

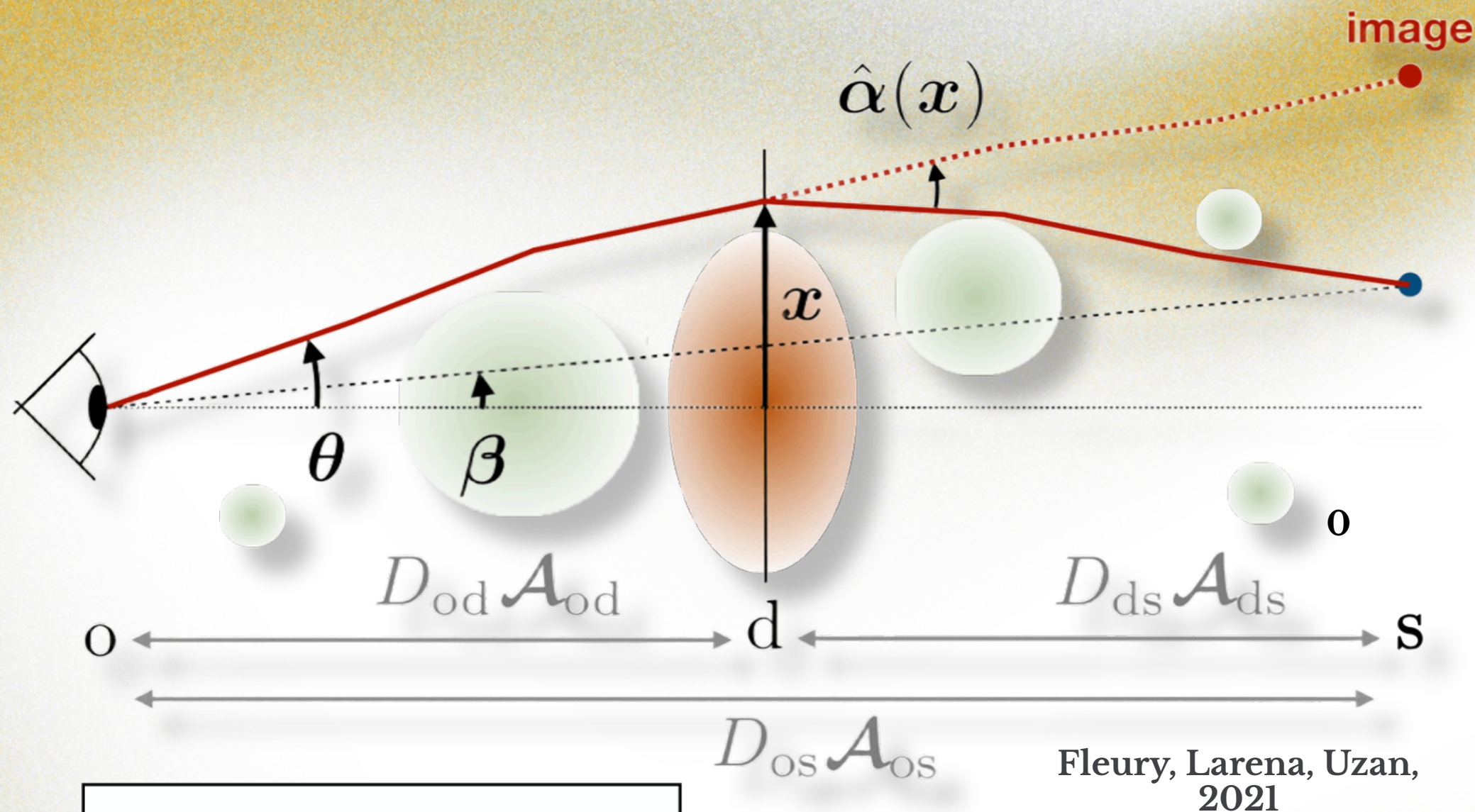
Studying LOS Shear in Hydrosimulated Lenses:

Challenges and opportunities

Giacomo Queirolo
CNRS - LUPM

Precision Cosmology
with Strong Lensing Time Delays
Tokyo, 5 August 2026

LOS Shear: A Brief Introduction



All mass along the line of sight (LOS) will weakly lens the images. Rather than a simple external shear, we can encode this effect with the *minimal model* of the LOS shear. This is equivalent to the cosmic shear and is theoretically independent from the lens mass profile.

Fleury, Larena, Uzan, 2021

Lens equation

$$\beta = \mathcal{A}_{os}\theta - \mathcal{A}_{ds}\alpha(\mathcal{A}_{od}\theta)$$

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

Lens equation

$$\beta' = \mathcal{A}_{\text{LOS}}\theta - \alpha_{\text{eff}}(\theta)$$

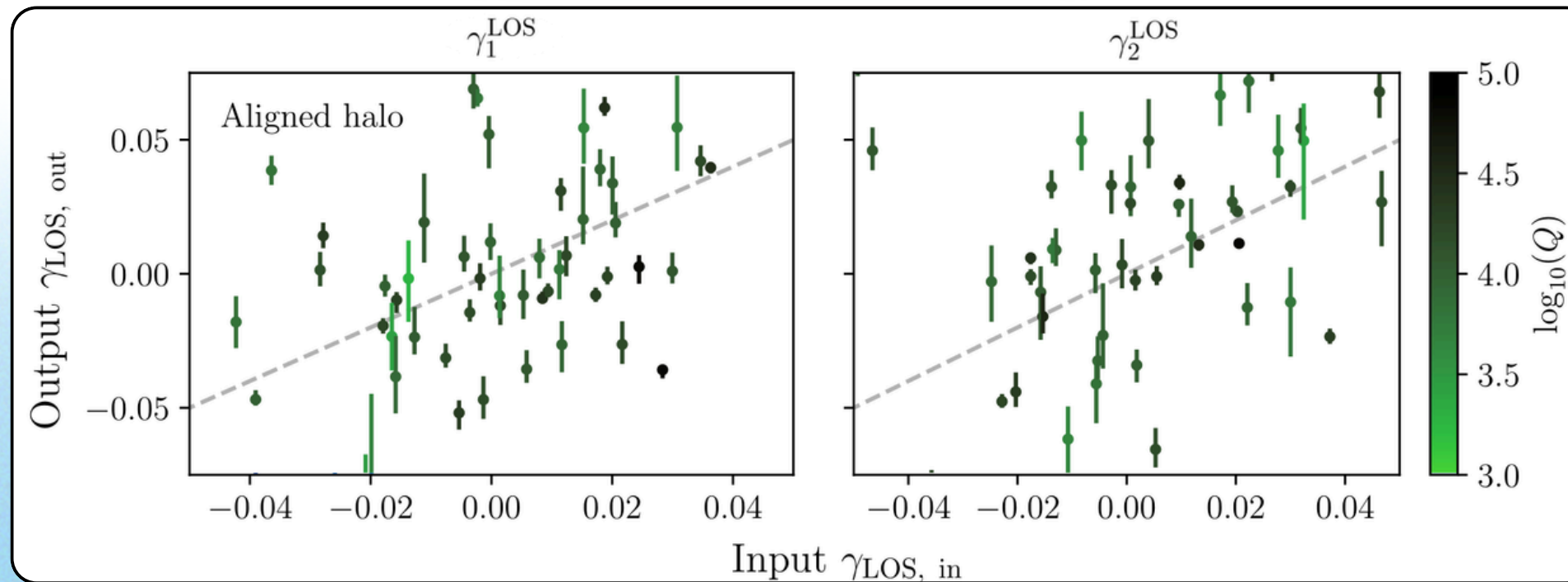
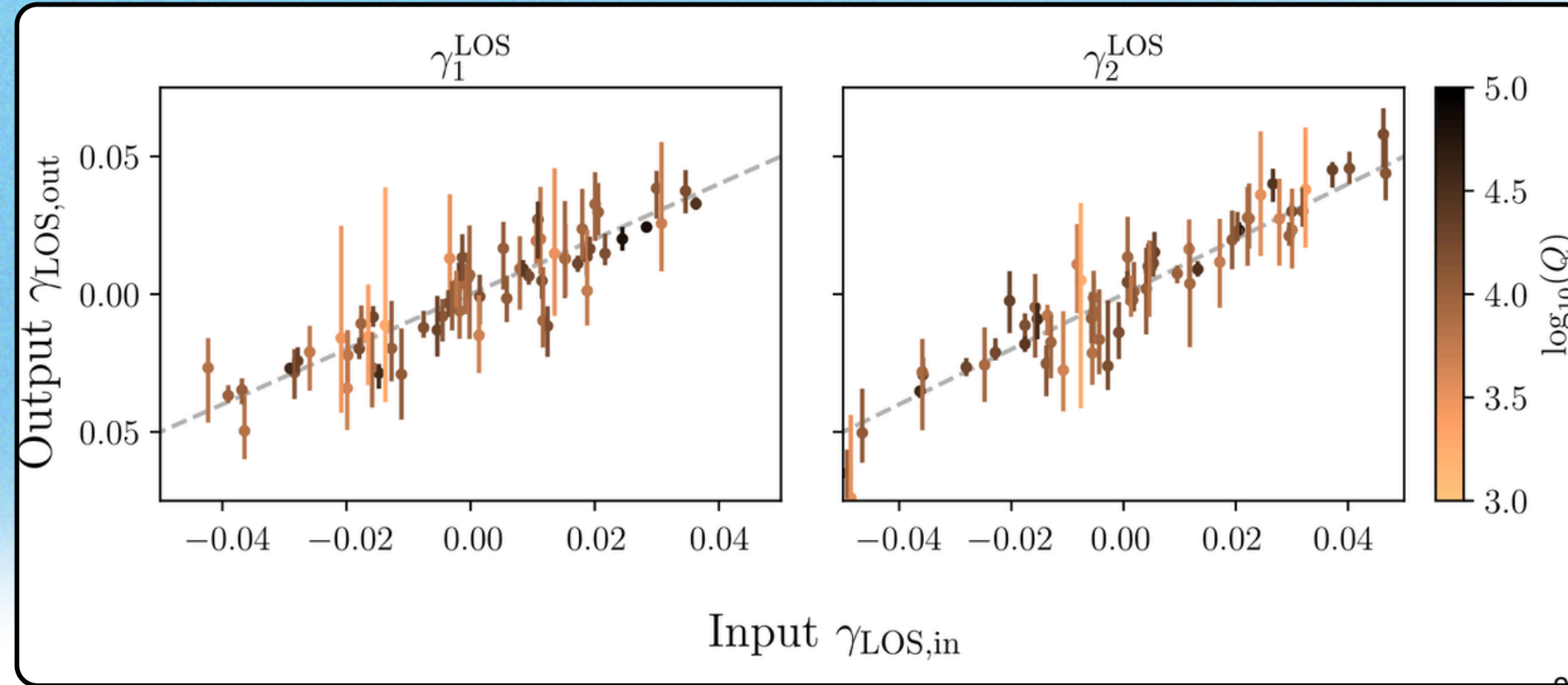
$$\mathcal{A}_{ab} = \mathbf{1} - \begin{bmatrix} \text{Re}(\gamma_{ab}) & \text{Im}(\gamma_{ab}) \\ \text{Im}(\gamma_{ab}) & -\text{Re}(\gamma_{ab}) \end{bmatrix}$$

$a, b \in \{o, d, s\}$

A promising cosmological probe if we can accurately measure it

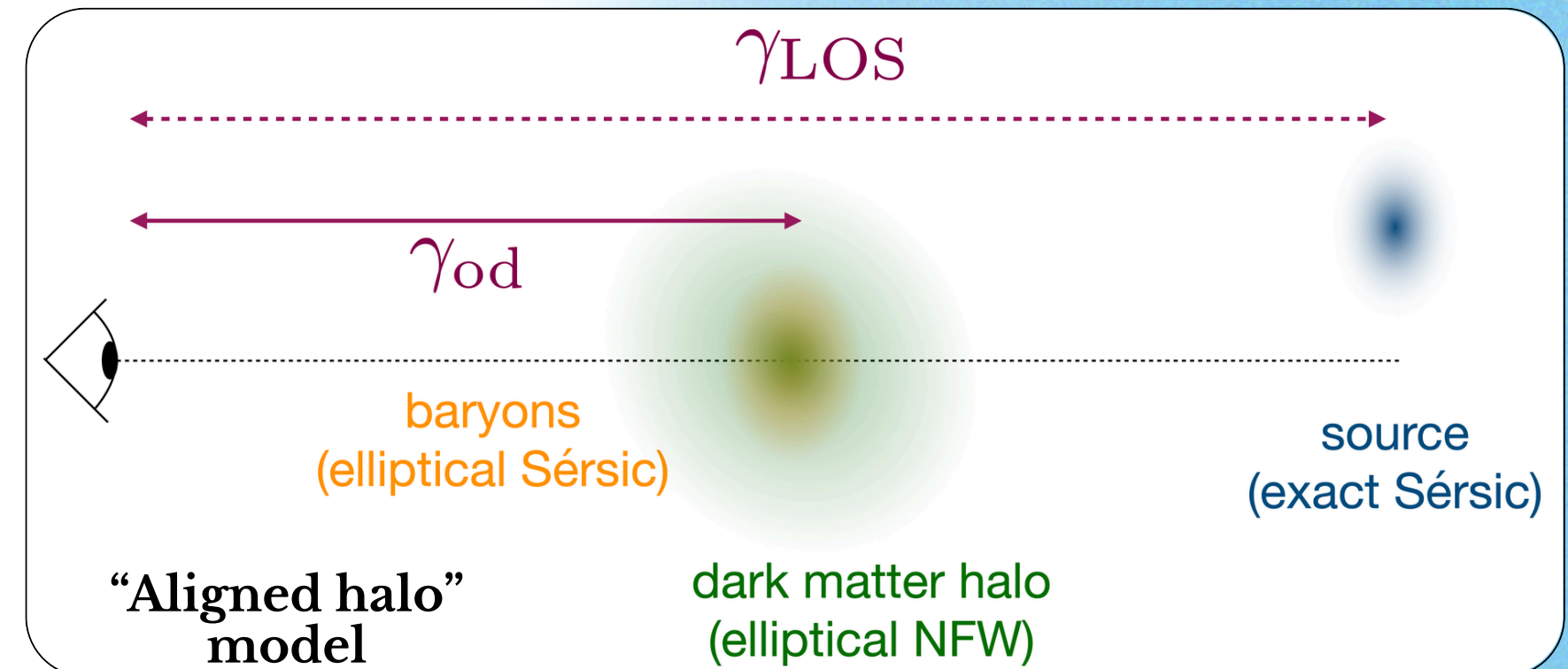
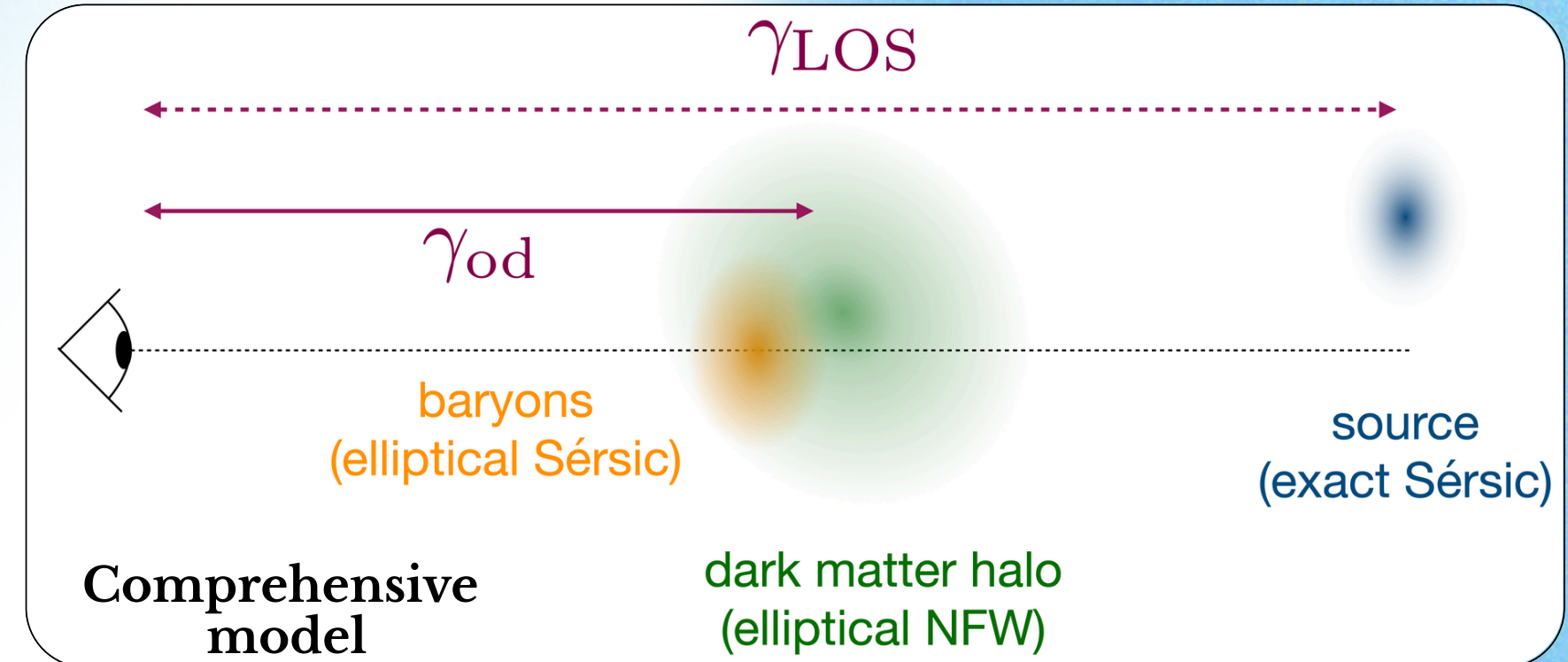
$$\mathcal{A}_{\text{LOS}} = \mathbf{1} - \begin{bmatrix} \text{Re}(\gamma_{\text{LOS}}) & \text{Im}(\gamma_{\text{LOS}}) \\ \text{Im}(\gamma_{\text{LOS}}) & -\text{Re}(\gamma_{\text{LOS}}) \end{bmatrix}$$

Proof of Concept



Hogg et al., 2023

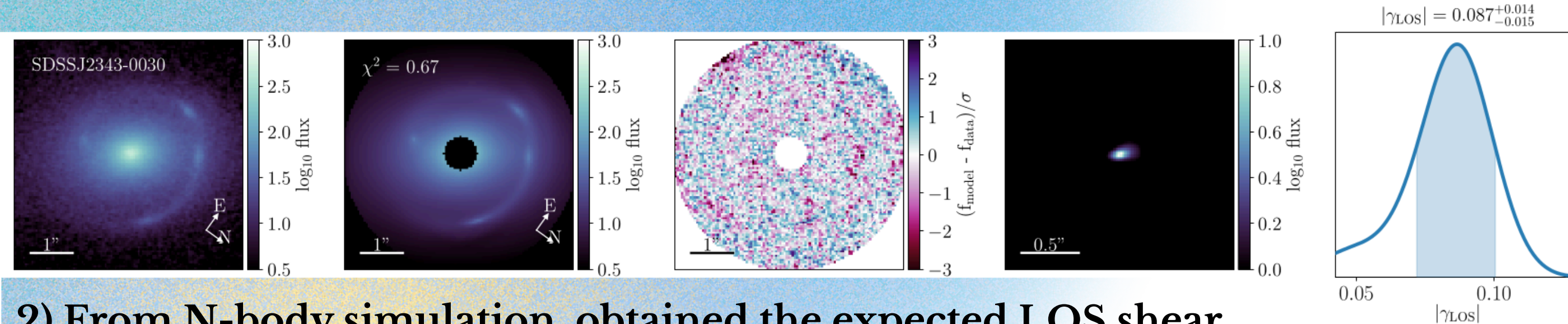
With **same** lens model as the input simulation, we recover $\gamma_{\text{LOS}, \text{in}}$ with $\sigma_{\text{LOS}} \sim 0.01$



But when the model is **not representative** of the real lens, we fail to recover $\gamma_{\text{LOS}, \text{in}}$

Looking at real data: Modelling Crisis

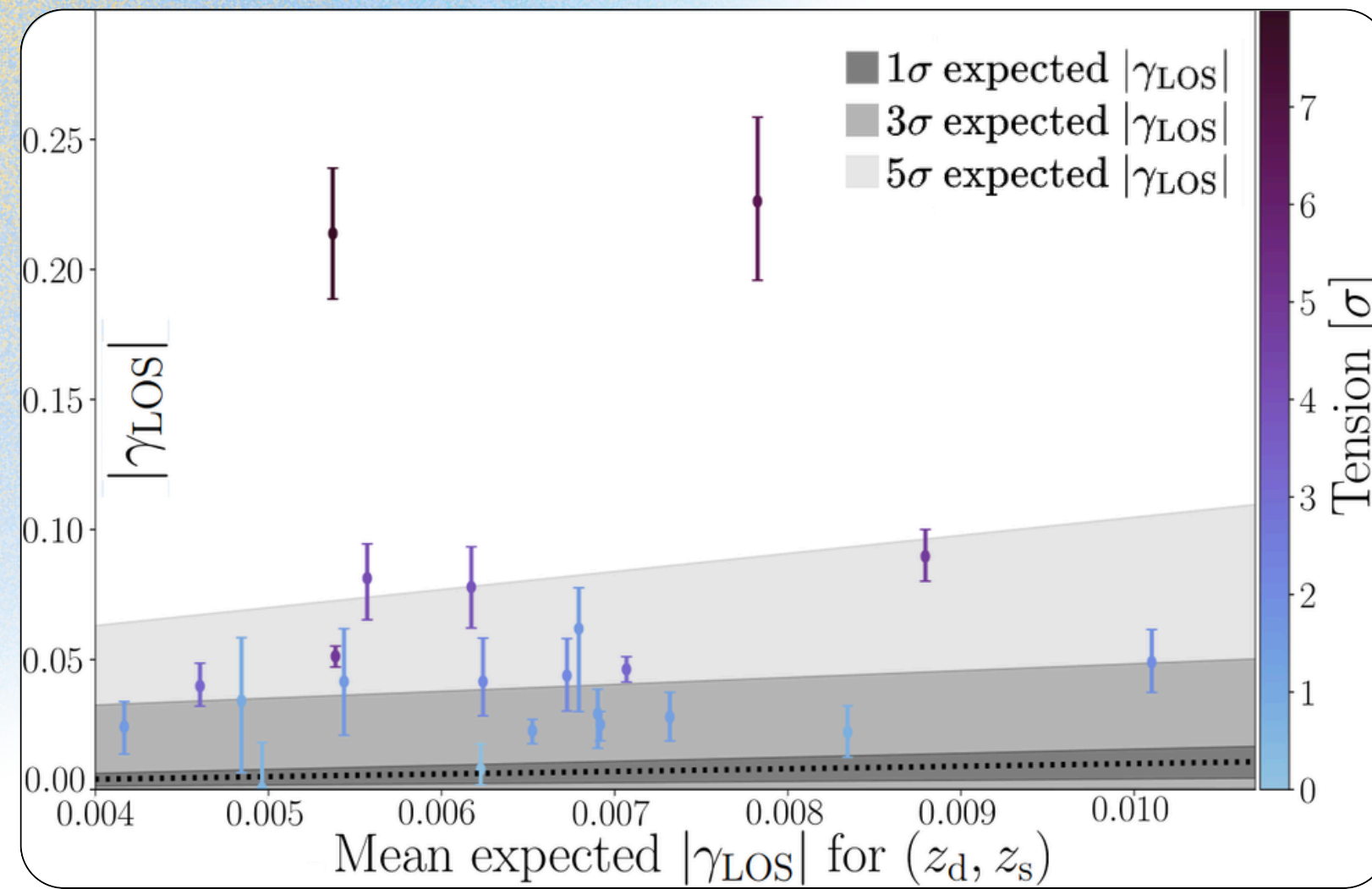
1) Modelled the SLACS Lenses with the LOS minimal model $\rightarrow \gamma_{\text{LOS}}$



Hogg et al., 2025
(a,b)

2) From N-body simulation, obtained the expected LOS shear
given z_{lens} and z_{source}

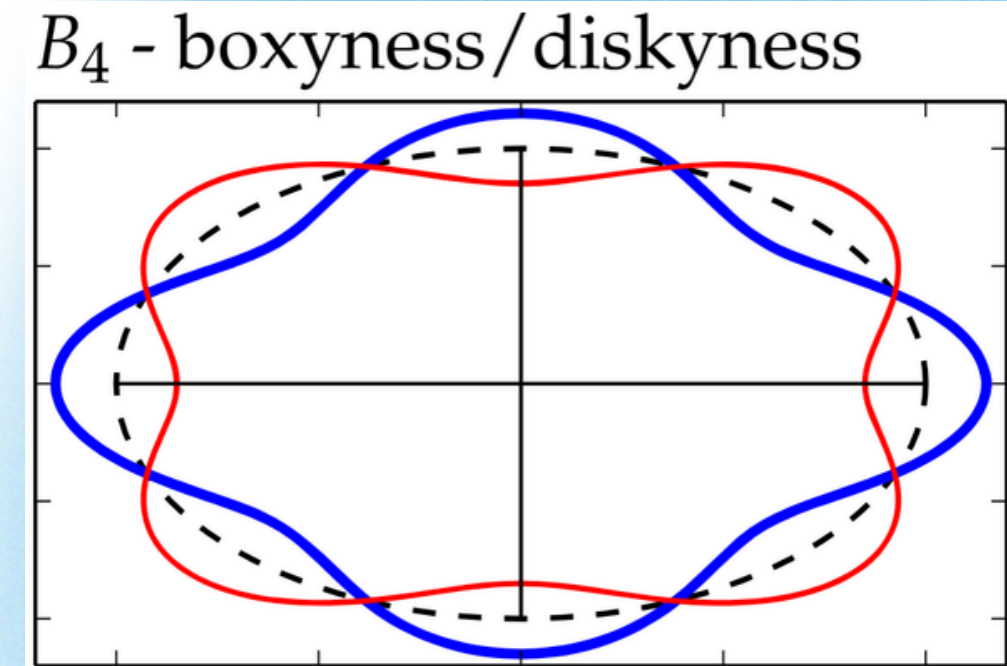
Johnson et al., 2025



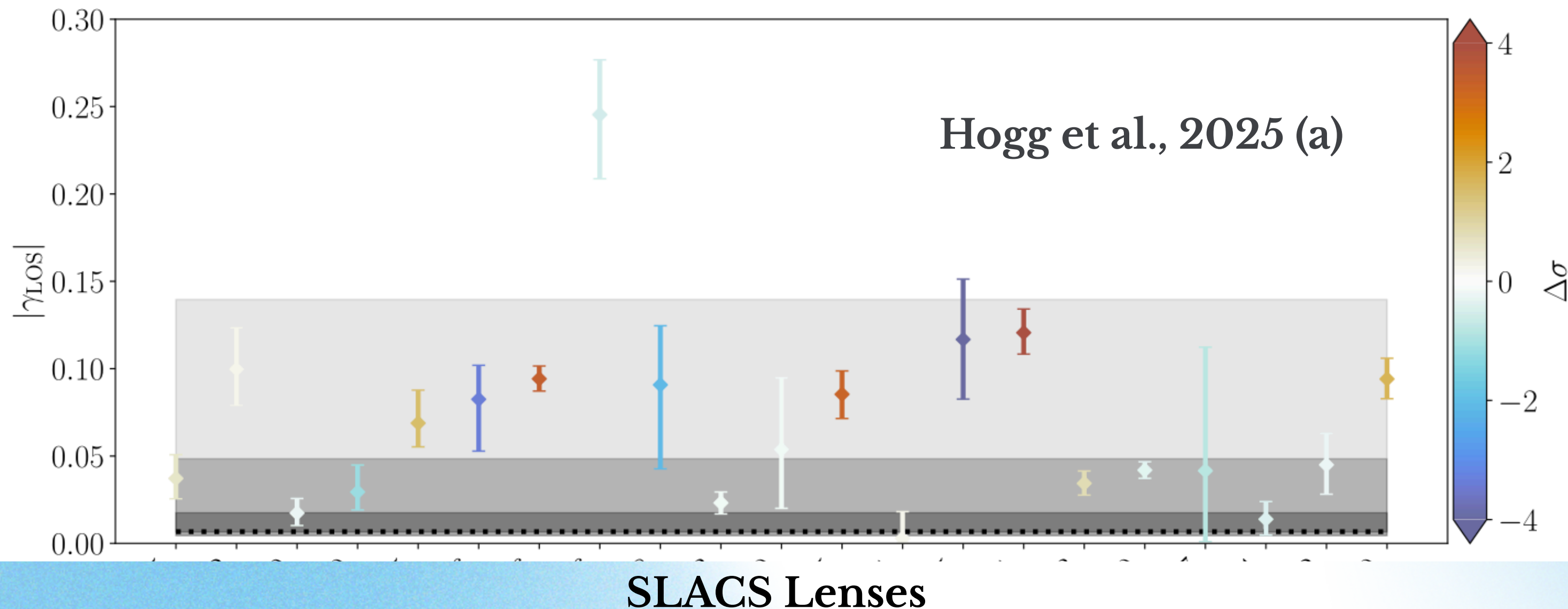
$\gamma_{\text{LOS}}(z_{\text{lens}}, z_{\text{source}})$

Modelling Crisis: Multipoles

A proposed solution is to account for deviation from perfect elliptical profiles:
the multipole distortion
in particular the multipole of order 4: “disky” vs “boxy” galaxies



Ciambur, 2015



However, surprisingly, it seems not to solve the tension for all models

Likely still needed in some cases, but no panacea

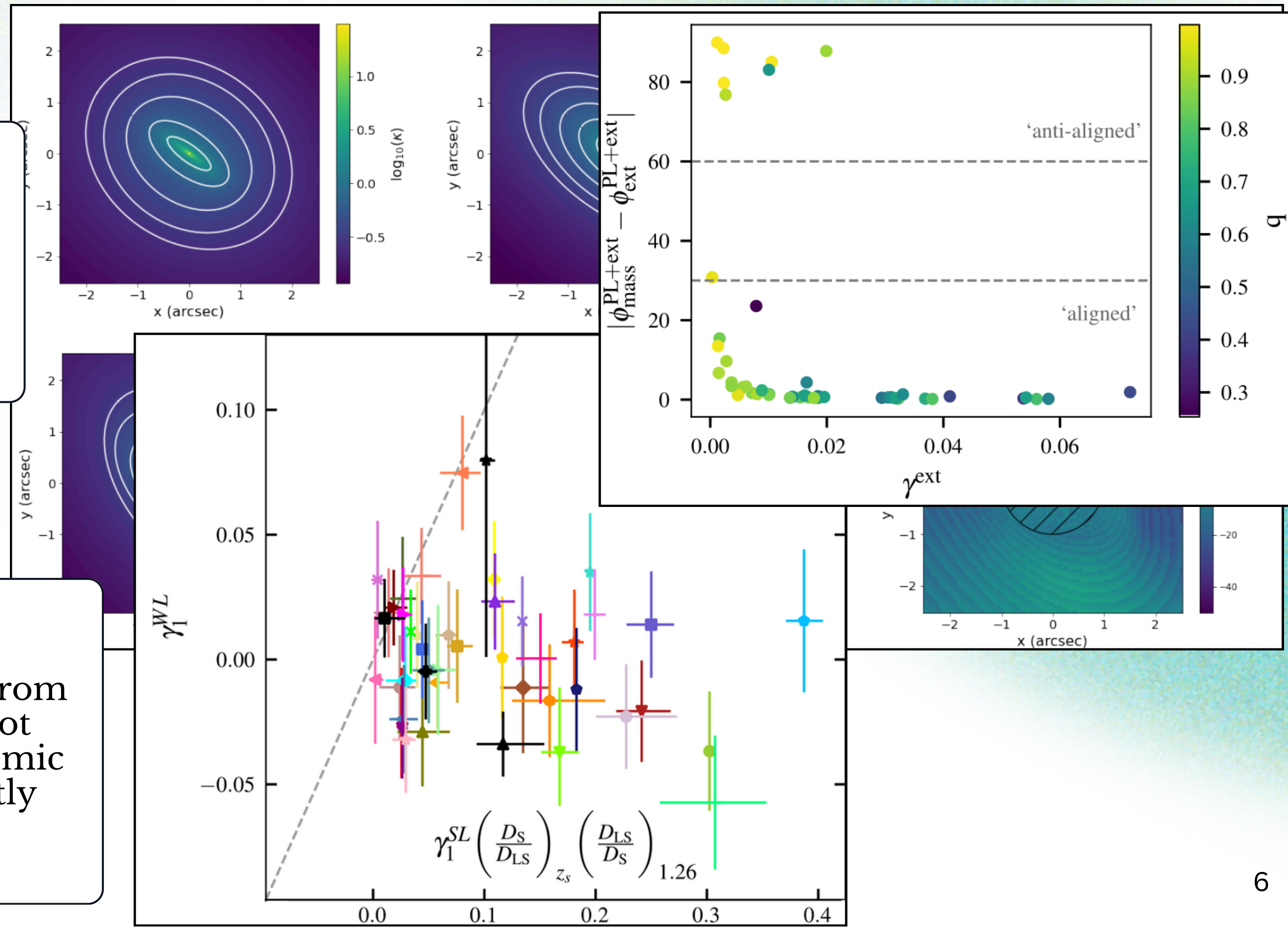
Modelling Crisis: Beyond the LOS Shear

Vyvere et al., 2022

Twists and ellipticity gradients of the mass distribution, if not taken into account, will mimic the effect of an external shear

Etherington et al., 2024

The “external” shear measured from strong gravitational lenses is not correlated with weak lensing cosmic shear, and is usually significantly higher and aligned with the ellipticity of the lens model



Modelling Crisis: A New Hope

To accurately constrain γ_{LOS} , we need more flexible lens mass models.
But how do we validate them?

Analytical Profiles	As complex as we want Known background truth Not representative of real galaxies	✓ ✓ ✗
Real Data	Fairly complex Unknown background truth As physically motivated as is can be	✓ ✗ ✓
Possible solution: Hydrodynamical Simulations	Fairly complex Physically motivated* Known background truth	✓ ✓ ✓

NAZGUL

Inspired by SEAGLE
(Mukherjee et al., 2019)

Translator

Extract Galaxies
From Hydrosimulation
(EAGLE, COLIBRE)

Load and convert particles in
the correct physical coordinates

Mount Doom

Compute lensing maps
directly from Particles

Inject LOS shear effects

Obtain realistic mock
lensed images
(PSF, resolution, noise)

Iterate and tune
model complexity

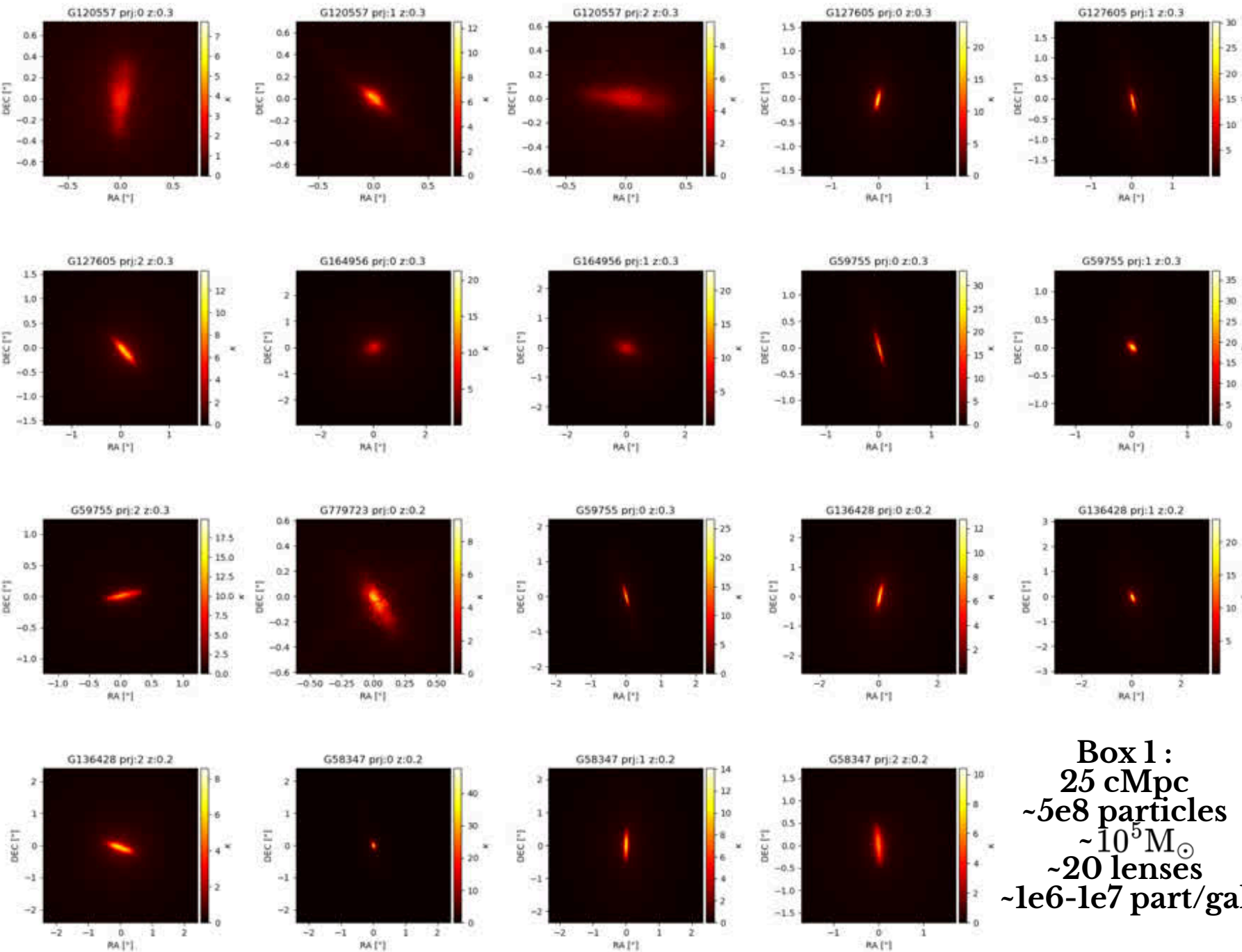
Model the
mock
image

Compare LOS

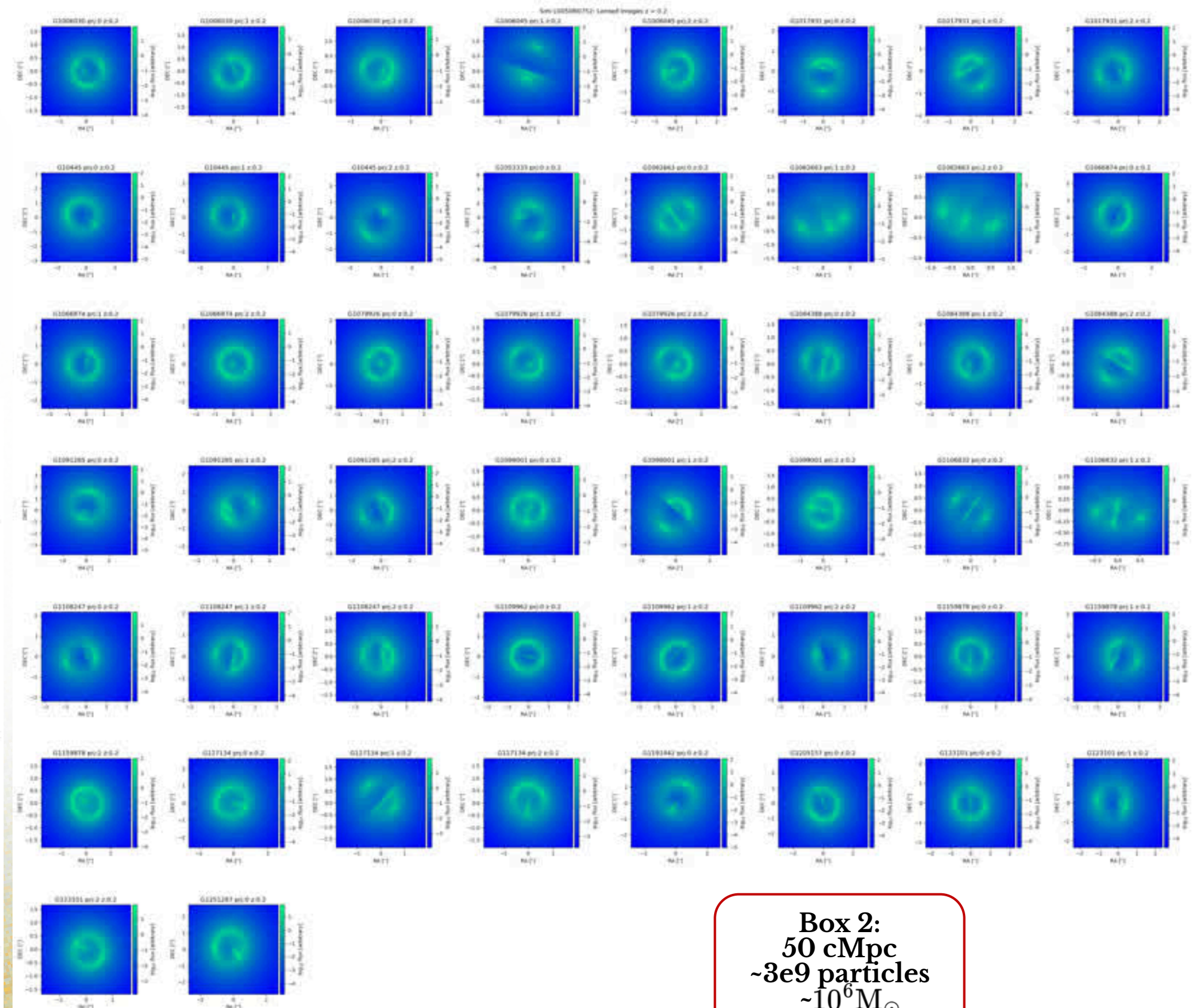


NAZGUL: COLIBRE Lens Systems

Sim L0025N0752: Convergence Map $0.2 < z < 0.3$



Box 1:
25 cMpc
~5e8 particles
~ $10^5 M_\odot$
~20 lenses
~1e6-1e7 part/gal



Box 2:
50 cMpc
~3e9 particles
~ $10^6 M_\odot$
~200 lenses
~1e5-1e6 part/gal

Coming soon: boxes with 50cMpc and 100cMpc with same particle resolution as box 1

NAZGUL Modelling results

High Resolution
Mock

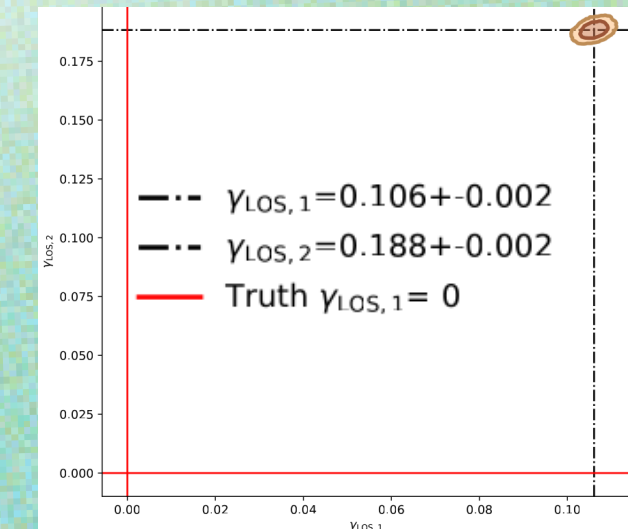
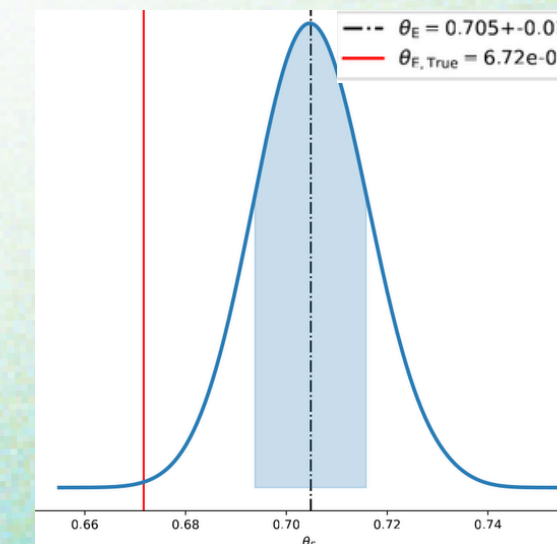
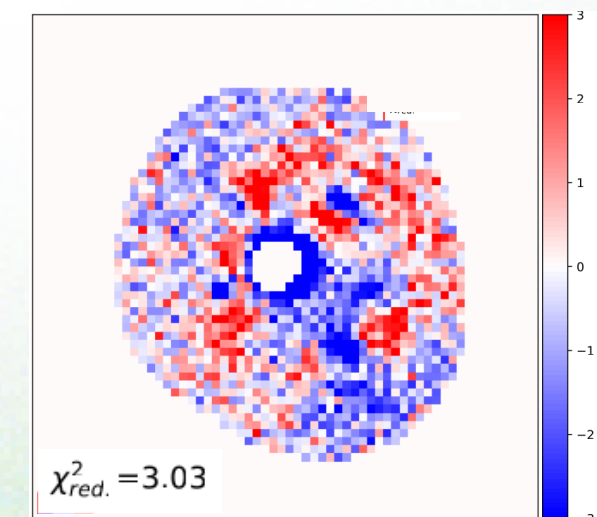
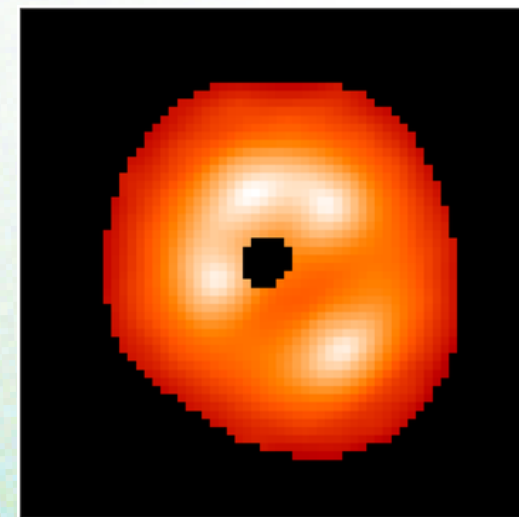
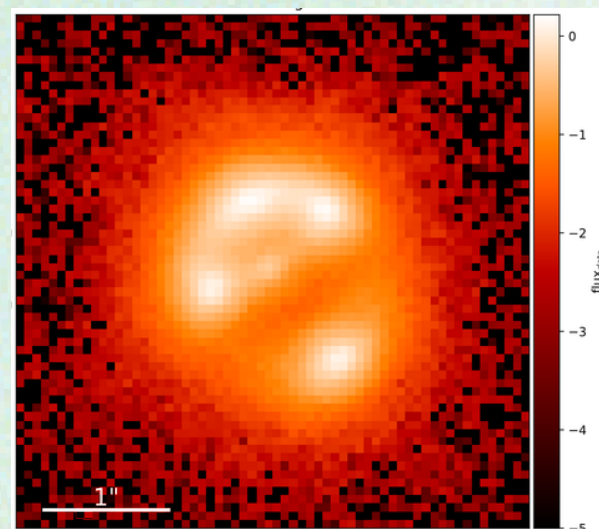
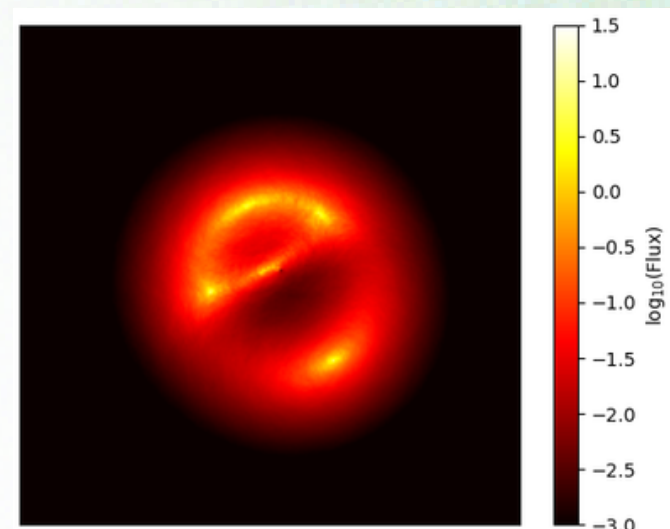
HST-like
Observation

Parametric Model

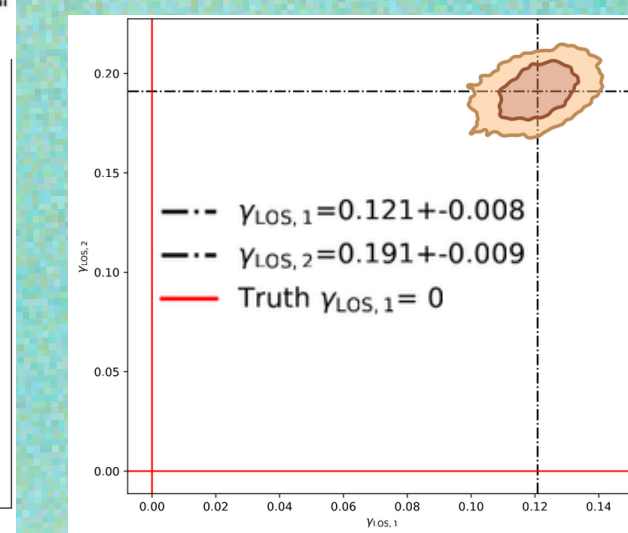
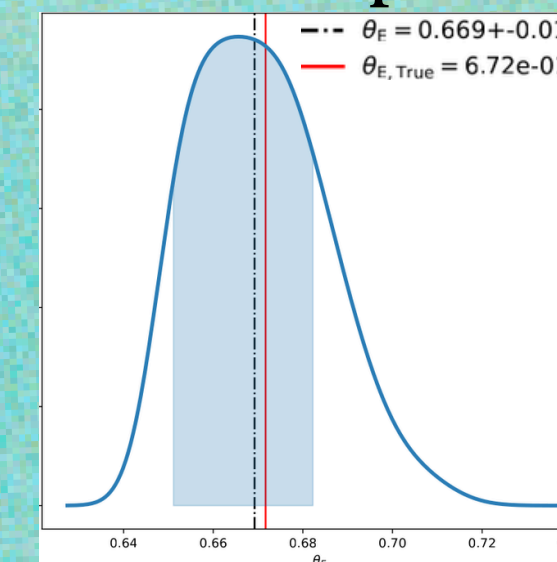
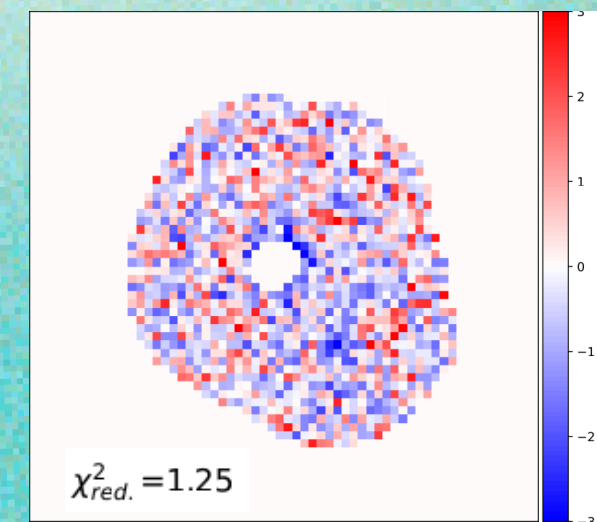
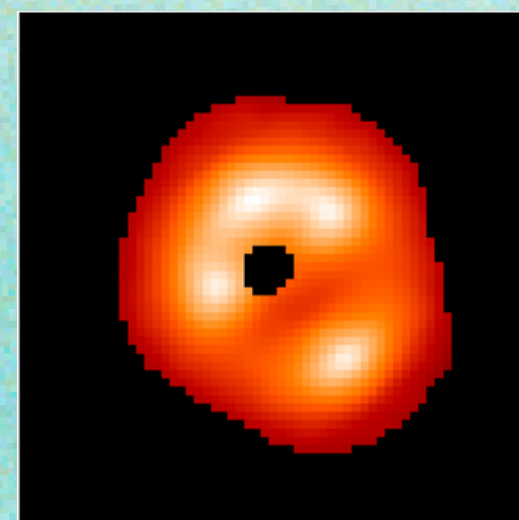
Normalised
Residual

Recover lens parameters

EPL + LOS Shear



EPL + LOS Shear+ m4 multipole



NAZGUL Modelling results

High Resolution
Mock

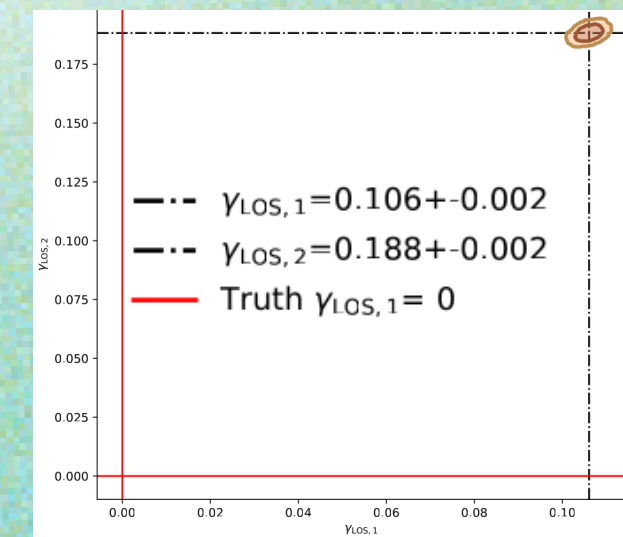
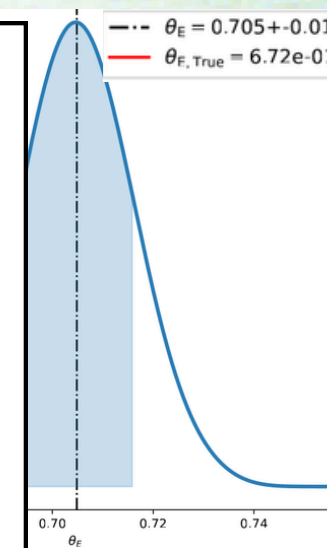
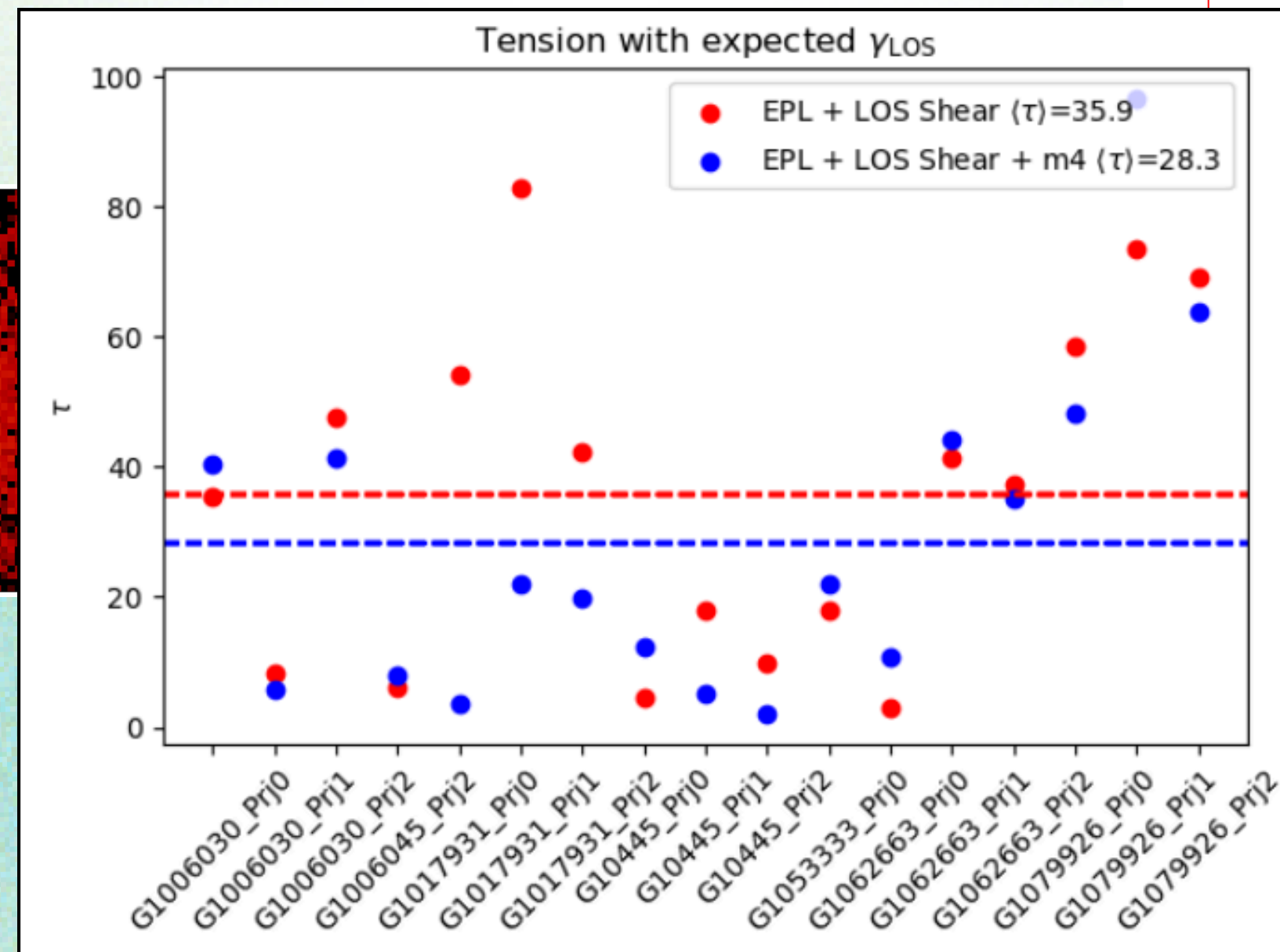
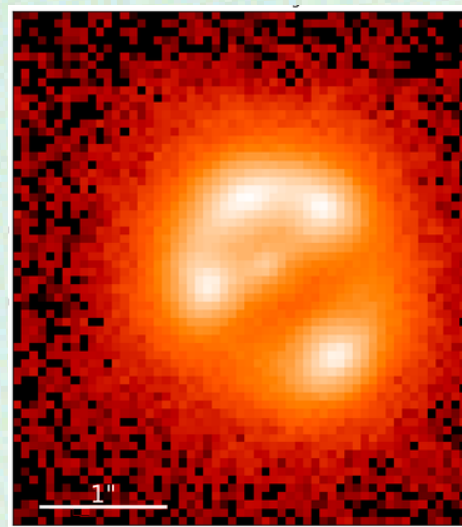
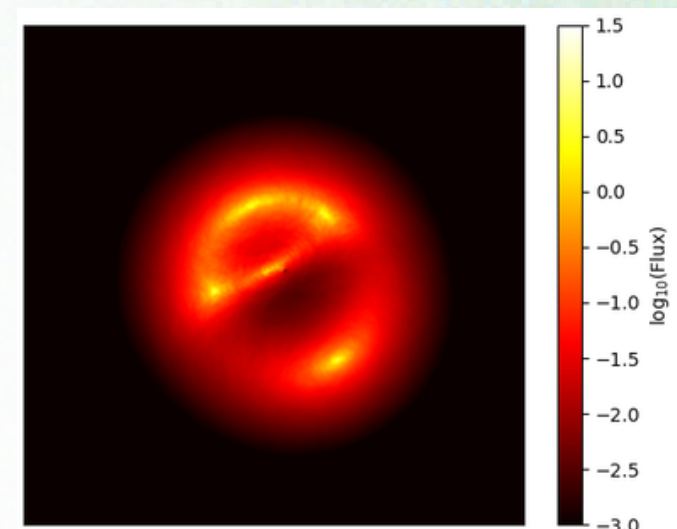
HST-like
Observation

Parametric Model

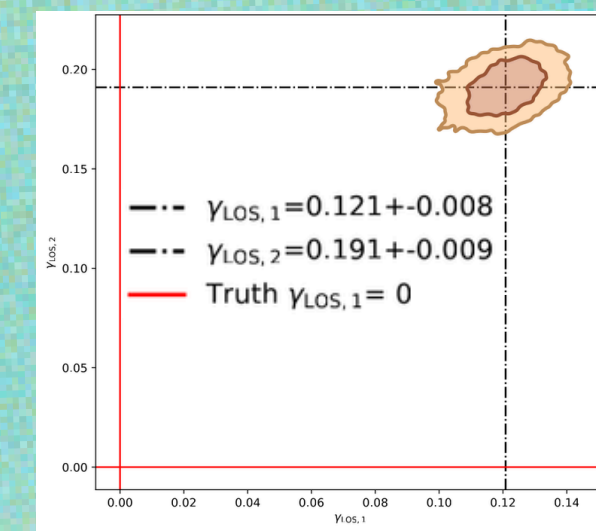
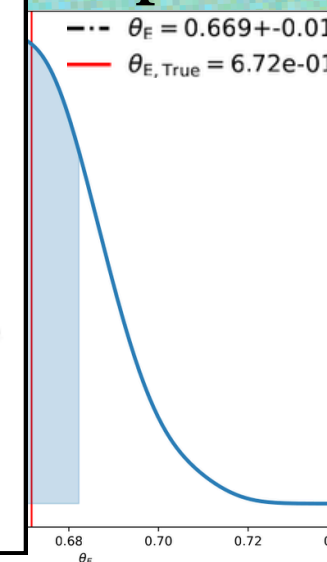
Normalised
Residual

Recover lens parameters

EPL + LOS Shear



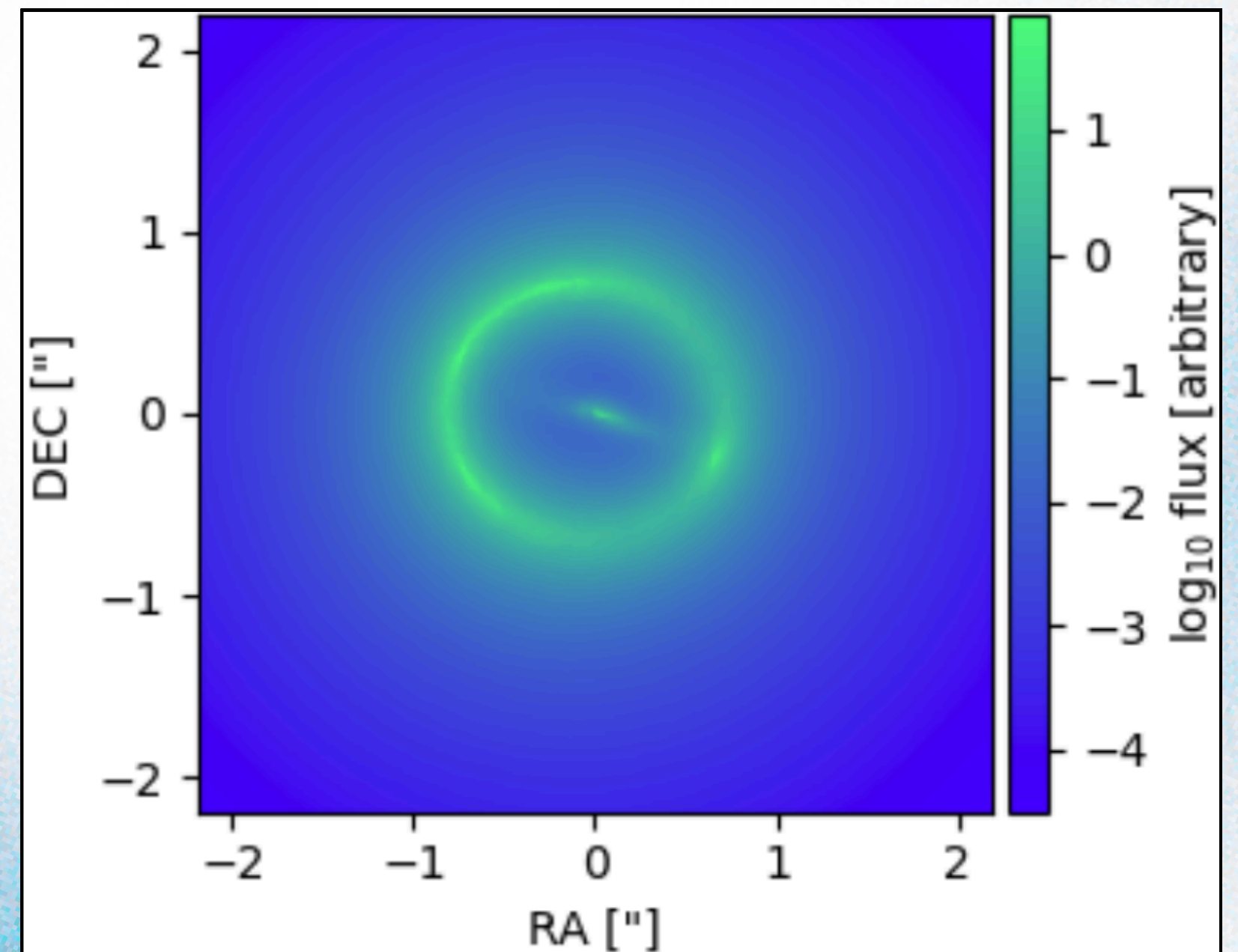
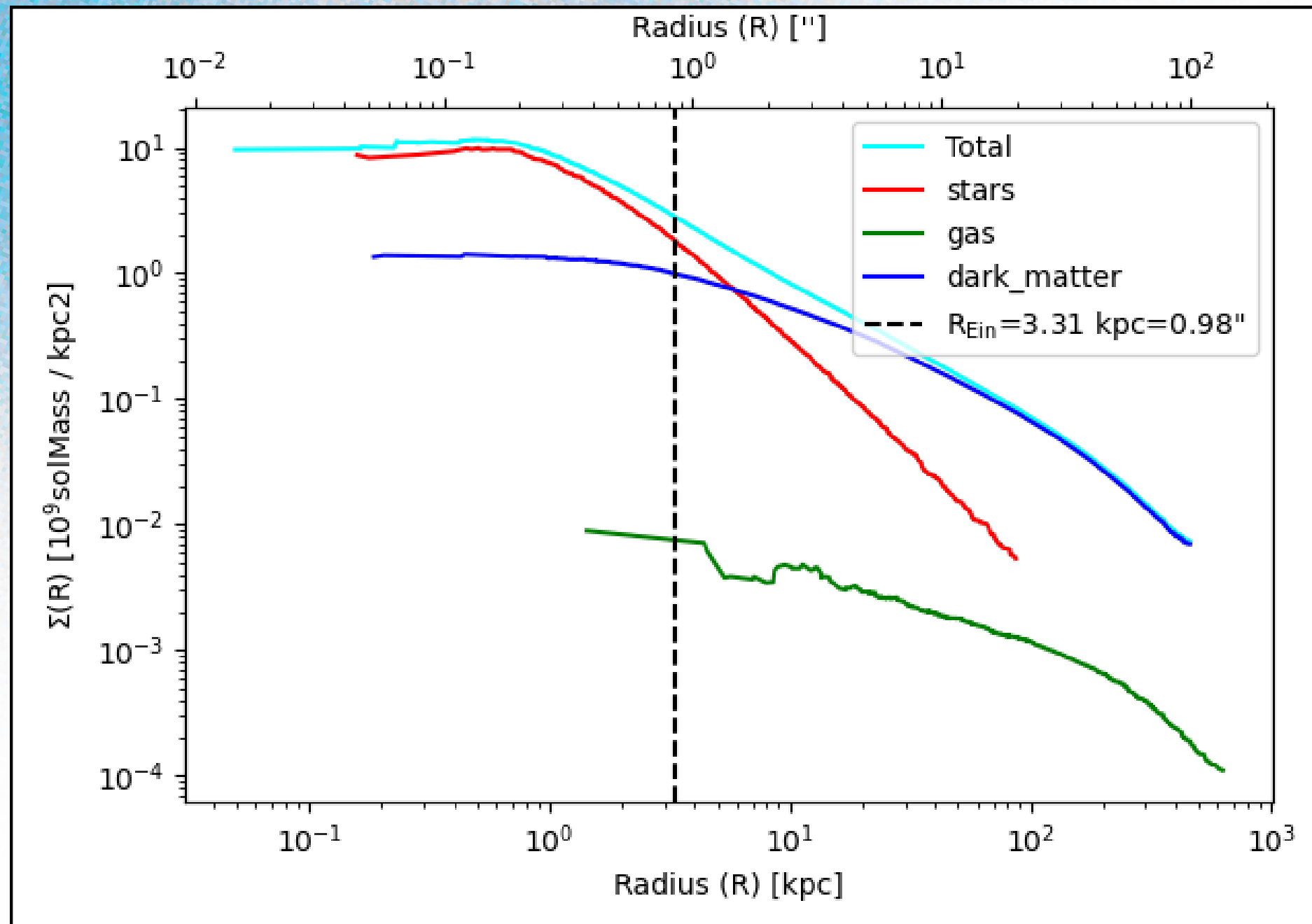
multipole



NAZGUL Caveats

Hydrosimulated galaxies are not real(istic) lenses

Example of COLIBRE Galaxy mass profile

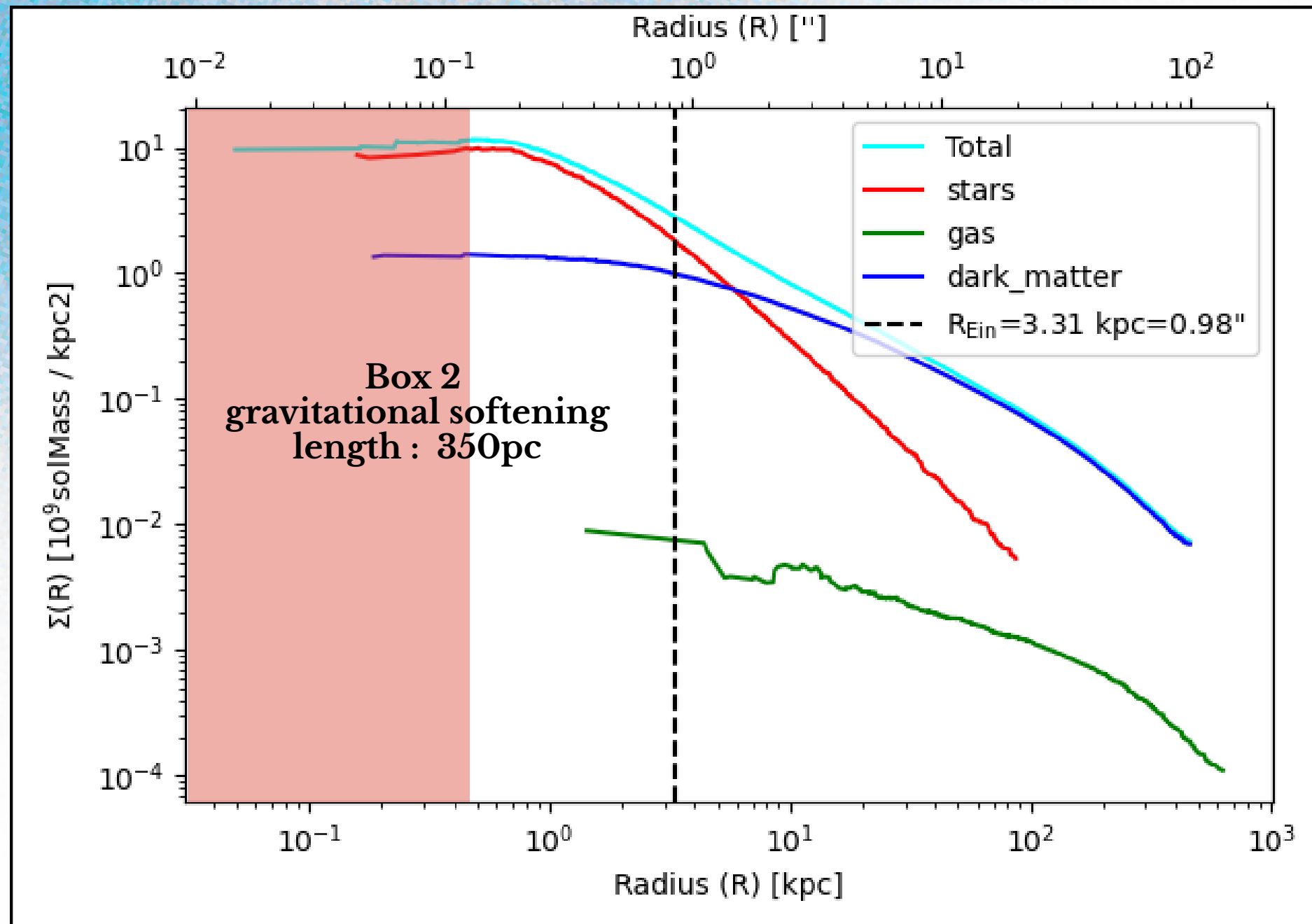


(not the same lens)

NAZGUL Caveats

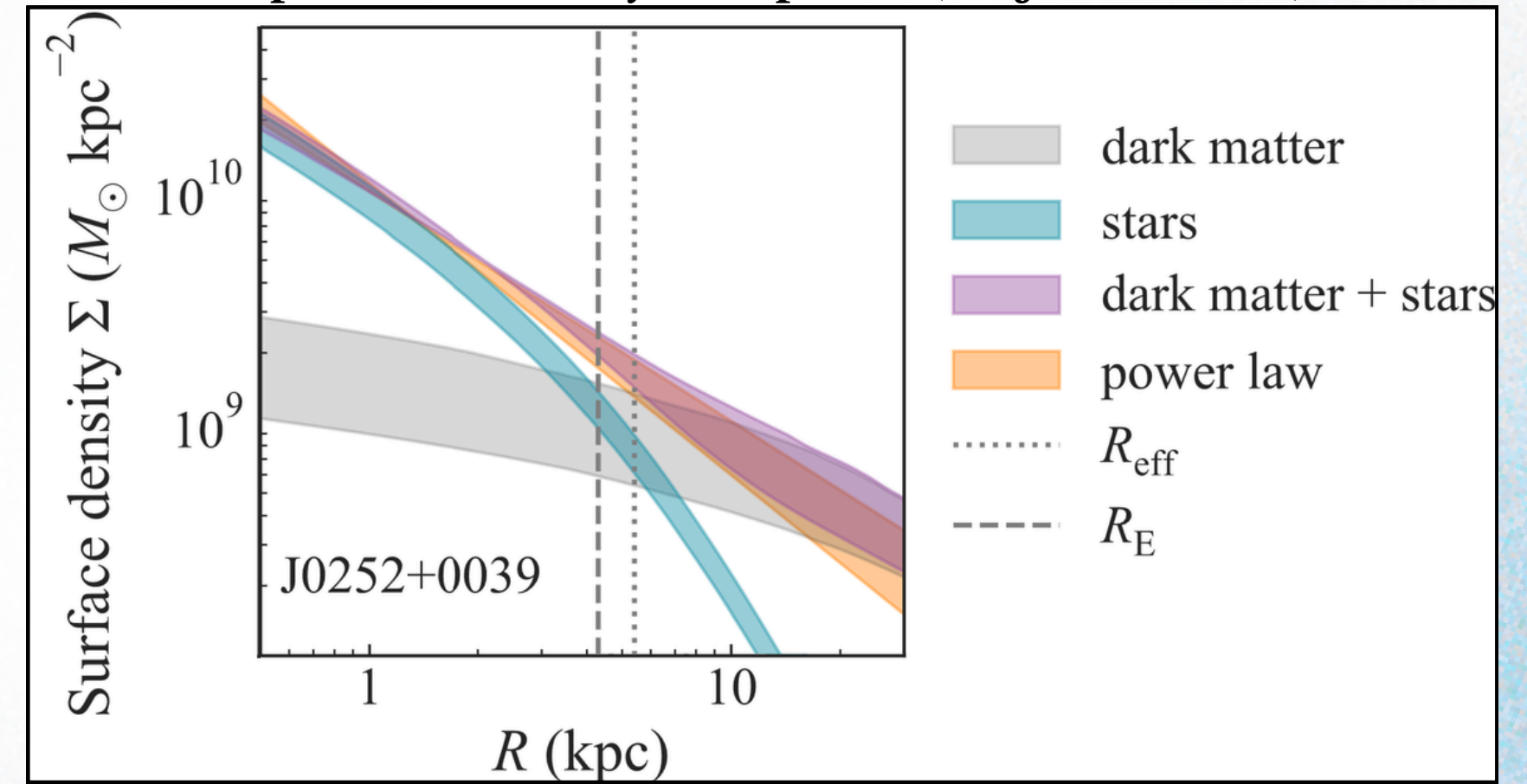
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Example of COLIBRE Galaxy mass profile

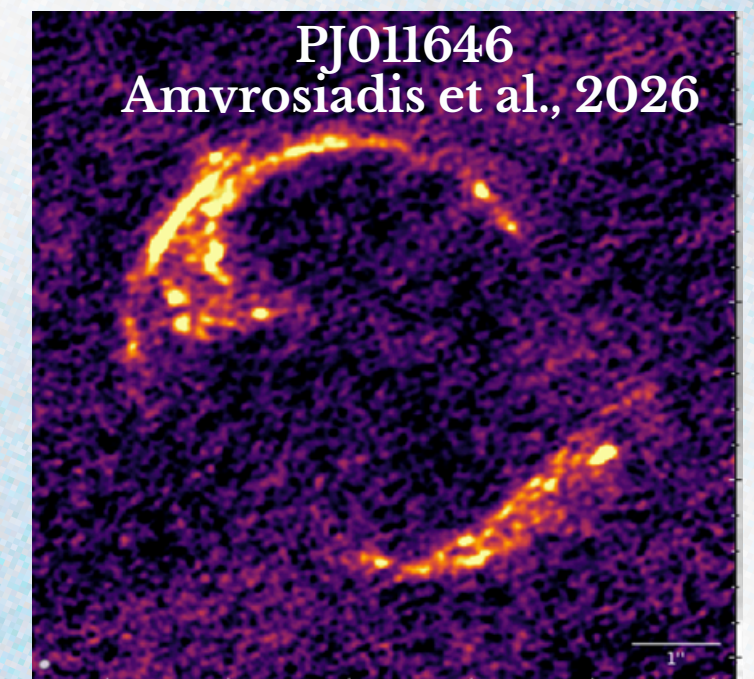
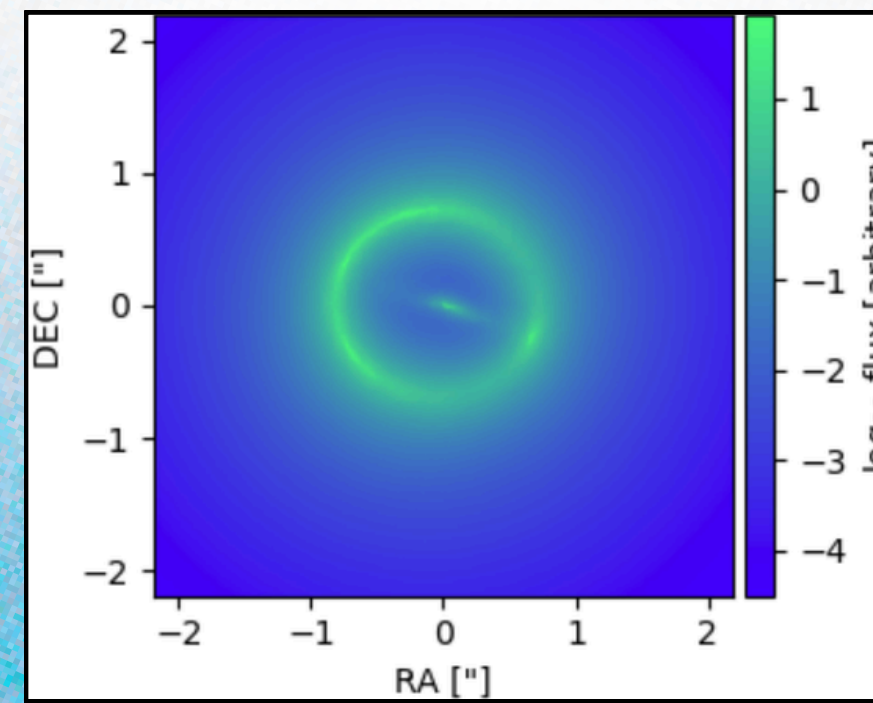


see e.g. Ding et al. 2021

Example of Real Galaxy mass profile (Shajib et al. 2021)



Central images and radial arcs:



NAZGUL

Caveats - Counterarguments

“All science is built on hope”
Yours truly, Avignon, 2026

- Shear is a tidal, i.e. global, effect
- The project aims to learn how to model, not to learn what real galaxies look like
- This seemed the simplest and most consistent way to do such a test
- Future simulations, with higher fidelity, will help reduce the issue

Still, all conclusions from this study will have to be further tested
on real data before we can fully trust them



Conclusion

Context

Strong Lenses' LOS Shear is a promising cosmological probe

Issue

Current lens models are known to be too constraining:
What are we actually measuring when we are modelling the shear?

Question

How can we validate new models?

Method

NAZGUL: Generate realistic mock lenses from hydro-sims as a testbed for new models

Caveats

Hydrosimulations are tricky; conclusions might not be easily generalised

Thank You!

Appendix

Possible Applications to Time Delay Cosmography

Framework

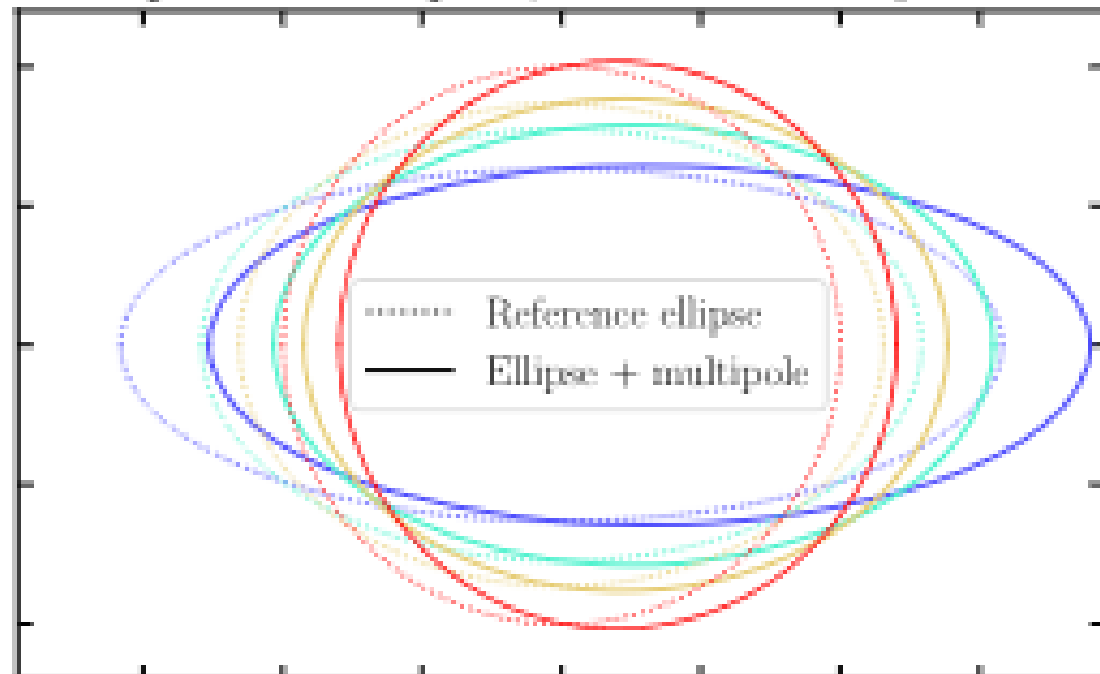
We can look at hydro-simulation to study the DM distribution at larger radii and how it affects the shear

Scientific Output

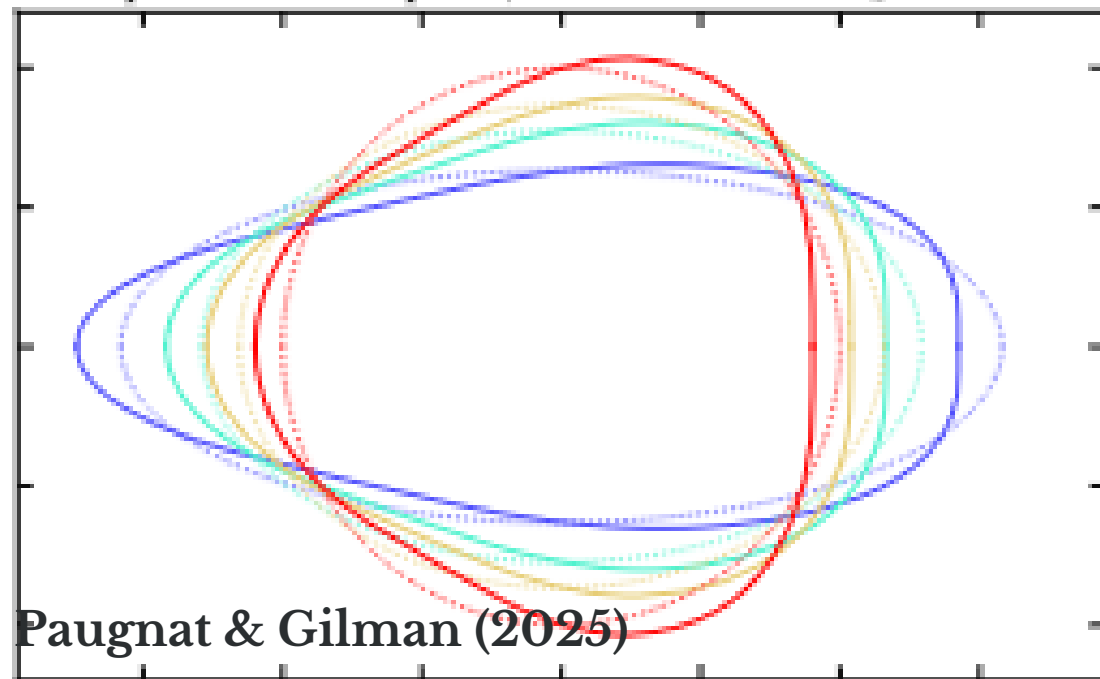
Accurate LOS shear measurements would add information to the simulation-based weighting used in external convergence estimation

Modelling with M134 multipoles

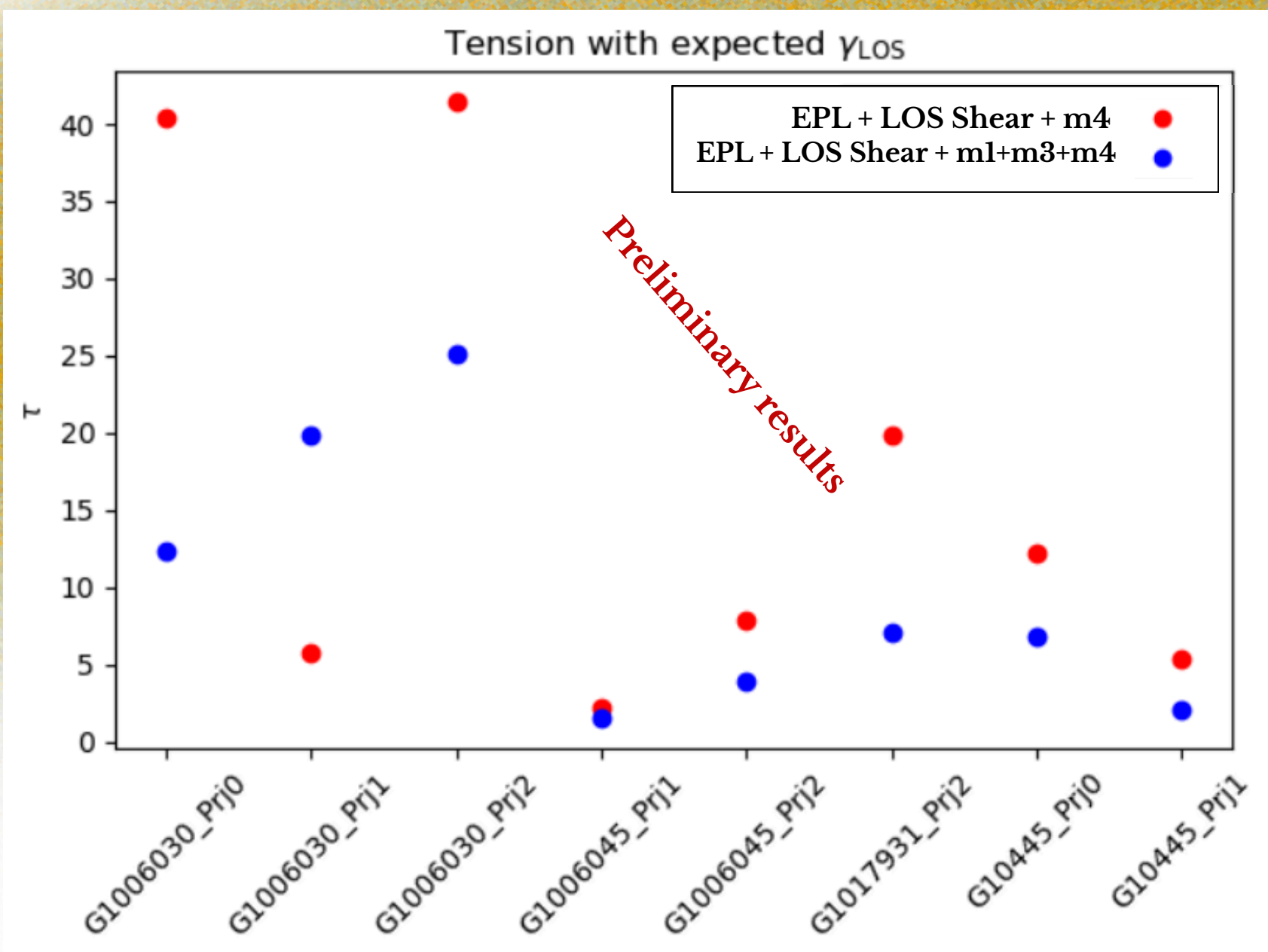
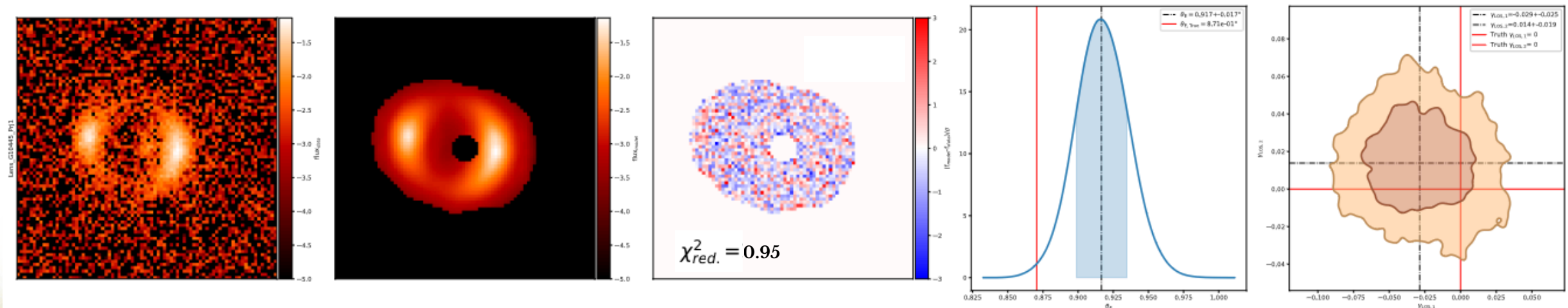
Elliptical multipole, $m = 1$ with $a_1 = 0.2$



Elliptical multipole, $m = 3$ with $a_3 = -0.1$



Paugnat & Gilman (2025)



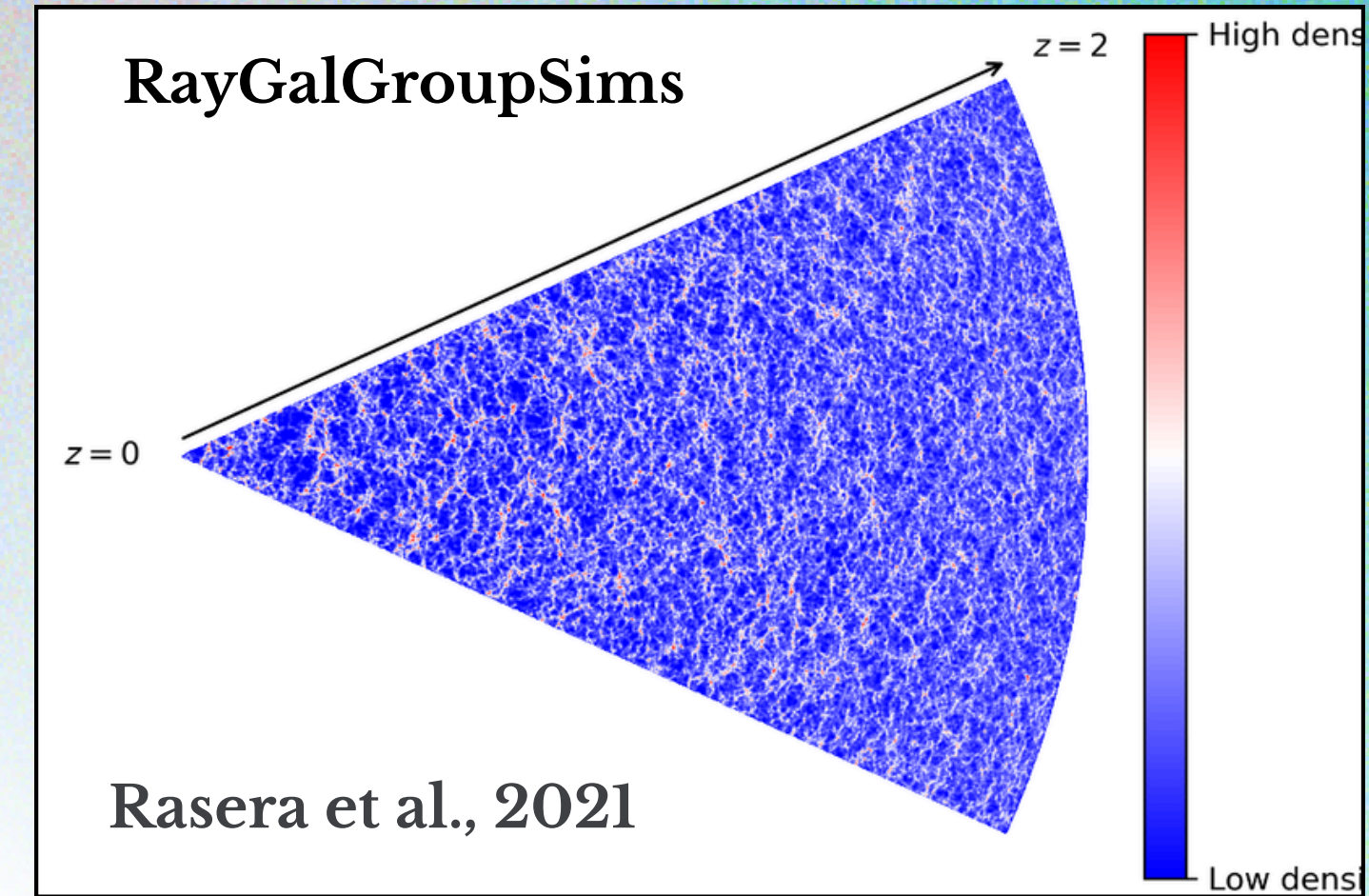
LOS Shear from N-Body Simulations

Work lead by Daniel Johnson

- Extract shear from exact raytraced lightpath on simulation (post-Born)

- Interpolate z between snapshots

- Fit for different LOS components given z_{lens} and $z_{\text{source}} \longrightarrow \gamma_{\text{LOS}}(z_{\text{lens}}, z_{\text{lens}})$



Nazgul - Verification

- Take an analytical profile (SIS)
- Sample particles (position and mass)
- Pass it to Nazgul as a “real” galaxy
- Compute the lensing maps (i.e. deflection map)
- Compare with analytical expectations

