Shining Through the Darkness:

detecting dark matter with stellar astrometry

Adrienne Erickcek
CITA & Perimeter Institute

with
Nicholas Law
U of T Dunlap Institute

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Overview

I. Our clumpy dark matter halo
What do numerical simulations tell us about substructure?

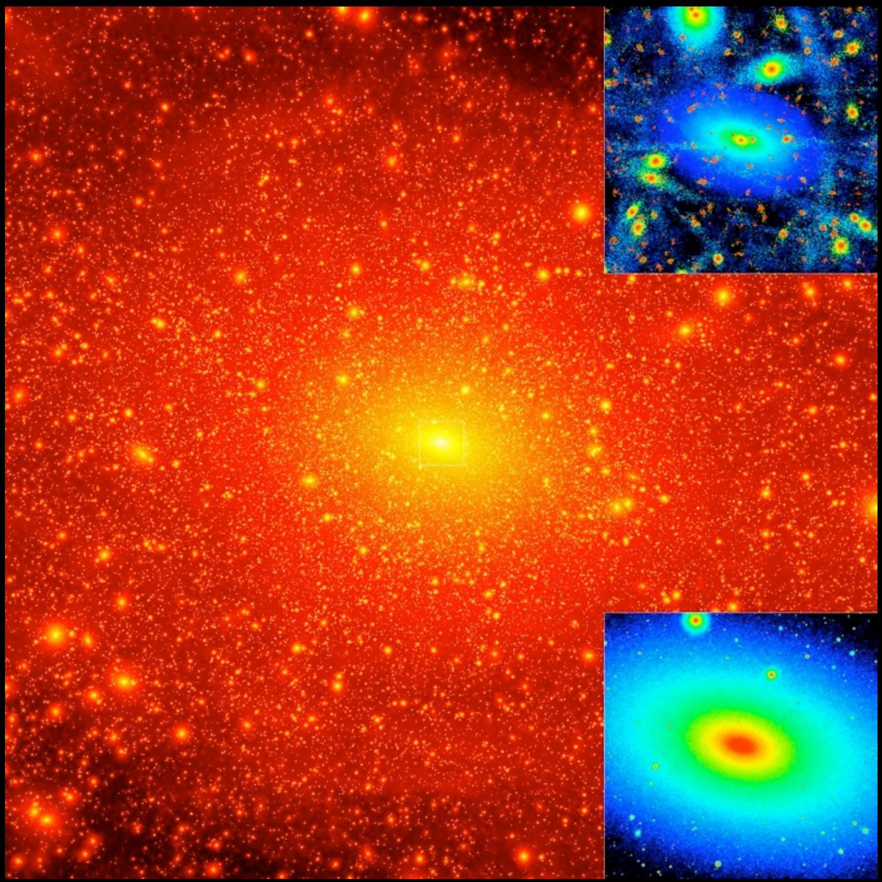
II. Astrometric microlensing by subhalos
What happens when a subhalo passes between us and a star?

III. High-precision astrometry
Can we measure stellar separations in microarcseconds?

IV. Cross sections, event rates, and detection prospects
How close does the star need to be to the subhalo center?
What hope do we have of observing these events?

Simulated Dark Matter Halos

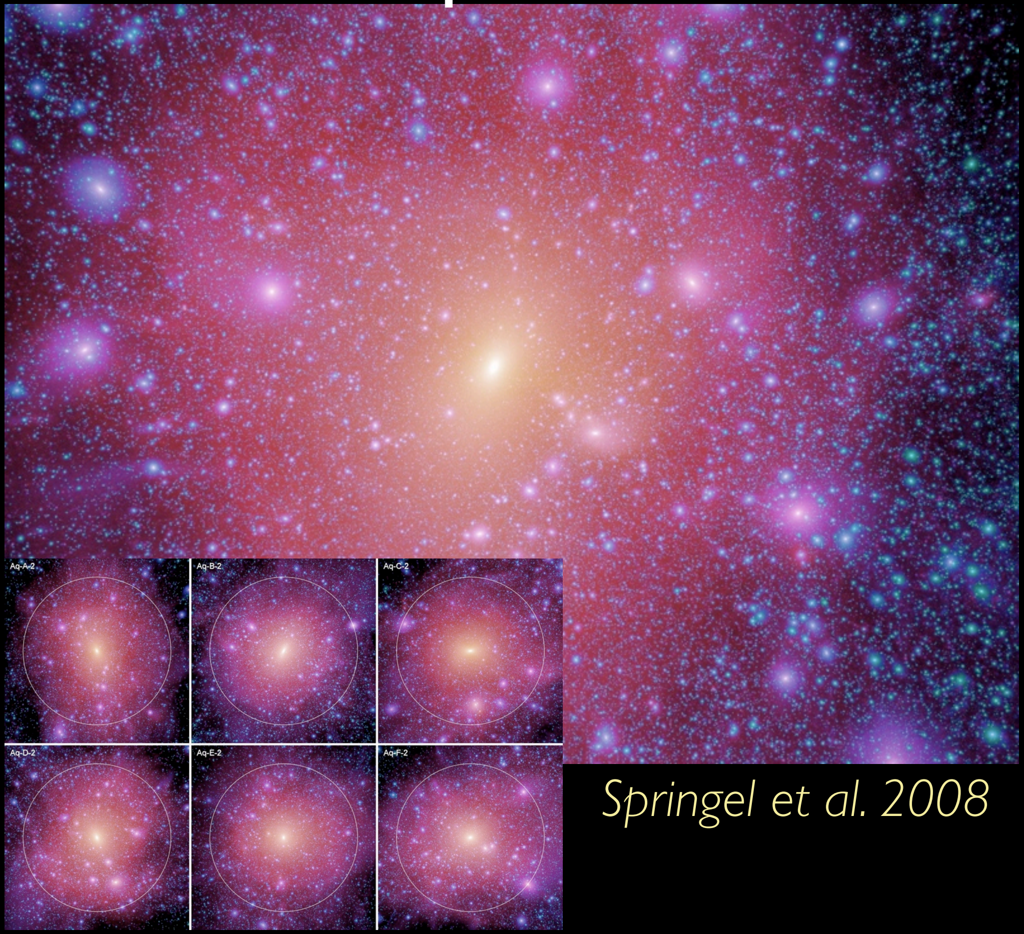
Via Lactea II



Diemand et al. 2008

- One halo with 1.1 billion particles
- 4,100 Msun per particle

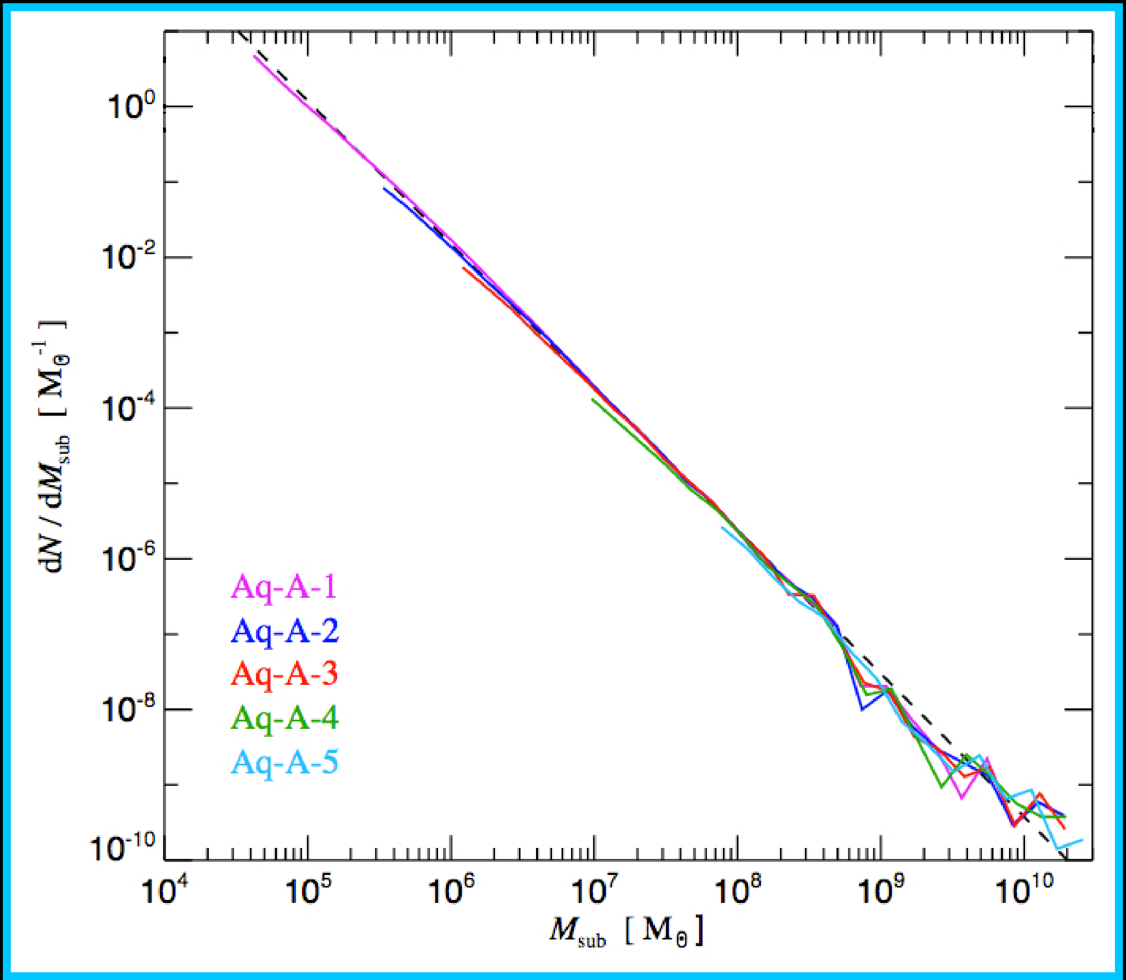
Aquarius



Springel et al. 2008

- One halo with 4.2 billion particles
- 1,712 Msun per particle
- Five additional halos with lower res.

Dark Matter Halos are Clumpy!



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Aquarius can resolve

$$M_{\rm sub} \gtrsim 4 \times 10^4 M_\odot$$

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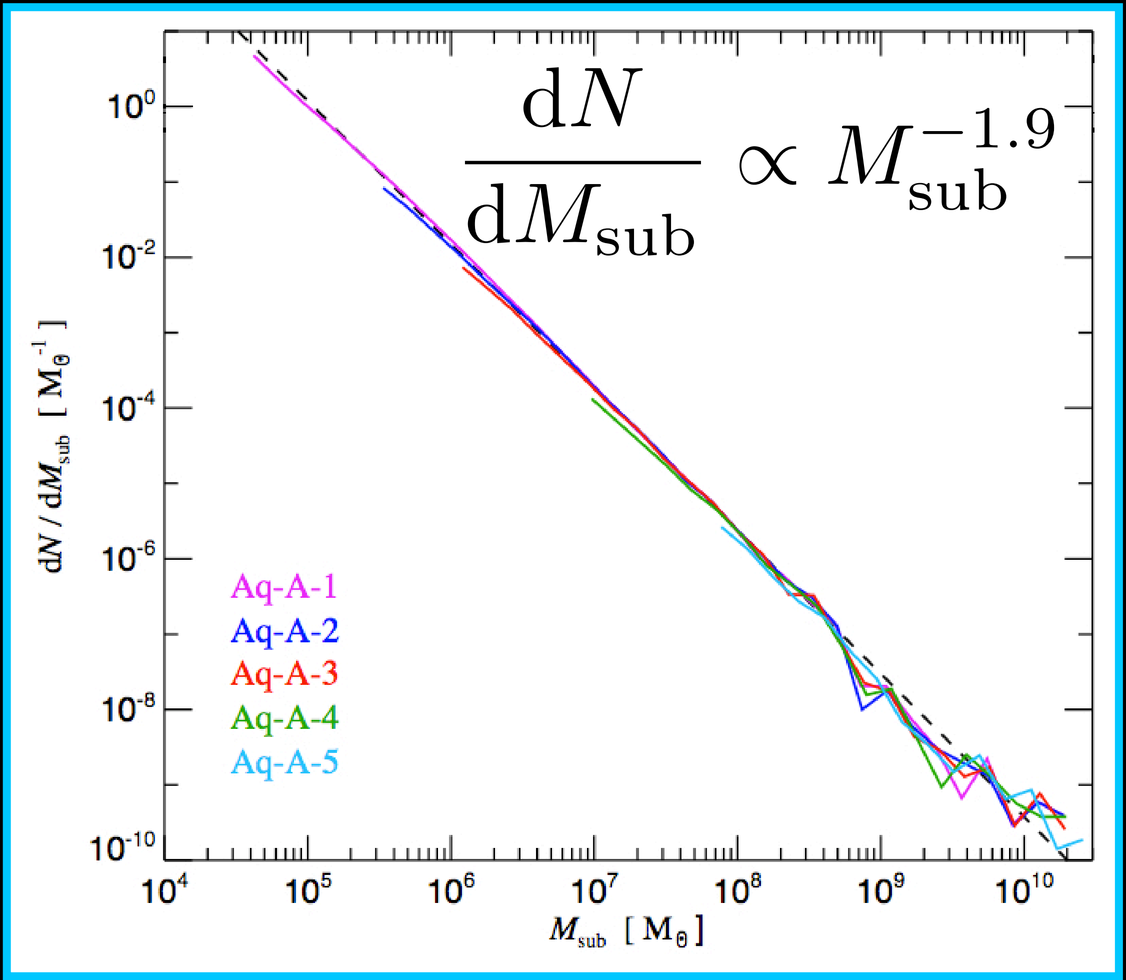

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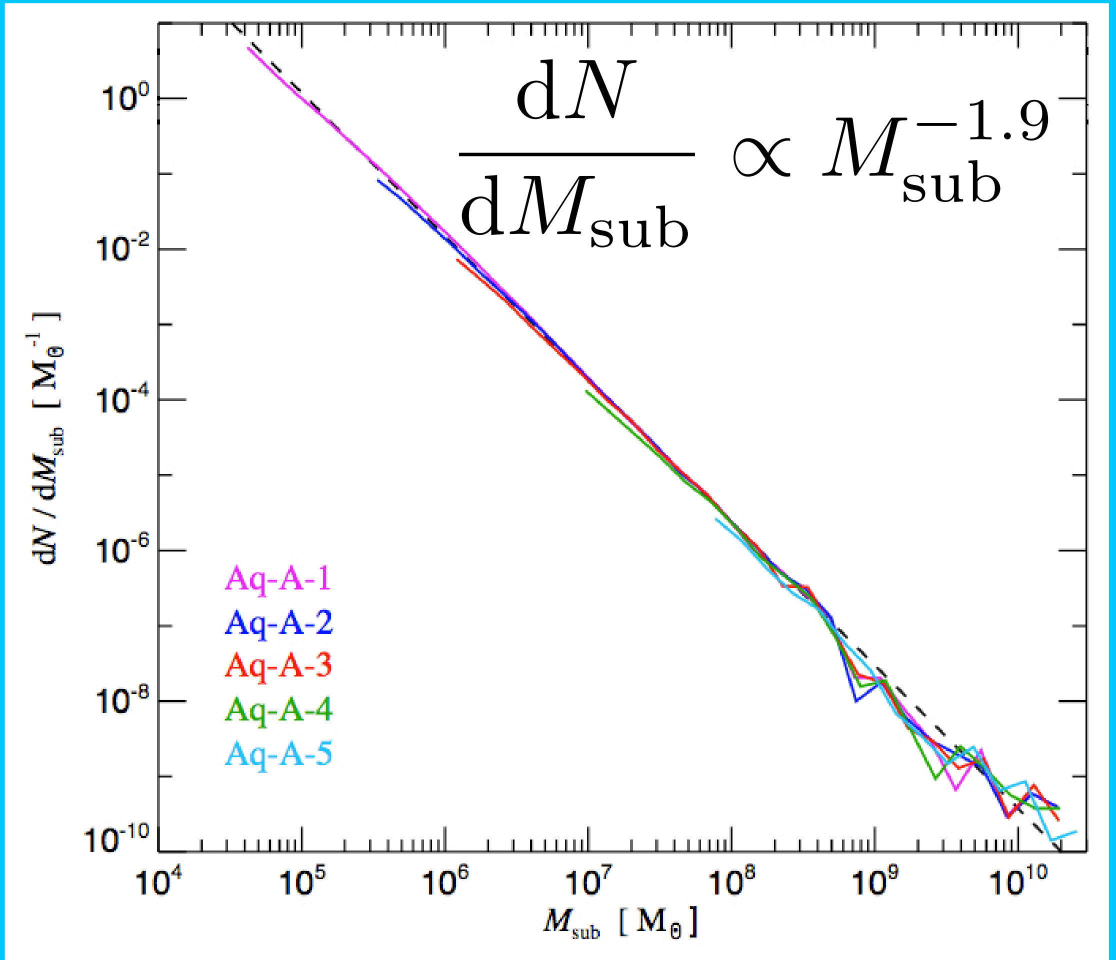

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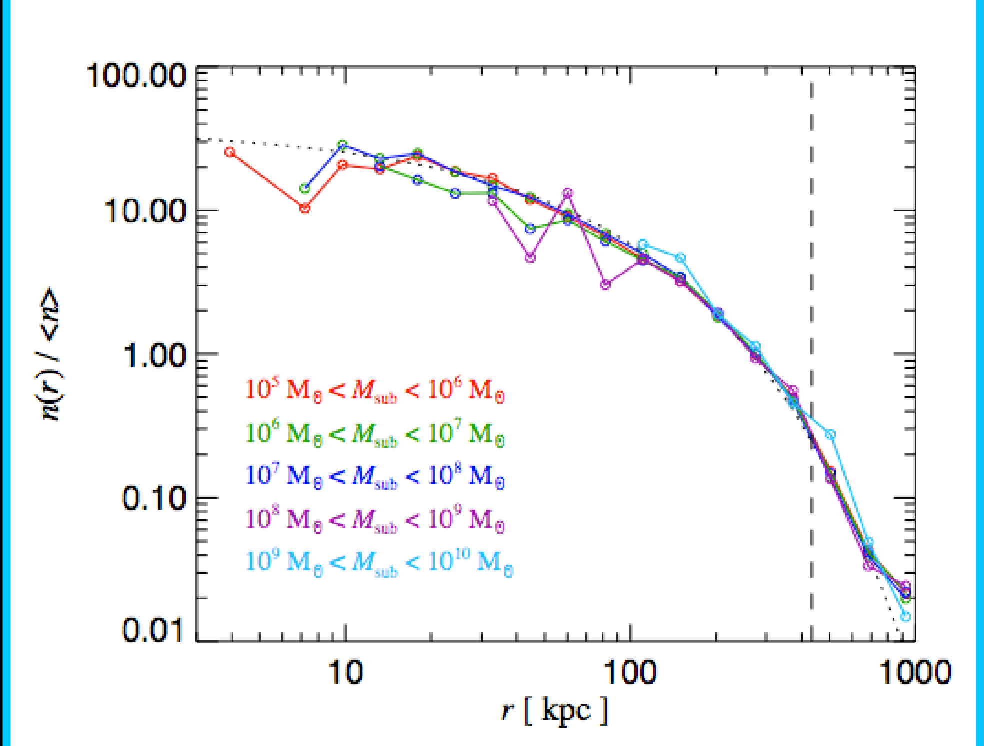

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Spatial distribution of subhalos within host is independent of subhalo mass.

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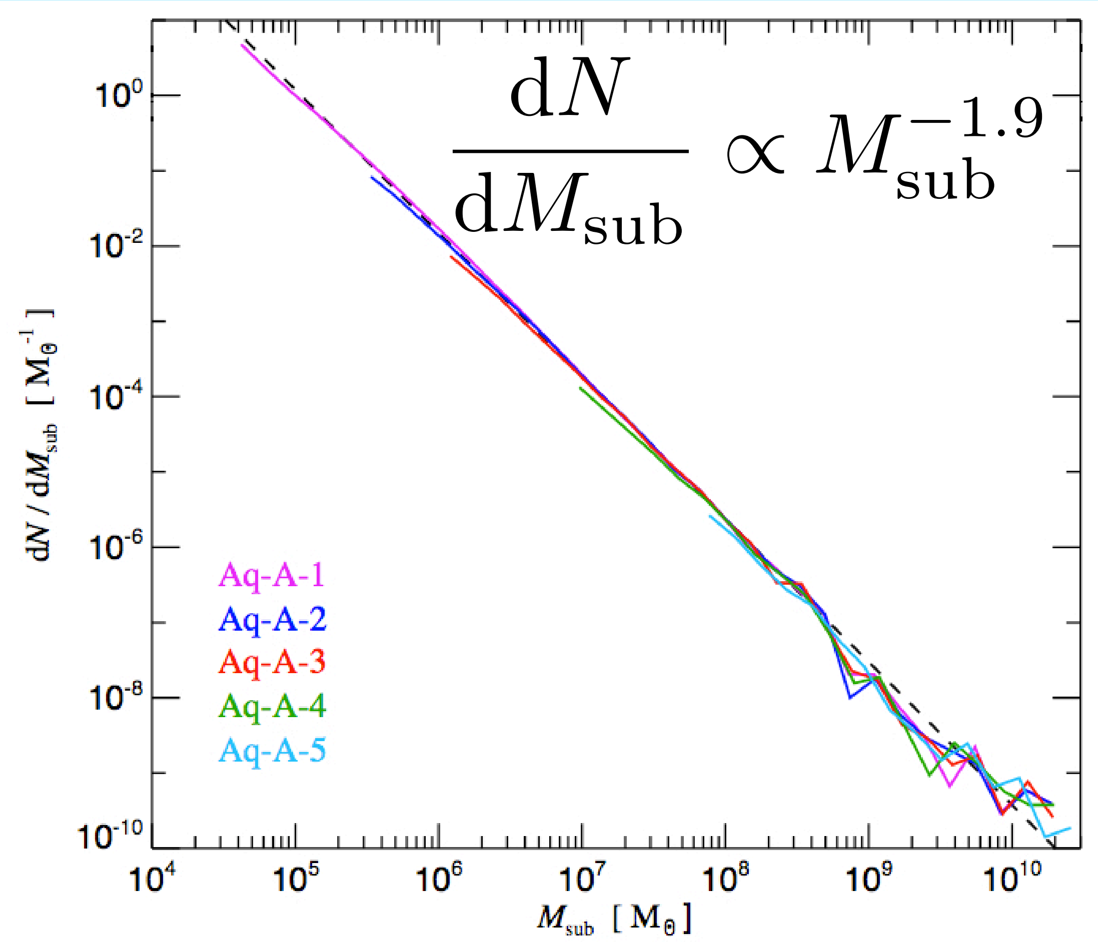
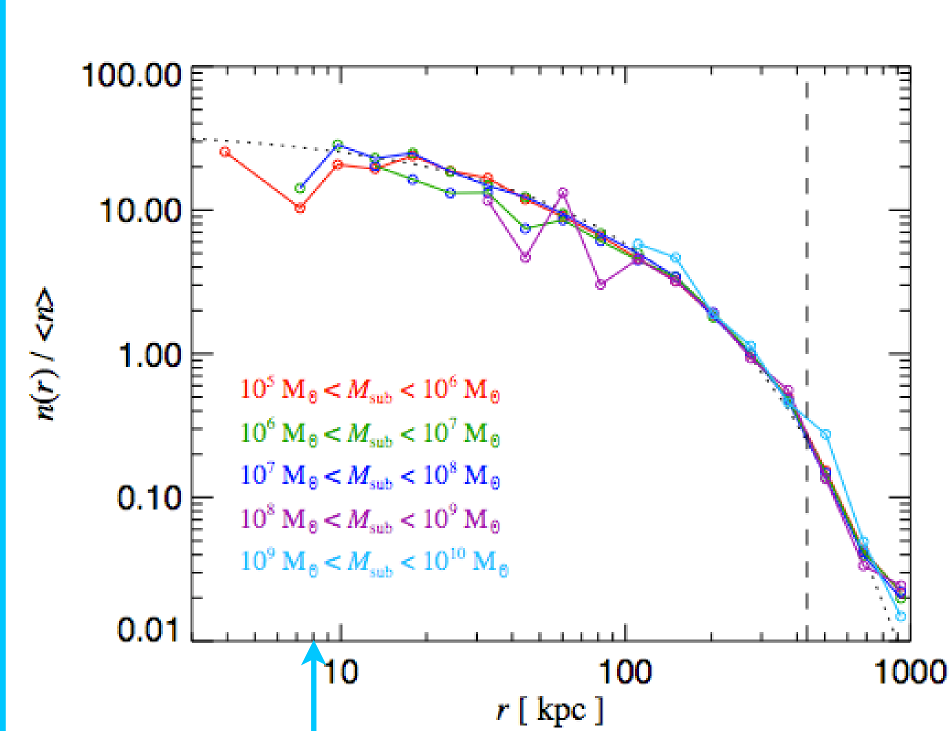


Springel et al. 2008



Springel et al. 2008

We are here!

Aquarius can resolve
$M_{sub} \gtrsim 4 \times 10^4 M_\odot$

Spatial distribution of subhalos within host is independent of subhalo mass.

Subhalos are Gravitational Lenses

When galaxies produce multiple images of a quasar; subhalos can modify the properties of these images.

- subhalos magnify one image, leading to flux-ratio anomalies.
  Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002; Dalal & Kochanek 2002
- subhalos alter the time delays between images
  Keeton& Moustakas 2009; Congdon et al. 2010
- subhalos deflect one image
  Koopmans et al. 2002; Chen et al. 2007; Williams et al. 2008; More et al. 2009
- subhalos can split one image into two
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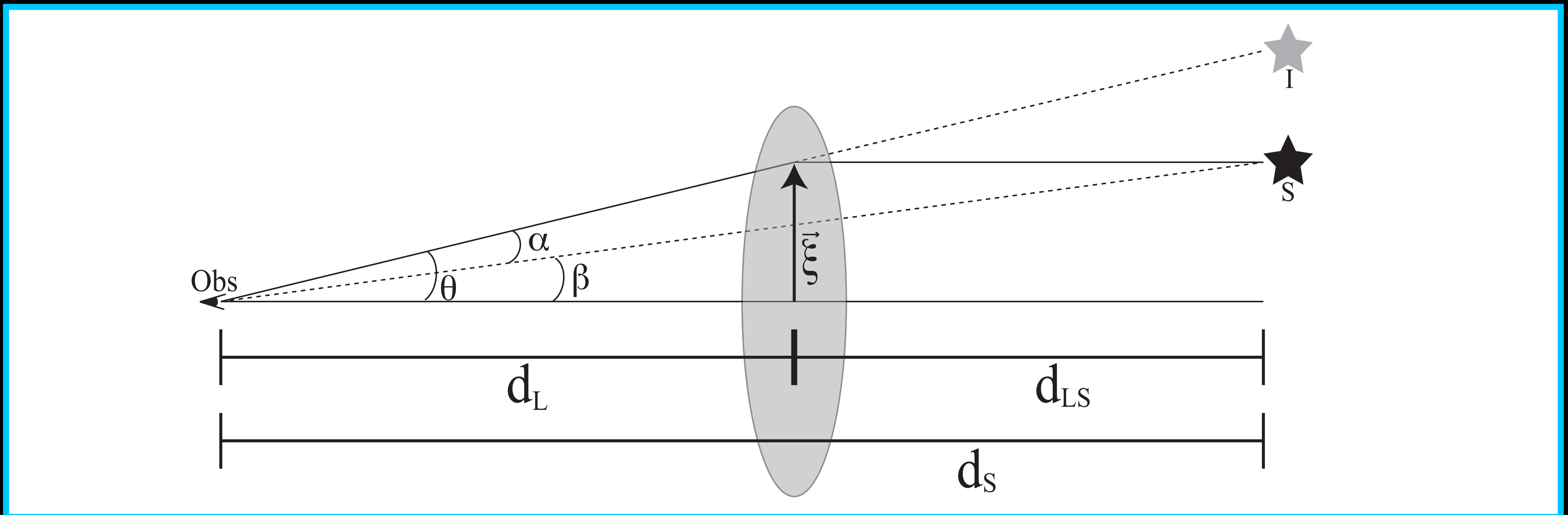
Only the last possibility can detect individual subhalos, and it's unlikely. Astrometric lensing is more promising:

- split images are hard to resolve; changes in image position are much easier
- larger impact parameters can give detectable image deflections
- we're looking for a dynamical signature from a local subhalo

Astrometric Microlensing



- thin lens approximation: lens thickness is small compared to $d_{\rm L}$, $d_{\rm S}$
- weak lensing: one image with $\alpha \ll \beta$ so that $\xi \simeq d_{\rm L}\beta$
- thin lens equation: $\vec{\alpha} = \frac{d_{\rm LS}}{d_{\rm S}} \left[\frac{4GM_{\rm 2D}(\xi)}{\xi} \right] \hat{\xi}$

$$\text{Deflection Angle} \propto \frac{\text{Projected mass enclosed}}{\text{Distance from lens center}}$$

Lens: Singular Isothermal Sphere

Density profile: $\rho(r) \propto r^{-2}$

Projected mass enclosed: $M_{\rm 2D}(r) \propto r$

Constant Deflection Angle!

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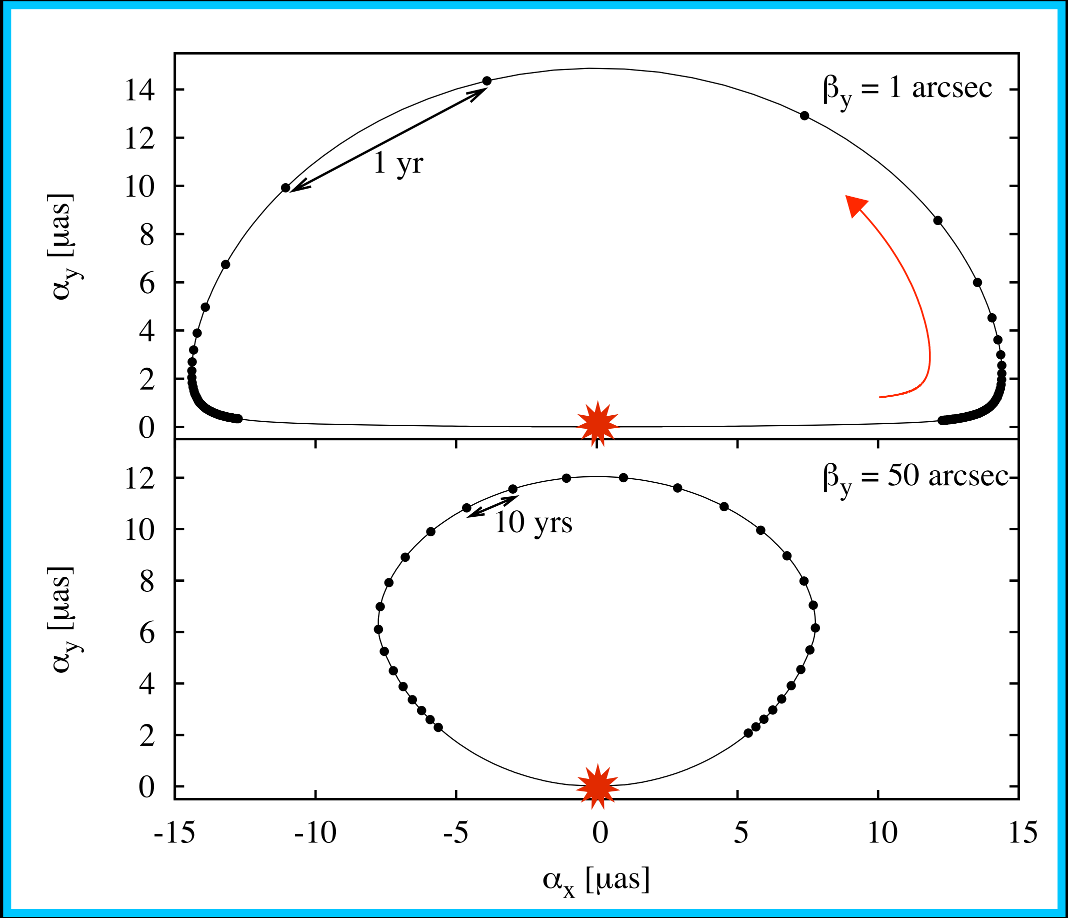
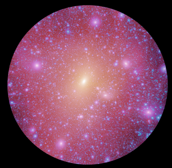


- If the SIS is infinite, the star traces a semi-circle on the sky.
- The radius of the semi-circle is the Einstein angle:

$$\theta_{\mathrm{E}}^{\mathrm{SIS}} = 10\,\mu\mathrm{as}\left(\frac{\sigma_v}{0.6\,\mathrm{km/s}}\right)^2\left(1-\frac{d_\mathrm{L}}{d_\mathrm{S}}\right)$$



Lens path: 200 km/s

Lens distance: 50 pc

Lens mass: 5 Msun

Lens radius: 0.02 pc (85")

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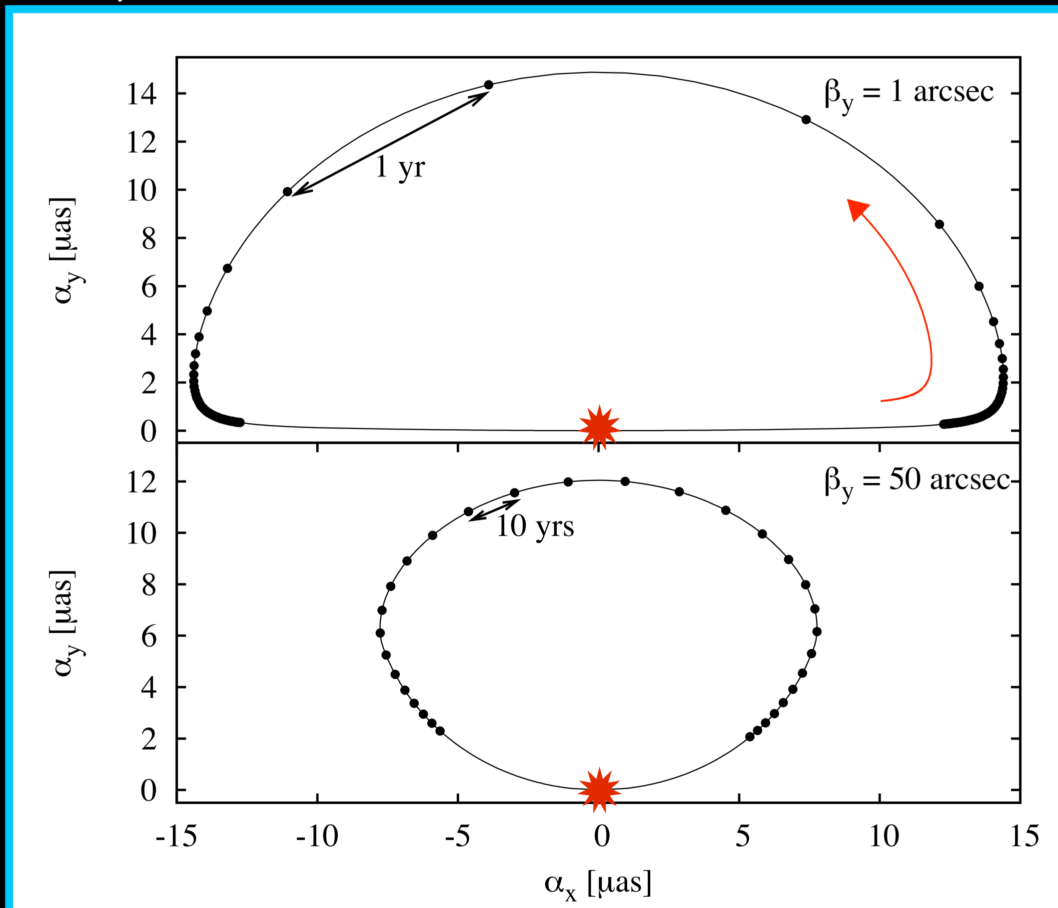

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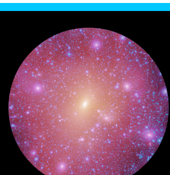
- Truncating the SIS completes the image path.
- Larger impact parameter: more circular image path, slower image movement.



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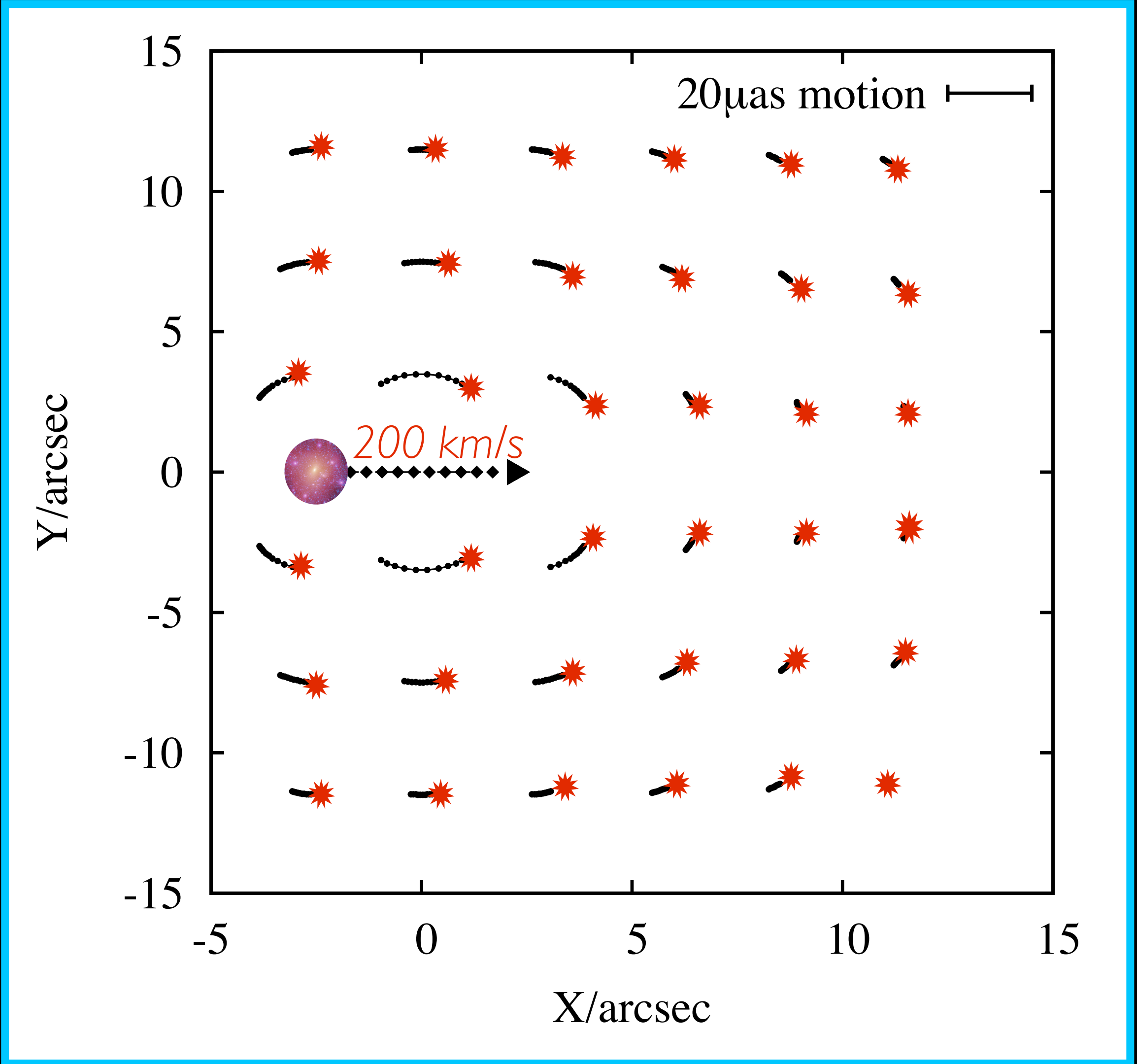
Star field over 4 years



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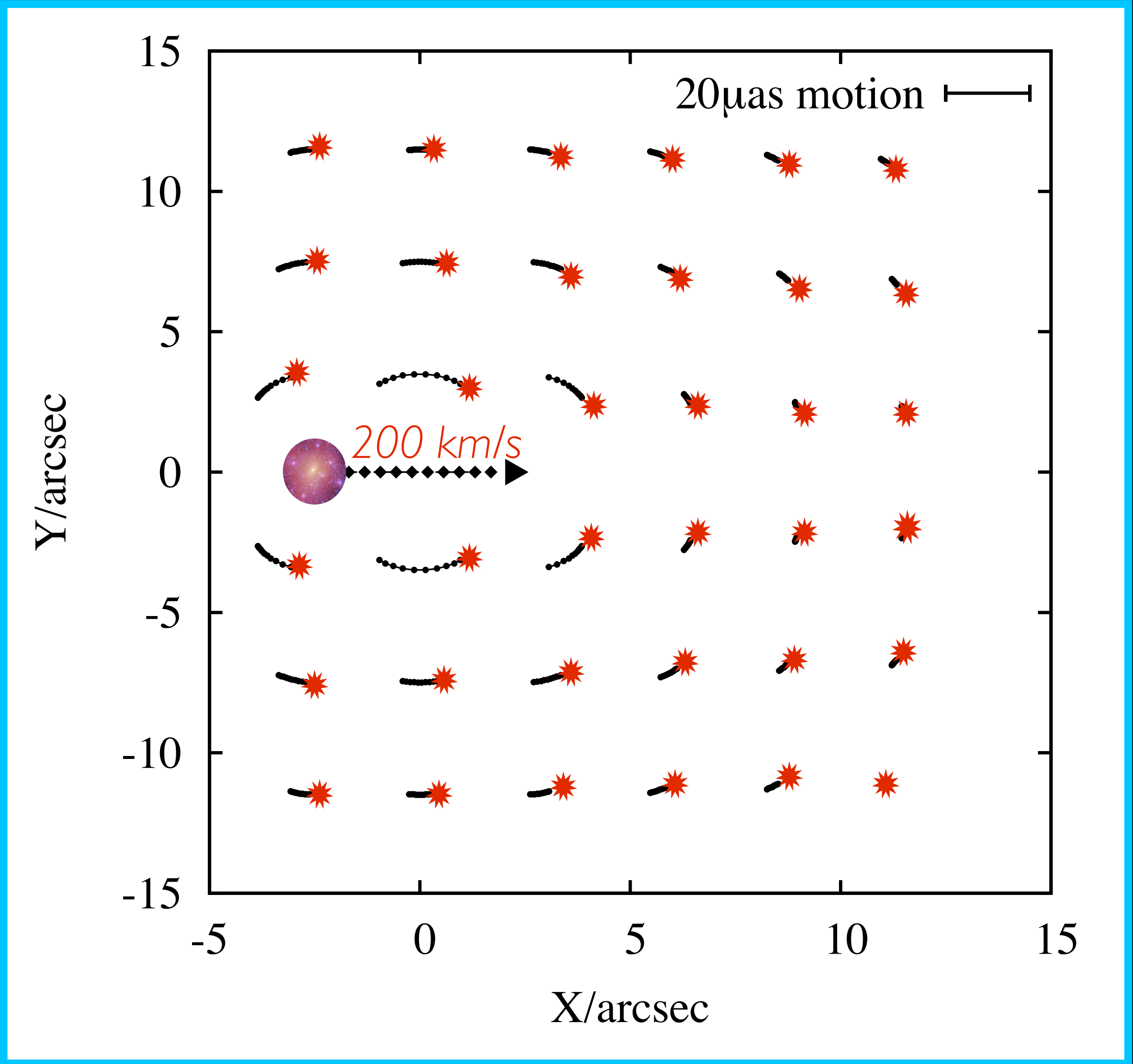

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Lens distance: 50 pc

We need a (projected) close encounter between the star and the subhalo center.

- the subhalo center must pass within 0.03 pc of the star
- at these small impact parameters, only the innermost region of the subhalo affects the lensing
- we only need to know the density profile within 0.1 pc of the subhalo center
- the truncation of the subhalo is not important; only the mass enclosed in the inner 0.1 pc matters

Subhalo Density Profiles

Unfortunately, even the best simulations can only probe the density profiles of the largest subhalos ($M_{\rm sub} \gtrsim 10^8 M_\odot$), and the inner 350 pc are unresolved.

- Via Lactea II: $\rho(r) \propto r^{-(\gamma \simeq 1.24)}$ for large subhalos. *Diemand et al. 2008*
- Aquarius: $\rho(r) \propto r^{-(\gamma < 1.7)}$ for large subhalos. *Springel et al. 2008*
- Simulations of first halos: Earth-mass halos at a redshift of 26 have $\rho(r) \propto r^{-(1.5 < \gamma < 2.0)}$ extending to within 20 AU of the center. *Diemand et al. 2005; Ishiyama et al. 2010*

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We'll assume a "generalized NFW profile:"

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_0}\right)^{\gamma}\left(1 + \frac{r}{r_0}\right)^{3-\gamma}}$$

r_0 is set by the concentration

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$r \ll r_0$	$r \gg r_0$
$\rho(r) \propto r^{-\gamma}$	$\rho(r) \propto r^{-3}$
$\alpha \propto r^{2-\gamma}$	$\alpha \propto r^{-1}$
deflection angle	*deflection angle*

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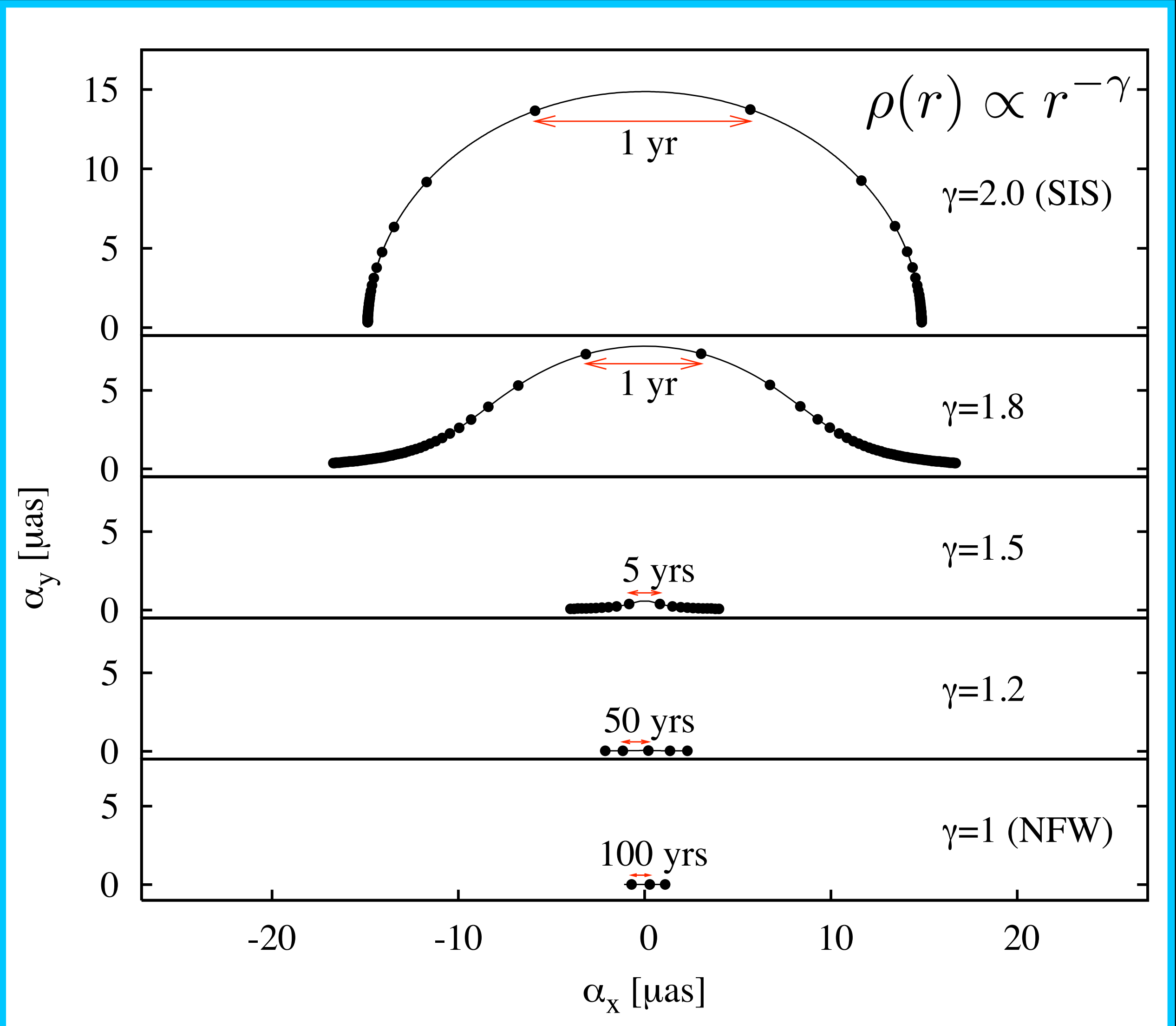
We'll assume a "generalized NFW profile:"

For $\gamma < 2$, the deflection angle decreases as the star approaches the subhalo center!

$r \ll r_0$	$r \gg r_0$
$\rho(r) \propto r^{-\gamma}$	$\rho(r) \propto r^{-3}$
$\alpha \propto r^{2-\gamma}$ deflection angle	$\alpha \propto r^{-1}$ deflection angle

Lensing with a General Profile



The steepness of the density profile determines the shape of the image's path across the sky.

- Steeper profiles give more vertical deflection as the subhalo passes under the star.
- Steeper profiles give more rapid image motion.

Lens virial mass: $5 \times 10^5 M_\odot$
Concentration: $R_{\rm vir}/r_{-2} = 99$
Impact parameter: 1 arcsecond

Lens path: 200 km/s

Lens distance: 50 pc

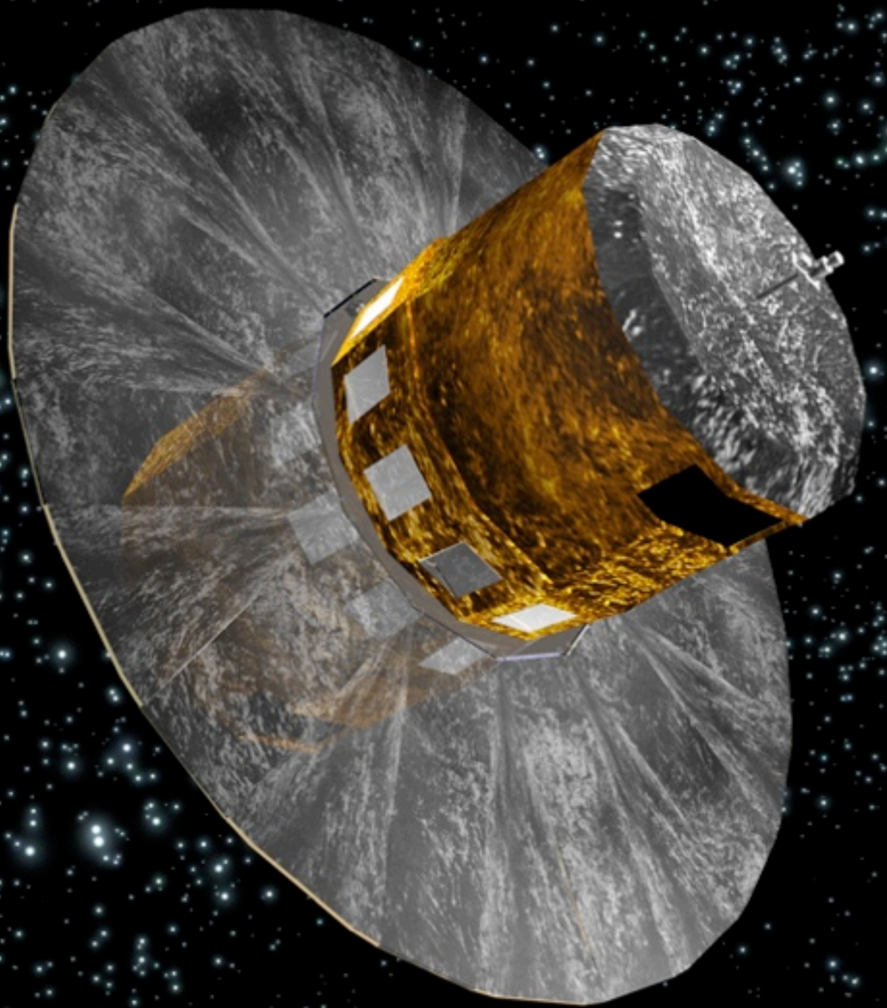
Lensing with a $\rho(r) \propto r^{-1.5}$ Profile

Can we detect microarcsecond astrometric changes?

High-Precision Astrometry: Gaia

Gaia is an ESO satellite scheduled to launch in Nov. 2012

- designed for all-sky astrometry
- broad search for astrometric variability
- two 1m-class telescopes imaging onto same detectors
- astrometric precision per epoch: ~35 ***micro***arcseconds for its brightest targets
- covers ~5,000,000 stars at this precision
- 83 epochs on average



High Precision Astrometry: SIM

SIM PlanetQuest was the top space mission recommended by NASA's Exoplanet Task Force.

- designed to find Earth-mass planets
- 6m-baseline interferometer
- astrometric precision per epoch:
  - 1 ***micro**arcsecond* for planet-finding
  - 4 ***micro**arcseconds* for general high-efficiency astrometry
- capable of observing faint stars
- targeted mission with adjustable number of visits per star

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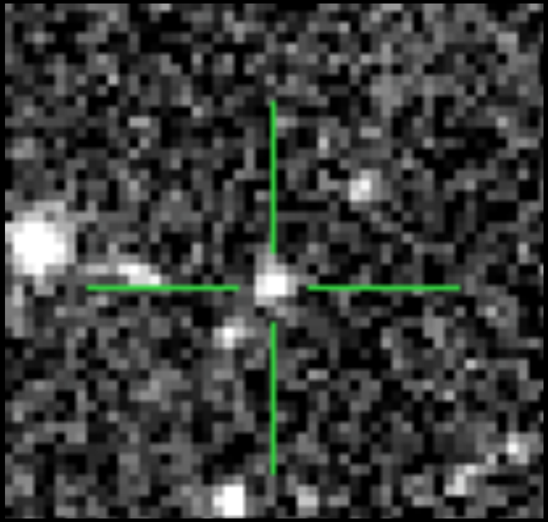
Astrometry from the Ground

Without SIM, our best hope is to detect astrometric microlensing from the ground. It'll be difficult, but techniques are being developed to make it possible!

The statistical error:

$$\sigma_x \propto \frac{\mathrm{FWHM}}{\mathrm{SNR}}$$

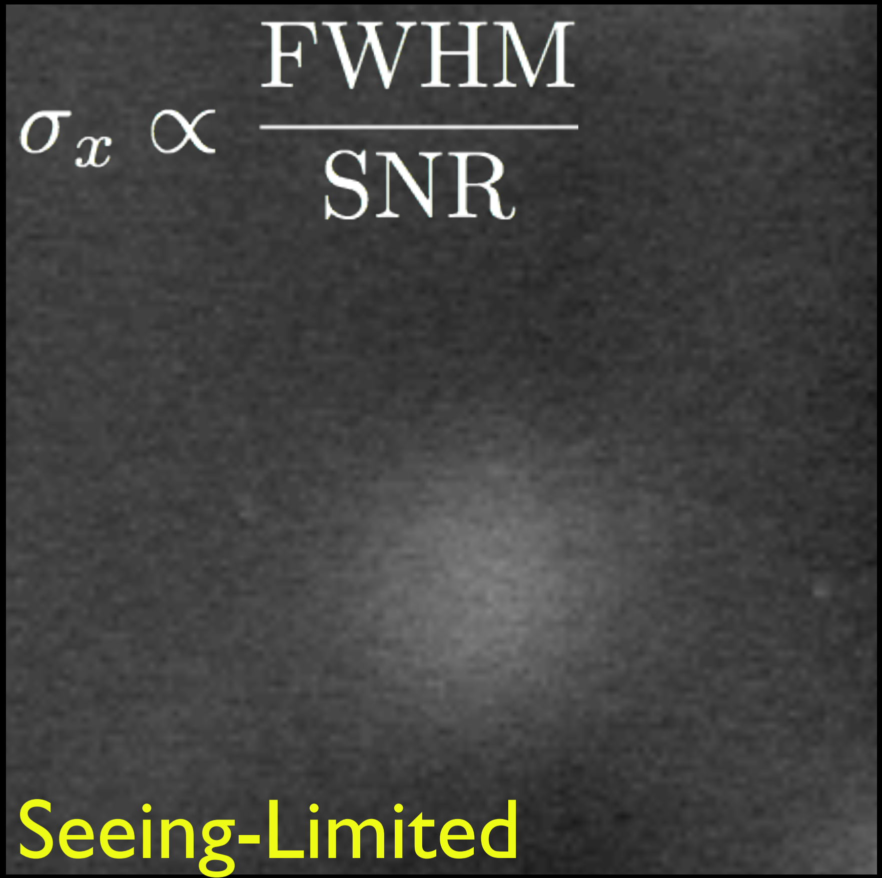


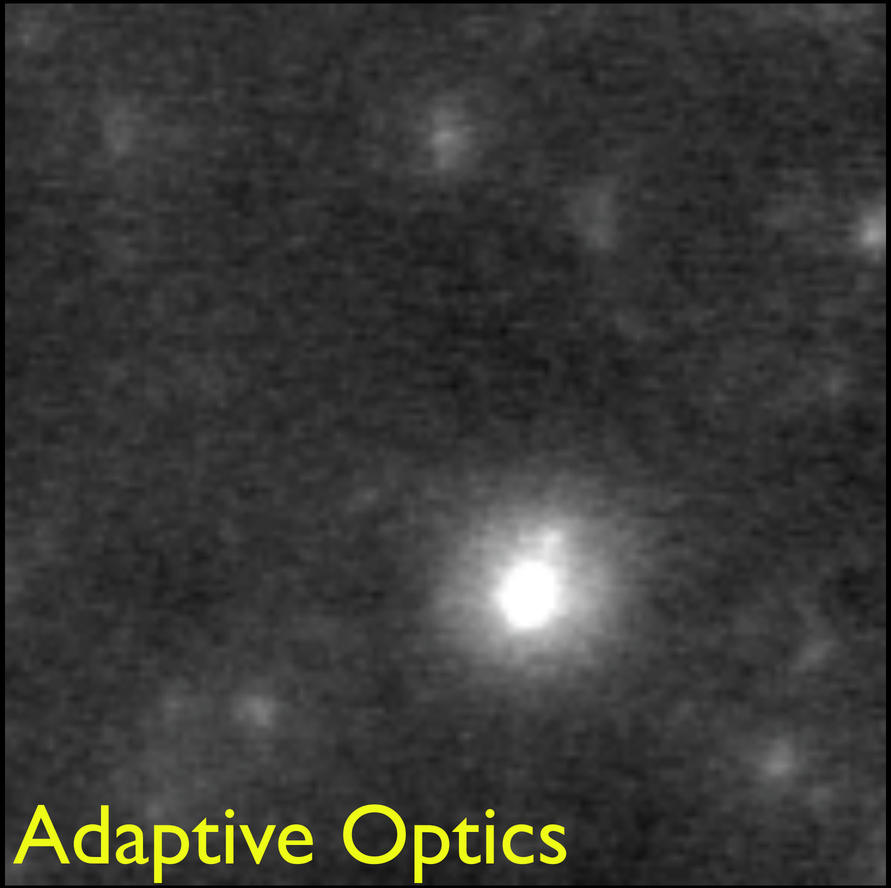
The systematic challenges:

- Focal plane distortion; characterize using crowded fields
- Atmospheric refraction; work in narrow bands in the near IR
- Changes in the instrument; guard your telescope
- Atmospheric turbulence; use adaptive optics, and be clever

Astrometry with Adaptive Optics

$$\sigma_x \propto \frac{\mathrm{FWHM}}{\mathrm{SNR}}$$



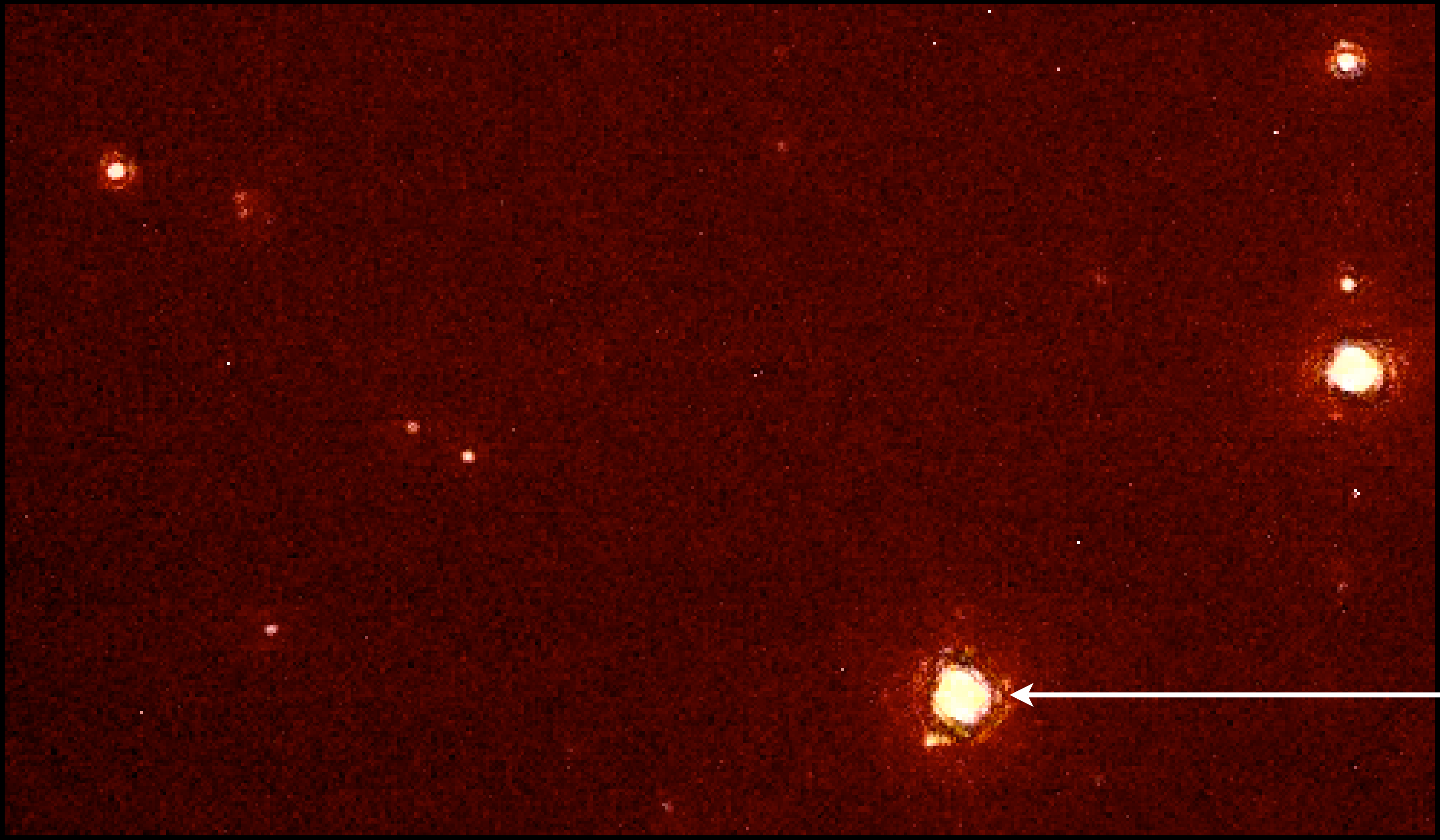


Adaptive optics makes astrometry much easier:

- reduces FWHM
- enhances SNR by concentrating photons relative to background
- provides more reference stars

Astrometry with Adaptive Optics

Unfortunately, adaptive optics has its limits.



- AO makes corrections based on the light from a guide star (or laser).
- Other stars are seen though different turbulence.
- The result: random (but correlated) motion between stars.

Optimizing AO Astrometric Precision

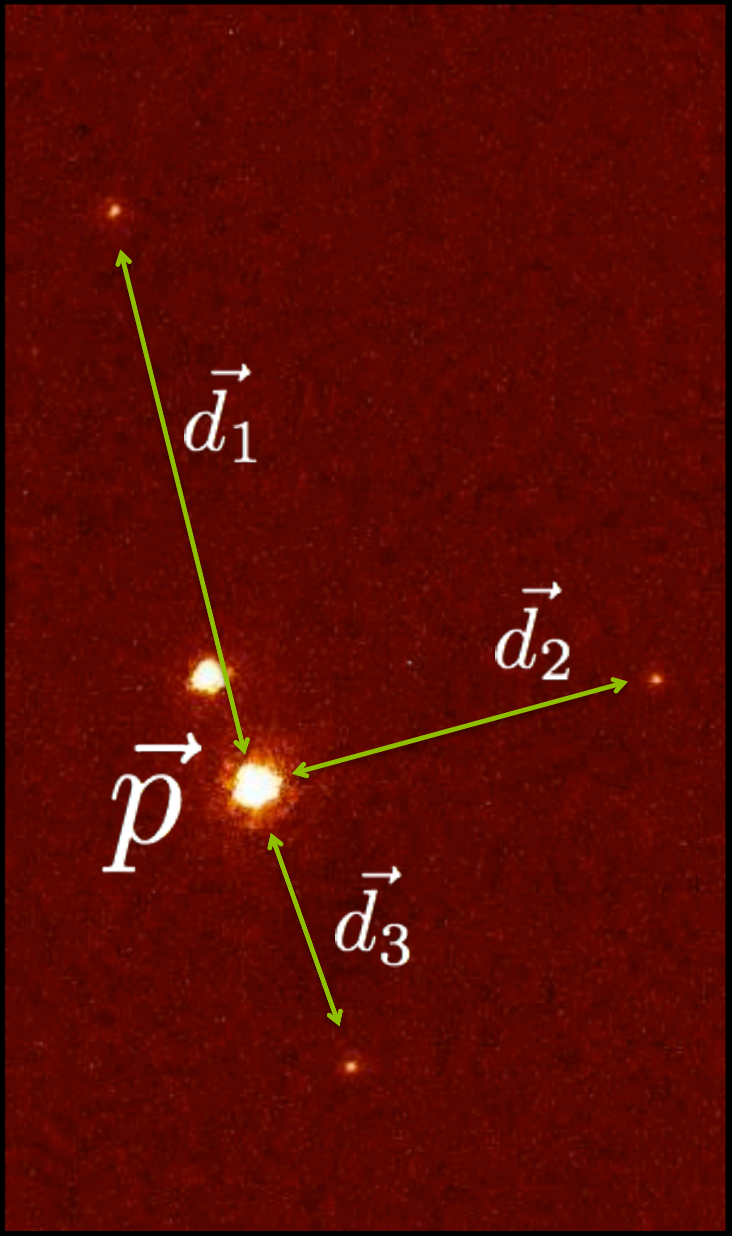
The correlations between the residual stellar jitters can be used to minimize their impact on astrometric measurements!

Cameron, Britton and Kulkarni (2009)

1) Make a vector from the target star to each reference star.

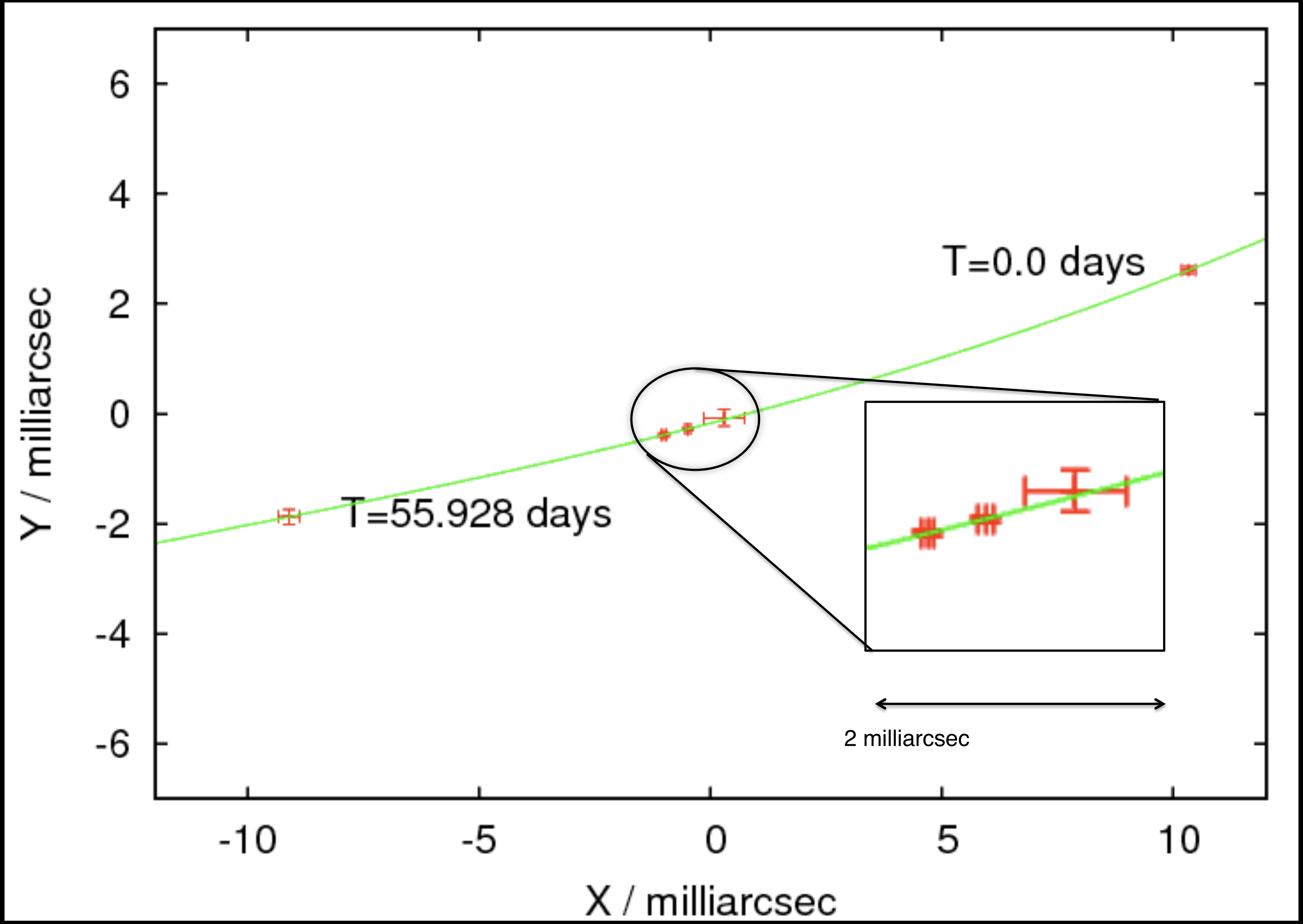
2) Apply weights to each vector to sum to the target position: $\vec{p} = \mathbf{W}\tilde{\mathbf{d}}$

3) Optimize the weights to minimize the covariance matrix for the target star's position: $\Sigma_{\vec{p}} = \mathbf{W}^{\mathrm{T}}\Sigma_{\vec{\mathbf{d}}}\mathbf{W}$



High Precision Astrometry!

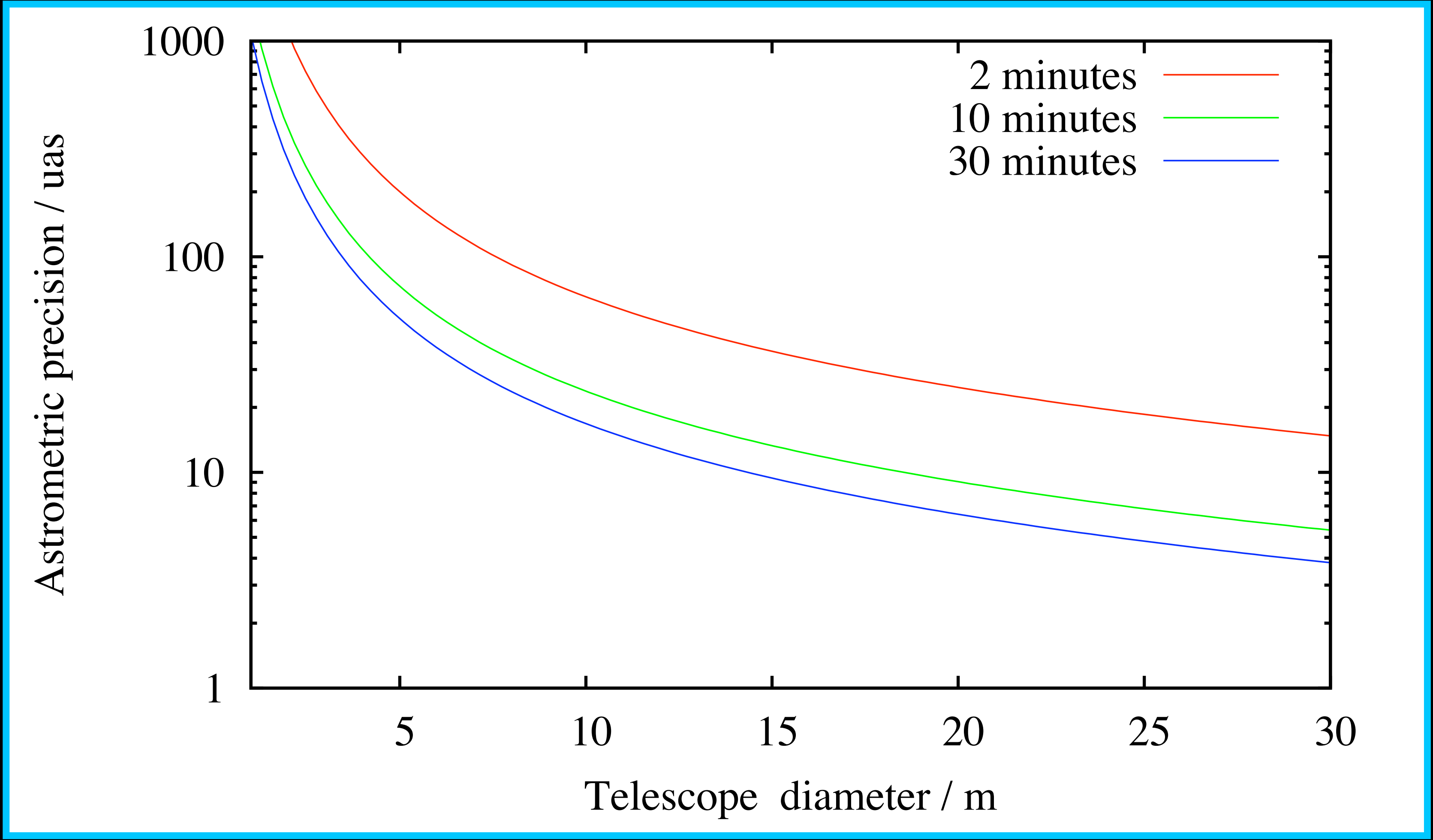
Observing the Proper Motion of an M-dwarf



Data taken on the Palomar 200-inch telescope

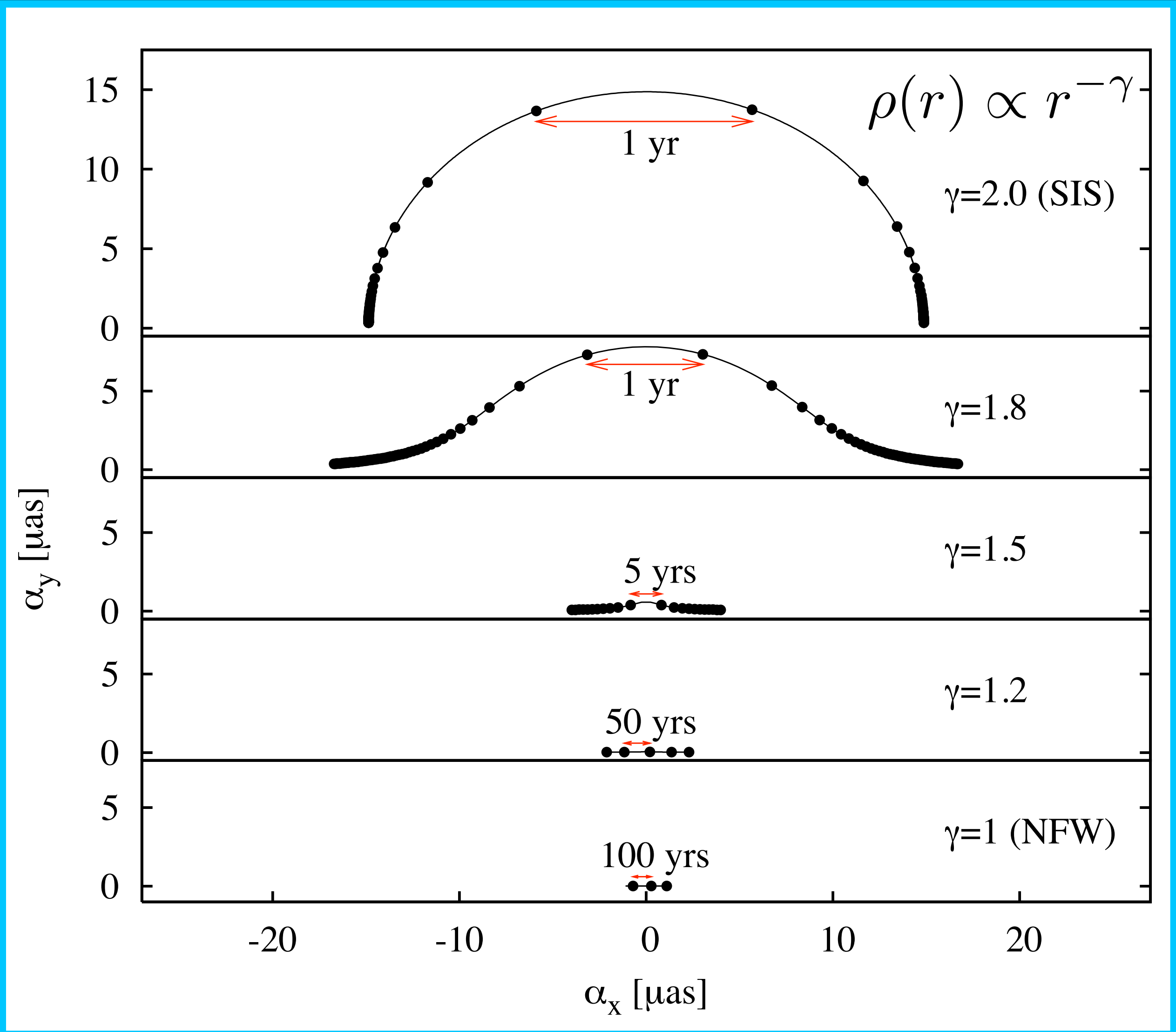
Give me a bigger telescope...

Statistical Astrometric Precision with Large Telescopes



Systematic errors currently limit Keck to ~100uas precision, but efforts are ongoing...

Our Detection Strategy



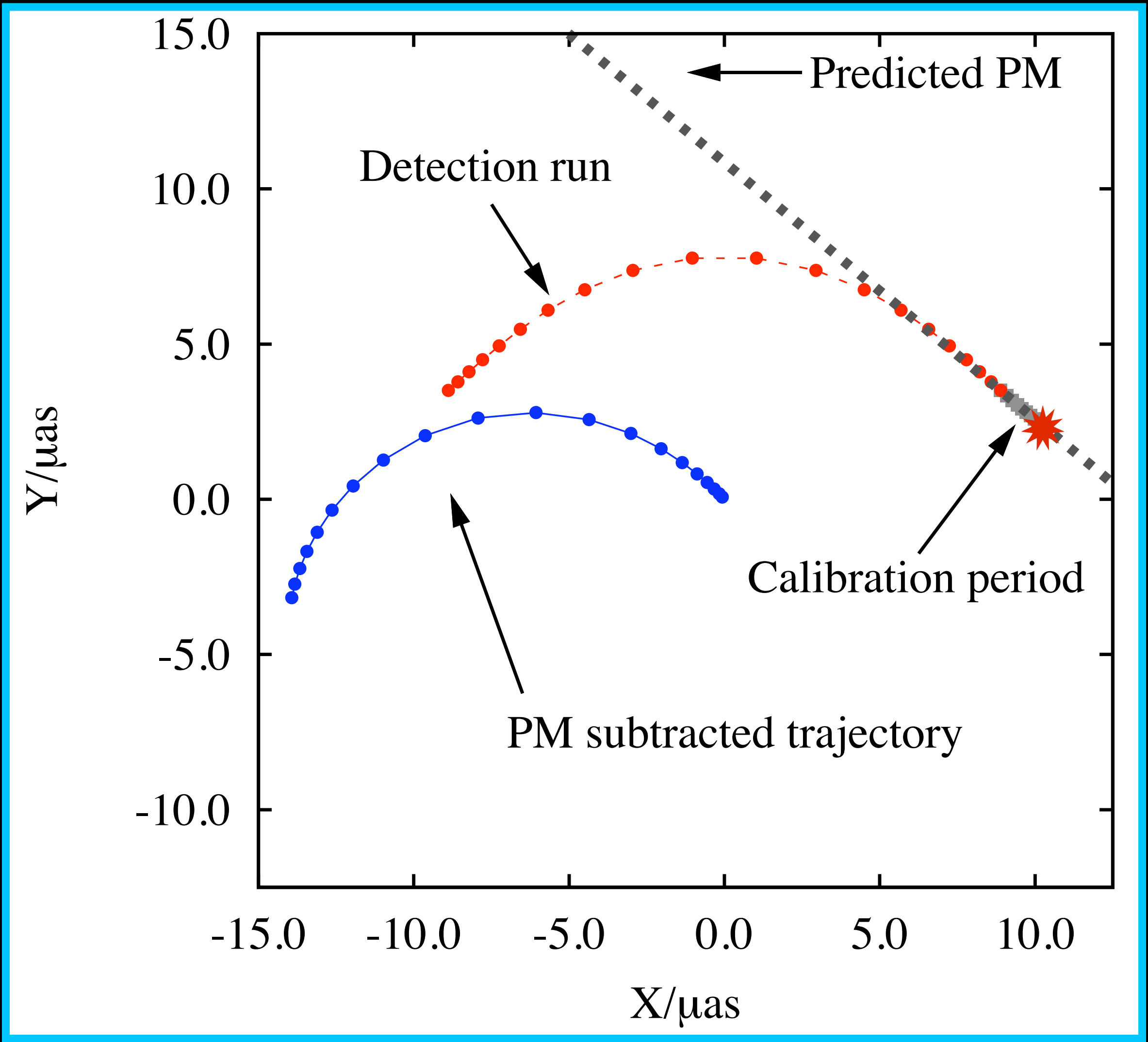
The typical subhalo lensing event has three stages:

1. The image barely moves when the subhalo center is approaching.
2. The image rapidly shifts position as the subhalo center passes by.
3. The image is nearly fixed at its new position as the subhalo center moves away.

This image motion is easily distinguished from lensing by a point mass; point masses give closed image trajectories.

Our Detection Strategy

To detect this image motion, we propose a simple strategy:



1. Observe stars for a calibration period (2 years).
2. Reject stars that accelerate during the calibration period (including binaries).
3. Measure each star's proper motion and parallax, and predict its future trajectory.
4. Observe the star during the detection run (4 years).
5. Measure deviations from the predicted trajectory.

Star's true position is at the origin.

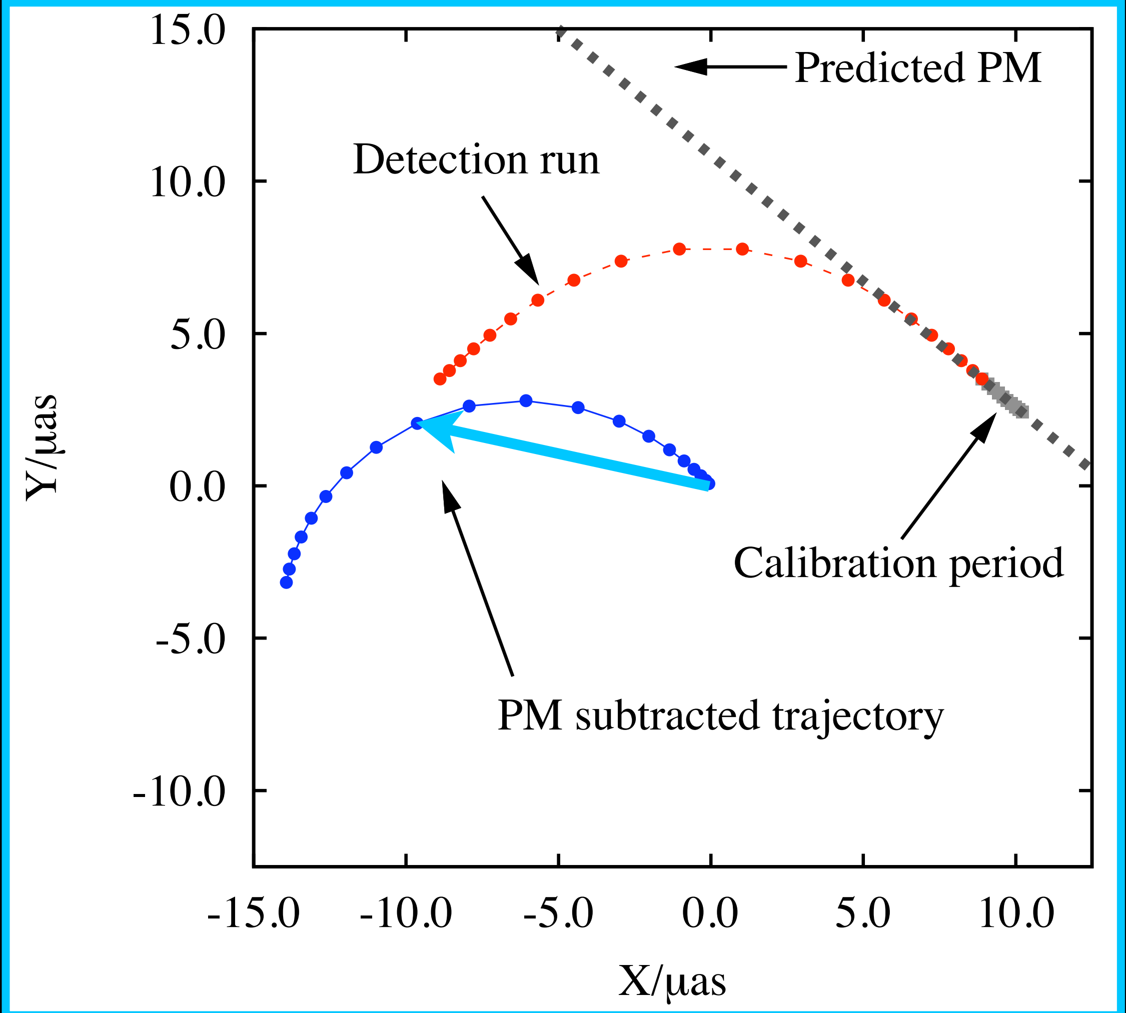
Subhalo center passes star two years into the detection run.

The Astrometric Signal for Lensing

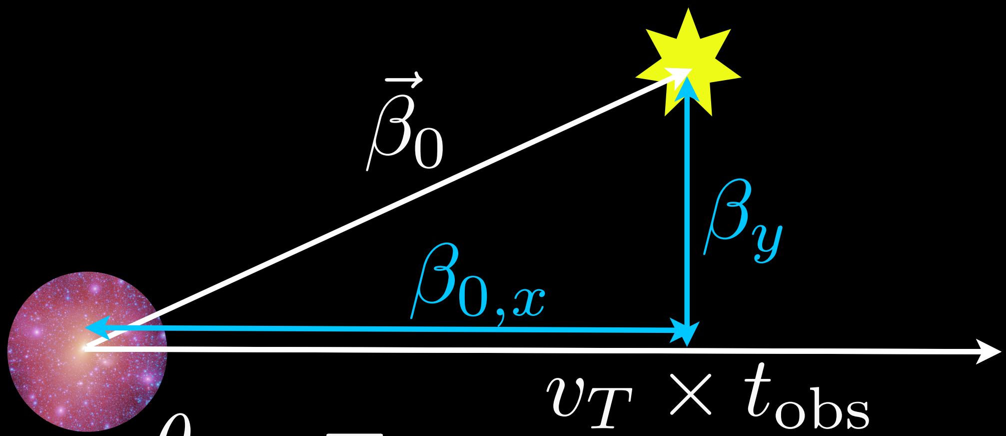
$$S = \sqrt{\sum_{i=1}^{N_{\mathrm{epochs}}} (Xm_i - Xp_i)^2 + (Ym_i - Yp_i)^2}$$

Lensing Signal (S) — *Magnitude squared of trajectory residuals* (the sum)

- The signal *S* measures the total displacement of the star from its expected position.
- SNR is *S* divided by the astrometric uncertainty per 1D datapoint (including both the intrinsic uncertainty and the uncertainty in the star's predicted position).
- S depends linearly on the deflection angle.



Calculating the Lensing Signal



$$\theta_{\rm sub} \equiv \frac{v_T \times t_{\rm obs}}{\text{distance to lens}}$$

To evaluate the lensing signal, we want to separate the lensing geometry from the characteristics of the lens.

Geometric Coordinates:

"phase"

$$\varphi \equiv \frac{\beta_{x,0}}{\theta_{\rm sub}}$$

impact parameter

$$\tilde{\beta} \equiv \frac{\beta_y}{\theta_{\rm sub}}$$

Factorize the Deflection Angle:

$$\vec{\alpha}(t) \equiv \mathcal{F}(\gamma, M_{\rm vir}, c, v_T, d_{\rm L}, d_{\rm S}, t_{\rm obs}) \times \vec{\eta}(\gamma, \varphi, \tilde{\beta}, t/t_{\rm obs},)$$

depends on subhalo density profile, velocity, distances to lens and source, observation time

only depends on geometry and γ in $\rho(r) \propto r^{-\gamma}$

Calculating the Lensing Signal

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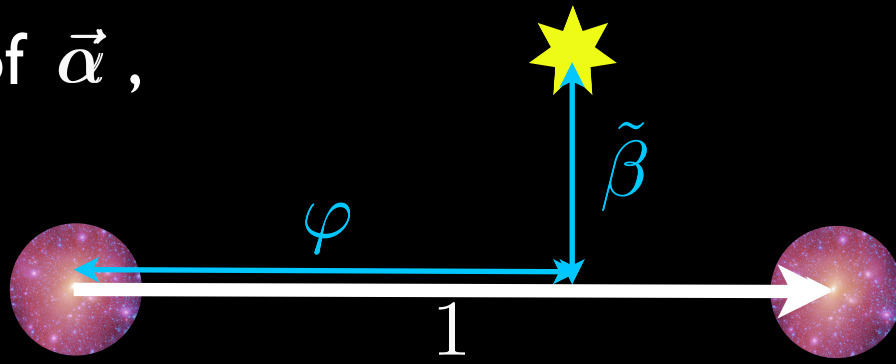
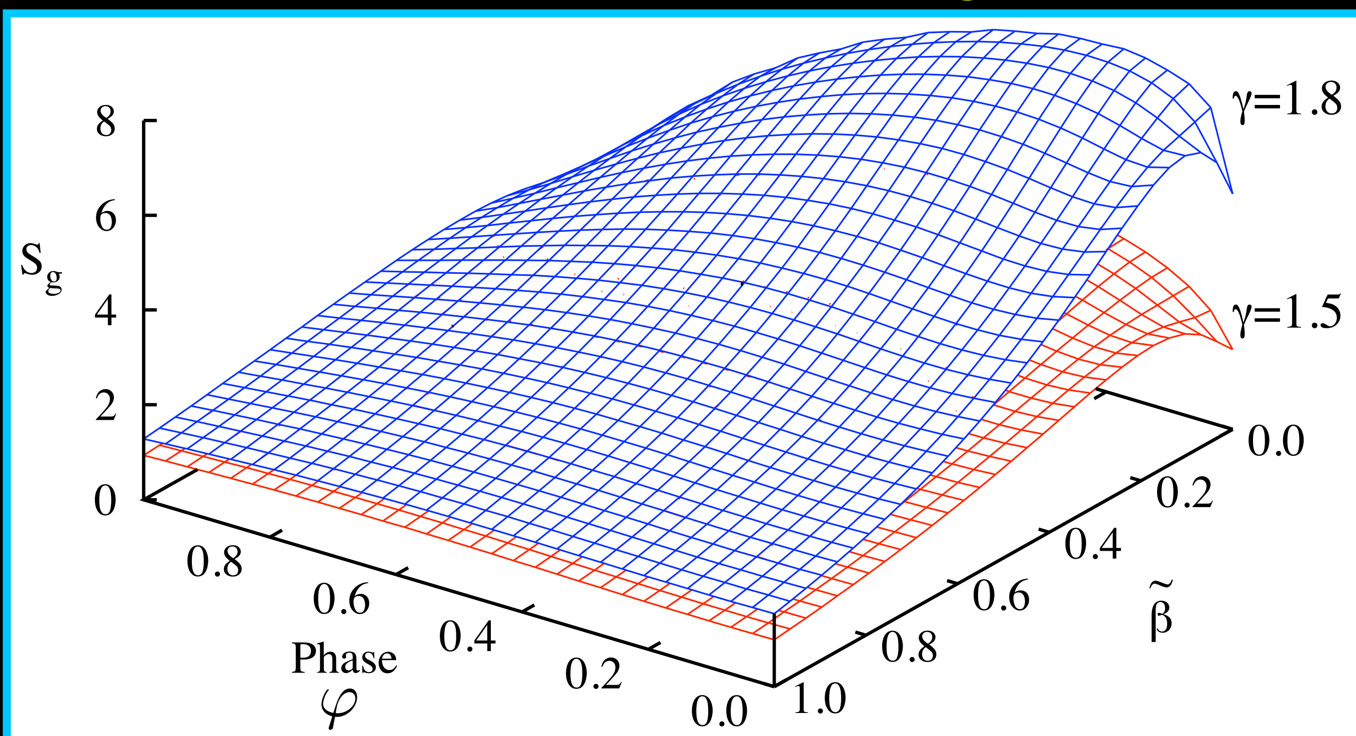
Calculate the signal using $\vec{\alpha}$ $\vec{\eta}$ instead of $\vec{\alpha}$, call this the "geometric signal" S_g.



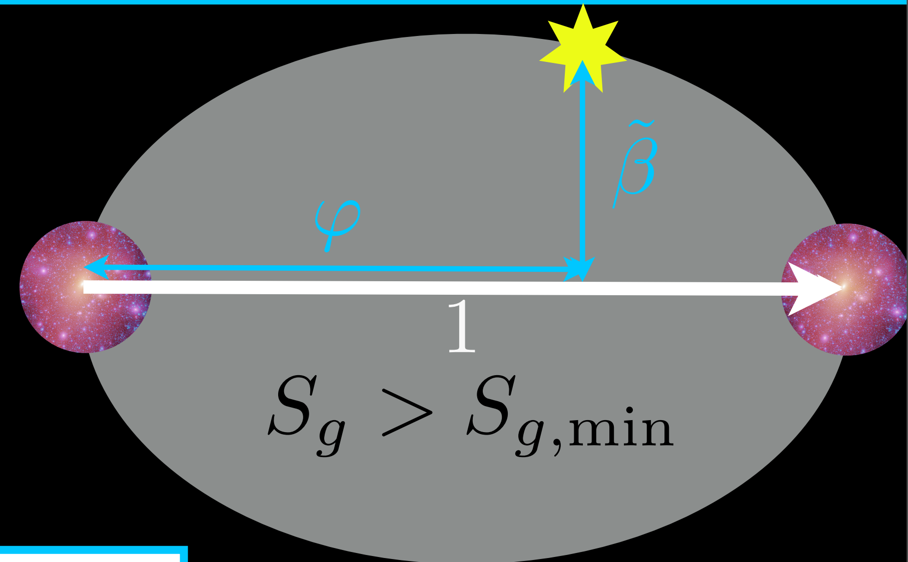
Since the signal depends linearly on the deflection angle, $S = \mathcal{F} \times S_g$.

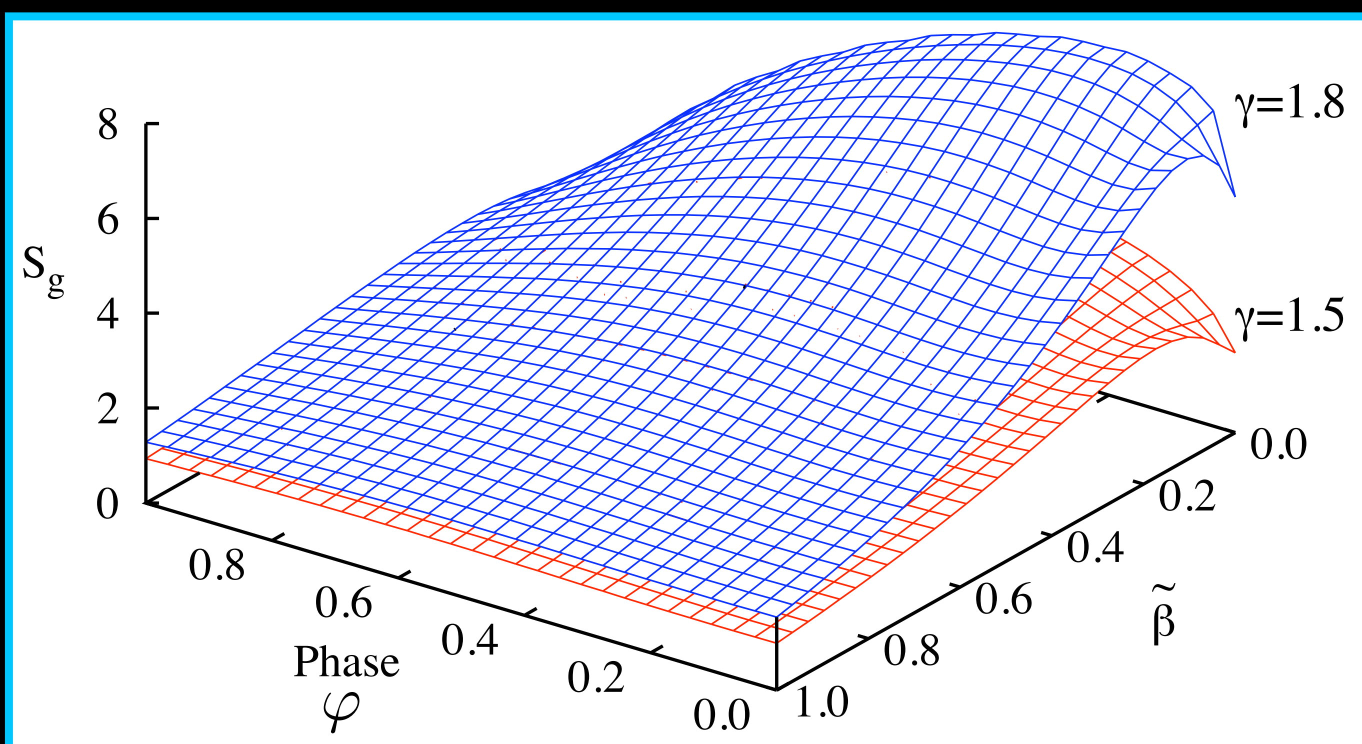


Two-year calibration run, four-year detection run.

Calculating Lensing Cross Sections

We define a **lensing cross-section** based on a minimum value for the lensing signal; all stars within this area will produce $S > S_{\min}$.





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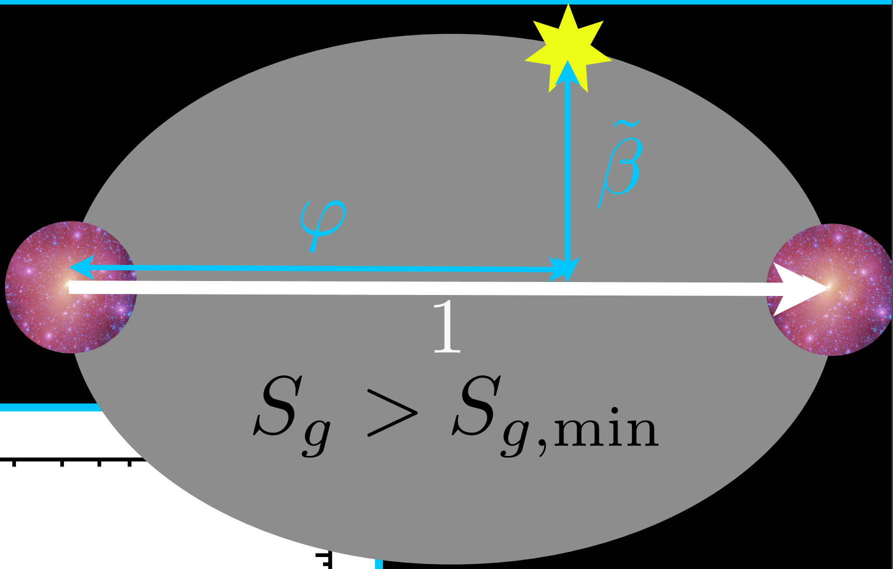

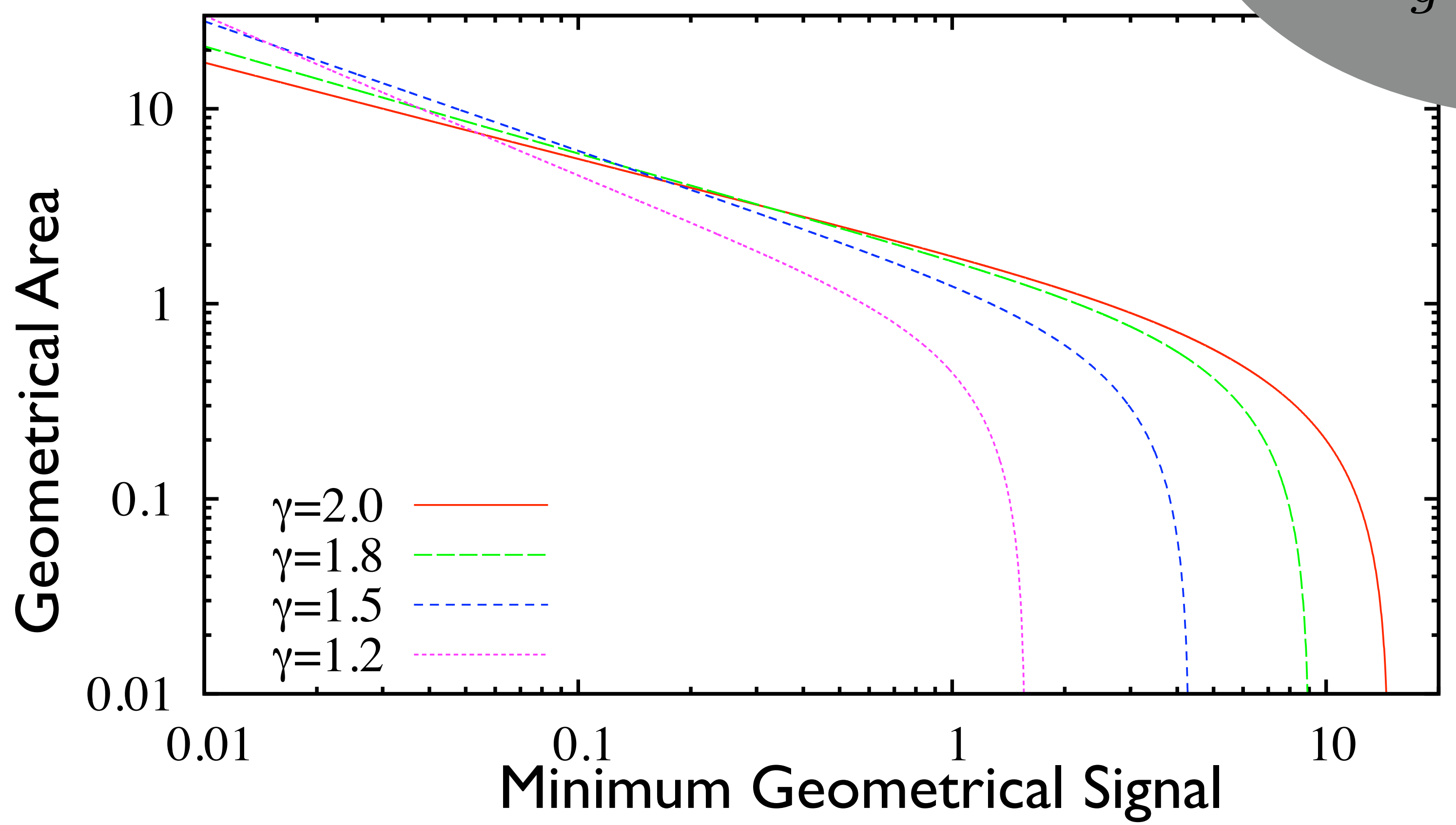

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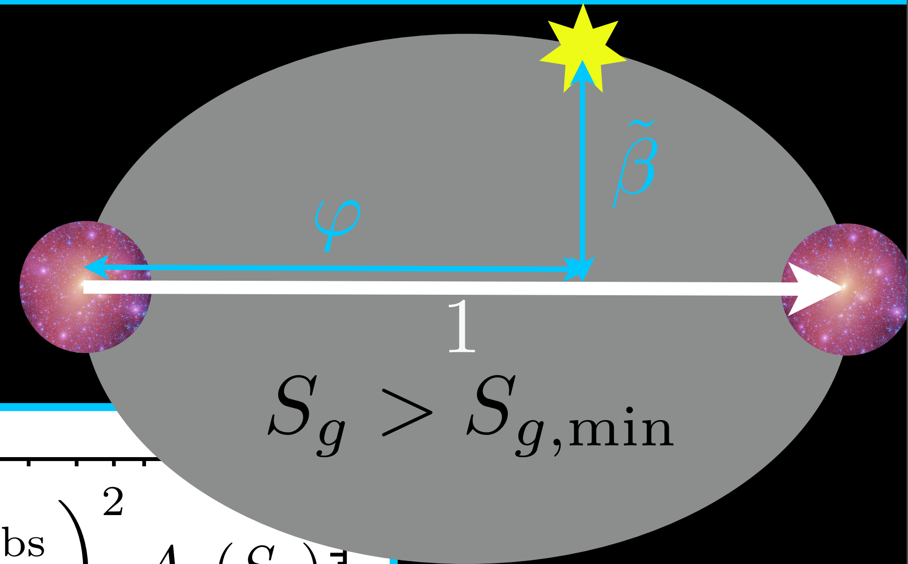
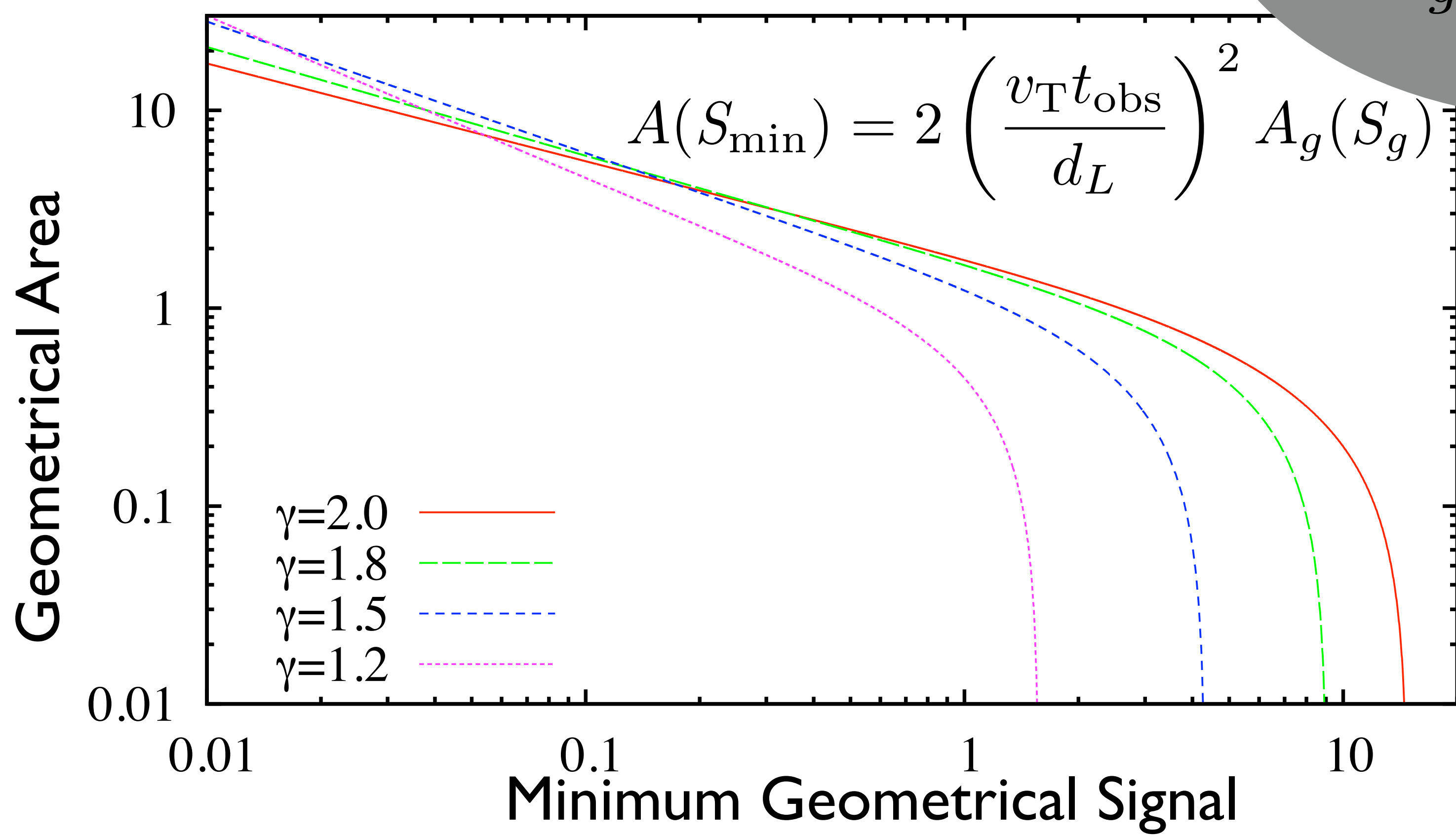
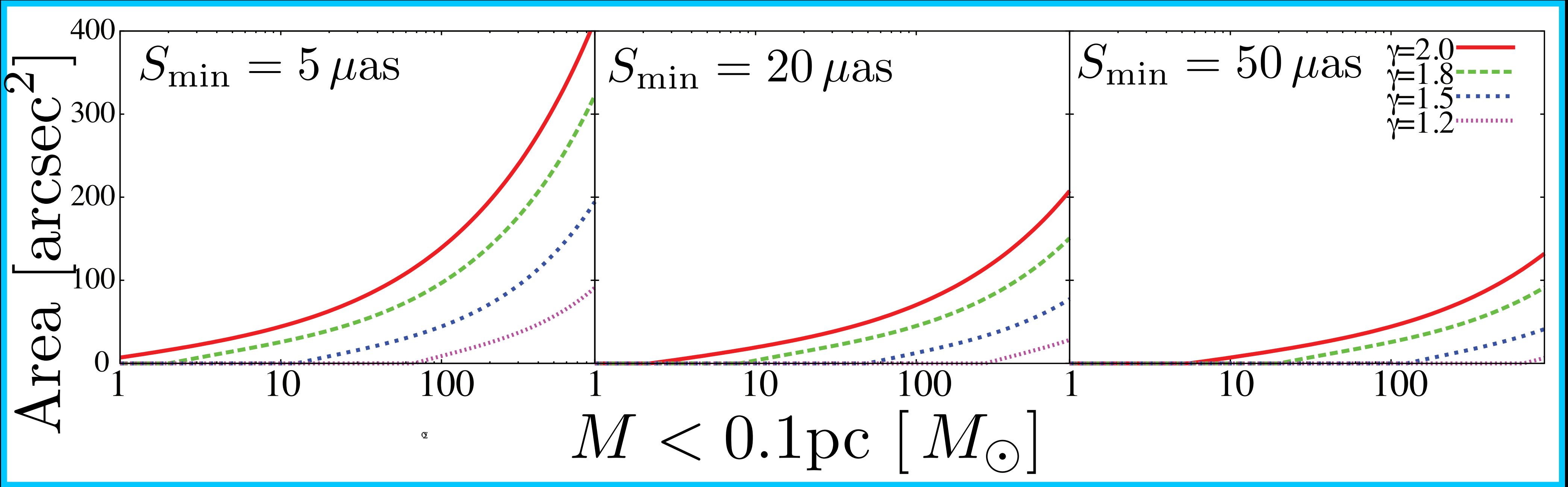




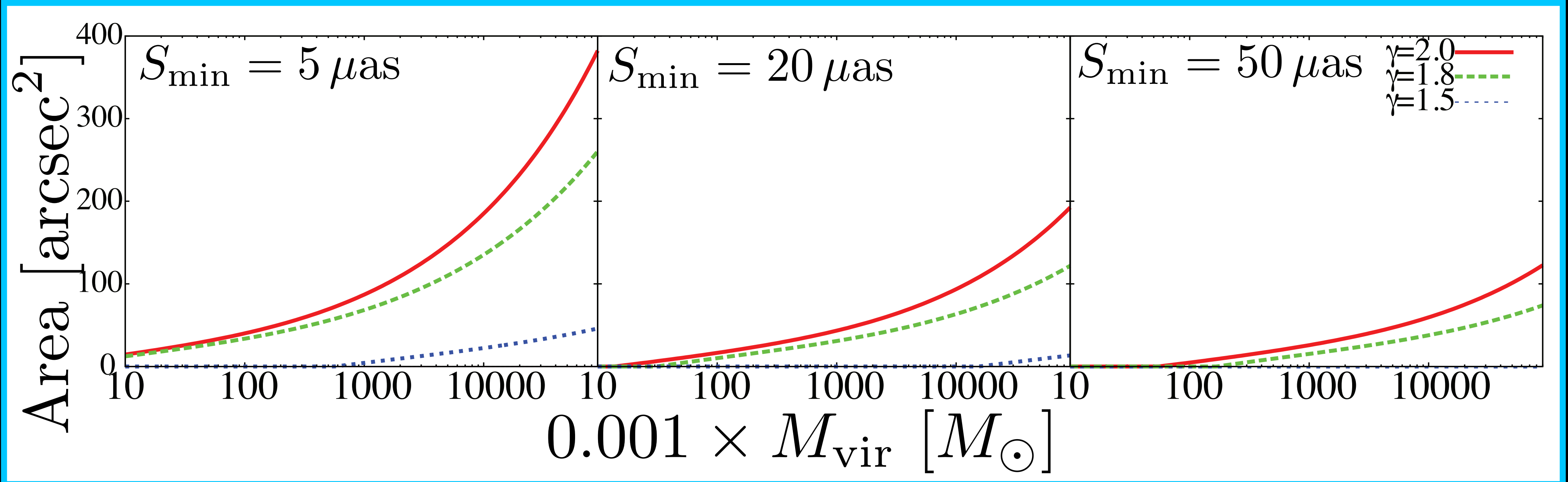
Lensing Cross Sections



Lens distance: 50 pc; Lens velocity: 200 km/s; Source Distance: 5 kpc

- The mass enclosed within 0.1 pc and the density profile completely determine the lensing cross section.
- For a given value for the minimum signal, there is a minimum subhalo mass that is capable of generating that signal.

Lensing Cross Sections



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- We assume that the subhalo loses 99.9% of its virial mass due to tidal stripping.
- We use a concentration-mass relation for subhalos derived from the findings of the Aquarius simulations.
- Steeper dependence on γ: for a given virial mass, subhalos with shallower density profiles have less mass within 0.1 pc.

Lensing Event Rates Calculation

We can combine the lensing cross sections with a subhalo mass function to calculate the fraction of the sky that is detectably lensed ($S > S_{\rm min}$) by a subhalo.

- We assume that all the source stars are a fixed distance away: $A_{\rm tot} \propto d_{\rm S}$
- We assume that the subhalos are isotropically distributed.
- We can interpret this sky fraction as the probability that a given star is detectably lensed.

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Three candidate subhalo mass functions:

- All subhalos have the same mass, and a fraction *f* of the halo mass is contained within 0.1 pc of a subhalo center.
- All subhalos had the same virial mass, and all the dark matter was once in these subhalos.
- We use a local subhalo mass function derived from the Aquarius simulations, with $\frac{{\rm d}N}{{\rm d}M_{\rm sub}} \propto M_{\rm sub}^{-1.9}$ and $M_{\rm sub} = 0.01 M_{\rm vir}$.

Mono-Mass Lensing Event Rates

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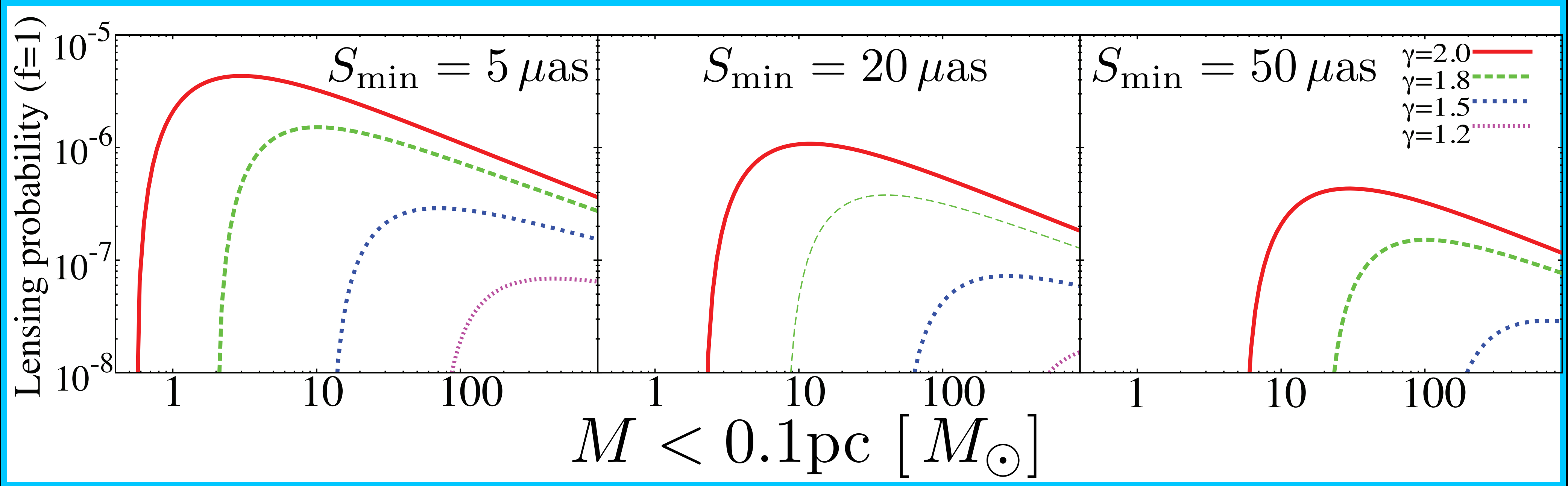
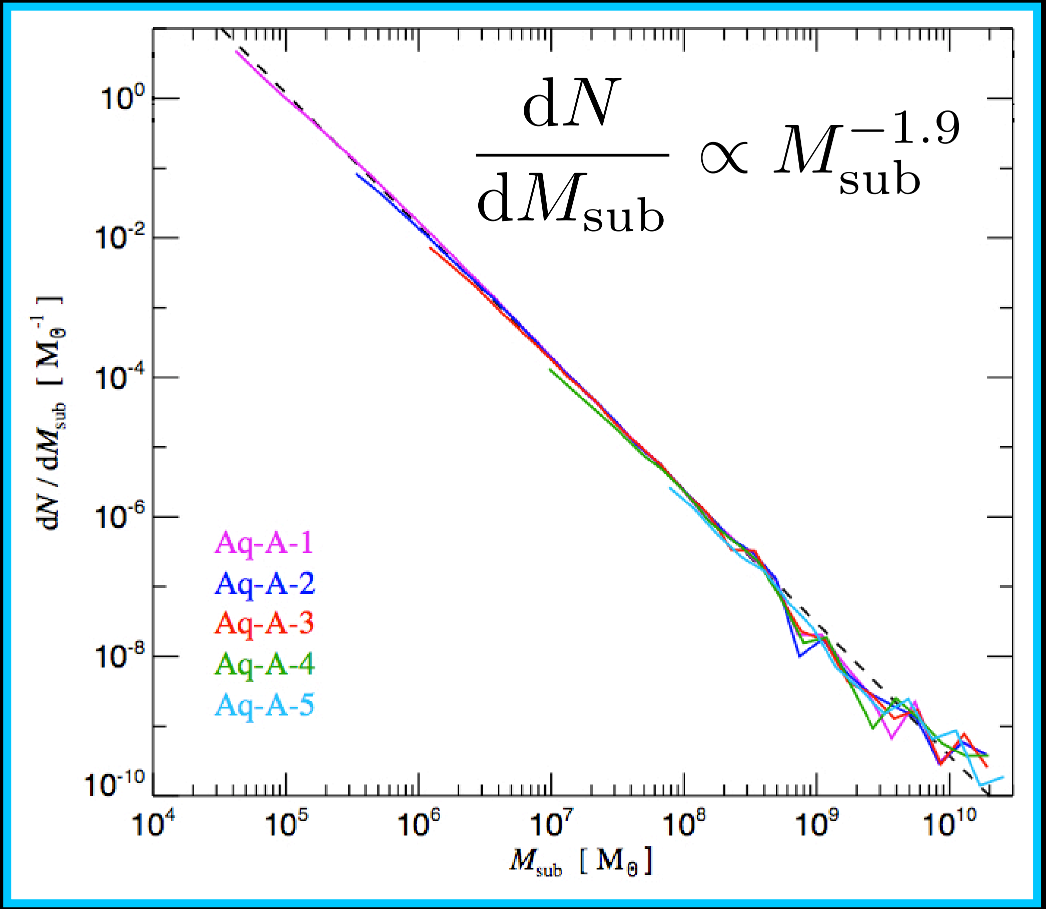


Lens velocity: 200 km/s; Source Distance: 2 kpc

- The number density of subhalos goes as $f \times M_{\rm sub}^{-1}$.
- The event rate peaks when the subhalos are just large enough to produce a sufficiently large lensing signal.
- Assuming that all dark matter was once in subhalos with the same viral mass is nearly the same as taking $f \simeq 10^{-4}$.

Event Rate from Aquarius



Springel et al. 2008

We derived a local subhalo mass function from the results of the Aquarius simulations.

- Aquarius gives a radial dependence for the number density of subhalos.
- We normalize our local mass function using Aquarius's subhalo mass function.
- $M_{\rm sub} = 0.01 M_{\rm vir}$

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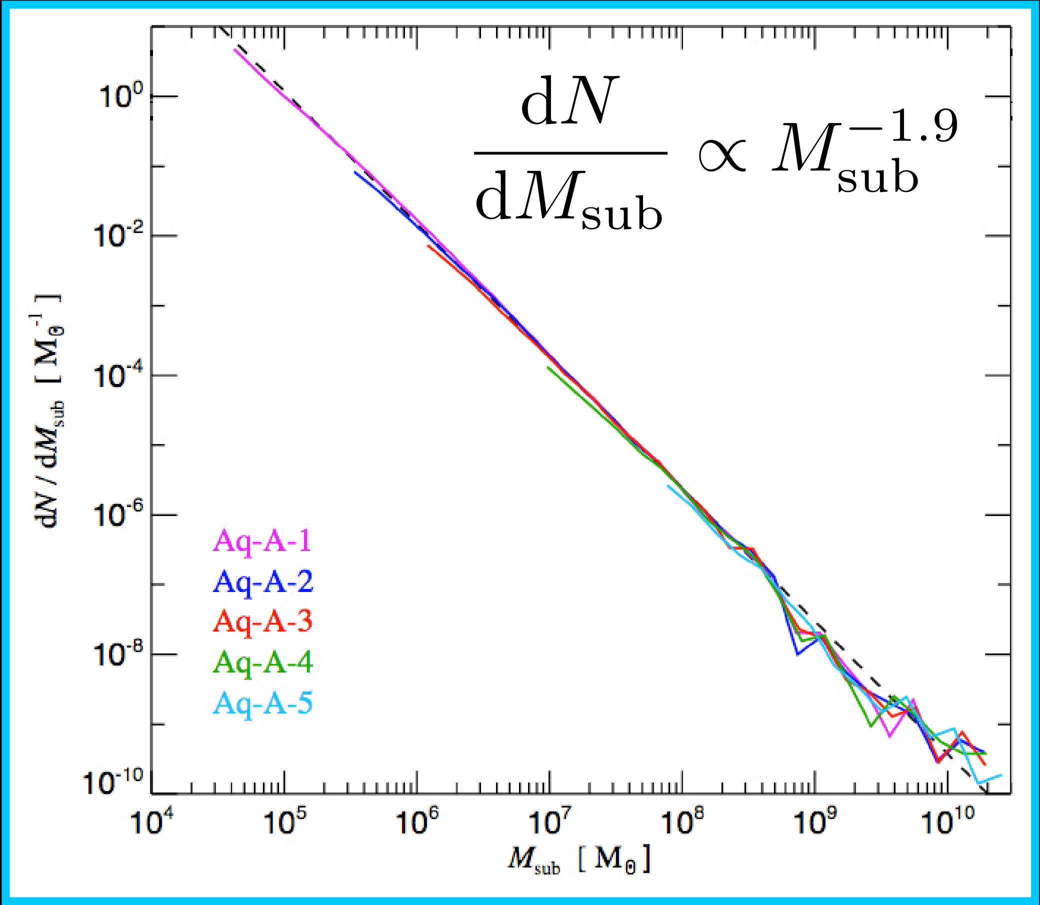

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$$\left.\frac{A_{\rm tot}}{A_{\rm sky}}\right|_{\gamma=1.8} = 8.7 \times 10^{-12} \left(\frac{S_{\rm min}}{5\,\mu{\rm as}}\right)^{-1.74} \quad \text{for } S_{\rm min} < 80\,\mu{\rm as},$$

$$\left.\frac{A_{\rm tot}}{A_{\rm sky}}\right|_{\gamma=2.0} = 1.3 \times 10^{-11} \left(\frac{S_{\rm min}}{5\,\mu{\rm as}}\right)^{-1.44} \quad \text{for } S_{\rm min} < 200\,\mu{\rm as}.$$

Detection Prospects: Full Sky

The minimum detectable signal depends on the instrument and the desired signal-to-noise ratio.

- SNR is the signal divided by the astrometric uncertainty per epoch.
- The total astrometric uncertainty includes the uncertainty in the predicted position of the star: $\sigma = 1.47\sigma_{\rm inst}$ for a 2 yr + 4 yr observation.
- The SNR should be sufficiently large to make false positives unlikely.

Instrument	$\sigma_{\rm inst}$	# Stars	SNR	$S_{\rm min}$

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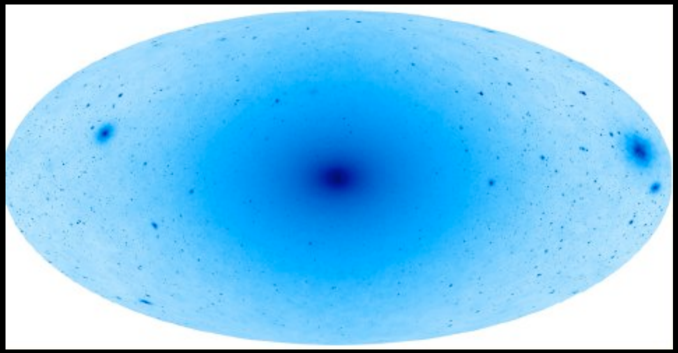
Subhalo Finder 2100	$0.5\,\mu$as	10^{11}	7	$5\,\mu$as

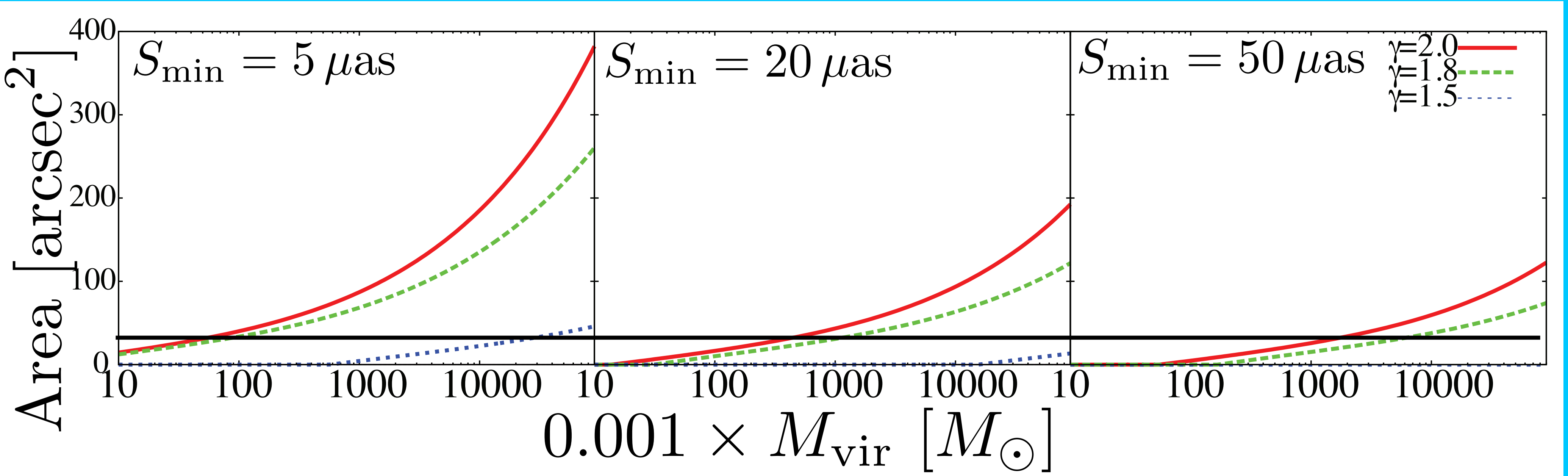
Detection with Targeted Observations

Finding a subhalo through astrometric microlensing is unlikely, but what if you know where to look?



Kuhlen et al. 2009

Fermi may detect emission from dark matter annihilation in subhalos and could localize the center of emission down to a few sq. arcminutes.



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Summary

Local subhalos deflect the light from background stars, producing a unique astrometric microlensing signature.

- only the innermost 0.1 pc of the subhalo can produce a signal
- the star's apparent motion depends on the subhalo density profile
- the image deflection is measured in microarcseconds -- we can do that!

We can find these events by observing stars, predicting their motions, and then waiting for deviations.

- we can calculate cross sections for lensing with a minimum signal
- with a subhalo mass function, we can predict event rates

To see a subhalo lensing event, we'd have to get lucky!

- nearly impossible to find a subhalo through lensing, unless subhalos are more numerous and/or more concentrated than expected
- if Fermi points the way, high-precision astrometry can follow; we can detect subhalos within 100 pc of us with (stripped) masses $\gtrsim 1000\, M_{\odot}$.