Detecting Local Dark Matter Subhalos with Stellar Astronomy

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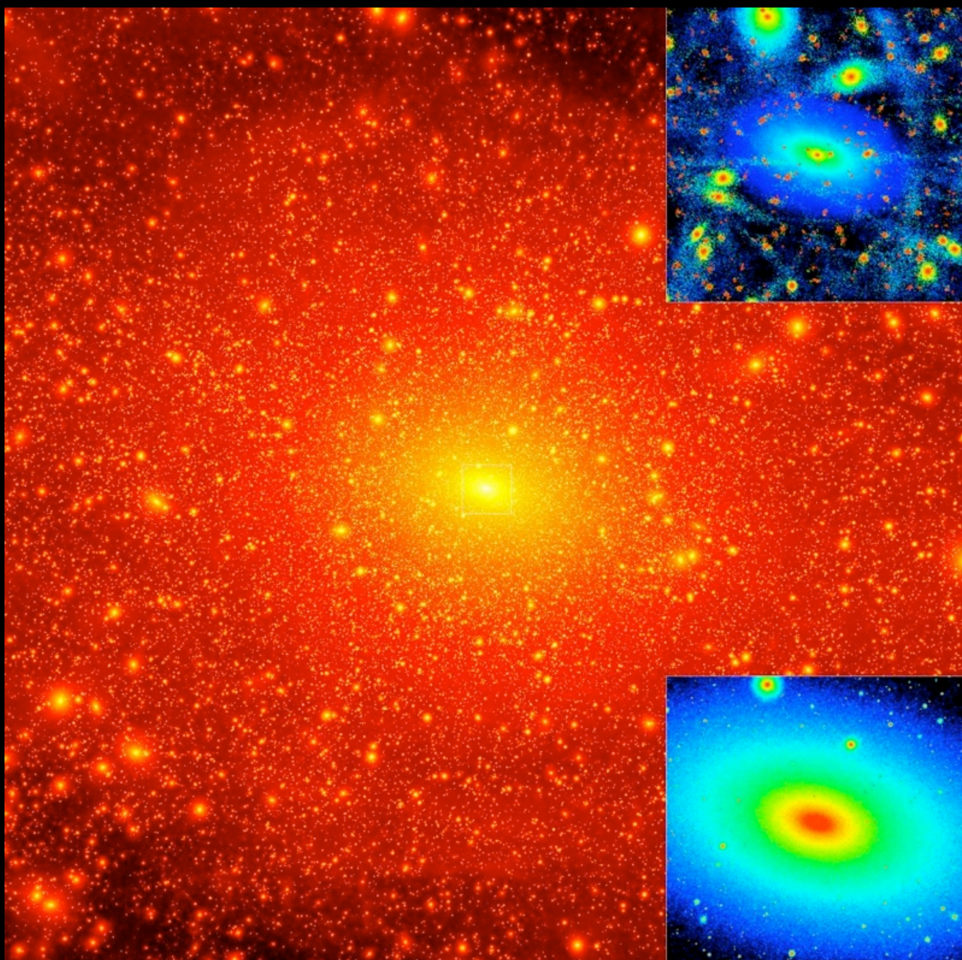
arXiv: 1007.4228
ApJ 729, 49 (2011)

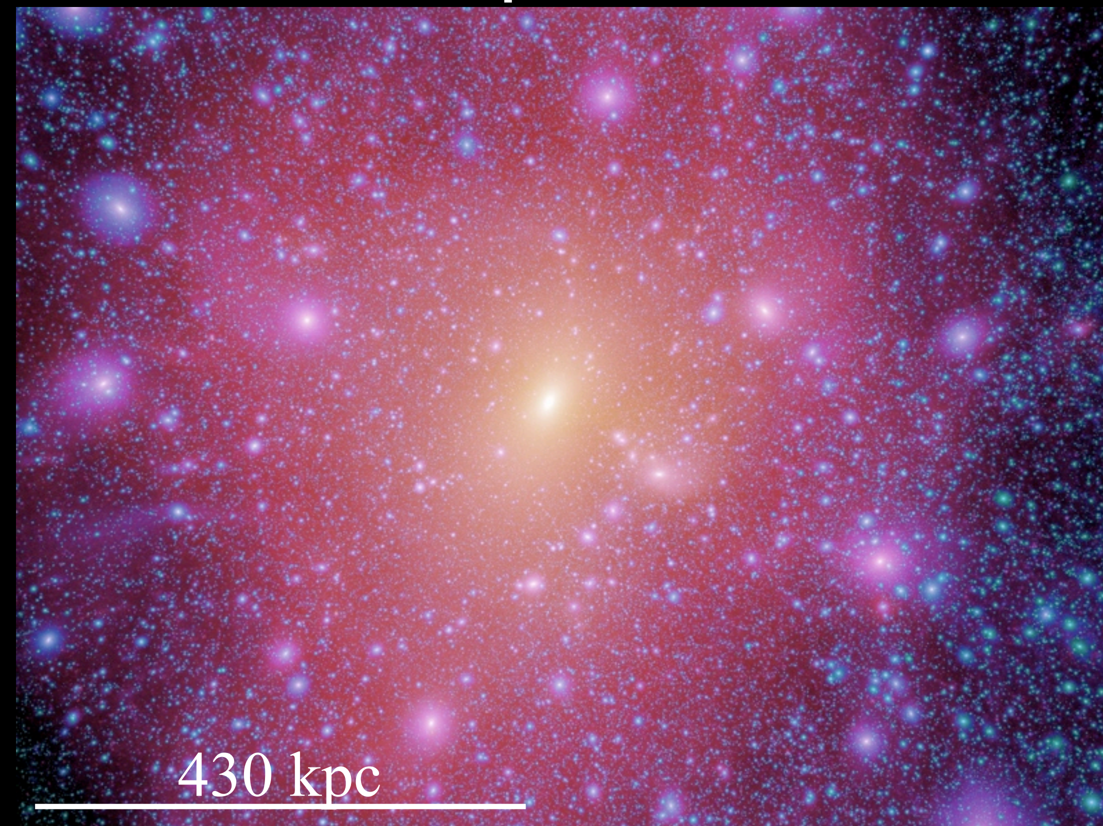
Dark Matter Halos are Clumpy!

Via Lactea II



Diemand et al. 2008

Aquarius

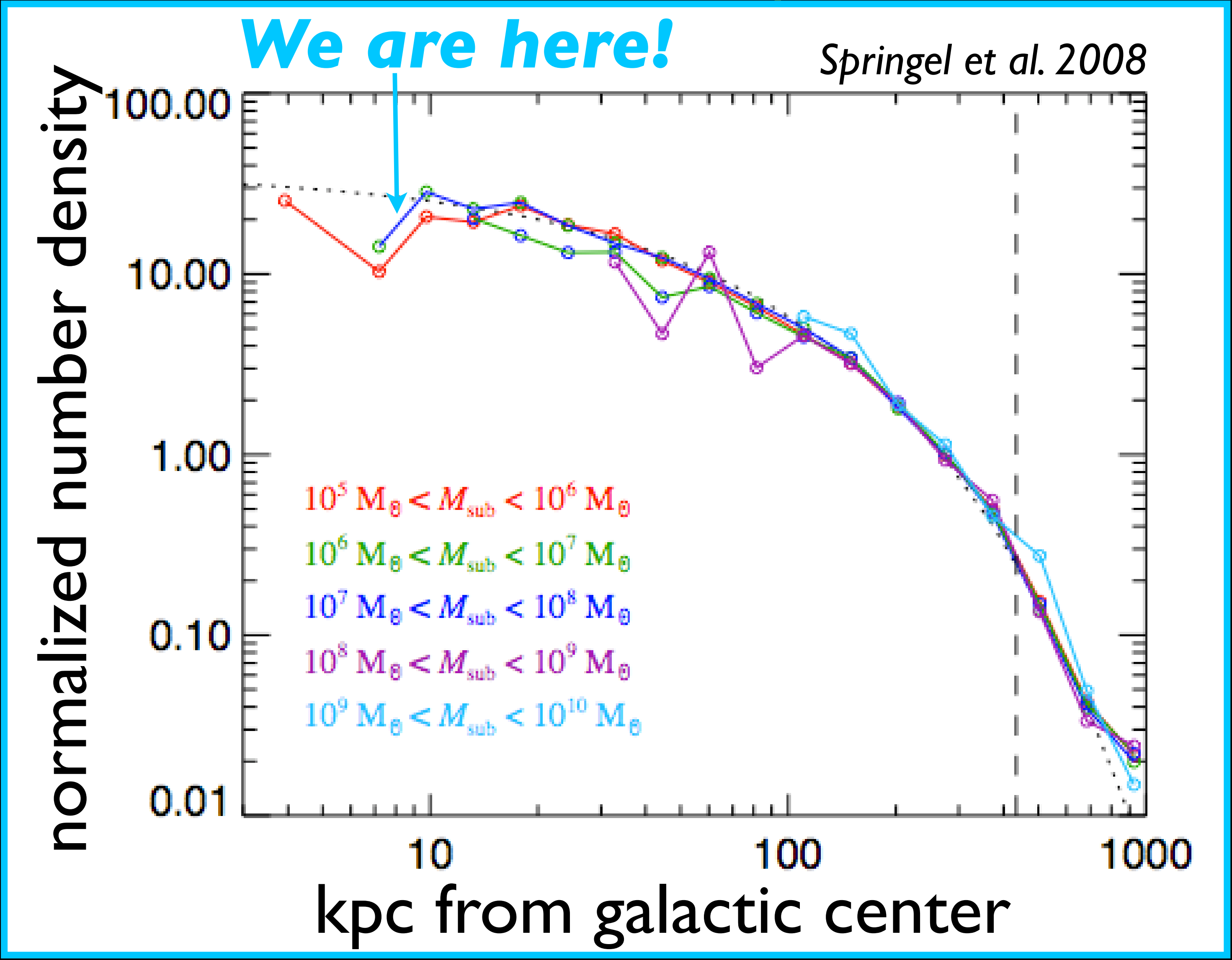


Springel et al. 2008

- High-resolution simulations of Galaxy-sized halos with billions of particles
- Aquarius halo has >200,000 resolved subhalos with $M_{\rm sub} \gtrsim 4 \times 10^4 M_\odot$

Subhalos in our Neighborhood

Locations of Subhalos in Aquarius Simulation



Via Lactea II also sees subhalos with r <10 kpc.

Diemand et al. 2008

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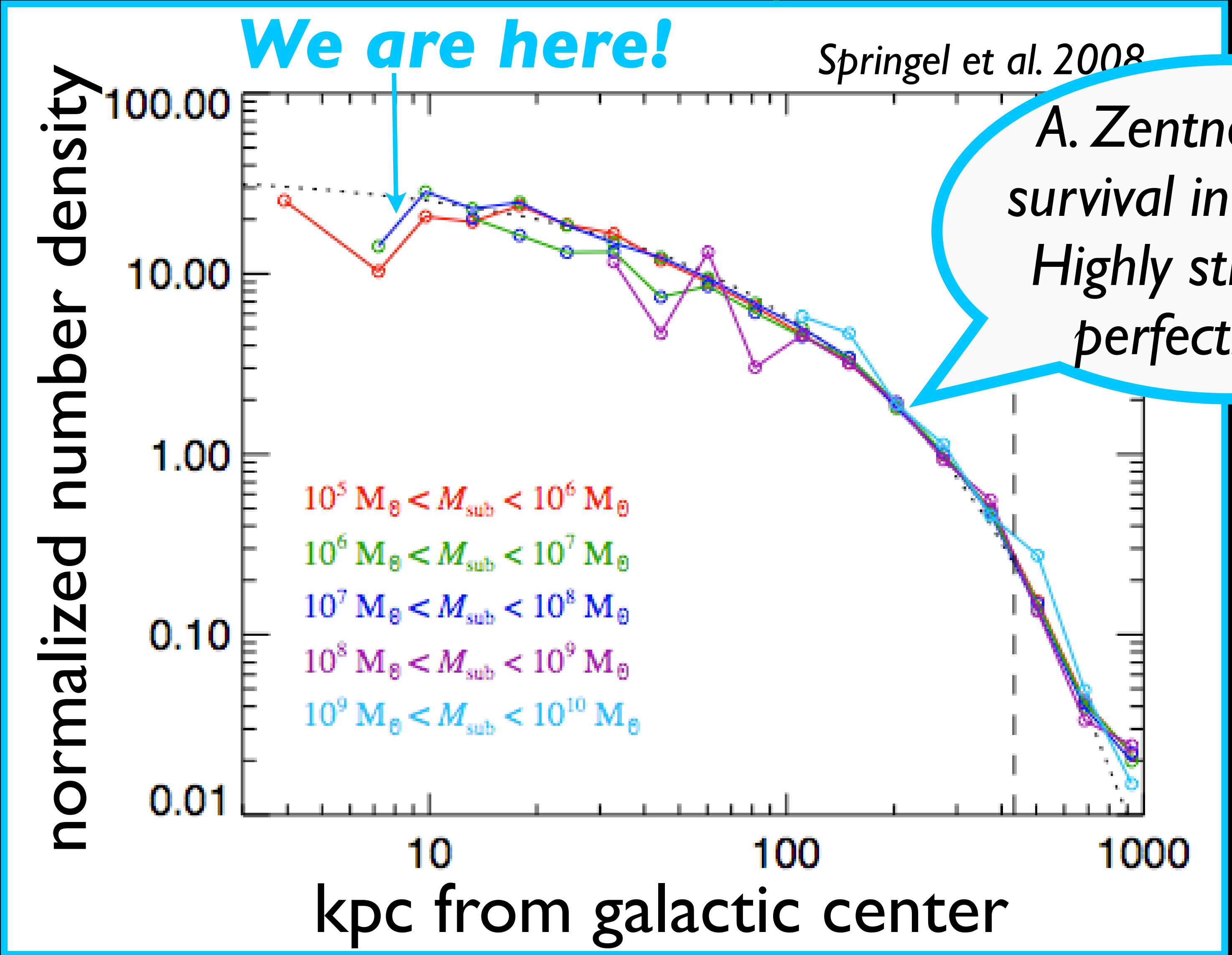

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Overview

I. Astrometric microlensing by subhalos

What happens when a subhalo passes between us and a star?

II. High-precision astrometry

Can we measure stellar separations in microarcseconds?

III. 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?

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
  Yonehara et al. 2003; Inoue & Chiba 2005; Zackrisson et al. 2008; Riehm et al. 2009

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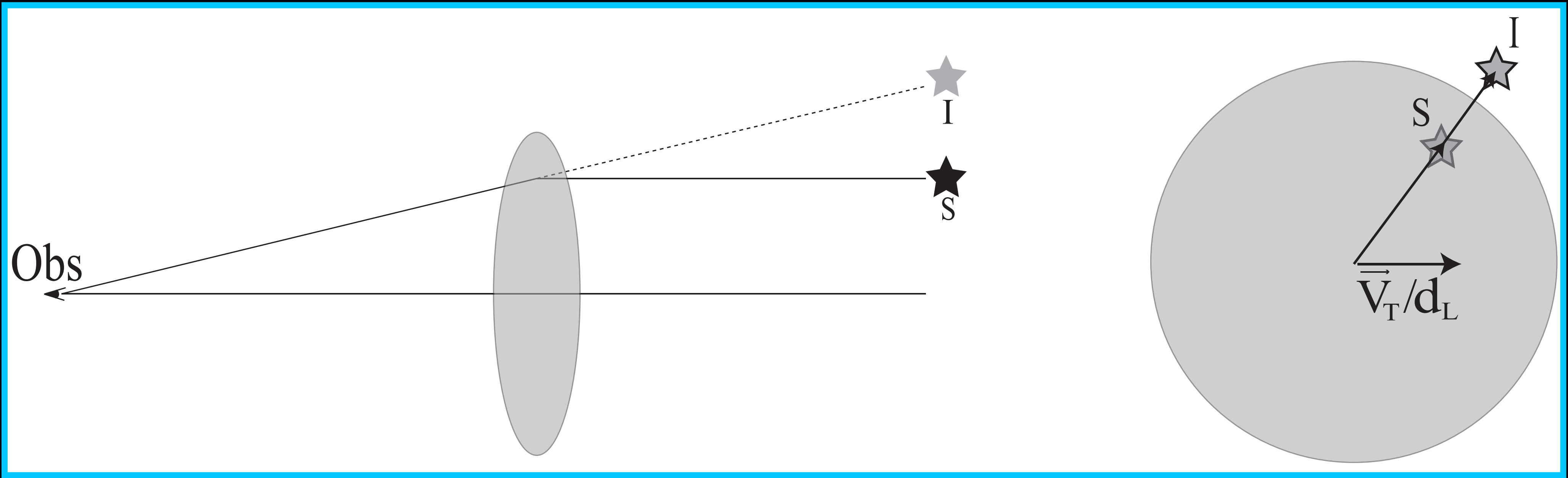
Astrometric lensing is also promising!

- 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



- Assume a spherical density profile for the subhalo
- Weak lensing: one image with a small deflection angle
- Image is always along line connecting subhalo center to source
- Thin lens equation:

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

Lens: Singular Isothermal Sphere

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

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

Constant Deflection Angle!

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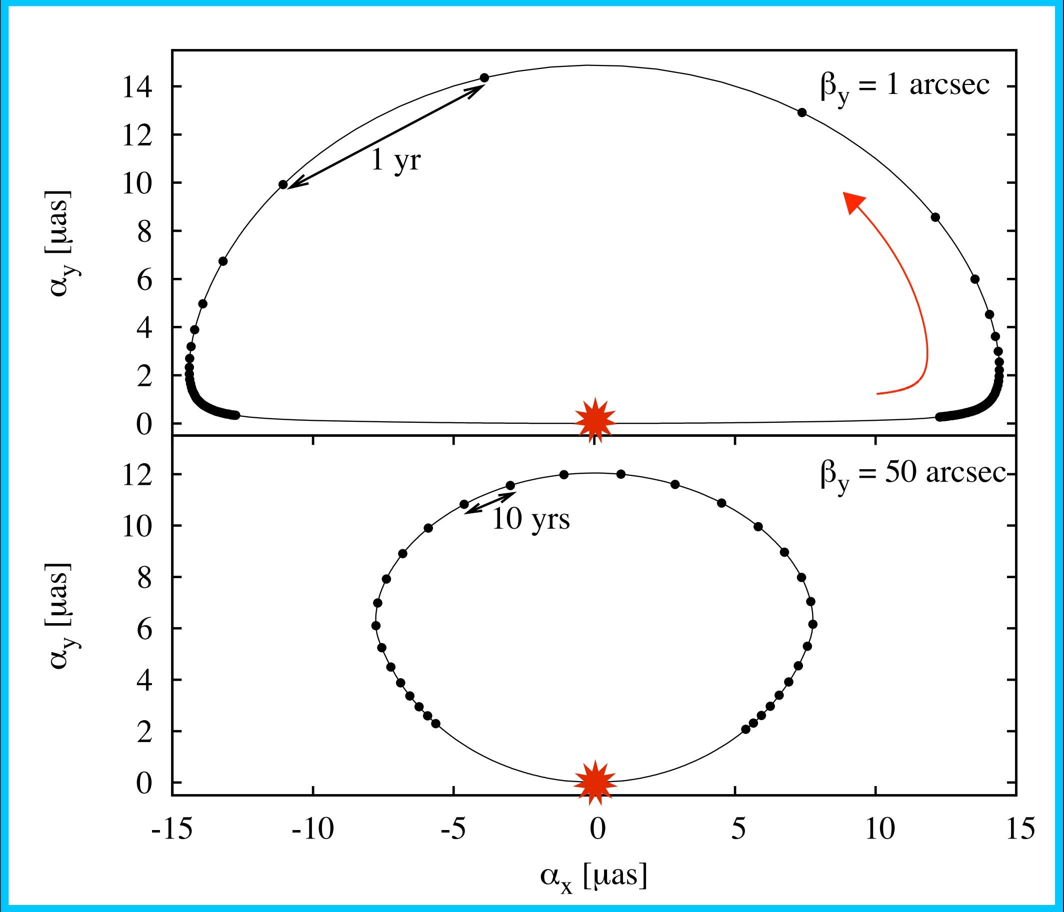
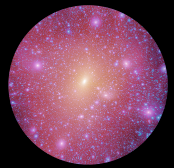


- If the SIS is infinite, the star traces a semi-circle on the sky.
- The radius of the semi-circle is the Einstein angle:

$$\theta_E^{\rm SIS} = 10\,\mu{\rm as}\left(\frac{\sigma_v}{0.6\,{\rm km/s}}\right)^2\left(1-\frac{d_L}{d_S}\right)$$



Lens path: 200 km/s

Lens distance: 50 pc

Lens mass: 5 Msun

Lens radius: 0.02 pc (85")

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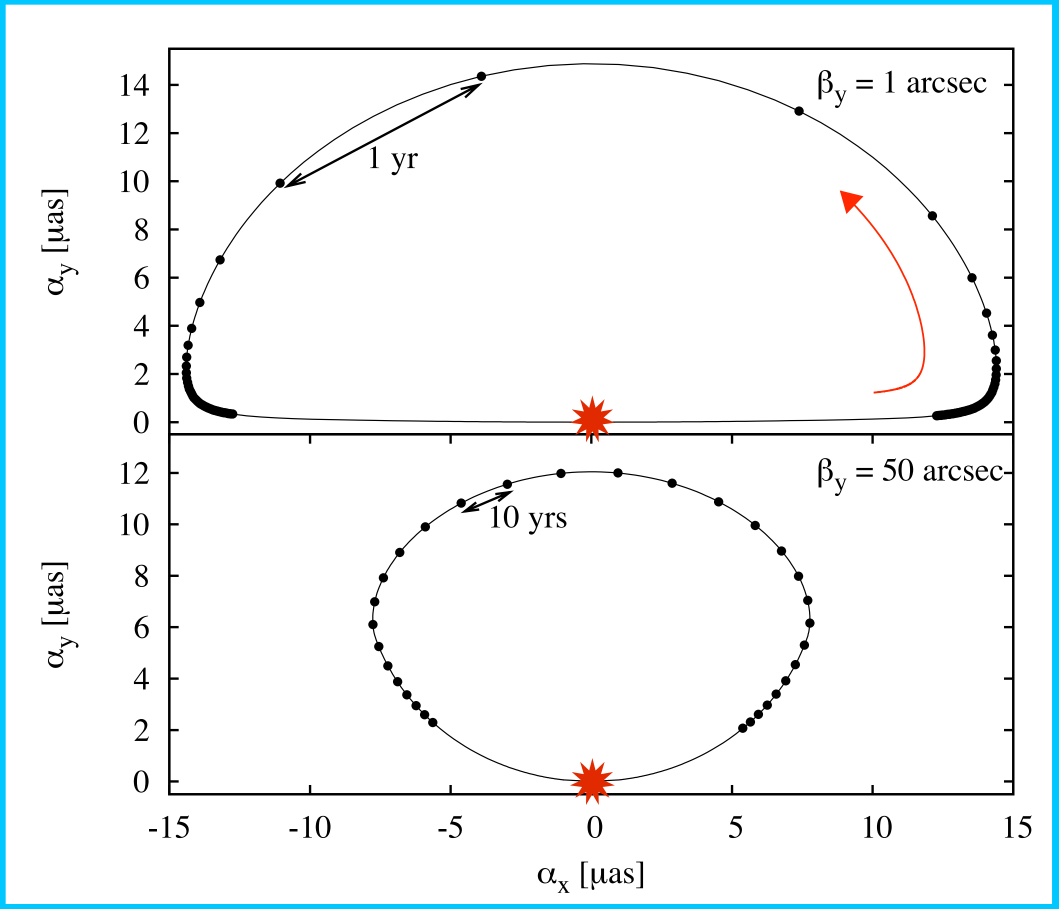

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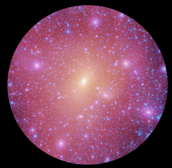
- Truncating the SIS completes the image path.
- Larger impact parameter: more circular image path, slower image movement.



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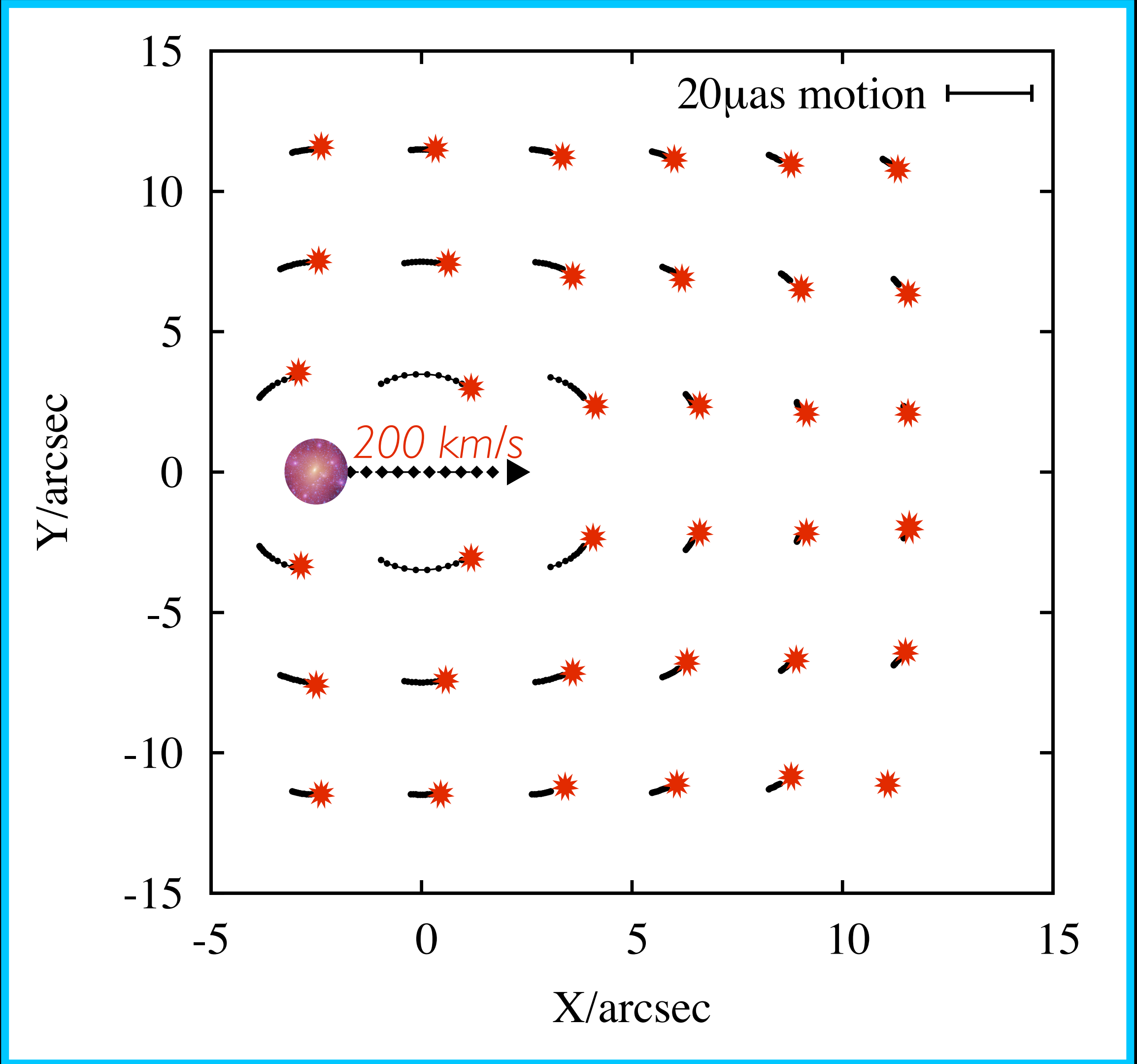
Star field over 4 years



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Singular Isothermal Sphere

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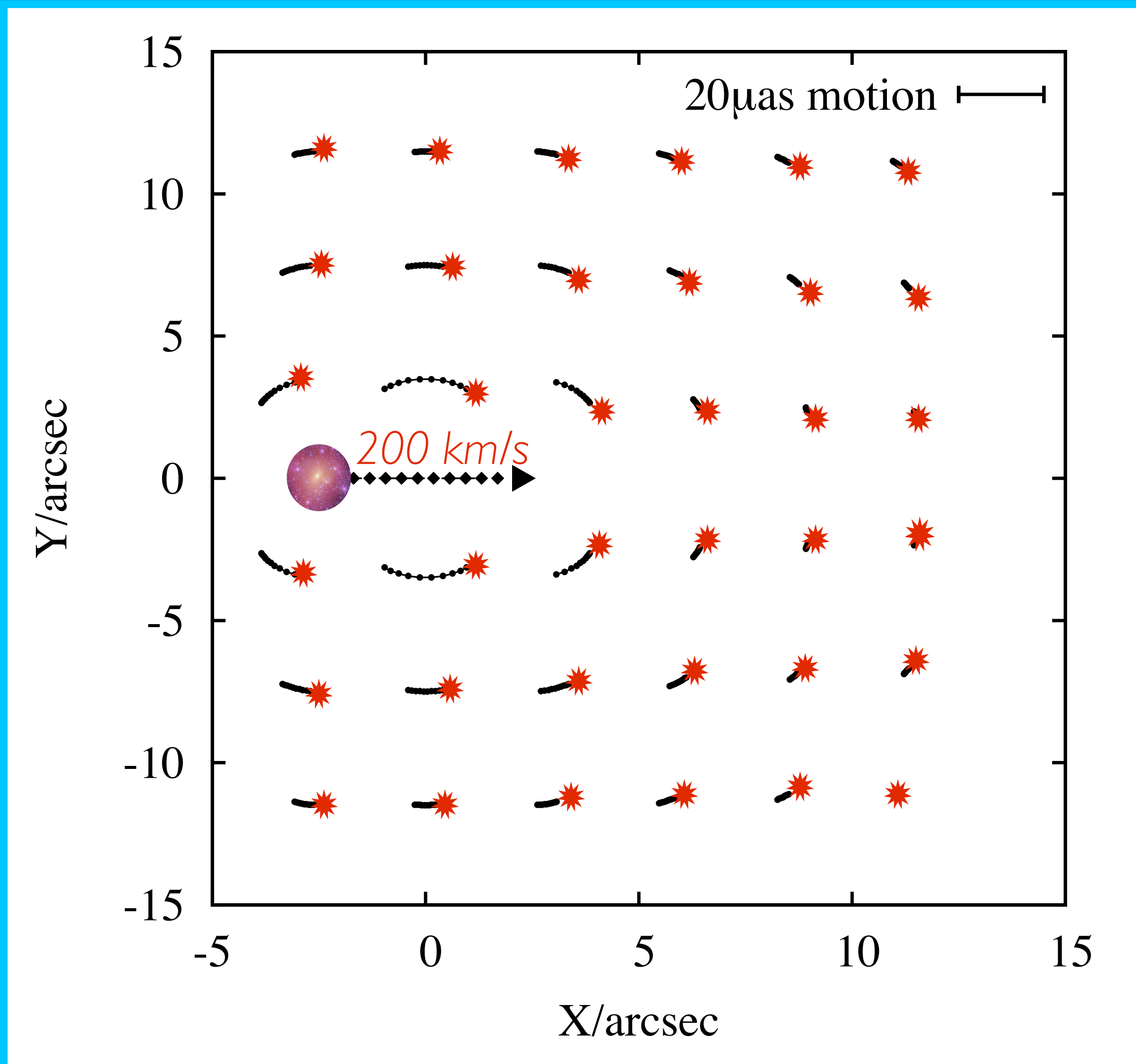

Lens mass: 5 Msun

Lens distance: 50 pc

Lens radius: 0.02 pc (85")

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

- the subhalo center must pass within 0.05 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:"

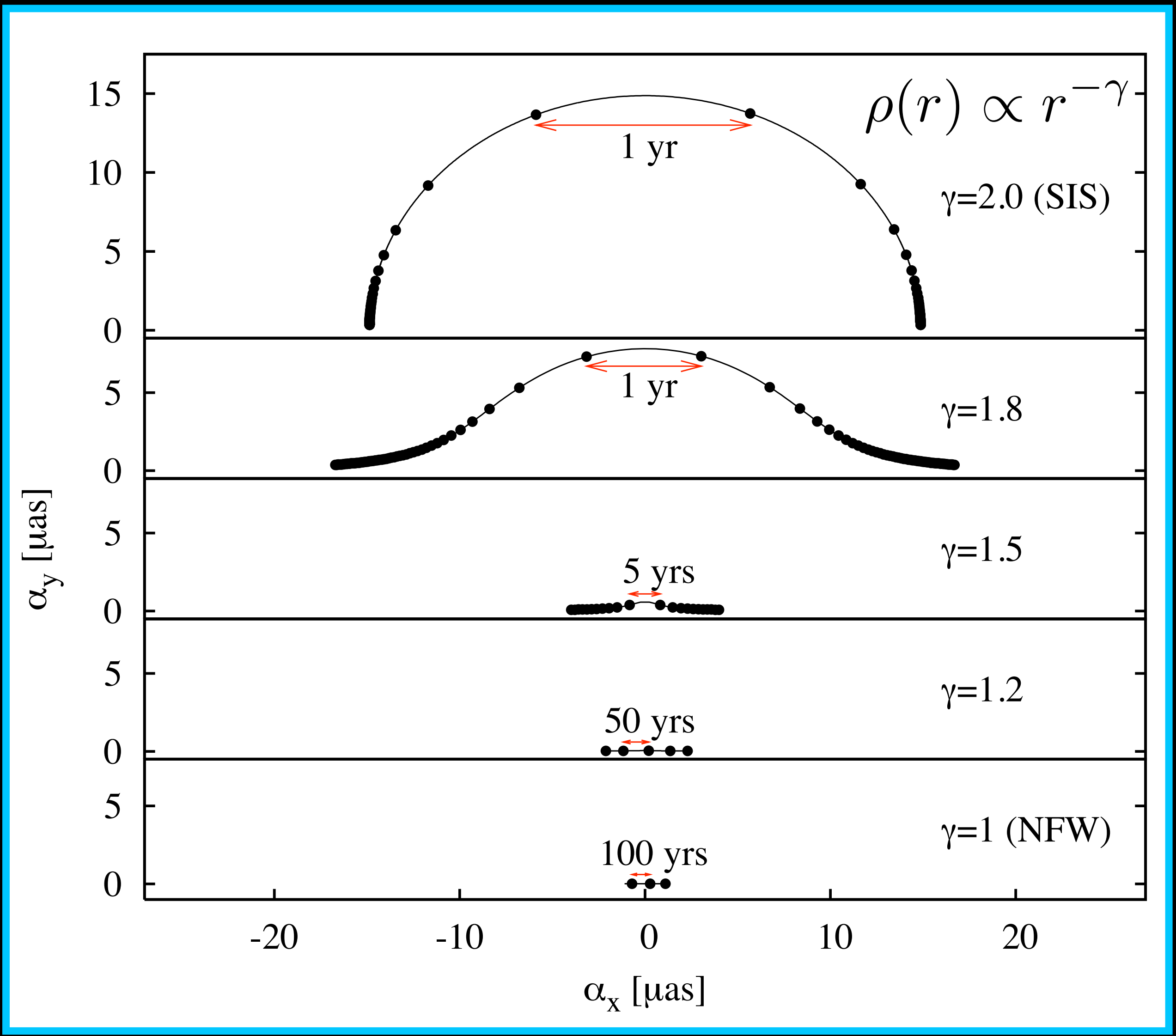
$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_0}\right)^{\gamma}\left(1+\frac{r}{r_0}\right)^{3-\gamma}}$$

r_0 is set by the concentration

ρ_0 is set by the virial mass

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

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

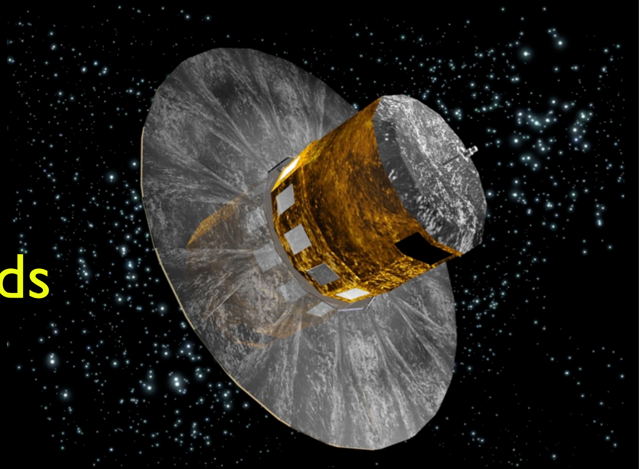
Lens path: 200 km/s

Lens distance: 50 pc

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

Can we detect microarcsecond astrometric changes?

Astrometry in Space



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

- astrometric precision per epoch: ~35 ***micro***arcseconds for its brightest targets (~5 million stars)

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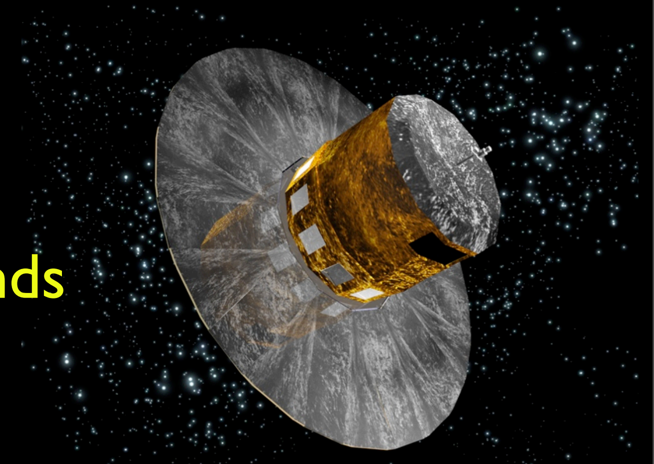

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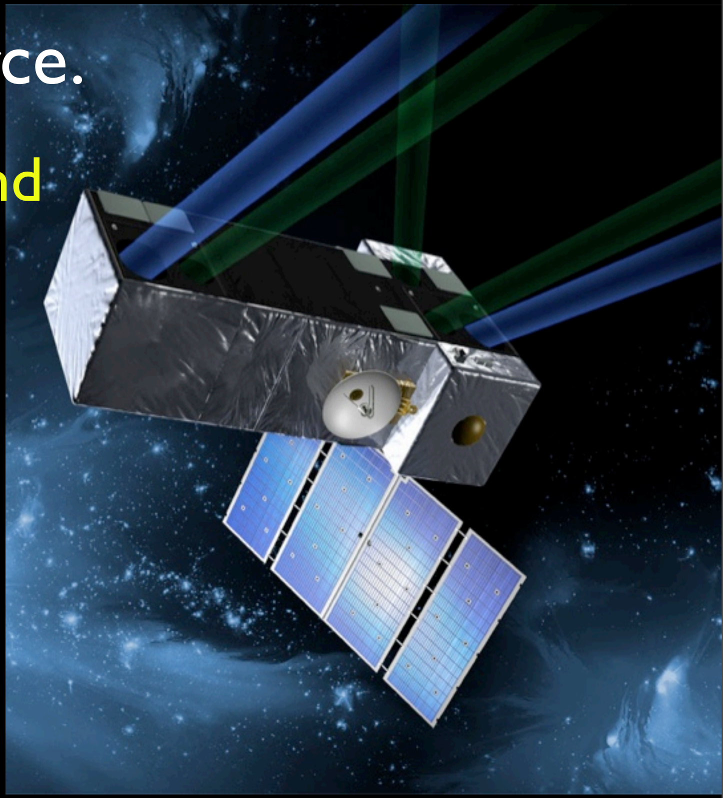
SIM PlanetQuest was the top space mission recommended by NASA's Exoplanet Task Force.



- astrometric precision per epoch: 1 ***micro***arcsecond for planet-finding, 4 ***micro***arcseconds for general high-efficiency astrometry (~10,000 stars)
- capable of observing faint stars
- targeted observations with adjustable number of visits per star

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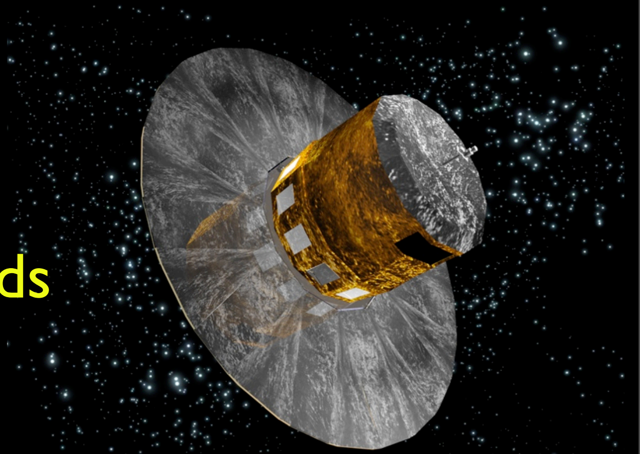

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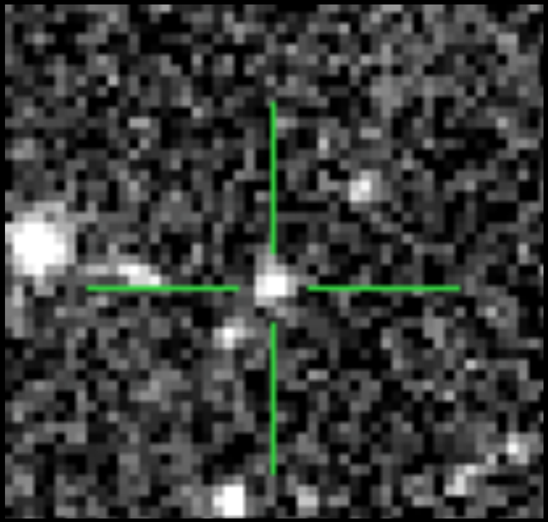
Astrometry from the Ground

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:

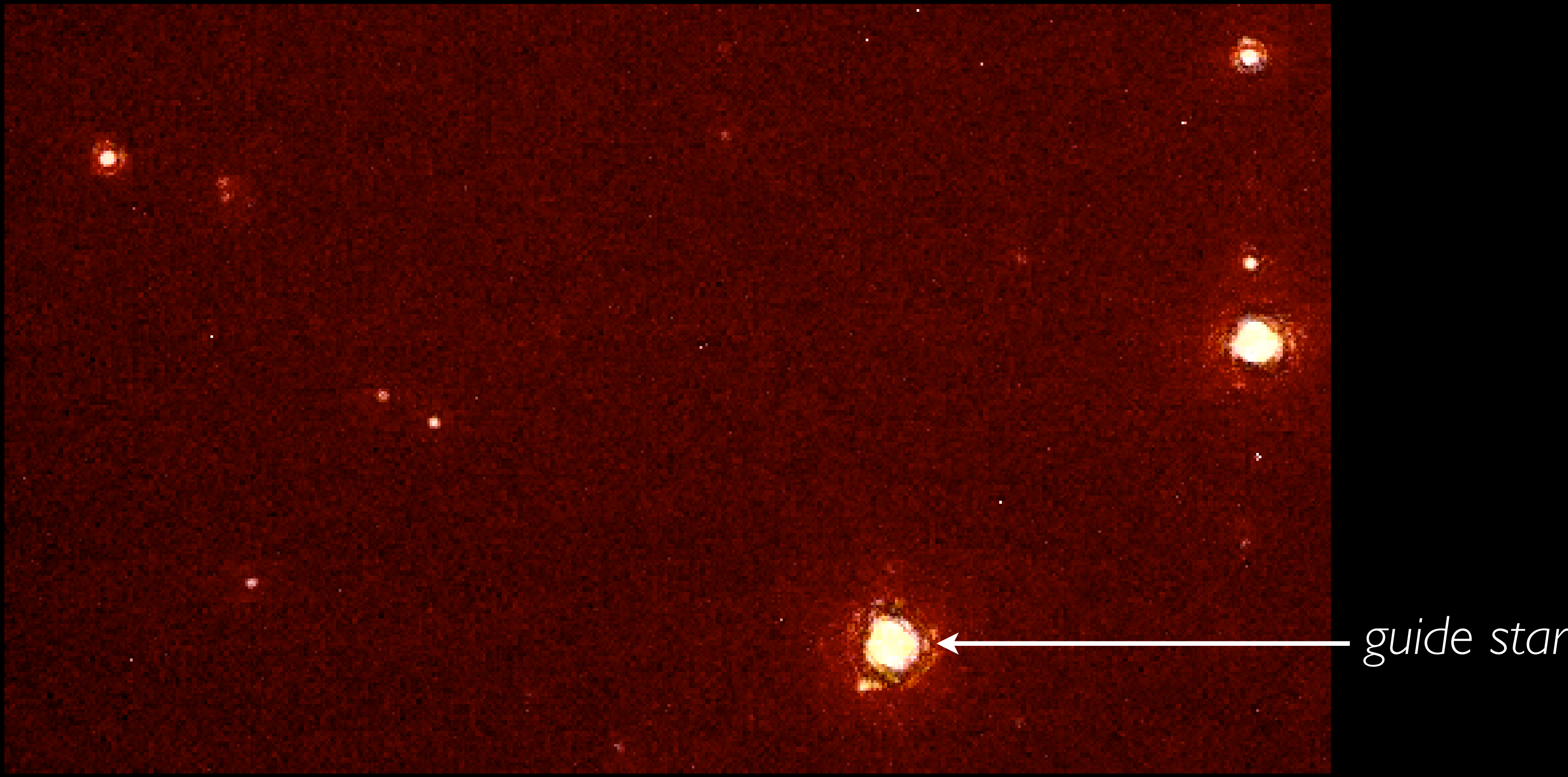
$$\sigma_x \propto \frac{\mathrm{FWHM}}{\mathrm{SNR}}$$

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

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

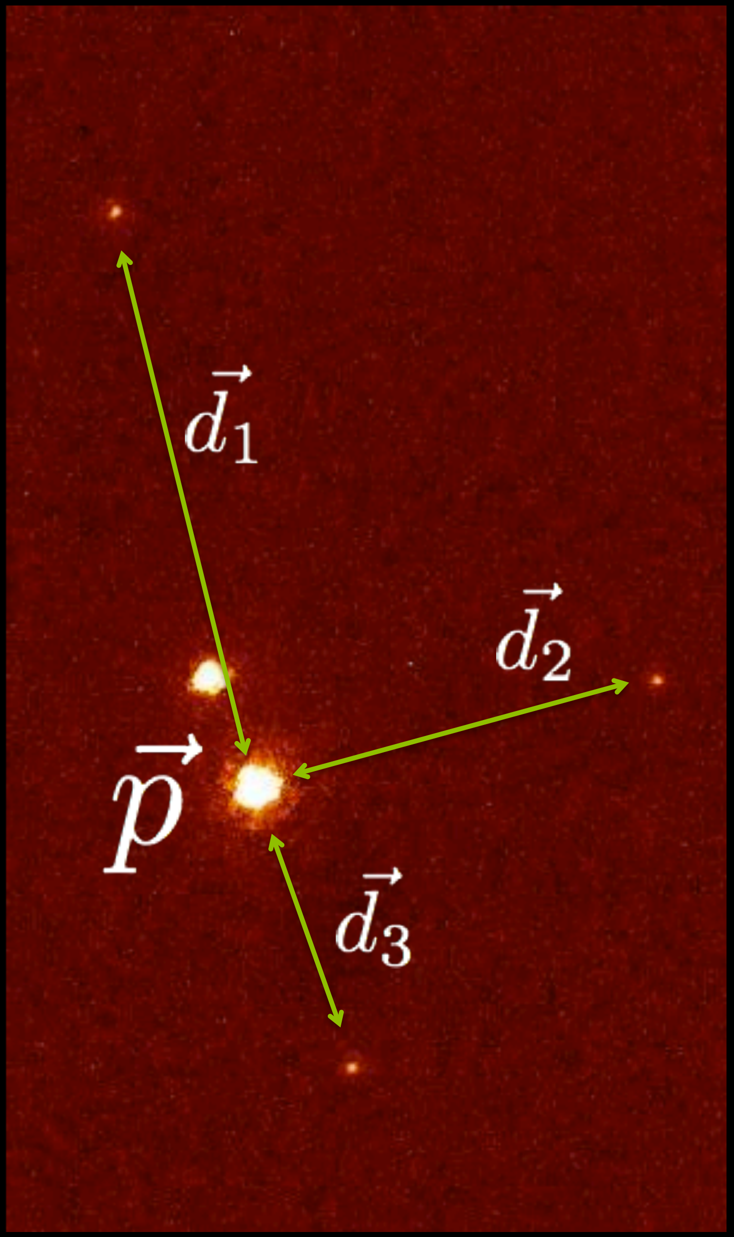
The correlations between the residual stellar jitters can be used to minimize their impact on astrometric measurements!

Cameron, Britton and Kulkarni (2009)

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

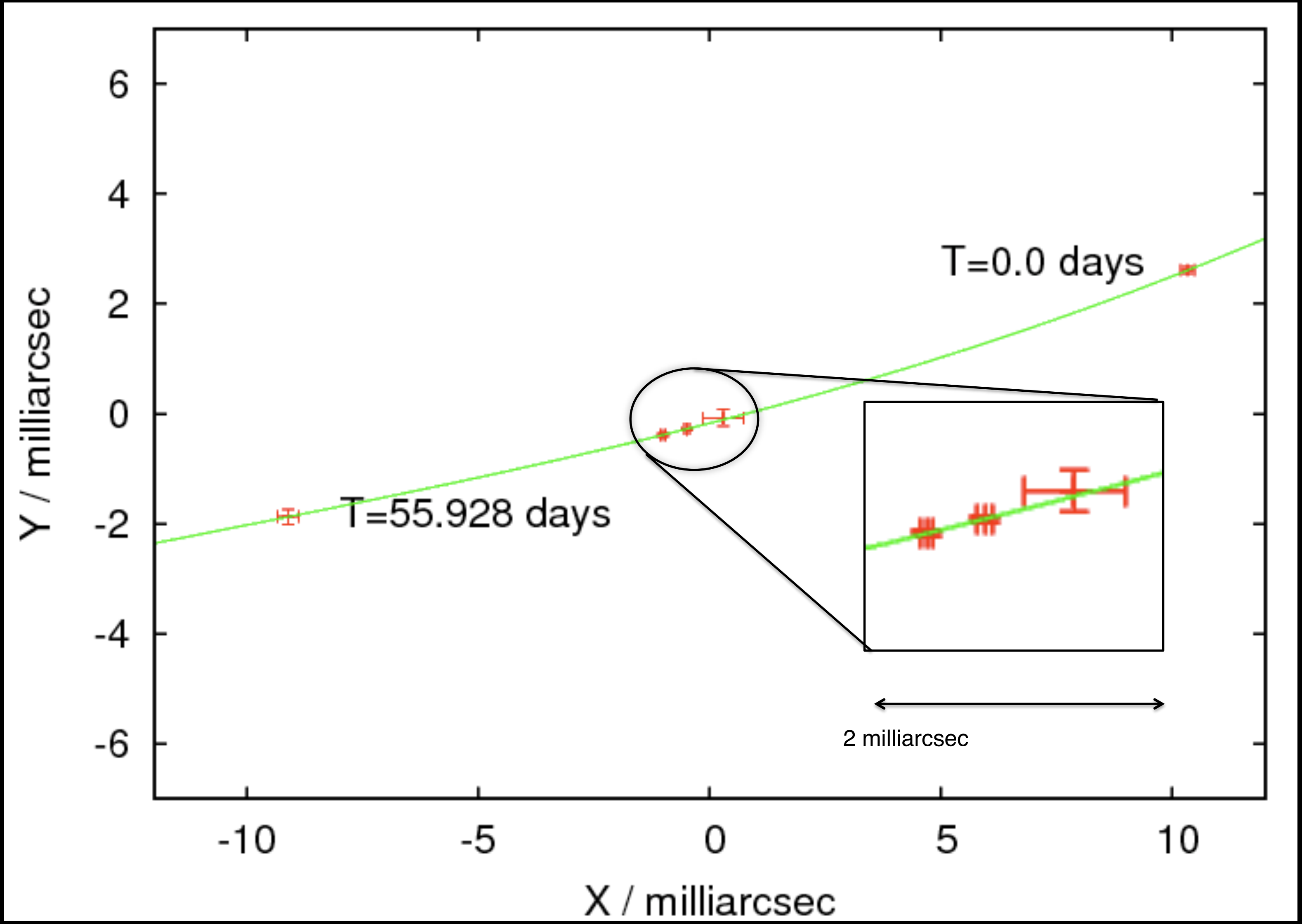
2) Apply weights to each vector to sum to the target position: $\vec{p} = \mathbf{W}\tilde{\mathbf{d}}$

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!

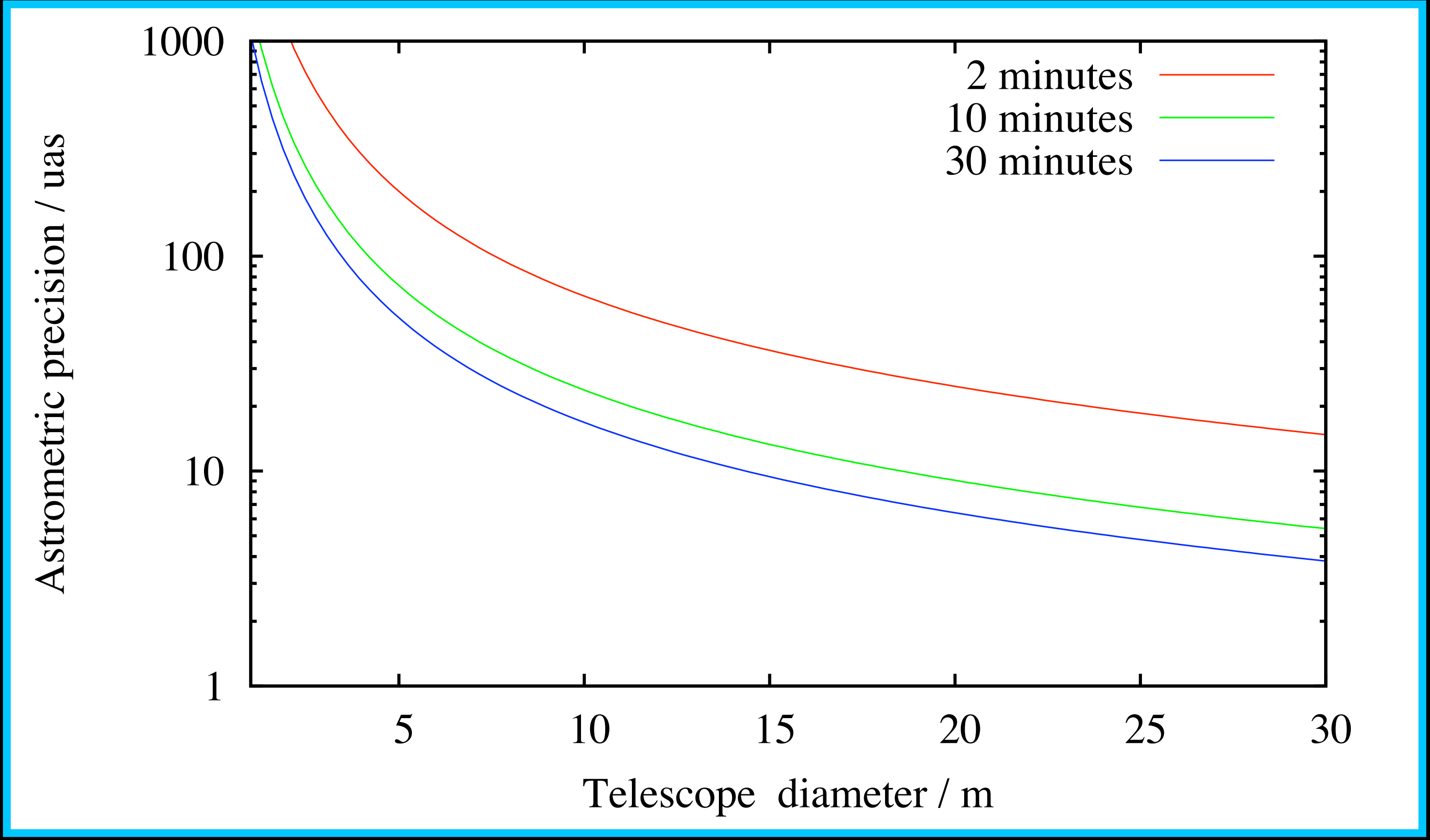
Observing the Proper Motion of an M-dwarf



Data taken on the Palomar 200-inch telescope

Give me a bigger telescope...

Statistical Astrometric Precision with Large Telescopes



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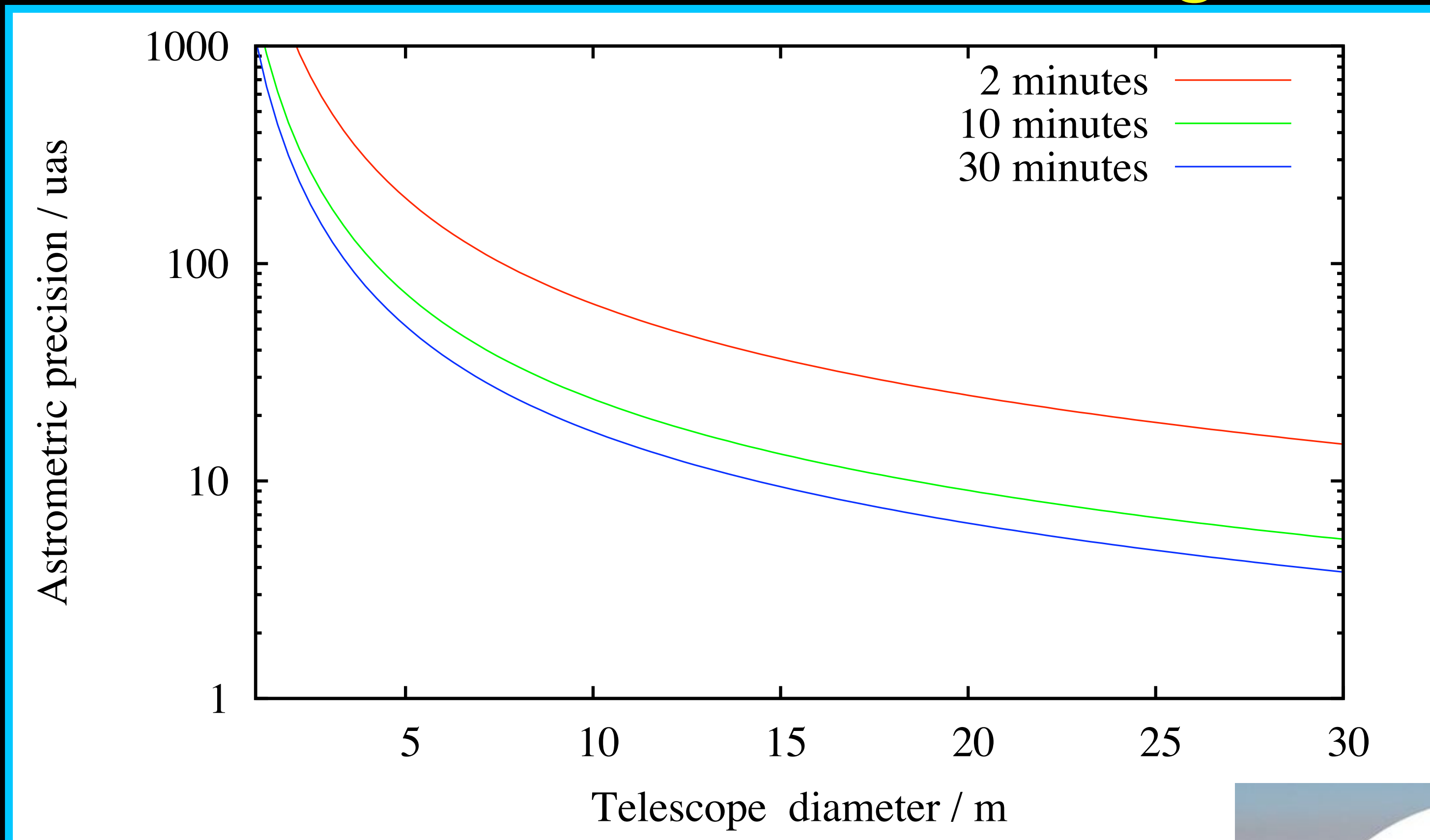
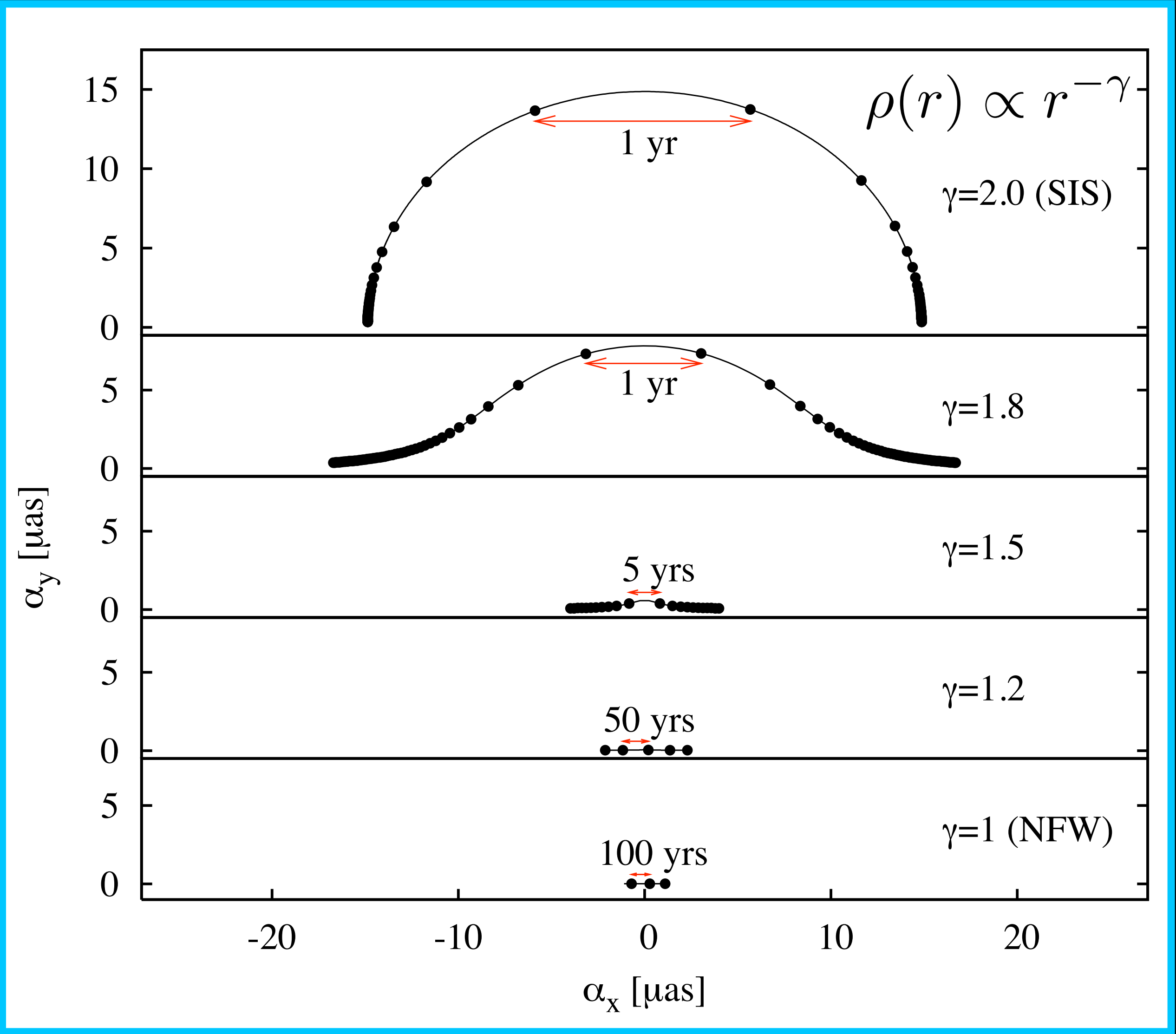


- Keck can reach 100 ***micro***arcsecond precision -- limited by systematics, but efforts are ongoing.
- TMT is designed for 50 ***micro***arcsecond precision and could reach much higher precision (Cameron *et al.* 2009)

Our Detection Strategy



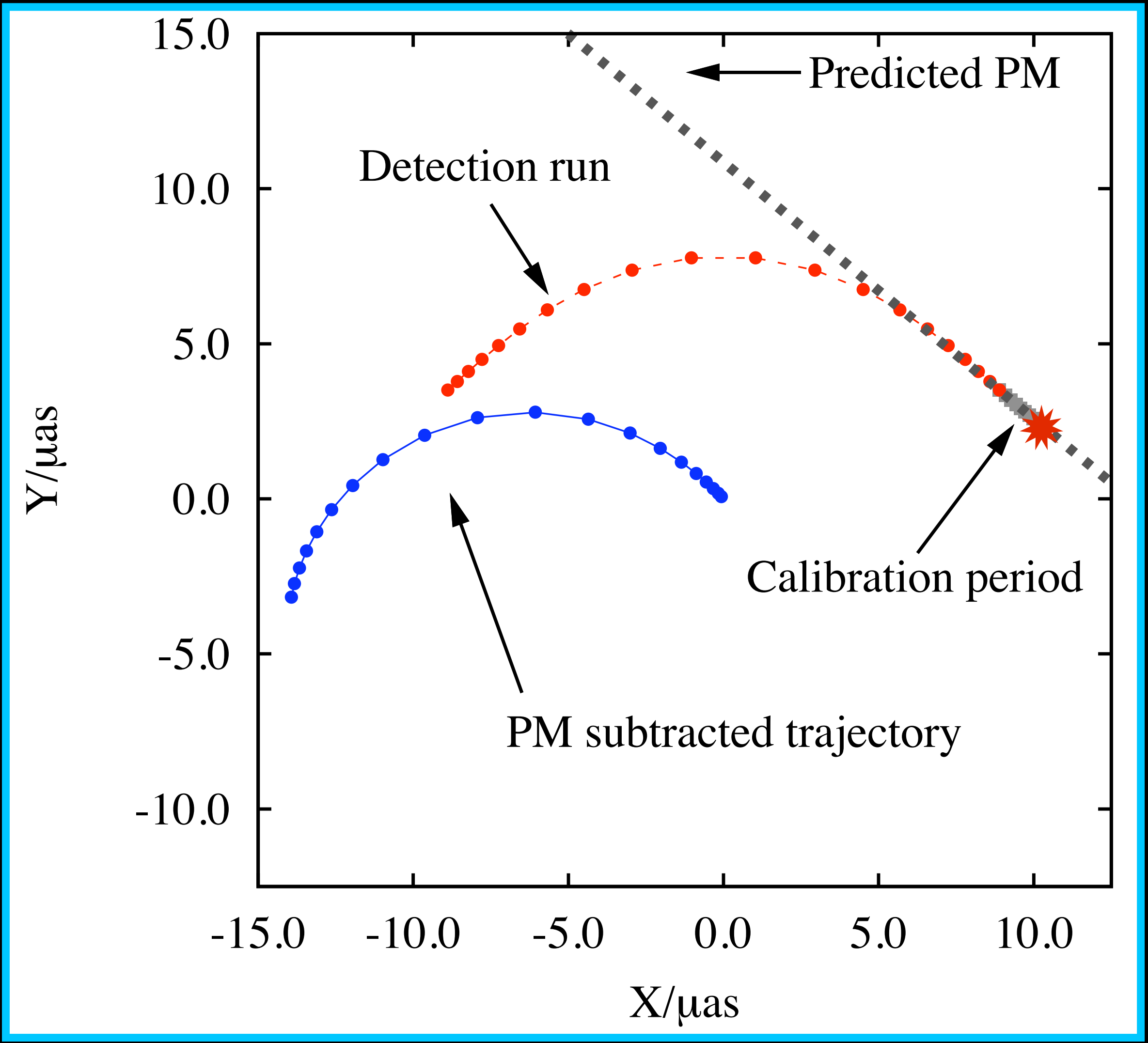
The typical subhalo lensing event has three stages:

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:



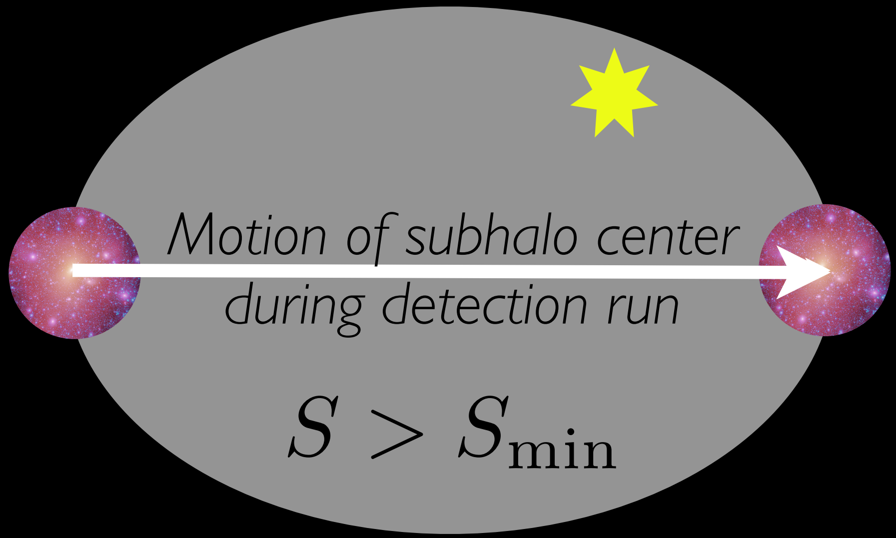
1. Observe stars for a calibration period (2 years).
2. Reject stars that significantly accelerate during the calibration period (including binaries).
3. Measure each star's proper motion and parallax, and predict its future trajectory.
4. Observe the star during the detection run (4 years).
5. Measure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

Star's true position is at the origin.
Subhalo center passes star two years into the detection run.

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 $S > S_{\rm min}$.

$$S_{\rm min} \simeq {\rm SNR} \times 1.5\sigma_{\rm inst}$$



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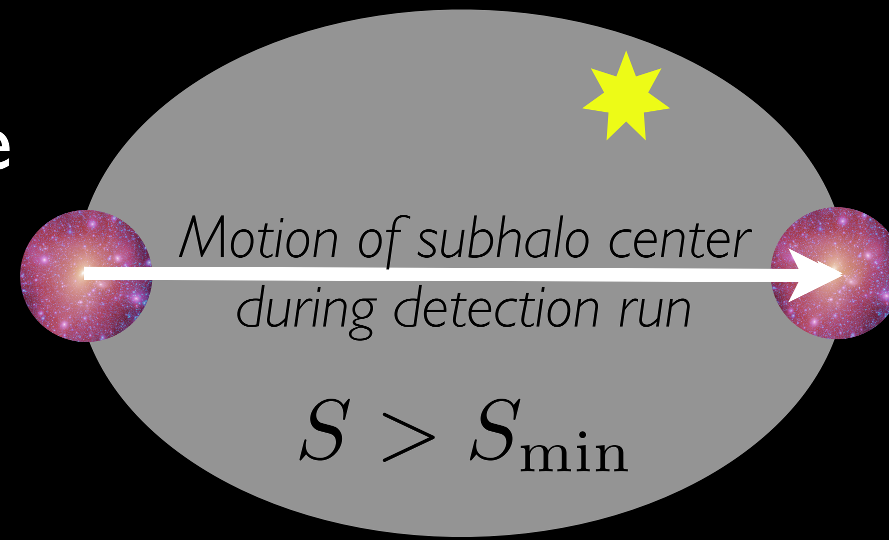
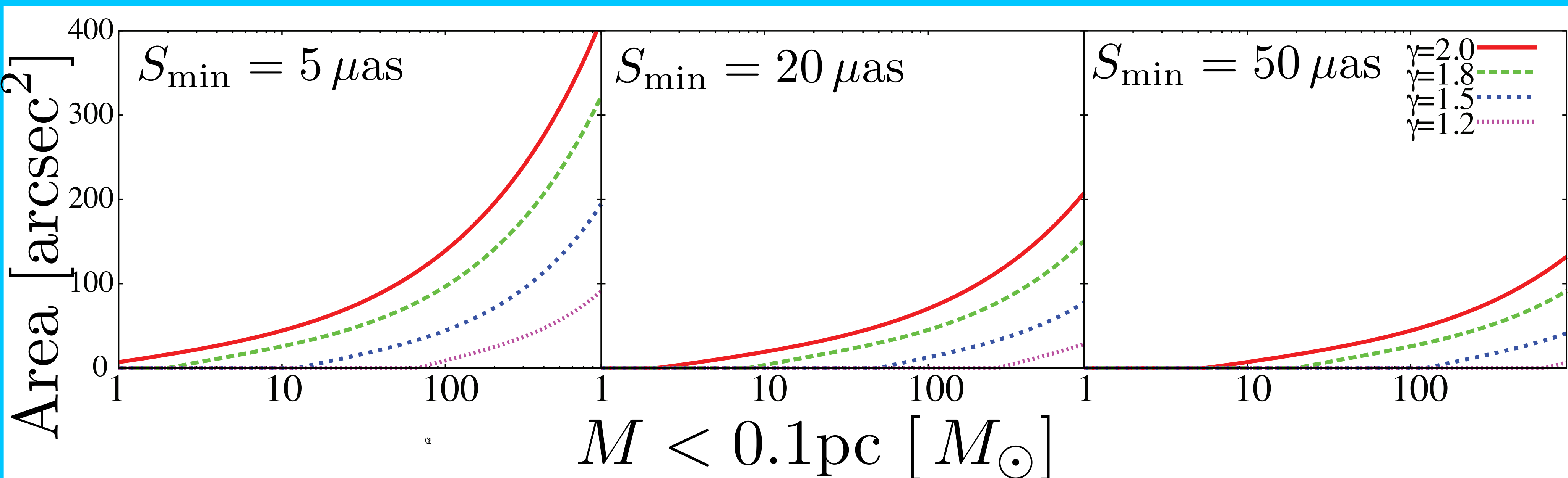
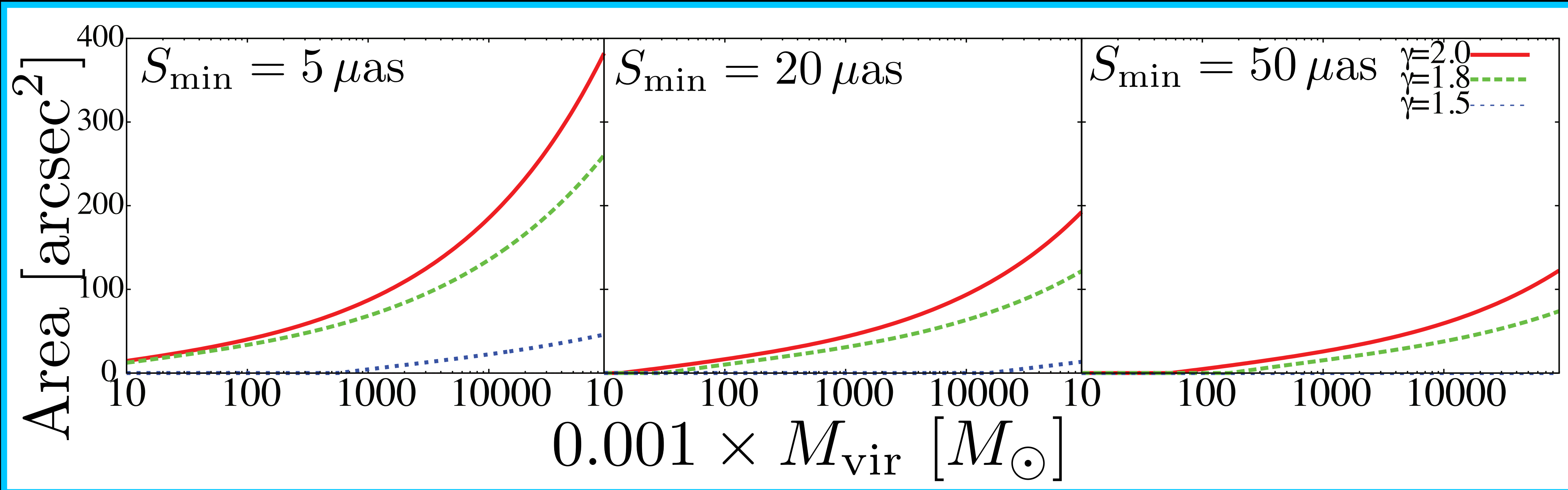




Lens distance: 50 pc; Lens velocity: 200 km/s; Source Distance: 5 kpc

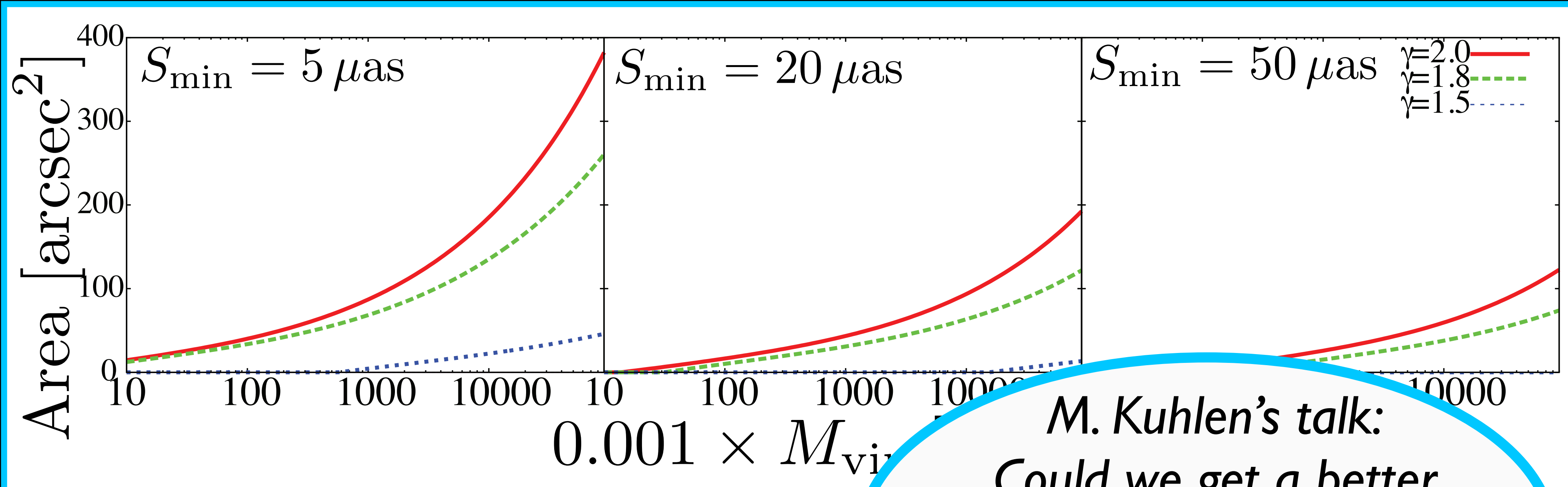
Lensing Cross Sections



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

- We assume that the subhalo loses 99.9% of its virial mass due to tidal stripping.
- We use a concentration-mass relation for local 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 Cross Sections



Lens distance: 50 pc; Lens velocity: 200

M. Kuhlen's talk:
Could we get a better concentration-mass relation by studying the origins of NFW?

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- We use a concentration-mass relation for local 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

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

$$\begin{array}{c}\text{Fraction of Sky}\\ \text{Lensed by a Subhalo}\\ (1.8 \lesssim \gamma \lesssim 2.0)\end{array} \simeq 10^{-11} \left(\frac{S_{\rm min}}{5\,\mu{\rm as}}\right)^{-1.6}$$

But what if dark matter is clumpier?

Lensing Event Rates

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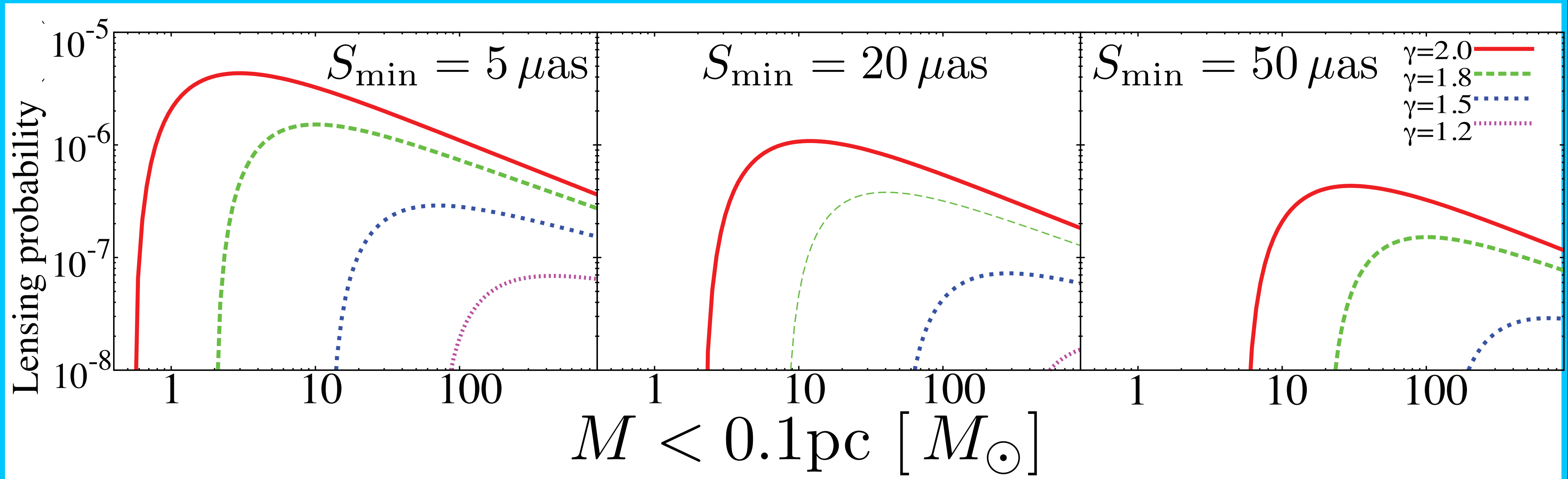
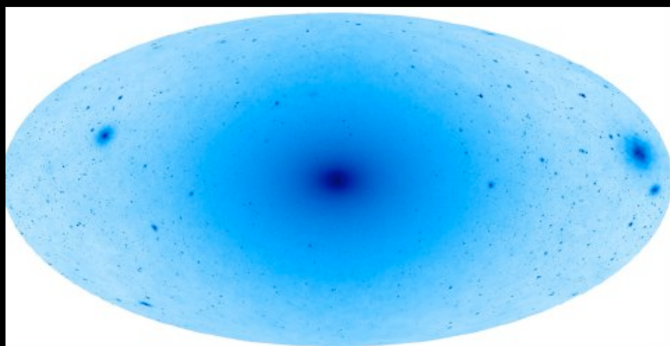
All the halo mass is contained within 0.1 pc of a subhalo center



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

Detection with Targeted Observations

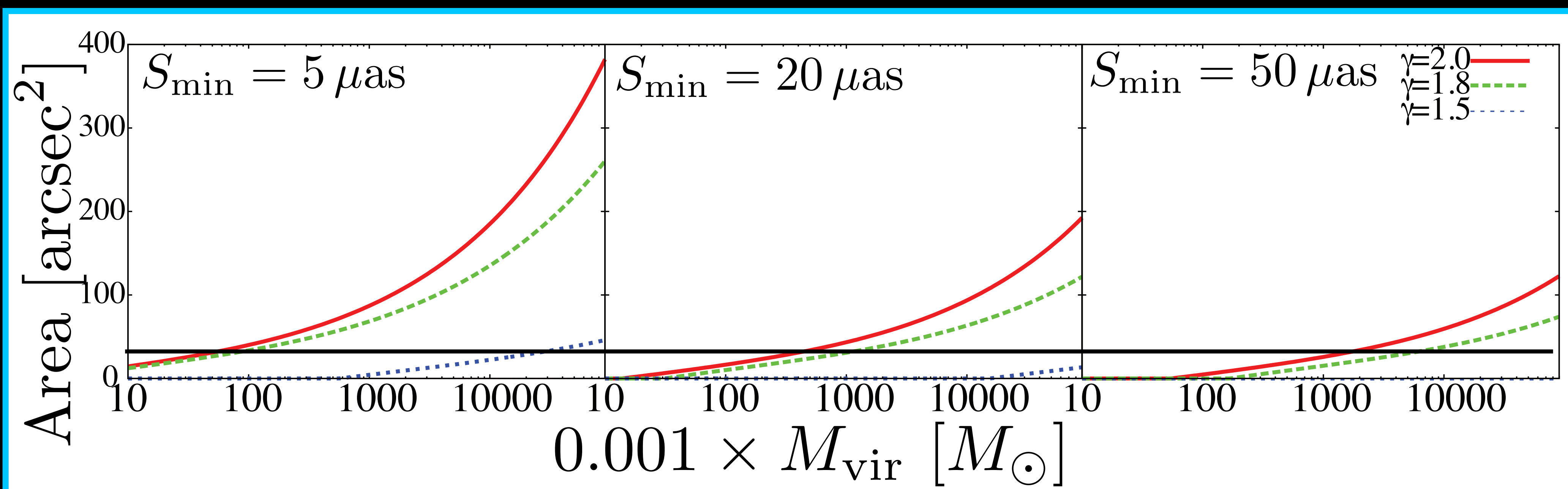
Finding a subhalo through astrometric microlensing is unlikely, but what if you know where to look?



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.

Buckley & Hooper 2010 ?



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

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!

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 $\gtrsim 1000\, M_{\odot}$.

For more details see
Erickcek & Law 2011 (arXiv:1007.4228)

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P. Sandick's talk:
Subhalos with IMBHs
at their centers!

P. Scott's talk:
Ultra-compact microhalos!

T… g event, we'd h…

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