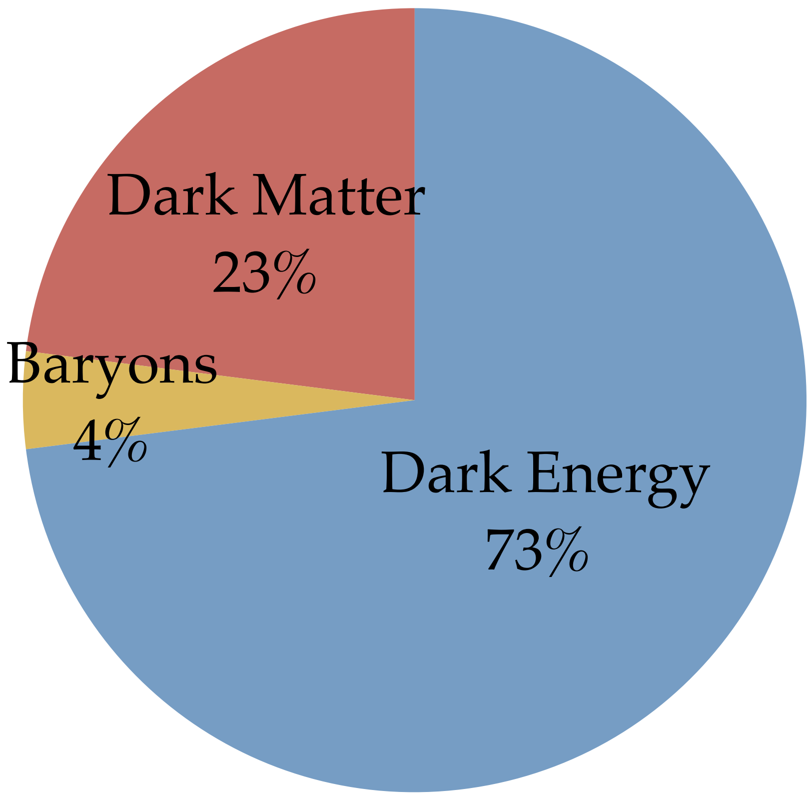
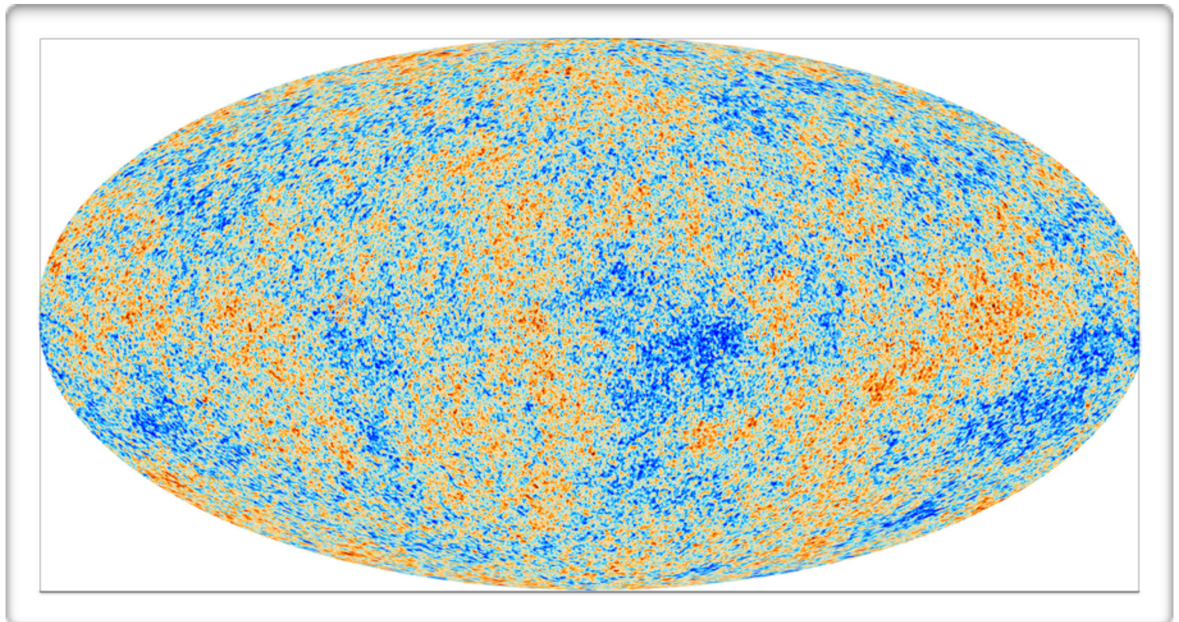
Gravitationally Imagining Dark Matter

Simona Vegetti - MPA

Matt Auger - IoA
Chris Fassnacht - UCD
John McKean - RuG
Leon Koopmans - RuG
Matus Rybak - MPA
Tommaso Treu - UCLA

Structure formation





Planck Cosmic Microwave Background

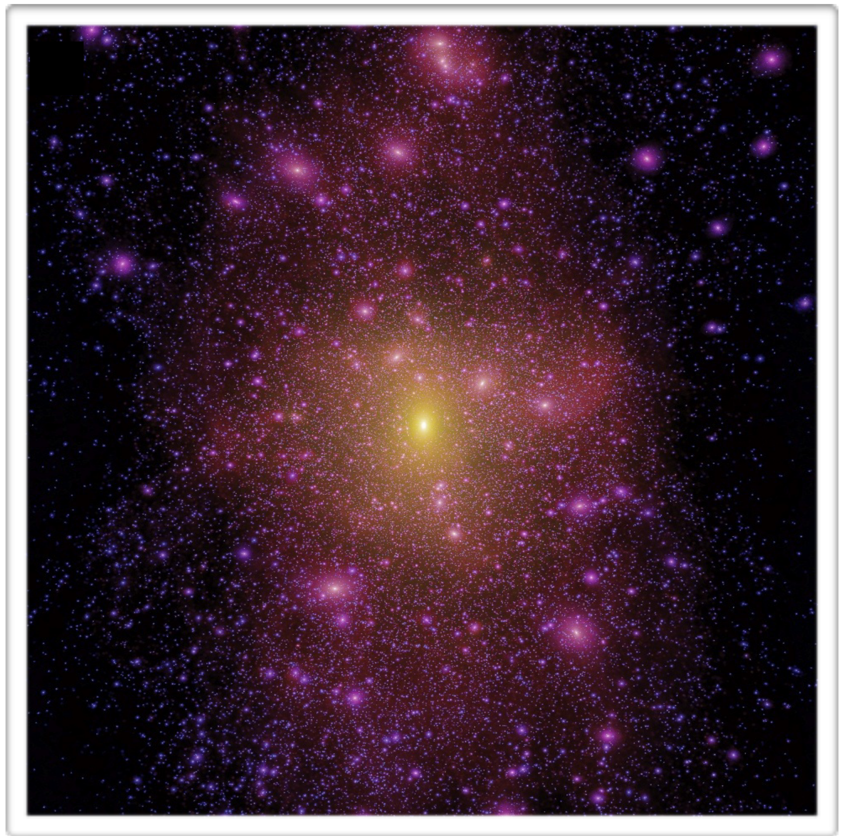
The nature of dark matter shapes the formation of structures in the Universe

Three complementary approaches exist to decipher the nature of dark matter:

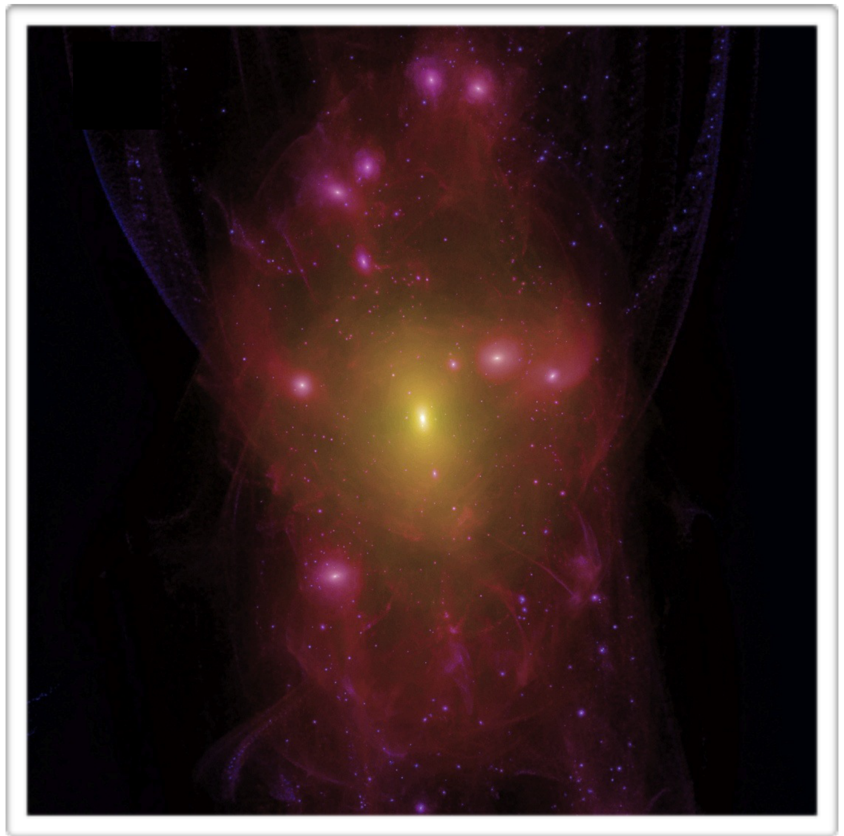
- produce DM particles in an accelerator
- direct/indirect detections
- measure the level of clumpiness of the Universe at the smallest scales

Substructure in the Milky Way Halo

Cold Dark Matter / WIMPs, Axions

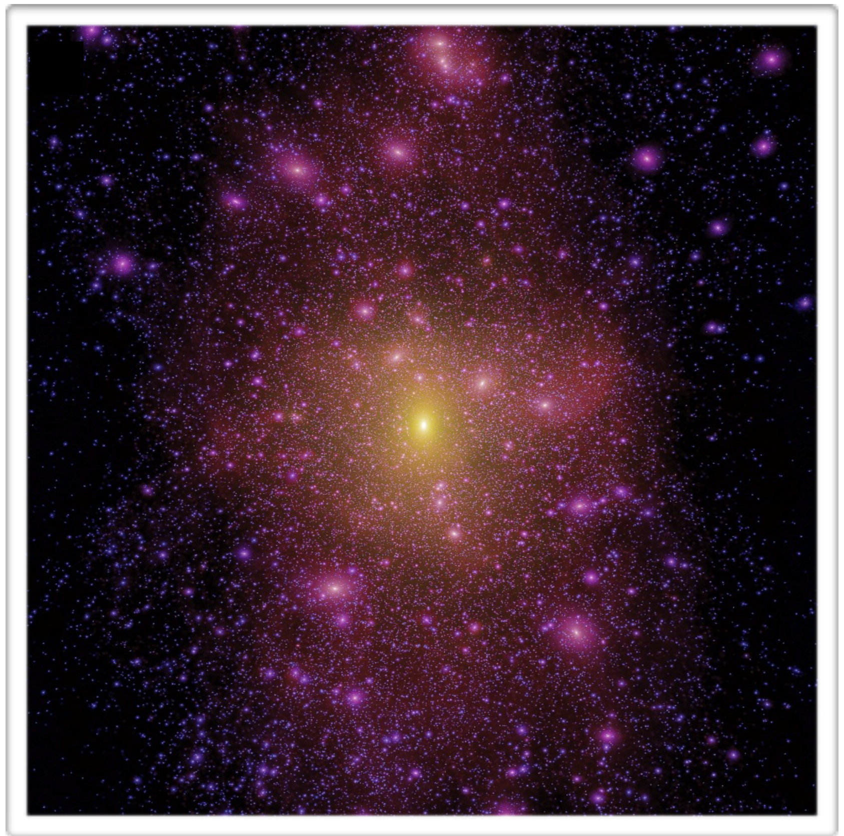


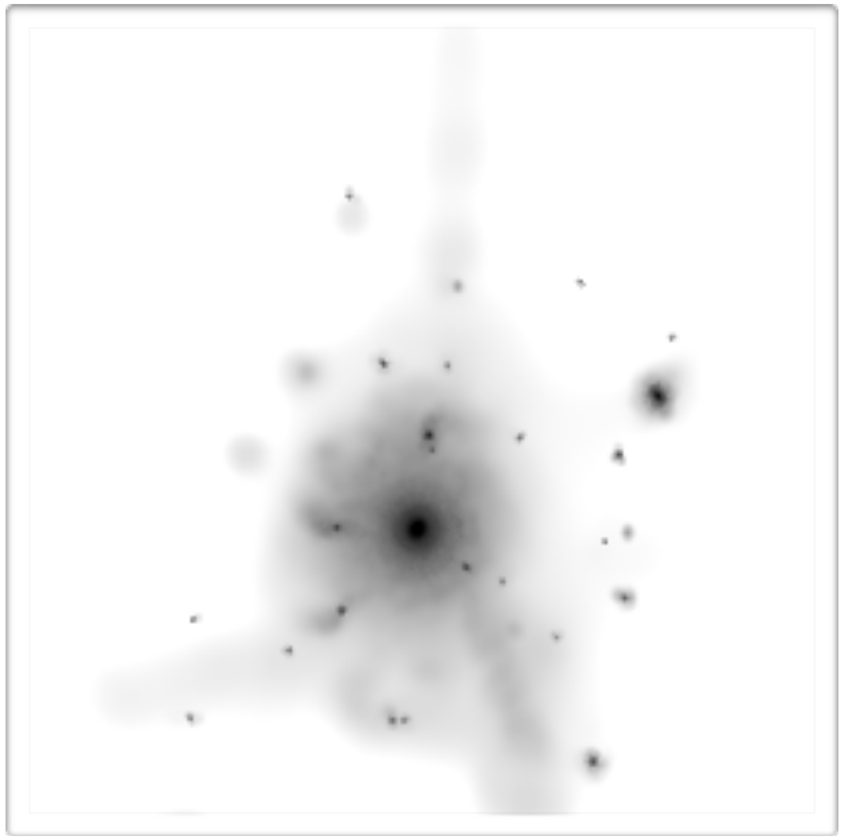
Warm Dark Matter / e.g. sterile neutrinos

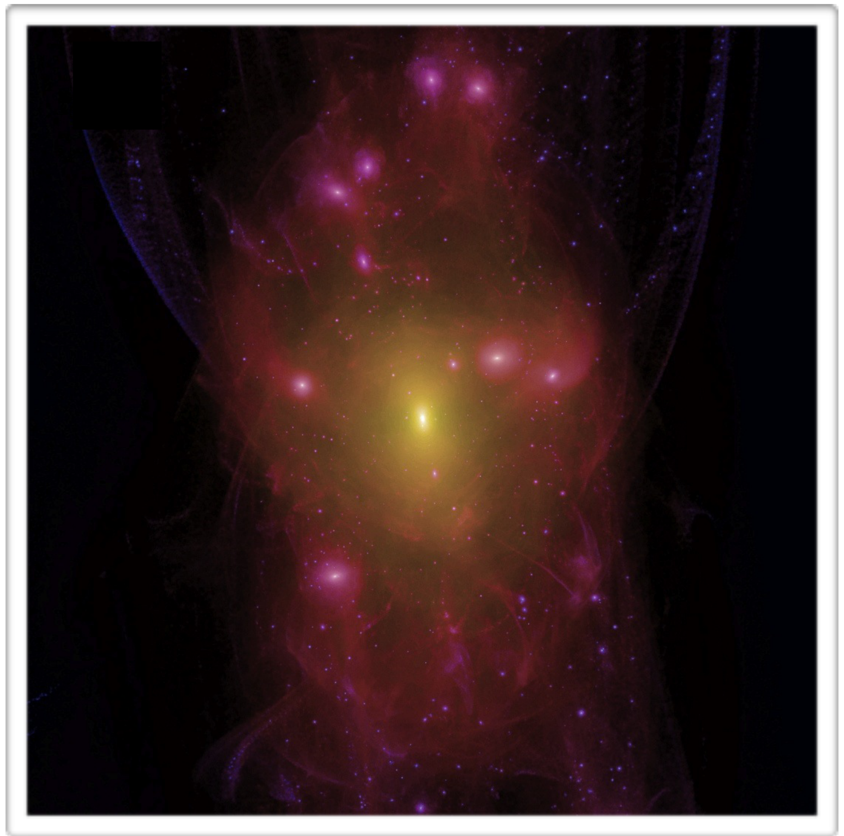


The total number of substructure strongly depends on the nature of dark matter

Substructure in the Milky Way Halo







Cold Dark Matter

CDM - Stars

Warm Dark Matter

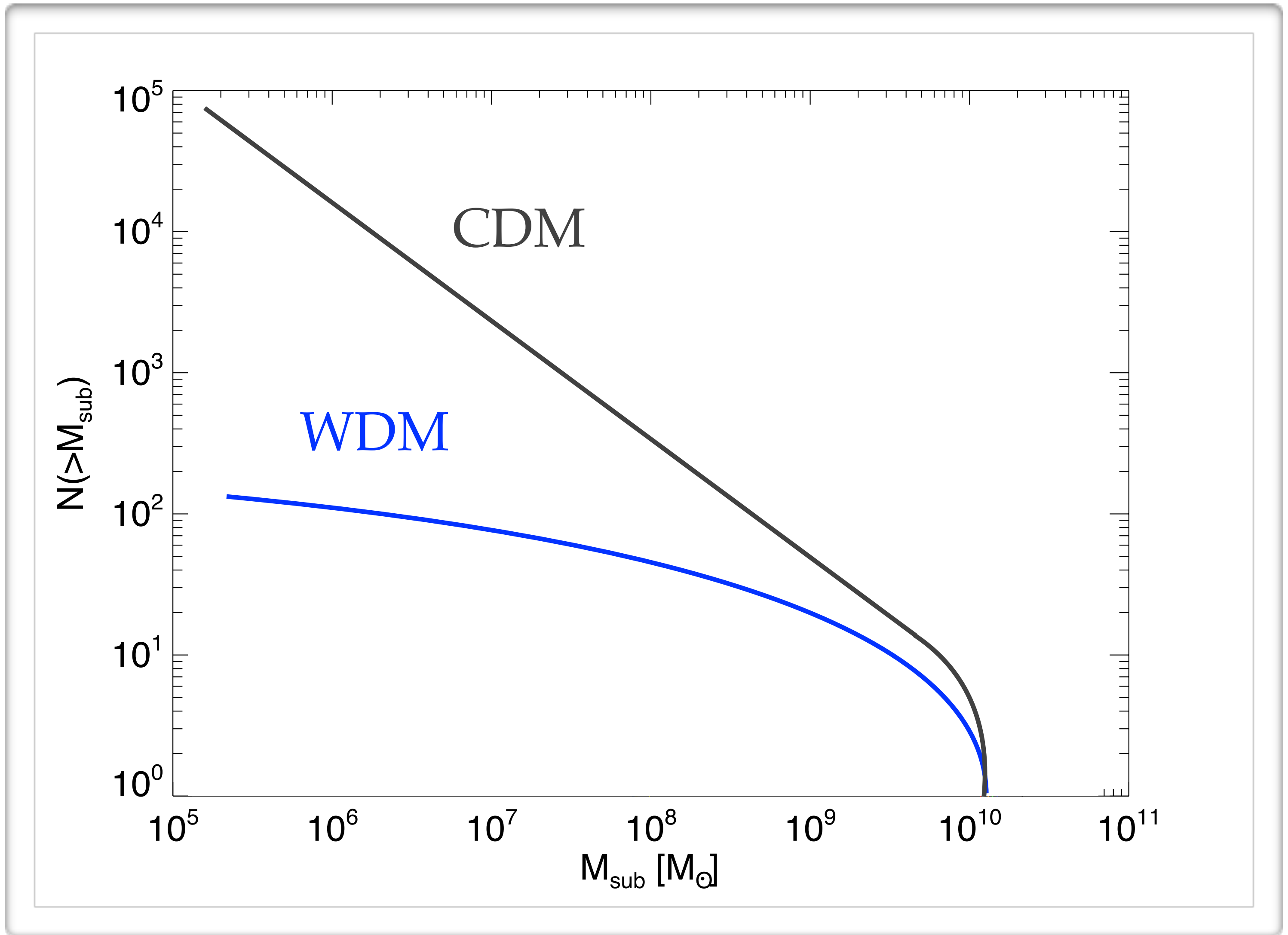
- There is a degeneracy in the number of observable substructures between dark and galaxy formation models
- Most of the low mass substructure are dark

Substructure mass function

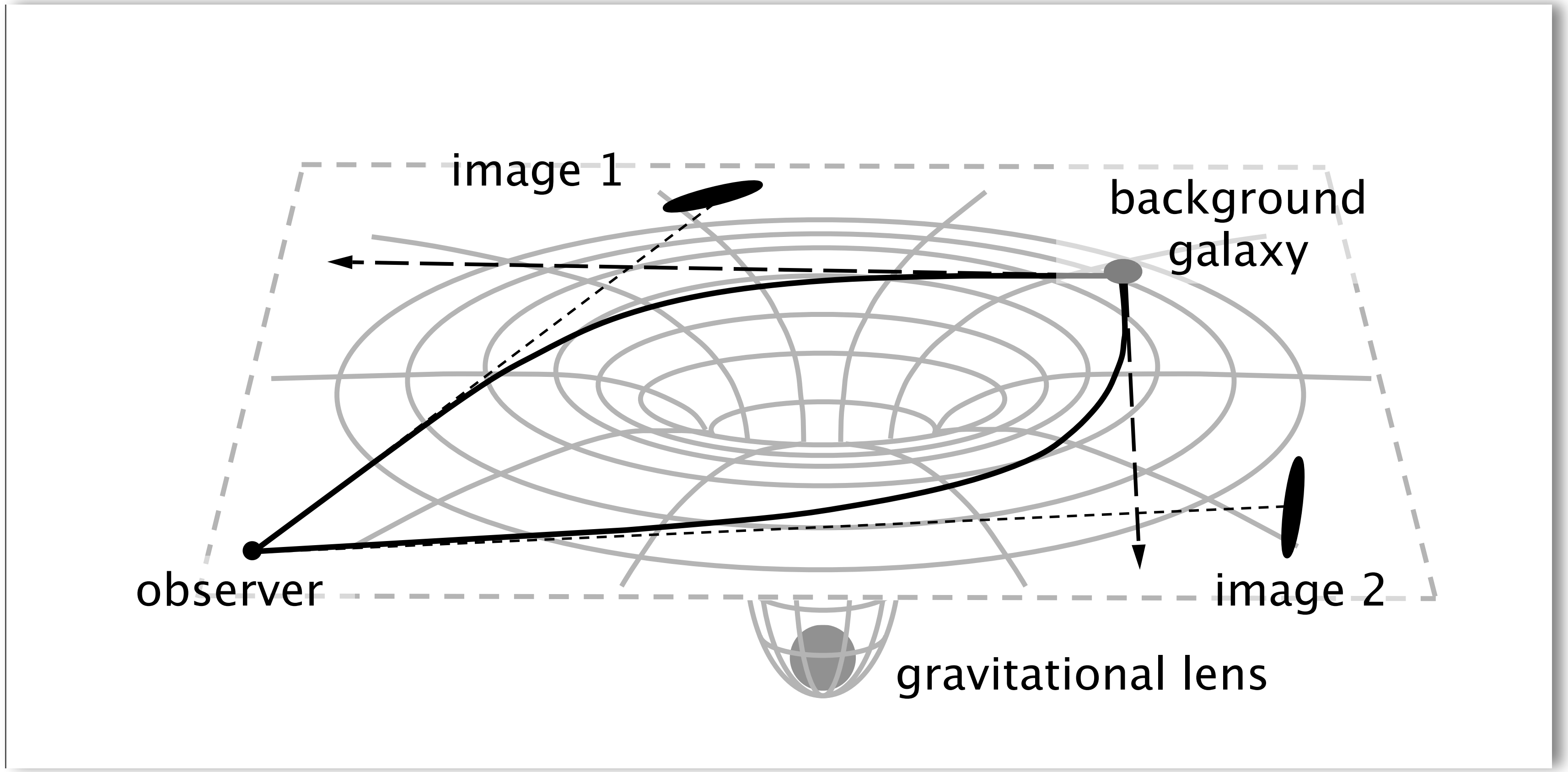
Measuring the substructure mass function is a key probe of the nature of dark matter

Predicted abundance of substructure in the Milky Way halo

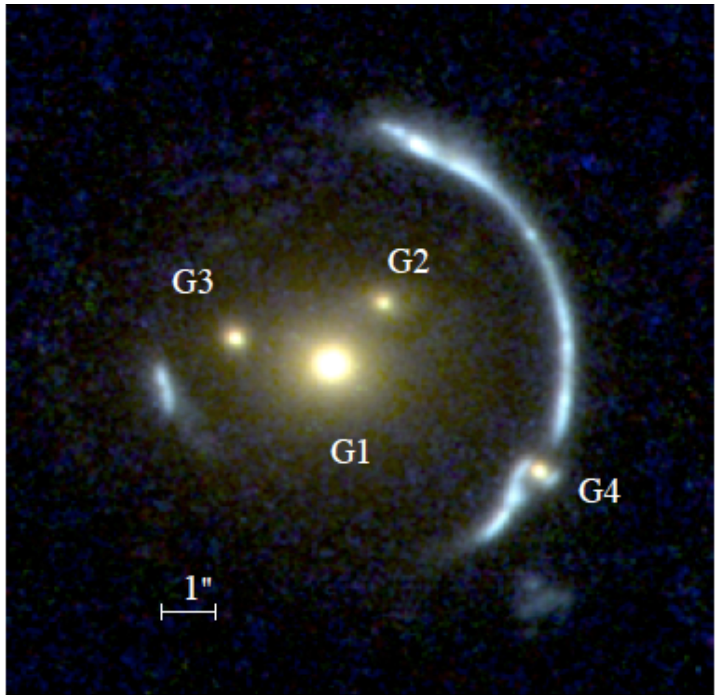
$$dN/dM \propto f M^{-\alpha}$$



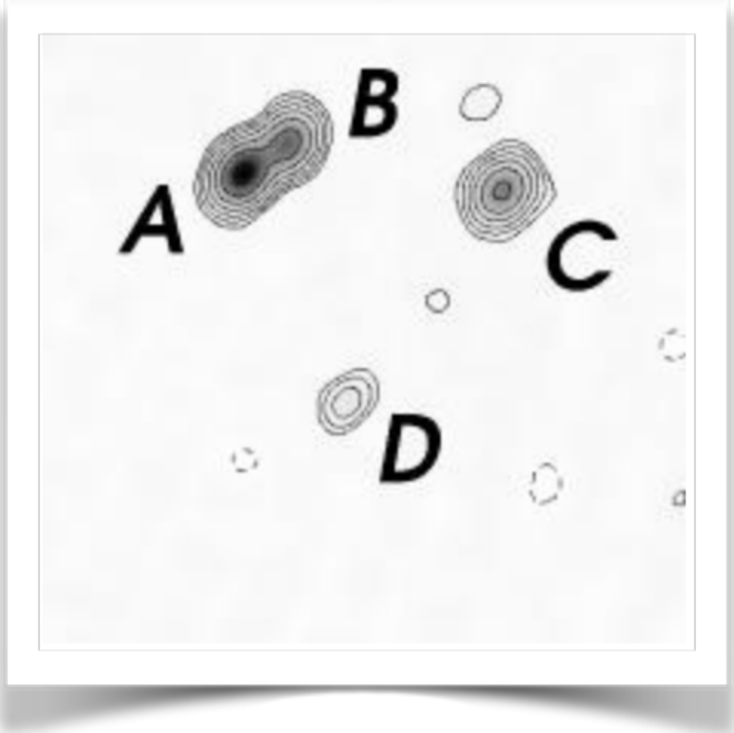
Substructure Lensing



Substructure Lensing

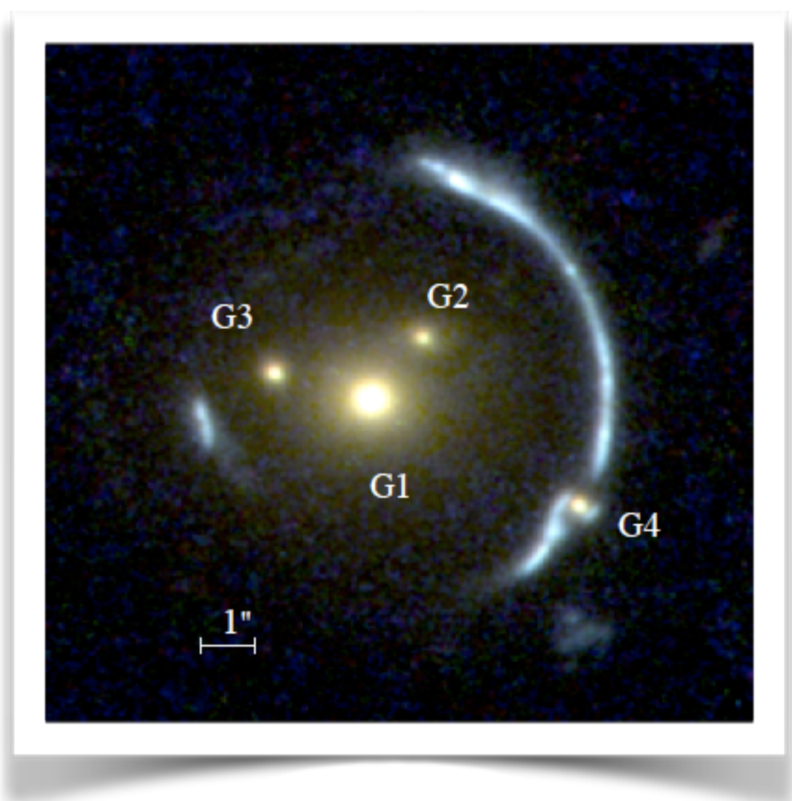


- substructures are detected as magnification anomalies
- Compact sources are easy to model
- Sensitive to a wide range of masses
- degenerate in the mass model



- 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

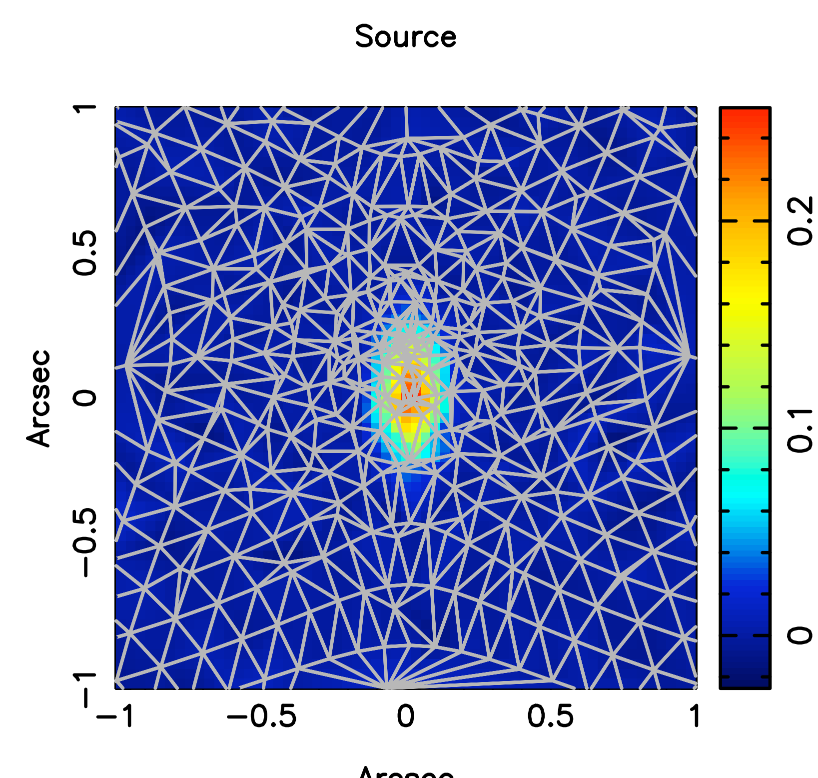
Gravitational Imaging



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

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

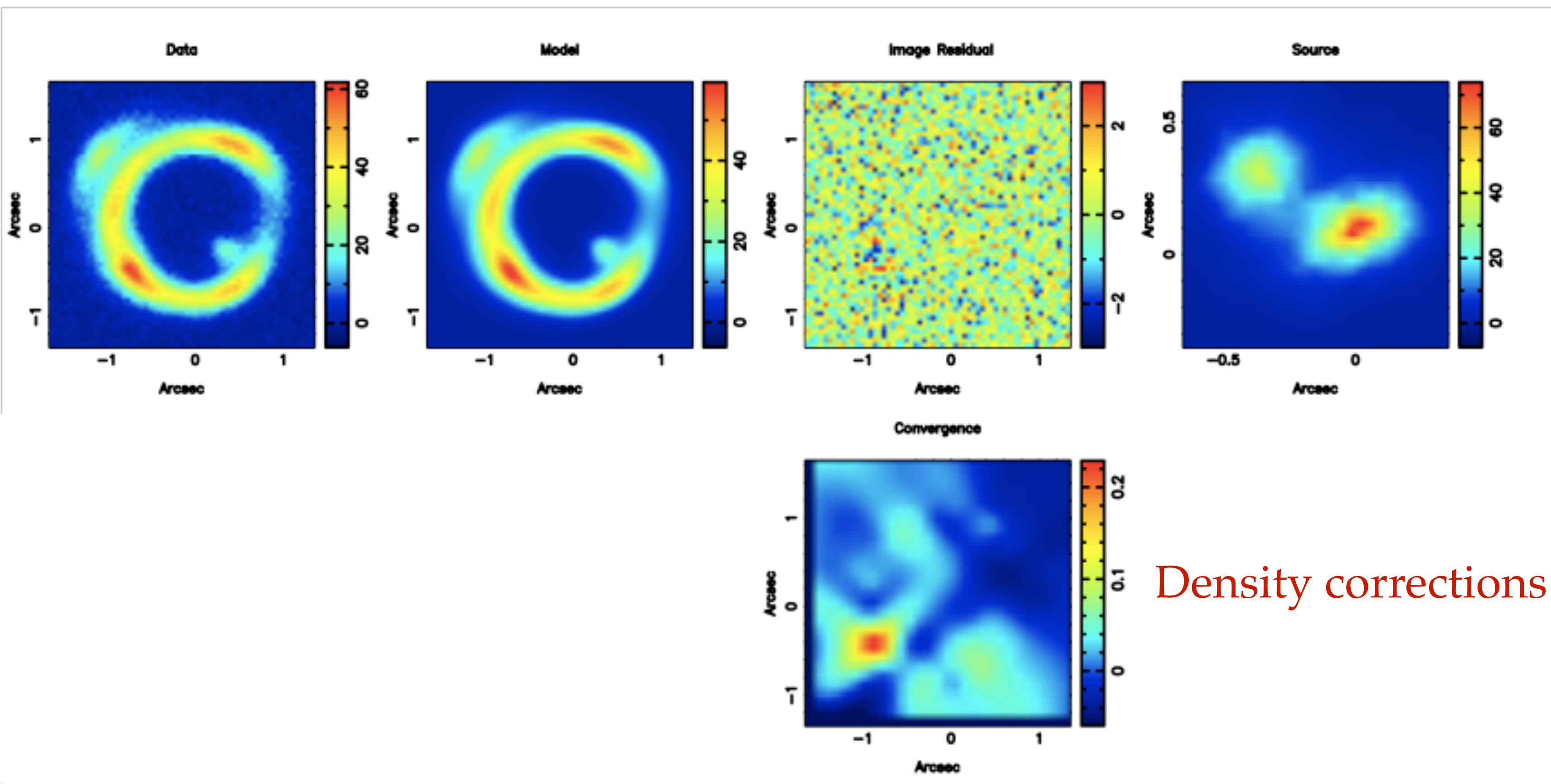
$\delta\psi(\mathbf{x})$ pixellated potential correction



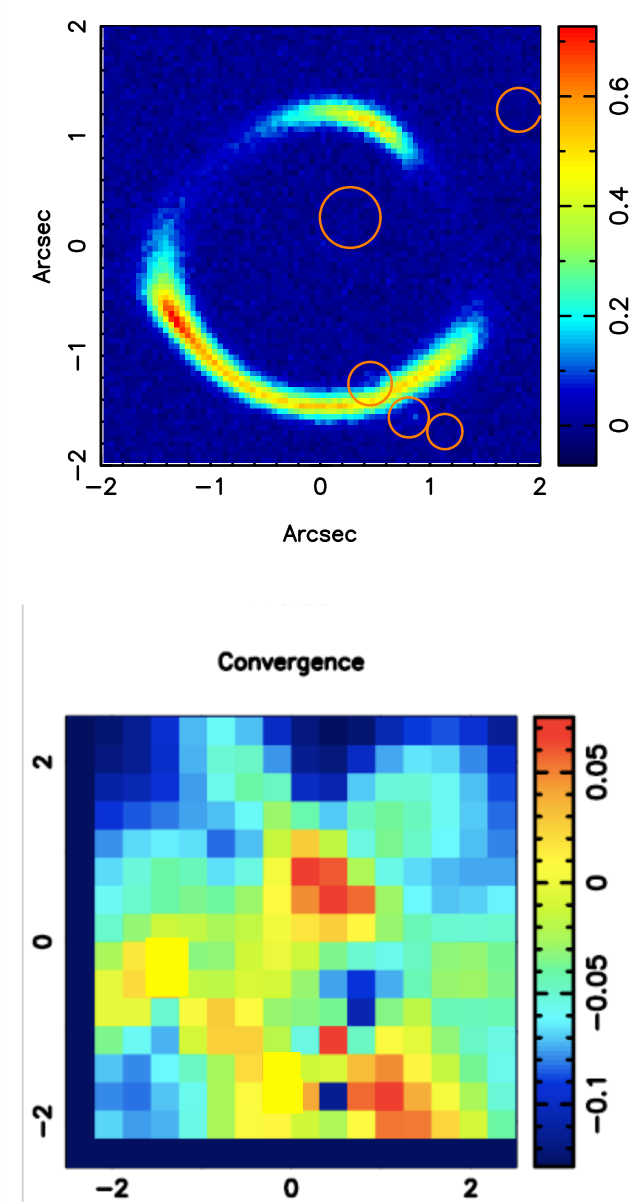
Pixelated source reconstructed on an adaptive Delaunay tessellation

Gravitational Imaging

Data Model Residuals Source

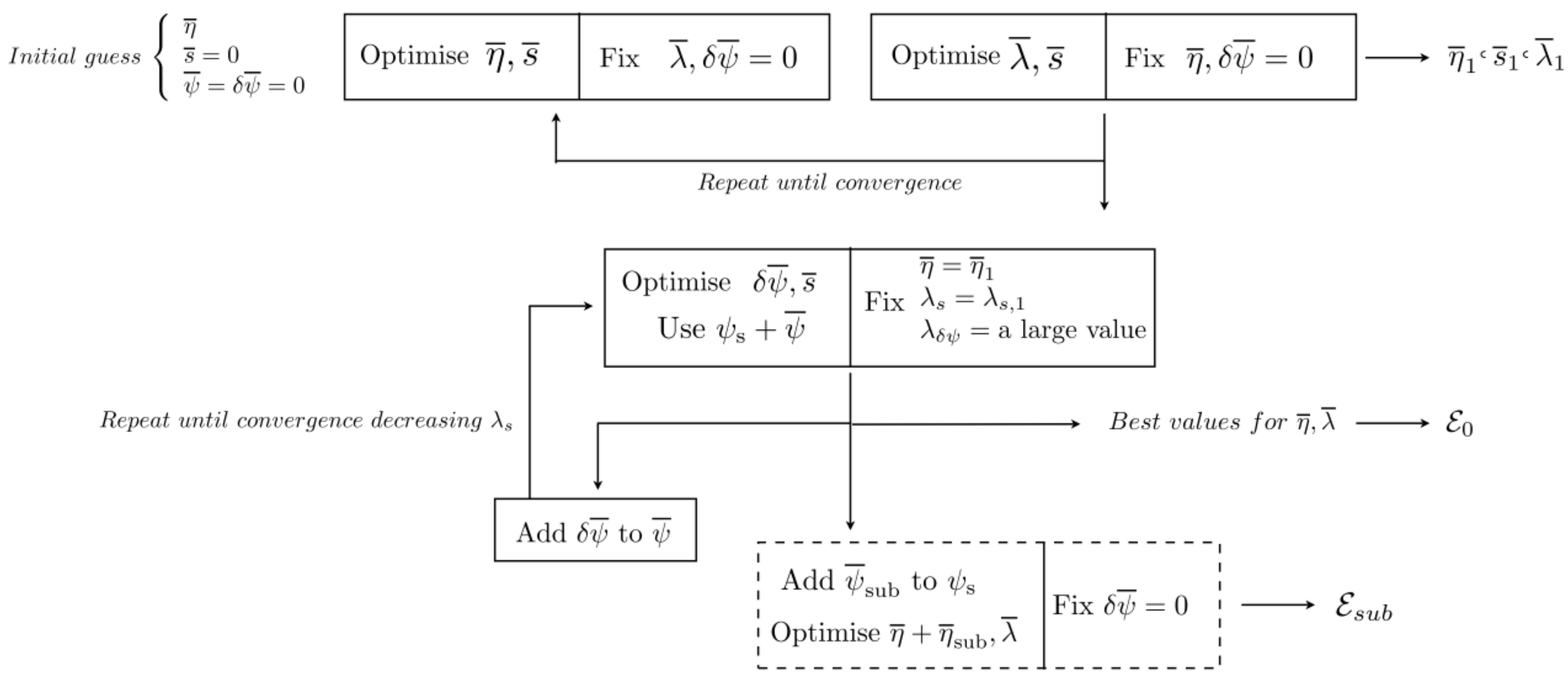


Density corrections



- Substructures are detected as corrections to an overall smooth potential
- If present, more than one substructure can be detected and quantified

Modelling 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

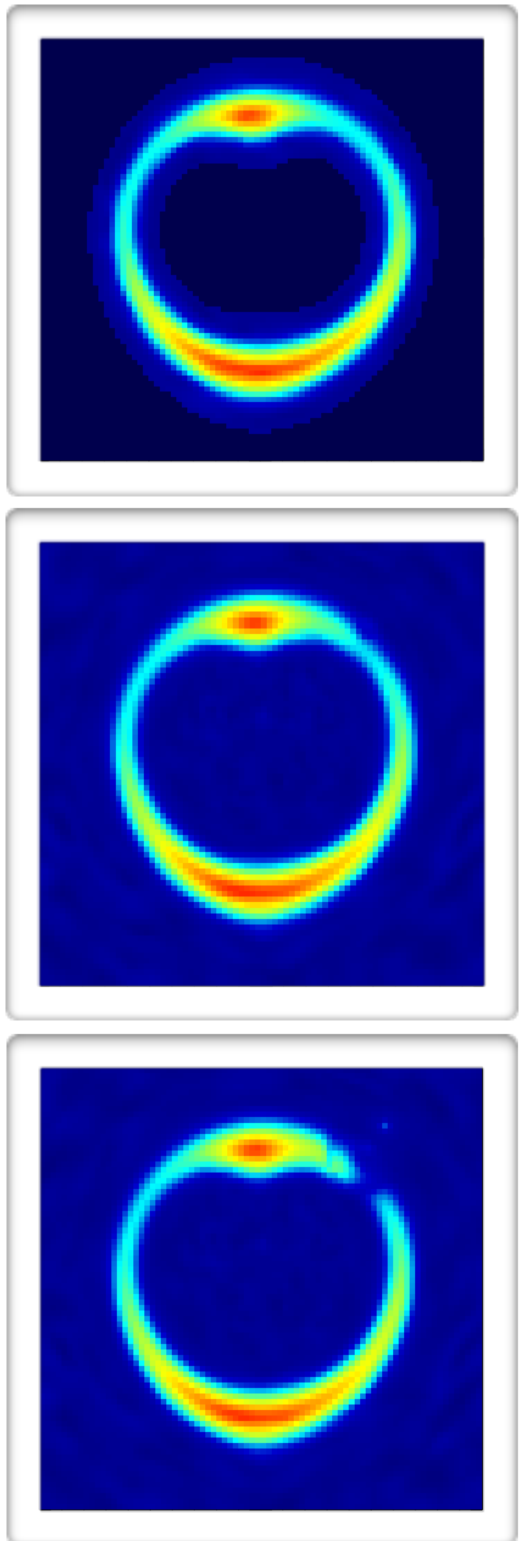
- a positive convergence correction that improves the image residuals is found independently from the potential regularization, number of source pixels, PSF rotations, and galaxy subtraction procedure;

- 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);

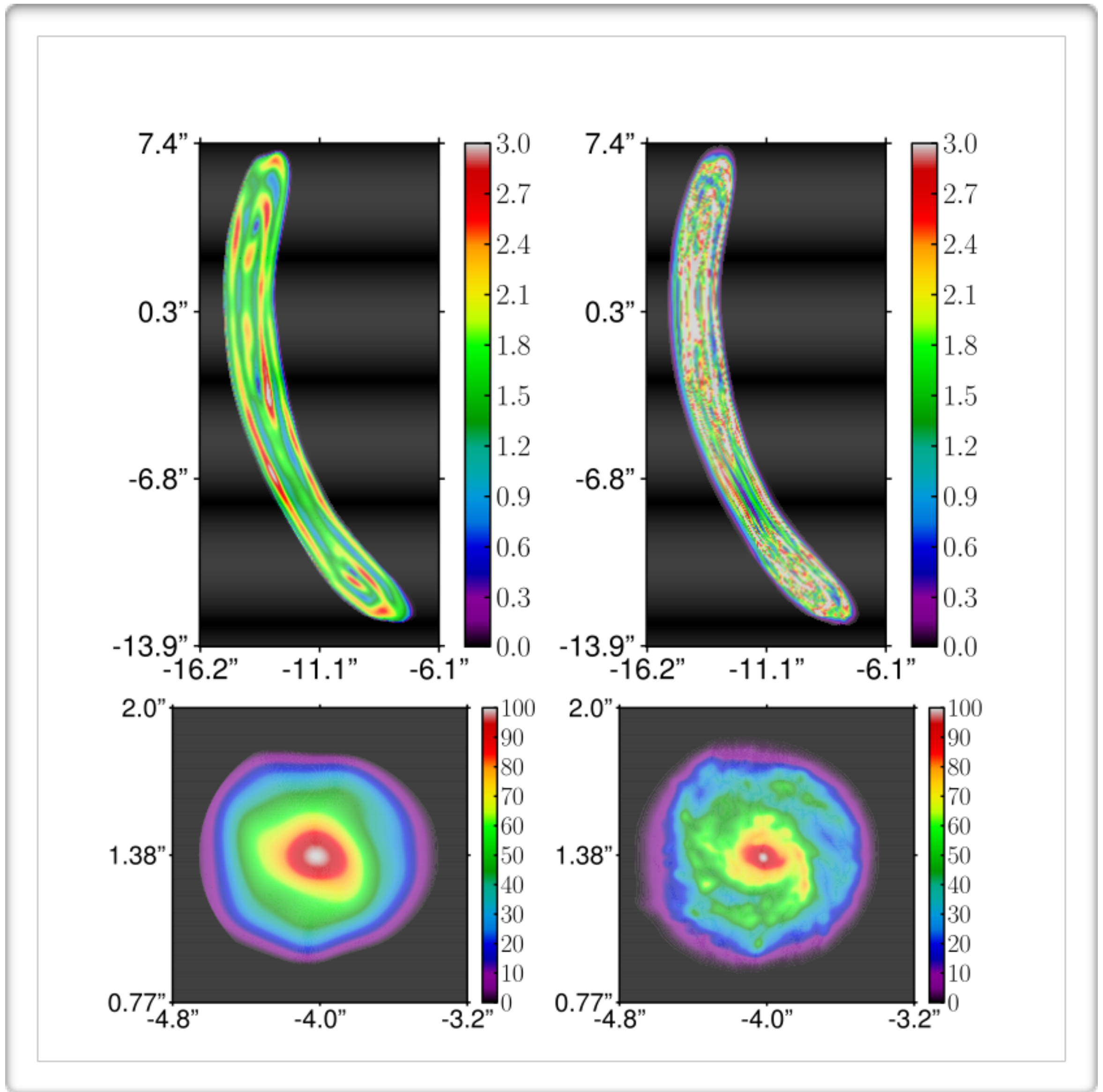
- the results are consistent among the different filters, where available.

Substructure Sensitivity



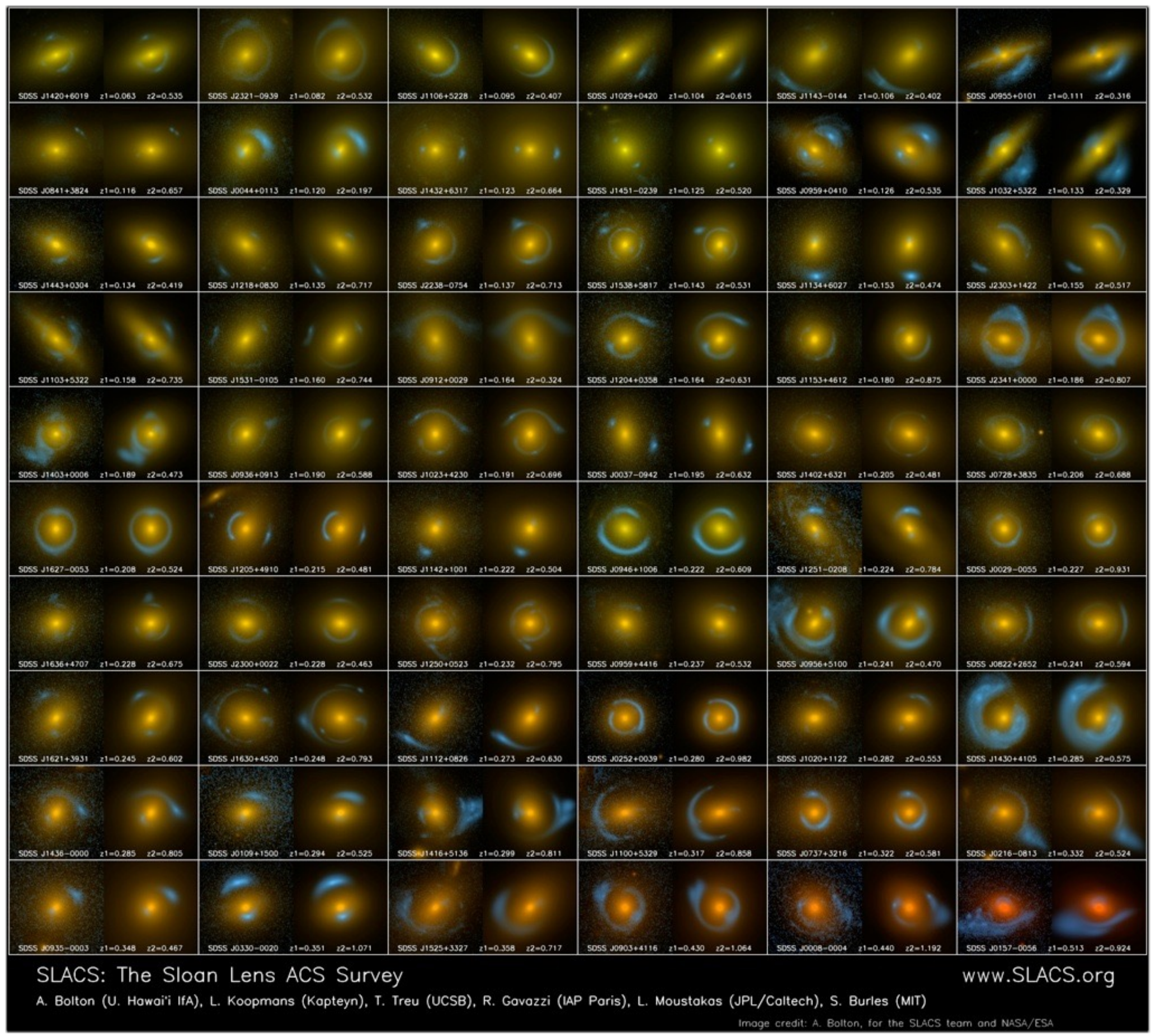
Increasing mass

Rau, Vegetti & White 2013, MNRAS



Increasing level of source complexity

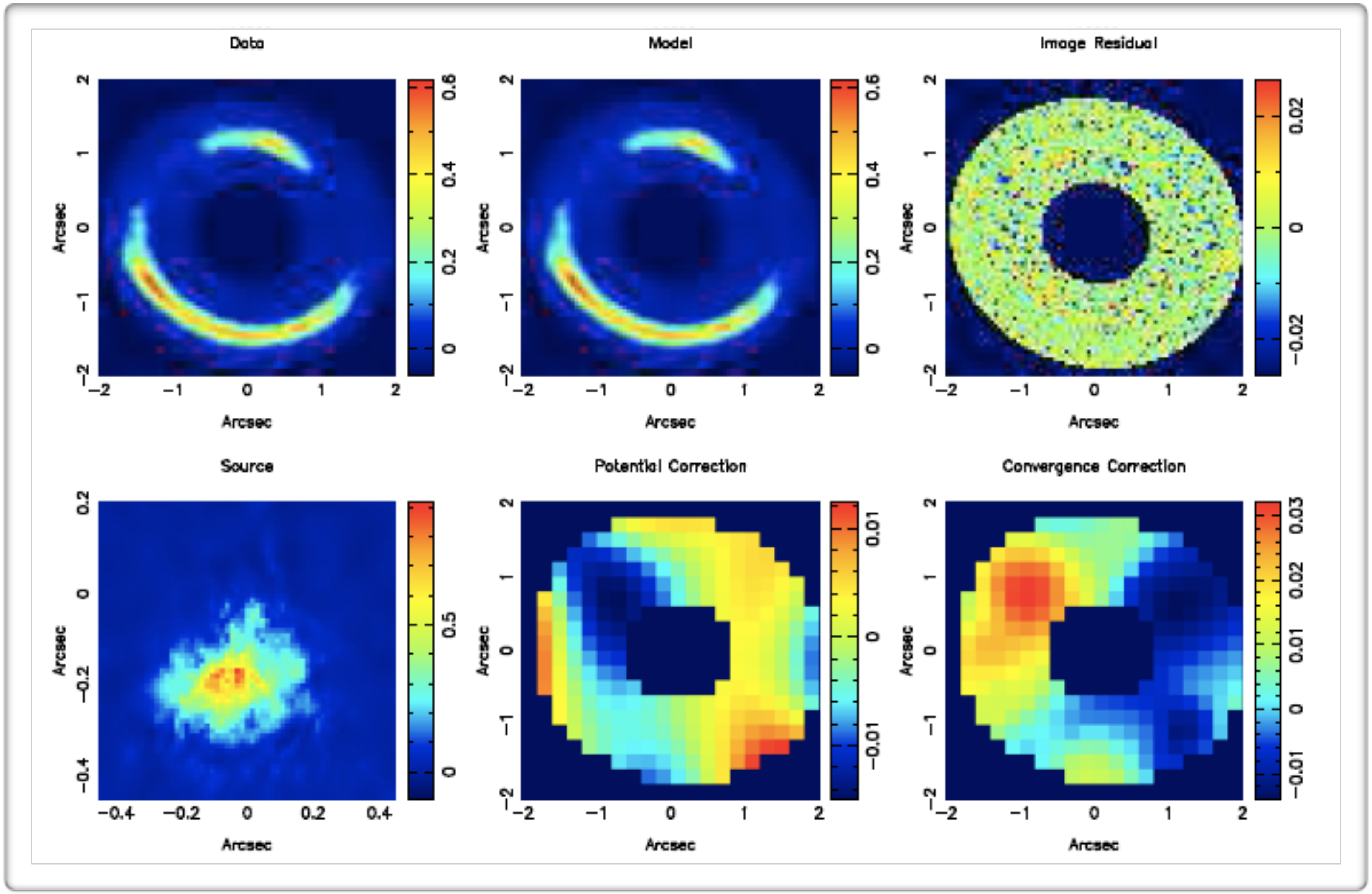
SLACS



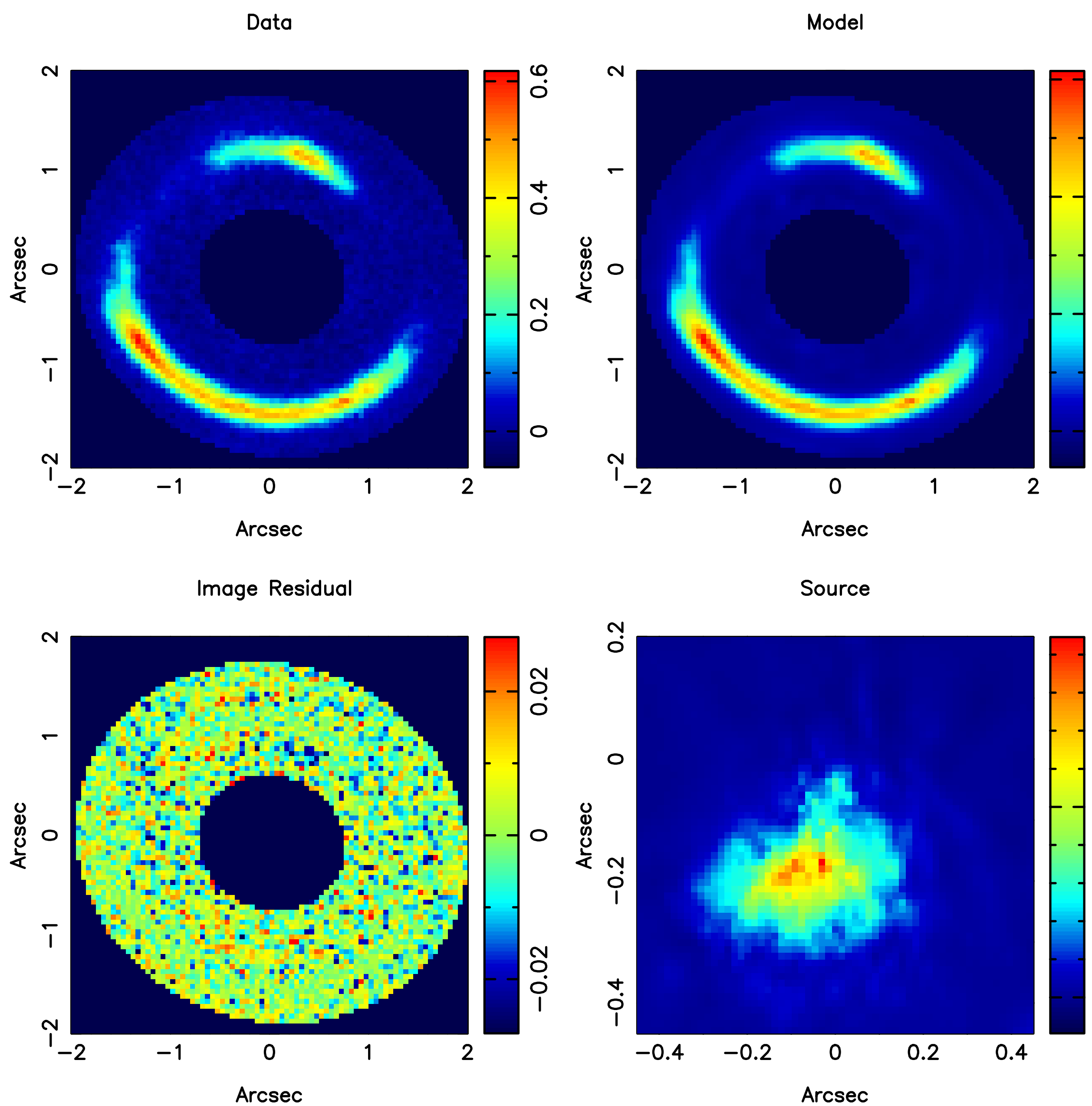
$$z = 0.06 - 0.36$$

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

Very First Detection



Very First Detection



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

$$r_t = 1.1 \ kpc$$

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

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

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

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

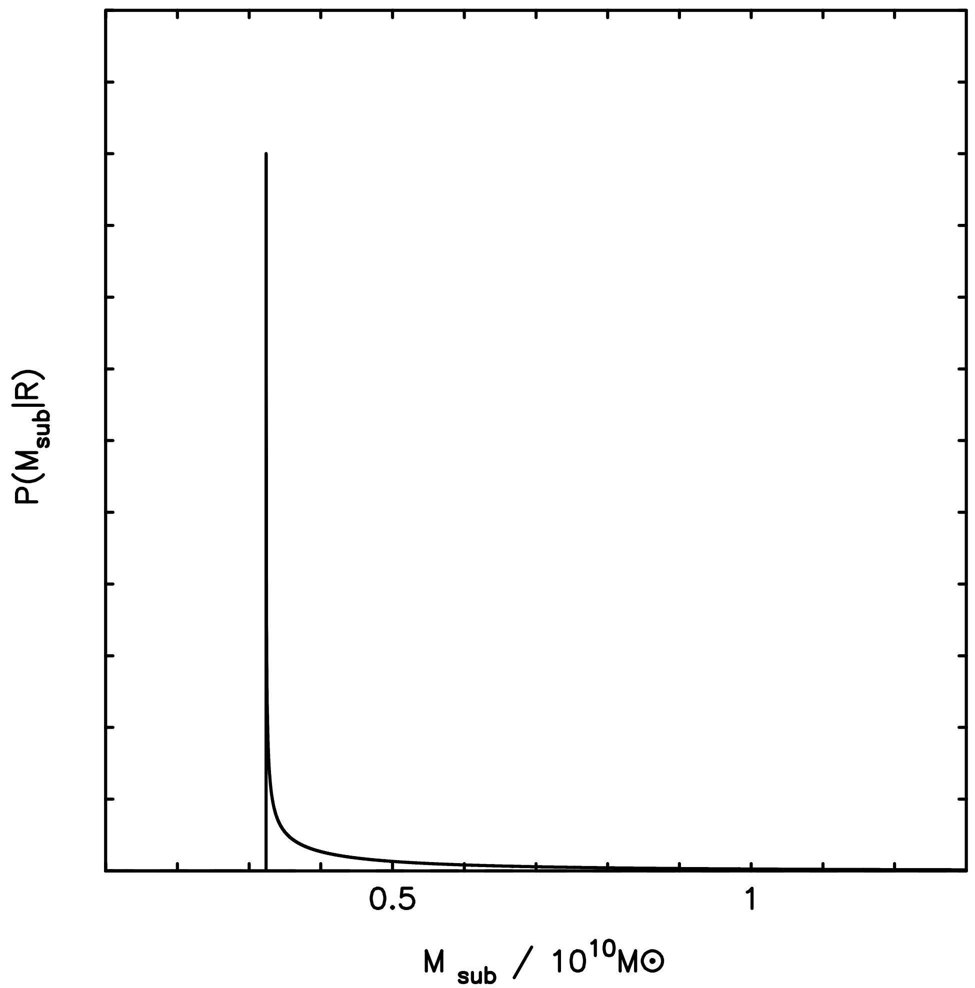
Mass Error

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

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

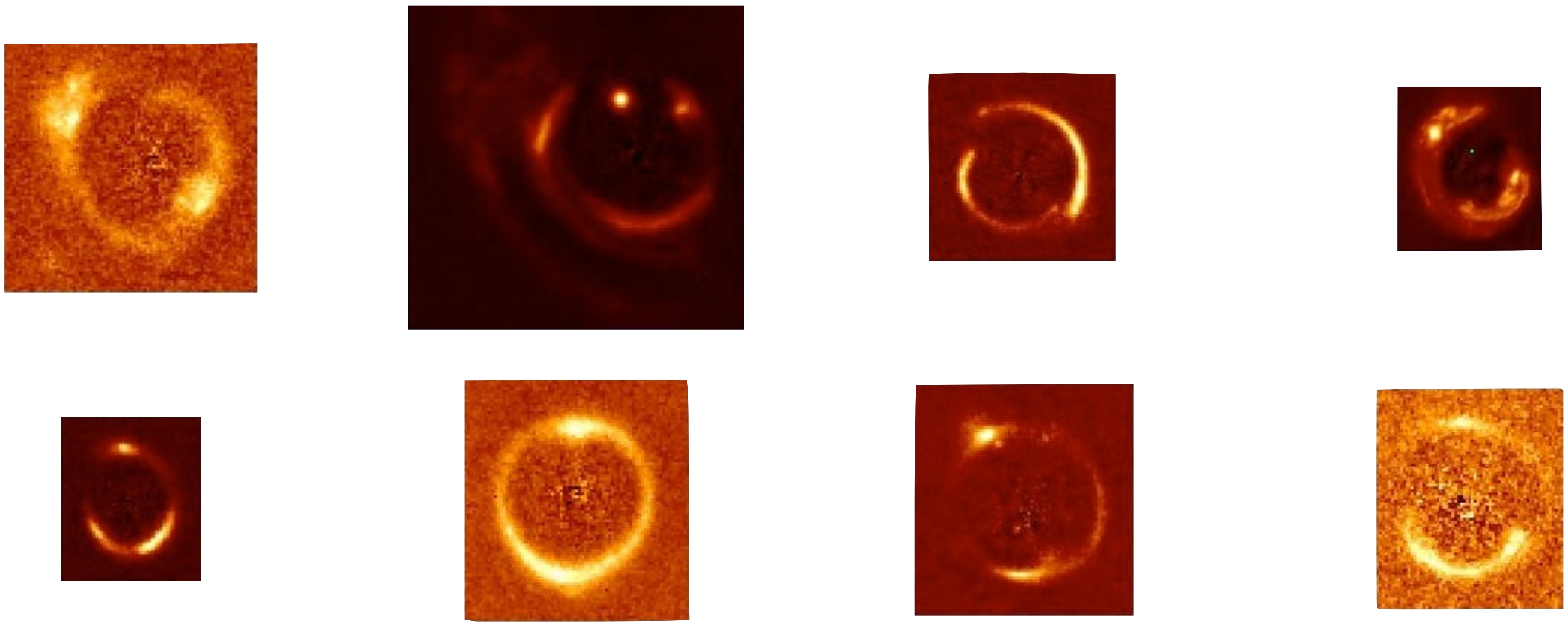
$$P(M_{\mathrm{sub}}|R) = \frac{1}{M_{\mathrm{sub}}\sqrt{\frac{2M_{\mathrm{sub}}^2\beta\kappa_0}{R^2\kappa_{\mathrm{sub}}^3\pi^3\Sigma_c^2} - 1}\,\arccos[R/r_{\mathrm{max}}]}$$

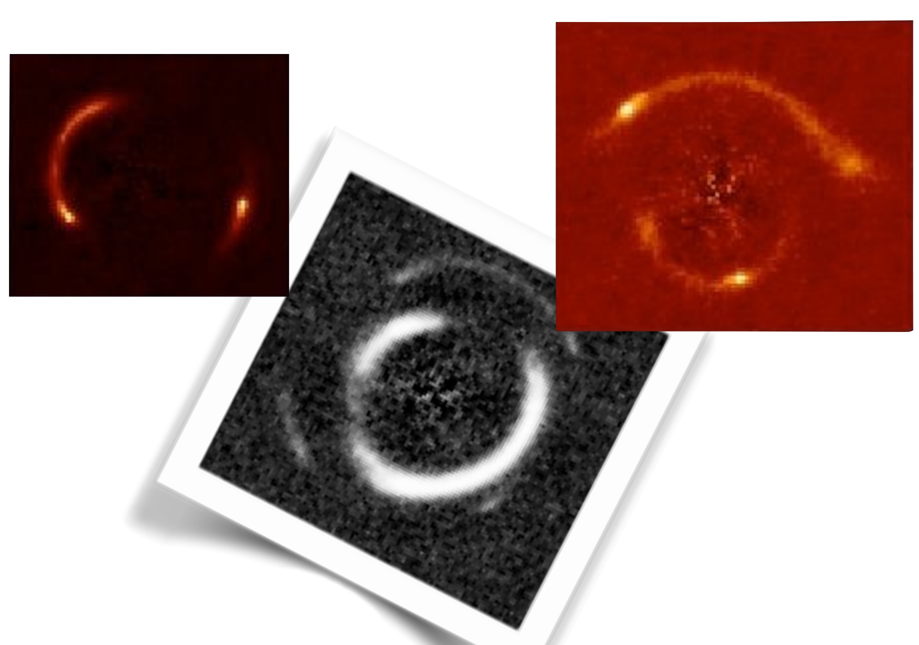
$$\sigma_{M_{\mathrm{sub}}} = ^{+1.17}_{-0.17}$$



de-projection is the dominant contribution to the mass error

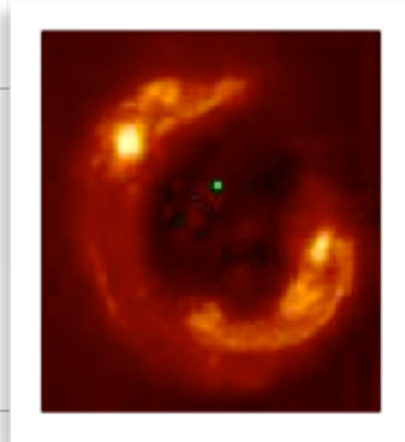
SLACS



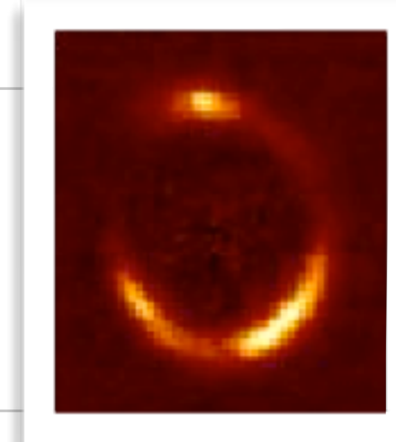


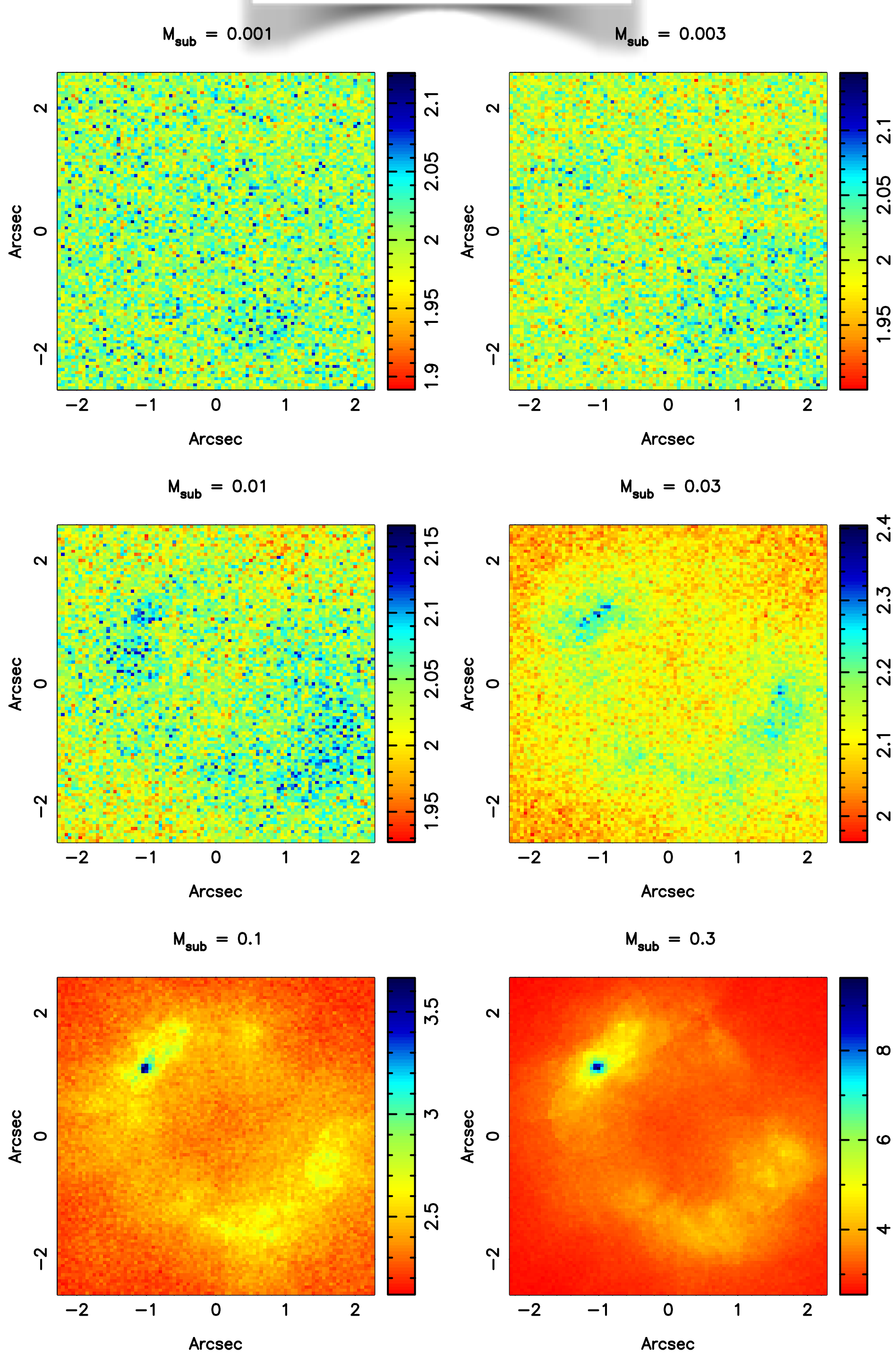
- Chosen on a s/n basis
- Representative sub-sample of the SLACS lenses
- Representative sample of massive early-type galaxies

Vegetti + 2014



SLACS





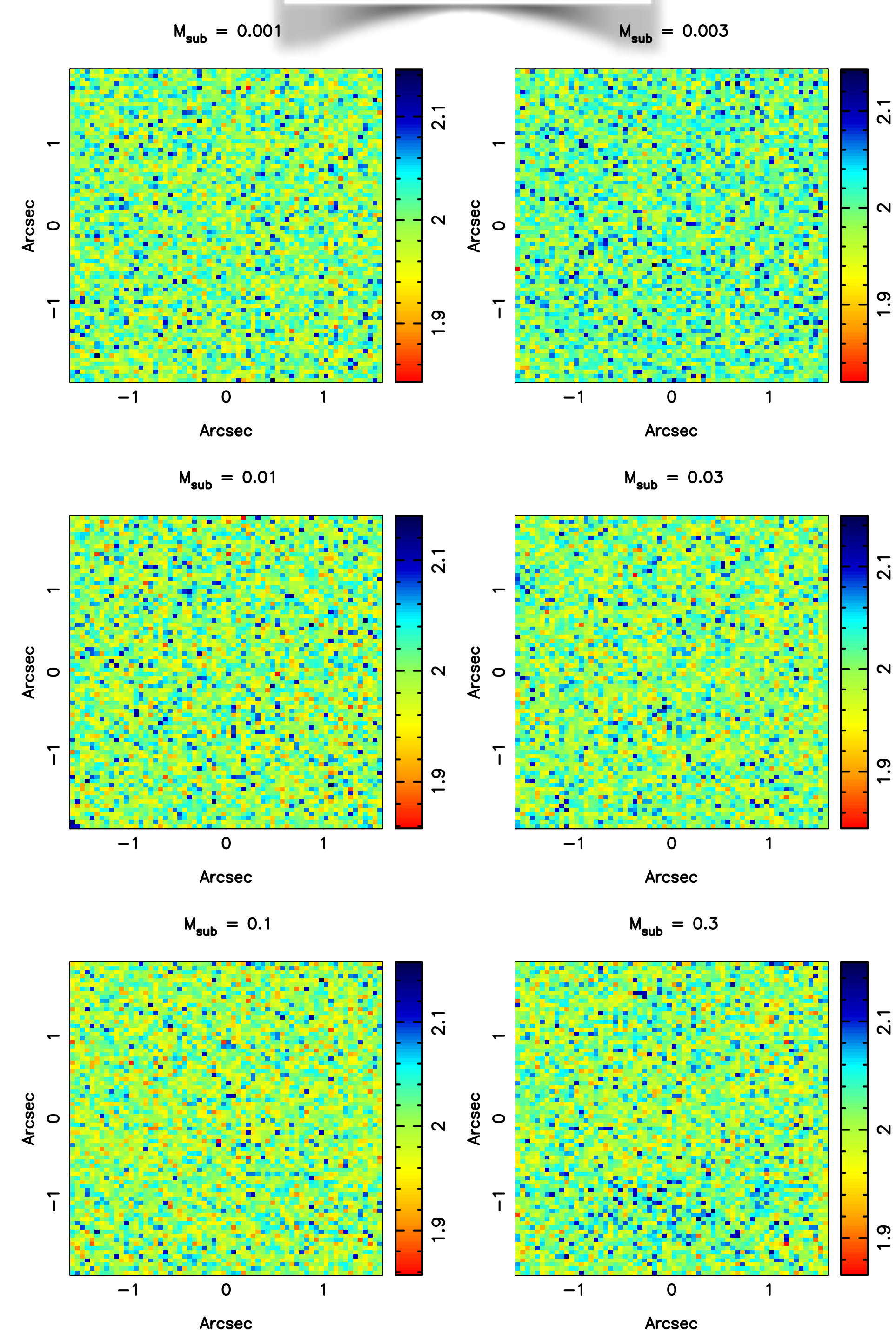
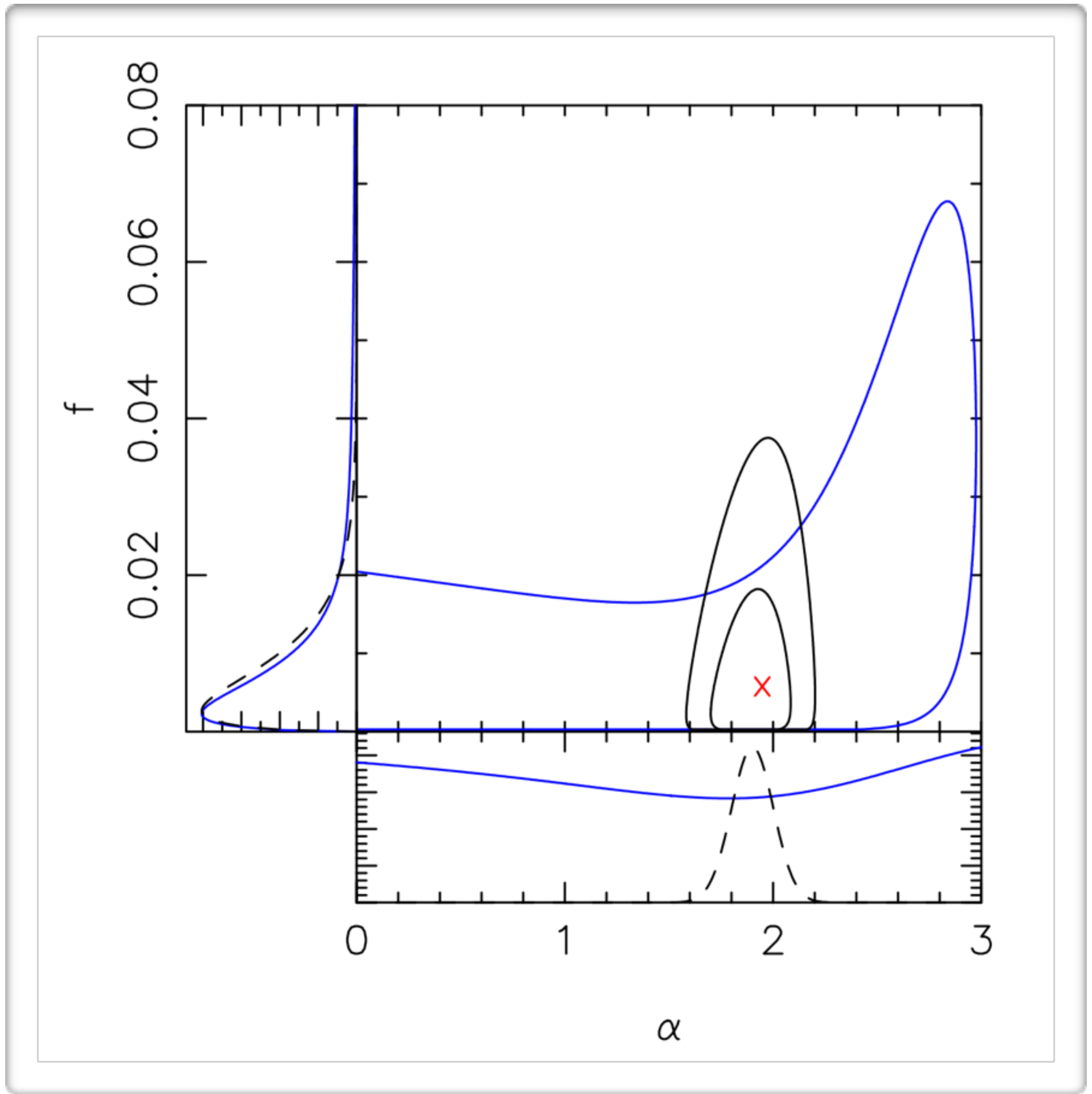


Image residuals lead to an over-estimate of the sensitivity

First measure of the mass function

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

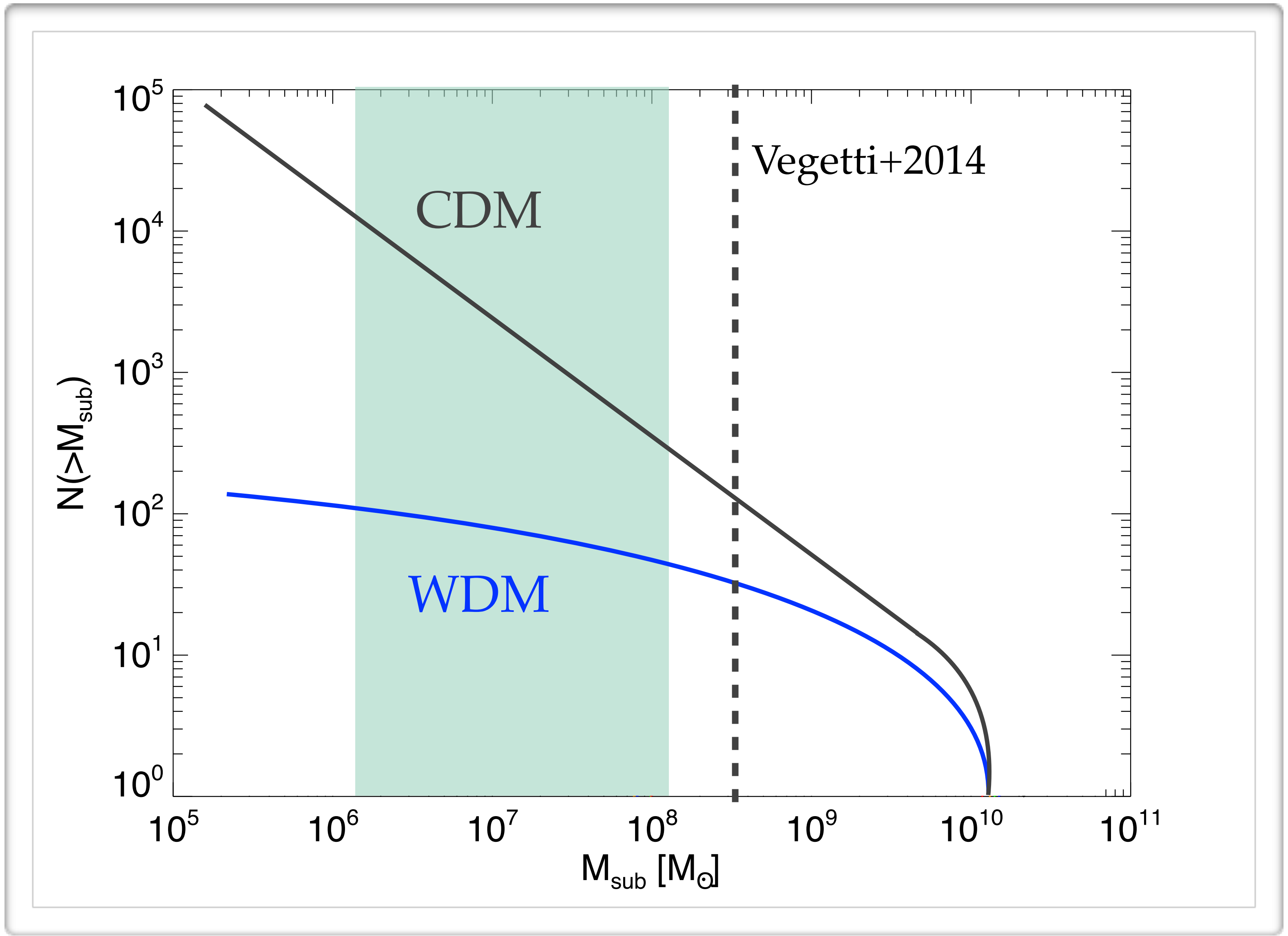
Derived mass function parameters



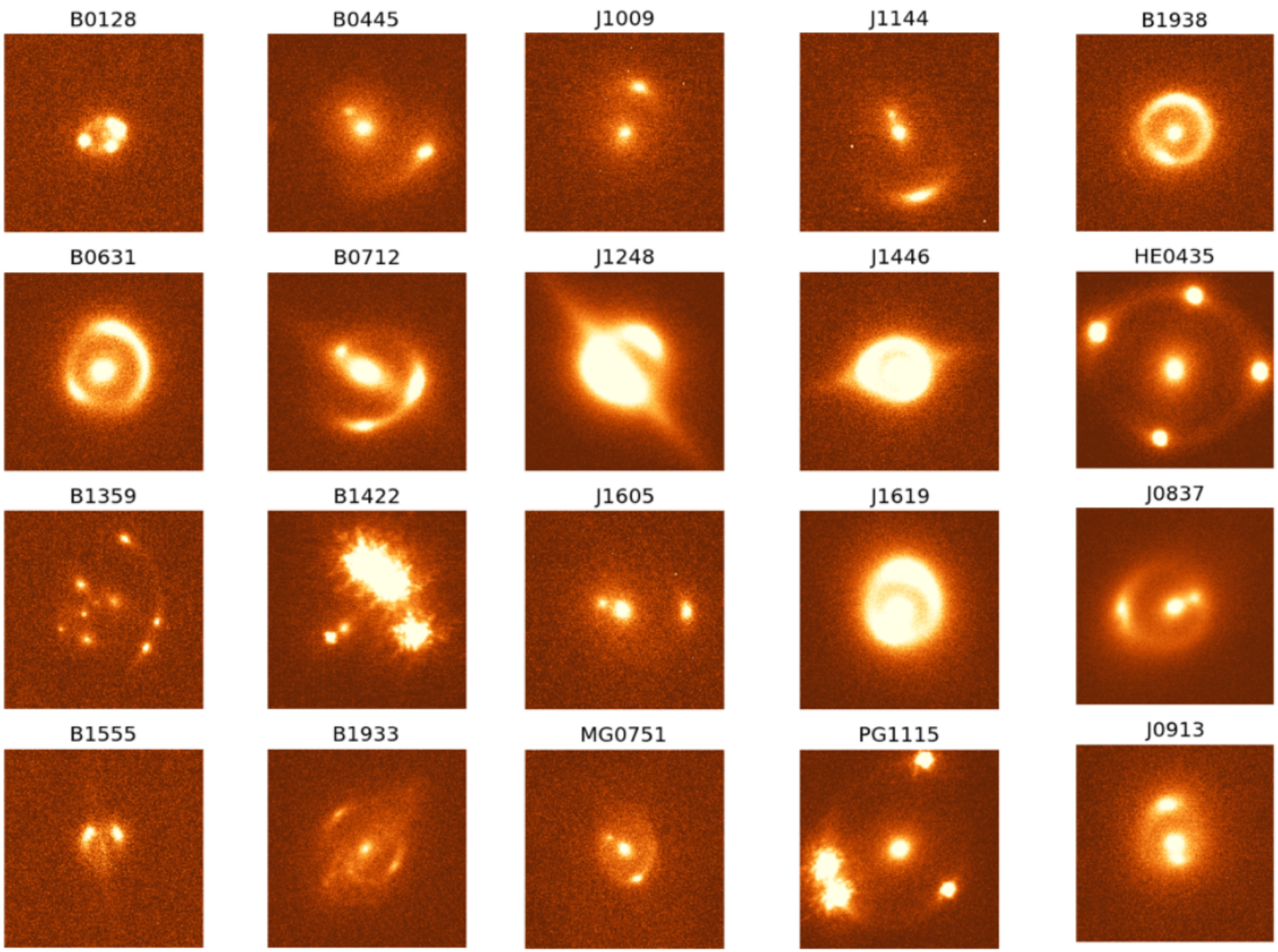
Results are consistent with Cold Dark Matter predictions, but due to the low sensitivity they do not rule out Warm Dark Matter models

The quest for the smallest substructure

Lowering the detection threshold by two orders of magnitude and more



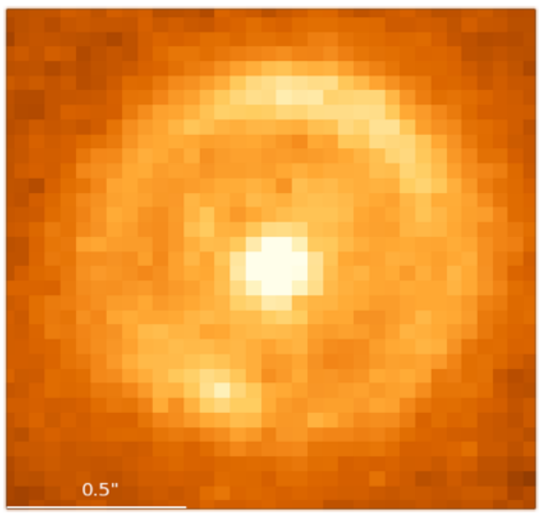
SHARP


B0128
B0445
J1009
J1144
B1938
B0631
B0712
J1248
J1446
HE0435
B1359
B1422
J1605
J1619
J0837
B1555
B1933
MG0751
PG1115
J0913

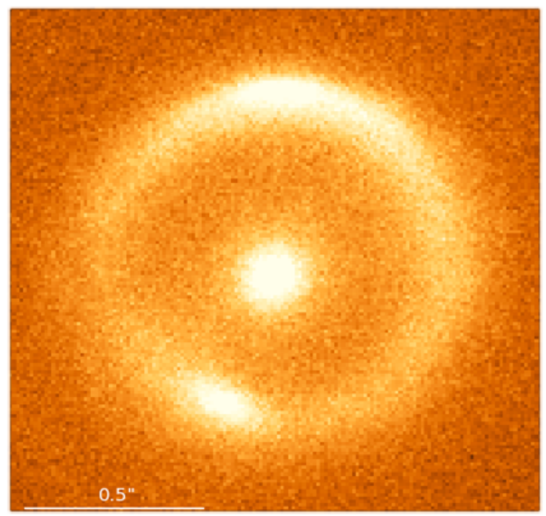
SHARP & FRIENDS

Strong lensing at High Angular Resolution Program

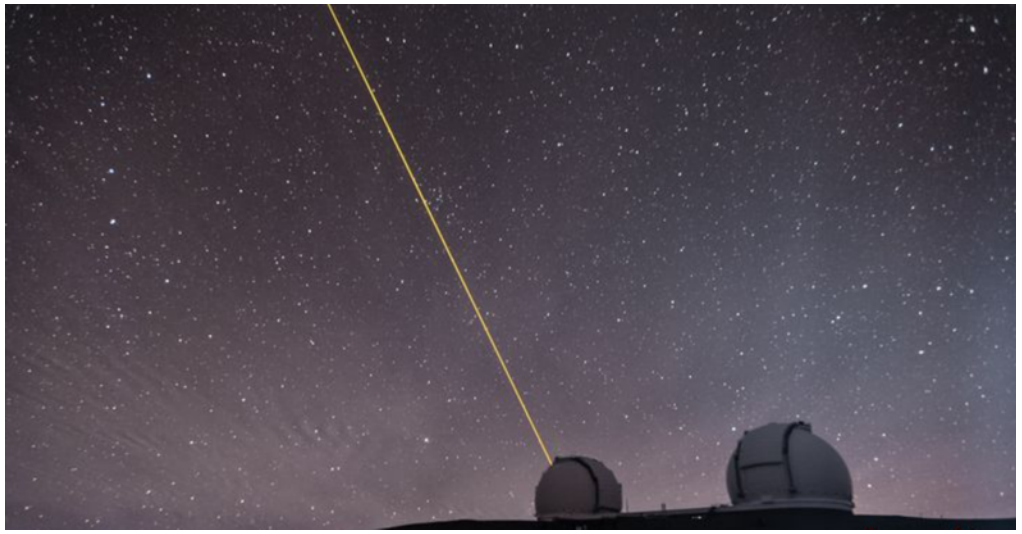
HST



Keck Adaptive Optics

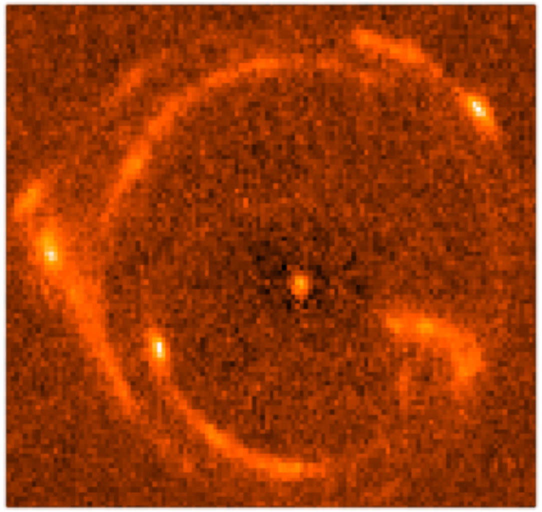


Increasing angular resolution

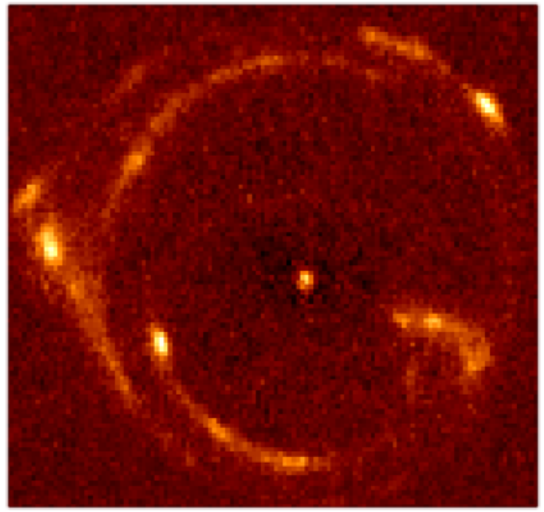


10 systems

HST



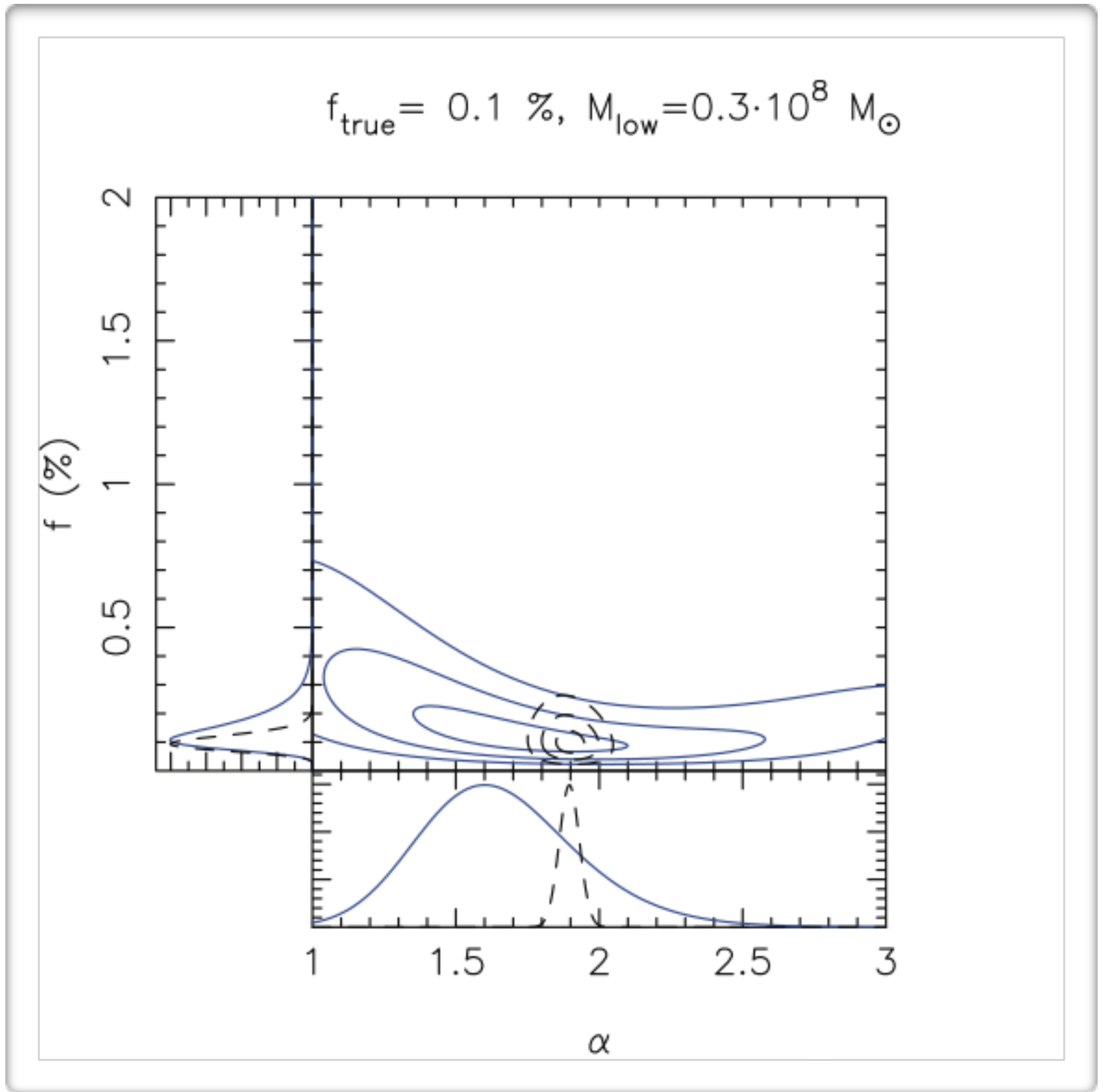
HST-UV



Increasing level of source structure

30 systems

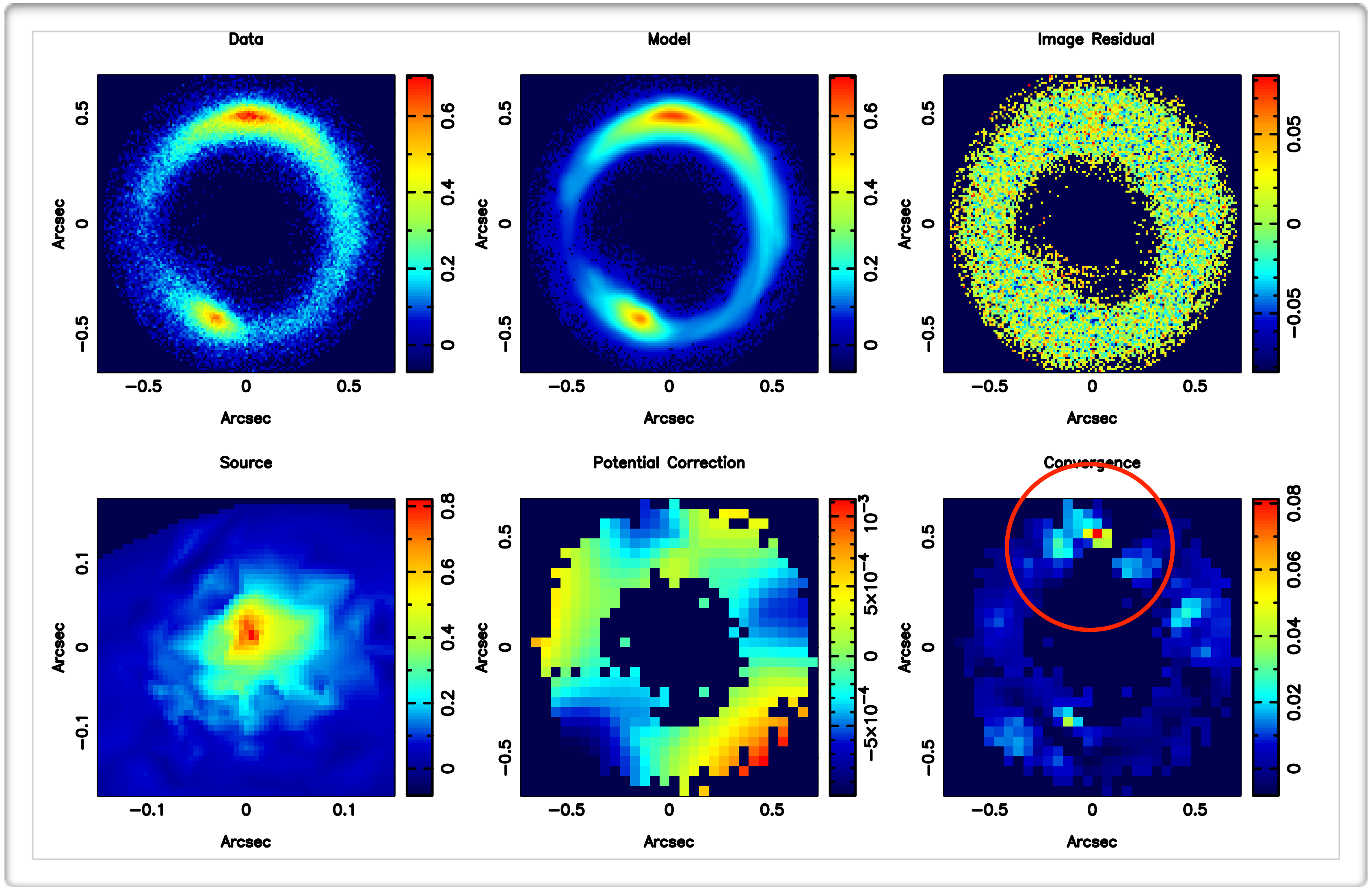
Projected Results



30 SHARP gravitational lens systems will allow us to set tight constraints on the substructure mass fraction.

SHARP first detection/z=0.9!

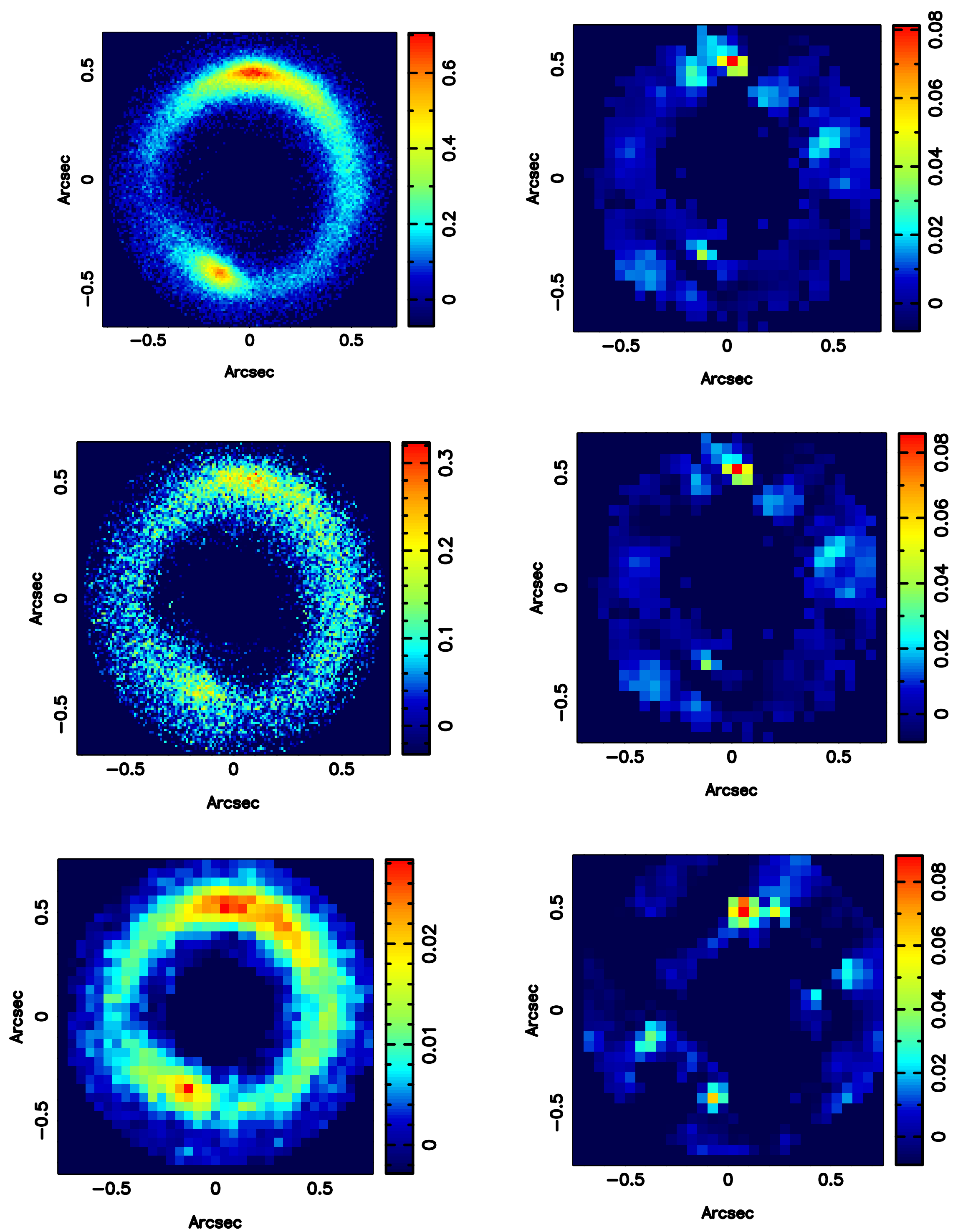
Vegetti + 2012

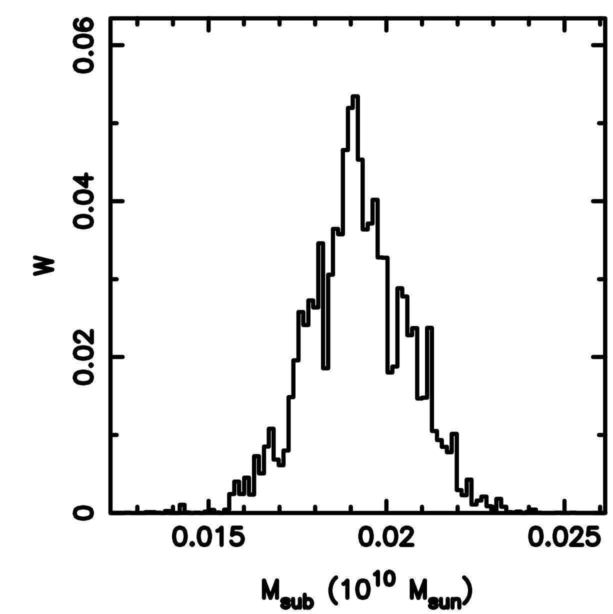


With a mass of $1.8 \times 10^8 M_{sun}$ this is currently the smallest and farthest substructure currently known

Vegetti + 2012

SHARP first detection/z=0.9!





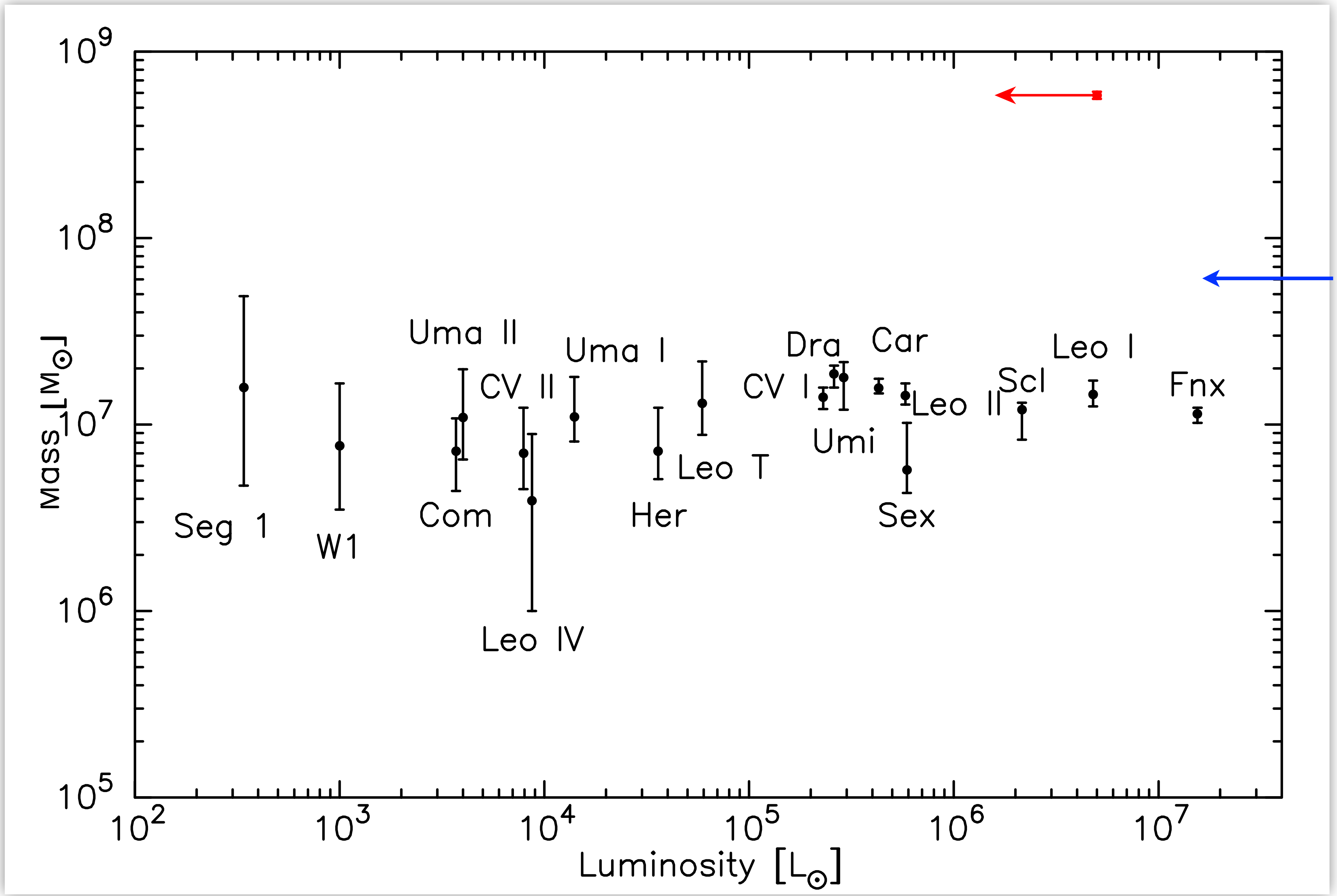
$$M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$$

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

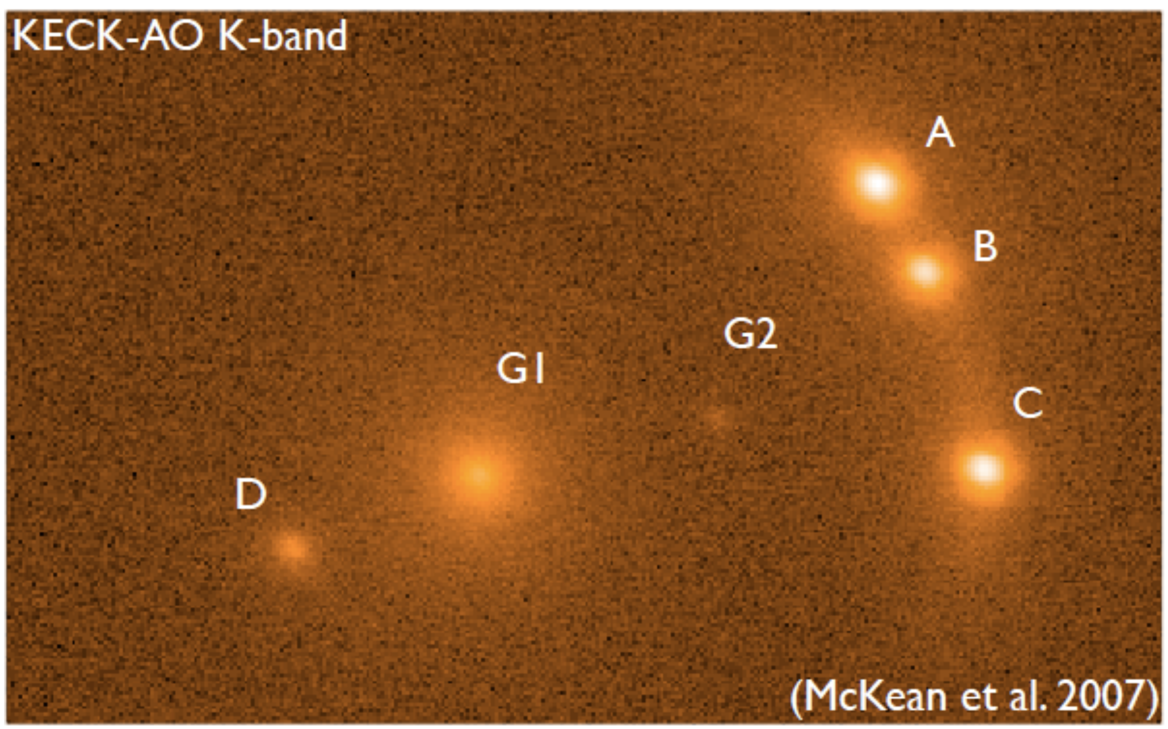
$$M(< 0.3) = (7.24 \pm 0.6) \times 10^7 M_\odot$$

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

SHARP first detection/z=0.9!



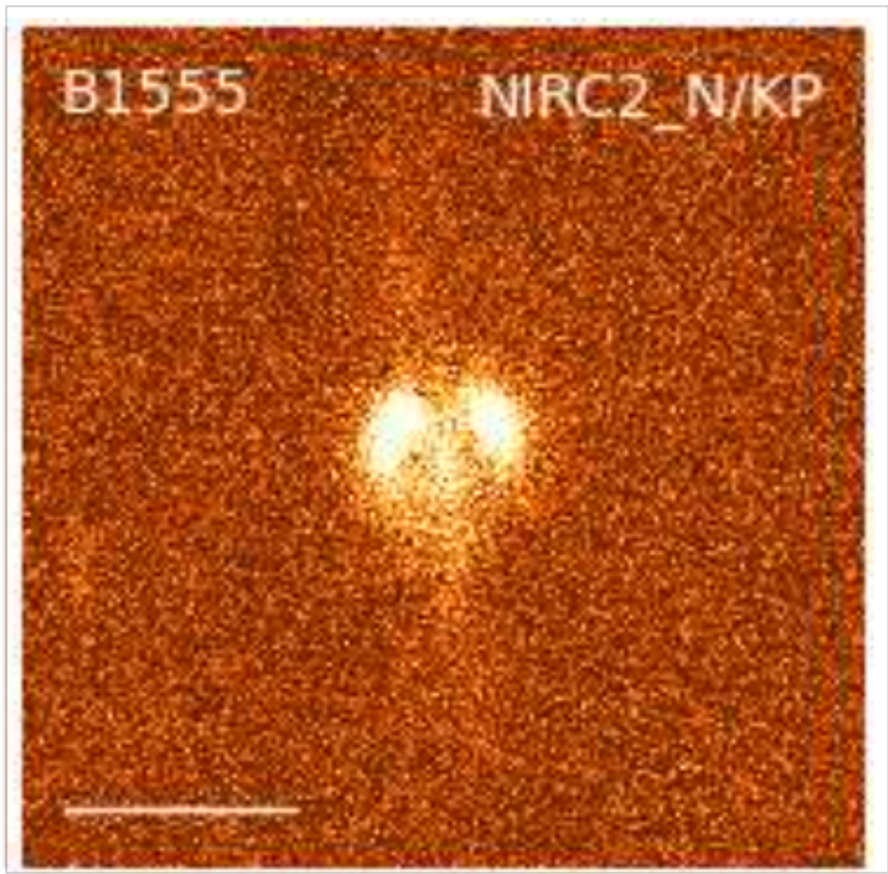
SHARP and Flux Ratio Anomalies

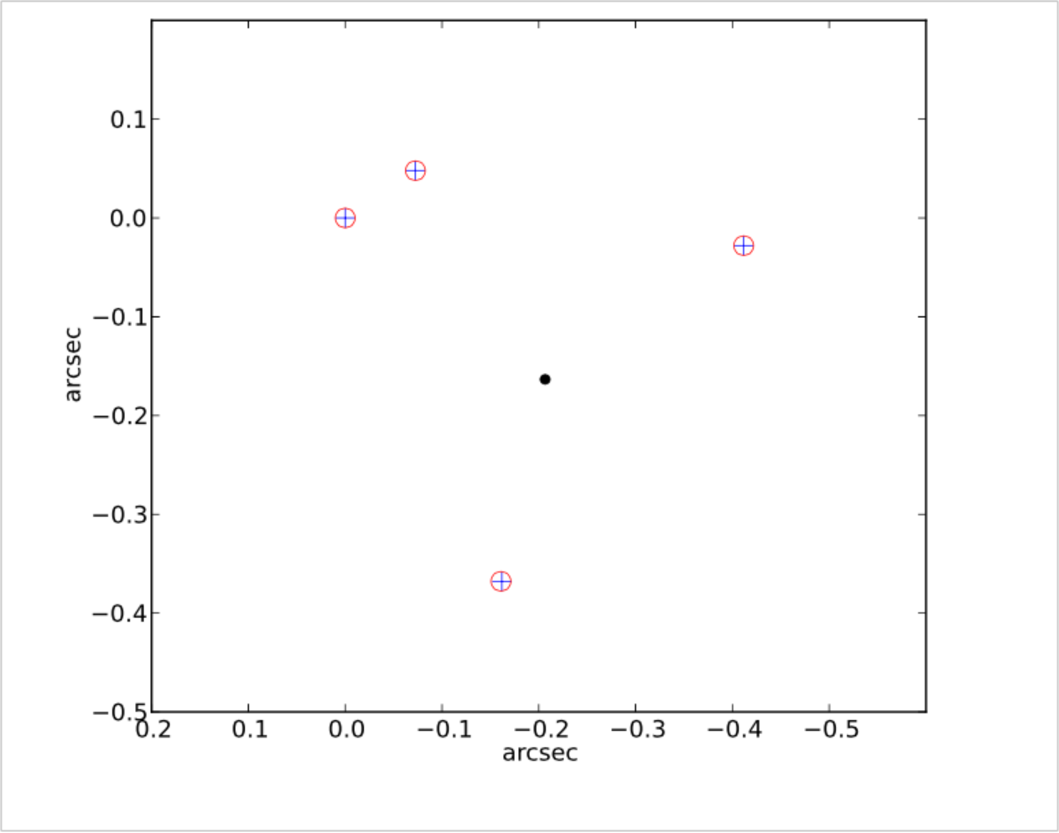


- 3/6 radio loud systems show evidence of a luminous satellite within 5 kpc from the host galaxy
- once these are included in the mass model the flux ratios can be reproduced along side with the images positions
- up to 1% of the host mass is contained in these systems
- 5/22 of all CLASS lenses have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

Beware of luminous satellites

SHARP and Flux Ratio Anomalies



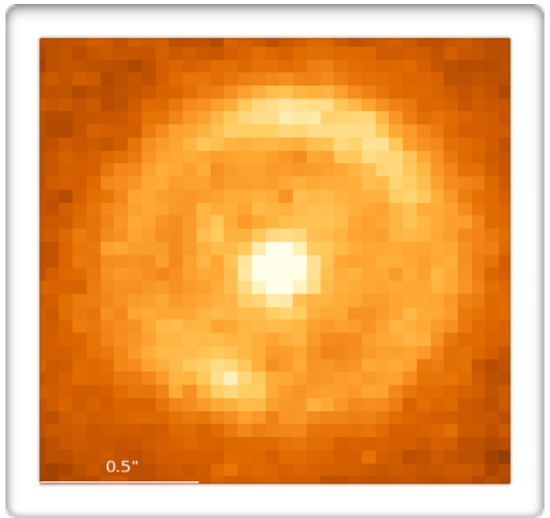


Beware of edge on disks

	MERLIN 5 GHz	VLA 15 GHz	Model 1-SIE	SIE+expdisk	2-SIE
f_A/f_B	1.75	1.78	1.07	1.66	1.75
f_A/f_C	2.05	2.37	2.95	1.33	2.16
f_A/f_D	13.08	12.86	2.00	5.83	7.96

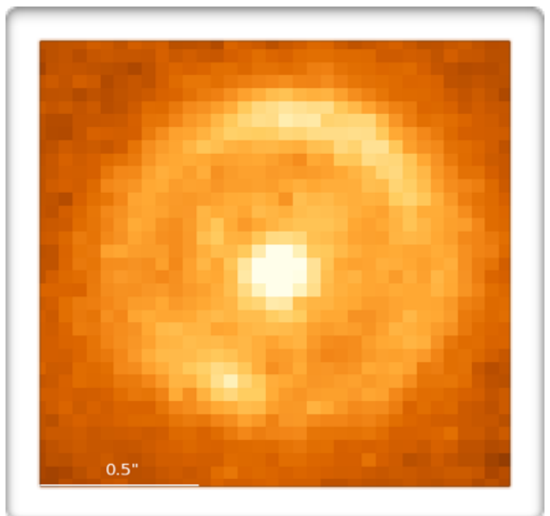
SHARPER & SHARPER

SHARPER & SHARPER

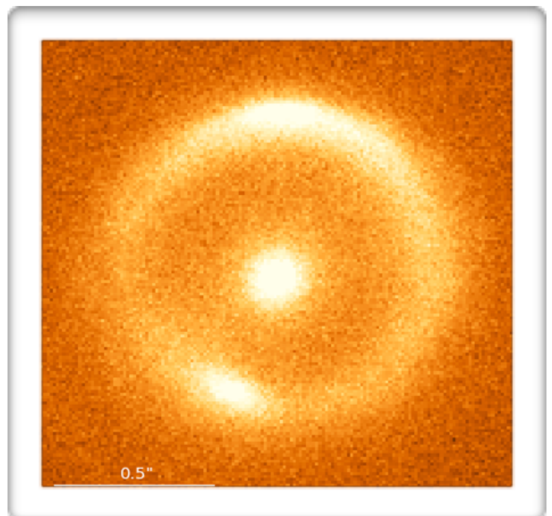


HST

SHARPER & SHARPER

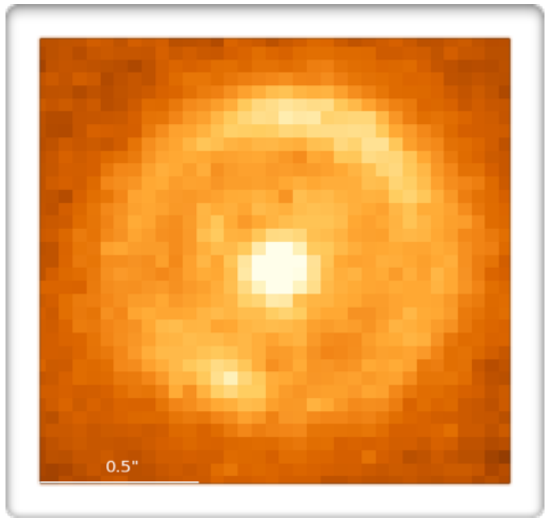


HST

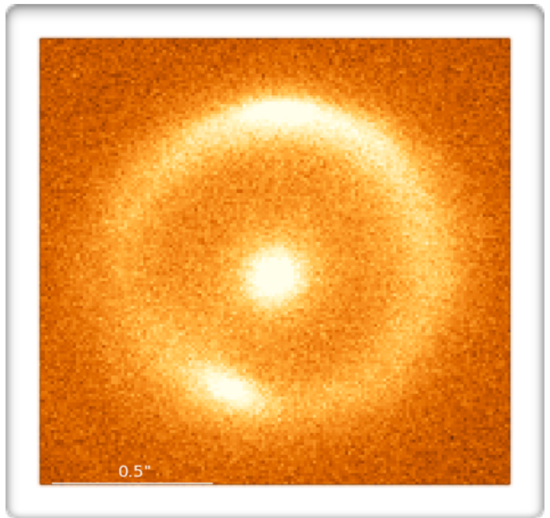


Keck AO

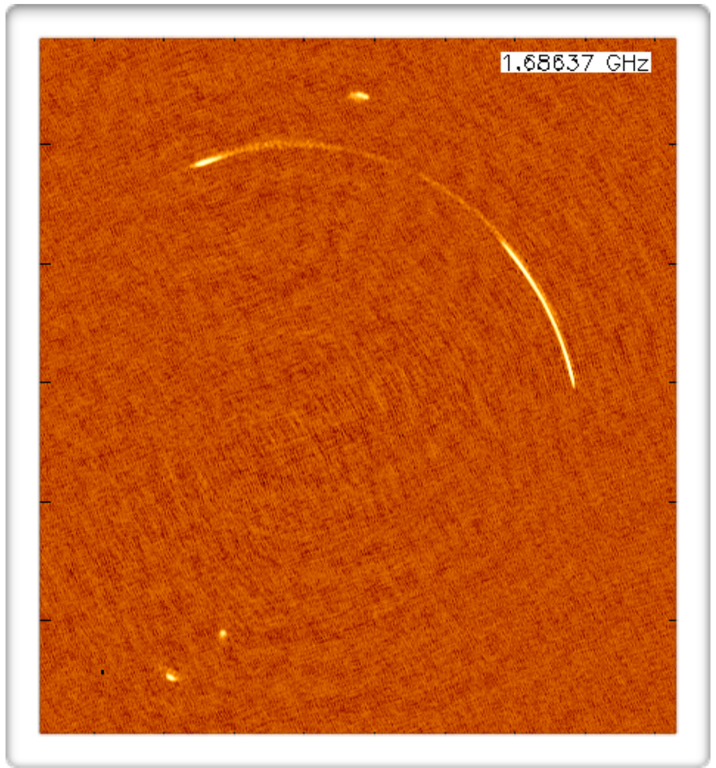
SHARPER & SHARPER



HST

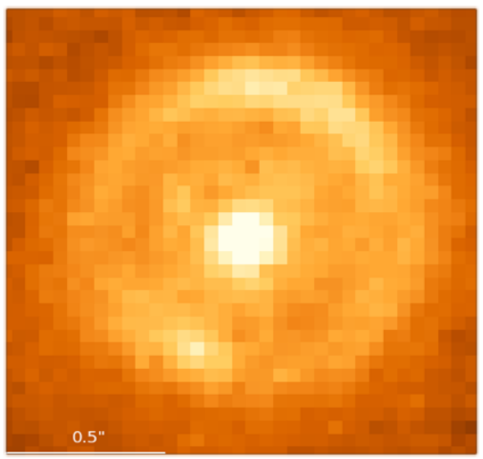


Keck AO

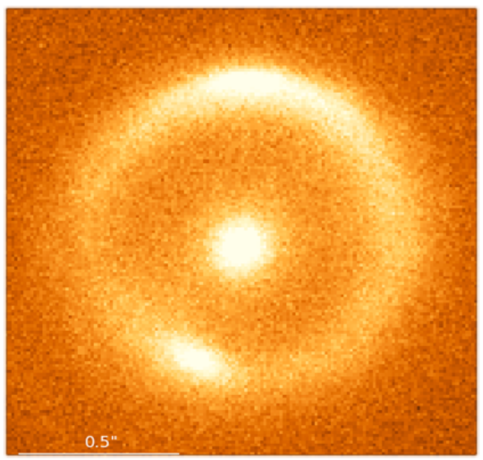


GVLBI

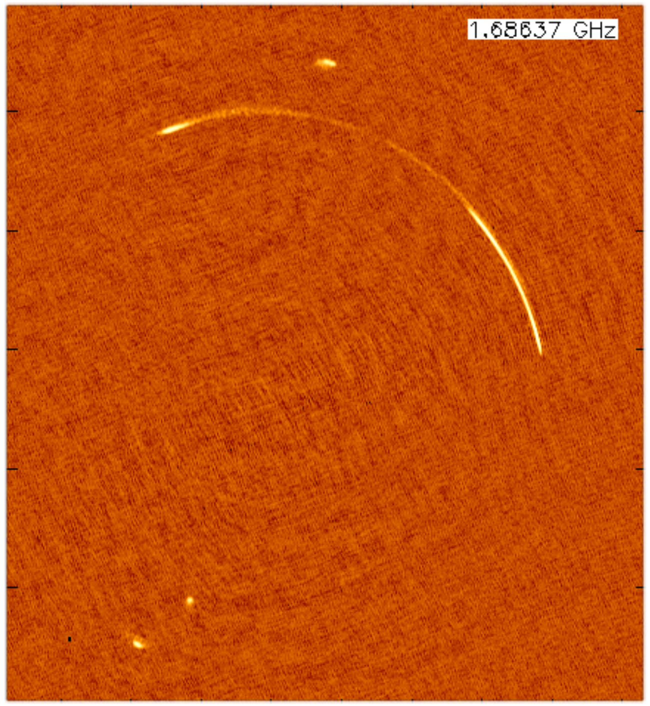
SHARPER & SHARPER



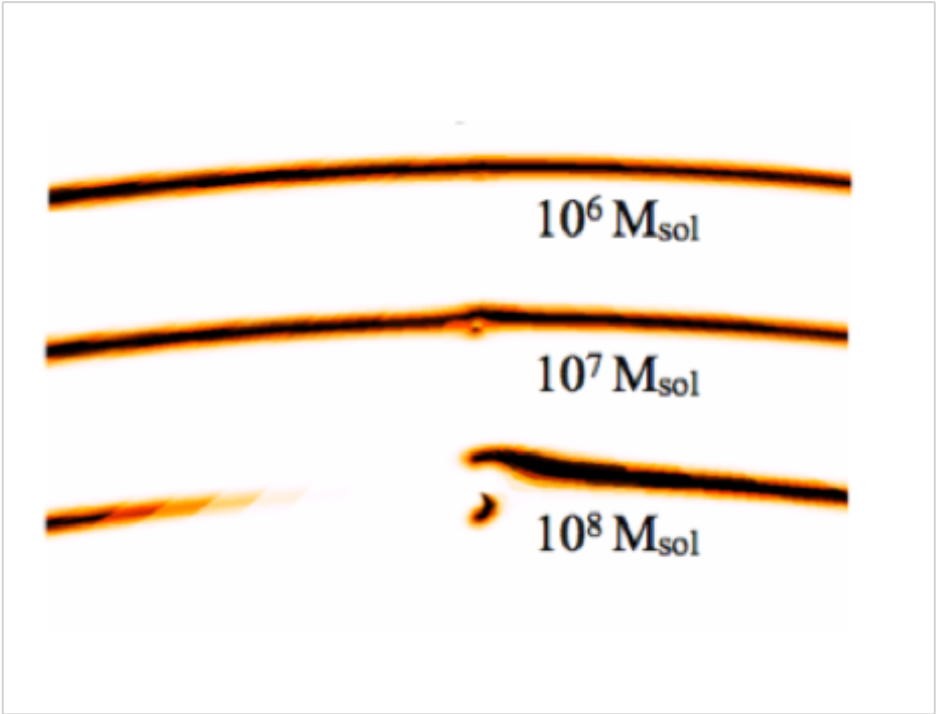
HST



Keck AO

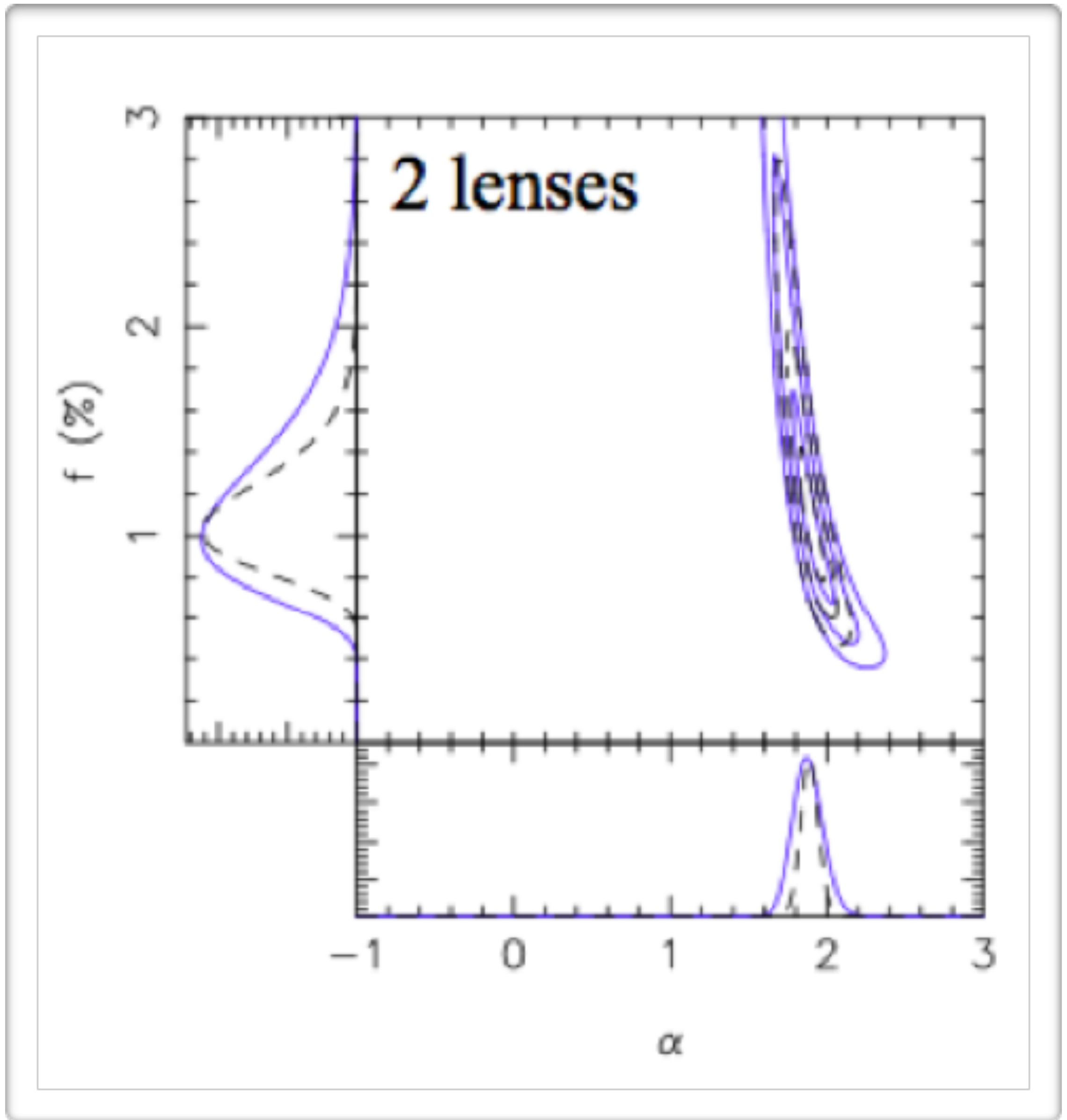


GVLBI



Projected Results

At present there are only two systems with this quality, but this is already enough to set tight constraints on the substructure mass function.



Modelling the **visibilities**

Important not to use the image data (unlike for optical/IR observations)

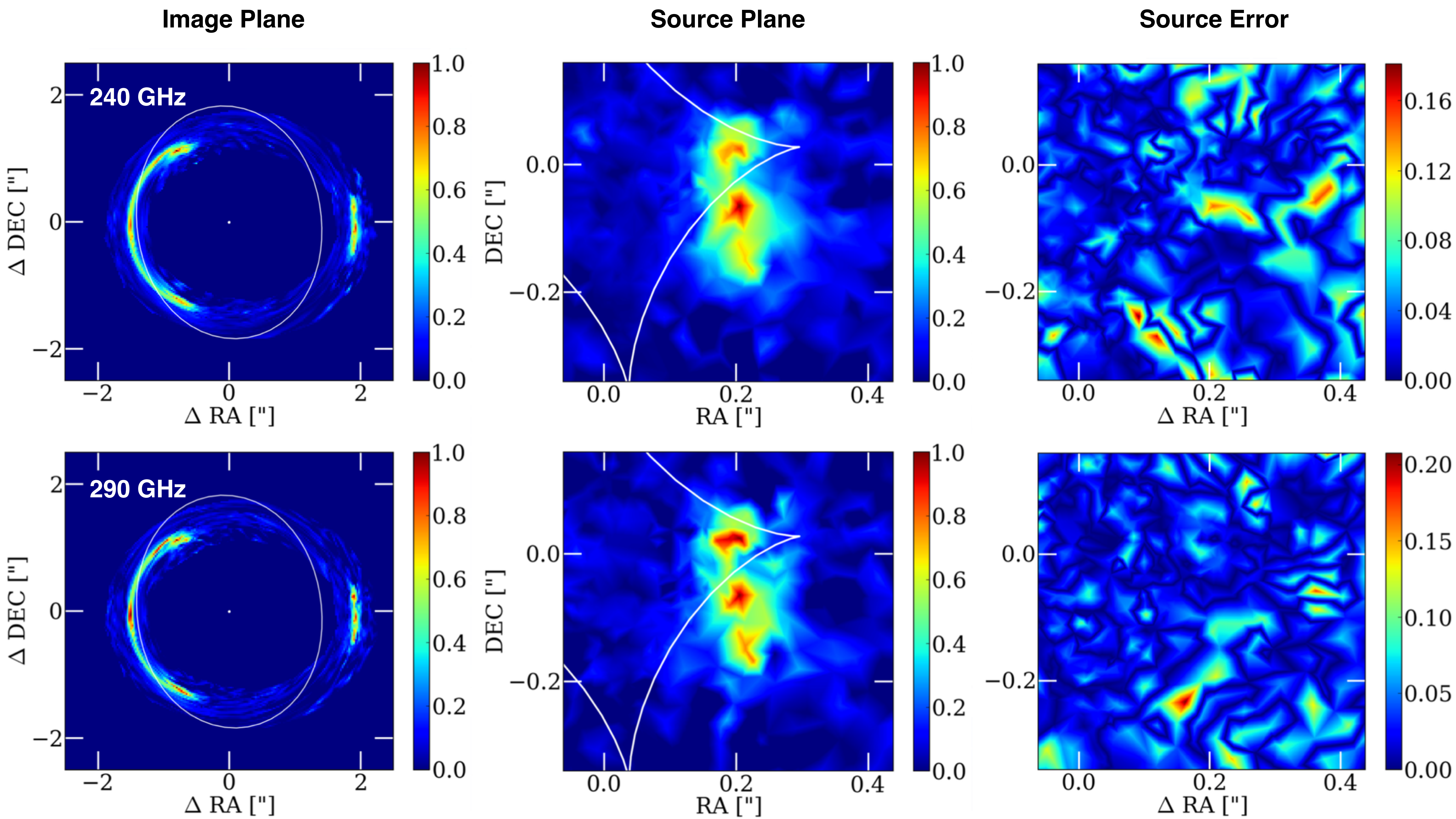
- The visibilities (and errors) are the data
- The noise in the image plane is correlated
- Image plane data dependent on
  - Gridding
  - Weighting of the visibilities (natural / uniform)
  - Tapering
  - Deconvolution (clean, MS-Clean, MEM, CS,…)
  - Surface brightness is no longer conserved

Instead, fit directly to the visibilities (Fourier plane lens modelling)

- The visibilities (and errors) are the data (need a supercomputer).
- Better handle on the noise properties.
- We use a pixellated source model built within a fully Bayesian statistical framework — determines best model, given the data.
- Based on image plane technique devised by Vegetti & Koopmans (2009)
- See Rybak, Vegetti & McKean (2015) for details.

- ALMA provides angular resolution (0.5–0.01 arcsec).
- Science Verification LB dataset for SDP.81 released Feb 17!
- Proper analysis requires lens modelling codes that operate on the visibilities because image plane has,
    1. Deconvolution biases
    2. Correlated noise
    3. Irregular uv-coverage does not conserve surface brightness.

Pixellated source model



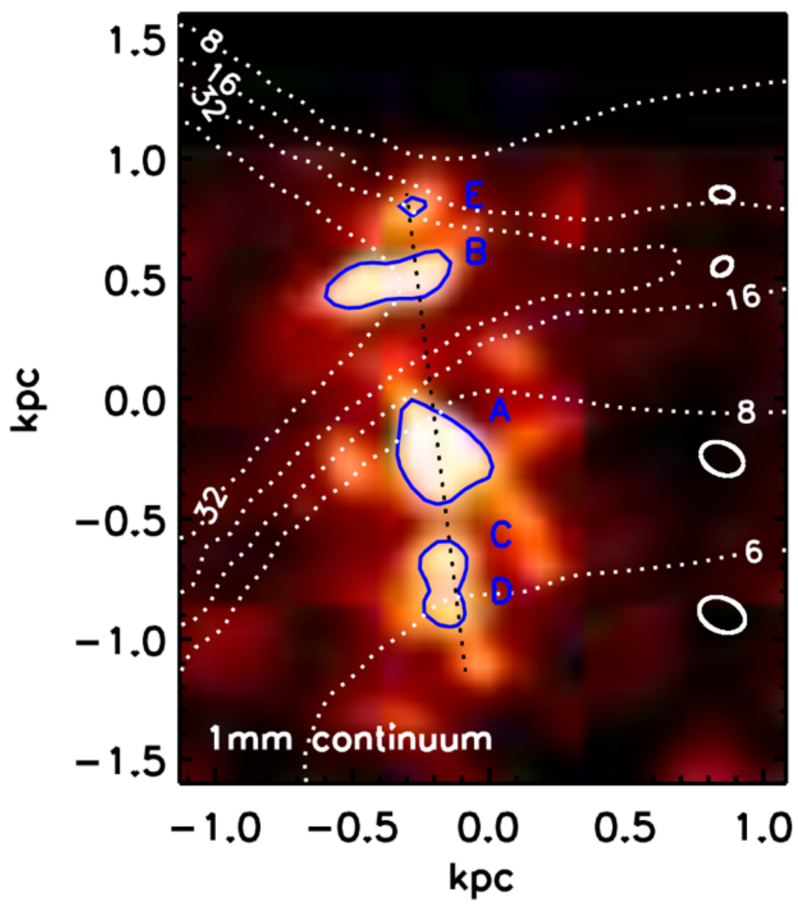
- Whole source: μ = 17.6 ± 0.4
- Central region: μ = 25.2 ± 2.6

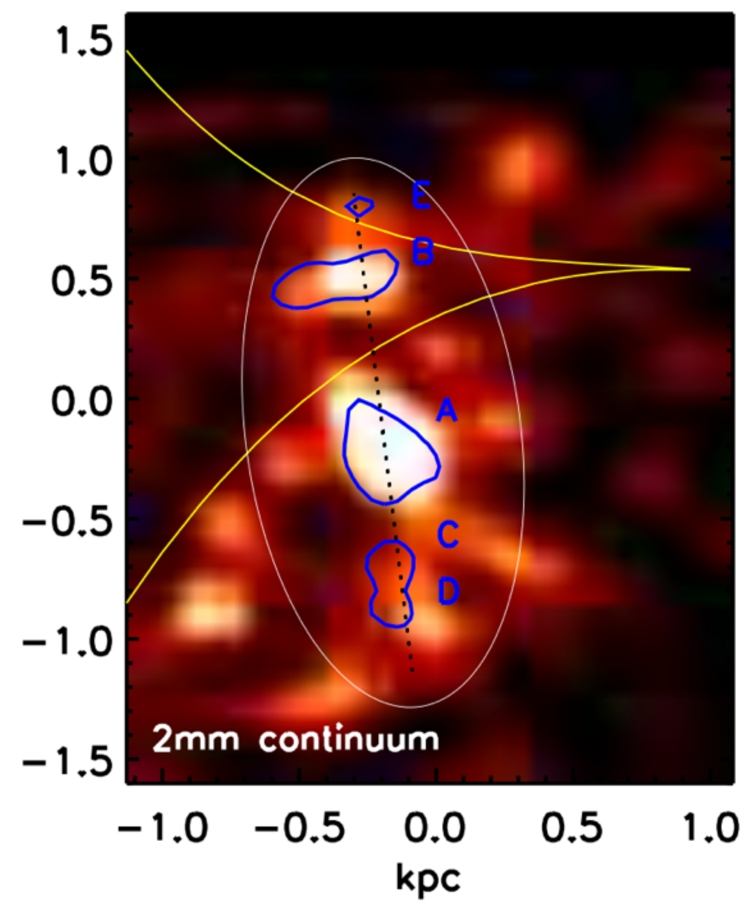
Rybak et al. 2015a

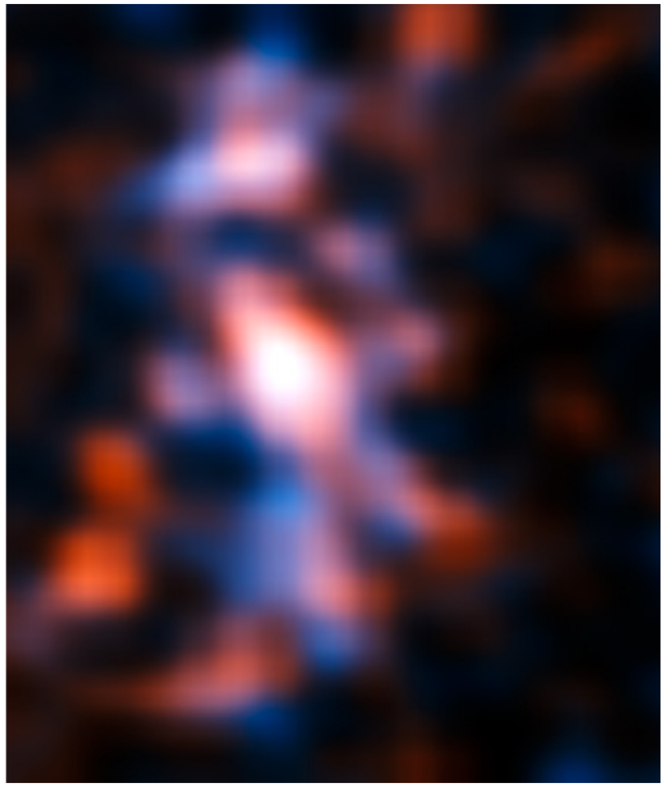
Comparison with image-plane

Swinbank et al. 2015

The compact components are seen to vary between the two methods

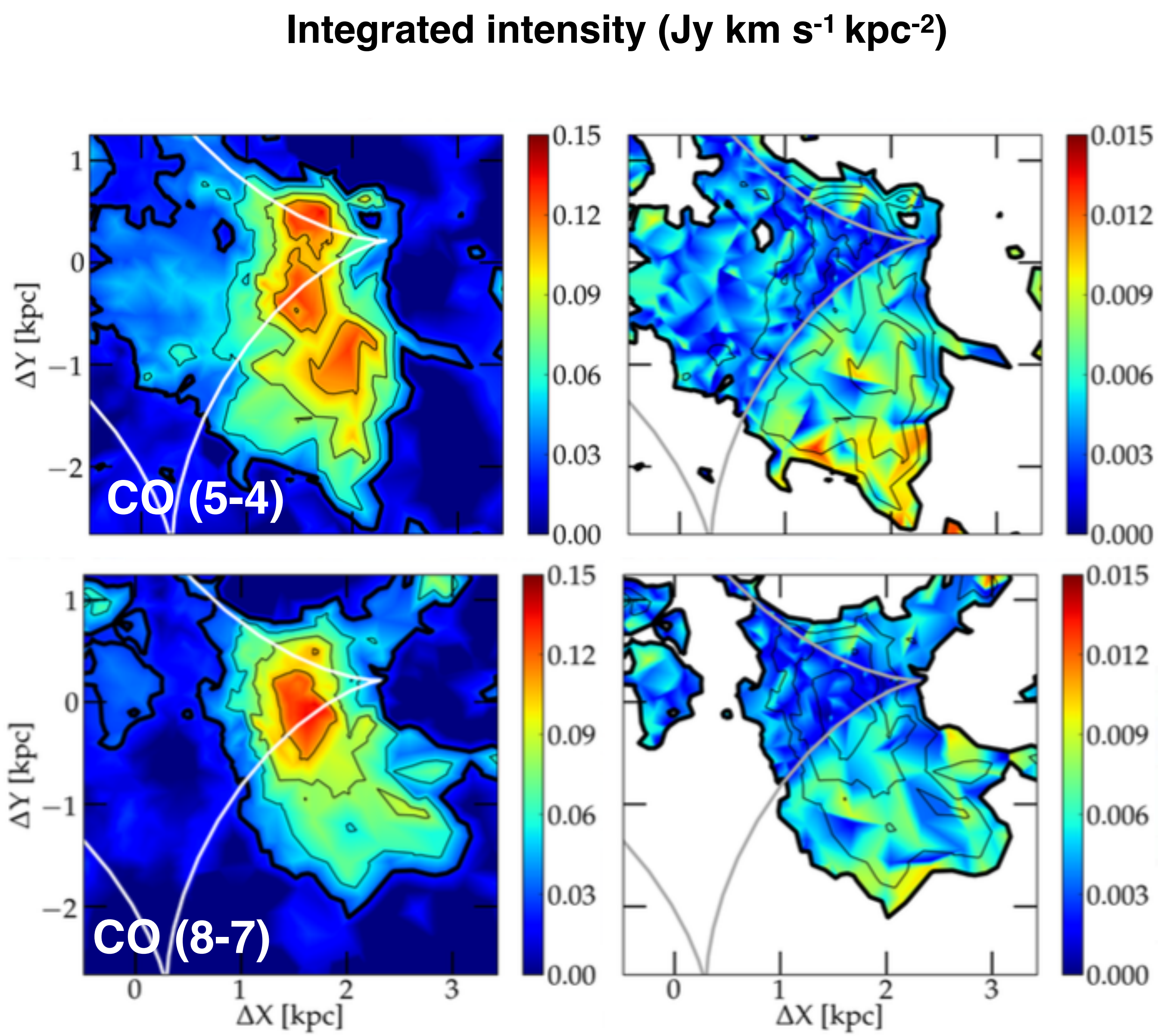






The compact structure varies significantly even within the individual image-plane analyses of the 1, 1.3 and 2 mm continuum data

Intrinsic properties of the gas



Clear transition dependent structure in the CO.

CO (5-4) has both diffuse and compact structures that extend of ~3 kpc

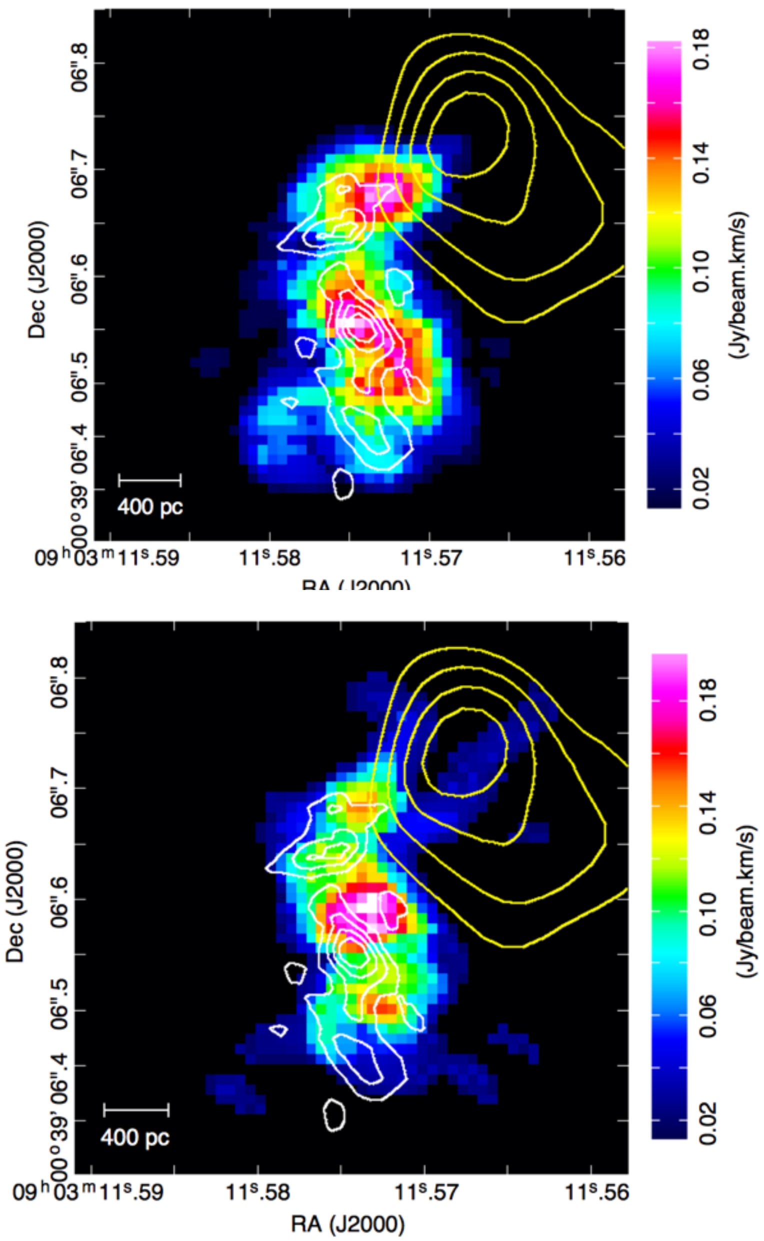
CO (8-7) is more compact and only ~1.5 kpc in size

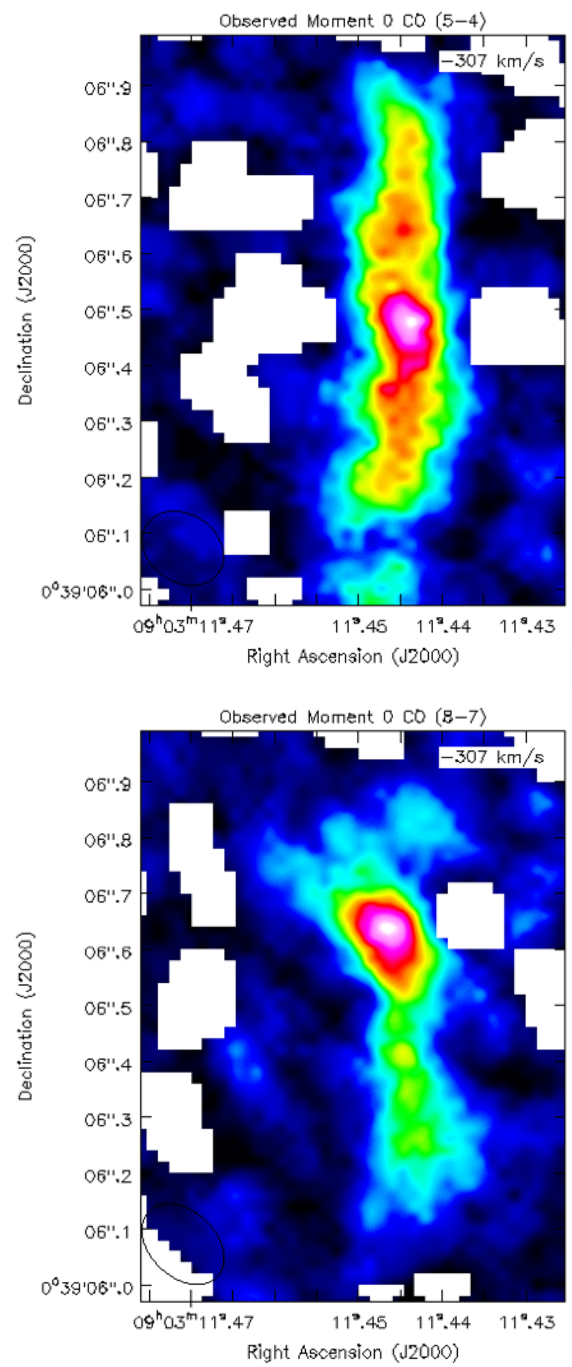
Results are consistent with the image-plane zeroth-moment maps of the counter arc as seen in ALMA partnership paper

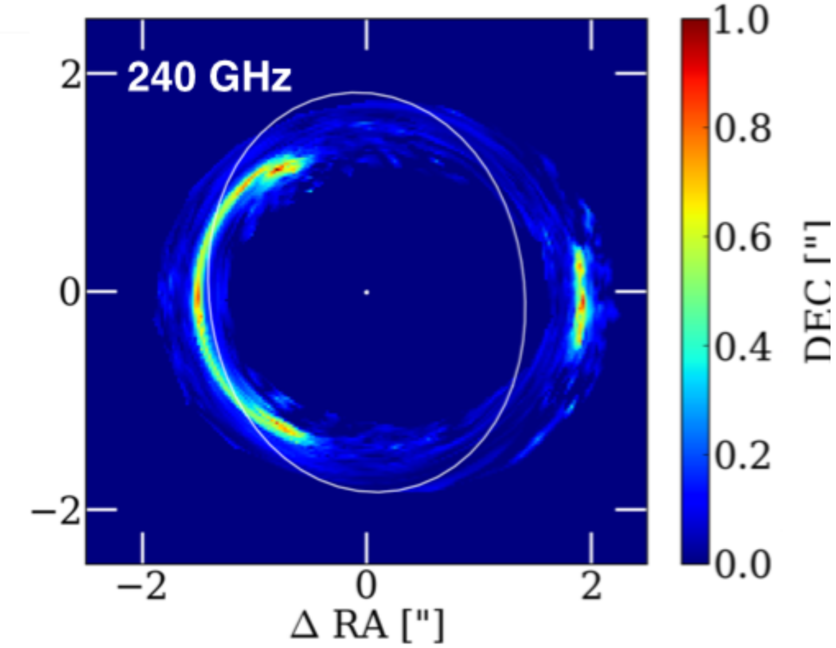
- CO (5-4): $\mu = 17.0 \pm 0.4$
- CO (8-7): $\mu = 16.9 \pm 1.1$
- $r_{8\text{-}7/5\text{-}4} = 0.3 \pm 0.04$

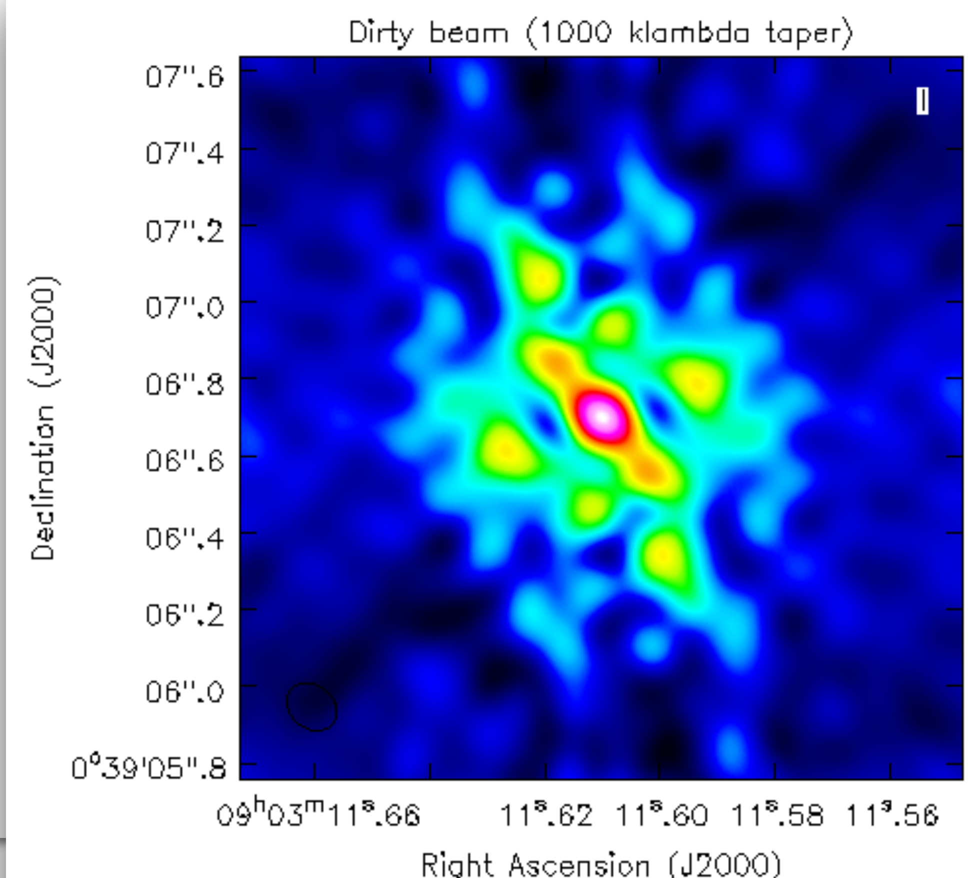
Rybak et al. 2015b

Comparison with image-plane









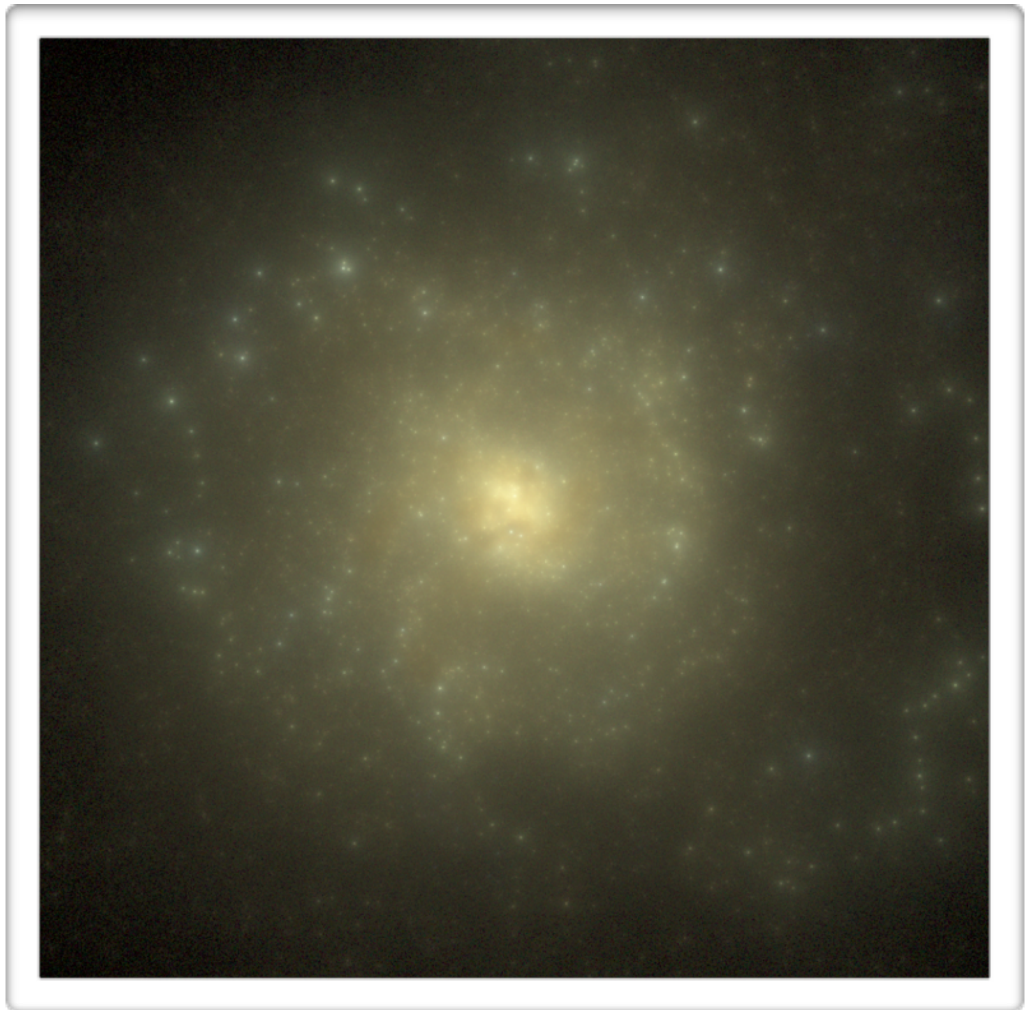
(Dye et al., submitted)

In summary

- We have developed a novel technique to detect dark substructure via their gravitational signature on gravitationally lensed arcs and Einstein rings:
    - This is currently the only method to detect dark and distant substructure and measure the abundance of low mass substructure
- We have initiated a new panchromatic observational campaign called SHARP to obtain a large sample of gravitational lens systems with improved sensitivity to substructures:
    - This survey has already delivered a sample of ~40 lenses;
- Using state of the art radio telescopes we have lowered the detection threshold to $10^6 M_{sun}$
- In the near future radio telescopes such as ALMA and GVLBI will deliver more systems with very high sensitivity

Open questions: predictions

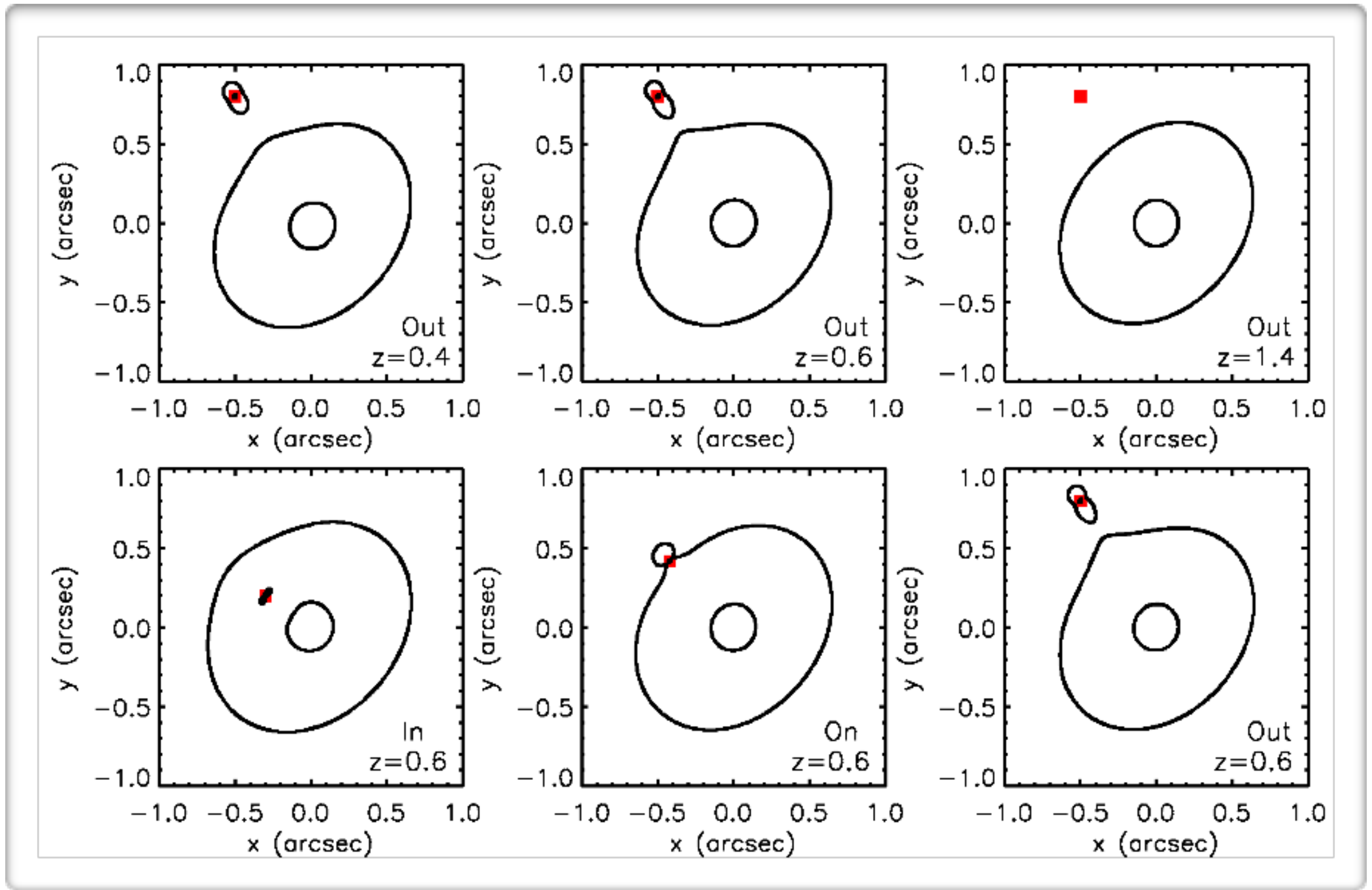
- Up to now most of the highest resolution numerical simulations have been focusing on dark matter only Milky-Way type of haloes
- There is indication that the amount of substructure is a function of host mass and redshift
- The role of baryons on the survivability of the substructure has yet to be quantifies



We will make use of publicly available numerical simulations as well as an ensemble of WDM and CDM simulations to quantify the amount of substructure in hosts with properties strictly matching those of the observed samples. We will also use the latest hydrodynamical simulations to investigate the effect of baryons.

Open questions: contaminations

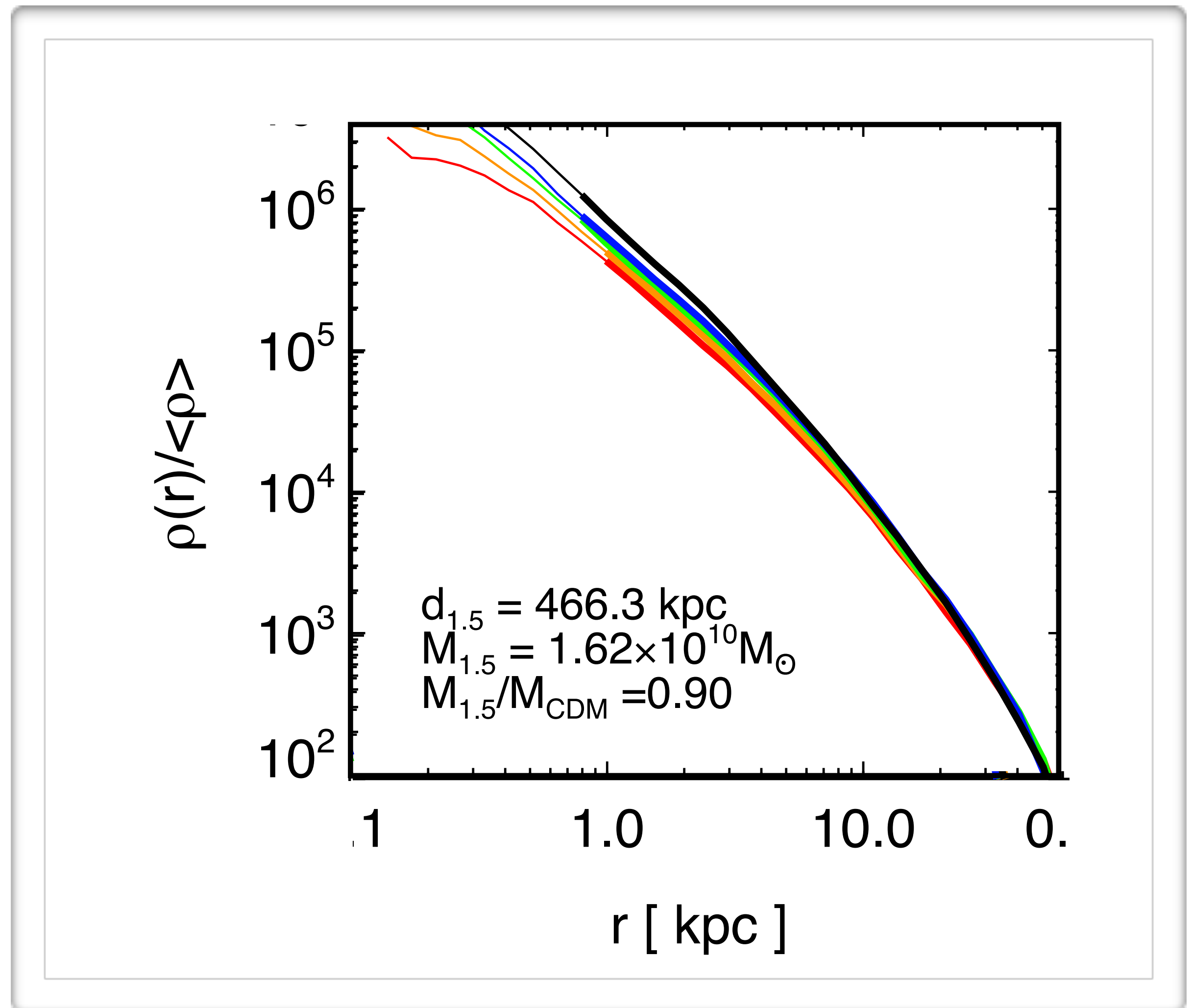
- Gravitational lensing is sensitive to all the mass between the observer and the background source
- Substructure detection could be therefore be contaminated by line-of-sight mass clump which are not physically associated with the lens
- There is indication that the lensing effect on Einstein rings and magnified arcs is different for the two components



We will make use of numerical simulations to quantify the level of line-of-sight contamination and will investigate its gravitational effect by and mock realistic observations of gravitational lens systems.

Open questions: mass density Bias

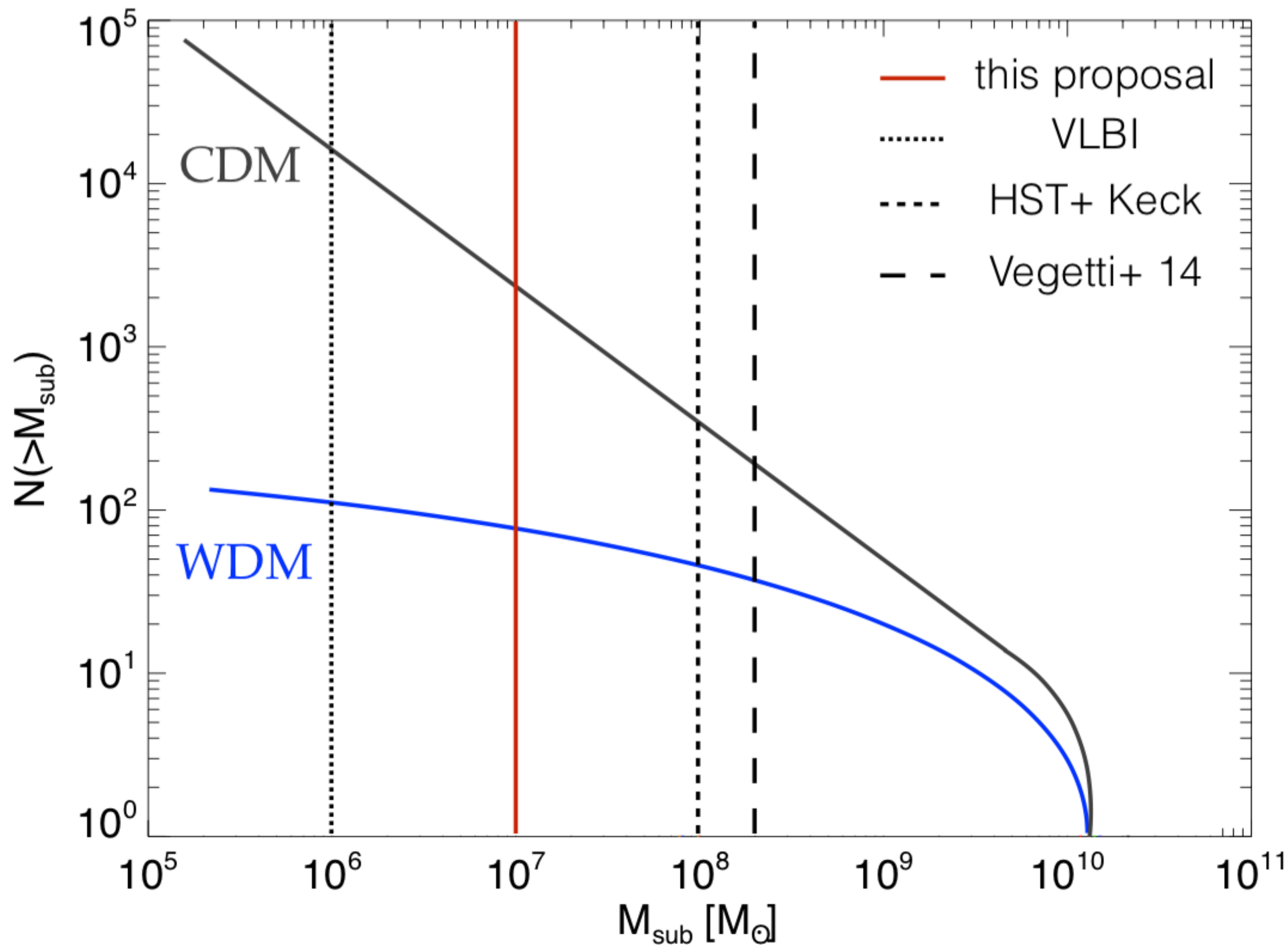
- Different dark matter models predict different mass density profiles for the substructure
- Are the non-detections biased by assumptions on the mass density profile?
- Is the mass within the Einstein radius a biased free measure for the estimation of the sensitivity function?
- Can we use the measured effect to exclude certain profiles and hence turn both detections and non detection into a constraint of more exotic dark matter models?



We will make use of publicly available numerical simulations and mock realistic observations of gravitational lens systems to address interesting issues of the profile of substructure.

In summary

- Over the next few years we will set a new observational constraints on the properties of dark matter by measuring the clumpiness of the Universe at the smallest scales.



Thank you!