"SHEDDING LIGHT"

Using Strong Gravitational Lensing to get to the Particle Nature of Dark Matter

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with Francis-Yan Cyr Racine, Chris Fassnacht, Chuck Keeton, Eric Linder, Phil Marshall, Tommaso Treu

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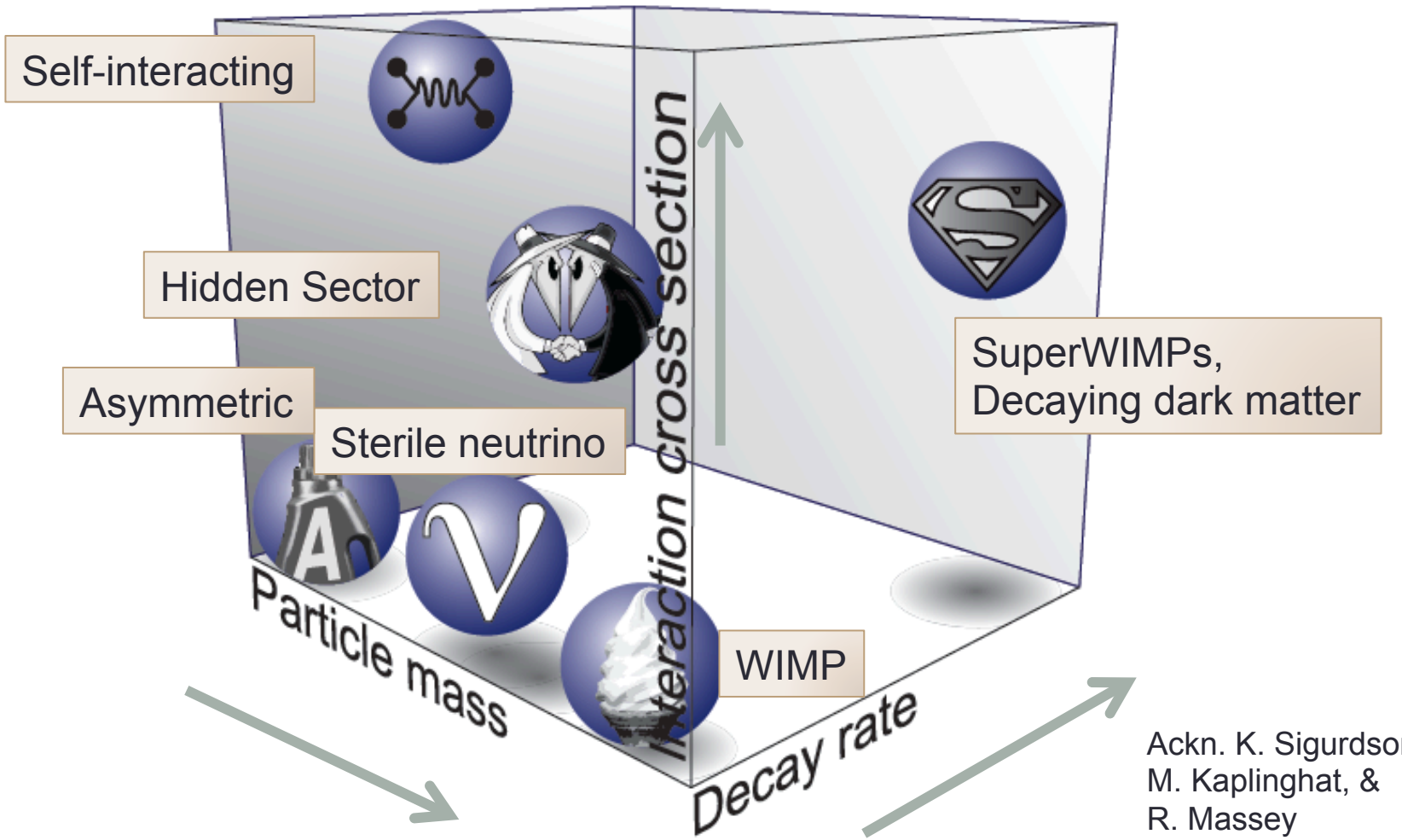
The take-home message

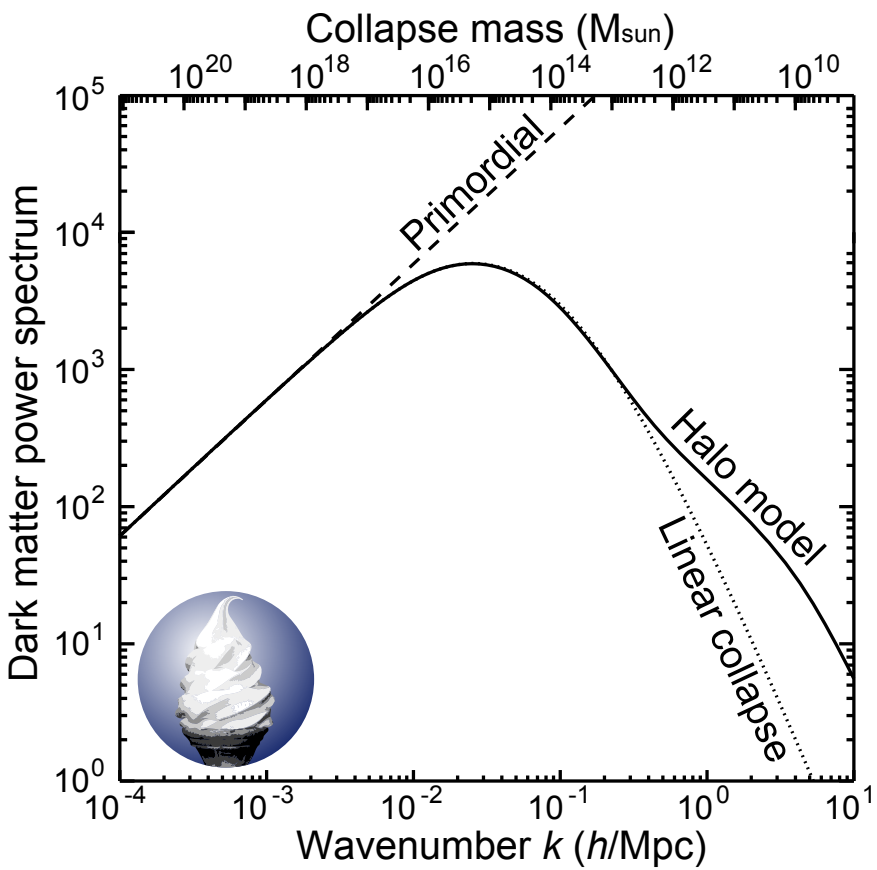
- Dark matter thermal and interaction properties have consequences on astrophysical-size structures
- Within galaxies, this means the populations and properties of self-gravitating dark matter dominated sub-halos (and streams)
- These sub-halos can be probed through their gravitational signature, in strong gravitational lensing
- Both individual and populations of subhalos have been discovered and characterized through strong lensing already!
- High potential for strong lensing techniques to get to discriminating levels of sensitivity, *even for dark matter candidates that may never produce direct or indirect signatures*

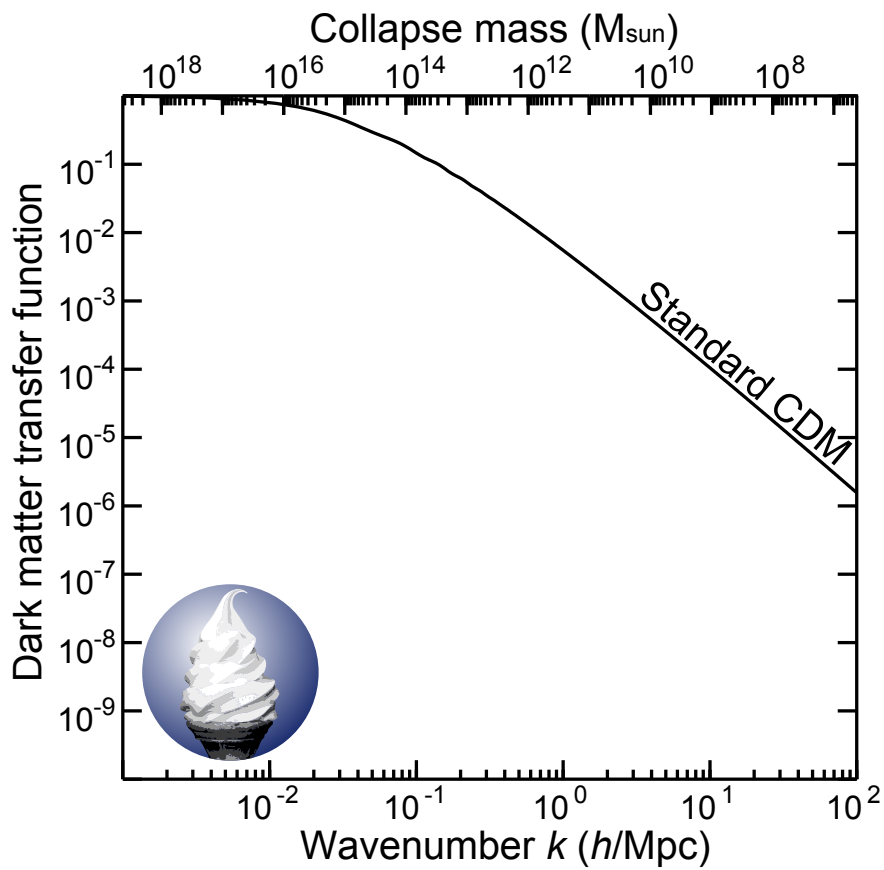
Physically motivated DM candidates



Ackn. K. Sigurdson,
M. Kaplinghat, &
R. Massey

LCDM power spectrum and T(k)

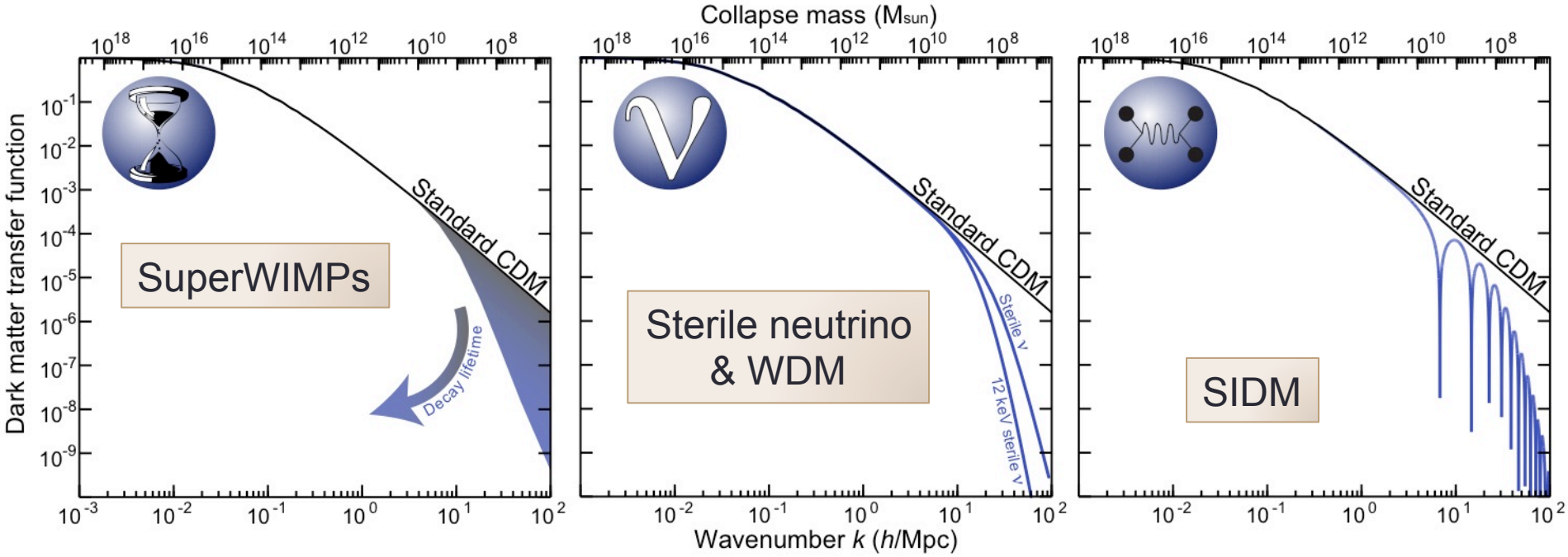




Ackn R Massey

Beyond LCDM transfer functions

Collapse Mass (Msun)



Wavenumber k (h/Mpc)

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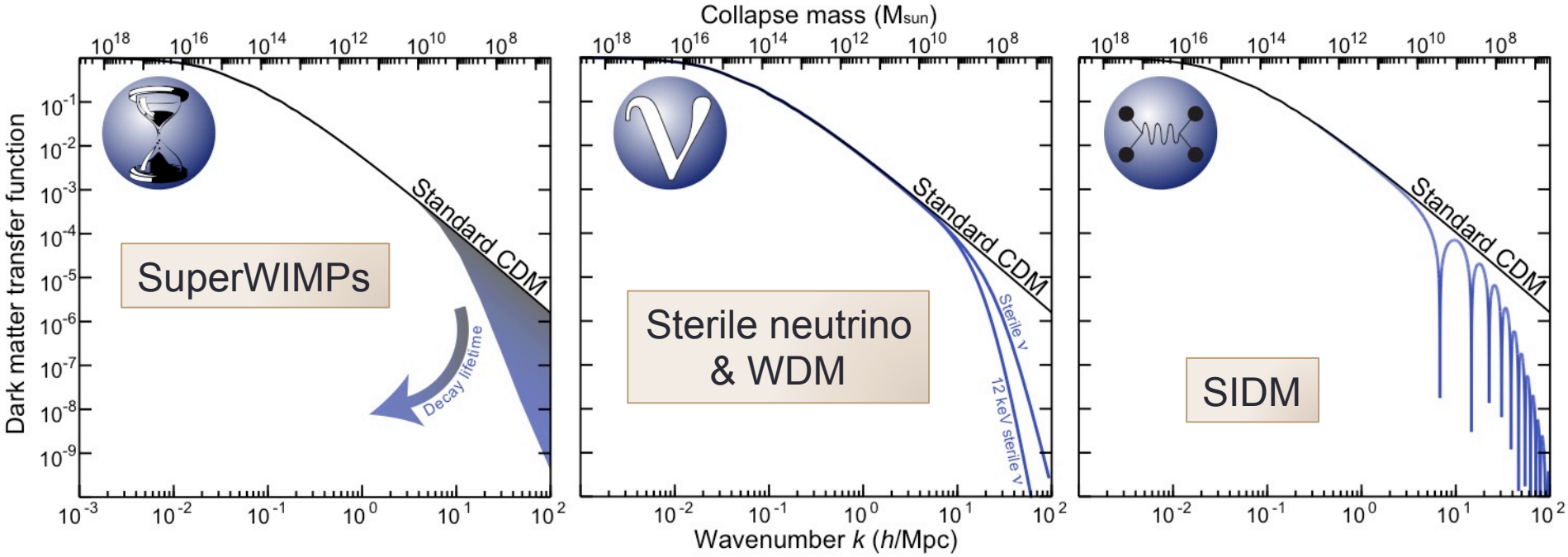
The cutoff scale is only the beginning

Collapse Mass (Msun)

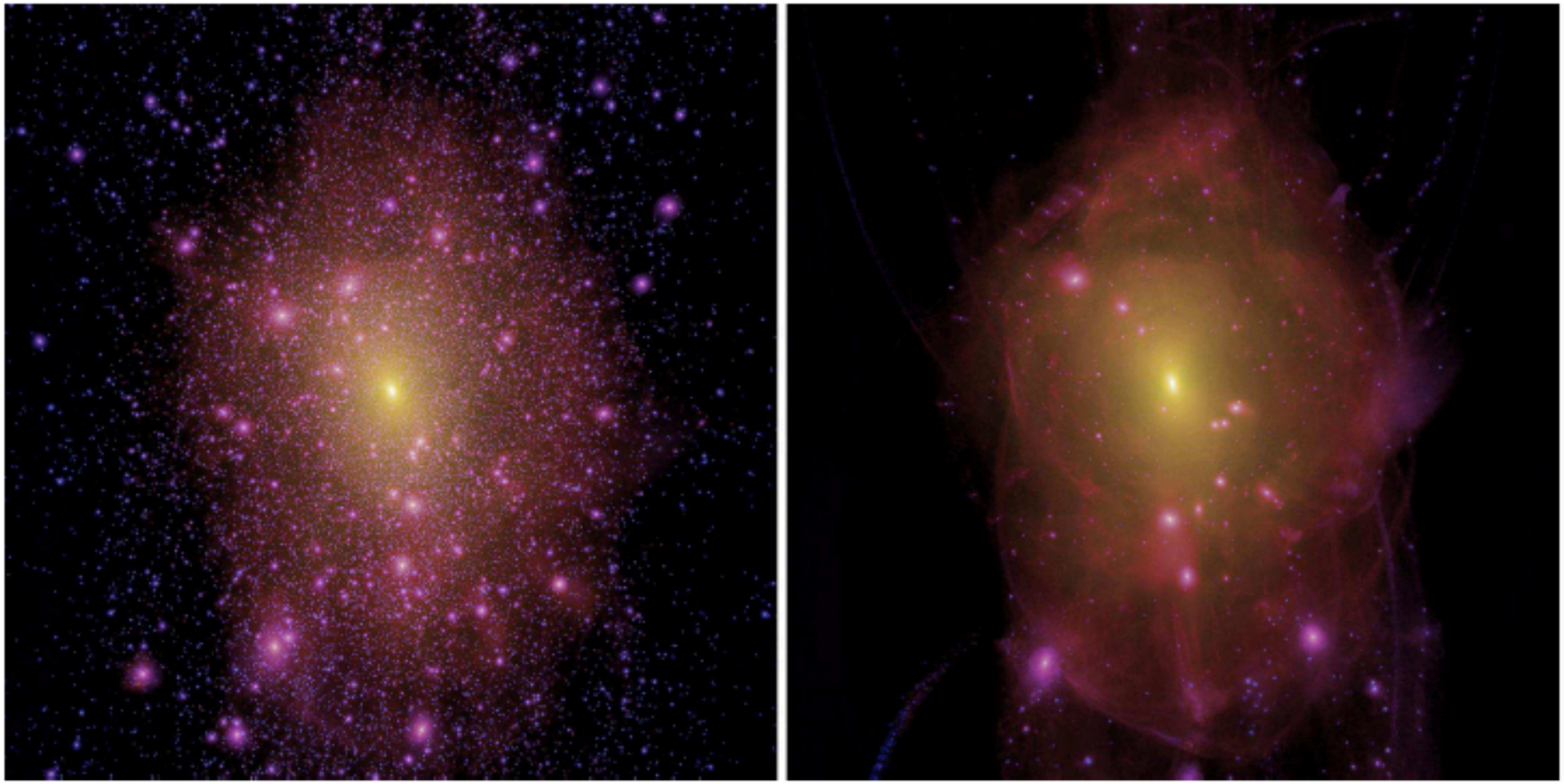


Wavenumber k (h/Mpc)

The collapse mass is just the beginning of the story, since within a halo, tidal evolution can strip 90% of a subhalo's mass, or fragmentation & other physics may be important.

Ackn R Massey

Example: LCDM vs ~2keV WDM

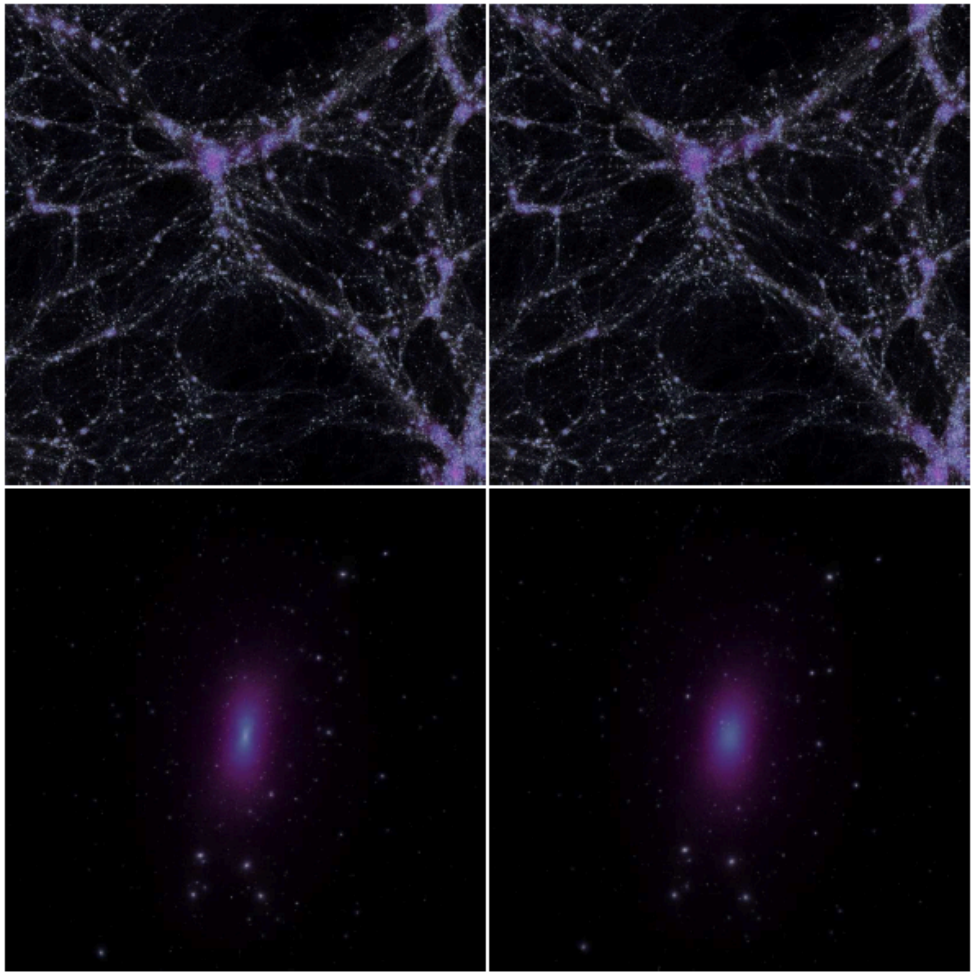


Lovell+2012, MNRAS, 420, 2318 Density-squared map. M200~1.8E12Msun; z=0

Example: LCDM vs ~1cm^2/g SIDM

50 x 50 x 10 Mpc

r < 200 kpc



No difference at all on large scales.

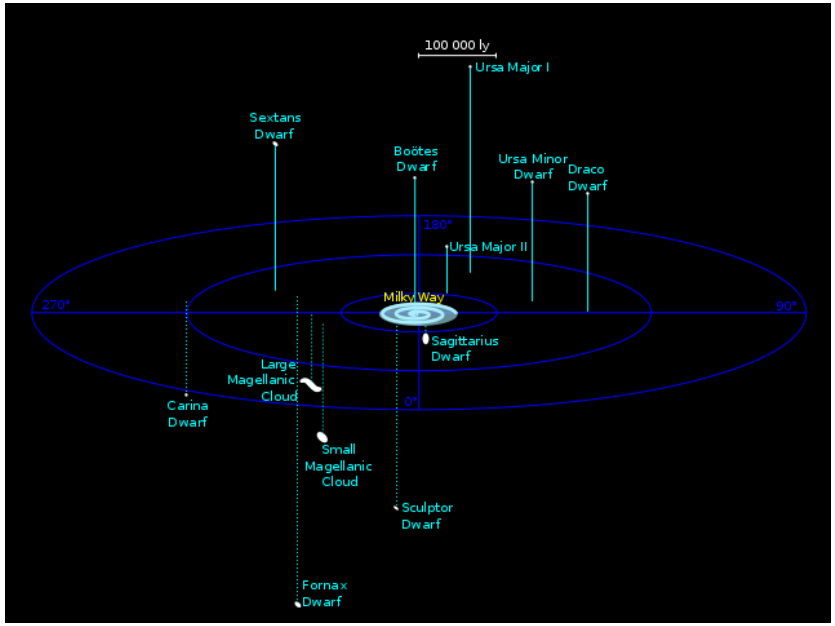
The phase density in the core is lower b/c of smaller density and higher particle velocities.

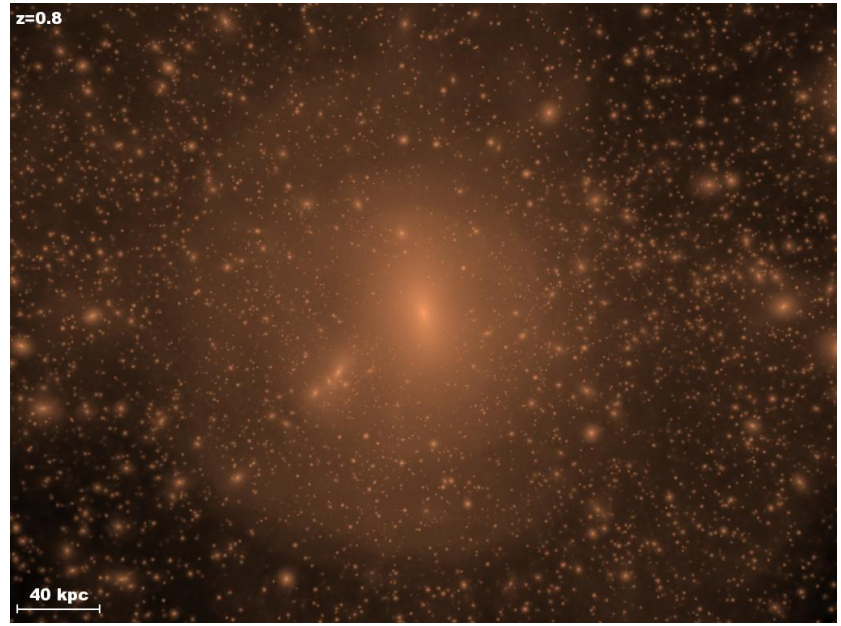
The core is rounder as well.

M. Rocha, LM, + 2013, 2013MNRAS.430...81R

Phase space density; M200~1.8E12Msun; z=0

The sub-halo population DM diagnostic





Dwarf galaxies in the Milky Way

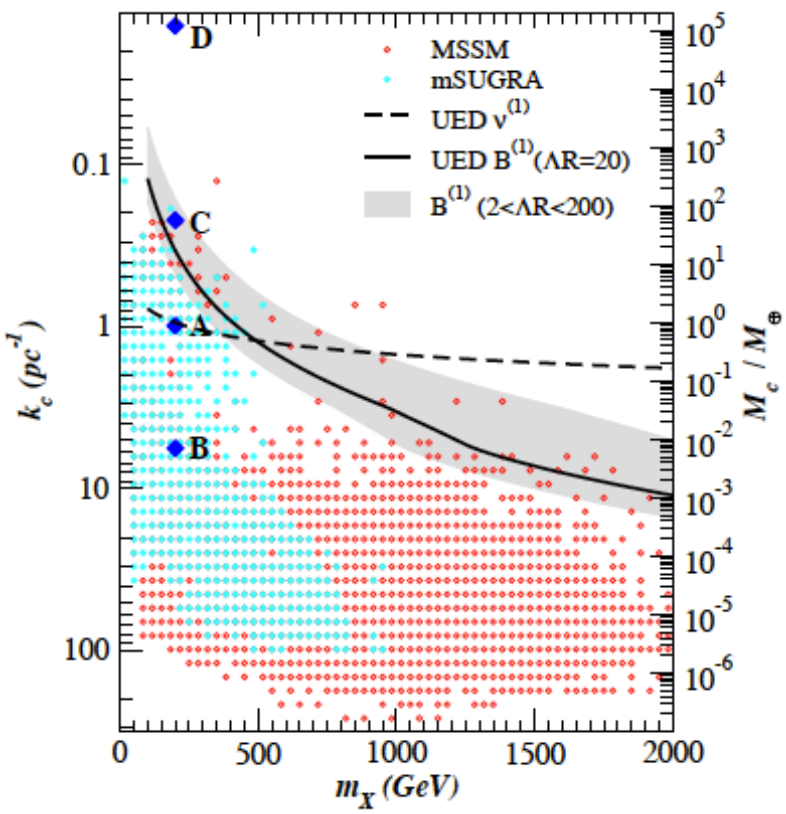
LCDM halo Via Lactea II, Diemand+ 2008

Wikipedia;
Creative Commons Attribution-Share Alike 2.5 Generic

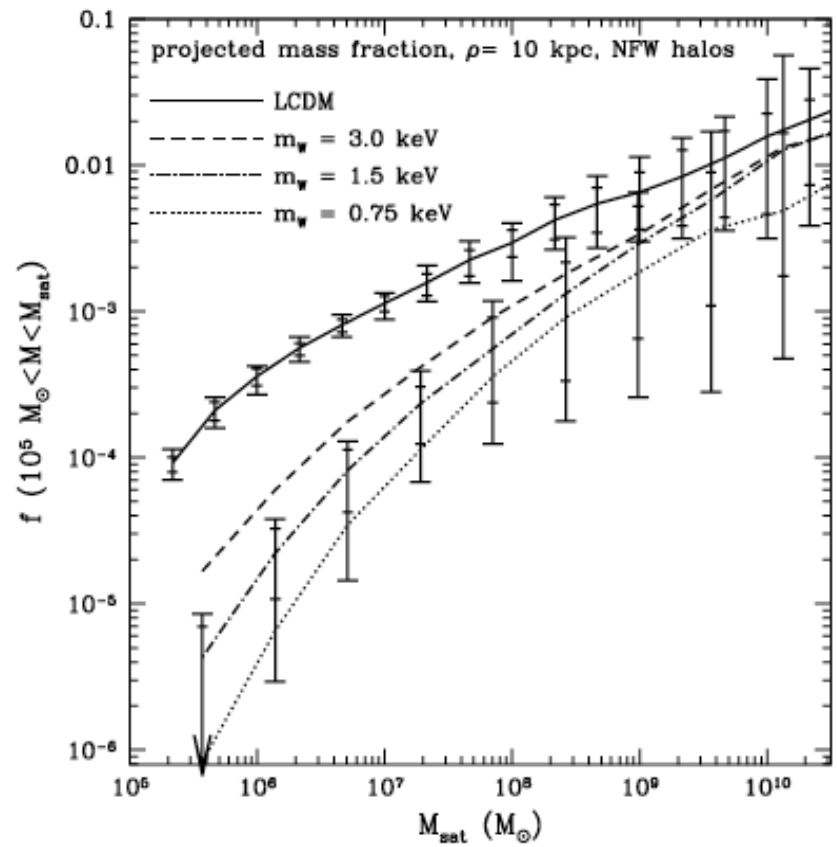
The sub-halo population DM diagnostic

- Fraction of dark matter substructure at ~Einstein radii
  - fsub ~ 0.1 – 0.3 % (but large variance, and dependence with host halo mass)
- Subhalo mass function shape
  - dN/dm ~ m ** (-1.9)
- Other considerations
  - Spatial distribution
  - Change with redshift
  - Nonlinear evolution effects
  - Projection effects
  - Baryonic features and effects

Sub-halo mass roll/truncation scales



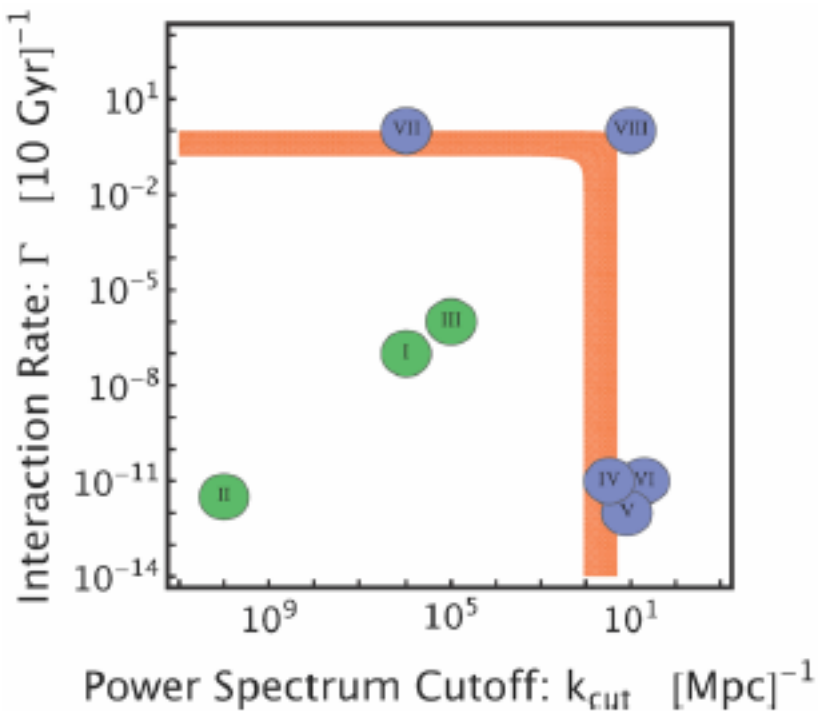
Profumo+ 2006 xxx/0603373

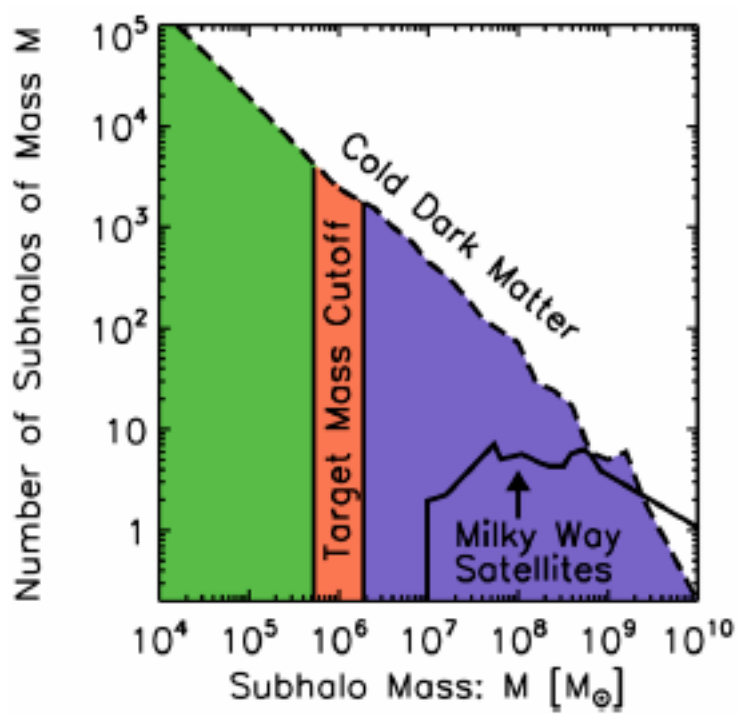


Zentner & Bullock 2005

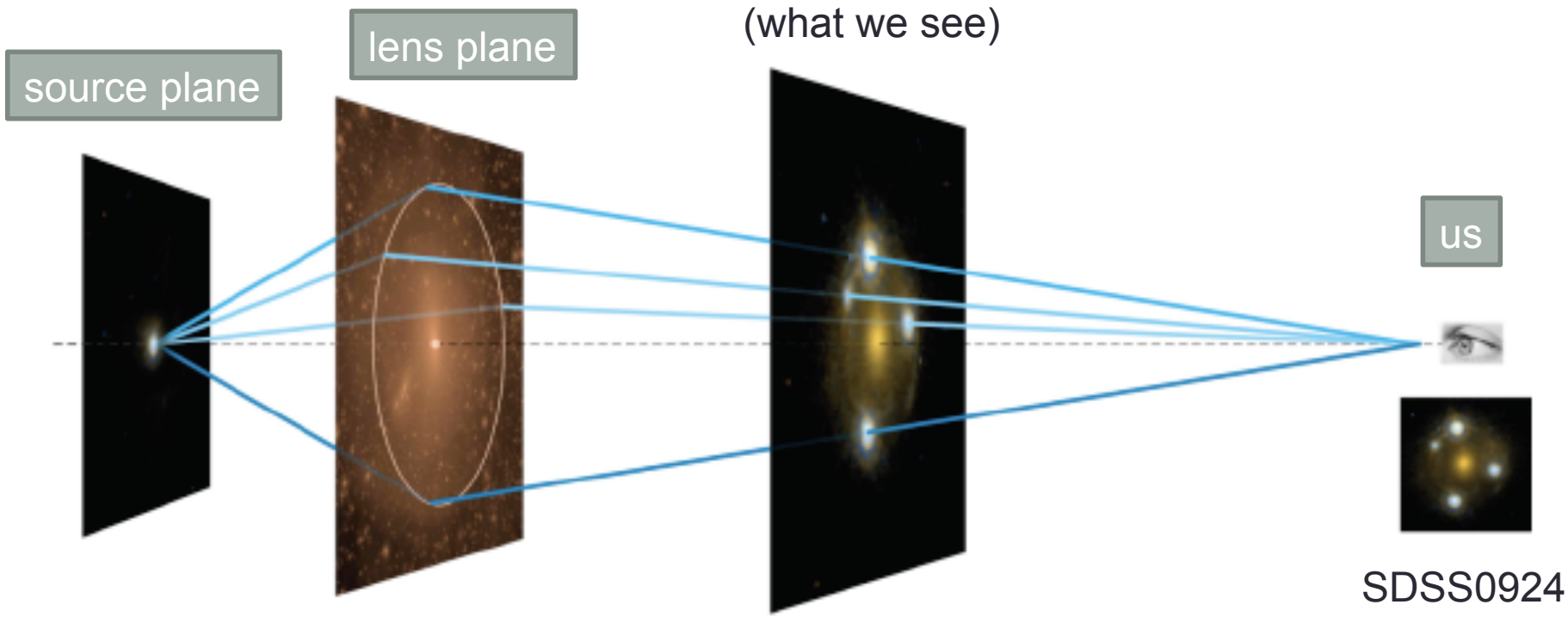
	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV–TeV	Cold
II	Axion	μeV–meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV–keV	Cold/Warm
VI	SuperWIMP	GeV–TeV	Cold/Warm
VII	Hidden Sector: WIMP-like	MeV–TeV	Cold/Warm
VIII	Hidden Sector: Bound State	GeV–TeV	Cold

Motivating the mass scales to target in pursuing measurements of the subhalo mass function…





Strong gravitational lensing



A simple geometric relation between the angular diameter distances between source, lens, and us determine the critical surface mass density for strong gravitational lensing.

Basic strong lensing geometry

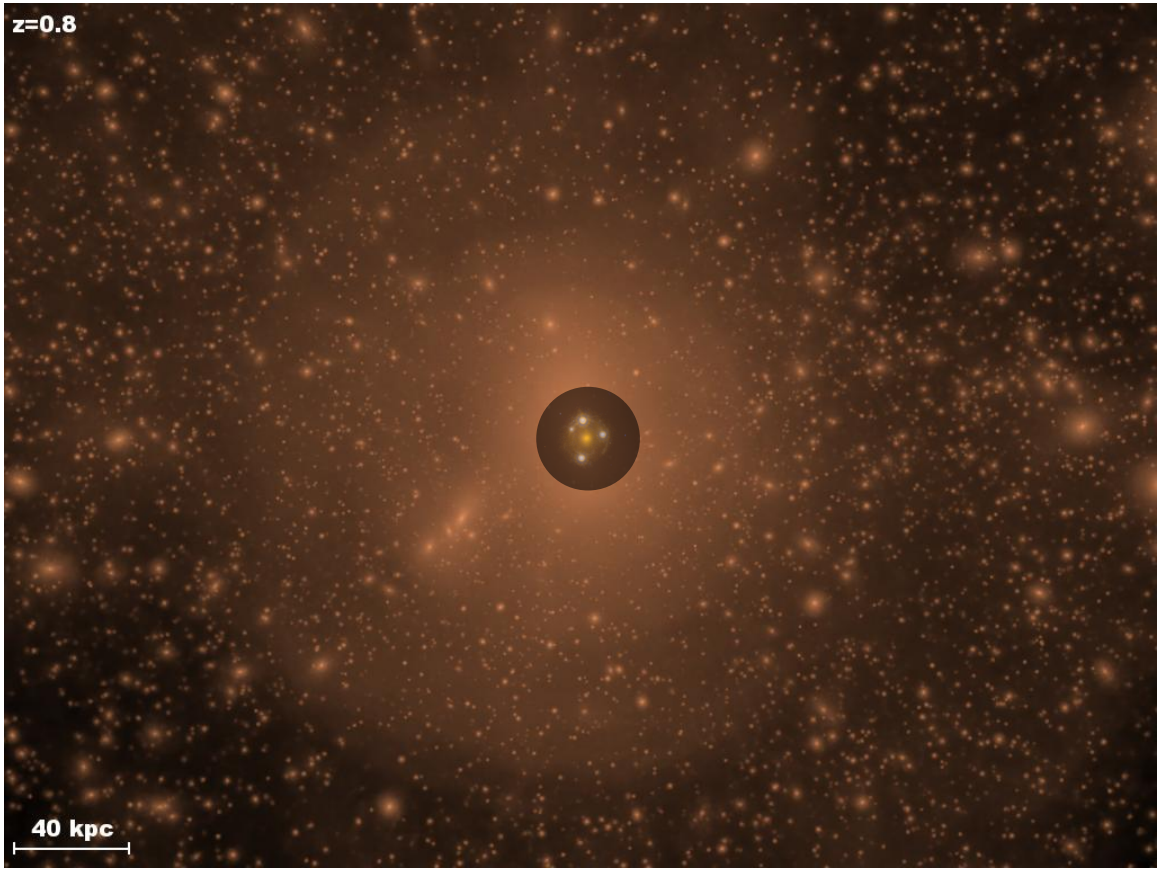
	Einstein Cross	Cusp Caustic	Fold Caustic
Source Plane			
Image Plane			

from icosmo

A strong lens' view of a galaxy halo

The Einstein Radius of a typical lens will correspond to a few or several kpc in projection.

Different observables have different "reach" around each image position, though.

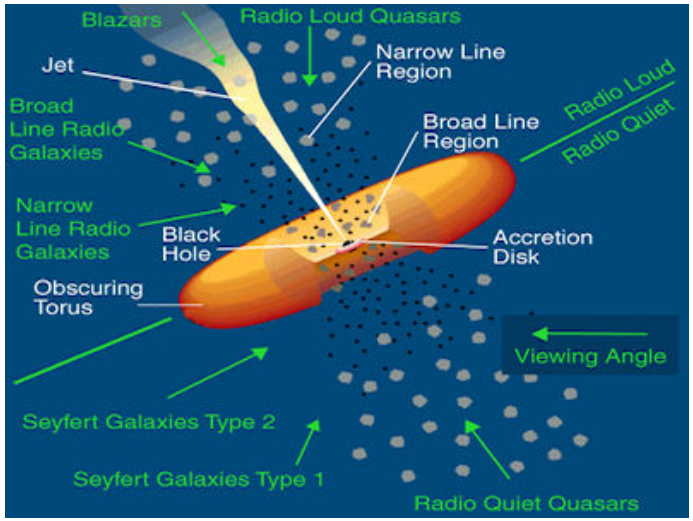


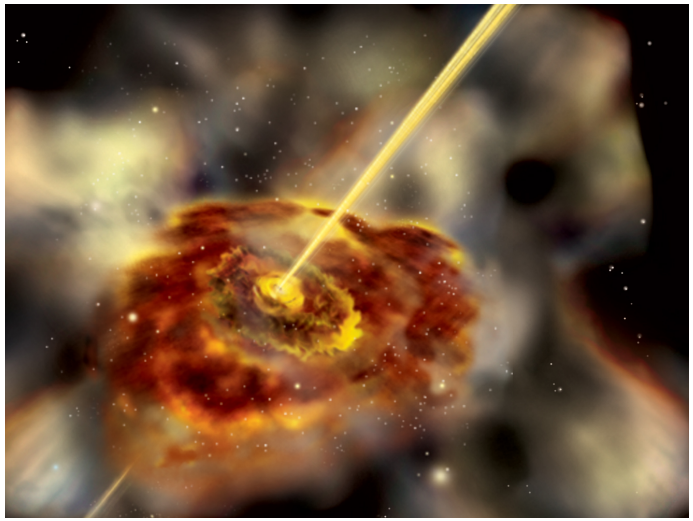
Diemand et al
Via Lactea

Mao & Schneider 1998 | Chiba 2002 | Metcalf & Zhao 2002 | Dalal & Kochanek 2002

Basic ingredients of gravitational lensing

- Arrival time equation for photons
- Image positions relative to the center of the potential
- Image magnification with respect to intrinsic brightness
- Surface brightness features in lensed host galaxy
- *(Plus dust, stellar microlensing, unassociated line of sight objects, local environment, nature of source uncertainties, &c. &c.)*

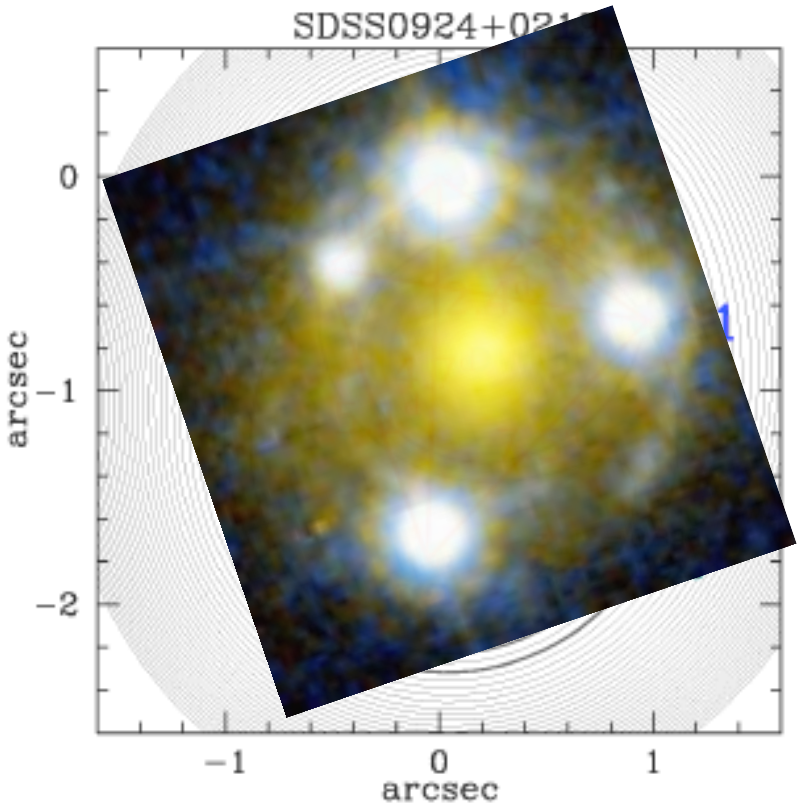




And of course, the source being lensed is a critical ingredient. A lensed Active Galactic Nucleus has an angular size of ~1 micro-arcsecond.

The lensing arrival time equation

$$\tau(\vec{x}) = \frac{1+z_l}{c}\,\frac{D_l D_s}{D_{ls}}\left[\frac{1}{2}|\vec{x}-\vec{u}|^2 - \phi(\vec{x})\right]$$



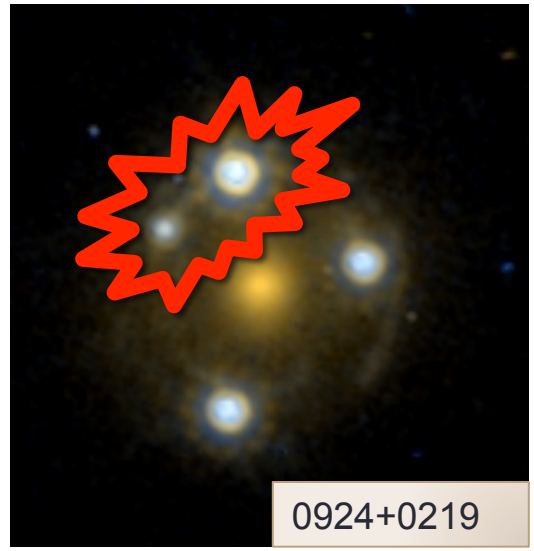
Time delays	$\Delta\tau$	$\propto \Delta\phi$
Image positions	$\nabla_\theta\tau$	$\propto \nabla_\theta\phi$
Magnifications	$\nabla\nabla_\theta\tau$	$\propto \nabla\nabla_\theta\phi$

So time delays depend *directly* on the potential perturbations over larger area.

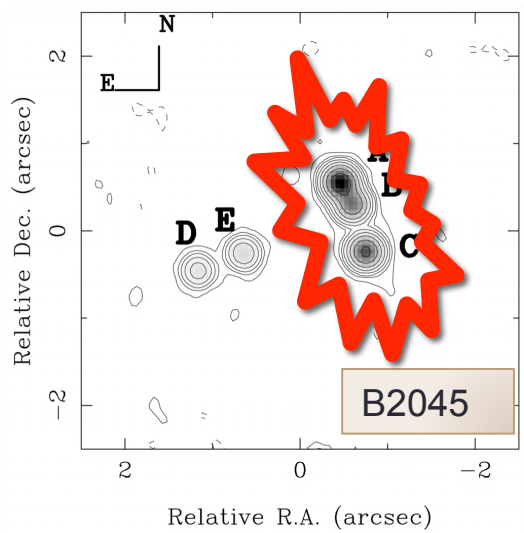
The magnifications are sensitive to very local potential variations – including stars.

Classic magnification anomalies

$$R_{fold} = \frac{F_A - F_B}{F_A + F_B} \approx A_{fold} d_1$$



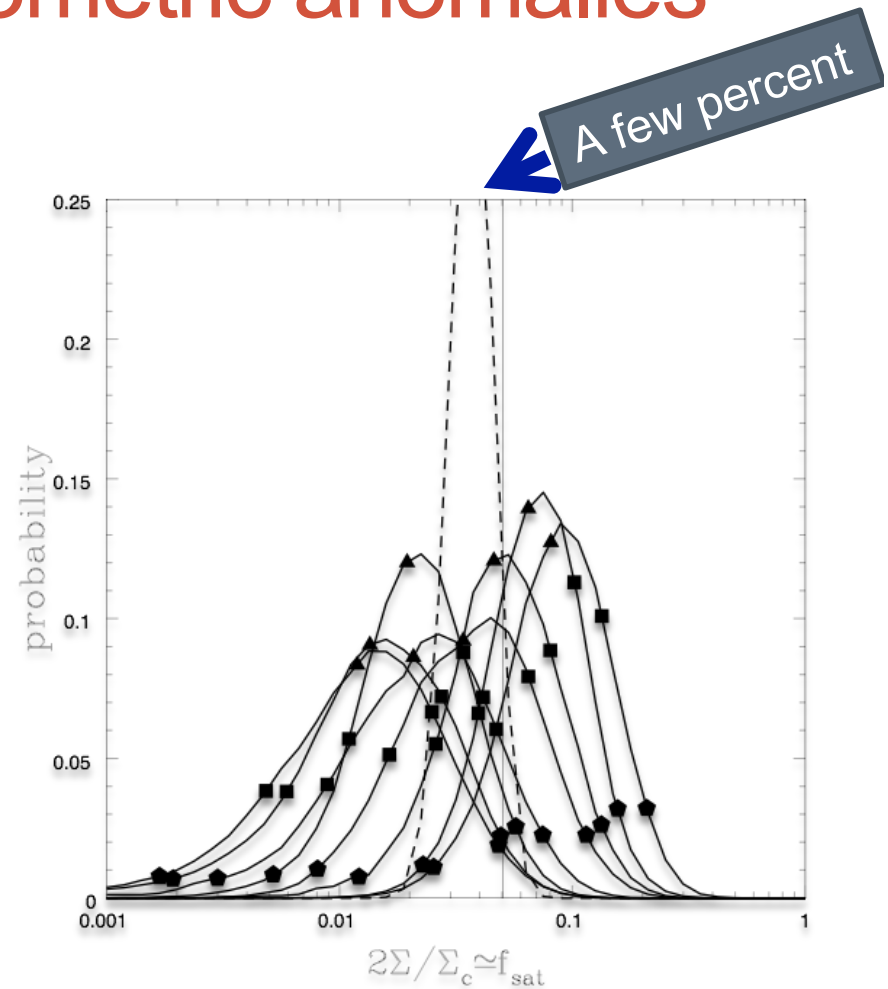
$$R_{cusp} = \frac{F_A - F_B + F_C}{F_A + F_B + F_C} \approx A_{cusp} d_1^2$$



So we KNOW that something interesting is going on. There is a significant onus on us to demonstrate that it is due to *subhalos.*

Magnification plus astrometric anomalies

Dalal & Kochanek **2002** combined radio-based magnification ratios & milli-arcsecond level astrometric positions of seven four-image lenses, to calculate the substructure surface density in ~1E9 solar mass subhalos.

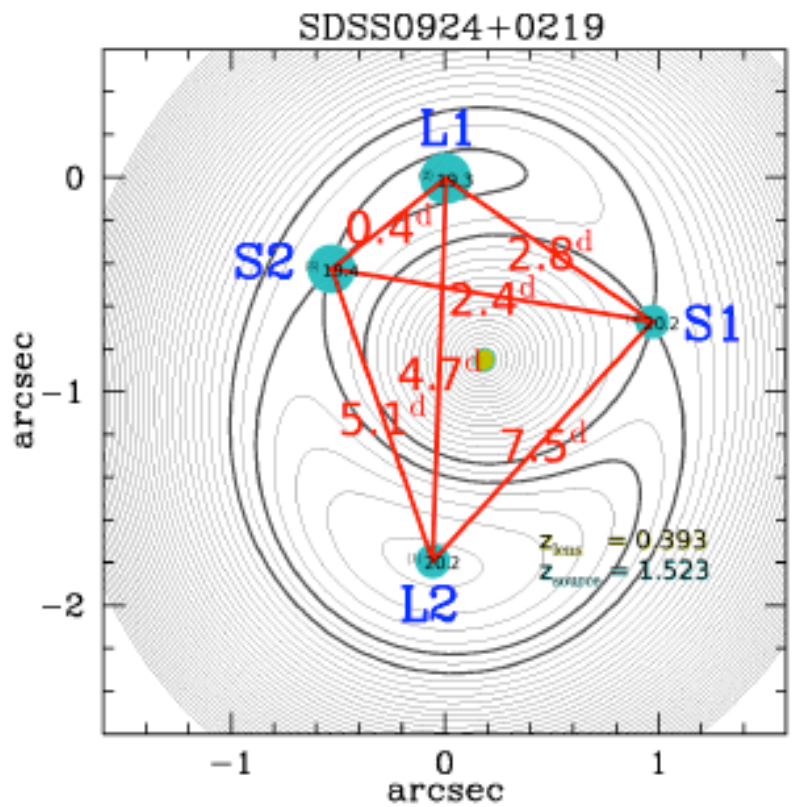


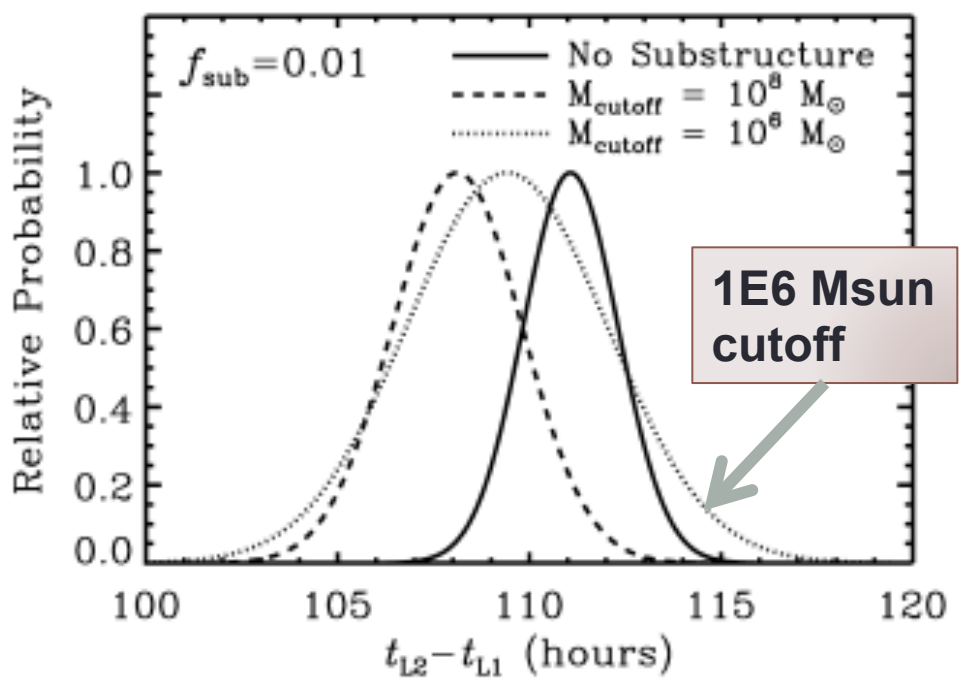
Surface density in substructure

Dwarf galaxy-scale dark matter substructures have been measured with strong lensing for ten years already.

Time delay perturbations

Substructure => offsets & changed *distributions* in the time delay probability.



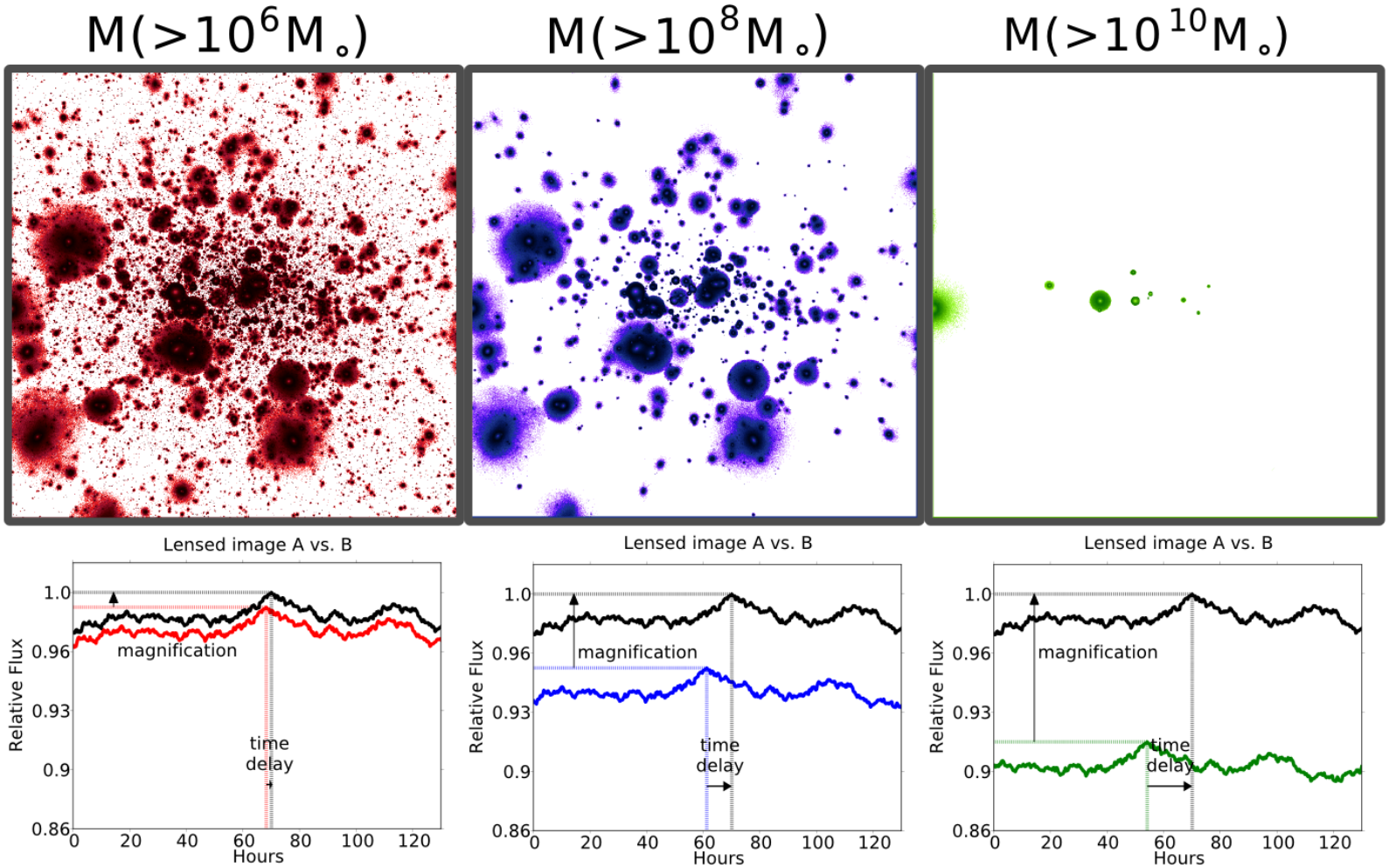


L. Moustakas+ 2013

Ackn. D. Coe, M. Oguri

Ackn R. Fadely

Magnification & time delay perturbations



flux vs time light curves, for image pairs

Ackn. M. Kuhlen, D. Coe, +

Observables & techniques

Lens Observables	Quasar source	Galaxy source
Surface brightness		X
Time Delays	X	
Positions	X	X
Brightnesses	X	
vs wavelength	X	X
vs time	X	(X)

Lensing galaxy
Stellar populations
Stellar dynamics
Angular power structure

Environment
Local galaxies (group)
Line of sight objects

Source structure
Wavelength dependent structure

Identifications of *individual* subhalos

Bayesian comparisons of models

Bayesian evidence allows objective model comparison, even with different numbers of parameters.

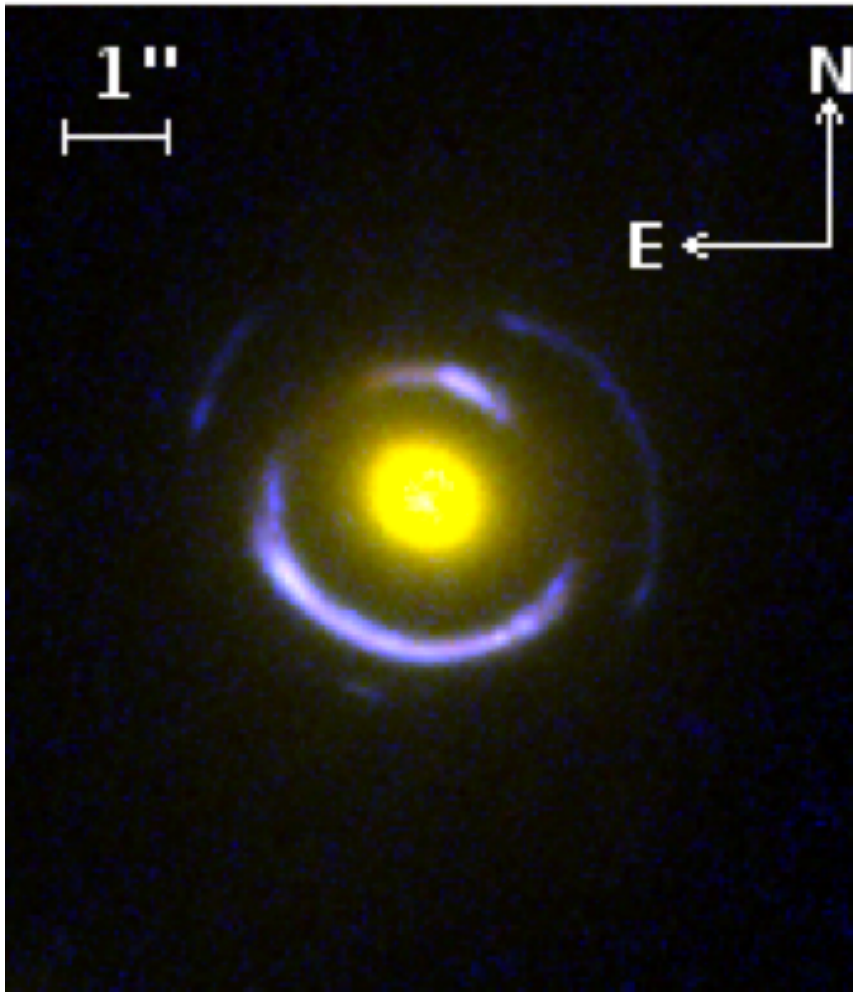
$$Z(M) = \int \mathcal{L}(d|\mathbf{q}, M)\ P(\mathbf{q}, M)\ d\mathbf{q}$$

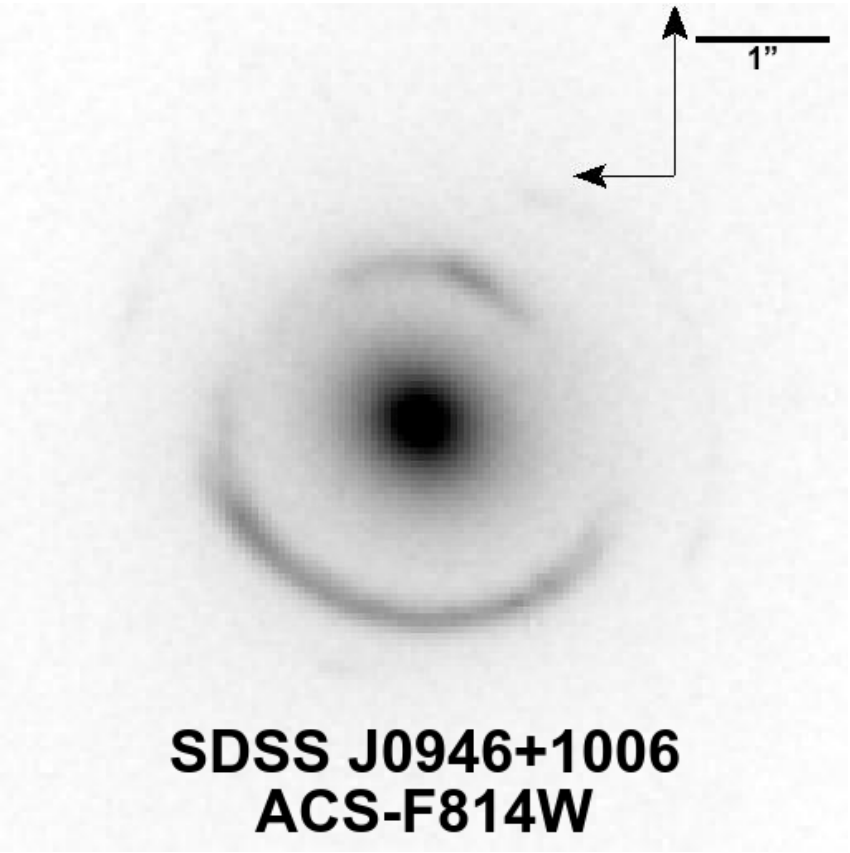
Compare two models via Z_2/Z_1 or $\log_{10}(Z_2/Z_1) = \Delta \log_{10}(Z)$.

Jeffreys (1961) scale:

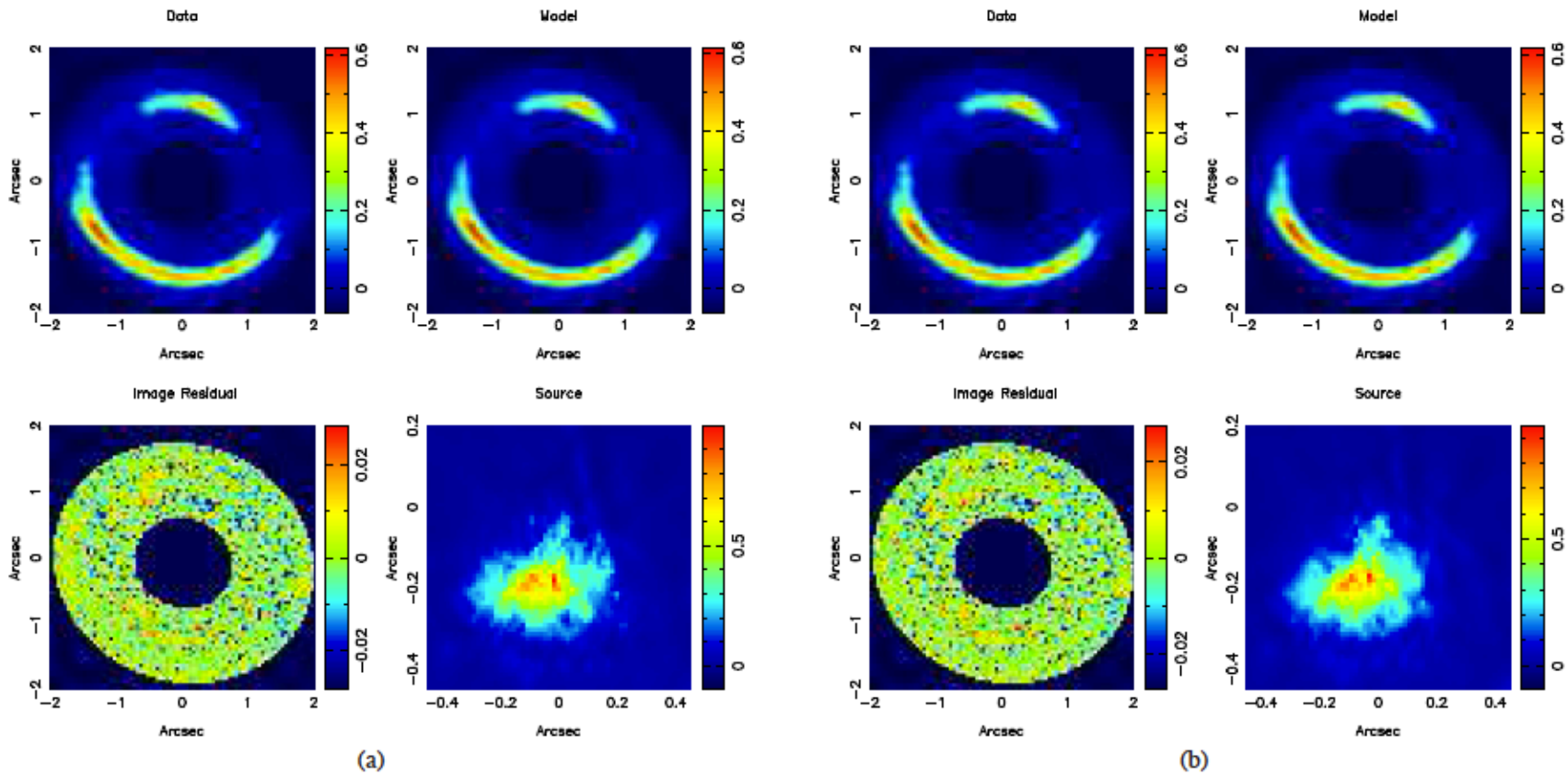
$\Delta \log_{10}(Z)$	Significance
0–0.5	Barely worth mentioning
0.5–1.0	Substantial
1.0–1.5	Strong
1.5–2.0	Very strong
> 2.0	Decisive

J0946+1006 (z=0.222, 2.7Gyr back)





J0946+1006 (z=0.222, 2.7Gyr back)



No subhalo

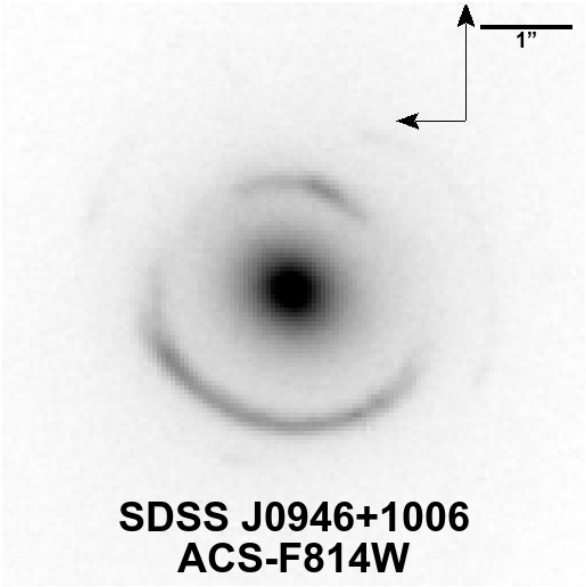
With a subhalo

Vegetti+2010
MNRAS, 408, 1969

"By eye": good luck. The Bayesian evidence: significant

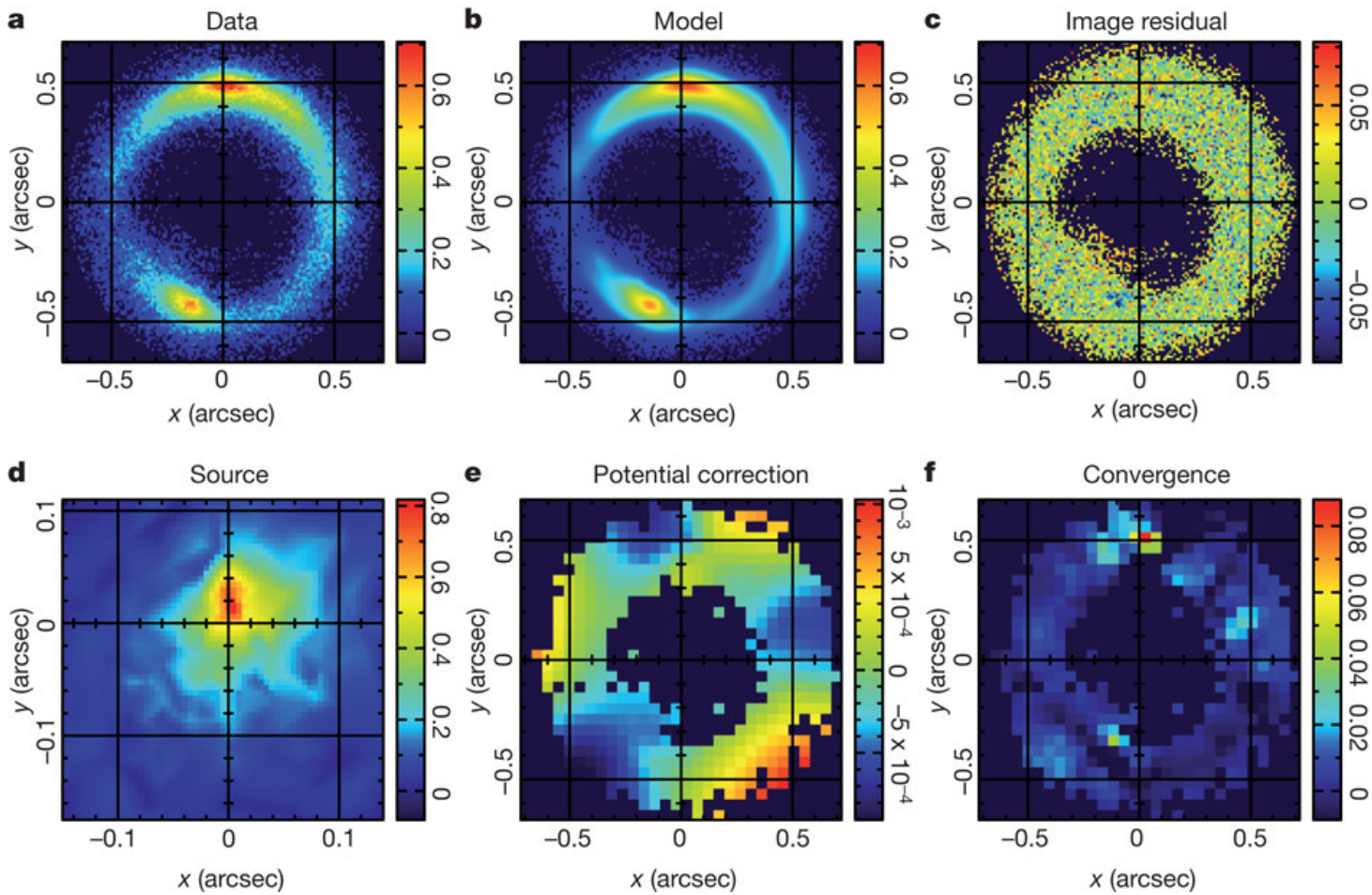
J0946+1006 (z=0.222, 2.7Gyr back)

- The Jackpot SLACS lens (Gavazzi+ 2008)
- Tidally truncated pseudo-Jaffe density profile
- ~3.5E9 solar masses (16sigma), at a specific position
- M/L>120 (V) (3sigma)
- f~2% (1sigma)



Vegetti+2010
MNRAS, 408, 1969

B1938+666 (z=0.881; 7.2Gyr back)



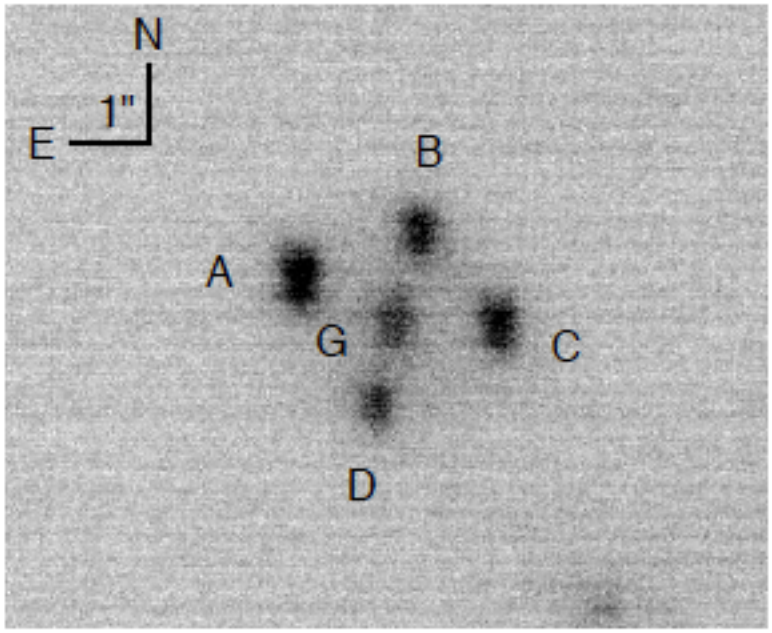
~2E8 solar masses

Vegetti+2012 Nature, 481, 341

B1938+666 (z=0.881; 7.2Gyr back)

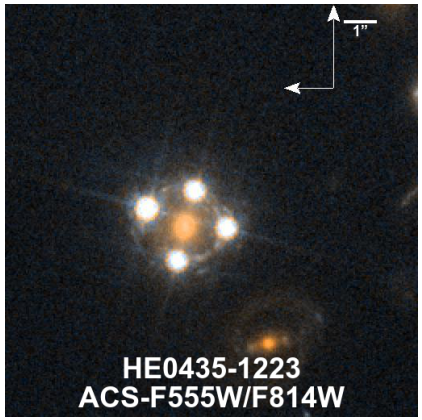
- Based on Bayesian evidence, this is a 12σ detection of the substructure
  - $\Delta \ln E = 65.0$
- Fit with an analytic model (truncated pseudo-Jaffe profile)
  - $M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$
  - $M_{sub}(r<600 \text{ pc}) = (1.15 \pm 0.06) \times 10^8 M_\odot$
  - $M_{sub}(r<300\text{pc})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

H0435-1223 (z=0.455, 4.7Gyr back)



Constraints

- HST positions, $\sigma = 3$–5 mas
- optical/IR fluxes, $\sigma \sim 5\%$
- (time delays, $\sigma = 0.8$ d)

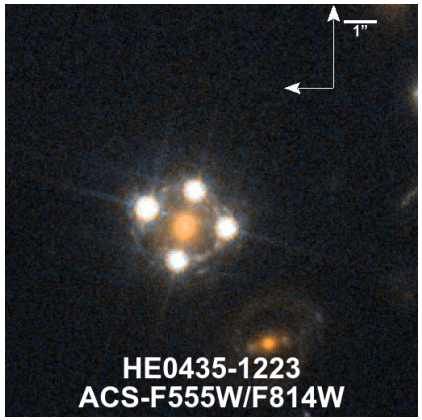


Fadely & Keeton 2012, MNRAS, 419, 936

H0435-1223 (z=0.455, 4.7Gyr back)

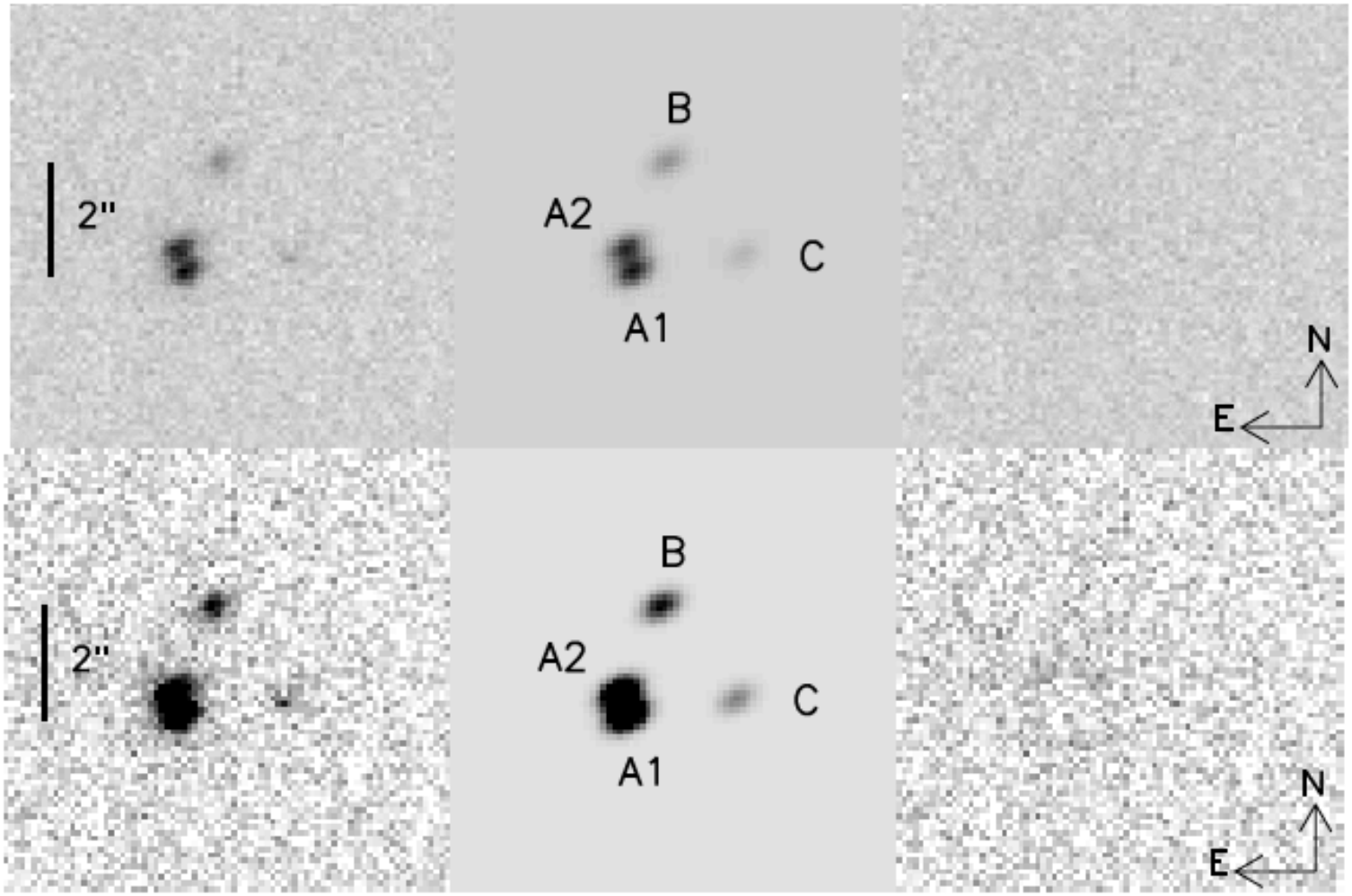
- Major clump near image A, ~5E7 solar masses
- Second clump near image B, ~4E6 solar masses

- fsub > 0.08% (but upper limit constraints are not strong)



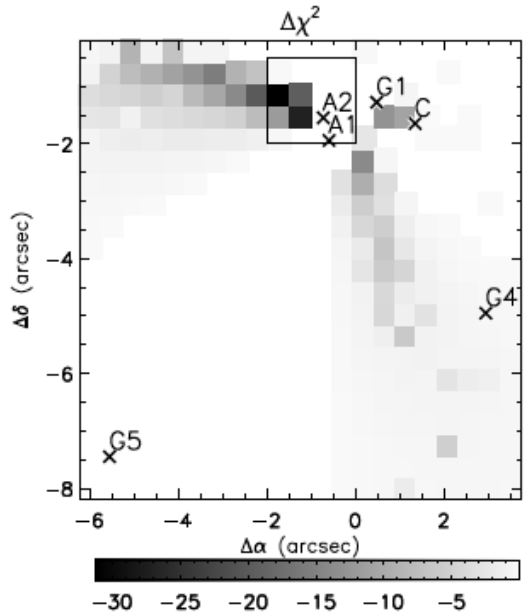
Fadely & Keeton 2012, MNRAS, 419, 936

MG0414+0534 (z=0.96; 7.6Gyr back)

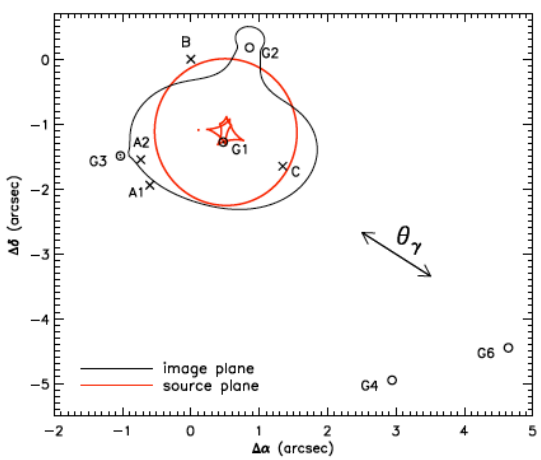


C. MacLeod+ 2012, arxiv:1212.2166

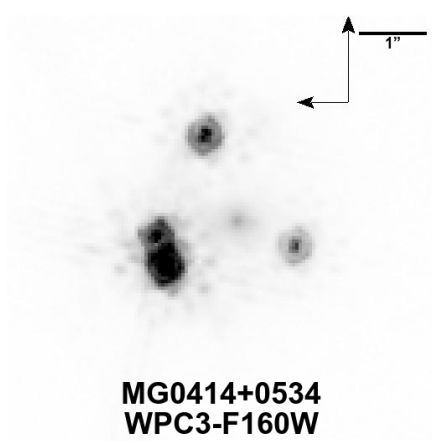
MG0414+0534 (z=0.96; 7.6Gyr back)



- Mid-infrared (11.2um Michele on Gemini-N) fluxes and VLBI radio positions
- Systematic search for improved fits
- “X”: 2E7 solar masses (SIS)

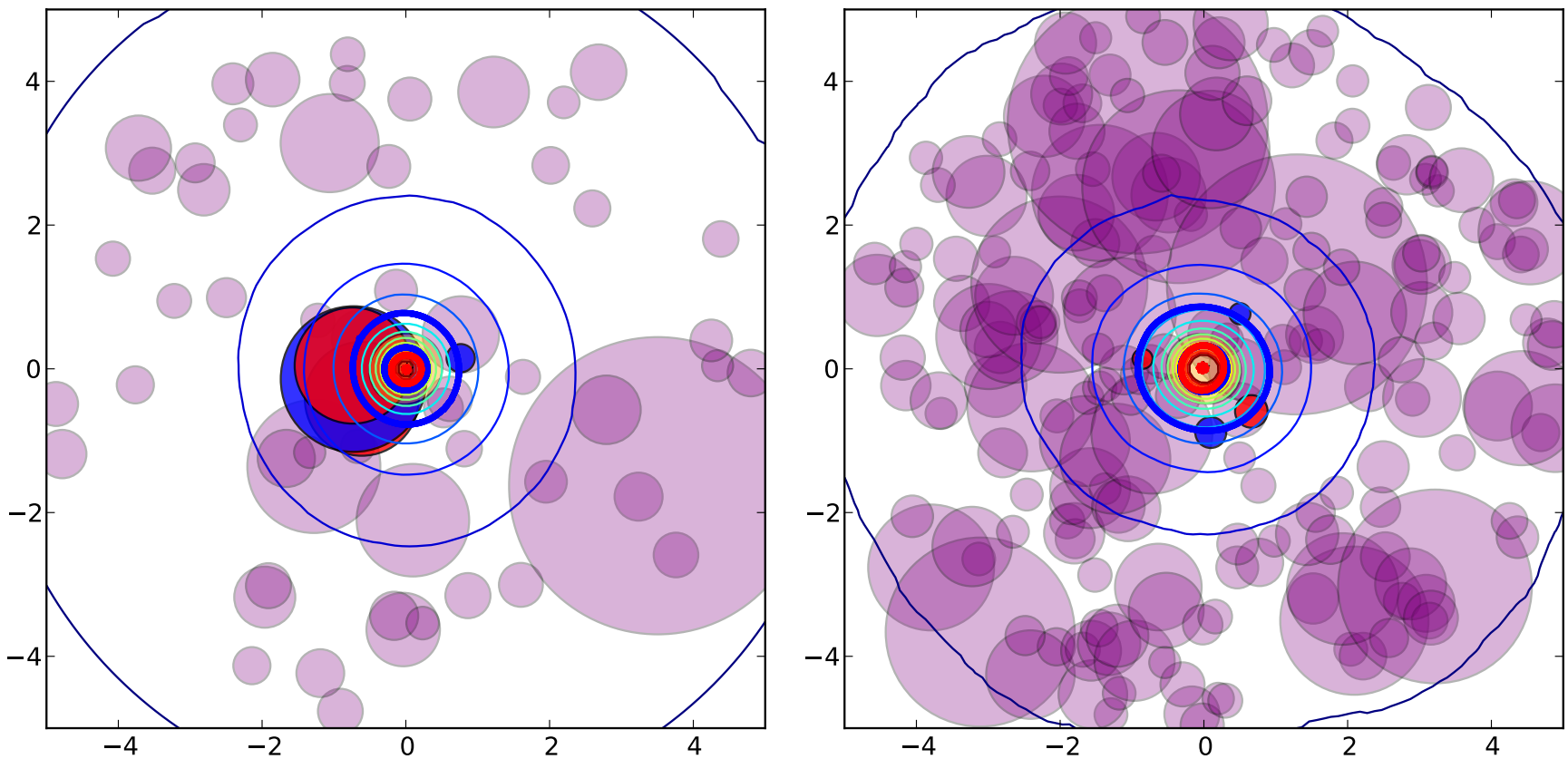


C. MacLeod+ 2012, arxiv:1212.2166



Towards *populations* of subhalos

Modeling populations of subhalos



Moustakas & Cyr-Racine + in prep

Modeling populations of subhalos

Parameters

- q = smooth model
- s = substructure *population* (abundance, mass function, etc.)
- c = individual clumps (position, mass, etc.)

Most interested in marginalized posterior for substructure population parameters:

$$P(s) \propto \int \mathcal{L}(c,q)\ P(c|s)\ P(s,q)\ dc\ dq$$

C. Keeton lectures

Modeling populations of subhalos

Need to evaluate

$$P(s) \propto \int \mathcal{L}(c,q)\ P(c|s)\ P(s,q)\ dc\ dq$$

We can't do the c integral explicitly!

Use Monte Carlo integration: let c_j be a realization of the clump population, drawn from $P(c|s)$. Then

$$P(s) \propto \sum_j \int \mathcal{L}(c_j,q)\ P(s,q)\ dq$$

C. Keeton lectures

Stepping stone: Forecasting

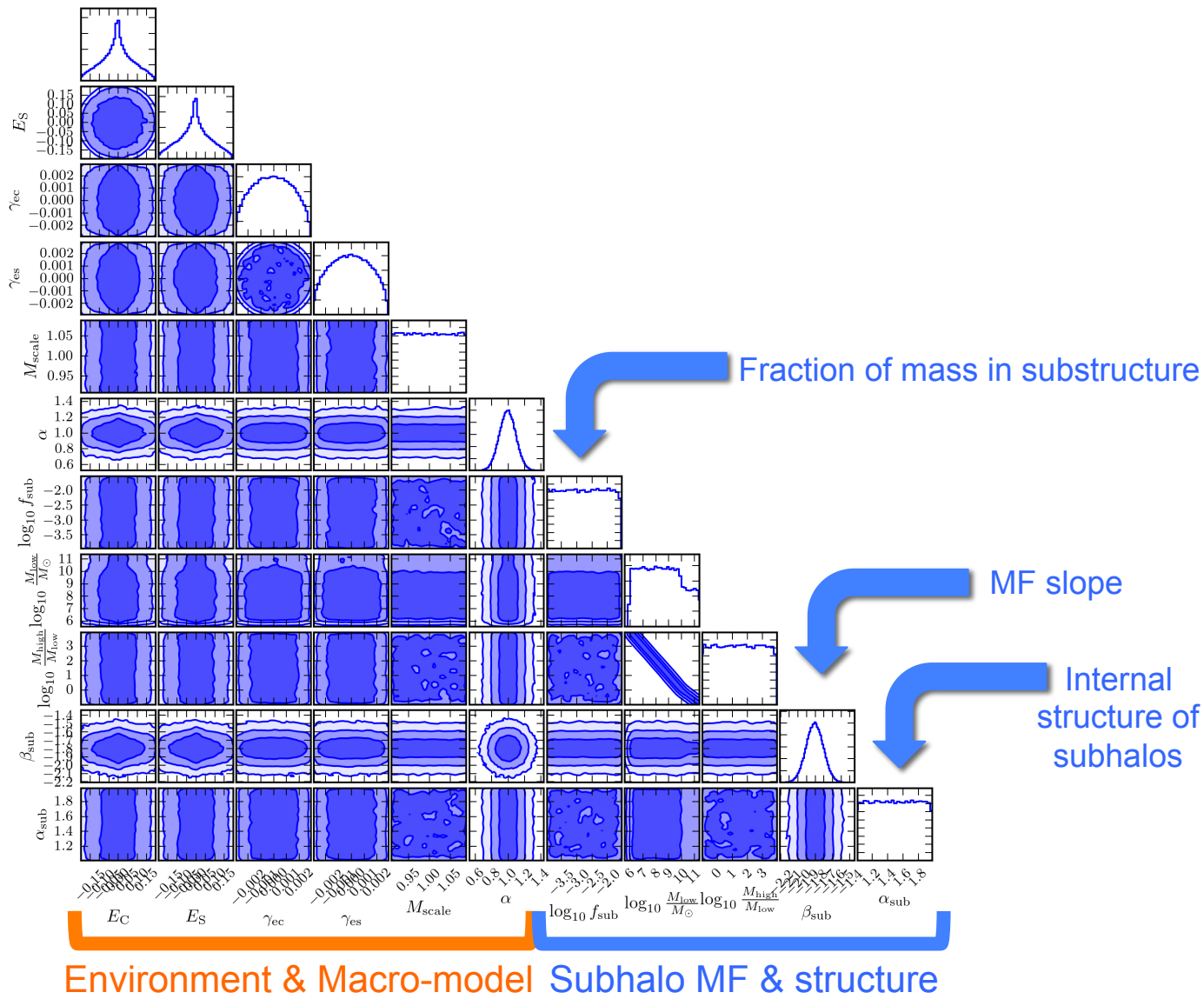
- Create a large set of realizations, with model input parameters varied based on plausible prior distributions.
- Create a large number of models for different “realities” of the subhalo mass function, for drawing specific fiducial model lenses. (By-passing the issues of fitting real lenses at present). We have a ~dozen scenarios, including:
  - CDM-like mass function
  - Mass function with severe truncation at dwarf galaxy scales
- Define experimental designs corresponding to different combinations of observables and associated constraints:
  - Present-day HST astrometry and crude flux ratios and time delays
  - LSST (some astrometry, and crude time delays for large sample)
  - Euclid (HST astrometry of large sample)
  - OMEGA (HST astrometry, reasonable flux ratios, and extremely precise time delays for ~100)
  - JWST (precise astrometry and infrared flux ratios for a moderately large sample)
- Calculate joint likelihoods for each “reality”, for each experimental design
- With this approach, we can adopt a nuisance parameter to reflect the modeling uncertainty.
- If there are priors we can adopt for the input perturbations to the macro-model, we can
  - a) Use them as weights in a Markov Chain Monte Carlo process
  - b) Use them as weights in evaluating the relative importance of gridded parameters

Stepping stone: Forecasting

- Pre-simulate 100s of millions of lensing realizations
  - Well defined model parametrization
  - Well defined and realistic priors for model parameters
- Pre-simulate “fiducial” lenses
  - With specific hyper-parameter choices for subhalo populations
- Define observational parameters and their precisions
  - Time delays, astrometry, positions, observational constraints, …

- Forecast! (Importance sampling)

Prior distributions of model parameters.



Strong lensing: ~2013-2015

- Improving analysis methodology as applied to both realization and real data
- Continue cherry-picking several hundred known lenses
- Likely outcome:
  - identification of several new distinct subhalos, 1E6-1E9 solar masses
  - better estimates of aggregate “mass in subhalo structures”
  - improving comparisons with CDM expectations
  - early comparisons with non-CDM expectations

Strong lensing: 2015-2020

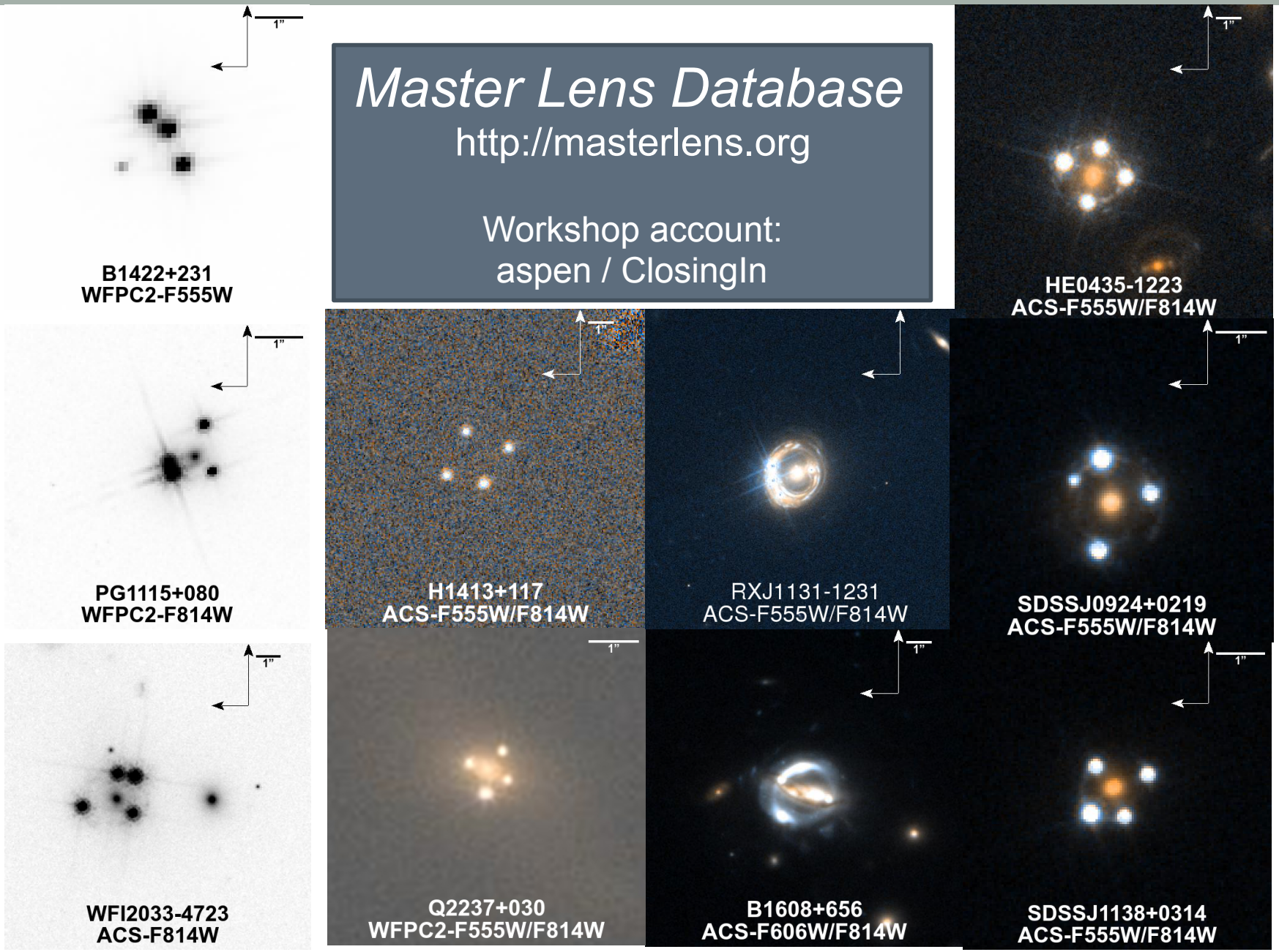
- Advances on the data front, emergence of large new samples of lenses (thousands)
  - Cherry picking
  - Ensembles
- Fairly definite observables:
  - astrometry (*HST, JWST, Euclid,* AO)
  - surface brightness / gravitational imaging
- Proposed-for observables:
  - time delays (OMEGA Explorer)

- Likely outcome:
  - Piece-wise subhalo mass function over from 1E6 solar masses and above
  - Rough scaling with host halo mass
  - Rough scaling with redshift
  - Sophisticated evidence comparisons with broad DM expectations

Master Lens Database

http://masterlens.org

Workshop account:
aspen / ClosingIn



L. Moustakas+ 2013

The near & medium future

- First: discovering many new lenses!
- Second: continuing to develop the analysis techniques
- Third: optimally combining observables
- Fourth: effective comparison of model hyper-parameters to salient and useful particle properties
  - This leads to interesting questions about how best to compare the Cosmic Frontier groups' constraint efforts with what will be done with lensing!