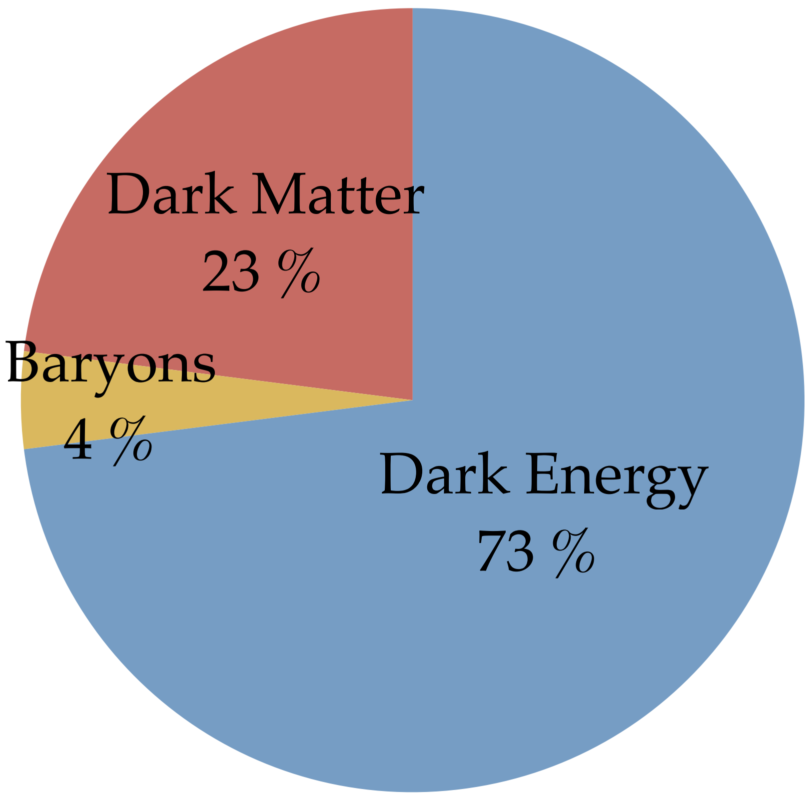
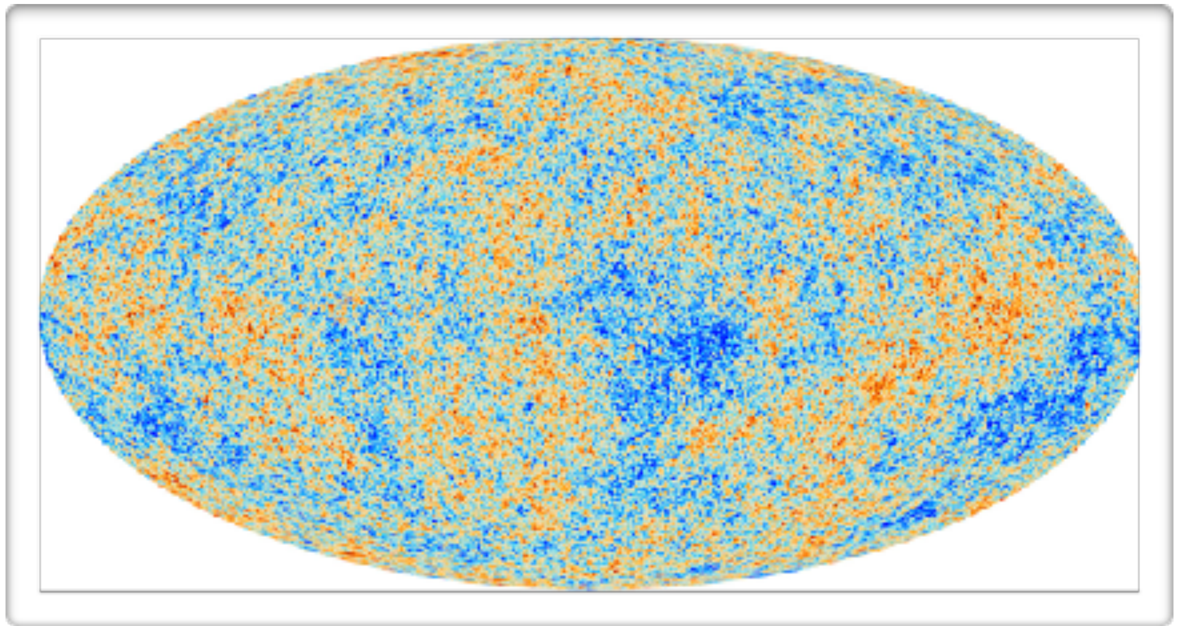
MILLI-LENSING AS A PROBE OF DARK MATTER

Simona Vegetti - Max Planck Institute for Astrophysics

STRUCTURE FORMATION





Planck Cosmic Microwave Background

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

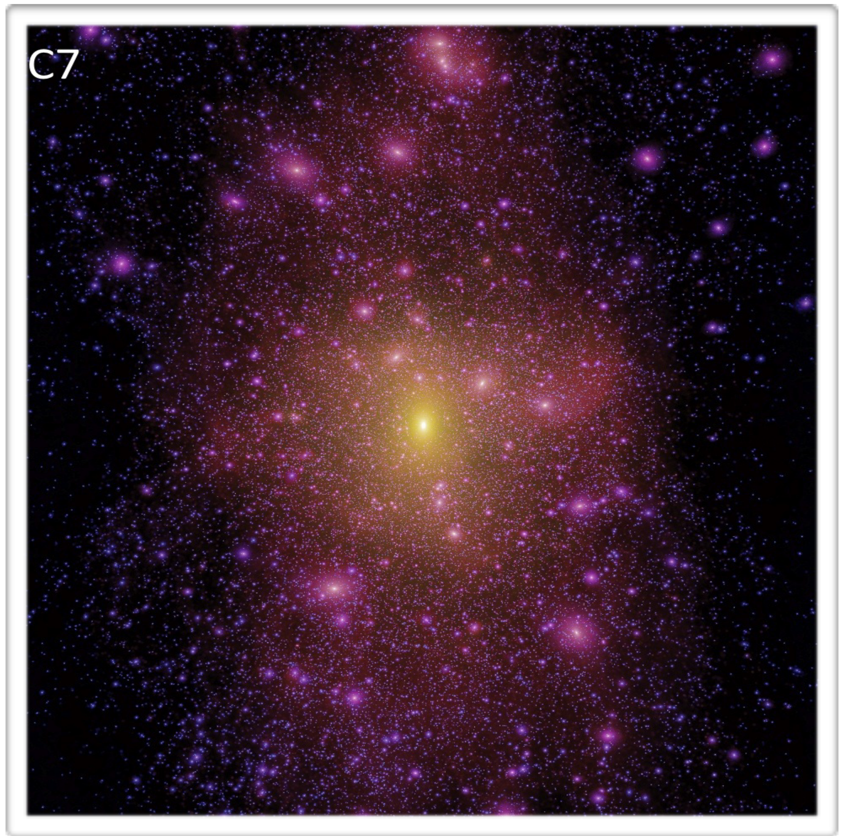
Three complementary approaches exist to decipher the nature of dark matter:

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

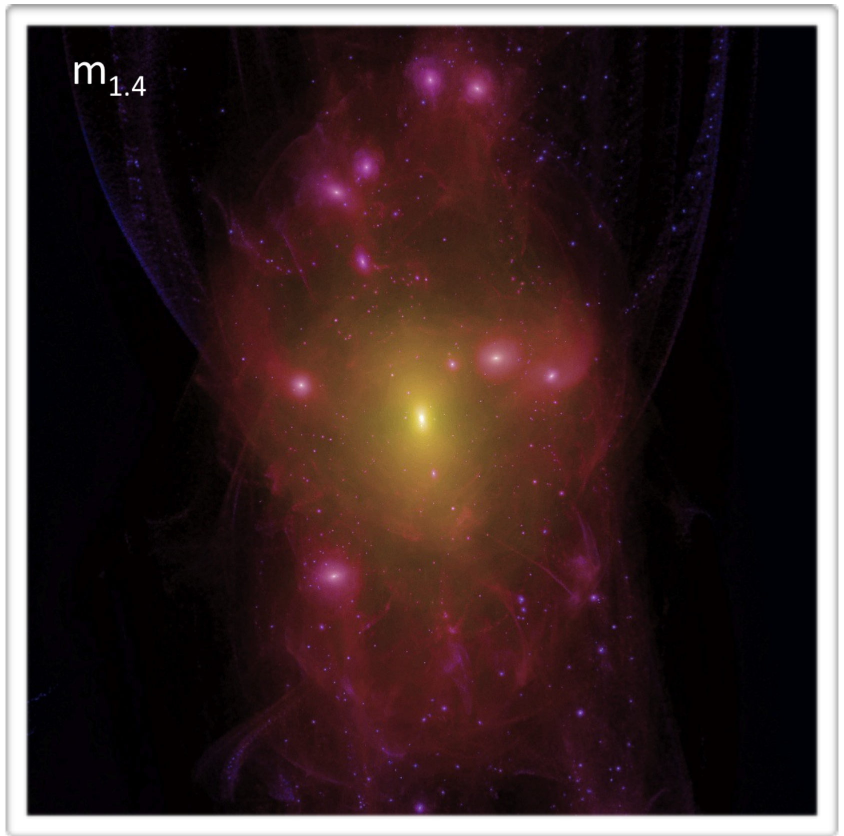
Springel+ 2008; Lovell+ 2012

SUBSTRUCTURE IN THE MILKY WAY HALO

Cold Dark Matter / WIMPs, Axions



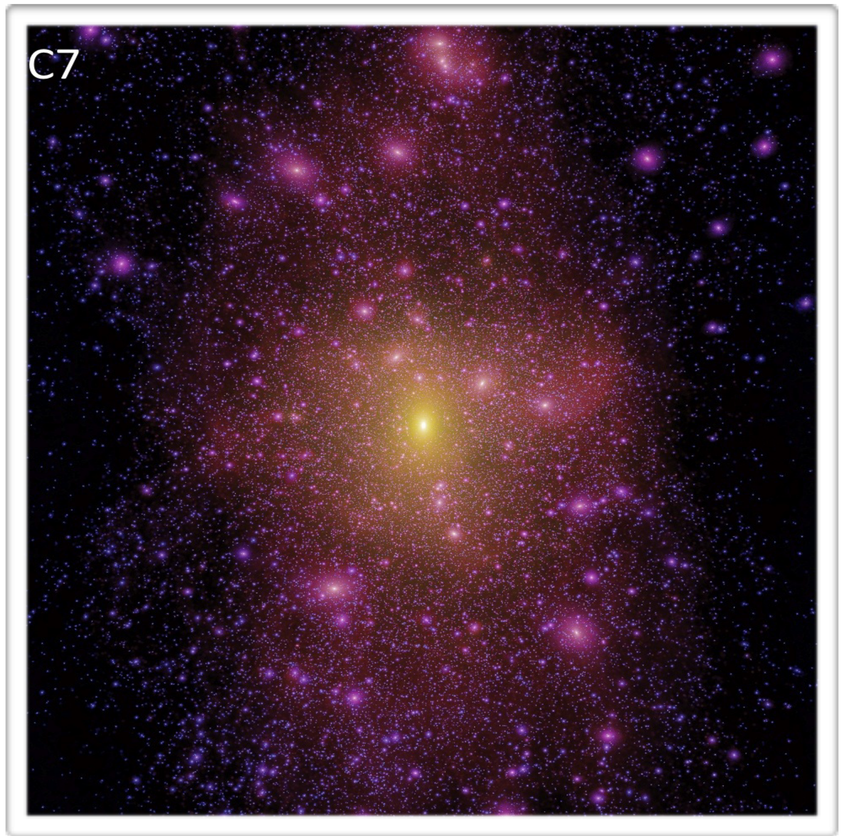
Warm Dark Matter / e.g. sterile neutrinos

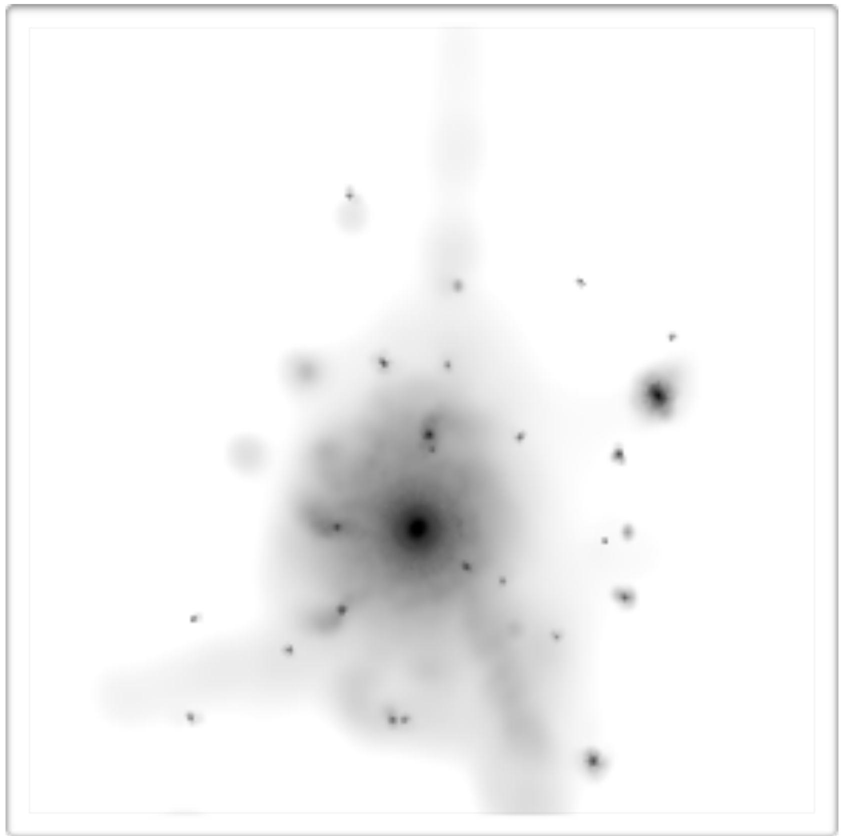


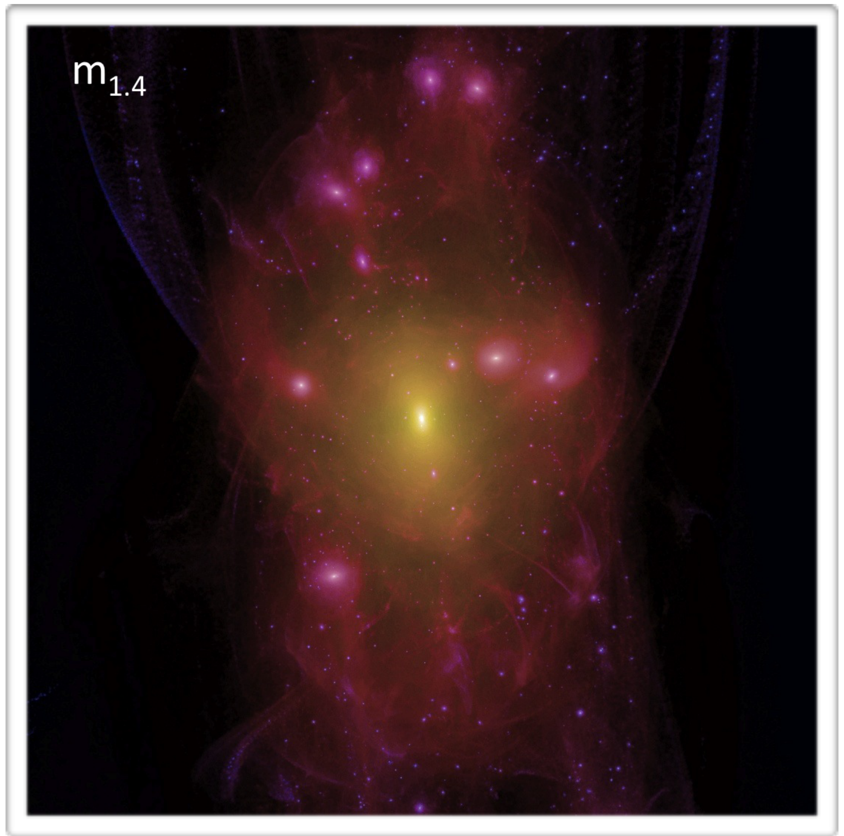
The total number of substructure strongly depends on the nature of dark matter

Springel+ 2008; Lovell+ 2012

SUBSTRUCTURE IN THE MILKY WAY HALO







Cold Dark Matter

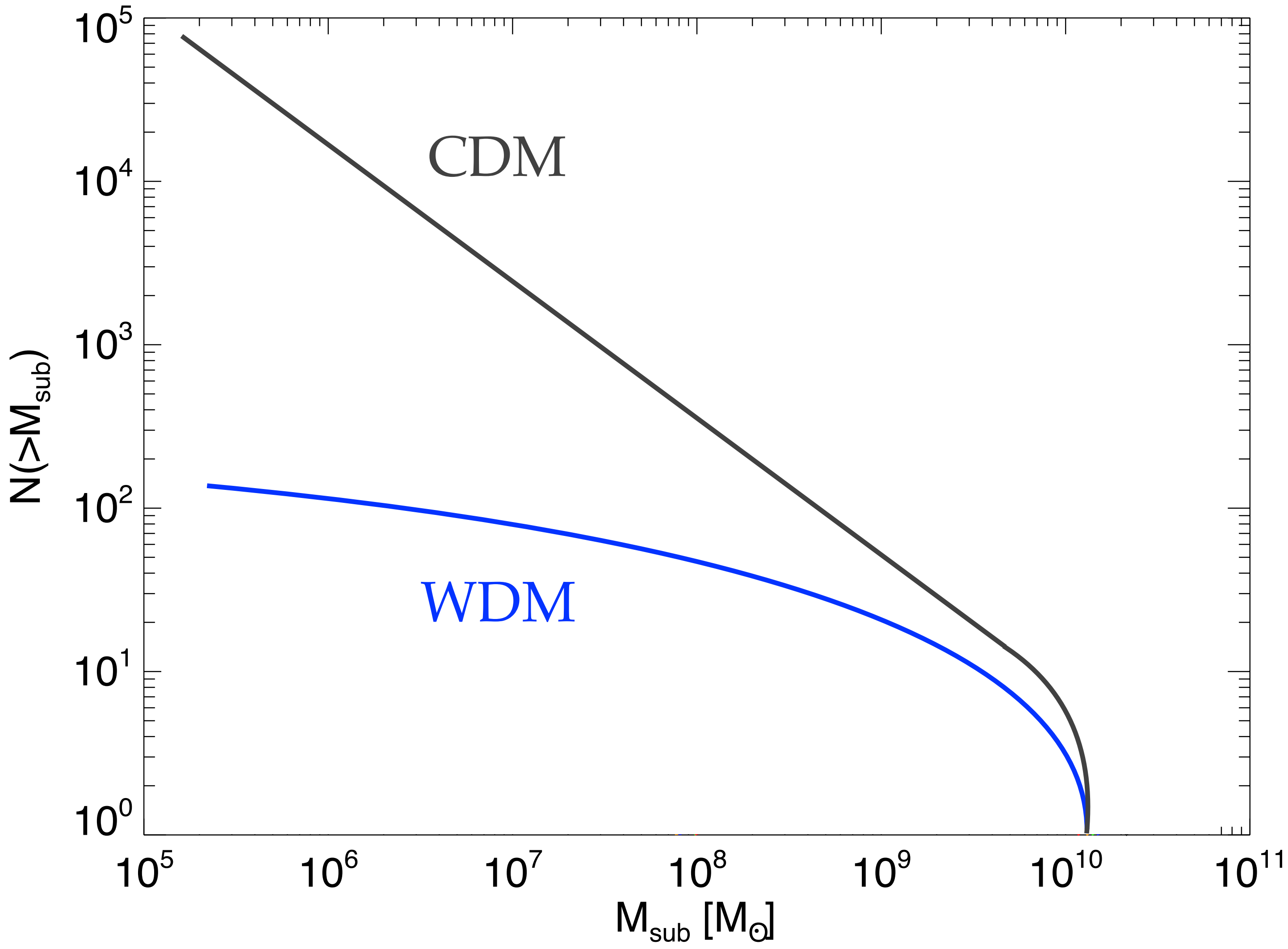
CDM - Stars

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

Predicted abundance of substructure in the Milky Way halo



$$T(k) = (1 + (\alpha k)^{2\nu})^{-5/\nu}$$

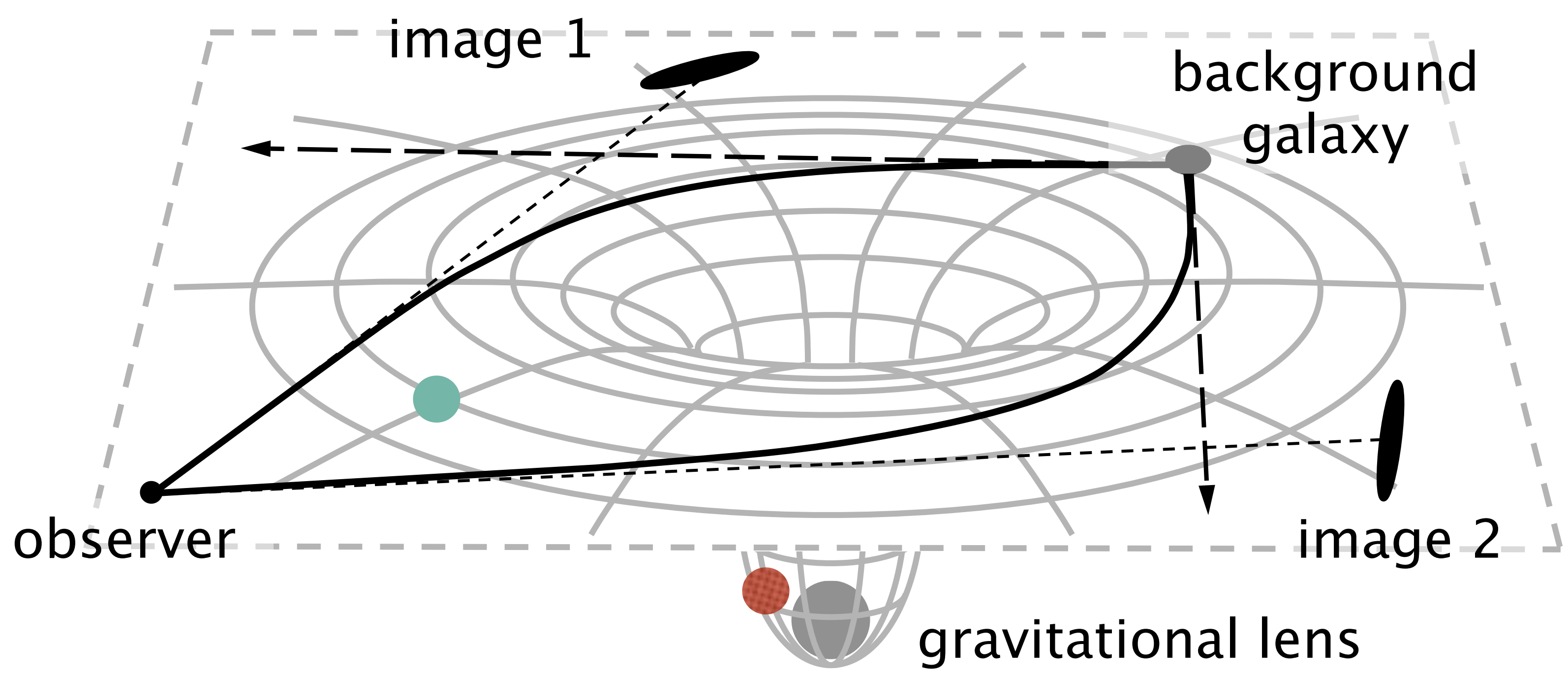
CDM

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

WDM models

$$dN/dM \propto f M^{-\alpha} \left(1 + M_c/M\right)^{\beta}$$

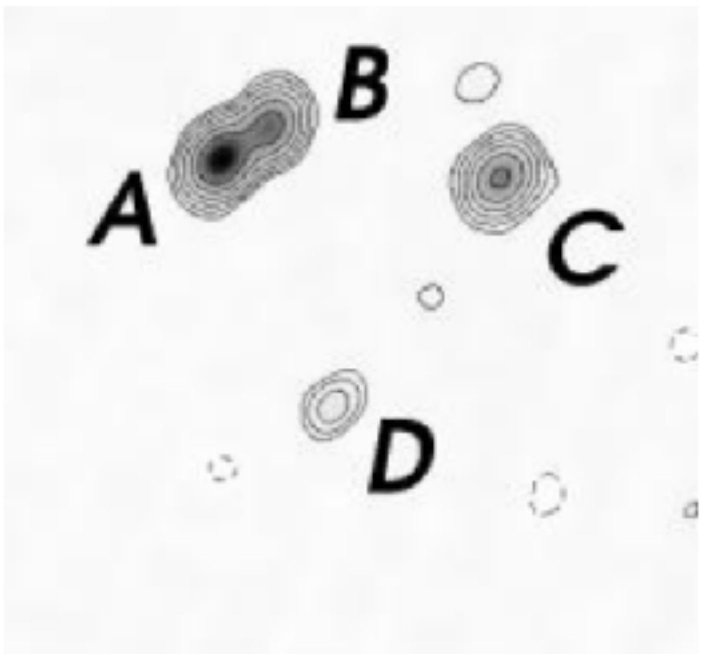
THE BASIC IDEA – STRONG LENSING



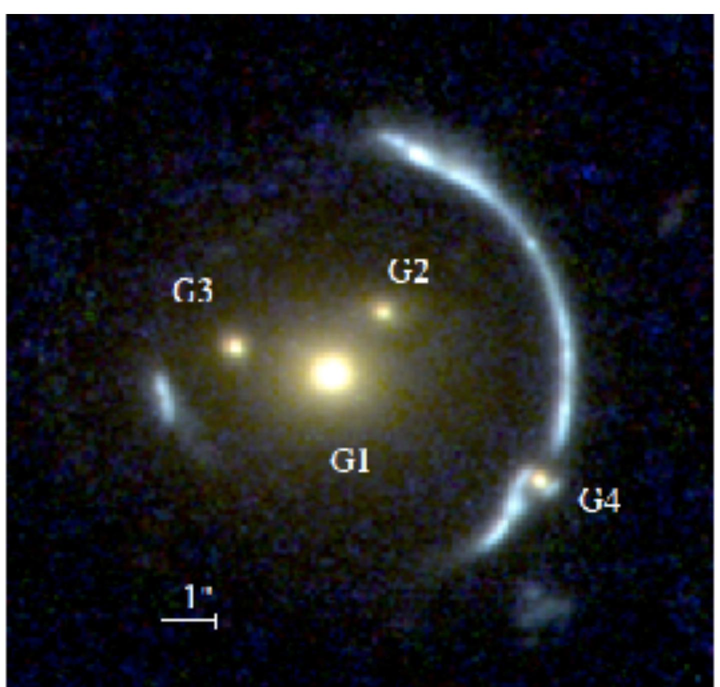
Strong lensing dark matter substructure probe	Dark matter mass function moment dependence	Dark matter substructure mass range sensitivity	Sensitivity to area around each lensed image	Sensitivity to the internal structure of substructure	Main observational challenges
Time delays	$\left(\langle m^2\rangle/\langle m\rangle\right)^2$	High mass ($<10^9$ M_{sun})	Long-range	Little	High time domain precision
Relative positions	$\left(\langle m^2\rangle/\langle m\rangle\right)^{3/2}$	Intermediate to high mass	Intermediate	Modest	High astrometric precision; lens modeling
Relative fluxes	$\left(\langle m^2\rangle/\langle m\rangle\right)$	Full mass range	Quasi-local	Sensitive	Microlensing; lens modeling

Vegetti + 2009, 2010, 2012, 2014 Dala & Kochanek 2002

THE BASIC IDEA – STRONG LENSING



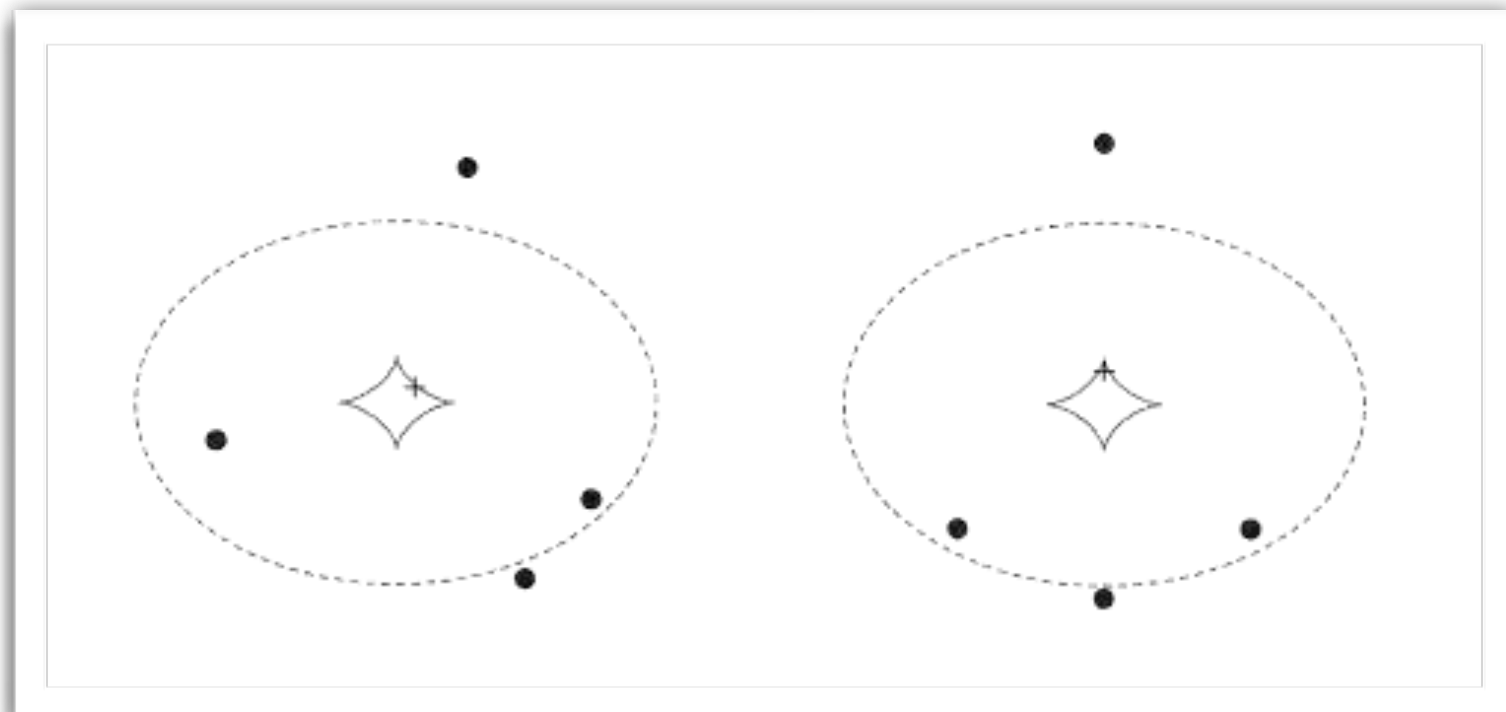
- substructures are detected as magnification anomalies
- Compact sources are easy to model
- Sensitive to a wide range of masses
- degenerate in the mass model

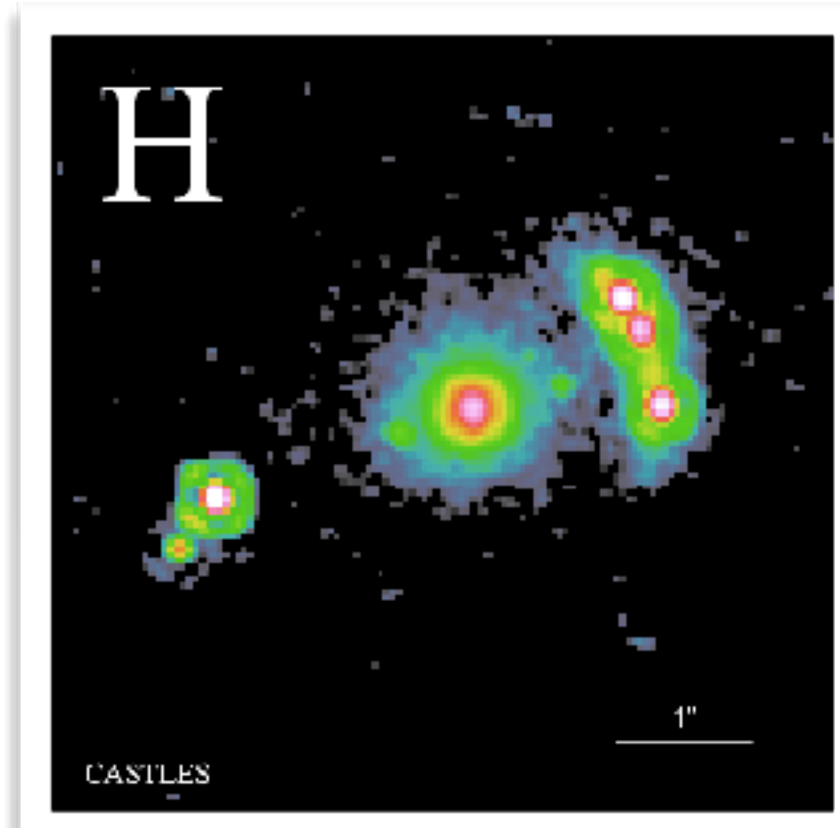


- substructures are detected as surface brightness anomalies
- need to disentangle structures in the potential from structures in the source
- Sensitive to higher masses
- NOT degenerate in the mass model

Mao & Schneider 1992 Dala & Kochanek 2002

FLUX RATIO ANOMALIES





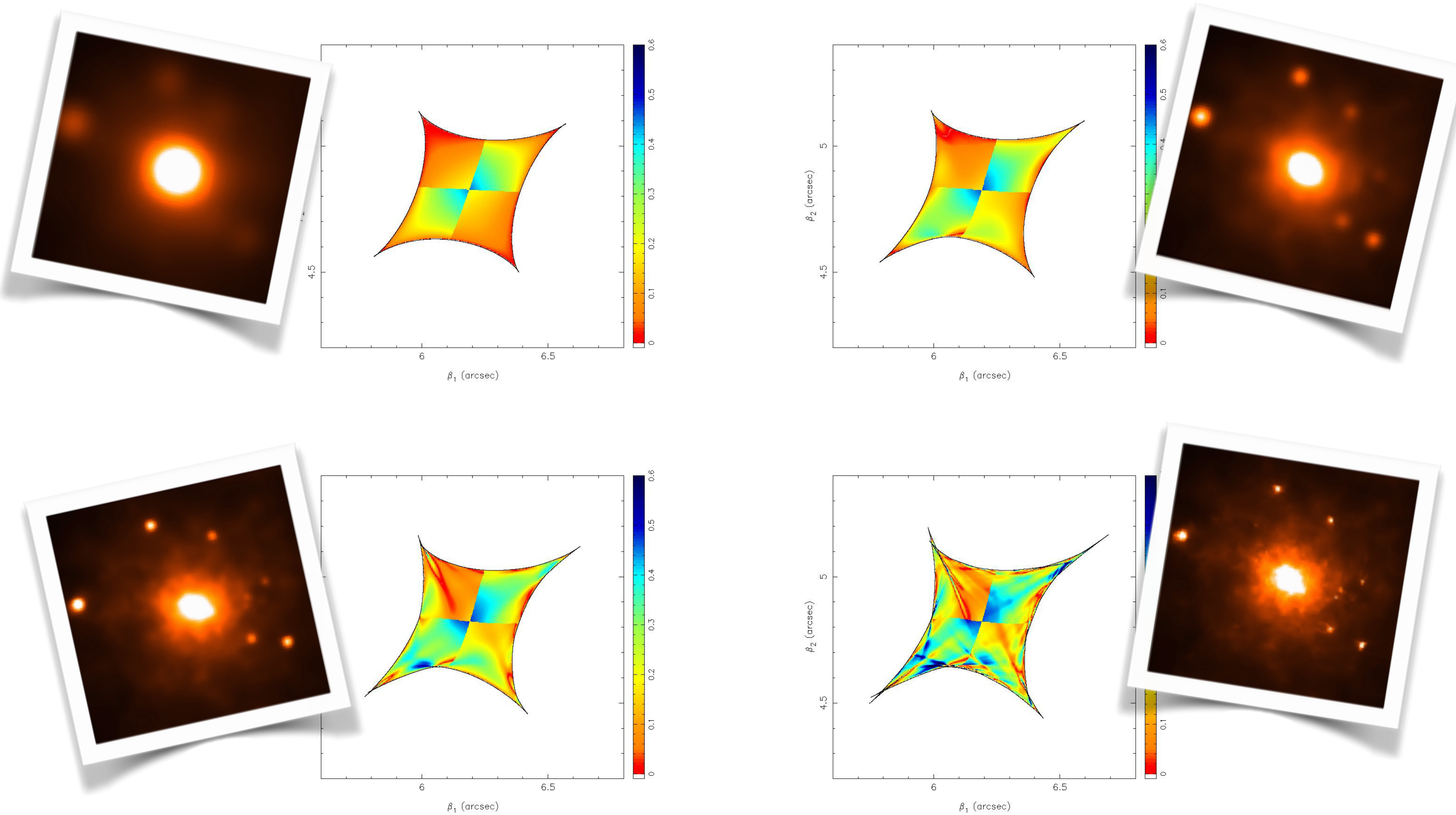
$$R_{\rm fold} = \frac{\mu_A + \mu_B}{|\mu_A| + |\mu_B|} \to 0$$

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

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

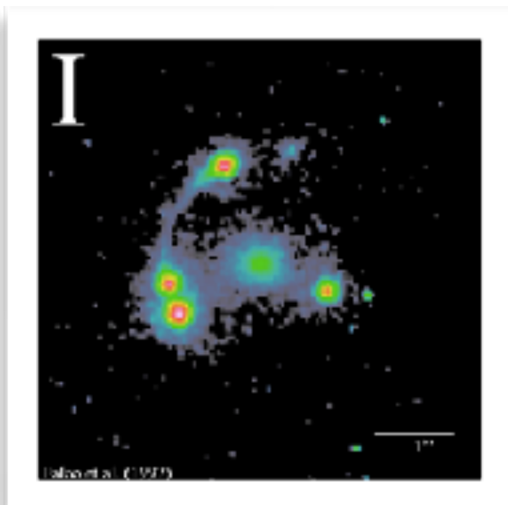
Bradac + 2002

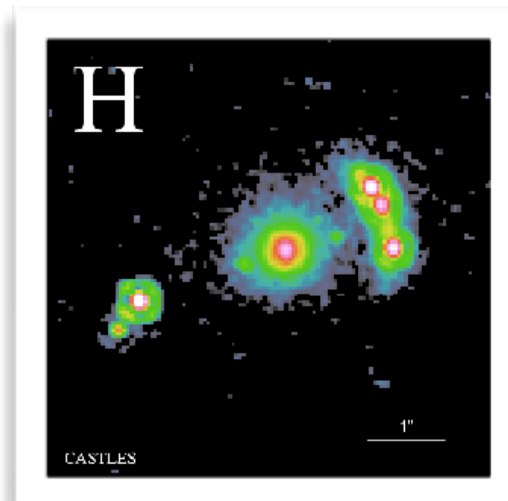
FLUX RATIO ANOMALIES

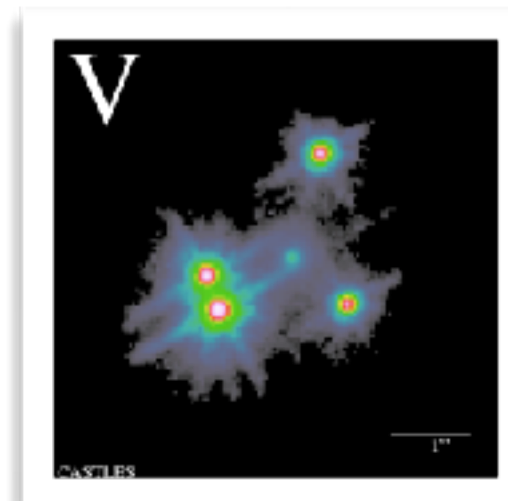


Dala & Kochanek 2002

FLUX RATIO ANOMALIES



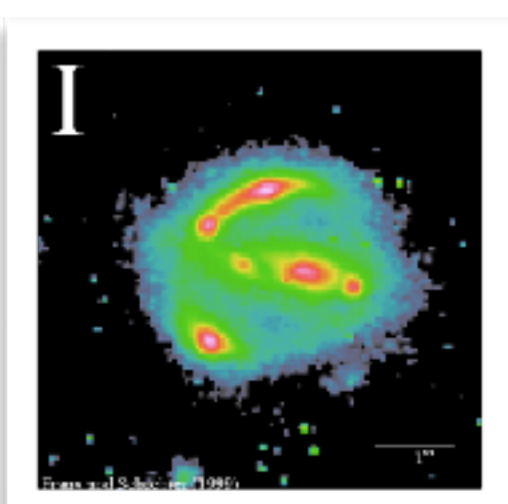


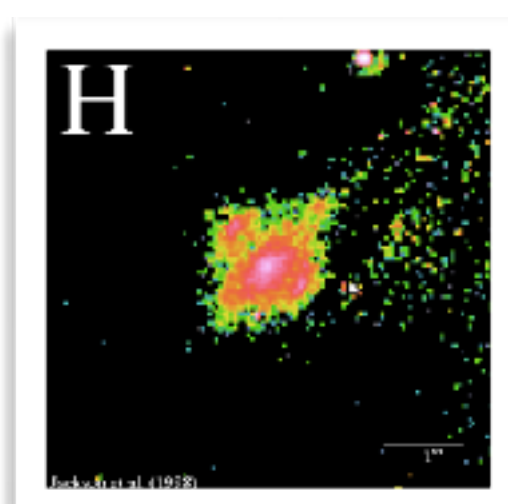


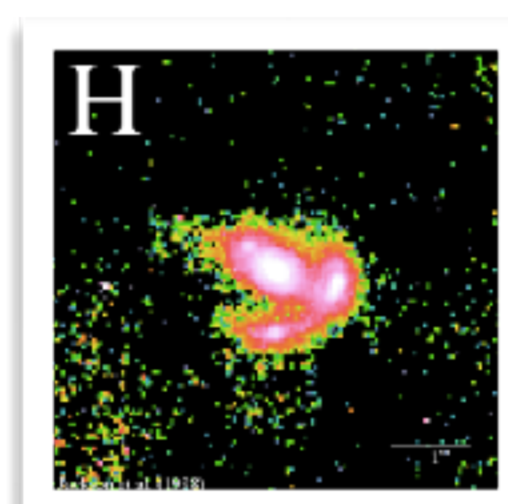
6/7 radio loud CLASS lenses show a flux ratio anomaly

No microlensing, or dust extinction but gravitational origin

Imply a projected dark matter fraction between 2 and 7 percent > CDM

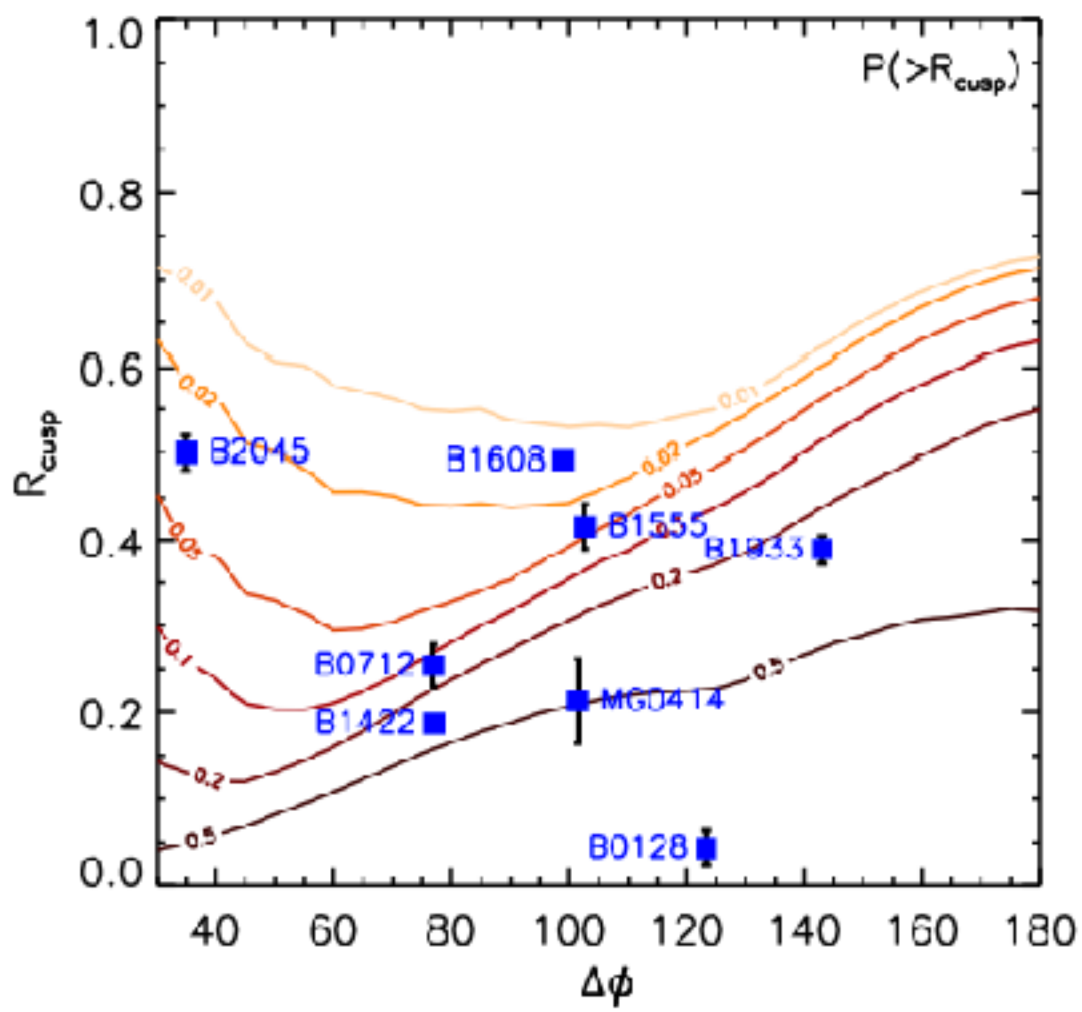






Xu + 2014

FLUX-RATIO ANOMALIES



From CDM-only simulations:

A couple of systems can be reproduced by adding CDM subhaloes to its macroscopic lens potential, with a probability of 5% – 20%

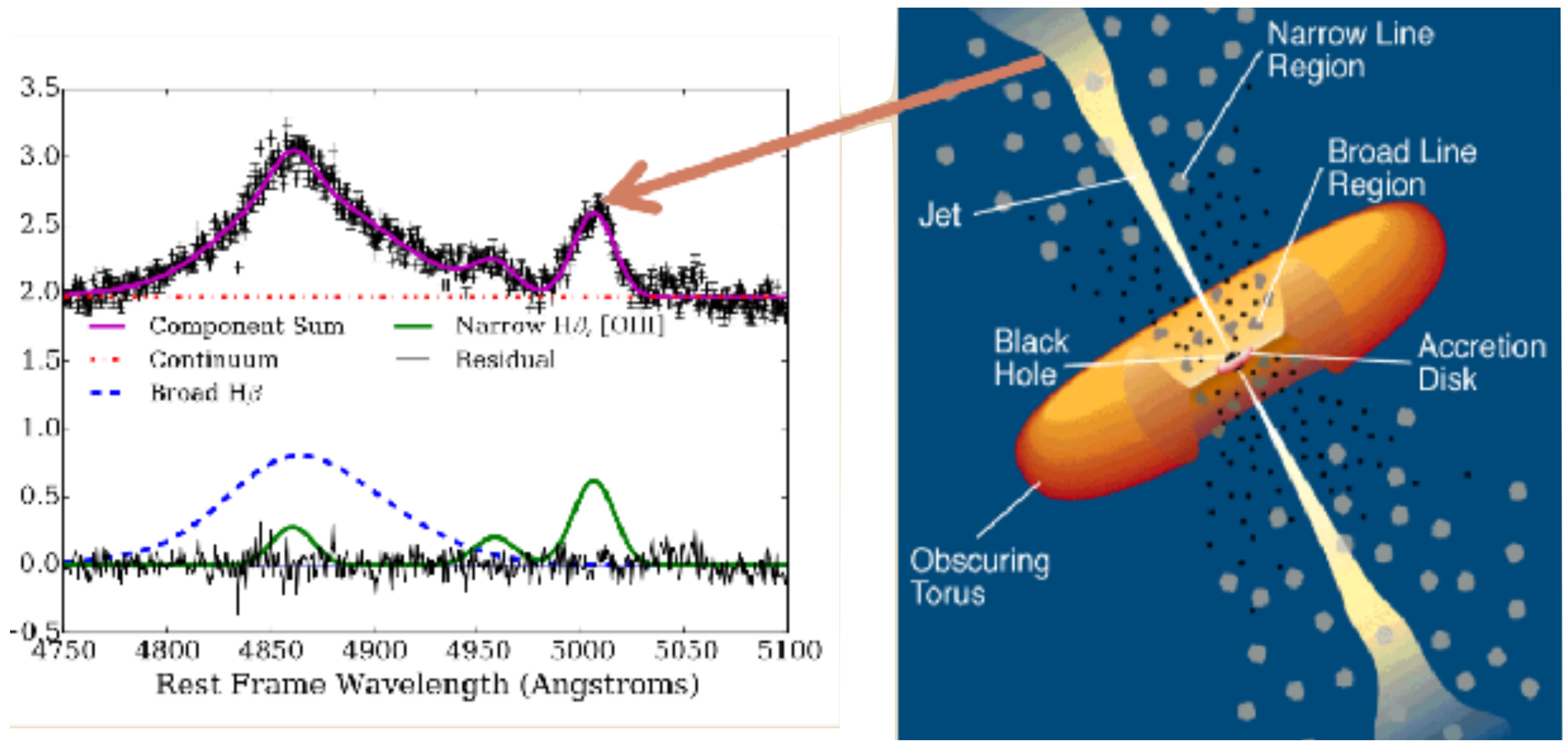
For B0712+472, B1422+231, B1555+375 and B2045+265, these probabilities are only of a few percent: are more likely to be caused by improper lens modelling

McKean et al. 2007: B2045+265 due to a massive companion

Hsueh et al. 2016a,b: B1555+375 and B0712+482 anomalies caused by stellar disc

Gilman et al. 2017, Hsueh et al. 2017: stellar structures can be responsible for errors on the FRA of 20%

FLUX-RATIO ANOMALIES - NARROW LINE LENSING



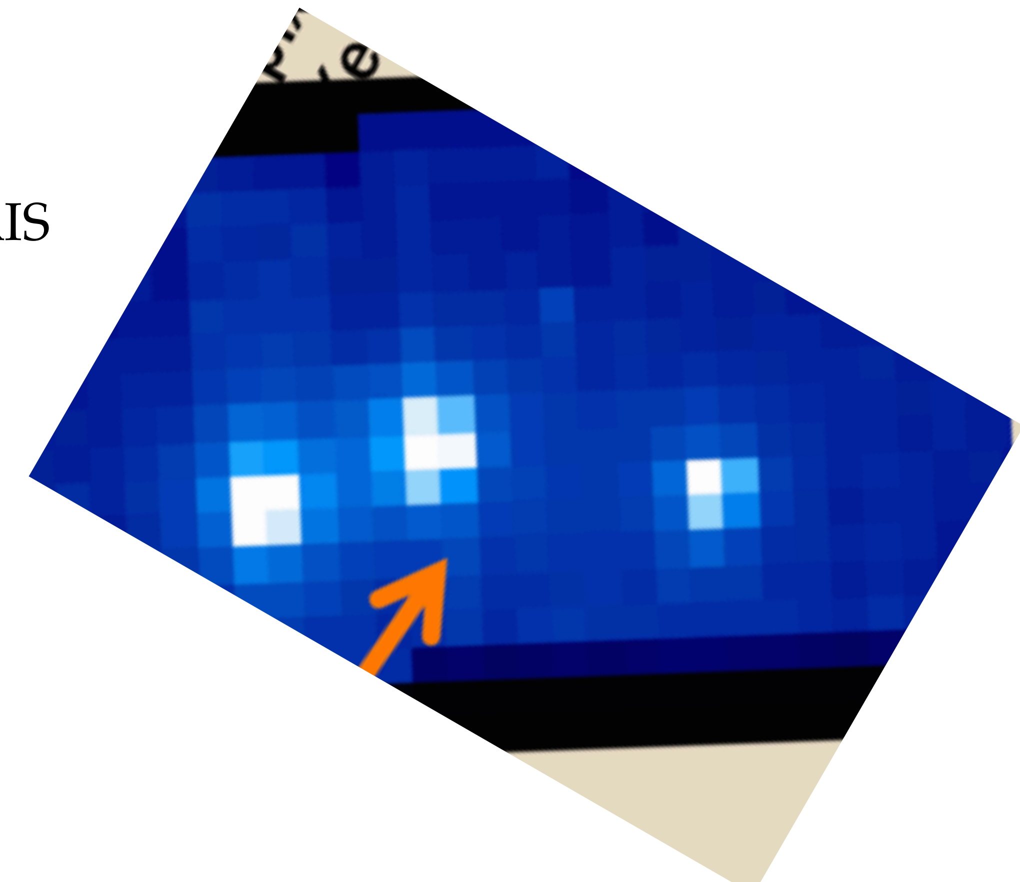
All QSOs show significant narrow line emission - can double the number of systems available

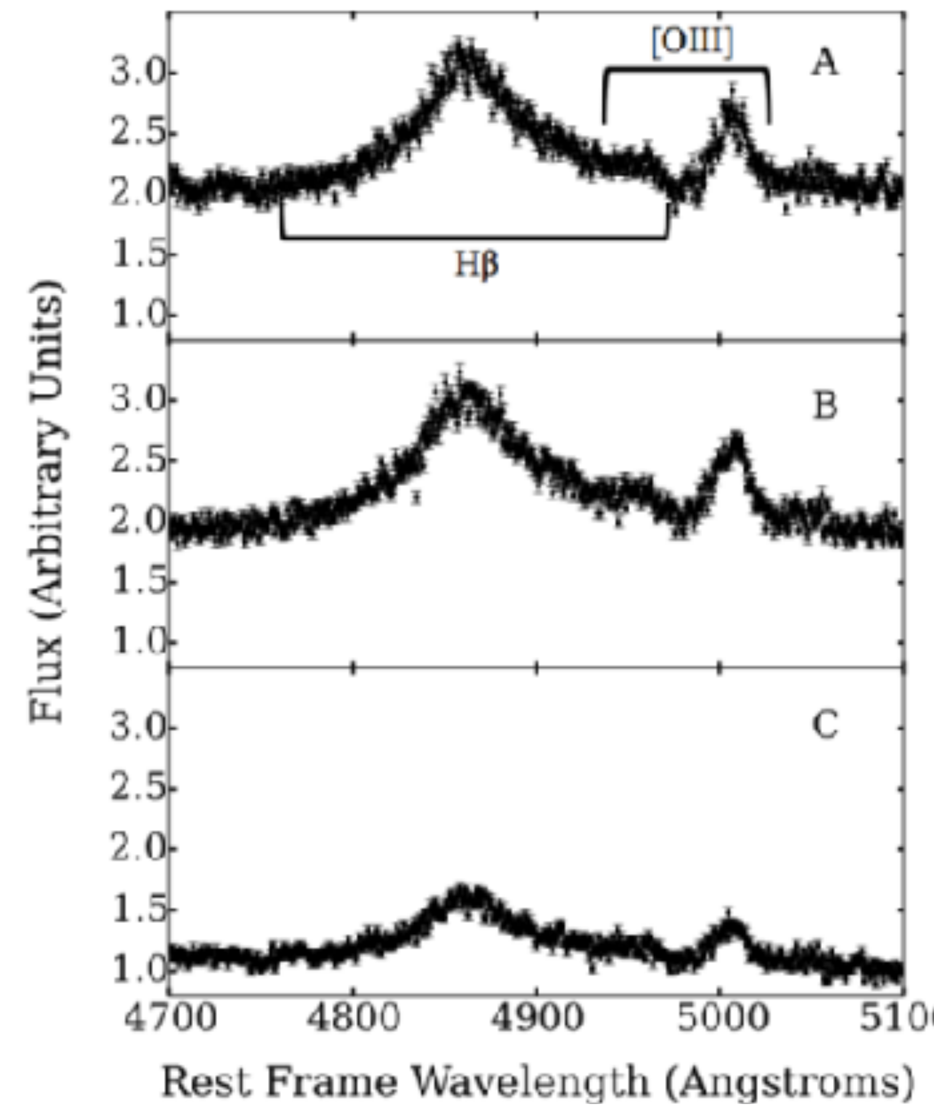
The sources are large enough to avoid micro-lensing and are not variable

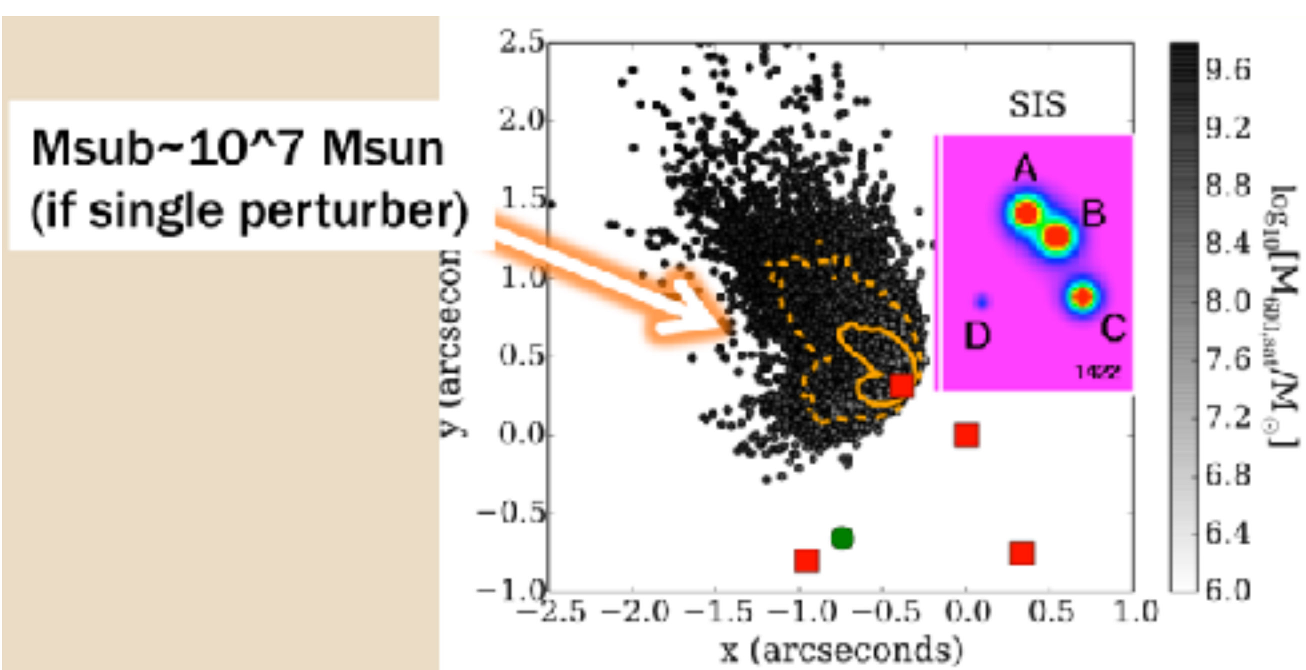
Needs high resolution spatially resolved spectroscopy

FLUX-RATIO ANOMALIES - NARROW LINE LENSING

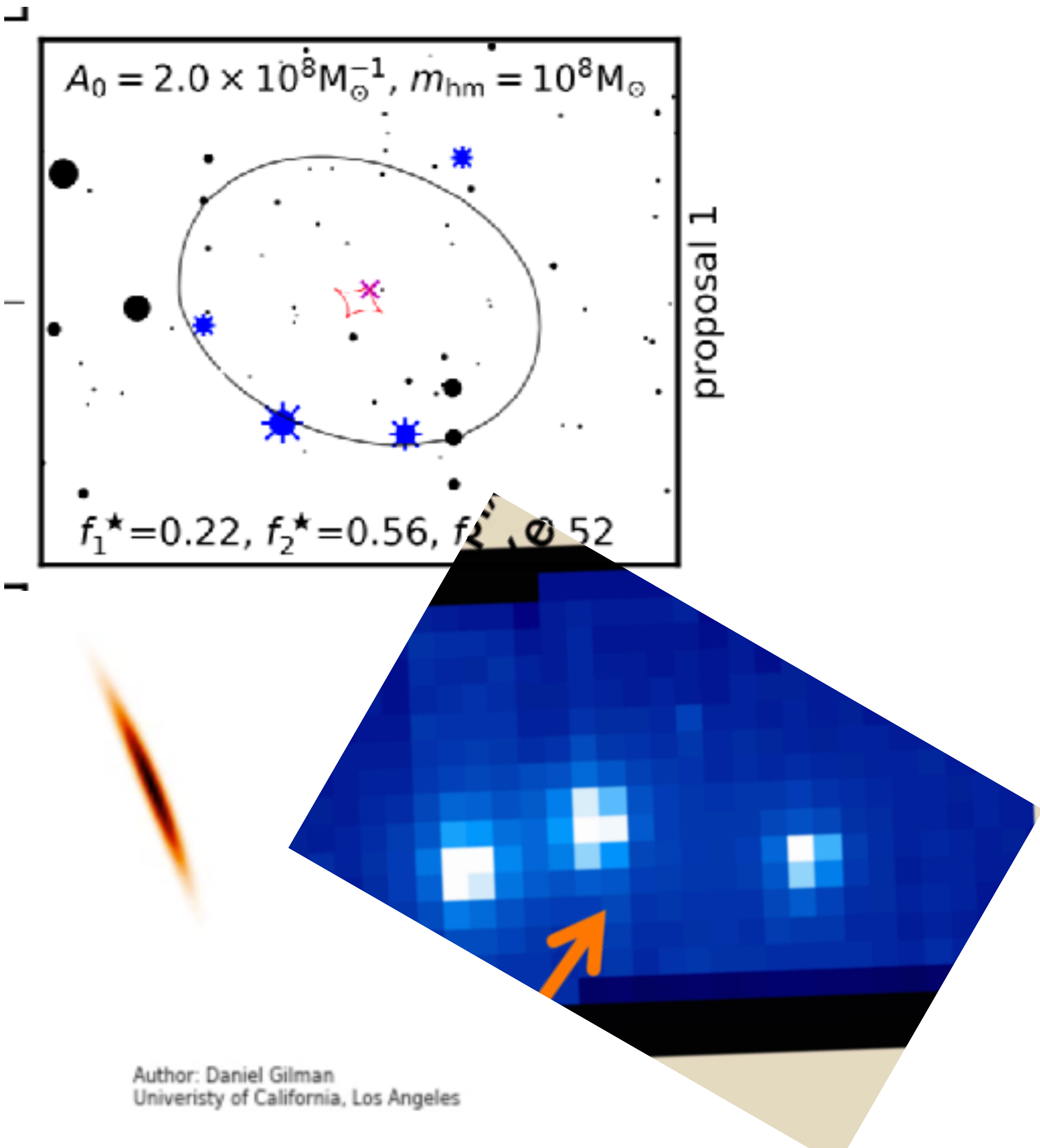
KECK-OSIRIS



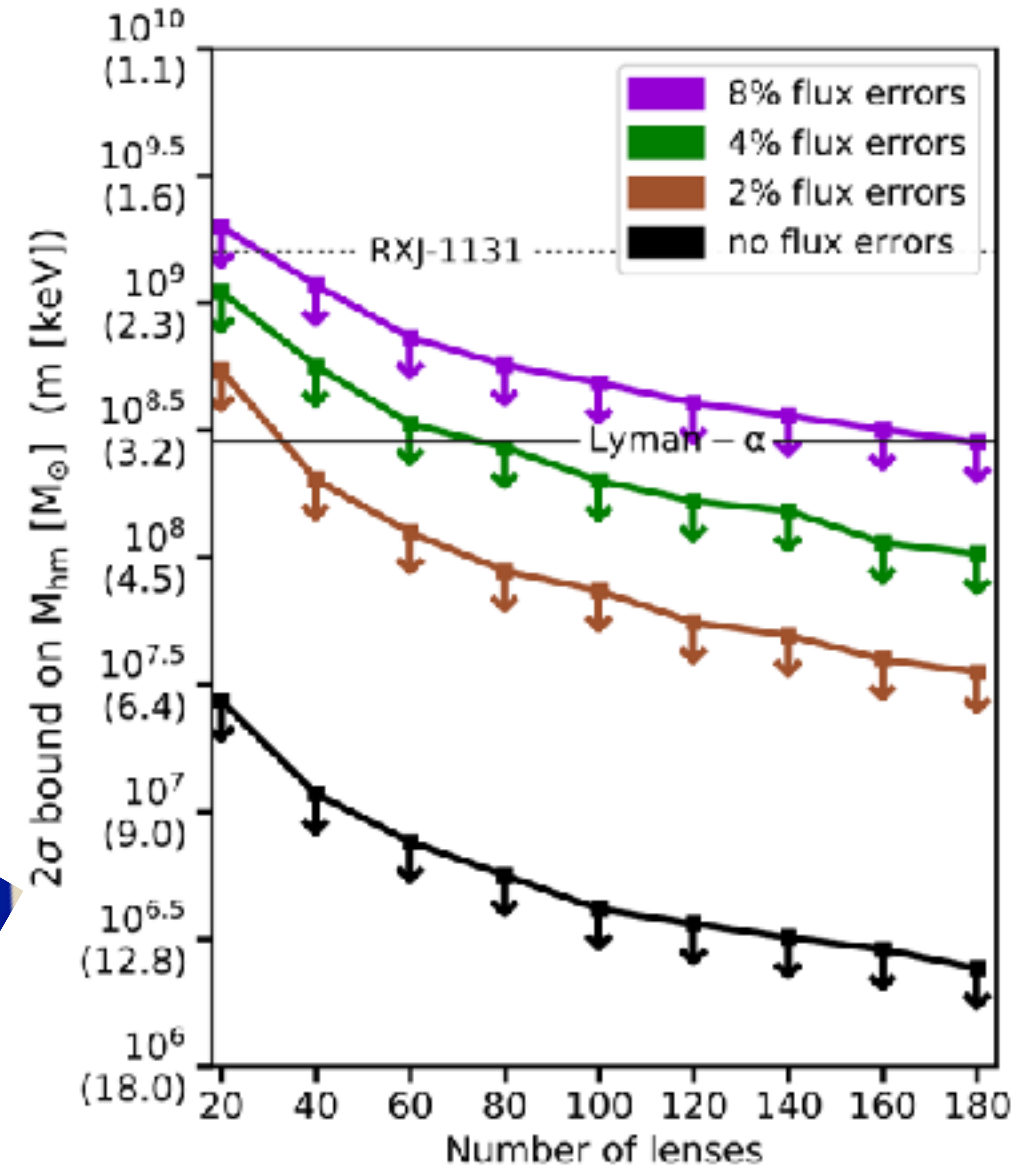




FLUX-RATIO ANOMALIES



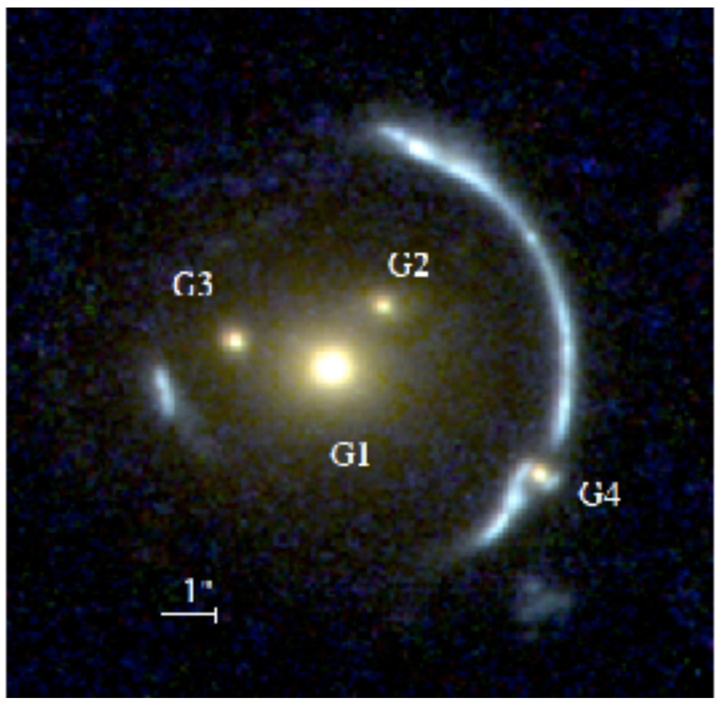
Gilman et al. 2018



With 180 quads: expected 2σ bounds of mhm < $10^{6.4} M_\odot$, $10^{7.5} M_\odot$, $10^8 M_\odot$, and $10^{8.4} M_\odot$

ASTROMETRIC (SURFACE BRIGHTNESS) ANOMALIES

Vegetti et al. 2010a

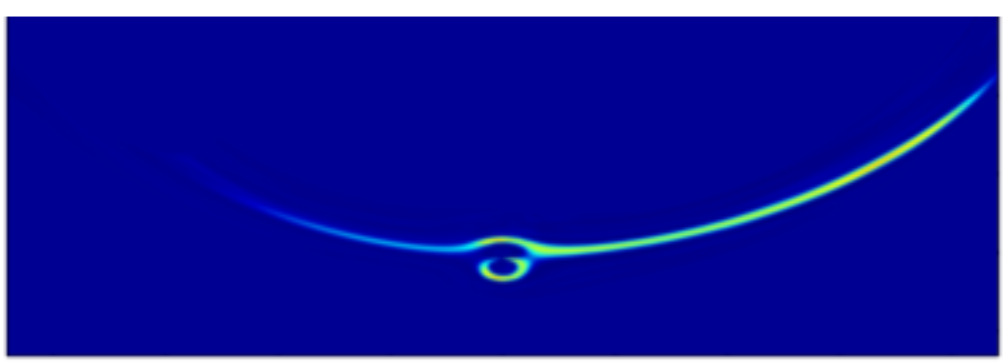


Haloes are detected as surface brightness anomalies

Need to disentangle structures in the potential from structures in the source

Sensitive to higher masses

Less degenerate in the mass model



Detections of individual haloes:

Pixel based: gravitational imaging - Vegetti & Koopmans 2009

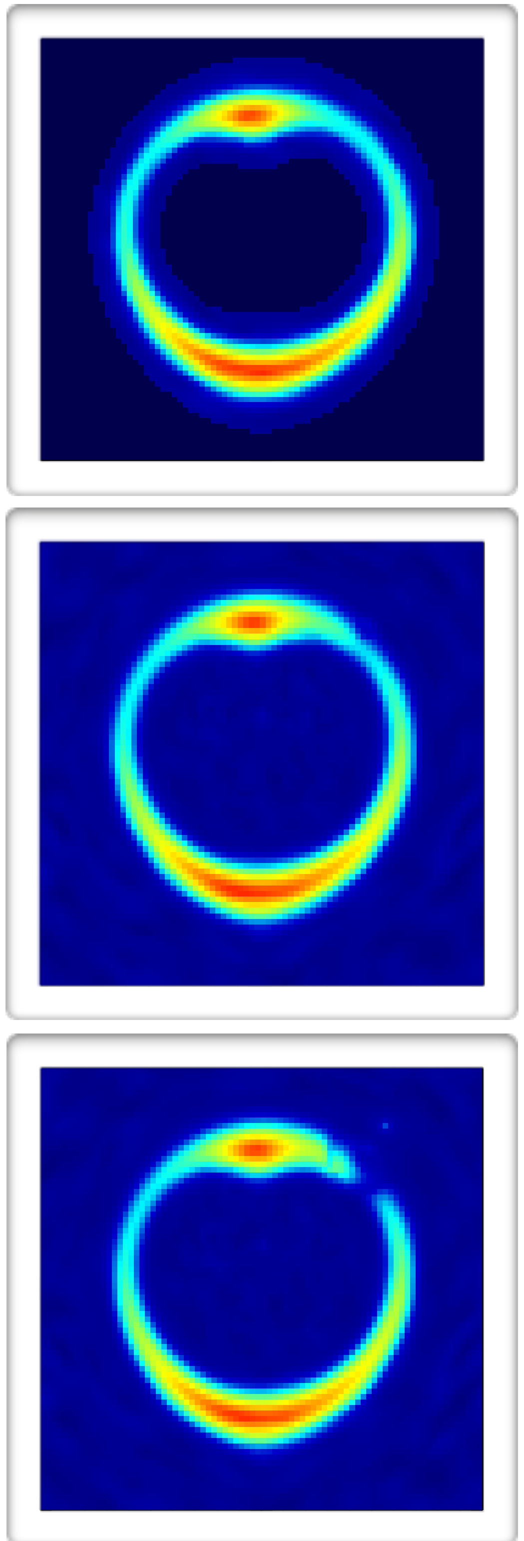
Parametric: e.g. Hezaveh et al. 2016

Statistical detections at the population level:

Parametric forward modelling: e.g. Birrer et al. 2017, Enzi & Vegetti in prep.

Power-spectrum: e.g Chatterjee & Koopmans 2017

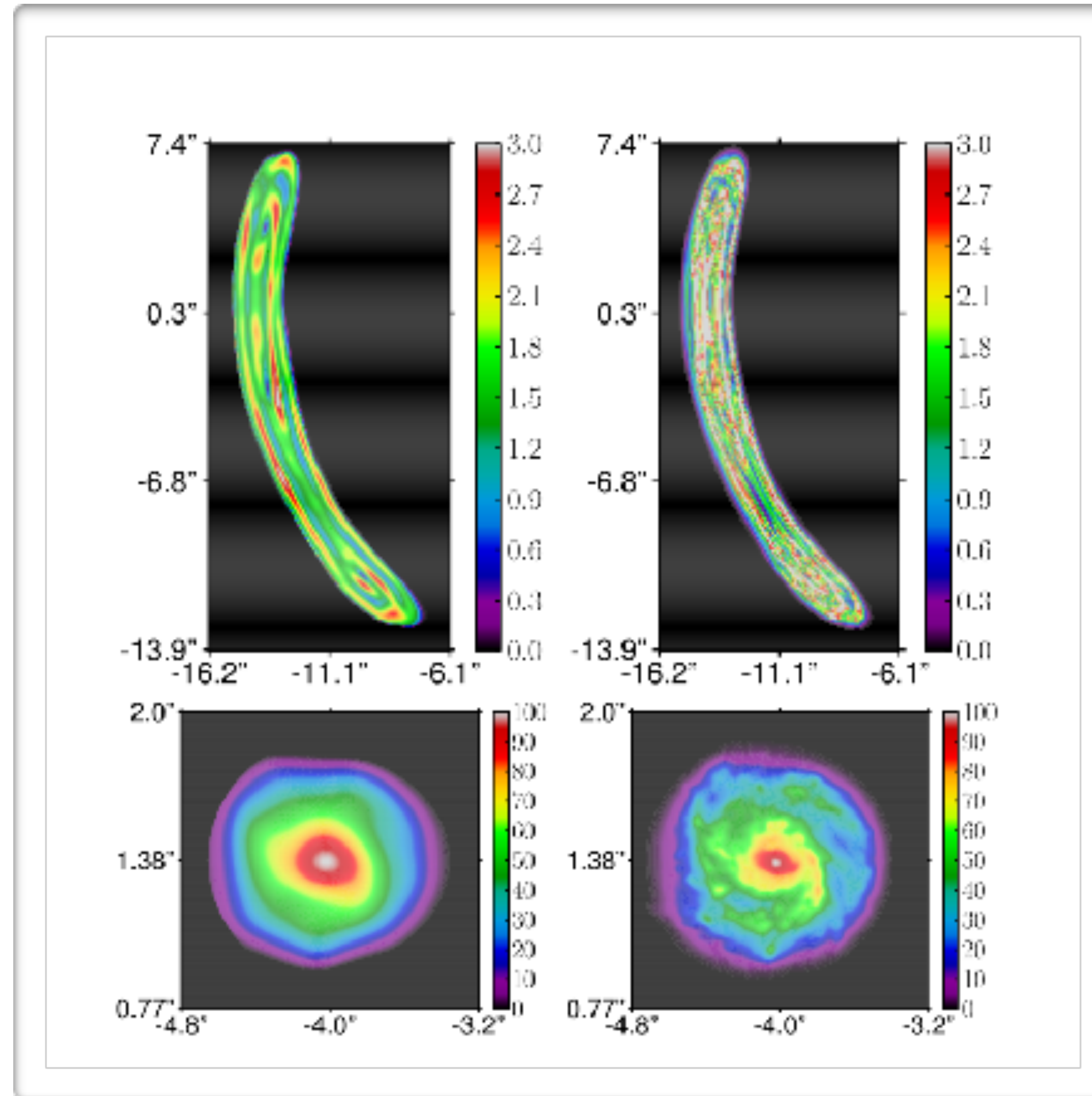
SENSITIVITY



Increasing mass

Vegetti & Koopmans 2009

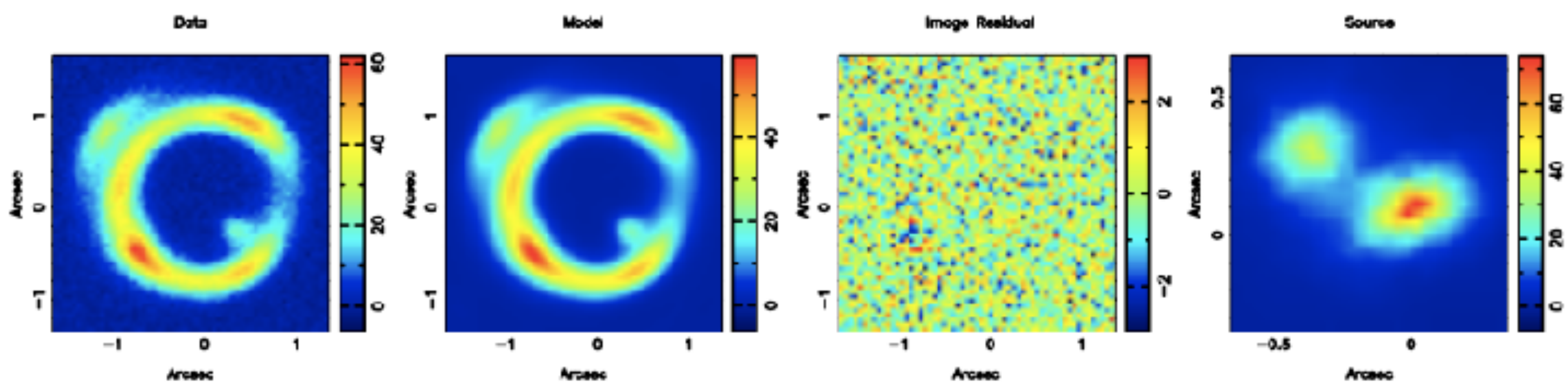
Rau et al. 2014



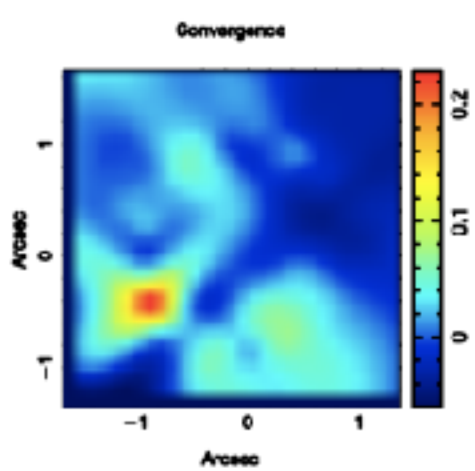
Increasing level of source complexity

GRAVITATIONAL IMAGING

Data Model Residuals Source



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



Density corrections

Haloes are detected as corrections to an overall smooth potential

If present, more than one halo can be detected and quantified

GRAVITATIONAL IMAGING – DETECTION CRITERIA

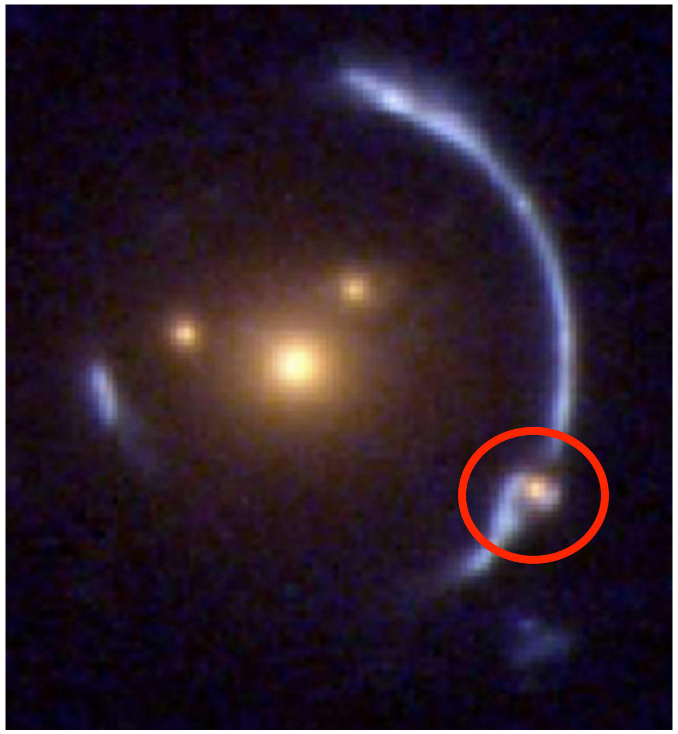
- a positive convergence correction that improves the image residuals is found independently from the potential regularization, number of source pixels, PSF rotations, and galaxy subtraction procedure;

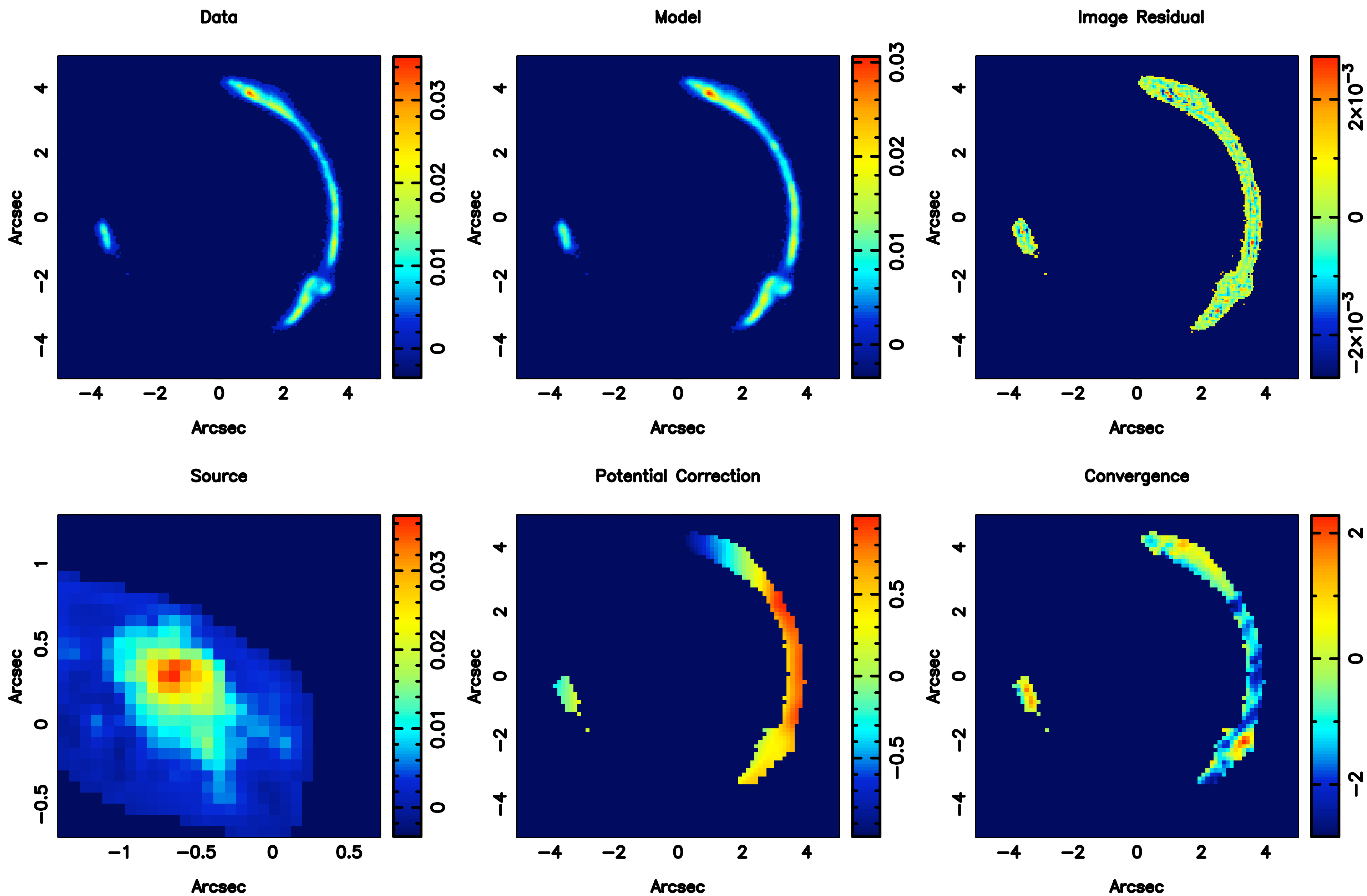
- the mass and the position of the substructure obtained via the posterior exploration is consistent with those independently obtained by the potential corrections and the MAP parametric clumpy model;

- a clumpy model is preferred over a smooth model with a Bayes factor $\Delta \log E = \log E_{smooth} - \log E_{clumpy} \geq -50$ (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.

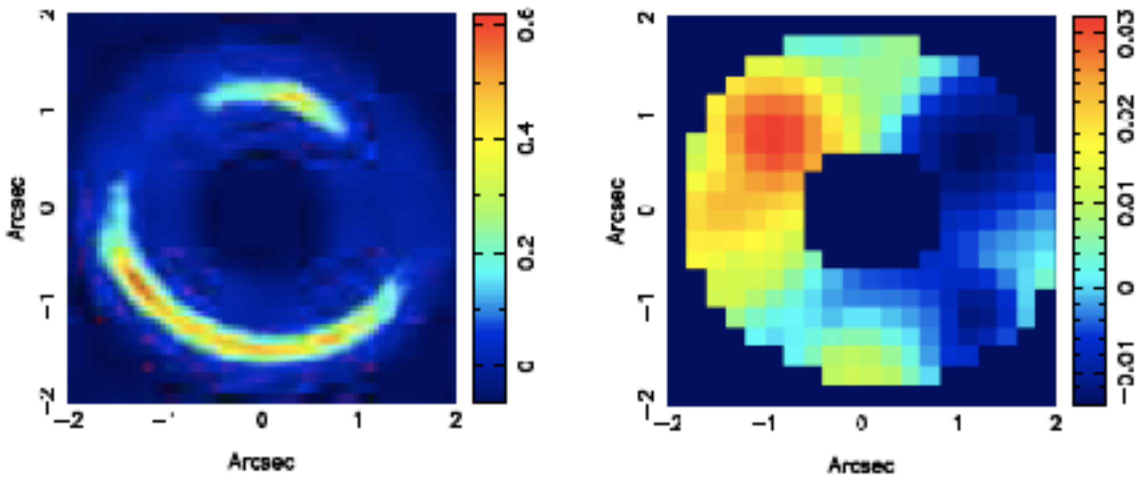
BASIC TEST





Vegetti et al. 2010a

DETECTIONS SO FAR



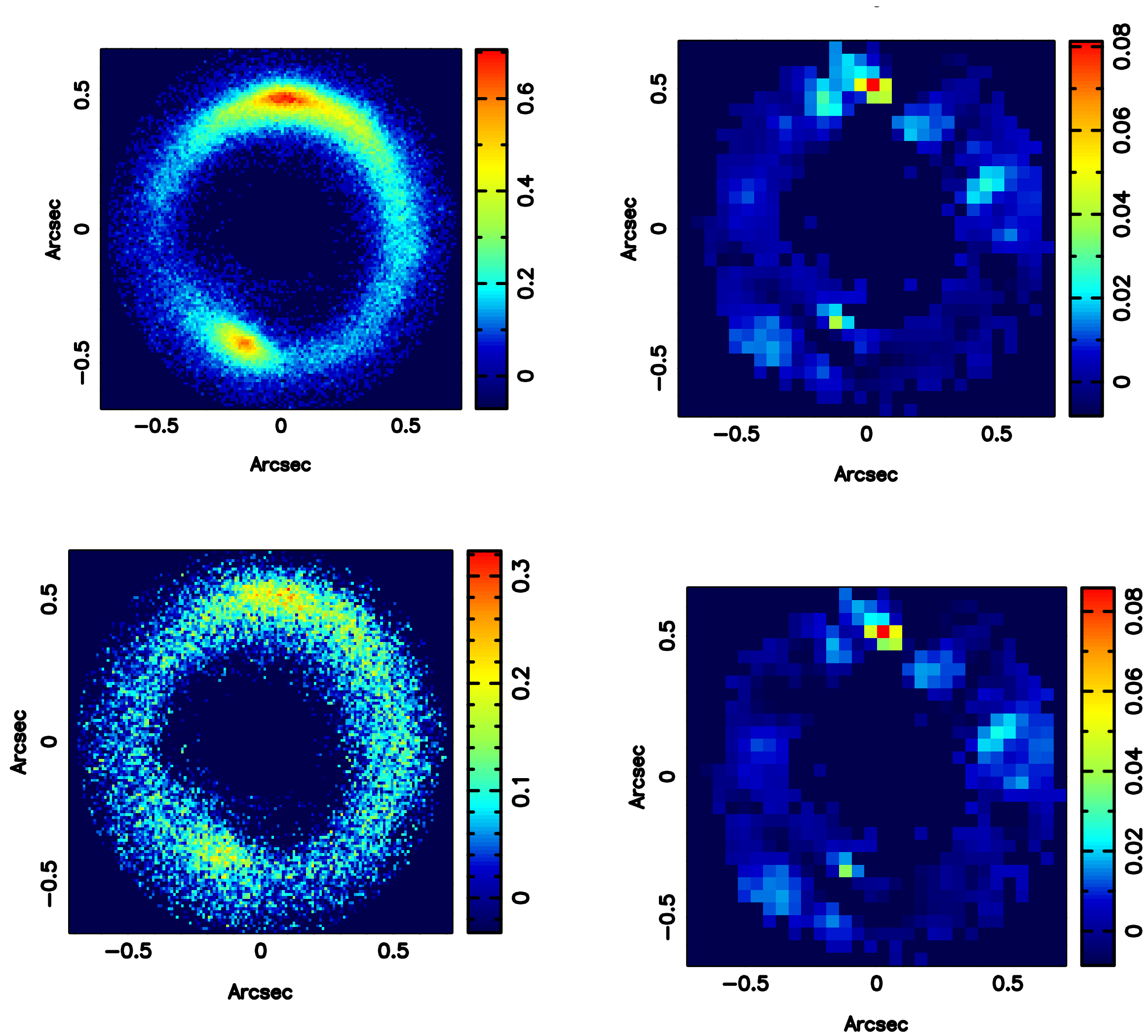
Vegetti et al. 2010 HST 16-sigma detection

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

$$M^{\rm NFW} \sim 3.51 \times 10^{10} M_\odot$$

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

z~0.2



Vegetti et al. 2012 Keck AO 12-sigma detection

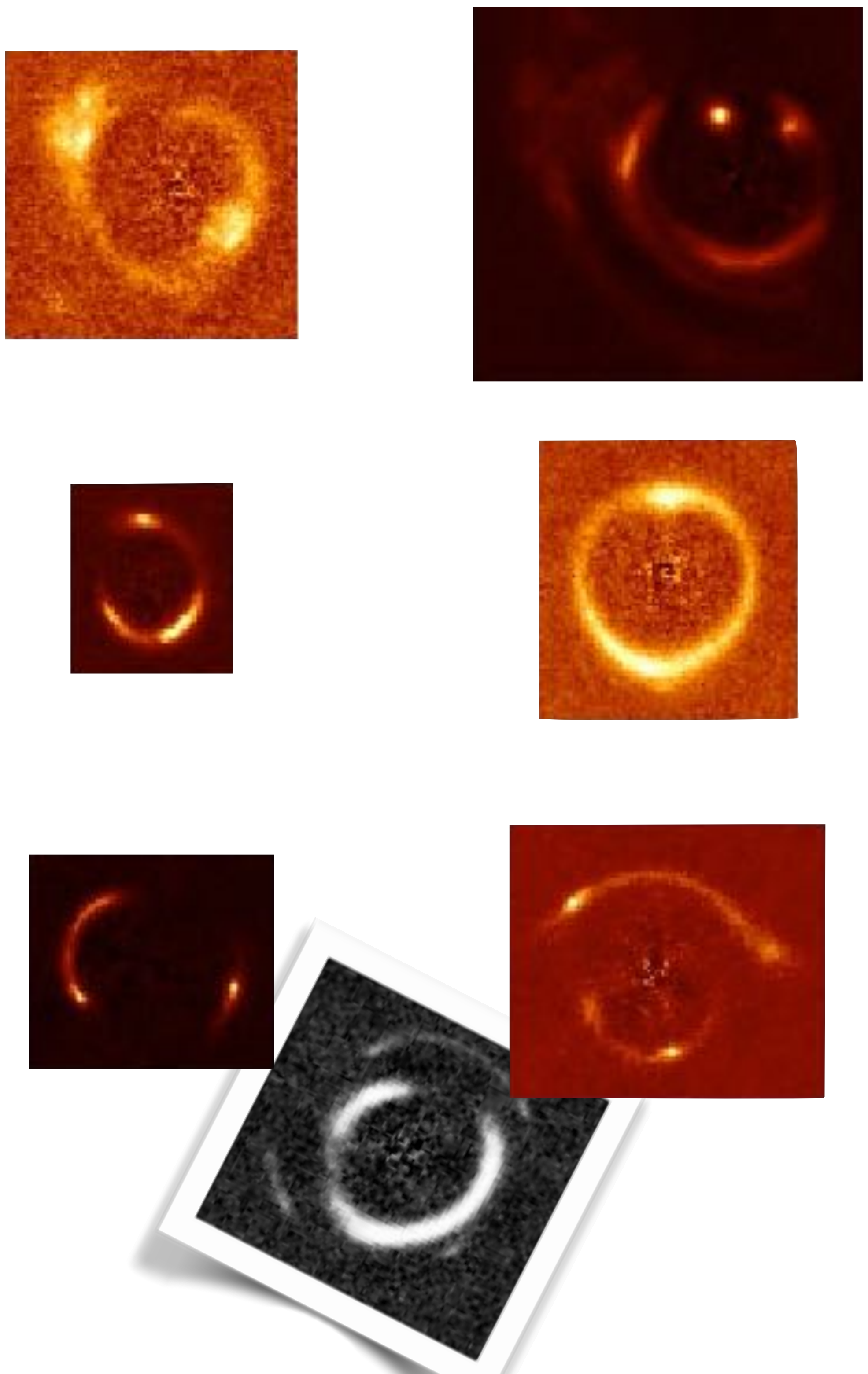
$$M^{PJ} = (1.9 \pm 0.1) \times 10^8 M_\odot$$

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

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

z~0.9

SUBSTRUCTURE CONSTRAINTS

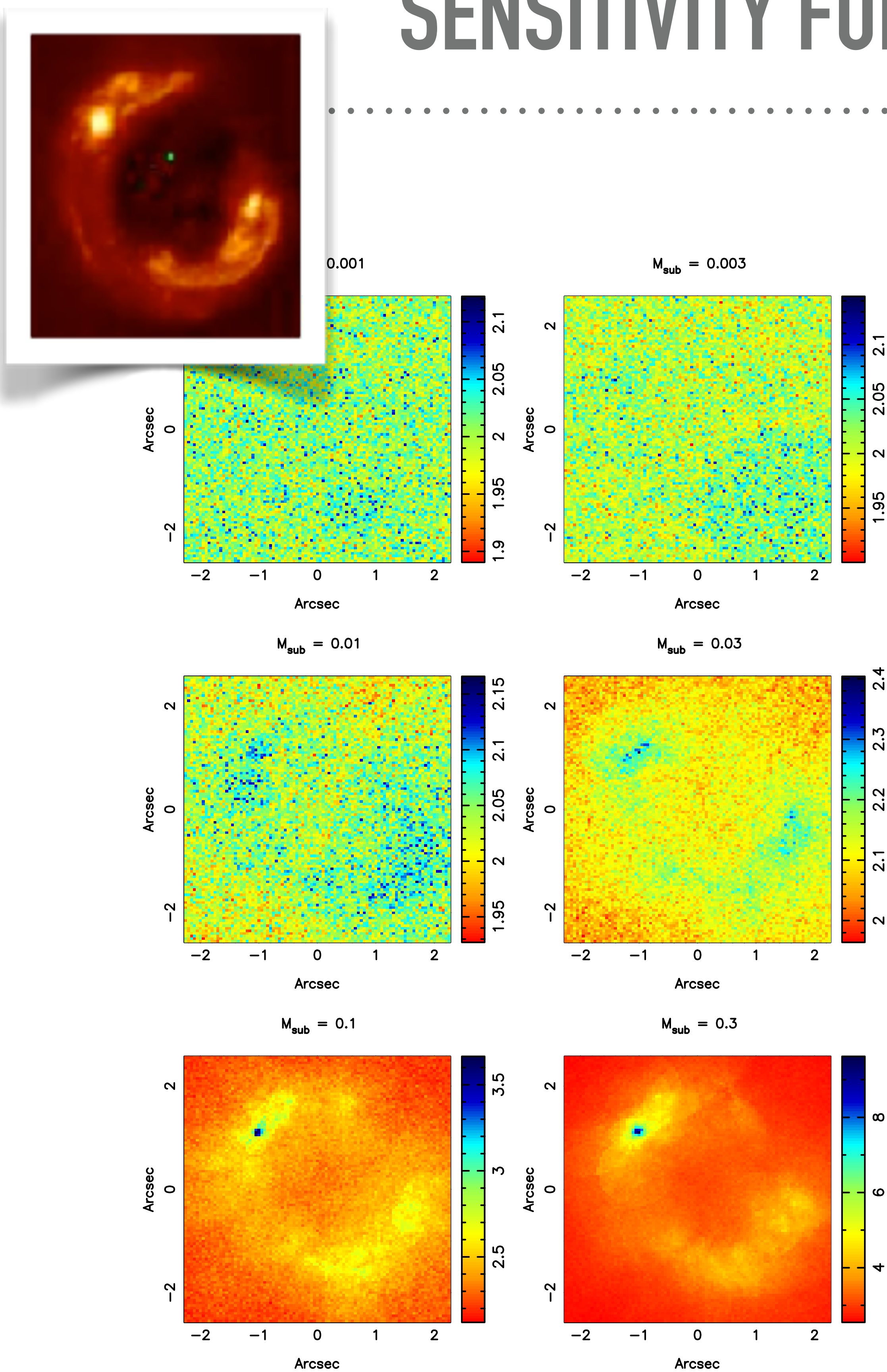


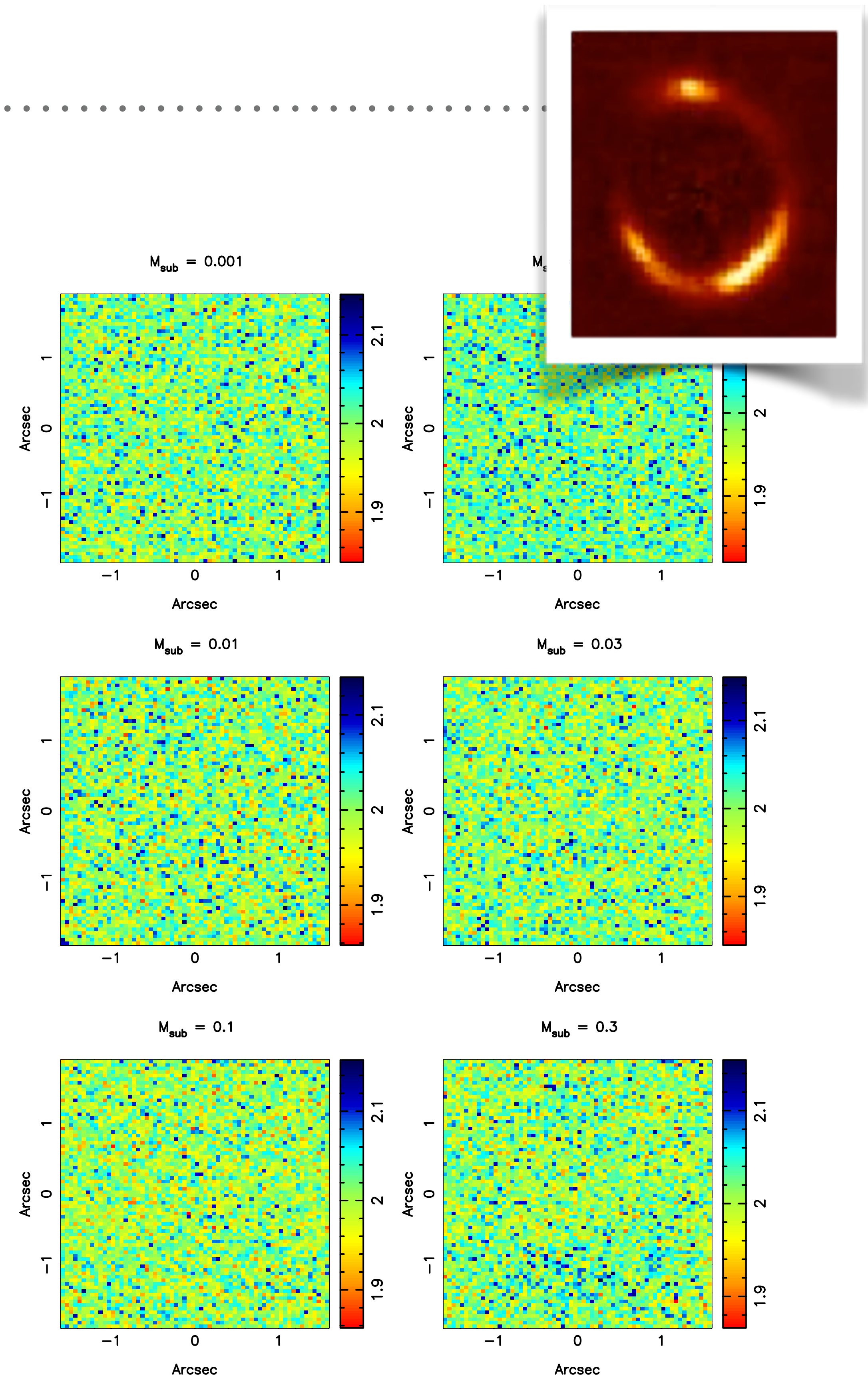
Chosen on a s/n basis

Representative sub-sample of the SLACS lenses

Representative sample of massive early-type galaxies

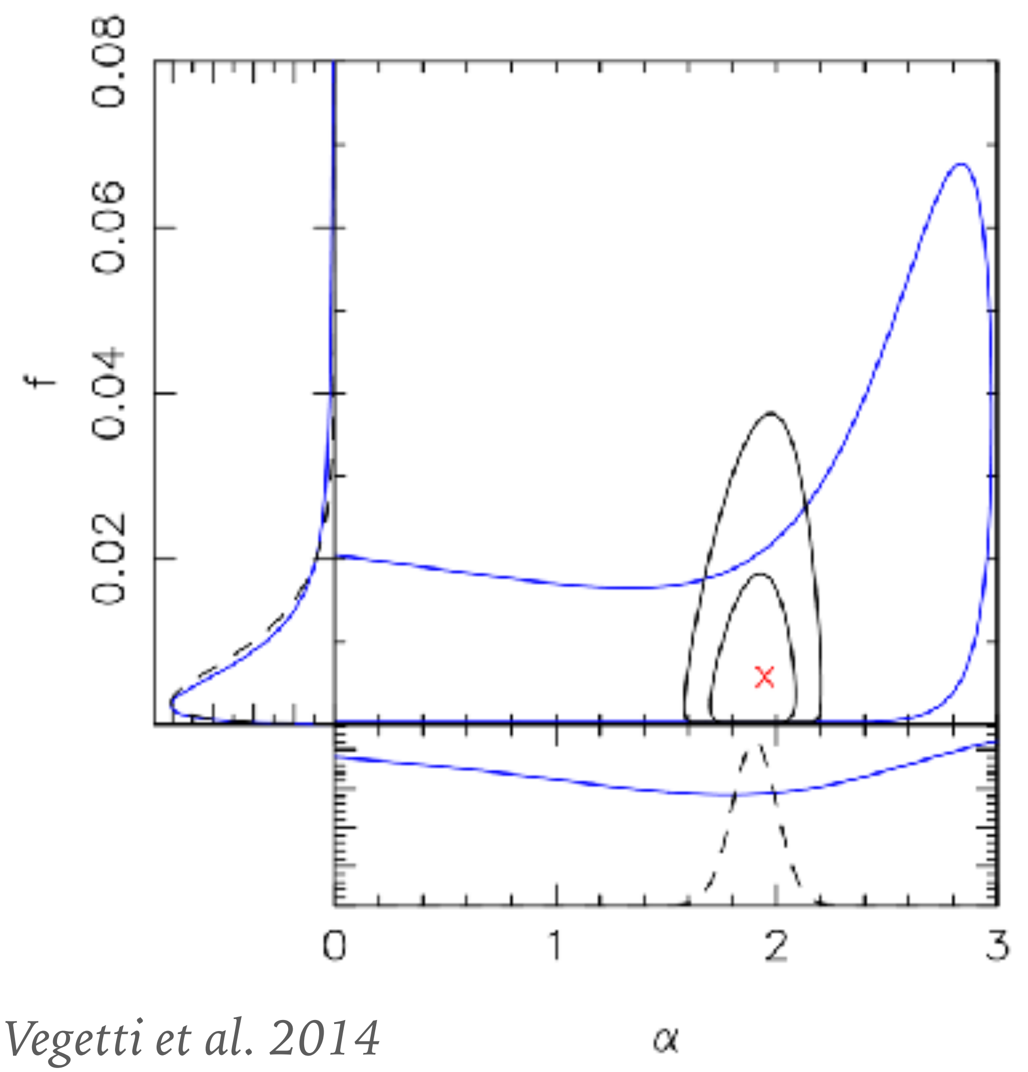
SENSITIVITY FUNCTION





SUBSTRUCTURE CONSTRAINTS

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



Vegetti et al. 2014

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

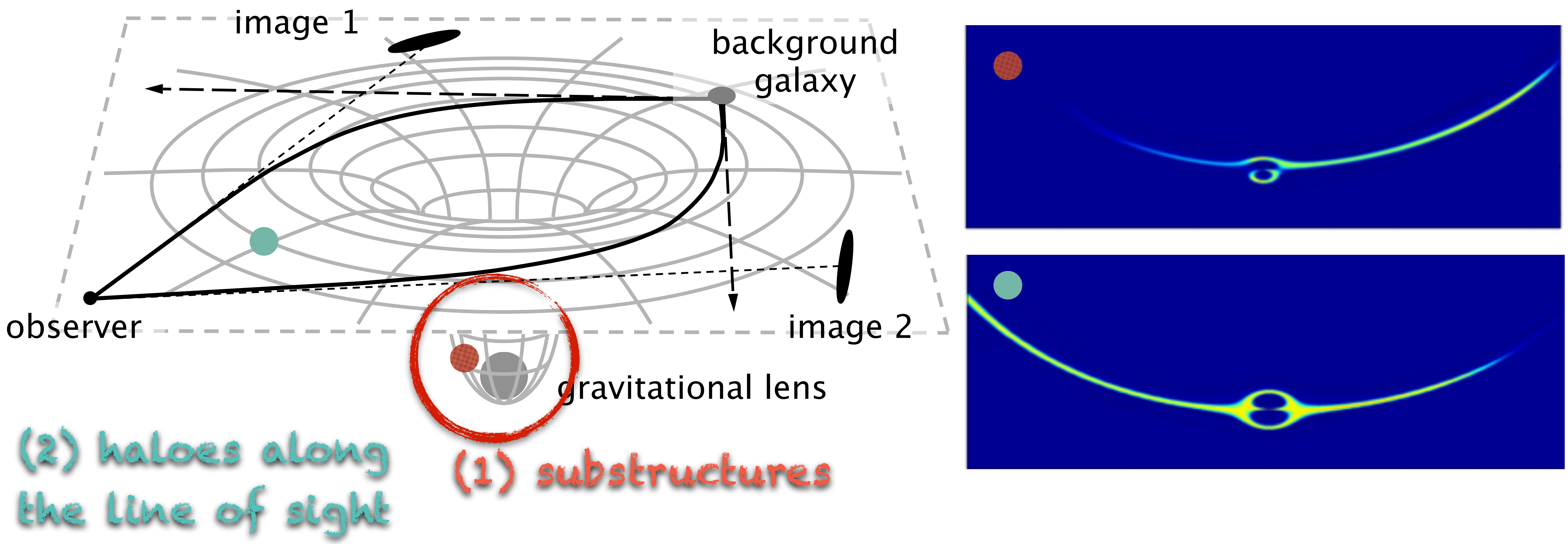
Derived mass function parameters from a sample of 11 SLACS lenses

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

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

LINE-OF-SIGHT CONTRIBUTION

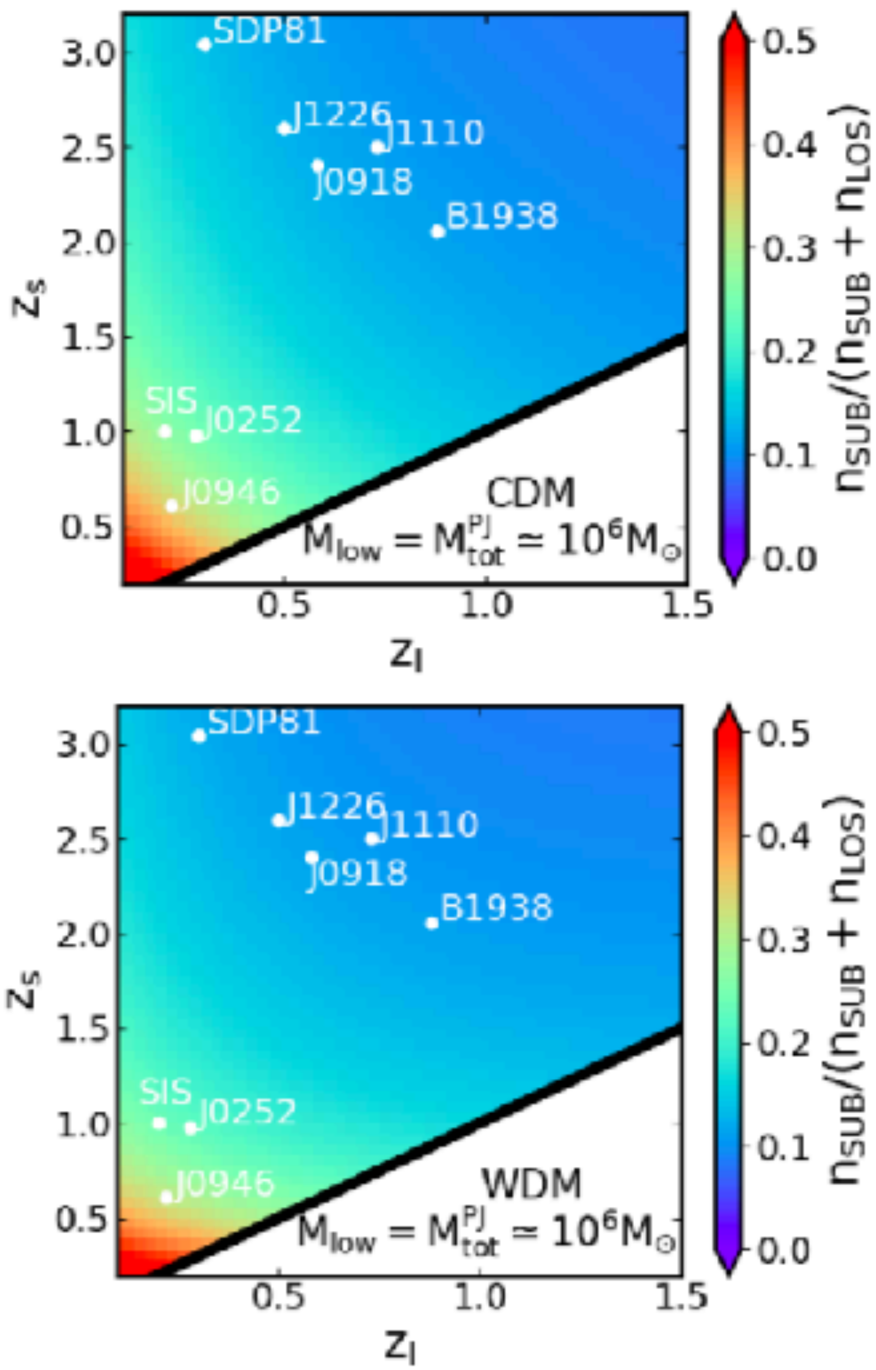
Gravitational lensing is sensitive not only to the mass distribution on the lensing galaxy but also to the general mass distribution along the line-of-sight



LOS is not a contamination but a powerful and clean probe on the nature of DM

LINE-OF-SIGHT CONTRIBUTION

Despali, Vegetti et al. 2018

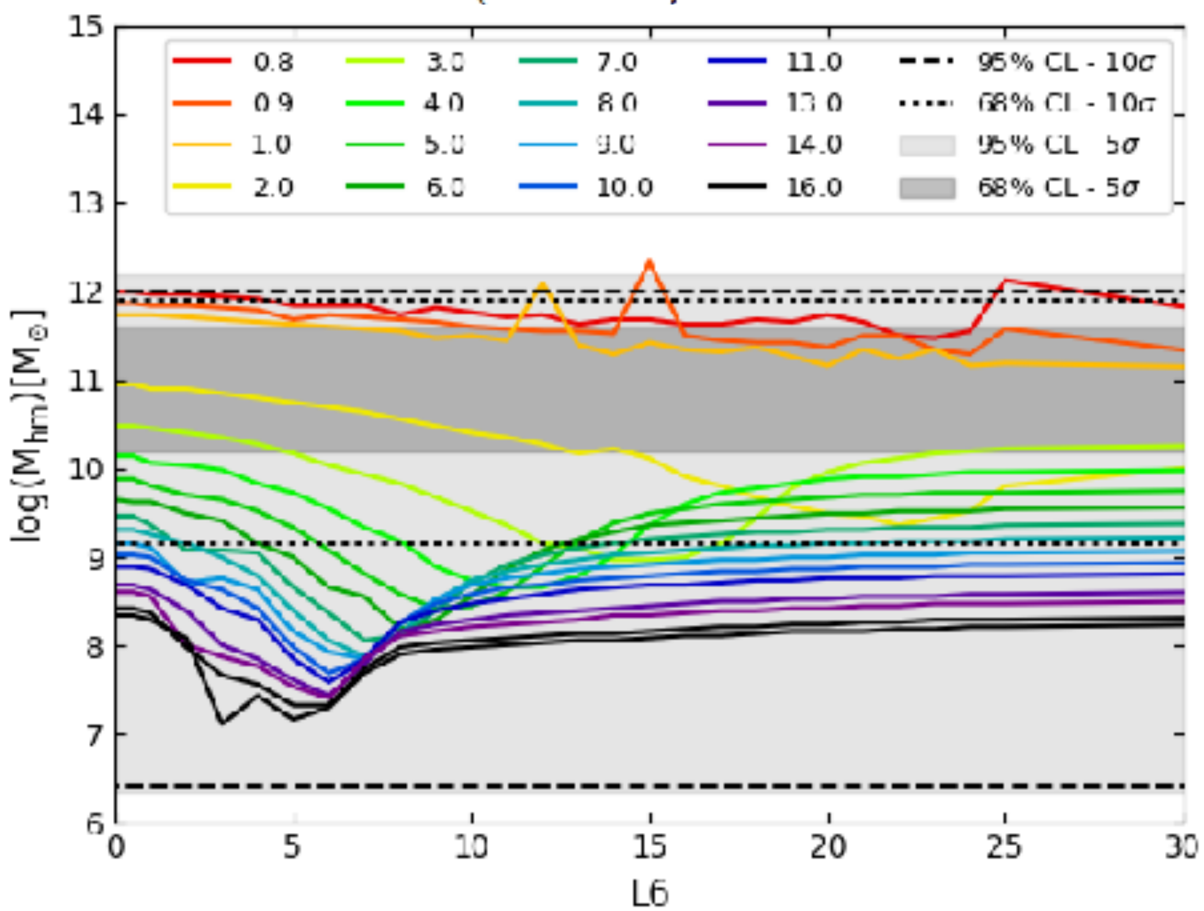


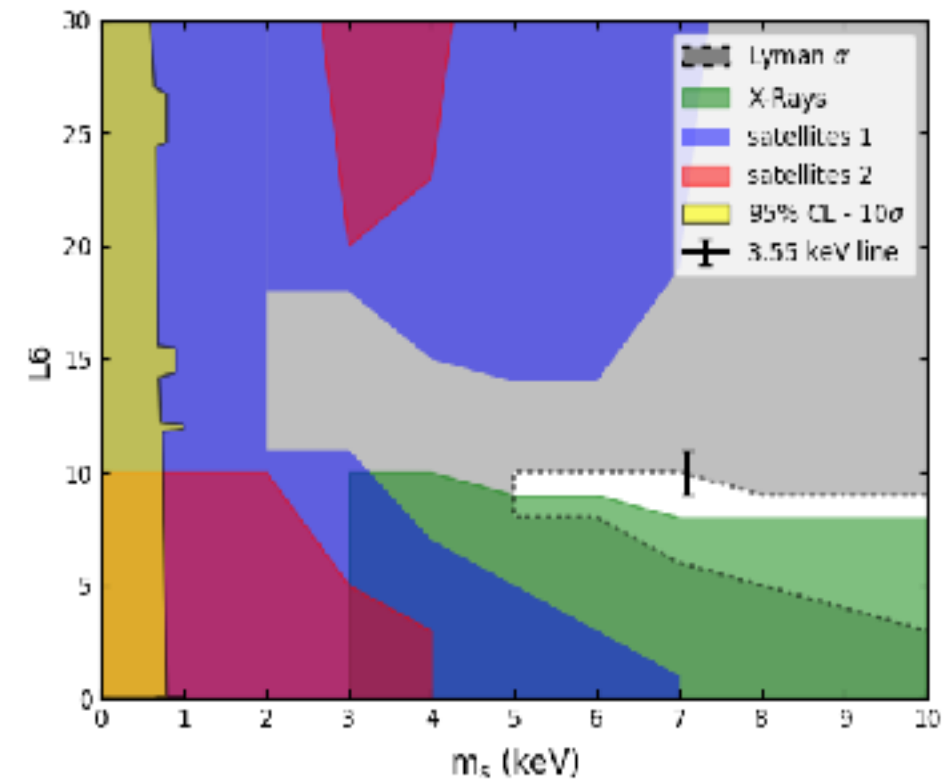
z_l	z_s	$M_{low}\,[M_\odot](z_l)$	n_{sub}(CDM)	n_{los}(CDM)	n_{sub} (WDM)	n_{los} (WDM)
0.2	1	10^6	0.67	1.85	0.065	0.209
		10^7	0.066	0.21	0.033	0.105
		10^8	0.0063	0.021	0.006	0.02
0.2	0.6	10^6	0.67	1.31	0.065	0.14
		10^7	0.066	0.15	0.033	0.073
		10^8	0.0063	0.016	0.006	0.014
0.58	2.403	10^6	3.22	22.81	0.309	2.384
		10^7	0.318	2.56	0.157	1.235
		10^8	0.030	0.271	0.029	0.243
0.881	2.059	10^6	5.95	46.33	0.571	4.482
		10^7	0.587	5.28	0.29	2.41
		10^8	0.0558	0.57	0.054	0.499

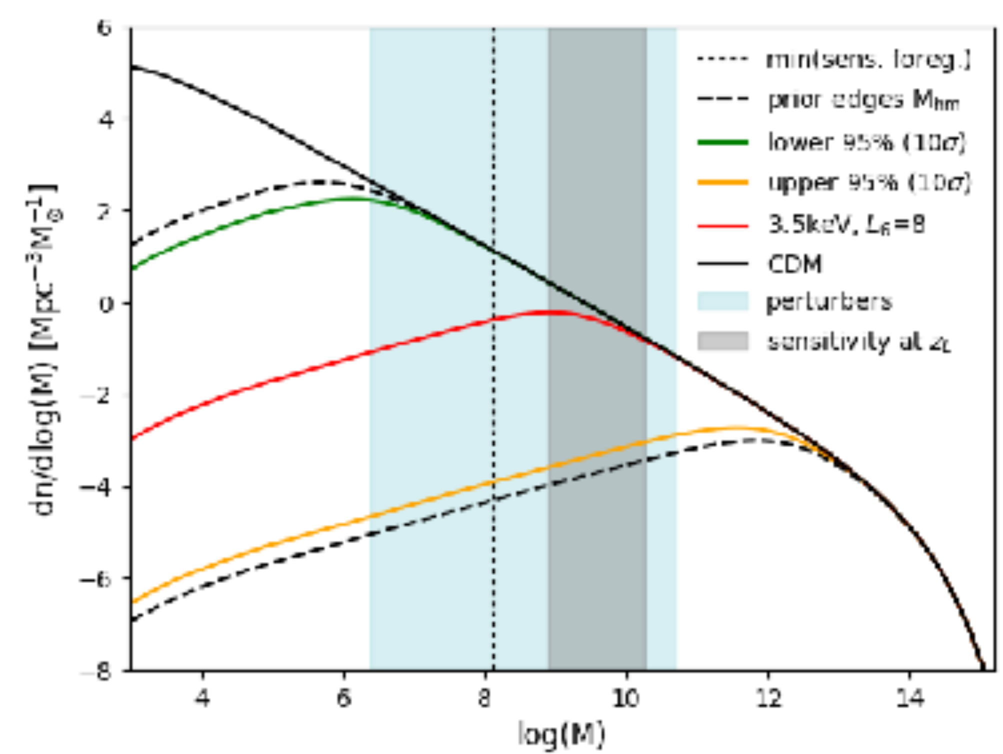
See Giulia's talk!

SUBSTRUCTURE + LINE-OF-SIGHT CONSTRAINTS

$$n(m) = n(m)^{\mathrm{CDM}} \left(1 + \frac{M_{\mathrm{hm}}}{m}\right)^{\beta}$$

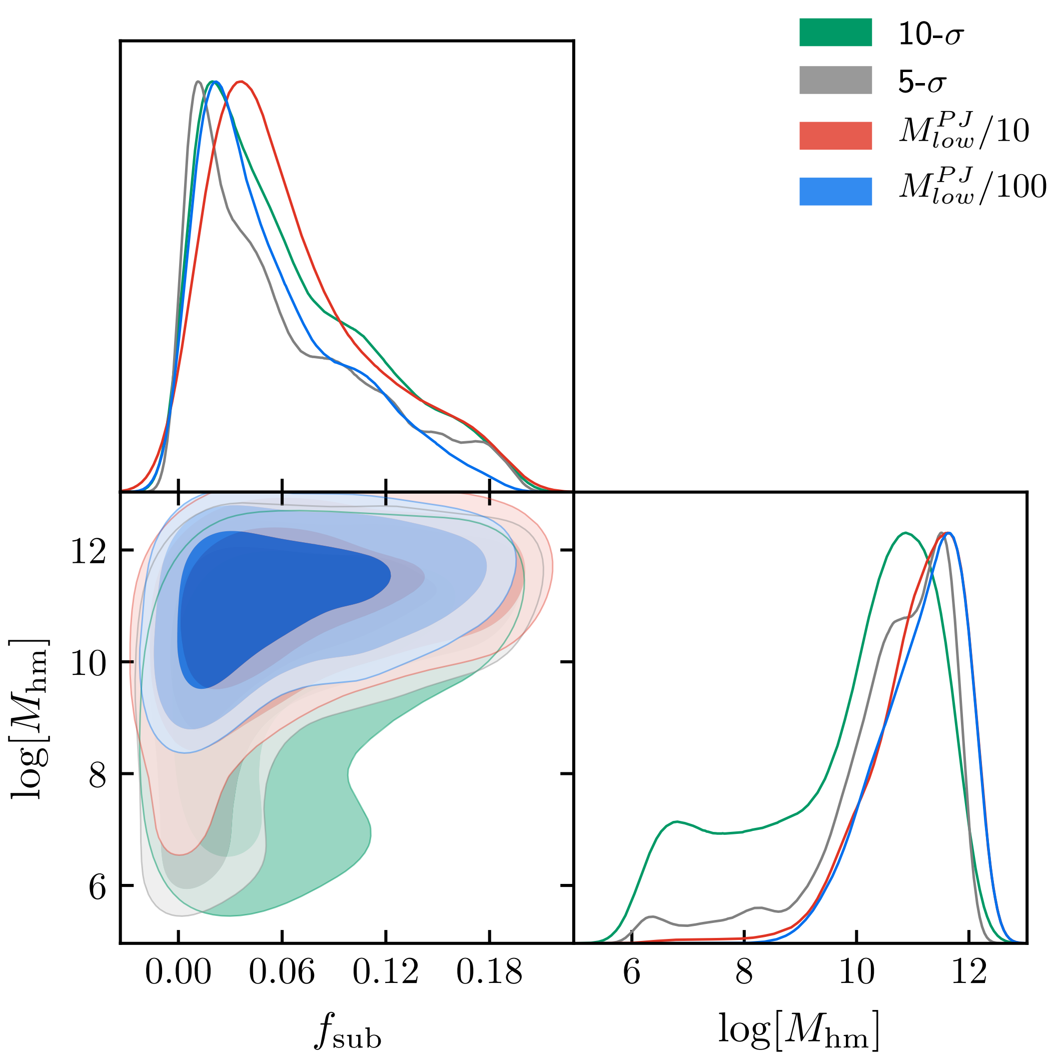


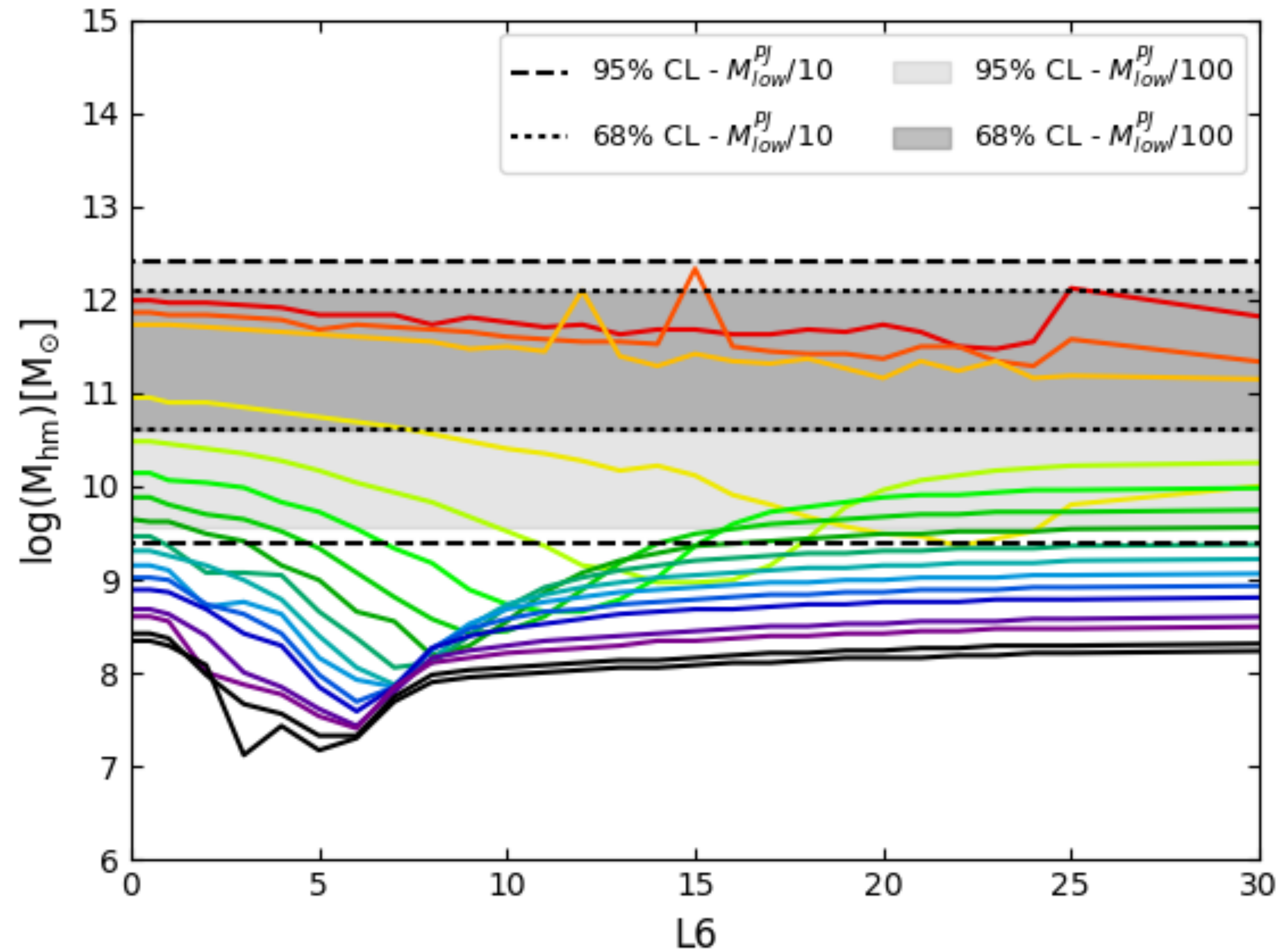




Vegetti et al. 2018

SUBSTRUCTURE + LINE-OF-SIGHT CONSTRAINTS



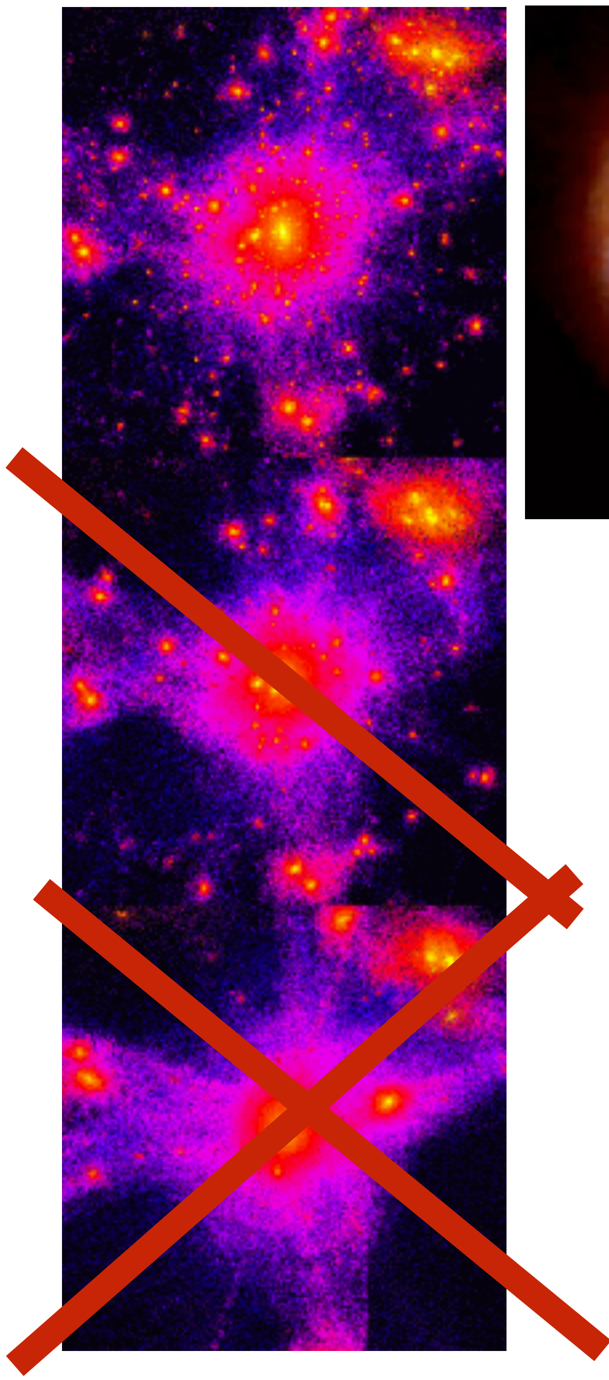


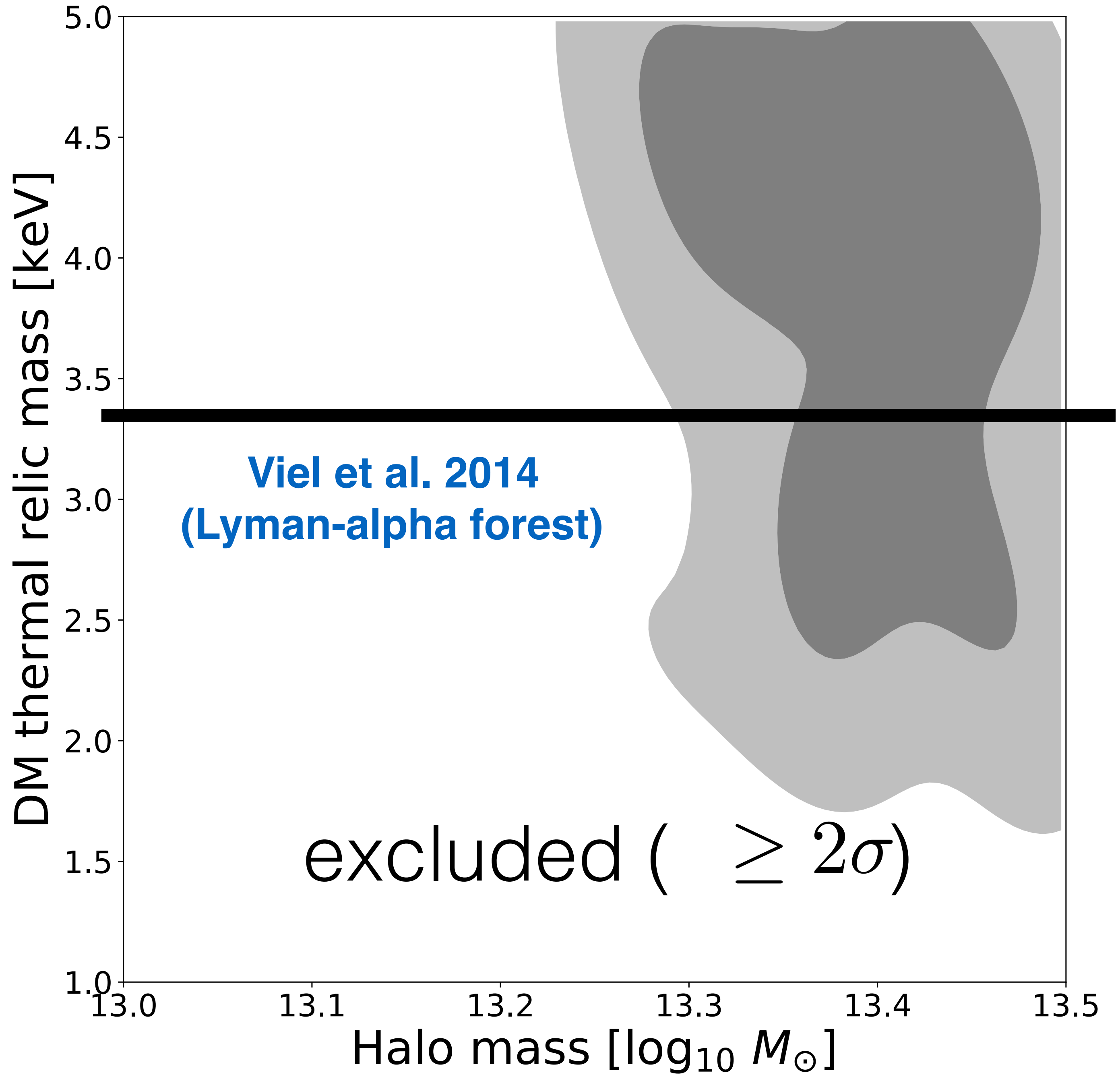
		σ_{68}	σ_{95}
log $M_{\rm hm}$ [$M_\odot$]	-	9.14 | 11.9	6.42 | 12.0

Vegetti et al. 2018

$0.30 < m_{\rm th} < 14.3$ keV

FORWARD MODELLING

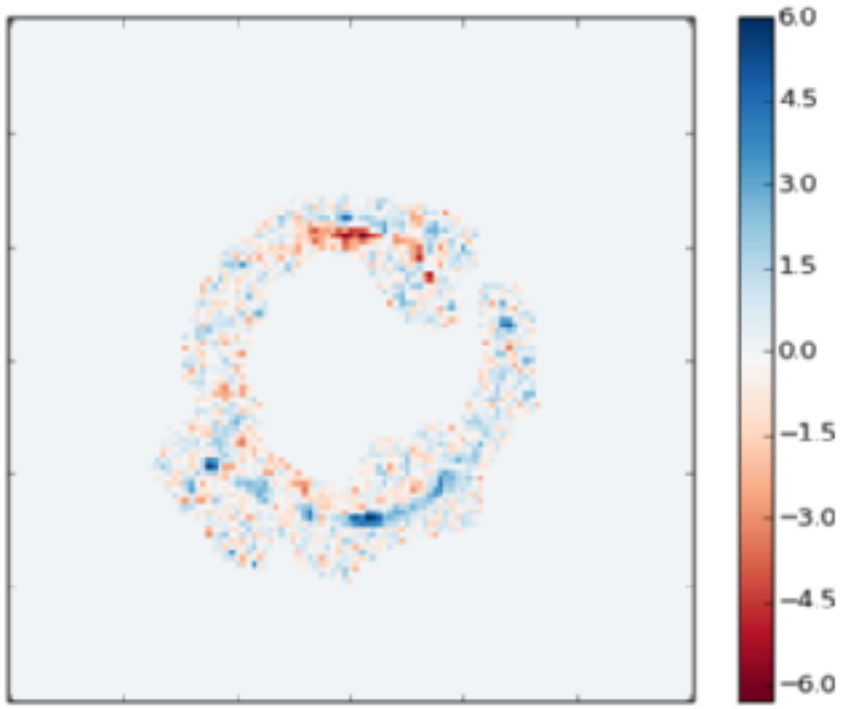


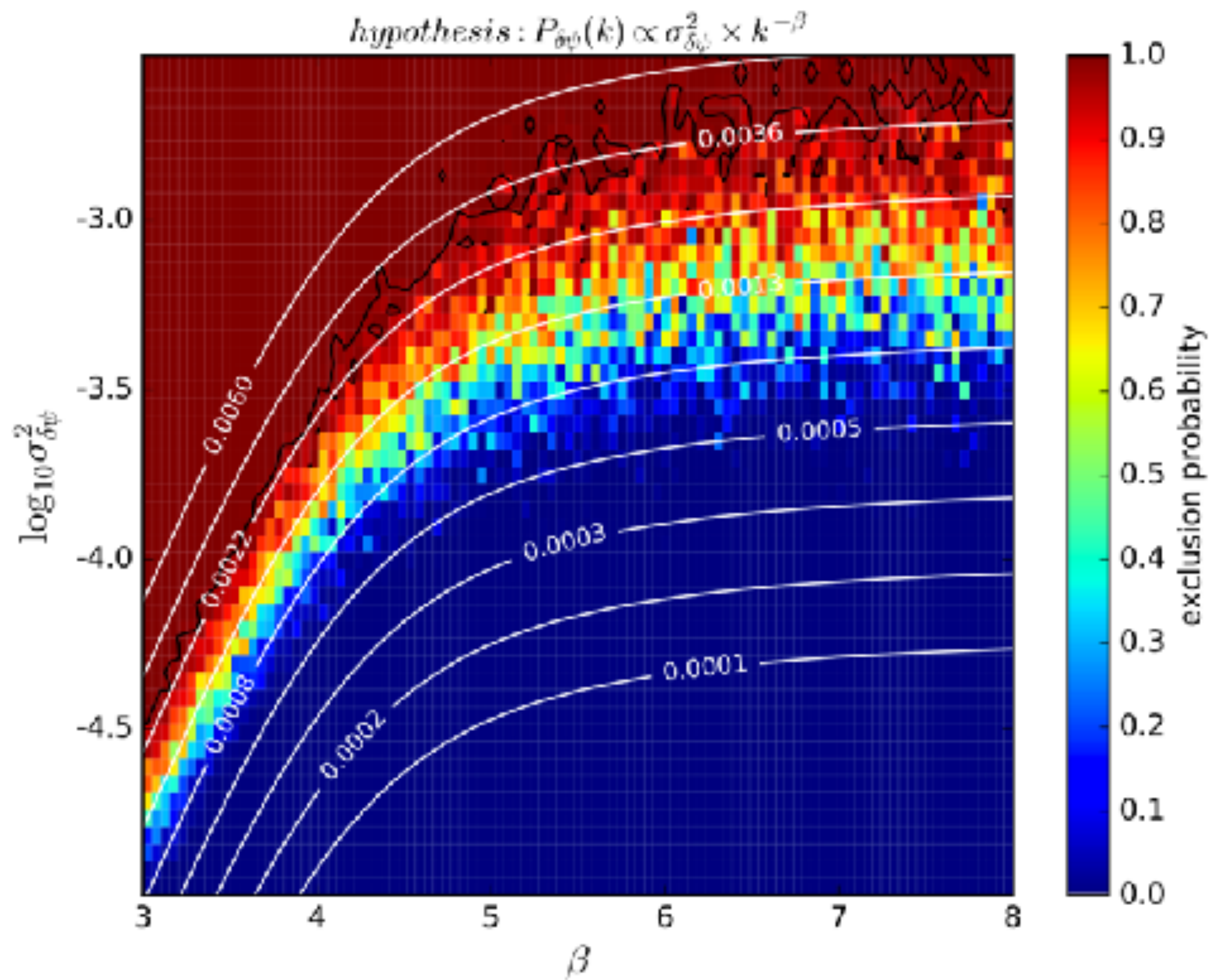


Birrer+ 2017

POWER SPECTRUM

Hezaveh et al. 2016, Chatterjee et al. 2017, Bayer et al. 2018

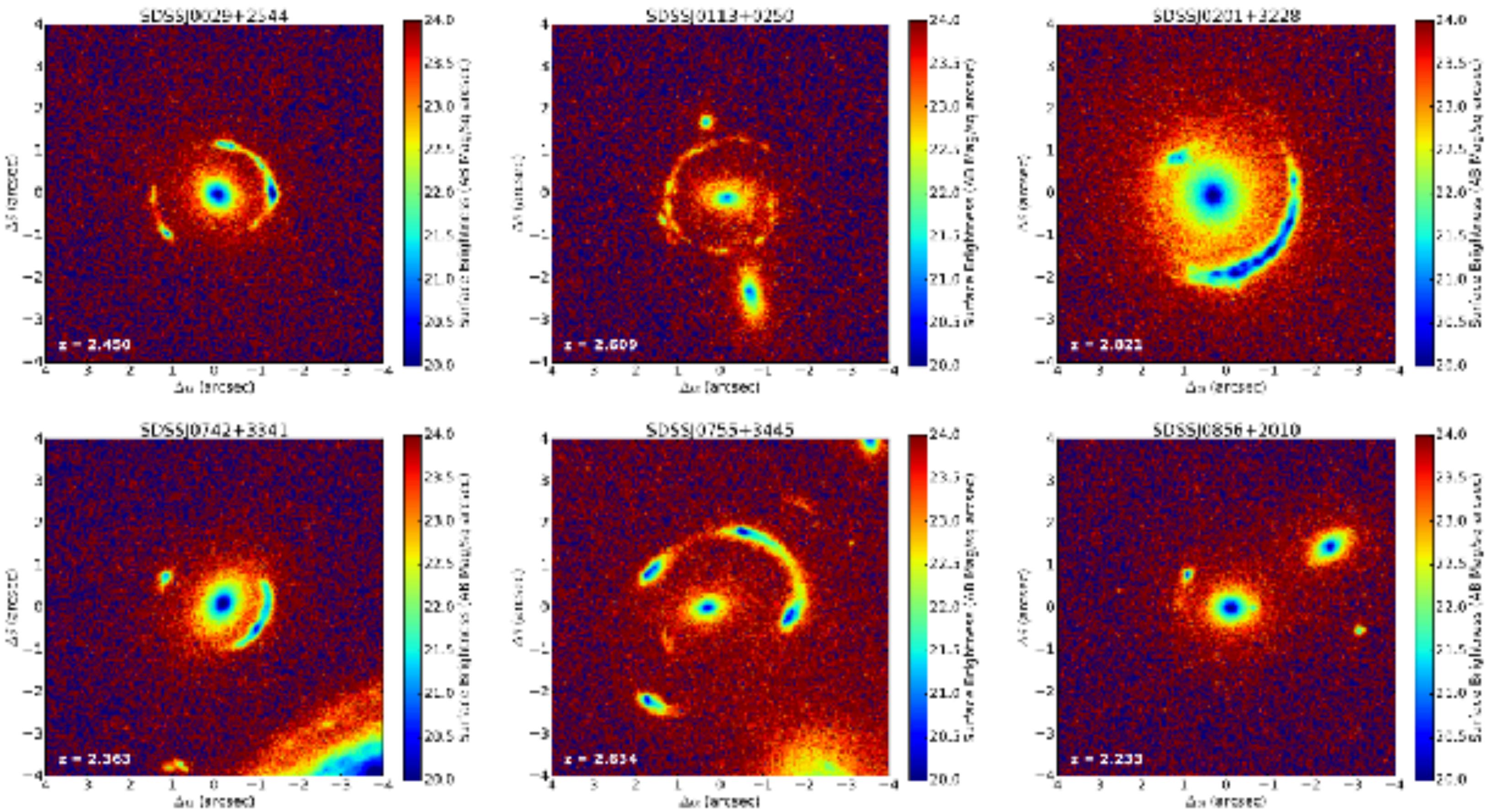




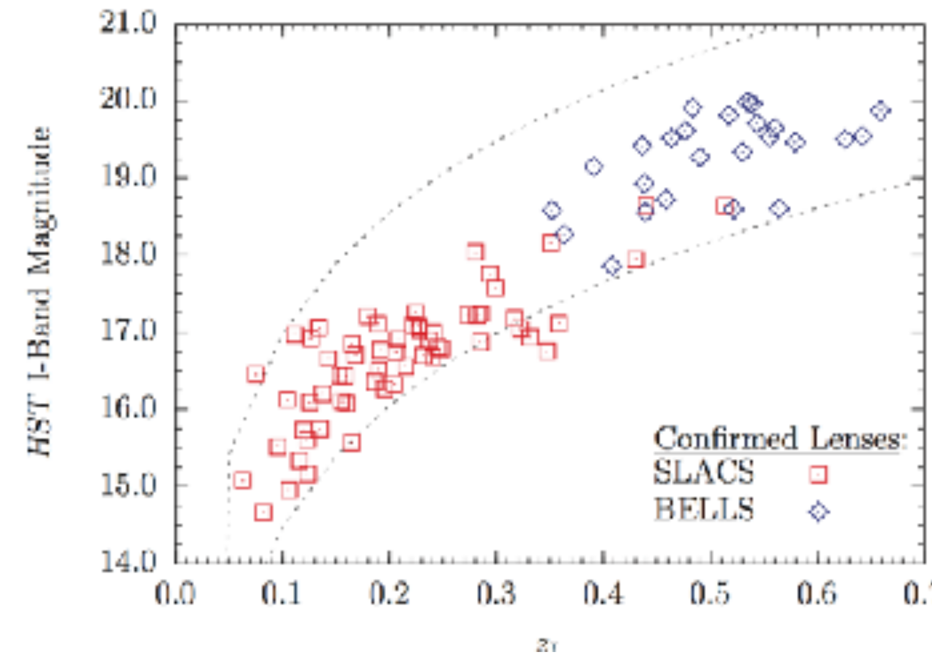
The observational upper-limits constraints inferred from the analysis of this first lens system significantly exceed the estimated effect of CDM substructure.

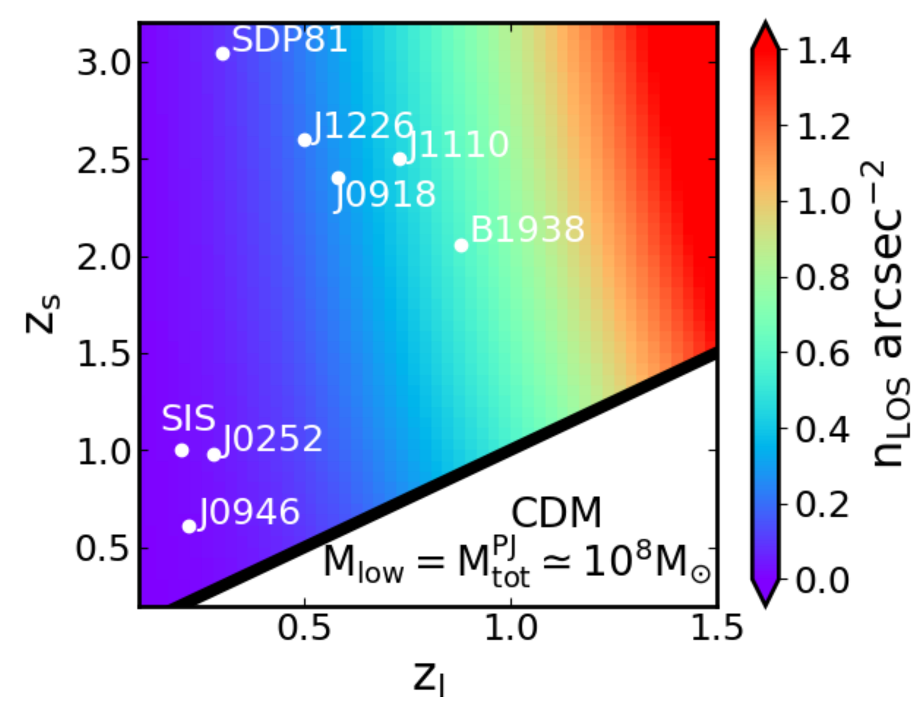
TOWARDS LARGER VOLUMES

Ritondale, Vegetti et al., in prep.



See Elisa's talk!

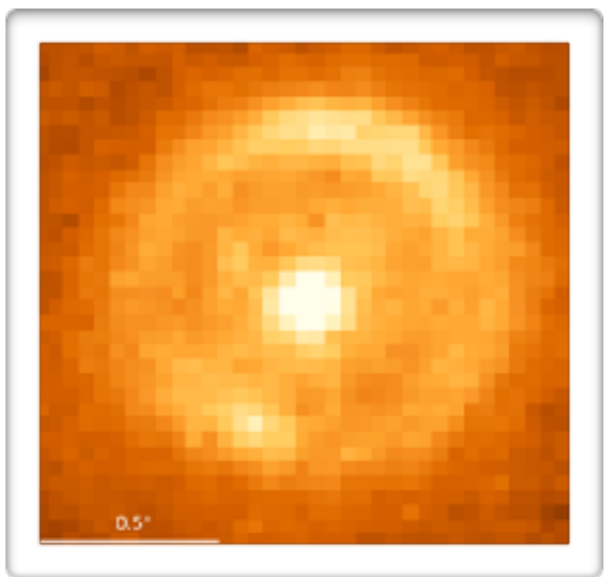




TOWARDS LOWER MASSES

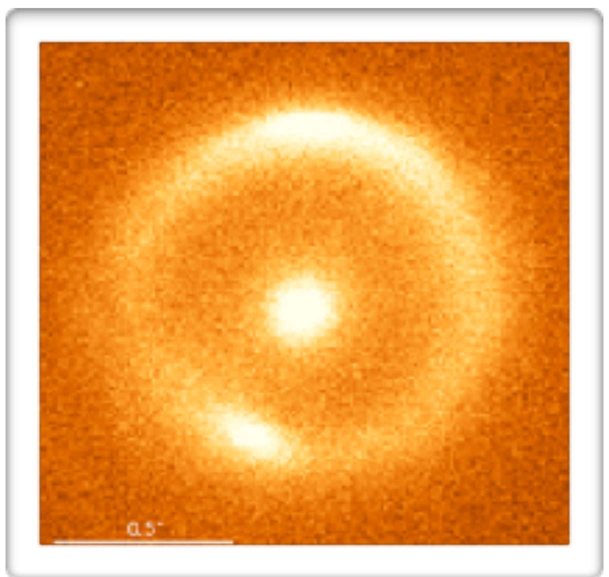
Increased angular resolution leads to an increase in sensitivity

HST

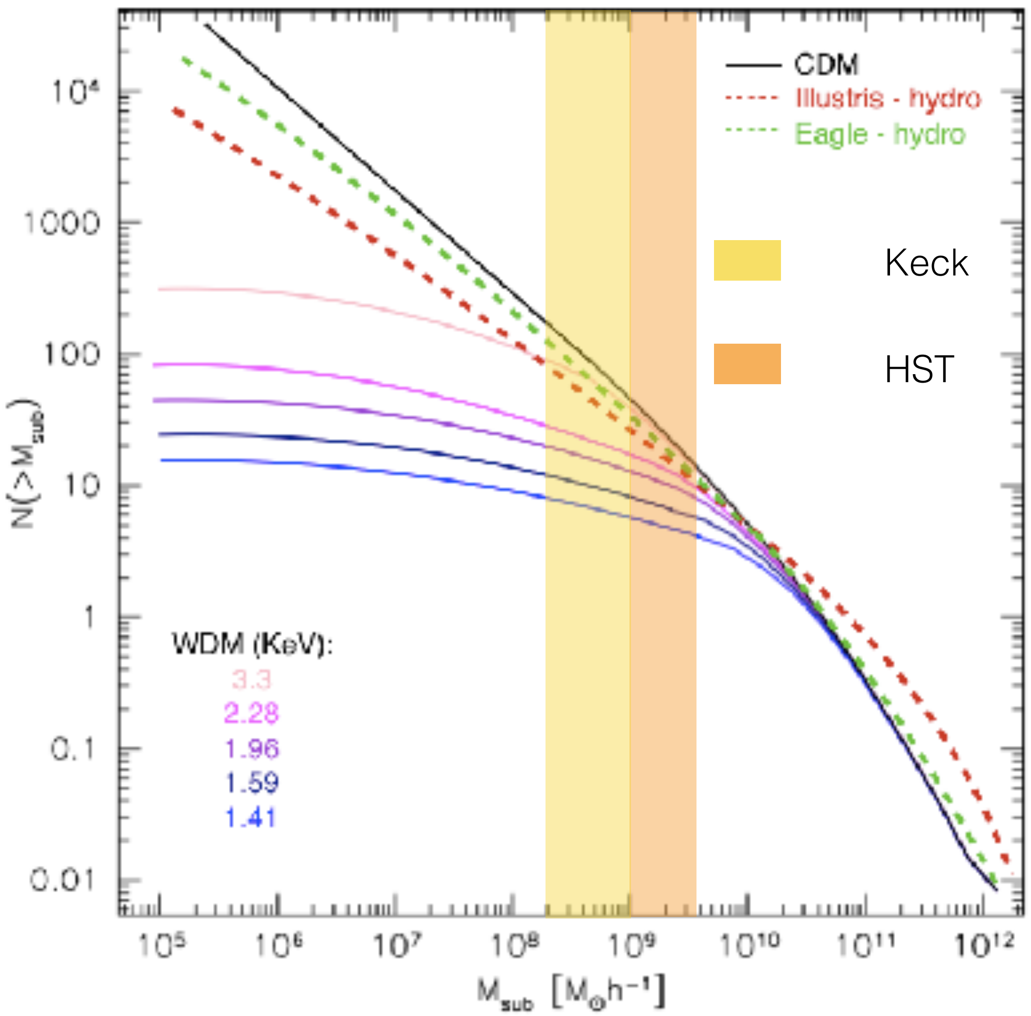


10^9 M_{sun}

Keck Adaptive Optics



10^8 M_{sun}



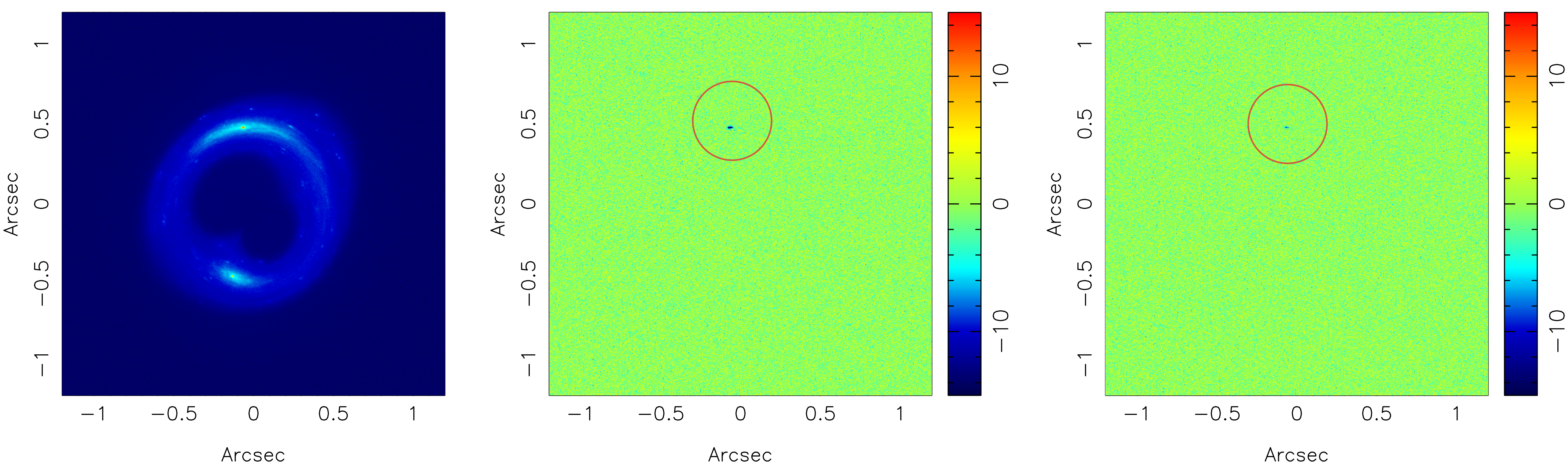
See Giulia's talk!

See John's talk!

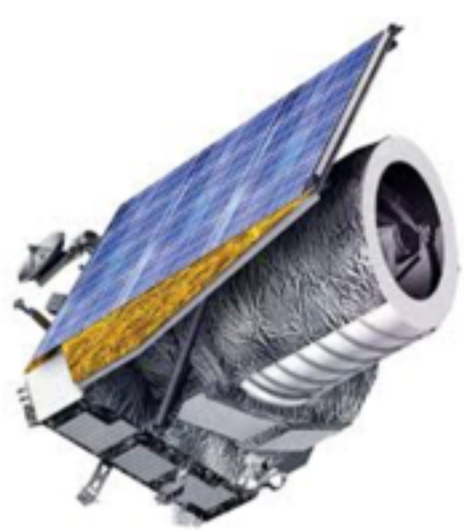
TOWARDS LOWER MASSES

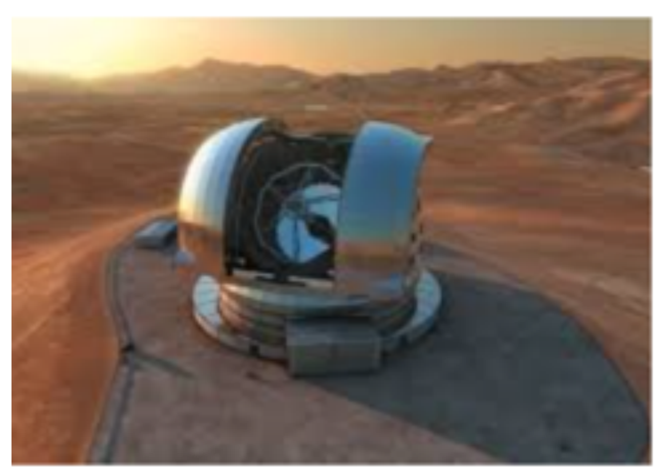
MICADO on E-ELT (SIMCADO- Czoske)

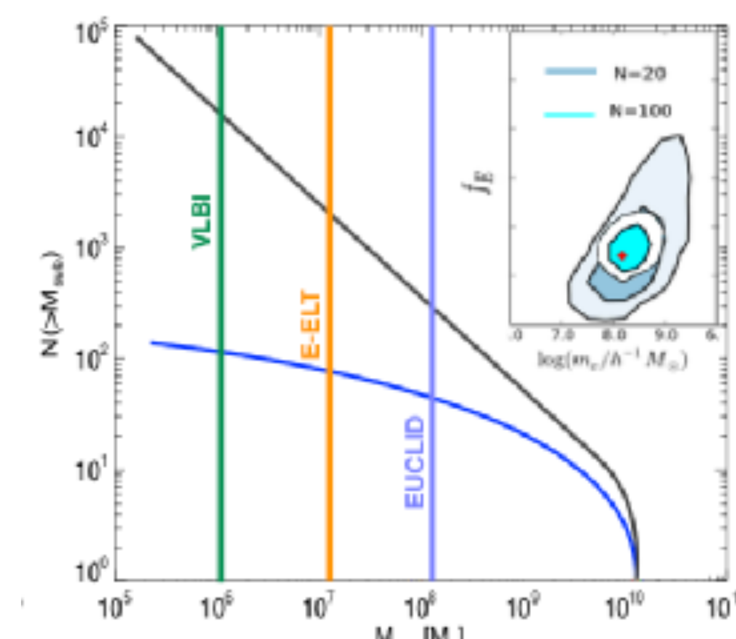
$M = 10^8\ M_\odot$ $M = 10^7\ M_\odot$



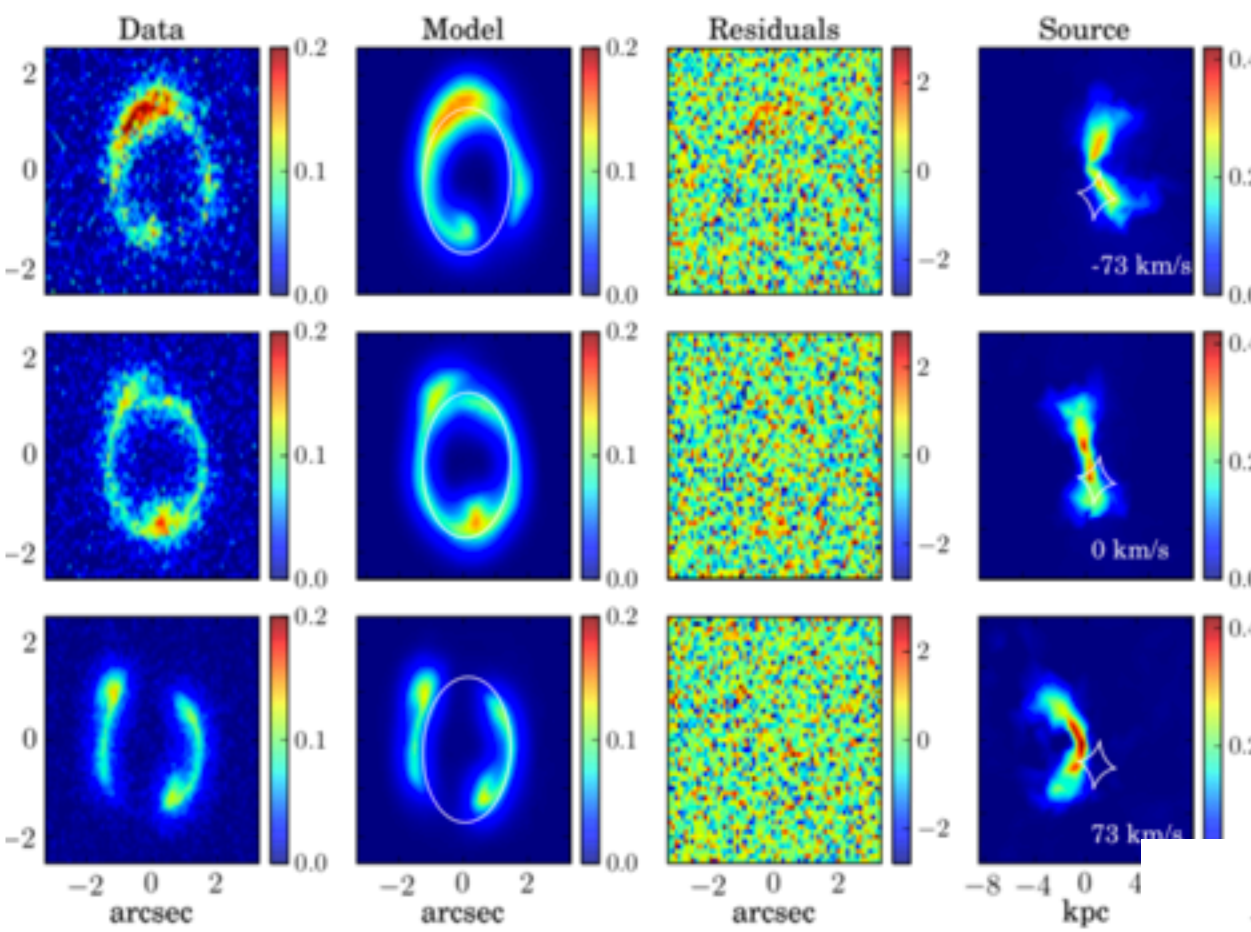
~10⁵ new lensed galaxies



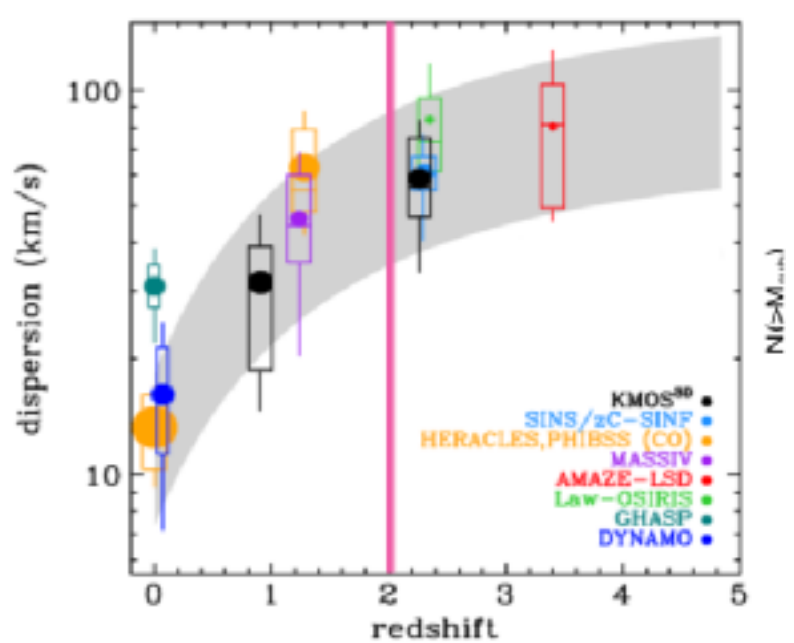


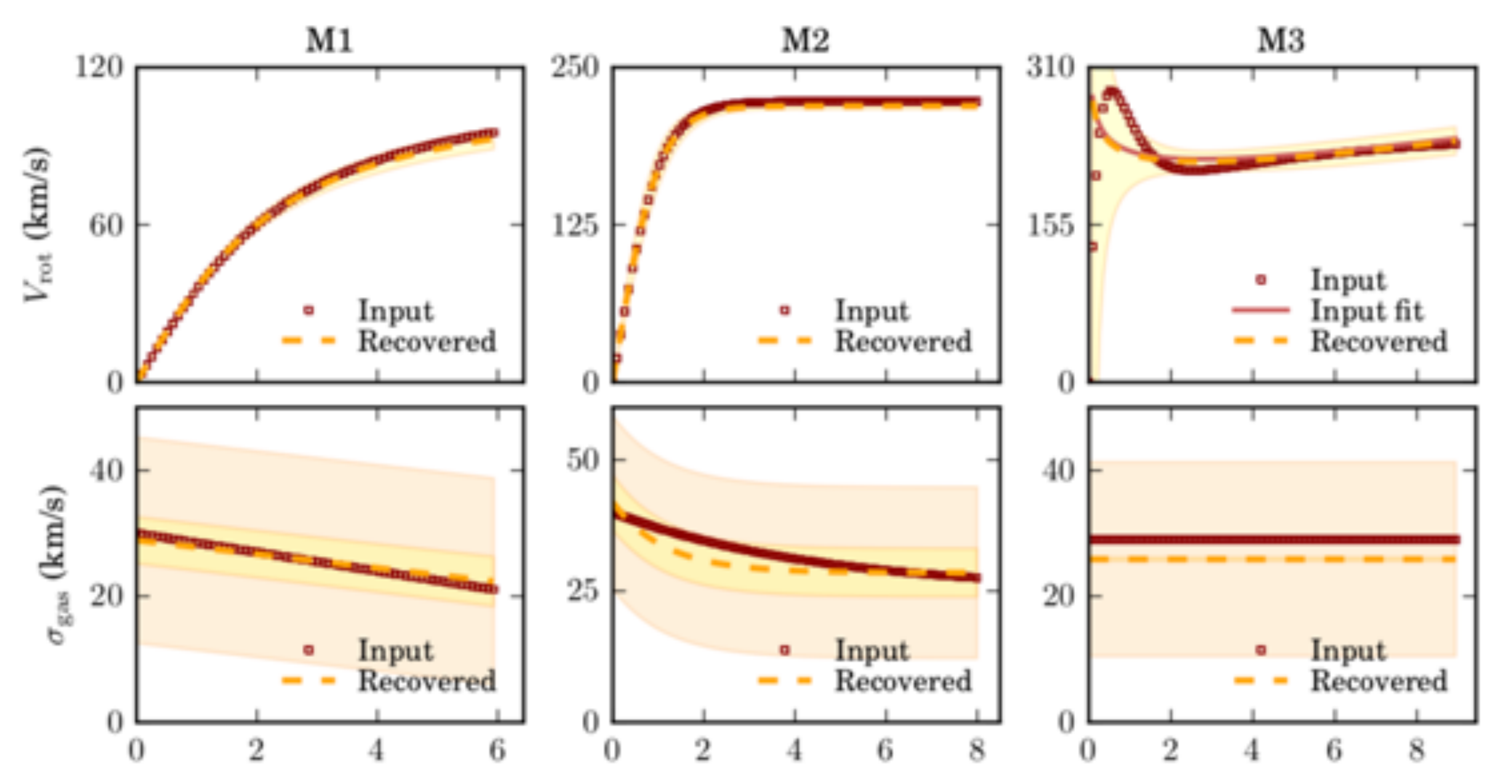


DARK MATTER ACROSS COSMIC TIME



Rizzo, Vegetti et al., submitted





CONCLUSIONS

- Gravitational lensing provides a key probe on the nature of dark matter
- Structures along the LOS represent a significant contribution and provide a cleaner probe on the properties of dark matter
- Upcoming surveys will lead to the discovery of thousands of new gravitational lens systems coupled with the angular resolution of ELTs this will open a unique window to constrain the dark matter properties with detail and statistical completeness.