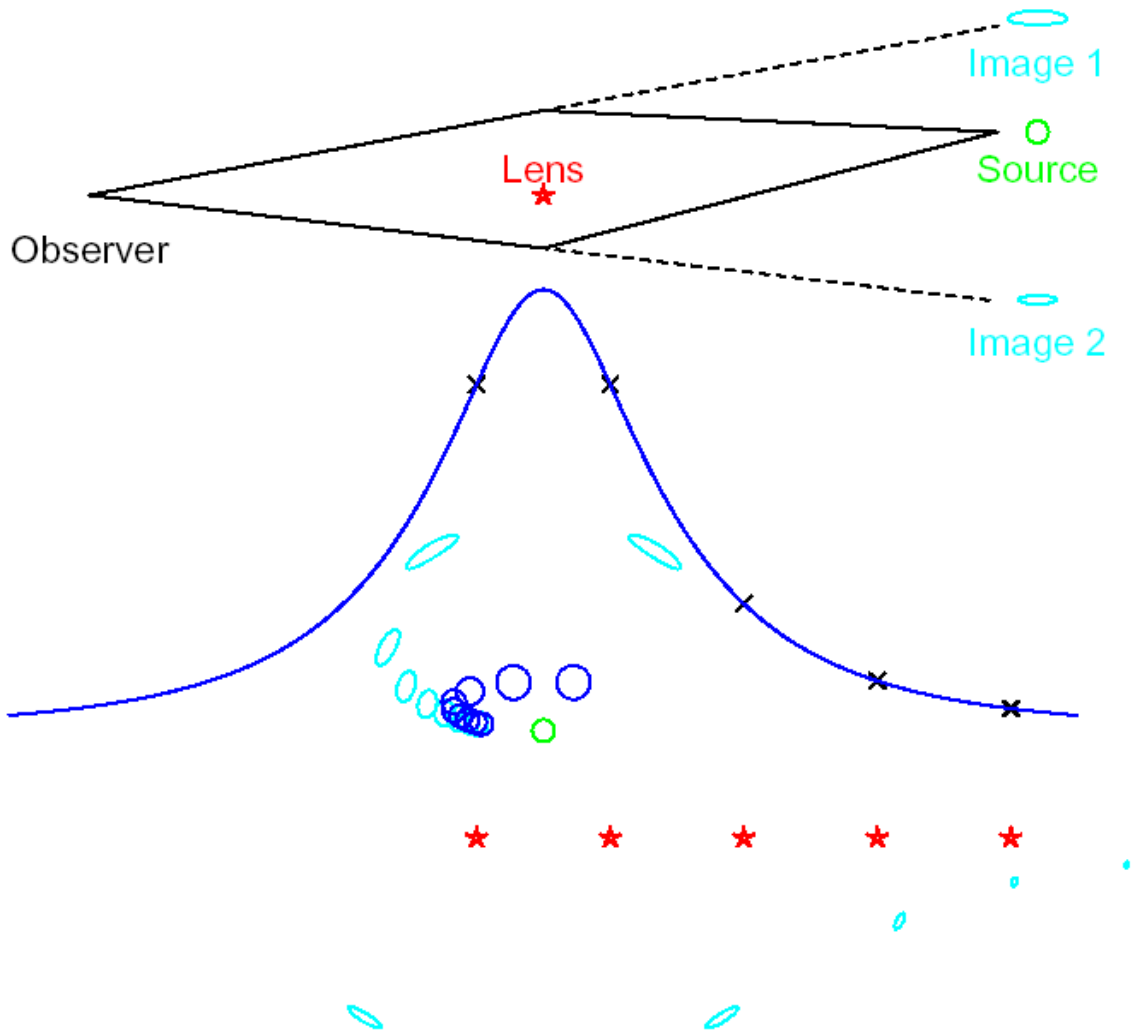
What is Needed Now to Prepare for WFIRST/AFTA Microlensing Planets?

Andy Gould (OSU) & Jennifer Yee (CfA)



What is Unique About WFIRST/AFTA?

- Systematic planet census at "snowline distances"
- Free-floating planets to Earth-mass and below
- Accurate planet masses for representative sample (i.e., subject to mild, well-understood selection)
- Accurate distances from here to Galactic Center (for representative sample)
  - "Galactic distribution of planets"

How will WFIRST/AFTA measure masses and distances?

(and why hasn't it been done before)?

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- Some Math Required

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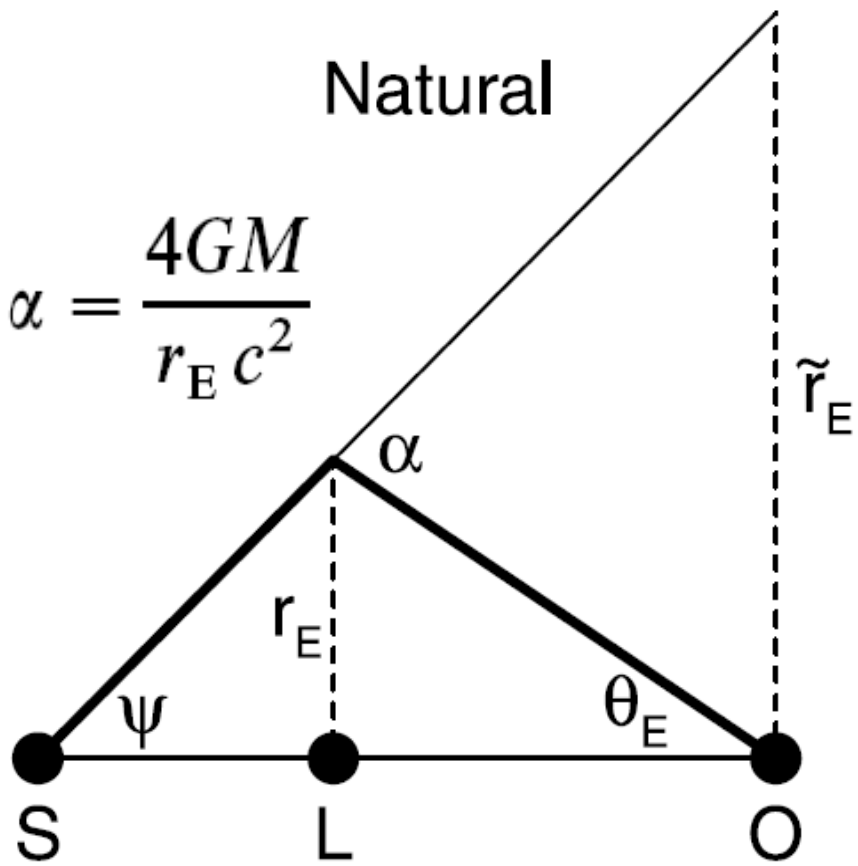
- $\pi_E = \pi_{rel} / \theta_E$

How will WFIRST/AFTA measure masses and distances?

(and why hasn't it been done before)?

- Some Math Required
- $\pi_E = \pi_{rel}/\theta_E$
- $M = \theta_E/(\kappa\pi_E)$
- $\kappa = 8$ mas/Msun

Relation of Mass and Distance to Lensing Observables



$$\alpha/\tilde{r}_E = \theta_E/r_E$$

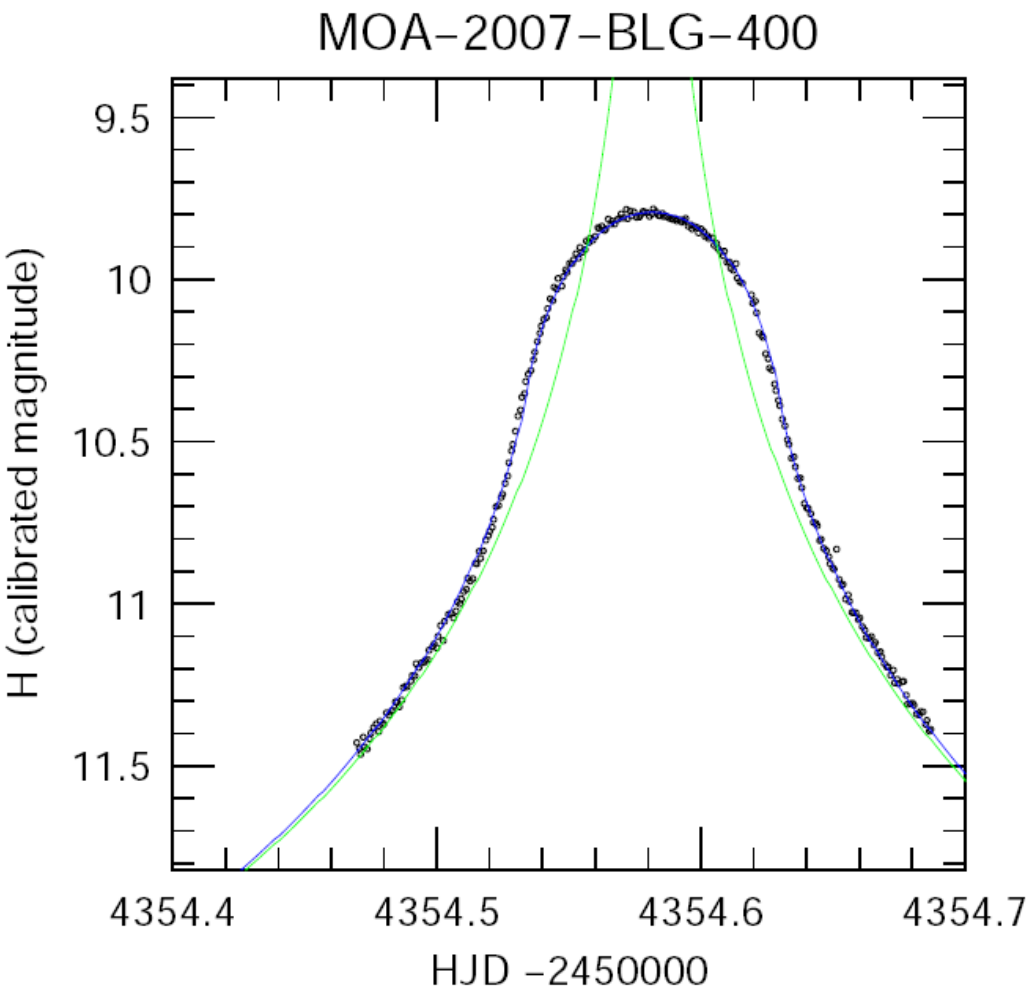
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

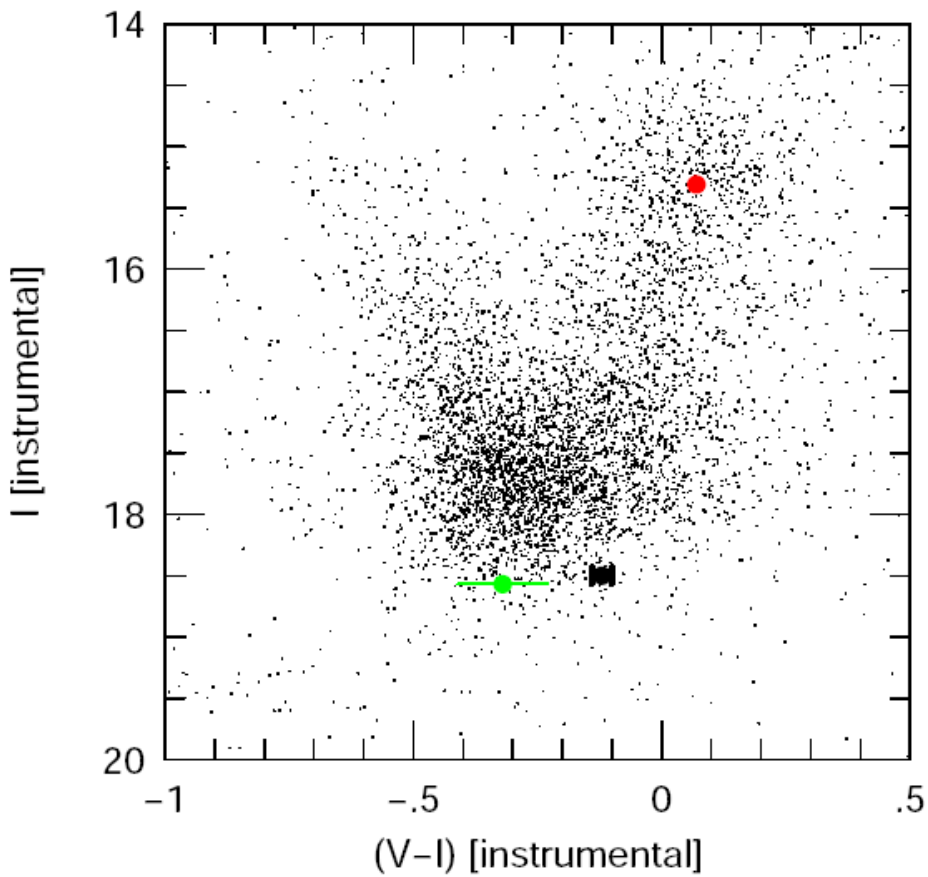
$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}}$$

$$\tilde{r}_E = \sqrt{\frac{4GMD_{rel}}{c^2}} \qquad \theta_E = \sqrt{\frac{4GM}{D_{rel}c^2}}$$

To measure angular Einstein radius:

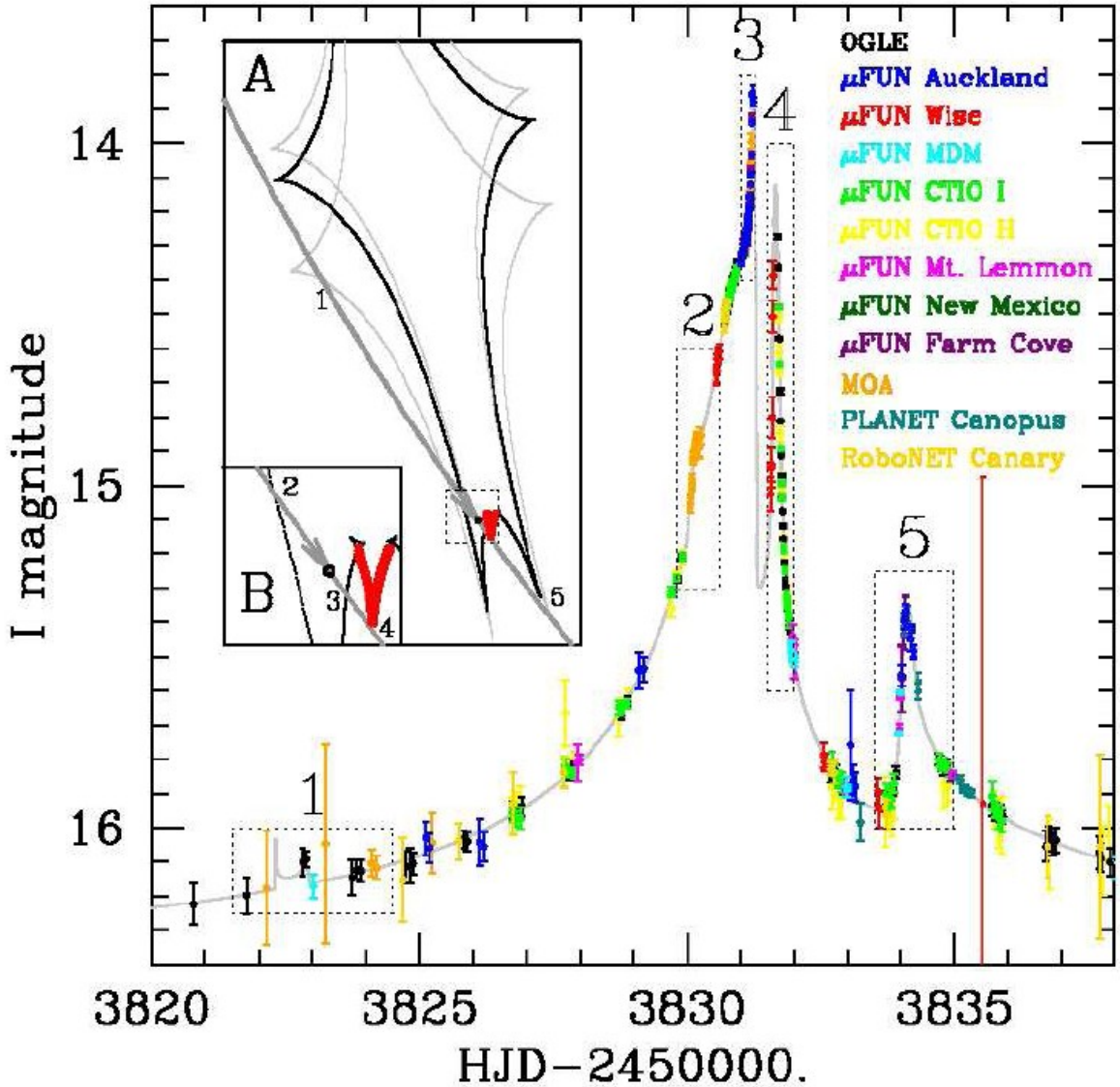
Standard Sky-Plane Rulers





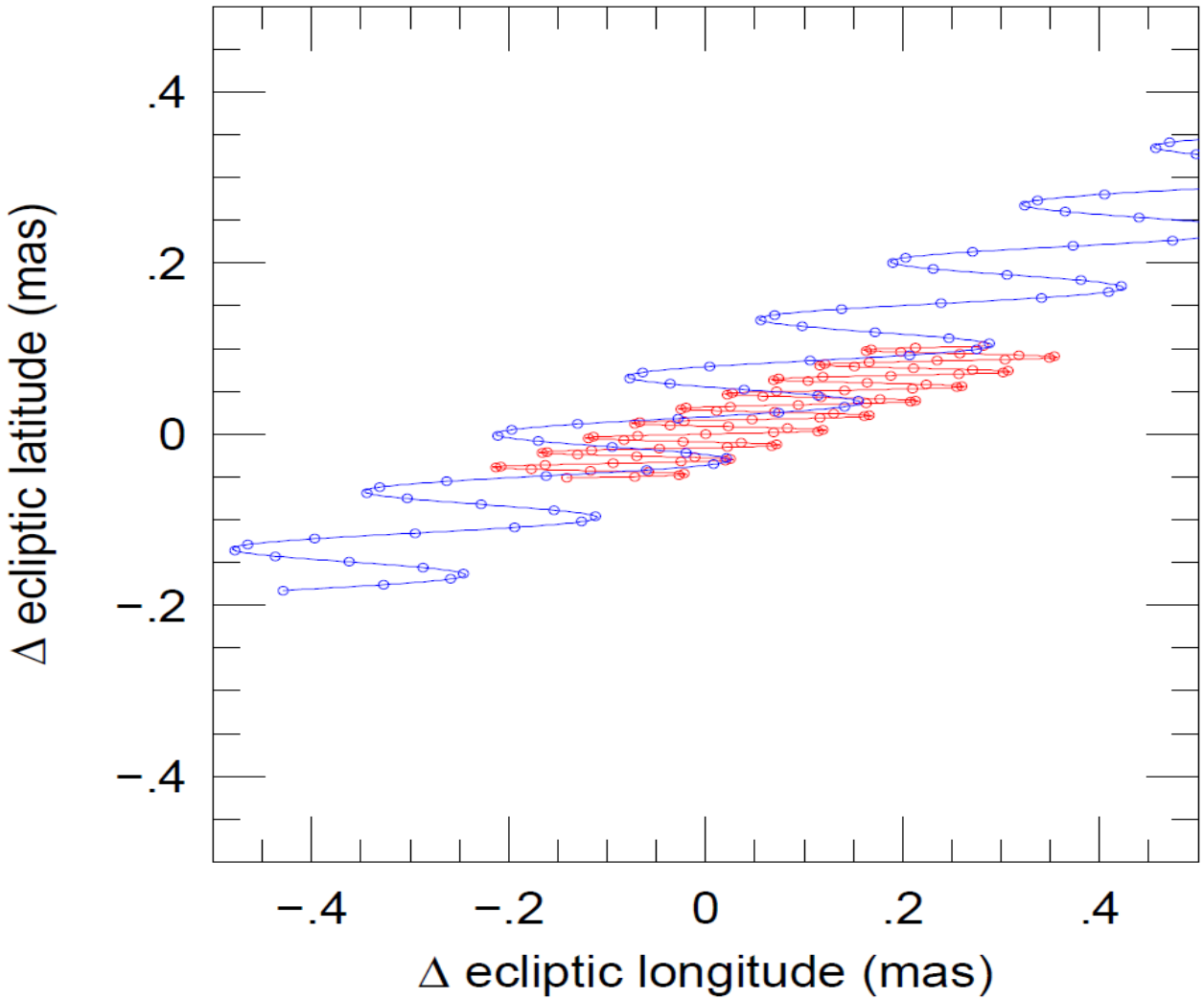
OGLE-2006-BLG-109

Finite-source effects generic in planetary events

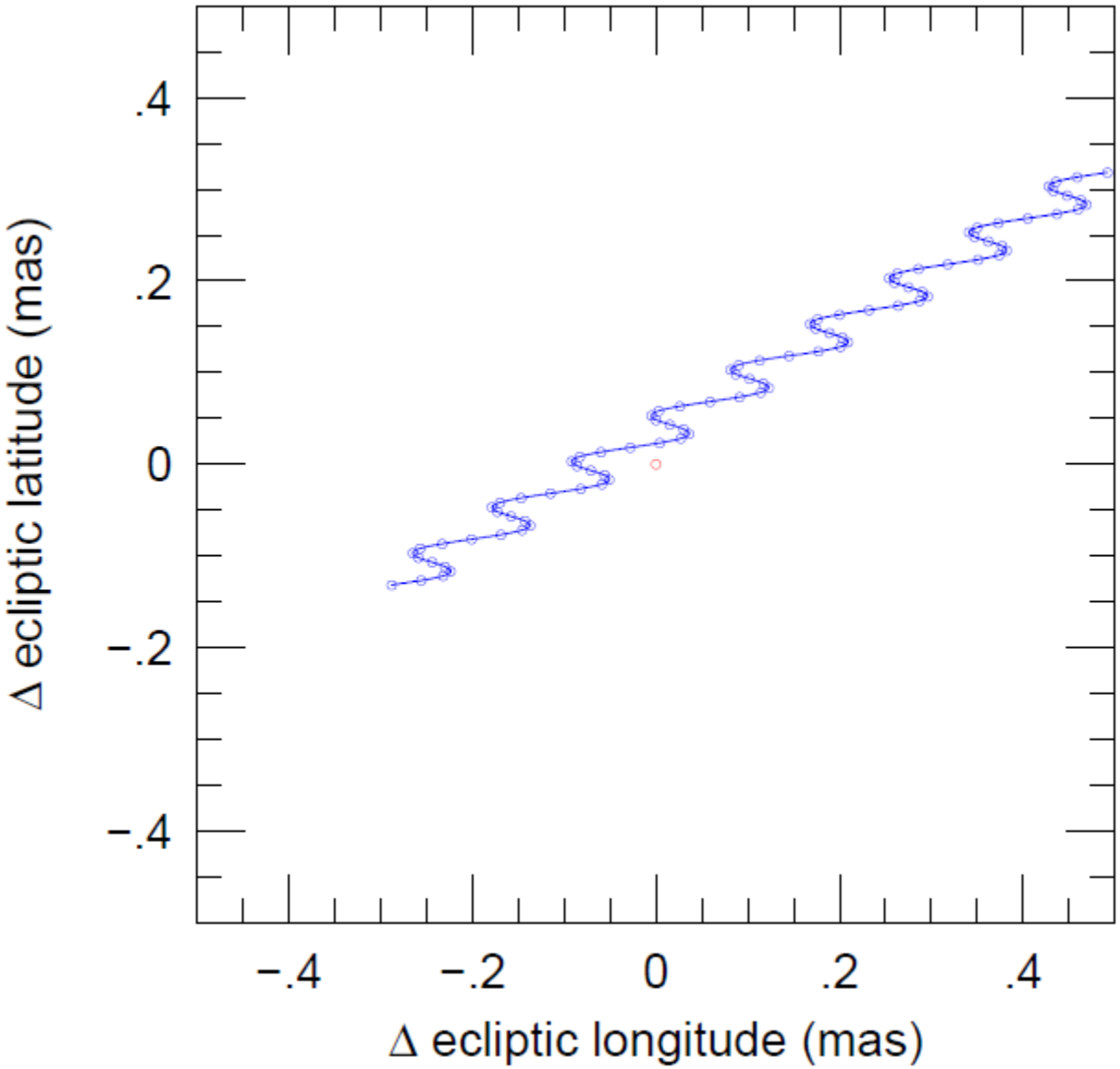


Gaudi et al. 2008, Science, 319, 927

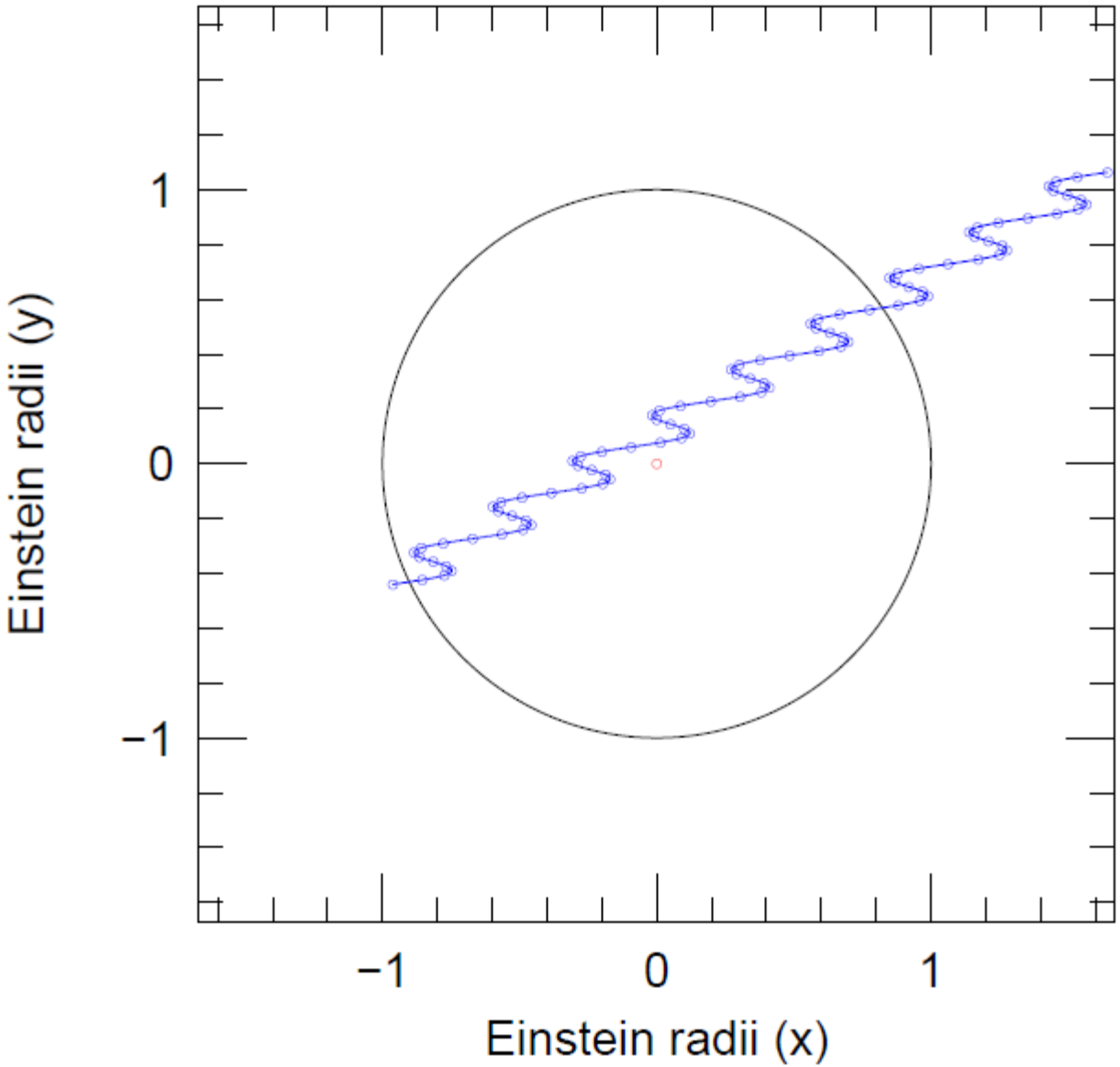
Absolute Parallax & Proper Motion (Trigonometric)

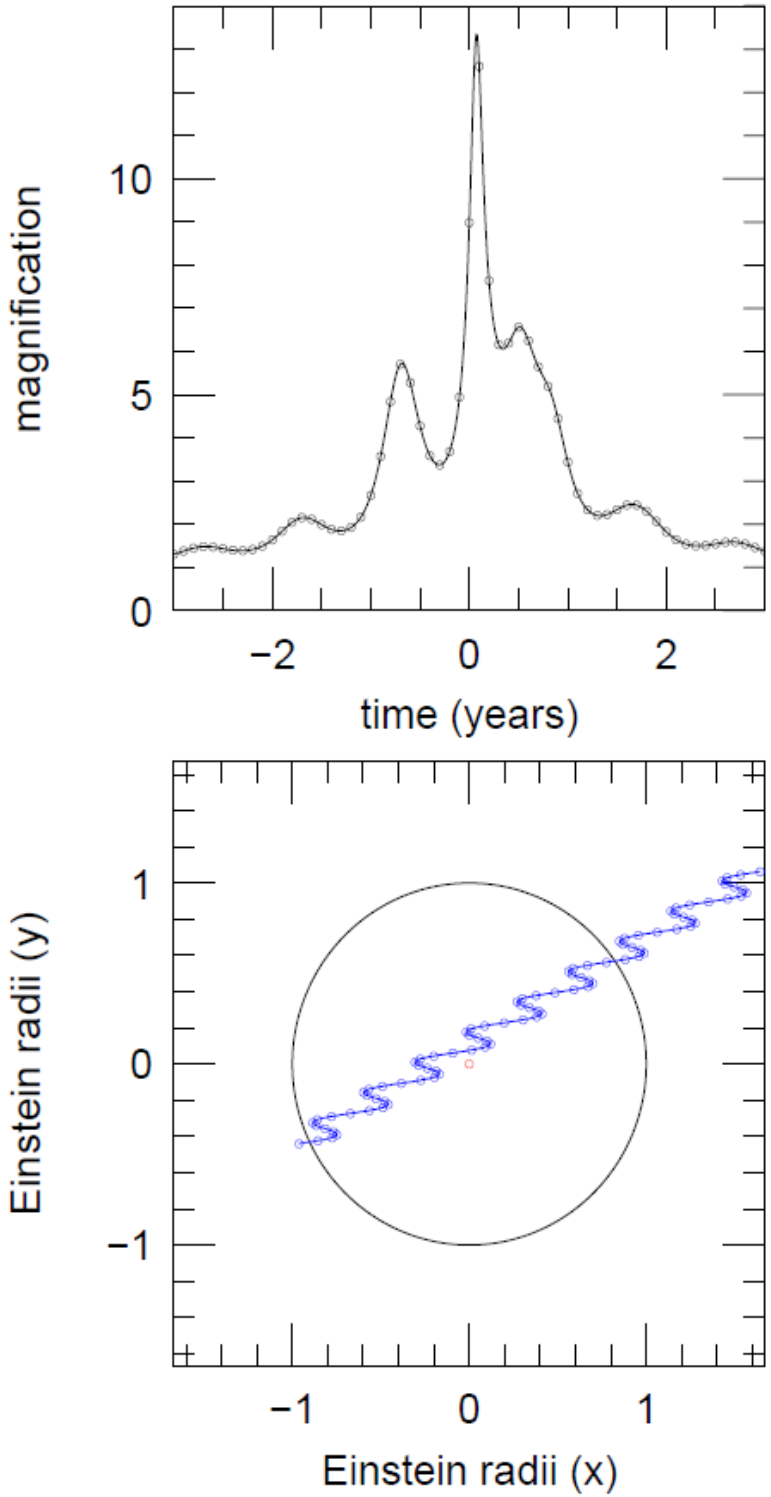


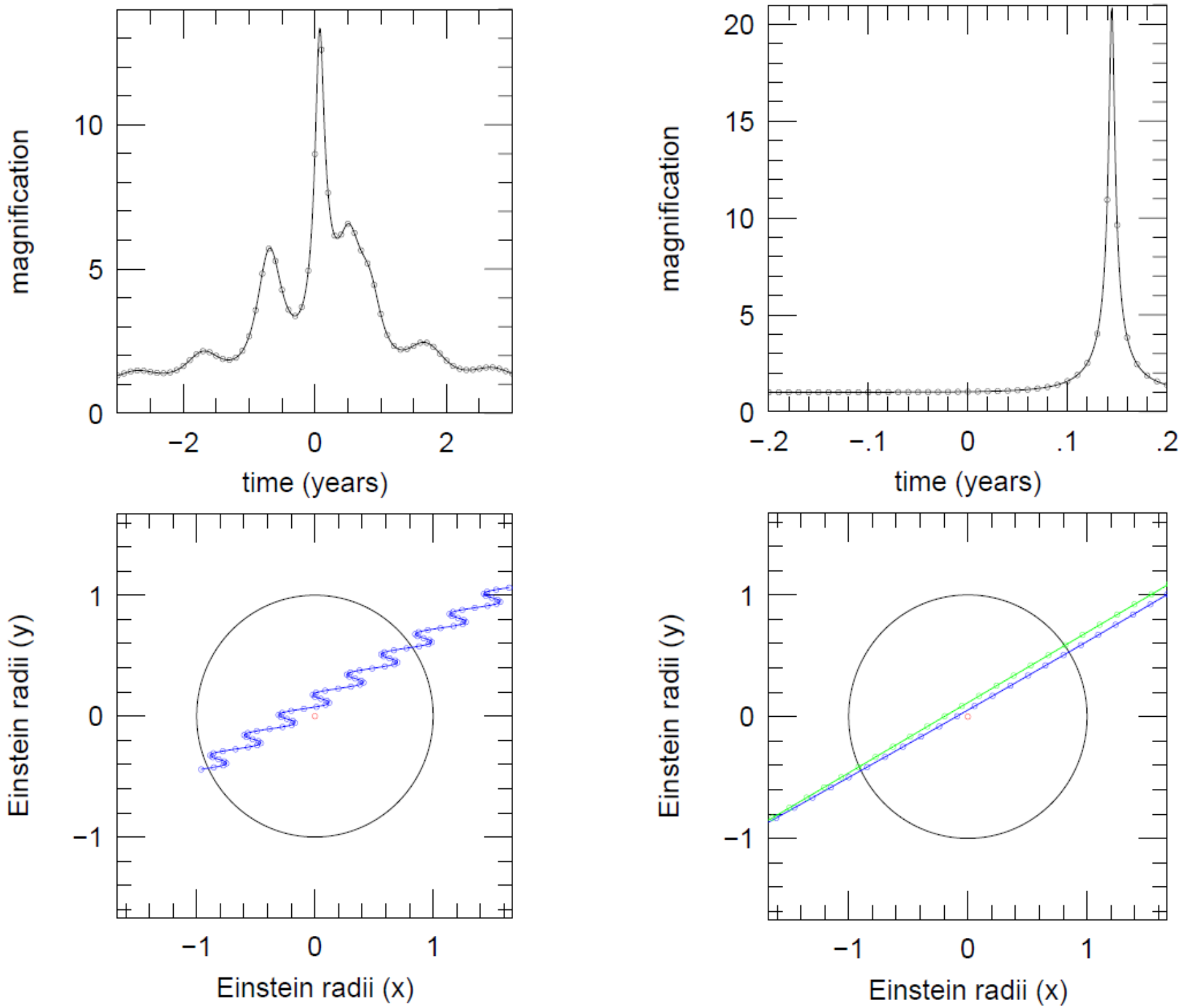
Relative Parallax & Proper Motion (Trigonometric)



Relative Parallax & Proper Motion (Microlensing)

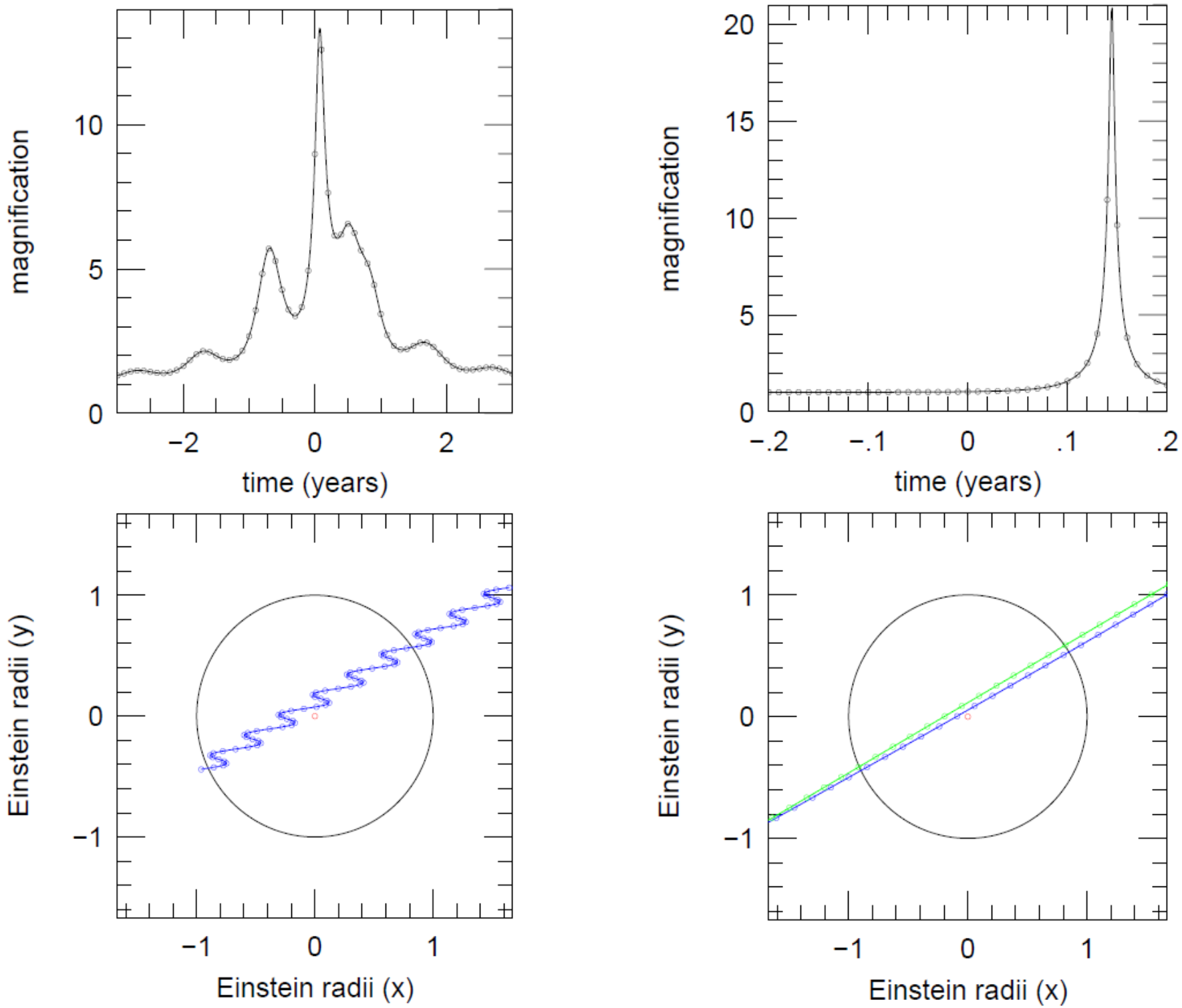



magnification
10
5
0
−2
0
2
time (years)
Einstein radii (y)
1
0
−1
−1
0
1
Einstein radii (x)

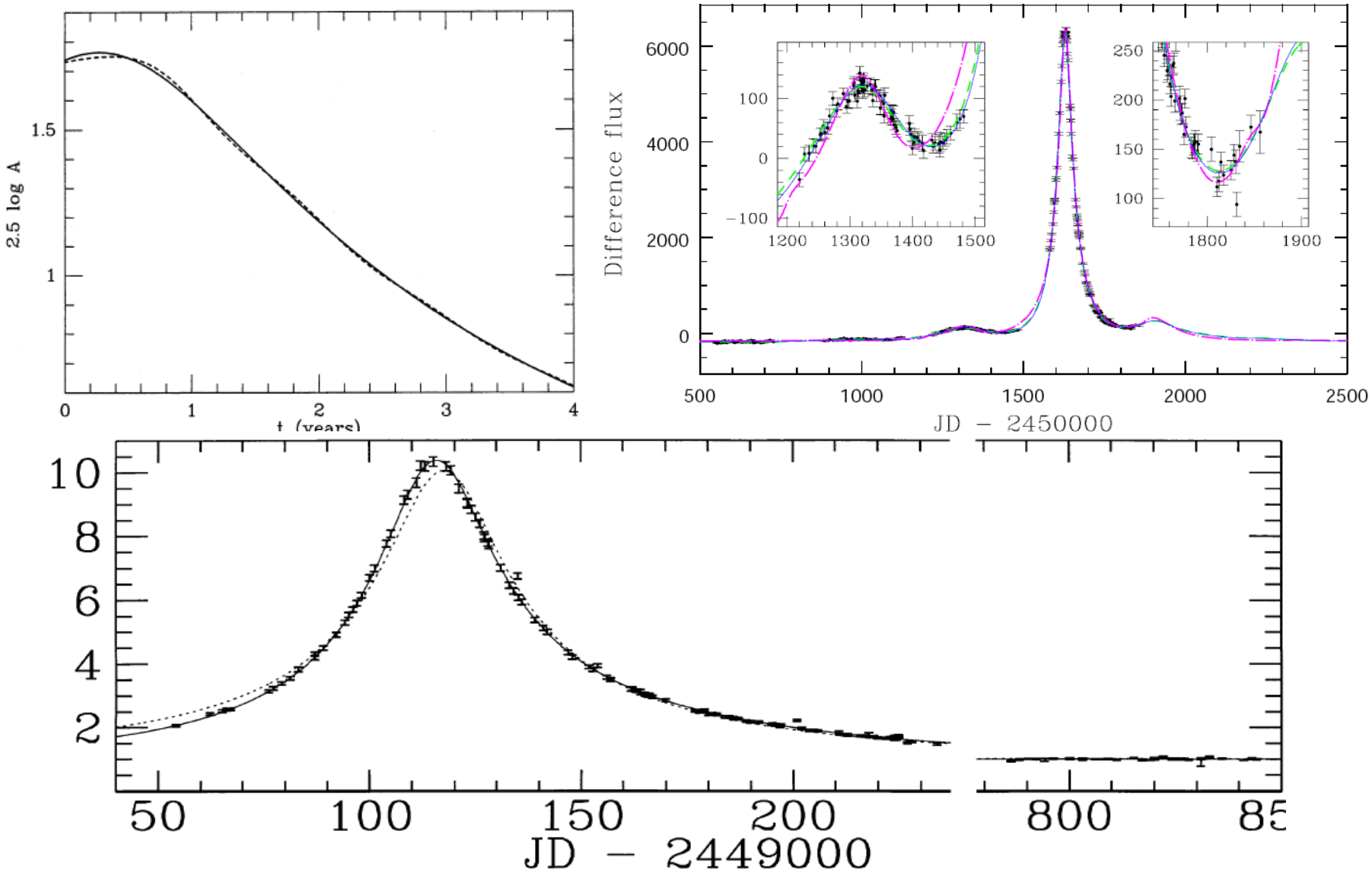

magnification
time (years)
magnification
time (years)
Einstein radii (y)
Einstein radii (x)
Einstein radii (y)
Einstein radii (x)

Major Difference Between Trig and μlens parallaxes

- Trig parallaxes and proper motions
  - (2-D) imaging
  - Proper motion: vector
  - Parallax: scalar
- μlens parallaxes and proper motions
  - (1-D) photometry
  - Proper motion: scalar
  - Parallax: vector

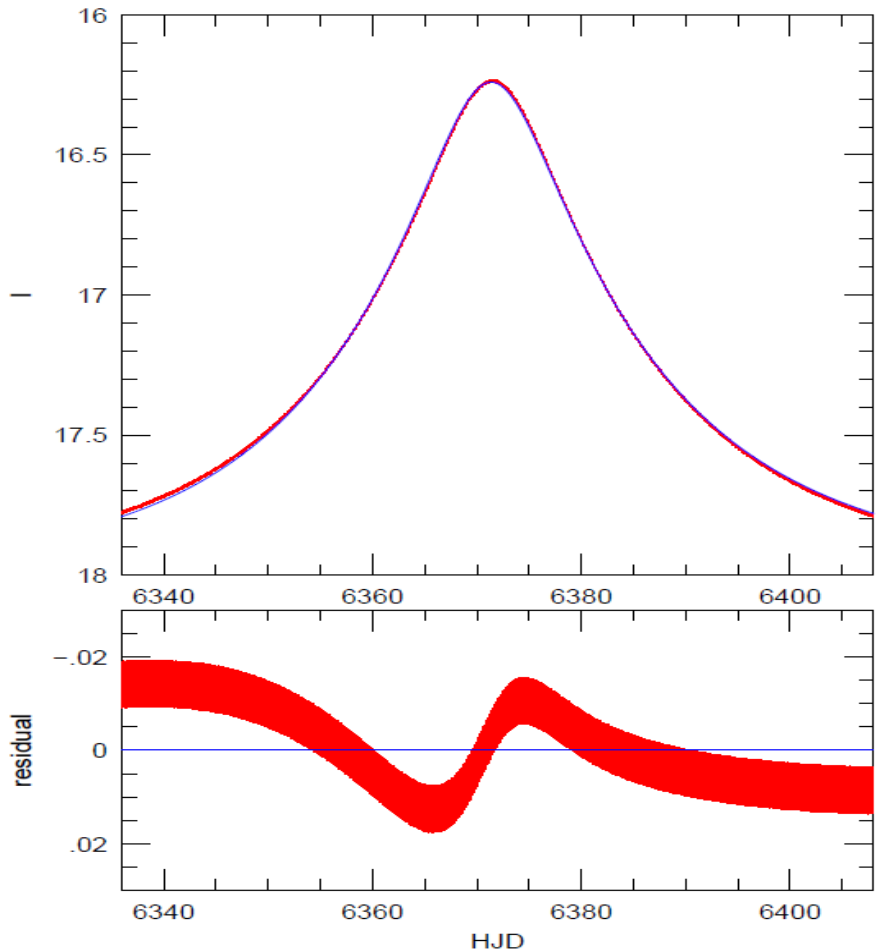

magnification
time (years)
magnification
time (years)
Einstein radii (y)
Einstein radii (x)
Einstein radii (y)
Einstein radii (x)

Parallax effects:
Predicted and Observed



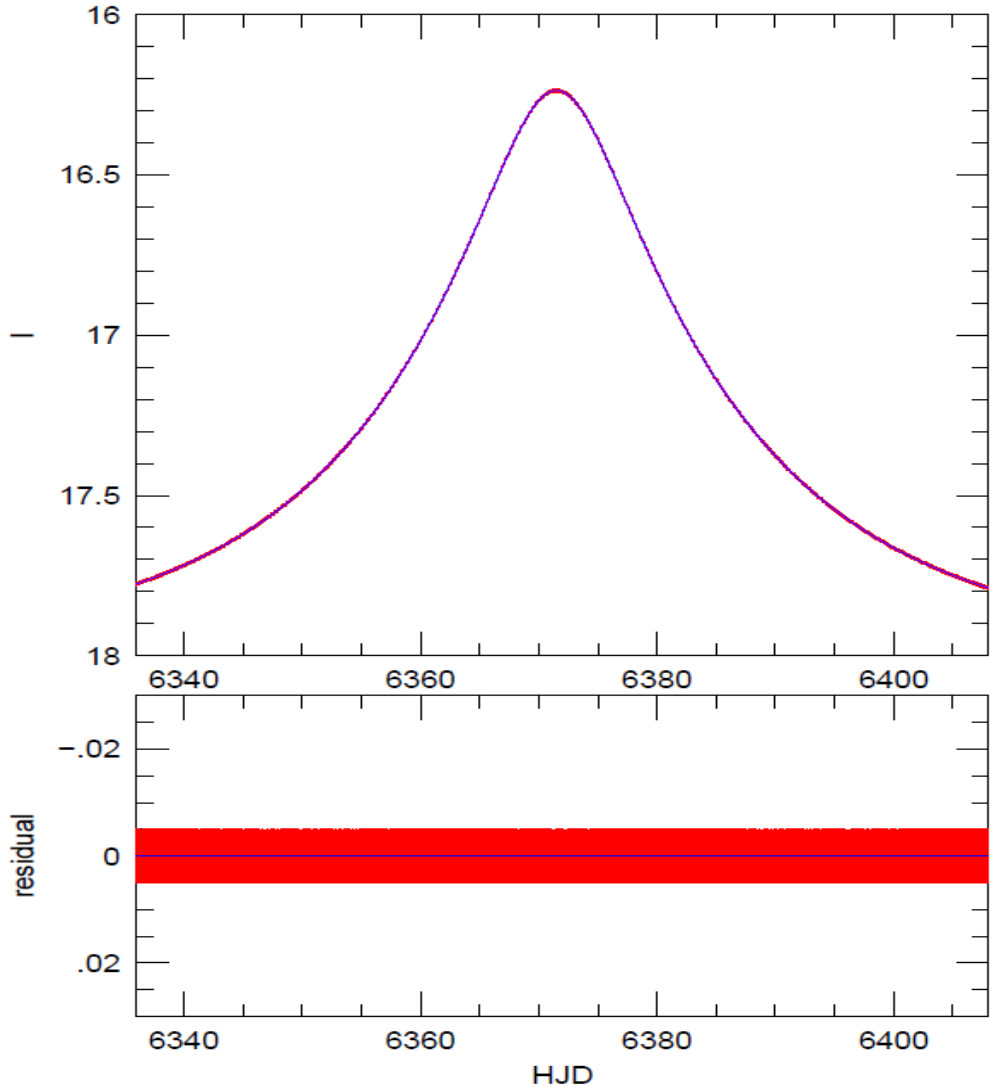
$\pi_{E,parallel}$ (square peg: round hole)

Component of π_E toward Sun



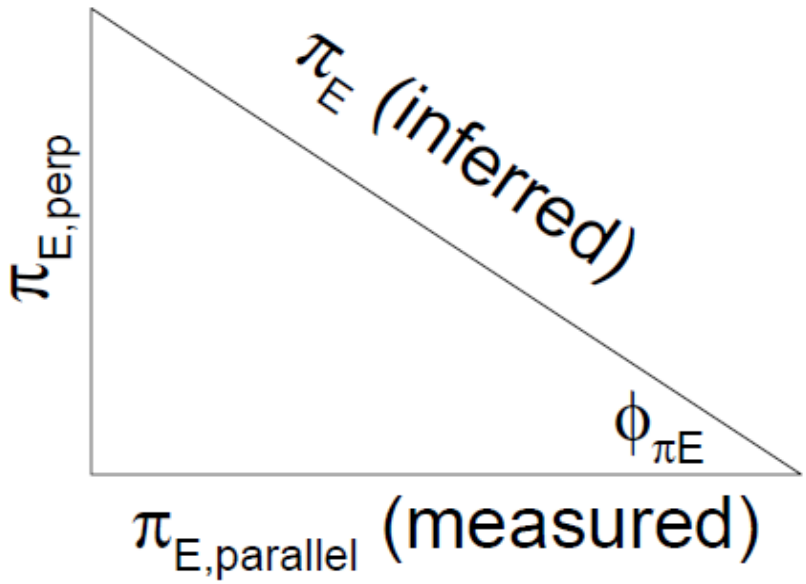
$\pi_{E,perp}$ (round peg: round hole)

Component of π_E perp to Sun



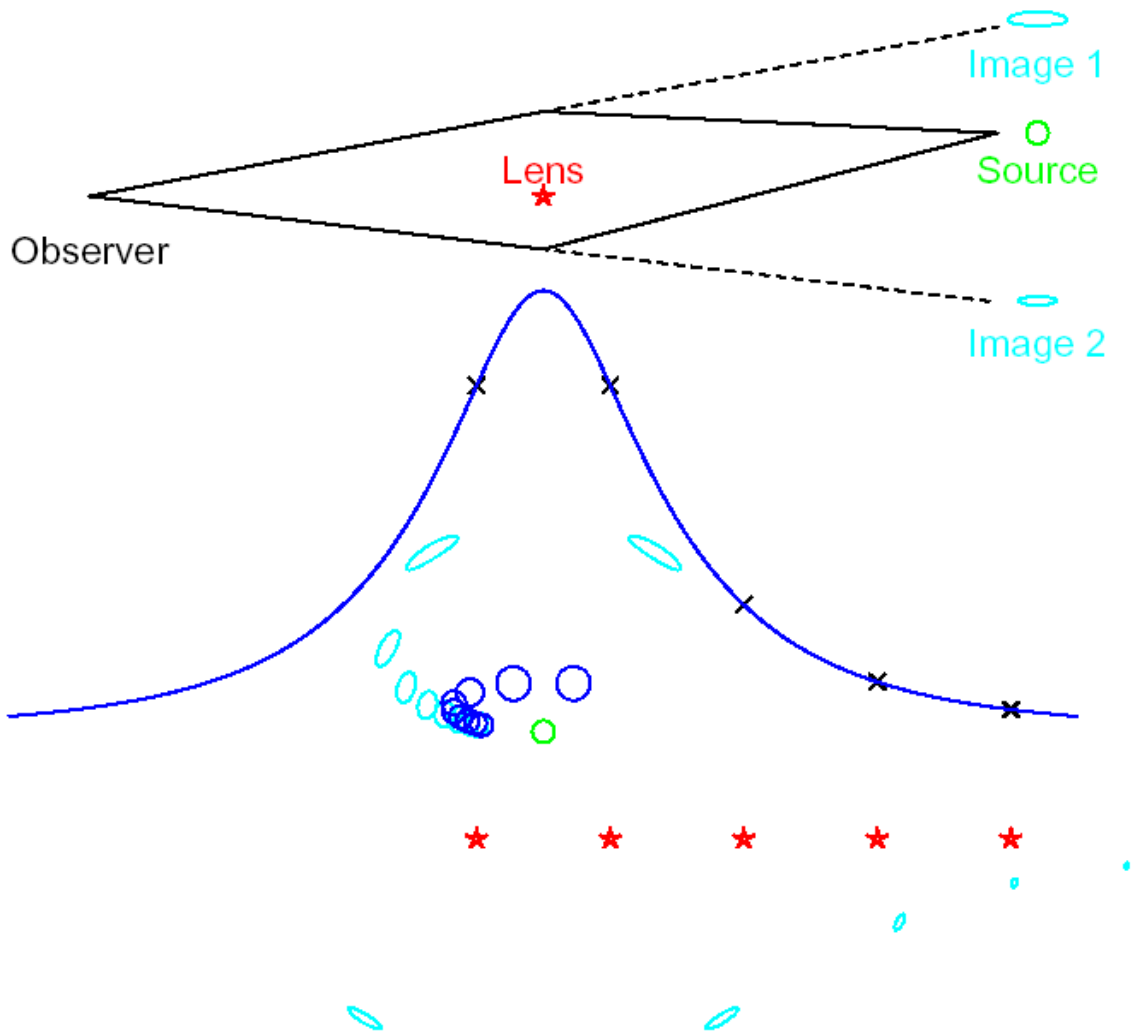
Direction of π_E = Direction of μ ... so

- Measure $\pi_{E,parallel}$ (robust)
- Measure direction of μ (ϕ_μ)
- Infer direction of π_E ($\phi_{\pi E} = \phi_\mu$)
- Derive magnitude of $\pi_E = \pi_{E,parallel}/\cos(\phi_{\pi E})$



Astrometric Microlensing

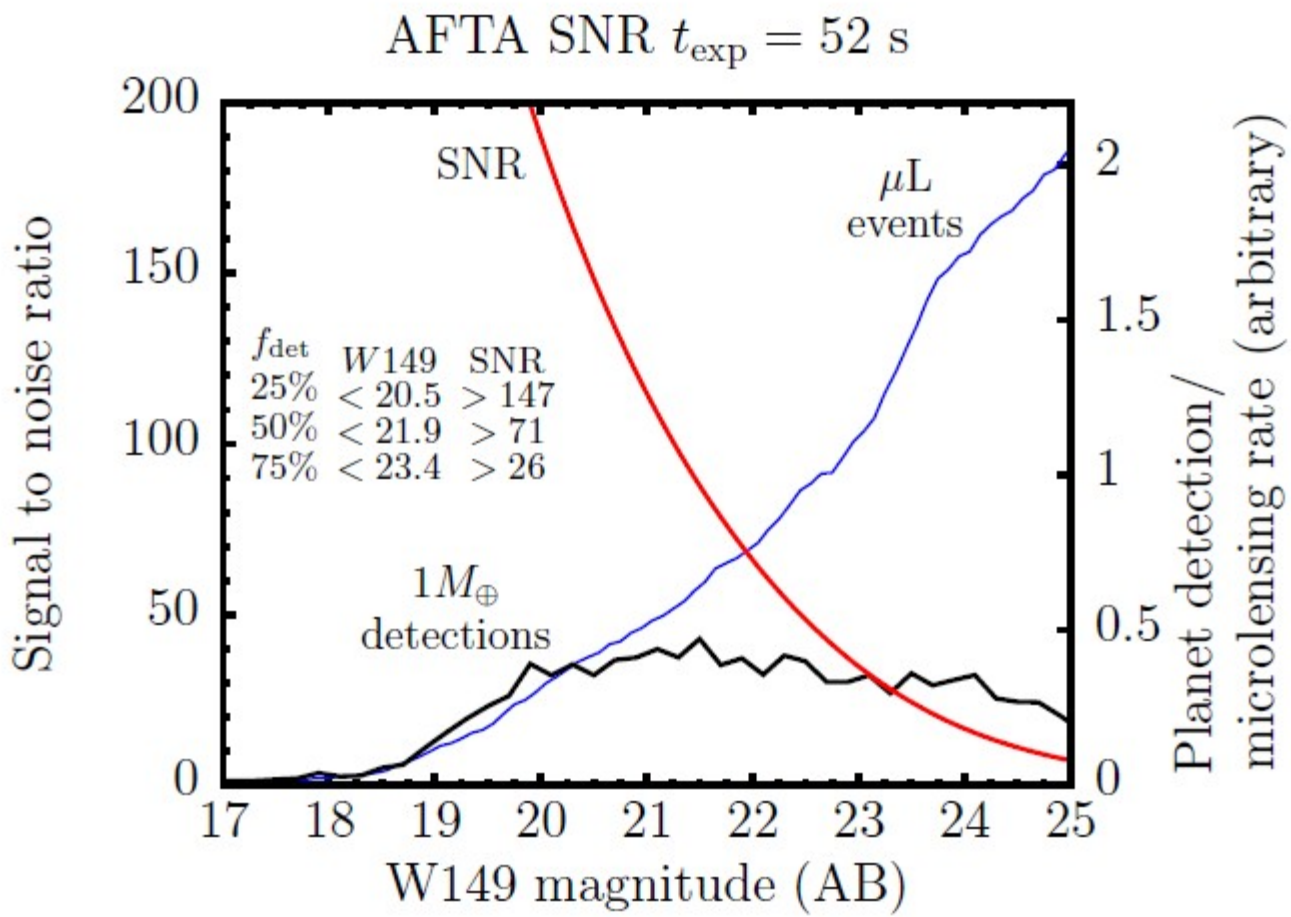
$$\Delta\theta = \theta_E/\mathrm{sqrt}(8) \sim \theta_E/3$$



Let's do a calculation!

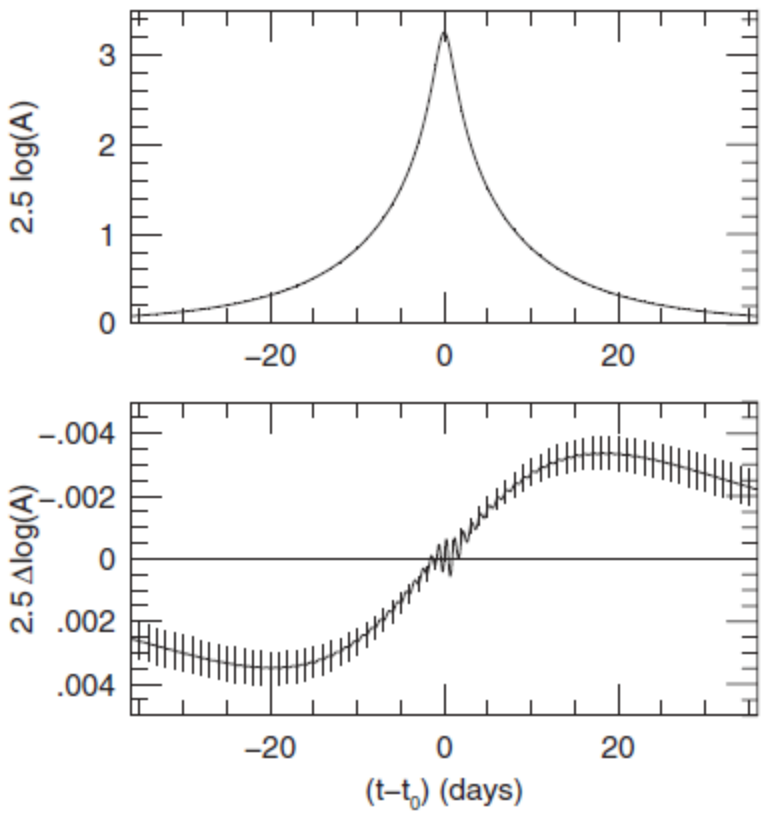
- $\theta_E \sim 300\ \mu as \Longrightarrow \Delta\theta \sim 100\ \mu as$
- PSF=175 mas => σ_θ = 75 mas/(S/N) -> 750 μas
- N = (94/day) X (15 days) = 1400
- $\sigma_{\theta,tot} = \sigma_\theta/sqrt(N) = 20\ \mu as$ (5 sigma)

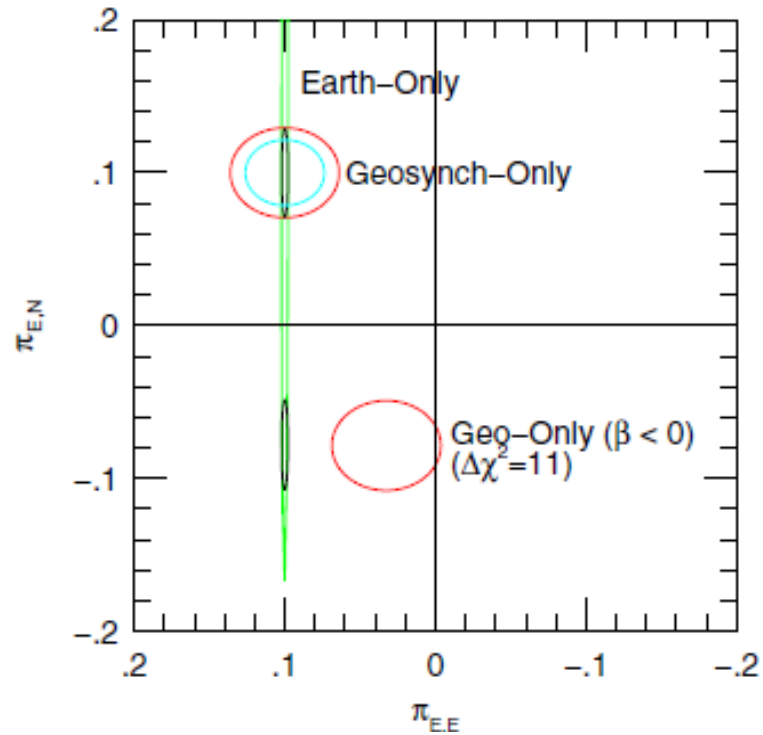
Simulations by Matthew Penny:
1/2 of planetary events have S/N>100



Other methods: similar challenges

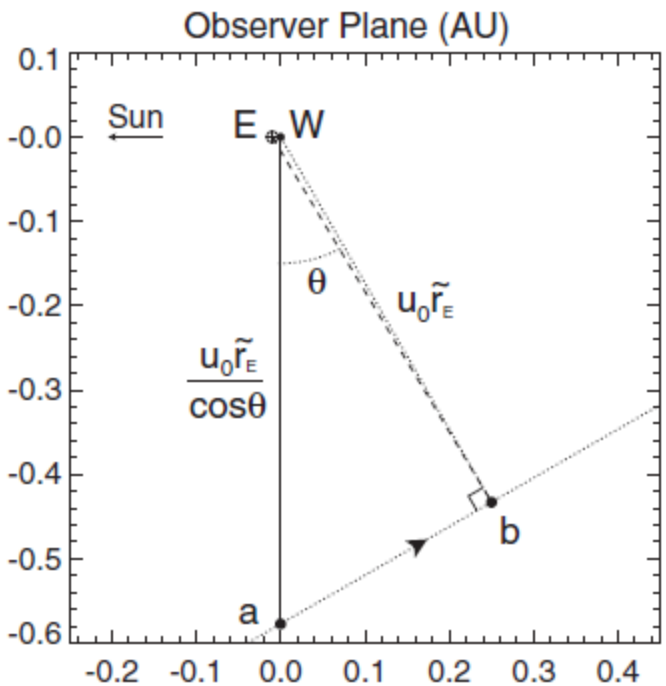
Geosynchronous Parallaxes

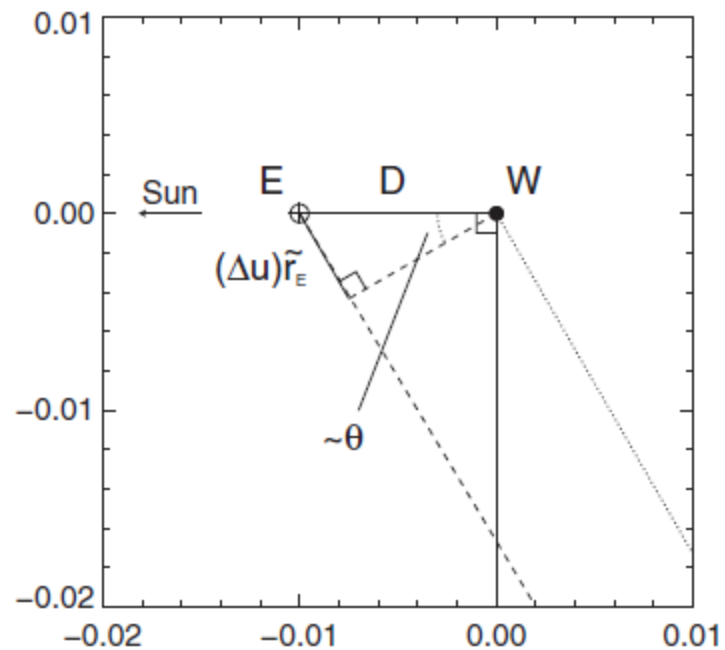




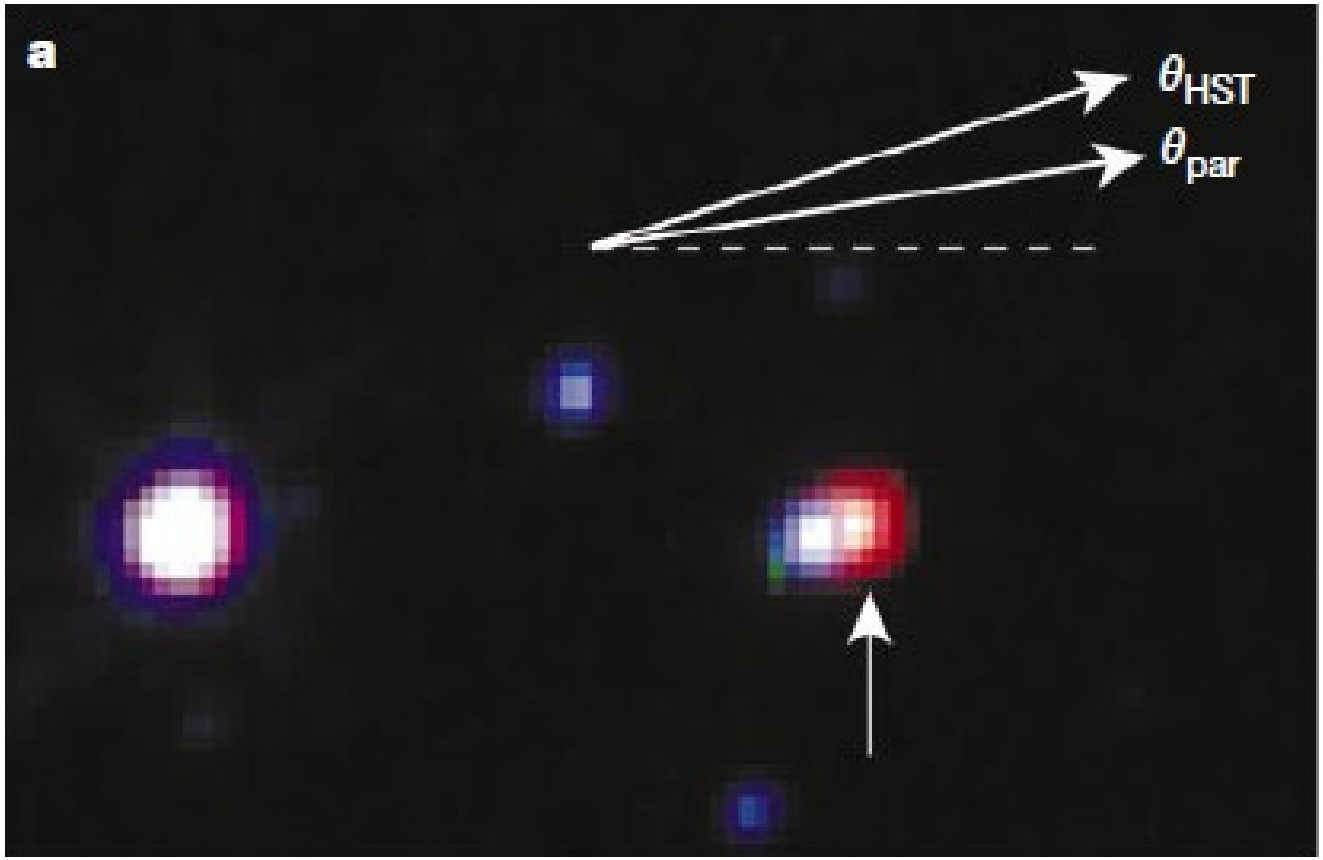
Other methods: similar challenges

L2 Parallaxes





For Ground Truth: HST (now!)

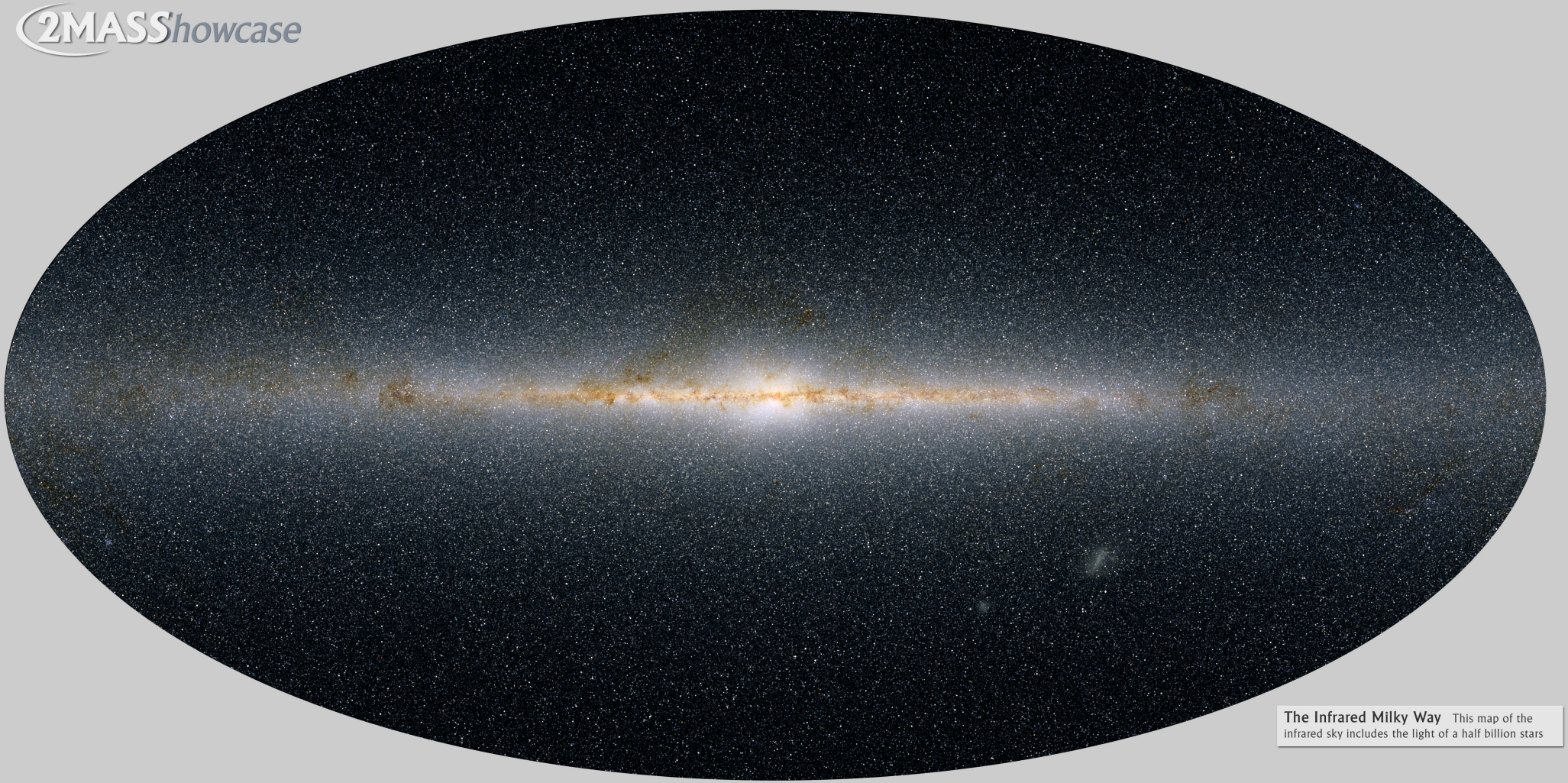


HST can check substantial subsample

- Must be bright enough to see (but not too bright!)
- Must move "FWHM" in $\Delta t \sim 10$ years
  - $\mu_{min} = (1.22\ \lambda/D)/\Delta t$ --> 8.5 mas/yr (I band!)
- $\sigma_\mu = 3.0$ mas/yr ($<< \mu_{min}$)
- $f = [2/\mathrm{sqrt}(\pi)] \times \exp(-x^2)$ $[x = \mu_{min}/2\sigma_\mu$ ––>1.4]
  - --> 21%

Milky Way

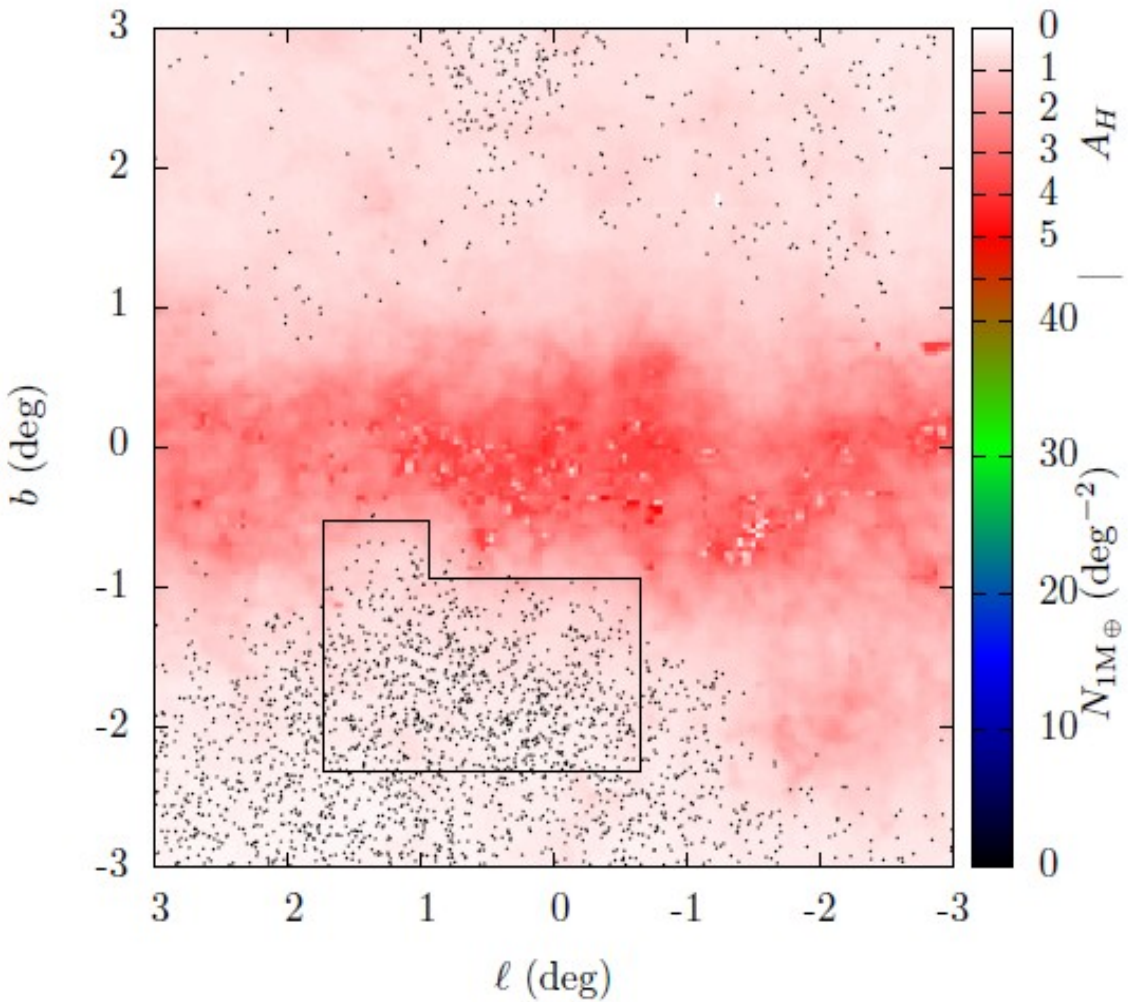
Milky Way



The Infrared Milky Way This map of the infrared sky includes the light of a half billion stars

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

I-band ok for ~60% of WFIRST field



Bottom Line

- Most astrometric (or geosynchronous, etc.) mass measurements will be near detection limit. Therefore, these techniques *must* be tested against HST "ground truth" to be reliable.

Other WFIRST Science from HST-NOW Observations

- Black Holes and Neutron Stars
  - Mass function
  - Galactic distribution
  - Transverse velocity distribution
- Brown Dwarfs
  - Binary mass and separation function
  - Additional isolated BD masses
- Stellar distribution (mass and distance)

Human Resources?

Human Resources?

- Build it and they will come

Complete list of US Planetary μLensing PhDs (2000+)

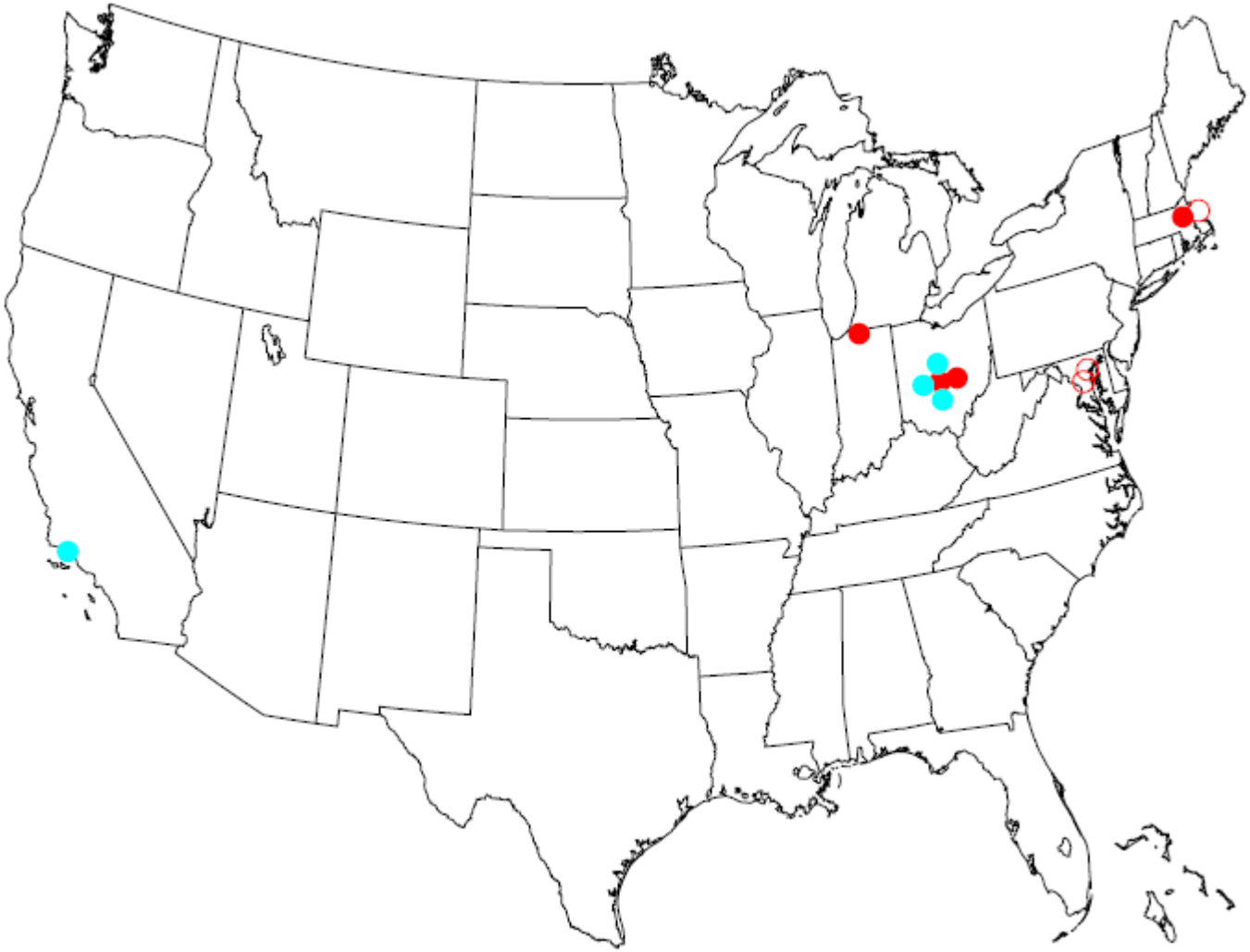
Table 1: US Planetary μLens Students (3rd Millenium)

Student	Graduation	Institution	Advisor
B. Scott Gaudi	2000	OSU	AG
Jin H. An	2002	OSU	AG
Subo Dong	2009	OSU	AG
Jennifer C. Yee	2013	OSU	AG

Complete list of US Planetary μLensing Postdocs (2000+)

Table 2: US Planetary μLens Postdocs (3rd Millenium)

Postdoc	Years	Country of Orig	Institution	Advisor
Rachel Street	2007-2009	United Kingdom	LCOGT	Tim Brown
Jan Skowron	2009-2012	Poland	OSU	AG
Virginie Batista	2011-2014	France	OSU	AG
Matthew Penny	2011-2014	United Kingdom	OSU	Scott Gaudi
Radek Poleski	2012-2015	Poland	OSU	AG
Jennifer Yee	2013-2016	US	CfA	John Johnson

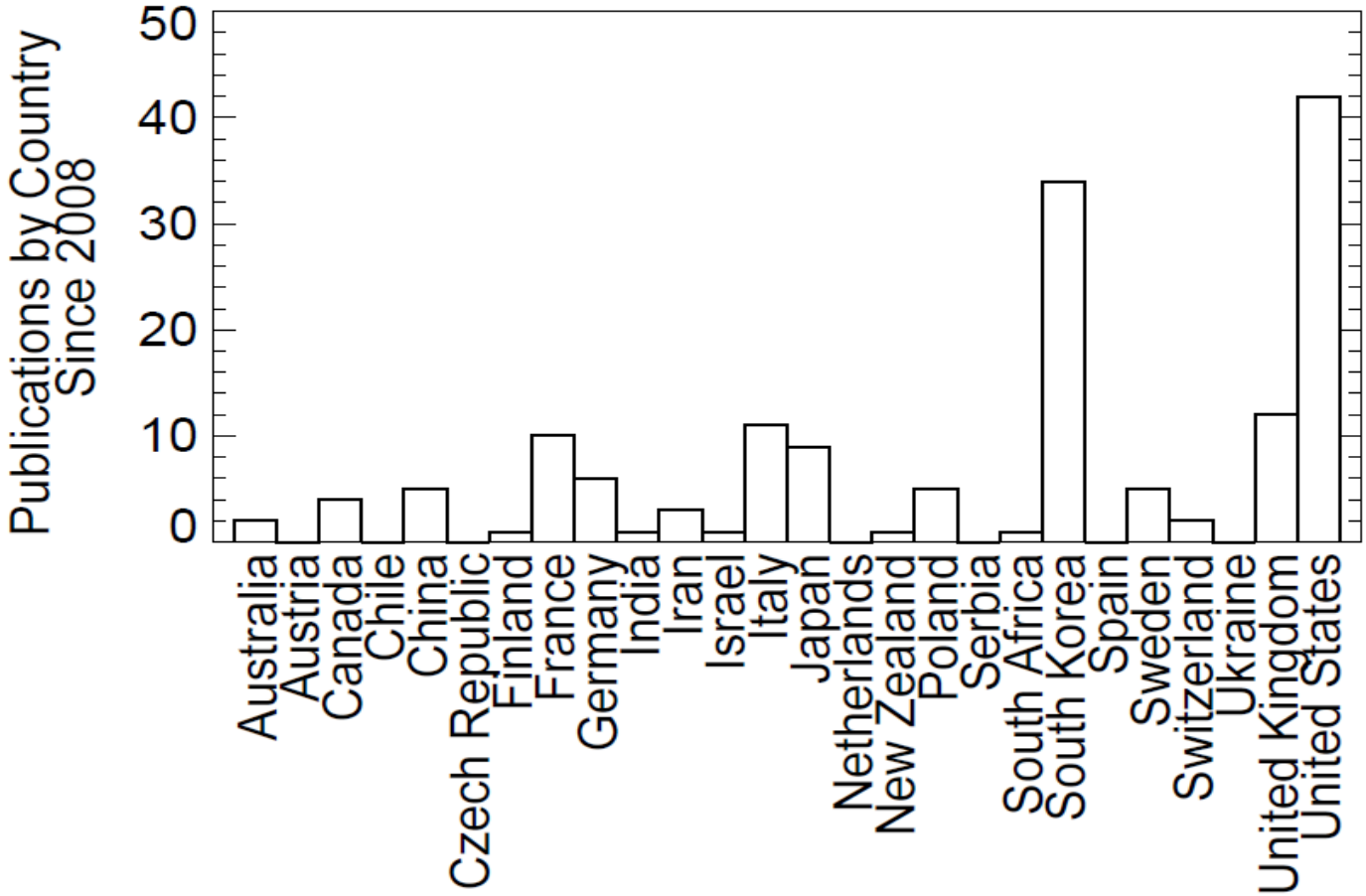


Complete list of World Planetary μLensing Surveys

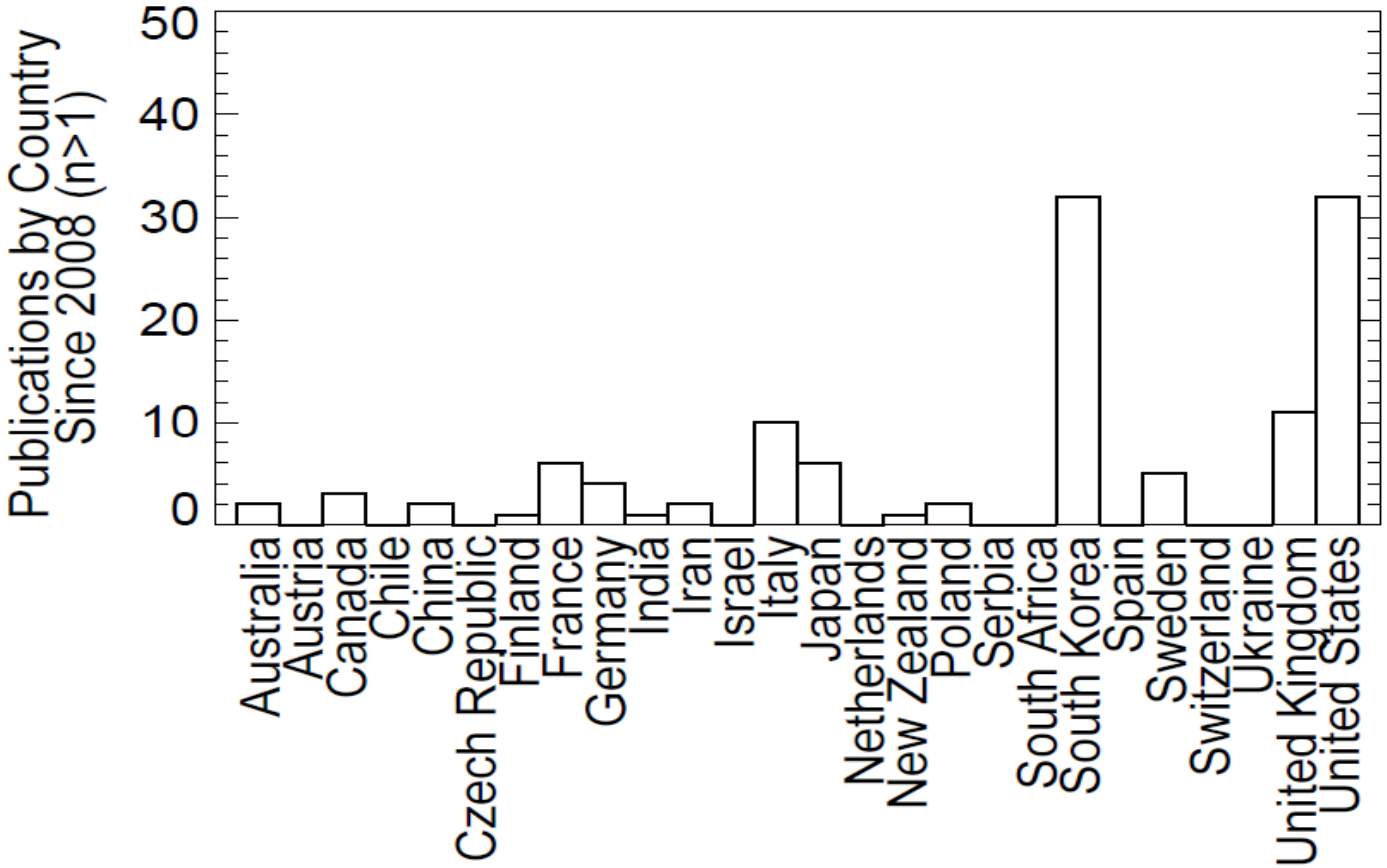
Table 3: World Planetary μLens Surveys

Name	Start	Country	Aperture	MegaPxl
OGLE-II	1998	Poland	1.3m	67
MOA-I	2000	Japan/NZ	0.6m	24
OGLE-III	2002	Poland	1.3m	67
MOA-II	2006	Japan/NZ	1.8m	84
OGLE-IV	2010	Poland	1.3m	268
KMTNet	2014	Korea	$3\times(1.6\text{m})$	3×324

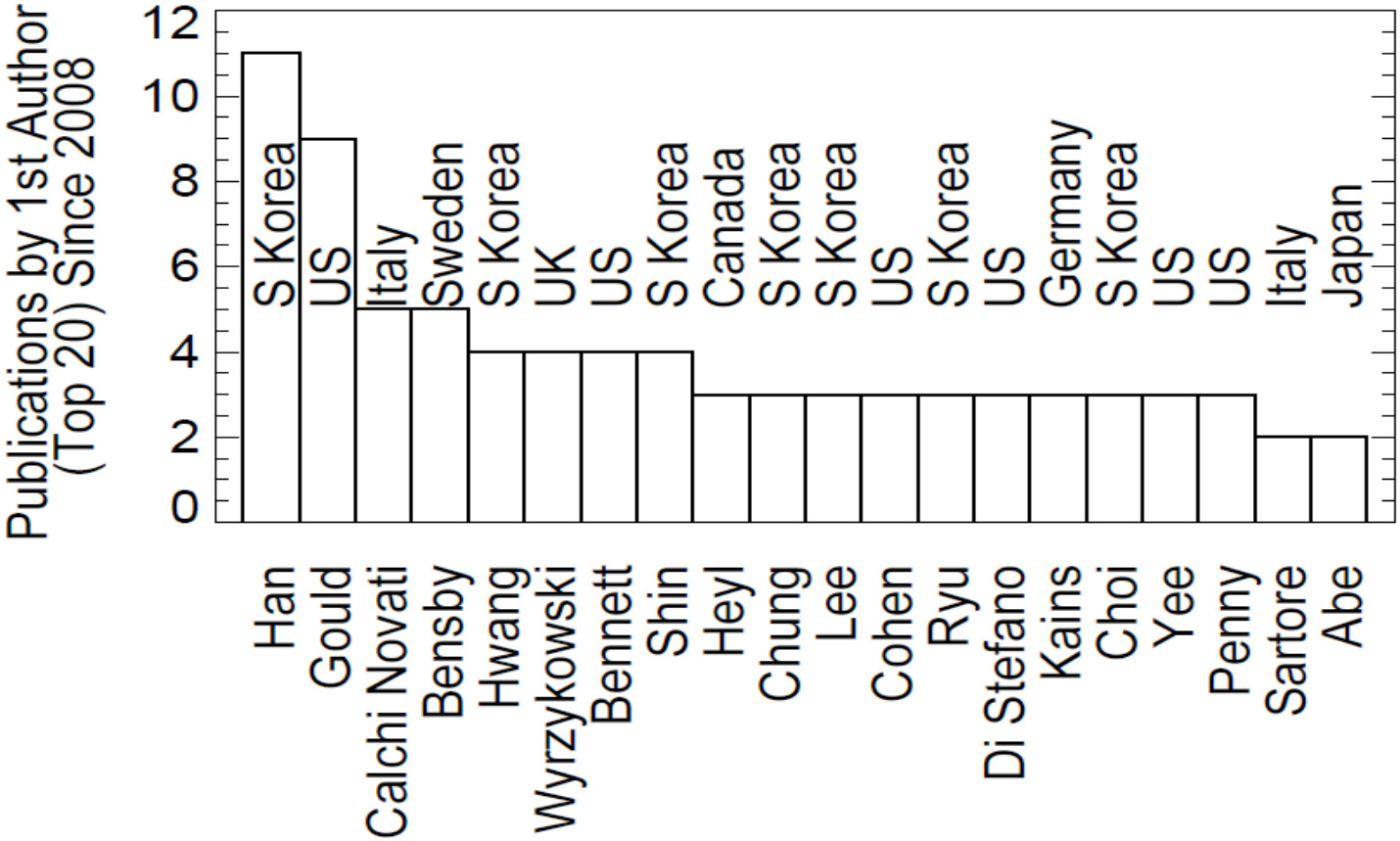
μlens papers by country of 1st author



μlens papers by country of 1st author
(excluding dilettantes)



μlens papers by 1st author
(with country)



Bottom Line

- To be competitive requires front-line experiments.

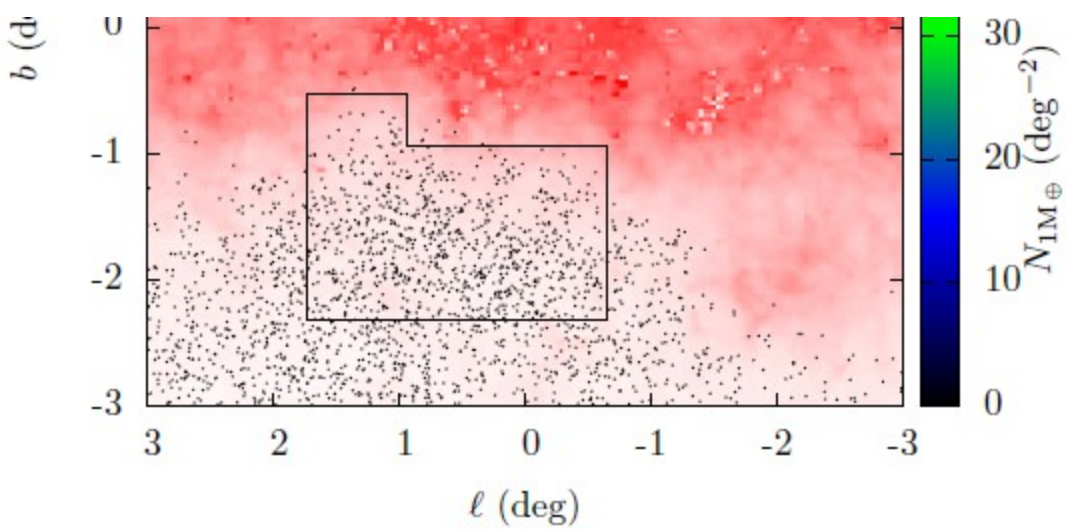
US Competitive Assets: Mostly NASA!

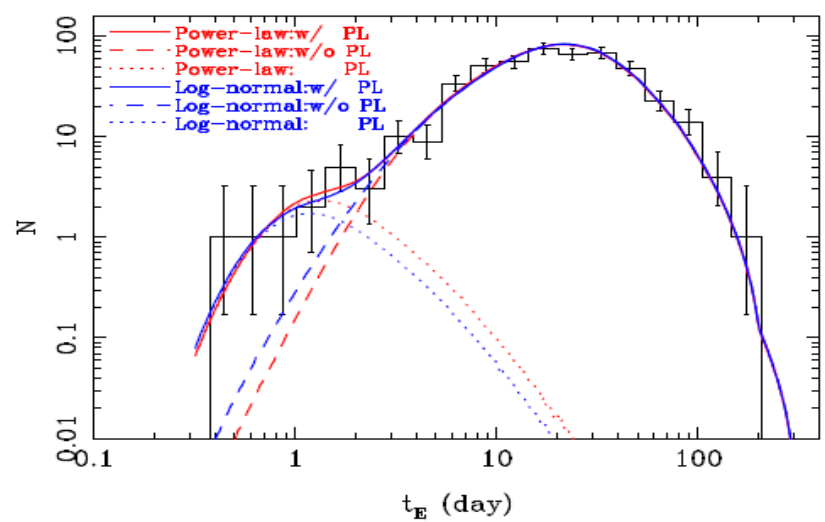
- *HST*-NOW survey (also yields science now)
- *HST* μLens event followup: instant science
- *Spitzer* μLens parallaxes
- *Kepler* μLens parallaxes
- H-band μLens planet survey
- LBT M31 μLens planet survey

HST-NOW Survey for WFIRST

Immediate Science

- Rough mass estimates (or upper limits) of all historic µlens events in this area
  - Much better characterization of lens population
  - Near perfect vetting of BH parallax candidates
- VG mass estimates (or upper limits) of all historic µlens planets in this area





HST μlens event followup
Instant science

- Precision mass/distance estimates for signficant fraction of planets being found in current surveys
- Proven technique:
  - 1st confirmed Mdwarf/sup-Jup (Dong et al. 2009)
  - 1st confirmed Cold Neptune (Bennett etal, in prep)
  - 1st probe of binary+planet (Dong etal, in prep)
  - Partial confirm of 1st μlens BD (AG etal, 2009)

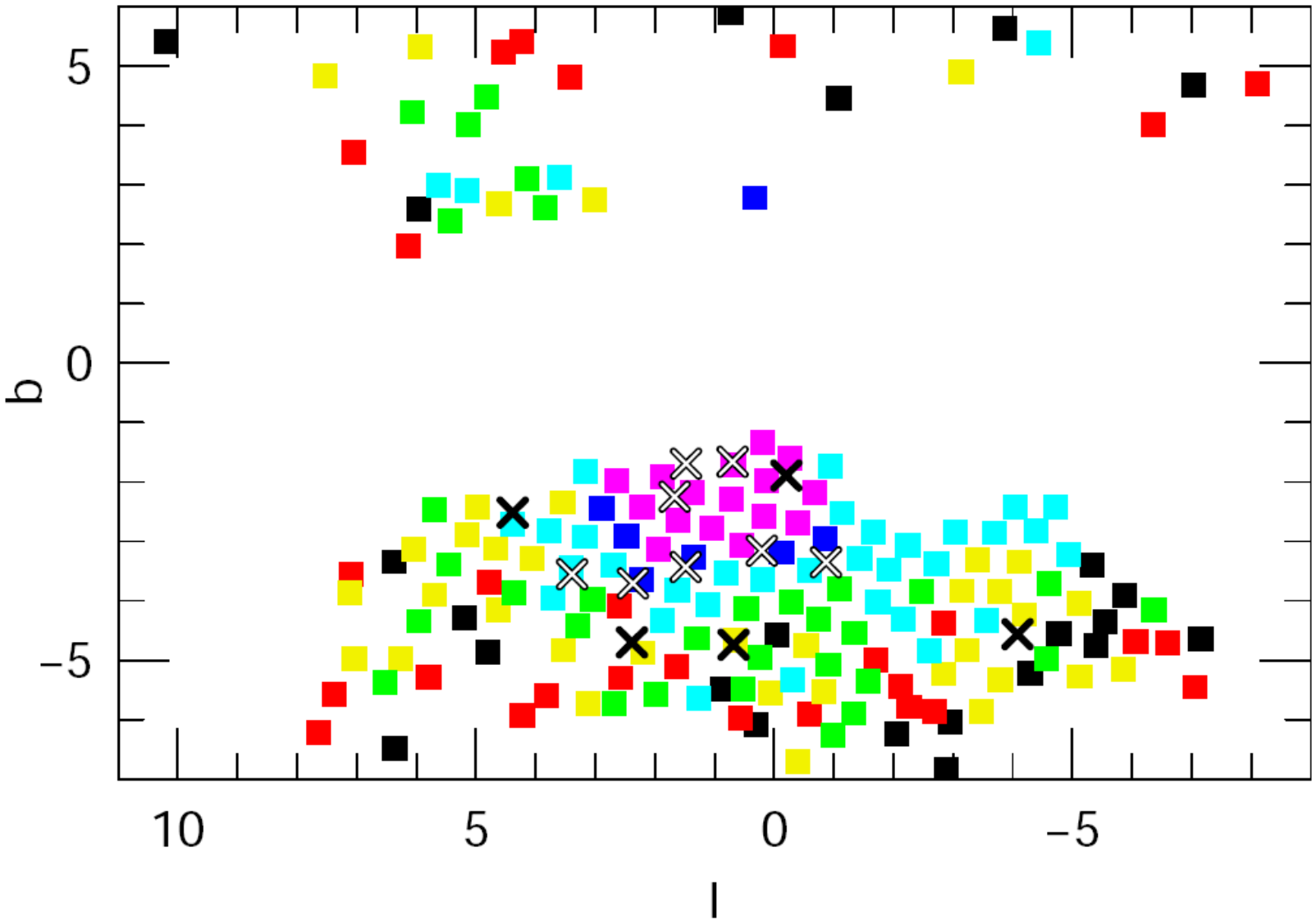
    [could be completed by additional data now]

Spitzer & *Kepler* μlens Parallaxes

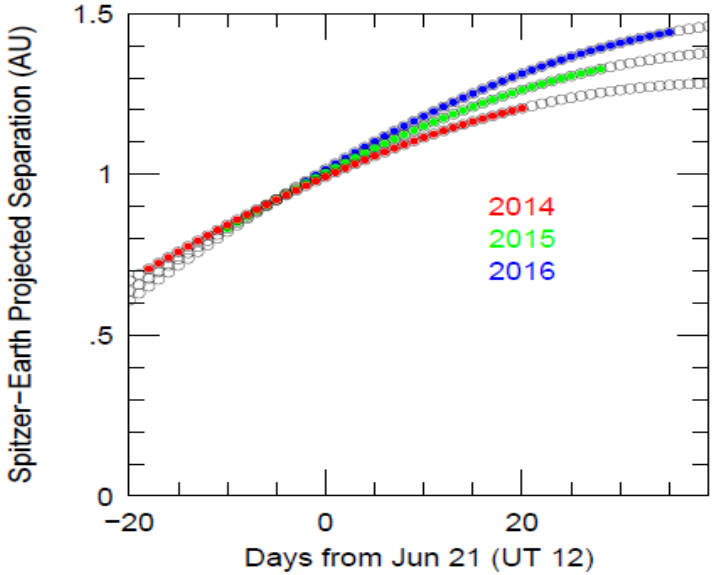
- ~4 μlens (mass+distance)/yr [for each]

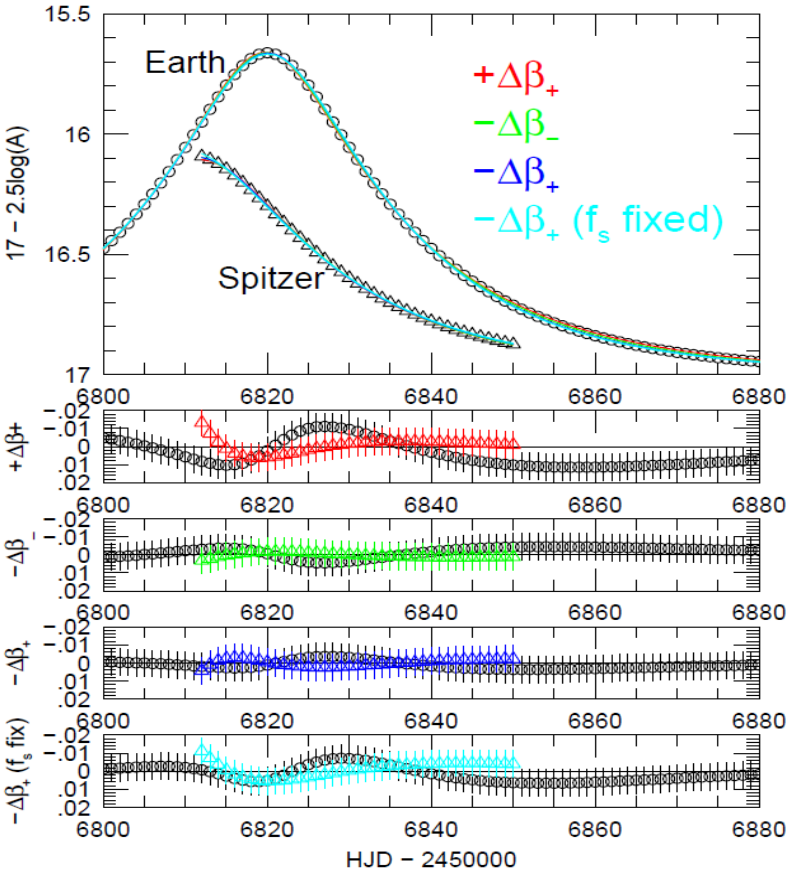
  (maybe more for *Kepler*)
- Galactic Distribution of Planets
- Complements WFIRST
  - Much shallower but wider area
- Potential path-finder for future mission

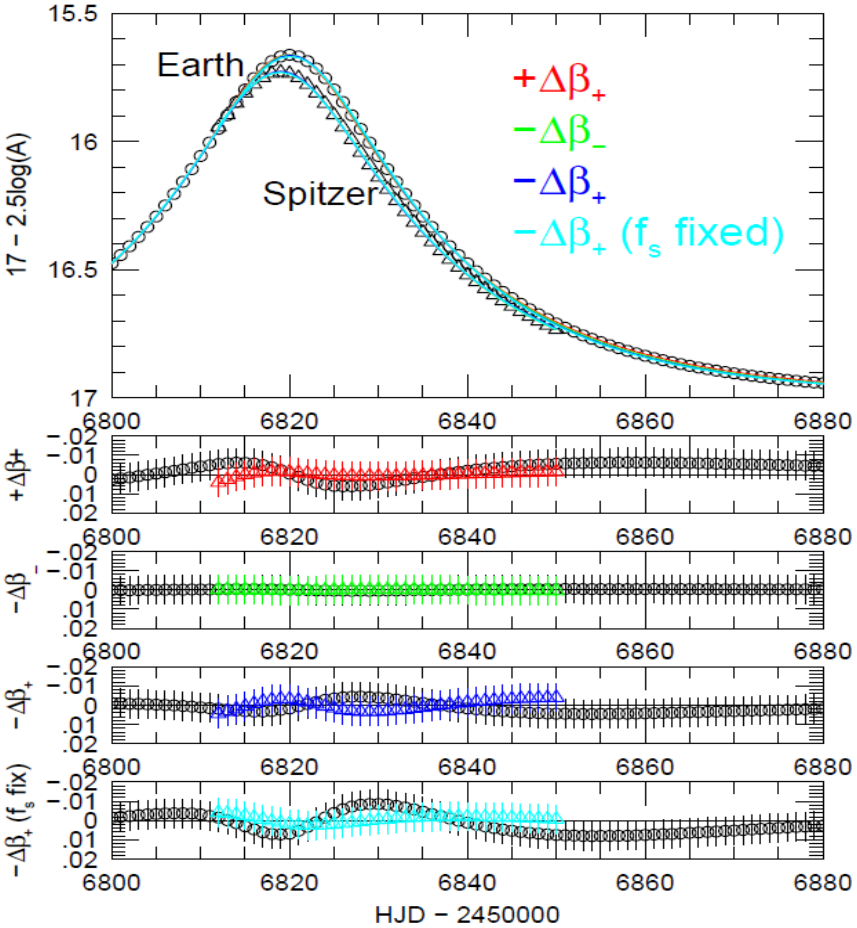
Distribution of Planets on Sky



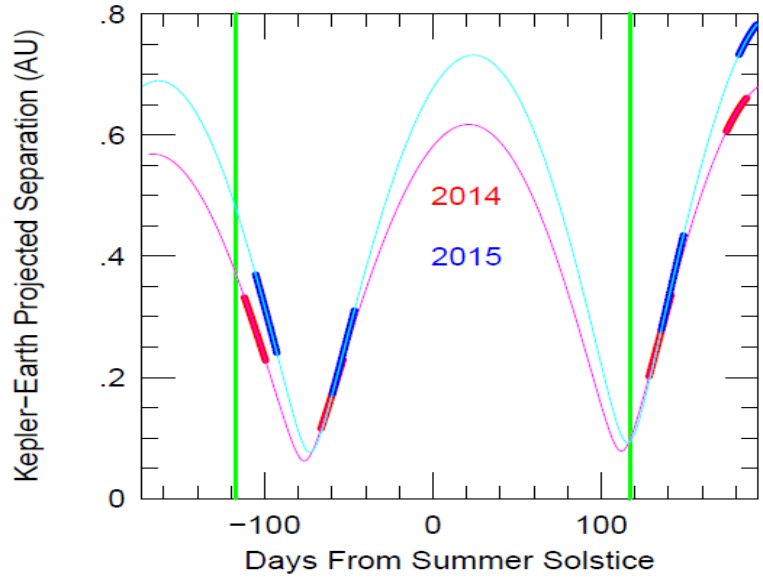
Spitzer

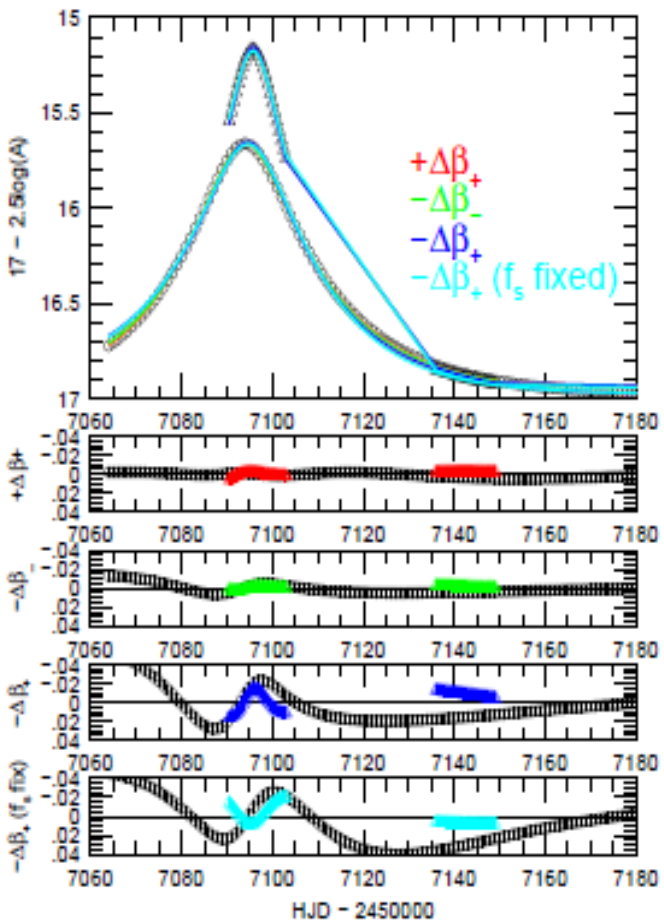

Spitzer−Earth Projected Separation (AU)
Days from Jun 21 (UT 12)
2014
2015
2016

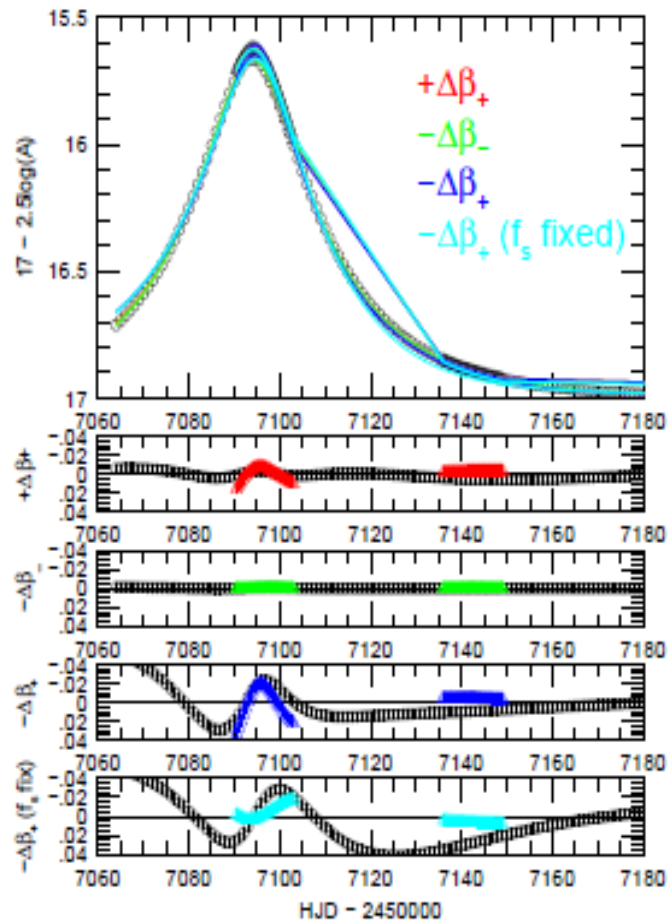

Earth
Spitzer
+Δβ+
−Δβ−
−Δβ+
−Δβ+ (fs fixed)
17 − 2.5log(A)
HJD − 2450000


Earth
Spitzer
+Δβ+
−Δβ−
−Δβ+
−Δβ+ (fs fixed)
17 − 2.5log(A)
HJD − 2450000

Kepler


Kepler−Earth Projected Separation (AU)
Days From Summer Solstice
2014
2015


17 − 2.5log(A)
+Δβ+
−Δβ−
−Δβ+
−Δβ+ (fs fixed)
HJD − 2450000


17 − 2.5log(A)
+Δβ+
−Δβ−
−Δβ+
−Δβ+ (fs fixed)
HJD − 2450000

H-band μlens Planet Survey

- Best way to understand WFIRST fields

  (obviously not as deep: probe faint sources using high-magnification events)

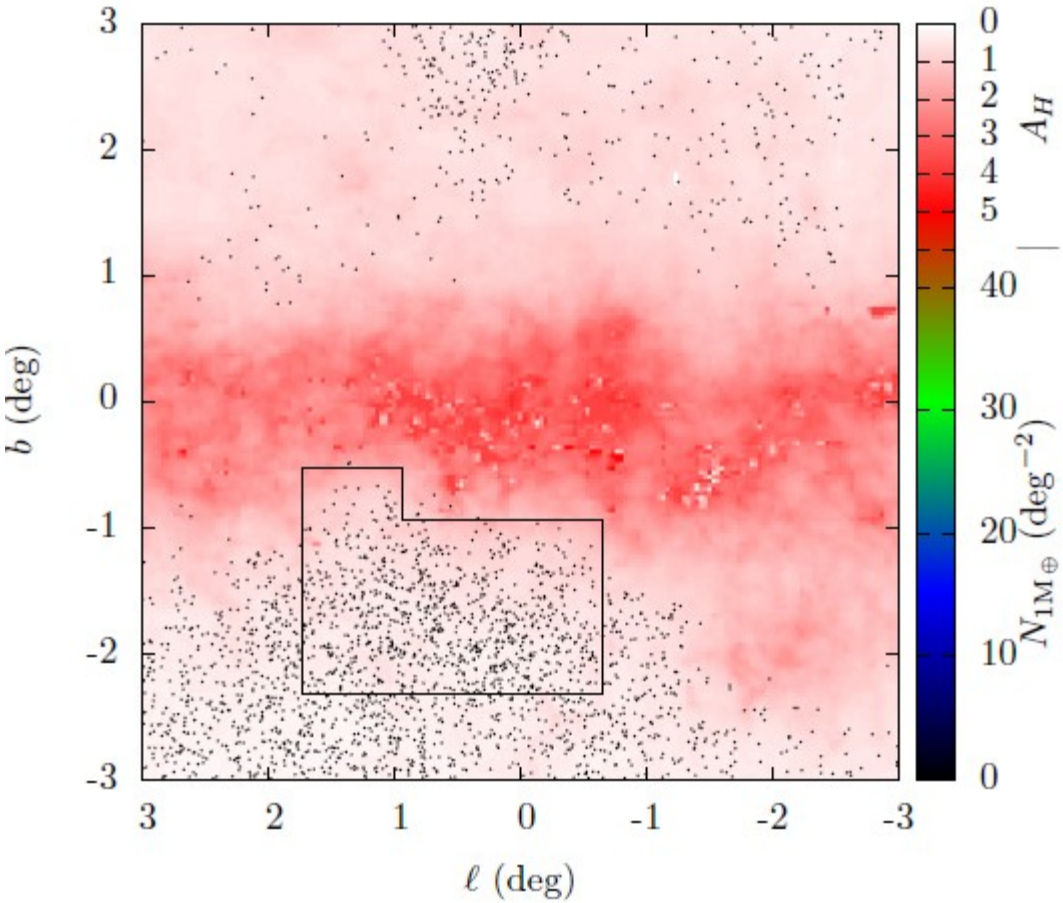
- Synergy with optical surveys (H_s for followup)

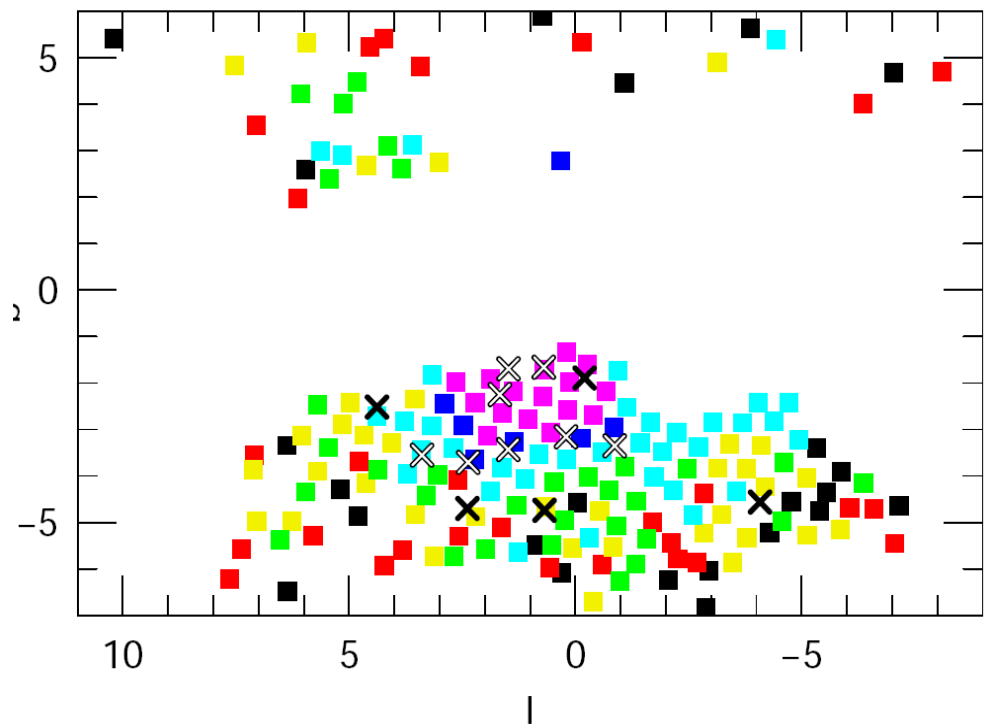
  (real value-added)

- How? B^4 = Beg, Borrow, Build, or Buy

  V^3 = VVV ($?^3$ = ???)

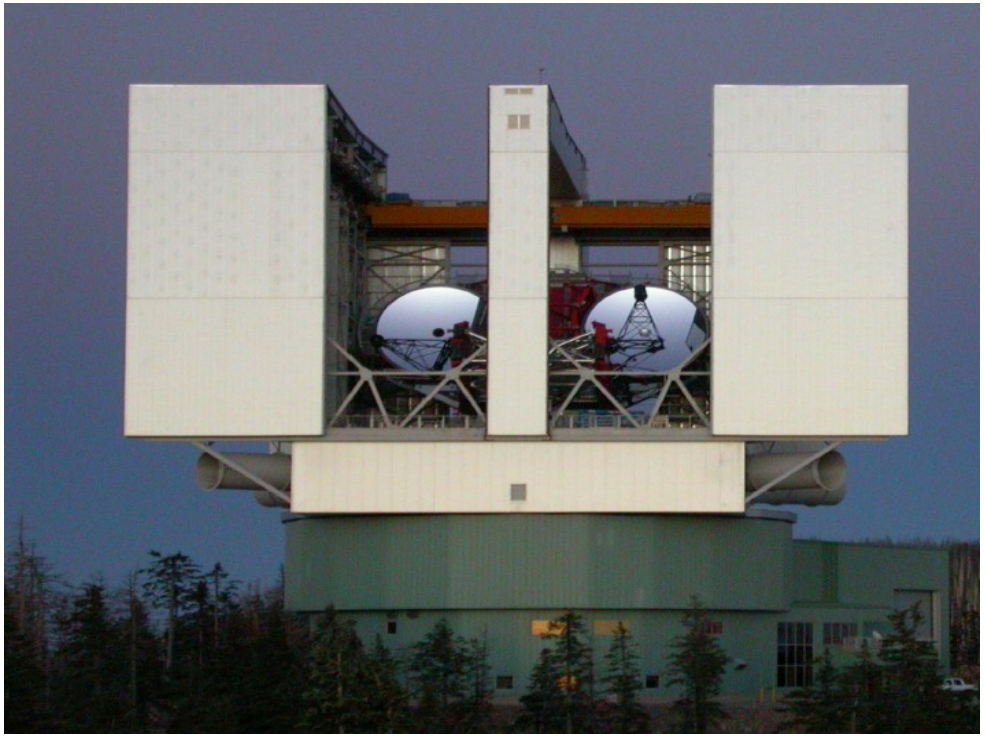
WFIRST-field Intensive
Optical-field Extensive
(overlap for ~1 deg^2)

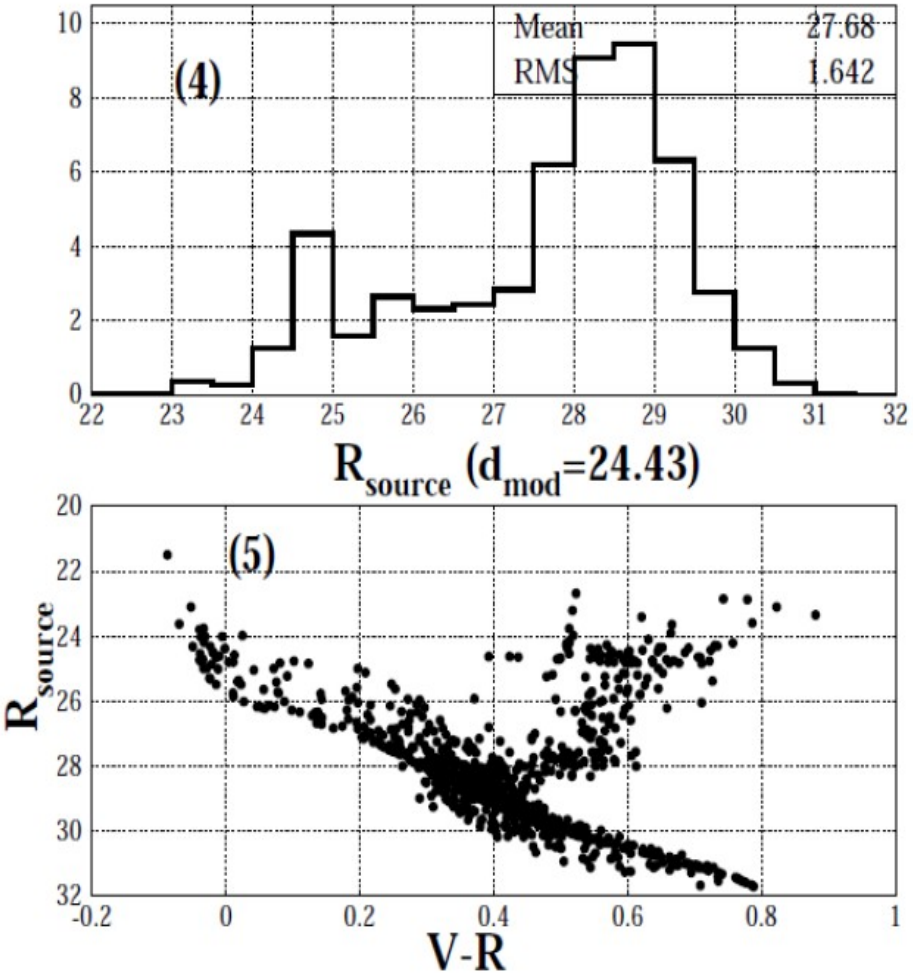




M31-LBT μlens Planet Survey

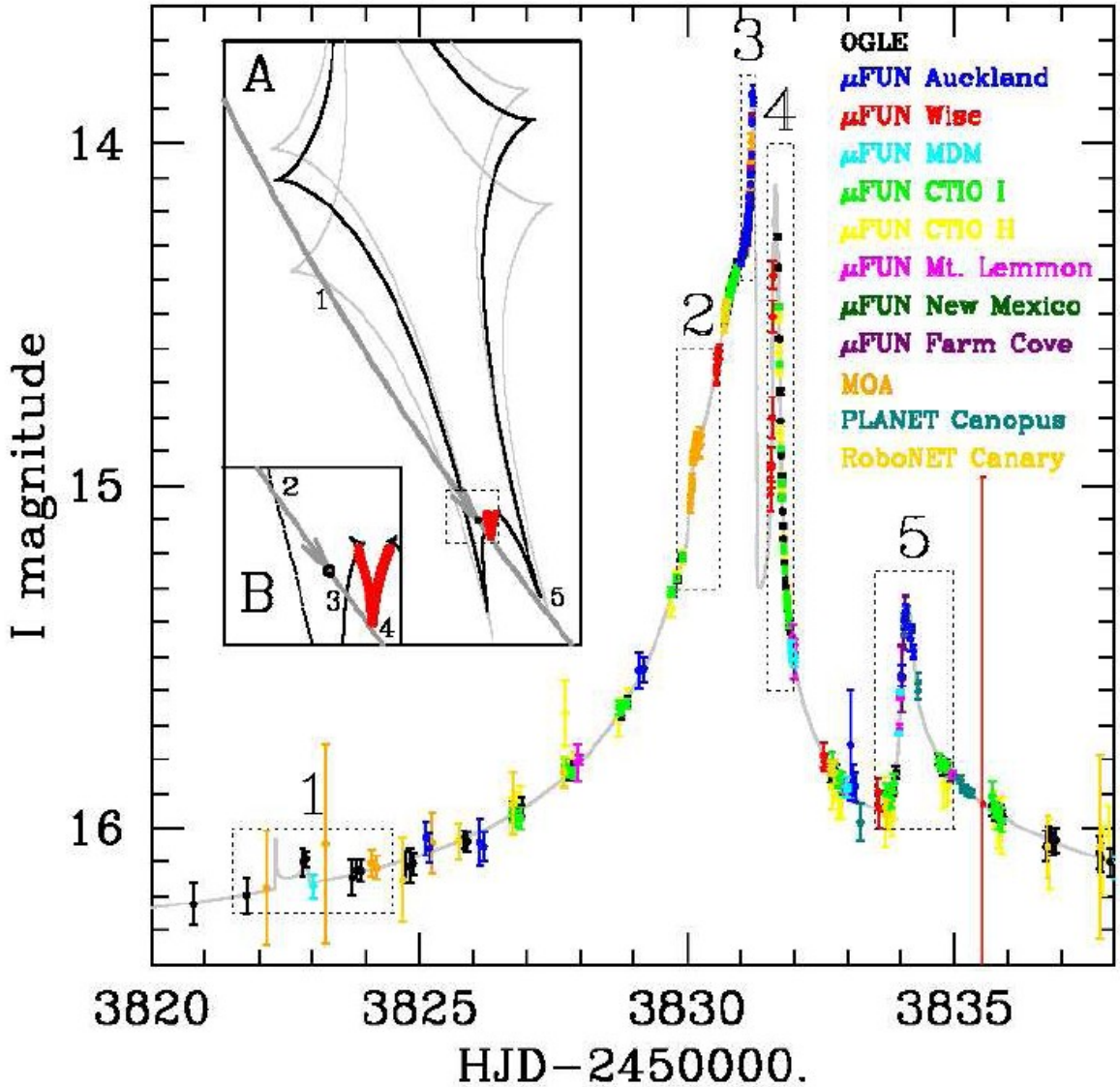
- Planet frequency/type by galactic environment
- Pathfinder for WFIRST M31 μlens survey
- Some data already acquired




(4)
Mean 27.68
RMS 1.642
R_{source} (d_{mod}=24.43)
(5)
R_{source}
V-R

OGLE-2006-BLG-109

Would Peak at R=24 in M31



Gaudi et al. 2008, Science, 319, 927

Conclusions

- *HST*-NOW most critical immediate requirement
  - 500—1000 orbits
  - I-band where possible, Y-band where necessary
- Many NASA assets could pave way for WFIRST
  - *Spitzer* and/or *Kepler* μlens parallaxes
  - *HST* followup of μlens planets
- Ground-based H-band survey to characterize sources, planet rates
- All would build human potential for WFIRST
  - More critical than anyone seems to realize