Introduction to Microlensing and its Historical Perspectives

Scott Gaudi (OSU) & Dave Bennett (GSFC)

2026 Sagan Summer Workshop

Exoplanets with Roman Surveys: Microlensing and Transits

7/20/2026

“No great chance” – Einstein 1936

- In 1936 Einstein published a paper in which he derived the equations of microlensing by a foreground star closely aligned to a background star (Einstein 1936).
- Einstein had been thinking about this idea as far back as 1912 (Renn et al. 1997).
- Perhaps had even hoped to use the phenomenon to explain the appearance of Nova Geminorum 1912 (Sauer 2008).
- However, by 1936 he had dismissed the practical significance of the microlensing effect
- He only wrote up the paper because he was harassed by Rudi Mandi

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

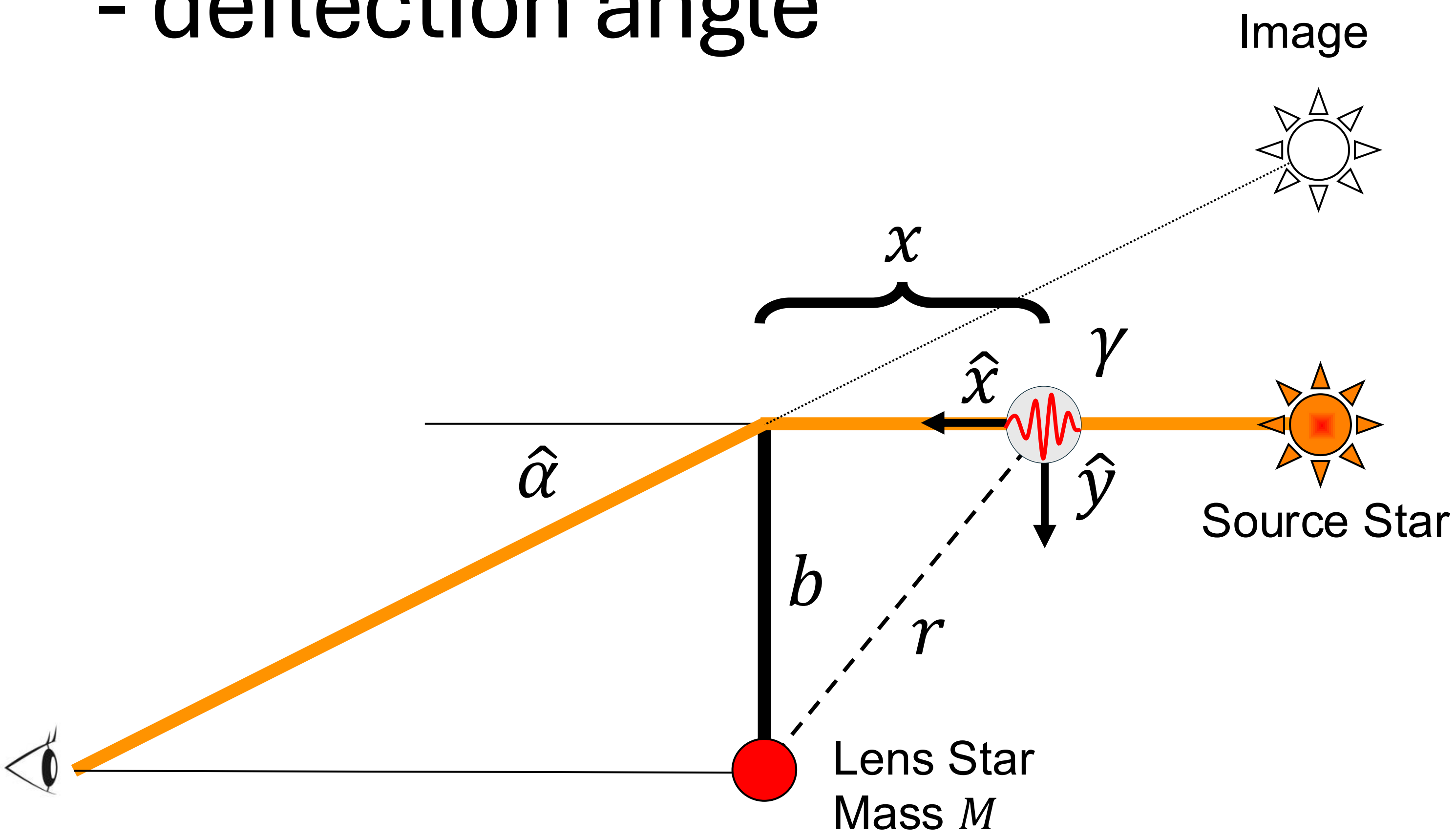
SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

Of course, there is no hope of observing this phenomenon directly.

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star *B* is disregarded.

Einstein 1936
Published in Science

Microlensing Basics
- deflection angle



Consider a photon γ that passes by a mass M at a distance b.

- Define coordinates x and y:

$$x = ct, \qquad y = b$$

- The distance between the photon and the mass is:

$$r = \sqrt{x^2 + y^2} = \sqrt{(ct)^2 + b^2}$$

- And the acceleration is:

$$\vec{a} = -\frac{GM}{r^3}\vec{r}$$

- The acceleration perpendicular to the trajectory is

$$a_\perp = -\frac{GMb}{(x^2 + b^2)^{3/2}}$$

- The change in velocity in this direction is:

$$\Delta v_\perp = \int_{-\infty}^{+\infty} a_\perp dt = -\frac{GMb}{c}\int_{-\infty}^{+\infty} \frac{dx}{(x^2+b^2)^{3/2}} = \frac{-2GM}{bc}$$

- Finally, the **deflection angle** is:

$$\hat{\alpha} \approx \frac{|\Delta v_\perp|}{c} = \frac{\overset{4}{\cancel{2}}GM}{bc^2}$$

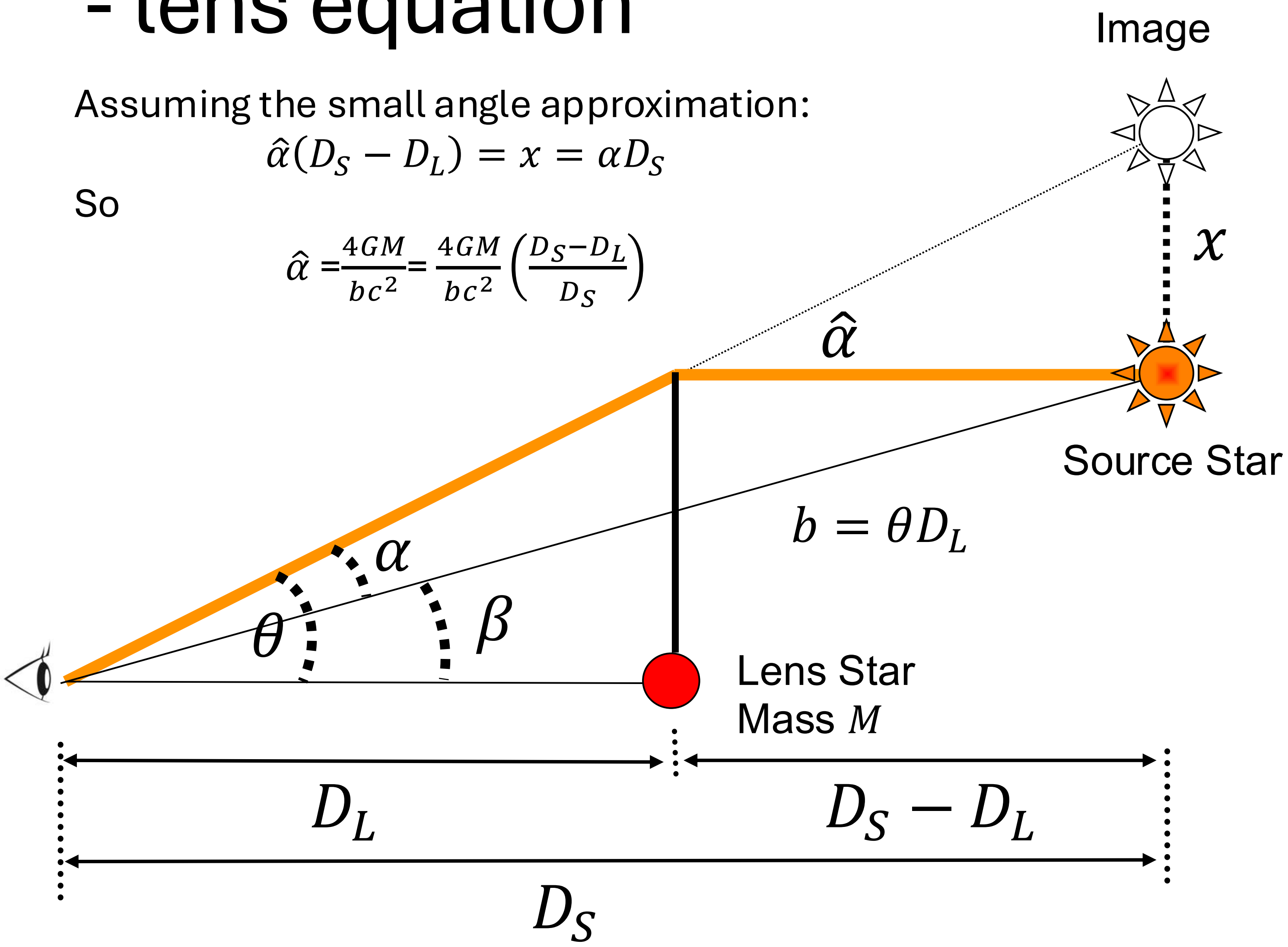
Microlensing Basics - lens equation

Assuming the small angle approximation:

$$\hat{\alpha}(D_S - D_L) = x = \alpha D_S$$

So

$$\hat{\alpha} = \frac{4GM}{bc^2} = \frac{4GM}{bc^2}\left(\frac{D_S - D_L}{D_S}\right)$$



The **lens equation** is the mapping between the source position β and the image position θ:

$$\beta = \theta - \alpha = \beta - \left(\frac{D_S - D_L}{D_S}\right)\hat{\alpha}$$

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$$= \theta - \frac{4GM}{c^2}\left(\frac{1}{D_L} - \frac{1}{D_S}\right)\frac{1}{\theta}$$

Defining the **angular Einstein ring radius**:

$$\theta_E = \left[\frac{4GM}{c^2}\left(\frac{1}{D_L} - \frac{1}{D_S}\right)\right]^{1/2} = \left(\frac{2R_{\rm Sch}}{D_{rel}}\right)^{1/2} = (\kappa M \pi_{rel})^{1/2},$$

where $D_{rel} = (D_L^{-1} - D_S^{-1})^{-1}$, the relative parallax is $\pi_{rel} = \pi_L - \pi_S = \frac{AU}{D_L} - \frac{AU}{D_S}$, and

$$\kappa \equiv \frac{4G}{c^2 AU} \cong 8.144 \text{ mas } M_\odot^{-1}.$$

We have that

$$\beta = \theta - \frac{\theta_E^2}{\theta}$$

Defining scaled units $y = \theta / \theta_E$ and $u = \beta / \theta_E$, the **dimensionless single lens equation** is:

$$u = y - y^{-1}$$

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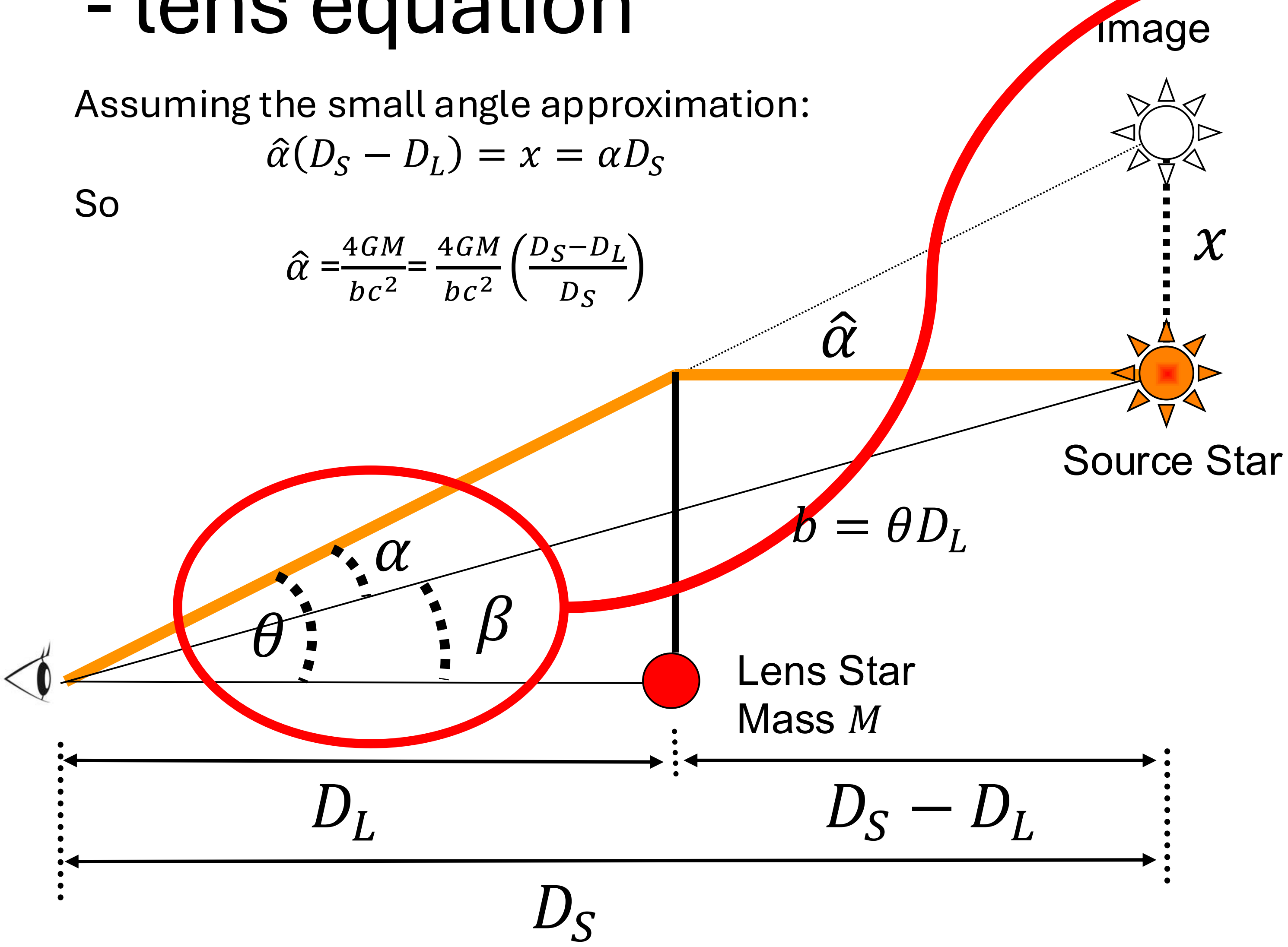

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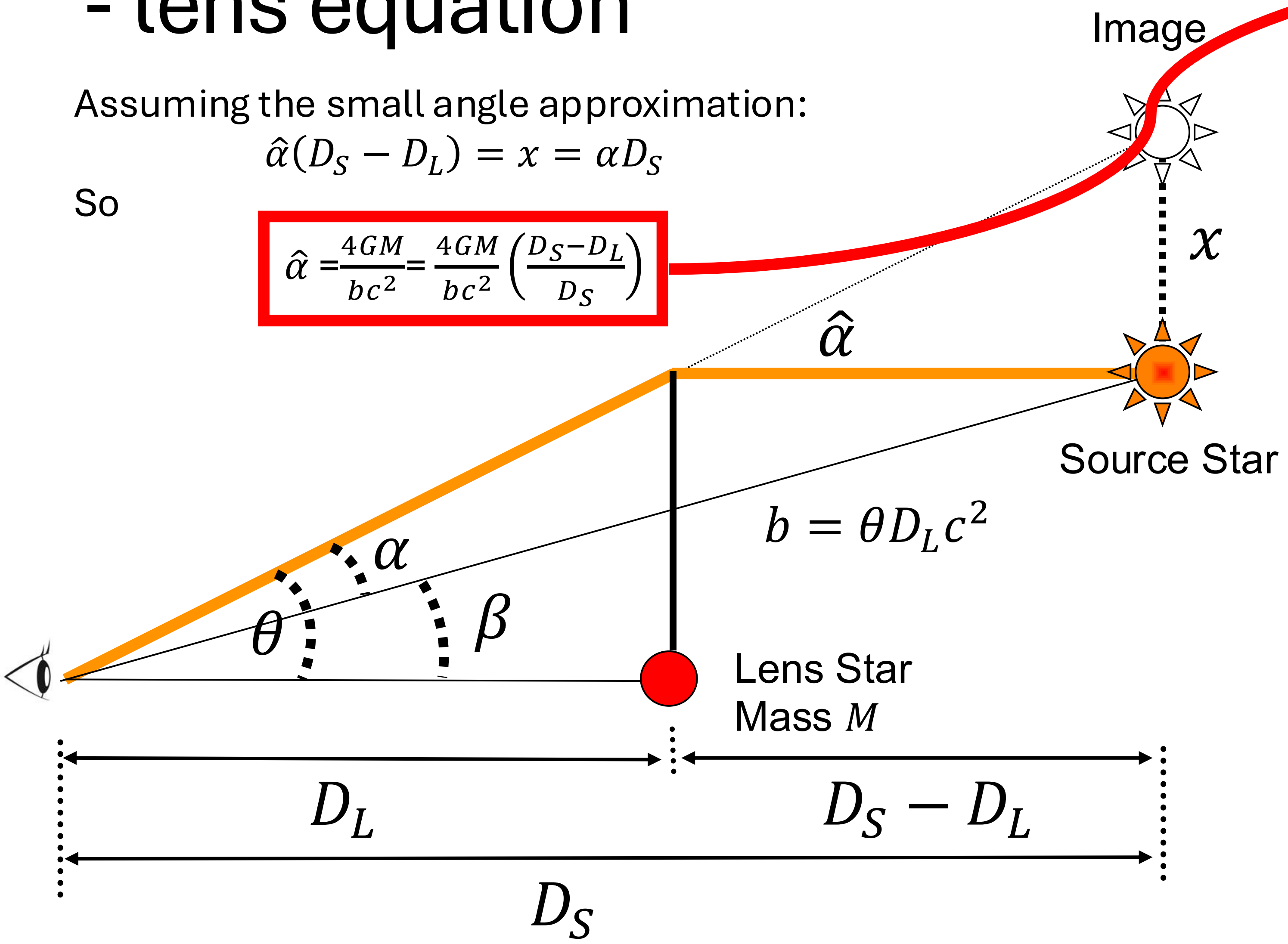

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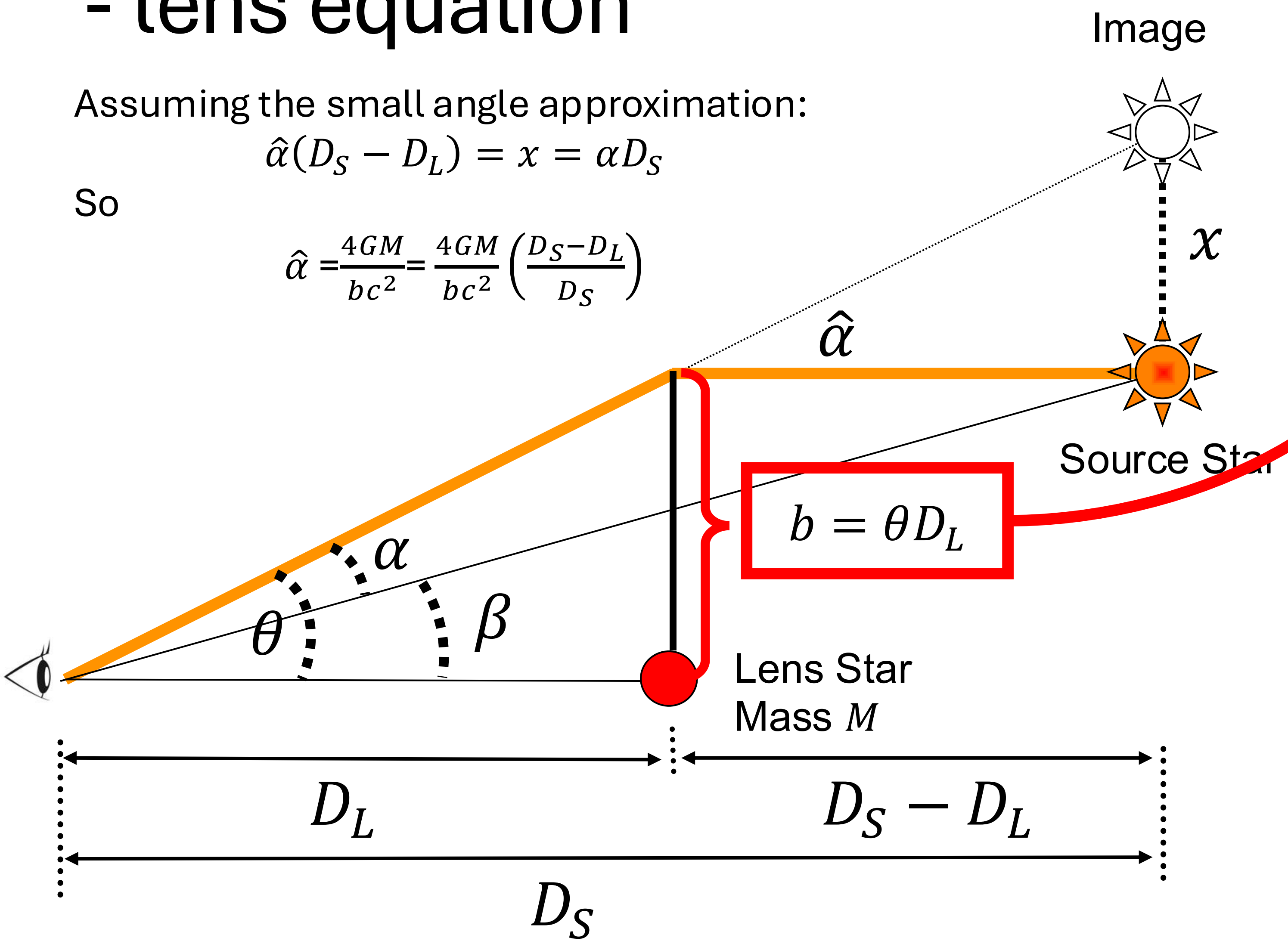

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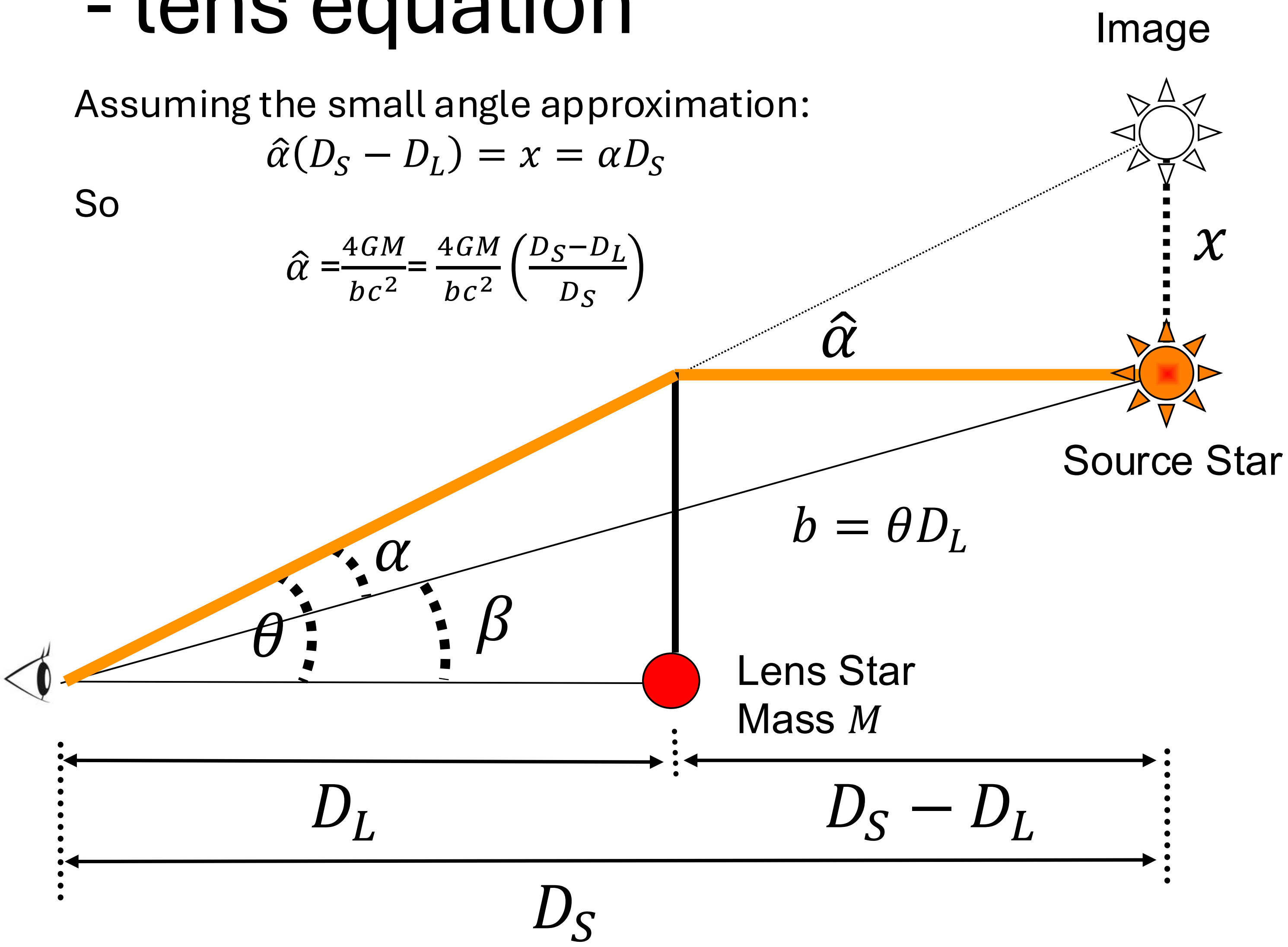

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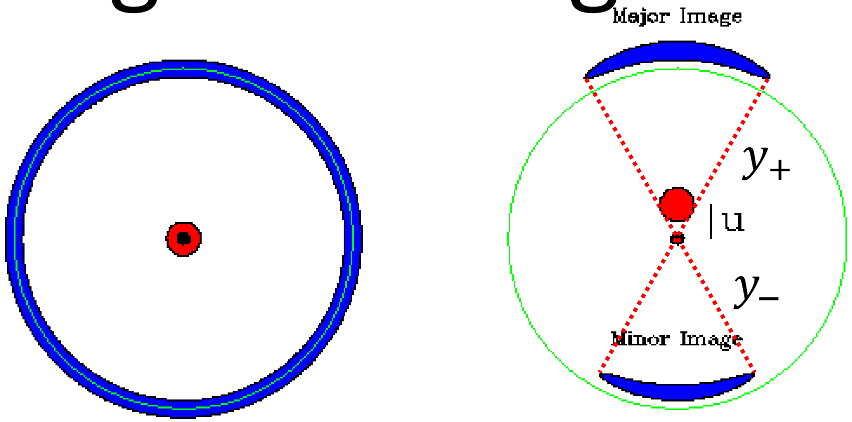
Microlensing Basics
- rings and images



The scaled **lens equation** is

$$u = y - y^{-1}.$$

For $u = 0, y = 1$, and the image is a ring of radius

$$\theta_E = \sqrt{\kappa M \pi_{rel}} \sim 0.71\mathrm{mas} \left(\frac{M}{0.5M_\odot}\right)^{1/2} \left(\frac{\pi_{rel}}{0.125\mathrm{mas}}\right)^{1/2}.$$

For $u \neq 0$, there are two images:

$$y_\pm = \pm 0.5\left[\sqrt{u^2+4} \pm u\right],$$

a **major/minor image** outside/inside the Einstein ring.
Note that as $u \to \infty$, $y_+ \to u$ and $y_- \to 0$.

The image separation is $\approx 2\theta_E$ and so is generally not resolvable with current technology for most events.

However, the images are magnified by an amount equal to the area of the image divided by the area of the source.

The images are elongated tangentially by an amount $y_\pm/u$ but compressed radially by an amount $dy_\pm/du$. The magnification of each image is thus:

$$A_\pm = \left|\frac{y_\pm}{u}\frac{dy_\pm}{du}\right| = \frac{1}{2}\left[\frac{u^2+2}{u\sqrt{u^2+4}} \pm 1\right]$$

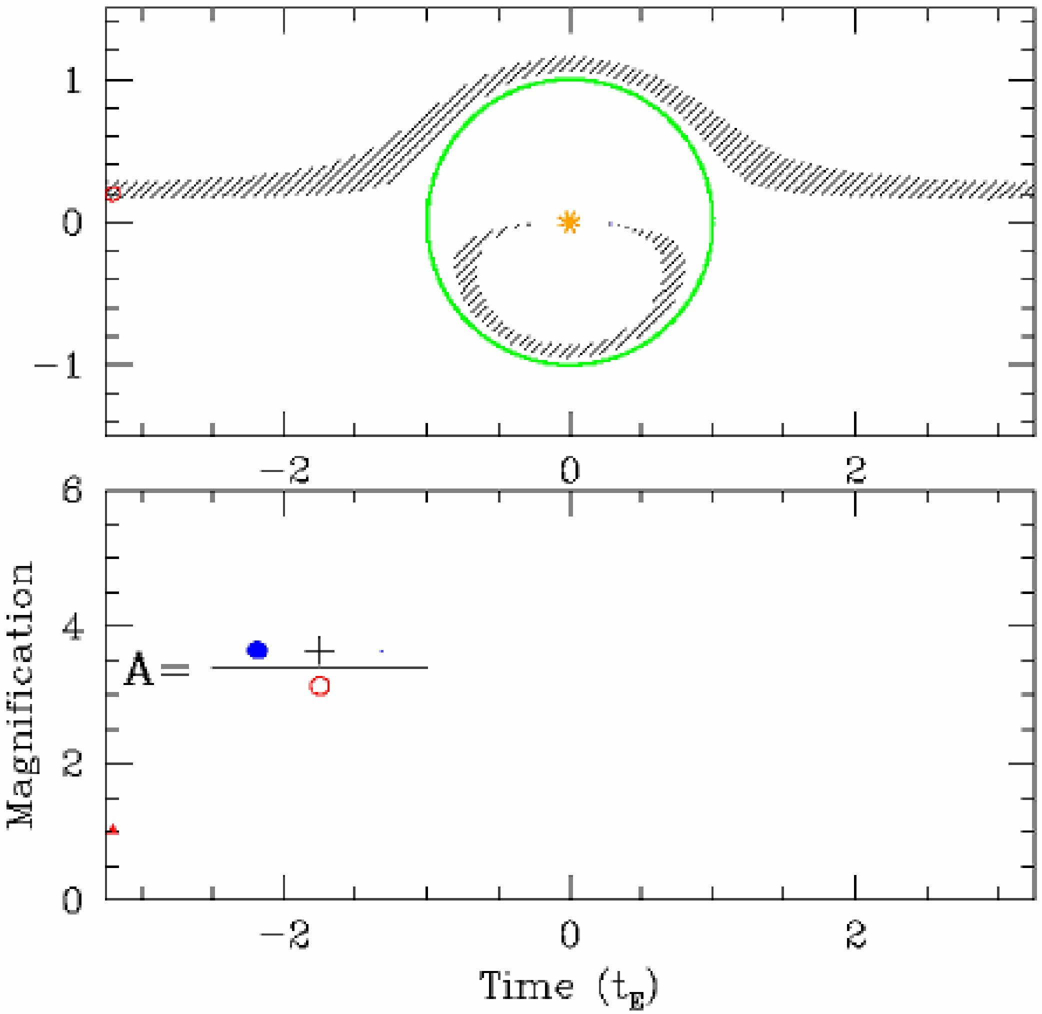
Since the images are typically unresolved, we observe the total **single-lens magnification**

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}$$

For a rectilinear trajectory,

$$u(t) = \sqrt{\left(\frac{t-t_0}{t_E}\right)^2 + u_0^2}$$

Microlensing Events



- The Einstein timescale is:

$$t_E = \frac{\theta_E}{\mu_{rel}} \approx 25 \text{ days} \left(\frac{M}{0.5M_\odot}\right)^{\frac{1}{2}} \left(\frac{\pi_{rel}}{0.125\text{mas}}\right)^{\frac{1}{2}} \left(\frac{\mu_{rel}}{10 \text{ mas yr}^{-1}}\right)^{-1},$$

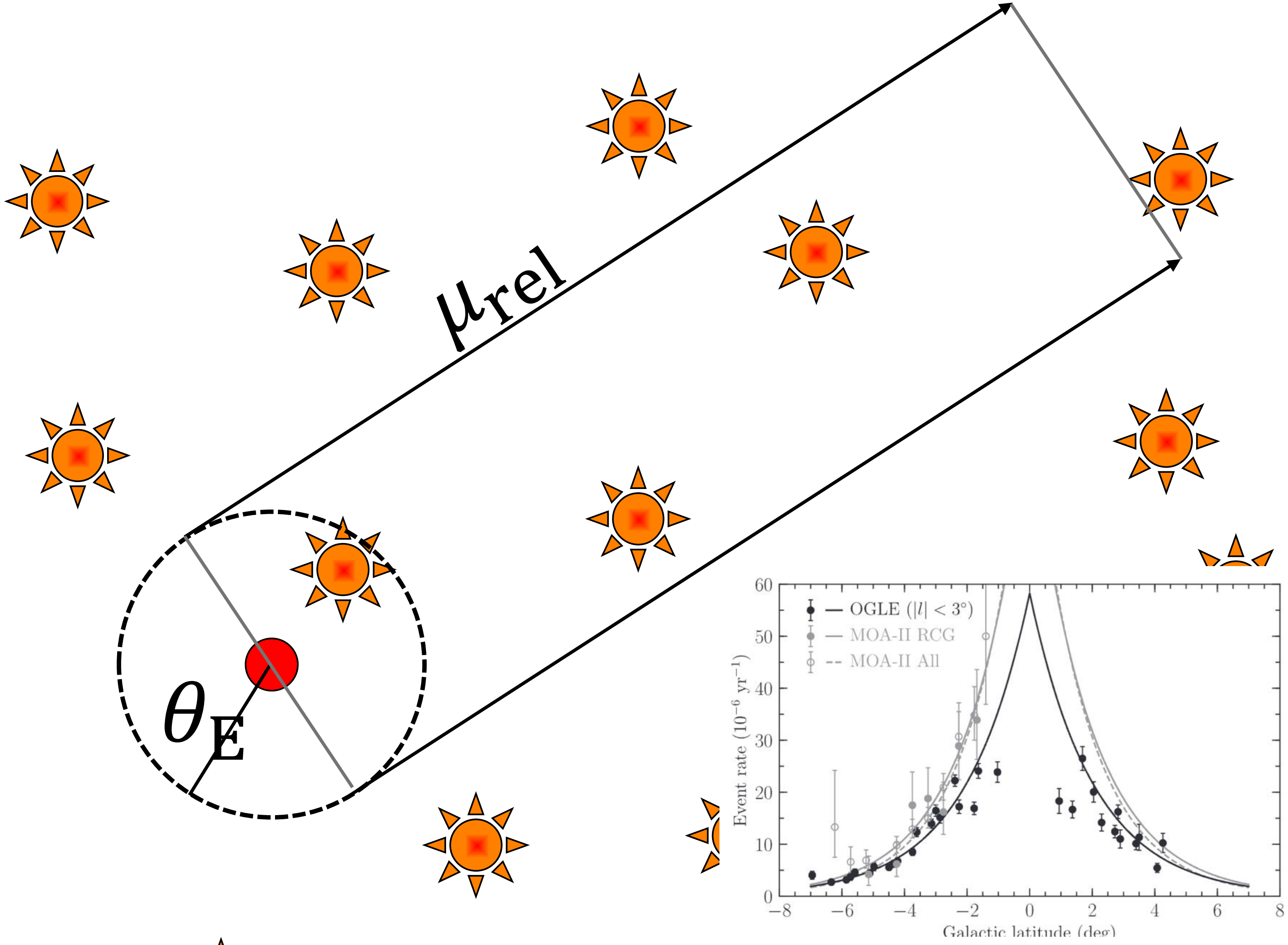
  where μ_{rel} is the relative lens-source proper motion
- Timescales range from a few days to hundreds of days for brown dwarf, stellar, and remnant lenses.
- The timescale is a degenerate combination M, π_{rel}, and μ_{rel}.
- Need additional information to infer the mass and distance to the lens.

Event rate

- Event rate per star is the faction of the sky swept out by the cross section of the Einstein ring per unit time

$$\Gamma \approx \int_0^{D_S} n_*(D_L)[2\mu_{\rm rel}\theta_{\rm E}]D_L^2 dD_L$$

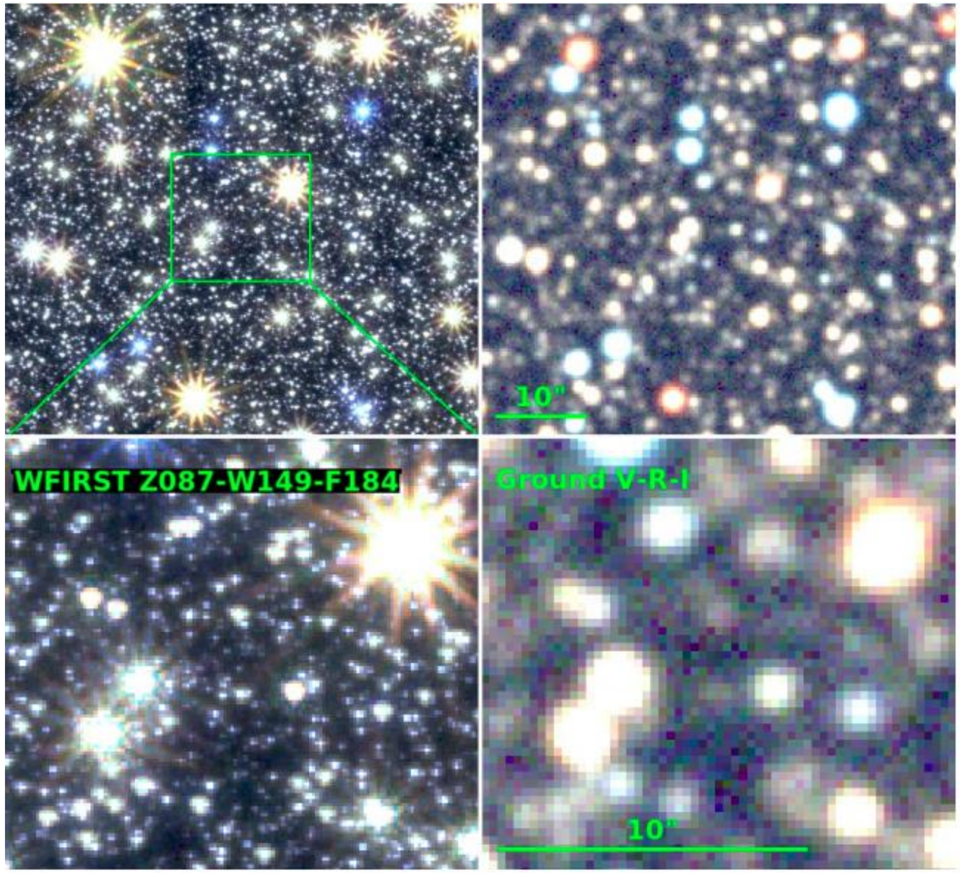
- Γ~0.5-3 $\times\ 10^{-5}{\rm yr}^{-1}$
- Microlensing events are rare and unpredictable



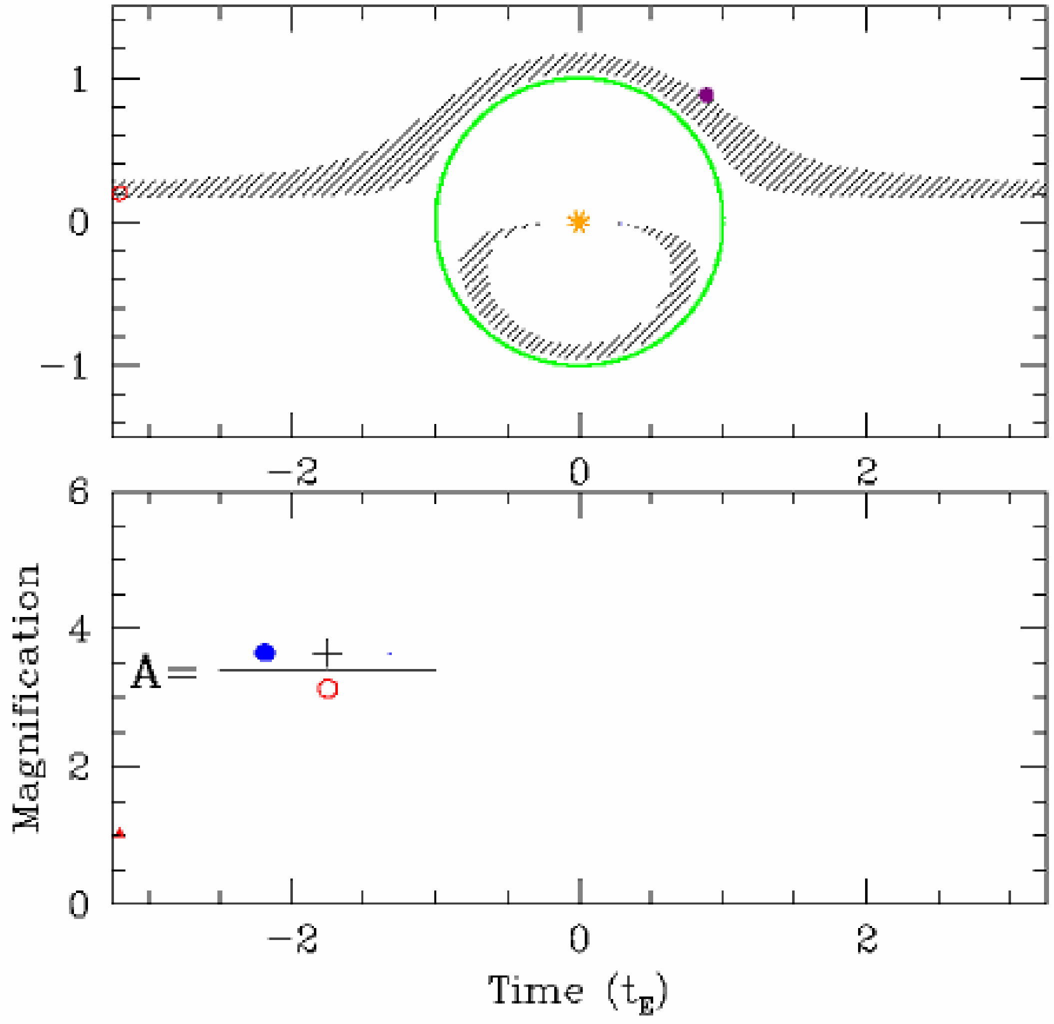
Event rate per star from OGLE-IV
(Mroz et al. 2019)

Need to monitor crowded stellar fields

- Given the event rates per star and the maximum sizes of ground and and space-based cameras, need to monitor dense fields to detect many microlensing events
- Fields toward galactic bulge are good targets
- But the drawback is that they are crowded and heavily extinguished
- Space and near-IR help a lot



Planets perturb images



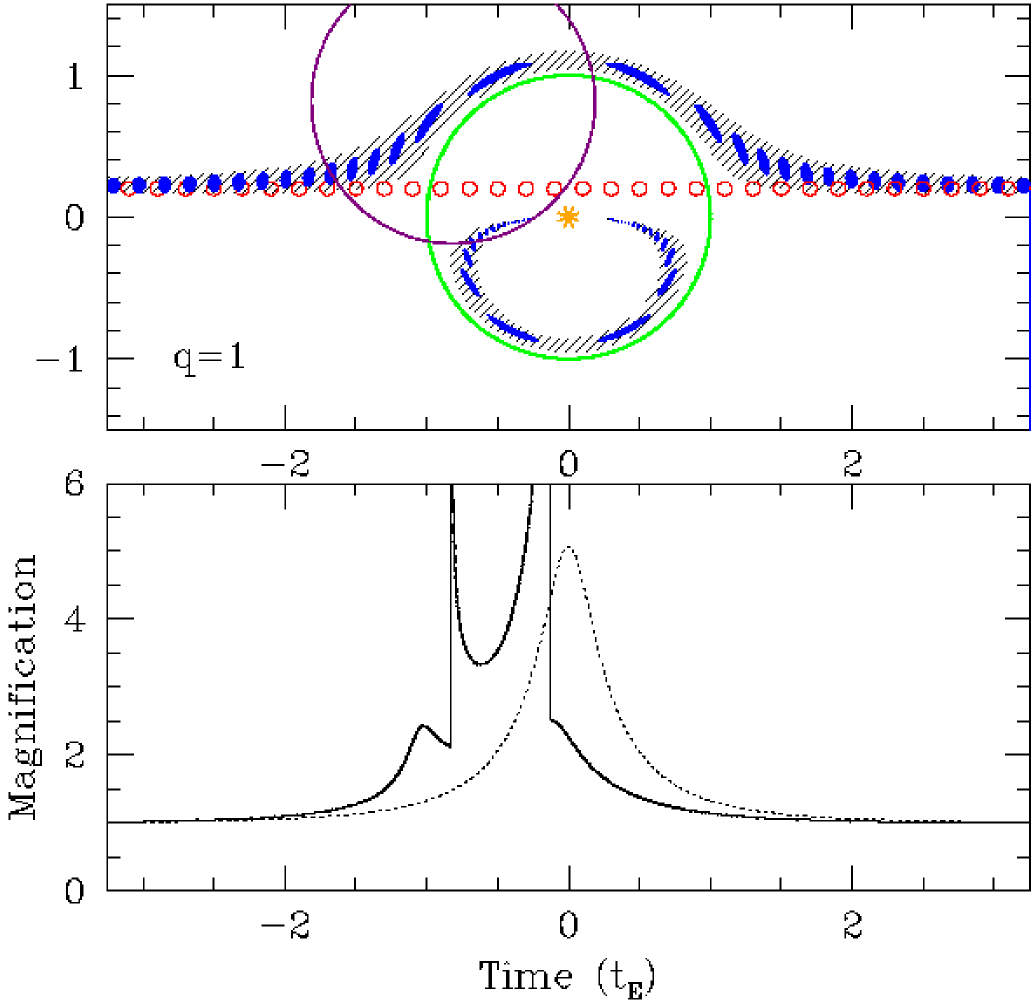
$$\Delta t_p \sim q^{1/2} t_E \sim 1 \text{ day } \left(\frac{M_p}{M_J}\right)^{1/2}$$

High-Magnification ⟶ High Efficiency

Maximized when the planet is close to the Einstein ring:

$$a \sim R_E = \theta_E D_L \sim 4 \text{ AU} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

Mass ratio dependence



- Magnitude depends on separation of planet from image.
- Duration depends on mass ratio.

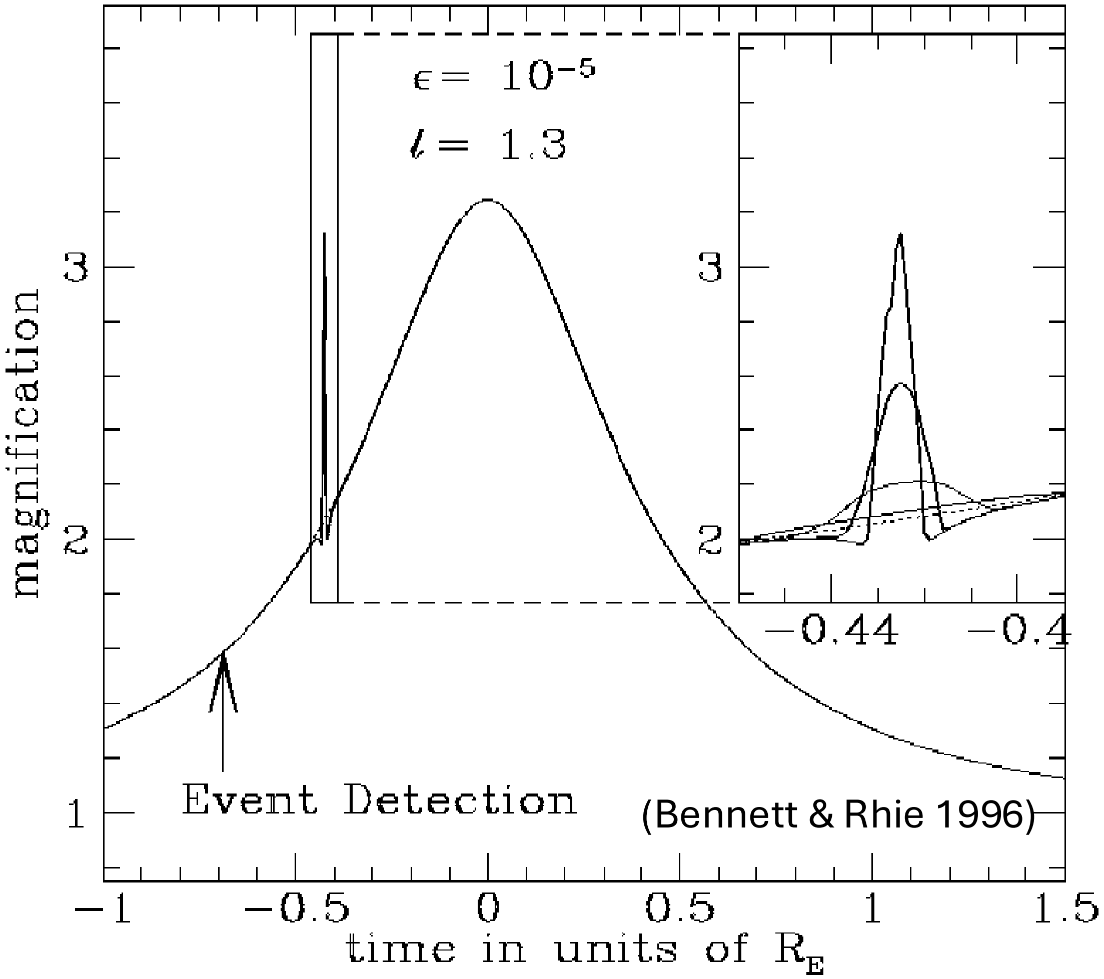
$$\Delta t_p \sim q^{1/2} t_E \sim 1 \text{ hr} \left(\frac{M_p}{M_\oplus}\right)^{1/2}$$

- Detection probability depends on mass ratio.

$$P \sim A_\pm \theta_p \sim \text{ few \%} \left(\frac{M_p}{M_\oplus}\right)^{\sim(0.5-0.7)}$$

- Signal magnitude is *independent* of planet mass ratio, but signals get *rarer* and *briefer*
- **Planetary perturbations are rare, short, and unpredictable, but generally large**

Low mass planets require small sources

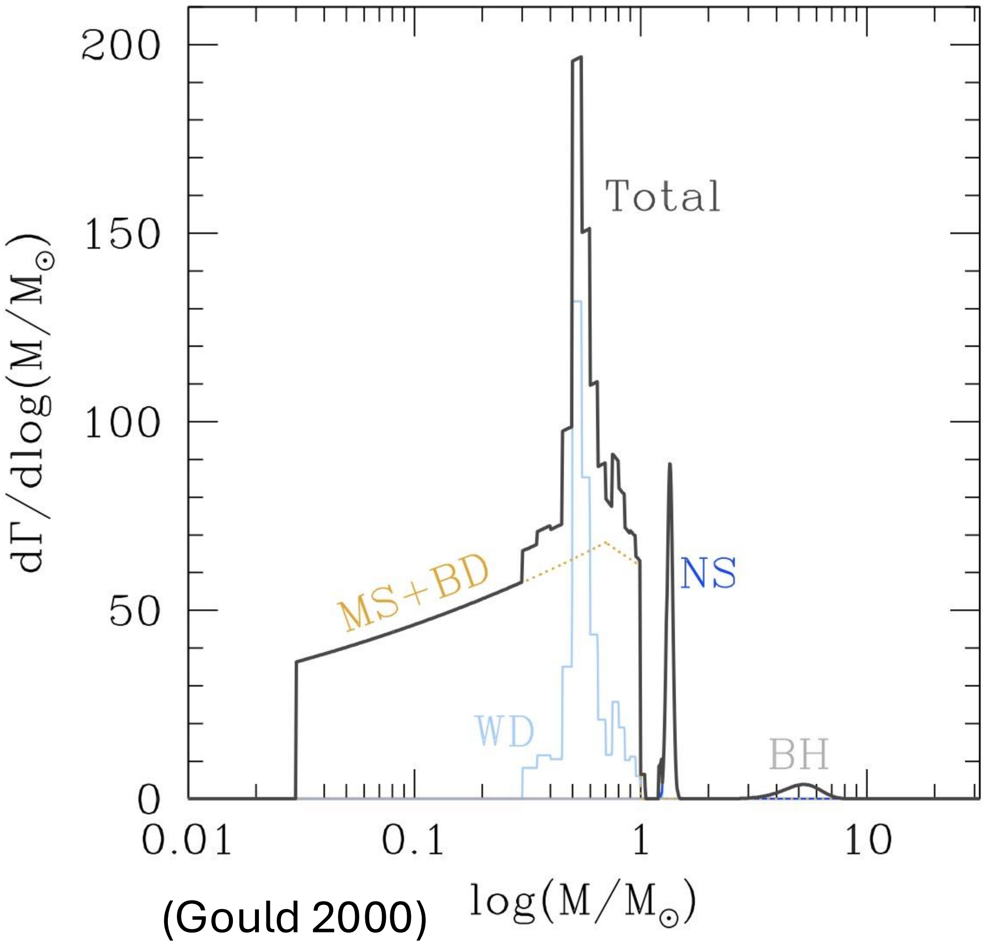


$$\theta_{E,p} \sim \mu as \left(\frac{M_p}{M_\oplus}\right)^{1/2} \leftrightarrow \theta_* \sim \mu as \left(\frac{R_*}{R_\odot}\right)$$

$$\rho_* = \frac{\theta_*}{\theta_E} \sim 1$$

- **Detecting low-mass planets requires monitoring main-sequence sources.**
- Lower mass limit of several lunar masses for M dwarf sources

Microlensing Host Stars?



(Gould 2000)

Sensitive to planets around:

- Bulge/disk MS stars (mostly M < $M_{\odot}$)
- Brown dwarfs
- Remnants (WD, BH, NS)

Not just low-mass stars!

Faint Lenses:

- Most lenses (but not all!) are fainter than (and blended with) the sources and other stars.
- Lenses distributed along the line of sight to the Galactic bulge (distances of ~1-8 kpc)
- **Most, but not all, host lenses are faint**
- **Planets can not be confirmed or characterized.**

Microlensing Challenges

- Microlensing events are rare and unpredictable

  → Need to monitor 10^7-10^8 stars toward the bulge continuously for a year to detect ~10^4 events

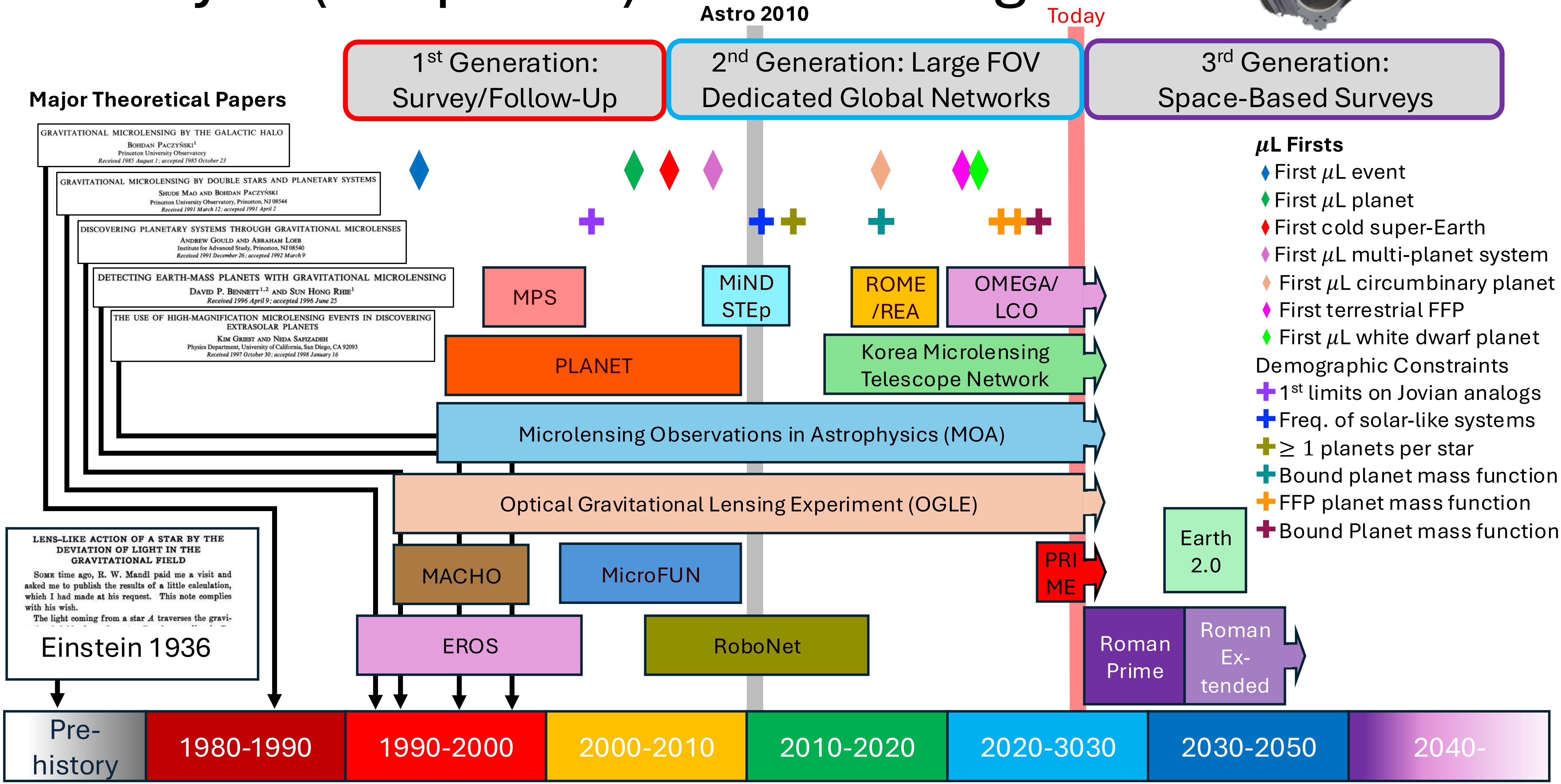
- Planetary perturbations are rare (probability ~ few %), brief (~ few hours-day), and unpredictable, but have relatively large ($\gtrsim$ 1%) deviations

  → Need good (but not exquisite), continuous photometry of all the stellar microlensing events.

- Most, but not all, host lenses are faint, and planets can not be confirmed or characterized
- Fields are very crowded for seeing-limited observations, and sources and lenses are blended during the event

  → Need ground AO or space-based observations and time (before or after) to directly detect and characterize the host stars

History of (Exoplanet) Microlensing



Gravitational Microlensing Dark Matter Search
Bohdan Paczyński 1986

THE ASTROPHYSICAL JOURNAL, 304:1–5, 1986 May 1

GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

BOHDAN PACZYŃSKI[1]
Princeton University Observatory
Received 1985 August 1; accepted 1985 October 23

ABSTRACT

The massive halo of our Galaxy has an optical depth to gravitational microlensing $\tau \approx 10^{-6}$. If the halo is made of objects more massive than $\sim 10^{-8}\ M_{\odot}$, then any star in a nearby galaxy has a probability of 10^{-6} to be strongly microlensed at any time. The lensing events last ~ 2 hr if a typical "dark halo" object has a mass of $10^{-6}\ M_{\odot}$, and they last ~ 2 yr for objects of $100\ M_{\odot}$. Monitoring the brightness of a few million stars in the Magellanic Clouds over a time scale between 2 hr and 2 yr may lead to a discovery of "dark halo" objects in the mass range 10^{-6}–$10^{2}\ M_{\odot}$ or it may put strong upper limits on the number of such objects.
Subject headings: galaxies: Magellanic Clouds — gravitation — stars: variables

Gravitational Microlensing could confirm or deny that the Milky Way's dark mater was made of brown dwarfs (too small be be stars or stelar remnants)

A young cosmology theorist was impressed and suggested this to Charles Alcock in 1989

Mao & Paczynski (1991); Gould & Loeb (1992)

ensing is a change in the apparent brightness of the and the phenomenon is usually referred to as gravita- nicrolensing. It was discussed in many papers (Einstein iebes 1964; Refsdal 1964; Chang & Refsdal 1979, 1984;

2. MODEL

All computational details involved in microlensing point masses can be found in Schneider & Weiss (19

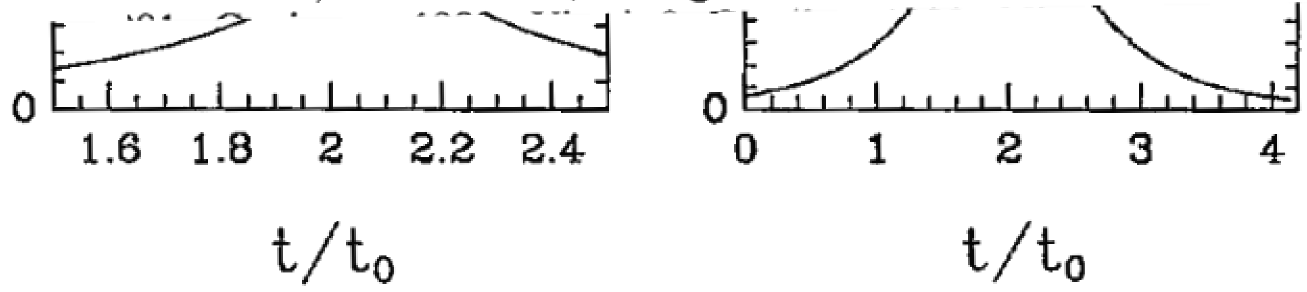
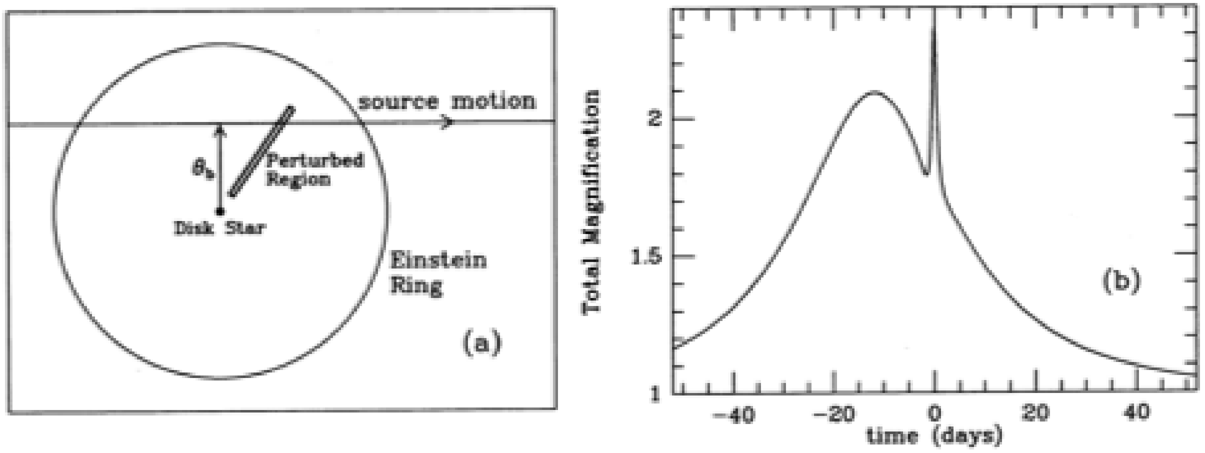


FIG. 2.—The light curves shown correspond to the six source trajectories i g. 1. The source is modeled as a uniform disk of radius $R_{\rm star} = 10^{11}$ cm. Th

t/t_E

t/t_E

5 years later Paczynski's student, Shude Mao led a paper showing that exoplanets could be detected by microlensing.



DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

ANDREW GOULD AND ABRAHAM LOEB
Institute for Advanced Study, Princeton, NJ 08540

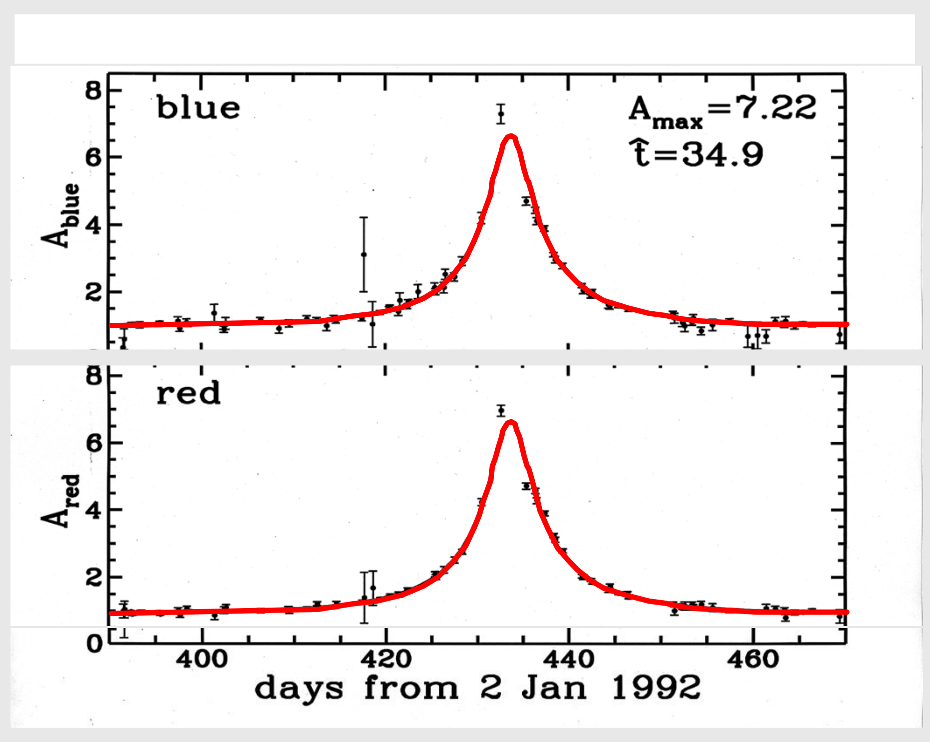
Received 1991 December 26; accepted 1992 March 9

Gould & Loeb present an alert+follow-up observing scheme and point out that microlensing is most sensitive at separations of a few AU.

1993: First Microlensing Event(s)

Alcock started the MACHO Project, including me, and the competing French EROS project was started based on a talk given by Alcock. In MACHO, we thought that OGLE was also started in response to discussions between Alcock and Paczyński.

- MACHO: LMC-1 event
  - Nature paper (and cover)
- OGLE: 1st bulge event
  - Acta Astronomica paper
- EROS: 2 microlensing “candidates”
  - (both later retracted)
- Discoveries came in the face of wide-spread skepticism of microlensing



Dark Matter Implications from Magellanic Cloud Microlensing

No survey supported a MACHO-dominated Milky Way Halo

- MACHO: MACHOs are < 50% of the halo dark matter at 95% confidence (Alcock et al. 2000)
- Eros: halo not dominated by MACHOs of $0.6 \times 10^{-7}\, M_{\odot} < M < 15\, M_{\odot}$ (Tisserand et al. 2007)
- OGLE: $1.3 \times 10^{-5}\, M_{\odot}$ to $860\, M_{\odot}$ cannot make up more than 10% of Halo Dark Matter (Mroz et al. 2024)

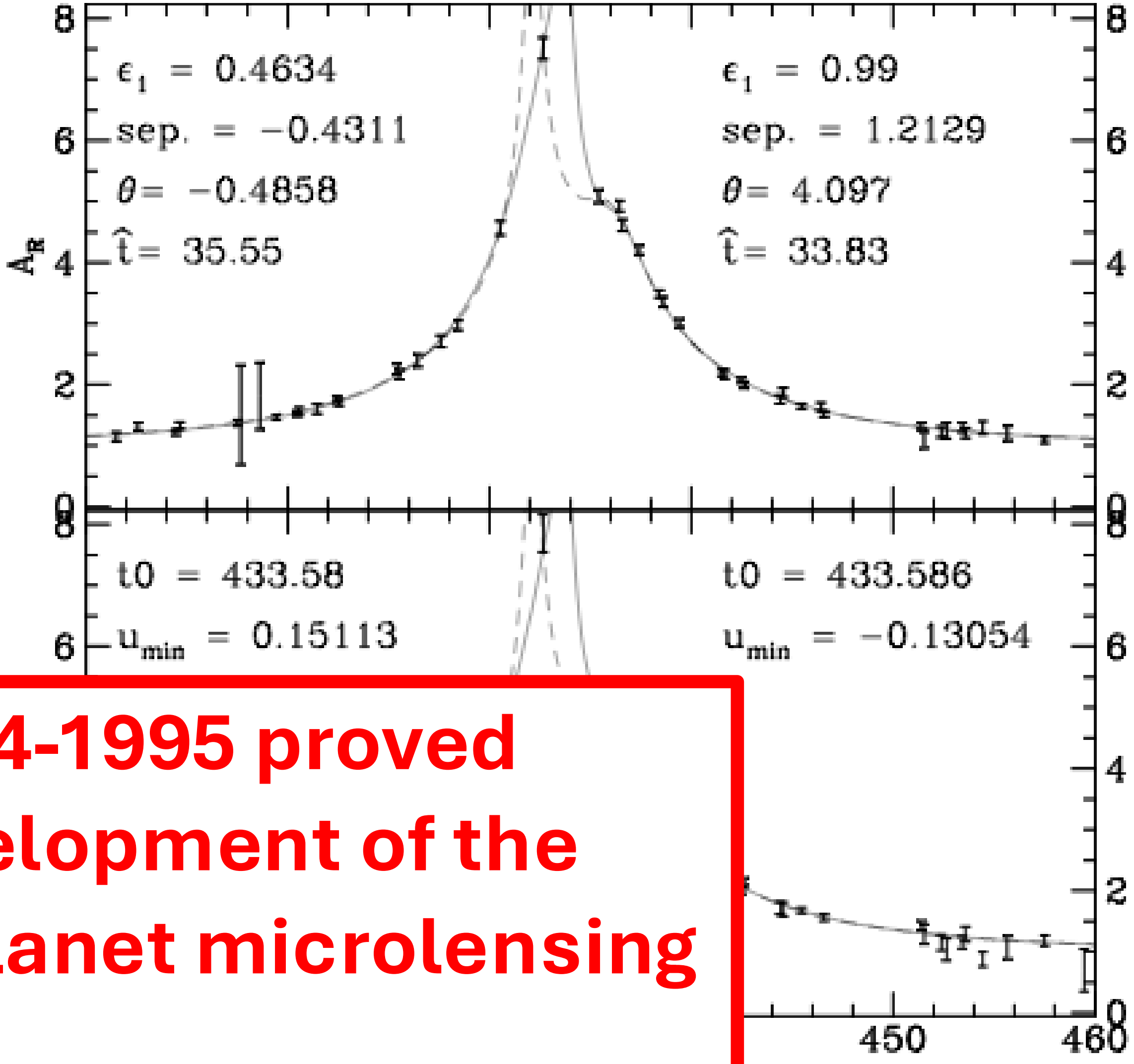
MACHO LMC-1: Extra Galactic Planet?

Sun Hong Rhie in October, 1993 thought this could show a planetary signal

- Started planet detection by microlensing work

Deviation at A ~ 5
planetary event,
(dashed curve) fi
Bennett 1996).

Also Dominik & H



Rhie's effort in 1994-1995 proved crucial for the development of the space-based exoplanet microlensing detection method.

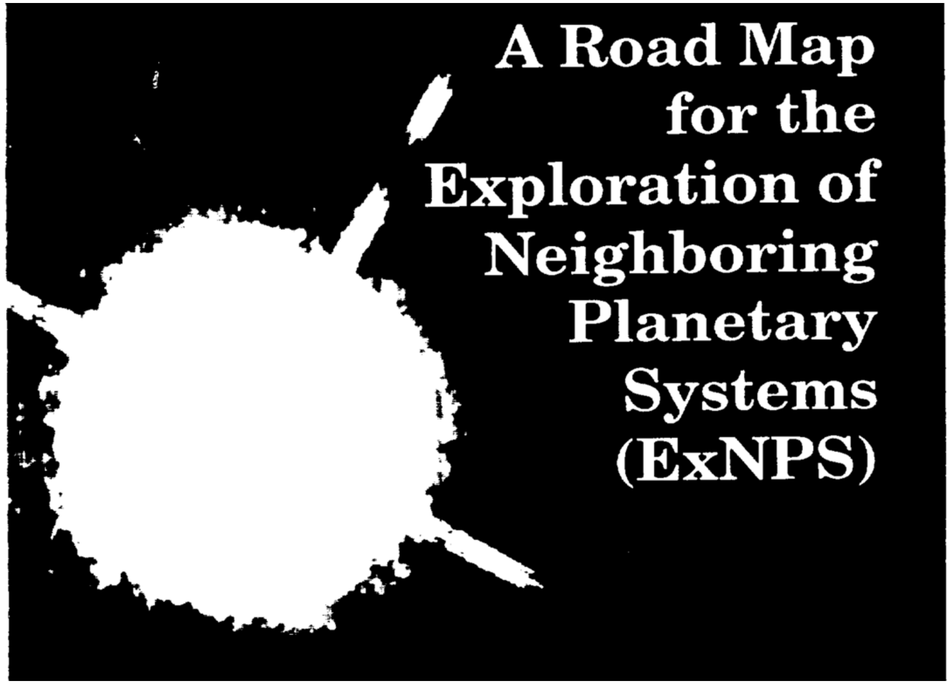
Microlensing as US Priority 1994-5: ExNPS

- Complicated process
  - 3 review teams selected via proposal process – produce 3 reports
  - Merged team with members of all 3 teams writes summary report
  - Blue Ribbon Panel gets summary report, tosses out what they don't like and writes their own report
- Members of 3 panels, David Tytler, Stan Peale, and Andy Gould push for a ground-based microlensing program to measure η_{earth}
- But, Microlensing must find Earth-mass planets to measure η_{earth}

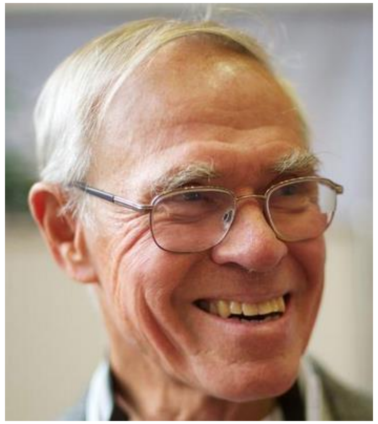
nsing surveys are now finding dozens of star-star micro
per year, and could discover a planet around an ordinary lo
ne near future. An expanded survey could find hundreds of p
asses, around hundreds of distant stars in a decade. Micro
ermine the frequency of planets, the star-planet mass ratios,
net separations using standard photometry.

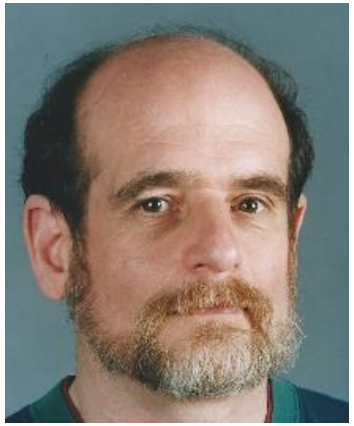
nsing events occur when two distant stars align by cha
" star at ~8 kpc and a "lens" star at 1–7 kpc (Figure 4-11). T
ses the light from the source producing a typical magnific
es which varies smoothly and predictably as the lens moves
connecting the source and the Earth (Figure 4-12).

orbiting the lens star can produce additional magnifi
nes exceeding 100% which last 1.5–50 hours, depending



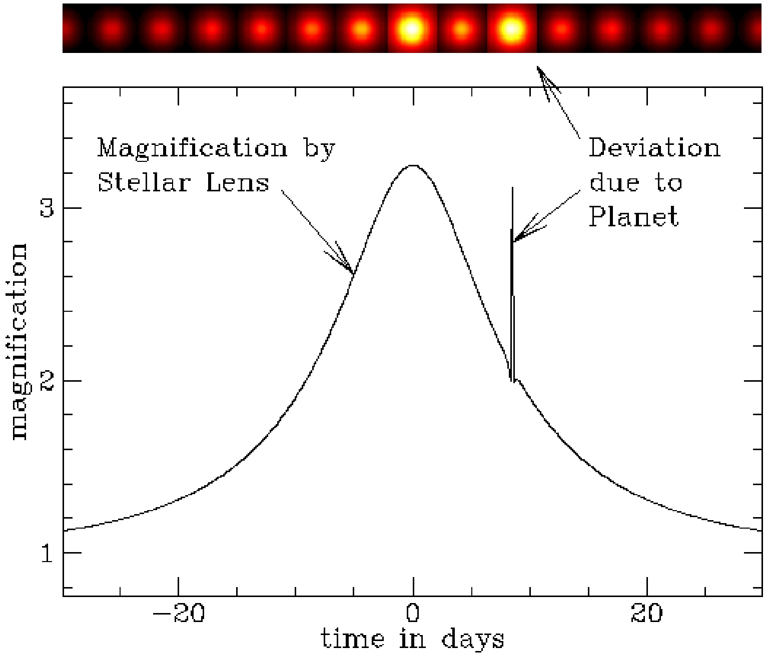

Tytler


Peale


Gould

Can Microlensing Find Earth-Mass Planets?

- Tytler assembled a small group of microlensers (including Gould & Peale) and demanded this question be answered
- Thanks to Rhie's MACHO-LMC-1 inspiration, Bennett & Rhie (1996) develop the image-centered ray-shooting code to calculate light curves with finite source effects to demonstrate microlensing's sensitivity to Earths



- Summary report recommends a ground-based microlensing with 1 survey telescope and 3 follow-up telescopes
  - A KMTNet-like 3-survey telescope option was considered, but seemed too expensive
- The Blue-Ribbon Panel rejected the microlensing program – to focus on a Terrestrial Planet Finder (TPF)-I program
  - But, luckily, this avoided the blending problem that had been neglected
- **But, there was another risk!!** Paczynski had written a draft of his 1996 Annual Reviews on microlensing, which stated that microlensing could not find Earths (based on single calculation assuming a planet at s = 1)
  - the Bennett & Rhie calculations convinced him to correct this.

ExNPS

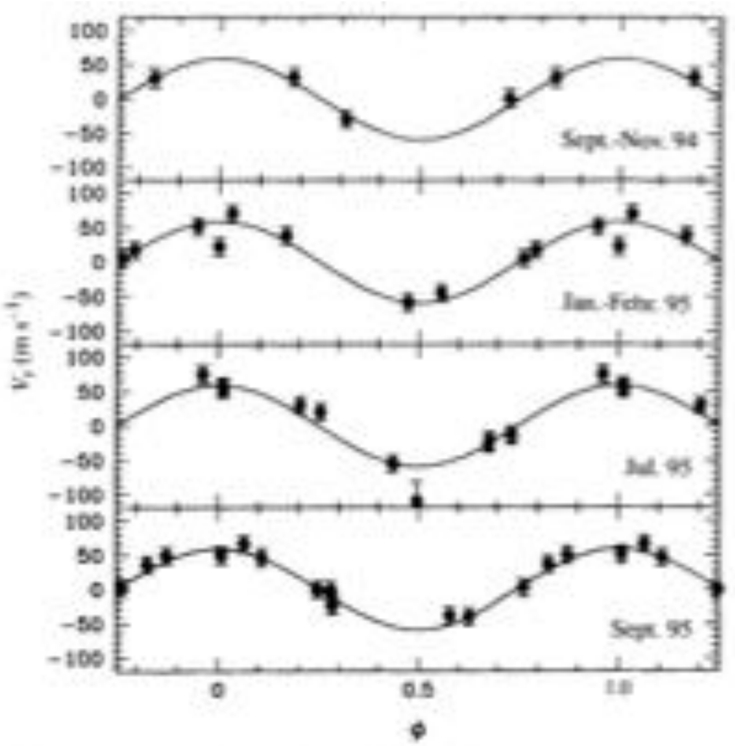
- Rejected the ground-based microlensing program
- In favor of a space-based IR interferometer for the direct detection of ExoEarths (later called TPF-I)
- Perhaps because the detection of Earth 2.0 was considered as the only worthy NASA Goal?
    - A prospect roundly rejected by the 2000 Decadal Survey
- But Nature had the last word

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

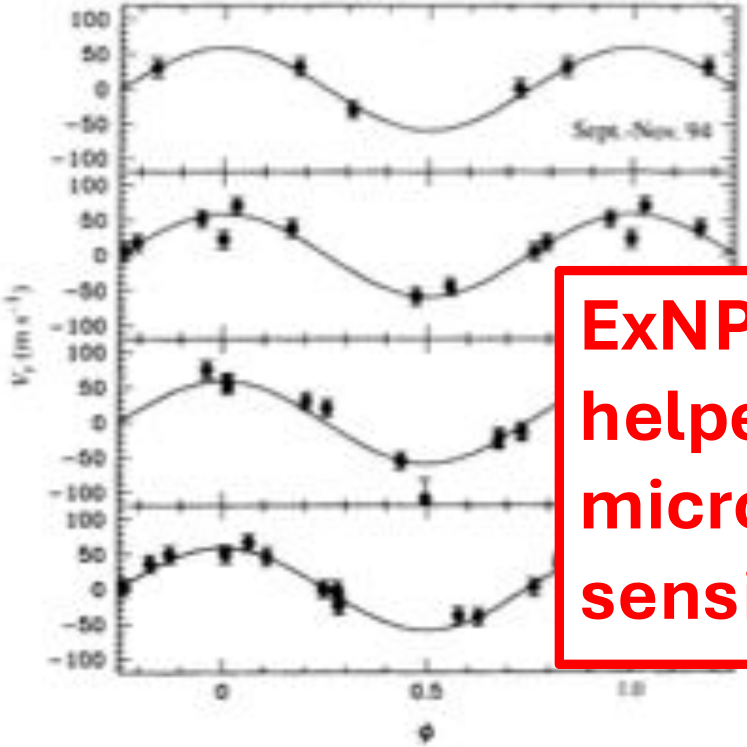
NATURE · VOL 378 · 23 NOVEMBER 1995 355



- **51 Peg b made it clear that a Kepler mission would see many planets easier to detect than Venus & Earth, undermining the ExNPS rejection of Kepler**

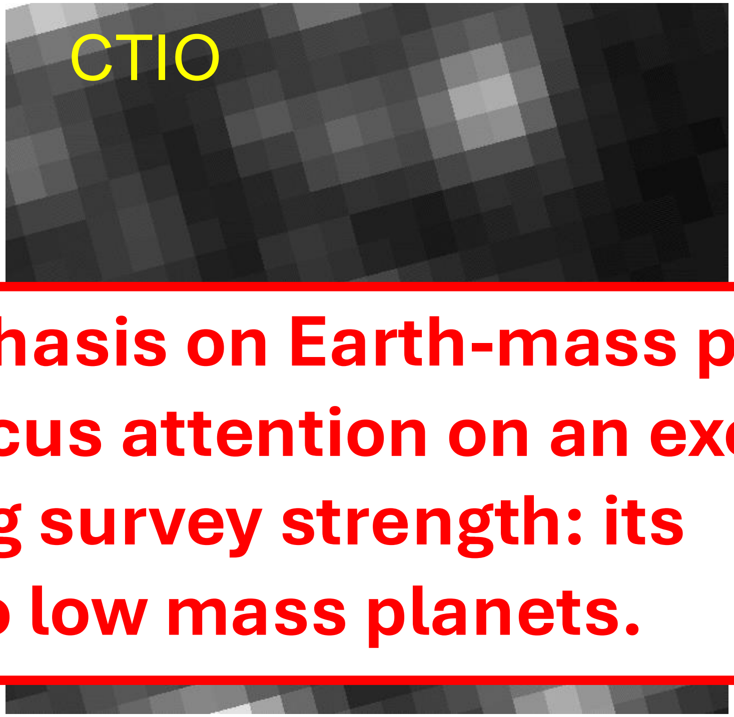
ExNPS Failures

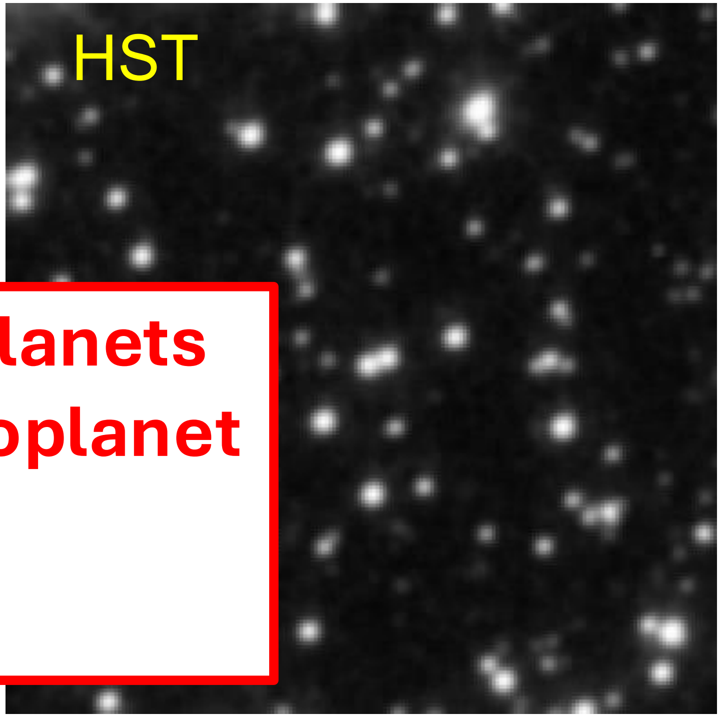
The Solar System Does Not Predict Transit Survey Yields



51 Peg b was discovered a month or 2 before the ExNPS report was released, but there were no changes to the conclusions (i.e. rejecting Kepler).

Ground-based confusion, space-based resolution





ExNPS' emphasis on Earth-mass planets helped to focus attention on an exoplanet microlensing survey strength: its sensitivity to low mass planets.

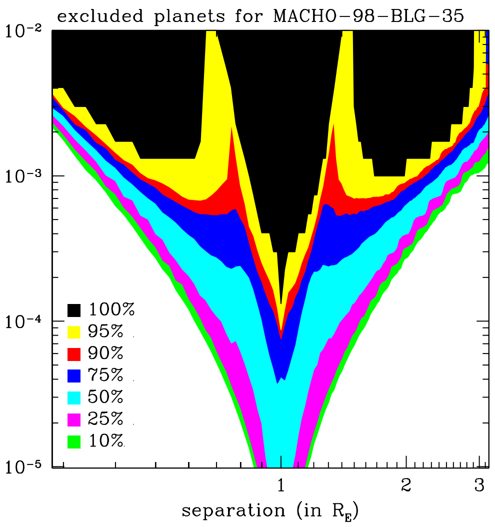
Bulge main sequence stars are resolved with HST, but not with ground-based seeing. "Turn-off stars" seen in ground-based imaging are actually blended main sequence stars – increasing the number of stars in survey but adding noise and interfering with host star detection.

Ground-based Microlensing Planet Searches

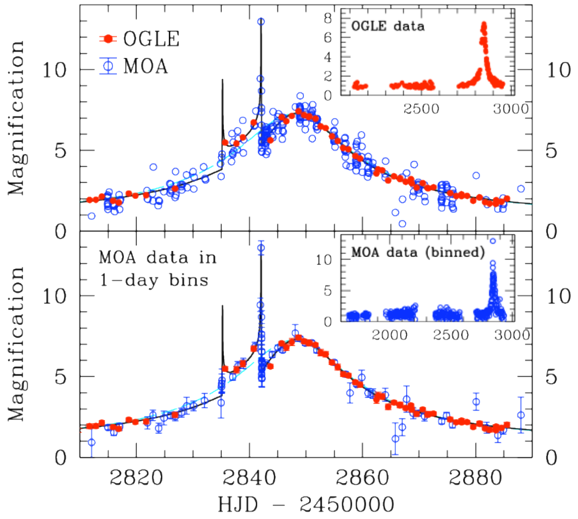
- 1st International Microlensing Meeting in 1995 at LLNL
  - Survey Groups promised alerts (MACHO and OGLE alert systems working)
  - Probing Lensing Anomalies NETwork (PLANET) formed, follow-up group led by Penny Sackett
- New Observing Programs
  - 1997 Microlensing Planet Search (Led by Rhie and Bennett)
  - 1998 Microlensing Observations in Astrophysics (MOA, led by Yasushi Muraki & Phil Yock)
    - began issuing alerts in 2000
  - 2002 Microlensing Follow-Up Network (MicroFUN, led by Andy Gould)
- High Cadence Surveys – enabling event detection and high cadence photometry at the same site.
  - 2006 MOA II
  - 2010 OGLE-IV
  - 2025 KMTNet

Early Planet Discoveries

- Early ground-based discoveries:

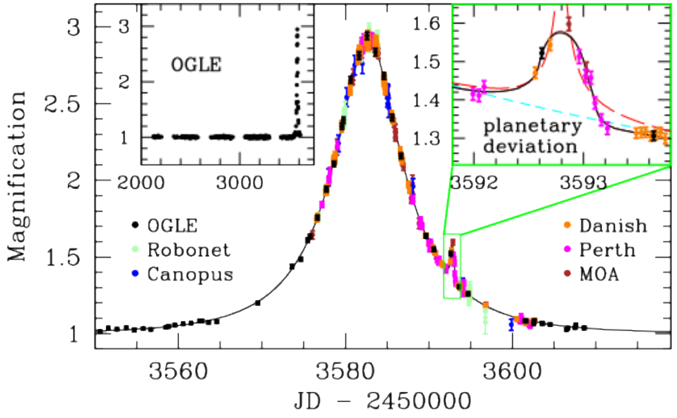


Demonstration of Earth-mass sensitivity (Rhie et . All 2000) MACHO-98-BLG-35, confirming sensitivity of high mag events (Griest & Safizadeh 1998)

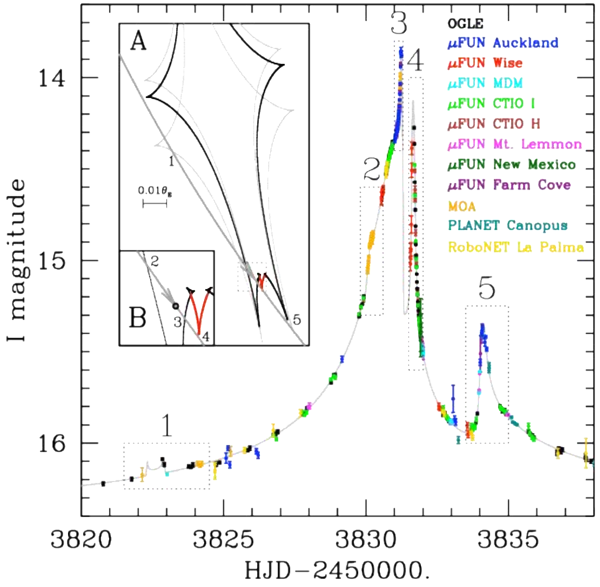


1st exoplanet discovery OB03235Lb (Bond et al. 2004) and 1st microlensing survey exoplanet discovery.

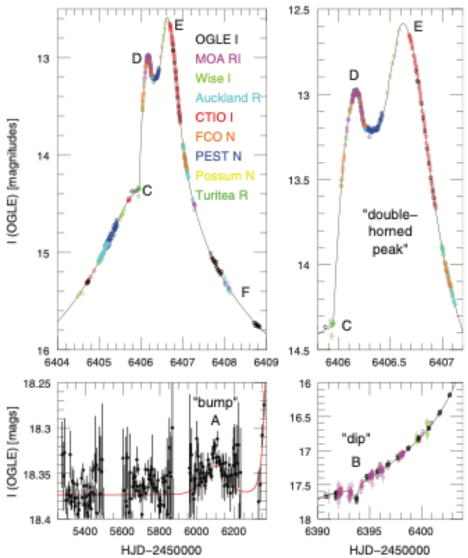
Also, HST images were used to determine the host mass to be $0.63^{+0.07}_{-0.09} M_{\circledast}$ Bennett et al. (2006), confirmed with recent Keck measurements (Bhattacharya et al. 2023)



1st low-mass exoplanet discovery OB05390Lb (Beaulieu et al. 2006) and 1st follow-up exoplanet discovery.

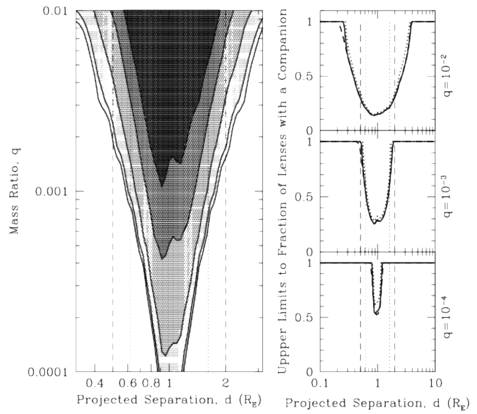


1st 2 planet (Gaudi et al. 2008, Bennett et al. 2010) discovery OB06109Lb,c

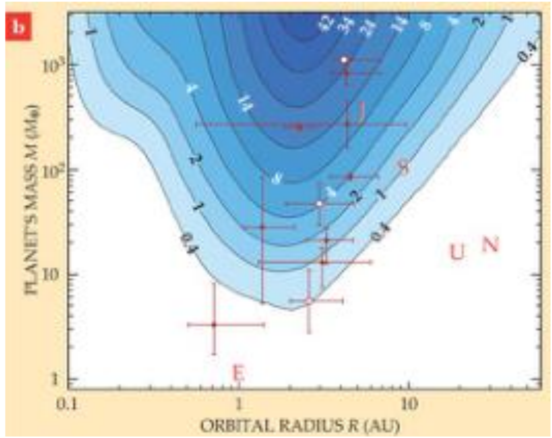


1st published planet in binary system OB130341LBb (Gould et al. 2014). (The planet in OB06284 was not recognized until later.)

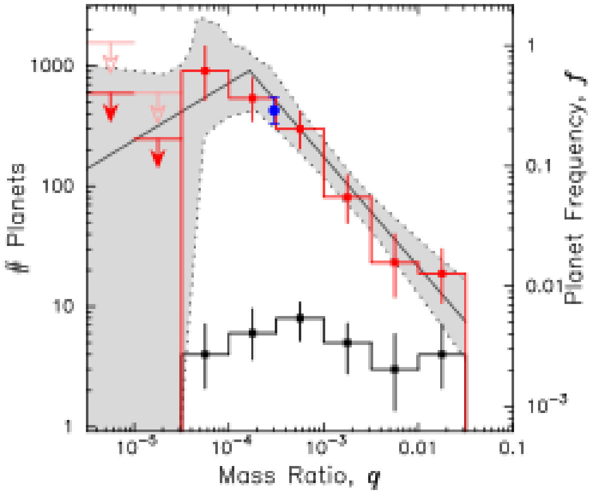
Demographics Results (see Suzuki's Wednesday talk for more)



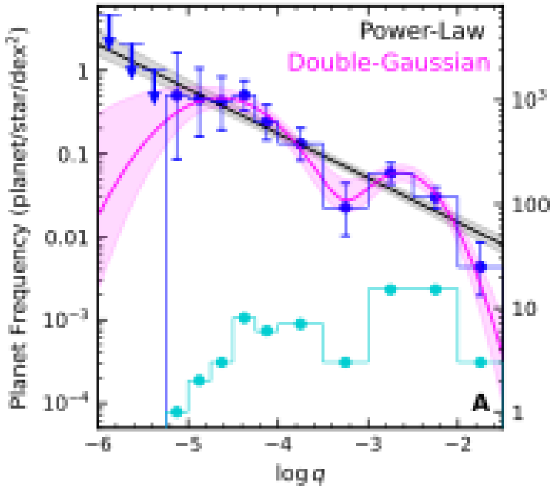
Most stars do not host cold Jupiters (Gaudi+2002)



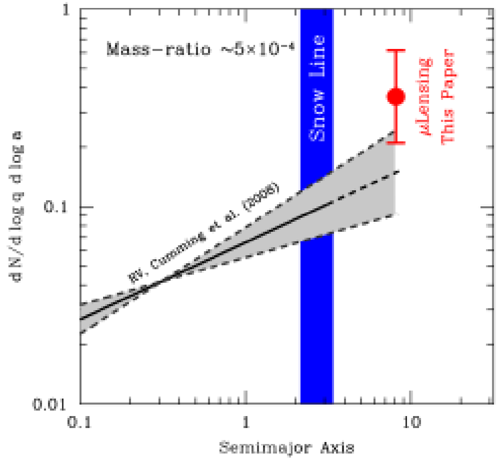
≥ 1 cold planet per Milky Way Star (Cassan+2012)



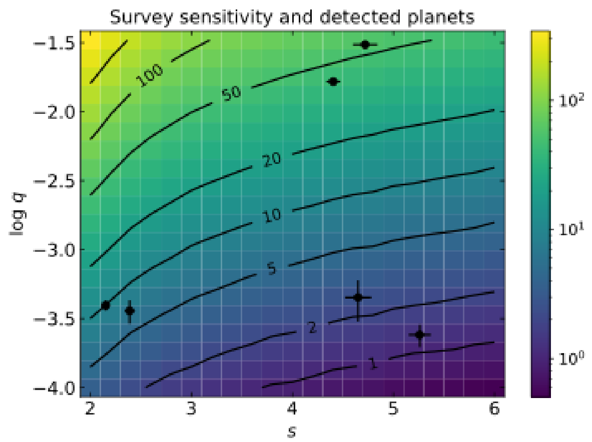
Cold exoplanet mass ratio function precludes predicted sub-Saturn desert at ~3 AU (Suzuki+16,18)



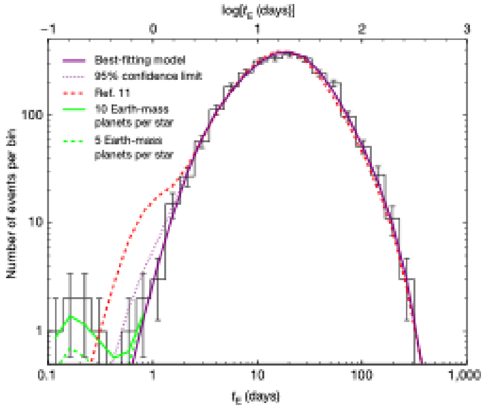
KMTNet Cold exoplanet mass ratio function down to $q < 10^{-5}$ sees hint of Saturn-Jupiter mass ratio gap (Zang+25)



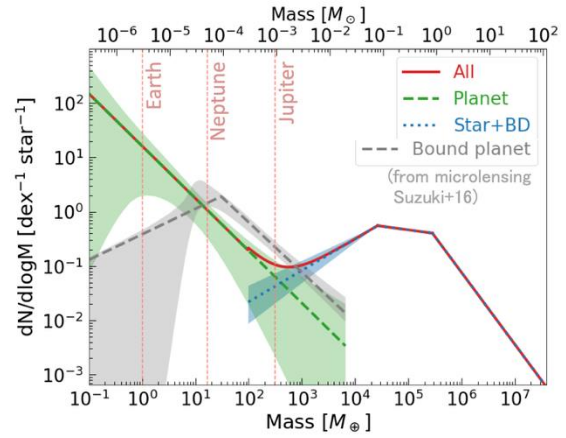
Neptunes and Jupiters are common beyond the snow line (Gould+2010)



Ice Giants are Common (Poleski+2021)

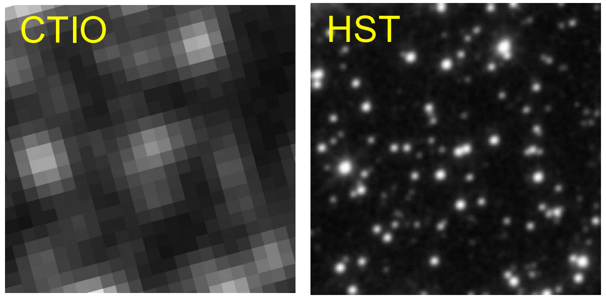


High-mass free-floating/wide planets are rare (Mróz+2017)

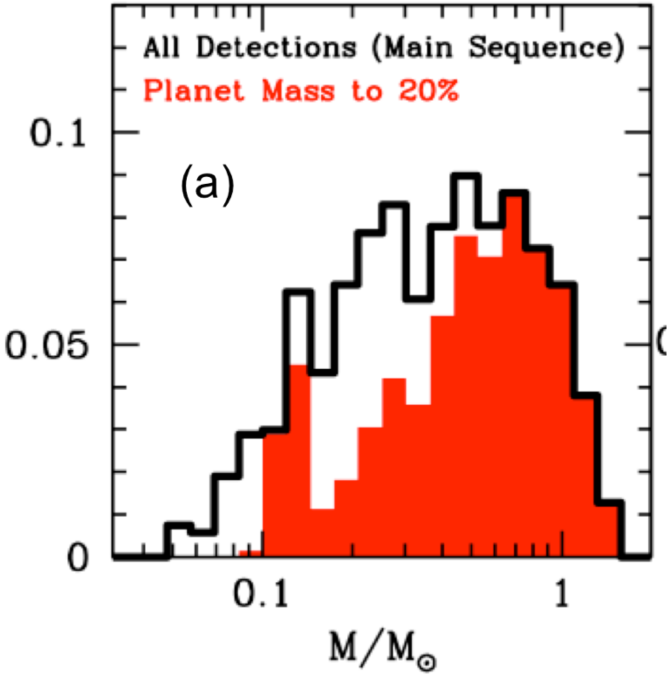


Low-mass free-floating/wide planets are the most common (Sumi+2023)

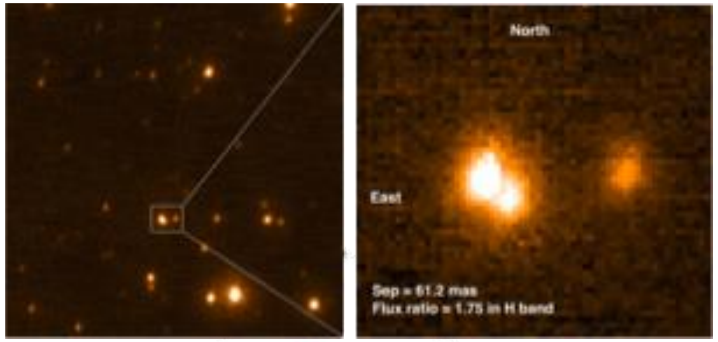
Mass Measurements from High Resolution Imaging a Key Feature of Roman

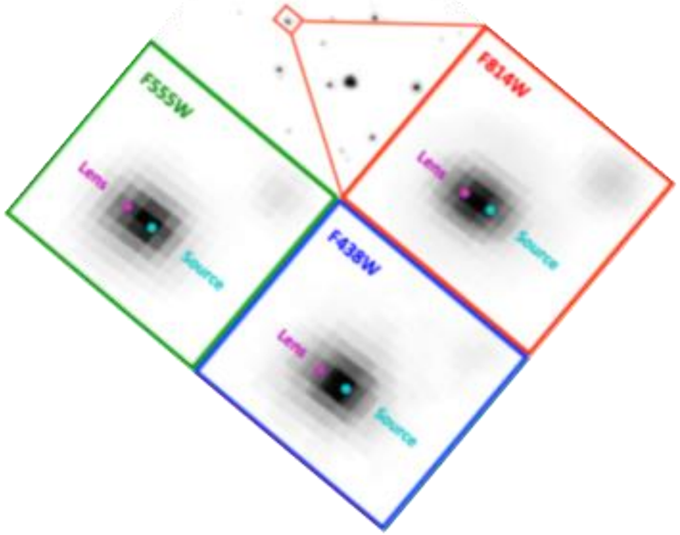


High Angular Resolution images indicate that bulge main sequence stars are not resolved by ground-based telescopes. This adds noise to ground-based photometry and prevents detection of host stars



Bennett, Anderson & Gaudi (2007) and Bennett+2006 presented methods to use high angular resolution images to detect microlens exoplanet host star mases



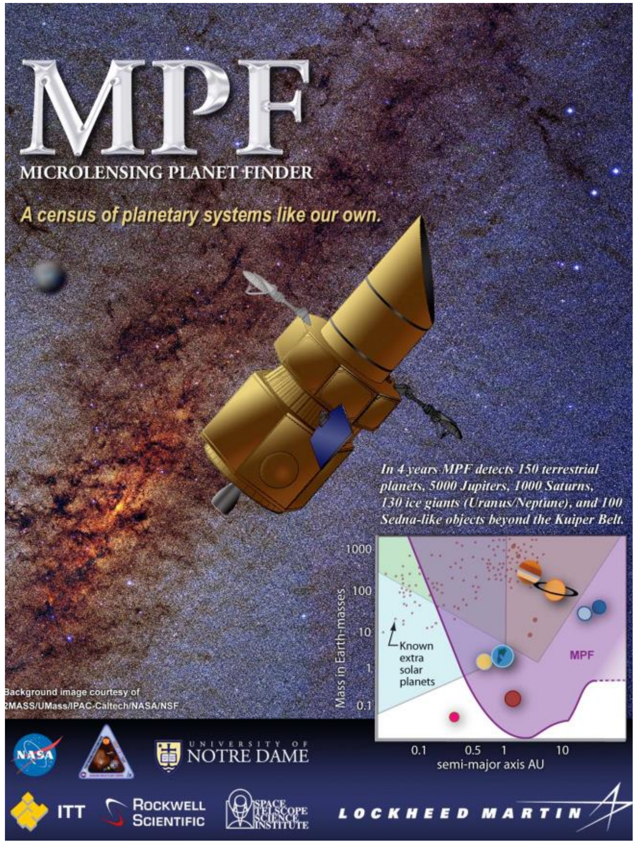


The first exoplanet host, OB05169L was detected separating from the source, allowing mass measurements (Batista+2015, Benentt+2015)

Mission Concepts: GEST ⇒ MPF ⇒ WFIRST ⇒ Roman

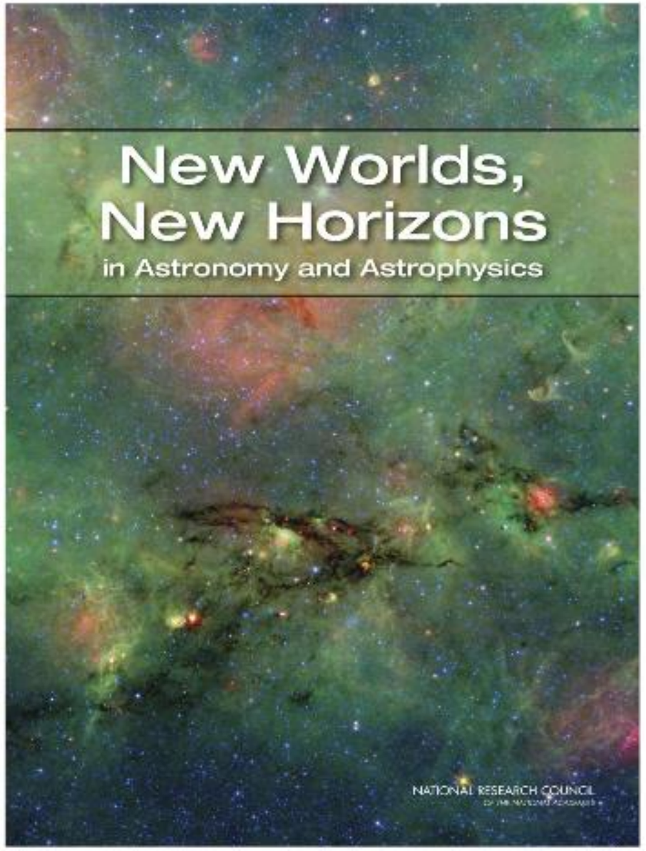
Galactic Exoplanet Survey Telescope (GEST)

- Large CCD focal plane
- Discovery proposal in 2000, MidEx proposal w/ dark energy program in 2001



Microlensing Planet Finder (MPF)

- Large IR detector focal plane
- NASA GSFC management
- Discovery Proposals in 2004, 2006, Decadal Survey 2010



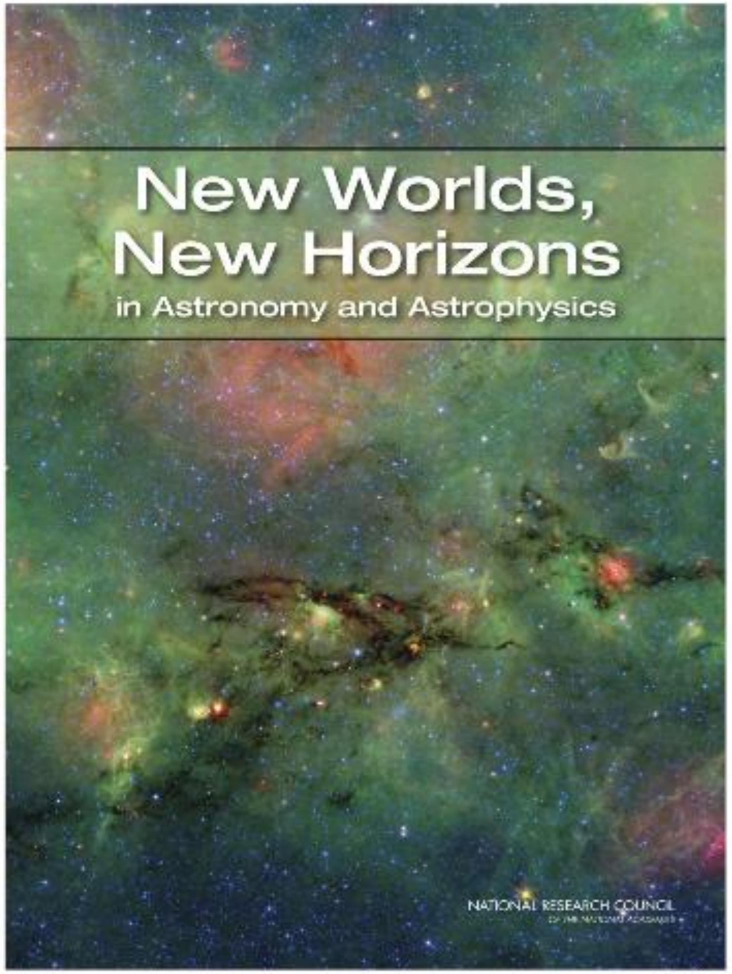
Astro2010 Decadal Survey Top Recommendation:

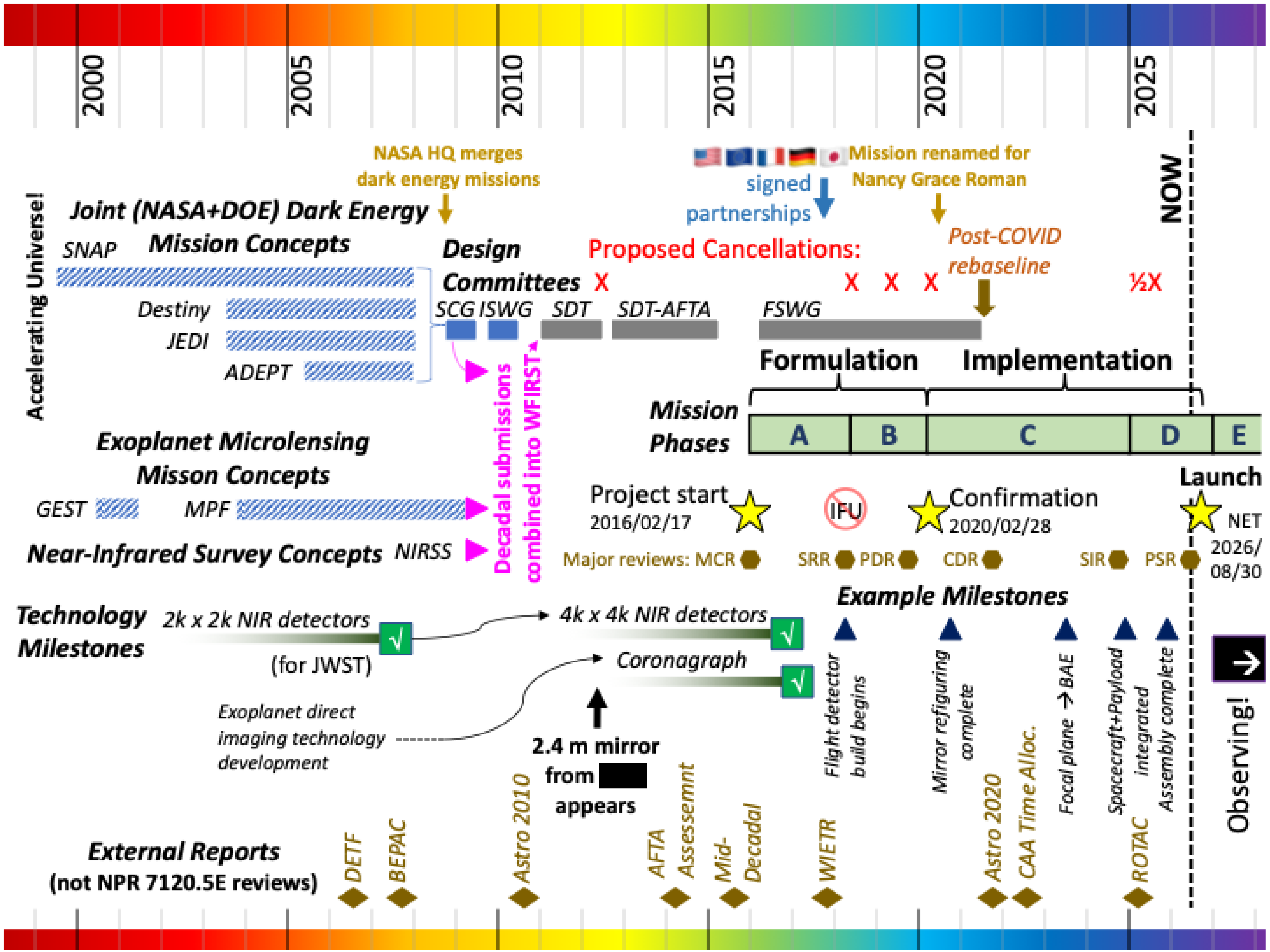
MPF + JDEMΩ + NIRSS = WFIRST

-> Nancy Grace Roman Space Telescope

2010 Decadal Survey Recommendation

- Wide Field Infrared Survey Telescope (WFIRST)
- #1 recommendation of the 2010 Decadal Survey for a large space mission.
- Notional mission, based on several different inputs, including:
  - JDEM-Omega (Gehrels et al.)
  - MPF (Bennett et al.)
  - NISS (Stern et al.)
- Three equal science areas:
  - Dark energy (SNe, Weak Lensing, BAO).
  - Exoplanet microlensing survey.
  - GO program (including a "survey our galaxy and other nearby galaxies")





Credit:
Chirs Hirata

From WFIRST to Roman to Launch!

Some milestones:

- Late 2020: NASA put together two science definition teams to come up with "Design Reference Missions"
- 2011-2012 Original Science Definition Team (Green et al. arXiv:1208.4012)
    - DRM1 (1.3m)
    - DRM2 (1.1m)
- 2012-2015 AFTA/WFIRST Science Definition Team (Spergel et al. 2015; arxiv: 1503.03757)
    - Studied the application of two telescopes donated to NASA by a government agency (which shall not be named) for WFIRST
        - Two 2.4m space-qualified telescopes.
        - Mirrors and spacecraft assemblies.
    - Also considered a coronagraph and serviceability.
- 2016-2021 Formulation Science Working Group
- Cancelled in 2018, 2019, and 2020 by the first Trump administration, funding restored by Congress.
- Feb 2020: Baseline schedule set launch for Oct 2026
- May 2020, WFIRST was renamed Roman.
- May 2021: COVID-19 rebaseline slipped the launch by 7 months with concurrent increase in budget. Set lunch date 2027
- Roman has stayed ahead a schedule and under budget!
- Launch August 30, 2026!

Postdoc Job Opportunities at OSU!

- We will be hiring two postdocs to work on the Roman Galactic Bulge Time Domain Survey starting this fall!
- Duties:
  - Contribute to the Roman Galactic Exoplanet Survey (RGES) Project Infrastructure Team (PIT) through
    - Development of gravitational microlensing theory
    - Analysis of Roman commissioning and early GBTDS observations,
    - Development and support of event-analysis and planet occurrence-rate pipelines
  - Supporting the Roman ecosystem and science community
  - Mentor junior researchers at OSU
- Focus will be on microlensing, but if you have expertise in transits, time-domain astronomy, gravitational lensing, large-scale Galactic surveys, or Milky Way population modeling, you are also strongly encouraged to apply!

Let us know if you have questions about microlensing, Roman, or anything else!

Thanks, and have a great workshop!