DECam Microlensing Studies of Intermediate Mass Black Holes

DECam Community Science Workshop 2018: Science Highlights, Coming Opportunities, LSST Synergies

2018 March 22

Will Dawson[1], Mark Ammons[1], Tim Axelrod[2], Josh Calcino[8], George Chapline[1], Agnieszka Cieplak[3], Alex Drlica-Wagner[4], Nathan Golovich[5], Casey Lam[6], Michael Medford[6], Peter Nugent[9], Jessica Lu[6], Michael Schneider[1], & Anja von der Linden[7]

1 Lawrence Livermore National Laboratory, 2 Arizona, 3 Maryland, 4 Fermi National Accelerator Laboratory, 5 UC Davis, 6 UC Berkeley, 7 SUNY, 8 U. Queensland, 9 LBL

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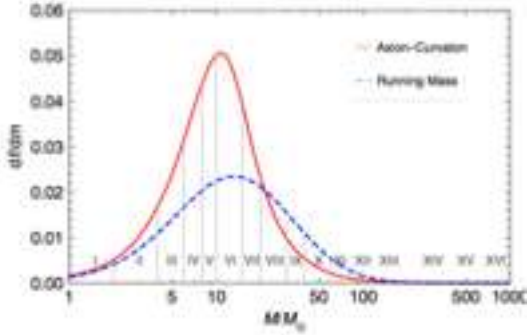
Lawrence Livermore National Laboratory

Intermediate Mass Black Holes have been observed

- Extensive primordial black hole literature: from Chapline (1975) to Carr et al. (2016).

- Black holes have been detected in mass range:

$$10 \lesssim M_{MACHO} \lesssim 10^{10}\ M_{\odot}$$

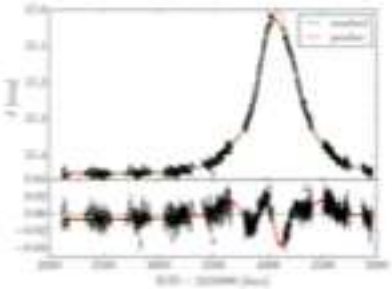


$2\times30\ M_{\odot}$

Abbott+ 2016

LIGO 2016

$9.3\ M_{\odot}$



Wyrzkowski + 2017

OGLE III 2016

$2200\ M_{\odot}$

Kiziltan+ 2017

47 Tucanae 2017

Goals

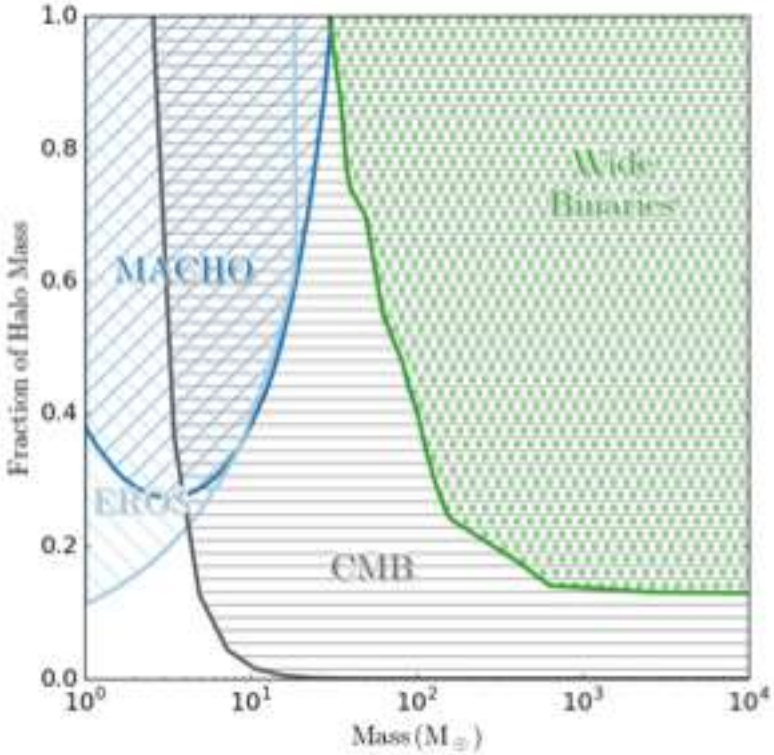
Revolutionary Goal

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

Conservative Goal

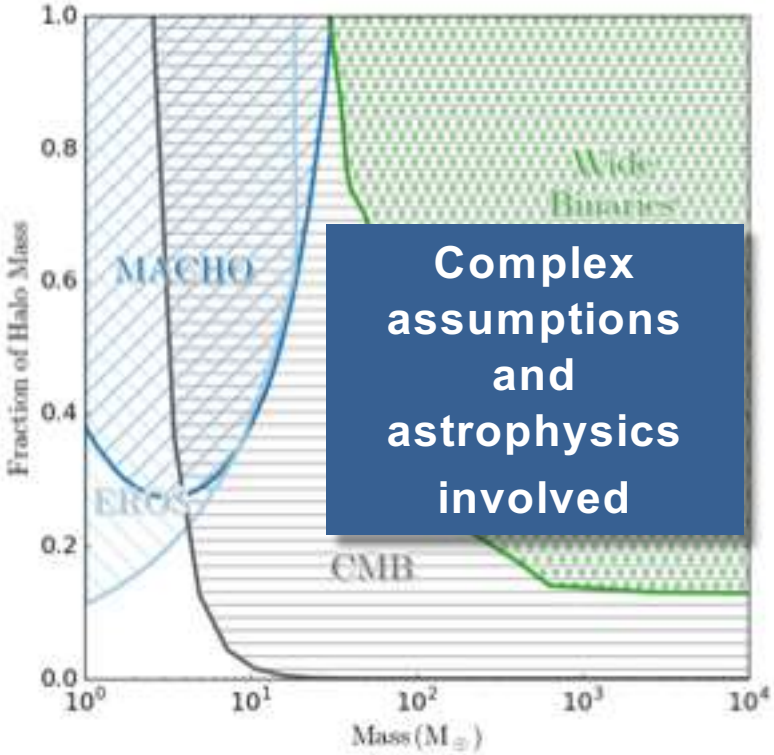
Make the first direct measurement of the mass spectrum of black holes in the Milky Way.

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 $\gtrsim 10^4 M_\odot$

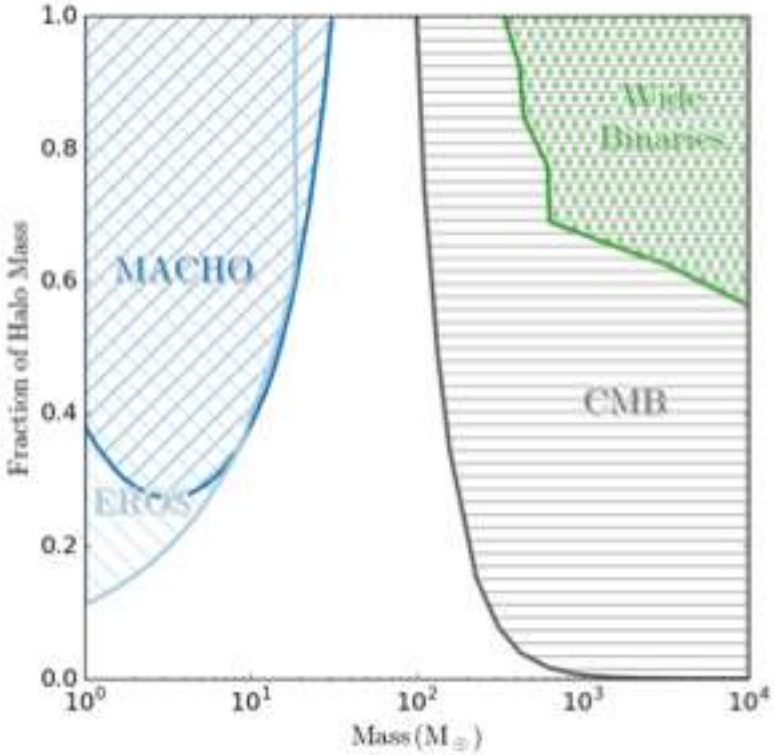
Massive MACHO Constraints circ. 2008
Completely ruled out massive MACHOs as Dark Matter



Complex assumptions and astrophysics involved

- 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
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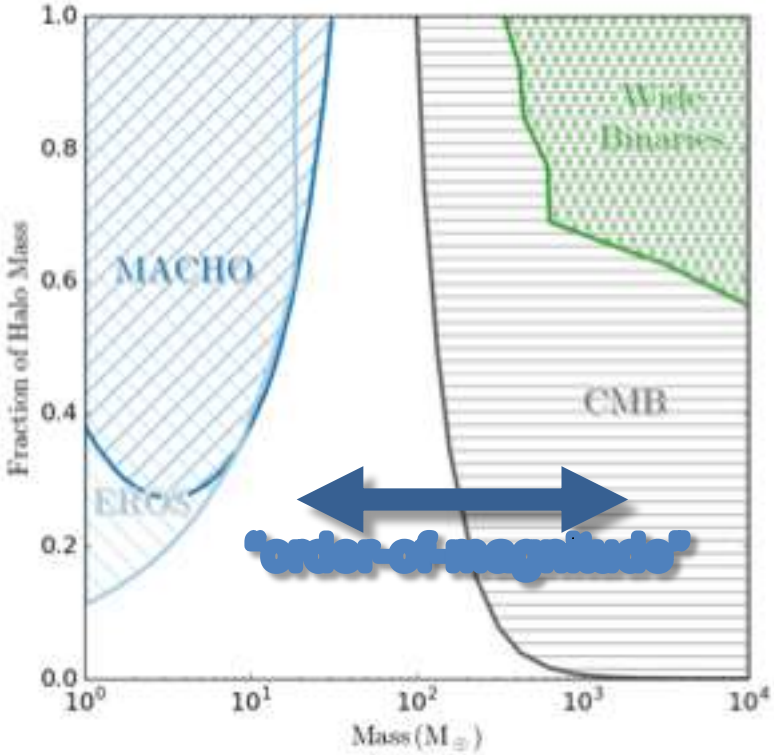
- CMB
  - Ali-Haïmoud & Kamionkowski 2016
- Wide Binary
  - Quinn et al. 2009

"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



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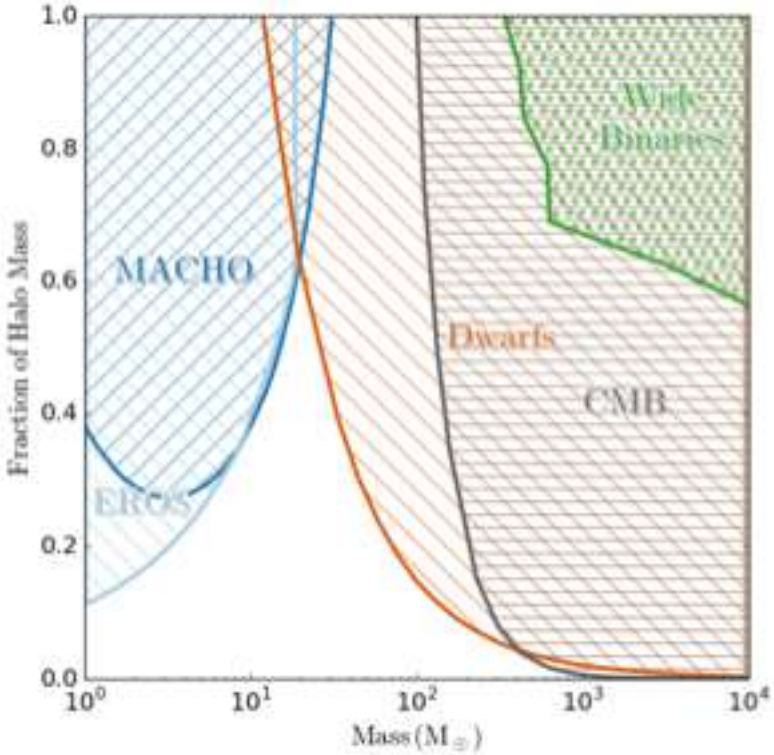
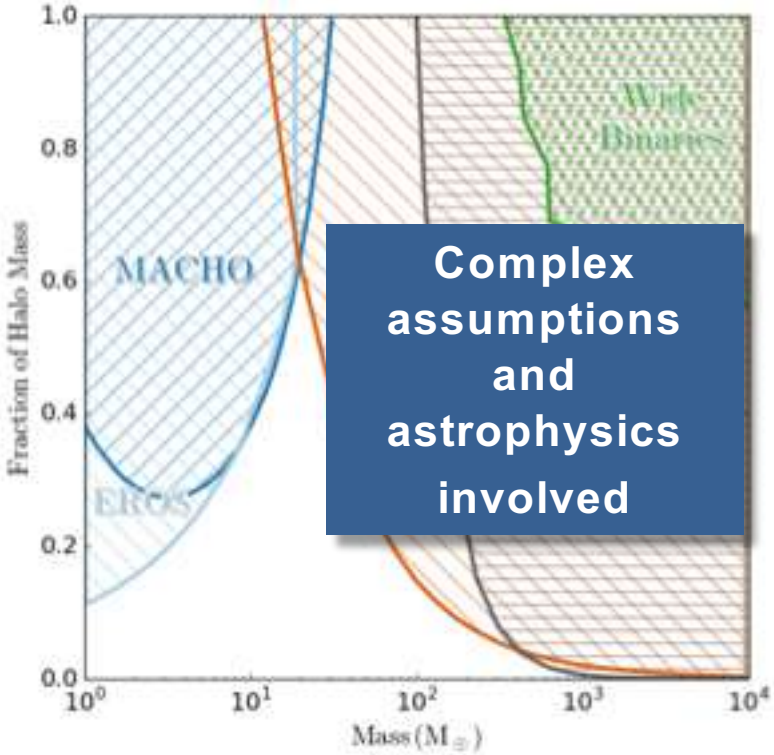
The latest astrophysical constraint from dwarf galaxies and star clusters



- 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

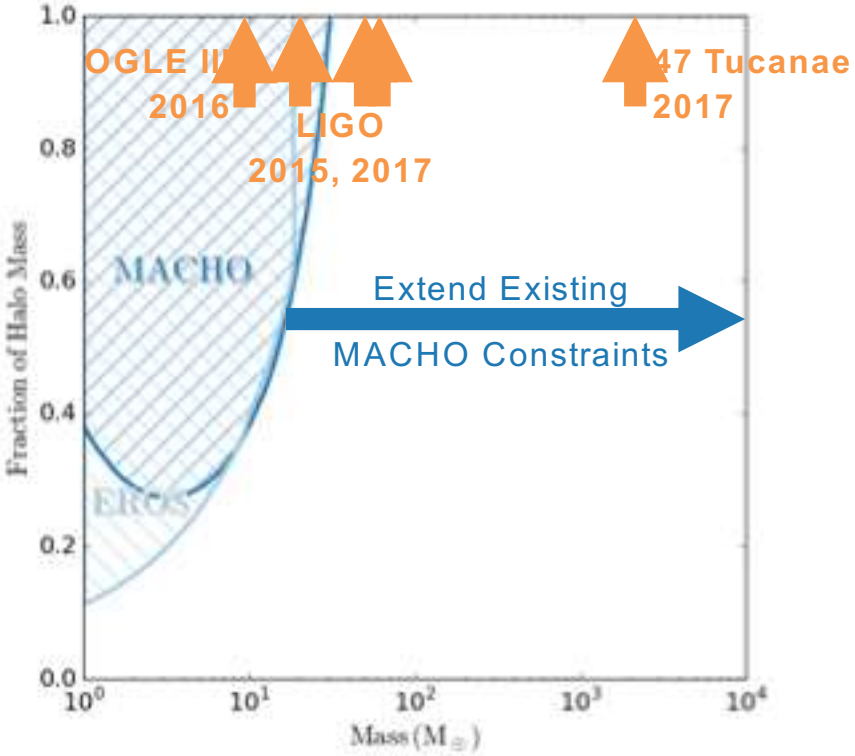
Features of Null Bias

- ✓ ‘Fringe’ science. A prevailing theoretical model (despite lack of confirmation).
- ✓ Small sample size
- ✓ Uncertainty characterization/propagation is rarely done correctly/thoroughly
- ✓ Qualitative rather than quantitative support of assumptions
- ✓ Complex to go from measurement to constraint
- ✓ Multiple existing null experiments

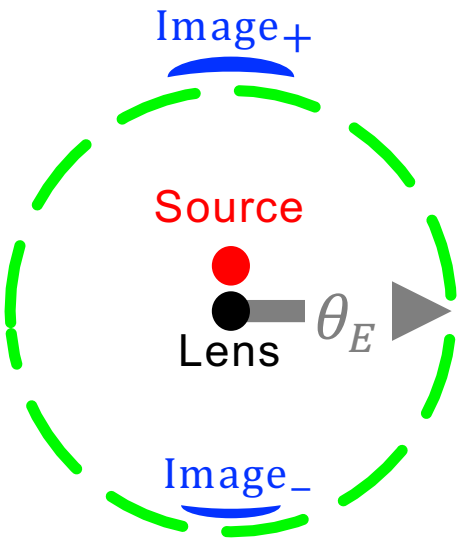
See Dec 2017 Texas A&M talk on Null Bias:
https://mediamatrix.tamu.edu/streams/579892/Will_Dawson_Seminar

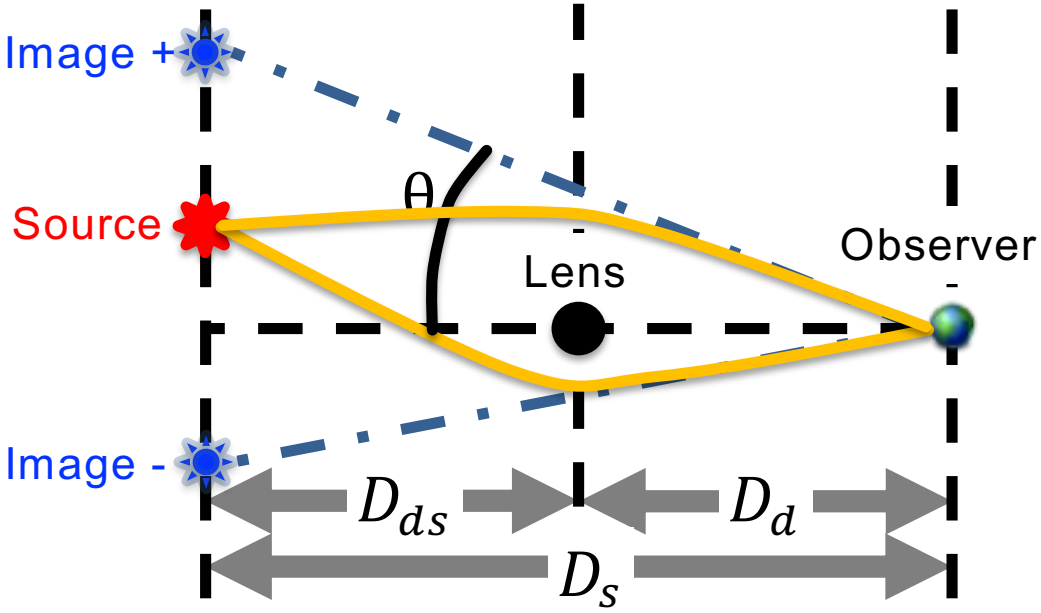
Microlensing is the closet thing we have to a direct measurement

- 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 dealing with an array of astrophysics we prefer a direct measurement.
- **Microlensing is the most direct way of constraining this parameter space.**



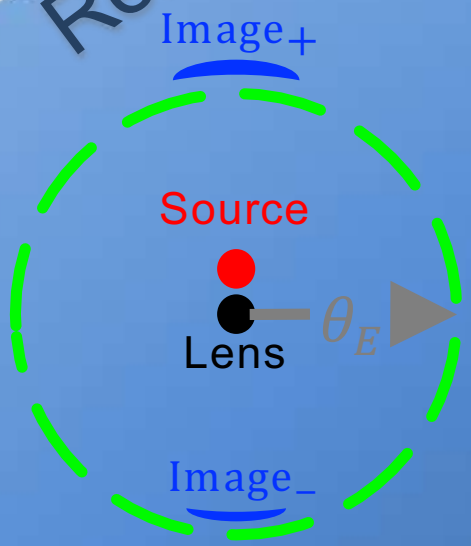
Gravitational microlensing basics





Total magnification is what is measured

Relative Ground Based Resolution

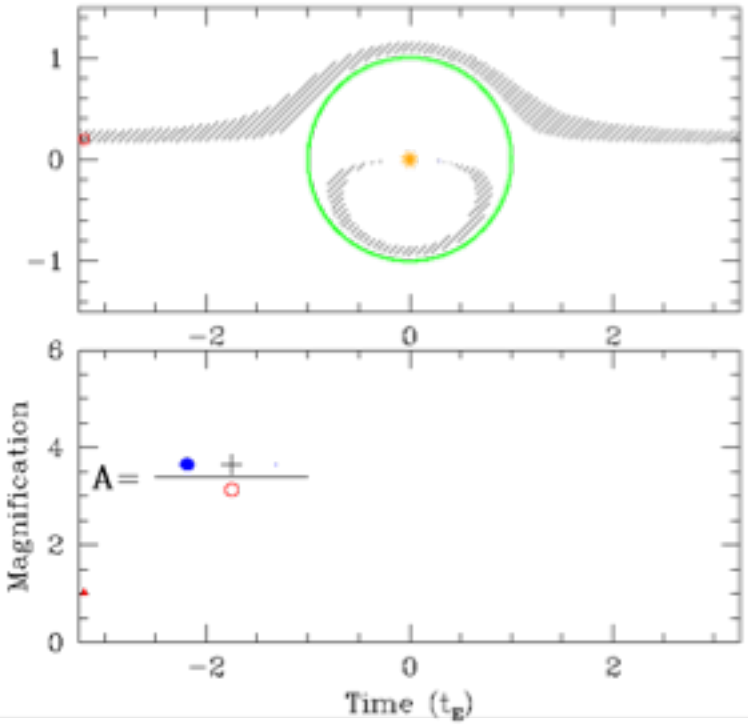


Total magnification:

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

Microlensing Basics

Black Hole – Observer Frame



Key

- Lensed Images
- Actual Source Location
- Black Hole Lens
- Einstein Ring

Gaudi

Microlensing statistical ensemble constraints on the fraction of MACHO dark matter

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

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

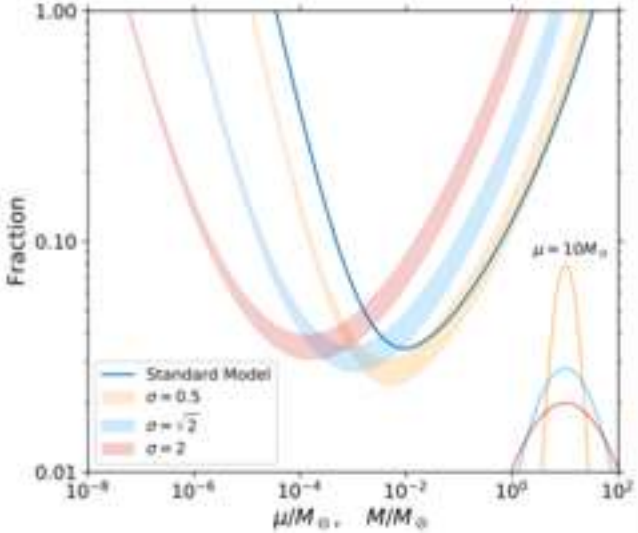
$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2} \rho(D_d) dD_d$$

Average dark matter density at D_d

Paczynski 1986, 1996

New Milky Way & Mass Spectrum Models
New MACHO Constraints

Josh Calcino
(Queensland)



Updating the MACHO fraction of the Milky Way dark halo with improved mass models

Josh Calcino,[1*] Juan García-Bellido,[2] Tamara M. Davis[1]

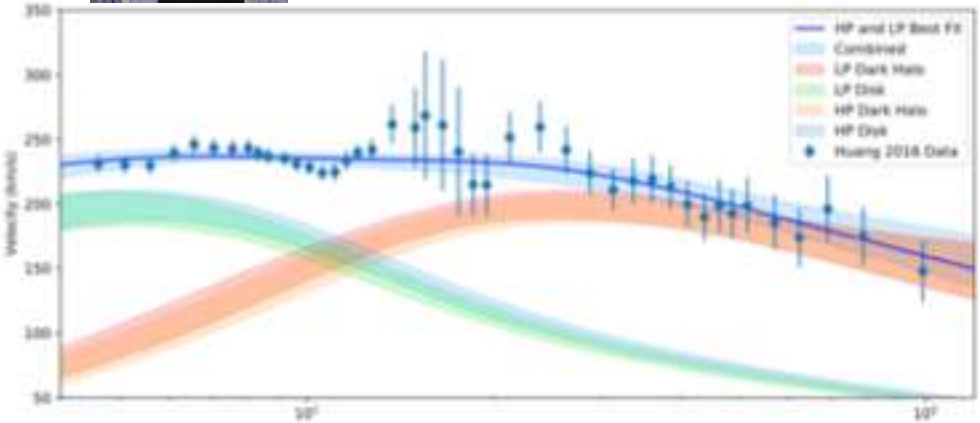
[1] School of Mathematics and Physics, The University of Queensland, QLD 4072, Australia

[2] Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

Last updated 28 March 2018; in original form 2013 September 3

ABSTRACT

Recent interest in primordial black holes as a possible dark matter candidate has motivated the reanalysis of previous methods for constraining massive astrophysical compact objects in the Milky Way halo and beyond. In order to derive these constraints, a model for the dark matter distribution around the Milky Way must be used. Previous microlensing searches have assumed a semi-isothermal density sphere for this task. We show that this model is no longer consistent with data from the Milky Way rotation curve, and recommend a replacement. With a new model, we rederive some of the previous microlensing constraints in the literature. We propagate some of the uncertainties associated with the size and shape of the Milky Way halo. However, we find that none of the models tested can sufficiently encapsulate the uncertainties in the shape of the Milky Way halo. Our analysis reveals that the microlensing constraints from the Large Magellanic Cloud weaken somewhat for MACHO masses around $10\,M_\odot$ when this uncertainty is taken into account, but the constraints tighten at lower masses. Exploring some of the simplifying assumptions of previous constraints we also study the effect of wide mass distributions of compact halo objects, as well as the effect of spatial clustering on microlensing constraints. We find that both effects induce a shift in the constraints towards smaller masses, and can effectively remove the microlensing constraints from $M \sim 1 - 10M_\odot$ for certain MACHO populations.



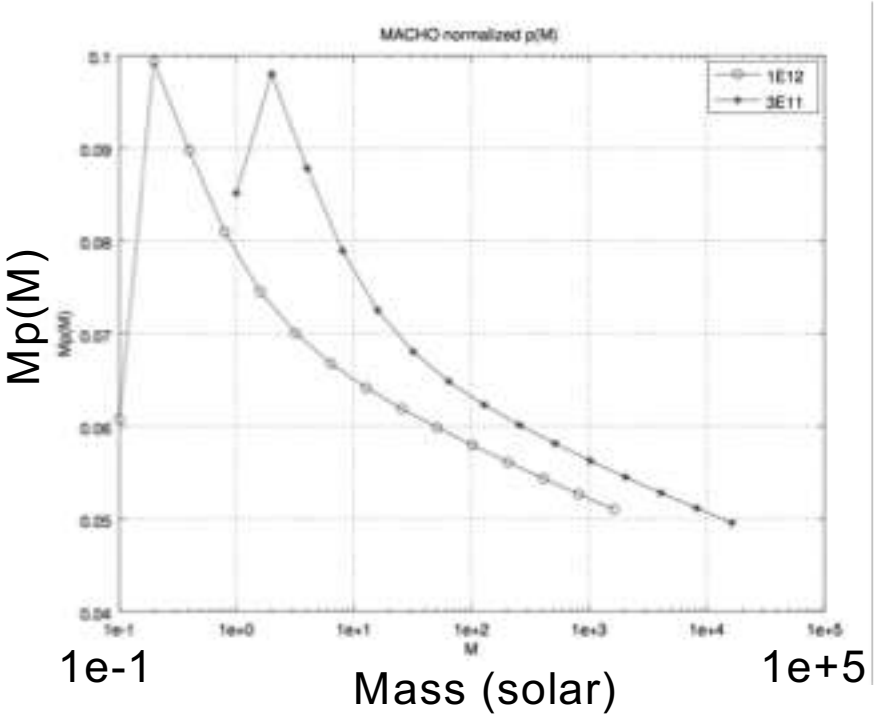
Primordial Black Hole Mass Function

MACHO Messages from the Big Bang

G. Chapline and J. Barbieri

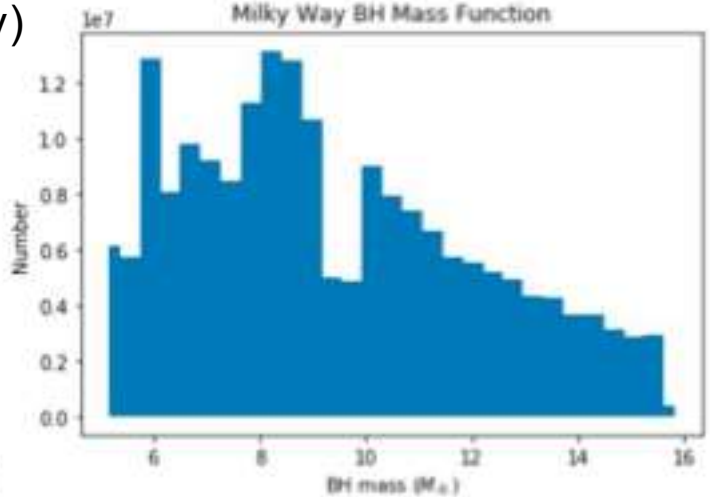
The present day mass spectrum for dark matter compact objects is calculated based on the assumption that a uniform population of PBHs was created at a definite red-shift, and that the mass spectrum evolved as a result of gravitational radiation. The predicted present day spectrum extends over many decades of mass and allows one to connect the abundance of MACHOs in the halo of our galaxy with the abundance of galactic seeds. Present day astrophysical constraints on the abundance of dark matter PBHs appear to be consistent with our predicted mass spectrum if it is assumed that the seeds for the present day dark matter MACHOs were created at a time ~ 10^{-4} second after the big bang. Remarkably the total cosmological energy density at this time obtained by extrapolating the sum of the present day dark matter and CMB energies backward in time is very close to the mass-energy density of an Einstein-de Sitter universe at the same time. This suggests that the radiation precursor to the CMB was created at about the same time as the seeds for the present day dark matter.

Accepted High Energy Physics Letters

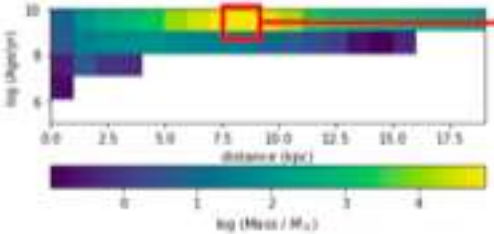


Stellar evolution black hole mass function

Casey Lam (UC Berkeley)

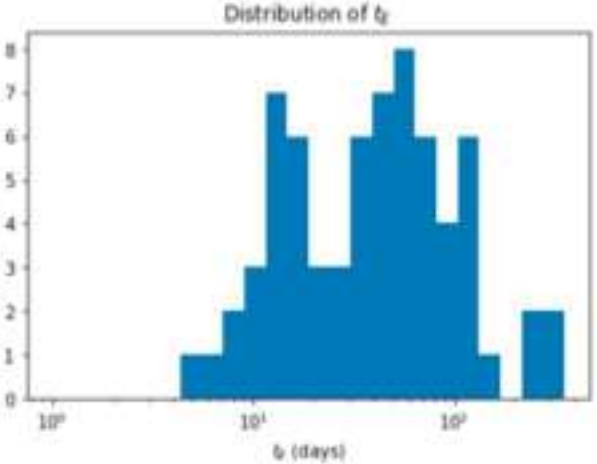


Star formation history, structure, dynamics from **Galaxia**



Make cluster w/ **PopStar**

List of compact objects + masses



The DOE-HEP community has endorsed our approach

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

4. WG4

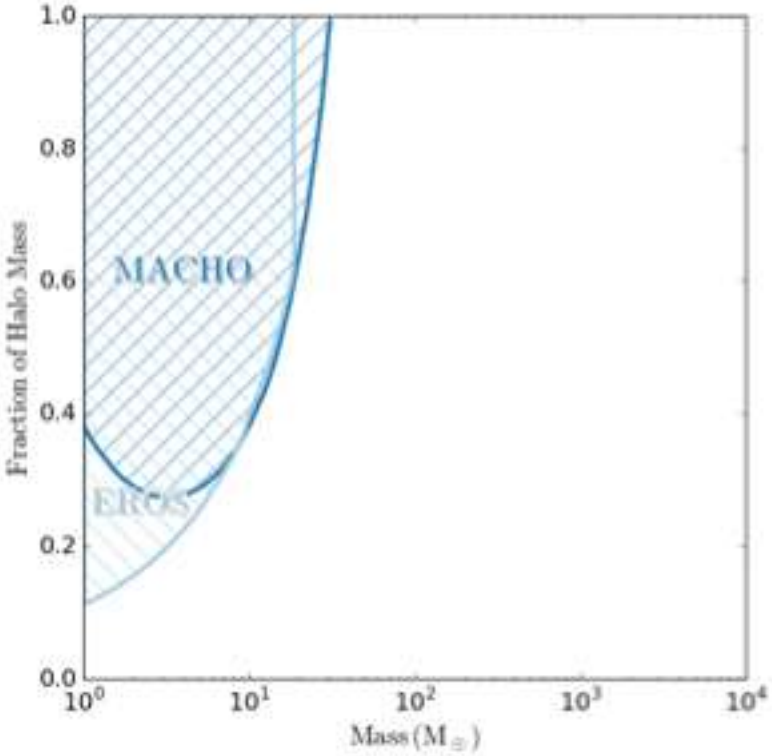
- *Importance of Investment in Theory.* Healthy support for theory is essential to maintaining the flow of creative and cross-disciplinary ideas that have been seen in recent years, and which may finally unmask the particle identity of dark matter.
- *Nuclear and Accelerator Tests of the ^{8}Be Anomaly.* The ^{8}Be anomaly strongly motivates proposed followup nuclear experiments that are fast (under 2 years) and cheap (a small fraction of the small projects threshold), as well as isotope shift spectroscopy experiments and accelerator searches for new bosons with masses ~ 10 MeV and electron couplings $\varepsilon \sim 10^{-4} - 10^{-3}$.
- *Synergy with Cosmology and Astrophysics*
- *Microlensing Searches for Solar Mass Black Hole Dark Matter.* The LIGO discovery of gravitational waves from colliding black holes strongly motivate a proposed microlensing search that can confirm or exclude the possibility of intermediate mass black hole

elloni (Coordinator),[2] Aaron Chou (WG2
,[4] Bertrand Echenard (WG3 Convener),[5]
ada (W Feng
nator) ner),[3]
all (Coordinator),[2] Roni Harnik (SAC
ordinator),[11] Eder
AC
Richard Van
SAC member),[19] Kathryn Zurek (SAC
asey,[20] James Alexander,[21] David Mark

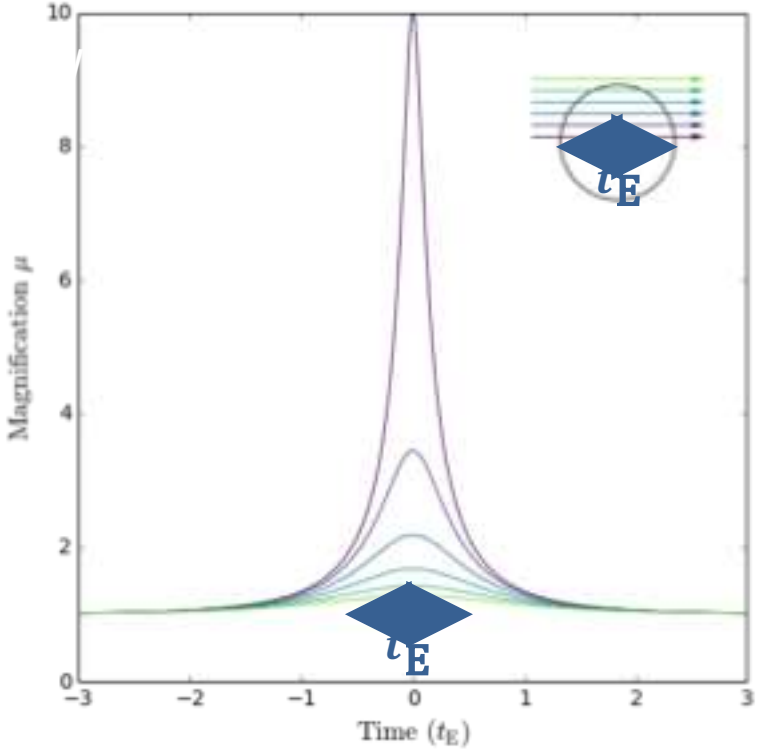
200+ Researchers

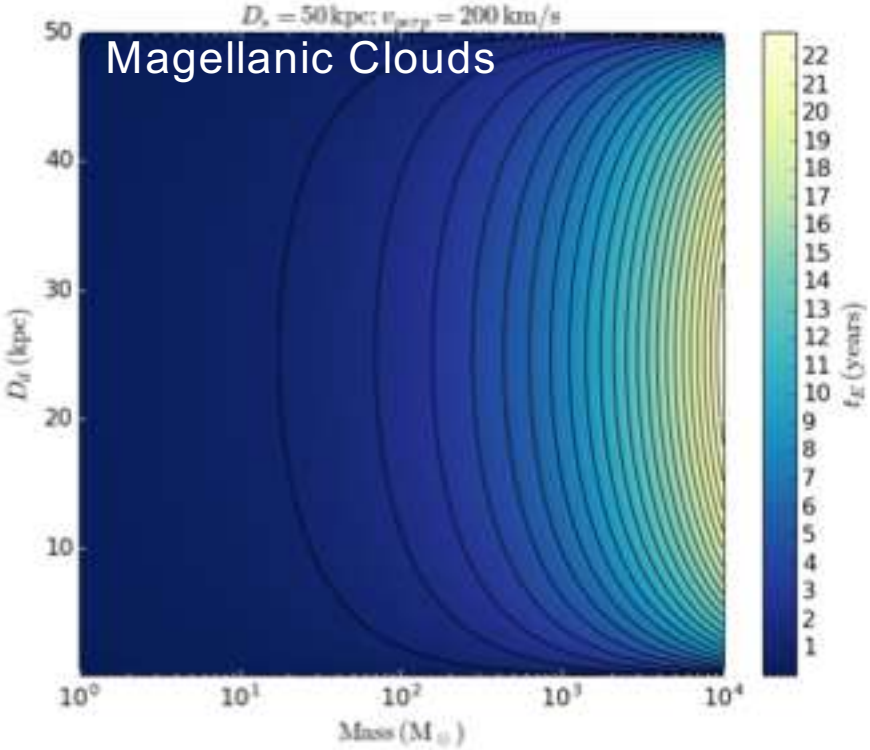
Existing microlensing constraints only go up to ~10 $M_\odot$

- How do we push beyond $\sim 10 M_\odot$?



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





Microlensing statistical ensemble constraints on the fraction of MACHO dark matter

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

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

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

Average dark matter density at D_d

Paczynski 1986, 1996

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

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

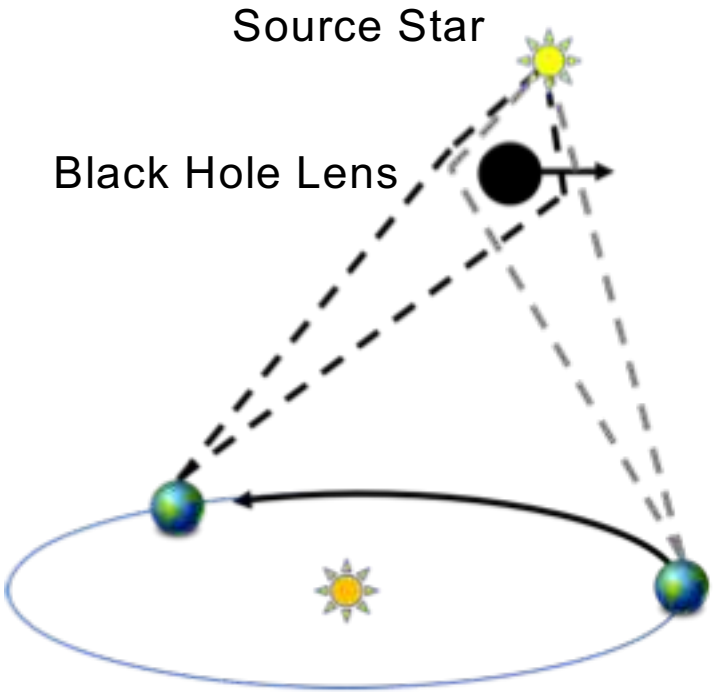
Note independent of MACHO mass.

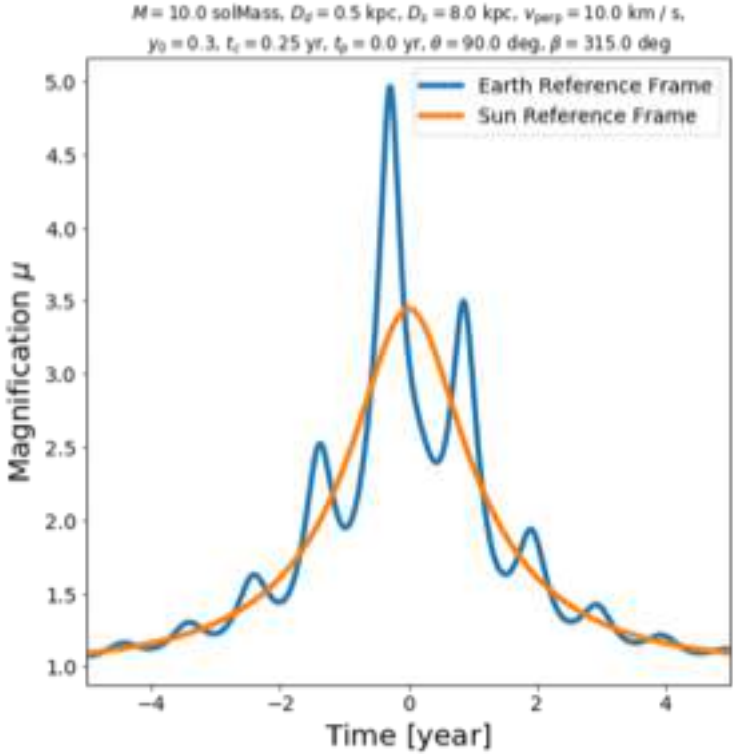
$$\tau = \int_0^{D_s} \frac{4\pi G D}{c^2} \rho(D_d) dD_d$$

Average dark matter density at D_d

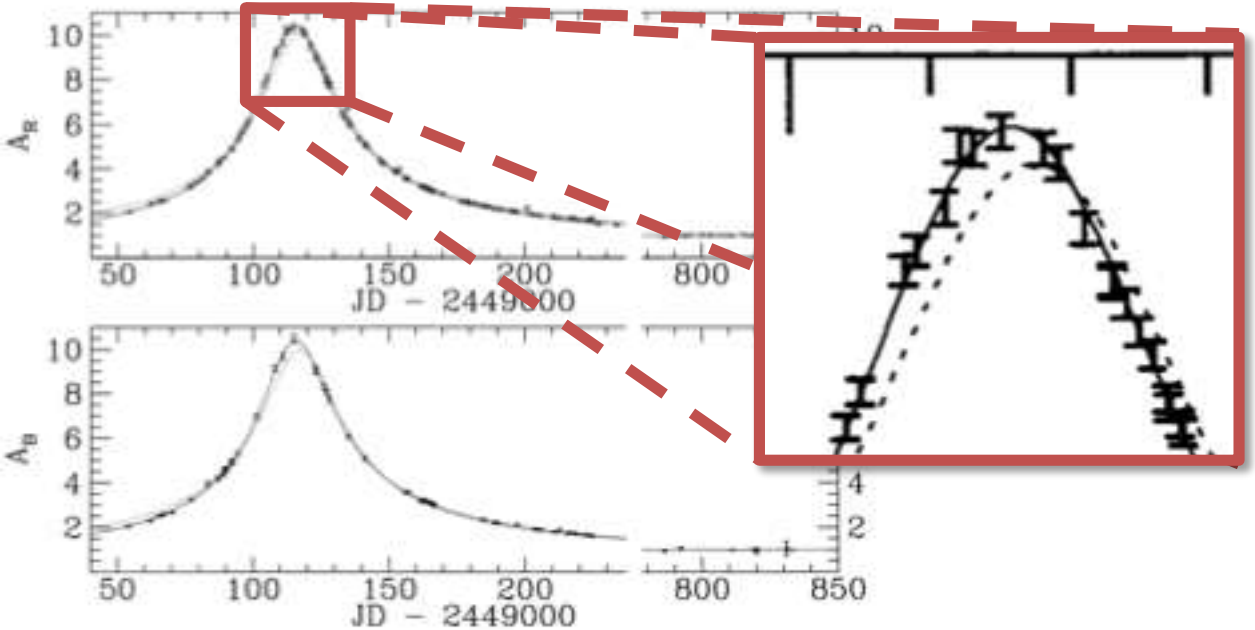
Paczynski 1986, 1996

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





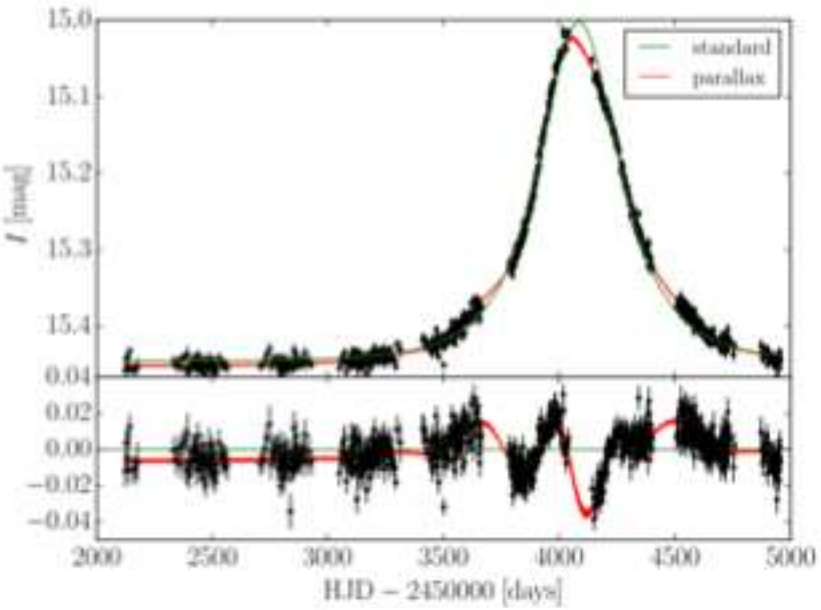
Parallactic effect first observed at LLNL



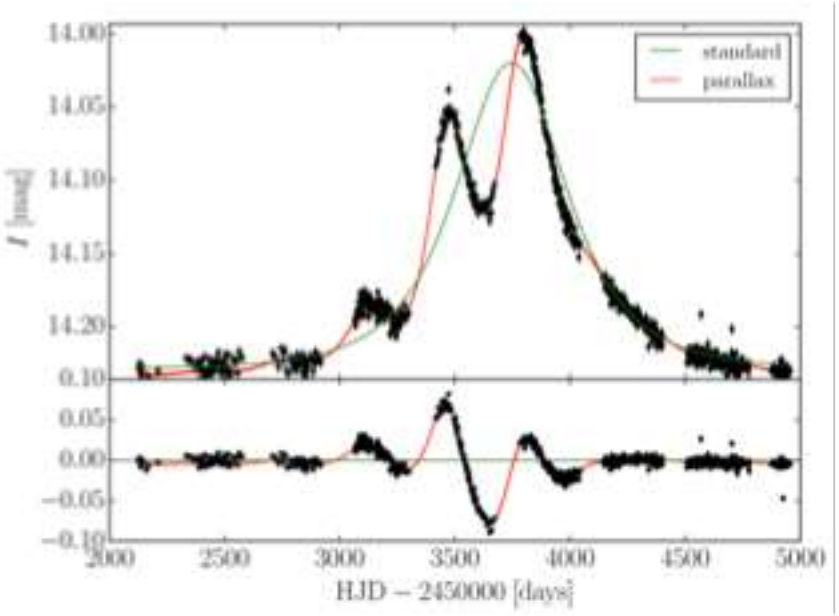
MACHO Survey (1995)

Recent OGLE III parallax events

9.3 $M_\odot$ Black Hole



1.0 $M_\odot$ Neutron Star

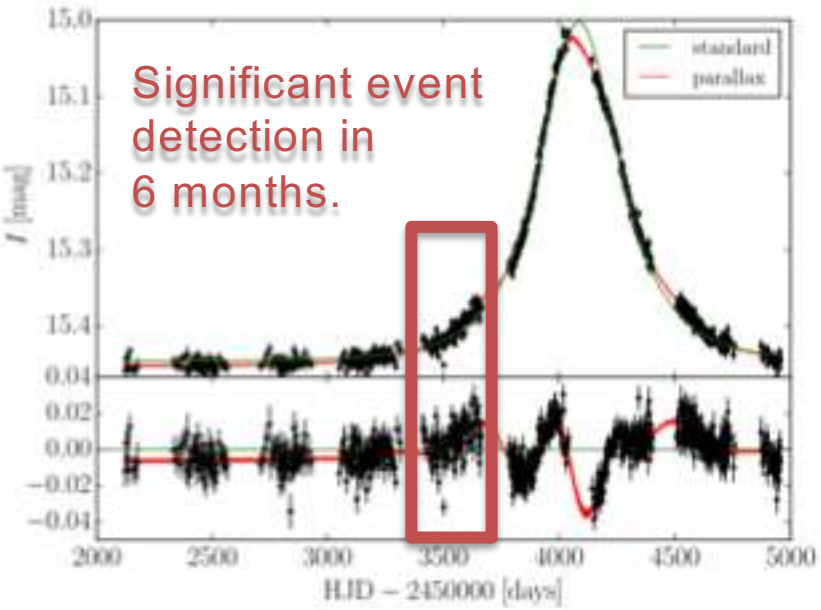


~8 years

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



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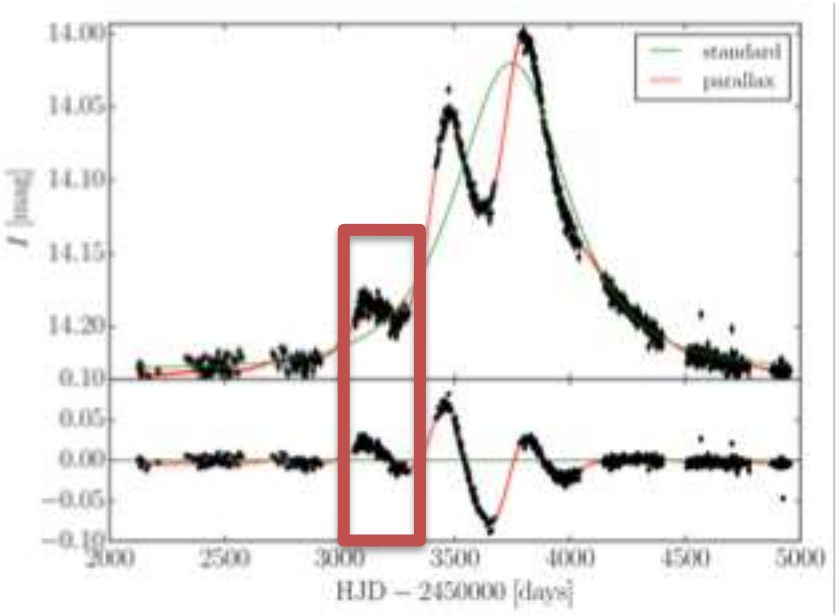


~8 years

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)

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

Number of monitored stars

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

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

Implementation is computationally intensive.
(Perhaps why it hasn't been done yet. We now have the resources.)

THE ASTROPHYSICAL JOURNAL, 392:442–451, 1992 June 20

1992 June 20

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

Requires signal detection in 10 dimensions.
5 constrained
5 unconstrained

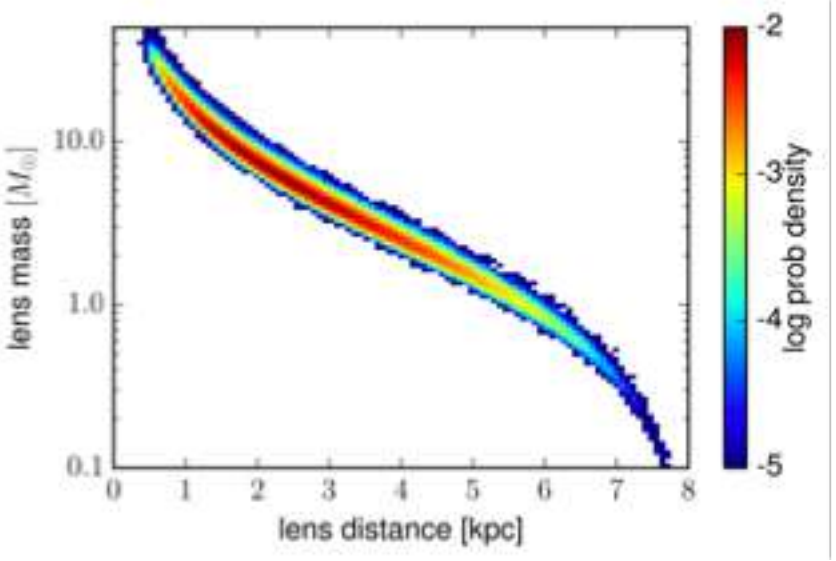
tion of an event. If the *HST*'s optics were repaired, it could resolve images for Machos $\gtrsim 300\ M_\odot$. The lower mass limit can be reduced to $4 \times 10^{-9}\ M_\odot$ by conducting 1 month of rapid repeat observations of a single field. The standard view is that a Macho light curve yields 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 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 ***ensemble can place tighter constraints on the population mass spectrum***, by utilizing our knowledge of the MW dark matter halo density function.

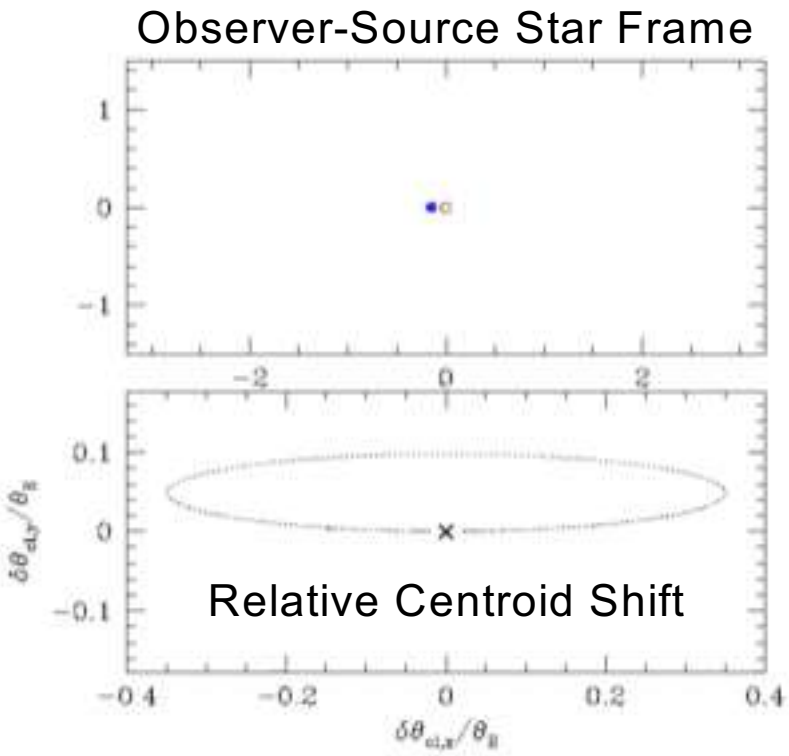
OGLE Black Hole

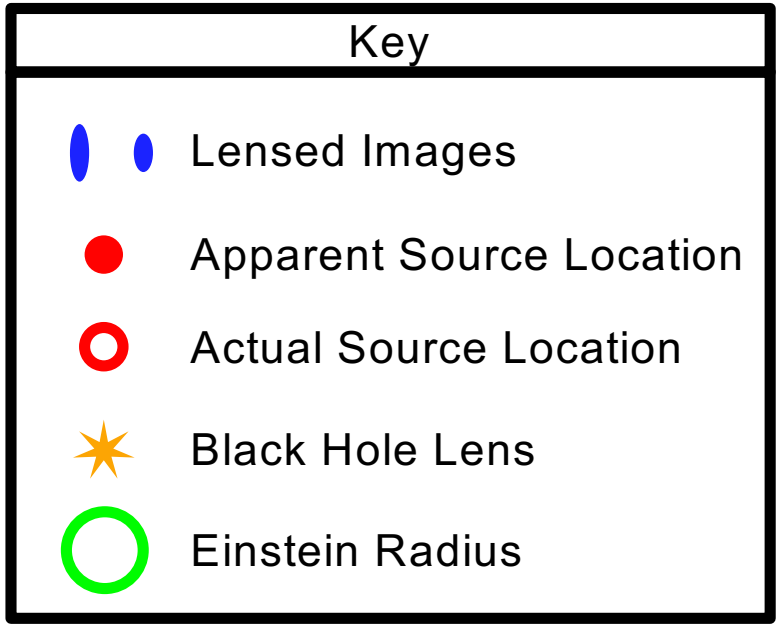


Wyrzkowski et al. 2016

Paralensing + Astrometric Lensing

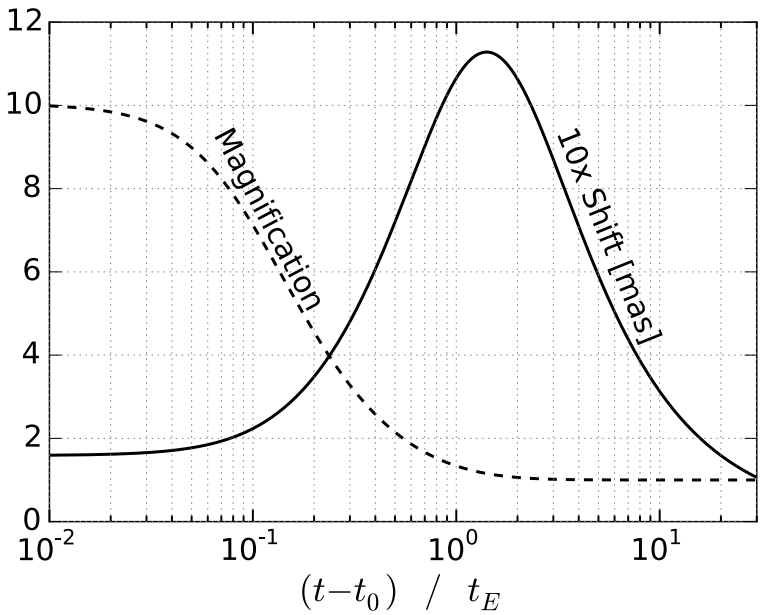
Microlensing also affects the astrometry of the source star



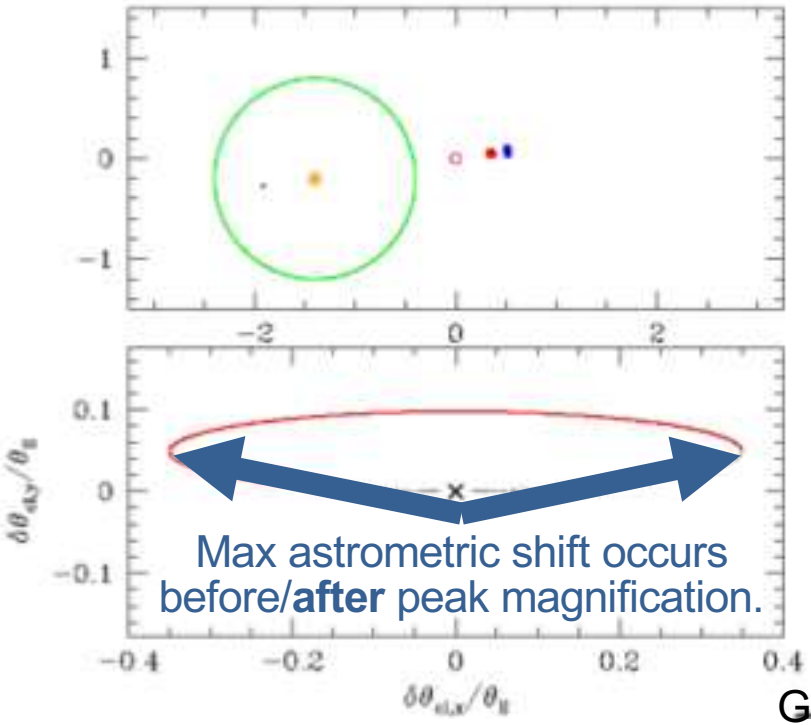


Gaudi

Astrometric follow-up is easily facilitated

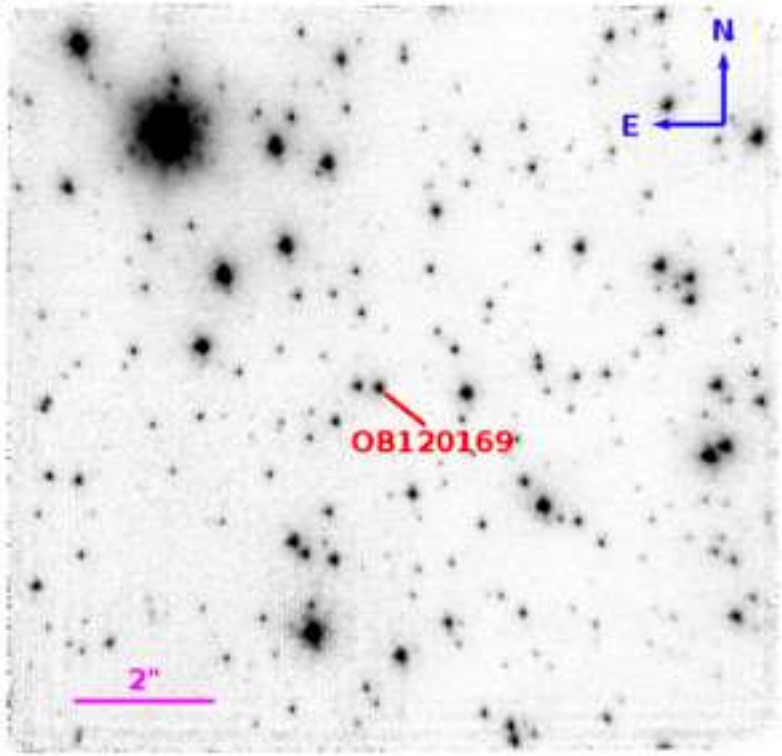


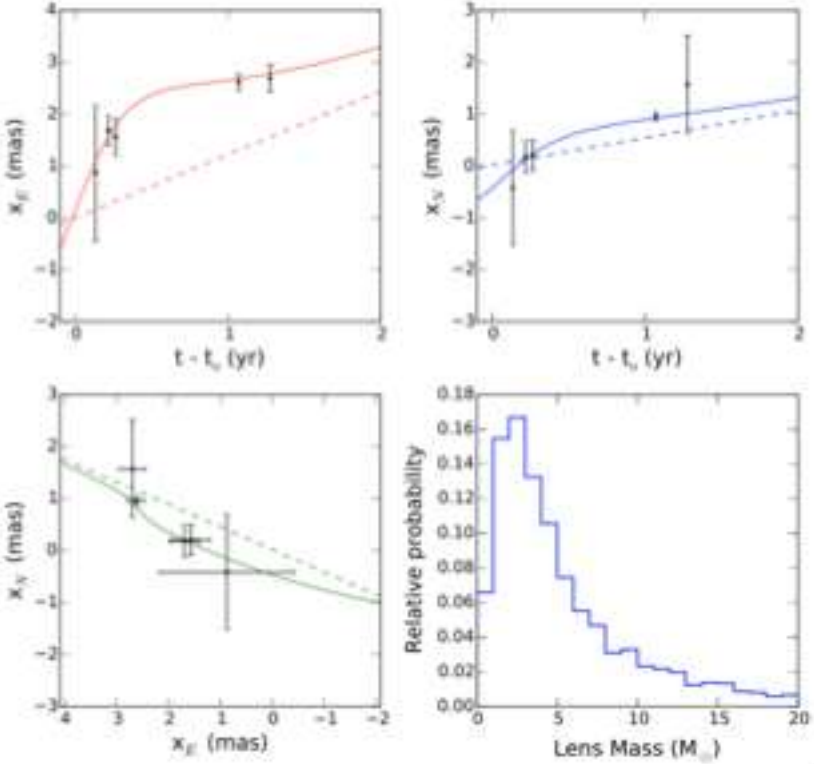
Lu et al. 2016



Gaudi

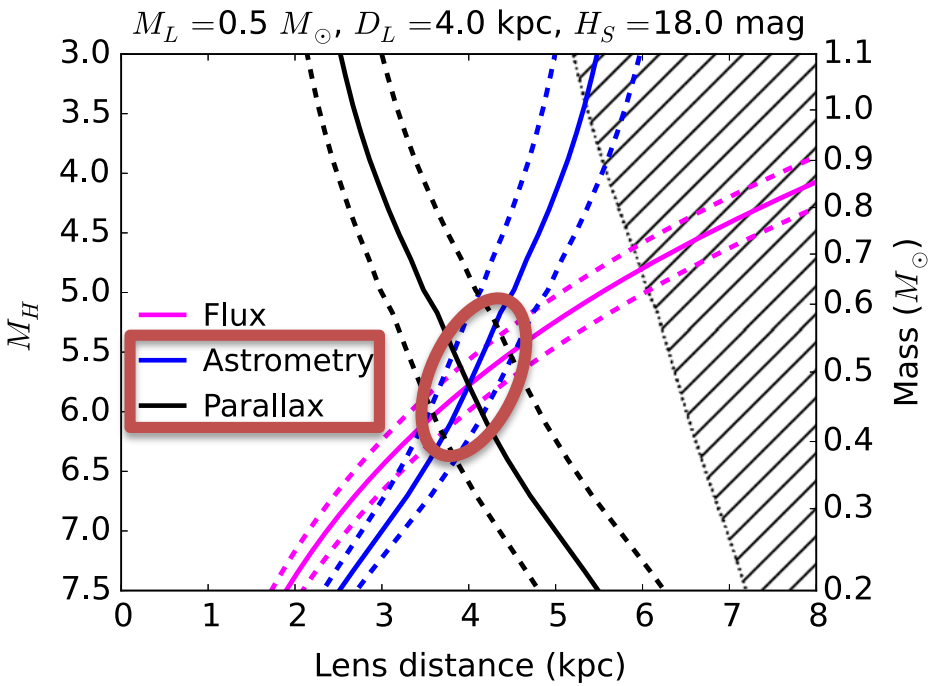
Co-I Jessica Lu is currently making these measurements with Keck adaptive optics!





Lu et al. (2017)

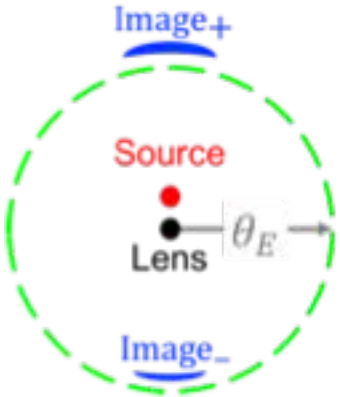
Parallax + Astrometric Microlensing = Tight Mass Constraint



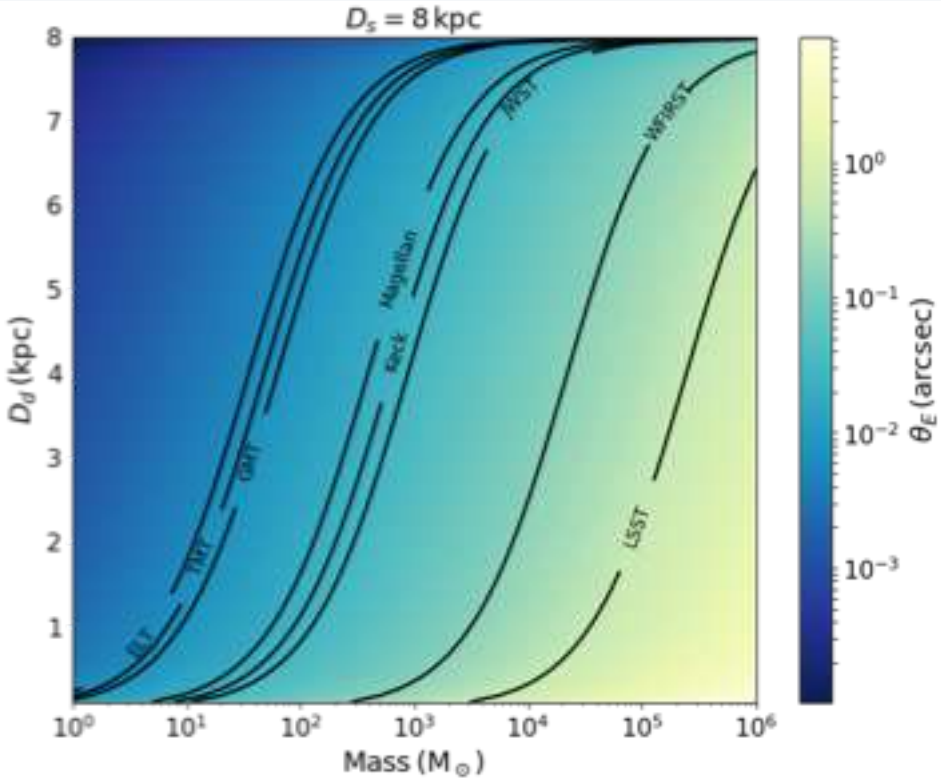
Yee 2015

Ability to resolve multiple lensed images

- Potential to resolve multiple images from IM MACHO events!

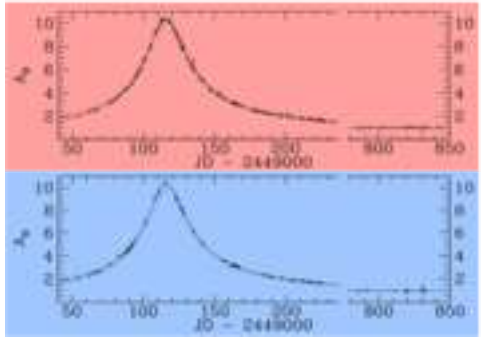


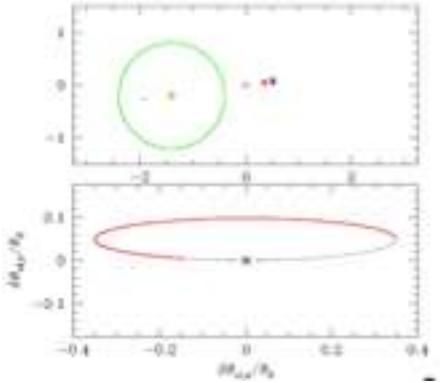
Adaptive Optics Resolution

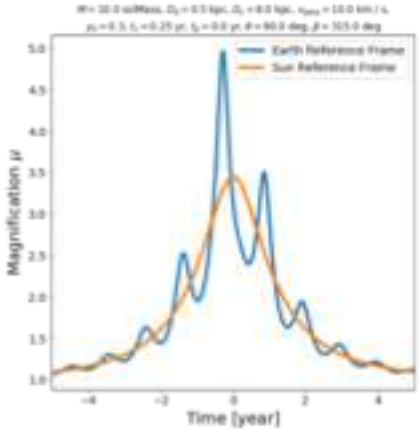


The Microlensing Triad

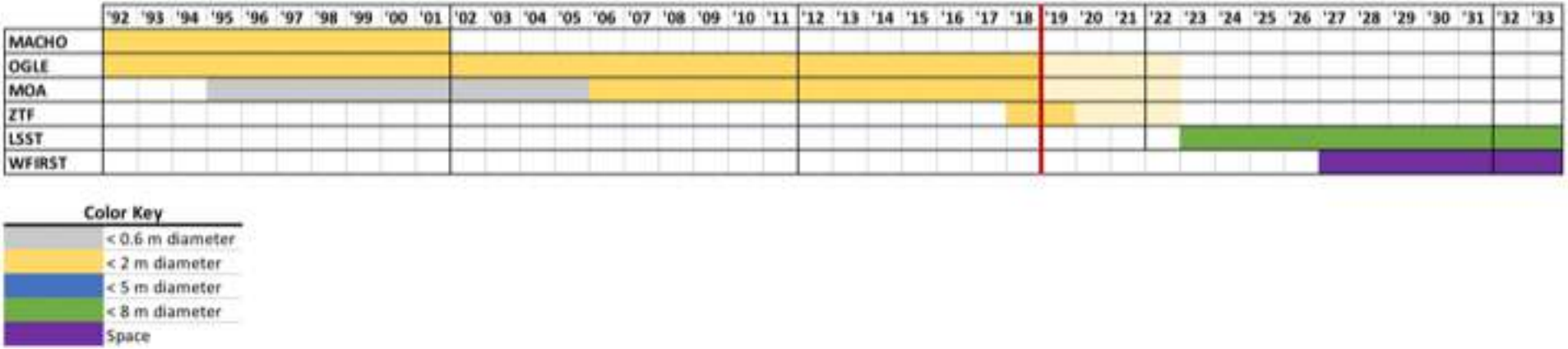
- Achromatic
  - Same signal across all wavelengths
- Parallax
  - Signal highly correlated with known motion around the sun
- Astrometry
  - Independent measurement; signal highly correlated with photometric signal







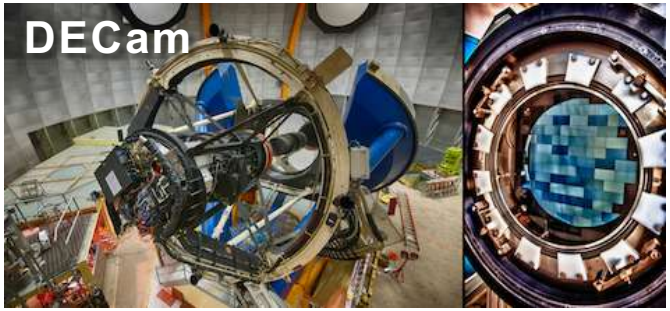
Potential for over 4 decades of microlensing measurements (but big step function at the end of 2022 with LSST)

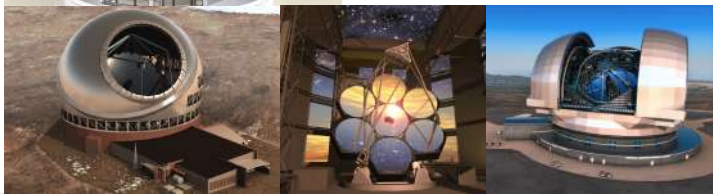


PALS DECam Microlensing Survey

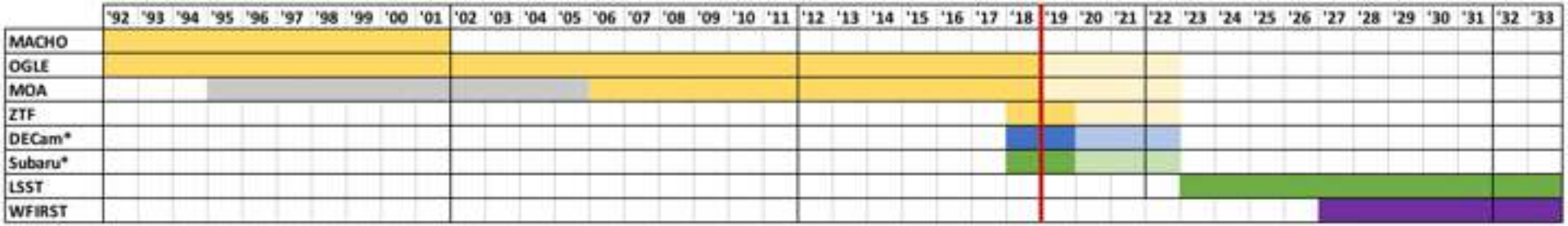
Near and long term plan for confirming or ruling out primordial black holes as dark matter

- Objective
  - Confirm or reject primordial black holes ($> 10M_{\odot}$) 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
    - Utilize existing WFIRST microlensing survey
    - Follow-up JWST, and 30 m class telescope astrometric microlensing measurements





Leading two new microlensing surveys on: CTIO/DECam and Subaru/HyperSuprimeCam



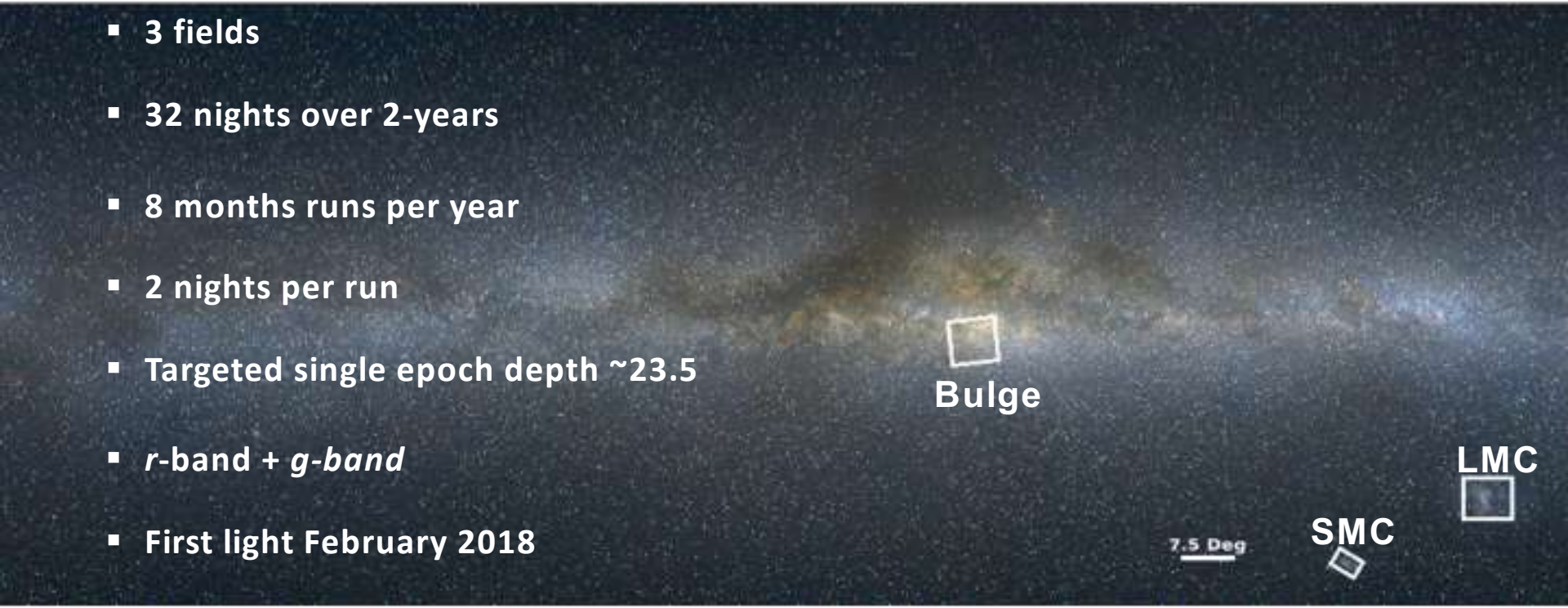
* PI Dawson

Color Key
< 0.6 m diameter
< 2 m diameter
< 5 m diameter
< 8 m diameter
Space

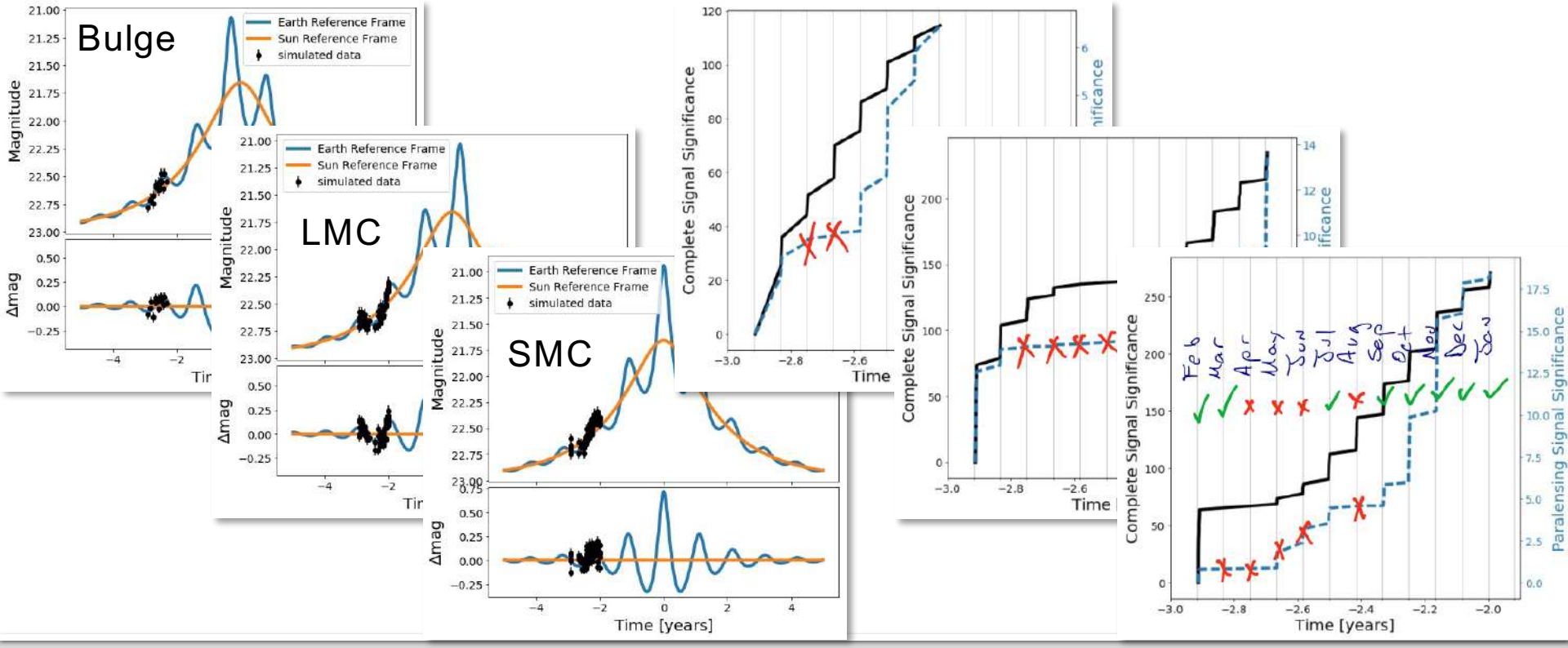
Can essentially extend the LSST baseline from 10-15 years.

PALS: Survey will overlap the MACHO Survey

- 3 fields
- 32 nights over 2-years
- 8 months runs per year
- 2 nights per run
- Targeted single epoch depth ~23.5
- *r*-band + *g-band*
- First light February 2018



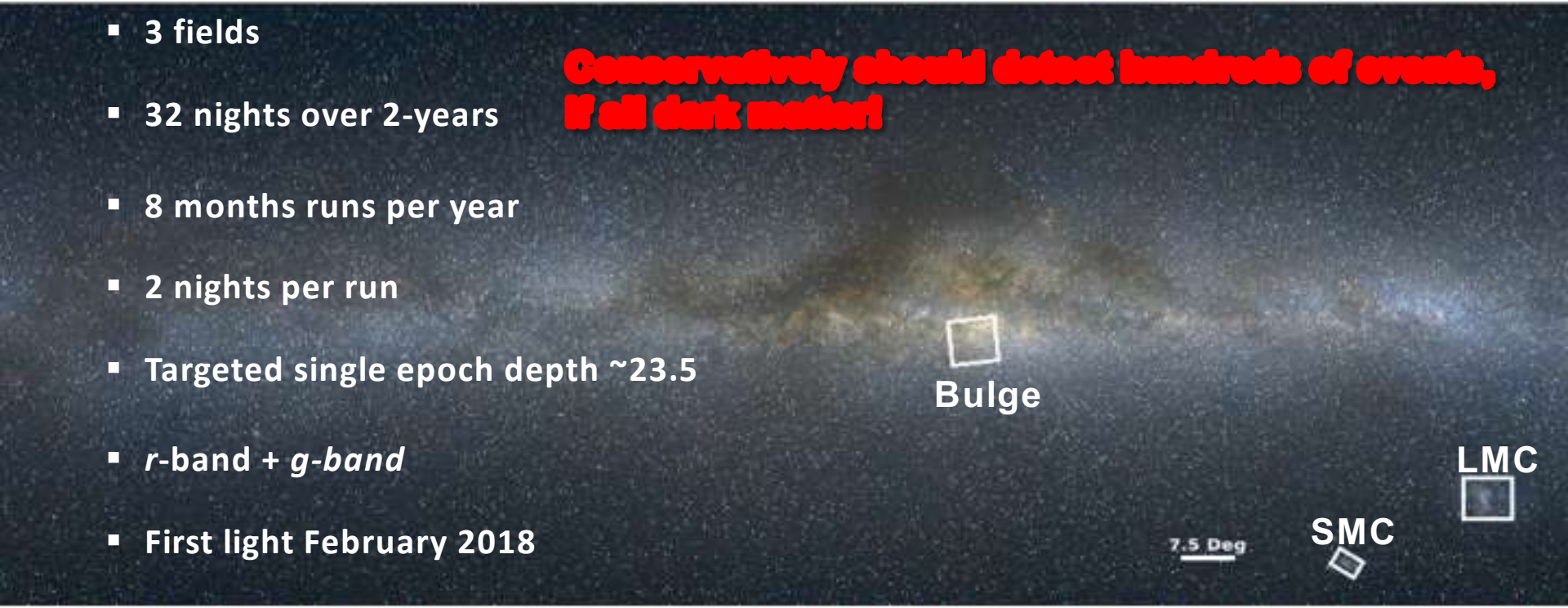
Efficient Survey Designed for Paralensing



PALS: Survey will overlap the MACHO Survey

- 3 fields
- 32 nights over 2-years
- 8 months runs per year
- 2 nights per run
- Targeted single epoch depth ~23.5
- *r*-band + *g-band*
- First light February 2018

Conservatively should detect hundreds of events, if all dark matter!

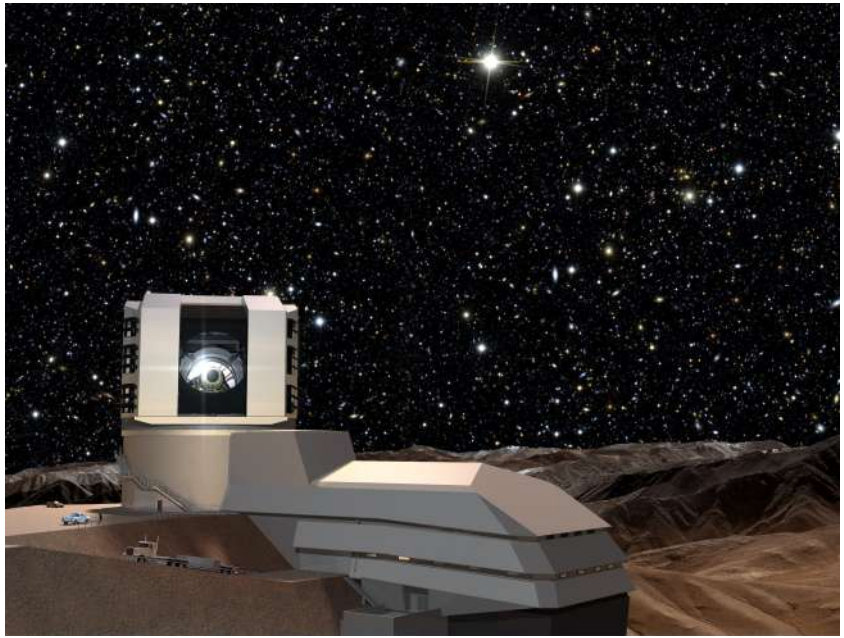


We are waiving the proprietary period.

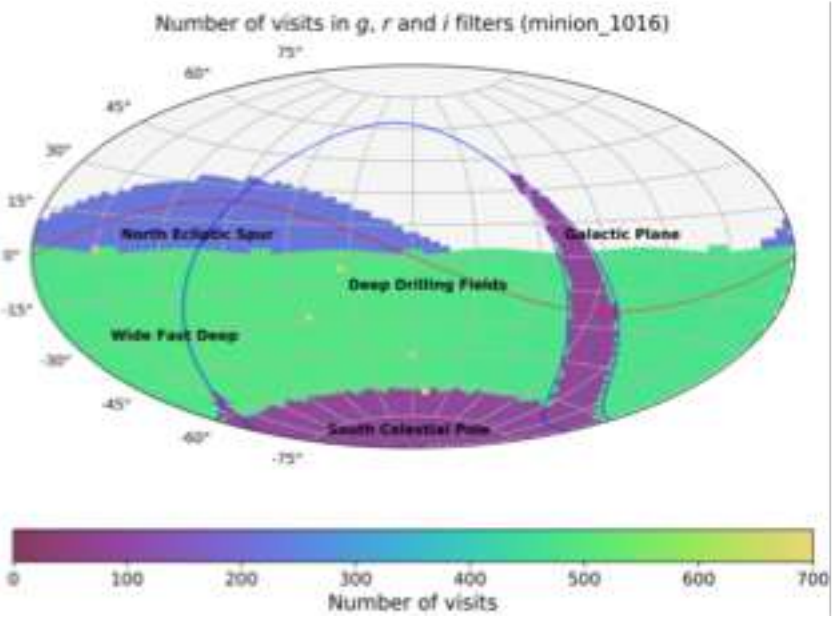
You can get the data as soon as we take the data!

LSST Forecast

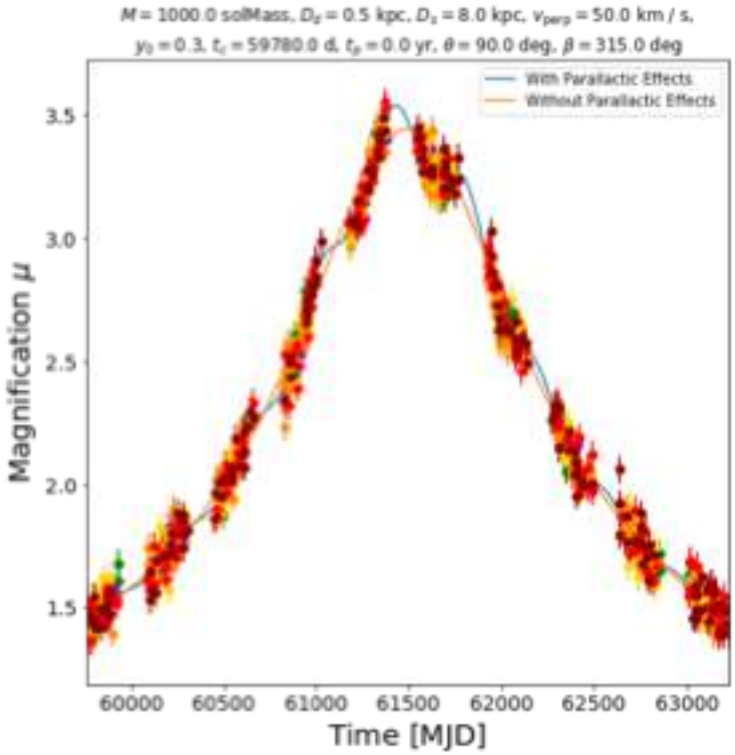
What this could look like with LSST, based on latest OpSim run.

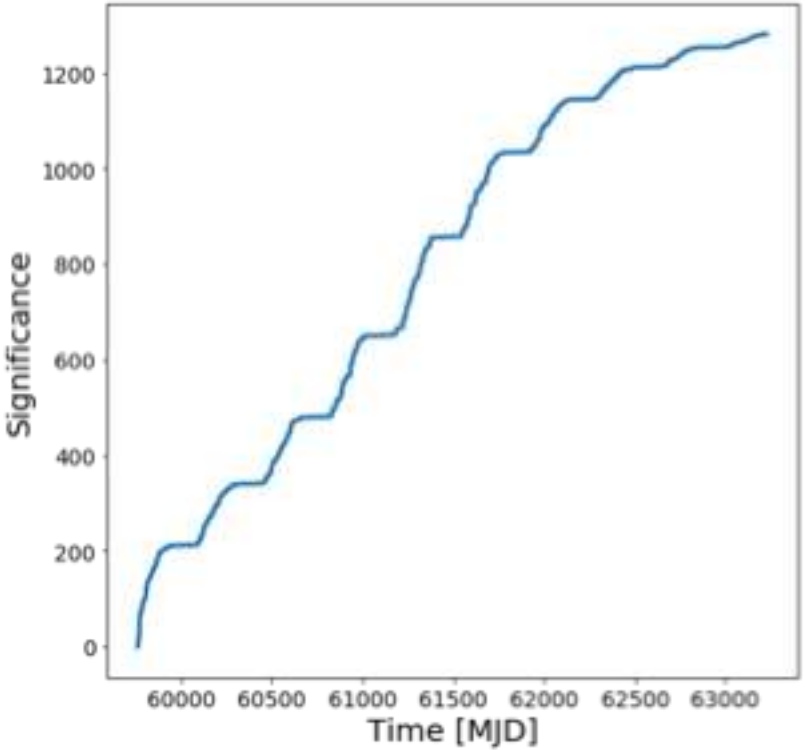


OpSim 'minion_1016' run.

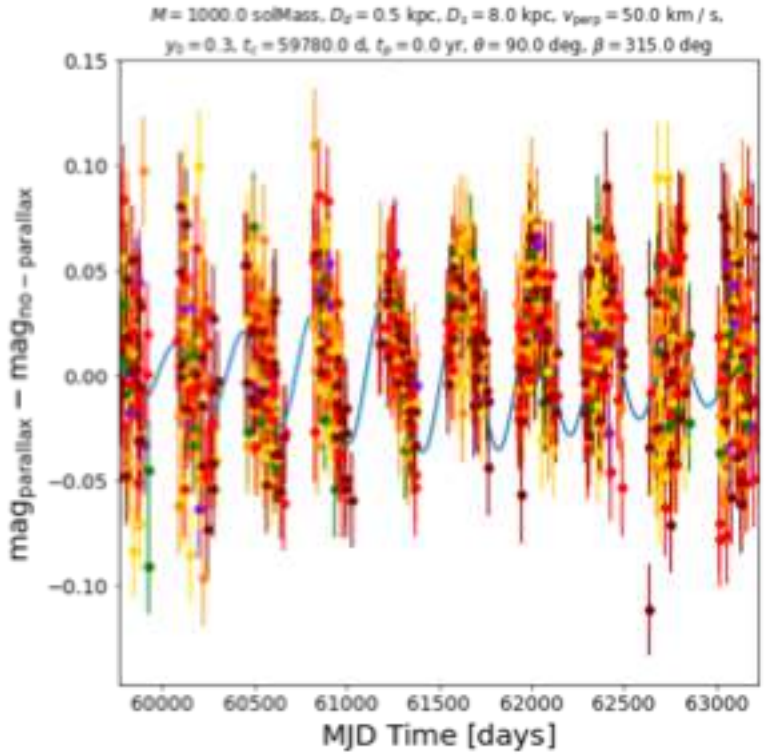


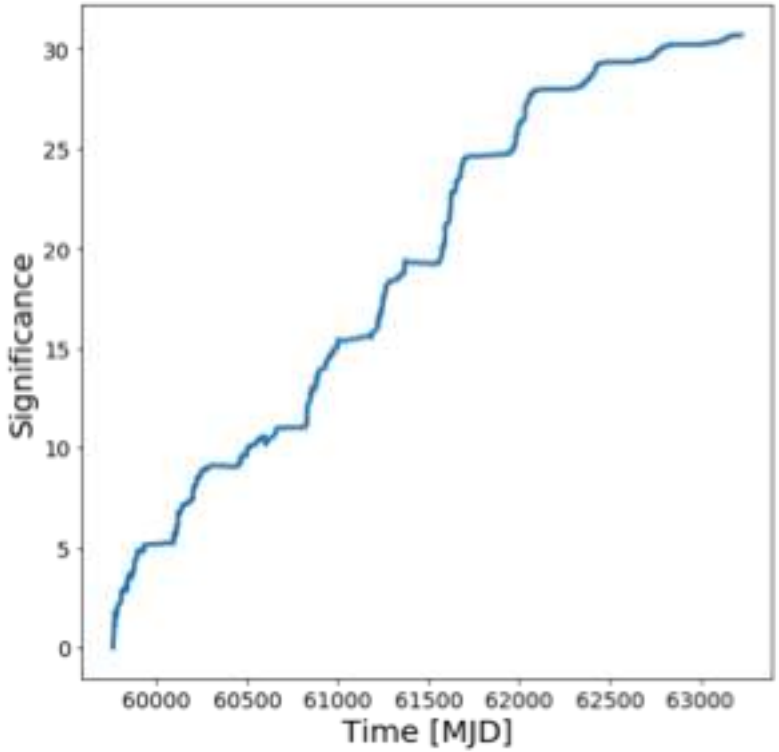
Intermediate mass black hole microlensing event injected into LSST OpSim data



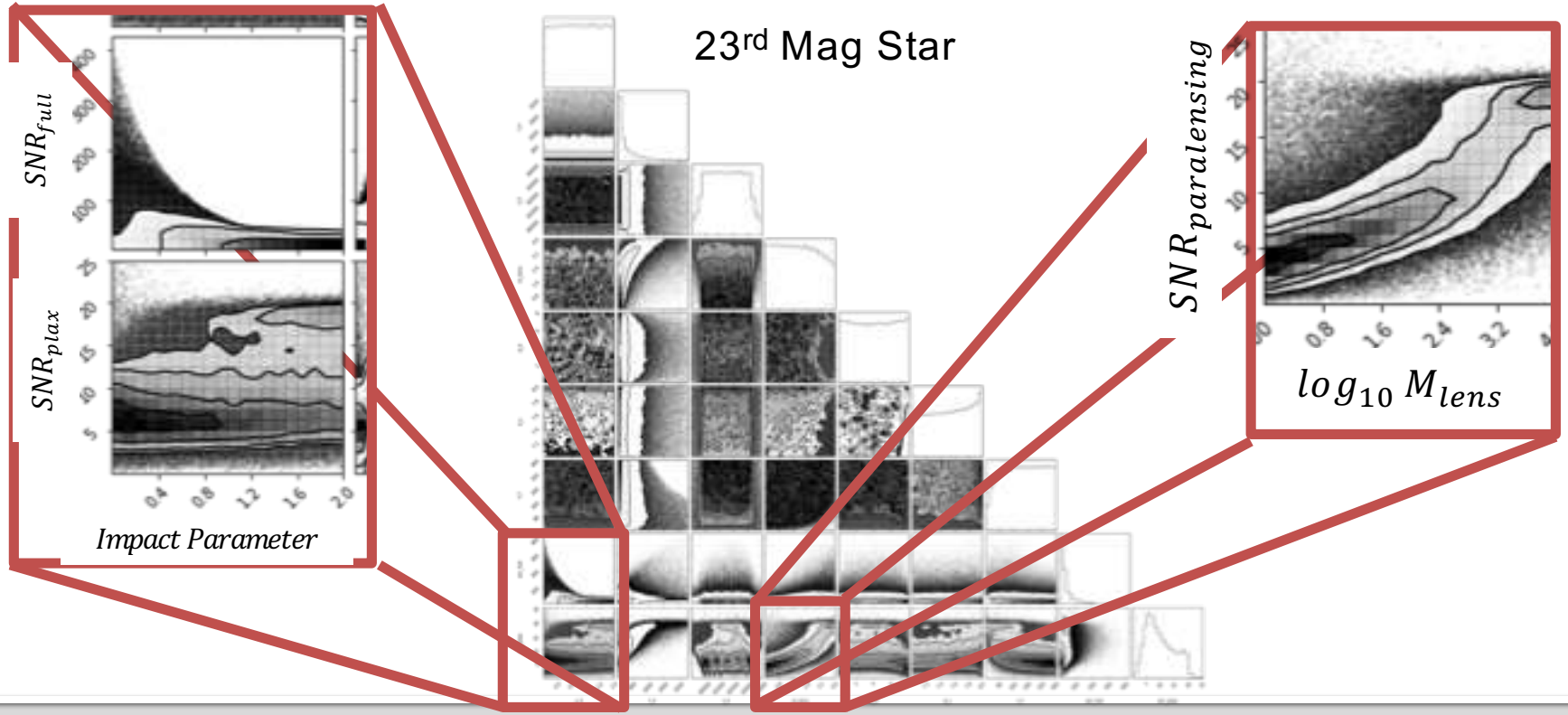


Events can purely be detected on by their paralensing signal

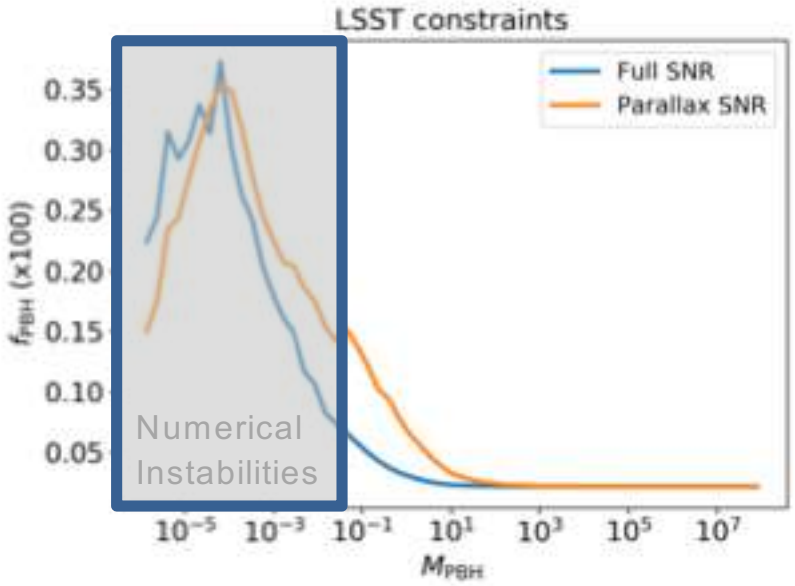




Have to tools to start exploring LSST's sensitivity to various black holes



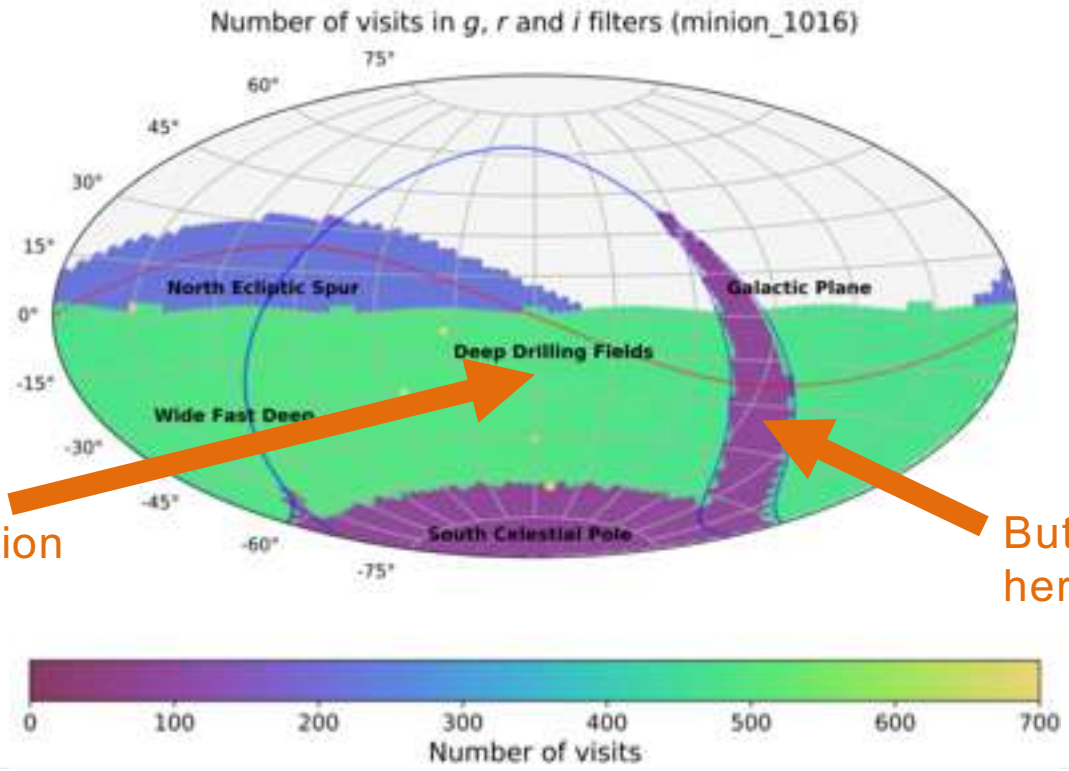
LSST has the potential to provide the most direct, tightest, and broadest constraints on the abundance of IMBH's



- Assumptions:
  - Gaussian noise
    - No variable star noise
    - Perfect differential photometry
  - Optimal signal-matched-filter
  - WFD Cadence
  - All 23rd magnitude source stars

https://github.com/lsstdarkmatter/dark-matter-paper/issues/8

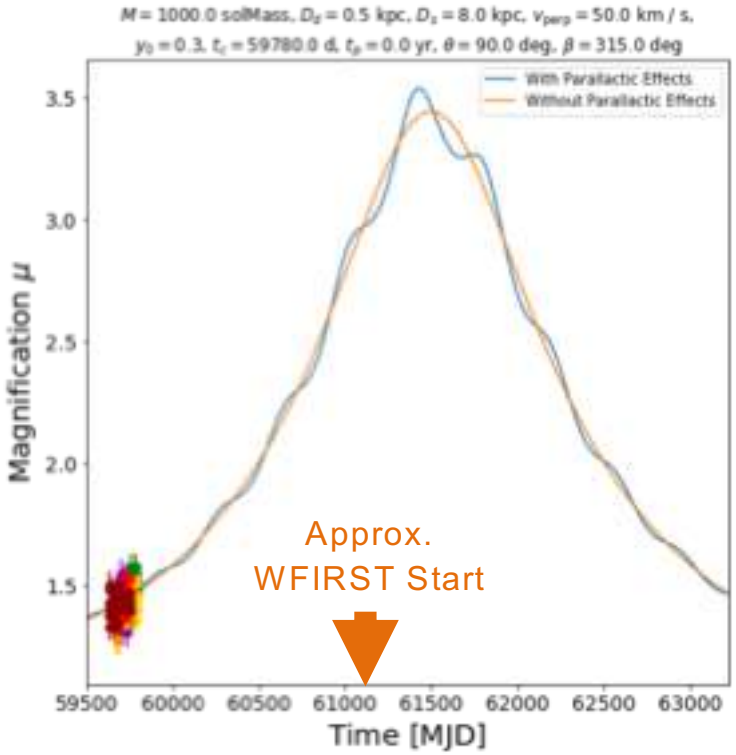
But that is from the Wide Fast Deep field, where there aren't many stars.

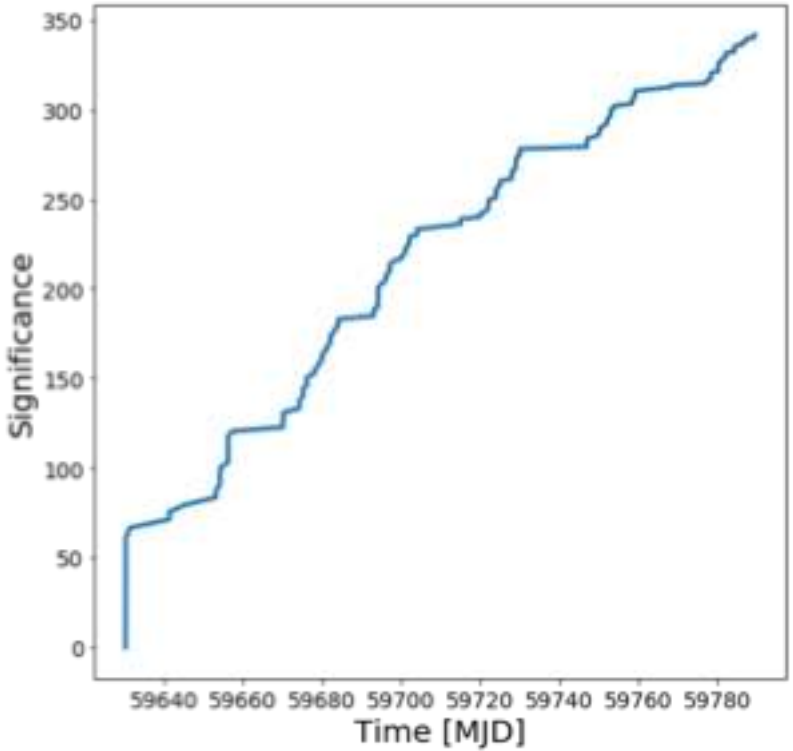


Previous simulation from here.

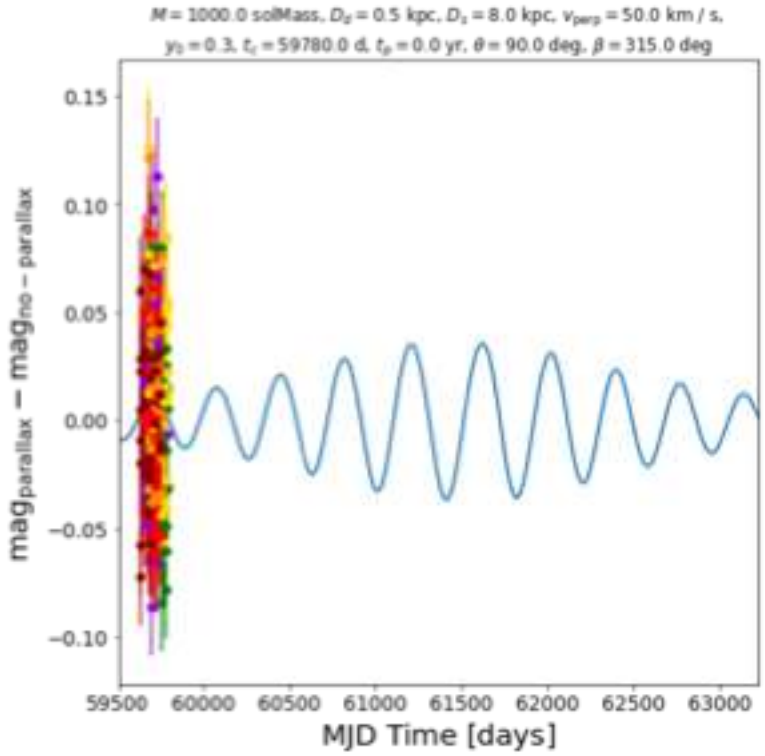
But most stars are here.

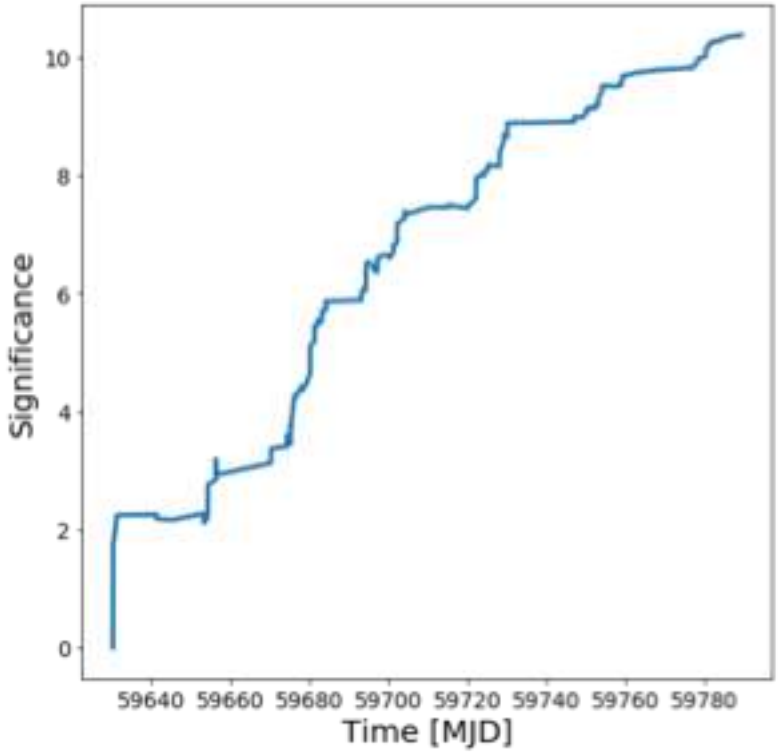
In latest plan LSST will only observe galaxy in first year.
TERRIBLE FOR THIS SCIENCE & SYNERGY WITH WFIRST!





While the signal in this case is still statistically significant, there is no way of discriminating signal from background.





Summary

- Microlensing is (one of) the best measurements of intermediate mass black holes
- Can either confirm or rule out primordial black holes with paralensing
- Potential to measure the intermediate mass black hole mass spectrum regardless of evolutionally nature of black holes
- We have started a two-year pilot survey on DECam capable of conservatively detecting hundreds of events if all dark matter.
- LSST could be great for this science if cadence of Milky Way and Magellanic Clouds adjusted.
- ELT's and JWST will enable a new observational microlensing regime.

Lawrence Livermore
National Laboratory