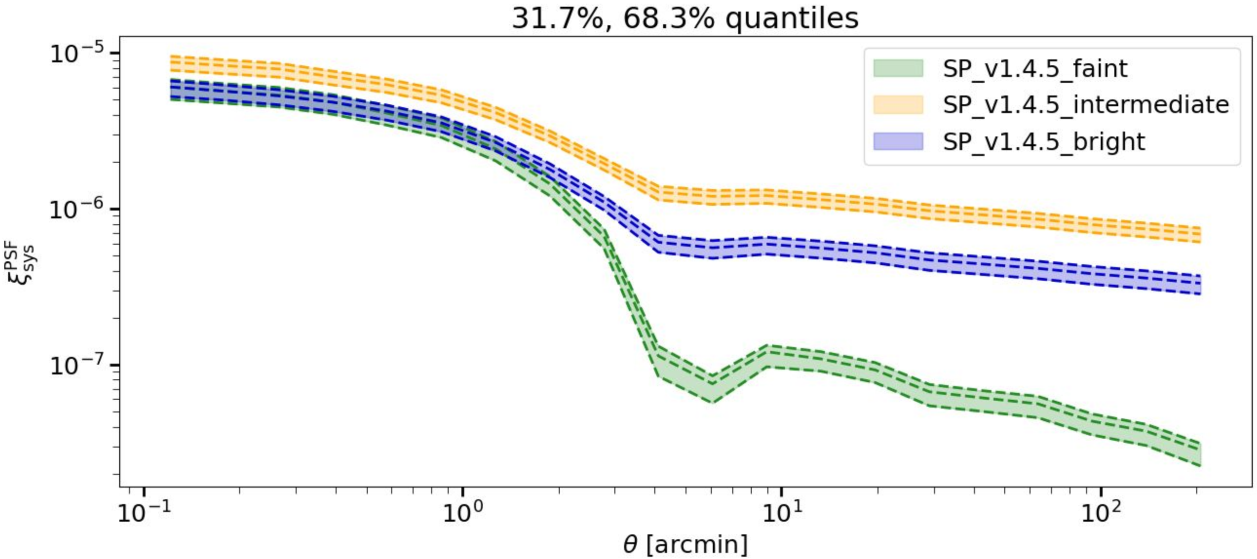
In addition to galaxy-galaxy shape correlation of interest ξ, we can measure the **star-star correlation ρ** and **galaxy-star correlation τ** to quantify PSF systematics.



PSF Systematics

- Leakage can be estimated for subsamples of the data to probe consistency.
- In the end, we jointly infer leakage and cosmological parameters to account for degeneracies.



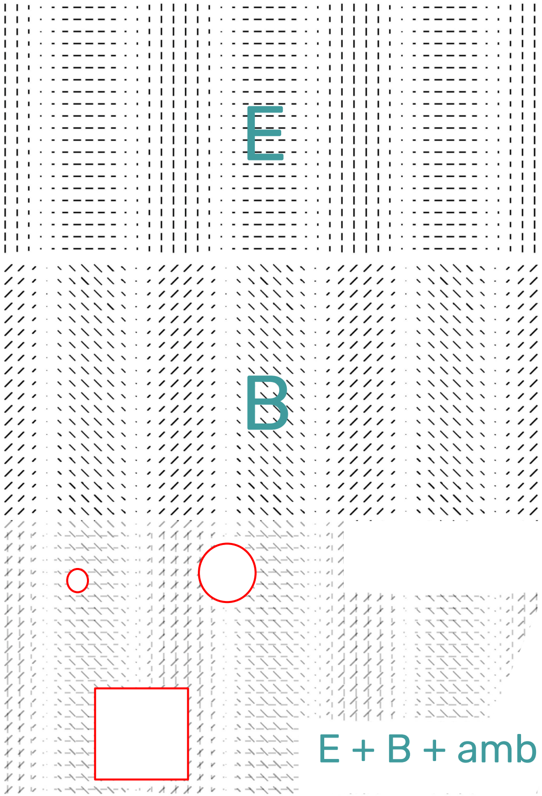


B-mode systematics

Spin-2 shear fields can be decomposed into **E-modes** containing the vast majority of lensing information and **B-modes** which are a probe of systematics at UNIONS noise levels.

In the presence of masking, some **ambiguous** modes cannot be cleanly attributed to E or B, although recent **purified** estimators can separate out these modes.

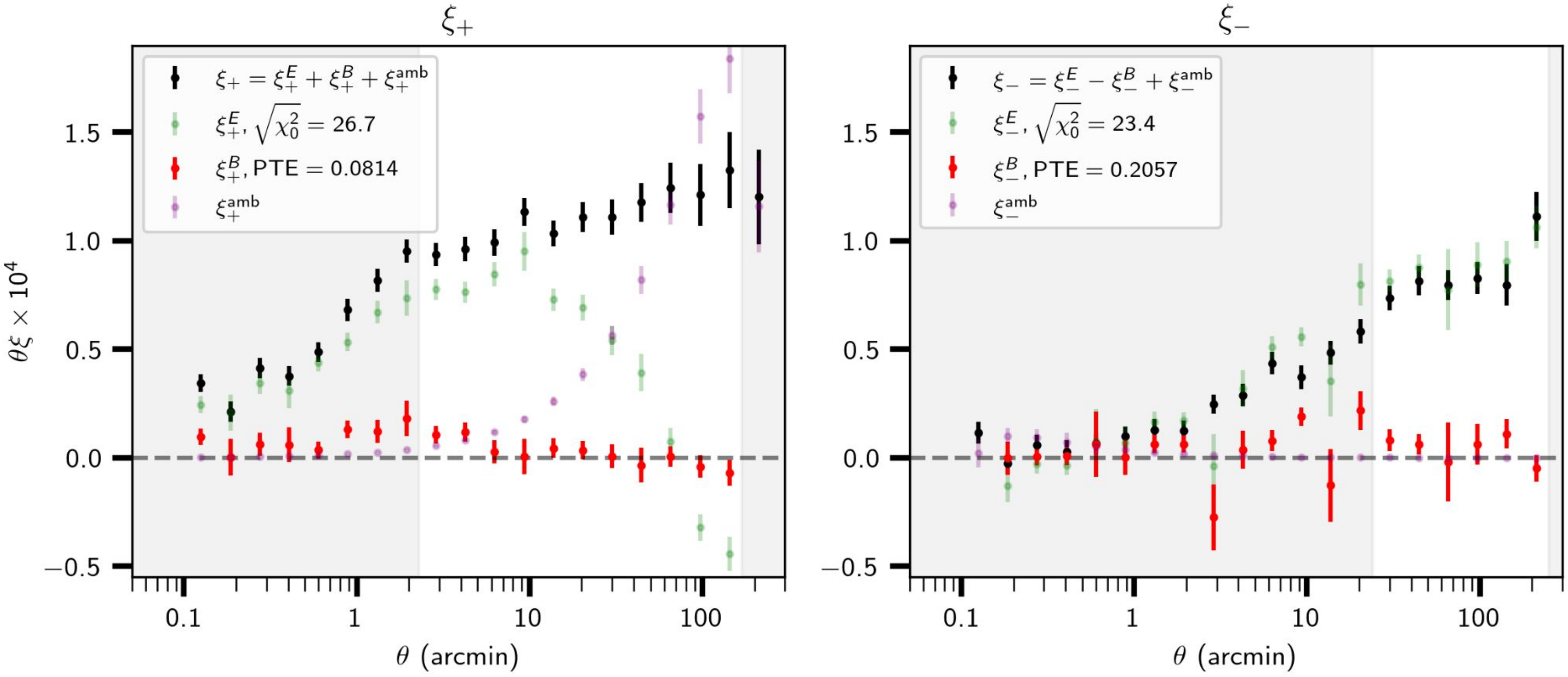
We use three B-mode approaches: pure correlation functions, COSEBIS, and bandpowers.



BICEP2 Collaboration

Pure B-mode correlation functions

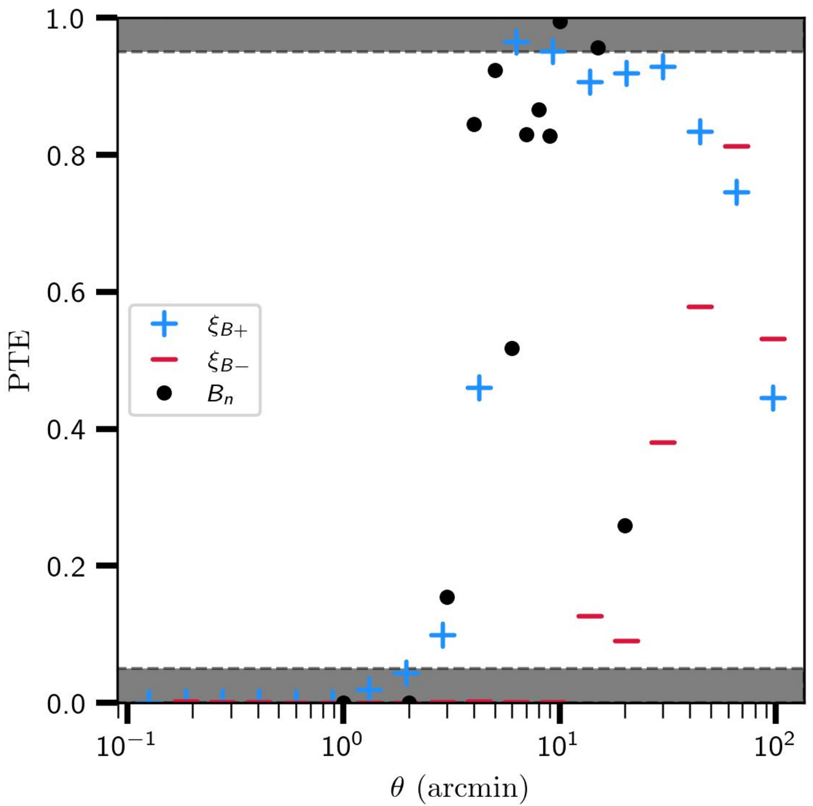
B-modes on small scales (~4' in ξ+ and ~30' in ξ-); large scales are ok.



B-mode scale cuts

Pure-B correlation functions and COSEBIS tell a similar story:

- ξ+ PTE is acceptable above θ~3-4
- B□ (dominated by ξ+) PTE is acceptable above θ~3-4
- ξ- (probing ≲10x smaller scales) PTE is acceptable above θ~20-30.

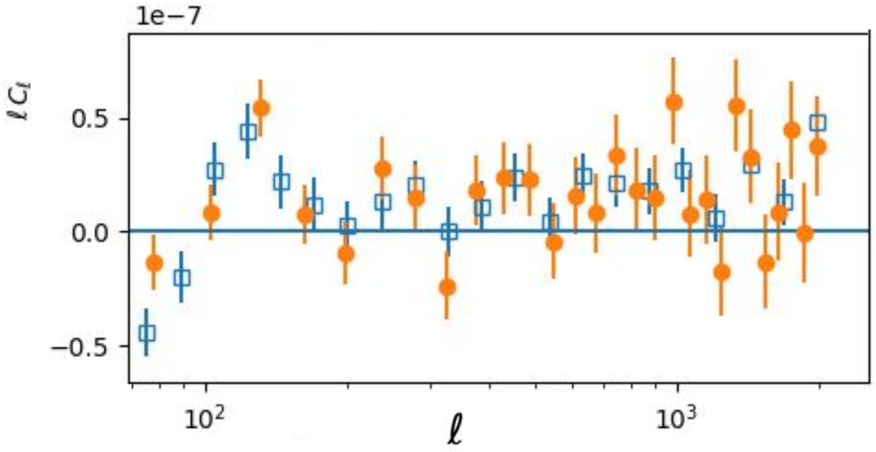


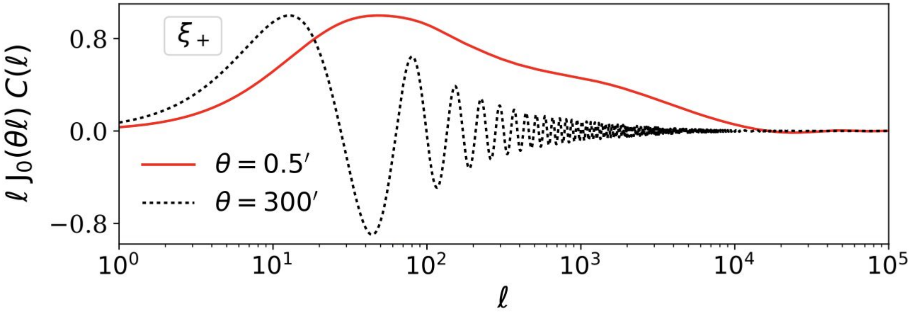
B-mode Bandpowers

Harmonic-space bandpowers can be calculated in two ways:

1. binning catalog into pixels and taking the power spectrum to get Cℓ,
2. transforming ξ± to Cℓ via integration.

Both approaches suggest strong B-modes at all ℓ, perhaps sourced by B-modes localized at small scales in θ.

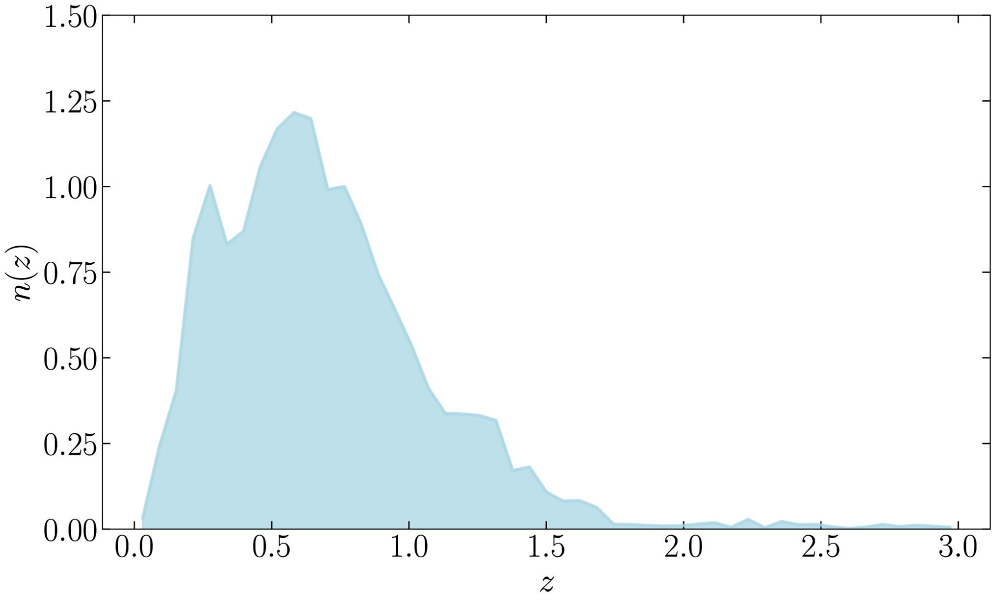




Redshift Distributions

Redshift distribution estimated using self-organizing maps (SOMs).

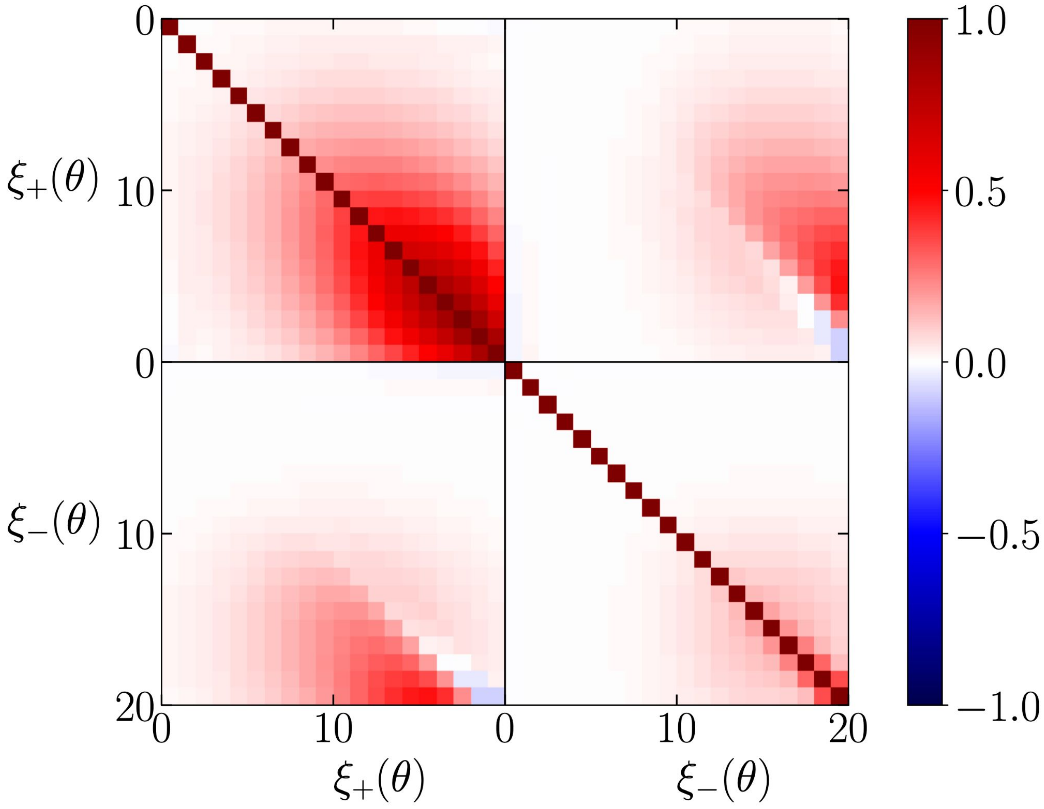
Three blinded redshift distributions produced—allows us to run the full inference pipeline on the data without risking confirmation bias.



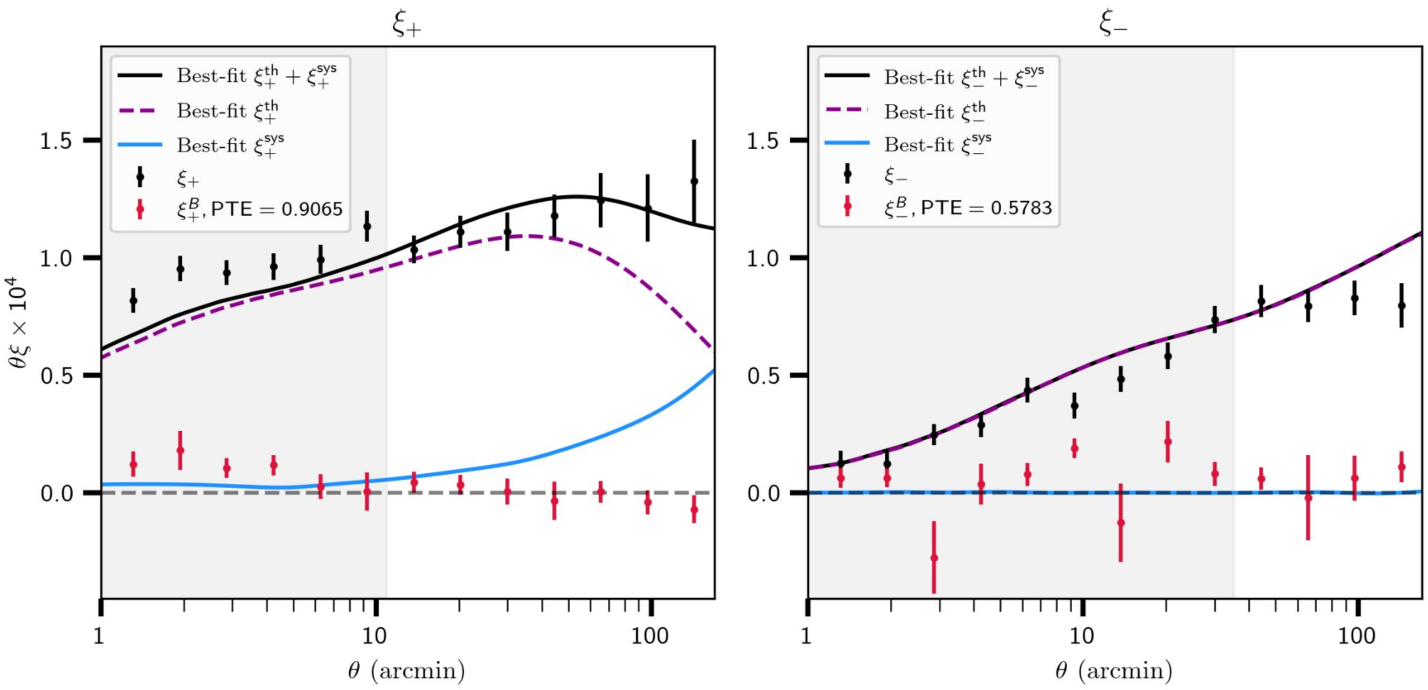
Covariance & Inference

Covariance estimated with CosmoCov and validated against data-driven jacknife.

Other parameters marginalized over in inference: intrinsic alignment, multiplicative bias, PSF systematics, n(z) bias.



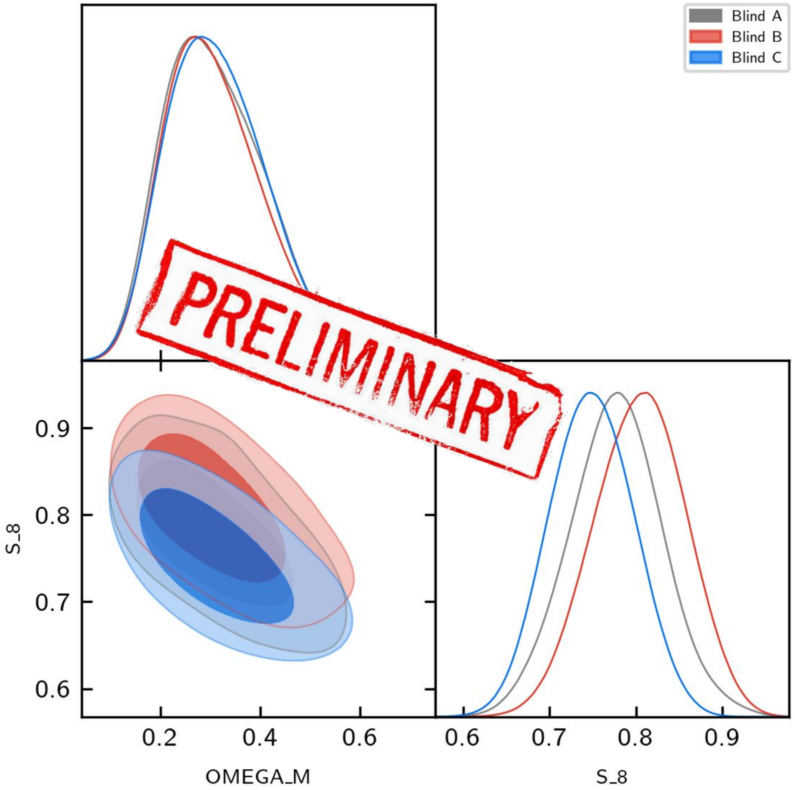
Current Best-fit Theory & Systematics



Cutting two 5’ < θ < 10’ data points in ξ+ improves χ² by 13..

Blinded Cosmological Contours

- **Constraints on S_8: ±0.052**
  - ~2x larger than best constraints from DES, HSC, & KiDS
  - ~0.015 comes from conservative θ > 10’ scale cut
  - Non-tomographic analysis significantly reduces constraining power as well.
- Shift between blinds is larger than shift from 5’ vs 10’ scale cuts.



Summary & Next Steps

- UNIONS is a unique dataset for weak lensing:
  - excellent image quality (Mauna Kea)
  - homogeneous survey depth (adaptive observing strategy).
  - Large area (> 6,000 deg2)
  - Very good photo-z’s (*u*-band @ CFHT)
- Competitive in the Euclid and Rubin era, in particular for cross-correlations with SDSS and DESI: lensing by galaxies, groups, clusters, voids; 3x2pt.
- First UNIONS cosmic shear results are imminent!
  - Analysis is in its final stages, tracking down potential scale-dependent systematics before unblinding.
  - Error bar on S_8 forecasted to be ~0.052, and may improve if we can reduce systematics on small scales.
- Up next: simulation-based inference, tomographic analysis, and much more!

Backup slides

UNIONS weak-lensing publications

Published/finished

UNIONS overview paper	Gwyn et al. 2024, submitted to AJ
Galaxy-galaxy lensing of mergers	Cheng et al. 2025, submitted to MNRAS
Cluster lensing	Mpetha et al. 2025, submitted to MNRAS
Intrinsic galaxy alignment	Hervas Peters et al. 2024, A&A,in press
Void lensing	Martin et al. 2025 in internal review
PSF systematics and diagnostics	Guerrini et al. 2024, A&A in press
PSF diagnostics for galaxy-galaxy lensing	Zhang et al. 2024, A&A 691, A75
Black-hole-mass - halo-mass relation	Li et al. 2024, arXiv:2402.10740
Peak counts	Ayçoberry et al., 2023, A&A, 671, A17
UNIONS first weak-lensing analysis	Guinot et al., 2022, A&A, 666, A1
Group & cluster masses	Spitzer et al., 2022, submitted to MNRAS
Dark-matter halo shapes	Robison et al., 2022, arXiv:2209.09088
Multi-CCD PSF model	Liaudat et al., 2021, A&A, 646, A27

In progress

2D cosmic shear	Goh et al. in prep.
Shear calibration & image simulations	Hervas Peters et al. in prep.
Simulation-based inference	Guerrini, Maupas in prep.
3x2pt cosmology	Hervas Peters et al. in prep.
3D intrinsic alignment	Corinaldi et al in prep.
Cosmic shear tomography	
Density split statistics	
Galaxy size - halo mass relation	
WL of ultra-diffuse galaxies	
Stellar-mass - halo-mass relation for mergers	

PSF Systematics

Three quantities can be used to form six ρ-statistics and three τ-statistics:

- Ellipticity
  (model & galaxy)
- Ellipticity errors
  (model evaluated at star locations)
- Size errors
  (model evaluated at star locations)

$$\delta \mathbf{e}^{\mathrm{sys}}_{\mathrm{model}} = \alpha \underbrace{\mathbf{e}_{\mathrm{model}}}_{\text{Leakage}} + \beta \underbrace{(\mathbf{e}_* - \mathbf{e}_{\mathrm{model}})}_{\text{Ellipticity error}} + \eta \underbrace{\left(\mathbf{e}_* \frac{T_* - T_{\mathrm{model}}}{T_*} \right)}_{\text{Size error}}$$

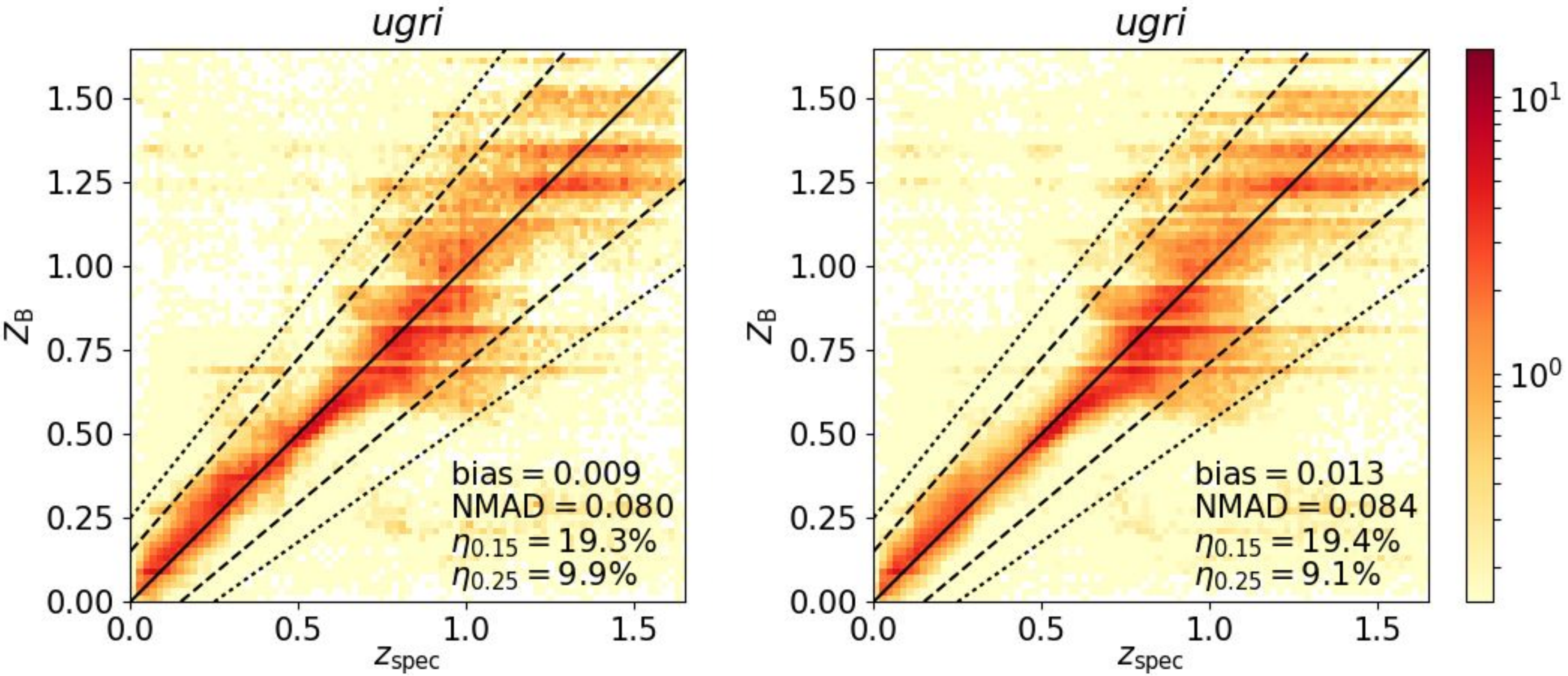
$$\begin{pmatrix} \tau_{0,1} \\ \tau_{2,1} \\ \tau_{5,1} \\ \vdots \\ \tau_{0,n} \\ \tau_{2,n} \\ \tau_{5,n} \end{pmatrix} = \begin{pmatrix} \rho_{0,1} & \rho_{2,1} & \rho_{5,1} \\ \rho_{2,1} & \rho_{1,1} & \rho_{4,1} \\ \rho_{5,1} & \rho_{4,1} & \rho_{3,1} \\ & \ddots & \\ \rho_{0,n} & \rho_{2,n} & \rho_{5,n} \\ \rho_{2,n} & \rho_{1,n} & \rho_{4,n} \\ \rho_{5,n} & \rho_{4,n} & \rho_{3,n} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \eta \end{pmatrix},$$

Solve system of linear equations to get leakage contribution to 2PCF:

$$\xi_{\mathrm{PSF,sys}}(\vartheta) = \alpha^2 \rho_0(\vartheta) + \beta^2 \rho_1(\vartheta) + \eta^2 \rho_3(\vartheta) + 2\alpha\beta\, \rho_2(\vartheta) + 2\alpha\eta\, \rho_5(\vartheta) + 2\beta\eta\, \rho_4(\vartheta)$$

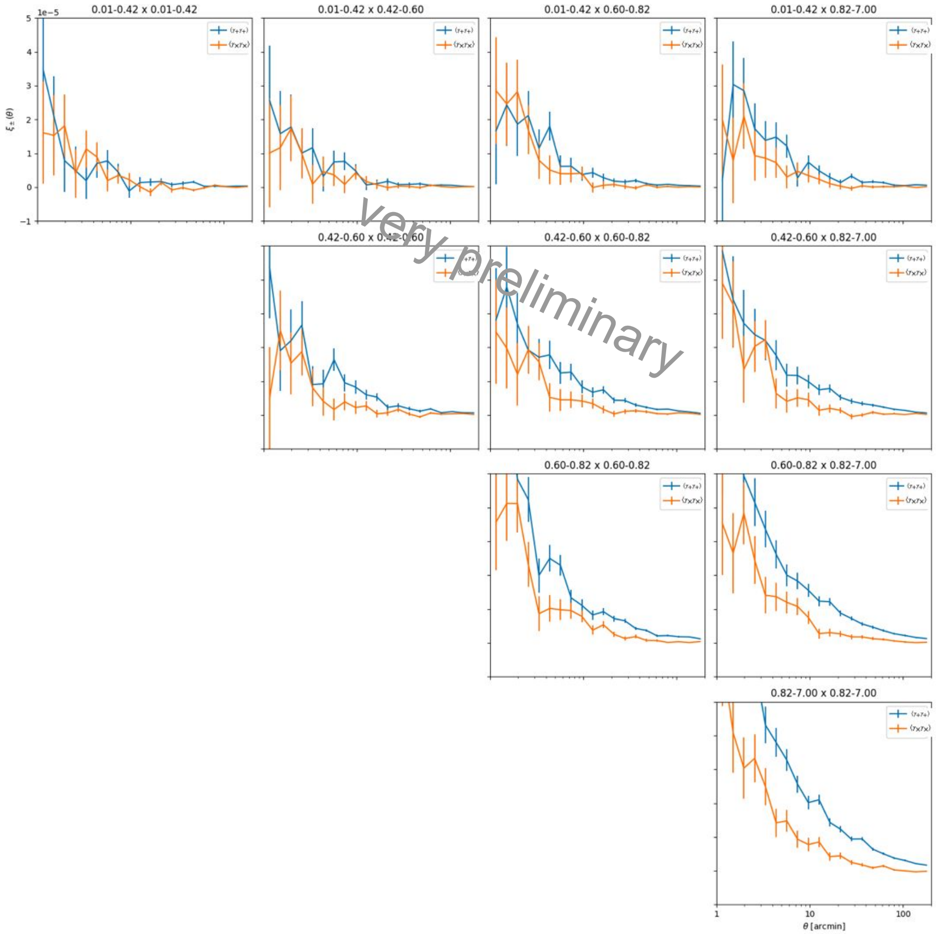
Photo-z's

WISHES area | PanSTARRS area



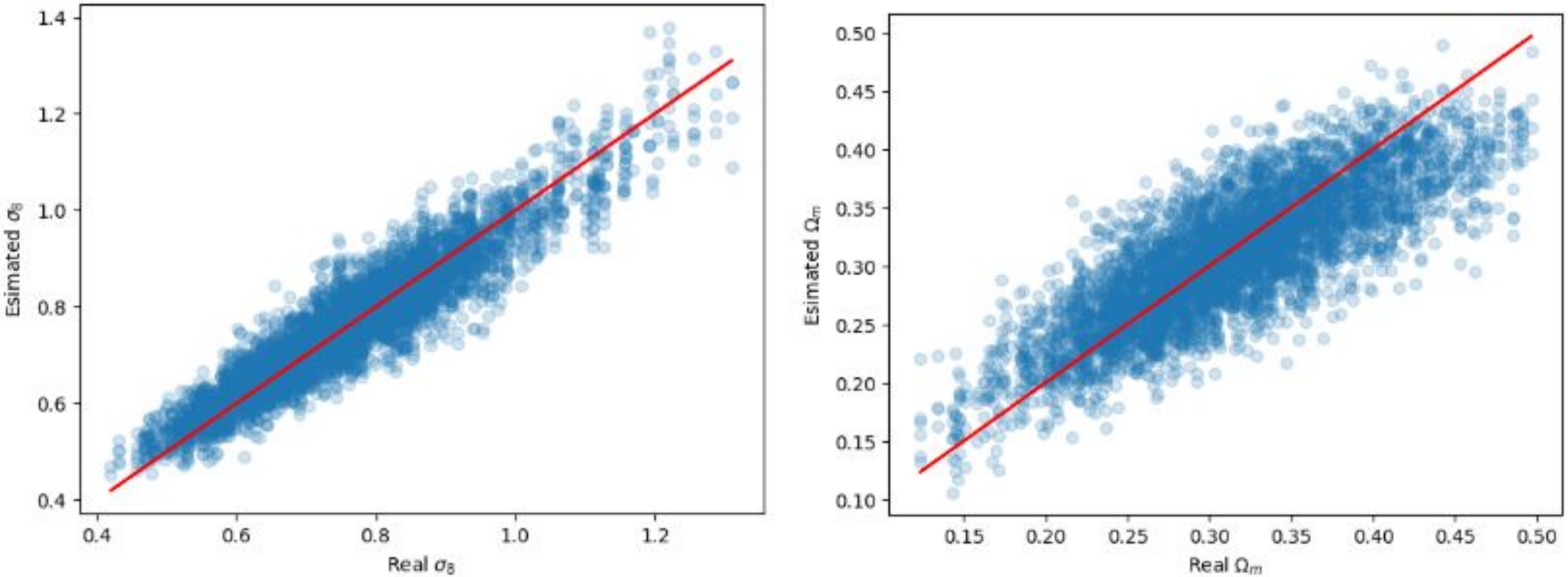
Almost identical performance => spec-z samples and *ugri* data comparable.

Tomography



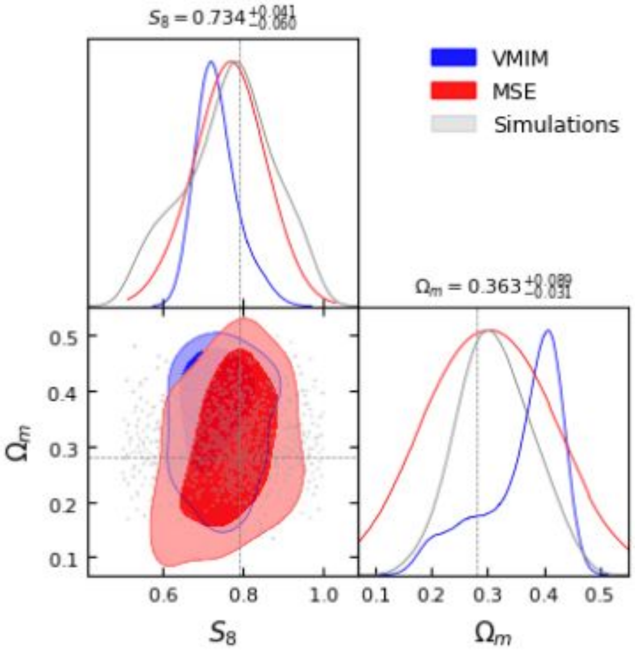
0.01-0.42 x 0.01-0.42
0.01-0.42 x 0.42-0.60
0.01-0.42 x 0.60-0.82
0.01-0.42 x 0.82-7.00
0.42-0.60 x 0.42-0.60
0.42-0.60 x 0.60-0.82
0.42-0.60 x 0.82-7.00
0.60-0.82 x 0.60-0.82
0.60-0.82 x 0.82-7.00
0.82-7.00 x 0.82-7.00
1e−5
$\xi_\pm(\theta)$
θ [arcmin]
very preliminary

Simulation-based inference

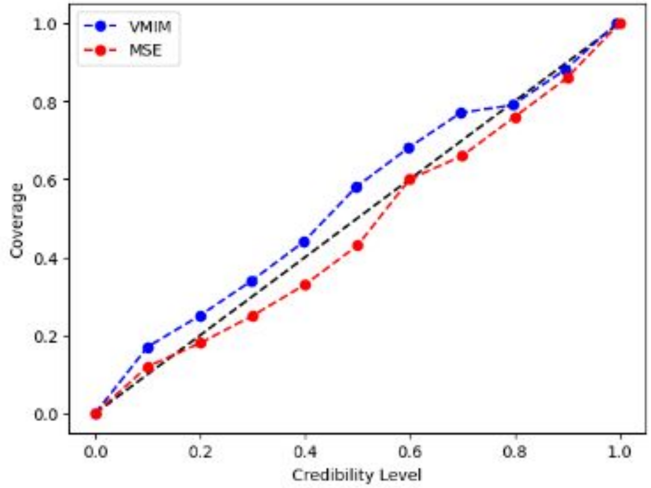


Mathis Maupas, Sacha Guerrini

Simulation-based inference

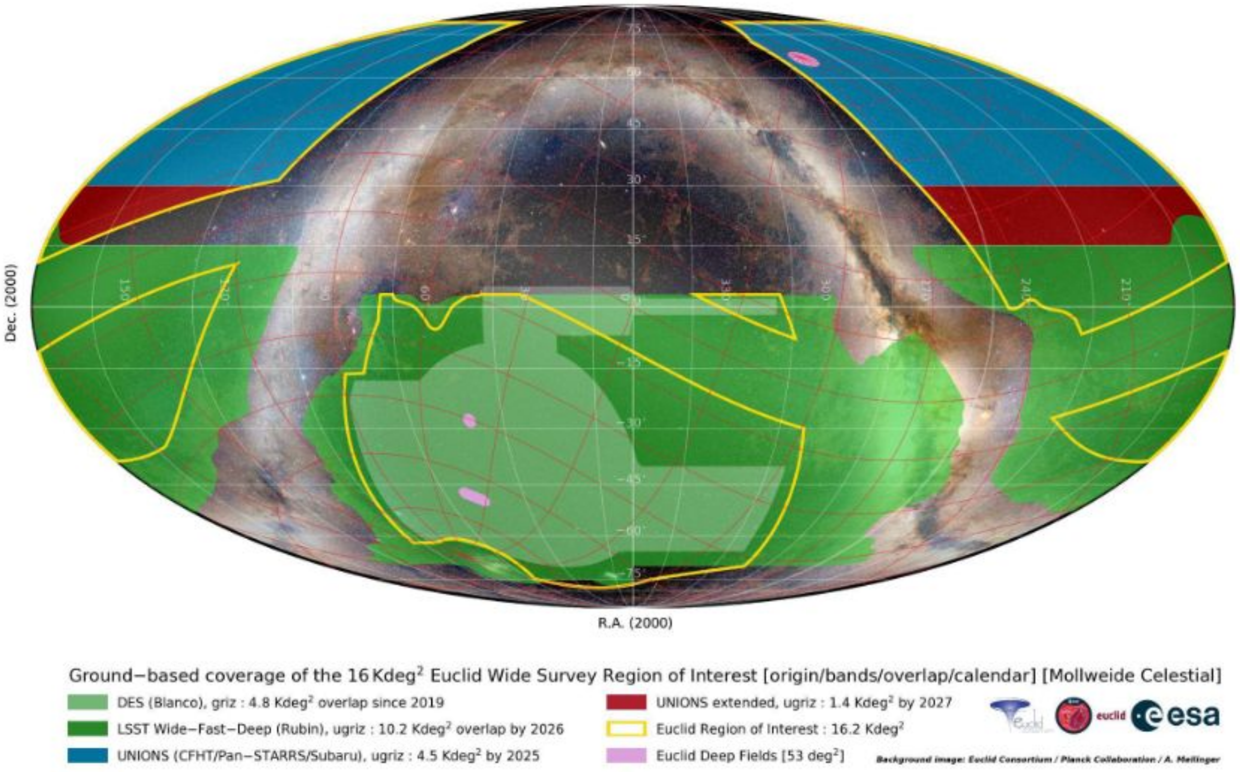


UNIONS-like simulations



Mathis Maupas, Sacha Guerrini

UNIONS extension, δ < 30°



27 accepted peer reviewed publications so far: **Resolved Stellar Populations** **Galaxy evolution** **Weak lensing**

< 2024

27. Robison, B., et al., 2023, in press, "The shape of dark matter haloes: results from weak lensing in the Ultraviolet-Near Infrared Optical Northern Survey (UNIONS)"
26. Lim, S., et al., 2023, MNRAS, in press, "Constraints on galaxy formation from the cosmic-infrared-background / optical-imaging cross-correlation using Herschel and UNIONS"
25. Smith, S., et al., 2023, ApJ, in press, "Discovery of a new Local Group galaxy candidate in UNIONS: Bo¨otes V"
24. Chu, A., et al., 2023, A&A, in press, A UNIONS view of the brightest central galaxies of candidate fossil groups
23. Bickley, R., et al., 2023, MNRAS, 519, 6149, "AGN in post mergers from the Ultraviolet Near Infrared Optical Northern Survey"
22. Ayc¸oberry, E., et al., 2023, A&A, 671, 17, "UNIONS : impact of systematic errors on weak-lensing peak counts"
21. Savary, E., et al . 2022, A&A, 666, 1 "A search for galaxy-scale strong gravitational lenses in UNIONS"
20. Chan, J. H. H., et al. 2022, A&A, 659, 140 "Discovery of Strongly Lensed Quasars in UNIONS"
19. Wilkinson, S., et al., 2022, MNRAS, 516, 4354, "The merger fraction of post-starburst galaxies in UNIONS"
18. Ellison, S., et al., MNRAS, 517, L92, "Galaxy mergers can rapidly shut down star formation"
17. Bickley, R., et al., 2022, MNRAS, 514, 3294, "Star formation characteristics of CNN-identified post-mergers in the Ultraviolet Near Infrared Optical Northern Survey (UNIONS)"
16. Farrens, S., et al., 2022, A&A, 664, A141, "A modular weak lensing processing and analysis pipeline"
15. Guinot, A., et al., 2022, A&A, 666, 162, "ShapePipe: a new shape measurement pipeline and weak-lensing application to UNIONS/CFIS data"
14. Sola, E., et al., 2022, A&A, 662, 124, "Characterization of LSB structures in annotated deep images"
13. Roberts, I., et al., 2022, MNRAS,509, 1342, "Ram Pressure Candidates in UNIONS"
12. Jensen, J., et al., 2021, MNRAS, 507, 1923, "Uncovering fossils of the distant Galaxy with UNIONS: NGC 5466 and its stellar stream"
11. Bickley, R., et al., 2021, MNRAS, 504, 372, "Convolutional neural network identification of galaxy post-mergers in UNIONS using IllustrisTNG"
10. Fantin, N., et al., 2021, ApJ, 913, 30, "The Mass and Age Distribution of Halo White Dwarf Candidates in the Canada-France Imaging Survey"
9. Liaudat, T., et al., 2021, A&A, A27, "Multi-CCD modelling of the point spread function"
8. Thomas, G., et al., 2020, ApJ, 902, 89, "The Hidden Past of M92: Detection and Characterization of a Newly Formed 17° Long Stellar Stream Using the Canada-France Imaging Survey "
7. Fantin N., et al., 2019, ApJ, 877, 148, "The Canada France Imaging Survey: Reconstructing the Milky Way from its white dwarf population"
6. Thomas, G., et al., 2019, ApJ, 866, 10, "Dwarfs or giants? Stellar metallicities and distances from ugrizG multi-band photometry"
5. Ellison, S., et al., 2019, MNRAS, 487, 2491, "A definitive merger-AGN connection at $z\sim0$ with CFIS: mergers have an excess of AGN and AGN hosts are more frequently disturbed"
4. Thomas, G., et al. 2019, MNRAS, 483, 3, "A-type stars in the Canada-France Imaging Survey - II. Tracing the height of the disc at large distances with Blue Stragglers"
3. Thomas, G., et al., 2018, MNRAS, 481, 4, "A-type stars in the Canada-France Imaging Survey I. The stellar halo of the Milky Way traced to large radius by blue horizontal branch stars"
2. Ibata, R., et al., 2017, ApJ, 848, 2, 129, "Chemical Mapping of the Milky Way with The Canada-France Imaging Survey: A Non-parametric Metallicity-Distance Decomposition of the Galaxy"
1. Ibata, R., et al., 2017, ApJ, 848, 2, 128, "The Canada-France Imaging Survey: First Results from the u-Band Component"

Visual inspection!