Black Holes Hiding in Plain Sight

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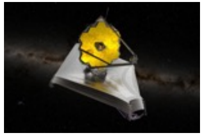
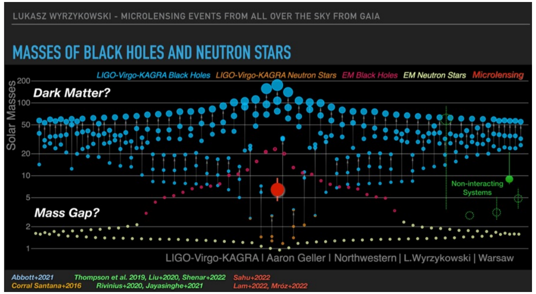
Black hole hiding in plain sight discovered
by Lukasz Wyrzykowski in ednesday Talk

What's up with the black holes?

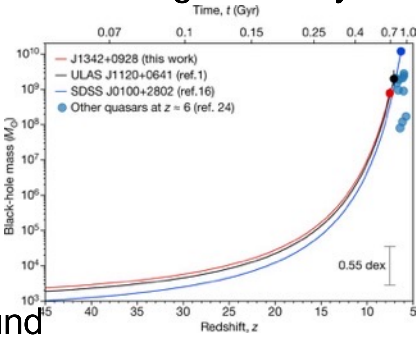


Black Holes in the NS-BH Mass Gap?



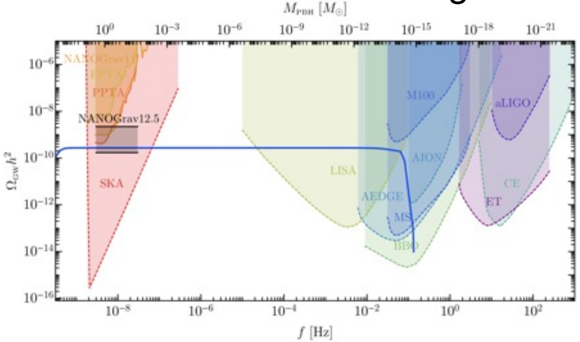
Credit Lukasz Wyrzykowski

Black Hole Quasars Too Big Too Early



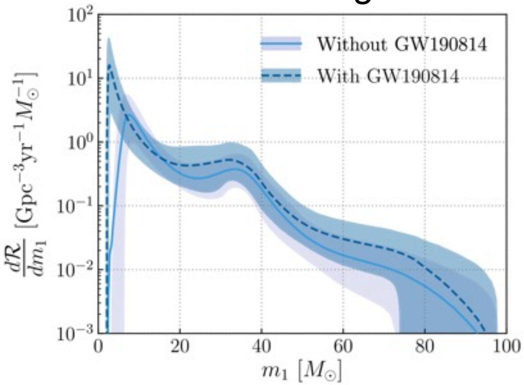
Bañados et al. (2017)

Milli-sec Pulsar Stochastic Gravitational Wave Background



De Luca et al. (2021)

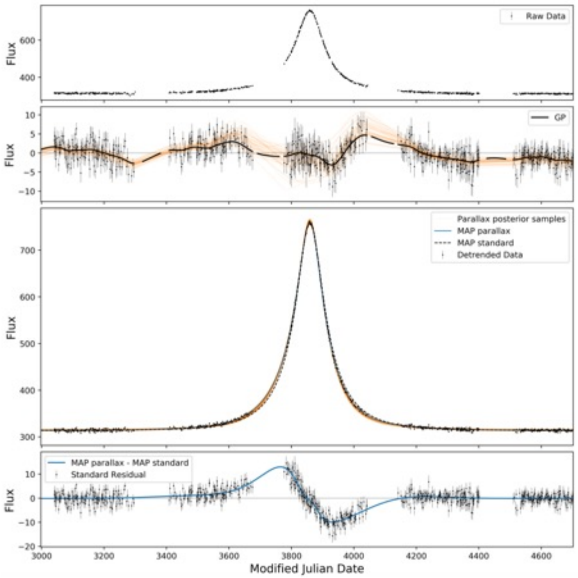
Two Component Black Hole Mass Function observed by LIGO-Virgo



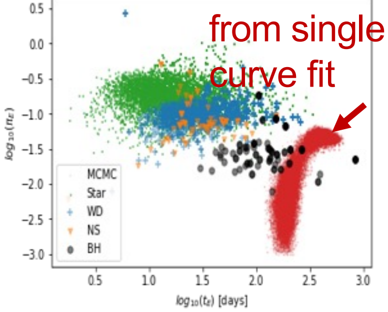
LIGO Collaboration (2021)

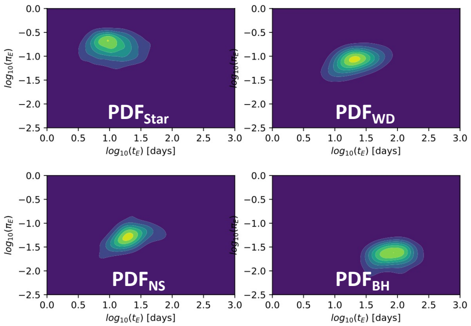
Approach to statistical constraints on the relative abundance of black holes

1) Parallax + GP MCMC



2) KDE Mixture Model





3) Model-based Population Statistics

Component	Relative fraction: Data / Theory
Stars	Is it 1?
White Dwarfs	Is it 1?
Neutron Stars	Is it 1?
Black Holes	Is it 1?

PopSyCLE: Simulating galactic microlensing events including black holes and neutron stars

Casey Lam (UC Berkeley)

The Astrophysical Journal, 889:31 (25pp), 2020 January 20
https://doi.org/10.3847/1538-4357/ab5fd3

CrossMark

PopSyCLE: A New Population Synthesis Code for Compact Object Microlensing Events

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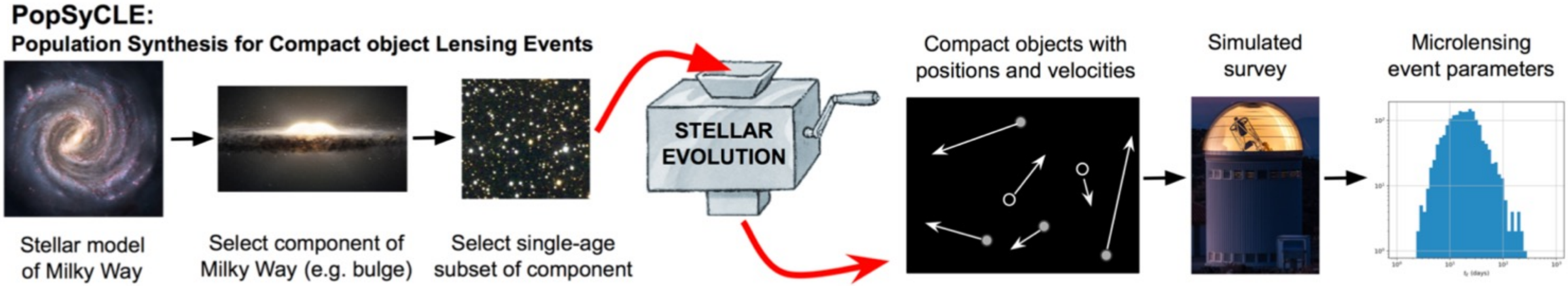
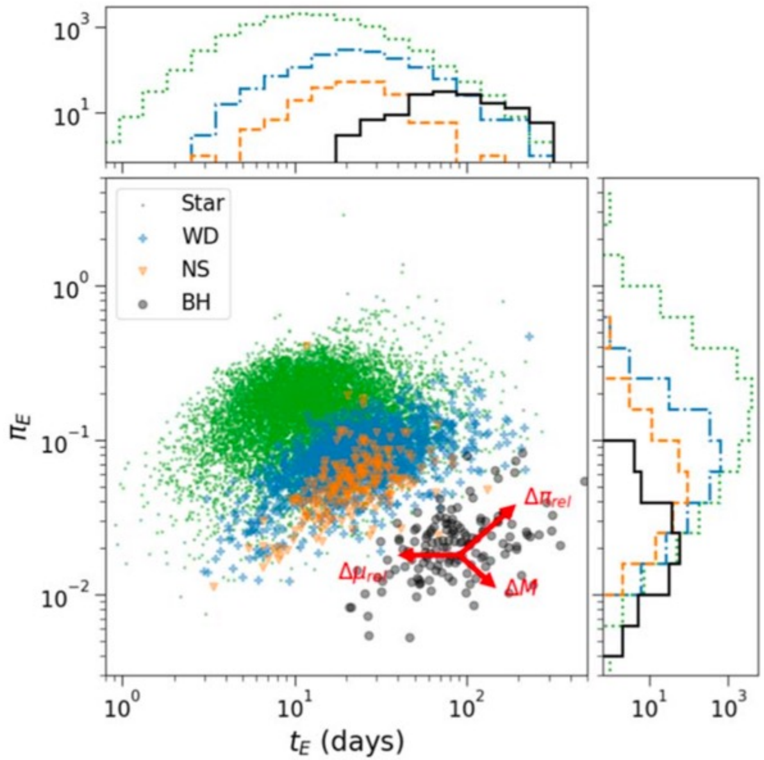
Received 2019 May 21; revised 2019 November 21; accepted 2019 December 5; published 2020 January 22



The $\pi_E - t_E$ space holds powerful potential to identify black holes



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

$$\pi_E = \sqrt{\frac{\pi_{rel}}{\kappa M}}$$

$$\pi_{rel} = 1\text{AU}\left(\frac{1}{d_L} - \frac{1}{d_S}\right)$$

$$\theta_E = \sqrt{\frac{4GM}{c^2}\left(\frac{1}{d_L} - \frac{1}{d_S}\right)}$$

OGLE has public light curves from their global analyses

- OGLE 3:
  - Wyrzykowski et al. 2014
  - 3560 lightcurves
  - High parallax separated out into Wyrzykowski et al. 2016

- OGLE 4:
  - Mroz et al. 2019
  - 5790 more events

Thank you OGLE!

But we need very accurate (but not necessarily precise) parallax estimates

The Astrophysical Journal Supplement Series, 260:2 (25pp), 2022 May https://doi.org/10.3847/1538-4365/ac5969

A Reanalysis of Public Galactic Bulge Gravitational Microlensing Events from OGLE-III and -IV

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Abstract

Modern surveys of gravitational microlensing events have progressed to detecting thousands per year, and surveys are capable of probing Galactic structure, stellar evolution, lens populations, black hole physics, and the nature of dark matter. One of the key avenues for doing this is the microlensing Einstein radius crossing time (t_E) distribution. However, systematics in individual light curves as well as oversimplistic modeling can lead to biased results. To address this, we developed a model to simultaneously handle the microlensing parallax due to Earth's motion, systematic instrumental effects, and unlensed stellar variability with a Gaussian process model. We used light curves for nearly 10,000 OGLE-III and -IV Milky Way bulge microlensing events and fit each with our model. We also developed a forward model approach to infer the t_E distribution by forward modeling from the data rather than using point estimates from individual events. We find that modeling the variability in the baseline removes a source of significant bias in individual events, and the previous analyses overestimated the number of $t_E > 100$ day events due to their oversimplistic model ignoring parallax effects. We use our fits to identify the hundreds filling a regime in the microlensing parameter space that are 50% pure of black holes. Finally, we have released the largest-ever catalog of Markov Chain Monte Carlo parameter estimates for microlensing events.

Unified Astronomy Thesaurus concepts: Gravitational microlensing (672); Astrophysical black holes (98); Time domain astronomy (2109); Astronomy data modeling (1859)

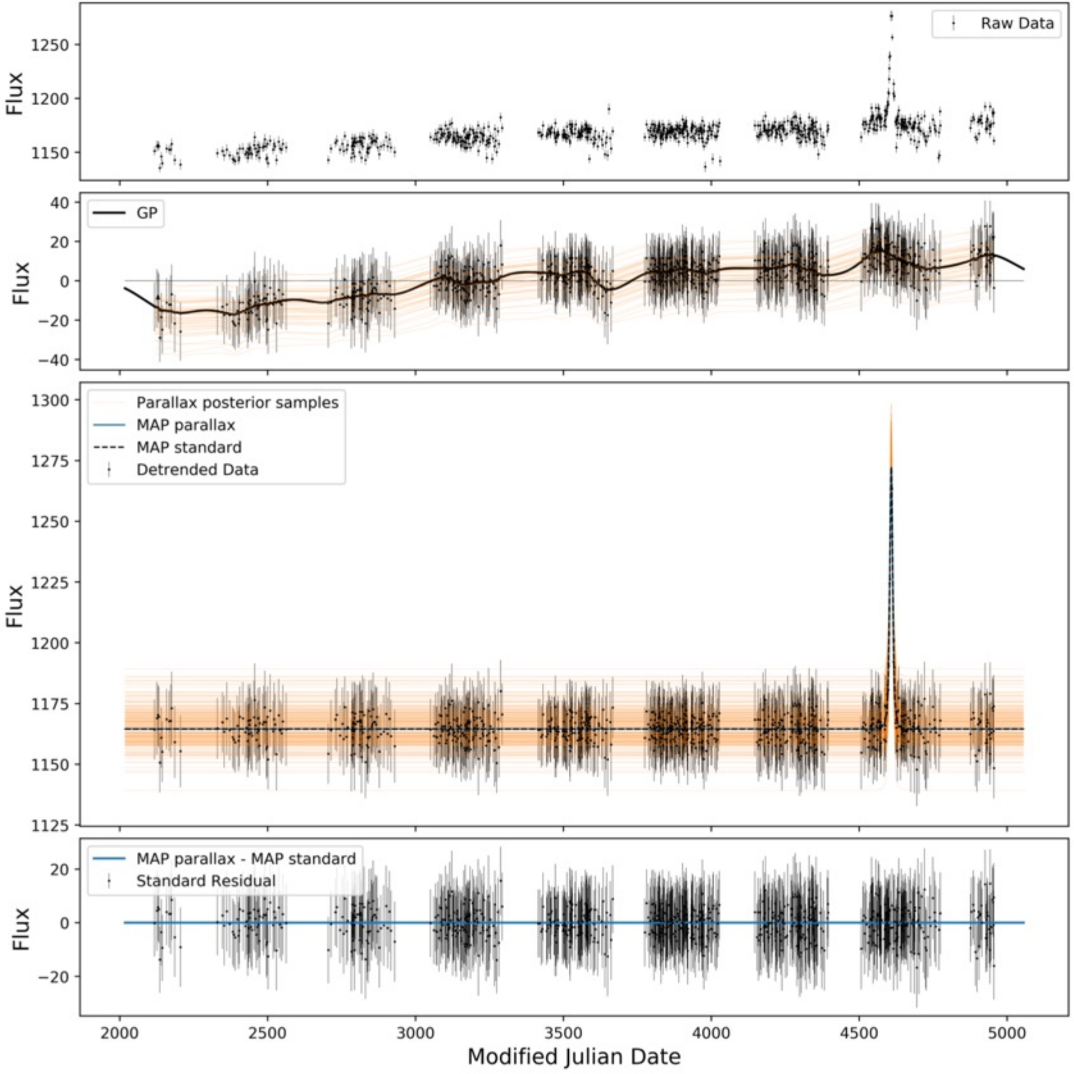
MCMC samples for
>11,500
OGLE events

Model = Microlensing Parallax + GP

All publicly available on
LLNL's Green Data Oasis
https://gdo-microlensing.llnl.gov/

Example events with Microlensing + GP fit

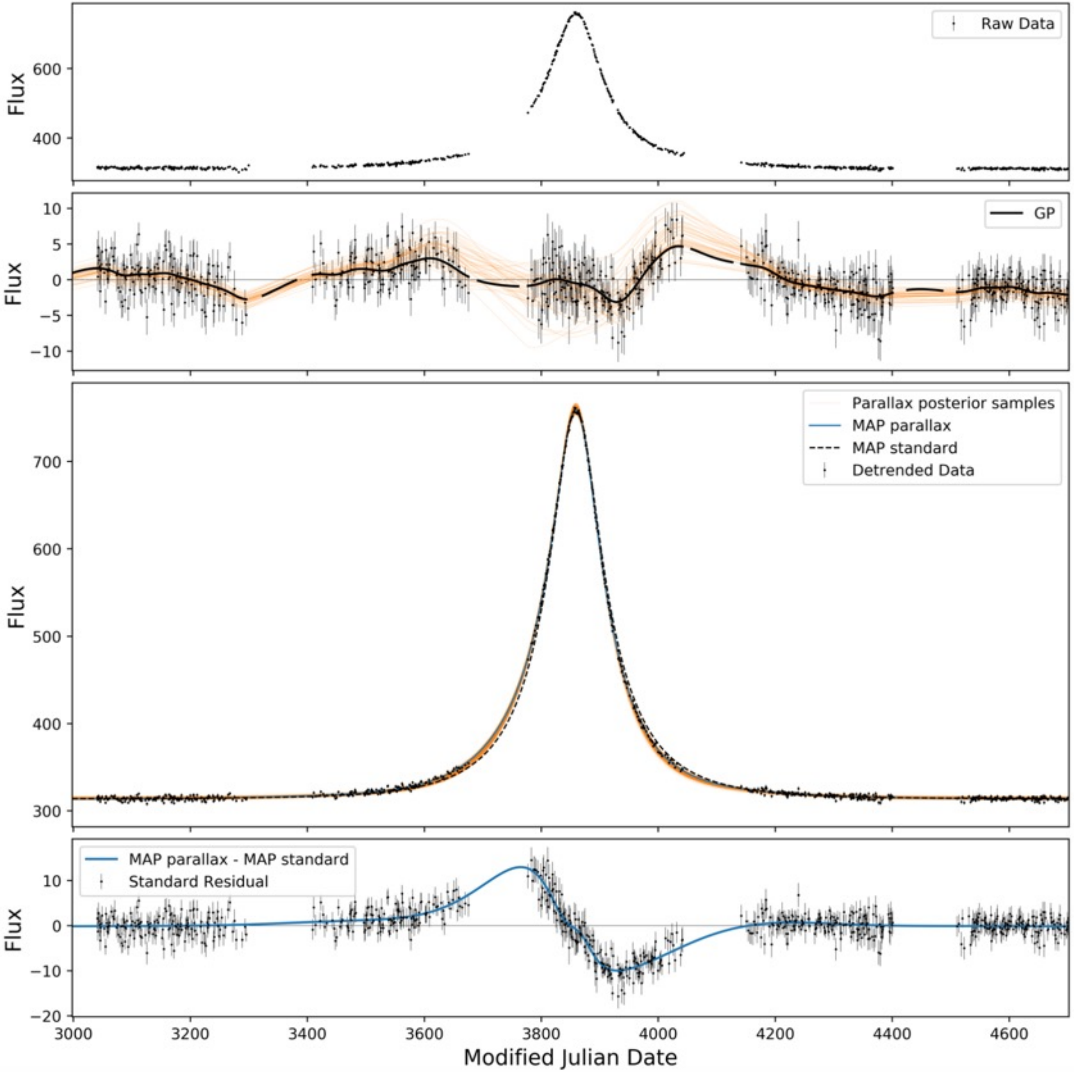
- The linear trend as well as other intrinsic variability is modeled by the GP
- Enables more accurate microlensing model estimates



Golovich, WD, et al. (2022)

Does the GP 'eat' the microlensing signal?

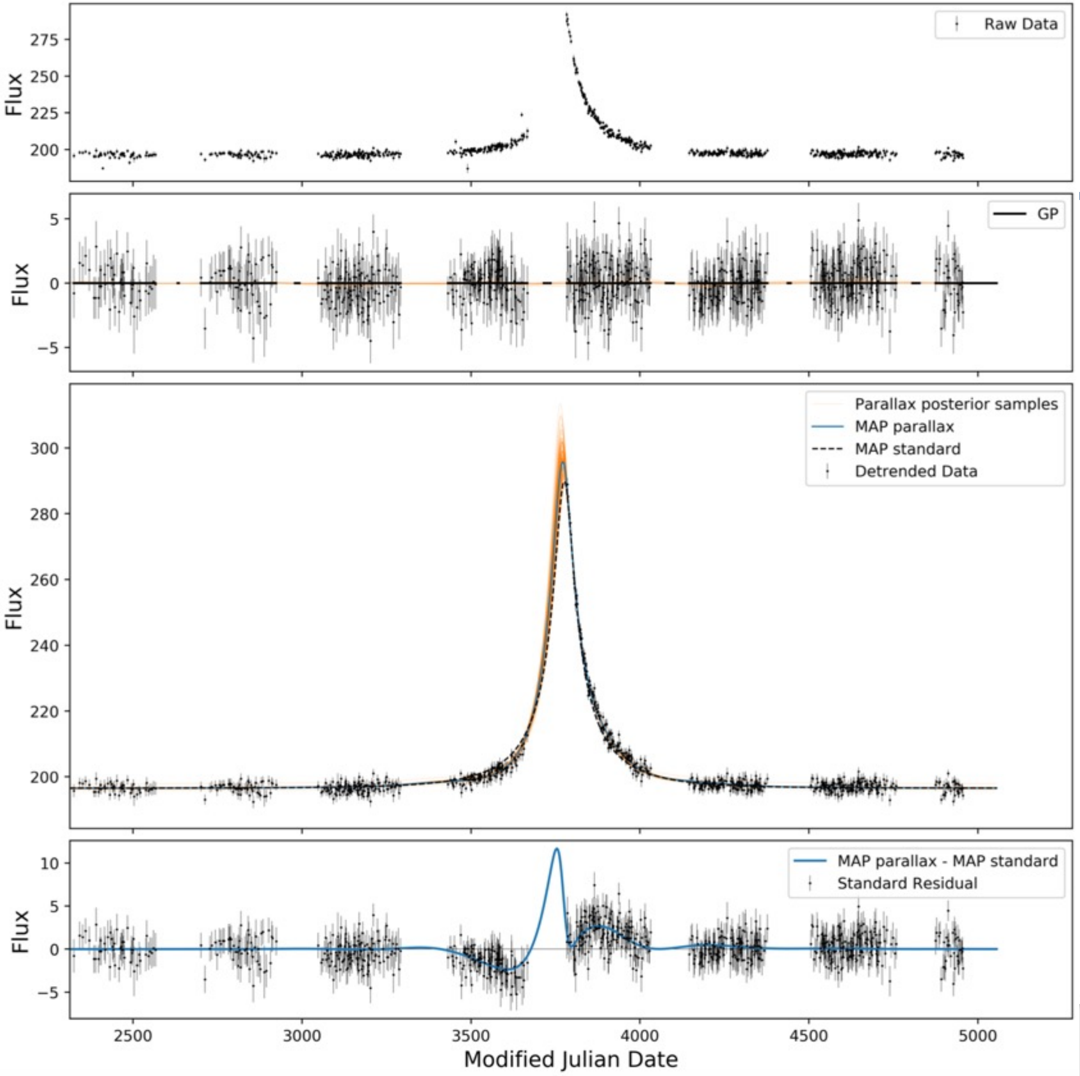
- Both relatively large GP and Parallax component



Golovich, WD, et al. (2022)

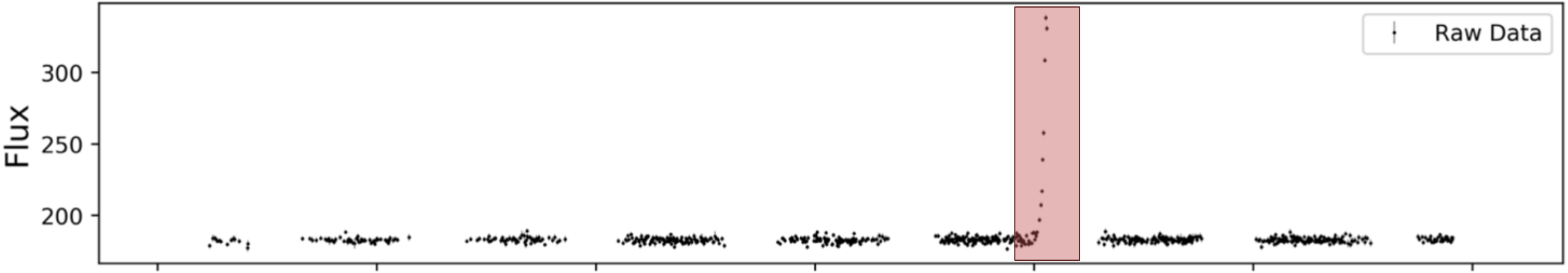
Does the GP ‘eat’ the microlensing signal?

- Almost no GP component but with significant parallax



Golovich, WD, et al. (2022)

Injected known parallax signal into masked short timescale events to investigate if GP fits are biased

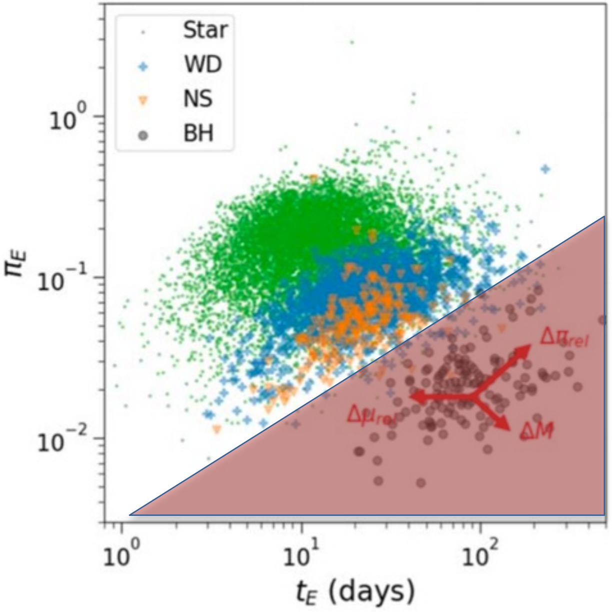


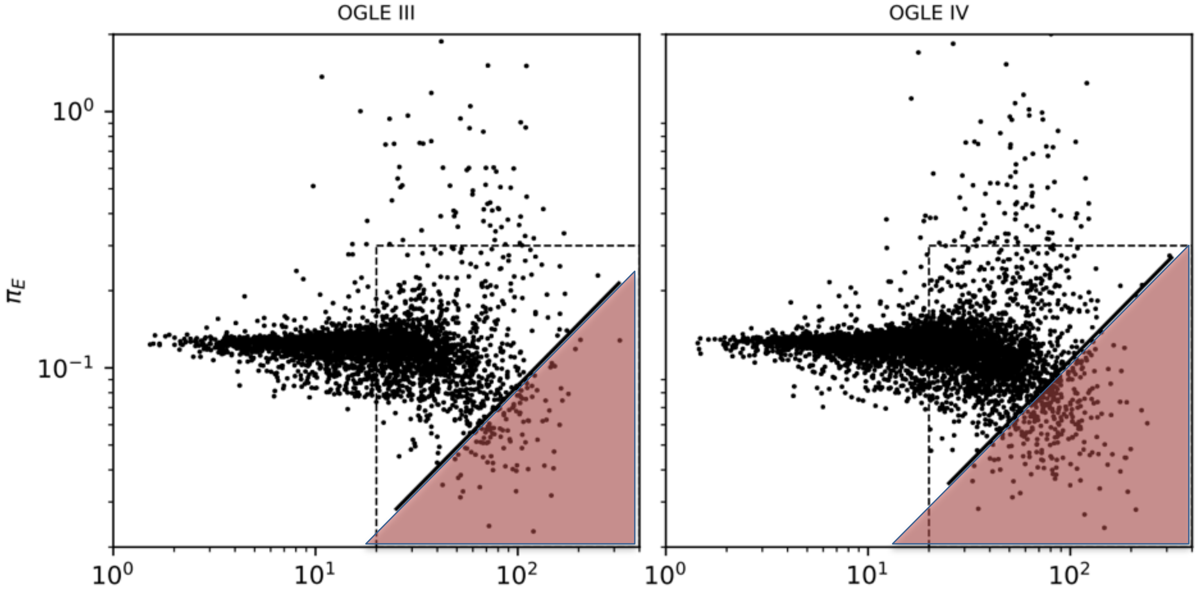
$$\text{bias} = \frac{\boldsymbol{\theta}_{\text{med}} - \boldsymbol{\theta}_{\text{inj}}}{\sigma_{\boldsymbol{\theta}}}$$

Parameter	μ_{bias}	σ_{bias}
F_{base}	-6.8×10^{-4}	0.040
b_{sff}	0.32	1.1
t_0	-7.8×10^{-3}	1.4
$\log_{10} u_0$	0.16	1.3
$\log_{10} t_E$	-0.12	0.52
$\log_{10} \pi_E$	0.11	0.77
ϕ_π	-0.029	0.97

Golovich, WD, et al. (2022)

Can we quickly identify any black holes?





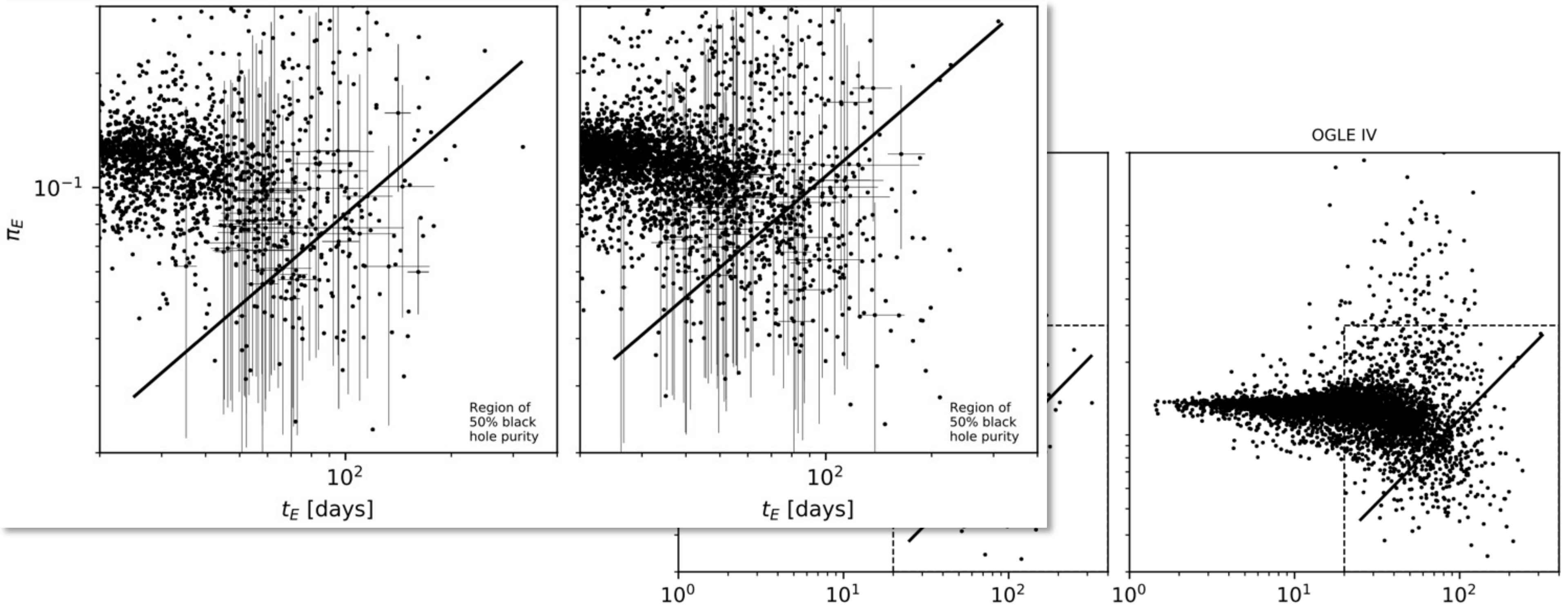
50% of PopSyCLE objects in red region are black holes

107 events ~3%

283 events ~4%

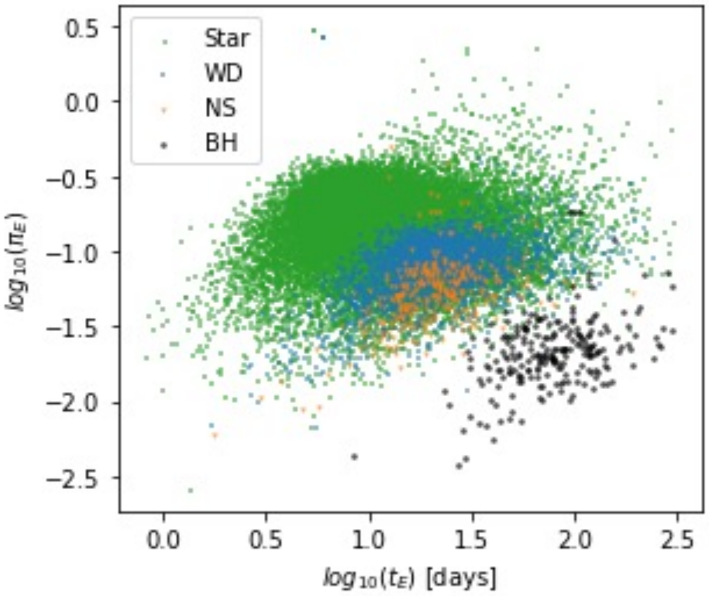
Golovich, WD, et al. (2022)

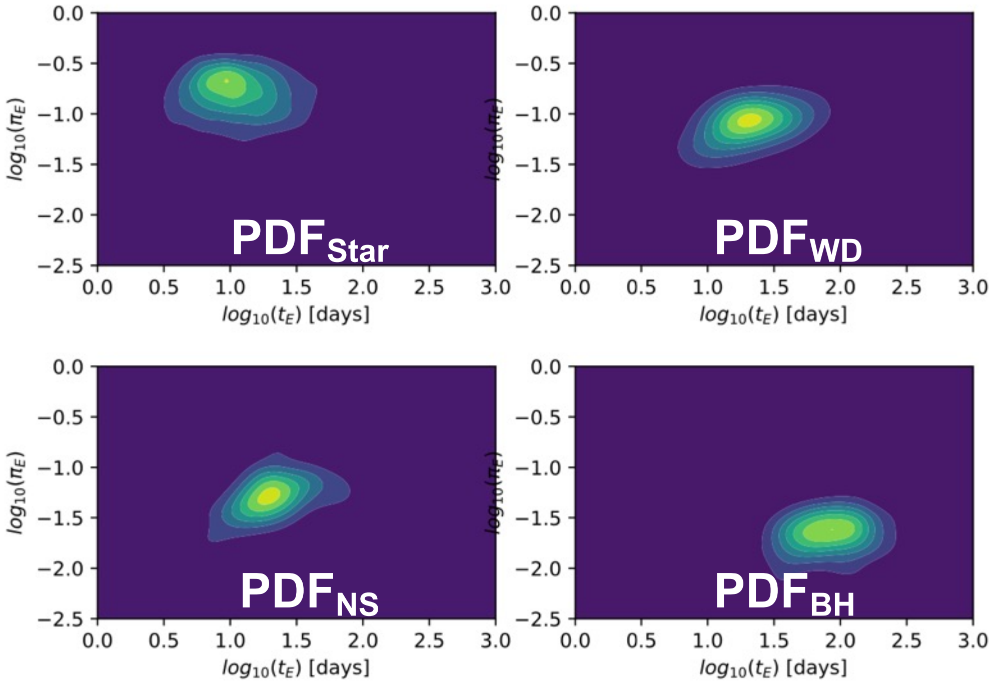
However, it is difficult to have confidence that any single event is a black hole, especially since the parallax SNR is so low



Golovich, WD, et al. (2022)

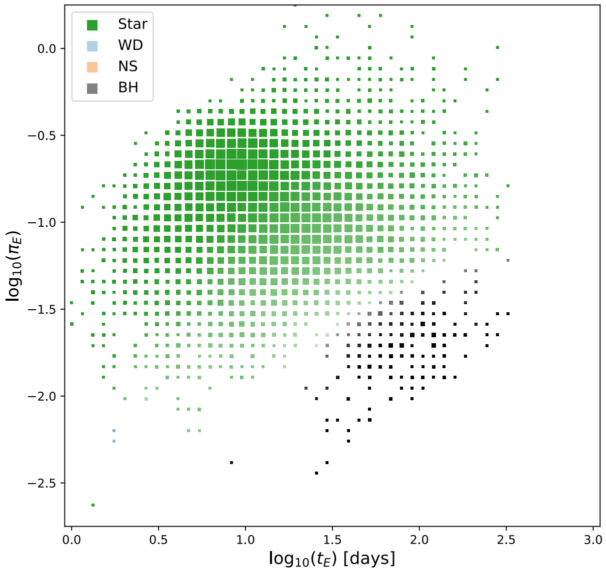
Need a more rigorous approach.
Step 1: Use kernel density estimation to create 'class' PDFs

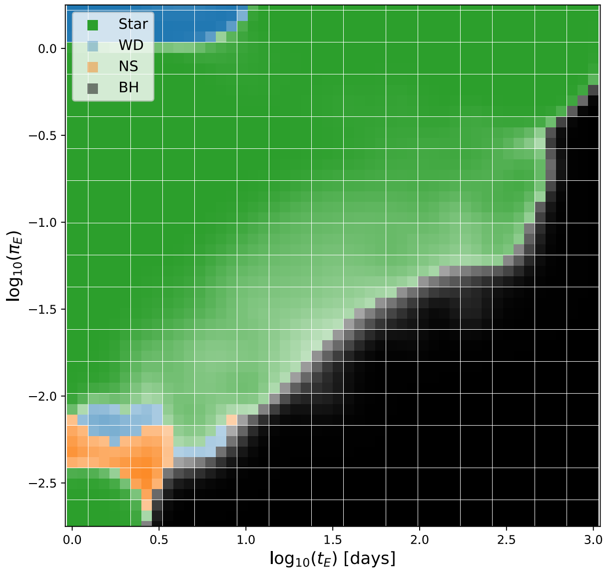




Necessary Prior $p(\text{class}_i) = \frac{n_{\text{class}_i}}{n_{\text{all}}}$

Step 2: Use the MCMC samples with the KDEs to estimate the relative probability of the event belonging to a given class.



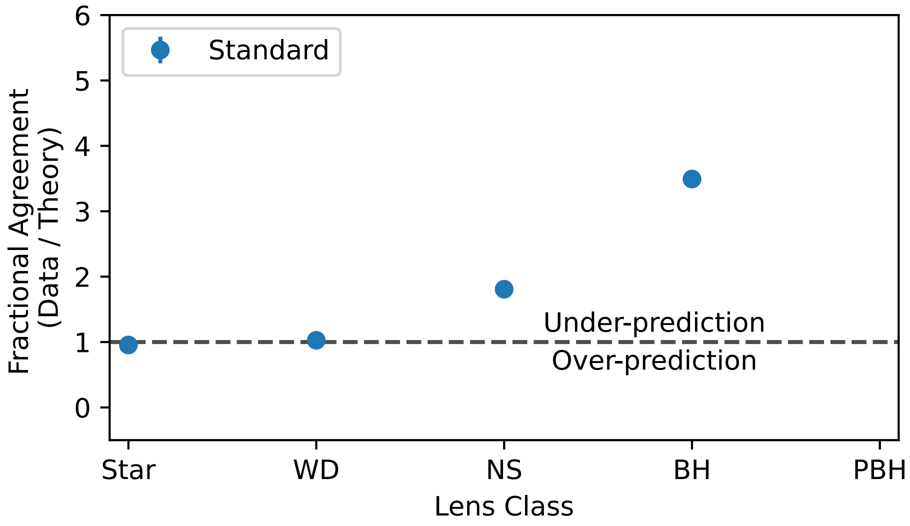


$$p(\text{class}_i|\Theta_{\text{MCMC}}, \Theta_{\text{sim}}) \approx \frac{1}{n_{\text{MCMC}}} \sum_{j=1}^{n_{\text{MCMC}}} p_{ij}$$

$$p(\text{class}_i|\Theta_{\text{MCMC}}, \Theta_{\text{sim}})_{rel} = \frac{p(\text{class}_i|\Theta_{\text{MCMC}}, \Theta_{\text{sim}})}{\sum_{i=1}^{n_{\text{class}}} p(\text{class}_i|\Theta_{\text{MCMC}}, \Theta_{\text{sim}})}$$

We are currently finding more black holes and neutron stars than the PopSyCLE simulations suggest

Component	Class Percentage	Relative fraction: Data / Theory
Stars	83%	0.946 +/- 0.001*
White Dwarfs	10%	1.061 +/- 0.005 *
Neutron Stars	2%	1.99 +/- 0.01*
Black Holes	4%	3.7 +/- 0.1*



* Uncertainty only accounts for light curve model parameter variance and bootstrap estimate over light curves. Neglected and likely important uncertainty terms are related to galaxy model and stellar evolution model variance.

Why might we be seeing an excess?

- There is a systematic that we have not thought of.

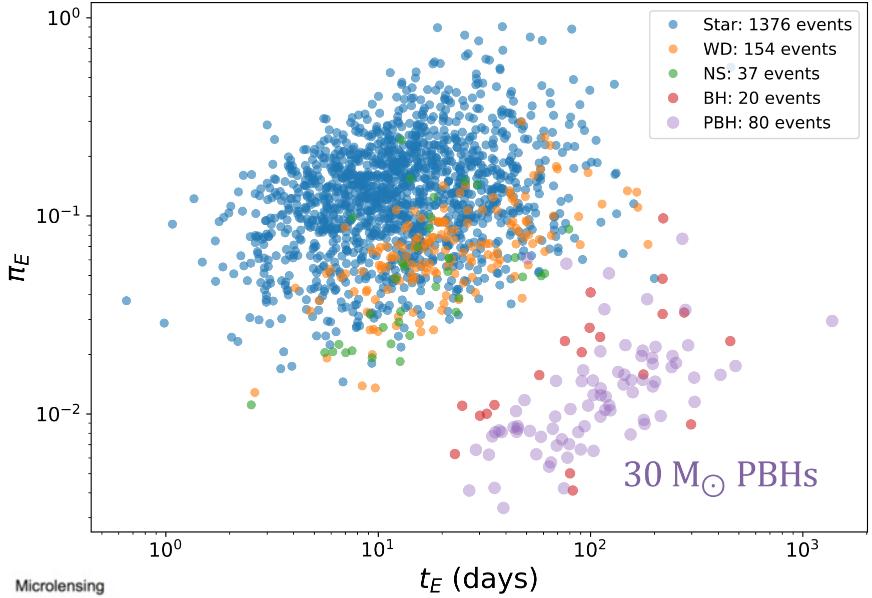
- Something is incorrect with the Milky Way model that PopSyCLE used.

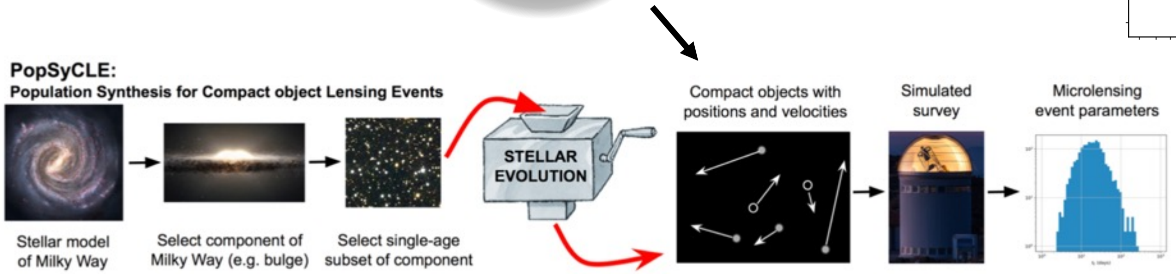
- Something is incorrect with the stellar evolution model used by PopSyCLE.

- There is an addition component to the MW that we have not modeled in PopSyCLE who's phase space overlaps with that of both the NSs & BHs.

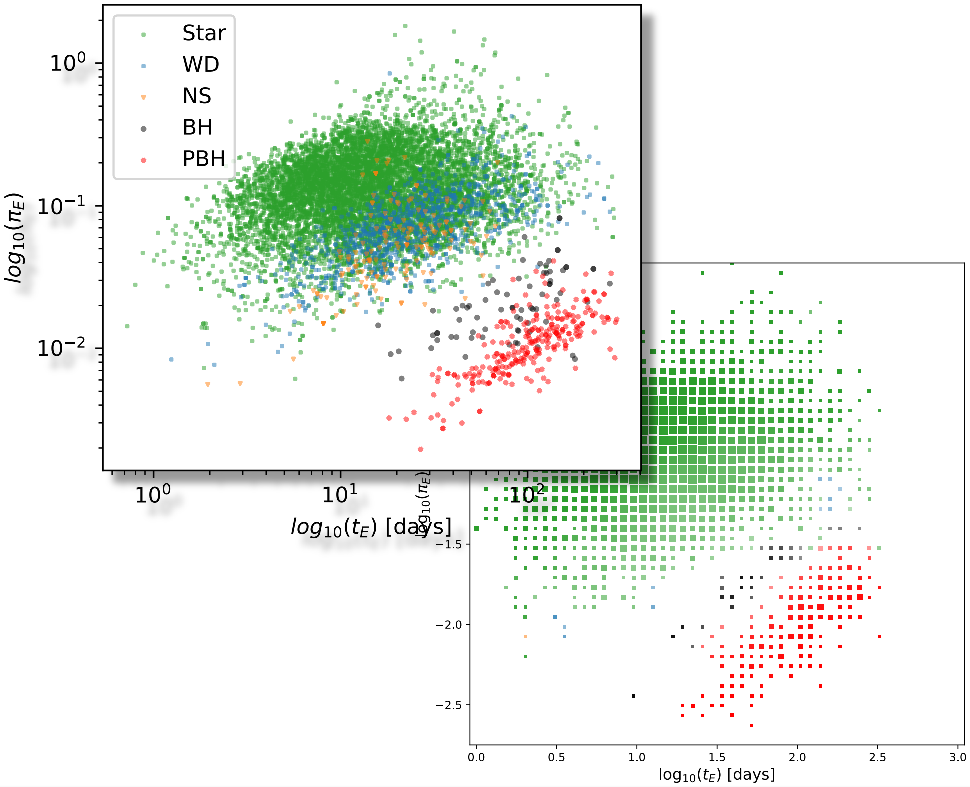
PopSyCLE + PBH Simulations
Simulating the number & distribution of expected events

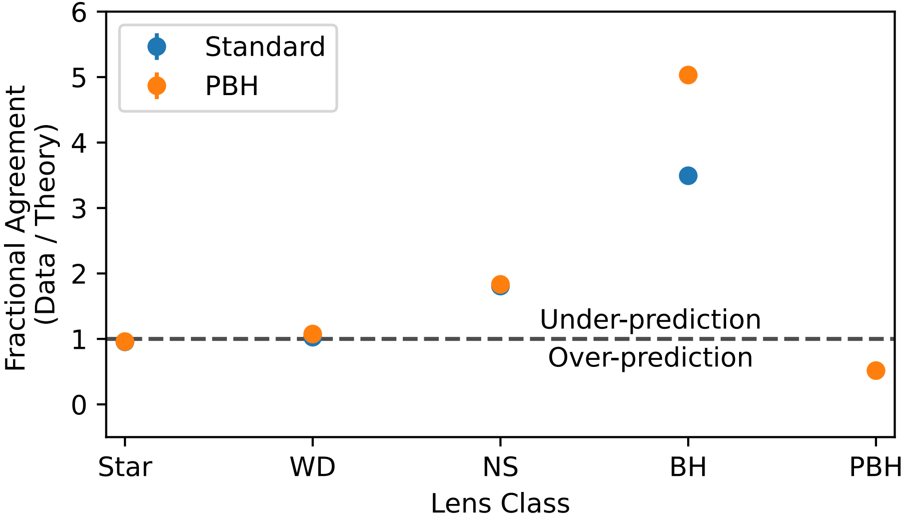
Work led by Co-I Pruett
See "Primordial Black Hole Dark Matter Simulations Using PopSyCLE" talk.





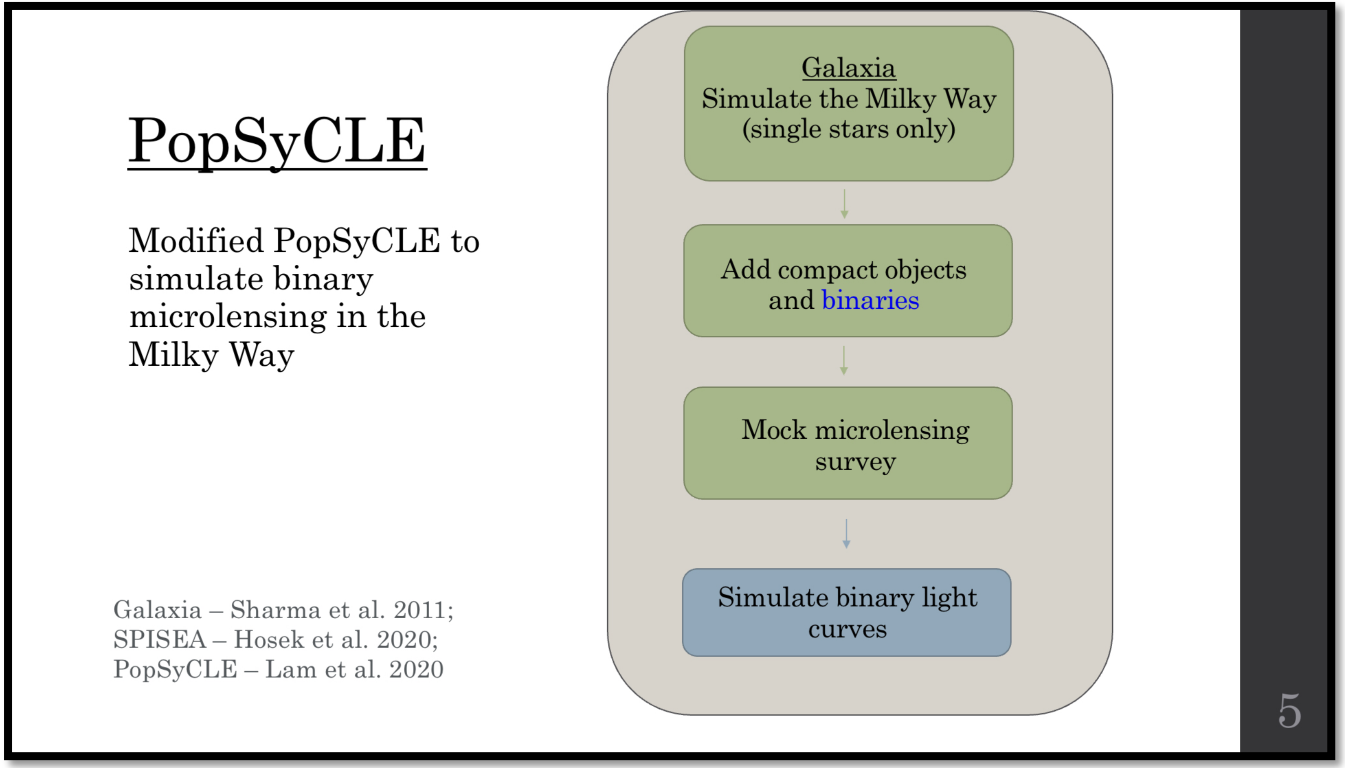
30 M_sun PBHs making up 100% dark matter not a good fit; Extended mass distribution with a lower tail would be a better



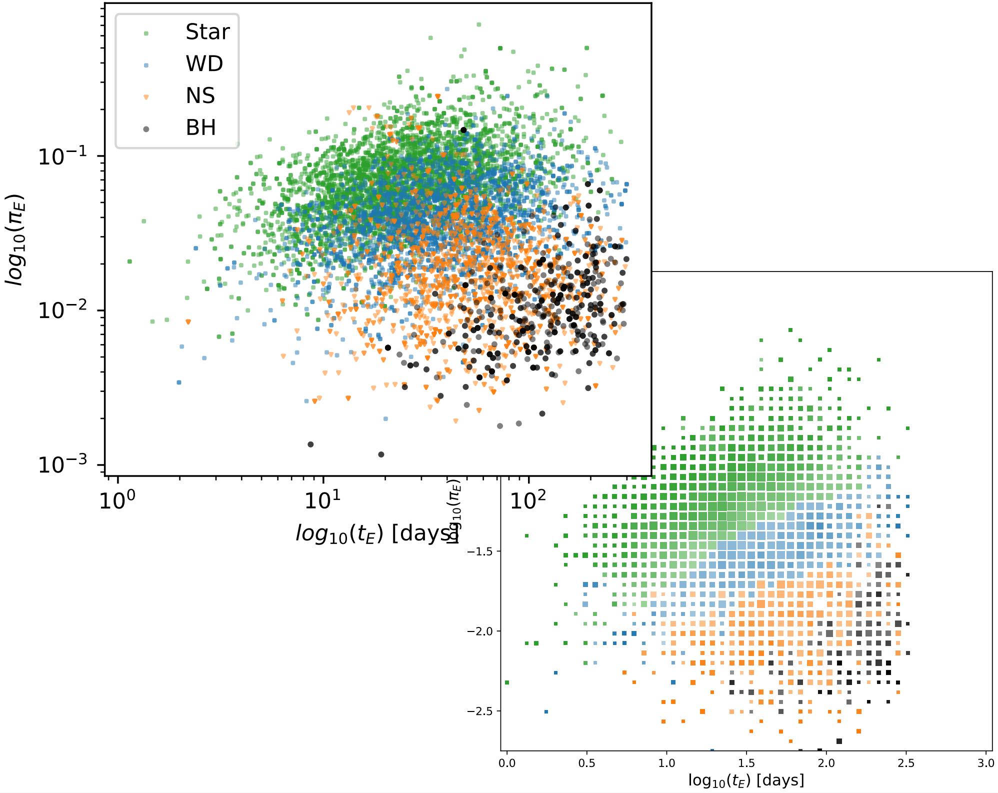


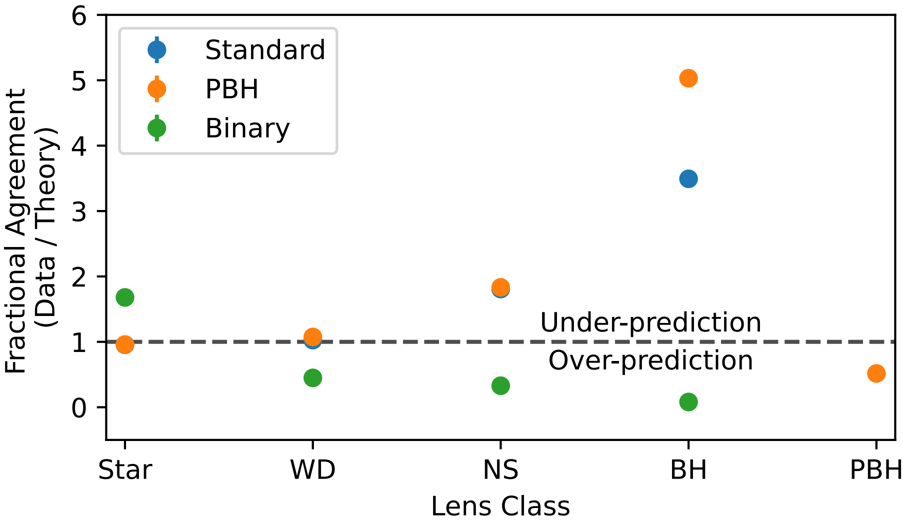
We are 100% positive there are binaries; we should probably add those to our simulation

Refer to previous talk “Assessing the Impact of Binary Systems on Microlensing” by Natasha Abrams



Including binary lenses shifts many objects in the the black hole region of parameters space, but need to resolve other discrepancies





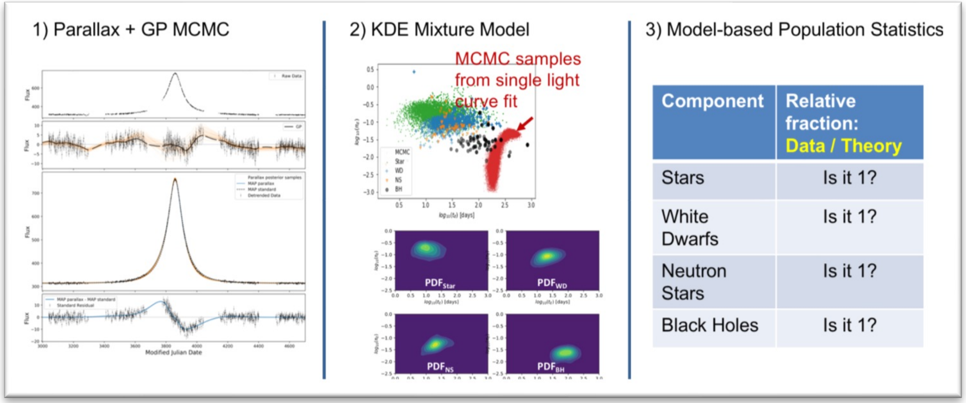
One person's systematic
is another person's signal.

Summary

- Introduced a new statistical means of constraining compact objects with microlensing

- Future Work
  - Disrupted binaries in PopSyCLE
  - Adding LMC & SMC to PopSyCLE
  - Extended PBH mass distributions
  - Marginalizing over ‘nuisance’ parameters through many PopSyCLE runs

- Roman is going to revolutionize black hole studies



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