

Everything Lenses

Jessica Lu
UC Berkeley

Andrew Hamilton (JILA)



Gravitational lensing has both a photometric and astrometric signal.



Microlensing
Basics
Lu et al. 2026

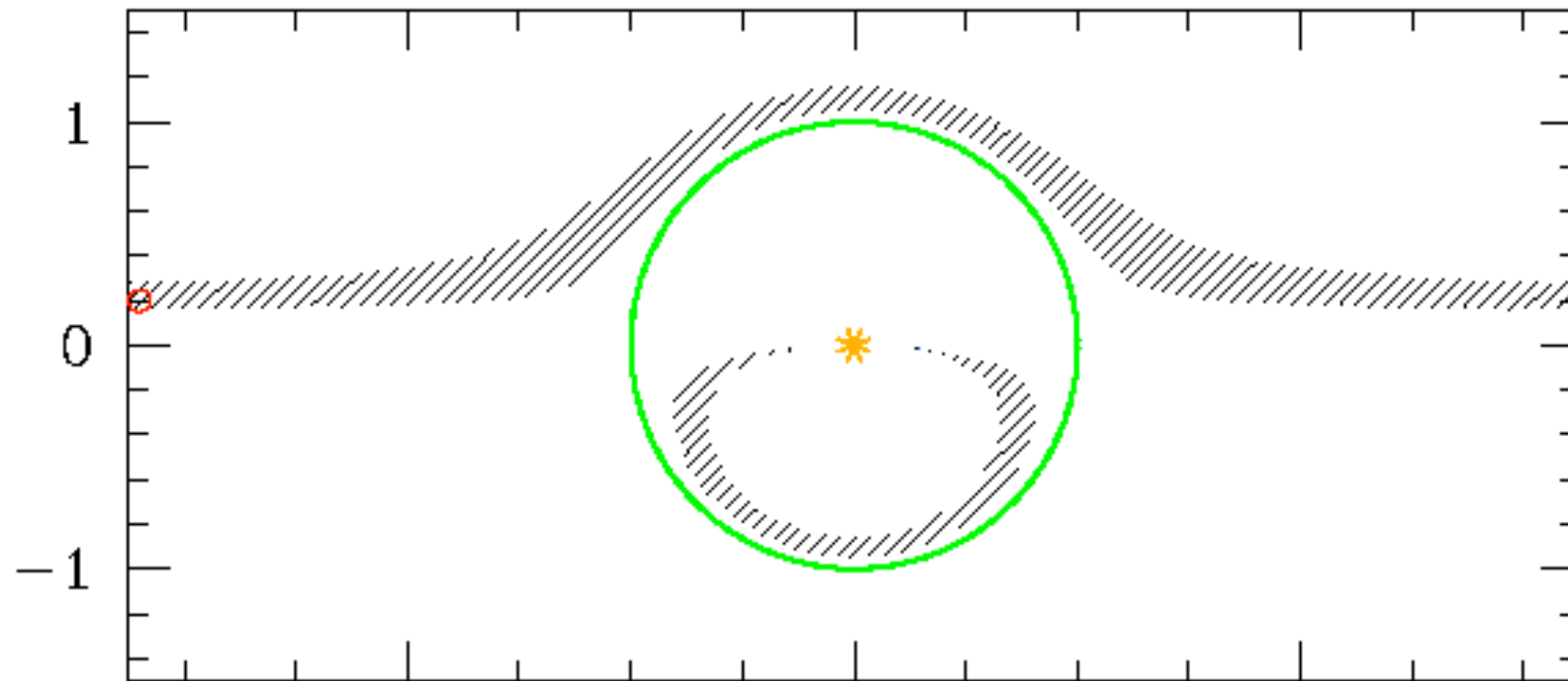
Background Star



Black Hole



The microlensing cross-section is called the “Einstein radius”.



$$\theta_E = \sqrt{\kappa M \pi_{rel}}$$

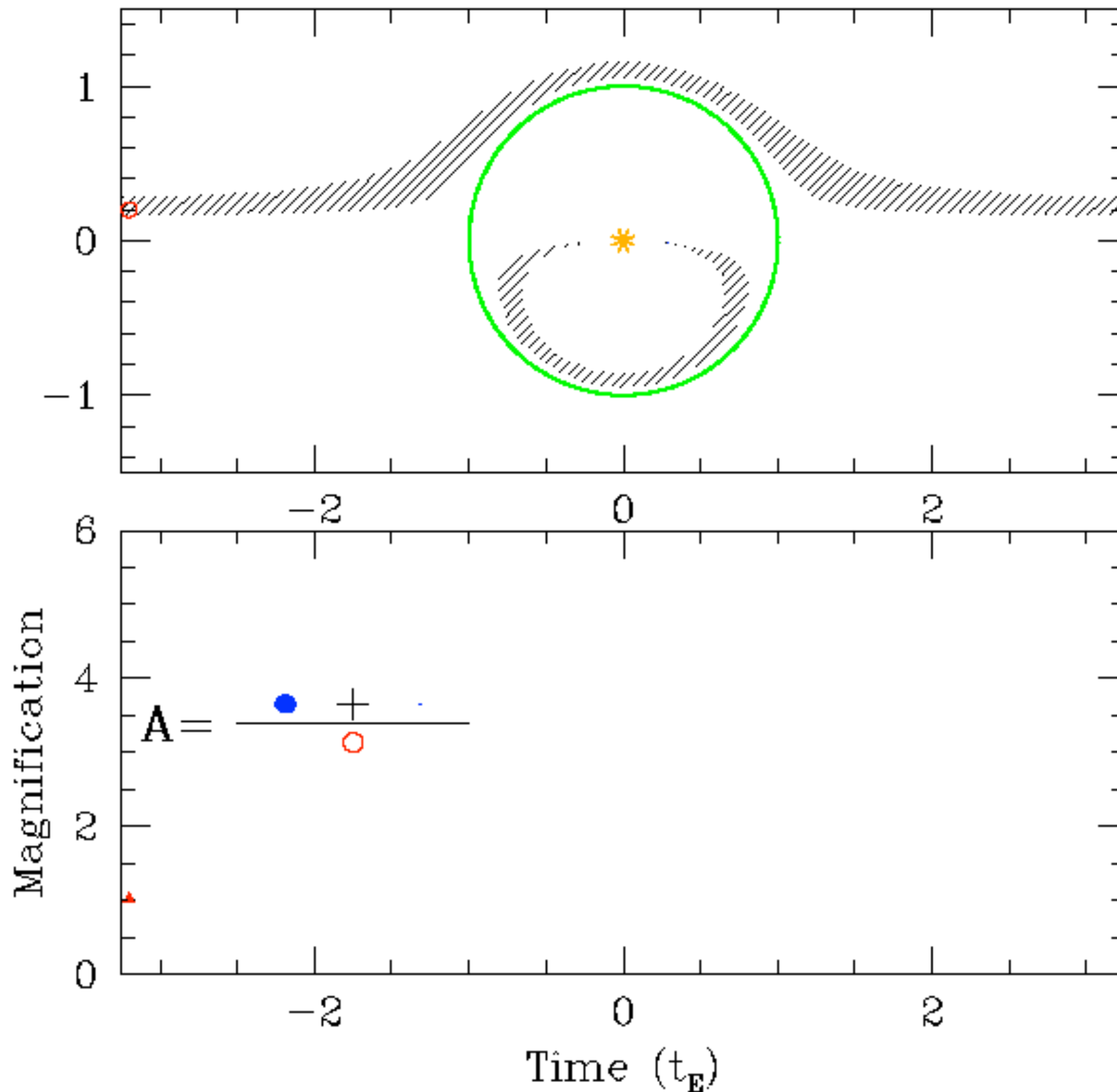
Einstein radius

constant

Lens Mass

Relative distance of lens and source.

Star passing behind a lens brightens — photometric microlensing.



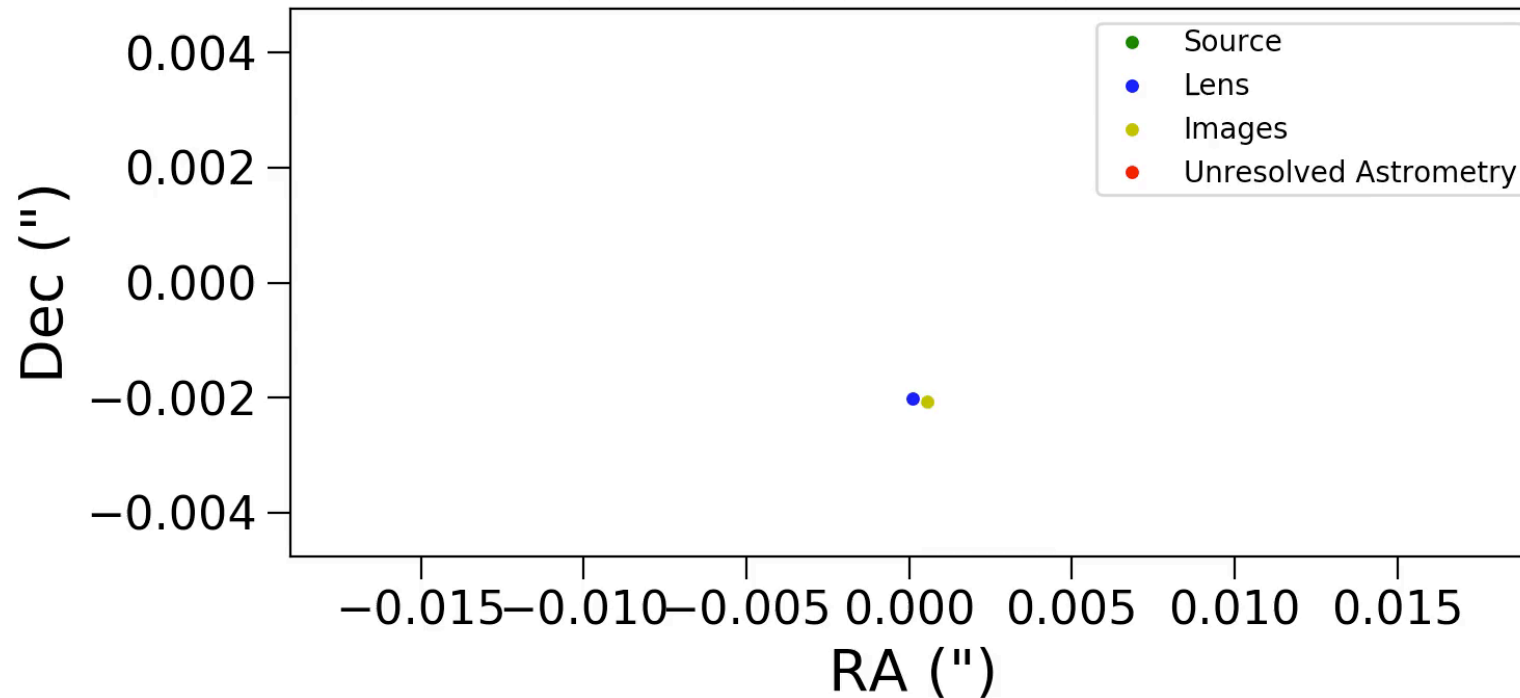
$$t_E = \frac{\theta_E}{\mu_{rel}}$$

$$\pi_E = \frac{\pi_{rel}}{\theta_E}$$

**No Mass
Info**

Star passing behind a lens shifts its position — astrometric microlensing.

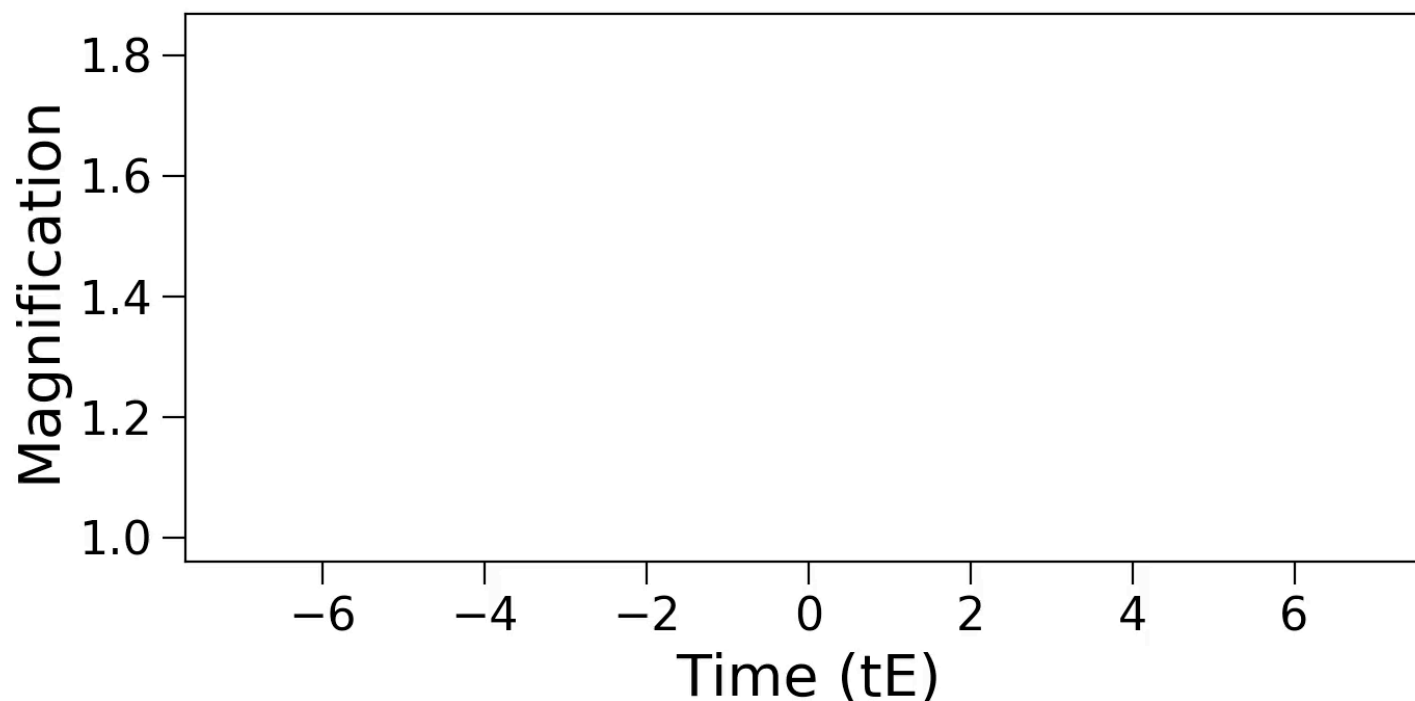
$m_L = 10.0 M_\odot$, $d_L = 4000$ pc, $d_S = 8000$ pc, $\theta_E = 3.2$ mas, $t_E = 233$ days



Typical BH:
 $\theta_E \sim \text{few mas}$

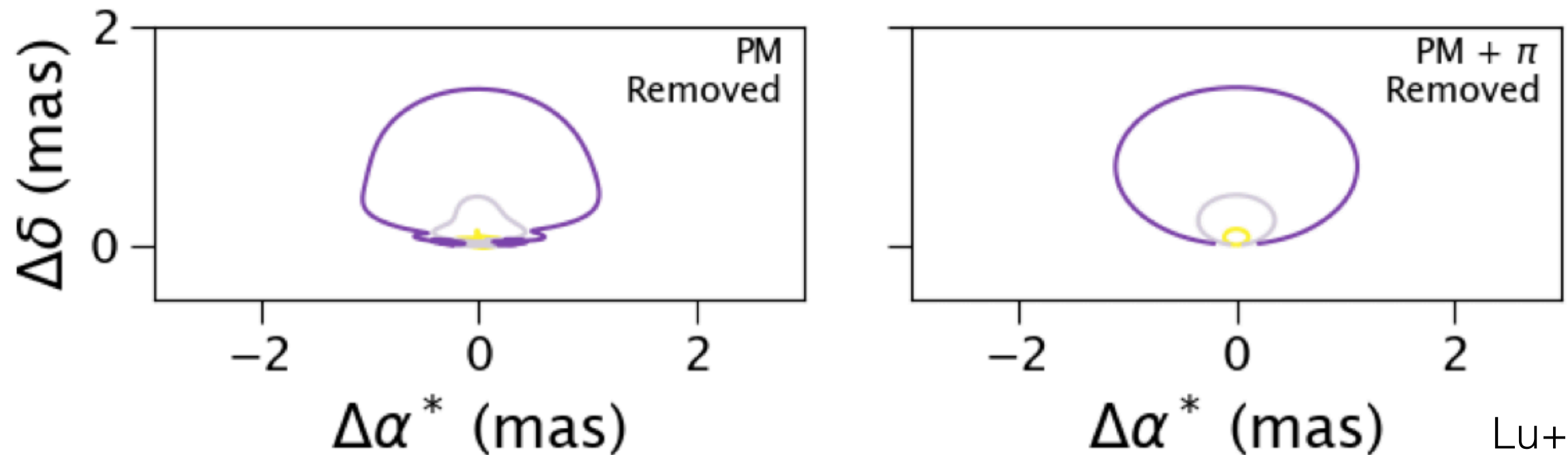
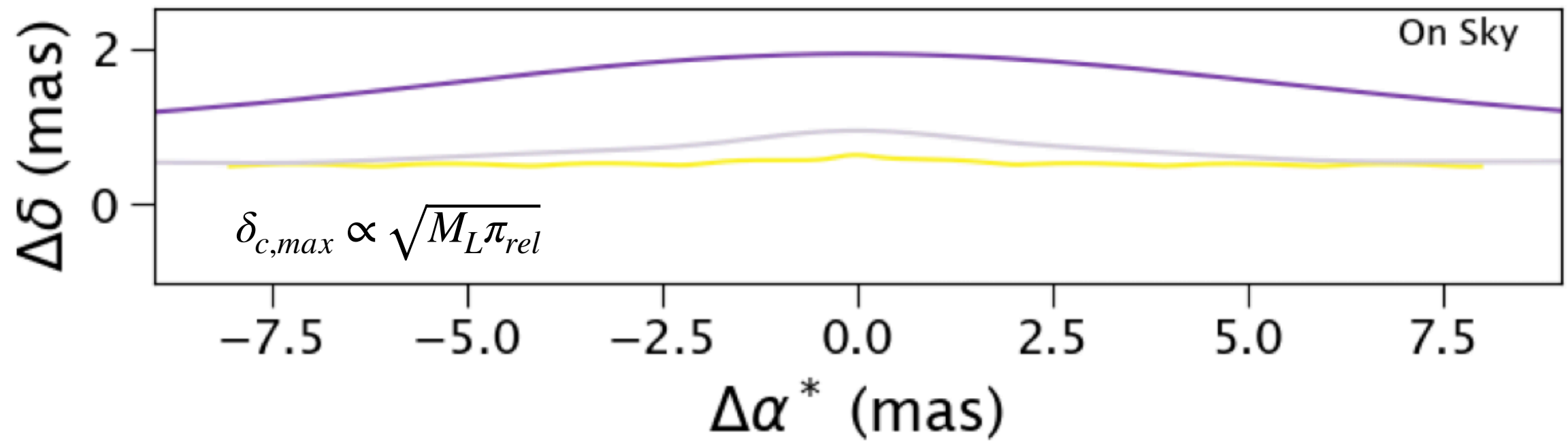
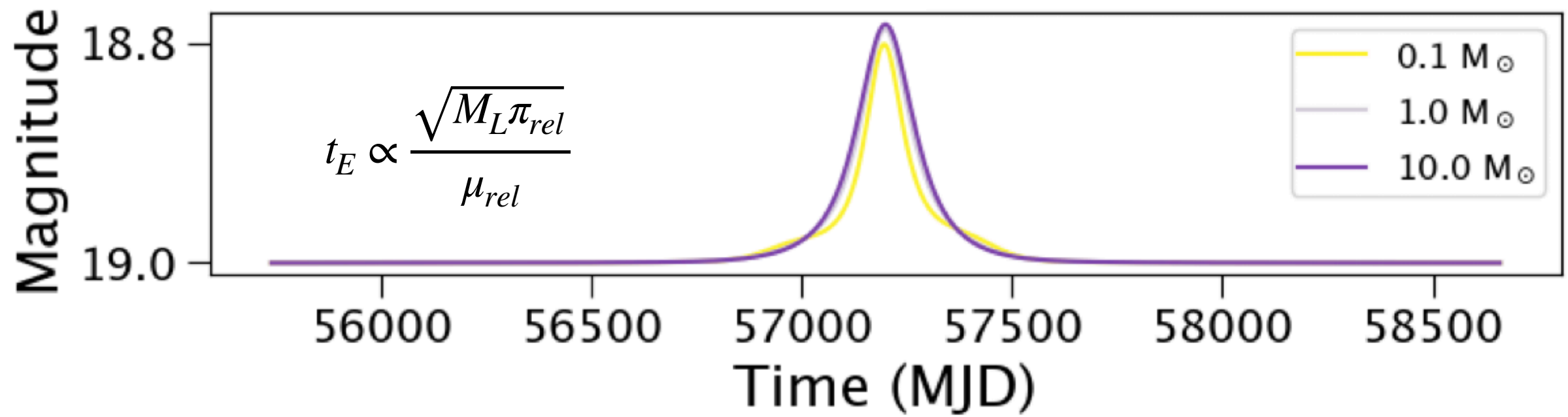
Astrometric shift:

$$\delta_c(t) = \frac{\theta_E}{u(t)^2 + 2} u(t),$$



$\text{max} \sim 0.35 \theta_E$

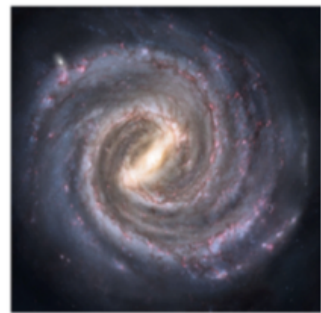
Gives Mass Info



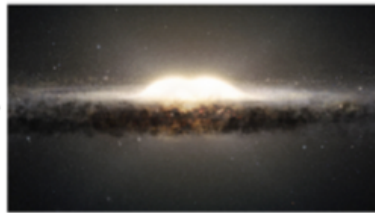
How do we know what lenses? Simulate a Milky Way and “observe” lensing.

PopSyCLE:

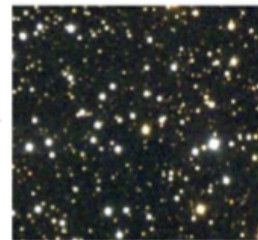
Population Synthesis for Compact object Lensing Events



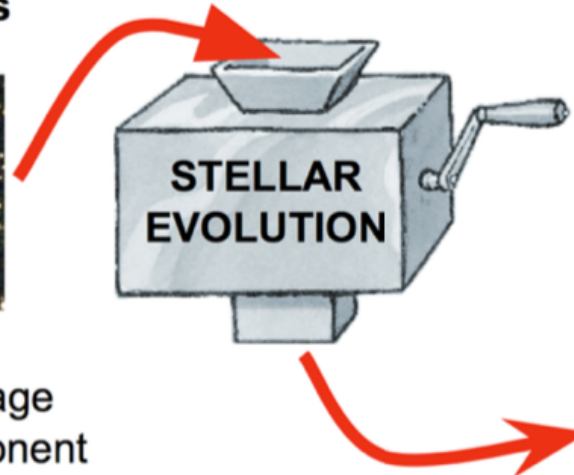
Stellar model of Milky Way



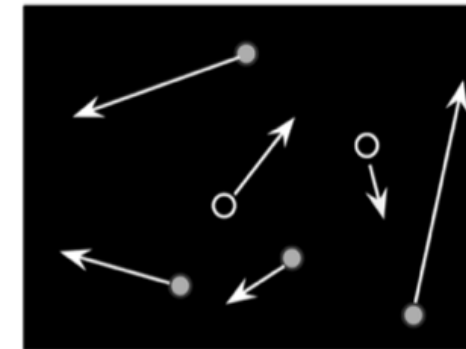
Select component of Milky Way (e.g. bulge)



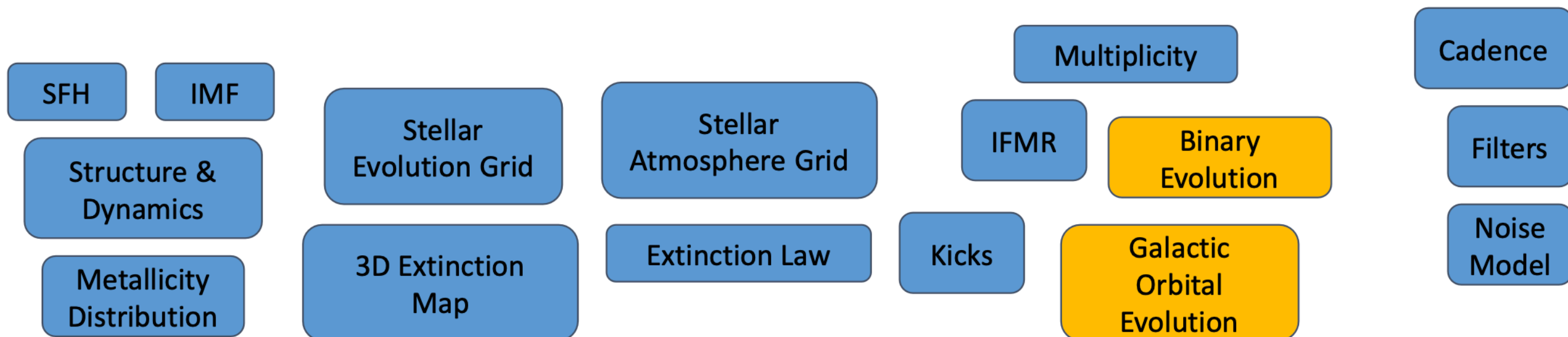
Select single-age subset of component



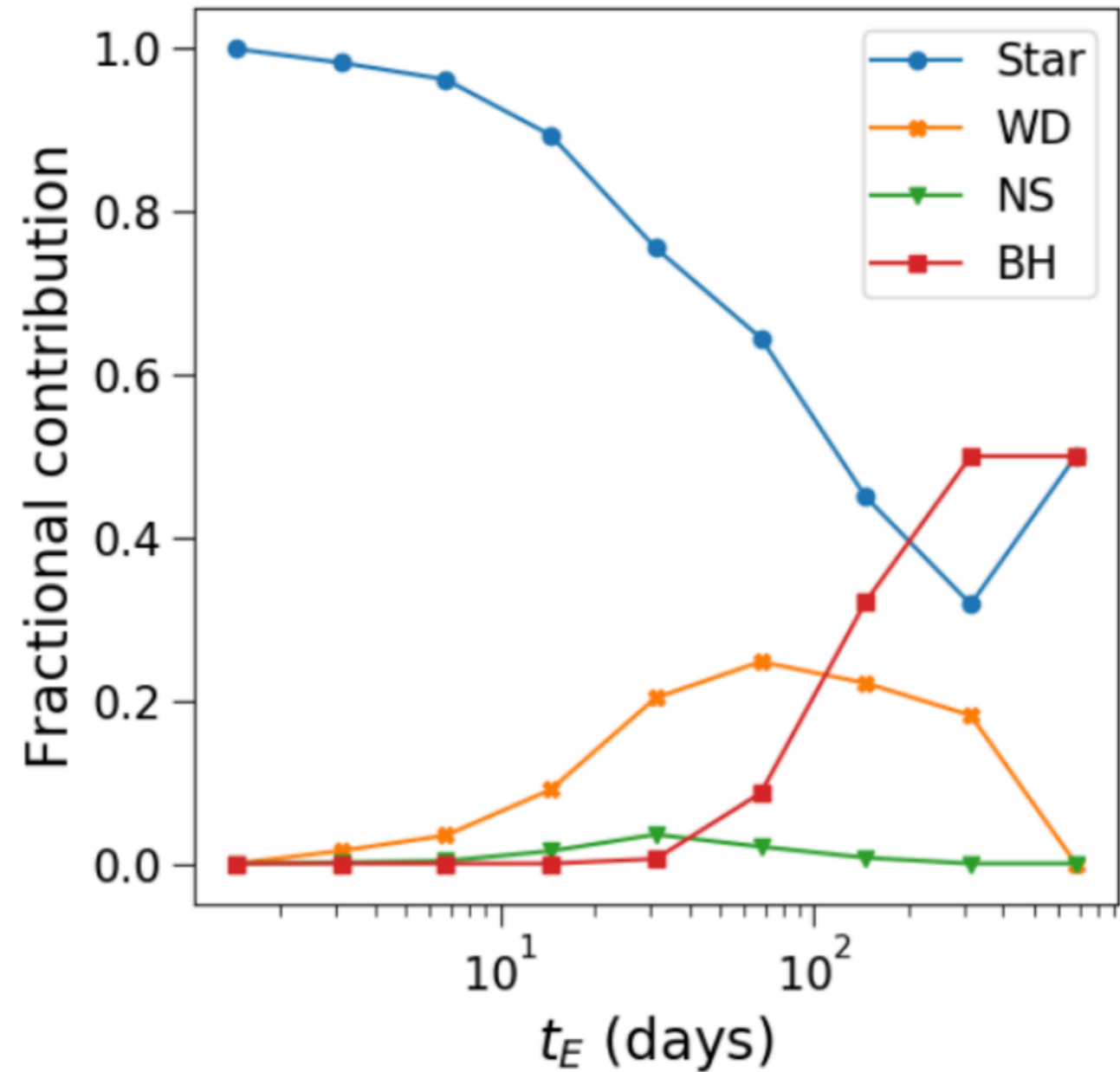
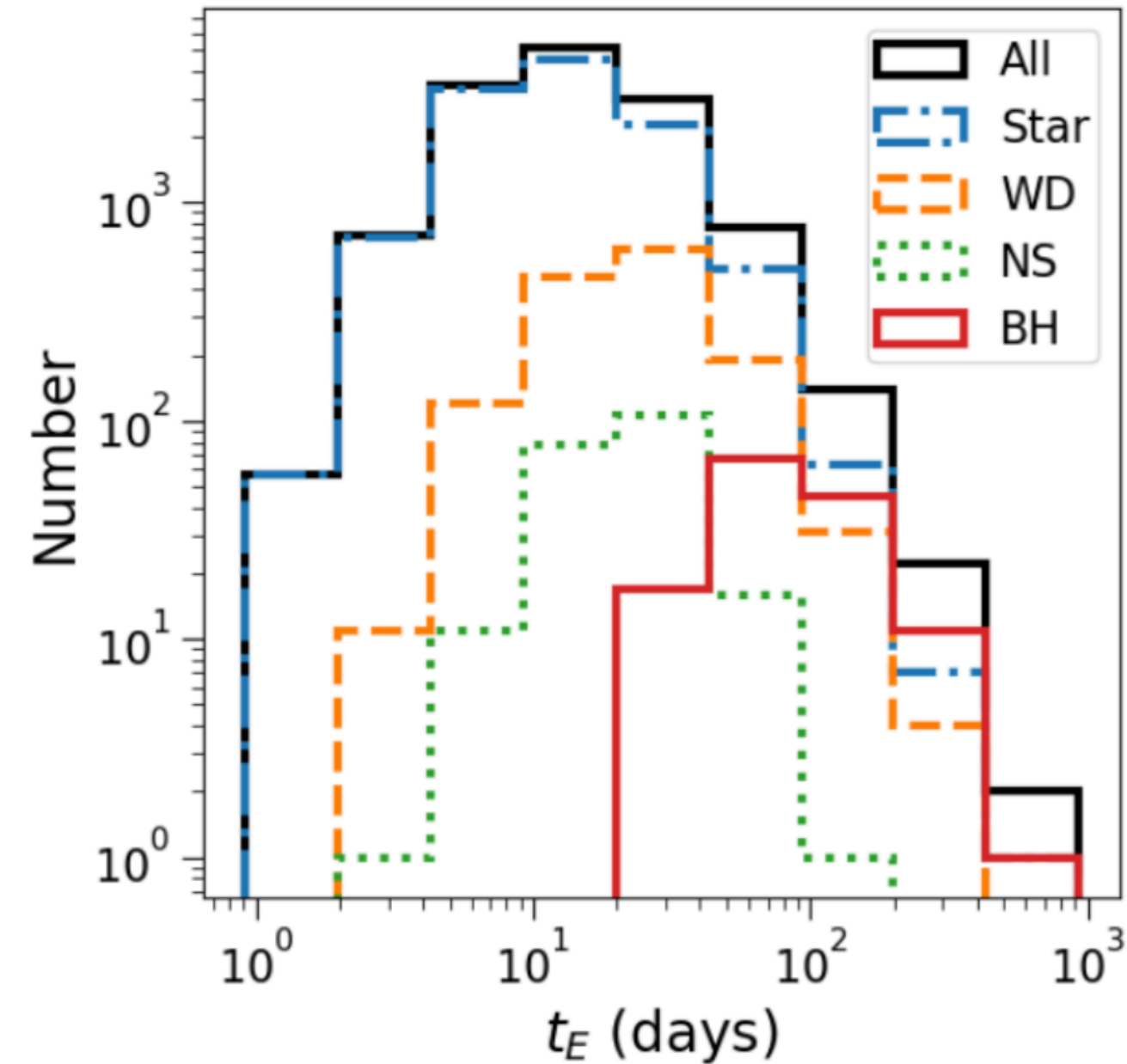
Compact objects with positions and velocities



Mock Survey: Microlensing

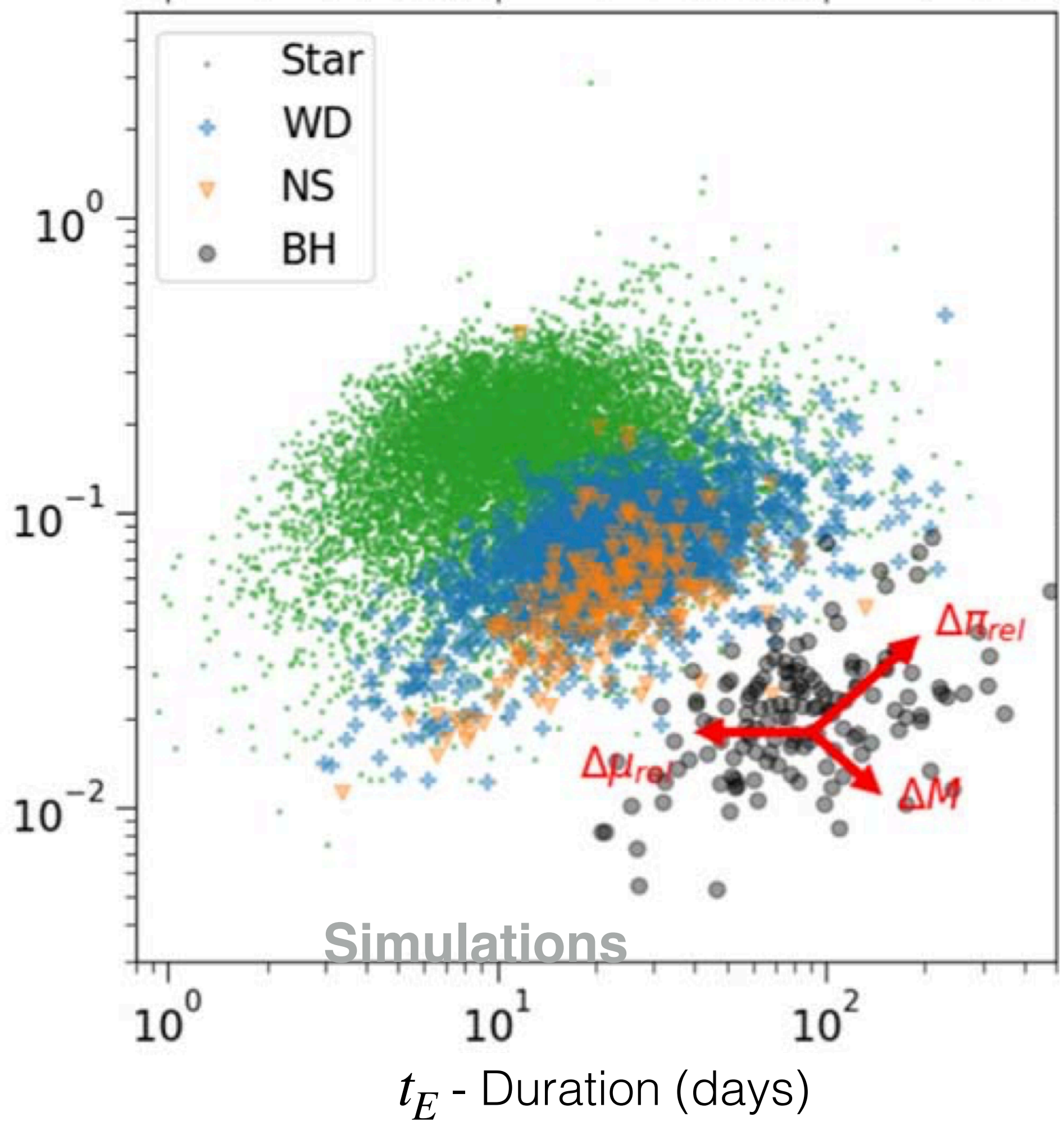


More massive lenses produce longer-duration microlensing events.

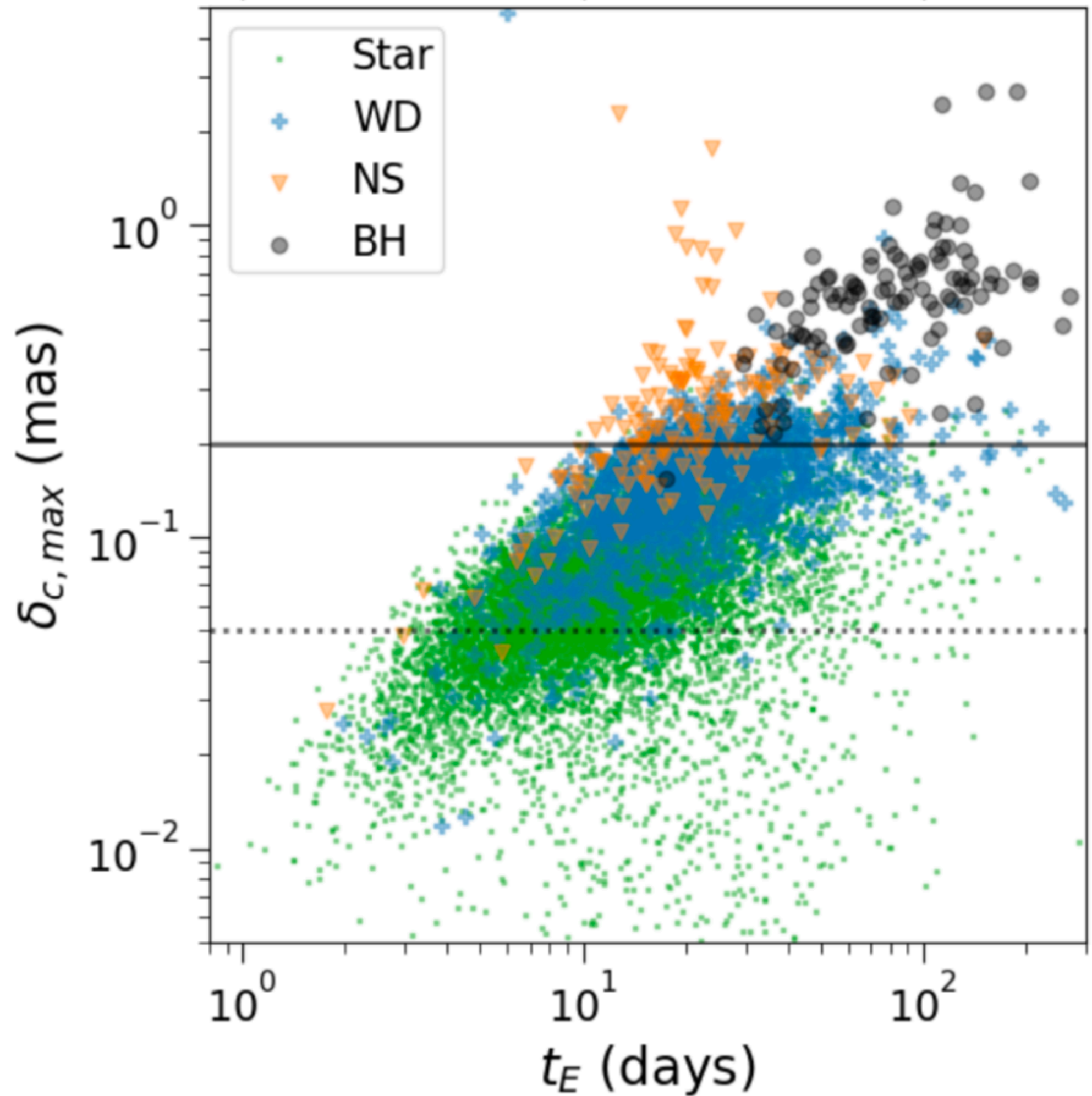


Microlensing parallax vs. duration

π_E - Shape due to Parallax



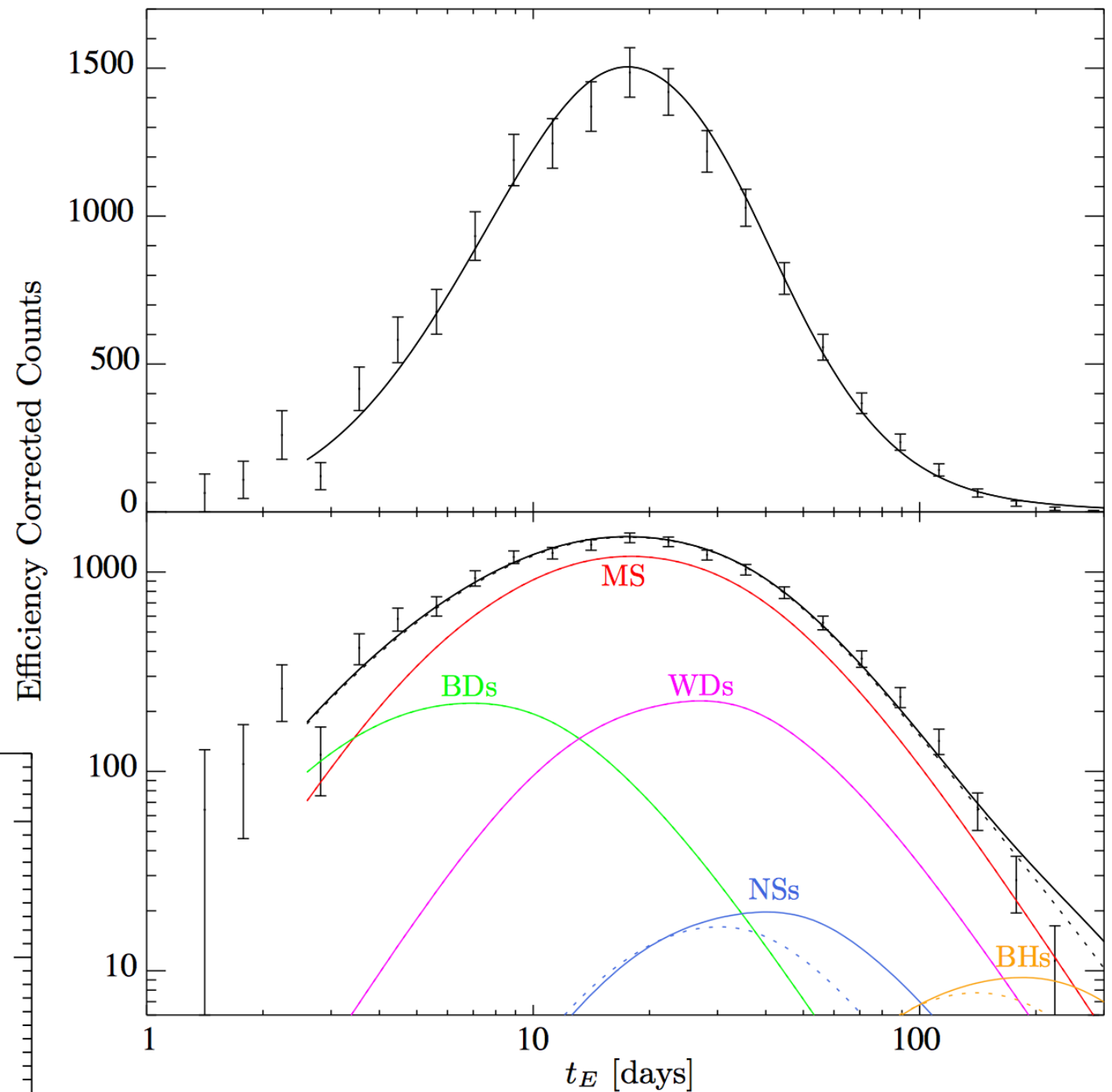
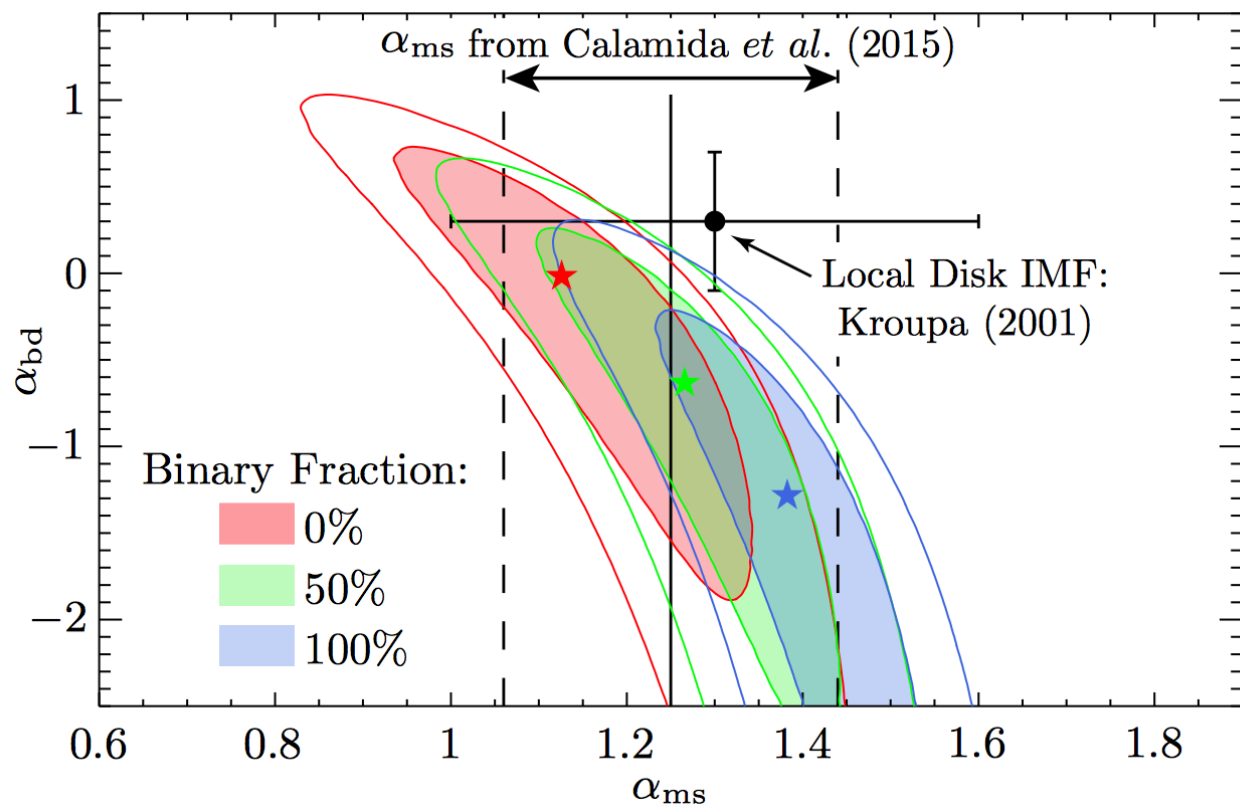
Astrometric microlensing signal vs. duration



Stars

Microlensing can probe the mass function of lens stars;

but difficult with only photometry (historically).



Black Holes

Microlensing can probe
“ordinary” black holes.

Stars with

$$M_{\odot} > 20\text{-}30 M_{\odot}$$

turn into black holes with

$$M_{\bullet} > 3 M_{\odot}$$

First predicted by theory

Michell 1784, Laplace 1799

(see Montgomery+ 2009 for history)

Schwarzschild 1916, Droste 1916

$10^8 - 10^9$ stellar remnant black
holes in the Milky Way

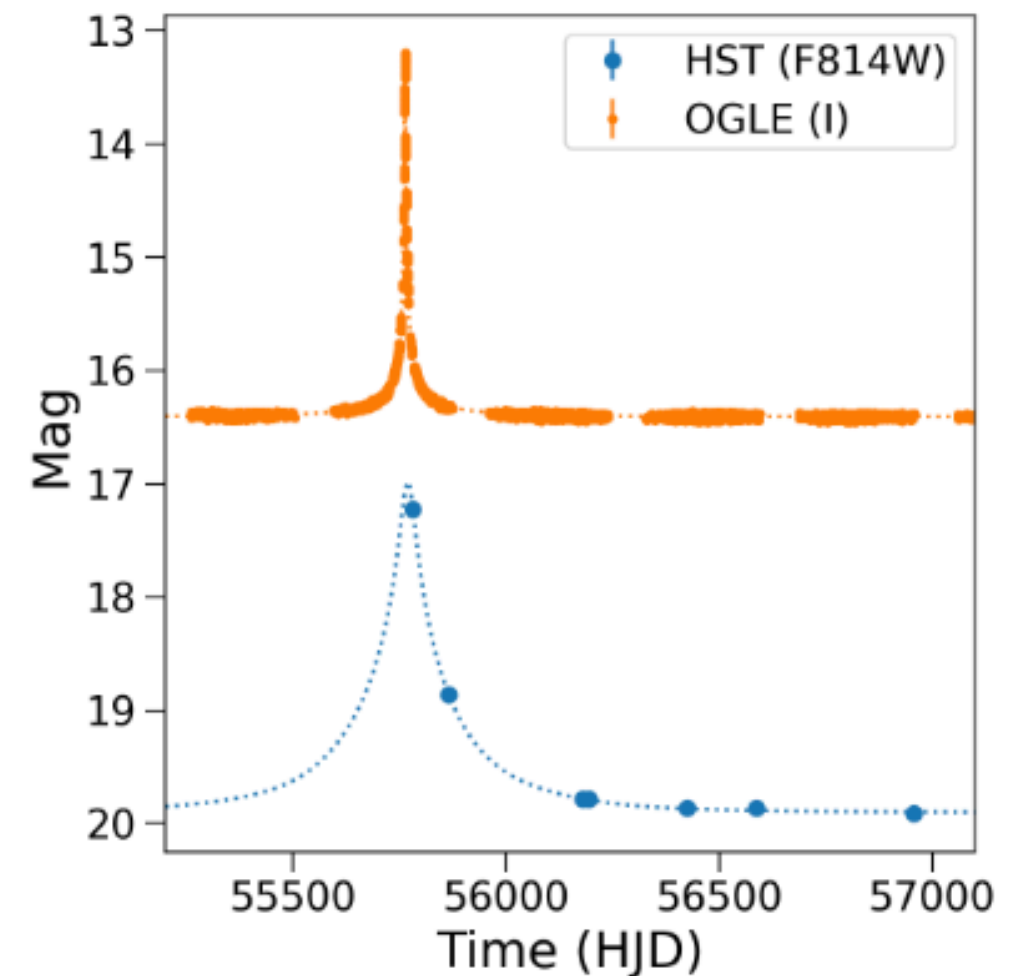
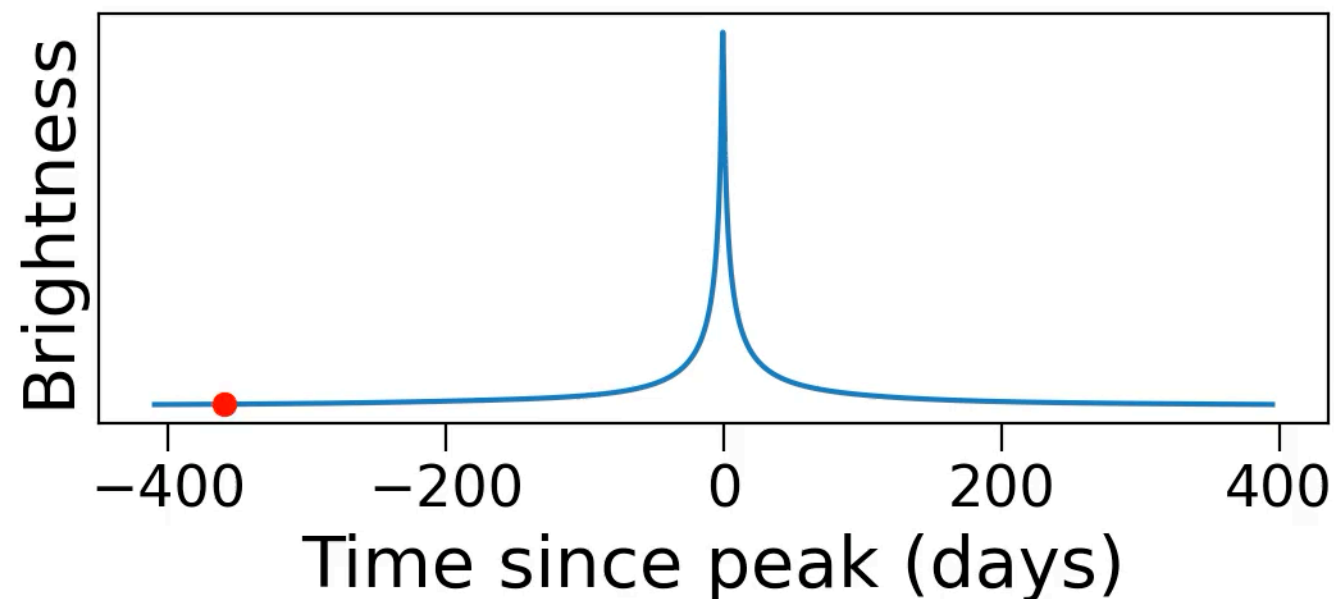
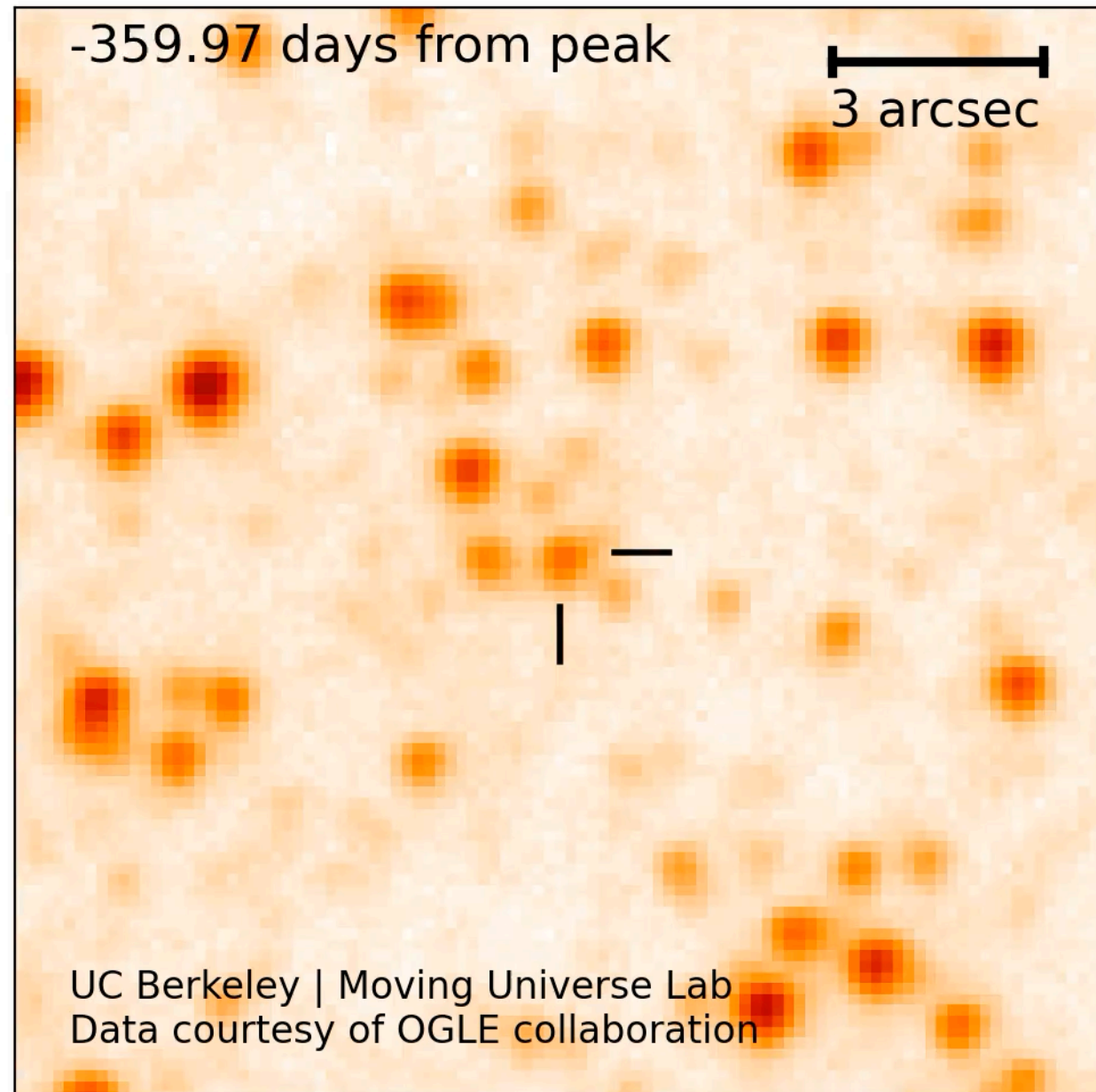
Gould 2000,

Agol and Kamiankowski 2002



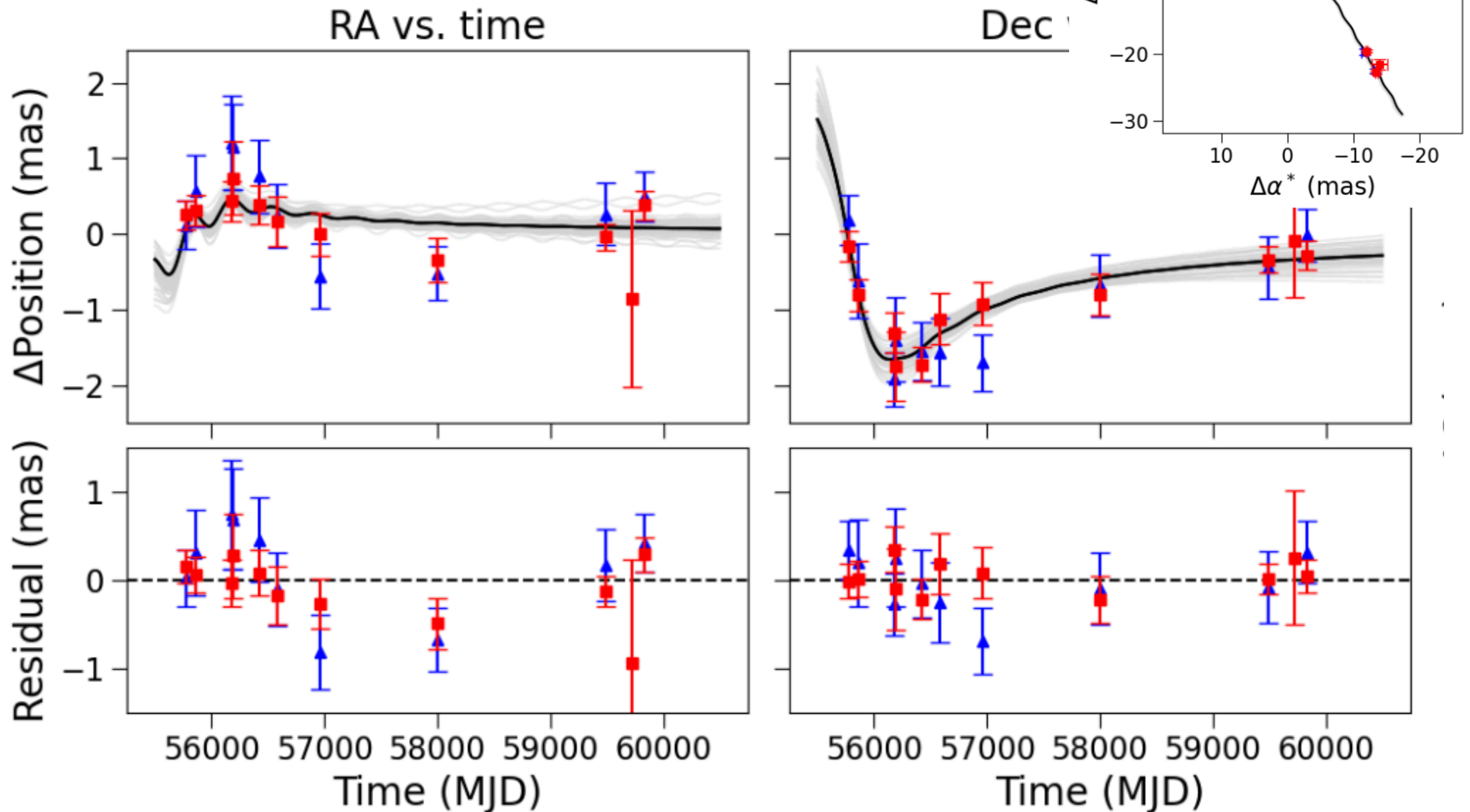
X-ray: NASA/CXC/MIT/Lopez+,
IR: Palomar, Radio: NSF/NRAO/

Keck and HST astrometric microlensing campaigns on-going for ~ 10 candidates (5 done).

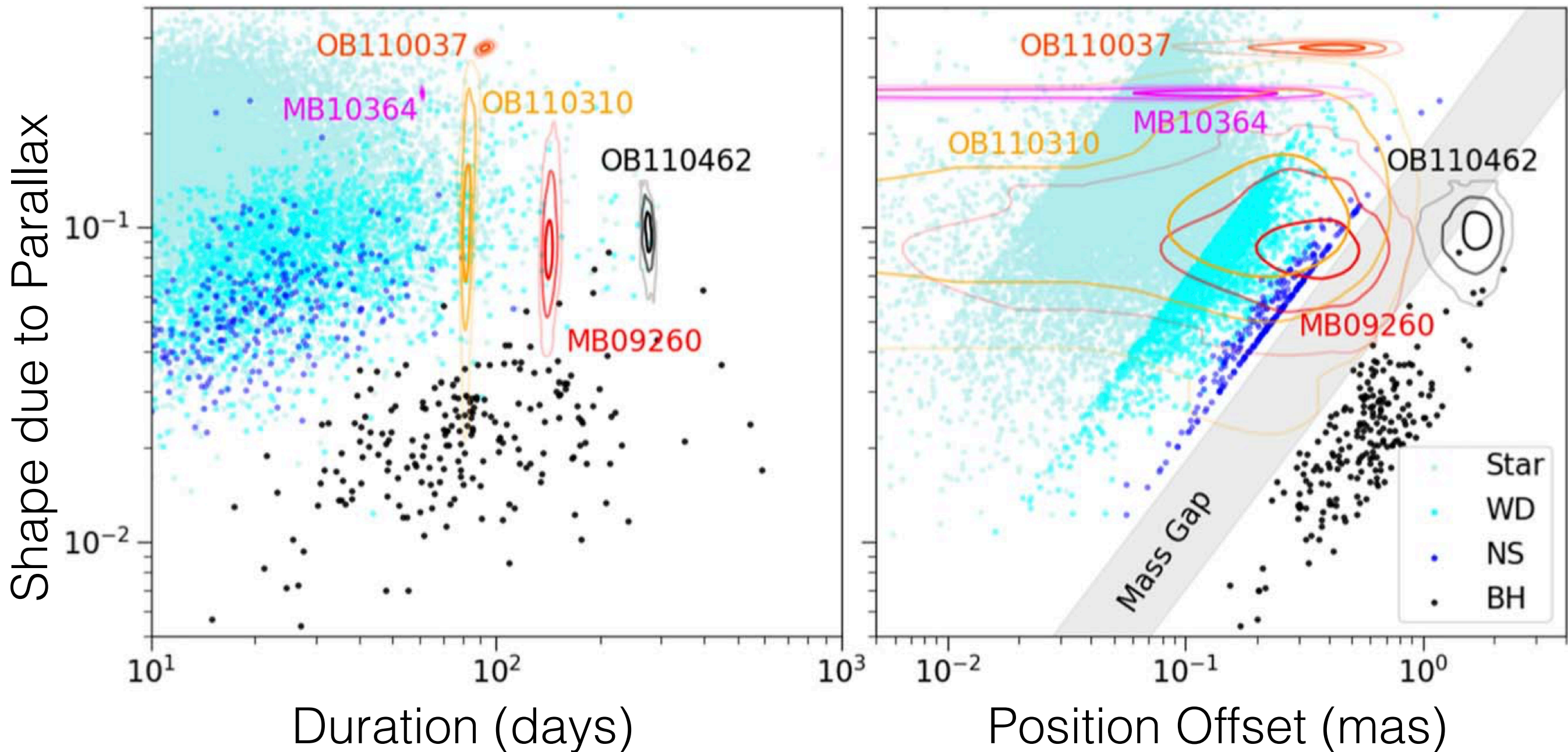


First isolated BH detected using astrometric microlensing:

$$M_{\text{BH}} = 6 \pm 1 M_{\text{sun}}$$



Astrometric microlensing in 2 of 5 events from Hubble and Keck — only 1 blackhole.



What is the total number of BHs in the Milky Way?

**Consistent with 200 million black holes in the Milky Way
(1 within 80 light years of Earth).**

How are binary systems formed and destroyed?

Binary lenses are common; but detectable?

BINARY MICROLENSING SIMULATIONS

9

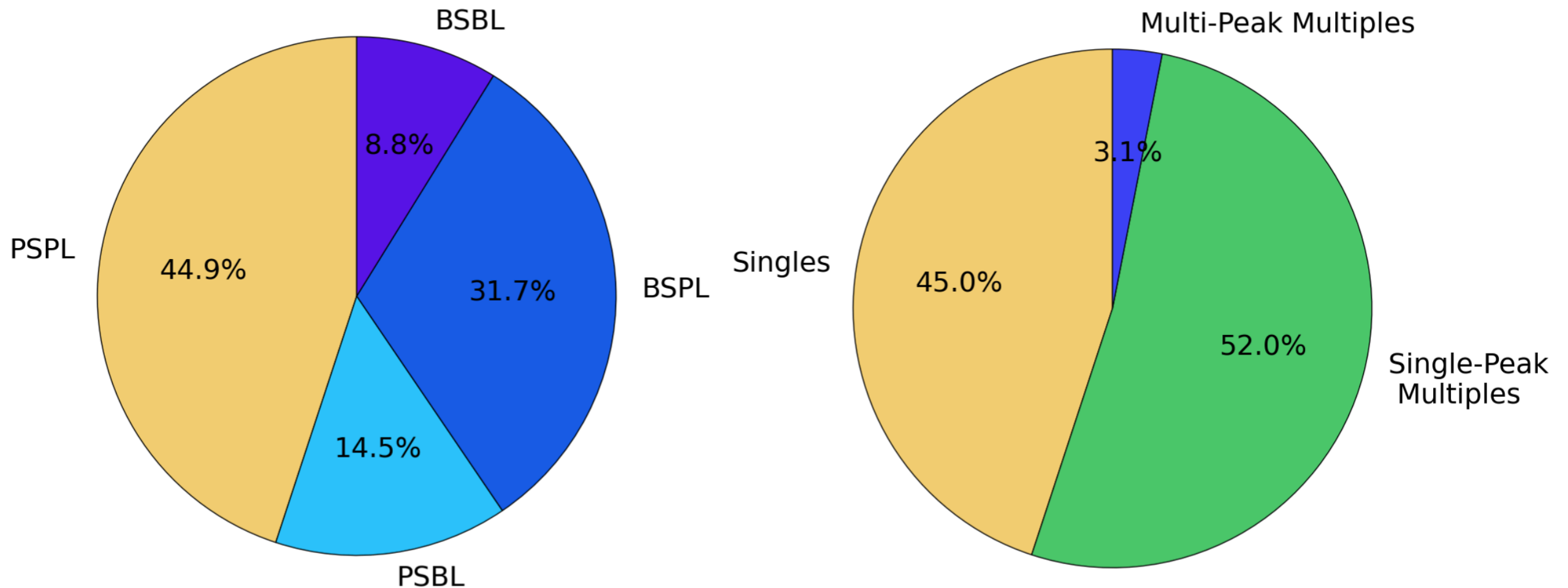
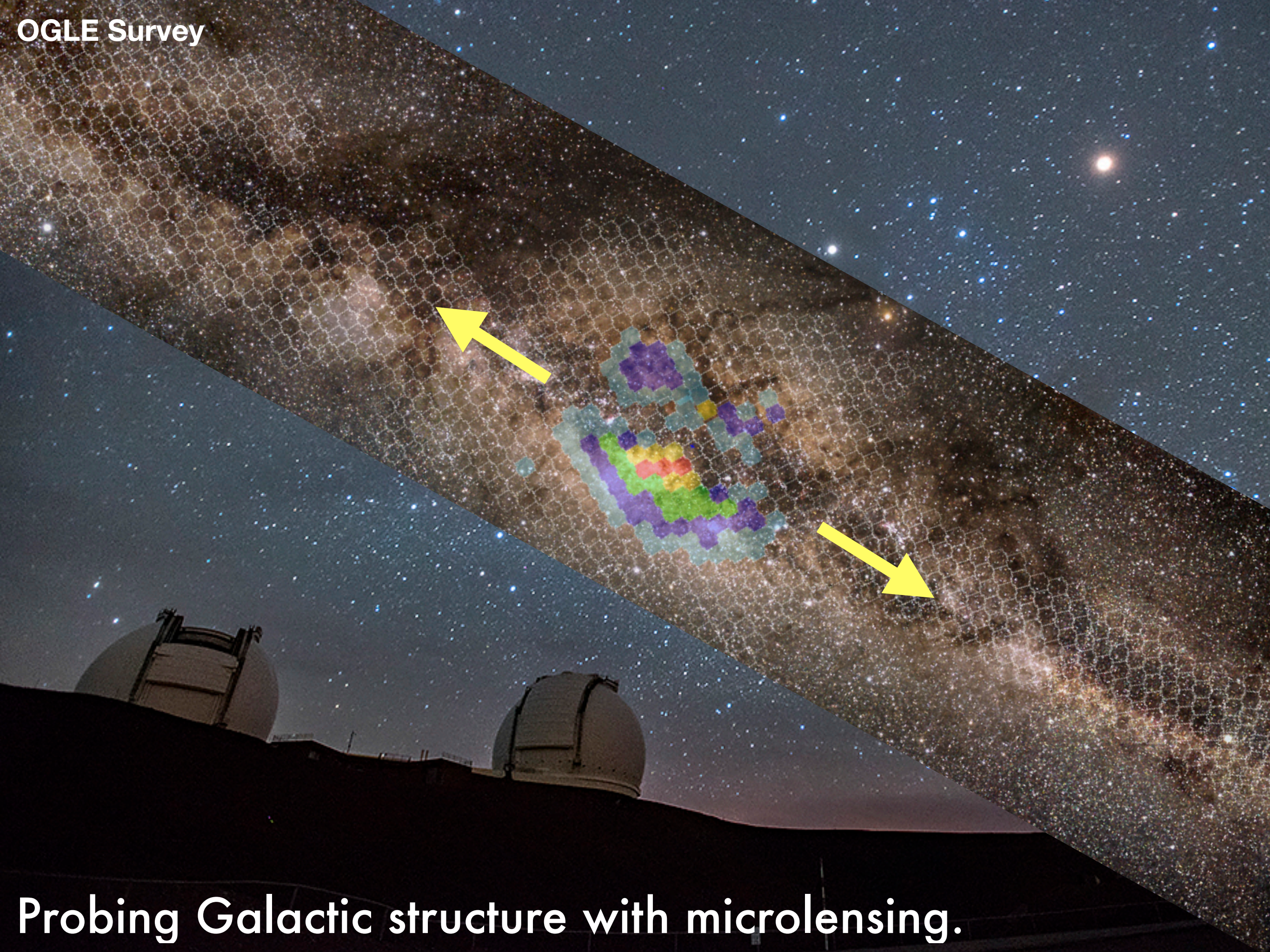


Figure 3. *Left* shows the percentage of the intrinsic population with OGLE EWS observability cuts with a single source and single lens (PSPL), a single source and multiple lens (PSBL; 19% of which have a triple lens), a multiple source and single lens (BSPL; 15% of which have a triple source), and multiple source and multiple lens (BSBL; 31% of which have a triple lens or source) as indicated in Table 4, where PSPL events are in yellow and events with a multiple system are in varying shades of blue. We find that more than half of microlensing events include at least one multiple system. *Right* shows the percentage of single (PSPL) events, single-peaked events with at least one multiple system (19% of which have a triple system), and multi-peaked events with at least one multiple system (20% of which have a triple system). We find that most multiple microlensing events have a single peak and have the possibility of being mistaken as a single-only event.

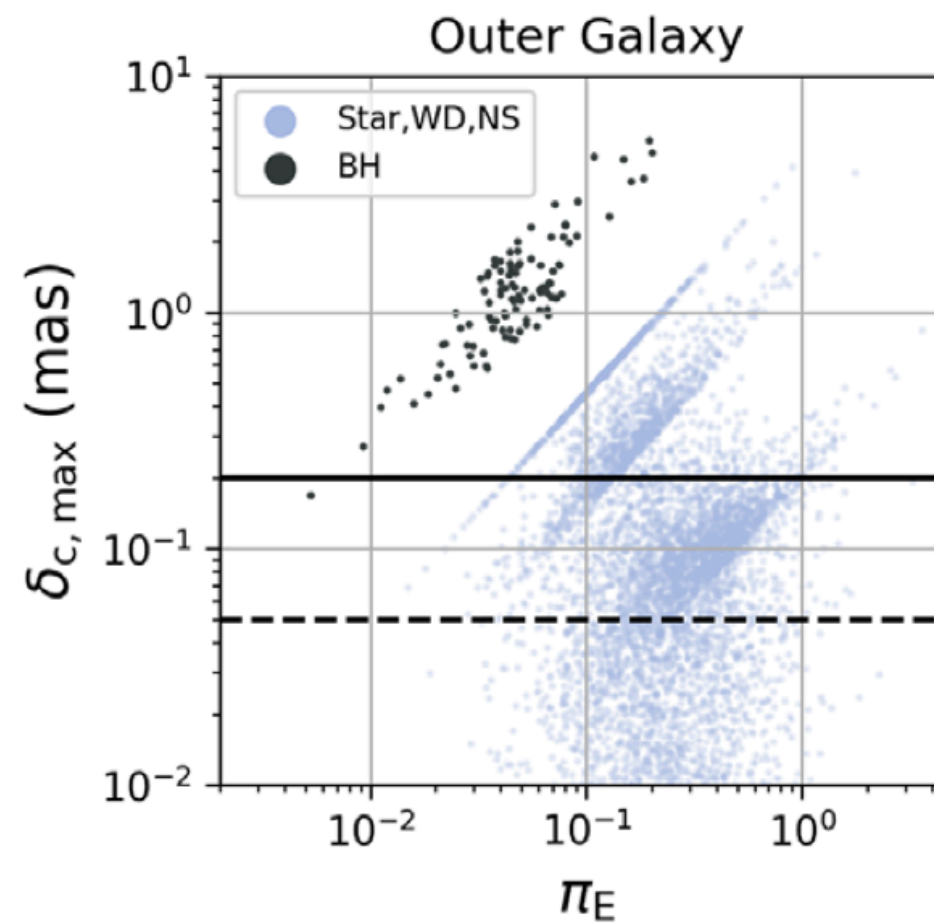
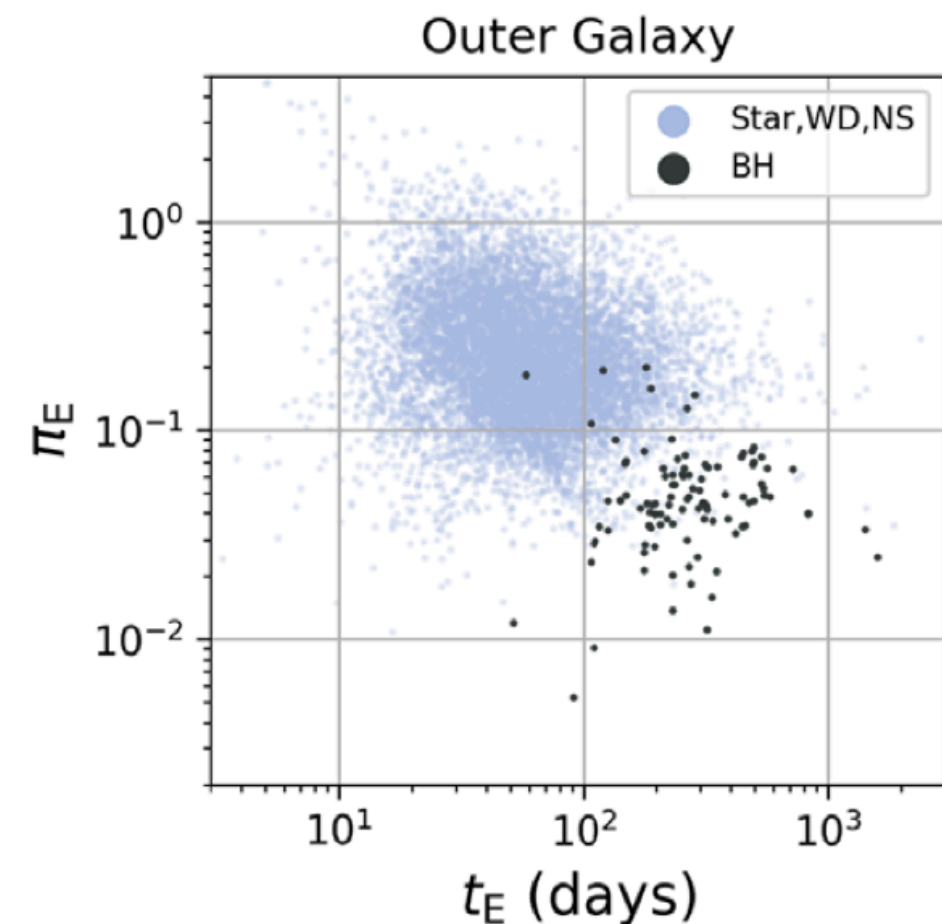
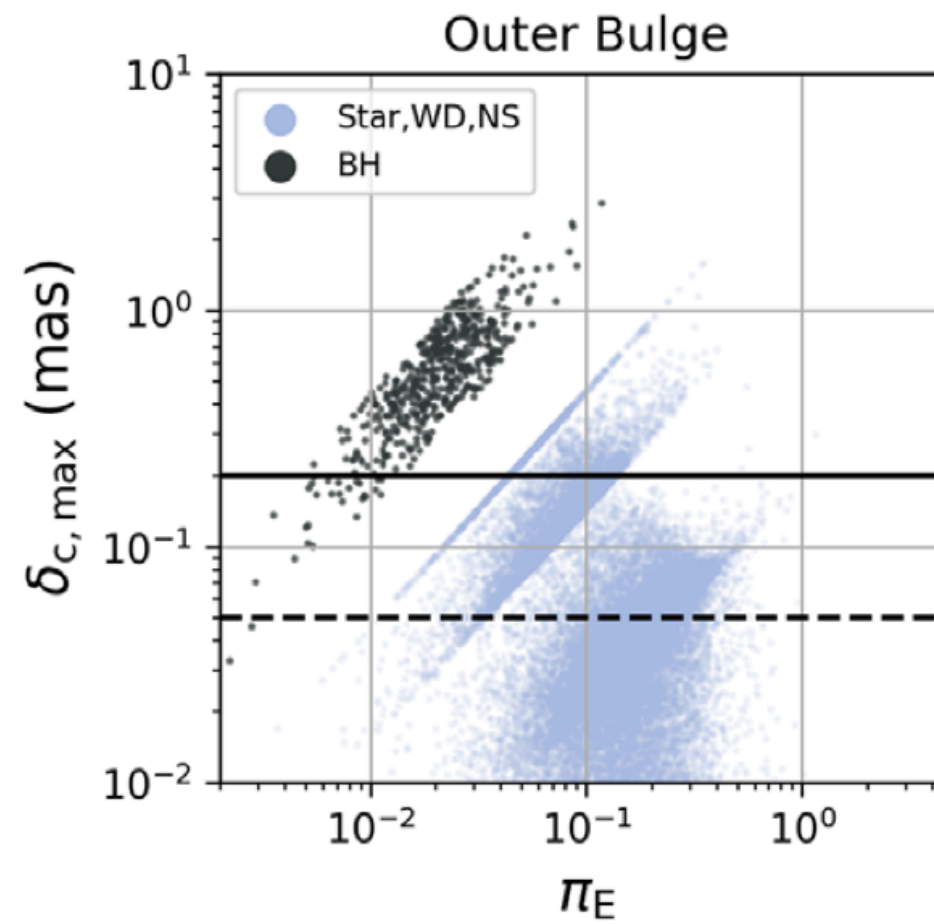
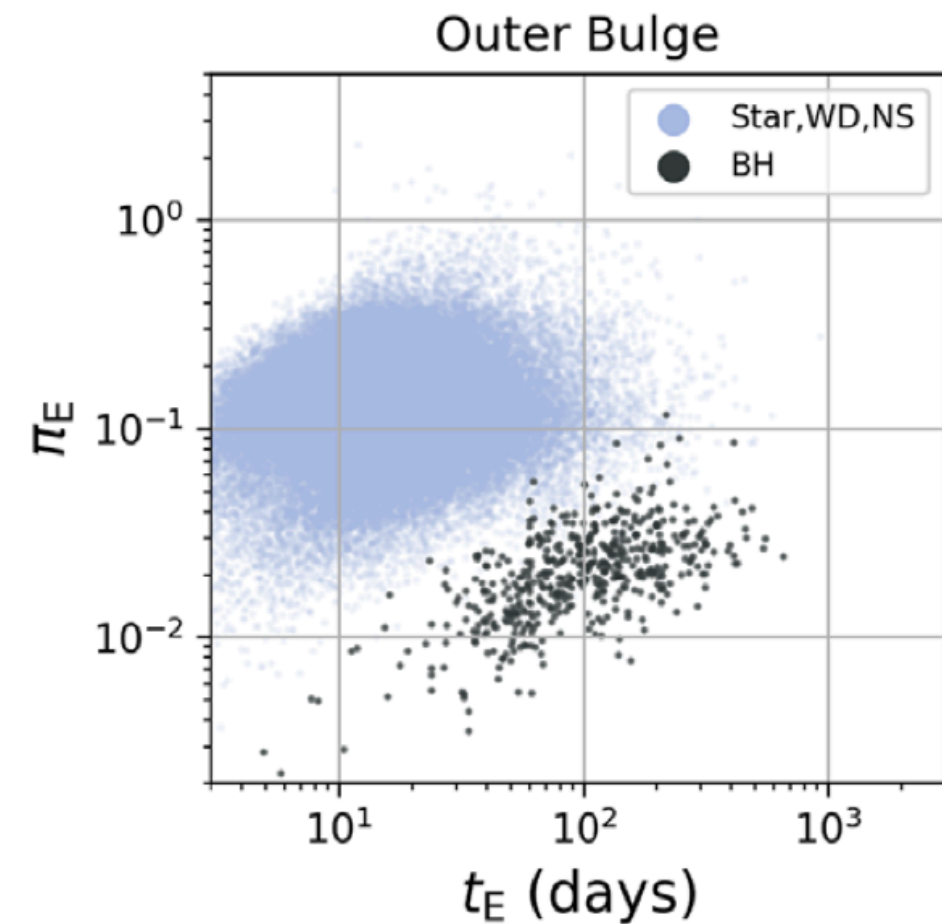


OGLE Survey

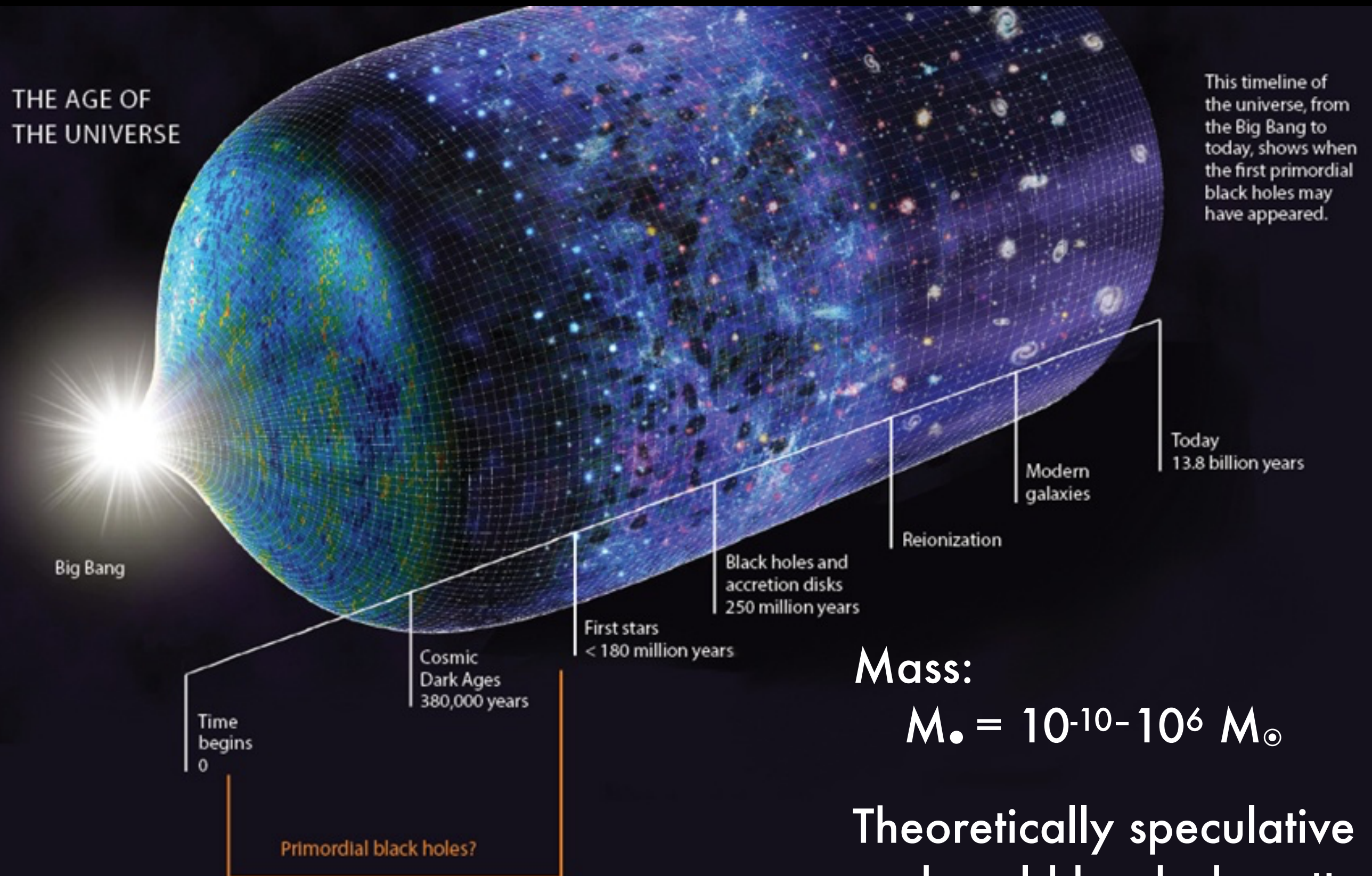
Probing Galactic structure with microlensing.

**Microlensing
properties
change
depending
on where
you look.**

**Surveys such as ZTF,
Rubin, Roman GPS**
will probe the disk and
constrain the lens mass
function in different
environments.



Primordial black holes — born during inflationary expansion of the universe.



Mass:

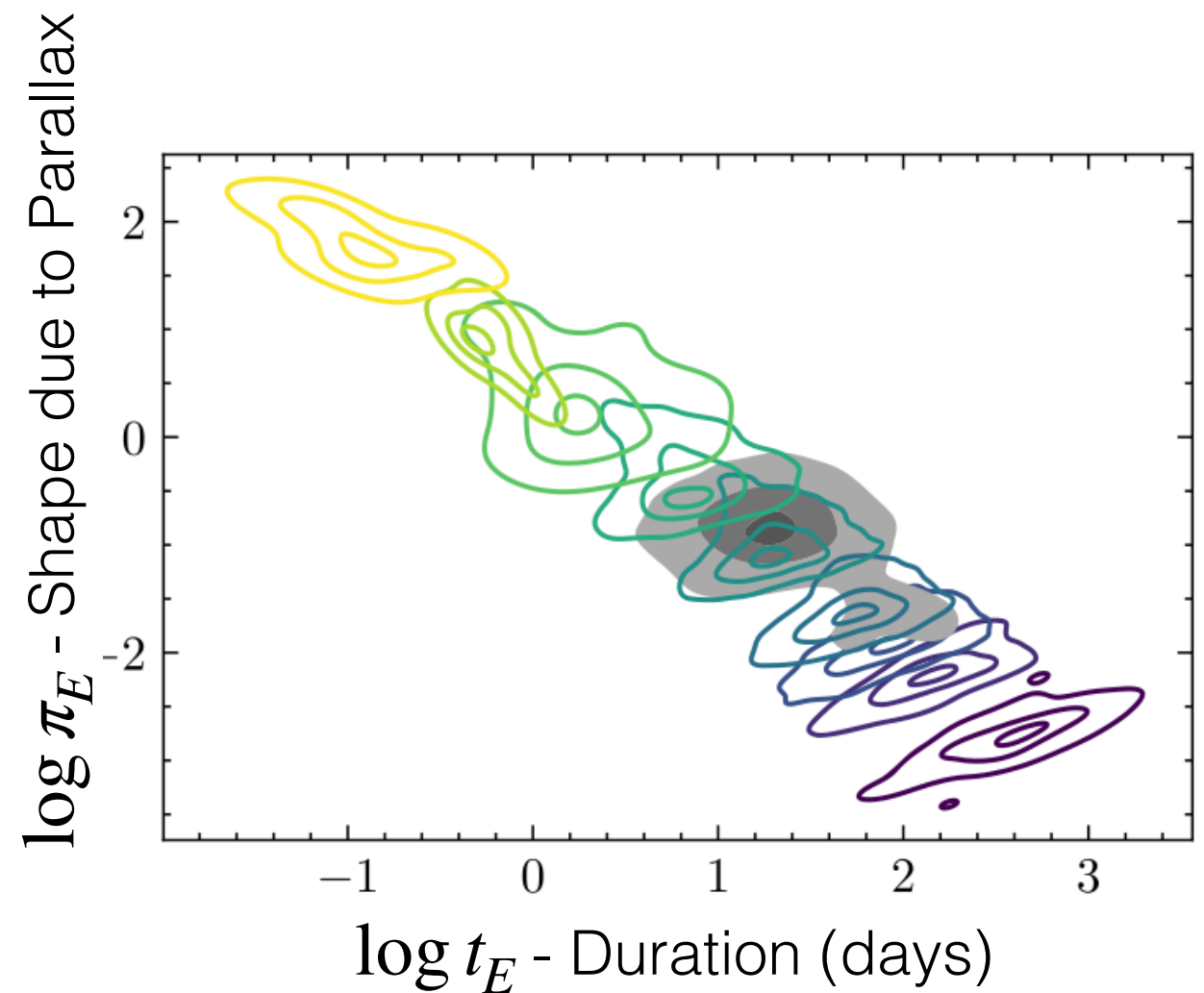
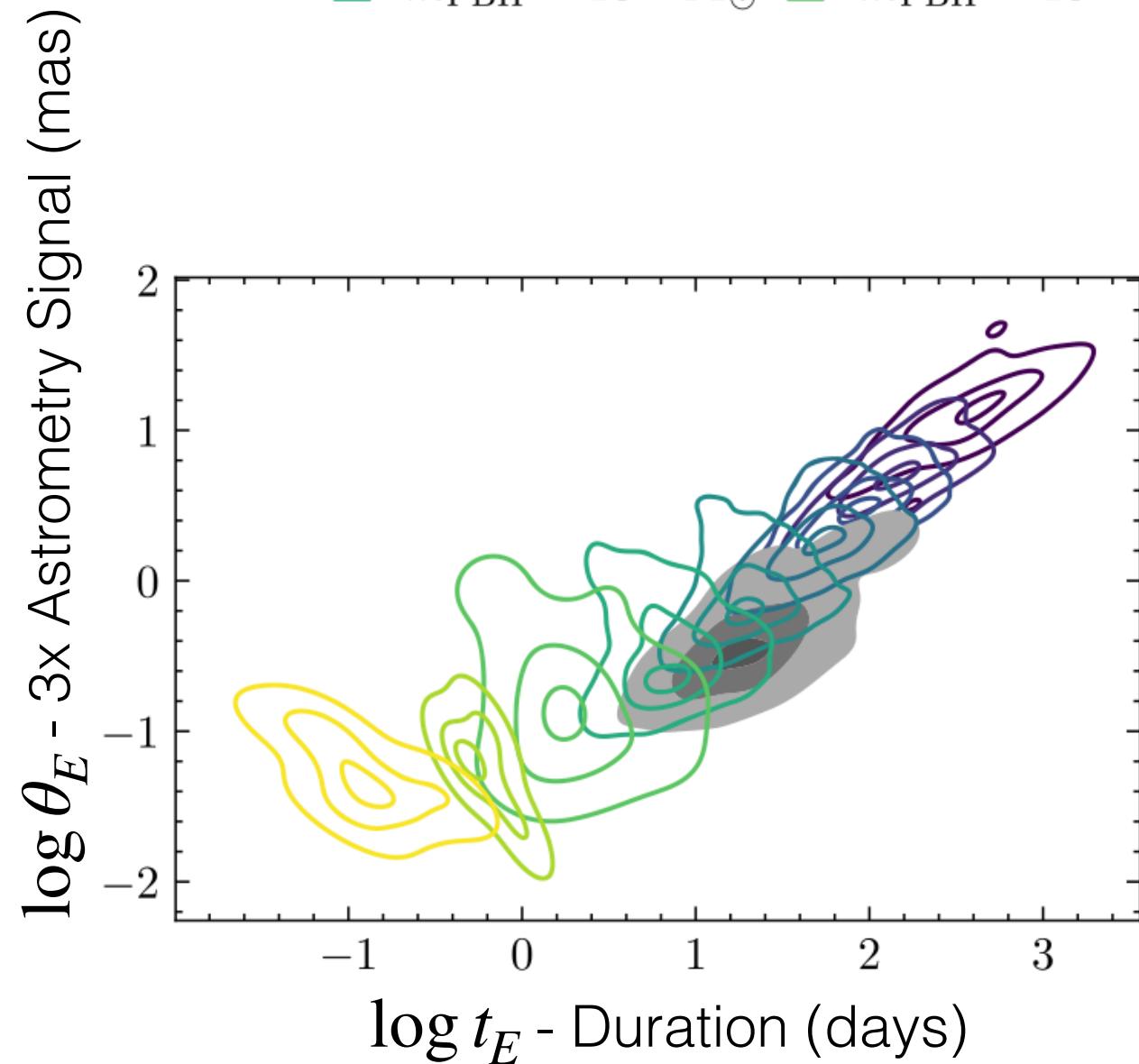
$$M_{\bullet} = 10^{-10} - 10^6 M_{\odot}$$

Theoretically speculative
and could be dark matter.

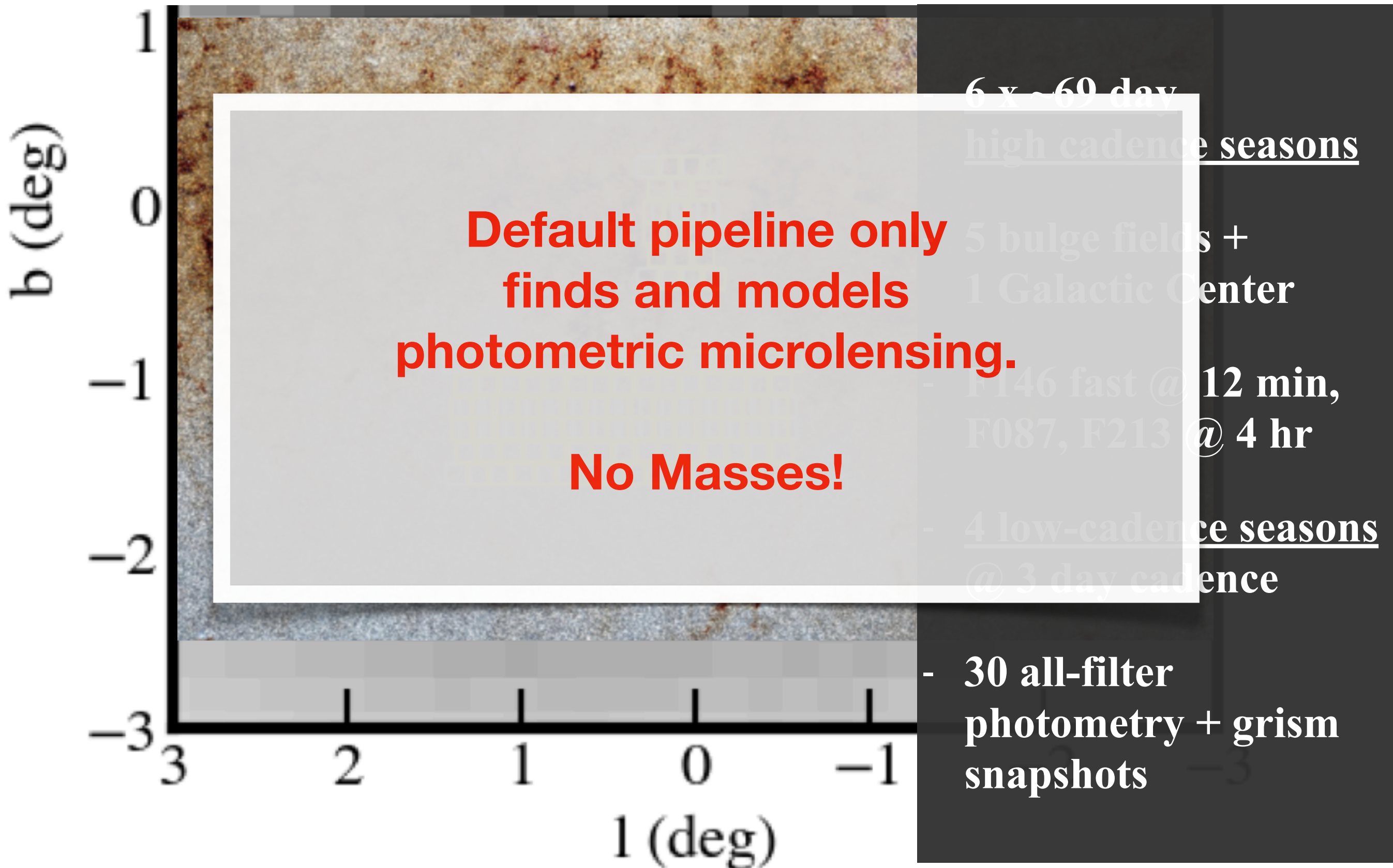
Do primordial black holes exist?

Detectable statistically.

■ Astrophysical ■ $m_{\text{PBH}} = 10^3 M_\odot$ ■ $m_{\text{PBH}} = 10^2 M_\odot$ ■ $m_{\text{PBH}} = 30 M_\odot$ ■ $m_{\text{PBH}} = 10 M_\odot$ ■ $m_{\text{PBH}} = 1 M_\odot$
■ $m_{\text{PBH}} = 10^{-1} M_\odot$ ■ $m_{\text{PBH}} = 10^{-2} M_\odot$ ■ $m_{\text{PBH}} = 10^{-3} M_\odot$ ■ $m_{\text{PBH}} = 10^{-4} M_\odot$

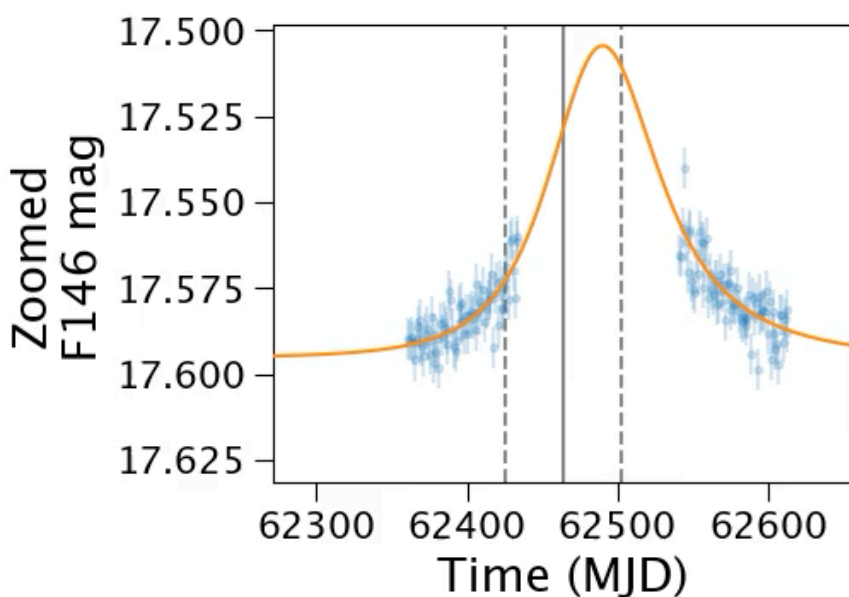
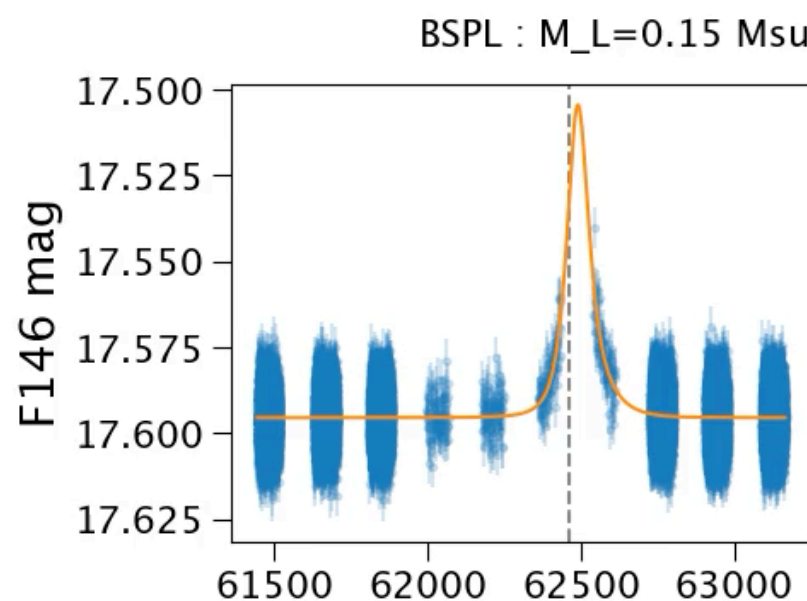


Roman's GBTDS is designed to find exoplanets via microlensing. But it will find black holes too!

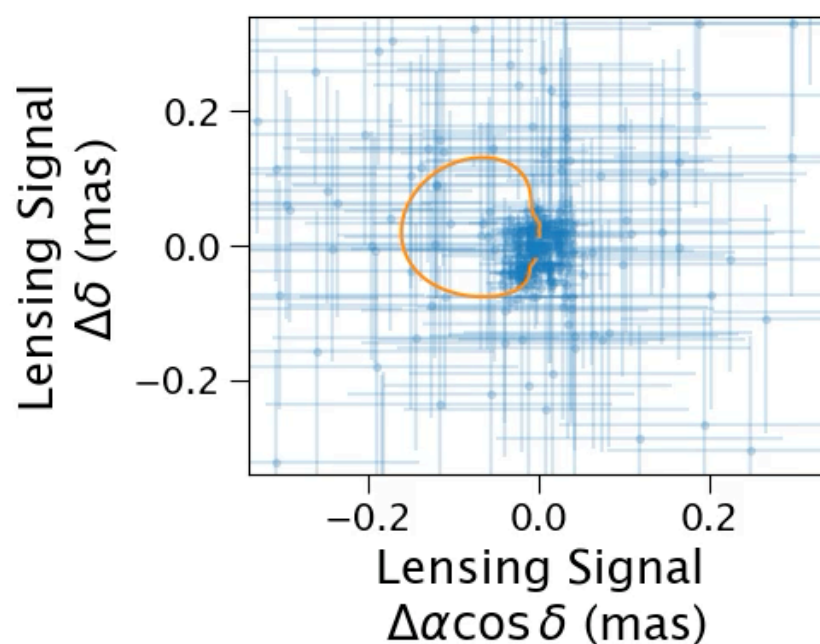
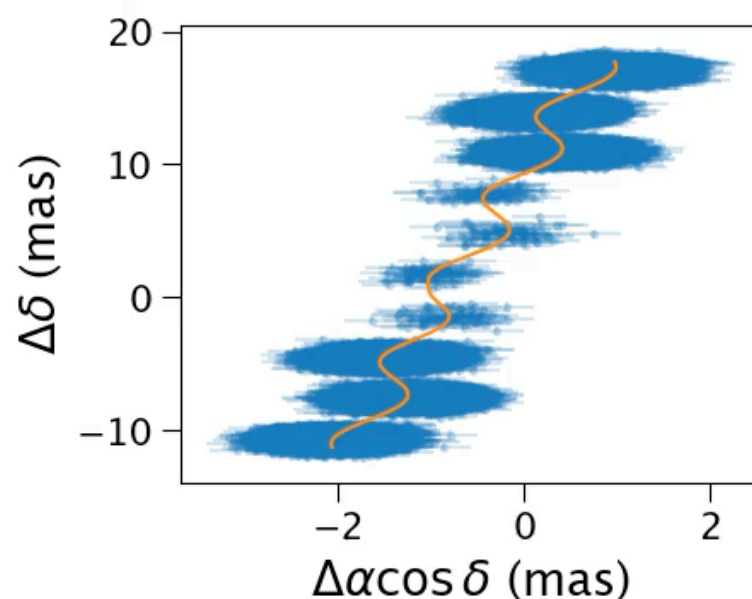


Example RGBTDS lightcurves and trajectories.

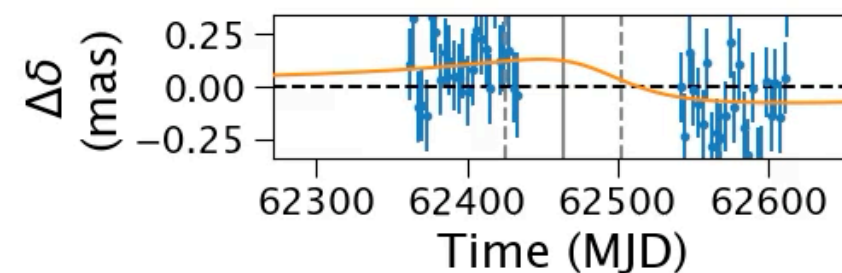
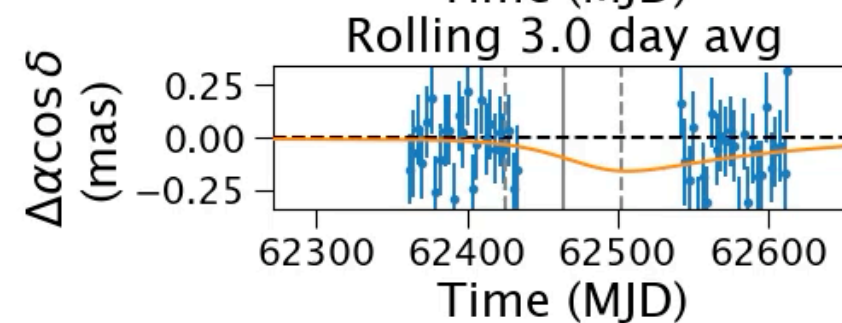
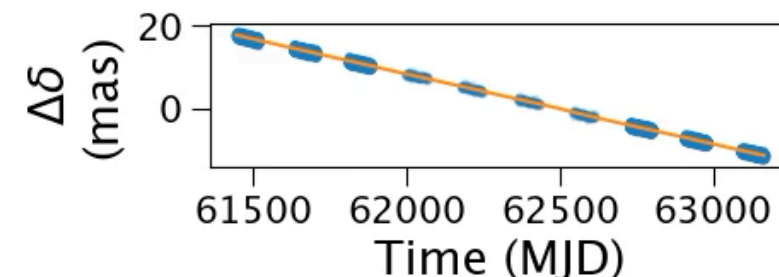
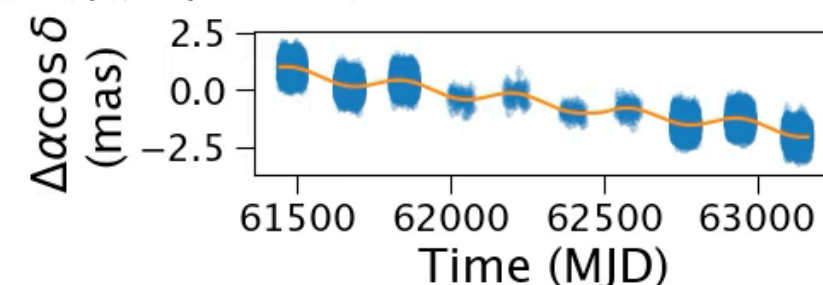
Photometry



On-Sky Astrometry



Astrometry Per Direction



Predicted Survey Statistics

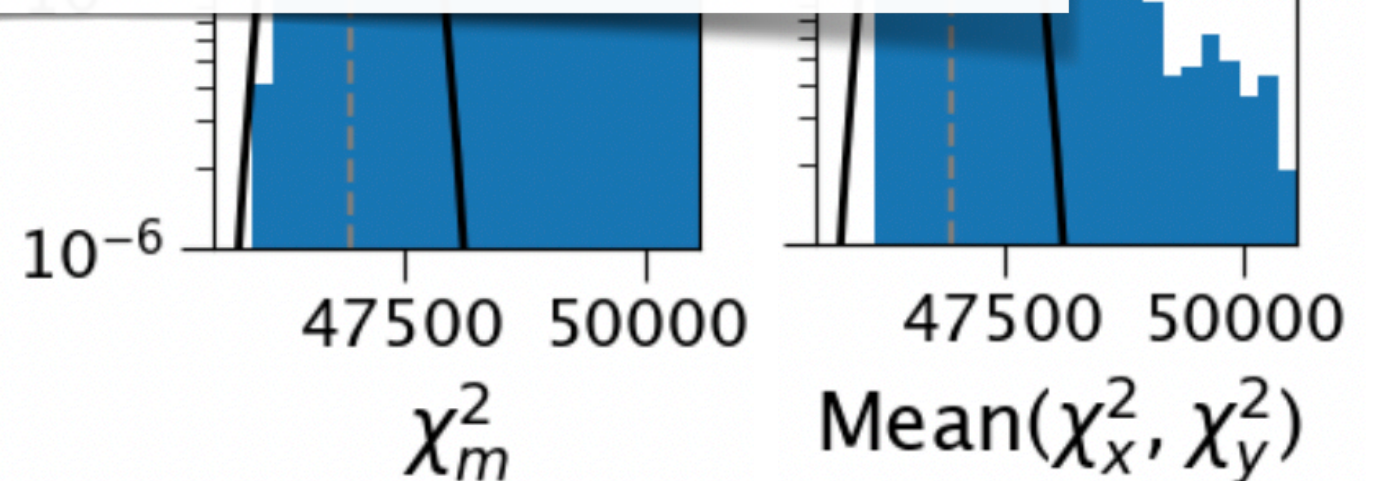
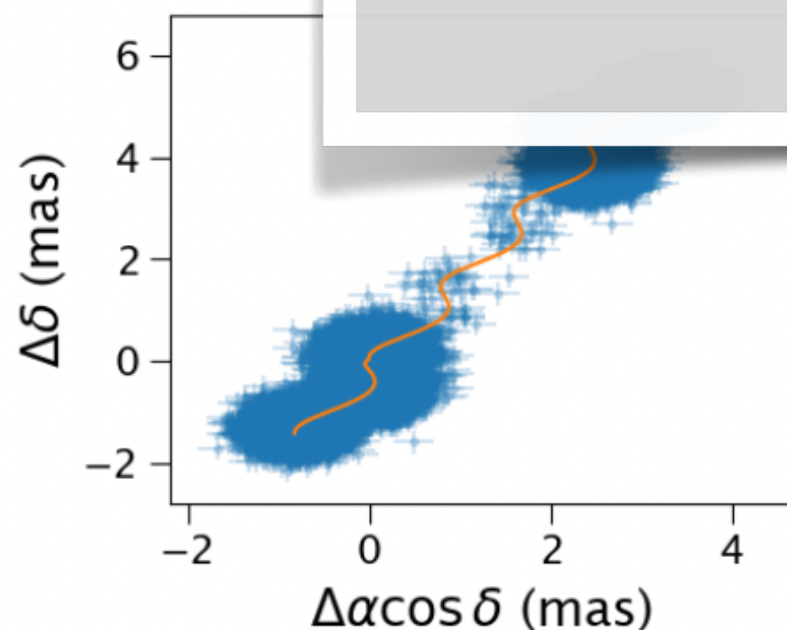
Number	Item
30,600	Events with $F146 < 24$ Vega, $u_0 < 2$, $\Delta m > 0.05$
12,500	Events with $N > 10$ points within $t_0 \pm t_E$

Fit all events with

- constant flux
- 5-parameter astrometric model
 - 2D position
 - 2D proper motion
 - parallax

>600 Photometric Events with Detectable Astrometry ($\chi^2 > 1000$)

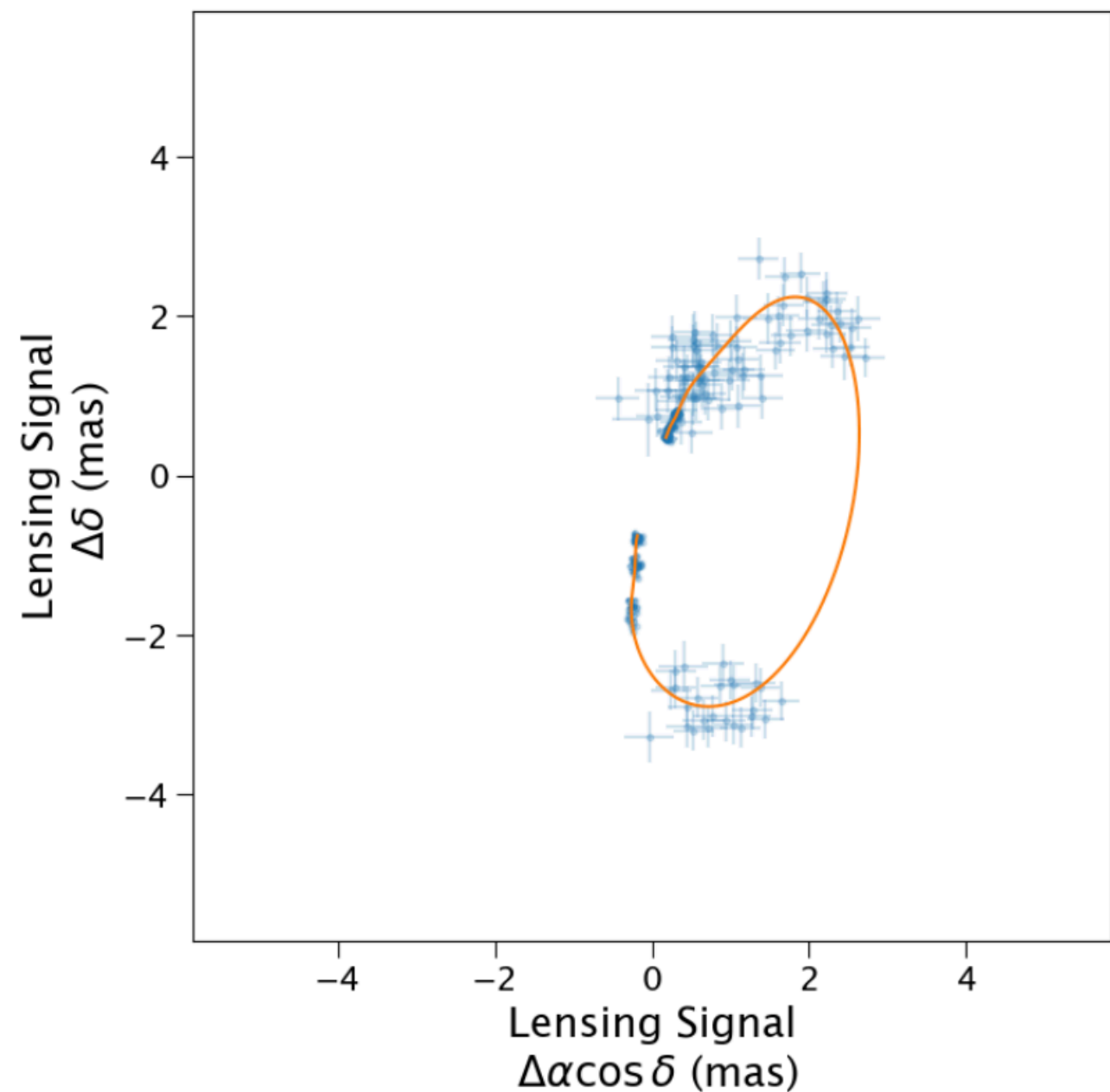
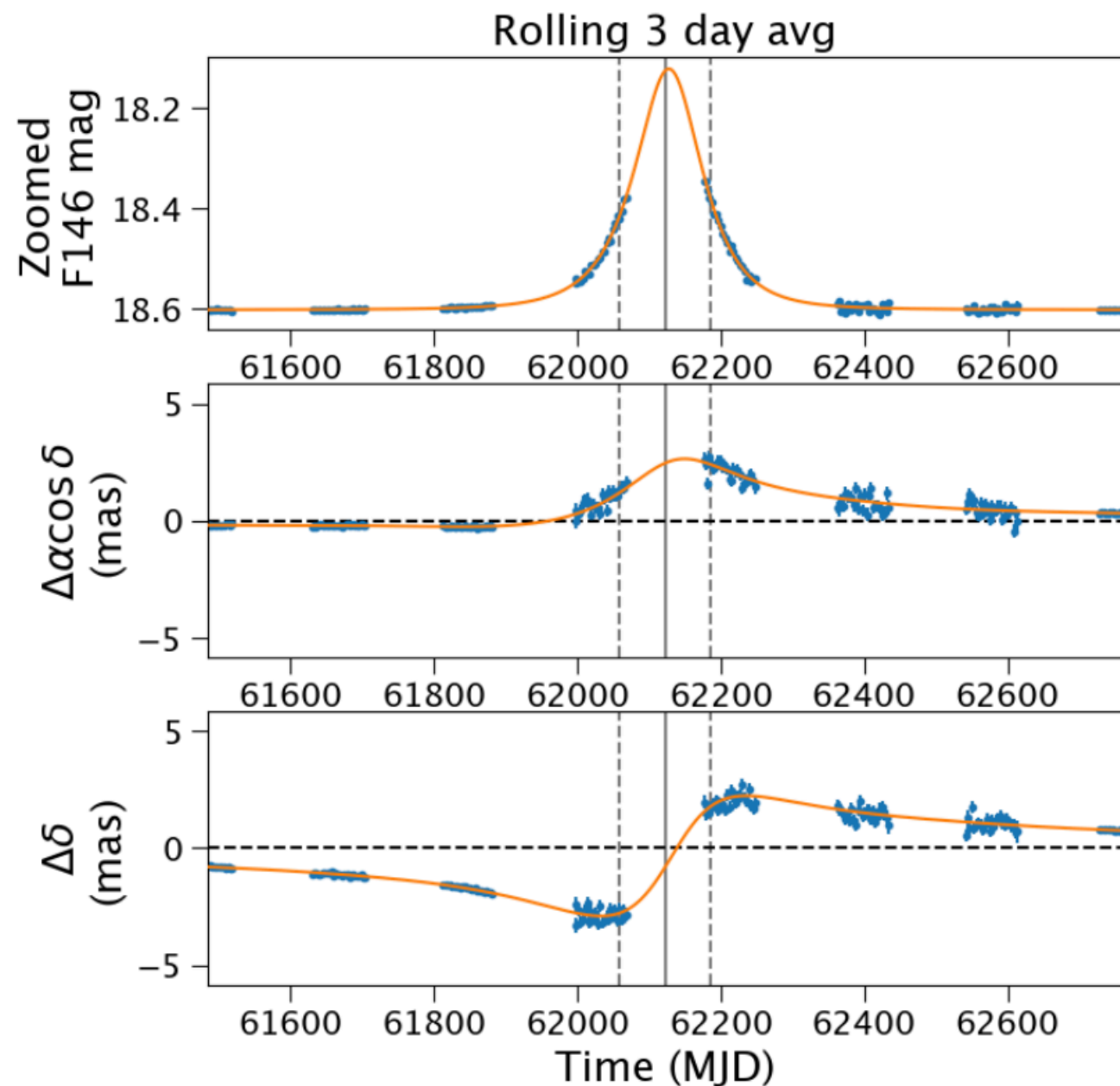
>1300 for $\chi^2 > 500$



Roman's GBTDS is great for finding isolated black holes via microlensing.

PSPL : $M_L=12.30$ Msun, $\pi_{\text{Rel}}=0.74$ mas, $\theta_E=8.6$ mas,

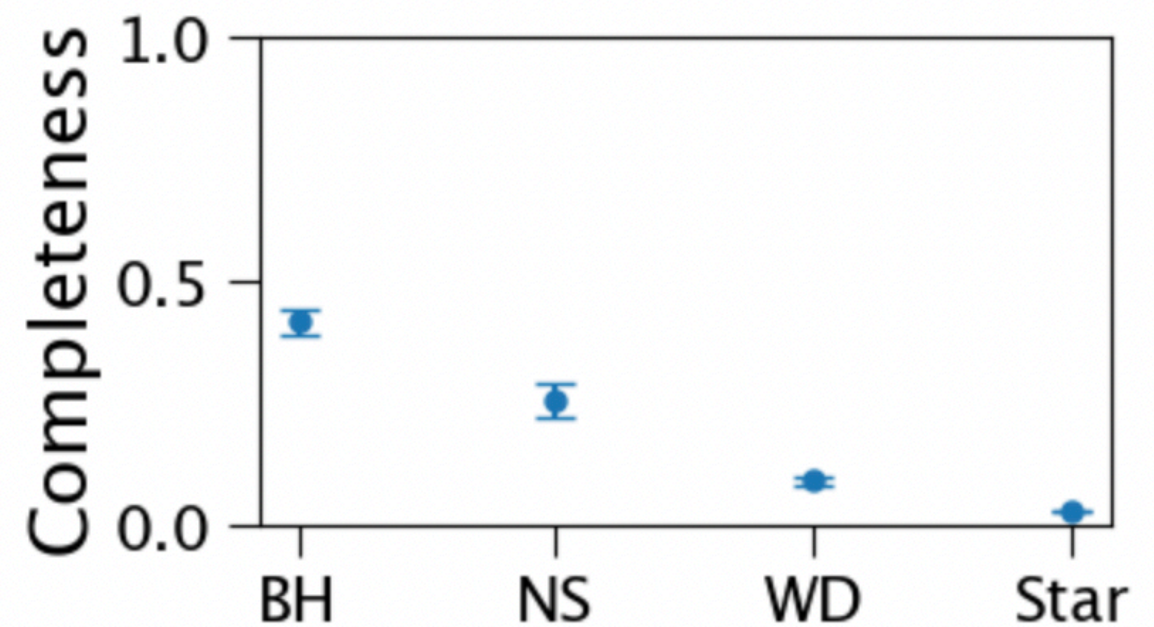
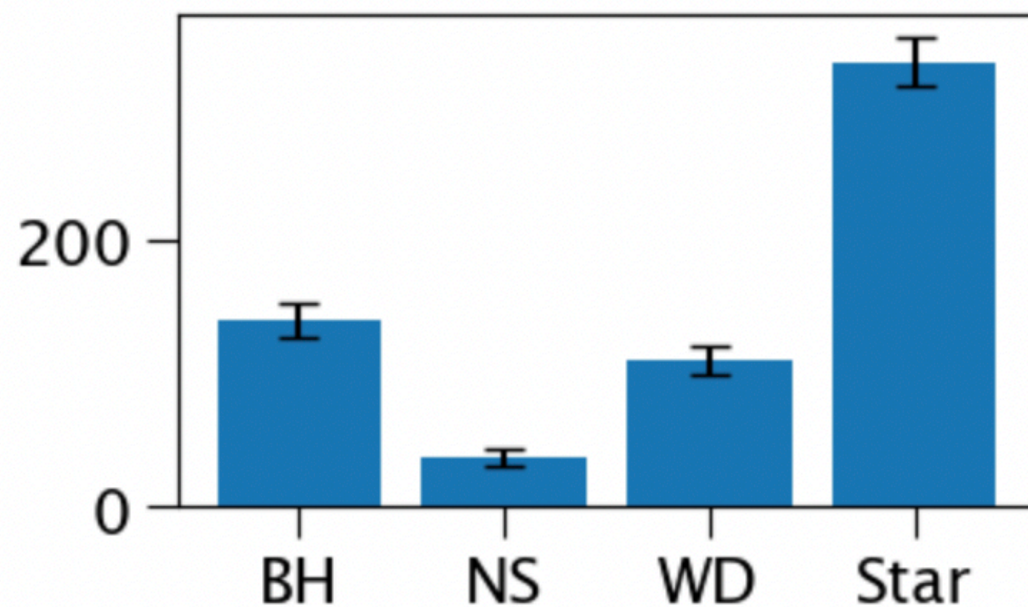
$\mu_{\text{Rel}}=49.4$ mas/yr, $\chi^2_p=39086$, $\chi^2_a=204484$



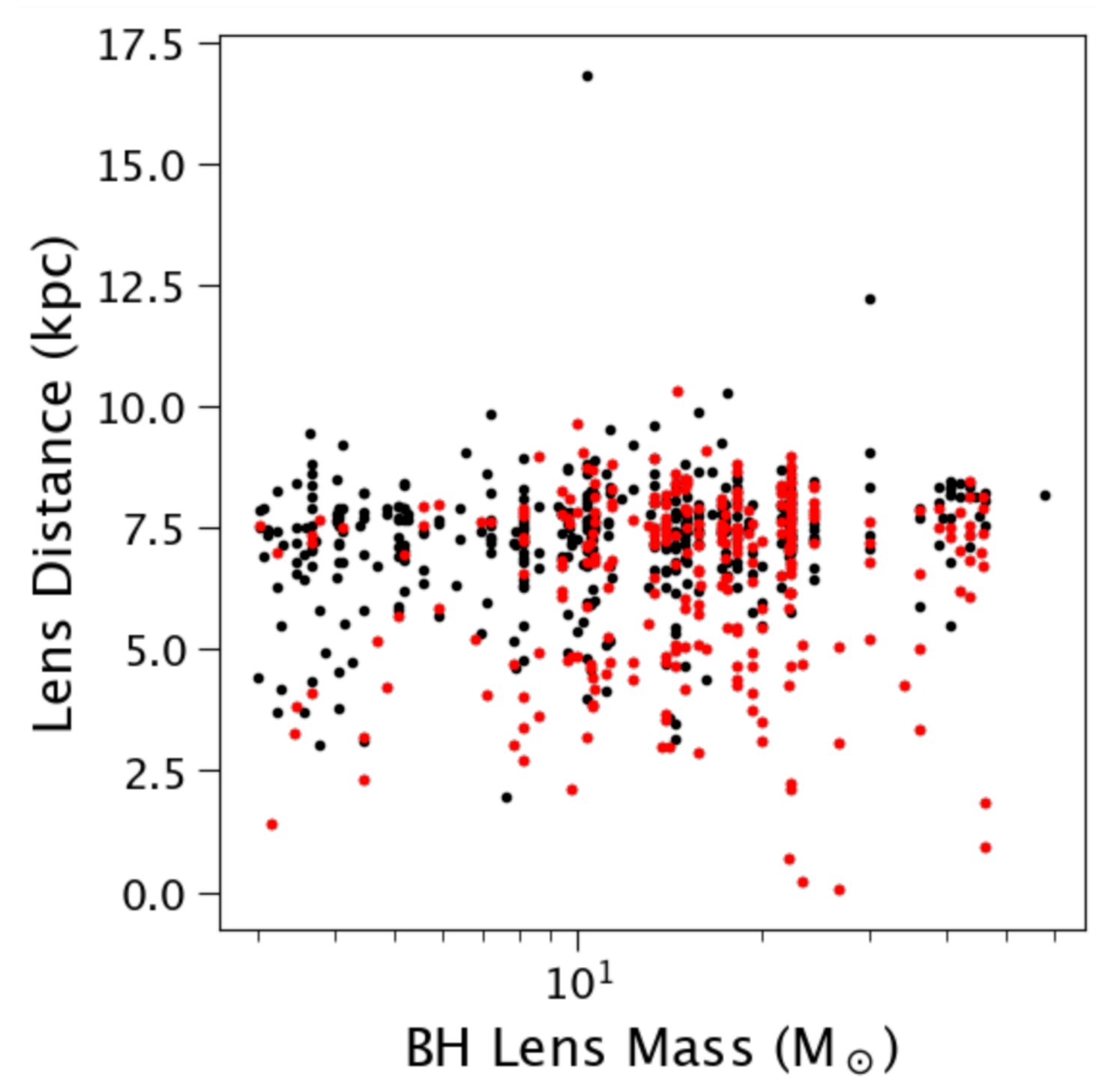
Roman will measure masses for over 100 black holes.

Lens Type	Detected	Undetected
Black Holes	139	195
Neutron Stars	37	109
White Dwarfs	109	1069
Stars	332	10,578

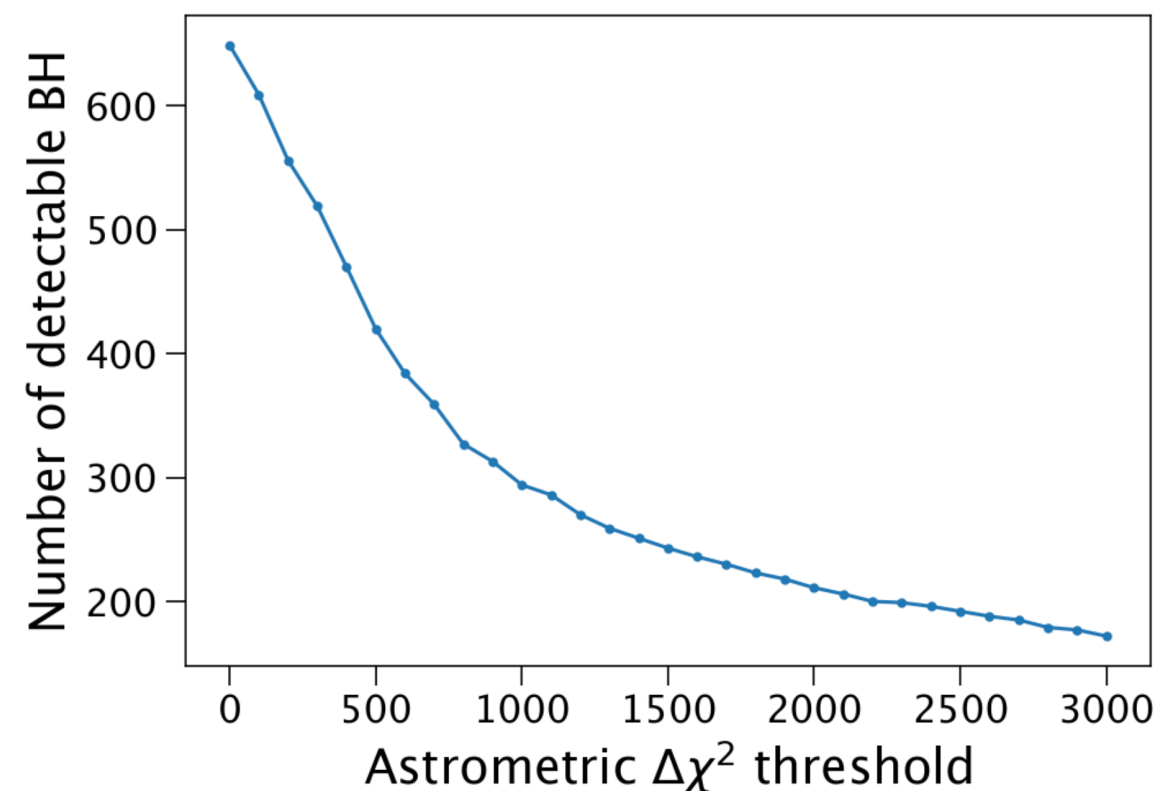
Events
Detected with
Astrometry



Photometric + astrometric microlensing is most sensitive to massive and close BHs.



Lower-mass black holes are detectable at lower significance.

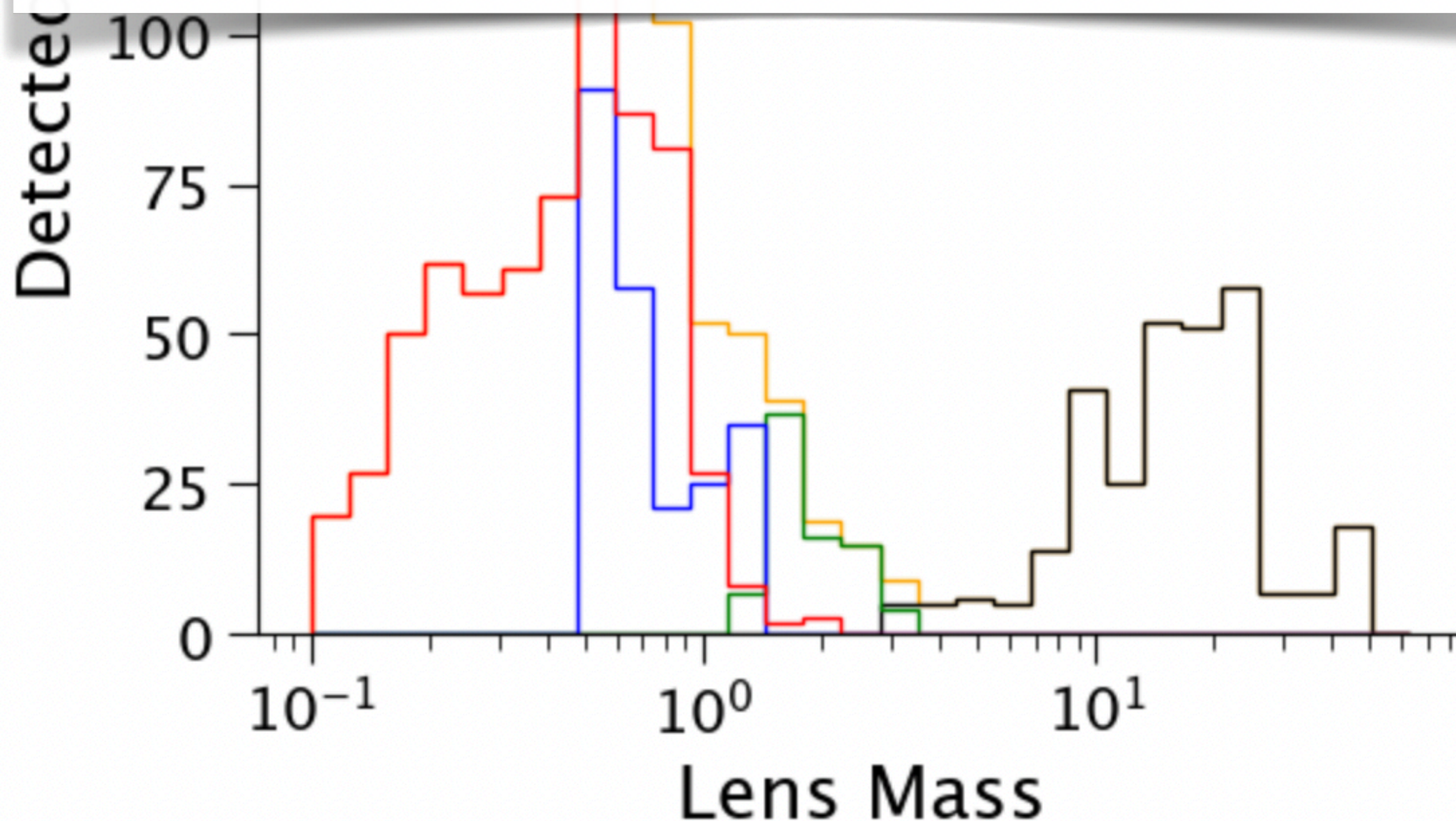


Roman's GBTDS is sensitive to binary systems in microlensing as well.

Lens Type	Single	Binary Lens	Binary Source	Binary Lens + Binary Source
Black Holes	88	14	33	4
Neutron Stars	22	0	16	0
White Dwarfs	29	46	9	25
Stars	172	50	72	39

Resulting mass function of detectable events.

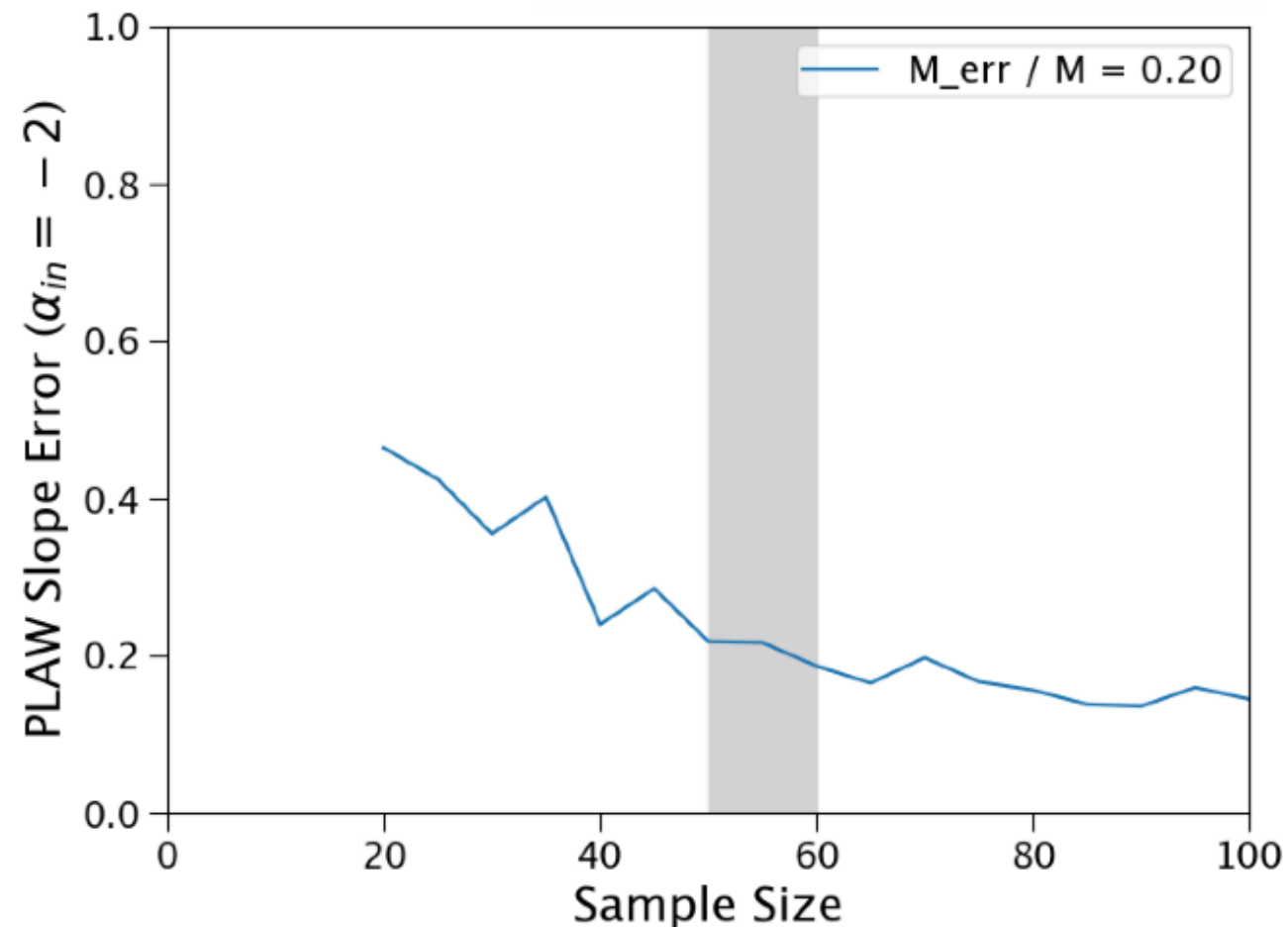
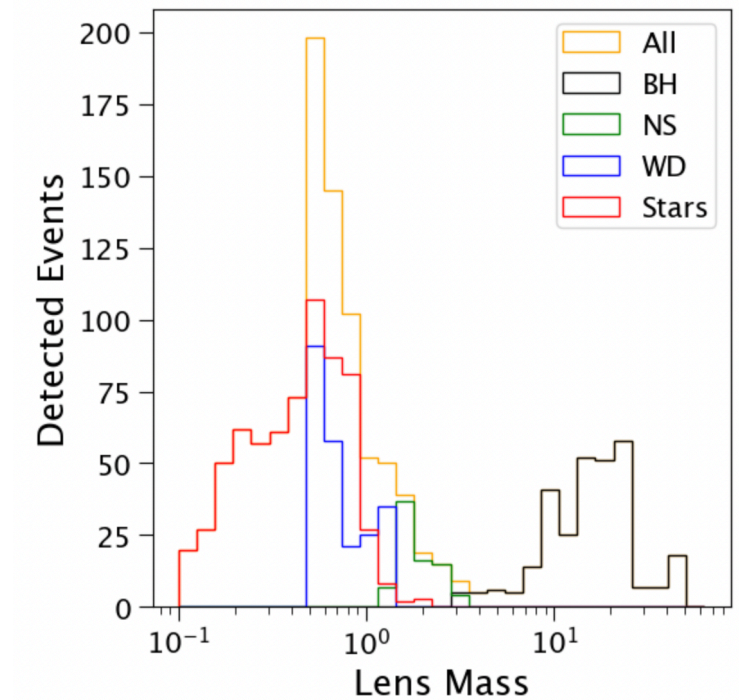
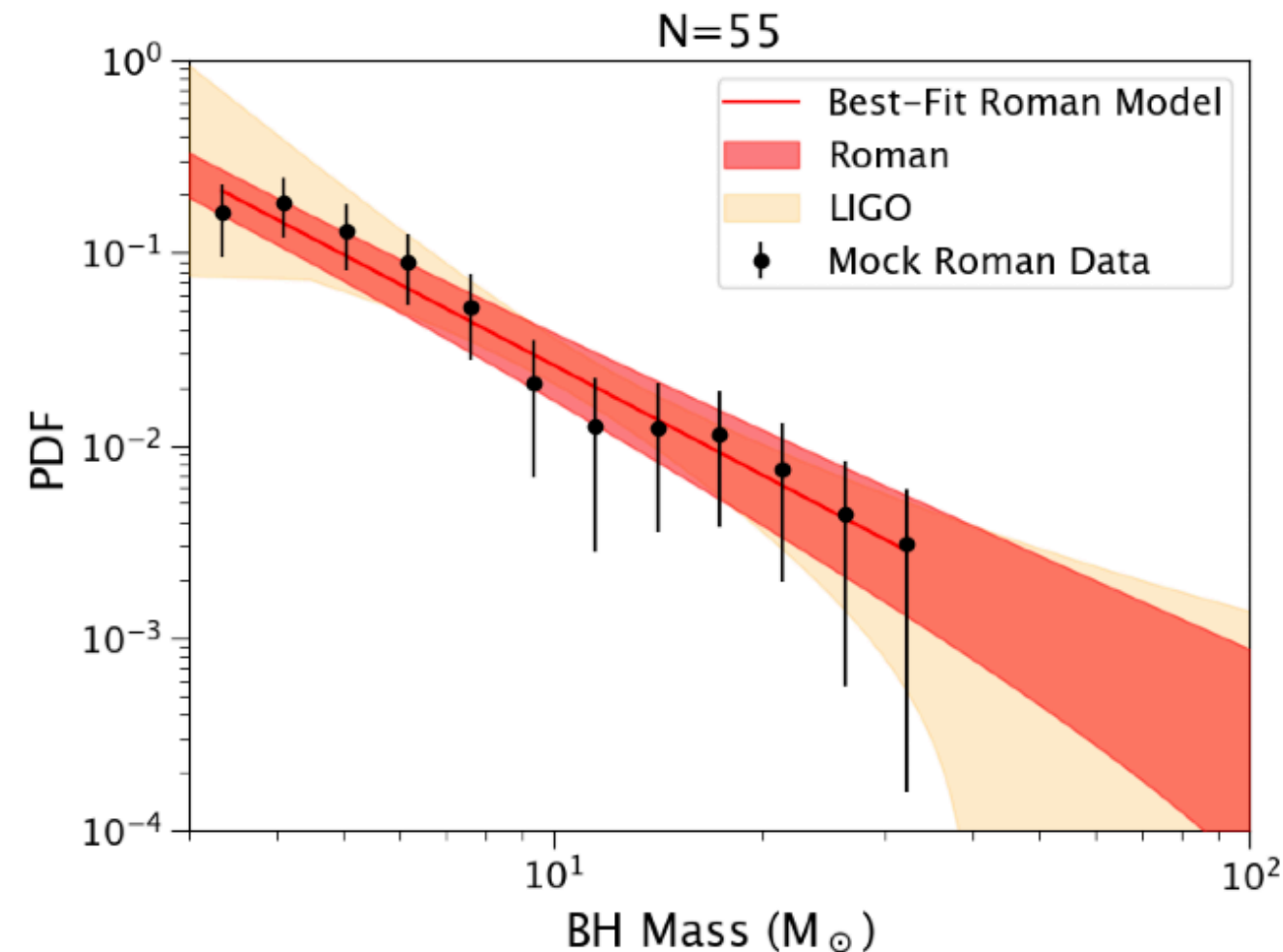
What follow-up do we need to confidently separate stars from WDs and NSs?



Raw (not completeness corrected).

Mass function constraints after 2 years of data: test power law models, high and low-mass cutoffs.

Big Caveat: Neglecting mass-dependent mass uncertainties.



These simulation tools are all public.

PopSyCLE:

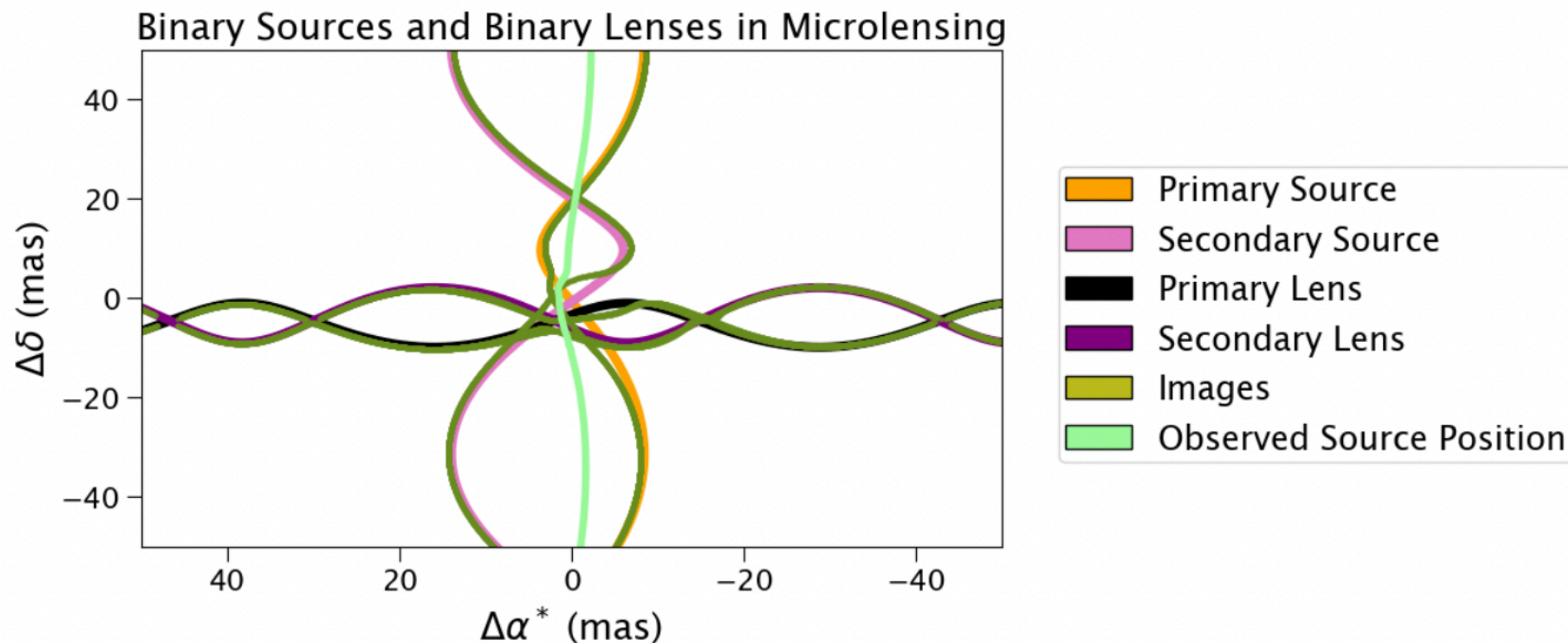
Population Synthesis for Compact object Lensing Events



Lam+ 2020, Rose+ 2022, Abrams+ 2025



PopSyCLE



Lu+ 2026, Bhadra+ 2026



BAGLE

Everything Lenses

Jessica Lu
UC Berkeley

Andrew Hamilton (JILA)