CDM substructure mass function at z ~0.2

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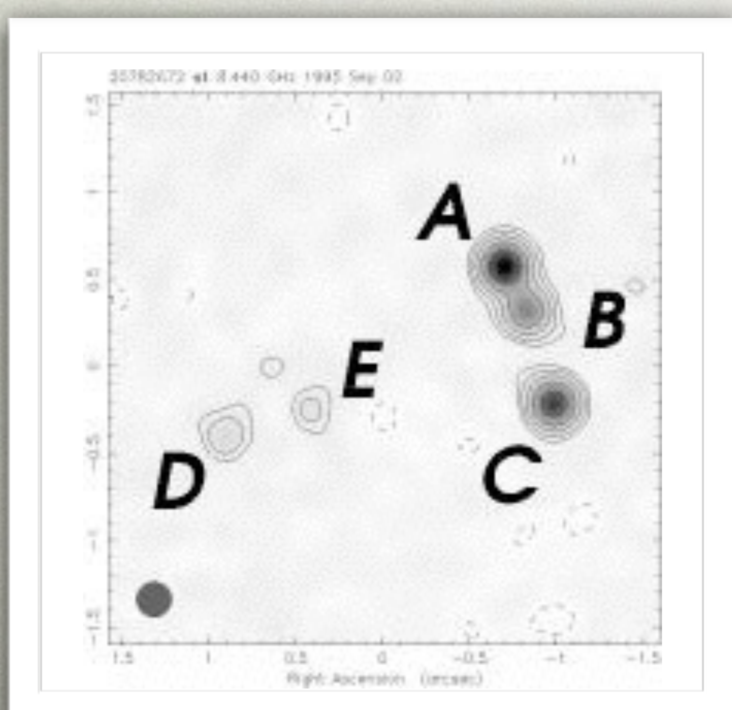
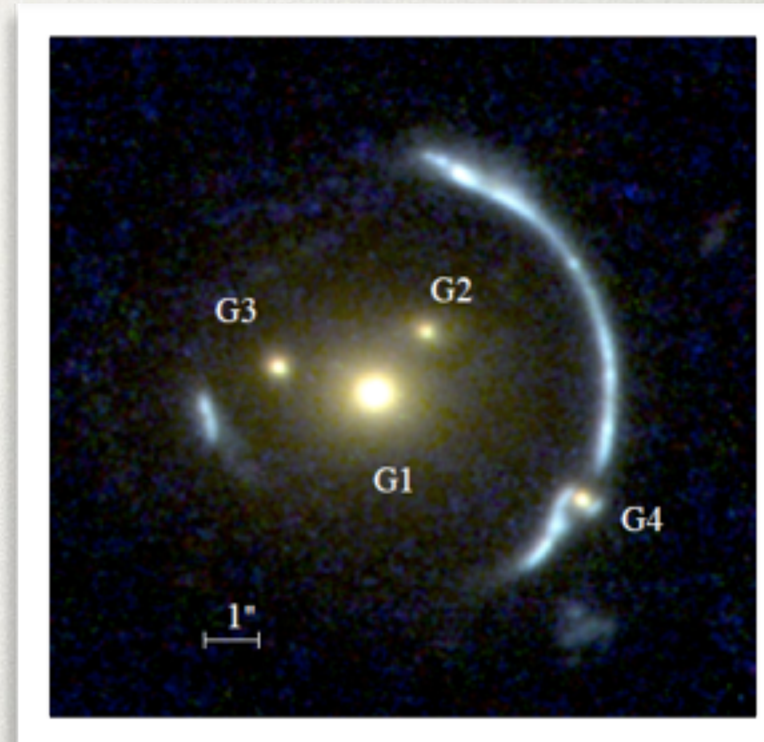
Gravitational Imaging

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



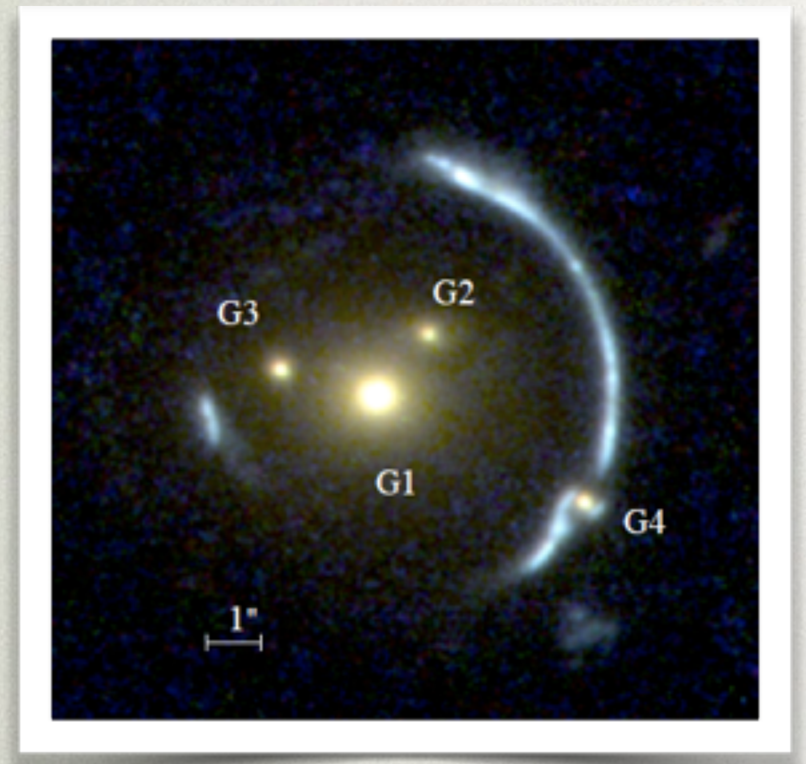


- substructures are detected as surface brightness anomalies
- need to disentangle structures in the potential from structures in the source
- Sensitive to higher masses
- NOT degenerate in the mass model

Koopmans 2005

Vegetti & Koopmans 2009

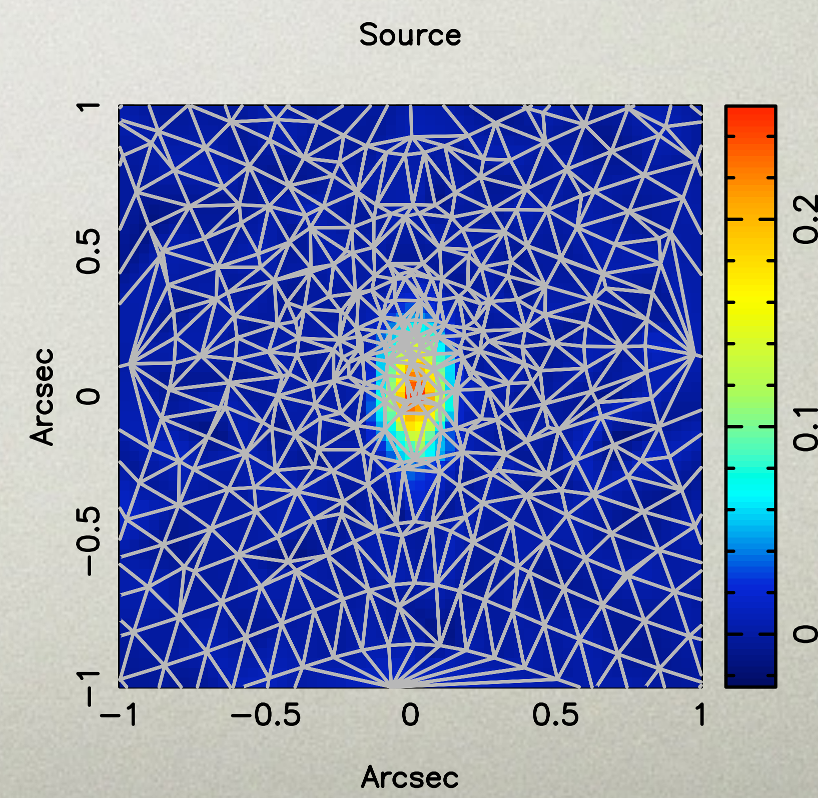
Gravitational Imaging



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

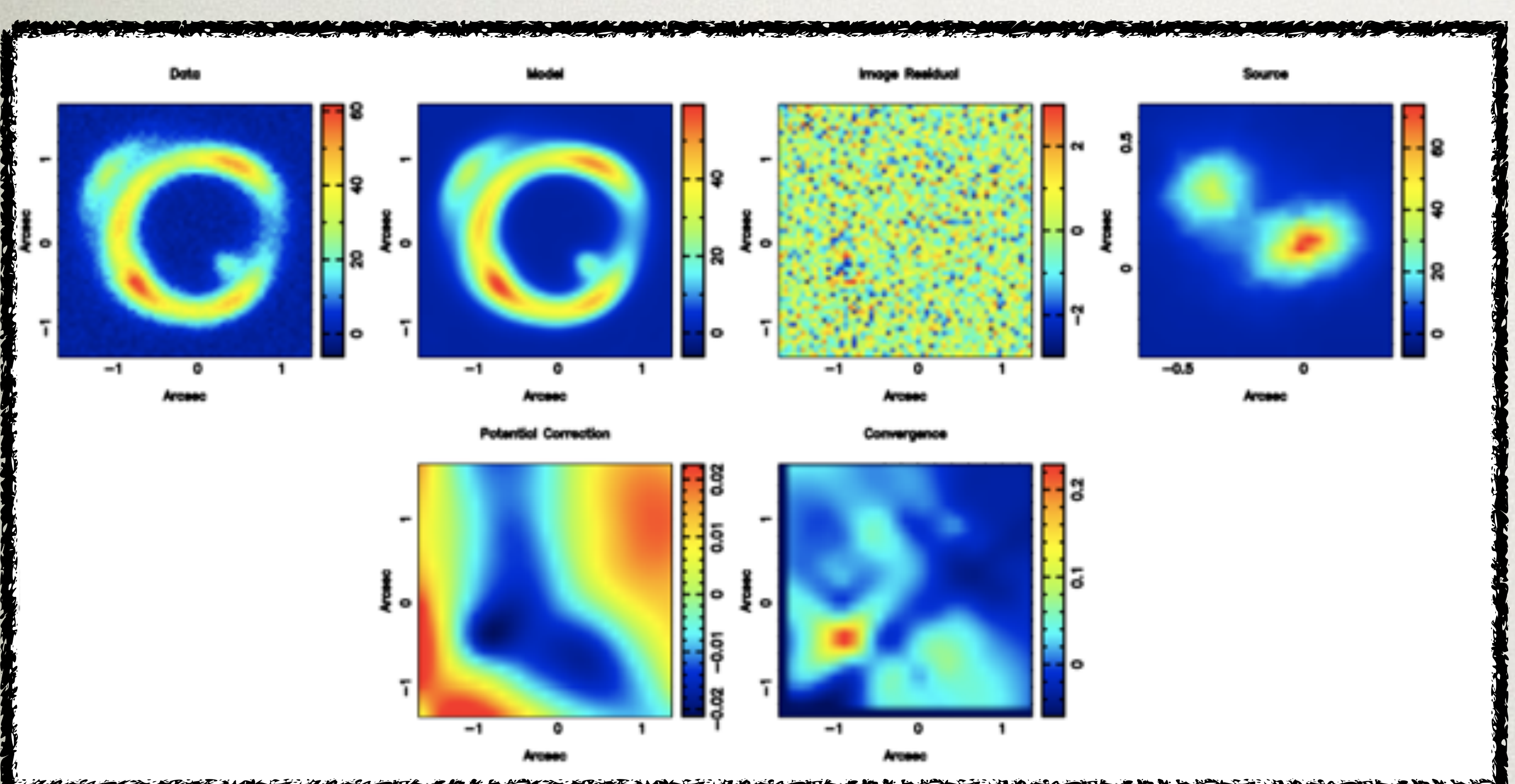
$\psi(\mathbf{x},\eta)$ Smooth analytic power-law model

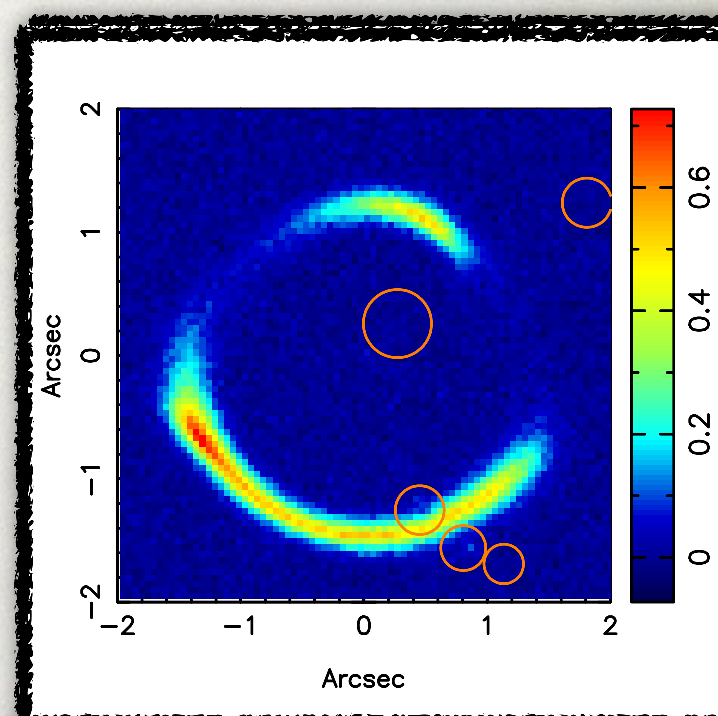
$\delta\psi(\mathbf{x})$ pixellated potential correction

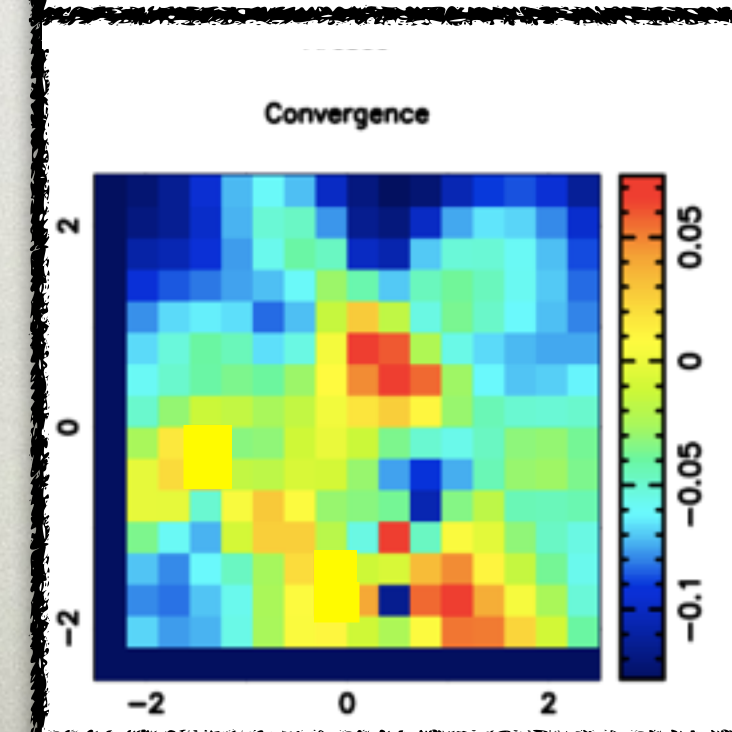


Pixelated source reconstructed on an adaptive Delaunay tessellation

Gravitational Imaging





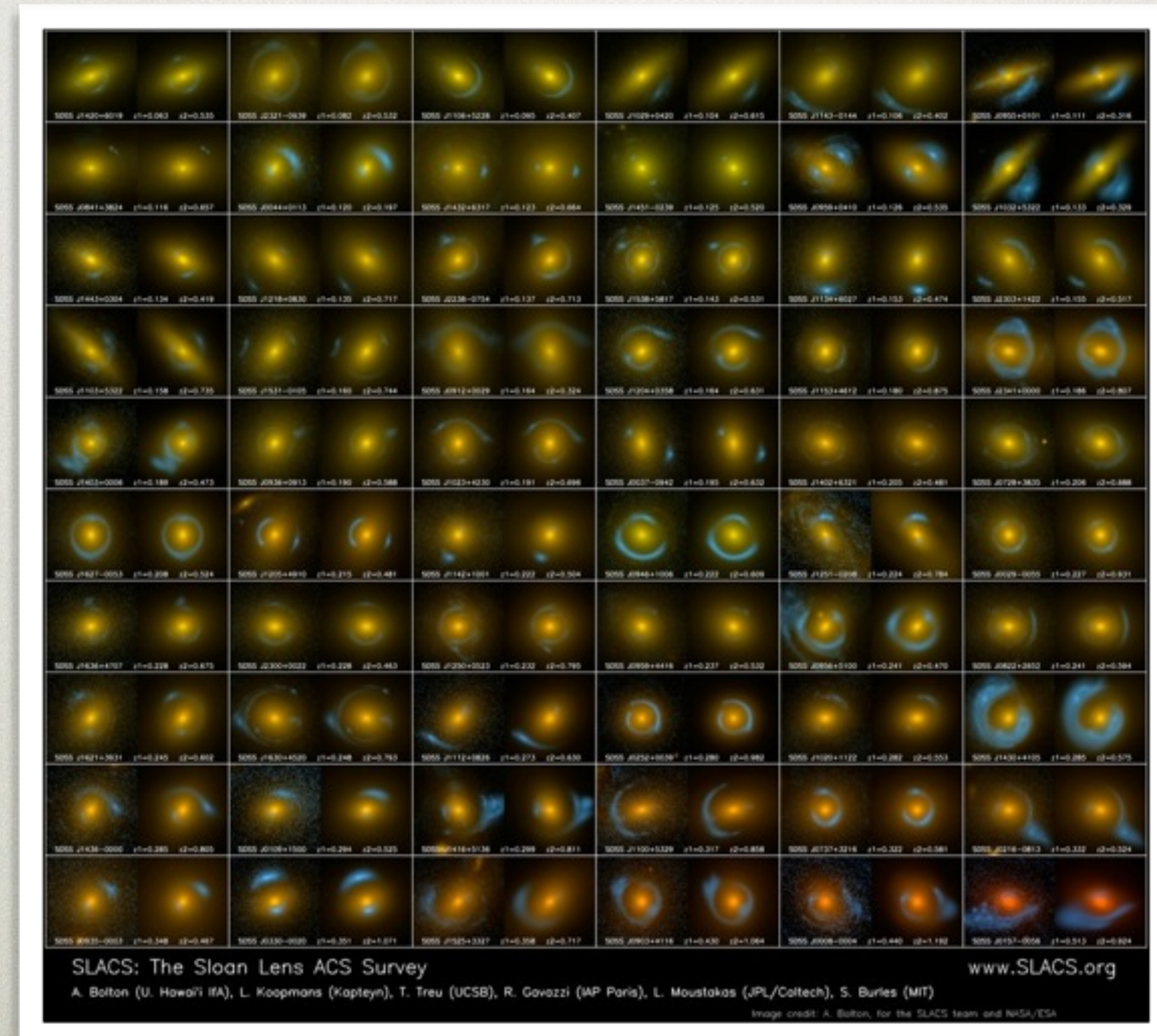


- substructures are responsible of localised surface brightness perturbations and are detected as localised potential corrections
- Any substructure can be detected provided it is massive enough and/or close enough to the Einstein ring
- For each substructure detected its mass can be measured by assuming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

Bolton et al. 2006

Bolton et al. 2008

SLACS



$$z = 0.06 - 0.36$$

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

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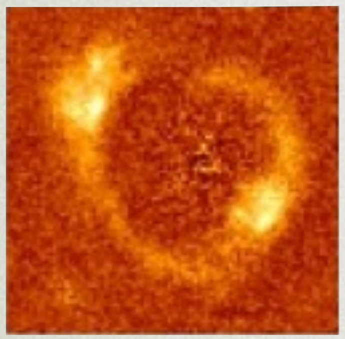
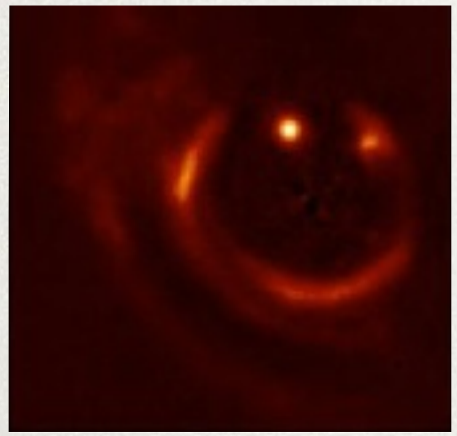
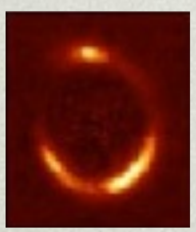
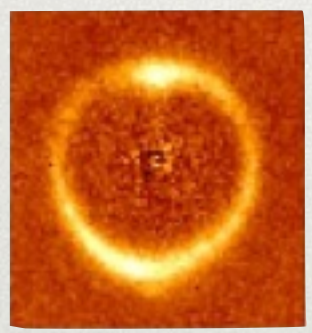
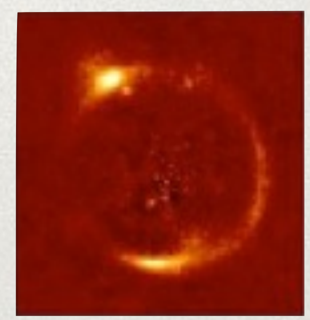
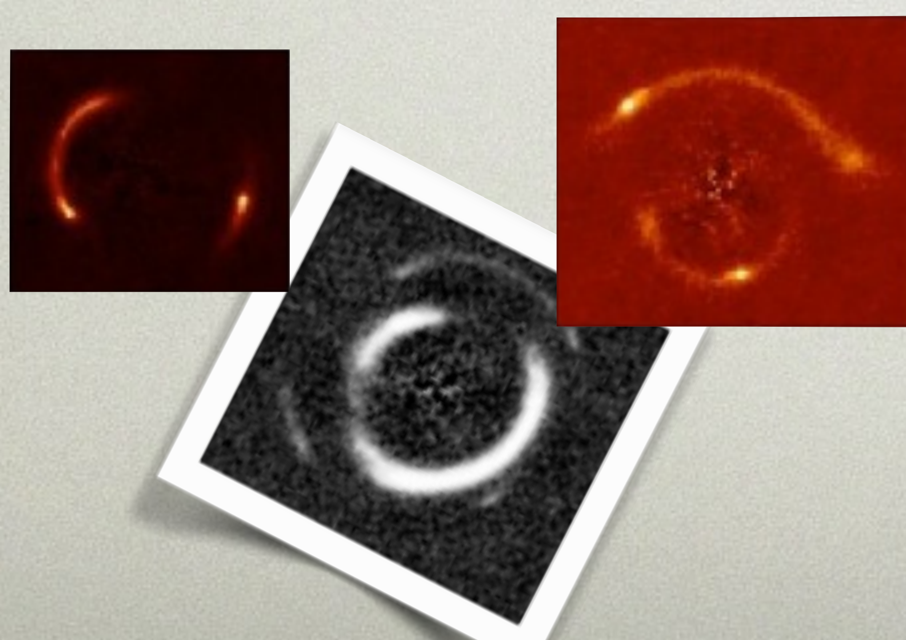
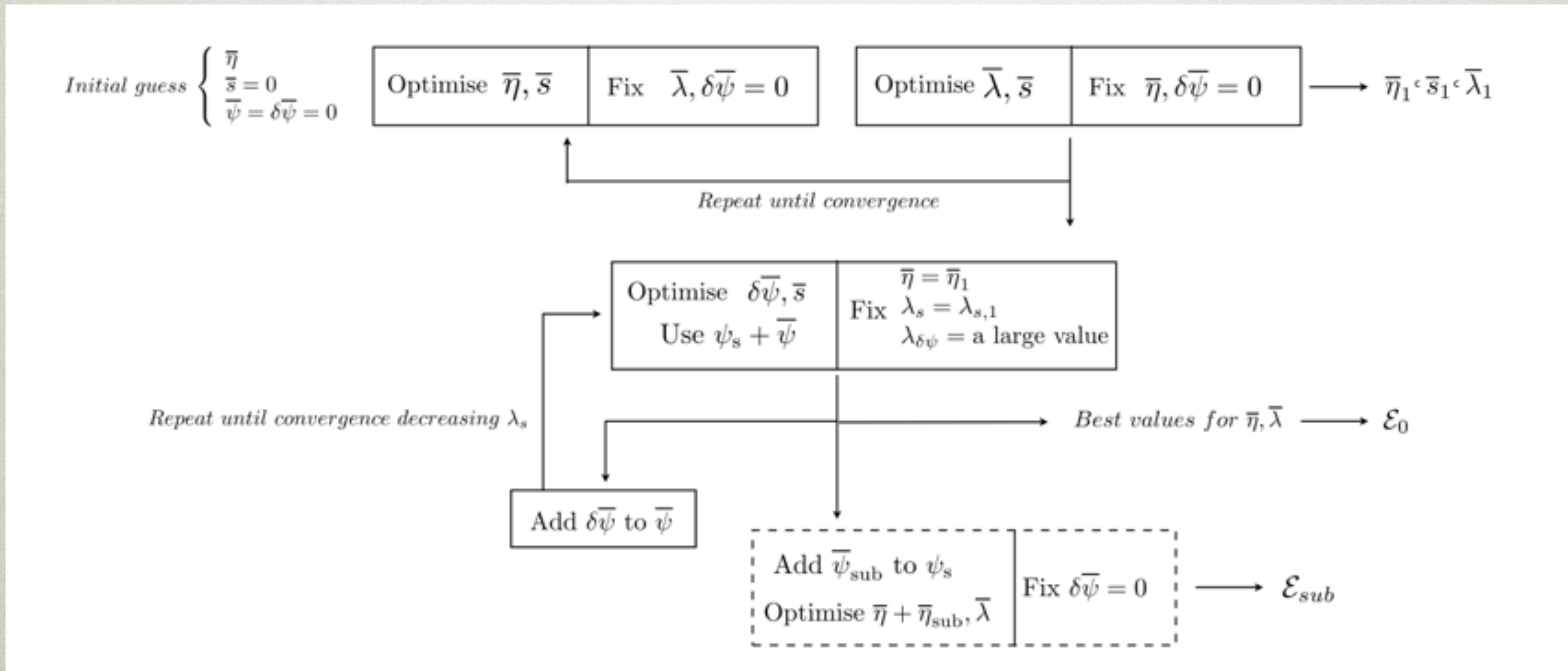





- Chosen on a s/n basis
- Representative sub-sample of the SLACS lenses
- Representative sample of massive early-type galaxies

Modeling Procedure



$$\kappa(x,y) = \frac{\kappa_0\left(2 - \frac{\gamma}{2}\right) q^{\gamma - 3/2}}{2(q^2(x^2 + r_c^2) + y^2)^{(\gamma-1)/2}}$$

$$\kappa(R) = \frac{\kappa_{0,\rm sub}}{2}\left[R^{-1} - (R^2 + r_t^2)^{-1/2}\right]$$

Criteria for Detection

- a positive convergence correction that improves the image residuals is found independently from the potential regularization, number of source pixels, PSF rotations, and galaxy subtraction procedure;

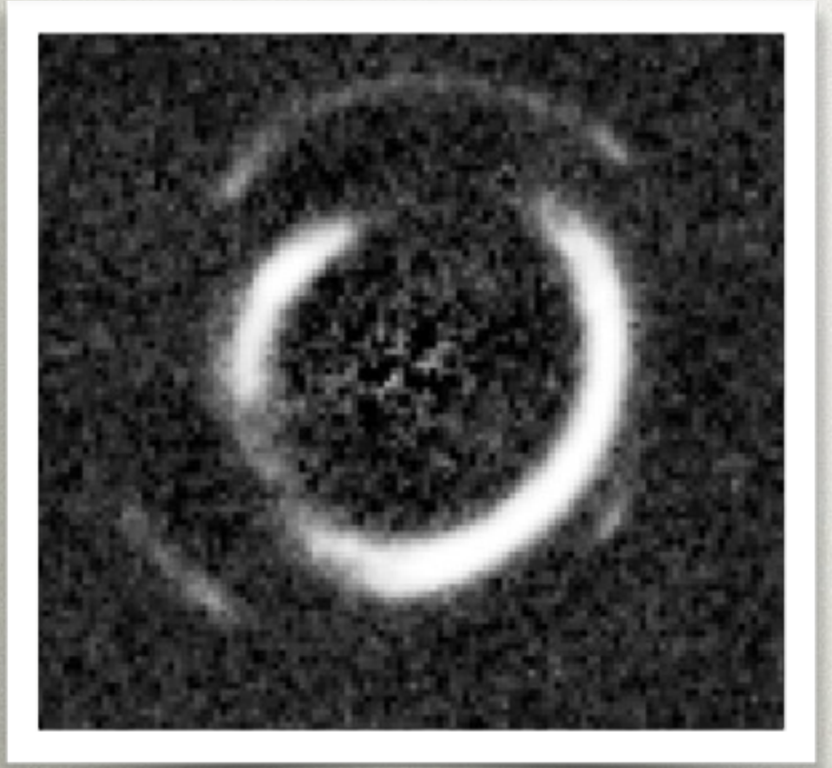
- the mass and the position of the substructure obtained via the Nested Sampling analysis is consistent with those independently obtained by the potential corrections and the MAP parametric clumpy model;

- a clumpy model is preferred over a smooth model with a Bayes factor $\Delta \log E = \log E_{smooth} - \log E_{clumpy} >= -50$ (to first order equivalent to a 10-σ detection, under the assumption of Gaussian noise);

- the results are consistent among the different HST filters, where available.

Gavazzi et al. 2008 Vegetti et al. 2010 Sonnenfeld et al. 2012 Collett et al. 20123

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

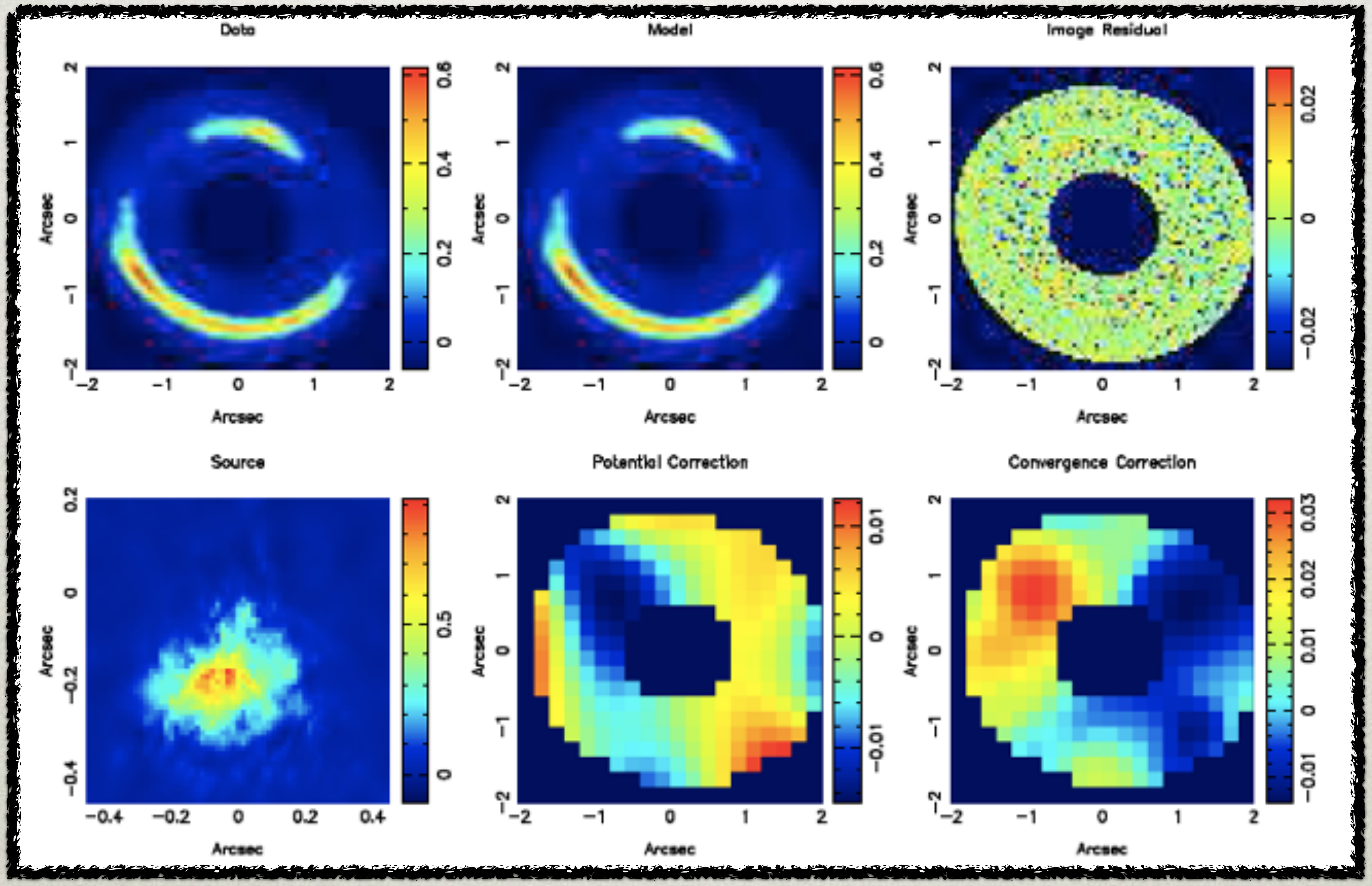
$$\Delta R = R_{ein} \pm 0.3$$

- 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

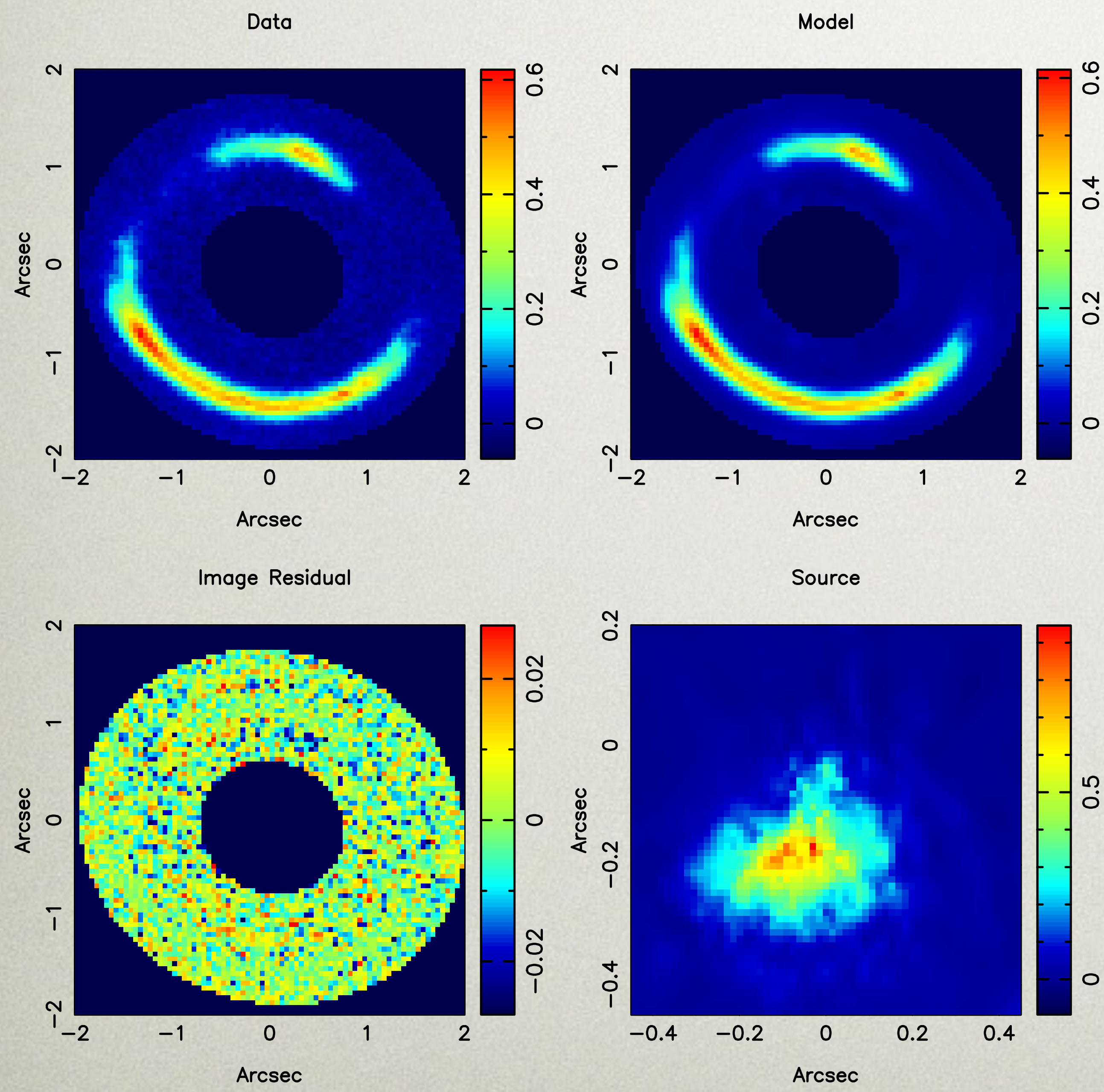
Double Ring



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

Vegetti et al. 2010

Double Ring



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

$$r_t = 1.1 \; kpc$$

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

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

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

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

Vegetti et al. 2014

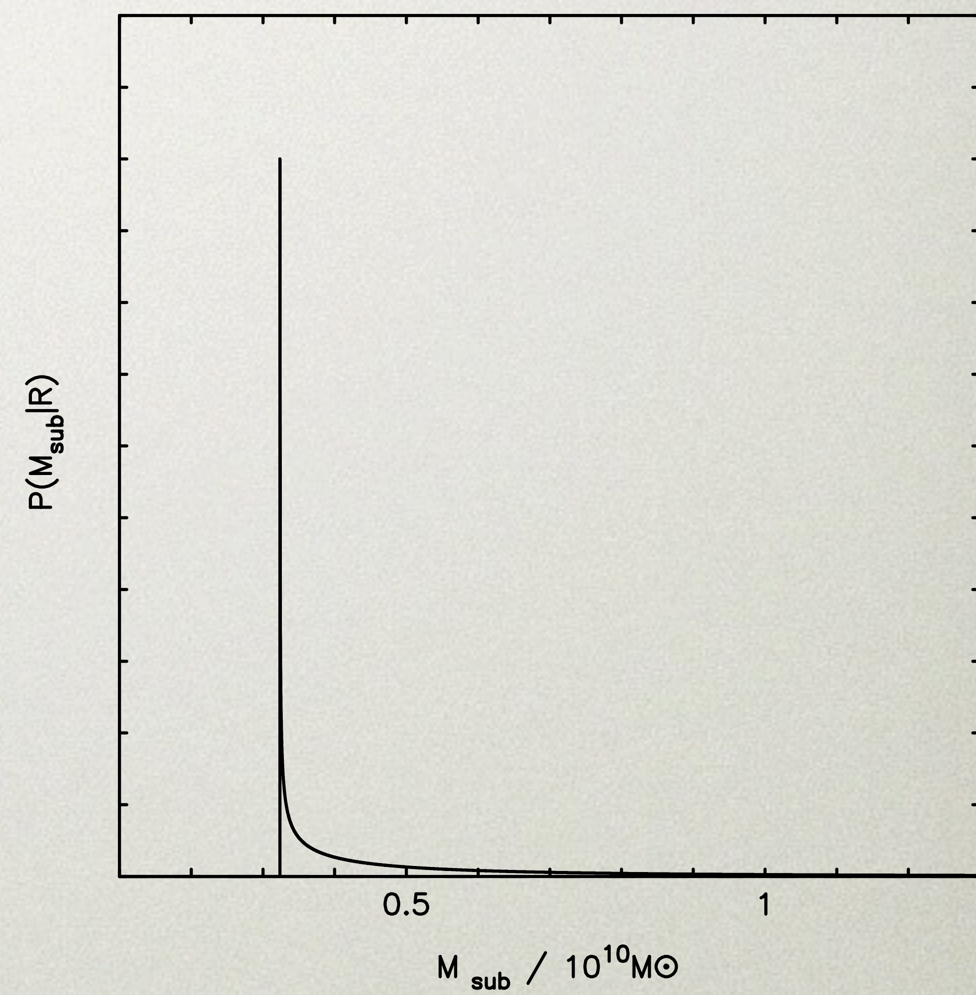
Mass Error

$$\rho(r) = \frac{\rho_{0,\mathrm{sub}}}{r^2(r^2 + r_t^2)}, \qquad r_t = r\left(\frac{M_{\mathrm{sub}}}{\beta M(<r)}\right)^{1/3}.$$

$$P(r|R) = \frac{P(R|r)P(r)}{P(R)} = \frac{1}{r\sqrt{r^2/R^2 - 1}\ \arccos[R/r_{\max}]}$$

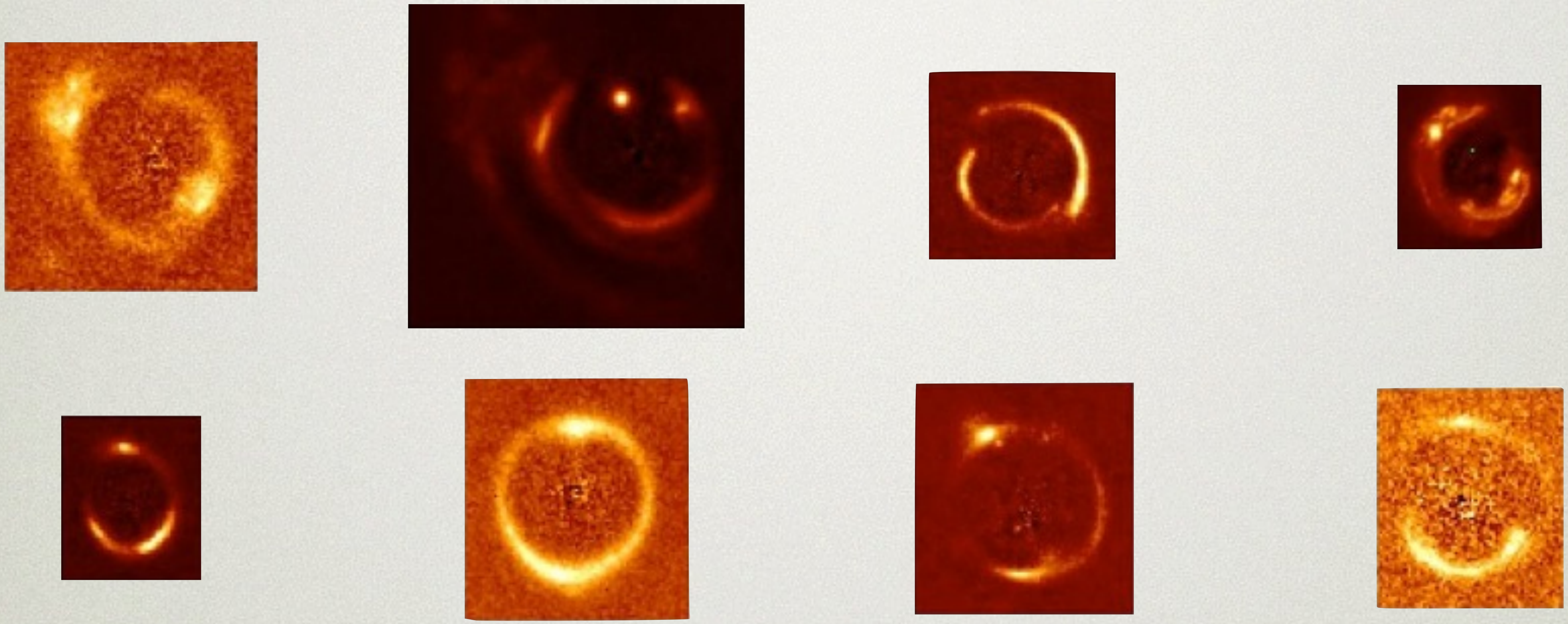
$$P(M_{\mathrm{sub}}|R) = \frac{1}{M_{\mathrm{sub}}\sqrt{\frac{2M_{\mathrm{sub}}^2\beta\kappa_0}{R^2\kappa_{\mathrm{sub}}^3\pi^3\Sigma_c^2} - 1}\ \arccos[R/r_{\max}]}$$

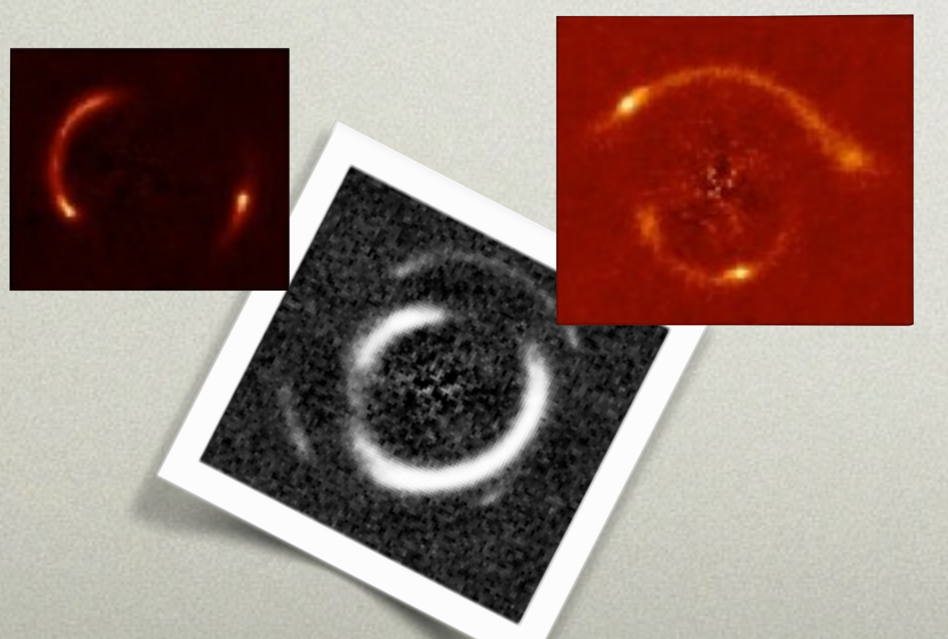
$$\sigma_{M_{\mathrm{sub}}} = ^{+1.17}_{-0.17}$$



de-projection is the dominant contribution to the mass error

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





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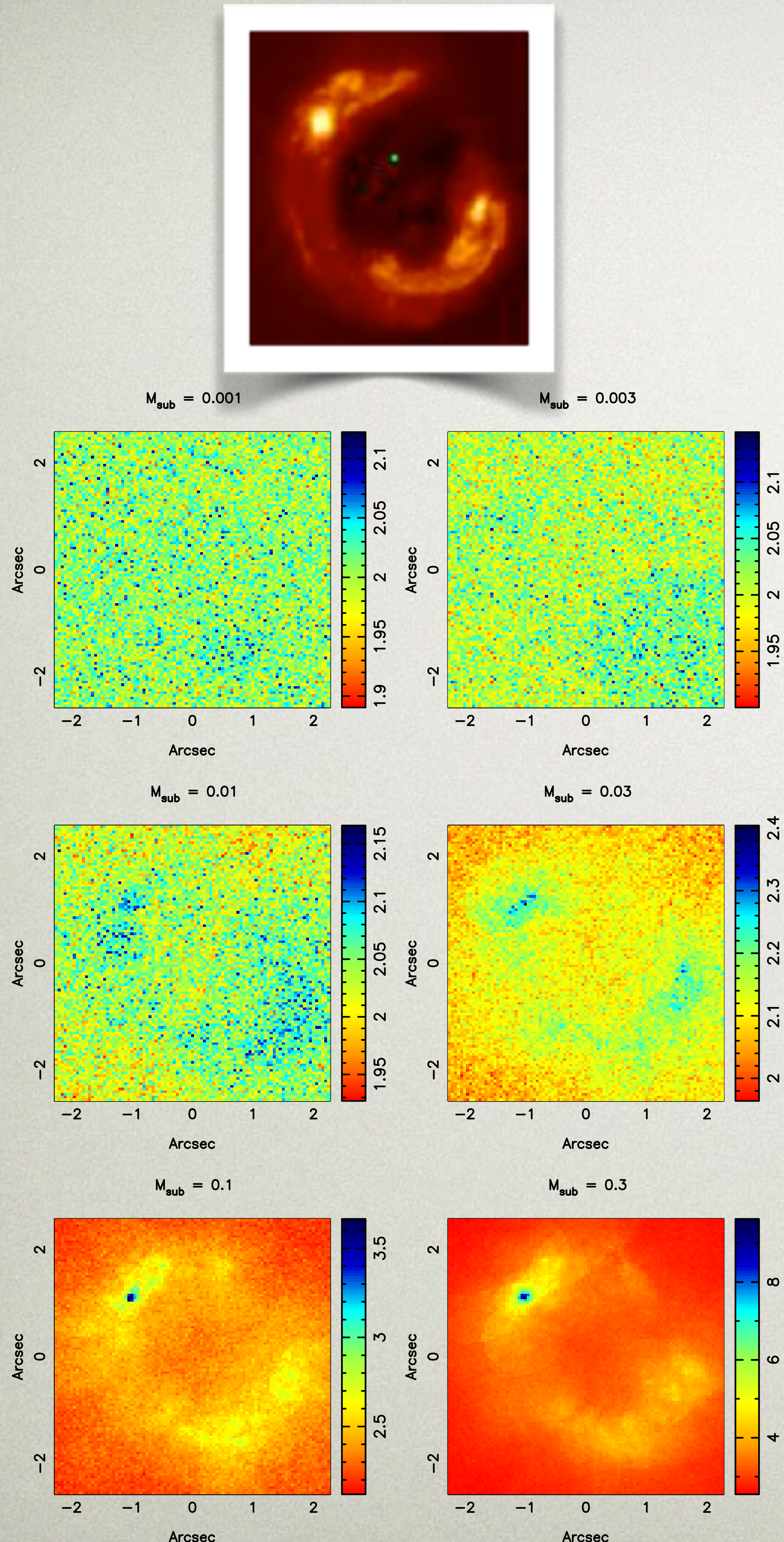


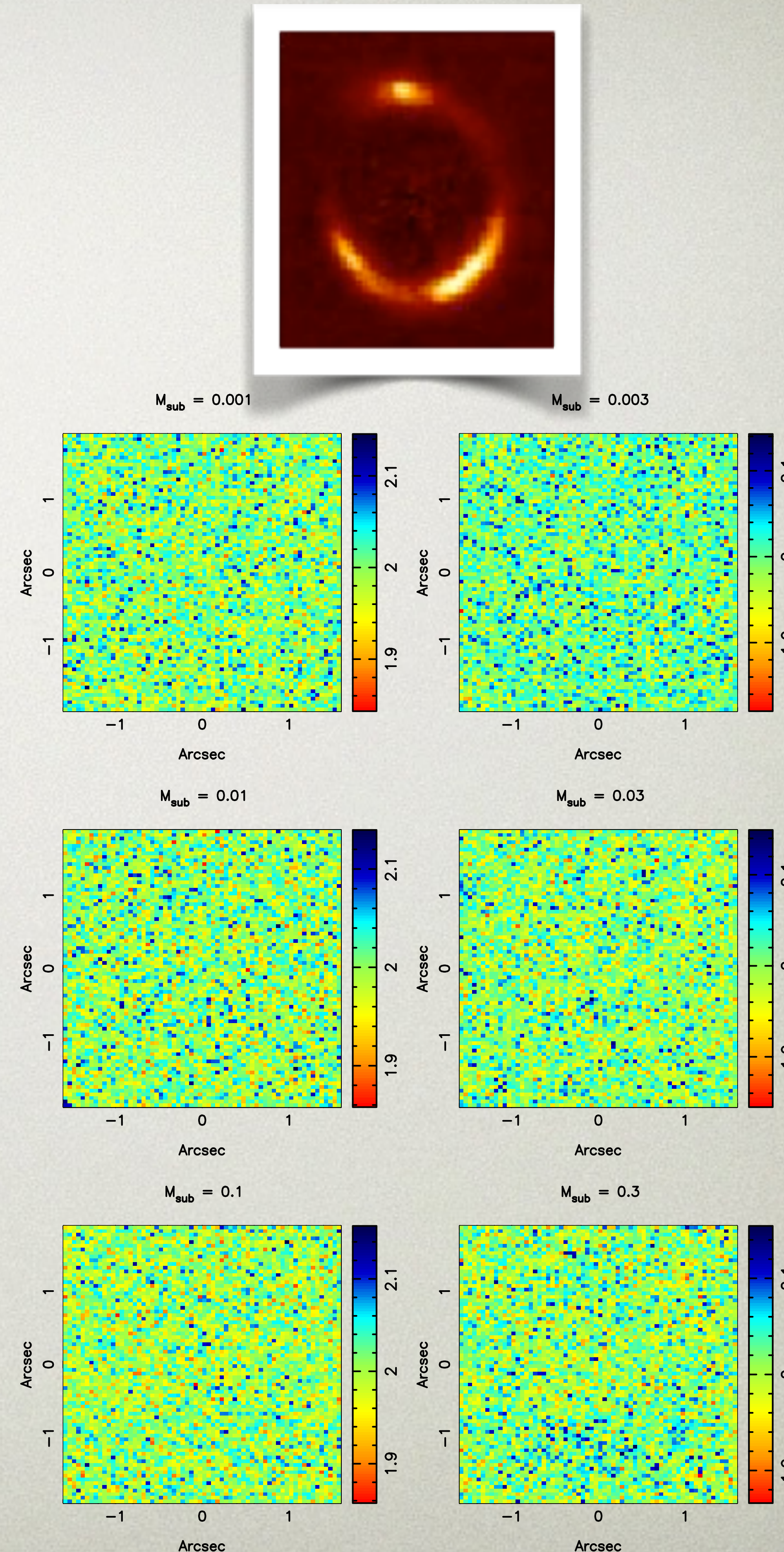


Image residuals lead to an over-estimate of the sensitivity

Mass Function

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

$$P\left(f\right) = \frac{1}{2\left(\sqrt{f_{\max}} - \sqrt{f_{\min}}\right)\sqrt{f}}$$

$$P_{\mathrm{U}}\left(\alpha\right) = \frac{1}{\alpha_{\max} - \alpha_{\min}},$$

and

$$P_{\mathrm{G}}\left(\alpha \mid \boldsymbol{p}\right) = \frac{1}{\sigma_\alpha\sqrt{2\pi}} \exp\left[-\frac{\left(\alpha - \alpha_{\mathrm{mean}}\right)^2}{2\sigma_\alpha^2}\right].$$

Vegetti & Koopmans 2009

Likelihood

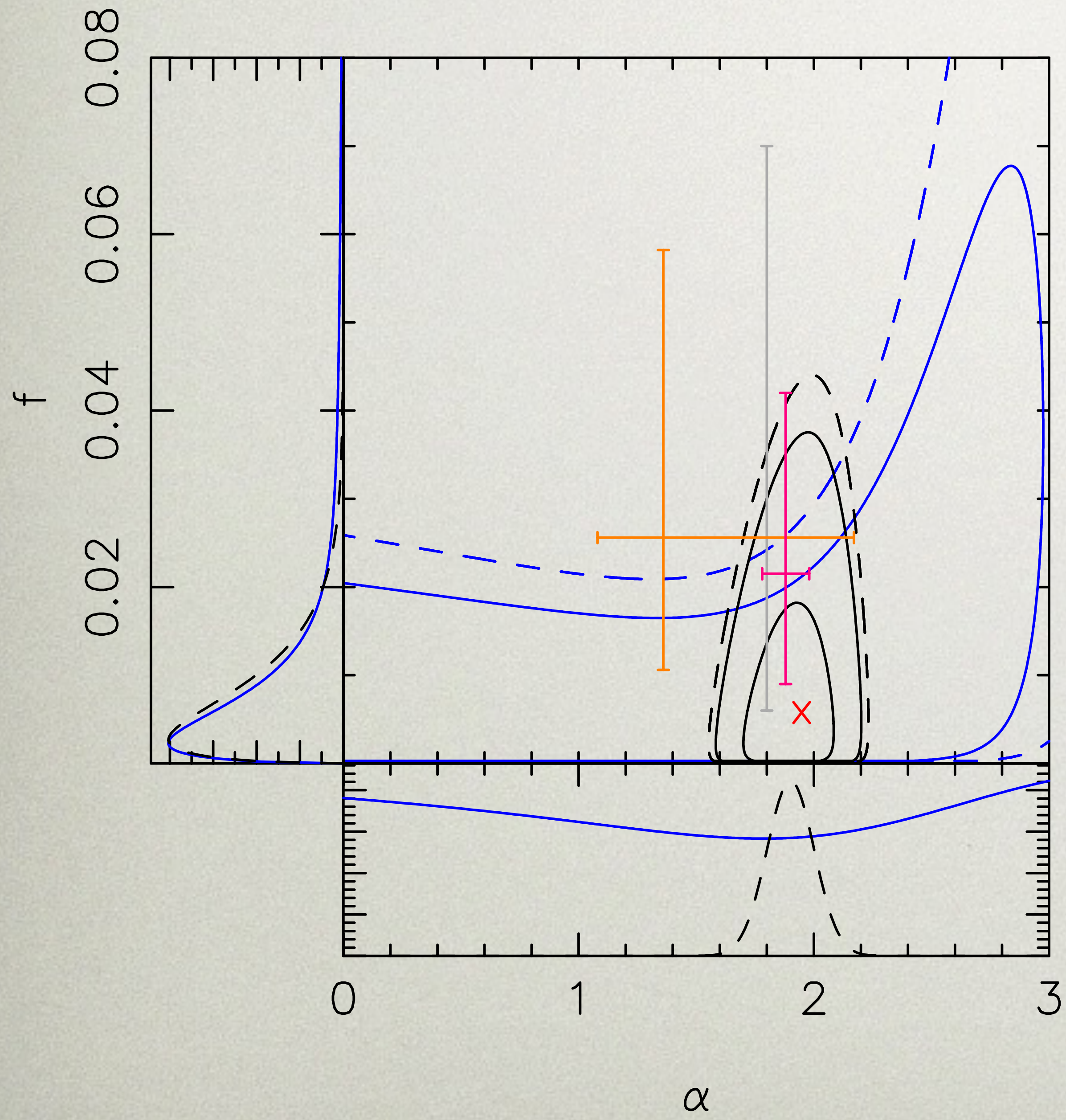
$$L\left(\{n_s, \mathbf{m_s}, \mathbf{R_s}\} \mid \alpha, f(<R), \mathbf{p}\right) = \frac{e^{-\mu(\alpha, f, \mathbf{p})}\ \mu(\alpha, f, \mathbf{p})^{n_s}}{n_s!} \prod_{k=1}^{n_s} P\left(m_k, R_k \mid \mathbf{p}, \alpha\right)$$

$$P\left(m_k, R_k \mid \boldsymbol{p}, \alpha\right) = \frac{\int_{M_{\rm low,k}}^{M_{\rm max}} \int_{R_k}^{r_{\rm max}} \mathcal{N}(m_k, \sigma_{m_k} | m_e) m^{-\alpha} P(R|r) P(r)\, dm\, dr}{\int_{M_{\rm min}}^{M_{\rm max}} \int_{R_k}^{r_{\rm max}} \mathcal{N}(m_k, \sigma_{m_k} | m_e) m^{-\alpha} P(R|r) P(r)\, dm\, dr}$$

$$P(R_k|r) = \frac{1}{r\sqrt{r^2/R_k^2 - 1}}$$

Vegetti et al. 2014

CDM Mass Function at z=0.2

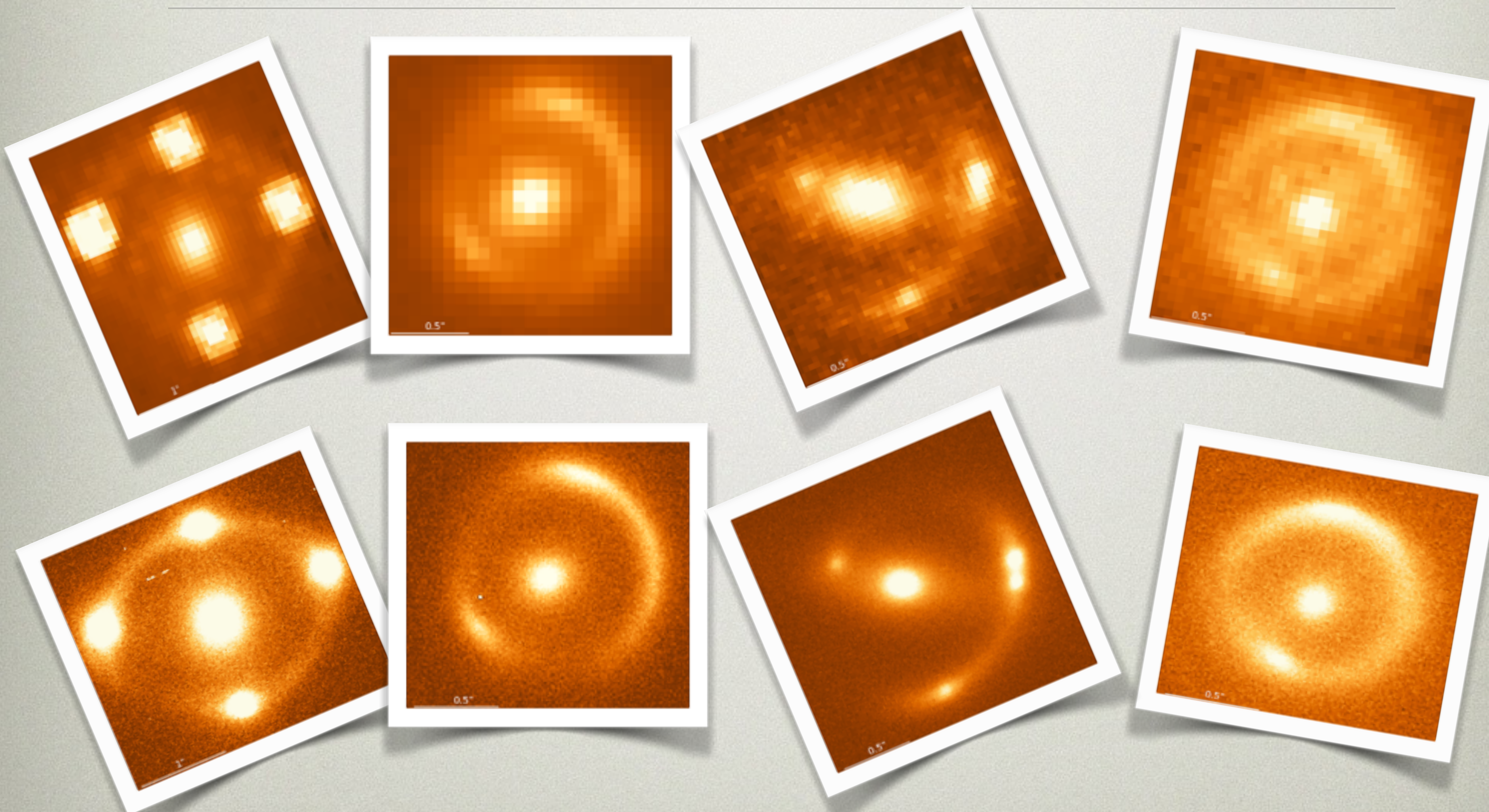


$P(\alpha)$	f (68% CL)	α	ln Ev
U	$0.0076^{+0.0208}_{-0.0052}$	< 2.93 (95% CL)	-5.98
G	$0.0064^{+0.0080}_{-0.0042}$	$1.90^{+0.098}_{-0.098}$ (68% CL)	-6.13

What is going on with the FRA?

Vegetti et al. 2012

SHARP

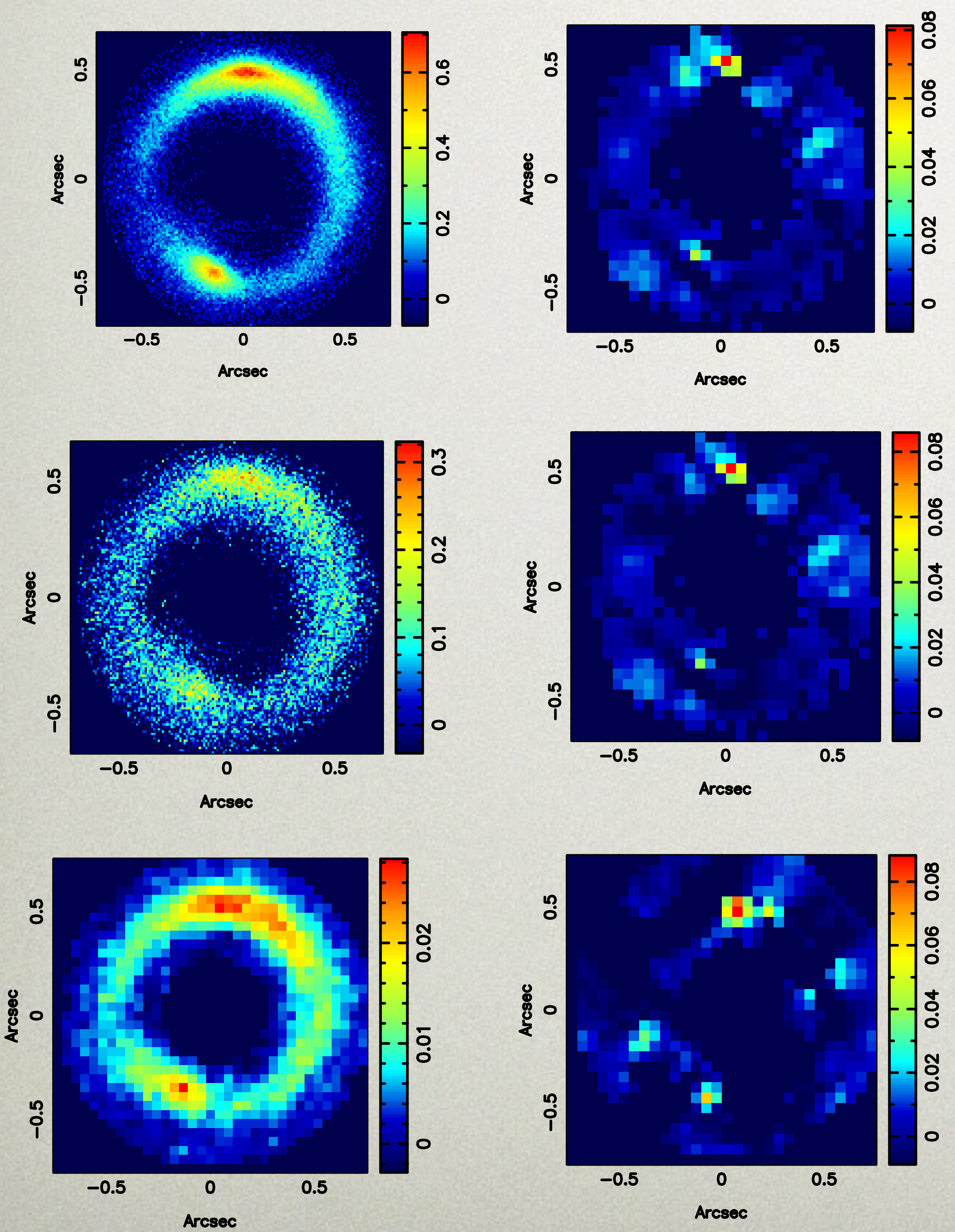


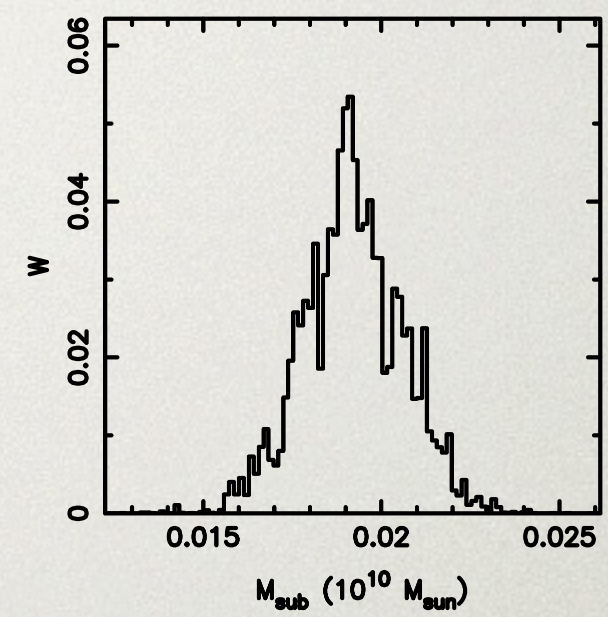
Medium sized sample of ~20 systems

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

Vegetti et al. 2012

SHARP





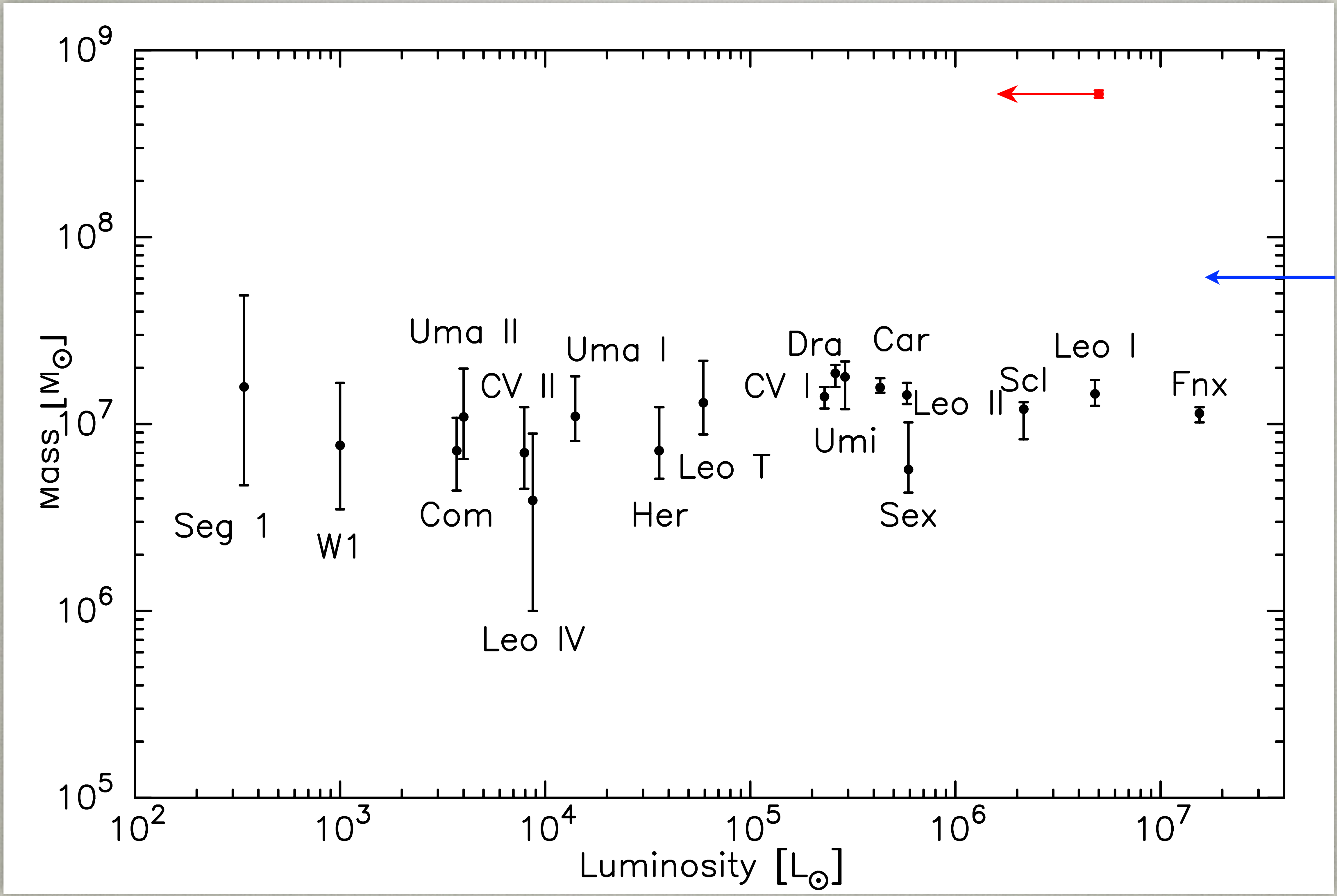
$$M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$$

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

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

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

Vegetti et al. 2012



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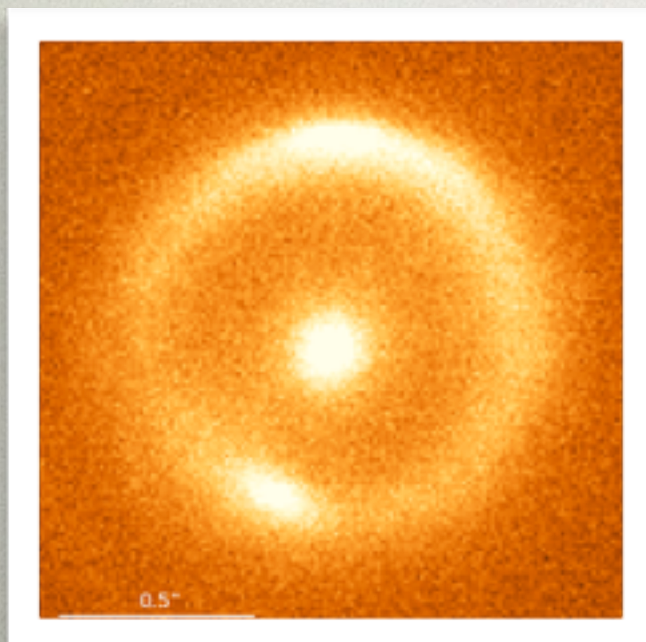
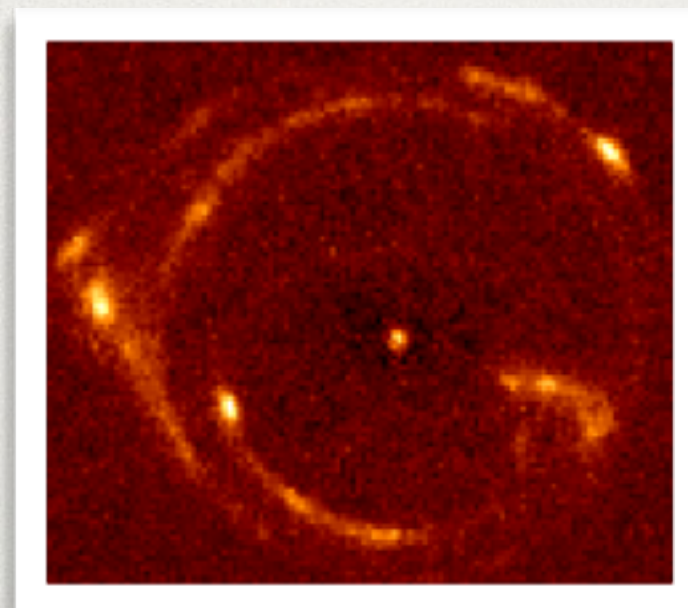
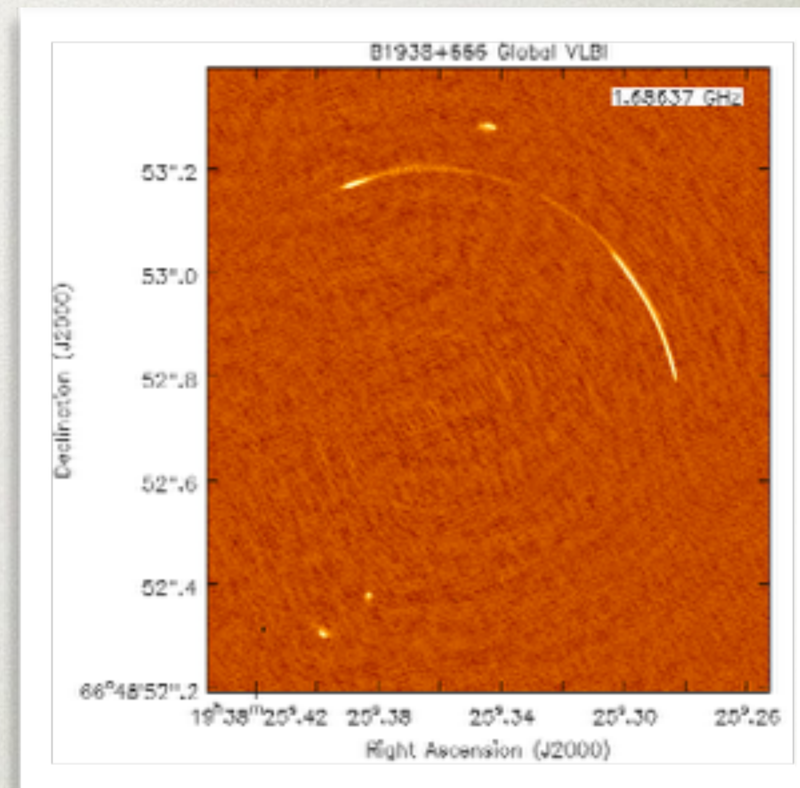


About 20 systems

Fassnacht et al. 2015



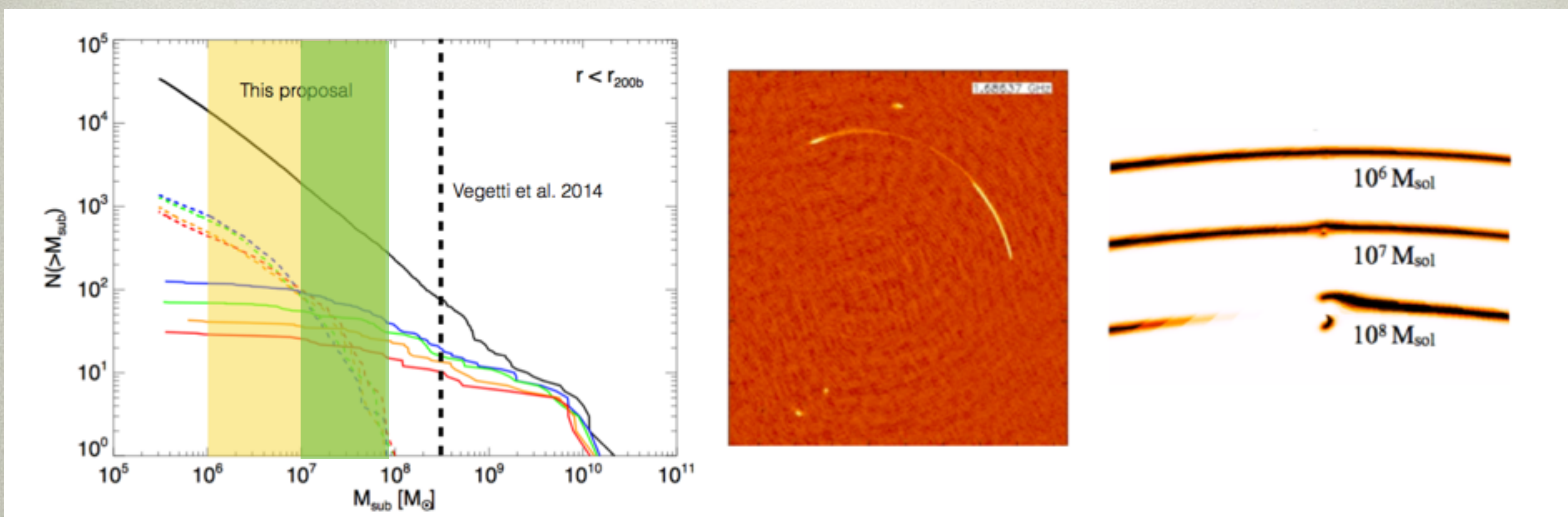
About 30 systems



only 2 but hopefully more to come

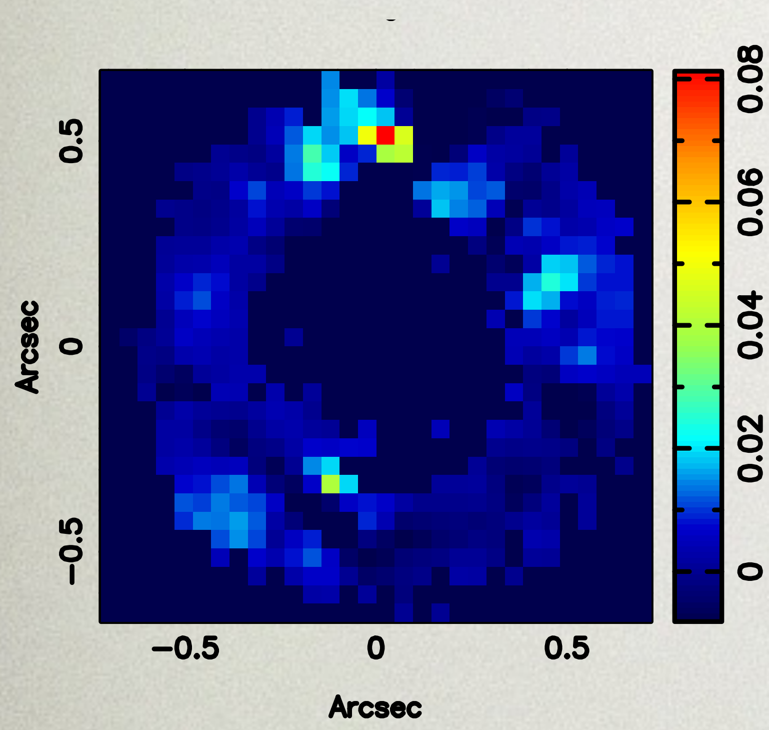
McKean et al. 2015, Rybak et al. 2015

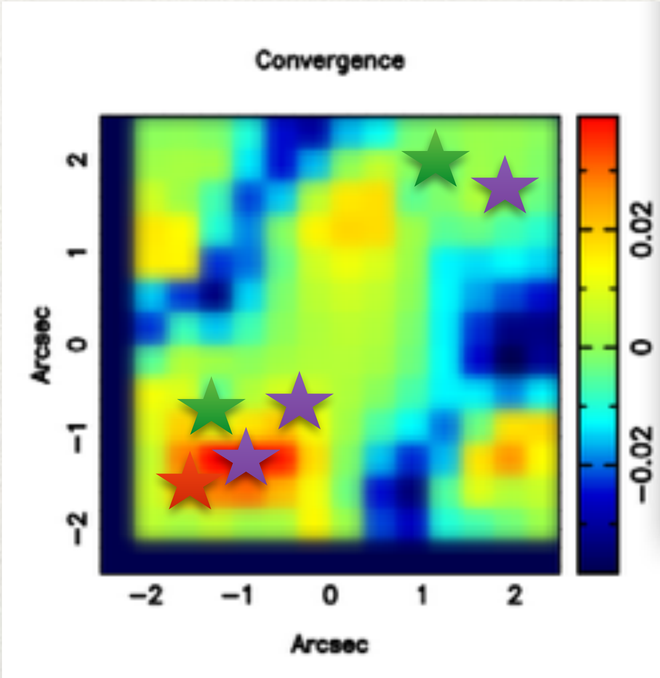
Radio - SHARP



See Matus' talk

The importance of looking at the corrections

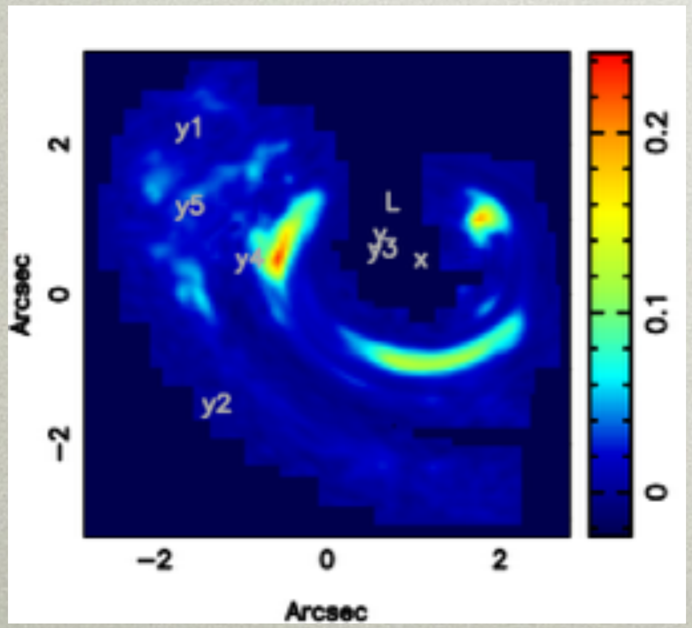


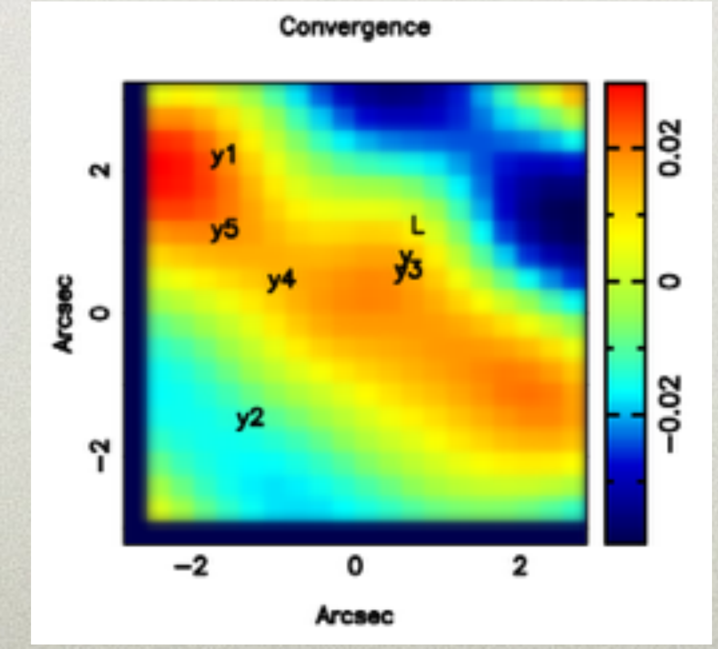


ΔE=1130.86

ΔE=1388.00

ΔE=1536.55





Conclusions

- Measuring the substructure mass function is an important test of the LCDM paradigm.
- Although most of the substructure could be dark or very faint gravitational lensing provides a great tool to probe the low mass end of substructure mass function
- Current results based on HST observations are in agreement with expectation from numerical simulation at masses ~ 10^8 M_sun
- Macro model inadequacies could mimic substructure in MCMC analysis
- By the end of next year we should have the first constraints on WDM models