Introduction to the Roman Galactic Bulge Time Domain Survey

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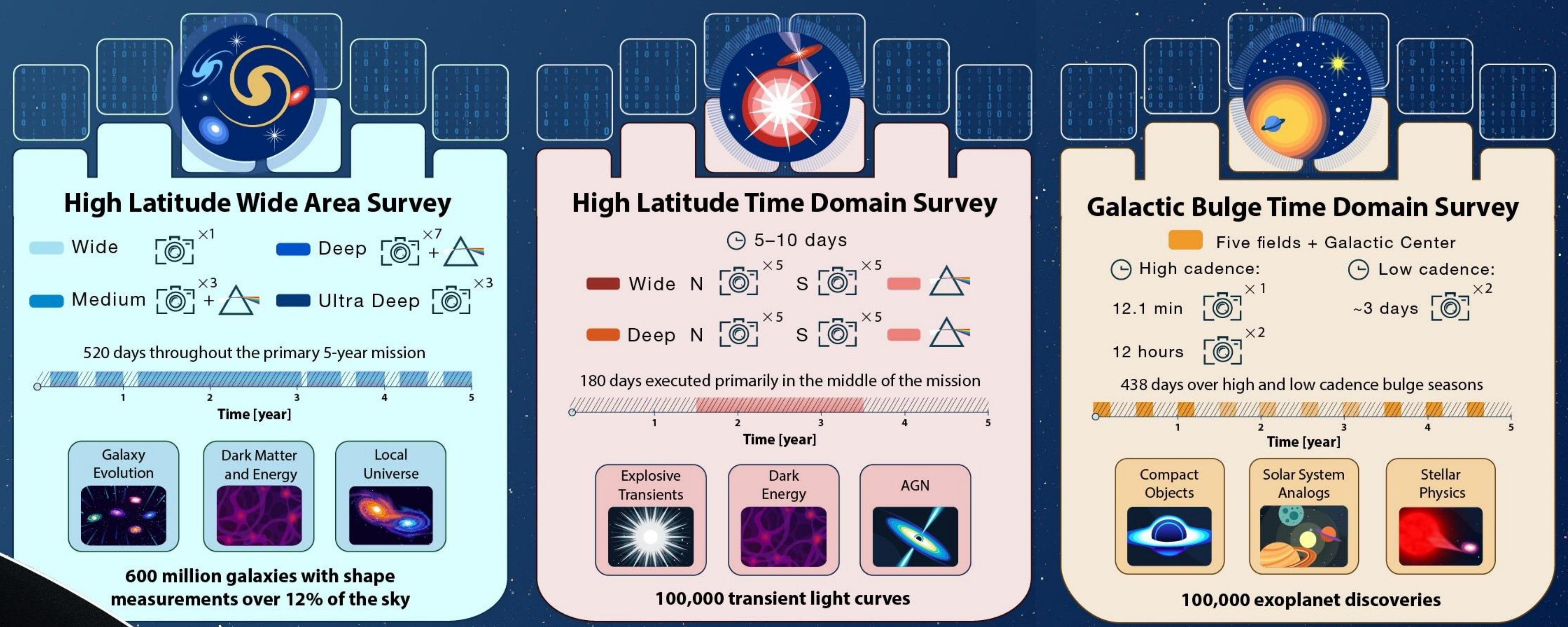
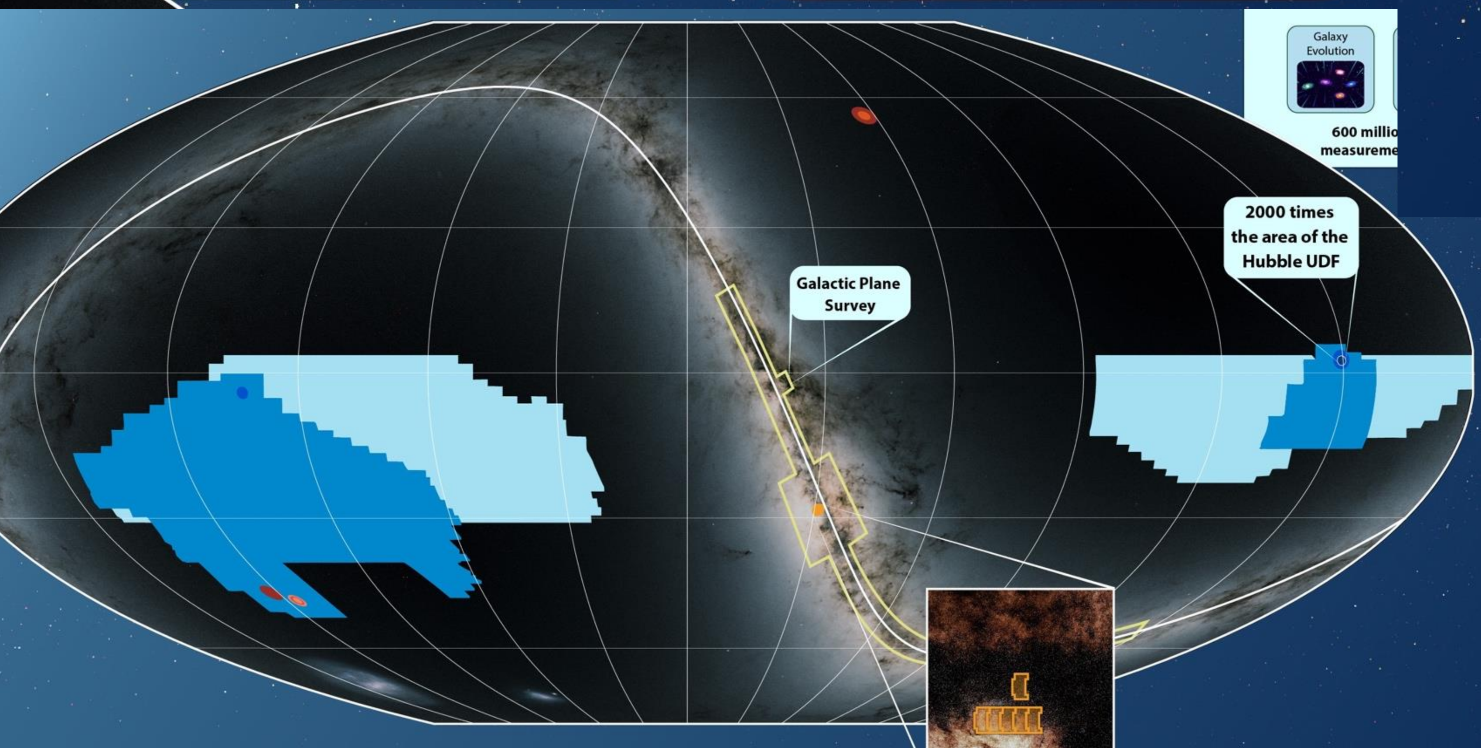
2026 Sagan Summer Workshop, Pasadena, July 2026

Learning Aims

- Motivation for the Survey
- Description of the Survey
- **What went into the Survey’s design?**

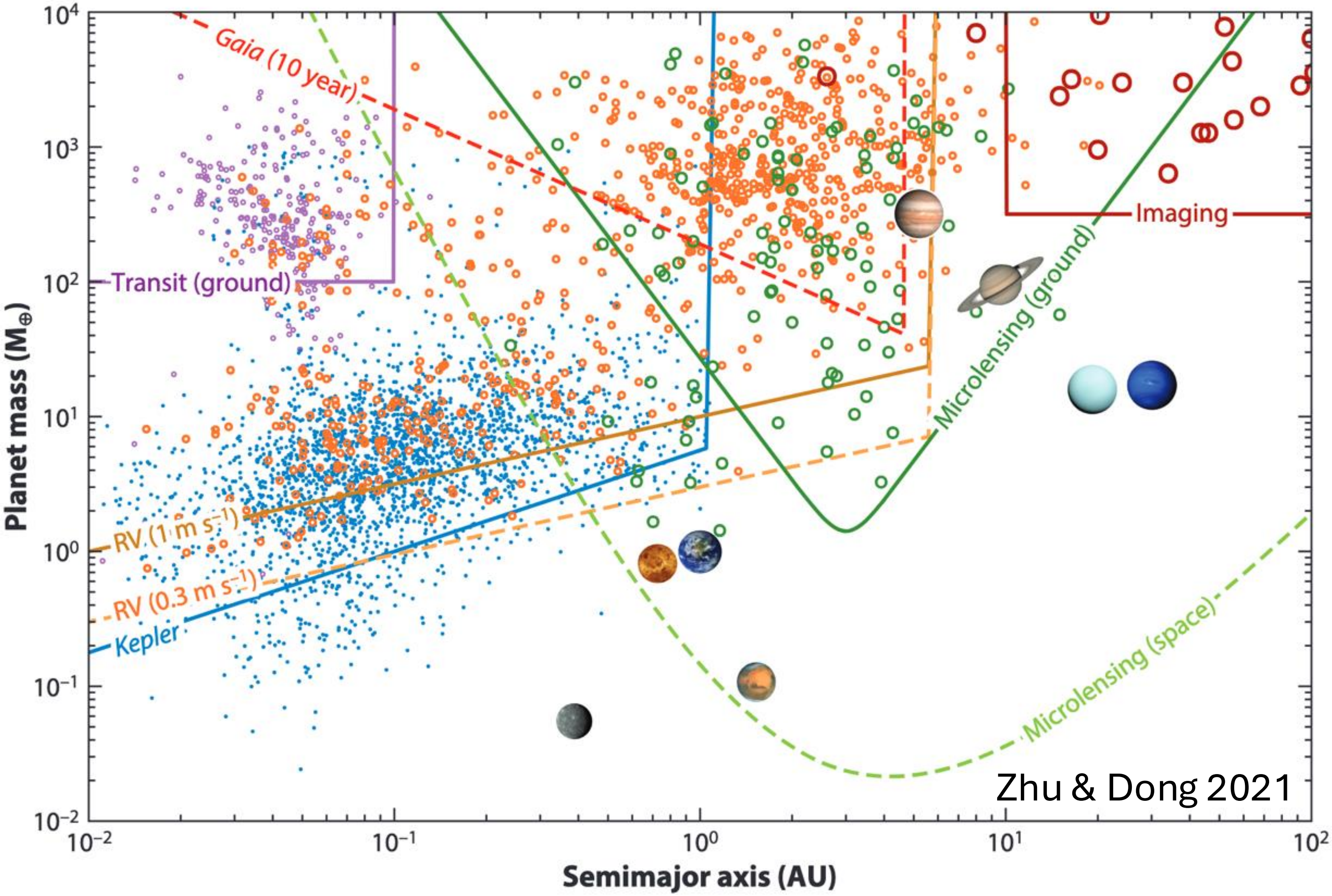




ROMAN
SPACE TELESCOPE

Image Composition: J. Olmsted, J. Kang, and C. Nieves (STScI). Background sky image: ESA/Gaia/DPAC. Acknowledgement: Javier Sanchez (STScI).

The problem



Gaia (10 year)
Transit (ground)
Imaging
Microlensing (ground)
Microlensing (space)
RV (1 m s⁻¹)
RV (0.3 m s⁻¹)
Kepler
Planet mass (M⊕)
Semimajor axis (AU)
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻²
10⁻¹
10⁰
10¹
10²
Zhu & Dong 2021

Roman’s Science Requirements

- EML 2.0.1: RST shall be capable of measuring the mass function of exoplanets with masses in the range 1 MEarth < m < 30 M Jupiter and orbital semi-major axes ≥ 1 AU to better than 15% per decade in mass.
- EML 2.0.2: RST shall be capable of measuring the frequency of bound exoplanets with masses in the range 0.1 M Earth < m < 0.3M Earth to better than 25%.
- EML 2.0.3: RST shall be capable of determining the masses of, and distances to, host stars of 40% of the detected planets with a precision of 20% or better.
- EML 2.0.4: RST shall be capable of measuring the frequency of free floating planetary-mass objects in the Galaxy from Mars to 10 Jupiter masses. If there is one M Earth free-floating planet per star, measure this frequency to better than 25%.
- EML 2.0.5: RST shall be capable of estimating ηEarth (defined as the frequency of planets orbiting FGK stars with mass ratio and estimated projected semimajor axis within 20% of the Earth-Sun system) to a precision of 0.2 dex via extrapolation from larger and longer-period planets.

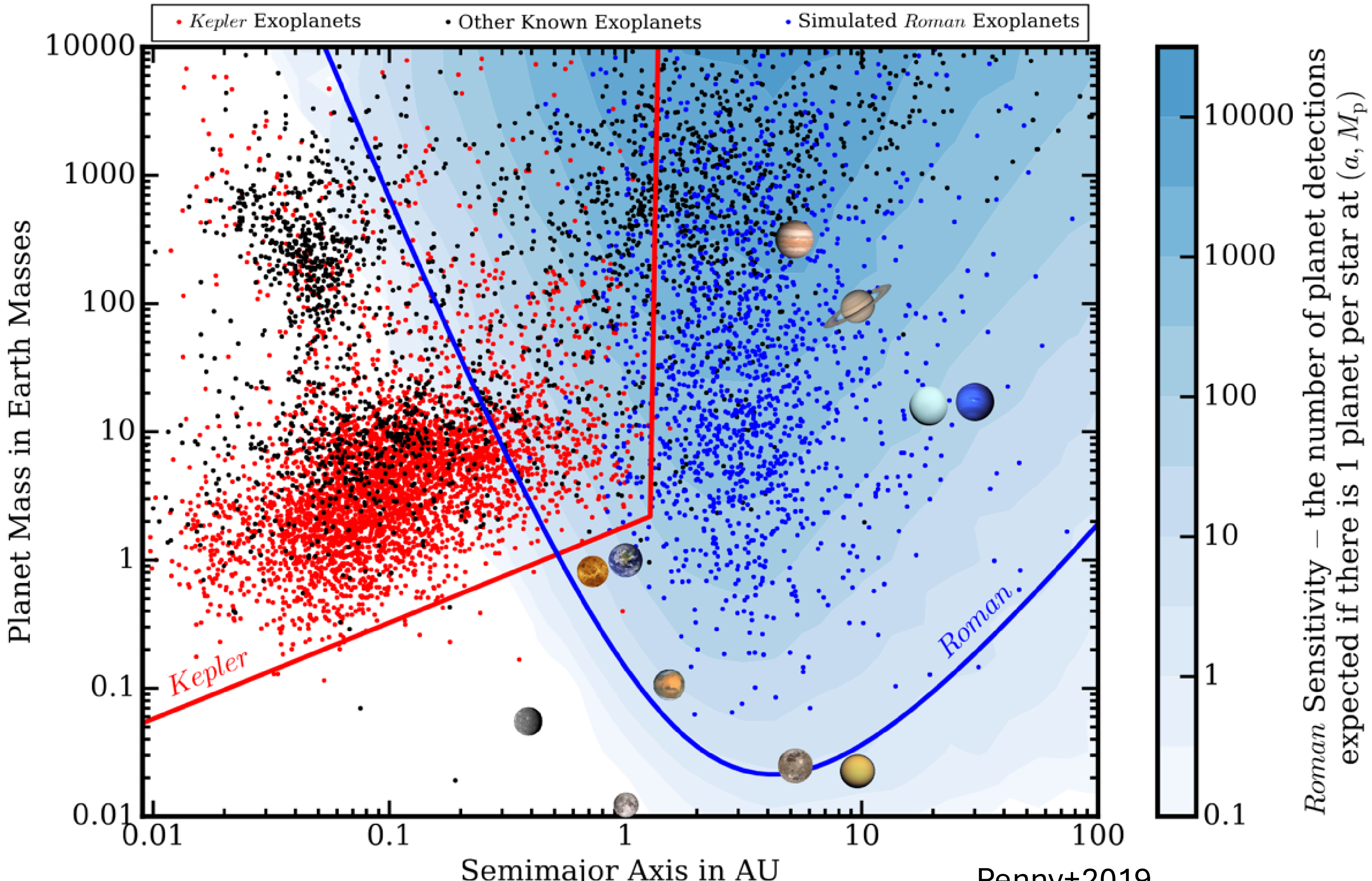
Roman's Science Requirements (in plain language)

1. Find lots of planets beyond 1 AU with masses 1 Earth-mass and up
2. Make sure that there is sensitivity to planets less massive than Earth, too
3. Measure the masses and distances of a significant fraction of the planets
4. Find lots of free-floating planets too
5. Make progress toward understanding the occurrence rate of habitable planets

Roman's Science Requirements

1. Find lots of planets beyond 1 AU with masses 1 Earth-mass and up
   - Duration+cadence, field-of-view+resolution
2. Make sure that there is sensitivity to planets less massive than Earth, too
   - Cadence, resolution
3. Measure the masses and distances of a significant fraction of the planets
   - Resolution, duration
4. Find lots of free-floating planets too
   - As requirement 1
5. Make progress toward understanding the occurrence rate of habitable planets
   - As requirement 1

Roman will fill out the M-a plane



Penny+2019
See talk by Farzaneh Zohrabi

Designing the GBTDS: a 100 Earth Survey

- For demographics we want to measure the occurrence rate

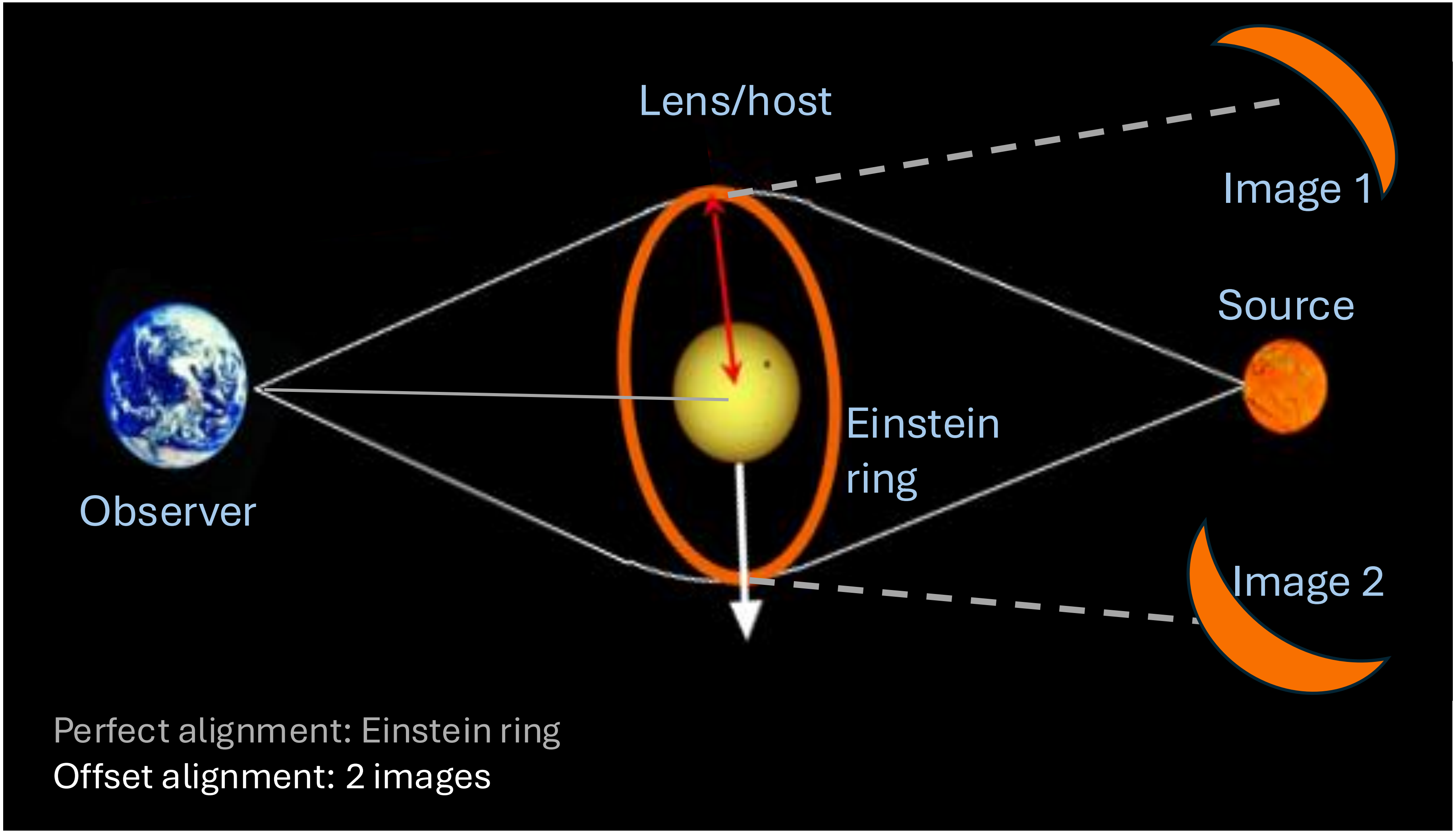
Fraction of stars with a planet $\eta = \frac{N_{\mathrm{detected}}}{\epsilon_{\mathrm{det}}\, N_{\mathrm{searched}}}$

- For a statistical survey with low detection efficiency, detections are Poisson distributed and the fractional uncertainty on η is

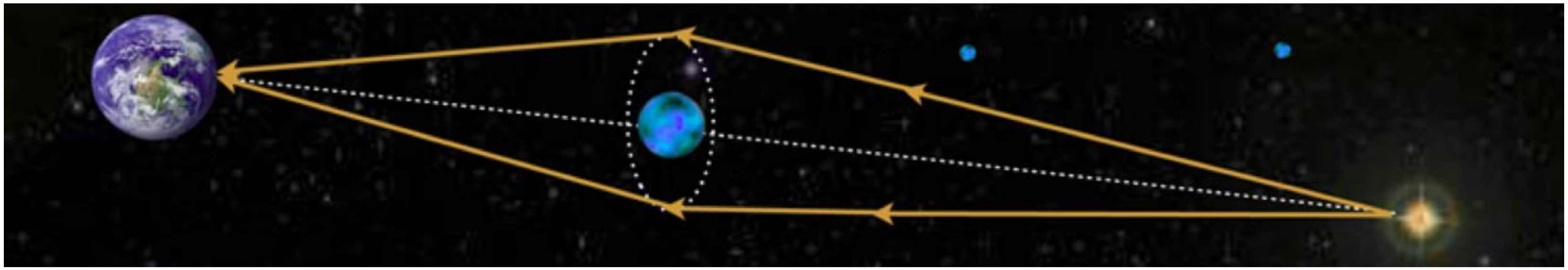
$$\frac{\sigma_\eta}{\eta} = \frac{1}{\sqrt{N_{\mathrm{detected}}}}$$

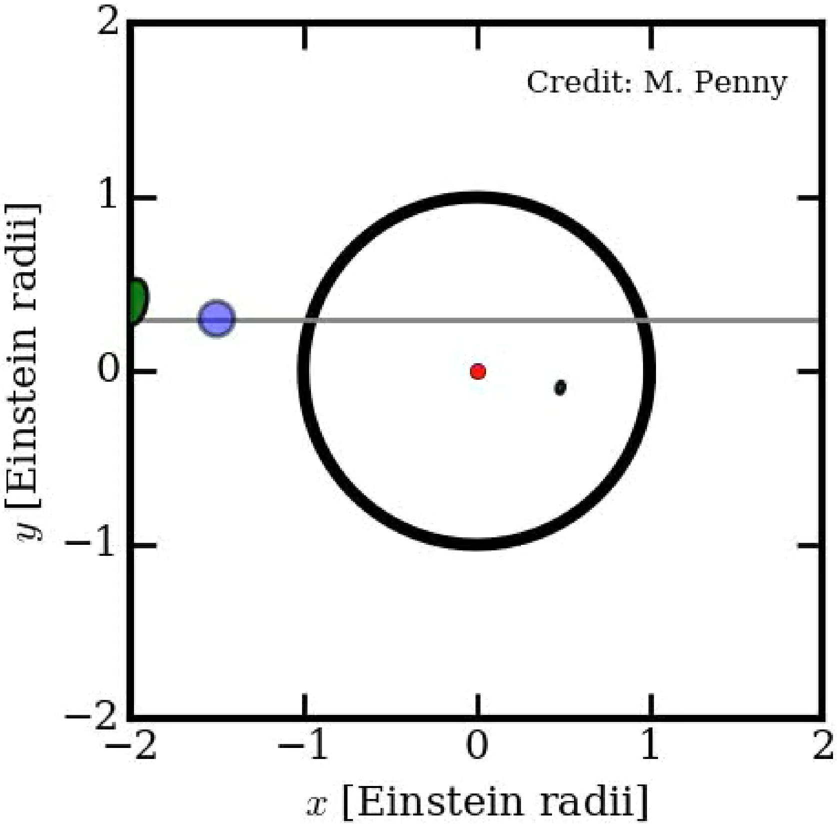
➢ 10% error needs 100 detections

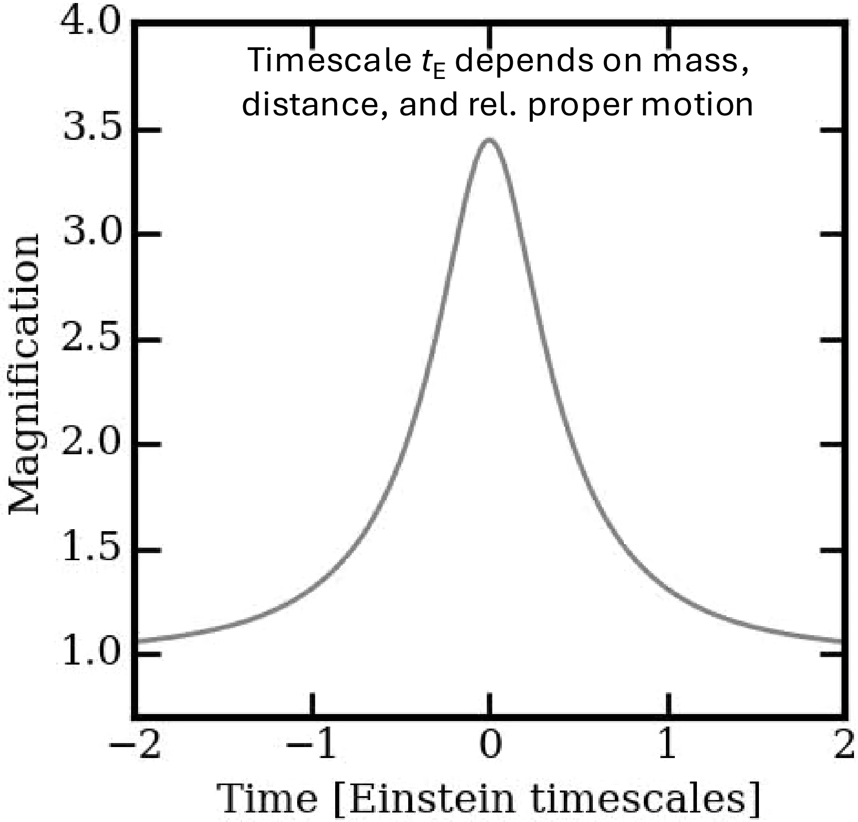
Gravitational Lensing



A single microlens

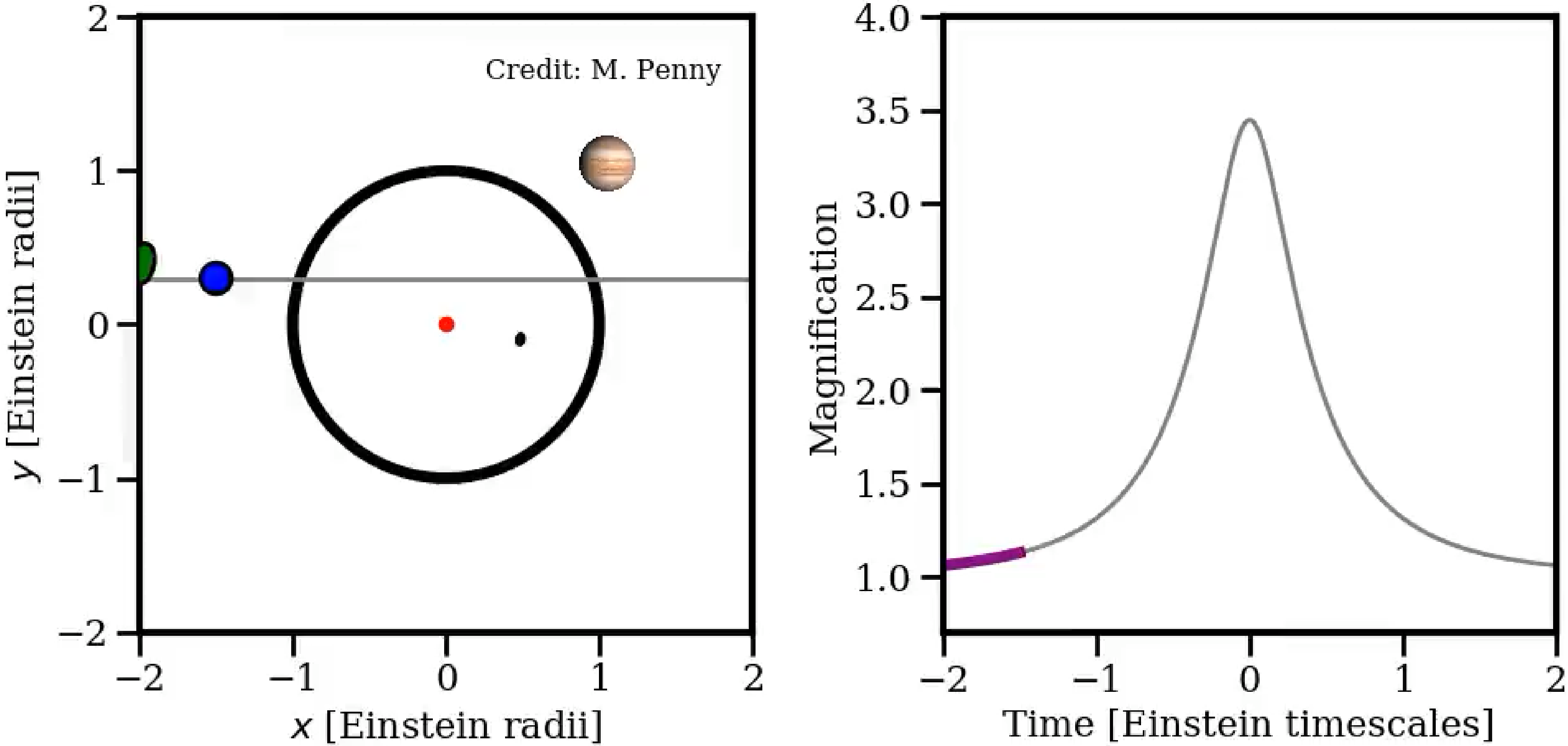






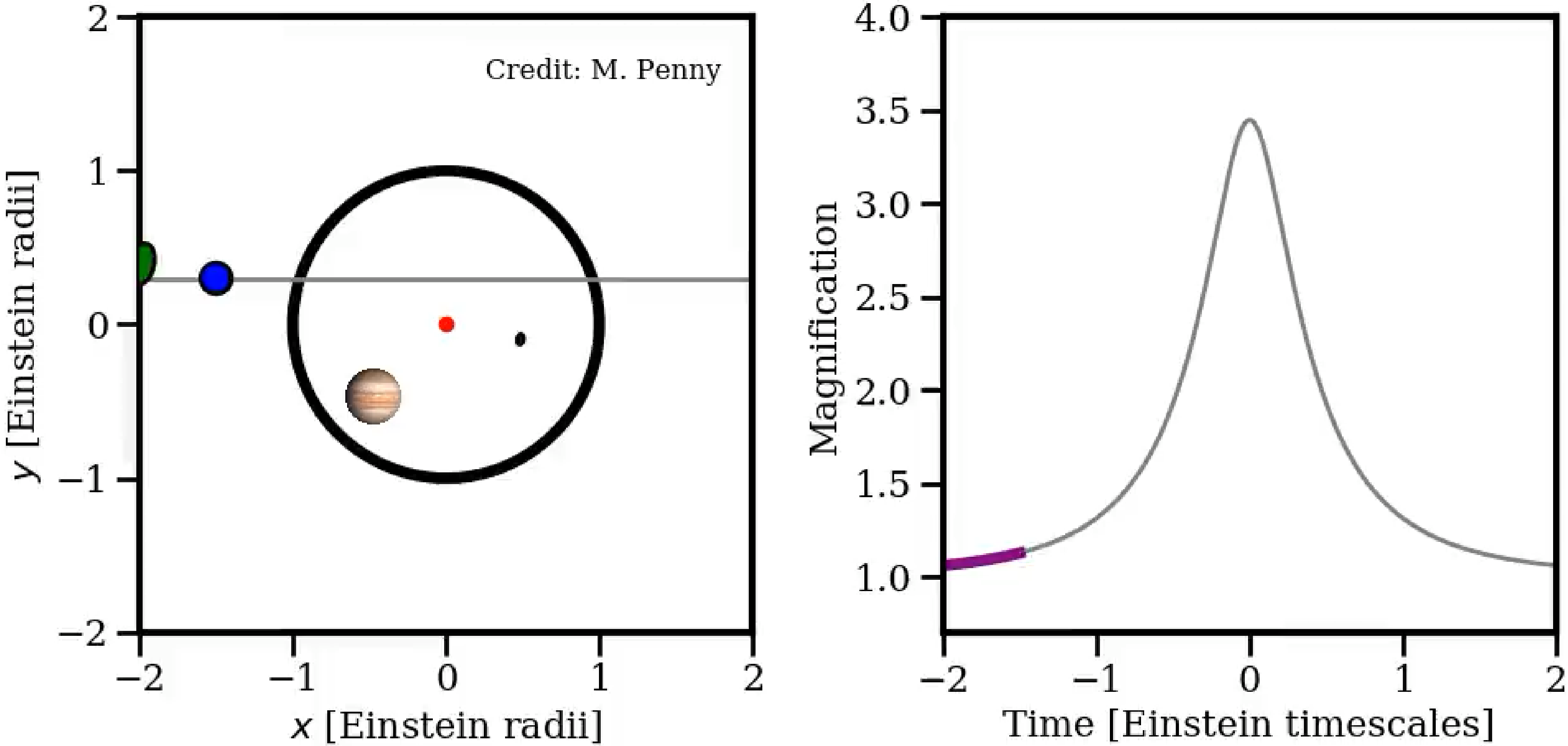
Planetary microlensing: image perturbations

Major image perturbation

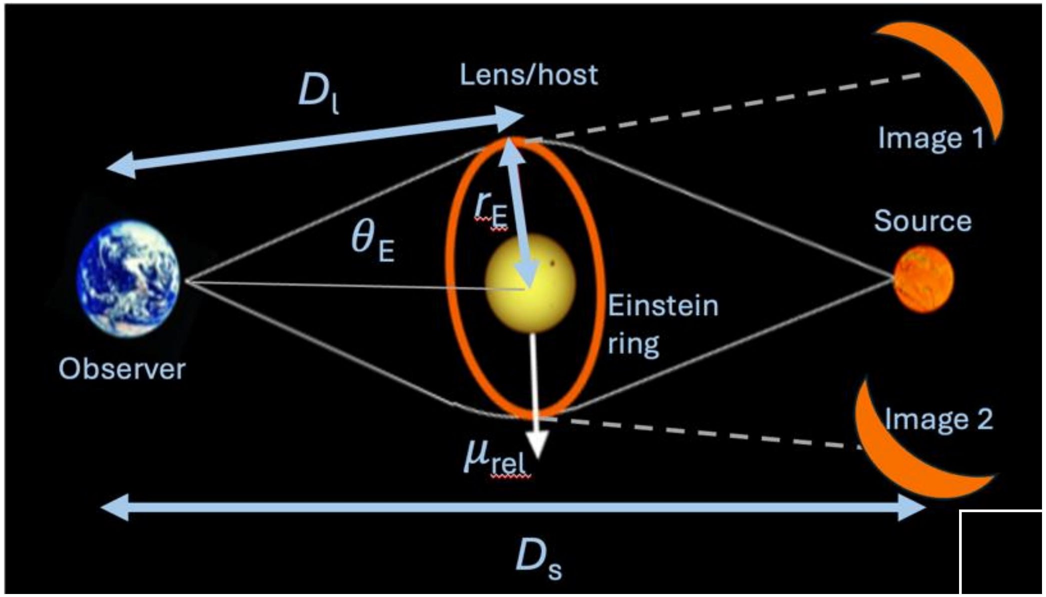


Planetary microlensing: image perturbations

Minor image perturbation



Microlensing Observables



$$\theta_{\mathrm{E}} \propto \sqrt{M}$$

$$r_{\mathrm{E}} \propto \sqrt{M}$$

$$t_{\mathrm{E}} \propto \sqrt{M}$$

Solar mass: ~months

Jupiter mass: ~day

Earth mass: ~hour

Dictates survey cadence

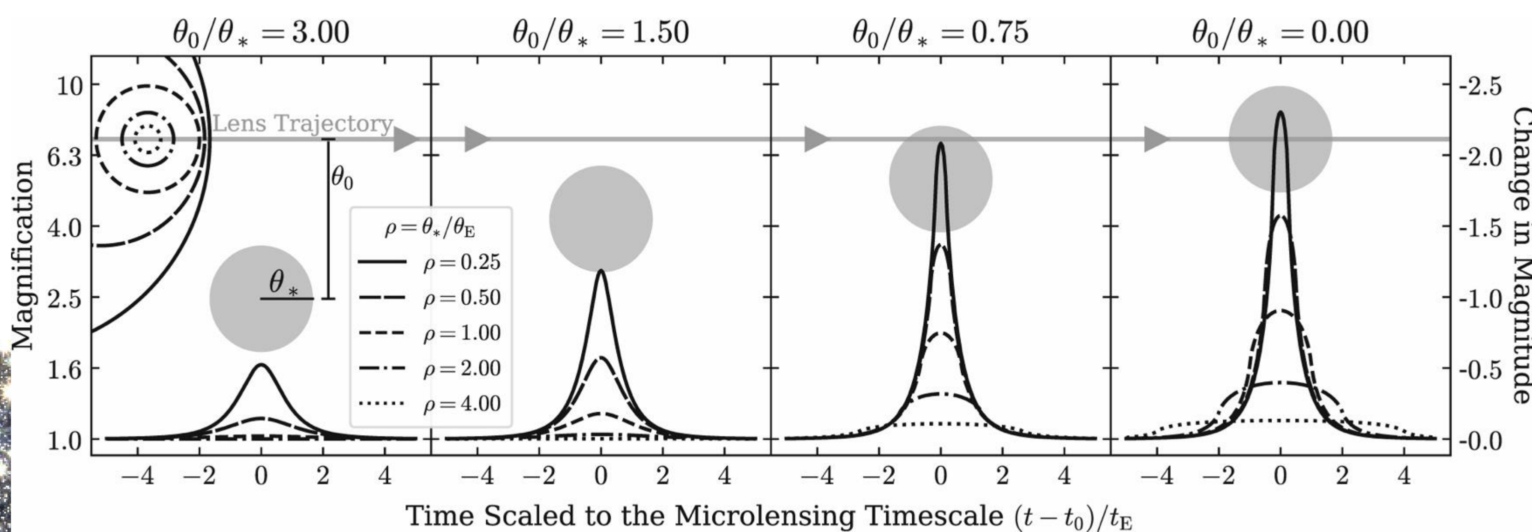
Planetary Microlensing Signals

Mass $\gtrsim$ Earth mass

- Amplitude is ~independent of mass
- Duration scales as $\sqrt{\text{mass}}$
- Detection probability ~$\sqrt{\text{mass ratio}}$

Mass $\lesssim$ Earth mass (finite source dominated)

- Amplitude scales as $\sqrt{\text{mass}}$
- Duration is ~independent of mass
- Detection probability – depends on photometric precision



Planetary Microlensing Signals

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Mass $\lesssim$ Earth mass (finite source dominated)

- Amplitude scales as $\sqrt{\text{mass}}$
- Duration is ~independent of mass
- Detection probability – depends on photometric precision

➢ Anomalies have an approx. duration minimum – the source star diameter crossing time

➢ Pick cadence to sample this

What cadence do we need?

- Roman targets main sequence source stars
  - Radius: 0.1–1 solar radii, ~few x 10^{-3} AU
  - Distance: Galactic bulge, ~10^4 pc
  - Angular diameter: ~few x 10^{-7} arcsec = few x 10^{-4} mas
- Crossing time
  - Stars move at ~100 km s^{-1}, @ ~10 kpc
    ~few x 10^{-4} mas/hour
  - Crossing time **~1 hour**, resolved with **~15 min cadence**

What cadence do we need?

- Roman targets main se
  - Radius: 0.1–1 solar rad
  - Distance: Galactic bul
  - Angular diameter: ~10
- Crossing time
  - Stars move at ~100 km
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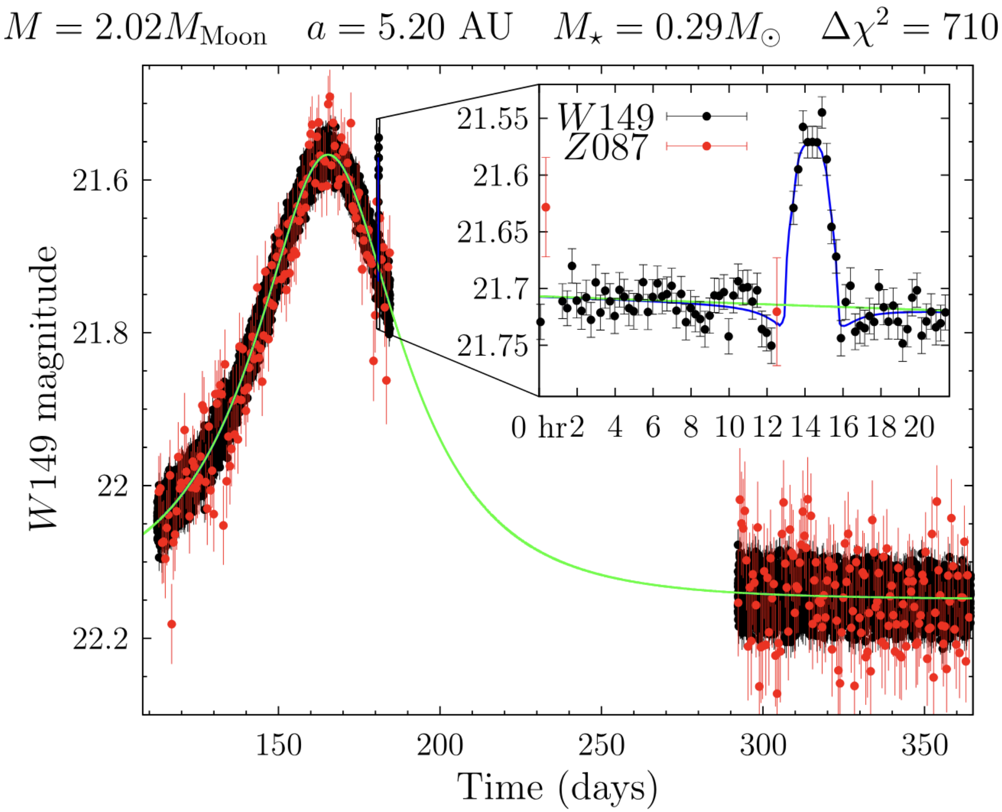
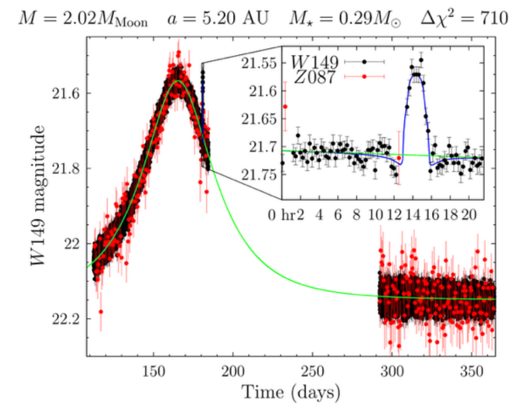


  - Crossing time **~1 hour**, resolved with **~15 min cadence**

Season duration?



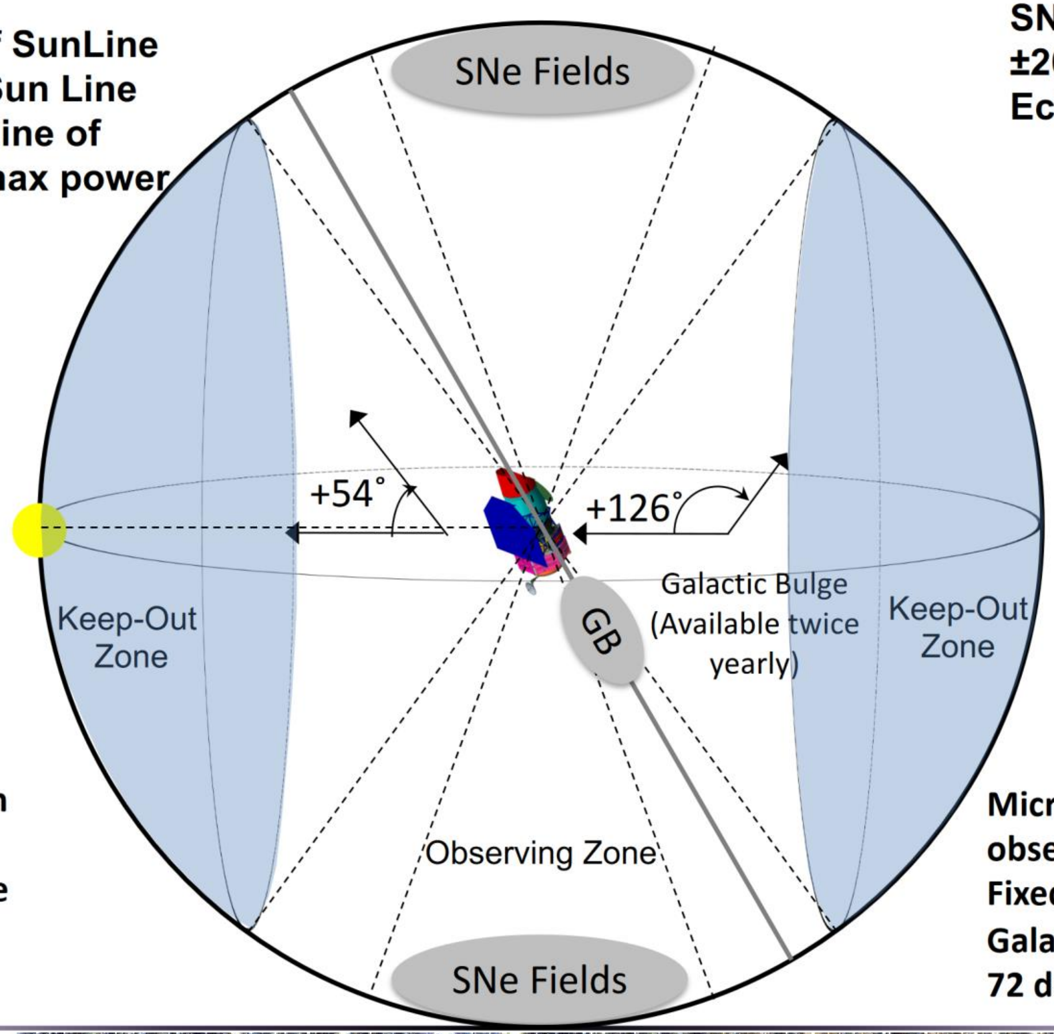
- Most planetary signals are unpredictable
- Can happen at any time during host microlensing event
- Need to observe most of the event to estimate its parameters for mass ratio and projected separation
  - Mass ratio $q \sim \sqrt{\frac{t_{\rm E,p}}{t_{\rm E,h}}}$, projected sep. $s \sim \sqrt{u_0^2 + \frac{(t_{0,\rm p} - t_{0,\rm h})^2}{t_{\rm E,h}^2}}$

➢ Want to observe continuously for ≳event duration **$>2t_{\rm E} \sim 60$ days**

Roman field of regard

Observing Zone:
- **54°-126° Pitch off SunLine**
- **360° Yaw about Sun Line**
- **±15° Roll about Line of Sight (LOS) off max power roll angle**

SNe Fixed Fields ±20° off the Ecliptic Poles



Earth/Moon LOS avoidance angles are a minor sporadic constraint

HL/GO/Coronagraph Surveys can be optimized within the full Observing Zone

Microlensing can observe Inertially Fixed Fields in the Galactic Bulge (GB) for 72 days twice a year

Survey area and duration?

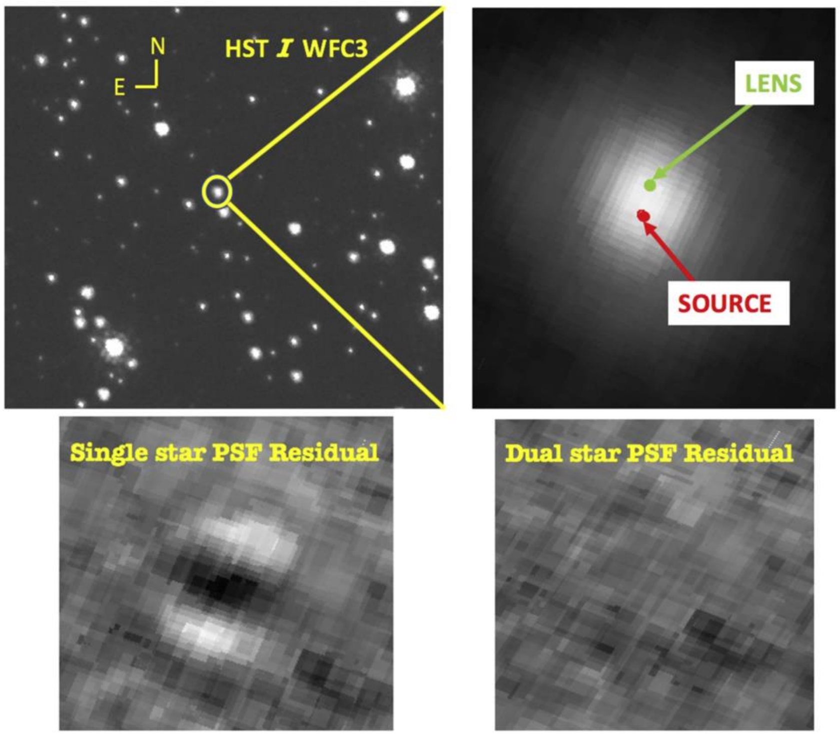
- Microlensing event rate: ~few x 10^{-5} $source^{-1}$ $year^{-1}$
- Detection efficiency: ~10^{-2} (Bennett & Rhie 1996)
- Planet detection rate: ~10^{-7} $source^{-1}$ $year^{-1}$

- Need ~few x 10^{8} star years to detect ~100 Earths
- Stellar density: ~few x 10^{8} deg^{-2} = ~10 stars/arcsec

➢ Need **~few square degree years** & **~0.1 arcsec resolution**

Resolution & Baseline?

Bhattacharya et al. (2018)

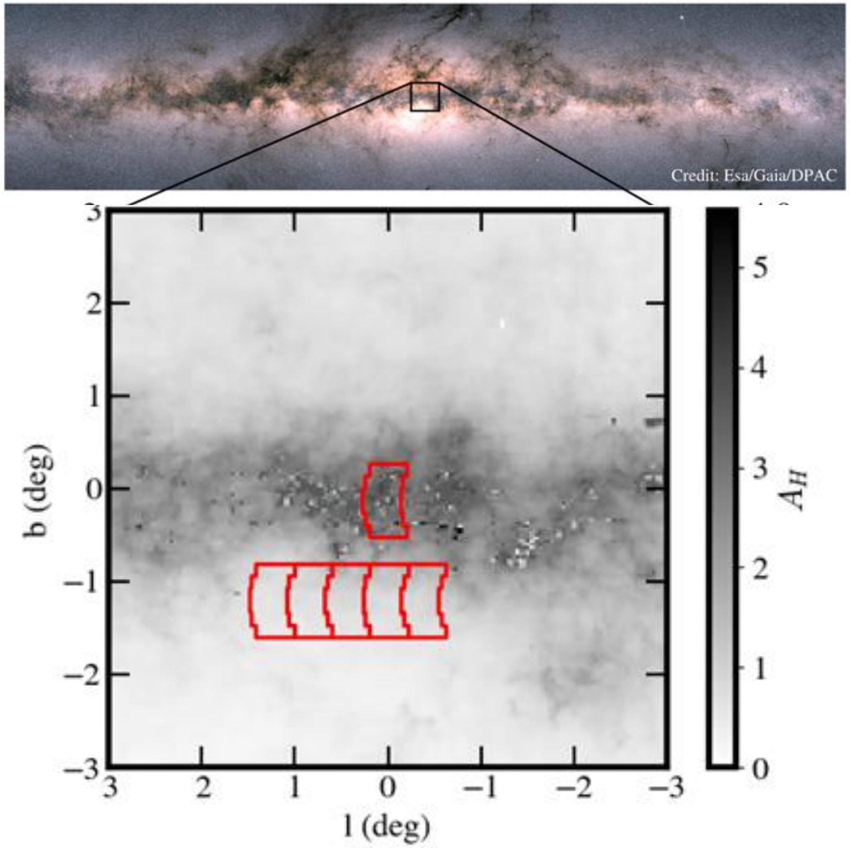


- See lens and source separate to measure lens mass
- Separate at ~few x 10^{-4} mas/hour = few mas/yr
- Can start to resolve stars at ~10% of a pixel or point spread function (λ/D~100 mas)

➢Need **~100 mas resolution** & a **few years baseline**

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

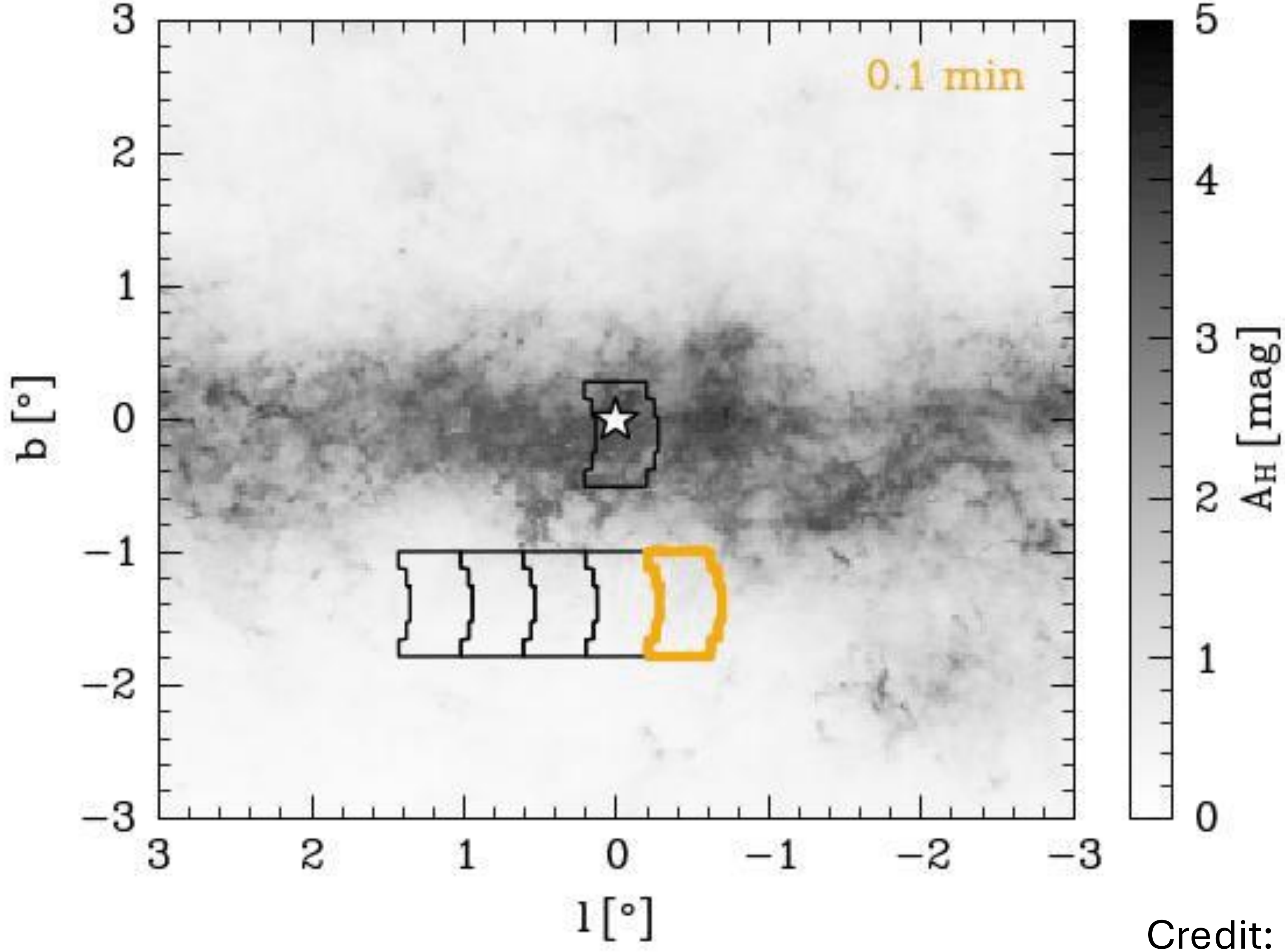
2.4-meter telescope
~100 mas resolution



- 6x72 day seasons = 1.2 yr
- 12-min cadence
  - ~50,000 images!
- 5-year baseline
- ~1.4-deg^2 area*
- ~200 million stars
- ~30,000 microlensing events
- ~1000+ bound planets
- ~100s free-floating

*excluding Galactic center field

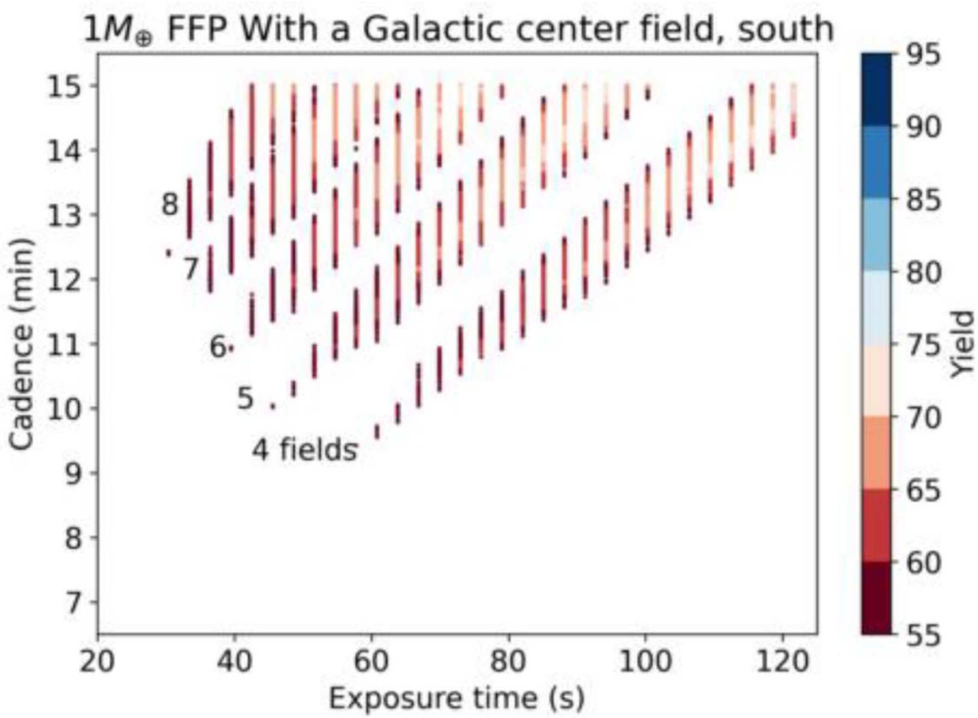
Point and move, not sit and stare

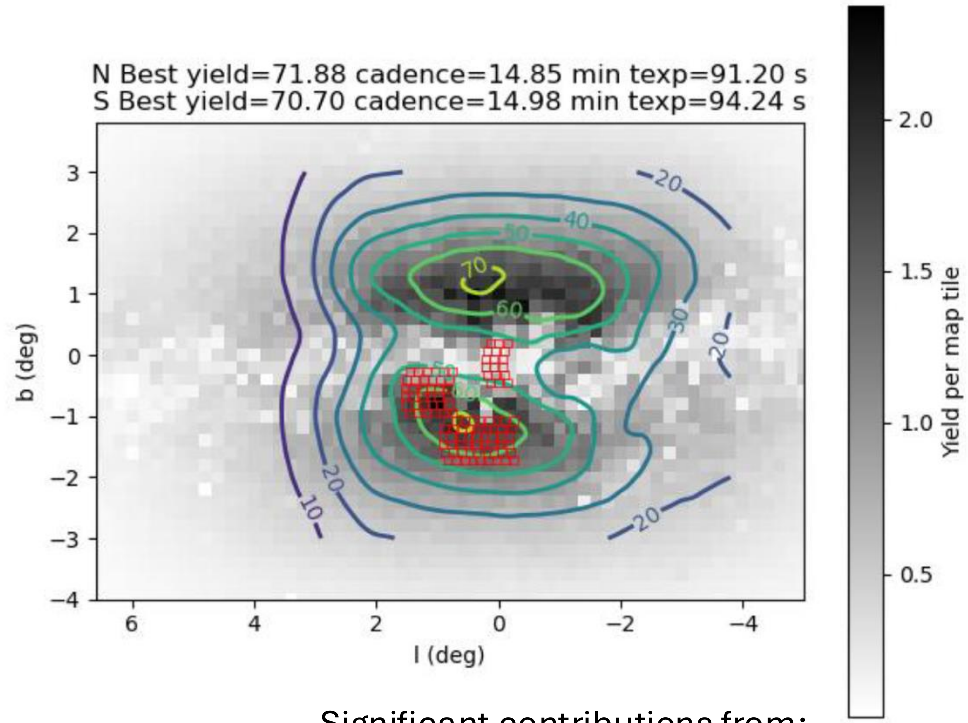


Credit: Robbie Wilson

Optimization process

https://github.com/mtpenny/gbtds_optimizer





Significant contributions from:
Farzaneh Zohrabi
Ali Crisp
Macy Huston
Jonas Klüter
+ many more

Constrained variables:

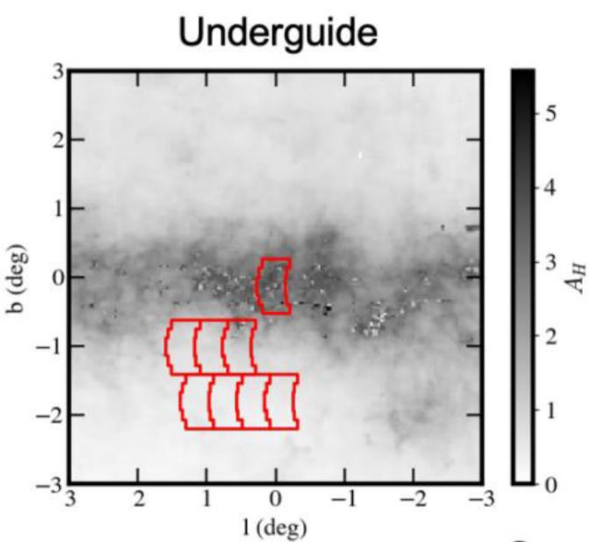
- Number & placement of fields
- Cadence
- Exposure time

Varying 2 fixes the other

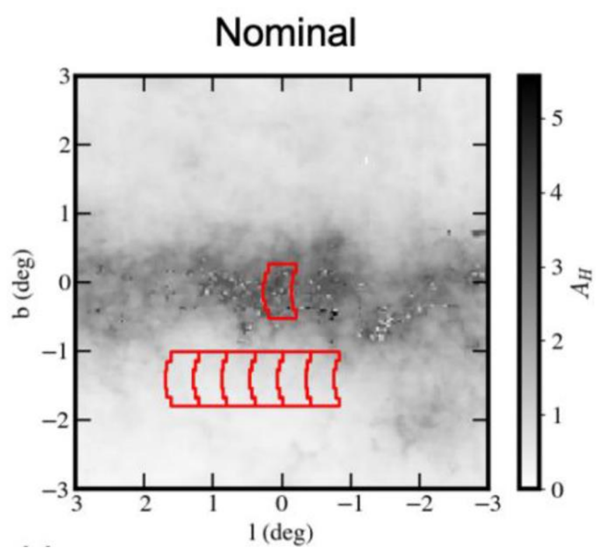
>23 Other science cases submitted as GBTDS CCS White Papers

- Stellar flares (Youngblood et al.)
- X-ray binaries (Bahramian et al.)
- Isolated black holes (Lam et al., Suzuki et al., Dawson et al., Sahu et al.)
- Astrometry (Kawata et al.)
- Supernovae (Maoz et al.)
- TTVs, White dwarf transits (Kipping et al.)
- Stellar characterization (Barclay et al.)
- Exomoons (Kalman et al., Poleski et al.)
- Pulsating stars & stellar variability (Das et al., Molnár et al., De et al.)
- Galactic center transients (Terry et al.)
- Mass measurements for past microlensing events (Koshimoto et al.)
- Cataclysmic variables (Morihana et al.)
- Planets that see Earth transit (Kerins et al.)
- Brown dwarf planets (Skowron et al.)
- Globular cluster transits & asteroseismology (Hoeijmakers et al., Molnár et al.)
- Eclipsing binaries (Kostov et al.)
- Solar system objects (Terai et al., Molnár et al.)
- Gravitational waves & their sources (Kupfer et al., Digman et al.)
- Quasars (Sumi et al.)
- Transiting planets & phase curves (Tamburo et al., Wilson et al., Grunblatt et al., Kalman et al.)
- Xallarap planets & brown dwarfs (Miyazaki et al.)
- Initial mass function (Poleski et al.)
- Asteroseismology (Pinsonneault et al., Molnár et al.)

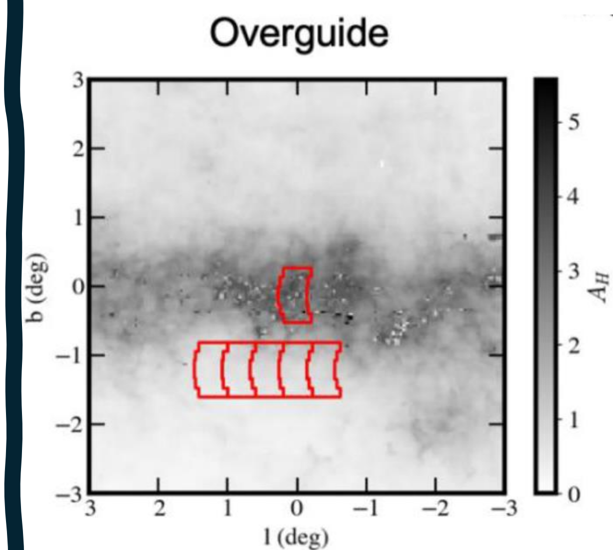
Core Community Survey Definition Committee Recommendations



63 days/season
12.6 min cadence
58s exposures
Low cadence GC
380 days total



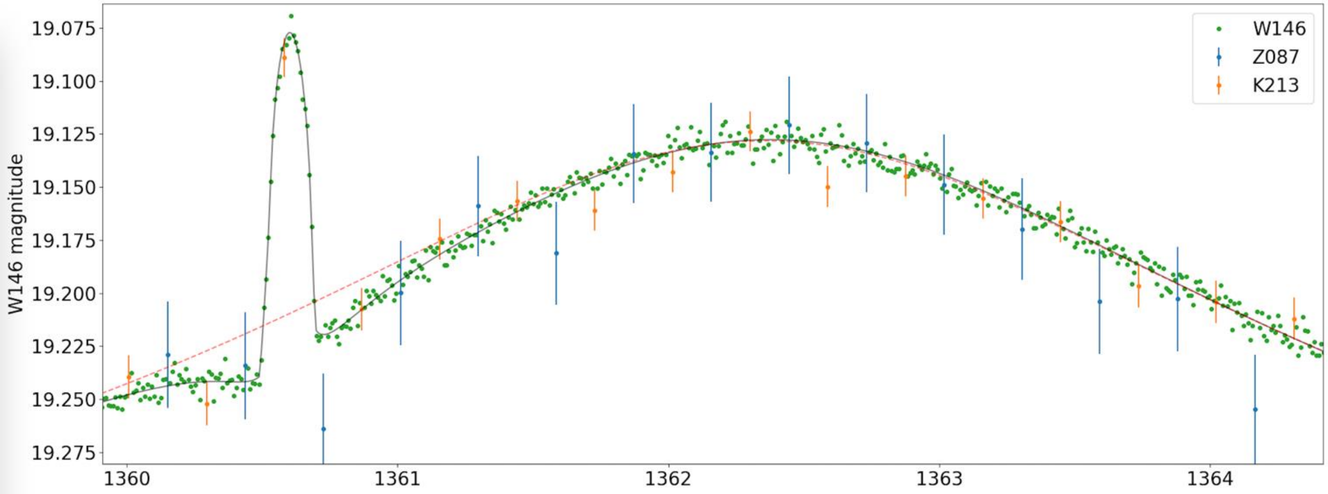
68.5 days/season
14.8 min cadence
73s exposures
High cadence GC
420 days total

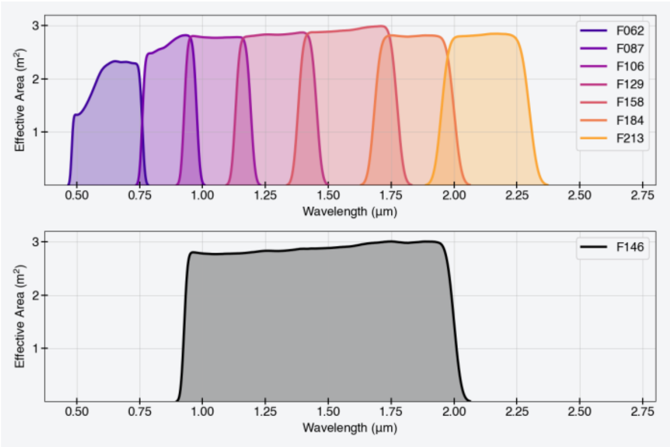


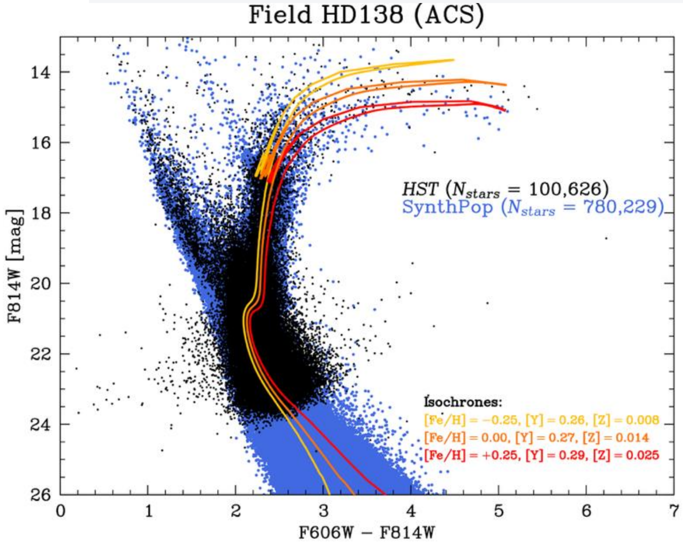
70.5 days/season
12.1 min cadence
66s exposures
High cadence GC
440 days total

Christiansen & Huber et al. (2024)

Color images every 3 hours – Z & K





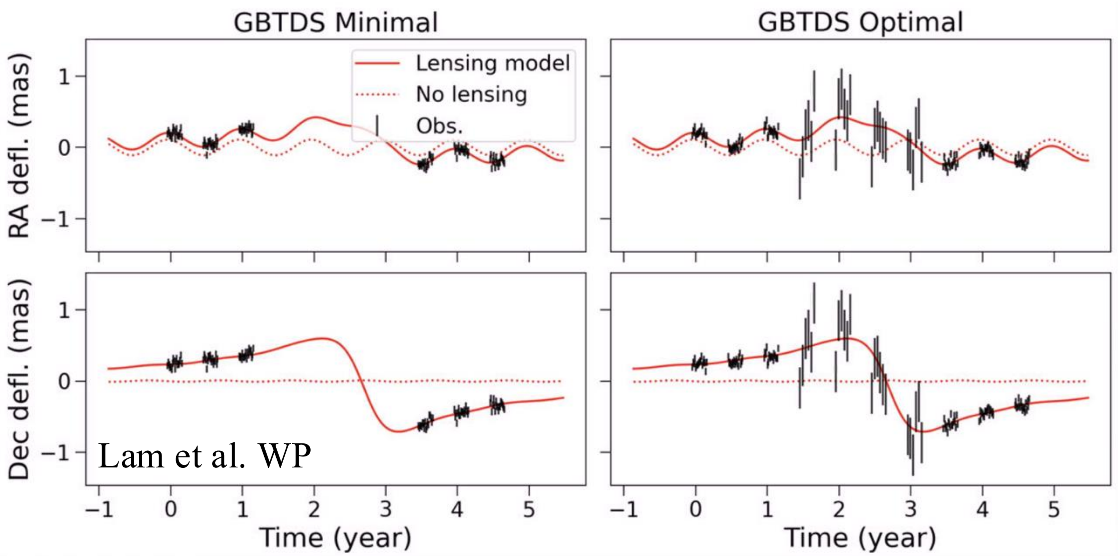


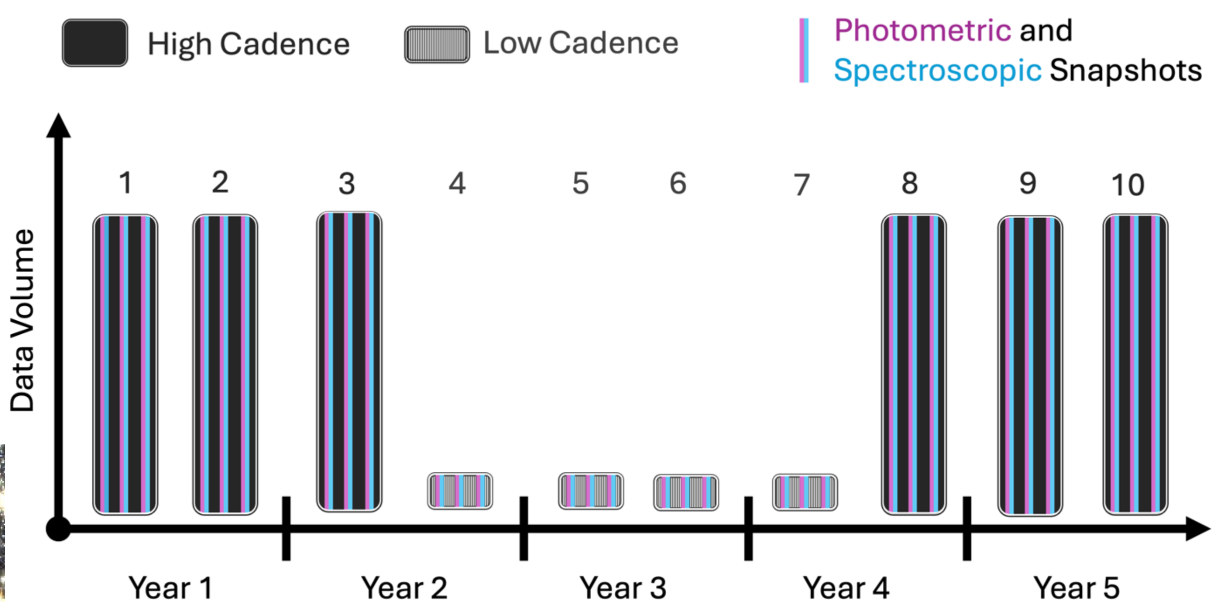
Terry et al. (2026)

- Finite source + (source color – reddening) + color-surface brightness relations
  $\Longrightarrow$ angular Einstein ring radius $\Longrightarrow$ masses
- Cadence for FFP event colors & depth

See poster by E. Tiburcio
talk by D. Nataf

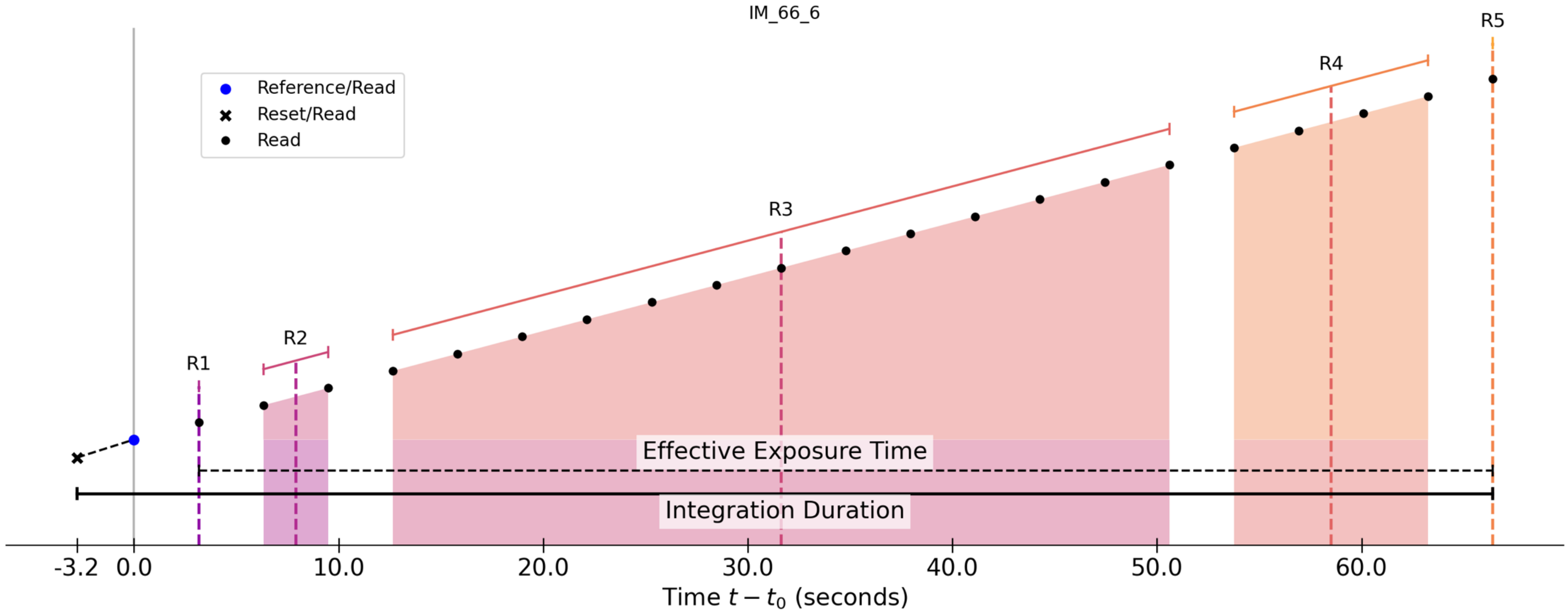
Low cadence & snapshots





- Adds low-cadence observations in all bulge seasons
  - See J. Lu talk
- Adds 3 snapshots/season in all Roman filters
- Adds grism snapshots
- See talks by M. Pinsonneault & R. Pike

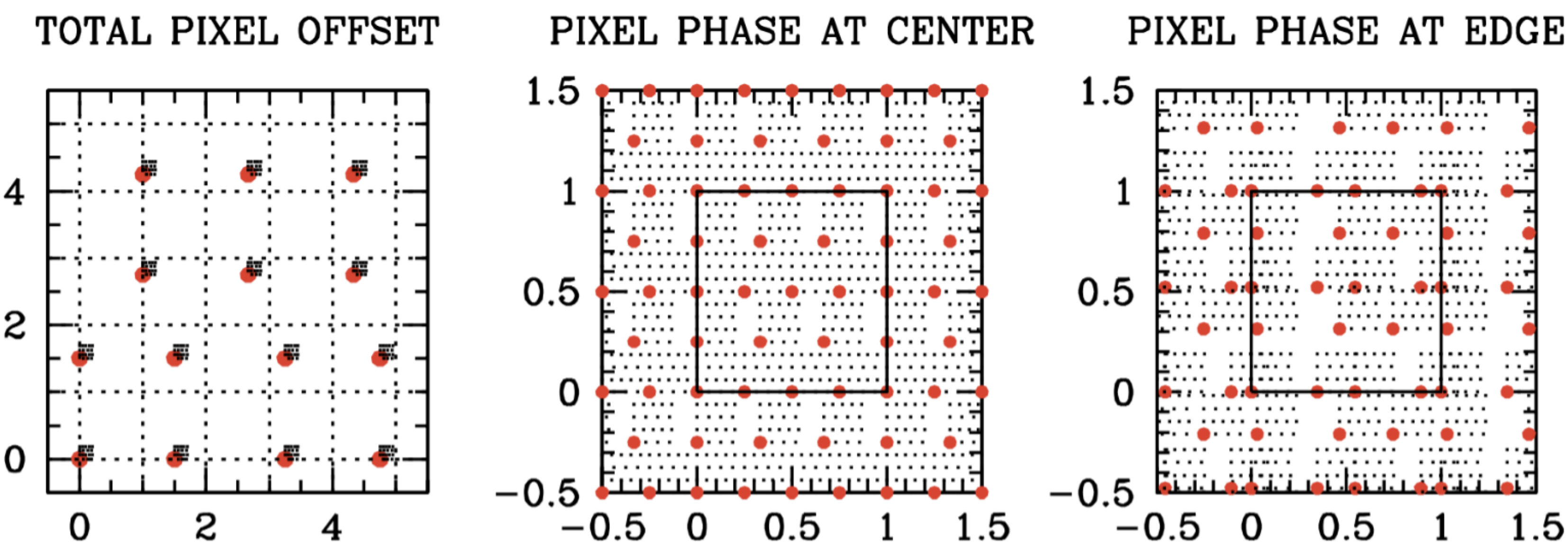
MultiAccum (MA) Tables

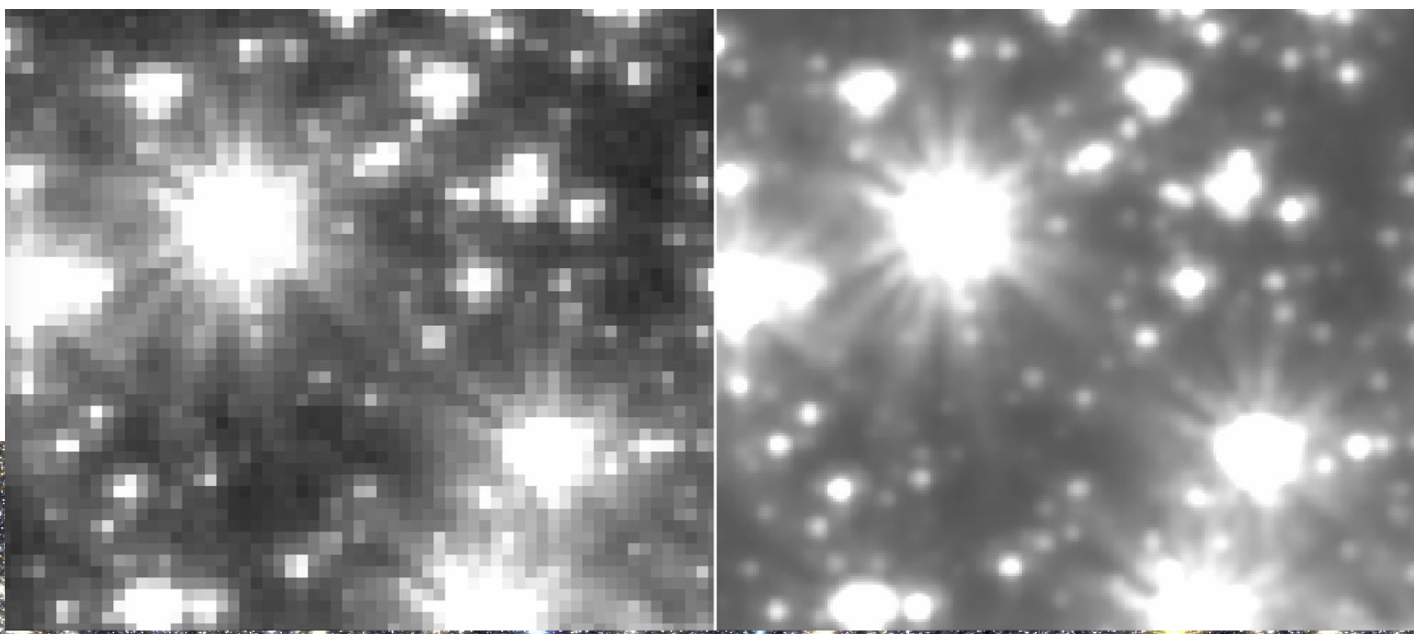


- 6 images per integration
- Sub-minute variability
- Bright stars
- May require special processing

Dithering

- Each pointing offset by a sub-pixel shift
- Enables construction of higher-resolution images
- Enables detrending due to intra-pixel sensitivity variations

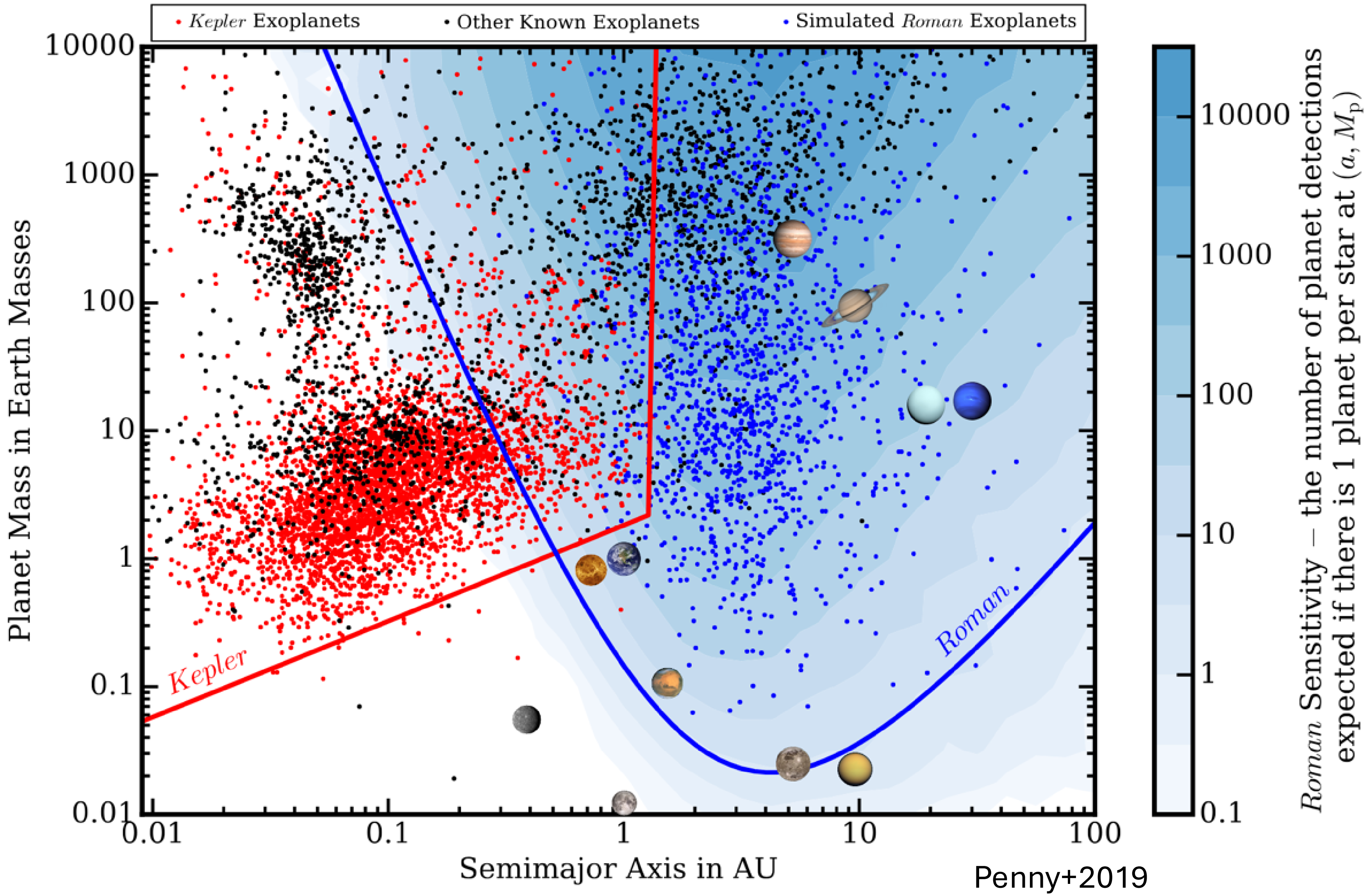




Credit: Jay Anderson

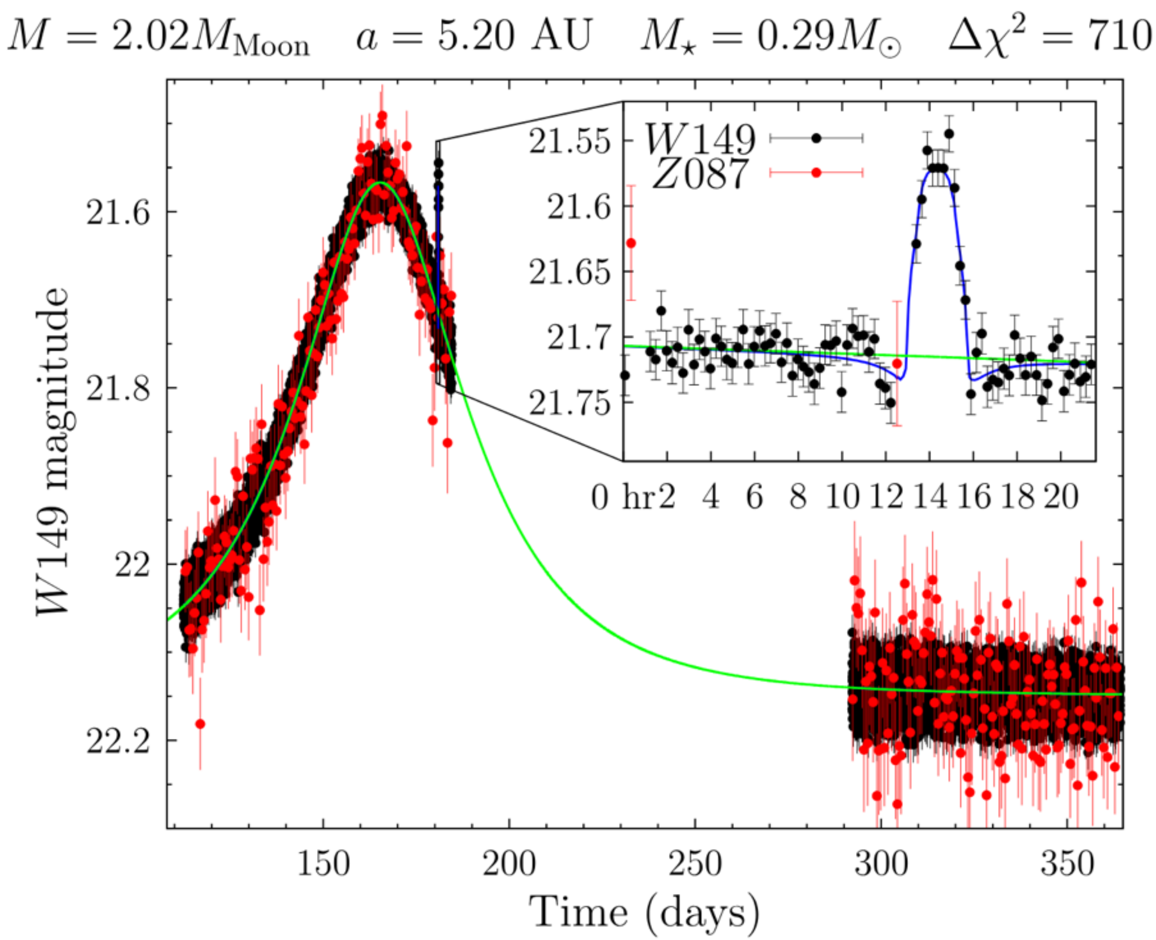
See J. Anderson talk

Roman will fill out the M-a plane

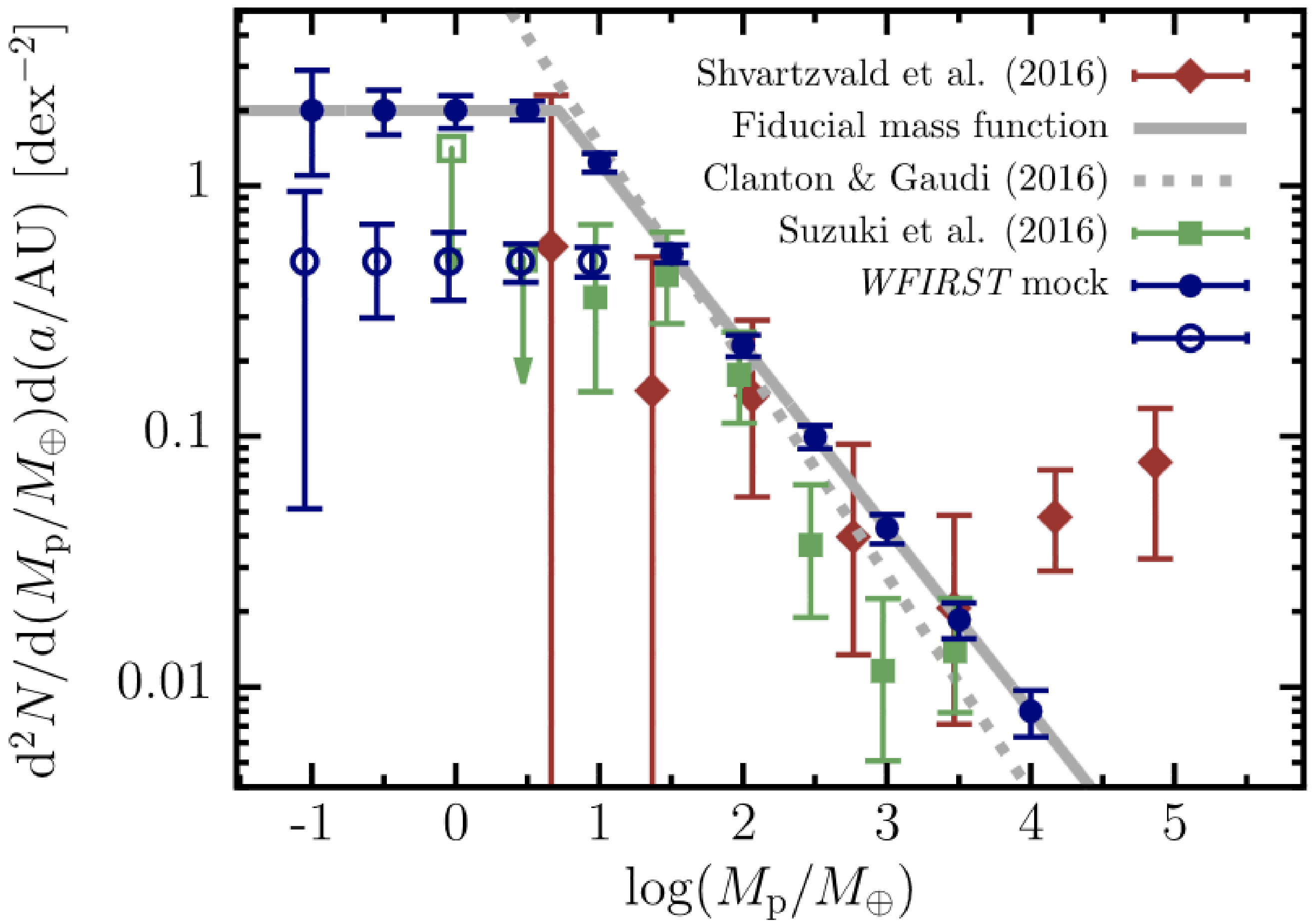


Penny+2019
See talk by Farzaneh Zohrabi

Sensitivity down to ~Moon mass

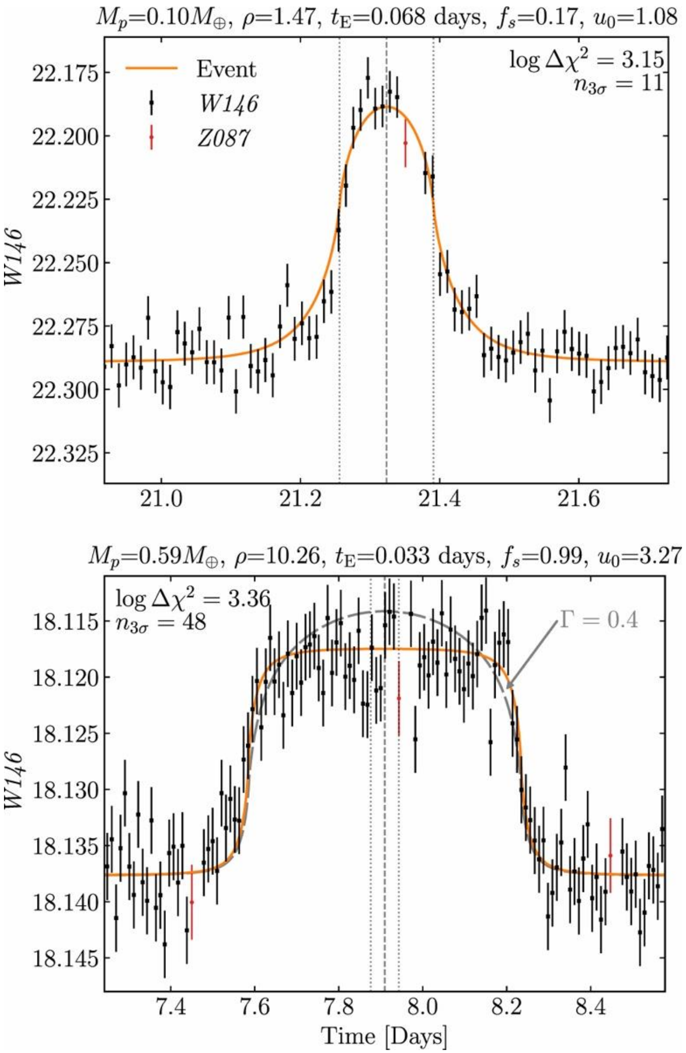


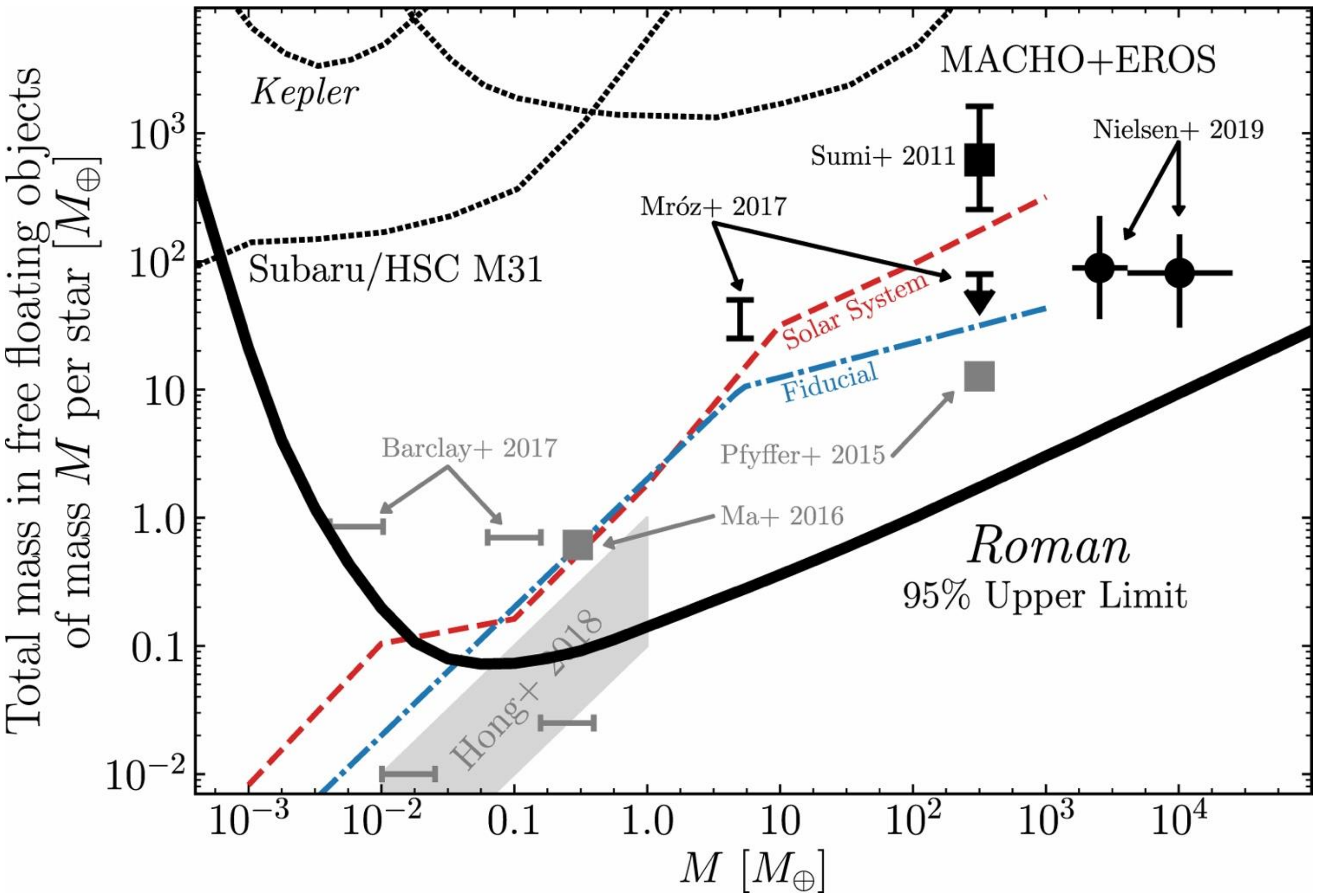
Vast improvement in demographics



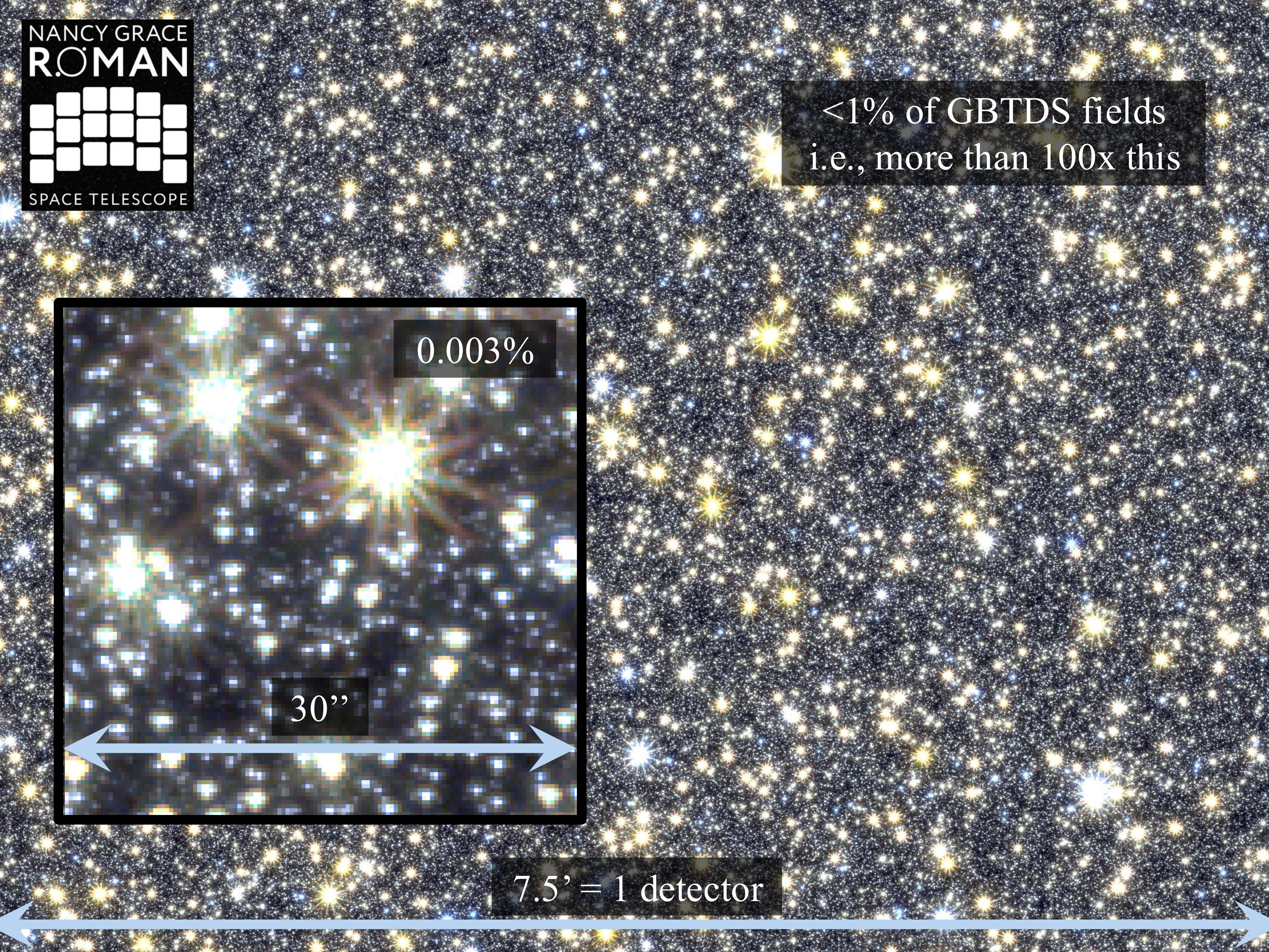
Penny et al. (2019)

Free-floating planets



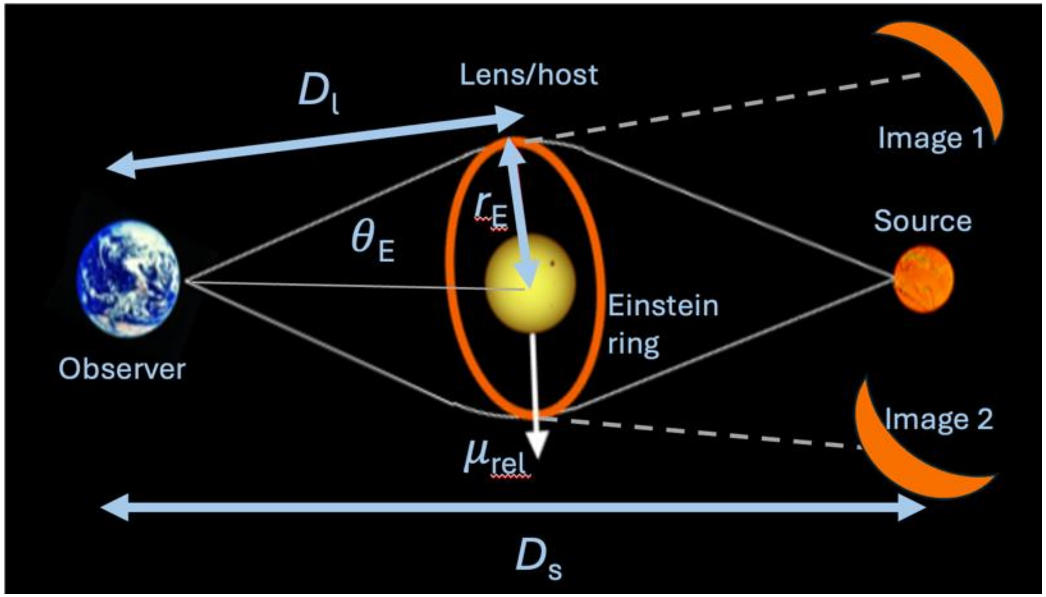


- Hundreds to thousands of detections expected
- Sensitivity down to ~Pluto mass if there are enough of them


NANCY GRACE ROMAN SPACE TELESCOPE
<1% of GBTDS fields
i.e., more than 100x this
0.003%
30”
7.5’ = 1 detector

Backup

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

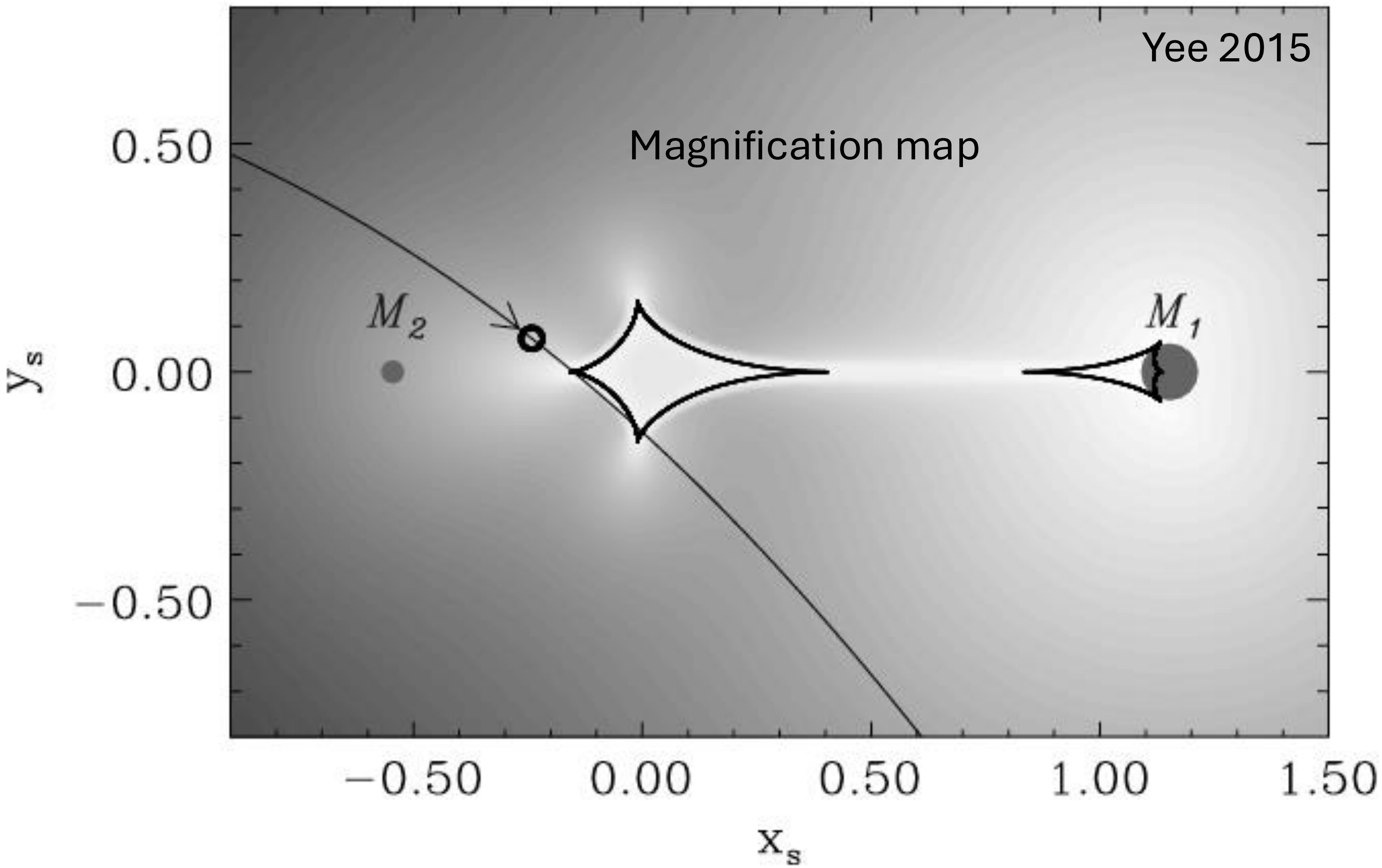
$$t_E = \frac{\theta_E}{\mu_{rel}} \sim 1 \text{ month}$$

- 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

Planetary microlensing: caustics

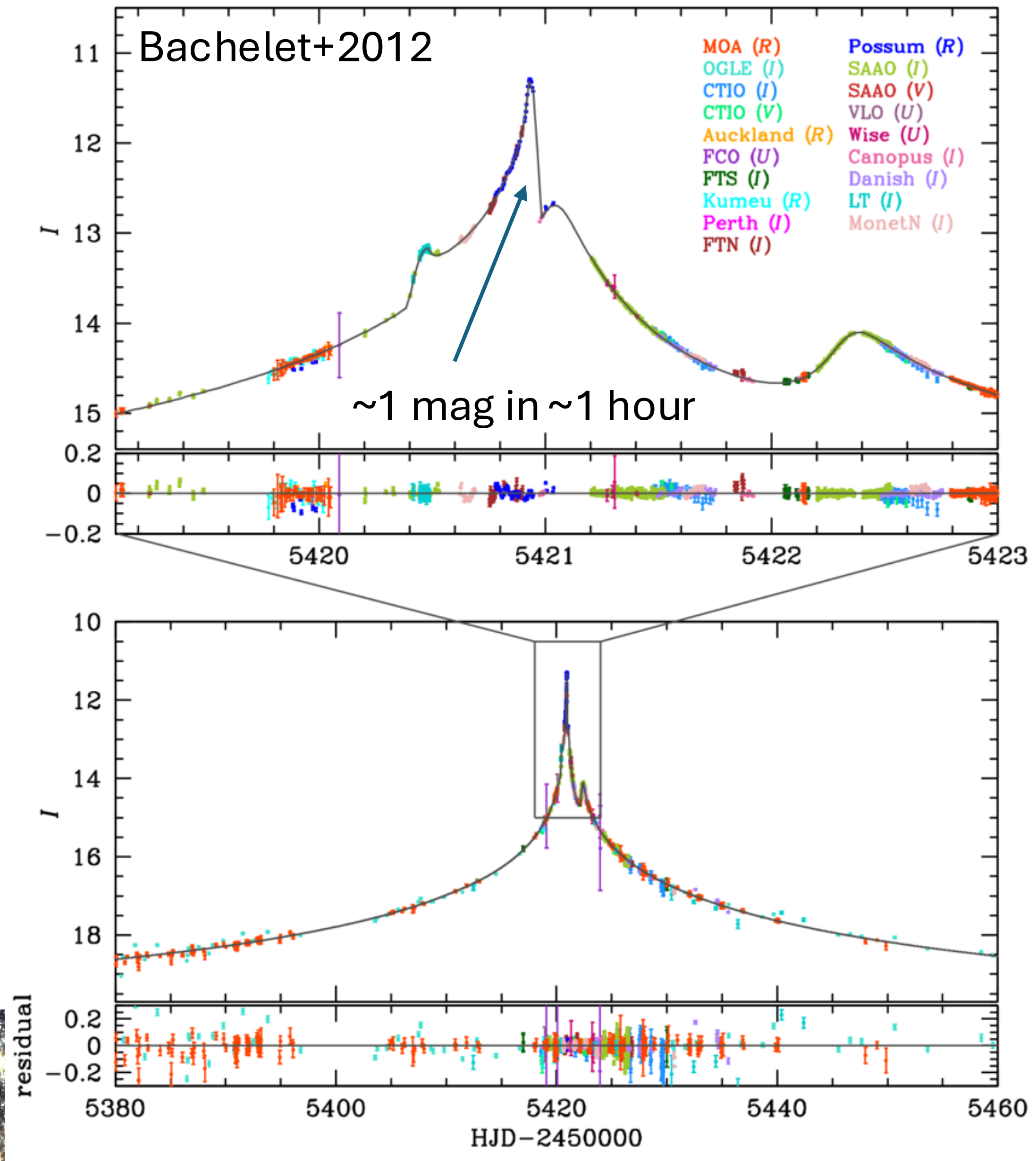


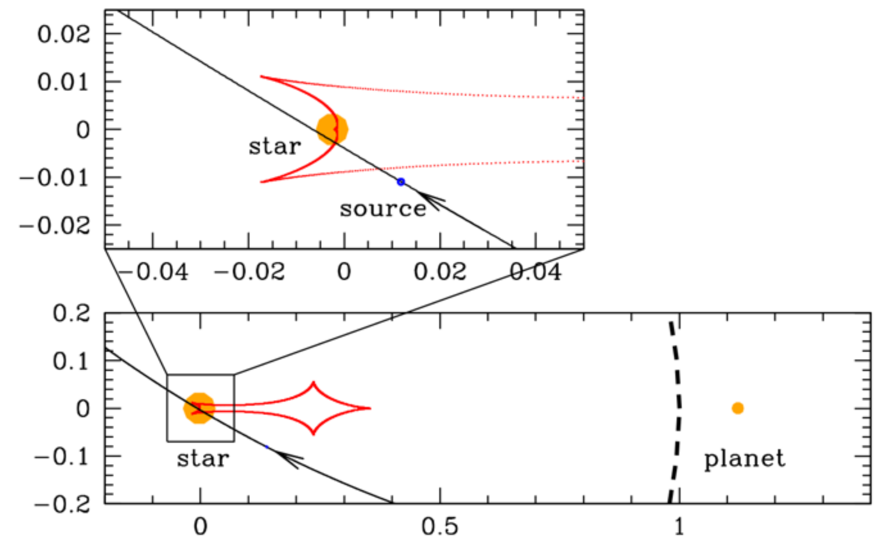
Caustics separate regions with different numbers of images

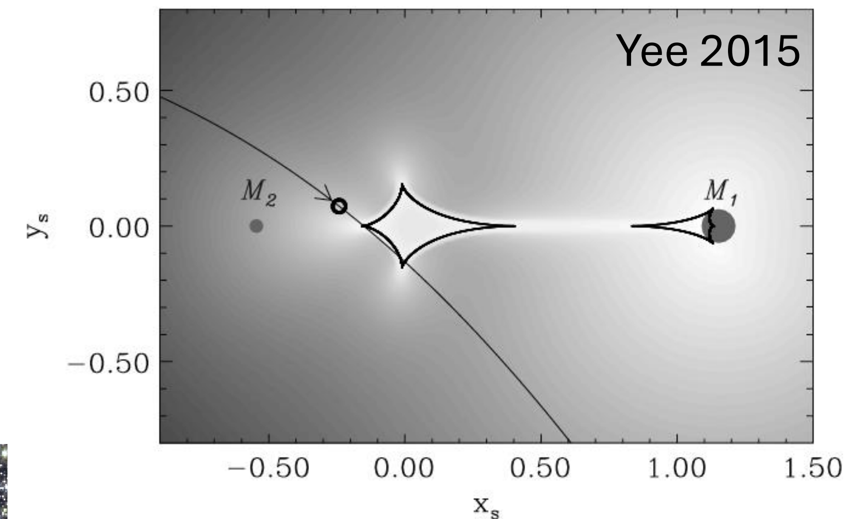
Magnification just on the inside is very high

Can lead to sharp changes in magnification

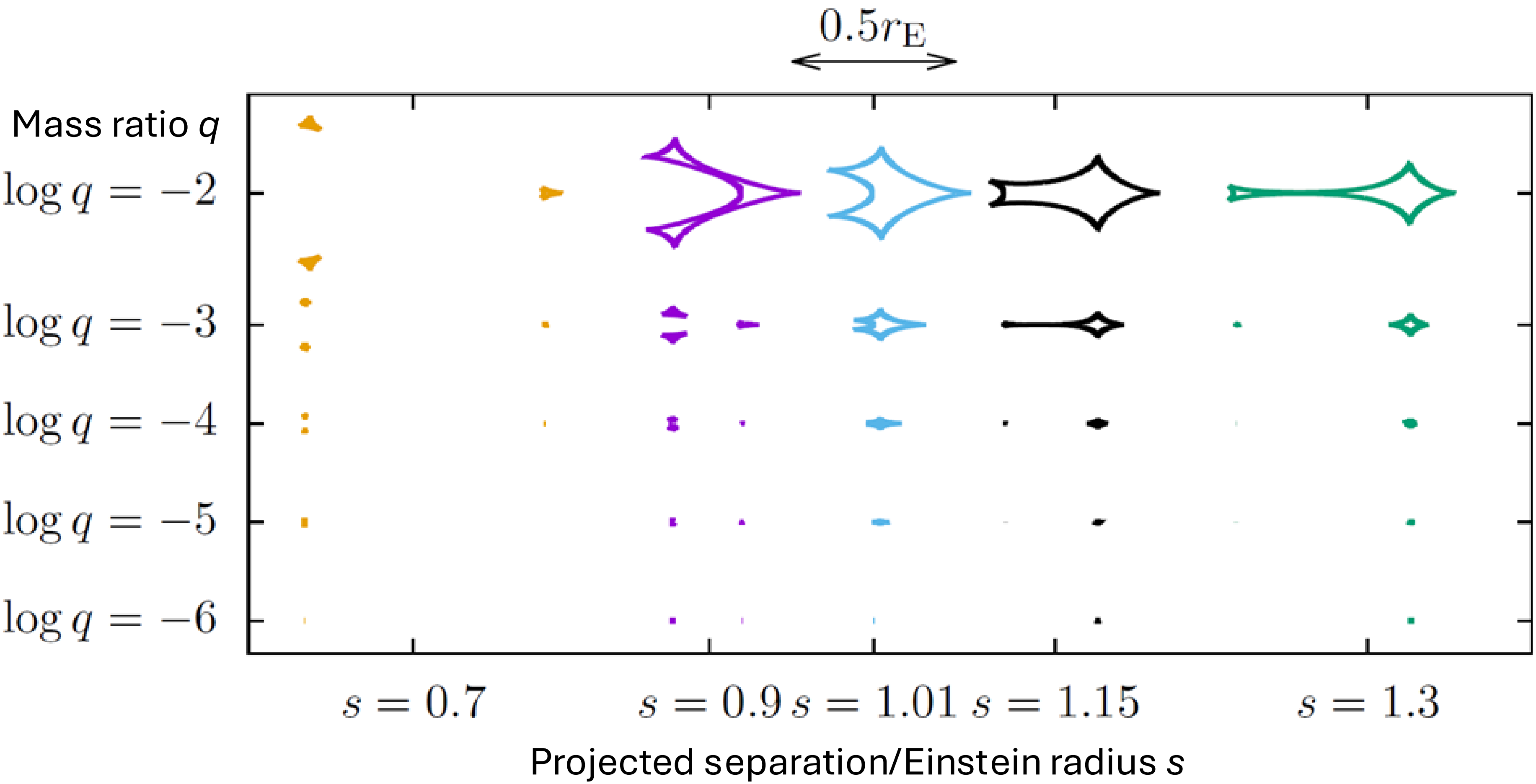
Lightcurve with Caustic Crossings

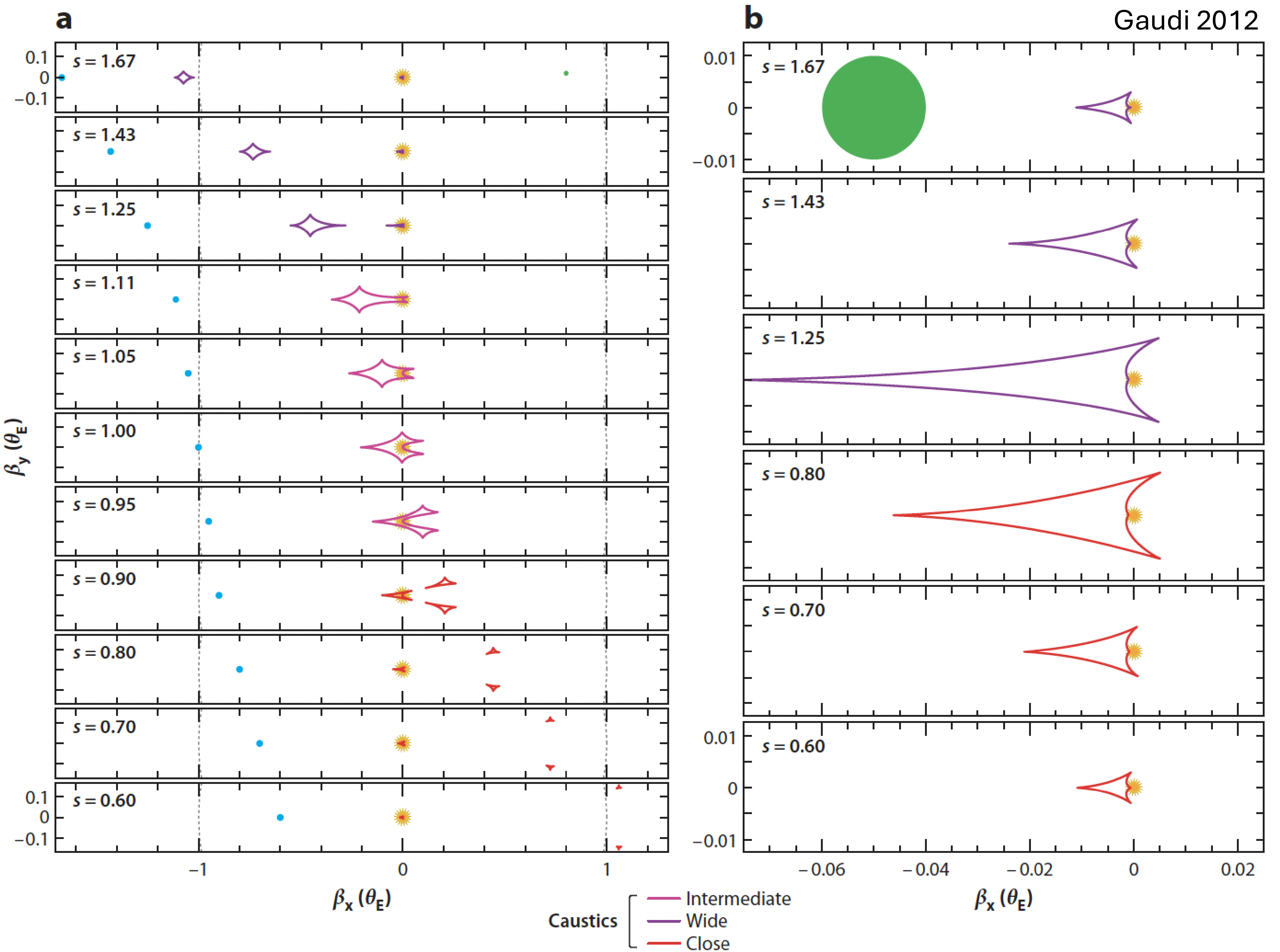






How caustics vary with planet properties

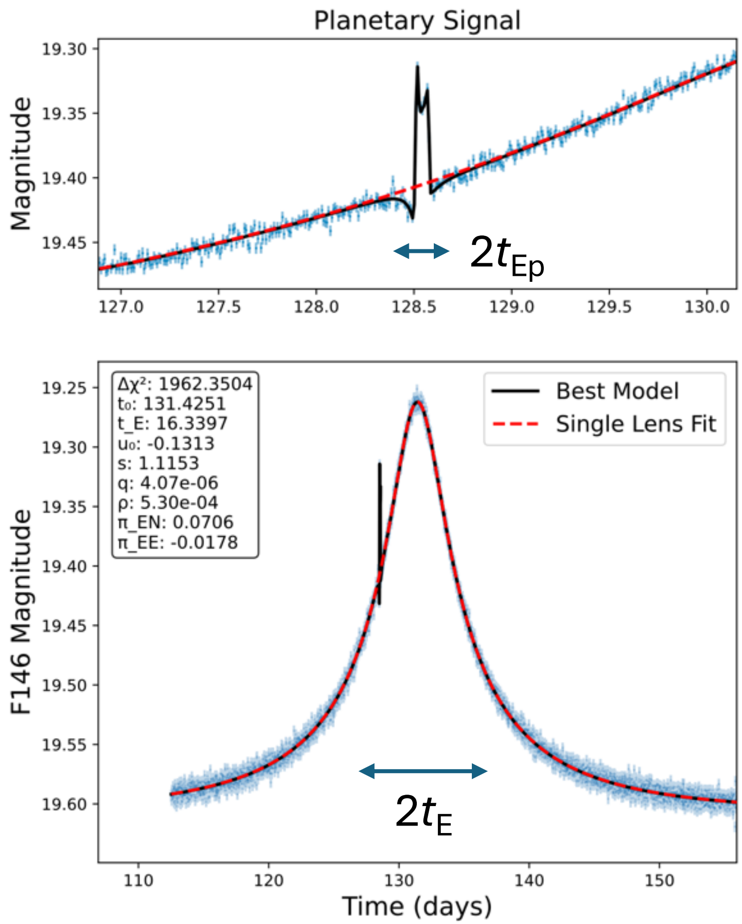


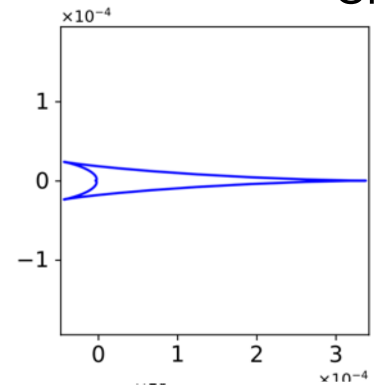


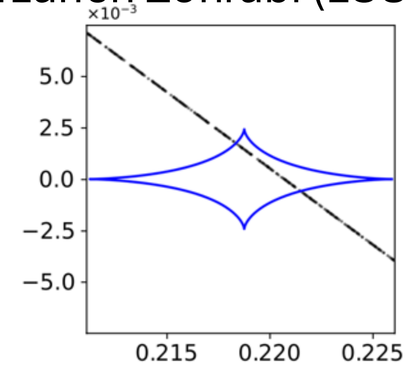
a
b
Gaudi 2012
s = 1.67
s = 1.43
s = 1.25
s = 1.11
s = 1.05
s = 1.00
s = 0.95
s = 0.90
s = 0.80
s = 0.70
s = 0.60
0.1
0
−0.1
−1
0
1
β_y (θ_E)
β_x (θ_E)
0.01
−0.01
−0.06
−0.04
−0.02
0.02
Caustics
Intermediate
Wide
Close

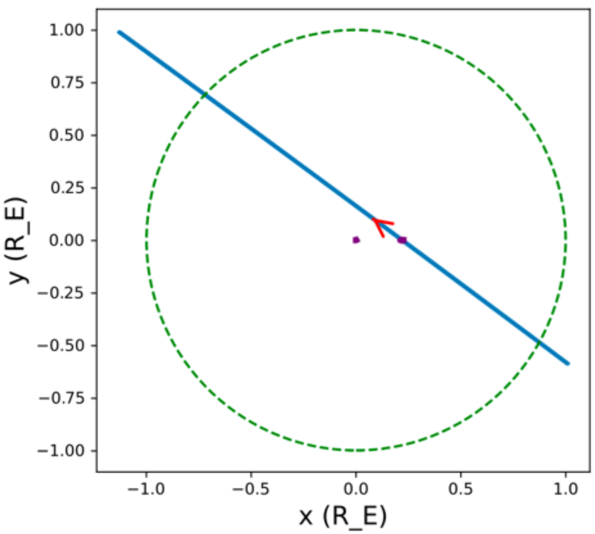
Measuring Planet Parameters image perturbations

Credit: Farzaneh Zohrabi (LSU)









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

Projected Separation

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

Cold Exoplanet Demographics

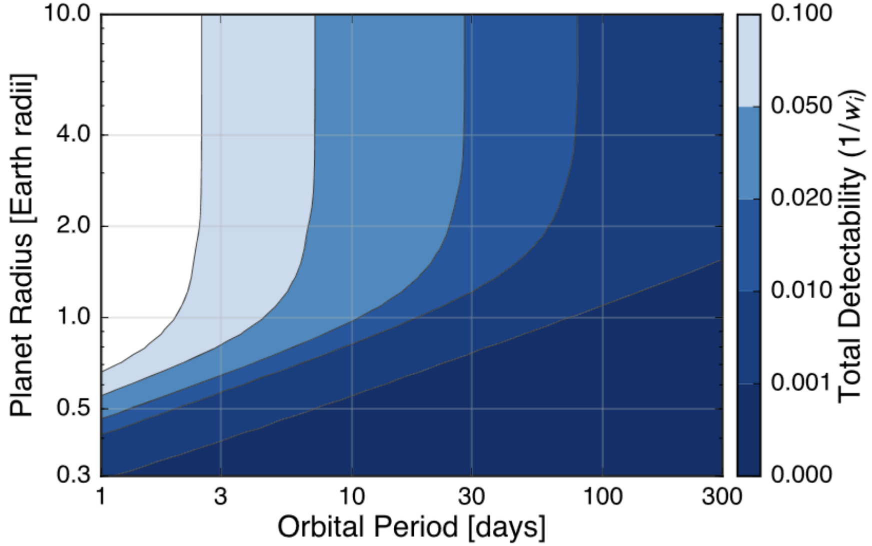
Measuring exoplanet demographics

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

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

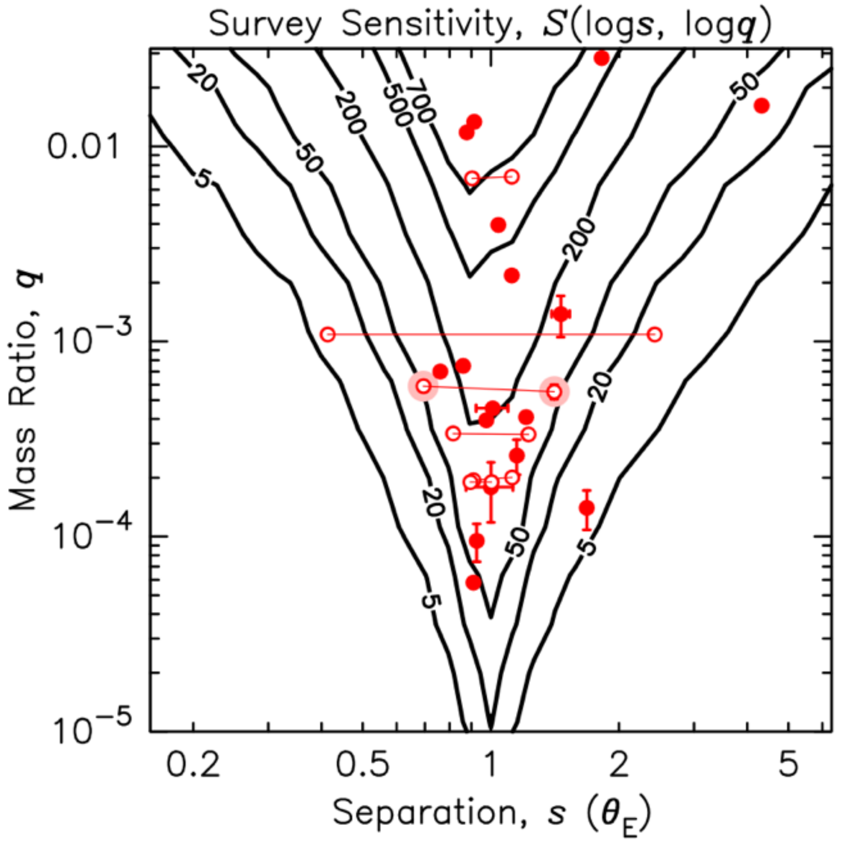
Detection efficiency

Transits



Fulton+2017

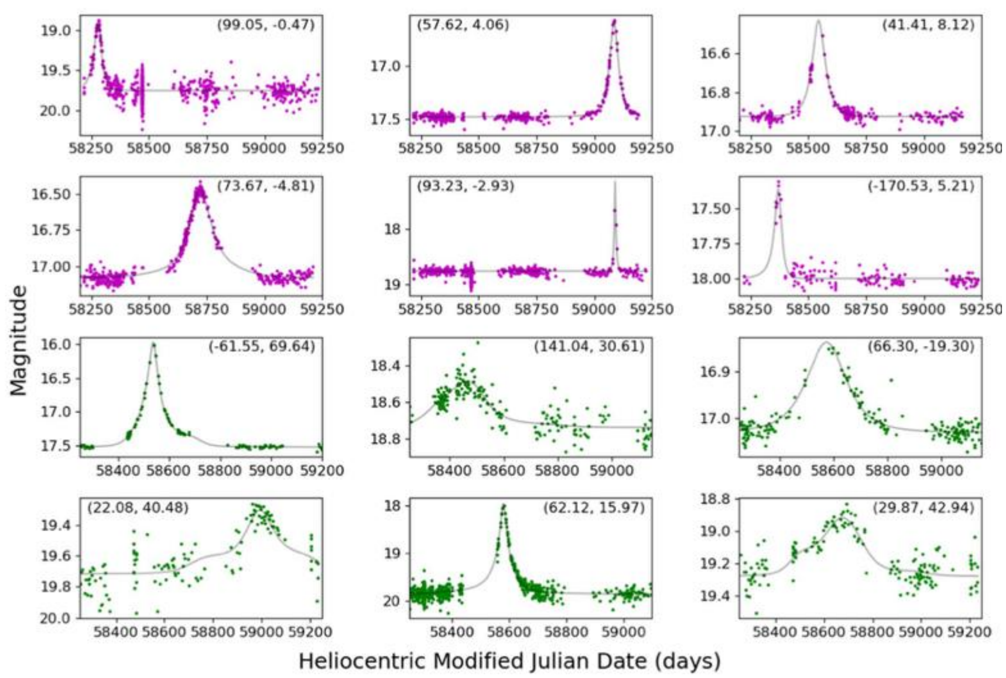
Microlensing



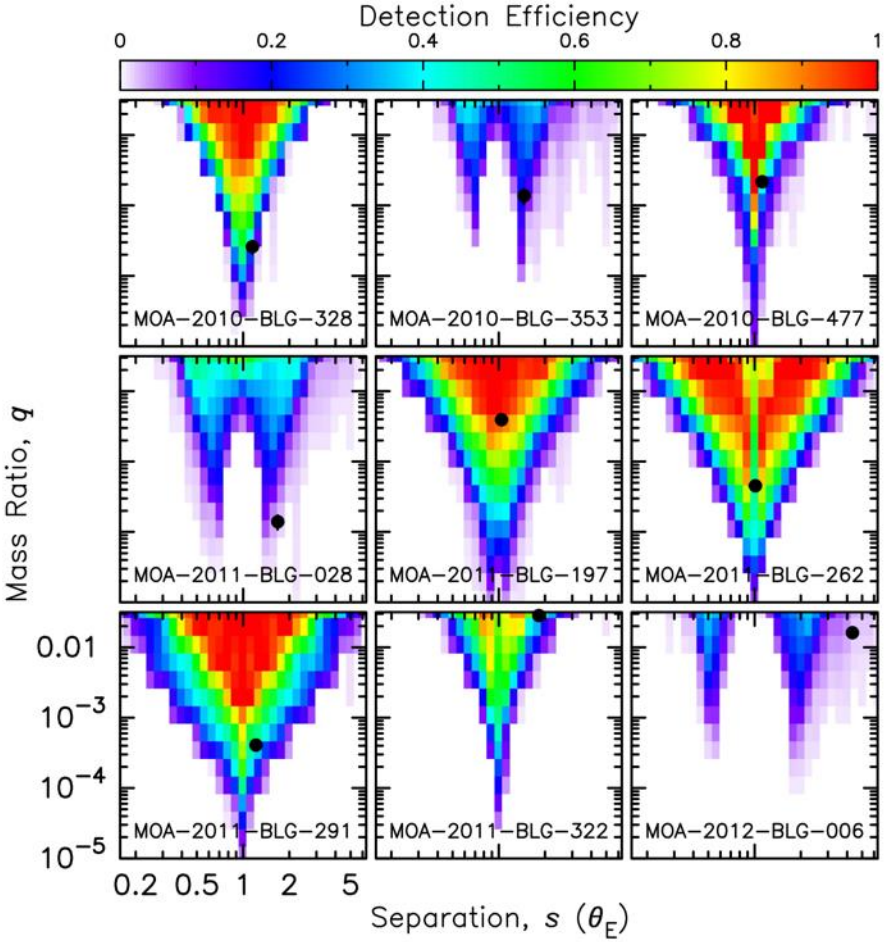
Suzuki+2016

Detection efficiency – strong event dependence

Medford+2023

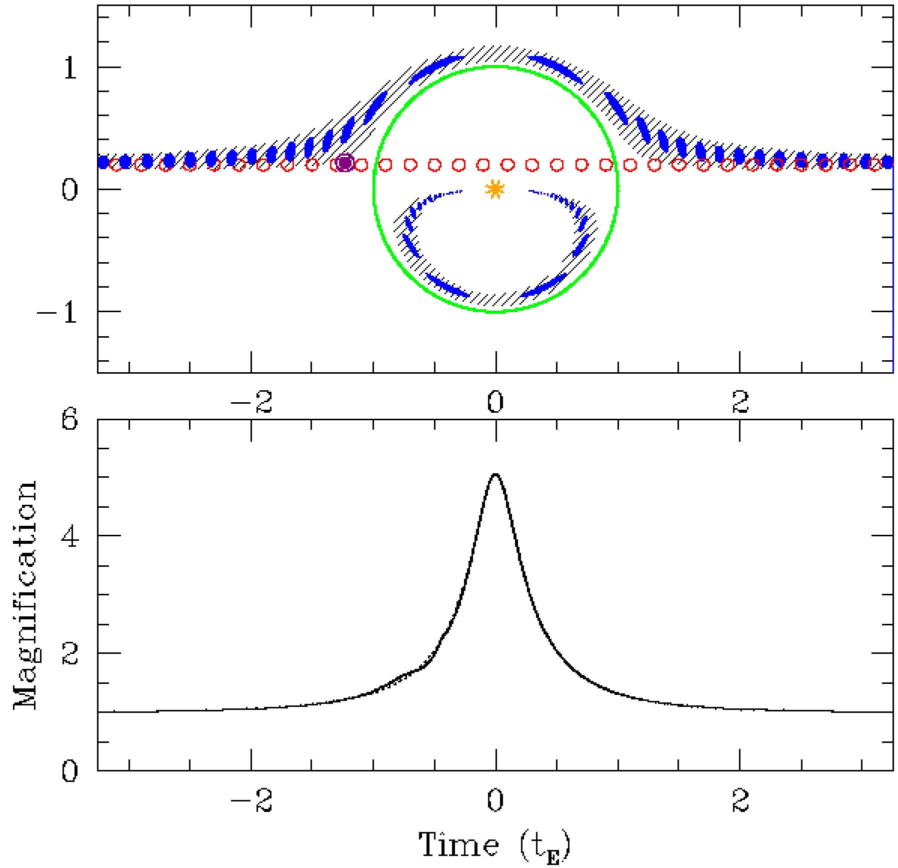


Suzuki+2016

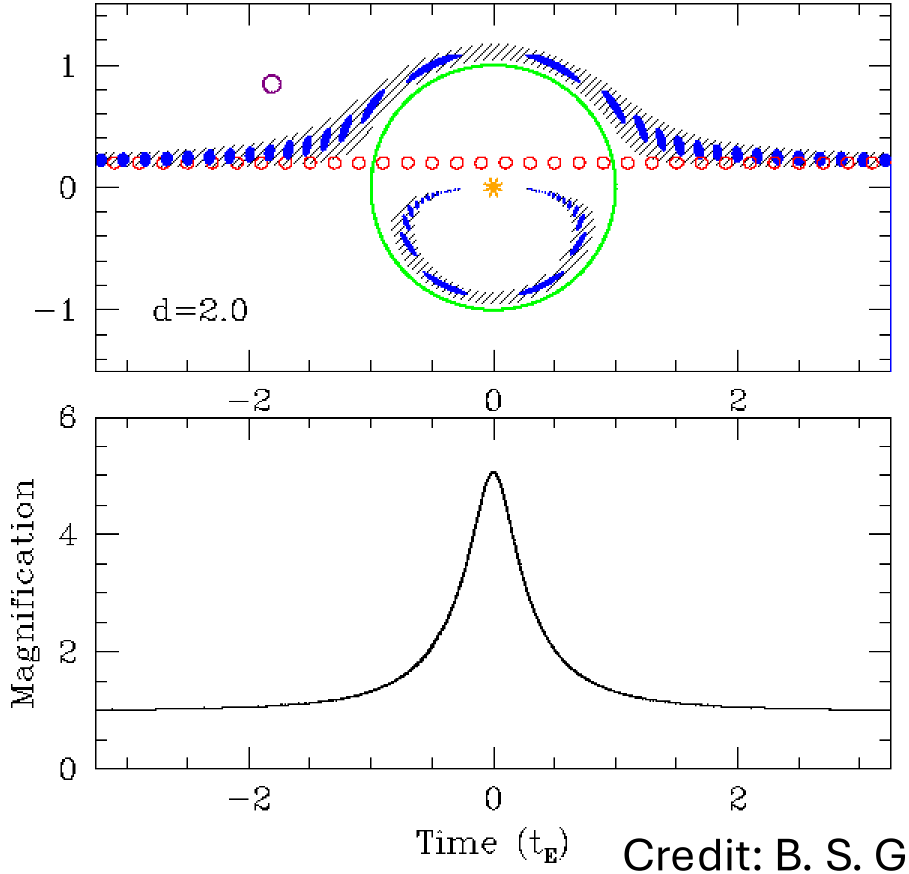


Marginalize over parameters

Angle



Projected separation

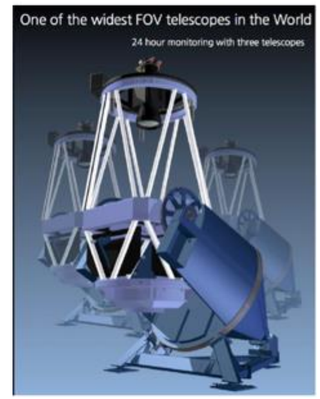


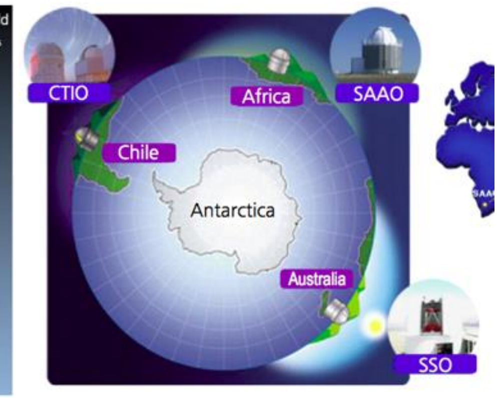
Credit: B. S. Gaudi

High-cadence microlensing surveys – mass ratio distributions

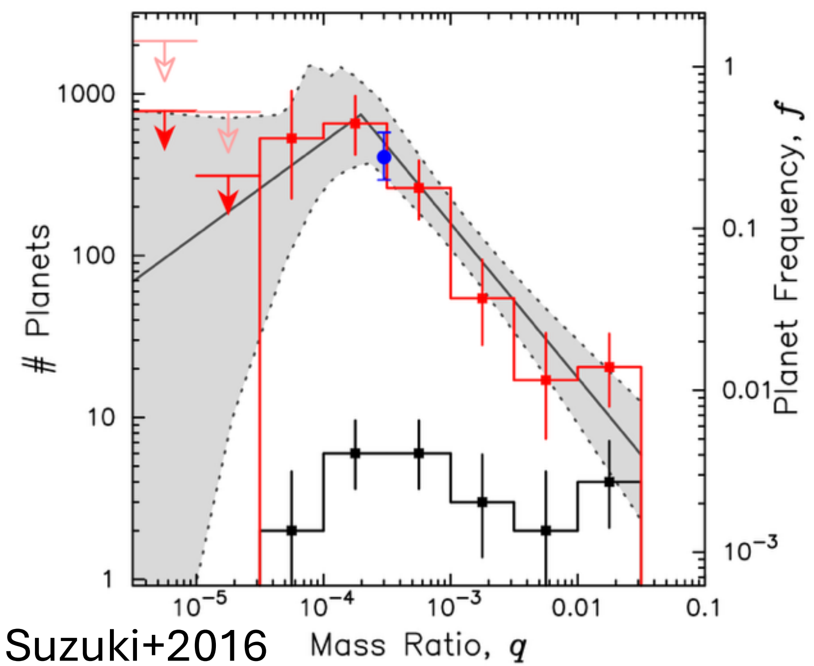
OGLE

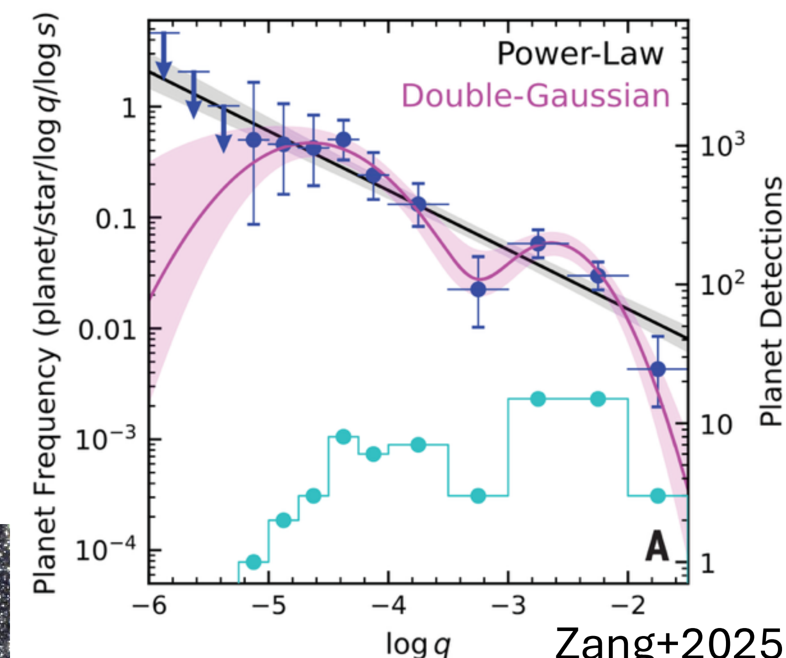
MOA





KMTNet





Measuring Masses & Distances

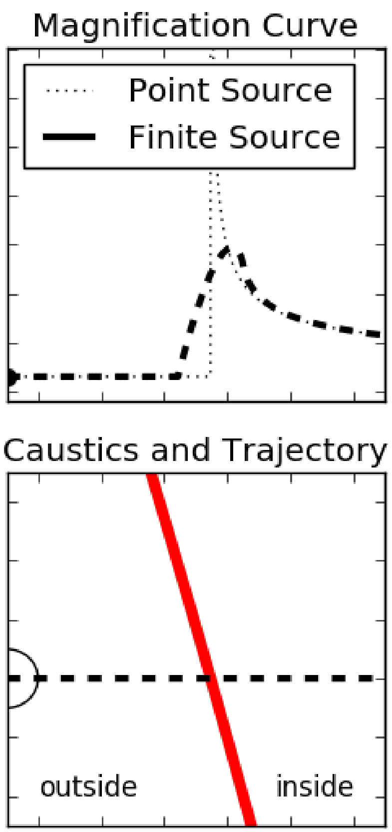
Mass & distance cf. observables

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

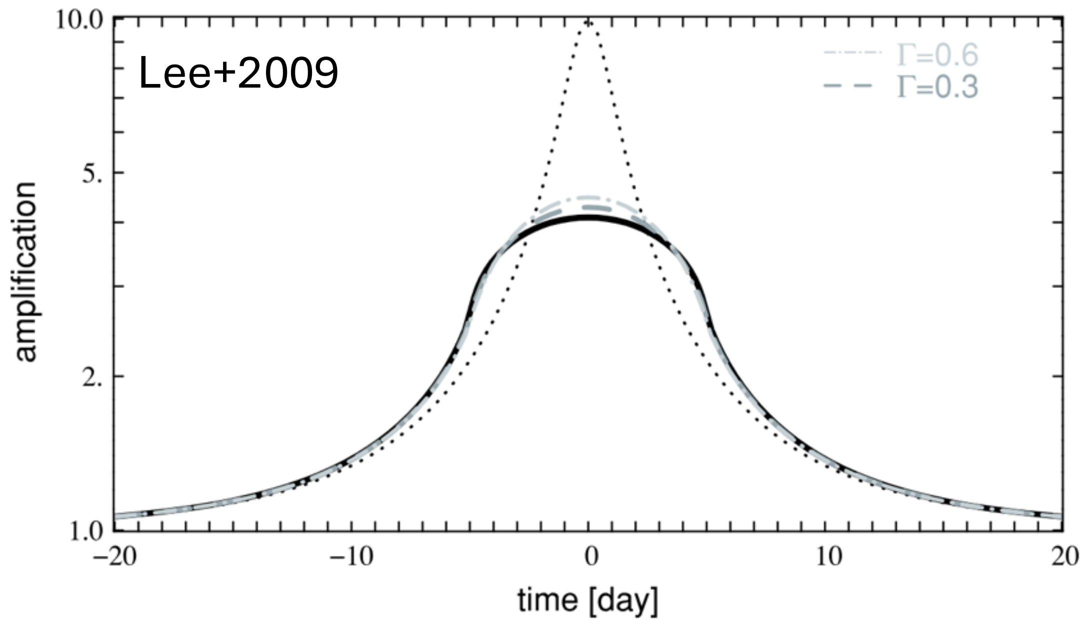
$$\pi_{\mathrm{E}} = \pi_{\mathrm{rel}} / \theta_{\mathrm{E}}$$

Method 1: Lightcurve, finite source

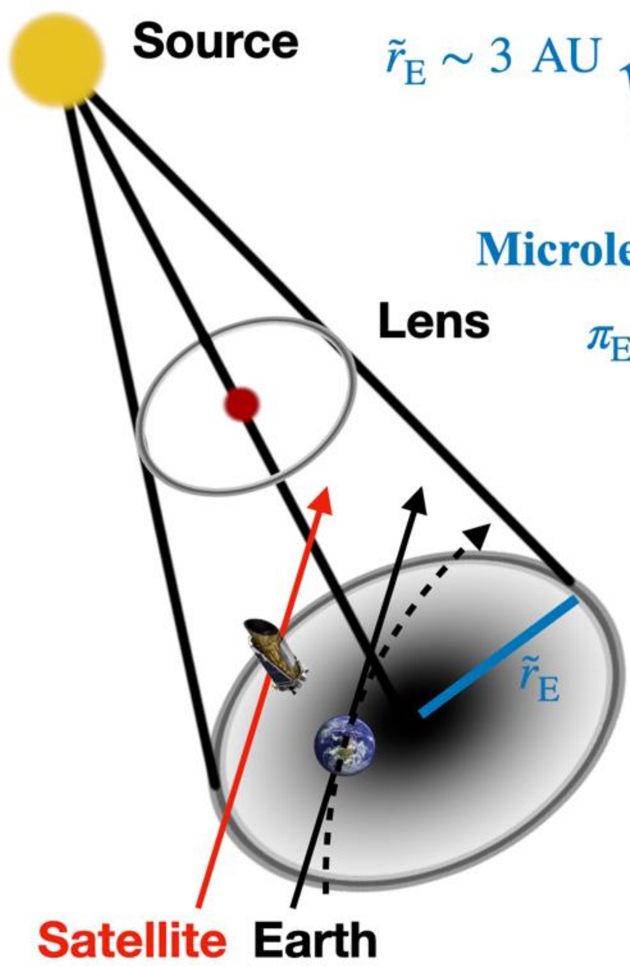
Finite source effects $\frac{\theta_\mathrm{E}}{\theta_*} = \frac{t_\mathrm{E}}{t_*}$



Credit: J. Yee



Method 1: Lightcurve, parallax

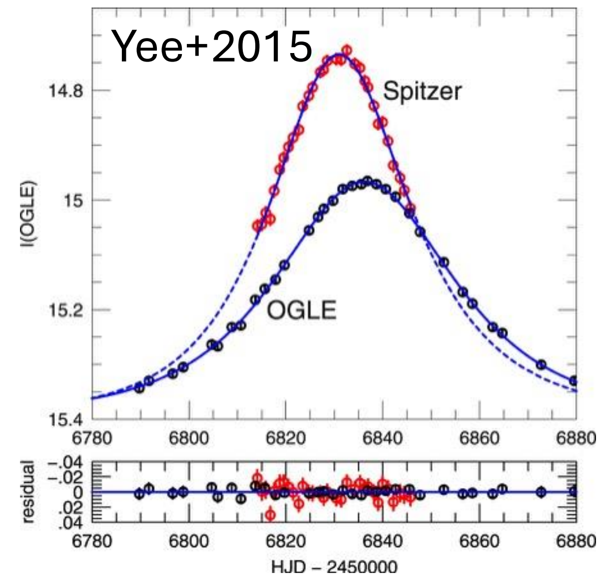


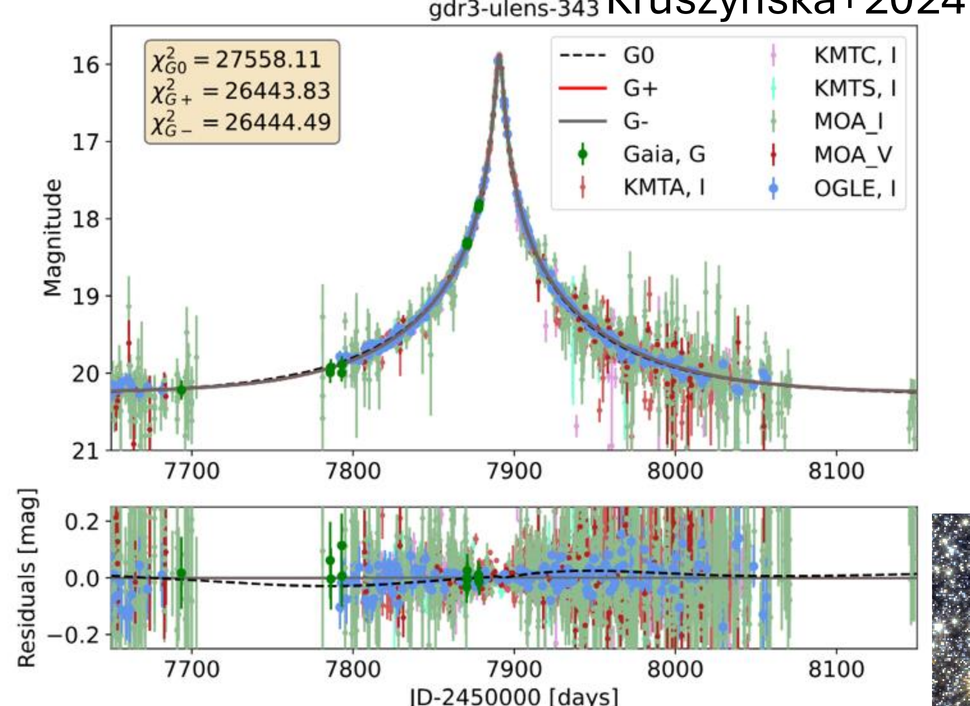
Projected Einstein radius:

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

Microlens parallax:

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





Credit: M. Penny

Finite source + parallax

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

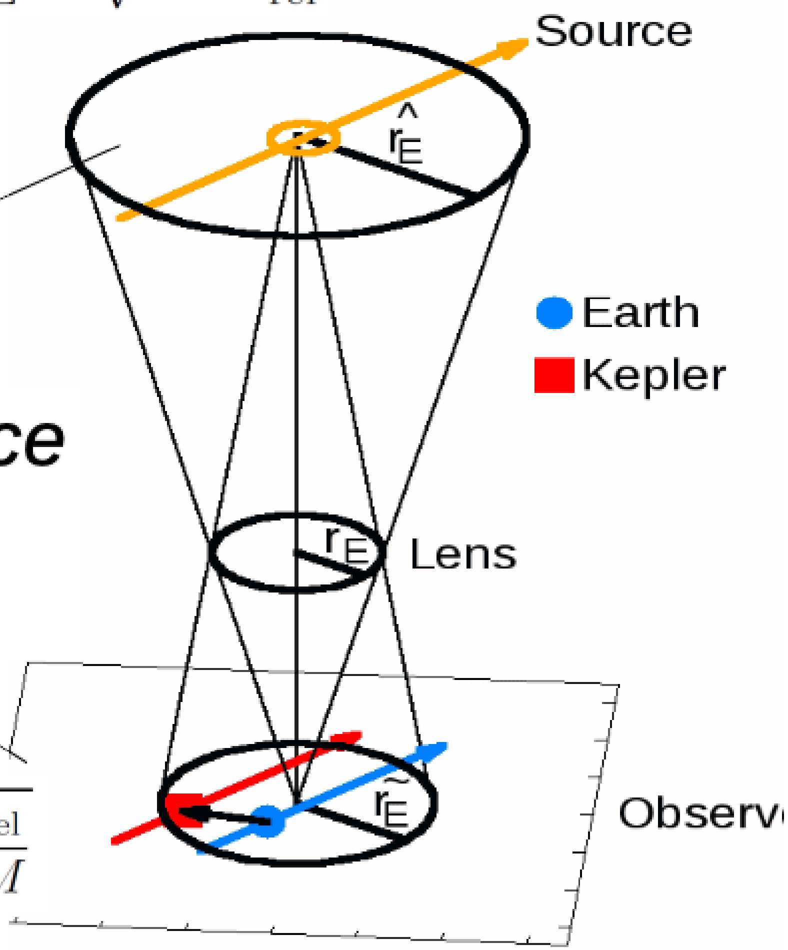
- Finite-source effects (common for FFPs, planets) measures one projection

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

Constant

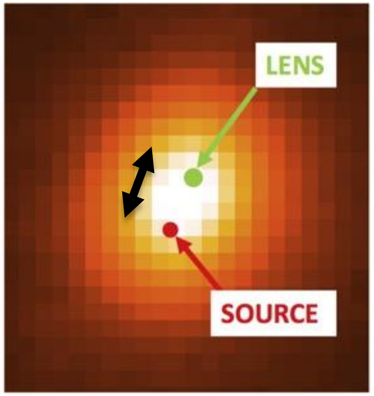
- Parallax baseline measures other projection

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



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

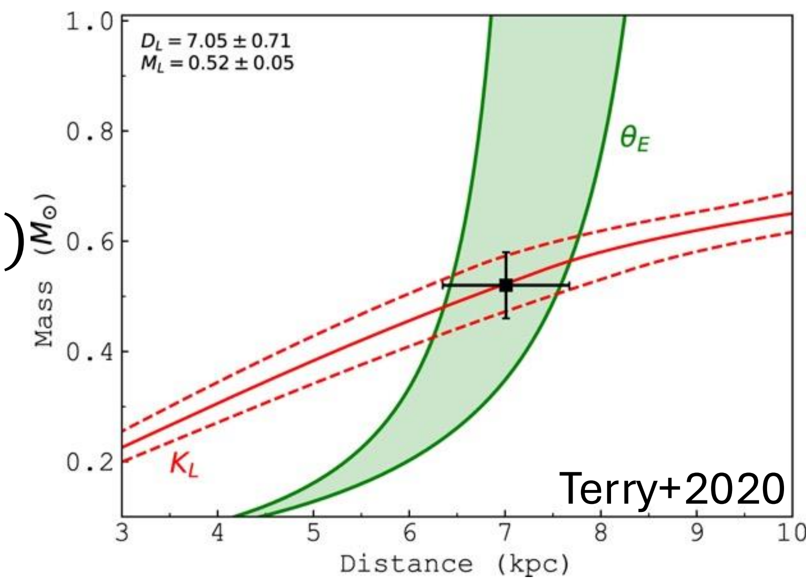
$$\theta_{\mathrm{E}} \approx 3\ \mathrm{mas}\sqrt{M\pi_{\mathrm{rel}}}$$

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

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

Lens flux
→ Luminosity vs distance
→ Mass vs distance relation

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

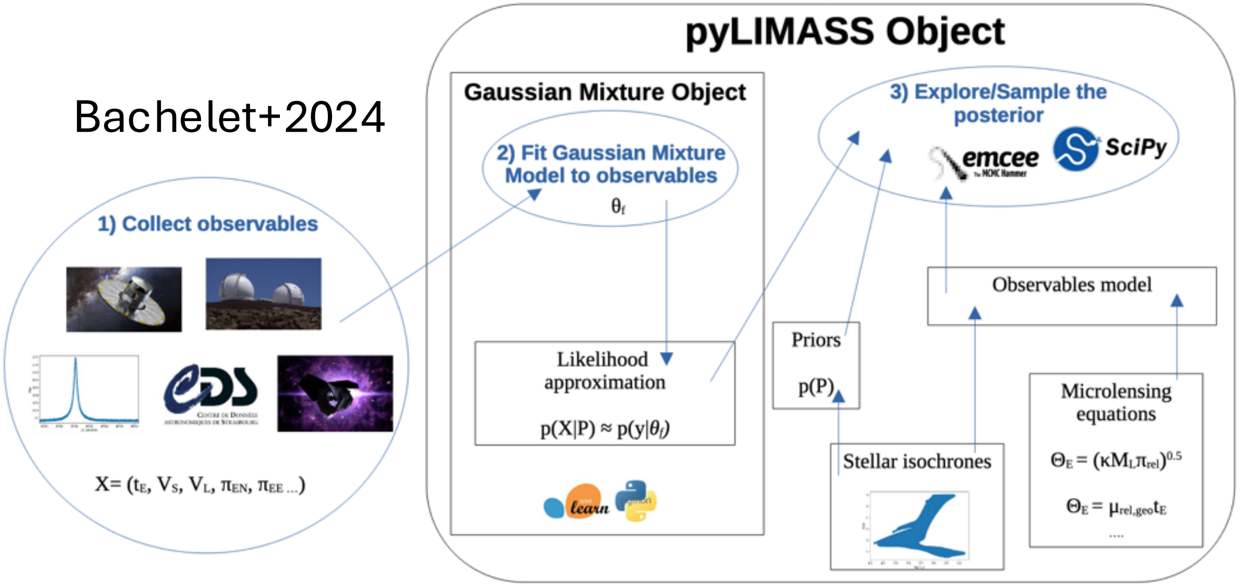


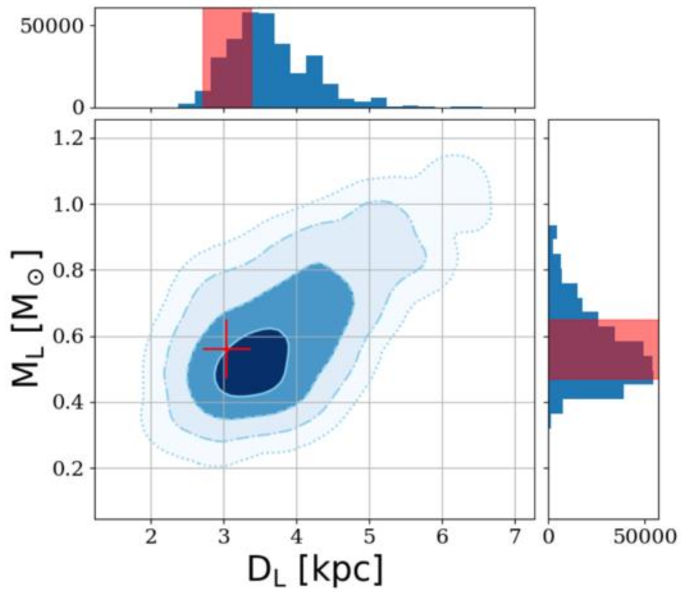
Terry+2020

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

If measurements fail, use models!

Bachelet+2024



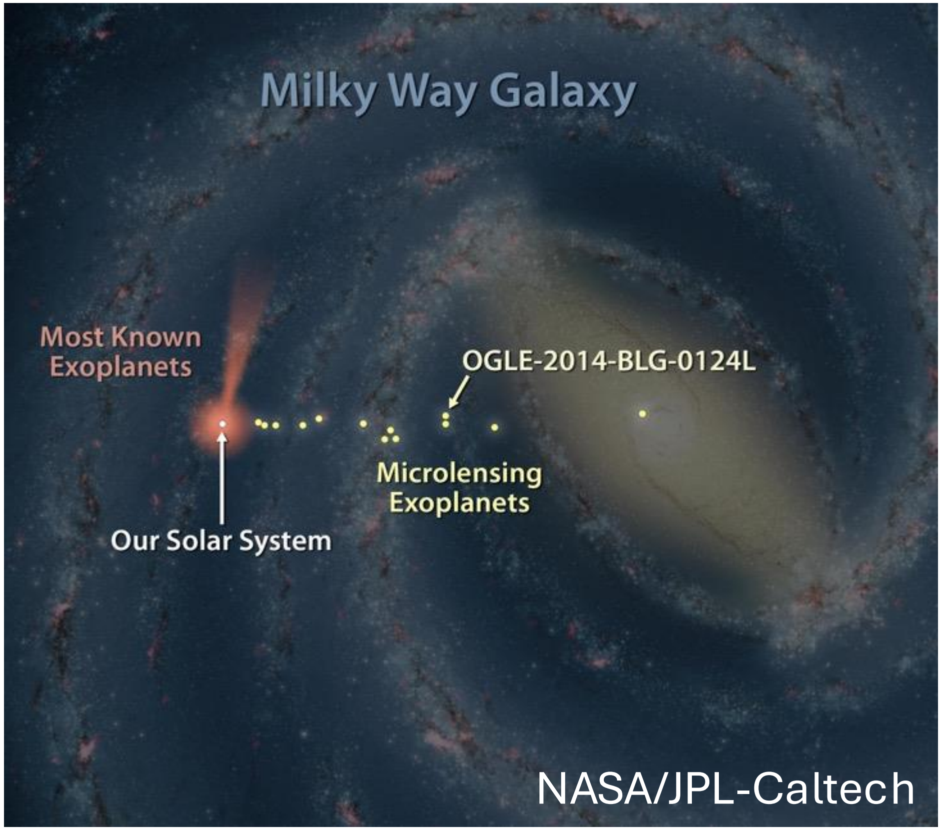


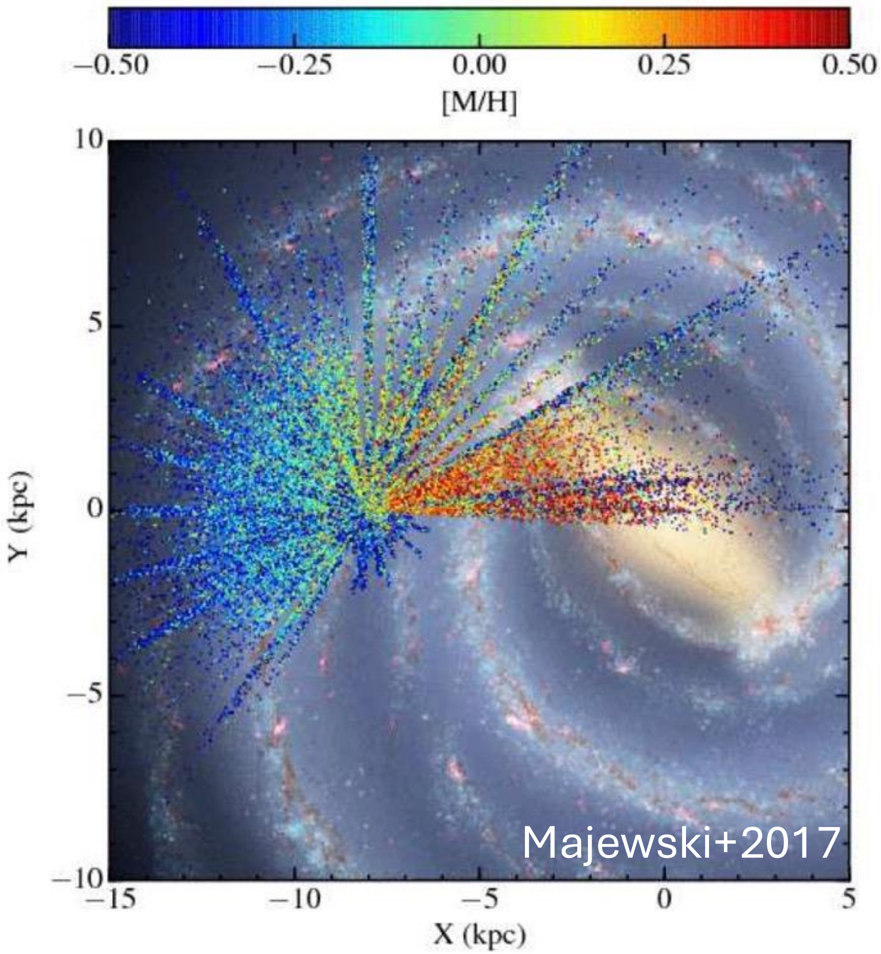
synthpop-galaxy/
synthpop

A modular Galactic population synthesis code

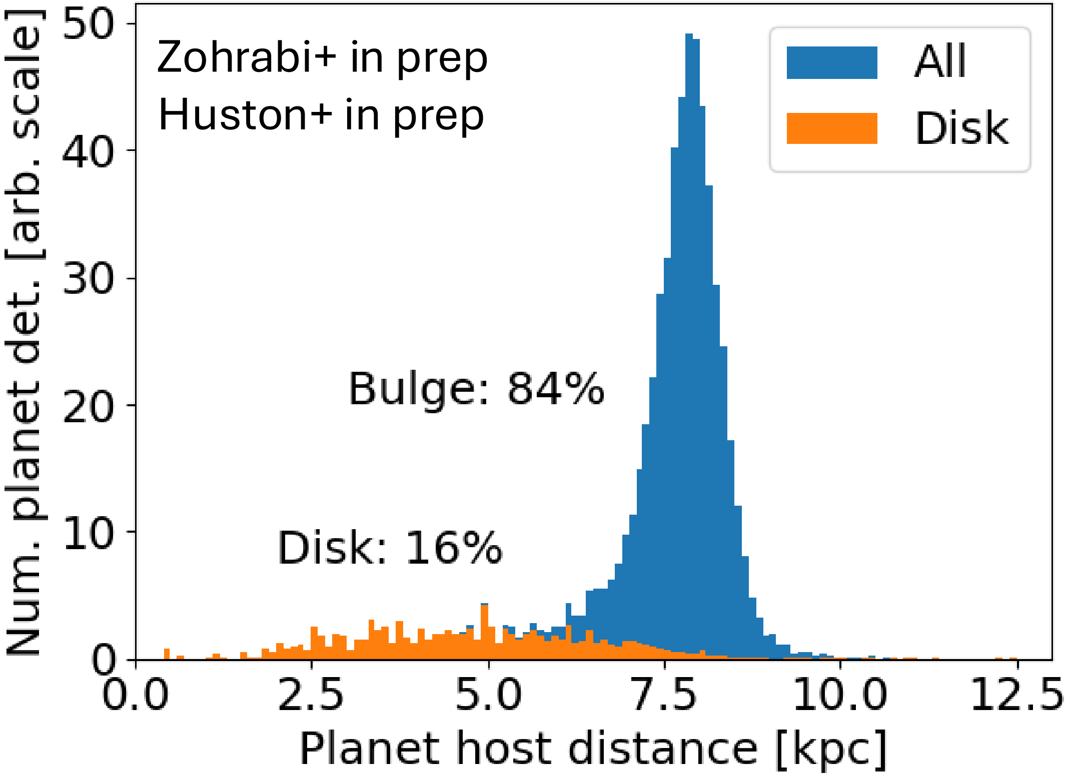
Klüter & Huston+ 2025

Where will the hosts be?

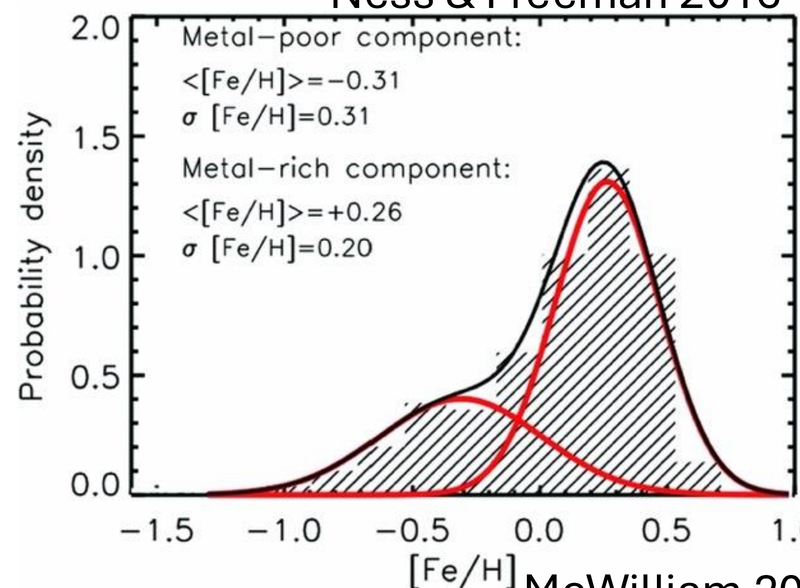




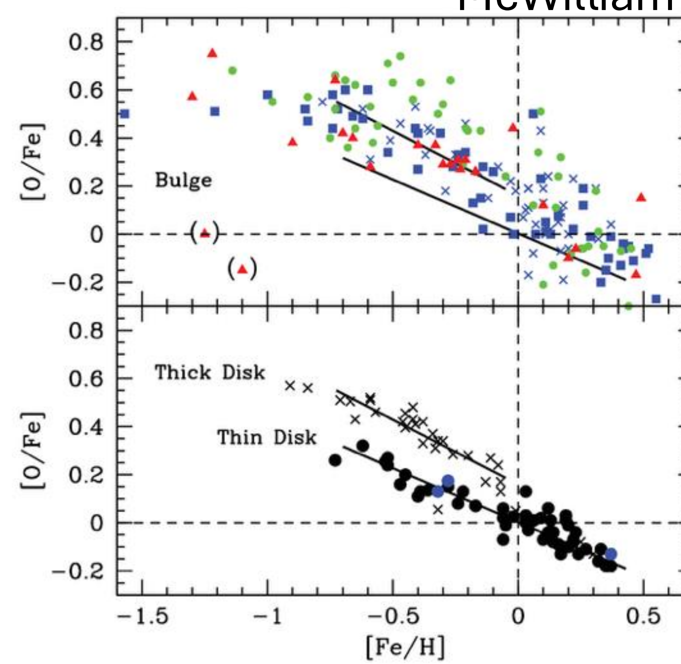
Roman’s Distance Distribution

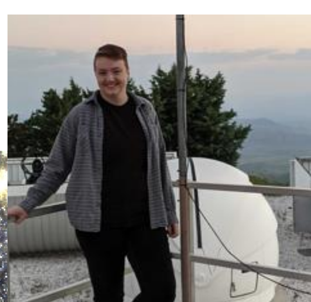


Ness & Freeman 2016

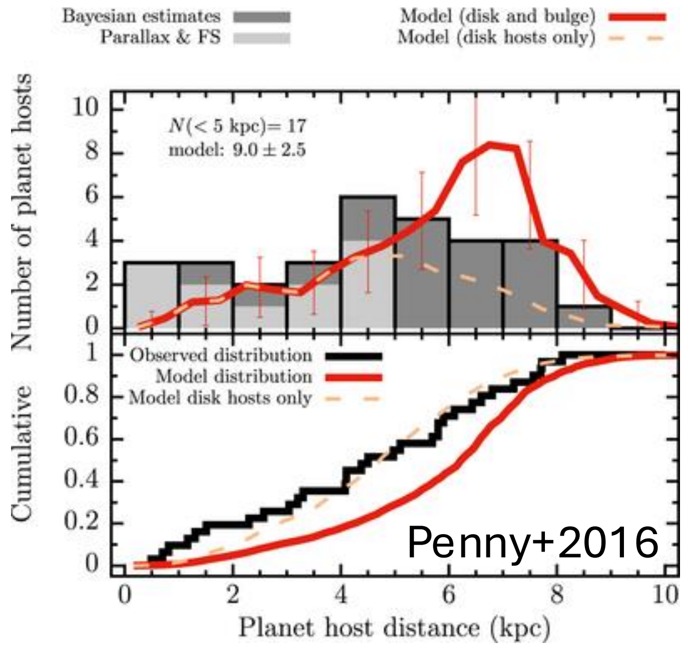


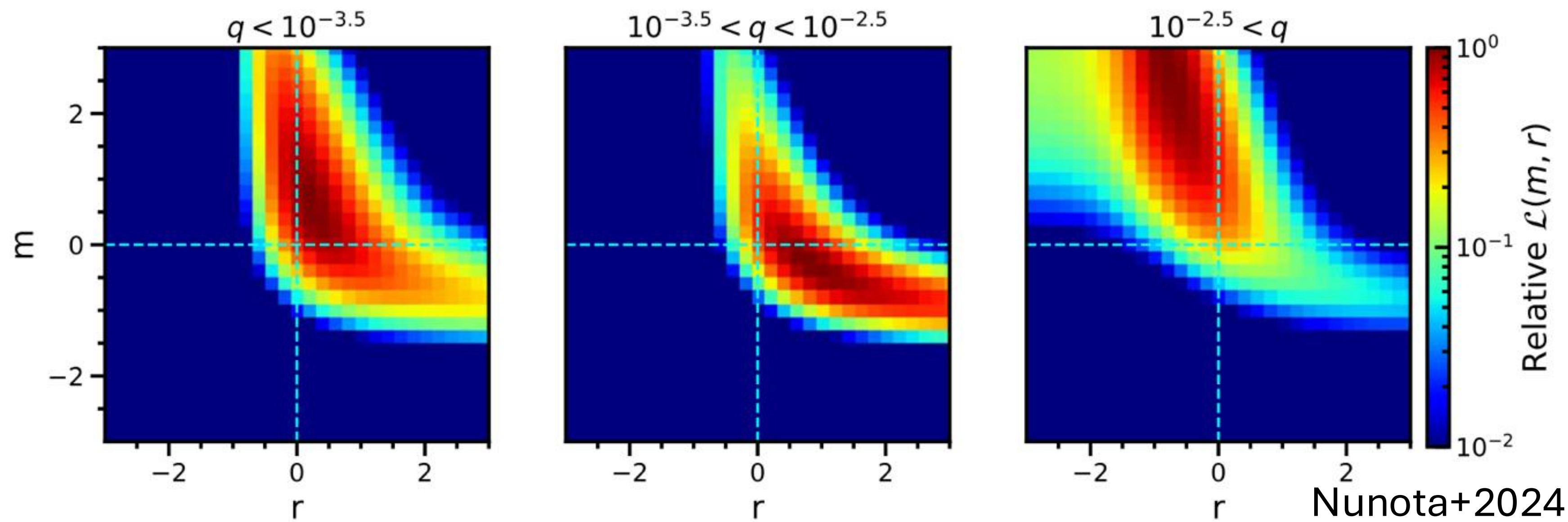
McWilliam 2016





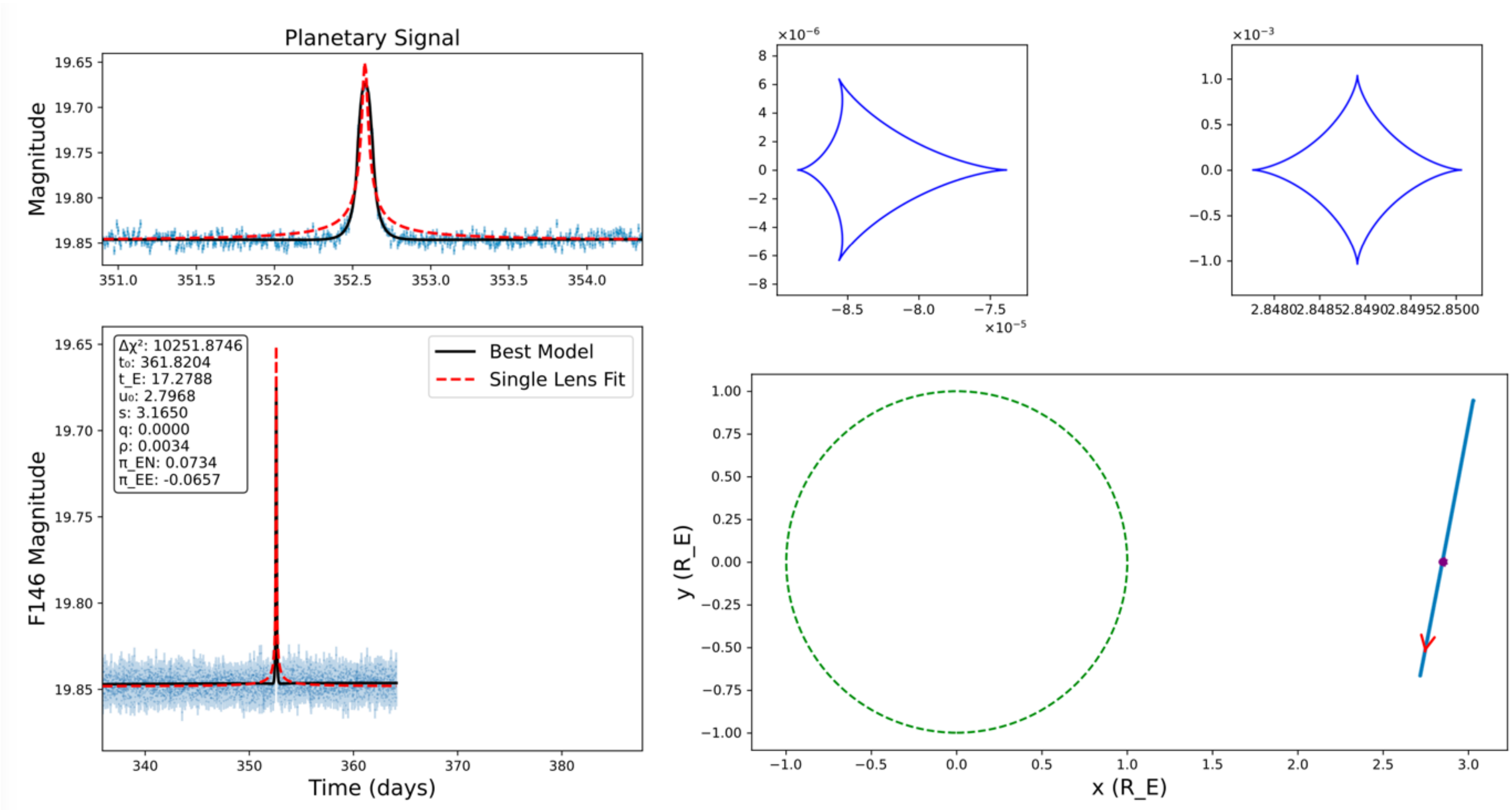
Population & host mass dependence





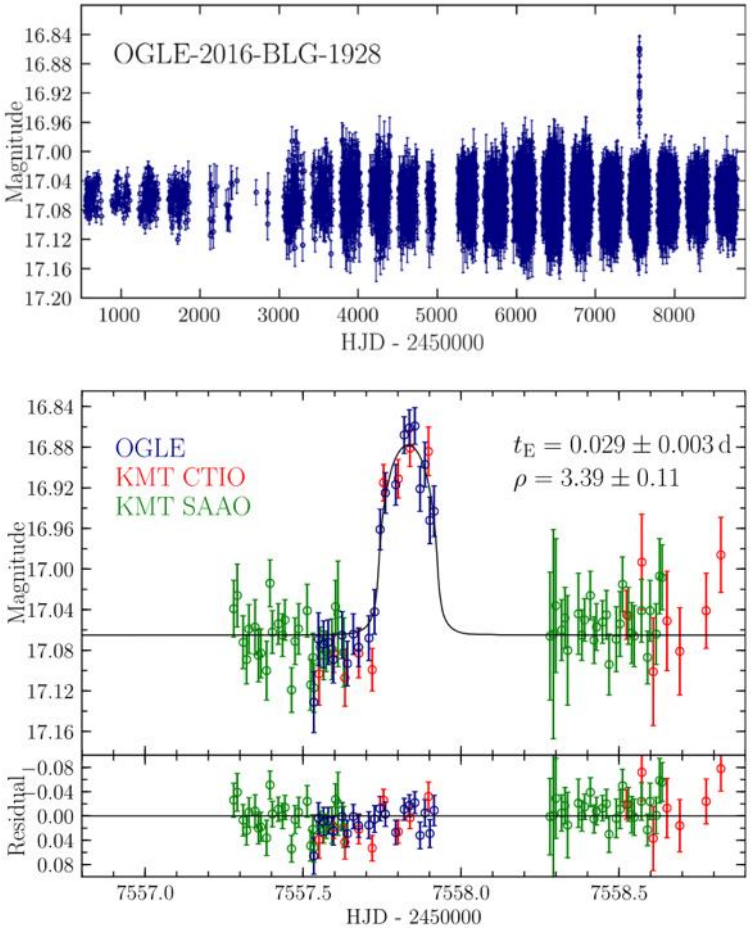
Free-floating planets

Wide orbit planets

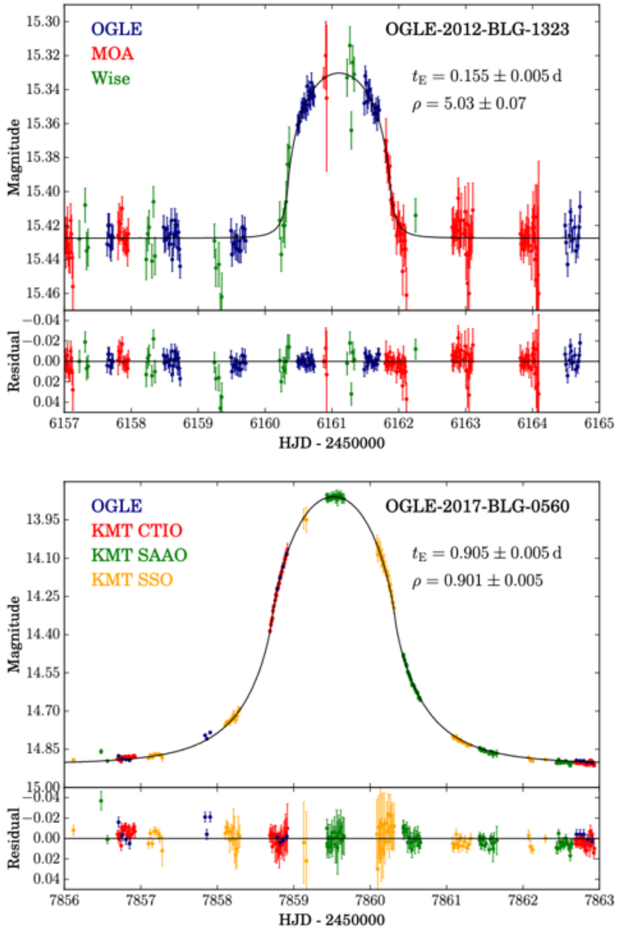


Free-floating planet candidates

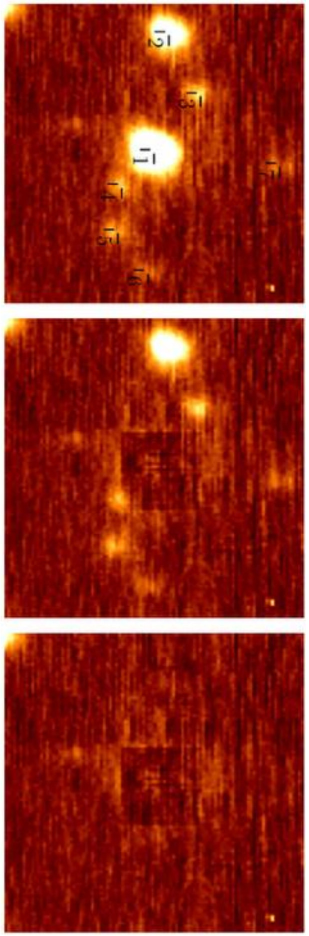
Mroz+2020



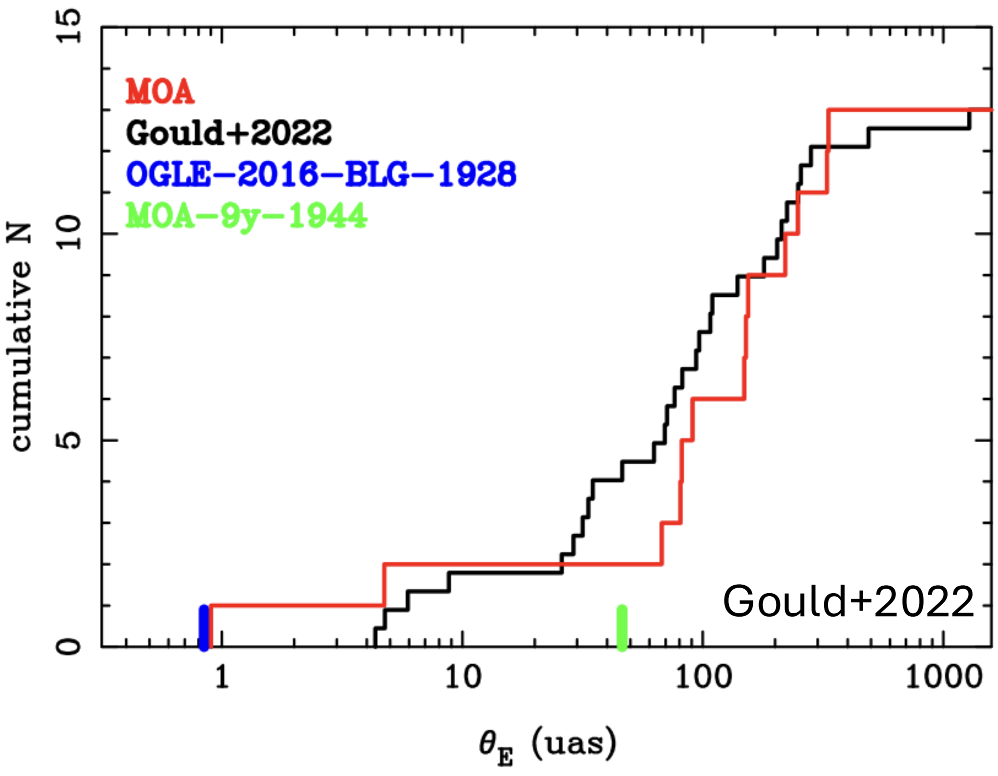
Mroz+2019

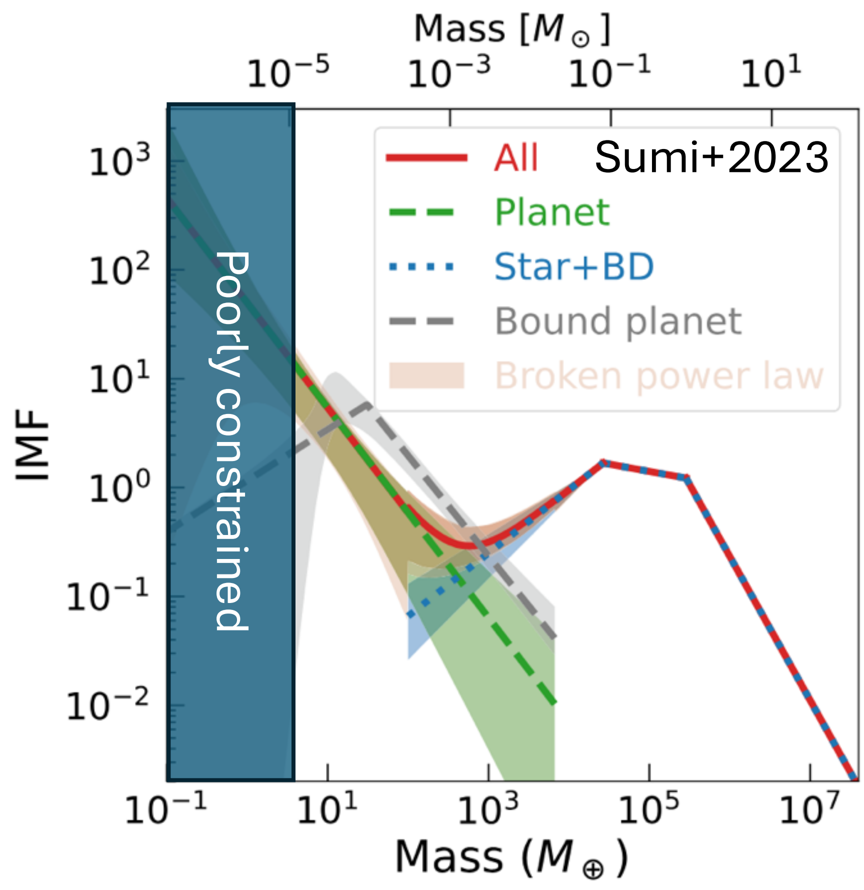


Mroz+2024



Free-floating planet demographics



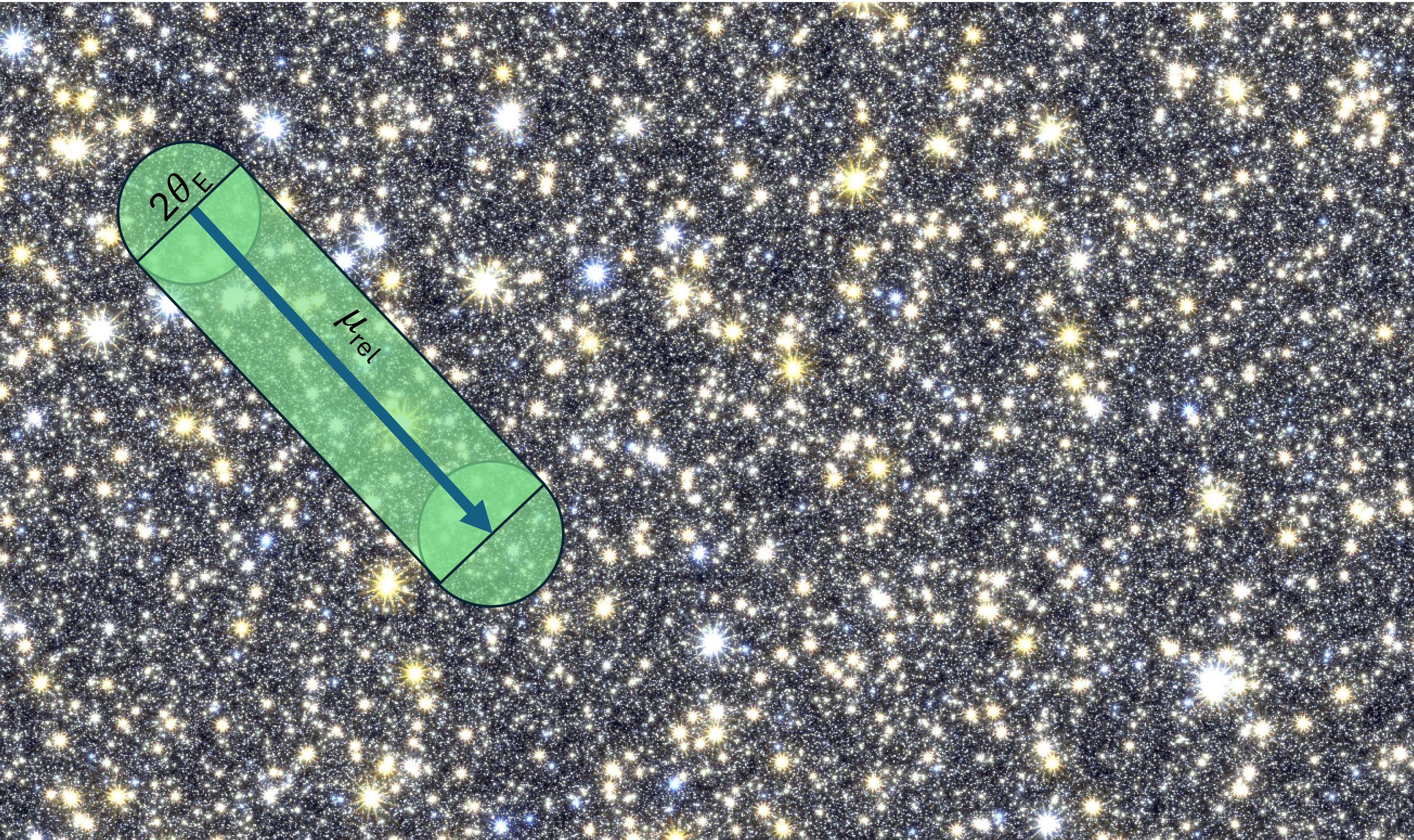


2025 Microlensing Data Challenge

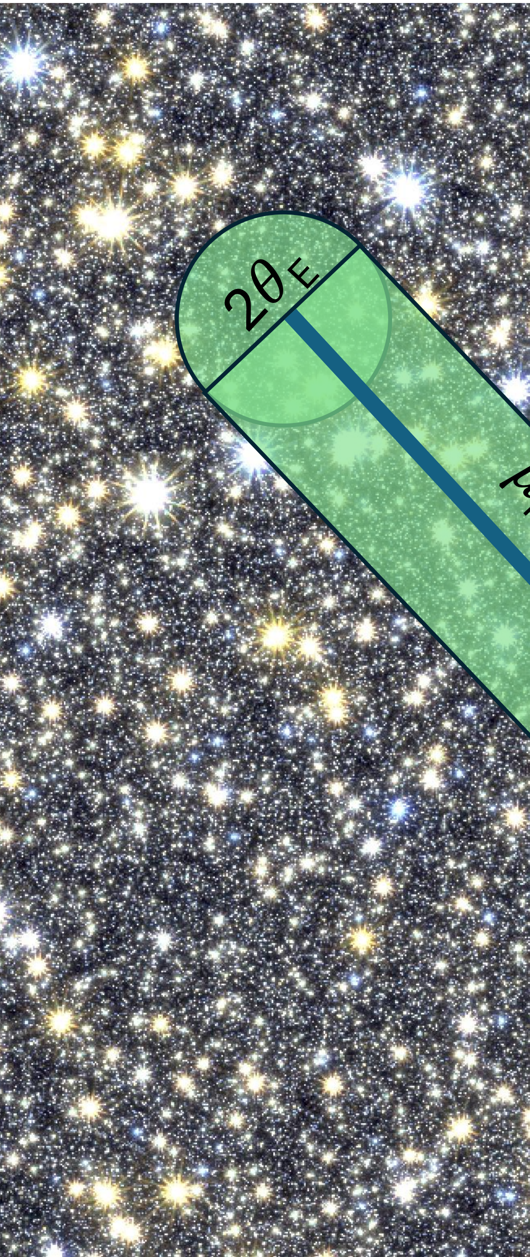
- A lightcurve modeling data challenge is planned to launch late 2025
- In the meantime, you can learn how through a 5-chapter Mini-course: https://rges-pit.org/outreach/
- Can't wait? Try out the 2018 data challenge: https://www.microlensing-source.org/data-challenge/

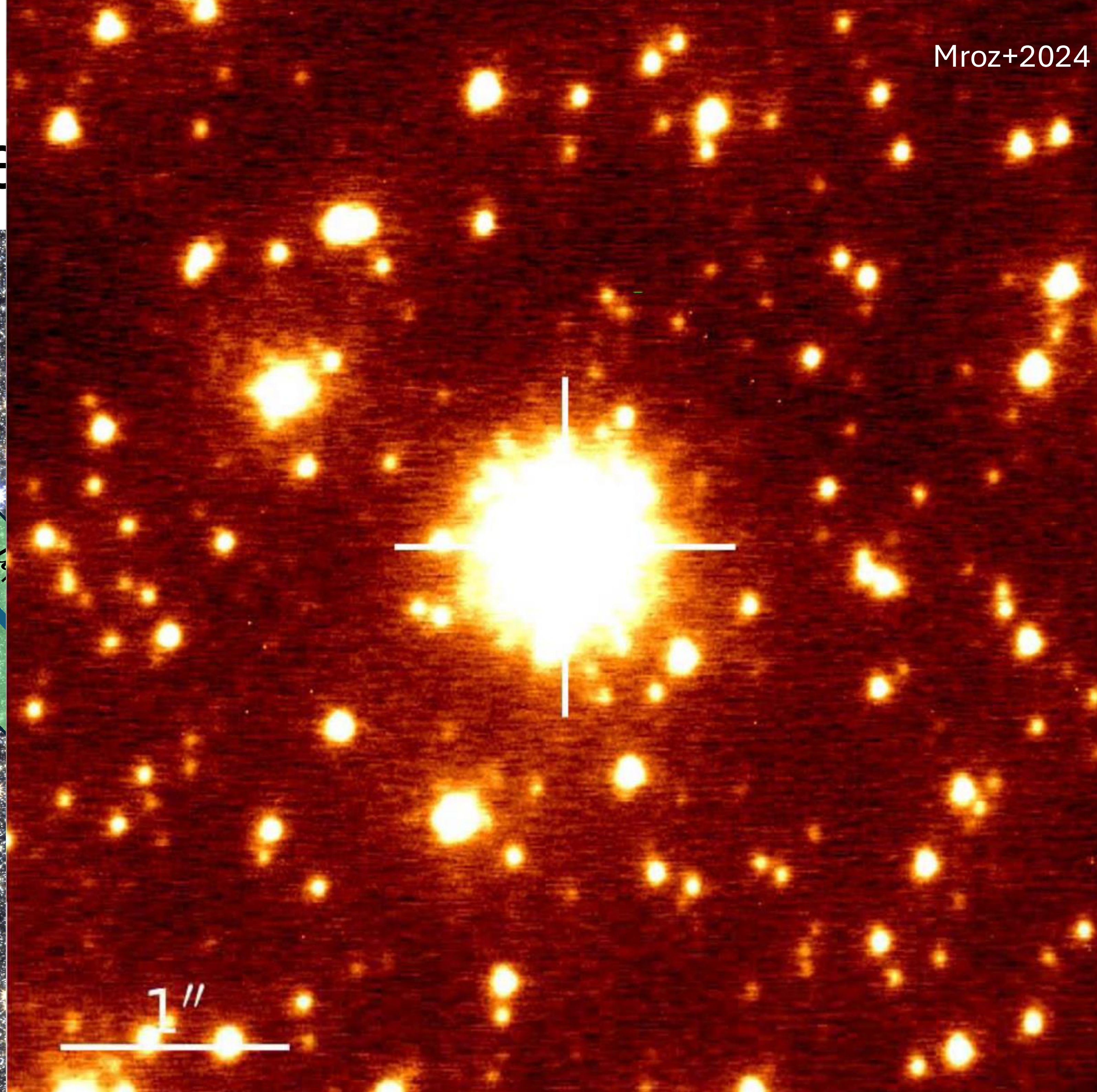
Backup slides

Microlensing Event Rate

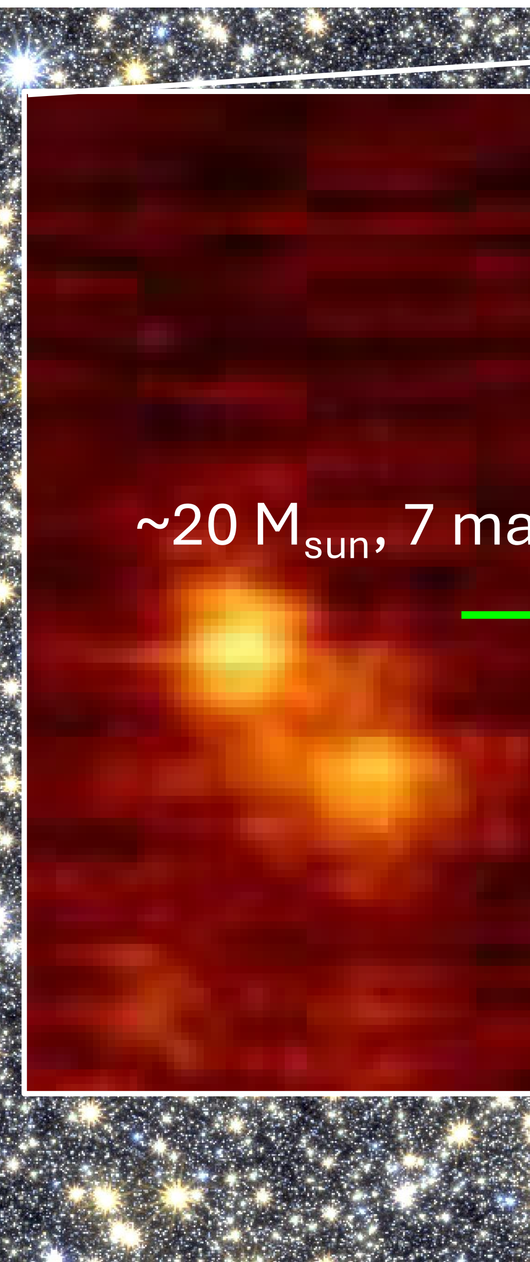


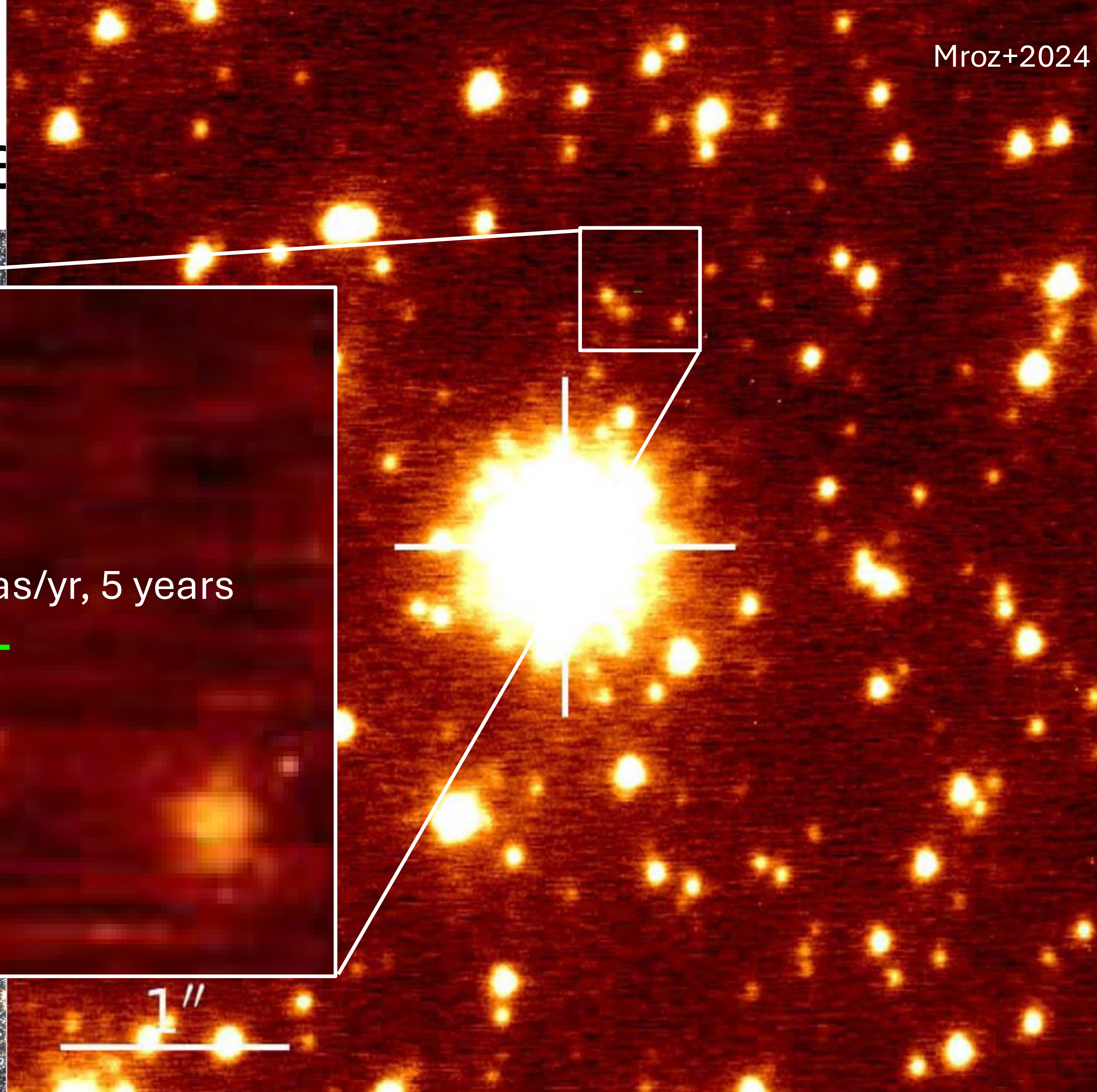
Microle



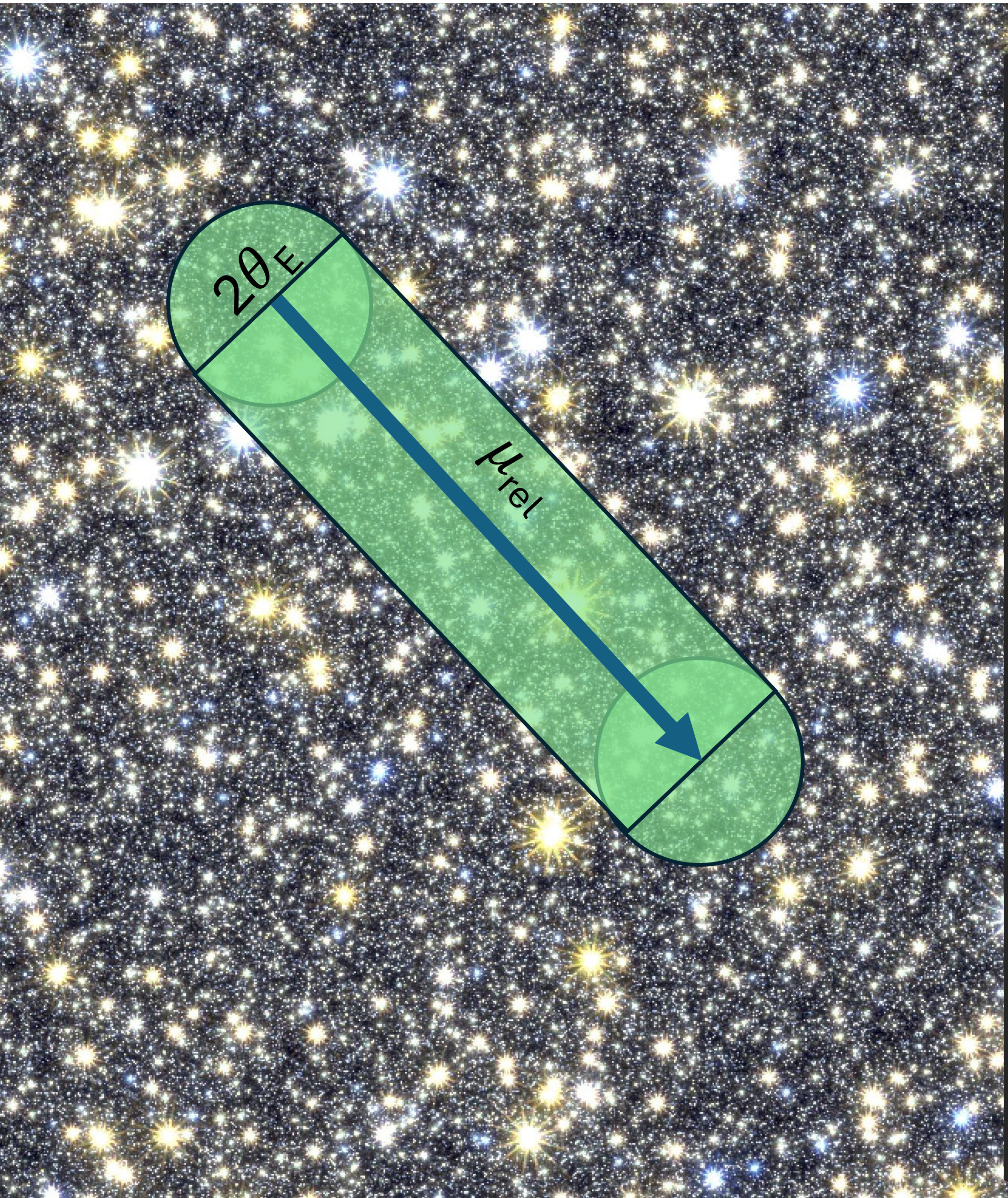


Microle





Microlensing Event Rate



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

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

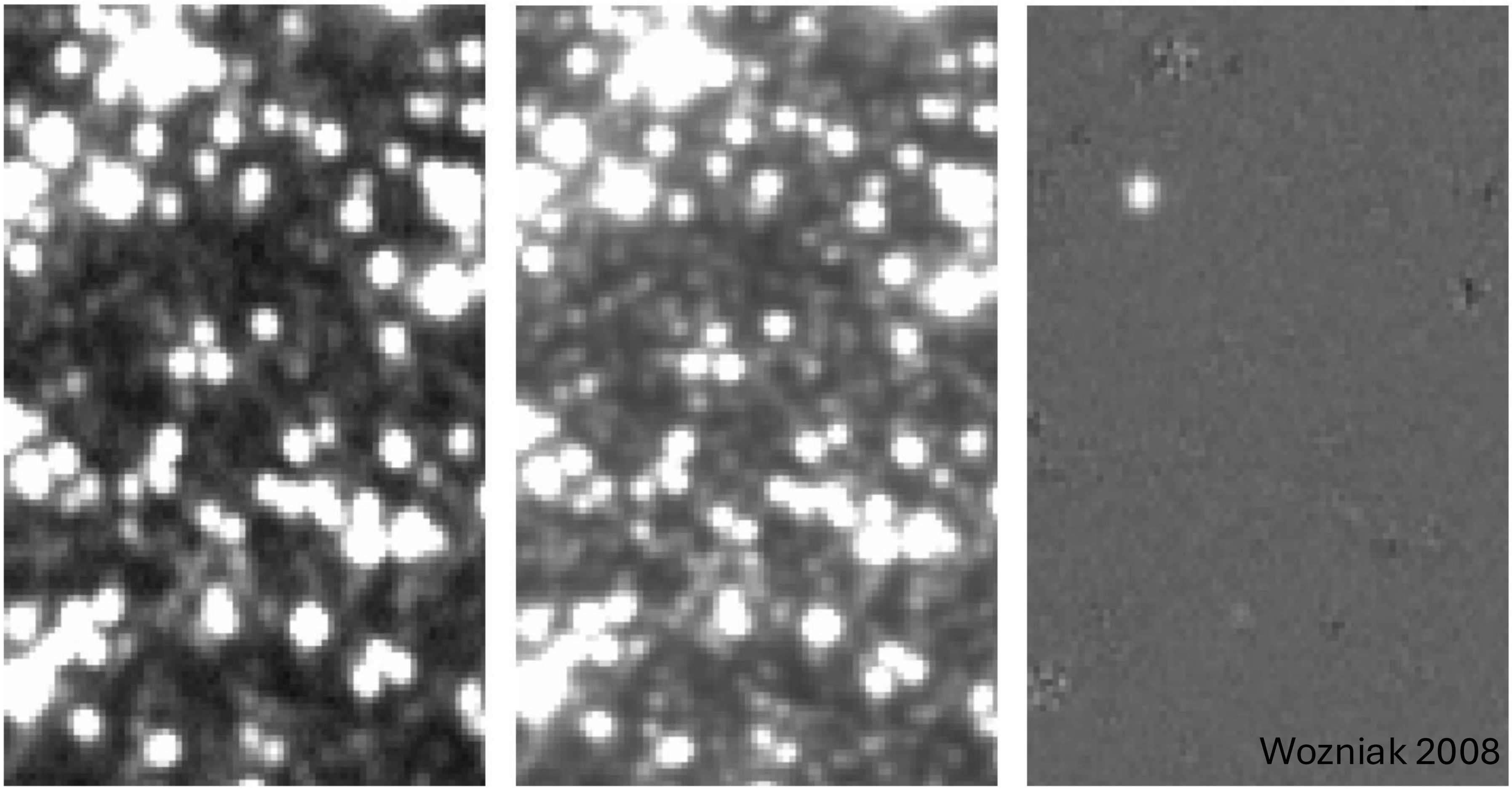
$$\Gamma \sim 10^{6-8}\,\text{deg}^{-2}\,10^{8}\,\frac{\text{mas}^2}{\text{deg}^2}\,\text{yr}^{-1}$$

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

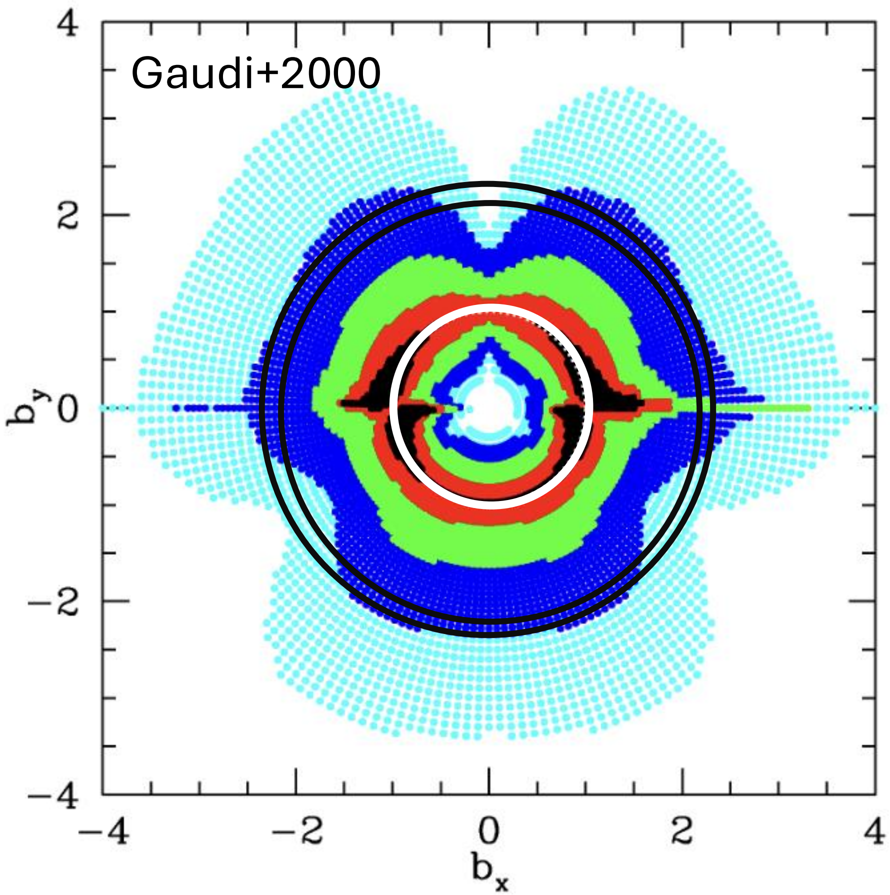
Dictates area

Finding microlensing events

Target - Reference = Difference



What do we mean by detection efficiency?



Points = planet detectable

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

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

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

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

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

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

Not just cold exoplanets

Wilson+2023