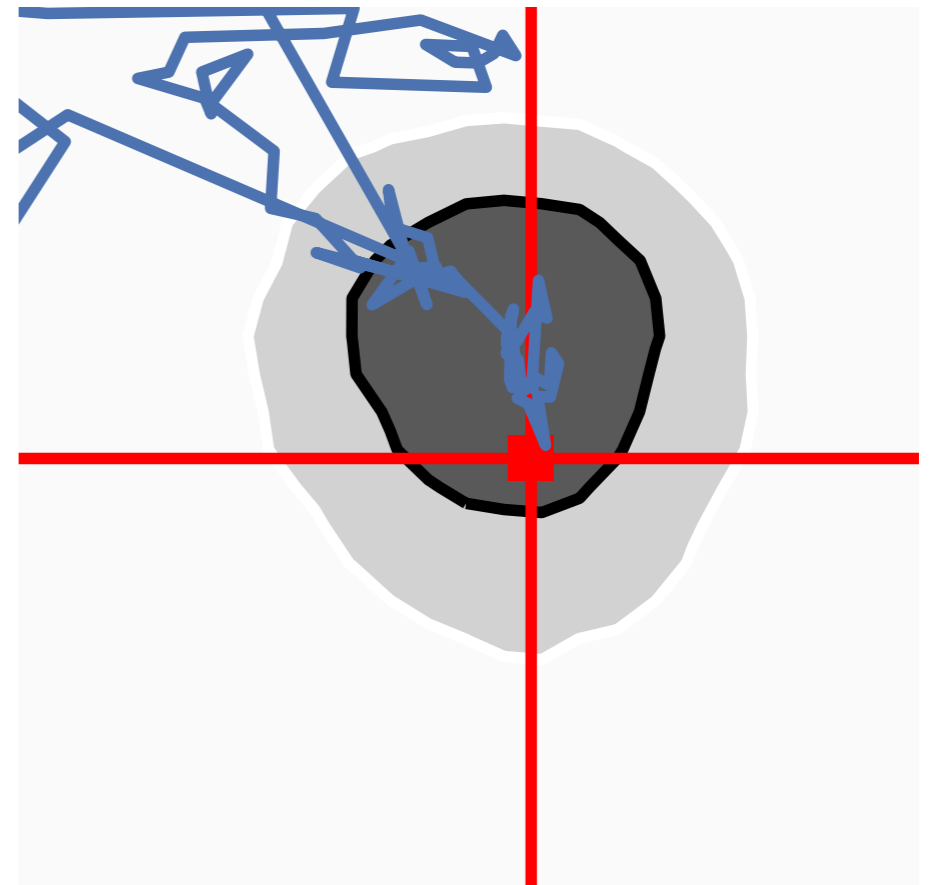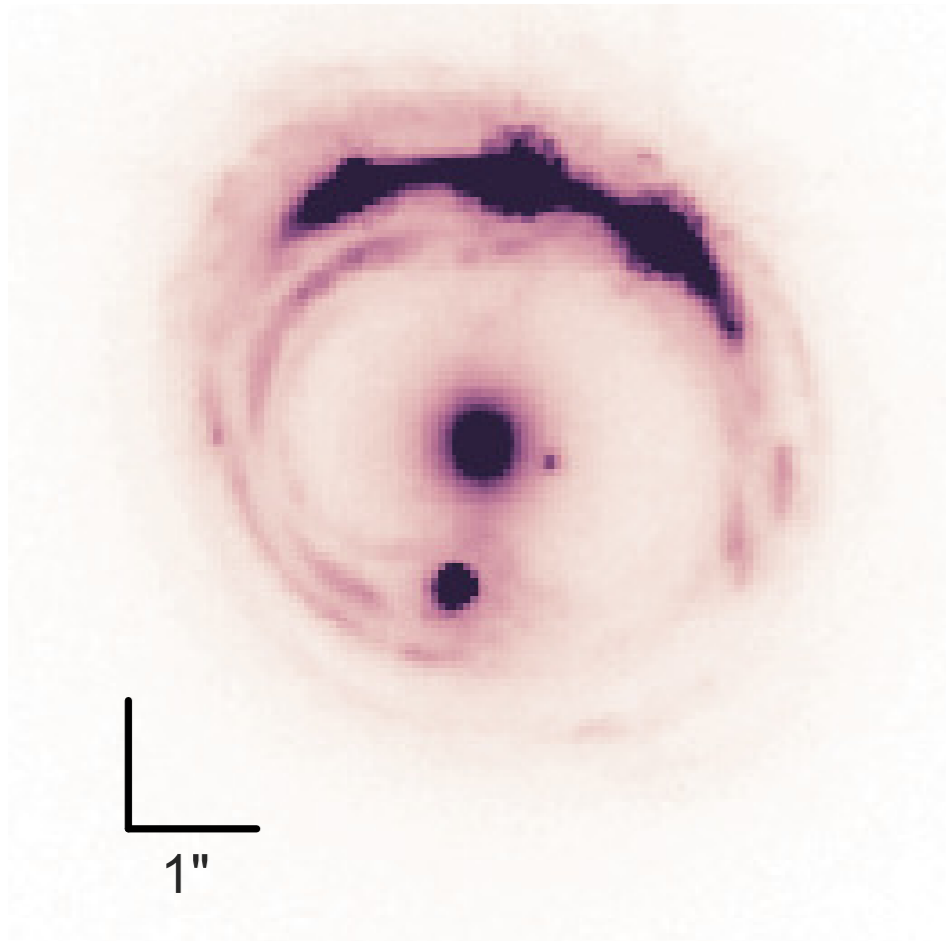# Strong lens modelling @ETH

Simon Birrer
with Adam Amara & Alexandre Refregier
and ETH Software Lab

Strong Lensing

- continuous mapping of source to image plane
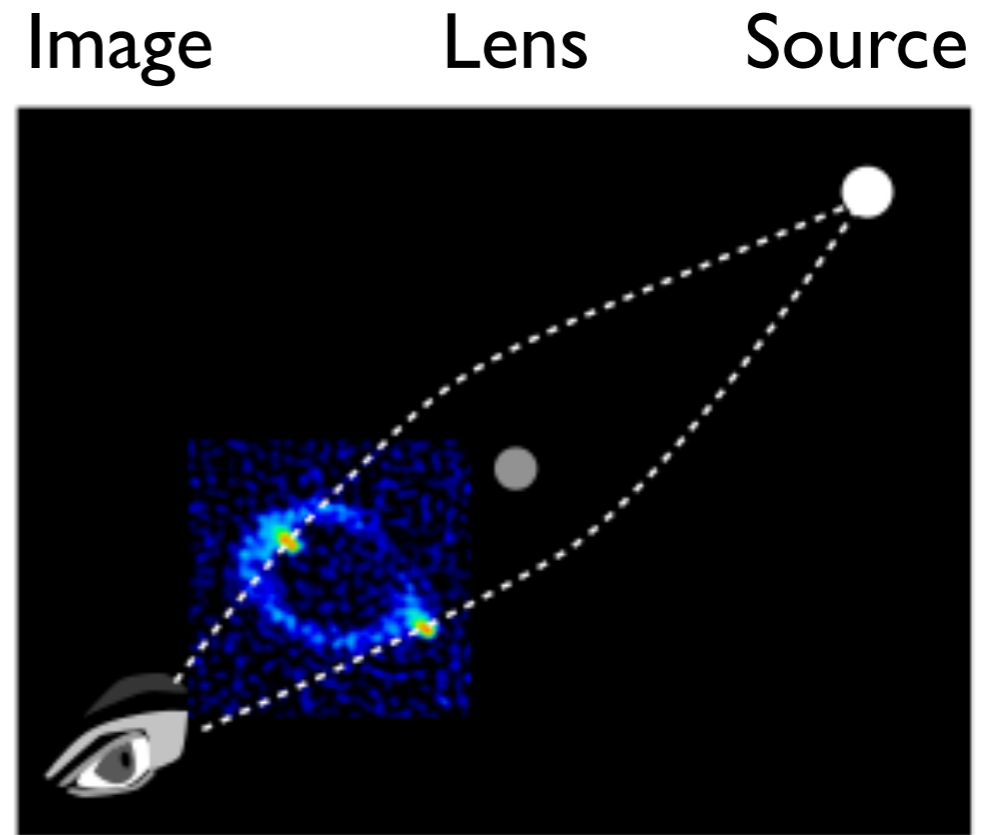- multiple image positions

image credit: Simple Nature, Benjamin Crowell

Change in…

brightness ➡ linear

mapping ➡ non-linear
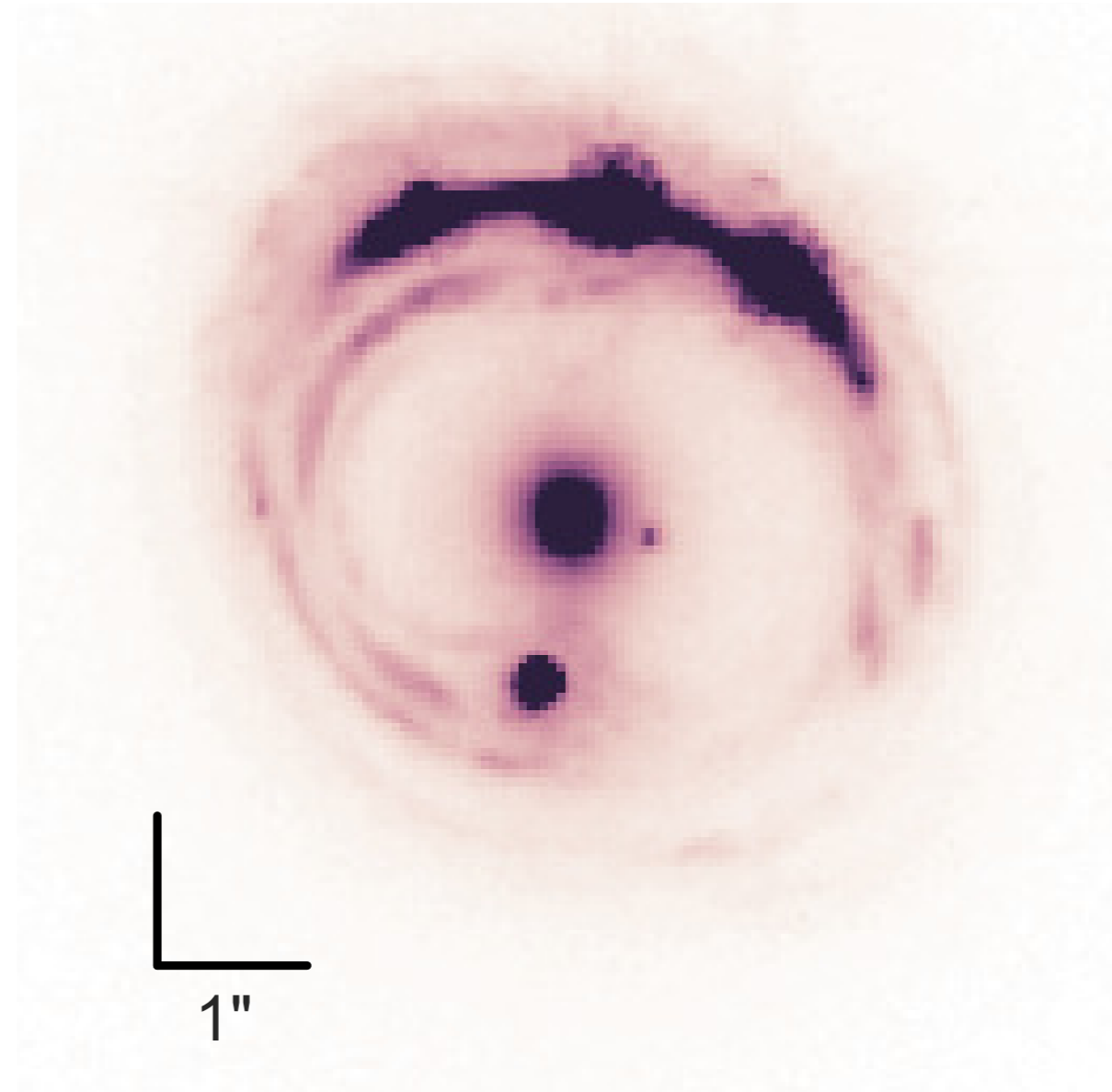
…response to pixel values

Lens modelling

To be modelled:

- lens mass (light deflection)
- lens light
- point source
- extended source
- PSF

Challenges:

- more than 30 non-linear parameters
- several hundred linear parameters
- many local minima (not under control)
- marginalisation over linear parameters
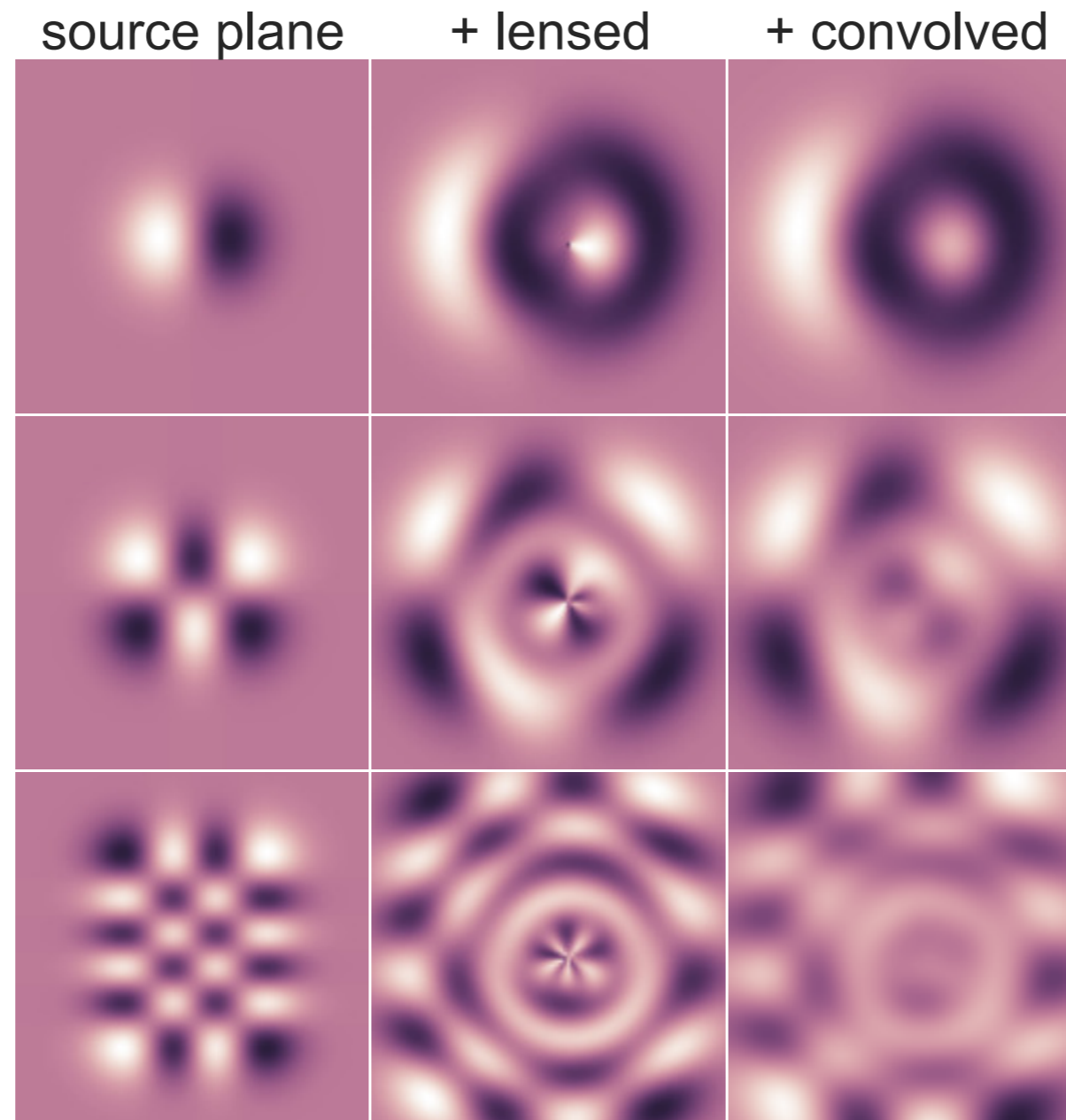- Hubble PSF is complex
- Known and unknown degeneracies

1"

HST ACS F814W image of RXJ1131-1231

Sluse+ 2003
Suyu+ 2013

Source reconstruction technique (linear)

Basis set: Shapelets

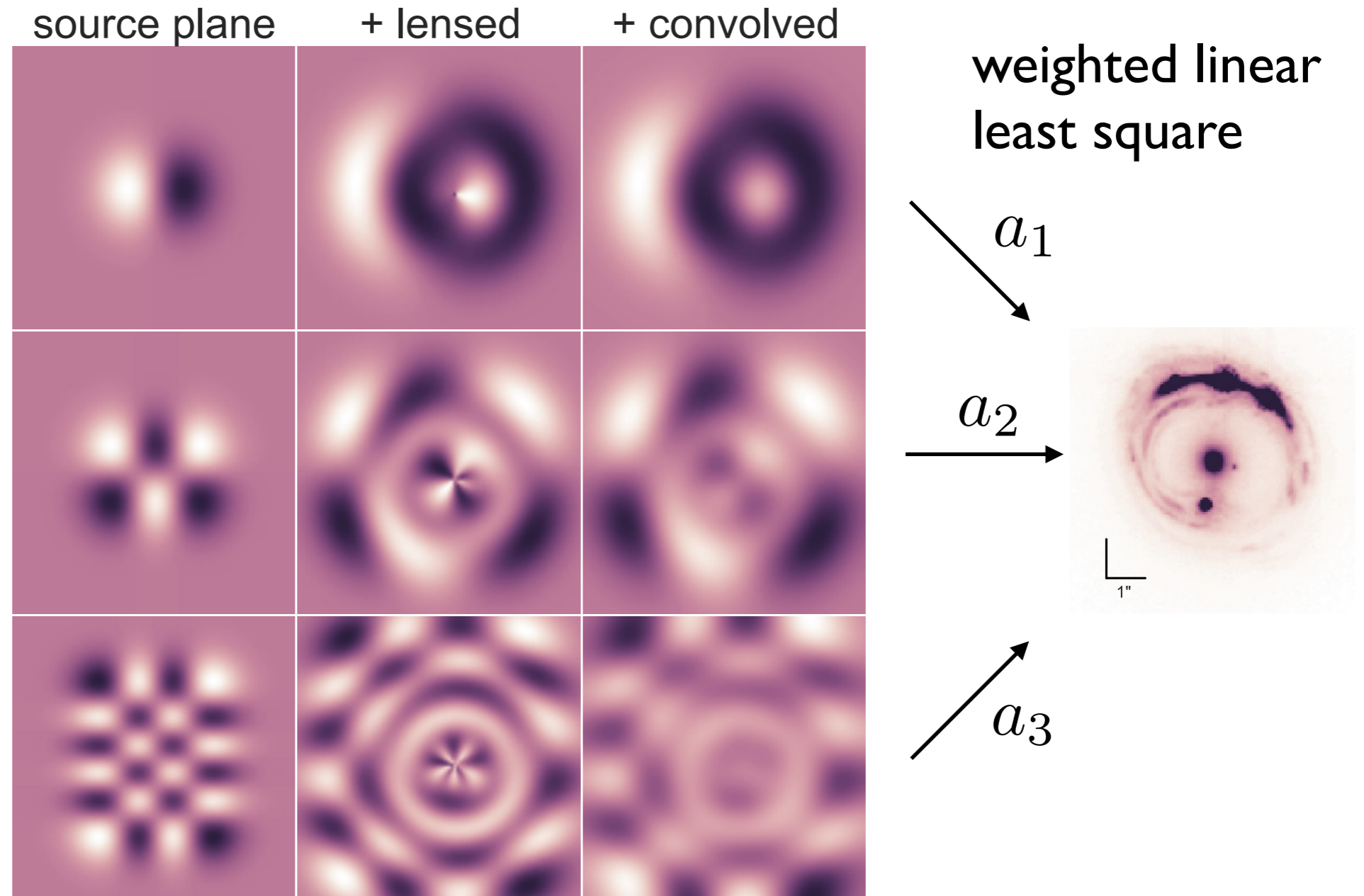source plane   + lensed   + convolved

Shapelets: Refregier 2003
Method: Birrer+ 2015

Source reconstruction technique (linear)

Basis set: Shapelets

source plane   + lensed   + convolved

weighted linear least square

a_1

a_2

a_3

1"

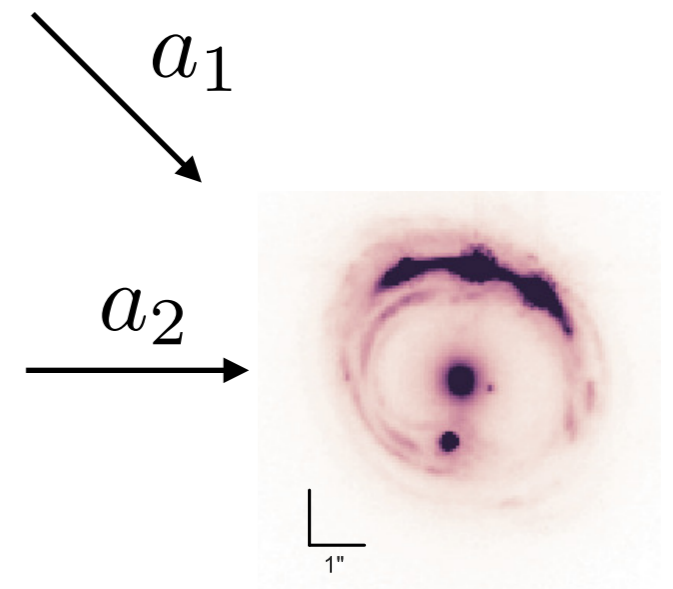Shapelets: Refregier 2003
Method: Birrer+ 2015

Source reconstruction technique (linear)

Basis set: Shapelets

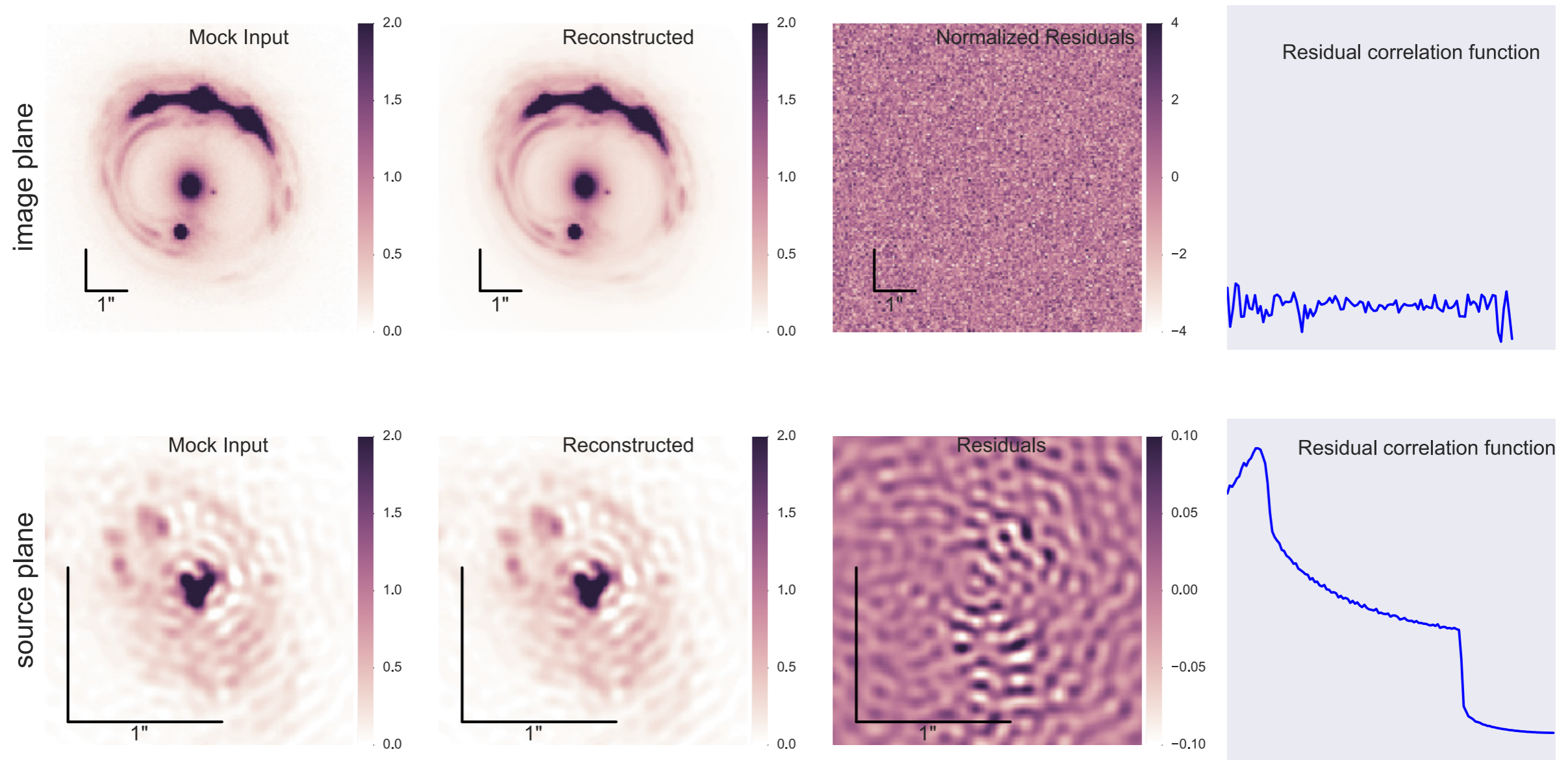source plane   + lensed   + convolved

weighted linear least square

a_1
a_2
a_3
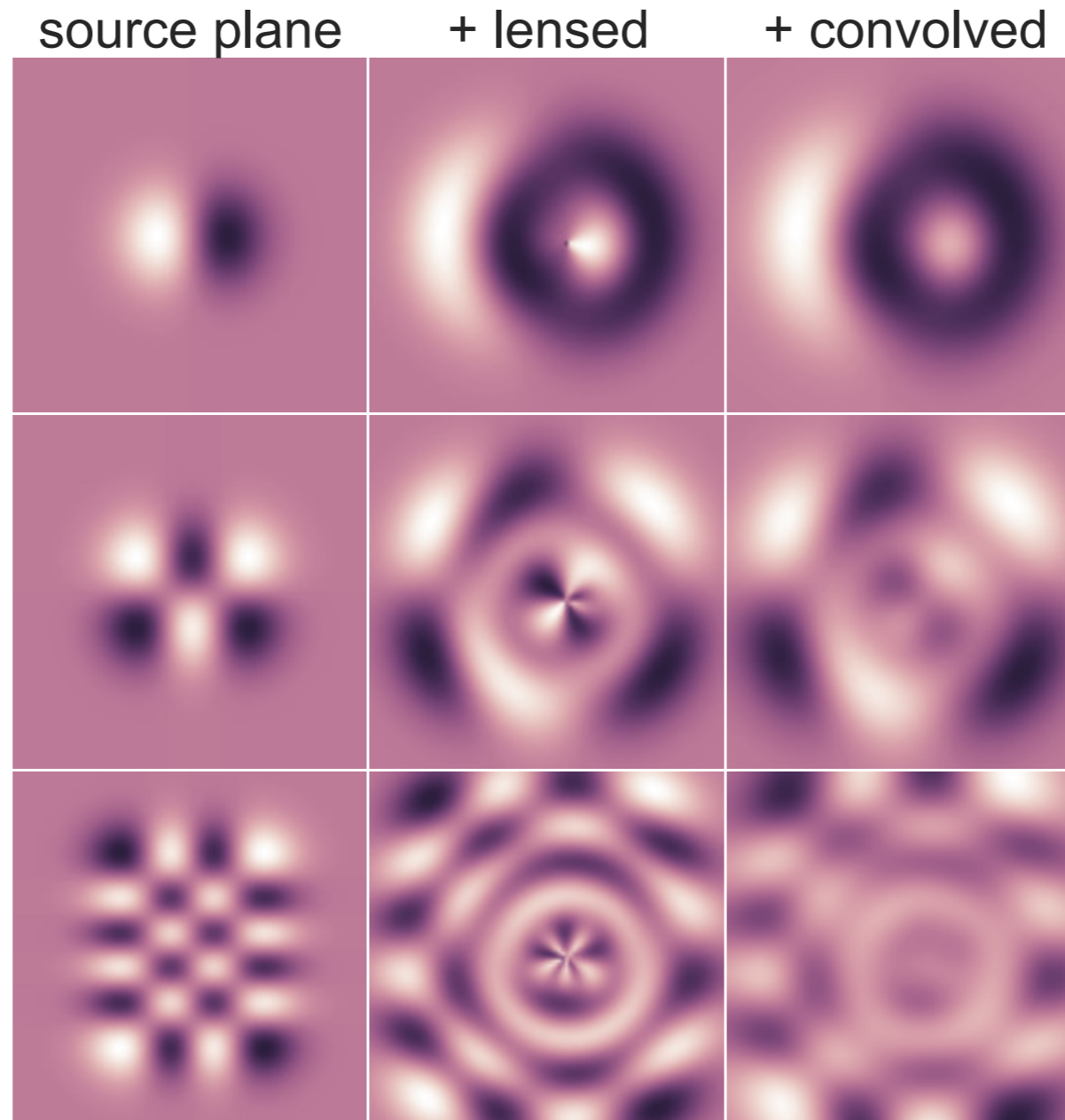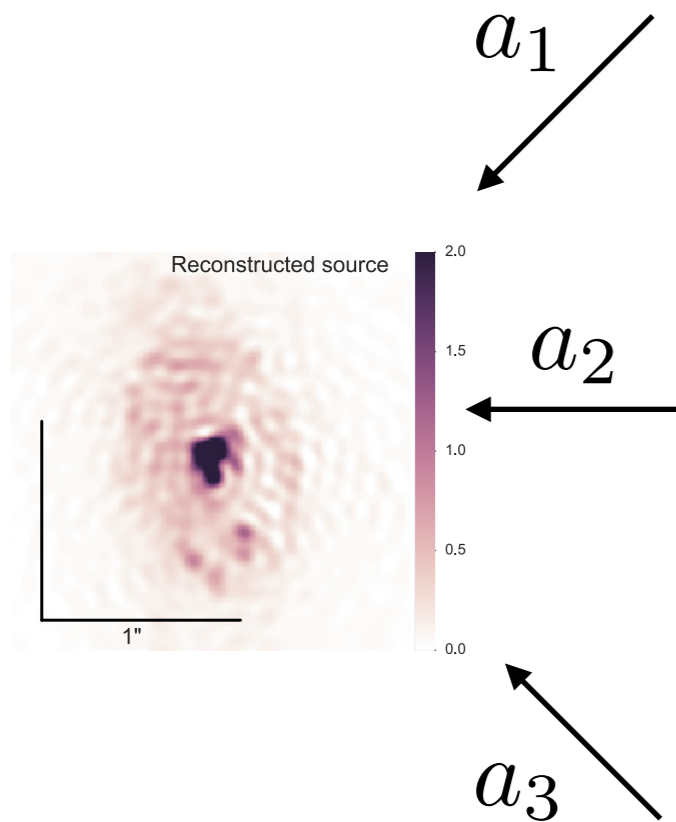
Shapelets: Refregier 2003
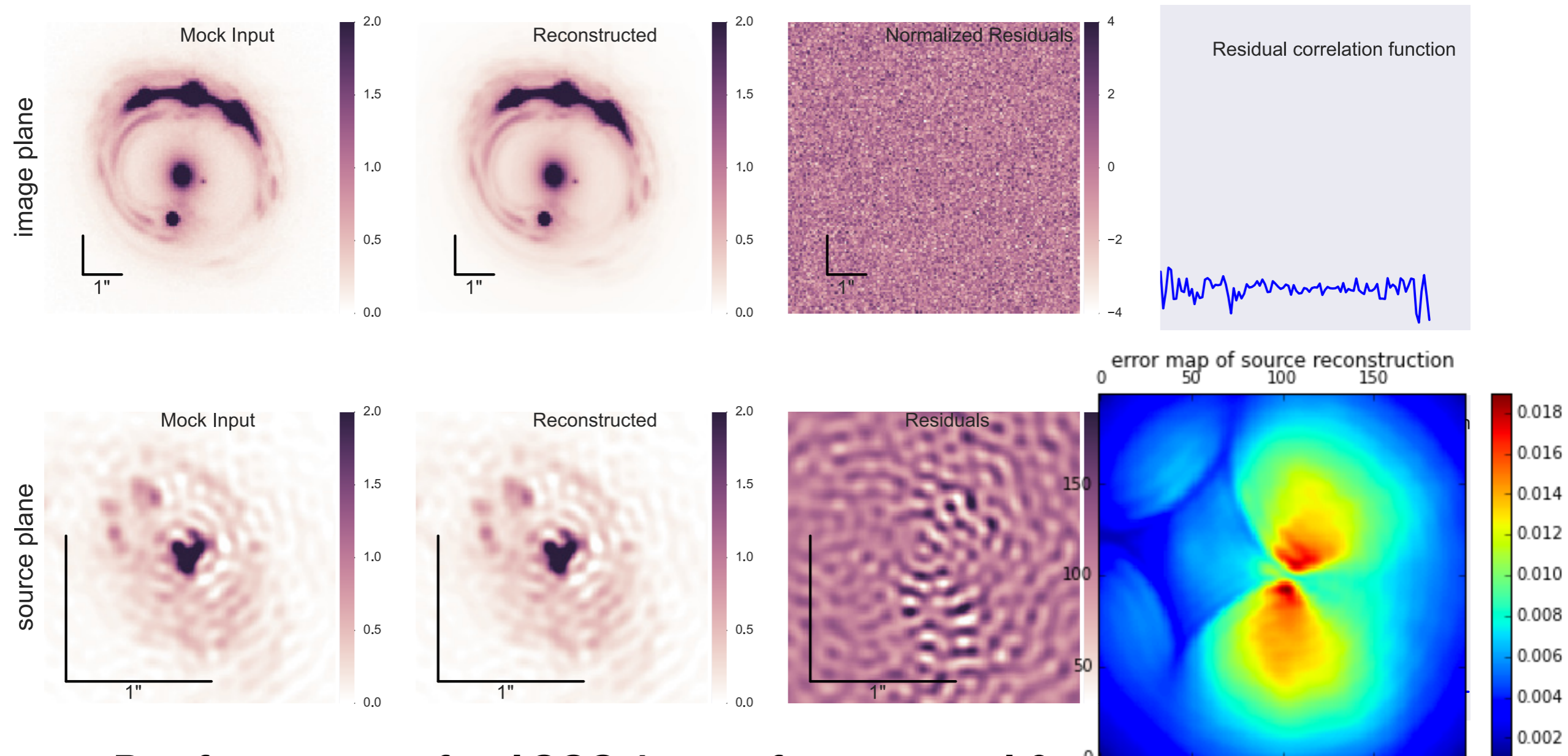Method: Birrer+ 2015

Source reconstruction technique: example

Performance for 1333 basis functions: 10s on 1 CPU

Source reconstruction technique: example

Performance for 1333 basis functions: 10s on 1 CPU

Lens model parameters (non-linear)

Non-linear parameters are expensive!

What is the minimal number of parameters
and the functional form to match the data?

- SIS, SPEP, SPEMD, NFW profiles
- sub-clumps (yet another profile)
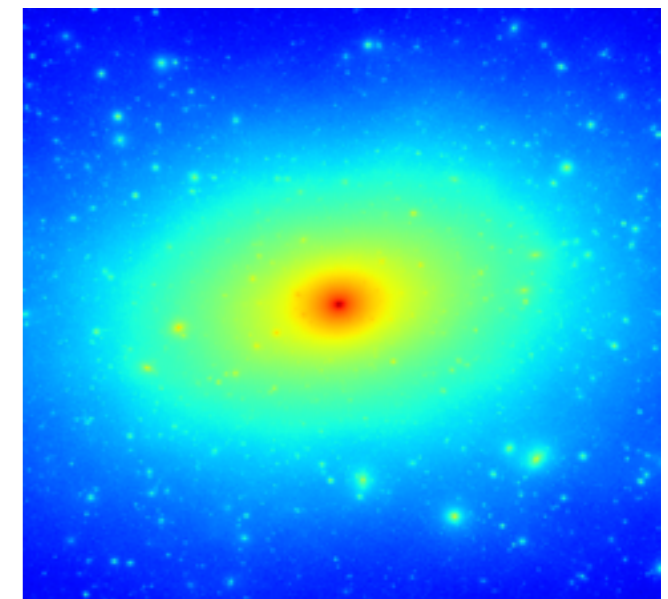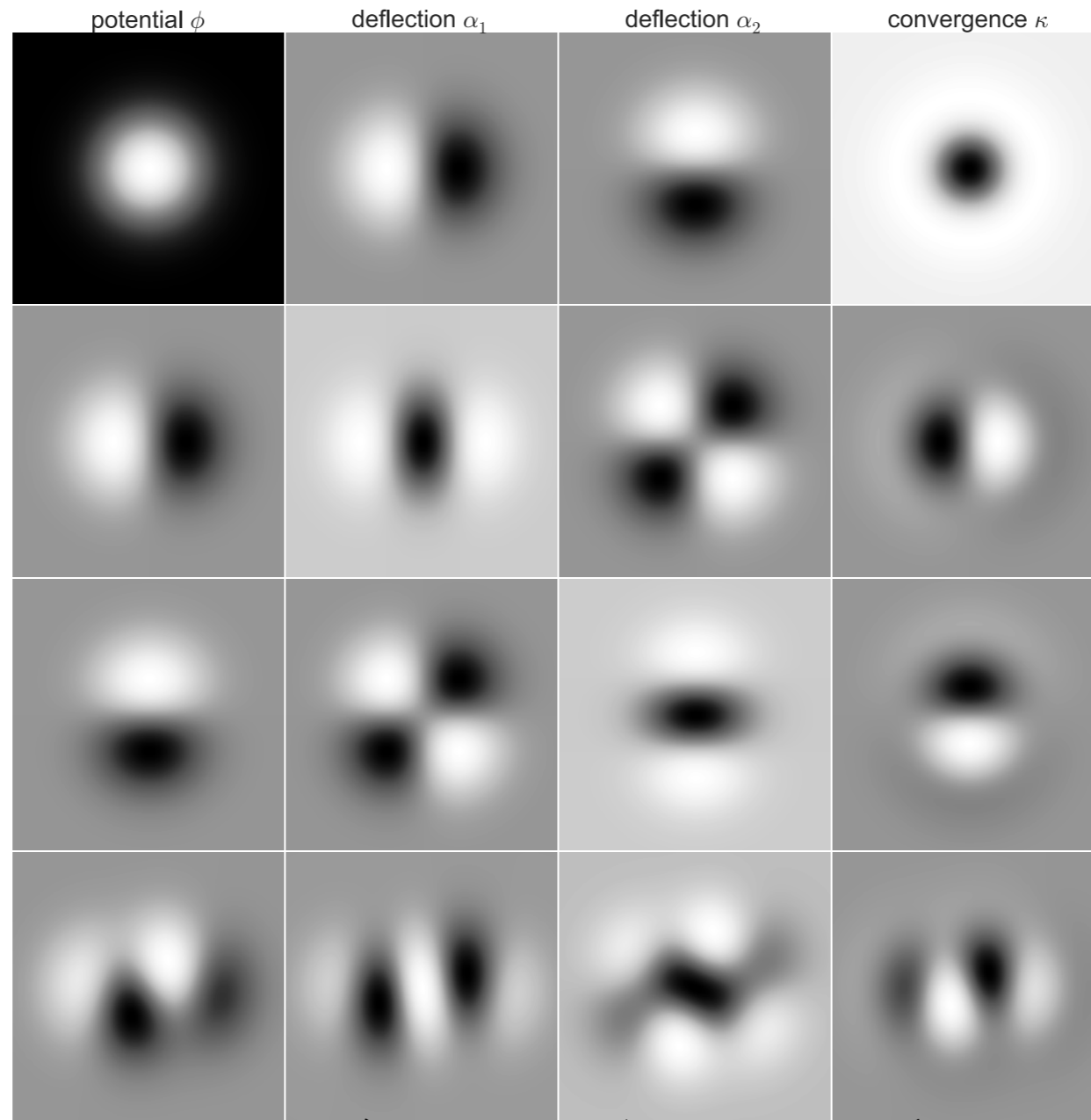- External Shear
- Smooth perturbations
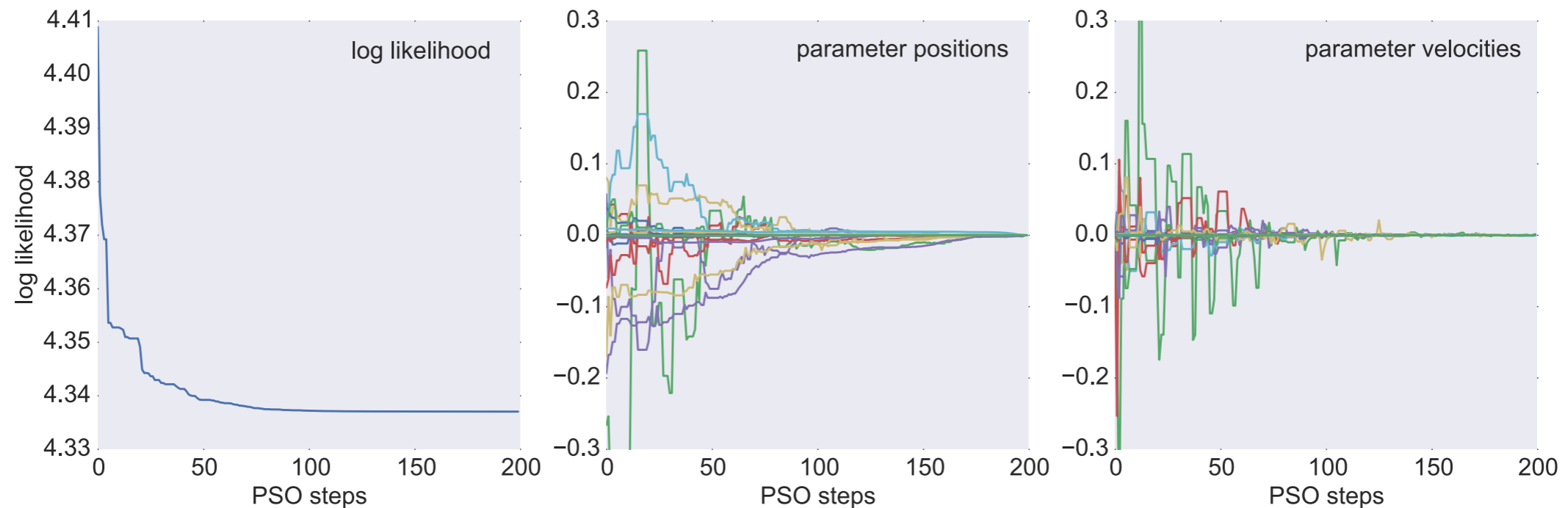- …

image from ViaLactea

Lens model perturbations (smooth component)

Analytic relations

Shapelets: Refregier 2003
Method: Birrer+ 2015

Convergence technique:
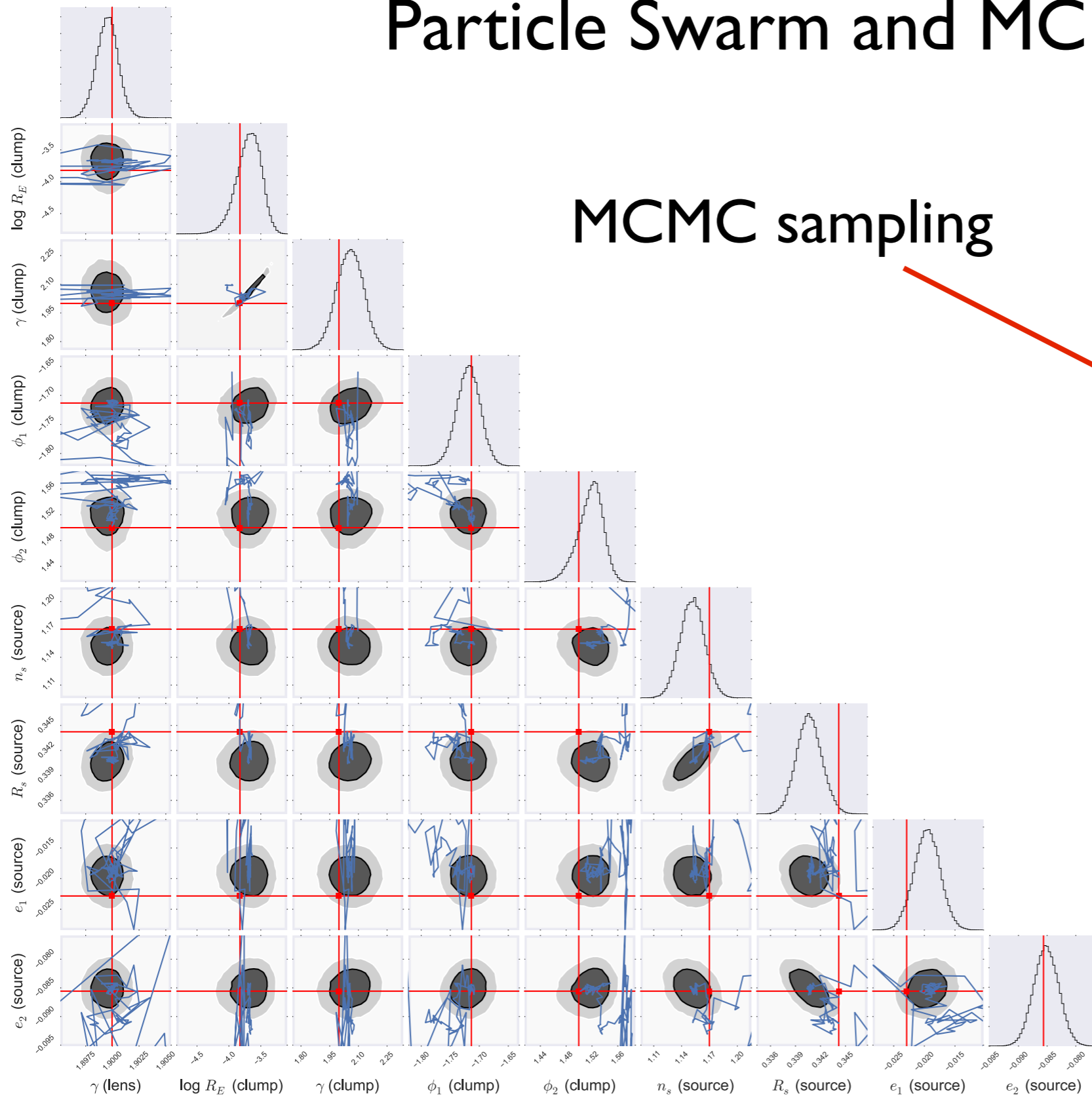# Particle Swarm Optimization (PSO)

Tricks:

- re-parameterisation along degeneracy axes
- analytic marginalisation over linear parameters
- reduce the effective number of parameters with constraints
(i.e. bright point source positions)
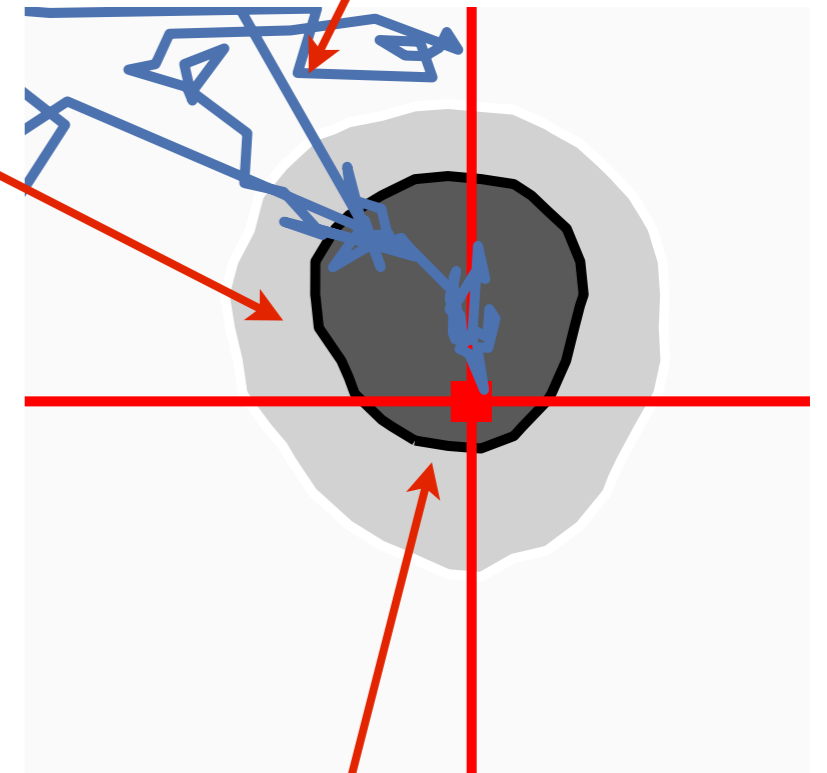- Use of Particle Swarm Optimisation (PSO)

Attention: This is only about finding the minima!

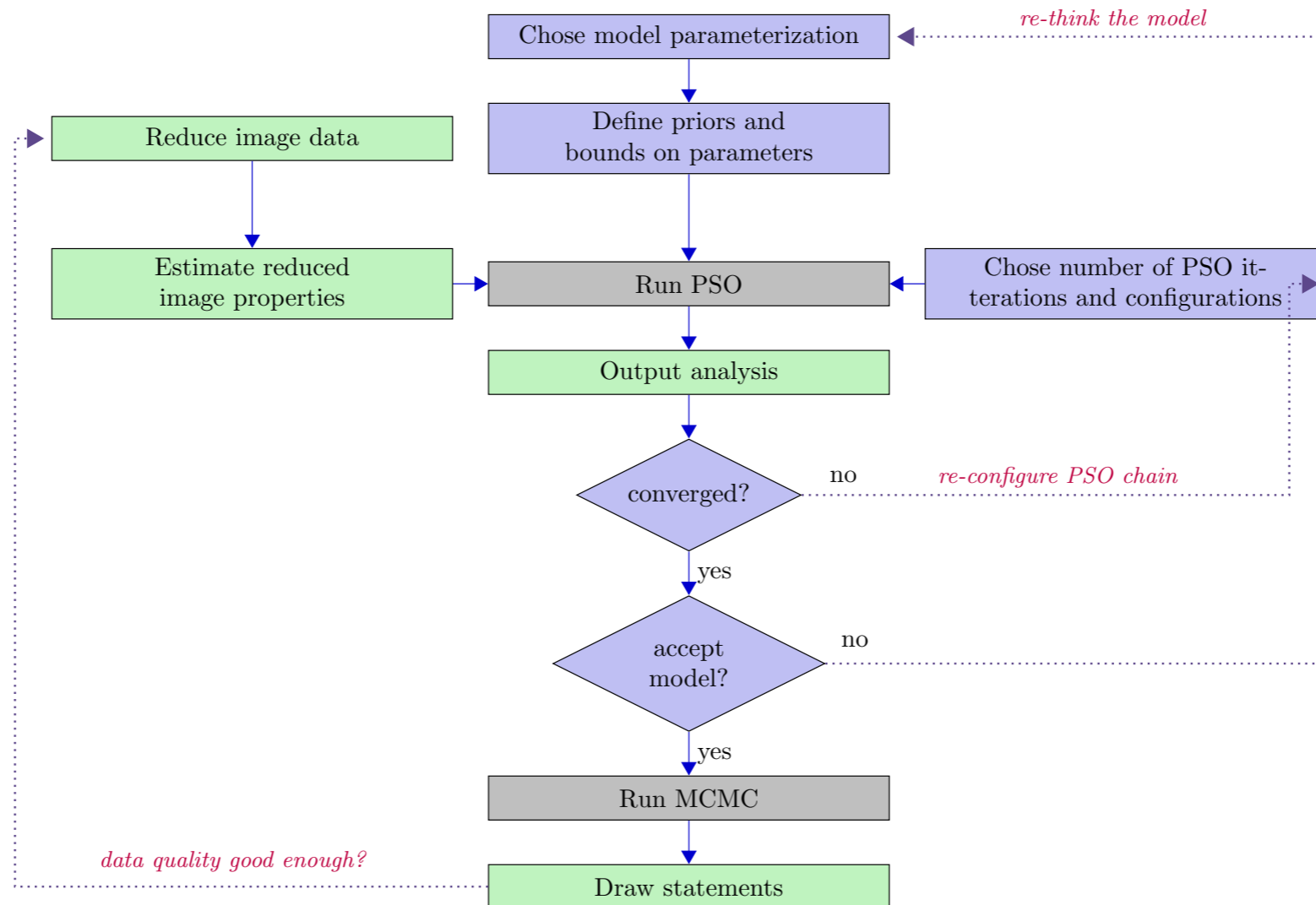# Particle Swarm and MCMC combined

MCMC sampling

PSO walking

truth

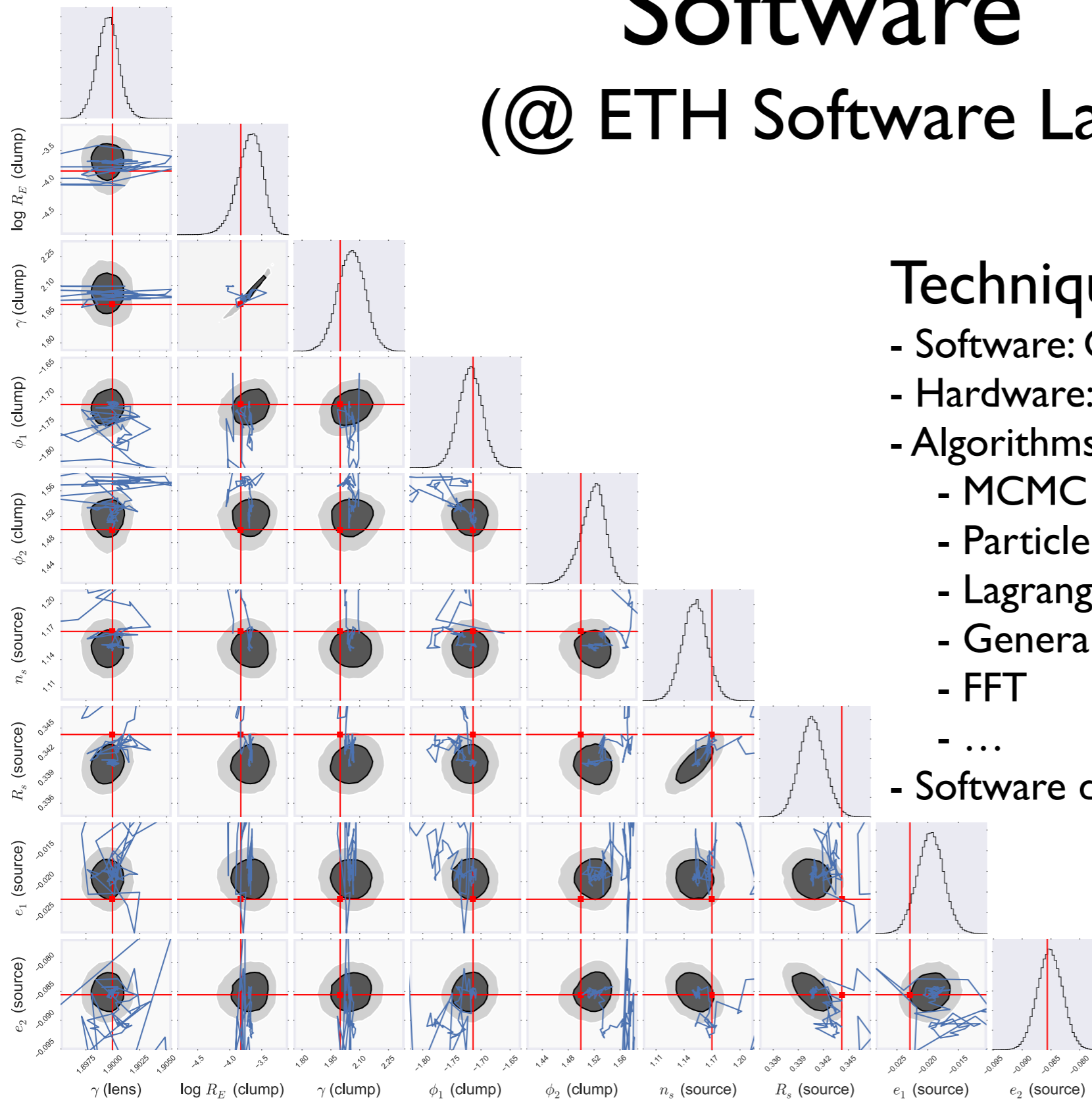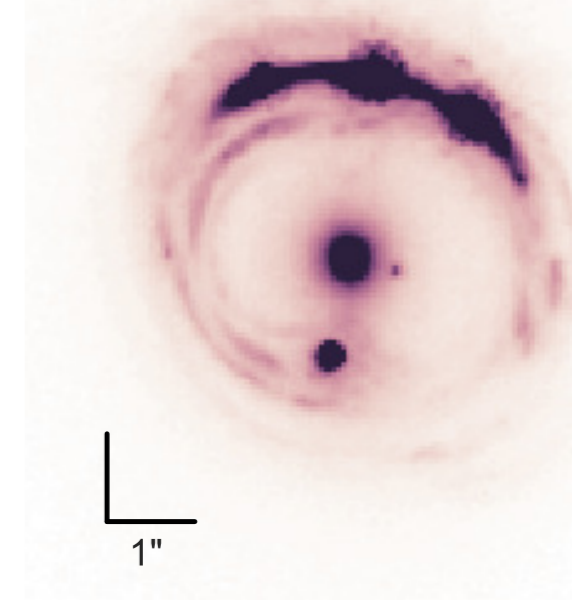Akeret, Seehars+ 2013
Birrer+ 2015, in prep

Overview on framework

- minimise human wall time per lens system
- split convergence and inference
- transparent setting
- focus on software design (@ ETH Software Lab)

Software
(@ ETH Software Lab)

Techniques:

- Software: CosmoHammer, Ufig, Hope,...
- Hardware: Clusters (Monch, Brutus)
- Algorithms:
    - MCMC
    - Particle Swarm Optimization
    - Lagrange multiplier/ optimal control
    - Generalized Least Square methods
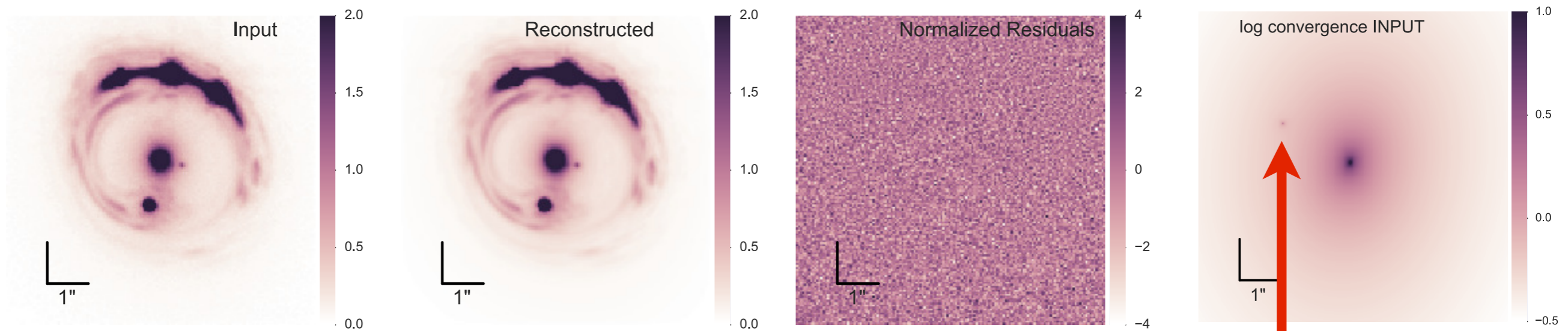   - FFT
    - …
- Software design, Python with speed-up

Akeret, Seehars+ 2013
Bergé+, 2013
Akeret, Gamper+, 2014
Birrer+ 2015, submitted
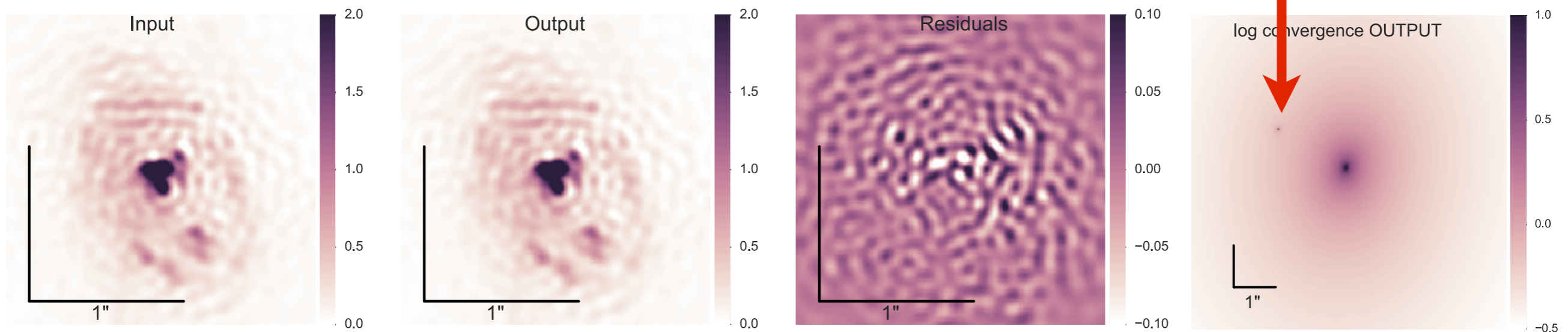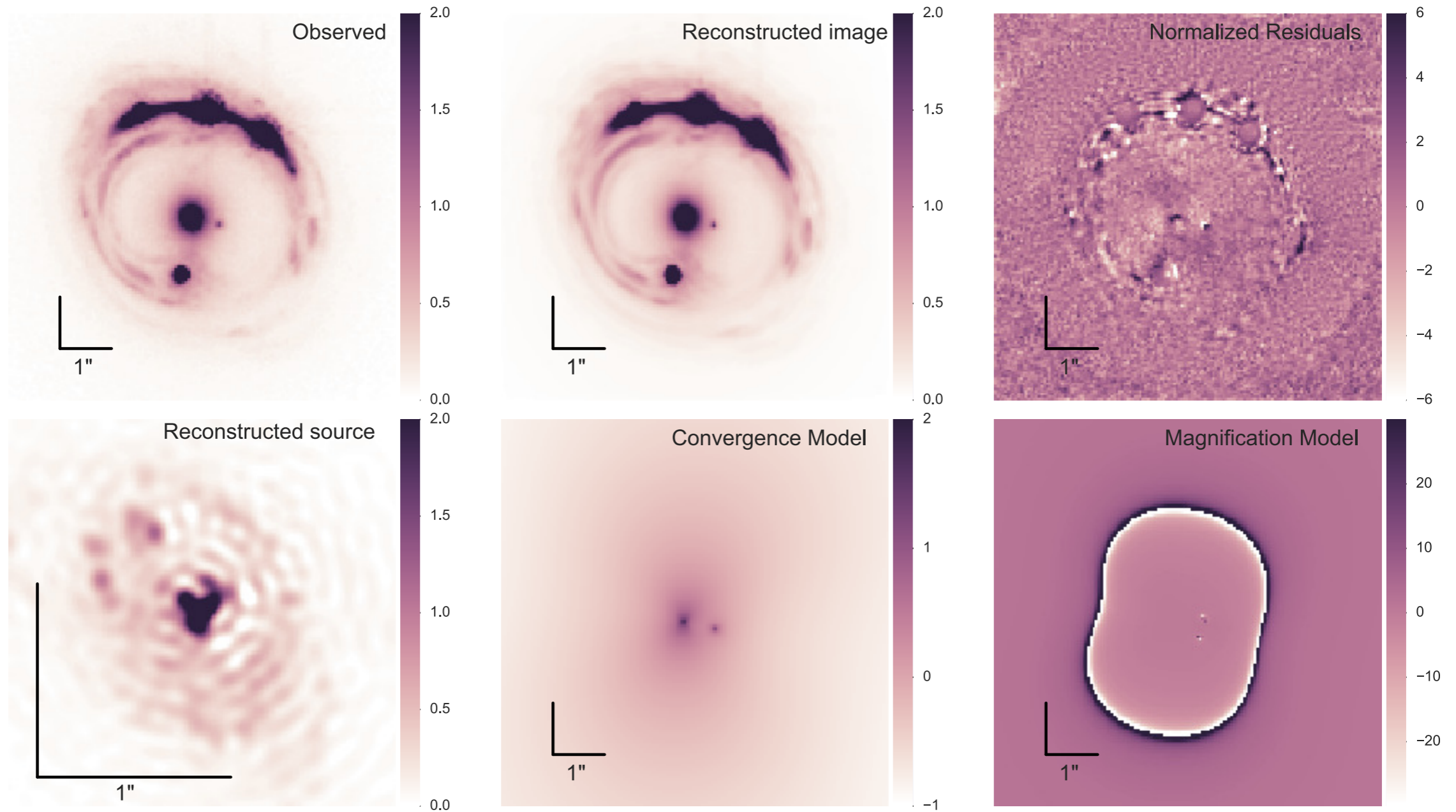
Sub-clump positioned in the arc of $10^8 M_\odot$
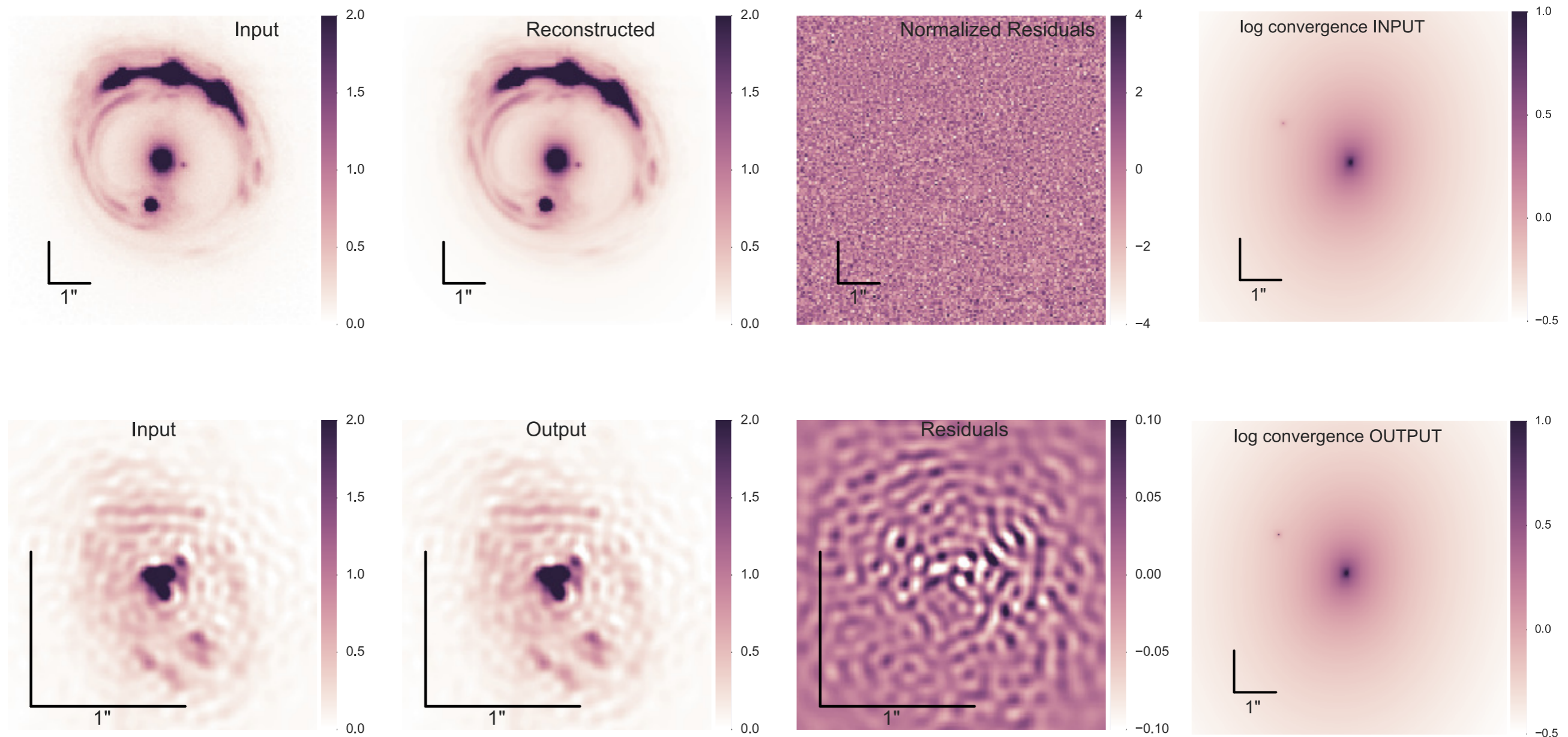
Sub-clump positioned in the arc of $10^8 M_\odot$

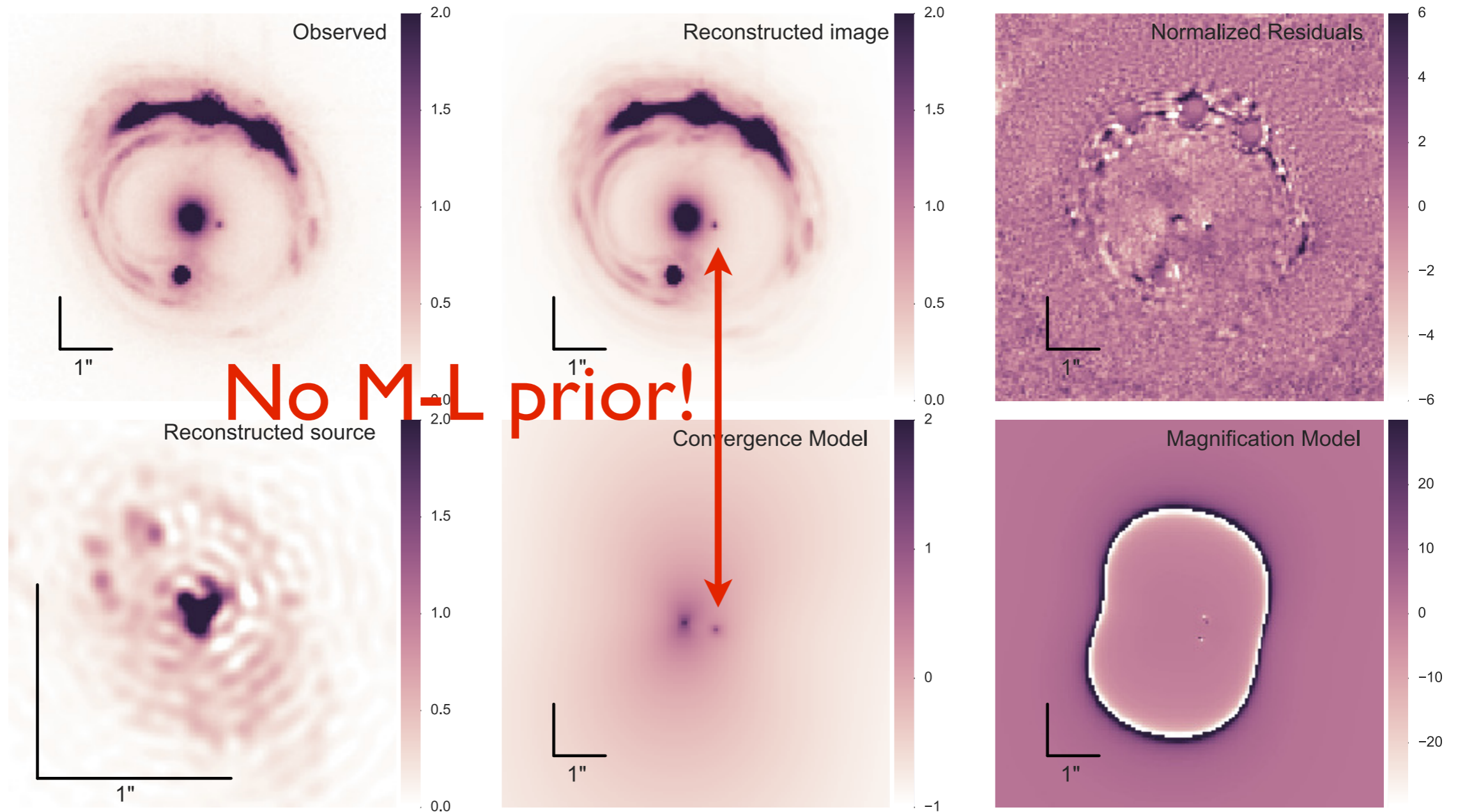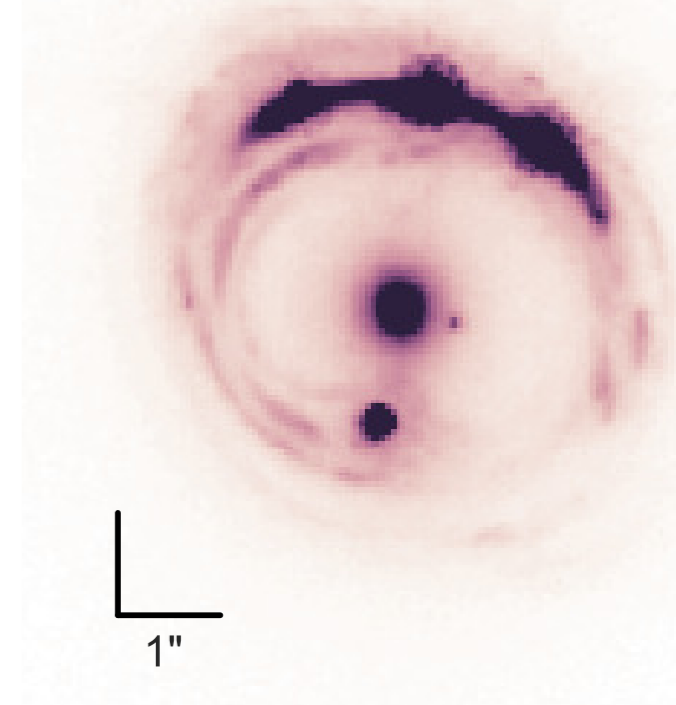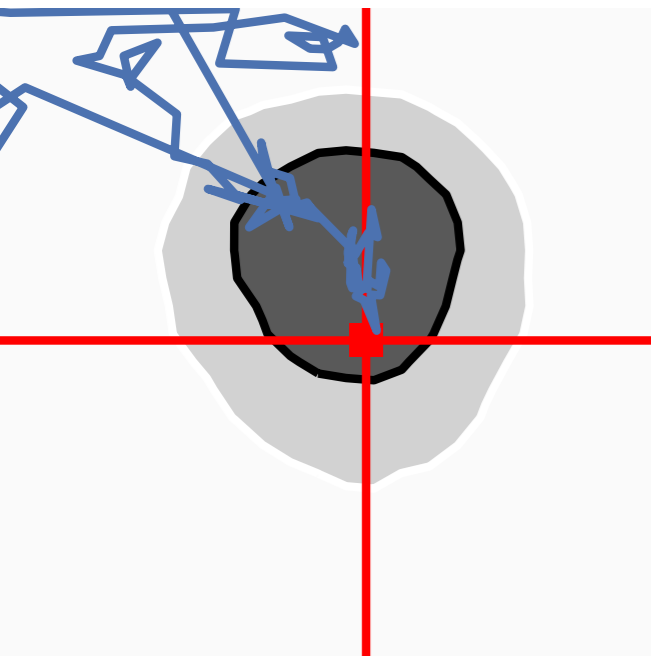We are **sensitive** and we **find** it!

Application to data: RXJ1131-1231

e.g modelled by Suyu+ 2013
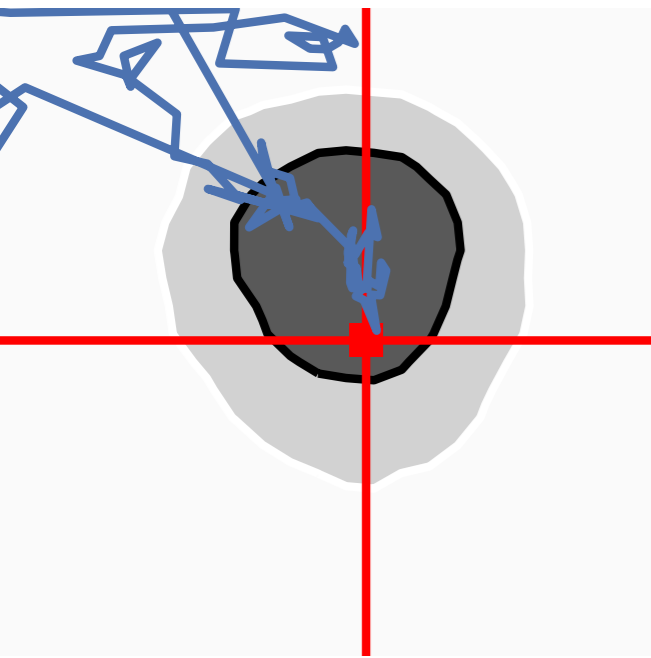discovered by Sluse+ 2003

Application to data: RXJ1131-1231

No M-L prior!

e.g modelled by Suyu+ 2013
discovered by Sluse+ 2003

Summary

- ui rk
- o lens systems
- ar e to DES/STRIDES/…
- t d (today on the arXiv)
- Happy to collaborate with you!

Supplementary material: Example of other systems
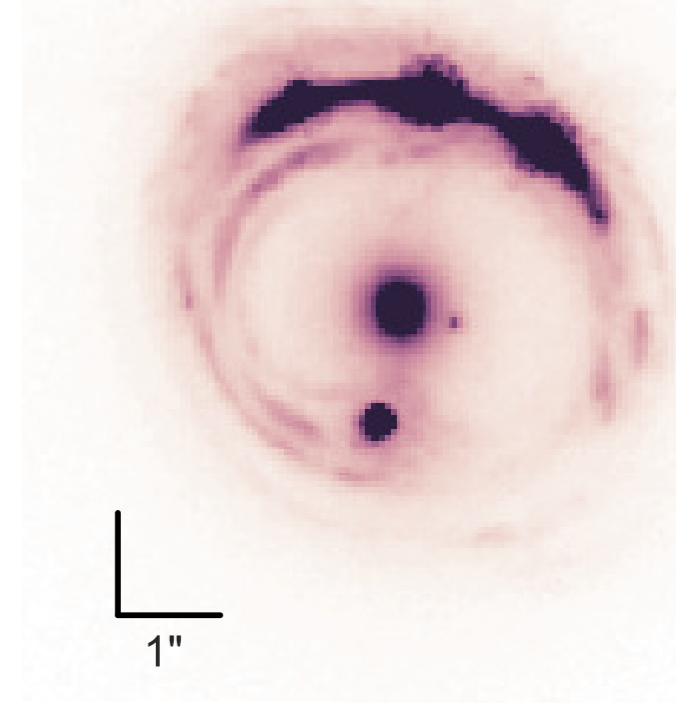
HE0435-1223

SDSS0924-0219

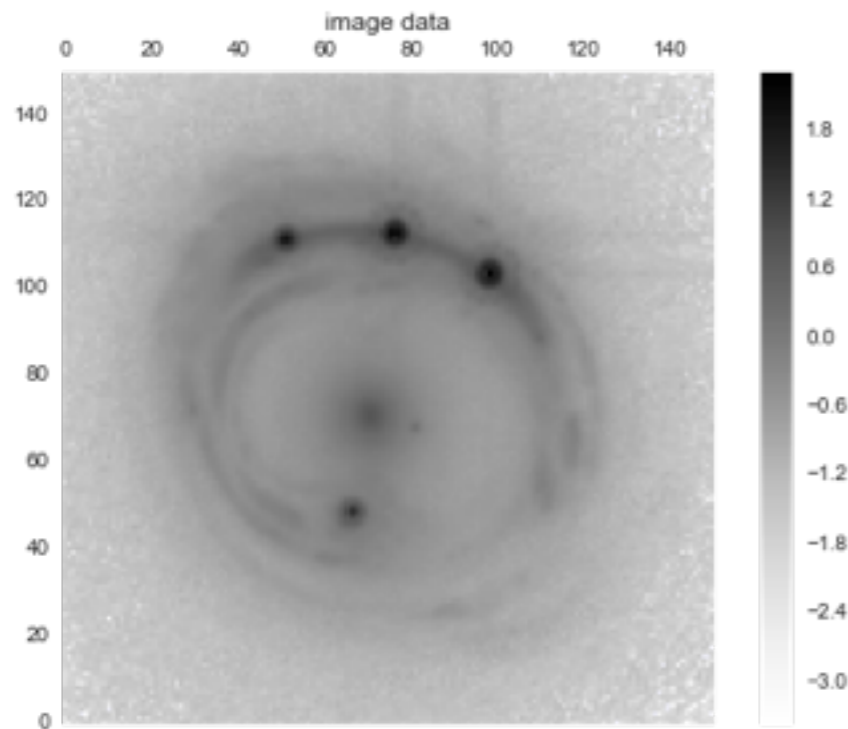Observed | Predicted | Normalized Residuals
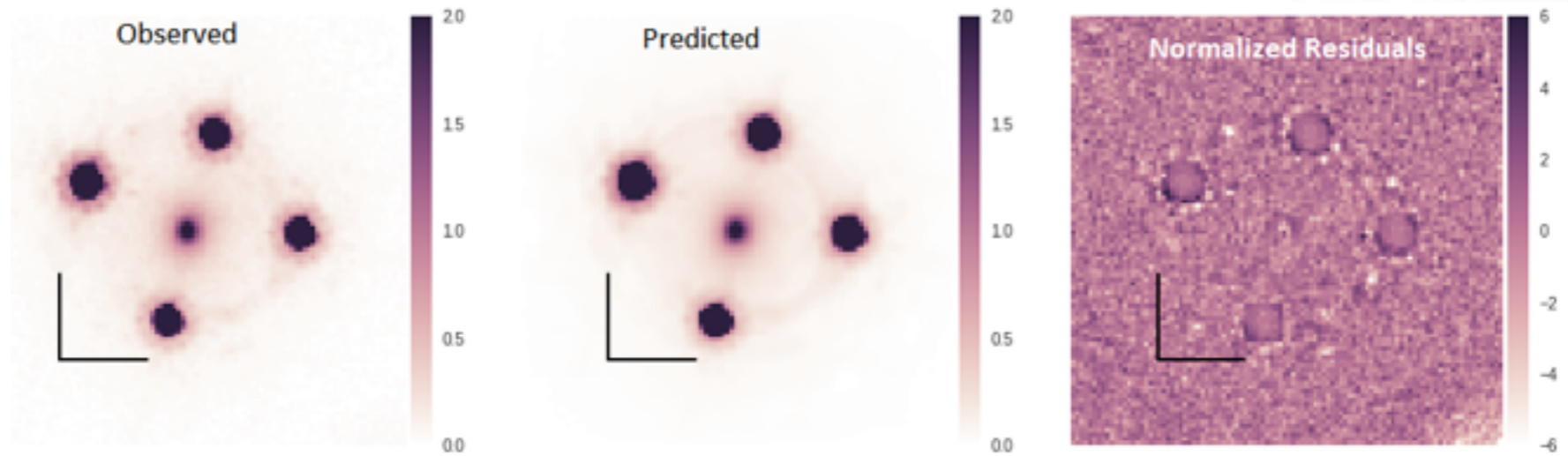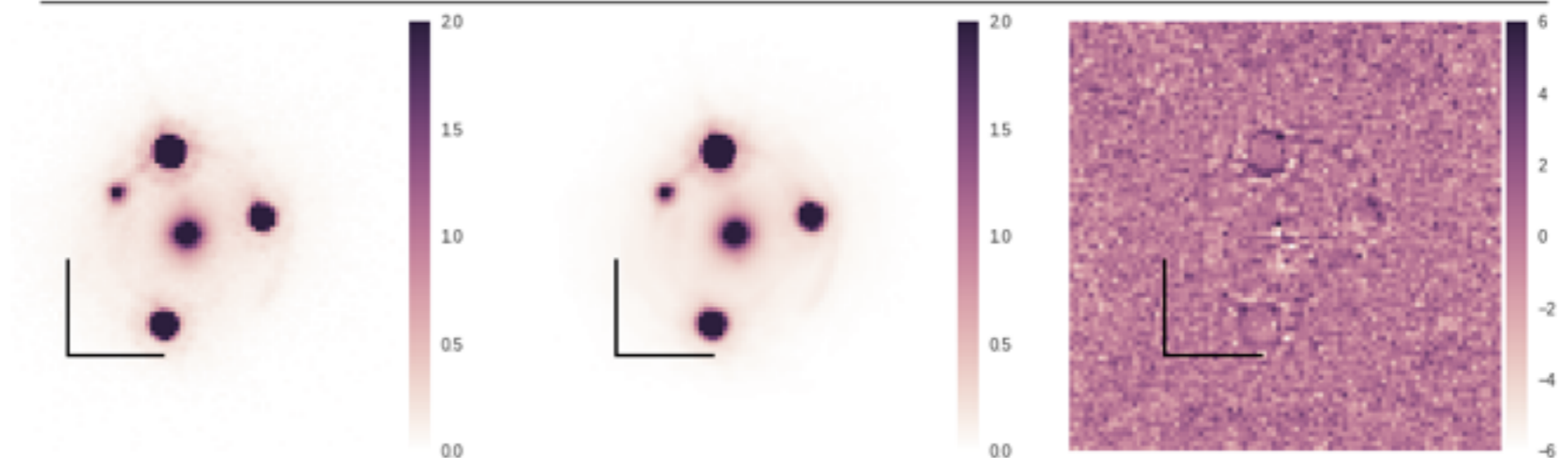
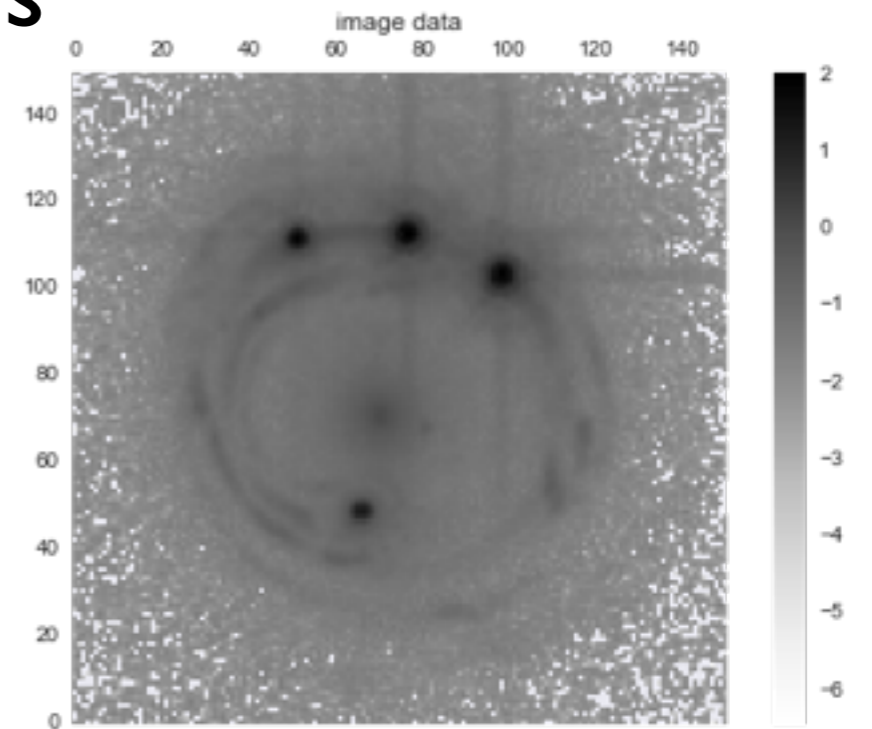Credit: Kevin Fusshoeller, semester project (about two days per system)

Supplementary material: Multiband analysis

F814W

F555W

image (data)

source (reconstructed)