Strong lensing images as standard shapes

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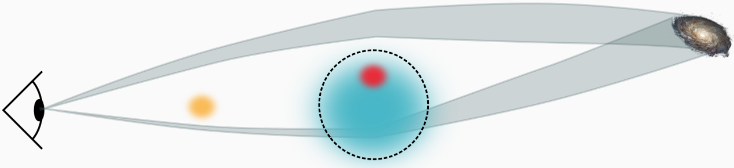
Particules, Astroparticules, Cosmologie: Théorie
Laboratoire Univers et Particules de Montpellier
Université de Montpellier

Introduction

Substructures perturb strong lensing

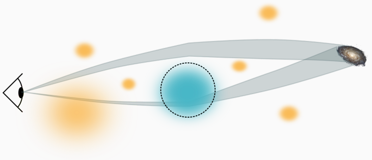
Small subhalo perturbs strong lensing



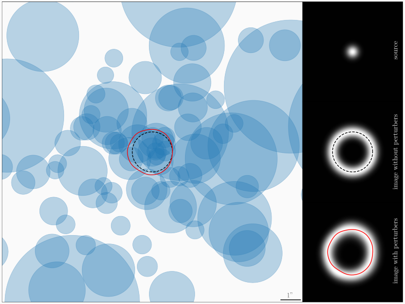
- Tool to detect individual dark halos [Vegetti et al, 2010]
- Promising way to constrain DM on very small scales
- Degenerate with LOS haloes

Substructures perturb strong lensing

Line-of-sight haloes perturb strong lensing



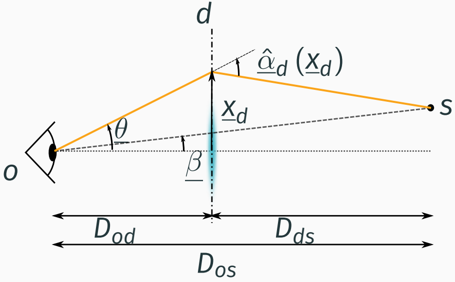
- Here: Population effects
- Noise in strong lensing (e.g. TDCOSMO)
- New window for cosmic shear [Birrer et al, 2016]



Can we use images as standard shapes?

Line-of-sight effects in strong gravitational lensing

Strong lensing in FLRW



Deflection angle:

$$\underline{\hat{\alpha}}_d\left(\underline{x}_d\right) = 4G\int d^2\underline{x}\,\Sigma_d(\underline{x})\frac{\underline{x}_d-\underline{x}}{|\underline{x}_d-\underline{x}|^2}$$

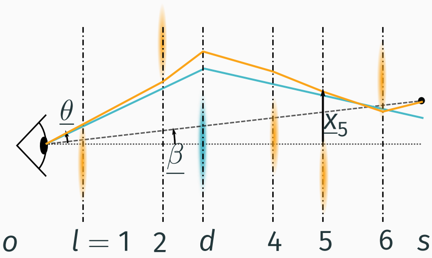
Displacement angle:

$$\underline{\alpha}(\underline{\theta}) = \frac{D_{ds}}{D_{os}}\underline{\hat{\alpha}}_d\left(D_{os}\underline{\theta}\right)$$

Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

Multiplane lensing

[Fleury, JL, Uzan, CQG 2021]

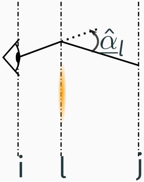


Deflection by lens l:

$$\underline{\hat{\alpha}}_l = 4G \int d^2\underline{x}\Sigma_l(\underline{x}) \frac{\underline{x}_l - \underline{x}}{|\underline{x}_l - \underline{x}|^2}$$

Partial displacement:

$$\underline{\alpha}_{ilj}(\underline{\theta}) = \frac{D_{lj}}{D_{ij}} \underline{\hat{\alpha}}_l \left(D_{il}\underline{\theta}\right)$$



Total displacement:

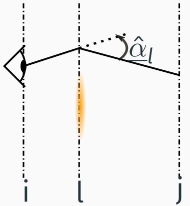
$$\underline{\alpha}(\underline{\theta}) = \sum_l \underline{\alpha}_{ols}$$

Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

see also [Blandford and Narayan, 1986] [McCully et al, 2014] [Schneider, 2019]

Multiplane lensing

[Fleury, JL, Uzan, CQG 2021]

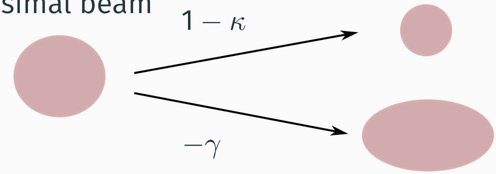


Partial shear matrices:

$$\underline{\Gamma}_{ilj} = \kappa_{ilj}\underline{1} + \begin{pmatrix} \mathrm{Re}\left(\gamma_{ilj}\right) & \mathrm{Im}\left(\gamma_{ilj}\right) \\ \mathrm{Im}\left(\gamma_{ilj}\right) & -\mathrm{Re}\left(\gamma_{ilj}\right) \end{pmatrix}$$

Partial distortions: $\underline{\mathcal{A}}_{ilj} = \underline{1} - \underline{\Gamma}_{ilj}$

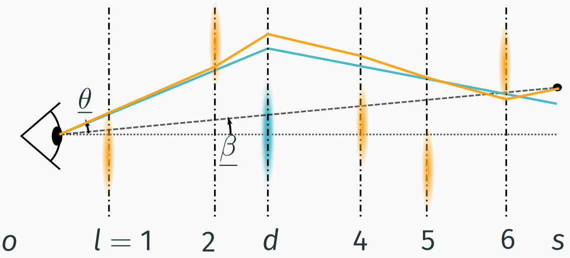
Infinitesimal beam



Local effect

Dominant lens approximation

[Fleury, JL, Uzan, JCAP 2021]



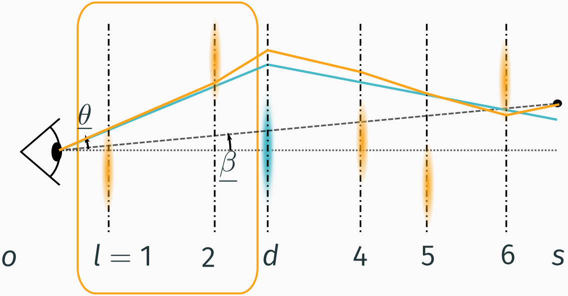
$\forall l \neq d \, , \, \kappa_{ilj} \, , \, \gamma_{ilj} \ll 1$

Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

$$\underline{\alpha}(\underline{\theta}) = \underline{\alpha}_{ods} \left[\underline{\theta} - \sum_{l<d} \underline{\alpha}_{old}(\underline{\theta})\right] + \sum_{l<d} \underline{\alpha}_{old} + \sum_{l>d} \underline{\alpha}_{ols} \left[\underline{\theta} - \underline{\alpha}_{odl}(\underline{\theta})\right]$$

Dominant lens approximation

[Fleury, JL, Uzan, JCAP 2021]



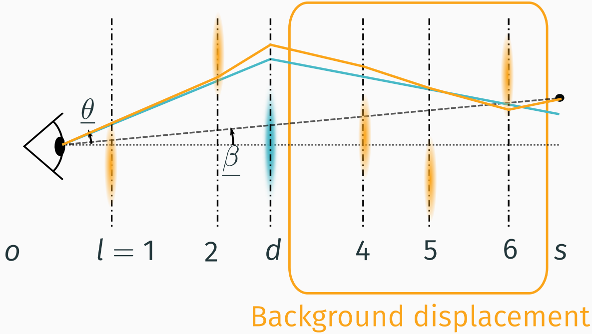
Foreground displacement

Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

$$\underline{\alpha}(\underline{\theta}) = \underline{\alpha}_{ods}\left[\underline{\theta} - \sum_{l<d} \underline{\alpha}_{old}(\underline{\theta})\right] + \sum_{l<d} \underline{\alpha}_{old} + \sum_{l>d} \underline{\alpha}_{ols}\left[\underline{\theta} - \underline{\alpha}_{odl}(\underline{\theta})\right]$$

Dominant lens approximation

[Fleury, JL, Uzan, JCAP 2021]



Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

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Dominant lens approximation

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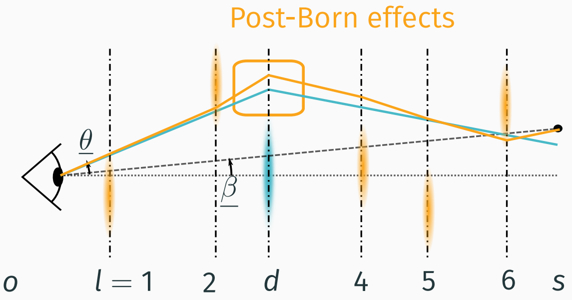


Lens equation: $\underline{\beta} = \underline{\theta} - \underline{\alpha}(\underline{\theta})$

$$\underline{\alpha}(\underline{\theta}) = \underline{\alpha}_{ods}\left[\underline{\theta} - \sum_{l<d} \underline{\alpha}_{old}(\underline{\theta})\right] + \sum_{l<d} \underline{\alpha}_{old} + \sum_{l>d} \underline{\alpha}_{ols}\left[\underline{\theta} - \underline{\alpha}_{odl}(\underline{\theta})\right]$$

Strong lensing images as standard shapes: Tidal approximation

LOS in tidal regime

[Fleury, JL, Uzan, JCAP 2021]

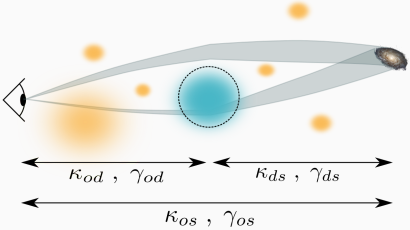
see also [Kovner, 1987] [Bar-Kana, 1996] [Schneider, 1997] [McCully, 2014]

- Partial distortions constant over beam:

$$\forall l \neq d \ , \ \underline{\alpha}_{ilj}(\underline{\theta}) \simeq \underline{\Gamma}_{ilj}\underline{\theta} \simeq \kappa_{ilj}\underline{\theta} + \gamma_{ilj}\underline{\theta}^*$$

- Tidal LOS:

$$\underline{\Gamma}_{ij} = \sum_{i<l<j} \Gamma_{ilj} = \kappa_{ij}\underline{1} + \begin{pmatrix} \mathrm{Re}(\gamma_{ij}) & \mathrm{Im}(\gamma_{ij}) \\ \mathrm{Im}(\gamma_{ij}) & -\mathrm{Re}(\gamma_{ij}) \end{pmatrix}$$



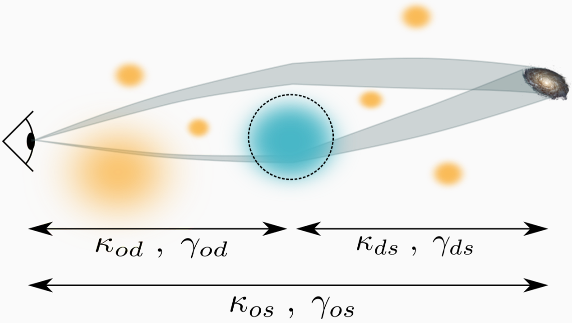
No external shear

With external shear

Tidal regime: Full model

[Fleury, JL, Uzan, JCAP 2021]

- LOS = 9 free parameters

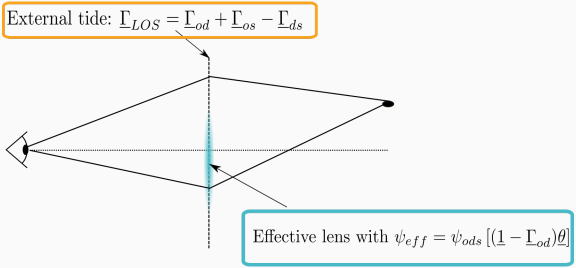


$$\underline{\alpha}(\theta) = (\underline{1} - \underline{\Gamma}_{ds})\, \underline{\alpha}_{ods}\left[(\underline{1} - \underline{\Gamma}_{od})\, \underline{\theta}\right] + \underline{\Gamma}_{os}\underline{\theta}$$

Tidal regime: Minimal lens model

[Fleury, JL, Uzan, JCAP 2021]

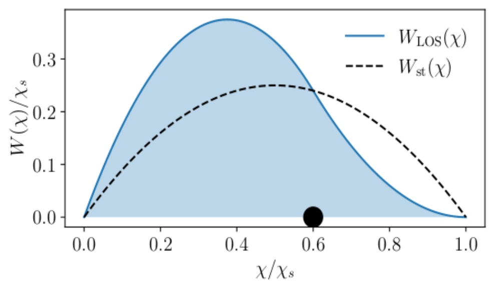
- Lens equation: $\underline{\beta} = (\underline{1} - \underline{\Gamma}_{os})\,\underline{\theta} - (\underline{1} - \underline{\Gamma}_{ds})\,\underline{\alpha}_{ods}\,[(\underline{1} - \underline{\Gamma}_{od})\,\underline{\theta}]$
- Freedom $\underline{\beta} \mapsto \underline{\tilde{\beta}} = (\underline{1} - \underline{\Gamma}_{od} + \underline{\Gamma}_{ds})\,\underline{\beta}$
- New equivalent lens equation: $\underline{\tilde{\beta}} = (\underline{1} - \underline{\Gamma}_{LOS})\,\underline{\theta} - \nabla_{\underline{\theta}}\psi_{eff}$
- 6 params



Contributions along the LOS

$$\gamma_{LOS} = \gamma_{od} + \gamma_{os} - \gamma_{ds}$$

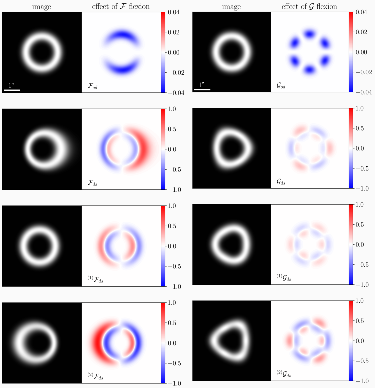
How much does a halo contribute to γ_{LOS}?



Beyond shear: Flexion

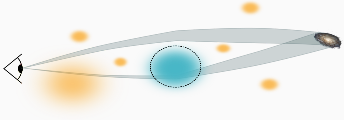
$$\alpha_{ilj}\left(\underline{\theta}\right) \simeq \kappa_{ilj}\underline{\theta} + \gamma_{ilj}\underline{\theta}^{*} + \frac{1}{2}\left[\mathcal{F}_{ilj}\underline{\theta}^{2} + 2\mathcal{F}^{*}_{ilj}\underline{\theta}^{*}\underline{\theta} + \mathcal{G}_{ilj}\left(\underline{\theta}^{*}\right)^{2}\right]$$

$$\mathcal{F} = \frac{\partial\kappa}{\partial\underline{\theta}^{*}} = \frac{\partial\gamma}{\partial\underline{\theta}} \quad \mathcal{G} = \frac{\partial\gamma}{\partial\underline{\theta}^{*}}$$

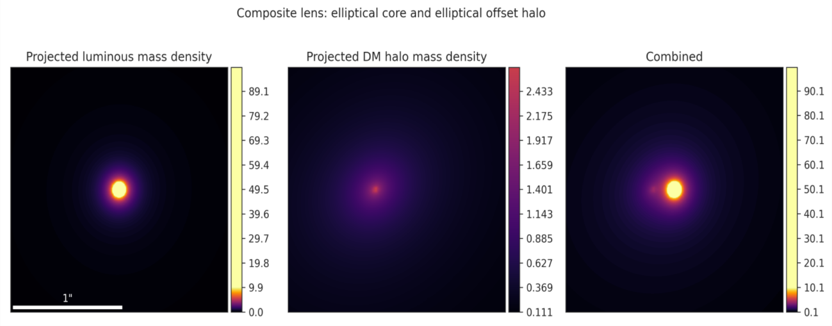


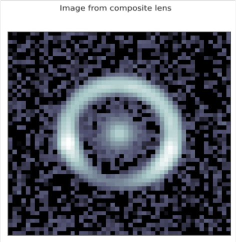
16 more parameters in LOS model

Prob many degeneracies



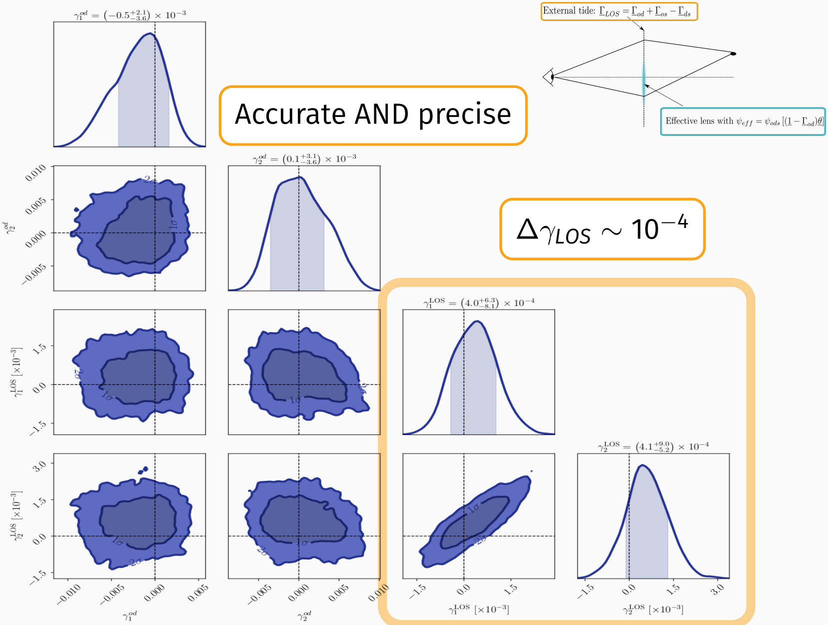
Extracting LOS shear: Mock images





Test sensitivity to/degeneracy with:
- intrinsic ellipticity of lens
- Mismatch of components' centres
- Mismatch of components ellipticity

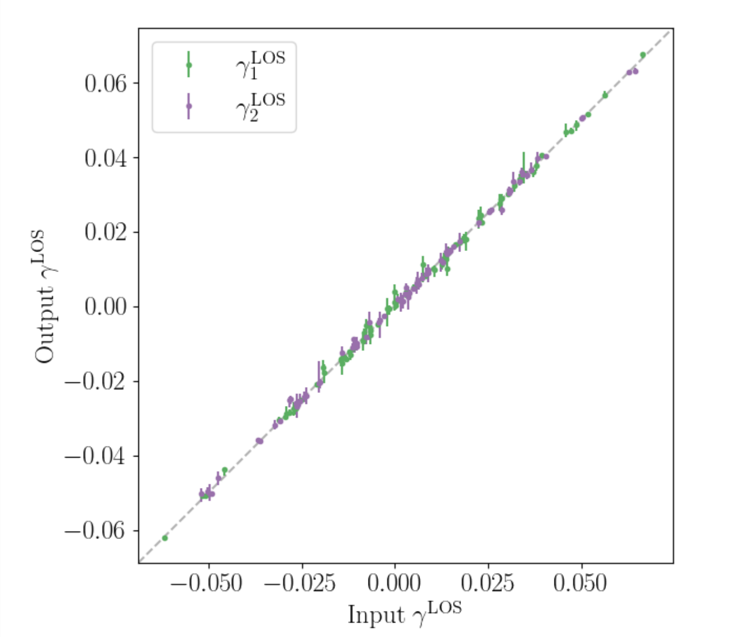
Extracting LOS shear: Minimal model



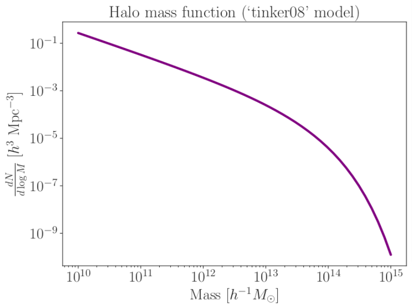
Accurate AND precise

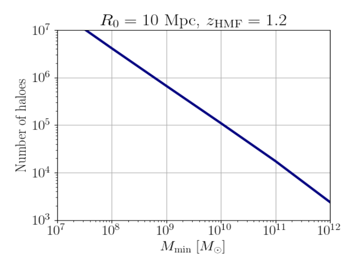
$\Delta\gamma_{LOS} \sim 10^{-4}$

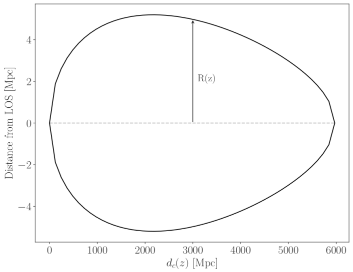
Stability of results

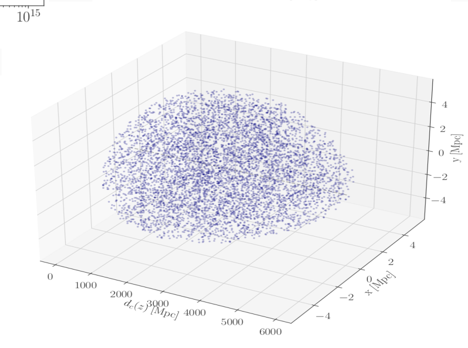


Probing a population of haloes



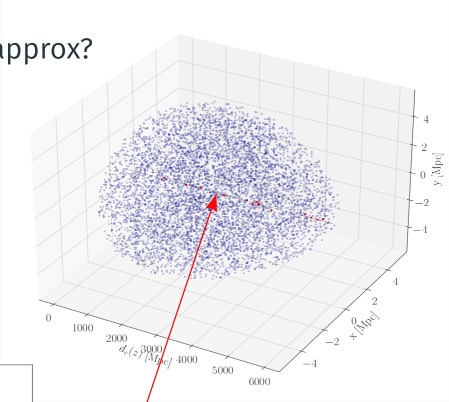




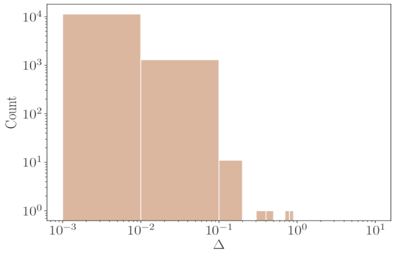


Probing a population of haloes

Are haloes all in tidal approx?



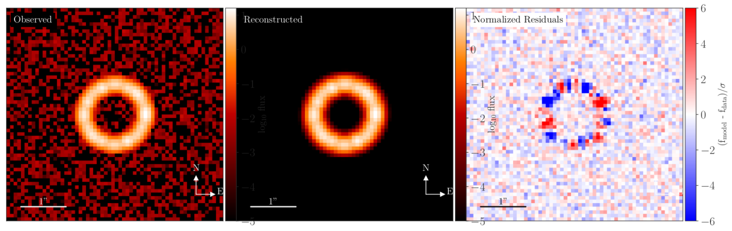
$$\Delta^2 = \frac{\theta_E^2}{2}\frac{|\mathcal{F}|^2+|\mathcal{G}|^2}{|\gamma|^2} \sim \left(\frac{\Delta\gamma}{\gamma}\right)^2$$

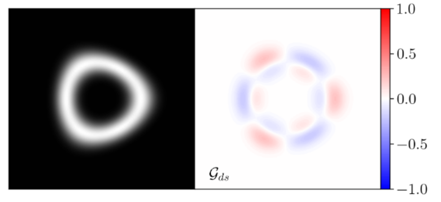


Haloes breaking the tidal approx.

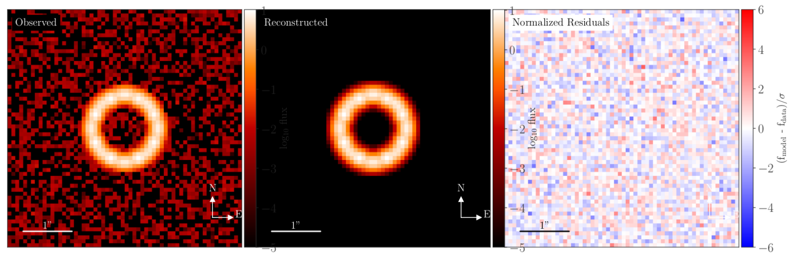
$$\Delta > 0.1$$

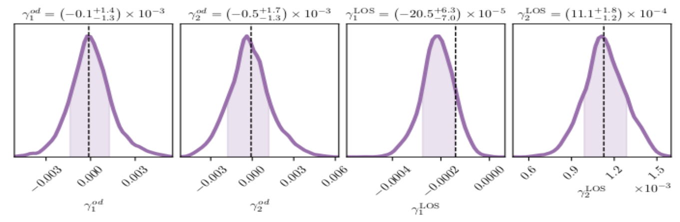
A flexion signal?





A flexion signal?





Conclusion and outlook

Conclusion

- LOS shear can be accurately and precisely measured
- Stable for a wide range of images (not just rings)
- Tidal-approximation-breaking haloes induce potentially measurable flexion
- To Do: LOS Minimal model with flexion.
- Cosmology with LOS shear?
- Study of DM structure on small scales?