Fabian Hervas Peters

UNIONS-3500: 3500 deg^2 of lensing in the northern sky

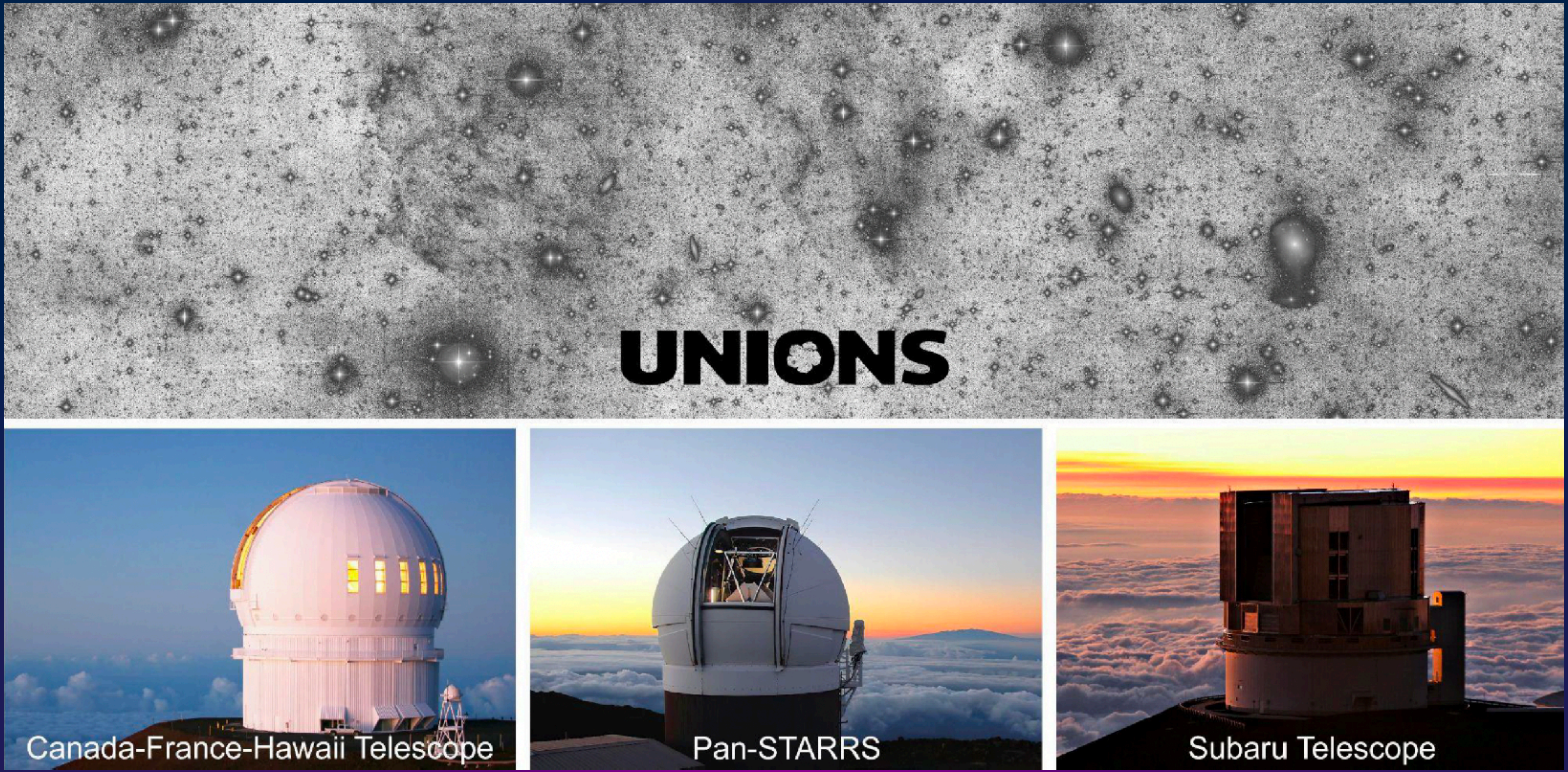
On behalf of the UNIONS collaboration

With: Romain Paviot, Lucie Baumont, Lisa Goh, Sacha Guerrini, Axel Guinot, Hendrik Hildebrandt, Mike Hudson, Martin Kilbinger, Ludovic van Waerbeke, Anna Wittje, et al.

DE LA RECHERCHE À L'INDUSTRIE cea

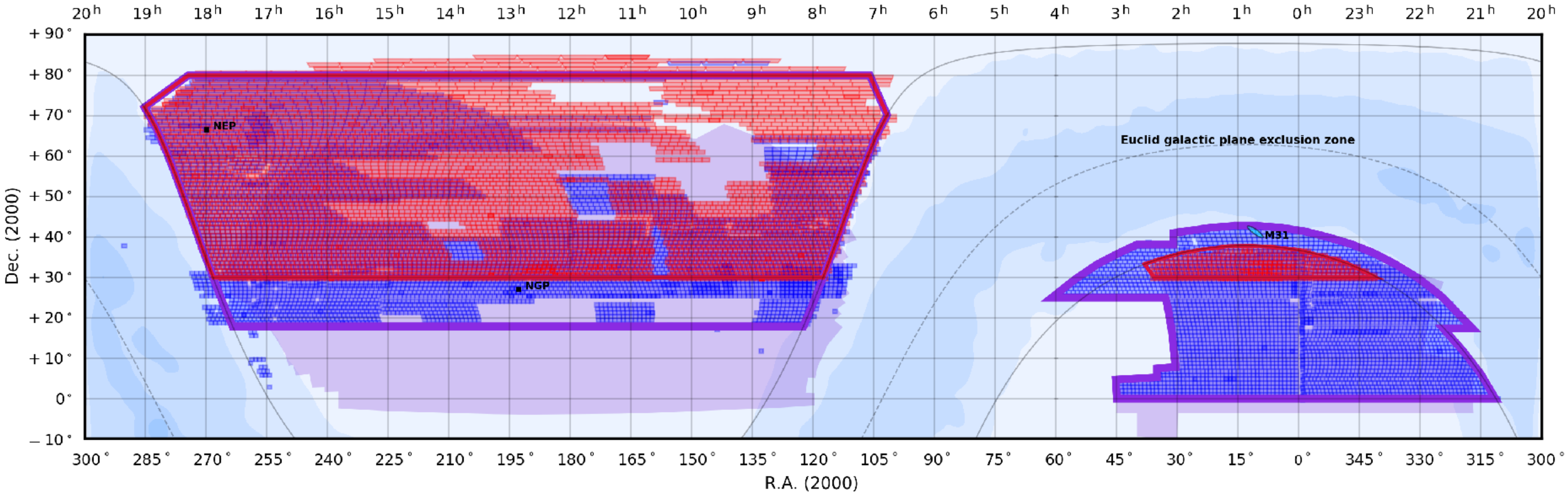
cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

A collaboration of 3 Hawai’i based telescopes



r, u bands | i band | g, z bands

Credit & PI: Jean-Charles Cuillandre



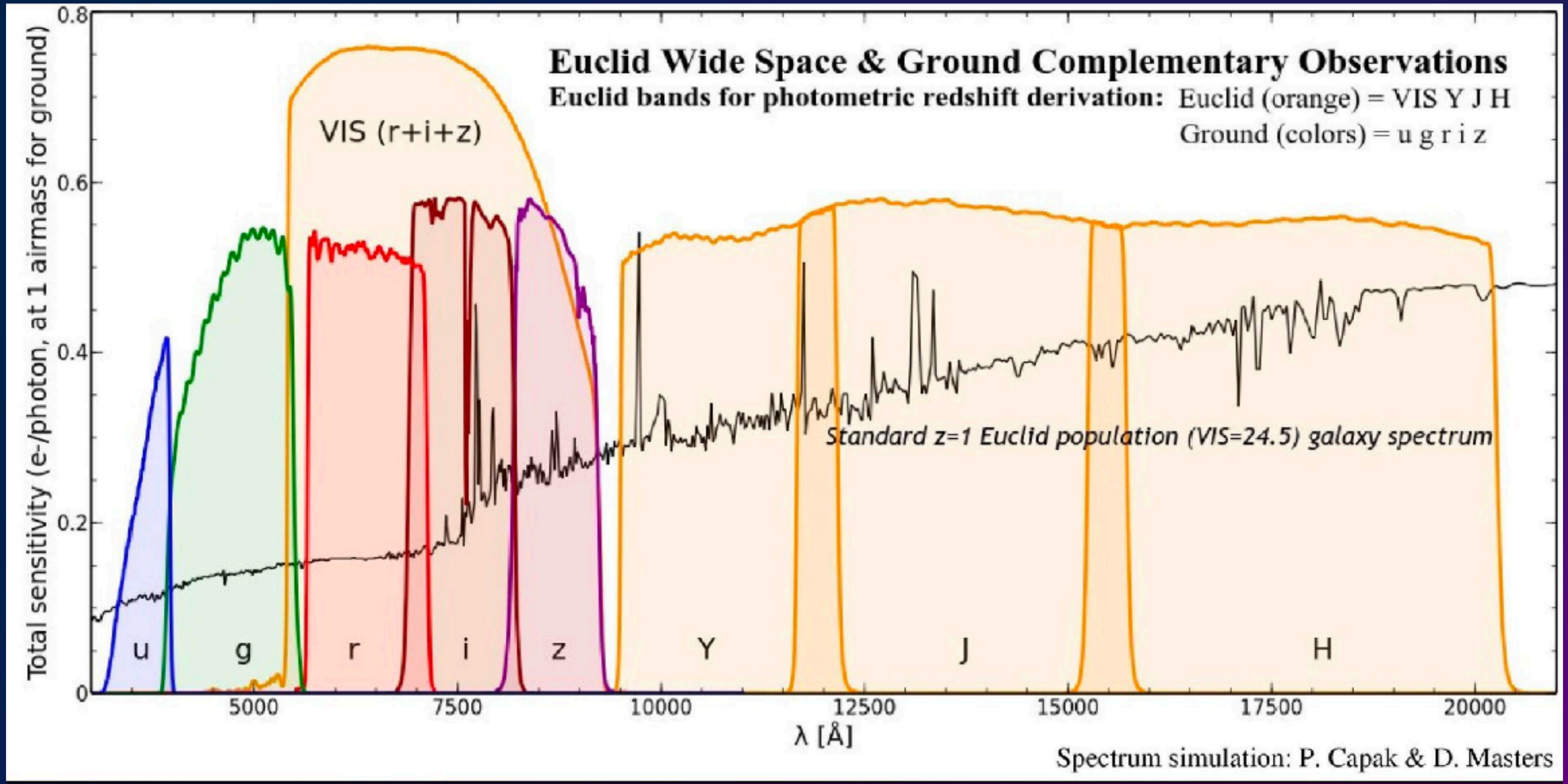
UNIONS sky coverage goal with current completion (November 2023)

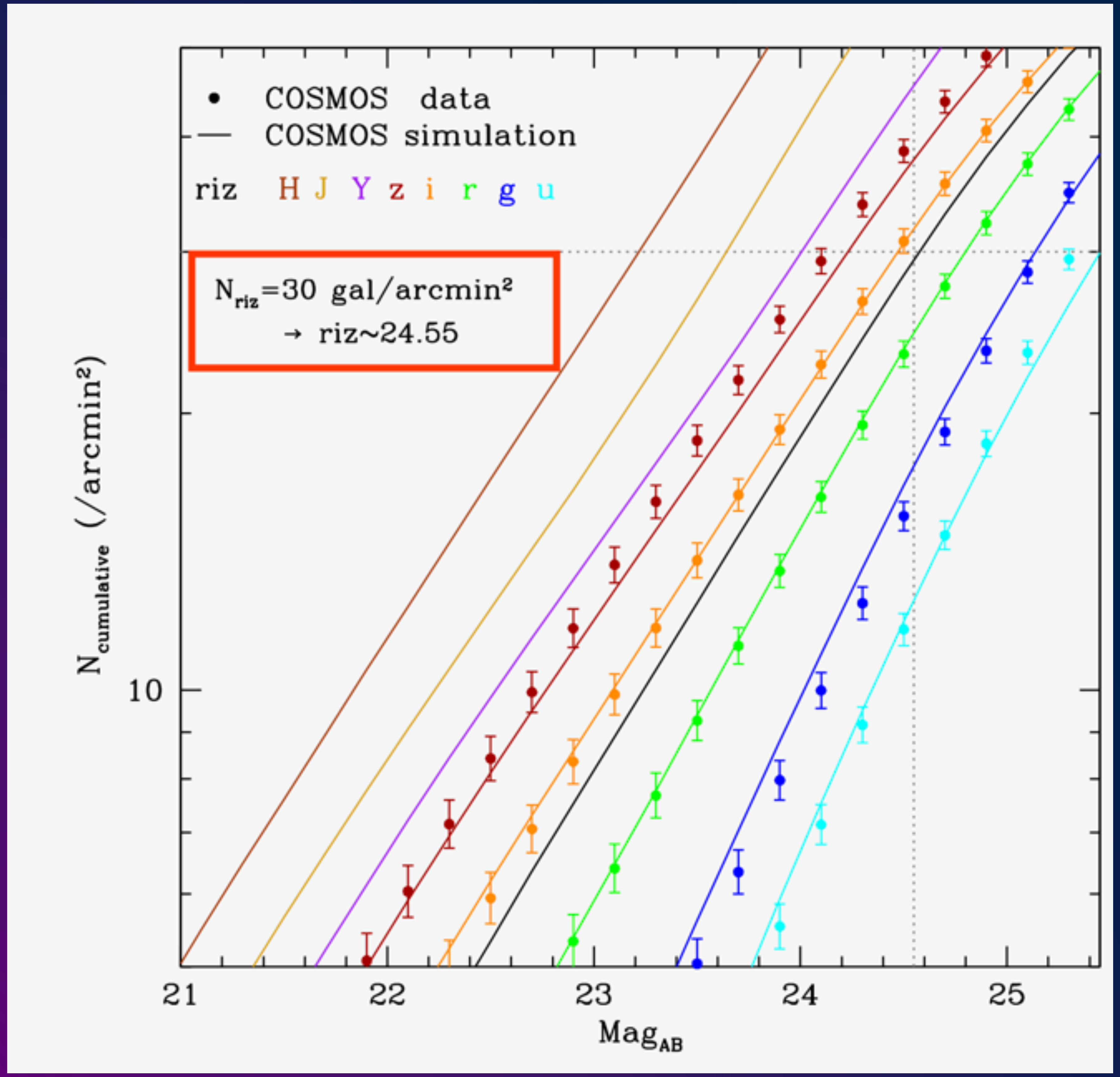
- Galactic plane
- BOSS
- UNIONS−u area goal : 9,000 deg.^{2}
- UNIONS−r area goal : 4,800 deg.^{2}
- UNIONS−u covered with 3 exposures (full depth) : 7195 deg.^{2}
- UNIONS−r covered with 3 exposures (full depth) : 4382 deg.^{2}

Plot&PI: Jean-Charles Cuillandre

Euclid photometry

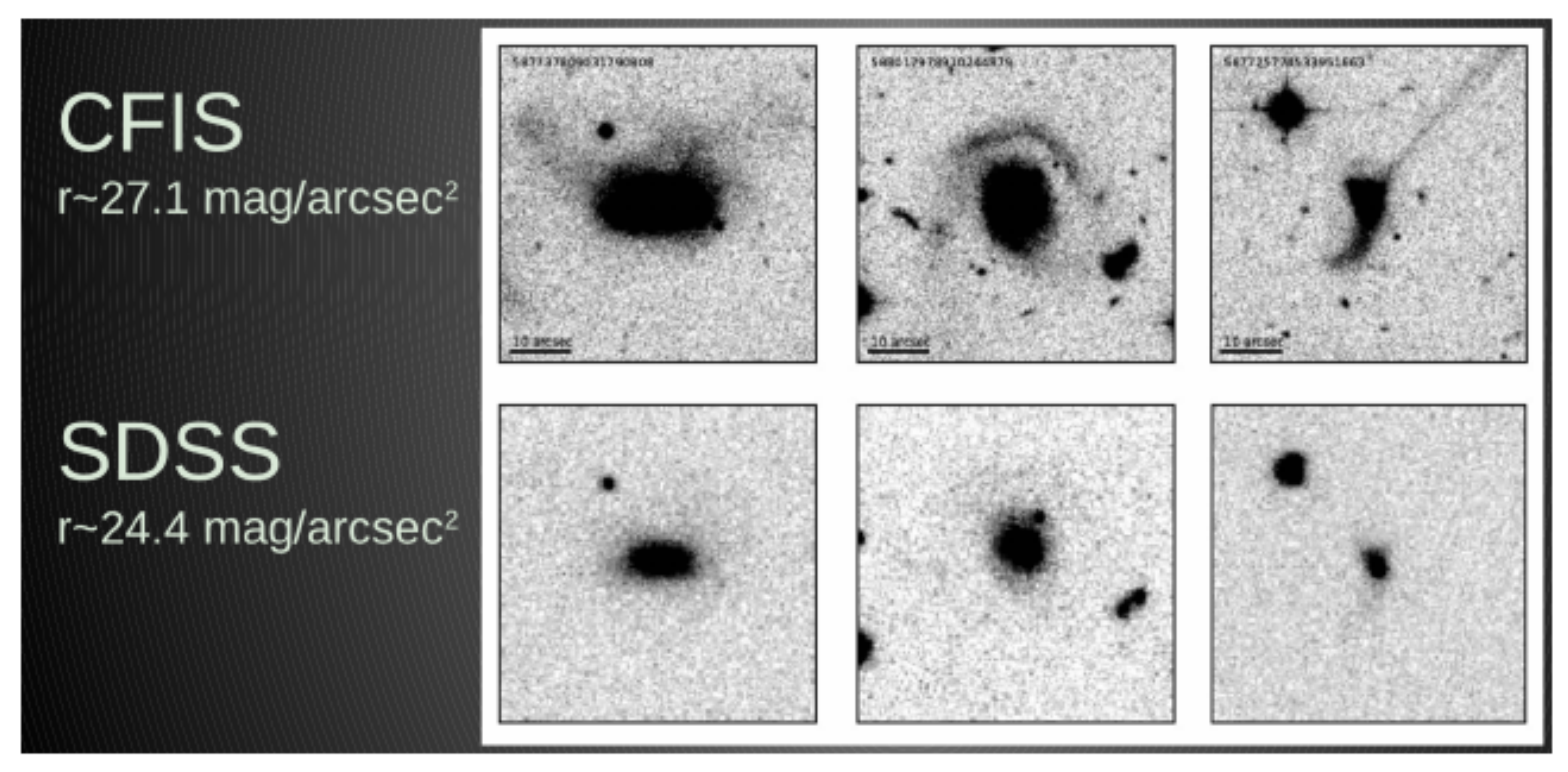
Photometry requirements set using COSMOS to reach N=30 gal/arcmin^2
Number density for photometry very different from lensing density!





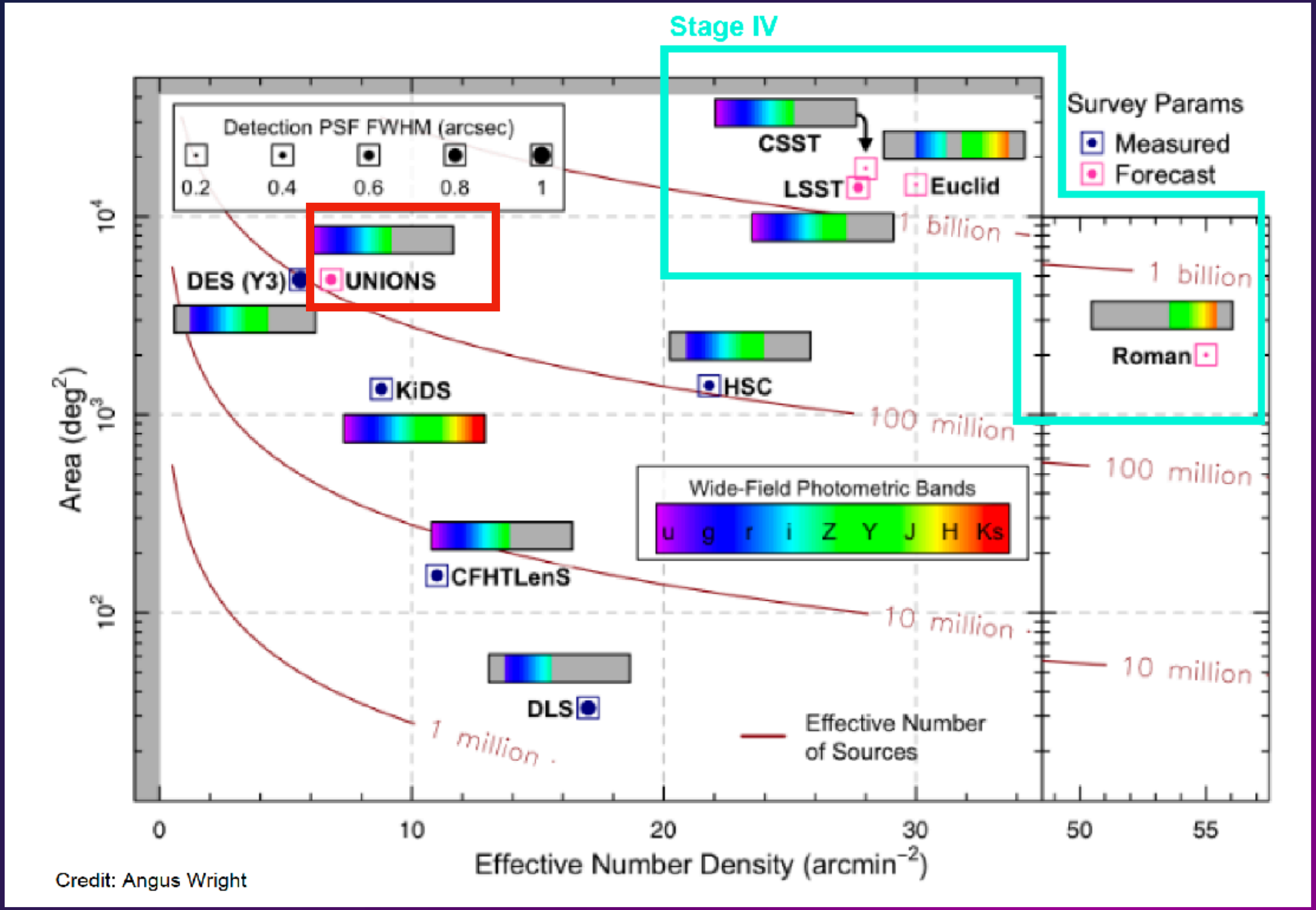
Credit: S. Arnouts

Competitive seeing for weak-lensing



The Landscape of lensing surveys

UNIONS: **U**ltraviolet **N**ear-**I**nfrared **O**ptical **N**orthern **S**urvey

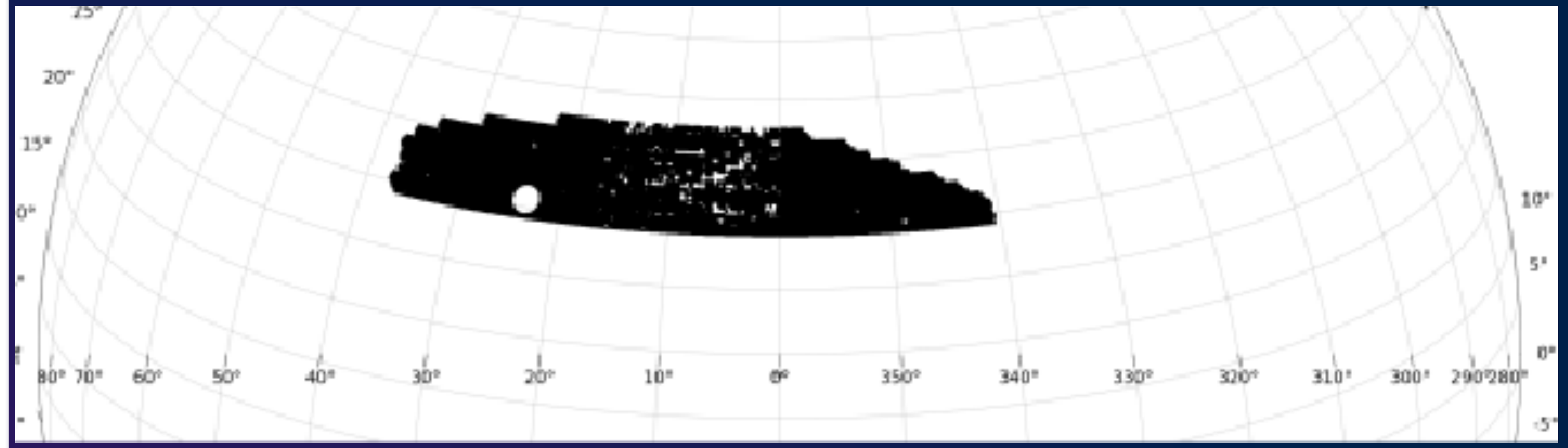


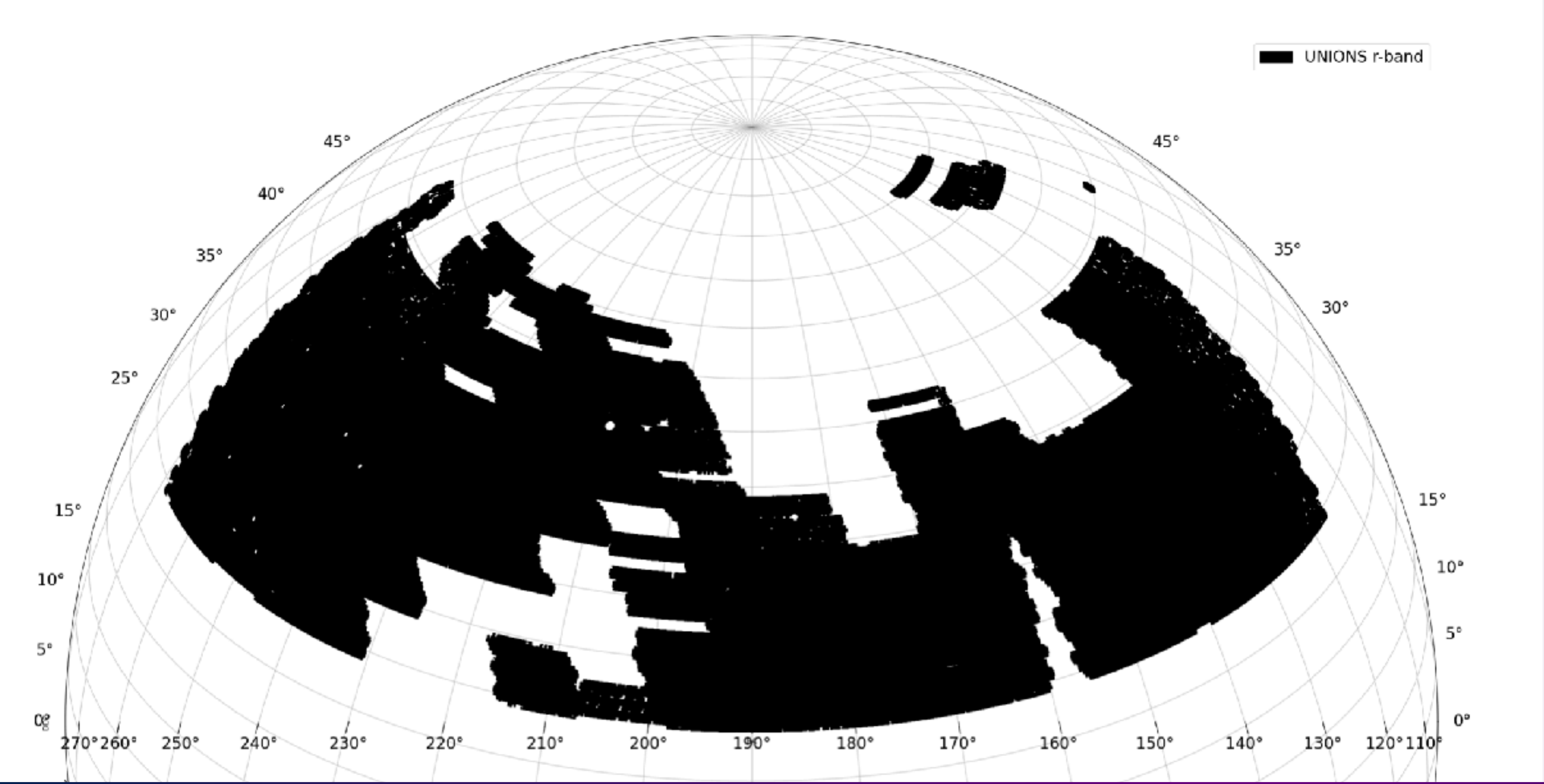
Technical specifications of UNIONS:

- Meant to cover 5000 deg^2, so far 3500 deg^2 processed
- Depth of 24.5 mag (in the r -band)
- Excellent seeing $\approx 0.69''$ in r-band
- u, g, r, i, and z coverage
- Processing was done with the ShapePipe pipeline (Farrens 2022)
- Systematics and first 1500 deg^2 catalog (Guinot 2022)
- ≈ 100 million galaxies

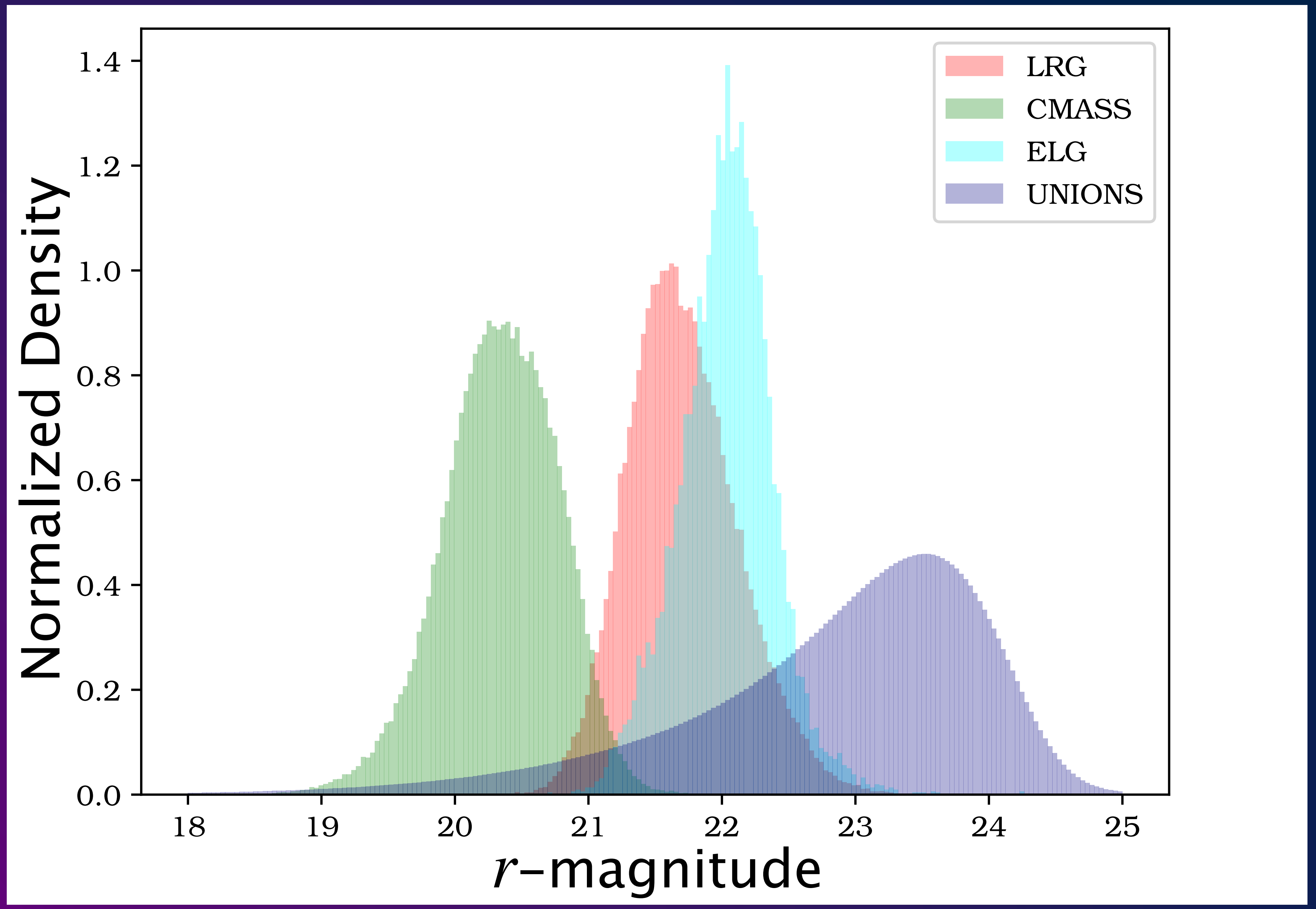
UNIONS Footprint

Southern Galactic Cap





Northern Galactic Cap



Magnitude distribution

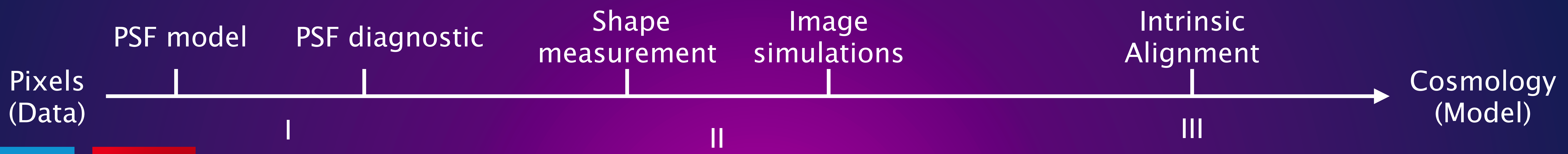
UNIONS status

I) PSF modelling & systematic diagnostics

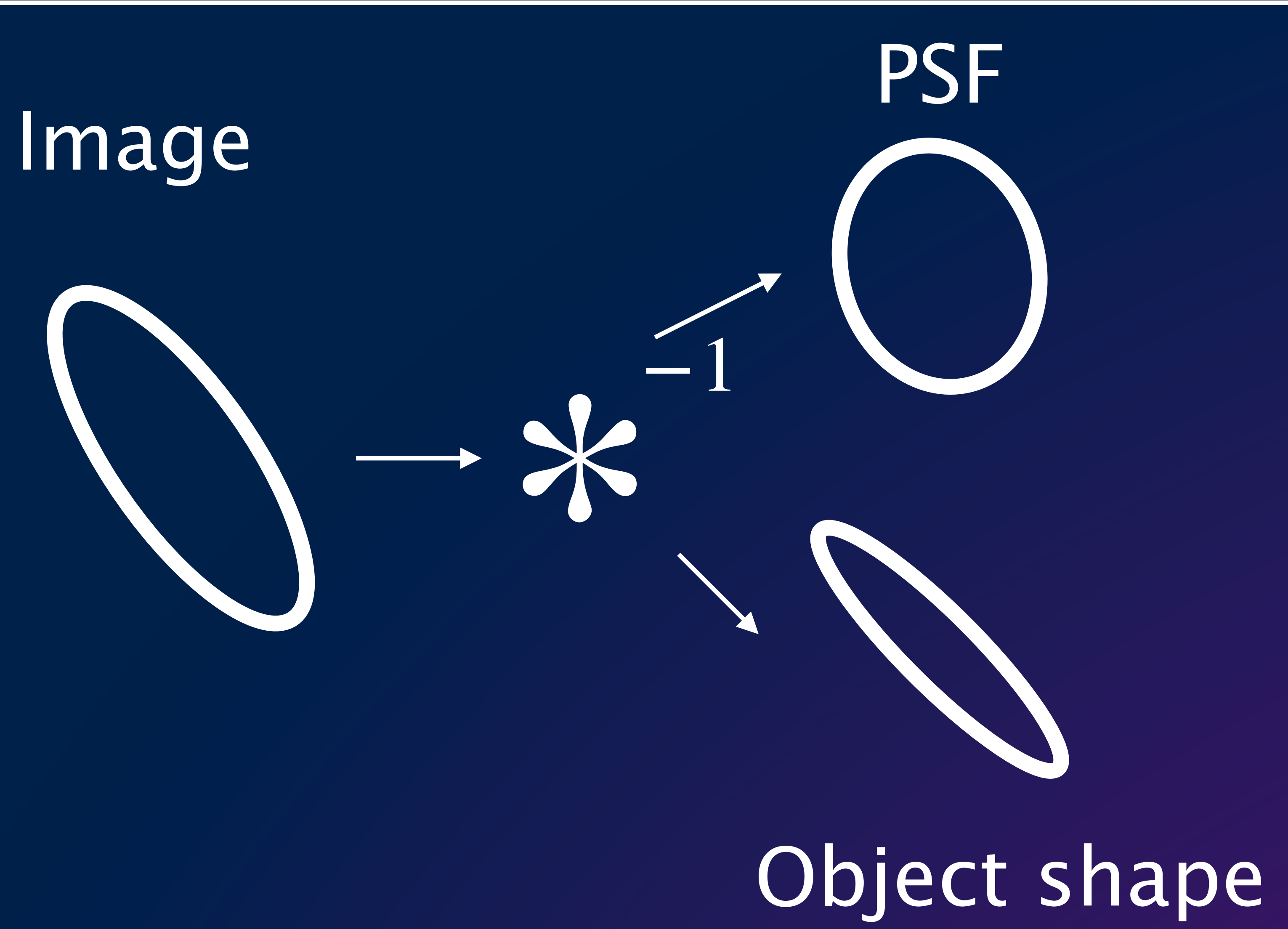
II) Shape measurement & image simulations

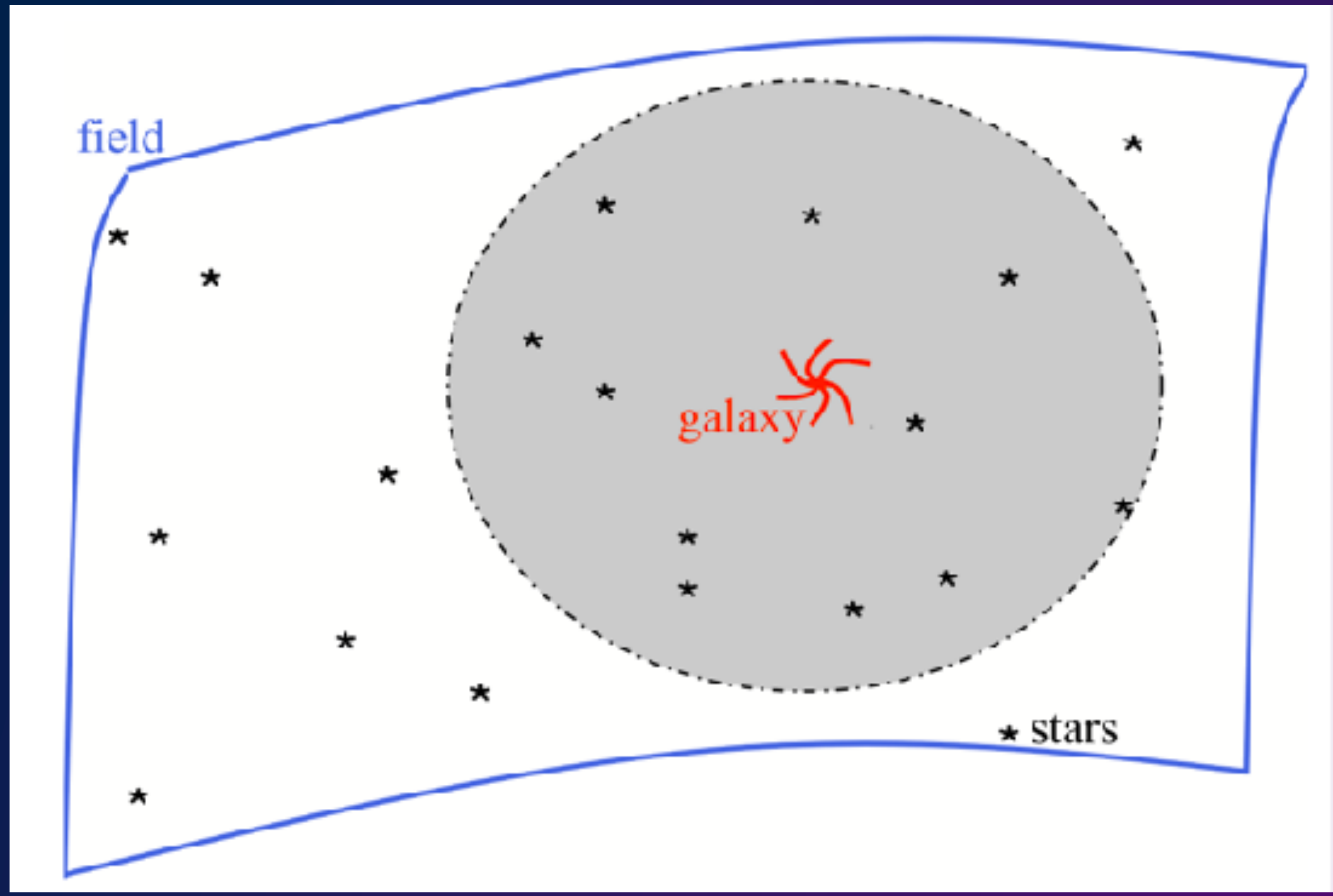
III) Direct measurement of intrinsic alignment with UNIONSxBOSS/eBOSS

IV) UNIONS overview & future synergies



I) PSF model





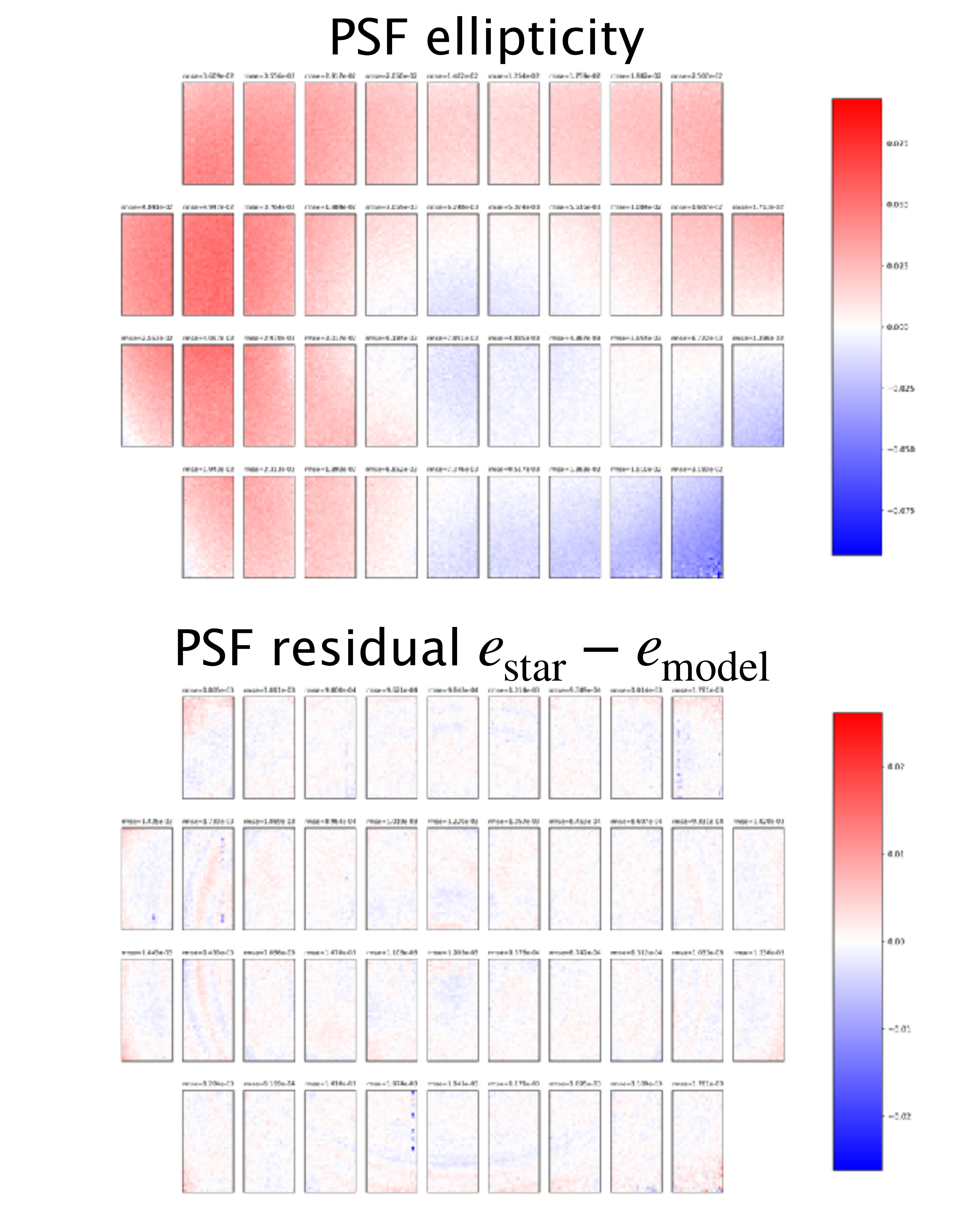
Credit: Paulin-Henriksson 2008

2 PSF models:

PSFEx (Bertin 2011)
- CCD by CCD modelling
- Fewer parameters
- Simple but robust

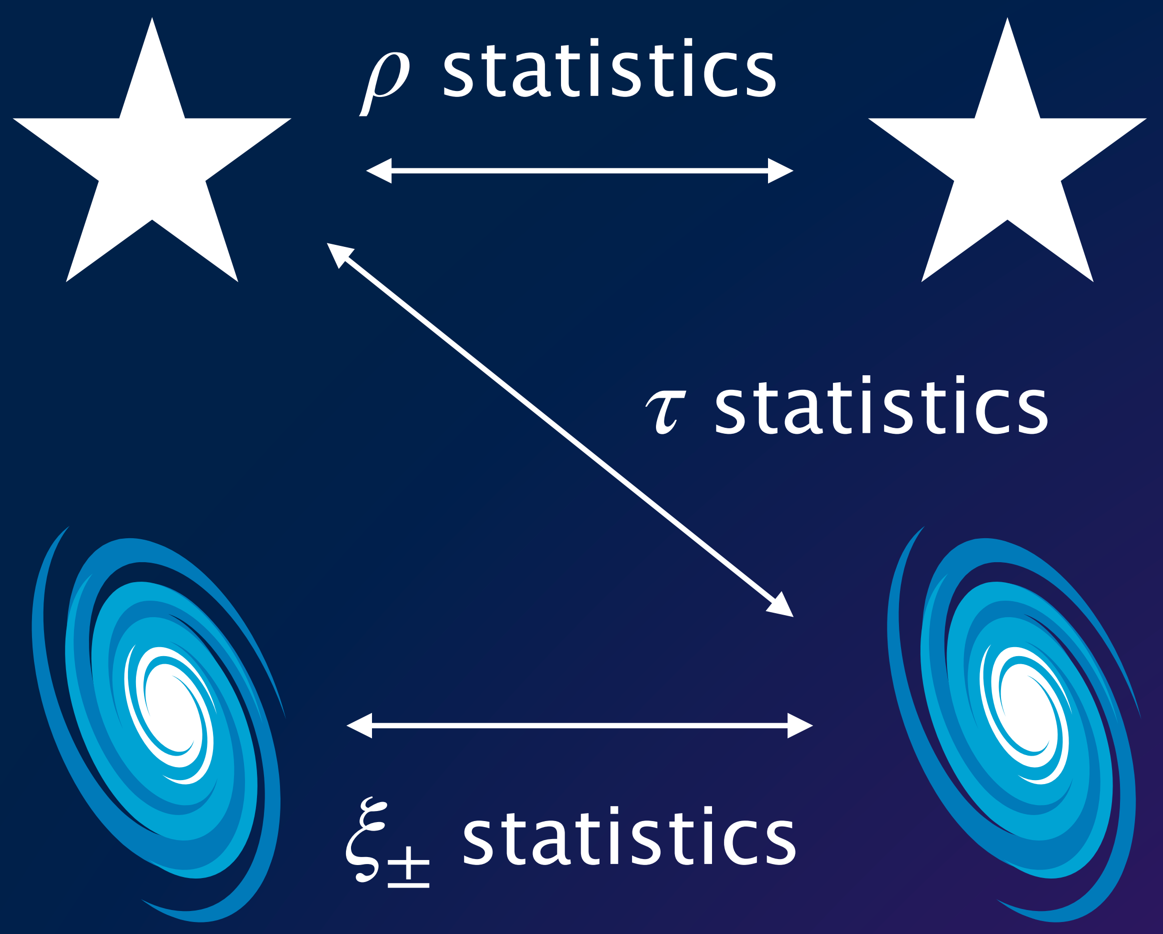
MCCD (Liaudat 2022)
- Models the full focal plane
- Can capture variation across the camera
- More parameters

For validation
→ 80% training stars, 20% validation stars



Credit: Axel Guinot

I) PSF diagnsotics

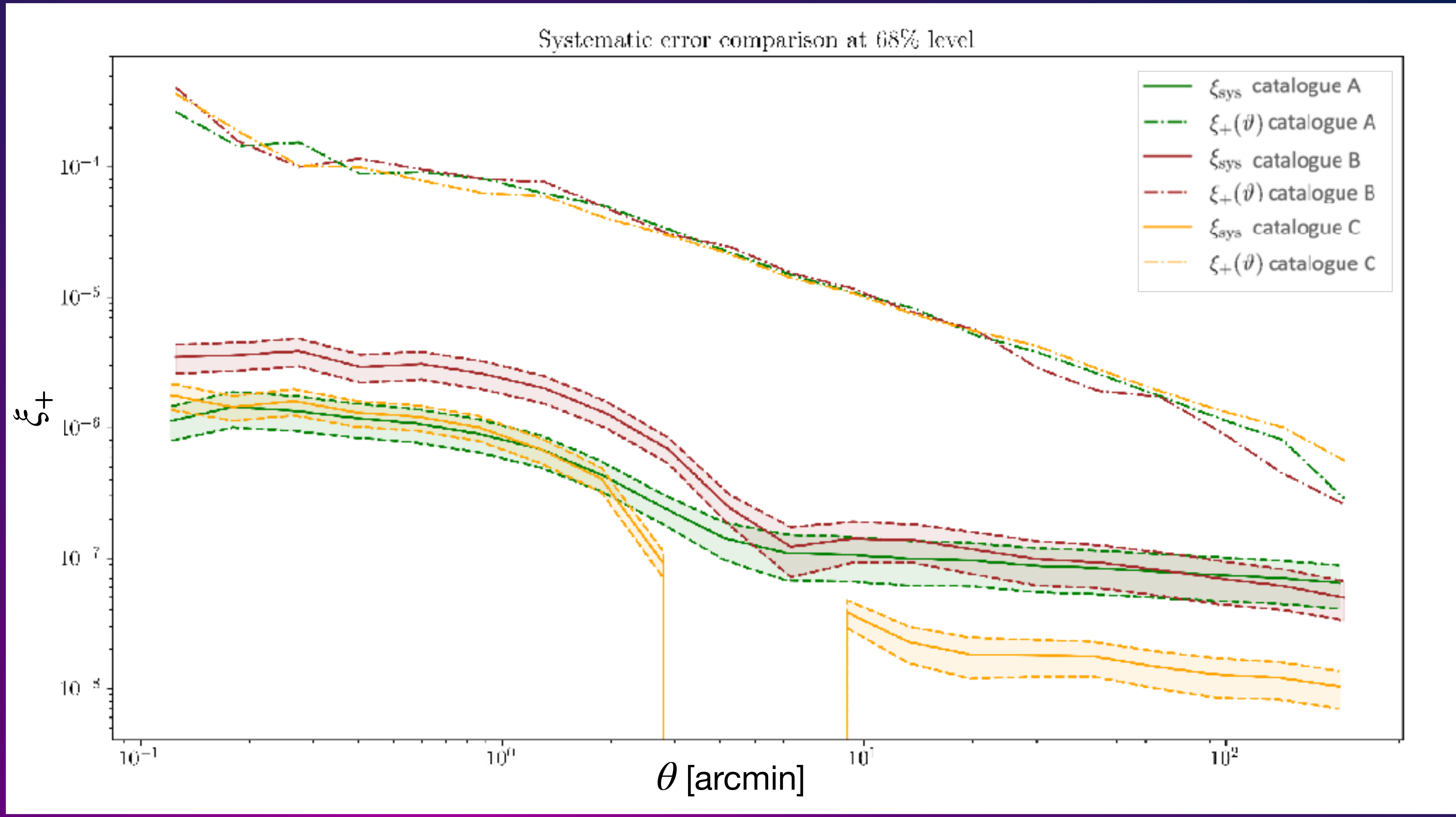


We can build an error model for our galaxy elipticities:

$$\delta e = c + \alpha\, e^{\text{PSF model}} + \beta \left(e^{star} - e^{\text{PSF model}}\right) + \eta \left(e^{star}\, \frac{T^{\text{star}} - T^{\text{PSF model}}}{T^{\text{star}}}\right)$$

Leakage $\langle e^{\text{gal}} e^{\text{PSF}} \rangle$ Ellipticity error Size error

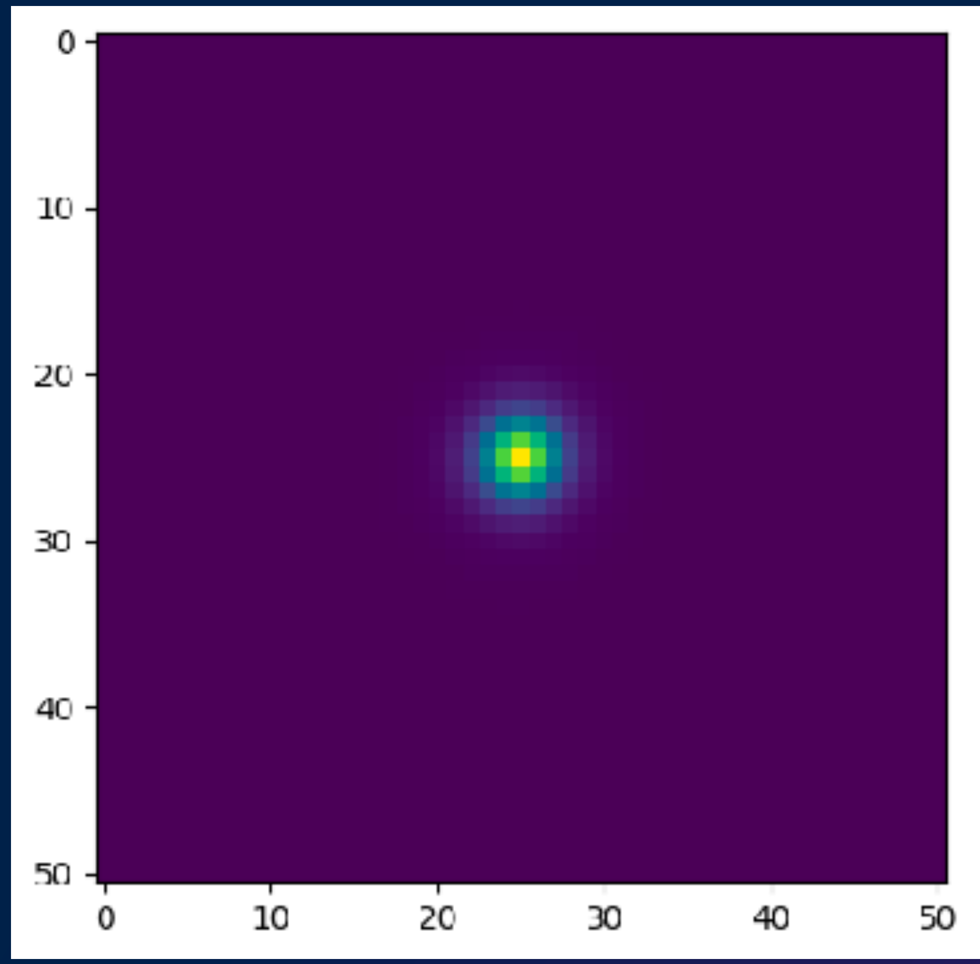
PSF error contribution ξ_{sys} to the cosmological shear $\xi_\pm = \xi_{\text{shear}} + \xi_{\text{sys}}$:



Credit: Sacha Guerrini

II) Shape measurement

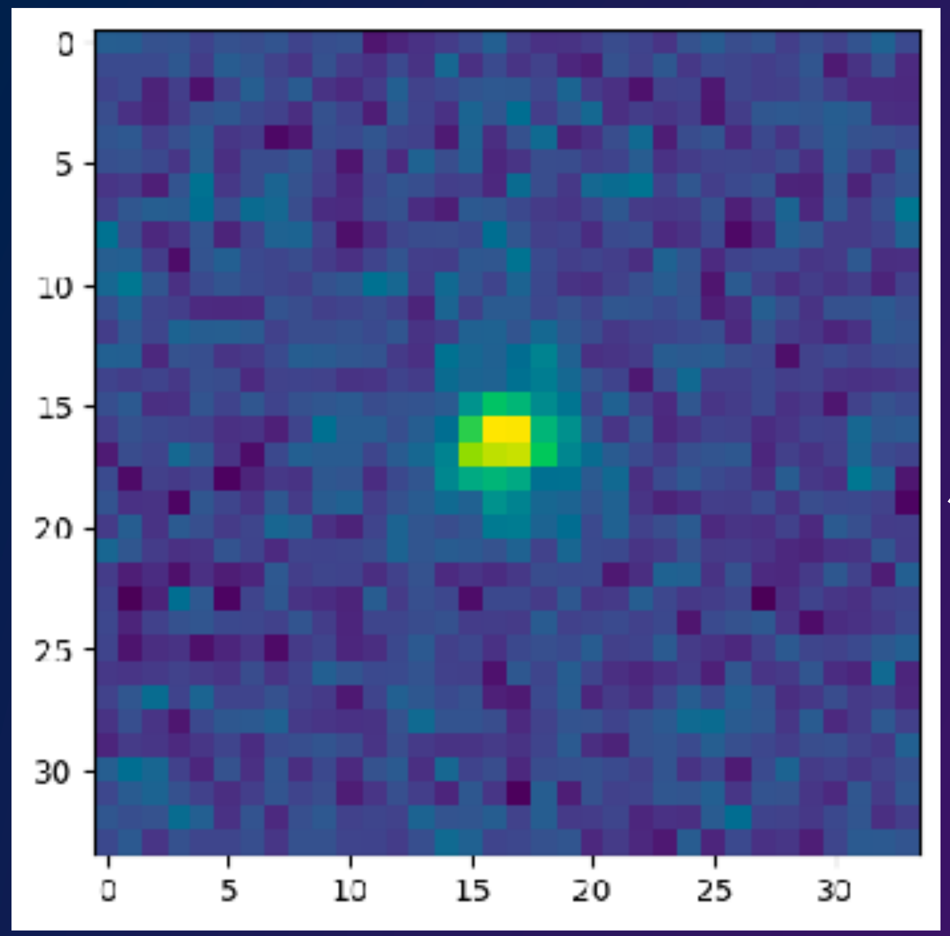
Initial PSF stamp



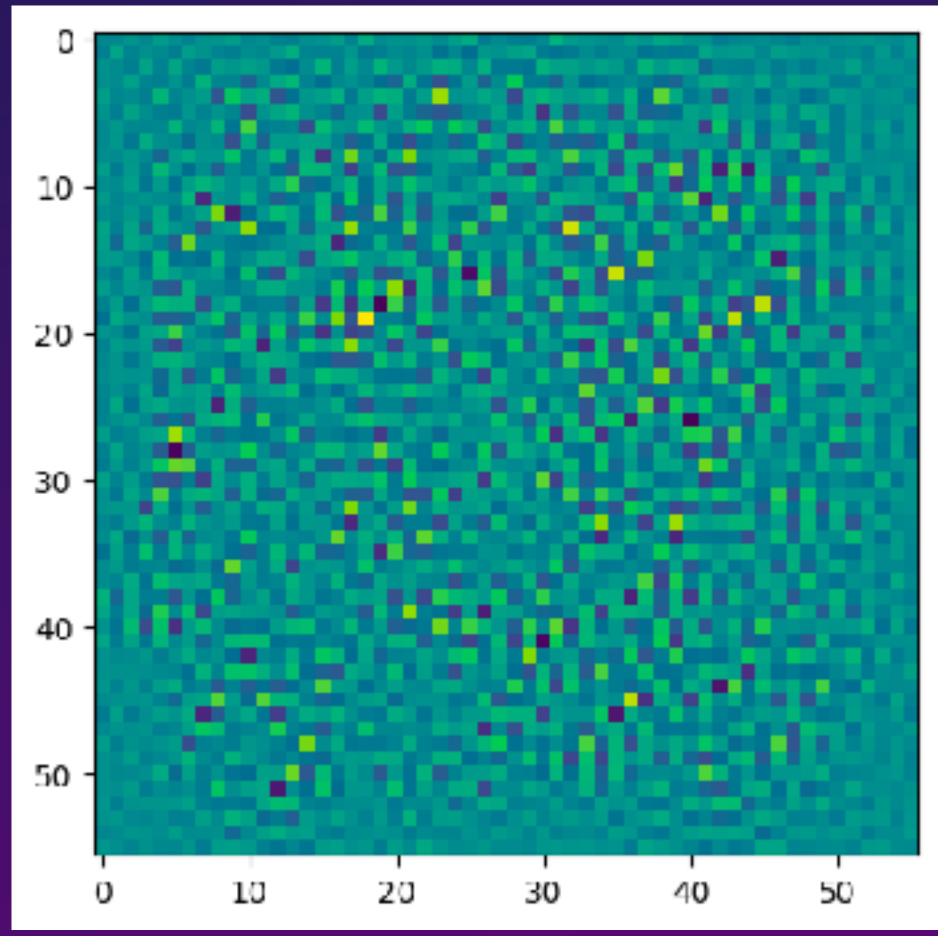
Metacalibration/ngmix

How well does my shape measurement method capture a kown change in ellipticity?
→ estimate a shear response

Initial galaxy stamp (SNR 120):



Deconvolve →



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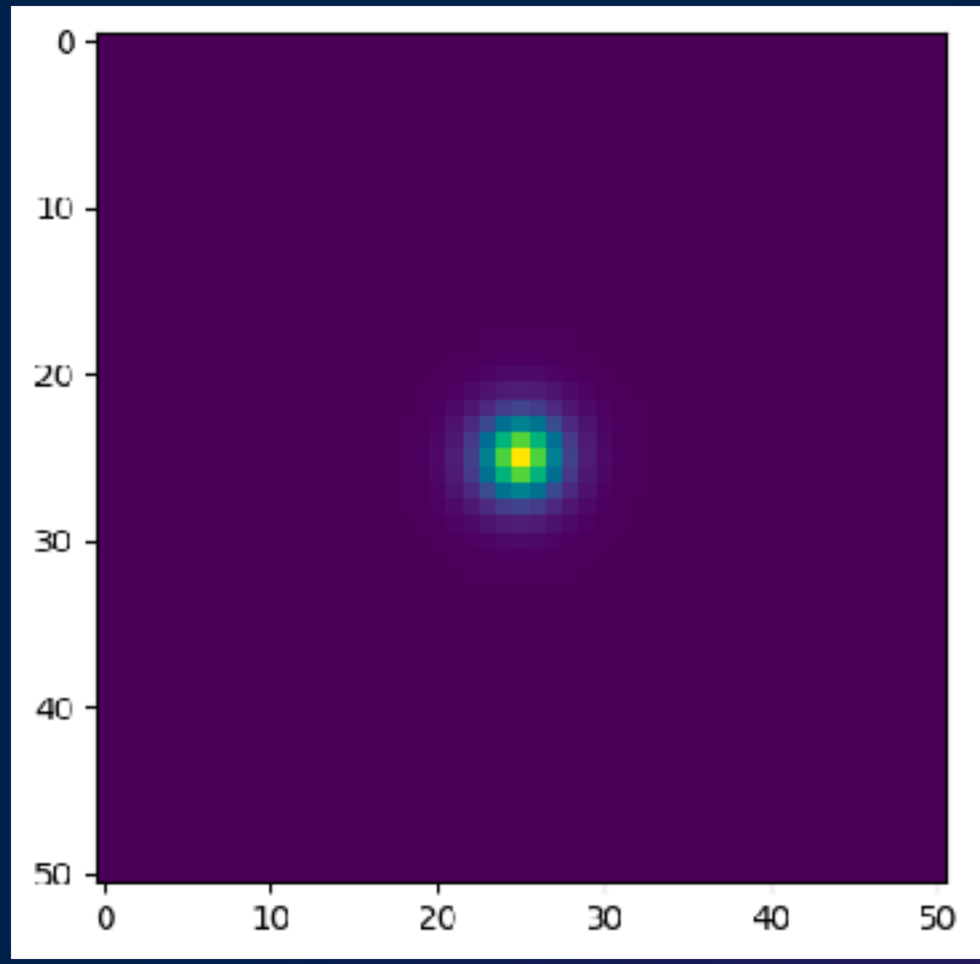

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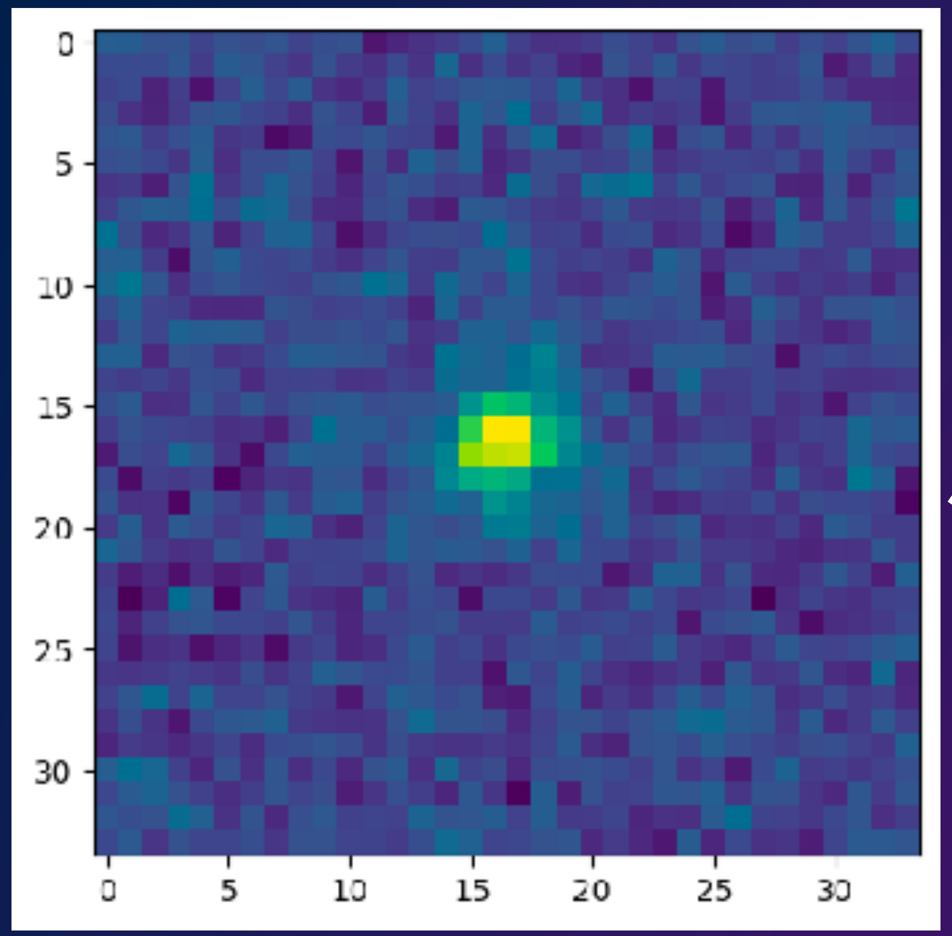
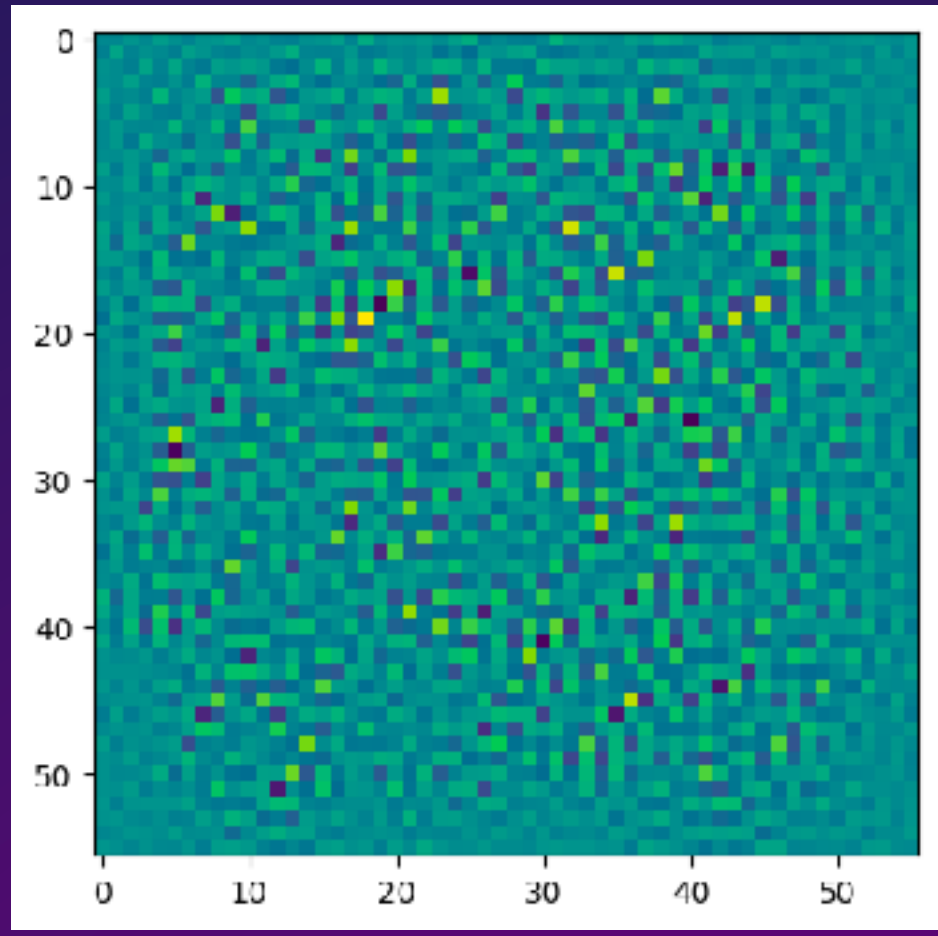
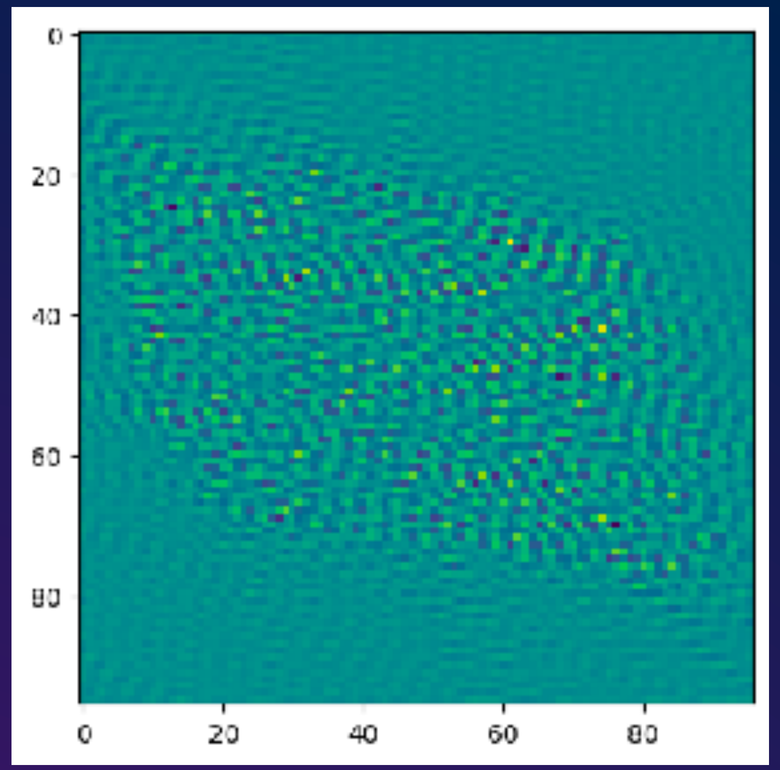


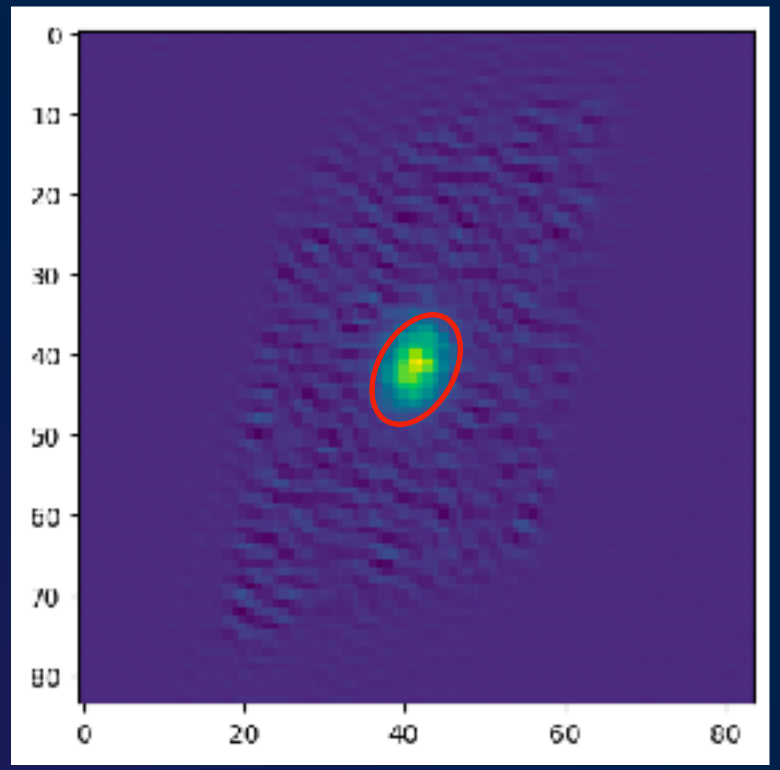
Deconvolve

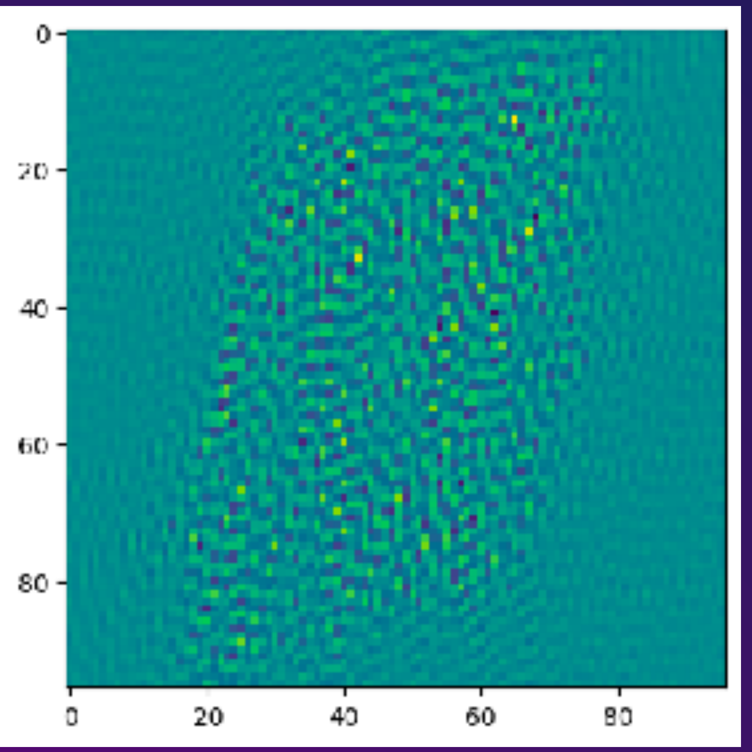


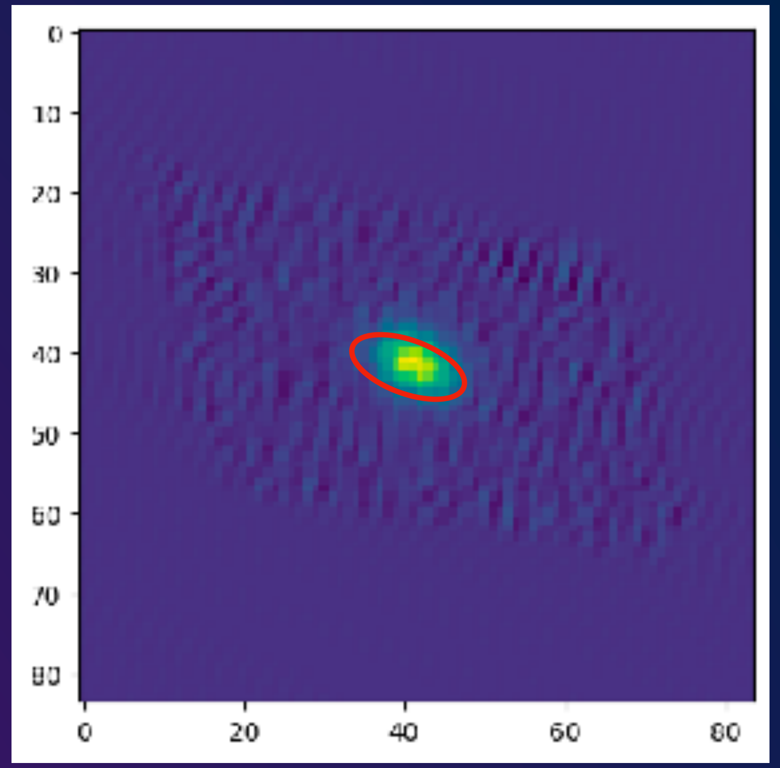
Shear $\Delta\gamma$

4 copies $(\epsilon_{1,+}, \epsilon_{1,}, \epsilon_{2,+}, \epsilon_{2,-})$ + unsheared







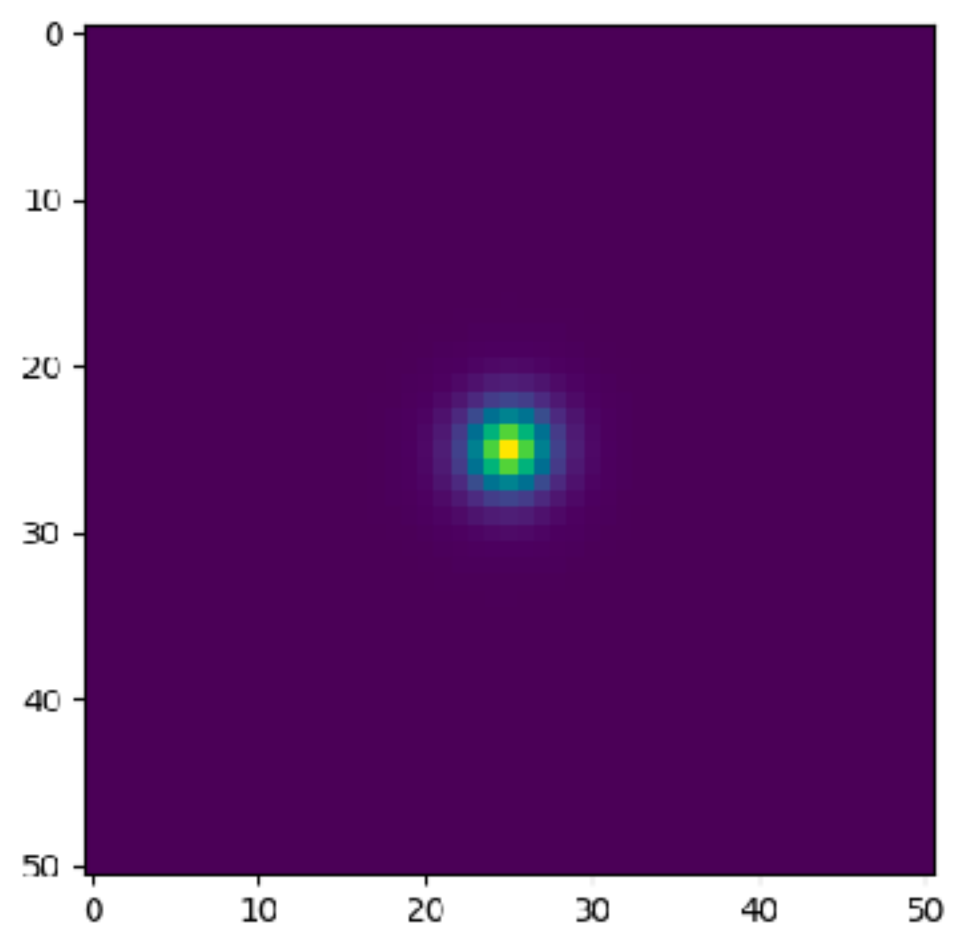


Convolve By dilated PSF

Fit 2D gaussian Covolved with fixed PSF

II) Shape measurement

Initial PSF stamp



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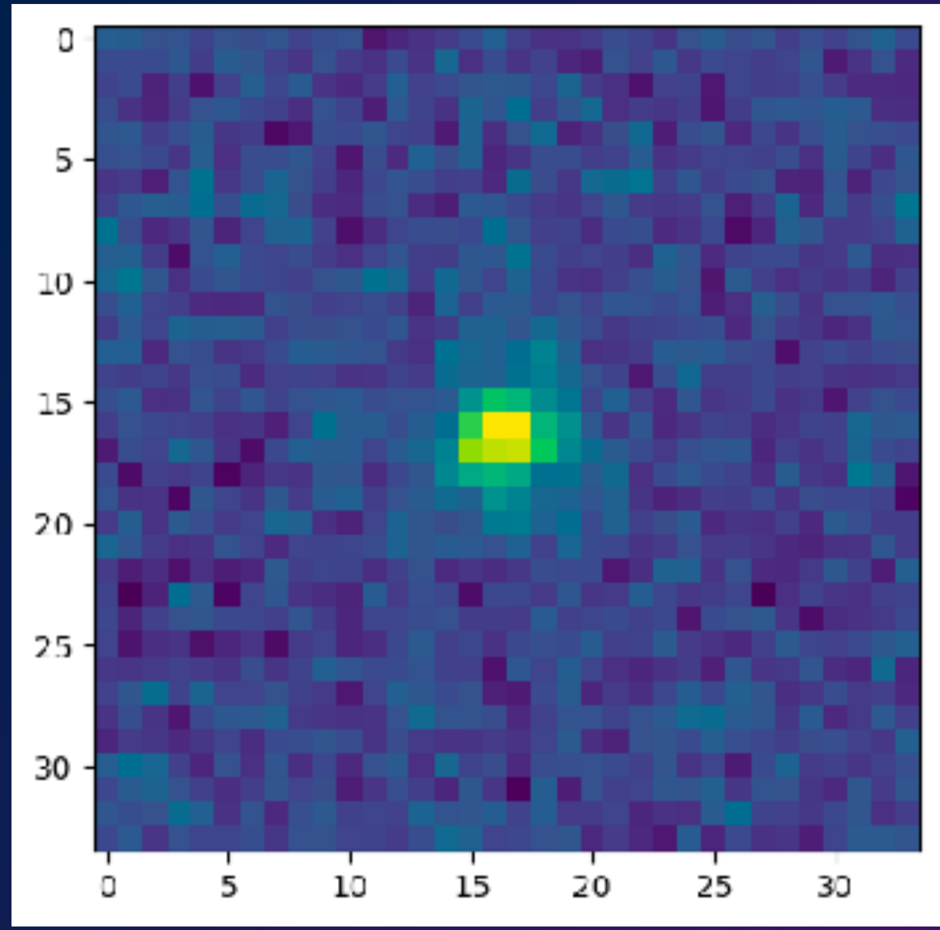
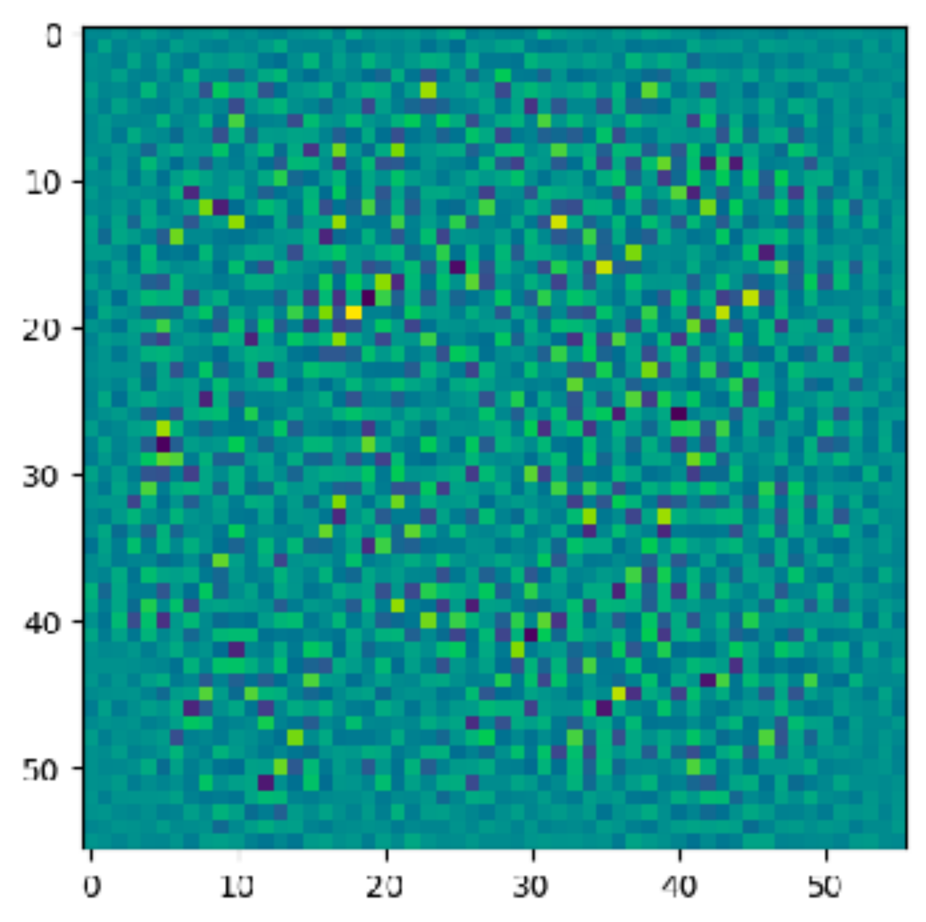
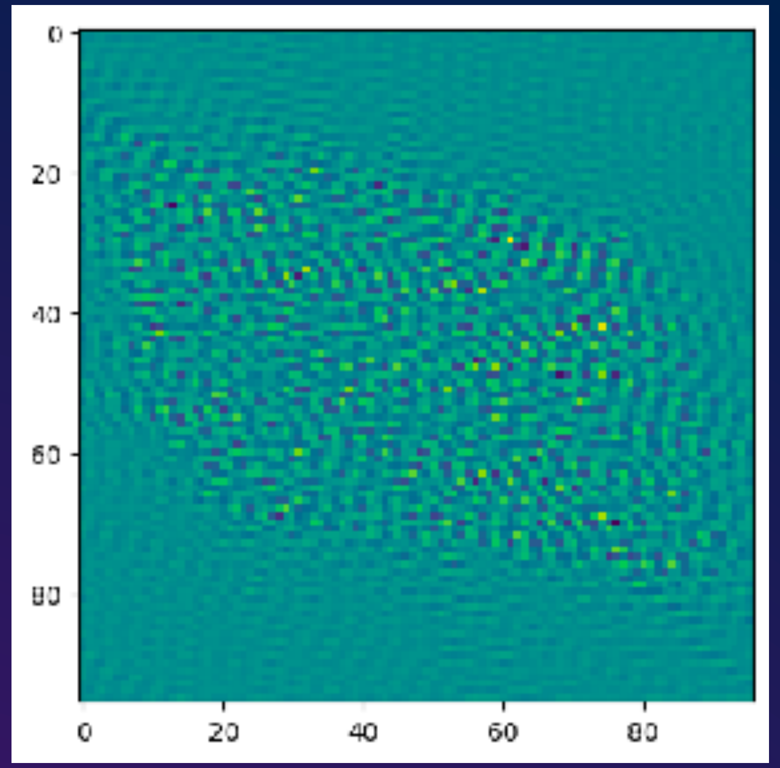


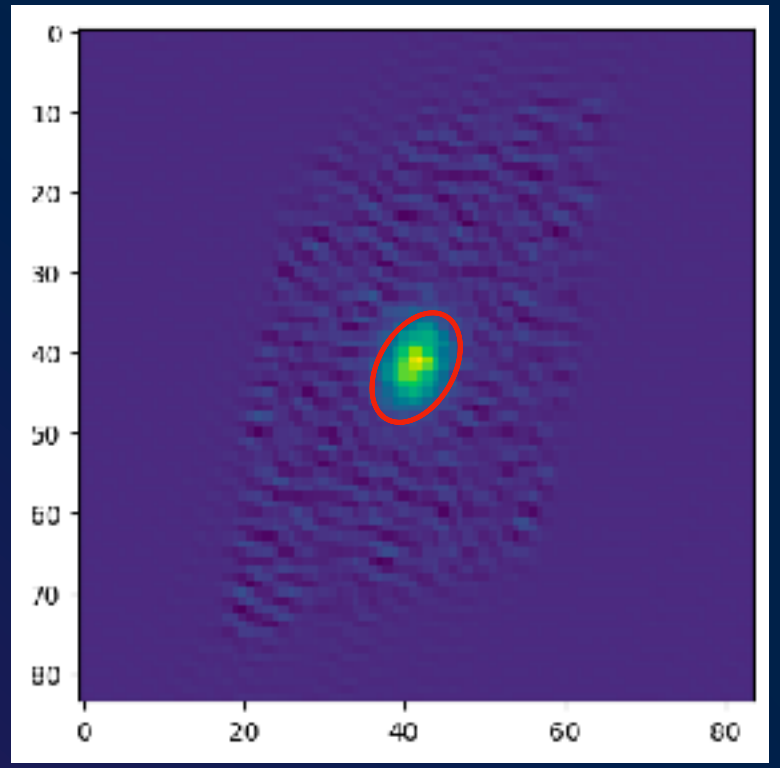
Deconvolve →

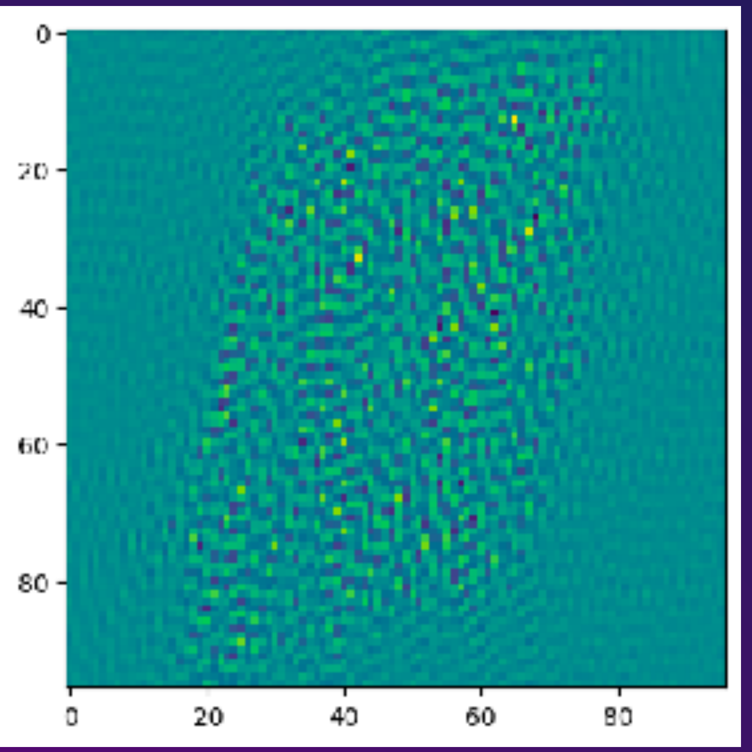


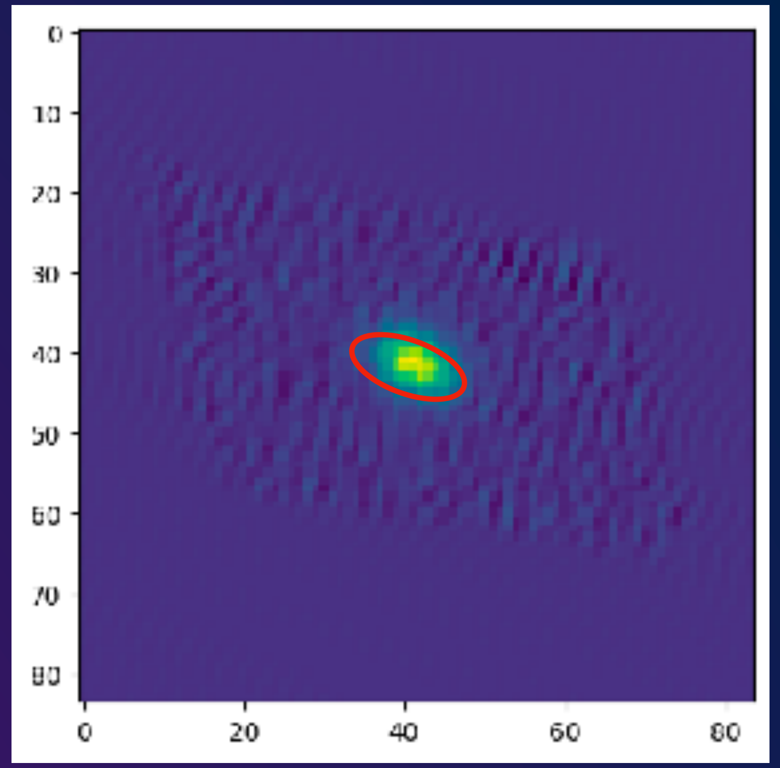
Shear $\Delta\gamma$

4 copies $(\epsilon_{1,+}, \epsilon_{1,-}, \epsilon_{2,+}, \epsilon_{2,-})$ + unsheared









Convolve By dilated PSF

Fit 2D gaussian Covolved with fixed PSF

Finite difference shear response:

$$R_{\gamma_{i,j}} = \frac{\epsilon_i^+ - \epsilon_i^-}{\Delta\gamma_j} \qquad \langle\gamma_{calibrated}\rangle = \langle R_\gamma\rangle^{-1}\langle\gamma\rangle$$

Shear biases

$$\gamma_{obs} = (1 + m)\ \gamma_{true} + c$$

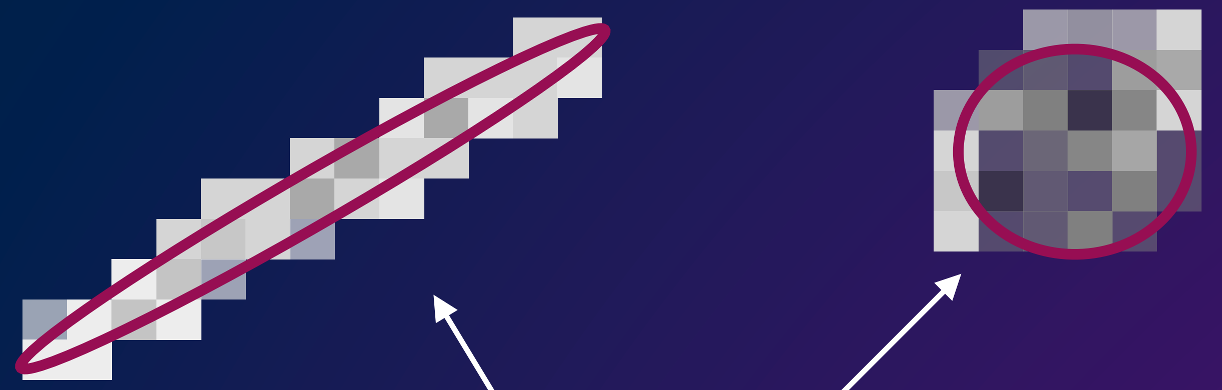
m multiplicative bias

c additive bias

Selection Bias

No detection

Detection



Noise Bias: continuous shape discretised by pixels, ellipticity is non-linear in pixels

Model Bias: Large diversity of morphologies captured by a simple model

Blending Bias: Close or overlapping galaxies might not be well disentangled due to the PSF and can bias the shear

Calibrated with Metacalibration

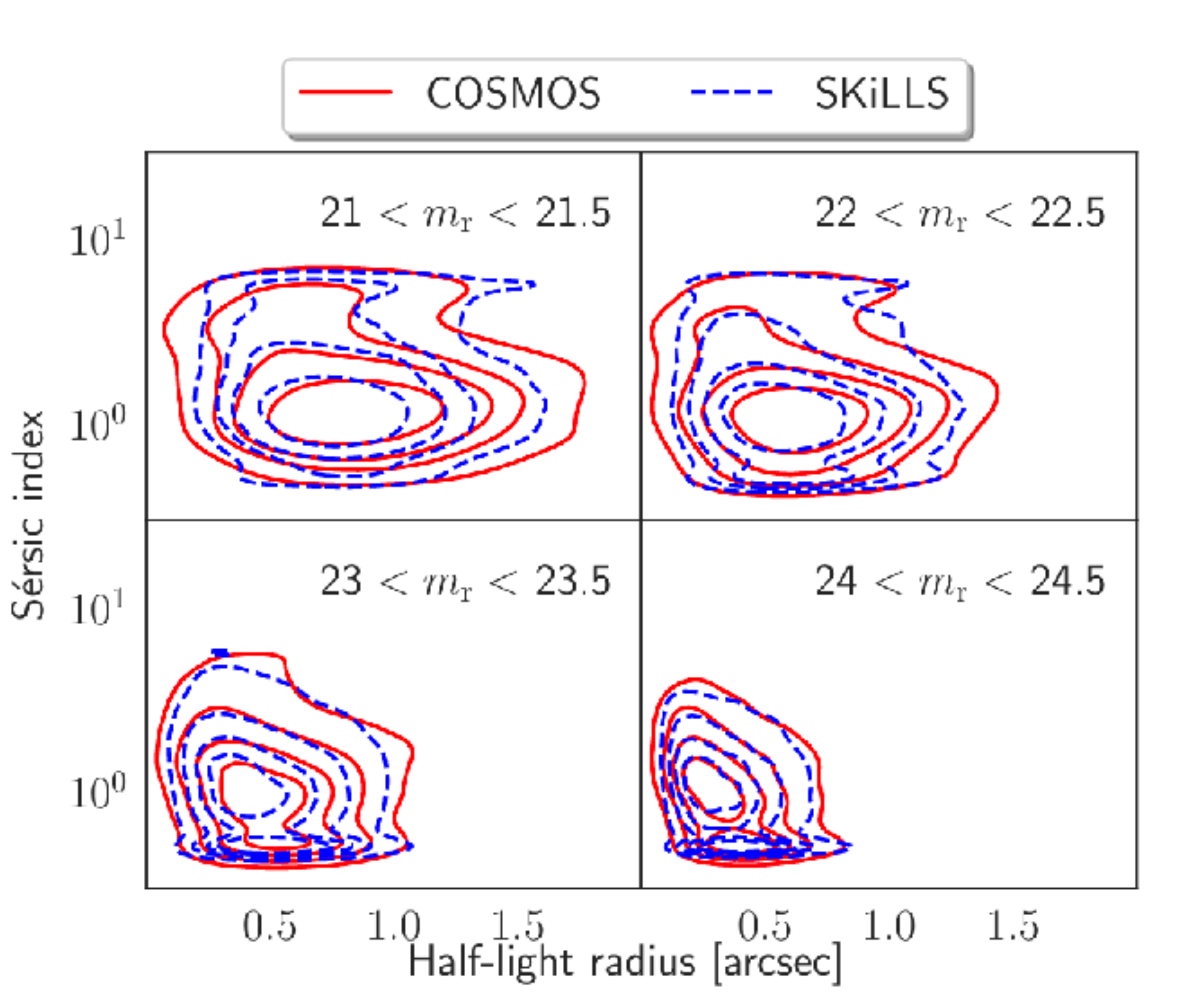
Calibrated with Image simulations (+ redshift biases)

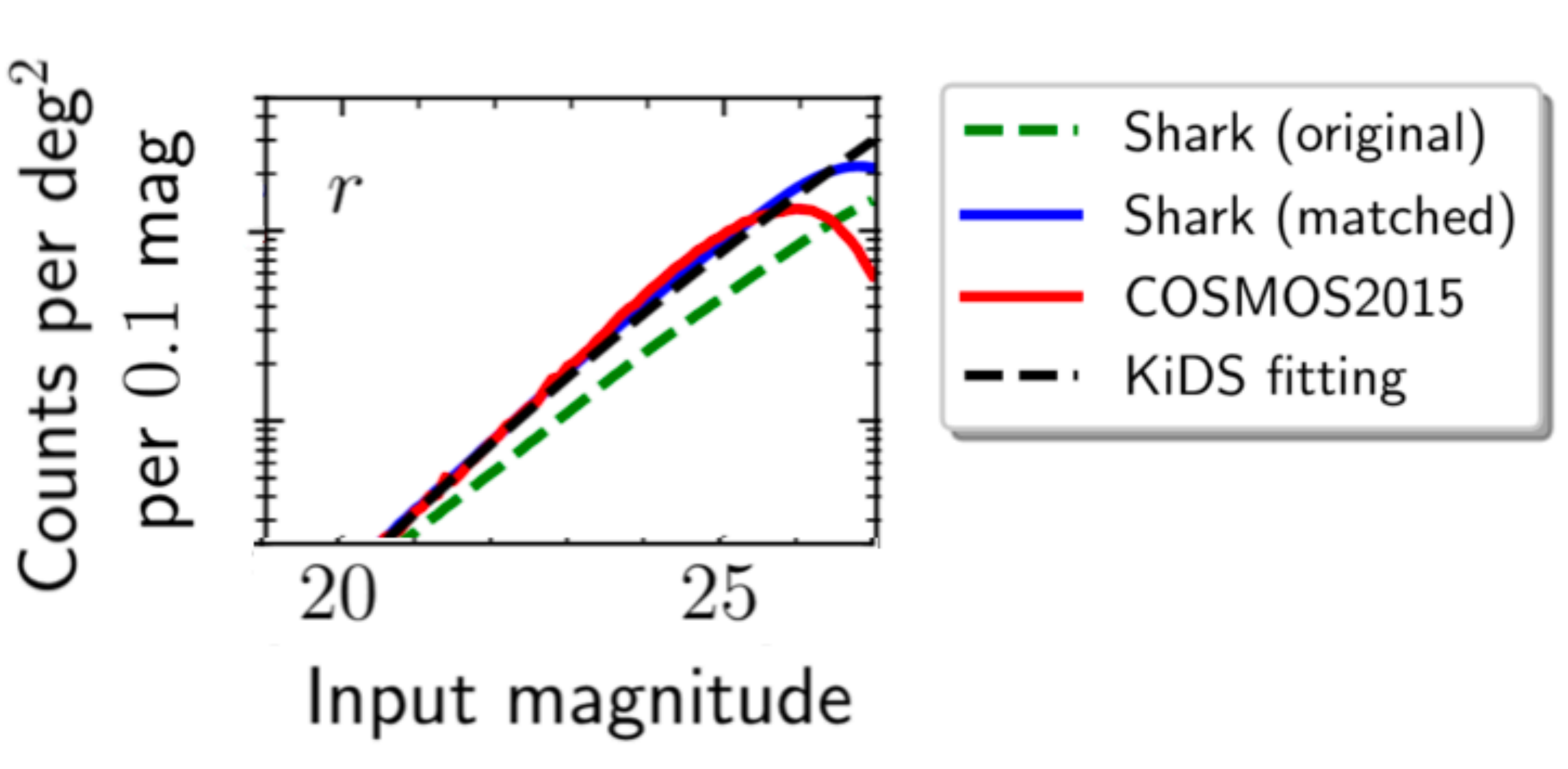
II) Image simulations – Input

Multiple biases need to be accounted for in a shear measurement, for example blending bias:

Input of the image simulations (Li 2023):

- Realistic galaxy distribution from simulations
- Galaxy morphologies from COSMOS
- Star catalog generated with TRILEGAL (Ghirardi)
- Realistic positions from N-body simulations





Credit: Li 2023

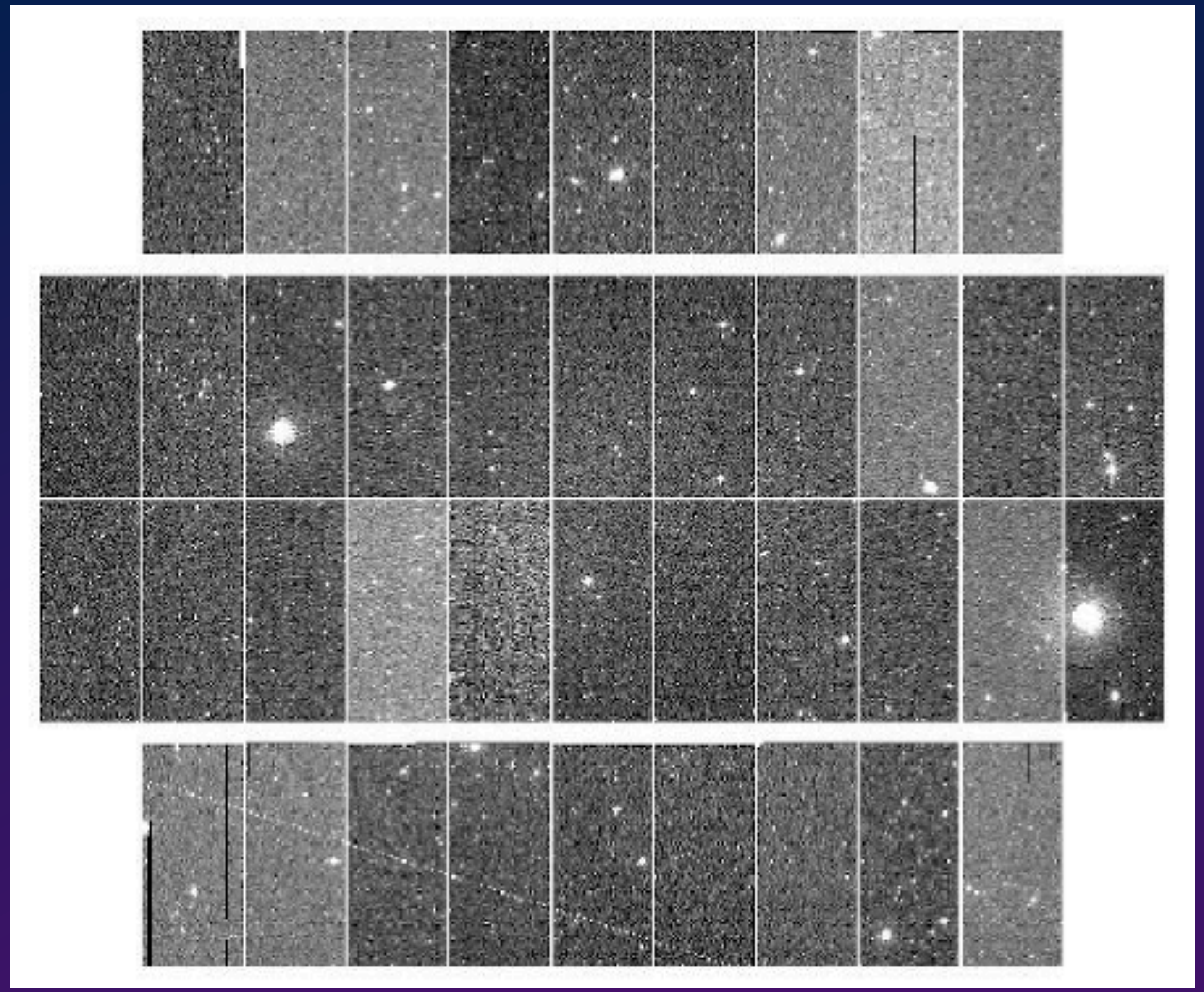
→ we need to match properties like depth, densities, elipticity, size, SNR…

→ simulating 100 deg^2 for calibration & to validate shear measurement

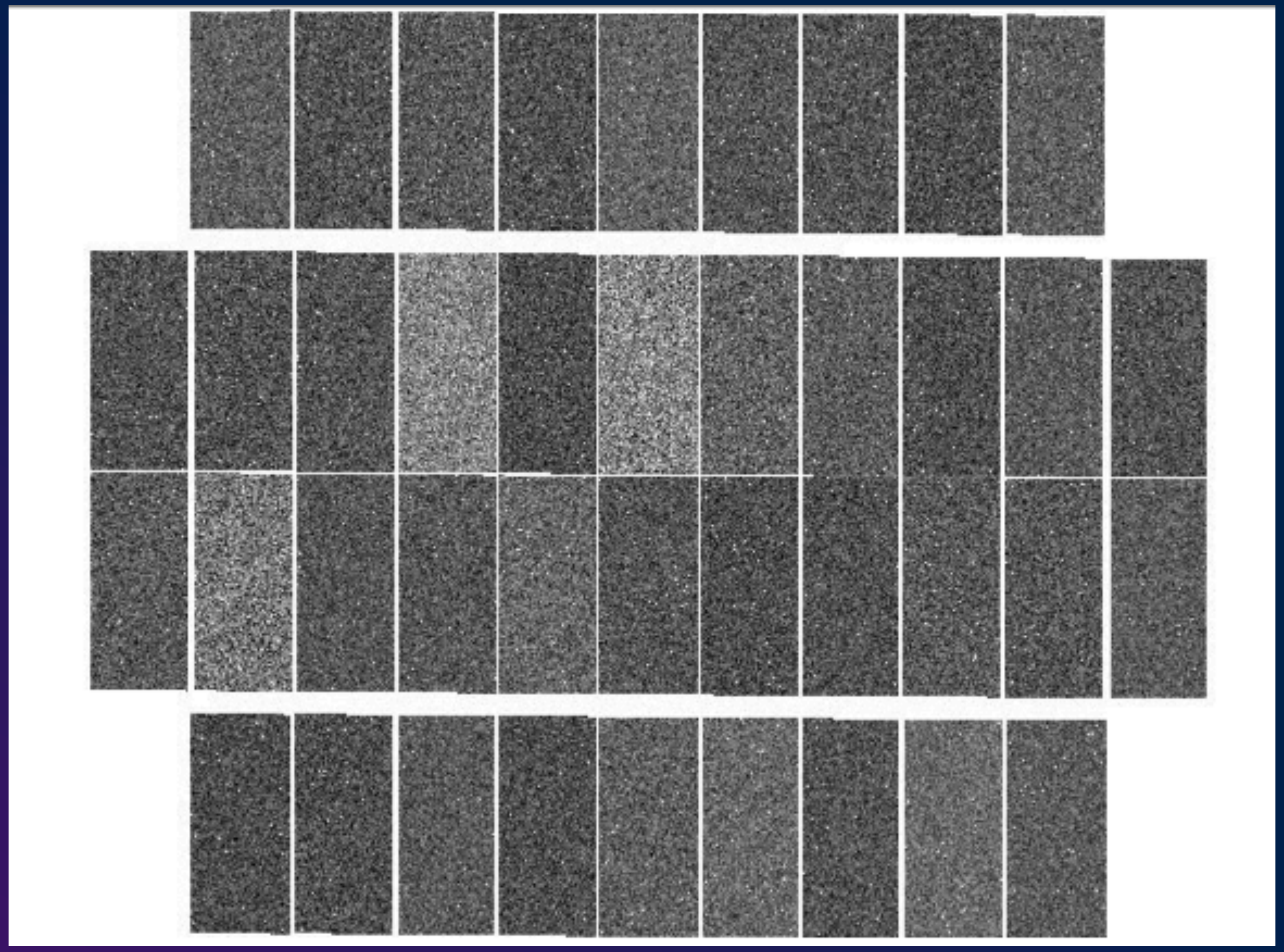
II) Image simulations – Survey strategy

Properties of the survey entering the image simulations:

- Focal plane setup
- Dither pattern (wide dither different from previous surveys)
- Noise (encodes exposure time/depth)
- Draw from our PSF model (Both MCCD and PSFEx)



Real CFHT Exposure



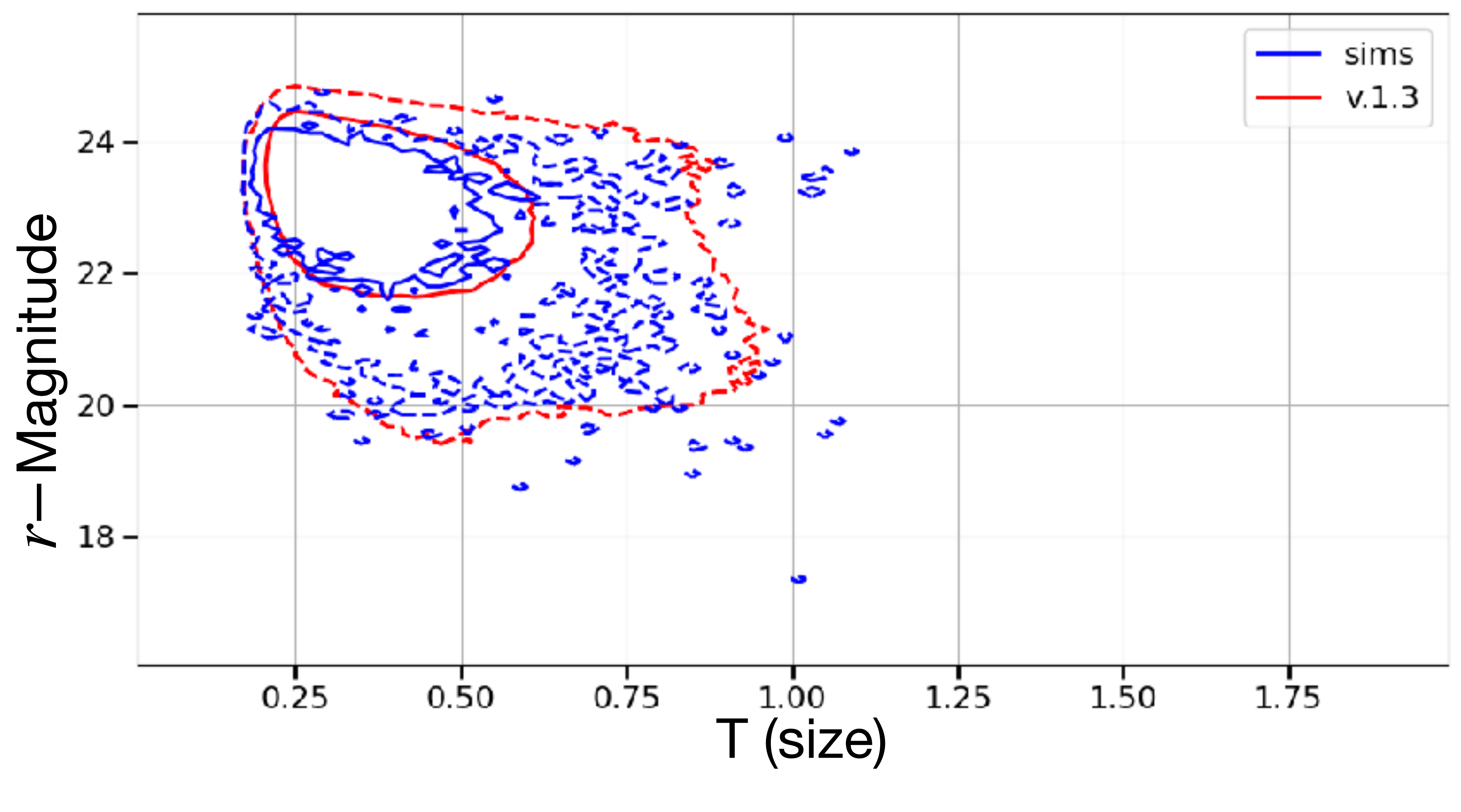
Simulated Exposure

Credit: Gwyn

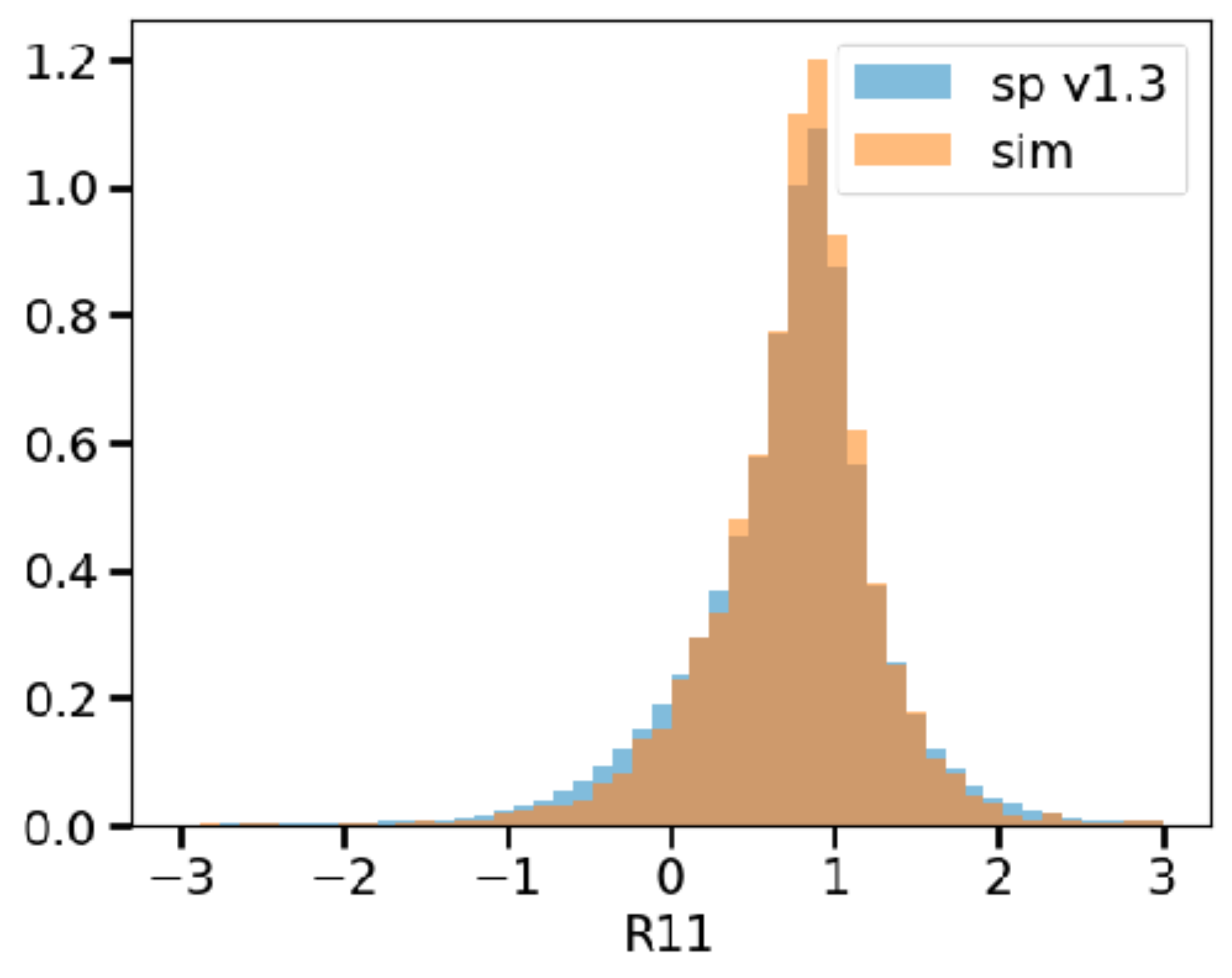
II) Image simulations – Realistic properties (preliminary)

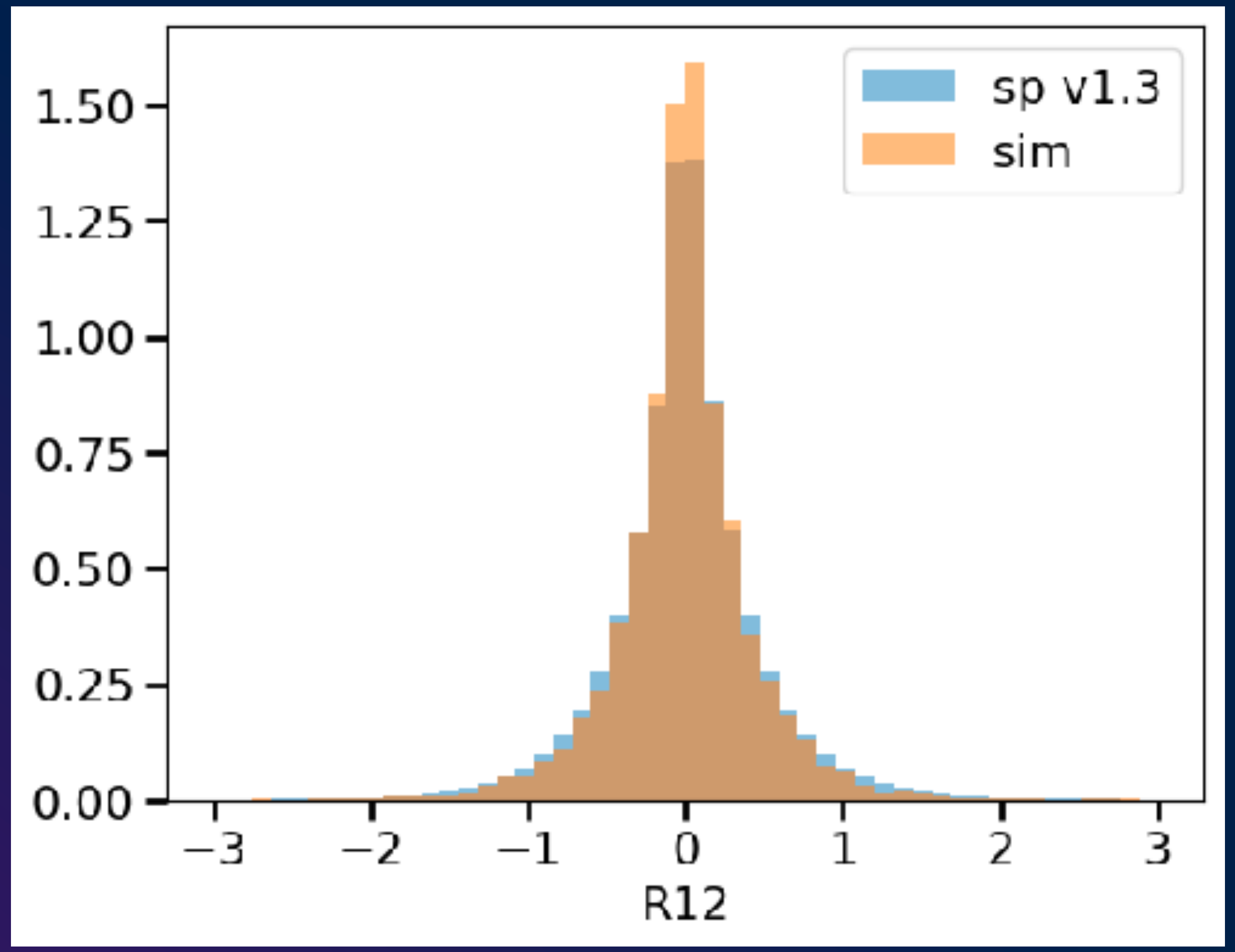
After running the shape measurement pipeline ShapePipe:

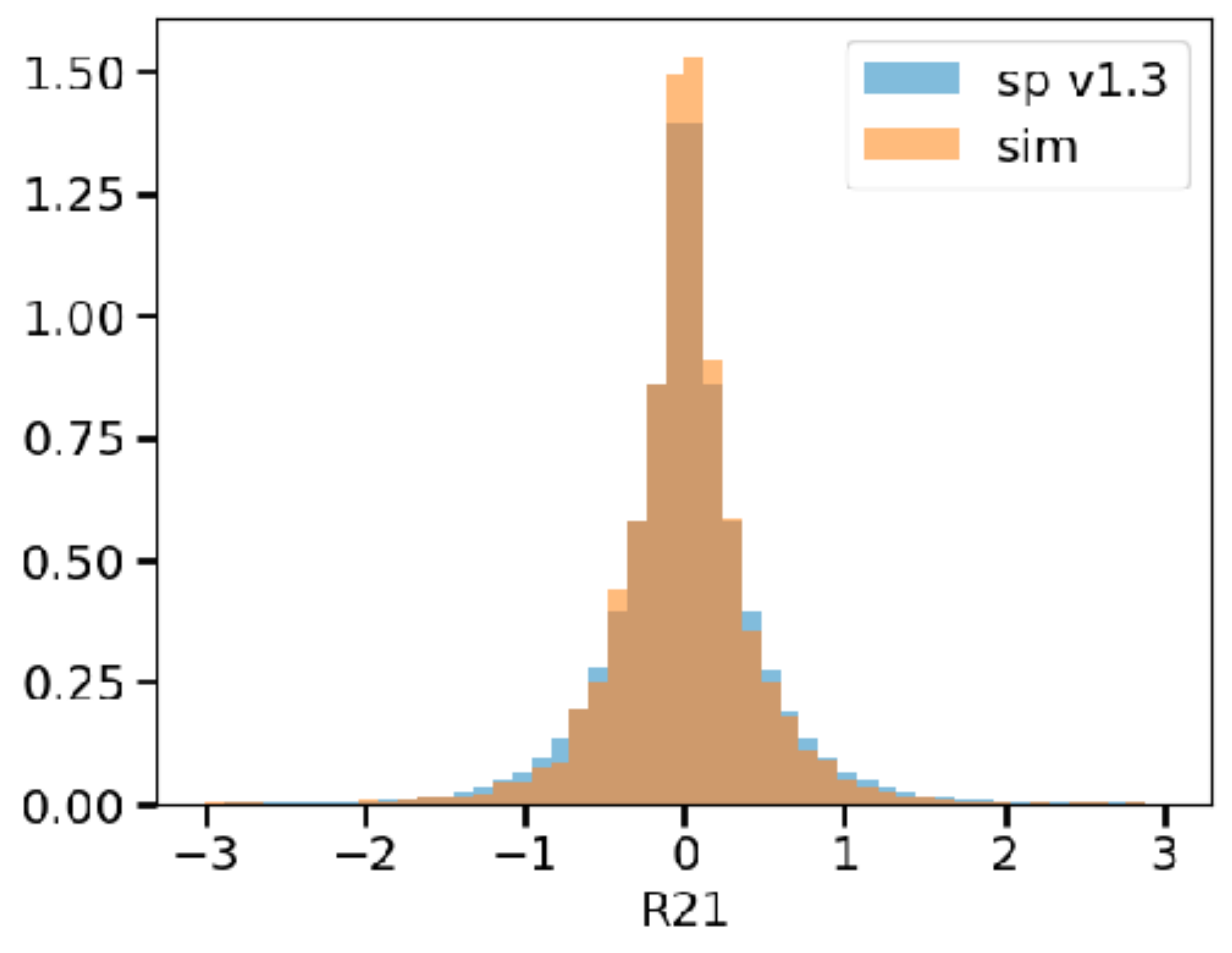
Size, magnitude plot:

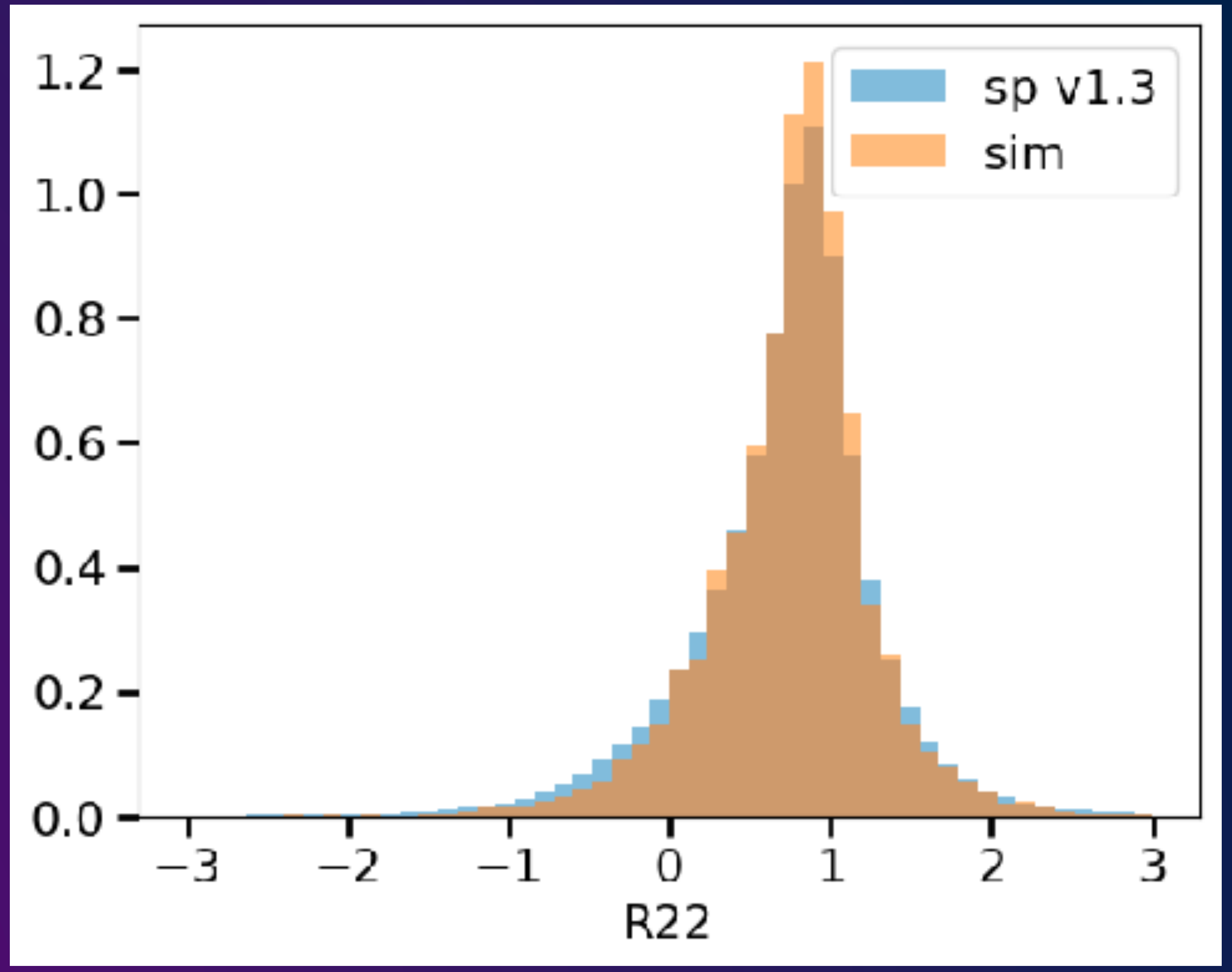


Shear response matrix:

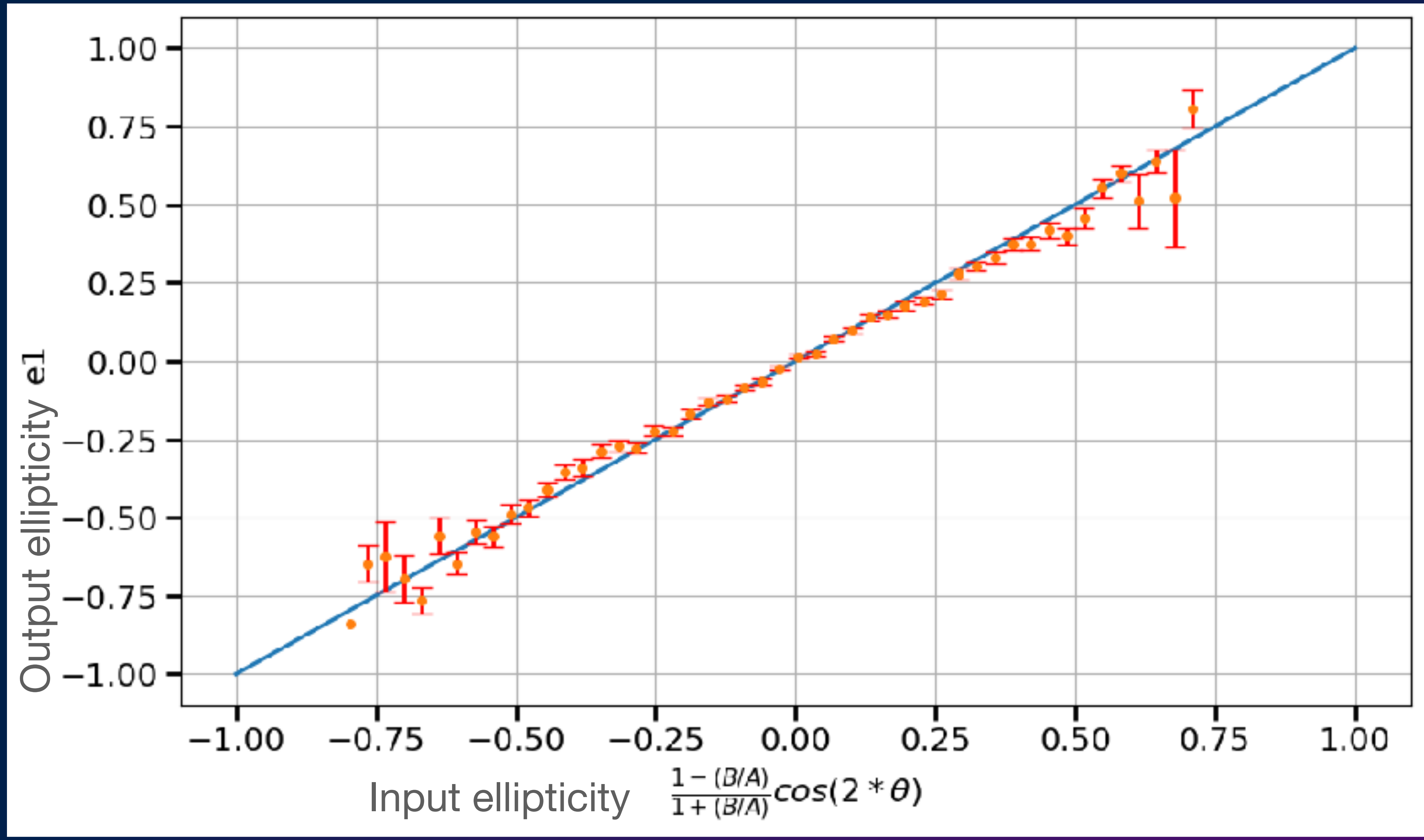


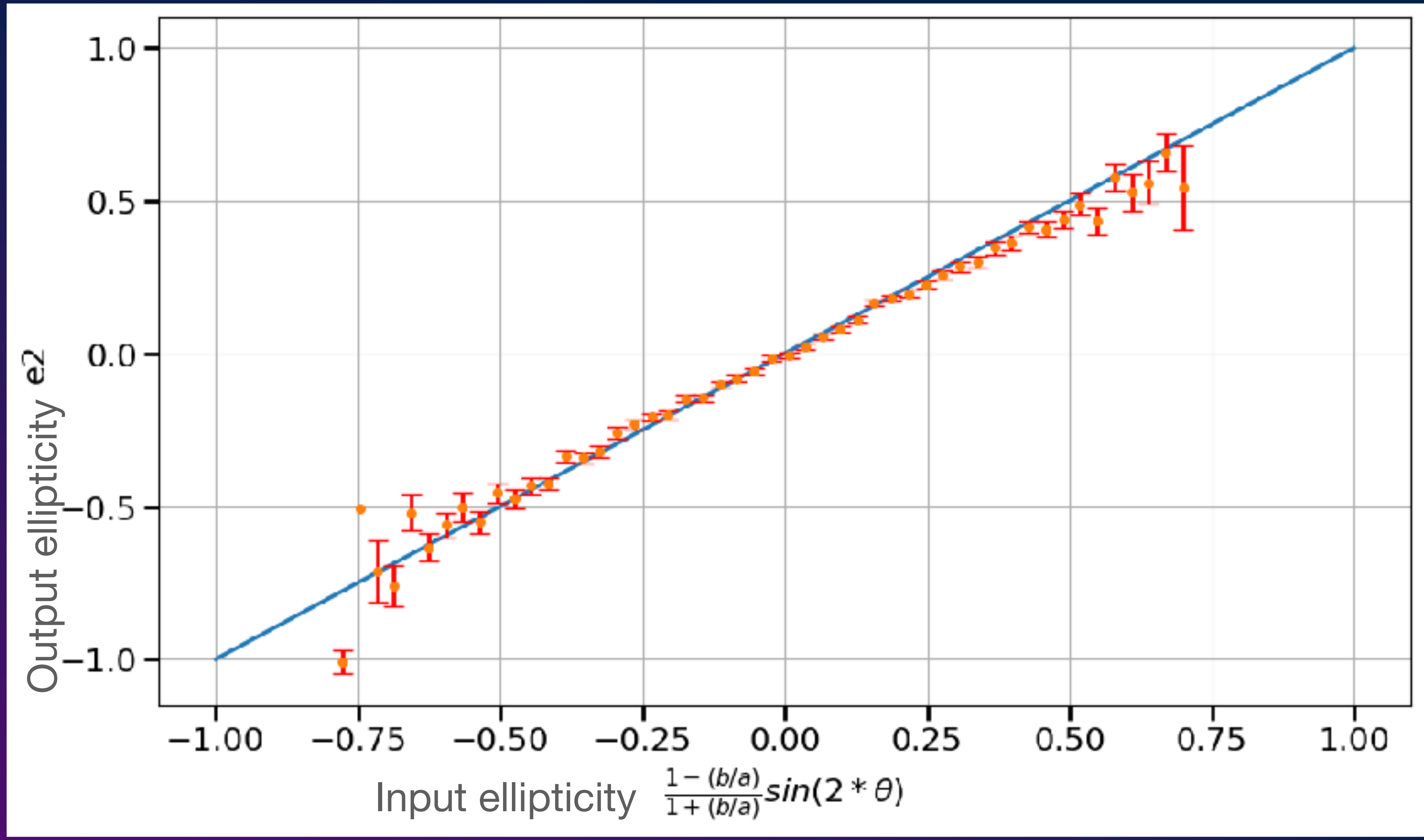






II) Image simulations – Ellipticity recovery (preliminary)





Current effort:

- 100 deg^2 with 4 shear realizations & 2 rotations to cancel shape noise → 800 deg^2
- Run simulations on a grid and with realistic placement to estimate blend bias

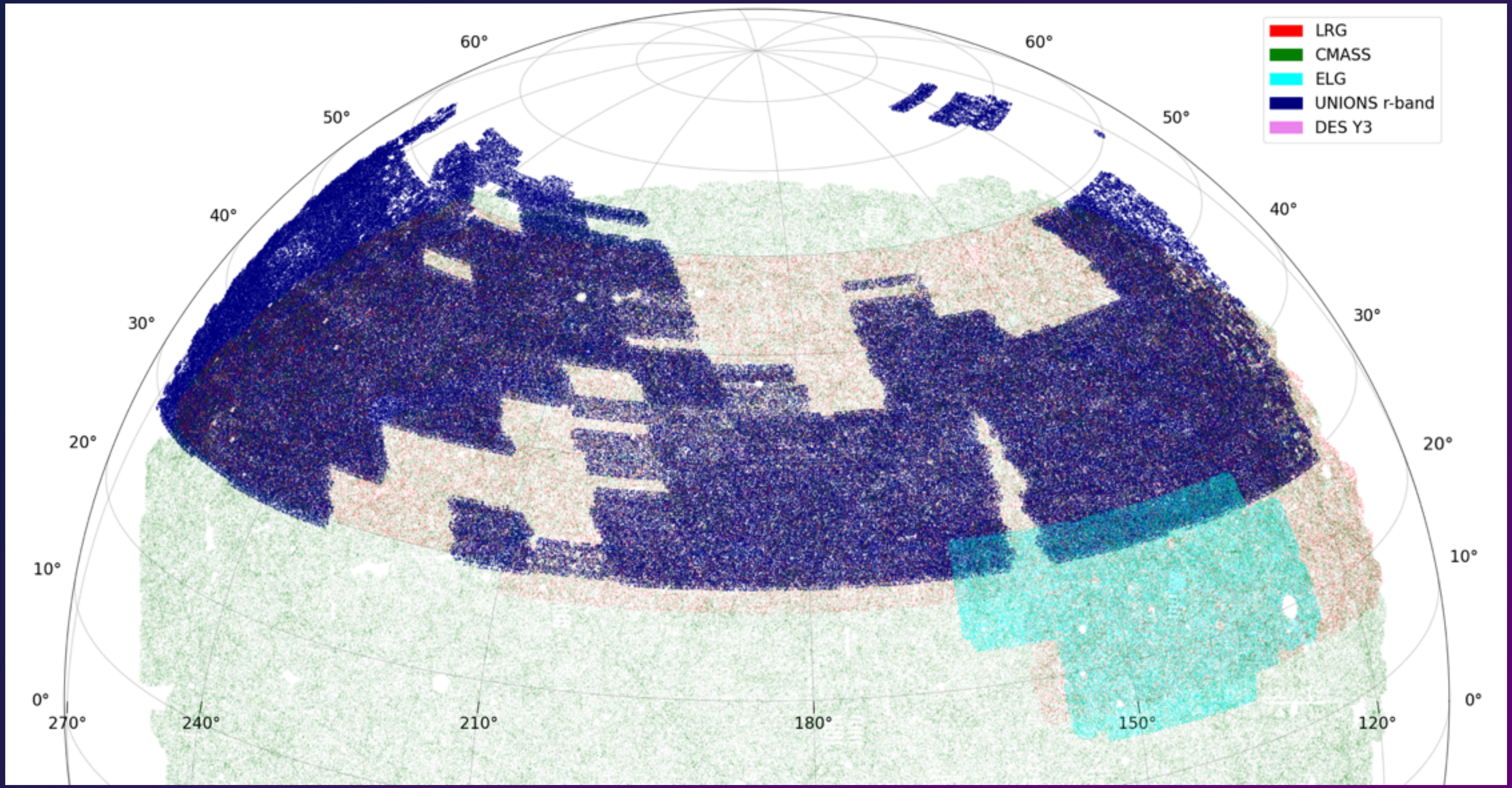
Validation plans

Roadmap for validation:

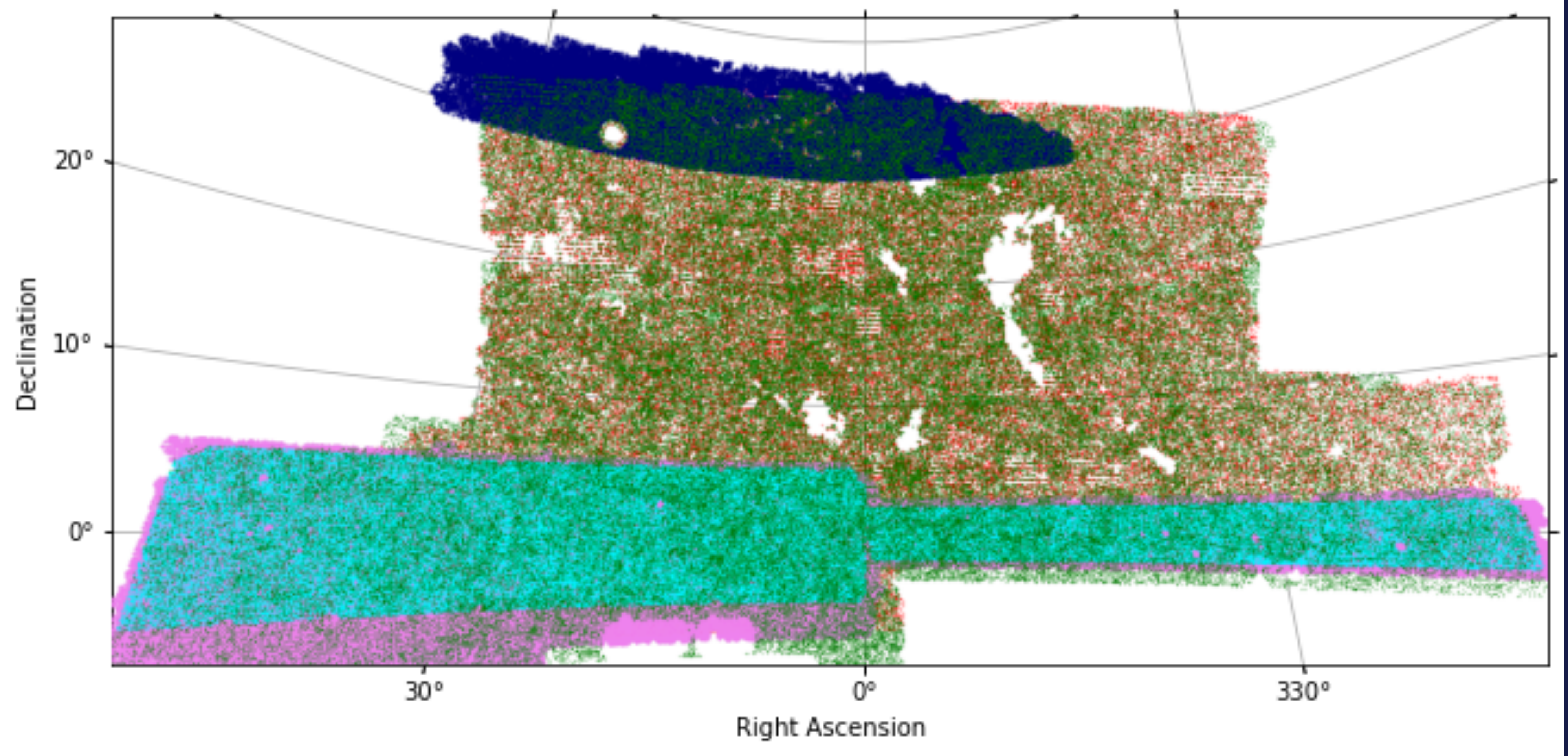
- PSF model residuals ✅
- PSF leakage ✅
- $\gamma_\times$ modes ✅
- B-modes ≅ (depends on scale)
- Simulation validation ≅ (in progress)

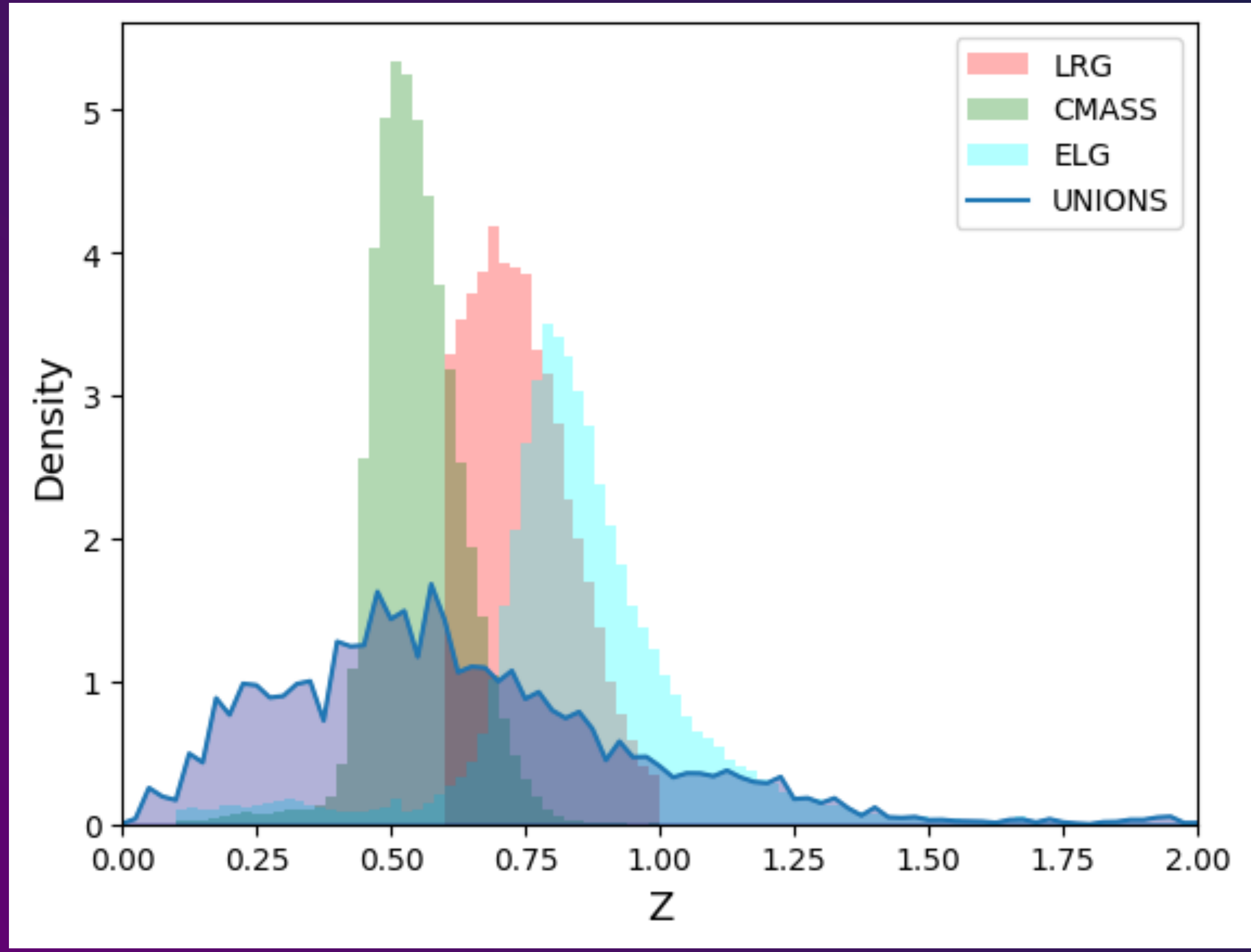
III) A direct measurement of intrinsic alignment

Combining spectroscopic and imaging information



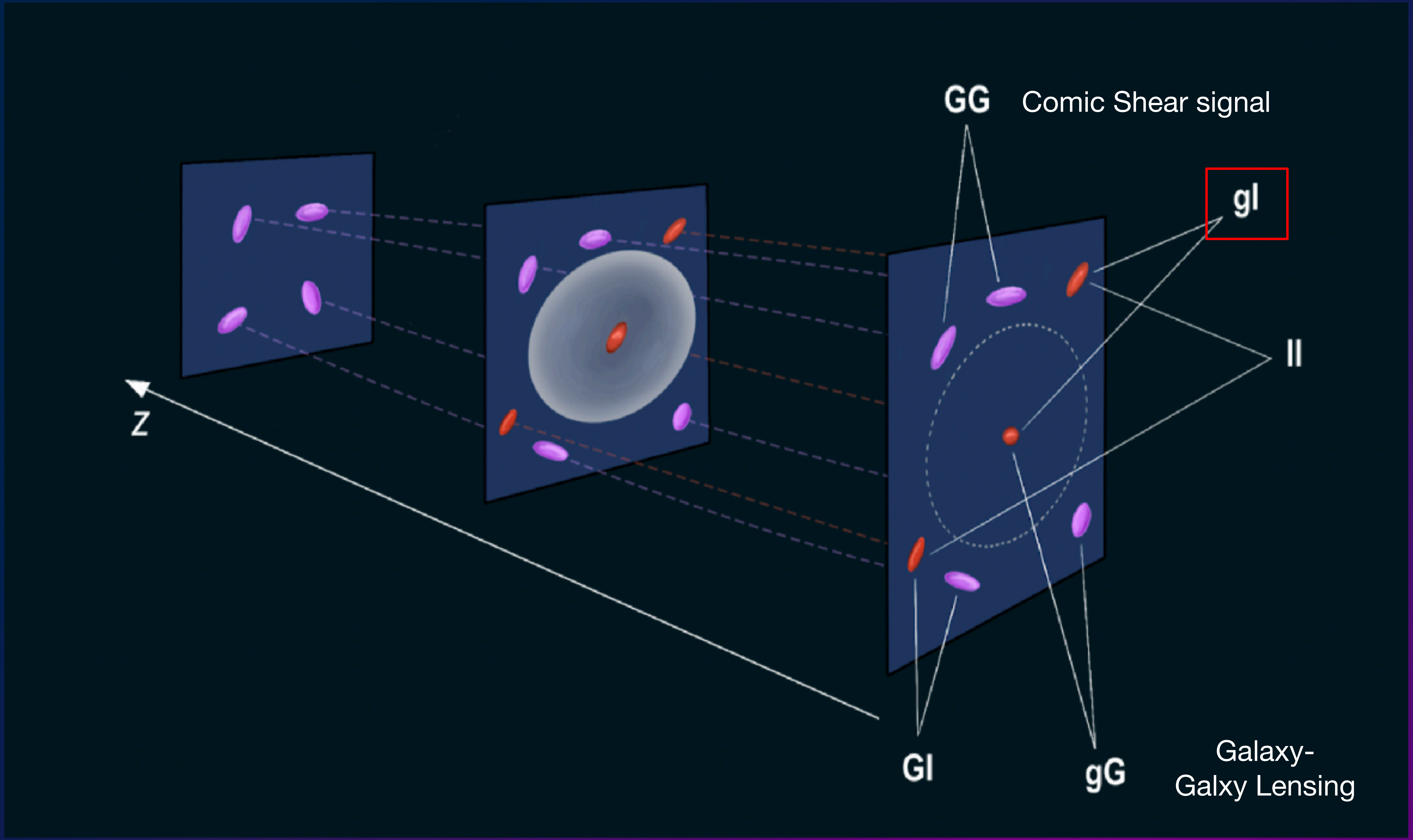
Northern Galactic Cap





n(z) distribution

III) A direct measurement of intrinsic alignment



Credit: *Fortuna and Chisari 2022*

Total ellipticity described as:

$$\gamma = \gamma_I + \gamma_G$$

Cosmic Shear 2PCF:

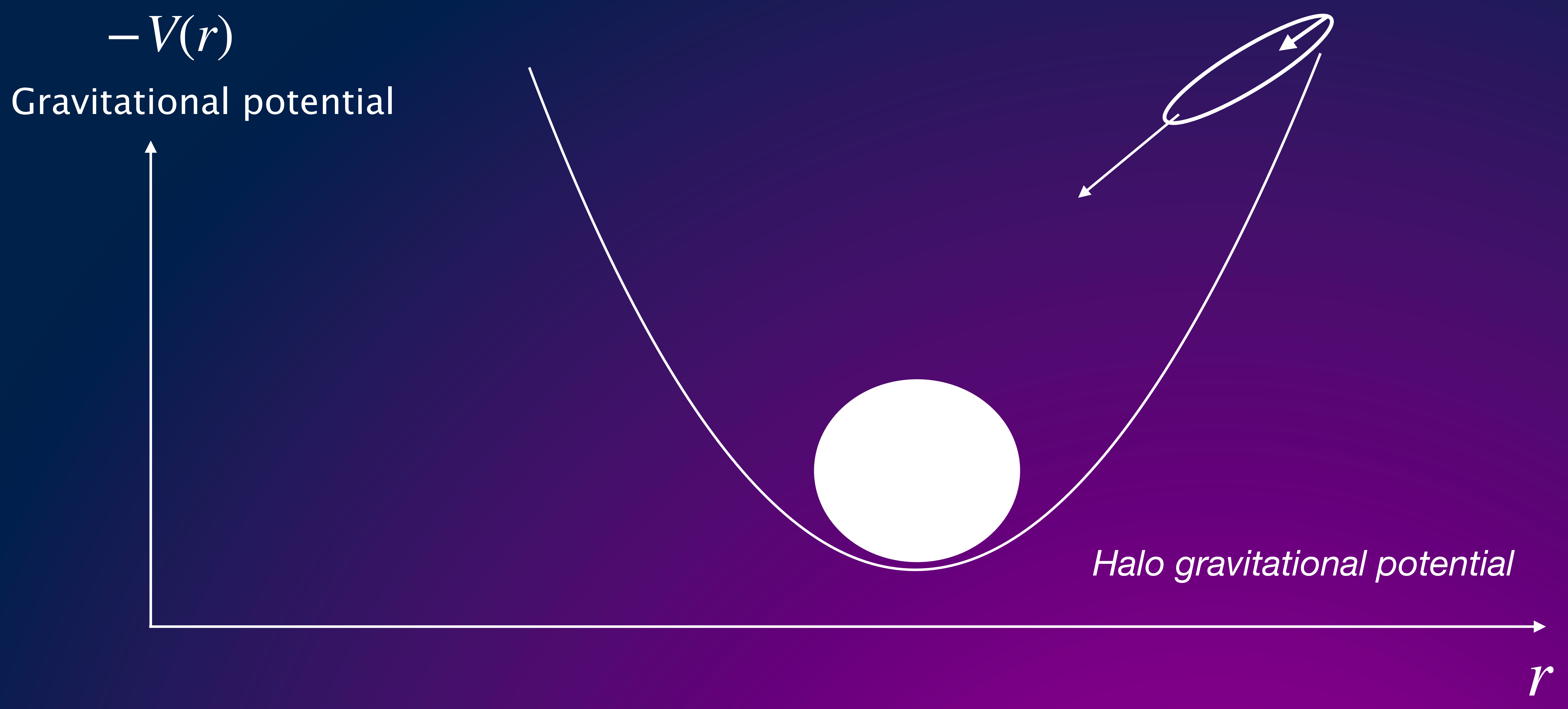
$$\langle \gamma\gamma \rangle = \underbrace{\gamma_G\gamma_G}_{\text{Lensing-Lensing}} + \overbrace{\gamma_I\gamma_I}^{\text{Intrinsic-Intrinsic}} + 2\underbrace{\gamma_I\gamma_G}_{\text{Lensing-Intrinsic}}$$

Want to measure for Cosmic shear

What we measure

→ Need to model both effects jointly

Testing the Non Linear Alignment Model:



Overdensities:

$$\delta(r) = \frac{\rho(r) - \bar{\rho}}{\bar{\rho}}$$

NLA parametrisation:

$$\gamma_I \propto A_1 \, \delta(r) \, \frac{\Omega_m}{D_+(z)}$$

-$D_+(z)$ linear growth factor

-A_1 (or A_{IA}) free parameter

Intrinsic Alignment models & measurement

Models: Non-Linear Alignment (NLA) & Tidal Alignment and Tidal Torque (TATT)

$$\langle\gamma\gamma\rangle = \underbrace{\gamma_G\gamma_G}_{\text{Cosmological}} + \overbrace{\gamma_I\gamma_I}^{\text{intrinsic-intrinsic}} + \underbrace{2\gamma_I\gamma_G}_{\text{intrinsic-gravitational}}$$

The tidal tensor field:

$$s_{ij}(k) = (\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij})\delta(k)$$

The Intrinsic contribution to shear is given by:

NLA — TATT

$$\gamma^I_{ij}(x) = \underbrace{C_1 s_{ij}}_{\propto A_1} + \underbrace{C_2(s_{ik}s_{kj} - \frac{1}{3}\delta_{ij}s^2)}_{\propto A_2} + \underbrace{C_{1\delta}(\delta s_{ij})}_{\propto b_{TA}} \ldots$$

Observable: Integrated correlation function w_{g+}

Landy-Szalay type estimator (Mandelbaum 2006):

$$\xi_{g+}(r_t, \Pi) = \frac{\text{Shape}_+(\text{Density} - \text{Rand}_D)}{\text{Rand}_D\text{Rand}_S}$$

Integrate the correlation function:

$$w_{g+}(r_t) = \int_{-\Pi_{max}}^{\Pi_{max}} \xi_{g+}(r_t, \Pi)\mathrm{d}\Pi \; ; \; \Pi_{max} = 150 \text{ Mpc}$$

→ × mode to diagnose systematics

$$w_{g+} \propto \int \frac{k\,dk}{2\pi} J_2(r_t k)\, P_{gI}(k, z)$$

⟶ $P_{gI} \propto b_g$ needs measure and modelling of w_{gg}

Direct measurement of intrinsic alignment

CMASS

$\langle z \rangle$=0.55

shape sample ≈ 200 000

$\sigma_\epsilon = 0.16$

$A_1 = 4.04^{+0.30}_{-0.30}$

LRG

$\langle z \rangle$=0.74

shape sample ≈ 80 000

$\sigma_\epsilon = 0.18$

$A_1 = 3.3 \pm 1.0$

ELG

$\langle z \rangle$=0.85

shape sample ≈ 15 000

$\sigma_\epsilon = 0.17$

$A_1 = 3.1^{+3.3}_{-2.9}$

Testing diagnostics: $w_{g\times}$

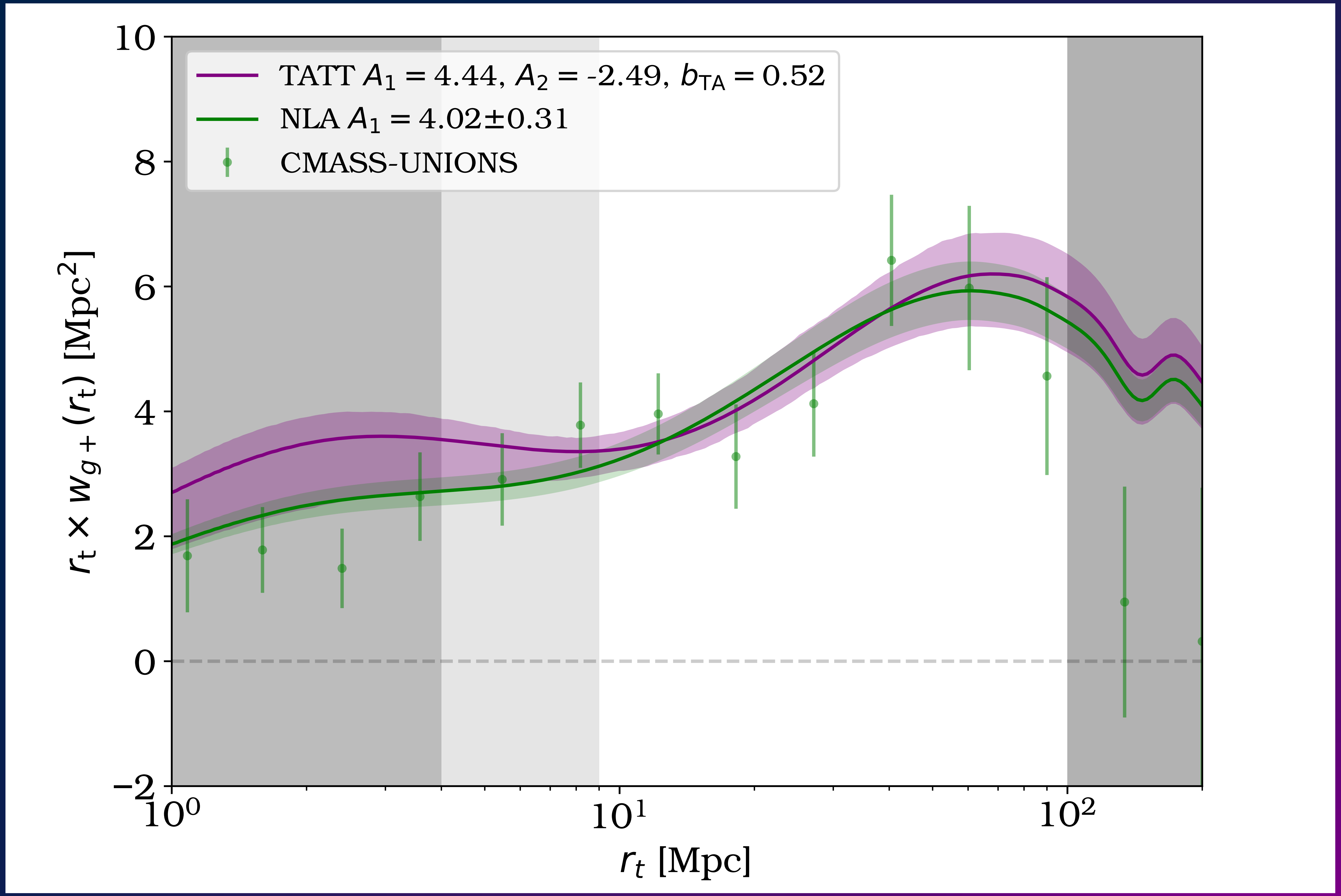
Null test (compatibility with 0):

	CMASS-UNIONS	LRG-UNIONS	ELG-UNIONS
$\chi^2(w_{g\times})$	0.65 (0.26σ)	1.238 (0.86σ)	0.66 (0.27σ)
$\chi^2(w_{g+})$	11.7 (7.05σ)	1.89 (1.54σ)	0.95 (0.56σ)

NLA or TATT ?

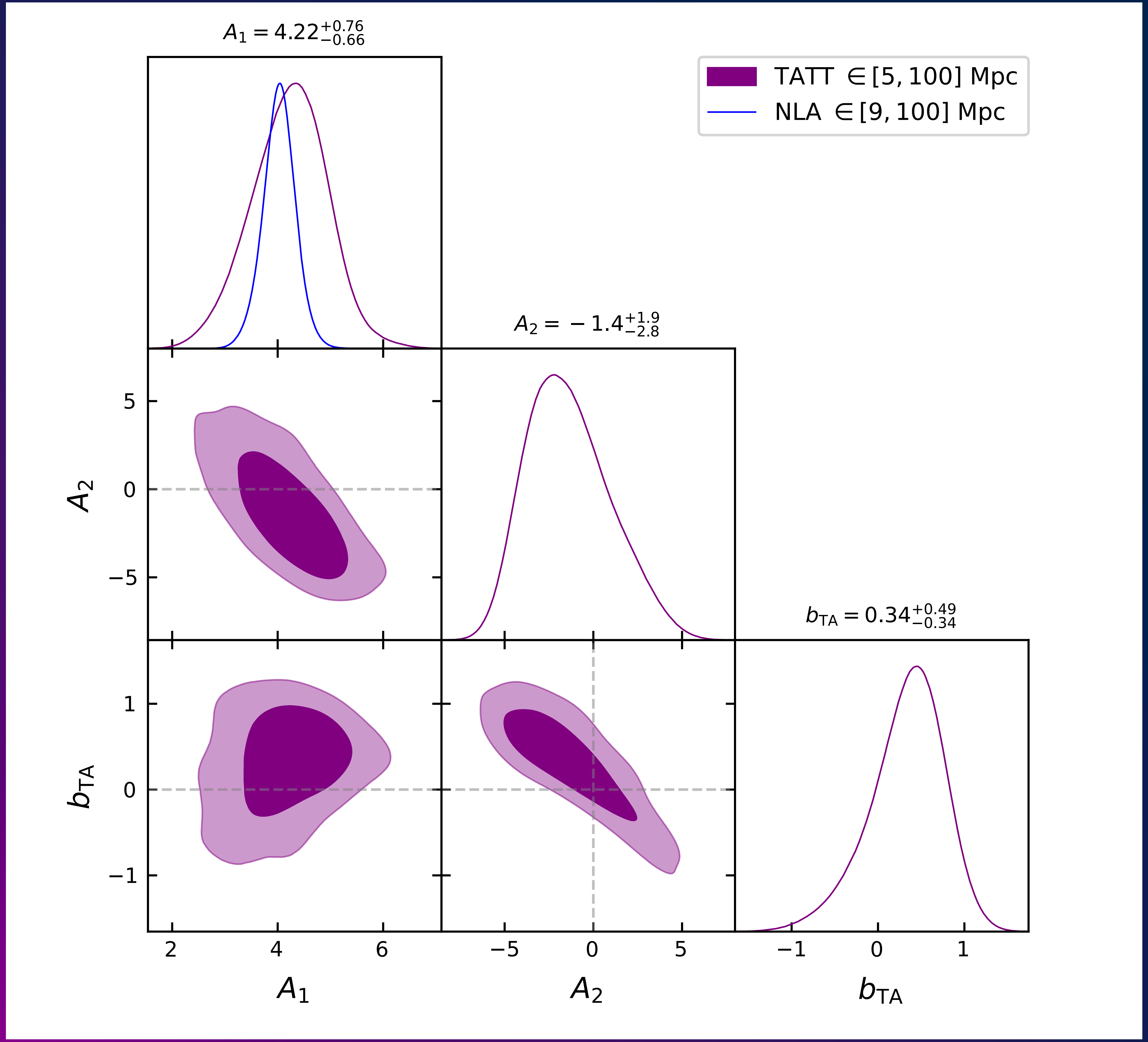
Best fit for NLA:

$\chi^2/\mathtt{d.o.f.}$=6.33/(6-1)=1.266



Best fit for TATT:

$\chi^2/\mathtt{d.o.f.}$= 7.18/(8-3)=1.436



Luminosity dependence of intrinsic alignment

–We see a strong dependence in luminosity

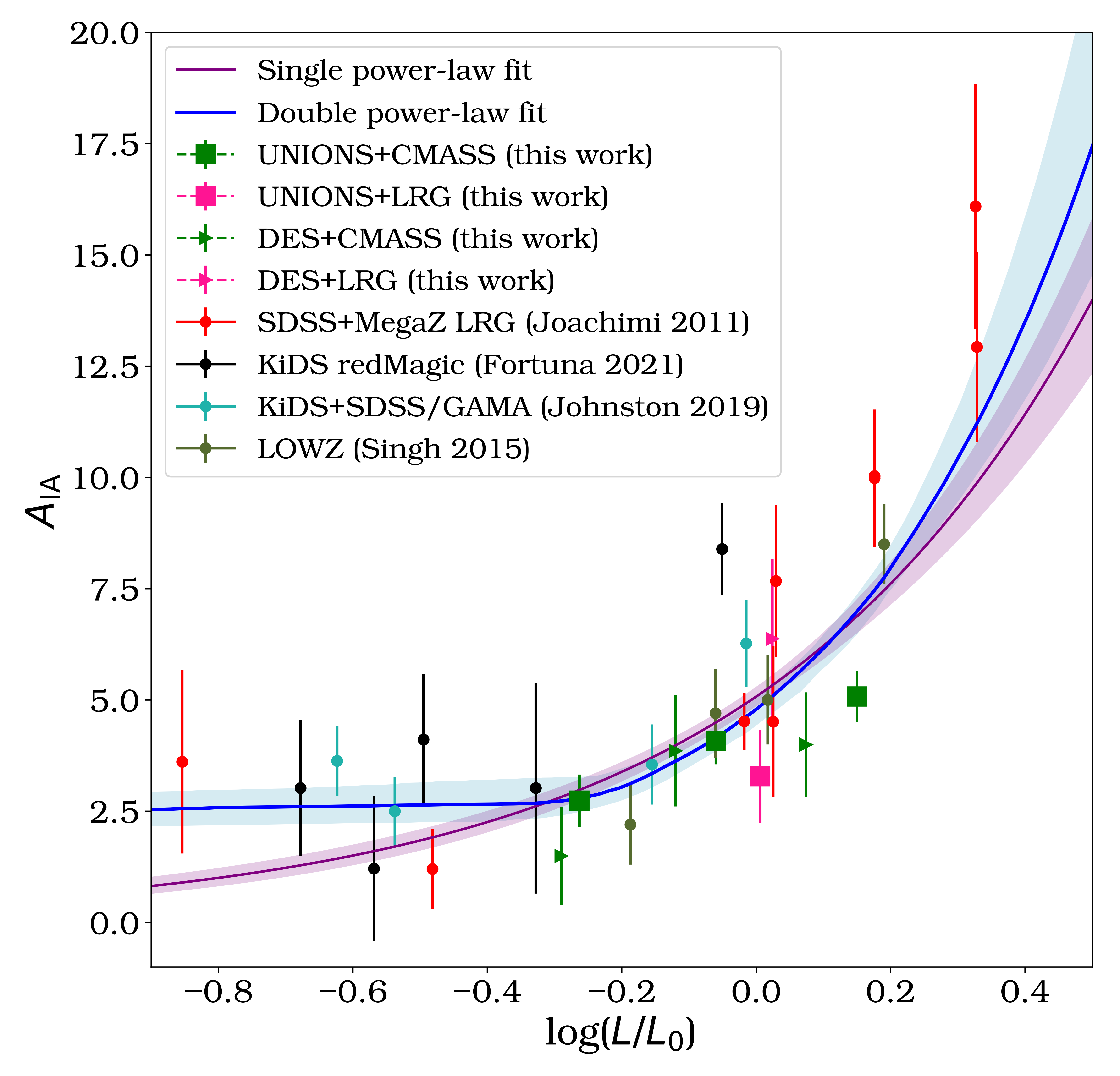
–Recover results in agreement with previous studies

–For a global prior for Euclid we need to understand some discrepancies

–Slight preference for the double power-law

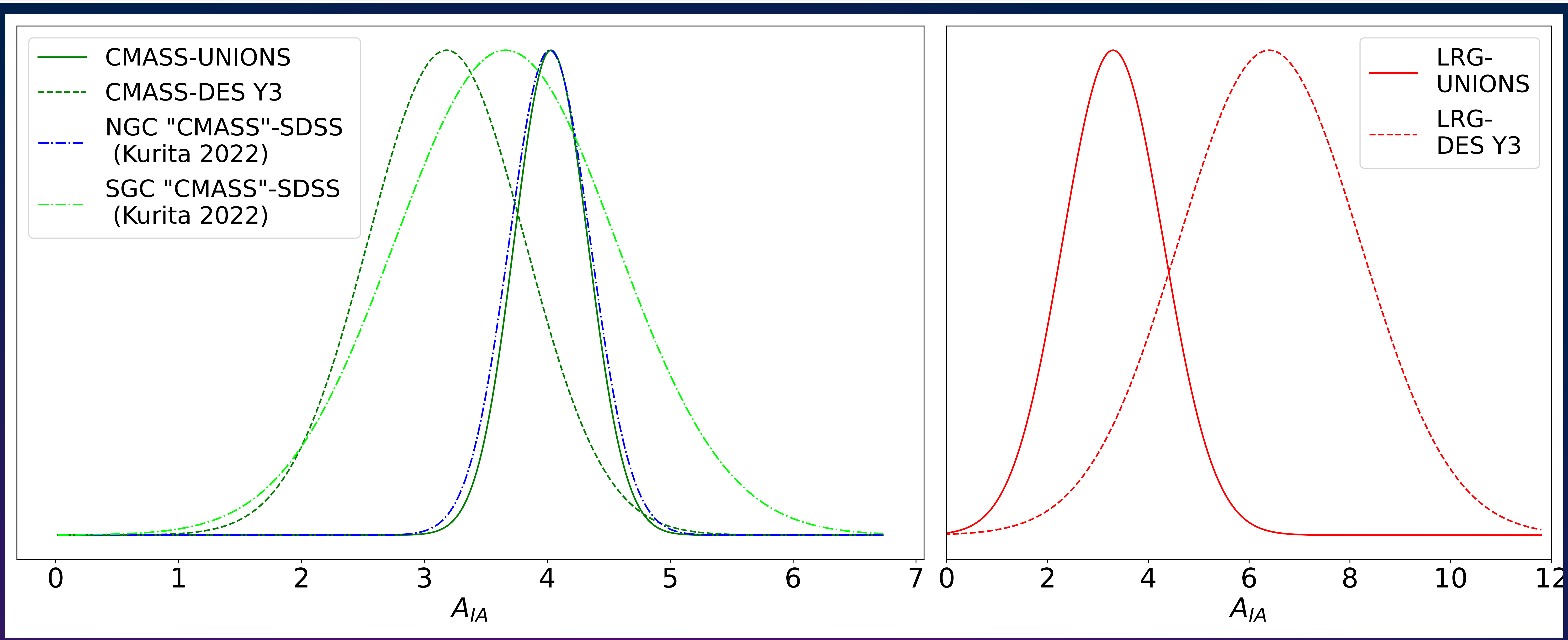
–Poor reduced χ^2:
$\chi^2 = 2.42$ (single power law)
$\chi^2 = 2.19$ (double power law)
indicate that other factors need to be considered (redness, shape measurement algorithm, redshift…)

–Recently shown (Fortuna 2024) that luminosity is a proxy for halo mass, $M_H - L$ scaling relation



Agreement with other measurements

Comparing intrinsic alignment from different lensing samples:



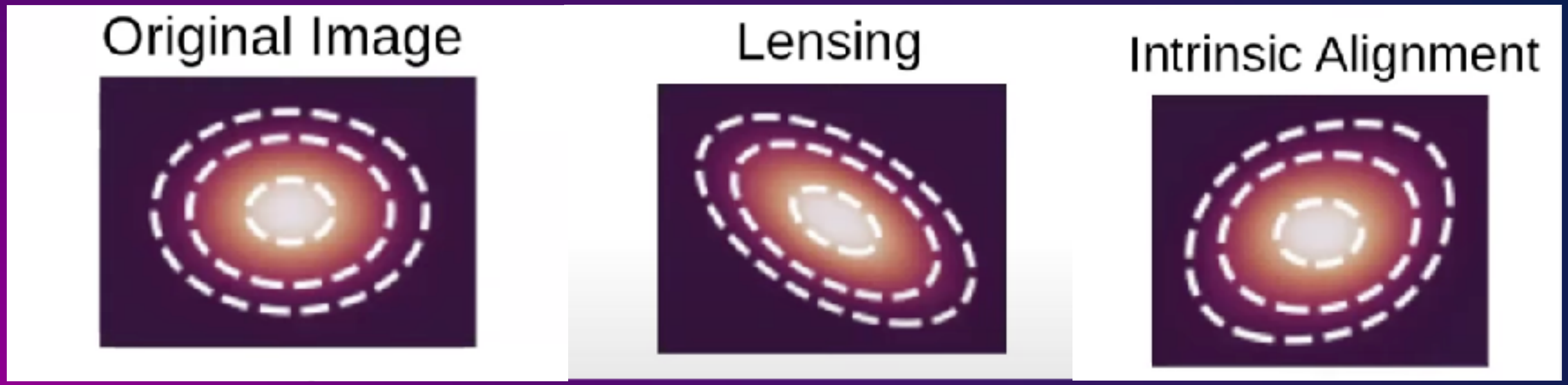
Statistical fluctuation or observational effects affecting Intrinsic Alignment:

–Color band in which the shape is measured (Georgiou 2019) (UNIONS r & DES riz)

–Shape measurement method (Singh 2015, Leonard 2018)

–Weight function, PSF? (UNIONS 0.65 arcsec & DES 0.95 arcsec)

–Extinction? Background subtraction?



Plot by Danielle Leonard

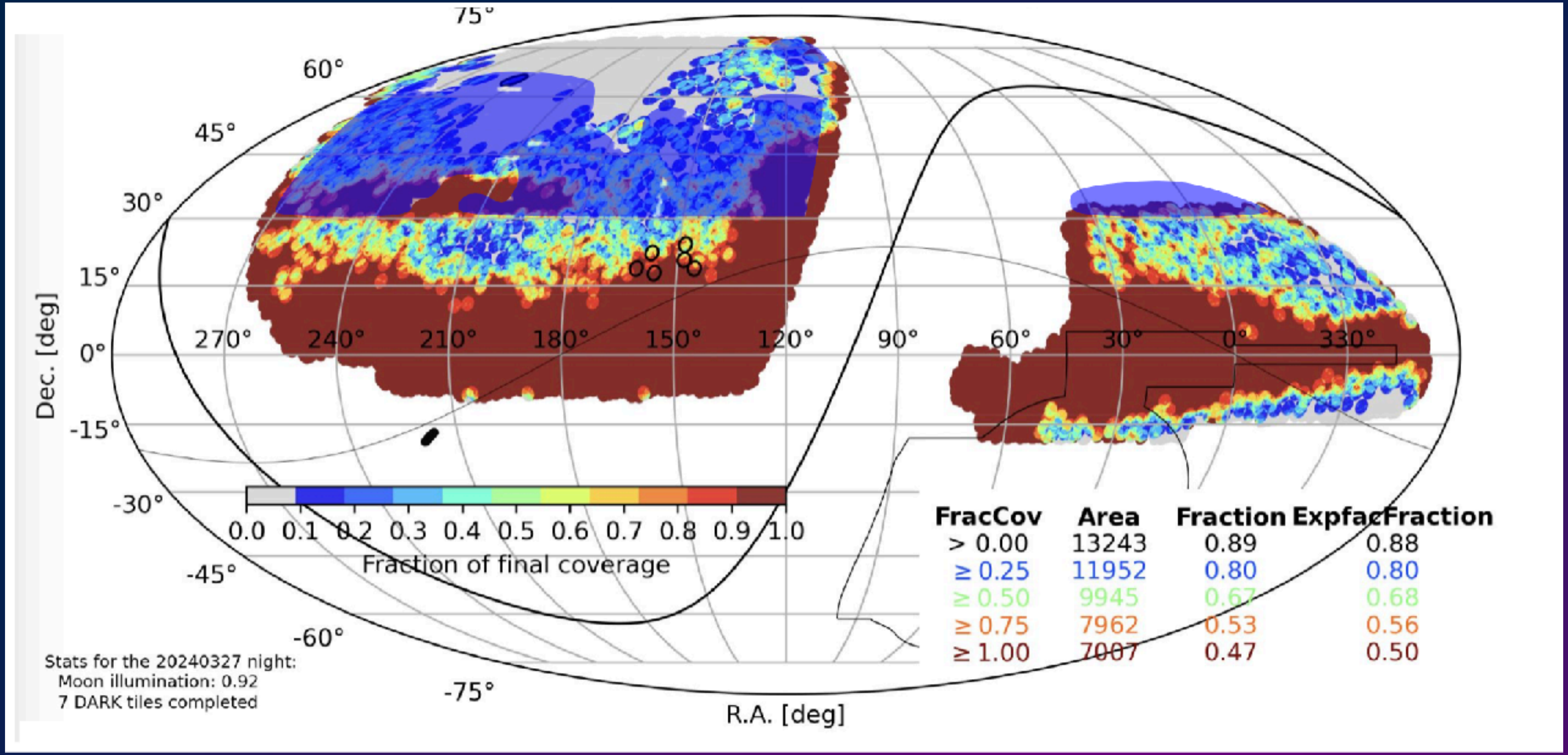
UNIONS status

Status:
- Shape catalogue close to being validated
- Pipelines for cosmic shear and 3x2 point ready
- Photo-z are being validated
- Masks are being validated

Existing papers:
- **ShapePipe: shape measurement pipeline and weak-lensing application to UNIONS/CFIS data**, Guinot et al., 2022, A&A
- **The shape of dark matter haloes: results from weak lensing in the Ultraviolet Near-Infrared Optical Northern Survey (UNIONS)**, Robison et al., 2023, MNRAS
- **UNIONS: The impact of systematic errors on weak-lensing peak counts**, Ayçoberry et al, 2023, A&A
- **Black-Hole-to-Halo Mass Relation From UNIONS Weak Lensing**, Li et al., 2024, A&A
- **Point-Spread Function errors for weak lensing - density cross-correlations. Application to UNIONS**, Zhang et al, 2024, A&A
- **τ-statistics as a probe of contamination from PSF systematics using a semi-analytical covariance matrix**, Guerrini et al. , (internal)
- **UNIONS-3500: a direct measurement of intrinsic alignment with BOSS/eBOSS spectroscopy**, FHP et al., (internal)

Stay tuned for:
Density split, mass mapping, simulation based inference, lensing of mergers, splahback radius & much more :)

Synergy: DESI Y1 & Y3



Credit: DESI collaboration

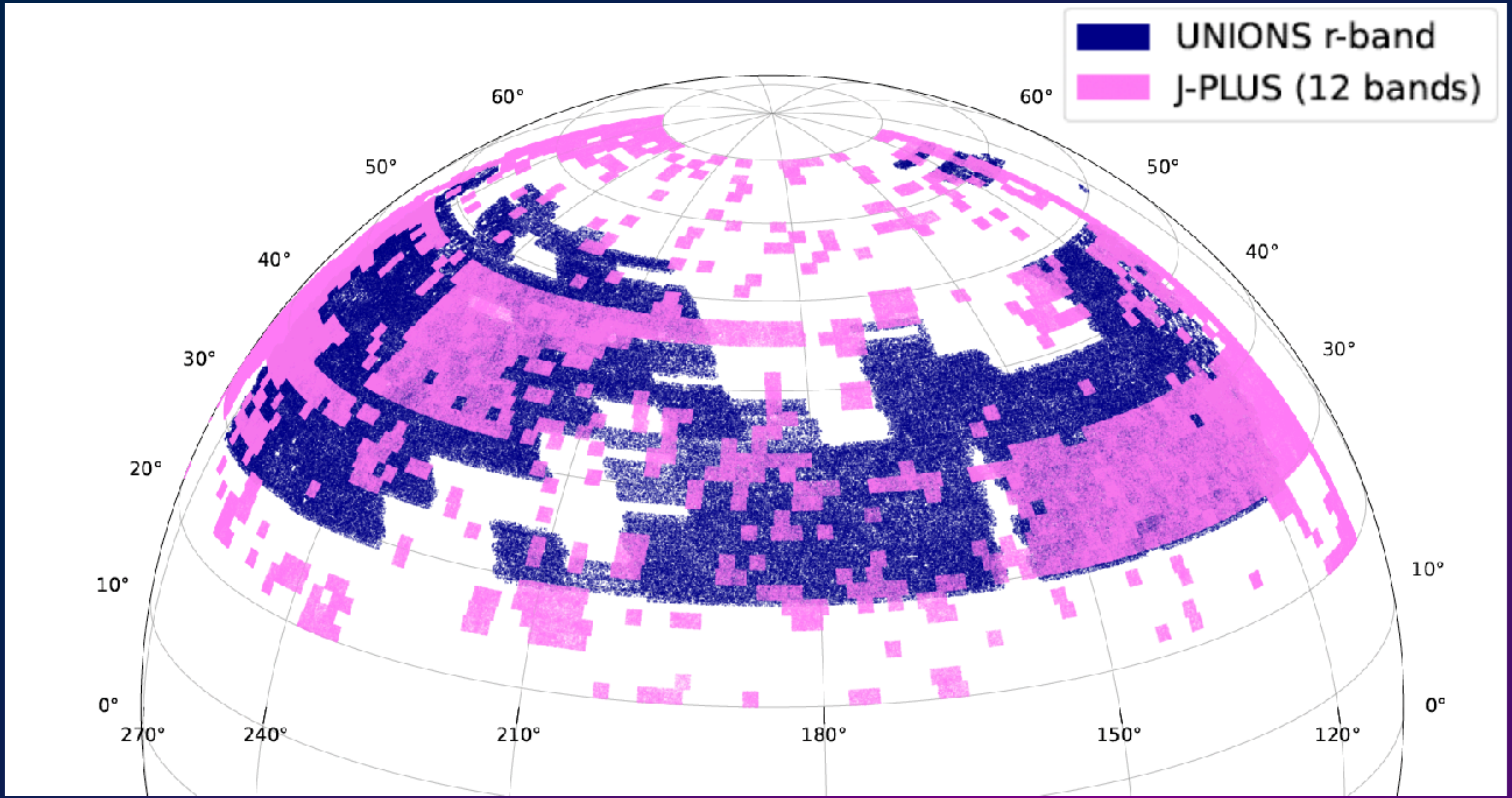
DESI Y1:

2 Million galaxies inside UNIONS footprint

DESI Y3:

Potentially more then all other stage III surveys combined

Synergy: J-PLUS (DR3) & J-PAS



J-PLUS DR3:

1.5 Million galaxies inside UNIONS footprint

CLASS_STAR>0.5

ODDS>0.5

Median redshift uncertainty : $\sigma(z) \approx 0.02$

J-PAS footprint similar? complementary lensing effort?

Looking for a job!

Set for PhD defense in October 2025:

Interested in: lensing data, spectroscopic data, cosmological analysis, dark matter models

https://www.cosmostat.org/people/fabian-hervas-peters

Thank you for your attention!

Stay tuned for

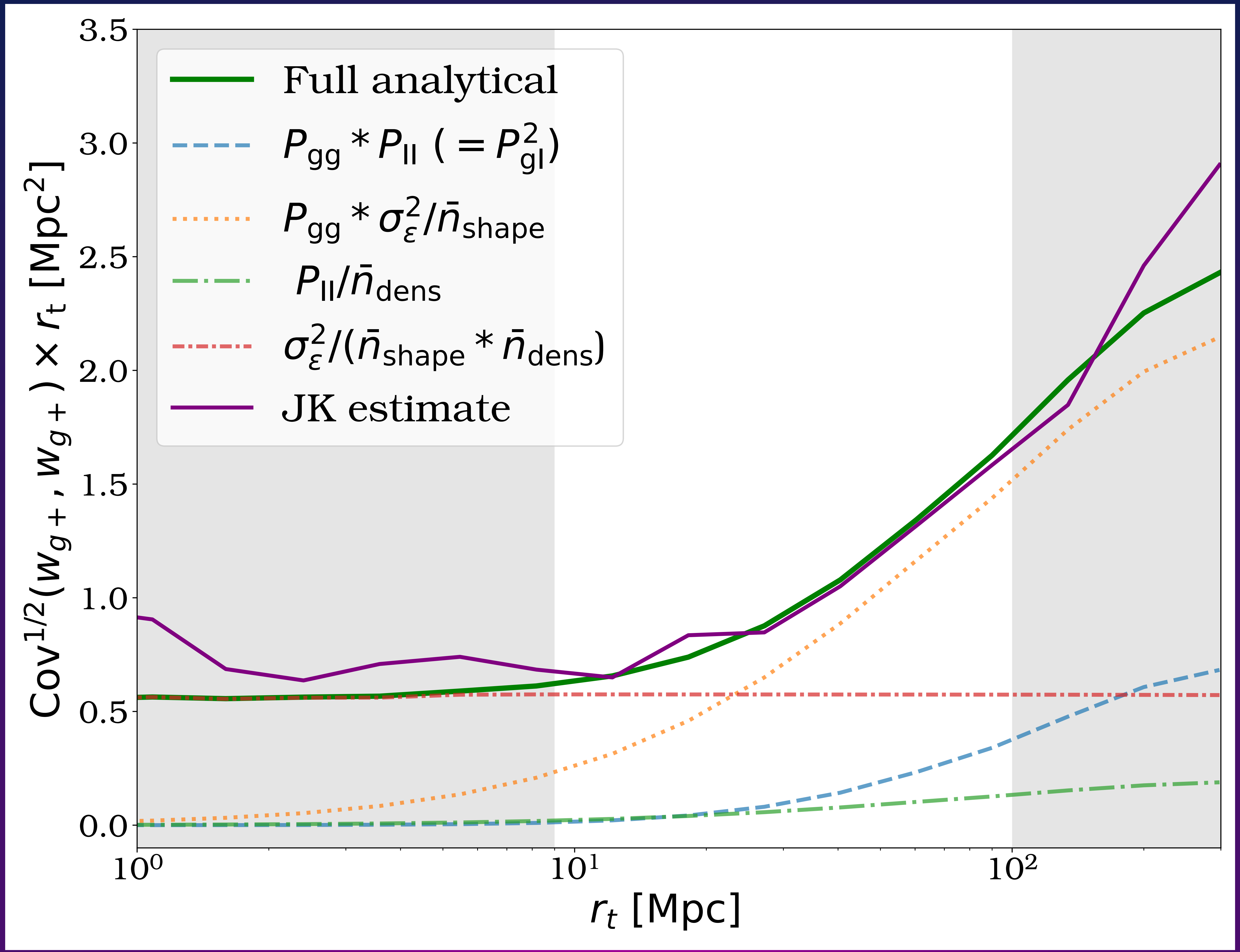
UNIONS

If you need shapes in the North, get in touch!

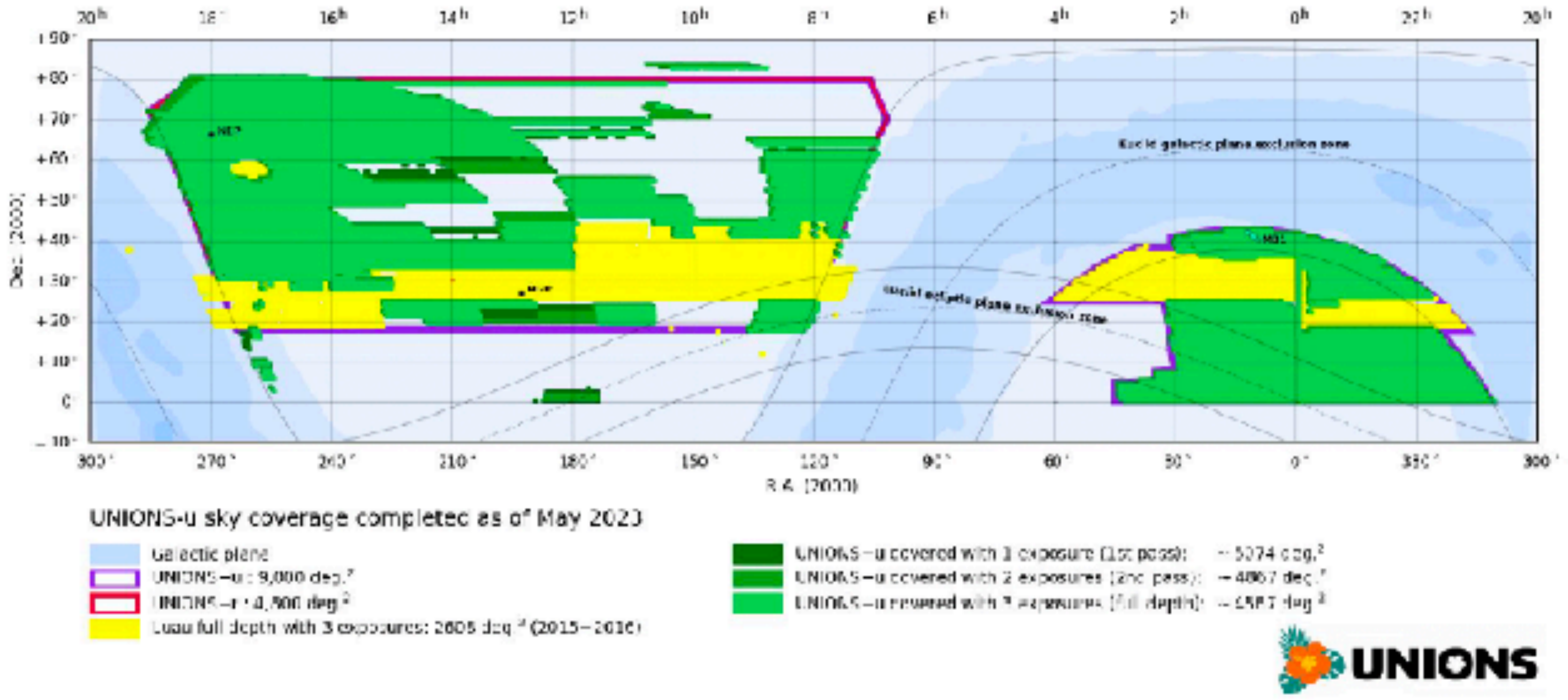
Analytical Covariance

$$\mathrm{Cov}^{\mathrm{TOT}}[w_{g+}w_{g+}] = \frac{1}{\mathcal{A}(\bar{z})}\int \frac{k\,dk}{2\pi} J_2(kr_t)\, J_2(kr_t) \left[\left(P_{gg} + \frac{1}{n_{\mathrm{lens}}}\right)\left(P_{\mathrm{II}} + \frac{\sigma_e^2}{n_{\mathrm{source}}}\right) + P_{gI}^2\right]$$

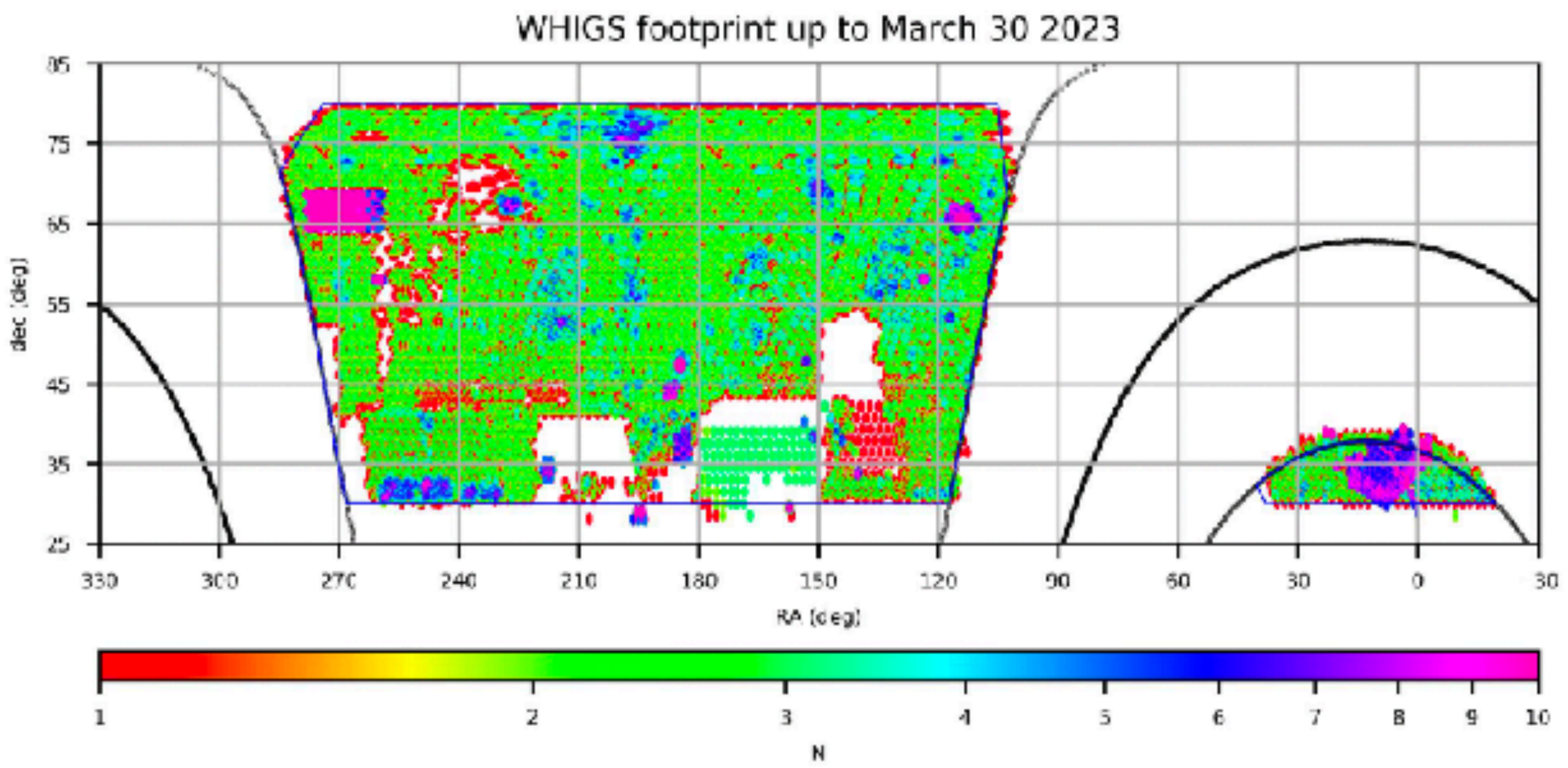
CV · NOISE · CV · CROSS A · CROSS B



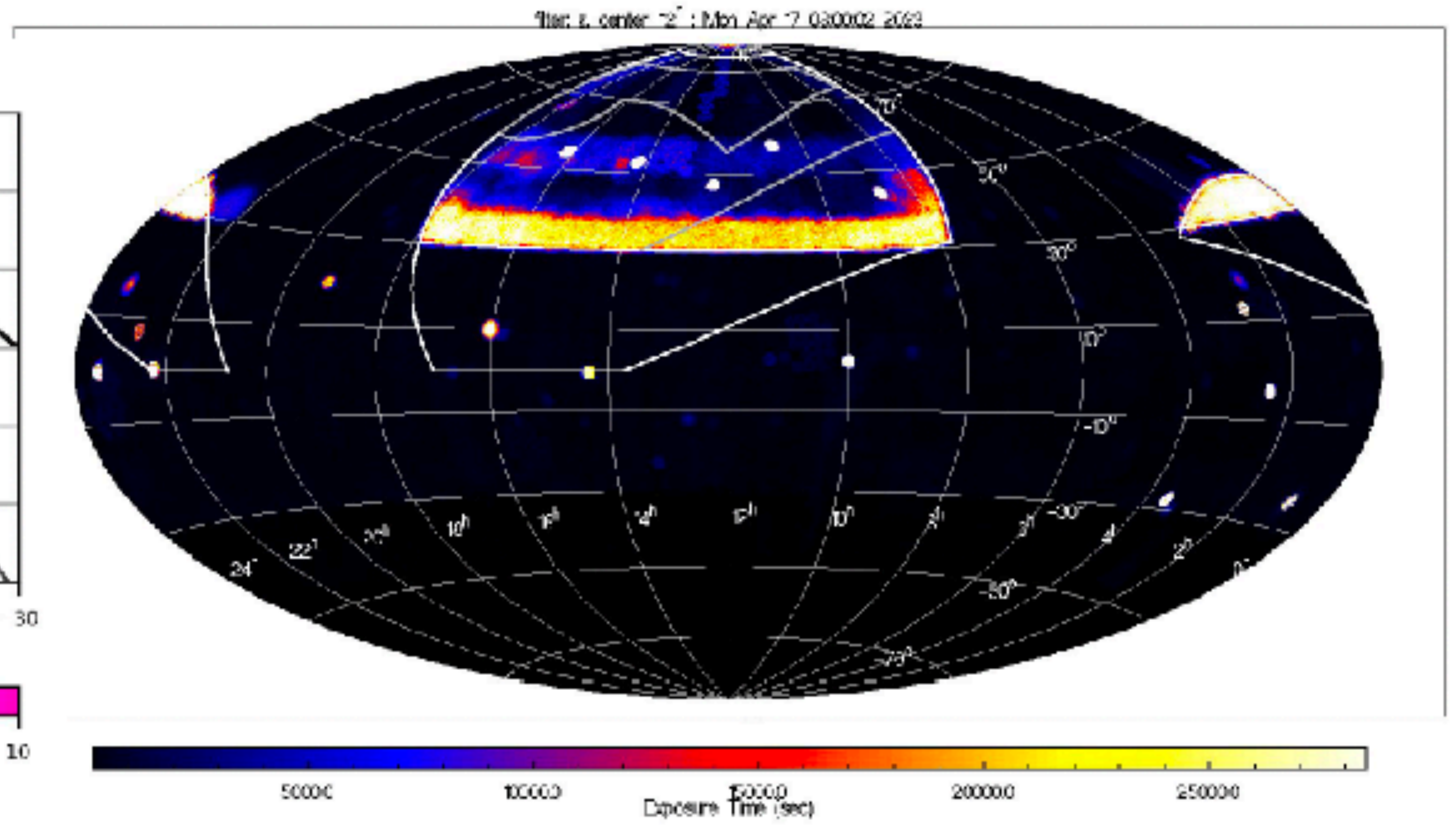
UNIONS ugriz sky coverage status (May 2023)



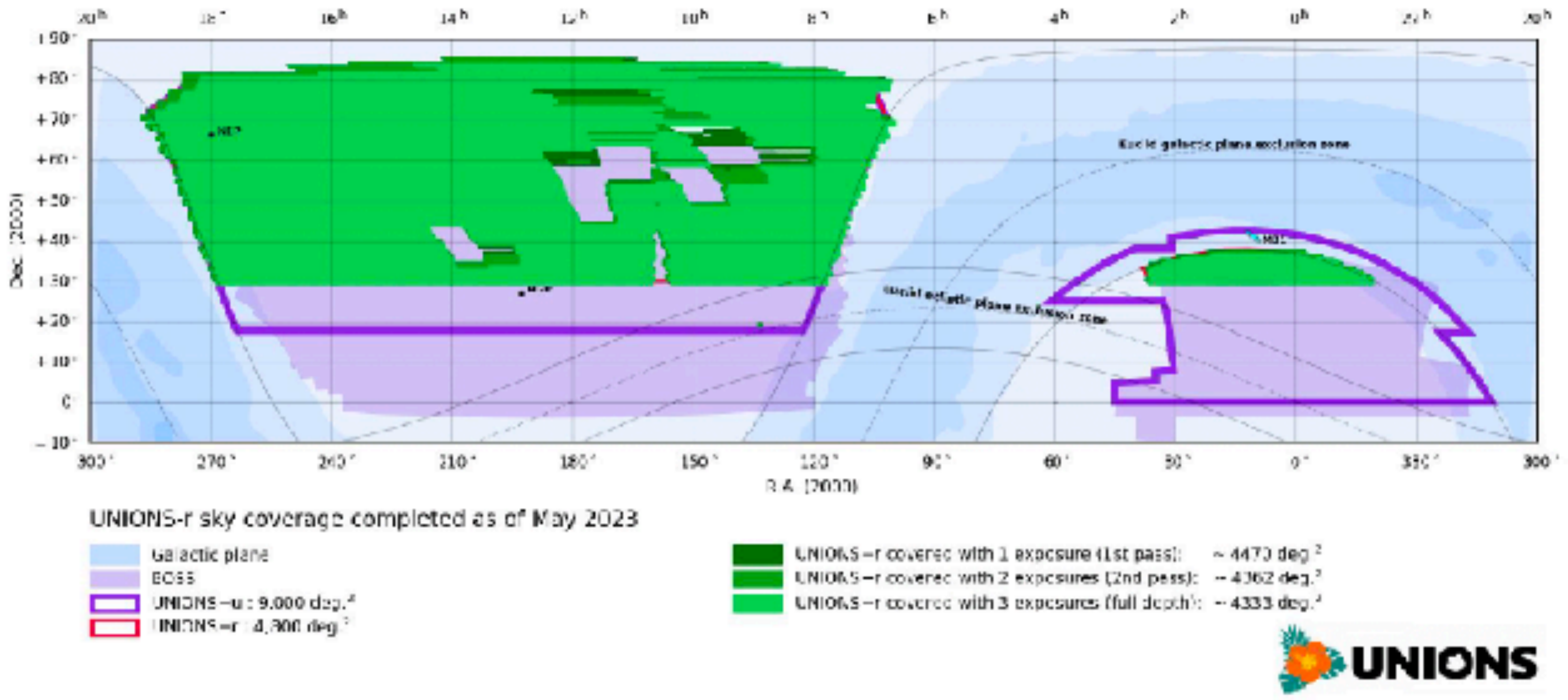
CFHT u



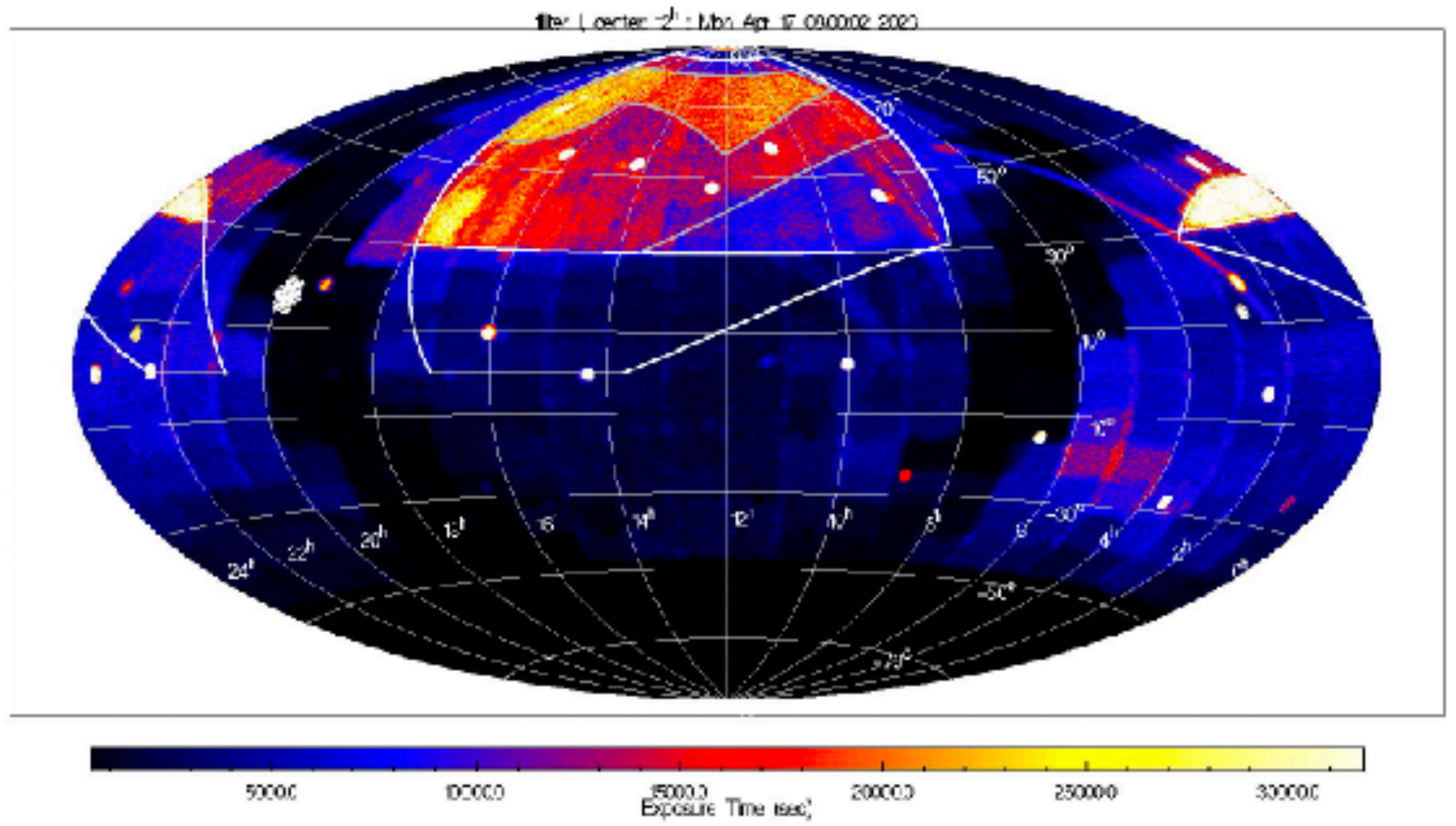
Subaru g



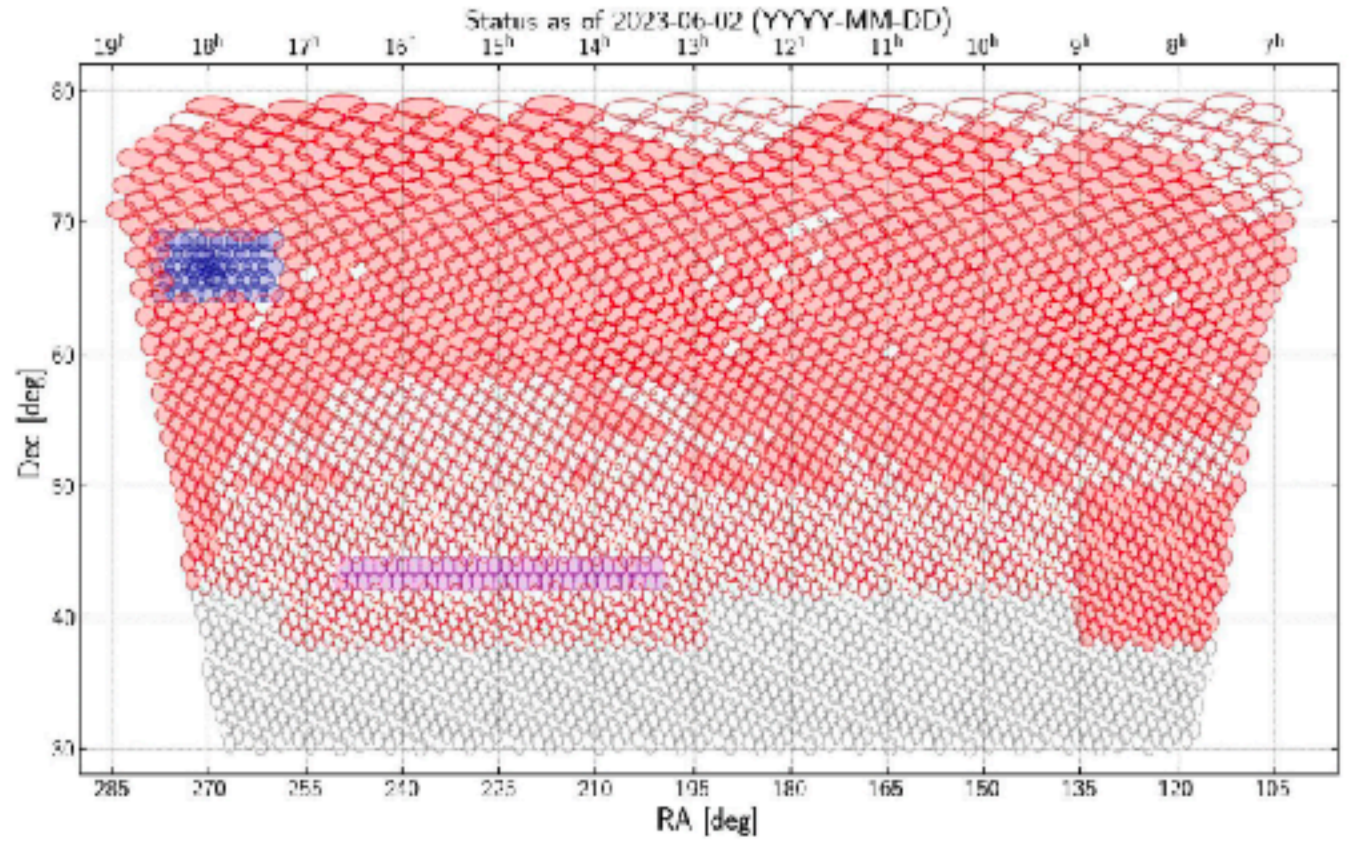
Pan-STARRS z



CFHT r

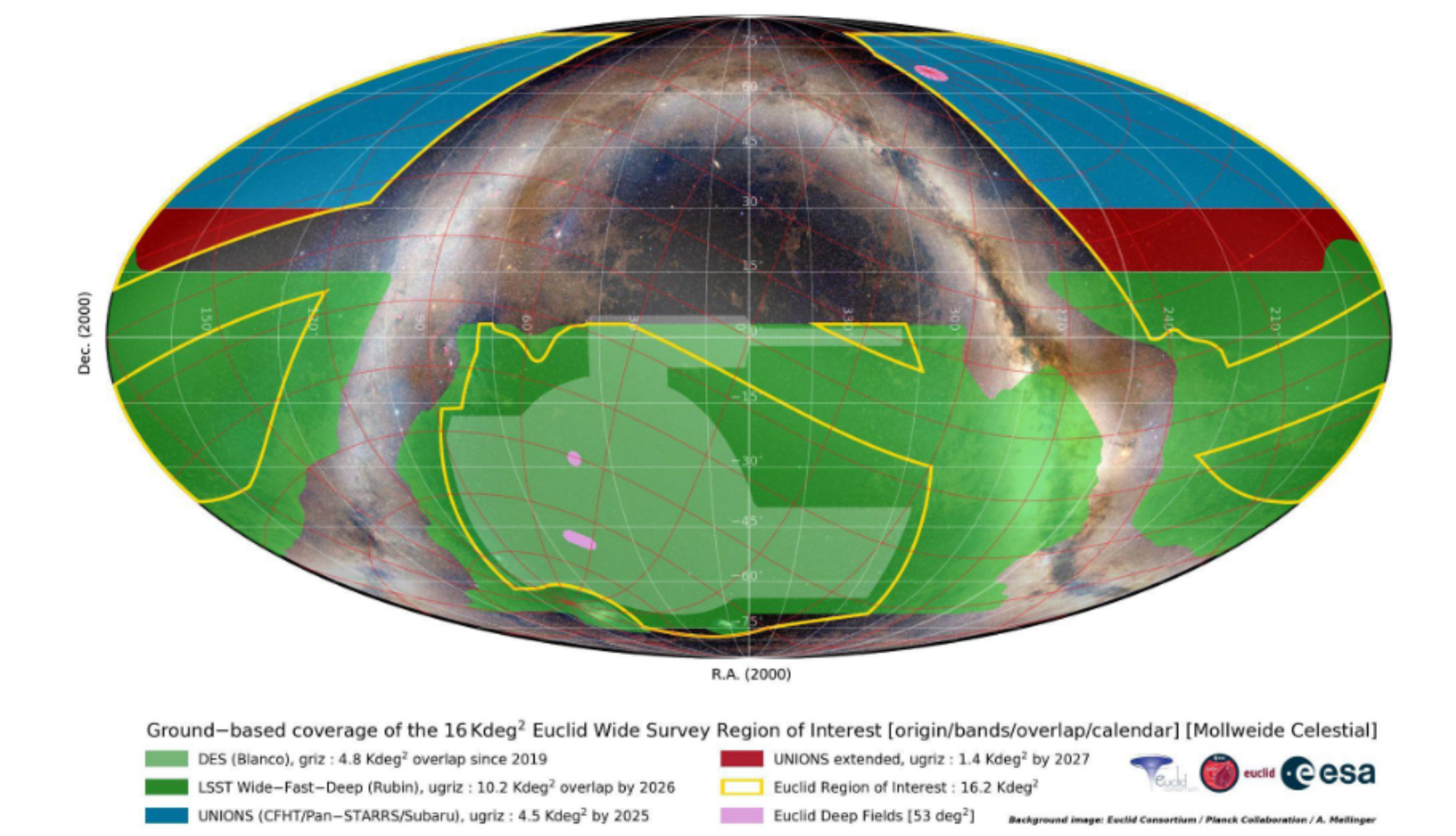


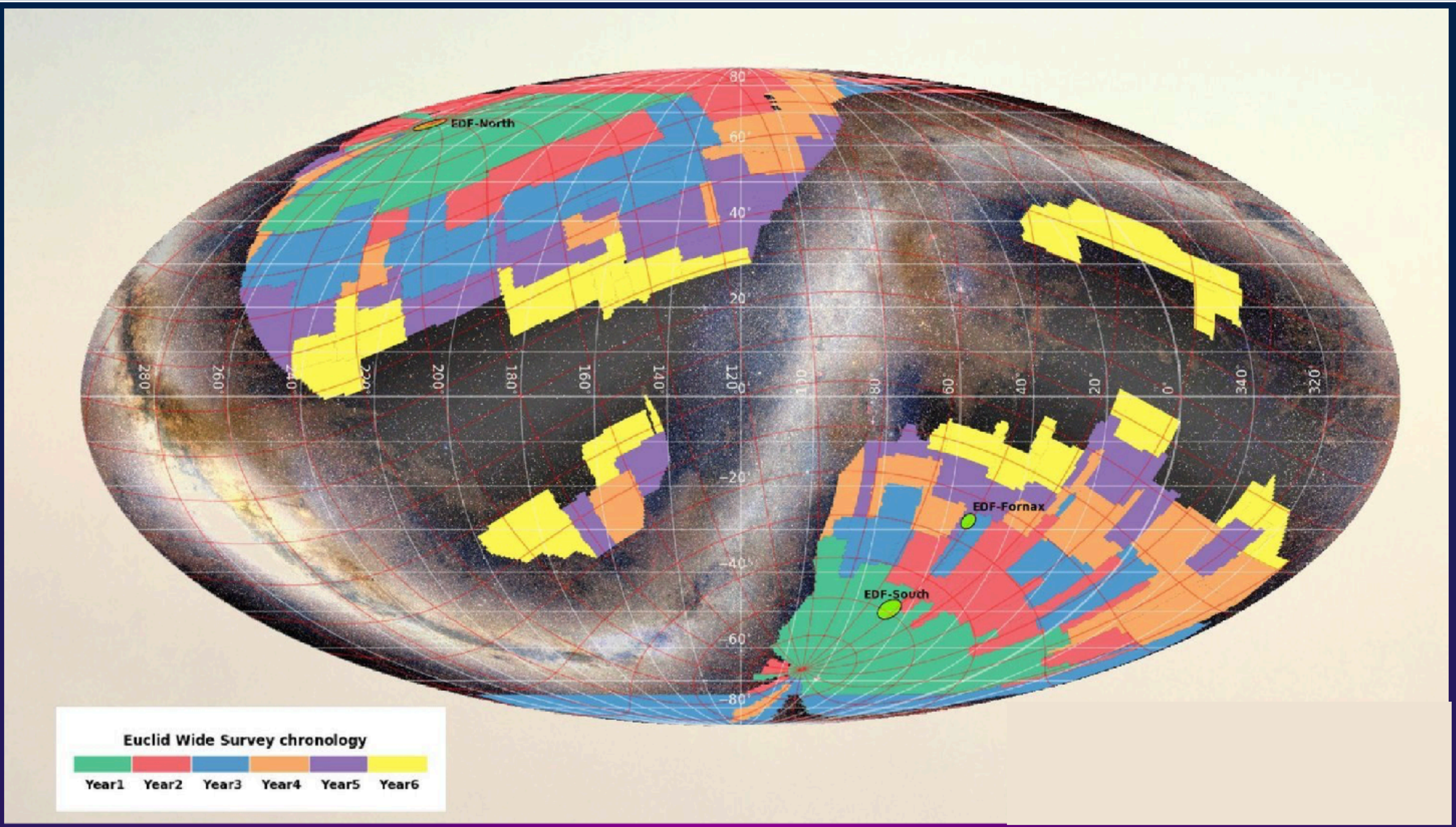
Pan-STARRS i



Subaru z

UNIONS extension




EDF-North
EDF-Fornax
EDF-South
Euclid Wide Survey chronology
Year1 Year2 Year3 Year4 Year5 Year6

Technical choices for UNIONS

Shape measurement: r-band from CFHT

Model fitting: gaussian mixture model NGMIX, (Sheldon 2005)

PSF-measurement: MCCD (Liaudat et al. 2022)

→ Fitting the whole focal plane at once

Calibration: METACALIBRATION (Huff & Sheldon 2017)

→ Shearing galaxies artificially to calibrate model, noise and selection bias

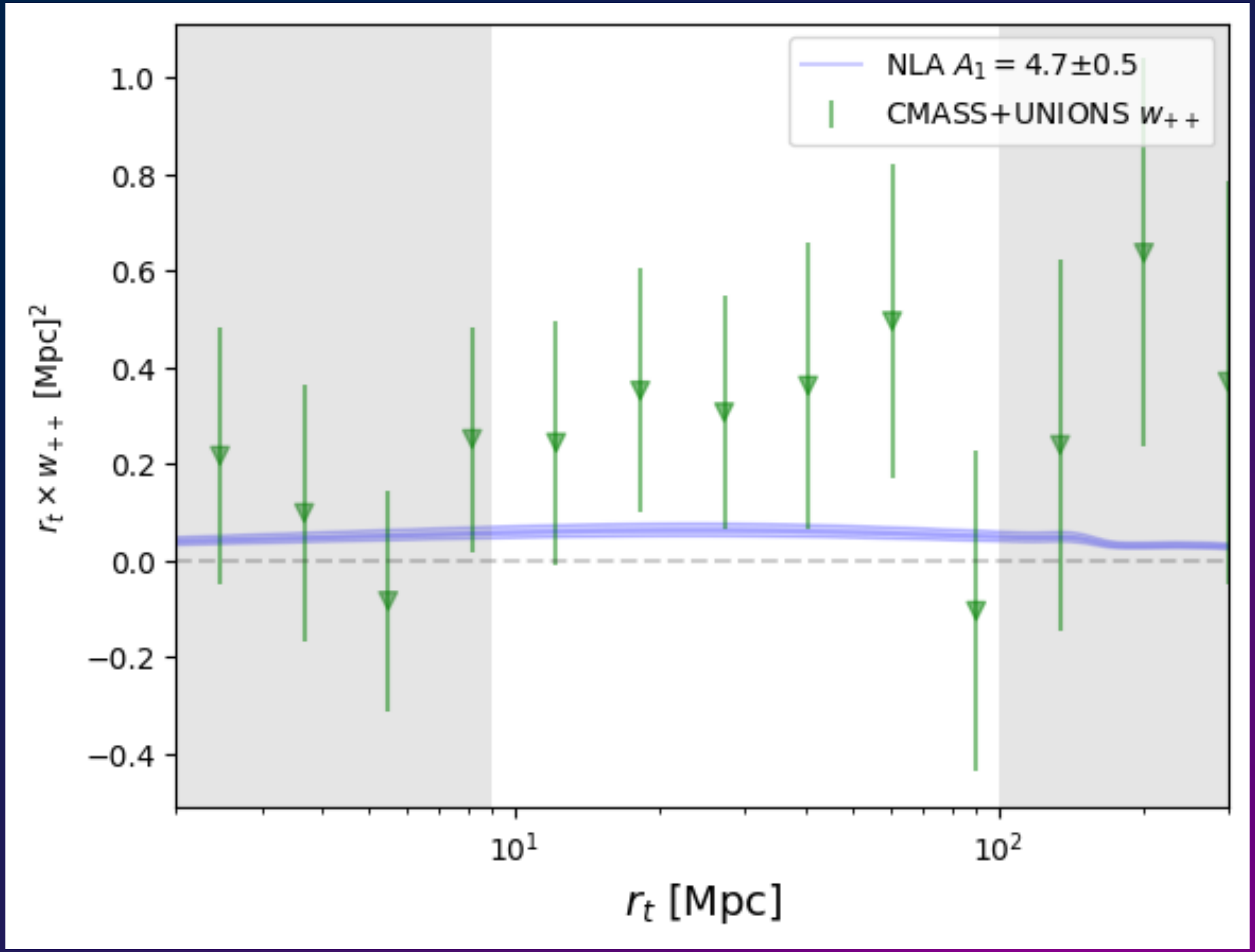
Technical paper : Guinot et al. 2022 (presenting systematics)

→ Shapepipe, publicly available software, Farrens et al. 2022

https://github.com/CosmoStat/shapepipe

New paper: *"Black-Hole-to-Halo Mass Relation From UNIONS Weak Lensing"* , Li et al. 2402.10740

Shape–Shape correlation function w_{++}

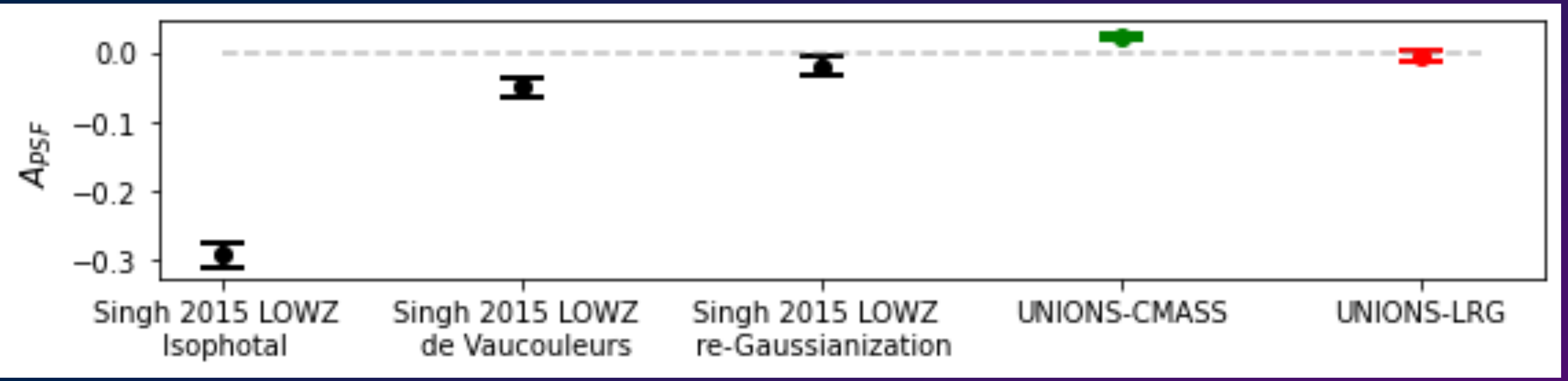


$$w_{++} = \int d\Pi \frac{\text{Shape}_+ \text{Shape}_+}{\text{Random}_s \ \text{Random}_S}$$

Diagnosing PSF Systematic contributions

From Singh 2016:

$$A_{PSF} = \frac{\int dr_t \langle e_{obs} e_{PSF} \rangle / \langle e_{PSF} e_{PSF} \rangle}{\int dr_t}$$



For CMASS: $A_{PSF} = 2.3^{+0.38}_{-0.38} \times 10^{-2}$

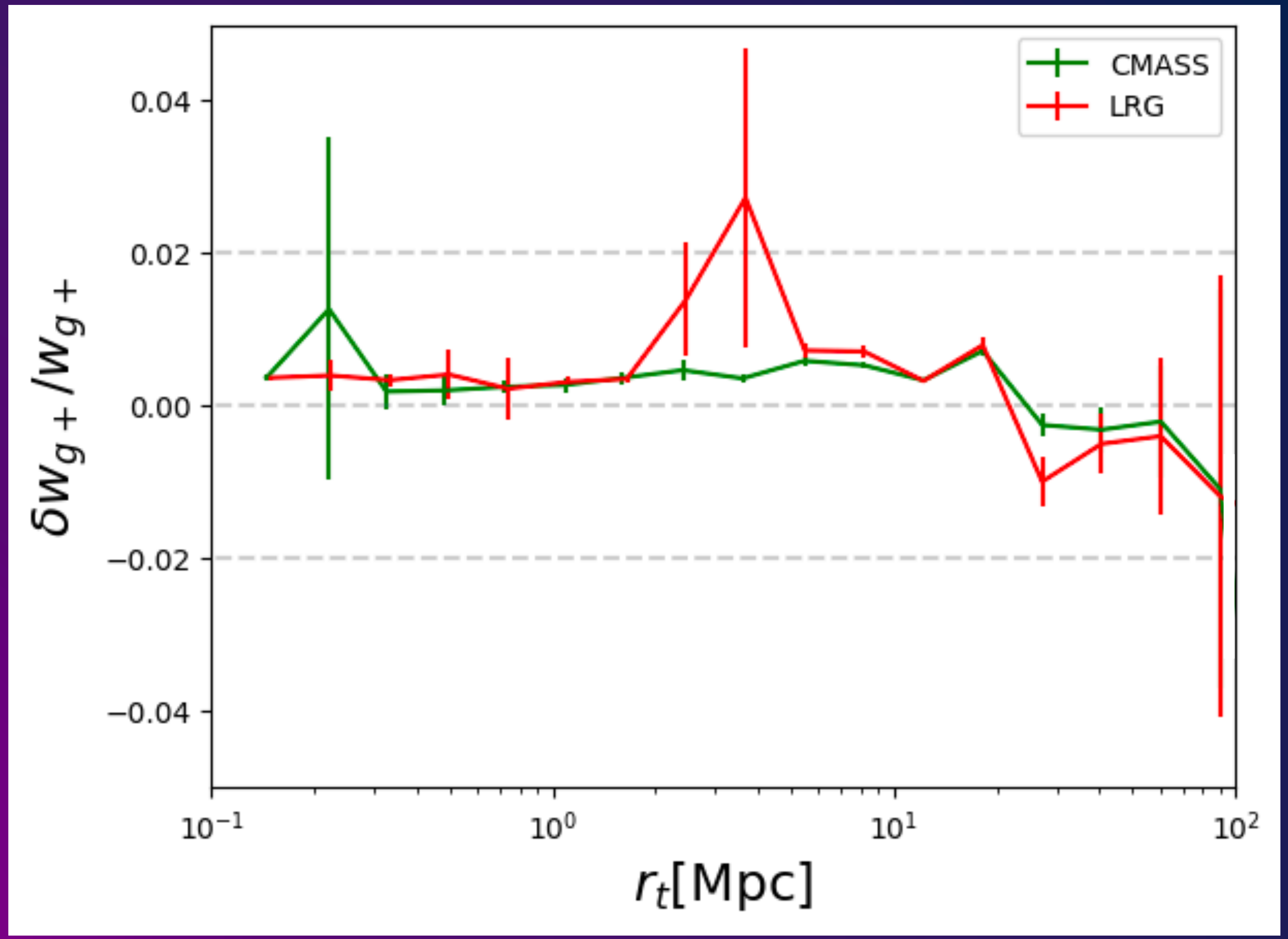
For LRG: $A_{PSF} = 6.1^{+6.2}_{-6.2} \times 10^{-3}$

δw_{g+} from PSF leakage: Zhang et al.2024 in prep

$$\alpha = \frac{\langle e_{obs} e_{PSF} \rangle - \langle e_{obs} \rangle \langle e_{PSF} \rangle}{\langle e_{PSF} e_{PSF} \rangle - |\langle e_{PSF} \rangle|^2}$$

PSF size & ellipticity residuals from validation stars

$$\delta \xi_{g+} = \xi_{g+} - \frac{\xi_{g+} - \alpha \langle e_{PSF}\, n \rangle + \langle \frac{T_{PSF}}{T} \rangle \left(\langle \frac{\delta T_{PSF}}{T} \rangle e_T^{PSF} n \rangle + \langle \delta e_T^{PSF} n \rangle \right)}{1 + \langle \frac{T_{PSF}}{T} \rangle \langle \frac{\delta T_{PSF}}{T} \rangle}$$



λ statistics–PSF error propagation

$$\varepsilon^{\text{obs}} = \varepsilon^{\text{s}} + (1+m)\gamma + c + \delta\varepsilon + \alpha\varepsilon^{PSF}$$

PSF residual from Gaussian error propagation in Paulin-Henriksson et al. (2008):

$$\delta\varepsilon = \left(\varepsilon^{\text{obs}} - \varepsilon^{PSF}\right)\frac{\delta T^{PSF}}{T} - \frac{T^{PSF}}{T}\delta\varepsilon^{PSF}$$

$$\lambda_1 = \left\langle \varepsilon T^{PSF}\, n \right\rangle \qquad \lambda_2 = \left\langle \frac{\delta T^{PSF}}{T^{PSF}}\varepsilon_T^{PSF}\, n \right\rangle \qquad \lambda_3 = \left\langle \delta\varepsilon T^{PSF}\, n \right\rangle$$

$$\delta\gamma_T = \left\langle \frac{T^{PSF}}{T} \right\rangle \left\langle \frac{\delta T^{PSF}}{T^{PSF}} \right\rangle \gamma_T^S + \alpha\lambda_1 - \left\langle \frac{T^{PSF}}{T} \right\rangle \left(\lambda_2 + \lambda_3\right).$$

PSF diagnostics

Model PSF errors as additive terms to ellipticity

$$\boldsymbol{e}^{\mathrm{g}} = \boldsymbol{e}^{\mathrm{s}} + \boldsymbol{g} + \delta\boldsymbol{e}^{\mathrm{g}}$$

with residual

$$\delta\boldsymbol{e}^{\mathrm{g}} = \boldsymbol{c} + \alpha\,\boldsymbol{e}^{\mathrm{p}} + \beta\,\delta\boldsymbol{e}^{\mathrm{p}} + \eta\,\delta\tilde{\boldsymbol{T}}^{\mathrm{p}}$$

PSF leakage

ellipticity & size
PSF model errors

Propagate to ξ_+, ξ_- as ξ_{sys}^{PSF} = sum of PSF-/star correlation functions or ρ-statistics (Rowe 2010, Jarvis et al. 2016).

τ-statistics [Gatti et al. 2021], separate PSF leakage and model errors, fit α, β, η:
cross-correlations between galaxies and stars &
ρ-statistics, ξ_{sys}^{PSF}:

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

Other PSF diagnostics:

- $\xi_{sys} = \langle e_g\, e_p \rangle^2 / \langle e_p\, e_p \rangle$
- α leakage
  - object-wise
  - scale-dependent

Thank you for your attention!