Search for Galactic Black Holes: Microlensing

TDA-MMS 2019: Time Domain Astronomy in the Era of Massively Multiplexed Spectroscopy

Will Dawson[1] and Shude Mao[2]
[1]Lawrence Livermore National Laboratory
[2]Tsinghua University

February 9-10, 2019

LLNL-PRES-XXXXXX 767497
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Assignment

- Format
  - 45 minutes broken as follows: a 15 minute (uninterruped) presentation of the major science goals, 5 minutes of discussion, 10 minutes (uninterrupted) of suggested projects and then 15 minutes of open discussion

Major Science Goals

Goals

Revolutionary Goal

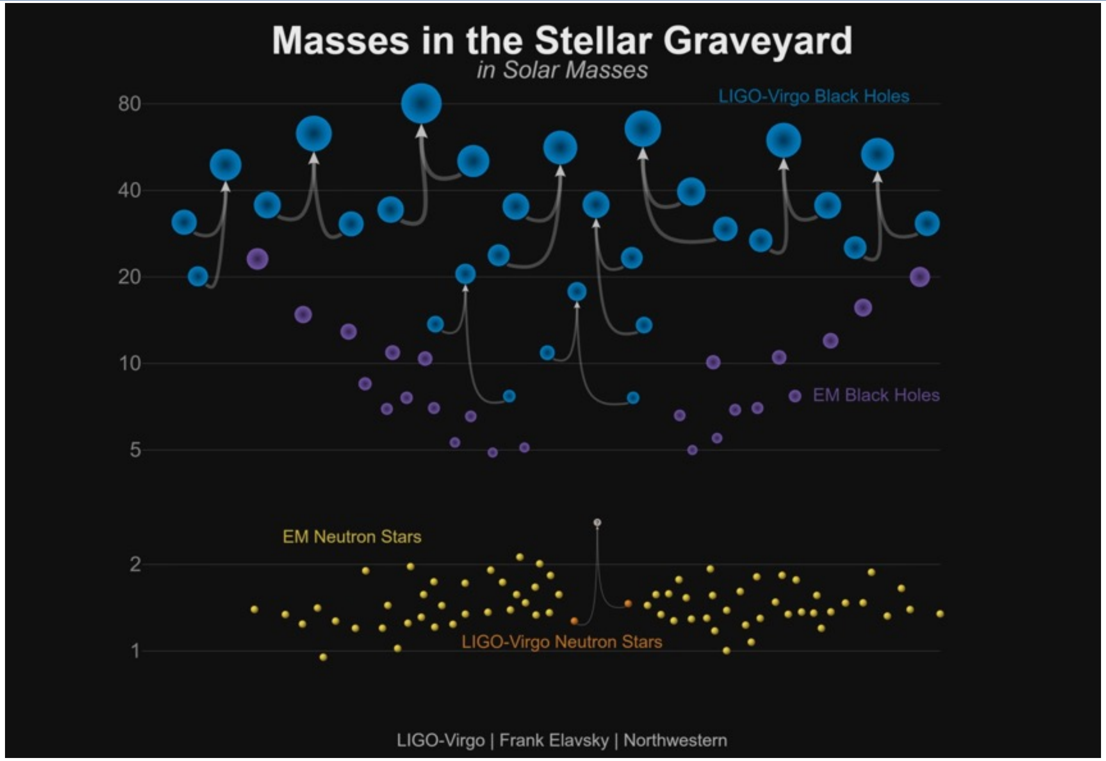
Confirm or reject Intermediate Mass MACHOs as the majority of dark matter.

Conservative Goal

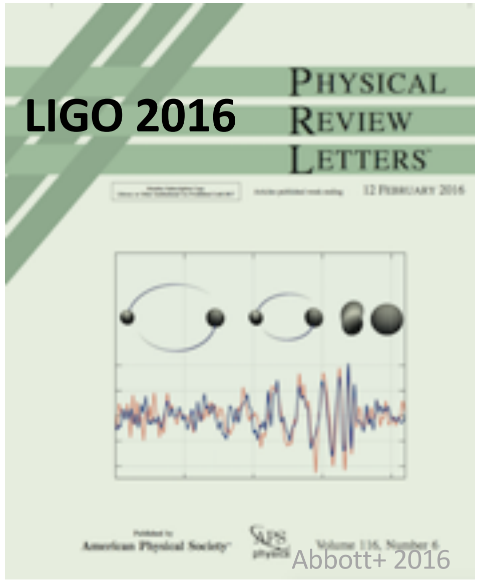
Make the first direct measurement of the mass spectrum of black holes in the Milky Way.

Black Hole Dark Matter

Intermediate Mass Black Holes Have been observed

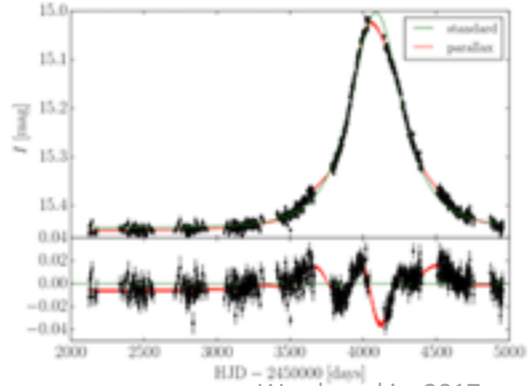


$2\times30\ M_\odot$



Abbott+ 2016

$9.3\ M_\odot$



Wyrzkowski + 2017

OGLE III 2016

$2200\ M_\odot$

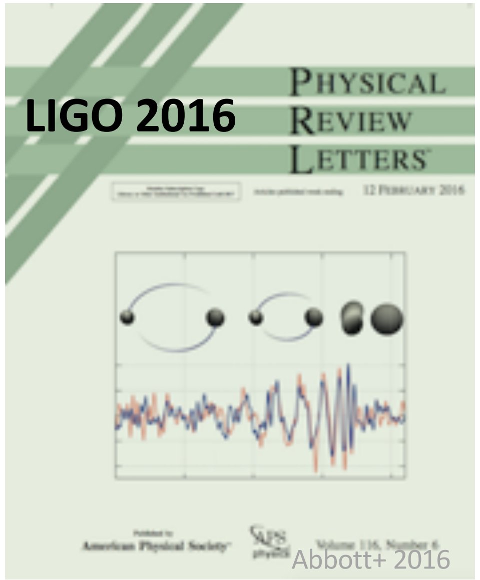
Kiziltan+ 2017

47 Tucanae 2017

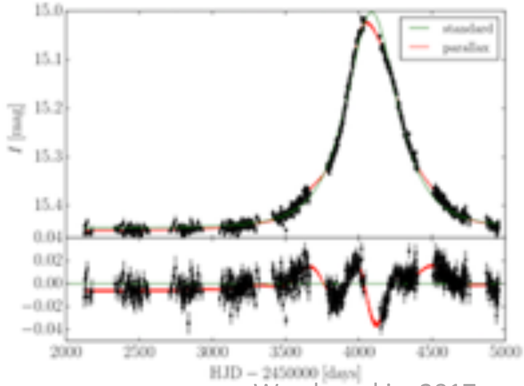
Intermediate Mass Black Holes Have been observed

- Also extensive primordial black hole literature: from Chapline (1975) to Carr et al. (2016).
- Current LIGO event rate is consistent with intermediate mass black holes making up all dark matter (Bird et al. 2016)
- If primordial BHs make up dark matter, then measuring their mass spectrum will be especially exciting because it will tell us something about the fundamental physics of the Big Bang.

$2\times30\ M_\odot$



$9.3\ M_\odot$



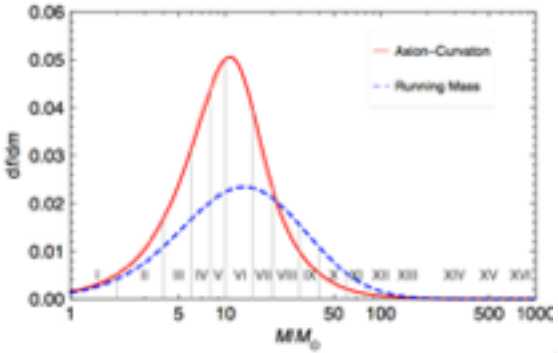
Wyrzkowski + 2017

OGLE III 2016

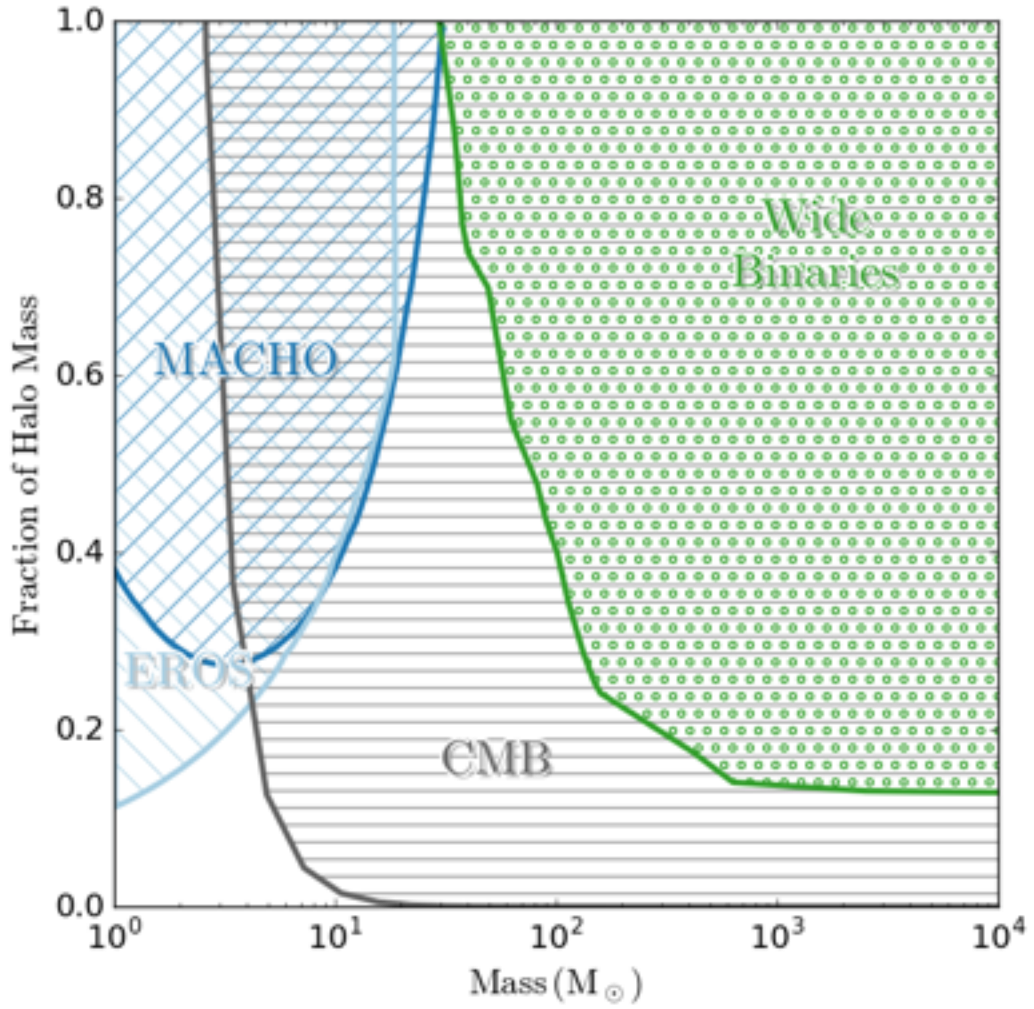
$2200\ M_\odot$

47 Tucanae 2017

Kiziltan+ 2017

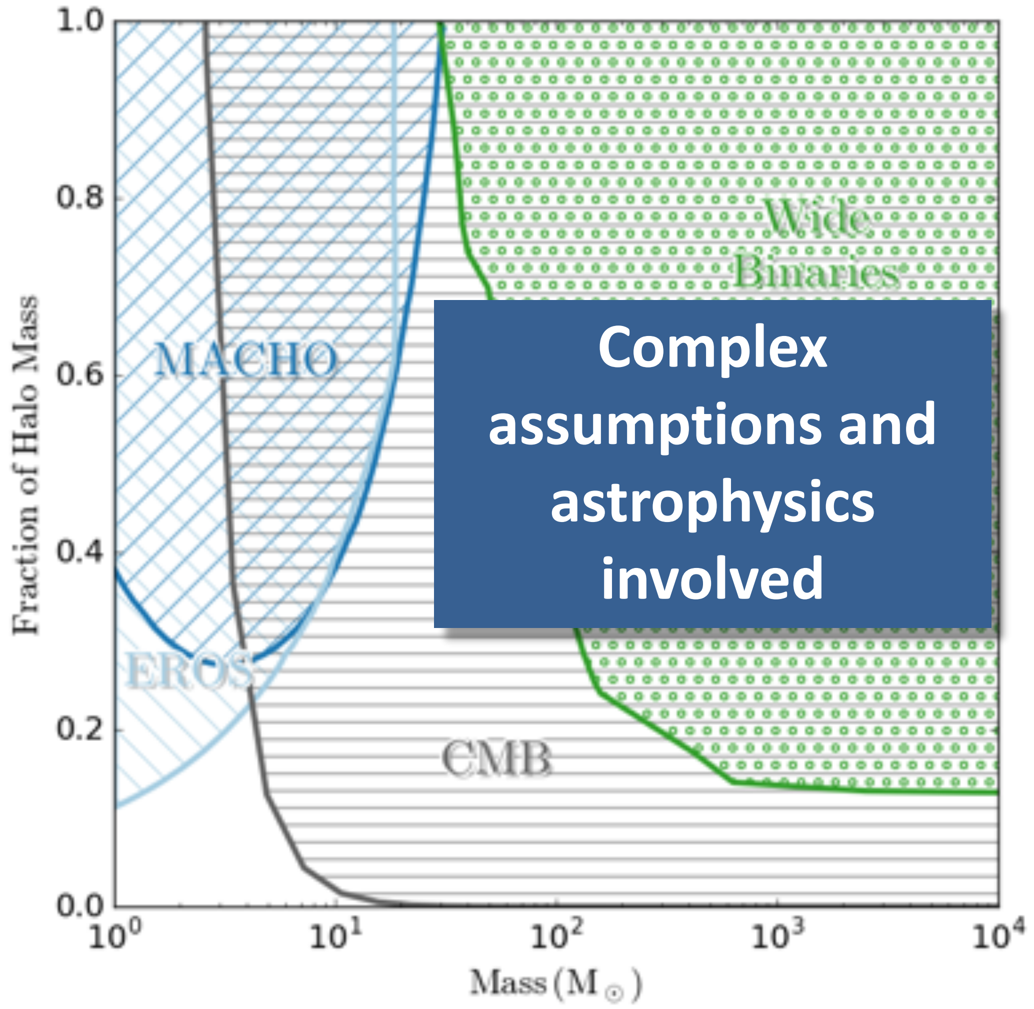


Massive MACHO Constraints circ. 2008
Completely ruled out massive MACHOs as Dark Matter



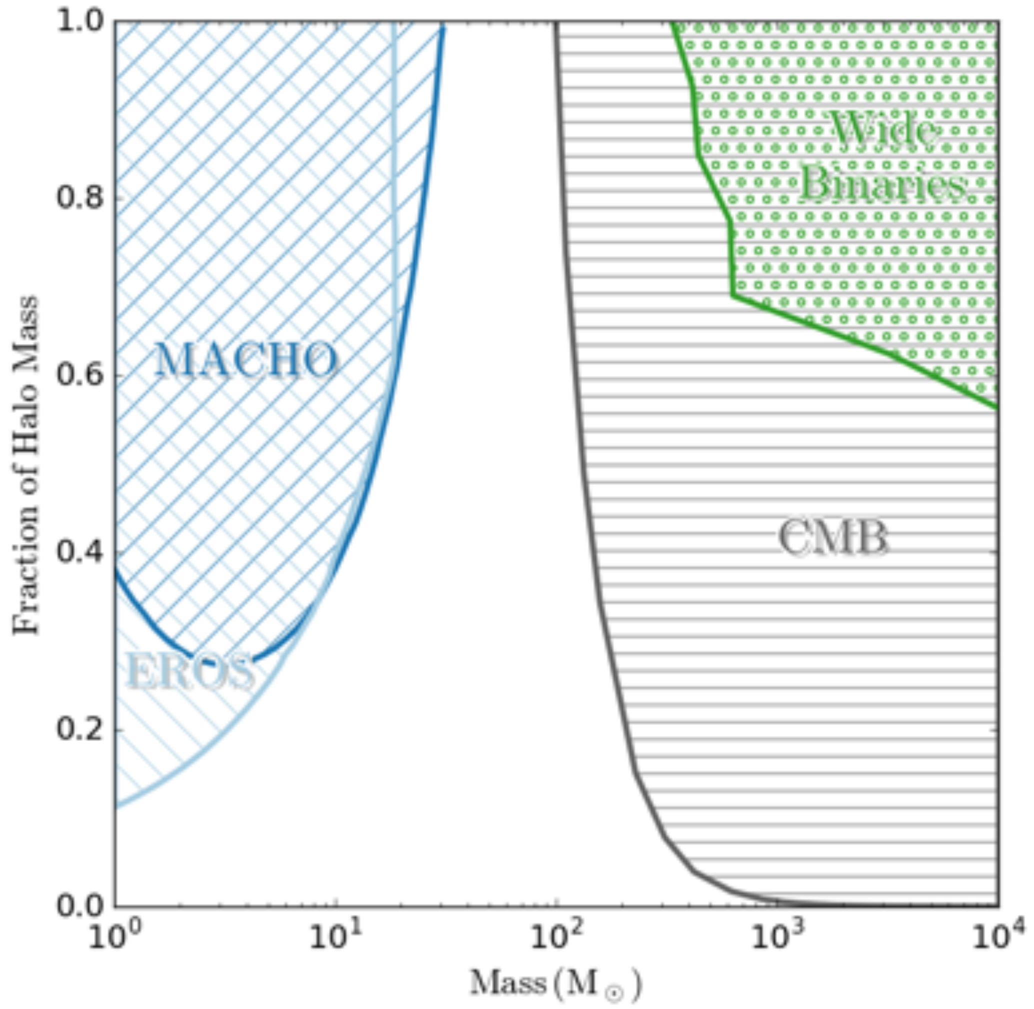
- Microlensing
  — Alcock et al. 2001
  — Tisserand et al. 2007
- CMB
  — Ricotti, Ostriker, & Mack 2008
- Wide Binary
  — Yoo et al. 2004
- Other constraints at masses $\gtrsim 10^4 M_\odot$

Massive MACHO Constraints circ. 2008
Completely ruled out massive MACHOs as Dark Matter



- Microlensing
  - Alcock et al. 2001
  - Tisserand et al. 2007
- CMB
  - Ricotti, Ostriker, & Mack 2008
- Wide Binary
  - Yoo et al. 2004
- Other constraints at masses $\gtrsim 10^4 M_\odot$

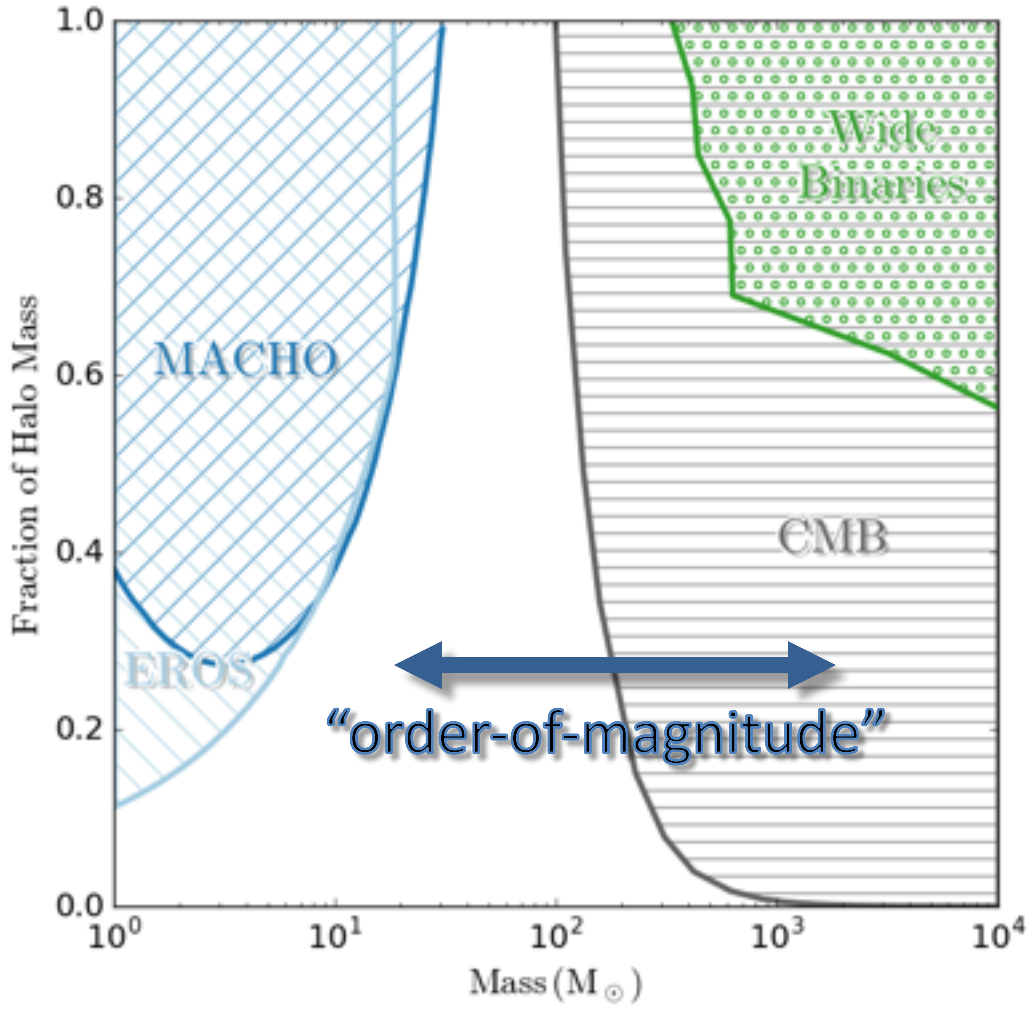
Massive MACHO Constraints circ. 2016
As assumptions and systematics explored constraints loosened



- Microlensing
  - Alcock et al. 2001
  - Tisserand et al. 2007
- CMB
  - Ali-Haïmoud & Kamionkowski 2016
- Wide Binary
  - Quinn et al. 2009

"The limits that Ricotti and I reached for BH numbers were far too severe."
-Ostriker

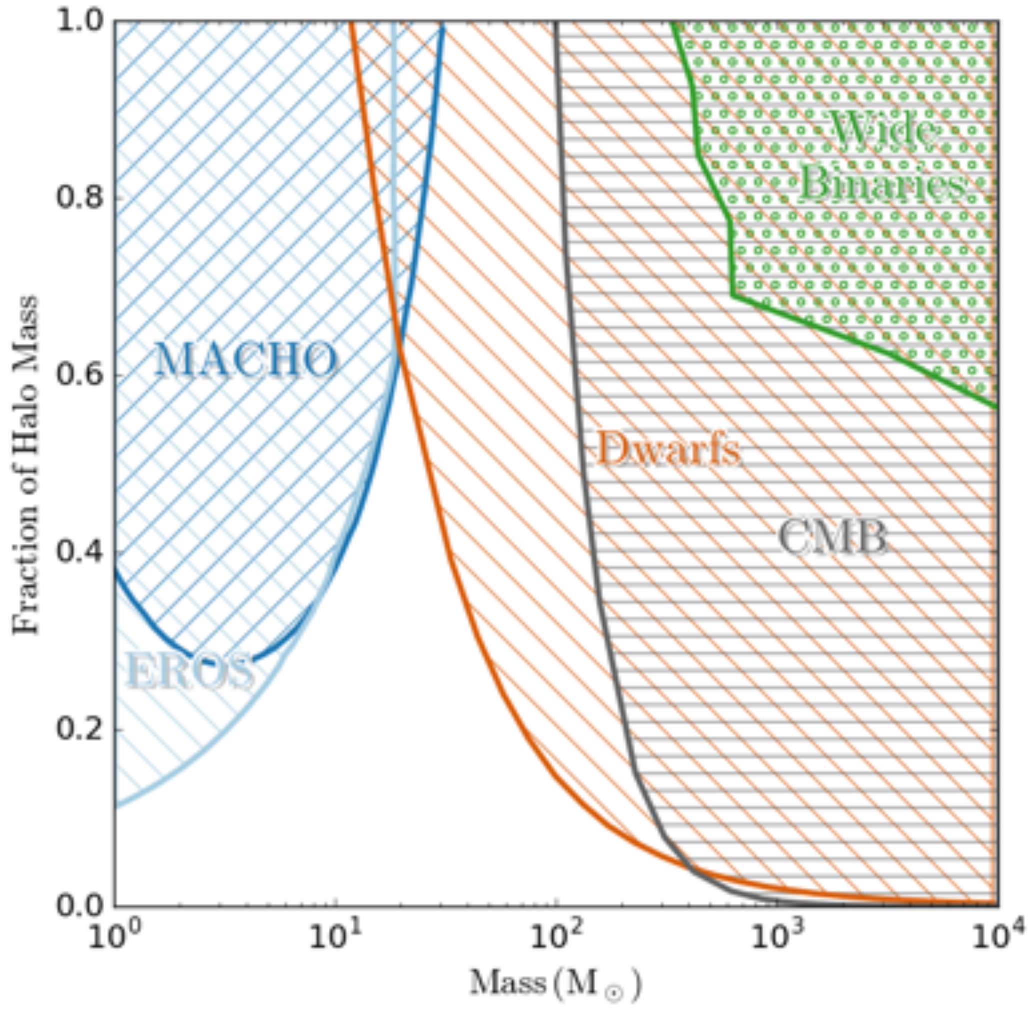
Because of limits in understanding of astrophysics still just order of magnitude estimate



- Microlensing
  - Alcock et al. 2001
  - Tisserand et al. 2007
- CMB
  - Ali-Haïmoud & Kamionkowski 2016
- Wide Binary
  - Quinn et al. 2009

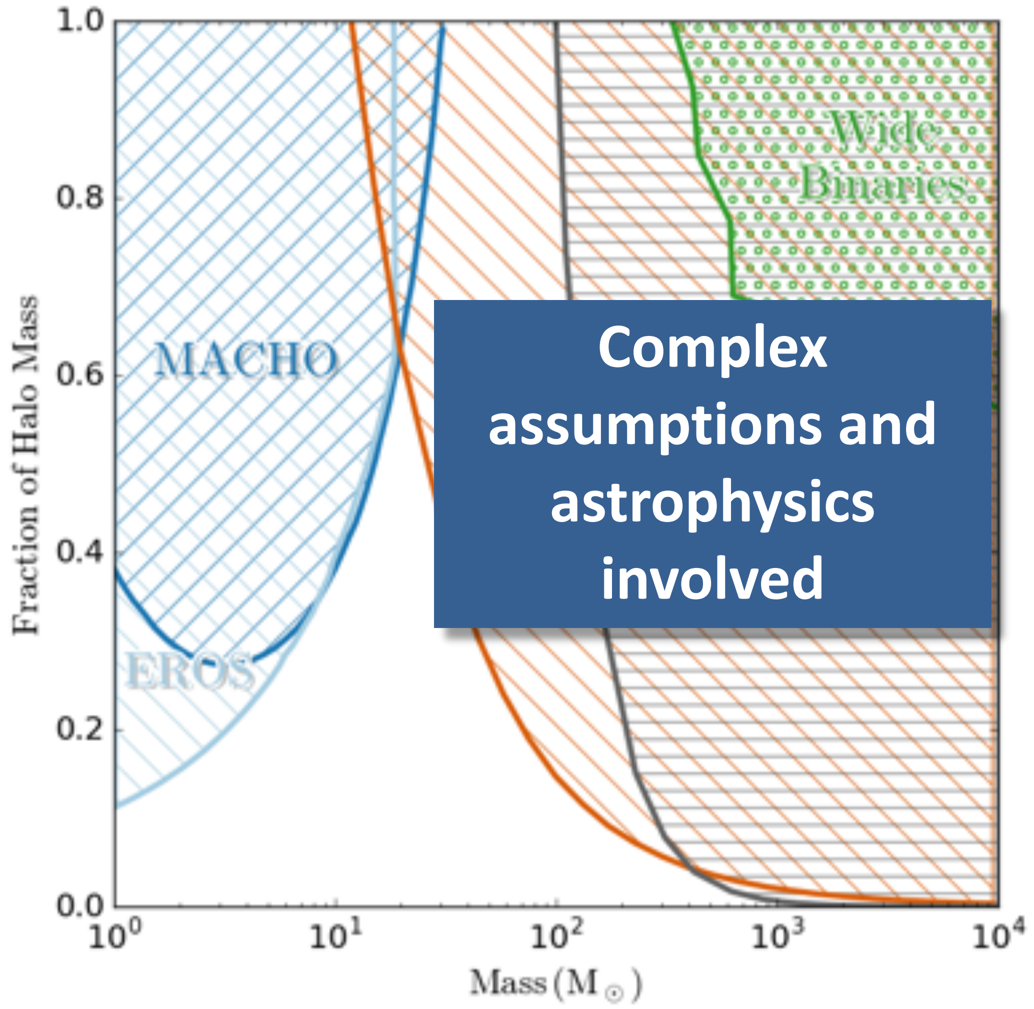
"The limits that Ricotti and I reached for BH numbers were far too severe."
-Ostriker

The latest astrophysical constraint from dwarf galaxies and star clusters



- Microlensing
  - Alcock et al. 2001
  - Tisserand et al. 2007
- CMB
  - Ali-Haïmoud & Kamionkowski 2016
- Wide Binary
  - Quinn et al. 2009
- Dwarf Galaxies
  - Brandt 2016, & Li et al. 2017

The dwarf galaxy constraint is reliant on several astrophysical assumptions, likely to be wrong



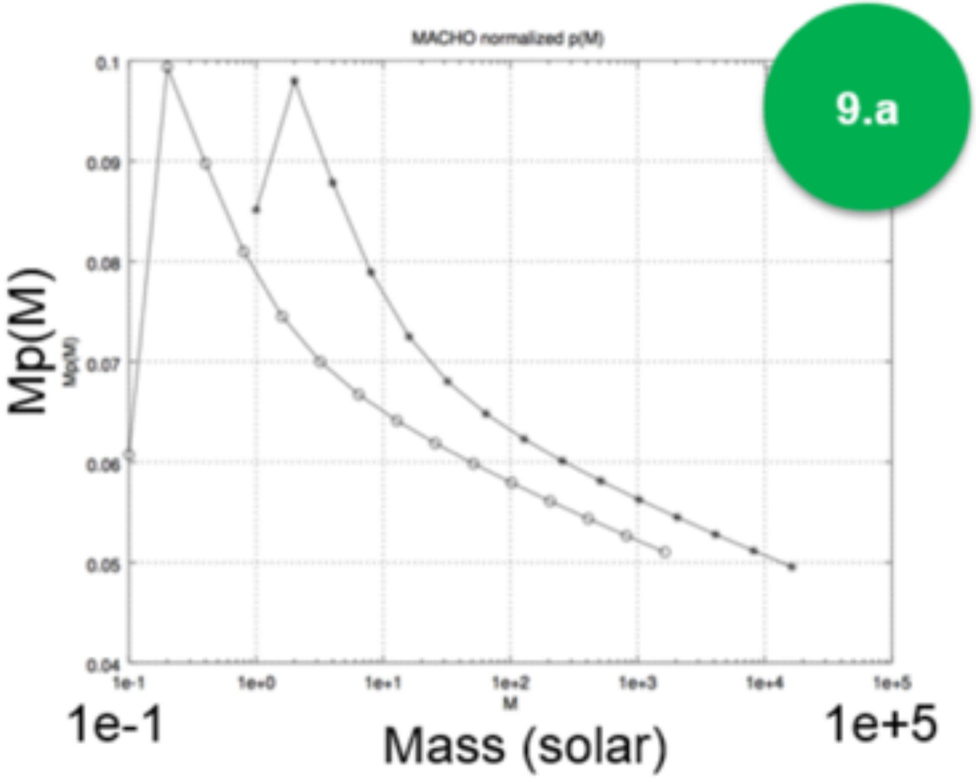
Complex assumptions and astrophysics involved

- No central massive black hole
  - Kilizman et al. 2017 found $2200 M_\odot$ black hole at the center of a star cluster
  - Li et al. 2017 show factor of ~30 decrease in constraint if $1500\ M_\odot$ black hole in center
- Delta function IM MACHO mass function
  - If broader distribution that extends to $\sim M_\odot$ (Carr et al. 2016) then result completely invalidated
- Eridanus II cluster assumed to be at center of the dark matter halo
- Satellites assumed to have had same mass for 10 billion years
  - Crnojevic et al. 2016 note evidence for tidal stripping due to Milky Way

Stellar Evolved Black Holes are Interesting Too

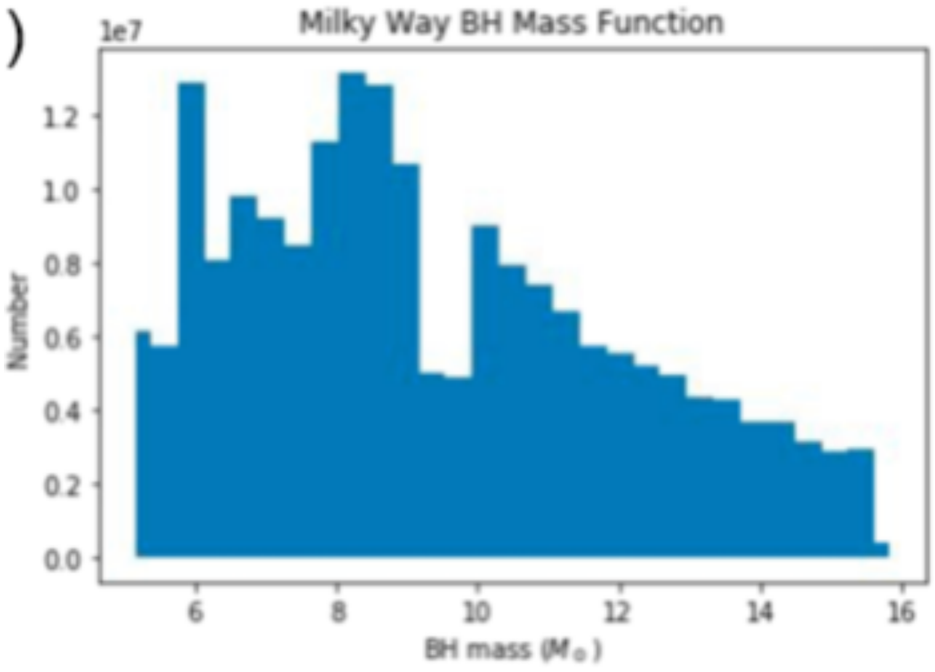
Primordial black holes and stellar evolved black hole have very different mass spectra; enabling discrimination

Primordial Black Holes



Chapline and Barbari (2018)

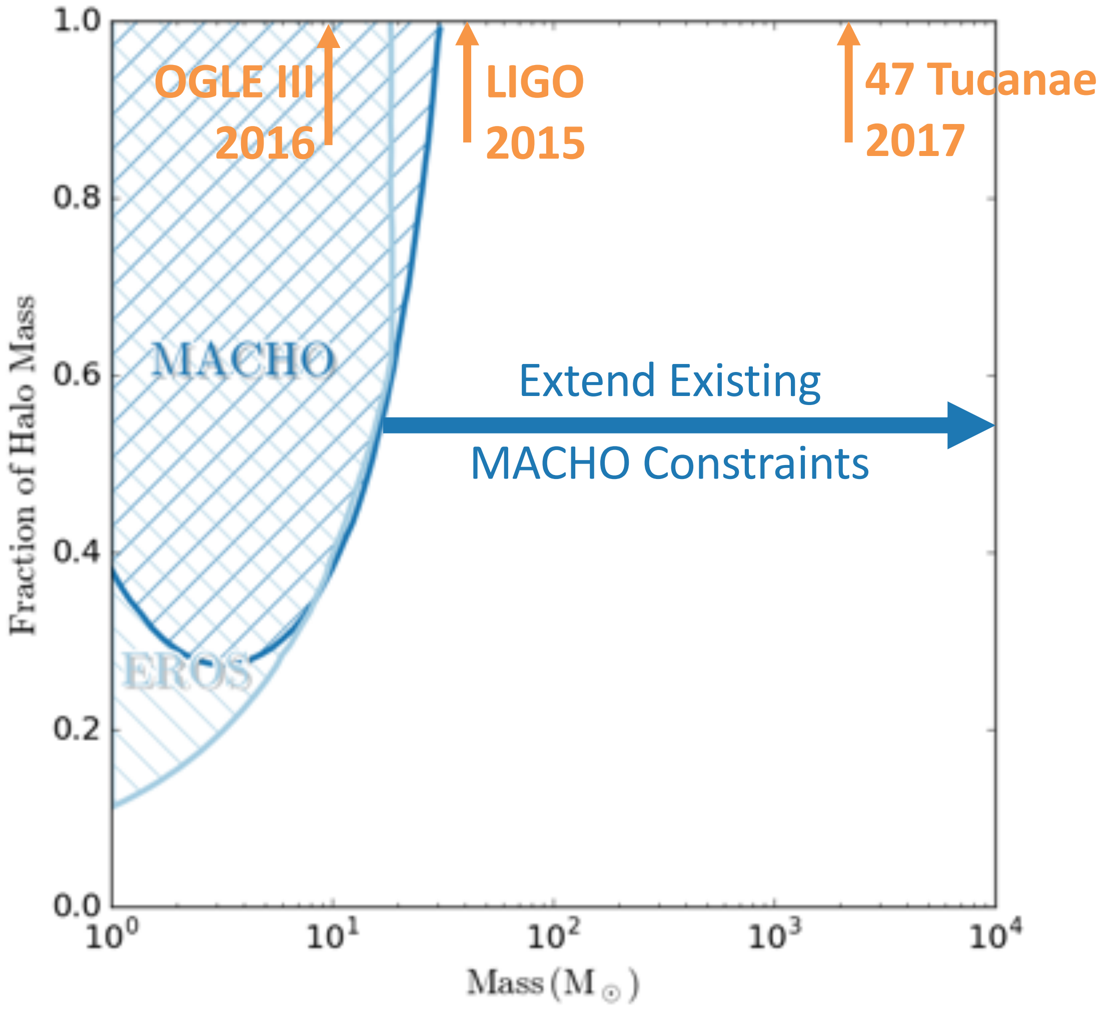
Stellar Evolved Black Holes



Casey Lam (in prep)

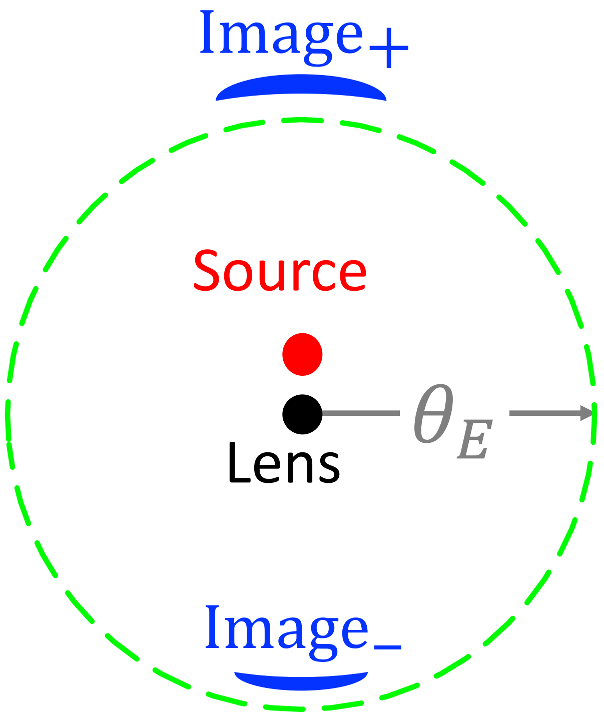
Microlensing is the closet thing we have to a direct measurement of intermediate mass black holes

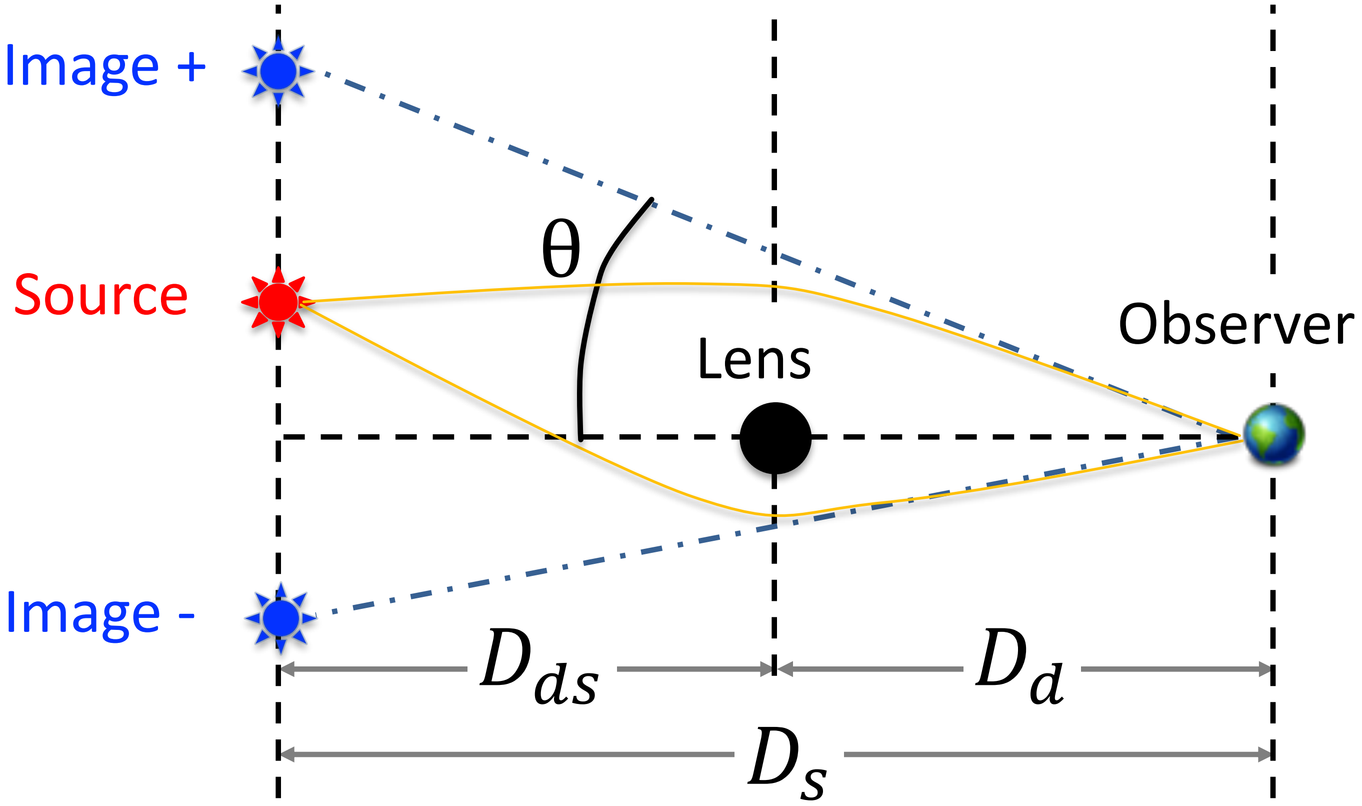
- We know there are black holes in this mass range.
  - Theoretical arguments for primordial black holes: from Chapline (1975) to Carr et al. (2016).
- Rather than indirect astrophysical inferences we prefer a direct measurement.
- **Microlensing is the most direct way of measuring black hole dark matter.**



Relevant Microlensing Basics

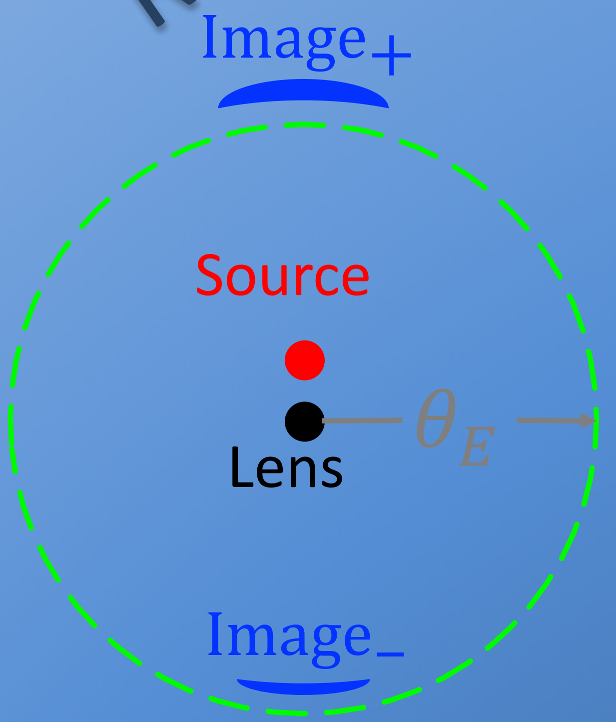
Gravitational microlensing basics





Total magnification is what is measured

Relative Ground Based Resolution

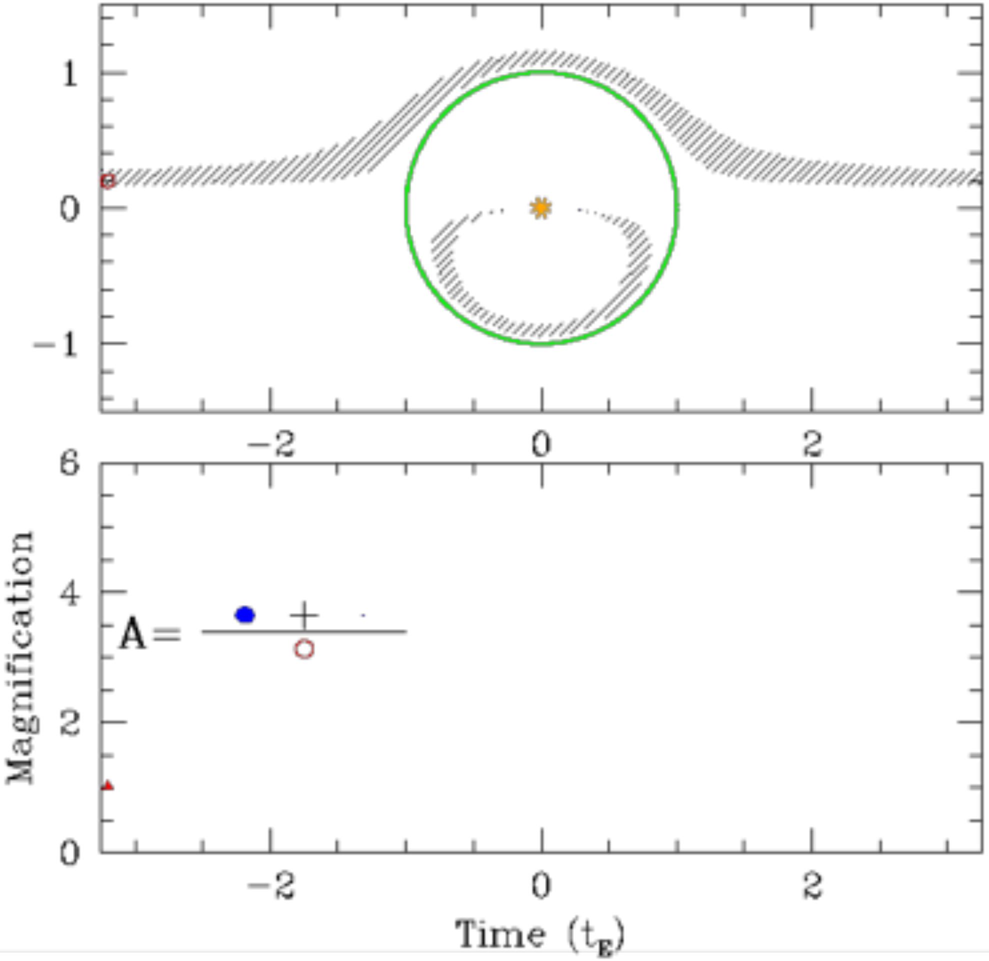


Total magnification:

$$\mu \equiv \mu_+ + |\mu_-|$$

Microlensing Basics

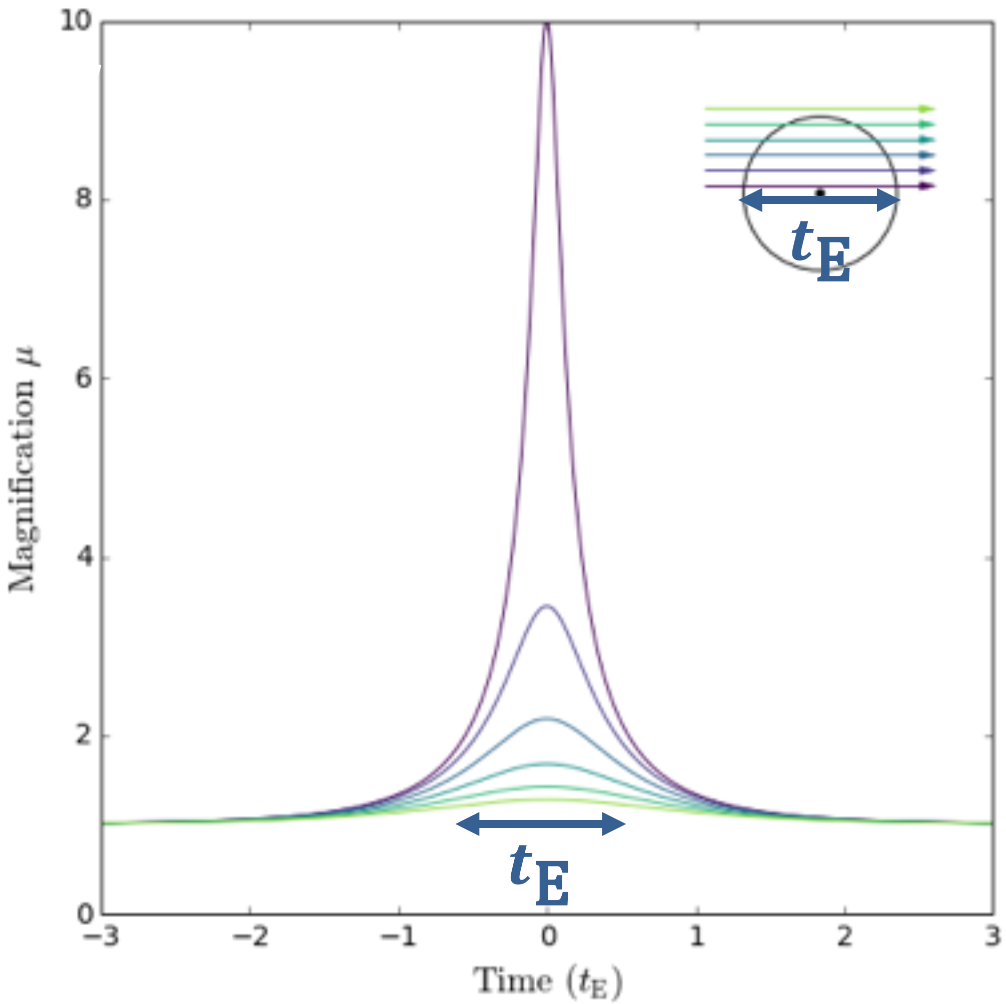
Black Hole – Observer Frame

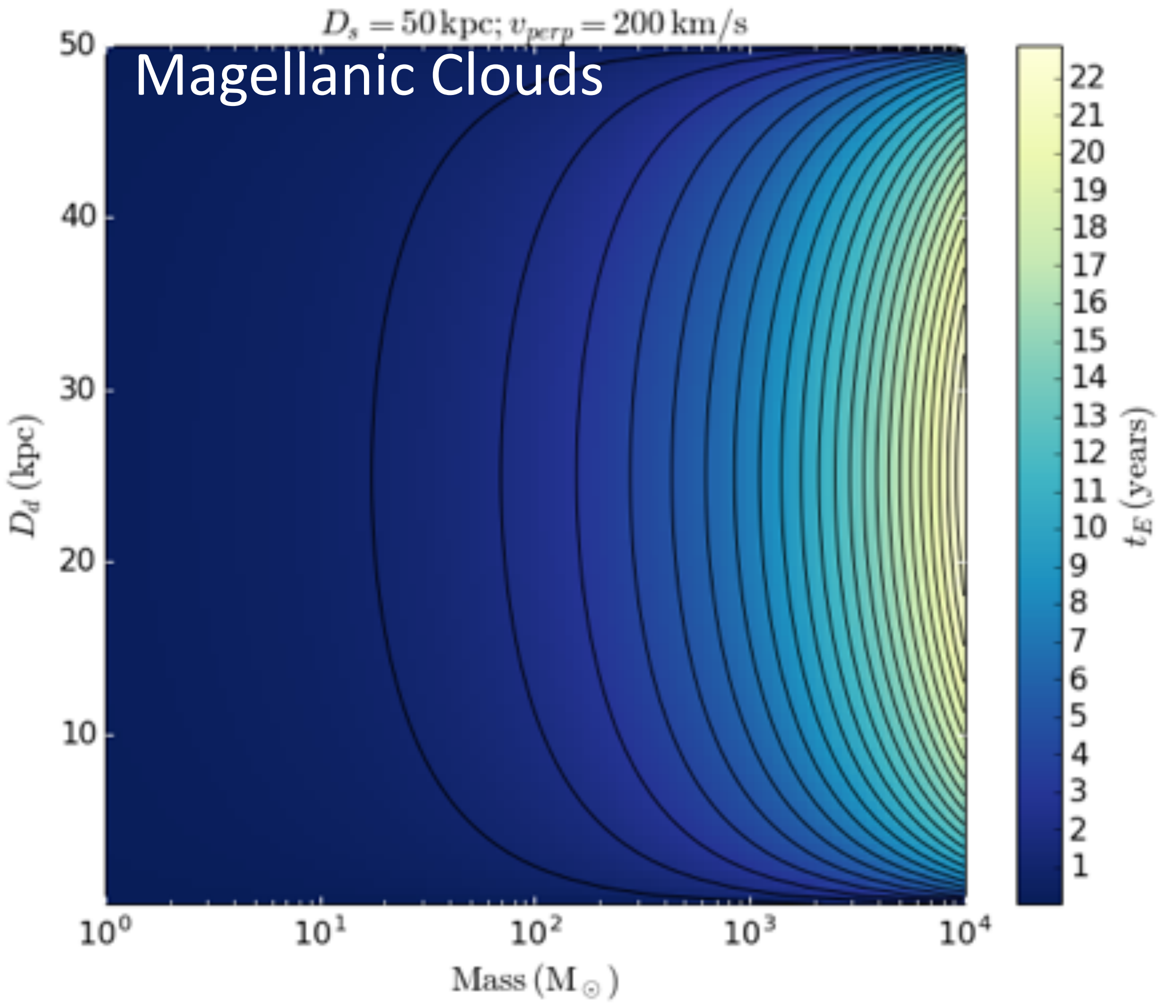


Key	
	Lensed Images
	Actual Source Location
	Black Hole Lens
	Einstein Ring

Gaudi

Previous surveys were limited by survey length relative to event time-scale and detection methods.





Statistical Ensembles

Expected number of events
(assuming all have same timescale)

$$N = \frac{2}{\pi} n \, \tau \, \frac{\Delta t}{t_0}$$

Number of monitored stars (n)

Timescale of Survey (Δt)

Timescale of lensing event (t_0)

Optical Depth (τ)

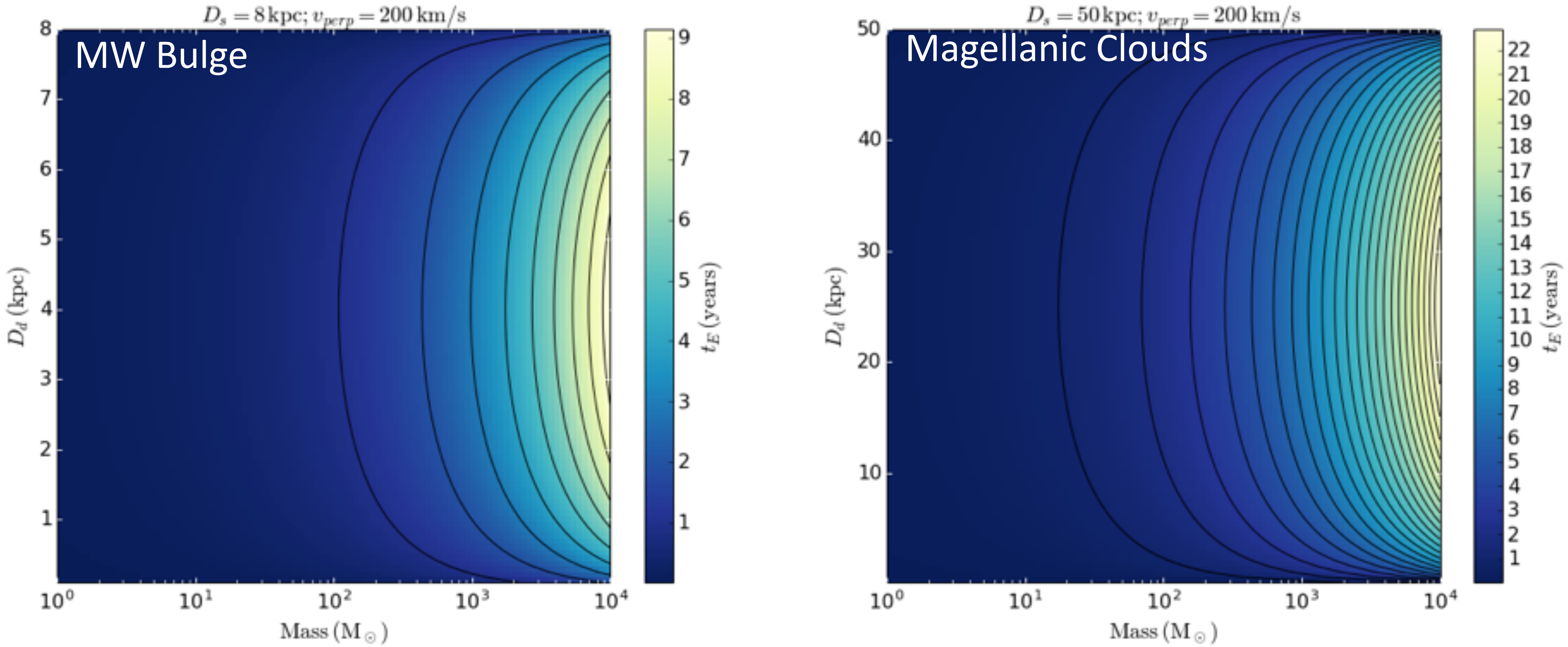
$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2} \rho(D_d) dD_d$$

$$D = (D_d D_{ds} / D_S)$$

Average dark matter density at D_d

Paczynski 1986, 1996

Time-scale of microlensing events.
For high mass MACHOs MW Bulge is better.



Statistical Ensembles

Expected number of events
(assuming all have same timescale)

$$N = \frac{2}{\pi} n \, \tau \, \frac{\Delta t}{t_0}$$

Number of monitored stars

Timescale of Survey

Timescale of lensing event

Optical Depth

$$D = (D_d D_{ds} / D_S)$$

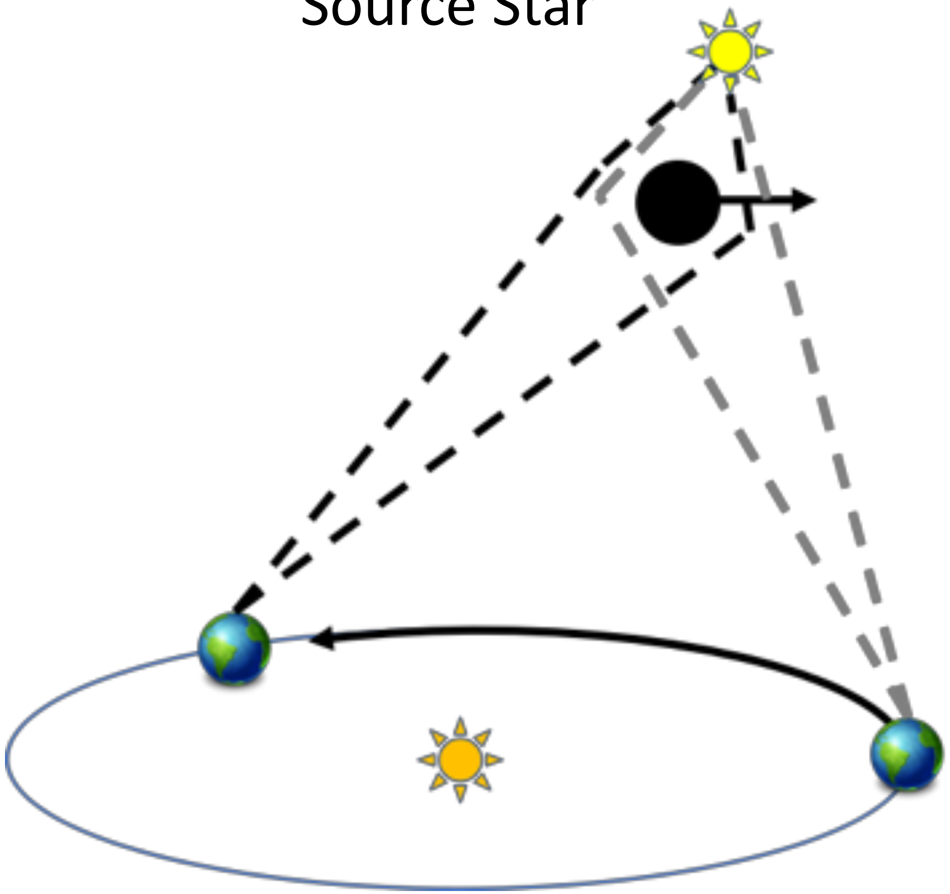
Note independent of MACHO mass.

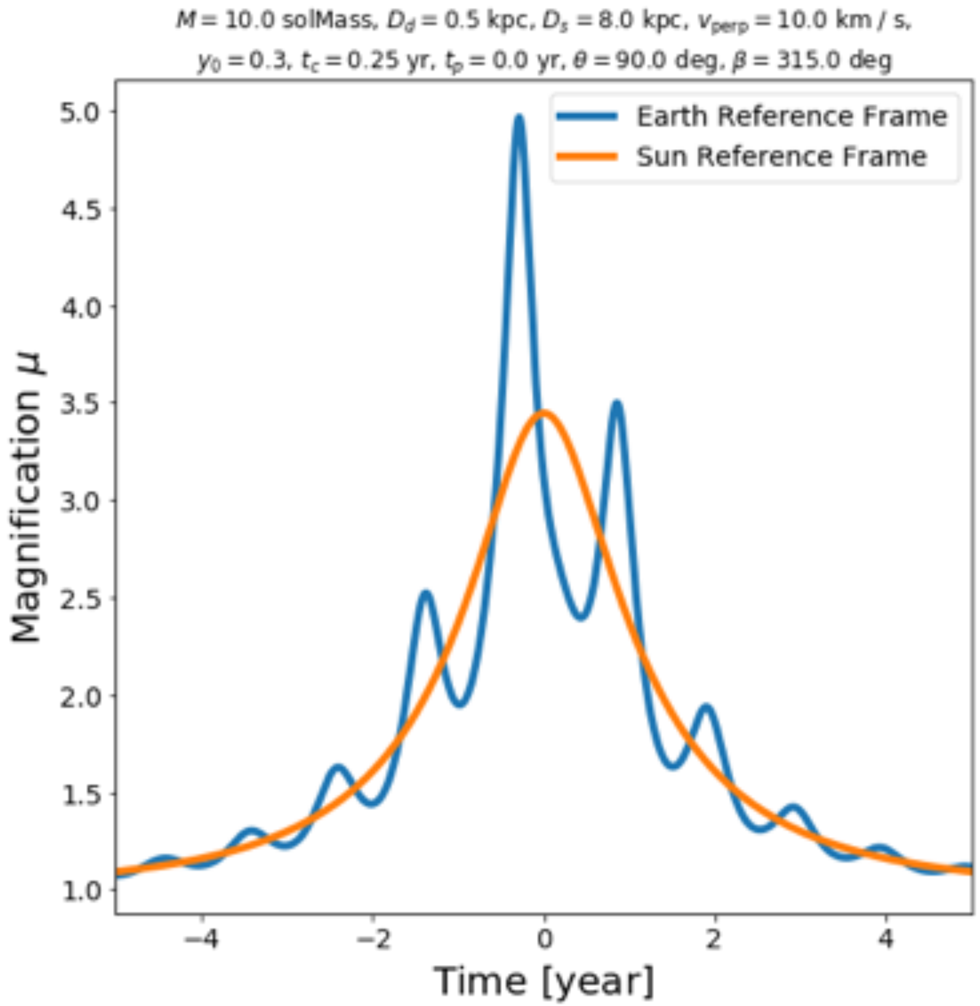
$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2} \rho(D_d) dD_d$$

Average dark matter density at D_d

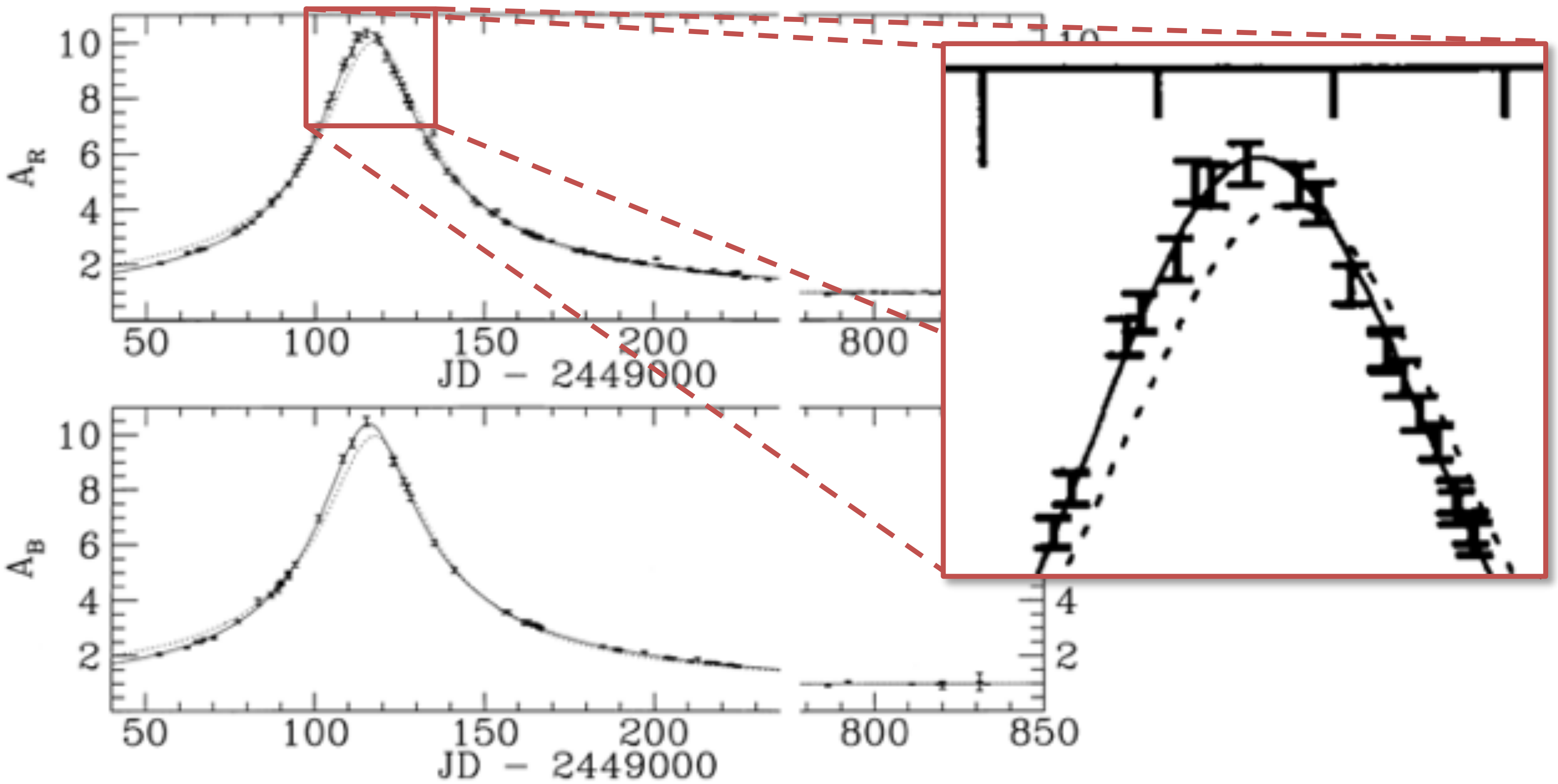
Paczynski 1986, 1996

Parallax:
Multi-year lensing events with 6 month periodic signal





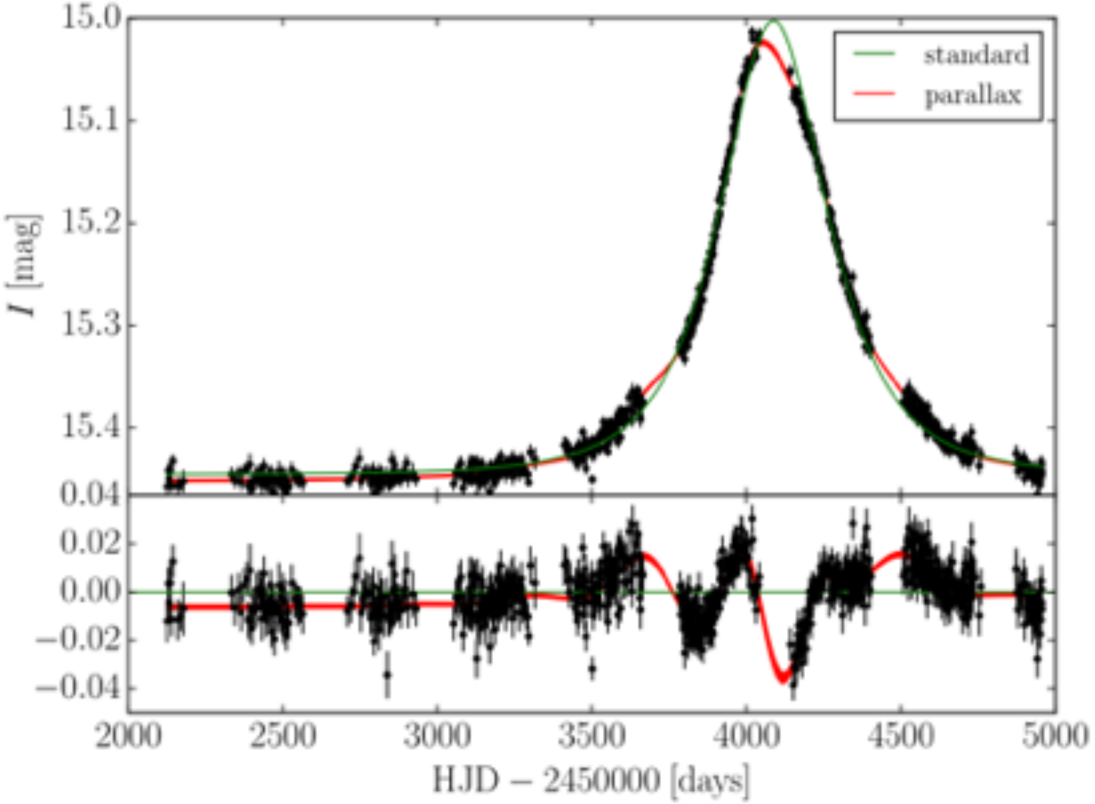
Parallactic effect first observed at LLNL



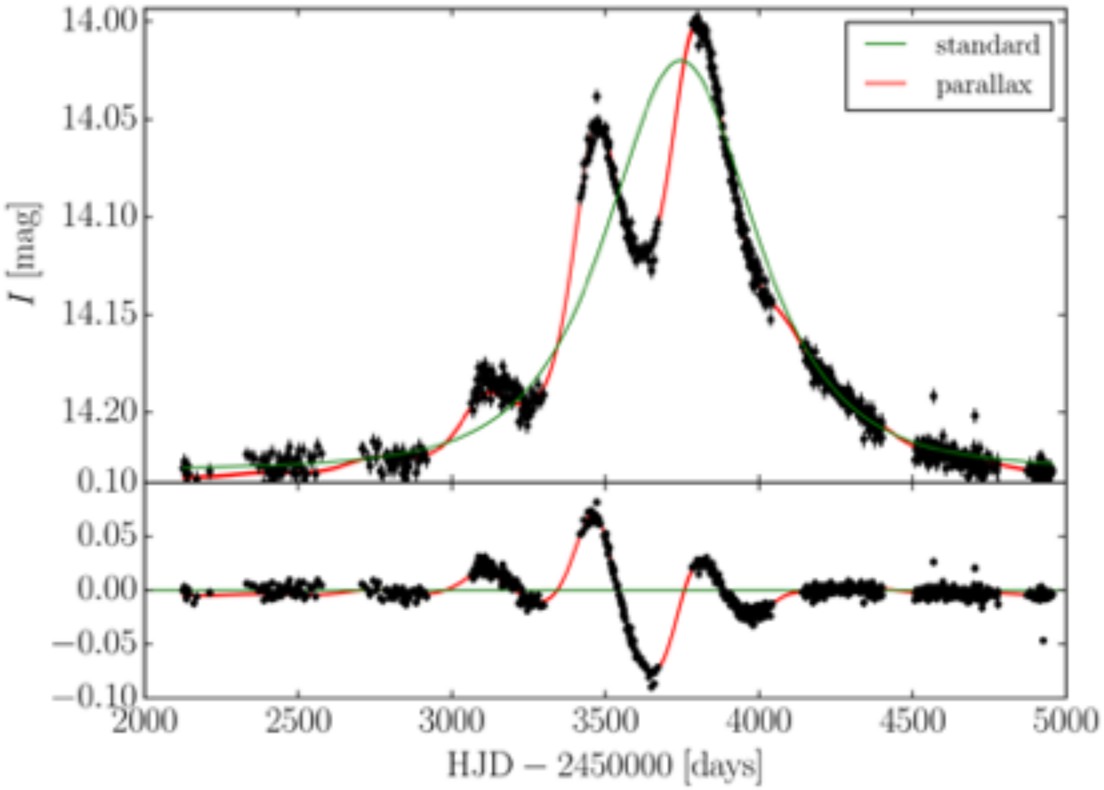
MACHO Survey (1995)

Recent OGLE III parallax events

$9.3\ M_{\odot}$ Black Hole



$1.0\ M_{\odot}$ Neutron Star

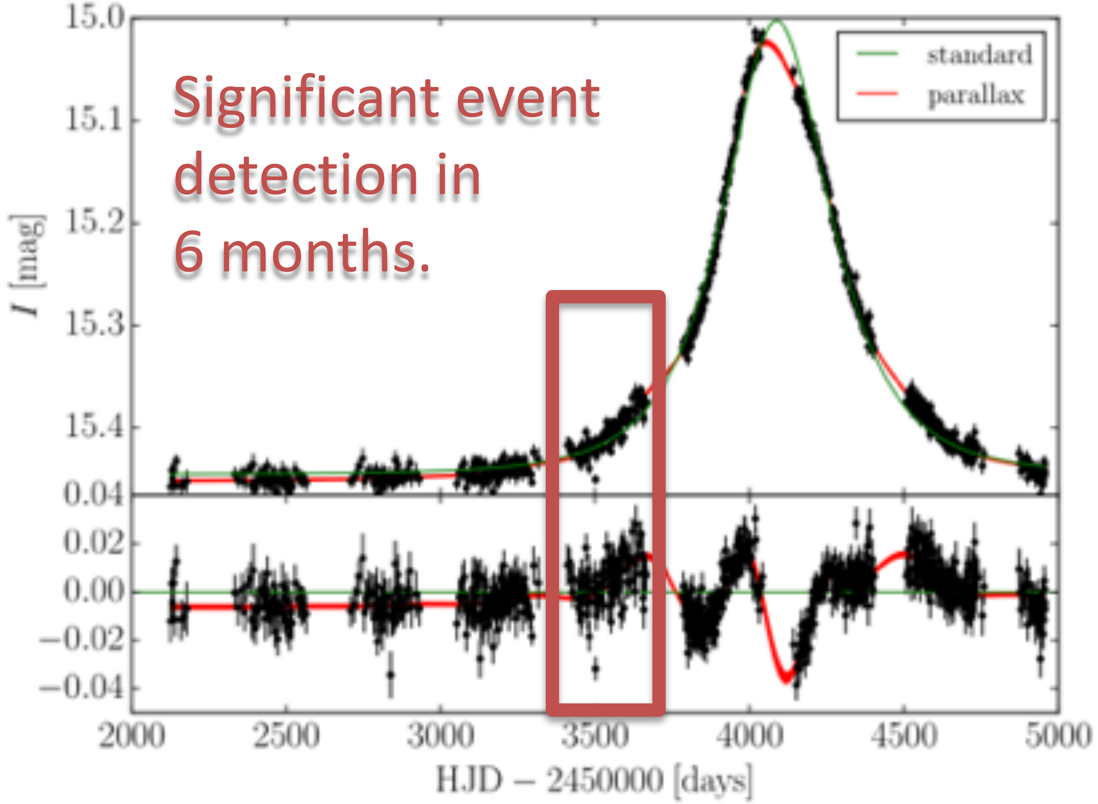


~8 years

Wyrzkowski et al. 2016

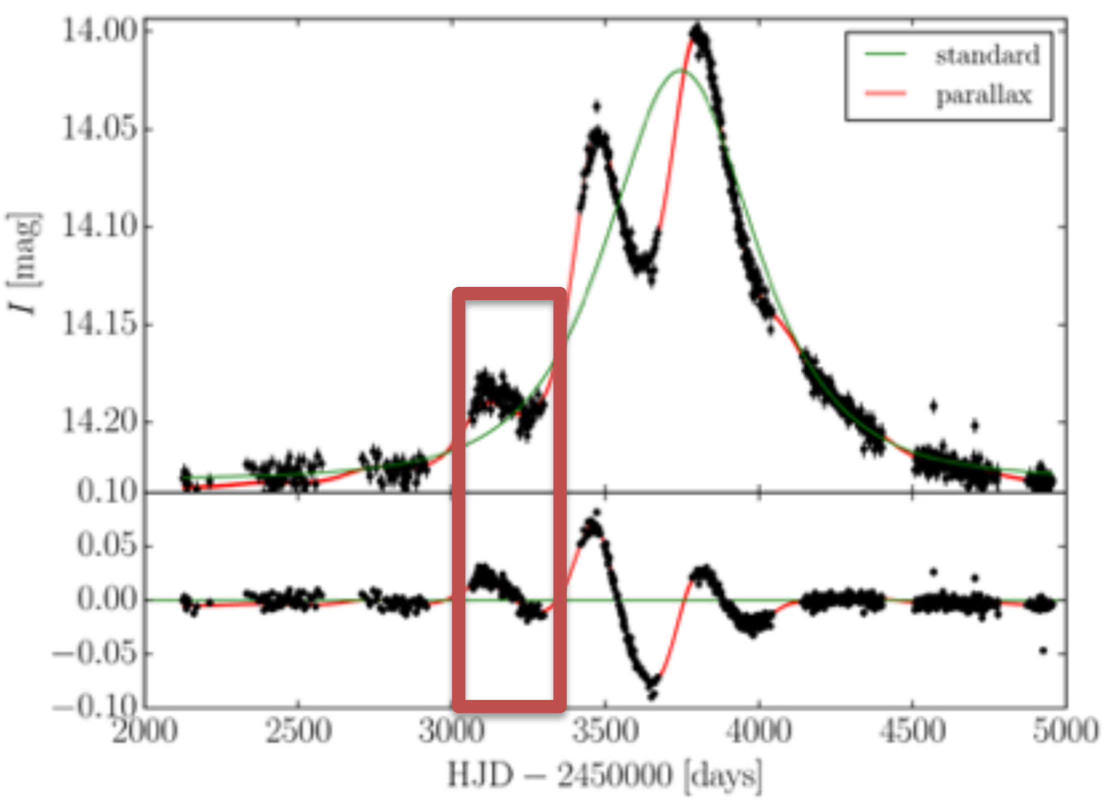
Can have a significant and secure detection of multi-year event with 6 months of data!

9.3 $M_\odot$ Black Hole



~8 years

1.0 $M_\odot$ Neutron Star



Wyrzkowski et al. 2016

Parallax fundamentally changes the MACHO constraint game. Can constrain all mass ranges $\gtrsim 10\ M_\odot$ with same survey!

Expected number of events
(assuming all have same timescale)

Number of monitored stars

Timescale of Survey

$$N = \frac{2}{\pi}\, n\, \tau\, \frac{\Delta t}{t_0}$$

From 10's of years to ~6 months!

Timescale of lensing event

Optical Depth

$$D = (D_d D_{ds}/D_S)$$

$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2}\rho(D_d)\, dD_d$$

Average matter density at D_d

Paczynski 1986, 1996

Gould did it…

The Astrophysical Journal, 392:442–451, 1992 June 20

1992 June 20

EXTENDING THE MACHO SEARCH TO $\sim 10^6\ M_\odot$

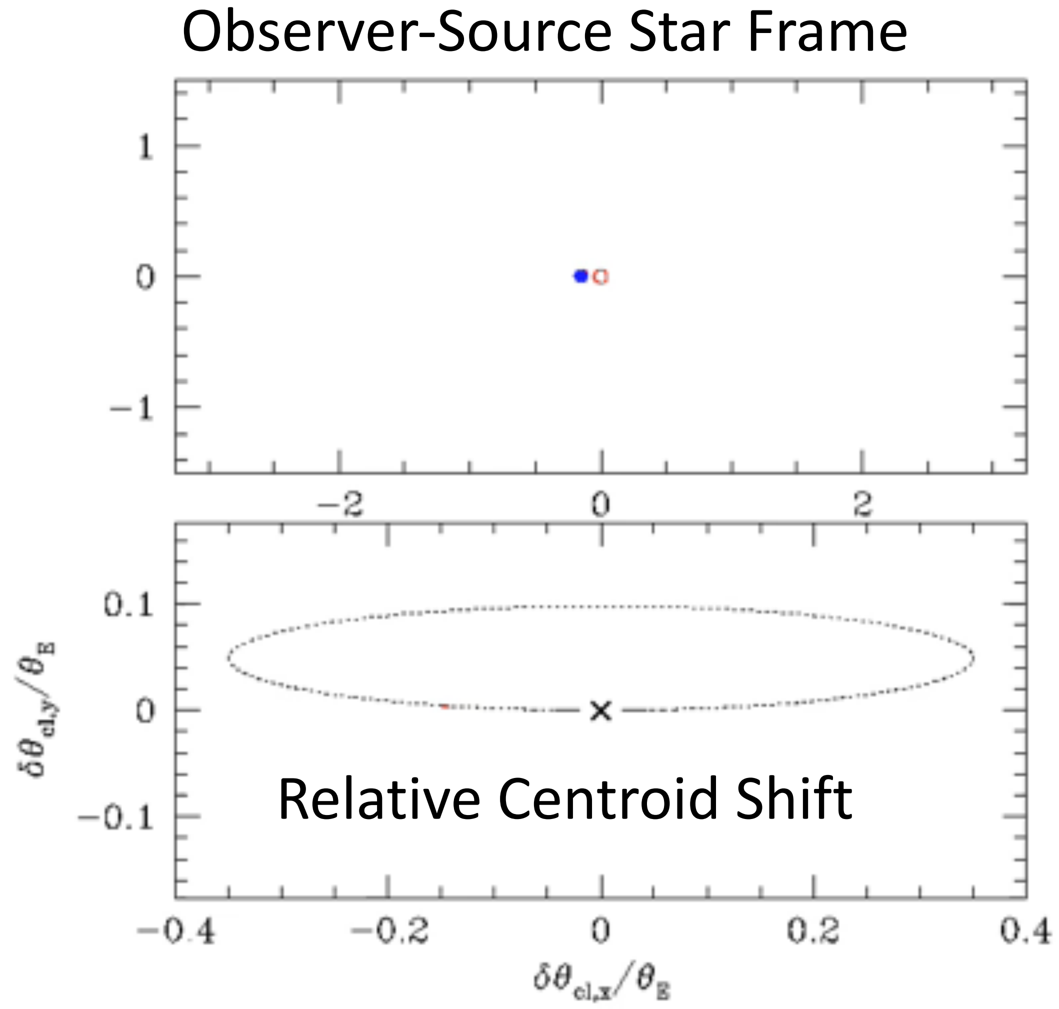
Andrew Gould
Institute for Advanced Study, Princeton, NJ 08540
Received 1991 November 4; accepted 1991 December 27

ABSTRACT

The search for a microlensing (changing light-curve) signature of massive compact halo objects (Machos) by the Macho Collaboration is currently believed to be sensitive in the range 10^{-7}–$10^2\ M_\odot$. Microlensing events from higher mass objects last longer than the 4 yr duration of the planned experiments and therefore, according to current beliefs, cannot be distinguished from long-term variables. In fact the signature of Machos in the range 10^2–$10^3\ M_\odot$ can be distinguished from background events by the annual modulation in light magnification induced by the Earth's motion. For Machos in the range 10^3–$10^6\ M_\odot$, *Hubble Space Telescope* (*HST*), or even ground-based measurements can resolve the split lensed images, thus confirming the lens interpretation of an event. If the *HST*'s optics were repaired, it could resolve images for Machos $\gtrsim 300\ M_\odot$. The lower mass limit can be reduced to $4 \times 10^{-9}\ M_\odot$ by conducting 1 month of rapid repeat observations of a single field. The standard view is that a Macho light curve yields only one physically relevant parameter, the time scale of the event. The time scale is a combination of the four parameters one would like to know: the mass, the distance, and the two components of transverse velocity of the Macho. I show that for masses 4–100 $M_\odot$, annual parallax oscillations in the light curve can be used to determine the transverse velocity. In the range 10^{-3}–$10^6\ M_\odot$ such measurements can be made using a small special-purpose satellite telescope. For masses 10^3–$10^6\ M_\odot$, one may determine all four Macho parameters by combining a number of techniques.

Subject headings: astrometry — Galaxy: halo — gravitational lensing — techniques: photometric

Microlensing also affects the astrometry of the source star

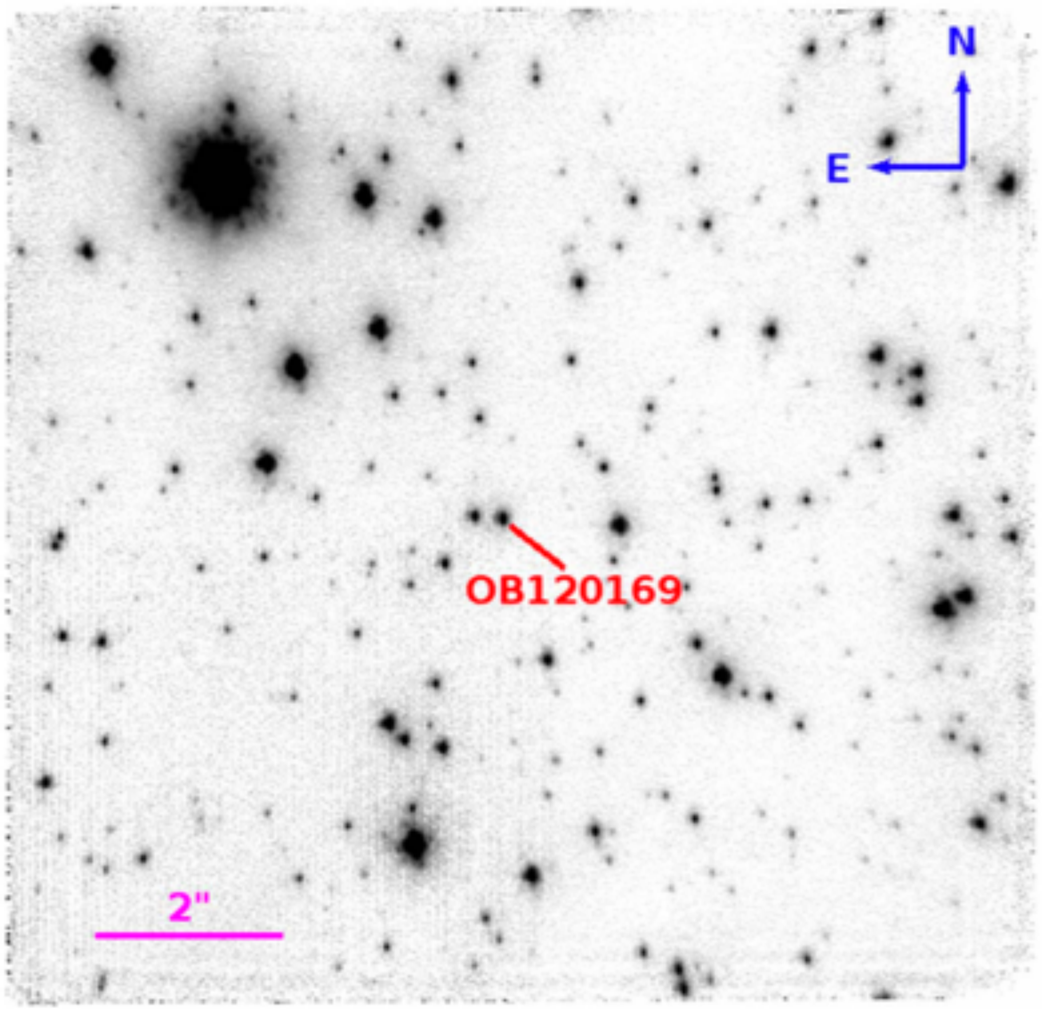


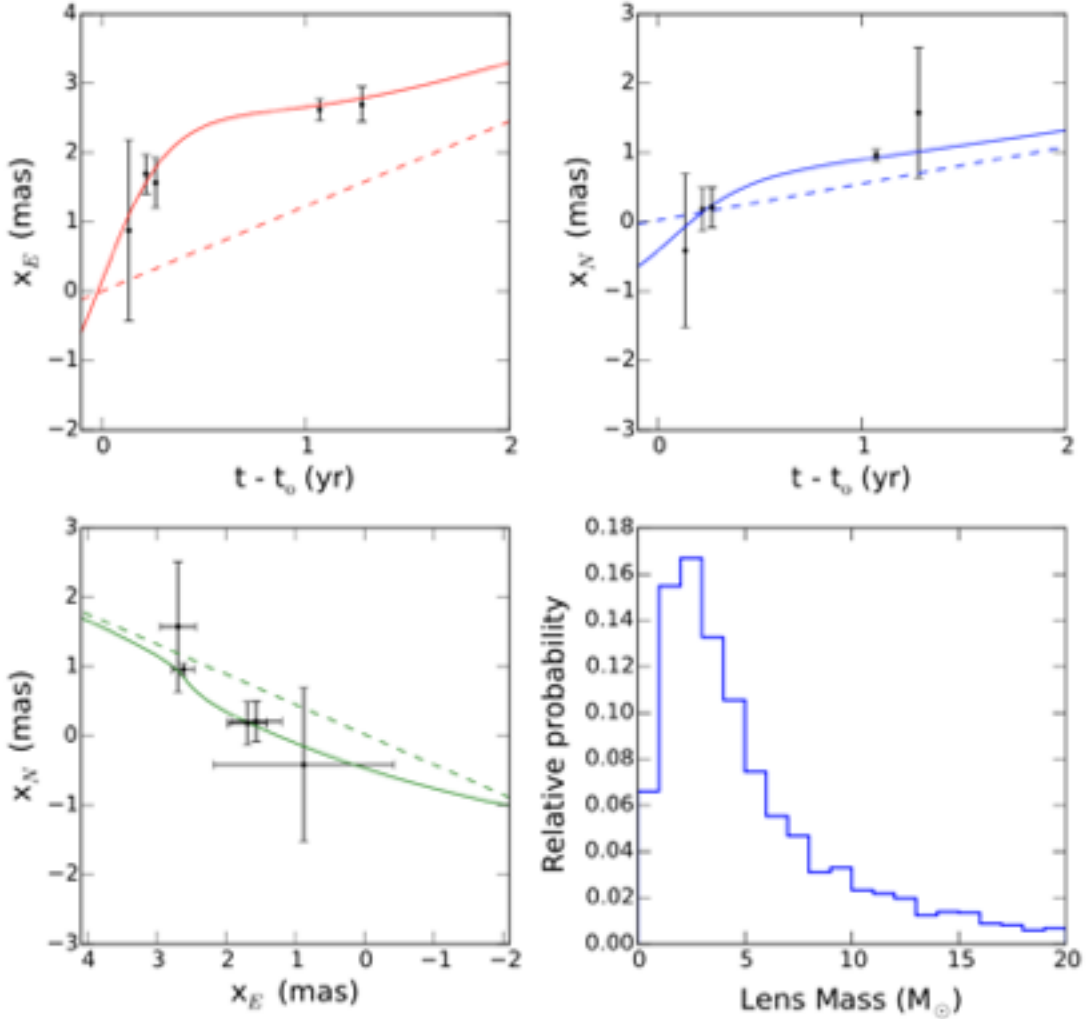
Key

- Lensed Images
- Apparent Source Location
- Actual Source Location
- Black Hole Lens
- Einstein Radius

Gaudi

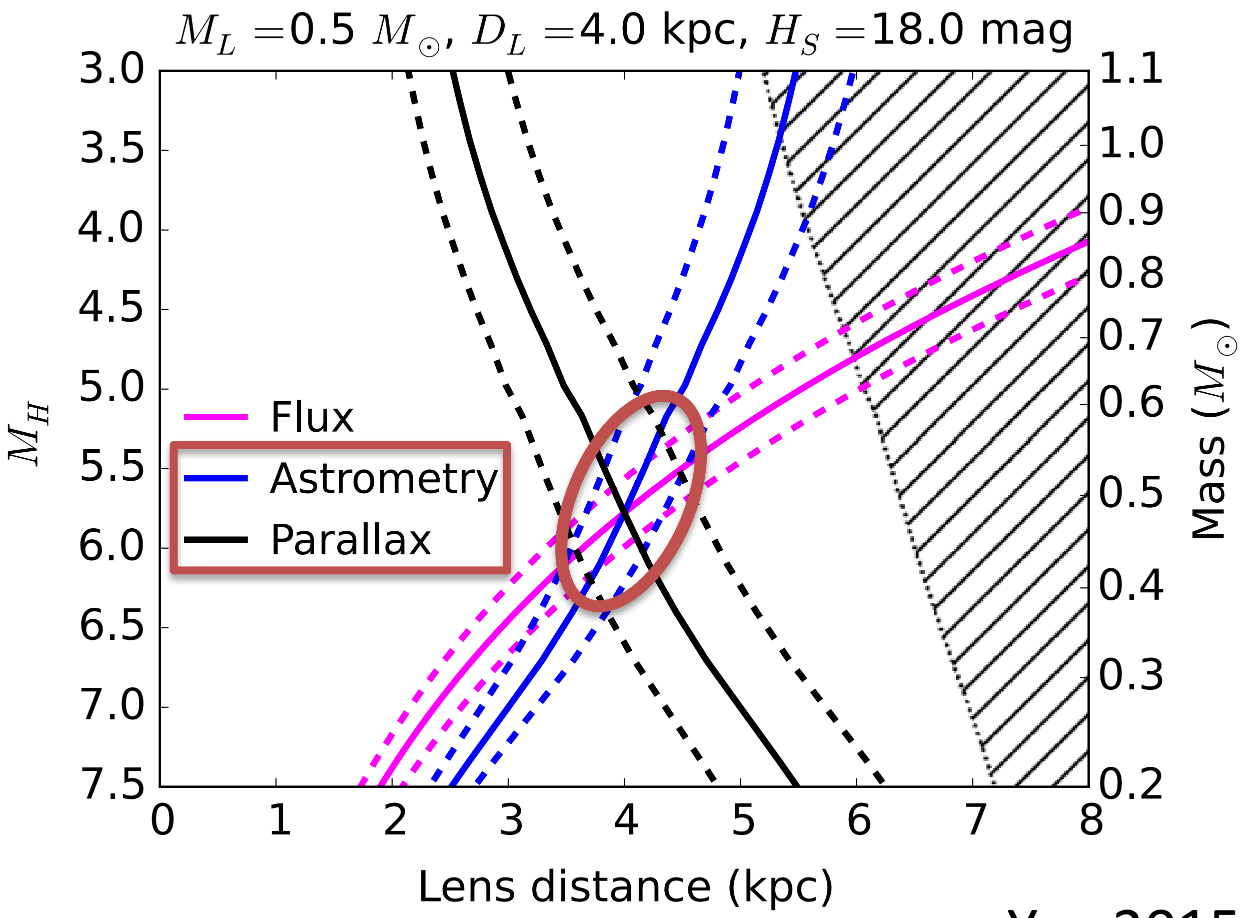
Co-I Jessica Lu is currently making these measurements with Keck adaptive optics!





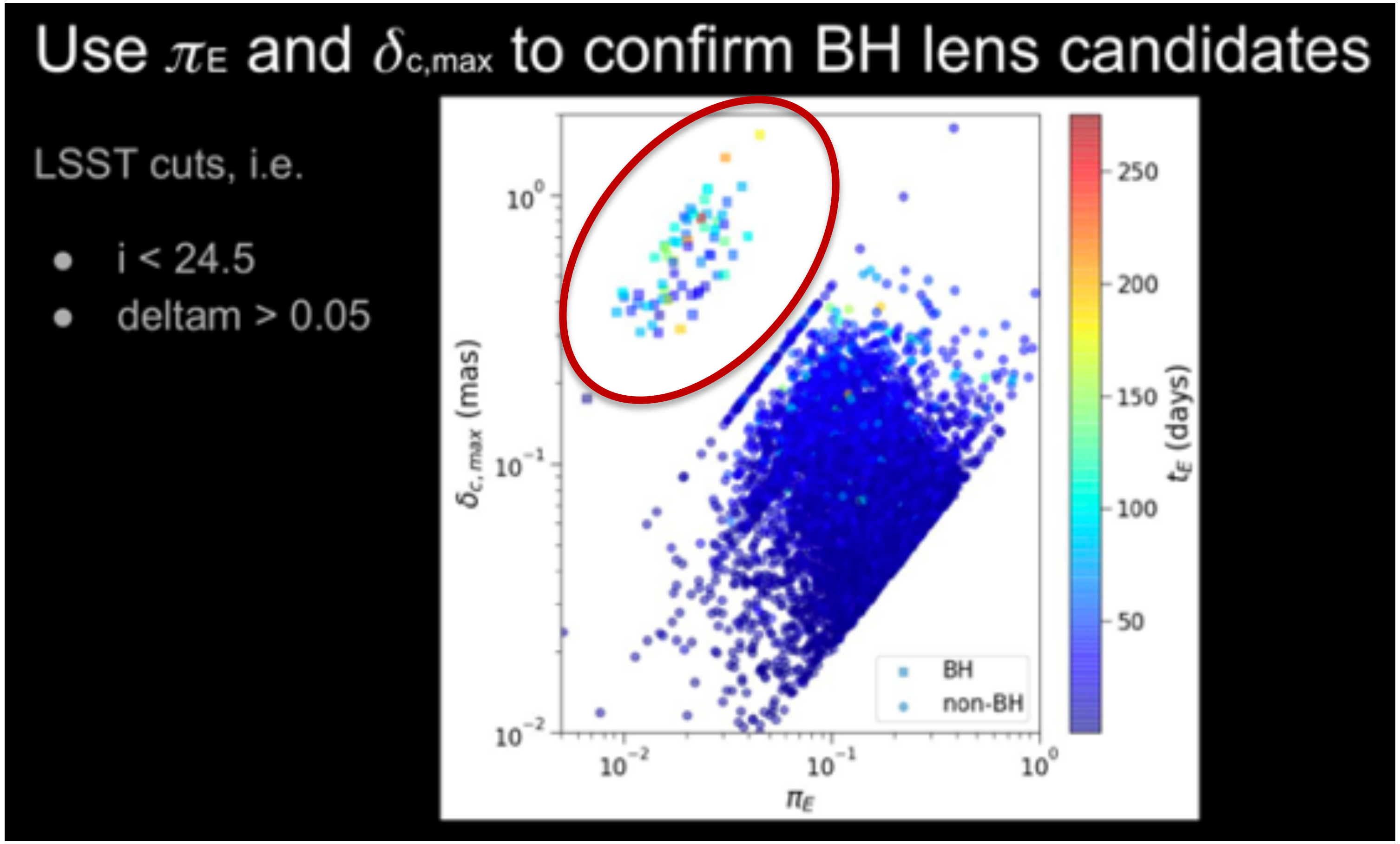
Lu et al. (2017)

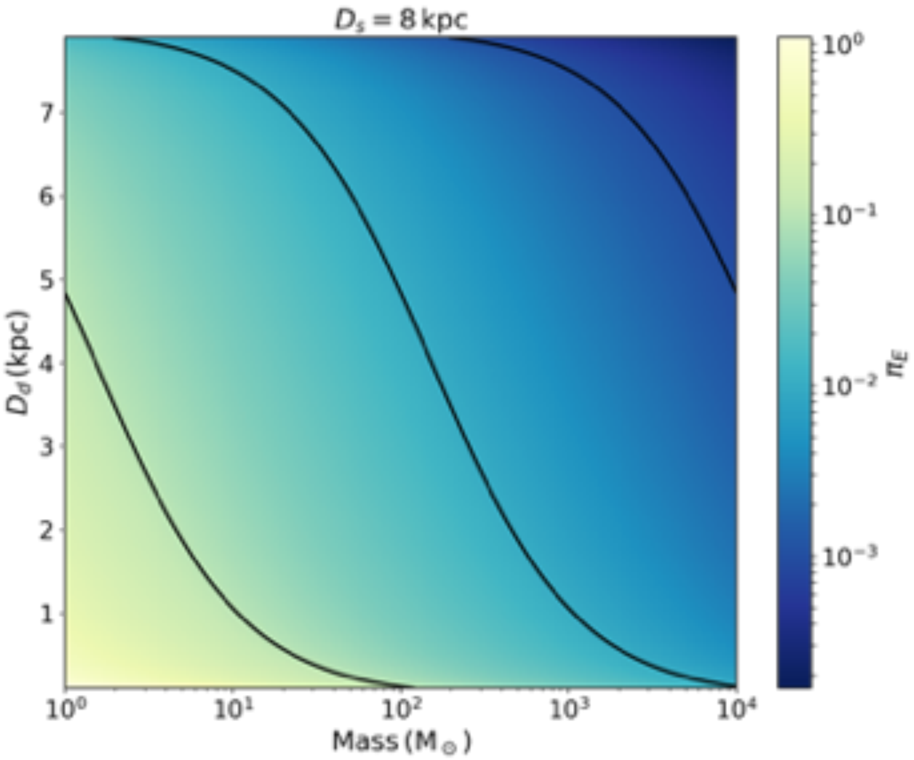
Parallax + Astrometric Microlensing = Tight Mass Constraint



Yee 2015

However parallax for most black hole events is small



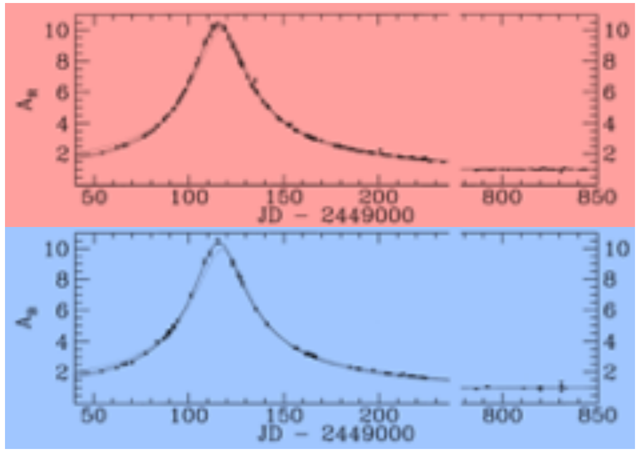


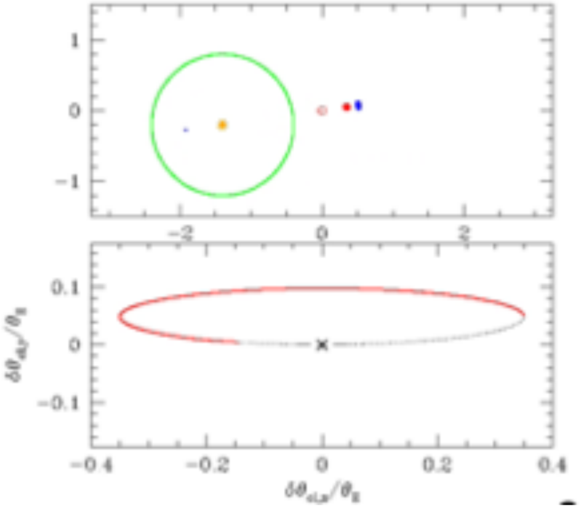
Casey Lam + 23rd Microlensing Conference 2019

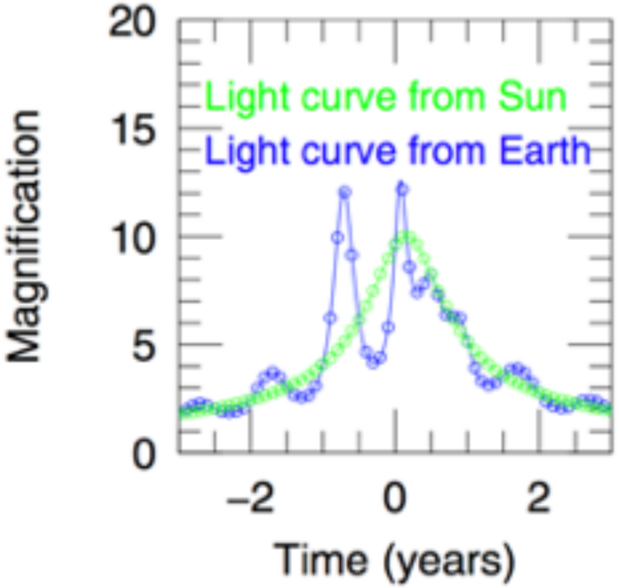
See also Fumio Abe's + 23rd Microlensing Conference 2019 talk

Intermediate Mass MACHO signal provides powerful background discrimination.

- Achromatic
  - Same signal across all wavelengths
- Parallax
  - Signal highly correlated with known motion around the sun
- Astrometry
  - Independent measurement; signal highly correlated with photometric signal







But microlensing is not the only way forward

- Astrometry (Gaia)
- Massively multiplexed spectroscopy (LAMOST, SDSS Phase V, DESI)
- Black hole accreting from stellar wind (Cygnus X-1)
- Black hole accreting from disk (MAXI; A0620-00)
- Accretion of ISM (SKA,SRG)
- Ellipsoidal Modulation (ZTF, TESS) followed by radial velocity (SDSS, DESI)
- Narrow & Wide-band H-alpha imaging (future ZTF project?)
- Strong lensing by a background star (OGLE, ZTF)
- Lensing of secondary star (orbital plane perpendicular to the plane of the sky)
- Variations in eclipse time (OGLE)
- Radio-X-ray "fundamental plane" relation (VLA, SRG)
- Sub-millimeter transients (future facility)
- **Your method here**

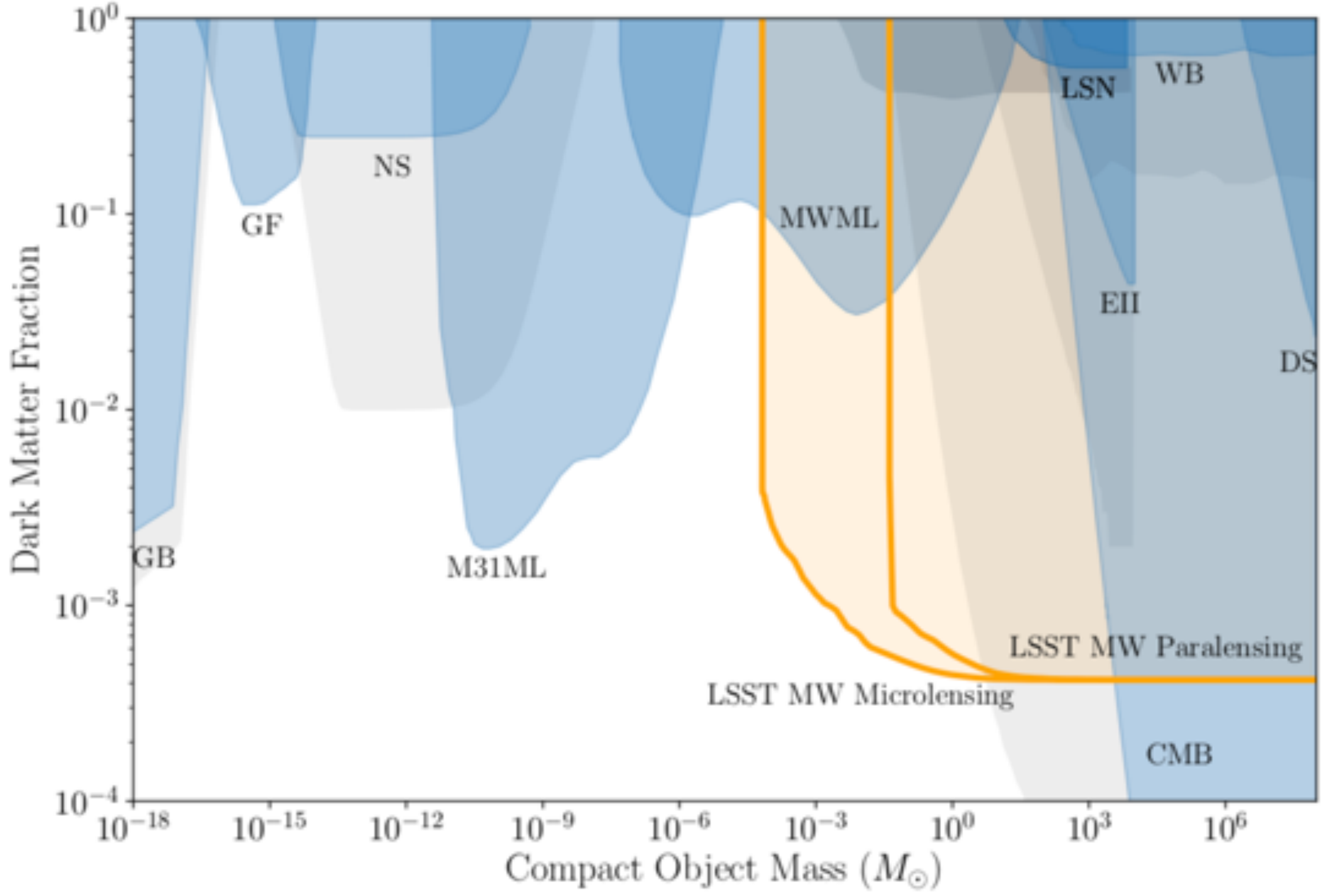
Shri Kulkarni
http://www.astro.caltech.edu/~srk/BlackHoles/BlackHoles.html

Suggested Projects

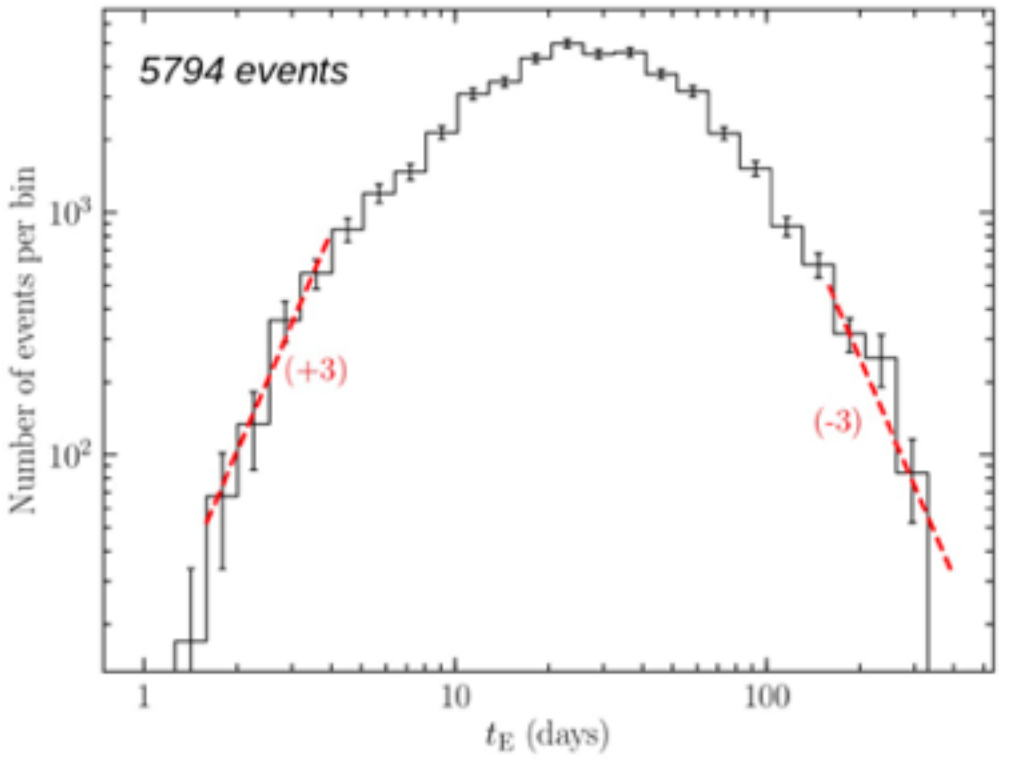
LSST and other deep/long ground microlensing surveys can probe this interesting region of parameter space

Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope

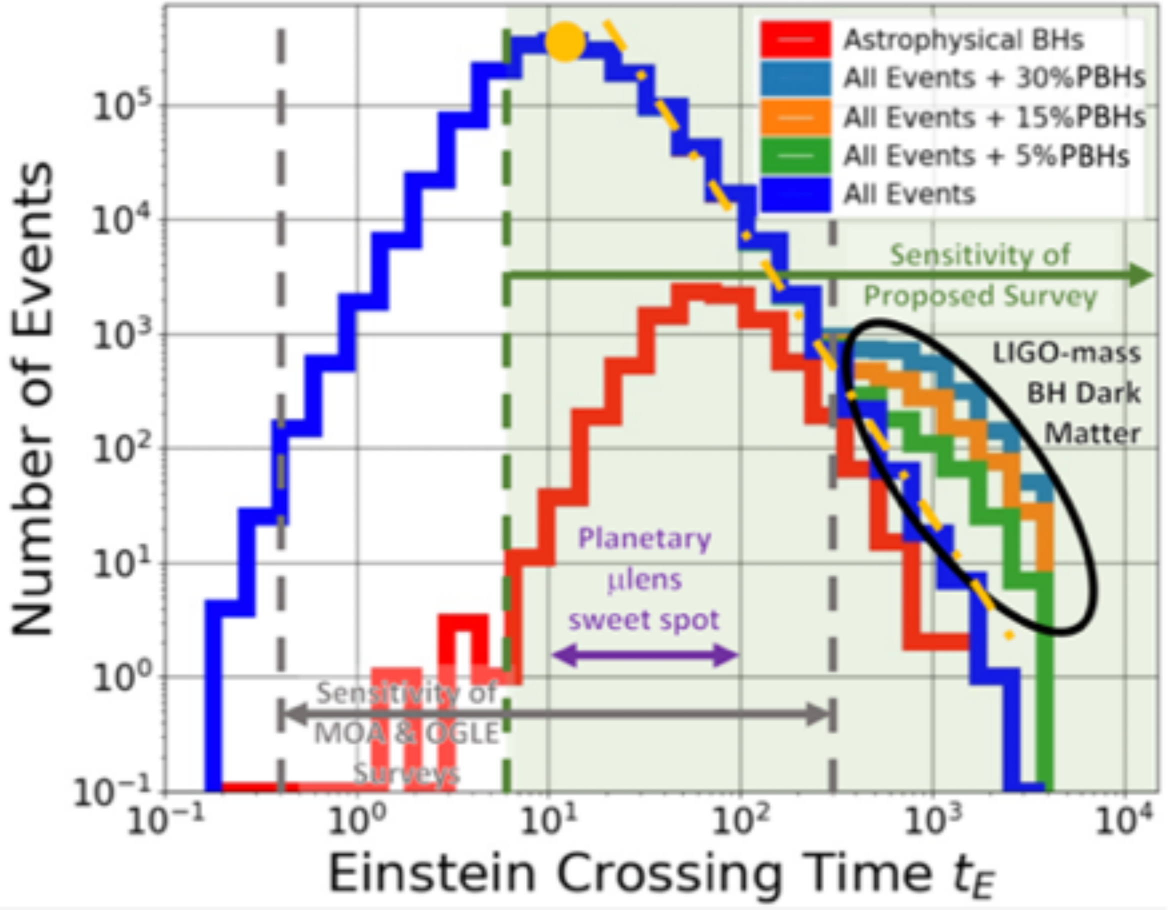
LSST Dark Matter Group



They should be able to start determining if there are signs of black holes in the matter power spectrum



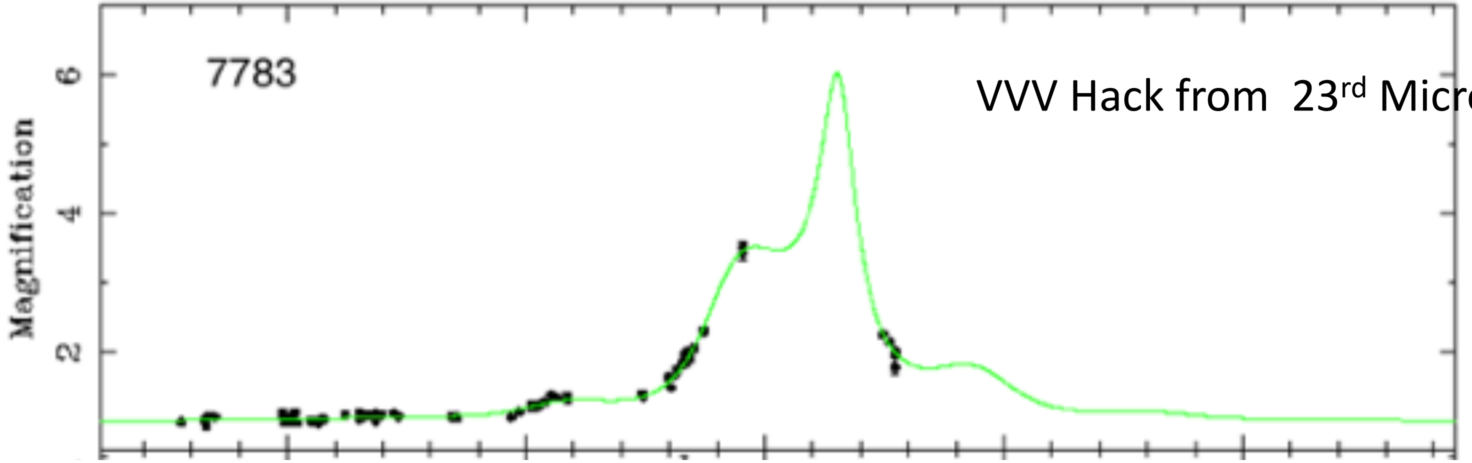
Corrected for detection efficiency, power-law tails



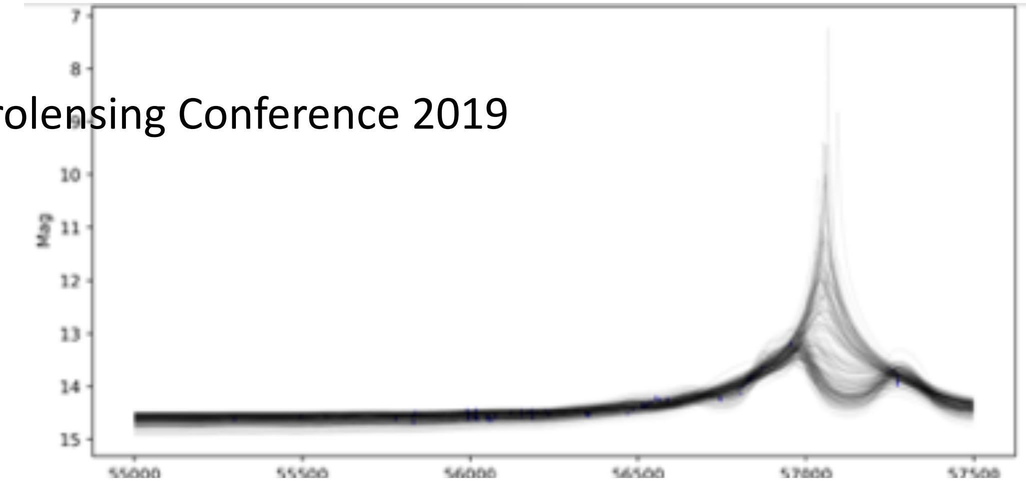
Mroz + 23rd Microlensing Conference 2019

Preliminary: Medford, Lam, & Lu

Implement fully Bayesian statistical methods



VVV Hack from 23rd Microlensing Conference 2019



The Astrophysical Journal, 725:2166–2175, 2010 December 20 doi:10.1088/0004-637X/725/2/2166

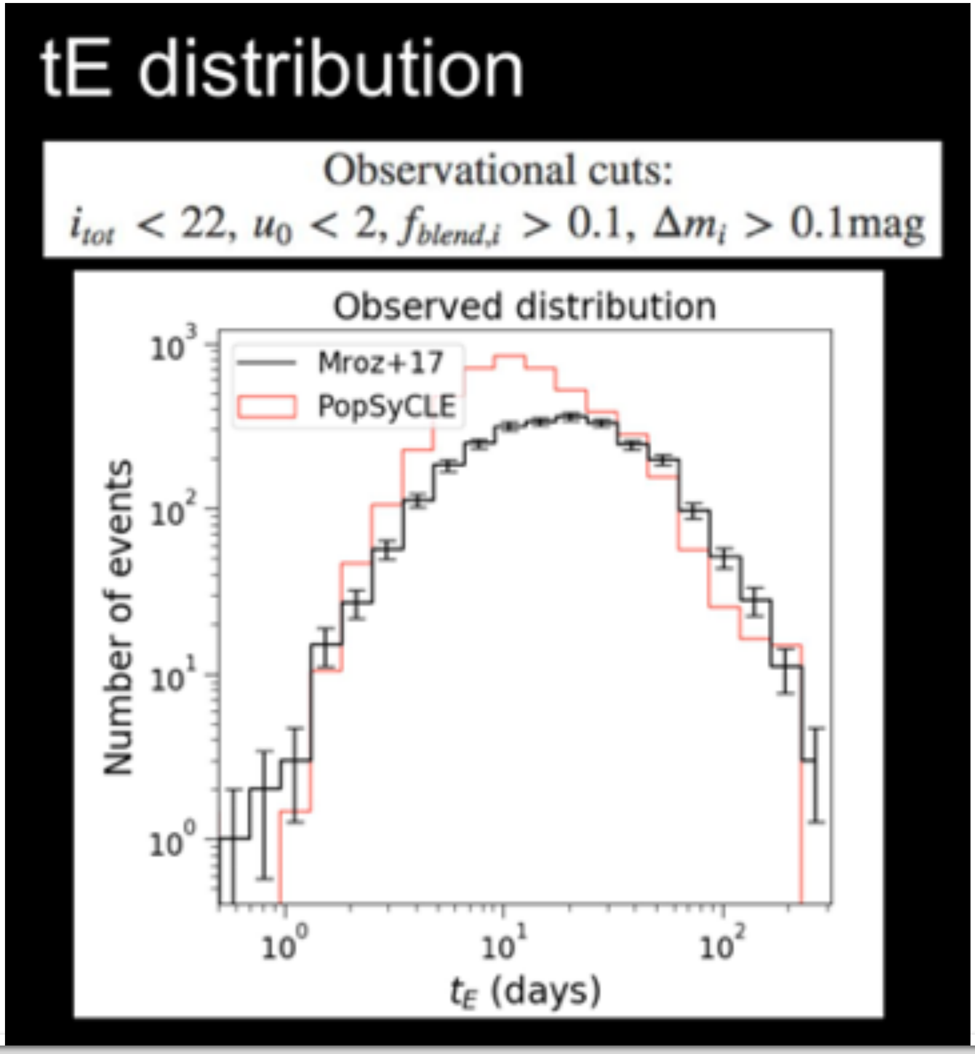
INFERRING THE ECCENTRICITY DISTRIBUTION

David W. Hogg[1,2], Adam D. Myers[2,3], and Jo Bovy[1]

[1] Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA; david.hogg@nyu.edu
[2] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[3] Department of Astronomy, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

Received 2010 August 24; accepted 2010 September 25; published 2010 December 6

Will such statistical and analytical methods resolve some of these discrepancies?

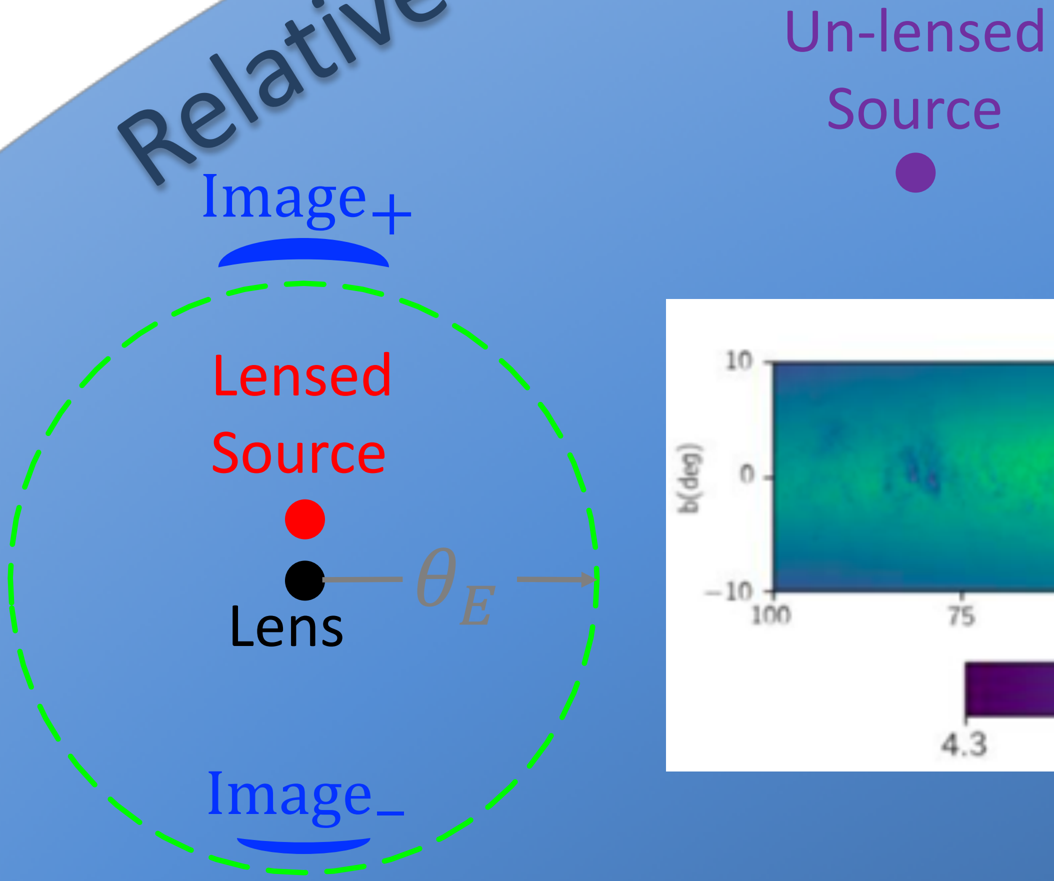


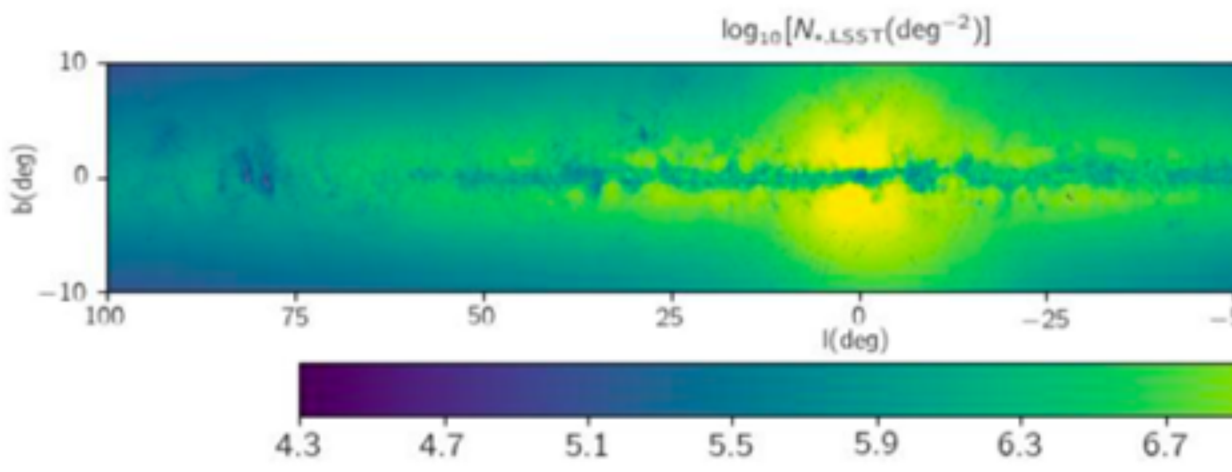
Lam + 23rd Microlensing Conference 2019

Chromatic Microlensing!?

Blending will be a large problem for LSST

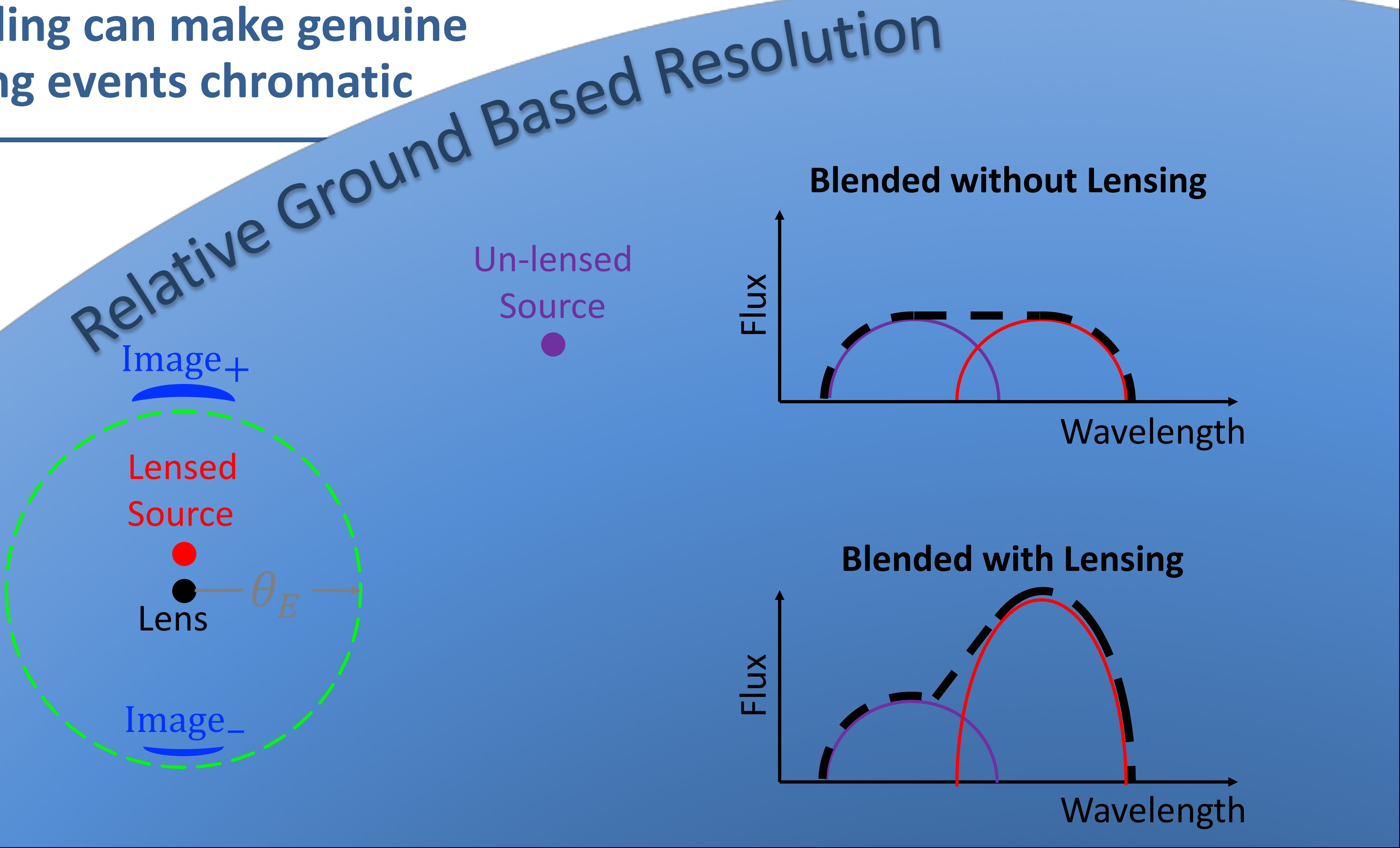
Relative Ground Based Resolution



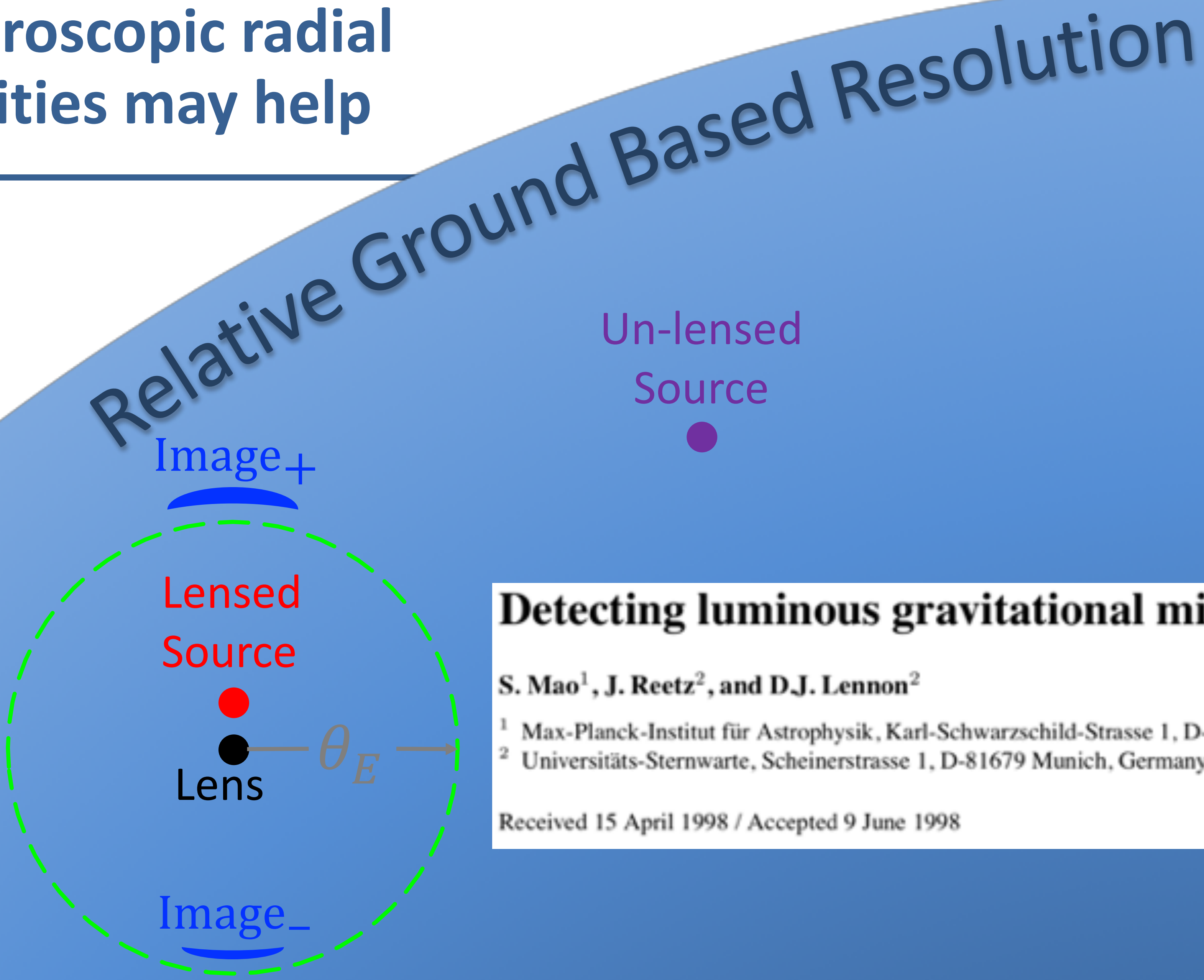


Sajadian & Poleski (2018)

Blending can make genuine lensing events chromatic



Spectroscopic radial velocities may help



Detecting luminous gravitational microlenses using spectroscopy

S. Mao[1], J. Reetz[2], and D.J. Lennon[2]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85740 Garching, Germany
[2] Universitäts-Sternwarte, Scheinerstrasse 1, D-81679 Munich, Germany

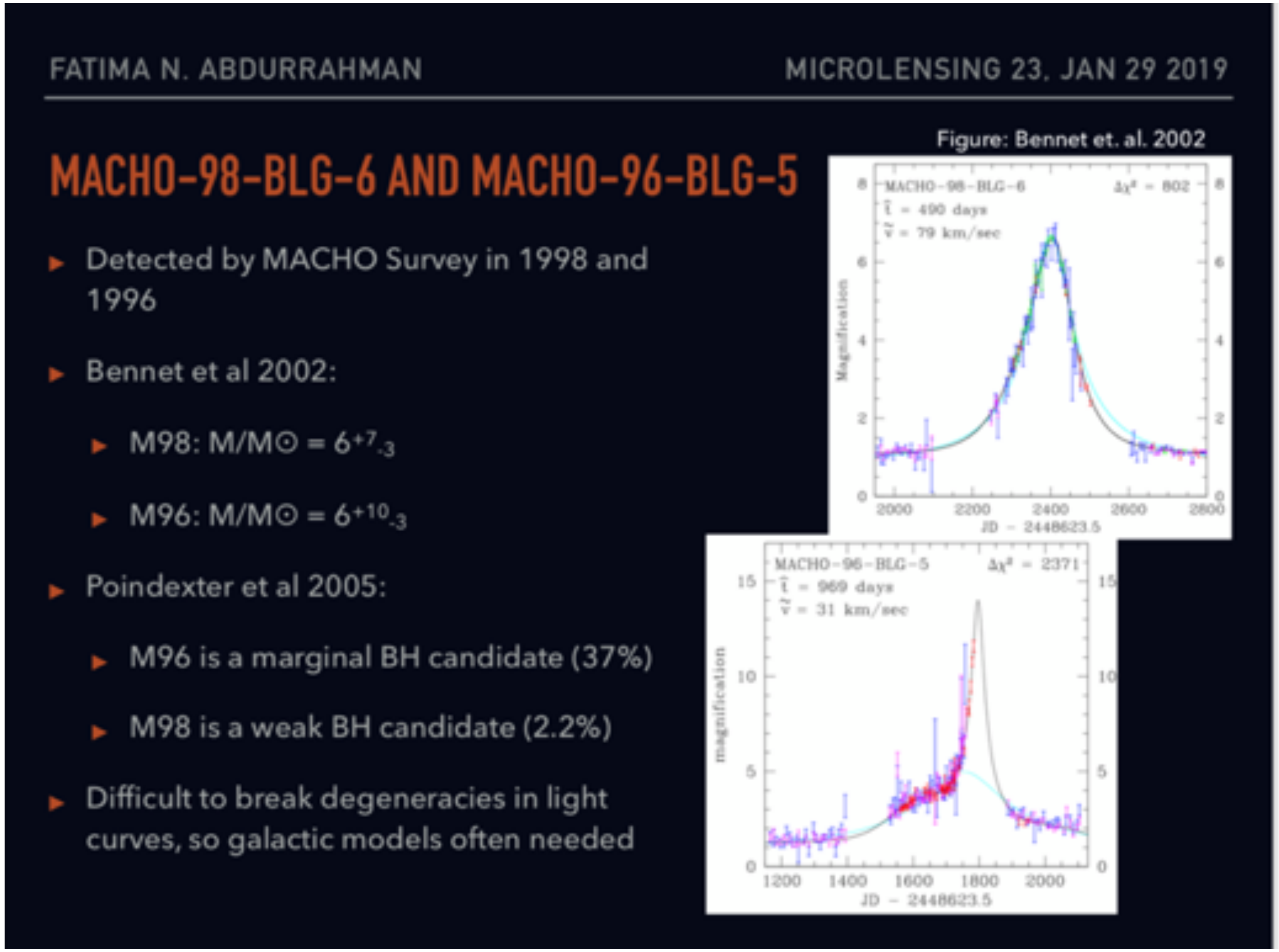
Received 15 April 1998 / Accepted 9 June 1998

Black hole lens or boring old star lens?

There is often ambiguity about whether a microlensing lens is truly dark

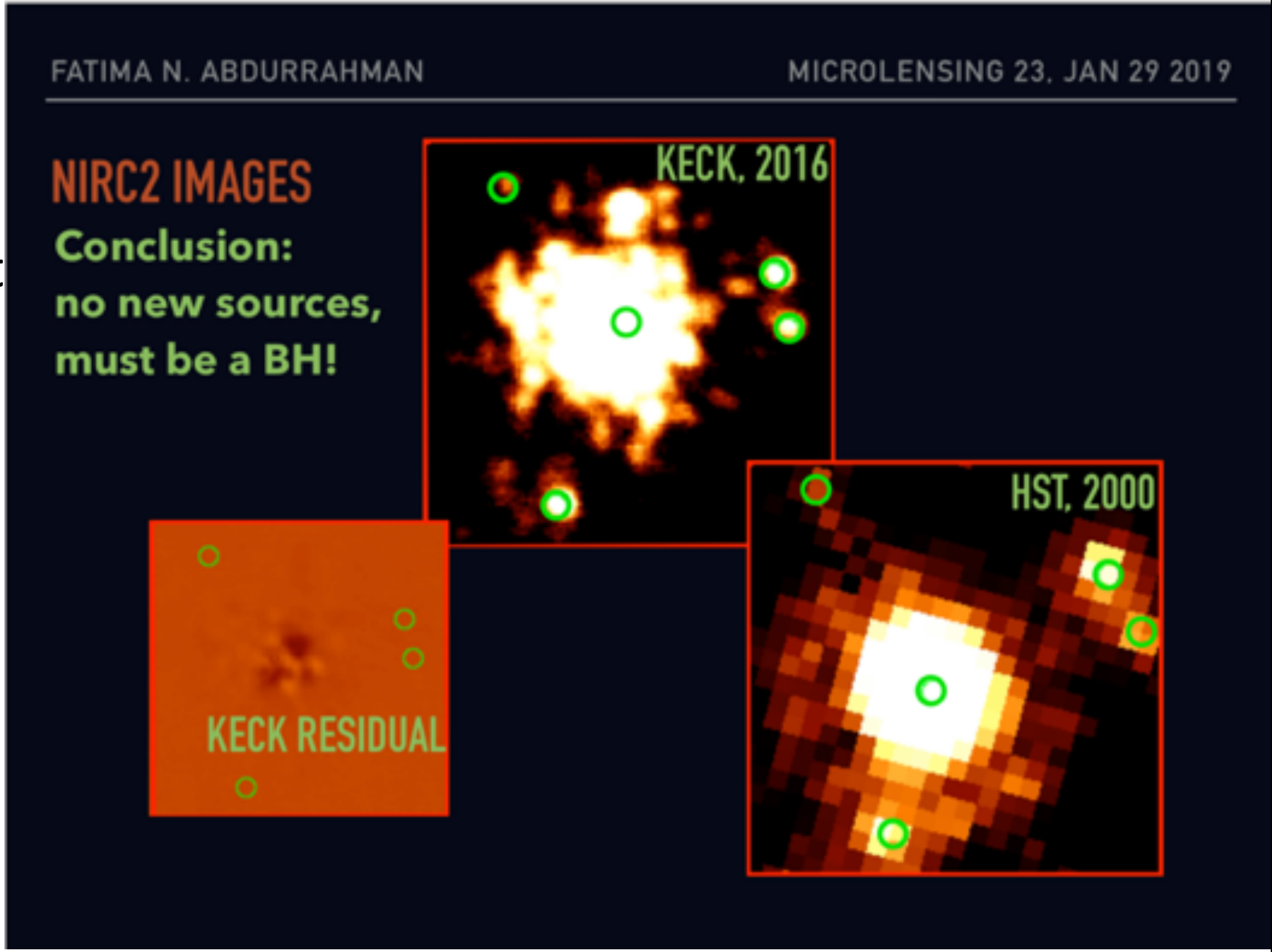
- Consider two MACHO microlensing candidate black hole events

- Possible black holes but also consistent with simple star-star lensing



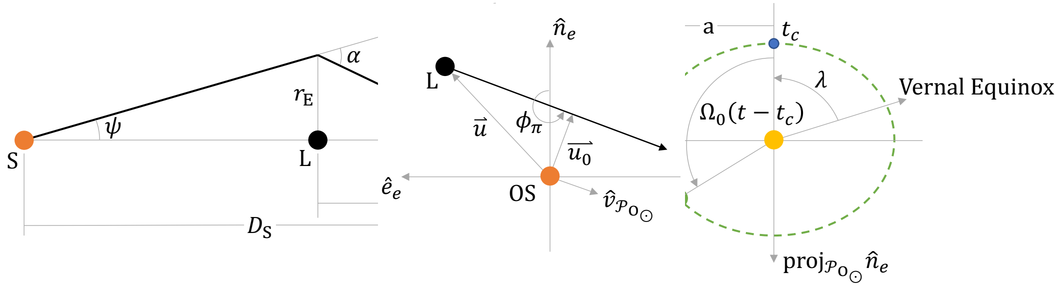
One option is to wait a decade or two and see if the lens moves into plane sight

- Requires high resolution imaging from space and ground over a very long temporal baseline, often much longer than the duration of the event
- Radial velocities and "chromatic microlensing" offer a way to break this degeneracy on much shorter timescales



Microlensing and Radial Velocity Complementarity

Lawrence Livermore National Laboratory



α
r_E
ψ
S
L
D_S
L
$\hat{n}_e$
$\vec{u}$
ϕ_π
$\overrightarrow{u_0}$
$\hat{e}_e$
OS
$\hat{v}_{\mathcal{P}_{O_\odot}}$
a
t_c
λ
Vernal Equinox
$\Omega_0(t - t_c)$
$\text{proj}_{\mathcal{P}_{O_\odot}} \hat{n}_e$