Cold Exoplanet Demographics from Jupiter to Mars Mass with Microlensing Surveys

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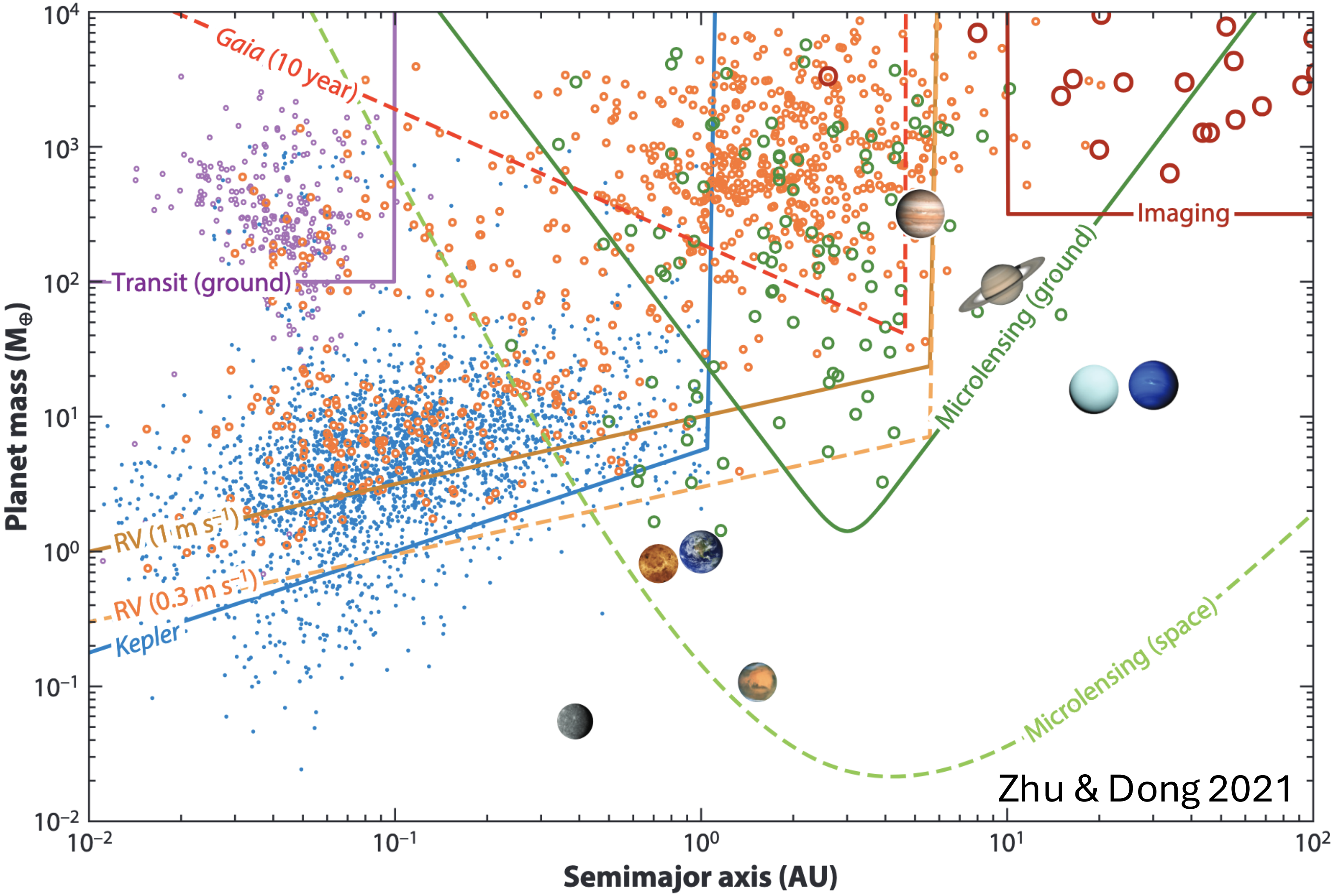
25^{th} Sagan Summer Workshop, Pasadena, July 2025

The problem



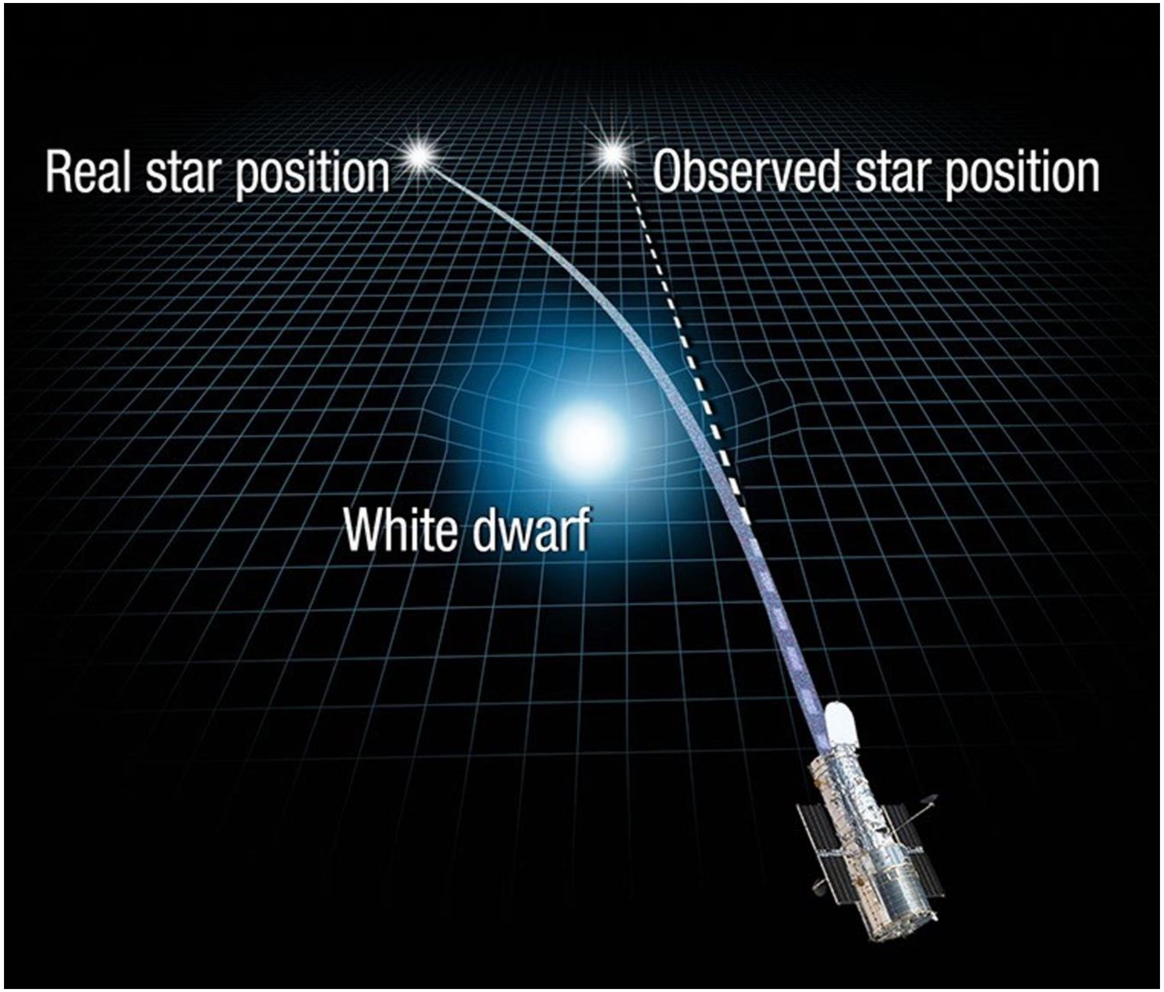
Gaia (10 year)
Transit (ground)
RV (1 m s⁻¹)
RV (0.3 m s⁻¹)
Kepler
Imaging
Microlensing (ground)
Microlensing (space)
Planet mass (M⊕)
Semimajor axis (AU)
Zhu & Dong 2021

Outline

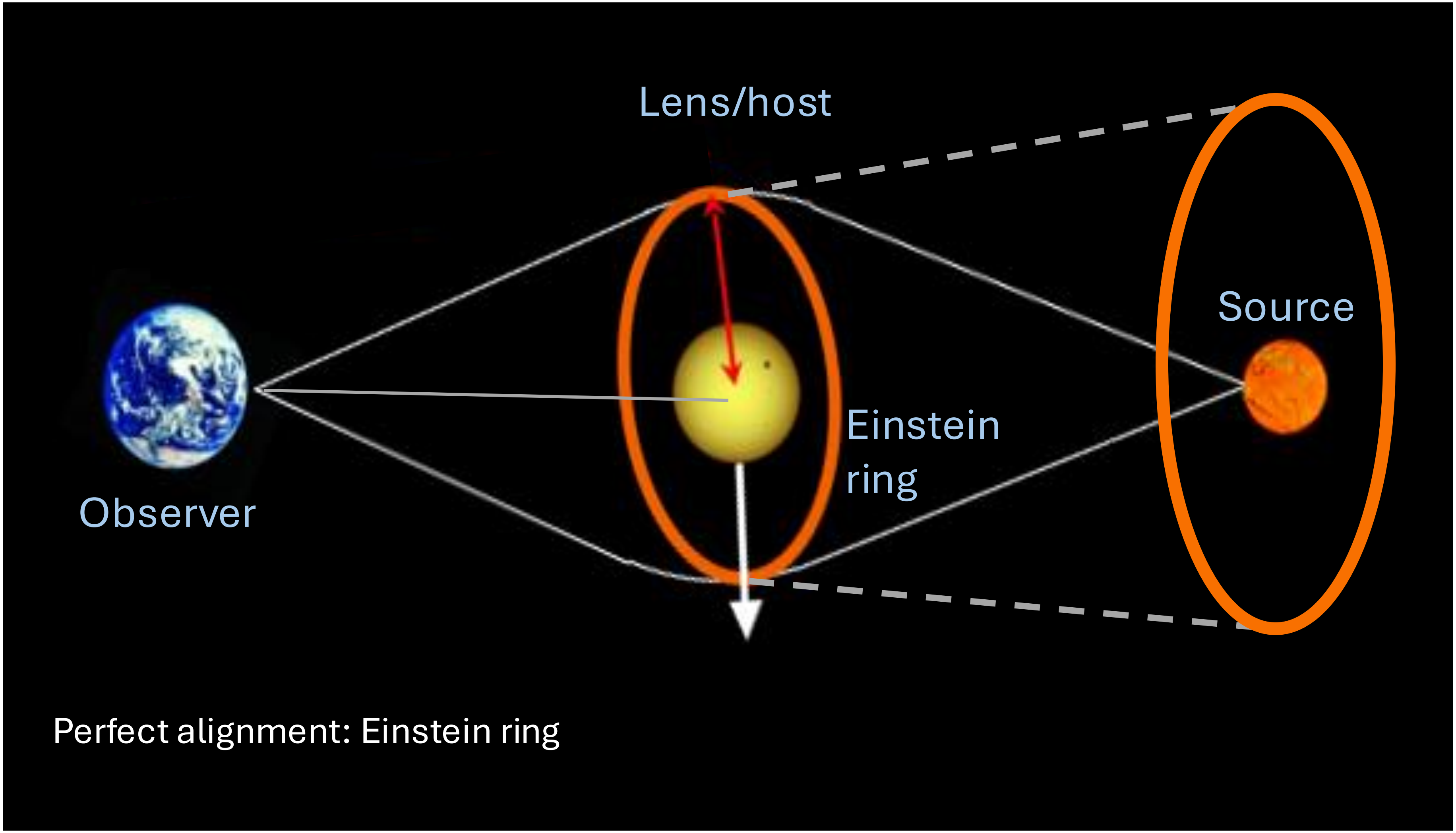
- Introduction to Microlensing
  - Gravitational lensing, single-lens microlensing
- Planetary microlensing
  - Microlensing parameters: timescale, mass ratio, separation
- Cold Exoplanet Demographics
  - How to do it
  - Results so far
- Measuring Masses
- Free-Floating Planets
- Future Surveys

Introduction to Microlensing

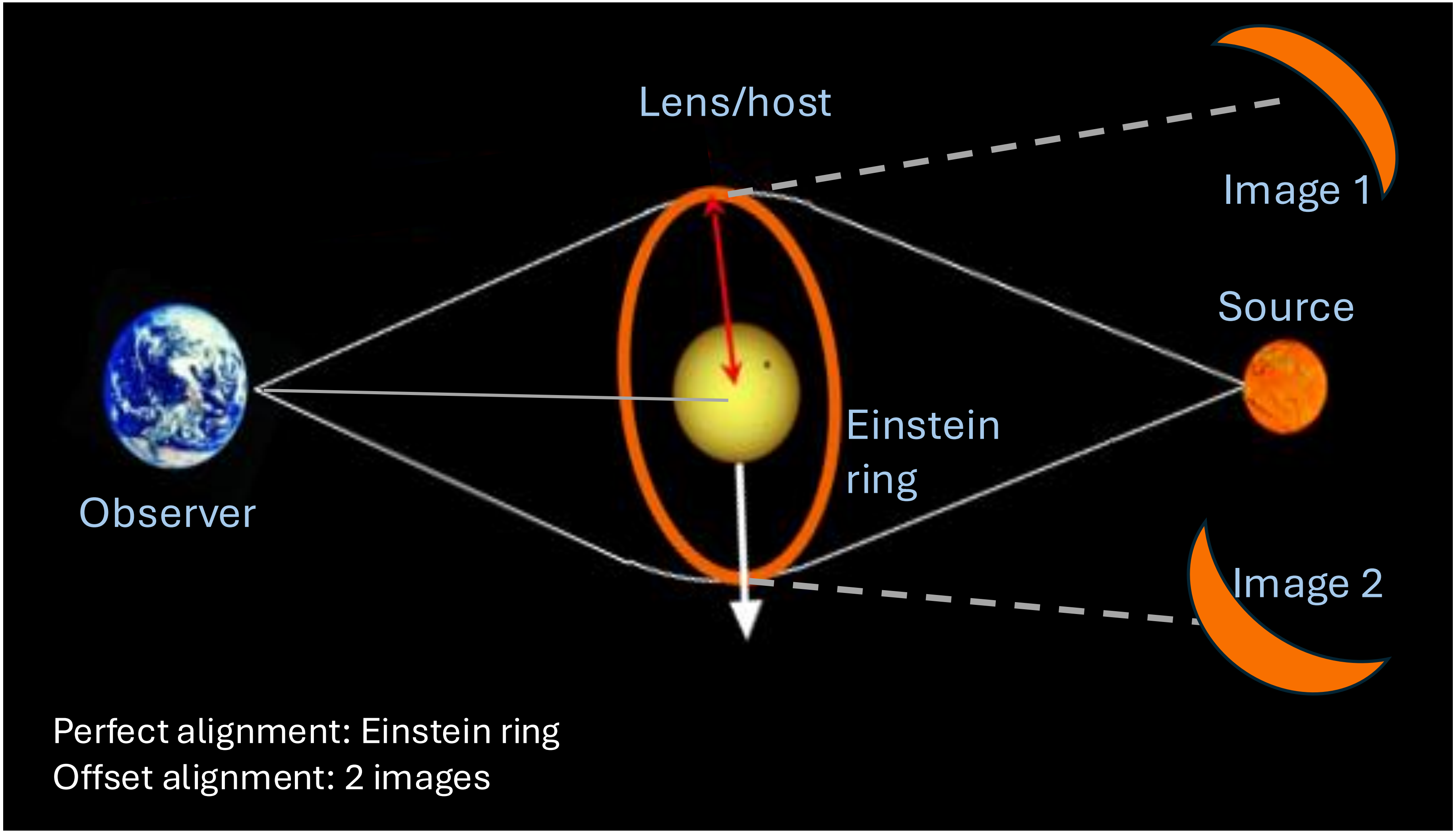
Mass bends light



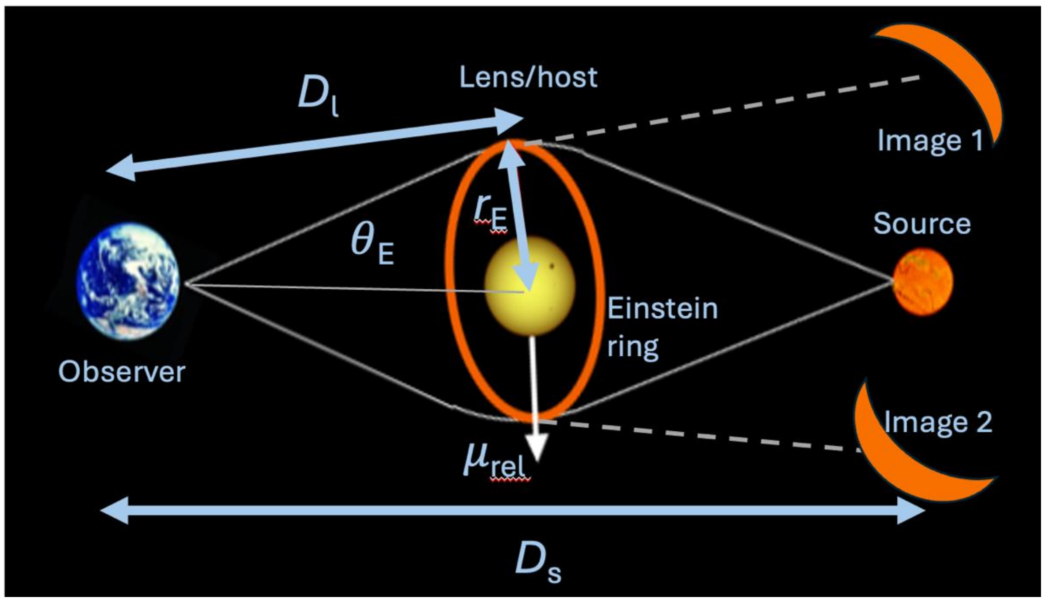
Gravitational Lensing



Gravitational Lensing



Microlensing Observables



- Units: $M_\odot$, kpc, mas
- Angular Einstein Radius

$$\theta_E \approx 3 \text{ mas} \sqrt{M\pi_{rel}}$$

$$\pi_{rel} = \pi_l - \pi_s = \frac{\text{AU}}{D_s} - \frac{\text{AU}}{D_l}$$

- Microlensing Timescale

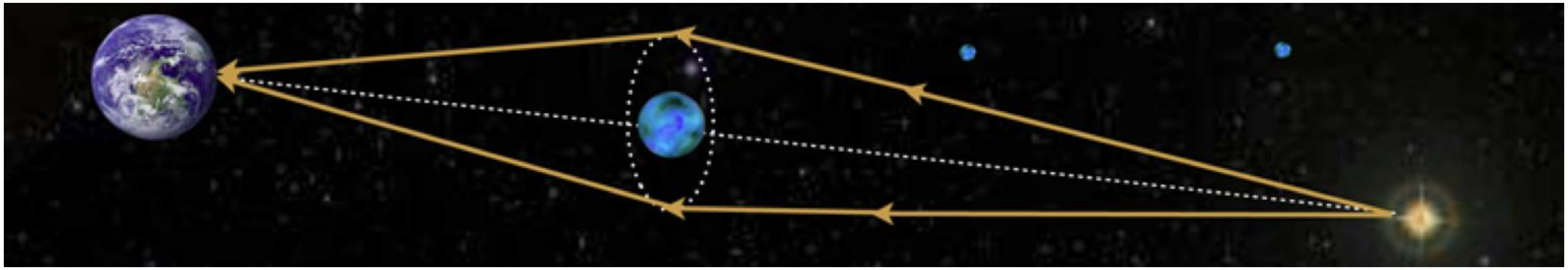
$$t_E = \frac{\theta_E}{\mu_{rel}} \sim 1 \text{ month}$$

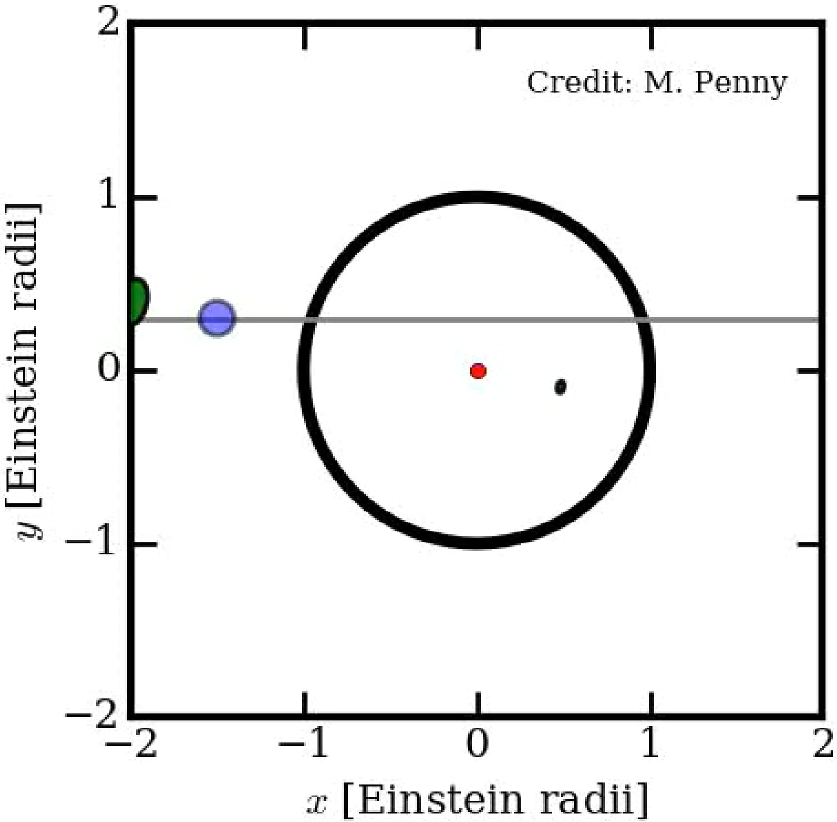
- Physical Einstein Radius

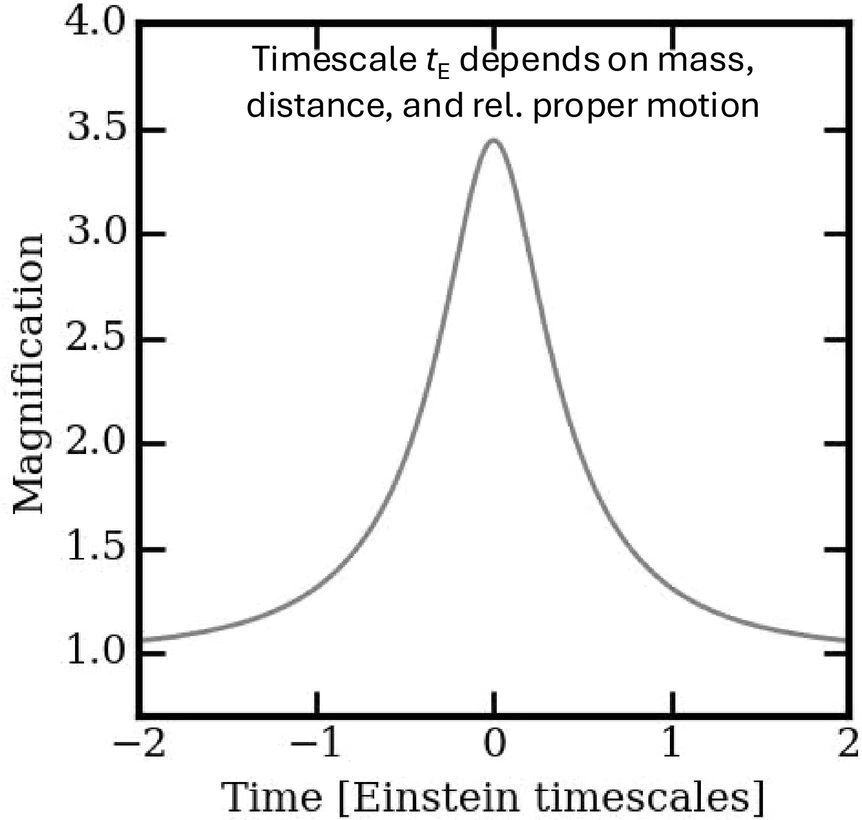
$$r_E = D_l\theta_E \approx 3 \text{ AU } D_l\sqrt{M\pi_{rel}}$$

Lens 6 kpc, Source 8.5 kpc, $\pi_{rel} = 0.05$ mas

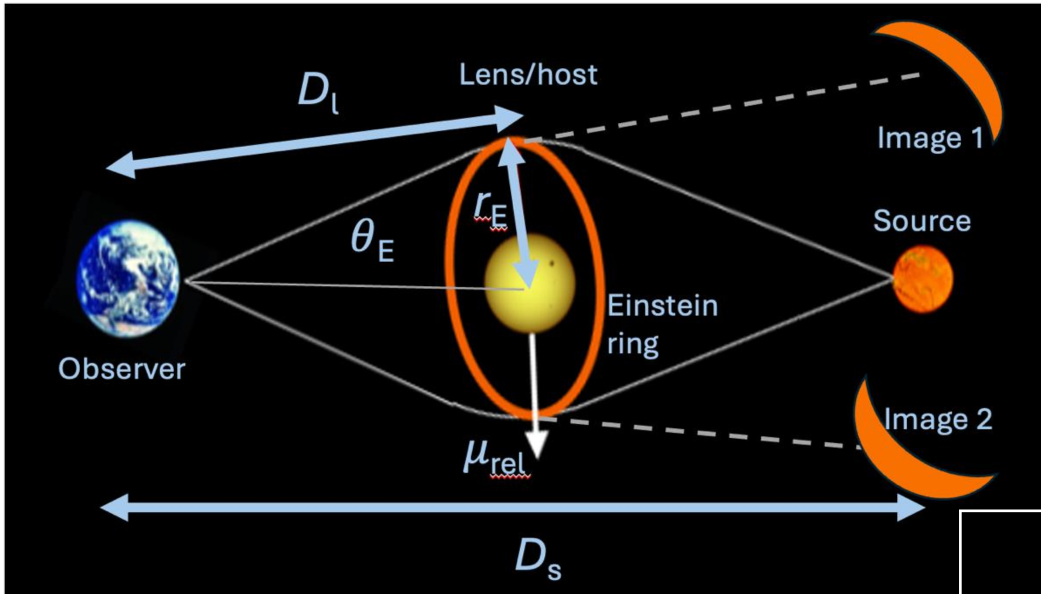
A single microlens







Microlensing Observables



$$\theta_E \propto \sqrt{M}$$

$$r_E \propto \sqrt{M}$$

$$t_E \propto \sqrt{M}$$

Solar mass: ~months

Jupiter mass: ~day

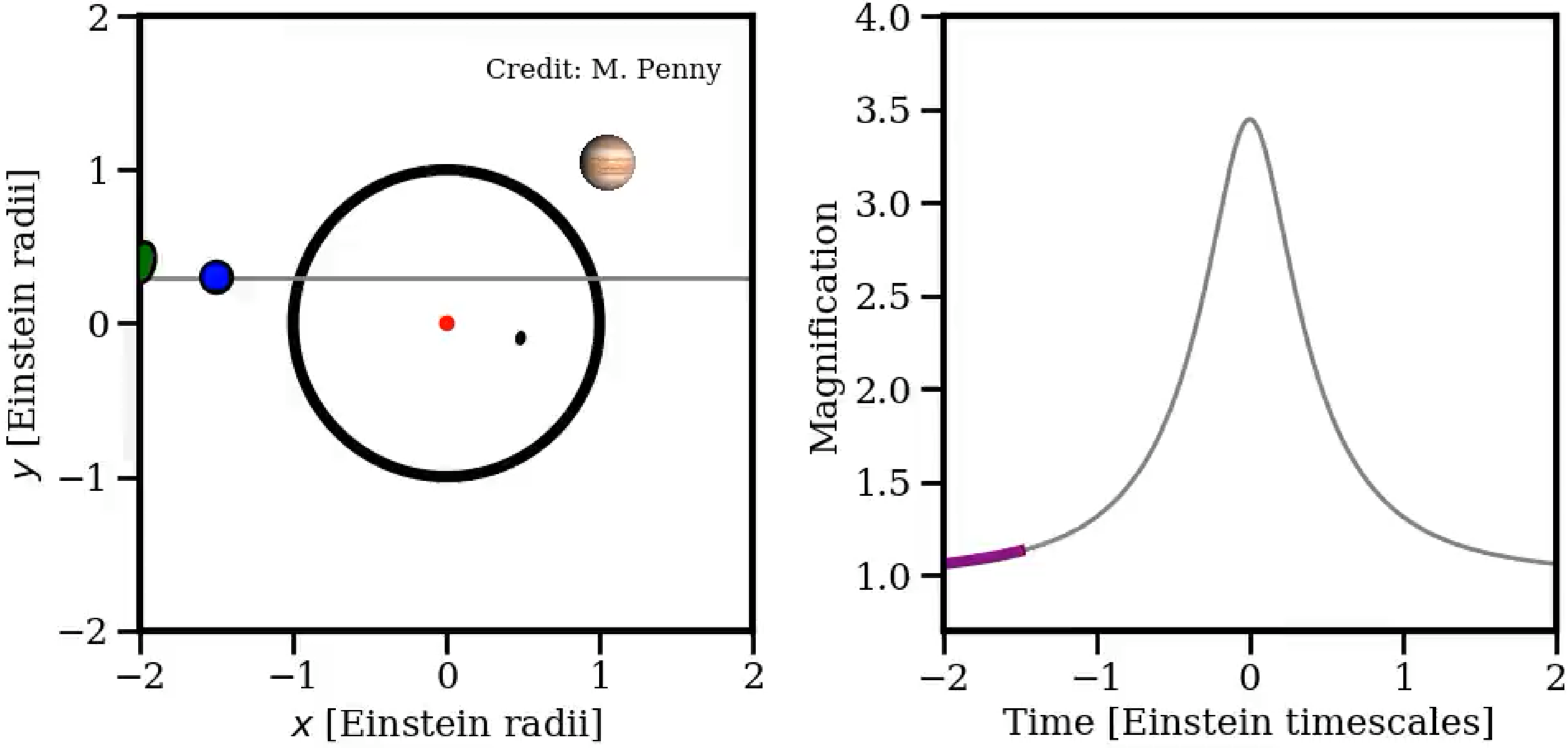
Earth mass: ~hour

Dictates survey cadence

Planetary microlensing

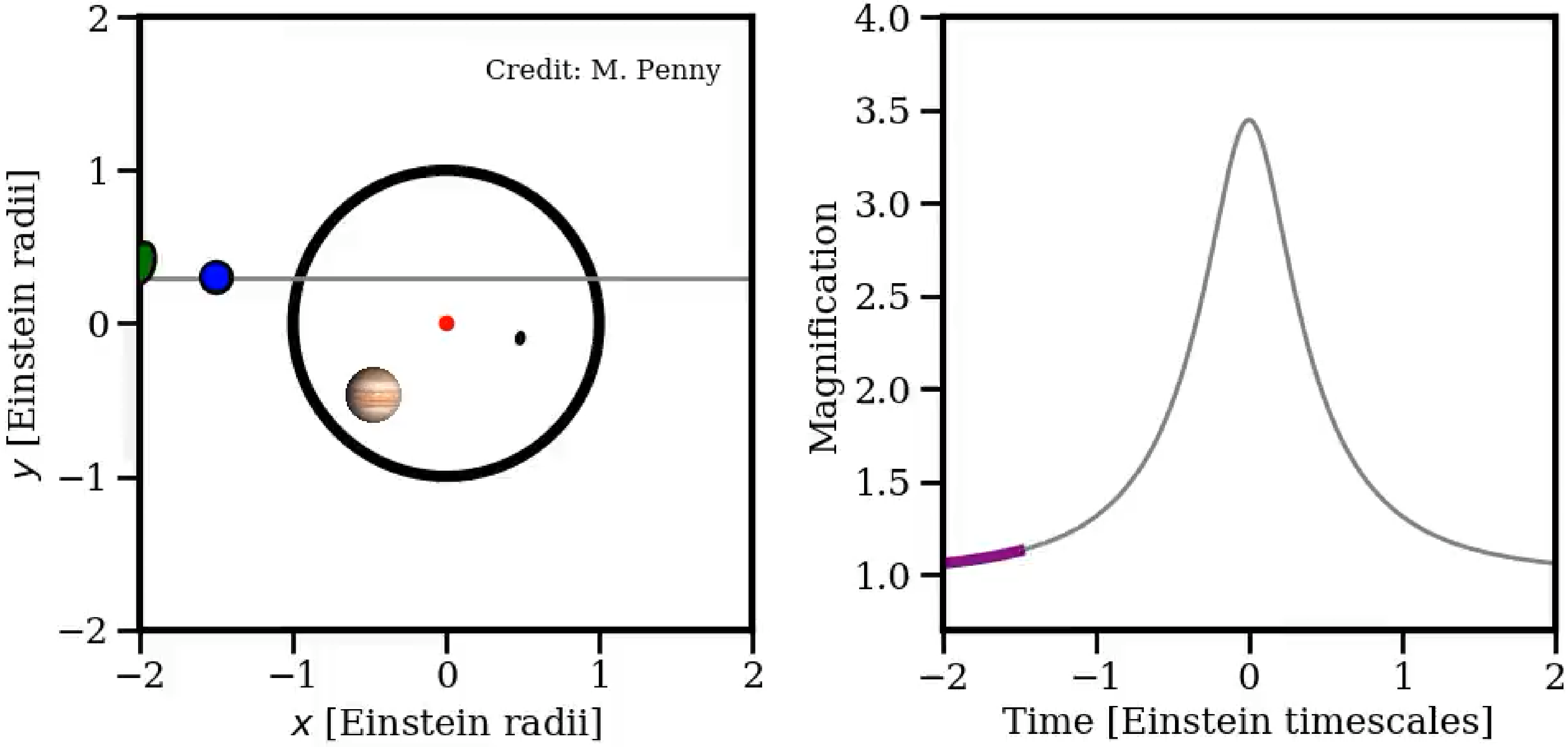
Planetary microlensing: image perturbations

Major image perturbation

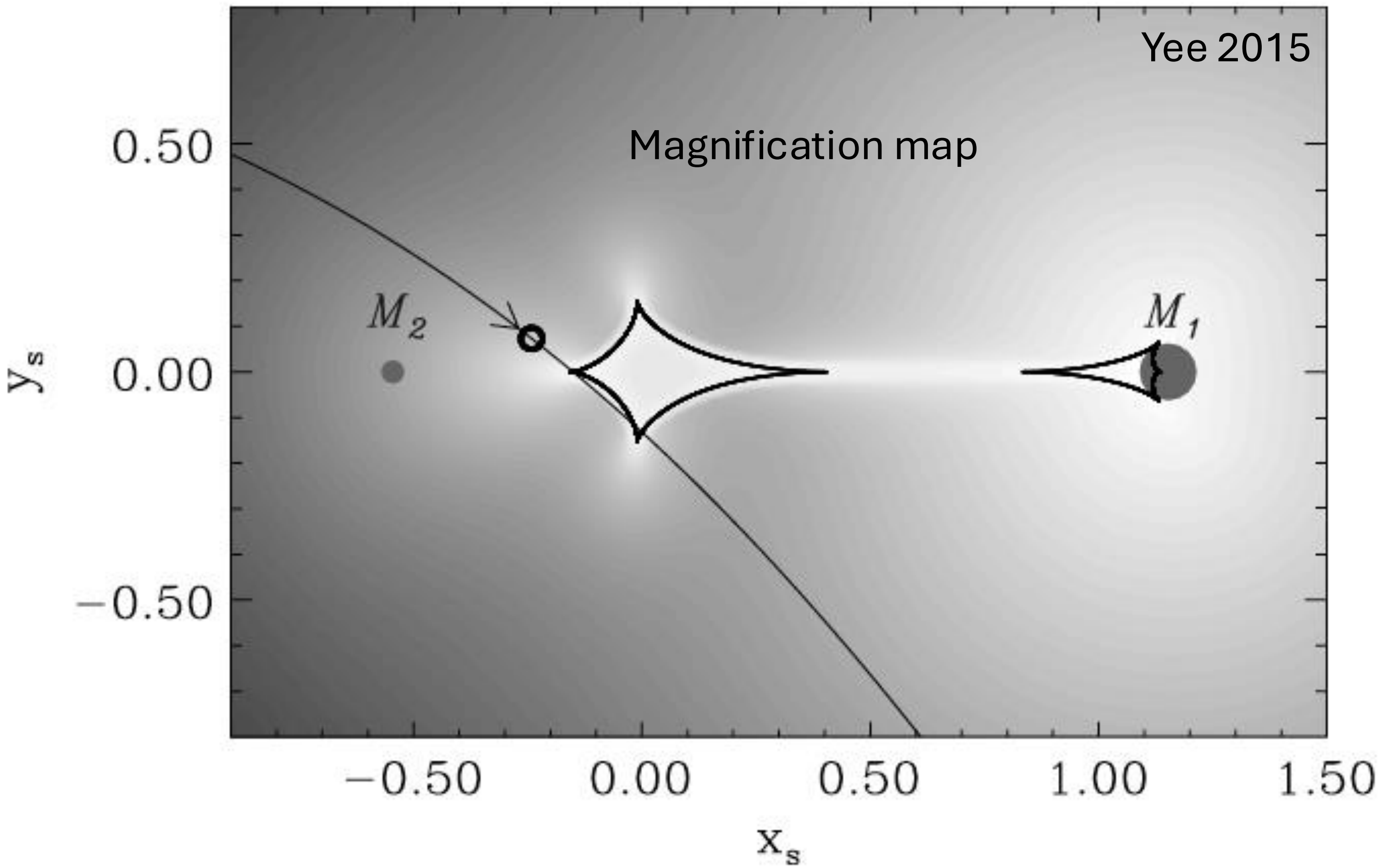


Planetary microlensing: image perturbations

Minor image perturbation



Planetary microlensing: caustics

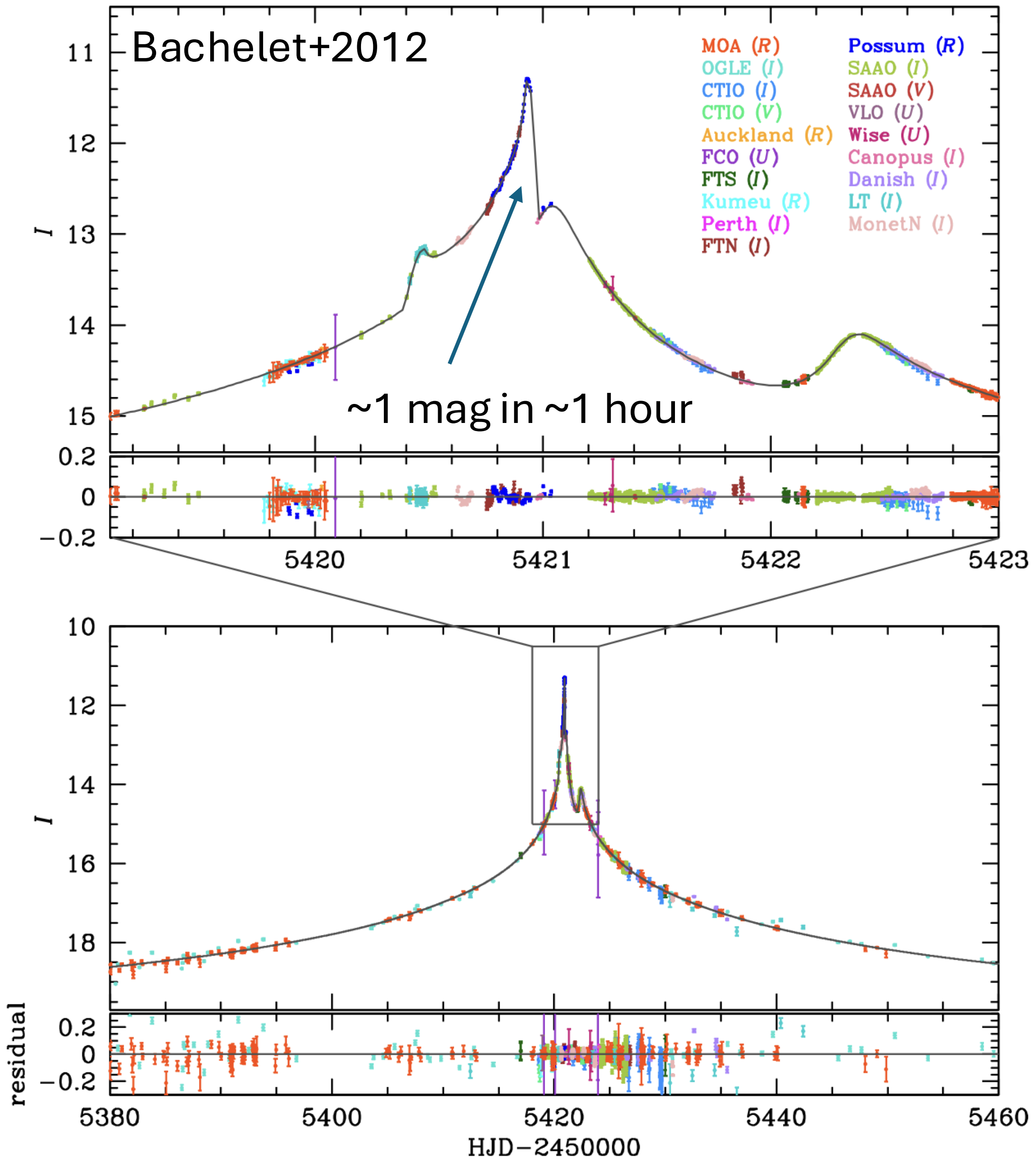


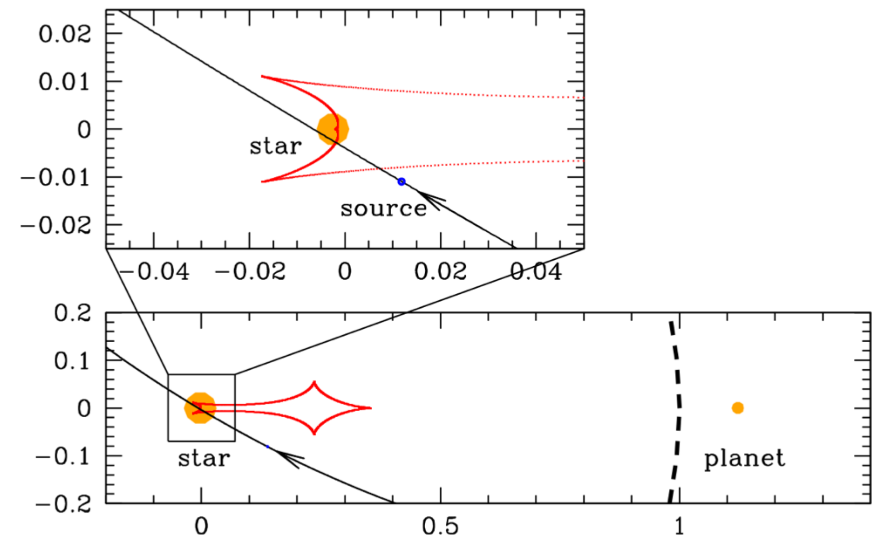
Caustics separate regions with different numbers of images

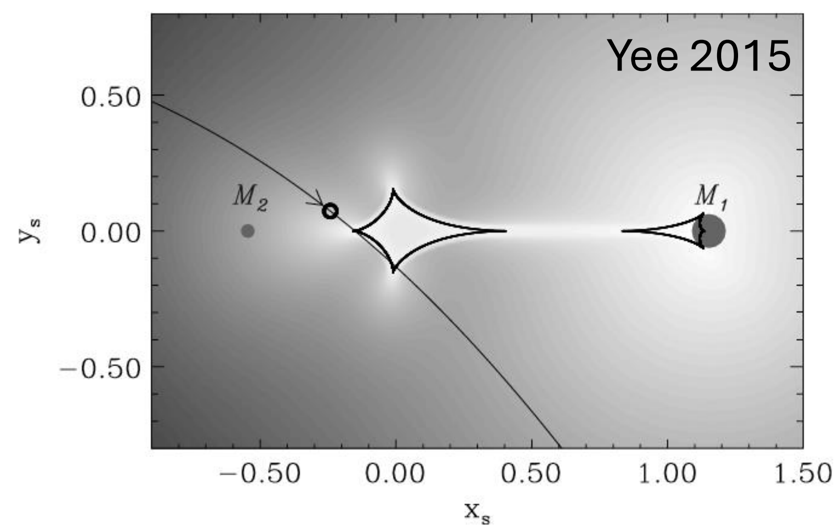
Magnification just on the inside is very high

Can lead to sharp changes in magnification

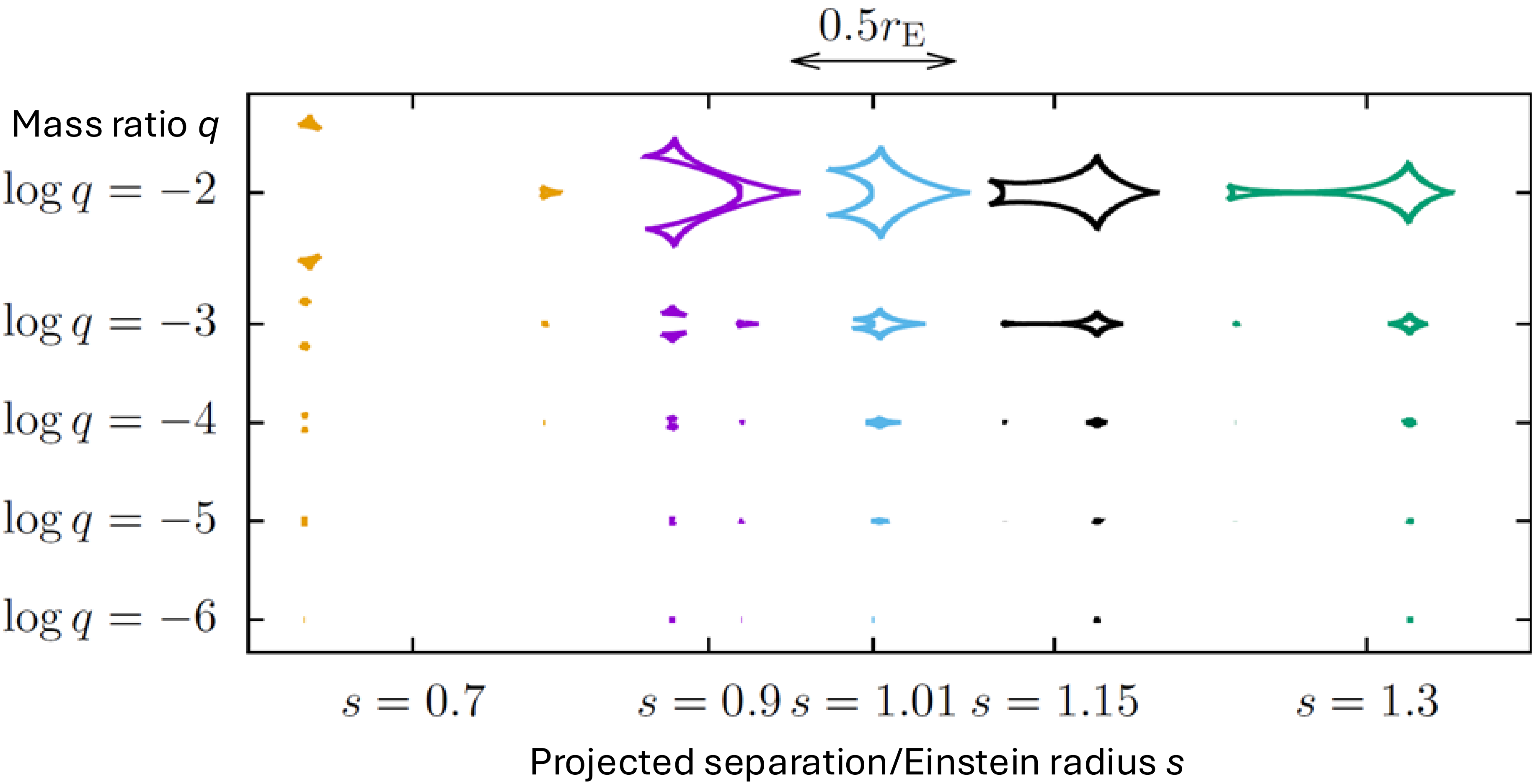
Lightcurve with Caustic Crossings





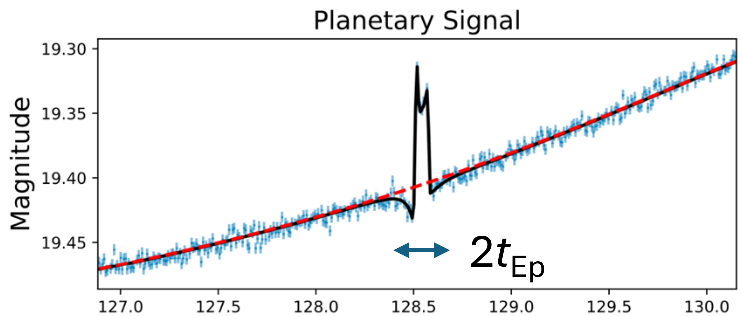


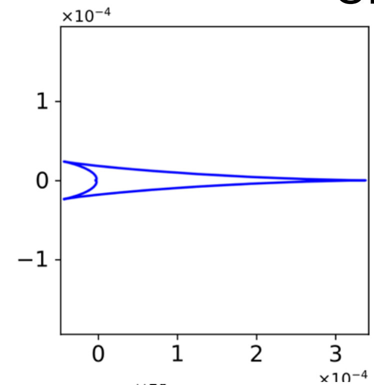
How caustics vary with planet properties

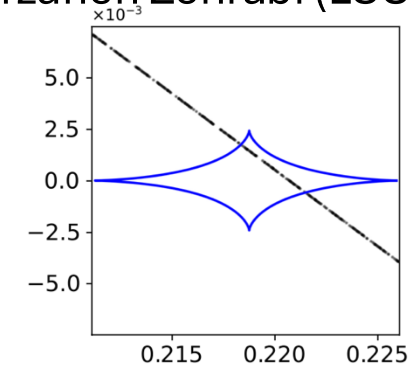


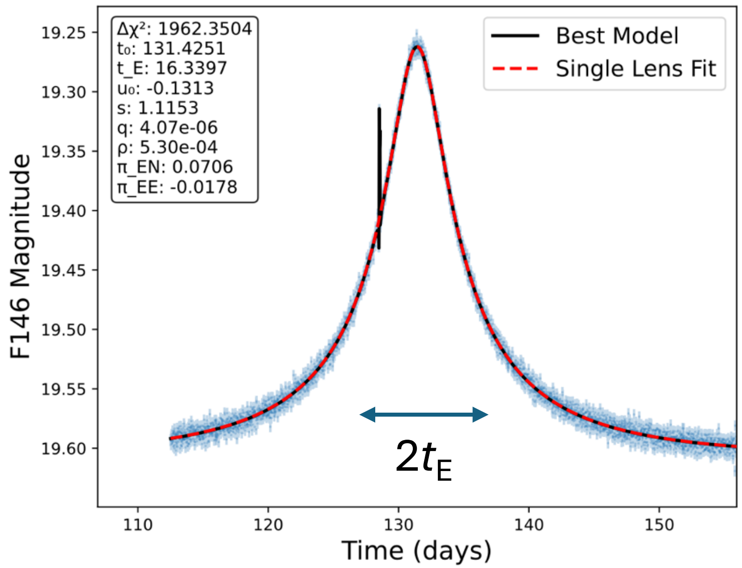
Measuring Planet Parameters image perturbations

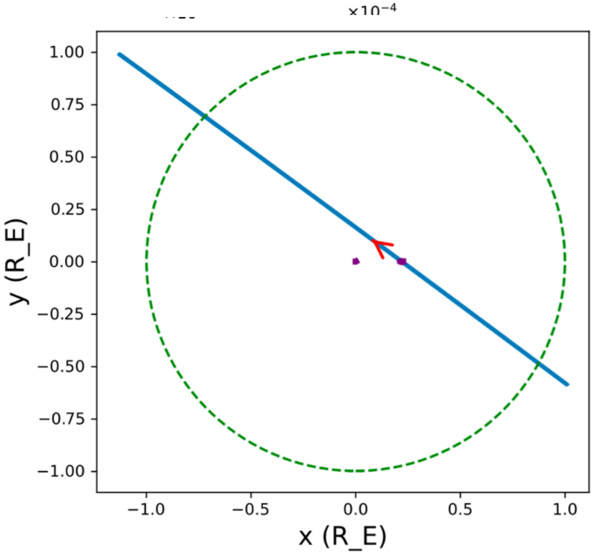
Credit: Farzaneh Zohrabi (LSU)











Mass ratio $q \sim \left(\frac{t_{\mathrm{E,p}}}{t_E}\right)^2$

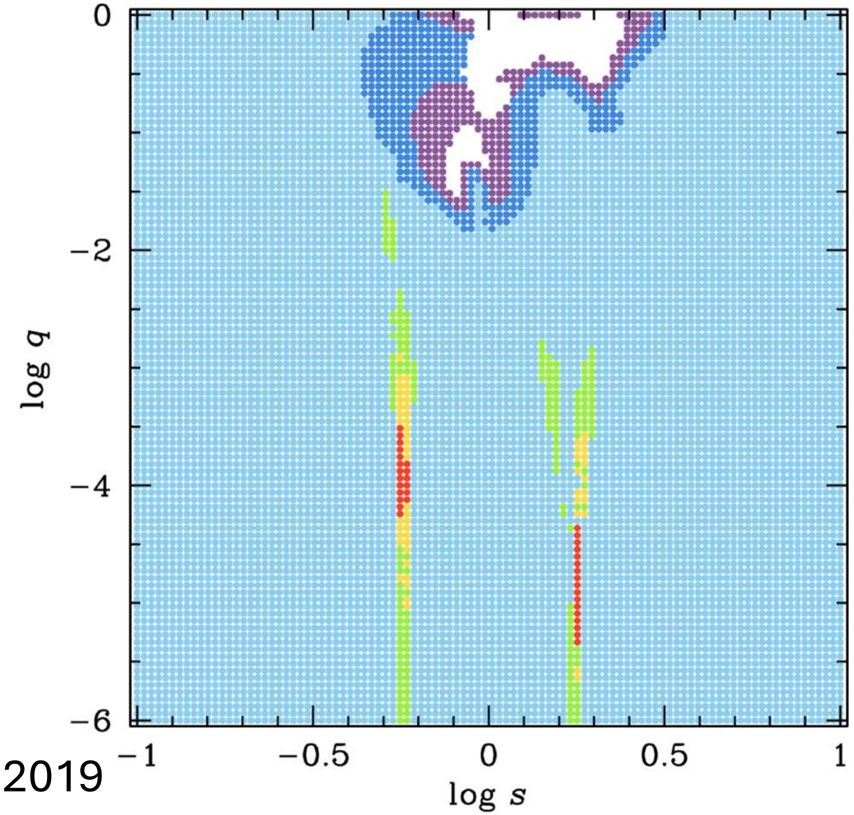
Projected Separation

$$s = \frac{a_\perp}{r_\mathrm{E}} \approx \frac{|t_{0,\mathrm{p}} - t_0|}{t_\mathrm{E}}$$

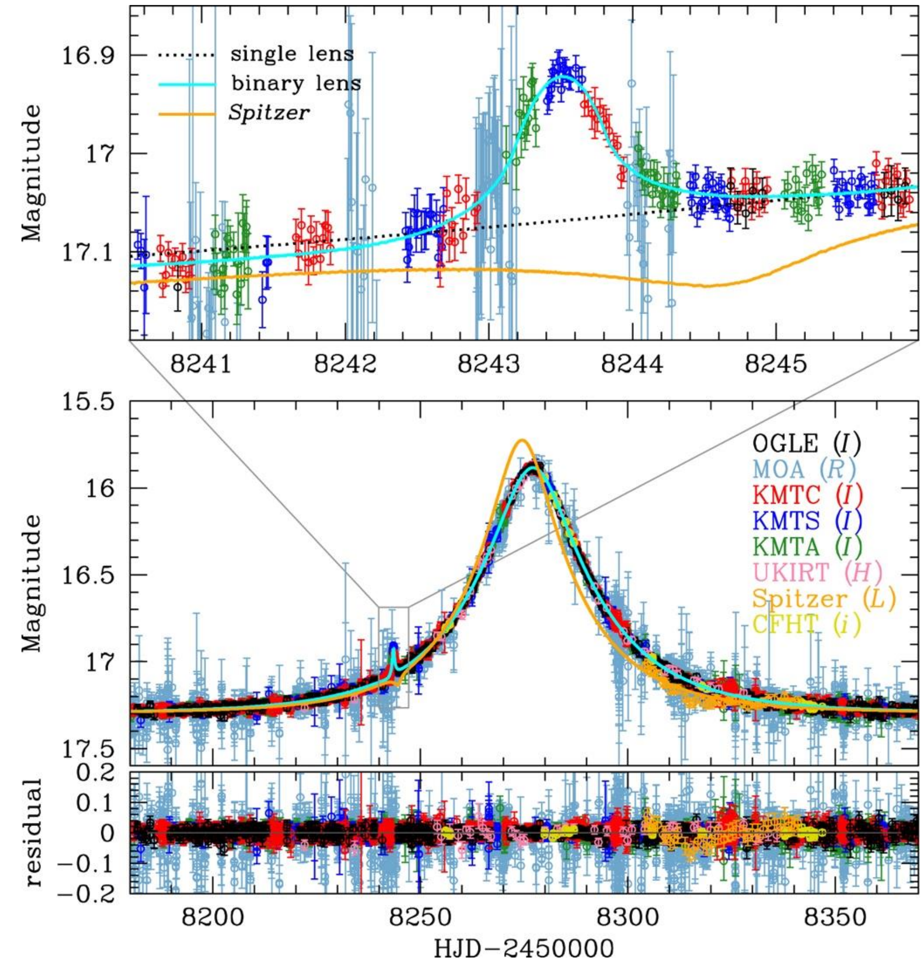
Measuring Planet Parameters: Modeling

Open Source Tools:
- BAGLE
- eesunhong
- MuLensModel
- PyLIMA
- RTModel

1. Grid search over s,q,α
2. Downhill fit of all parameters



Jung+ 2019



Cold Exoplanet Demographics

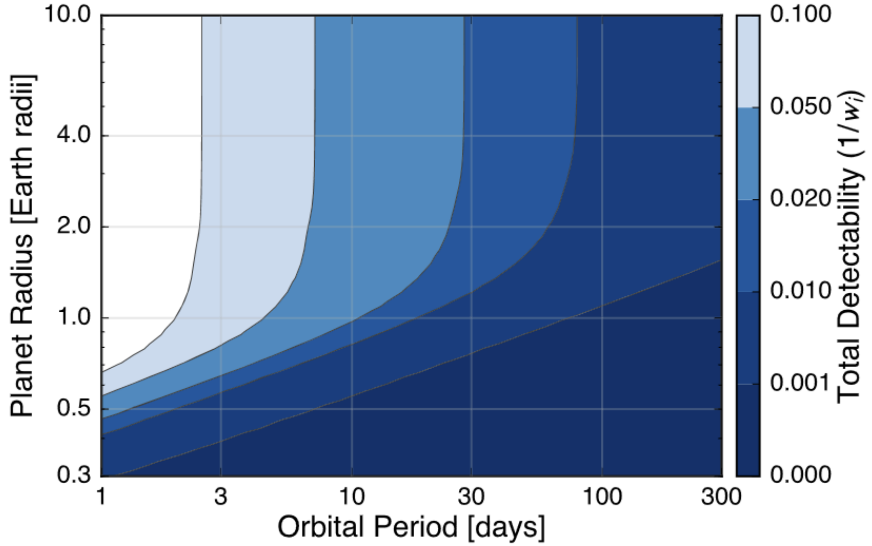
Measuring exoplanet demographics

$$Occ.Rate \approx \frac{No.detected}{No.of\ events \times Prob.of\ detection}$$

$$\approx \frac{No.detected}{No.expected\ if\ 1\ per\ star}$$

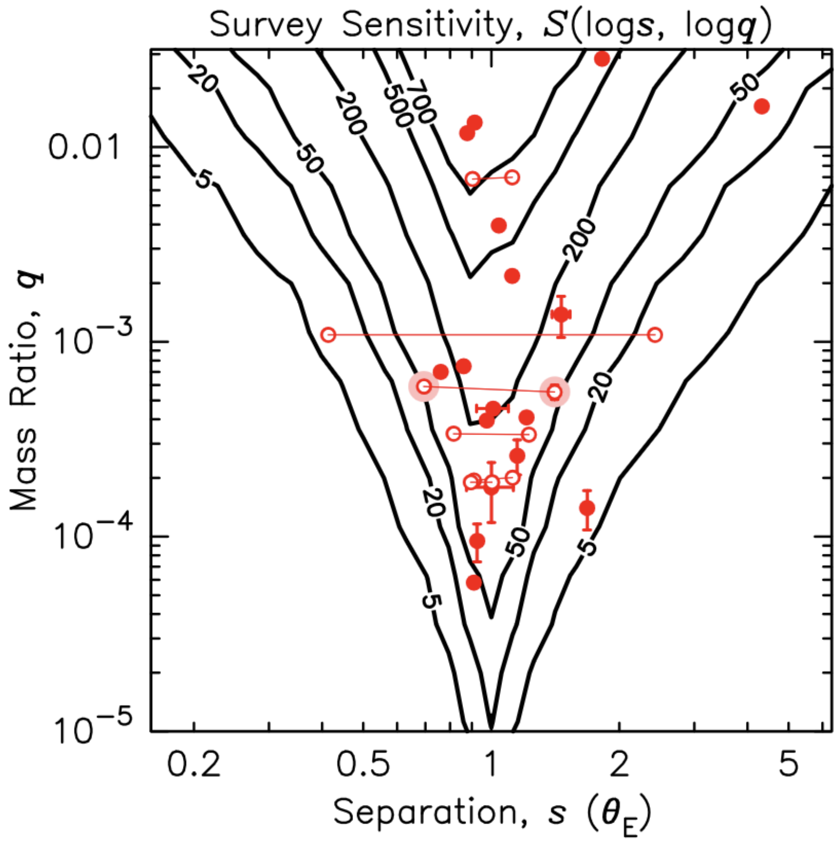
Detection efficiency

Transits



Fulton+2017

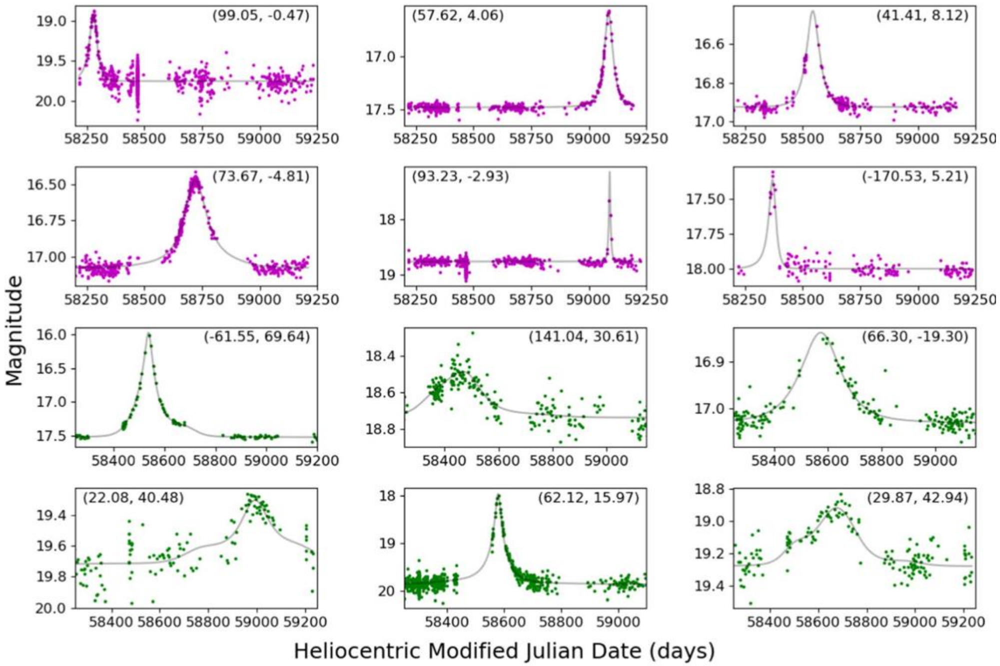
Microlensing



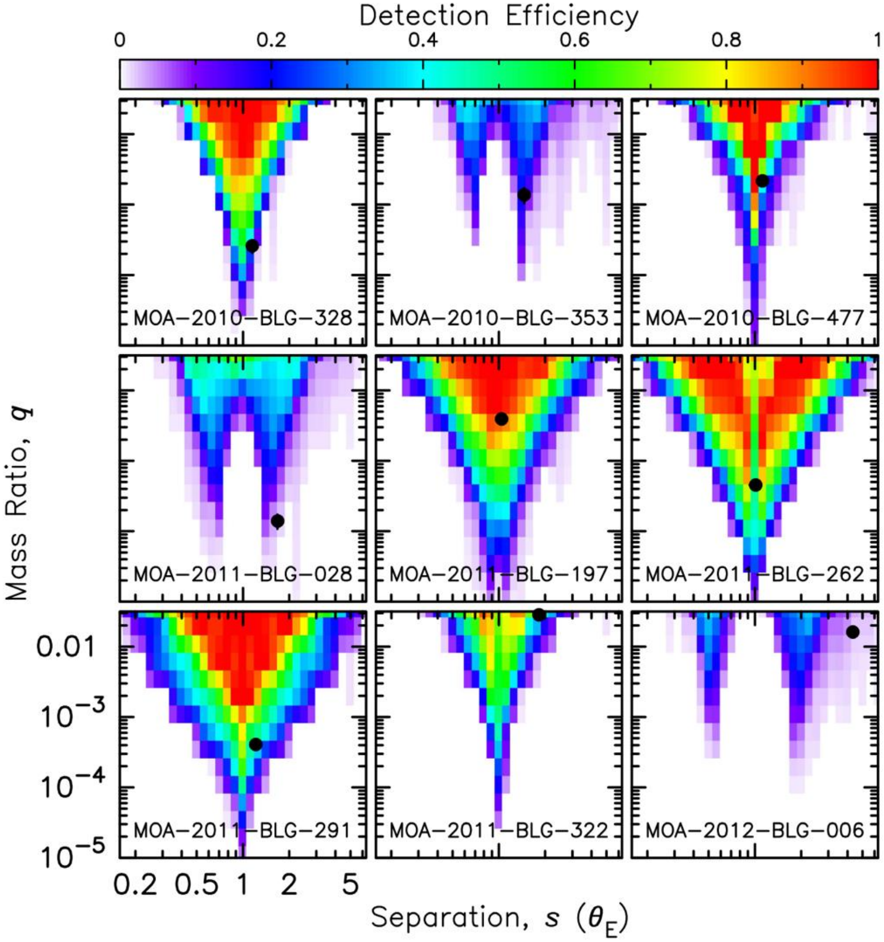
Suzuki+2016

Detection efficiency – strong event dependence

Medford+2023

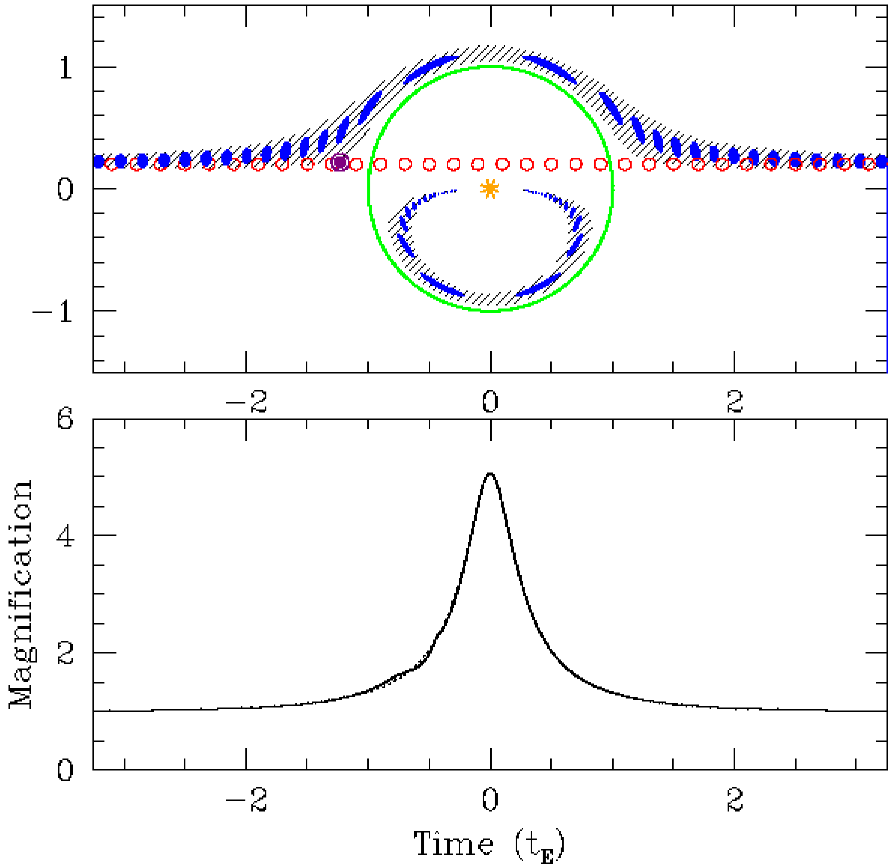


Suzuki+2016

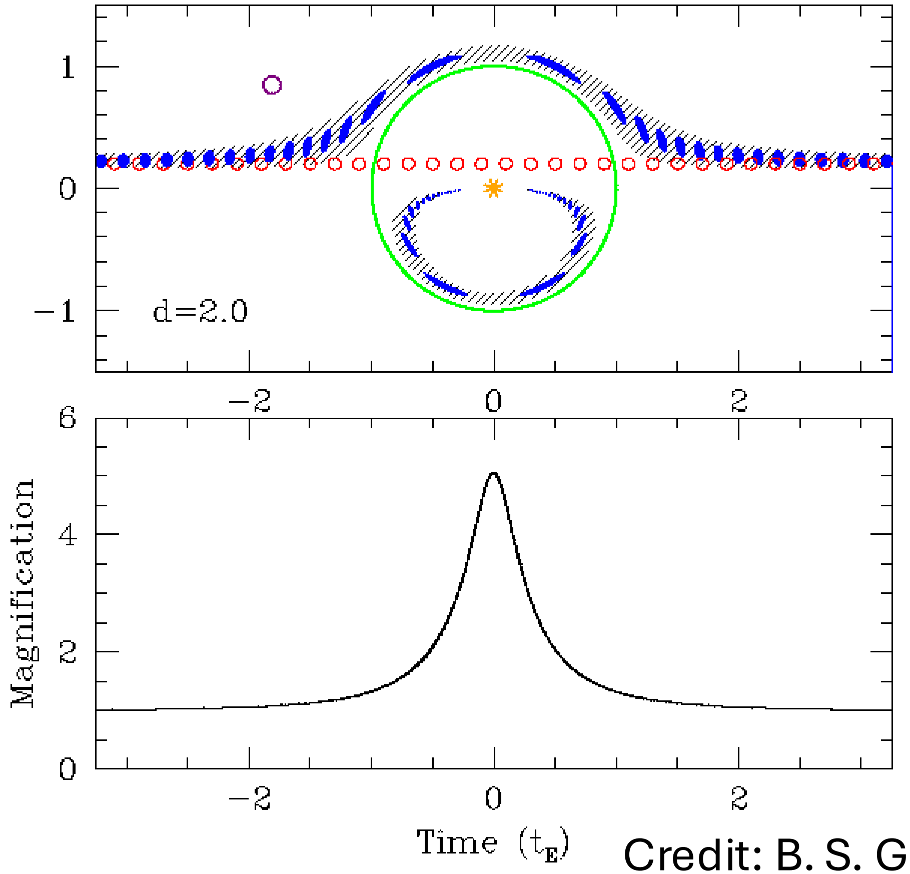


Marginalize over parameters

Angle



Projected separation

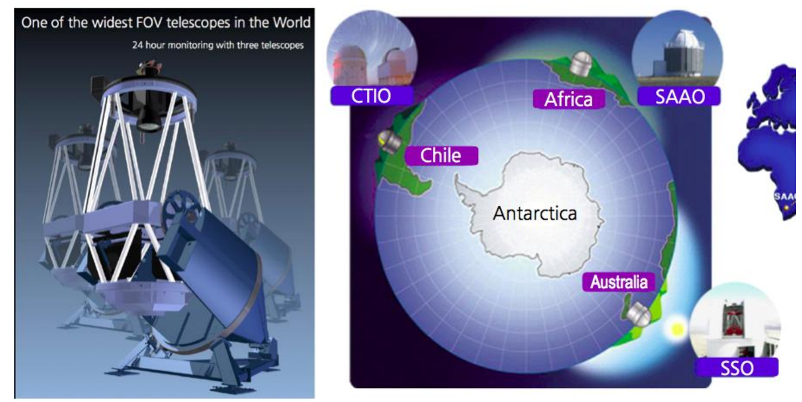


Credit: B. S. Gaudi

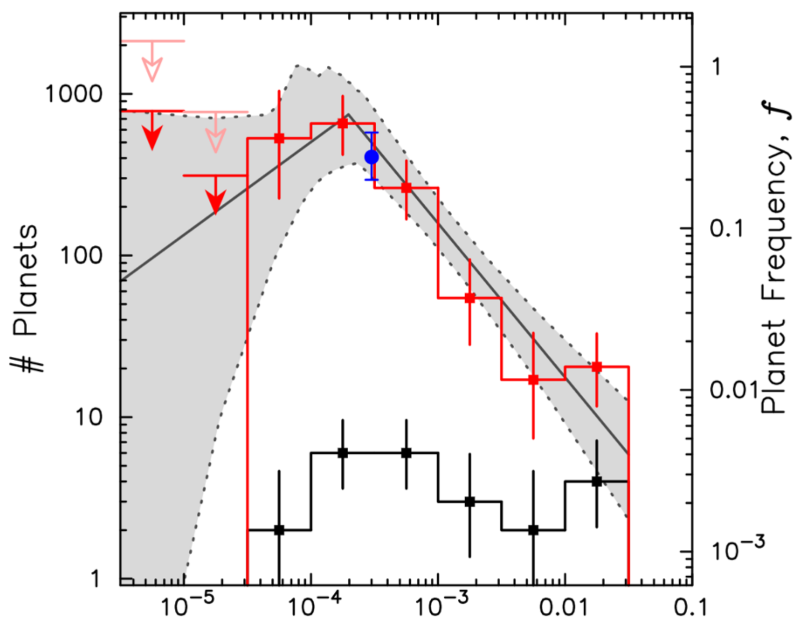
High-cadence microlensing surveys – mass ratio distributions

OGLE

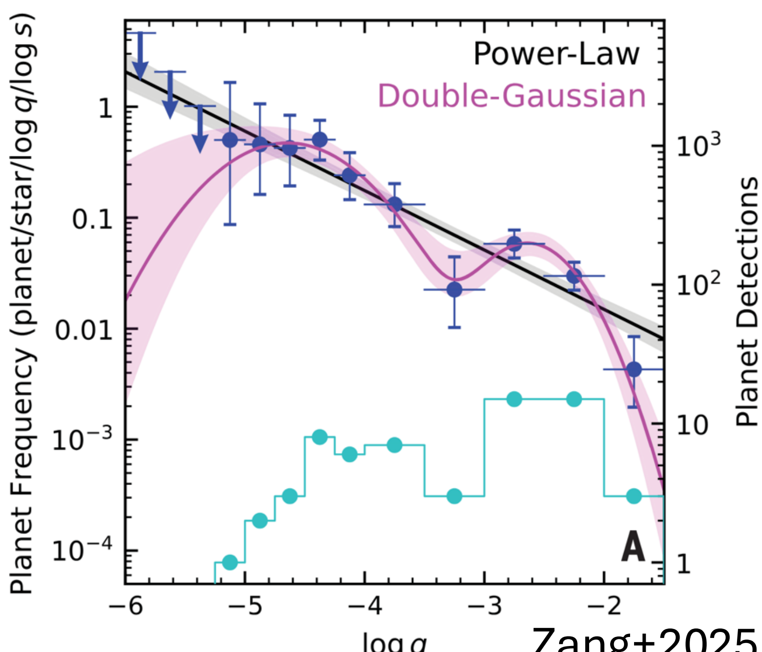
MOA



KMTNet



Suzuki+2016



Zang+2025

Measuring Masses & Distances

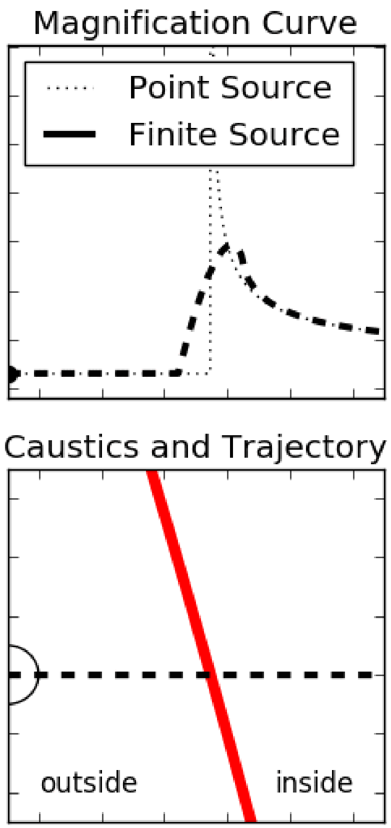
Mass & distance cf. observables

$$M = \frac{\theta_{\mathrm{E}}}{\kappa \pi_{\mathrm{E}}} \qquad \pi_{\mathrm{rel}} = \pi_l - \pi_s = \pi_E \theta_E$$

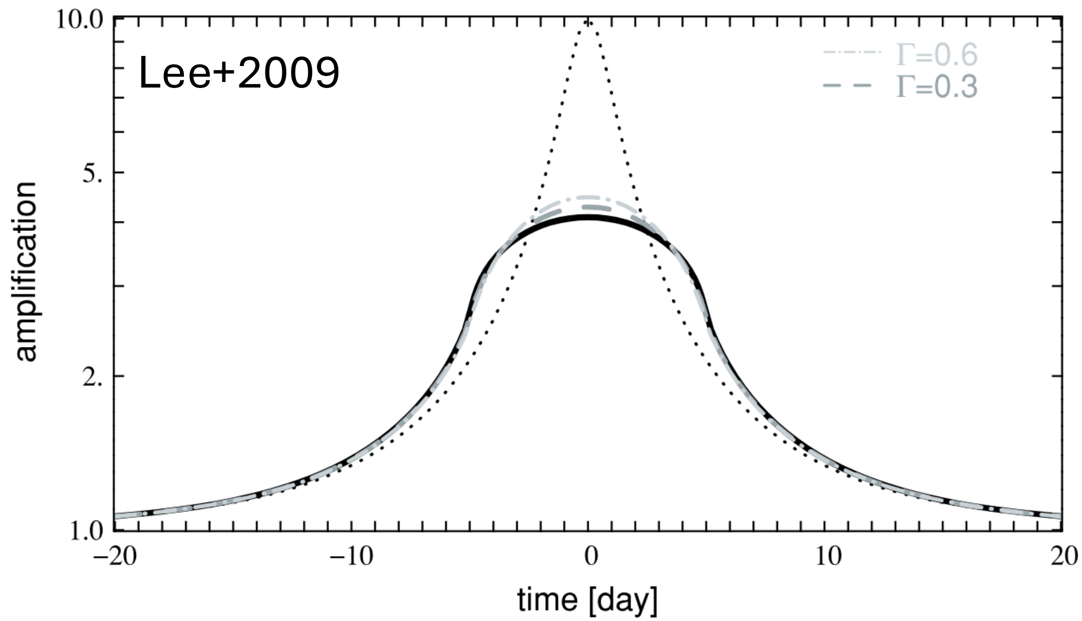
$$\pi_{\mathrm{E}} = \pi_{\mathrm{rel}} / \theta_{\mathrm{E}}$$

Method 1: Lightcurve, finite source

Finite source effects $\frac{\theta_{\mathrm{E}}}{\theta_*} = \frac{t_{\mathrm{E}}}{t_*}$



Credit: J. Yee



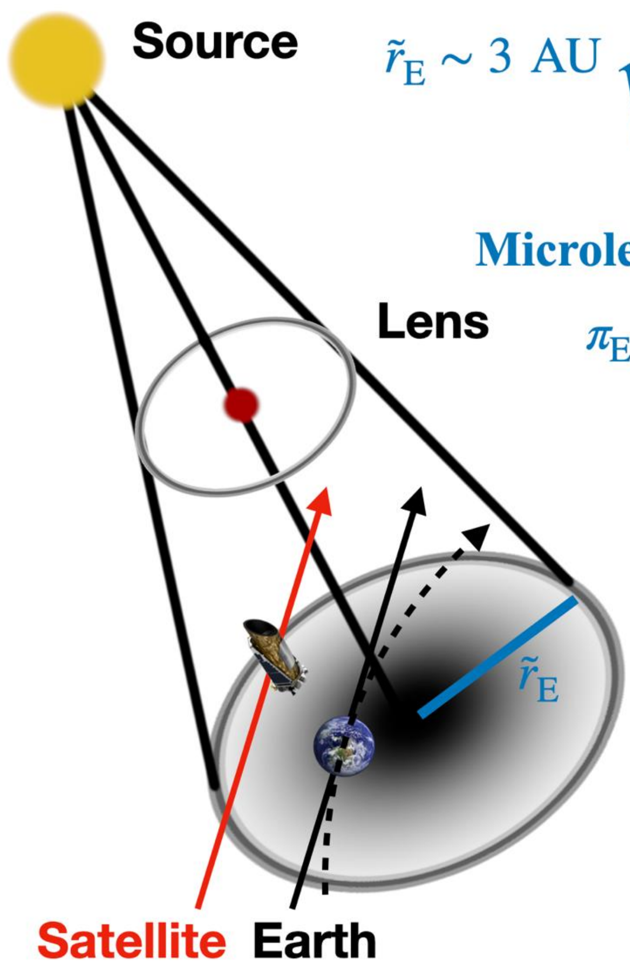
Method 1: Lightcurve, parallax

Projected Einstein radius:

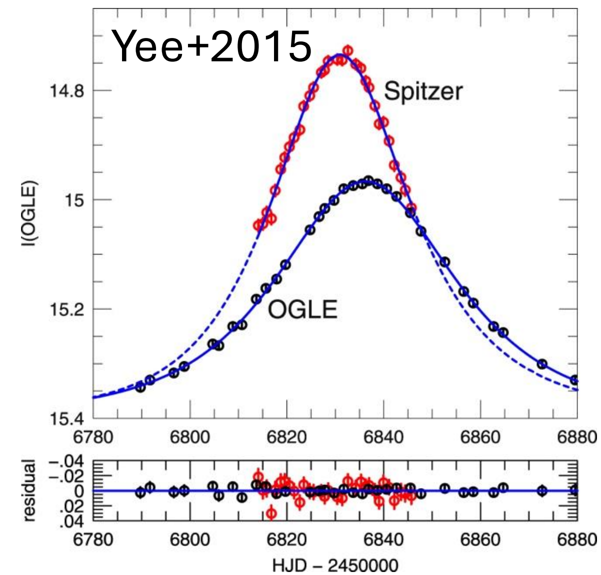
$$\tilde{r}_E \sim 3\ \mathrm{AU}\sqrt{\frac{M}{0.1M_\odot}\frac{0.1\mathrm{mas}}{\pi_{\mathrm{rel}}}}$$

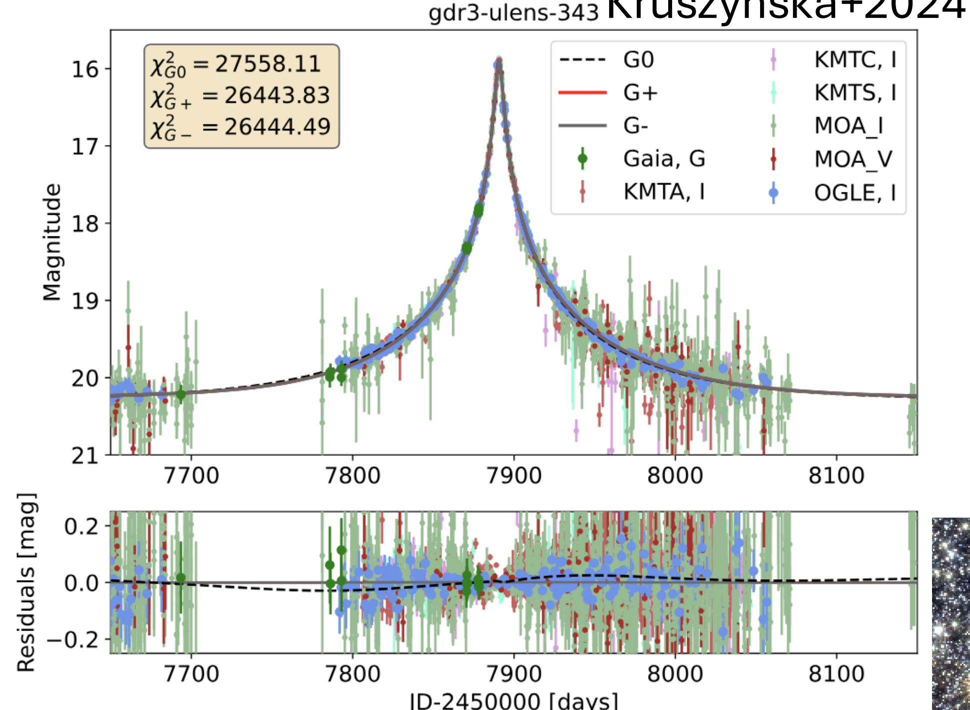
Microlens parallax:

$$\pi_E = \frac{\mathrm{AU}}{\tilde{r}_E}$$



Credit: M. Penny





Finite source + parallax

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

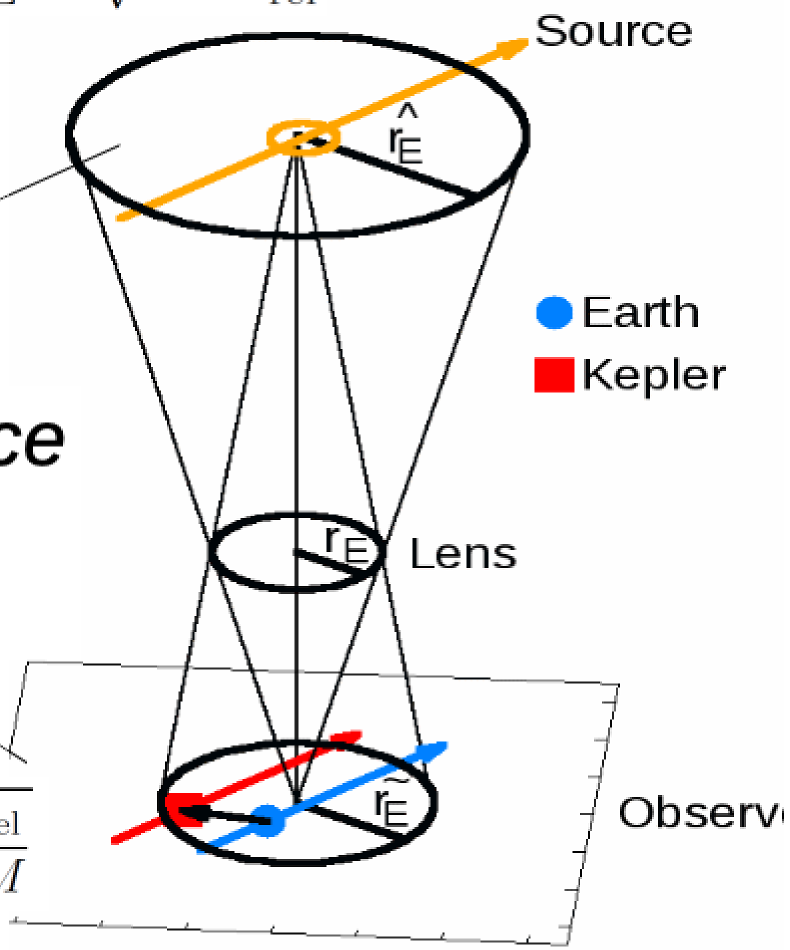
- Finite-source effects (common for FFPs, planets) measures one projection

$$\textit{Mass} = \frac{\theta_E}{\kappa \pi_E} \textit{ \& Distance}$$

Constant

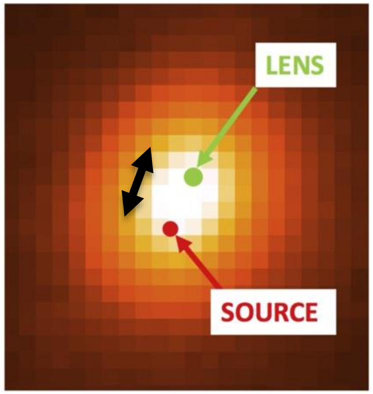
- Parallax baseline measures other projection

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



See Refsdal 1966, Gould 1994, Gould 2000

Method 2: Hi-res imaging + time



Bhattacharya+18

Proper Motion + μL Timescale
→ Angular Einstein Ring Radius
→ Mass vs distance relation

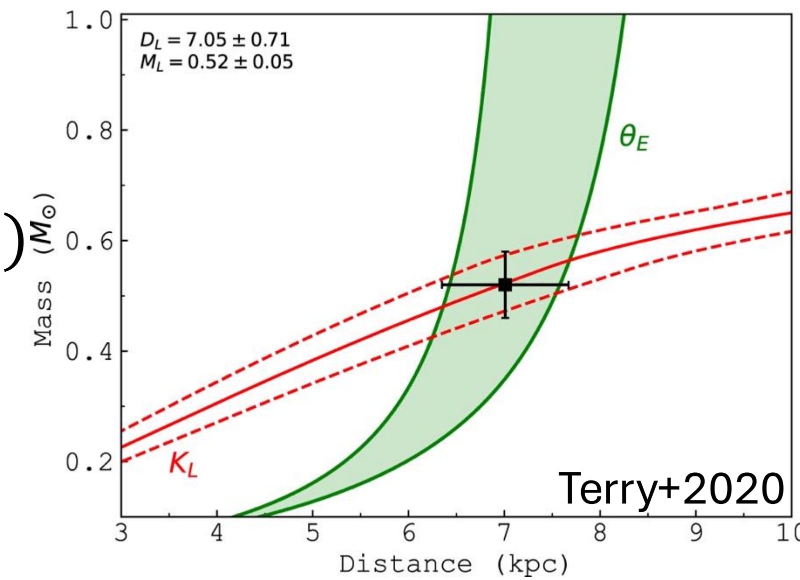
$$\theta_{\mathrm{E}} \approx 3 \text{ mas} \sqrt{M\pi_{\mathrm{rel}}}$$

$$\theta_{\mathrm{E}} = \mu_{\mathrm{rel}} t_{\mathrm{E}}$$

$$\pi_{\mathrm{rel}} = \frac{\mathrm{AU}}{D_{\mathrm{s}}} - \frac{\mathrm{AU}}{D_{\mathrm{l}}}$$

Lens flux
→ Luminosity vs distance
→ Mass vs distance relation

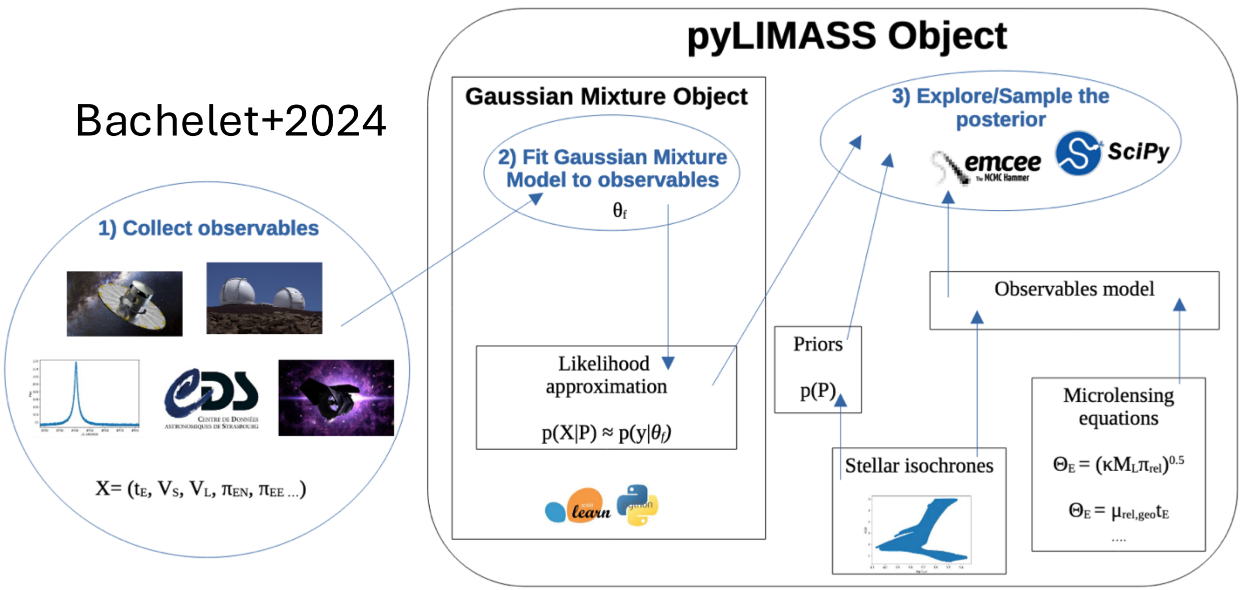
$$m_{\lambda} = M_{\lambda}(M) + 5 \log D_{\mathrm{l}} + 10 + A_{\lambda}(D_{\mathrm{l}})$$

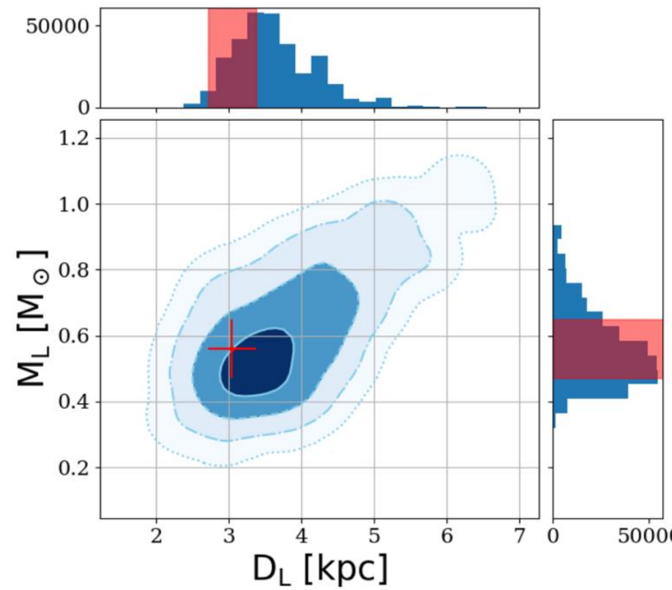


2 equations, 2 unknowns
→ Solve for M & D_{l}

If measurements fail, use models!

Bachelet+2024



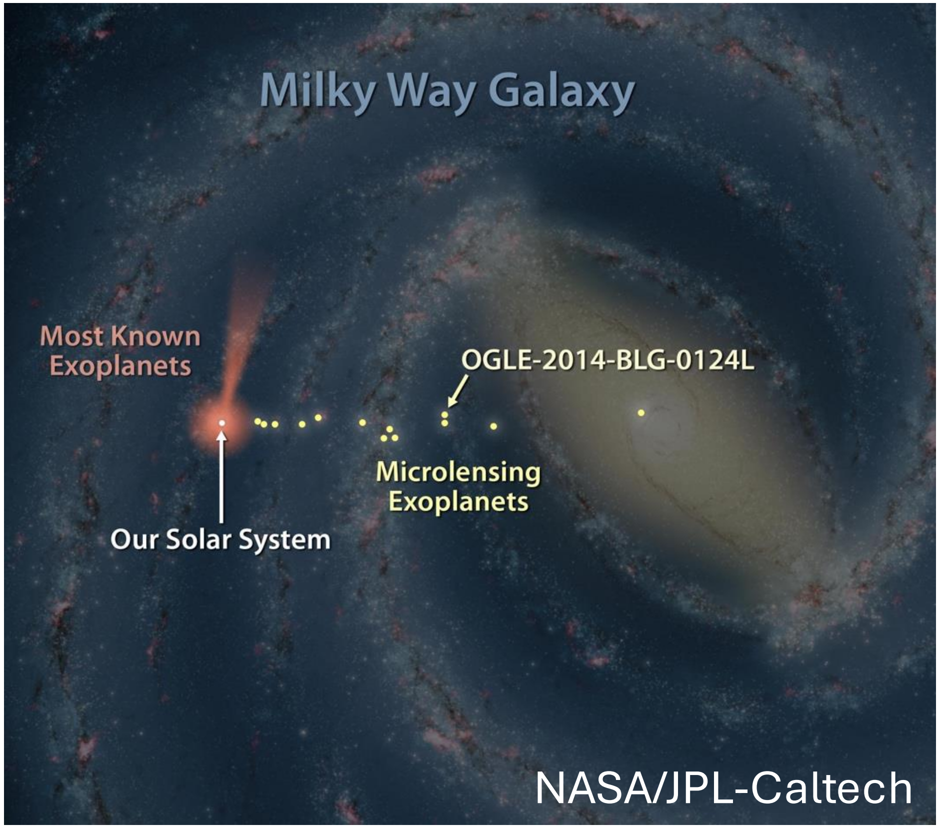


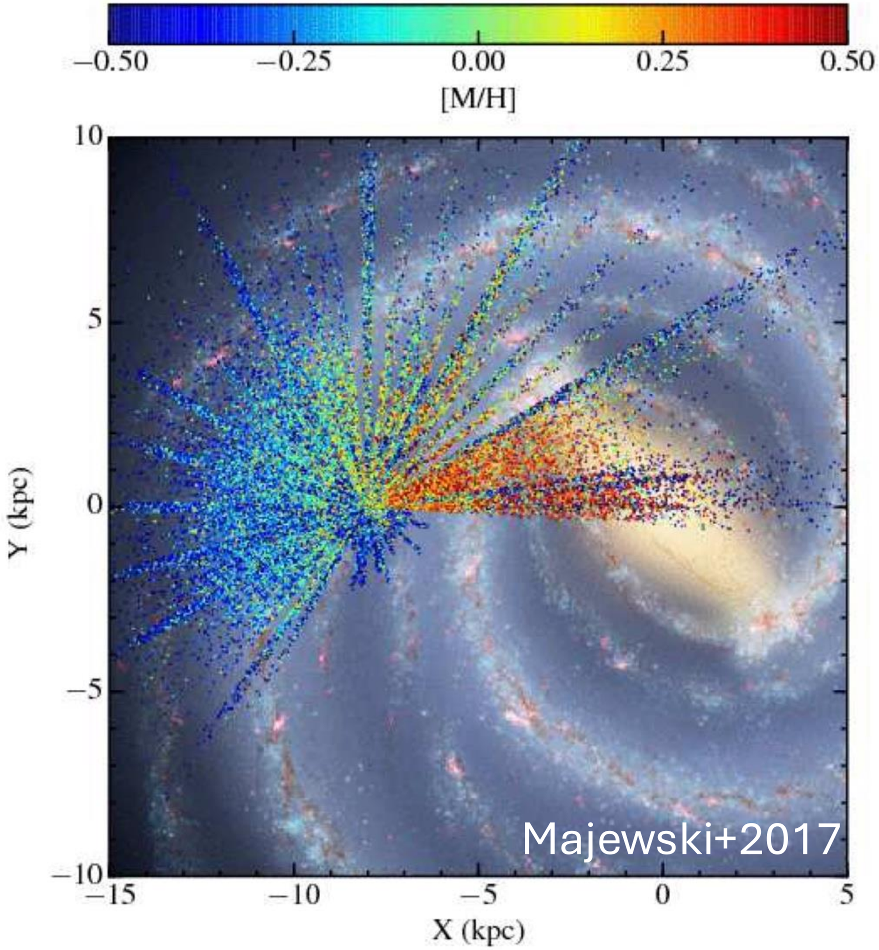
synthpop-galaxy/
synthpop

A modular Galactic population synthesis code

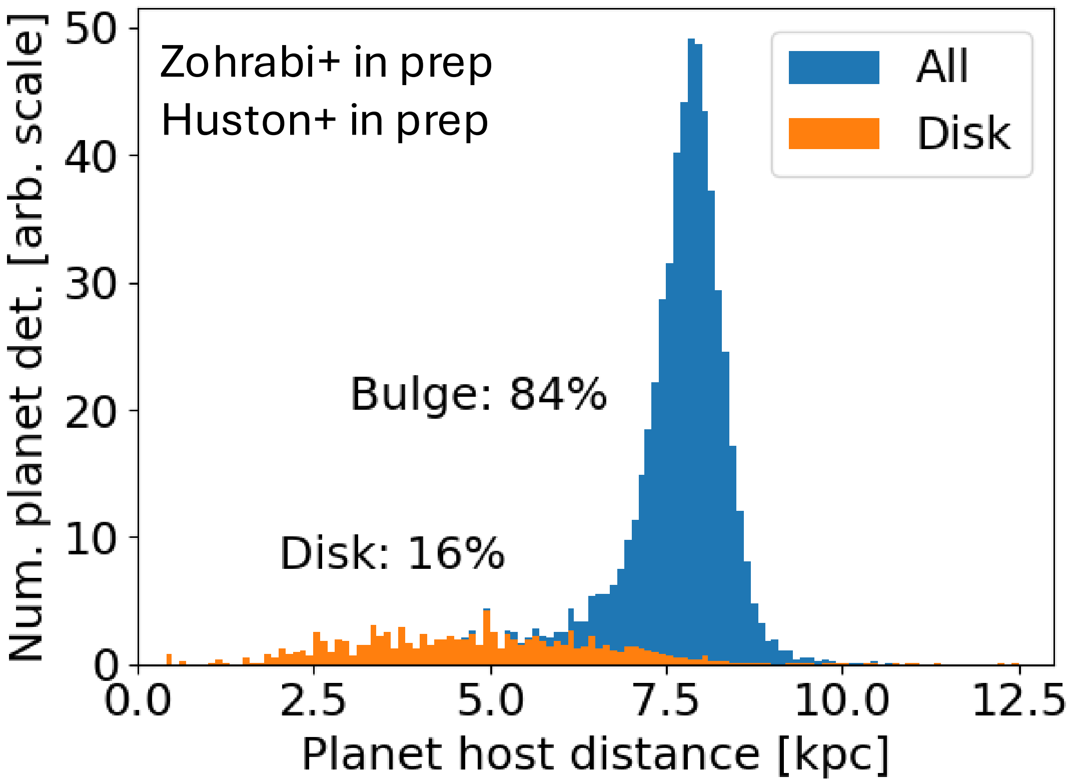
Klüter & Huston+ 2025

Where will the hosts be?

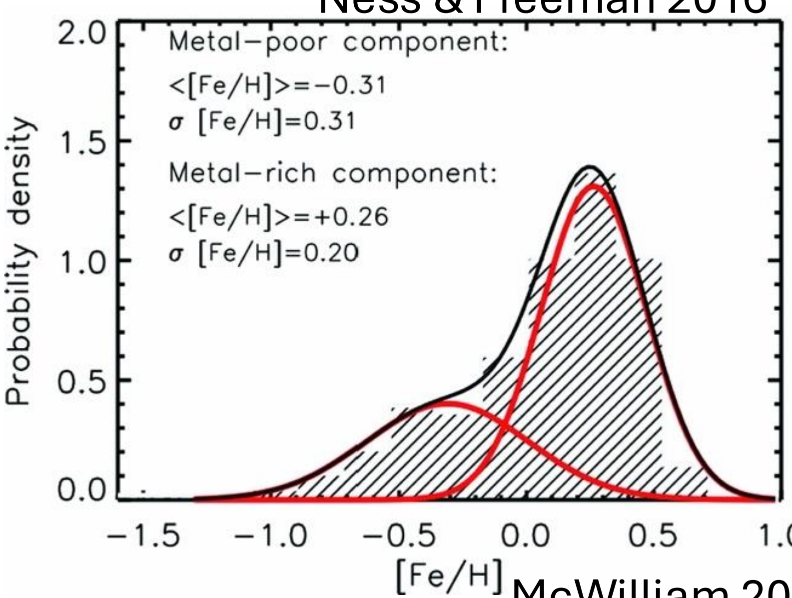




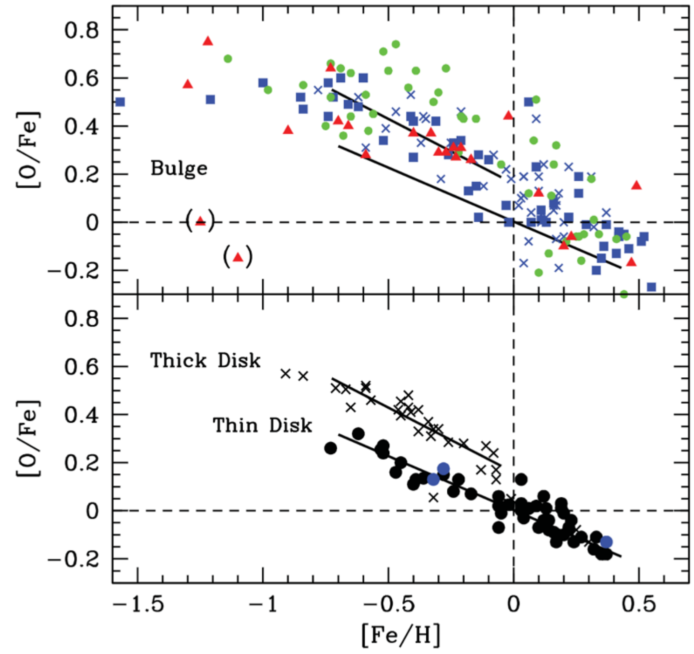
Roman's Distance Distribution



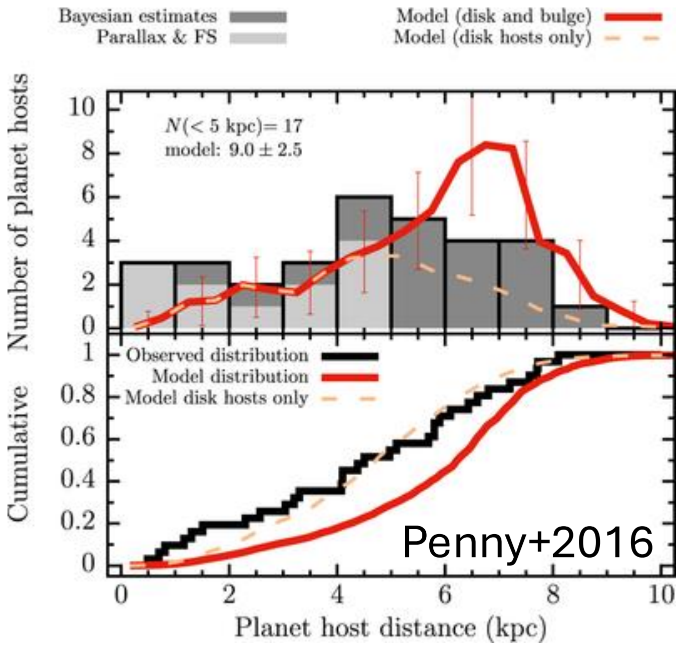
Ness & Freeman 2016

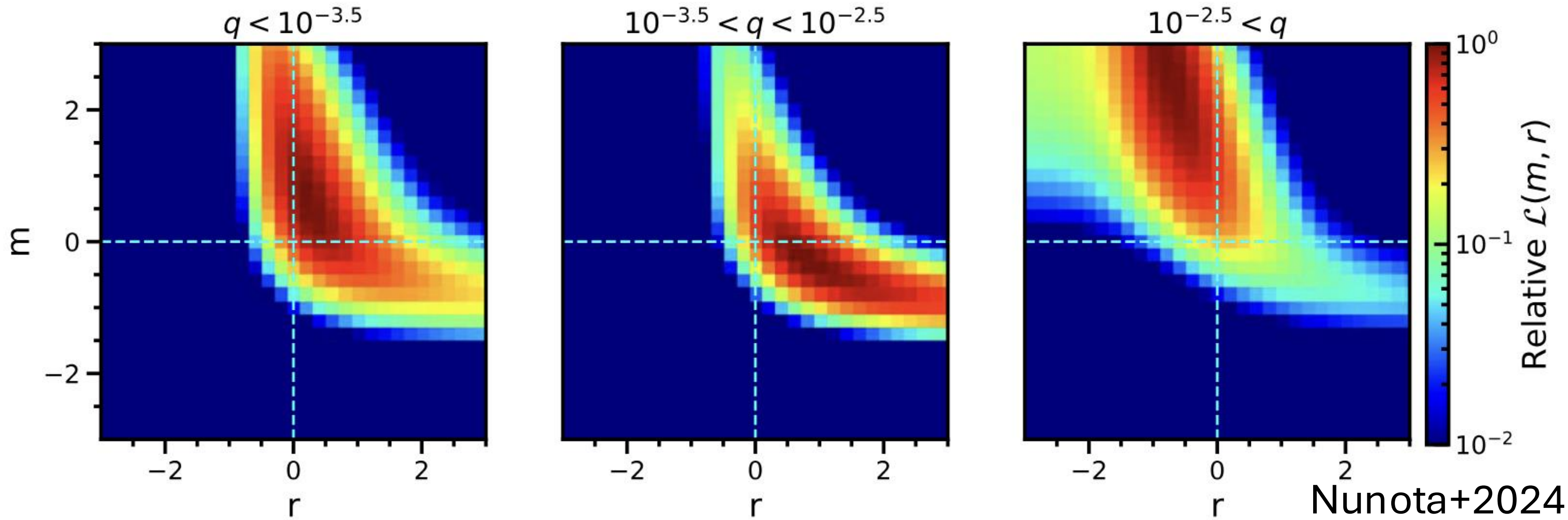


McWilliam 2016



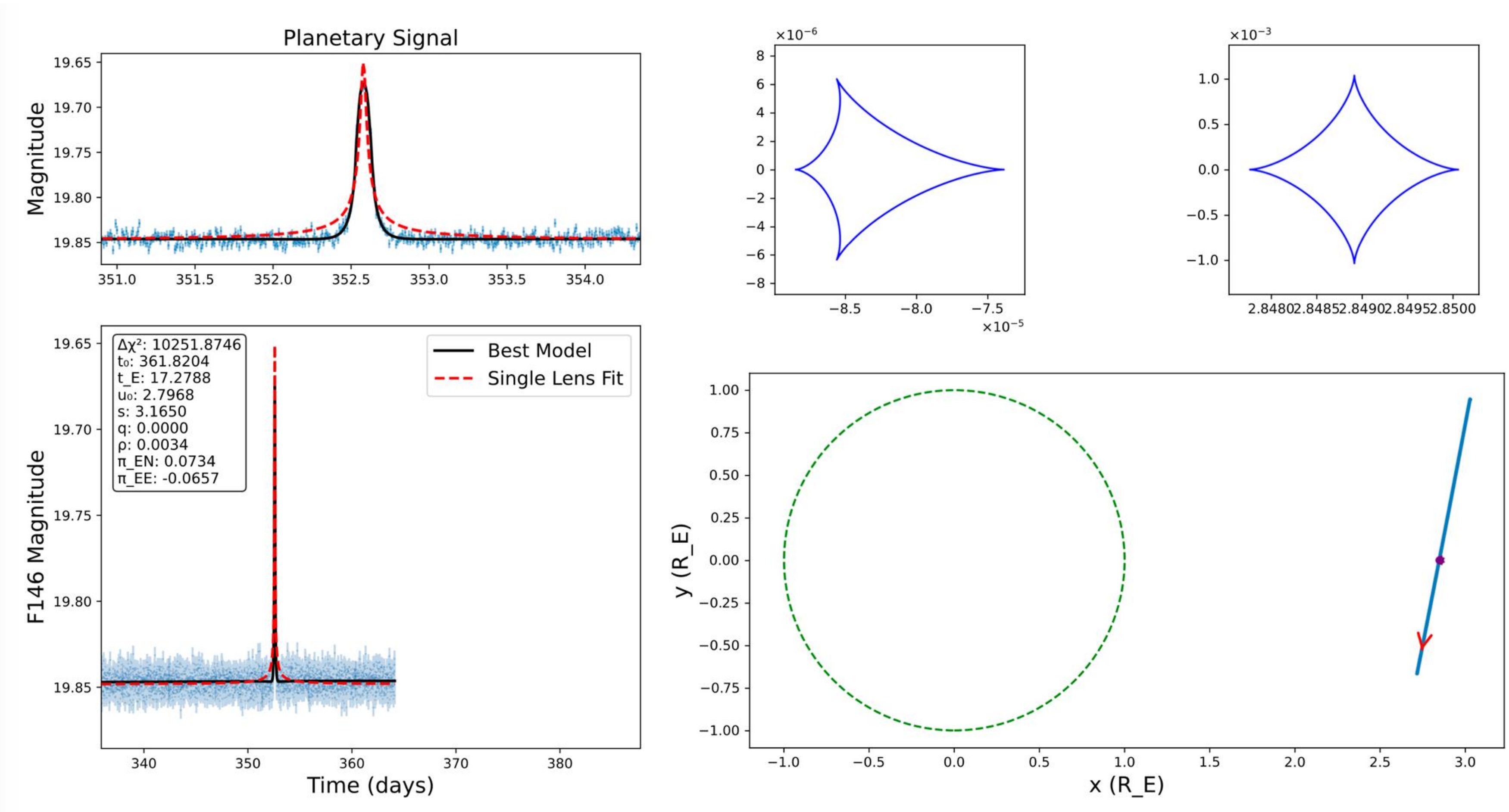
Population & host mass dependence





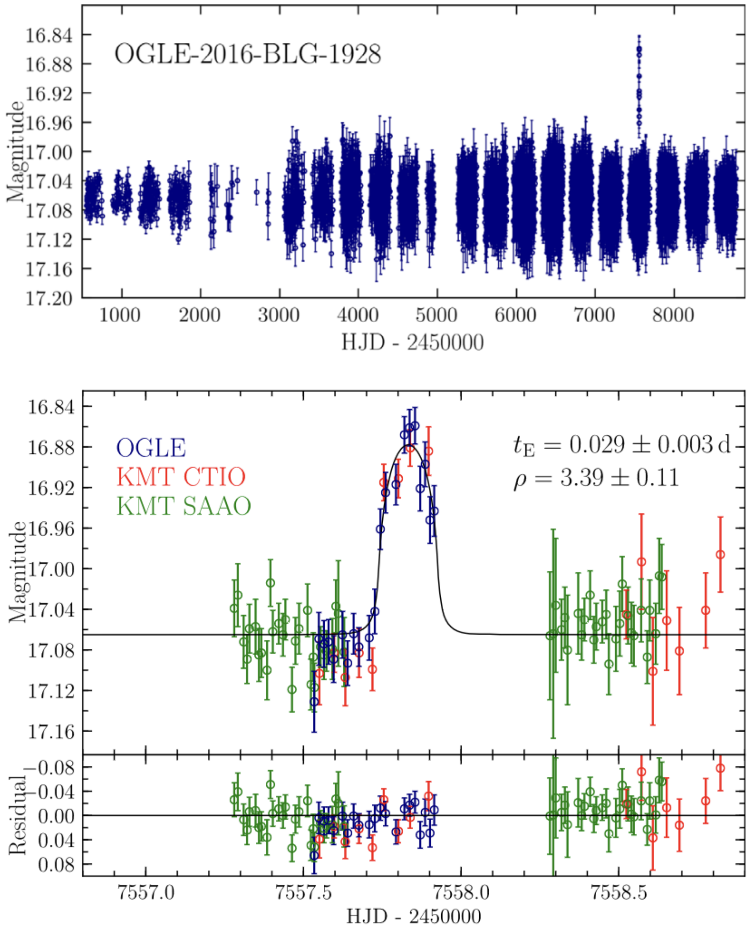
Free-floating planets

Wide orbit planets

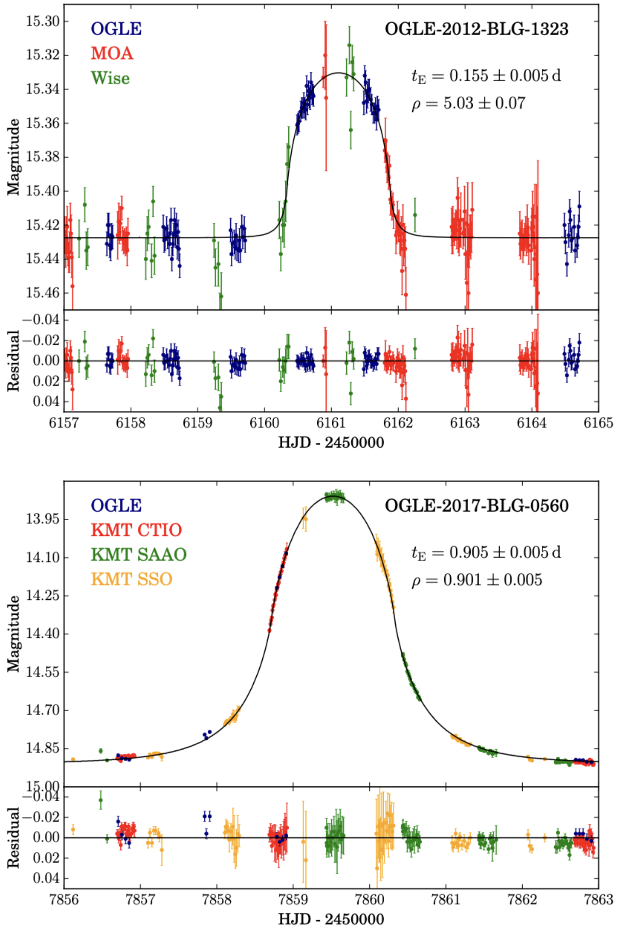


Free-floating planet candidates

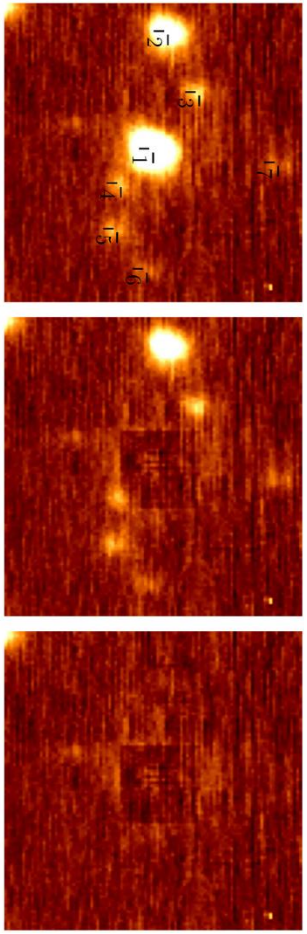
Mroz+2020



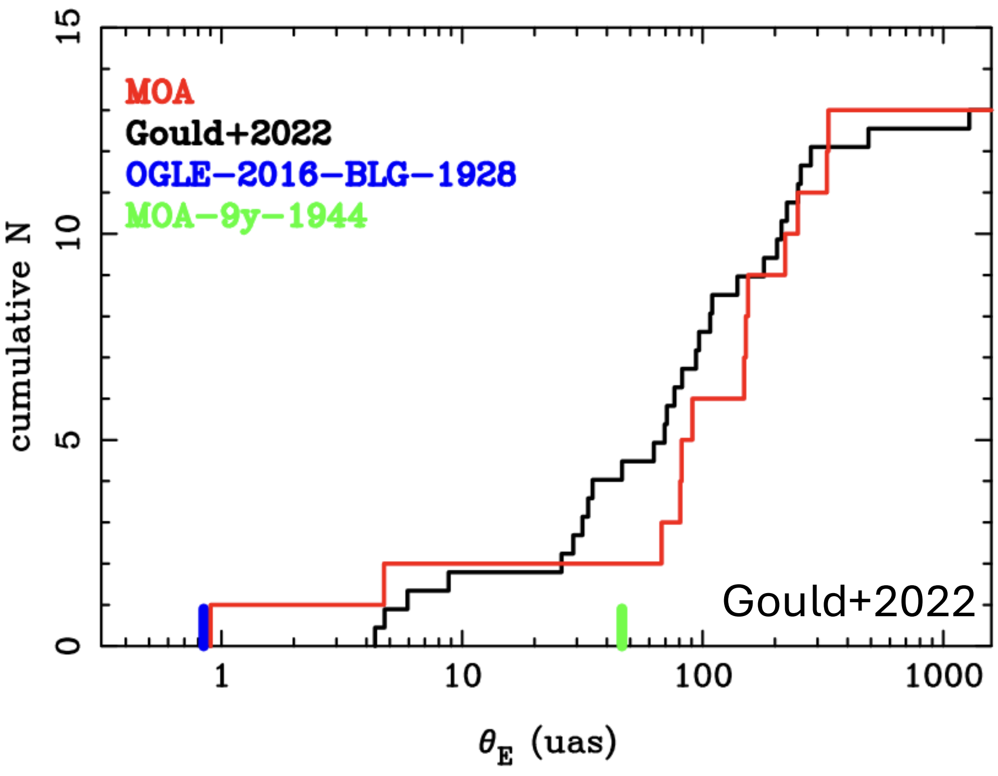
Mroz+2019

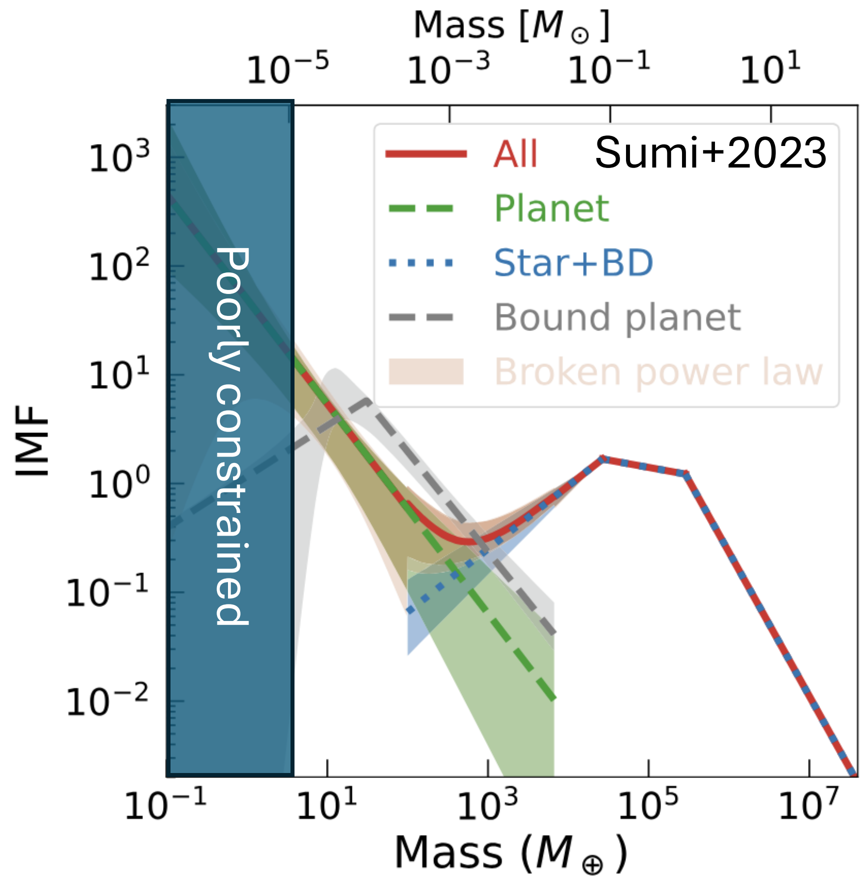


Mroz+2024



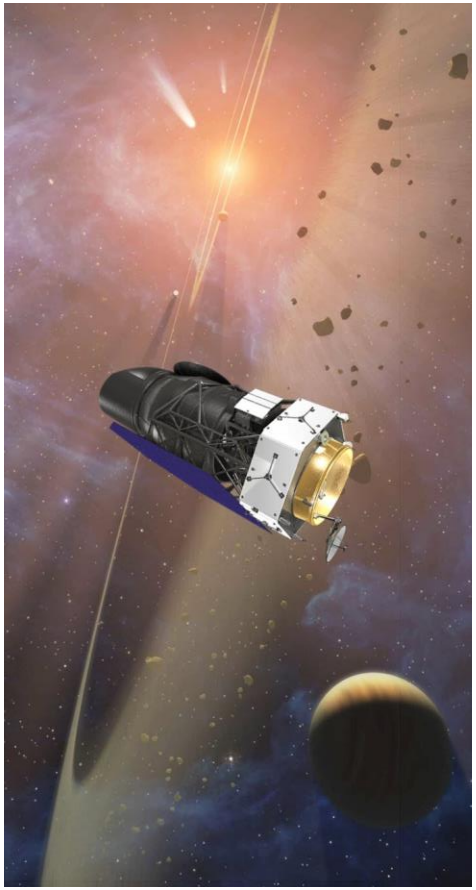
Free-floating planet demographics

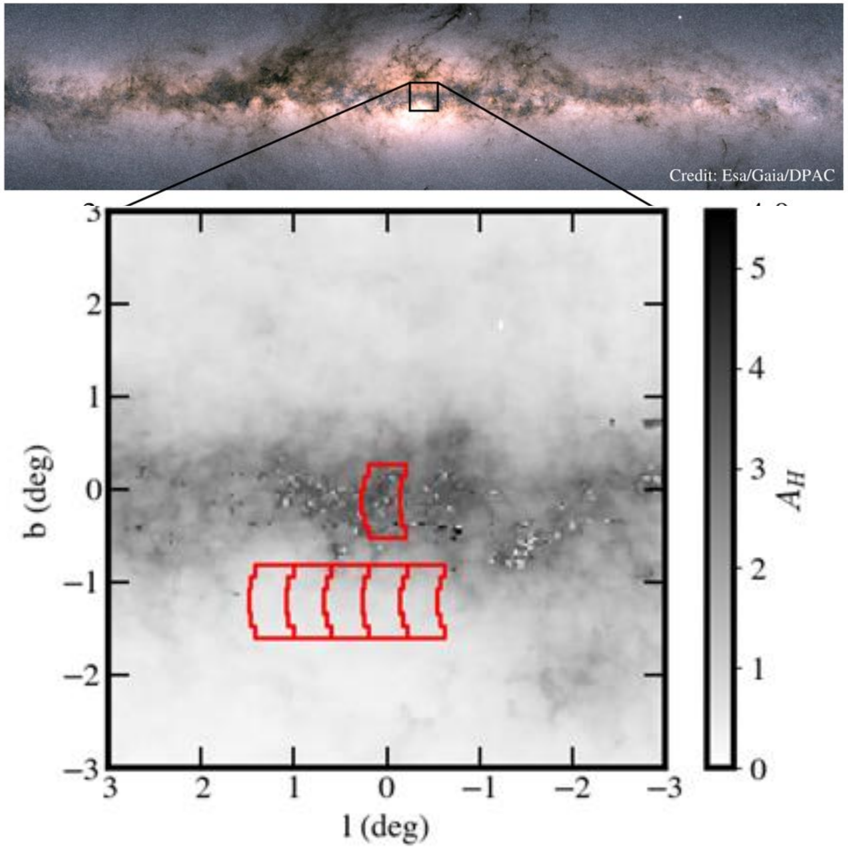




Future Surveys

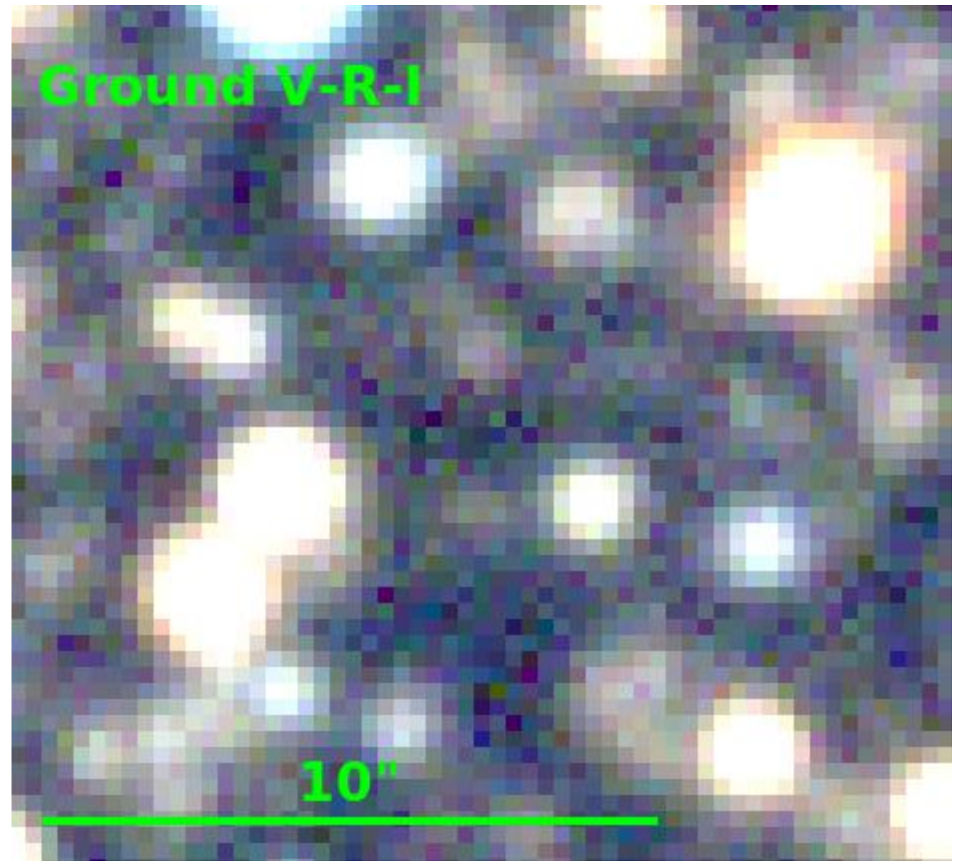
Nancy Grace Roman Space Telescope Galactic Bulge Time Domain Survey (GBTDS)



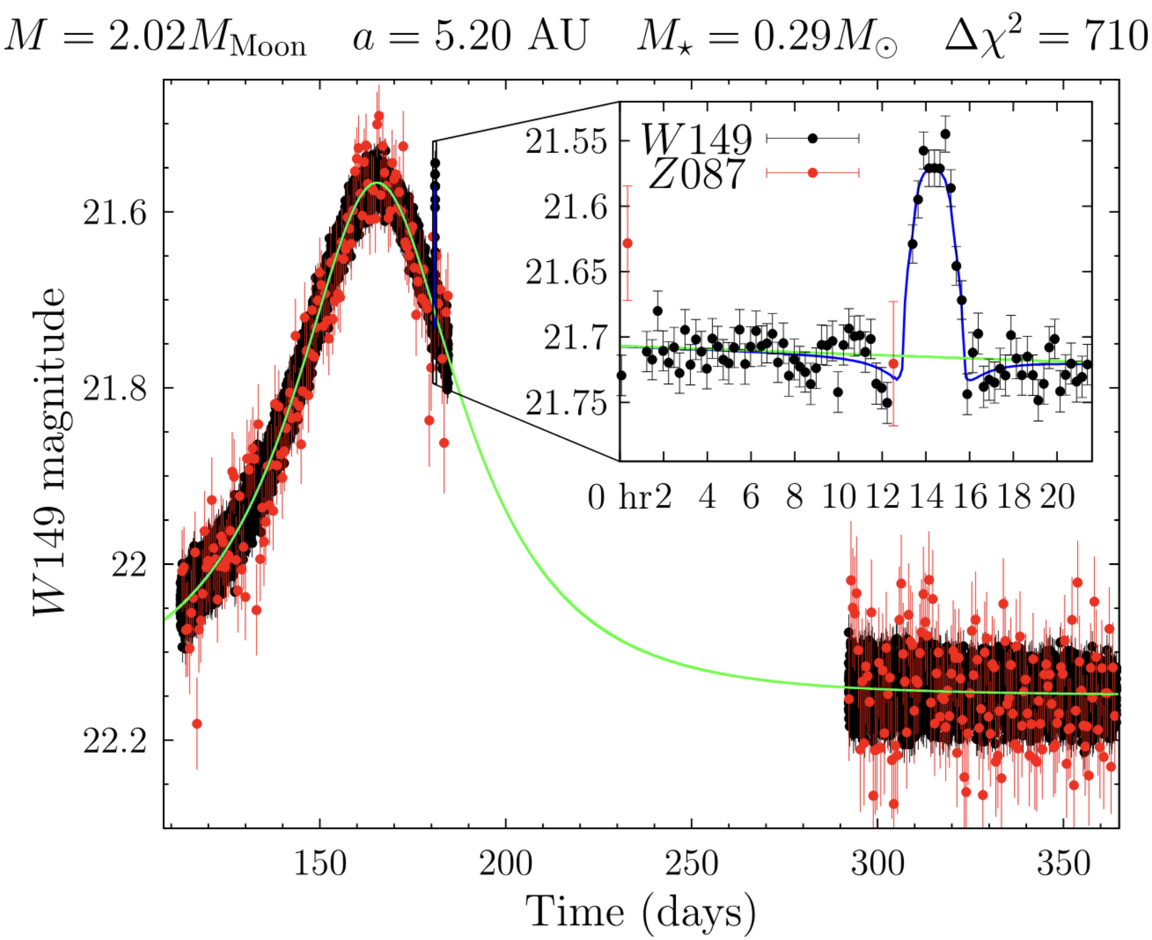


- 6x72 day seasons
- 12 min cadence
- 5 years
- ~1.4 deg^2
- ~200 million stars
- ~30,000 microlensing events
- ~1000 bound planets
- ~100s free-floating

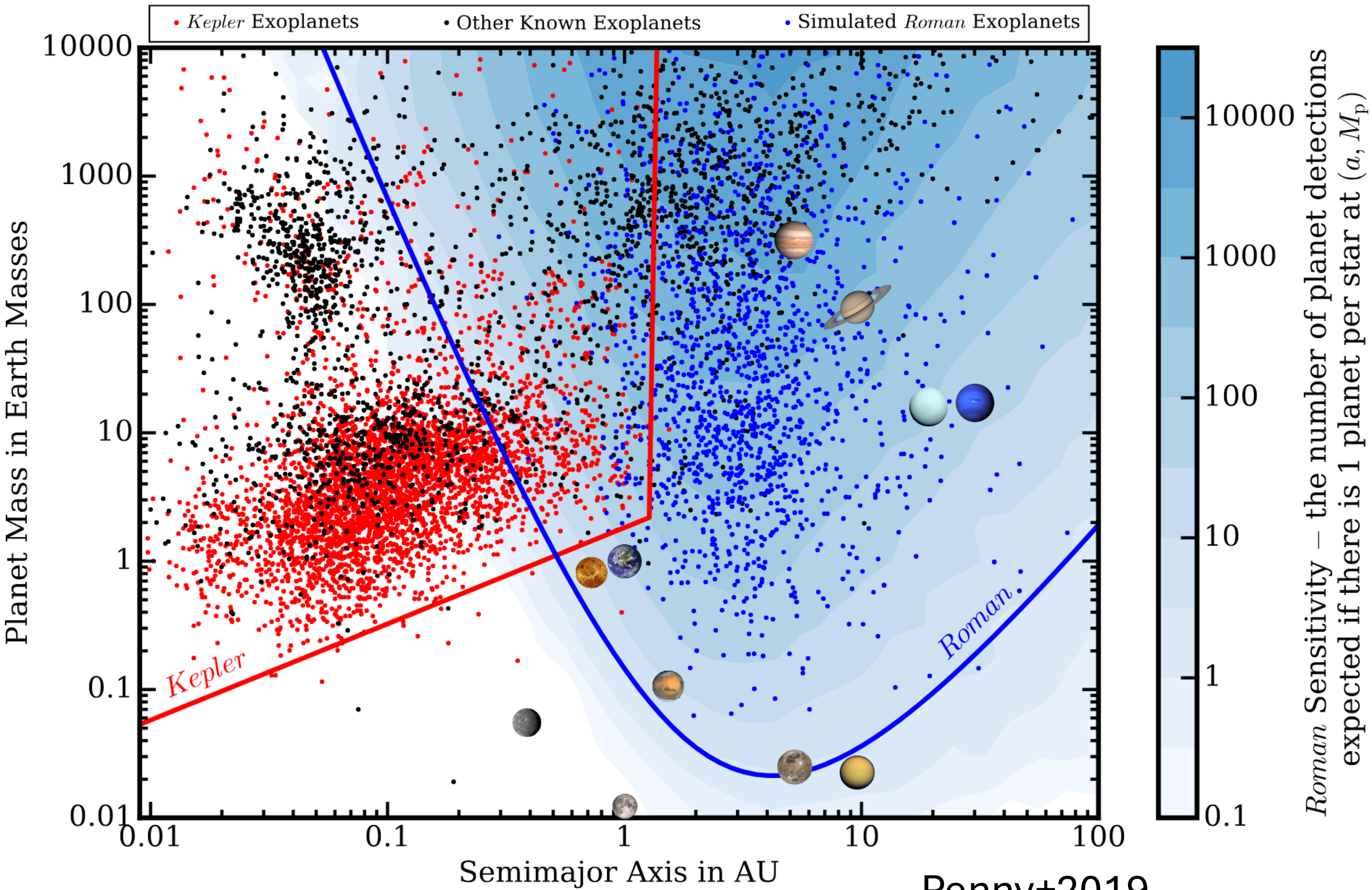
Roman improves resolution

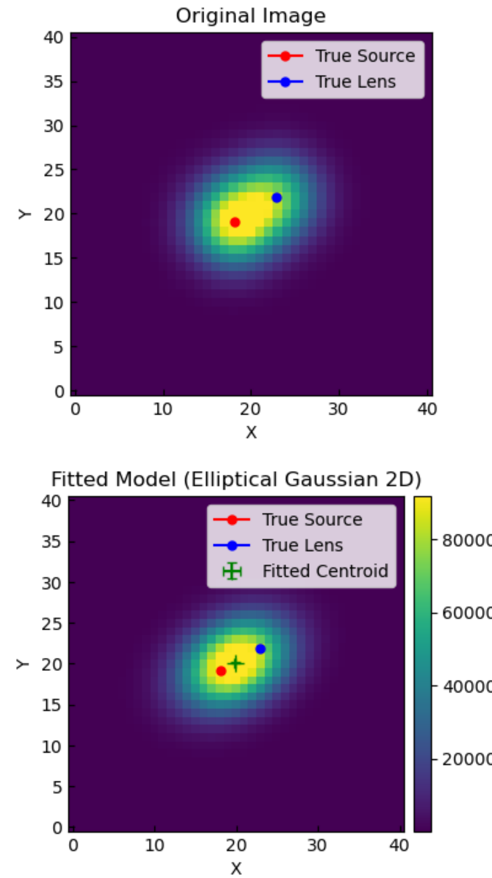


Sensitivity down to ~Moon mass



Expected Roman Demographics

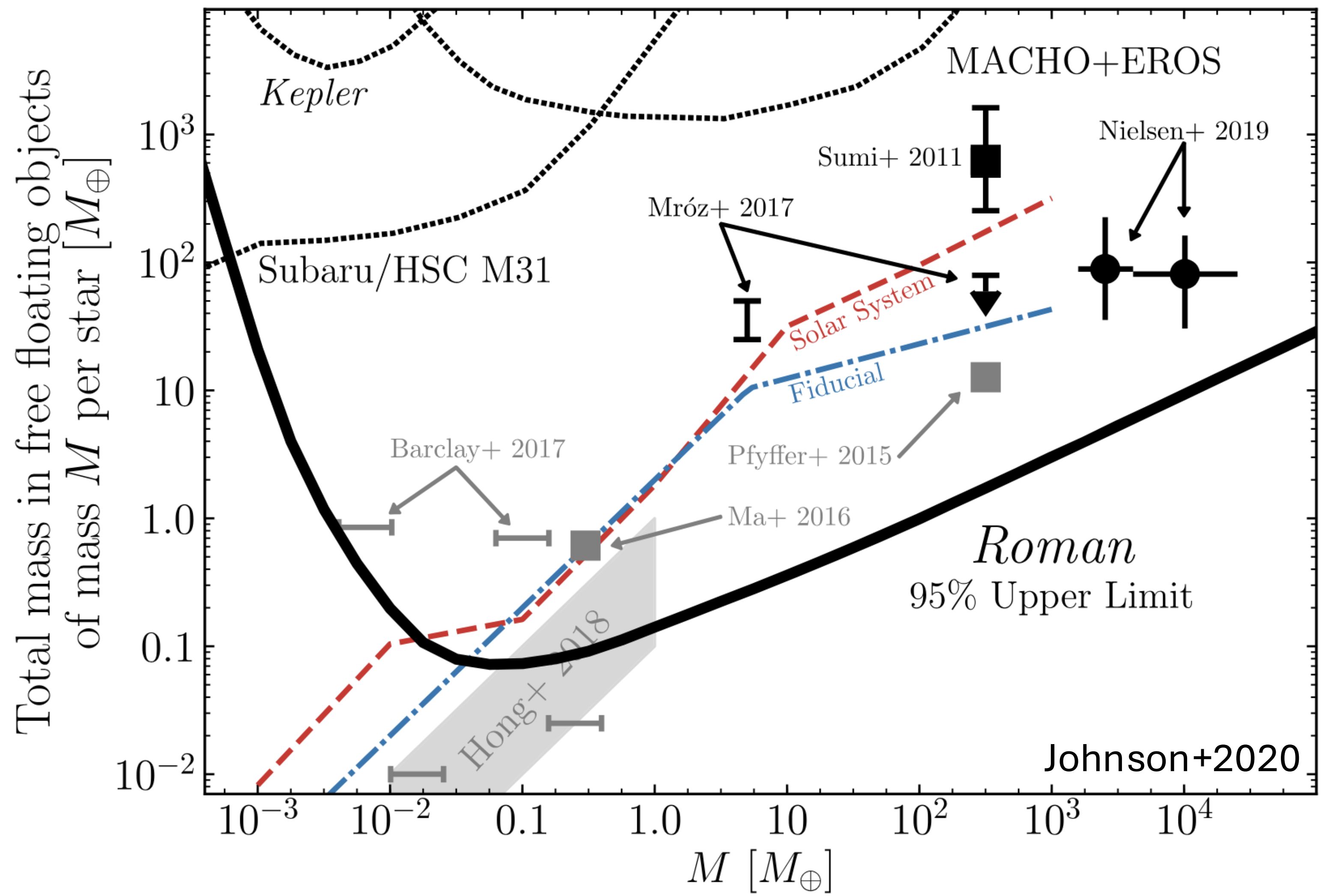




Verma+ in prep.
Terry+ in prep.

Penny+2019
Update: Zohrabi+ in prep

Expected FFP Demographics

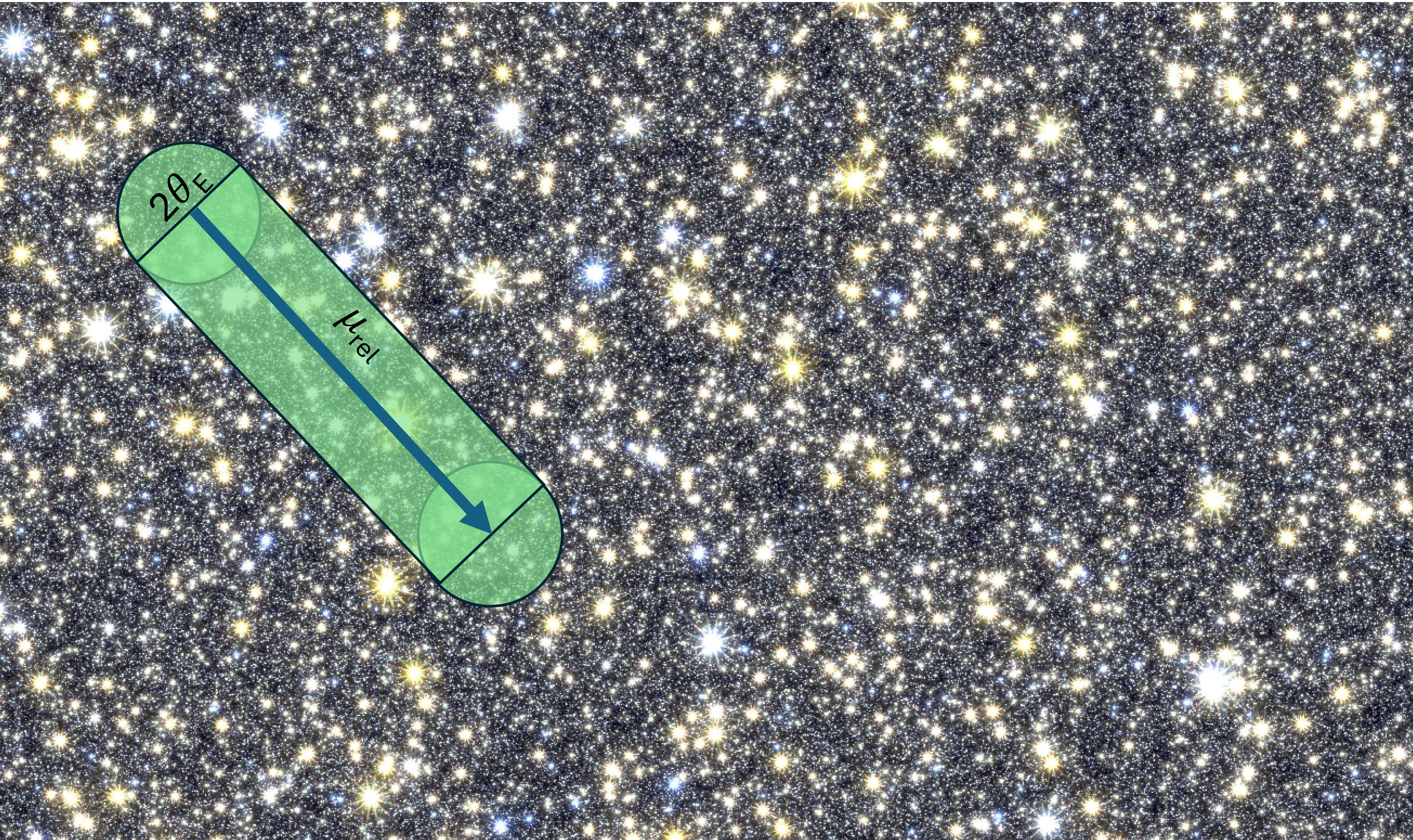


2025 Microlensing Data Challenge

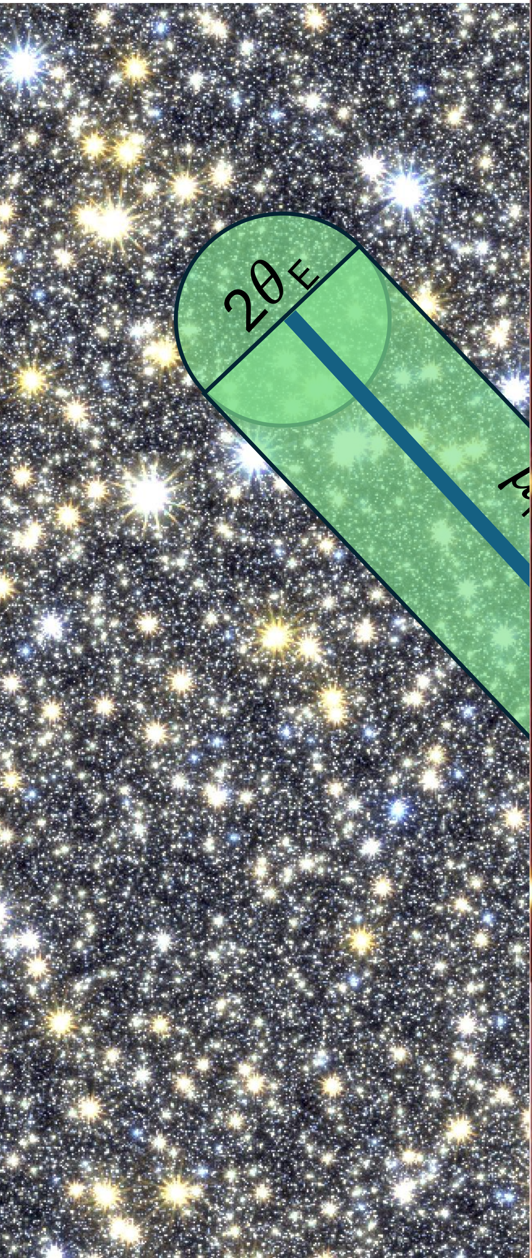
- A lightcurve modeling data challenge is planned to launch late 2025
- In the meantime, you can learn how through a 5-chapter Mini-course: https://rges-pit.org/outreach/
- Can't wait? Try out the 2018 data challenge: https://www.microlensing-source.org/data-challenge/

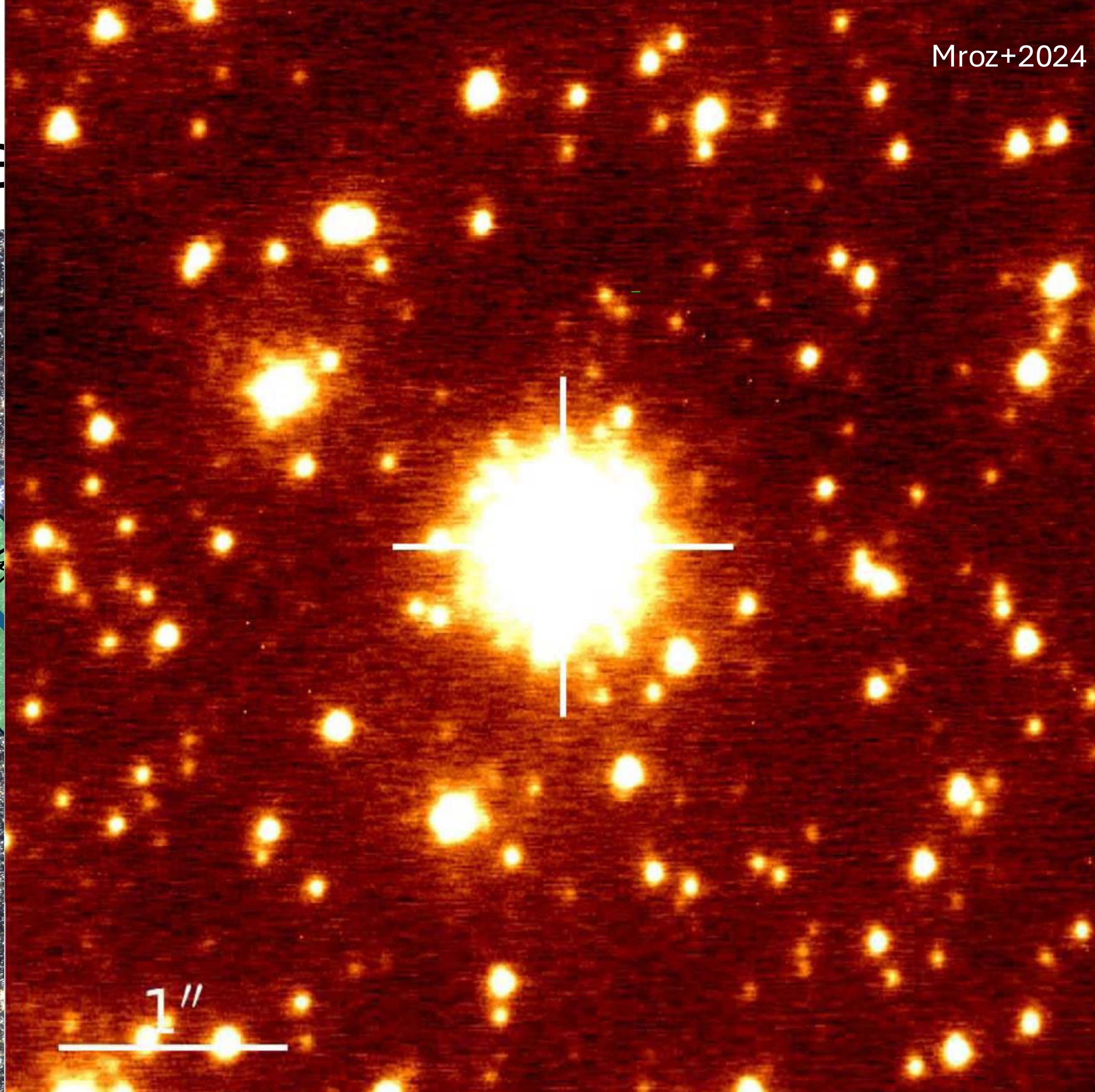
Backup slides

Microlensing Event Rate

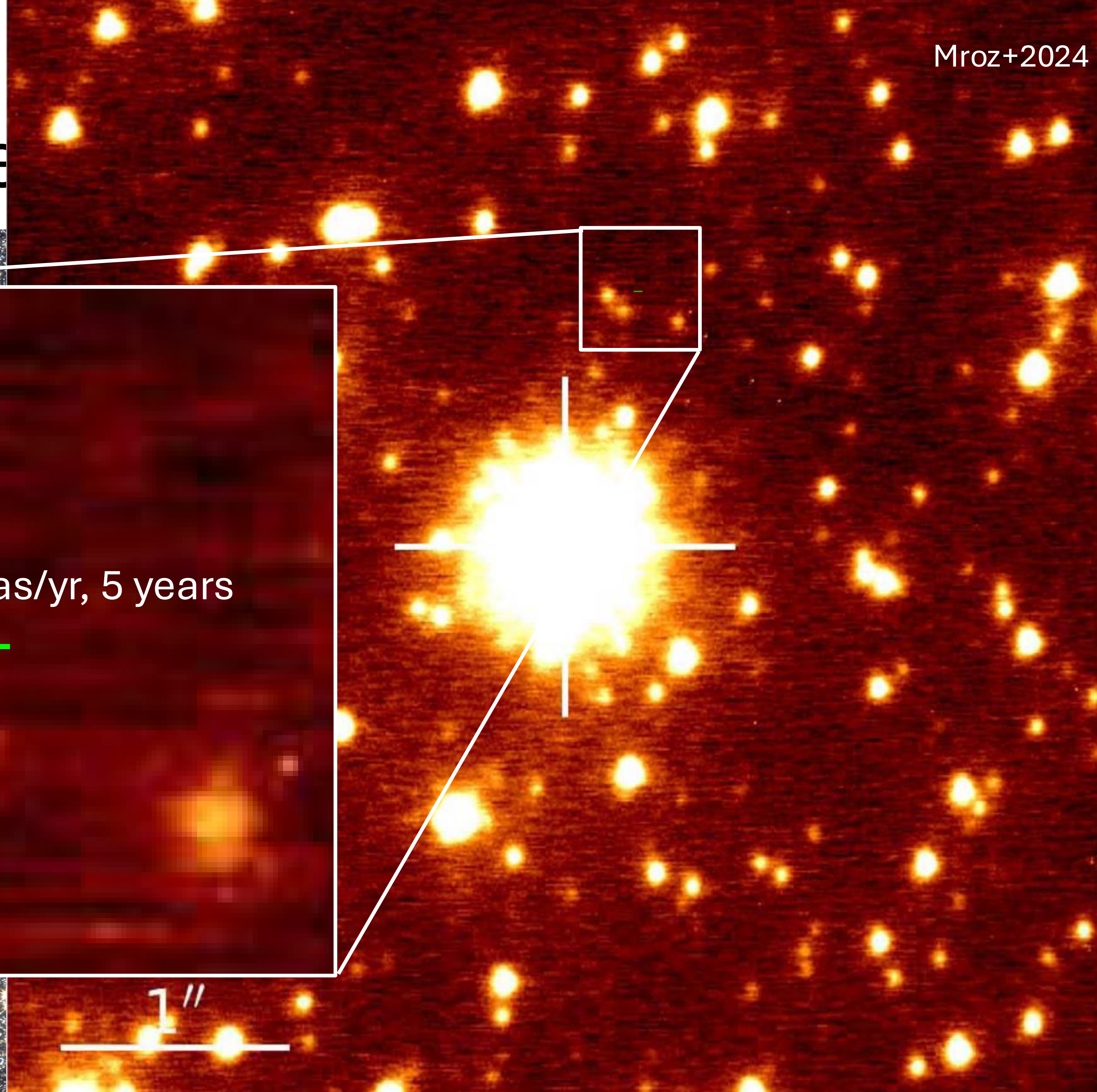


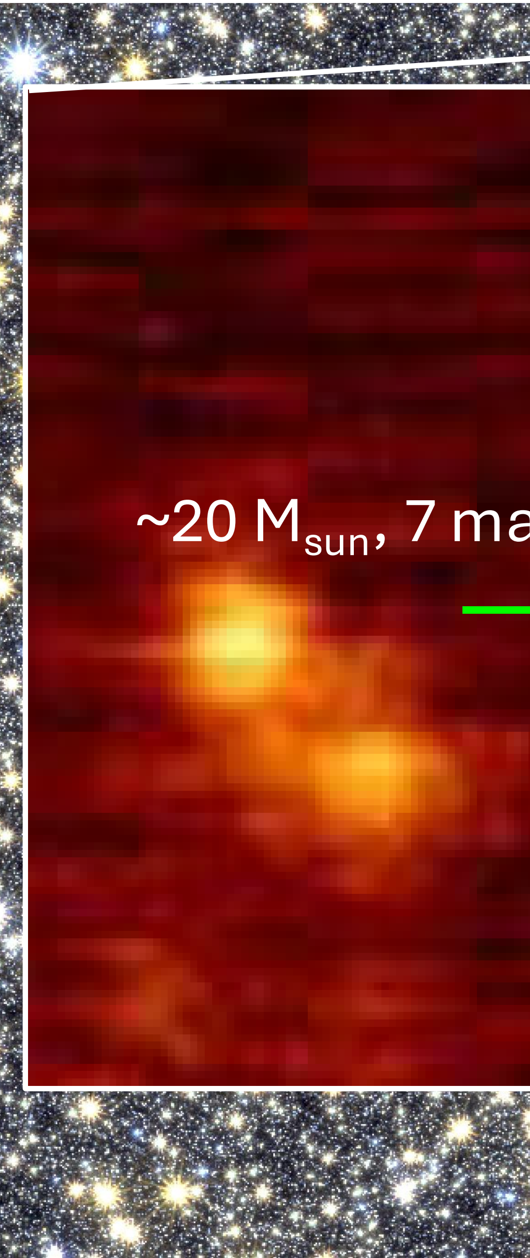
Microle



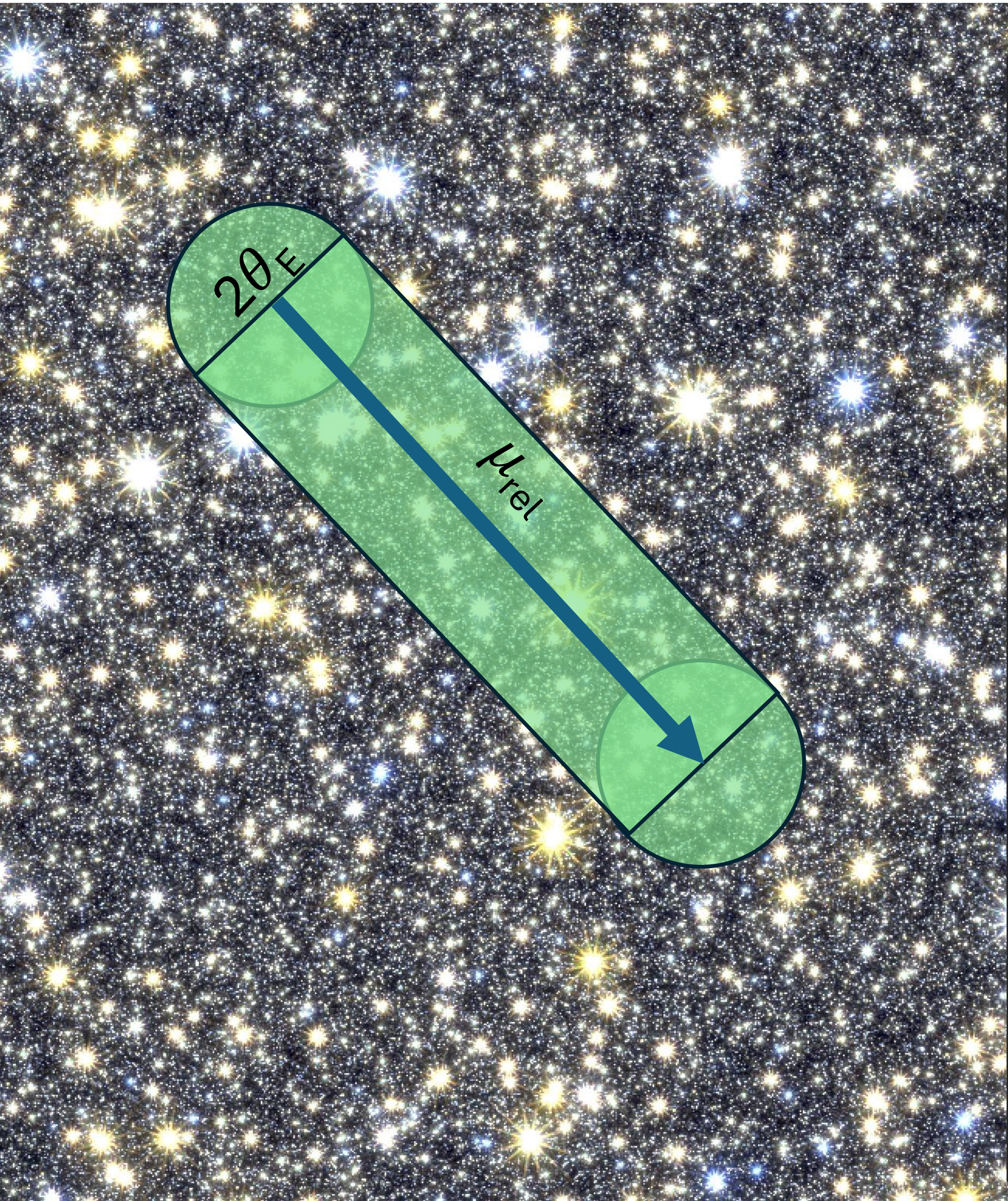


Microle





Microlensing Event Rate



Number density of sources
x
Fraction of area swept out by Einstein rings in front of sources per year:

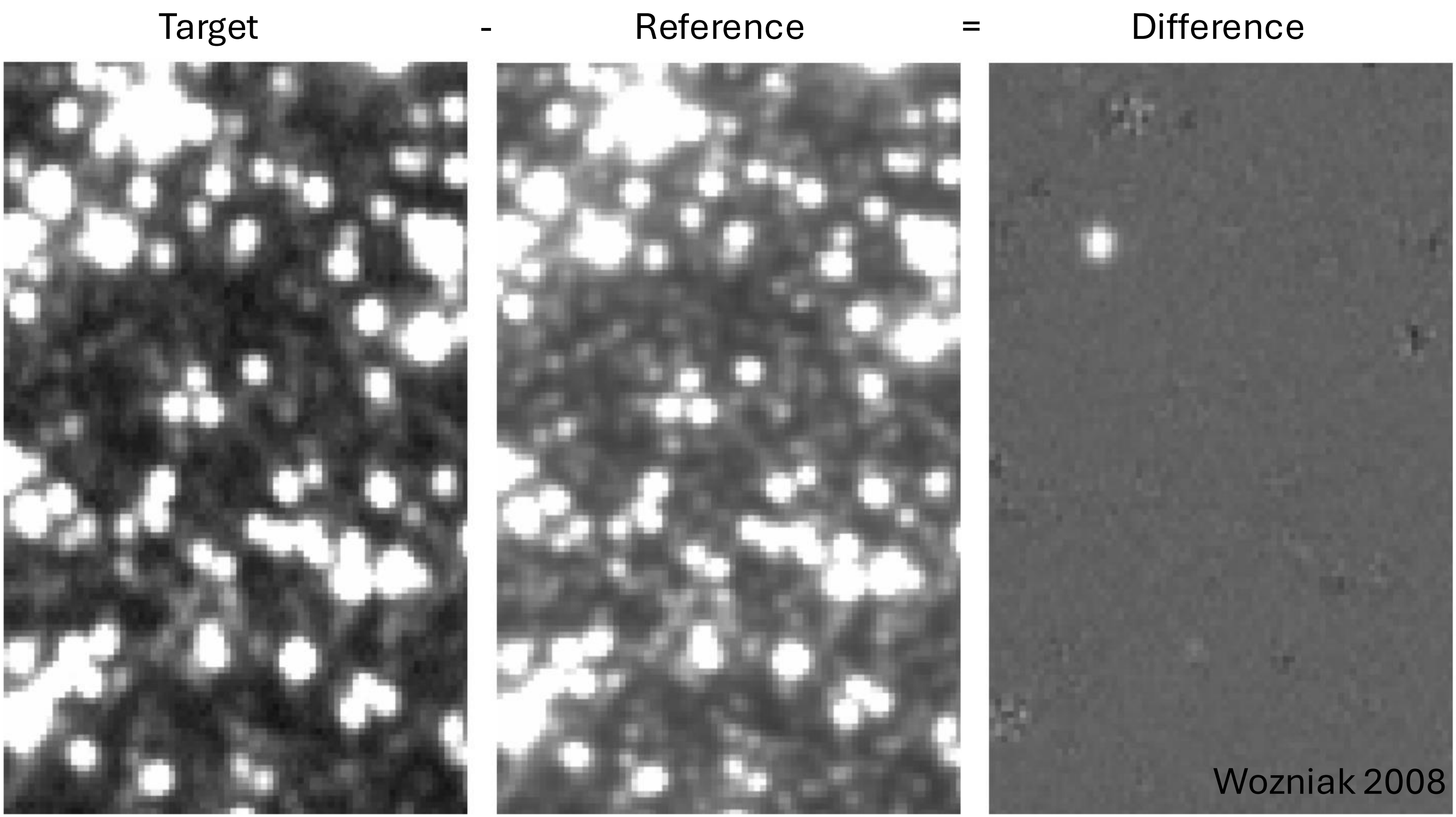
$$\Gamma \sim n_* \sum_{D_l < D_*} \frac{2\theta_E \mu_{rel}}{\text{Unit area}}$$

$$\Gamma \sim 10^{6-8}\ \text{deg}^{-2}\ 10^8\ \frac{\text{mas}^2}{\text{deg}^2}\ \text{yr}^{-1}$$

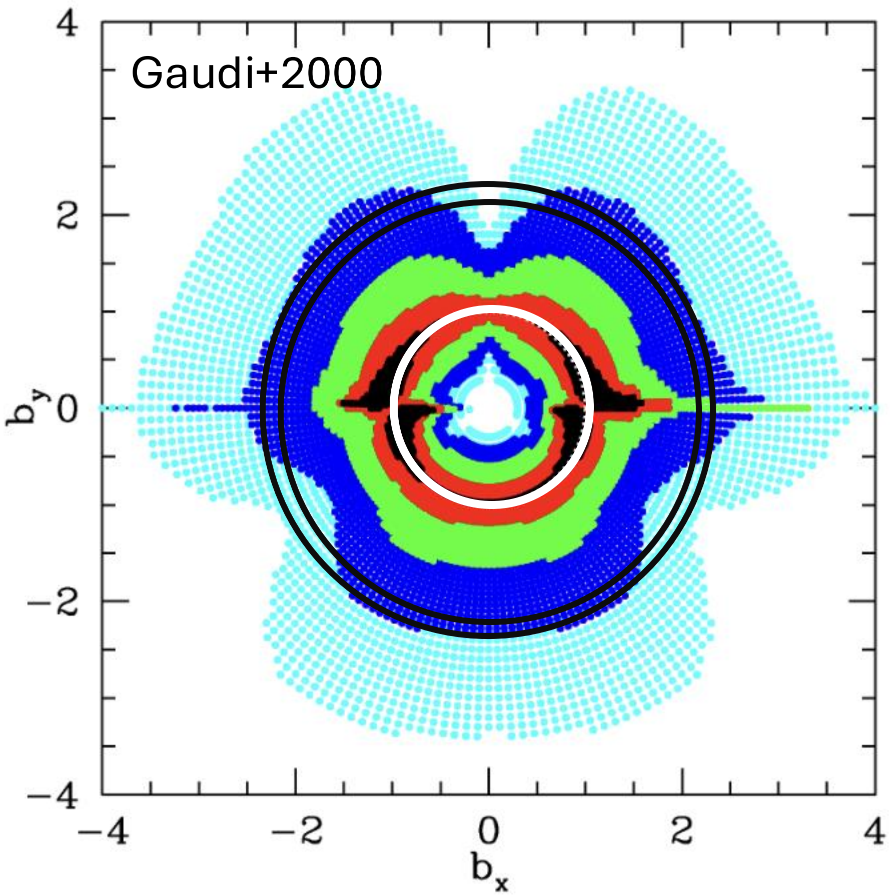
$$\Gamma \sim \text{few} \times 10 - 1000\ \text{deg}^{-2}\text{yr}^{-1}$$

Dictates area

Finding microlensing events



What do we mean by detection efficiency?



Points = planet detectable

$P_{\mathrm{det}}(s = 2, q = 10^{-2}) \approx 97\%$

$P_{\mathrm{det}}(s = 2, q = 10^{-3}) \approx 80\%$

$P_{\mathrm{det}}(s = 2, q = 10^{-4}) \approx 2\%$

$P_{\mathrm{det}}(s = 2, q = 10^{-5}) \approx 0\%$

$P_{\mathrm{det}}(s = 2, q = 10^{-6}) \approx 0\%$

$$N_{\mathrm{expected}}(s, q) = \sum_{i}^{N_{\mathrm{events}}} P_{\mathrm{det},i}(s, q)$$

See Yiwei Chai's poster #11

Not just cold exoplanets

Wilson+2023