CDM SUBSTRUCTURE DETECTION IN GRAVITATIONAL LENS GALAXIES

SIMONA VEGETTI - MPA

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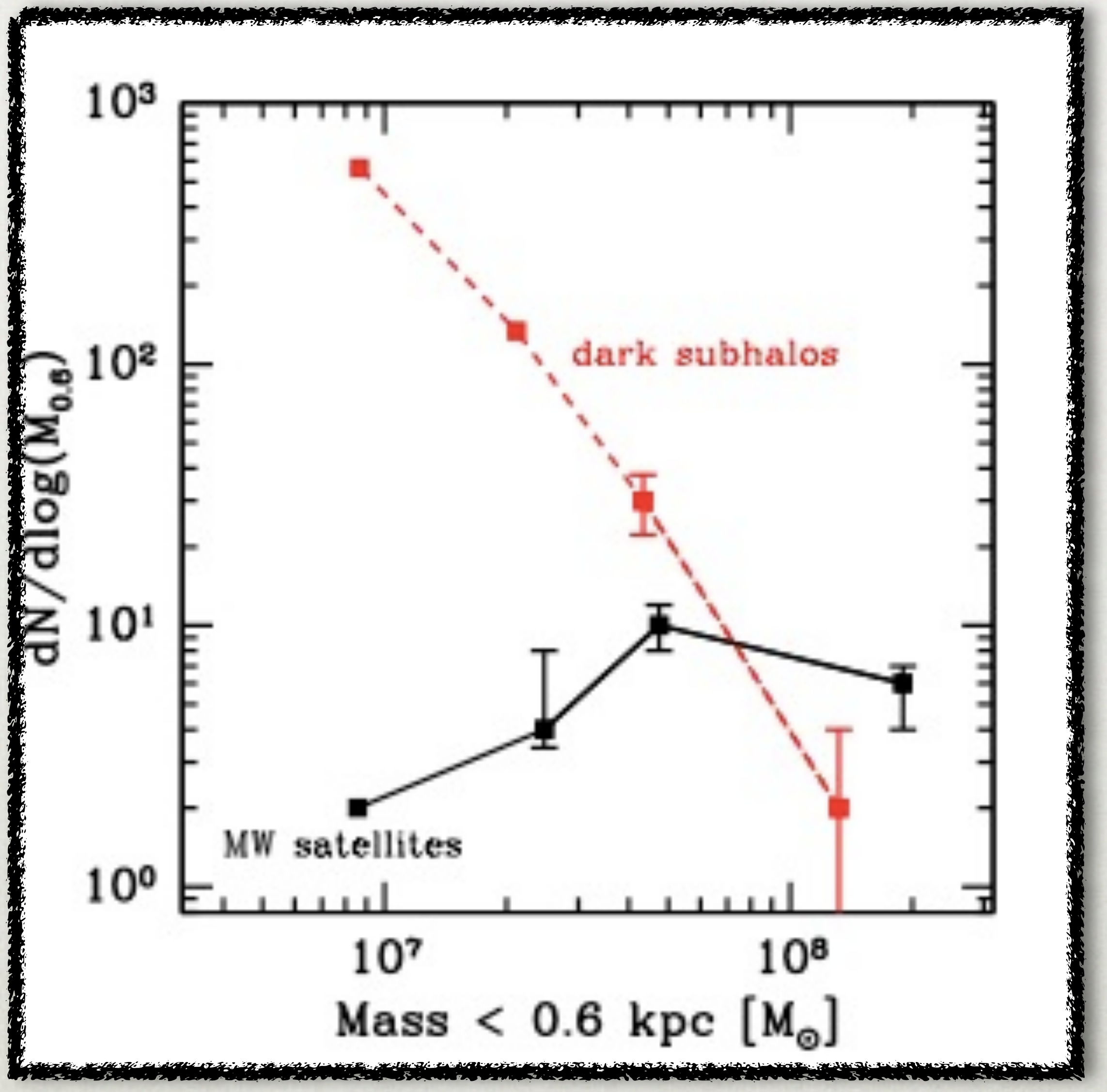
Kravtsov 2010

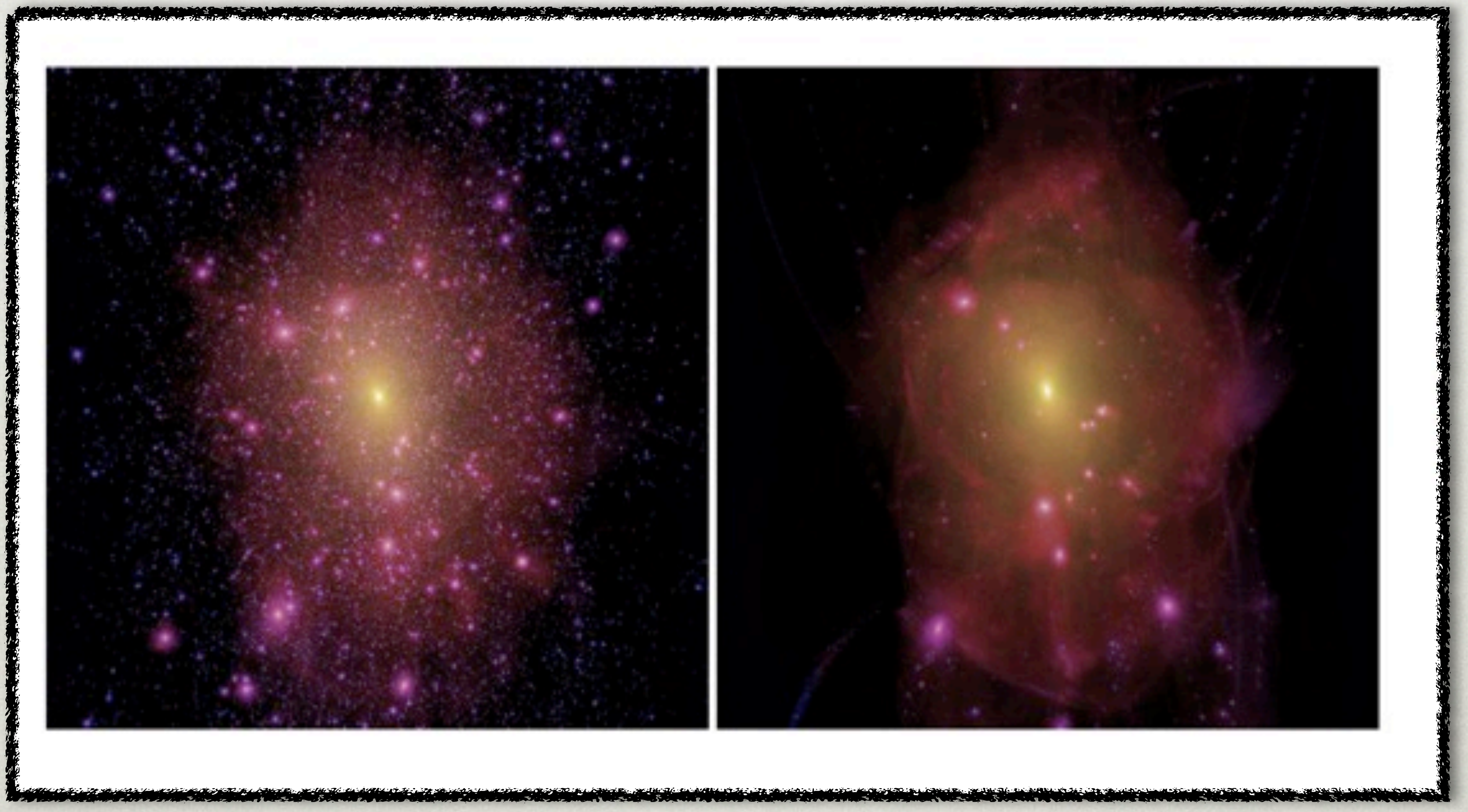
CHALLENGING LCDM



$dN/dm \propto m^{-1.0}$ $dN/dm \propto m^{-1.9}$

Lovell et al. 2012

CDM vs WDM

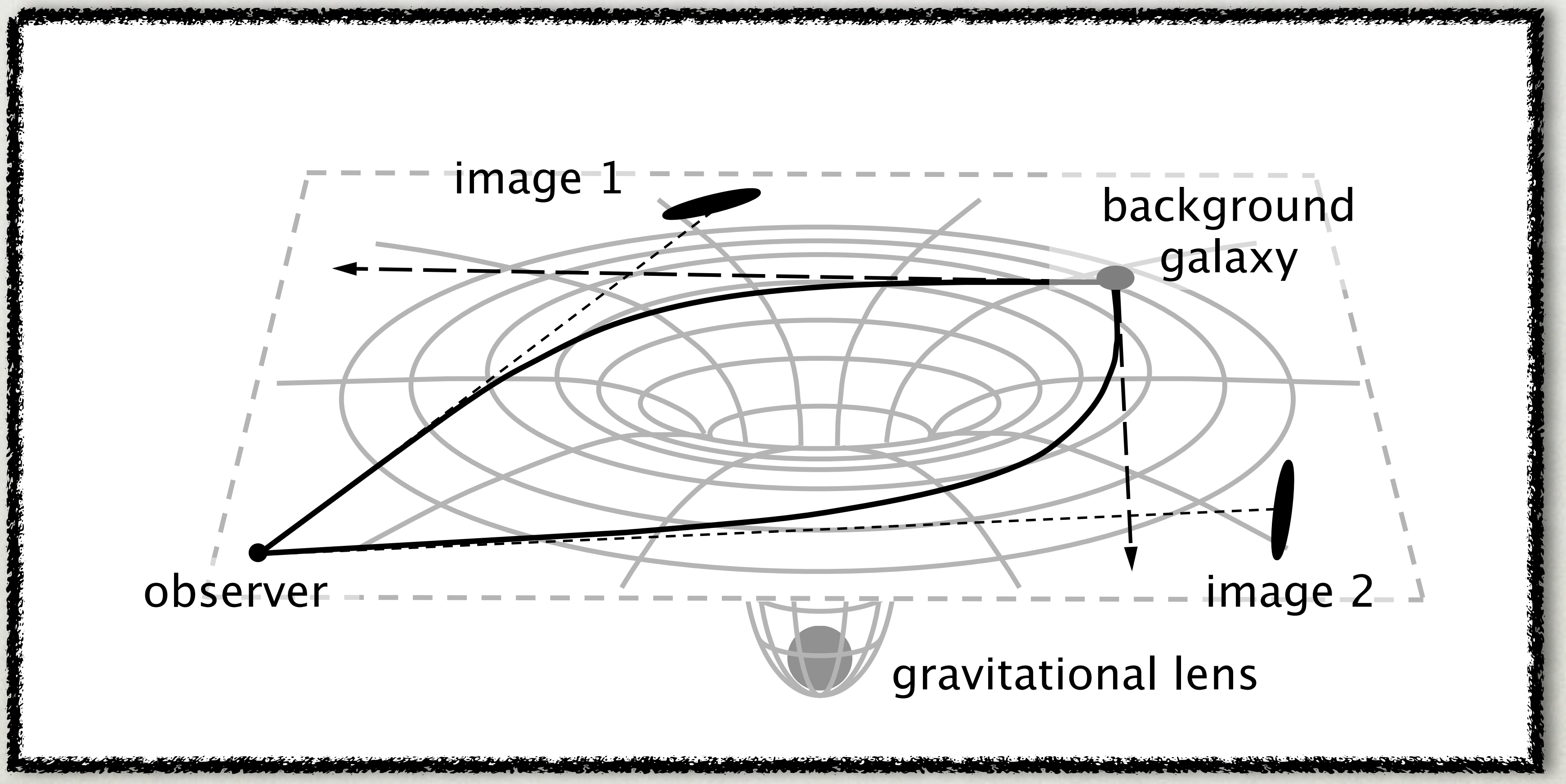


How do we probe the small scales beyond the Local Universe and independently from baryons?

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

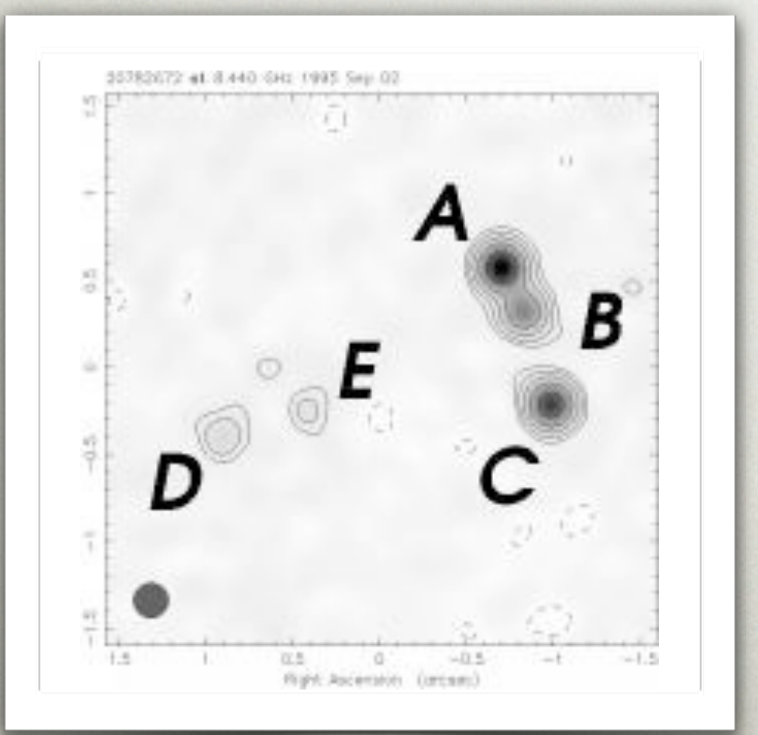
GRAVITATIONAL LENSING

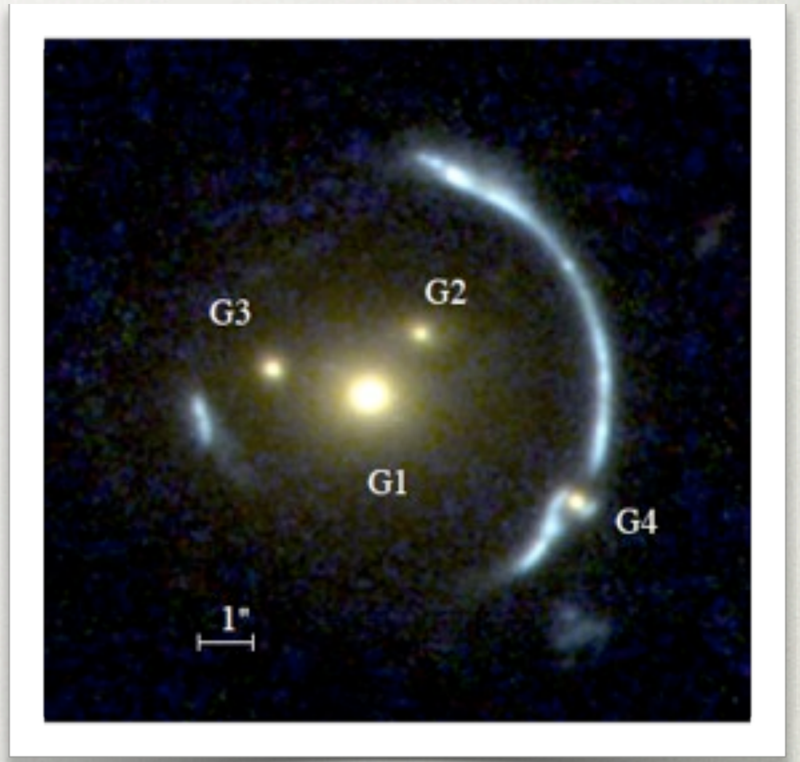


$$\mathbf{y} = \mathbf{x} - \alpha(\mathbf{x}) \qquad \alpha(\mathbf{x}) \propto \int d\mathbf{x}' \int dz \rho(\mathbf{x}', z) \frac{\mathbf{x} - \mathbf{x}'}{|\mathbf{x} - \mathbf{x}'|^2}$$

GRAVITATIONAL IMAGING

- substructures are detected as magnification anomalies
- Compact sources are easy to model
- Sensitive to a wide range of masses
- degenerate in the mass model

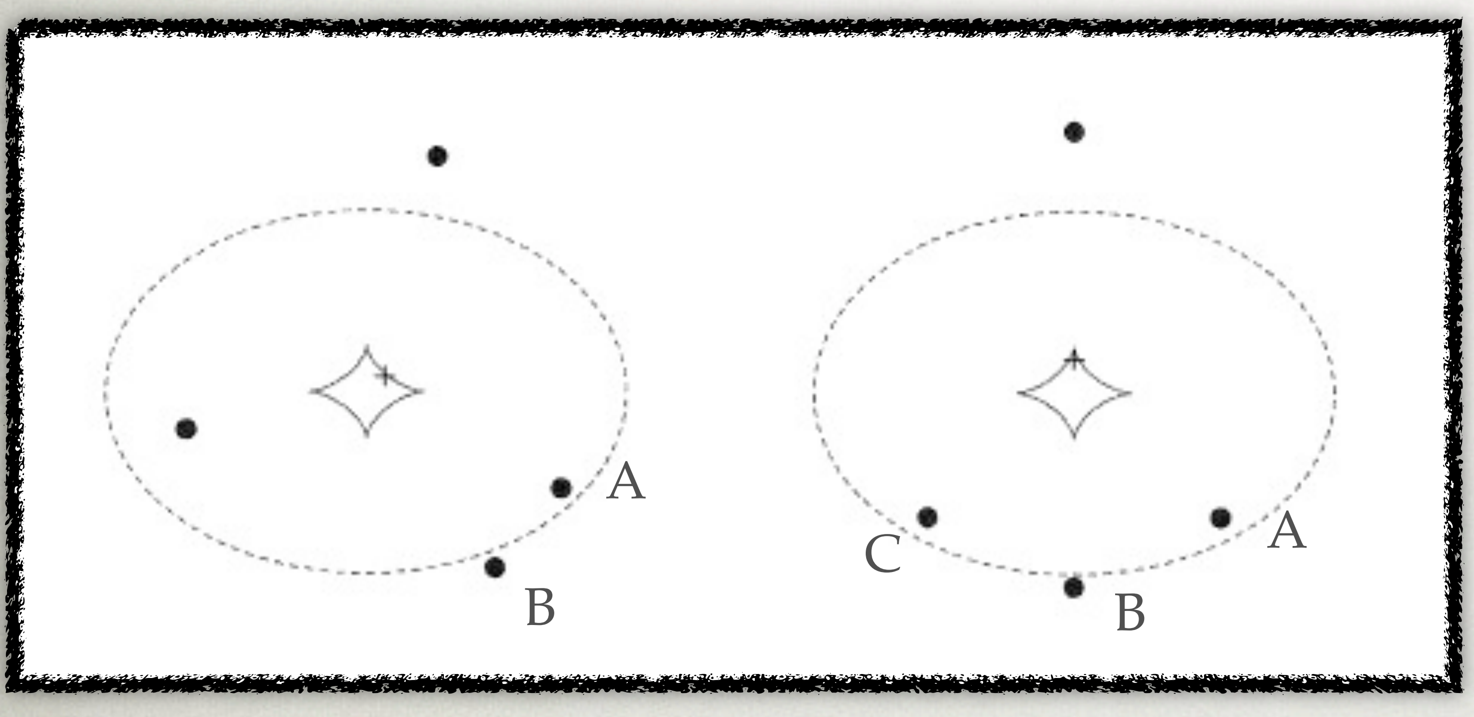


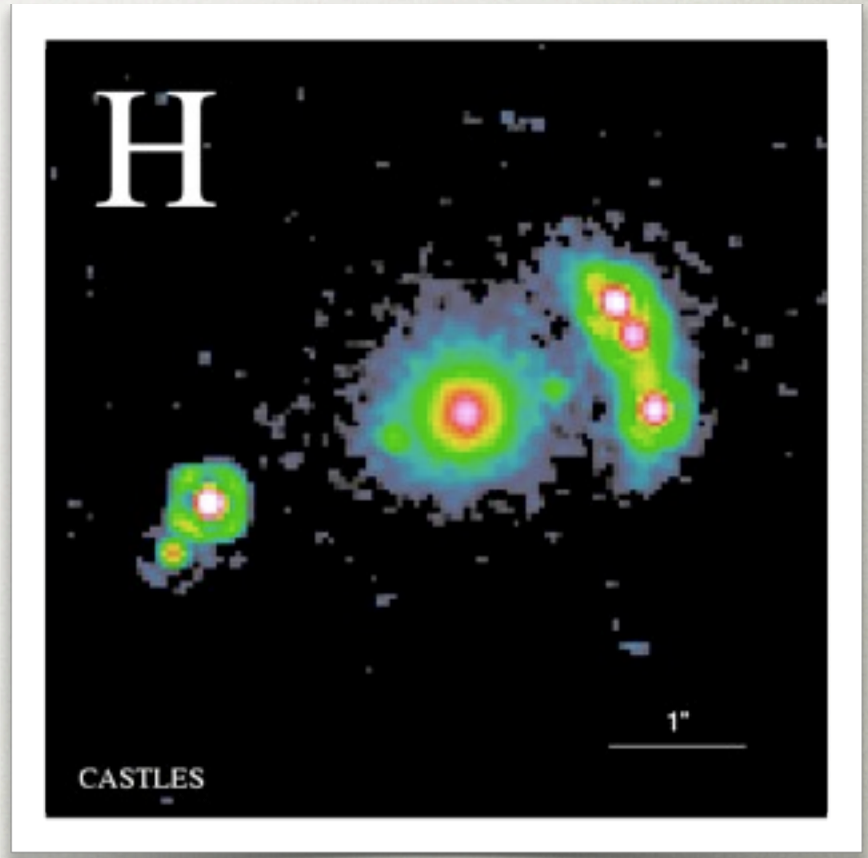


- substructures are detected as surface brightness anomalies
- need to disentangle structures in the potential from structures in the source
- Sensitive to higher masses
- NOT degenerate in the mass model

Mao & Schneider 1992
Dalal & Kochanek 2002

FOLDS & CUSPS





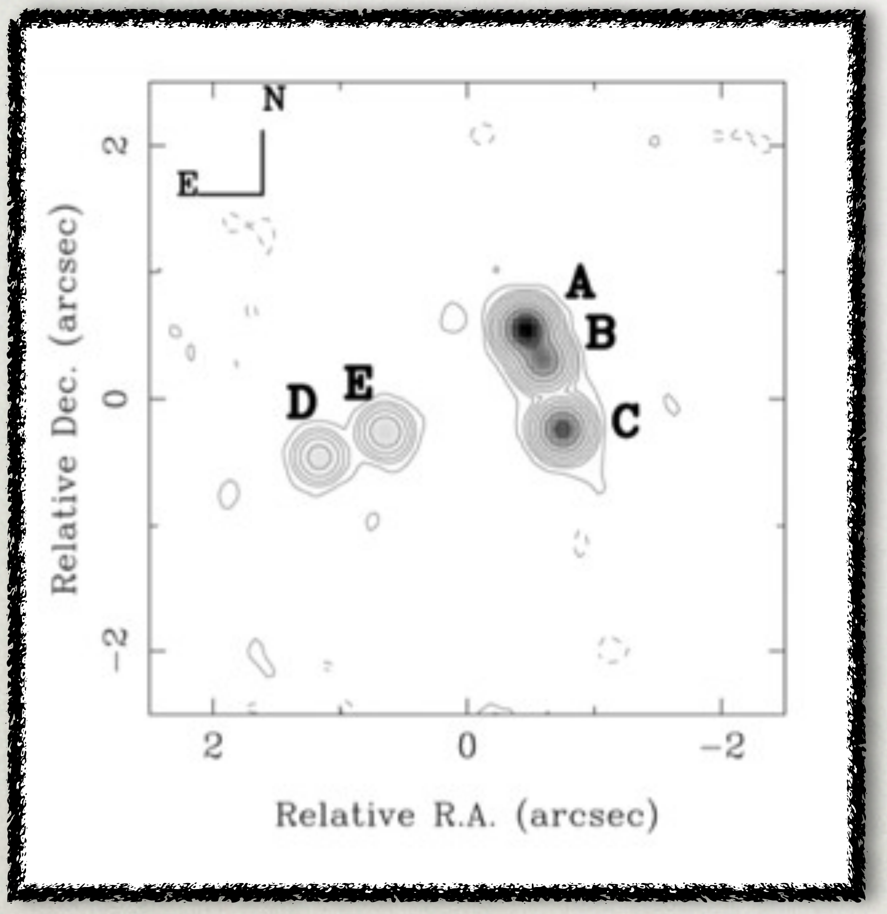
$$R_{\rm fold} = \frac{\mu_A + \mu_B}{|\mu_A| + |\mu_B|} \rightarrow 0$$

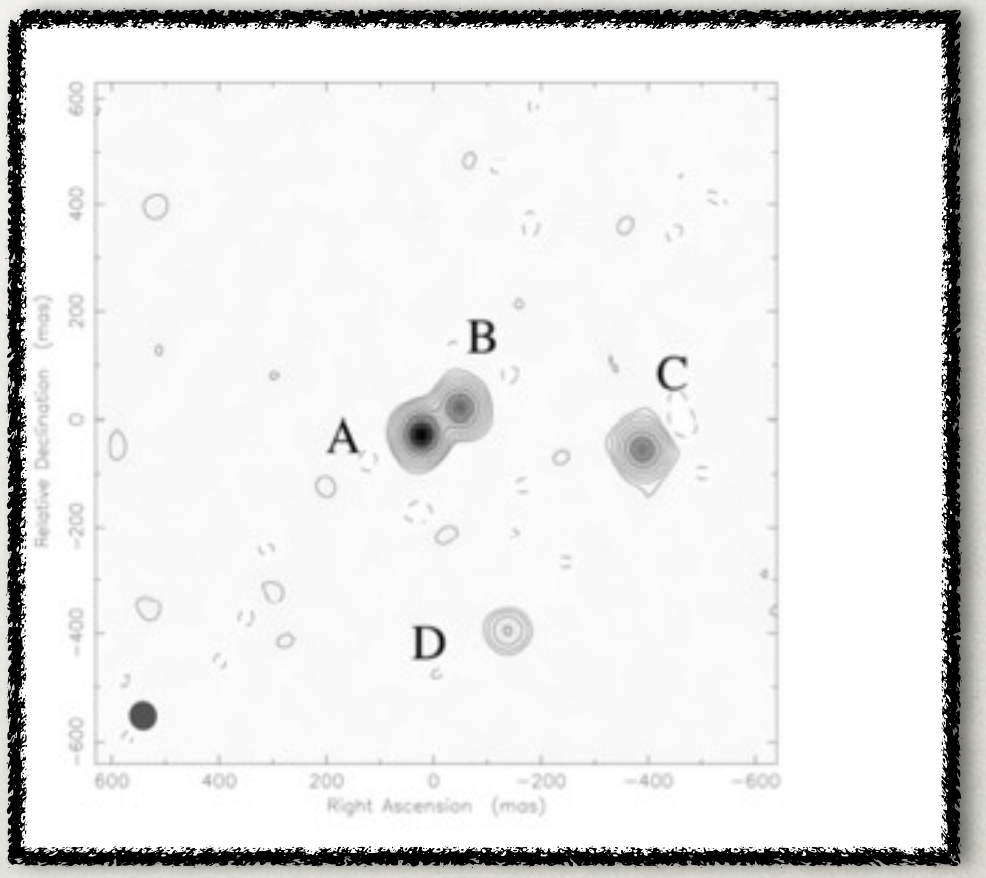
$$R_{\rm cusp} = \frac{\mu_A + \mu_B + \mu_C}{|\mu_A| + |\mu_B| + |\mu_C|} \rightarrow 0$$

In the optical and X-ray the quasar emission regions are small enough that the lens fluxes are sensitive to the effect of stars. In the radio the sources are large enough be insensitive to microlensing

FLUX RATIO ANOMALIES

Smooth lens modeling can fit the image positions well, but fail to reproduce the relative fluxes





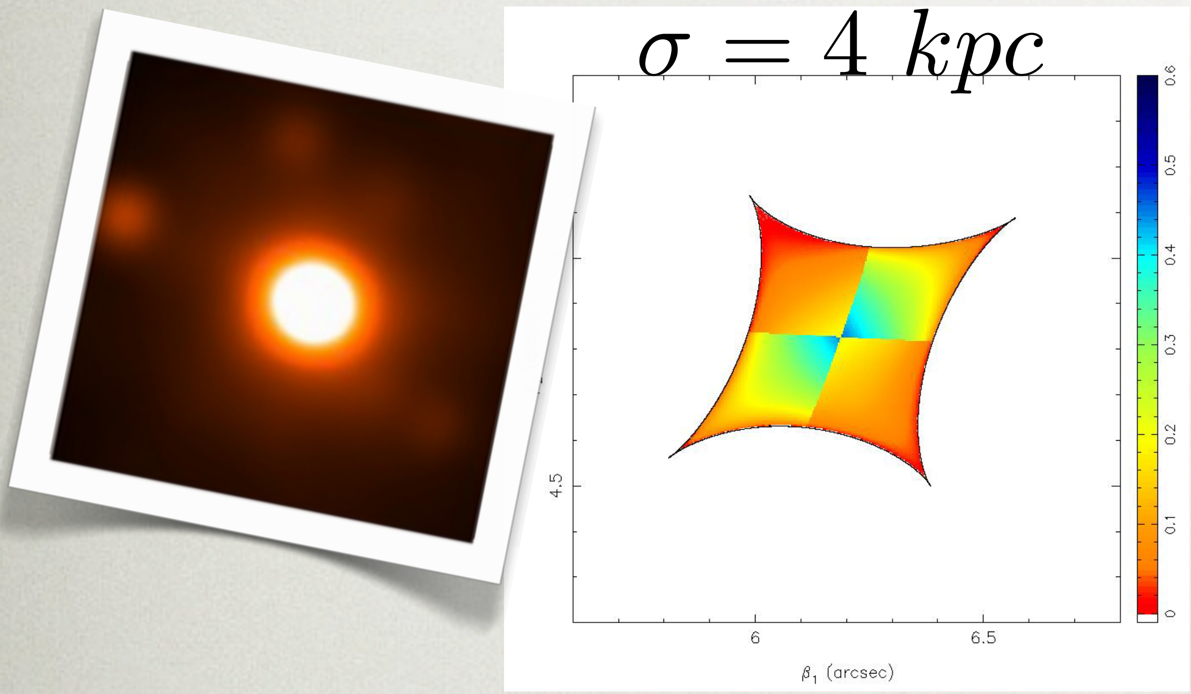
—| Smooth models produces images B which are as bright as A

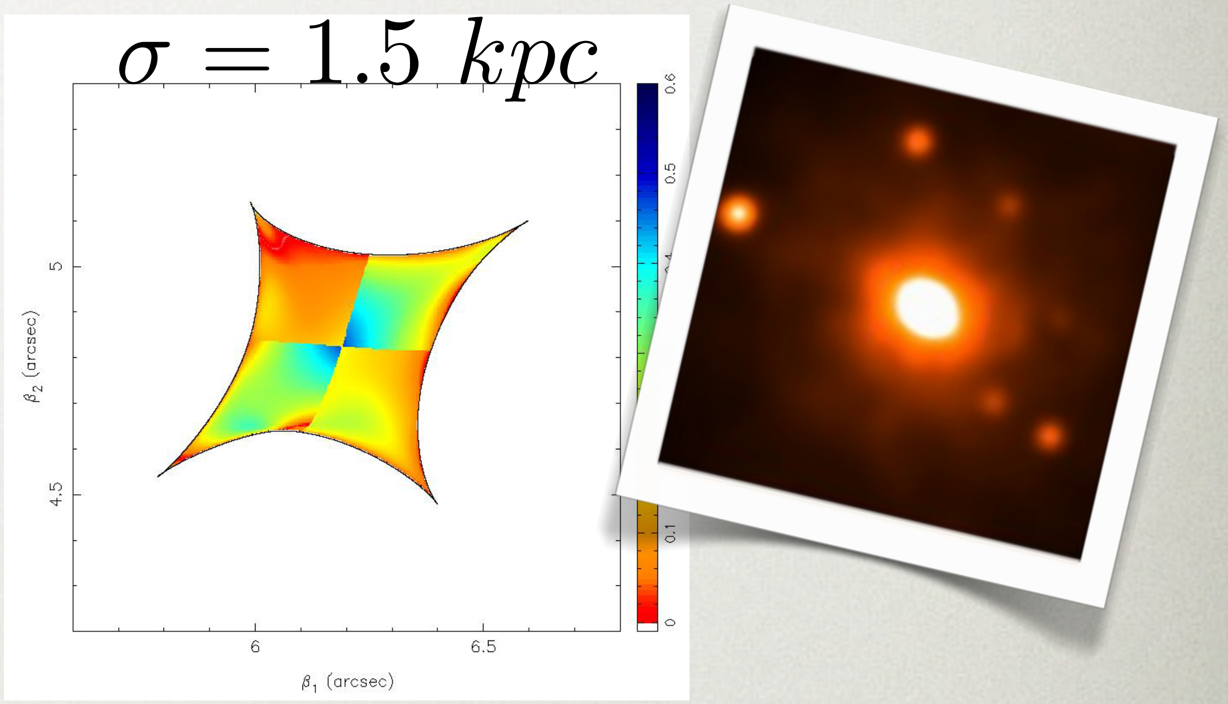
—| Smooth models produces images B which are as bright as A

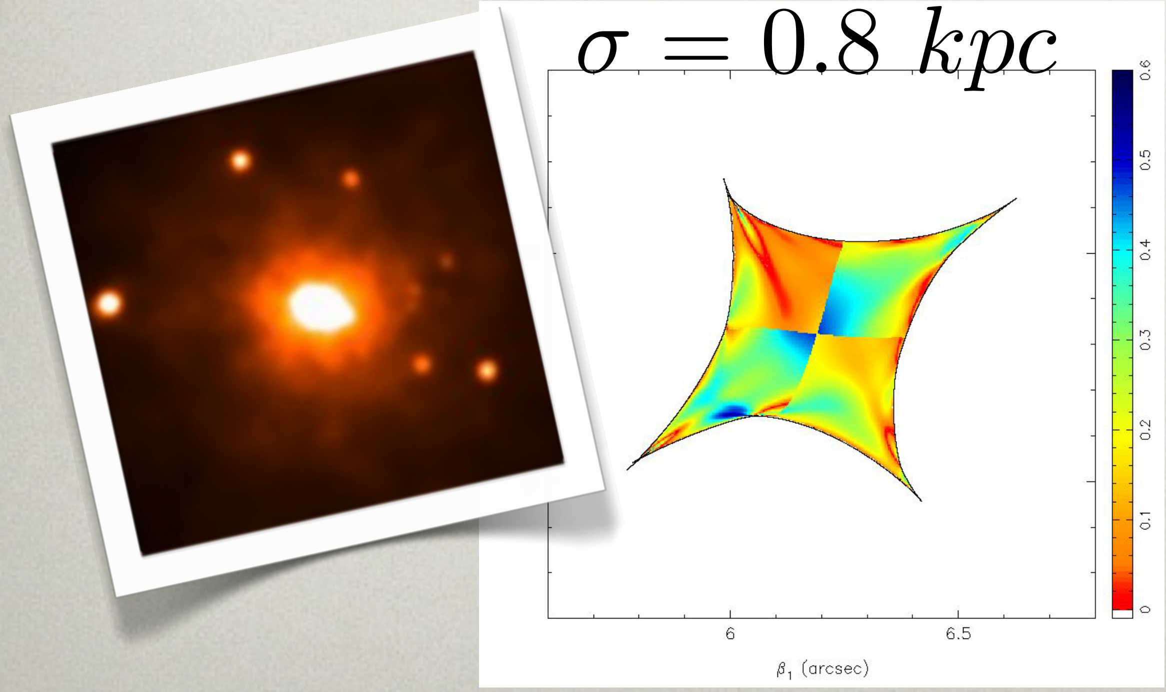
Bradac et al. 2002

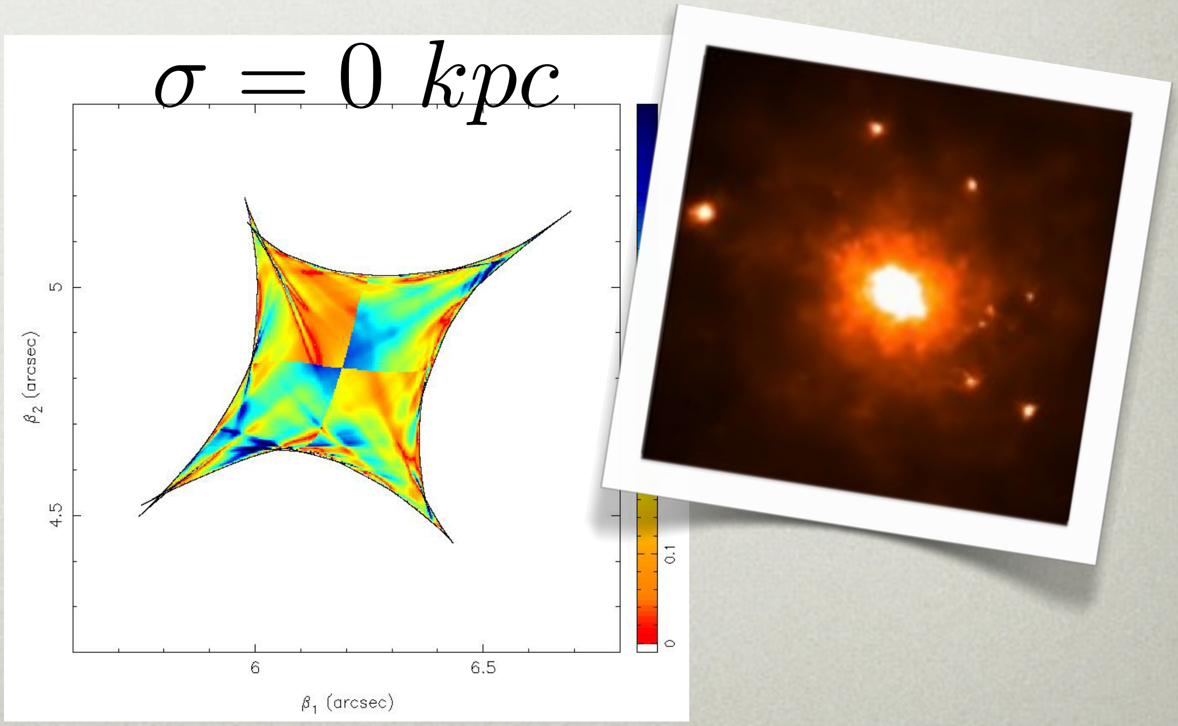
$$R_{\text{cusp}} = \frac{\mu_A + \mu_B + \mu_C}{|\mu_A| + |\mu_B| + |\mu_C|} \to 0$$

FLUX RATIO ANOMALIES


$\sigma = 4\ kpc$


$\sigma = 1.5\ kpc$

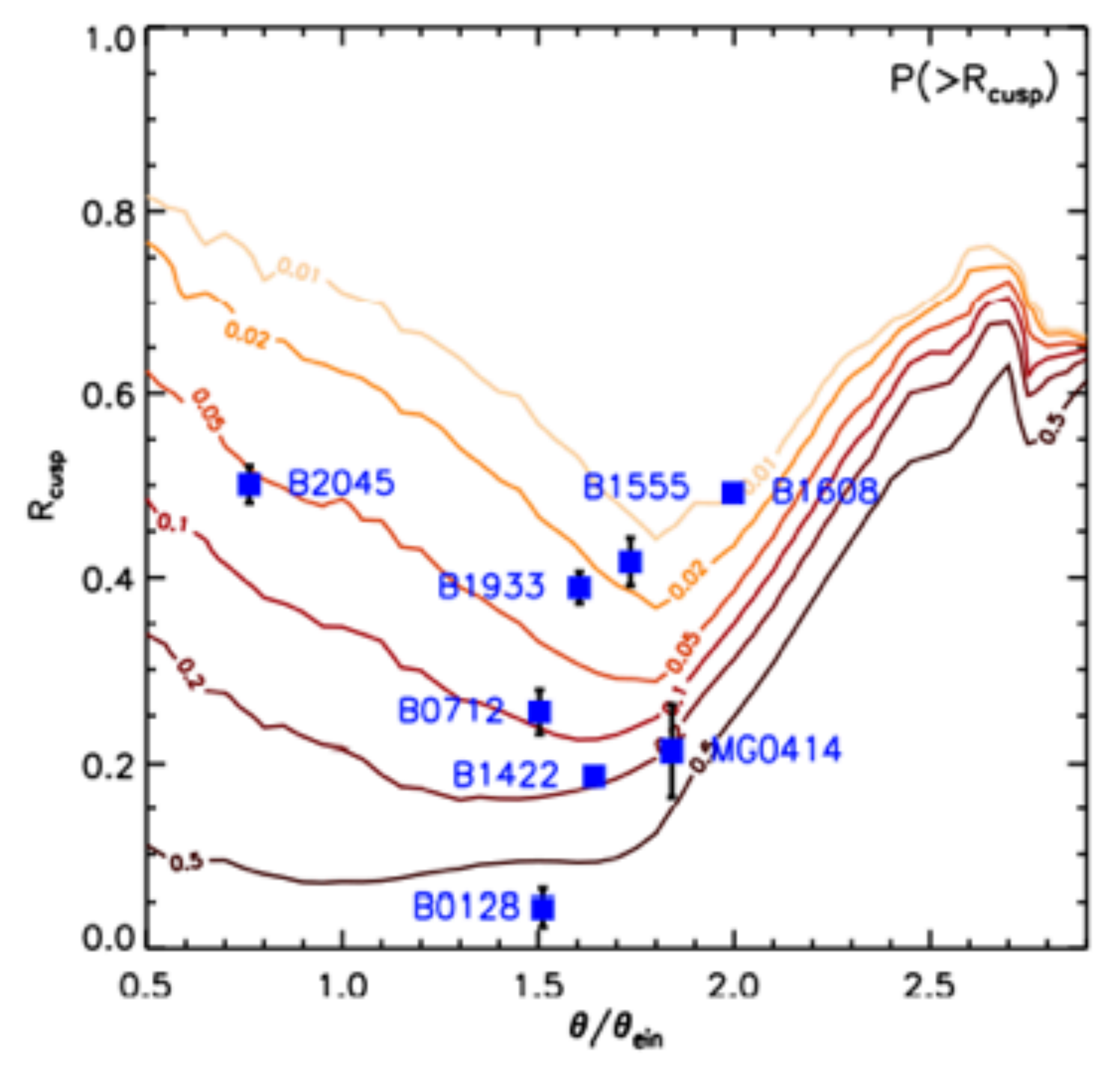

$\sigma = 0.8\ kpc$


$\sigma = 0\ kpc$

Xu et al. 2009

FLUX RATIO ANOMALIES IN SIMULATIONS

- the observed cusp lenses violate the cusp relation more frequently than predicted by the the Aquarius simulation
- the discrepancy is not related to the resolution of the simulation
- the probability of reproducing the observed rate is 0.2% and as high as 30% with the los is included
- maybe not a proper comparison
- proper masses and ellipticity increases the probability to 36%



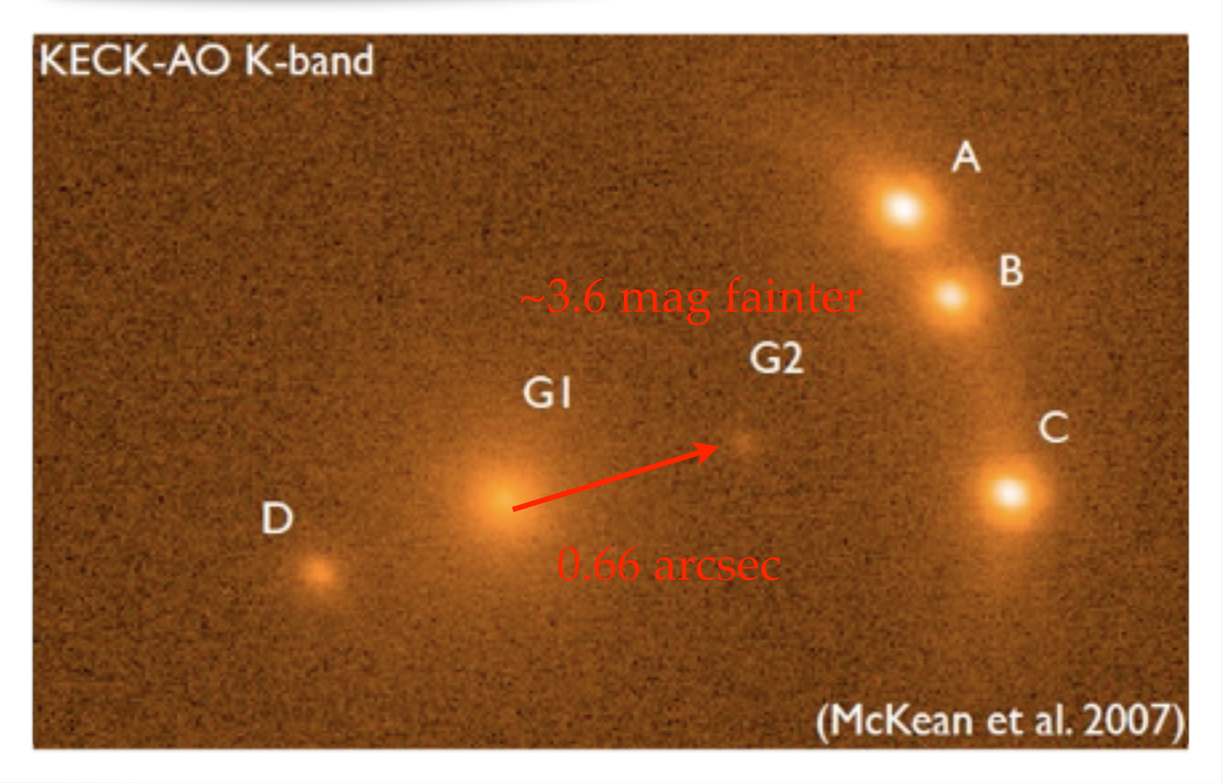
McKean et al. 2007

Schechter & Moore 1993

More et al. 2009

photometric redshift

UMINOUS SATELLITES



(McKean et al. 2007)

- 3/6 radio loud systems show evidence of a luminous satellite within 5 kpc from the host galaxy
- once these are included in the mass model the flux ratios can be reproduced along side with the images positions
- up to 1% of the host mass is contained in these systems
- 5/22 of all CLASS lenses have a luminous satellite within 5 kpc

- Are such luminous satellite galaxies expected this frequently?

Koopmans 2005

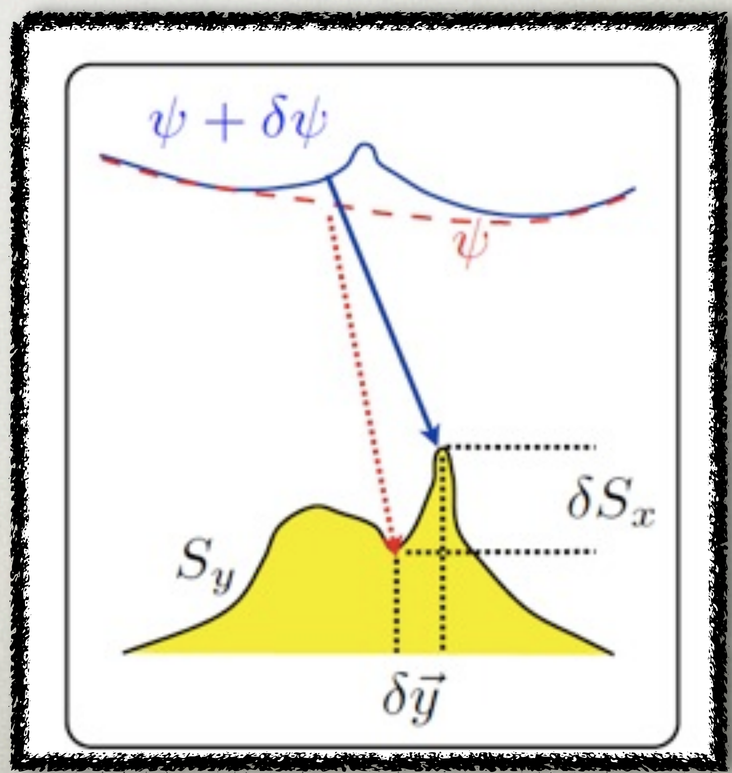
Vegetti & Koopmans 2009

GRAVITATIONAL IMAGING

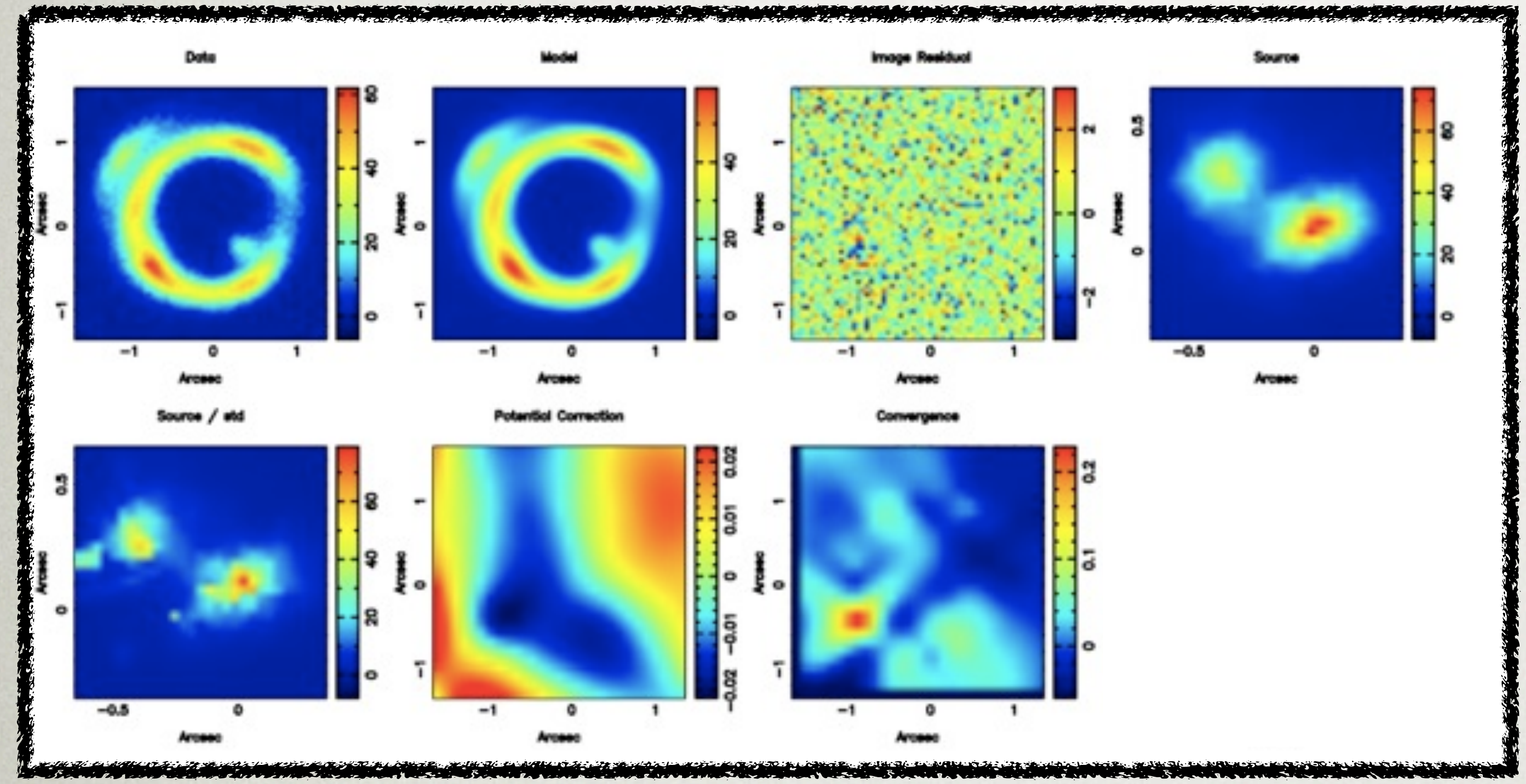
$$\psi(\mathbf{x},\eta)_{tot} = \psi(\mathbf{x},\eta) + \delta\psi(\mathbf{x})$$

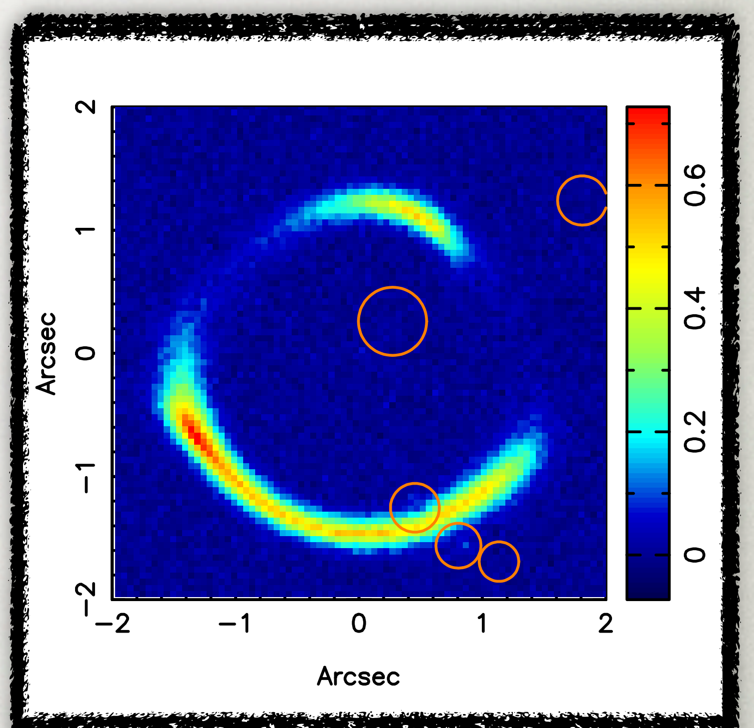
$\psi(\mathbf{x},\eta)$ Smooth analytic power-law model

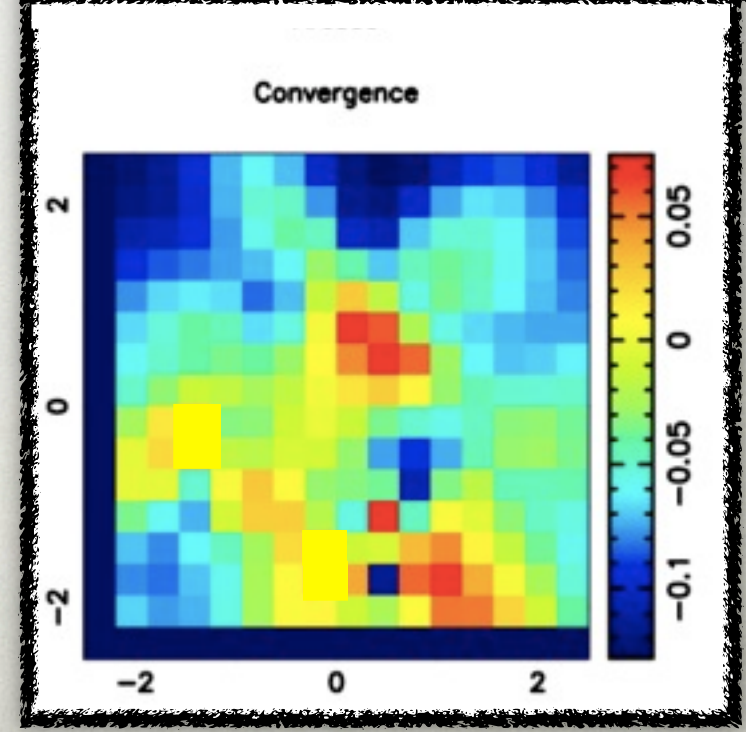
$\delta\psi(\mathbf{x})$ pixellated potential correction



GRAVITATIONAL IMAGING



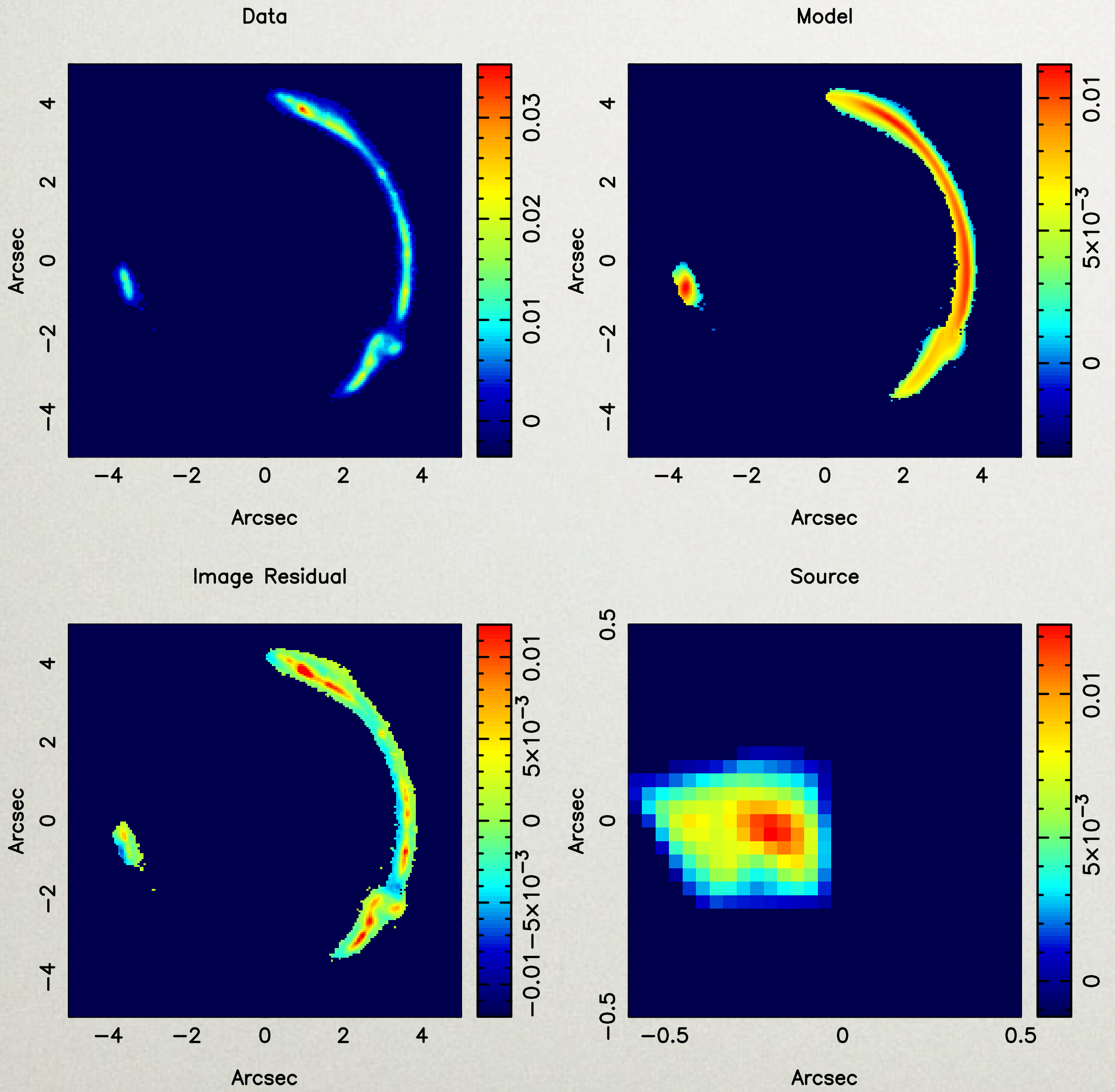


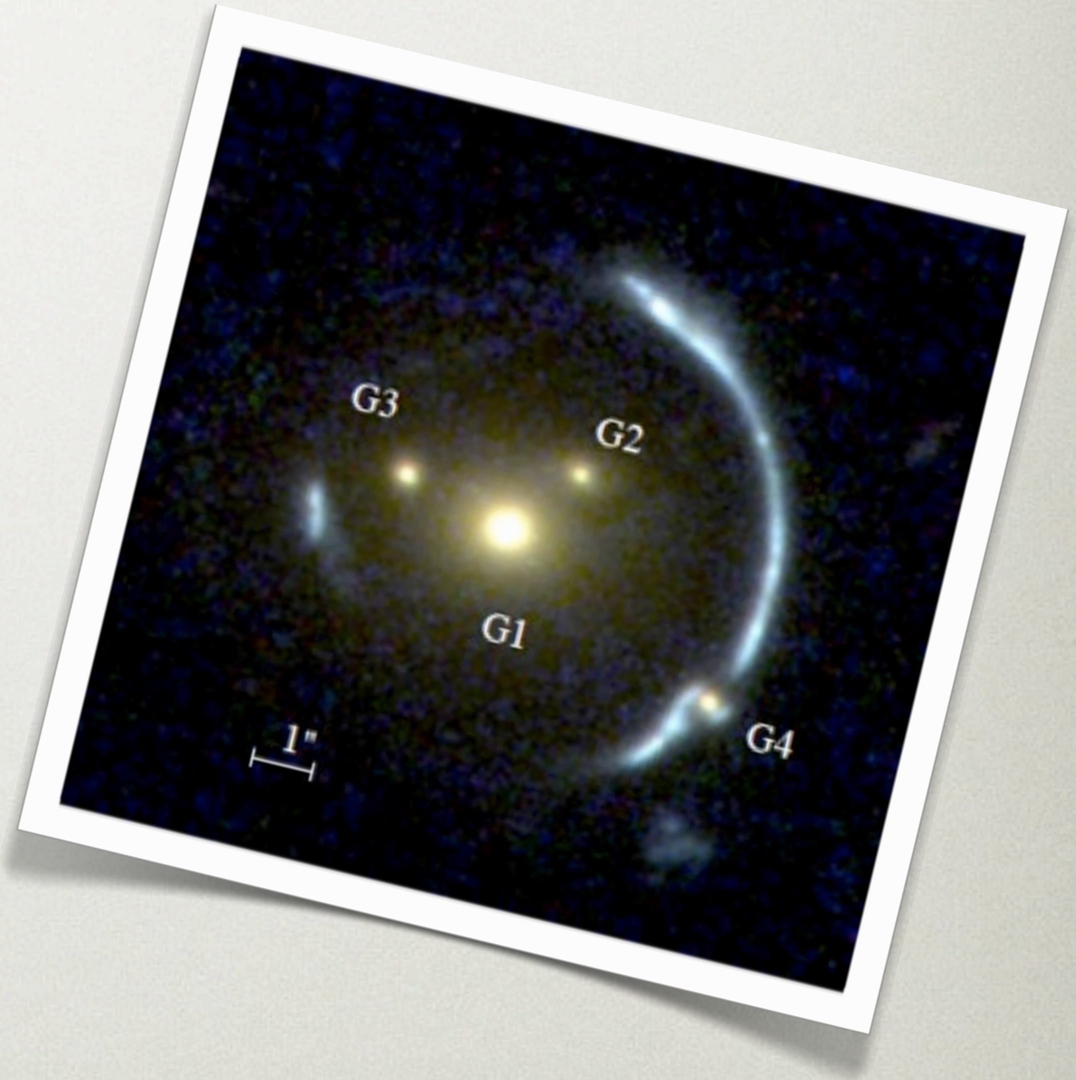


- substructures are responsible of localised surface brightness perturbations and are detected as localised potential corrections
- Any substructure can be detected provided it is mass enough and/or close enough to the Einstein ring
- For each substructure detected its mass can be measured by assuming a mass model or directly from the pixelated corrections in a model independent way

Vegetti et al. 2010

GRAVITATIONAL IMAGING

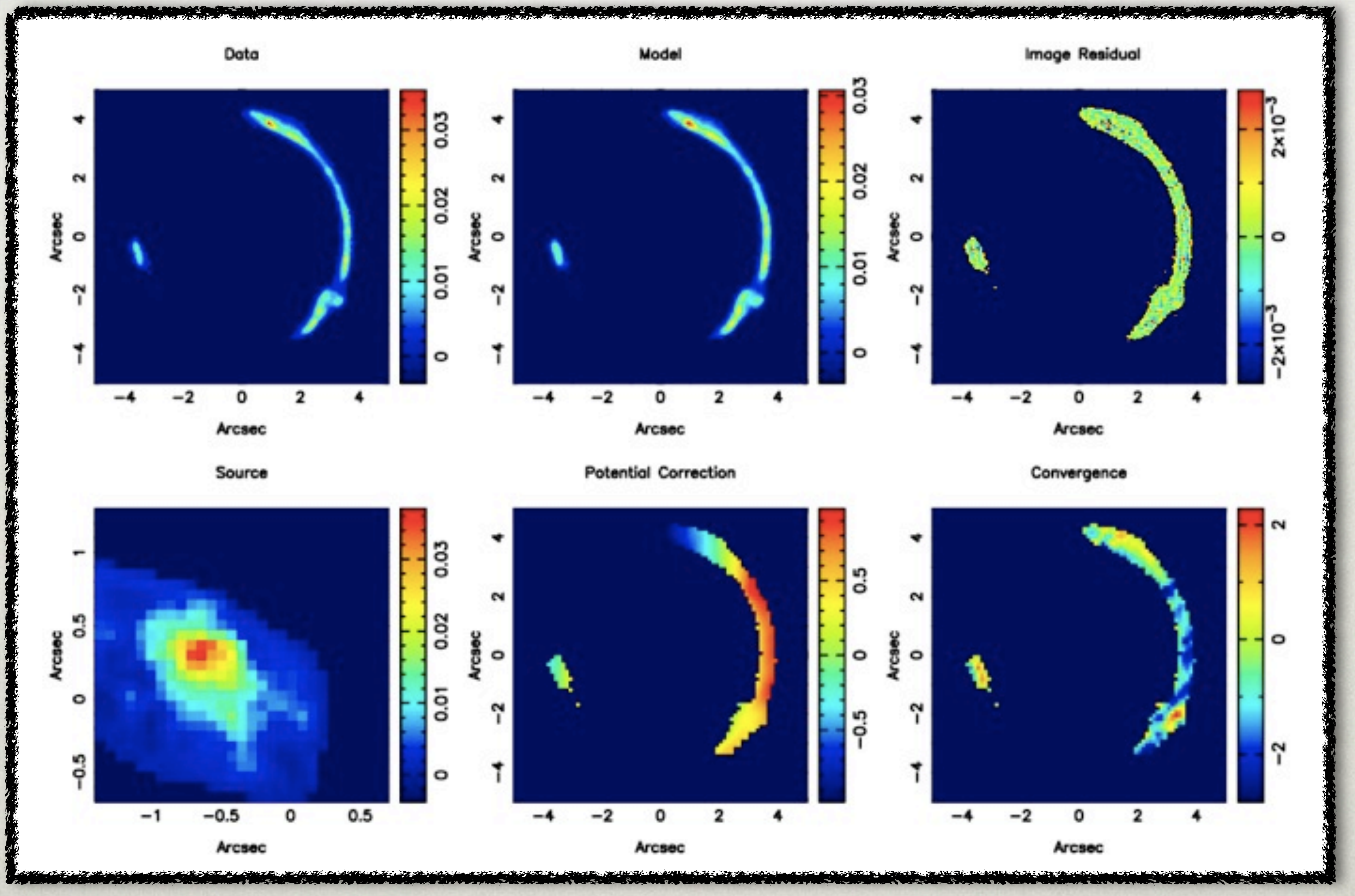




Simple smooth model with a power-law mass density profile

Vegetti et al. 2010

GRAVITATIONAL IMAGING

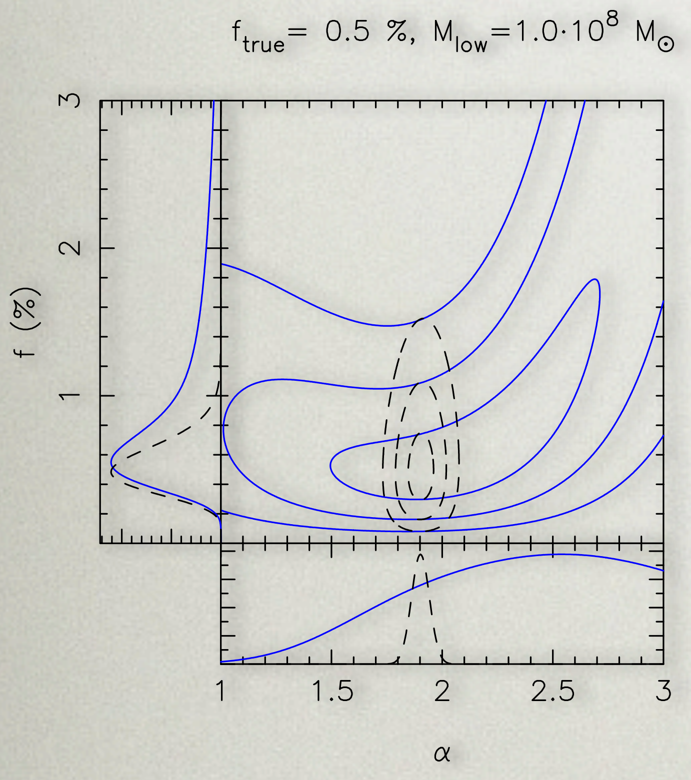


Smooth model plus potential corrections

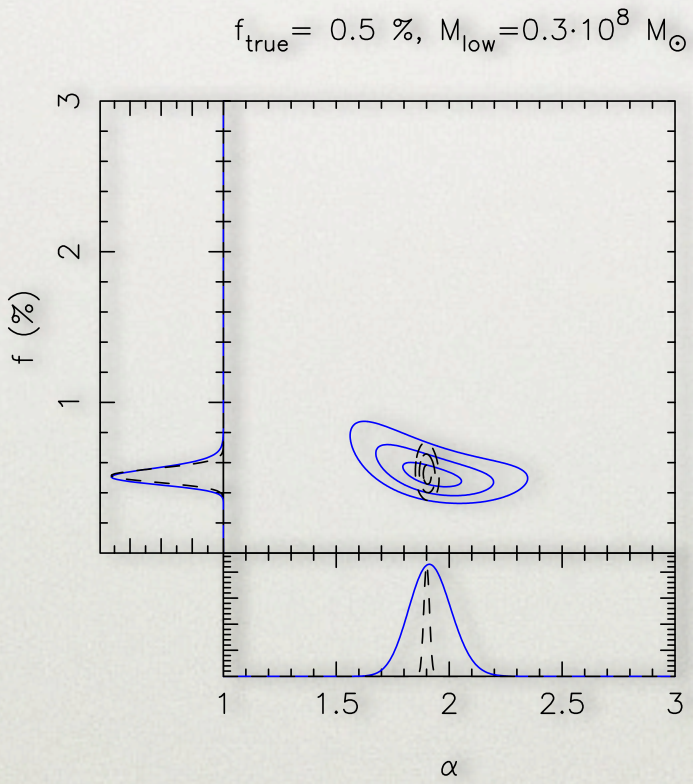
Vegetti & Koopmans 2009

STATISTICS OF DETECTIONS

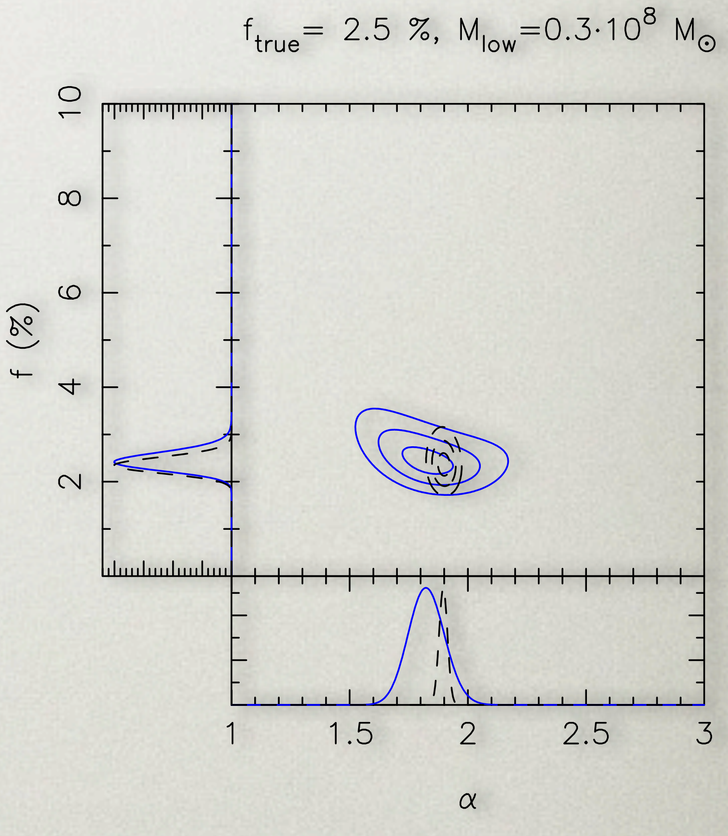
$$P(\alpha, f \mid \{n_s, \mathbf{m}\}, \mathbf{p}) = \frac{\mathcal{L}(\{n_s, \mathbf{m}\} \mid \alpha, f, \mathbf{p})\, P(\alpha, f \mid \mathbf{p})}{P(\{n_s, \mathbf{m}\} \mid \mathbf{p})}$$


f_{true} = 0.5 %, $M_{low}=1.0\cdot10^8\ M_\odot$

10 not-very sensitive lenses cannot constrain the slope of the mass function


f_{true} = 0.5 %, $M_{low}=0.3\cdot10^8\ M_\odot$

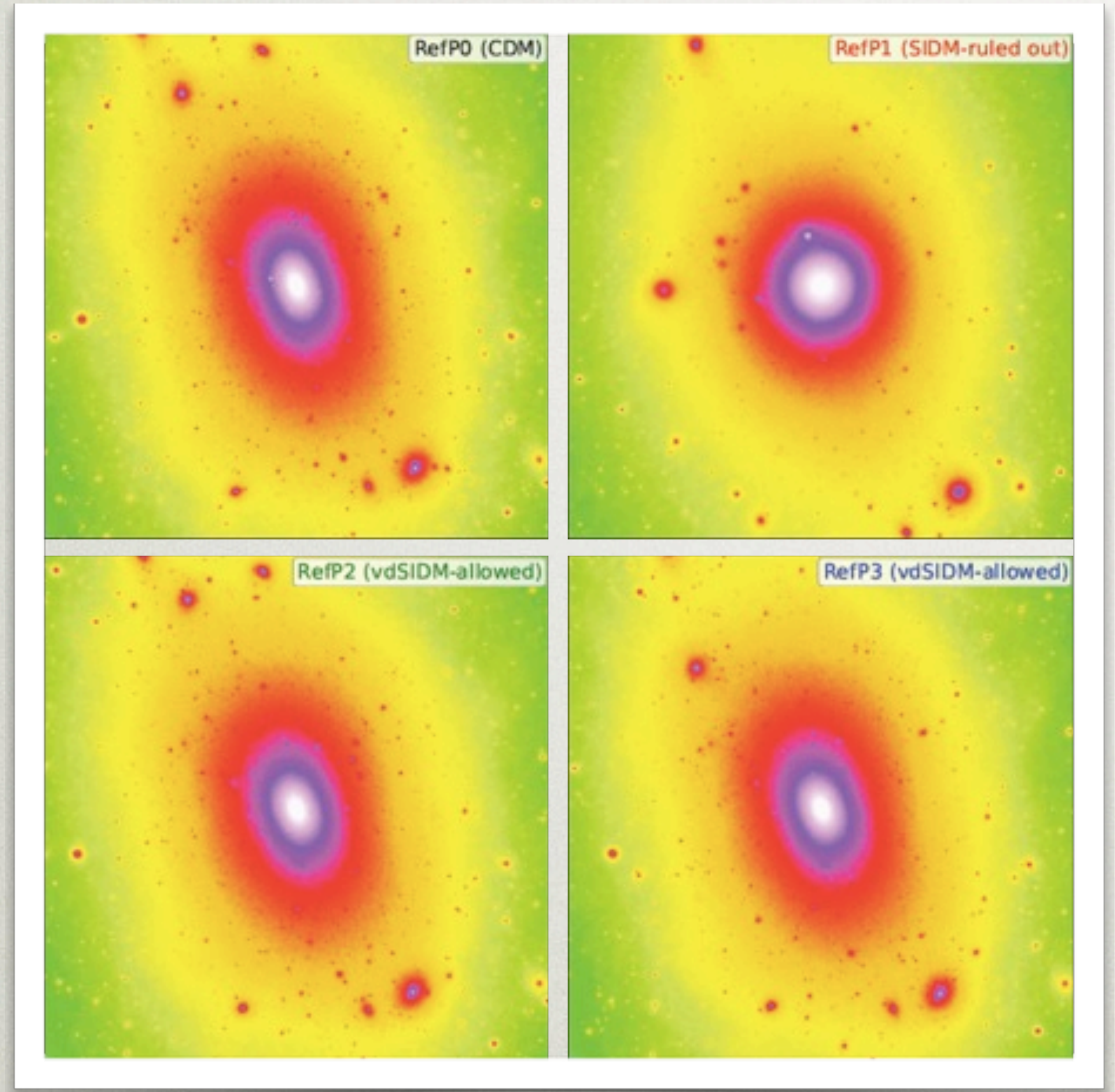
200 very sensitive lenses can constrain the mass function at the few percent level

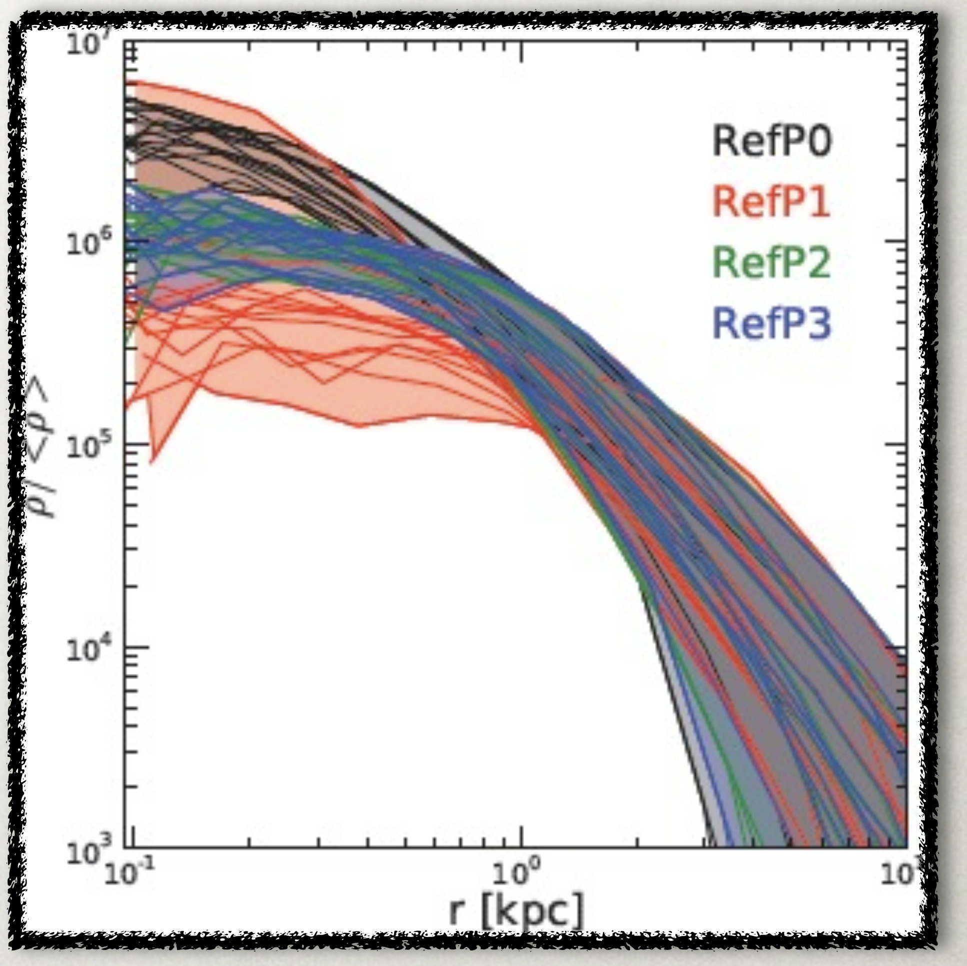

f_{true} = 2.5 %, $M_{low}=0.3\cdot10^8\ M_\odot$

but 10 may be just enough

Vogelsberger et a. 2012

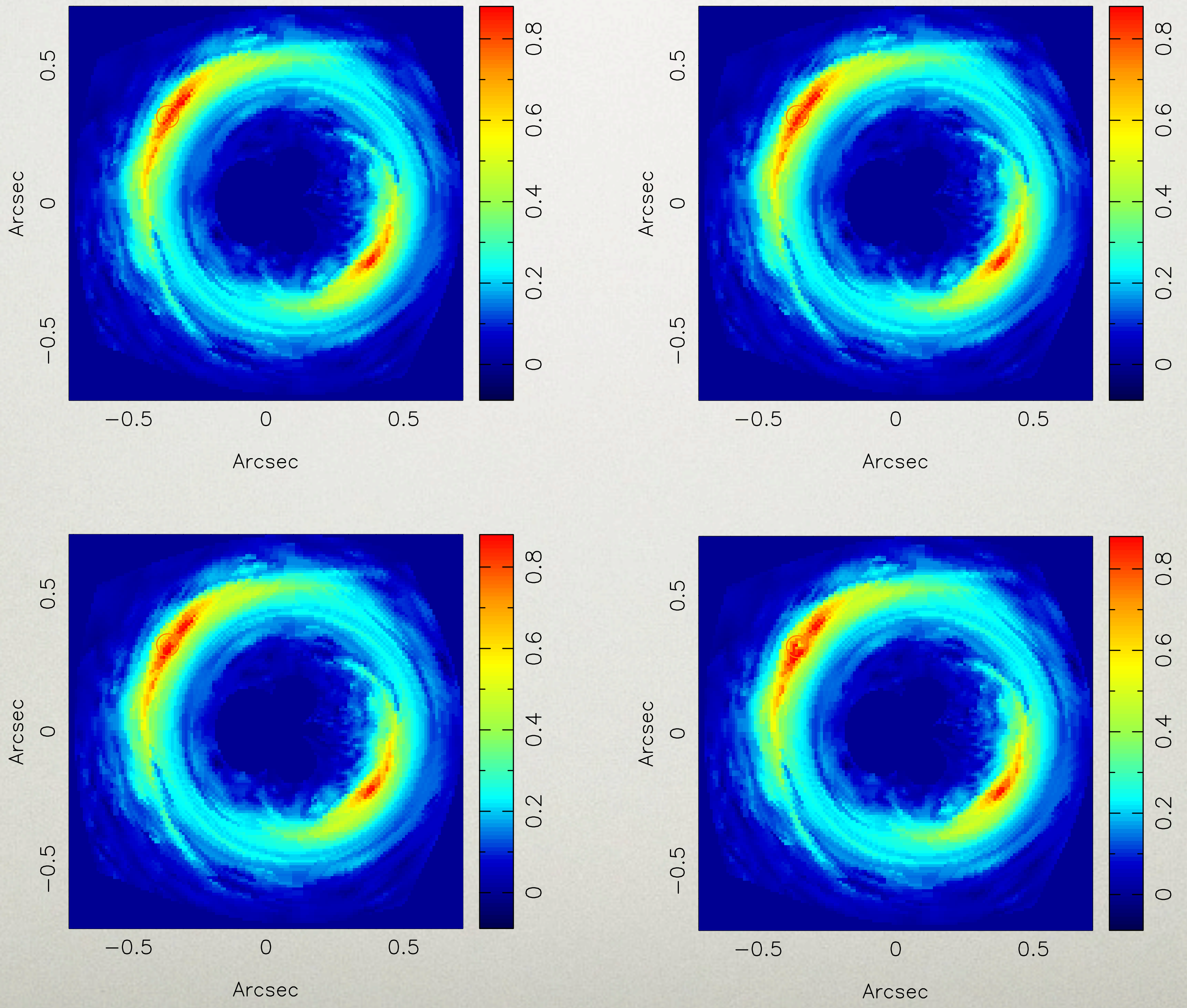
CDM vs SIDM





Vegetti & Vogelsberger in prep

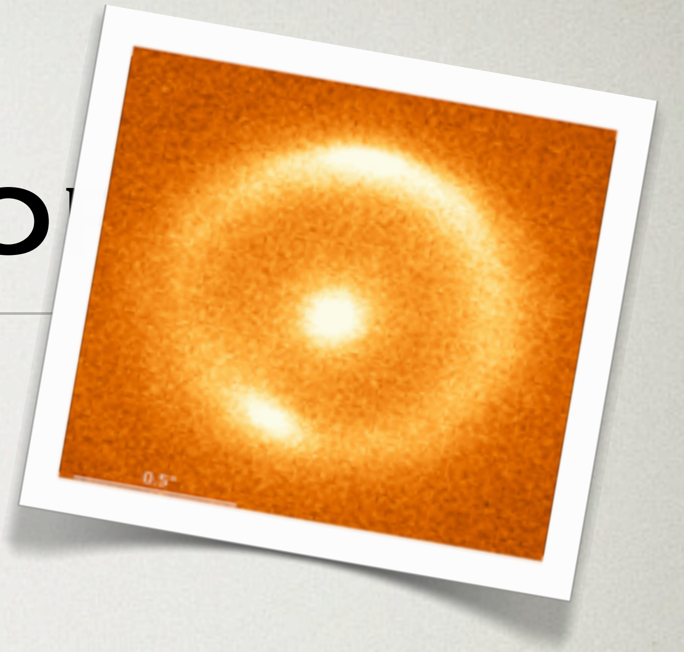
SENSITIVITY TO THE PROFILE


$M_{sub} = 10^9\ M_\odot$

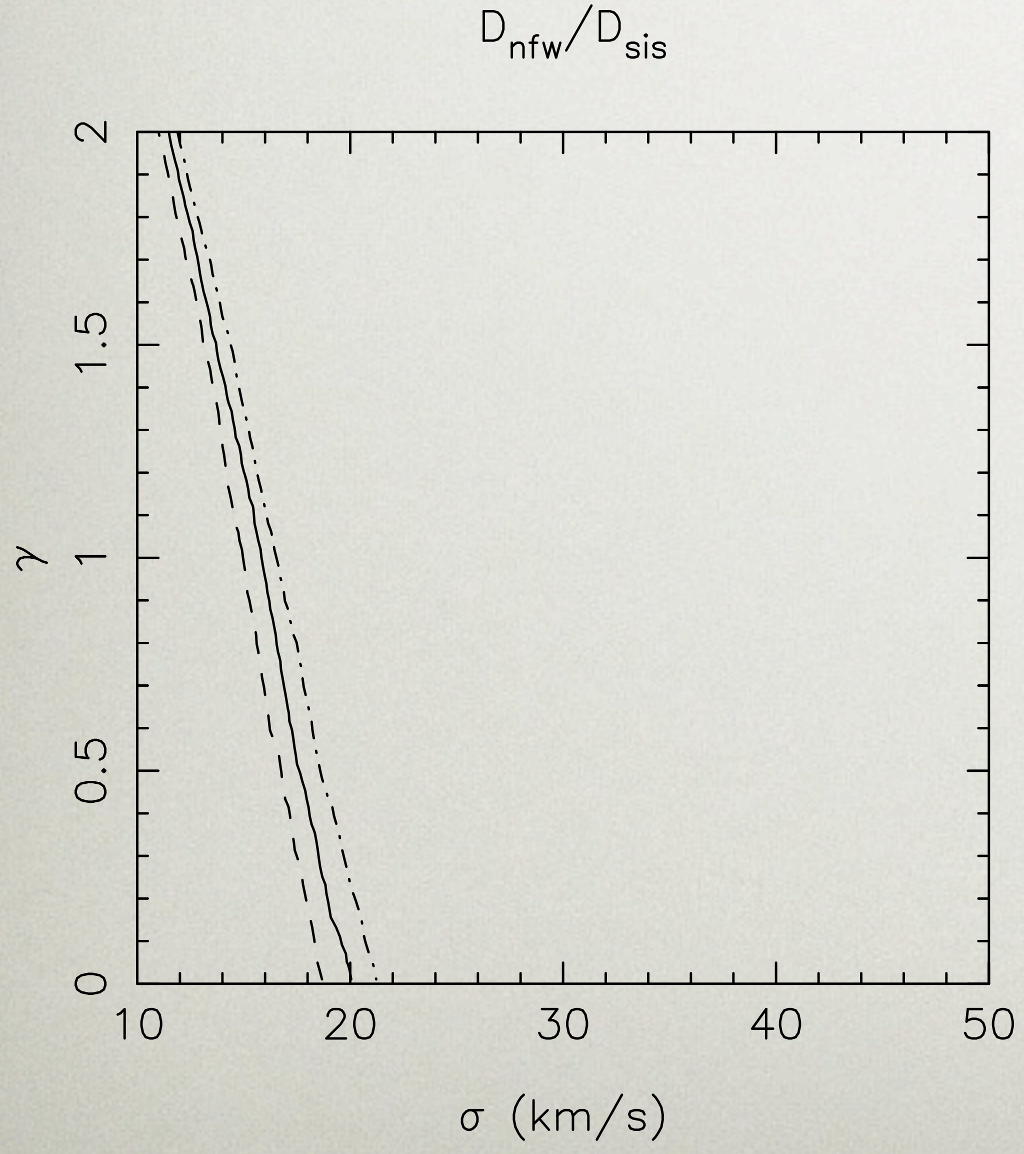
$r_c = 0 - 300\ pc$

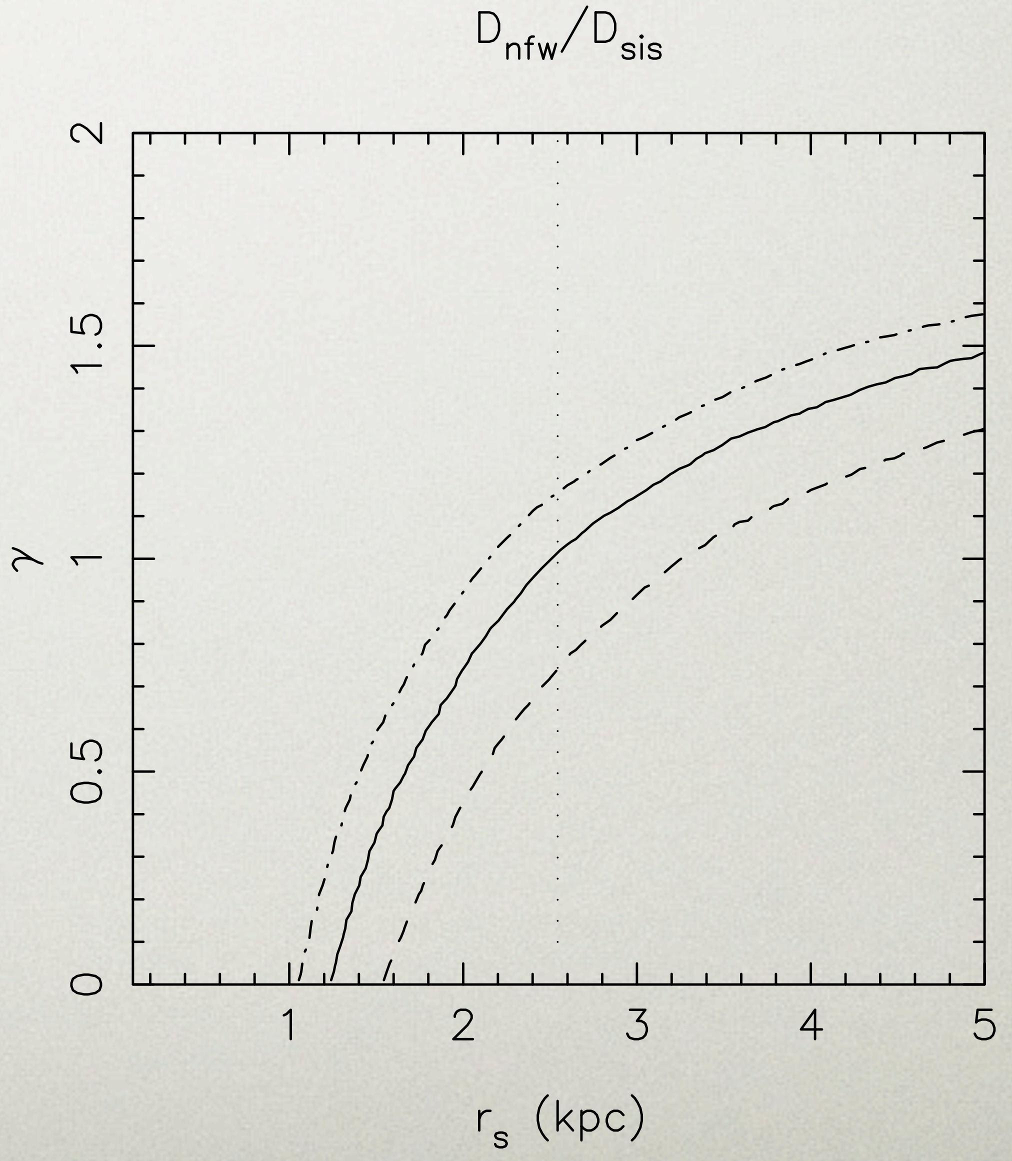
Vegetti & Vogelsberger in prep

SENSITIVITY TO THE PRO



$$\rho = \frac{\rho_s}{(r/r_s)^{\gamma}(1+r/r_s)^{3-\gamma}}$$

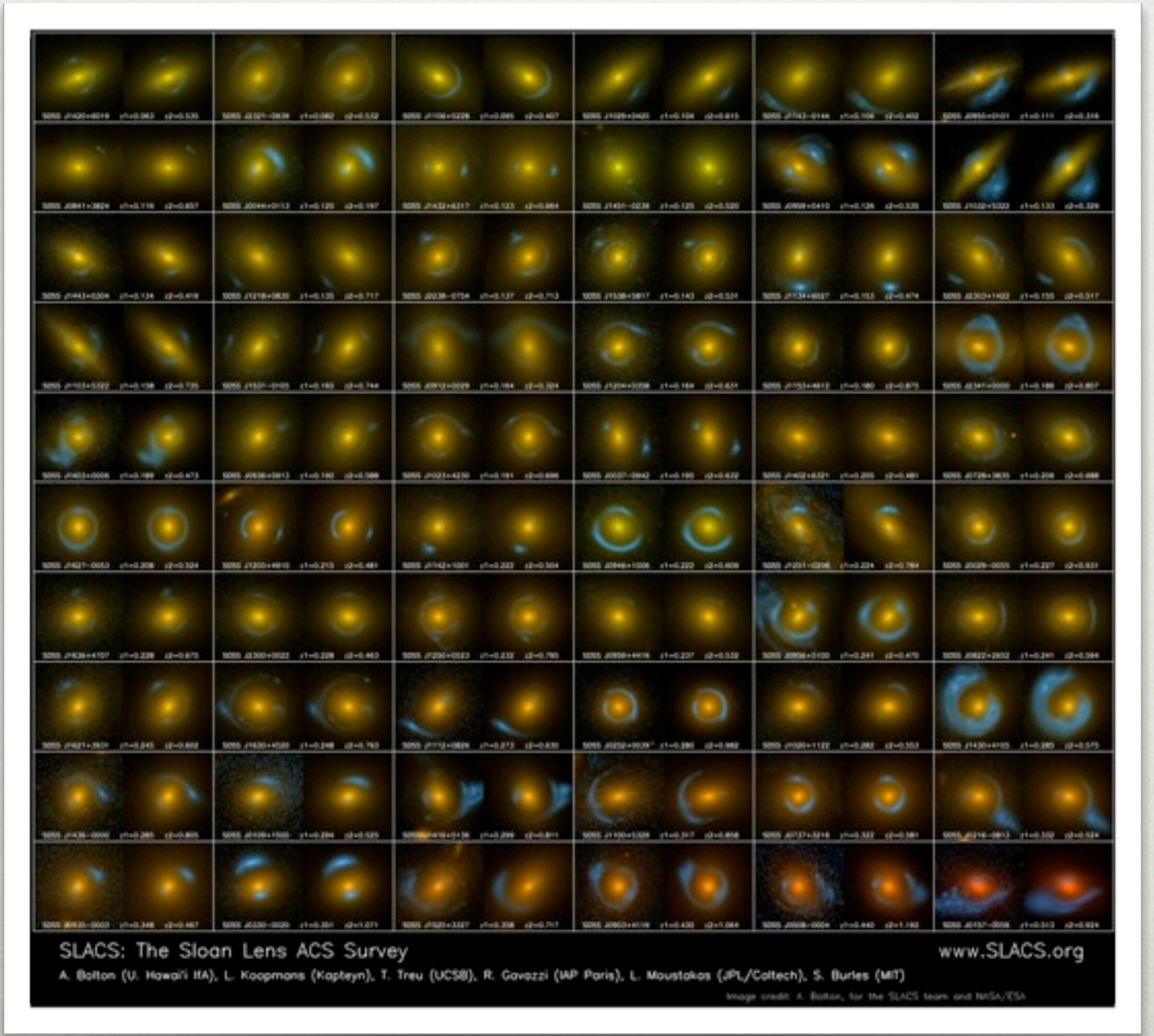




Bolton et al. 2006

Bolton et al. 2008

SLACS



$$z = 0.06 - 0.36$$

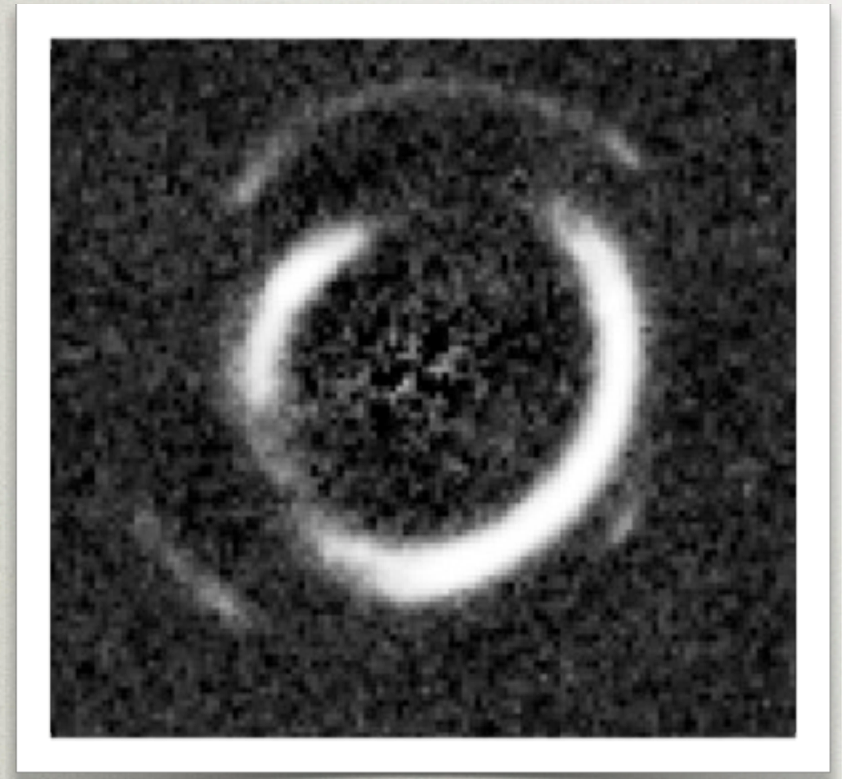
$$\sigma_\star = 175 - 400\ km\ s^{-1}$$

Gavazzi et al. 2008

Vegetti et al. 2010

Sonnenfeld et al. 2012

SLACS-DOUBLE RING



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

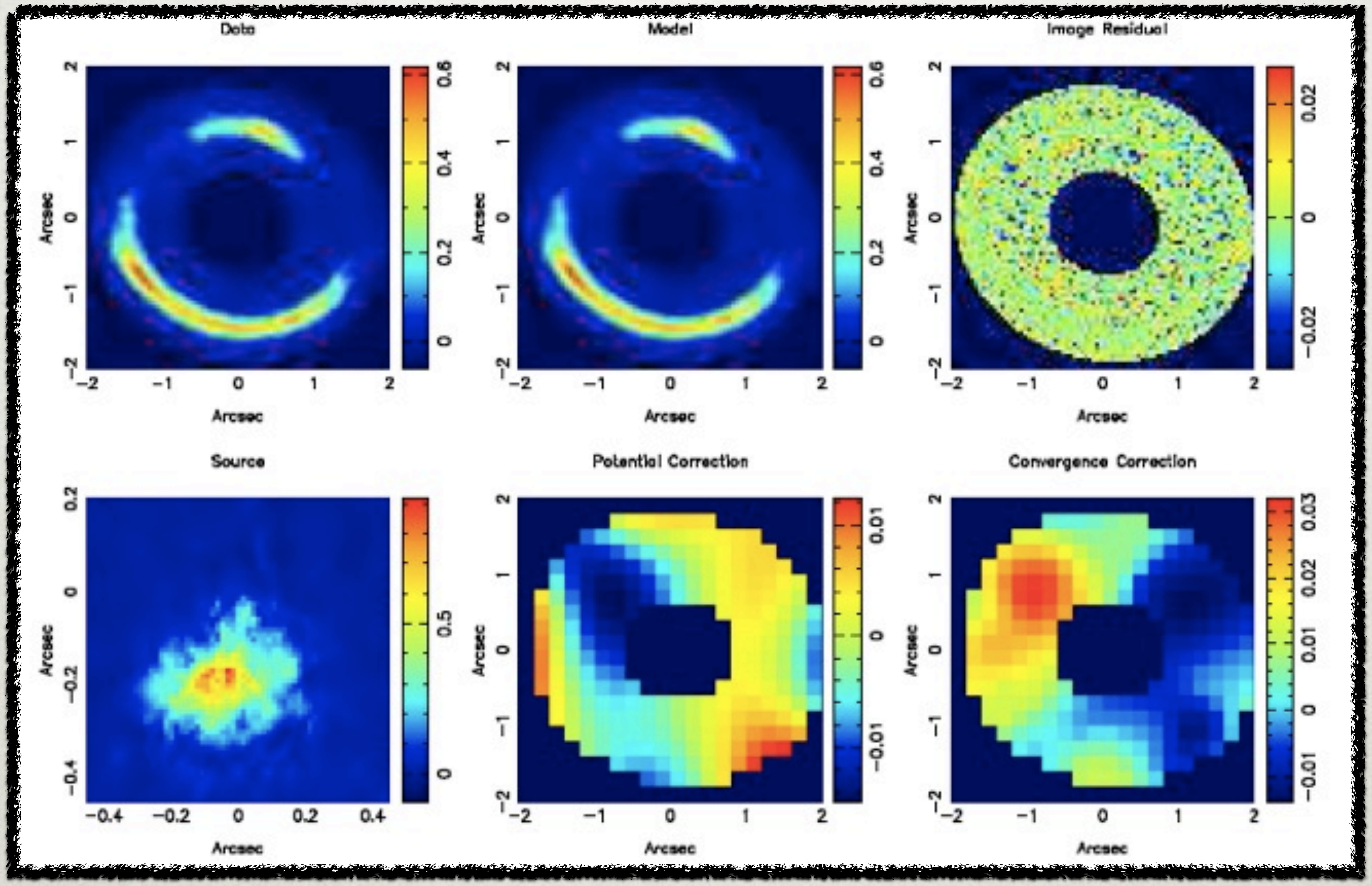
$$\Delta R = R_{ein} \pm 0.3$$

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

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

Vegetti et al. 2010

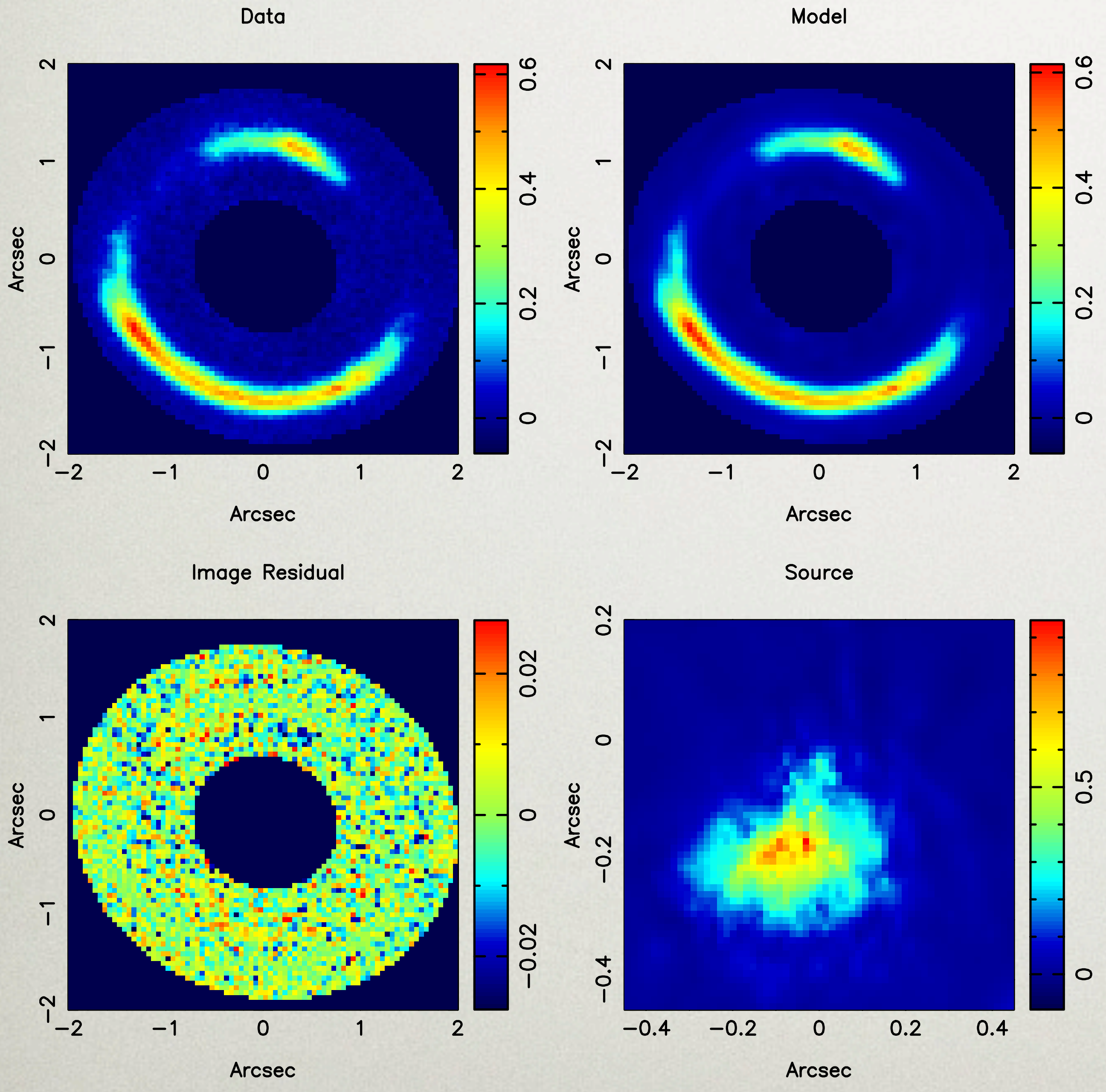
DOUBLE RING



Results are stable against changes in the PSF, lens galaxy subtraction, pixel scale and rotation

Vegetti et al. 2010

DOUBLE RING



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

$$r_t = 1.1 \; kpc$$

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

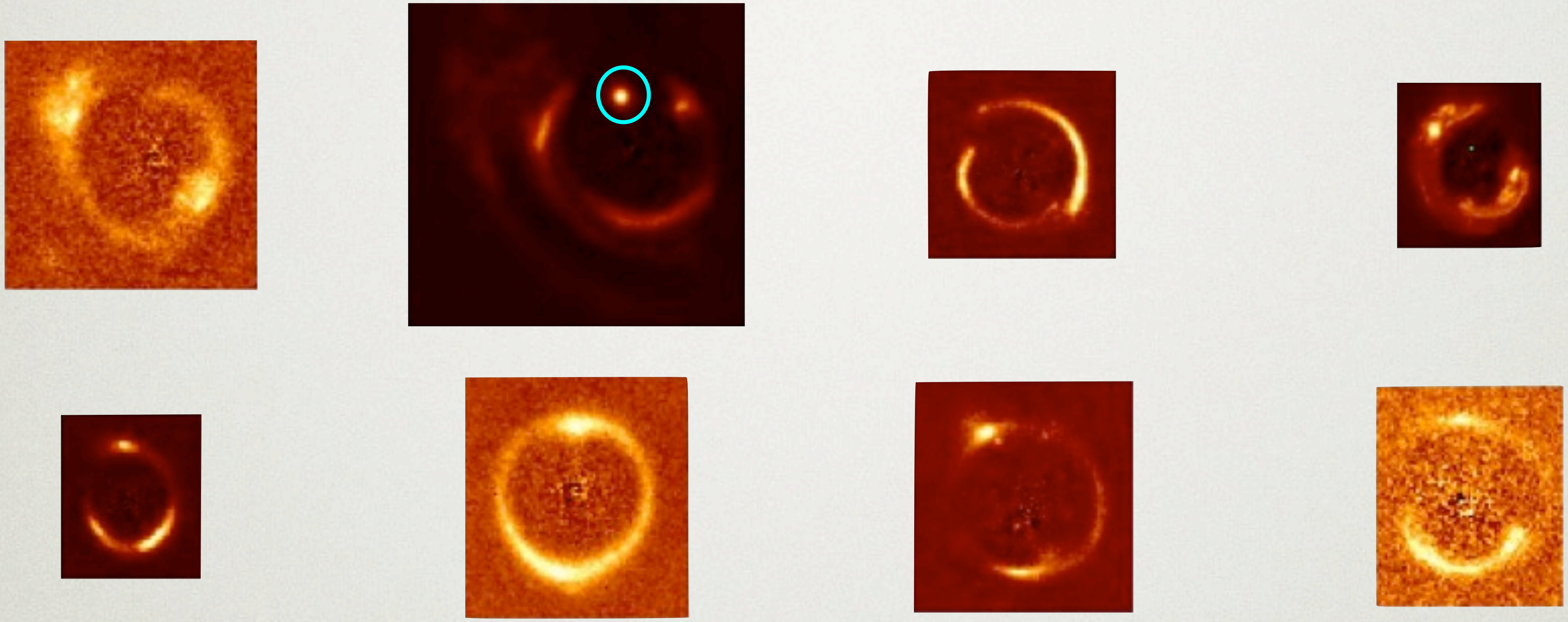
$$L_V \leq 5 \times 10^6 L_\odot$$

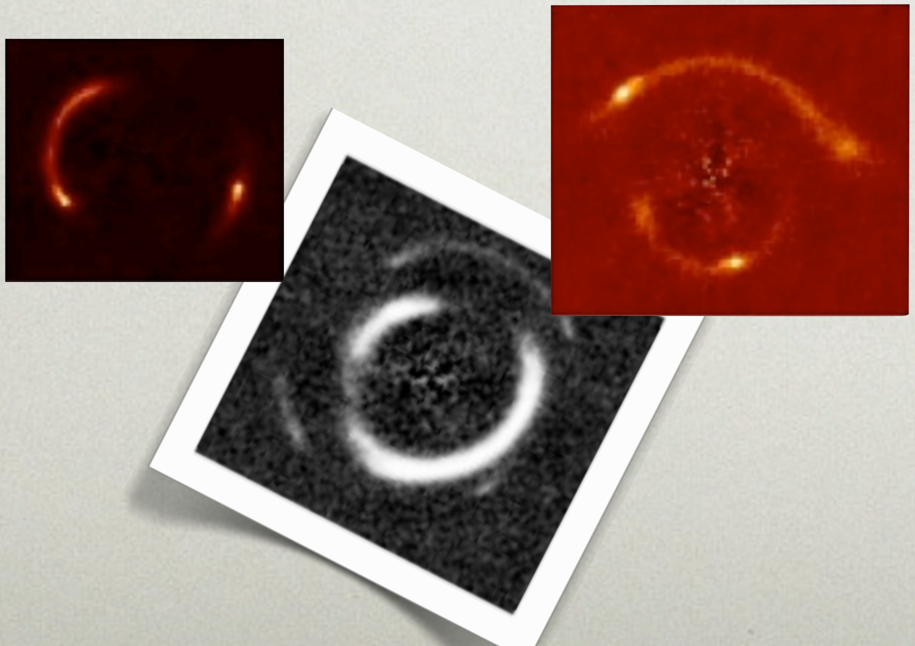
$$M_{\rm 3D}(<0.3) = 5.83 \times 10^8 M_\odot$$

$$({\rm M/L})_{{\rm V},\odot} \geq 120 \;\; M_\odot/{\rm L}_{{\rm V},\odot}$$

$z = 0.06 - 0.36 \quad \sigma_\star = 175 - 400\ km\ s^{-1}$

$$M_{tot} = 3.2 \times 10^9 M_\odot$$
$$M_{DM} = 7.0 \times 10^8 M_\odot$$





- Chosen on a s/n basis
- Representative sub-sample of the SLACS lenses
- Representative sample of massive early-type galaxies

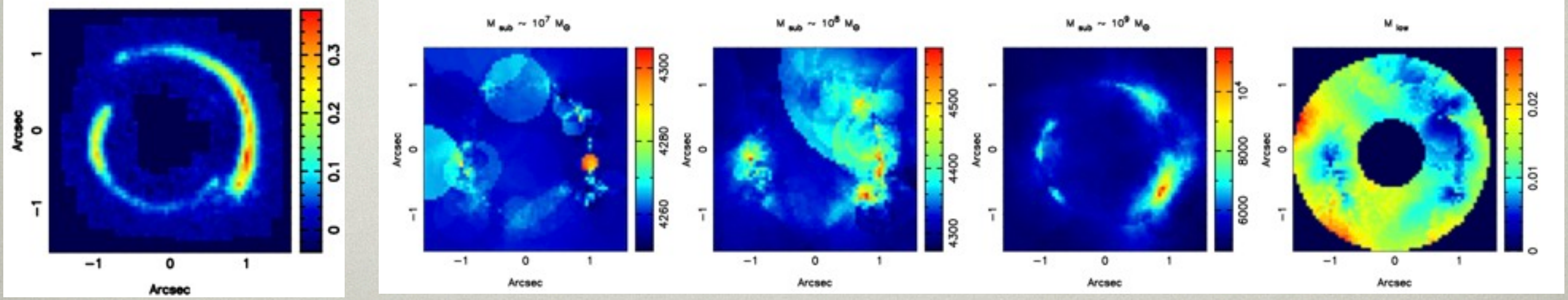
Vegetti & Koopmans 2009, Vegetti et al 2013

STATISTICS OF DETECTIONS

Constraining the substructure mass function

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

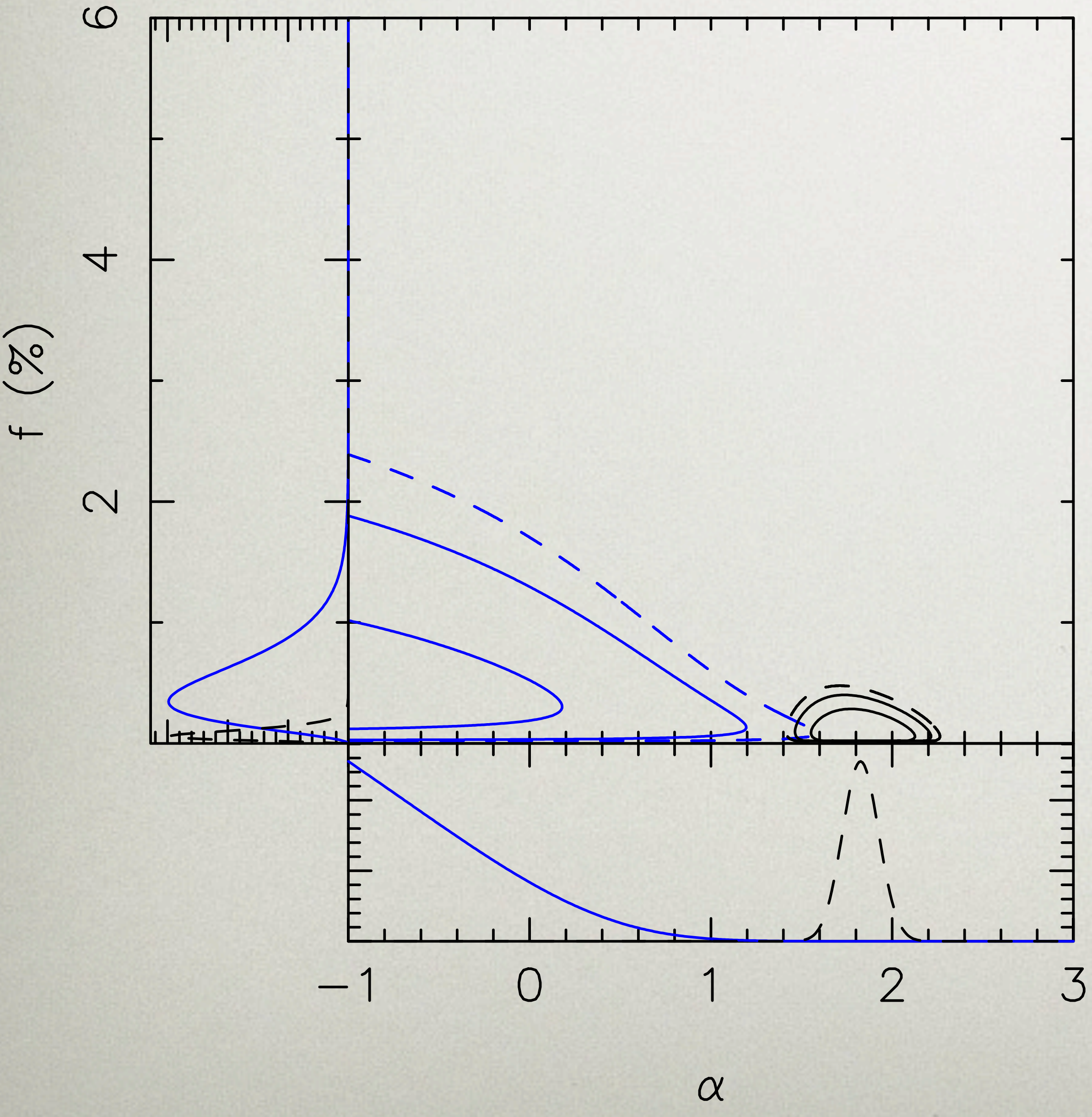
$$\mathcal{L}\left(n_s, \mathbf{m} \mid \alpha, f, \mathbf{p}\right) = \frac{e^{-\mu(\alpha, f, <R)} \; \mu(\alpha, f, < R)^{n_s}}{n_s!} \prod_{i=1}^{n_s} P\left(m_i, R \mid \mathbf{p}, \alpha\right)$$



Vegetti et al. 2013 in prep.

SLACS MASS FUNCTION

Preliminary!



Normalization: uniform prior between 0 and 100 percent

Slope: uniform prior between -1 and 3, Gaussian prior centred on 1.90

$$f = 0.48^{+0.48}_{-0.28}\%$$

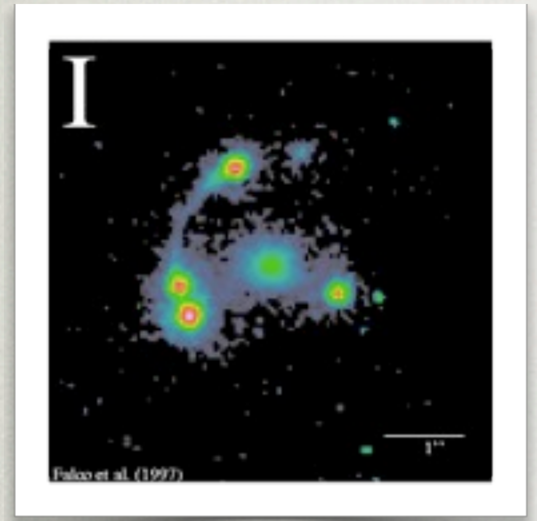
$$\alpha = -0.43^{+0.63}_{-0.41}$$

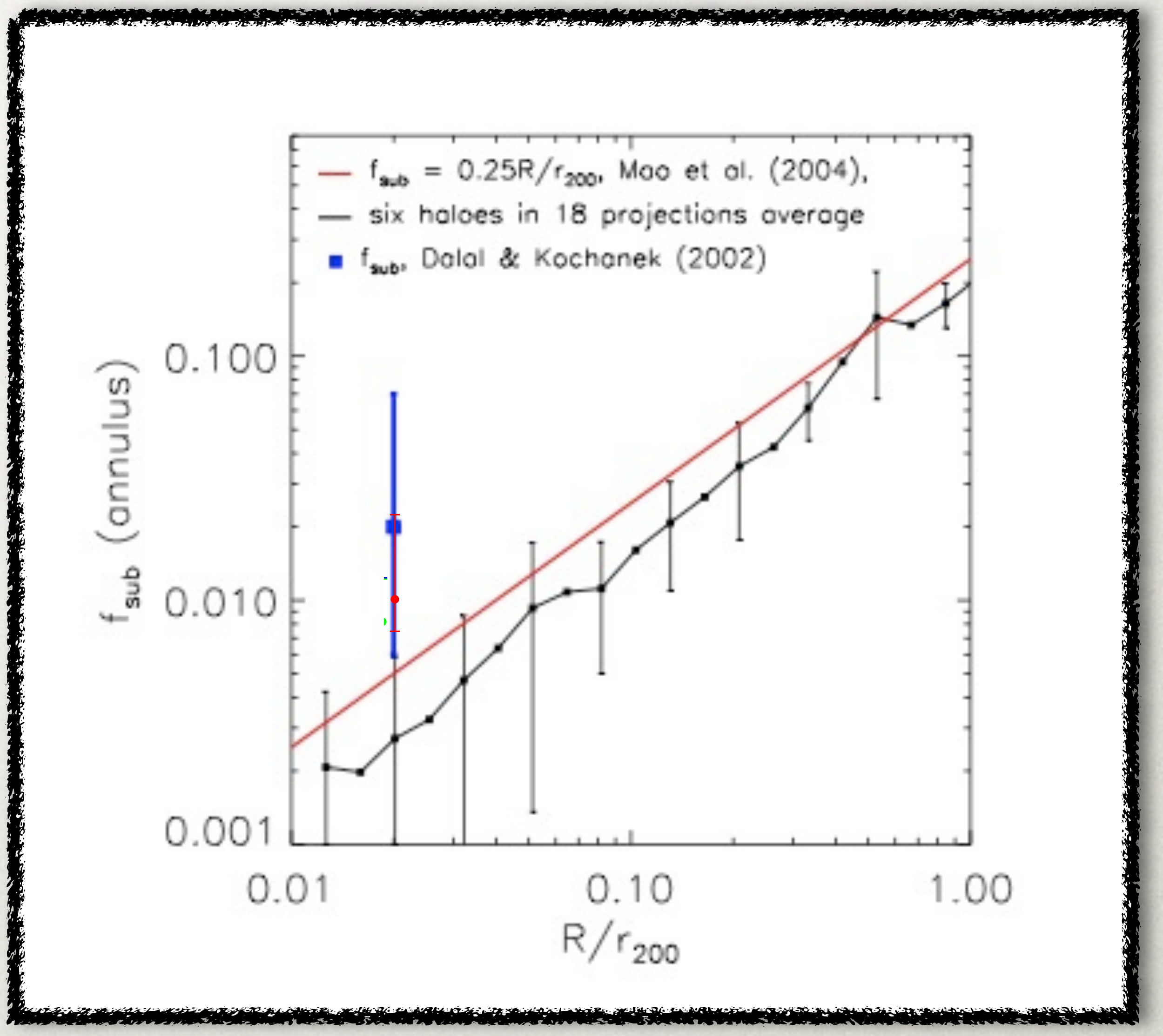
$$f = 0.06^{+0.07}_{-0.03}\%$$

Dalal & Kochanek 2002

Xu et al. 2009

OBSERVATIONS VS PREDICTIONS





- 6/7 radio loud CLASS lenses show a flux ratio anomaly
- No microlensing, or dust extinction but gravitational origin
- Imply a projected dark matter fraction between 2 and 7 percent
- Because of the mass degeneracy we don't know how this mass is distributed

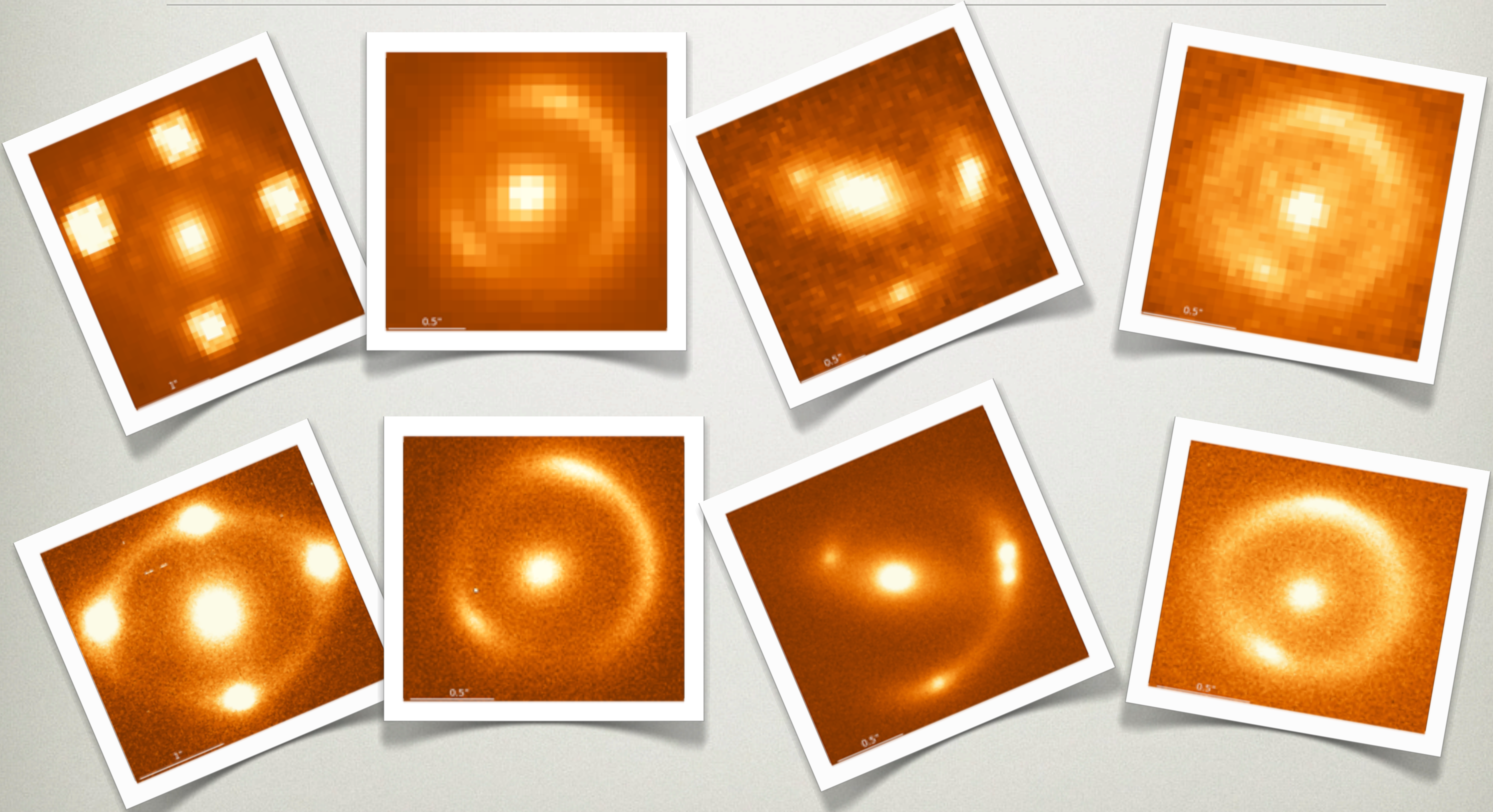
Preliminary!

$$f = 0.48^{+0.48}_{-0.28}\%$$

$$\alpha = -0.43^{+0.63}_{-0.41}$$

Vegetti et al. 2012

SHARP

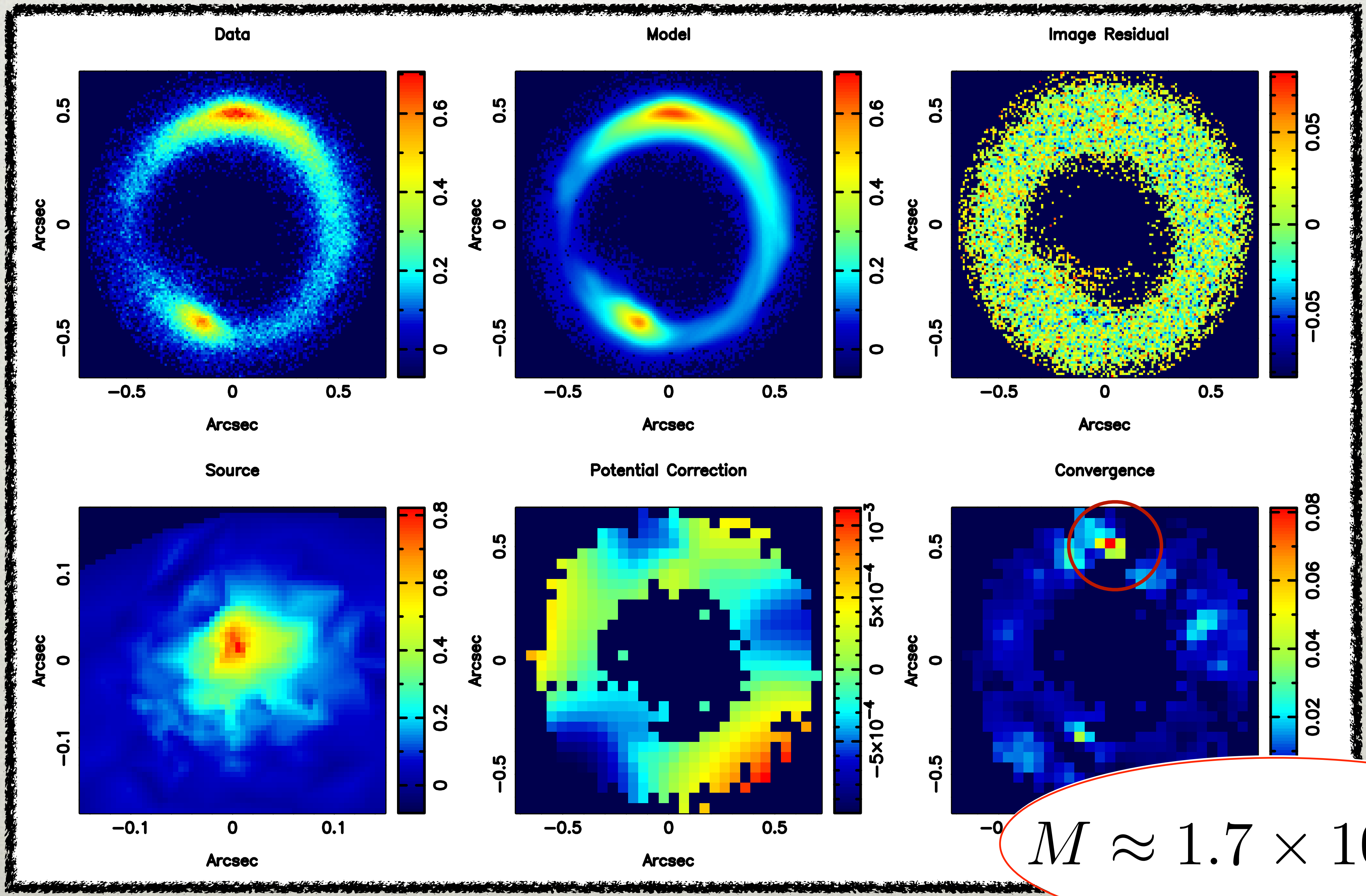


Medium sized sample of ~20 systems

$$M_{low} = 10^8 \ M_{\odot}$$

Vegetti et al. 2012

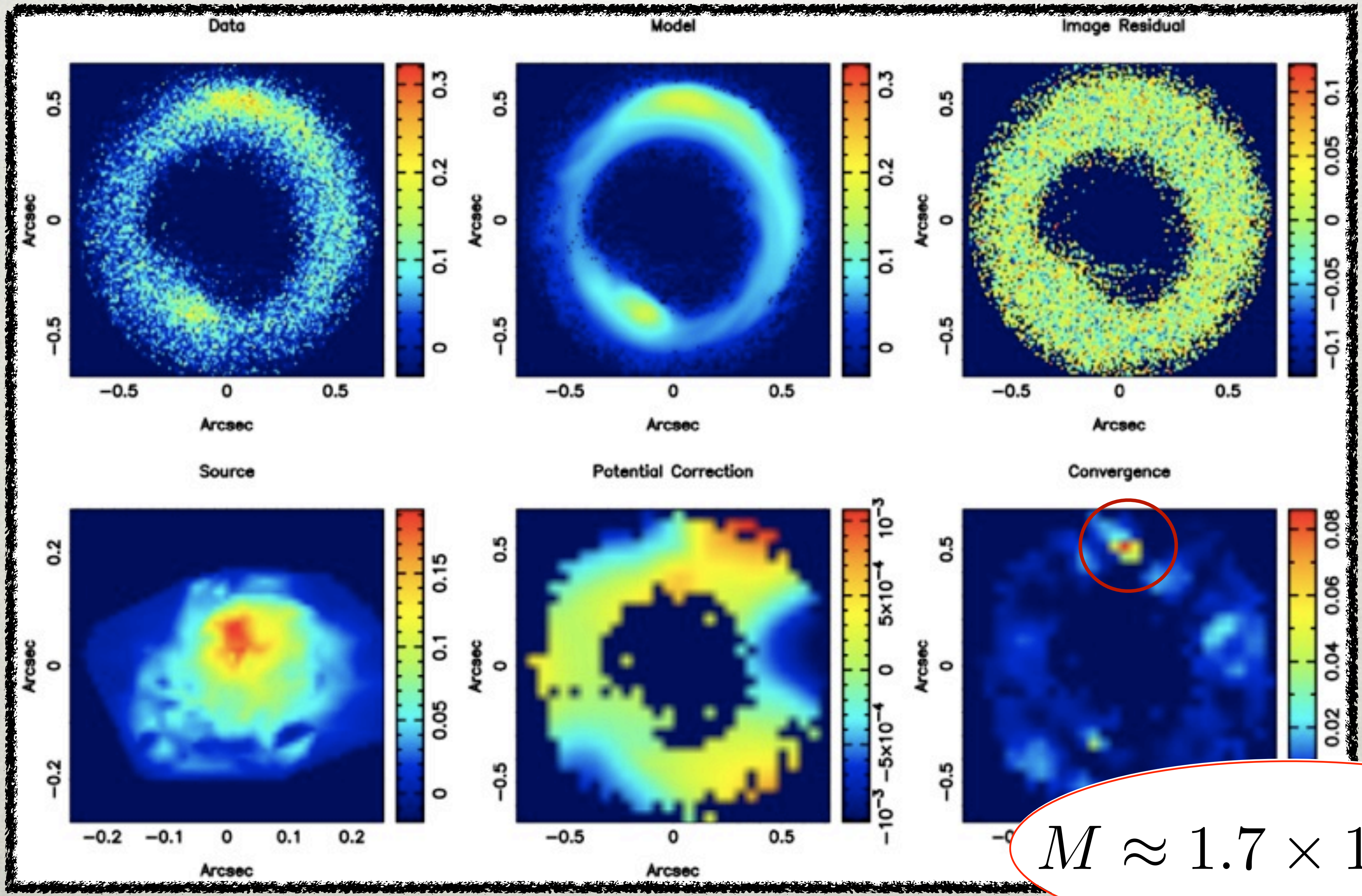
SHARP



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

Vegetti et al. 2012

SHARP



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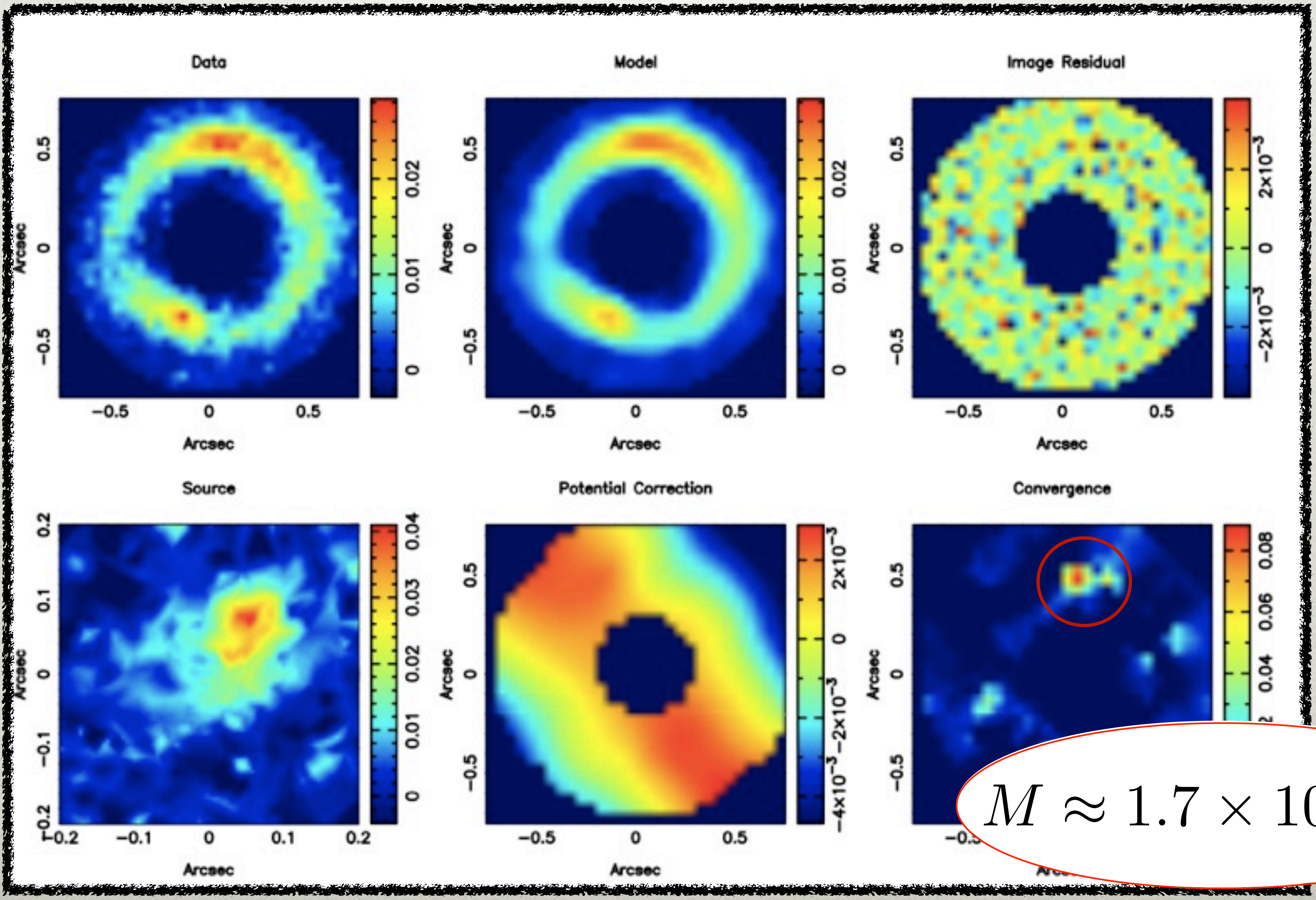
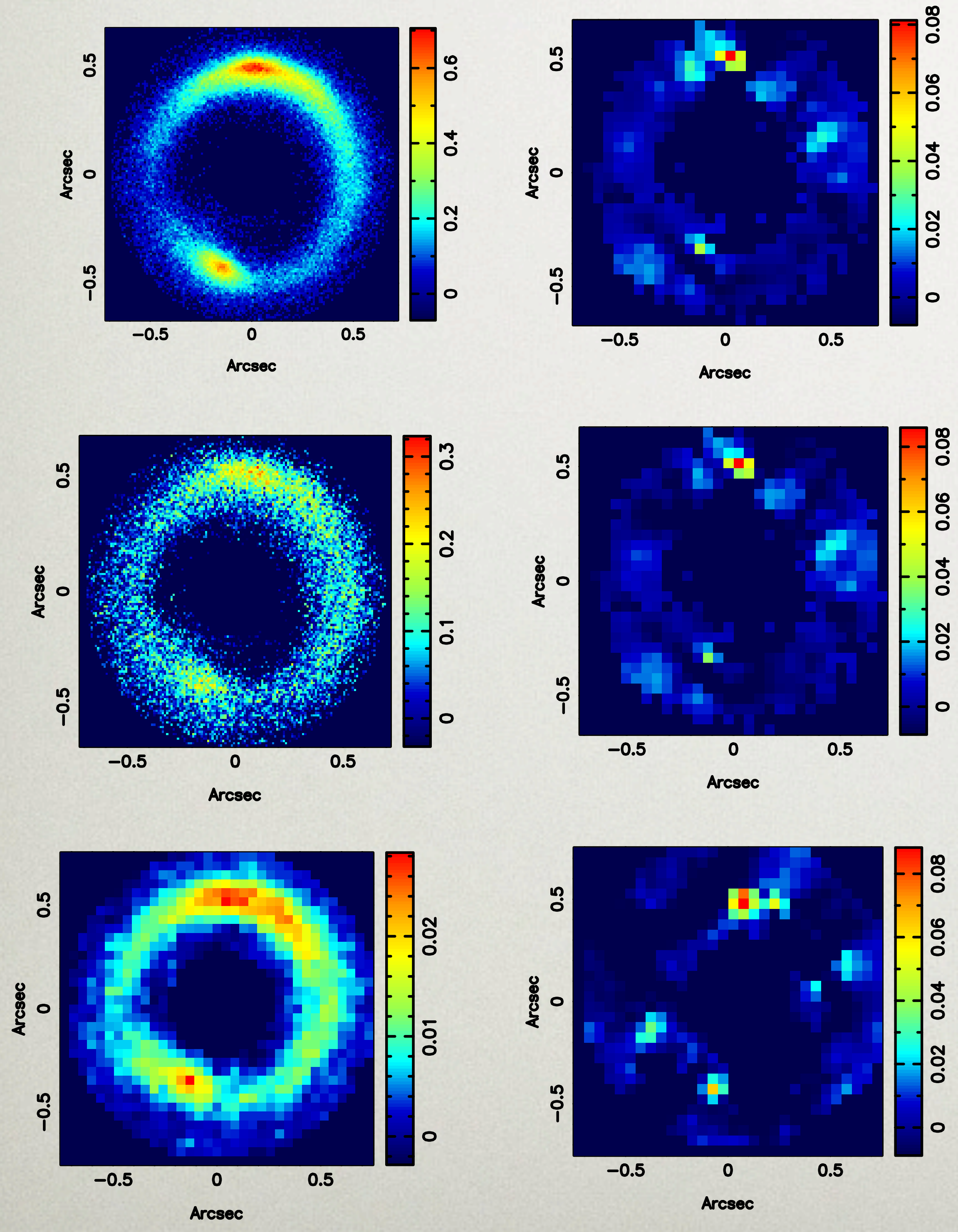
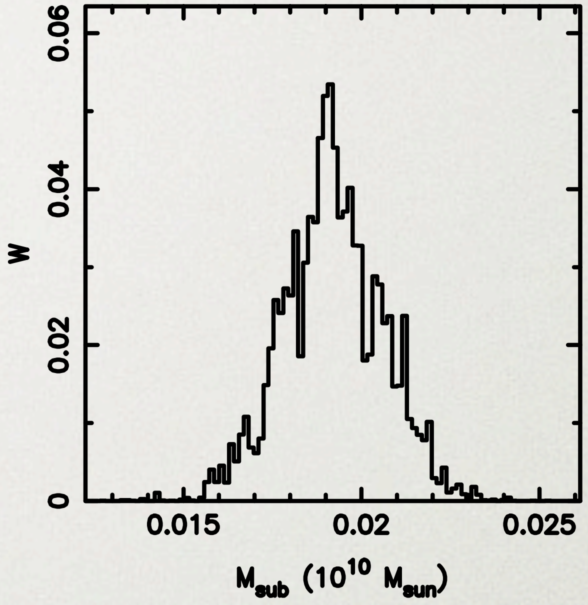


$$M \approx 1.7 \times 10^{8} M_{\odot}$$

Vegetti et al. 2012

SHARP





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

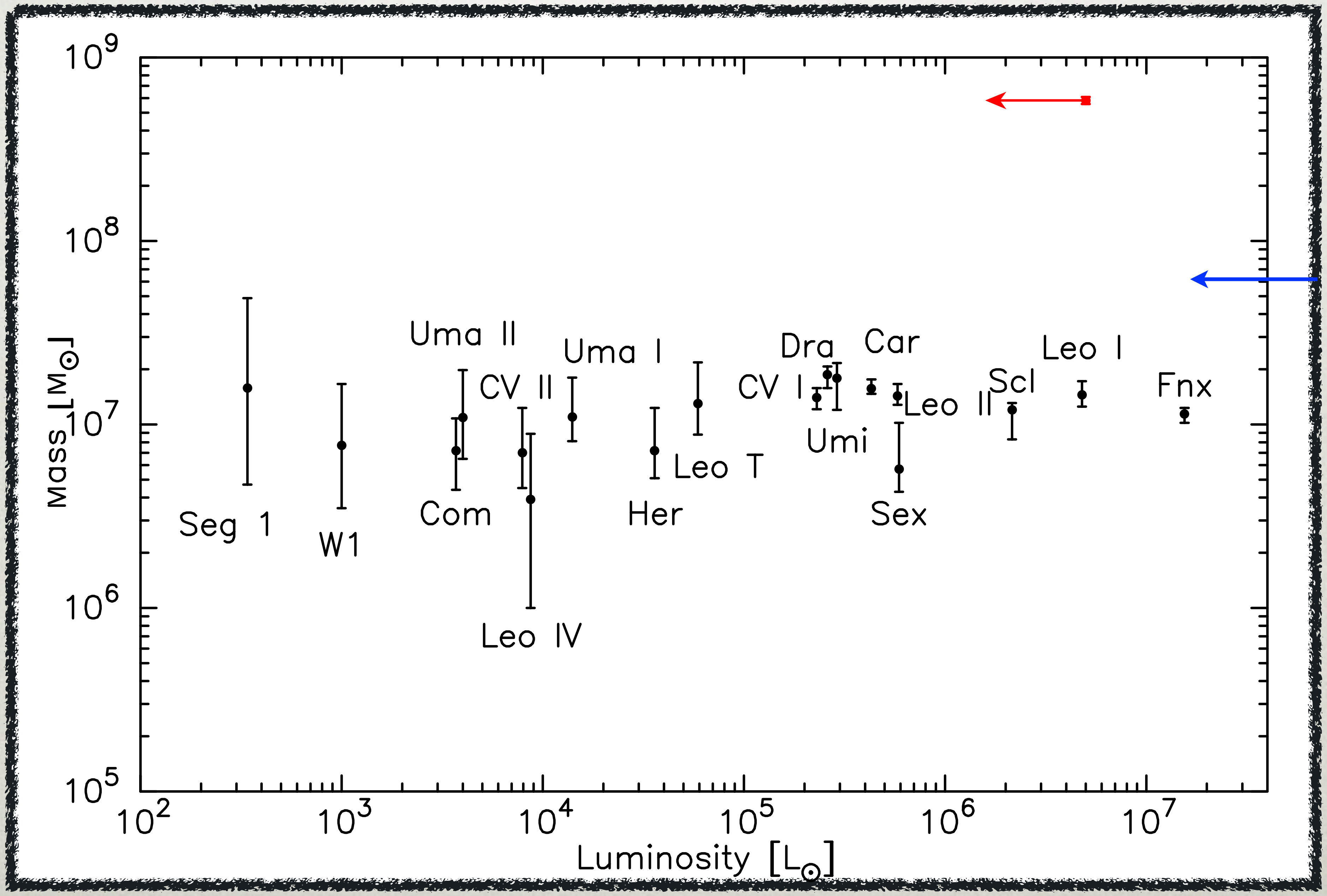
$$M(<0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot$$

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

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

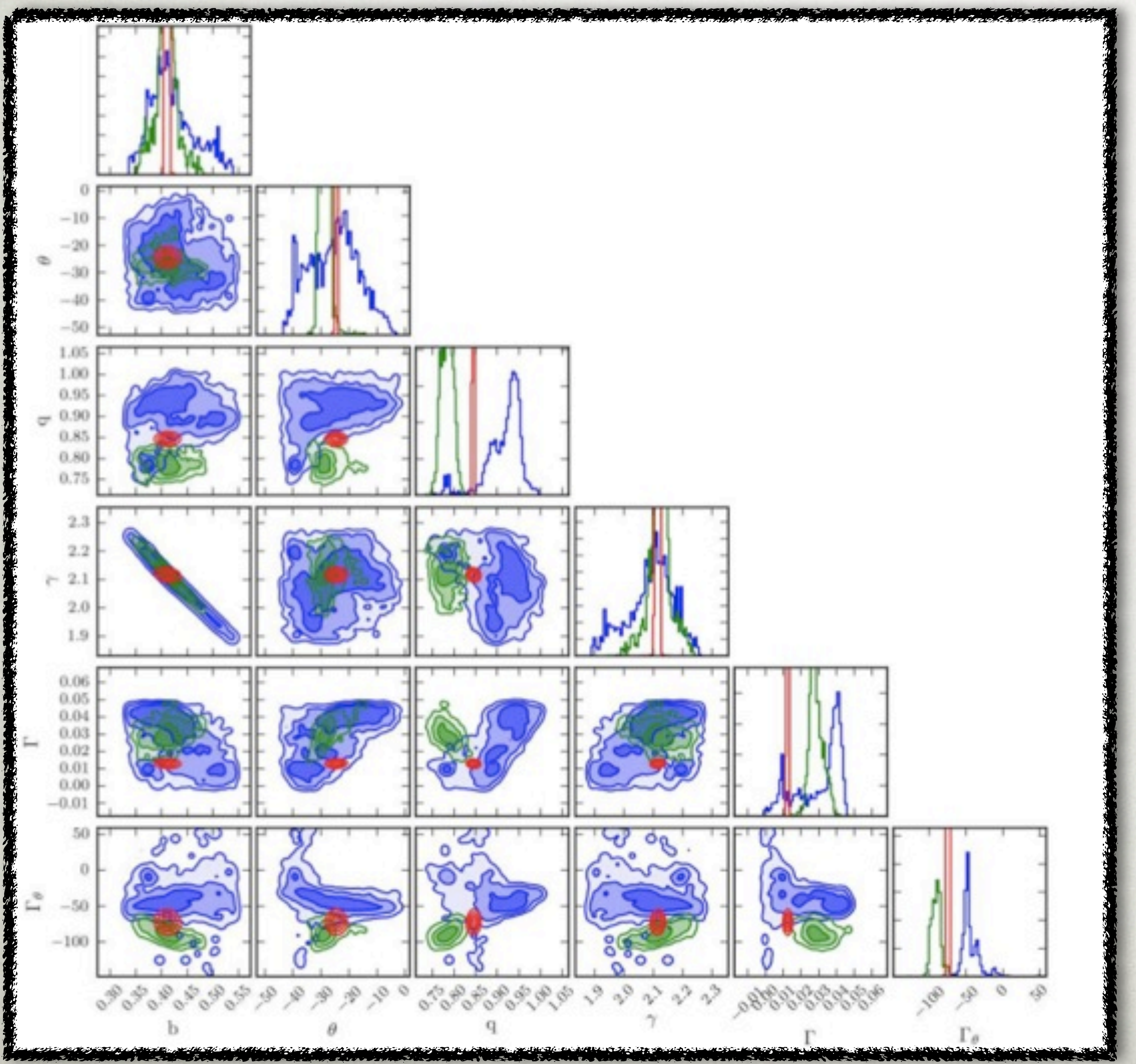
Vegetti et al. 2012

SHARP



Lagattuta et al. 2012

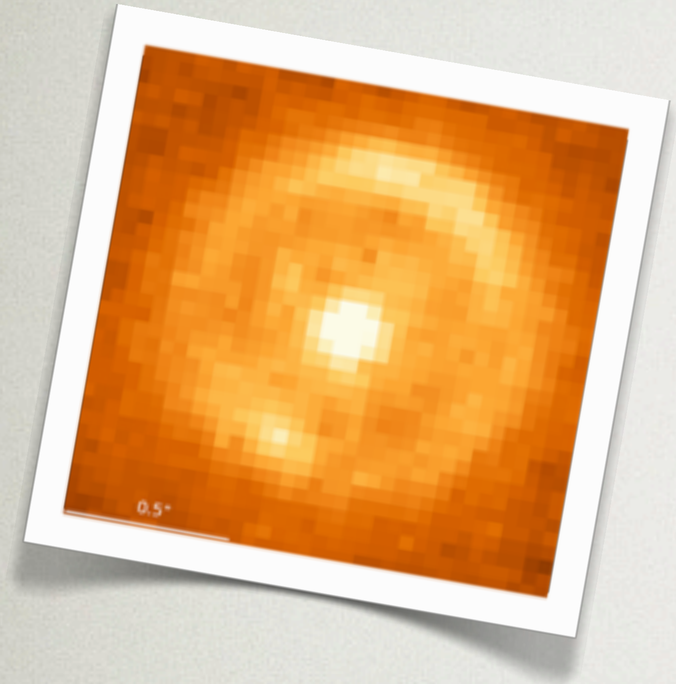
AO vs HST

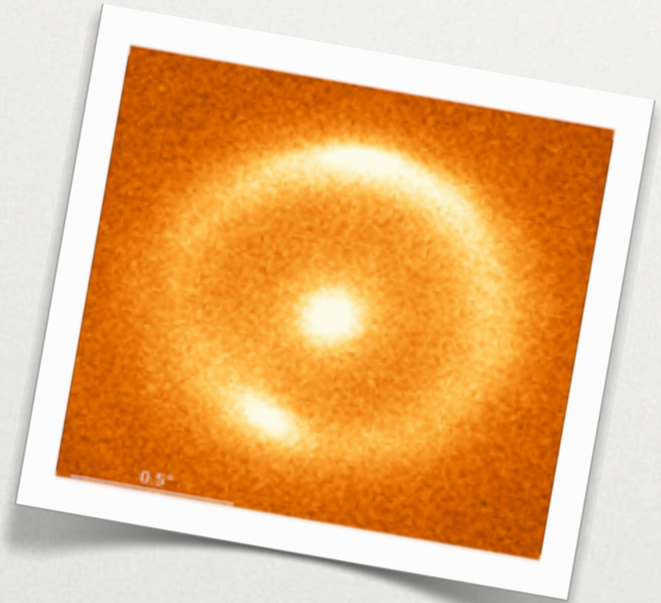


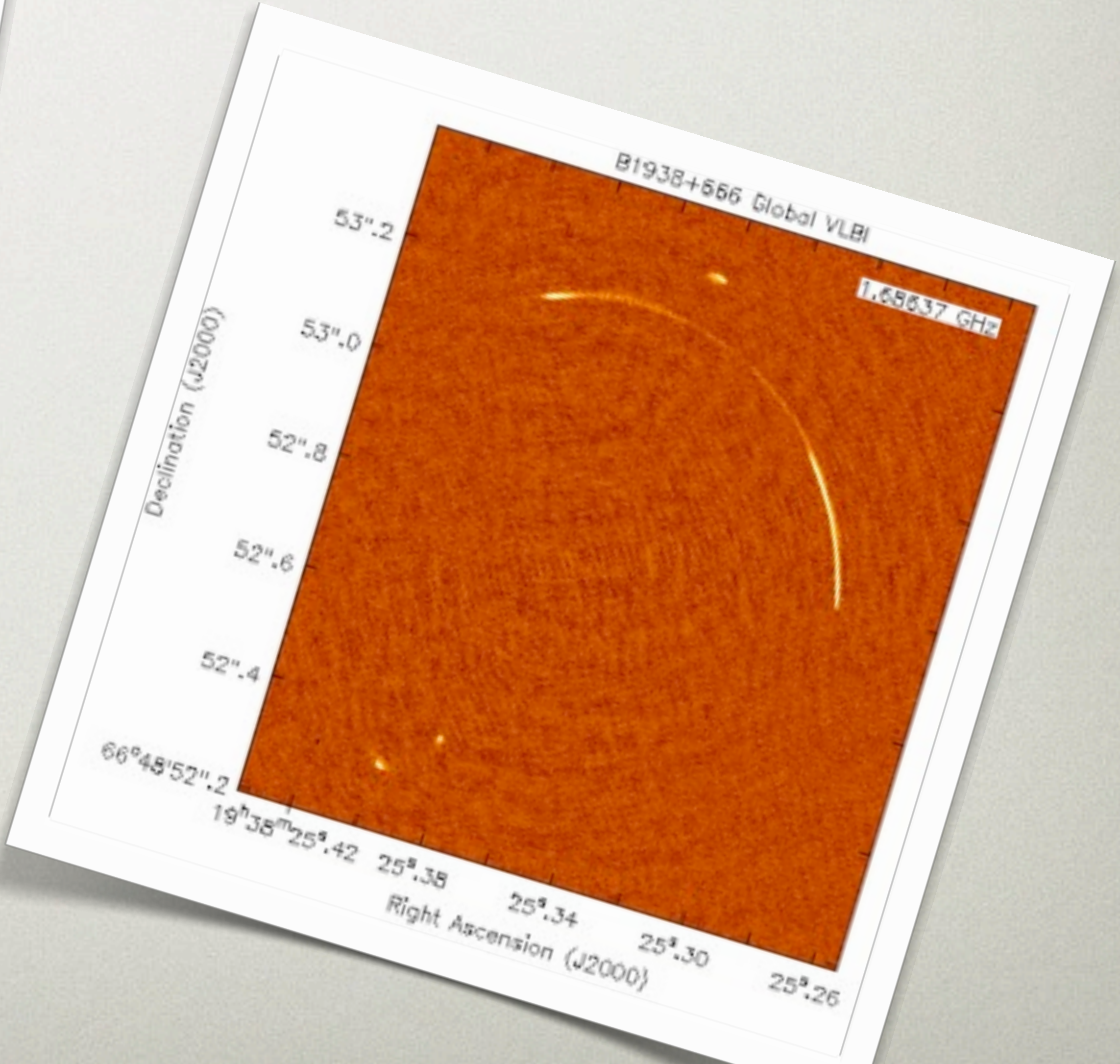
AO lens model parameters have significantly smaller measurement uncertainties than their HST counterpart

AO data with compact source galaxies, the higher resolution provided by AO cameras significantly outweighs any loss in S/N

SHARP, SHARPER, SHARPEST

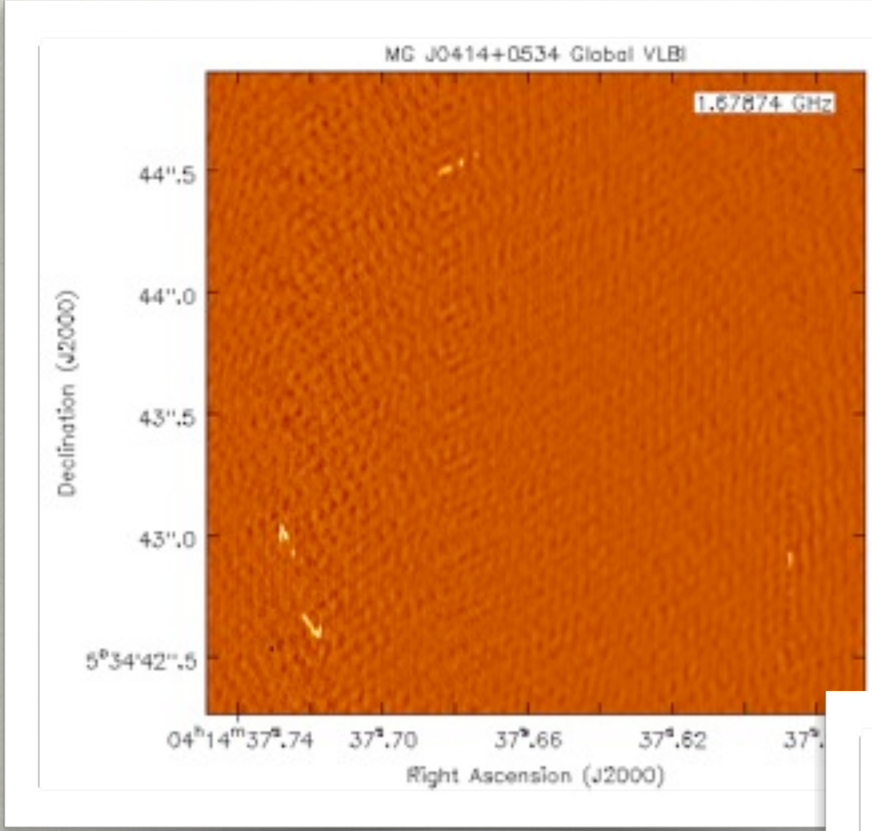


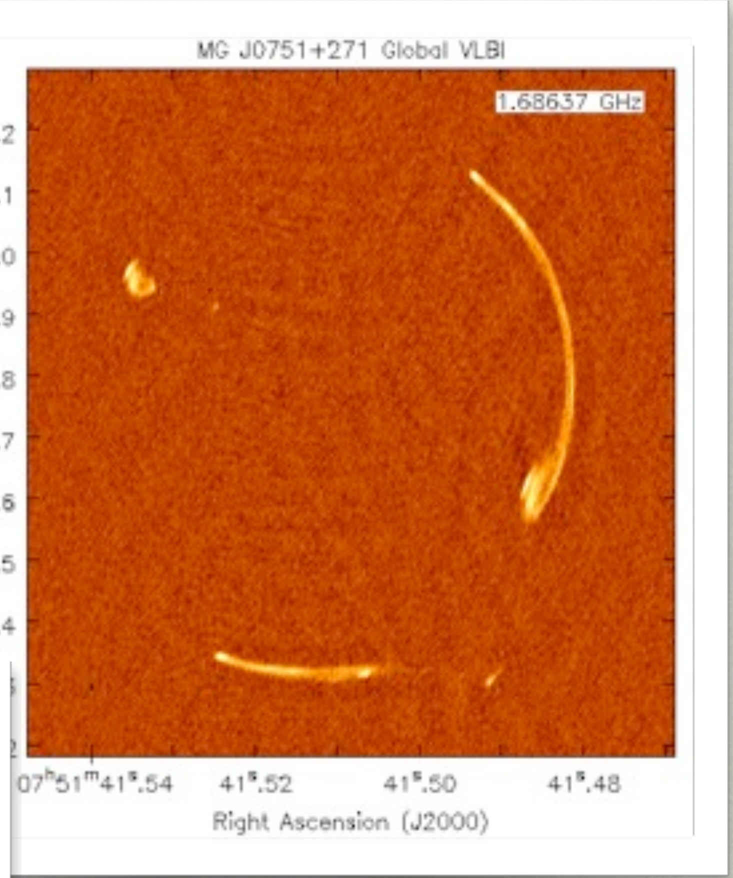


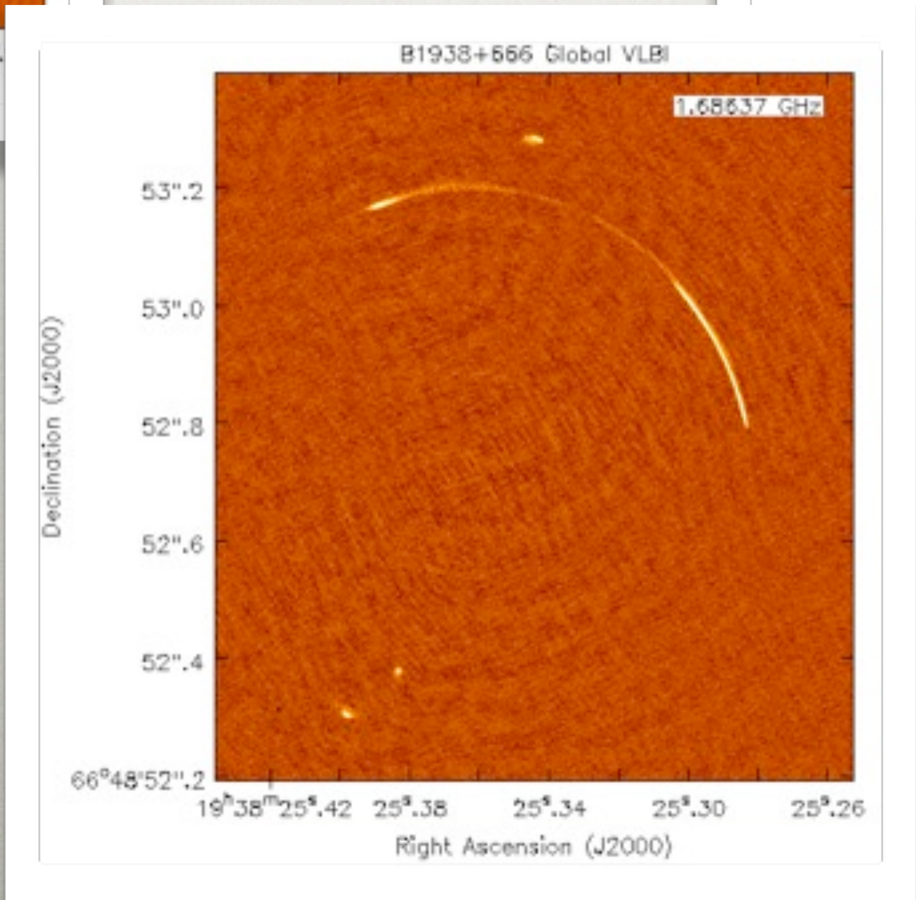


McKean et al. 2013

RADIO - SHARP



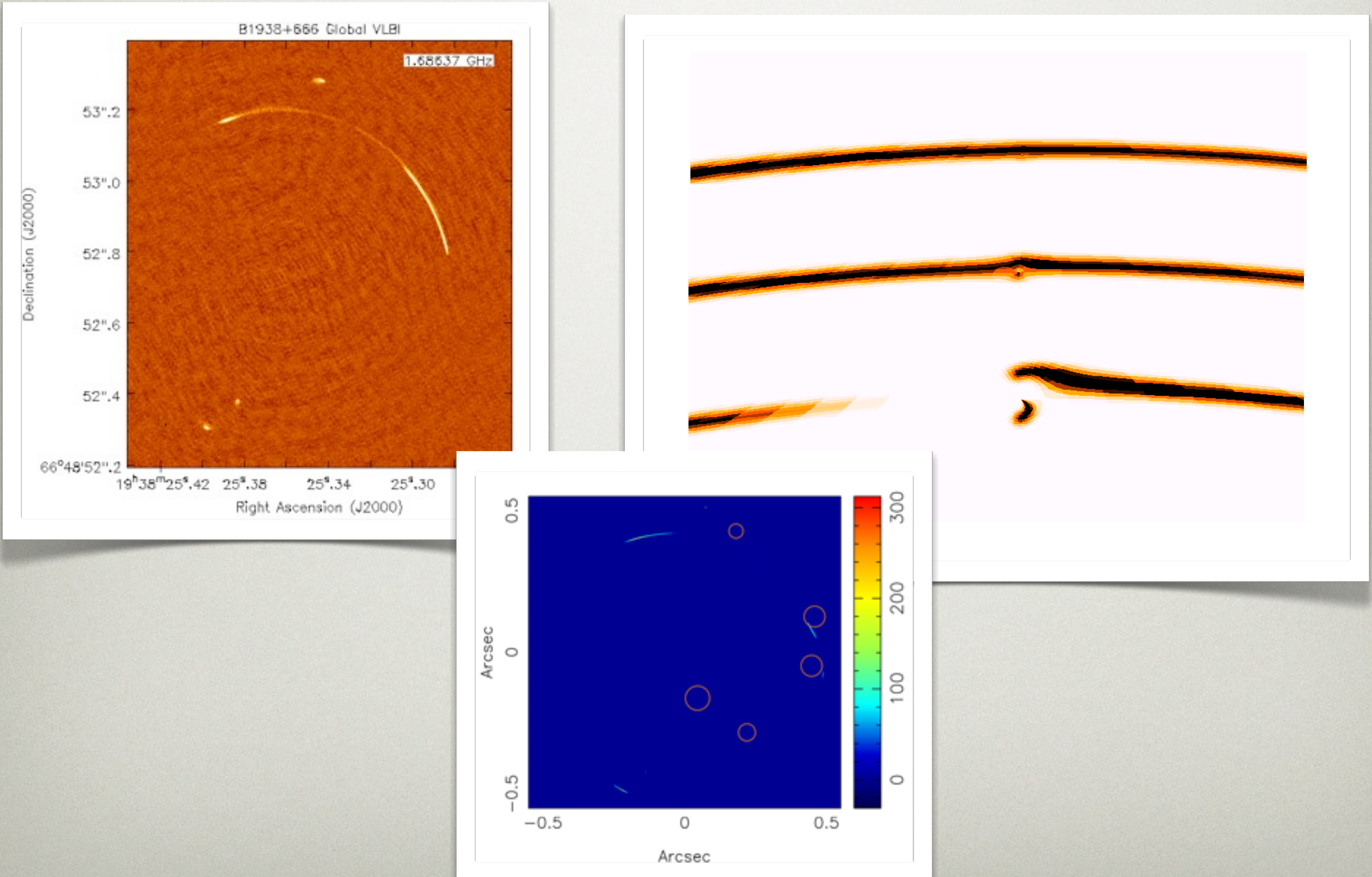




- Compact sources with a flat spectrum between 1.4 and 5 GHz: 10-20 mas
- A few with steep spectra: select arcs with 50 mas scales with MERLIN at 5 GHz and then observe them with VLBI

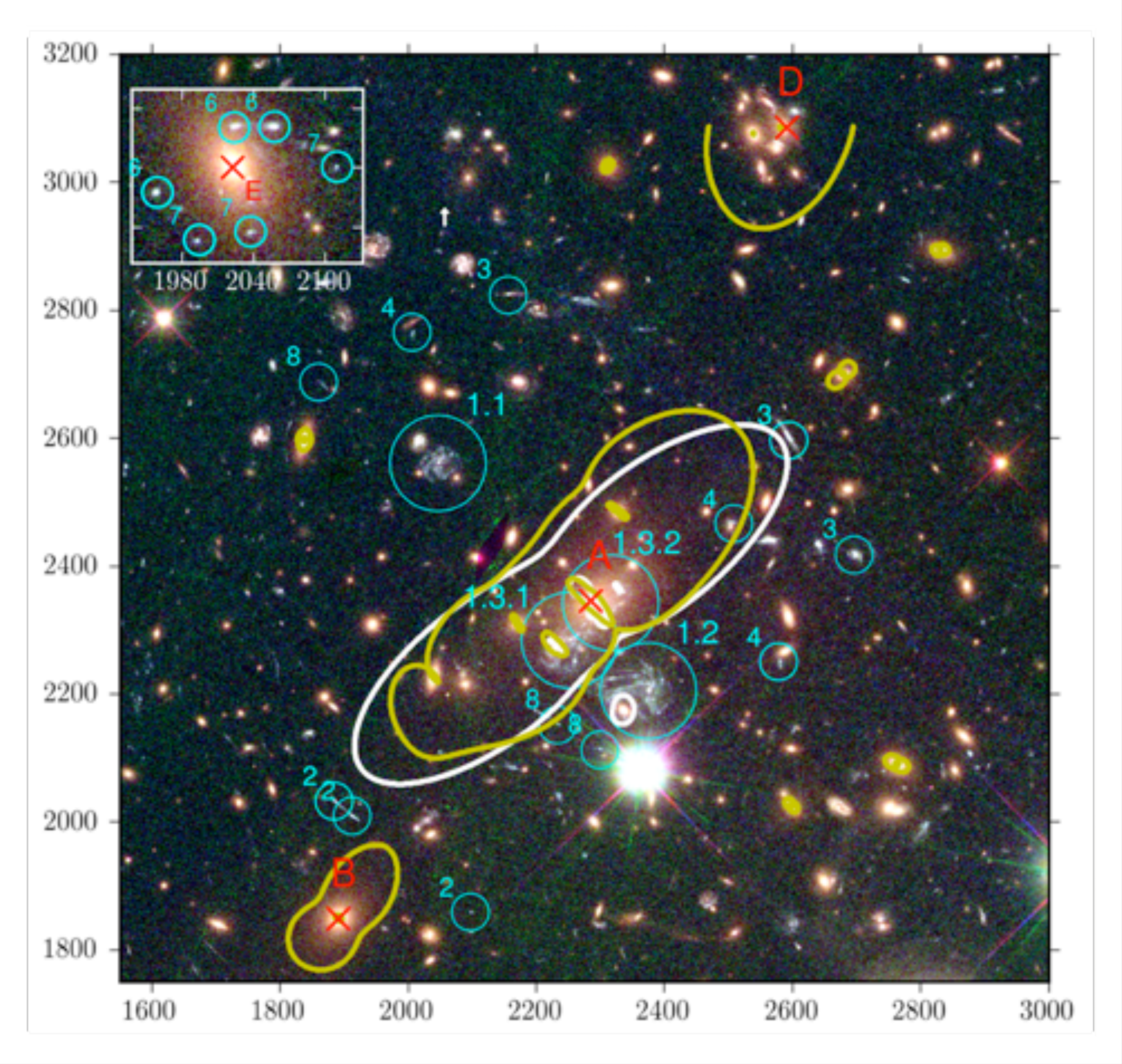
McKean et al. 2013

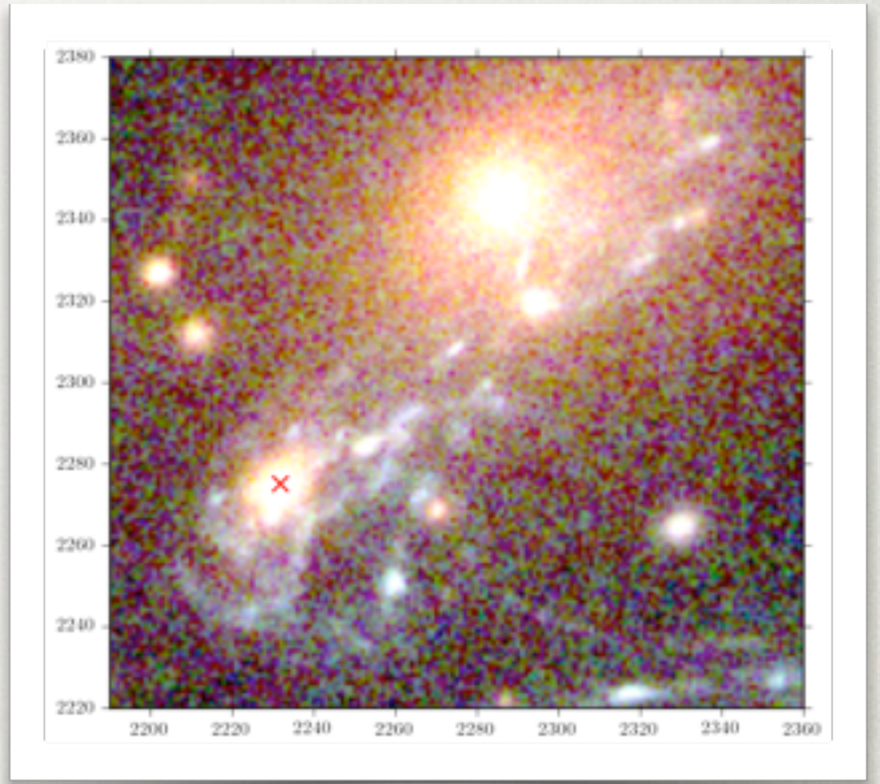
RADIO - SHARP

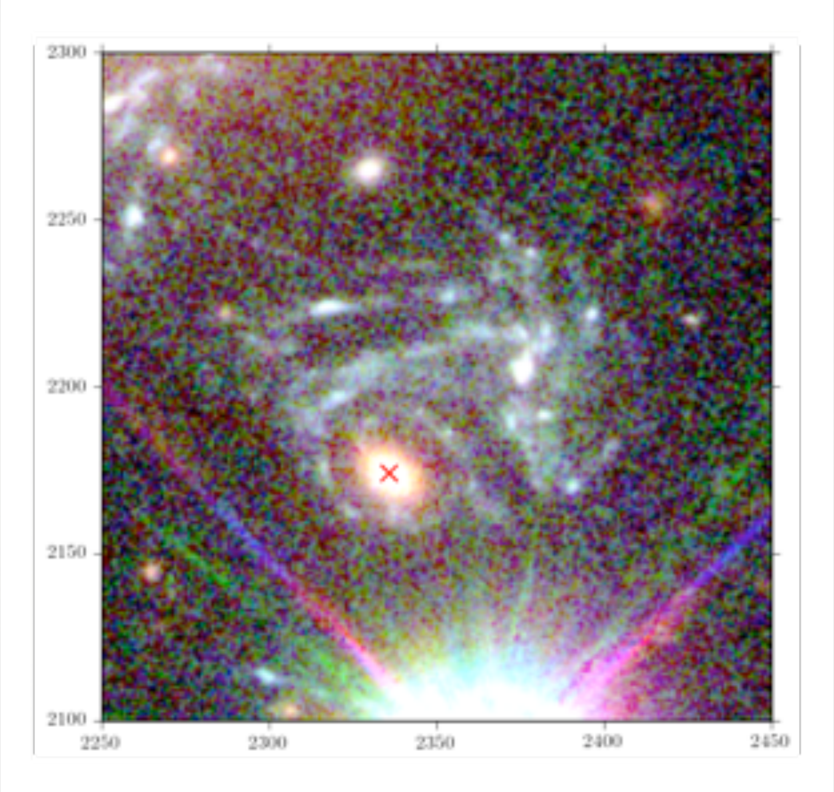


Rau et al. 2013

Galaxy size

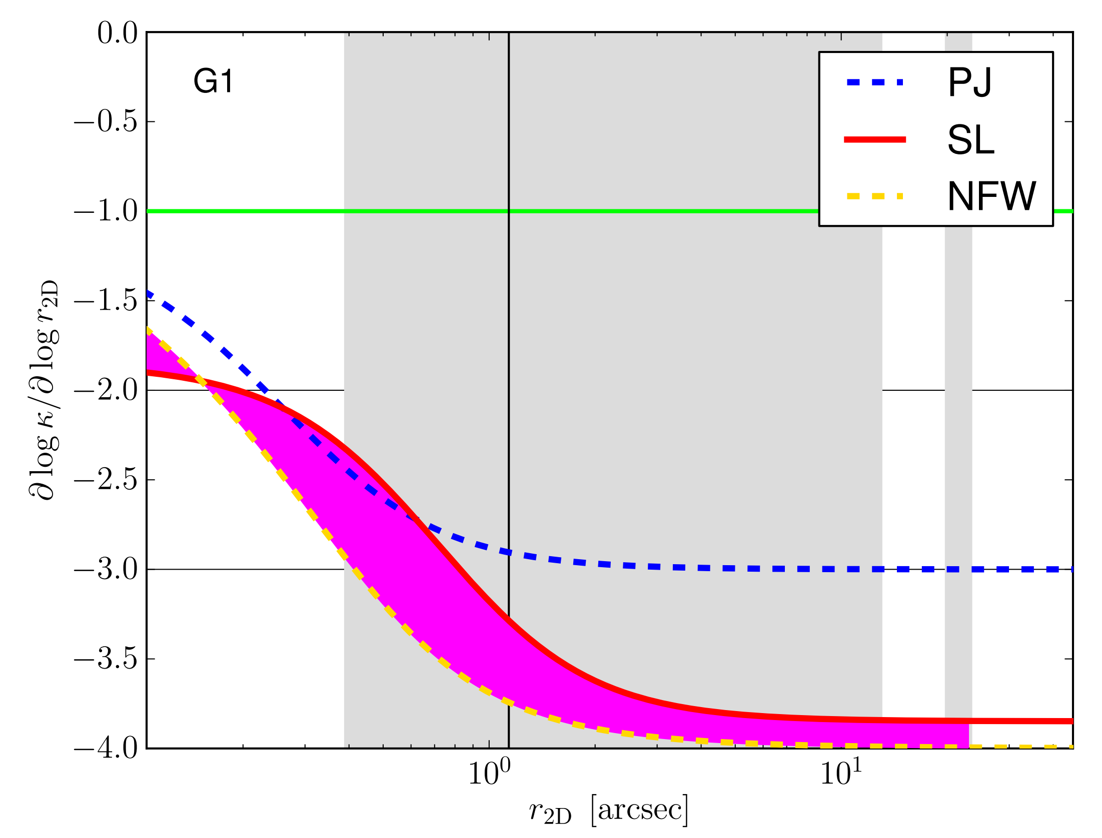


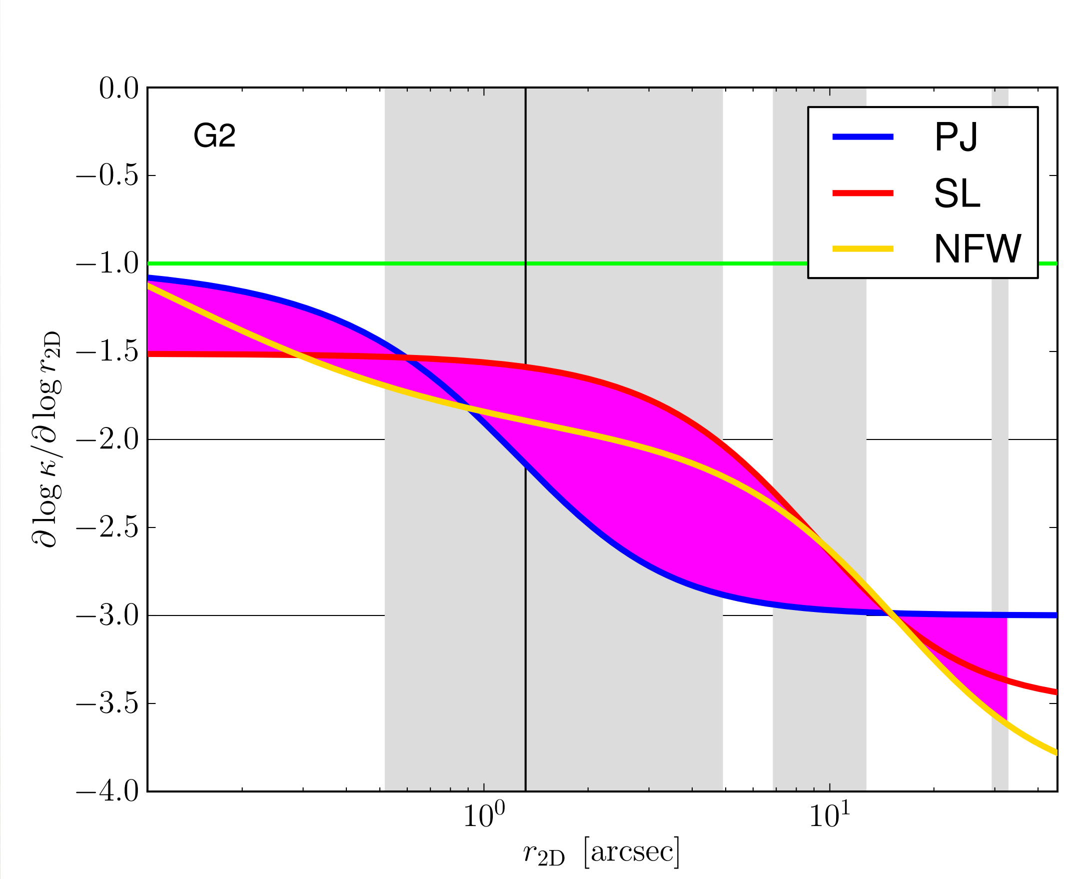




Rau et al. 2013

GALAXY SIZE





Preliminary!

CONCLUSIONS

Thank you

&

Stay tuned!