Substructure in lens galaxies: first constraints on the mass function

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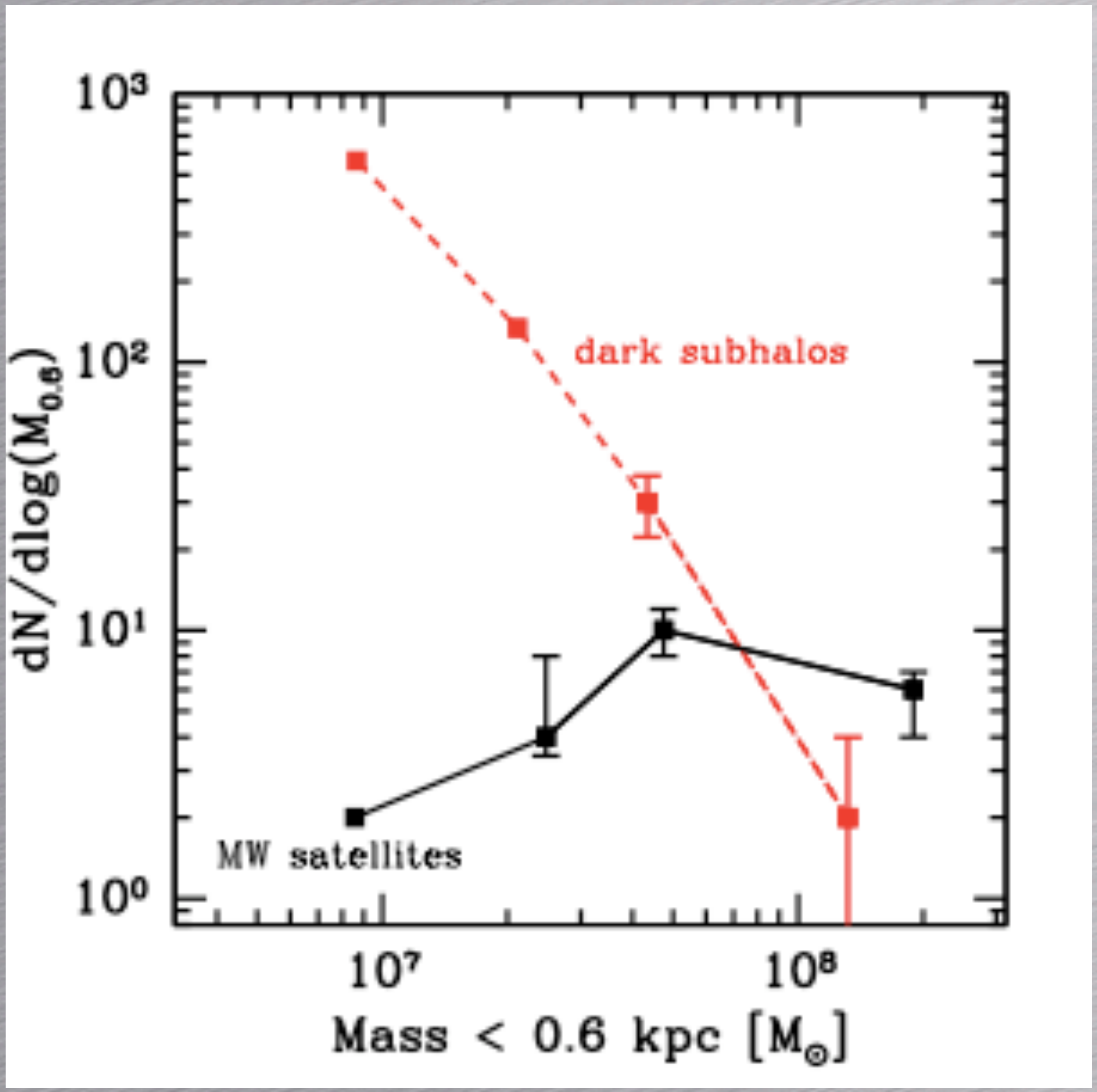
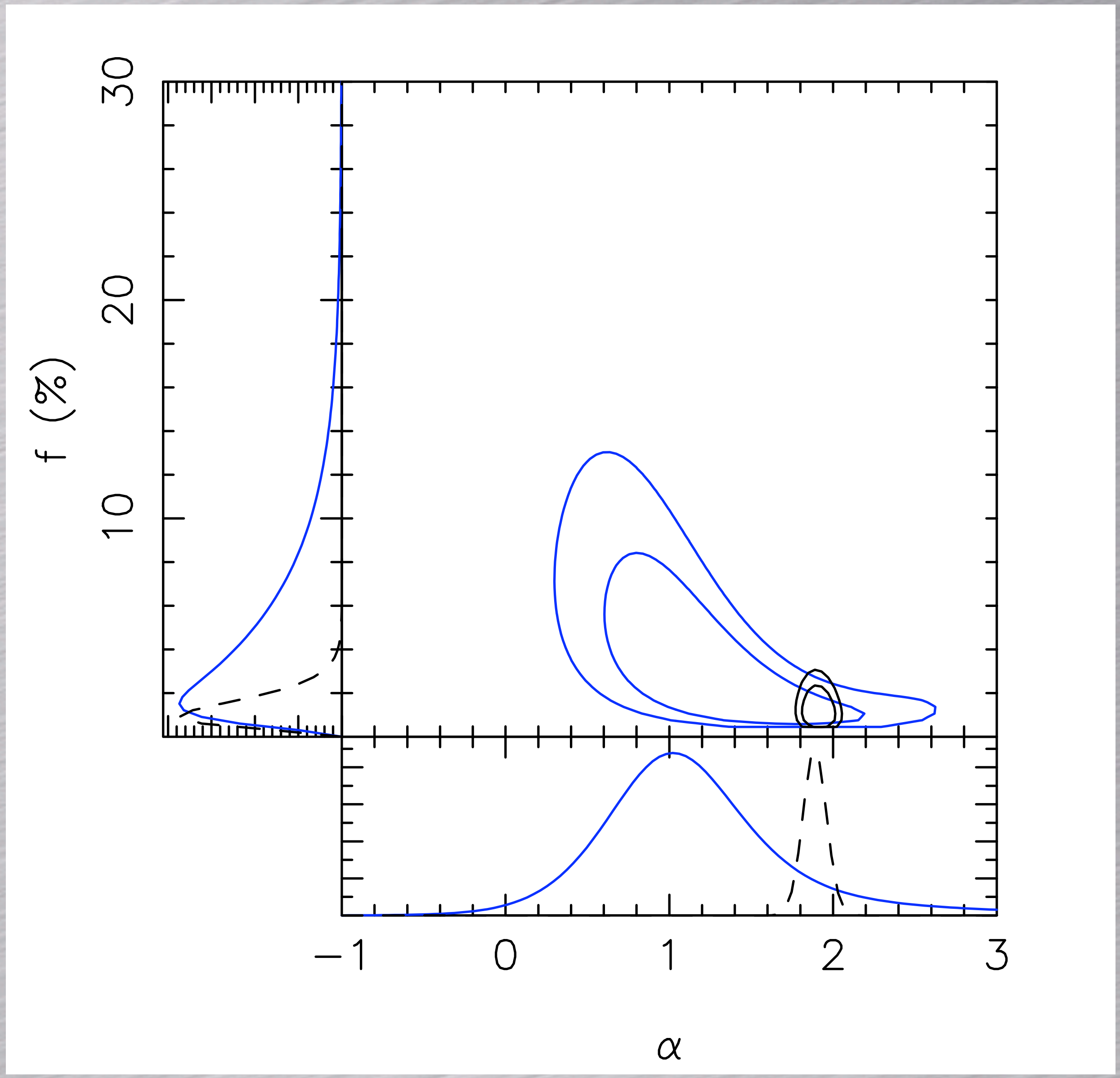
How do we probe the small scales beyond the Local Universe and independently from baryons?



Using strong gravitational lensing!



Independent of the baryonic content

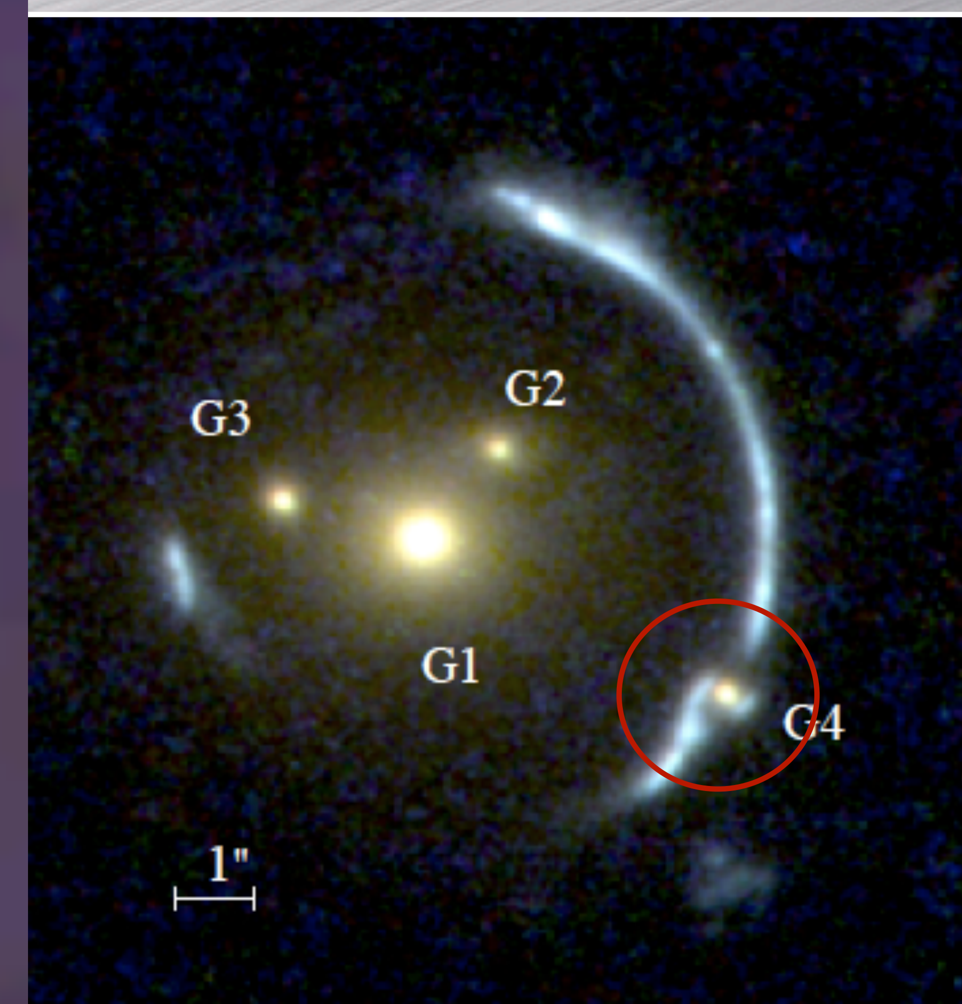
Independent of the dynamical state of the system

Only way to probe small satellites at high redshift

Substructure Effect

How do we recognise the effect of substructure?

Extended galaxy



Bayesian grid-based gravitational imaging

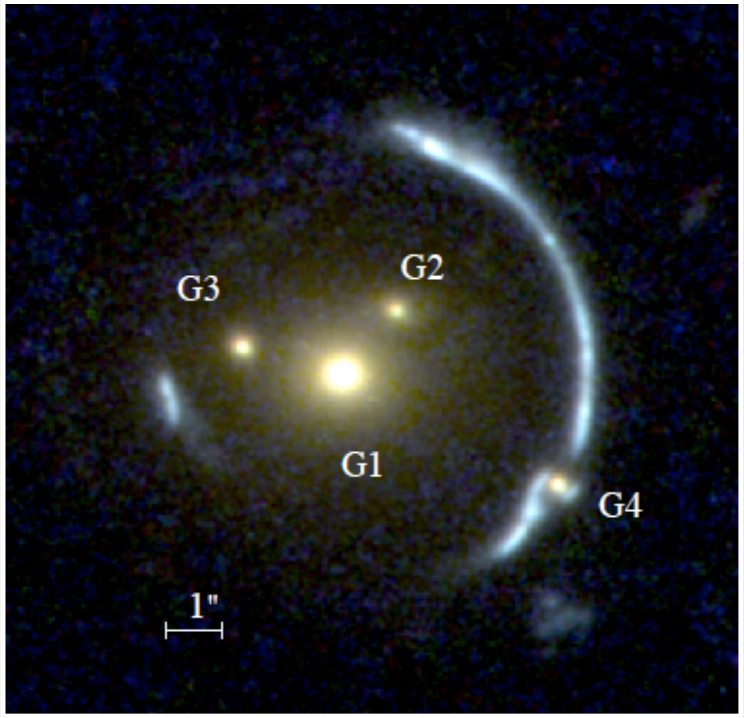
Potential corrections

Potential model $$\psi(x,\eta) = \psi_s\left(x,\eta\right) + \delta\psi\left(x\right)$$

$\psi_s(x,\eta)$ Families of (elliptical) parametric models

$\delta\psi(x)$ Potential corrections, pixelized on a Cartesian grid. Signature for substructure or general features that are not part of the parametric model.

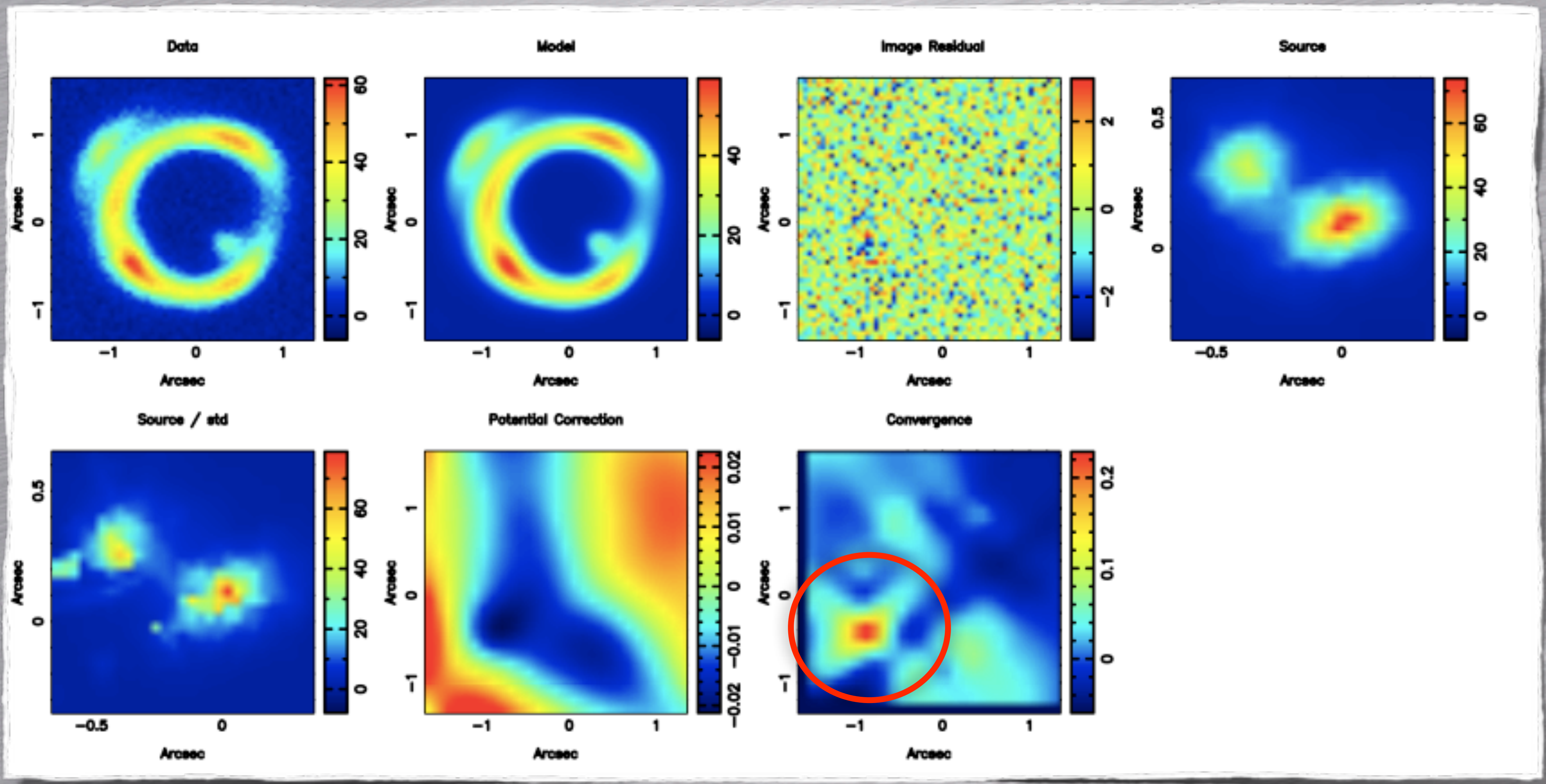
Conservation of surface brightness allows us to express the lens mapping as a set of linear equations:



Vegetti S., Koopmans L. V. E., 2009a

A Simulated Example

Koopmans L.V.E., 2005, MNRAS, 363,1136

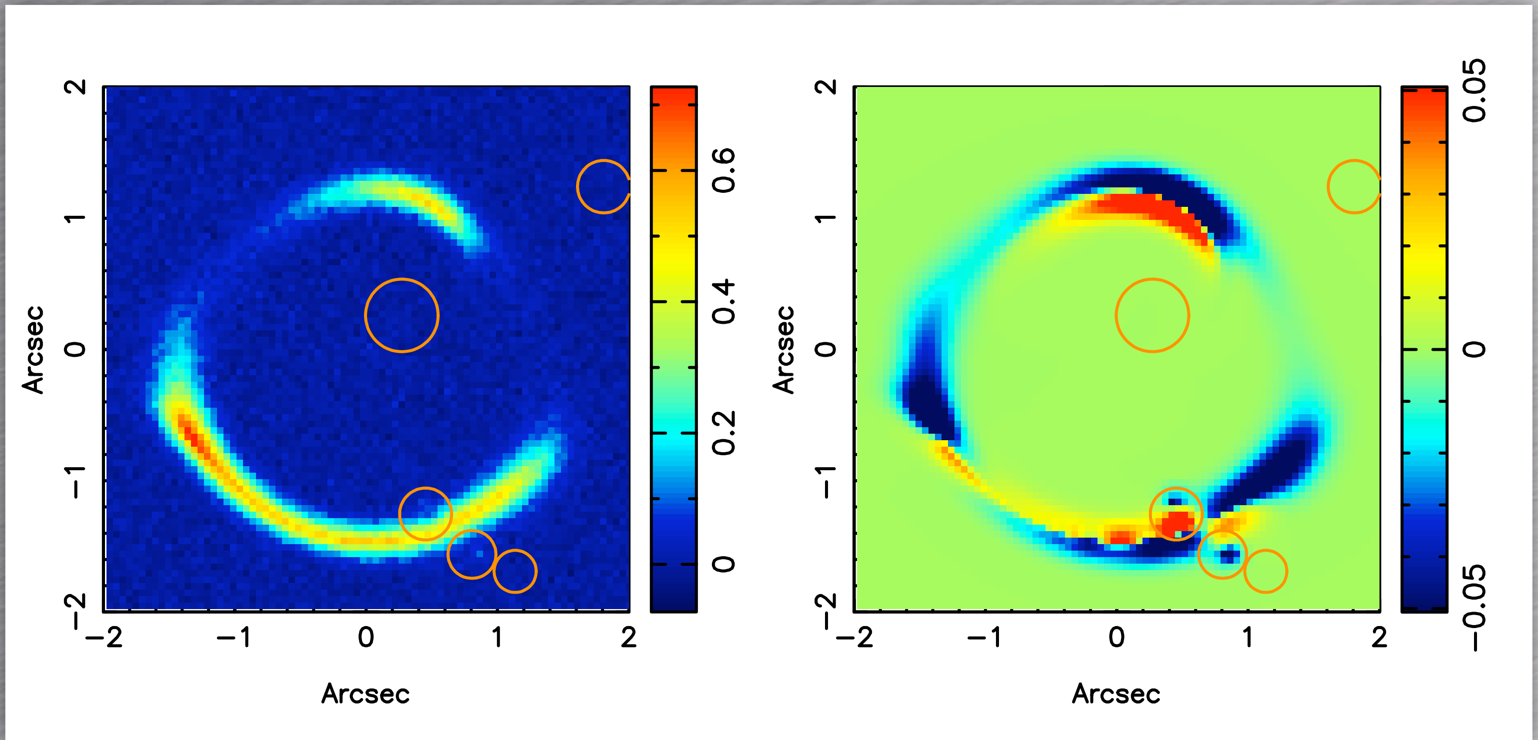


Substructure density profile as truncated isothermal

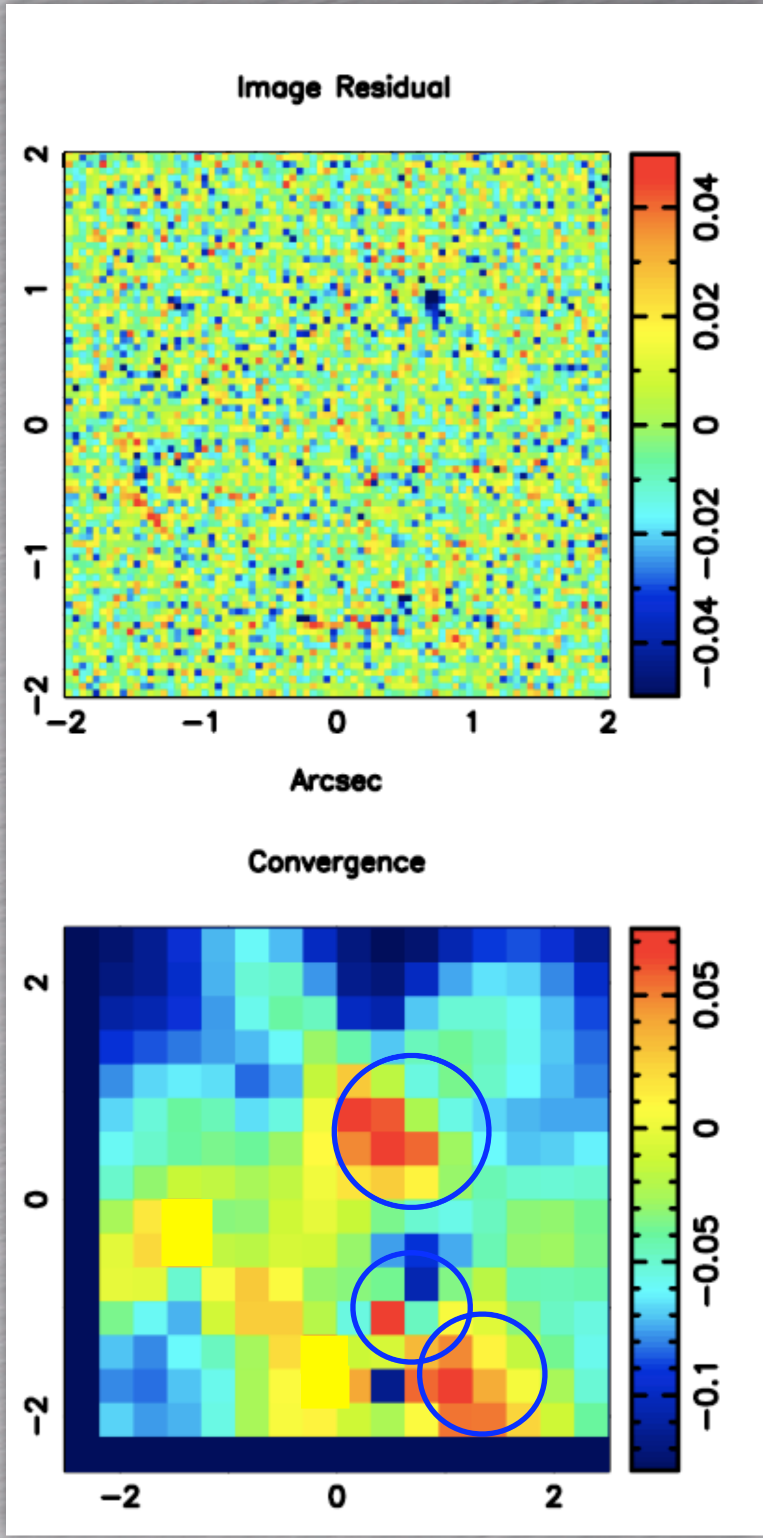
$$\rho_{sub} \propto r^{-2} \left(r^2 + a^2\right)^{-1} \qquad M_{sub} = 3.0 \times 10^9 M_\odot$$

Multiple Substructures

Blind test with simulated lens systems containing multiple massive substructures



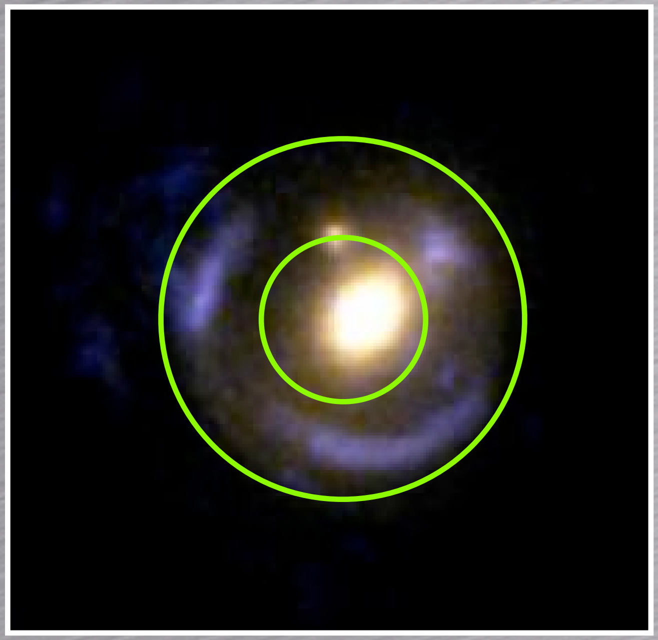
Substructure are draw randomly from a mass function



Substructure Statistics

Statistics of Detection

Constraining the substructure mass fraction and mass function



$$dN/dm \propto m^{-\alpha}$$

$$\mathcal{L}\left(n_s, \mathbf{m} \mid \alpha, f, \mathbf{p}\right) = \frac{e^{-\mu(\alpha, f, <R)} \ \mu(\alpha, f, < R)^{n_s}}{n_s!} \prod_{i=1}^{n_s} P\left(m_i, R \mid \mathbf{p}, \alpha\right)$$

$$P\left(\alpha, f \mid \{n_s, \mathbf{m}\}, \mathbf{p}\right) = \frac{\mathcal{L}\left(\{n_s, \mathbf{m}\} \mid \alpha, f, \mathbf{p}\right) P\left(\alpha, f \mid \mathbf{p}\right)}{P\left(\{n_s, \mathbf{m}\} \mid \mathbf{p}\right)}$$

Statistics of Detection

Constraining the substructure mass fraction and mass function

$$P(\alpha, f \mid \{n_s, \mathbf{m}\}, \mathbf{p}) = \frac{\mathcal{L}(\{n_s, \mathbf{m}\} \mid \alpha, f, \mathbf{p})\, P(\alpha, f \mid \mathbf{p})}{P(\{n_s, \mathbf{m}\} \mid \mathbf{p})}$$

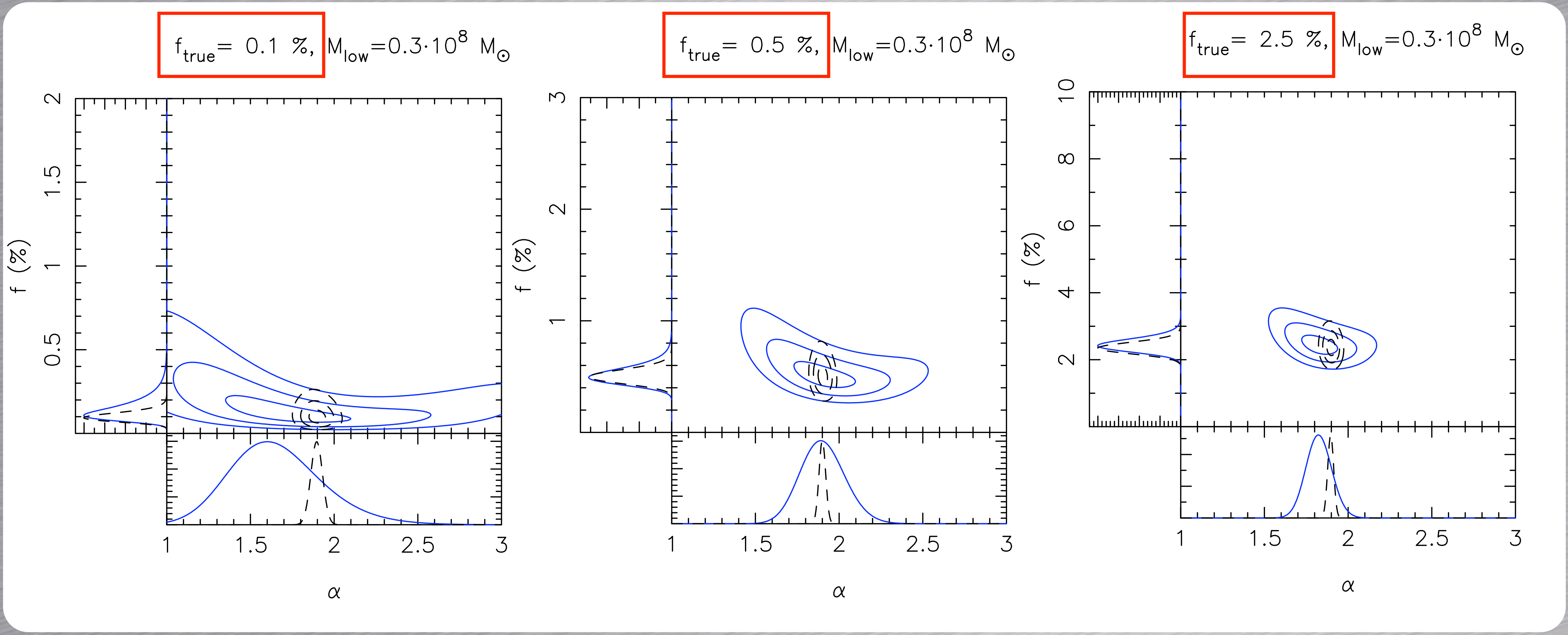
Results depend on:

- The mass function slope
- The mass fraction of substructure
- Number of galaxies in the survey
- Mass-detection threshold, i.e smallest mass you can detect
- Error on the substructure mass measurement/Prior on mass slope

Statistics of Detections: Changing the Mass Fraction

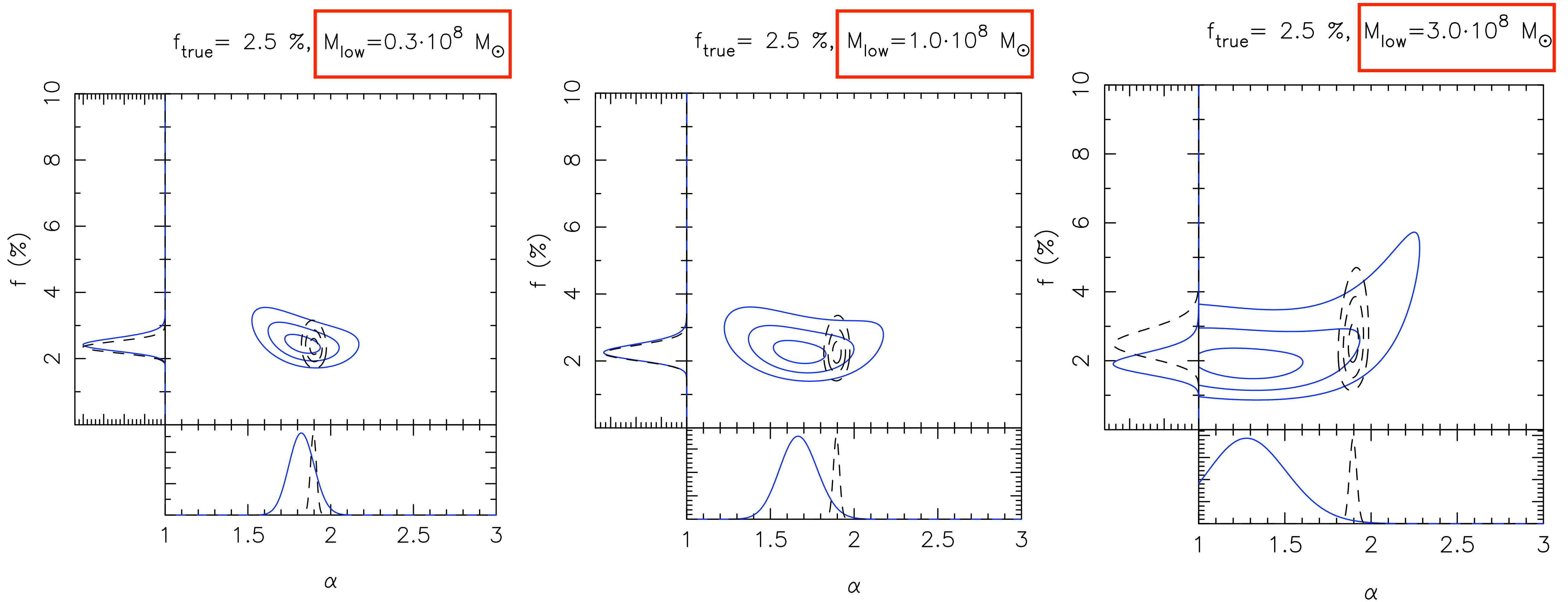
Vegetti S., Koopmans L. V. E. 2009b

Constraining the substructure mass fraction and mass function



Systems with 10 lenses

Statistics of Detections: Changing the Detection Limit



Systems with 10 lenses

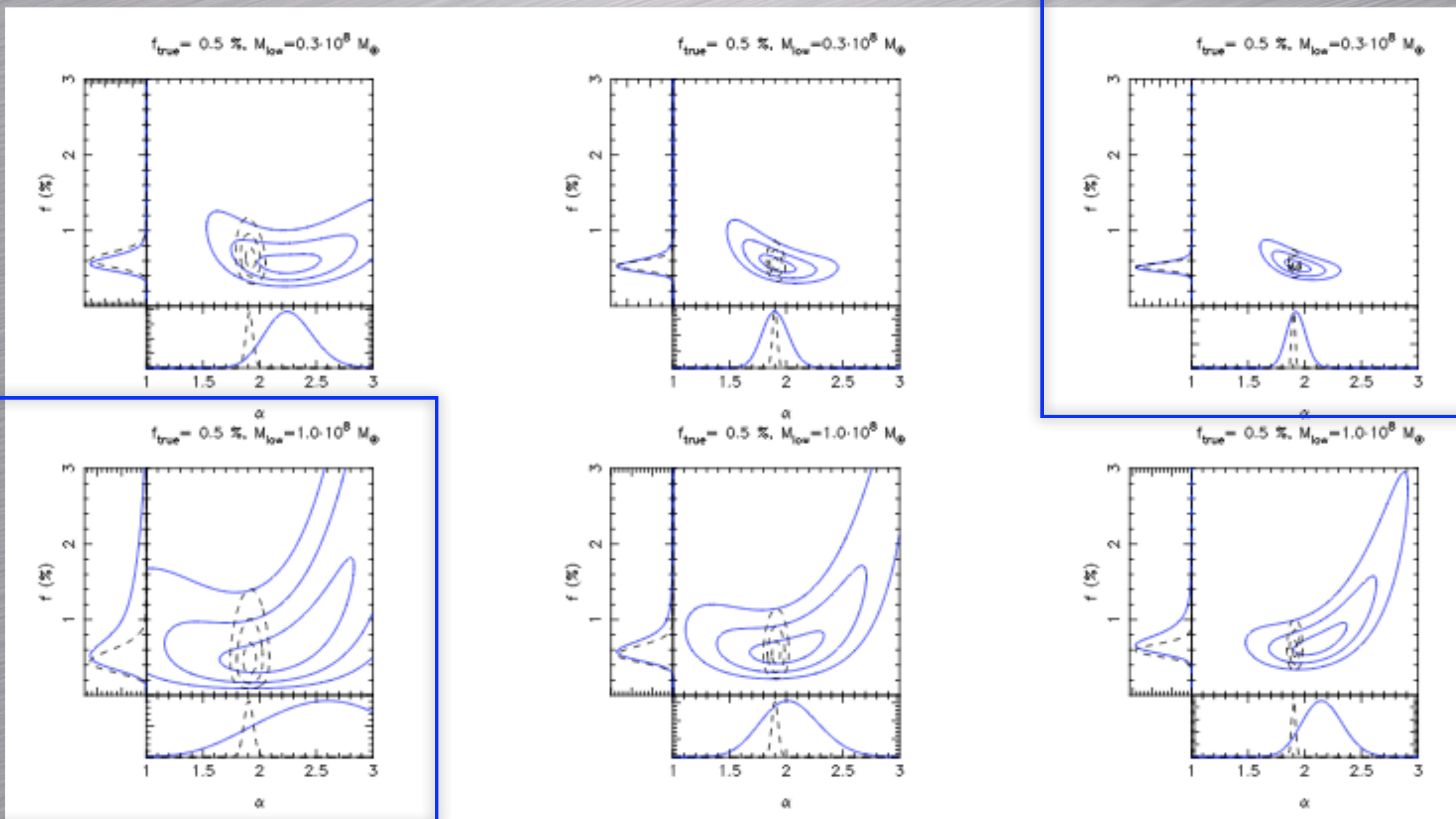
Statistics of Detections: Changing Survey Parameters

$N_{lens} = 10$ $N_{lens} = 30$ $N_{lens} = 200$

$M_{\rm low} = 0.3 \times 10^8$

$M_{\rm low} = 1.0 \times 10^8$

$\sigma = \frac{M_{\rm low}}{3}$



Statistics of Detection

Summary:

- Substructure detection threshold $3 \times 10^8 M_{\odot}$, 30 lenses and true dark-matter mass fraction is 1.0%:

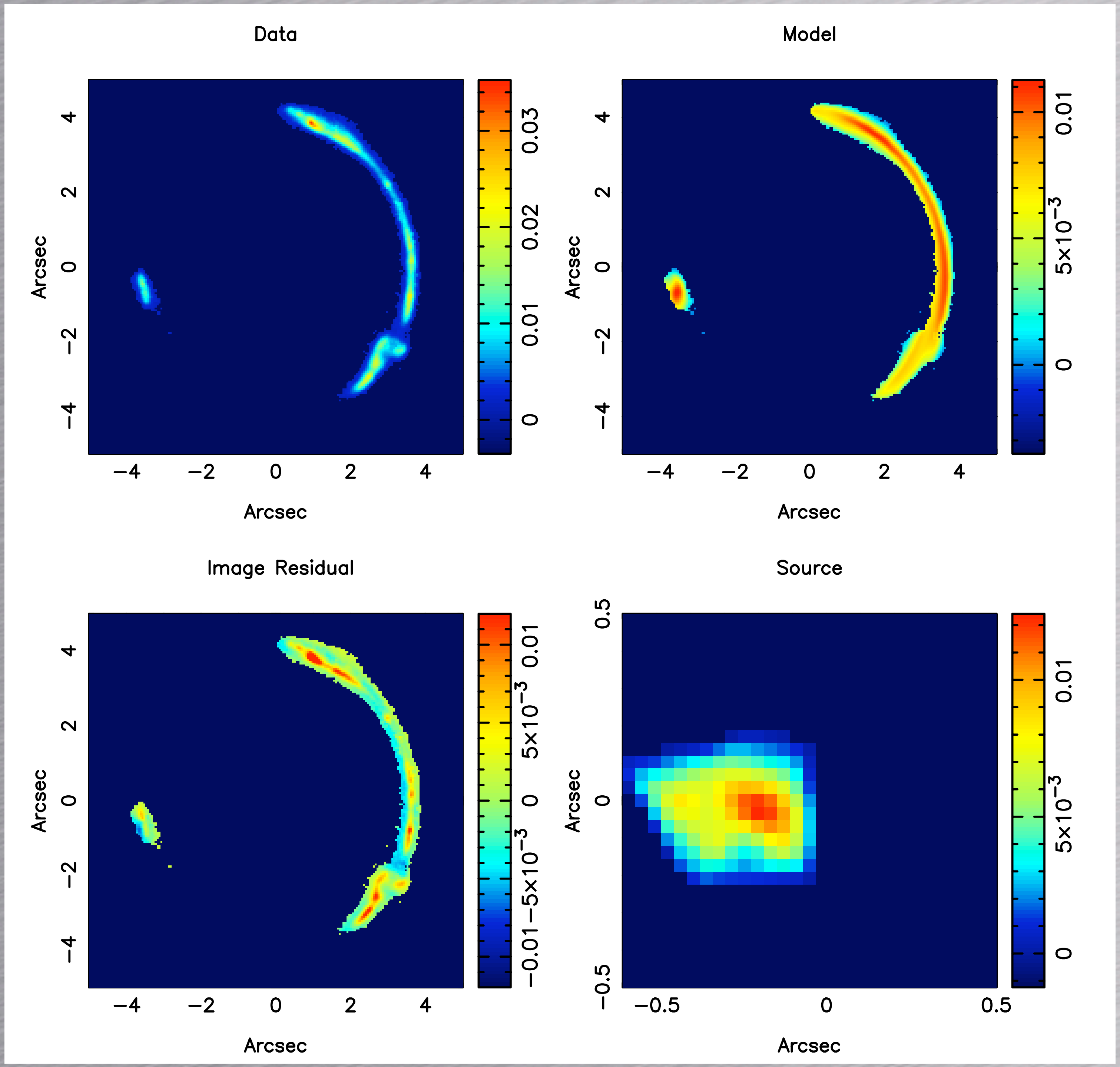
  f <1.0% (95% CL)

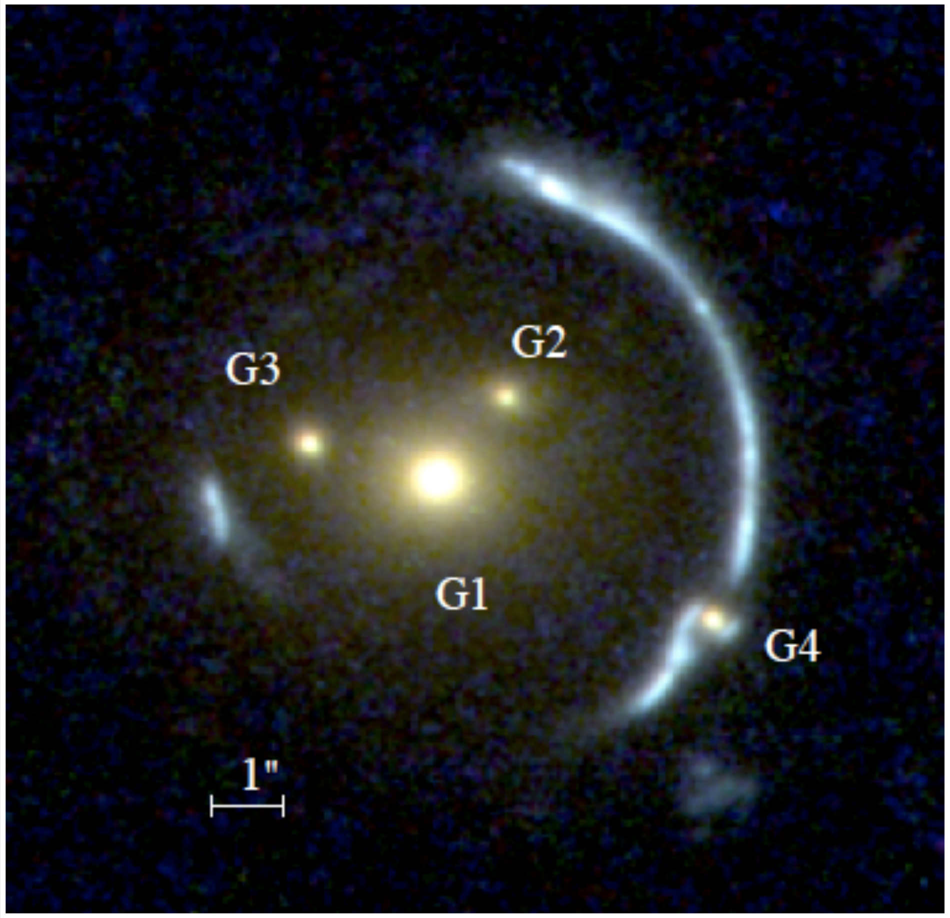
- Substructure detection threshold $3 \times 10^8 M_{\odot}$, 200 lenses and true dark-matter mass fraction is 0.5%:

  f = 0.5±0.1% (68% CL)
  α=1.90±0.2 (68% CL).

- Constraining the mass function slope requires a high number of detected substructures ~ 10

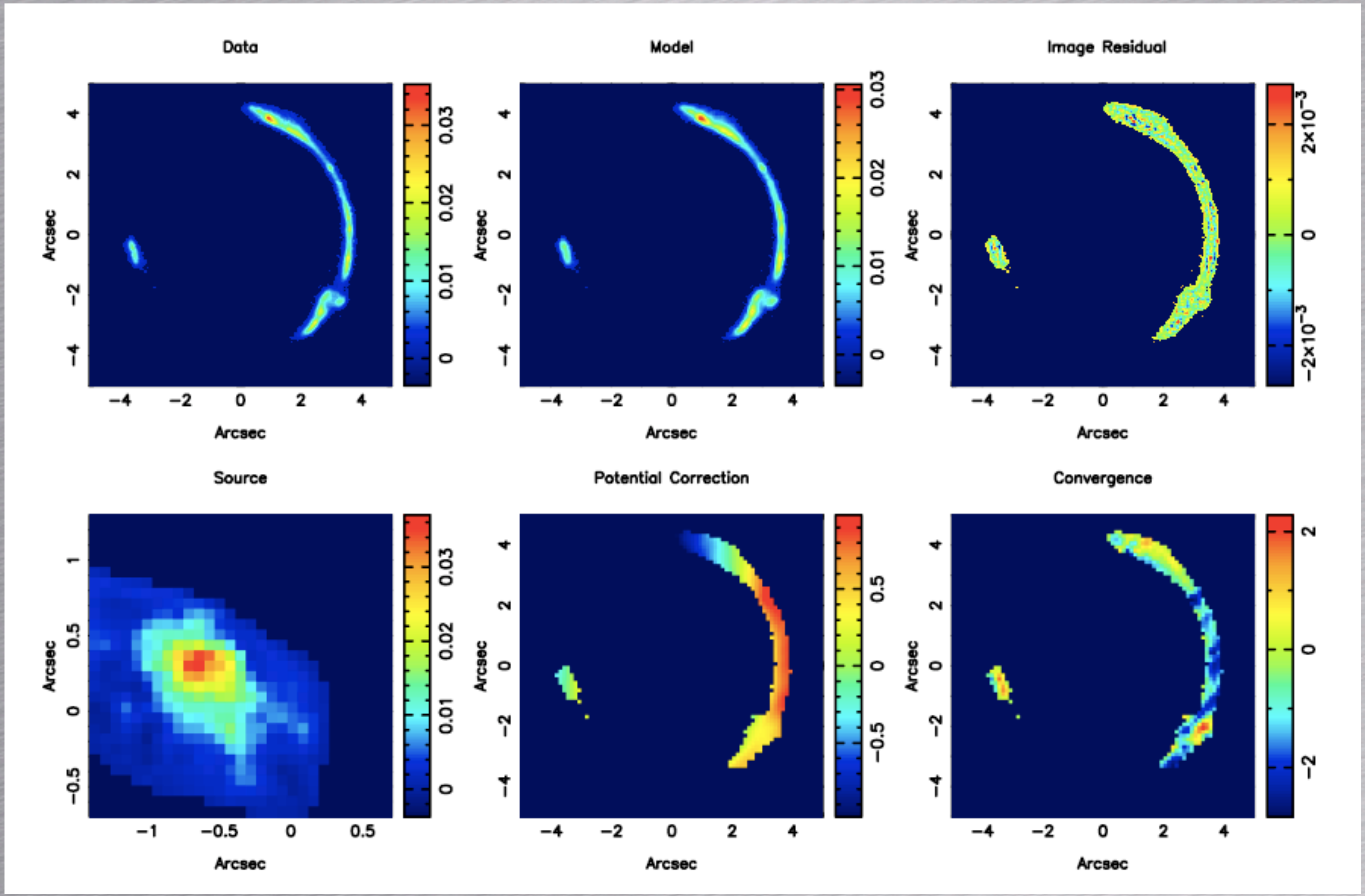
J12602+514229





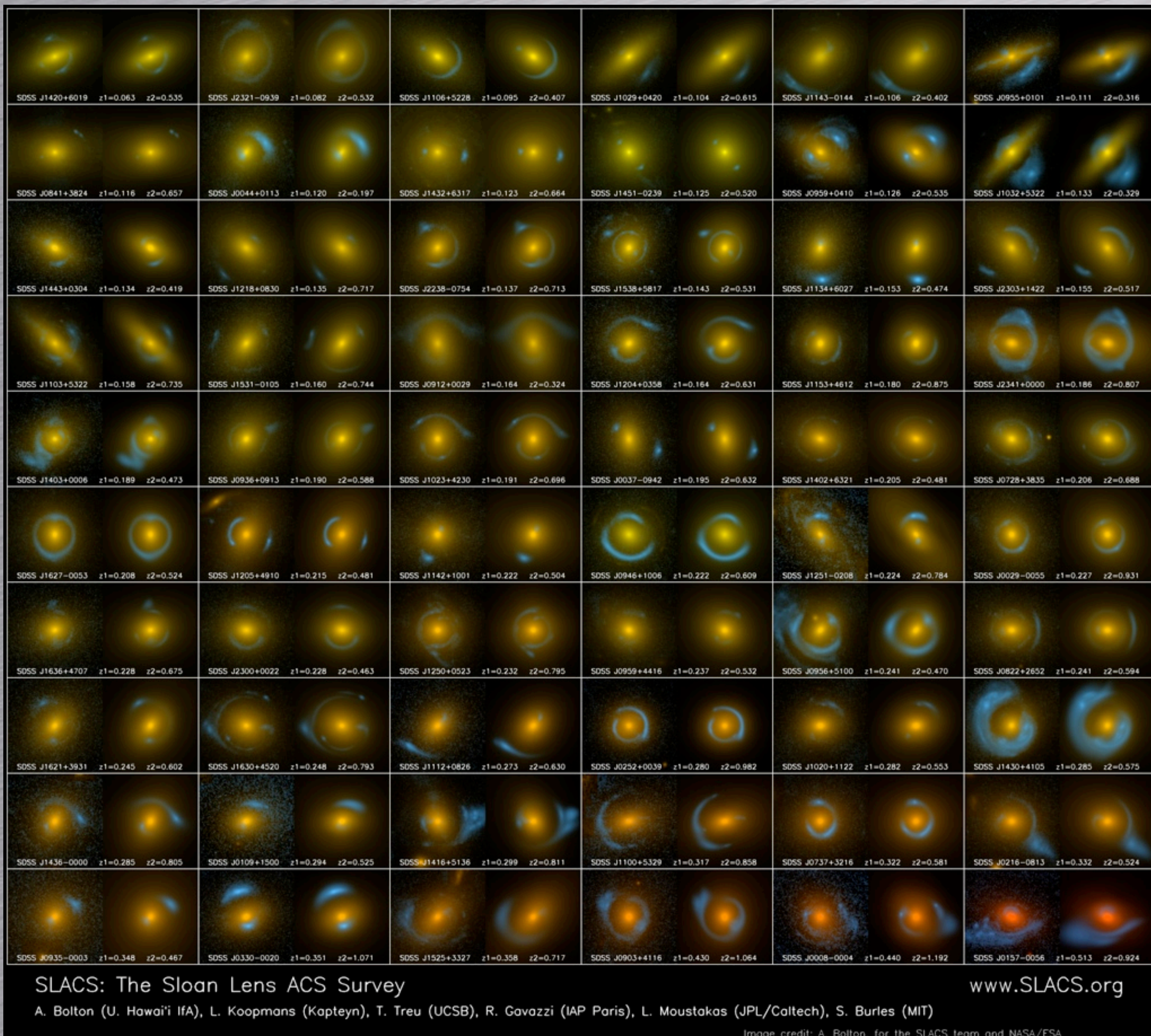
J12602+514229

Power Law + density corrections



The SLACS Survey

The SLACS Survey



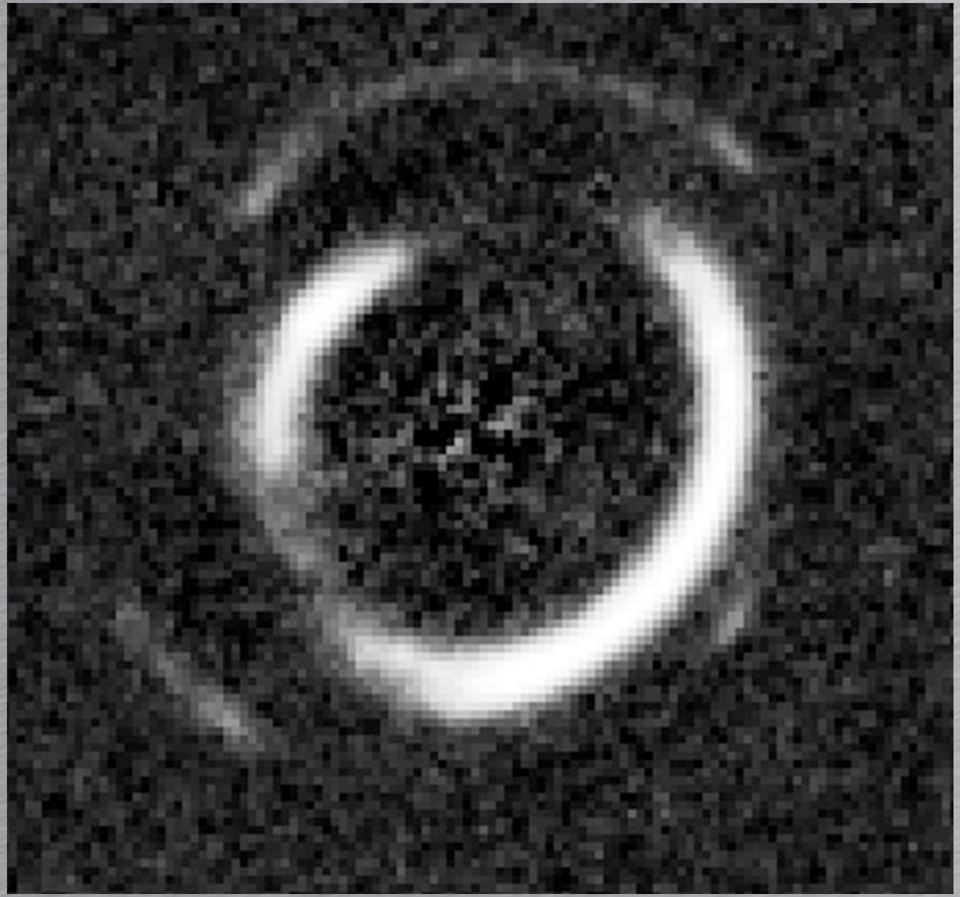
Bolton A. S. et al. 2006

SLACS:

- Lens selected
- Spectroscopy-selected
- Uniform lens-galaxy criteria: E/S0
- Emission-line selection
- Blue star-forming source provides good lens/source contrast
- State of the art: few x 10^5 targets
- Lensing rate: ~1/2000
- Results: ~100 confirmed lenses

J0946+1066 - Double Ring

High Signal-to-Noise Data & Large DM Fraction



- Two concentric ring-like structures
- Dark-matter fraction: $f\,(< R_{eff}) = 73\% \pm 9\%$
- Expected number of mass substructure from CDM paradigm within $\Delta R = R_{ein} \pm 0.3$

  $\mu(\alpha = 1.90, f = 0.3\%, R \in \Delta R) = 6.46 \pm 0.95$

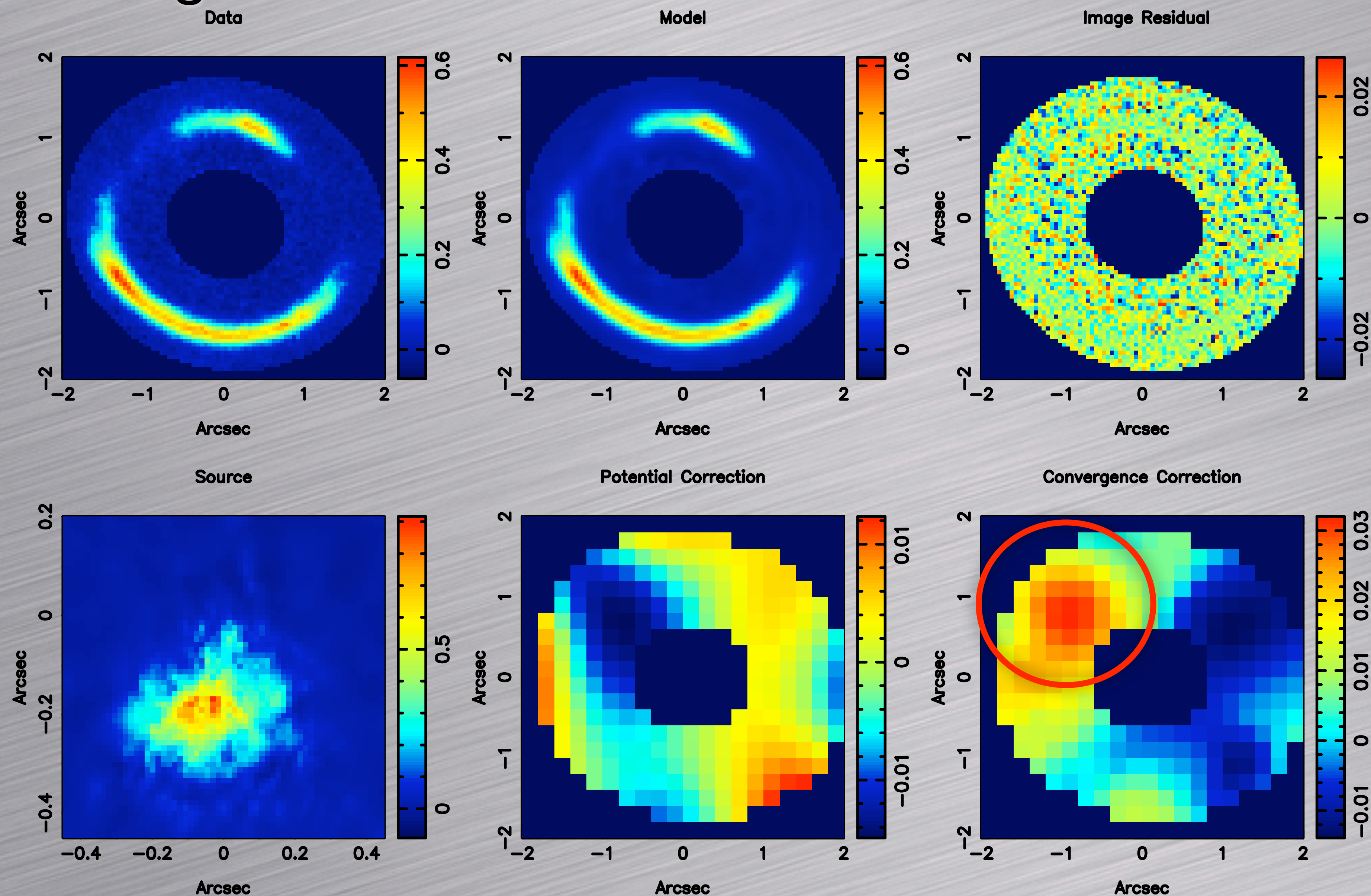
- If f~5% (Dalal & Kochanek 2002), the expectation values for mass substructure is ~50 substructures

Gavazzi et al. 2008

Vegetti S., Koopmans L. V. E. 2010

J0946+1066 - Double ring

Single Power-Law model + Potential Corrections

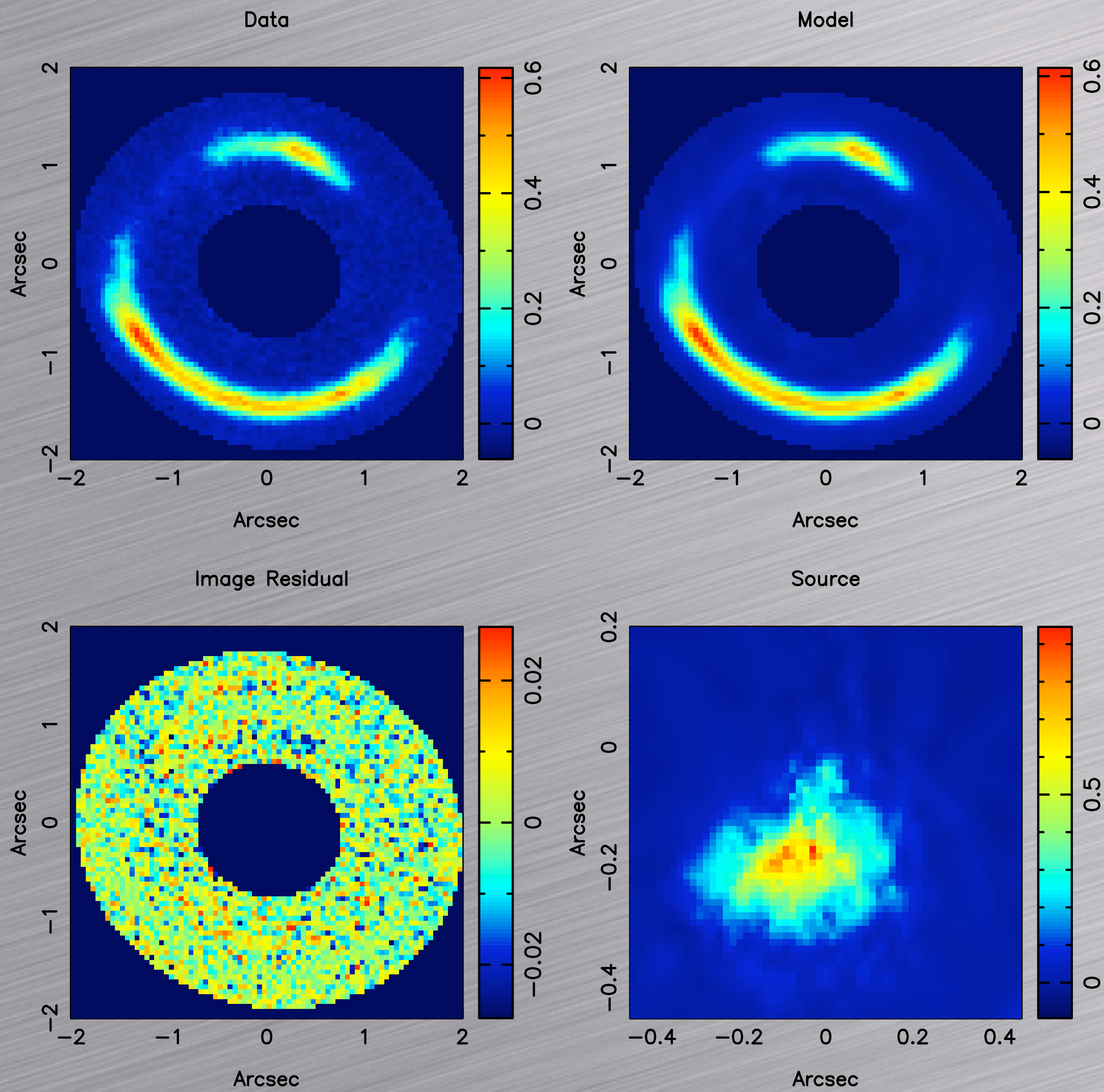


Results are stable against changes in the PSF, lens galaxy subtraction, number of pixels, pixel scale and rotations

$$\int k(r)dr = 0$$

J0946+1066 - Double ring

Power-Law smooth model + Power-Law substructure



$$M_{\rm sub} = (3.51 \pm 0.15) \times 10^9 M_\odot$$

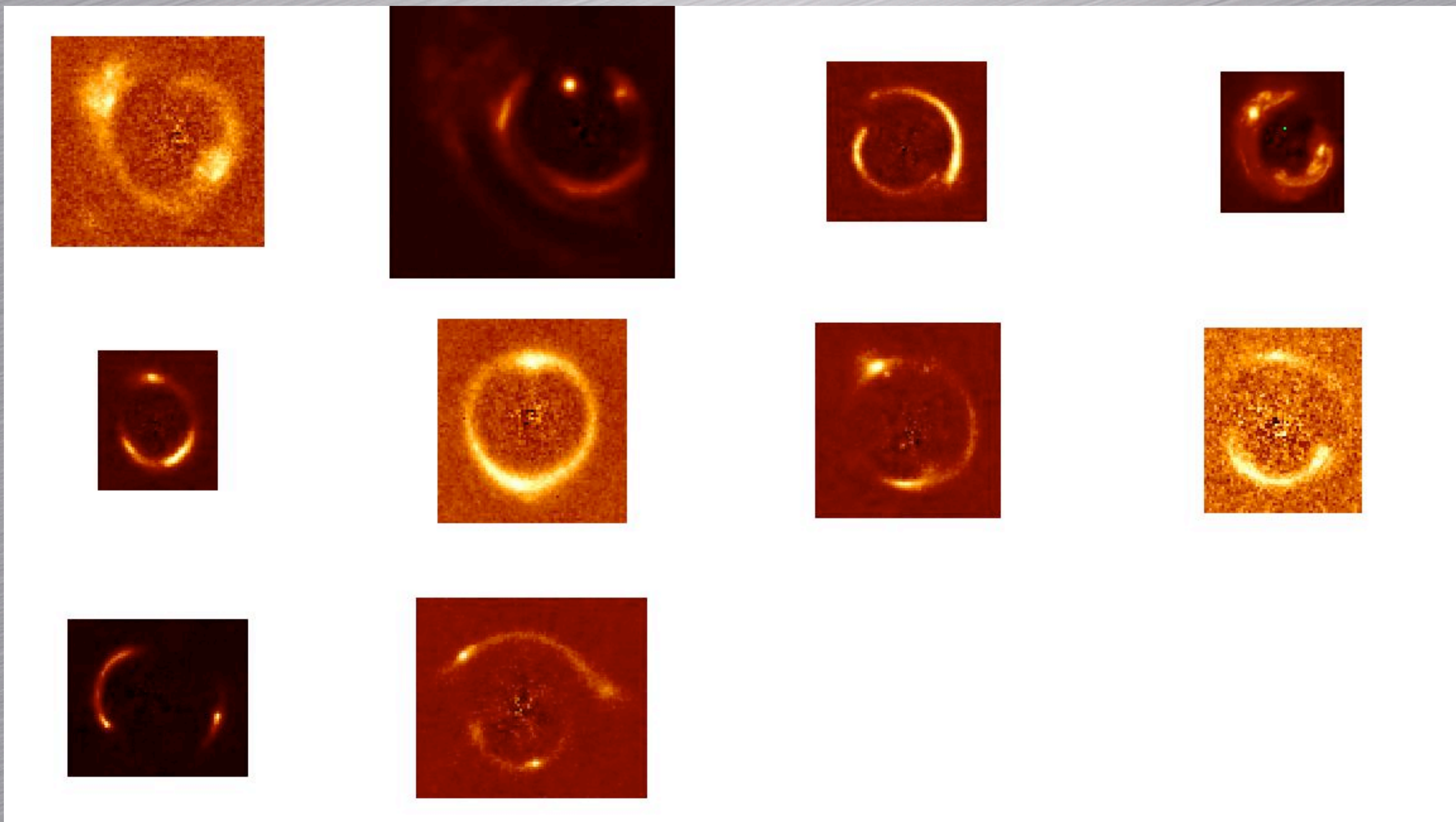
$$r_t = 1.1\ kpc$$

$$\Delta \log \mathcal{E} = -128.0$$

equivalent to a ~16σ detection

$$M_{\rm 3D}(< 0.3) = 5.83 \times 10^8 M_\odot$$

Work in Progress



The SHARP survey

SHARP

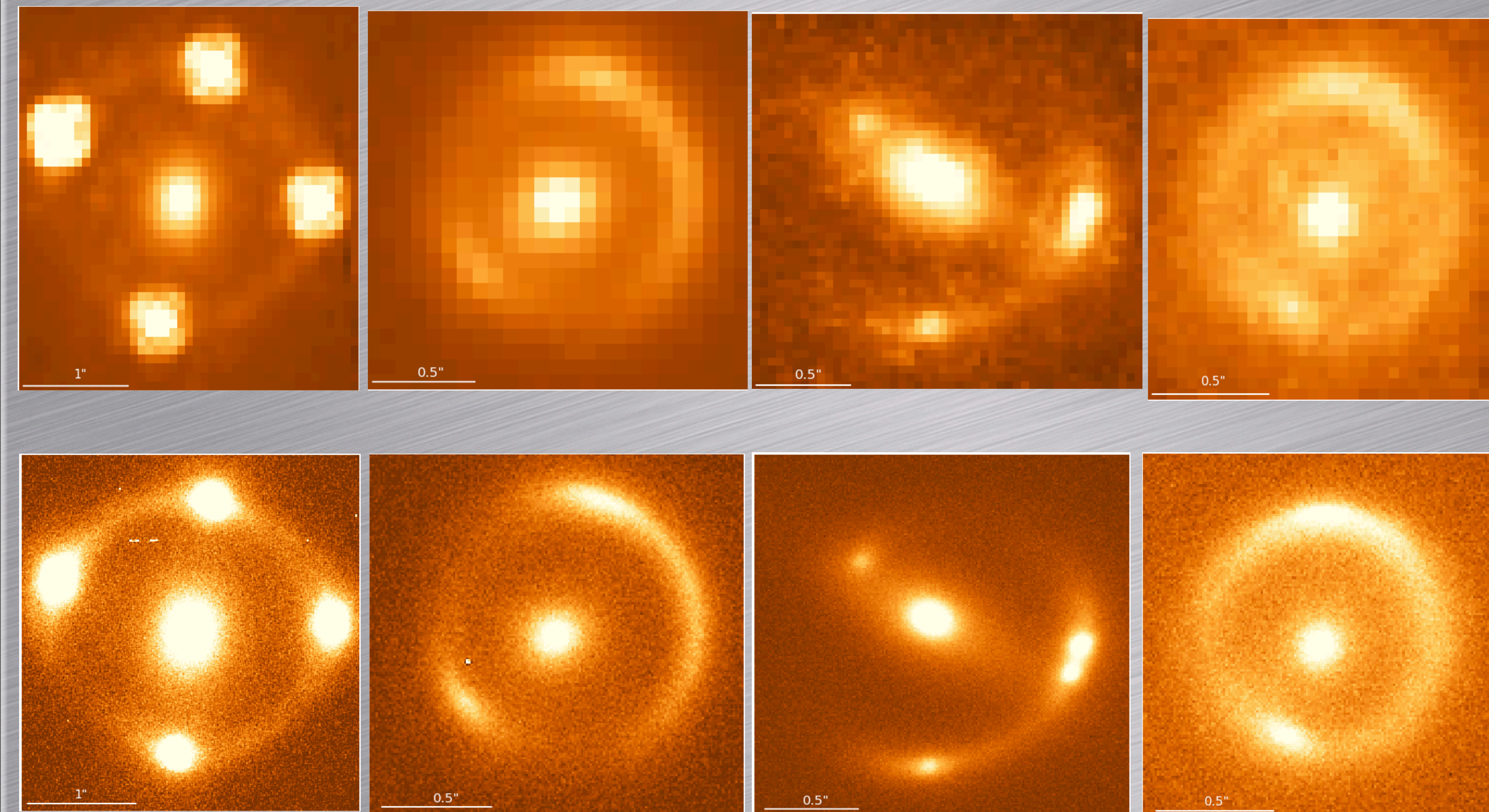
The Goals:

- search for evidence of mass substructure in cosmologically distant galaxies
- built up information on the substructure mass function and the dark matter mass fraction in substructure
- compare with prediction from simulations

The Tools:

- gravitational lensing imaging technique
- high angular resolution imaging

SHARP

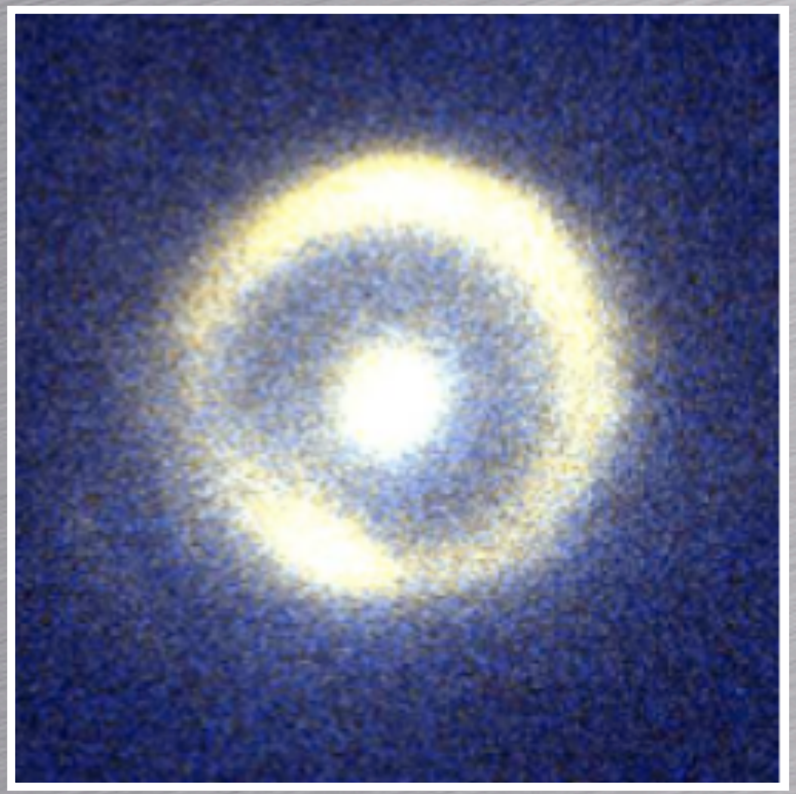


First Applications to SHARP

B1938+666

Radio Source at $z_s = 2.059$ with a Infrared Einstein ring lensed by an early-type galaxy at $z_l = 0.881$

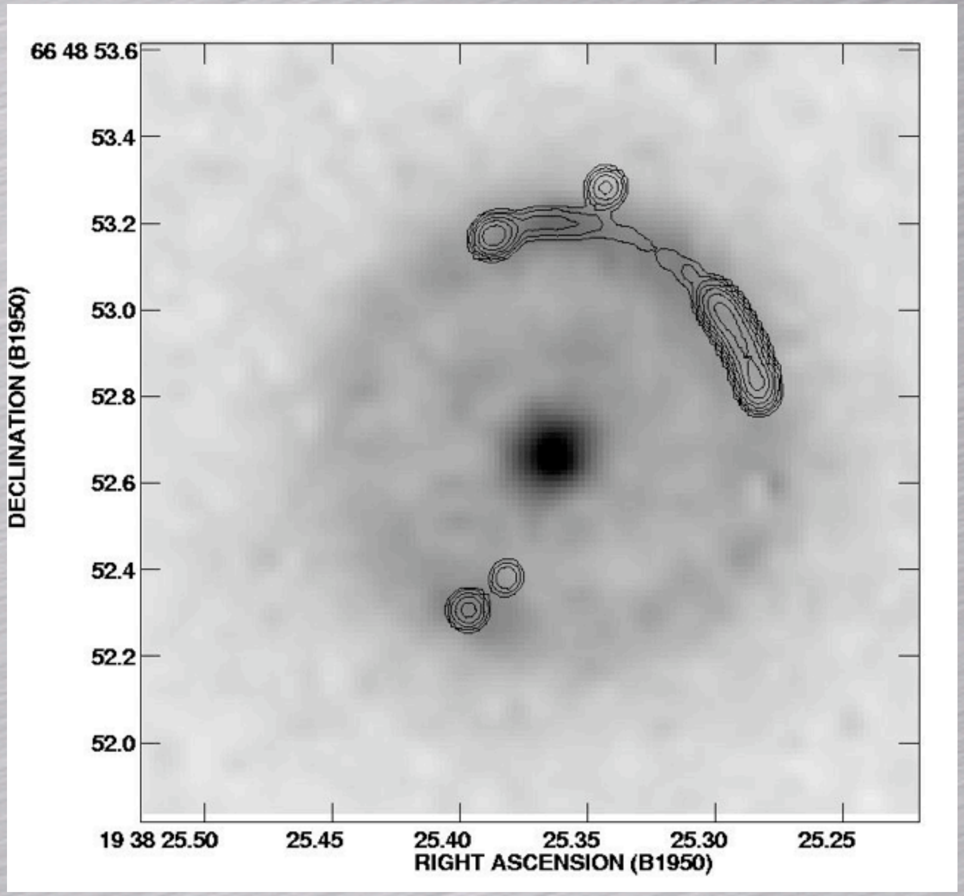
AO



Lagattuta et al. 2012

Vegetti et al. 2012

HST + Merlin

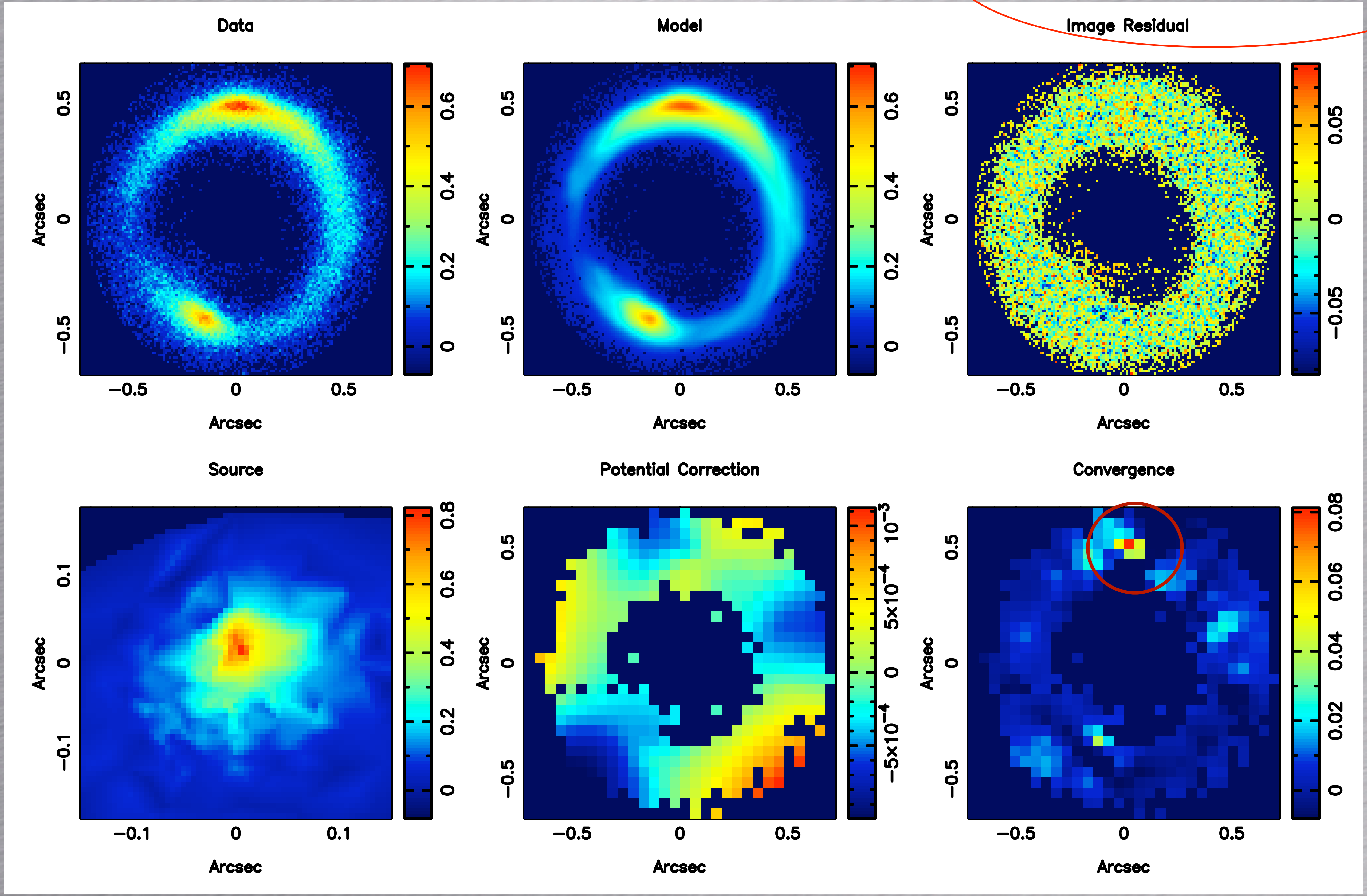


King et al. 1998

B1938+666

Keck K-band

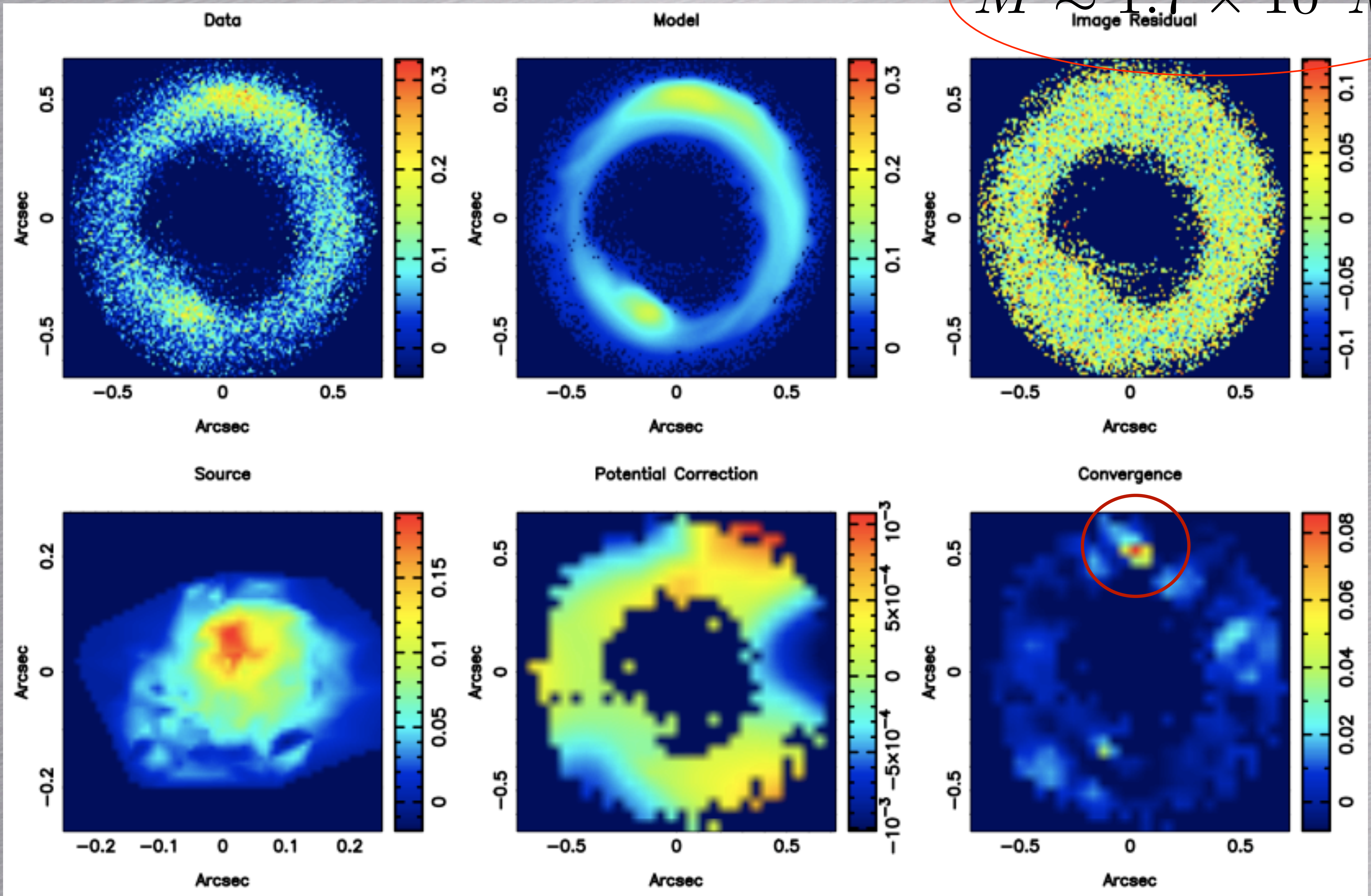
$M \approx 1.7 \times 10^8 M_\odot$



B1938+666

Keck H-band

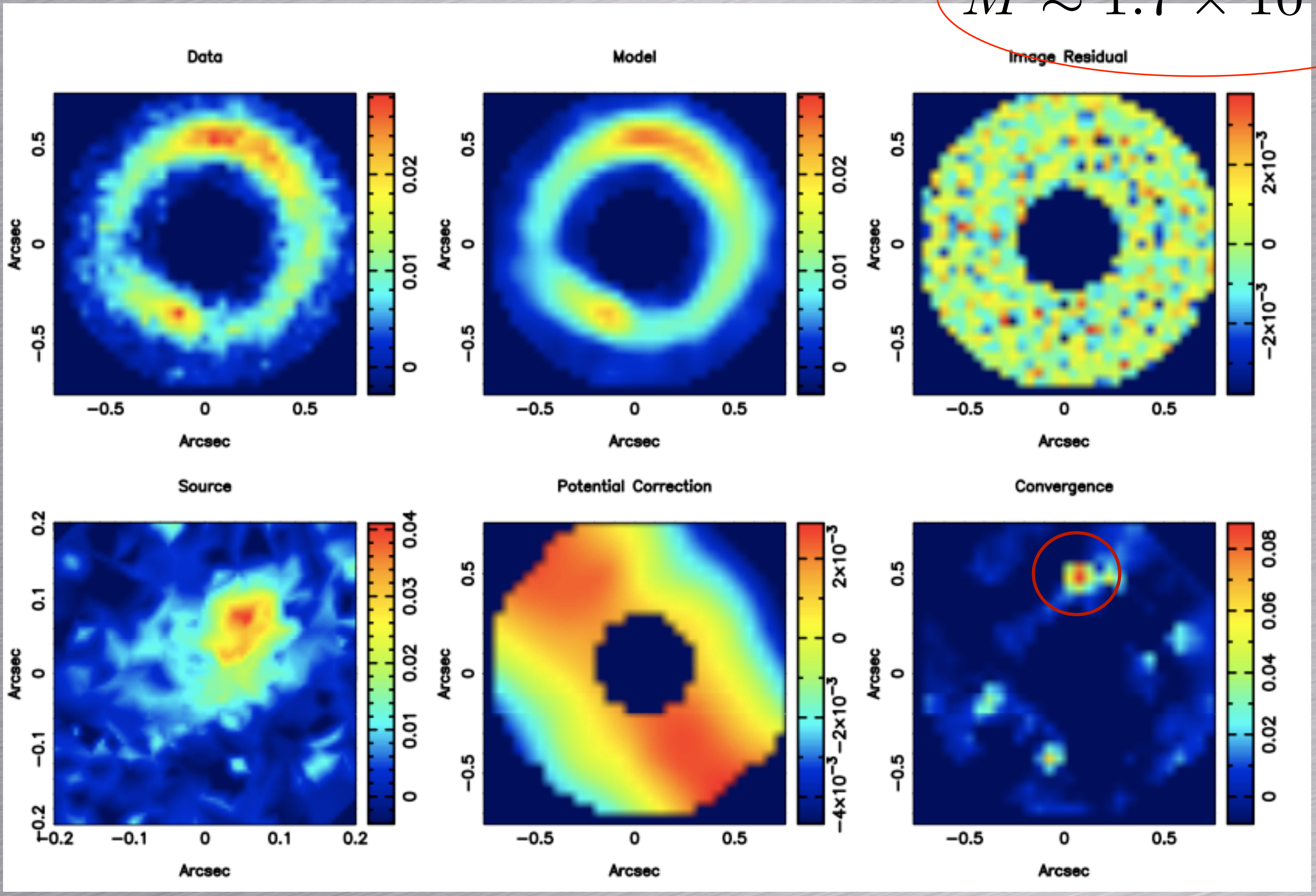
$M \approx 1.7 \times 10^8 M_\odot$



B1938+666

HST

$$M \approx 1.7 \times 10^8 M_\odot$$



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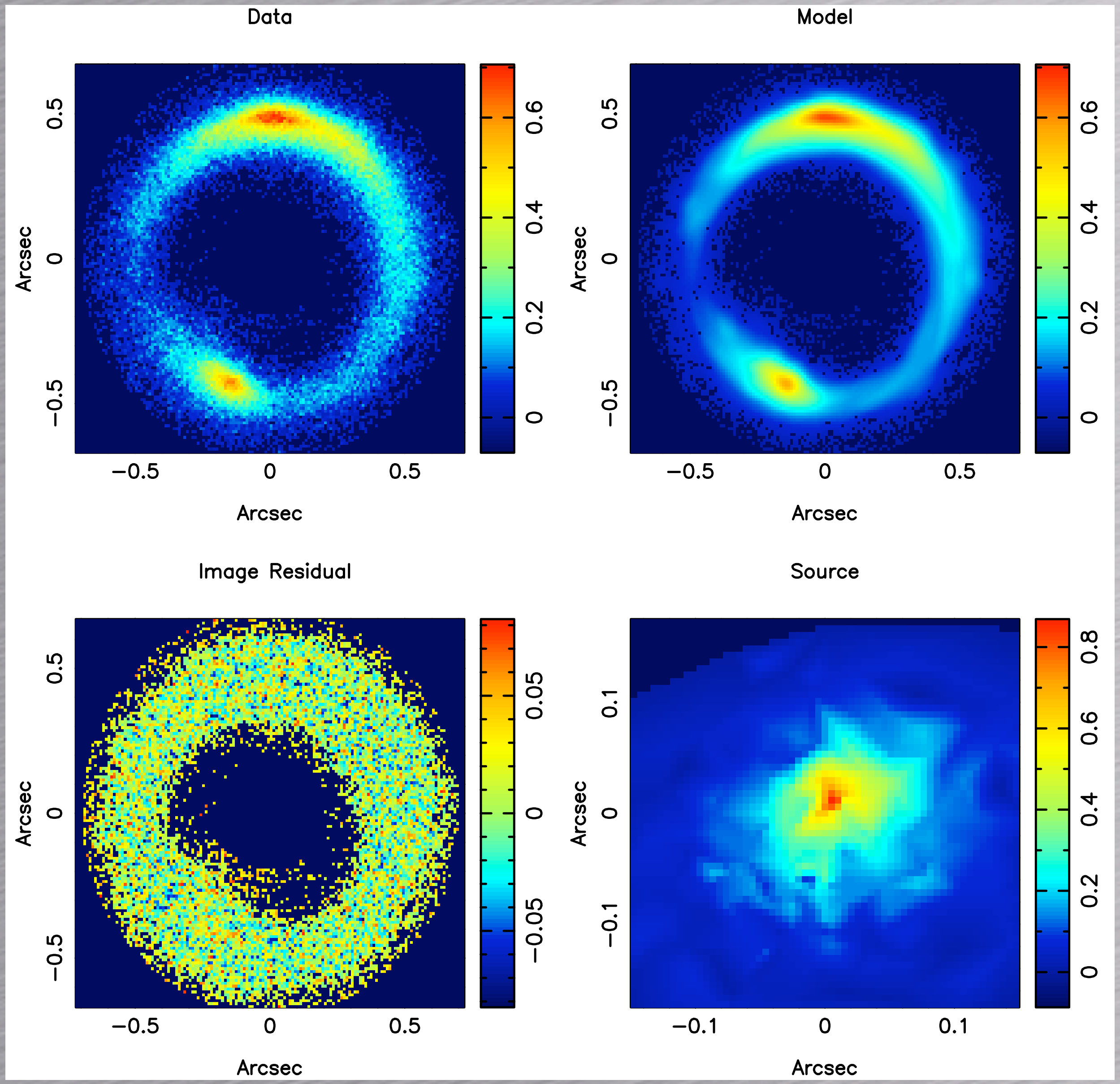


Substructure as a truncated pseudo Jaffe

$$M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$$

$$M(< 0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot$$

$$M(< 0.3) = (7.24 \pm 0.6) \times 10^7 M_\odot$$

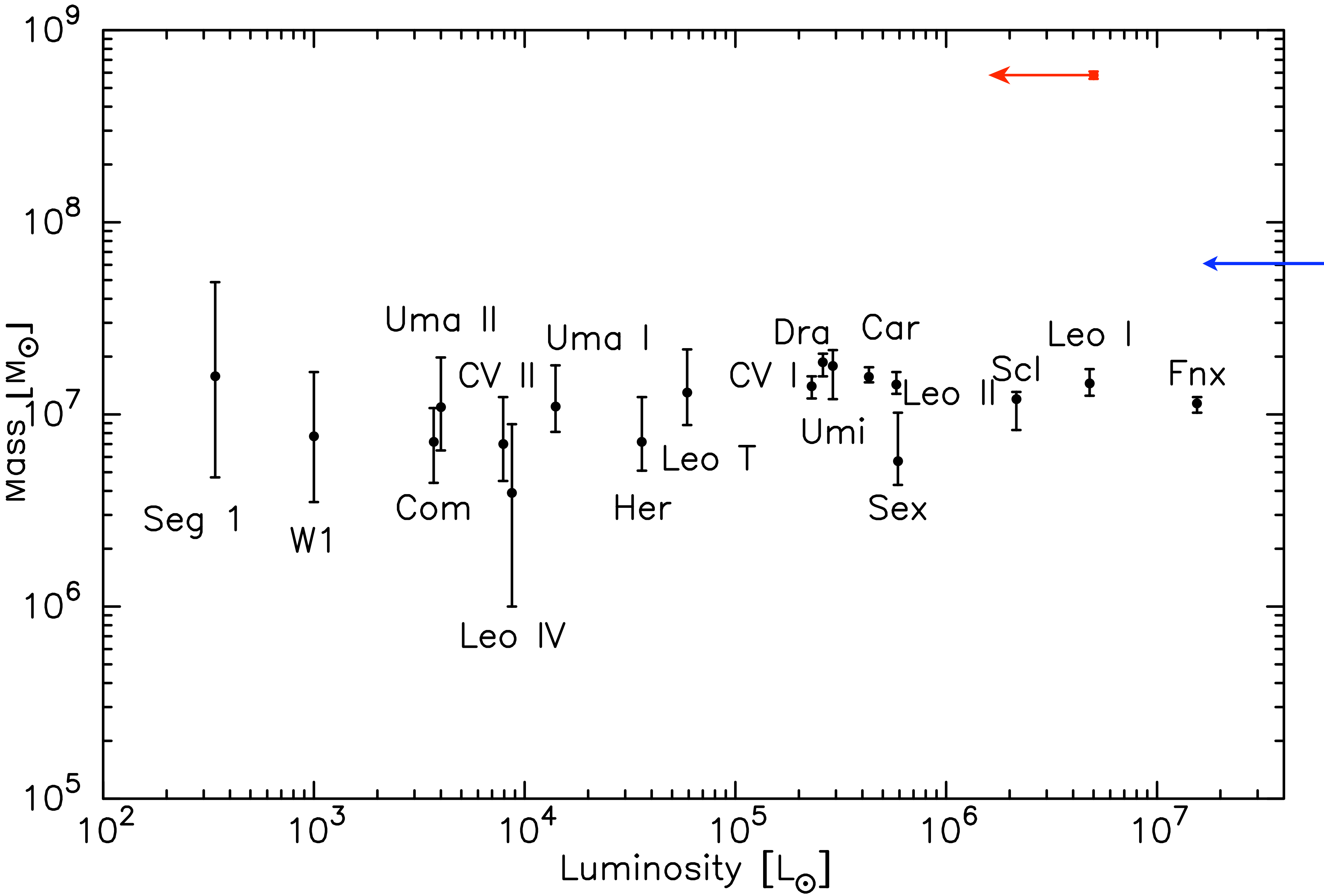
Substructure as SIS

$$M(< 0.3) = 3.4 \times 10^7 M_\odot$$

$$\sigma_v \approx 16 \ km \ s^{-1}$$

$$V_{max} \approx 27 \ km \ s^{-1}$$

$\Delta \log E = 65.0$ $\quad 12 \ \sigma \ detection$

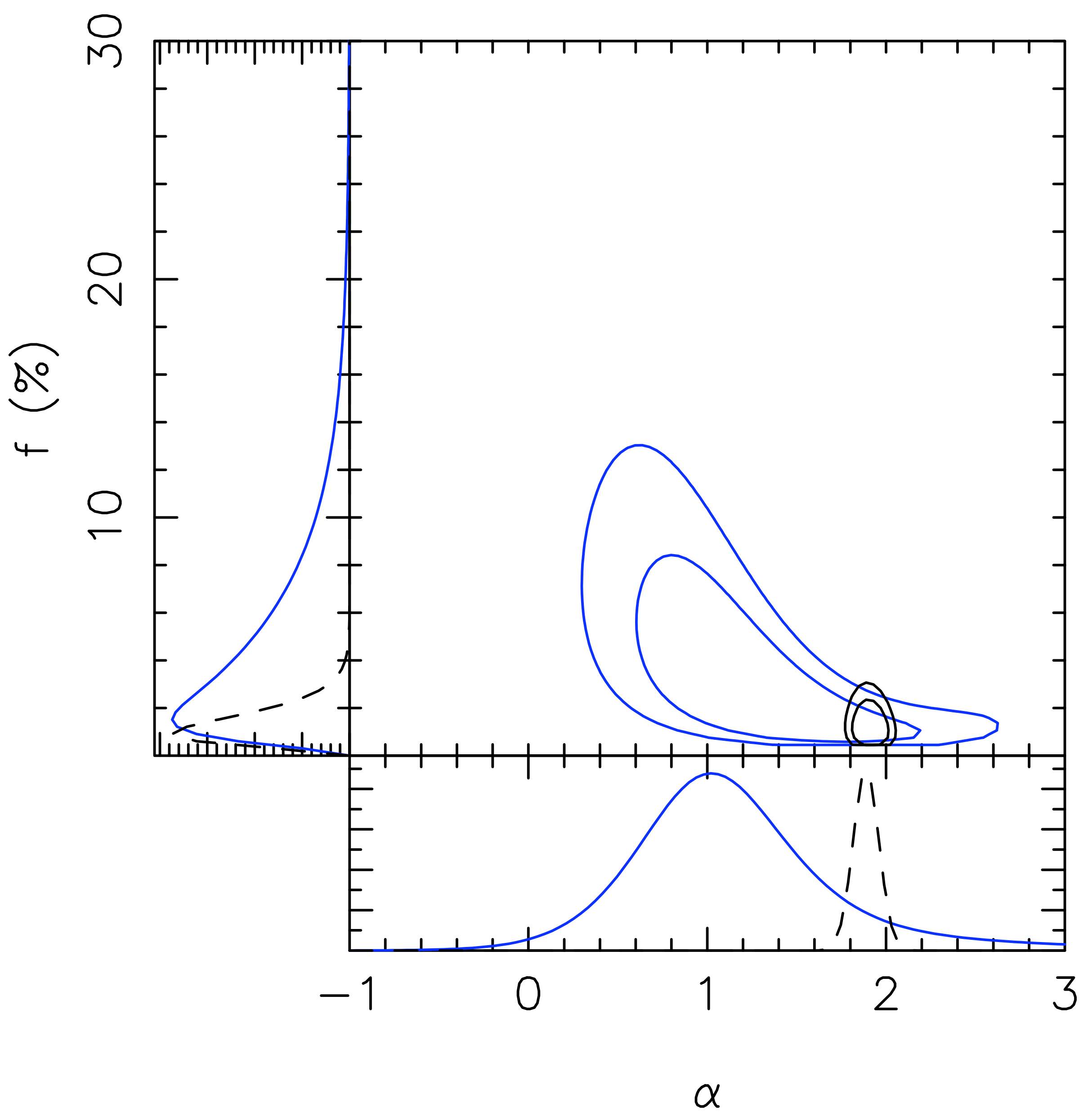


Mass [M☉]
Luminosity [L☉]
Seg 1
W1
Uma II
Com
CV II
Leo IV
Uma I
Her
Leo T
CV I
Dra
Umi
Car
Sex
Leo II
Scl
Leo I
Fnx

Substructure mass function

B1938+666 + double ring

$$P(\alpha, f \mid \{n_s, \mathbf{m}\}, \mathbf{p}) = \frac{\mathcal{L}(\{n_s, \mathbf{m}\} \mid \alpha, f, \mathbf{p})\, P(\alpha, f \mid \mathbf{p})}{P(\{n_s, \mathbf{m}\} \mid \mathbf{p})}$$



Within the inner 5 kpc

$$f = 3.33^{+3.64}_{-1.81}\%$$

$$\alpha = 1.06^{+0.56}_{-0.44}$$

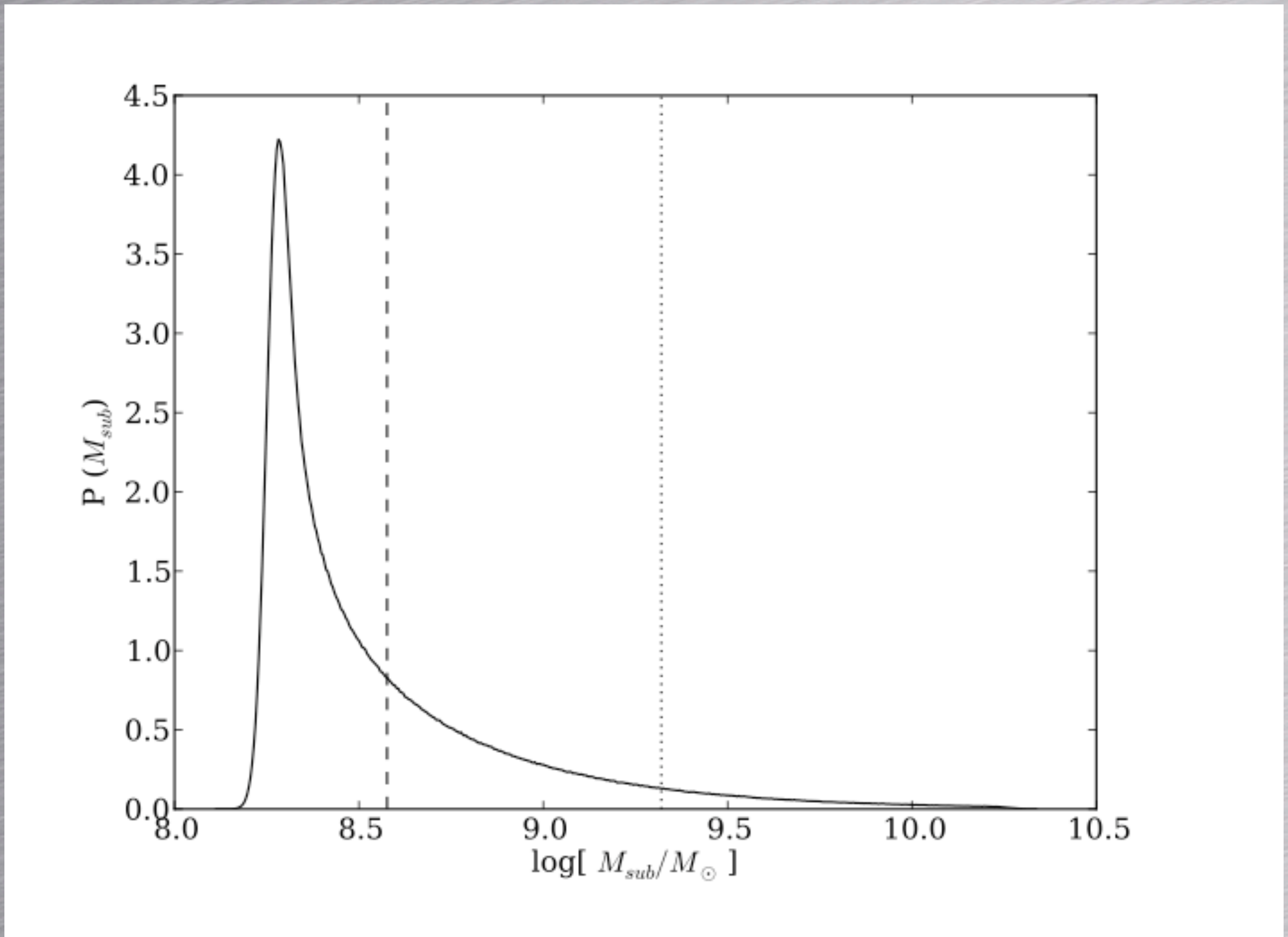
$$f = 1.21^{+0.6}_{-0.6}\%$$

$$\alpha = 1.87^{+0.08}_{-0.04}$$

$f_{CDM} \approx 0.1\%$ $\quad \alpha_{CDM} = 1.9$

LOS contamination

The major source of systematic error is de-projection of the substructure position within the host galaxy



Probability of M under the assumption that the satellites follow the host galaxy mass distribution

Contamination from LOS interlopers is also possible:

Chen et al. 2009: 1- 10 %

De-projection yields a systematic uncertainty on the total mass of 0.3 dex at the 68 per cent confidence level.

Conclusions

- Surface brightness anomalies can be used to find low mass galaxies at high z
- Simulations show that with HST quality data, 10 systems are sufficient to constrain the mass function
- Using high resolution adaptive optics data and the gravitational imaging technique we discovered an analogue of the Fornax satellite at redshift about 1
- The first constraints on the mass function are consistent with prediction from CDM (large errors ....)
- LOS contamination is not necessarily bad