Finding black holes with microlensing: current and future prospects

Casey Lam (Carnegie Observatories)

With Jessica Lu + group (UC Berkeley), PALS group (LLNL), OGLE collaboration, MOA collaborations, and others…

With funding support from:

Characterizing the stellar-mass black hole population is needed to understand a broad range of astrophysics

Unknown properties of Galactic black holes:

- Number
- Mass function
- Binary fraction
- Formation channel(s)
- Birth kick velocity

Properties needed to understand:

- Massive star evolution, death
- Initial-final mass relation
- Chemical enrichment, feedback
- Binary interaction, mass transfer

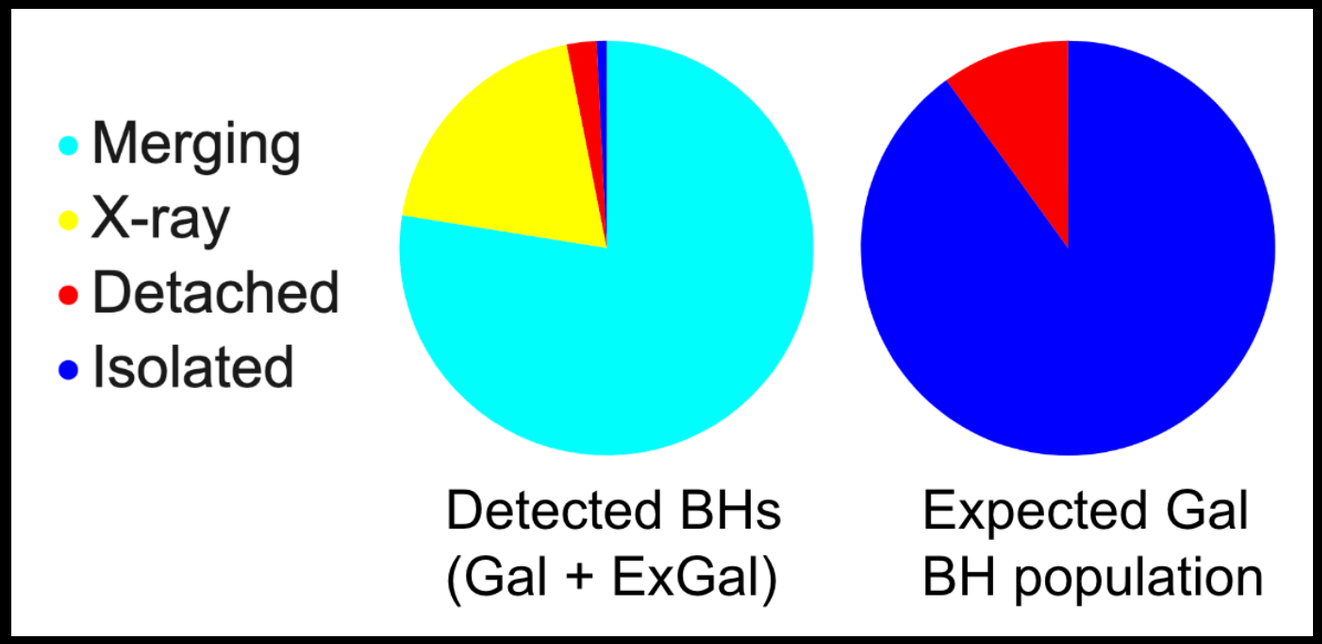
Characterizing the stellar-mass black hole population is needed to understand a broad range of astrophysics

Unknown properties of Galactic black holes:

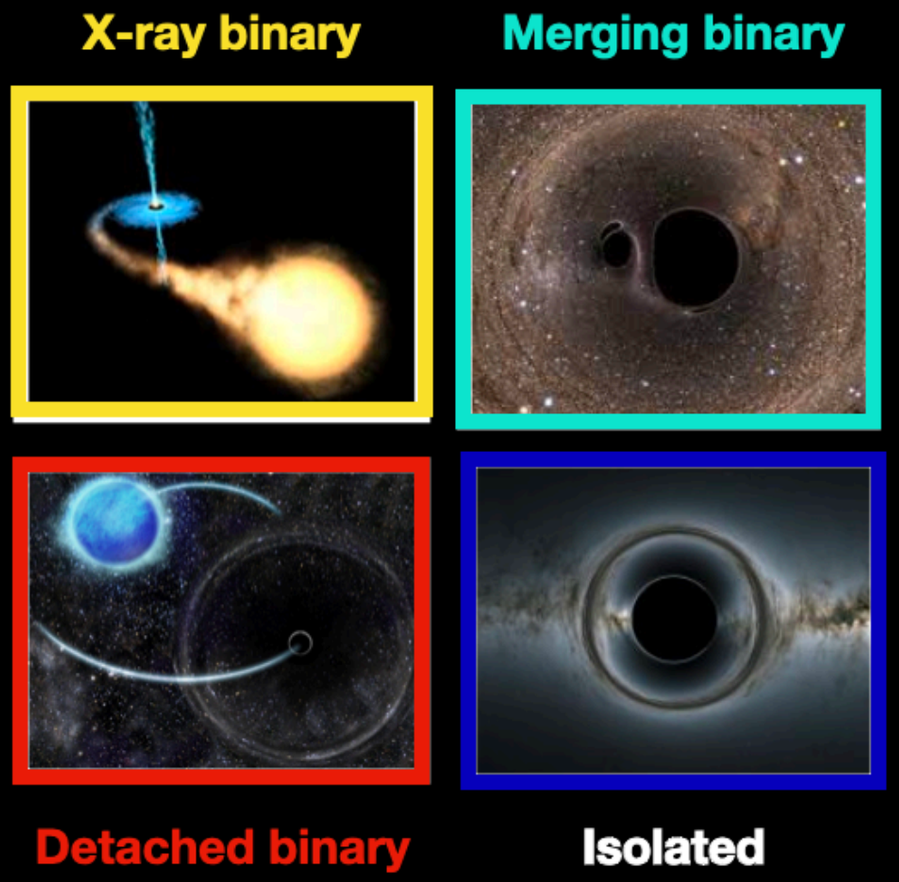
- Number
- Mass function
- Binary fraction
- Formation channel(s)
- Birth kick velocity

Properties needed to understand:

- Massive star evolution, death
- Initial-final mass relation
- Chemical enrichment, feedback
- Binary interaction, mass transfer

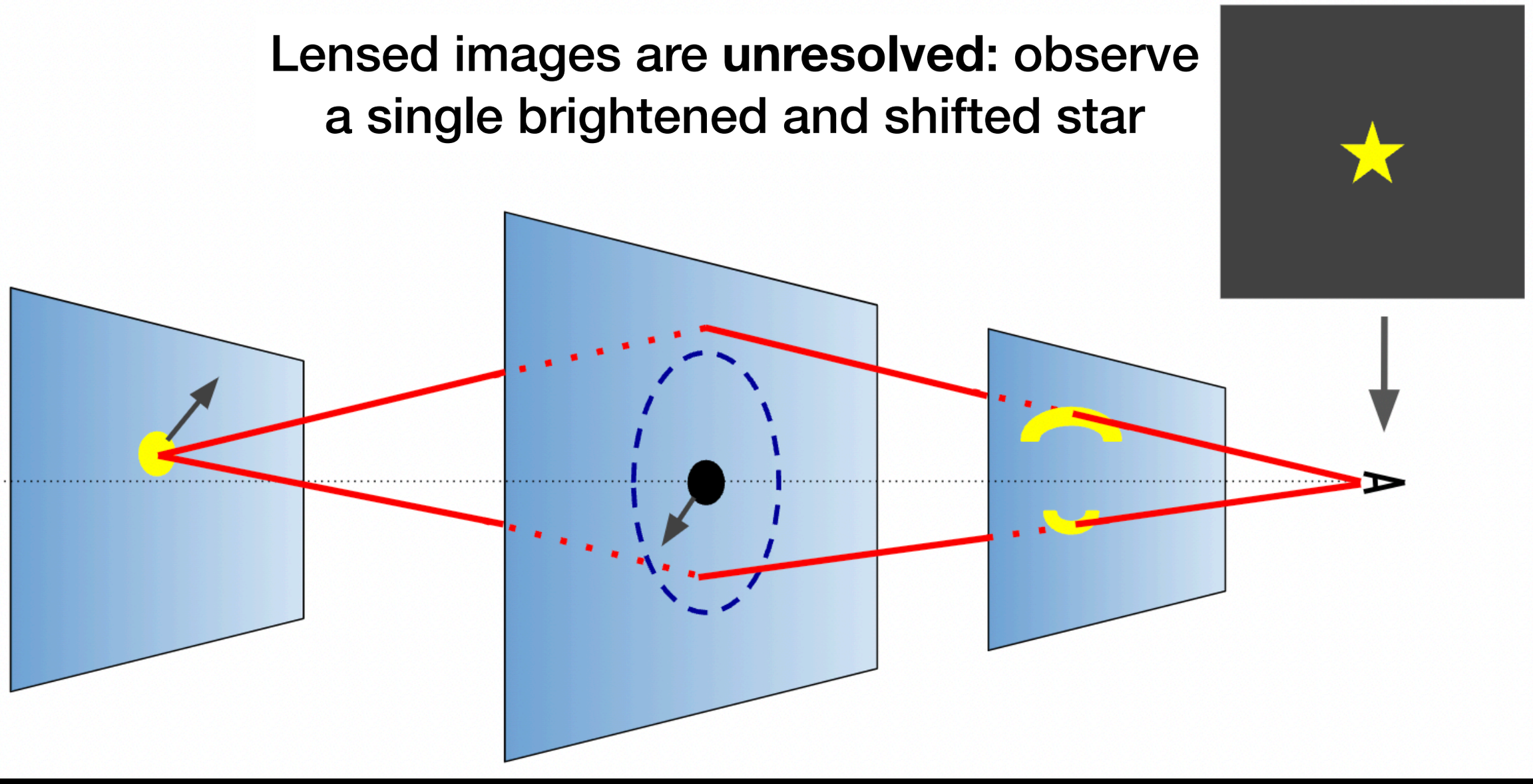


We need to find isolated black holes!



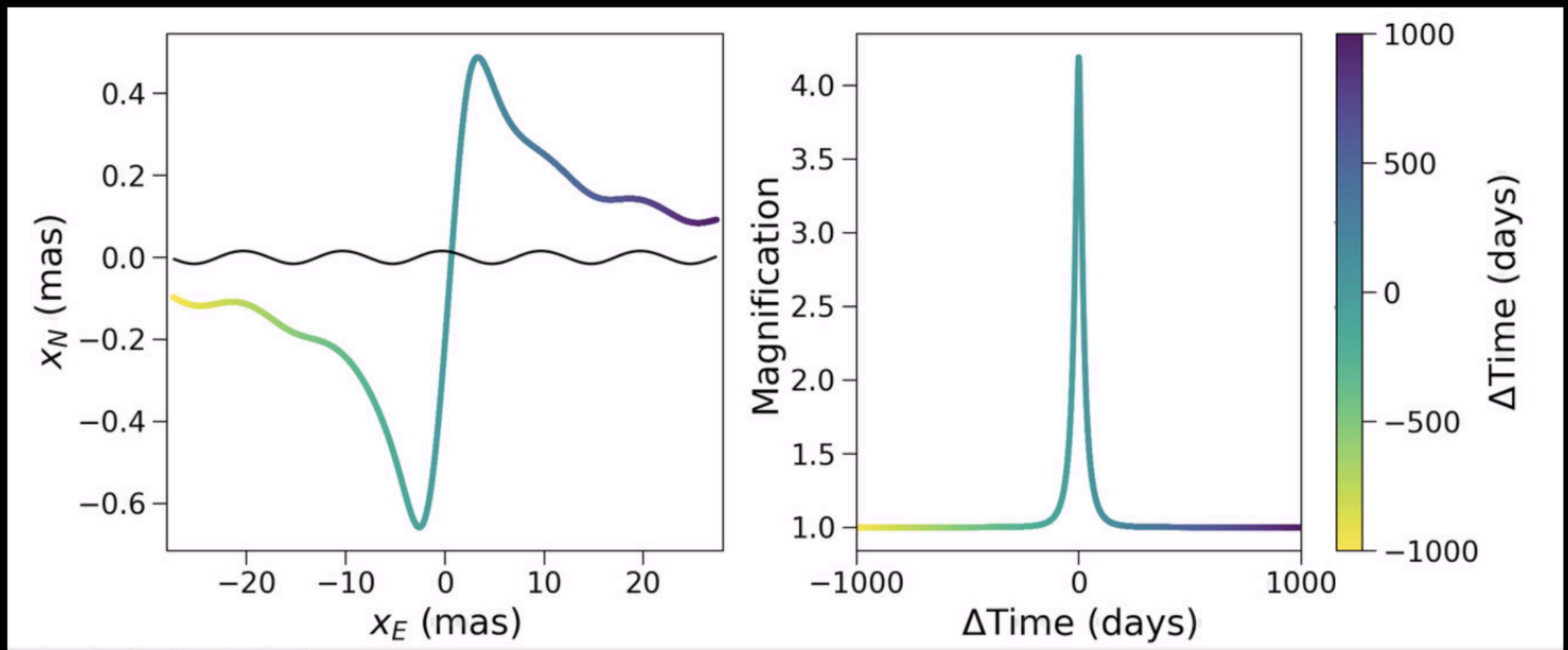
Gravitational lensing depends on mass (not luminosity) of foreground lens = Good for finding black holes

Lensed images are **unresolved:** observe a single brightened and shifted star



Photometric + astrometric microlensing = lens mass measurements

$$M_L = \frac{\theta_E}{\kappa \pi_E}$$

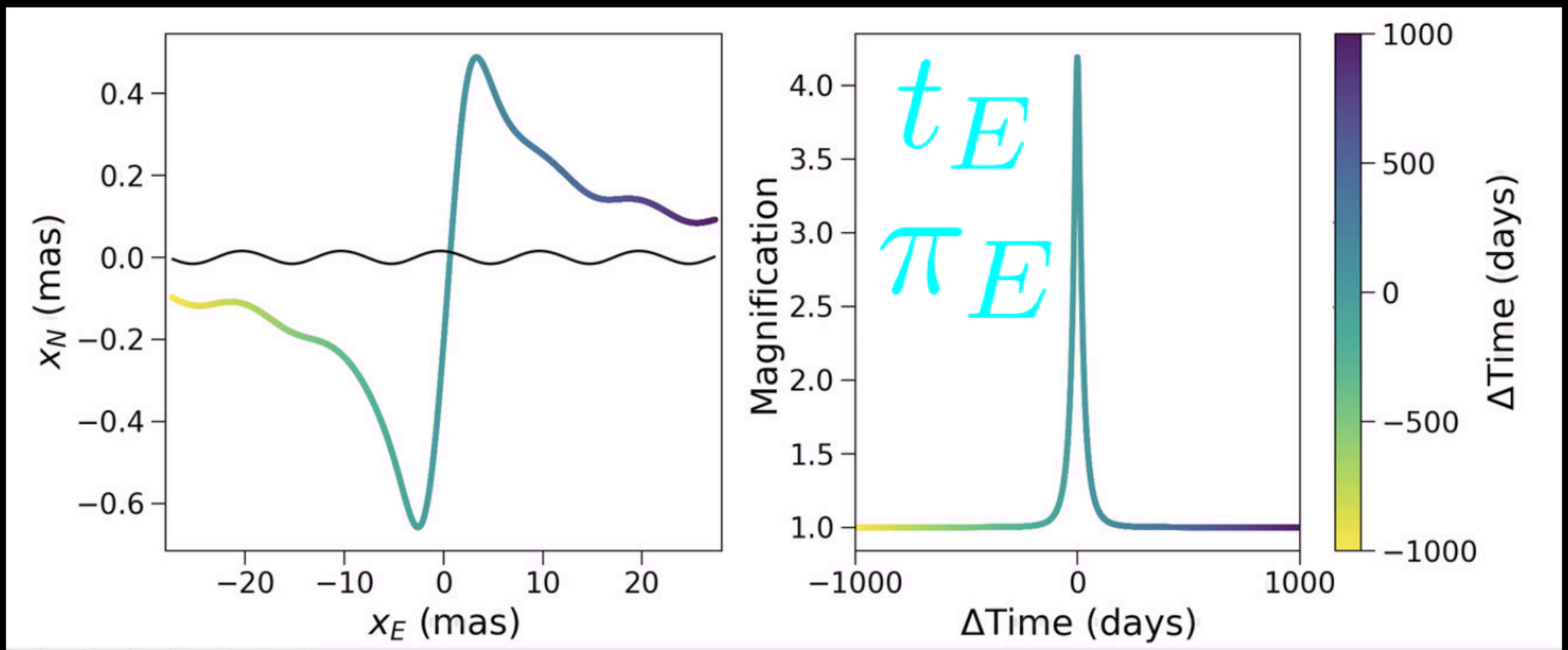


Photometric + astrometric microlensing = lens mass measurements

$$M_L = \frac{\theta_E}{\kappa \pi_E} \quad \begin{matrix} t_E \\ \pi_E \end{matrix}$$

Time scale

Relative distance



Photometric brightening

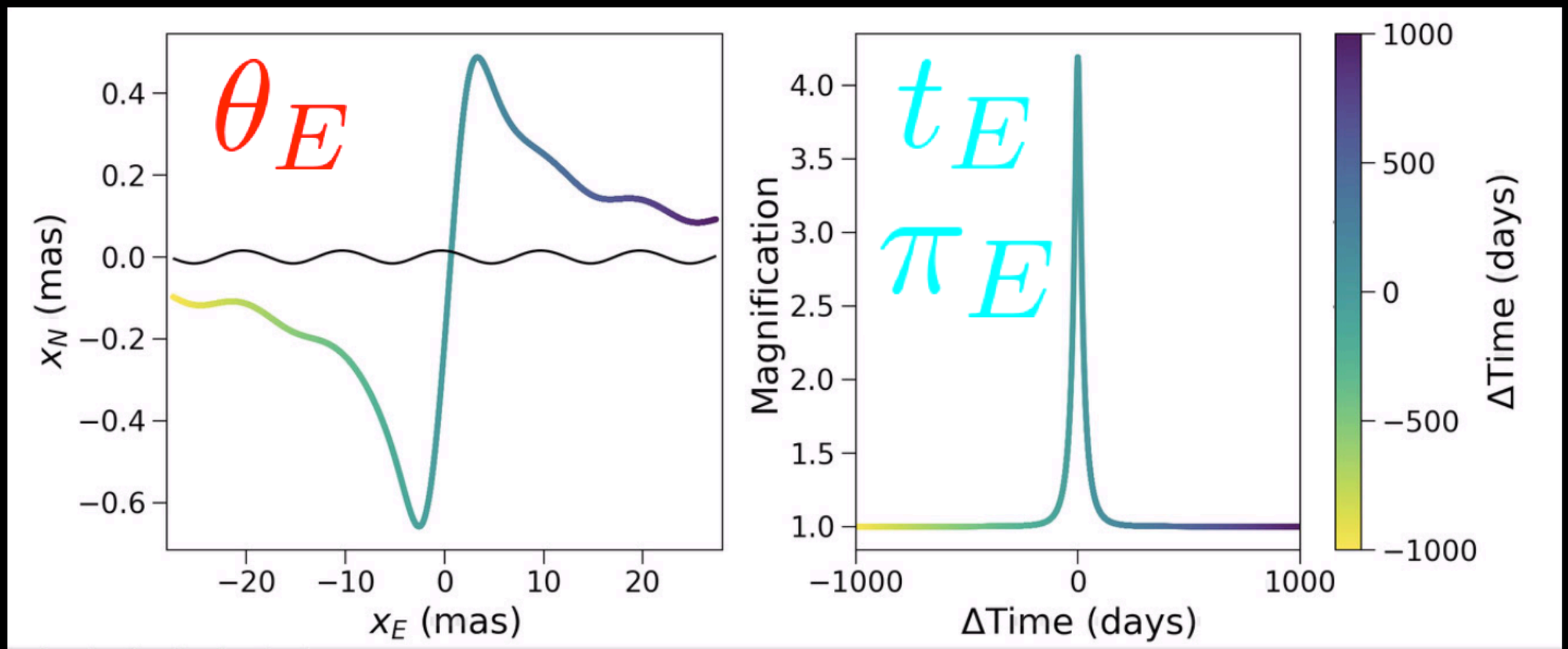
Photometric + astrometric microlensing = lens mass measurements

$$M_L = \frac{\theta_E}{\kappa \pi_E}$$

t_E **Time scale**

π_E **Relative distance**

θ_E **Angular scale**



Astrometric shift

Photometric brightening

How to find isolated black holes (now)

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST)

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST)
    - Astrometric deflection decays much more slowly than photometric magnification: ~10 t_E vs. ~1 t_E

How to find isolated black holes (now)

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST)
    - Astrometric deflection decays much more slowly than photometric magnification: ~10 t_E vs. ~1 t_E

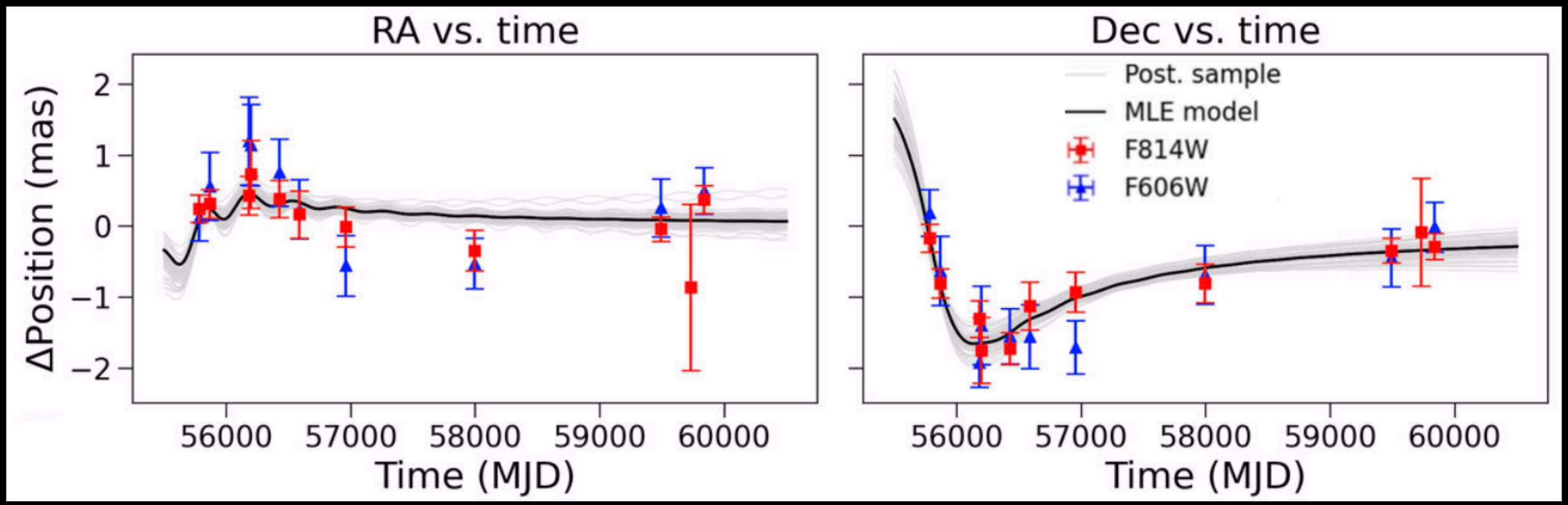
    → ~10 epochs, spread over ~5-10 years

OGLE-2011-BLG-0462: First isolated black hole characterized with microlensing

Ground-based photometry + HST WFC3-UVIS astrometry

Mass = 6±1 $M_\odot$, Distance = 1.7±0.3 kpc, v_{trans} = 38±5 km/s

1 detection out of sample of 5 consistent with population of 100 million Galactic BHs (Lam+22)



Lam & Lu 2023 (see also **Lam+22**, Sahu+22, Mroz+22)

How to find isolated black holes (now)

It works! But…

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST)
    - Astrometric deflection decays much more slowly than photometric magnification: ~10 t_E vs. ~1 t_E

    → ~10 epochs, spread over ~5-10 years

How to find isolated black holes (now)

It works! But…

1. Select BH candidates from photometric microlensing alerts
    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST) **$$$**
    - Astrometric deflection decays much more slowly than photometric magnification: ~10 t_E vs. ~1 t_E

    → ~10 epochs, spread over ~5-10 years

How to find isolated black holes (now)

It works! But…

1. Select BH candidates from photometric microlensing alerts

    - ~2000 alerts/yr, ~1% of those due to BHs
    - Timescale t_E ~ (Lens mass)$^{1/2}$

    → Long-duration events (t_E > 120 days)

Throws away lots of black holes

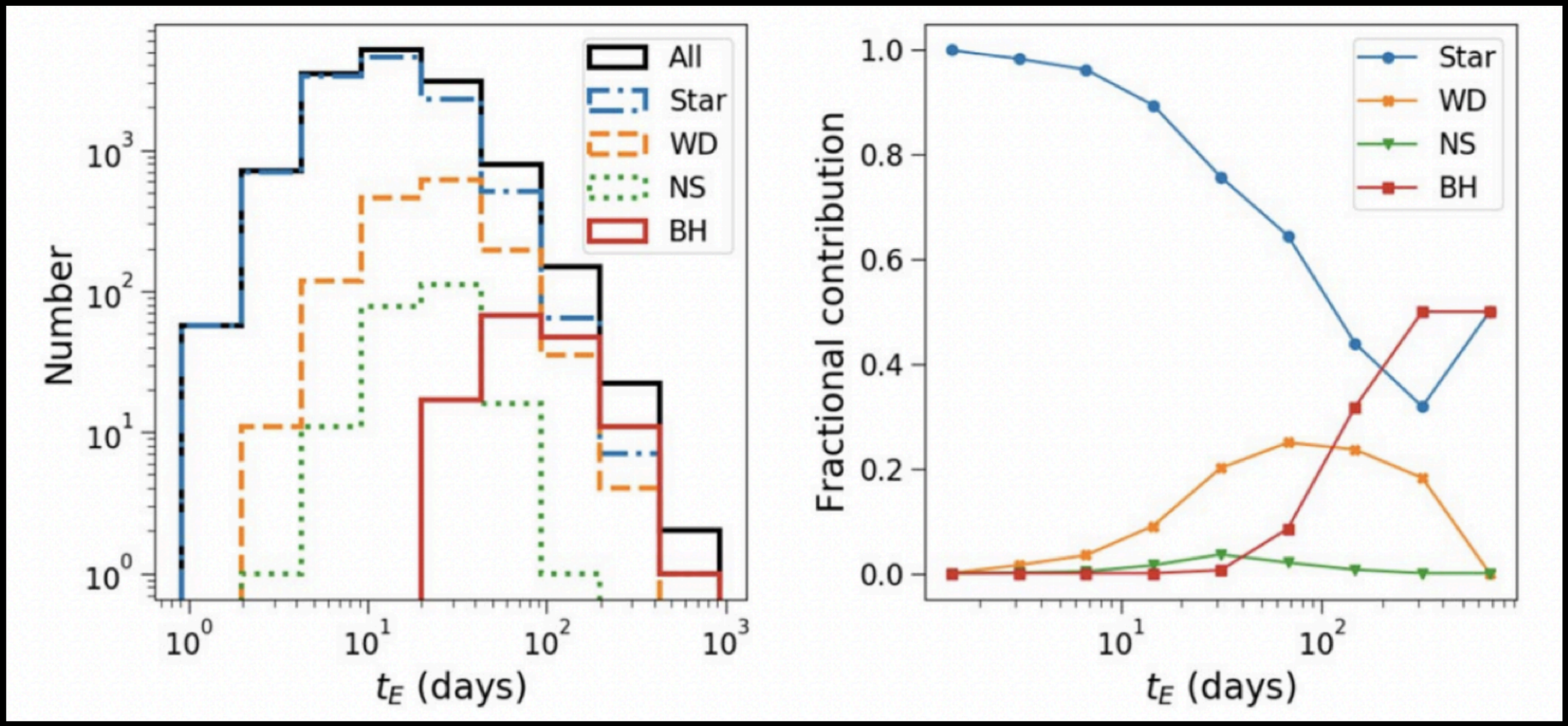
2. Follow up with high-precision (sub-mas) astrometry (e.g. HST) **$$$**

    - Astrometric deflection decays much more slowly than photometric magnification: ~10 t_E vs. ~1 t_E

    → ~10 epochs, spread over ~5-10 years

Problem selecting BH candidates as long-t_E events:

1. Throw away lots of BHs of modest t_E
2. Selection effects (e.g. BH mass vs. kick velocity)



Lam et al. 2020

Current BH searches prioritize **purity** over **completeness**: a practical choice because astrometric follow-up is so expensive

How to find isolated black holes (now)

It works! But…

1. Select BH candidates from photometric microlensing alerts
    - Long-duration events (t_E > 120 days)

Throws away lots of black holes

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST) **$$$**
    - ~10 epochs, spread over ~5-10 years

How to find isolated black holes (now)

It works! But…

1. Select BH candidates from photometric microlensing alerts
   - Long-duration events (t_E > 120 days)

Throws away lots of black holes

2. Follow up with high-precision (sub-mas) astrometry (e.g. HST) **$$$**
   - ~10 epochs, spread over ~5-10 years

Roman's BH characterizing superpower: **simultaneous photometry + astrometry over wide FOV**

No longer limited to small and biased samples for follow-up

Roman’s Galactic Bulge Time Domain Survey will detect lots of black holes

Roman's Galactic Bulge Time Domain Survey will detect lots of black holes

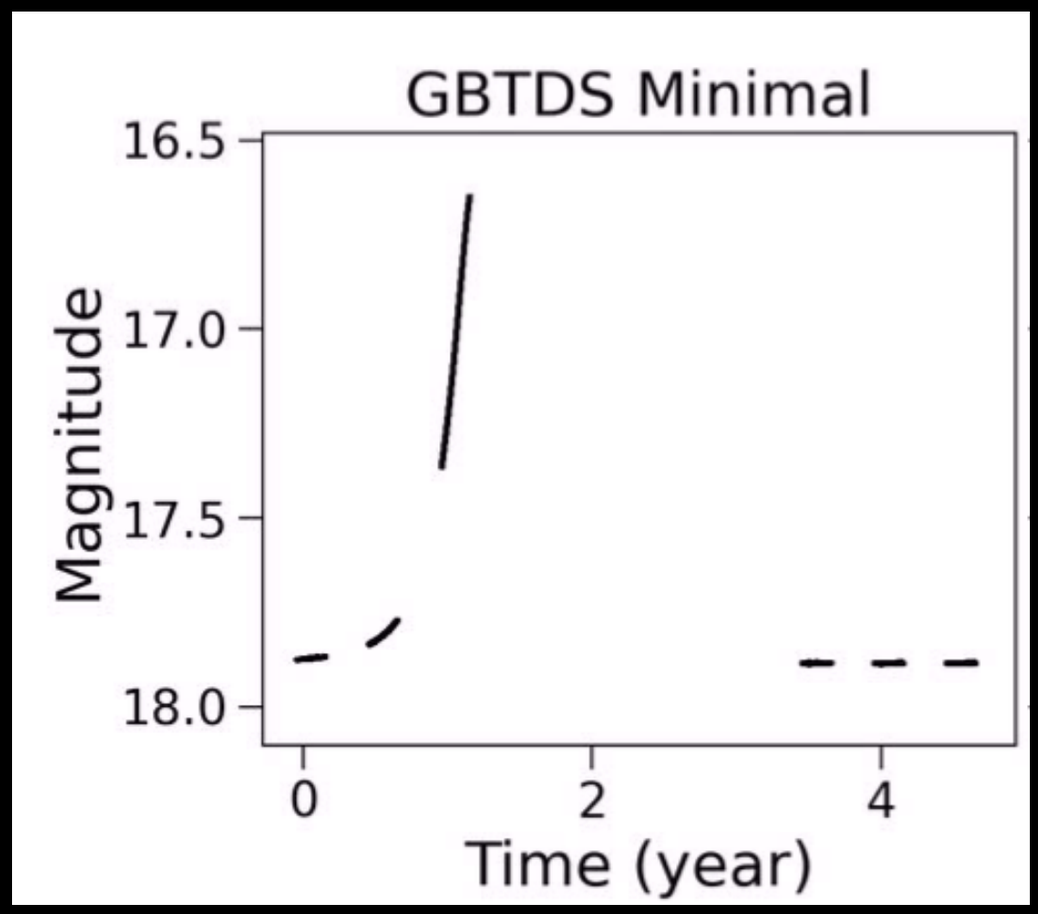
- 3 x 10^5 events (Penny+19) → 3000 BHs

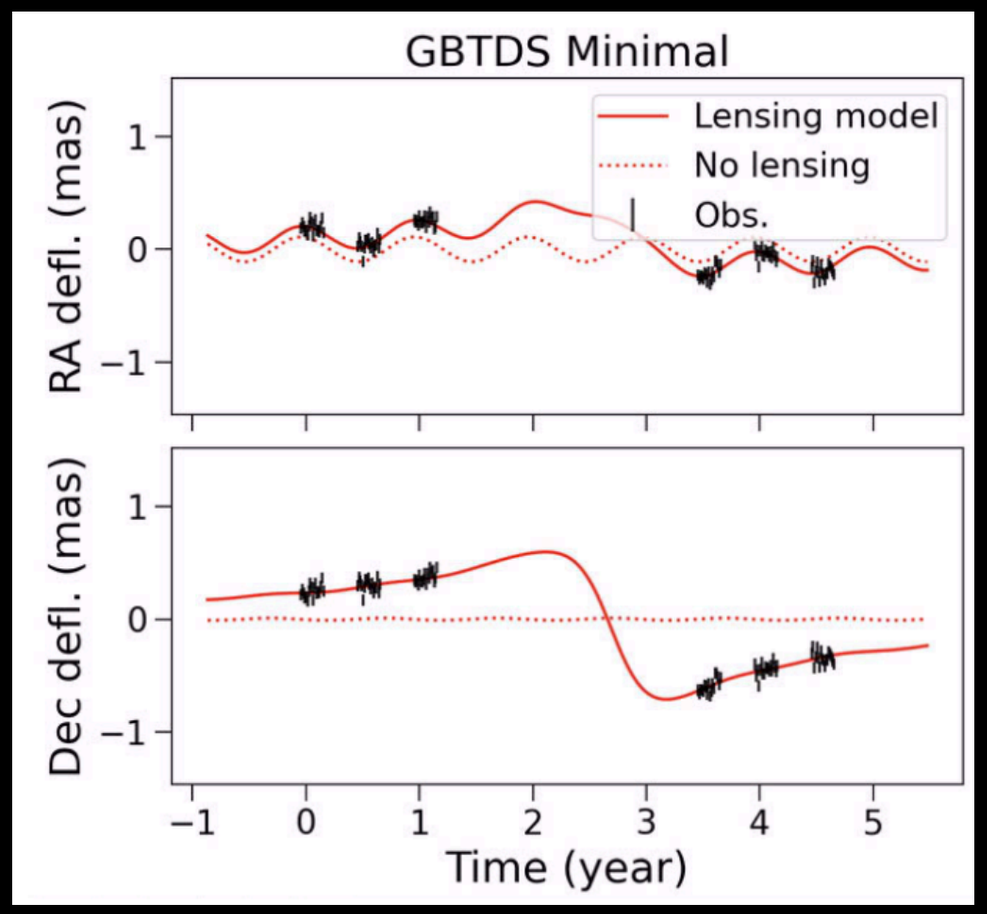
Roman's Galactic Bulge Time Domain Survey will detect lots of black holes

- 3 x 10^5 events (Penny+19) → 3000 BHs
- Only 5—25 *characterizable* (Sajadian & Sahu 23)

Roman's Galactic Bulge Time Domain Survey will detect lots of black holes

- 3 x 10^5 events (Penny+19) → 3000 BHs
- Only 5—25 *characterizable* (Sajadian & Sahu 23)
- Problem: 2.3 yr gap between first and last 3 seasons

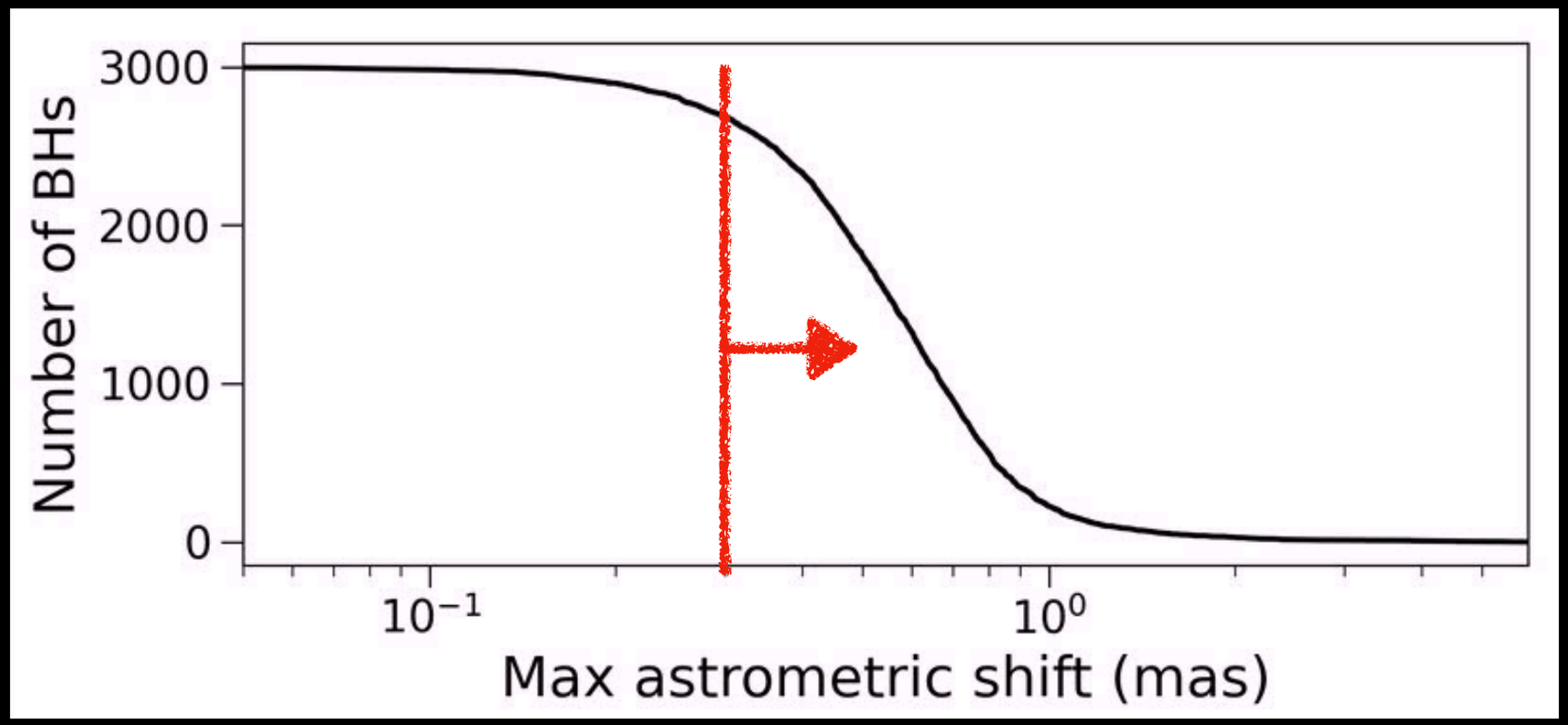




Lam+23 white paper

Roman's Galactic Bulge Time Domain Survey will detect lots of black holes and characterize them if the 2.3 yr gap is filled

- 1 obs/day = 0.3 mas ast. precision every 10 days, provide good photometric coverage
- Enable the robust characterization of many more BHs



Lam+23 white paper

Characterizing the Galactic BH population will enable a broad range of astrophysics

An isolated BH has recently been characterized with microlensing, and Roman can characterize many more (esp. if observing gaps are filled)

Characterizing the Galactic BH population will enable a broad range of astrophysics

An isolated BH has recently been characterized with microlensing, and Roman can characterize many more (esp. if observing gaps are filled)

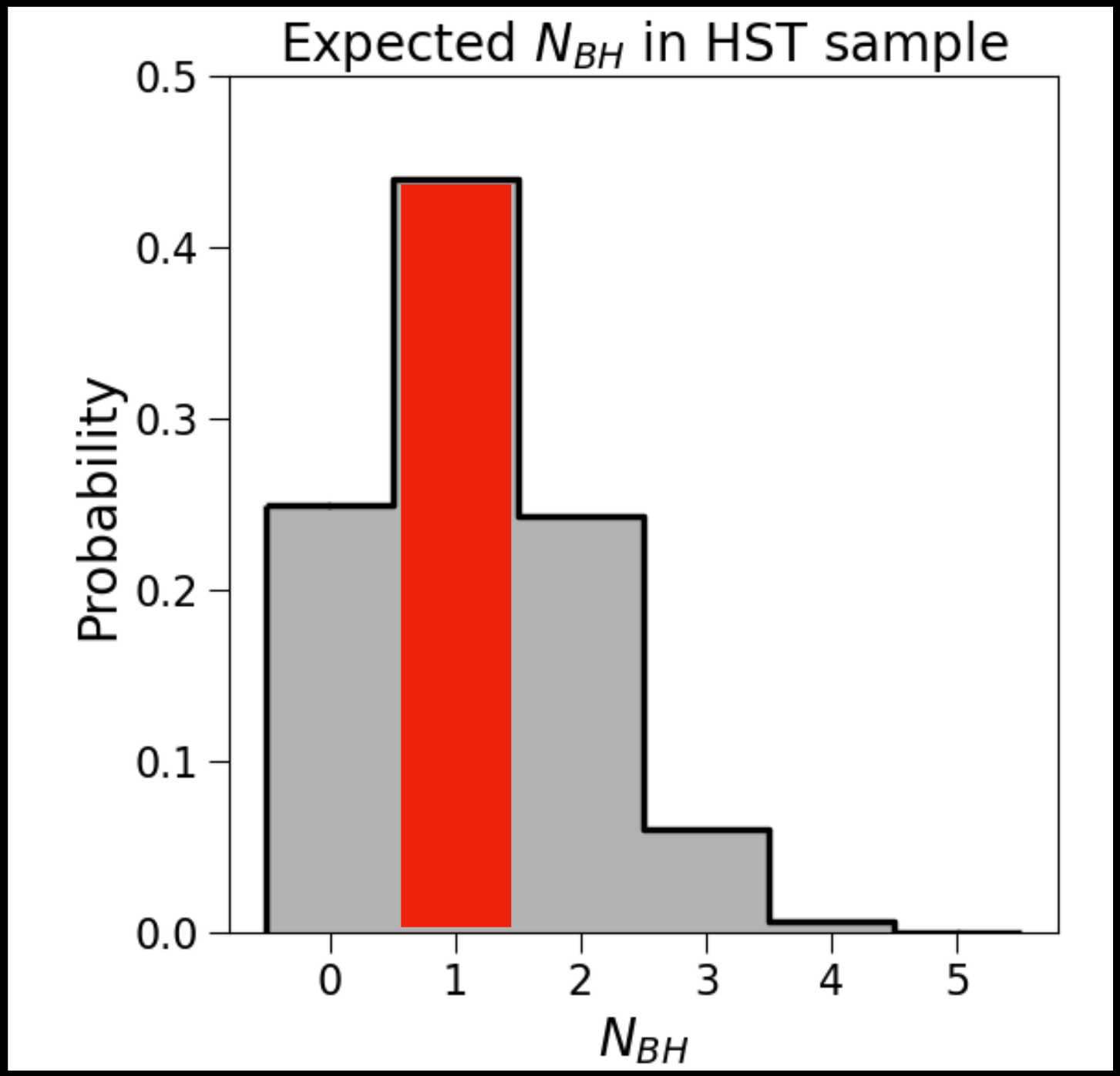
Other points of discussion and consideration:

- More stars in the IR = more crowding and blending
  - No methods yet for treating blended astrometry
  - (Pre- and post-) imaging with JWST?
- Bulge gaps in GBTDS need to be filled with other facilities
- Alerts + catalog of microlensing events (RAPID PIT, please?)

Questions, comments, ideas for collaboration:
Email me at clam@carnegiescience.edu

Extra slides

1 BH detection out of 5 candidates consistent with 10^8 isolated Galactic BHs



Correct for selection bias: longer events more likely to have BH lens

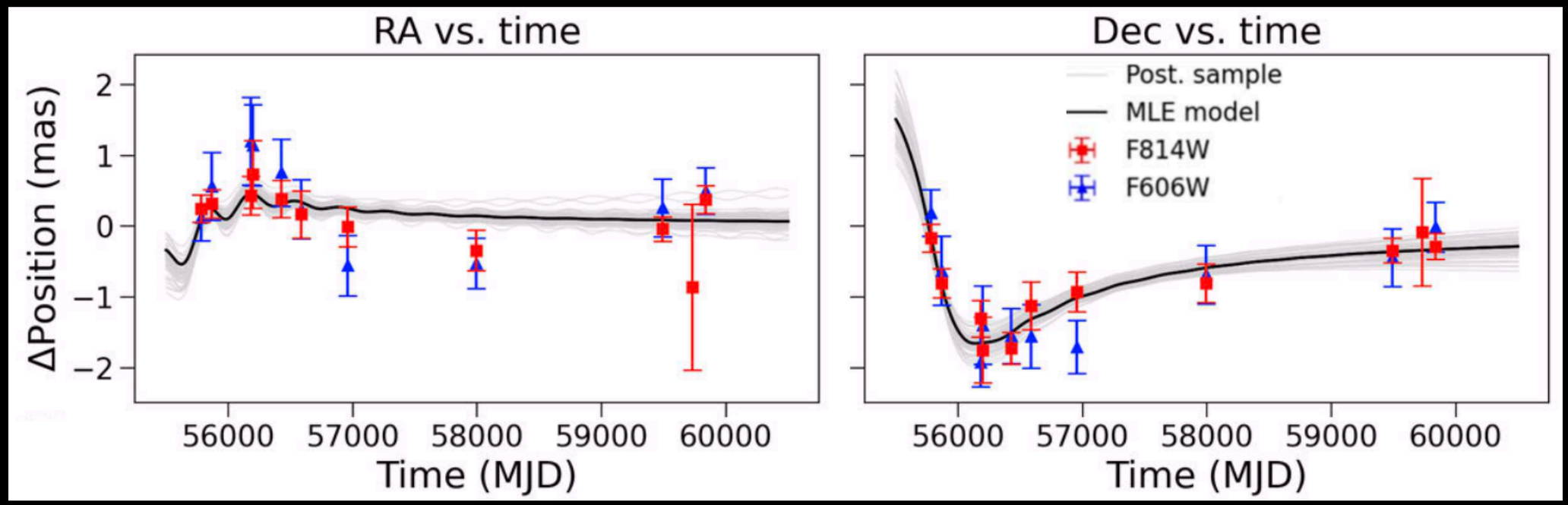
Weak constraint (for now): need a larger sample + more detections

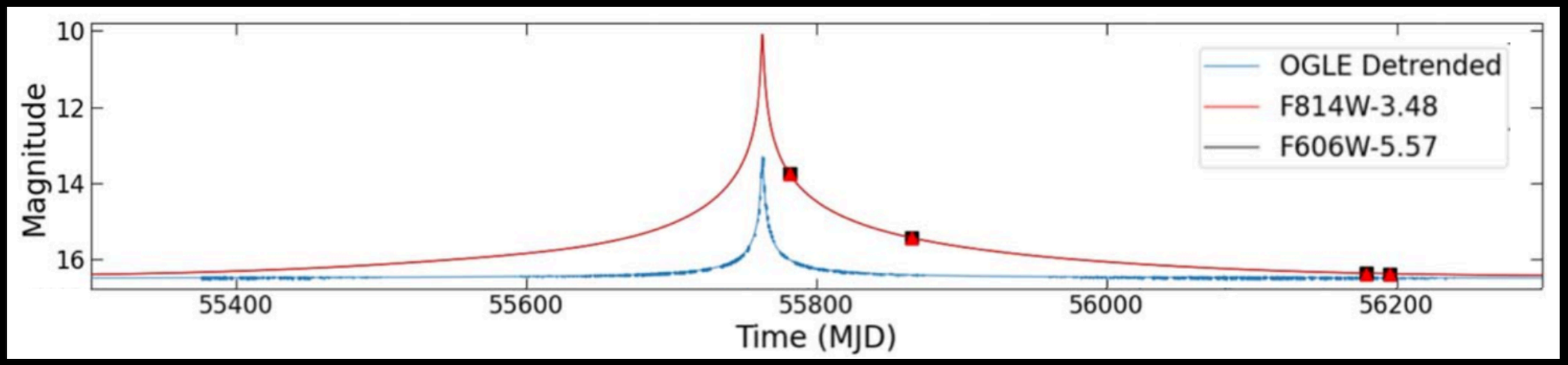
Updated from **Lam+22a**

OGLE-2011-BLG-0462: First isolated black hole characterized with microlensing

Ground-based photometry + HST WFC3-UVIS astrometry =

Mass = 6±1 $M_\odot$, Distance = 1.7±0.3 kpc, v_{trans} = 38±5 km/s





Lam & Lu 2023 (see also **Lam+22ab**, Sahu+22, Mroz+22)