PSF Systematics Quantification

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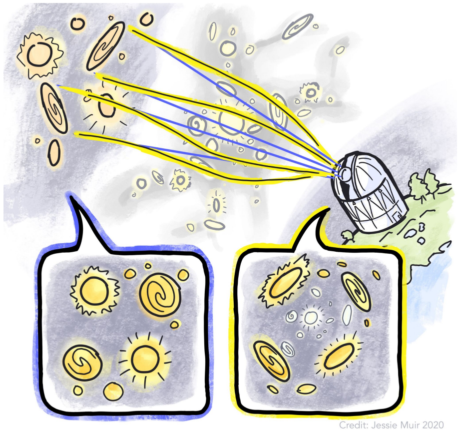
With Sacha Guerrini, Fabian Hervas Peters, Ziwen Zhang and others

Outline

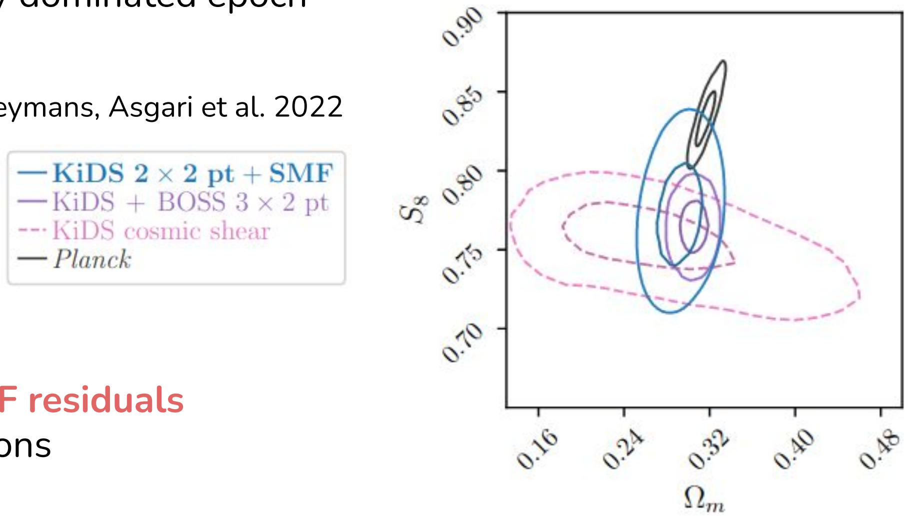
- Weak lensing shapes and the PSF
- PSF, star & galaxy cross-correlations
- Quantifying and calibrating PSF systematics
- Spin-consistent calculations

Weak gravitational lensing



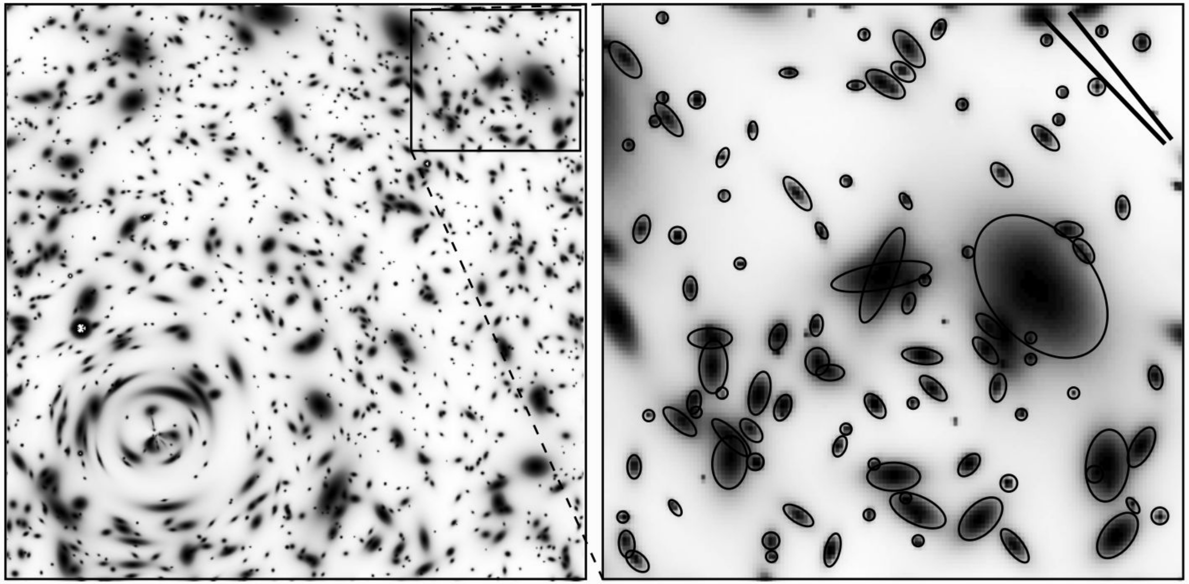
- Probe of (dark) matter distribution at large scales, and in clusters and galaxies
- Measures density amount and fluctuations amplitude ("σ_8 / S_8 tension")
- Dark-energy dominated epoch

Dvornik, Heymans, Asgari et al. 2022



- "Weak" = galaxy shape distortions at %-level
  - ≪ intrinsic galaxy shapes
  - ≪ atmosphere & telescope distortions: **PSF residuals**
- ➛ Need to quantify and calibrate PSF contributions

Weak lensing and galaxy shapes



[from Y. Mellier]
Galaxy ellipticities are an estimator of the local shear.

Observed galaxy ellipticity is (complex) sum of intrinsic ellipticity and shear

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

Galaxy shapes and PSF

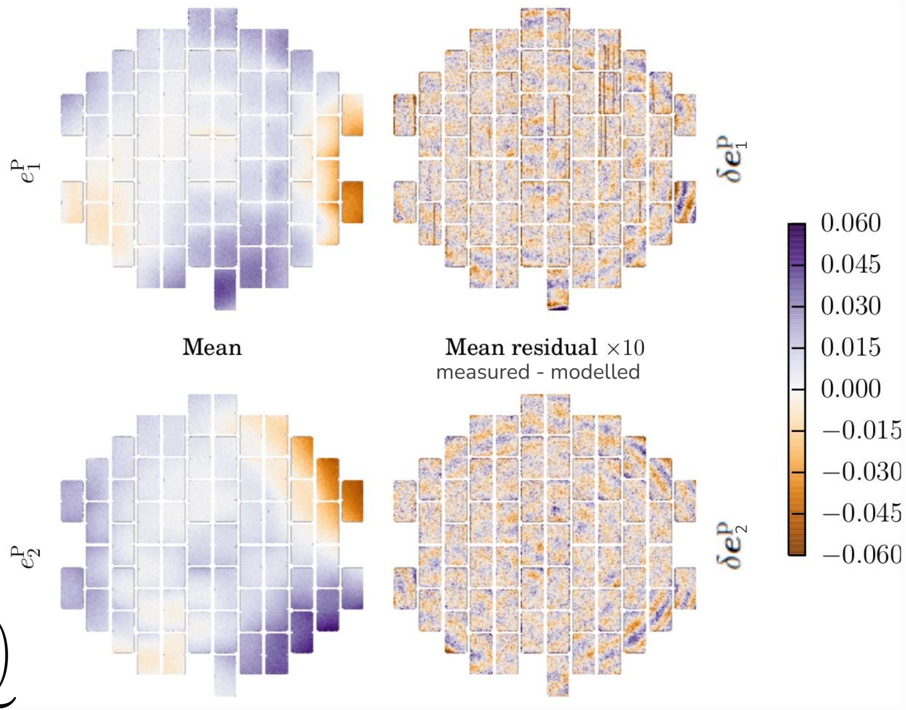
- Effect of PSF on galaxies:
  - Rounding from isotropic part (seeing)
  - Shearing from anisotropic part
- If not corrected:
  - biased shape and estimated shear
  - spurious shear correlations
- Imperfect correction:
  - Leakage (of PSF into galaxy shape)
  - Errors from PSF residuals

add residual

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

with

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



DES-Y1, (Zuntz et al. 2018)

PSF error propagation

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

the PSF residuals are additive biases:

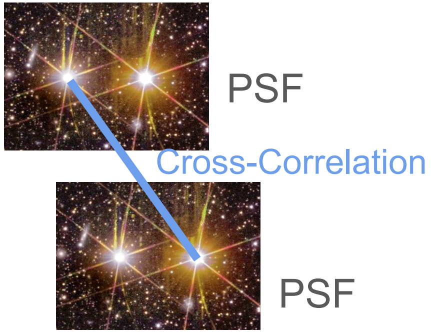
$$\underbrace{\langle e^{\mathrm{g}} e^{\mathrm{g}} \rangle}_{\text{observed corr.}} = \underbrace{\langle g g \rangle}_{\text{cosmic shear}} + \underbrace{\langle \delta e^{\mathrm{g}} \delta e^{\mathrm{g}} \rangle}_{\rho\text{-statistics}} + \text{mixed terms}$$

[Rowe 2010, Jarvis et al. 2016]

Past assumption [Paulin-Henriksson 2008]: $\beta = \eta = 1$.
But: we can infer α, β, η from the catalogues.

[Zhang, MK et al. 2024] small multiplicative bias from PSF

6 ϱ-statistics



Galaxy - star cross-correlations

Measure galaxy - PSF cross-correlations (τ-statistics): $\langle \boldsymbol{e}^{\mathrm{g}} \boldsymbol{\delta} e^{\mathrm{g}} \rangle$

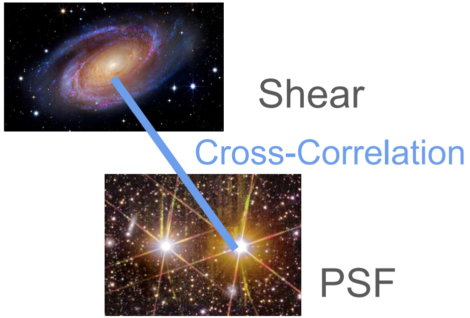
and solve

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

for free parameters α, β, η, using MCMC [Gatti et al. 2021] or least squares.

Need covariance of τ.

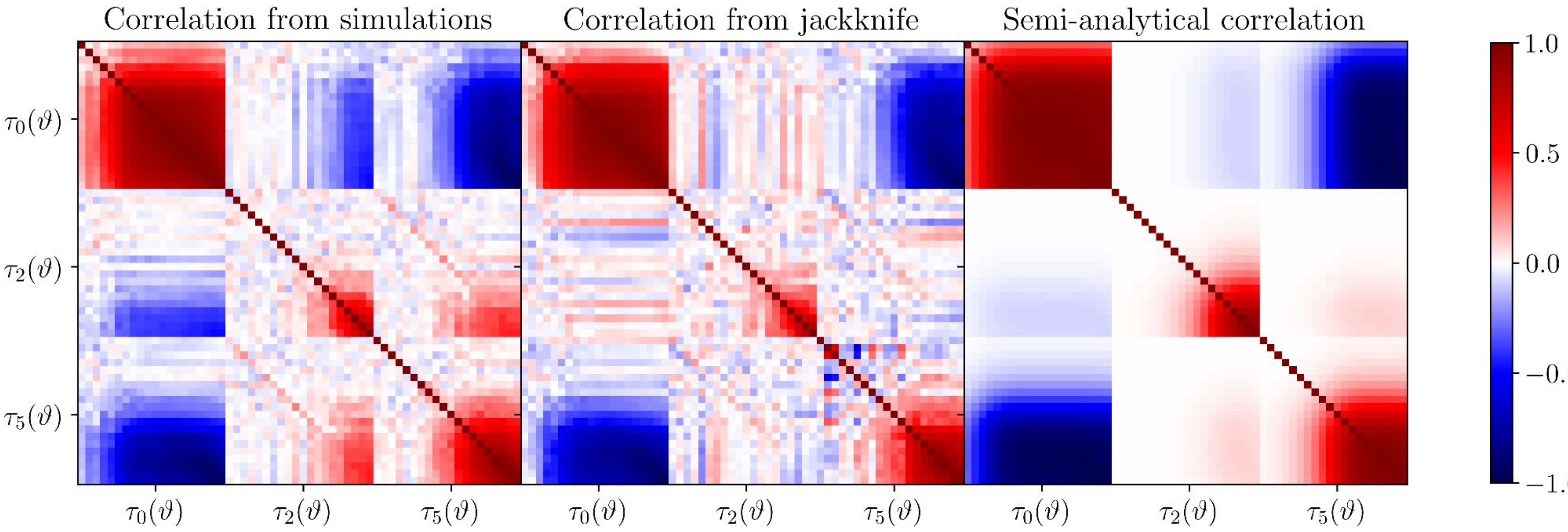
3 τ-statistics



Covariance of τ-statistics

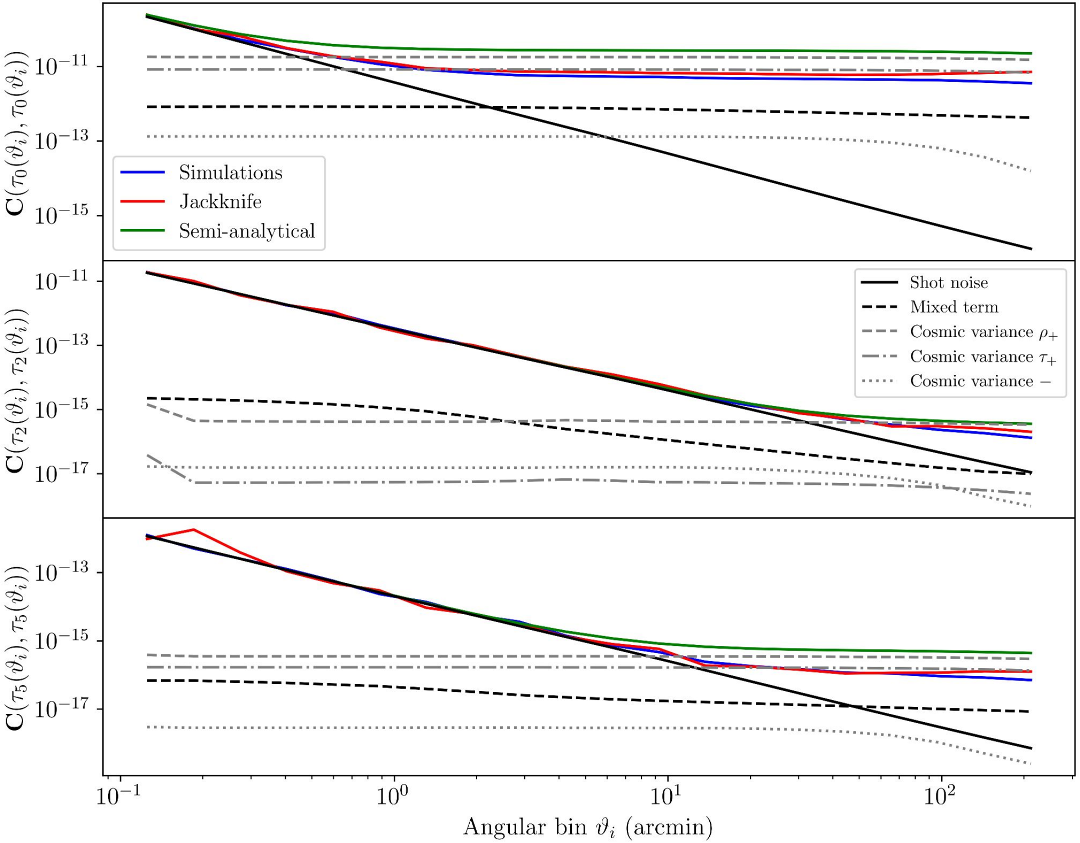
- **Jackknife resampling**.
  Noisy, biased low on large scales, sensitive to patching & number density fluctuations, need large sky area.
- **Mock simulations.**
  Need large number, slow, difficult to include PSF (residuals) and galaxy - PSF correlations.
- **Semi-analytical.**
  Follows analytical formalism from Schneider, van Waerbeke, MK & Mellier (2002).
  Uses measured τ- and ϱ-statistics.
  Assumes normal distributions, extrapolates correlations.
  Noise-free, fast, any sky area, includes all correlations.
  [Guerrini, MK, Leterme et al. to be submitted.]

Covariance of τ-statistics

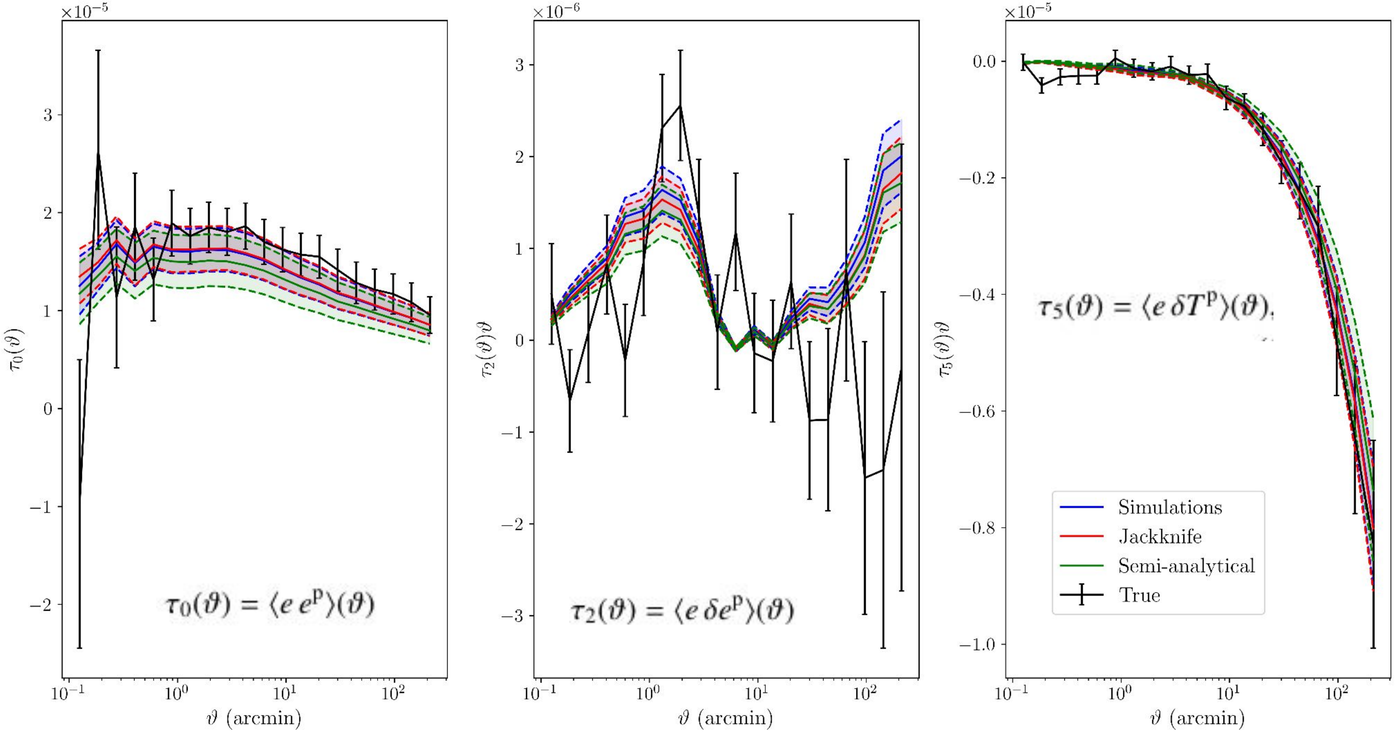


Variance of τ

- Good agreement on small scales
- Slight offset on large scales
- Shot noise on small scales
- Cosmic variance on large scales



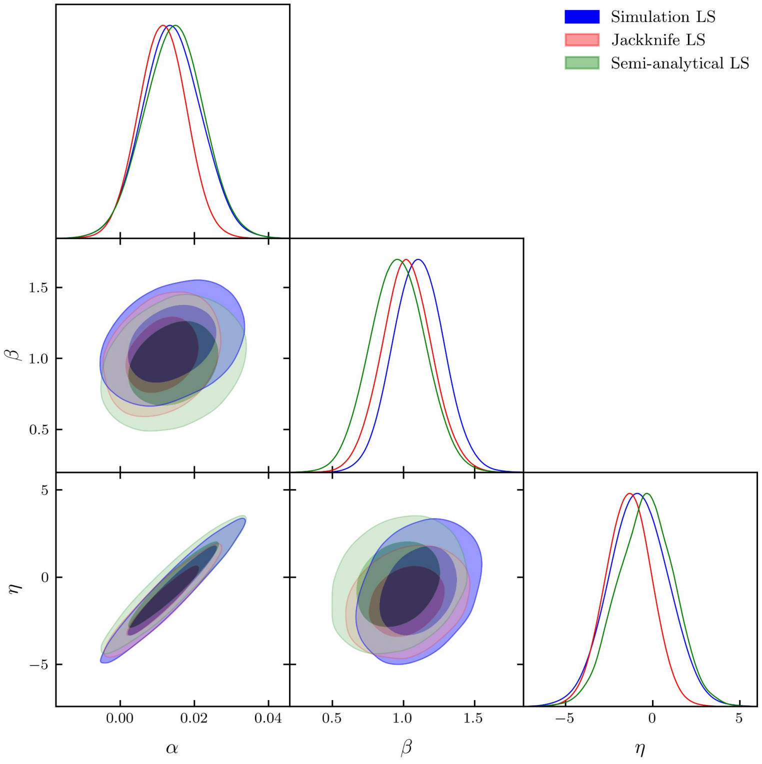
Fit to τ-statistics



Parameter inference

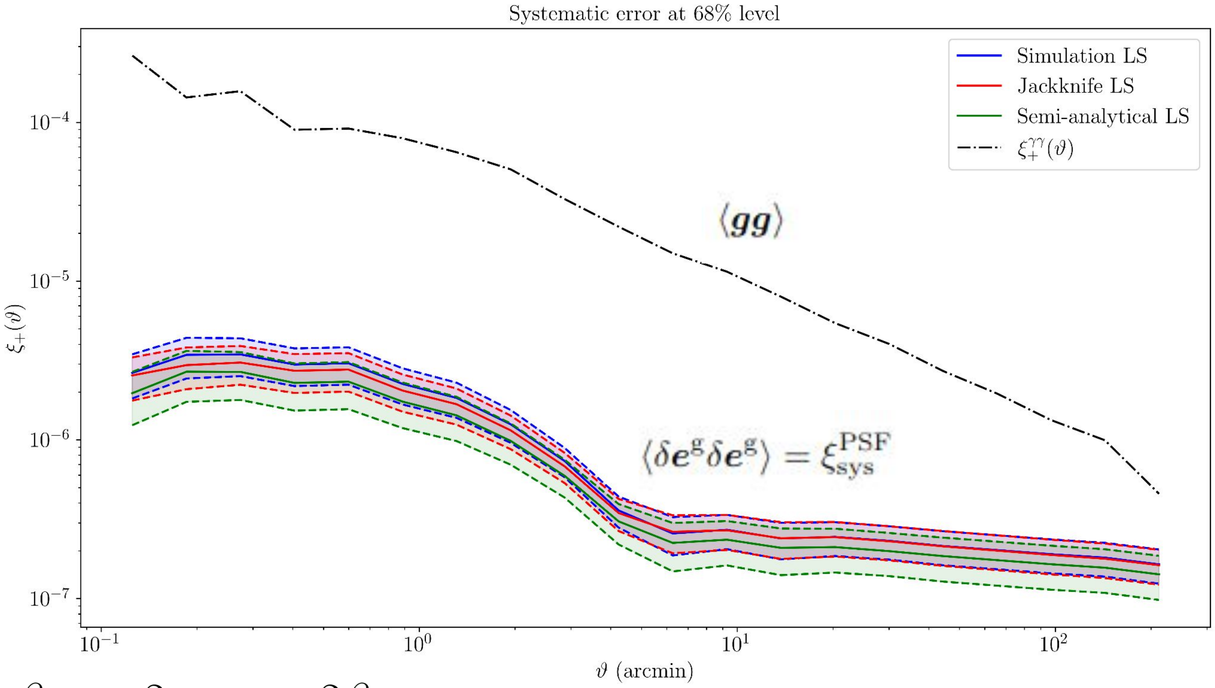
$$\delta \boldsymbol{e}^{\mathrm{g}} = \alpha \underbrace{\mathbf{e}_{\mathrm{model}}}_{\text{Leakage}} + \beta \underbrace{\left(\mathbf{e}_{*} - \mathbf{e}_{\mathrm{model}}\right)}_{\text{Ellipticity error}} + \eta \underbrace{\left(\mathbf{e}_{*} \frac{T_{*} - T_{\mathrm{model}}}{T_{*}}\right)}_{\text{Size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

Here, PSF leakage α is the dominant contamination.



Additive PSF bias

$$\underbrace{\langle \boldsymbol{e}^{\rm g}\boldsymbol{e}^{\rm g}\rangle}_{\text{observed corr.}} = \underbrace{\langle \boldsymbol{g}\boldsymbol{g}\rangle}_{\text{cosmic shear}} + \underbrace{\langle \delta\boldsymbol{e}^{\rm g}\delta\boldsymbol{e}^{\rm g}\rangle}_{\rho\text{-statistics}}$$

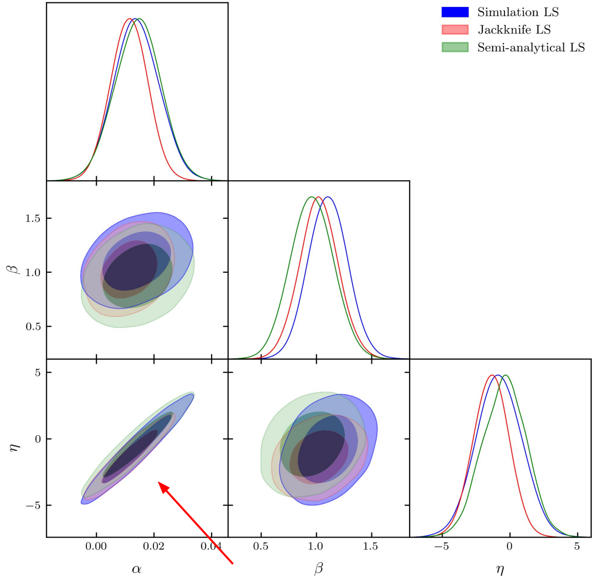


$$\xi_{\rm sys}^{\rm PSF} = \alpha^2\rho_0 + \beta^2\rho_1 + \eta^2\rho_3 + 2\alpha\beta\rho_2 + 2\alpha\eta\rho_5 + 2\beta\eta\rho_4$$

Parameter degeneracy

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

redundant information



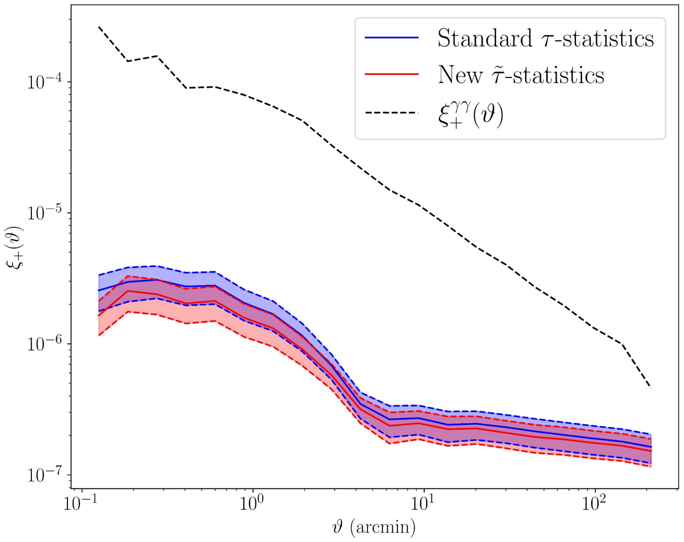
strong degeneracy

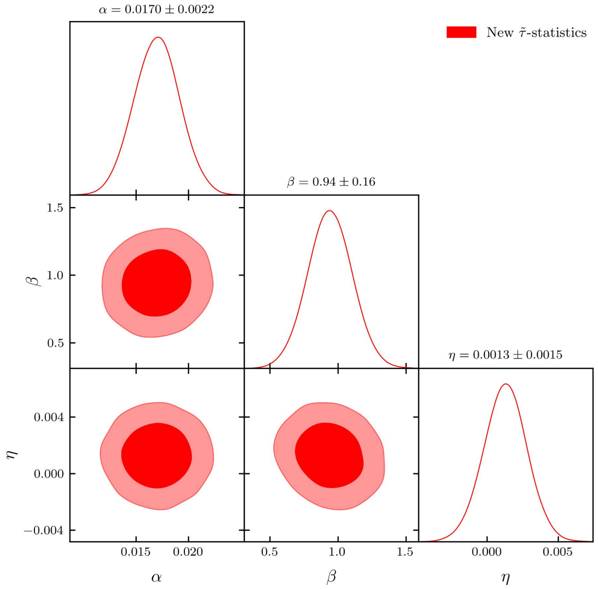
Redefine size residual term to $\eta \left(e^{2i\varphi} \frac{T_* - T_{\rm model}}{T_{\rm model}} \right)$

Lifts the degeneracy:

Parameter degeneracy

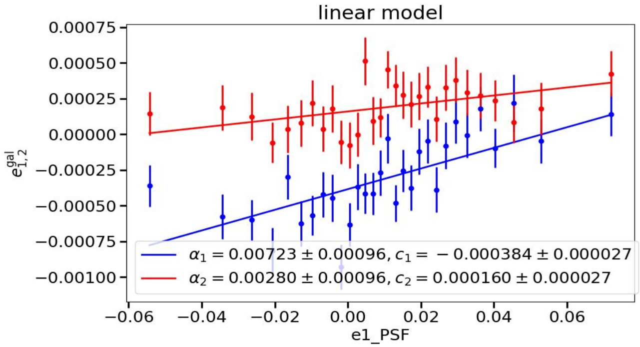
$$\delta\tilde{\mathbf{e}}^{\mathrm{sys}}_{\mathrm{model}} = \alpha\mathbf{e}_{\mathrm{model}} + \beta(\mathbf{e}_* - \mathbf{e}_{\mathrm{model}}) + \eta\underbrace{\left(e^{2i\varphi}\frac{T_* - T_{\mathrm{model}}}{T_{\mathrm{model}}}\right)}_{\text{remove the leakage information}}$$

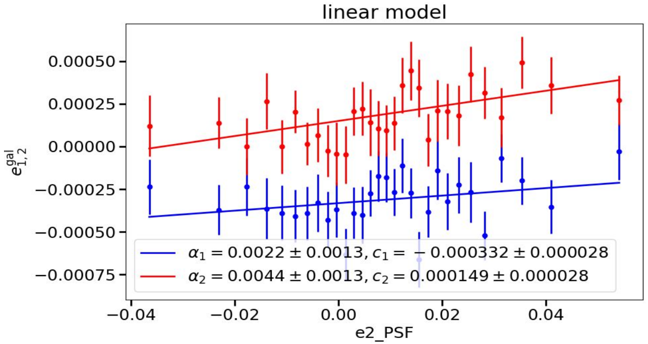




PSF leakage calibration

Ignoring PSF residuals, we can estimate PSF leakage $\delta \boldsymbol{e}^{\mathrm{g}} = \alpha \boldsymbol{e}_{\mathrm{model}} + \boldsymbol{c}$ via regression, using PSF interpolated to galaxy positions.



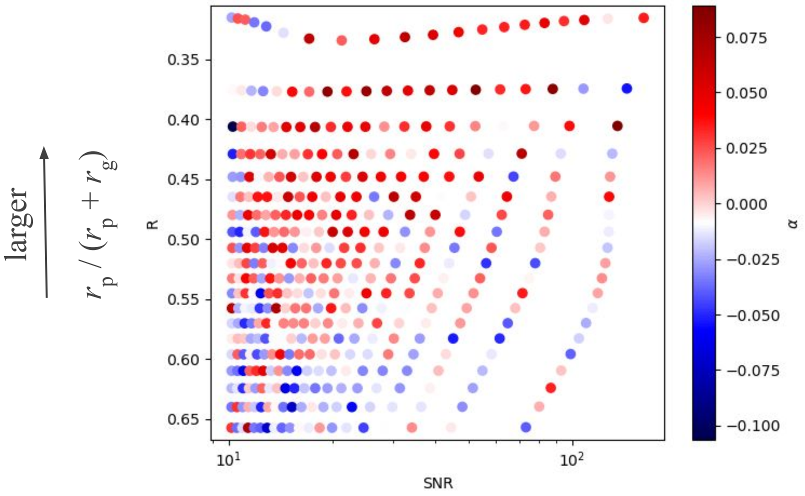


Calibrate by subtracting best-fit $\alpha \boldsymbol{e}_{\mathrm{model}} + \boldsymbol{c}$ from each galaxy.

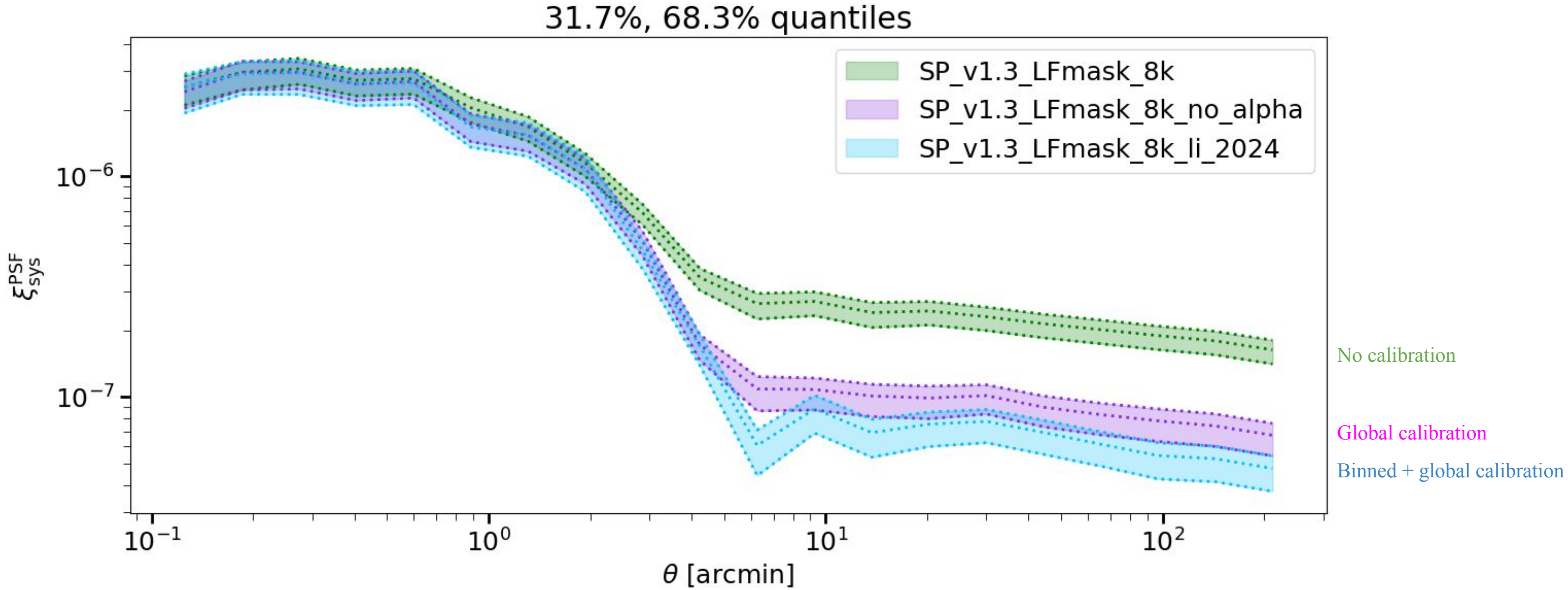
PSF leakage calibration

Ignoring PSF residuals, we can estimate PSF leakage $\delta \boldsymbol{e}^{\mathrm{g}} = \alpha \boldsymbol{e}_{\mathrm{model}} + \boldsymbol{c}$ via regression, using PSF interpolated to galaxy positions.

Either compute global α or bin by galaxy property. Important if correlated with shear, redshift, ...



PSF leakage calibration



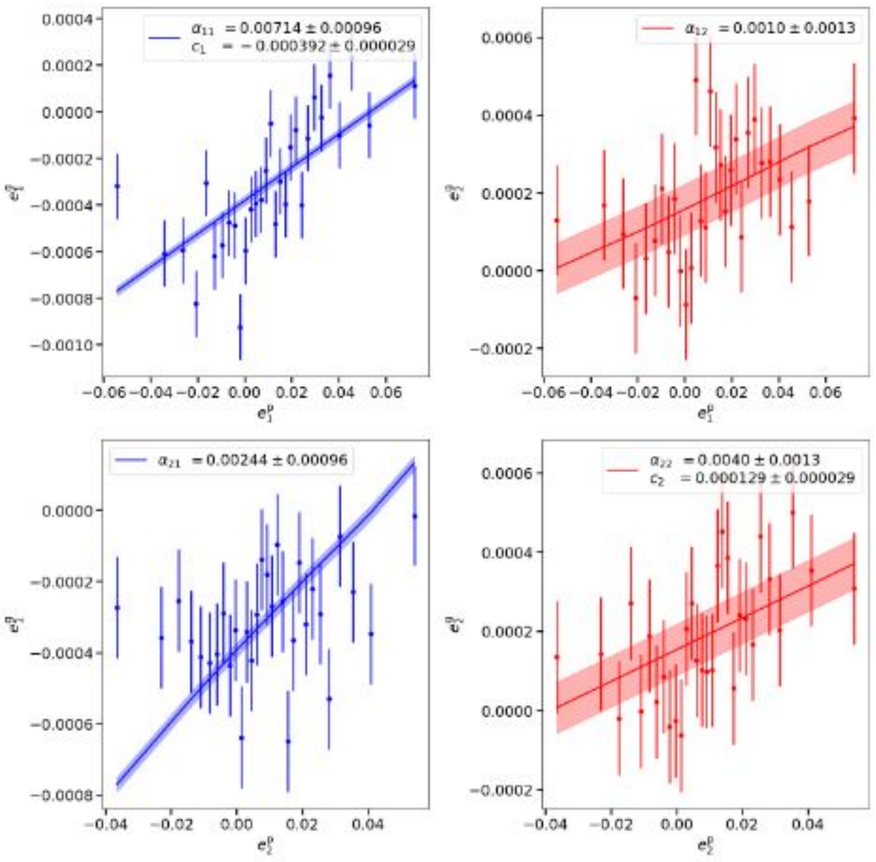
PSF leakage

What about a mixed-component leakage,

e.g. $\delta e_1^{\mathrm{g}} = \alpha_{12}\, e_2^{\mathrm{p}} + c_1$?

Leakage is 2x2 matrix equation, need to fit coupled 2D function

$$\delta e_i^{\mathrm{g}} = c_i + \sum_{j=1}^{2} \alpha_{ij} e_j^{\mathrm{p}}$$



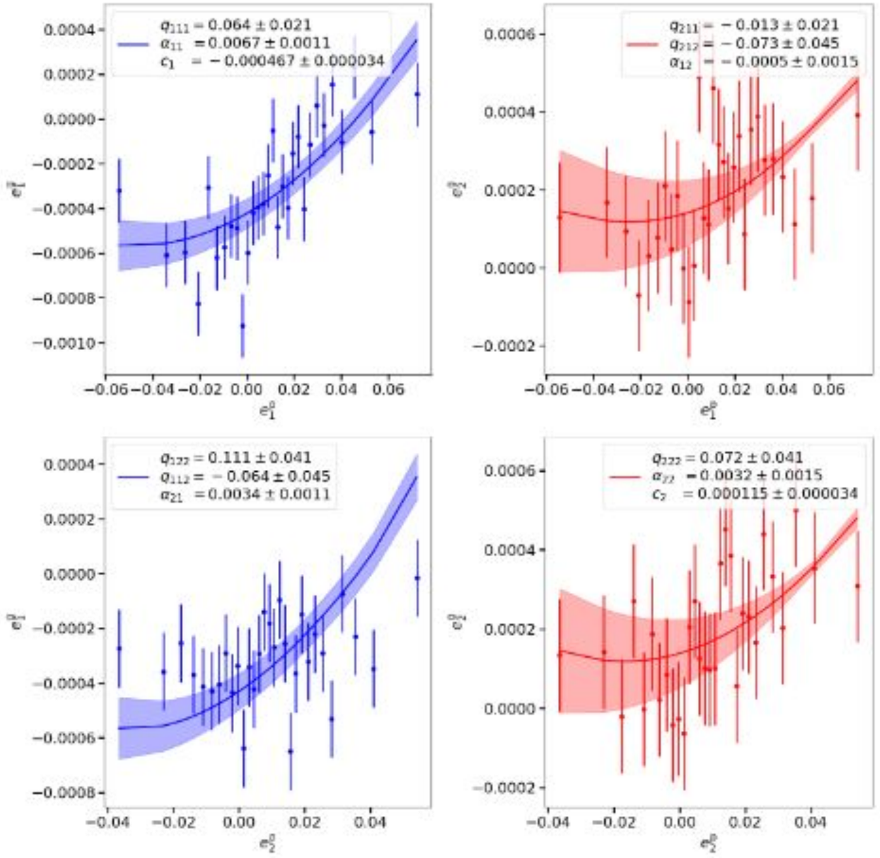
PSF leakage

What about a mixed-component leakage,

e.g. $\delta e_1^{\rm g} = \alpha_{12}\, e_{2,\rm model} + c_1$?

Can use quadratic model

$$\delta e_i^{\rm g} = c_i + \sum_{j=1}^{2} \alpha_{ij} e_j^{\rm p} + \sum_{j=1}^{2} \sum_{k=j}^{2} q_{ijk} e_j^{\rm p} e_k^{\rm p}$$



PSF leakage

Can decompose leakage matrix into spin components

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix}$$

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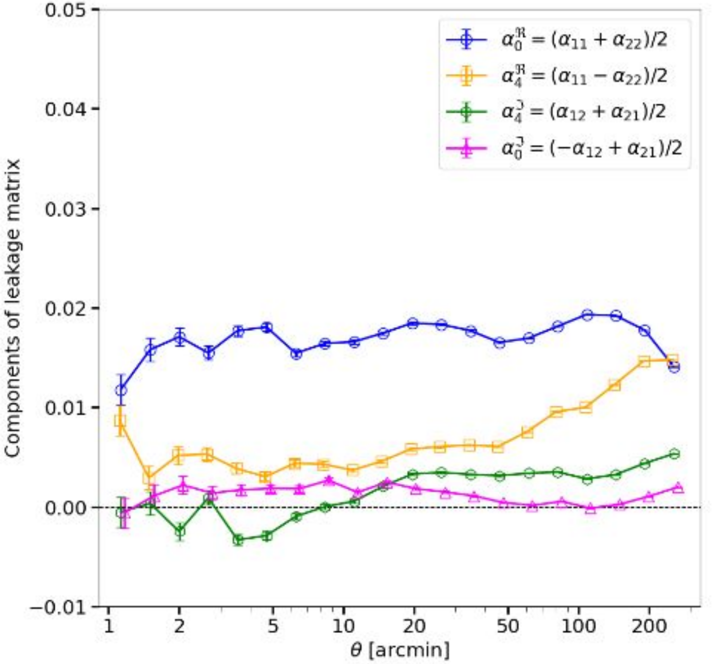

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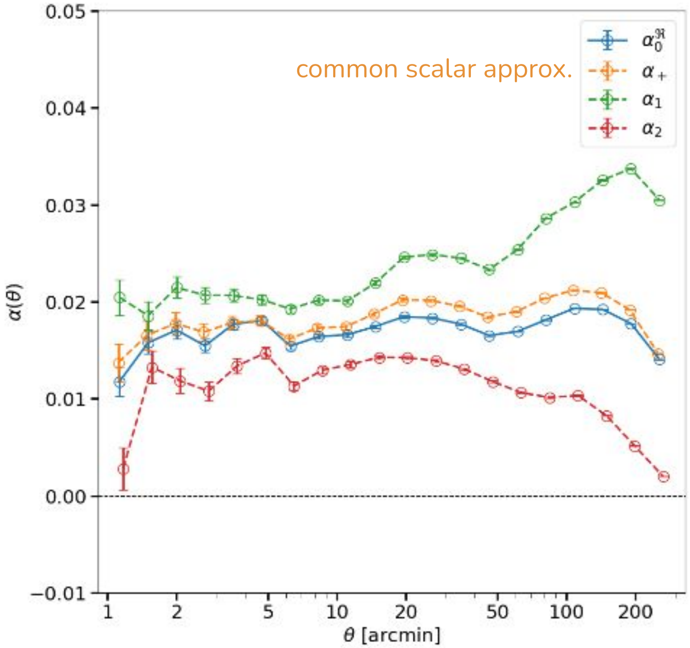


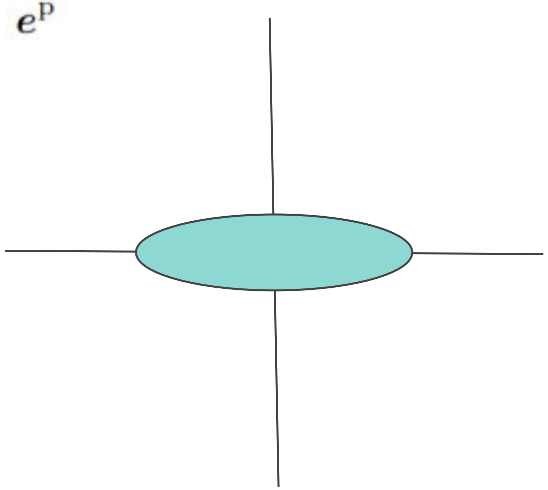
PSF leakage

$$\delta \boldsymbol{e}^{\mathrm{g}} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \boldsymbol{e}^{\mathrm{p}}$$

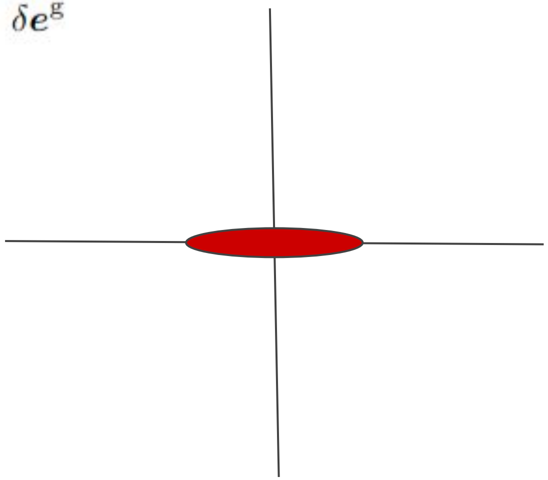
spin-0 real

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} & 0 \\ 0 & \alpha_0^{\Re} \end{pmatrix}$$

$\boldsymbol{e}^{\mathrm{p}}$



$\delta \boldsymbol{e}^{\mathrm{g}}$



PSF leakage

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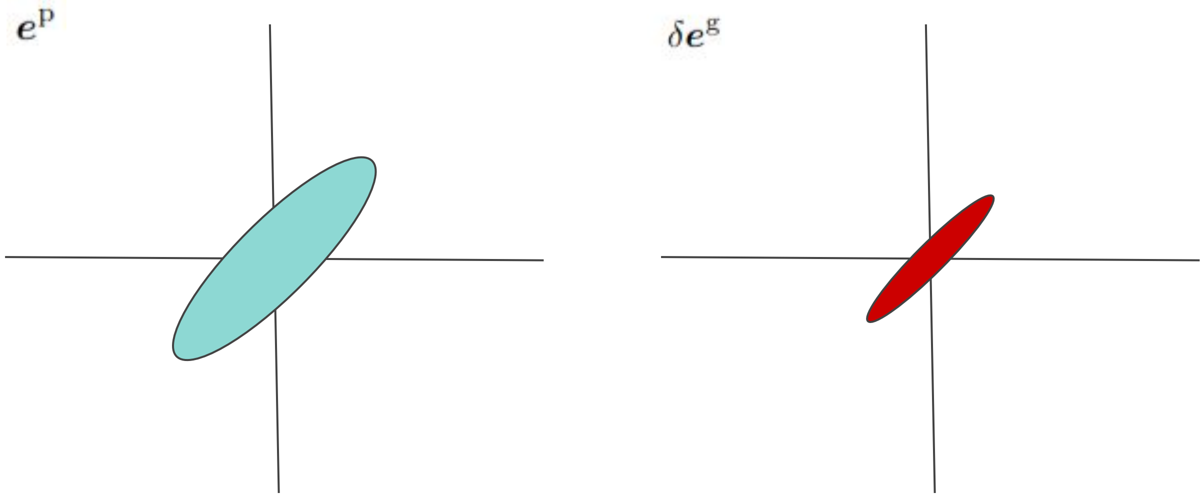

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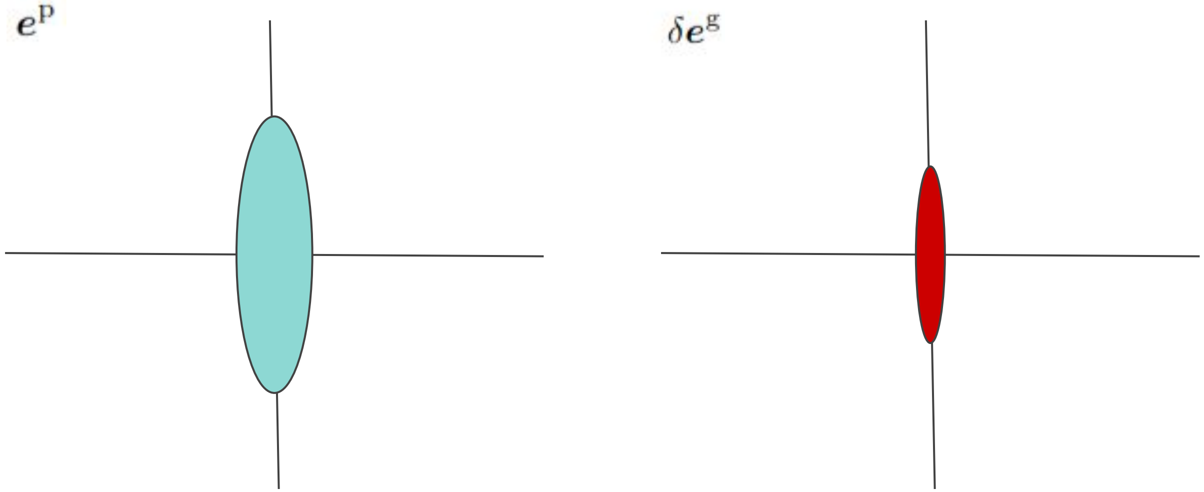

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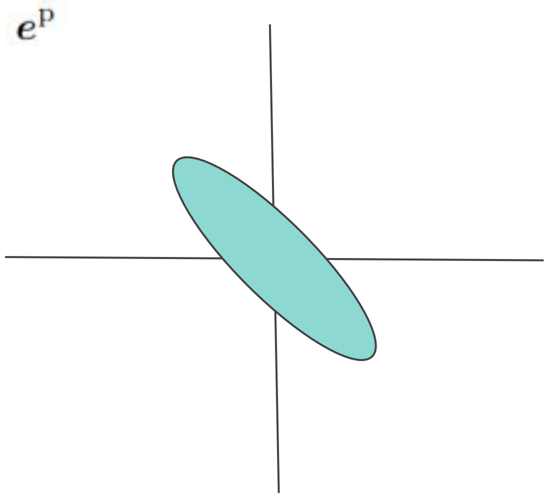

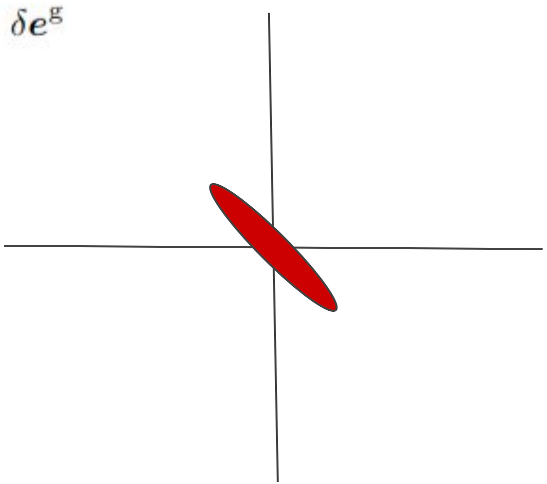

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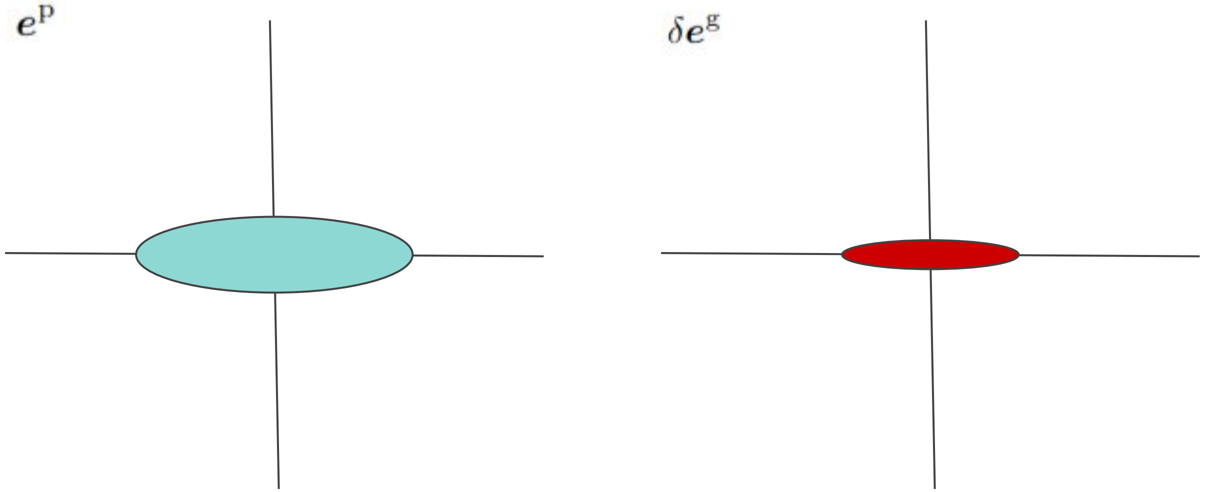

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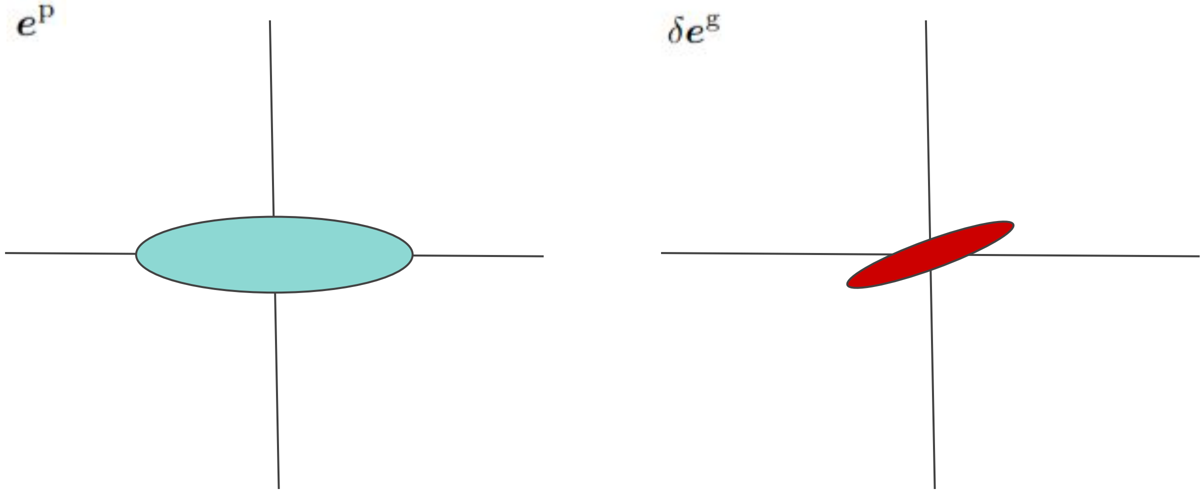
spin-0 complex

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} & -\alpha_0^{\Im} \\ \alpha_0^{\Im} & \alpha_0^{\Re} \end{pmatrix}$$



PSF leakage

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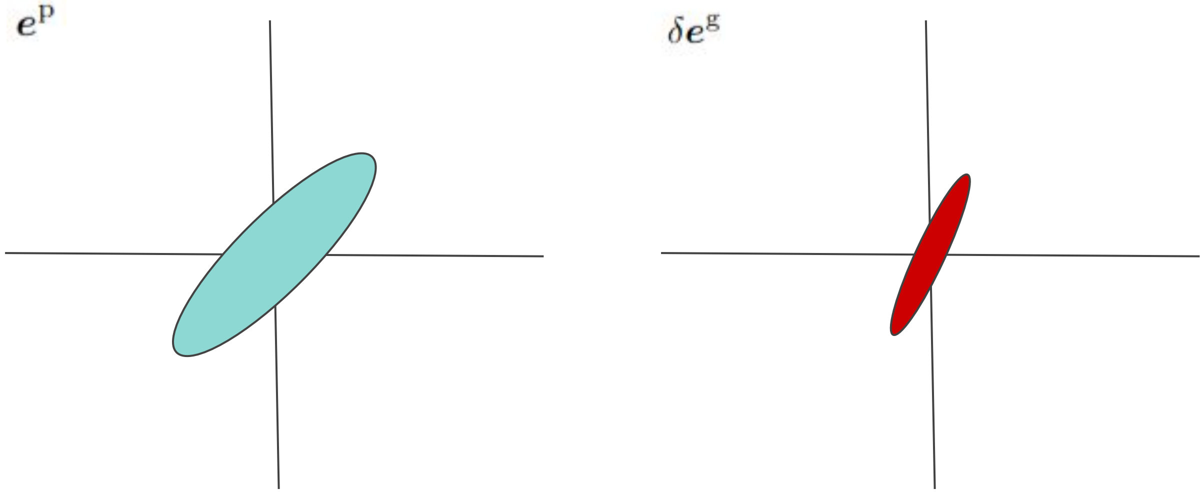

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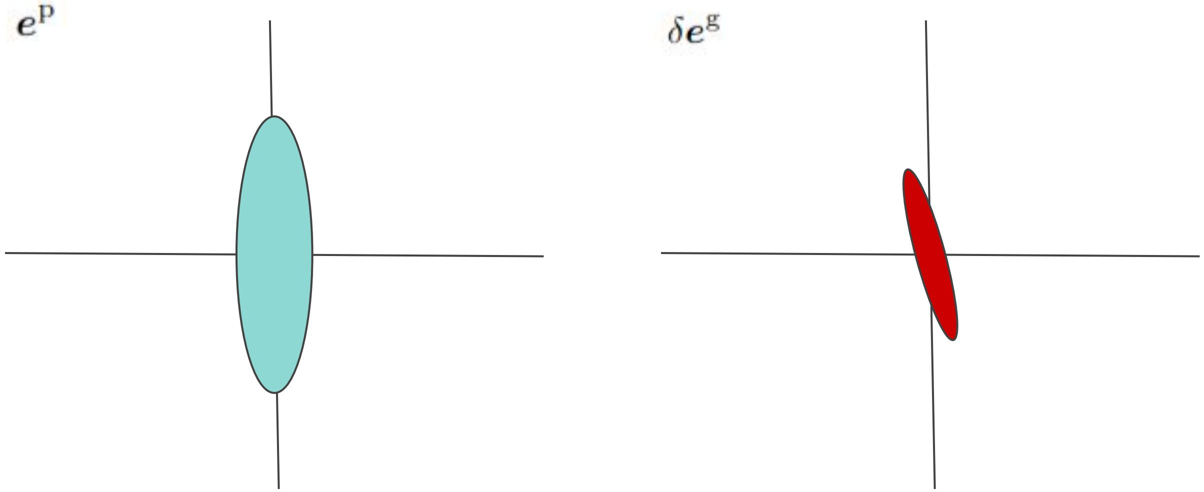

PSF leakage

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spin-0 complex

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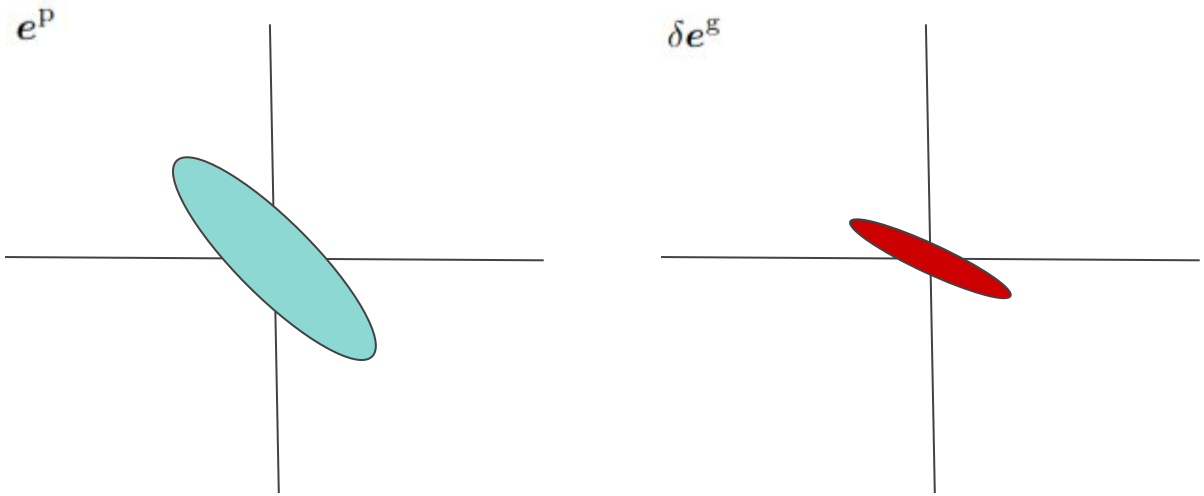

PSF leakage

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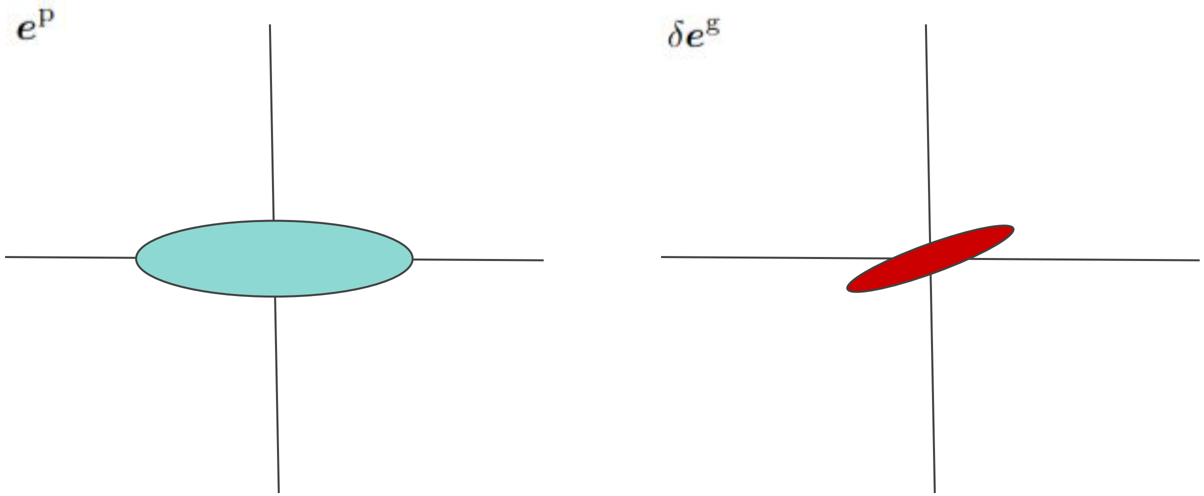


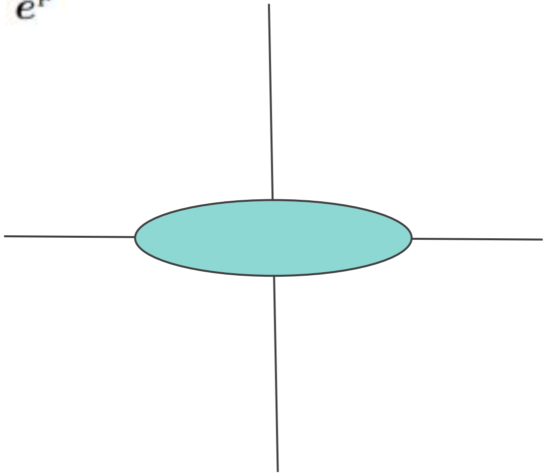
PSF leakage

$$\delta \boldsymbol{e}^{\mathrm{g}} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \boldsymbol{e}^{\mathrm{p}}$$

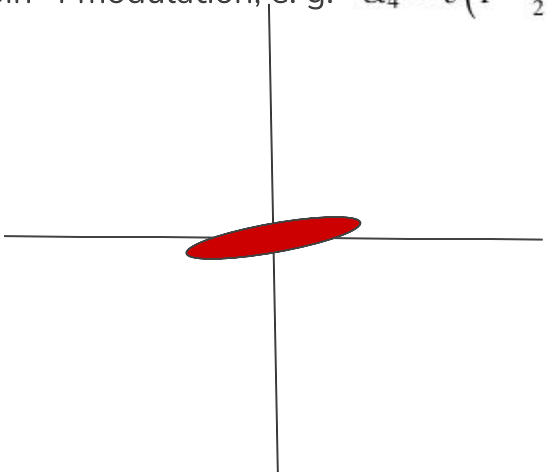
spin-0 + spin-4 complex

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix}$$

$\boldsymbol{e}^{\mathrm{p}}$



spin-4 modulation, e. g. $\boldsymbol{\alpha}_4 = c\left(1 - \frac{1}{2}\cos^4\phi\right) e^{4\mathrm{i}\phi}$



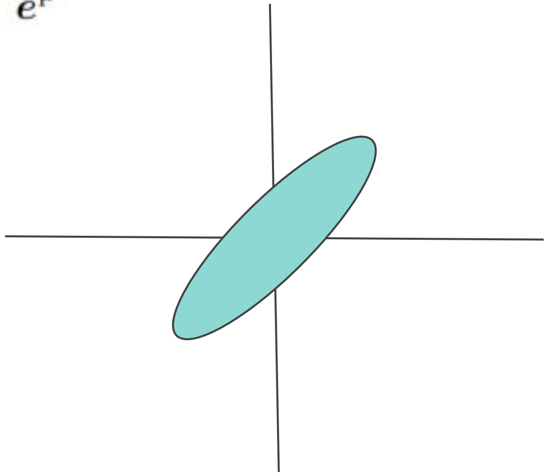
PSF leakage

$$\delta \mathbf{e}^{\rm g} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \mathbf{e}^{\rm p}$$

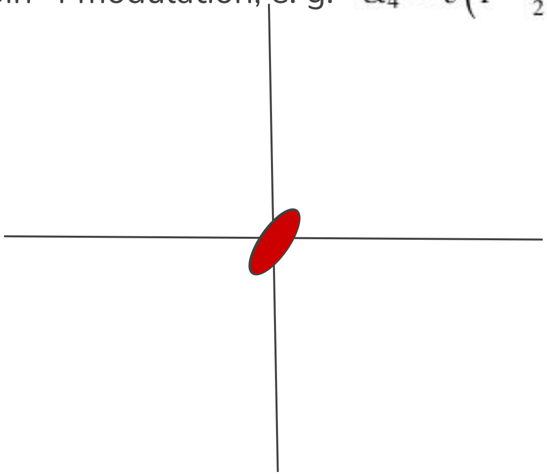
spin-0 + spin-4 complex

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix}$$

$\mathbf{e}^{\rm p}$



spin-4 modulation, e. g. $\boldsymbol{\alpha}_4 = c\left(1 - \frac{1}{2}\cos^4\phi\right)e^{4{\rm i}\phi}$



PSF leakage

$$\delta \boldsymbol{e}^{\rm g} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \boldsymbol{e}^{\rm p}$$

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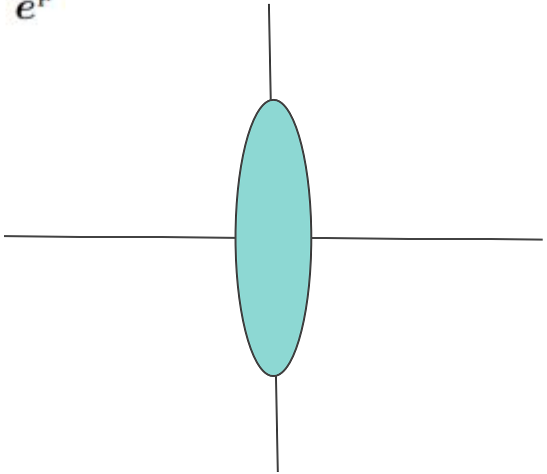
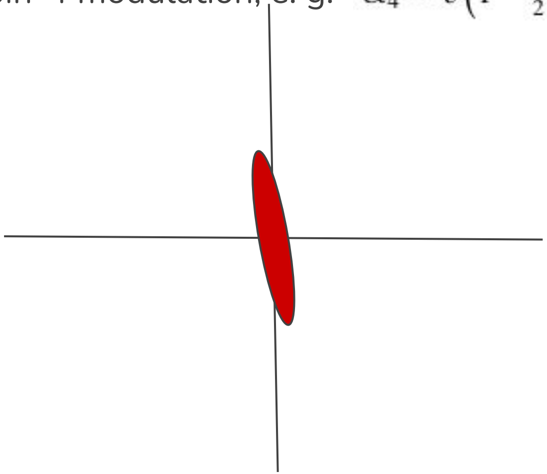
$\boldsymbol{e}^{\rm p}$



spin-4 modulation, e. g. $\boldsymbol{\alpha}_4 = c\left(1 - \frac{1}{2}\cos^4\phi\right) e^{4{\rm i}\phi}$



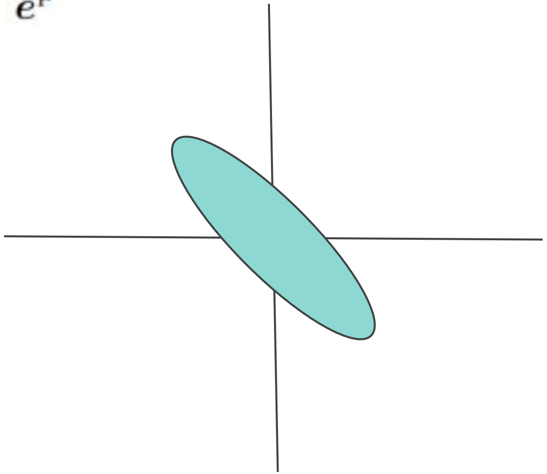
PSF leakage

$$\delta \boldsymbol{e}^{\rm g} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \boldsymbol{e}^{\rm p}$$

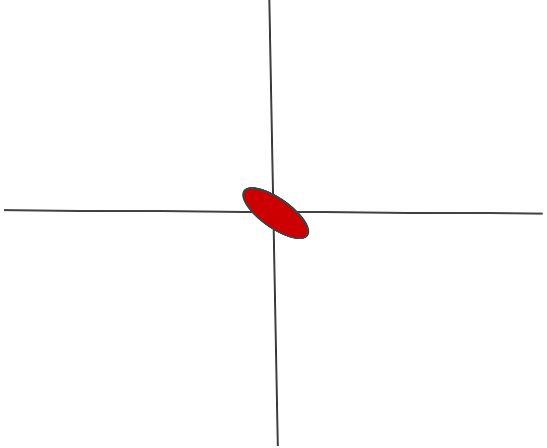
spin-0 + spin-4 complex

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix}$$

$\boldsymbol{e}^{\rm p}$



spin-4 modulation, e. g. $\boldsymbol{\alpha}_4 = c\left(1 - \frac{1}{2}\cos^4\phi\right)e^{4{\rm i}\phi}$



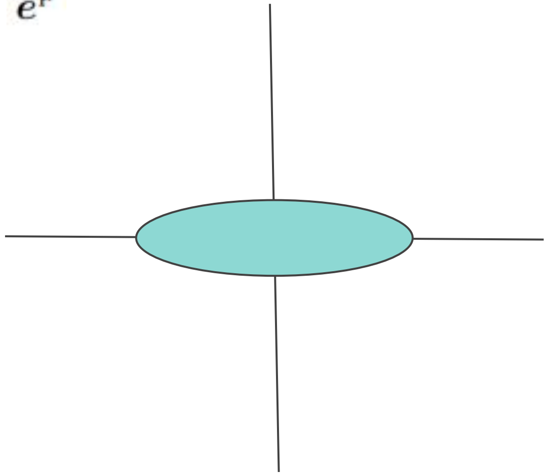
PSF leakage

$$\delta \boldsymbol{e}^{\mathrm{g}} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix} \boldsymbol{e}^{\mathrm{p}}$$

spin-0 + spin-4 complex

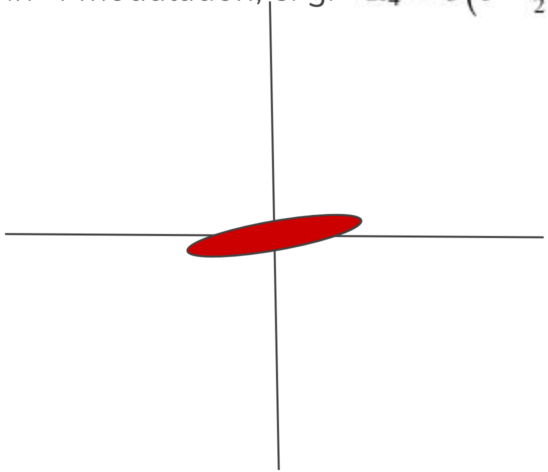
$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_0^{\Re} + \alpha_4^{\Re} & -\alpha_0^{\Im} + \alpha_4^{\Im} \\ \alpha_0^{\Im} + \alpha_4^{\Im} & \alpha_0^{\Re} - \alpha_4^{\Re} \end{pmatrix}$$

$\boldsymbol{e}^{\mathrm{p}}$



rotates through $\pi \to$ spin-2

spin-4 modulation, e. g. $\boldsymbol{\alpha}_4 = c\left(1 - \frac{1}{2}\cos^4\phi\right)e^{4\mathrm{i}\phi}$



modulates through $\pi/2 \to$ spin-4

Summary

- Quantify PSF additive biases to cosmic-shear two-point function.

- Calibrate by:
    - Subtracting $\xi_{\mathrm{PSF}}{}^{\mathrm{sys}}$ from cosmological signal
    - Marginalising over α, $\boldsymbol{\beta}$, η, provide priors.
    - Subtract PSF leakage α e^p

- Create PSF systematics maps for forward modelling (e.g. SBI). Use for any (higher-order) statistics.

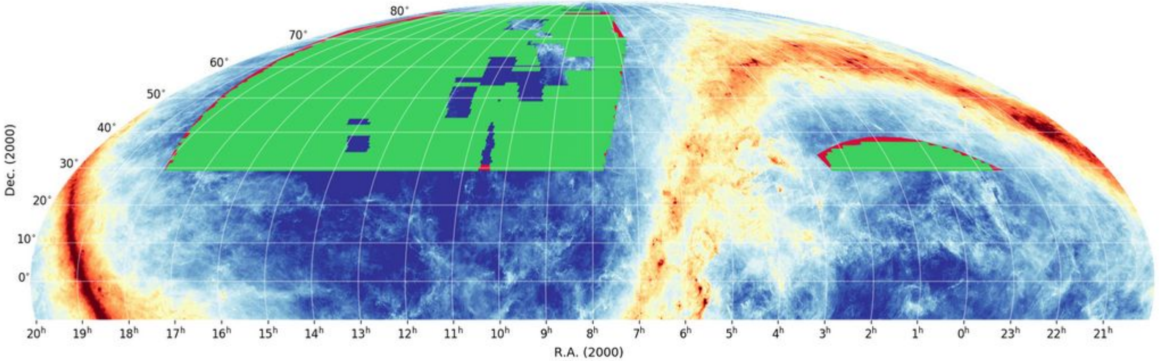
- Full spin-consistent allow for flexible, physically meaningful PSF contamination model

Backup slides

UNIONS: Ultra-violet Near-Infrared Optical Northern Survey
CFIS: Canada-France Imaging Survey

Large imaging survey (4,800 deg^2) in the Northern hemisphere with CFTH in optical bands
P.I.: Jean-Charles Cuillandre (DAp) & Alain McConnachie (Victoria/Canada)

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

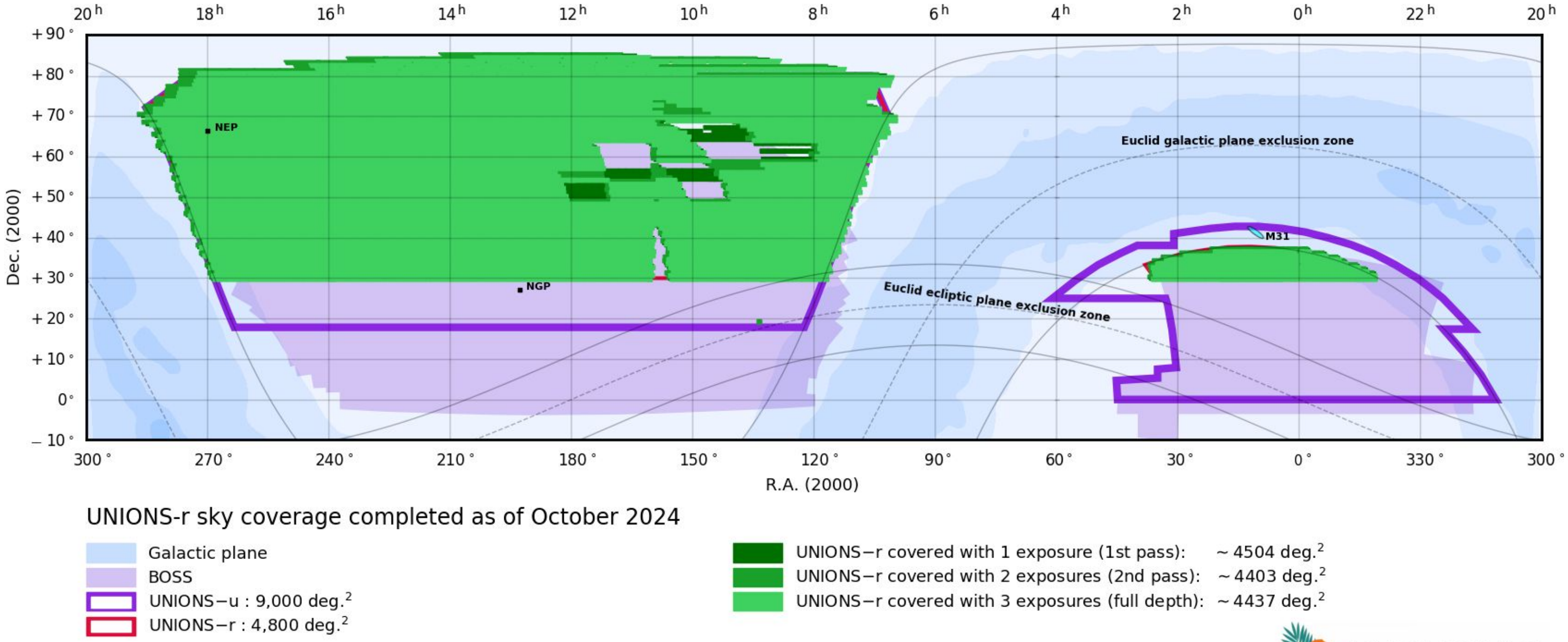


UNIONS-r survey area and realized coverage as of November 2023
Total survey area: 4.800 deg.^{2}
Covered area: 4382 deg.^{2} (91%), left to cover: 418 deg.^{2} (9%)

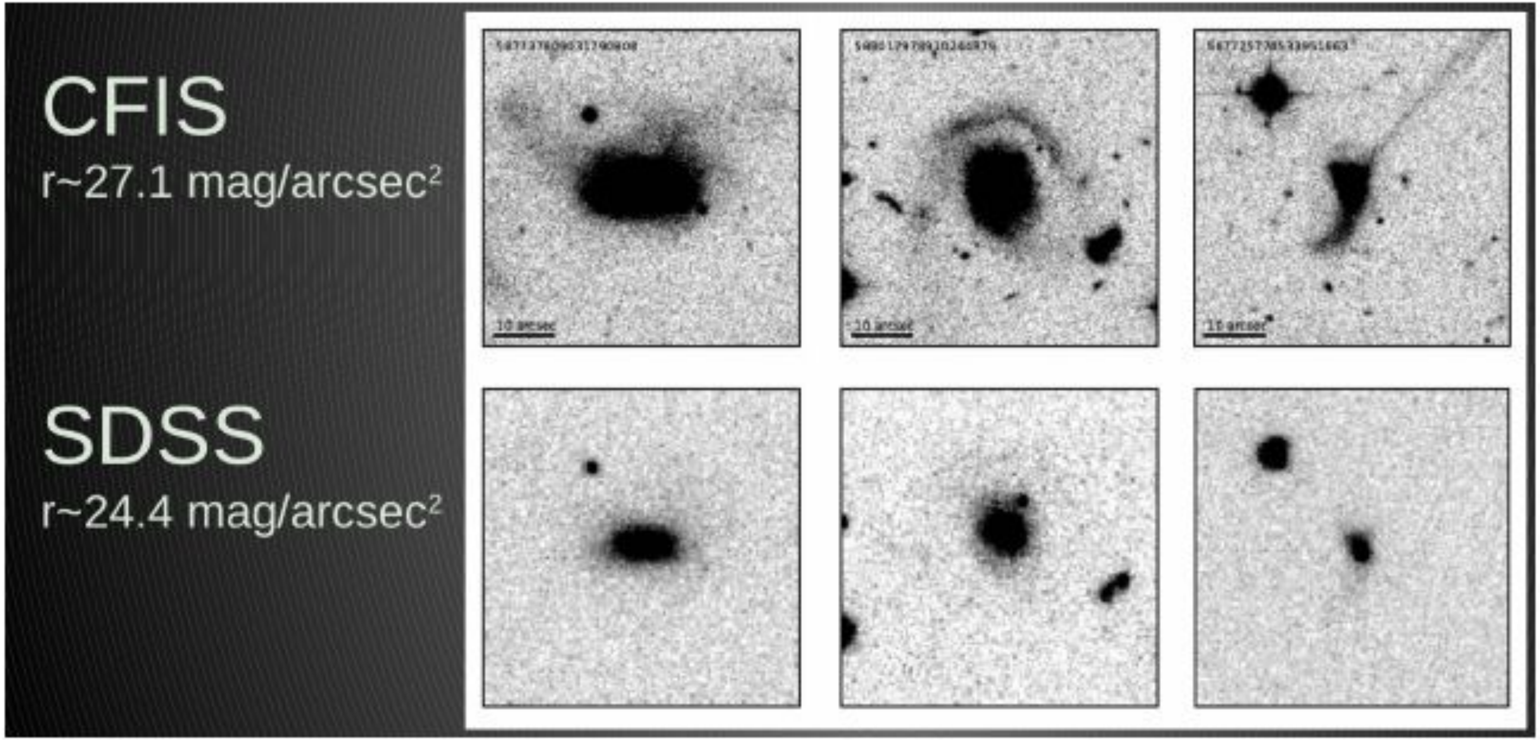
UNIONS

www.skysurvey.cc

UNIONS footprint & Euclid



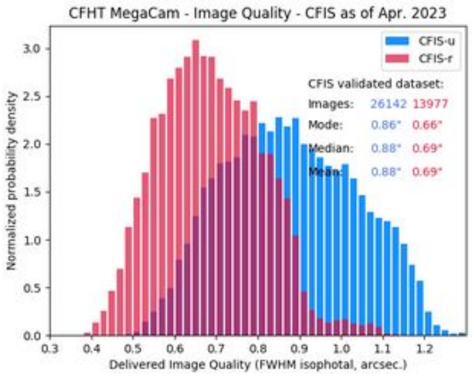
UNIONS/CFIS vs. SDSS

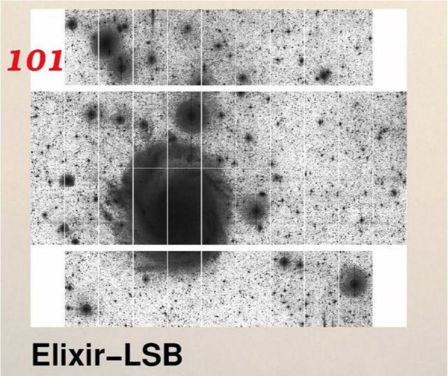


UNIONS/CFIS

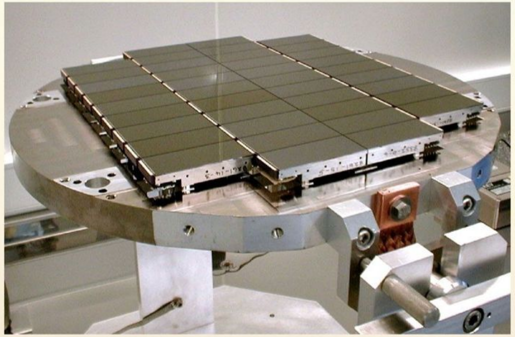
Best wide-field imager on CFHT ever.

Improvements (2011 - 2014)

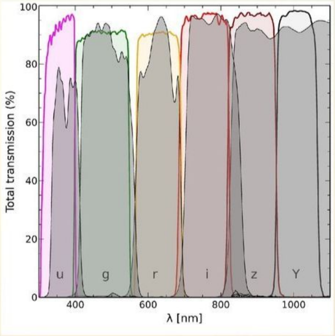




Dome venting



40 CCDs + Fast readout



New "square" filters

UNIONS is basically a static LSST in the North. Unique combination of depth, area, and image quality (unmatched before Euclid, Rubin, Roman, CSS-OS, WFST!)

UNIONS depth

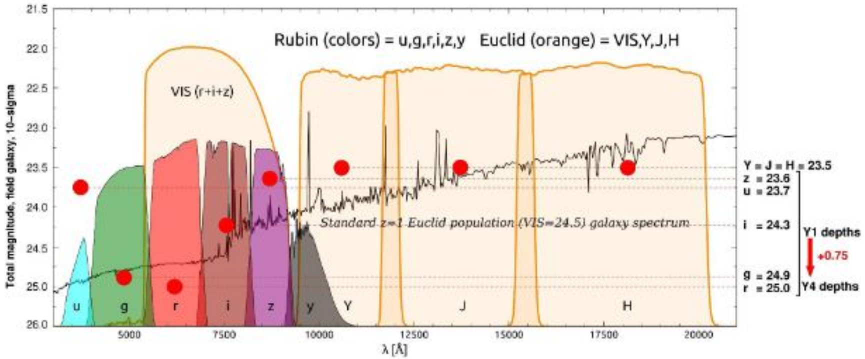


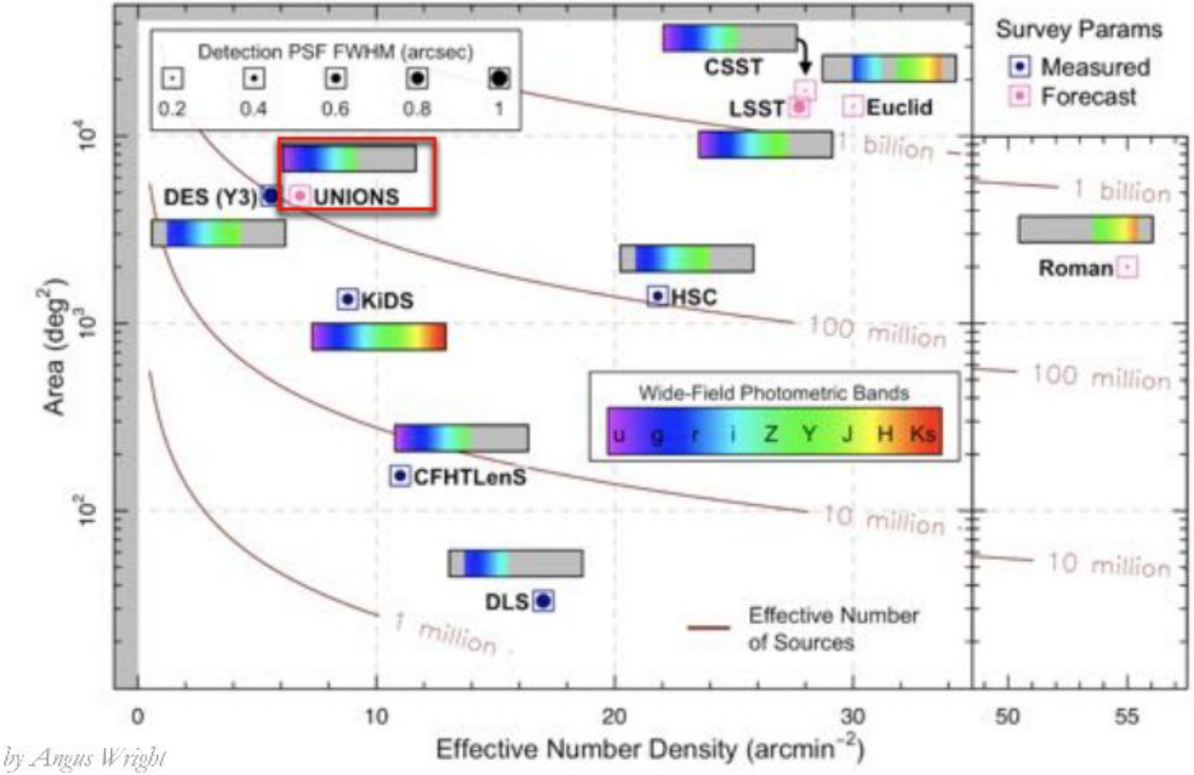
Photo-z depth metric proxy (for all): point source in 2 arcseconds diameter aperture, 10σ

- Euclid (median over the Euclid sky): *VIS=25.0, Y=J=H=23.5*
- DES in Euclid DR1/2/3: *g=24.7, r=24.4, i=23.8, z=23.1*
- UNIONS in Euclid DR1: *u=23.6, g=24.5, r=24.1, i=23.2, z=23.4*
- UNIONS in Euclid DR2: *u=23.6, g=24.5, r=24.1, i=23.4, z=23.4*
- UNIONS in Euclid DR3: *u=23.6, g=24.5, r=24.1, i=23.6, z=23.4*
- Rubin LSST* Y1 in Euclid DR2: *u=23.7, g=24.9, r=25.0, i=24.3, z=23.6*
- Rubin LSST* Y1 to Y4 in Euclid DR3: *u=24.4, g=25.6, r=25.7, i=25.0, z=24.3*

UNIONS ≈ LSST Year 1 depths

*Rubin-LSST main releases depth with point source PSF performance scaled to the 2" diam. metric

UNIONS and other surveys



Galaxy - star cross-correlations

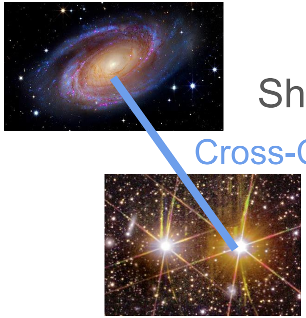
Measure galaxy - PSF cross-correlations (τ-statistics): $\langle \boldsymbol{e}^{\mathrm{g}} \boldsymbol{\delta} e^{\mathrm{g}} \rangle$

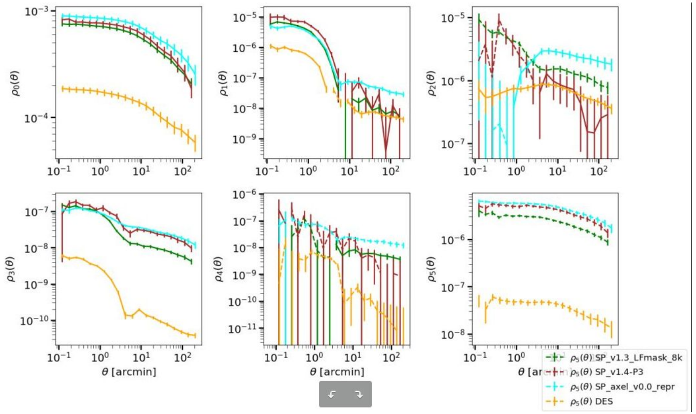
and solve

$$
\begin{aligned}
\tau_0(\vartheta) &= \alpha\, \rho_0(\vartheta) + \beta\, \rho_2(\vartheta) + \eta\, \rho_5(\vartheta);\\
\tau_2(\vartheta) &= \alpha\, \rho_2(\vartheta) + \beta\, \rho_1(\vartheta) + \eta\, \rho_4(\vartheta);\\
\tau_5(\vartheta) &= \alpha\, \rho_5(\vartheta) + \beta\, \rho_4(\vartheta) + \eta\, \rho_3(\vartheta).
\end{aligned}
$$

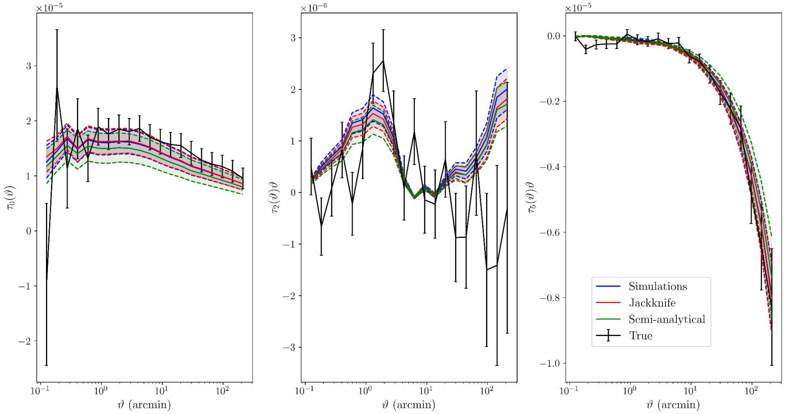
for free parameters α, β, η, using MCMC [Gatti et al. 2021] or least squares.

Need covariance of τ.





ρ0(θ)
ρ1(θ)
ρ2(θ)
ρ3(θ)
ρ4(θ)
ρ5(θ)
θ [arcmin]
ρ5(θ) SP_v1.3_LFmask_8k
ρ5(θ) SP_v1.4-P3
ρ5(θ) SP_axel_v0.0_repr
ρ5(θ) DES



τ0(ϑ)
τ2(ϑ)ϑ
τ5(ϑ)
ϑ (arcmin)
Simulations
Jackknife
Semi-analytical
True