Taking a Sharp Look at Galaxies and Gravitational Lenses

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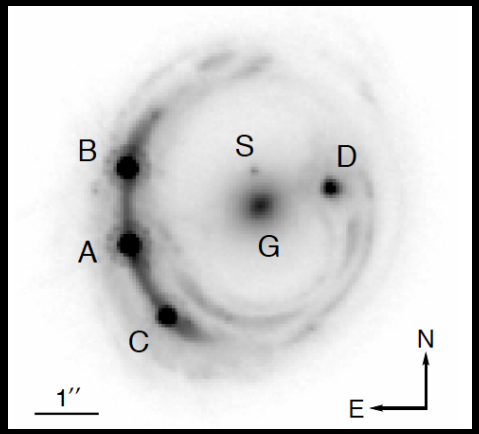
Motivation

- The big goals
  - Explore the nature of dark matter
    - Quantify the substructure mass distribution in distant galaxies
    - Compare to predictions from simulations
  - Obtain independent measurements of cosmological parameters, including dark energy
- The tools
  - Gravitational lensing
  - High-resolution imaging

Take away messages

- High resolution imaging enhances our ability to detect low-mass (dark matter) substructures in galaxies
- Measuring dark energy with time-delay lenses requires high-resolution imaging



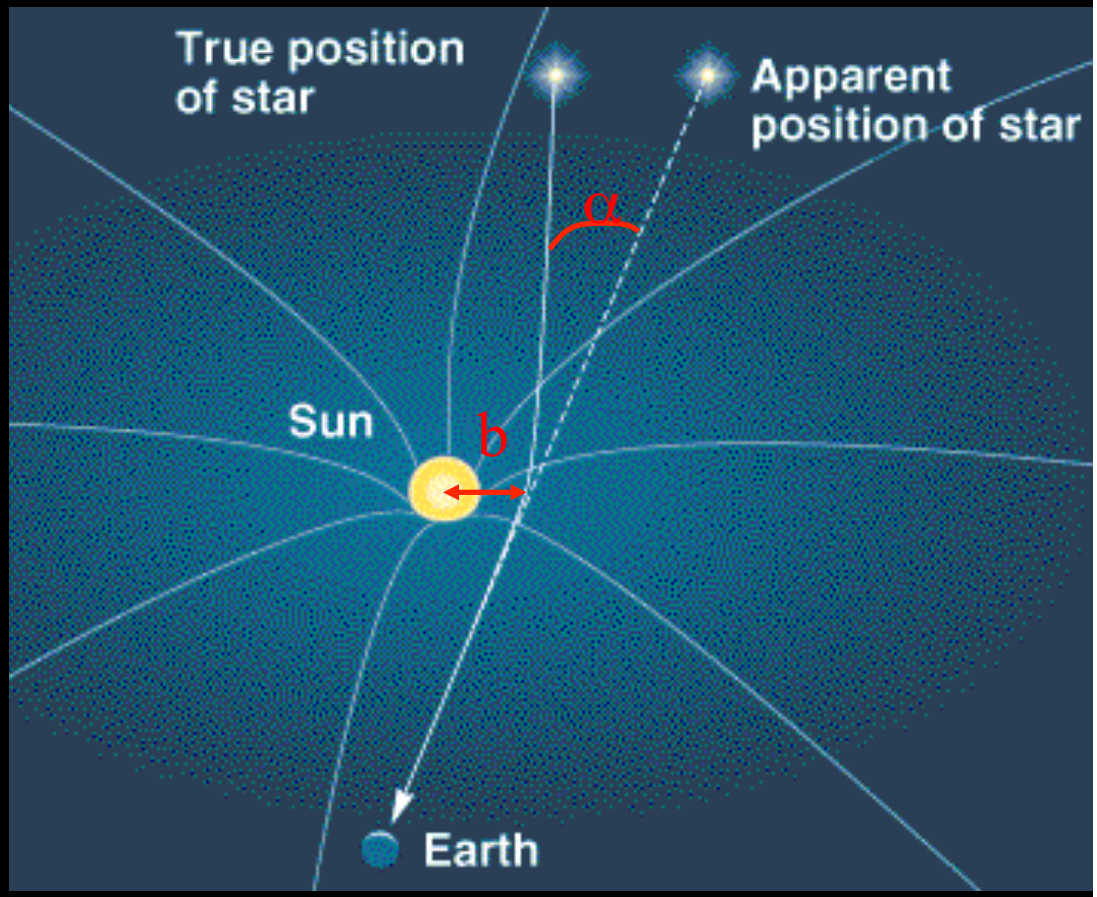
The First Tool:
Strong Gravitational Lensing

Gravitational Lenses: The Basic Idea

- General relativity: mass can deflect light from its original path

$$\alpha = \frac{4GM}{c^2 b} = \frac{2R_s}{b}$$

- Images of the background object will be magnified and distorted.



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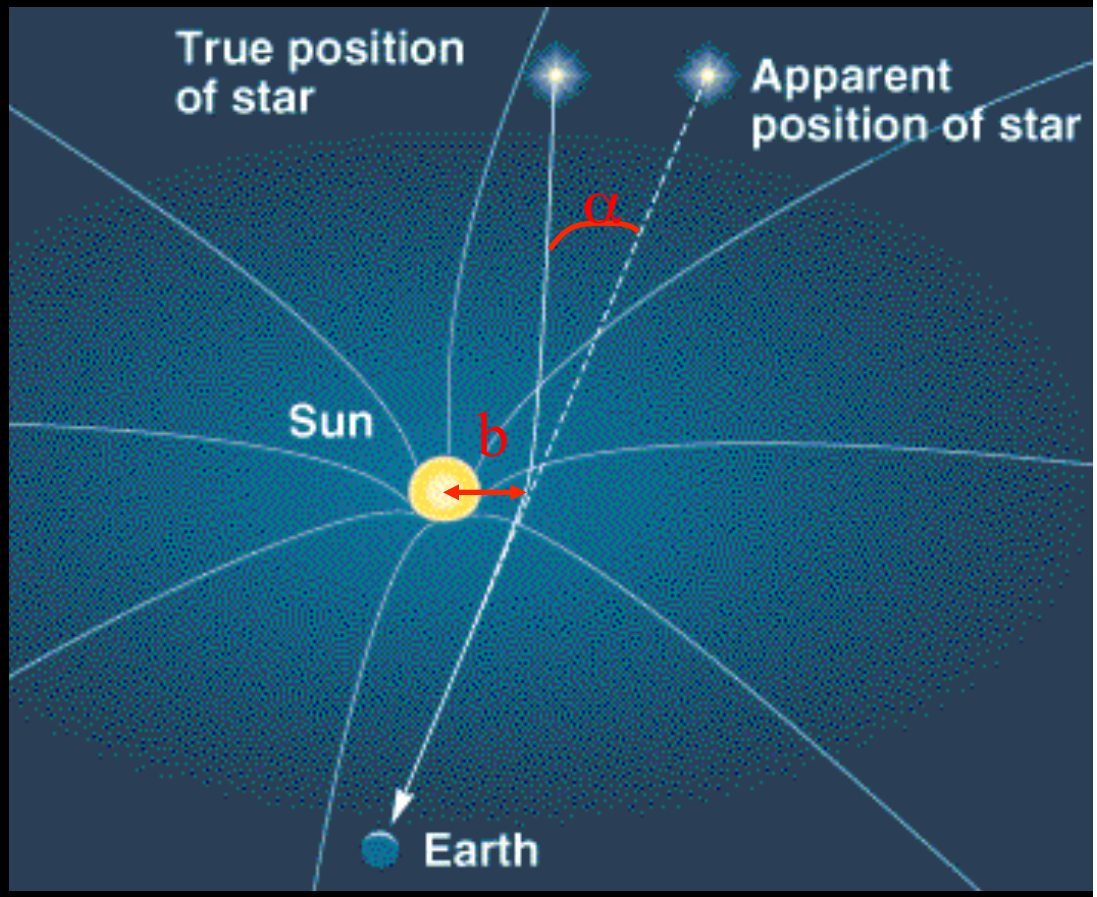
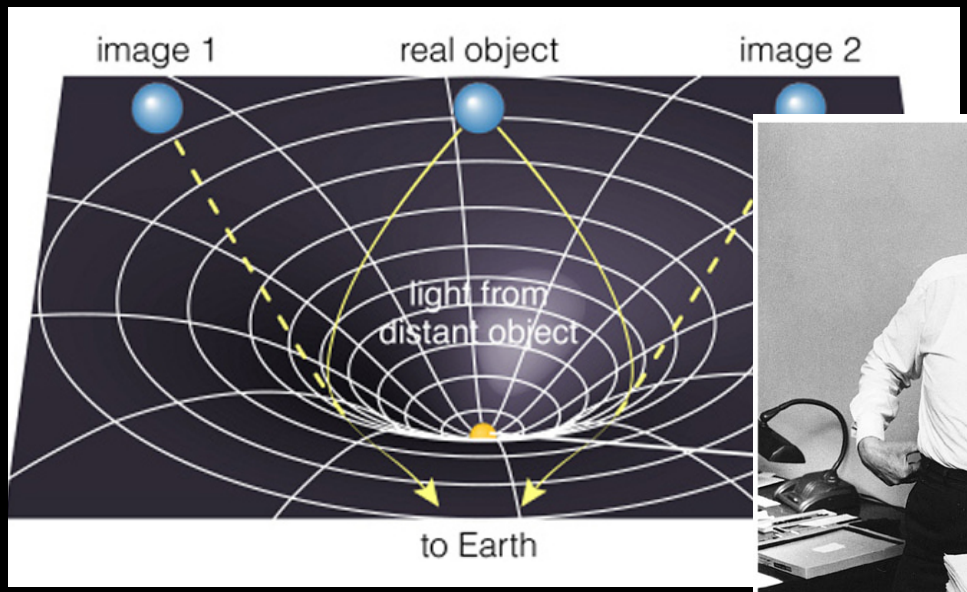
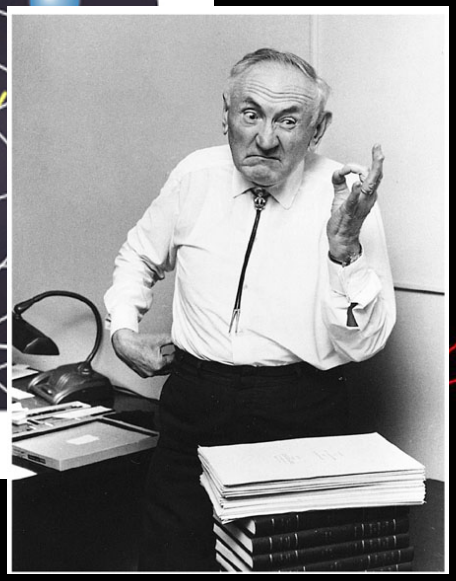
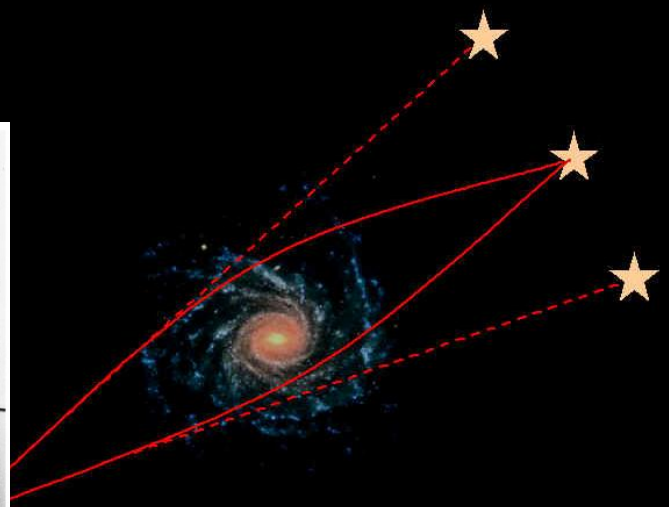


A high degree of alignment leads to multiple images (strong lensing)



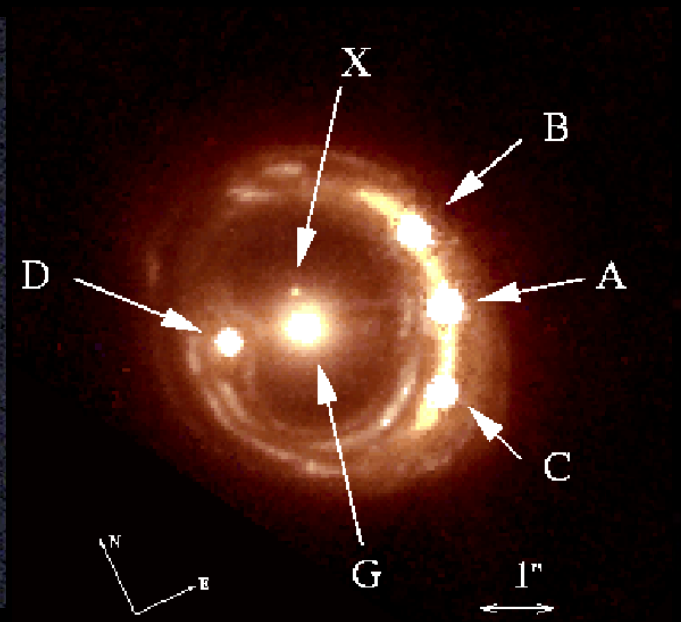




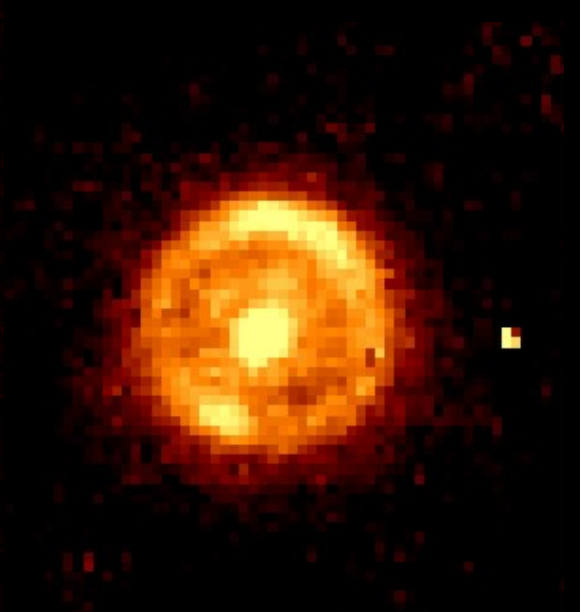
The mass of the lens (roughly) sets the angular separation of the lensed images

Basic Strong Lensing by Galaxies

2 images

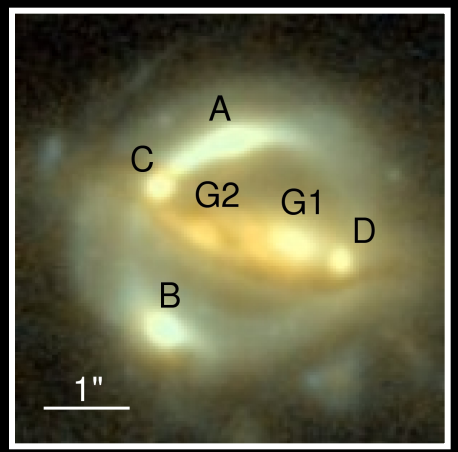


4 images

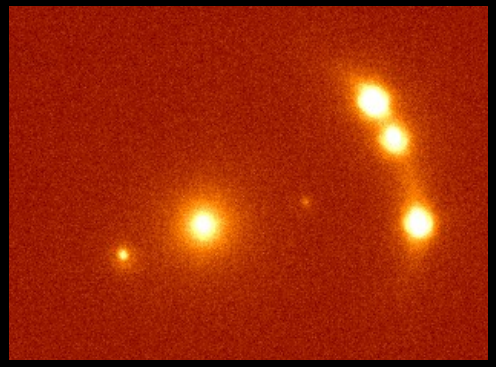


Einstein ring

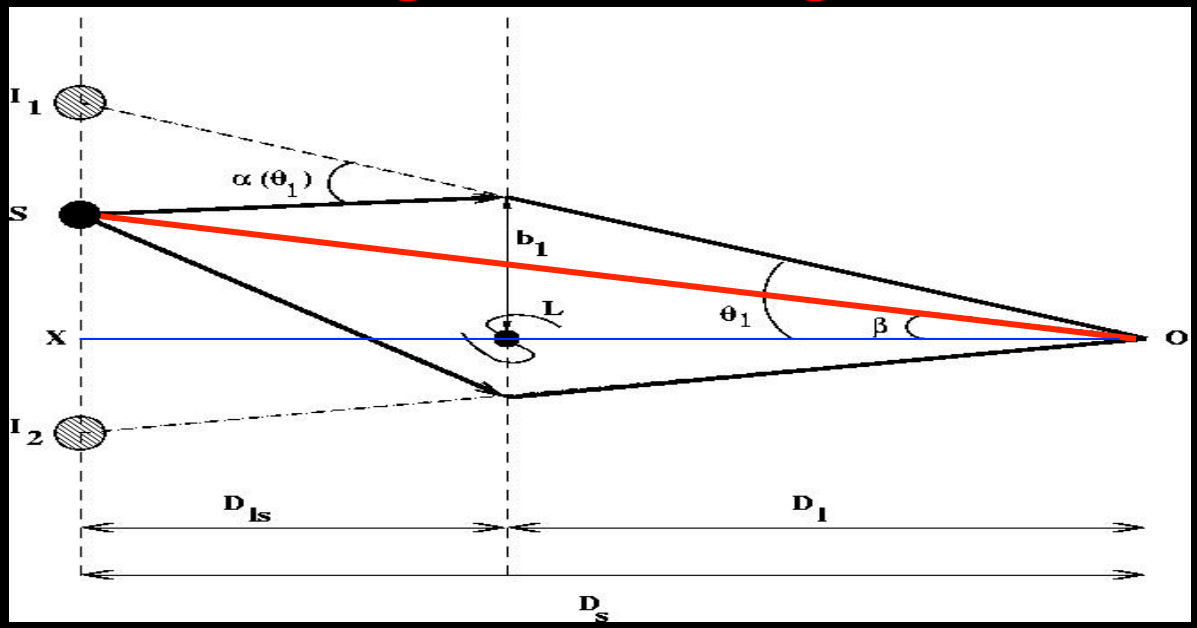
My favorite lens



My 2nd favorite lens

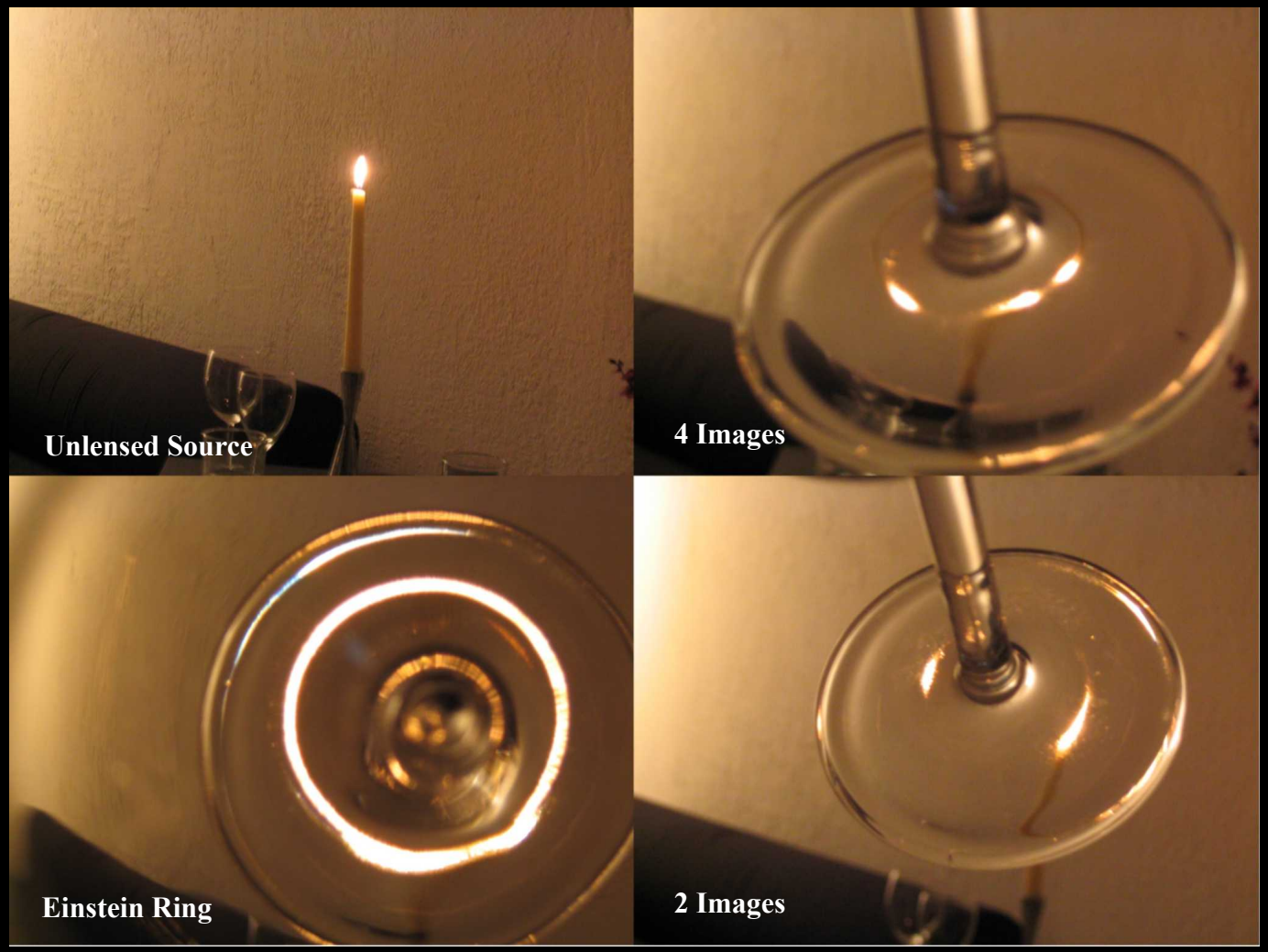


Strong Lensing 101



- $\Delta t_{tot} = \Delta t_{geom} + \Delta t_{grav}$
- $\Delta t(\theta_i) = (D_{\Delta t} / c) \; [(1/2) |\theta_i - \beta|^2 - \psi(\theta_i)]$
- Images form where $d(\Delta t)/d\theta = 0$
- Measure time delays through variability
- $D_{\Delta t} = (1+z_l) (D_l D_s / D_{ls})$

Everyday analogy of gravitational lensing



Courtesy of Phil Marshall (Oxford)

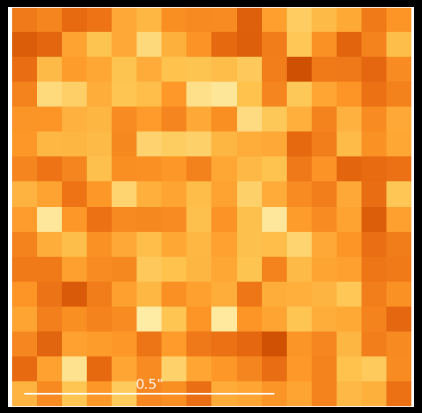
The Second Tool:
Adaptive Optics Imaging

Our new approach: Use Keck adaptive optics imaging

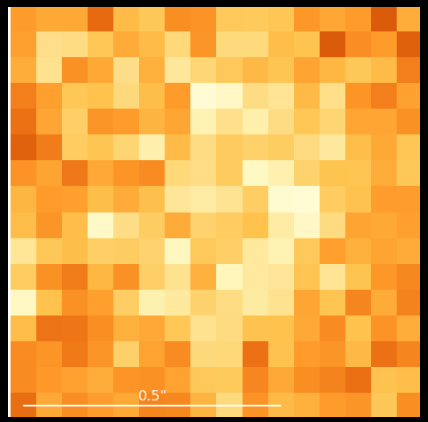
- Use Keck adaptive optics imaging of lens systems to search for substructures and constrain cosmology
- Get resolution comparable to or better than HST, while using a mirror that has 16 times the collecting area
  - especially good for red objects that are faint at optical wavelengths

$$\theta \sim \lambda / D$$

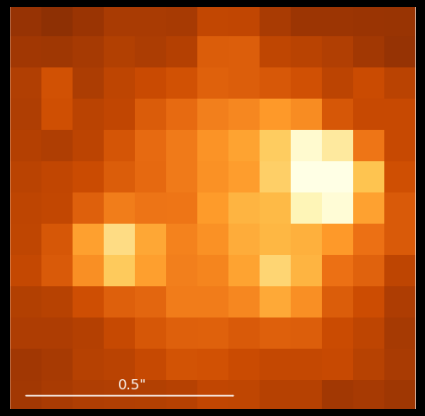
AO vs. Space: B0128+437



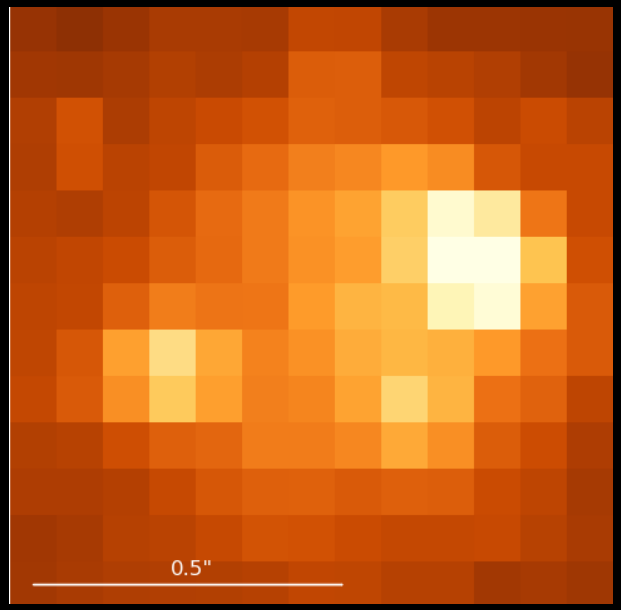
F555W



F814W

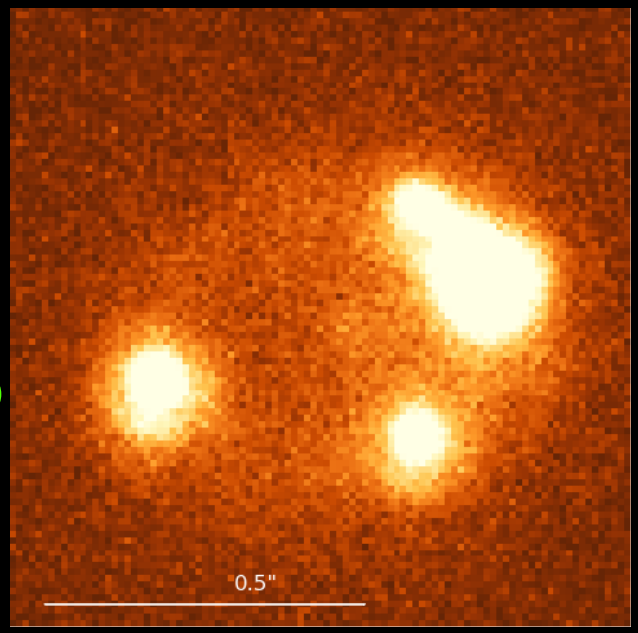


F160W



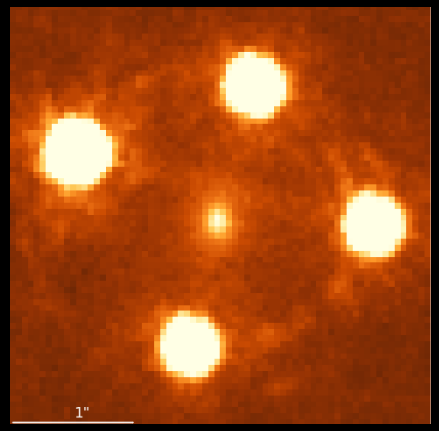
F160W, again

Keck AO K'-band



Lagattuta et al. 2010

AO vs. Space: HE0435-1223



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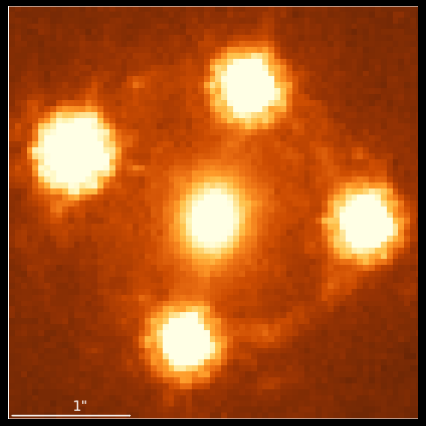

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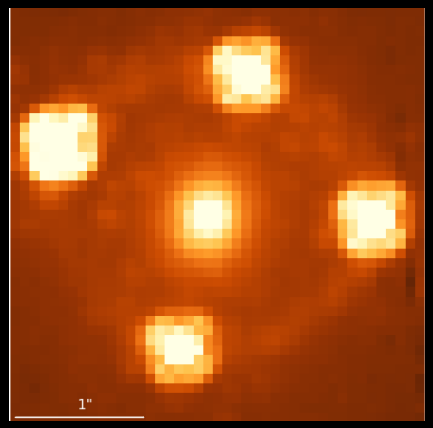
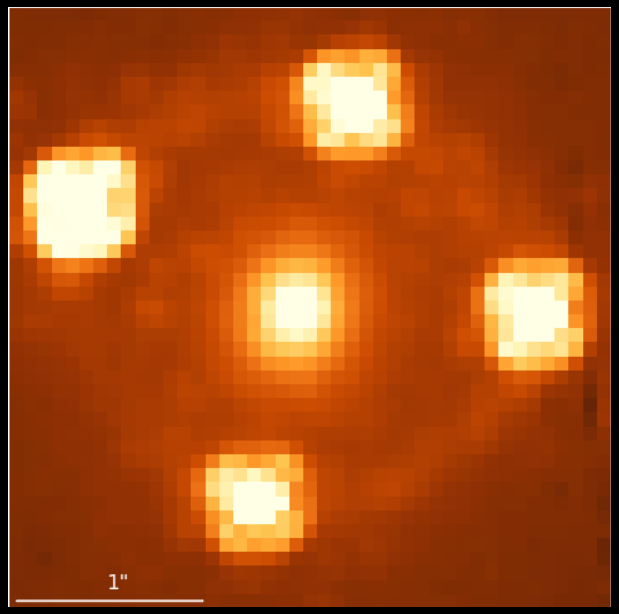


F160W



F160W, again

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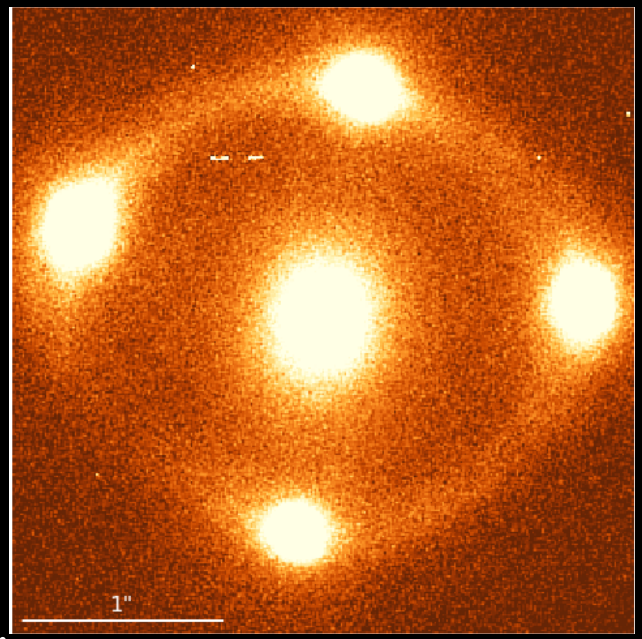
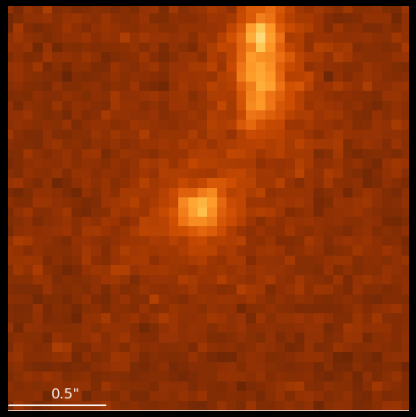


Fassnacht et al. in prep

AO vs. Space: B0631+519



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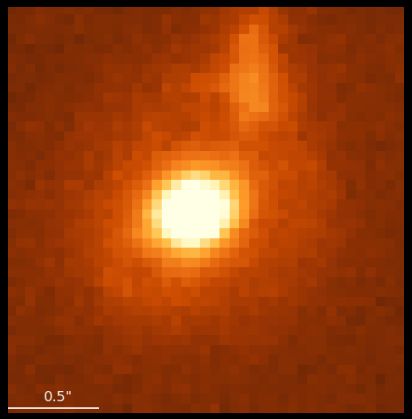
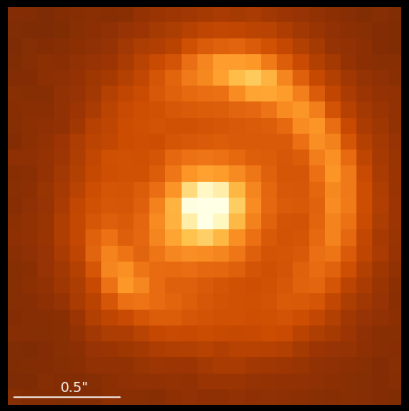


F814W



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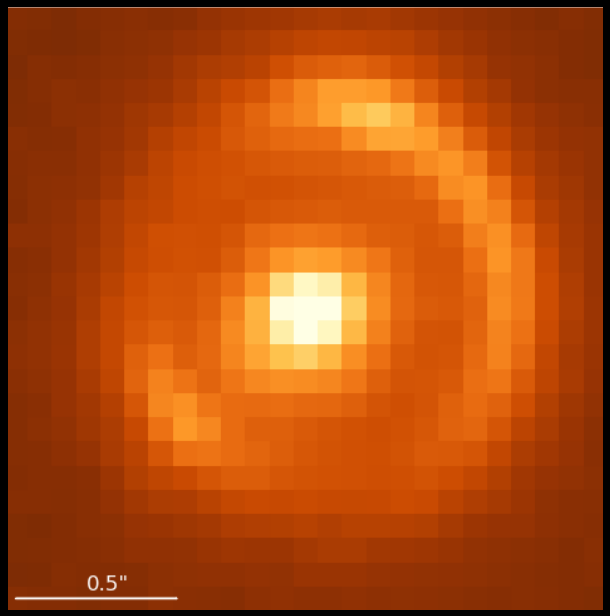

F160W, again

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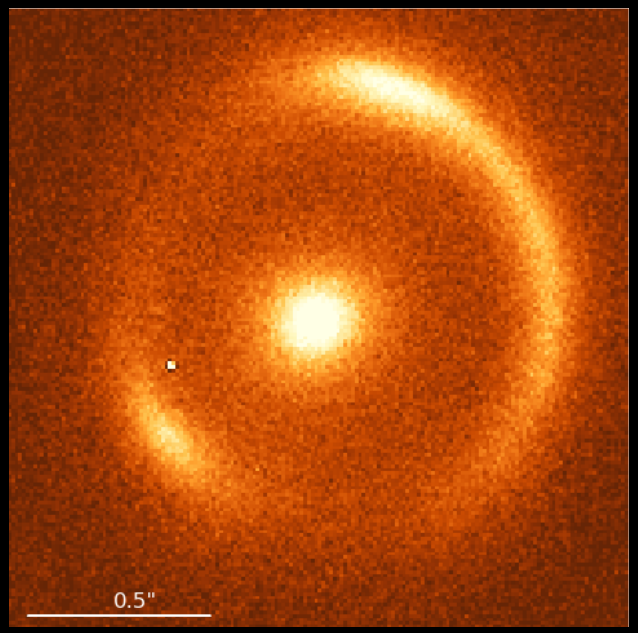
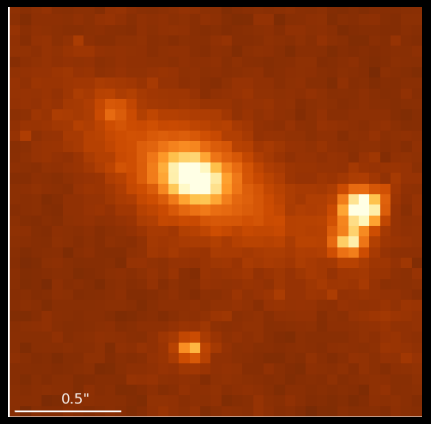


Fassnacht et al. in prep

AO vs. Space: B0712+472



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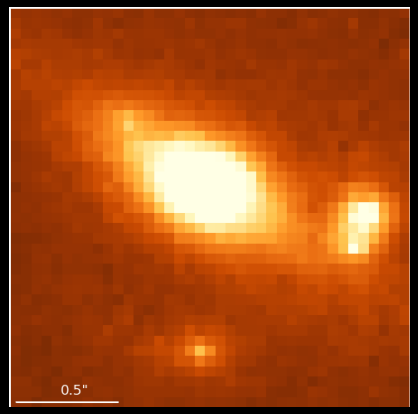

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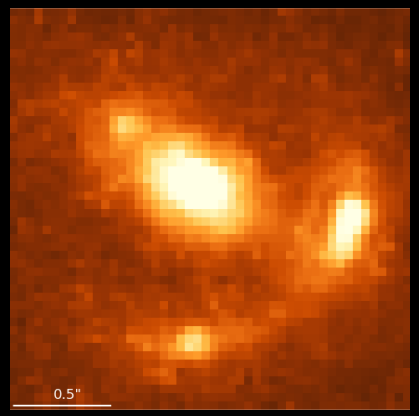

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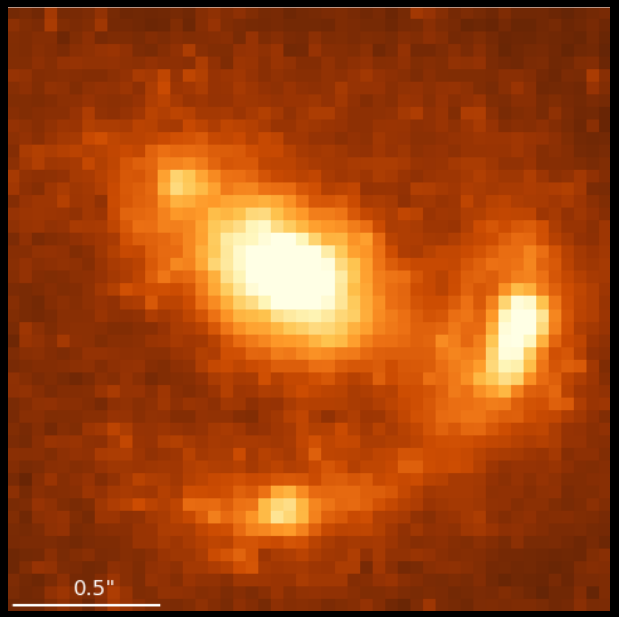
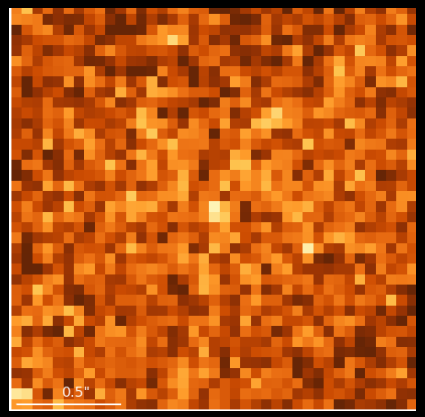


F160W, again

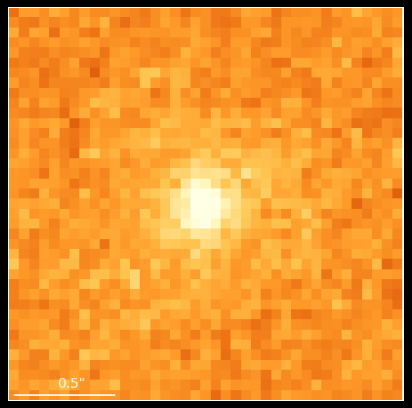
Keck AO K'-band

Fassnacht et al. in prep

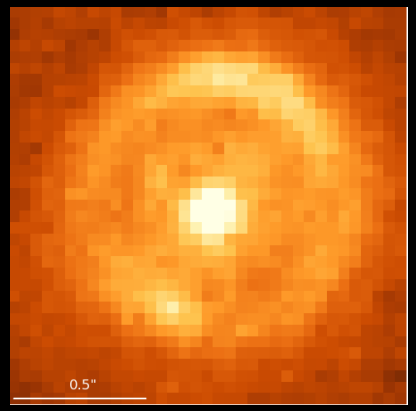
AO vs. Space: B1938+666



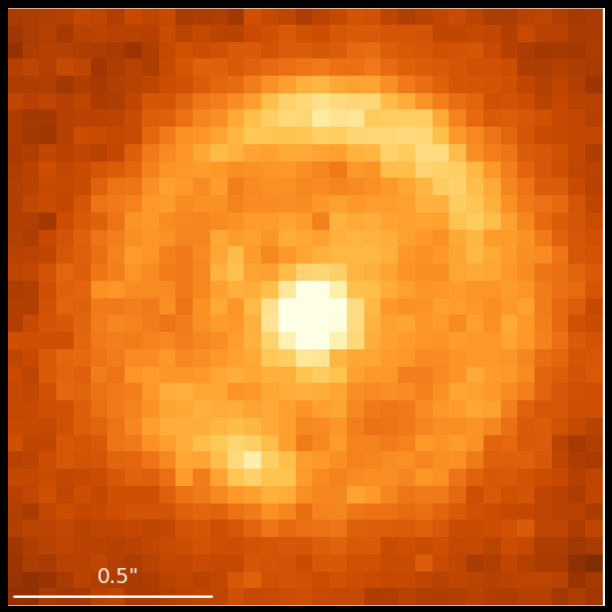
F555W



F814W

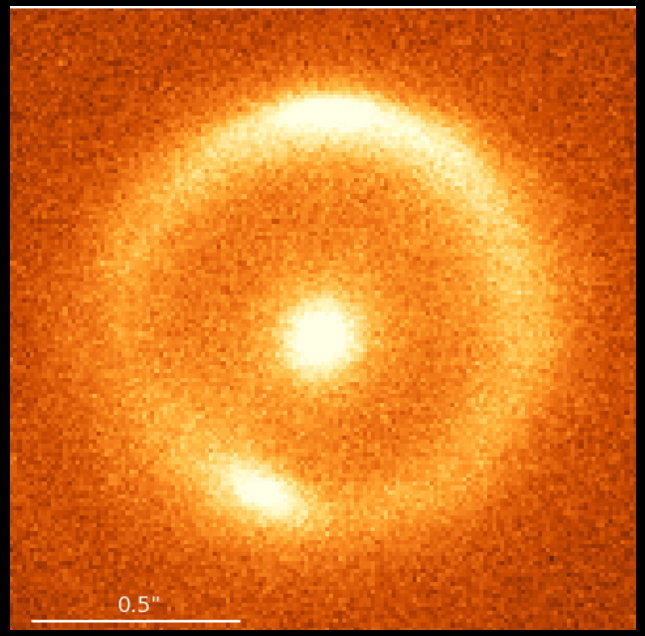


F160W



F160W, again

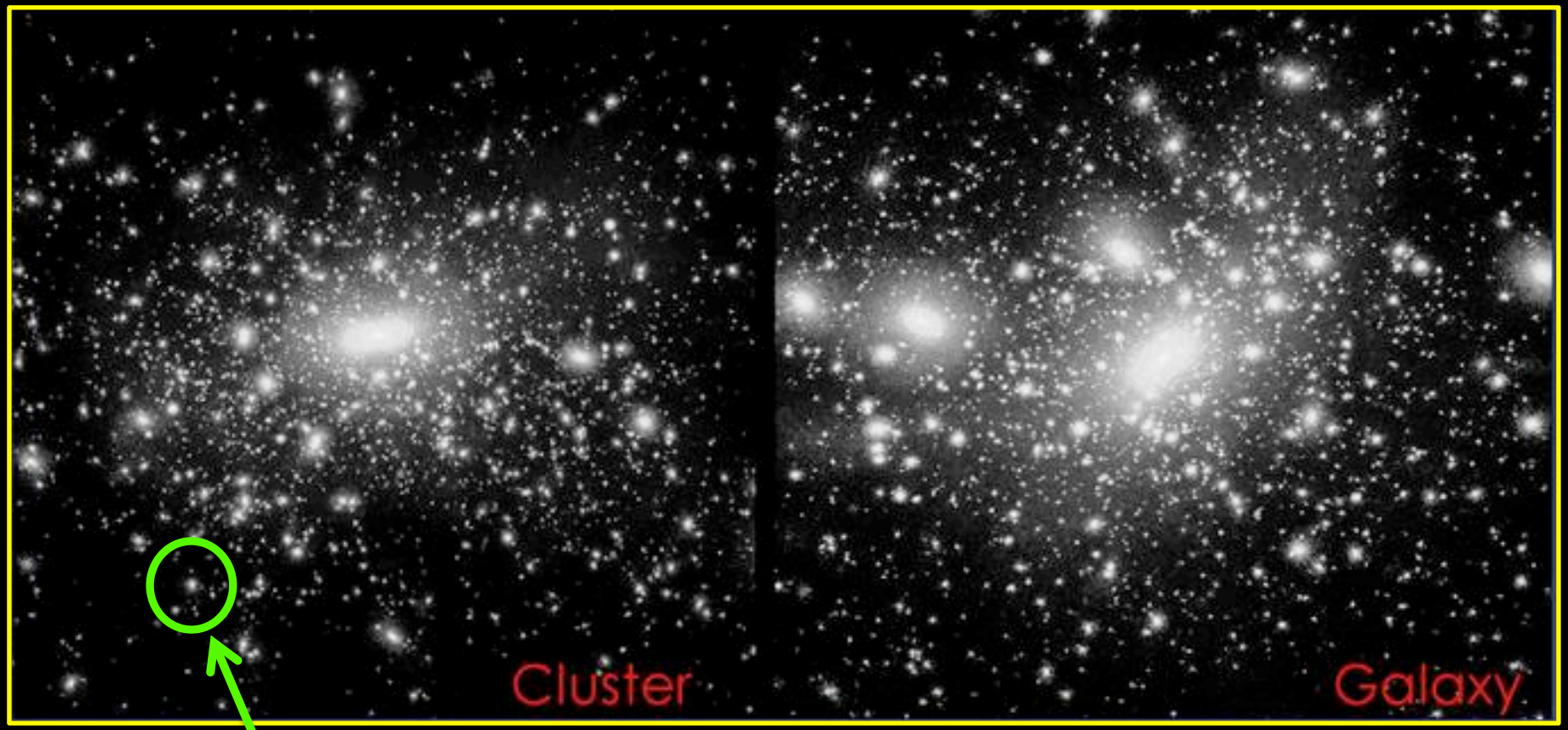
Keck AO K'-band



Fassnacht et al. in prep

The search for substructure via gravitational imaging

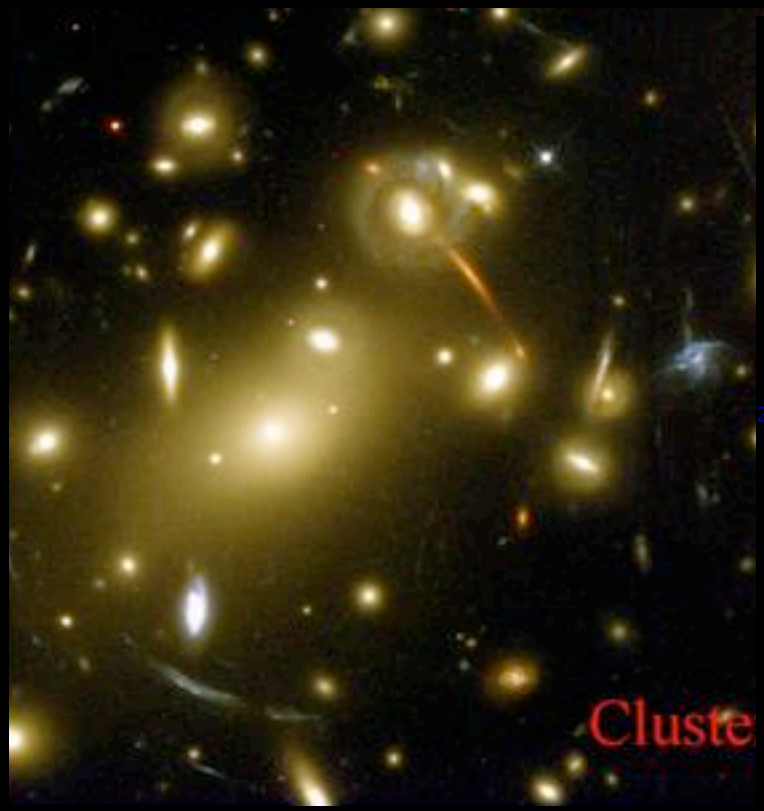
Substructure: Theory

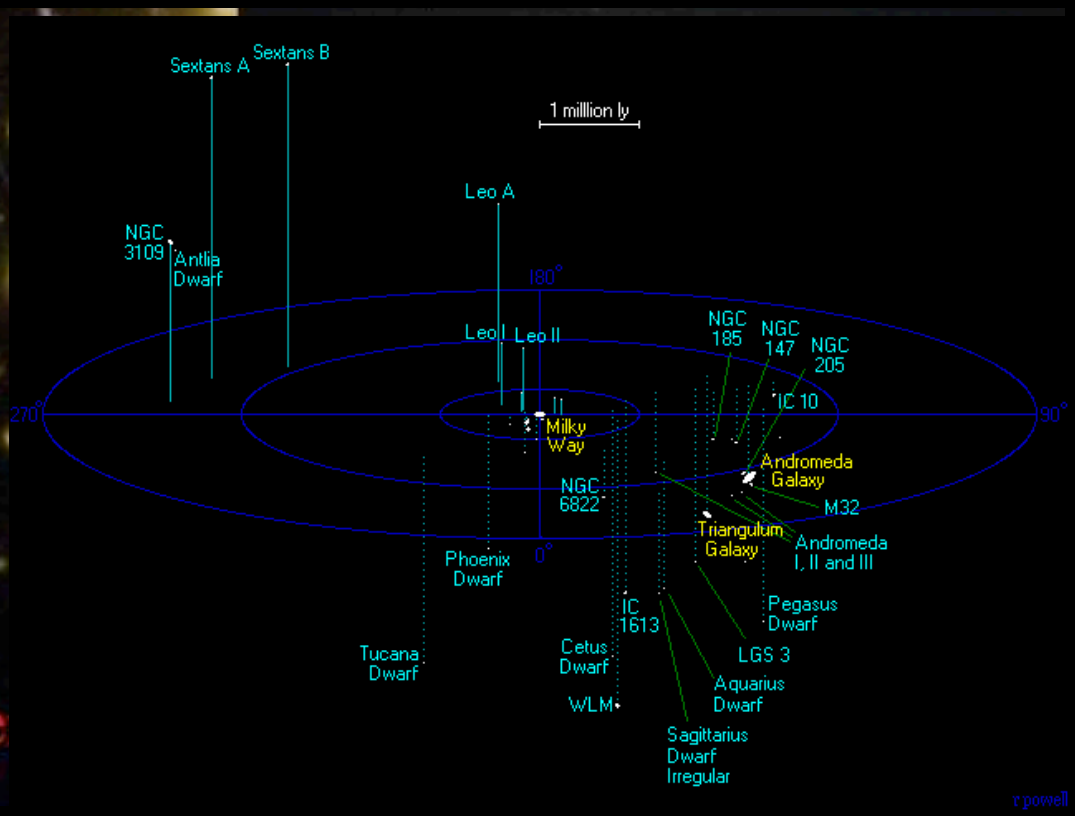


"Subhalo" or "substructure"

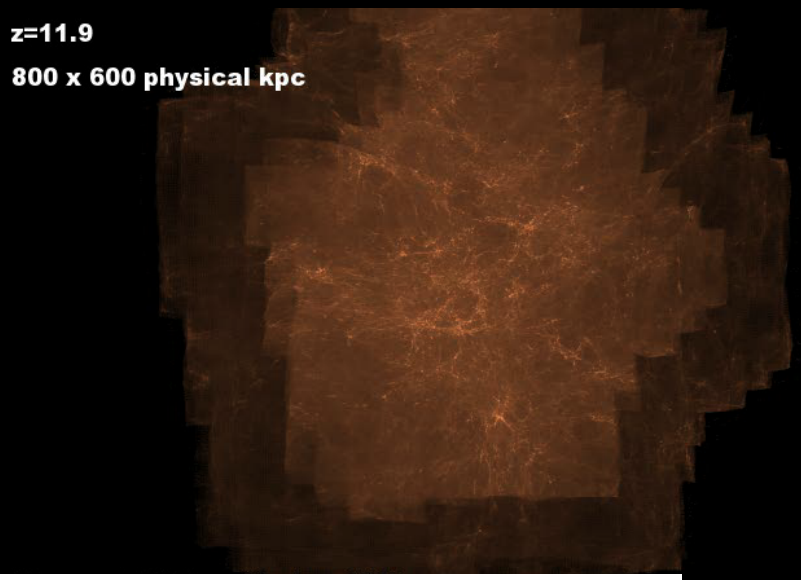
Kravtsov 2010

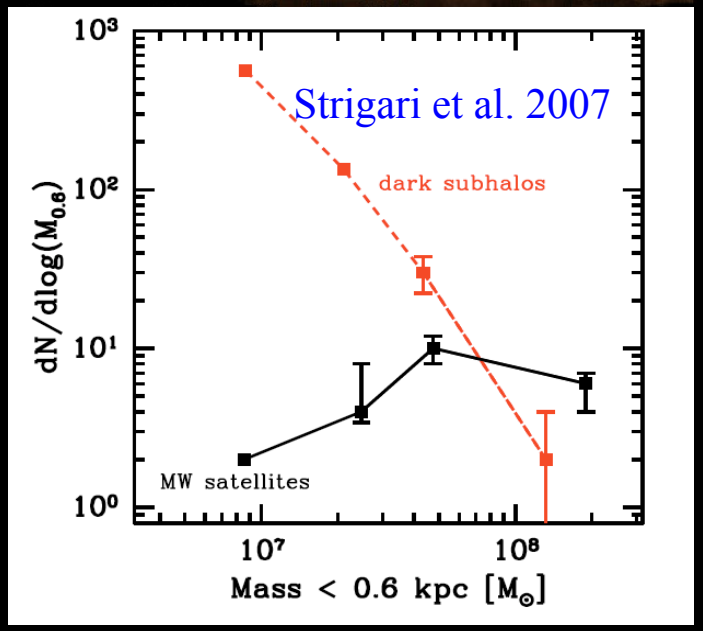
Substructure: Observations





Observations confront Simulations





- Simulations predict:
  - slope of mass function, α
  - normalization, f_{sub}
- MW observations don't match the simulations
- Explanations:
  - substructures are there but are not visible
  - some property of dark matter suppresses structure formation on small scales
  - the MW is an outlier
- The MW only is one system: We need better statistics!

How to make progress

- To distinguish between hypotheses, we need a method that can:
  - Detect substructure around many galaxies, in order to build up statistical samples
  - Detect substructure even if it is purely dark
  - Directly measure the masses of the substructures
- Gravitational lensing to the rescue – search for gravitational signatures of substructure
  - Works for cosmologically distant galaxies
  - Works for even purely dark substructure
  - Provides a direct measurement of the substructure mass

Gravitational Imaging

- Lensed extended emission (arcs/rings) provides many samples of the lensing gravitational potential
- Look for distortions in the arcs or ring that are due to substructure.
  - Substructure can be purely dark and still be detected
- Note: this is just of several methods to find substructure in lenses.

Gravitational imaging in a group-scale lens

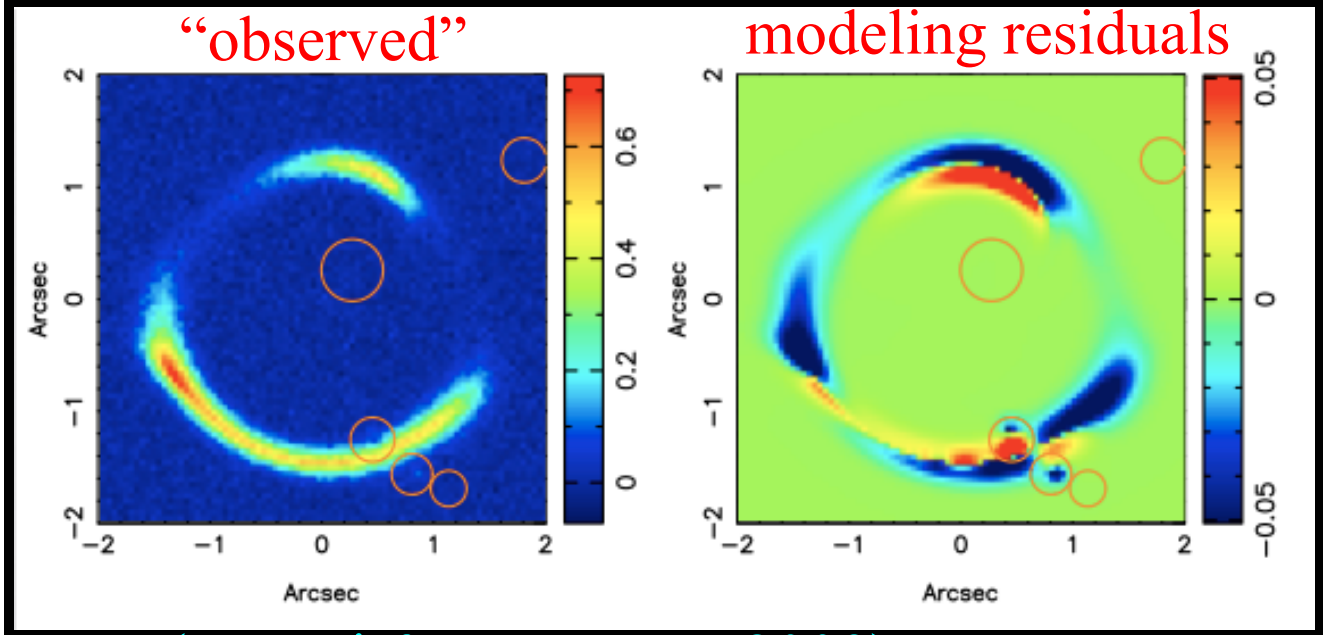
"The Clone" (Vegetti et al. 2010)

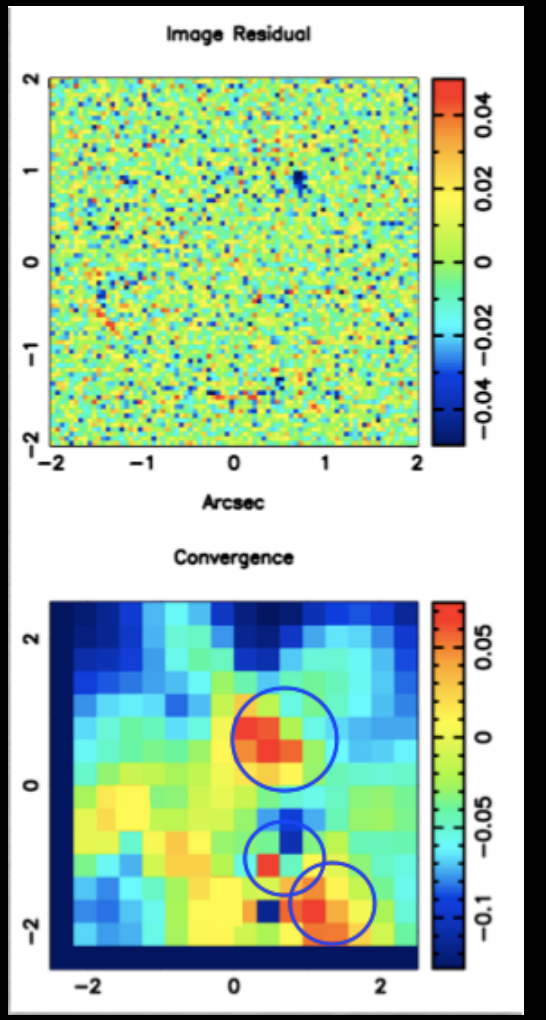
Gravitational imaging in a group-scale lens

Remember, larger masses mean larger image splitting
=> need better resolution to detect smaller masses

Can this work for galaxy-scale lenses?

- Simulated observations say yes
- Blind test with multiple substructures
- Detect down to ~10^8 M_{sun} near ring





(Vegetti & Koopmans 2009)

Observations Confront Simulations

- Look at simulated halos and predict the number of expected detections
- Simulations predict:
  - $P(N_{det} \mid \alpha, f_{sub}, M_{lim}, N_{lens})$
  - Compare to number actually detected
- Turn around to get:
  - $P(\alpha, f_{sub} \mid N_{det}, M_{lim}, N_{lens})$

$f_{sub} \sim 5\%$ within virial radius

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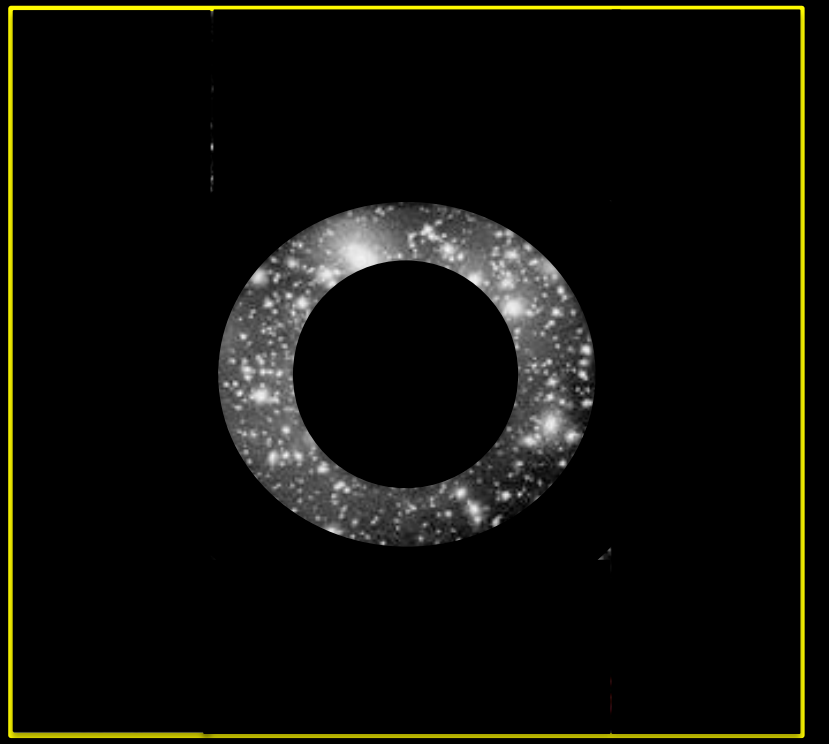


$f_{sub} <\sim 0.4\%$ within 10 kpc

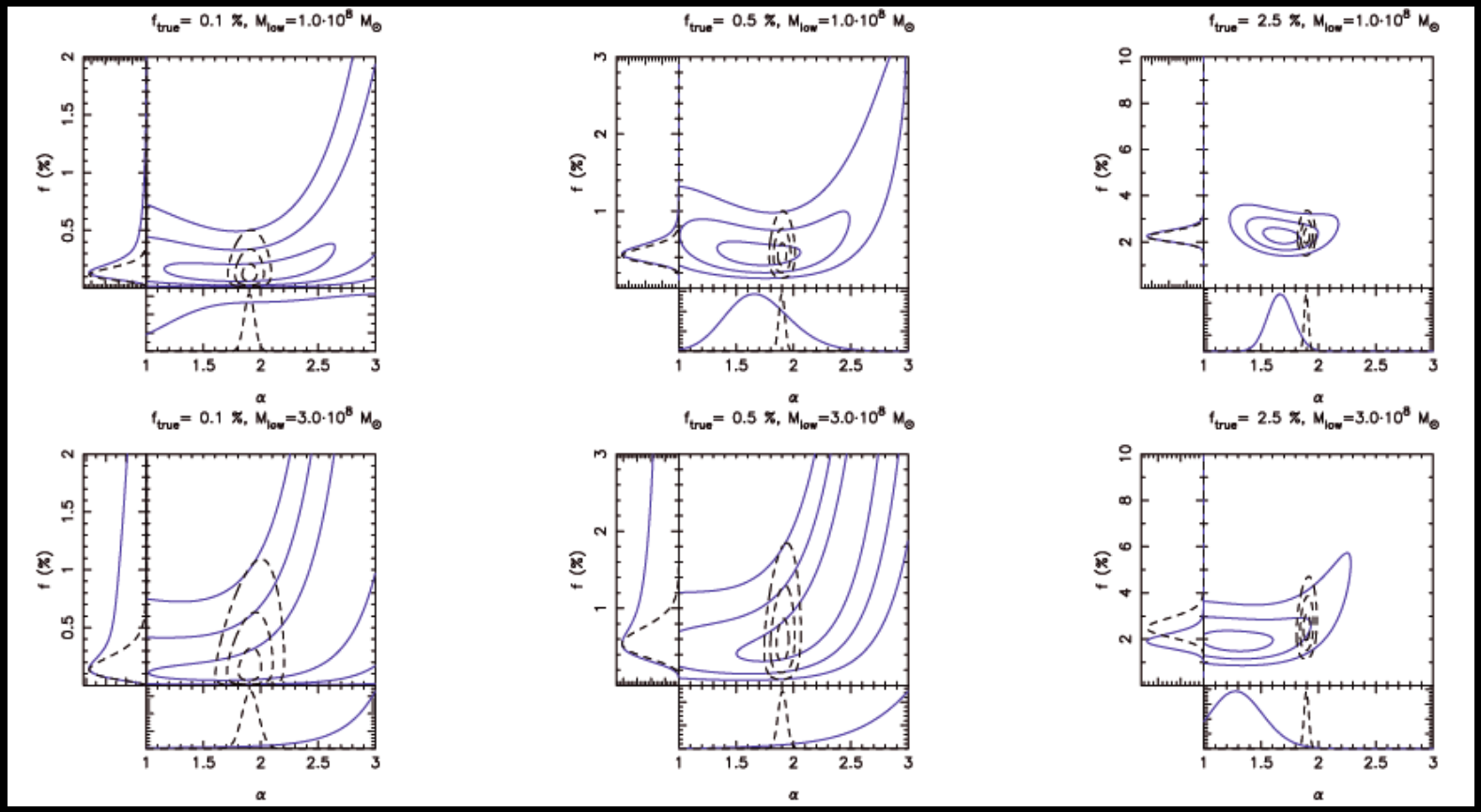
Quantifying the substructure mass distribution

- Precision in α and f_{sub} is set by N_{lens}, N_{det}, and M_{lim}

Simulations for $N_{lens} = 30$

f_{sub} (true) →

f_{sub}



$M_{lim} = 10^8\ M_{sun}$

$M_{lim} = 3x10^8\ M_{sun}$

α

What sets M_{lim}?

- Angular resolution of the observations
- Signal to noise ratio of the ring
- Surface-brightness structure of the lensed object
  - lots of knots of star formation is better than a smoothly-distributed old stellar population

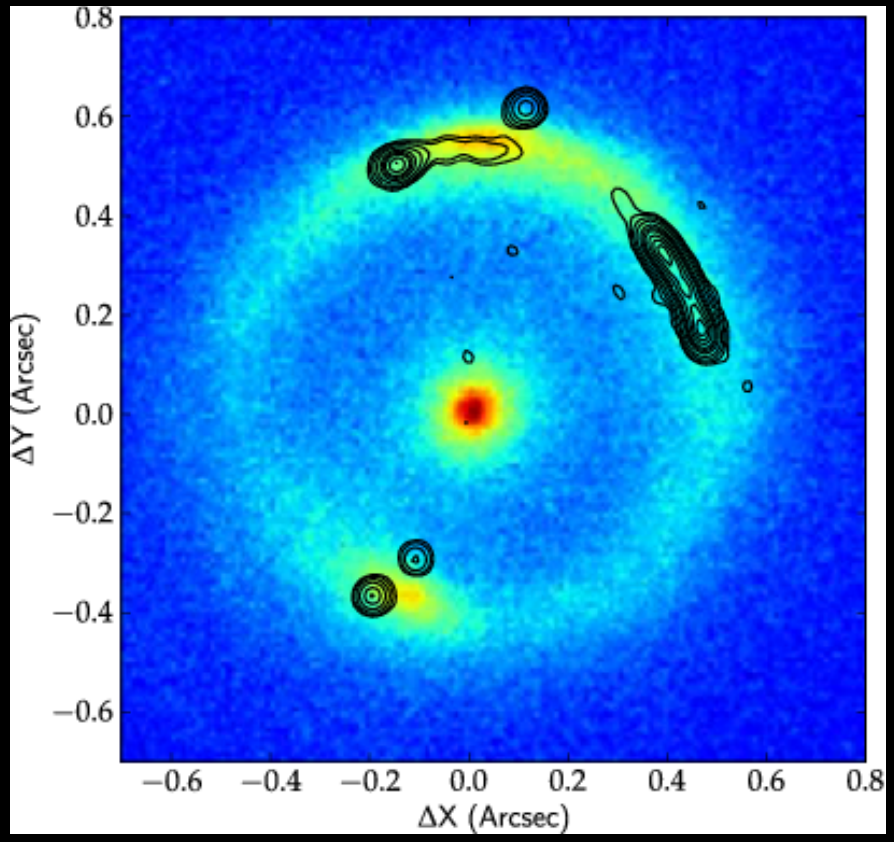
SHARP: The Strong-lensing High Angular Resolution Program

- Collaborators
  - Simona Vegetti (MIT)
  - Dave Lagattuta (Swinburne)
  - Matt Auger (Cambridge)
  - John McKean (ASTRON)
  - Leon Koopmans (Kapteyn)

SHARP Logistics

- Focus on systems with 4 lensed images or prominent arcs/rings
- For AO, need bright (R<17) tip-tilt star within ~60 arcsec
  - restricts size of available sample
- Ultimate goal for depth of AO imaging: ~3-4 hours integration time per target
  - enables search for substructure less massive than LMC/SMC
- Goal for sample size: ~20 systems

Gravitational Imaging: B1938+666



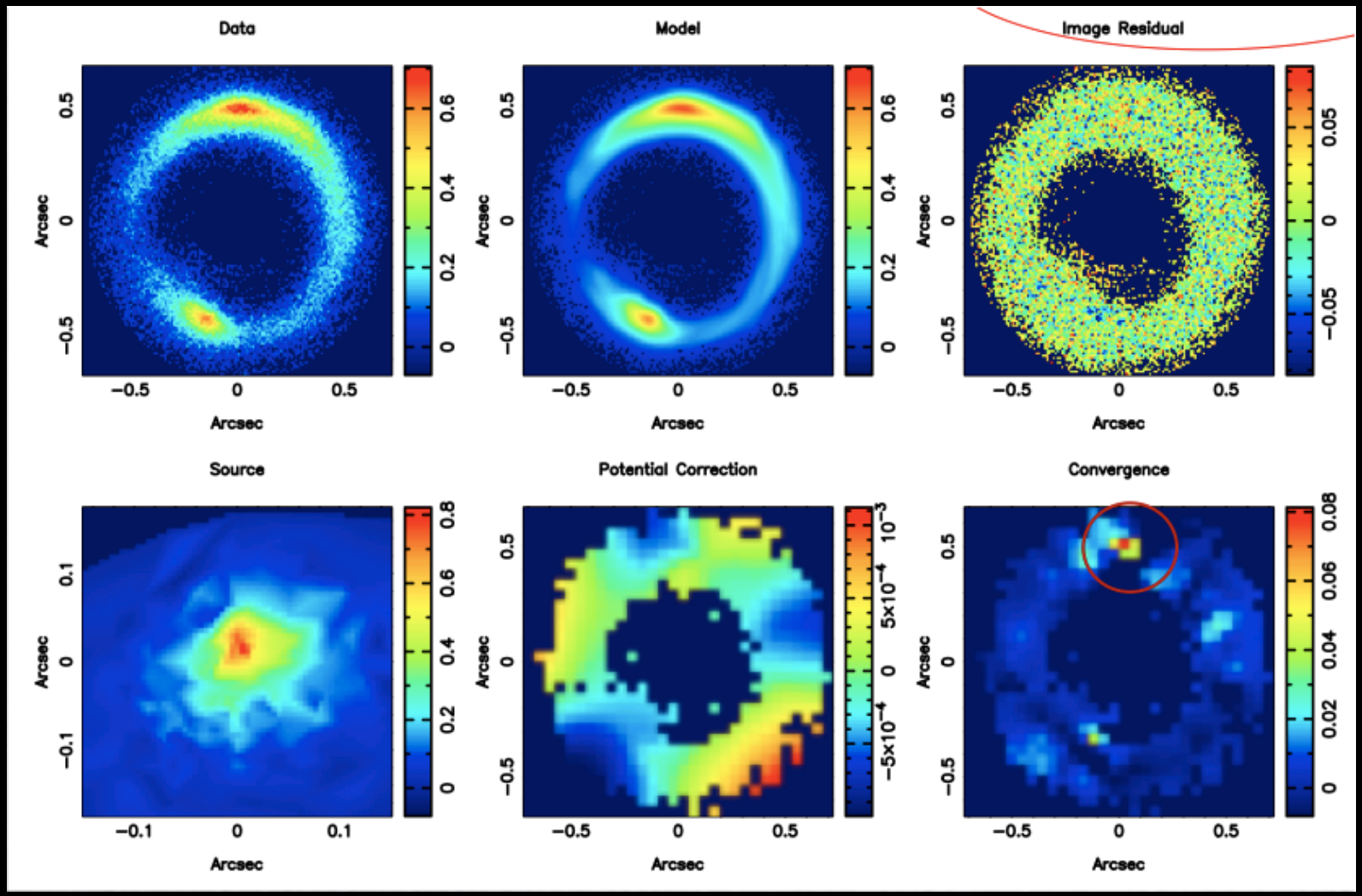
Color: AO data
Contours: Radio data from MERLIN

Lagattuta et al., 2012

z_{lens}= 0.881 (Tonry & Kochanek 2000)
z_{source} = 2.059 (Riechers et al. 2011)

B1938+666: Keck AO K'

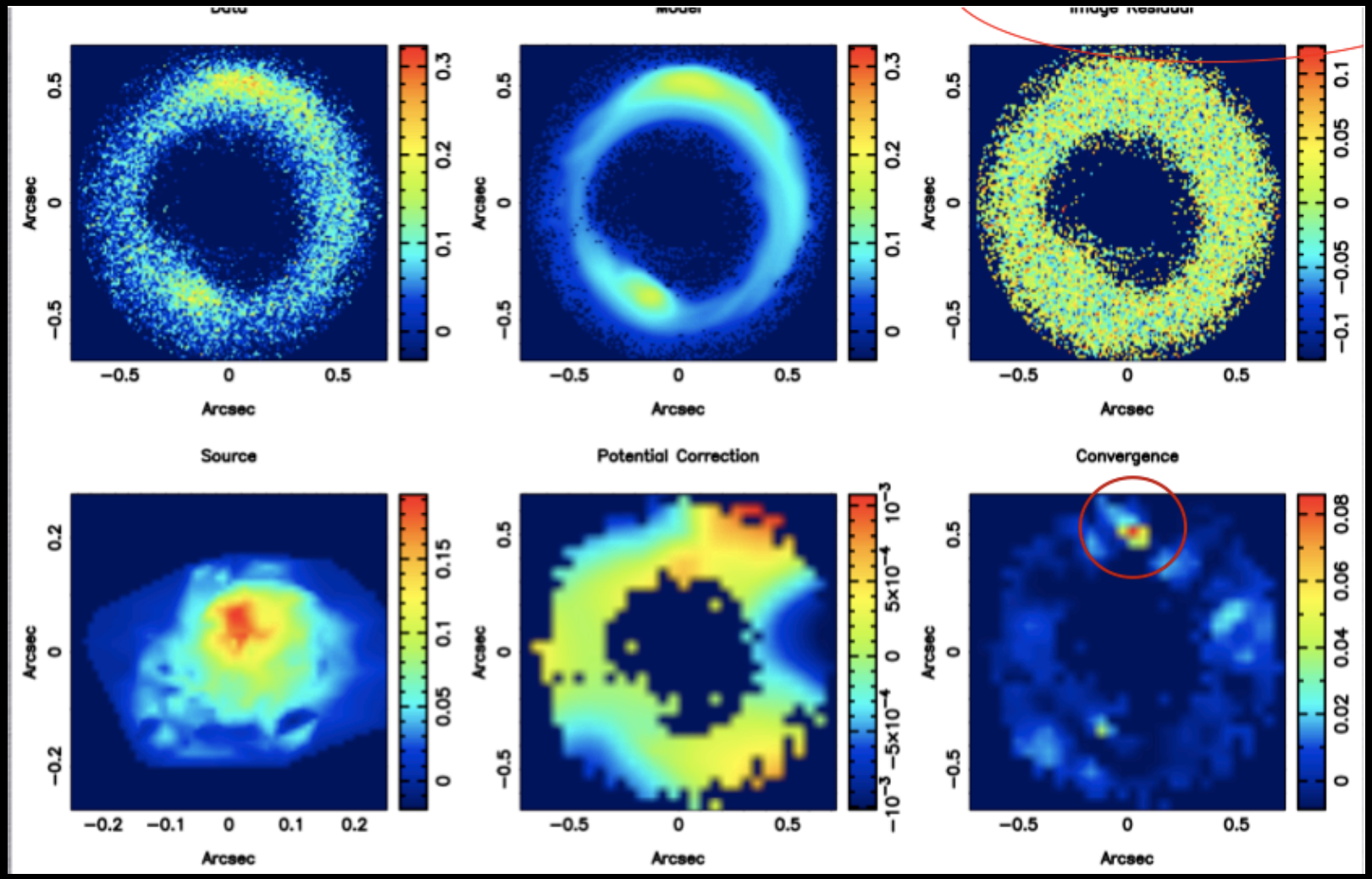
$M \sim 1.7 \times 10^8 M_{sun}$



Vegetti et al. (2012)

B1938+666: Keck AO H

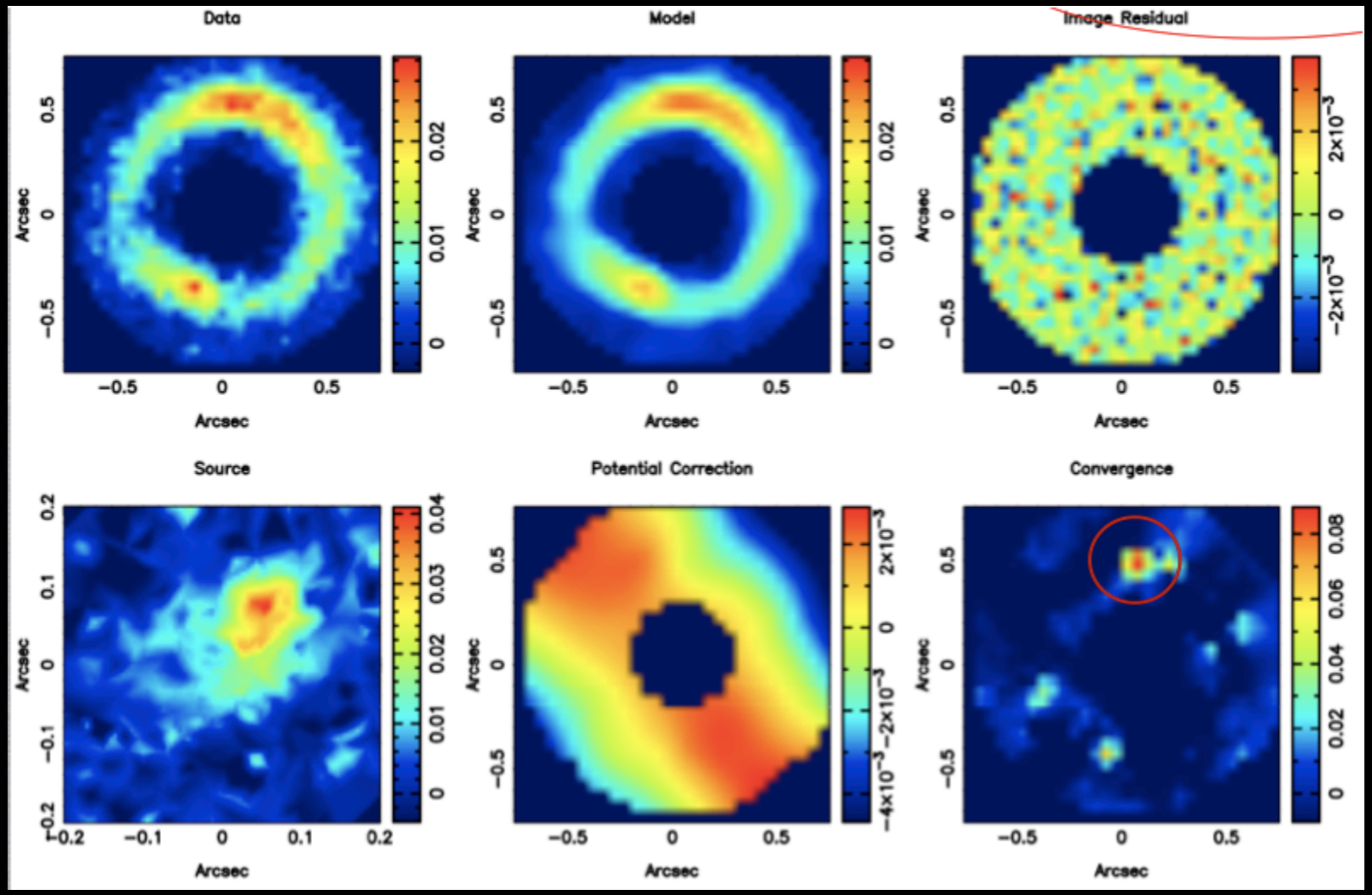
$M \sim 1.7 \times 10^8 M_{sun}$



Vegetti et al. (2012)

B1938+666: NICMOS F160W

$M \sim 1.7 \times 10^8 M_{sun}$

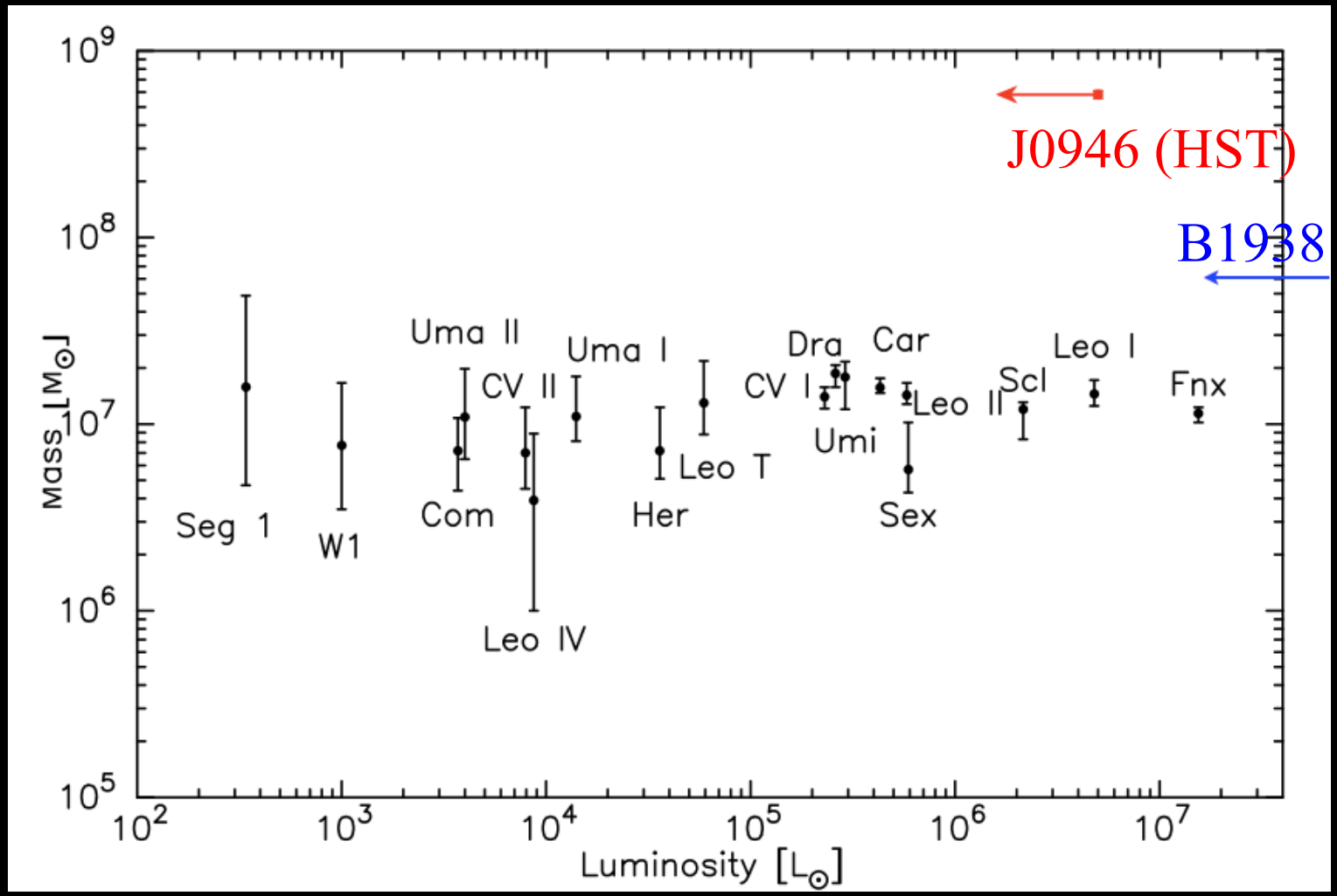


Vegetti et al. (2012)

Substructure properties

- Based on Bayesian evidence, this is a 12σ detection of the substructure
  - $\Delta \ln E = 65.0$
- Fit with an analytic model (truncated pseudo-Jaffe profile)
  - $M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$
  - $M_{sub}(r<600 \text{ pc}) = (1.15 \pm 0.06) \times 10^8 M_\odot$
  - $M_{sub}(r<300\text{pc}) = (7.2 \pm 0.6) \times 10^7 M_\odot$
- This is ~20 times less massive than the only other substructure detected via gravitational imaging (HST data only)

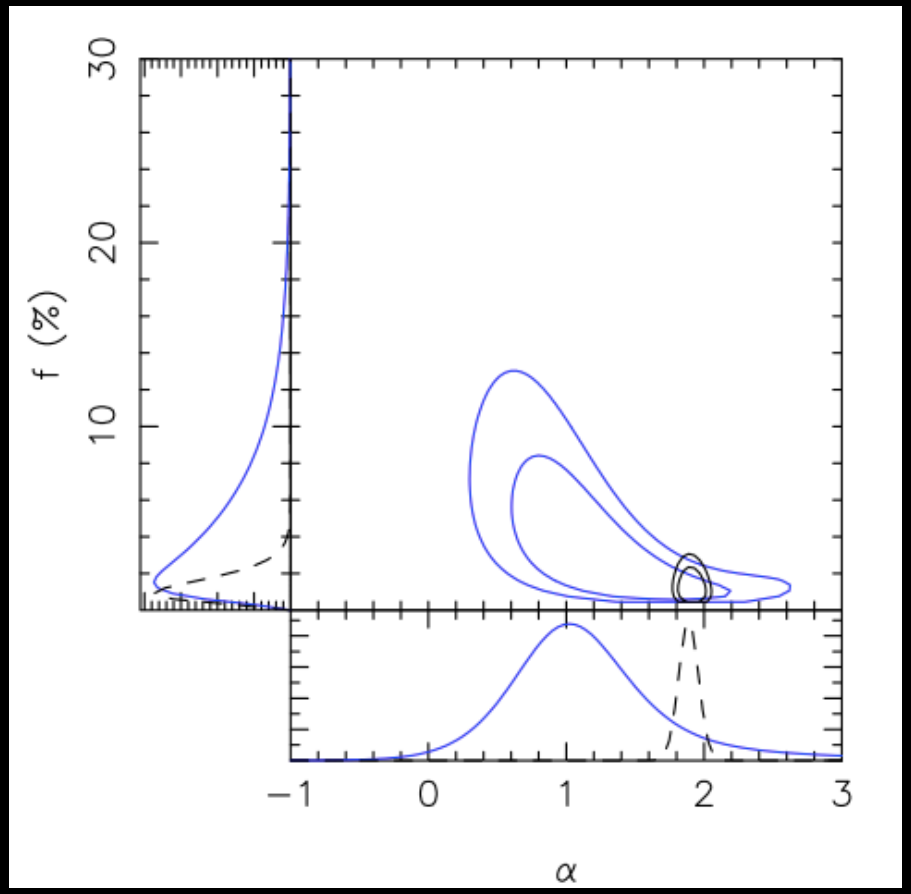
Comparison to MW satellites



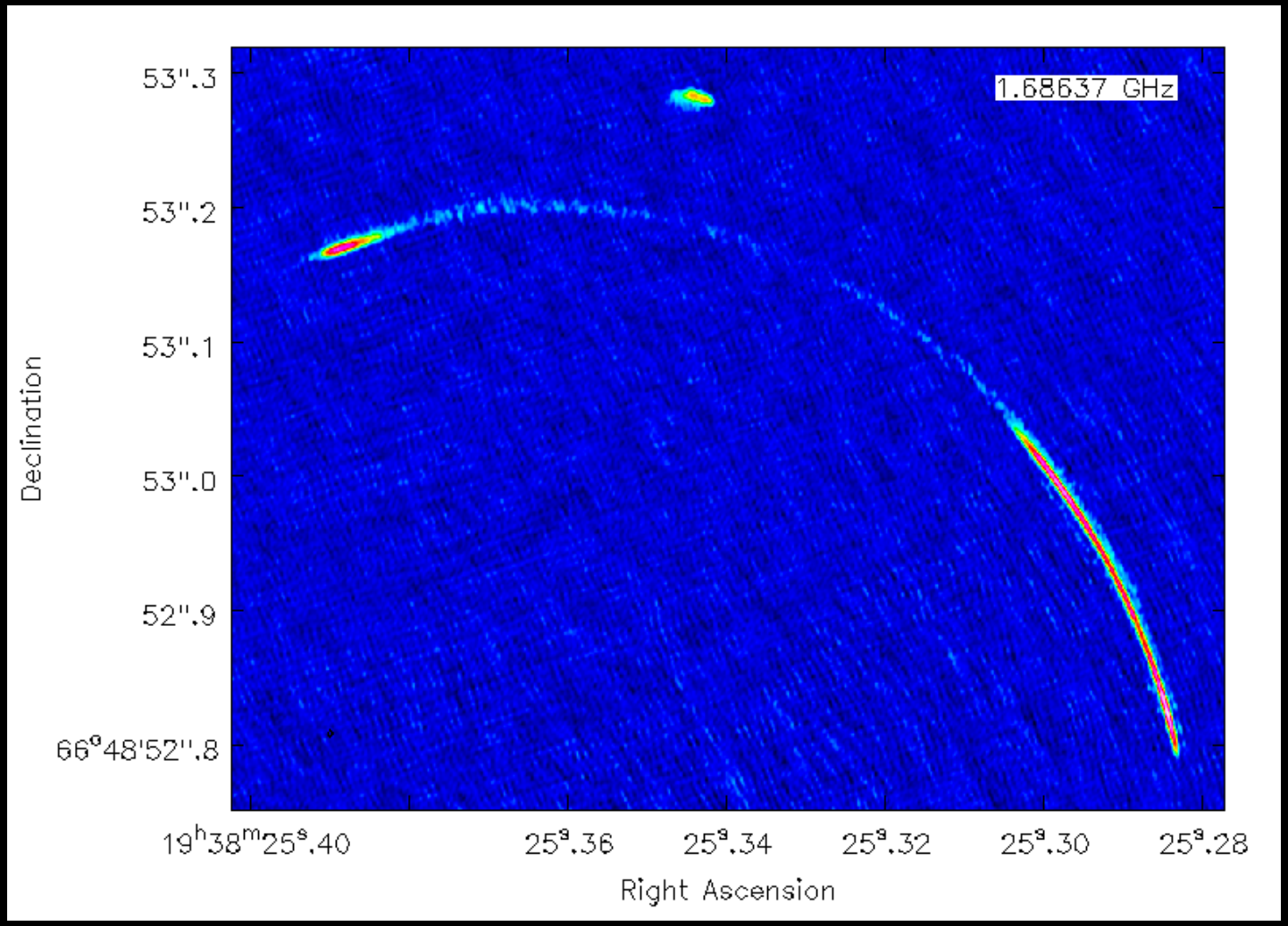
Strigari et al. 2008

Quantifying substructure (first steps)

- Use 2 systems that we've analyzed so far (B1938, J0946)
- With a flat prior on α:
  - $f_{sub} = 3^{+4}_{-2}$ %
  - $\alpha = 1.0^{+0.6}_{-0.4}$
- With a Gaussian prior on α:
  - $f_{sub} = 1.2 \pm 0.6$%
  - $\alpha = 1.87^{+0.08}_{-0.04}$
- Simulations predict:
  - $f_{sub} \sim 0.1$% (with caveats)
  - $\alpha \sim 1.9$



B1938+666 VLBI



Gravitational imaging with radio data – McKean et al., in prep

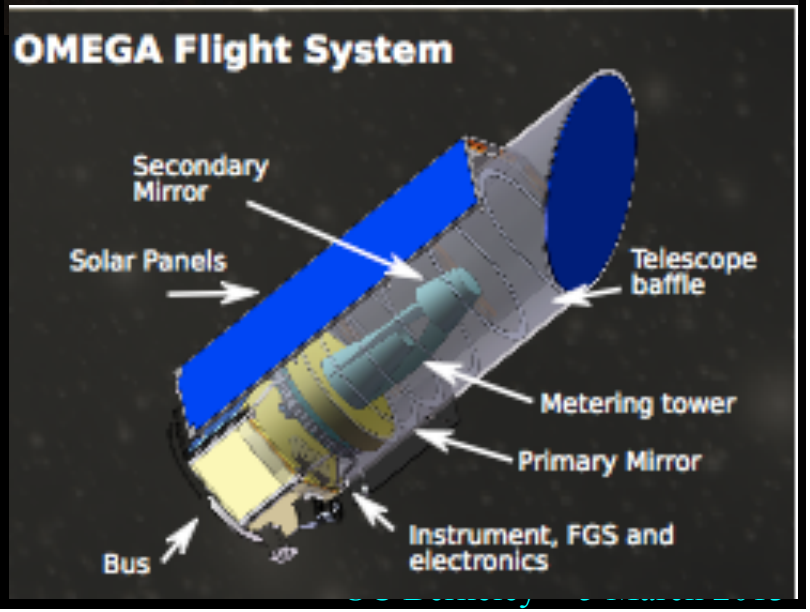
SHARP results in the literature

- SHARP –I : McKean et al. 2007, MNRAS
  - Luminous substructure in B2045+265
- SHARP 0: Lagattuta et al. 2010, ApJL
  - B0128+357 results
- SHARP **: Vegetti et al. 2012, Nature
  - B1938+666 substructure
- SHARP I: Lagattuta et al., 2012, MNRAS
  - More info on B1938+666
- SHARP II: Fassnacht et al., in prep
  - Survey description and smooth modeling
- SHARP III: McKean et al. in prep
  - Radio observations of B1938+666

Also: Suyu et al. 2012, ApJ, 750, 10

Future work

- Short term
  - increase the sample to ~20
- Midterm
  - NGAO on Keck (improve Strehl to 90%)
- Long-term
  - Pan-STARRS/LSST/Euclid, etc. should give thousands of new lenses
  - TMT will give ~9 times the collecting area and ~3 times the resolution
  - OMEGA provides a possible alternative path (See Keeton & Moustakas 2009)

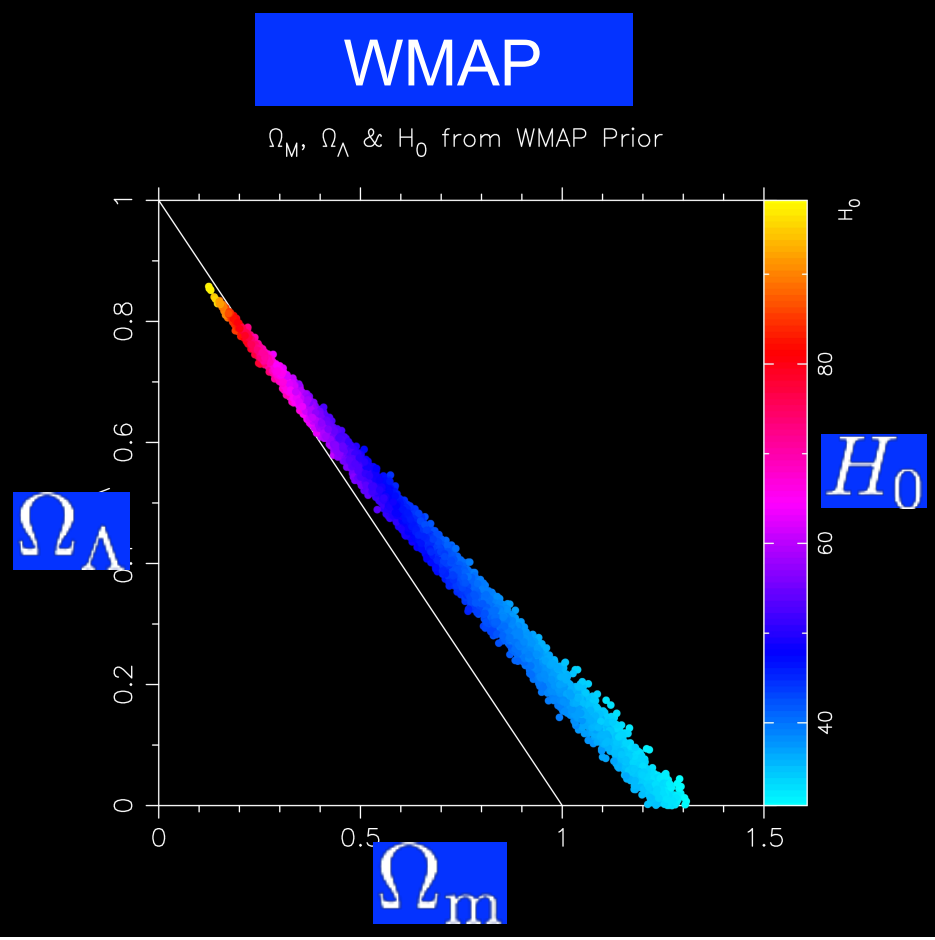


Dark energy measurements with time-delay lenses

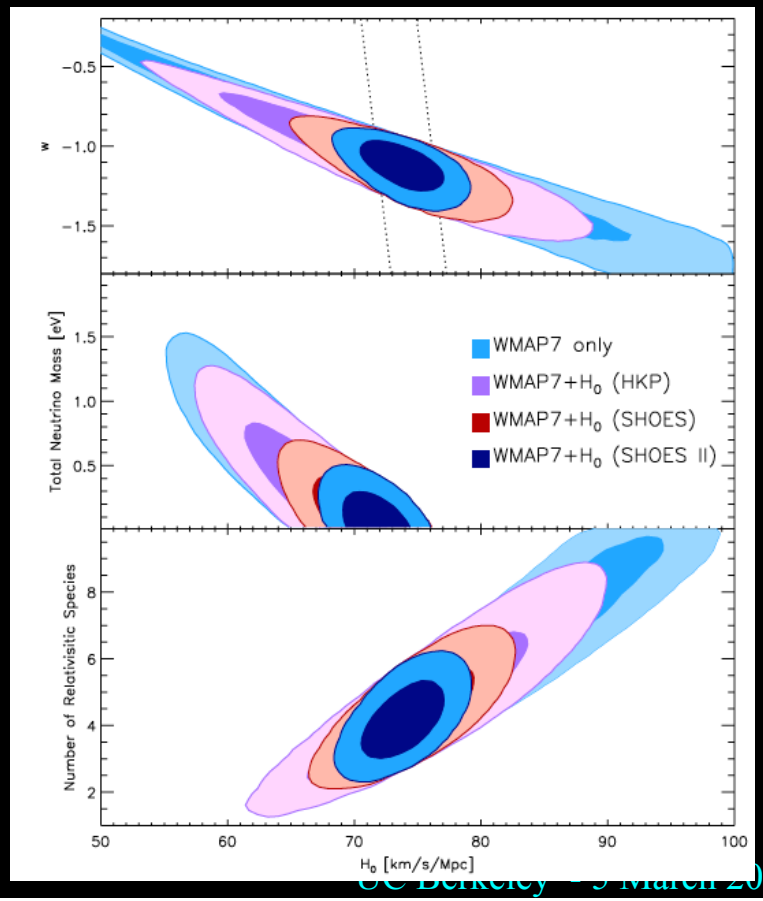
Motivation

Key Question: *What is the nature of dark energy?*

H_0 is the single most useful complement to CMB parameters for dark energy studies [e.g. Hu 2005, Riess et al. 2009, 2011]



Riess et al. 2011



Motivation, continued

- Several methods to break the degeneracy
  - each provides a big improvement when combined with CMB
  - each has (possibly unknown) systematics
- So, obtain high-precision measurements with several *independent* methods to test for systematics and improve accuracy
- Lensing is an important part of this effort

$$D_{\Delta t} = \frac{c\Delta t}{\frac{1}{2}(\theta - \beta)^2 - \psi(\theta)}$$

From time delays to cosmology

$$D_{\Delta t} = \frac{c\Delta t}{\frac{1}{2}(\theta - \beta)^2 - \psi(\theta)}$$

- Observables
  - Δt , θ, z_l, z_s
- Model of the mass distribution in the lens
  - β, $\psi(\theta)$
- Cosmology
  - $D_{\Delta t} = f(z_l, z_s, H_0, \Omega_M, \Omega_\Lambda, w)$

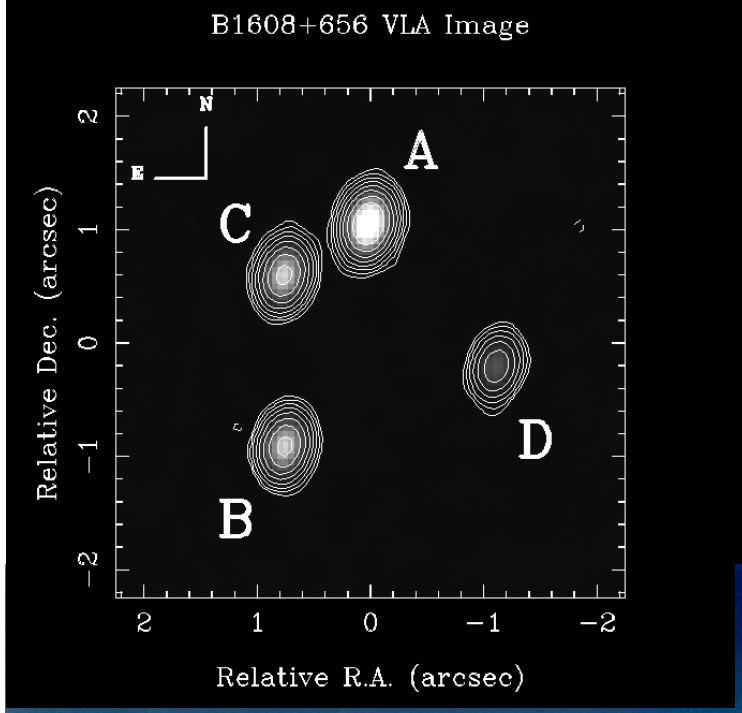
A very brief history of cosmology from lenses

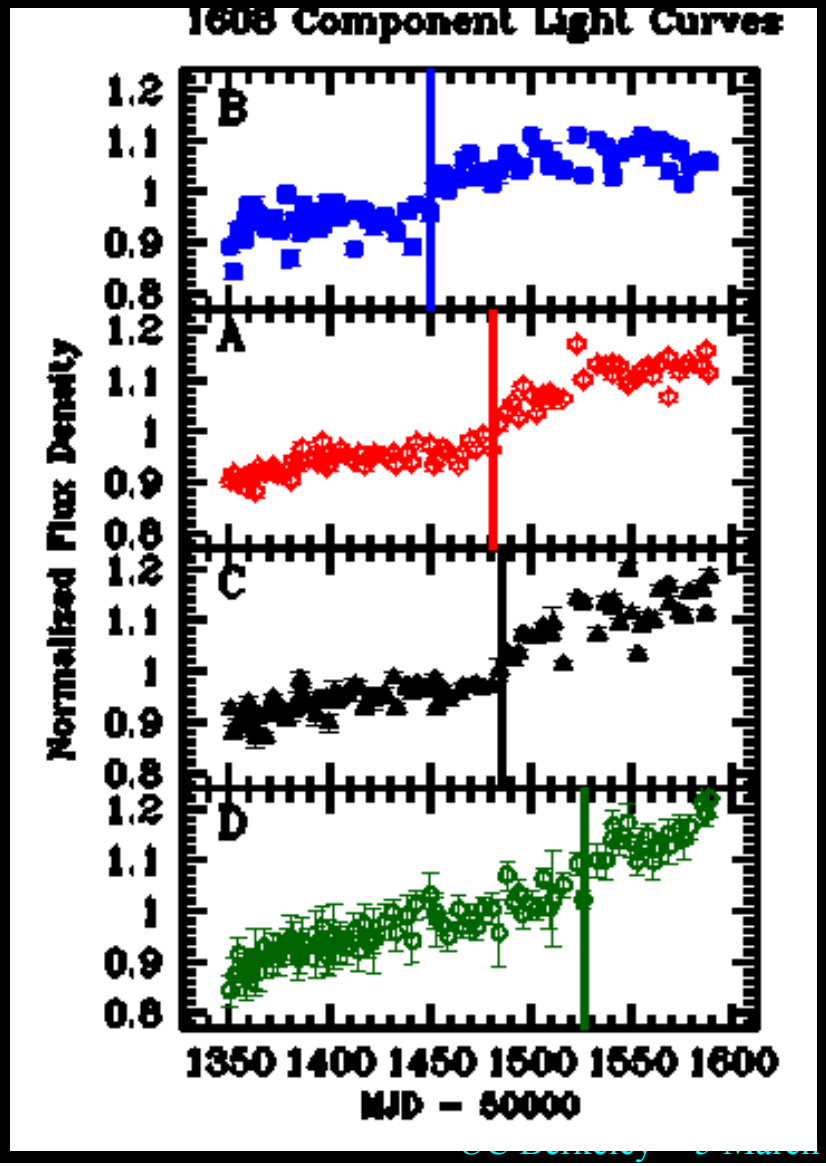
- 1979: First gravitational lens discovered
- 1980s and early 90s:
  - Only a few lenses known.
  - Time delays are very controversial
- Mid 1990s – mid 2000s:
  - Dedicated time delay programs produce high-precision measurements
  - Modeling makes unwarranted assumptions, giving big spread in derived values of H_0
- Late 2000s – today:
  - Improvements in modeling and data lead to first robust high precision measurements
  - Two best cases so far: B1608+656 and RXJ1131-1231 (Suyu et al. 2010,2013)

A tale of two lenses

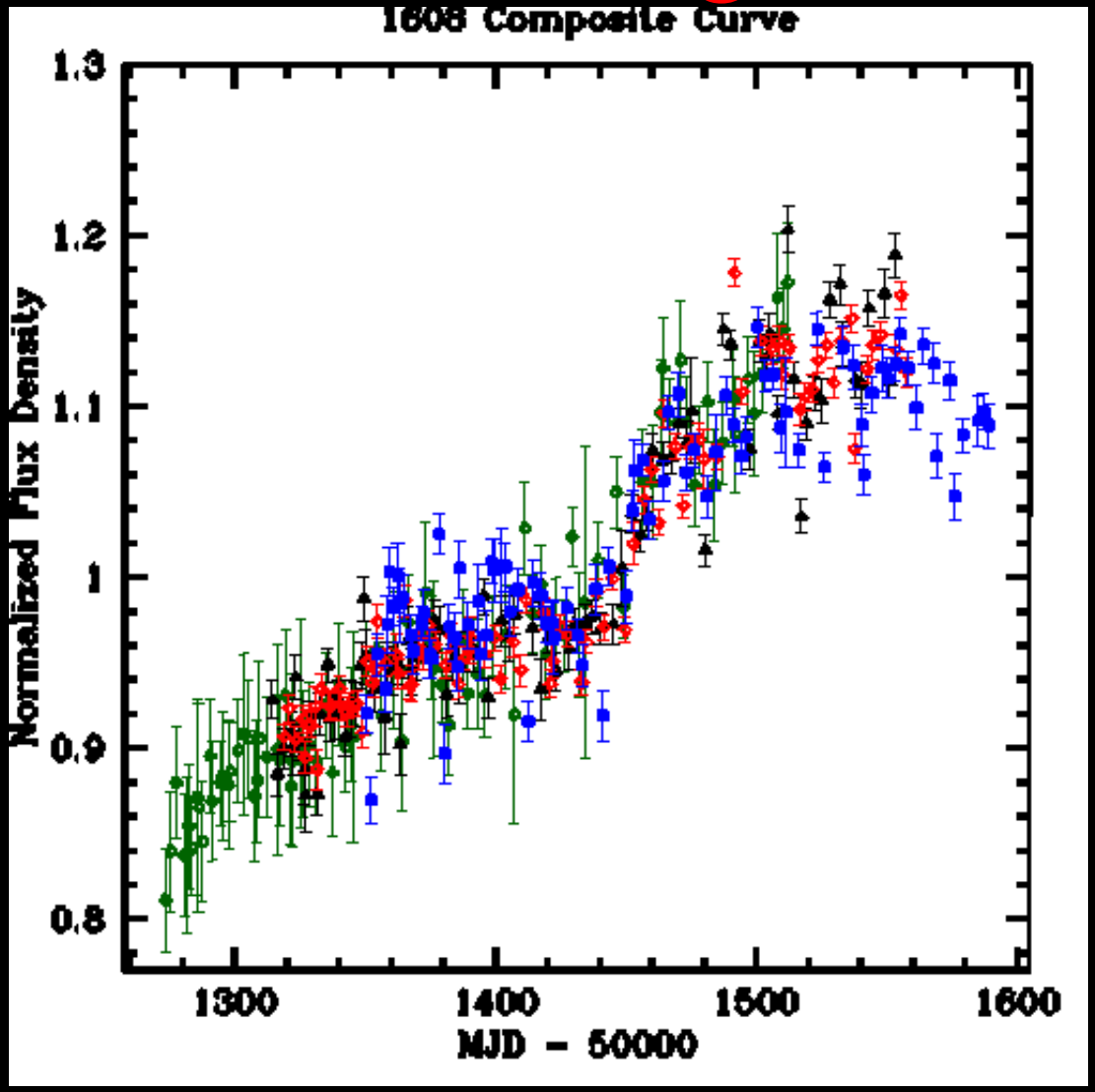
- B1608+656 and RXJ1131-1231 are the only two strong lens systems for which we currently have all of the required high-quality data
- Need
  - High-precision time delays
  - Well-constrained mass model
  - Redshifts of lens and background object

Measuring Δt in B1608+656





Measuring Δt in B1608+656



Fassnacht et al. (2002)

- Relative time delays (Fassnacht et al. 1999, 2002)

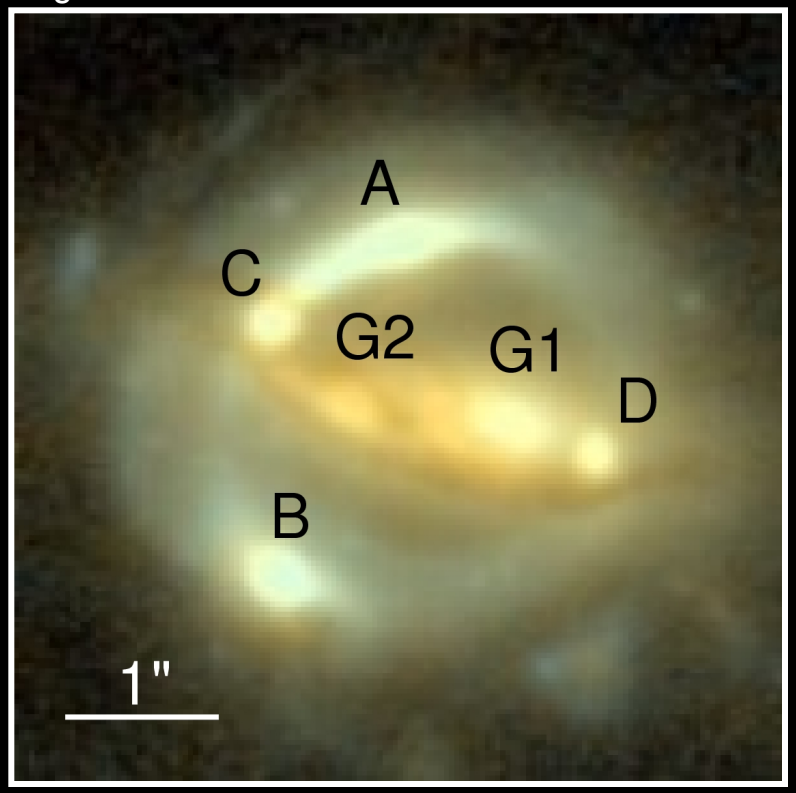
$$\Delta t_{AB} = 31.5\ ^{+2.0}_{-1.0}\ \text{days}$$

$$\Delta t_{CB} = 36.0 \pm 1.5\text{days}$$

$$\Delta t_{DB} = 77.0\ ^{+2.0}_{-1.0}\ \text{days}$$

Mass models: B1608+656

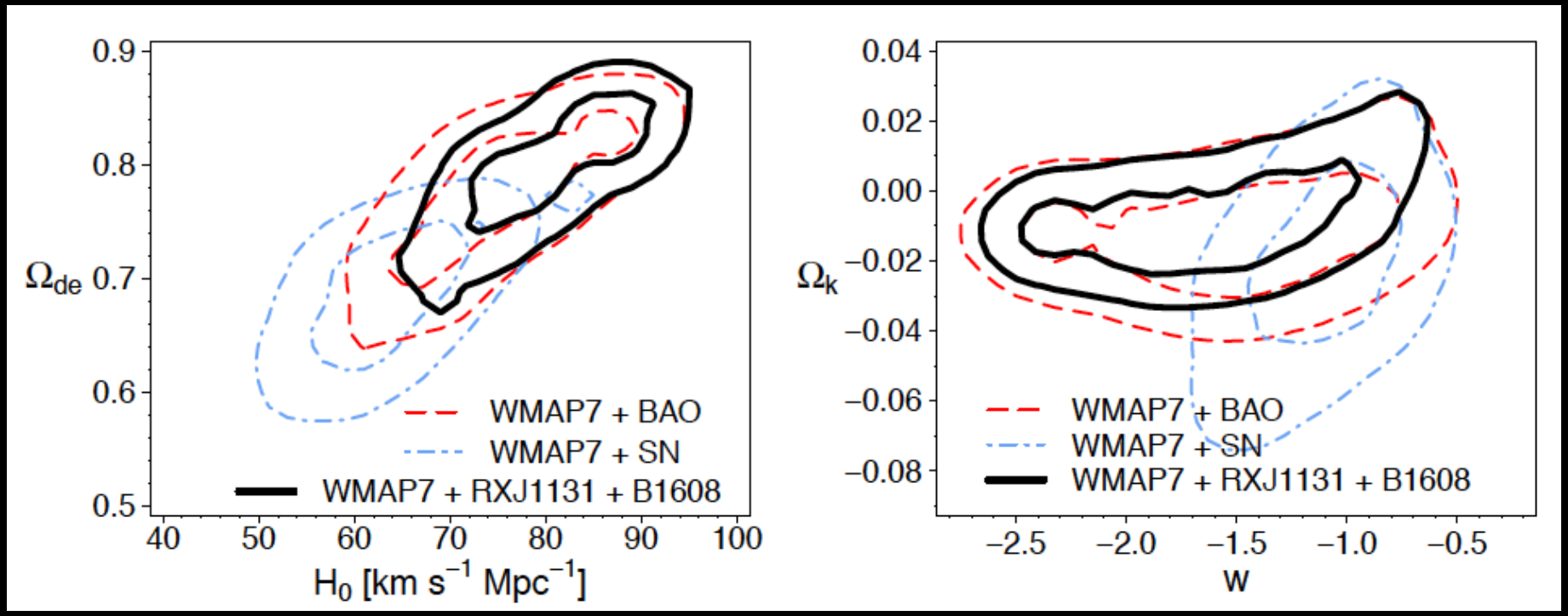
z_d = 0.63 (Myers et al. 1995)
z_s = 1.39 (Fassnacht et al. 1996)



B1608+656 provides a good opportunity to measure $D_{\Delta t}$ with high precision

- One of the biggest systematic errors for lenses: *the mass-slope degeneracy*
- This can be broken with high SNR detections of the lensed extended emission in the Einstein ring
- For B1608+656 we did this through deep (20 orbits) HST/ACS imaging (PI: Fassnacht)
- For RXJ1131-1231 this also came from HST

Constraints from 2 lenses

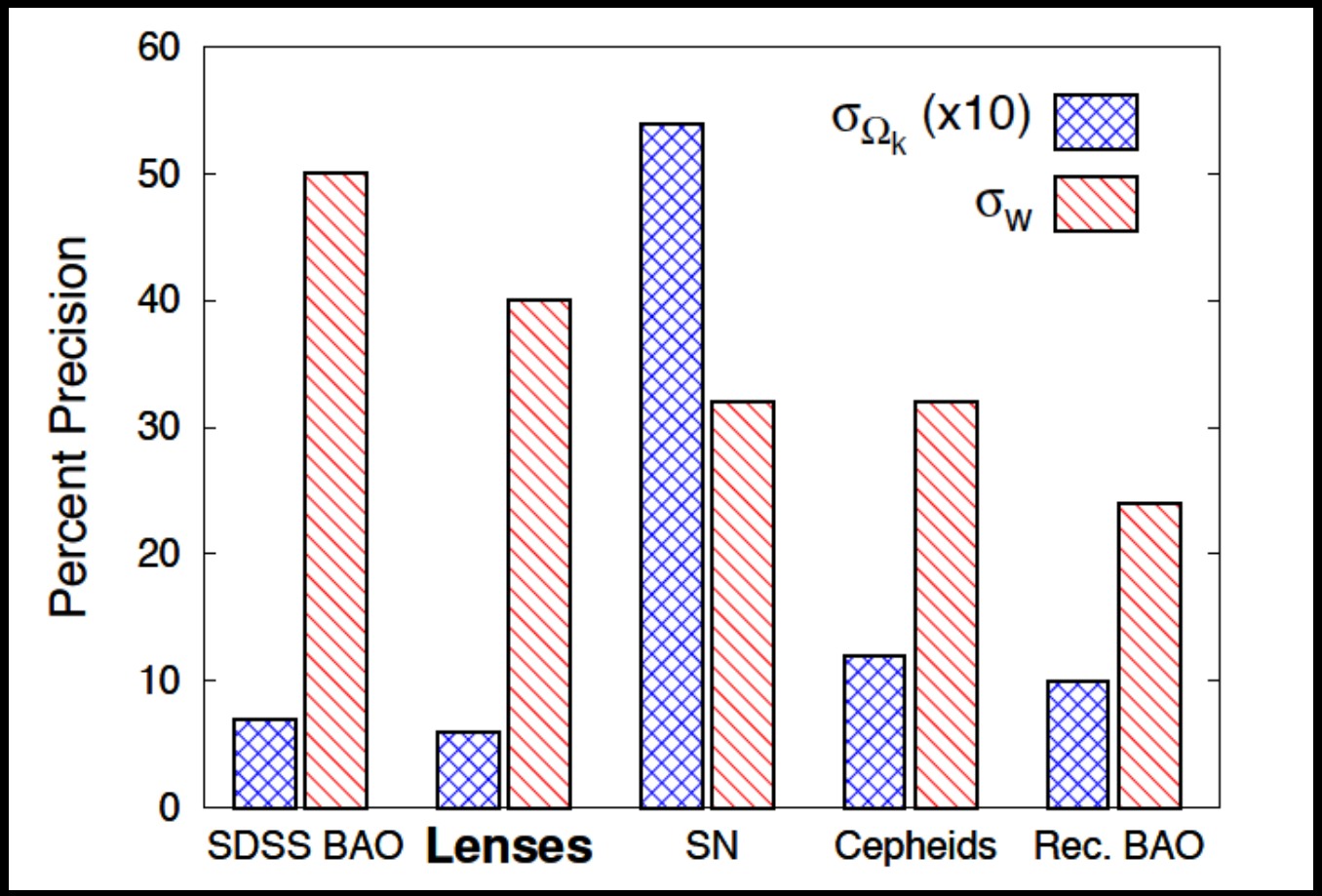


Suyu et al. 2012

(BAO data from Percival et al. 2010; SN data from Hicken et al. 2009)

NB: Blind analysis used for RXJ1131, and will be used for all of our future lens systems.

Constraints from 2 lenses: Measurement precisions



Suyu et al. 2012

Future prospects

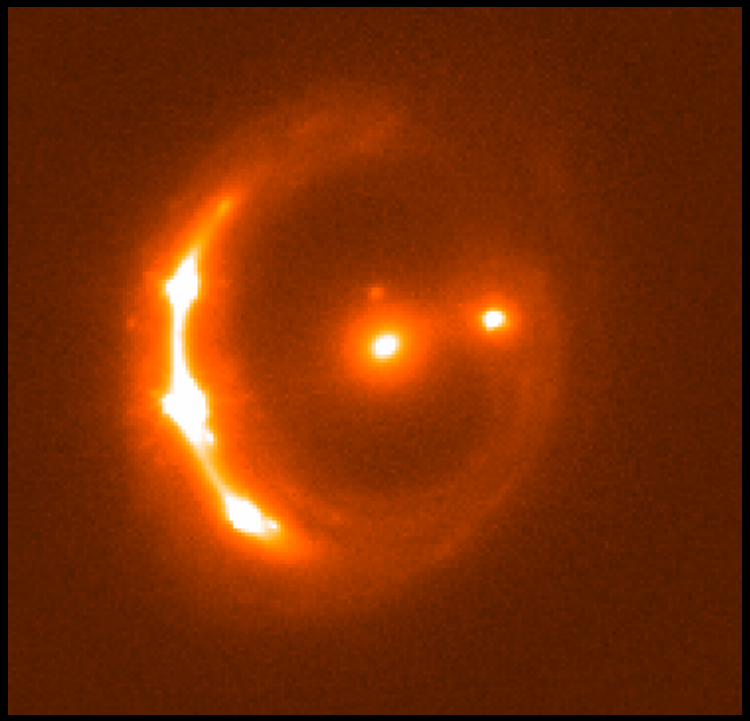
- Our simulations have shown that, once systematics have been controlled (e.g., mass-slope degeneracy), precision on cosmological parameters improves as ~1/sqrt(N)
  - See also Coe & Moustakas (2009), Dobke et al. (2009)
- Right now we only have 2 lenses (B1608+656 and RX J1131-1231) with all required data
- Need to increase the sample size of well-measured lenses

Can AO contribute?

- Quick answer: probably yes
- To break mass-slope degeneracy, need to detect arcs/rings at high SNR and *resolve them in the radial direction*
  - => need excellent angular resolution and sensitivity
- Right now, this is being approached with expensive HST observations
- AO provides an excellent alternative path

AO vs. Space: RXJ 1131

HST/ACS F814W



Keck AO Ks

Fassnacht et al. in prep

Requirements and Wishes

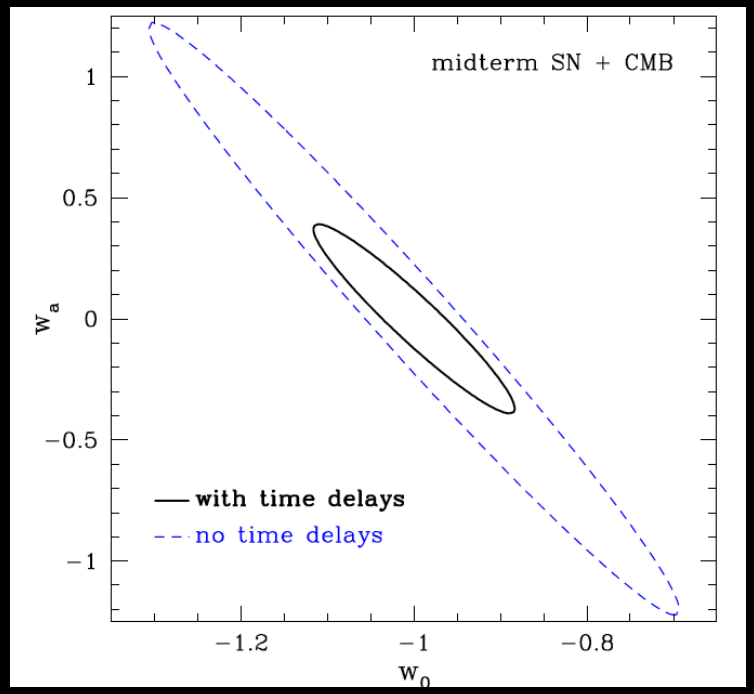
- Diffraction-limited imaging is a must
  - need to resolve the ring in the radial direction
- Must understand the PSF
  - disentangle lens and background source emission
  - We're testing now with Keck AO data, but lack of knowledge of the PSF may be the biggest problem with current data
  - Best if we could reconstruct the PSF from the data
- Small FOV is OK
  - most lens systems are 1-3 arcsec across
  - although bigger FOV can be beneficial if a PSF star is in the field
- We need lots of potential targets, to improve statistics
  - Set by tip-tilt star availability
  - Can we use the quasar images as TT objects?

Mid-to-long-term future

- Big new surveys (Pan-STARRS, DES, Euclid, LSST) should discover hundreds to thousands of time delay systems
- Statistical power inherent in large samples can lead to significant improvements in precision of cosmographic measurements
  - e.g., Coe & Moustakas 2009
    - LSST+Planck give sub-percent precision for H_0 and w to 3% if κ_{ext} is known
  - e.g., Linder 2011

Mid-to-long-term future

- Lensing time delays give superb complementarity with SN/BAO distances plus CMB.
- For Stage III (Cosmology 2017), SL improves dark energy FOM by 30% (25 systems of 5% distances, 150 HST orbits).
- SL+SN+CMB distances do 5x better on constraining DE in presence of curvature than SN +CMB alone.
- SL with 1% systematics at z<0.6 improves SN+CMB FOM by 5x.



Linder 2011

Take-away messages

- A small sample of gravitational lens systems can produce interesting measurements of cosmological parameters
- These measurements have comparable precision to other approaches.
- They are also independent and complementary to the traditional methods.
- The lens-based measurements contain internal checks for systematics

Overall Summary

- High-resolution imaging combined with strong lensing is a powerful technique for finding (dark matter) substructures and for constraining cosmological parameters
- Current projects show the promise of these techniques, future telescopes and surveys will greatly advance the science