Detection of a small mass substructure at cosmological distance

By

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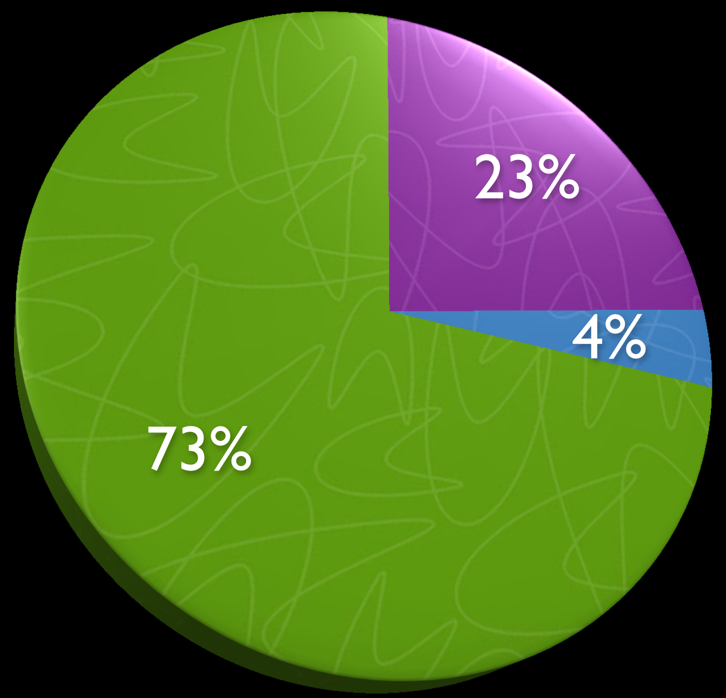
The dark Universe



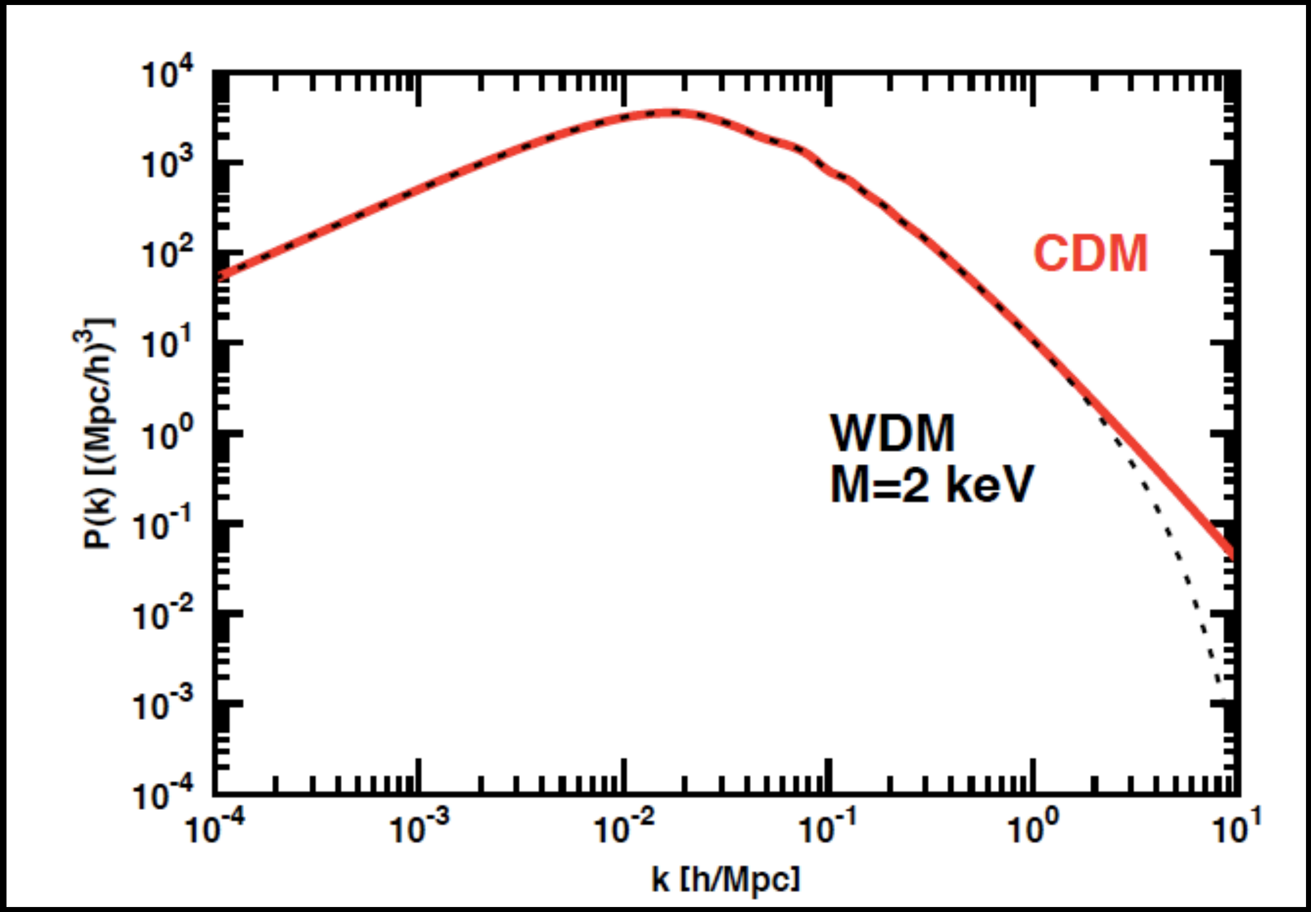
Dark Matter
Baryons
Dark Energy

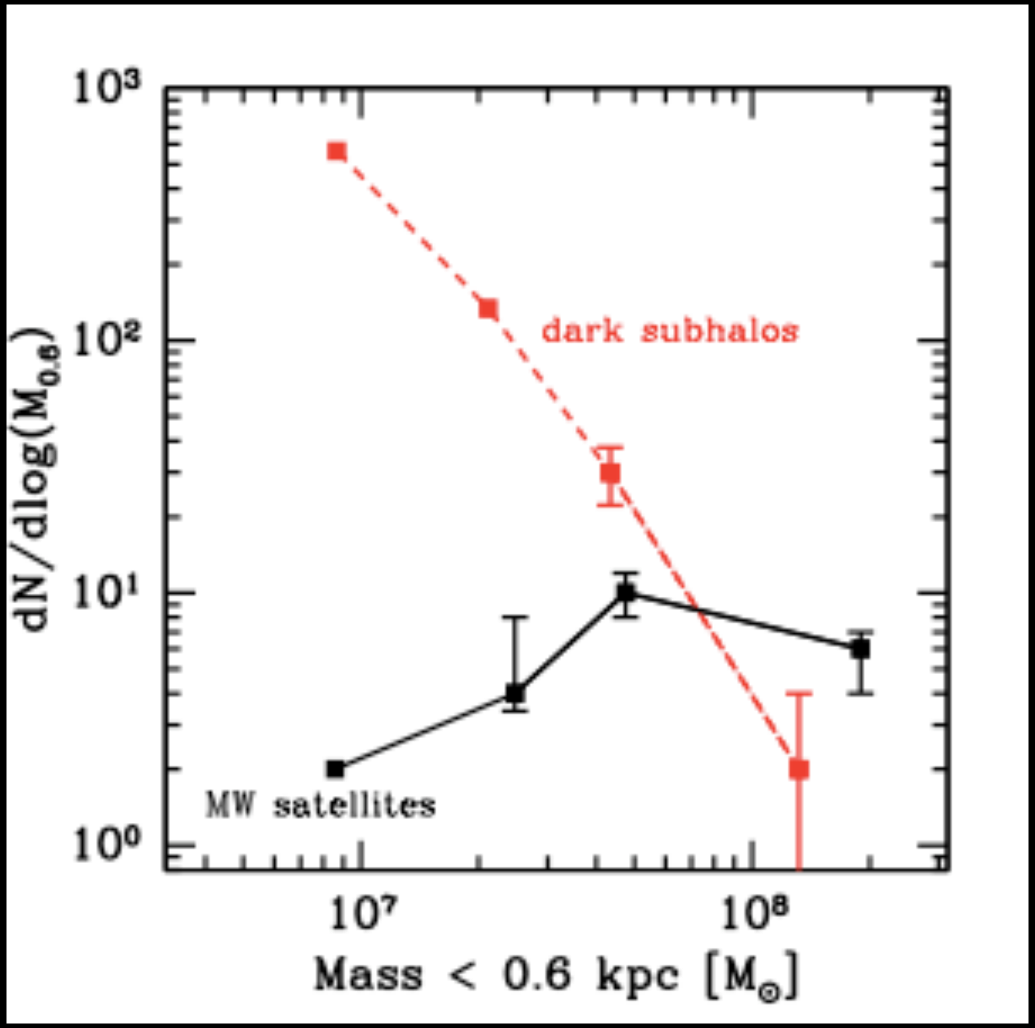
Dark matter particles are probably *super-weakly interacting* particles: e.g sterile neutrinos, axion, Majorana particles ...

Direct detection from particle labs is currently very challenging

Astrophysics and cosmology may be our main tools to constrain the true nature of dark matter

Dark Matter & Mass Function





$$\lambda_{FS} = \int_0^t \frac{v(t)dt}{a(t)}$$

— $dN/dm \propto m^{-1.0}$

— $dN/dm \propto m^{-1.9}$

Dwarf spheroidal galaxies: lower bound on the DM mass = 400 eV

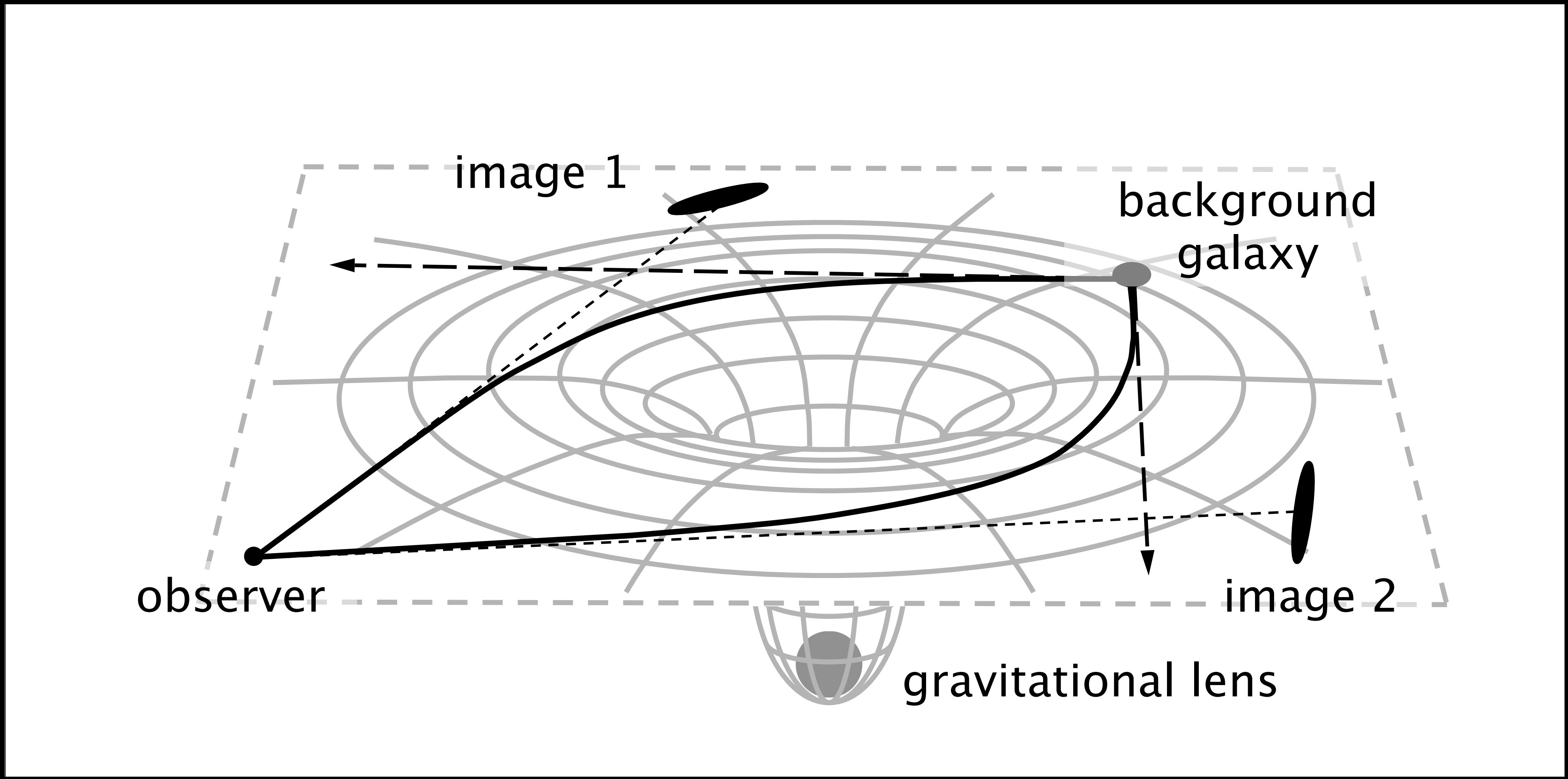
... but there may be a strong bias between luminosity and mass functions

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

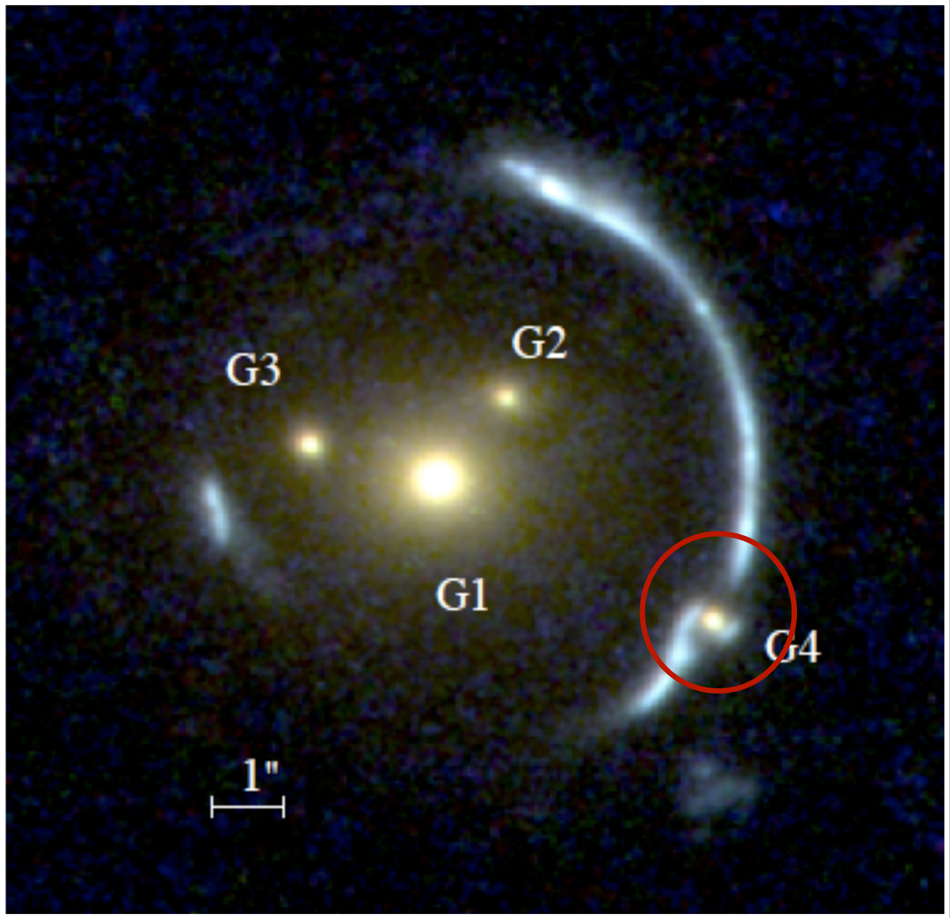


- Multiple images of the same background source
- Each image position gives a constrain to the lens potential
- Extended images give an extra constrain for each resolution element

Substructure as potential corrections

How do we recognise the effect of substructure?

$$\Delta\theta \approx \theta_E \mu$$



Not degenerate in the mass model

Potential model

$$\psi\left(\mathbf{x},\eta\right) = \psi_{smooth}\left(\mathbf{x},\eta\right) + \delta\psi\left(\mathbf{x}\right)$$

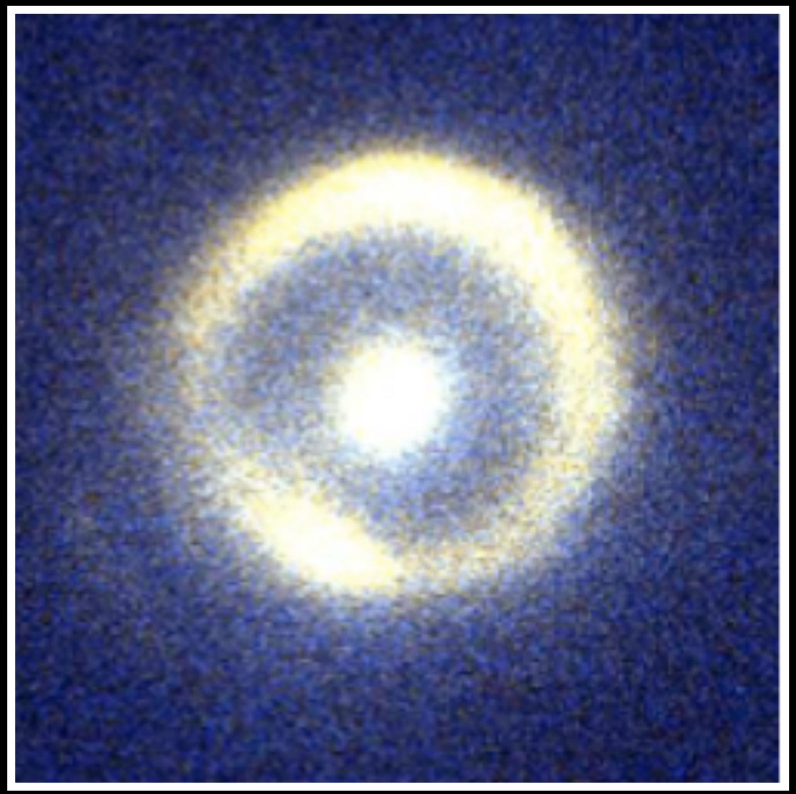
$\psi\left(\mathbf{x},\eta\right)$ Family of elliptical power-law

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

B1938+666

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

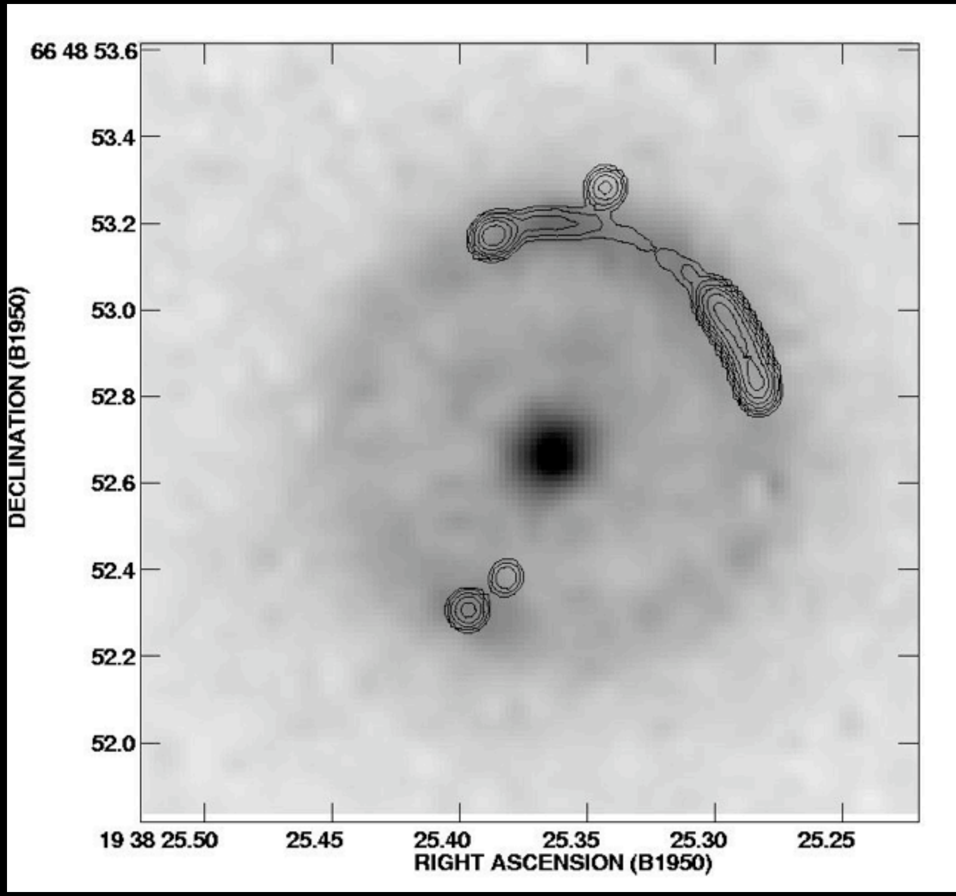
AO



Lagattuta et al. 2011 in preparation

Vegetti et al. 2011 under review

HST + Merlin



King et al. 1998

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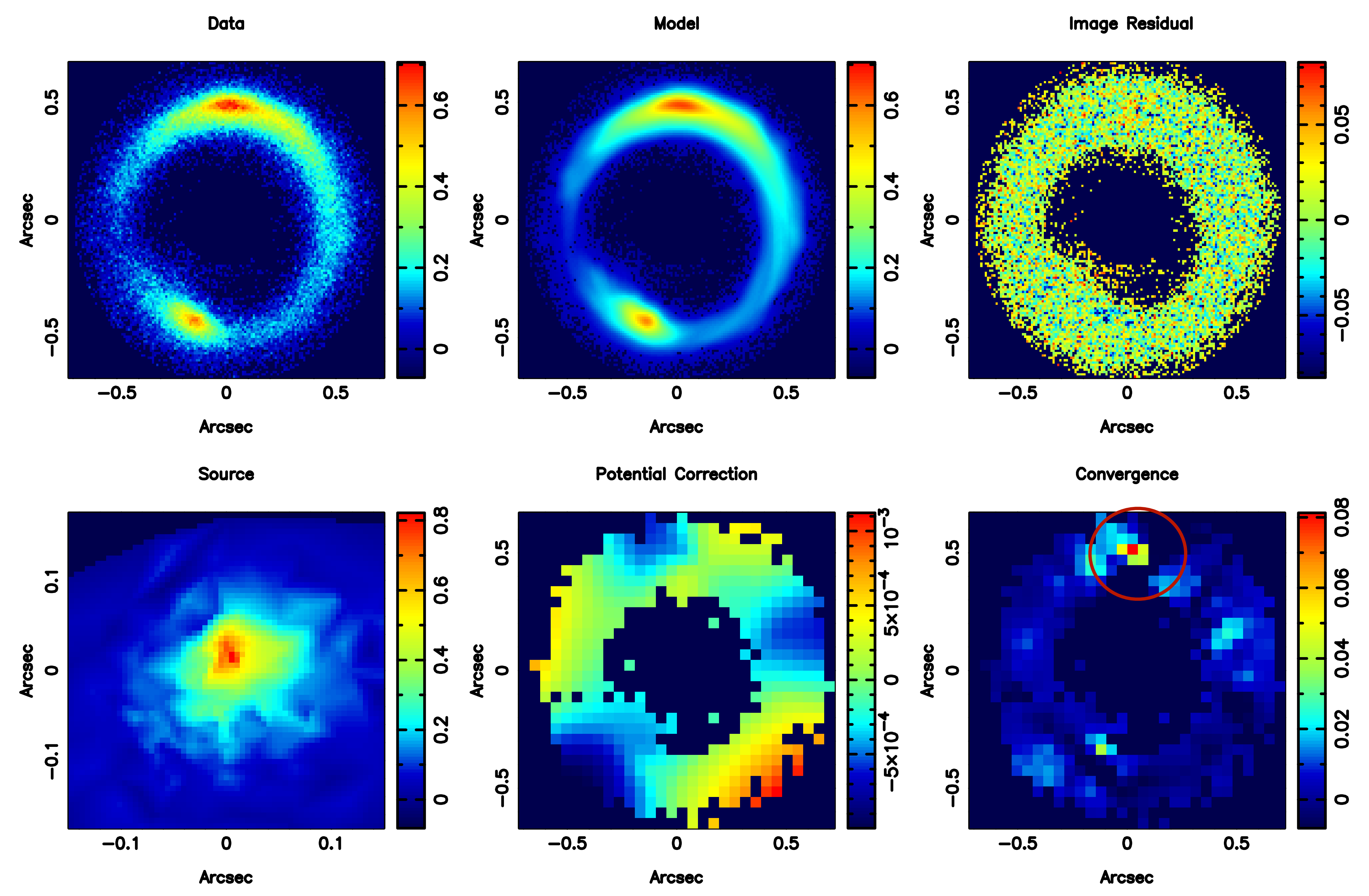
Keck K-band



Vegetti et al. 2011 submitted

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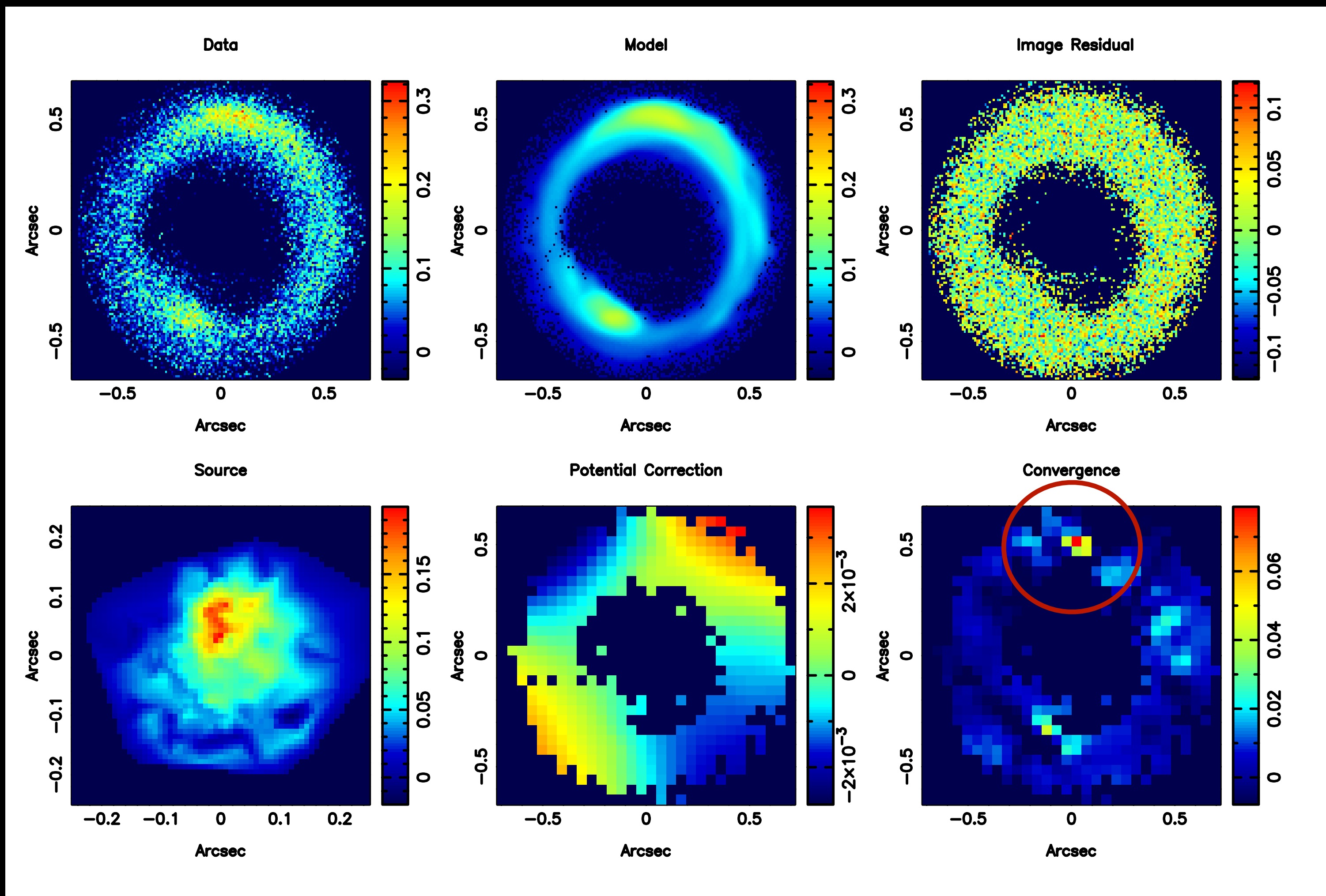
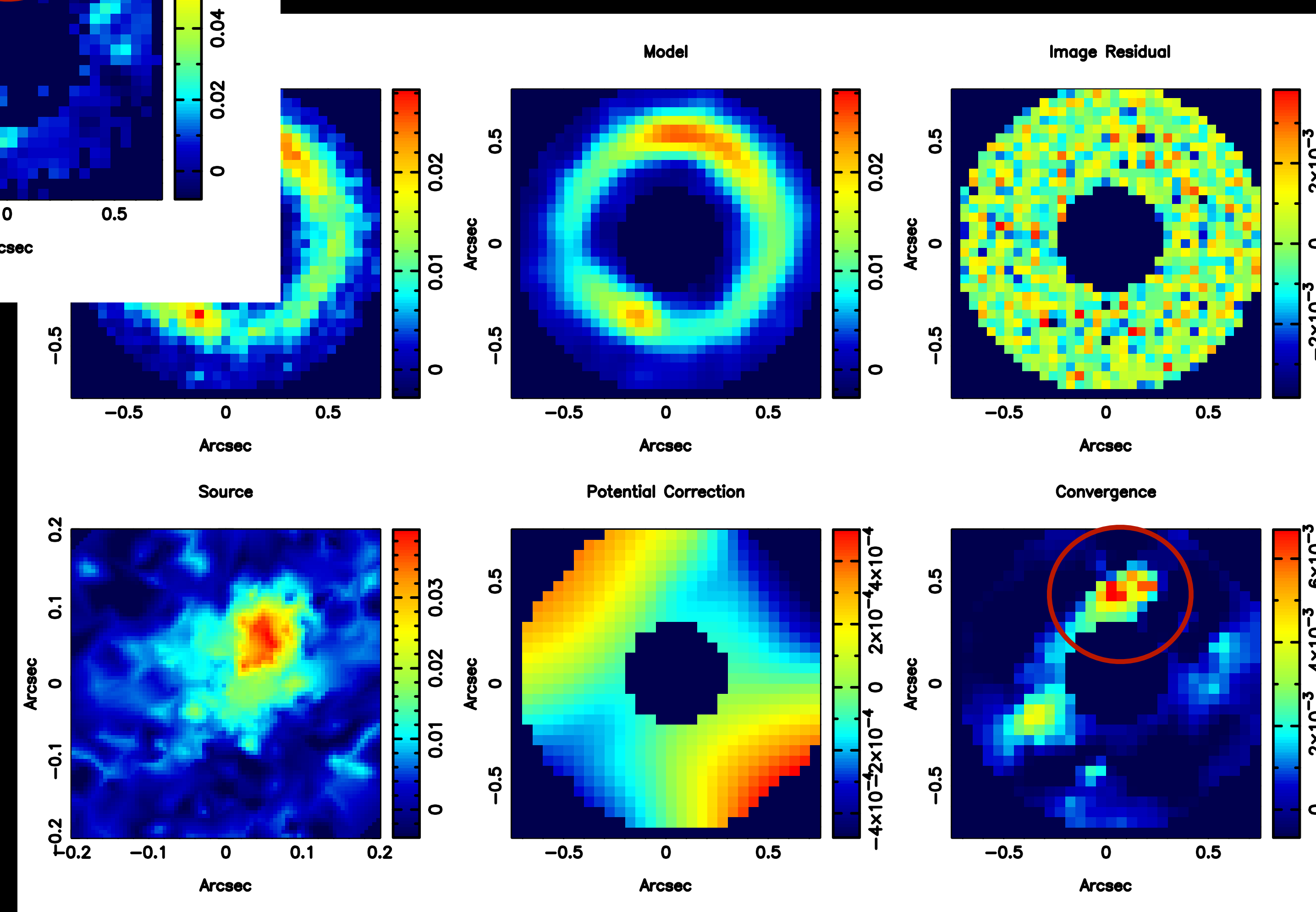


HST H-band

Keck H-band



Can we image its ring with VLBI?

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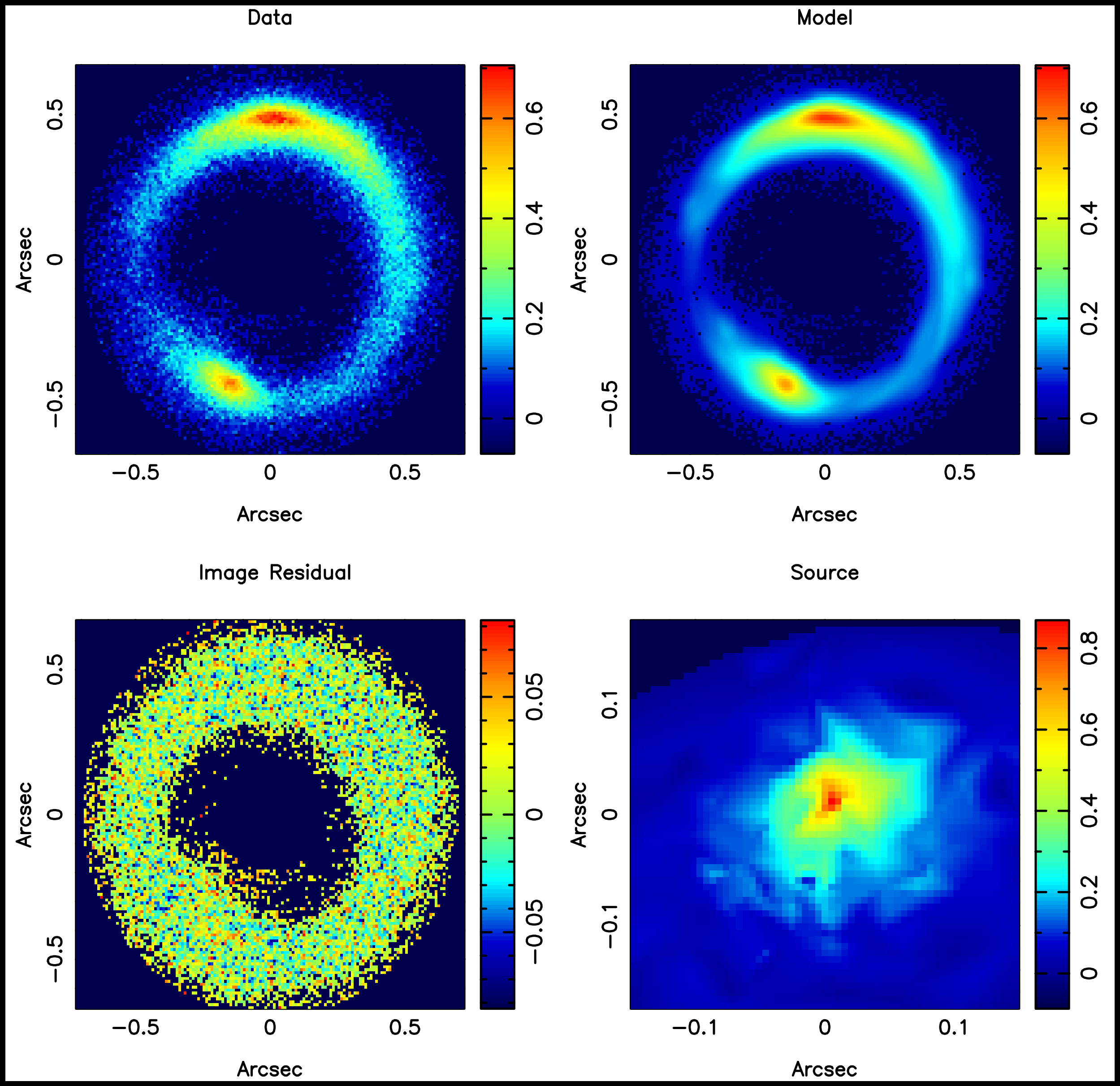


Substructure as a truncated pseudo Jaffe

$$M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$$
$$r_t = 440pc$$

$$M_{3D}(< 0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot$$

$$M_{3D}(< 0.3) = (7.24 \pm 0.4) \times 10^7 M_\odot$$

Substructure as SIS

$\sigma_v \sim 16\ km\ s^{-1}$ $V_{max} \approx 27 kms^{-1}$

$$M_{3D}(< 0.3) = 3.4 \times 10^7 M_\odot$$

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

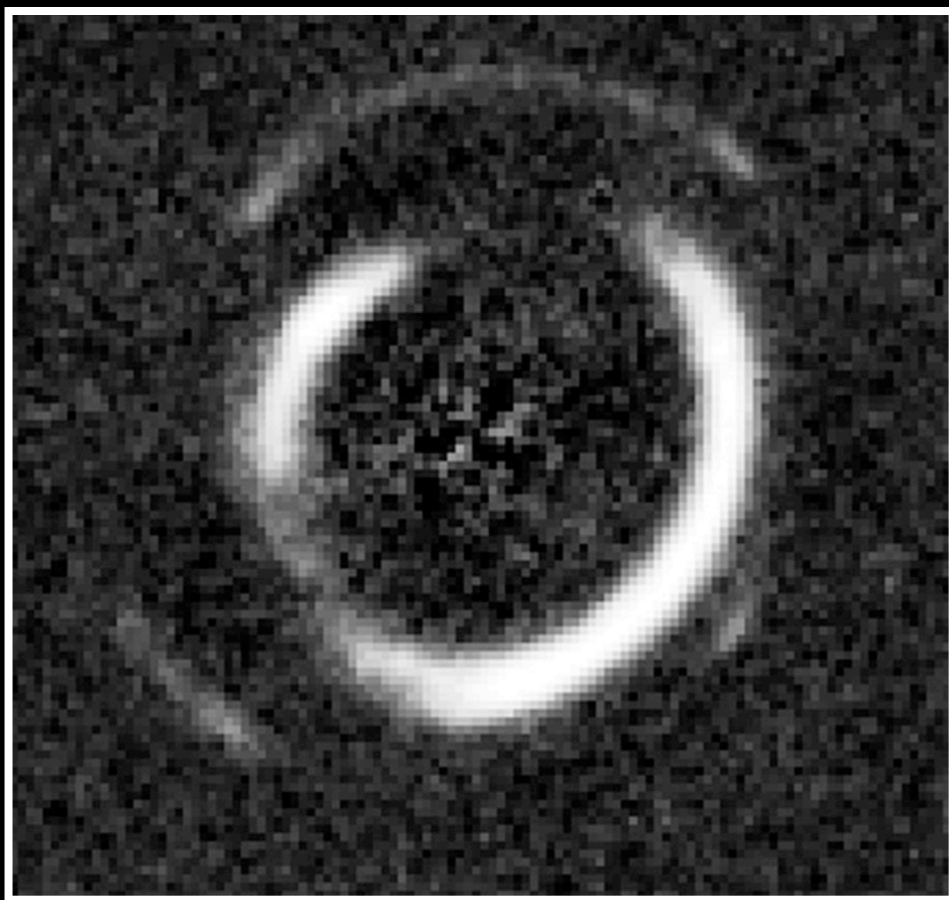
De-projection yields a systematic uncertainty on the total mass of 0.3 dex at the 68 per cent confidence level.

J0946+1006 - Double Ring

Gavazzi et al. 2008

$z_s = 0.609 \quad z_l = 0.222$

Vegetti et al. 2010b



Two concentric ring-like structures

Dark-matter fraction: $f\,(< R_{eff}) = 73\% \pm 9\%$

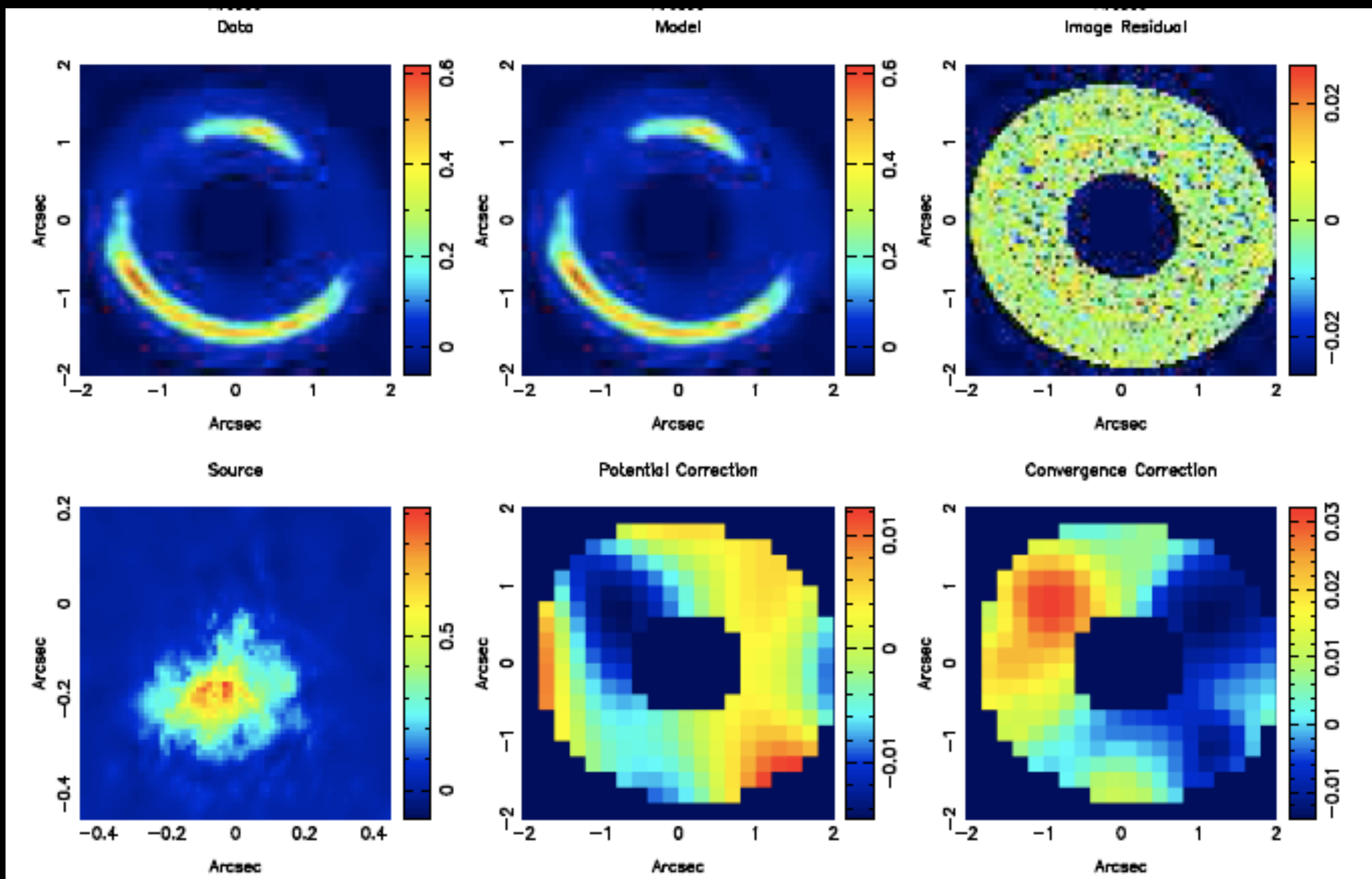
Expected number of mass substructure from CDM paradigm within $\Delta R = R_{ein} \pm 0.3$

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

Unfortunately we can only use one ring

J0946+1006 - Double Ring

Vegetti et al. 2010b



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

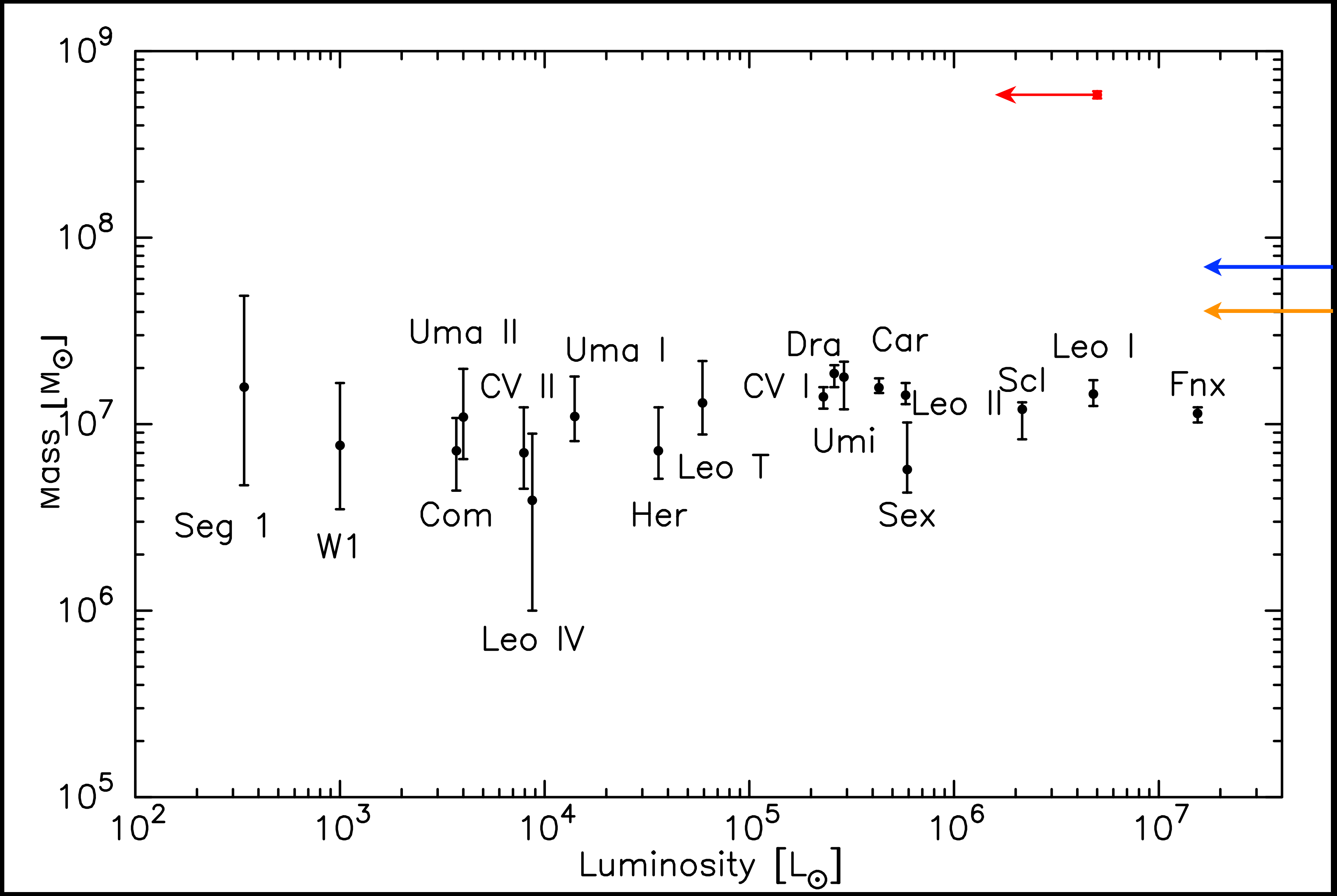
$$r_t = 1.1 \ kpc$$

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

equivalent to a ~16σ detection

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

J0946+1006 - B1938+666



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$$M_{3D}(<0.3) = (7.24 \pm 0.4) \times 10^7 M_\odot$$

$$M_{3D}(<0.3) = 3.4 \times 10^7 M_\odot$$

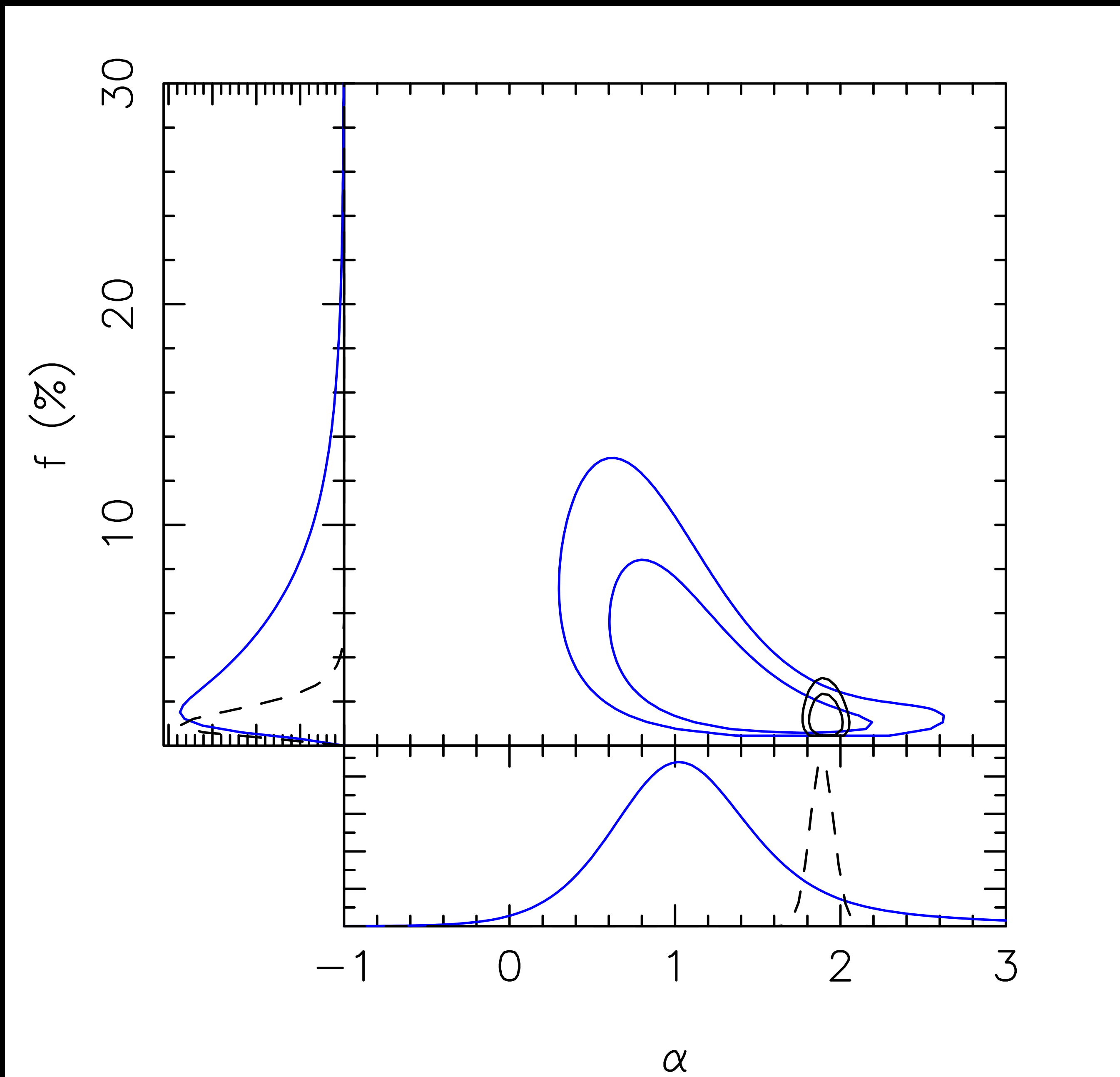
J0946+1006

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

OK if the subhalo formed at very high redshift

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

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

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

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

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

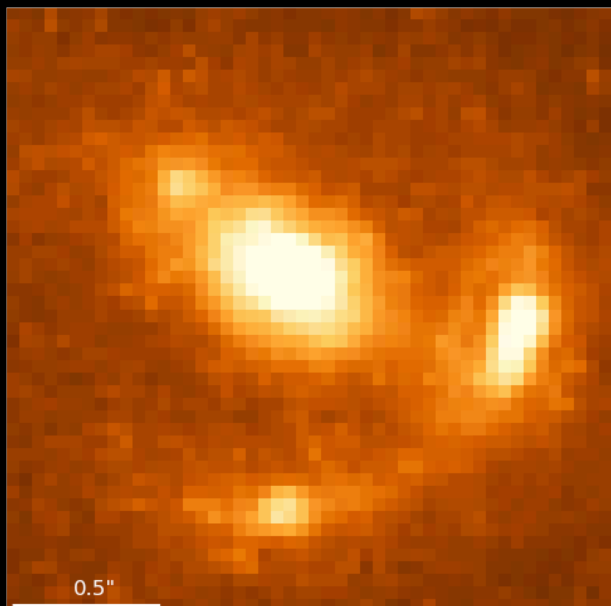
$$f_{CDM} \sim 0.1\%$$

The fraction is consistent but higher than CDM

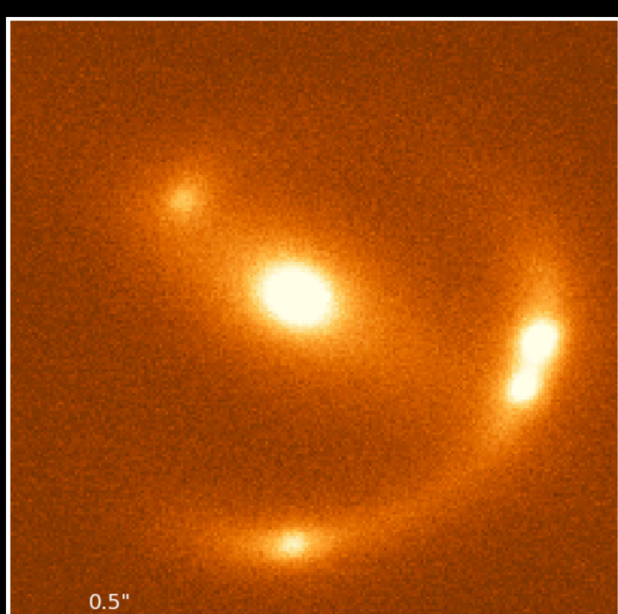
The mass function is closer to the observed Milky Way mass function and shallower than what predicted from CDM.

SLACS & SHARP

HST



Keck AO



$M_{min} \approx 10^7 M_\odot$

Strong-lensing at High Angular Resolution Program

Uniform sample of almost 100 early-type galaxies

$M_{min} \approx 10^8 M_\odot$

Conclusions

- The mass function of dark matter structures allows us to constrain the properties of the dark matter particles
- Strong gravitational lensing is at the moment the only tool we have to detect dark/faint structures beyond the local universe
- Adaptive Optics data is sensitive to smaller structure masses than HST thanks to the improved resolution
- Line-of-sight contamination may be relevant for the fraction but not for the mass function