A DECam and LSST microlensing survey of intermediate mass black hole dark matter

U.S. Cosmic Visions: New Ideas in Dark Matter

2017 March 24

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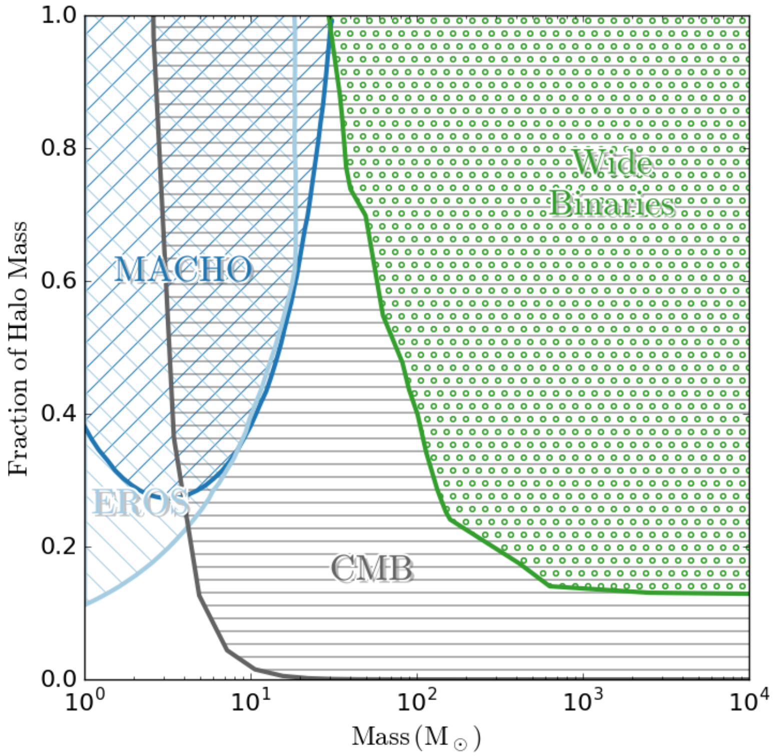
What you might not know about MACHOs could SHOCK YOU!

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 $\gtrsim 10^4 M_\odot$

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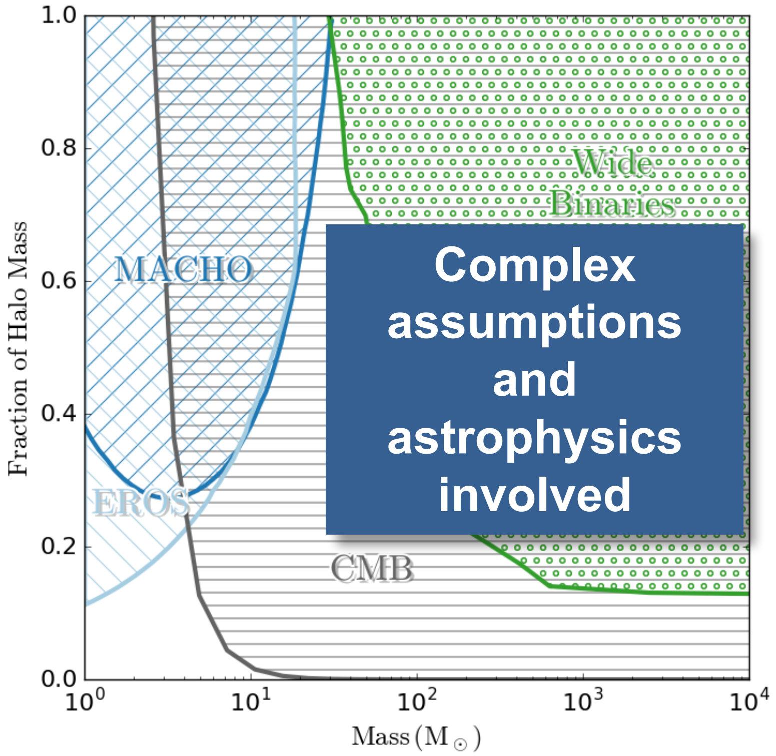

Complex assumptions and astrophysics involved

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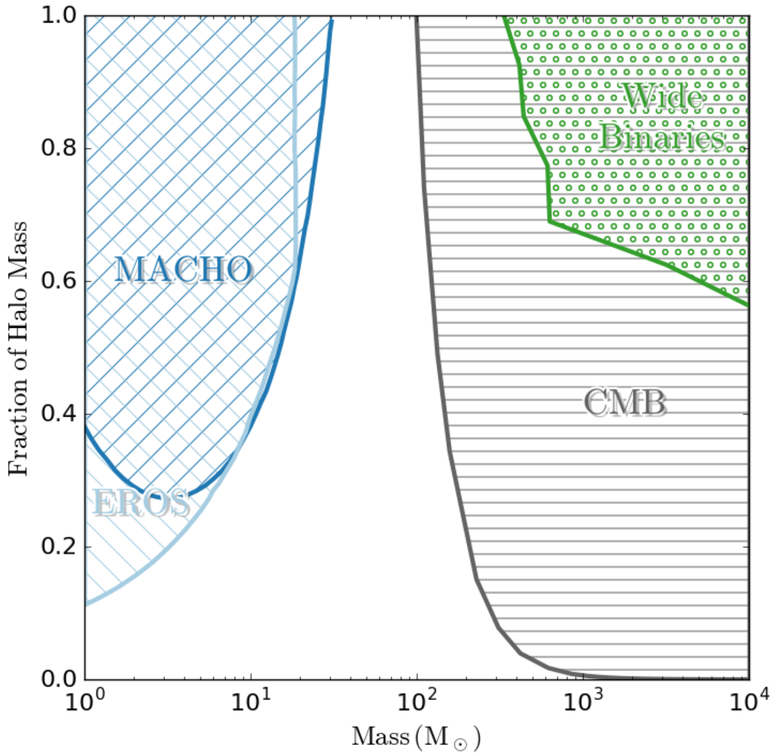
Massive MACHO Constraints circ. 2016
As assumptions and systematics explored constraints loosened



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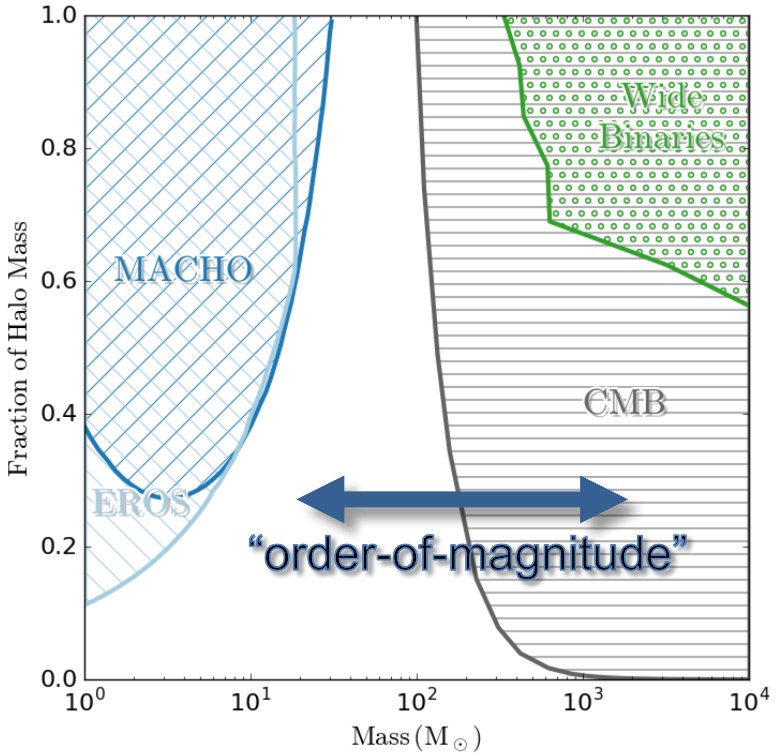
"The limits that Ricotti and I reached for BH numbers were far to severe."
-Ostriker

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



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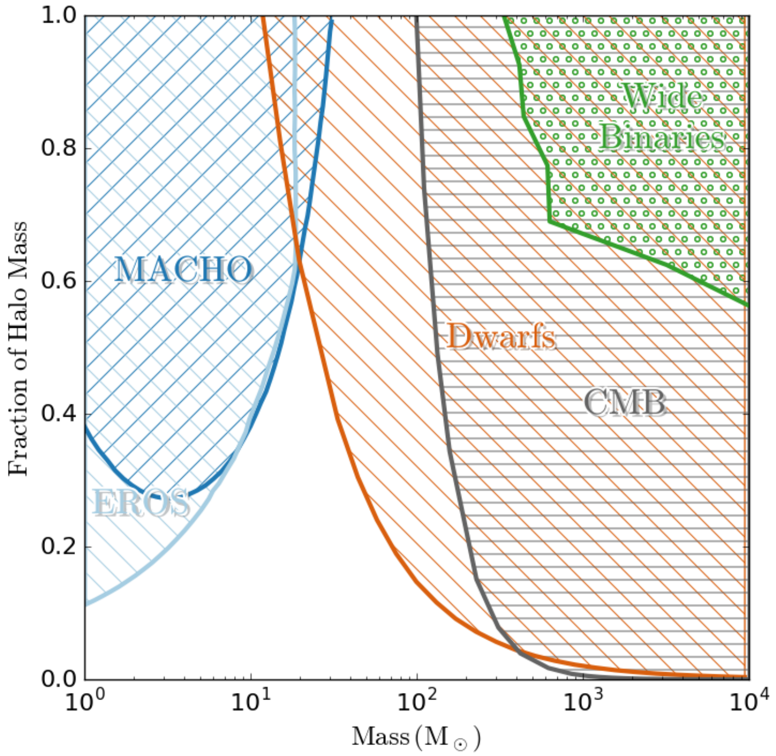
The latest astrophysical constraint from dwarf galaxies and star clusters



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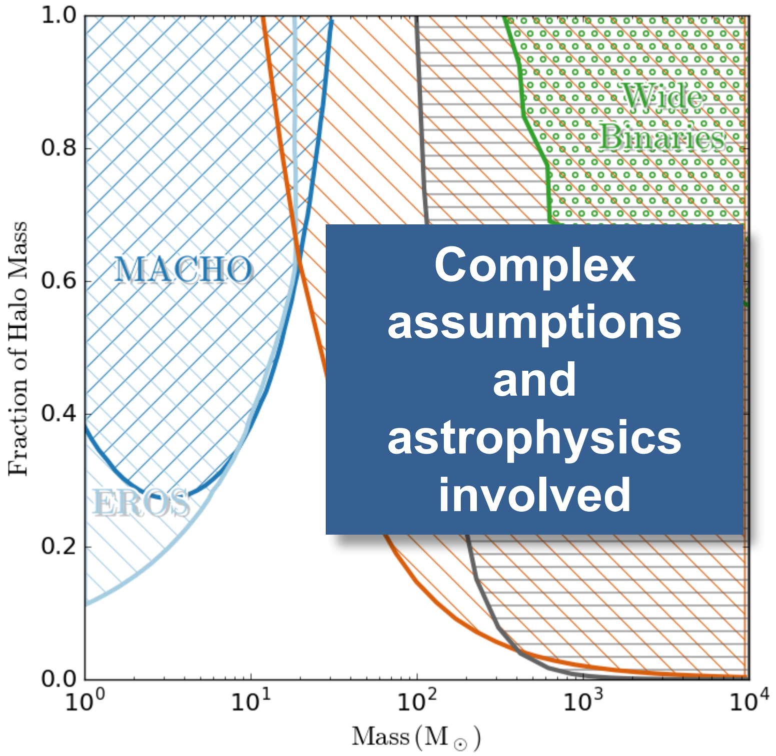
- CMB
  - Ali-Haïmoud & Kamionkowski 2016
- Wide Binary
  - Quinn et al. 2009
- Dwarf Galaxies
  - Brandt 2016, & Li et al. 2017

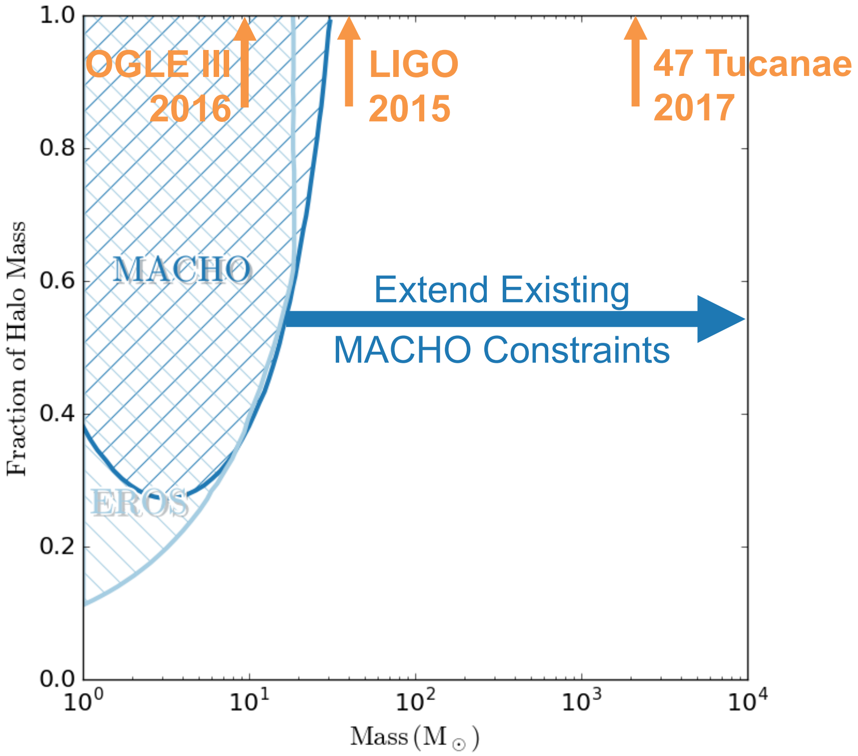
The dwarf galaxy constraint is reliant on several astrophysical assumptions, likely to be wrong



- 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

Microlensing is the closet thing we have to a direct measurement

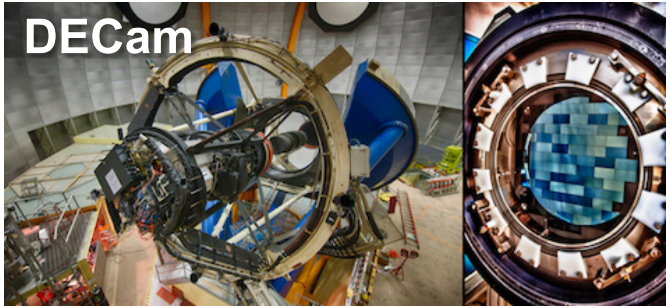
- We know there are black holes in this mass range.
  - Extensive primordial black hole literature: from Chapline (1976) to Carr et al. (2016).
- Rather than tackle an array of astrophysics we prefer a direct measurement.
- **Microlensing is the most direct way of constraining this parameter space.**

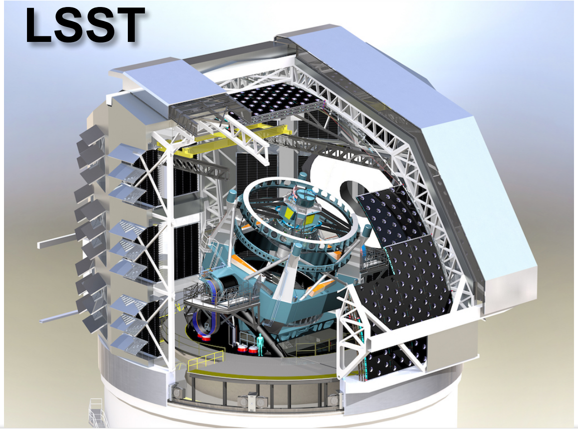


How do we discover or rule out primordial black holes as dark matter

- Objective
  - Confirm or reject primordial black holes ($> 10 M_{\odot}$) as the predominant form of dark matter

- Method
  - Near Term: A multi-band low cadence DOE DECam microlensing survey of Milky Way Bulge
    - LLNL investing with LDRD now to verify plan via simulations
  - Long Term: LSST microlensing survey of the Milky Way and its local group
    - Follow-up JWST, and 30 m class telescope astrometric microlensing measurements
  - DOE is 96% of the way there: leverages DOE investments in DECam, DECam survey computation, and LSST

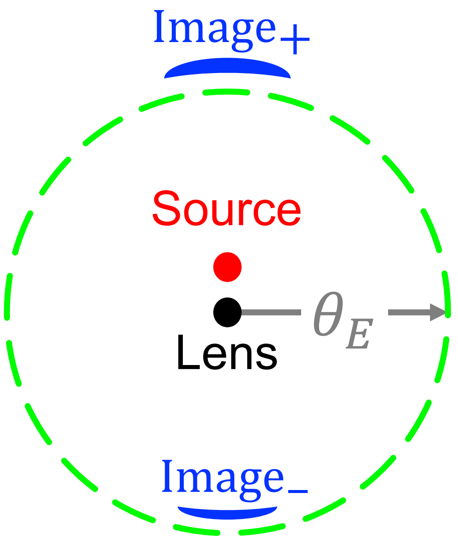


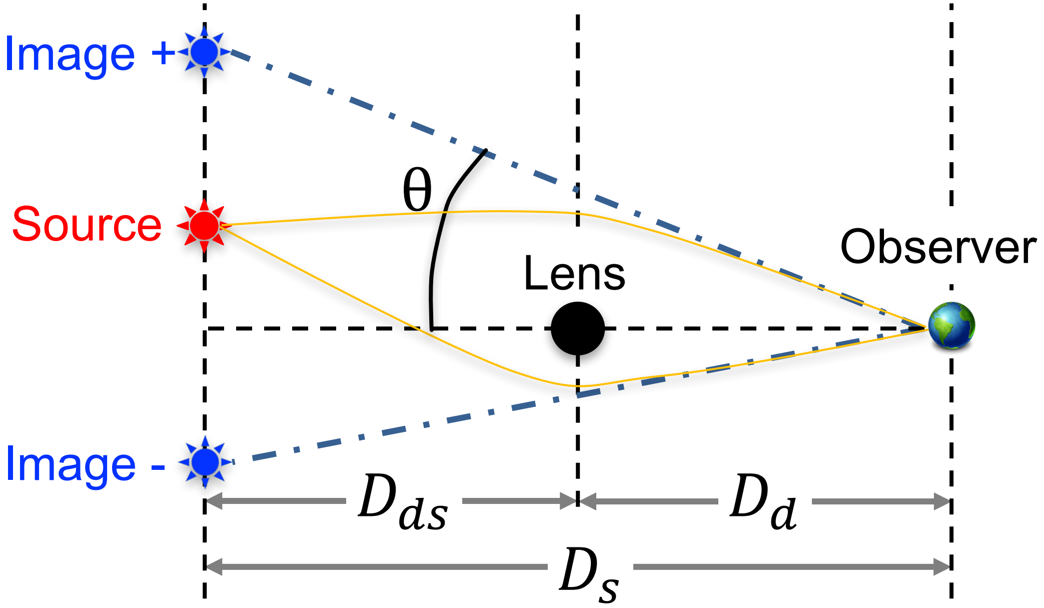


Gravitational microlensing basics

Einstein Radius

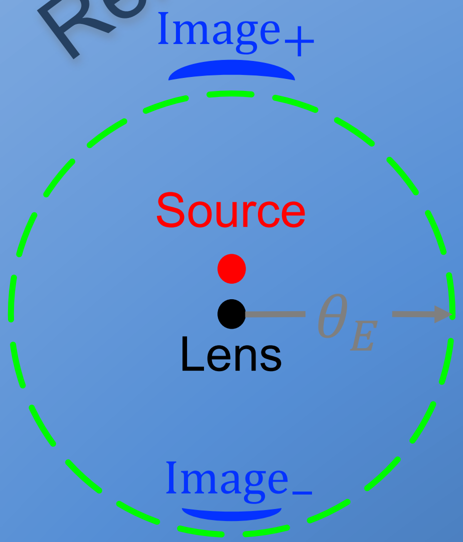
$$\theta_{\mathrm{E}} = \left(\frac{4GM}{c^2} \frac{D_{\mathrm{ds}}}{D_{\mathrm{d}} D_{\mathrm{s}}} \right)^{1/2}$$





Total magnification is what is measured

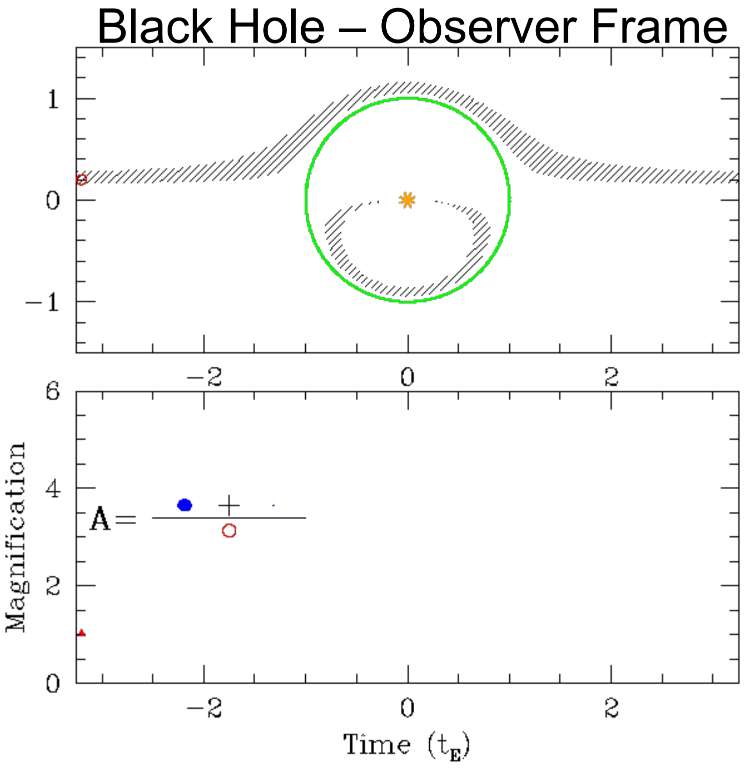
Relative Ground Based Resolution



Total magnification:

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

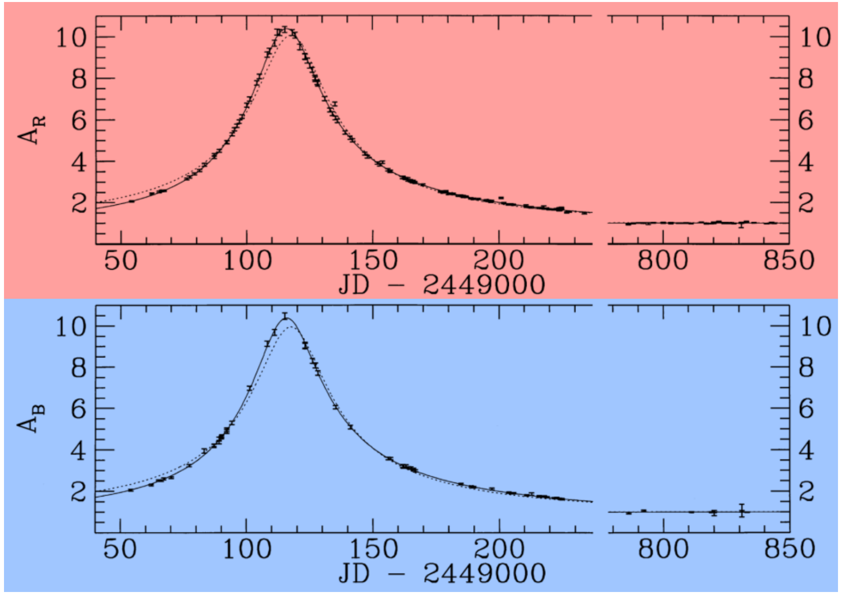
Microlensing Basics



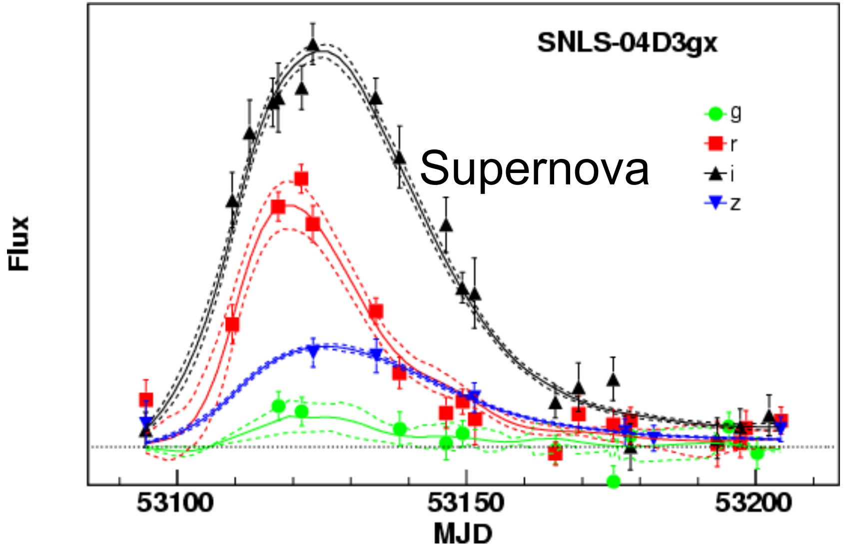
Gaudi

Microlensing is achromatic. Powerful discriminator. Motivates multi-band microlensing survey.

Microlensing signal does not vary with color!



Typically astrophysical variable sources vary with color.

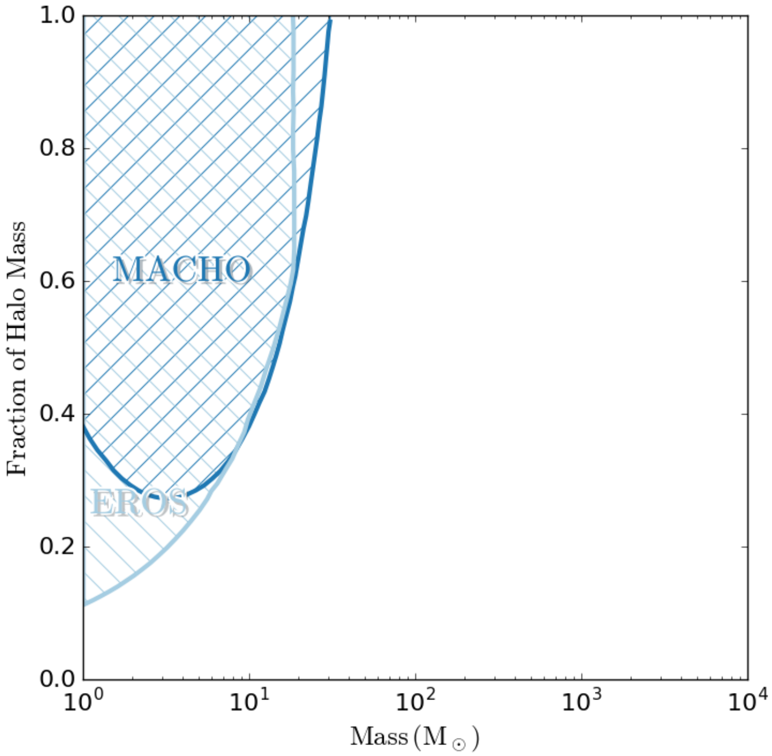


Alcock et al. 1995

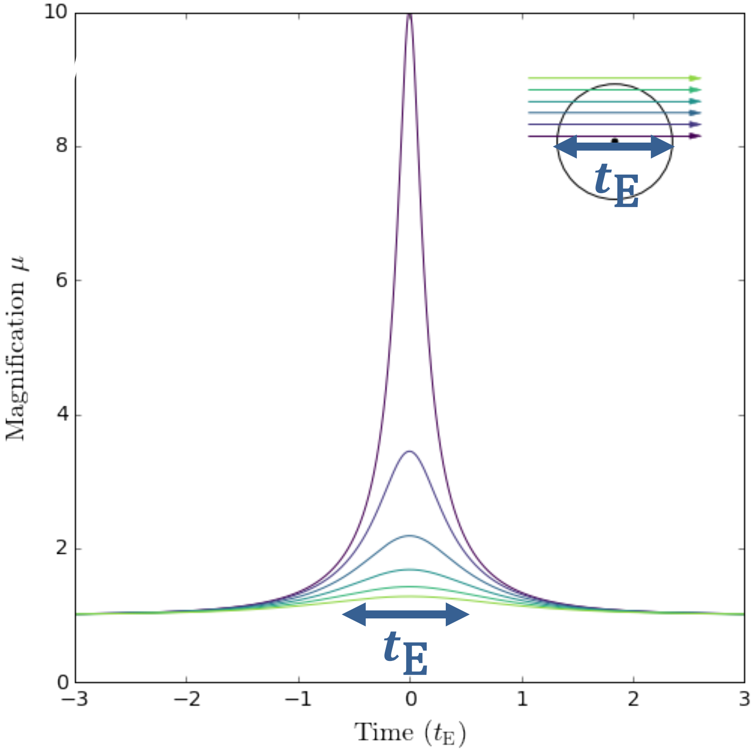
Guy et al. 2007

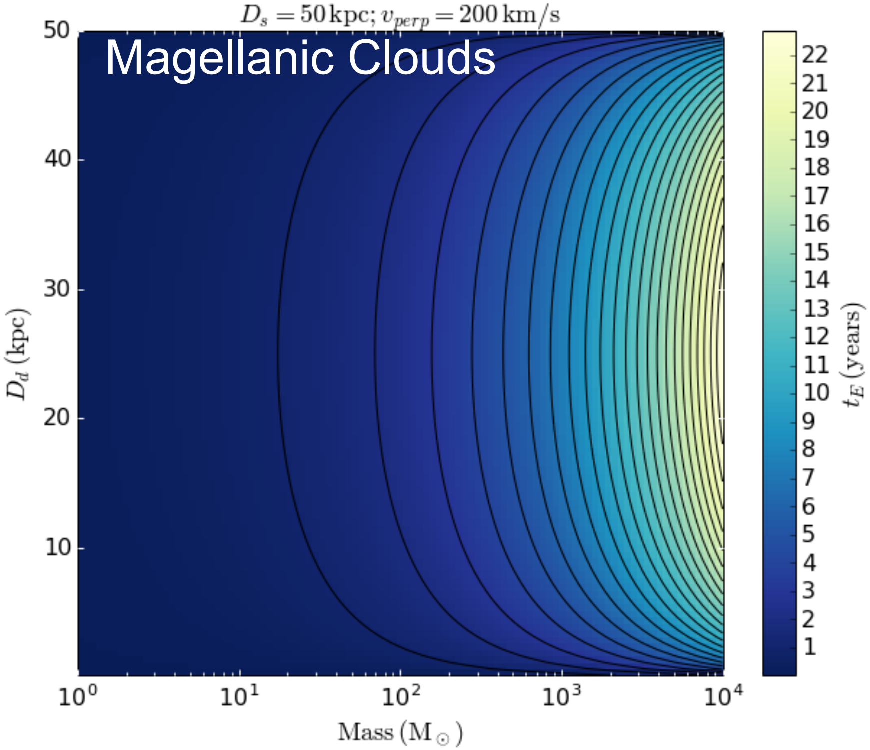
Existing microlensing constraints only go up to

- Why did they stop at $\sim 30 M_\odot$?



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)

Number of monitored stars

Timescale of Survey

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

Timescale of lensing event

Optical Depth

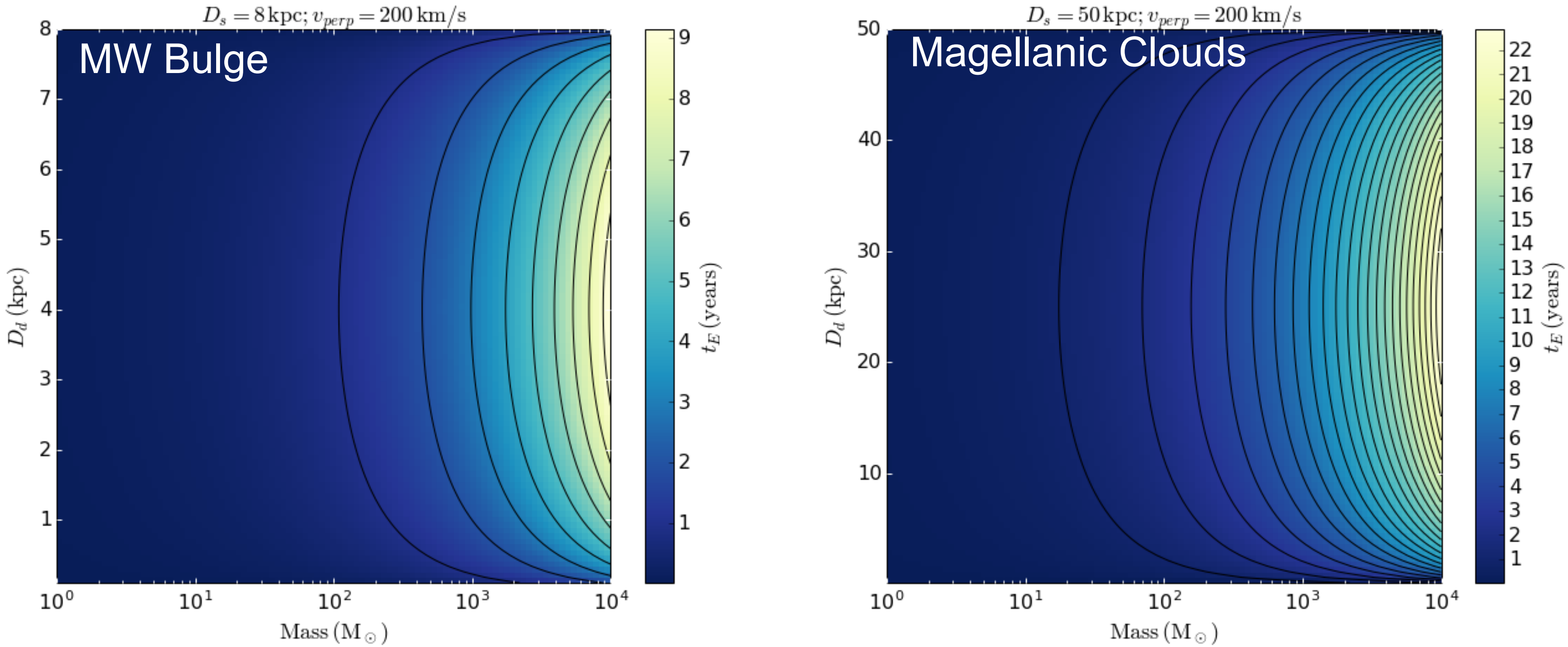
$$D = (D_d D_{ds} / D_S)$$

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

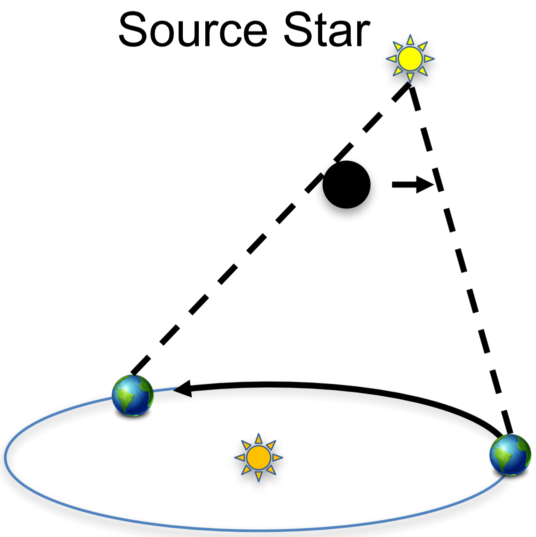
Average dark matter density at D_d

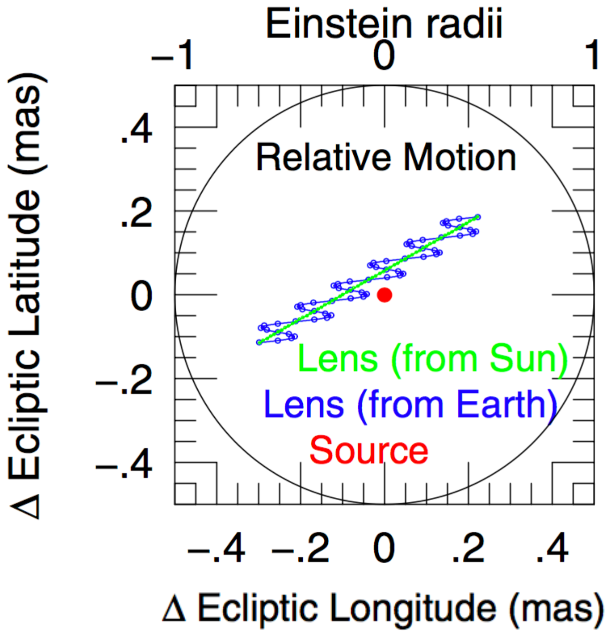
Paczynski 1986, 1996

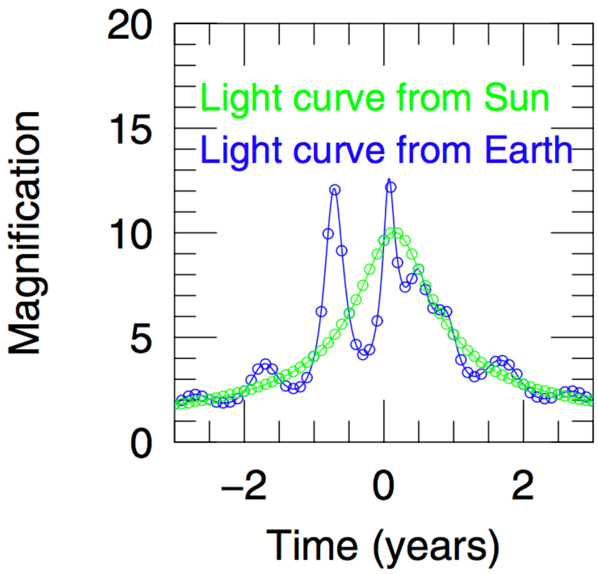
Time-scale of microlensing events.
For high mass MACHOs MW Bulge is better.



Parallax:
Multi-year lensing events detected on order of 6 months

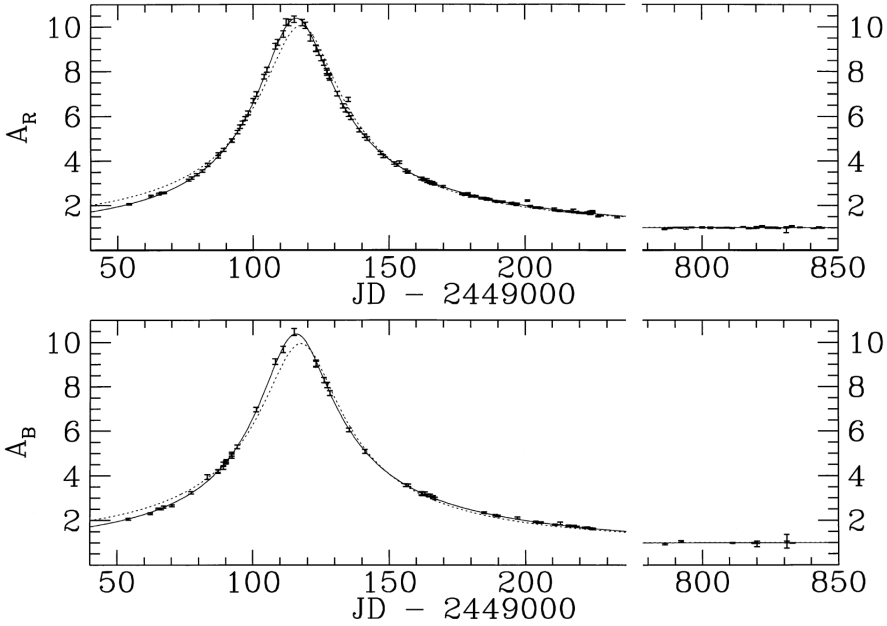






Gould & Horne 2013

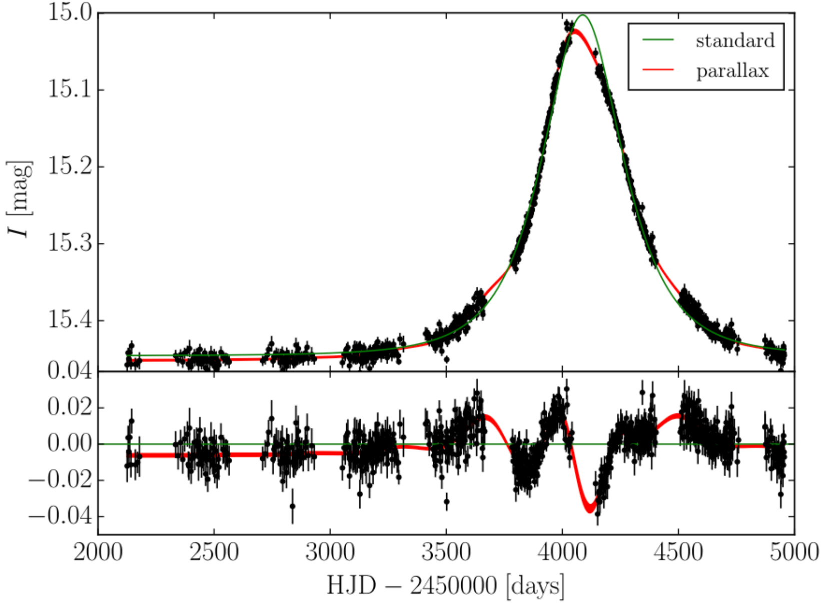
Parallactic effect first discovered at LLNL
Enables even short baseline surveys detect IM MACHOs



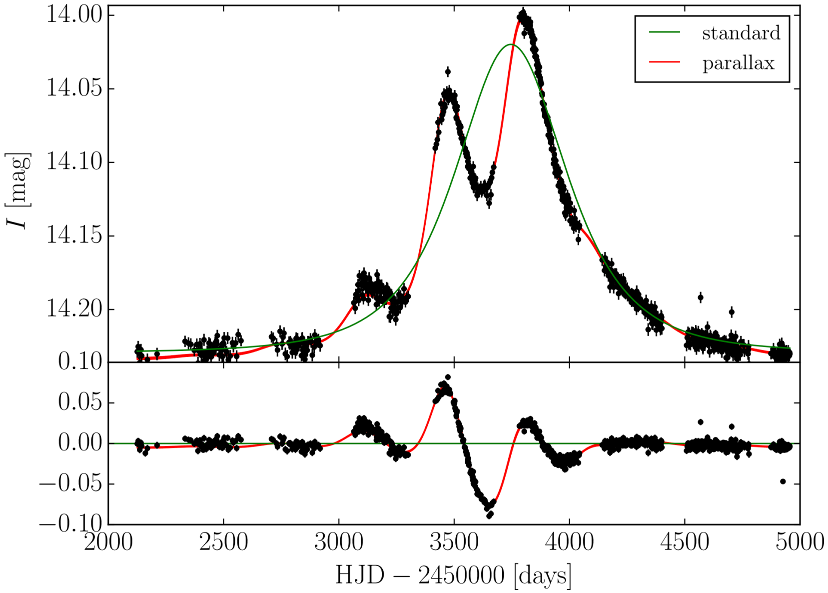
MACHO Survey (1995)

Recent OGLE III parallax events

9.3 $M_\odot$ Black Hole



1.0 $M_\odot$ Neutron Star

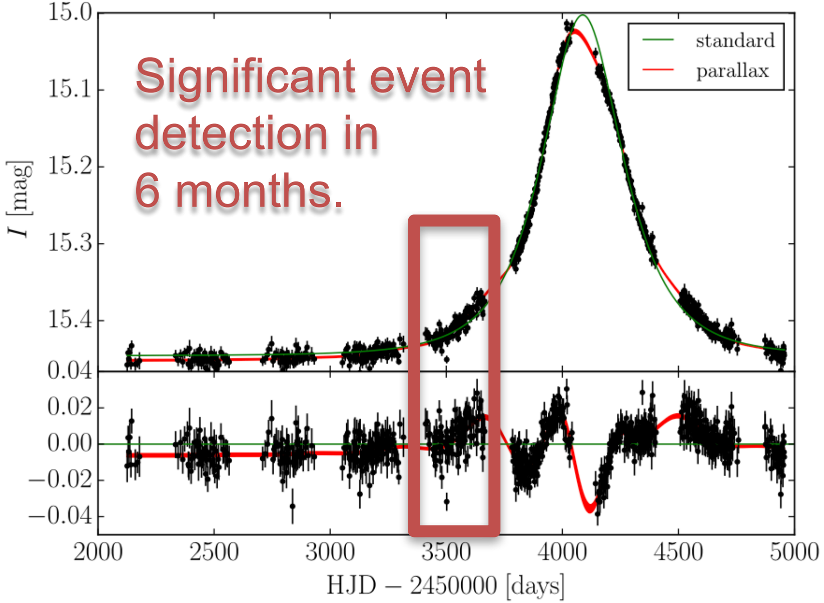


~8 years

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



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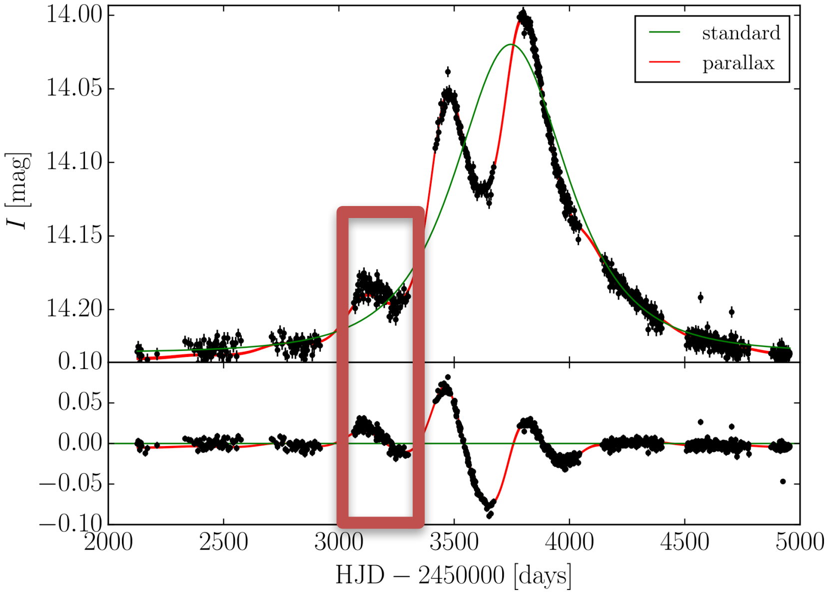


Wyrzkowski et al. 2016

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

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

Timescale of Survey

Timescale of lensing event

From 10's of years to ~6 months!

Optical Depth

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

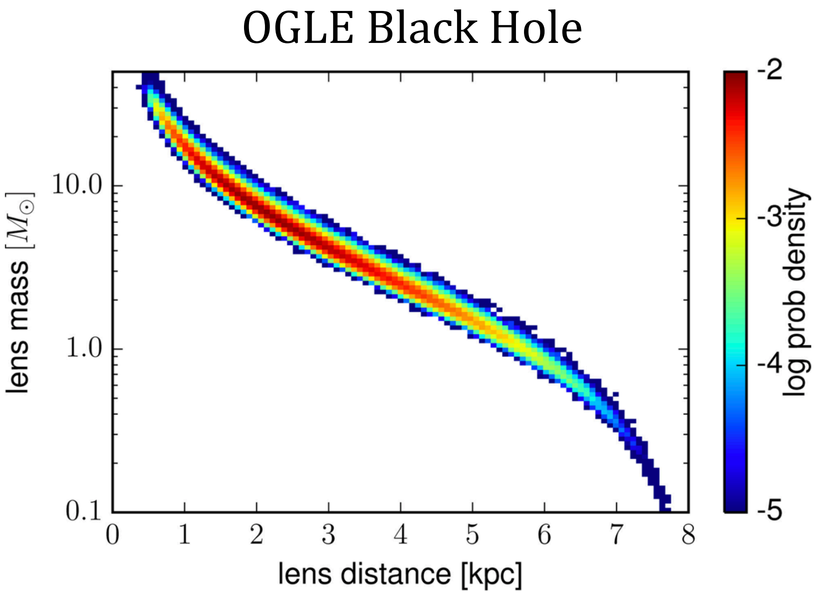
$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2} \rho(D_d)\, dD_d$$

Average matter density at D_d

Paczynski 1986, 1996

Microlensing parallax constraint on black hole mass

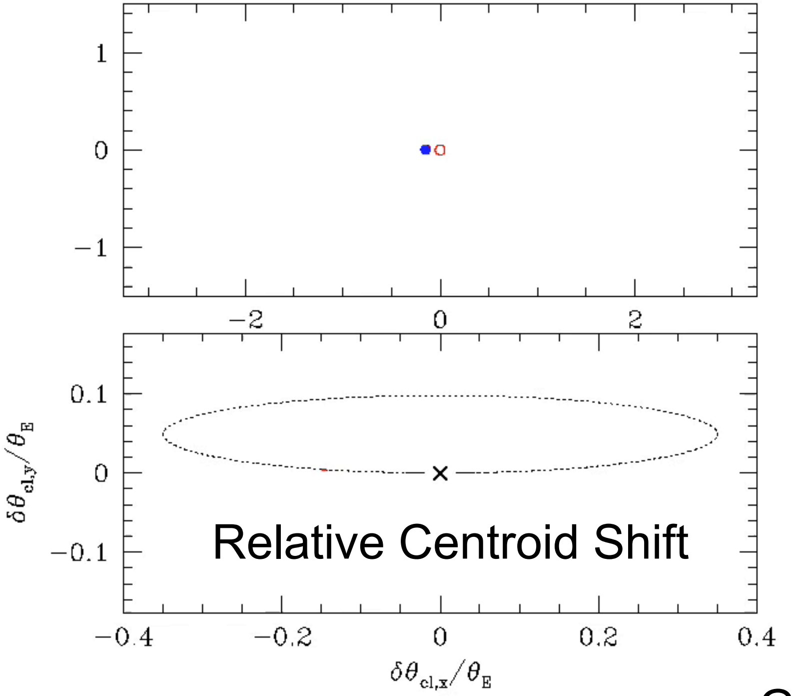
- Parallactic signal is a strong function of mass
  - Without the parallax you basically have no constraint on the lens mass.
- However there is still a degeneracy between lens mass and lens distance.
- With an <u>*ensemble can place tighter constraints on the population mass spectrum*</u>, by utilizing our knowledge of the MW dark matter halo density function.



Wyrzkowski et al. 2016

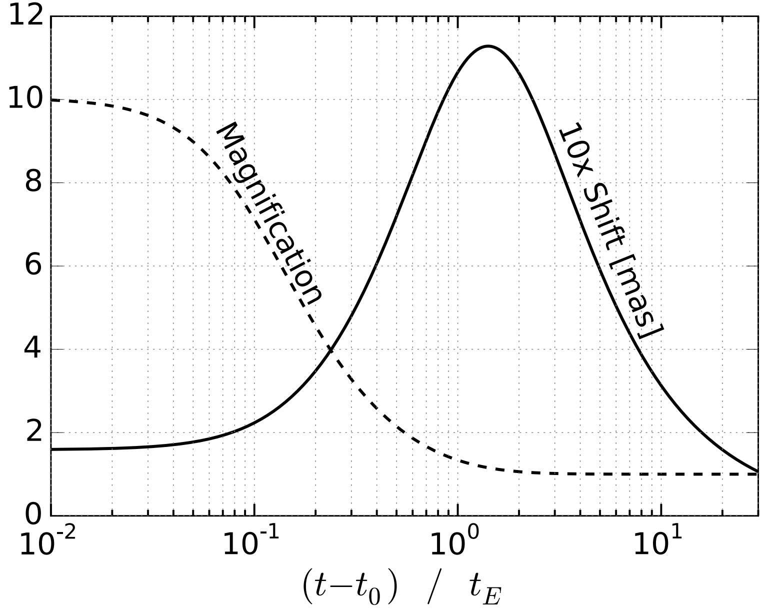
Microlensing also affects the astrometry of the source star

- We can break the mass – lens distance degeneracy by measuring the microlensing astrometric signal
- Current Keck (Lu et al.) and HST (Kains et al.) studies underway to measure astrometric shifts



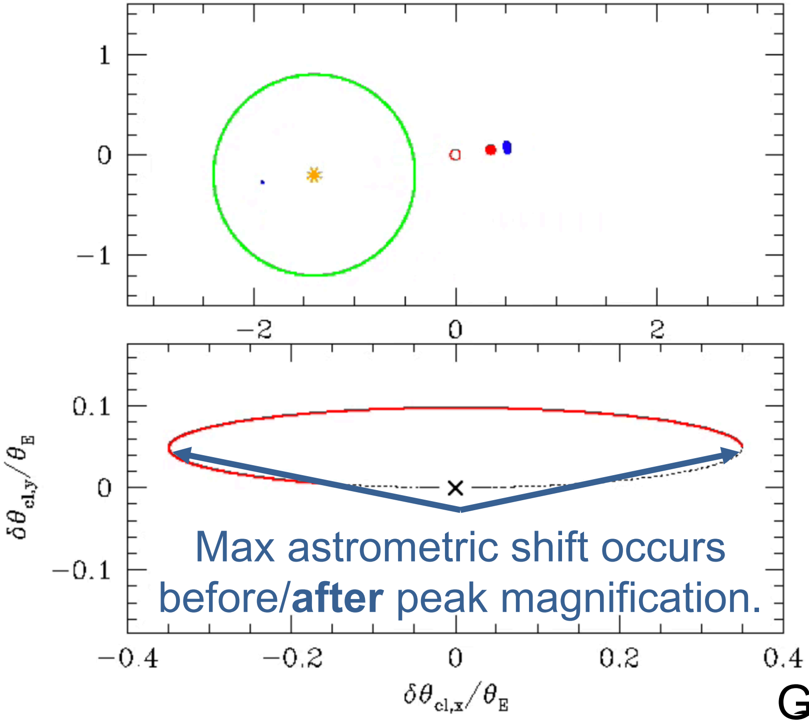
Gaudi

Astrometric follow-up is easily facilitated



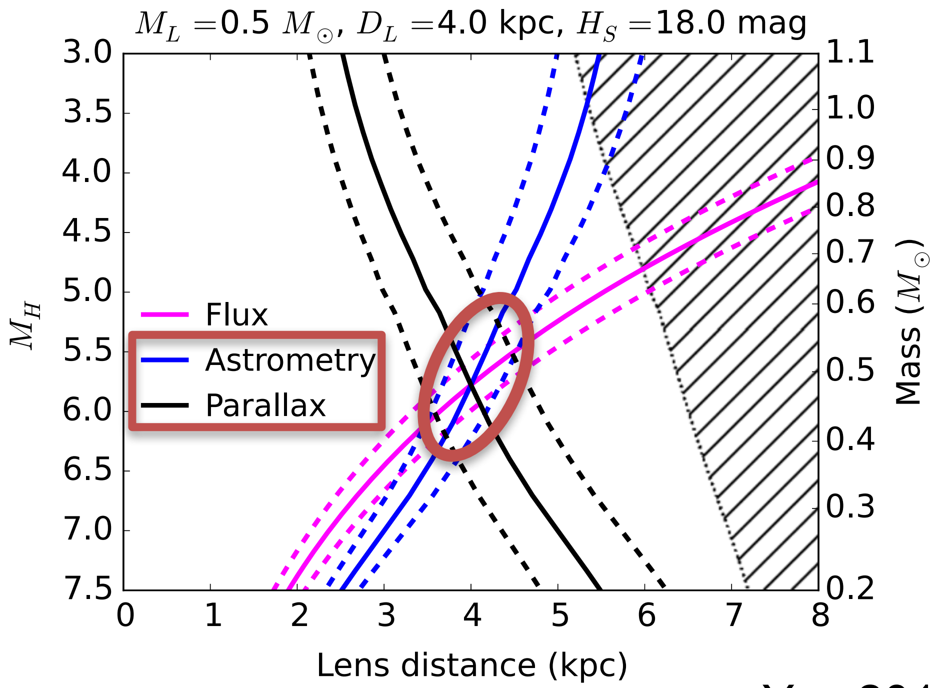
Time Since Closest Approach

Lu et al. 2016



Gaudi

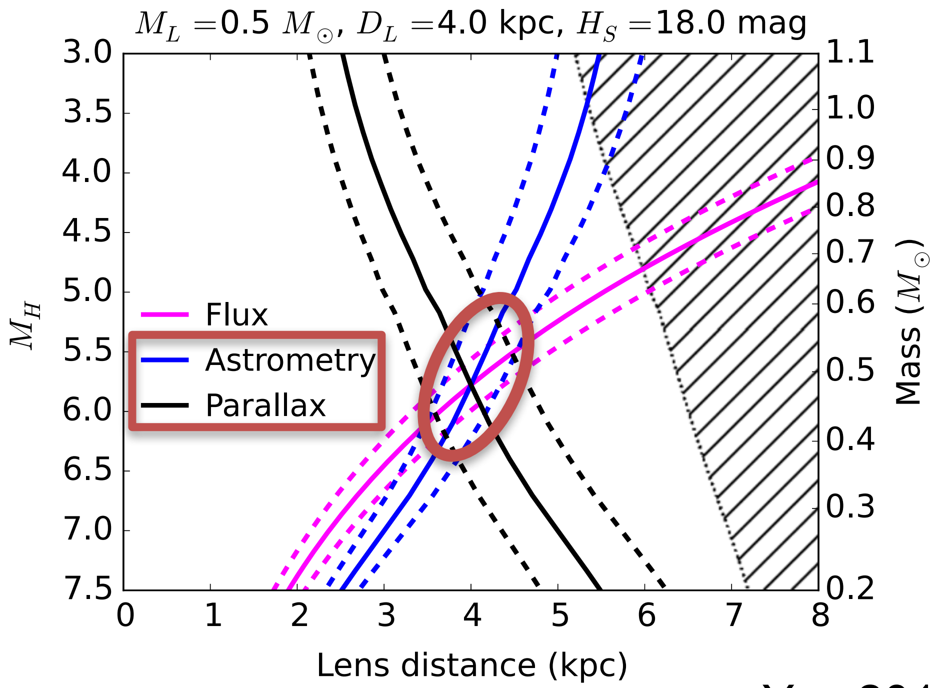
Parallax + Astrometric Microlensing = Tight Mass Constraint



Yee 2015

Parallax + Astrometric Microlensing = Tight Mass Constraint

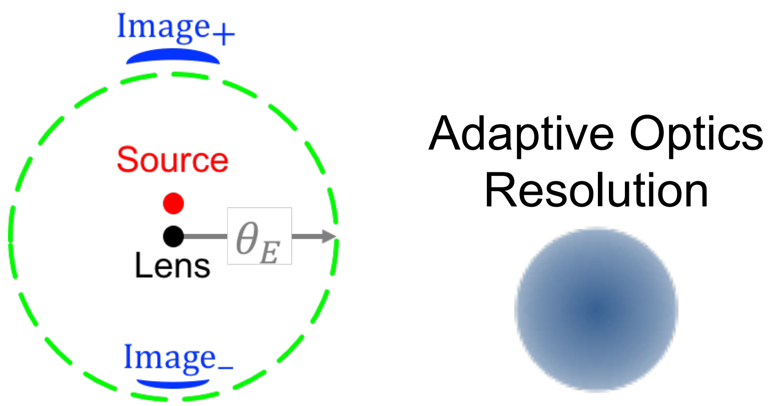
If primordial BHs make up dark matter, then measuring their mass spectrum will be especially exciting because it will tell us something about the fundamental physics of the Big Bang.

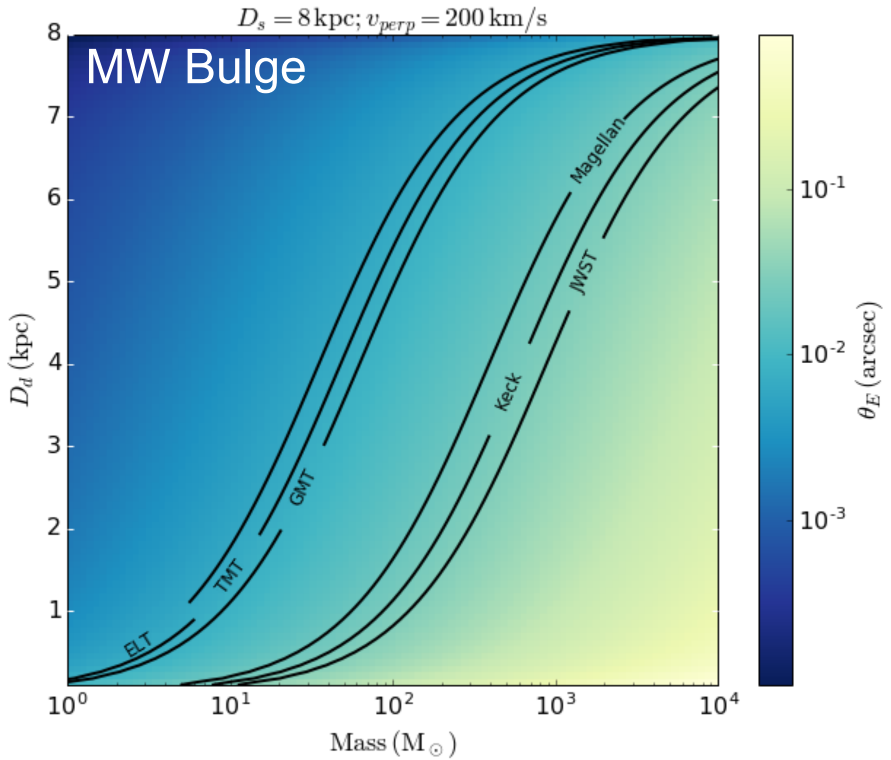


Yee 2015

Ability to resolve multiple lensed images

- Potential to resolve multiple images from IM MACHO events!



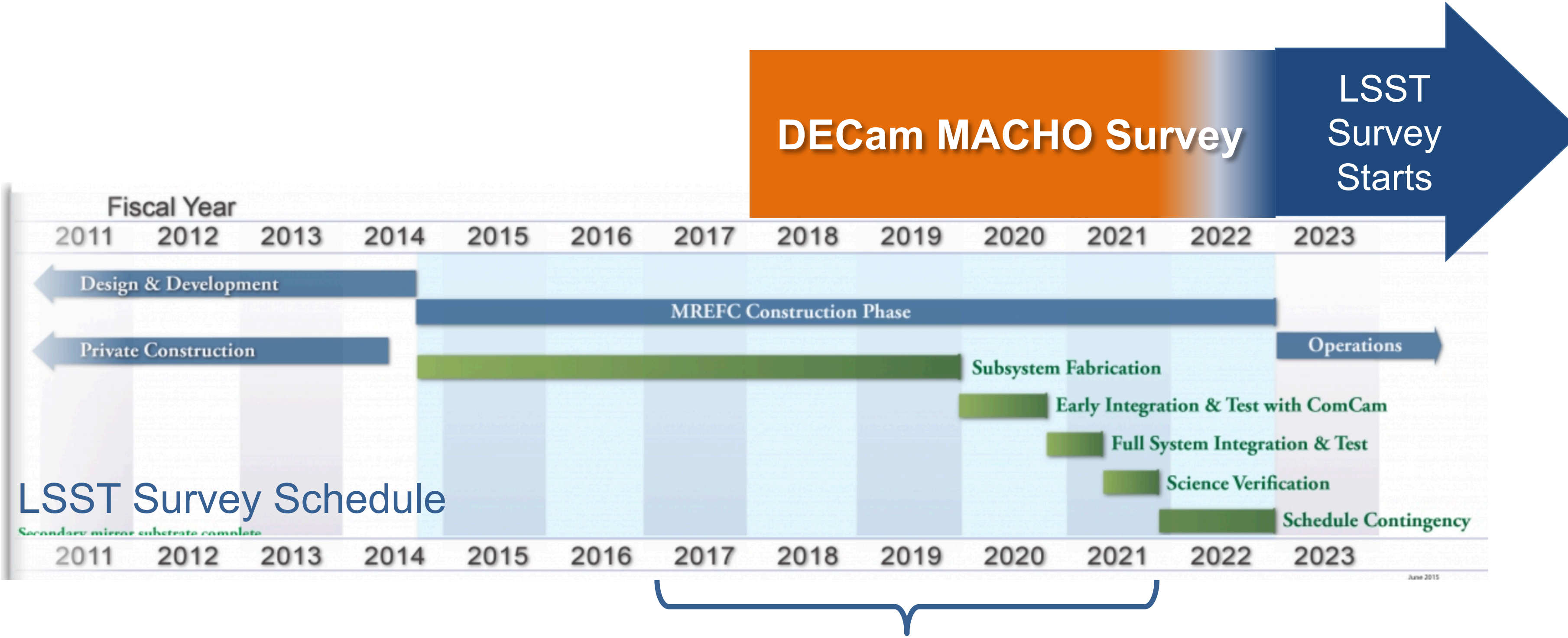


What are we actually proposing

- Model a microlensing survey off DOE supported DECaLS
  - DECam imaging survey
  - Survey time through NOAO
  - Data analysis on LLNL and FNAL computing
  - Project effort funded through DOE

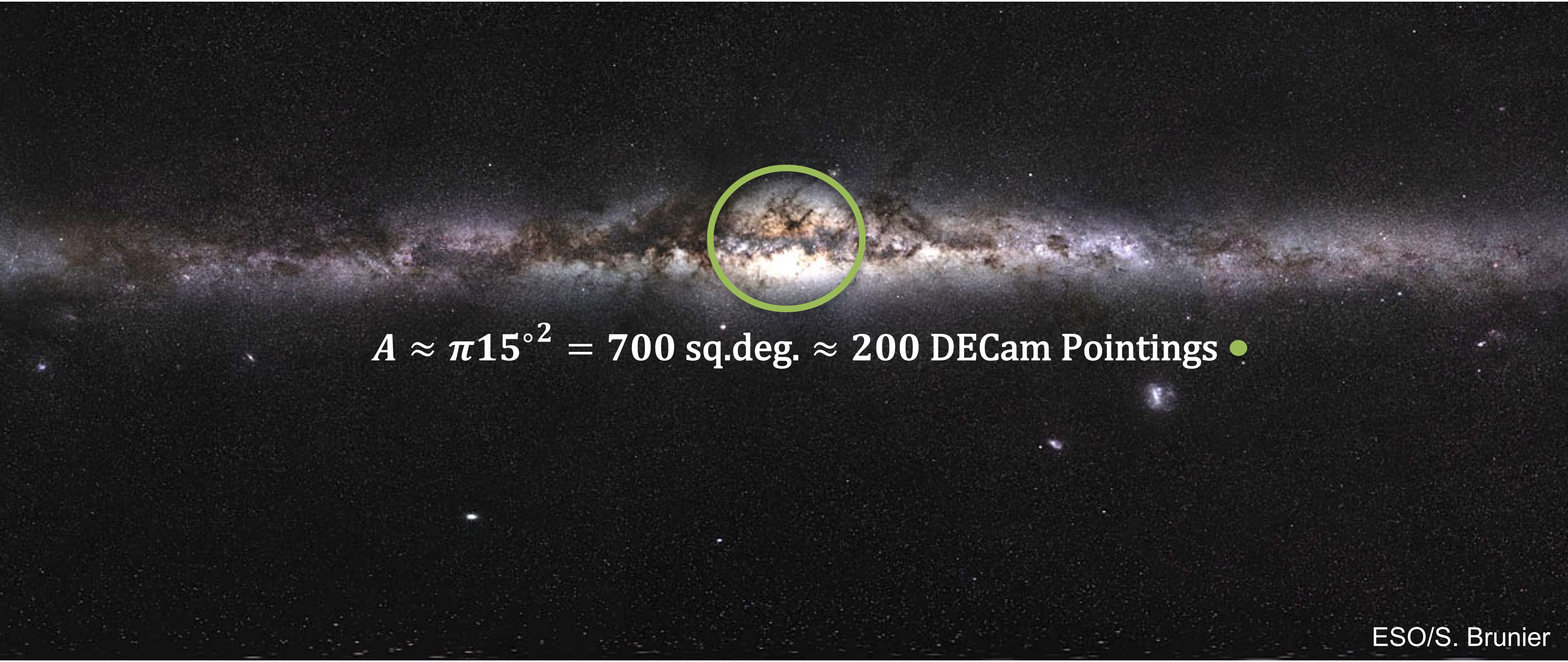
- Building to and supplementing the LSST microlensing survey
  - LSST is currently not optimized for microlensing science
  - LSST will survey the Milky Way Galaxy, but not as much as the extragalactic fields. Need to supplement the survey with DECam microlensing survey

Proposing a 5 year DECam MACHO Survey Influence and bridge to LSST



LSST Survey Strategy Determined

Survey Footprint



$$A \approx \pi 15^{\circ 2} = 700 \text{ sq.deg.} \approx 200 \text{ DECam Pointings}$$ ●

Survey Numbers

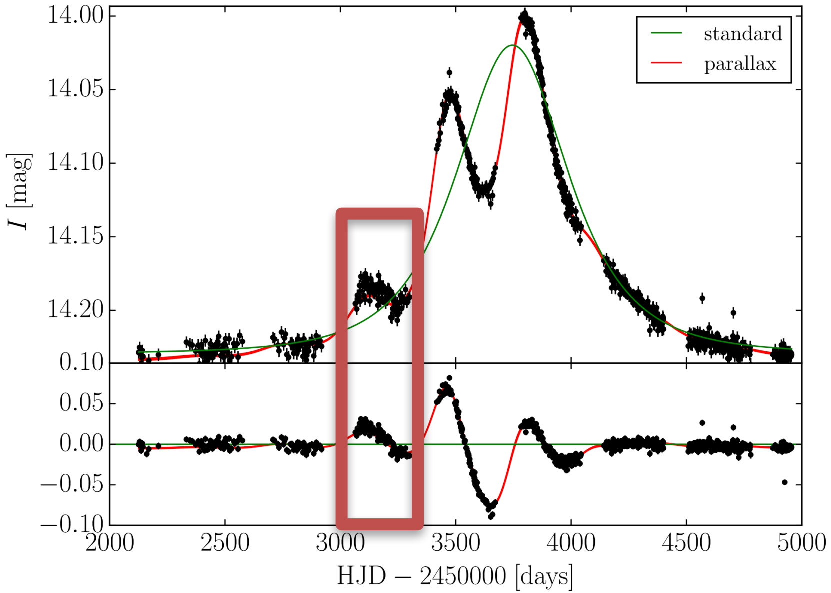
- 10σ limiting magnitude of 23.3
  - 70 s in g; 130 s in r = 200 s per g & r epoch
- ~500 Million stars
- 13 hours per g & r epoch
- 4 nights per month
- 8 months per year
- 5 years
- ~60 measurements per year per star

≈ 100
black hole
microlensing events
(if all dark matter)

Algorithm focus

- Old
  - Detect based off complete rise and fall
  - Photometry from difference imaging

- Modern computation enables better new ways
  - Maximum likelihood parallactic event detection (see e.g. Dawson, Schneider, & Kamath 2016)
  - Bayesian image analysis to forward model variability (Schneider & Dawson in prep)
  - Leverage experience with first weak lensing measurement through galactic plane (Dawson et al. 2015; Jee et al. 2015)



Leveraging existing DOE investments in pipeline development: LLNL will develop the Level 3 microlensing plugin

LSST From the Astronomer's Perspective

LSST

Level 1

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Level 2

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), and ~30 trillion measurements ("forced sources"), produced annually, accessible through online databases.
- Deep co-added images.

Level 3

- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and APIs enabling development of analysis codes.

CFA CODE COFFEE | HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS | JUNE 4, 2014. 17

Leverage existing DECam & LSST pipeline investments

We develop the Level 3 microlensing analysis plugin

M. Juric

DOE has already invested in the vast majority of the needed resources

Office of Science Current Investment

Item	Investment
DECam	~$50 M
LSST	~$175 M
DECam data reduction	FNAL Computing

LLNL Current Investment

Item	Investment
Staff Support	0.5 FTE
Postdoc	1 FTE
Microlensing analysis	LLNL Computing

New Investment

Item	Investment
Obs. Travel	8 runs/year
Univ. Summer Salary	2 months/year
Postdocs	2 FTE
Grad. Student	2 FTE

LLNL and FNAL will contribute staff support.

Summary

- A direct measurement of black hole MACHOs via microlensing
  - Shortcut astrophysical complications of other methods

- DOE 96% of the way there. Leveraging:
  - DECam & LSST
  - LLNL & FNAL computing
  - Current investments by DOE labs

- DECam 5 year survey
  - ≈ 100 black hole microlensing events if all dark matter

- Measure the mass of each black hole with parallax and astrometry
  - Black hole mass spectrum could give insight into fundamental physics of the big bang.

Lawrence Livermore National Laboratory

Microlensing Basics

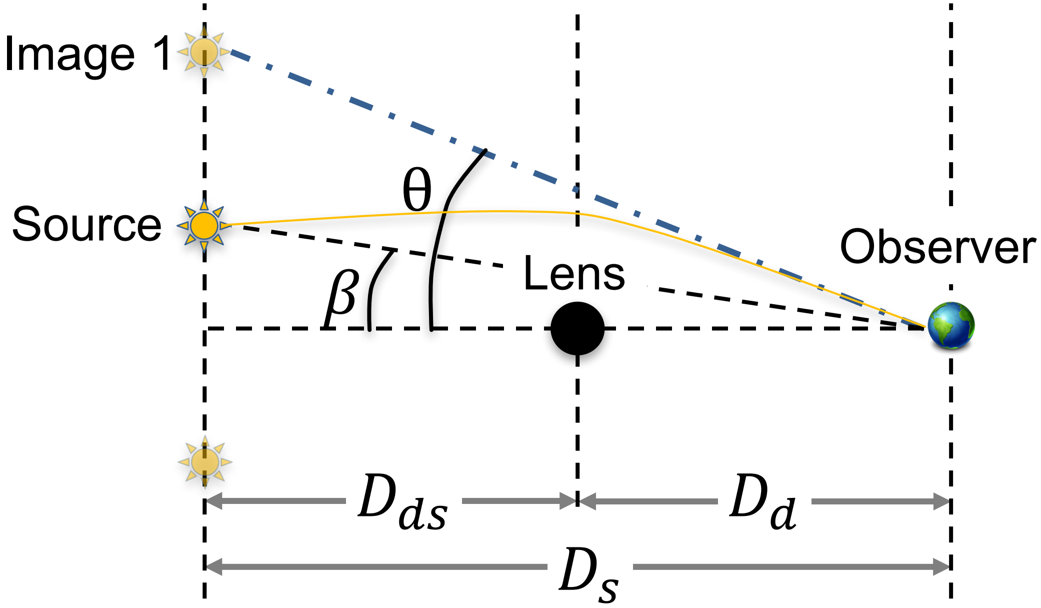
Einstein Radius

$$\theta_{\mathrm{E}} = \left(\frac{4GM}{c^2} \frac{D_{\mathrm{ds}}}{D_{\mathrm{d}} D_{\mathrm{s}}} \right)^{1/2}$$

Convenient coord. system

$$y \equiv \beta / \theta_{\mathrm{E}}$$

$$x \equiv \theta / \theta_{\mathrm{E}}$$



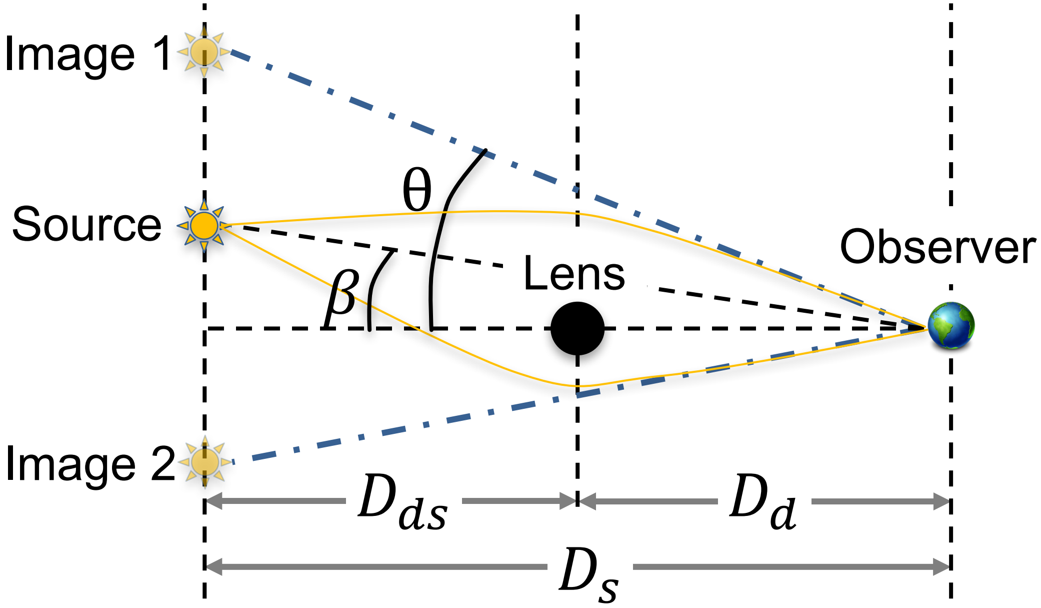
Microlensing Basics

Solving the lensing equation:

$$y = x - \frac{1}{x}$$

2 solutions… 2 images

$$x_{\pm} = \frac{1}{2}\left(y \pm \sqrt{y^2 + 4}\right)$$



Microlensing Basics

Einstein Radius

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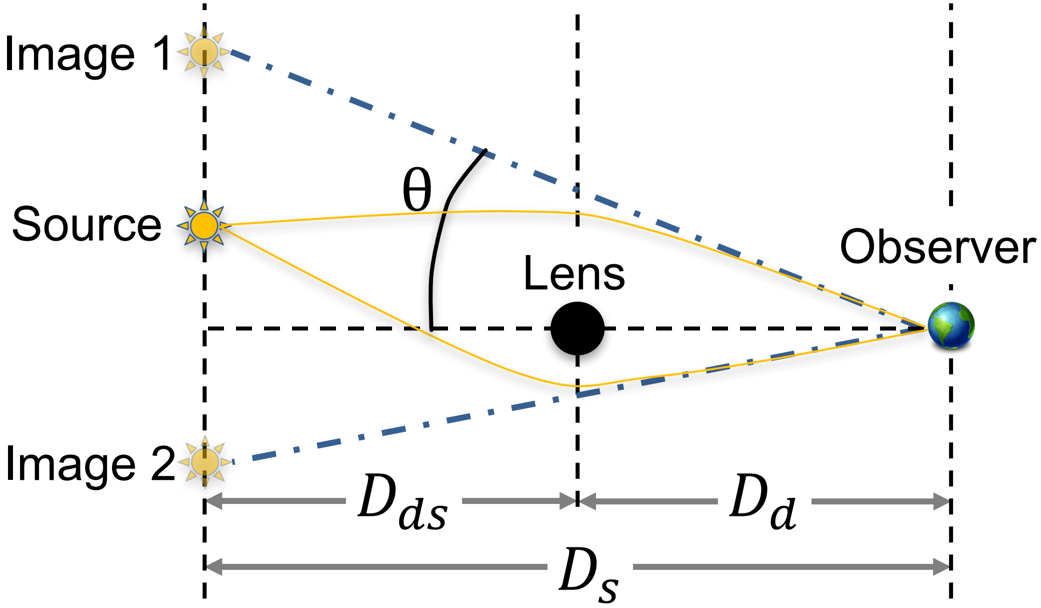
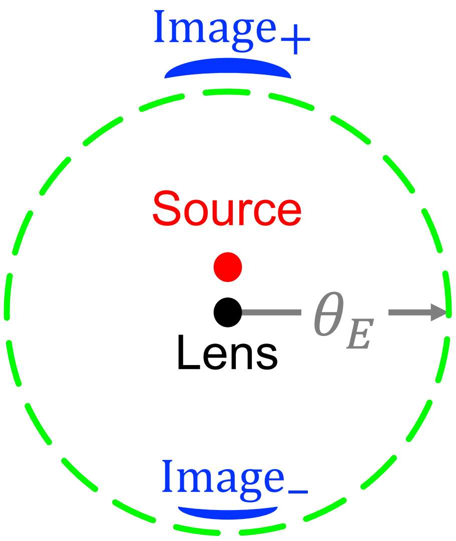


Microlensing Basics

Magnification of the two images:

$$\mu_{\pm} = \pm\frac{1}{4}\left[\frac{y}{\sqrt{y^2+4}} + \frac{\sqrt{y^2+4}}{y} \pm 2\right]$$



Microlensing Basics

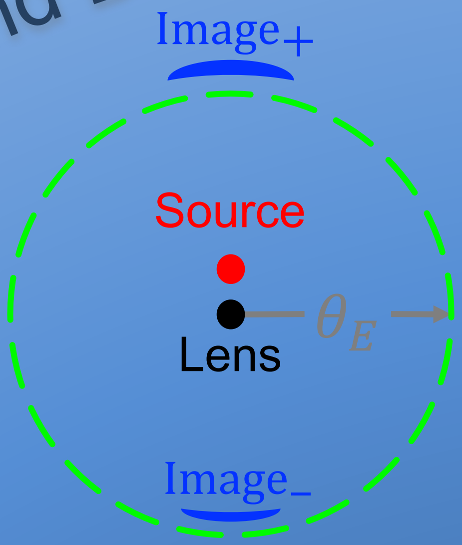
Magnification of the two images:

$$\mu_\pm = \pm\frac{1}{4}\left[\frac{y}{\sqrt{y^2+4}} + \frac{\sqrt{y^2+4}}{y} \pm 2\right]$$

Total magnification:

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

Relative Ground Based Resolutio



Statistical Ensembles

Optical Depth

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

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

Average matter density at D_d

Expected number of events
(assuming all have same timescale)

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

Number of monitored stars

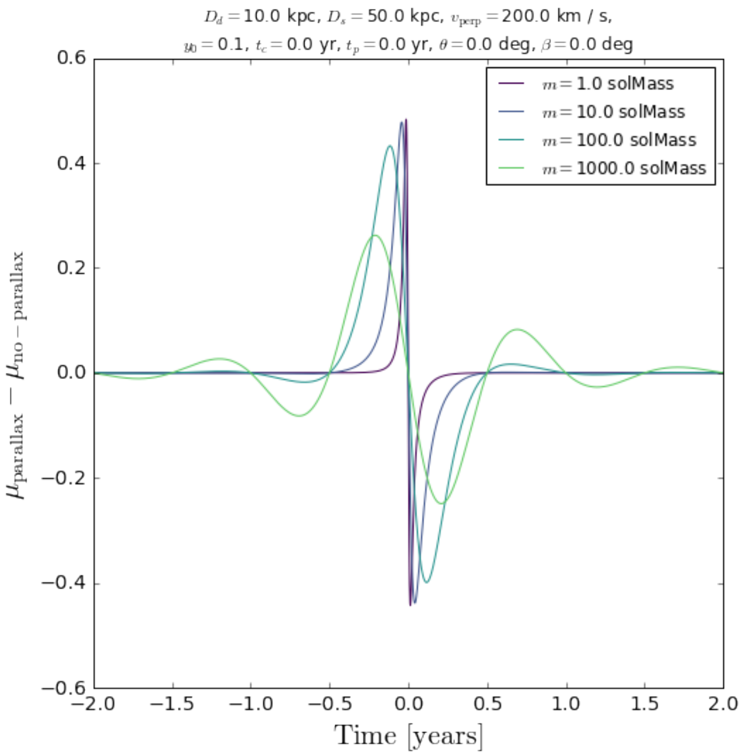
Timescale of Survey

Timescale of lensing event

Paczynski 1986, 1996

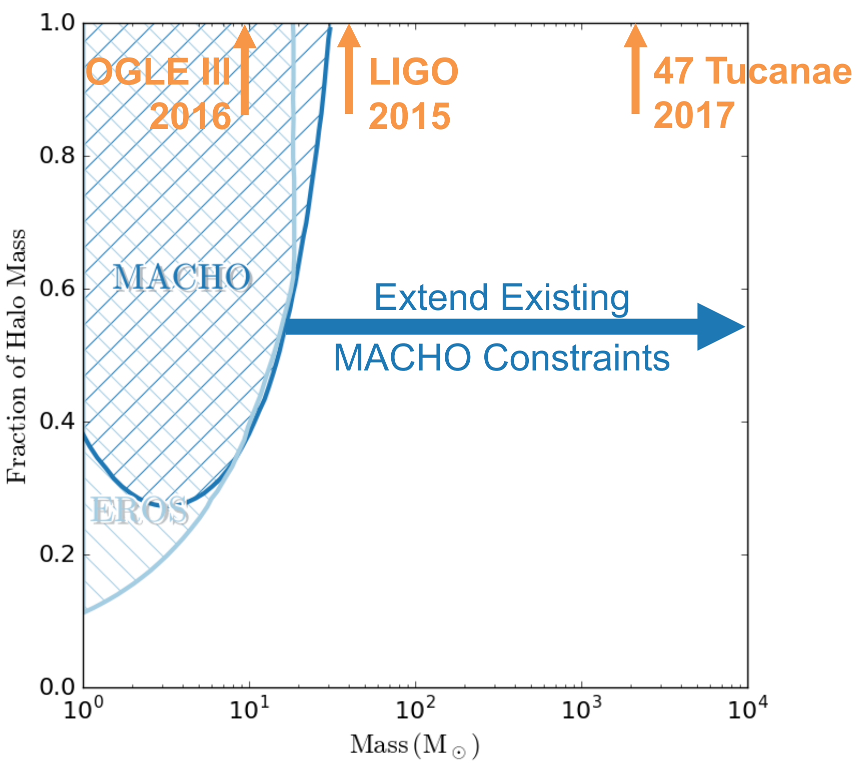
Microlensing parallax also provides constraint on black hole mass

- Parallactic signal is a strong function of mass
  - Without the parallax you basically have no constraint on the lens mass.



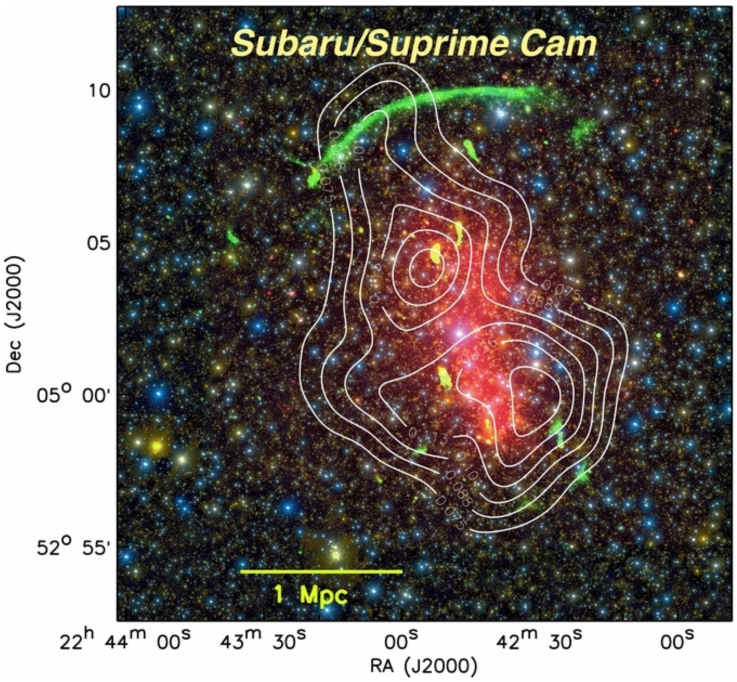
Method Summary

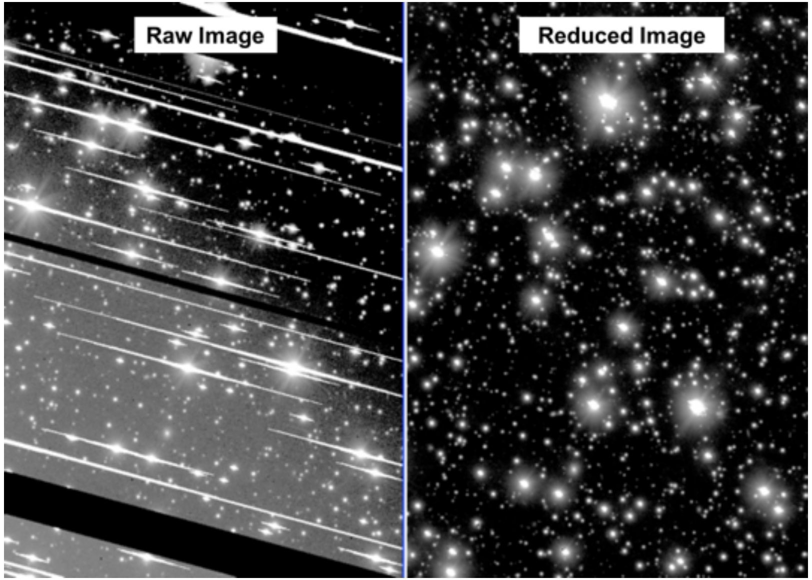
- Parallax means no high mass limit to the constraining power of a microlensing survey
- Parallax provides constraint on the black hole mass
  - Despite degeneracies with lens distance, powerful for an ensemble
- Parallactic + astrometric = tight mass constraints
- New telescopes can resolve the multiple images
- Achromatic, parallax, and astrometric microlensing signals are extremely powerful


1.0
0.8
0.6
0.4
0.2
0.0
Fraction of Halo Mass
10^0
10^1
10^2
10^3
10^4
Mass $(M_\odot)$
OGLE III 2016
LIGO 2015
47 Tucanae 2017
MACHO
EROS
Extend Existing MACHO Constraints

We have experience in dense environment survey planning and analysis

First weak lensing measurement through the galactic plane.





Dawson et al. 2015

Jee, Stroe, Dawson et al. 2015