CDM substructure mass function at z ~0.2

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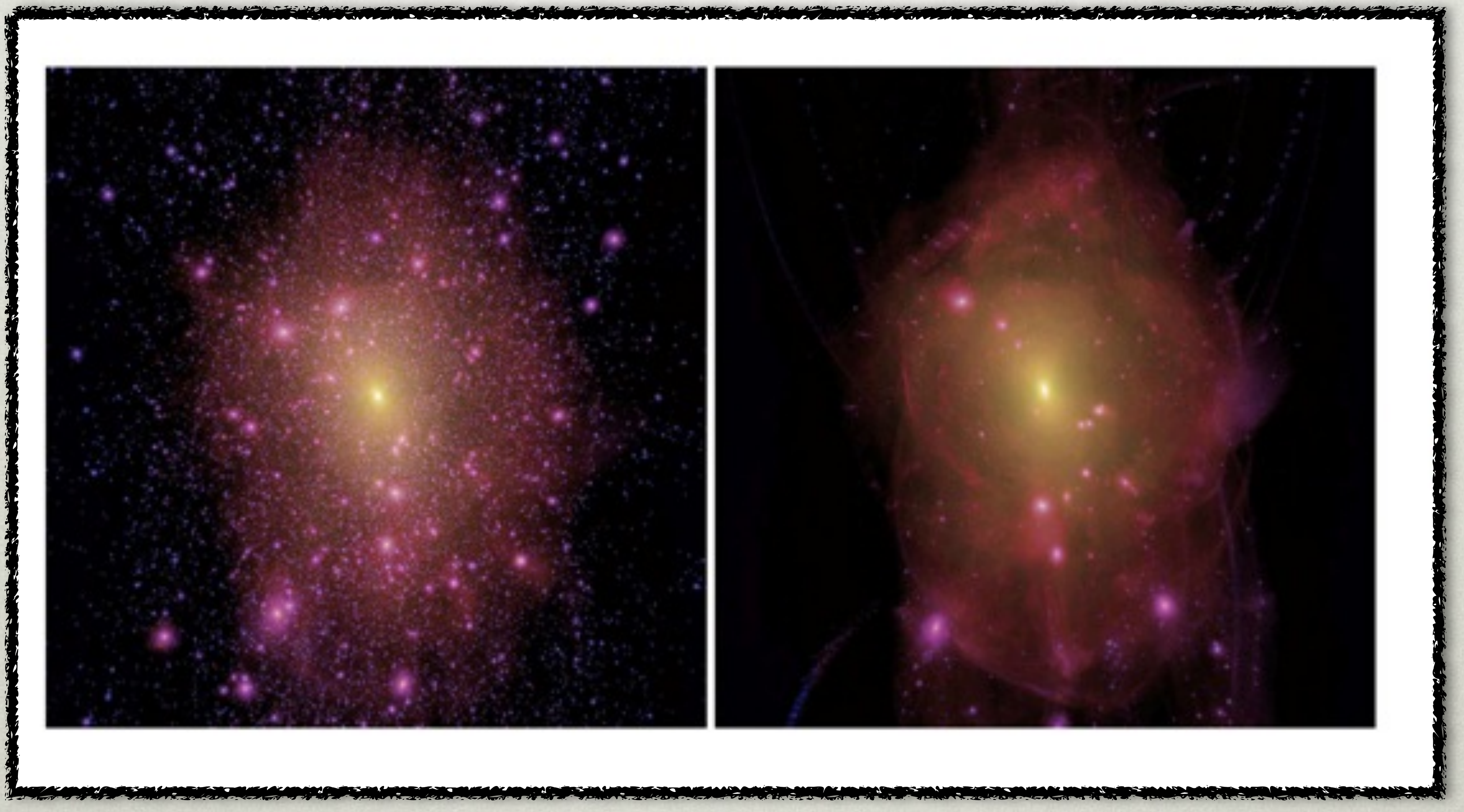
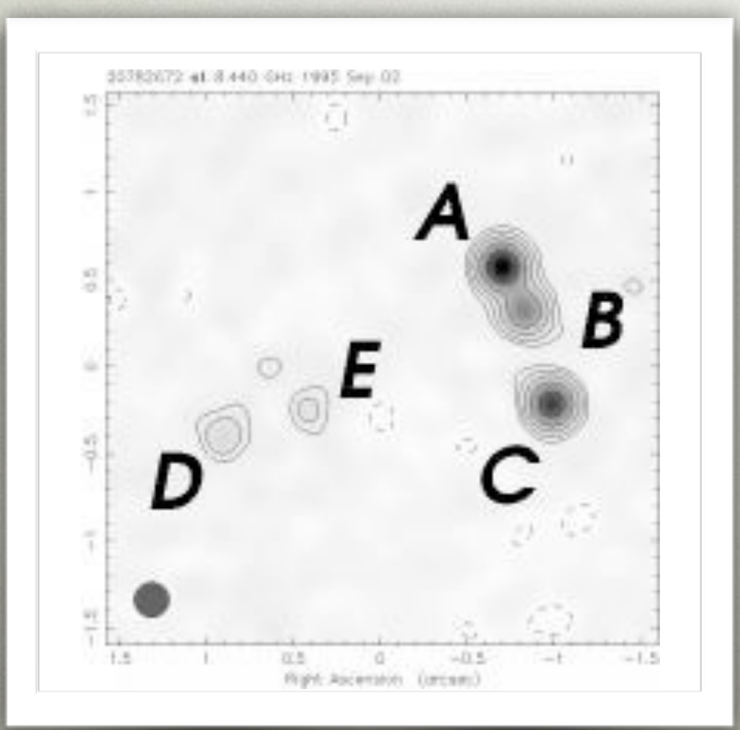
Lovell et al. 2012

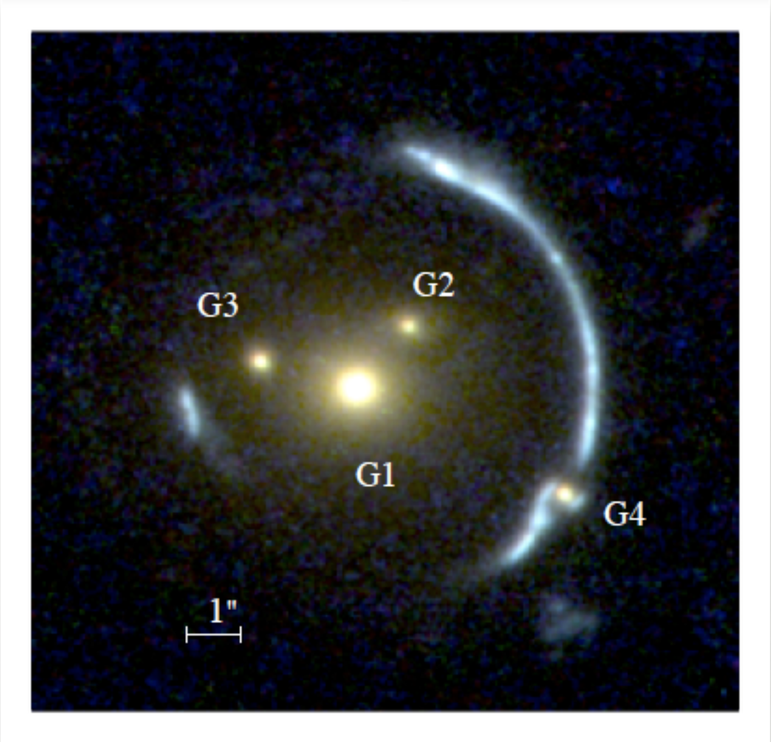
CDM vs WDM



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



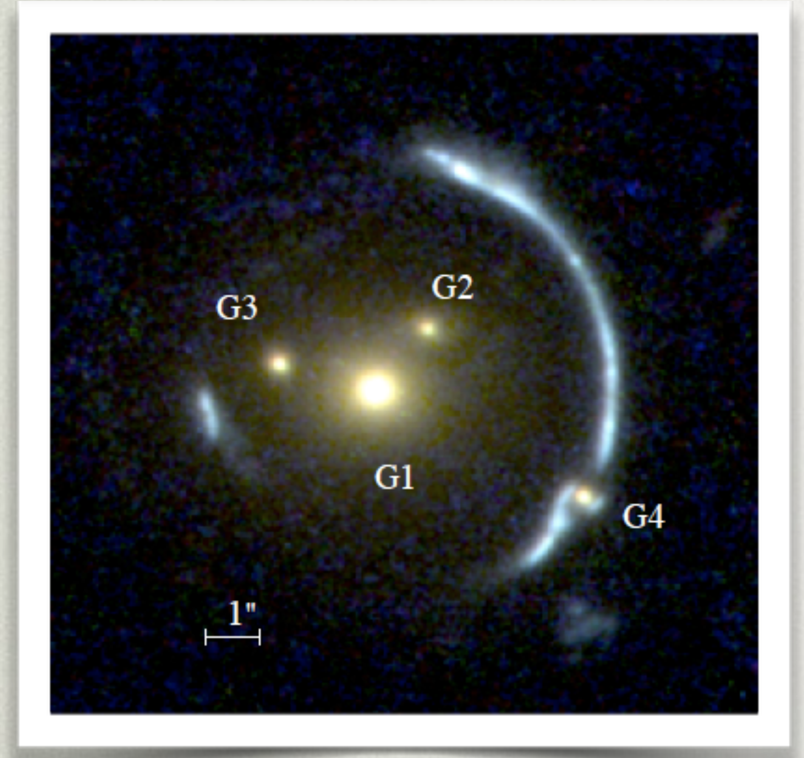


- substructures are detected as surface brightness anomalies
- need to disentangle structures in the potential from structures in the source
- Sensitive to higher masses
- NOT degenerate in the mass model

Koopmans 2005

Vegetti & Koopmans 2009

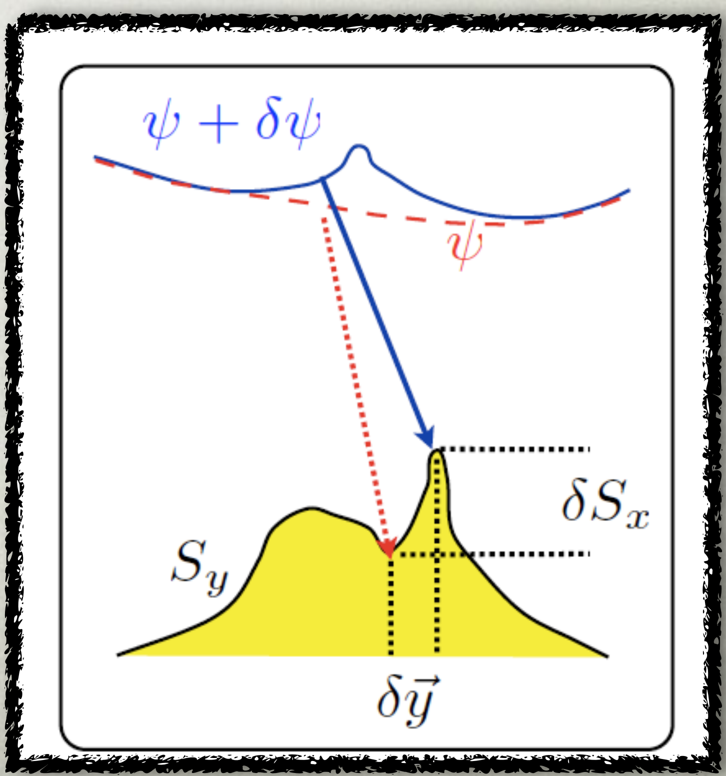
Gravitational Imaging



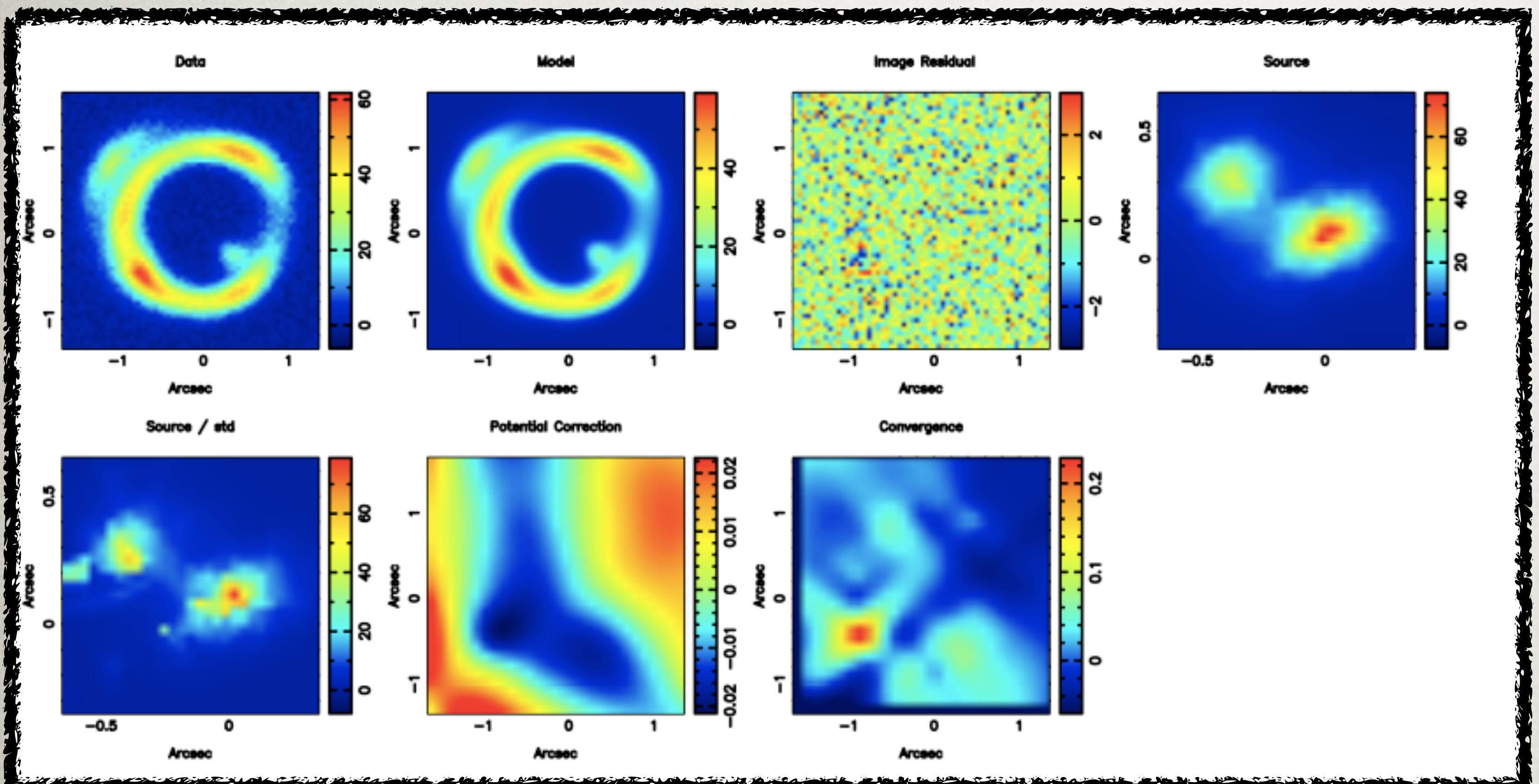
$$\psi(\mathbf{x},\eta)_{tot} = \psi(\mathbf{x},\eta) + \delta\psi(\mathbf{x})$$

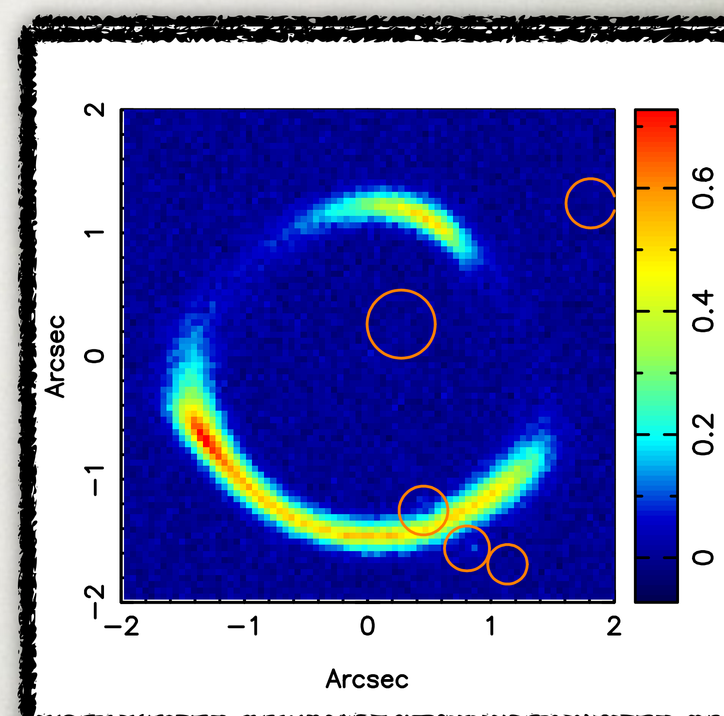
$\psi(\mathbf{x},\eta)$ Smooth analytic power-law model

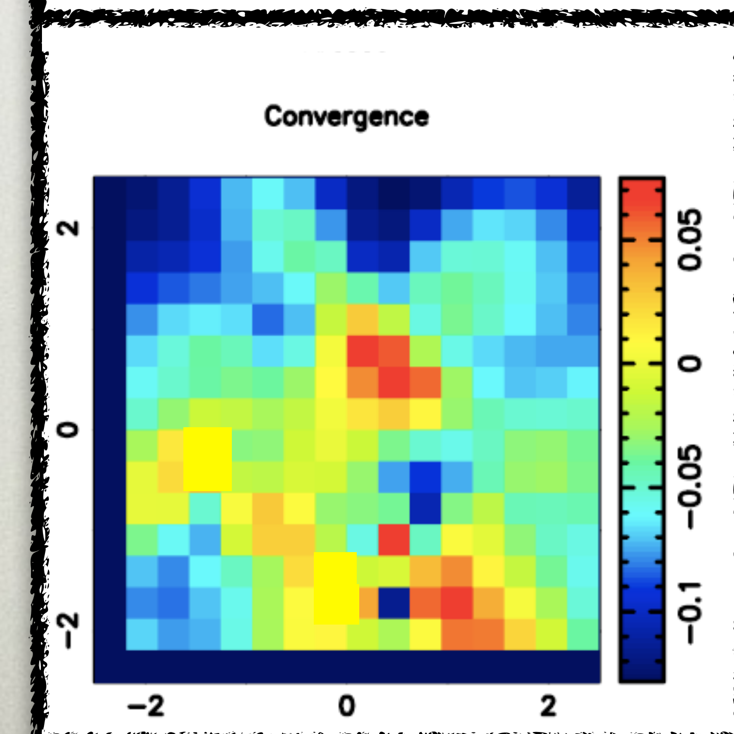
$\delta\psi(\mathbf{x})$ pixellated potential correction



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

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;

- 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);

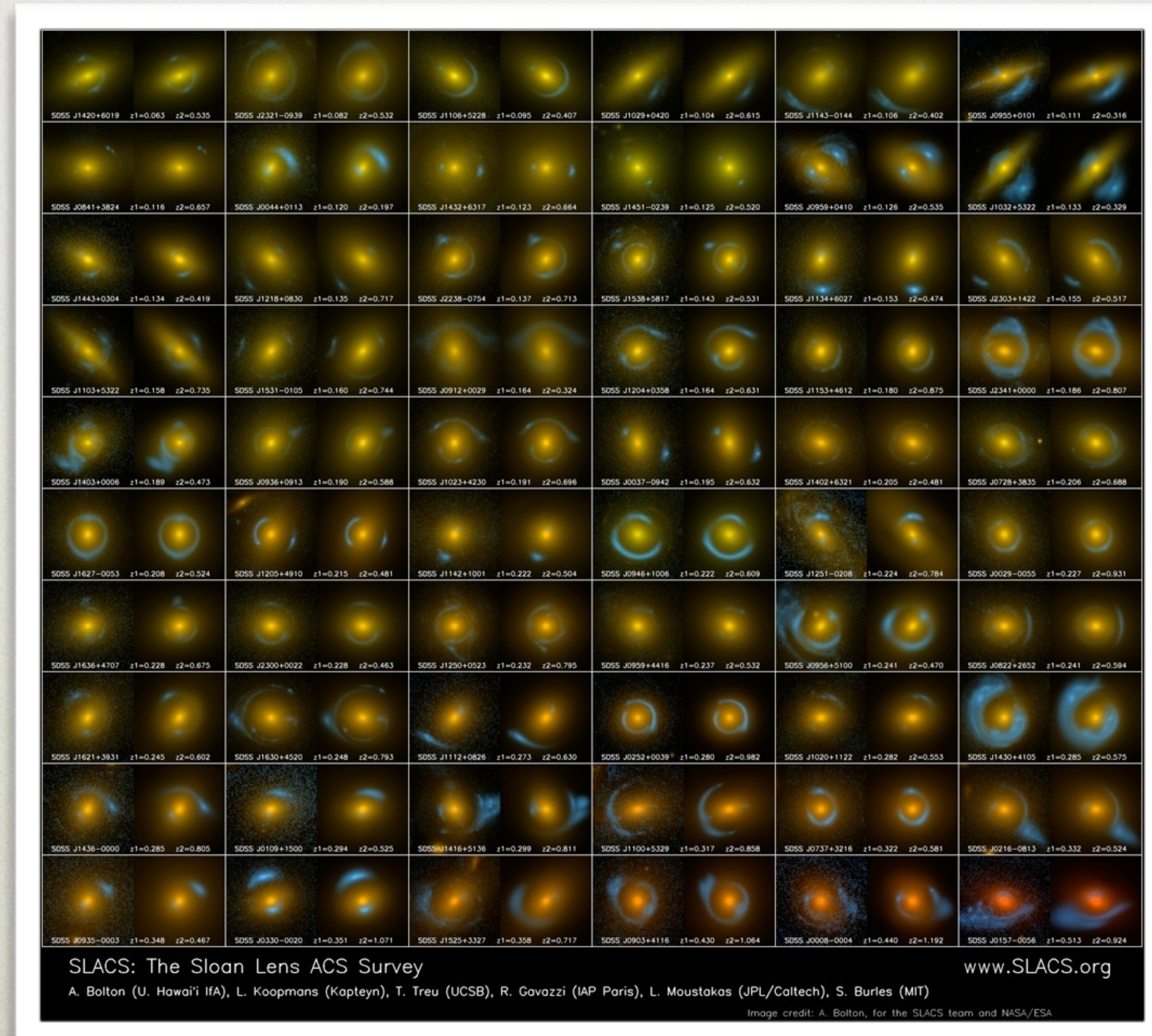
- the mass and the position of the substructure obtained via the Nested Sampling analysis is consistent with those independently obtained by the potential corrections and the MAP parametric clumpy model;

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

Bolton et al. 2006

Bolton et al. 2008

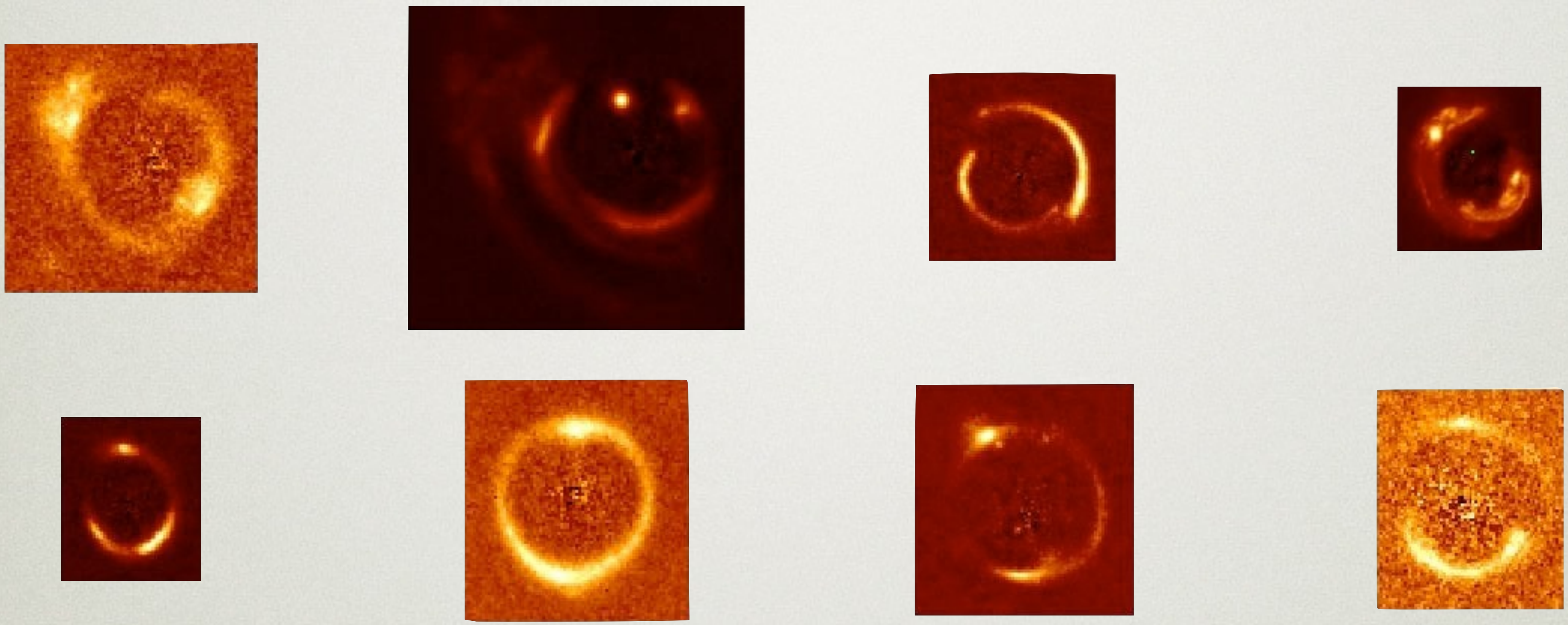
SLACS

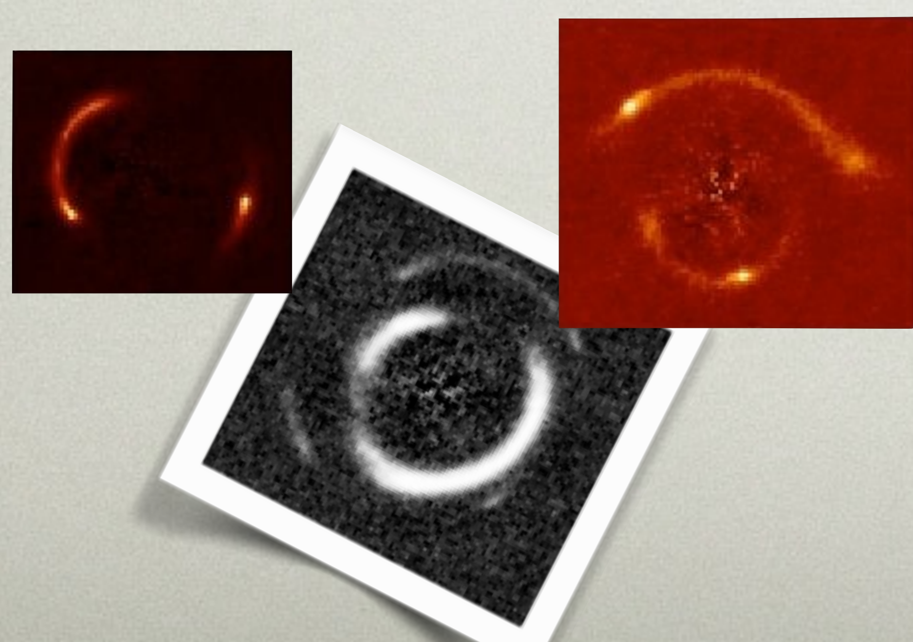


$$z = 0.06 - 0.36$$

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

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





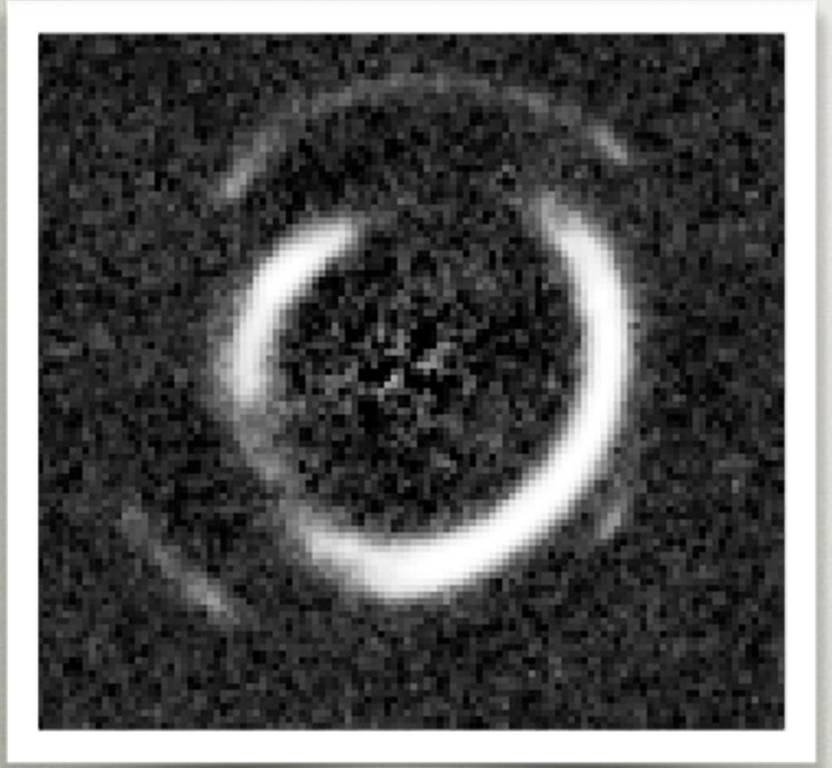
- Chosen on a s/n basis
- Representative sub-sample of the SLACS lenses
- Representative sample of massive early-type galaxies

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

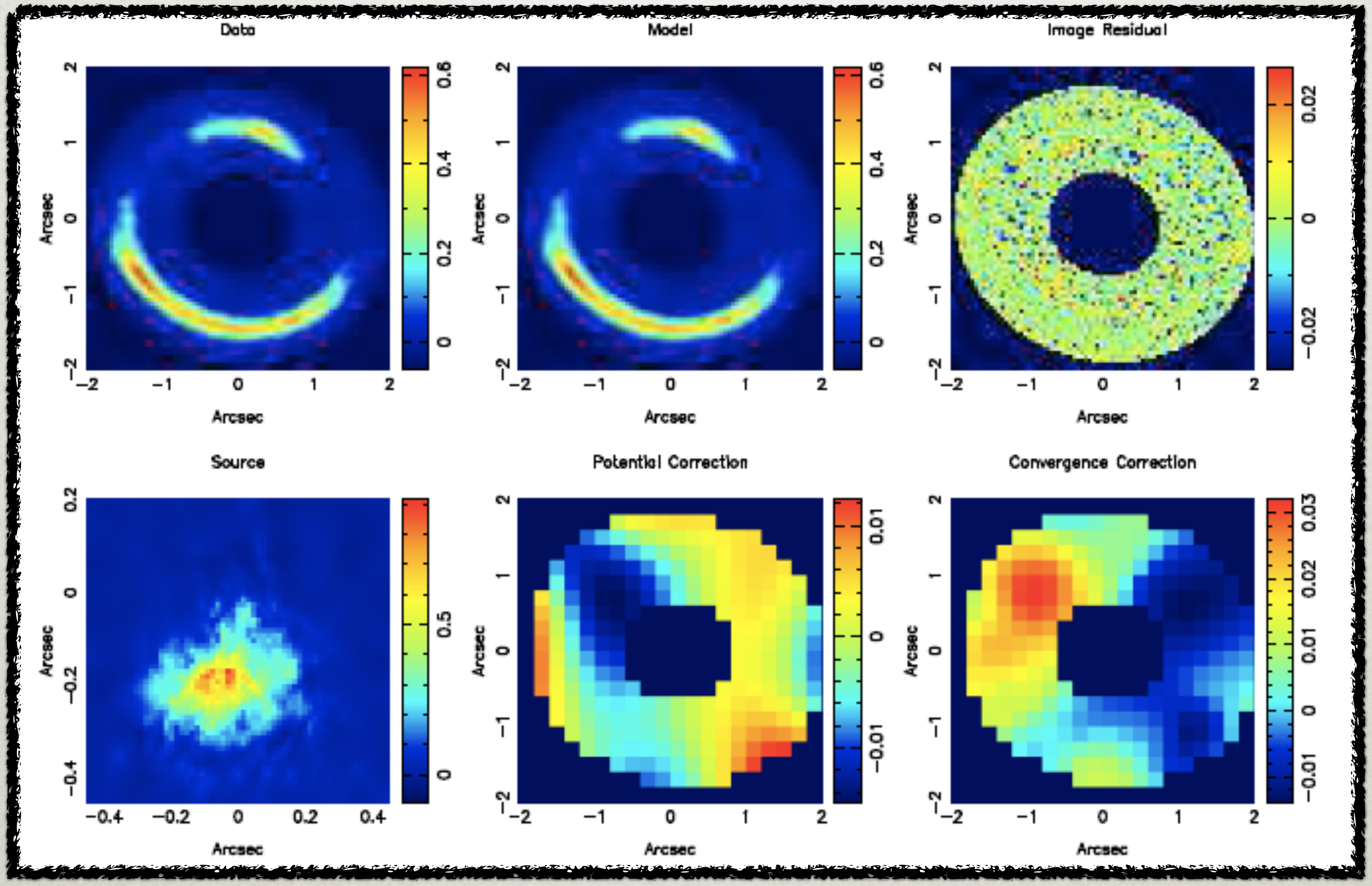
$$\Delta R = R_{ein} \pm 0.3$$

- 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

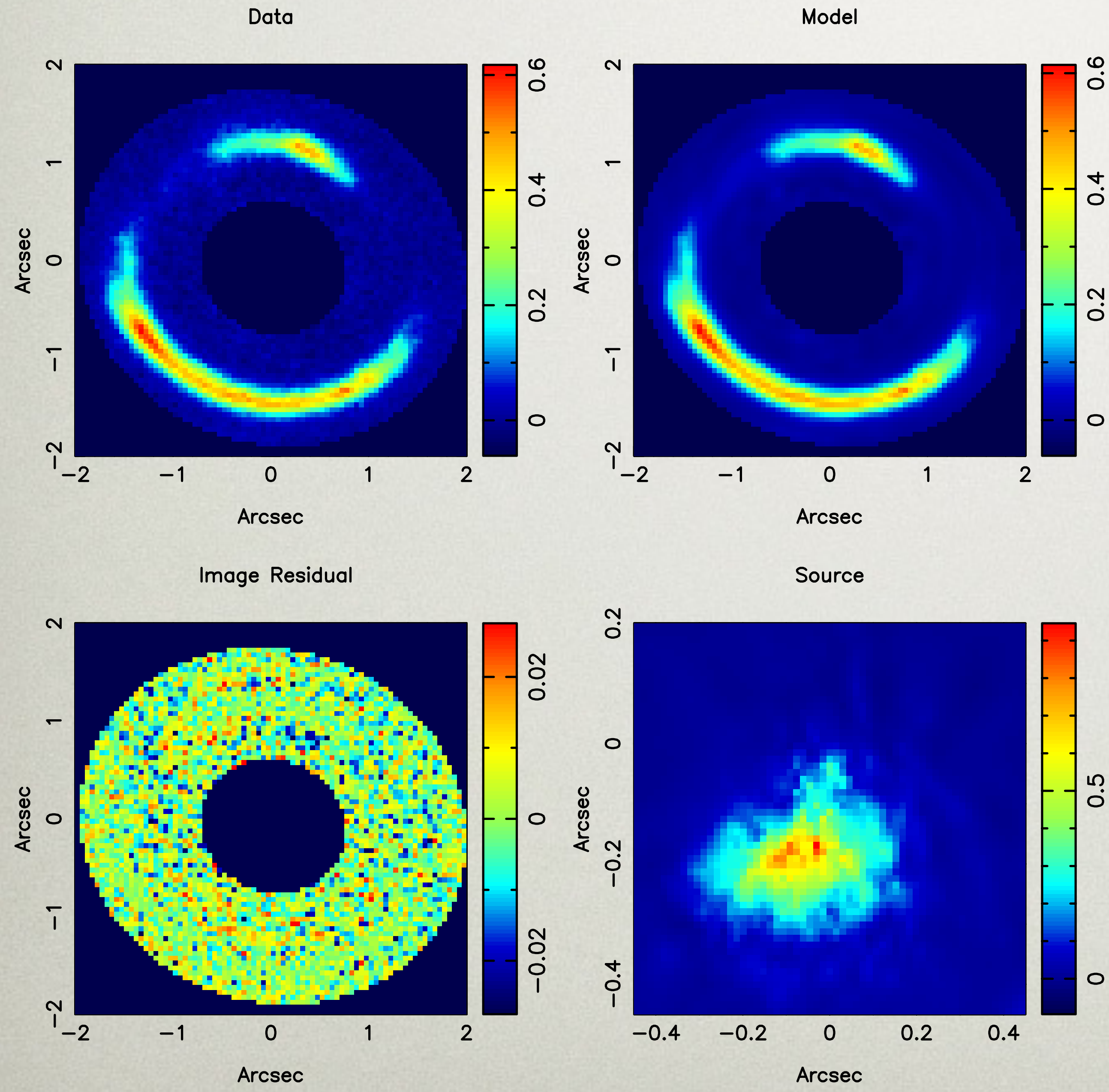
Double Ring



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

Vegetti et al. 2010

Double Ring



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

$$r_t = 1.1\ kpc$$

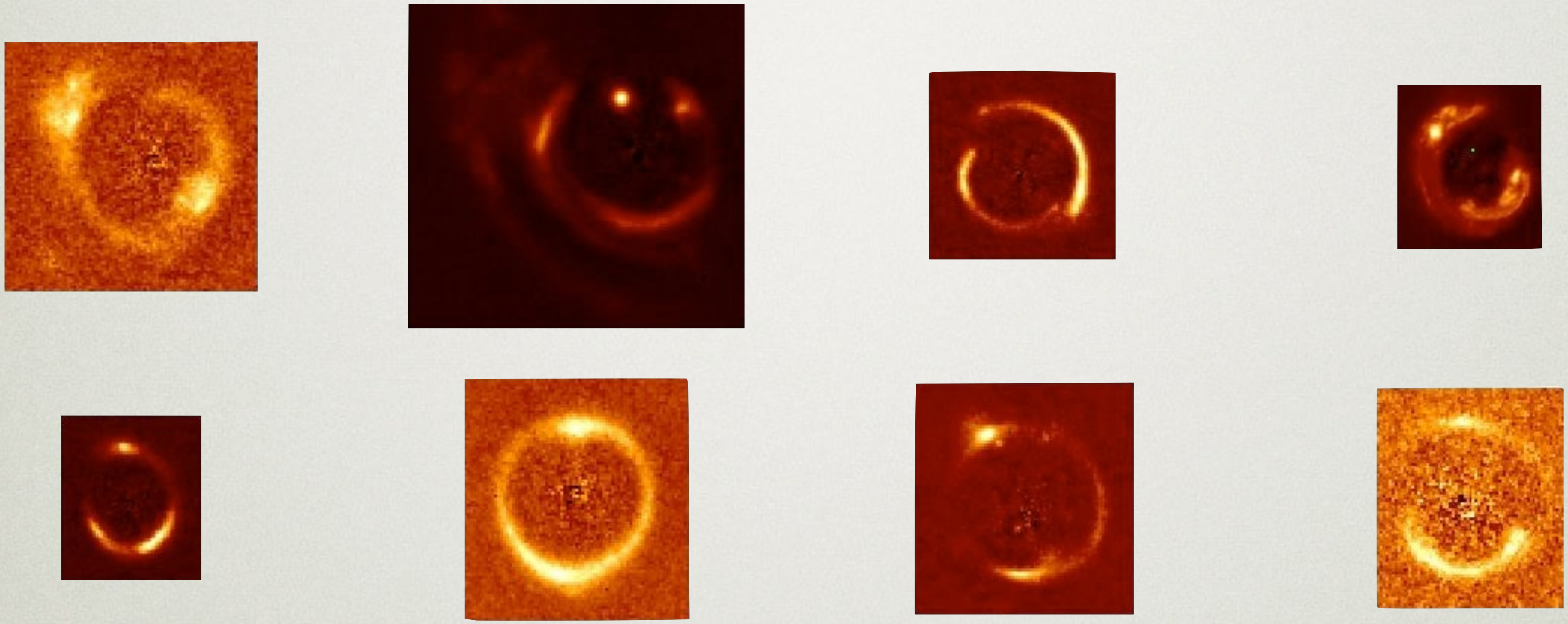
$$\Delta \log \mathcal{E} = -128.0$$

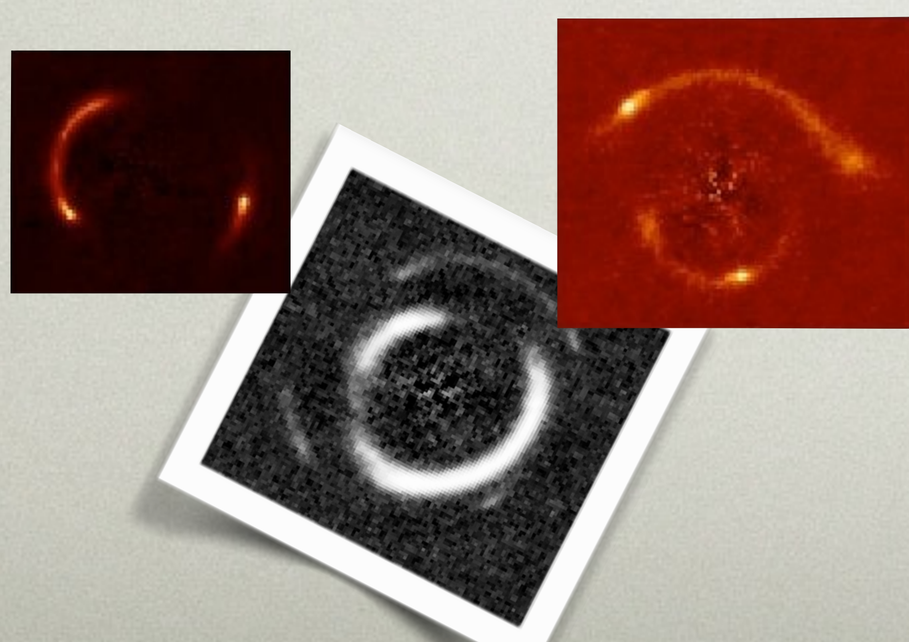
$$L_V \leq 5 \times 10^6 L_\odot$$

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

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

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





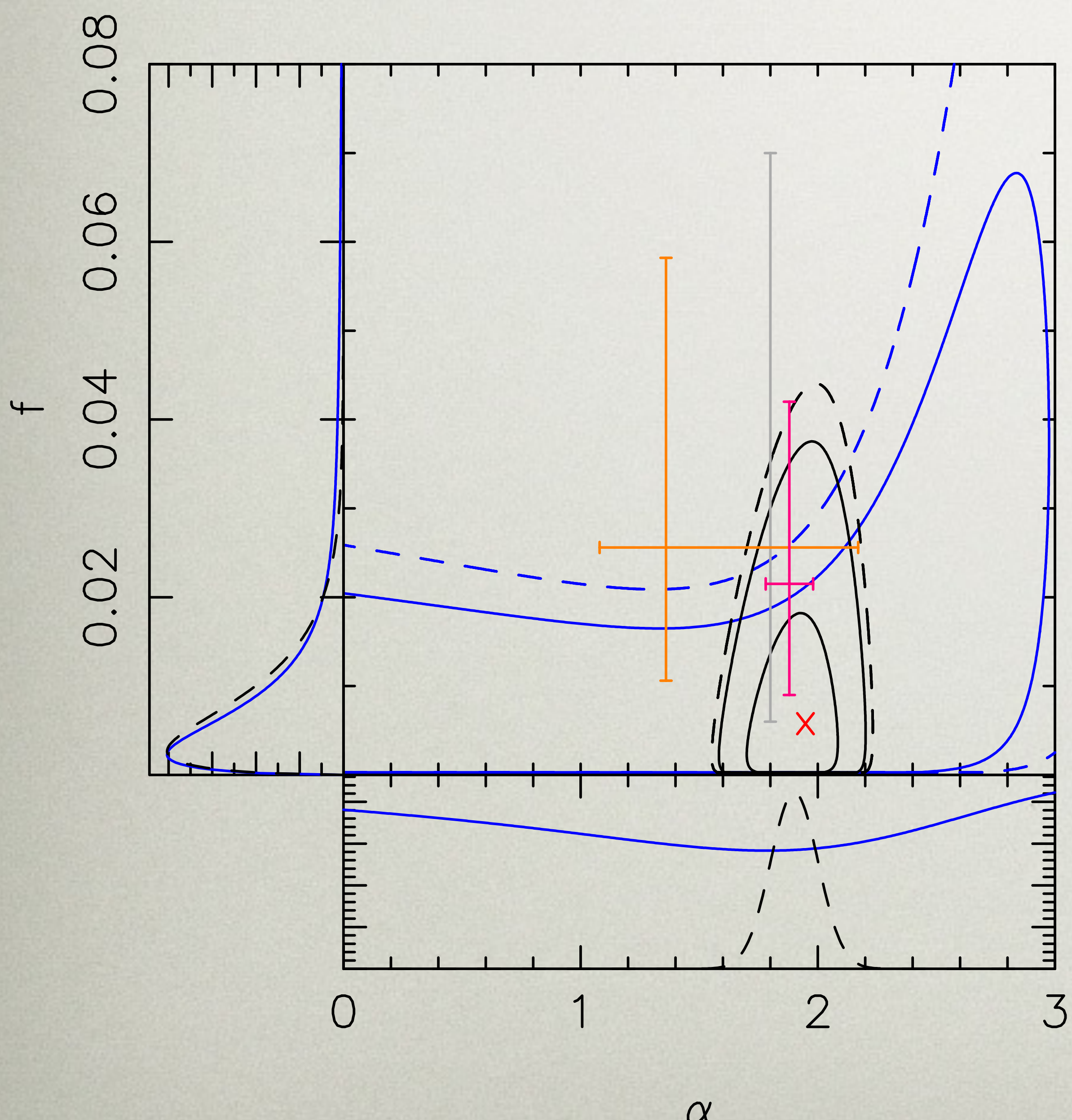
Chosen on a s/n basis

Representative sub-sample of the SLACS lenses

Representative sample of massive early-type galaxies

Vegetti et al. 2014

CDM Mass Function at z=0.2



P(α)	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

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

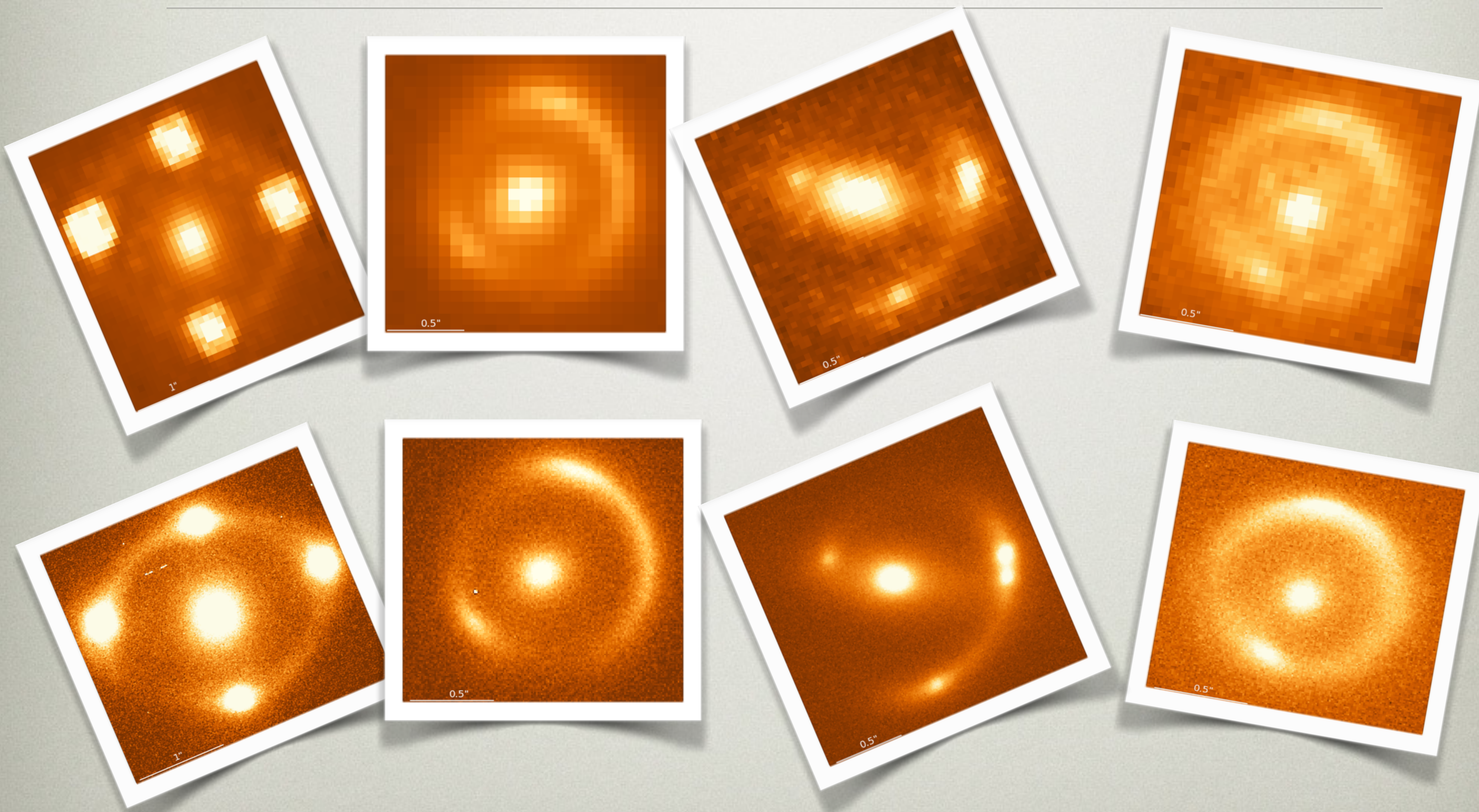
$$P_{\rm U}(\alpha) = \frac{1}{\alpha_{\rm max} - \alpha_{\rm min}},$$

and

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

Vegetti et al. 2012

SHARP

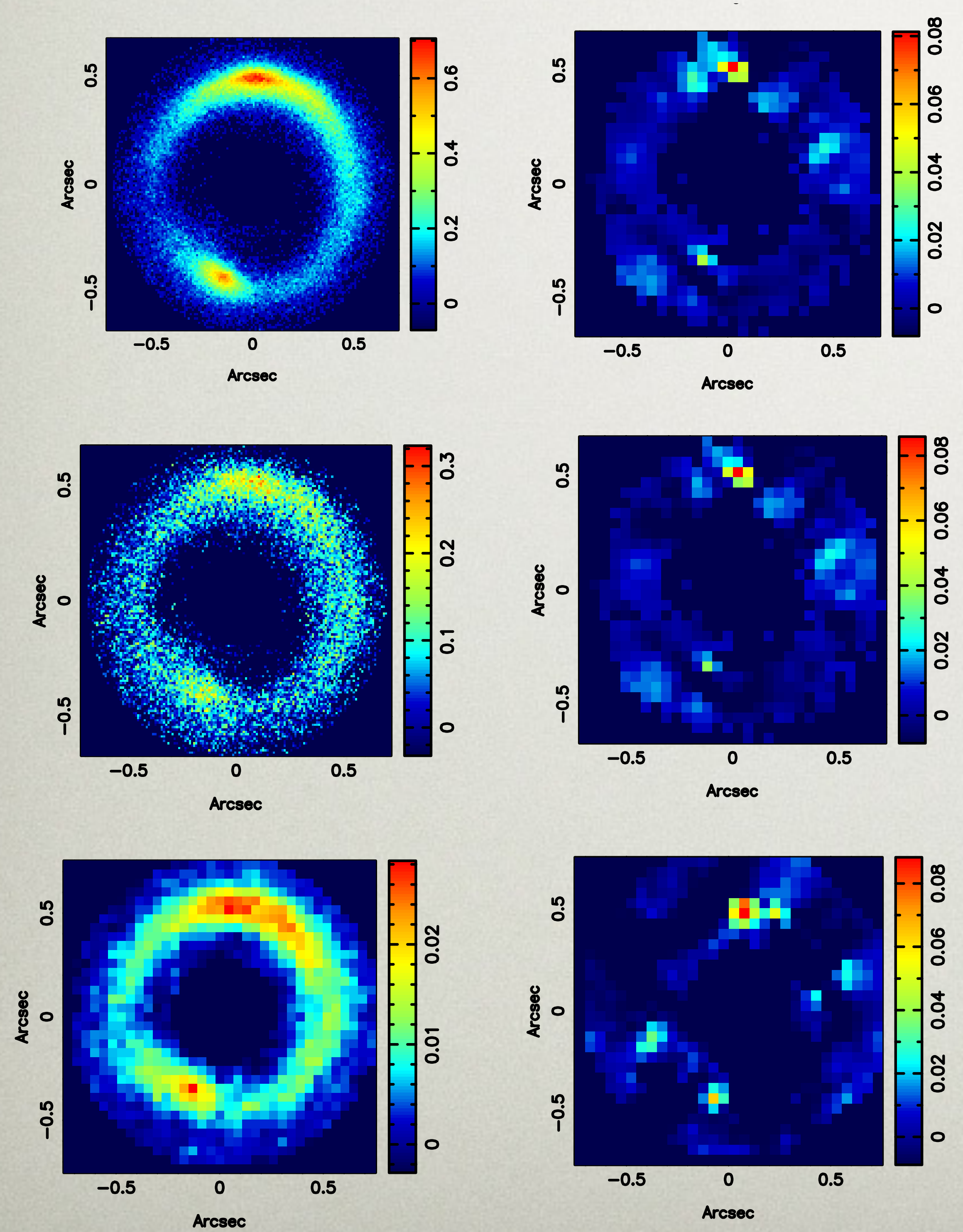


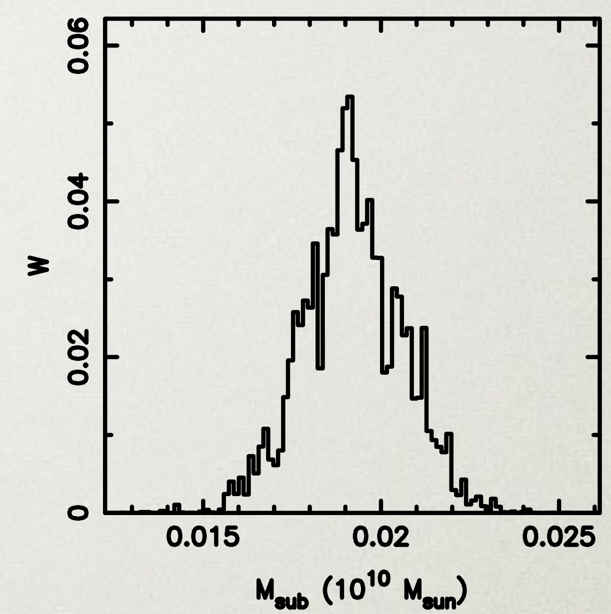
- Medium sized sample of ~20 systems

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

Vegetti et al. 2012

SHARP





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

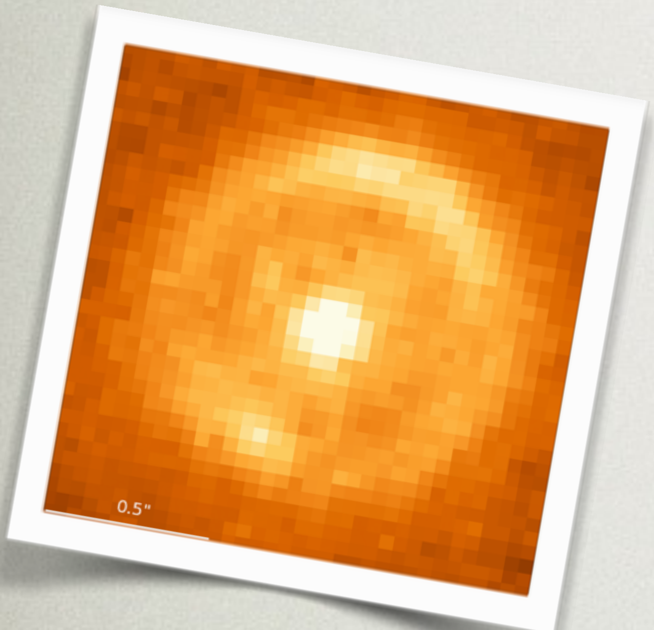
$$M(< 0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot$$

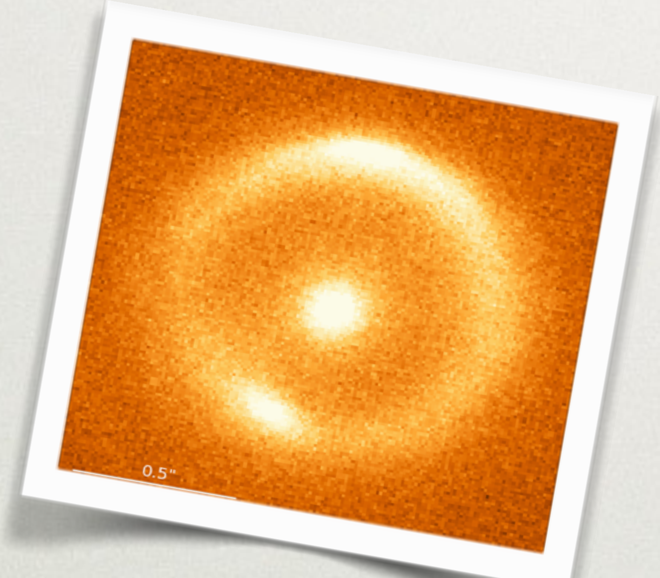
$$M(< 0.3) = (7.24 \pm 0.6) \times 10^7 M_\odot$$

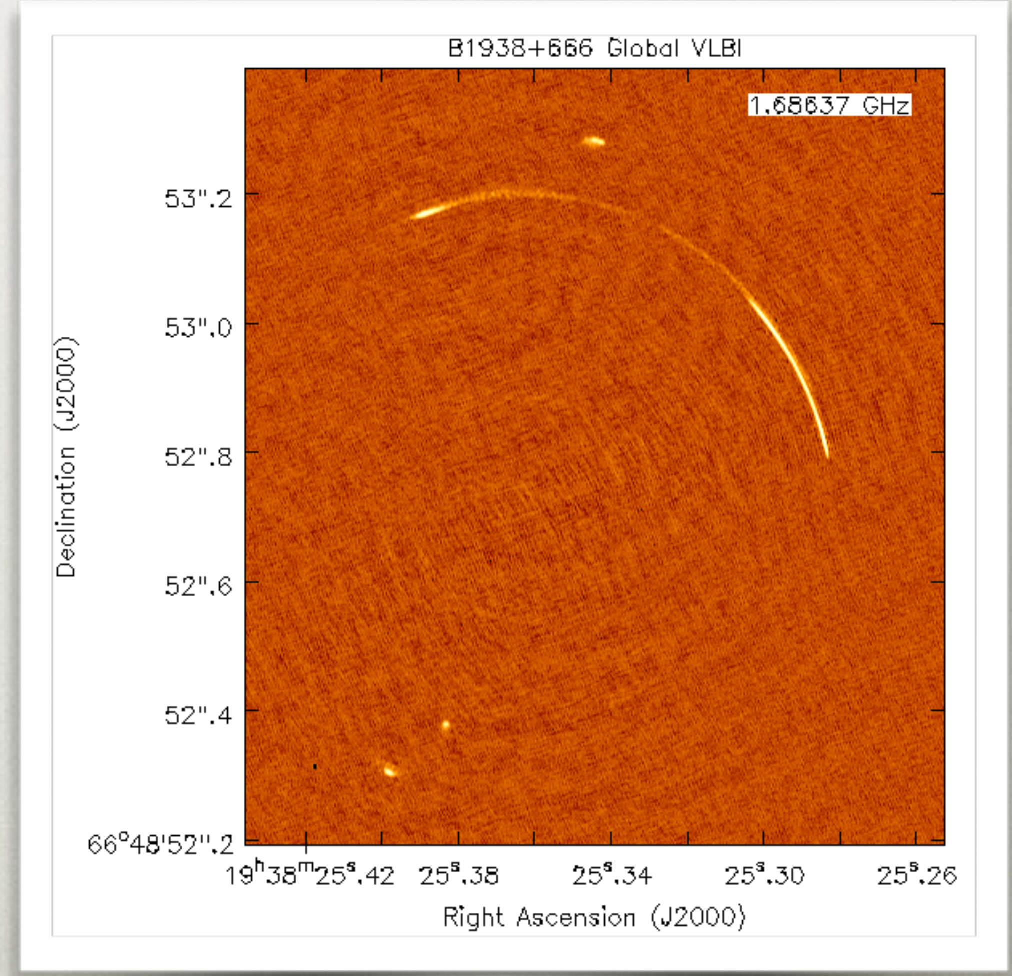
$$V_{max} \approx 27\ km\ s^{-1}$$

Vegetti et al. 2012

SHARP



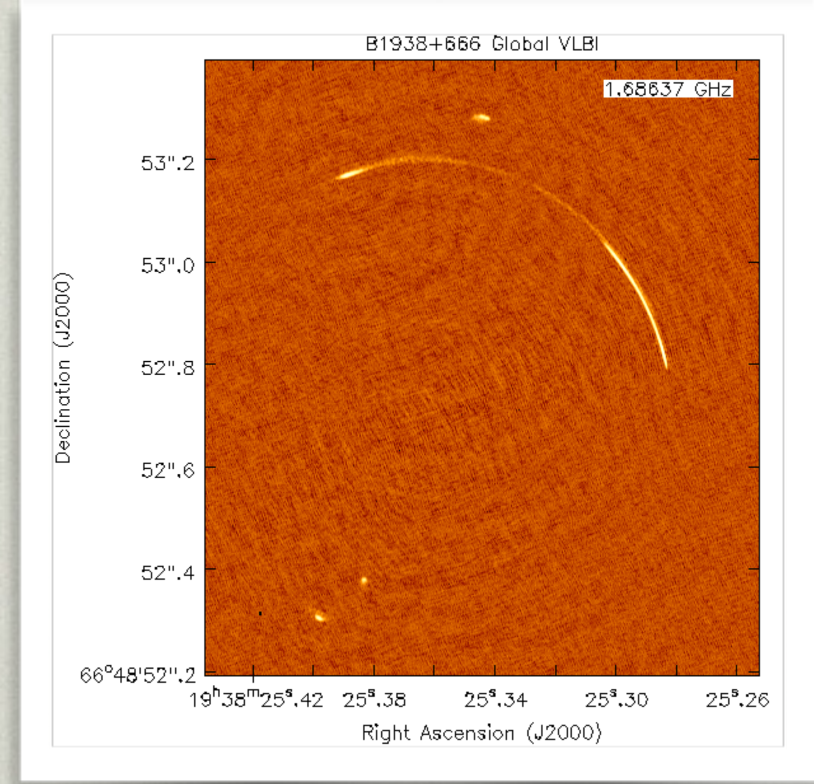


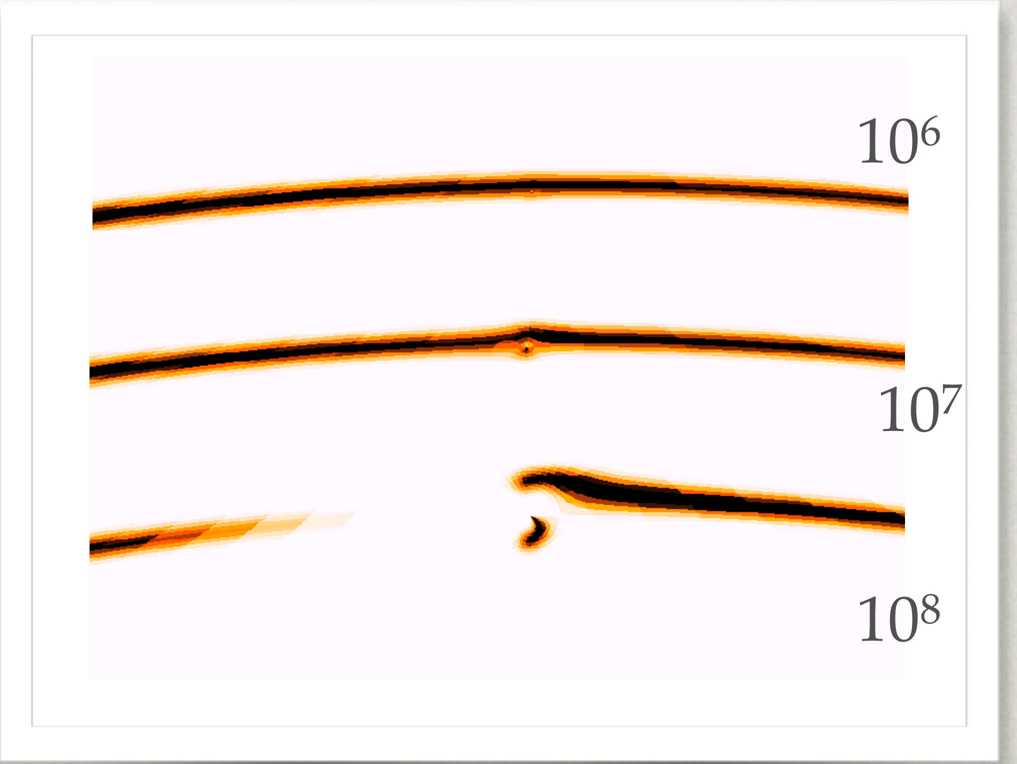


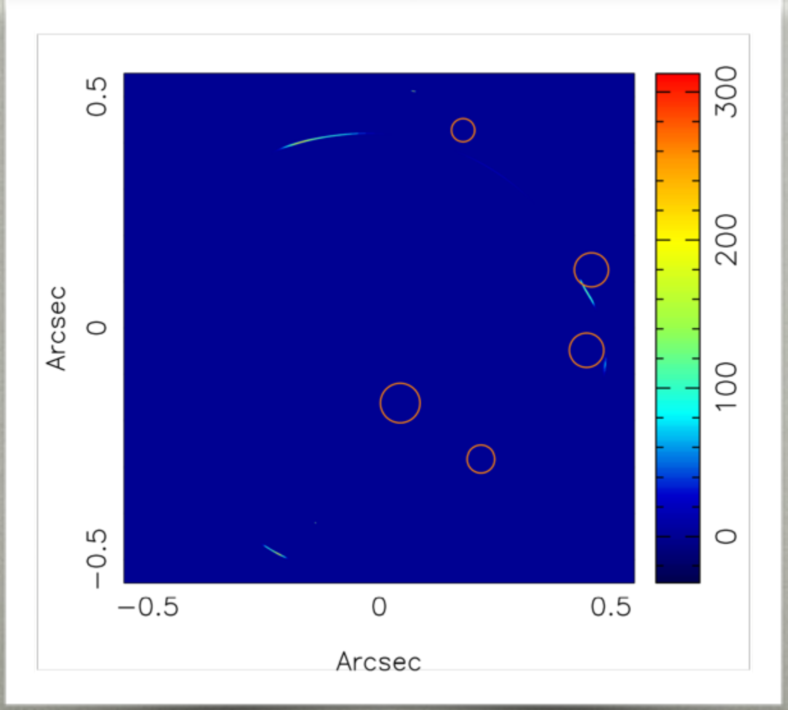
McKean et al. in prep.

Rybak et al. in prep.

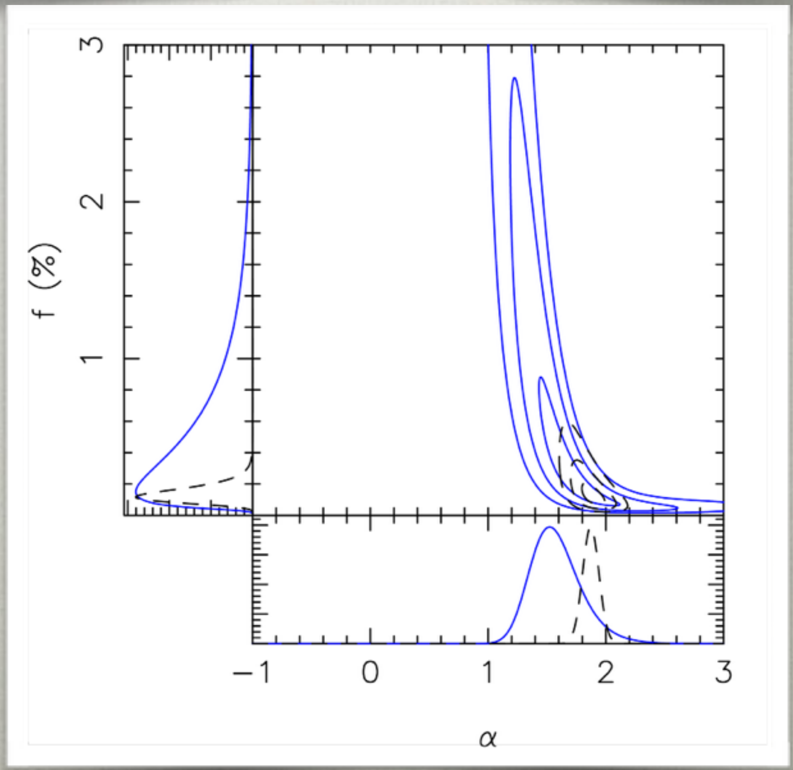
Radio - SHARP







$f \leq 0.1\%$



Conclusions

- Measuring the substructure mass function is an important test of the LCDM paradigm.
- The substructure mass function provides constraints on the dark matter properties
- 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