# Exoplanetary Microlensing

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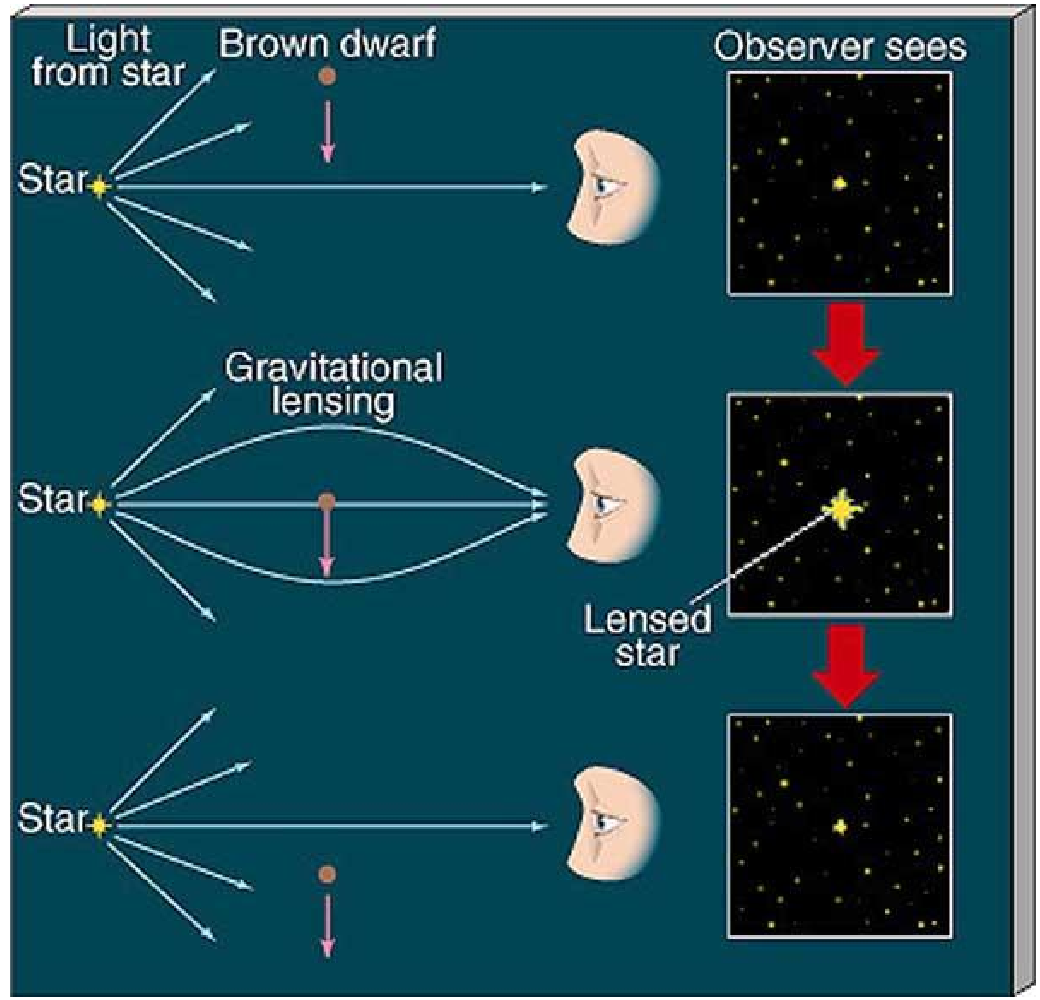
**11 July 2011**

**With material from Dave Bennett, Scott Gaudi, and others.**

# Part 1. Microlensing Phenomenology

- **When the path of a foreground star crosses near a background star, its gravity bends and focuses the light from the background star.**
- **The background star is the 'source', and the foreground star is the 'lens'.**
- **The result is a time-dependent magnification of the light we receive from the 'source' star.**



# Stellar microlensing was predicted by Einstein in 1912

In the preface to his 1936 paper in *Science*, Einstein wrote

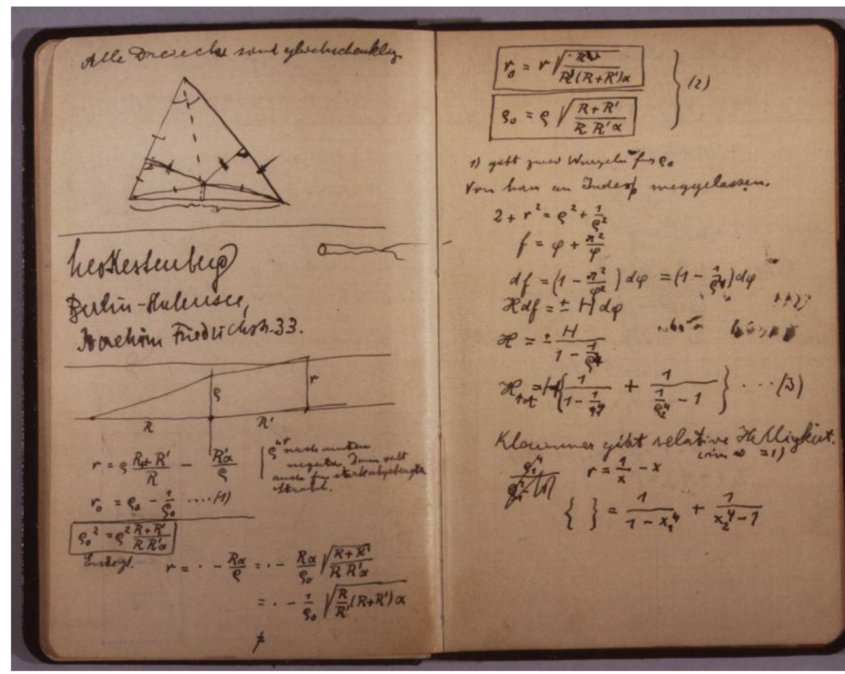
"Some time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish".

In a private letter to the editor, he wrote

"Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy"

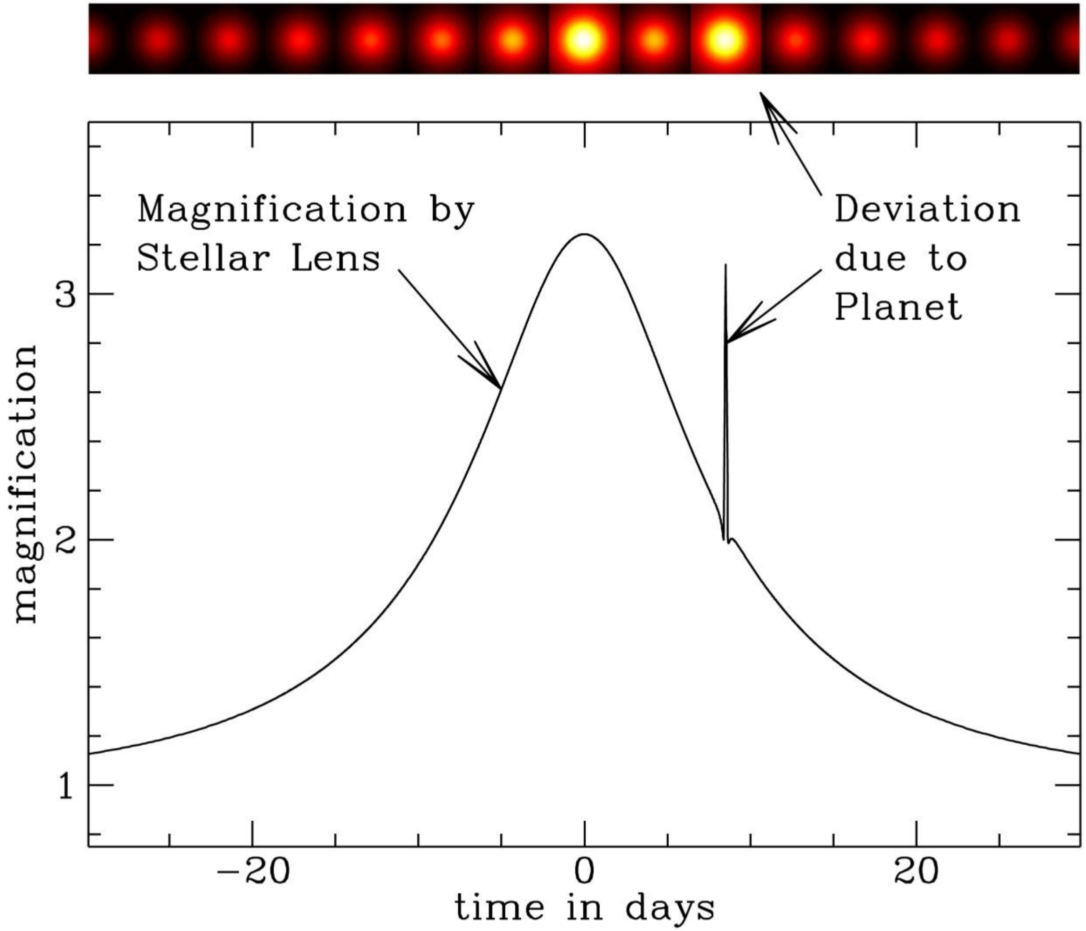
Gravitational lensing was observationally confirmed in 1979…

**Notebook entry from 1912**



# Stellar and exoplanetary microlensing

- **Typical time scale for a stellar event is 1 to 2 months.**
- **If the ’lens’ star has a planet, its gravity may also contribute to lensing the light from the ’source’.**
- **This produces a secondary peak in the light curve.**
- **Typical exoplanetary deviation lasts only hours to days.**



# Microlensing movies

- moa53_anim1.mpeg
- mag4_dfischer.mov

*"I don't understand.  You are looking for planets you can't see around stars you can't see."*

Debra Fischer

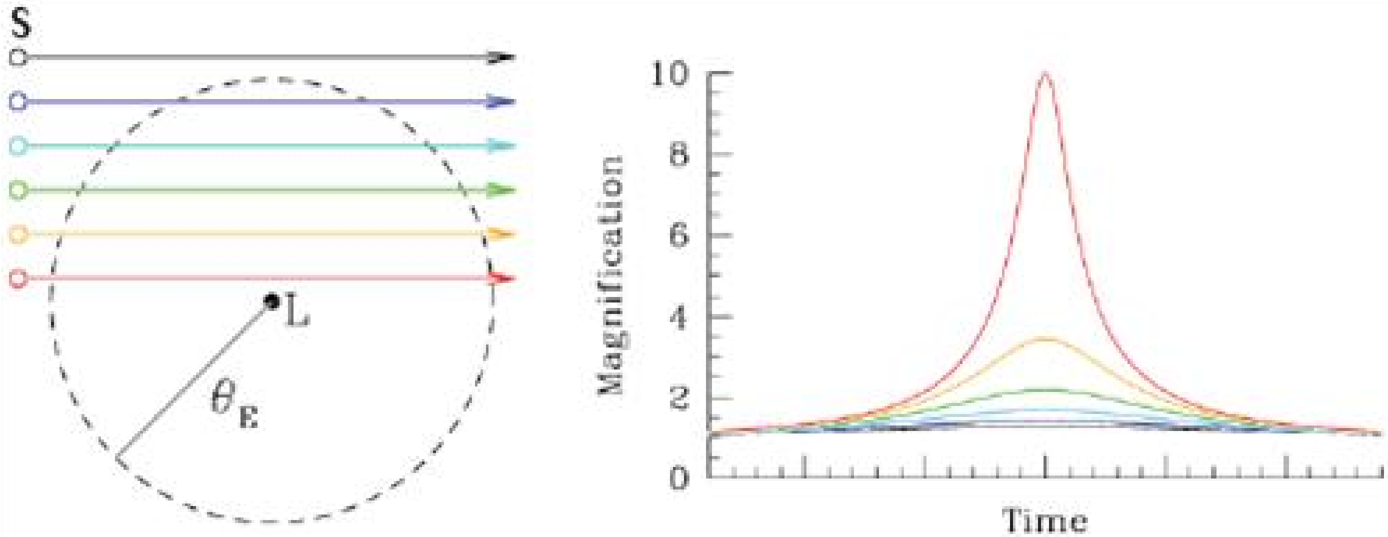
RV planet hunter (now at Yale University)

2000 Microlensing Workshop

# Part 2. Basic microlensing concepts

- Magnification
- Images
- Angular Einstein radius is the lensing star's 'zone of influence'
  - Sets the angular scale of microlensing
  - Typically ~few milliarcsec (mas)
  - 1 mas is the angular size of a human hair seen from 10 kilometers away
- Geometry of microlensing

# Magnification and impact parameter




S … source object
L … lens object
$\theta_E$ … Einstein ring radius

$$\theta_E = \left( \frac{4GM}{c^2} \, \frac{d_{LS}}{d_L d_S} \right)^{1/2}$$

if source much further away than lens $(d_{LS} \approx d_S)$

$$\theta_E \approx 0.1 \left( \frac{M \text{ in } M_\odot}{d_L \text{ in parsecs}} \right)^{1/2} \text{arcsec}$$

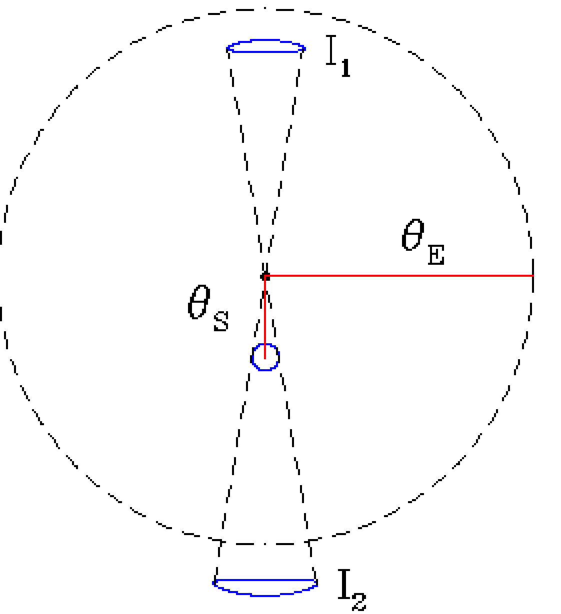
for galaxy with $10^{15} M_\odot$ at 1 Gpc, $\theta_E \approx 100$ arcsec,
for star with 1 $M_\odot$ at 1 kpc, $\theta_E \approx 3$ milliarcsec

**$d_L$ = distance to lens**
**$d_S$ = distance to source**
**$d_{LS}$ = lens to source distance = $d_S$ - $d_L$**

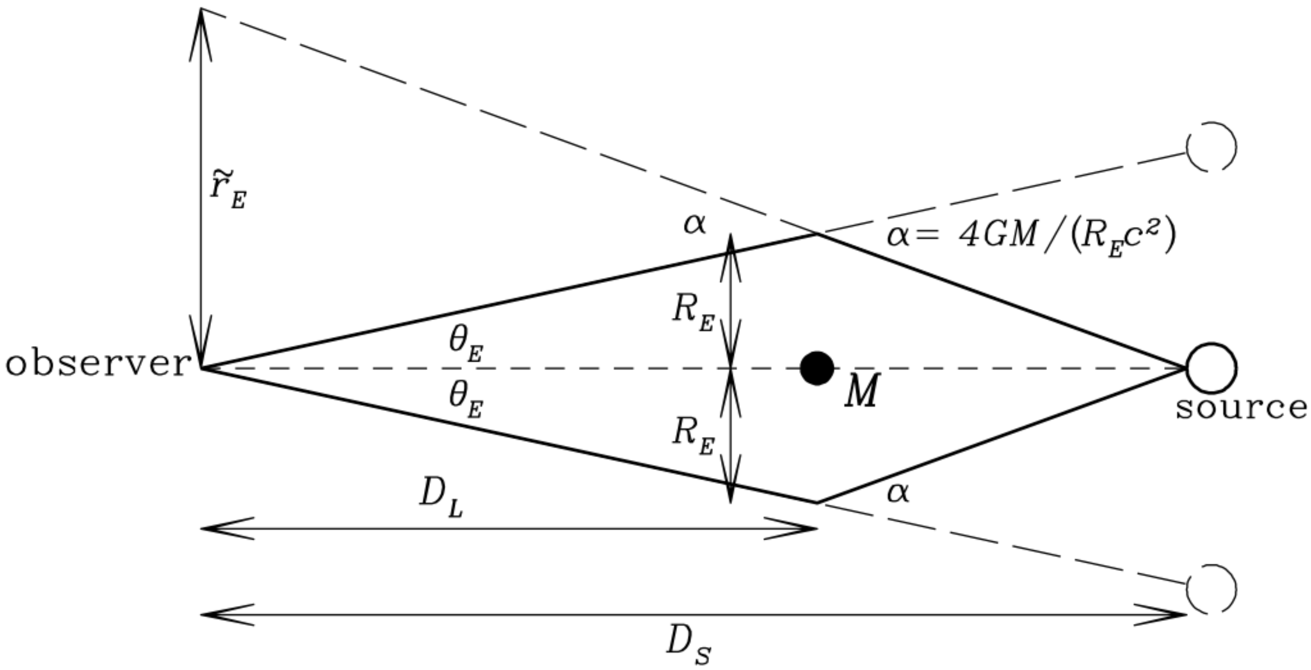
# Major and minor images

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_S - d_L}{d_L d_S}}$$

- $\theta_E$ is the angular Einstein radius
  - $d_S$ and $d_L$ are the distances to the source and lens stars
  - M is the mass of the lens star
- $I_1$ is the minor image, inside the Einstein radius.
- $I_2$ is the major image , outside the Einstein radius.
- $\theta_S$ is the 'impact parameter', the angular distance between source (blue circle) and lens (black dot).
- The images are unresolved; only the sum of their flux is observed.



# Lens System Geometry




**The formula for the deflection angle α is from General Relativity, the rest is elementary geometry!**

$$R_E = \theta_E d_L$$

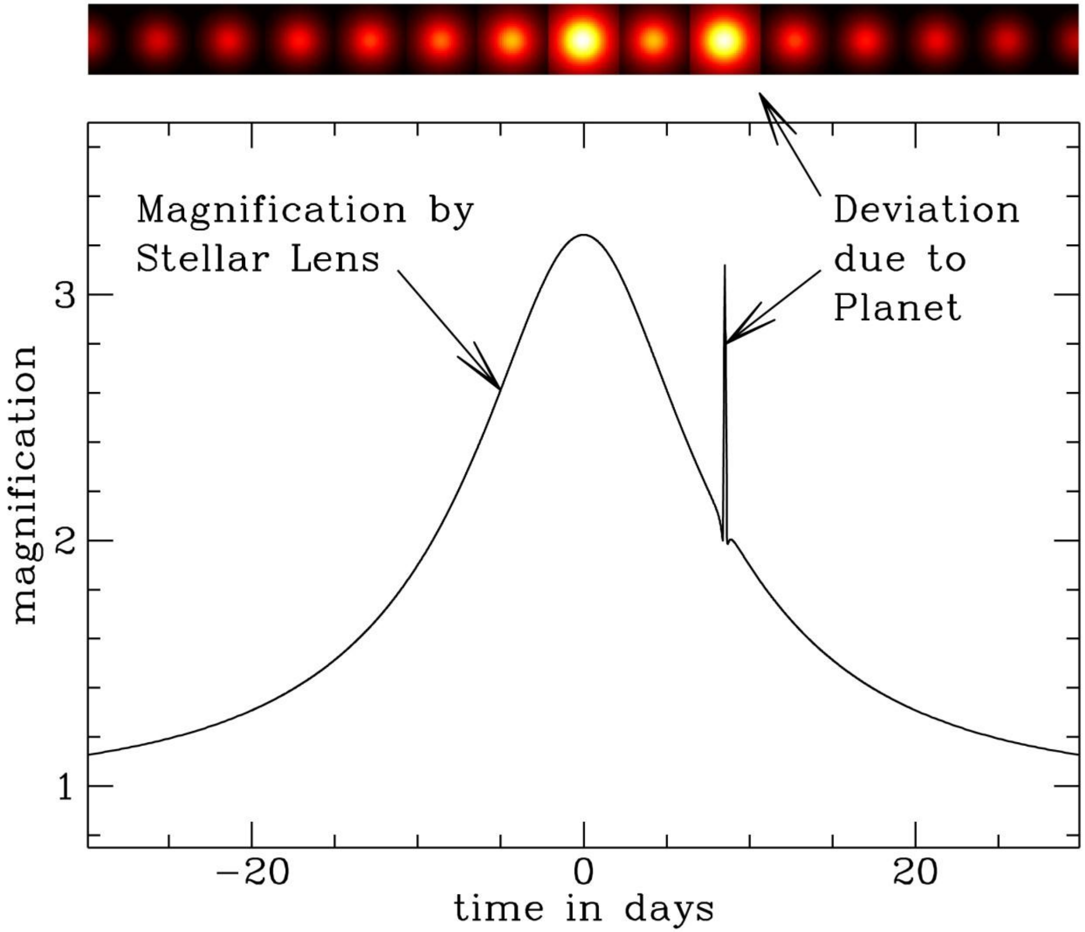
$$\tilde{r}_E = \alpha\, d_L$$

Projected Einstein radius $\tilde{r}_E$ is determined from the microlensing parallax effect (due to Earth's orbital motion).

Mass of the lensing object is determined:

$$\alpha = \frac{4G M_L}{R_E c^2} = \frac{4G M_L}{c^2 \theta_E d_L} = \frac{\tilde{r}_E}{d_L} \qquad M_L = \frac{c^2}{4G}\theta_E \tilde{r}_E$$

# Part 3. Exoplanets




The light curve is the only observable: the magnification as a function of time.

# From light curve to planet parameters

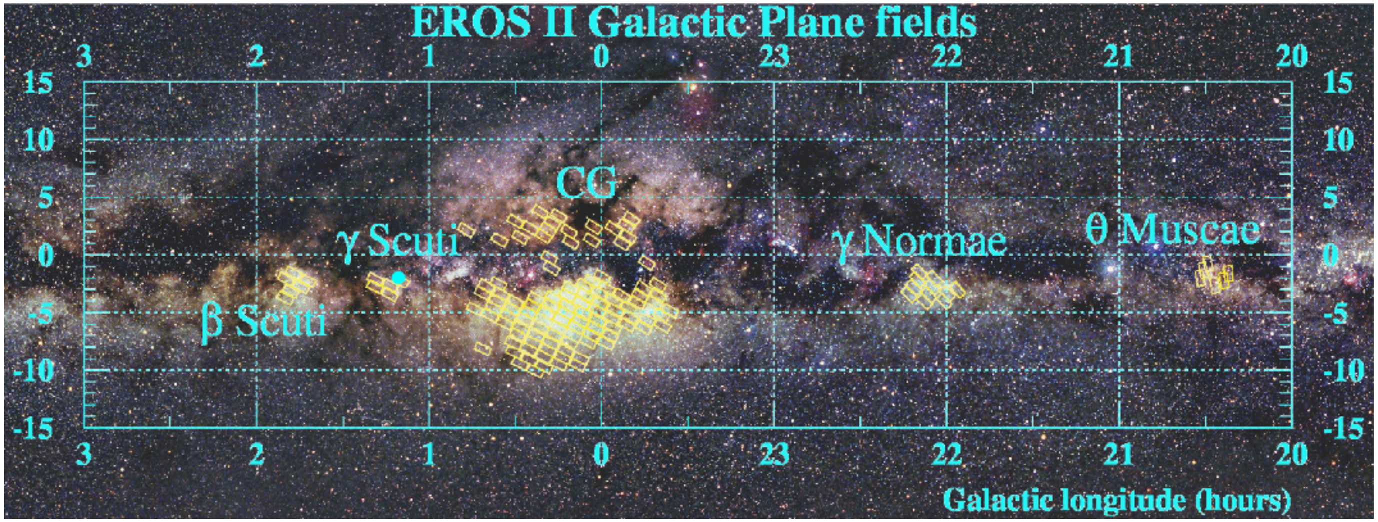
- The ‘widths’ of the star and planet peaks in the light curve are proportional to the square root of the respective masses, so the planet-to-star mass ratio comes from the ratio of widths.
- The time delay of the planet peak with respect to the stellar peak gives the projected separation of the lensing star and its planet, in units of the Einstein radius

$$R_E = d_L \theta_E = d_L \sqrt{\frac{4GM}{c^2} \frac{d_S - d_L}{d_L d_S}}$$

# Advantage of observing the lens star

- With HST we can sometimes resolve the ‘lens’ star, and estimate its distance and mass.
- The estimate of the lensing star’s mass allows us to extract the planet mass from measurement of the mass ratio $M_{planet}/M_{star}$
- With the mass and distance estimates, the Einstein radius is determined, and we can get an absolute projected separation.

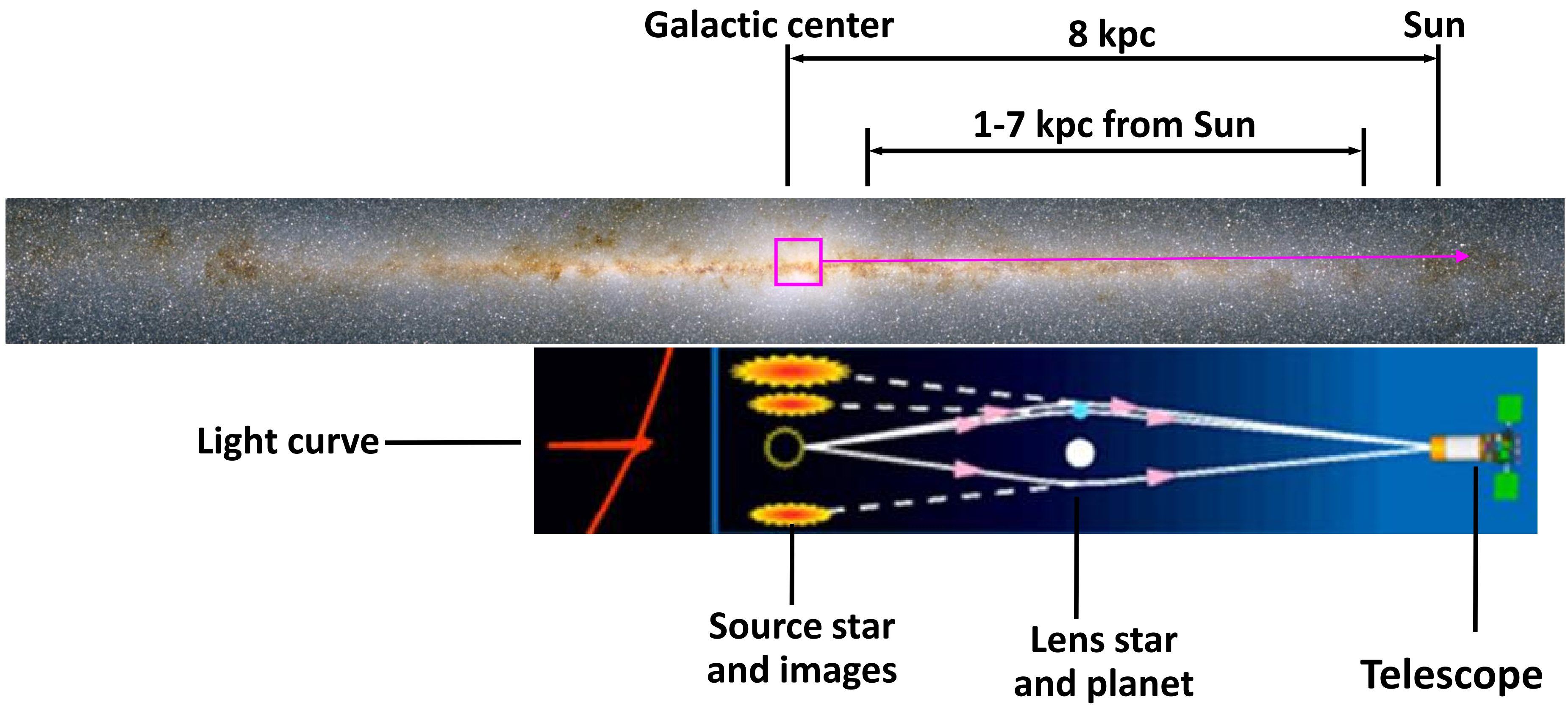
# Part 4. Exoplanet surveys, real and imagined




- Exoplanetary microlensing is a low probability phenomenon.
- In order to monitor many potential events, we need
  - A Wide-field survey
  - Pointed at a region that is dense in stars, e.g. the galactic bulge
- High-cadence continuous sampling

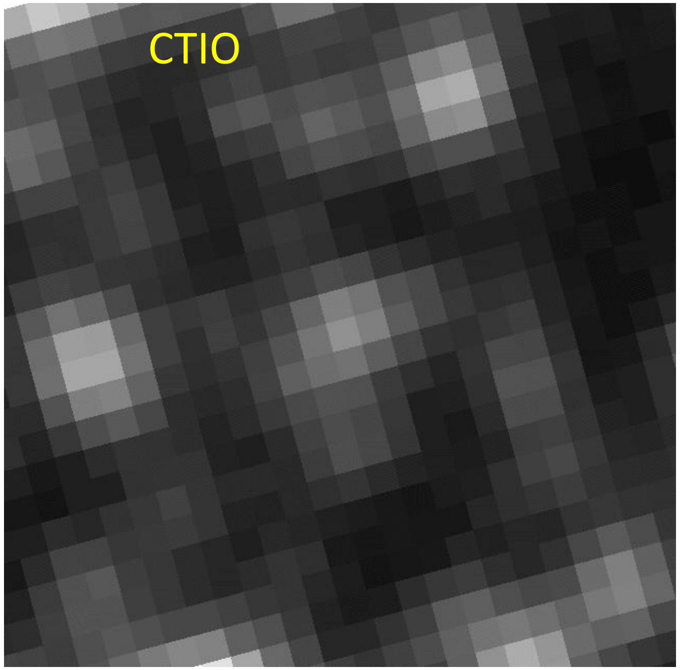
- IR telescope can see farther through dust
- Most stars are M stars, which strongly radiate in the IR
- **Typical 'Source' star is a giant or dwarf in the bulge.**
- **Typical 'Lens' star is a red main-sequence star in the foreground disk or bulge**

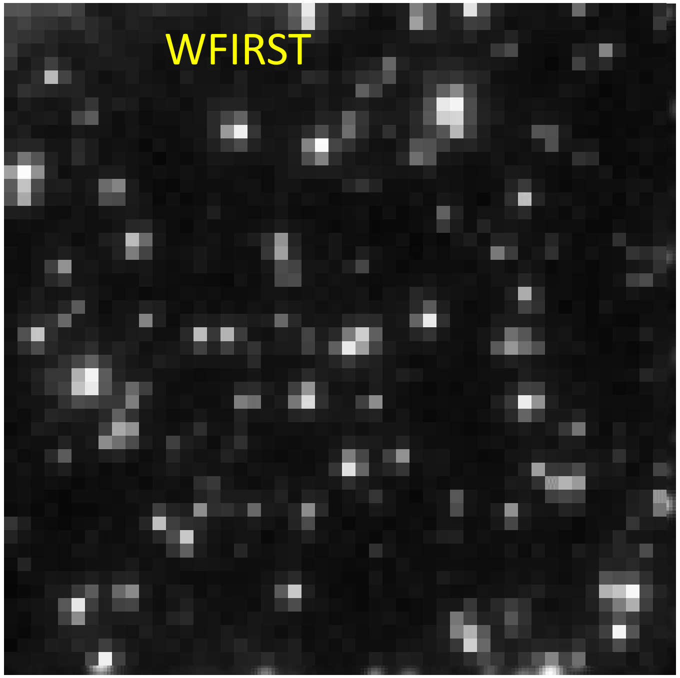
# The Best Microlensing Target Fields are in the Galactic Bulge




**Monitor hundreds of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.**

# Why do we need a space-based survey?



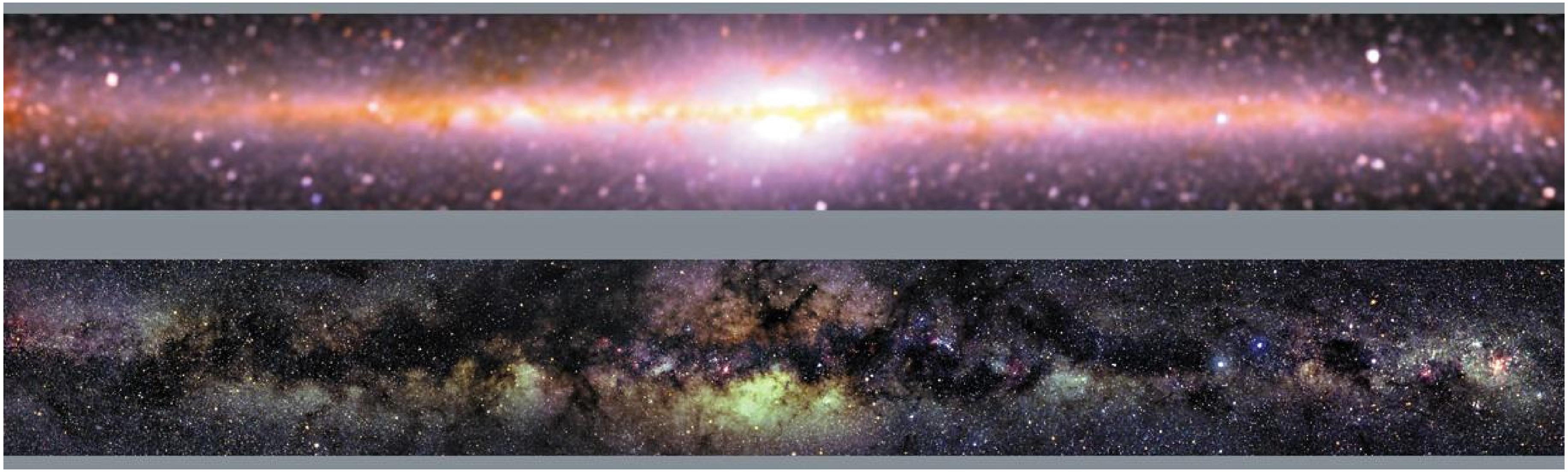




- **Space-based imaging is needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection**
- **High Resolution + large field + 24 hr duty cycle => WFIRST Microlensing program**
- **Space observations needed for sensitivity at a range of separations and mass determinations.**

# Infrared Observations Are Best

The central Milky Way:

Near-infrared

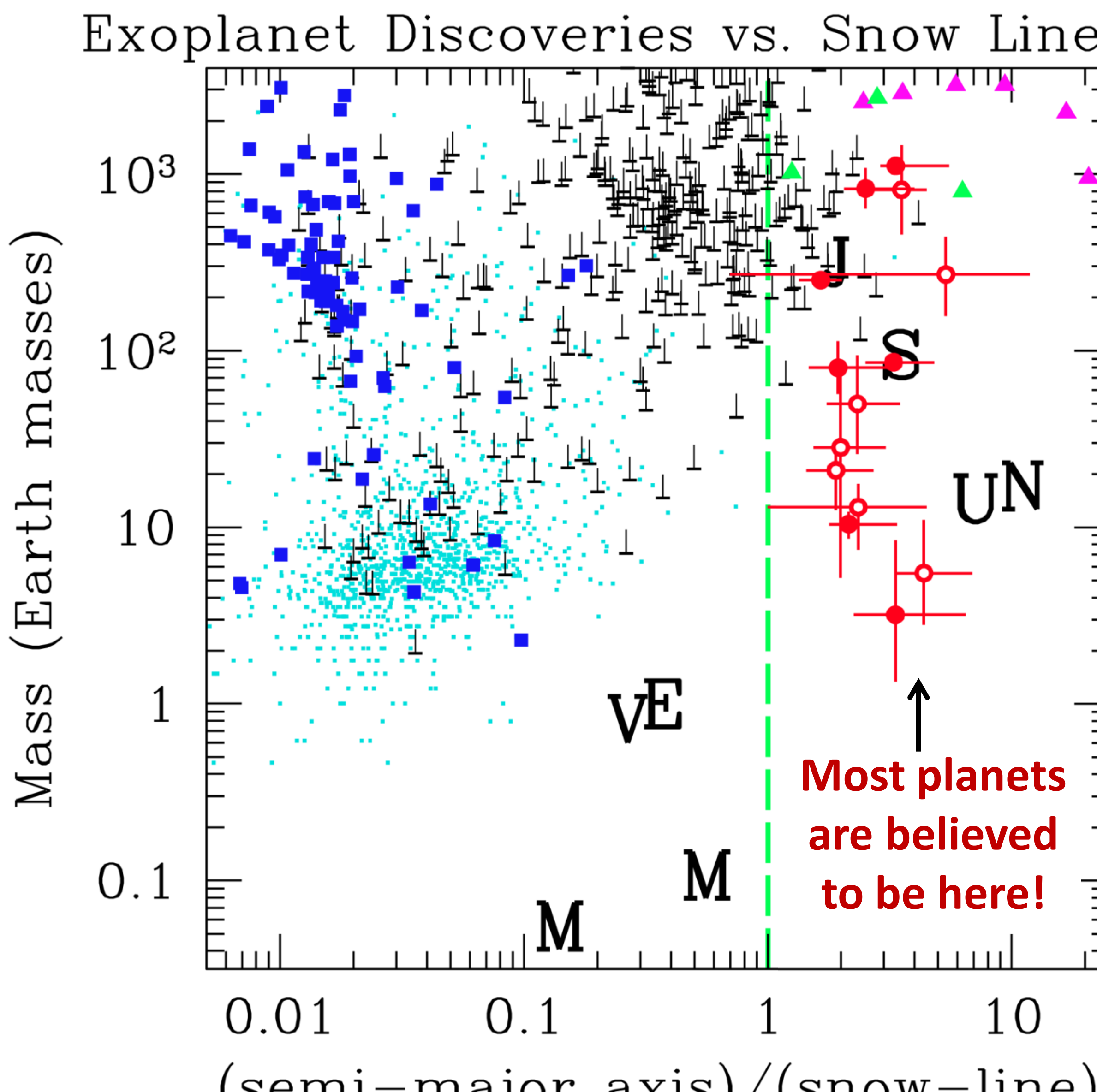


Optical

**Dust obscures the best microlensing fields toward the center of the Galaxy**

# Part 5. Exoplanet Science

- "Snow-line" defined to be 2.7 AU ($M/M_{\odot}$)
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles
- Kepler candidates are cyan dots
- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



# 12 known microlensing exoplanets

**Candidates detected by microlensing** update : 05 February 2011

<< Back to the Index Catalog | Data Catalog | Histograms | Correlation Diagrams | Planet Table

( sorted by **increasing planet alphabetical order** )

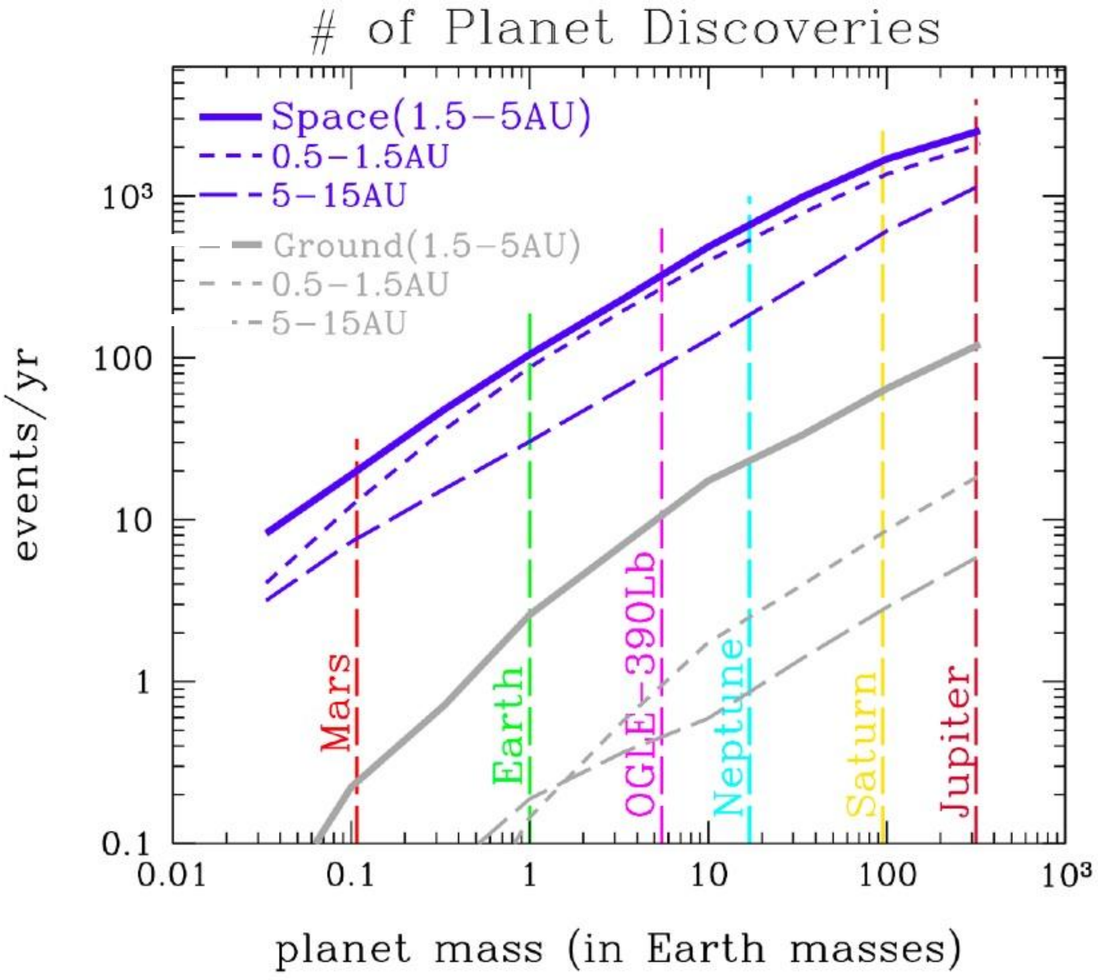
**Statistics :** 11 planetary systems / 12 planets / 1 multiple planet systems

**Planet Data** ( - ALL FORMATS ) MORE DATA >>

| PLANET | M. ($M_{Jup}$) - stats | RADIUS ($R_{Jup}$) - stats | PERIOD (days) - stats | SEM-MAJ AXIS (AU) - stats | ECC. | INCL. (deg) - stats | STATUS | DISCOV. (year) | UPDATE |
|---|---|---|---|---|---|---|---|---|---|
| MOA-2007-BLG-192-L b | 0.01 | - | - | 0.66 | - | - | R | 2008 | 29/09/10 |
| MOA-2007-BLG-400-L b | 0.9 | - | - | 0.85 | - | - | S | 2008 | 06/12/10 |
| MOA-2008-BLG-310-L b | 0.23 | - | - | 1.25 | - | - | S | 2009 | 10/08/09 |
| MOA-2009-BLG-319 b | 0.157 | - | - | 2 | - | - | S | 2010 | 12/10/10 |
| MOA-2009-BLG-387L b | 2.6 | - | 1970 | 1.8 | - | - | R | 2011 | 05/02/11 |
| OGLE-05-071L b | 3.5 | - | ~ 3600 | 3.6 | - | - | R | 2005 | 10/04/08 |
| OGLE-05-169L b | 0.04 | - | 3300 | 2.8 | - | - | S | 2005 | 12/04/06 |
| OGLE-05-390L b | 0.017 | - | 3500 | 2.1 | - | - | R | 2005 | 12/04/06 |
| OGLE-06-109L b | 0.727 | - | 1790 | 2.3 | - | 64 | R | 2008 | 24/11/09 |
| OGLE-06-109L c | 0.271 | - | 4931 | 4.5 | 0.15 | 64 | R | 2008 | 24/11/09 |
| OGLE-2007-BLG-368L b | 0.0694 | - | - | 3.3 | - | - | R | 2008 | 08/12/09 |
| OGLE235-MOA53 b | 2.6 | - | - | 5.1 | - | - | R | 2004 | 10/06/06 |

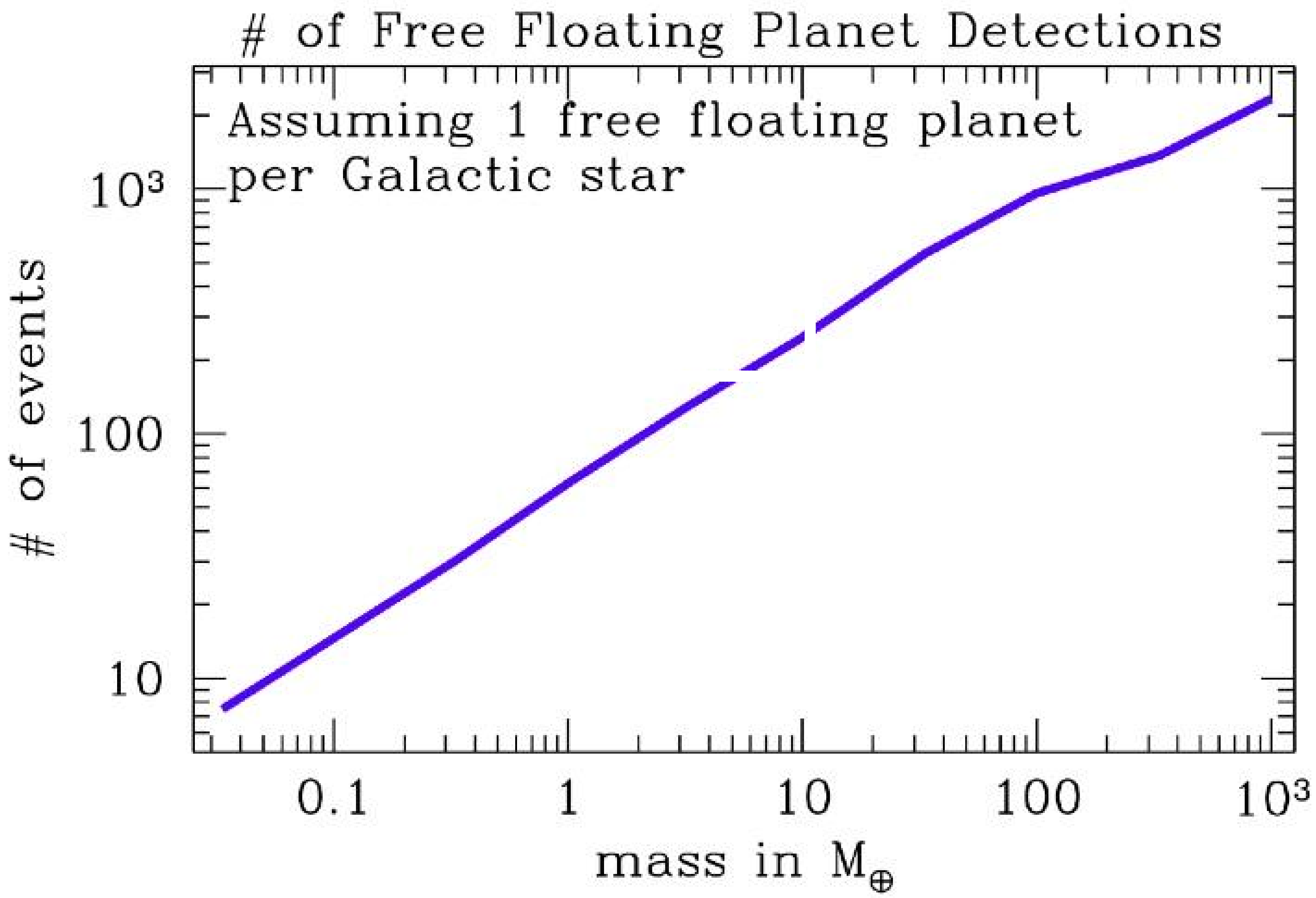
# WFIRST planet discoveries

- The number of expected WFIRST planet discoveries per 9-month observing season as a function of planet mass.
- Microlensing is most sensitive to planets beyond the 'snow line', 1 to 5 AU.
- This is where planets are believed to form most efficiently.




Detection sensitivity rises with mass

# WFIRST detection of free-floating planets




Detection sensitivity rises with mass

# Free-floating planets!

- Bennett  et al., Nature, May 2011
- Survey found 10  Jupiter mass free–floating planets.
- Results imply  that there are ~2 of these per star!

# Why is microlensing important for exoplanet science?

- Measuring the ‘demographics’ of planets beyond the ‘snow line’ – out past 1 AU.
- I.e., what is the distribution of planet masses and separations, as a function of stellar type?
  - RV is sensitive to close-in planets more massive than Neptune.
  - Kepler is sensitive to planets inward of 1 AU.
- Frequency of habitable earth-like planets
- Frequency of free-floating (ejected?) planets
- Frequency of massive moons
- All these items are important to test planet formation theories.

# Part 6. You and the future of microlensing

- From Scott Gaudi's article in the Exoplanets book: "In general, no robust, practical, universal, and efficient algorithm exists for fitting an arbitrary binary lens light curve in an automated way that is not highly user-intensive…there is an urgent and growing need for the development of (more automated) analysis software."

# 2011 Sagan Exoplanet Summer Workshop

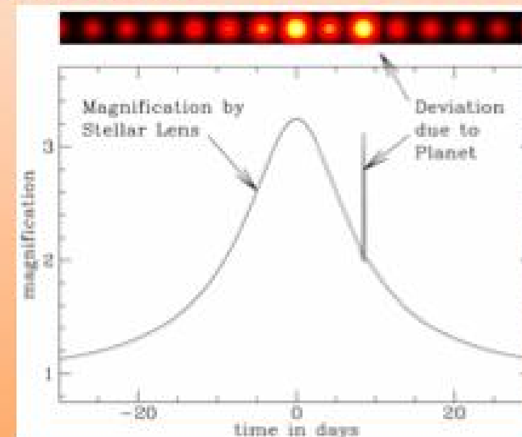
# Exploring Exoplanets with Microlensing

## July 25-29, 2011, California Institute of Technology

**June 7, 2011: Early Registration Fee deadline**

***Topics include:***

- History of Microlensing, Theory, Detection and Follow-up
- Introduction to Microlensing Photometric Techniques
- HST/AO Data Reduction
- Microlensing with Space-based Telescopes
- Modeling of Microlensing Data
- Extracting the Physical Parameters of Planetary Events
- Null Results and Detection Efficiency
- Future Prospects and Challenges of Microlensing




***Hands-on Sessions*** during the week will allow attendees to work with microlensing data.

***Scientific Organizing Committee***

Dave Bennett (University of Notre Dame)
Ian Bond (Massey University, New Zealand)
Subo Dong (Institute for Advanced Study)
Scott Gaudi (Ohio State University)
Stephen Kane (NExScI)
Rachel Street (LCOGT)
Takahiro Sumi (Nagoya University)

http://nexsci.caltech.edu/workshop/2011

# References

- ‘Exoplanetary Microlensing‘ by Scott Gaudi, in Exoplanets, ed. Sara Seager, University of Arizona Press, 2010. Also on astro-ph at http://arxiv.org/abs/1002.0332
- Papers on exoplanet detection efficiencies with ground based microlensing data (provided by Dave Bennett):

Rhie et al. (2000): first detection efficiency calculation - using a single event, but with sensitivity down to an Earth-mass. Uses a simple and relatively fast method: http://adsabs.harvard.edu/abs/2000ApJ...533..378R

Gaudi & Sackett (2000): 1st paper on planetary detection efficiencies - laying out the method: http://adsabs.harvard.edu/abs/2000ApJ...528...56G

Albrow et al. (2000): applying Gaudi method to a single event. http://adsabs.harvard.edu/abs/2000ApJ...535..176A

Gaudi et al. (2002): Full analysis of 5 years of PLANET data: http://adsabs.harvard.edu/abs/2002ApJ...566..463G

See also Albrow et al. (2001) http://adsabs.harvard.edu/abs/2001ApJ...556L.113A

Bond et al. (2002): Limits on planets in 3 high magnification limits, including the first limits on planets orbiting a star in another galaxy. http://adsabs.harvard.edu/abs/2002MNRAS.333...71B

Yoo et al. (2004): Limits on planets in a single high magnification event: http://adsabs.harvard.edu/abs/2004ApJ...616.1204Y

Dong et al. (2006): Limits on planets in a single high magnification event: http://adsabs.harvard.edu/abs/2006ApJ...642..842D

Sumi et al. (2010): A planet discovery paper, with a small section on relative detection efficiencies: http://adsabs.harvard.edu/abs/2010ApJ...710.1641S

Gould et al. (2010): Analysis of a uniform sample of high magnification events: http://adsabs.harvard.edu/abs/2010ApJ...720.1073G

# Appendix

# Scott Gaudi's microlensing movies

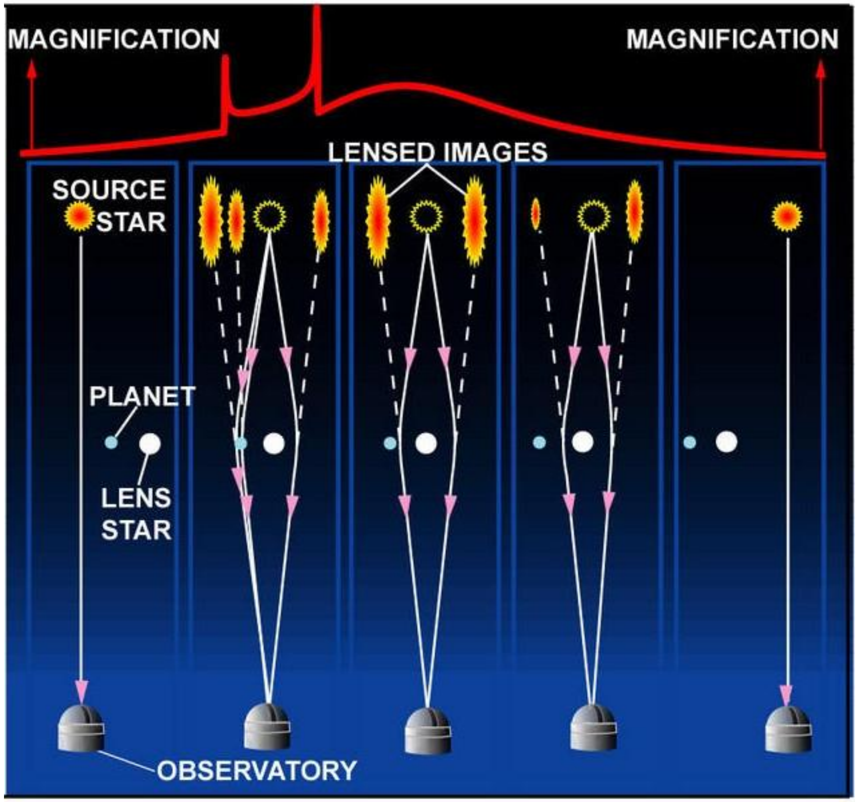
- Single (point) lens
- Binary lens -- major image
- Binary lens -- minor image

- Three parameters describe the planet orbiting the lens star
  - Mass ratio $q = M_{planet}/M_{star}$
  - Projected separation in units of Einstein radius

    $d = s/R_E$, where s is projected separation
  - Planet position angle
- These movies show how each parameter affects the observed microlensing event.

# Review: the Physics of Microlensing

- Foreground "lens" star + planet bend light of "source" star
- Multiple distorted images
  - Total brightness change is the only observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, $R_E$



# Backup

# Introduction: 6 known methods of finding planets

- Astrometric wobble
- Radial velocity (Doppler effect)
- Transit
- Timing (pulsars, transits)
- Direct imaging
- Microlensing

# Exoplanet characterization

- Mass ratio of the exoplanet to the lensing star
- Projected star-planet separation (in units of Einstein radius)
- Angle between source trajectory and lens star-planet axis (in units of angular Einstein radius)
- If the lens star is observed, we can get absolute mass and separation
- In rare cases it’s possible to solve the planet’ orbit!
- Lensing happens only once, we don’t get to come back and see the planet again.