Cosmology with strong lensing images

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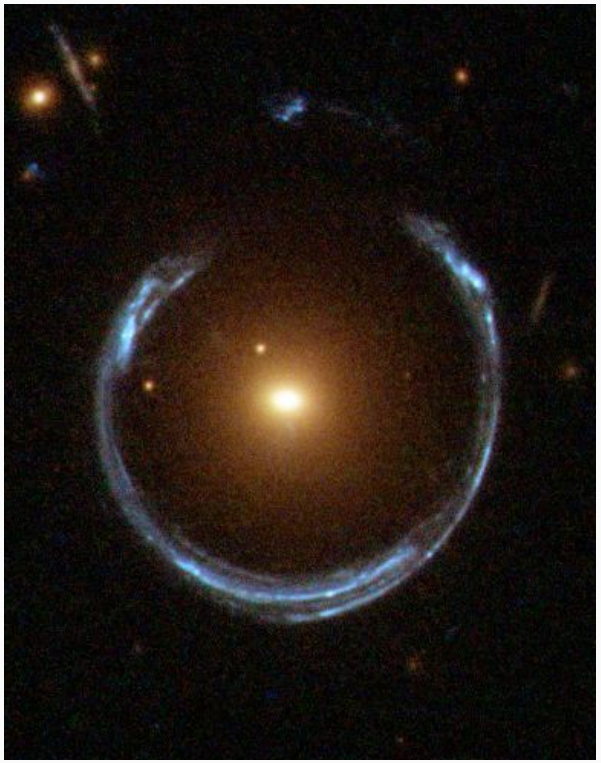
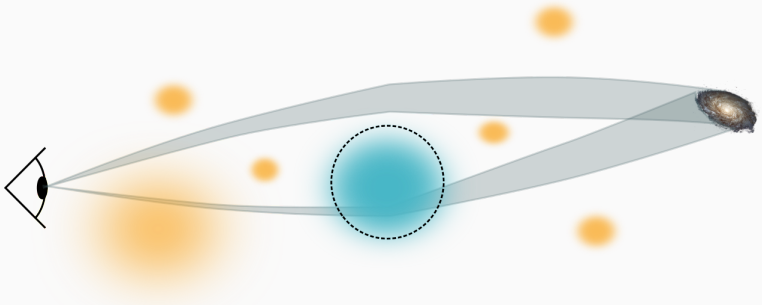


TUG 2025, CEA Saclay
15 October 2025

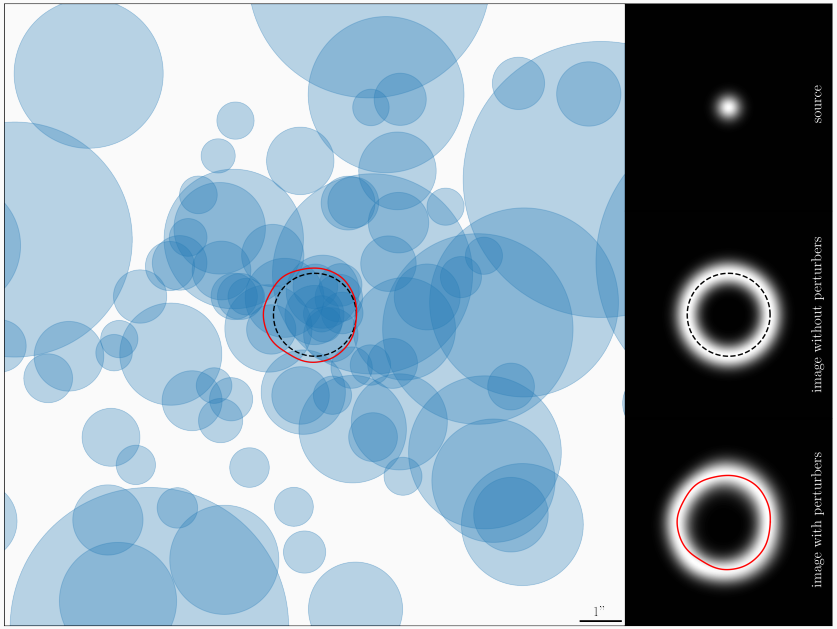
Einstein rings as standard shapes

Strong lensing in a clumpy Universe

Line-of-sight haloes perturb strong lensing



- Population effects
- Noise in strong lensing (e.g. TDCOSMO)
- New window for cosmic shear [Birrer et al, 2016]



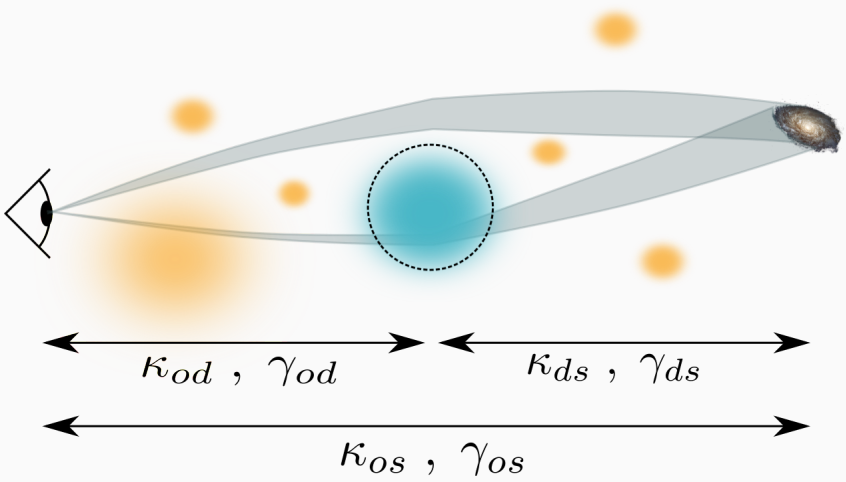
Can we use images as standard shapes?

LOS in tidal regime

[Fleury, JL, Uzan, JCAP 2021]

- Diffuse lenses along LOS or dense ones far away: LSS.
- Distortions due to individual lenses constant over beam:
- Tidal collective LOS effects:

$$\mathbf{\Gamma}_{ij} = \kappa_{ij}\mathbf{1} + \begin{pmatrix} \mathrm{Re}(\gamma_{ij}) & \mathrm{Im}(\gamma_{ij}) \\ \mathrm{Im}(\gamma_{ij}) & -\mathrm{Re}(\gamma_{ij}) \end{pmatrix}$$



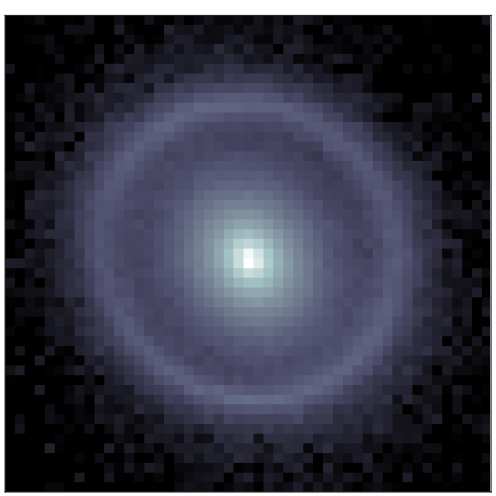
No external shear

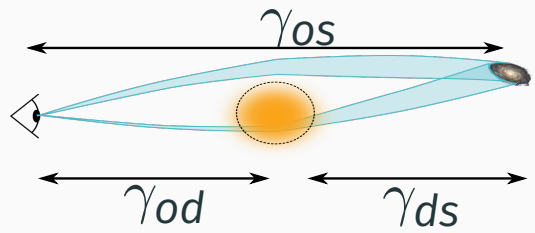
With external shear

Measuring γ_{ij}: info on LSS.
Is it doable?

Tidal regime: Degeneracies

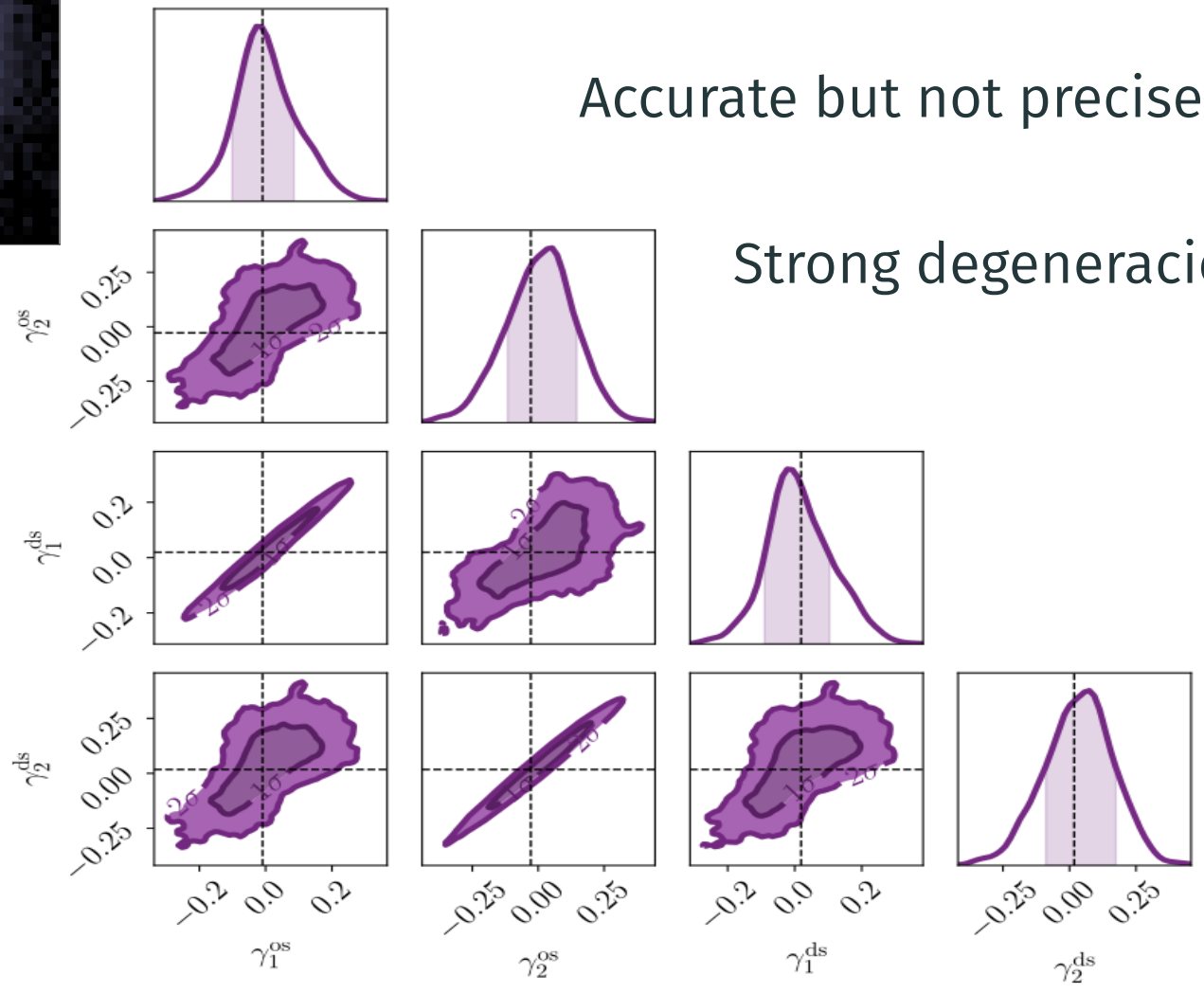
[Hogg, Fleury, JL, Martinelli, MNRAS 2023]





Accurate but not precise

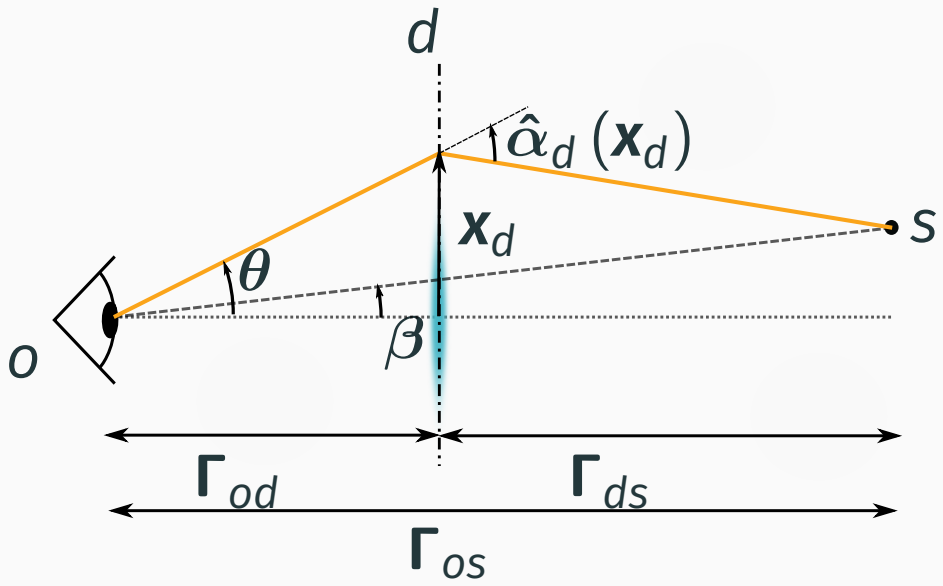
Strong degeneracies



Tidal regime: Minimal lens model

[Fleury, JL, Uzan, JCAP 2021]

- Lens equation:
  $\boldsymbol{\beta} = (\mathbf{1} - \boldsymbol{\Gamma}_{os})\,\boldsymbol{\theta} - (\mathbf{1} - \boldsymbol{\Gamma}_{ds})\,\frac{D_{ds}}{D_{os}}\,\hat{\boldsymbol{\alpha}}_d\,[D_{os}\,(\mathbf{1} - \boldsymbol{\Gamma}_{od})\,\boldsymbol{\theta}]$
- Foreground and main lens degenerate.
- Source structure unknown: $\boldsymbol{\beta} \mapsto \tilde{\boldsymbol{\beta}} = (\mathbf{1} - \boldsymbol{\Gamma}_{od} + \boldsymbol{\Gamma}_{ds})\,\boldsymbol{\beta}$



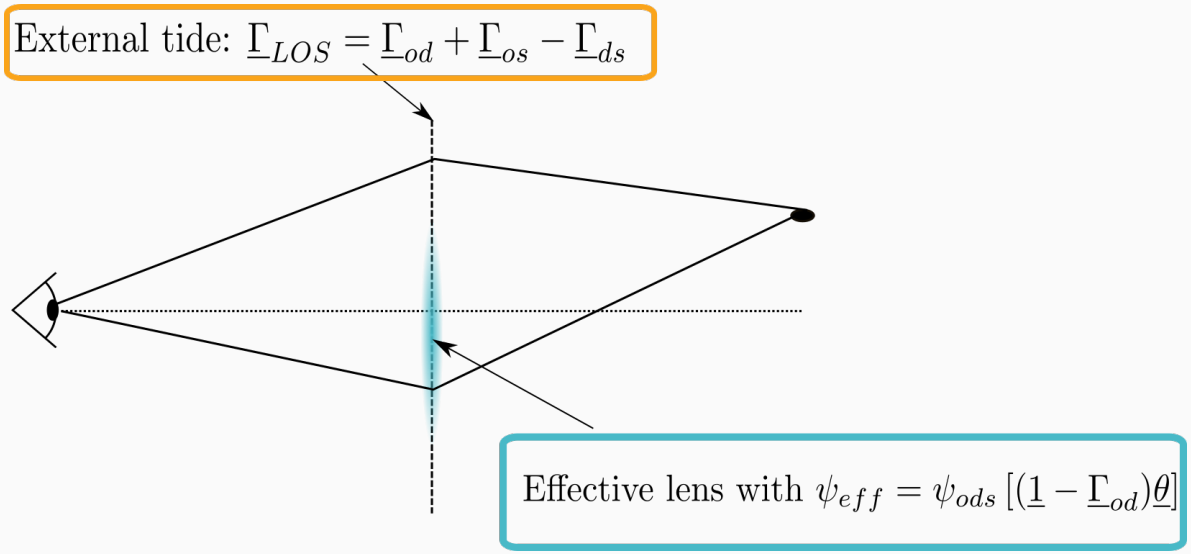
Tidal regime: Minimal lens model

[Fleury, JL, Uzan, JCAP 2021]

- Equivalent lens equation:

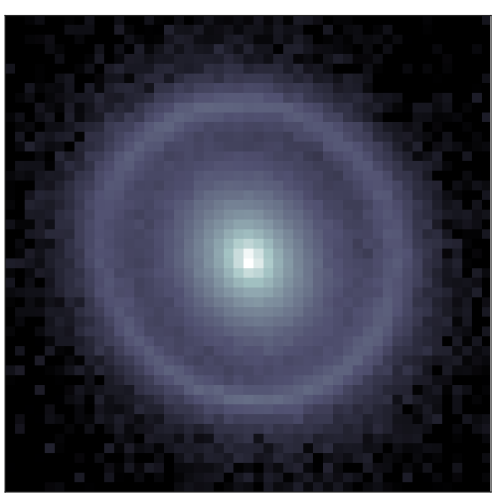
$$\tilde{\boldsymbol{\beta}} = (\mathbf{1} - \boldsymbol{\Gamma}_{LOS})\,\boldsymbol{\theta} - \nabla_{\boldsymbol{\theta}}\psi_{eff}$$

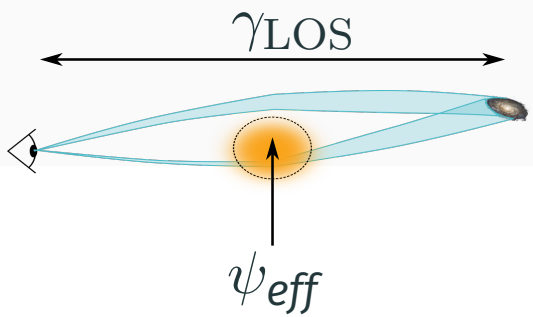
- From 3+9 to 6 parameters.

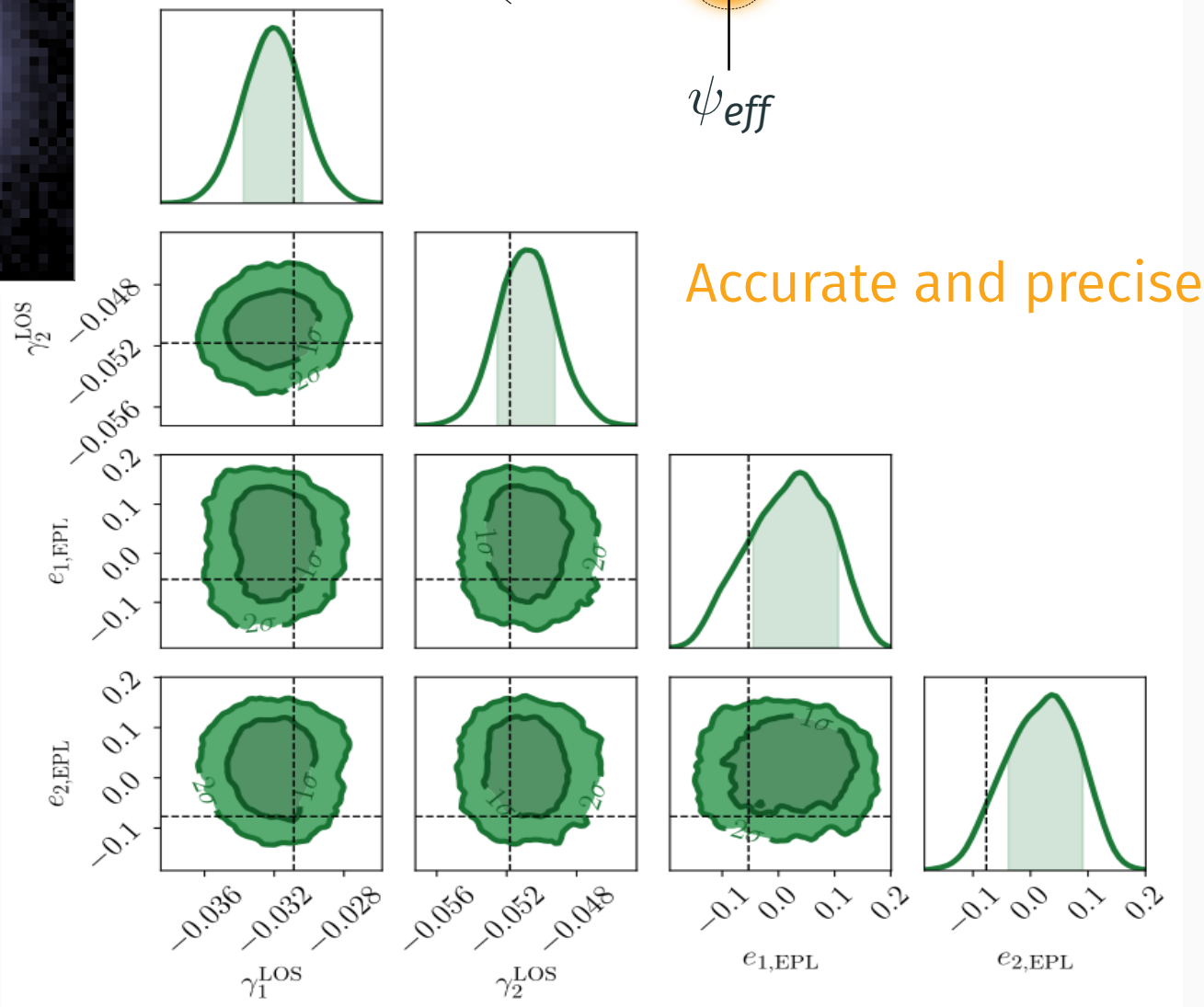


Tidal regime: Minimal lens model

[Hogg, Fleury, JL, Martinelli, MNRAS 2023]







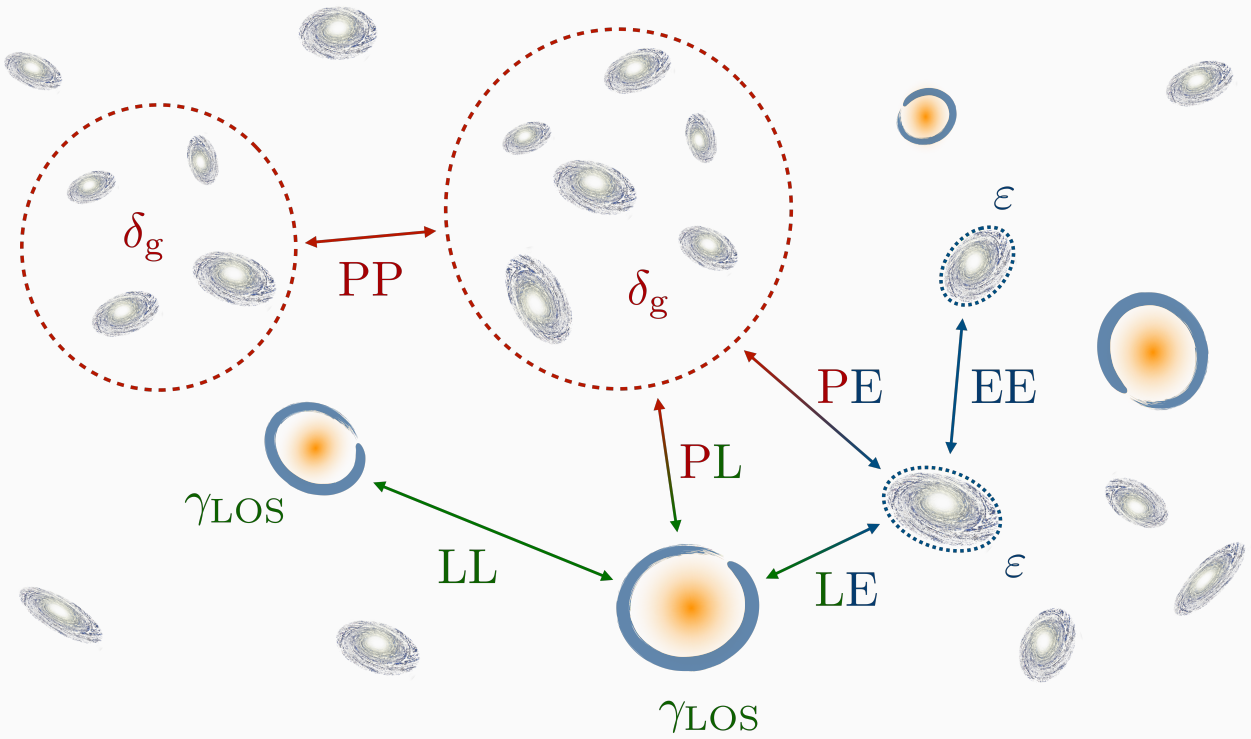
Accurate and precise

Cosmology with LOS shear

6×2 pt correlation

[Duboscq, Jonhson, Fleury, JL, in prep.]

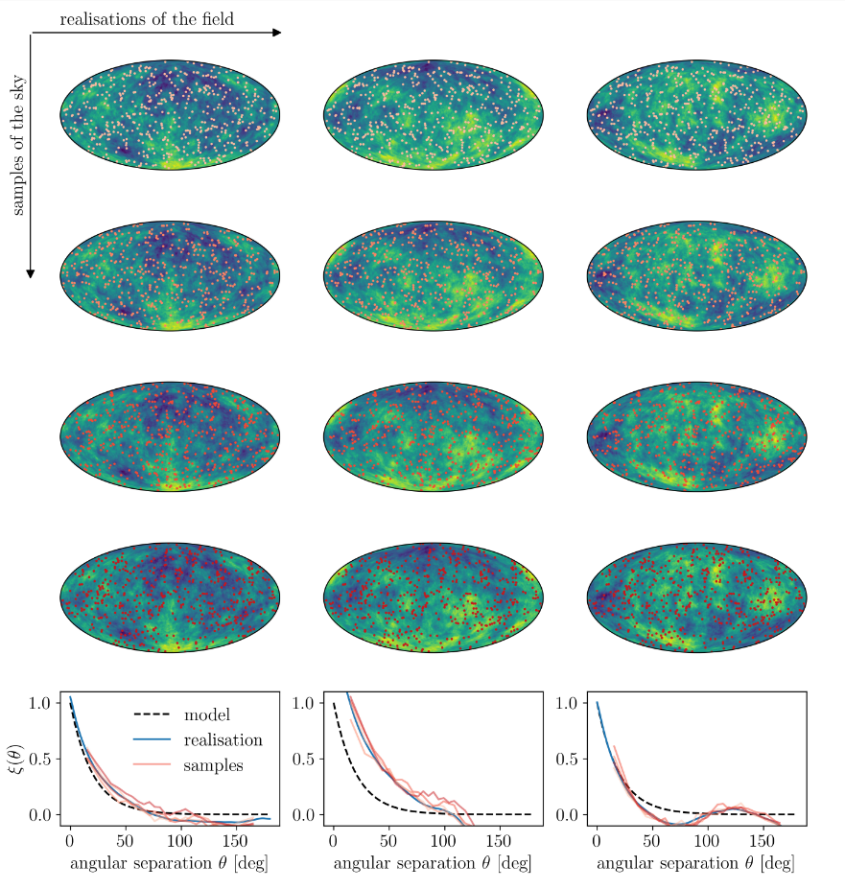
- Standard 3×2 pt: PP, PE, EE
- Adding $\gamma_{\rm LOS}$: 6×2 pt
- "Very" precise: $\Delta\gamma_{\rm LOS} \sim 0.1 \sim \gamma_{\rm LOS}$ while shape noise: $\Delta\epsilon \sim 0.3 \sim 30\epsilon$.
- Different systematics at small scales.



6×2 pt correlation

[Duboscq, Jonhson, Fleury, JL, in prep.]

- Measured LOS shear: $\Gamma_{\rm LOS} = \gamma_{\rm LOS} + n_{\rm LOS}$.
- Euclid like survey [Collett, ApJ 2015]
- Lens sample: $N_{\rm lens} = 10^5$
- $\Delta\gamma_{\rm LOS} \sim 0.05$ thus $\langle |n_{\rm LOS}|^2 \rangle = 2.5 \times 10^{-3}$.
- Sparsity noise dominant

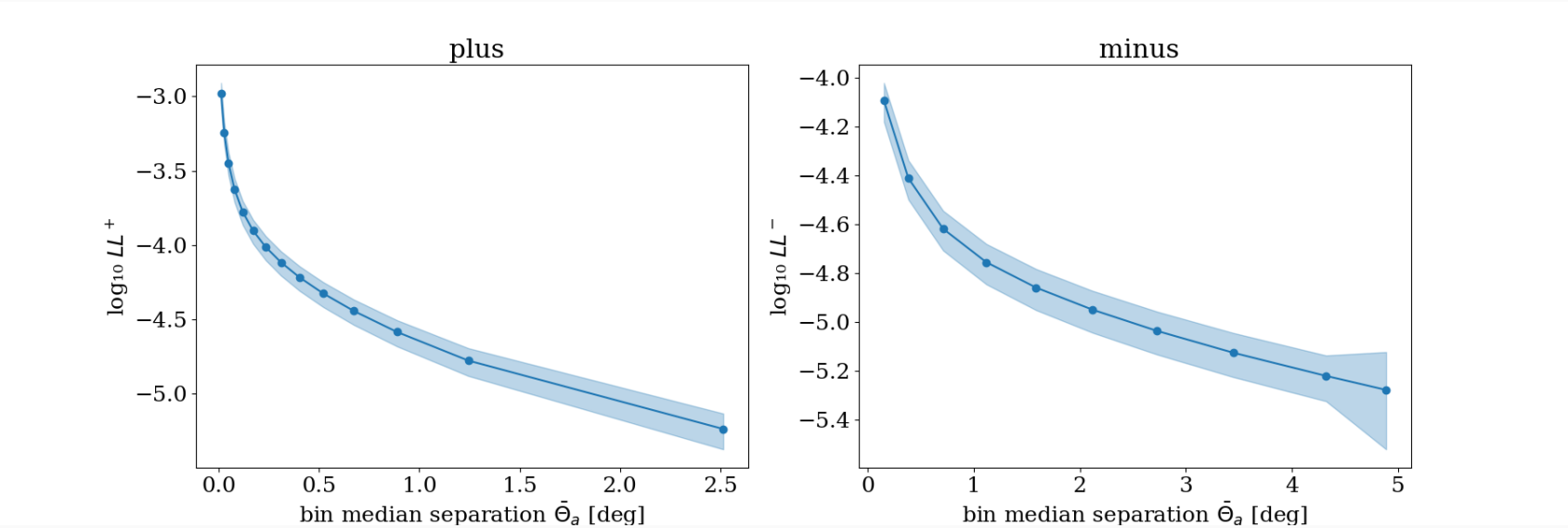


[Fleury, OpJA, 2025]

Forecast: LOS shear autocorrelation

[Duboscq, Jonhson, Fleury, JL, in prep.]

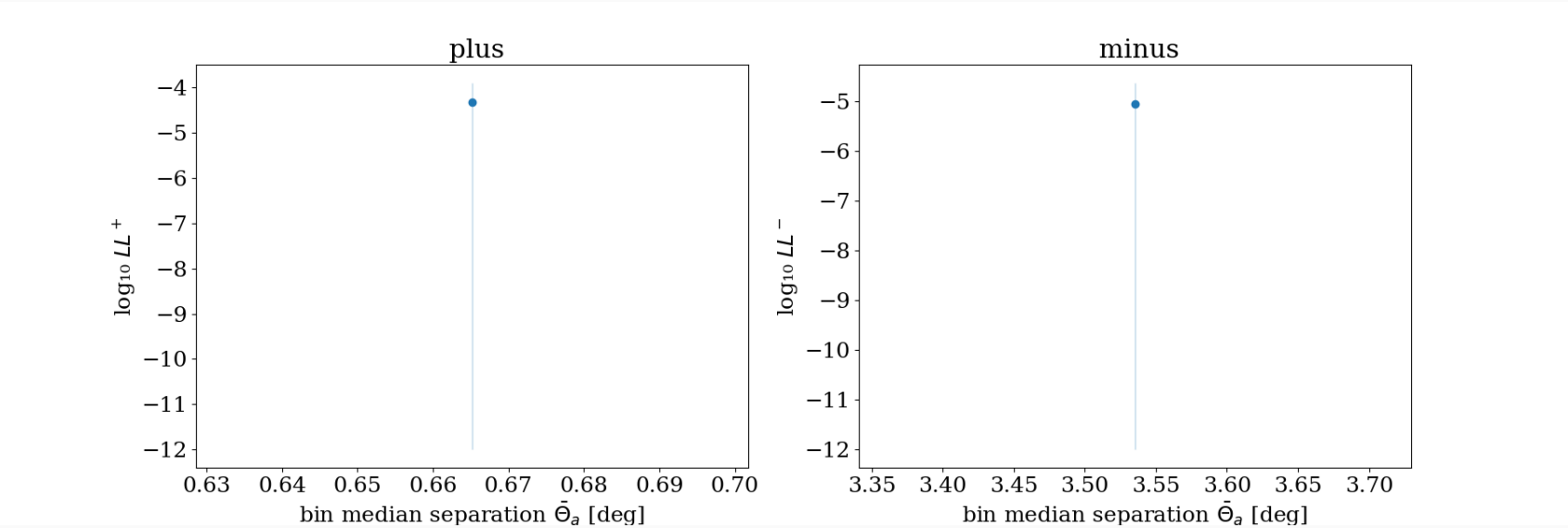
- $N_{\rm lens} = 10^5$
- $\Delta\gamma_{\rm LOS} \sim 0.05$



Forecast: LOS shear autocorrelation

[Duboscq, Jonhson, Fleury, JL, in prep.]

- $N_{\rm lens} = 10^4$
- $\Delta\gamma_{\rm LOS} \sim 0.1$



Forecast: LOS shear $\times$ Cosmic shear

[Duboscq, Jonhson, Fleury, JL, in prep.]

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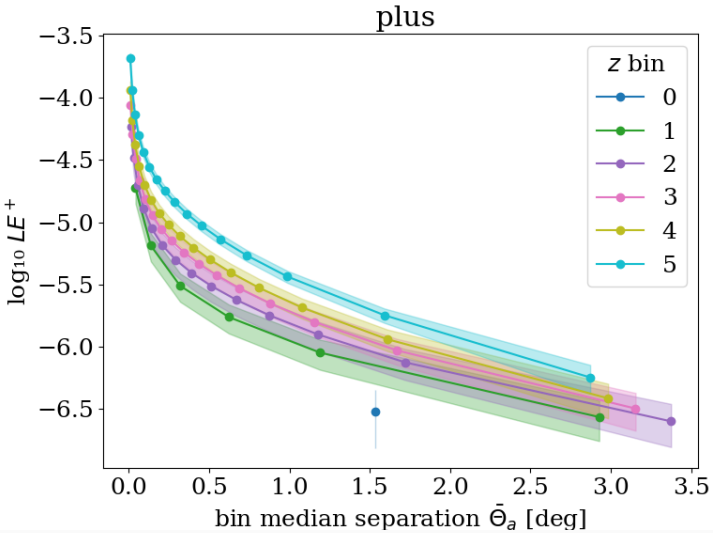

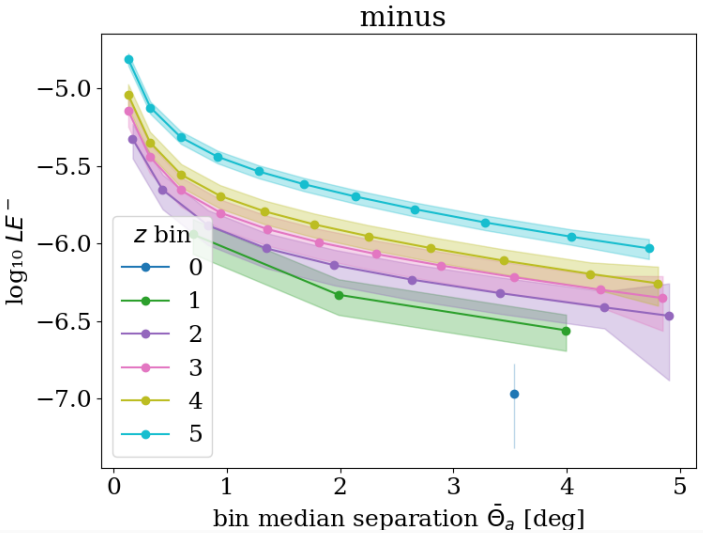

- Importance of tomography: integrated effect large at high redshift

Forecast: LOS shear $\times$ Cosmic shear

[Duboscq, Jonhson, Fleury, JL, in prep.]

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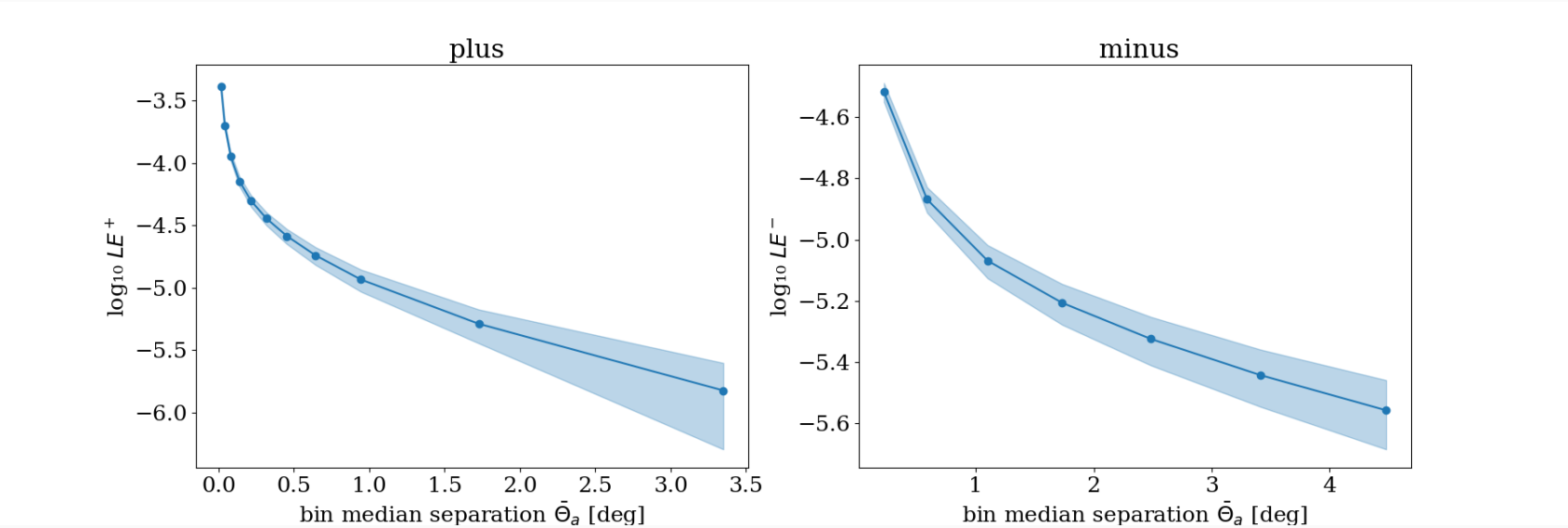

Forecast: LOS shear $\times$ Galaxy position

[Duboscq, Jonhson, Fleury, JL, in prep.]

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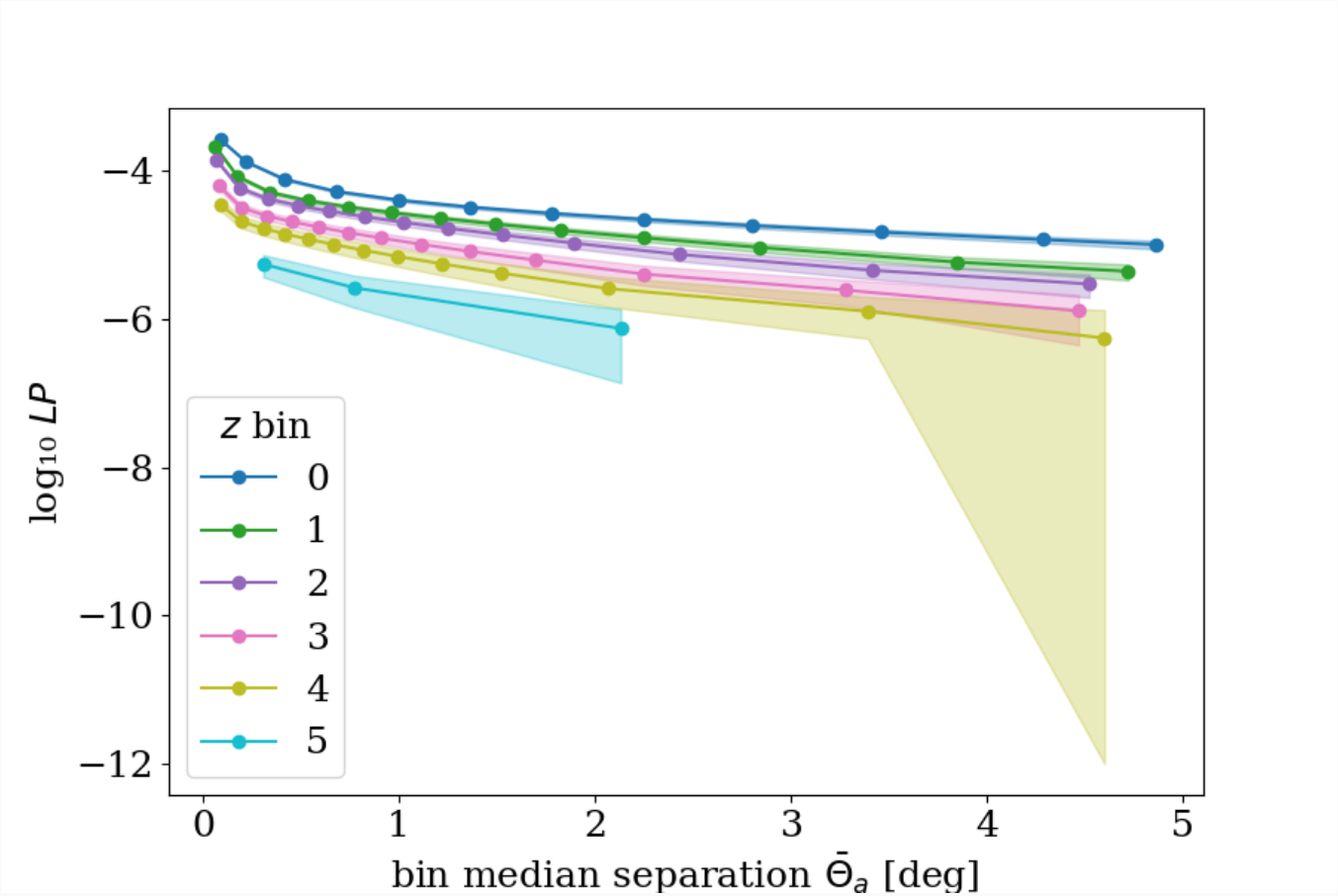

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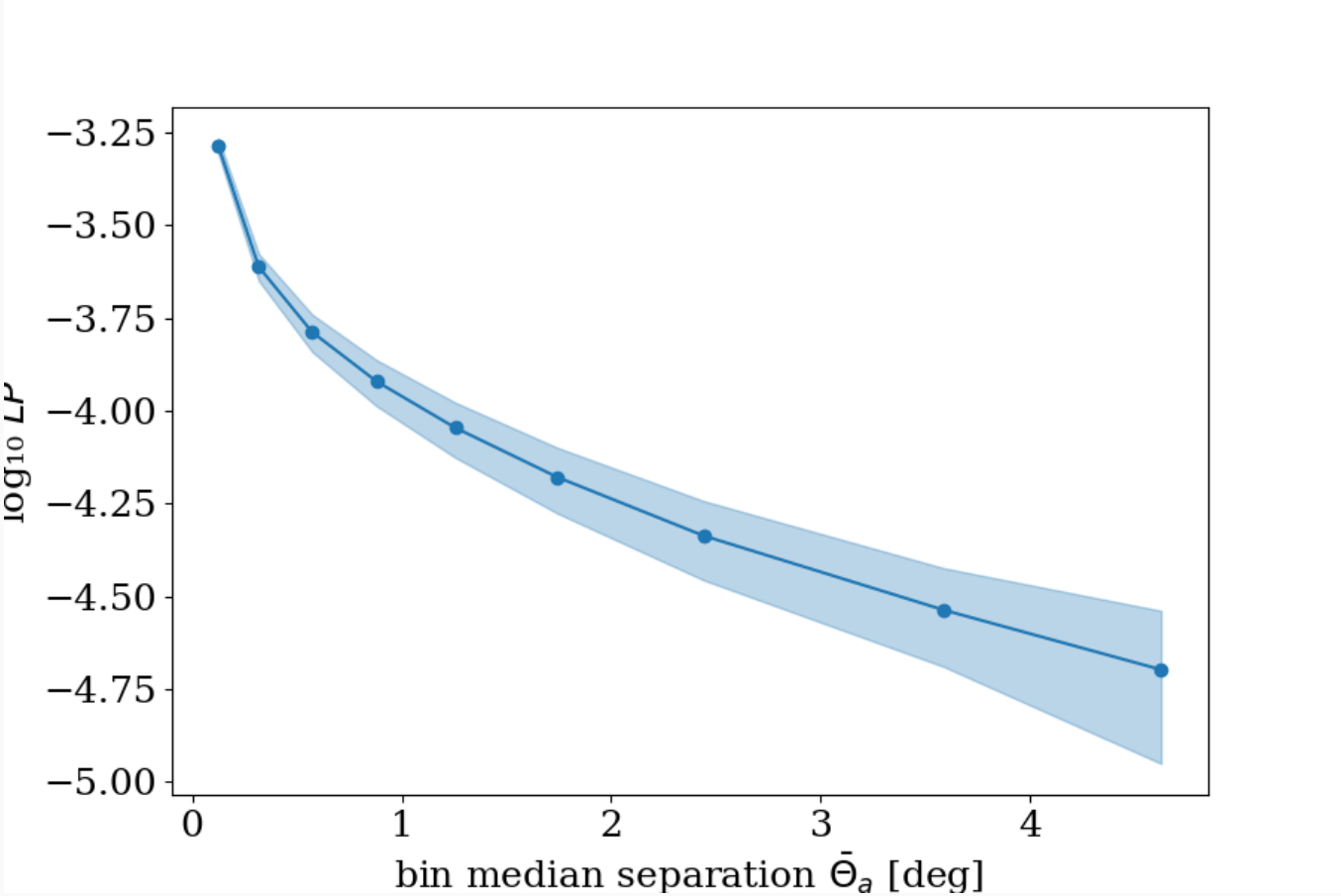
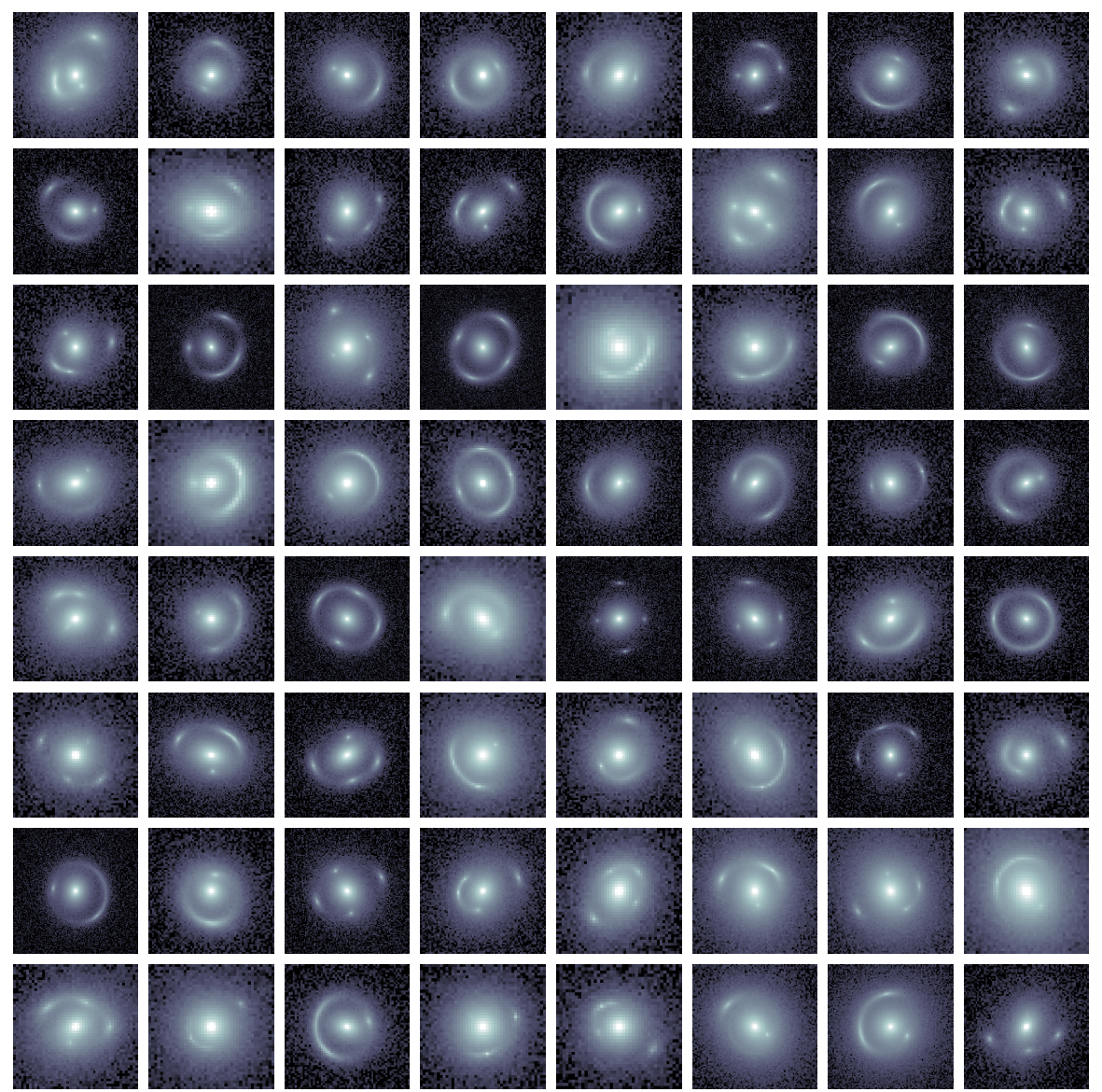


Is LOS shear measurable?

A catalogue of mock images

[Hogg, Fleury, JL, Martinelli, MNRAS 2023]

Can we measure $\gamma_{LOS} = \gamma_{od} + \gamma_{os} - \gamma_{ds}$?



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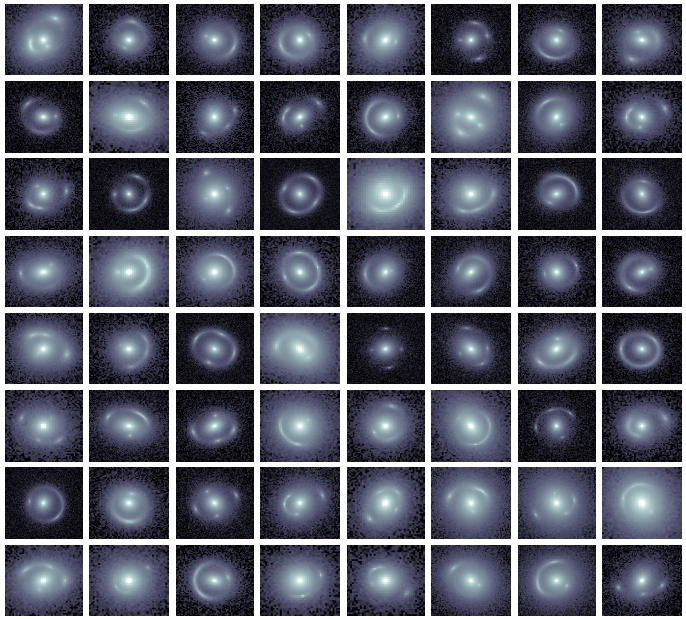
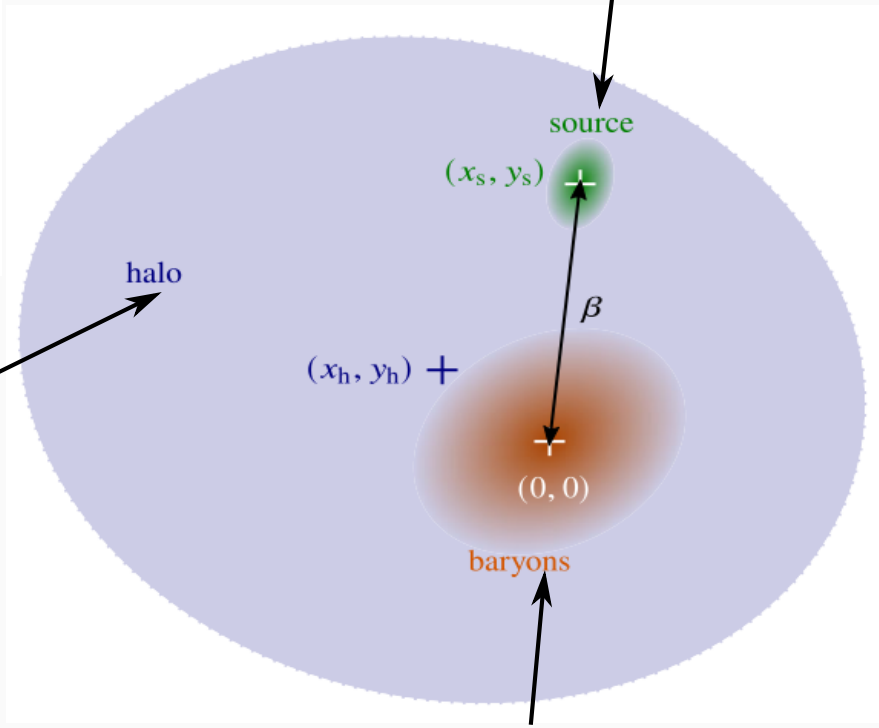
[Hogg, Fleury, JL, Martinelli, MNRAS 2023]



Perturbed Elliptical Sérsic

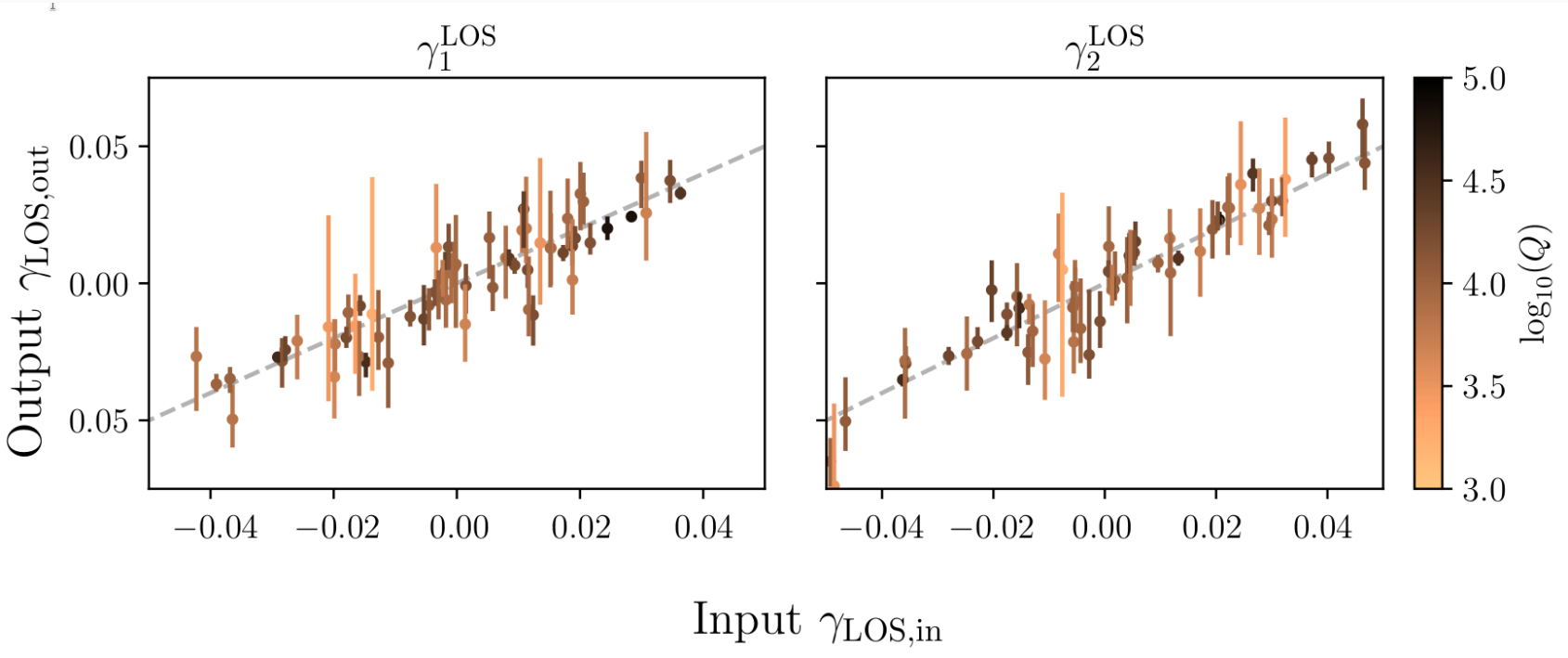


Elliptical NFW

Elliptical Sérsic

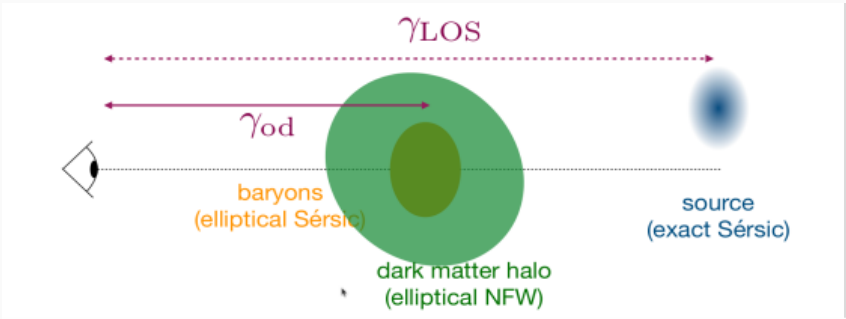
Results: LOS shear is measurable

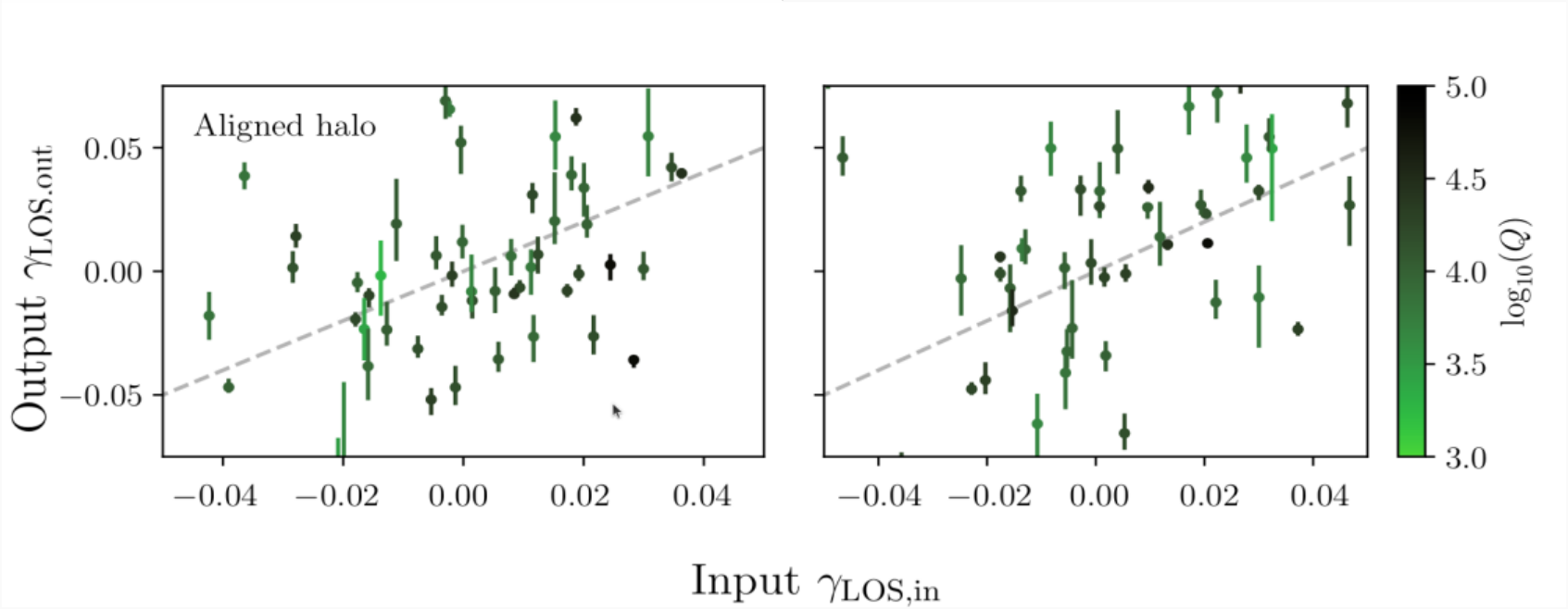
[Hogg, Fleury, JL, Martinelli, MNRAS 2023]



Beware oversimplifying the lens model

[Hogg, Fleury, JL, Martinelli, MNRAS 2023]

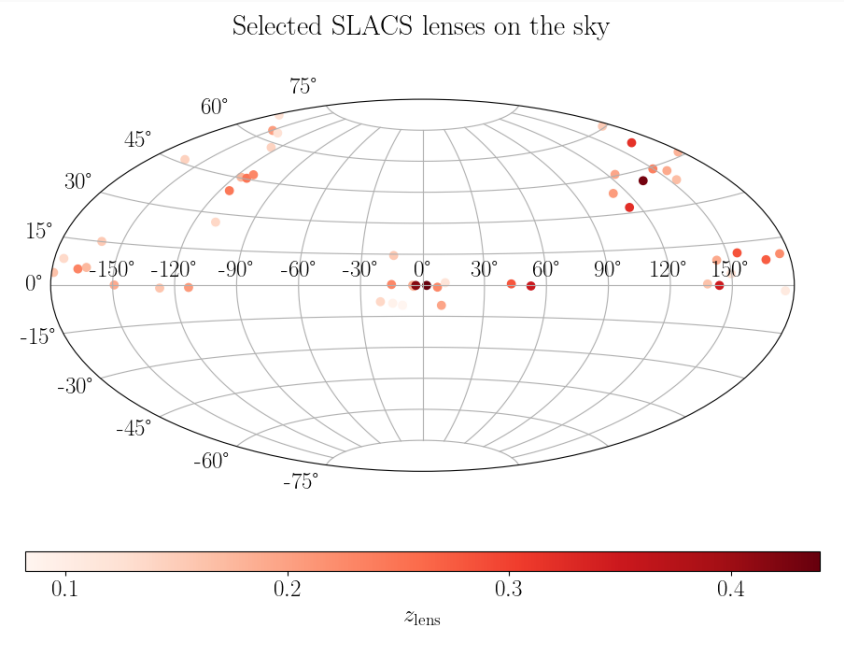


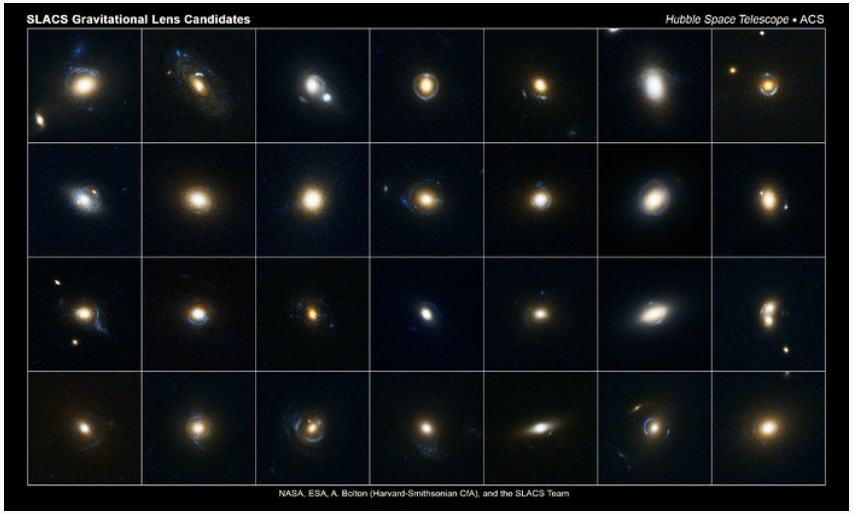


Measuring LOS shear on SLACS lenses

[Hogg, Shajib, Johnson, JL, in prep]

- Sloan Lens ACS
- Spectro identified in SDSS, followed up with HST
- Subset of 50 ”nice” images
- Standard lens modelling: Elliptical Power Law

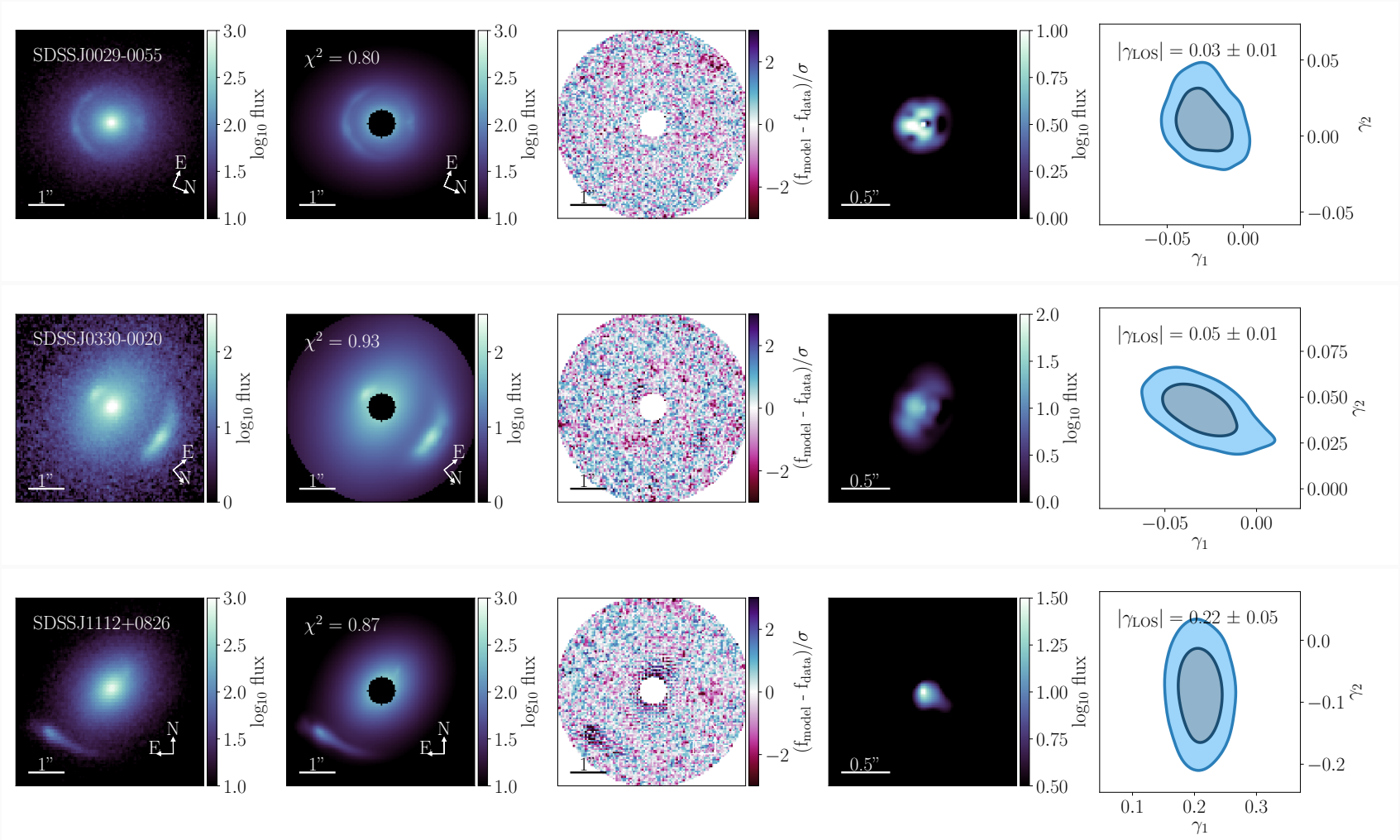




Measuring LOS shear on SLACS lenses

[Hogg, Shajib, Johnson, JL, in prep]

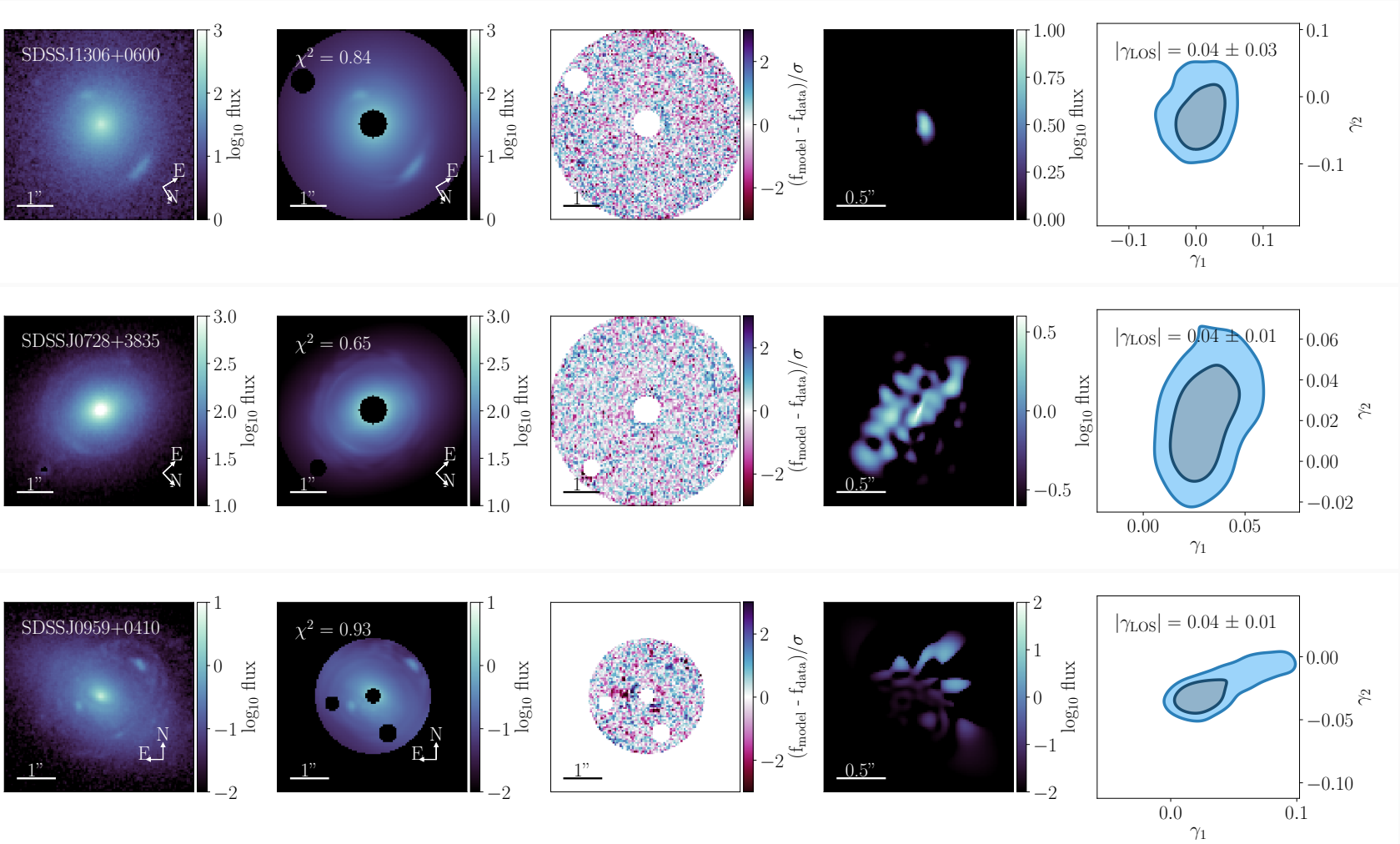
- The very good news.
- 46 out of 50 good fits with good constraints on $\gamma_{\rm LOS}$



Measuring LOS shear on SLACS lenses

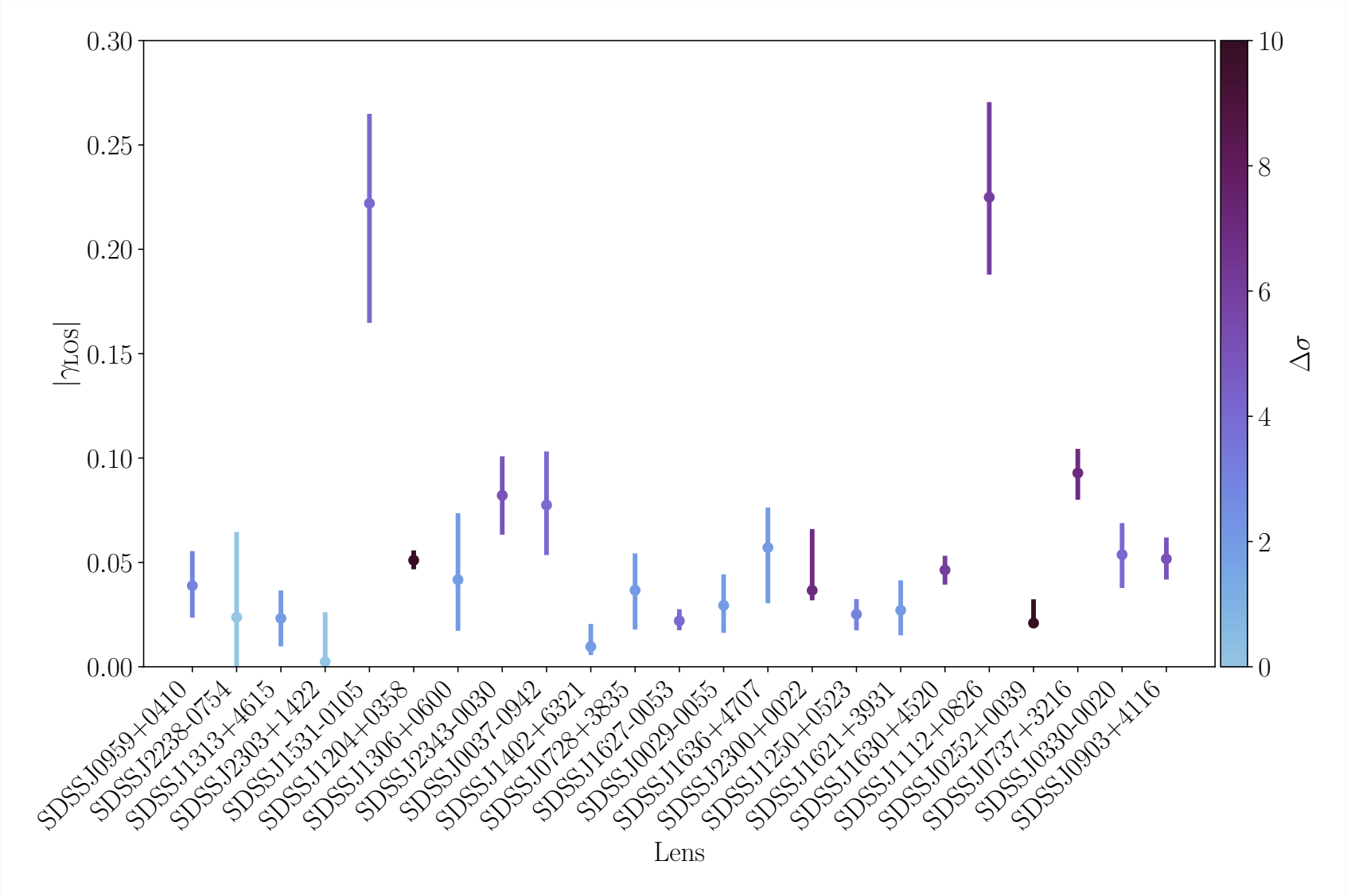
[Hogg, Shajib, Johnson, JL, in prep]

- The challenges.
- Masking of interlopers: Automation for Euclid and cosmology?



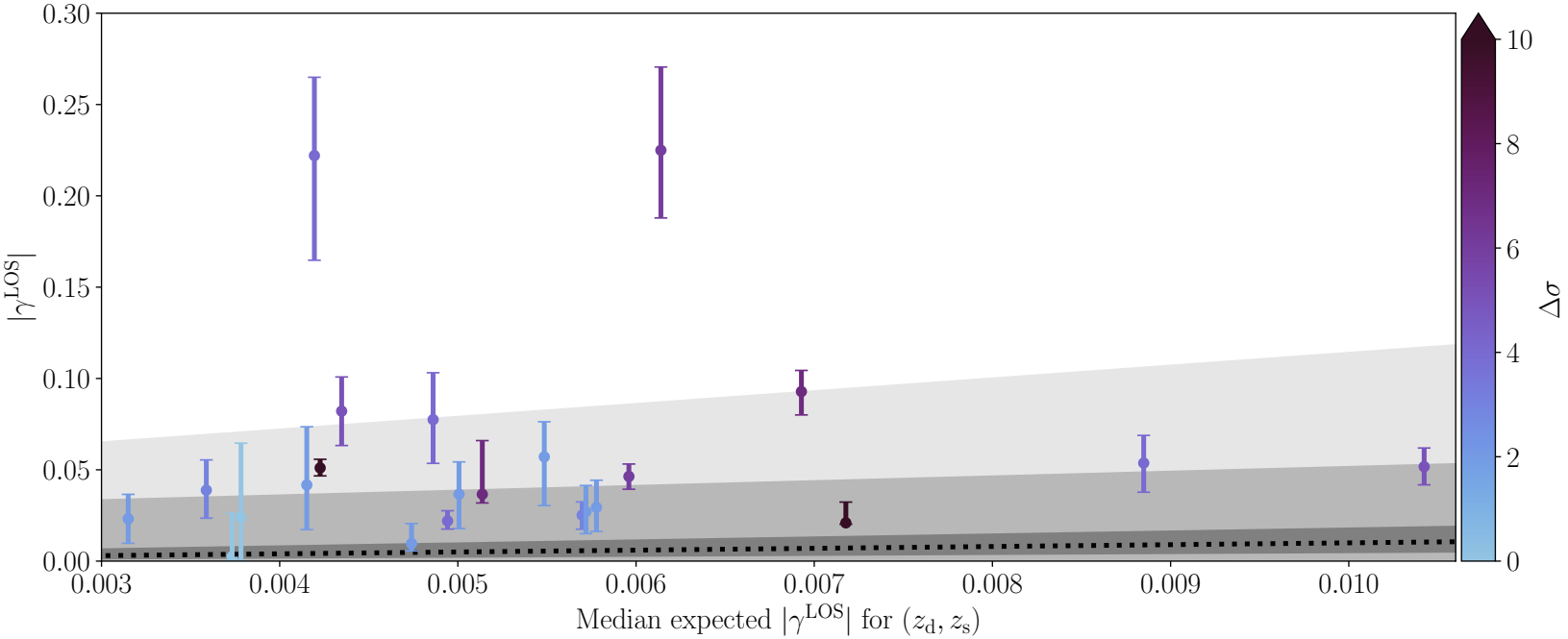
Measuring LOS shear on SLACS lenses

[Hogg, Shajib, Johnson, JL, in prep]



Measuring LOS shear on SLACS lenses

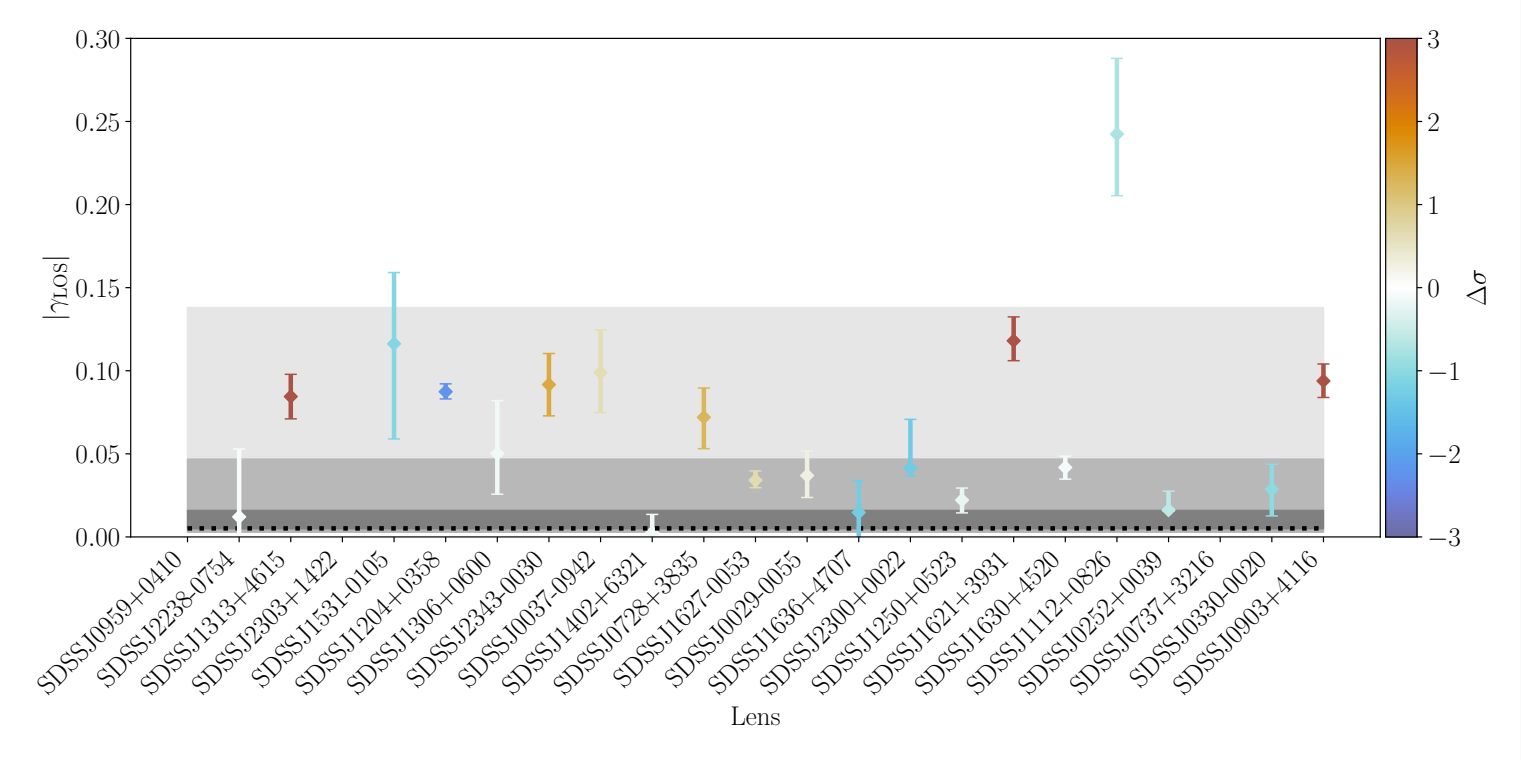
[Hogg, Shajib, Johnson, JL, in prep]



- Very high compared to weak lensing expectations!
- Systematic LOS/WL bias?
- E.g.: Strongly lensed LOS are biased sample of LOS?
- Lens modelling too simplistic.

Measuring LOS shear on SLACS lenses

[Hogg, Shajib, Johnson, JL, in prep]



- Simplest (octupolar) deformation of lens model not working [Etherington, MNRAS 2024]
- Most gains come from larger error bars

Conclusion

Conclusion and outlook

- Einstein rings can be used as standard shapes
- Supplement cosmic shear and galaxy number counts in 6×2 pt
- Different systematics than cosmic shear
- Next step (WIP): Fisher forecast for cosmological parameters
- Challenges remain:
  - Line-of-sight sampling
  - Lens modelling
  - Automation of shear measurements

THANK YOU!