Title: Revealing the Invisible: Strong Gravitational Lensing & Particle Dark Matter

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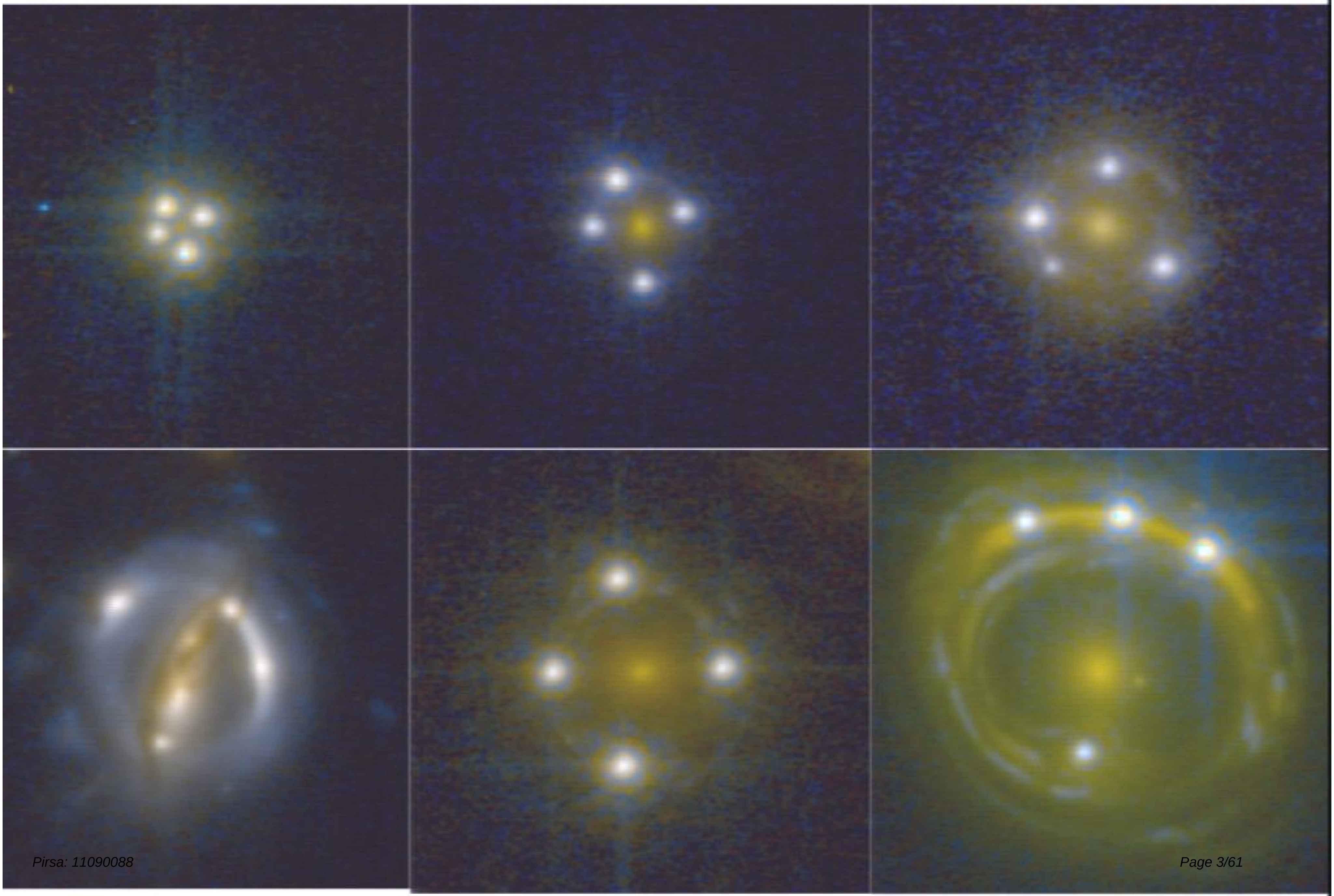
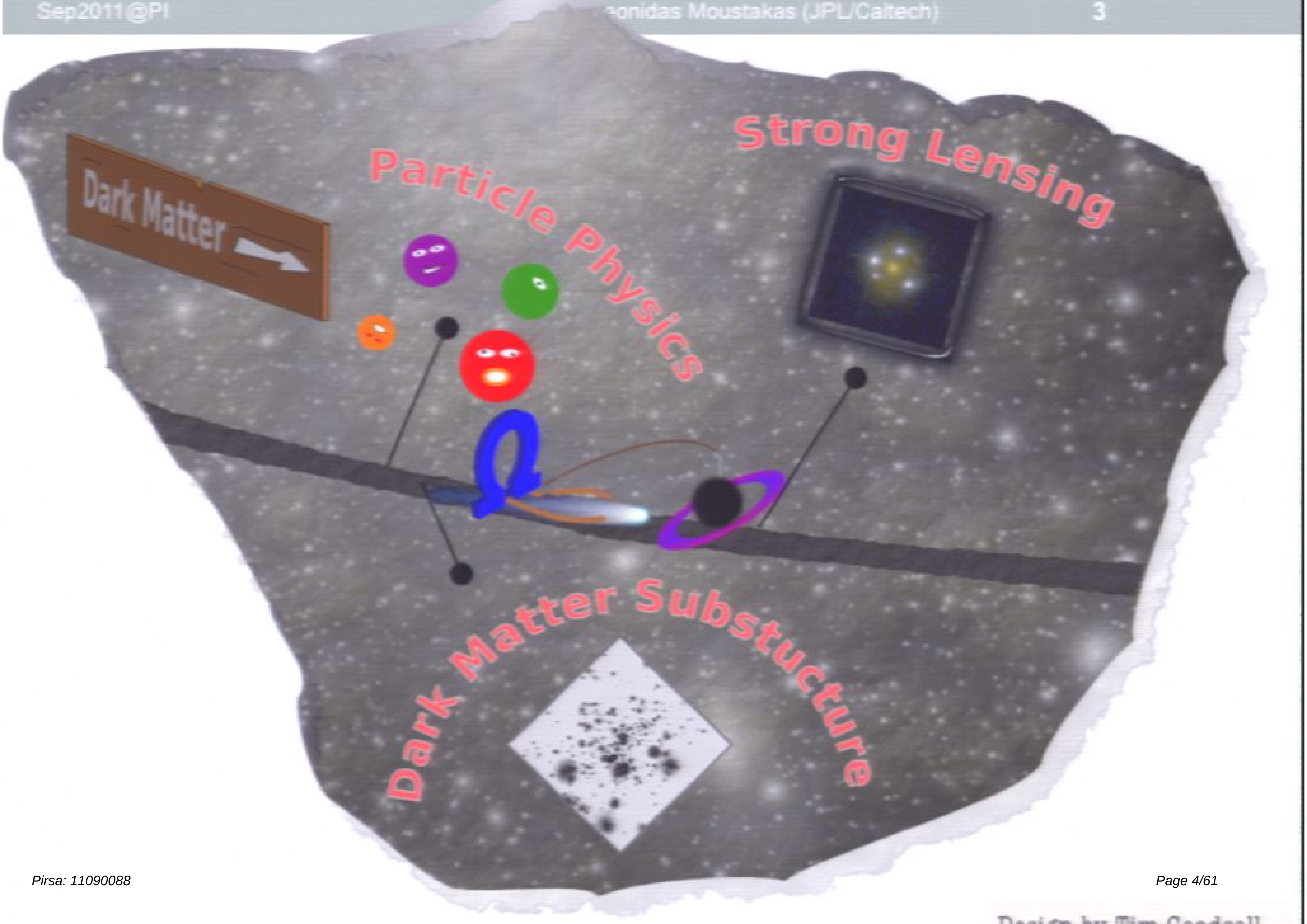
Abstract: The particular properties of different dark matter particle candidates can lead to different properties and distributions of sub-structure within galaxies; structure that may uniquely be probed through specific state of the art observations of galaxy-scale dark matter halos that happen to be acting as strong gravitational lenses. I will discuss how the matter power spectrum and non-linear evolution within galaxies depend on the specific properties of dark matter particle candidates, develop the types of strong gravitational lenses that lend themselves to probing substructure, and give both the current state of the art and the prospects for quantitative constraints in the near future. Throughout, I will emphasize what cross-germination opportunities there are between such astrophysical structure measurements, and other exciting avenues of insight into the nature of dark matter.

REVEALING THE INVISIBLE

Strong Gravitational Lensing & the Particle Nature of Dark Matter

Leonidas Moustakas, JPL/Caltech





Design by Tim Goodsall

Probes of dark matter

- Cosmic background radiation + BBN
  - relic density
- Production
  - existence & estimates of Omega_chi
- Direct detection experiments
  - mass and interaction cross section
- Indirect detection signatures
  - interaction cross section (annihilation)
- Astrophysical dynamics (clusters and galaxies)
  - interaction cross section (self-interaction, dark sector forces)
- Linear astrophysical structure (Lyman-alpha Forest)
  - thermal nature, interaction cross section
- Non-linear astrophysical structure (<< 1/h Mpc scales)
  - thermal nature, interaction cross section
- Strong lens AGN microlensing at << kpc scales

Path to observables beyond CBR & LSS

- Background cosmology
- Primordial P(k) (inflation)
- Transfer function (dark sector)
  - Cutoff scale evolution (WDM vs SIDM vs …)
- Linear regime (Lyman alpha forest)
- Non-linear regime
  - Evolution within parent halos
    - Mass function
    - Spatial 3D distribution
    - Subhalo internal mass density profile
- => Gravitational potential perturbations
- => Effects on lensing observables
- Observations, experiments, & insight

Path to observables beyond CBR & LSS

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OMEGA Explorer Science Team

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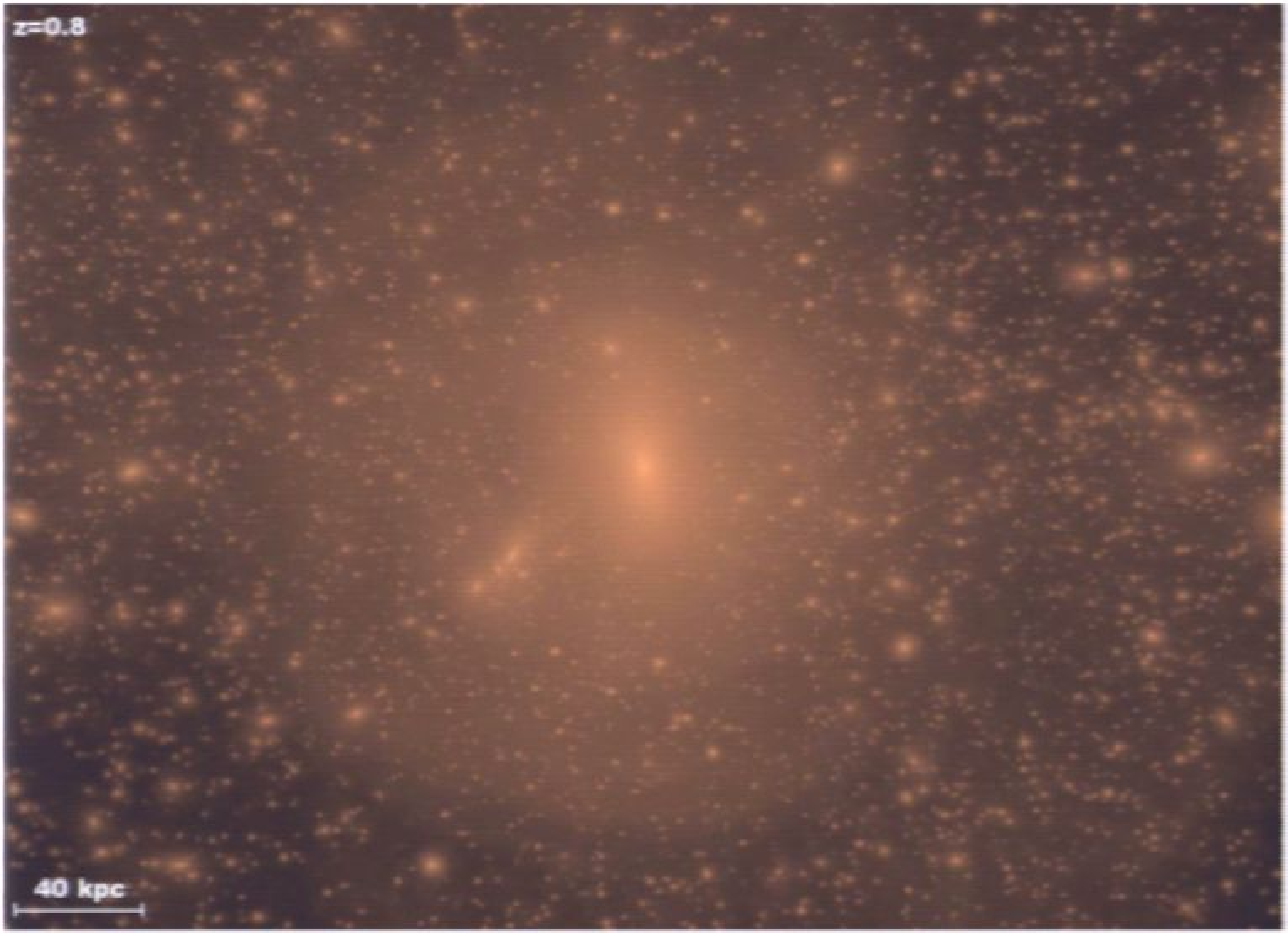
Tommaso Treu
Joachim Wambsganss

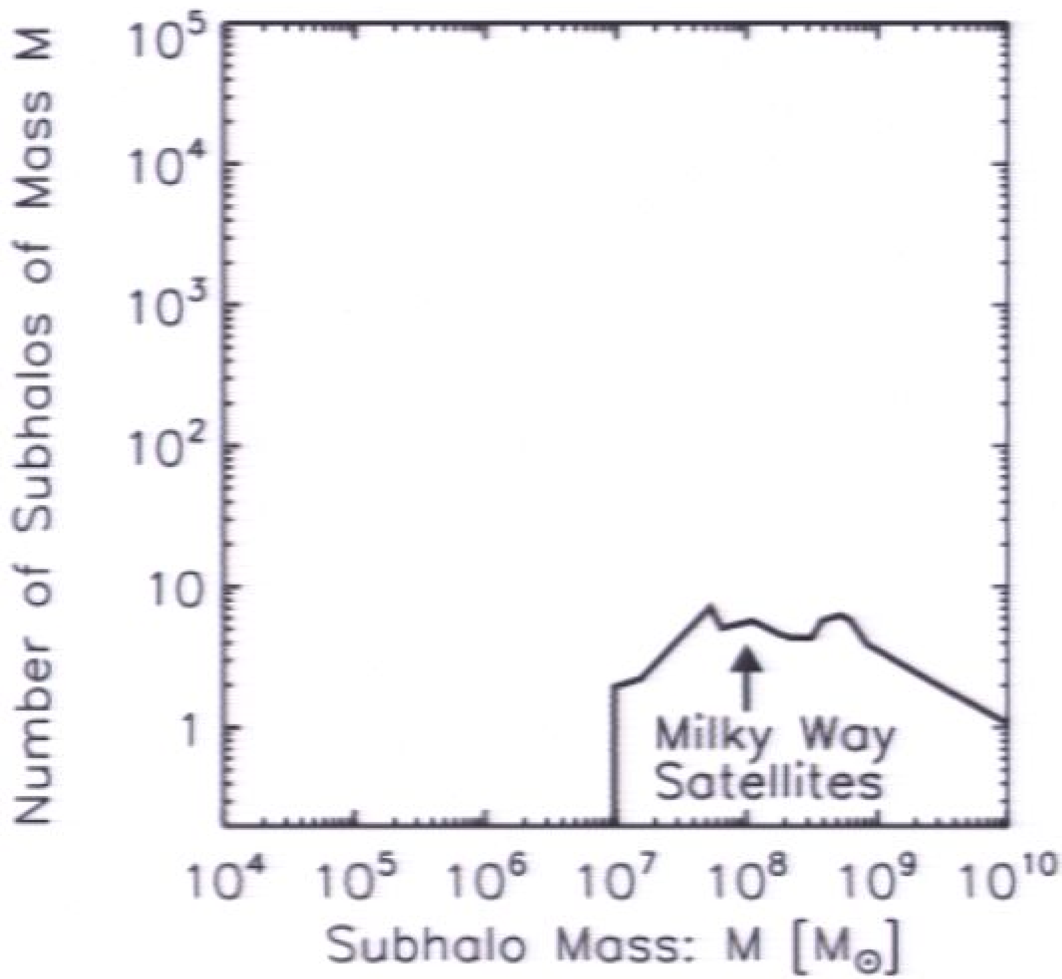
Andrew Benson; Chris Kochanek


rsa Minor dwarf galaxy
ourtesy Josh Simon

LCDM substructure



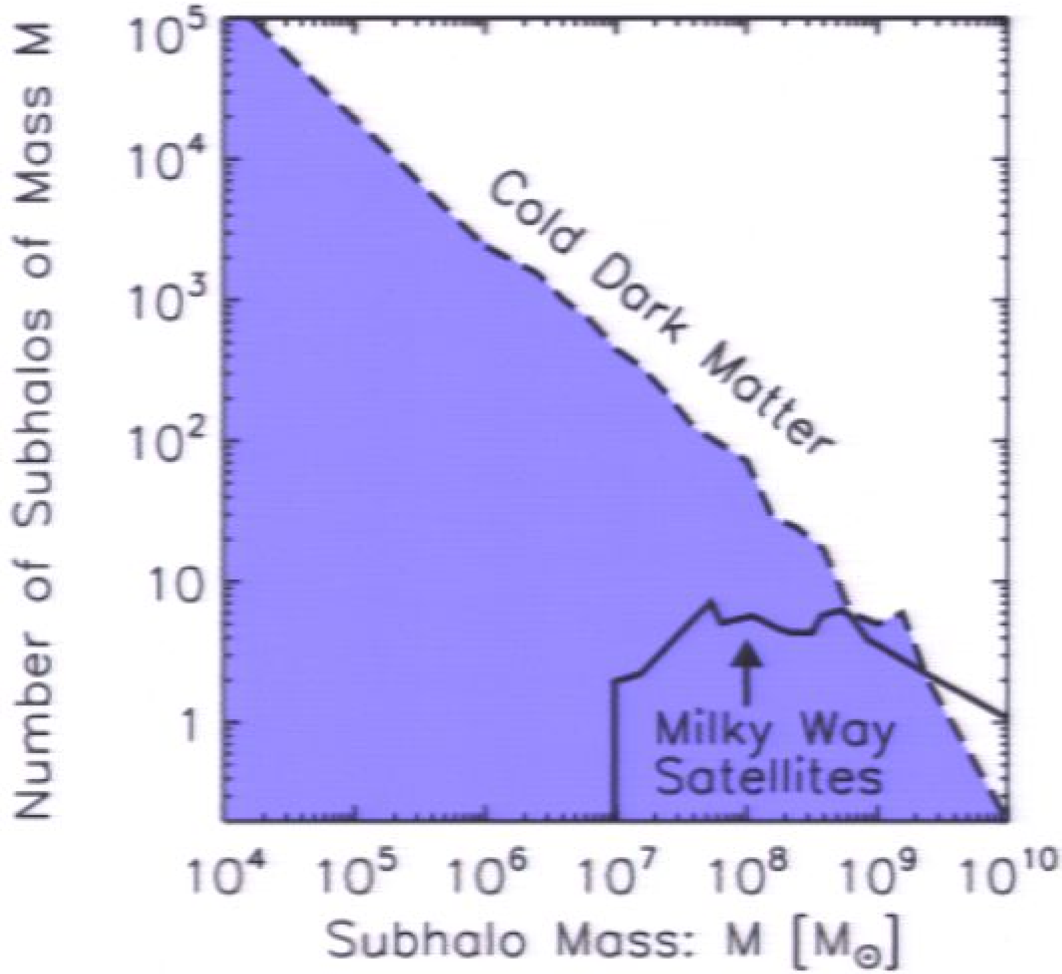
The dN/dM mass function of dwarfs



tidal mass, converted from estimated Vmax

Ackn. K. Stewart & J. Bullock

LCDM substructure



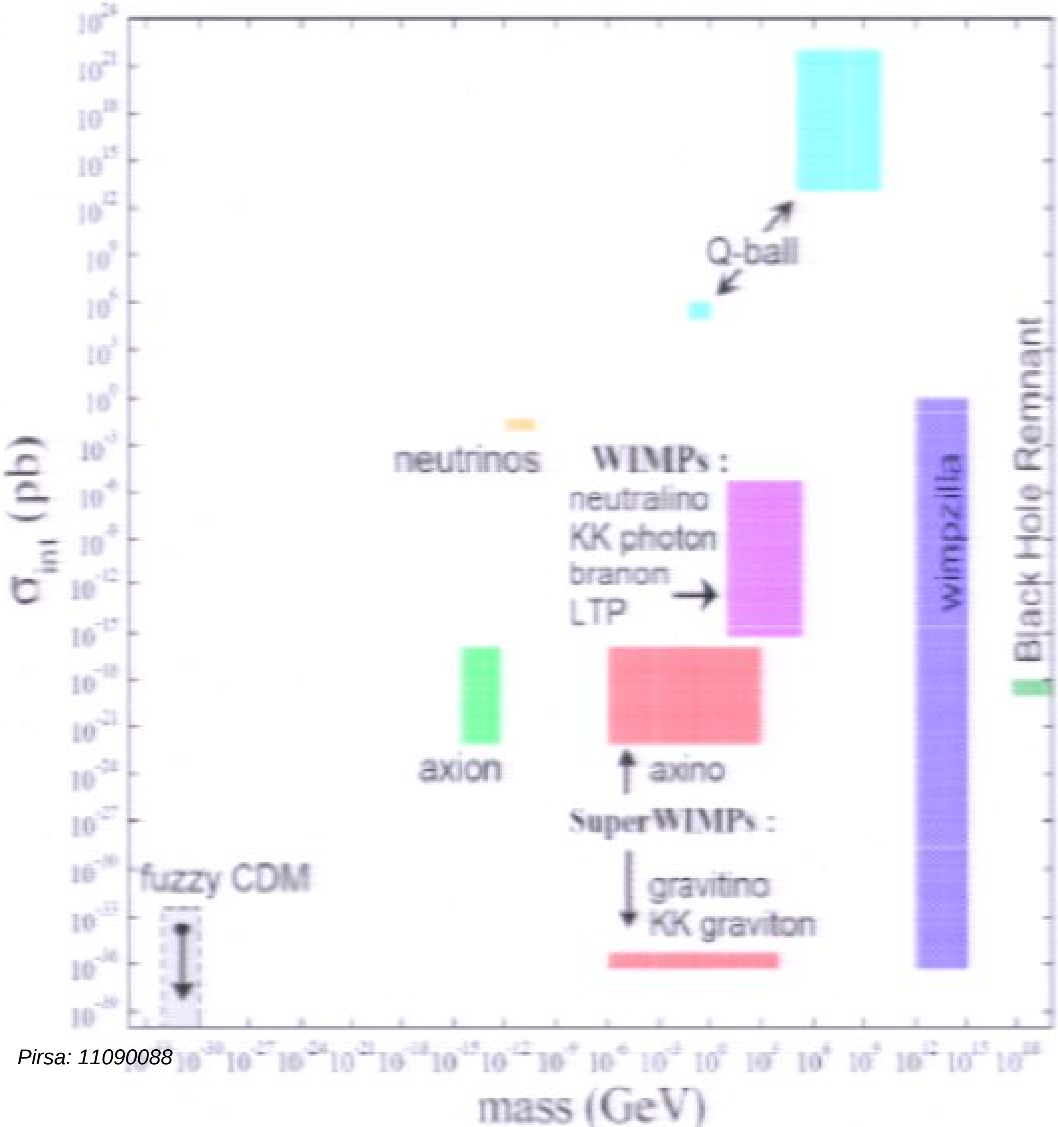
tidal mass, converted from estimated Vmax

Ackn. K. Stewart & J. Bullock

LCDM: substructure measurements

- LCDM galaxy-scale halo simulations with large dynamic range, going to below ~1E7 Msun measure for subhalos within a radius of ~10kpc:
  - Xu+ 2009 (Aquarius): f_sub ~ 0.0025
  - Diemand+ 2007 (Via Lactea): f_sub ~ 0.003

Dark matter particle candidates

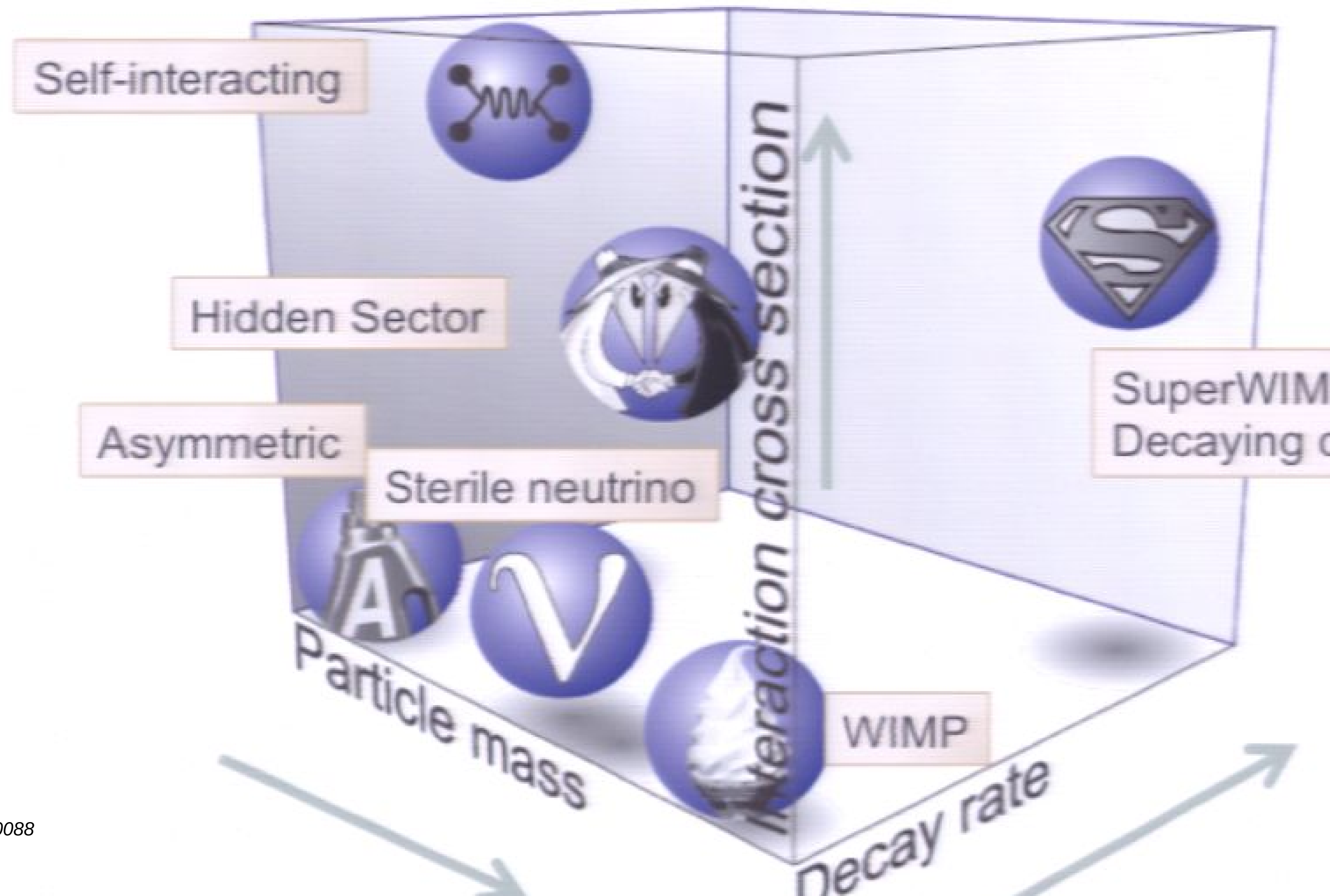


Interaction cross section vs mass.

From the Dark Matter Scientific Assessment Group report.

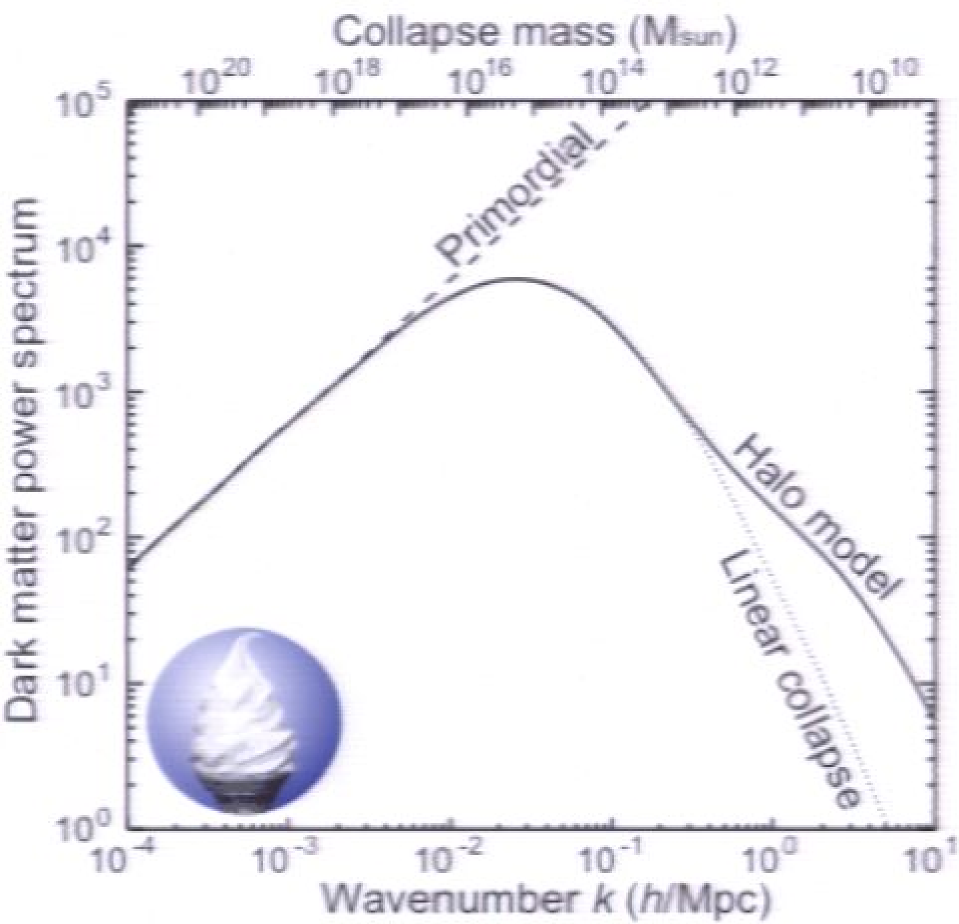
theories vs proofs…

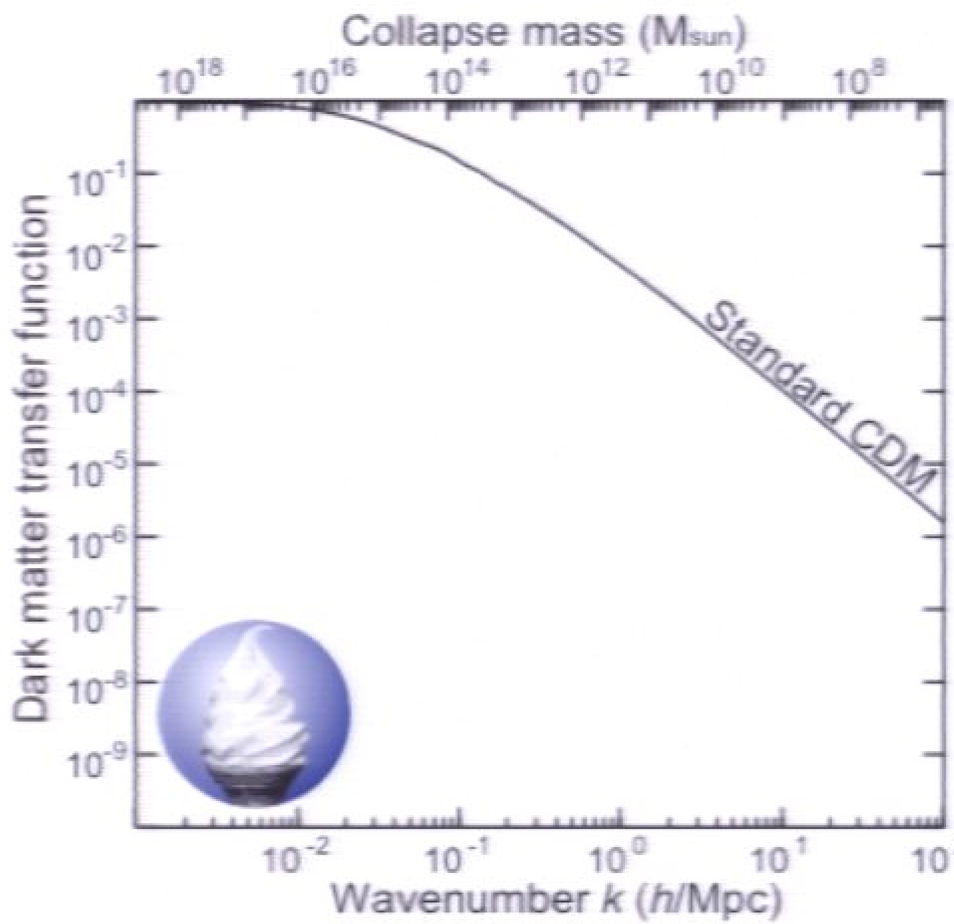
Physically motivated DM candidates



Ackn R Massey
M Kaplinghat
P Natarajan

LCDM power spectrum and T(k)





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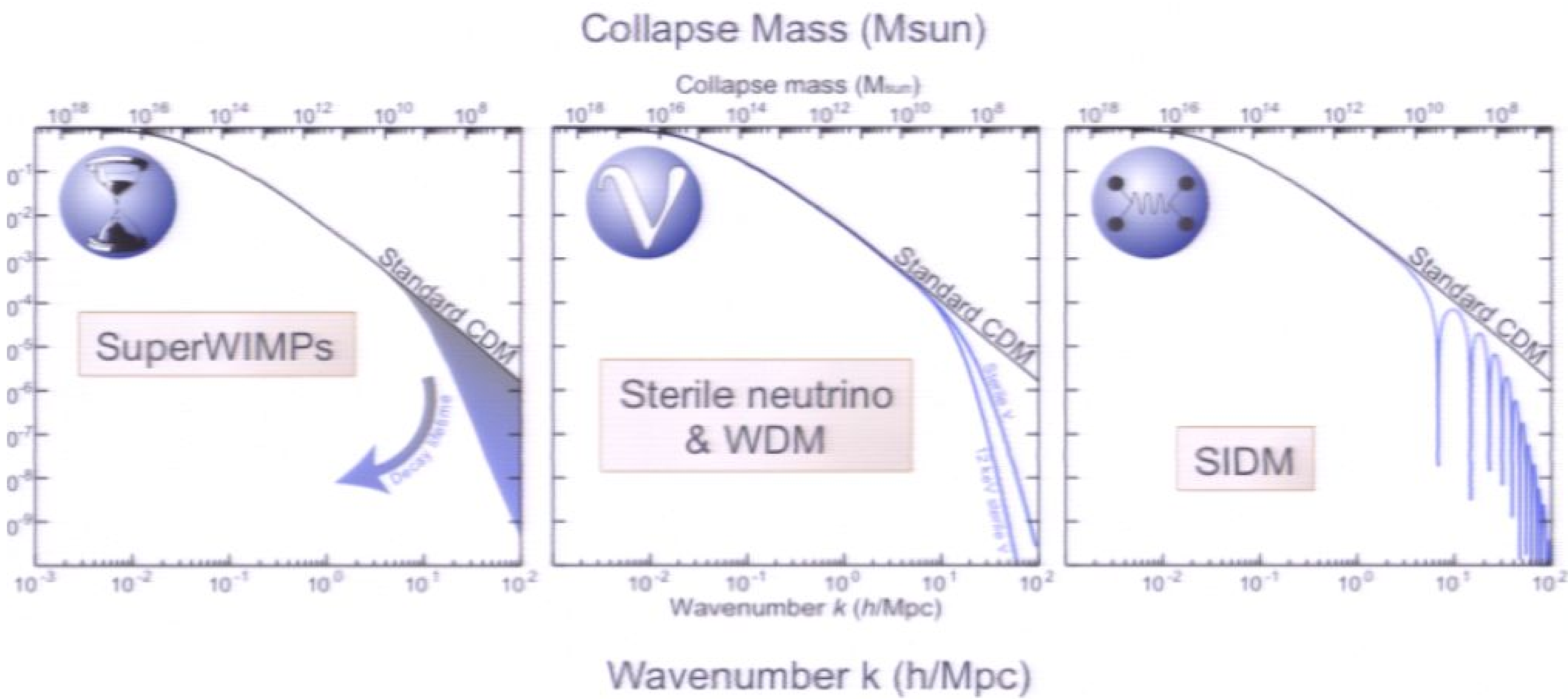
Beyond LCDM transfer functions



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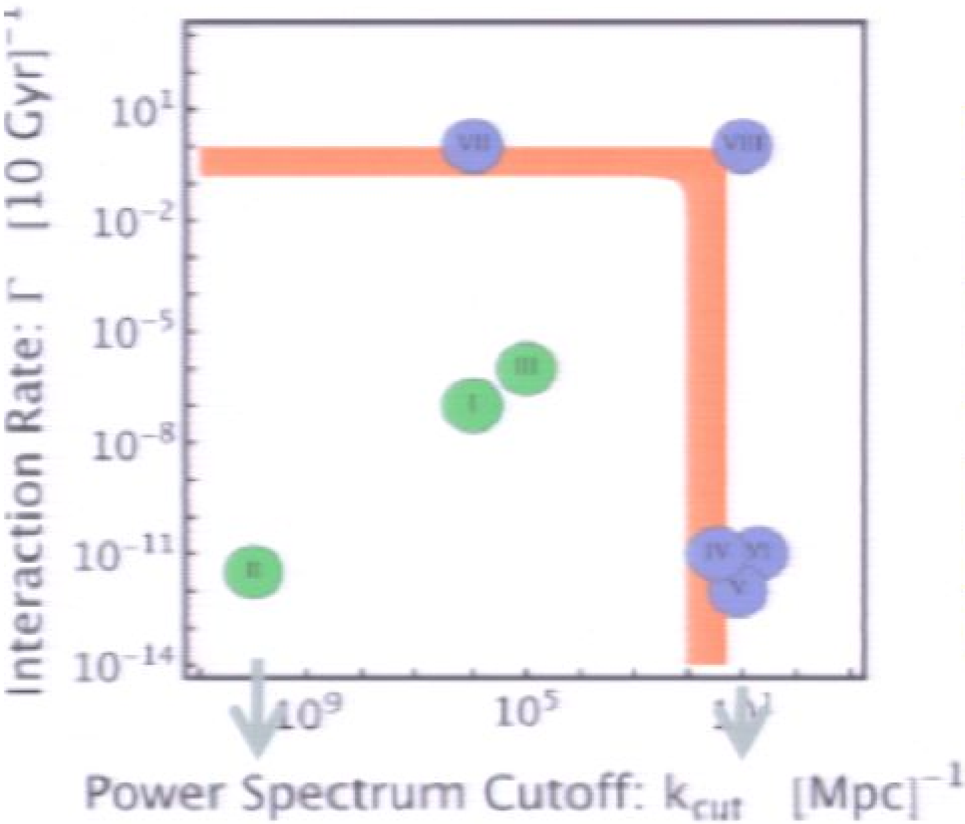
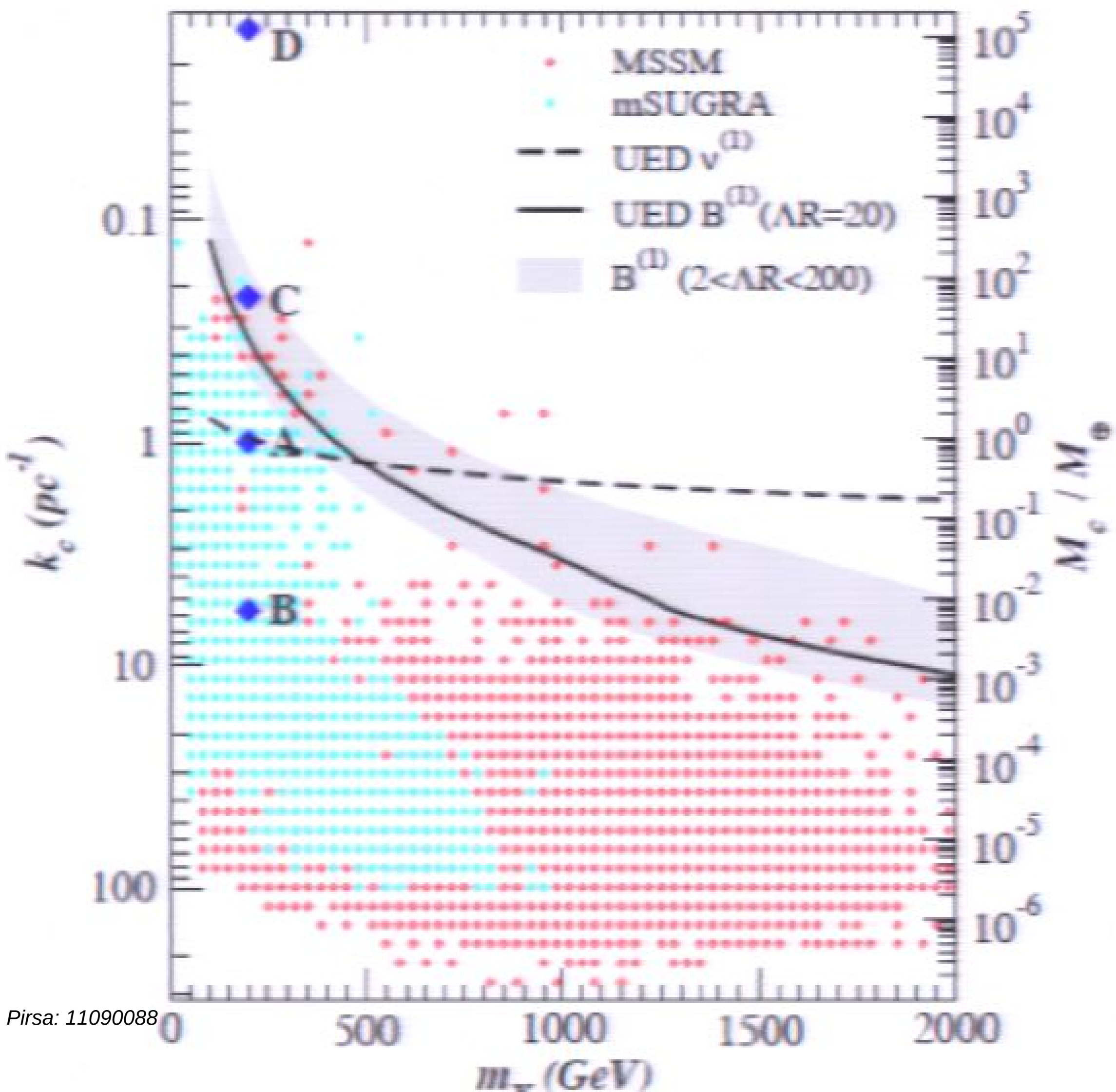


	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV–TeV	Cold
II	Axion	μeV–meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV–keV	Cold/Warm
VI	SuperWIMP	GeV–TeV	Cold/Warm
VII	Hidden Sector: WIMP-like	MeV–TeV	Cold/Warm
VIII	Hidden Sector: Bound State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

The interaction rate vs power spectrum cutoff, based on the mass/interaction/decay cube.

Sigurdson, Kaplinghat, Peter, + in prep

Power & mass cutoff for LCDM



For WIMP-scale low interaction rates, the lowest mass halos are far sub-solar.

Profumo+ 2006 xxx/0603373

Subhalo mass function cutoffs: beyond (or rather above) WIMP predictions

- Many candidates have (relatively) high self-interaction, or a power spectrum cutoff that is (relatively) high, or both, which can lead to allowed cutoff mass scales even approaching the dwarf galaxy mass scales – while being consistent with all other data of cosmic abundance, large scale structure, etc.

	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV–TeV	Cold
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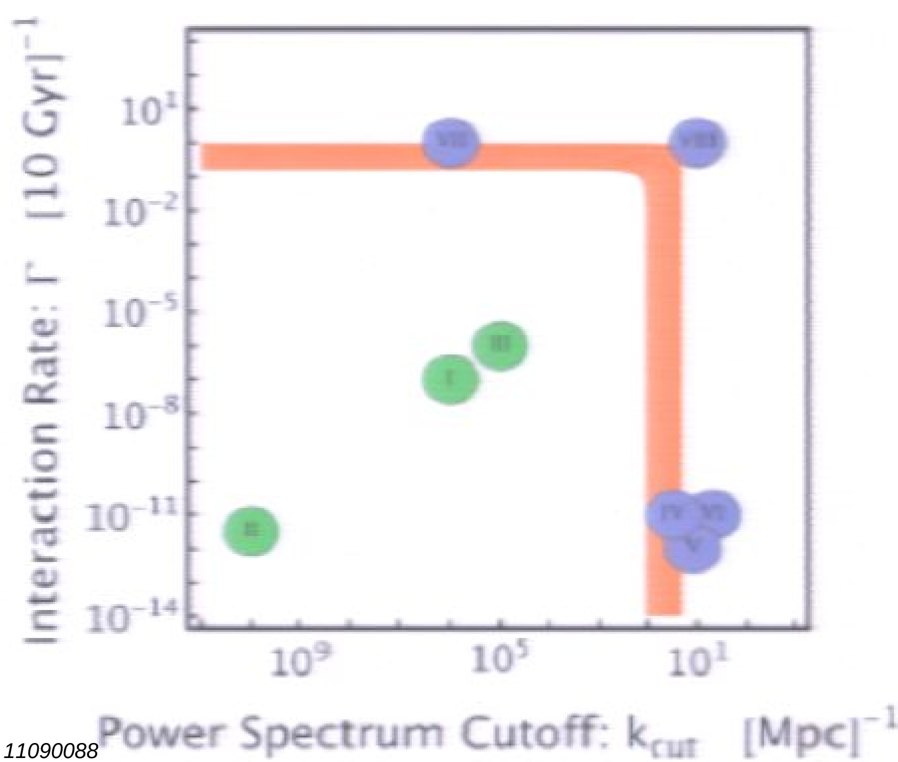
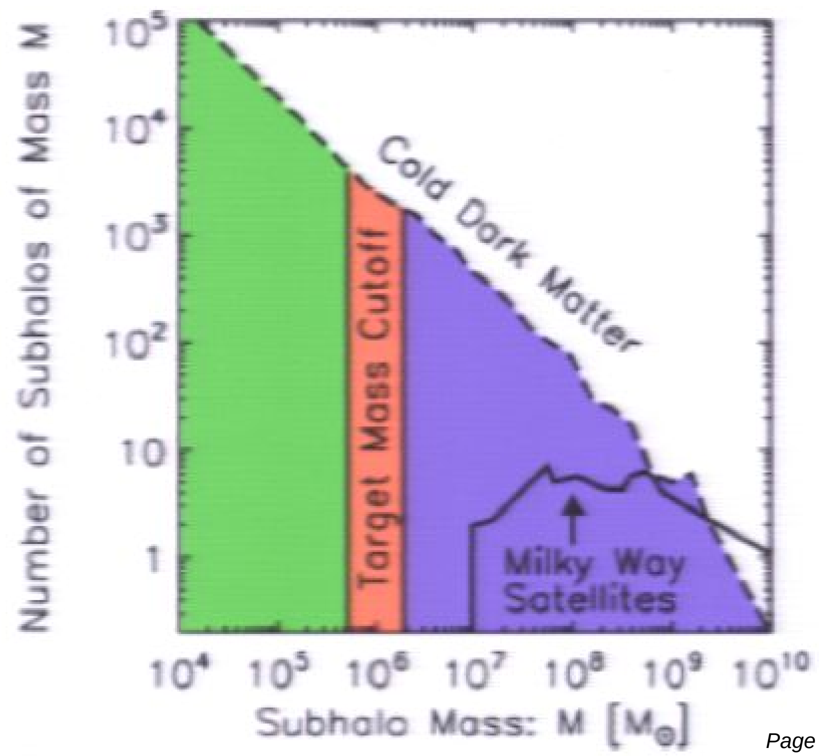
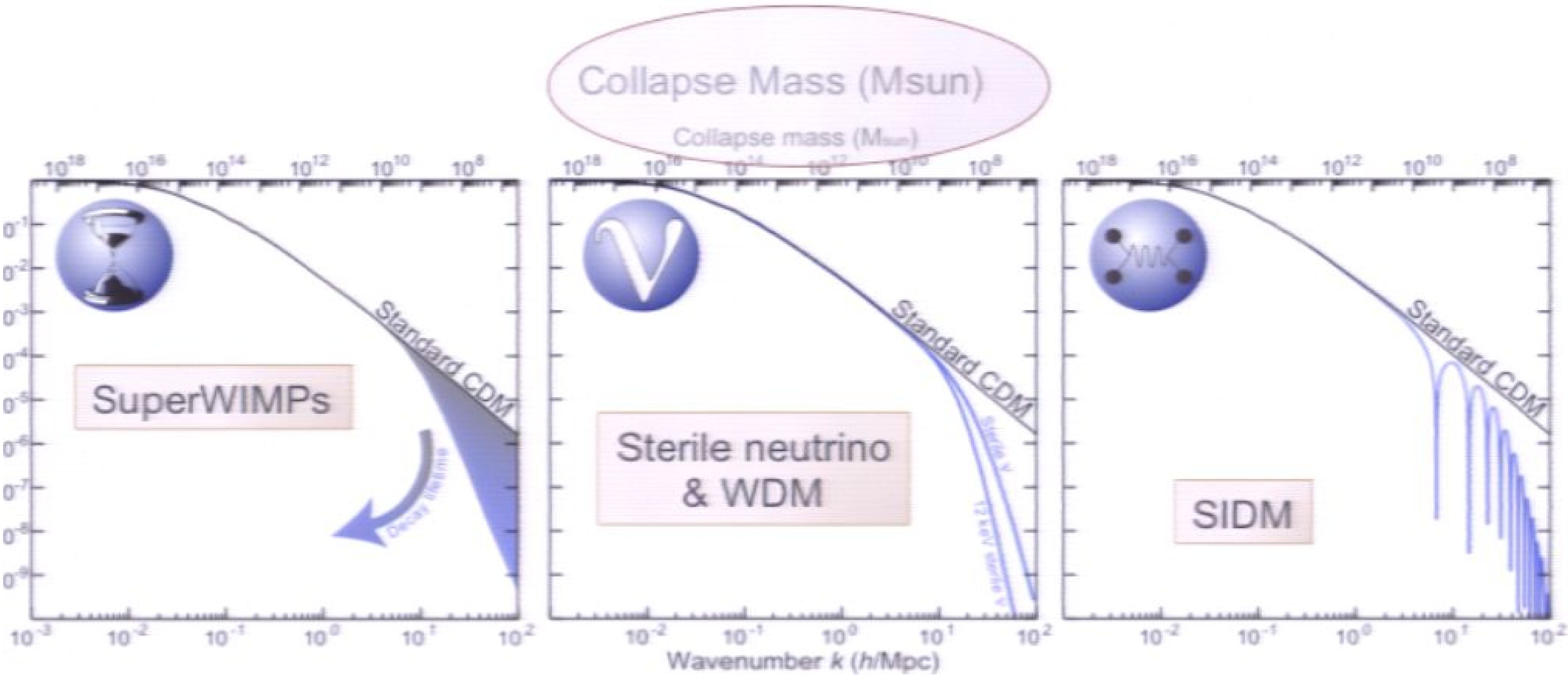
Motivating the mass scales to target in pursuing measurements of the subhalo mass function…





The cutoff scale is only the beginning

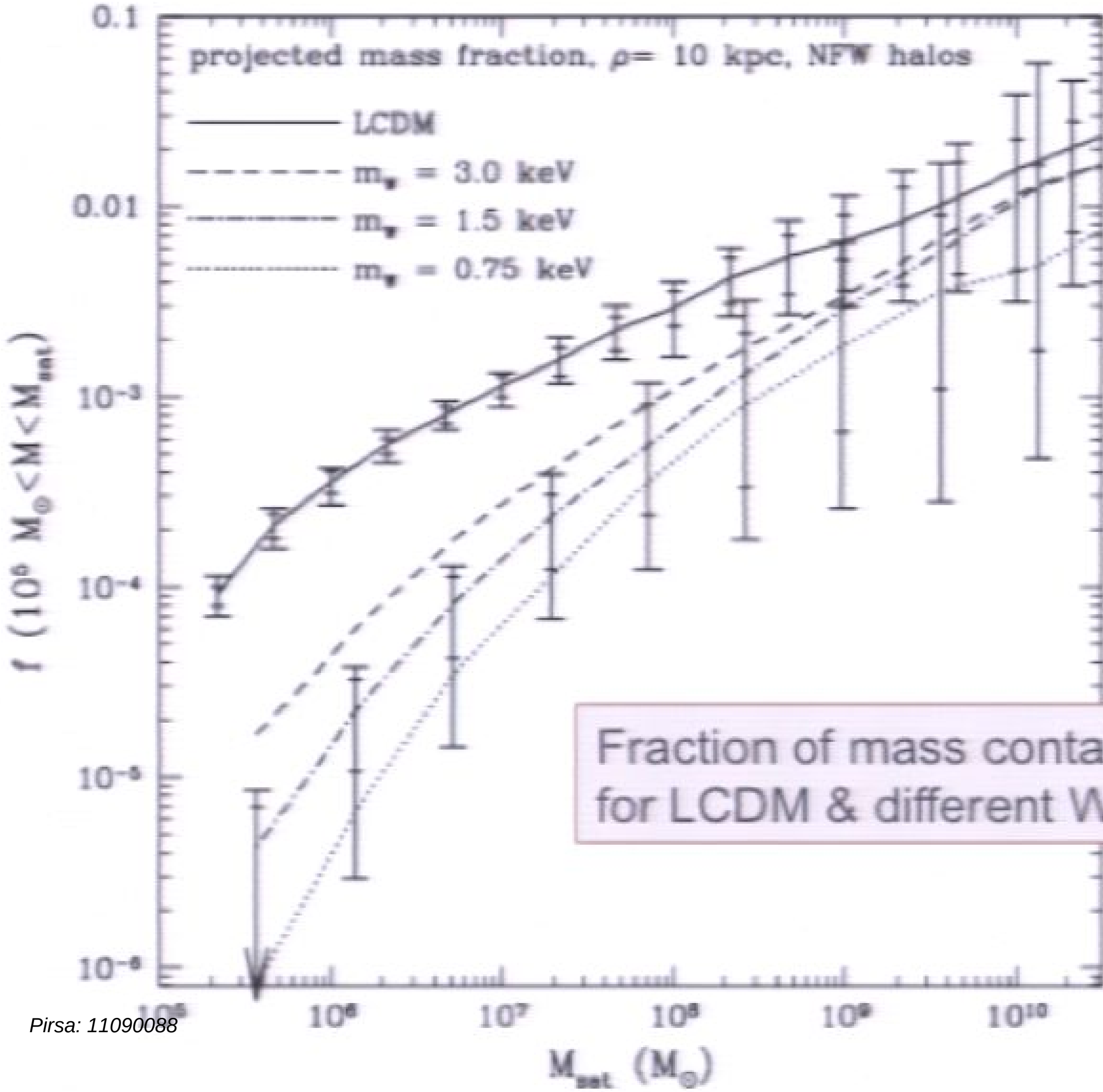


Wavenumber k (h/Mpc)

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

Ackn R Massey

Dipping into nonlinear evolution



Zentner & Bullock 2005:

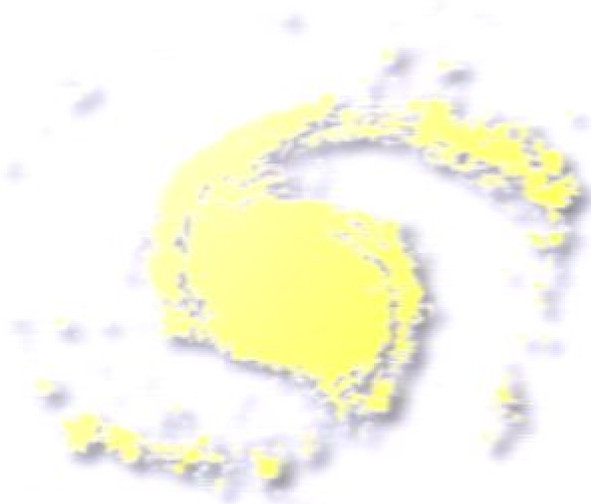
Exploration of truncated power spectra (due to free-streaming cuts), and resulting subhalo mass functions.

Fraction of mass contained in different mass subhalos for LCDM & different WDM mass levels

Dipping into nonlinear evolution

Galacticus

Andrew Benson, Caltech



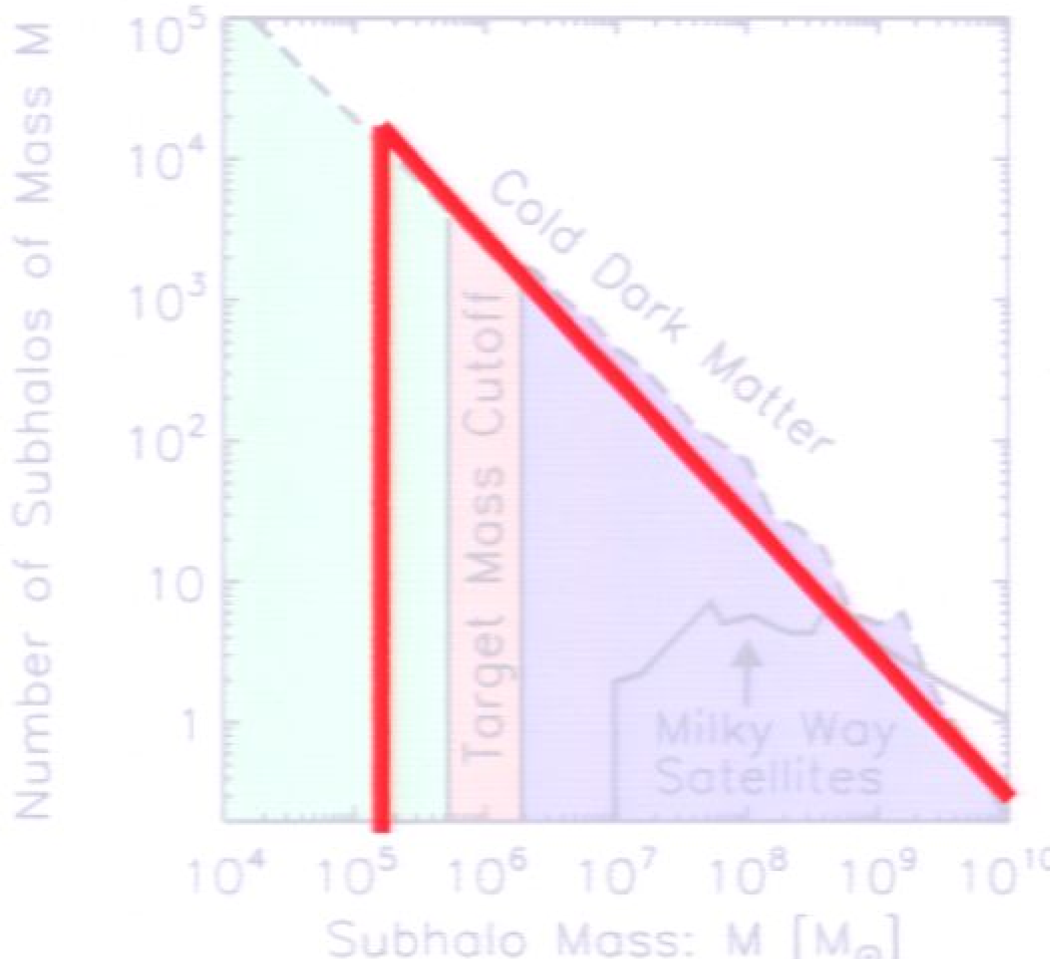
Semi-analytic approach to structure predictions

- Full hierarchical structure and galaxy & formation.
- Highly modularized.
  - Nodes can have multiple components (DM, disks, etc), each with multiple **function** implementations describing their behavior.
  - User beware, of course!
- OpenMP parallelized.
- Open source, freely available under GPL v3.

- Tidal stripping & WDM PS mass function incorporated.
- Extended Press Schechter and merger tree formalism is more complicated, but we're making progress!

LM & A Benson 2011

Mass function parametrization



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

Cross-germination: scenario I

- LHC identifies missing energy in a Beyond Standard Model decay chain.
  - This implies a particle candidate exists, which may be stable for … at least a microsecond.
- Direct detection experiments expect to see the above *if it were stable*, but do not.

- Then, if a subhalo mass function cutoff is detected, the majority of dark matter cannot be a thermally-produced WIMP or axion. In that case, the LHC results may be pointing to a particle that decays on short timescales (though longer than a ~microsecond), into possibly a stable candidate.

Credit: Annika Peter

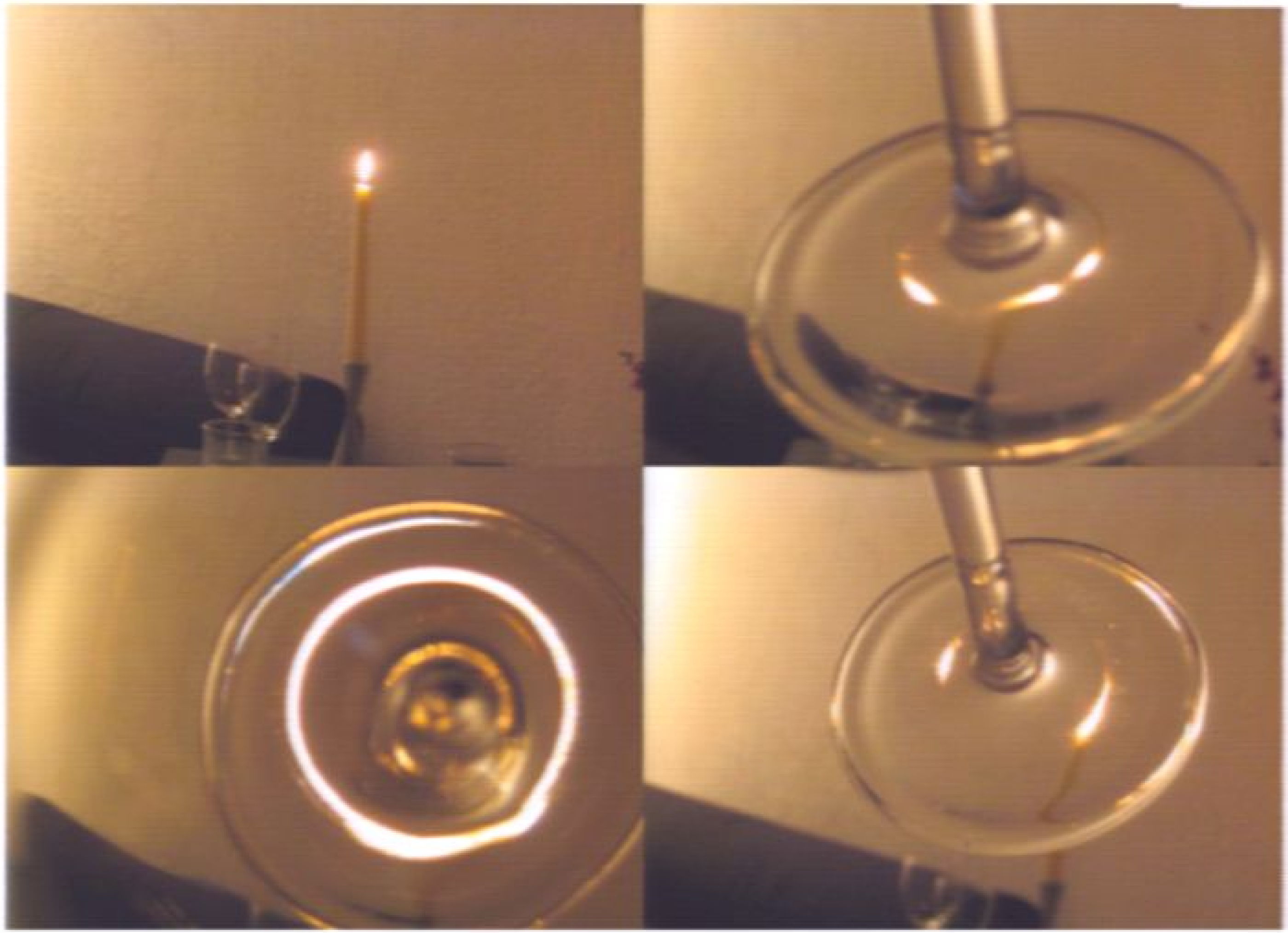
Cross-germination: scenario II

- LHC does not go Beyond the Standard Model
- Direct detection experiments keep pushing limits
- Axion experiments keep pushing limits

- Then if there is NO detectable mass function cutoff, WIMP dark matter is still allowed.
- If there IS a detected mass function cutoff, then dark matter may arise non-thermally through decays, or sterile neutrinos or hidden sector particles are in play.

Credit: Annika Peter

Lensing… with a wineglass



Courtesy Phil Marshall

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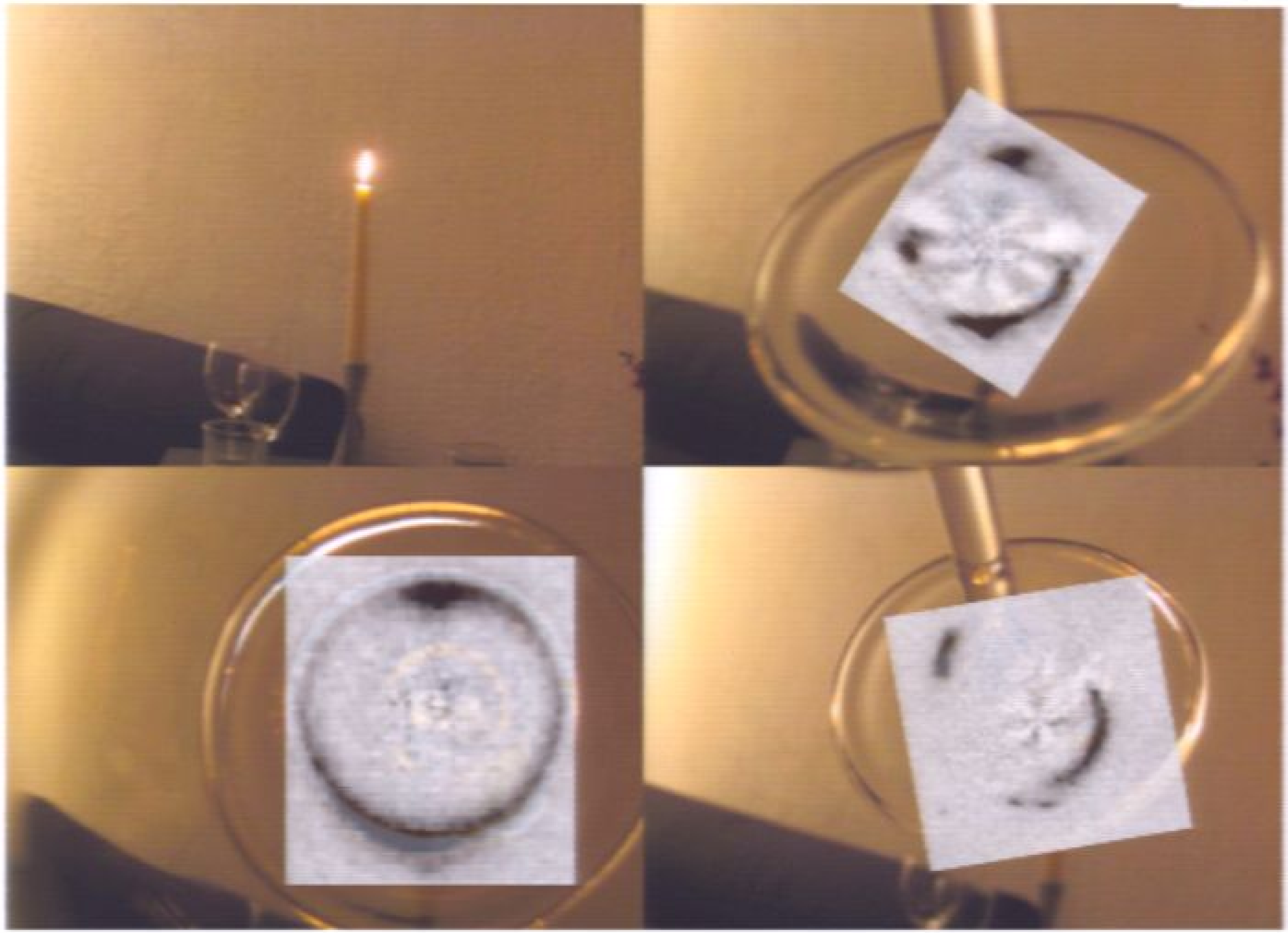

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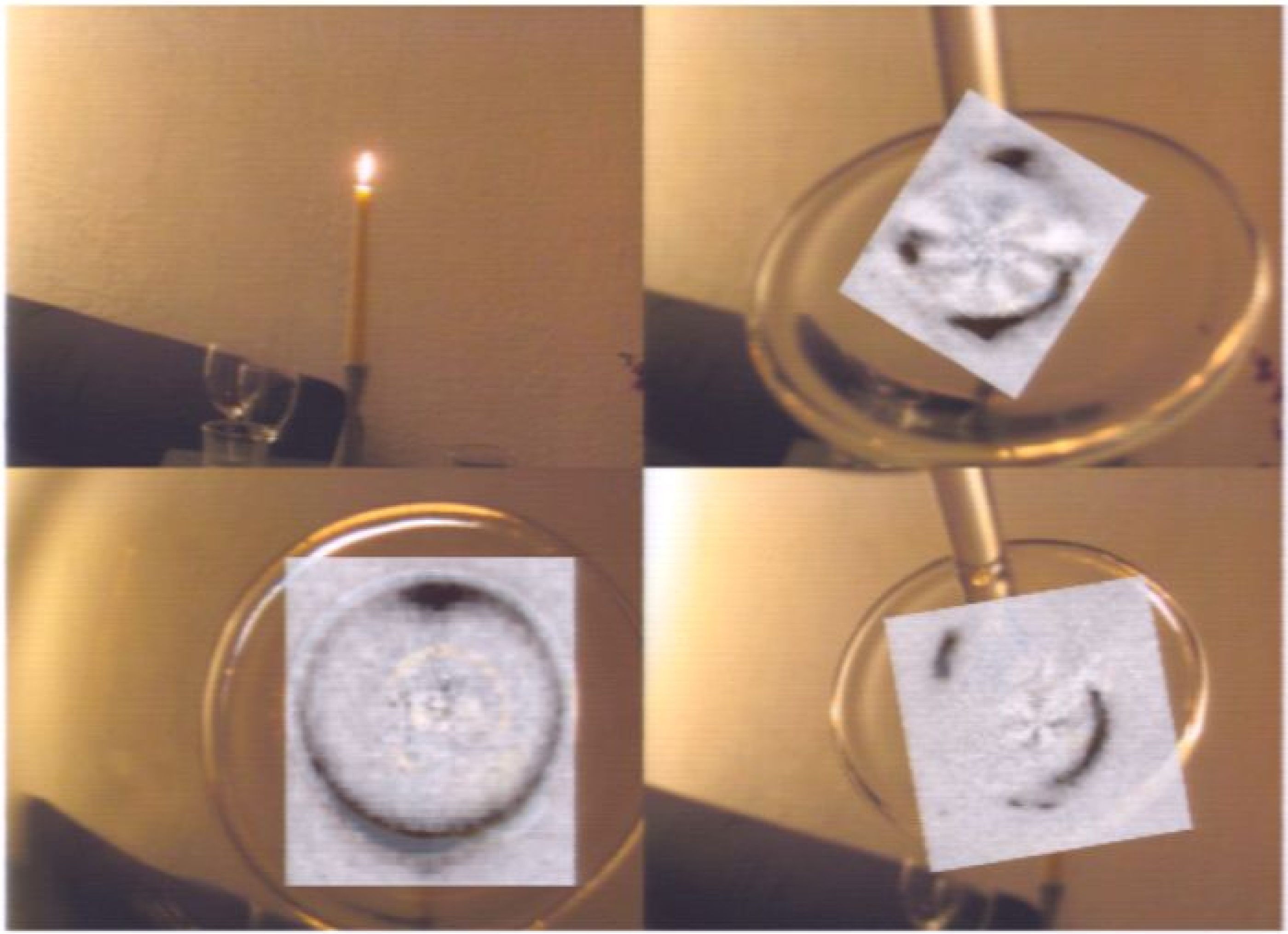
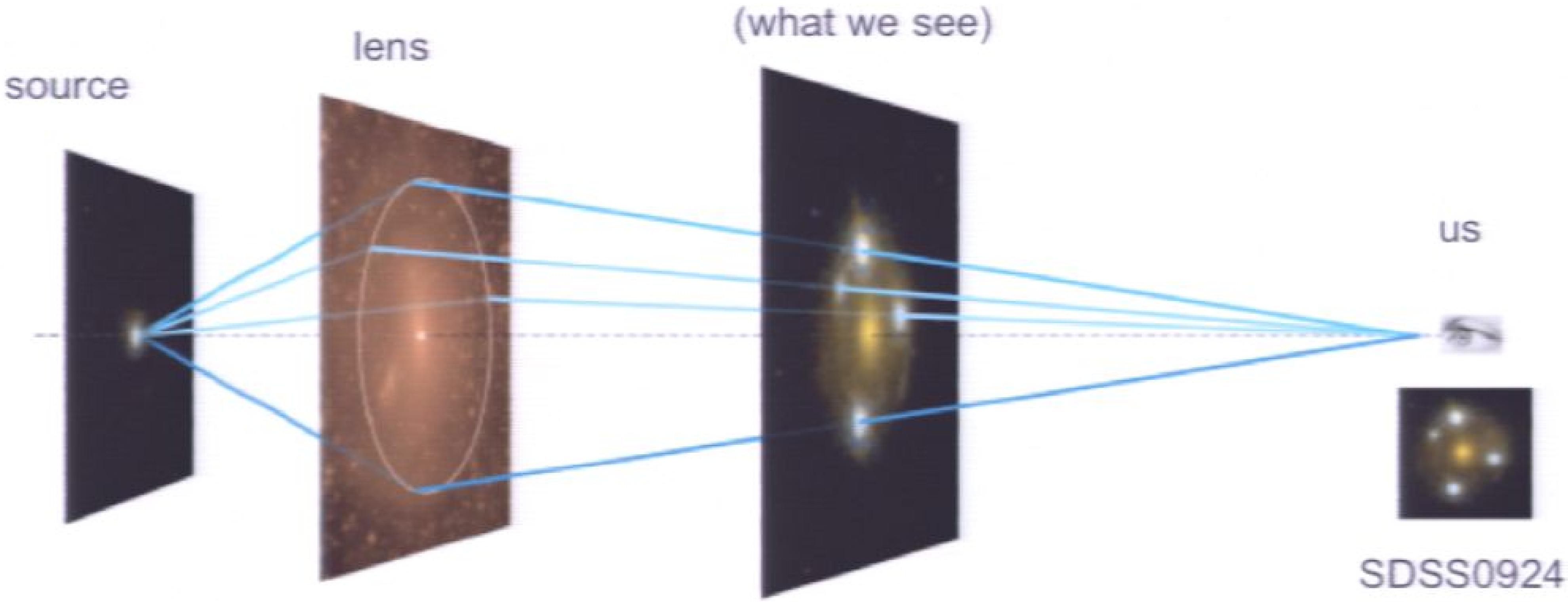


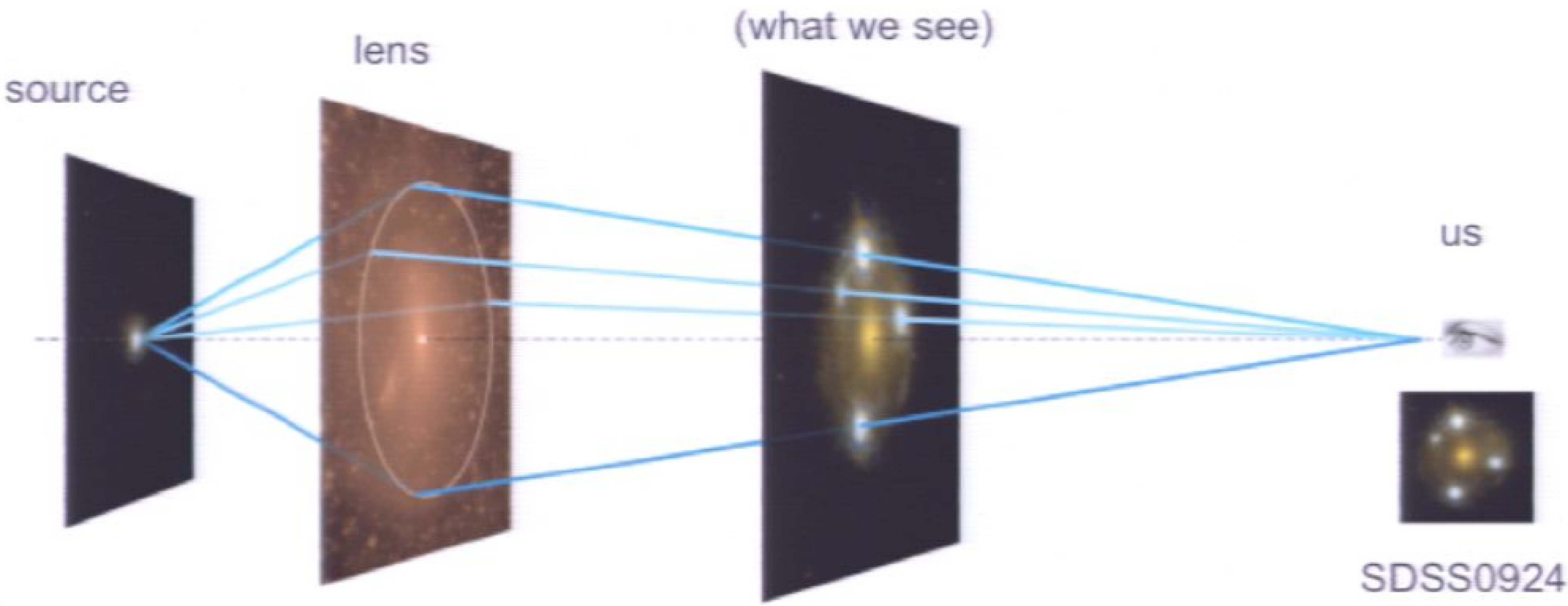
Courtesy Phil Marshall

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.

Strong gravitational lensing



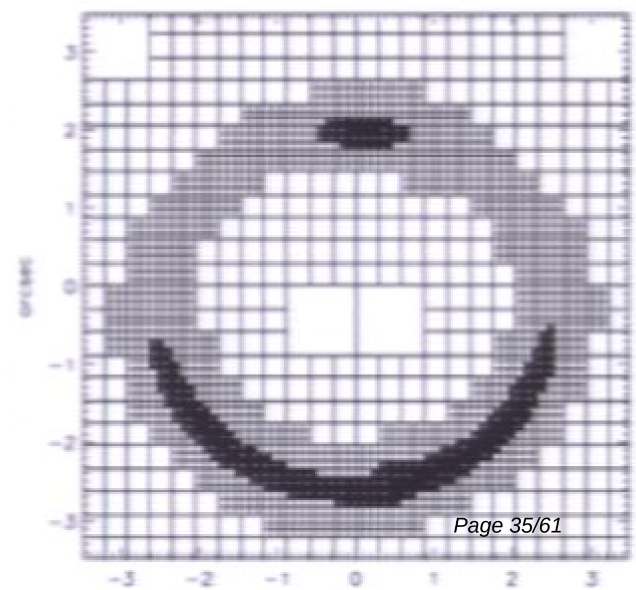
A simple geometric relation between the angular diameter distances between source, lens, and us determine the critical surface mass density for strong gravitational lensing.

Strong lens realizations

- We are using two completely independent state of the art lens modeling and simulation codes, GLAMER (Metcalf) and lensmodel/gravlens (Keeton).

Strong lens realizations: GLAMER

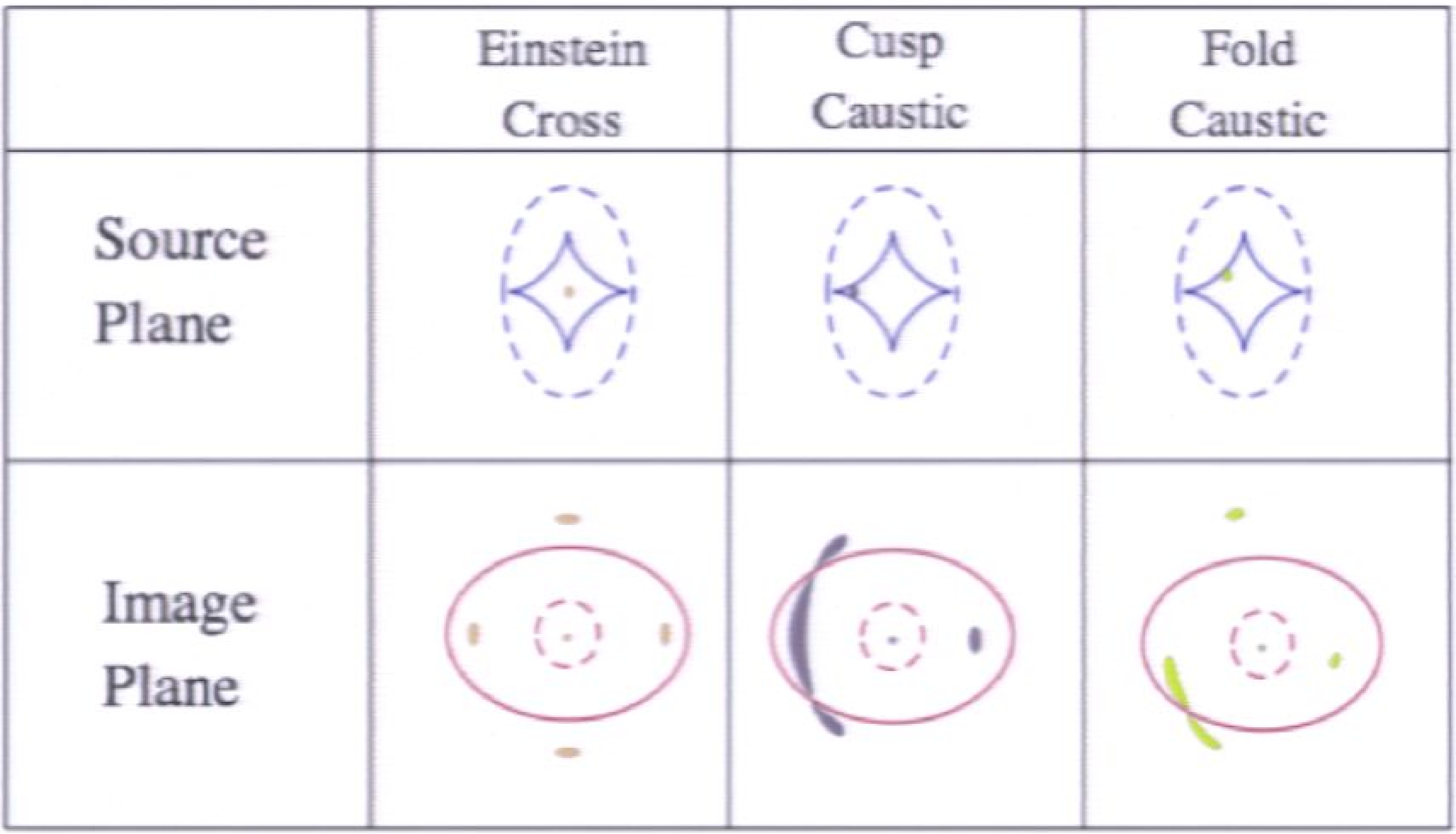
- Ben Metcalf (Metcalf & Amara 2010, 1007.1599)
- Lensing approach:
  - Adaptive Mesh Refinement for enormous dynamic range
- General lensing potential
  - Distorted Singular Isothermal Ellipsoid default, but flexible
- Stellar component possible
  - Microlensing
- Dark Matter Substructure
  - Internal structure
  - Convergence fraction
  - Spatial distribution



Strong lens realizations: lensmodel

- Models, in a reasonable time, distributions of clumps using power-law and NFW profiles, with tidal radii scaling relations specified by the user.
- Clumps are stochastically drawn from global spatial and mass distributions, which are set by the user.
- 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 (**Keeton**, astro-ph/1102.0996)
- Capabilities exist to explore finite source effects.

Basic geometry of gravitational lensing

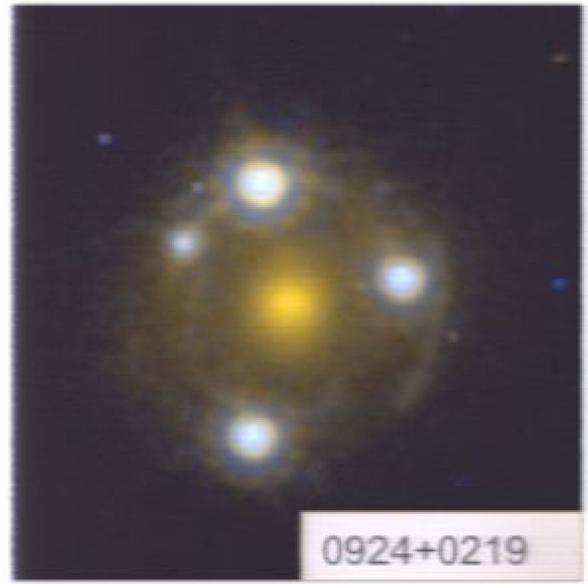


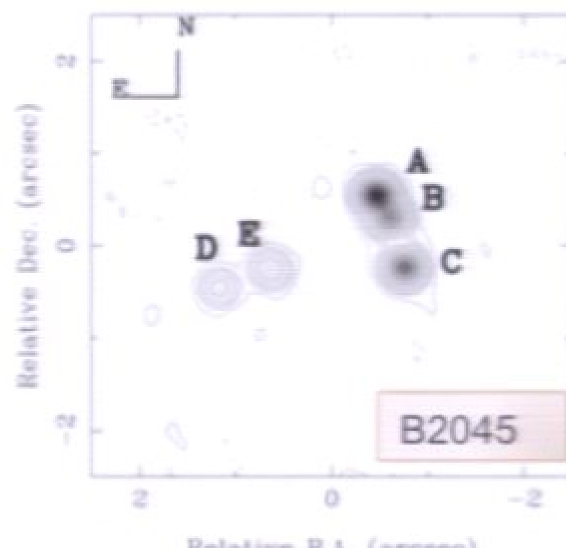
from icosmo

Classic magnification anomalies

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

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





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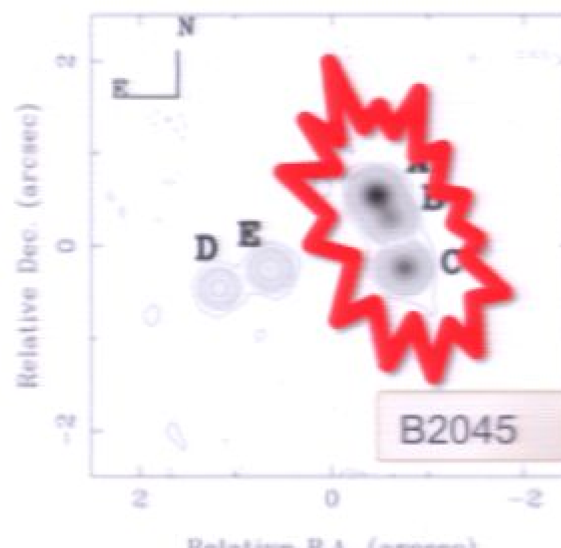

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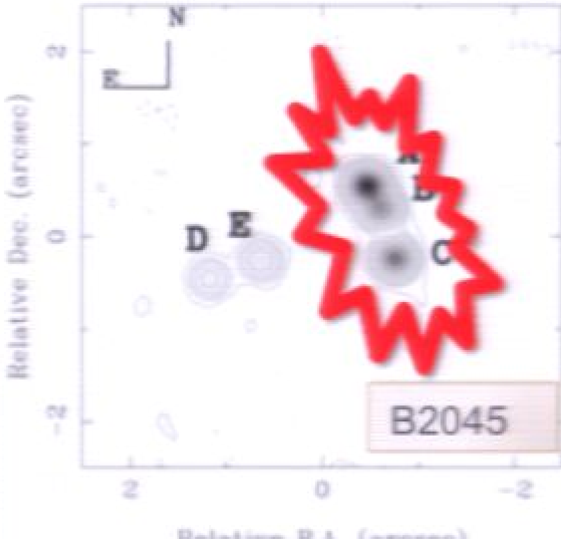
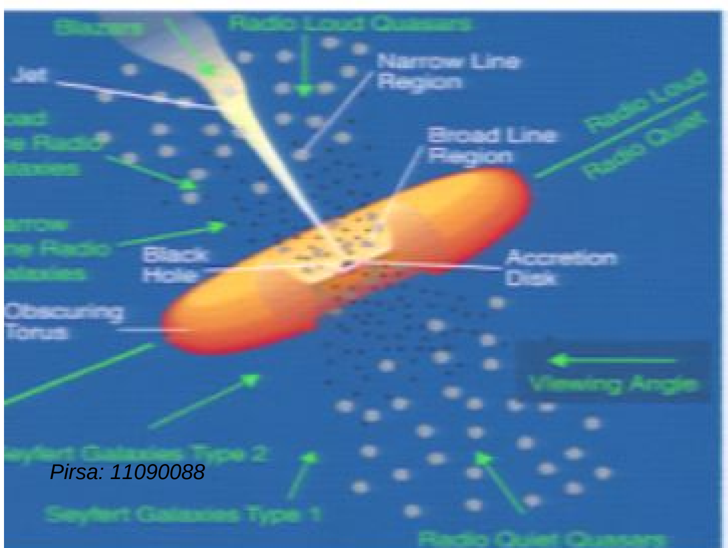


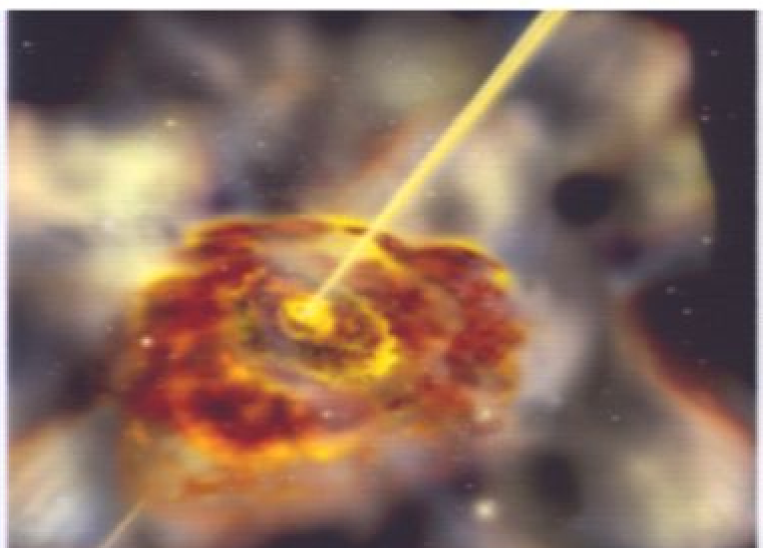
So we KNOW that something interesting is going on. There is a significant onus on us to demonstrate that it is due to *subhalos* though!

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

- *(Plus dust, microlensing, line of sight objects, environment, nature of source uncertainties, &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.

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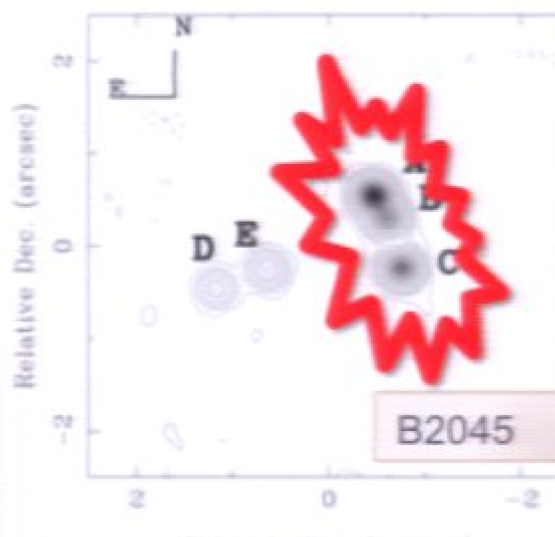

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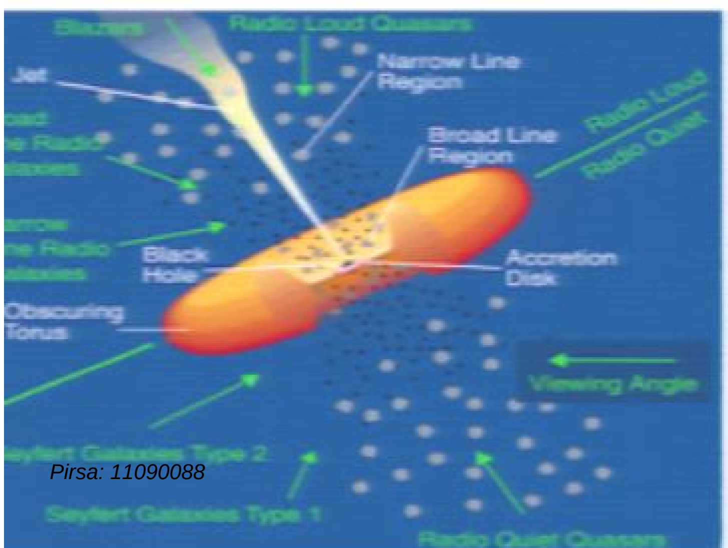

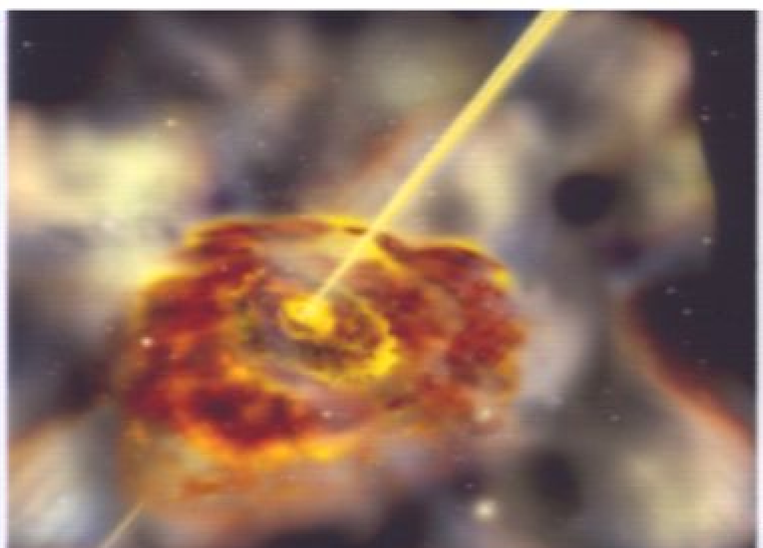

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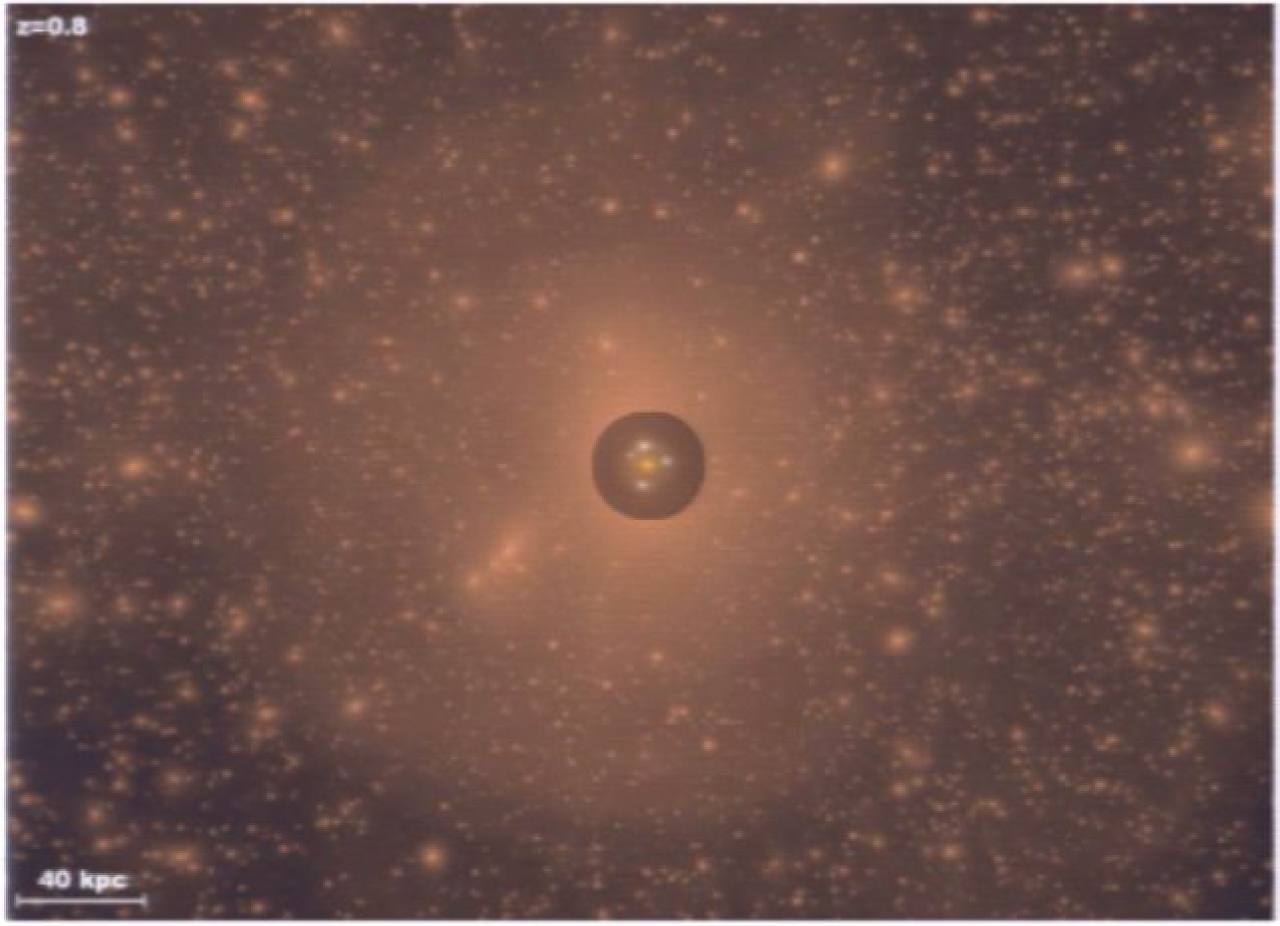
A strong lens' view of a halo

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.

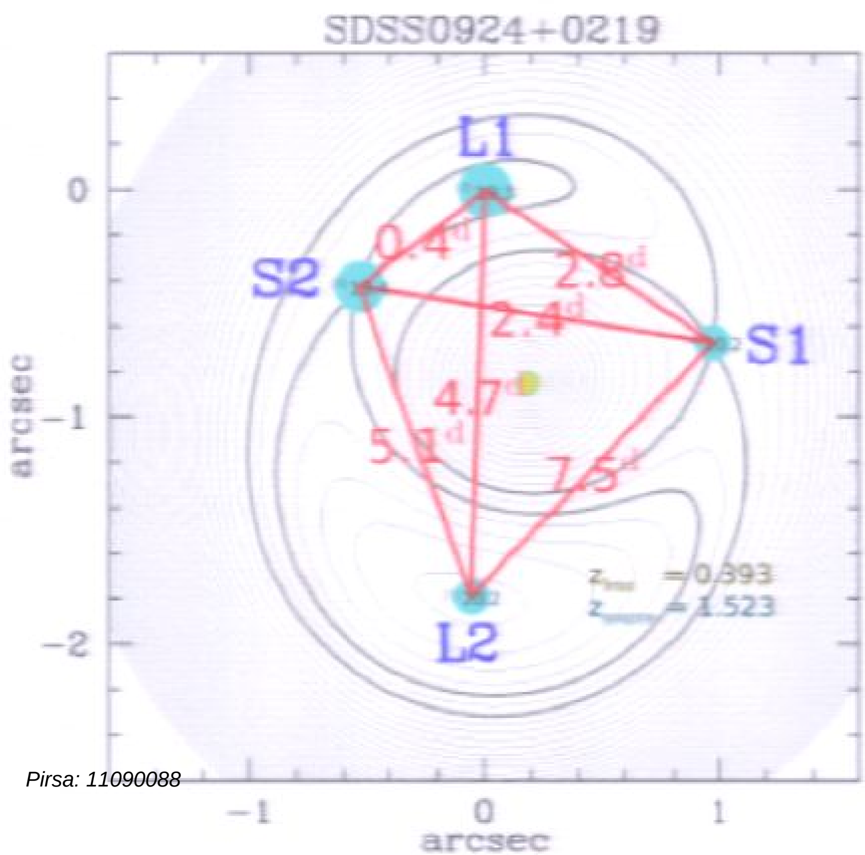


Diemand et al
Via Lactea

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

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.

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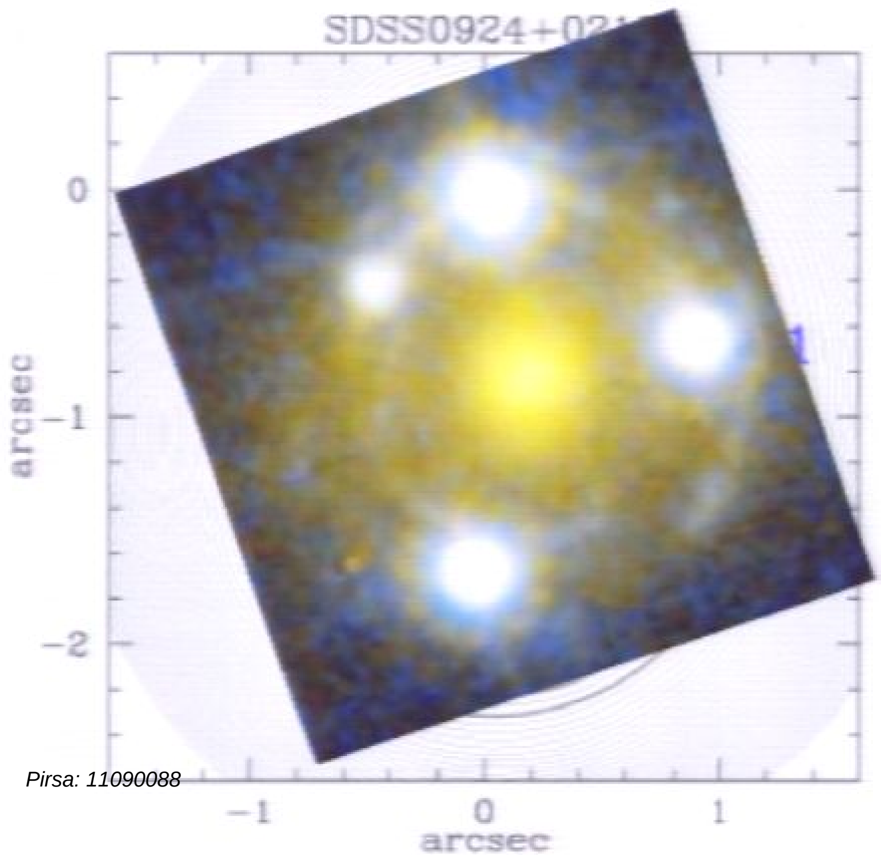

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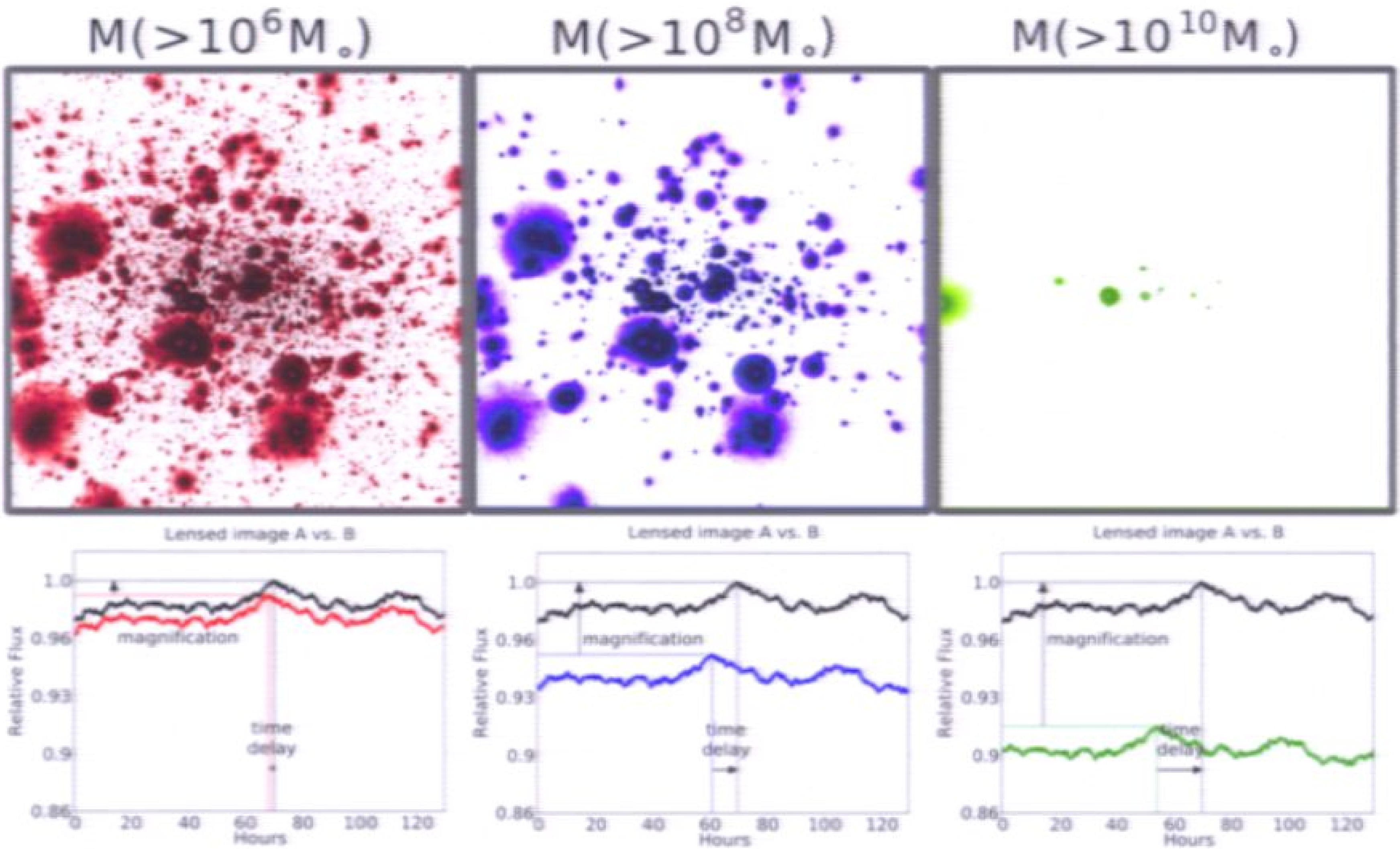
Magnification & time delay perturbations



flux vs time light curves, for image pairs

Ackn. M. Kuhlen, D. Coe, +

"Regions of impact" of observables

The level to which perturbations affect the observables depends on the perturbers' potential profile – point source, NFW, power law, isothermal, …

- Magnifications: $\delta\gamma \sim \frac{1}{\hat{r}^2}$

Very sensitive to profile. Low limits: ~1E3 Msun (NFW) to sub-solar (point)

- Positions: $\delta x \sim \frac{R_{\rm ein}}{\hat{r}}$
- Time delays: $\delta t \sim R_{\rm ein}^2 \ln \hat{r}$

Not very sensitive to profile. Low limits: ~1E5 Msun (?).

The potential of lensing

There are powerful advantages to combining observables in lenses:

- Magnifications are sensitive to local perturbers, but as they have a *large* dynamic range of sensitivity, there are also potentially many more perturbers to contribute.

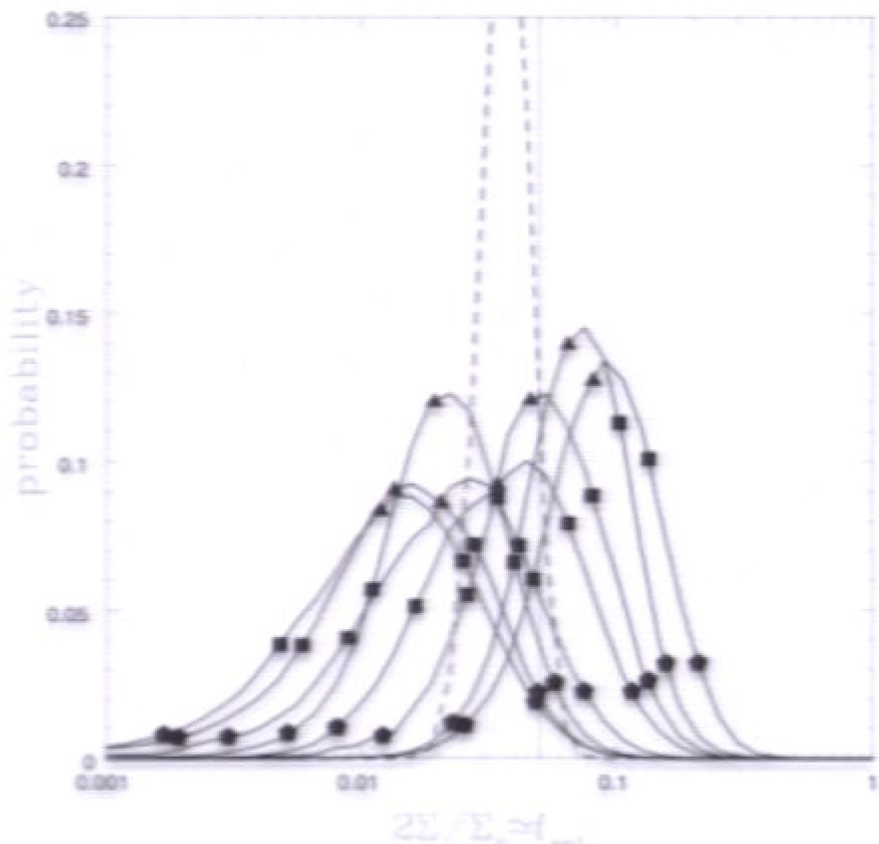
- Time delays are not as sensitive to as large a mass range (though still 3-4 orders of magnitude lower than dwarf galaxy scales). There are fewer such beasties, but this may be compensated by the very large region of impact, because of the direct dependence of the time delay on potential (and perturbations thereof).

- Astrometry is in between! This is a nuanced problem, which I can discuss.

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 subhalos.

High precision *astrometry* will play a great role in the future. AO, JWST, TMT, GMT.



Surface density in substructure

Time delay perturbations

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

$$\Delta\phi(\vec{x}) = \sum_i \frac{\hat{m}_i}{\pi}\ln|\vec{x}-\vec{r}_i|$$

$$\sigma_t \propto \left(f_s\,\frac{\langle m^2\rangle}{\langle m\rangle}\right)^{1/2}$$

Potential perturbations for an ensemble of substructure.
This leads to a corresponding *time delay* perturbation.
This is worked out analytically for point sources (Keeton & Moustakas 2009), but through simulations we find that the perturbations behave similarly for *any* subhalo profile (Moustakas+ 2011).

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)

Time delay perturbations

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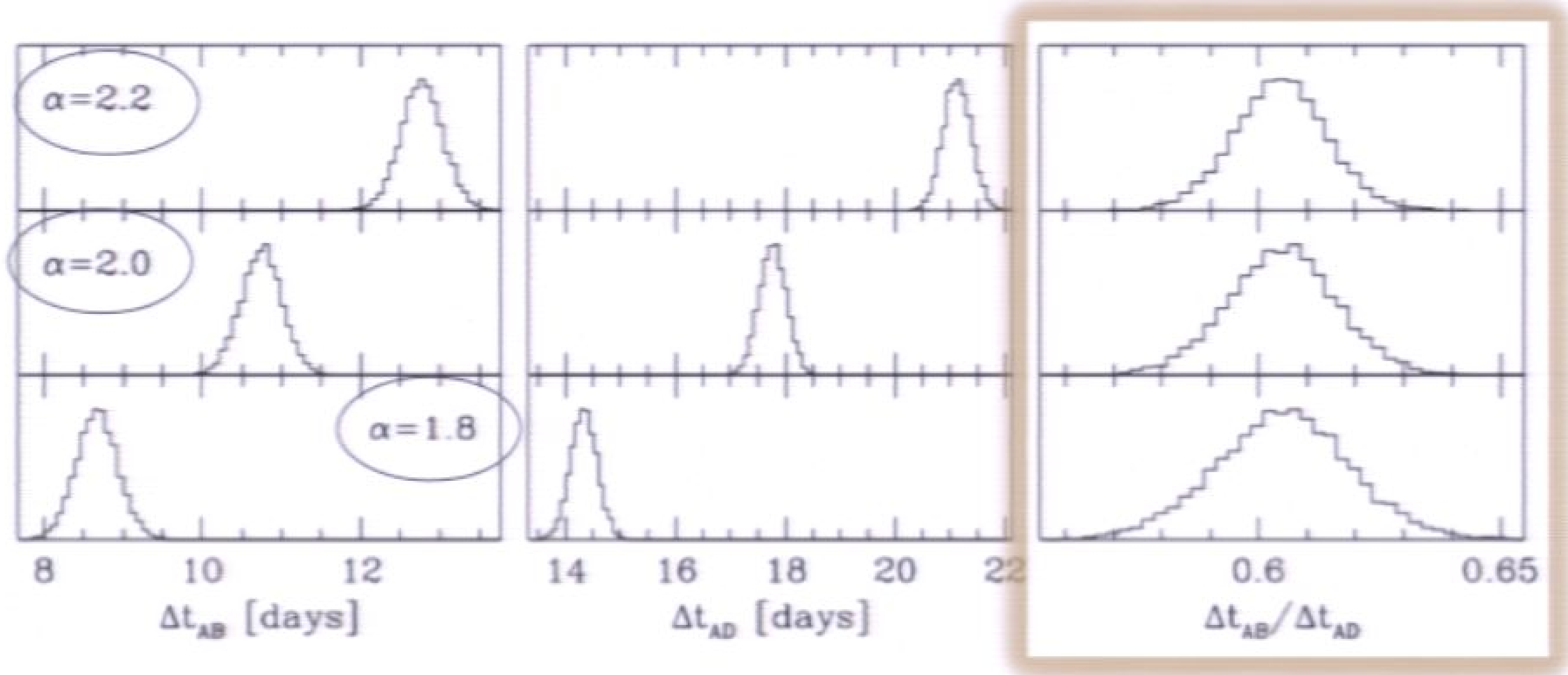
Time delay perturbations

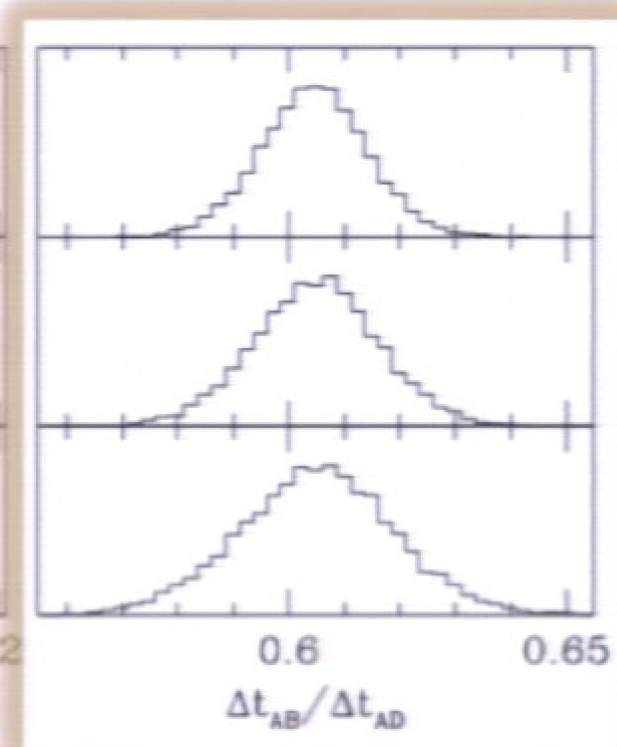
The classic radial profile / mass sheet degeneracy is the most insidious in lensing!



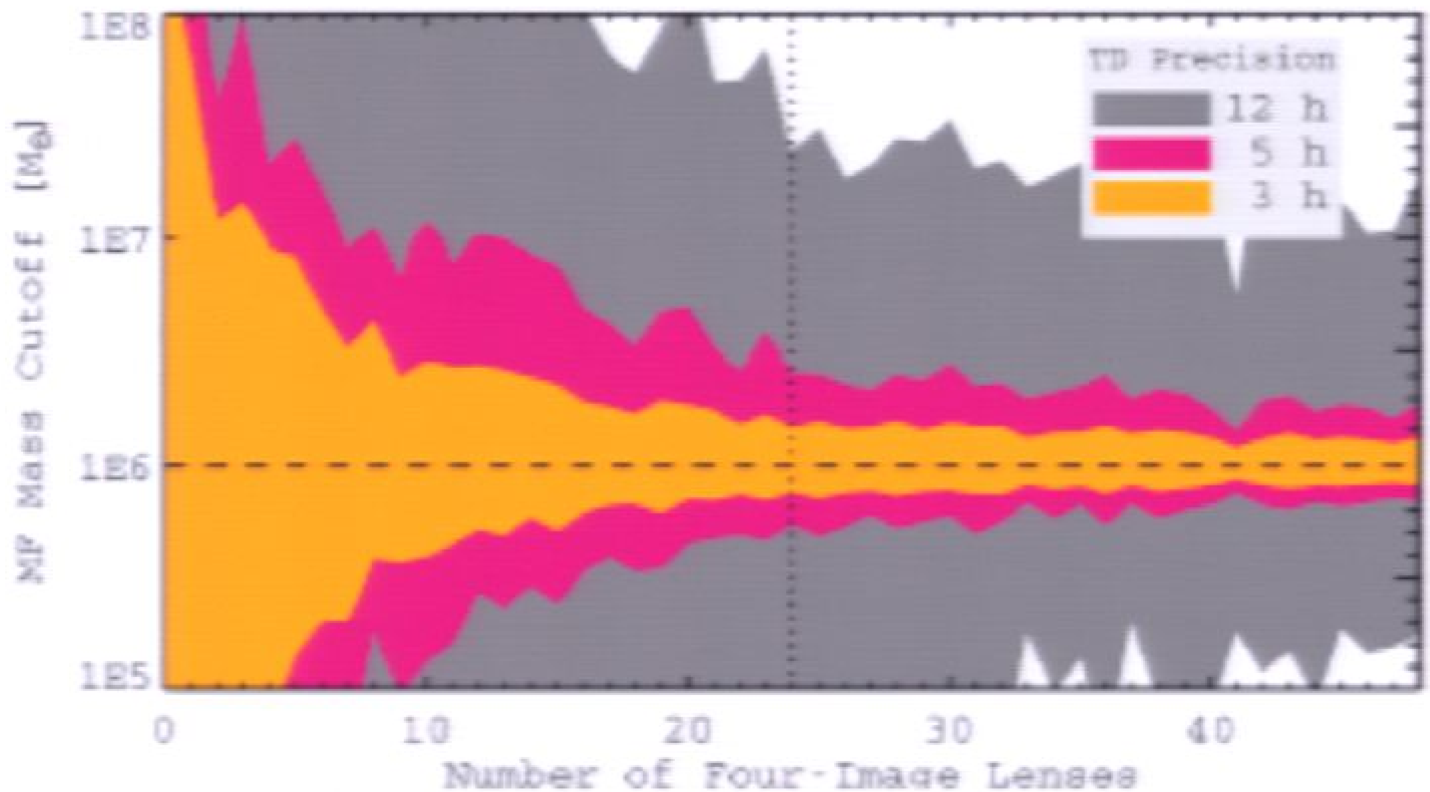
Time delay perturbations

The classic radial profile / mass sheet degeneracy is the most insidious in lensing!

Time delay *ratios* mitigate the radial profile / mass-sheet degeneracy in any one lens.



Detectability of a 1E6 Msun MF cutoff



The OMEGA Explorer 2011

- 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 lenswith 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.
- This has driven us to design a space-based observatory dedicated to accomplishing this.

The OMEGA Explorer 2011

- Implementation & controlling systematics

- *Persistence, flexibility, precision, and stability*

The OMEGA Explorer 2011 proposal was submitted to NASA in February.

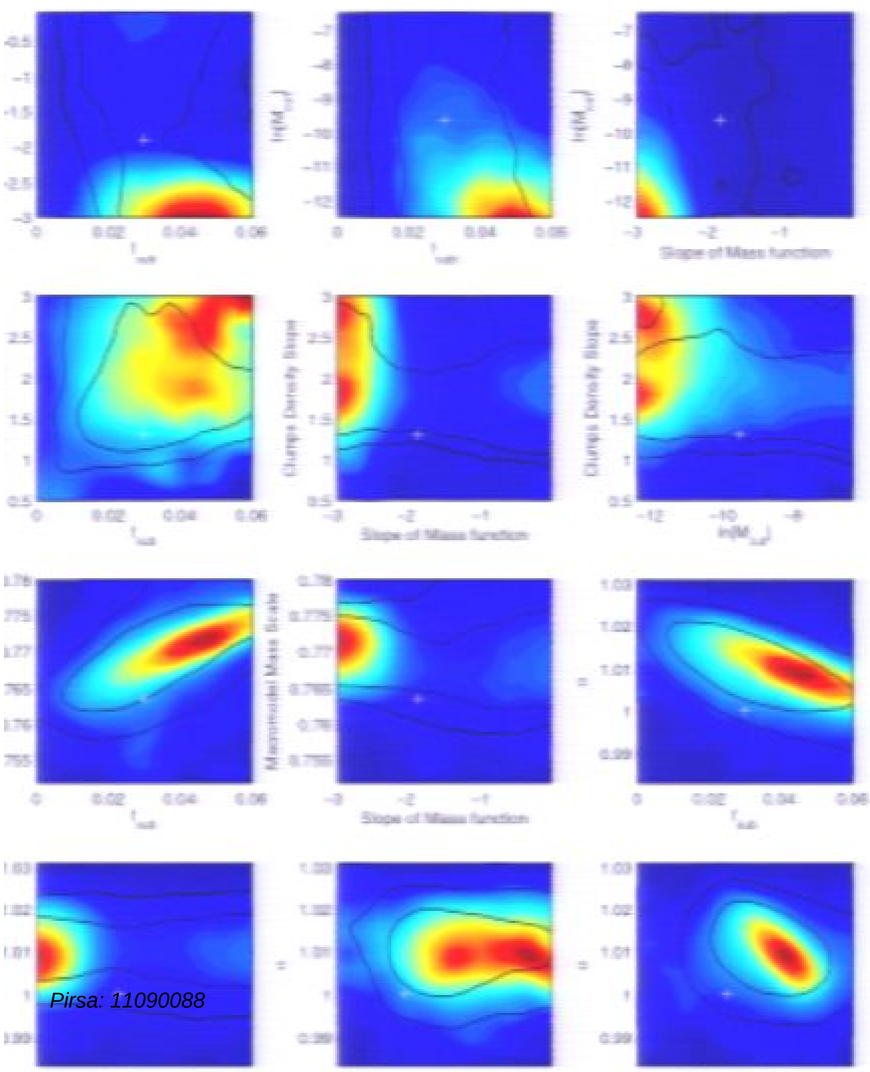
This is for $200M – capped missions.

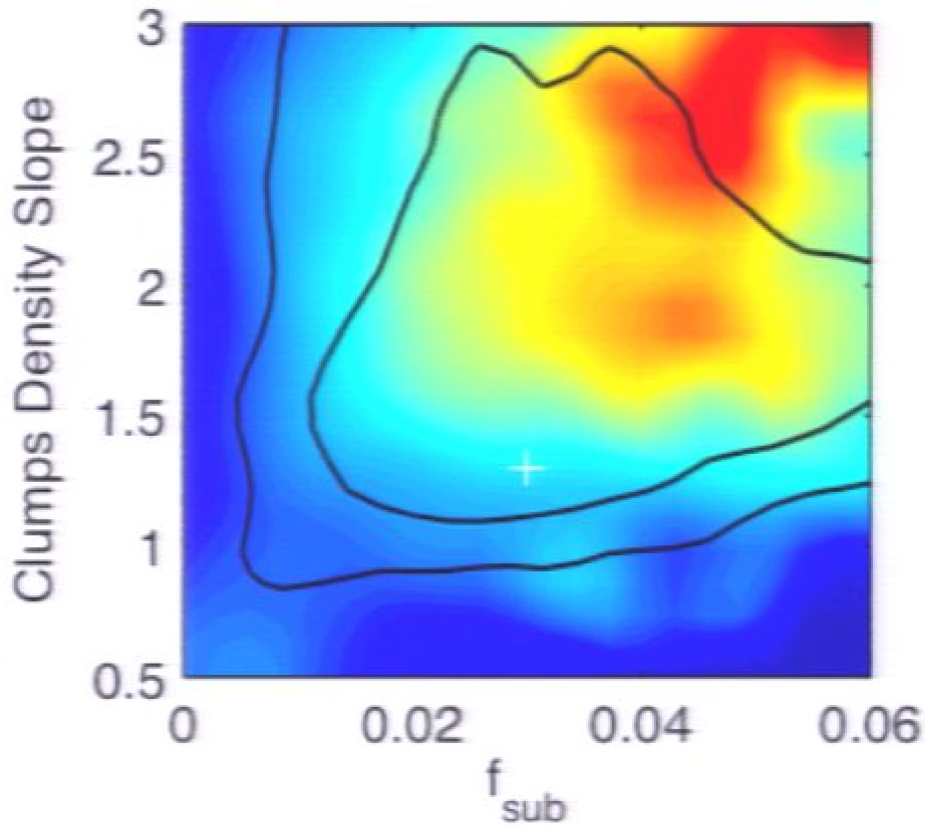
Our launch date will be Equinox 2016, with a two-year mission to achieve the goal of measuring the dark matter subhalo mass function to (at least) 1E6 Msun cutoff sensitivity.

We will find out whether we are successful around August 2011.

The 89-cm diffraction limited imaging observatory we have designed *will continue to be operational for nearly two decades*, and available for use.

MCMC exploration of parameters





Cyr-Racine, Sigurdson, LM, ++