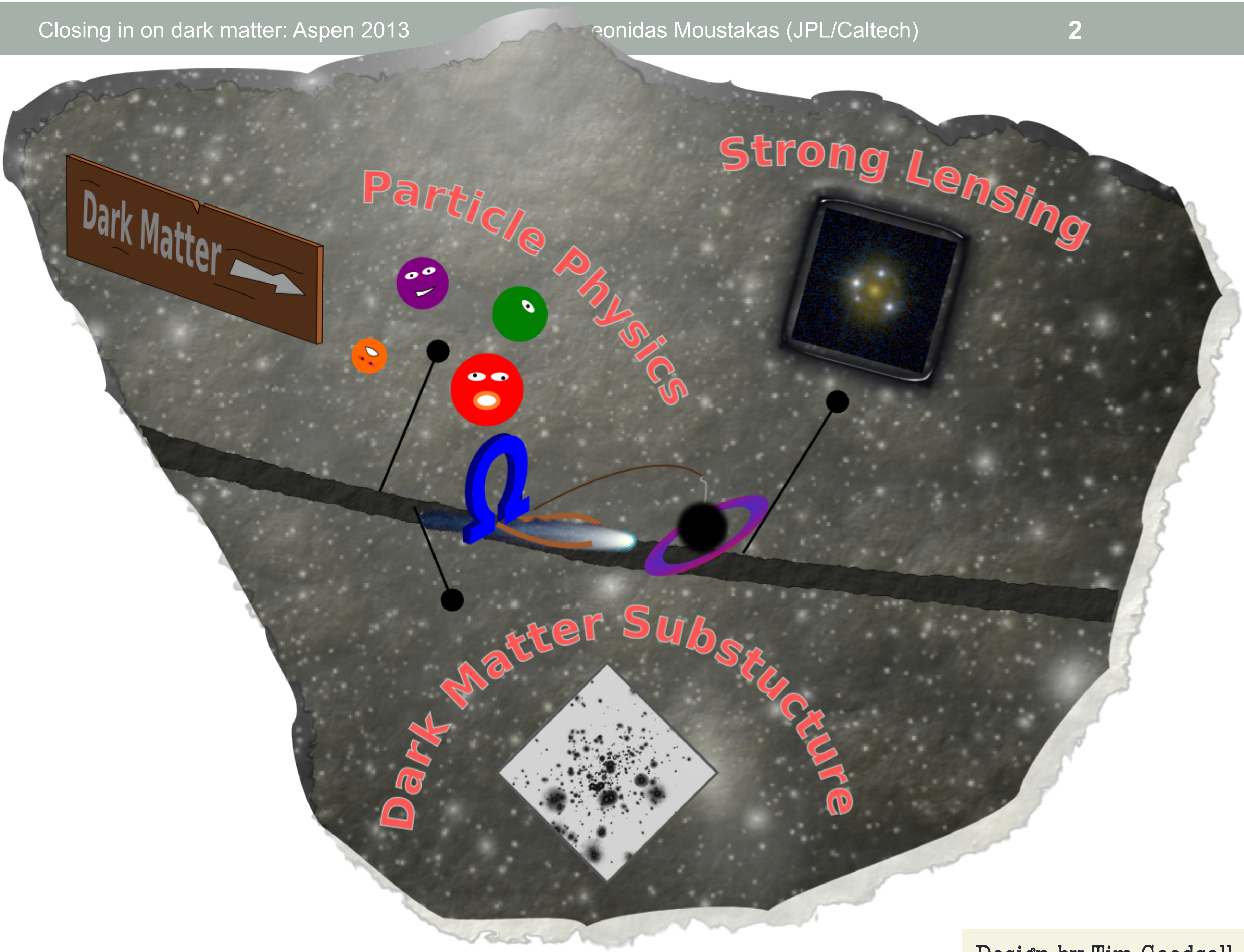
“SHEDDING LIGHT”

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

Leonidas Moustakas, JPL/Caltech

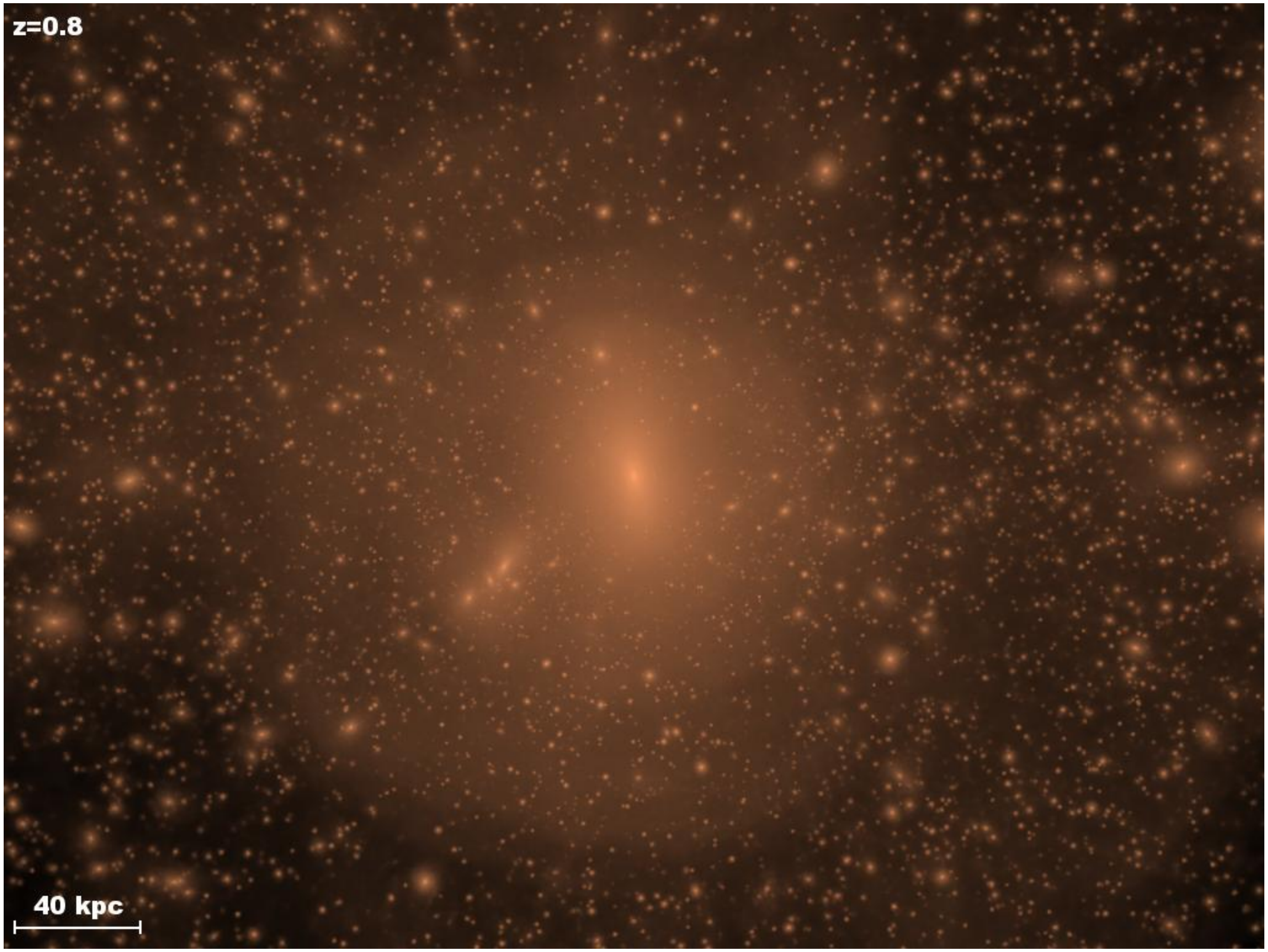
+Francis-Yan Cyr-Racine
+Julian Merten



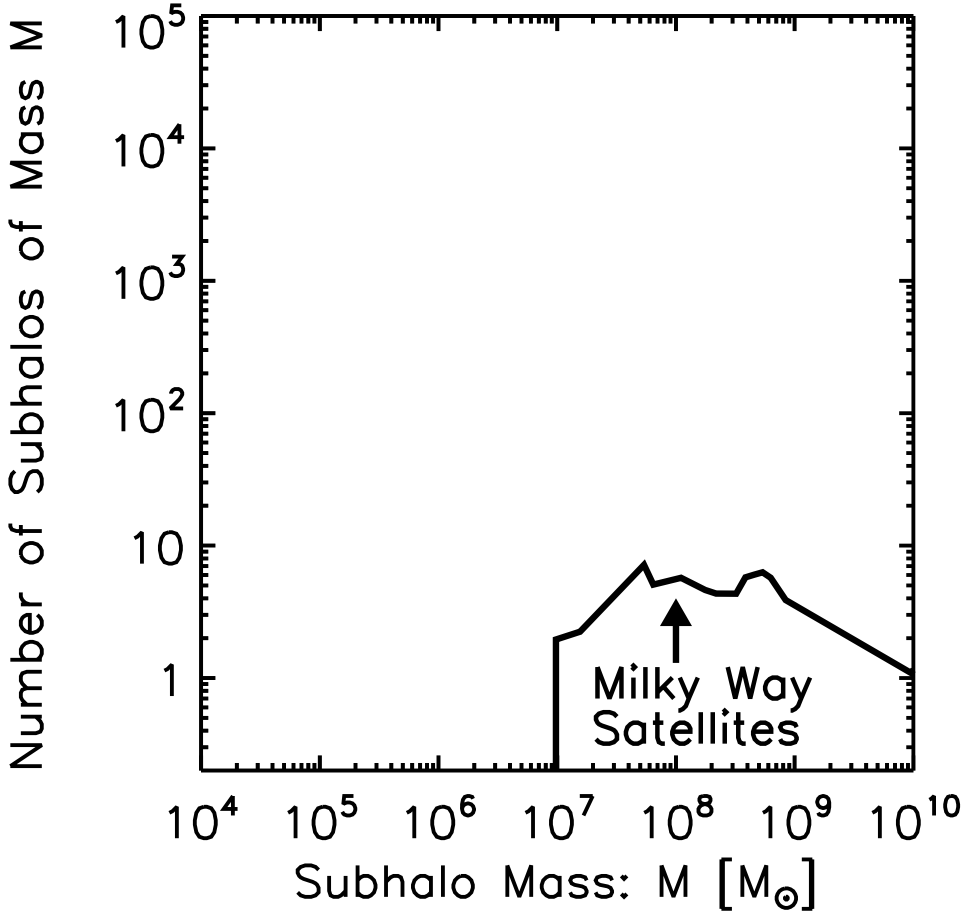
Design by Tim Goodsall

Ursa Minor dwarf galaxy
Courtesy Josh Simon

LCDM substructure



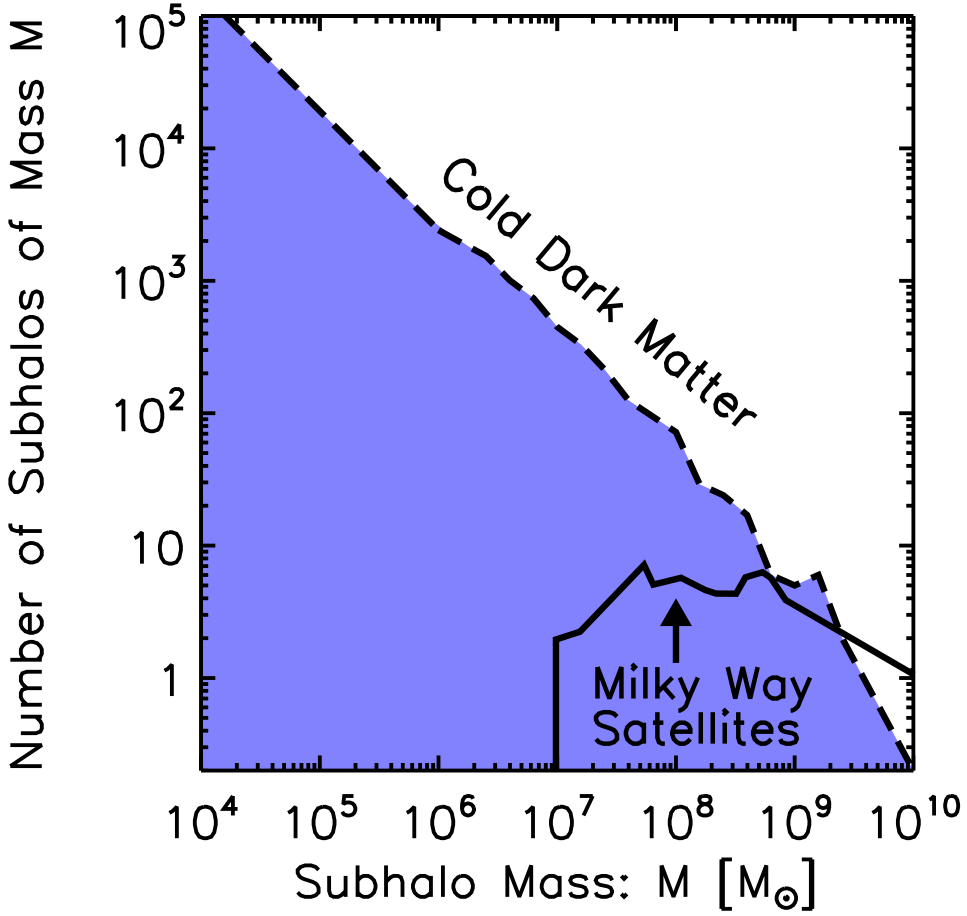
The dN/dM mass function of dwarfs



tidal mass, converted from estimated Vmax

Ackn. K. Stewart & J. Bullock

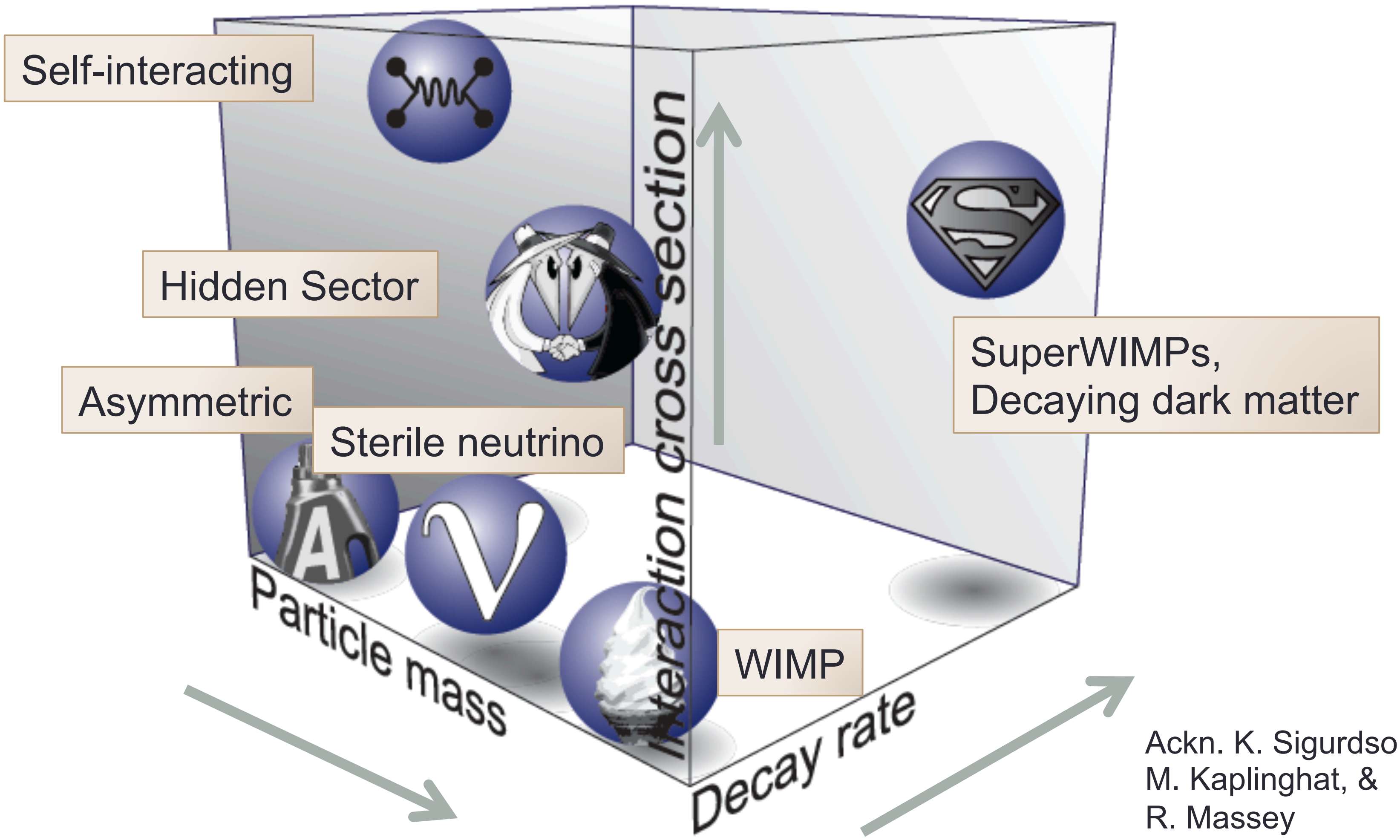
LCDM substructure



tidal mass, converted from estimated Vmax

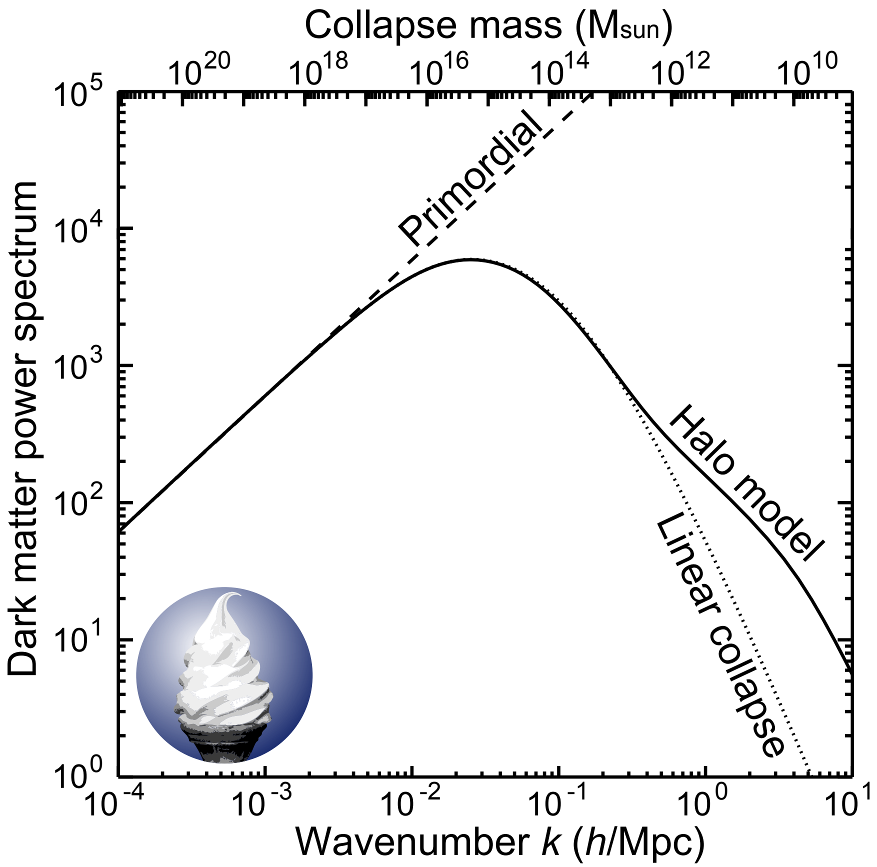
Ackn. K. Stewart & J. Bullock

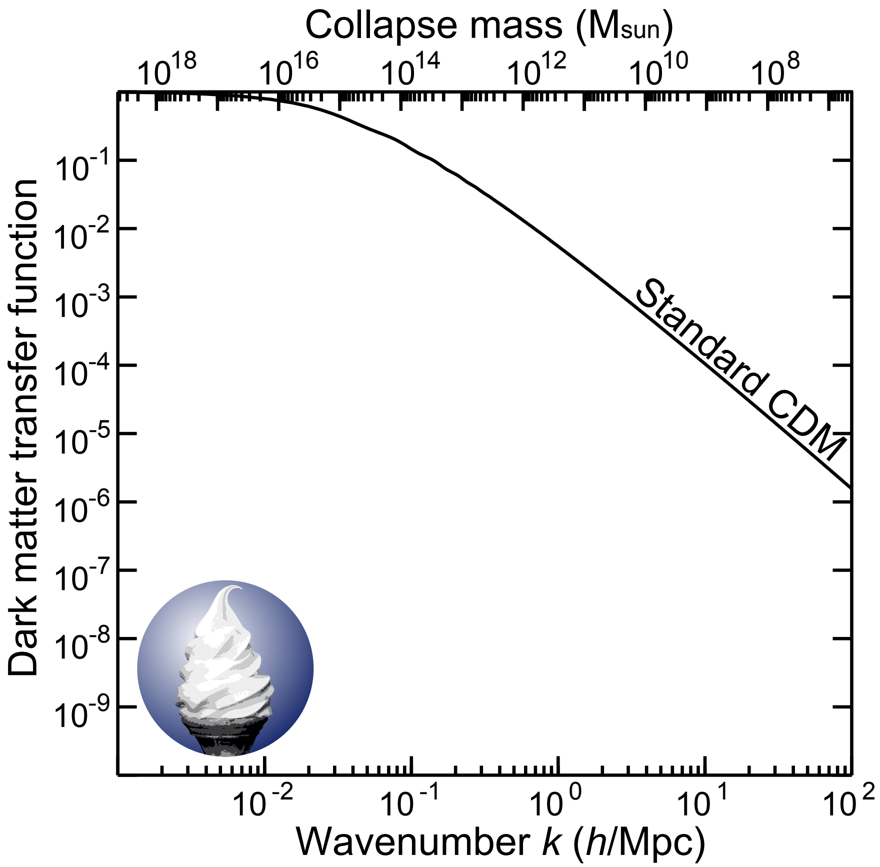
Physically motivated DM candidates



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

LCDM power spectrum and T(k)

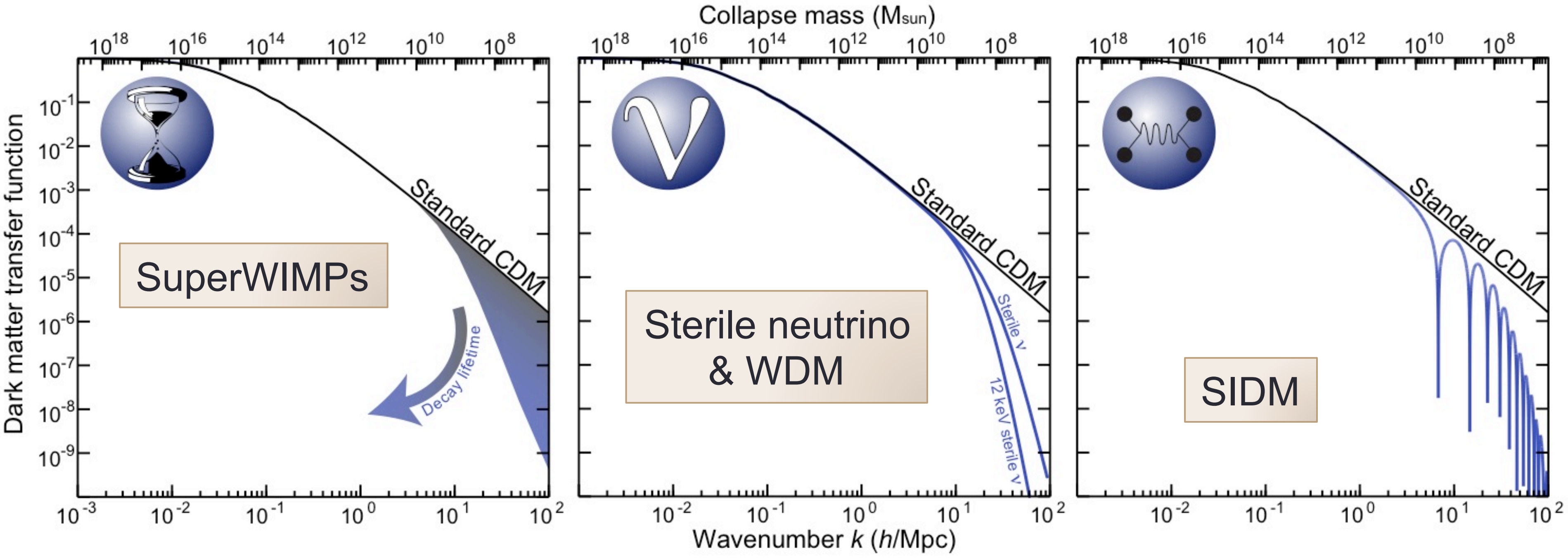




Ackn R Massey

Beyond LCDM transfer functions

Collapse Mass (Msun)

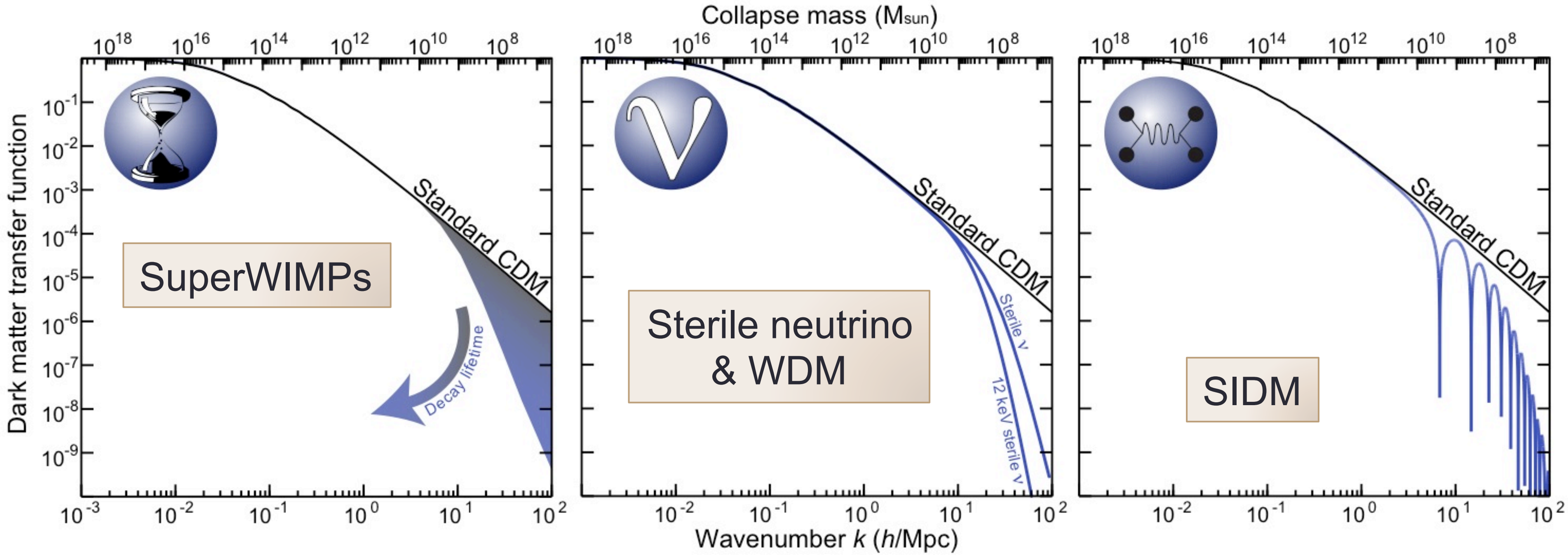


Wavenumber k (h/Mpc)

Ackn R Massey

The cutoff scale is only the beginning

Collapse Mass (Msun)



SuperWIMPs

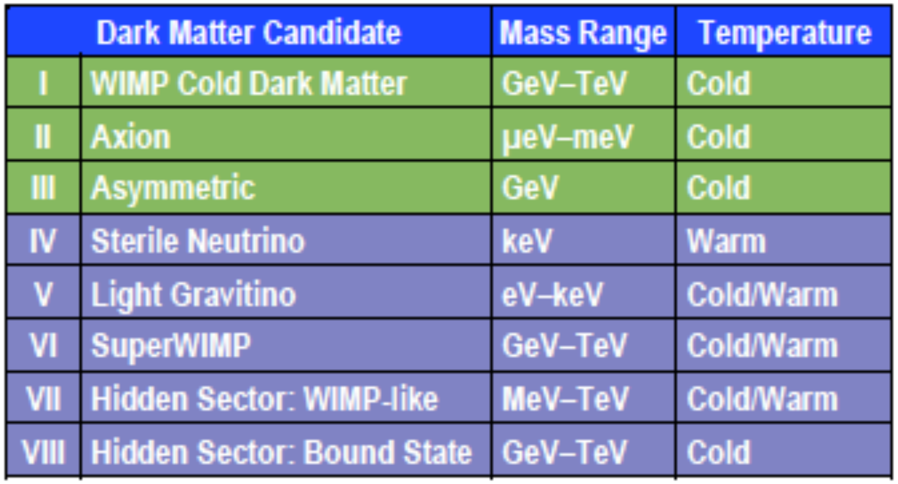
Sterile neutrino & WDM

SIDM

Wavenumber k (h/Mpc)

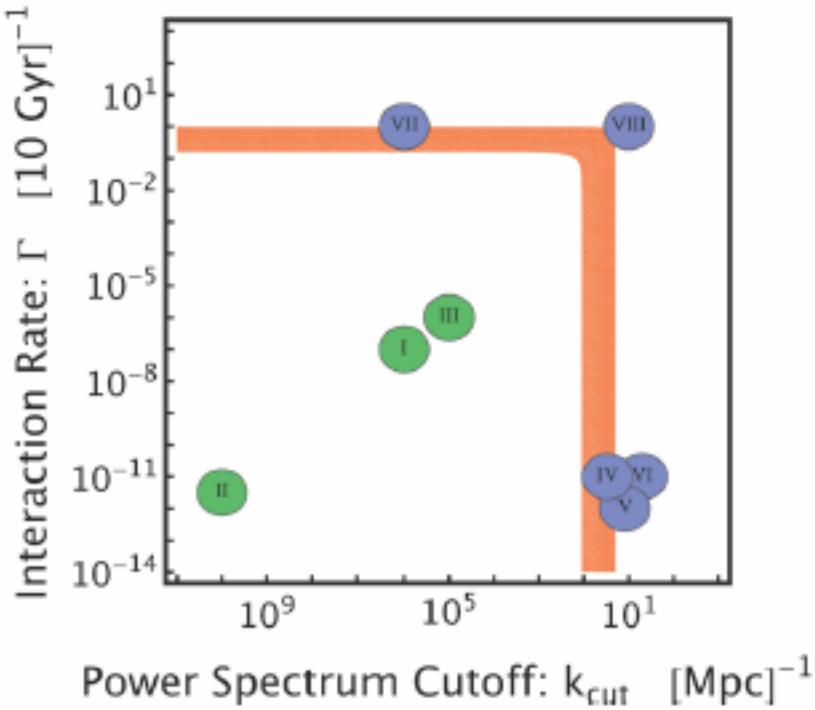
The collapse mass is just the beginning of the story, since within a halo, tidal evolution can strip 90% of a subhalo's mass, or fragmentation & other physics may be important.

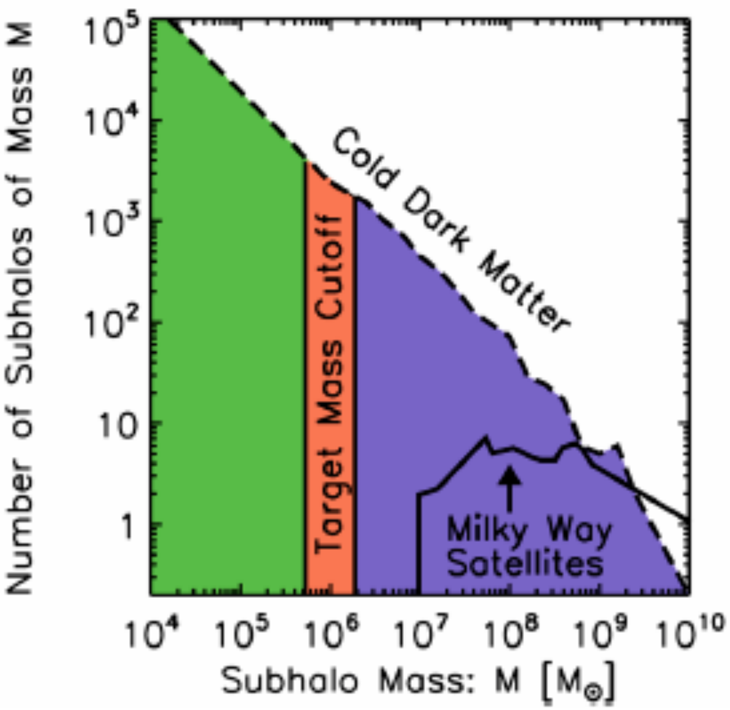
Ackn R Massey



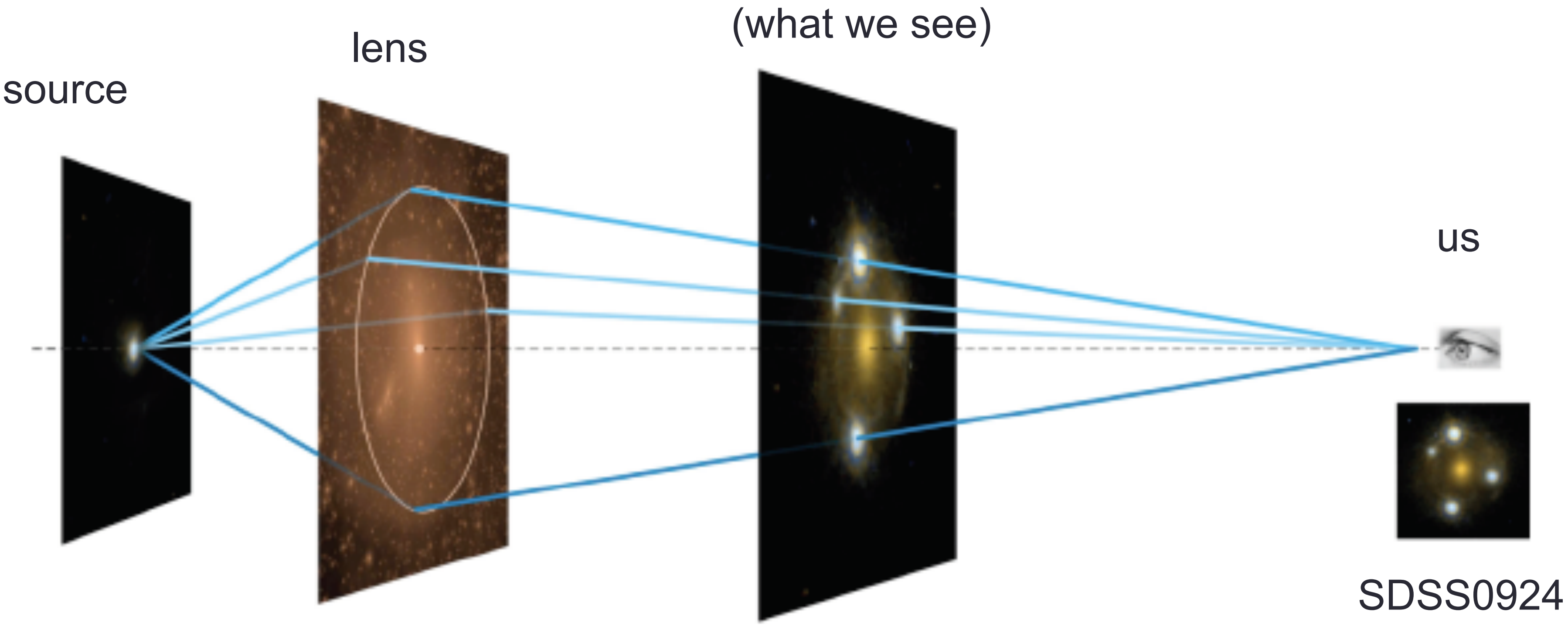
	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV–TeV	Cold
II	Axion	μeV–meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV–keV	Cold/Warm
VI	SuperWIMP	GeV–TeV	Cold/Warm
VII	Hidden Sector: WIMP-like	MeV–TeV	Cold/Warm
VIII	Hidden Sector: Bound State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

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





Strong gravitational lensing

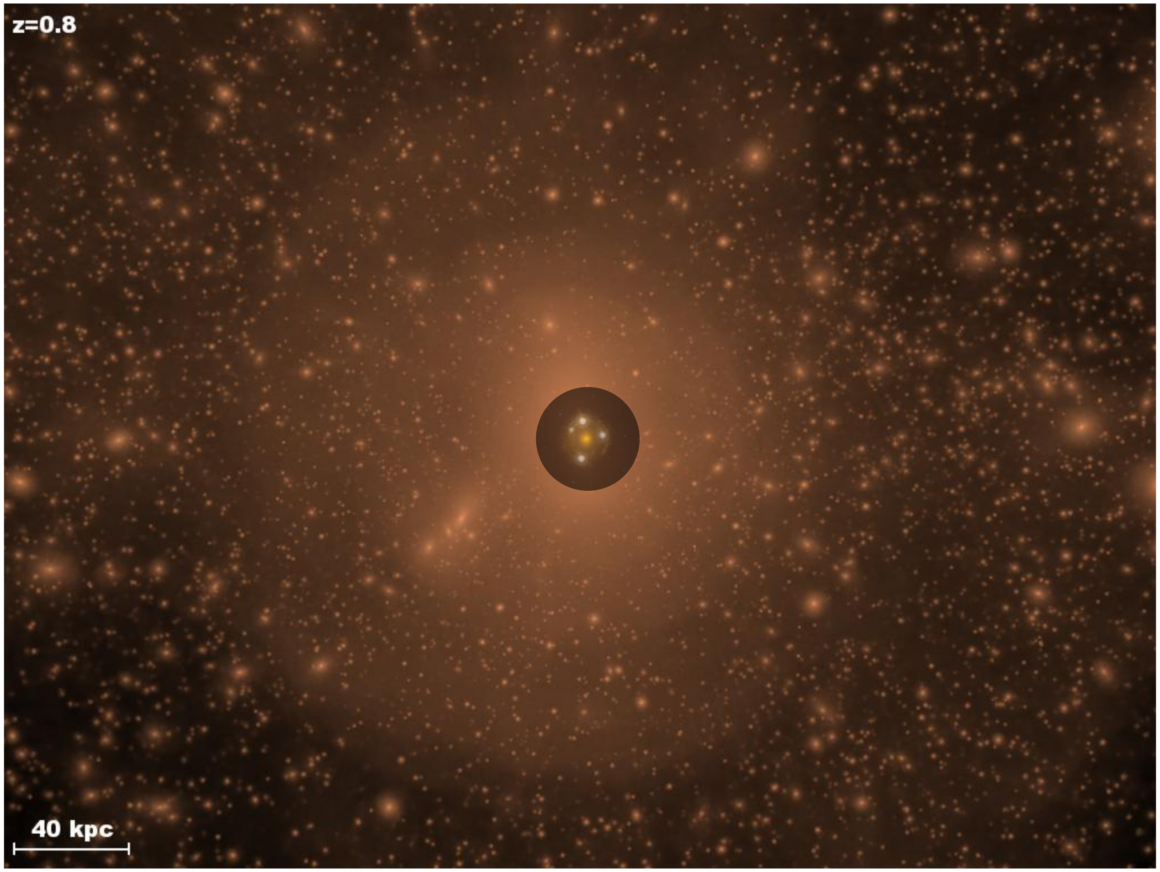


A simple geometric relation between the angular diameter distances between source, lens, and us determine the critical surface mass density for strong gravitational lensing.

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.

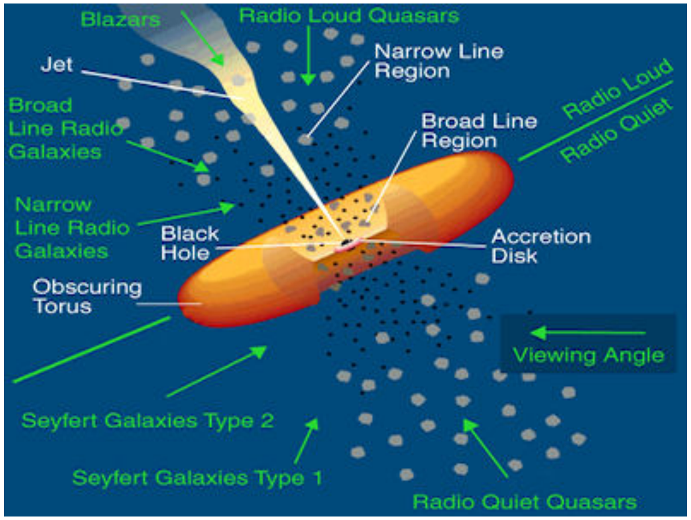


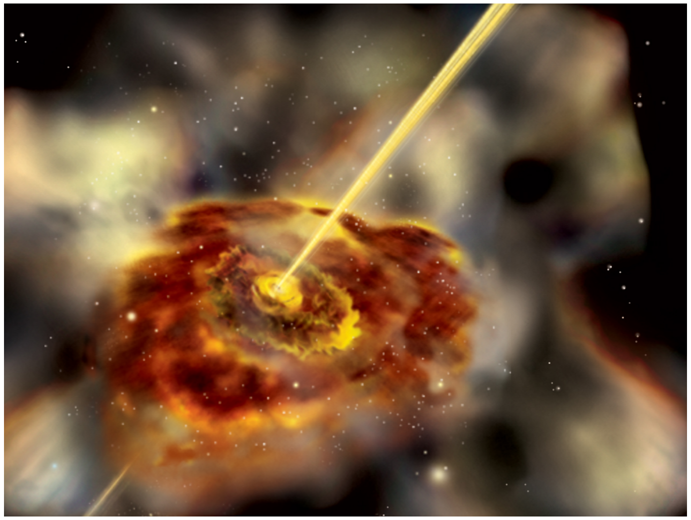
Diemand et al
Via Lactea

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.)*

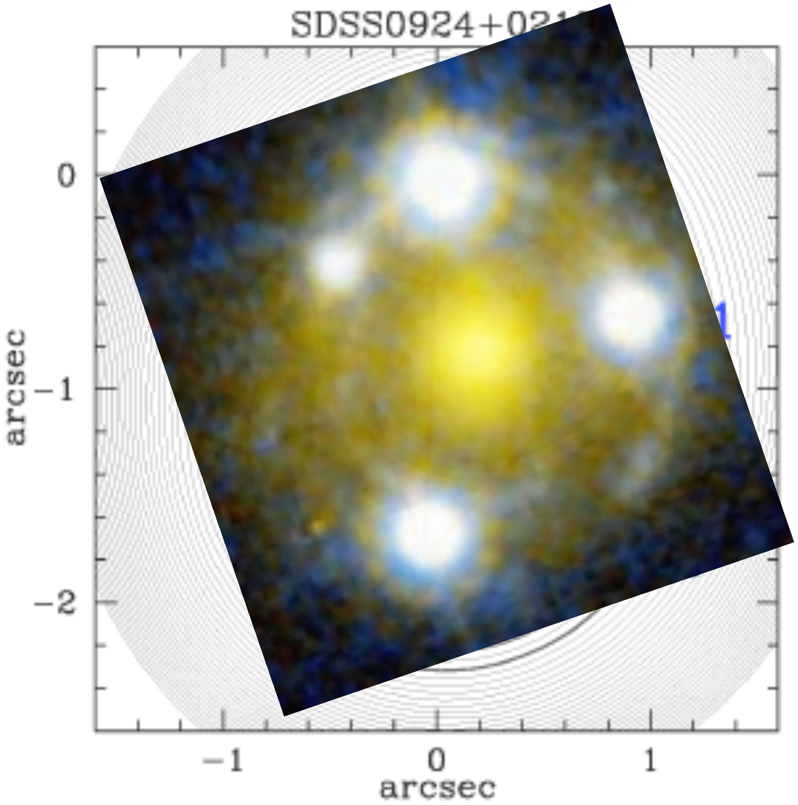




And of course, the source being lensed is a critical ingredient. A lensed Active Galactic Nucleus has an angular size of ~1 micro-arcsecond.

The lensing arrival time equation

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

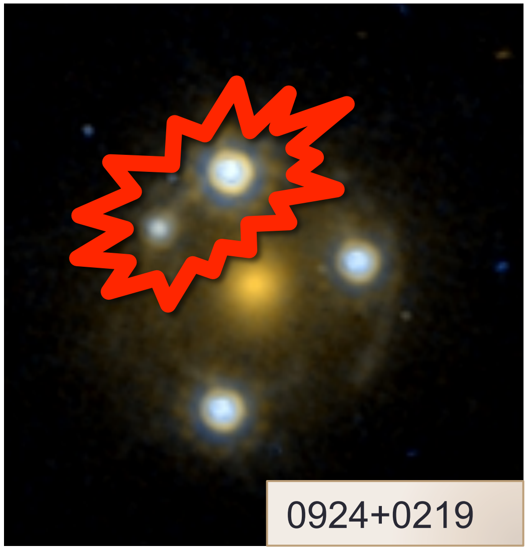


Time delays	$\Delta\tau$	$\propto \Delta\phi$
Image positions	$\nabla_\theta \tau$	$\propto \nabla_\theta \phi$
Magnifications	$\nabla\nabla_\theta \tau$	$\propto \nabla\nabla_\theta \phi$

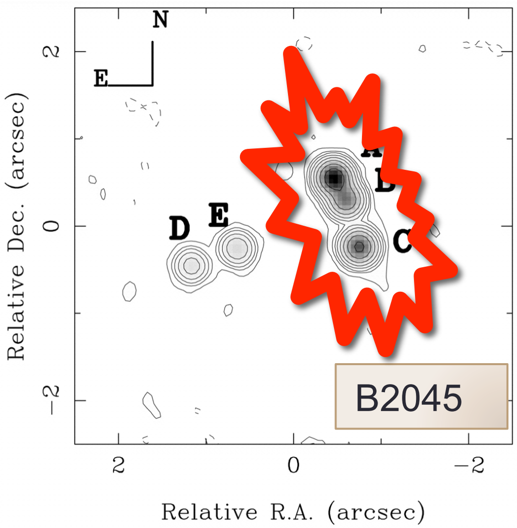
So time delays depend *directly* on the potential perturbations over larger area.

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

Classic magnification anomalies



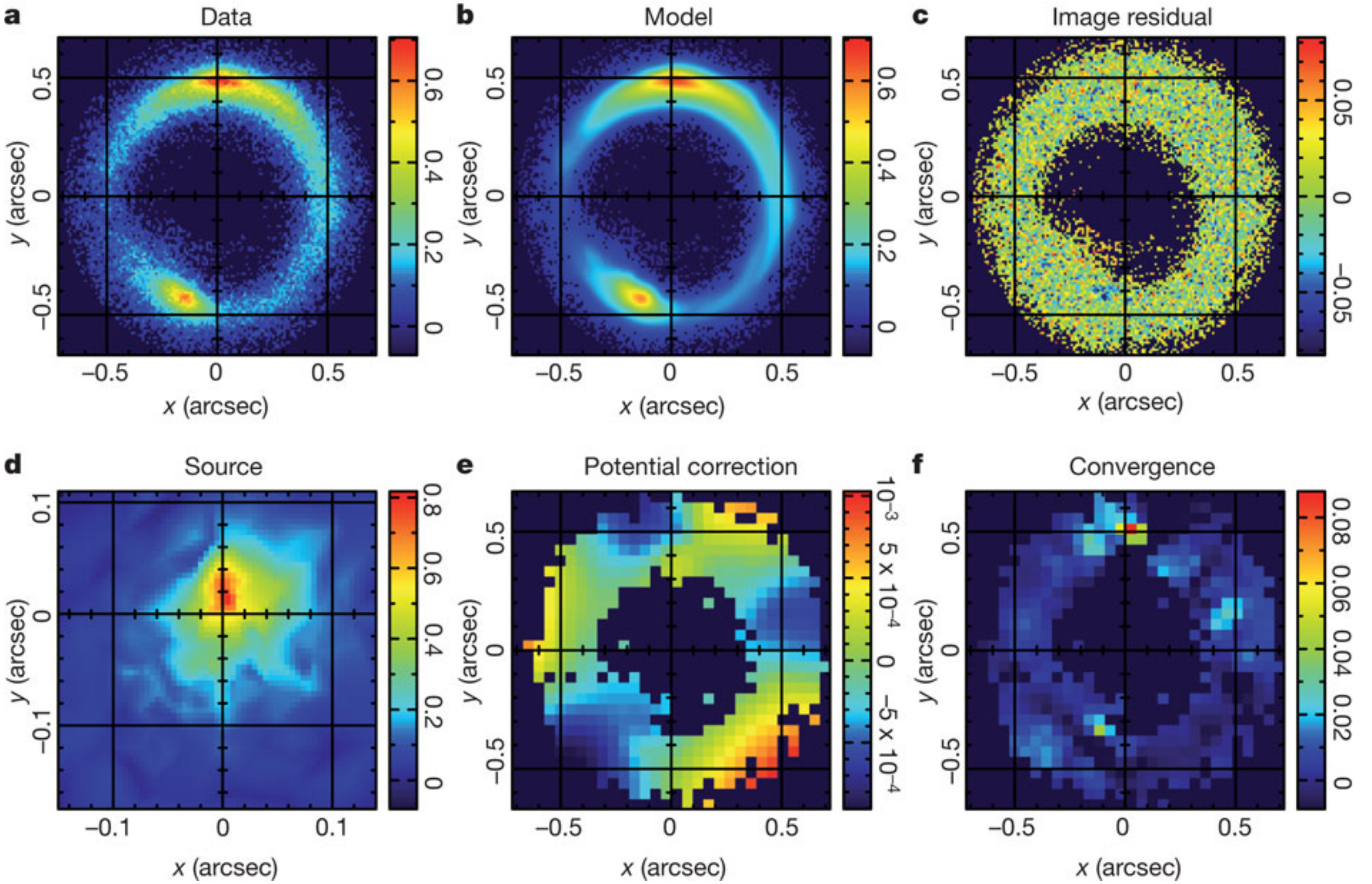
$$R_{fold} = \frac{F_A - F_B}{F_A + F_B} \approx A_{fold} d_1$$



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

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

Gravitational Imaging

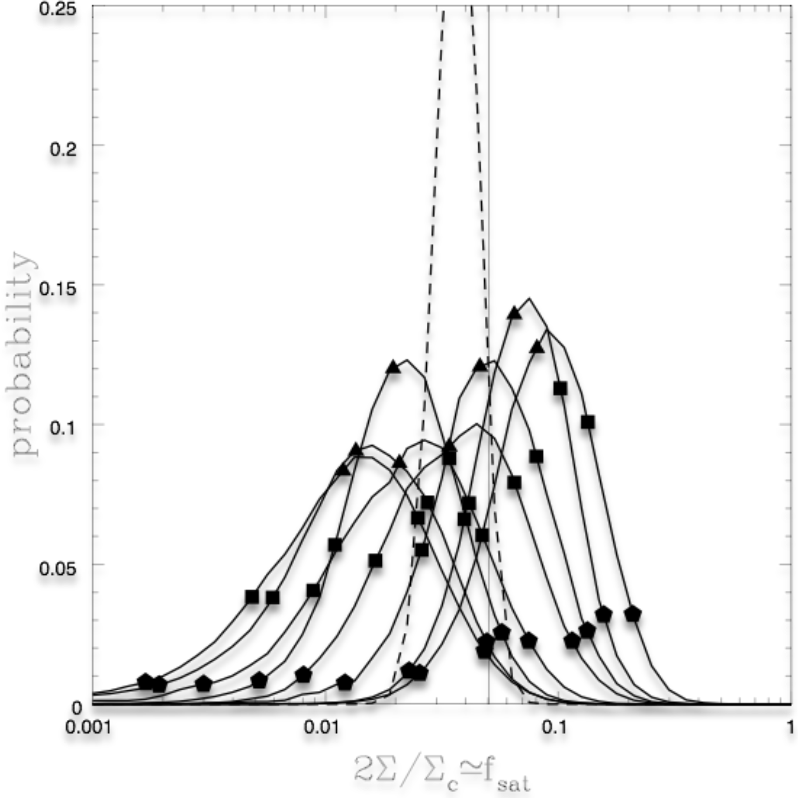


Vegetti+2012 Nature

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.

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



A few percent

Surface density in substructure

Strong lensing substructure detection

Investigation Technique	**Lenses**	**Mass Upper/Lower Limits and/or Range Investigated**	**Inferred DM Substructure Mass Fraction (f_{sub})**	**References**
Time delays	RX J1131-1231	$> 5 \times 10^{10}$ M_{sun}	---	Morgan et al. (2006)
Astrometric positions	MG 2016+112	10^7-10^9 M_{sun}	$f_{sub} < 0.09$	More et al. (2006)
Magnification ratios	MG 0414+0534, B0712+472, PG 1115+080, B1422+231, B1608+656, B1933+503, B2045+265	10^6- 10^9	$0.006 < f_{sub} < 0.07$	Dalal & Kochanek (2002)
Magnification ratios	2045+265, 0712+472, 1555+375, 1422+231, 0414+053, 2237+030, 1115+080	10^7-10^9 M_{sun}	0.003 < fsub < 0.02	Metcalf & Amara (2010)
Spectroscopic lensing	Q2237	10^5-10^8 M_{sun}	0.04 < fsub < 0.07	Metcalf+ (2004)
Gravitational Imaging	SDSS J0946+1006	4×10^6- 4×10^9	0.009 < fsub < 0.042	Vegetti+ (2010)

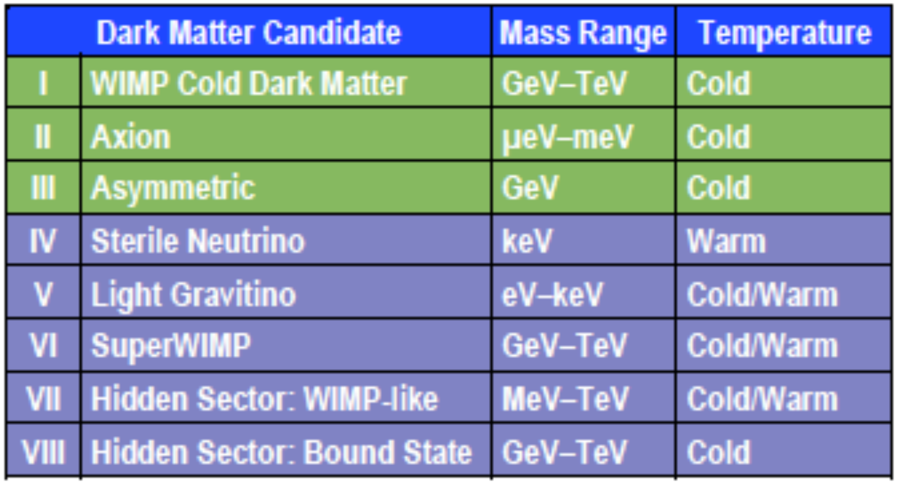
Also: Vegetti+ 2012, Fadely+ 2012, and much in-prep work!

Strong lensing substructure detection

Investigation Technique	Lenses	Mass Upper/Lower Limits and/or Range Investigated	Inferred DM Substructure Mass Fraction (f_{sub})	References
Time delays	RX J1131-1231	$> 5 \times 10^{10}$ M_{sun}	---	Morgan et al. (2006)
Astrometric positions	MG 2016+112	10^7-10^9 M_{sun}	$f_{sub} < 0.09$	More et al. (2006)
Magnification ratios	MG 0414+0534, B0712+472, PG 1115+080, B1422+231, B1608+656, B1933+503, B2045+265	10^6- 10^9	$0.006 < f_{sub} < 0.07$	Dalal & Kochanek (2002)
Magnification ratios	2045+265, 0712+472, 1555+375, 1422+231, 0414+053, 2237+030, 1115+080	10^7-10^9 M_{sun}	0.003 < fsub < 0.02	Metcalf & Amara (2010)
Spectroscopic lensing	Q2237	10^5-10^8 M_{sun}	0.04 < fsub < 0.07	Metcalf+ (2004)
Gravitational Imaging	SDSS J0946+1006	4×10^6- 4×10^9	0.009 < fsub < 0.042	Vegetti+ (2010)

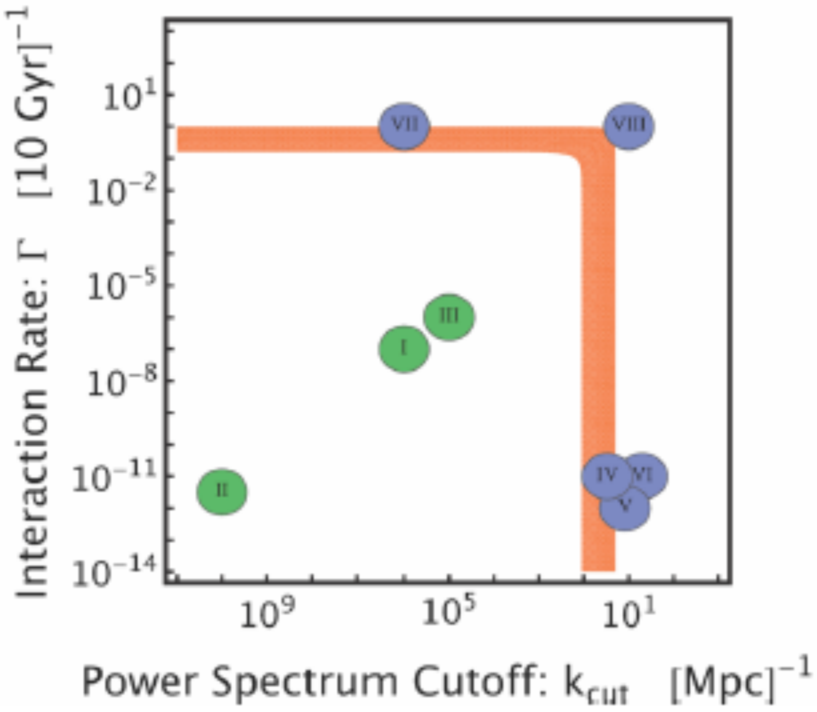
Ie: A broad agreement with the *cumulative* expectations from CDM, concentrated around ~1E7 – 1E9 Msun scale subhalos & ~1% in substructure.

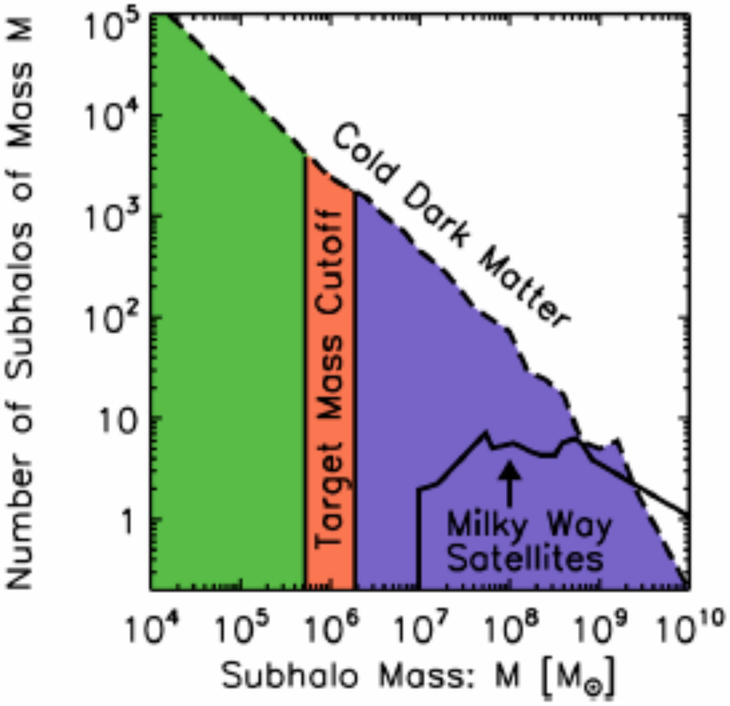
There are caveats with systematics, precision issues, & modeling limitations, in each and every one of these cases – and to consider for future work.



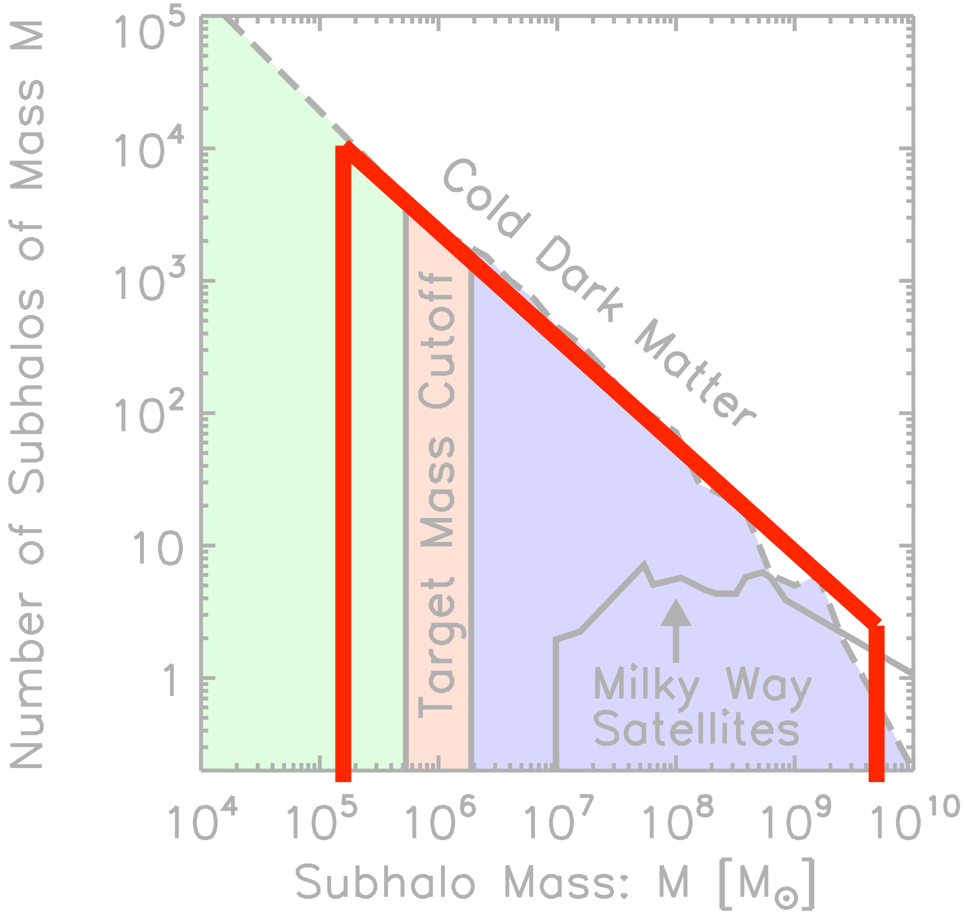
	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV–TeV	Cold
II	Axion	μeV–meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV–keV	Cold/Warm
VI	SuperWIMP	GeV–TeV	Cold/Warm
VII	Hidden Sector: WIMP-like	MeV–TeV	Cold/Warm
VIII	Hidden Sector: Bound State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

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





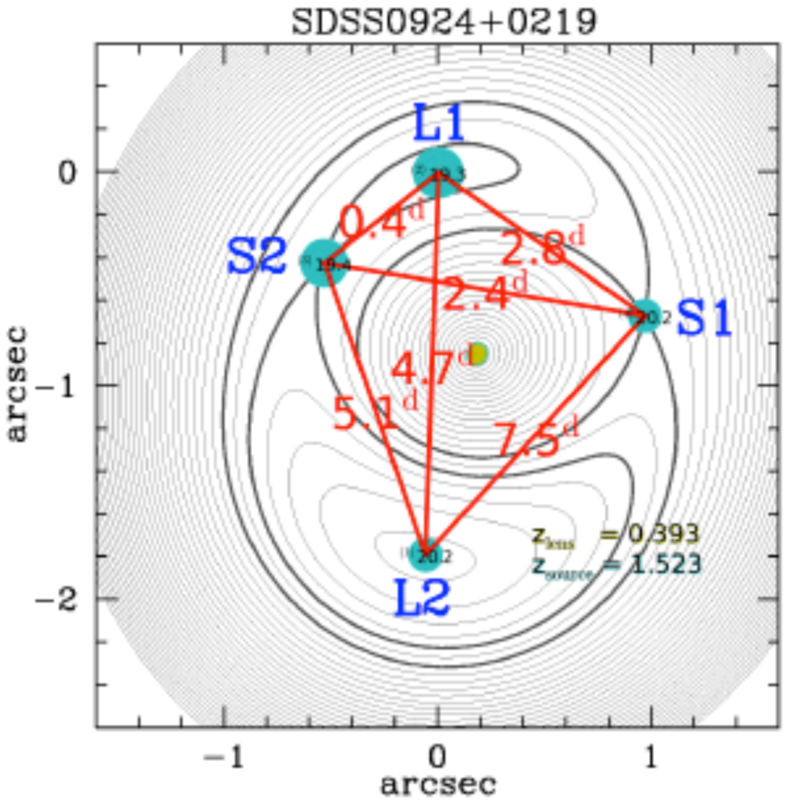
Mass function parametrization

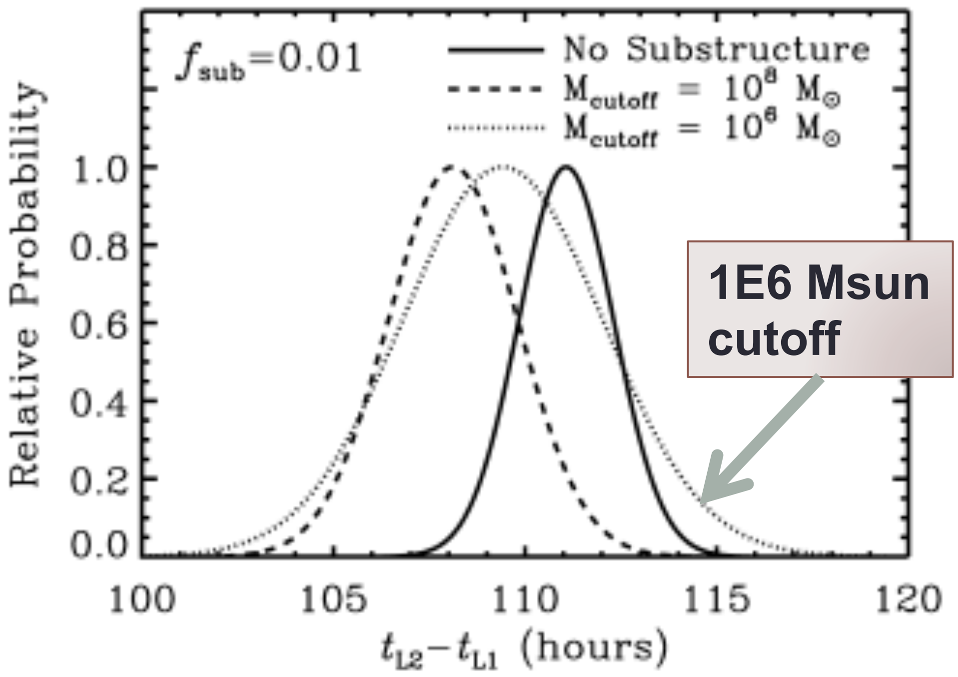


- normalization
- power law slope
- upper mass cut
- lower mass cut

Time delay perturbations

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





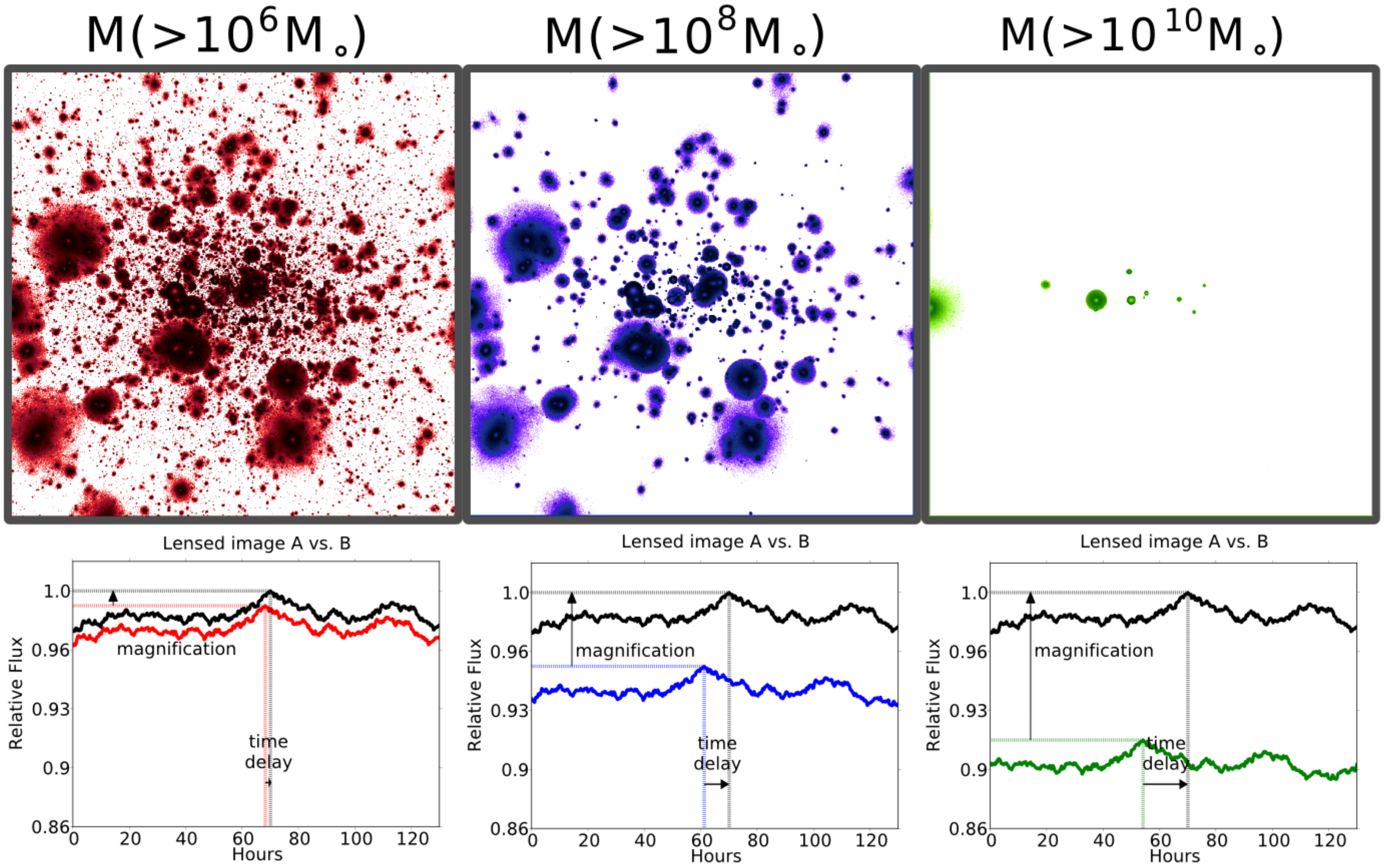
1E6 Msun cutoff

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, +

Strong lens realizations: lensmodel

- Flexible lensing models for macro-models which can feature deviations from axi-symmetry, embedded in a specified environment, and including sub-clumps with a broad set of adjustable parameters for their spatial and mass function distribution, and internal structure.

- Efficiently calculates the net observable effects (time delays, positions, magnifications) from ~ a few million subhalos. E.g. for f_sub~5%, we can calculate the effects down to ~10^3 Msun.

- MCMC & nested sampling calculations for inference (e.g. Keeton astro-ph/1102.0996)

- Capabilities exist to explore finite source effects, we are ignoring these presently.

Strong lens realizations: lensmodel

- F
  d
  e
  a
  di

- E
  p
  fo
  Msun.

- State of the art strong lensing code with the necessary flexibility -- 15 years in development (Keeton)
- Deals with millions of subhalos in complex environments.

- MCMC & nested sampling calculations for inference (e.g. Keeton astro-ph/1102.0996)

- Capabilities exist to explore finite source effects, we are ignoring these presently.

Putting it all together…

- The goal: Map observational modes and precision to dark matter subhalo structure and ensemble constraints.
  - The potential Observables:
    - {Astrometric positions relative to the lens center,
    - Magnifications vs wavelength vs time vs image parity,
    - Stellar microlensing statistics vs image parity,
    - Matched surface brightness mapping of Einstein Ring,
    - Time delays between each image pair,
    - Line of sight structure, and environment,
    - Color information}
  - Model Parameters:
    - {Cosmological parameters,
    - AGN structure and variability model for black hole mass, redshift, etc,
    - Mass function, velocity dispersion, and relative motion of lens galaxy stars,
    - Lensing galaxy reddening,
    - Lensing potential macro-model shape perturbations (boxiness, disks),
    - SUBHALO MASS FUNCTION PARAMETERS}

Bayesian Inference

$\vec{M} = \{M_k\}$, model parameters for the DM mass function with a normalization, slope, and cutoff scale.

$\vec{D} = \{D_k\}$, each D_k is a distinct measurement by perturbative technique or wavelength.

Then, $p(\{D_k\} \mid \vec{M}, I) = \prod_k p(D_k \mid \vec{M}, I)$

and: $p(\vec{M} \mid \vec{D}) = \dfrac{p(\vec{D} \mid \vec{M}, I) \times p(\vec{M}, I)}{p(\vec{D})}$

Bayesian Inference

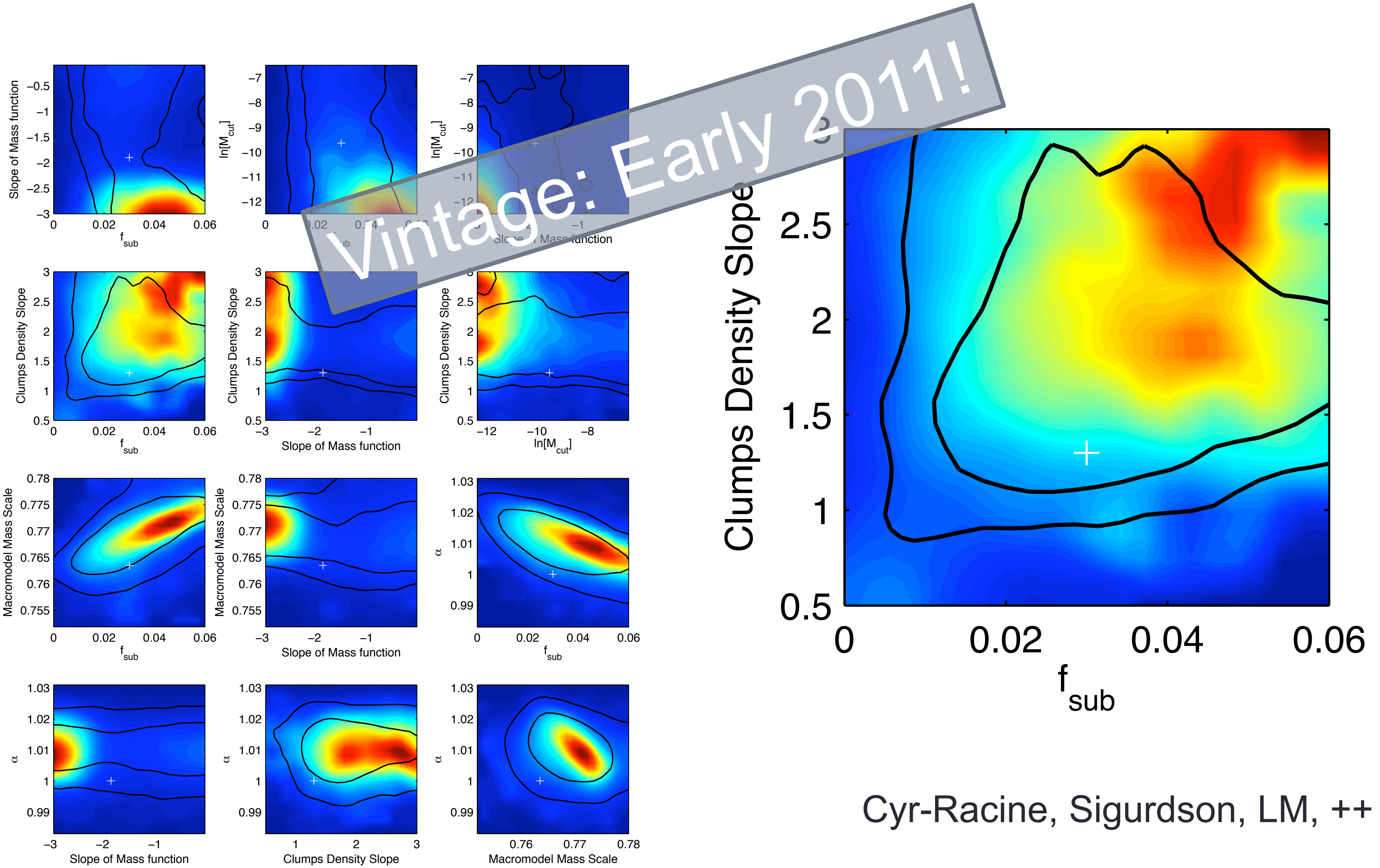
$\vec{M} = \{M_i\}$ model parameters for the DM

- Many unsolved modeling and framework-setup issues
- Extremely computationally intensive
- *Soon, but not quite yet*

Then, $p(\{\vec{D}_k\} \mid \vec{M}, I) = \prod_k p(\vec{D}_k \mid \vec{M}, I)$

$$\text{and}: \quad p(\vec{M} \mid \vec{D}) = \frac{p(\vec{D} \mid \vec{M}, I) \times p(\vec{M}, I)}{p(\vec{D})}$$

Stepping stones: MCMC

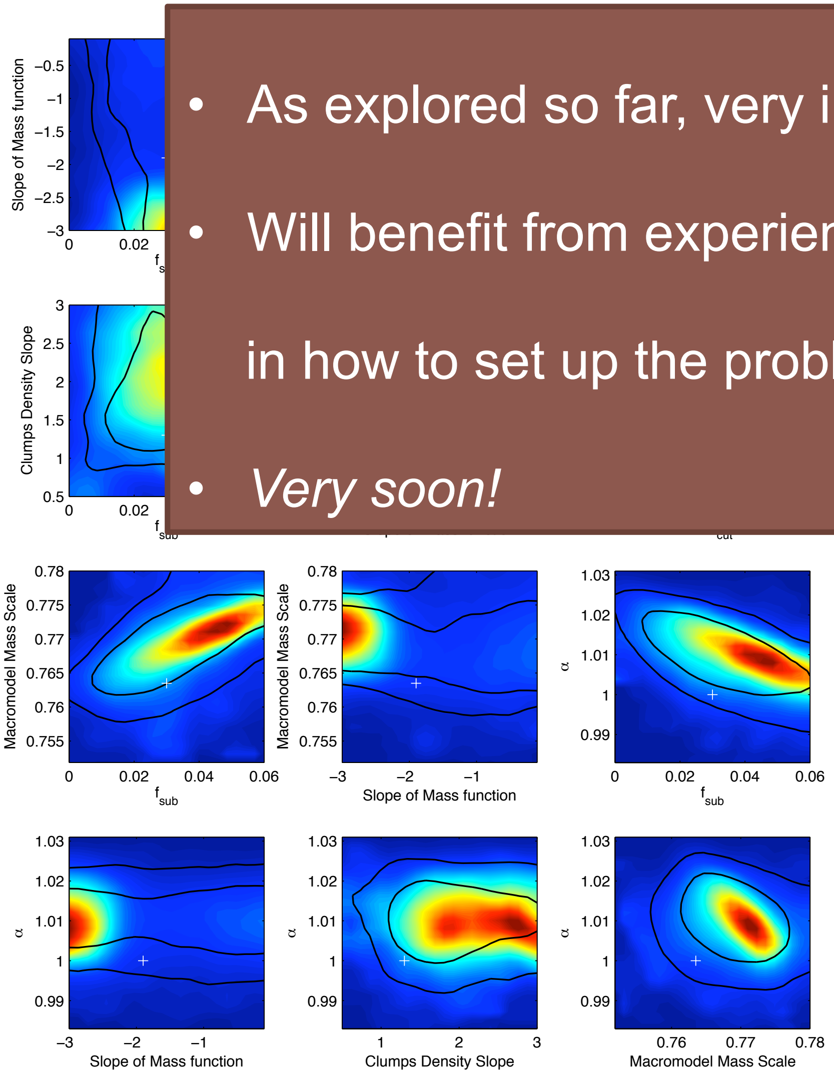


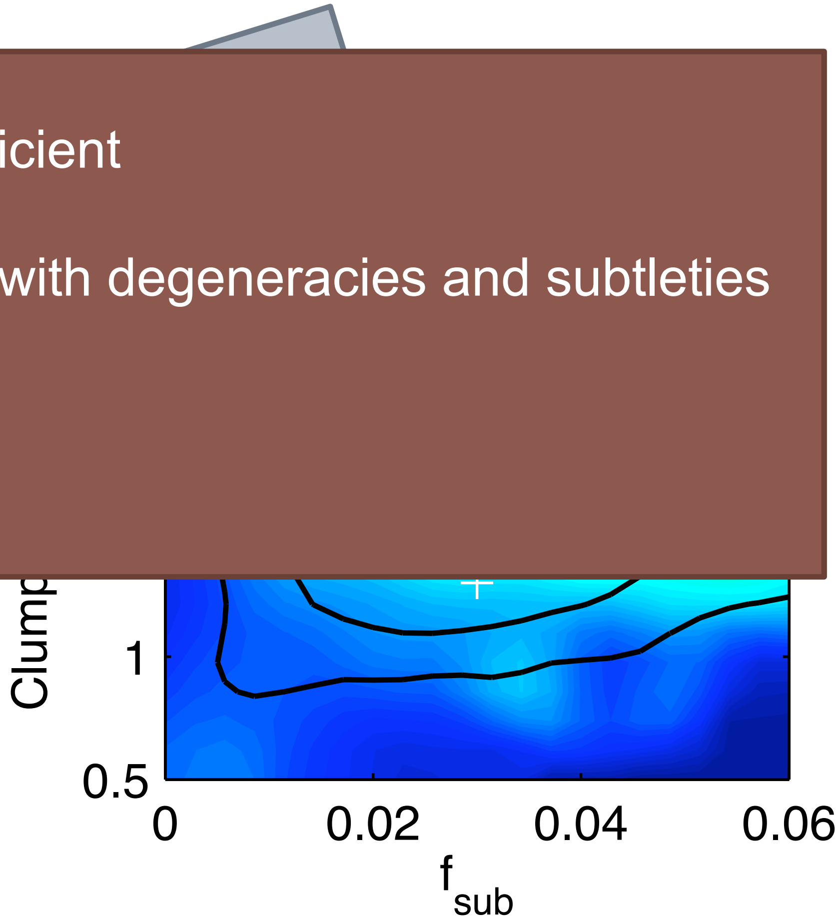
Vintage: Early 2011!

Cyr-Racine, Sigurdson, LM, ++

Stepping stones: MCMC

- As explored so far, very inefficient
- Will benefit from experience with degeneracies and subtleties in how to set up the problem
- *Very soon!*





Cyr-Racine, Sigurdson, LM, ++

Stepping stones: Forecasting

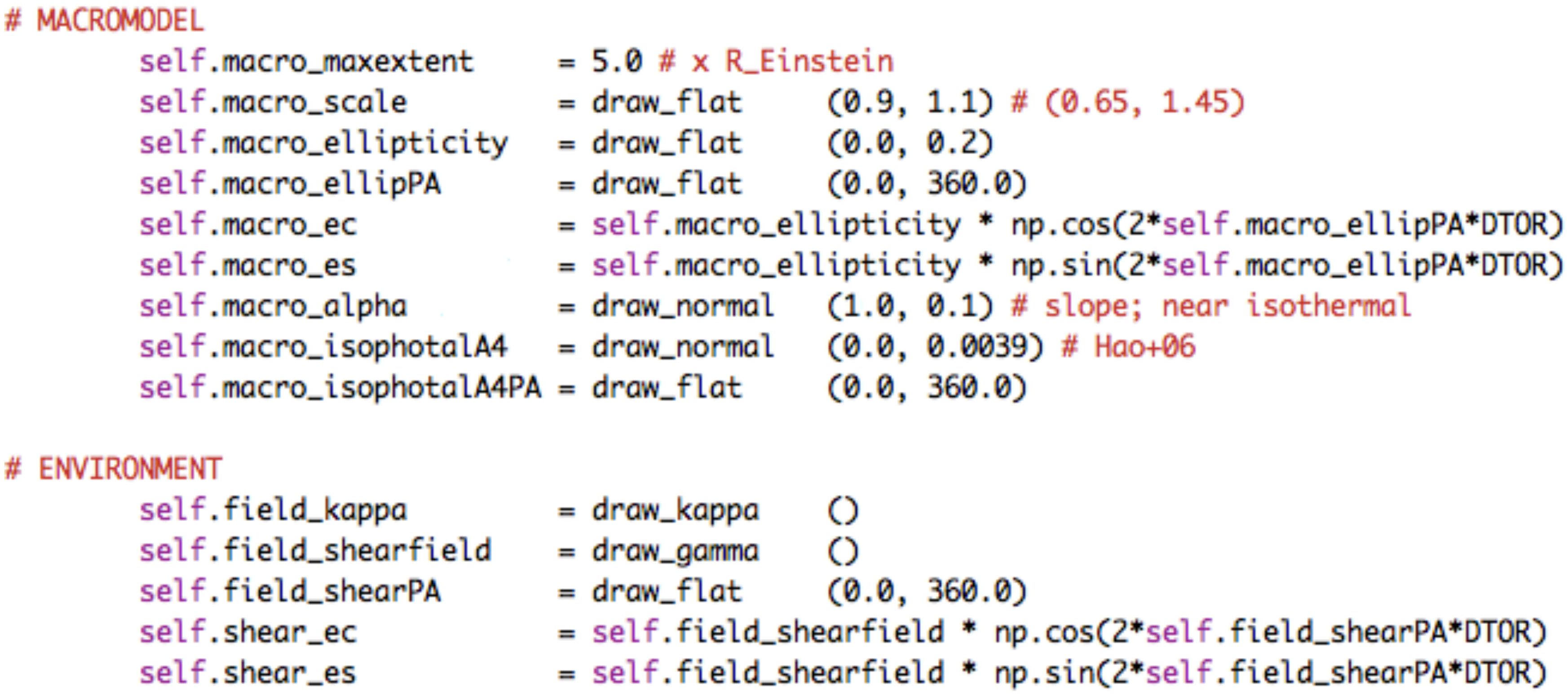
- Create a large set of realizations, with model input parameters varied based on plausible prior distributions.
- Create a large number of models for different "realities" of the subhalo mass function, for drawing specific fiducial model lenses. (By-passing the issues of fitting real lenses at present). 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 stones: Forecasting

- Create a large set of realizations, with model input parameters varied based on plausible prior distributions.
- Cr fo at
- De ar
- Ca
- 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

- (Expensively!) pre-compute models to sample the full posterior
  - ~1 Billion models!
- Define an experimental setup (observational constraints)
- Create fiducial models representing different DM scenarios
- Combine these to Importance Sample the posterior & explore model parameters.

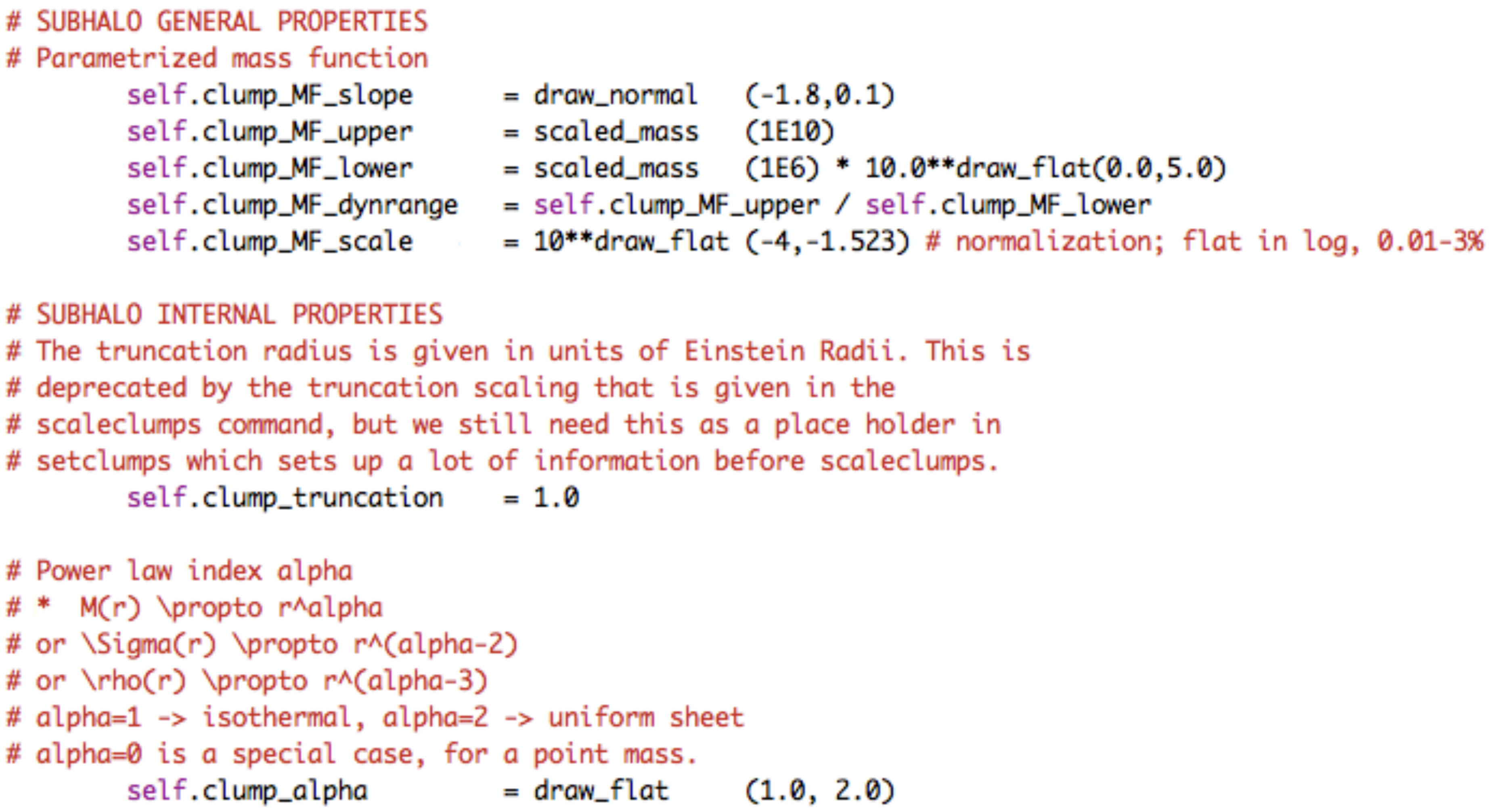
Forward realizations: big picture stuff



```
# MACROMODEL
        self.macro_maxextent     = 5.0 # x R_Einstein
        self.macro_scale         = draw_flat     (0.9, 1.1) # (0.65, 1.45)
        self.macro_ellipticity   = draw_flat     (0.0, 0.2)
        self.macro_ellipPA       = draw_flat     (0.0, 360.0)
        self.macro_ec            = self.macro_ellipticity * np.cos(2*self.macro_ellipPA*DTOR)
        self.macro_es            = self.macro_ellipticity * np.sin(2*self.macro_ellipPA*DTOR)
        self.macro_alpha         = draw_normal   (1.0, 0.1) # slope; near isothermal
        self.macro_isophotalA4   = draw_normal   (0.0, 0.0039) # Hao+06
        self.macro_isophotalA4PA = draw_flat     (0.0, 360.0)

# ENVIRONMENT
        self.field_kappa         = draw_kappa    ()
        self.field_shearfield    = draw_gamma    ()
        self.field_shearPA       = draw_flat     (0.0, 360.0)
        self.shear_ec            = self.field_shearfield * np.cos(2*self.field_shearPA*DTOR)
        self.shear_es            = self.field_shearfield * np.sin(2*self.field_shearPA*DTOR)
```

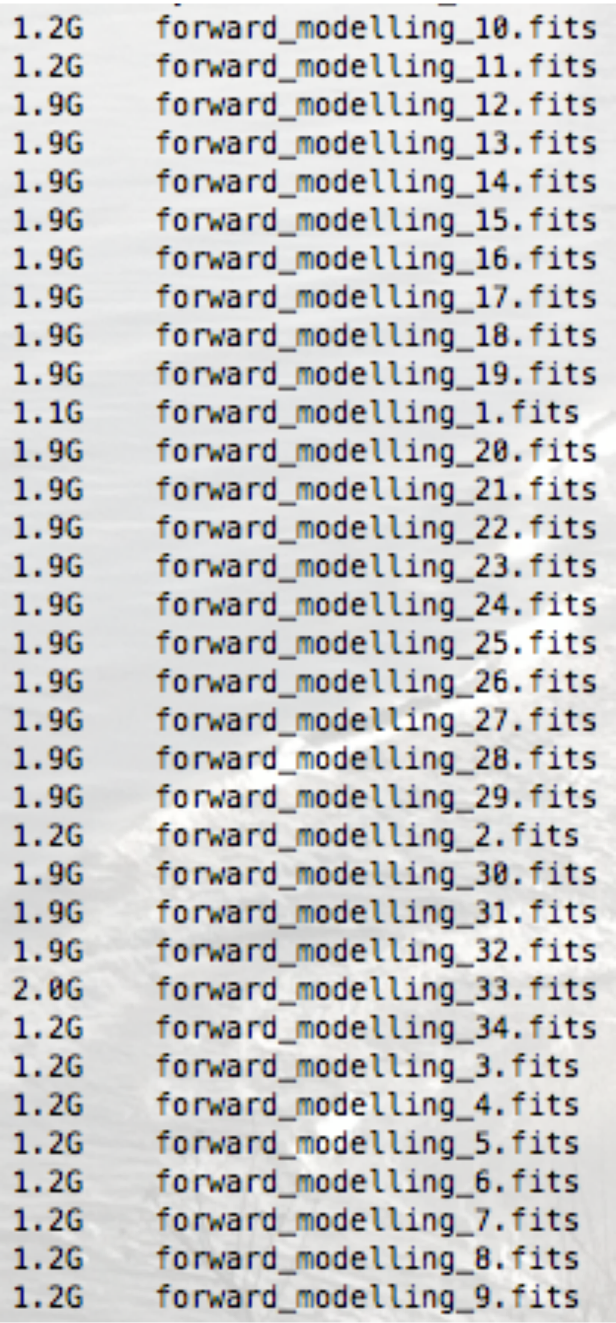
Forward realizations: the small stuff



```
# SUBHALO GENERAL PROPERTIES
# Parametrized mass function
        self.clump_MF_slope       = draw_normal   (-1.8,0.1)
        self.clump_MF_upper       = scaled_mass   (1E10)
        self.clump_MF_lower       = scaled_mass   (1E6) * 10.0**draw_flat(0.0,5.0)
        self.clump_MF_dynrange    = self.clump_MF_upper / self.clump_MF_lower
        self.clump_MF_scale       = 10**draw_flat (-4,-1.523) # normalization; flat in log, 0.01-3%

# SUBHALO INTERNAL PROPERTIES
# The truncation radius is given in units of Einstein Radii. This is
# deprecated by the truncation scaling that is given in the
# scaleclumps command, but we still need this as a place holder in
# setclumps which sets up a lot of information before scaleclumps.
        self.clump_truncation     = 1.0

# Power law index alpha
# *  M(r) \propto r^alpha
# or \Sigma(r) \propto r^(alpha-2)
# or \rho(r) \propto r^(alpha-3)
# alpha=1 -> isothermal, alpha=2 -> uniform sheet
# alpha=0 is a special case, for a point mass.
        self.clump_alpha          = draw_flat     (1.0, 2.0)
```



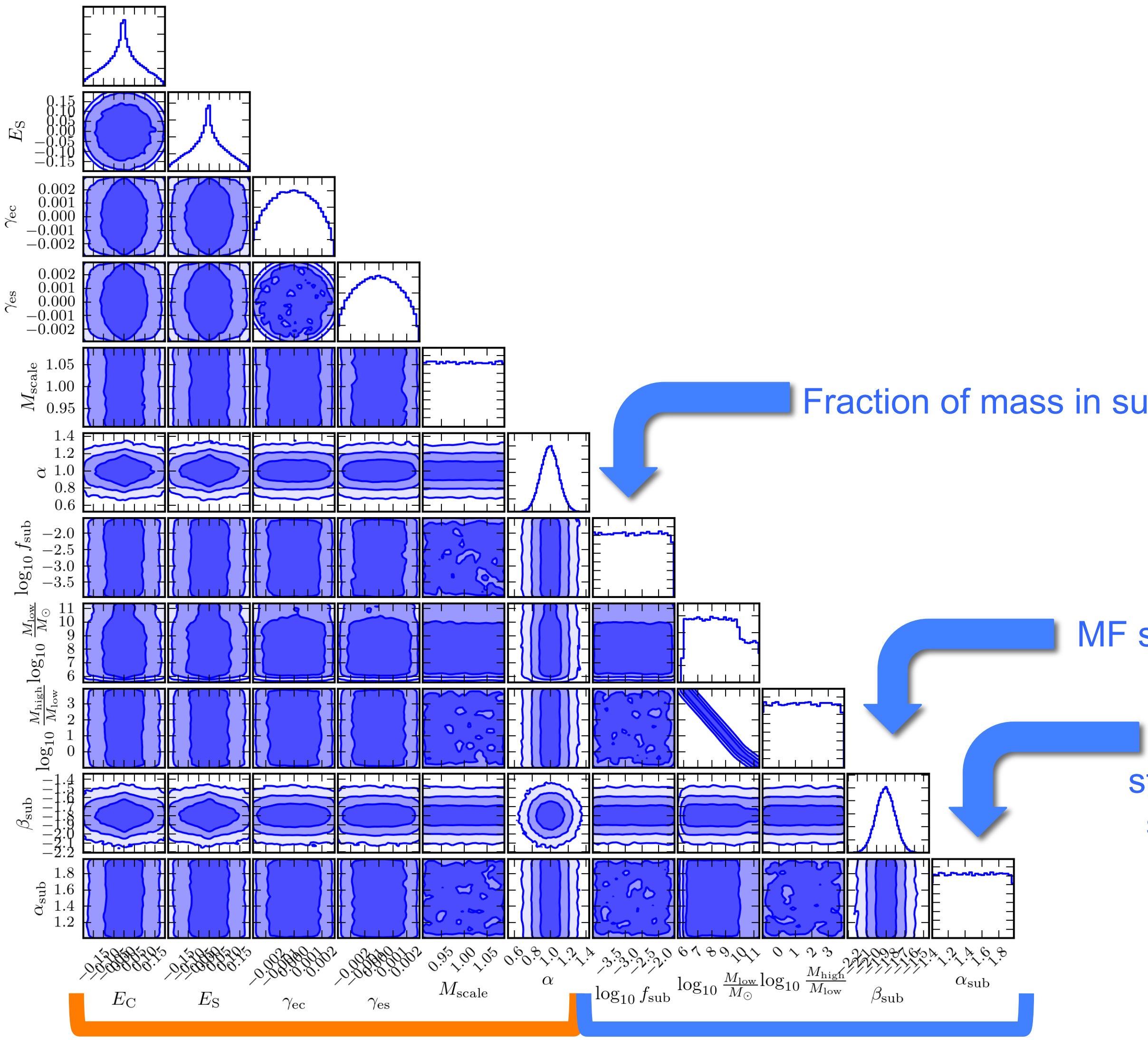
```
1.2G     forward_modelling_10.fits
1.2G     forward_modelling_11.fits
1.9G     forward_modelling_12.fits
1.9G     forward_modelling_13.fits
1.9G     forward_modelling_14.fits
1.9G     forward_modelling_15.fits
1.9G     forward_modelling_16.fits
1.9G     forward_modelling_17.fits
1.9G     forward_modelling_18.fits
1.9G     forward_modelling_19.fits
1.1G     forward_modelling_1.fits
1.9G     forward_modelling_20.fits
1.9G     forward_modelling_21.fits
1.9G     forward_modelling_22.fits
1.9G     forward_modelling_23.fits
1.9G     forward_modelling_24.fits
1.9G     forward_modelling_25.fits
1.9G     forward_modelling_26.fits
1.9G     forward_modelling_27.fits
1.9G     forward_modelling_28.fits
1.9G     forward_modelling_29.fits
1.2G     forward_modelling_2.fits
1.9G     forward_modelling_30.fits
1.9G     forward_modelling_31.fits
1.9G     forward_modelling_32.fits
2.0G     forward_modelling_33.fits
1.2G     forward_modelling_34.fits
1.2G     forward_modelling_3.fits
1.2G     forward_modelling_4.fits
1.2G     forward_modelling_5.fits
1.2G     forward_modelling_6.fits
1.2G     forward_modelling_7.fits
1.2G     forward_modelling_8.fits
1.2G     forward_modelling_9.fits
```

Current snapshot (29Jan2013): **140M** realizations, organized into manageable fits chunks of 1-2GB each, with ~3.5M realizations in each file.

The goal: 1B realizations

These are running as we speak, at the JPL zodiac supercomputer.

Prior distributions of model parameters.



Fraction of mass in substructure

MF slope

Internal structure of subhalos

Environment & Macro-model

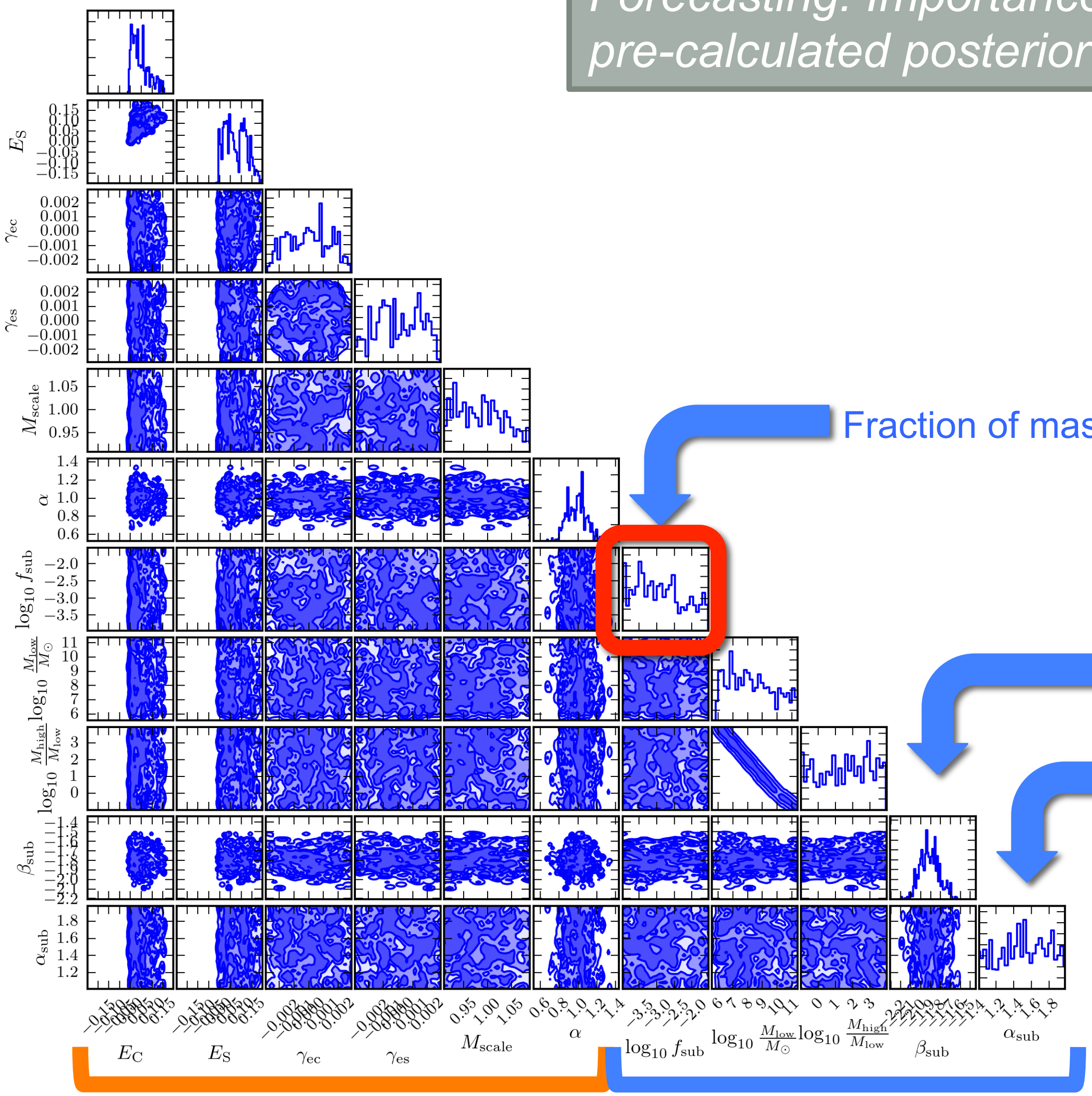
Subhalo MF & structure

Forecasting: Importance Sampling the pre-calculated posterior distributions.

"Today":

- Time delays ~2days
- Flux ratios ~50%
- Astrometry HST-quality

Single lens.



Fraction of mass in substructure

MF slope

Internal structure of subhalos

Environment & Macro-model

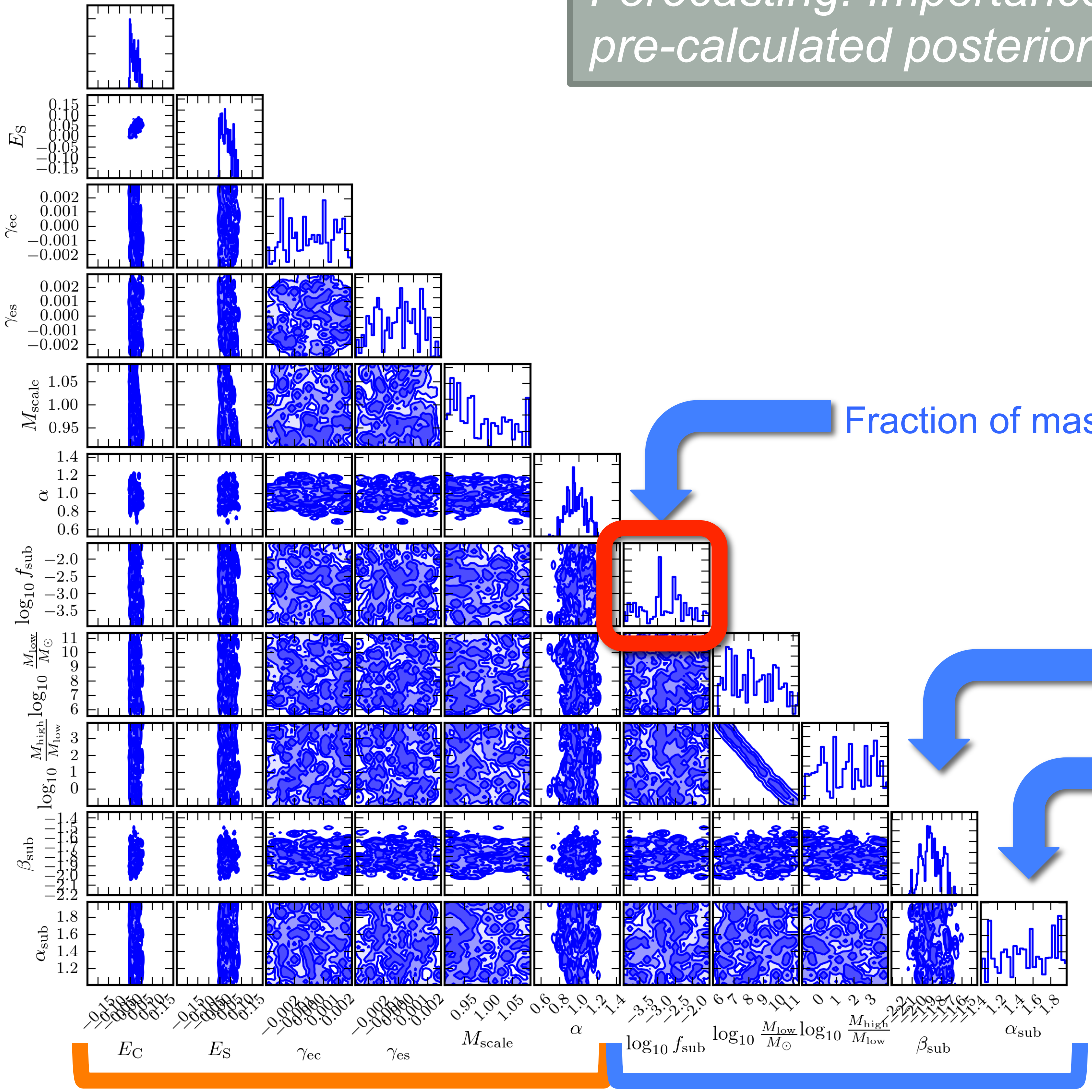
Subhalo MF & structure

High-precision time delays (the OMEGA Explorer):

- Time delays ~2 hours
- Flux ratios 50%
- Astrometry HST quality

Single lens.

Forecasting: Importance Sampling the pre-calculated posterior distributions.



Fraction of mass in substructure

MF slope

Internal structure of subhalos

Environment & Macro-model

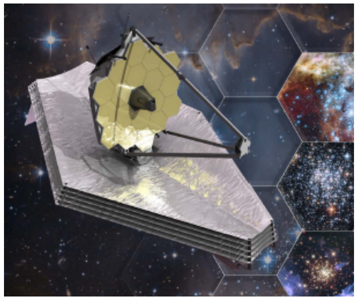
Subhalo MF & structure

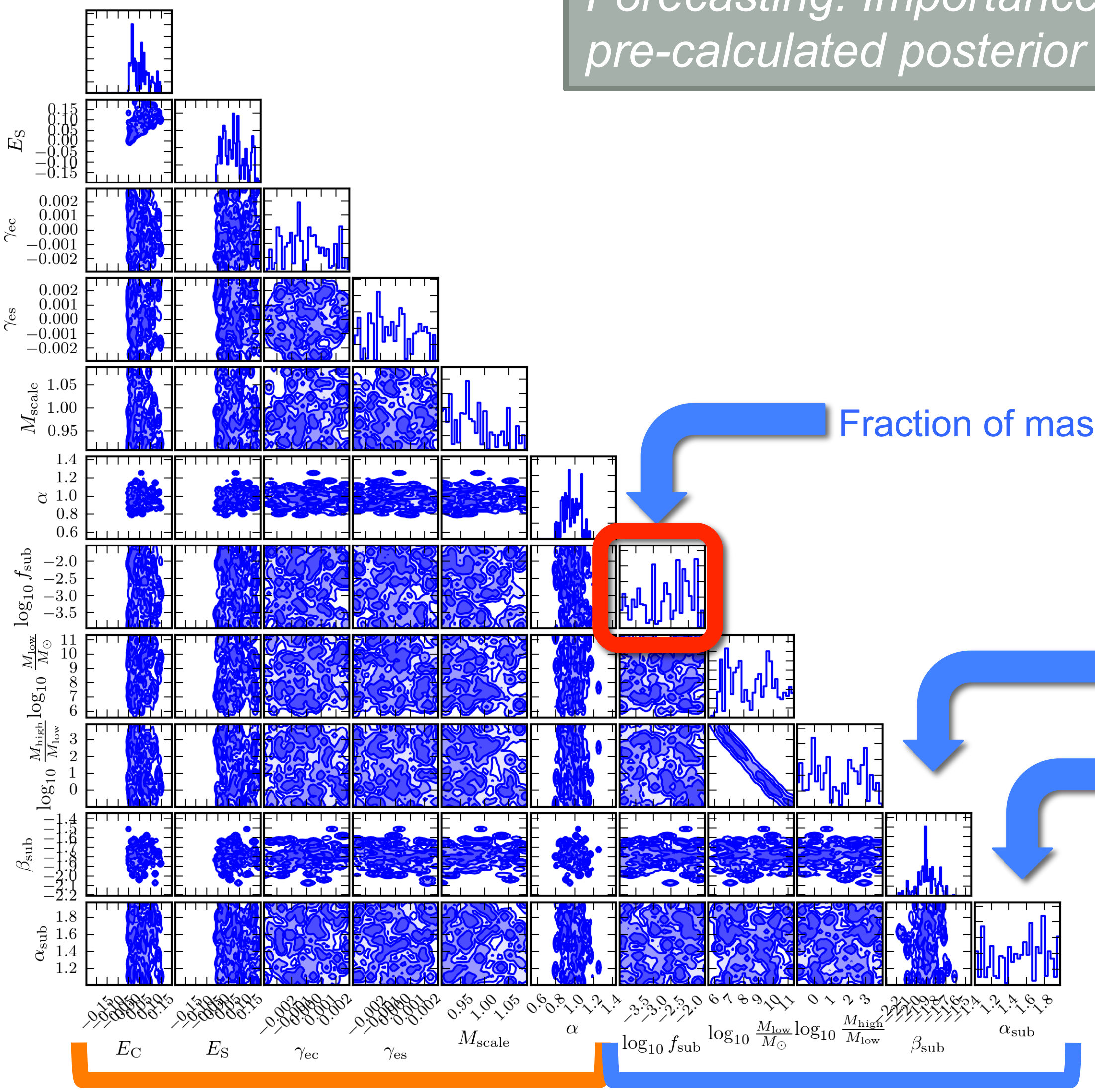
Forecasting: Importance Sampling the pre-calculated posterior distributions.

JWST:

- No time delays
- Flux ratios few %
- Astrometry JWST quality

Single lens.





Fraction of mass in substructure

MF slope

Internal structure of subhalos

Environment & Macro-model

Subhalo MF & structure

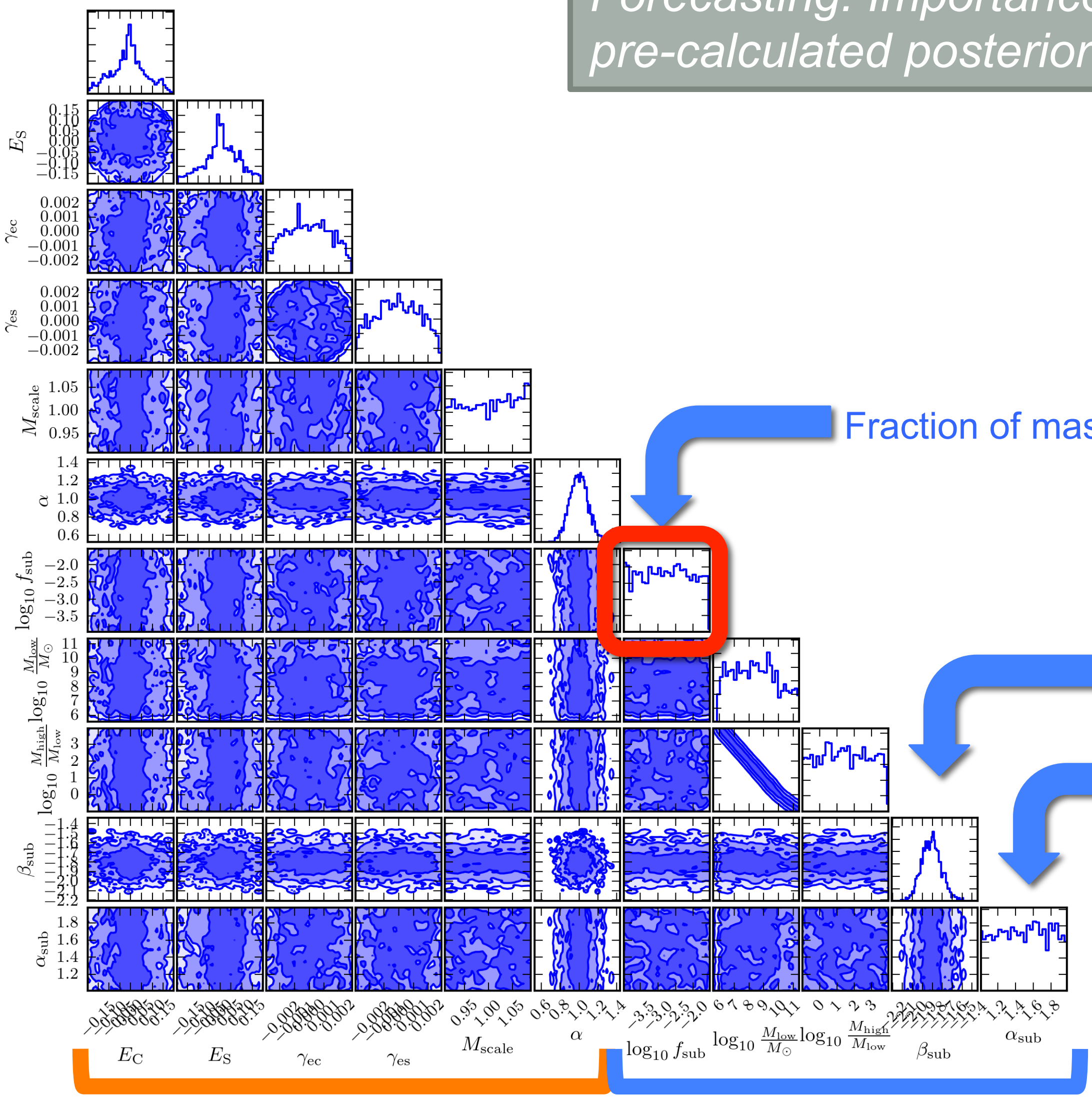
LSST:

- Time delays ~several days
- Flux ratios ~50%
- Astrometry HST quality

Single lens.

Large Synoptic Survey Telescope

Forecasting: Importance Sampling the pre-calculated posterior distributions.



Fraction of mass in substructure

MF slope

Internal structure of subhalos

Environment & Macro-model

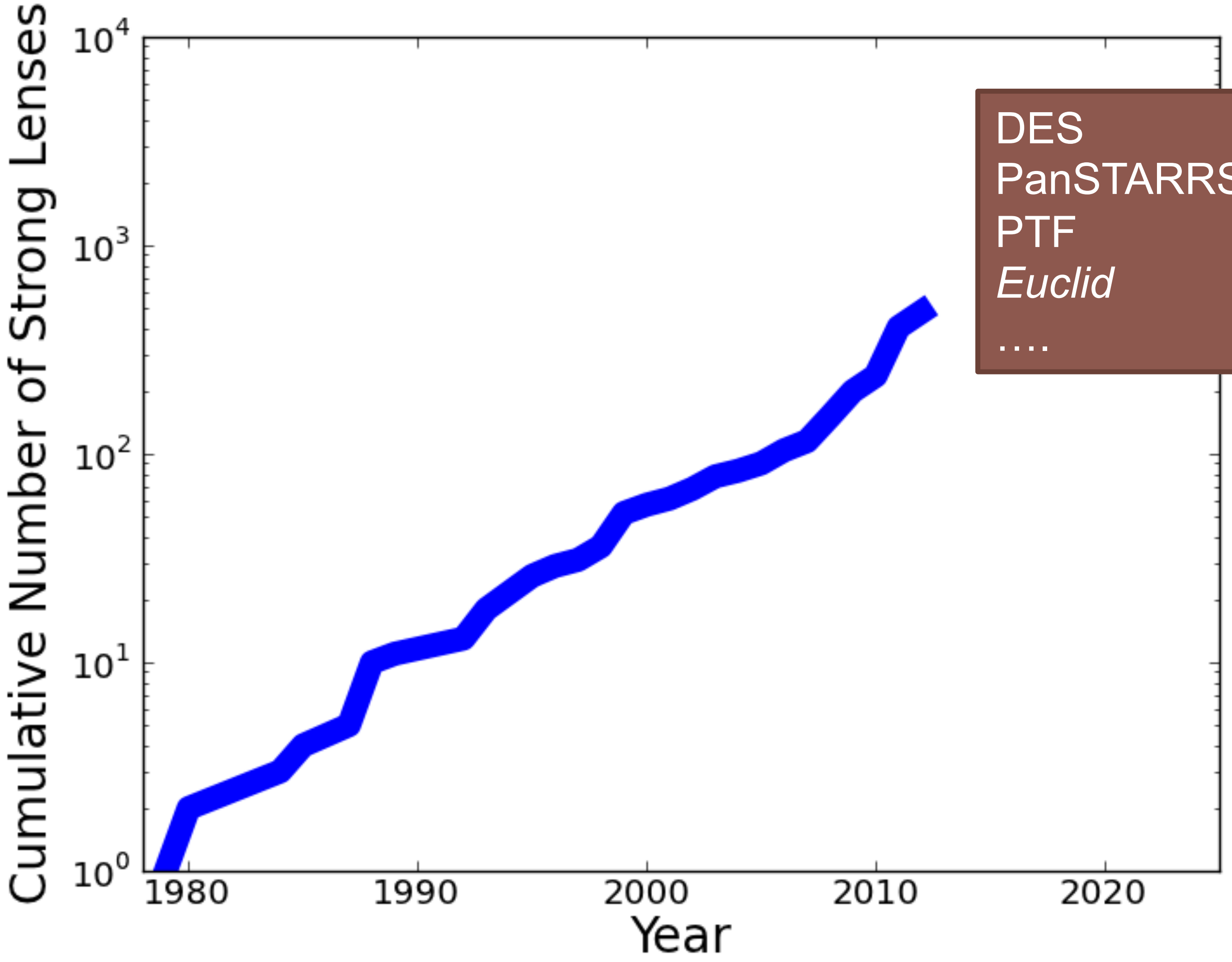
Subhalo MF & structure

Astrophysical dark matter properties

- The *combinations* of precise observables breaks degeneracies and gives traction on even the internal structure of dark matter subhalos.
  - From preliminary work, the OMEGA (sensitive time delay) approach may be sensitive to substructure ensembles to mass scales orders of magnitude below dwarf galaxies.
- Appropriate experimental design with *ensembles* of lenses is going to be key.
- Each experiment, “today”, JWST, OMEGA, LSST, etc, to be designed.

- Are there (or will there be) enough of the “right” lenses?

The Master Lens Database



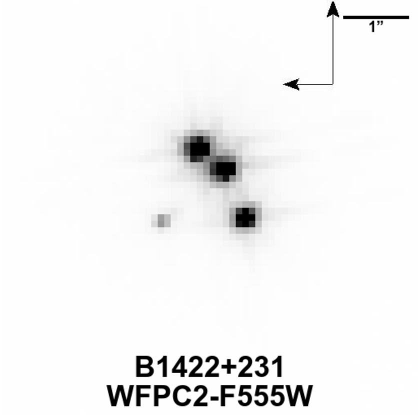
DES
PanSTARRS
PTF
Euclid
….

L. Moustakas+ 2013

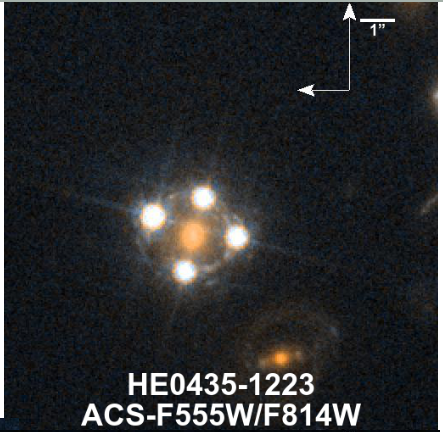
Master Lens Database

http://masterlens.org

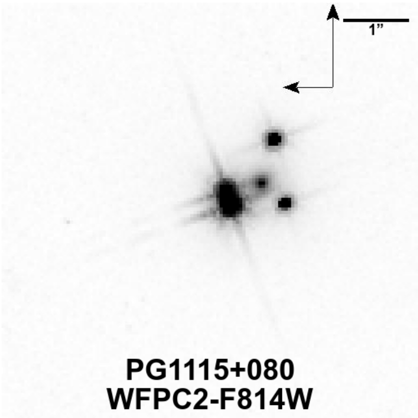
Workshop account:
aspen / ClosingIn



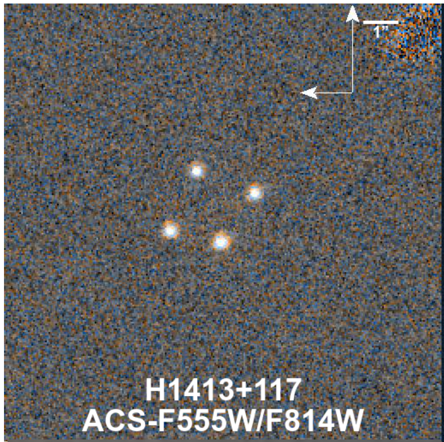
B1422+231
WFPC2-F555W



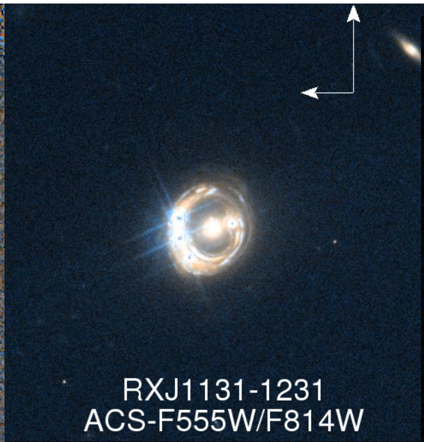
HE0435-1223
ACS-F555W/F814W



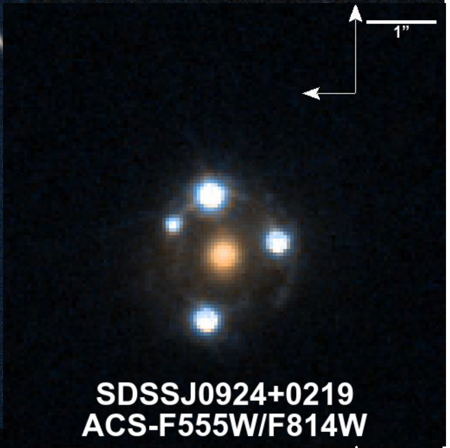
PG1115+080
WFPC2-F814W



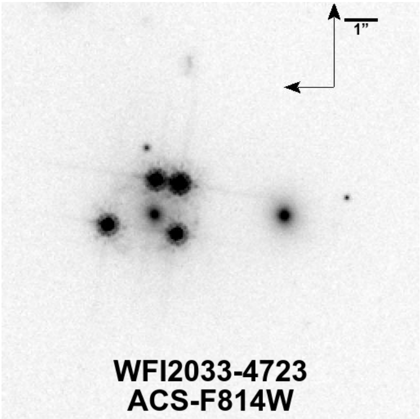
H1413+117
ACS-F555W/F814W



RXJ1131-1231
ACS-F555W/F814W

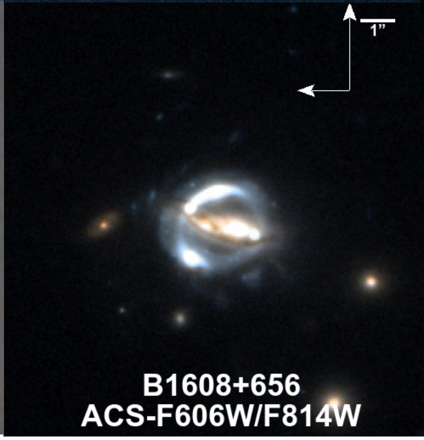


SDSSJ0924+0219
ACS-F555W/F814W

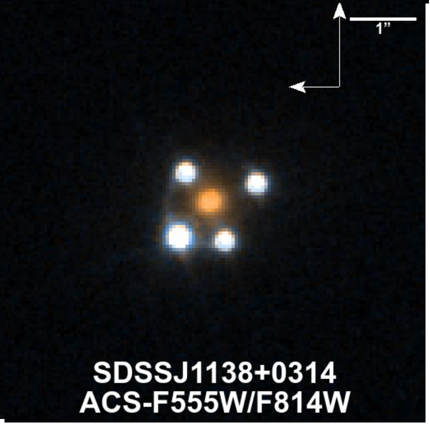


WFI2033-4723
ACS-F814W

Q2237+030
WFPC2-F555W/F814W



B1608+656
ACS-F606W/F814W



SDSSJ1138+0314
ACS-F555W/F814W

L. Moustakas+ 2013

Lensing versus near-field (e.g. dwarfs)

- The lensing approach is sensitive to a large dynamic range of subhalo mass-scales (>1E4 or more).
- The (average) internal structure of subhalos may be constrainable.
- Large ensembles of lens samples are possible even today, enabling a statistically robust measurement of dark matter subhalo mass functions and structure.
- Distinct measurements are possible over several Gyr of cosmic time (z~0.1 to z~0.7) => evolution of dark matter small scale structure.
- => Great complementarity!

Conclusions

- Dark matter interaction or thermal properties currently allowed by observations result in sub-galactic level consequences.
- The dark matter sub-structure can be probed gravitationally, with observations of strong lenses.
- Current observations detect substructure but not (yet?) ensemble properties useful for DM studies.
- We are making detail forecasts for what experimental designs will succeed!
- Combinations of observables (high resolution, precise photometry, precise time delays) are critical.
- This is likely to require new and dedicated observations.

The proposed OMEGA Explorer

- These measurements need a *dedicated* space-based platform. The reasons include the *combination* of the following:
    - <0.2 arcsecond angular resolution
    - Months-long photometric stability, and ~1% photometric precision
    - Ability to efficiently target and observe a lens with a cadence of multiple times every 24 hours, …
    - … contiguously over 6-week or longer campaigns, …
    - … multiple times to accommodate the time baseline differences between images.
    - Need a statistically significant sample… A couple dozen at minimum, ~100 better.
- This has driven us to design a space-based observatory dedicated to accomplishing this. The OMEGA Explorer 2011 proposal was ranked "Selectable" by NASA.
- We are pushing ahead towards a 2016 proposal!