Exoplanet Discovery Methods

(1) Direct imaging

(2) Astrometry → position wobbles

(3) Radial velocity → velocity wobbles

(4) Transits → “winks”

Today: How to find Earths

(5) Space Transits (Hot Earths)

(6) Gravitational microlensing (Cool Earths)

Later:

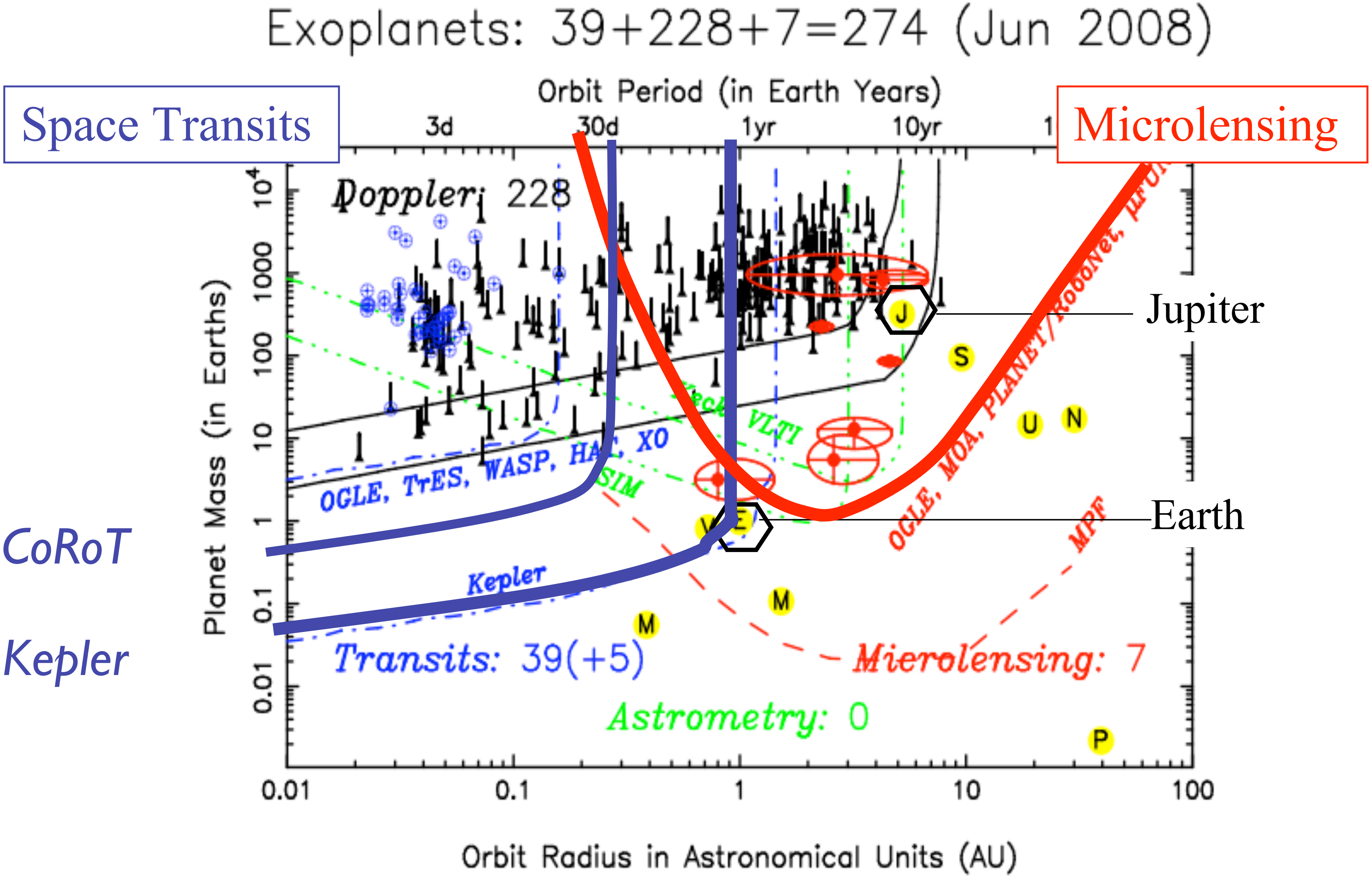
(7) Pulsar timing

How to find Earths ?

- ***Hot Earths***: ***Transits from Space***
  - 2007-10 … CoRoT -- Launched Dec 2006
  - 2009-15 … Kepler -- Launched Mar 2009
  - 2017 ? … PLATO
- ***Habitable Earths:*** ***Hard to Find***
  - Habitable Zone: T~300K liquid water on rocky planet surface
- ***Cool Earths***: ***Gravitational Lensing***
  - 2004-15 … OGLE, MOA, μFUN, PLANET RoboNet

+ KMTNet + LCOGT + SUPA-2 Planet Hunter

“Habitable” Earths: common or rare ?



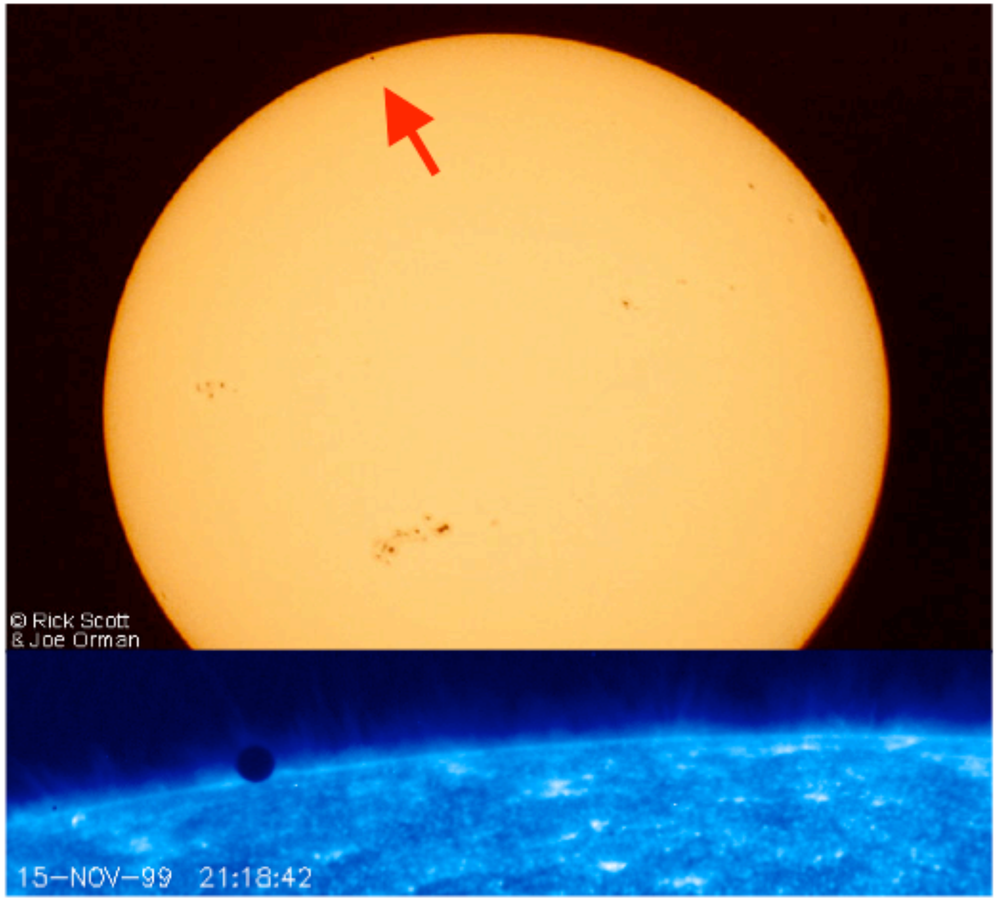
Hot Earths
Transits from Space

Earth transit depth:

$$\frac{\Delta f}{f} \sim 10^{-4} = 0.01\%$$

HST and CoRoT results suggest this is detectable.

Mercury transiting the Sun
15 Nov 1999



Mercury transits:
2003 May 07
2006 Nov 08

Venus transits:
2004 Jun 08
2012 Jun 06

CoRoT (CNES/ESA)

Launch 27 Dec 2006

First CoRoT planet:
3 May 2007

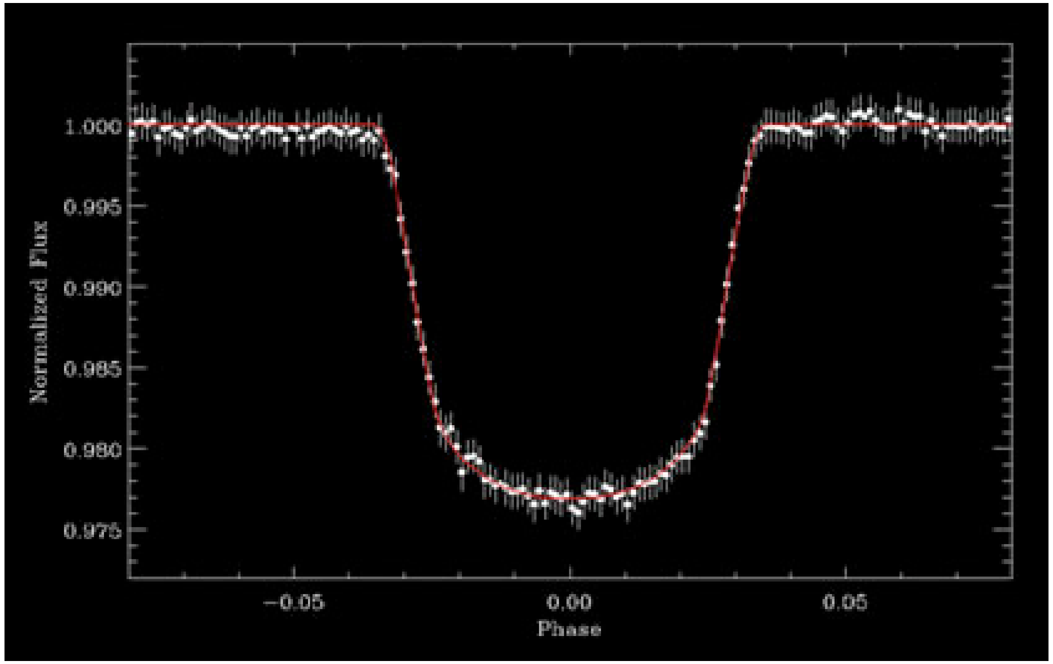
6 months/field

$$\sigma \sim 10^{-3}\left(t/\mathrm{min}\right)^{1/2}$$

CoRoT-Exo-1b:

$P = 1.5$ d

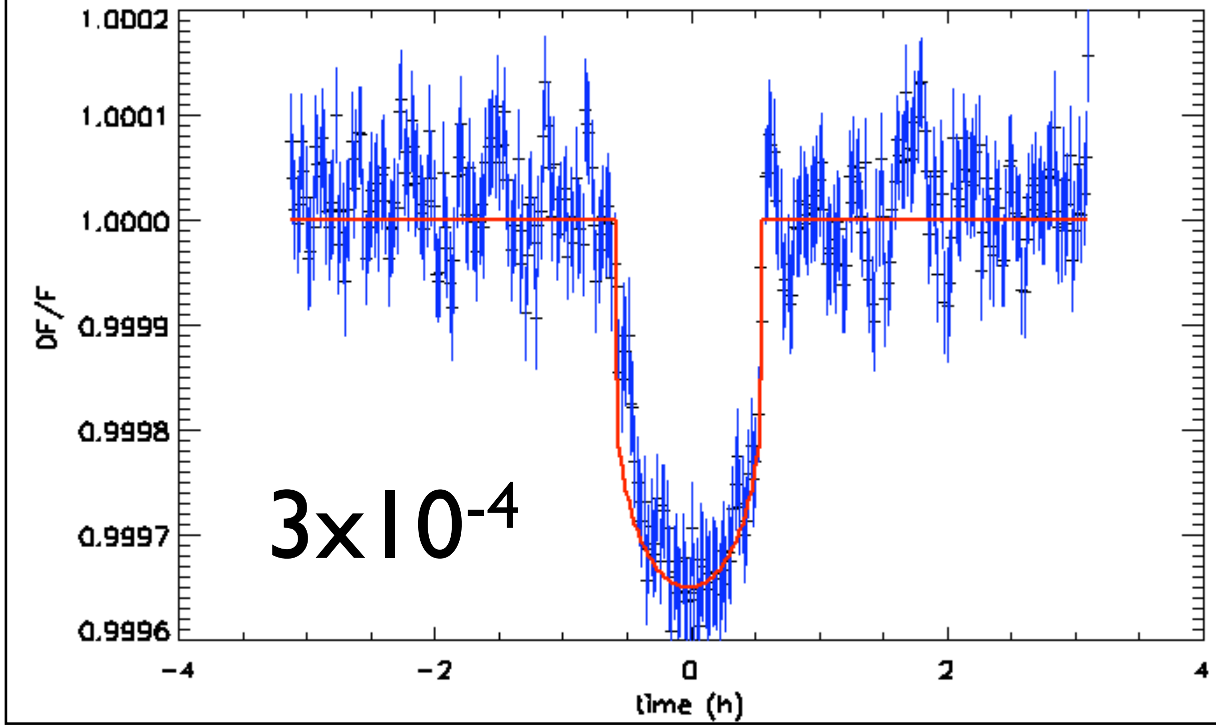
$m \sin(i) = 1.3\ m_J$

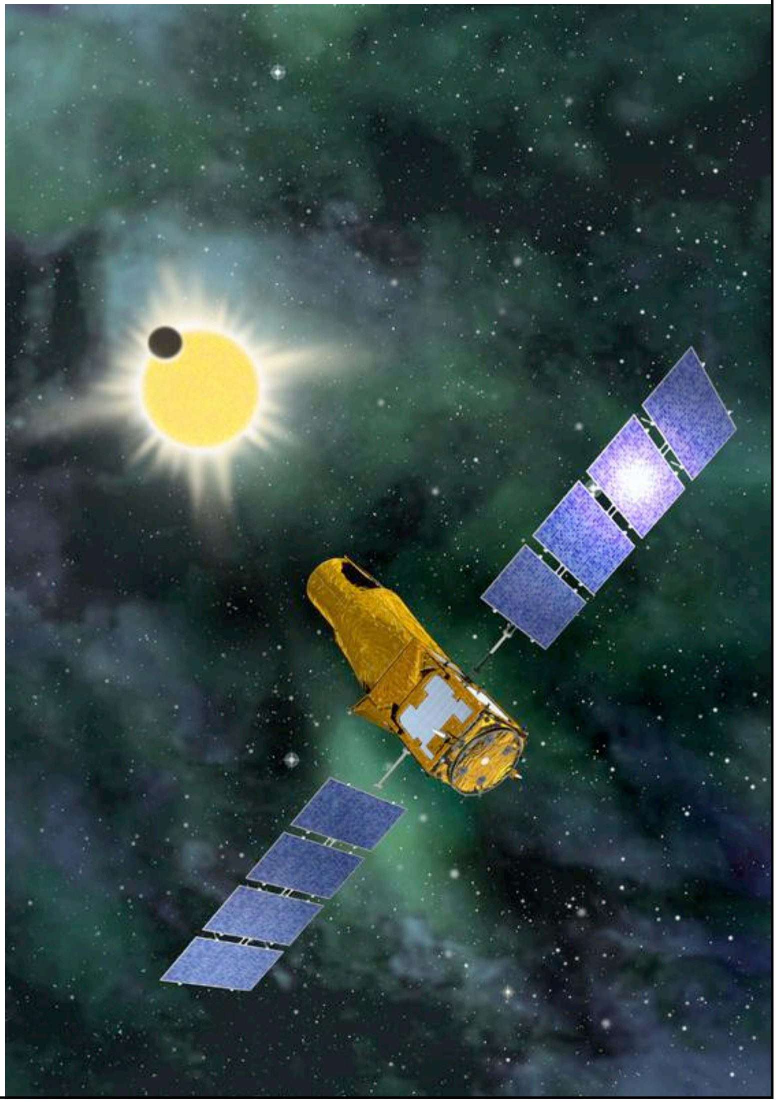


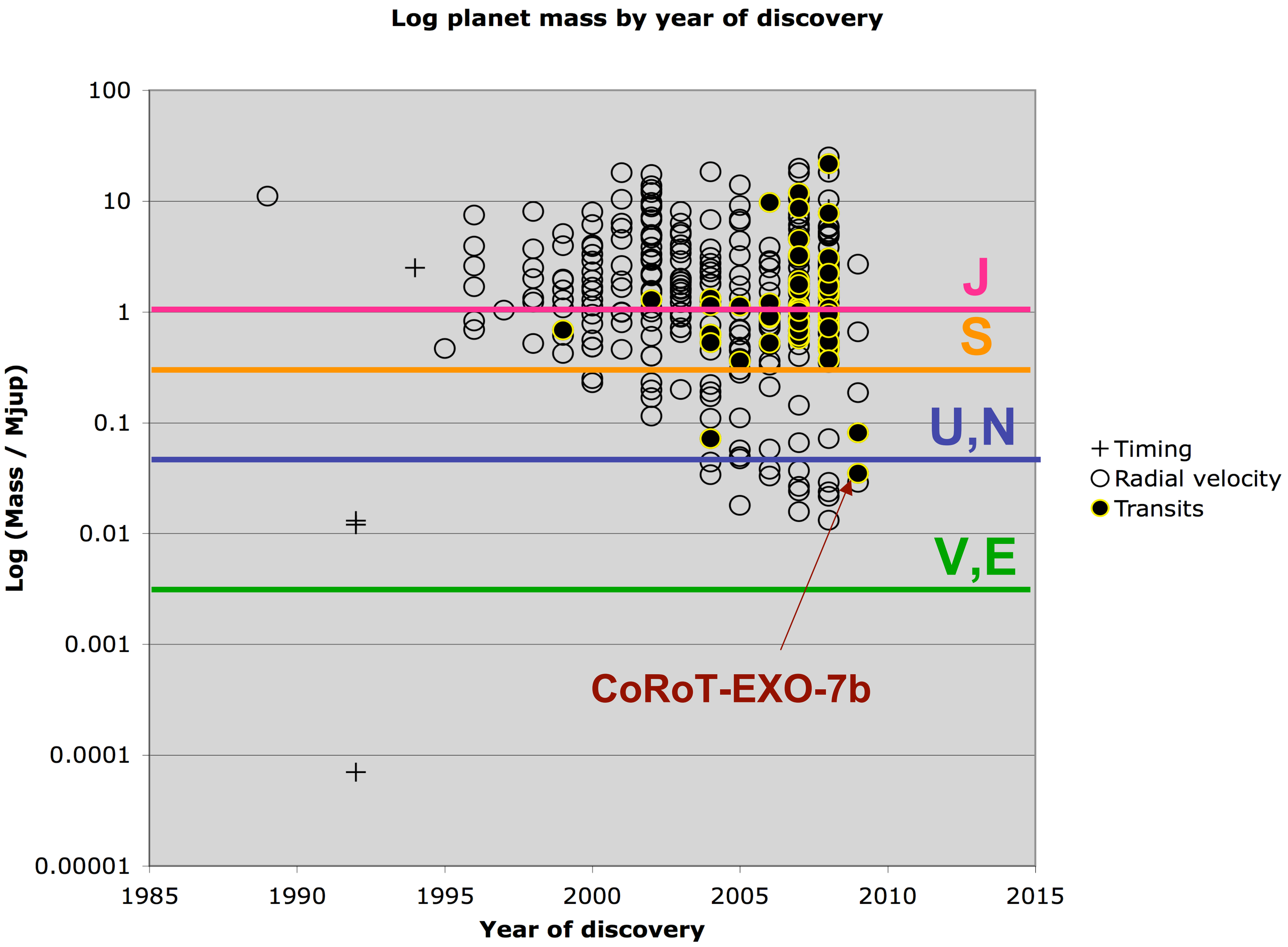
CoRoT-EXO-7b

Smallest Transiting Planet

CNES/ESA CoRoT Mission
First transiting Super-Earth
Announced 2009 Feb 3
Planet radius **1.8 Earth radii**
Planet mass 6 - 11 Earth masses

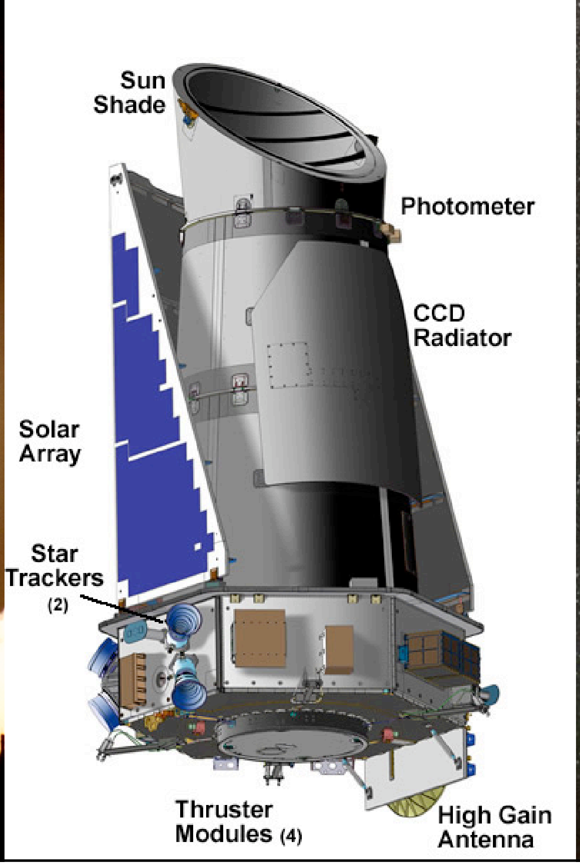


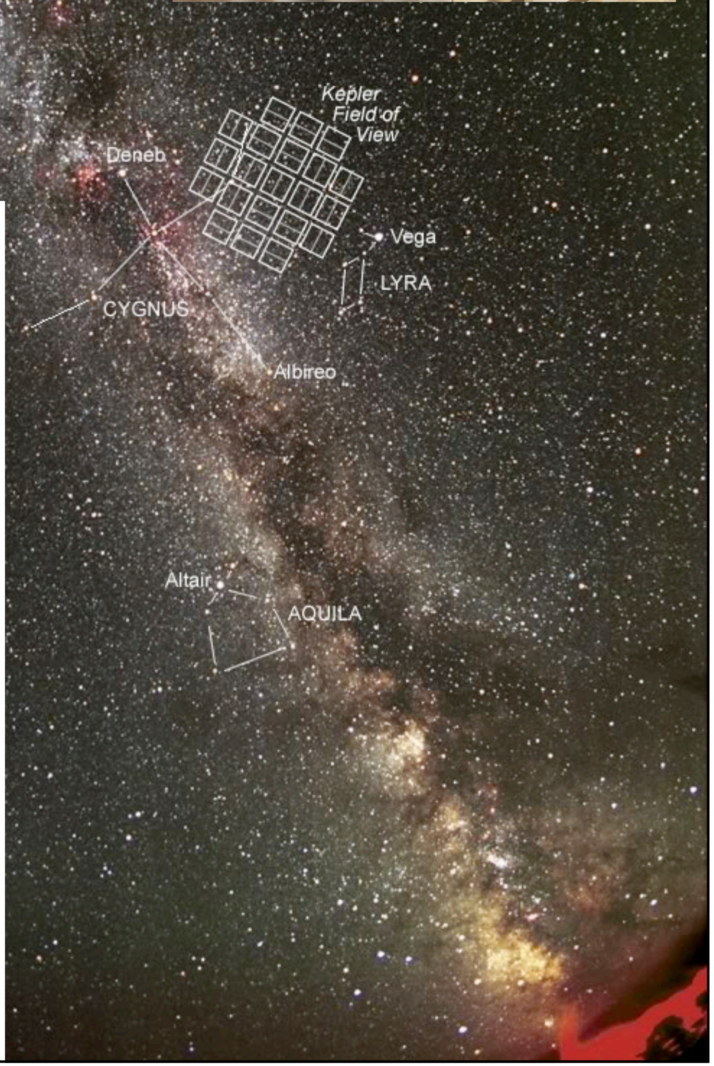



Log planet mass by year of discovery
Log (Mass / Mjup)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
1985
1990
1995
2000
2005
2010
2015
Year of discovery
J
S
U,N
V,E
CoRoT-EXO-7b
+ Timing
○ Radial velocity
● Transits

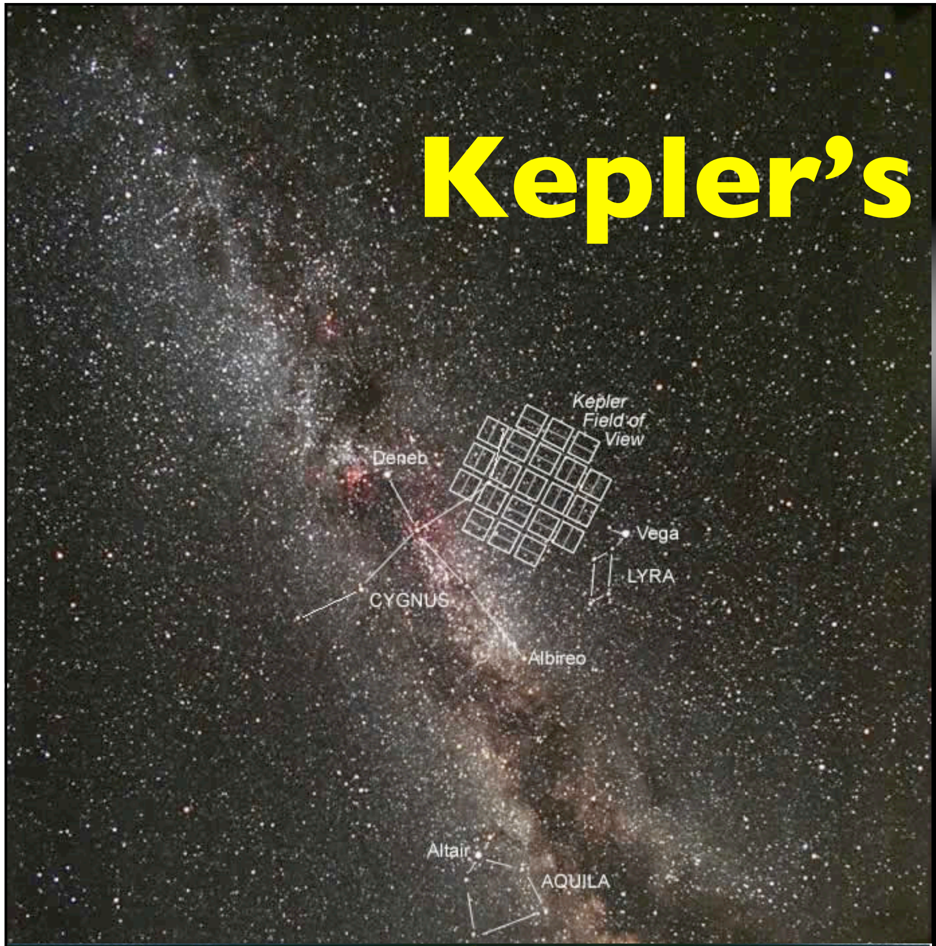
NASA's Kepler

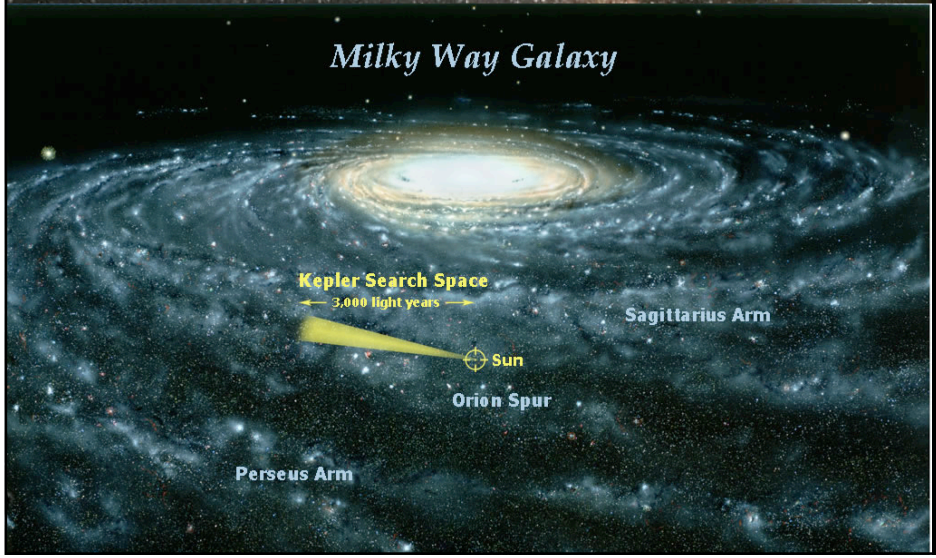
- Launched in Mar 2009
- 0.8m Schmidt Telescope
- CCD Mosaic   FoV~10º
- Stare for 4+ years.

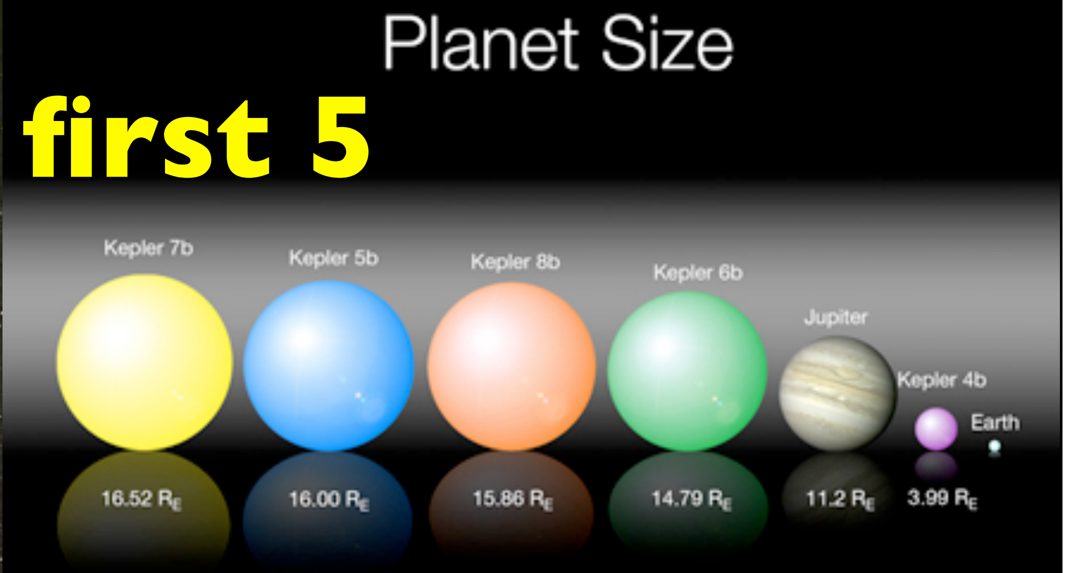


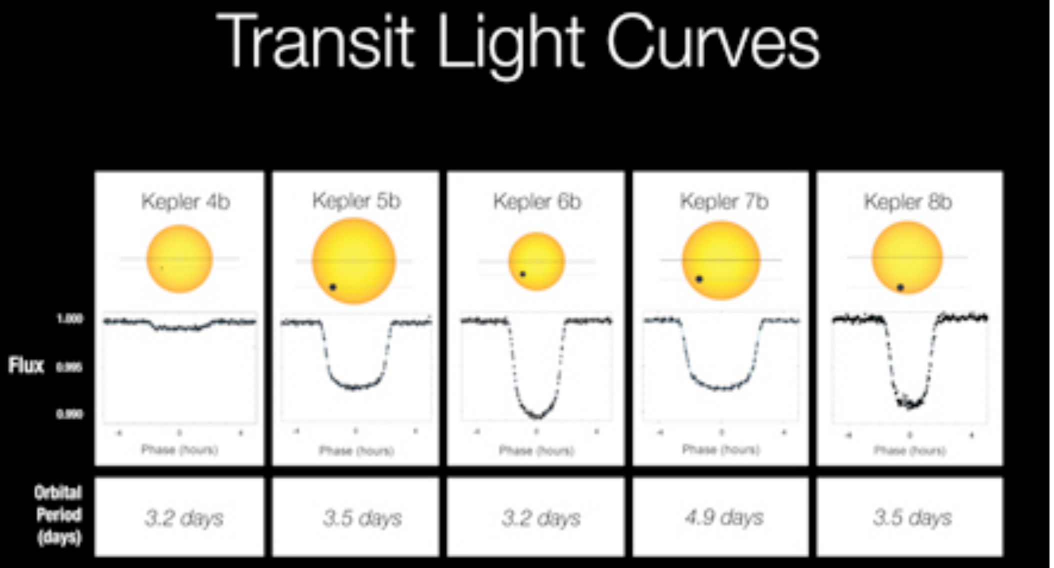


Kepler's first 5









Jan 2010

Space Transit Missions

Kepler *(4+ years) designed to detect* ***Earth analogs***

$r \sim r_\oplus \sim 0.01\ R_{sun}$

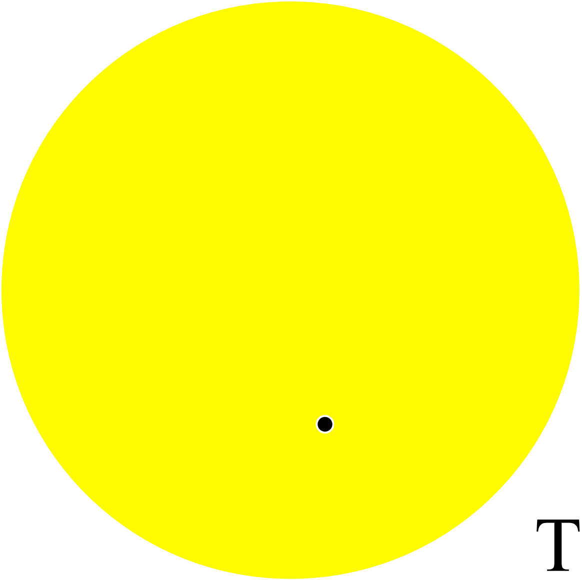
$T \approx 300\mathrm{K}$

$P \sim 1\ \mathrm{yr}$

$a \sim 1\ \mathrm{au}$

$\Delta t \sim 13\ \mathrm{h}$

$\Delta f / f \sim 10^{-4}$



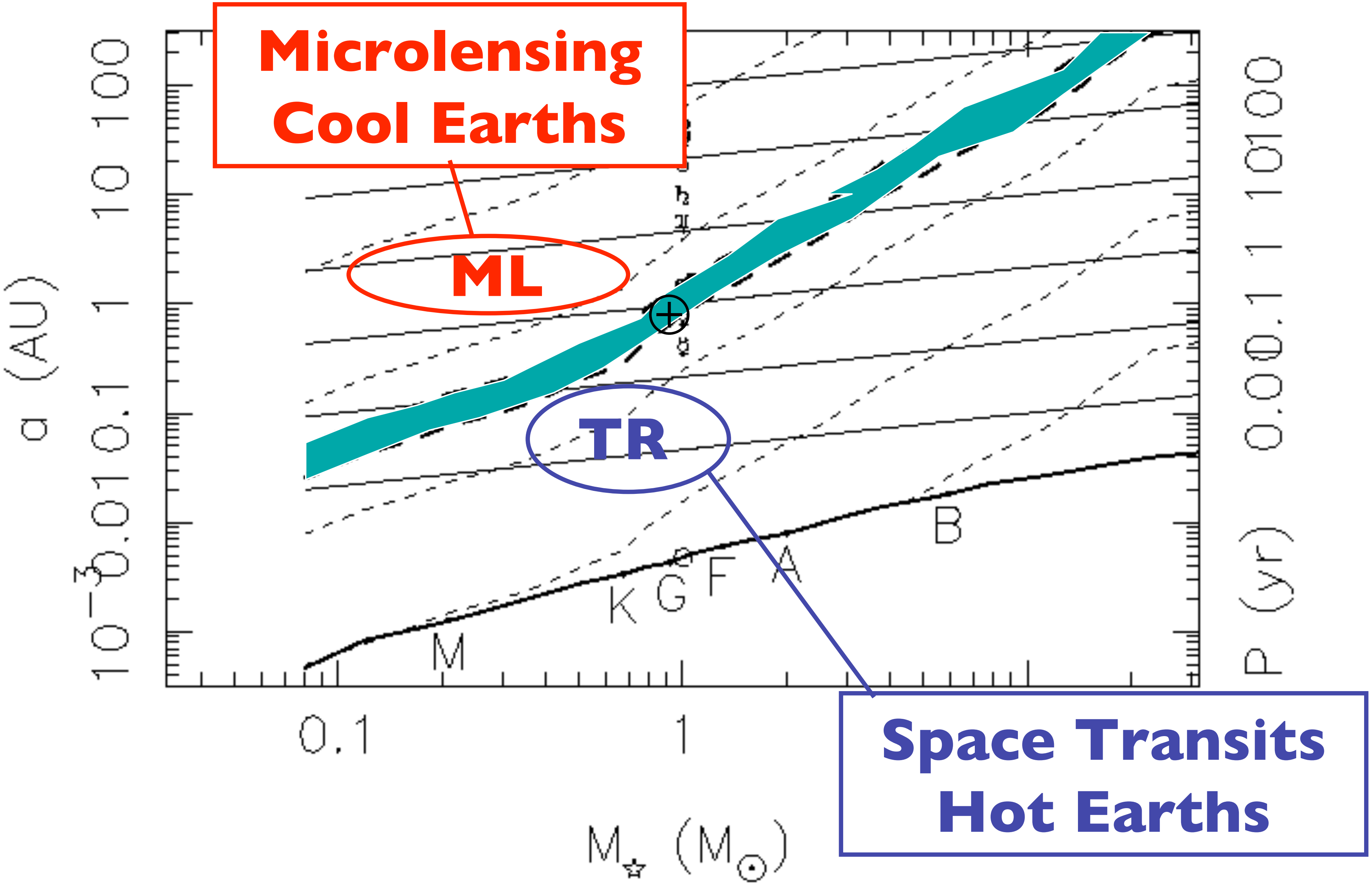
Transit probability: $P_t \sim 0.5\%$

Transit detection may be limited by stellar micro-variability.

Faint targets, so radial velocity confirmations will be difficult.

“Habitable” Earths common or rare ?

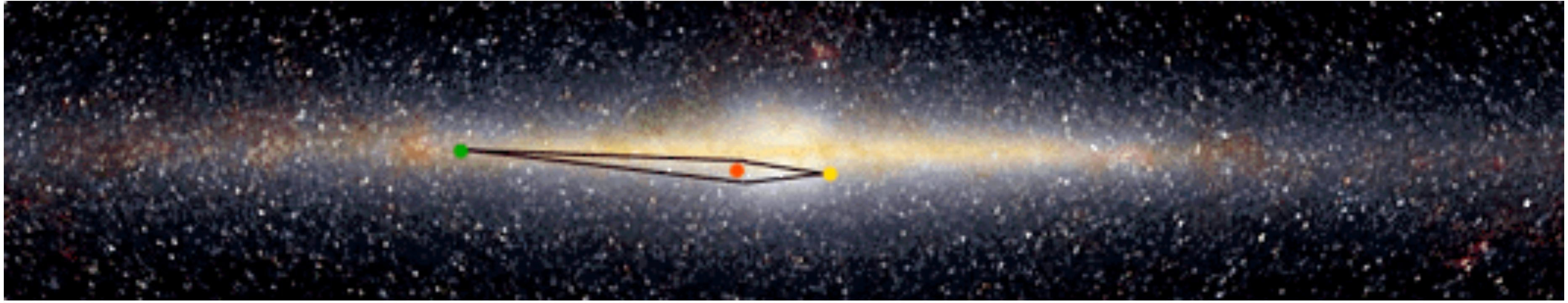
T~300K

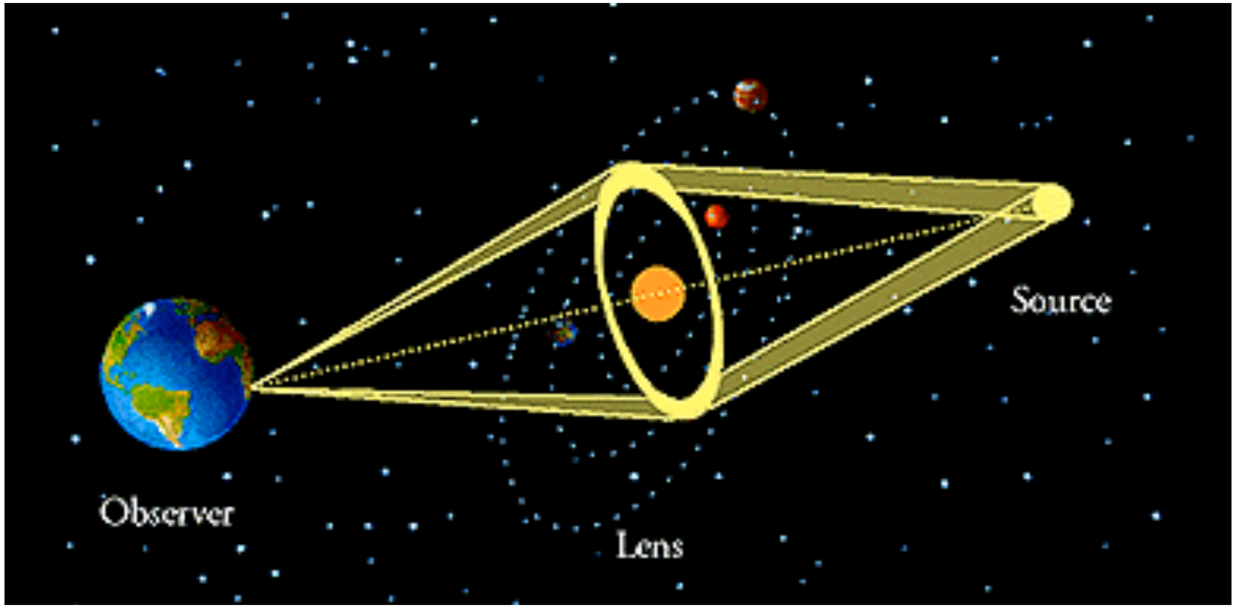


Microlensing Cool Earths

Space Transits Hot Earths

Gravitational Microlensing





Hunting for
Cool Planets
near the
lens stars

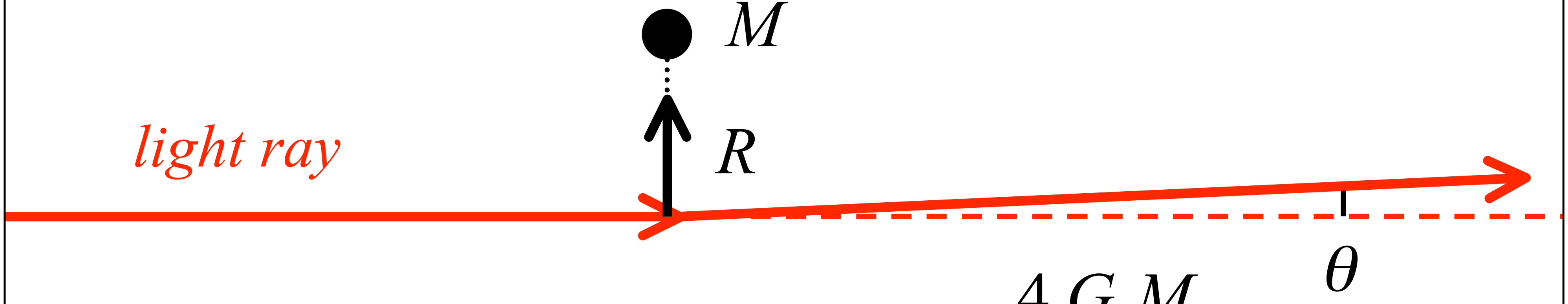
$M_{\mathrm{Lens}} \sim 0.3\, M_{\mathrm{Sun}} \quad R_{\mathrm{E}} \sim 3\,\mathrm{AU} \sim 10^{-3}\,\mathrm{arcsec}$

Cool Earths detectable!

Einstein's General Relativity

Particles (and light) follow shortest available paths (geodessics) through Space-Time.

Mass (energy) causes Space-Time to warp.

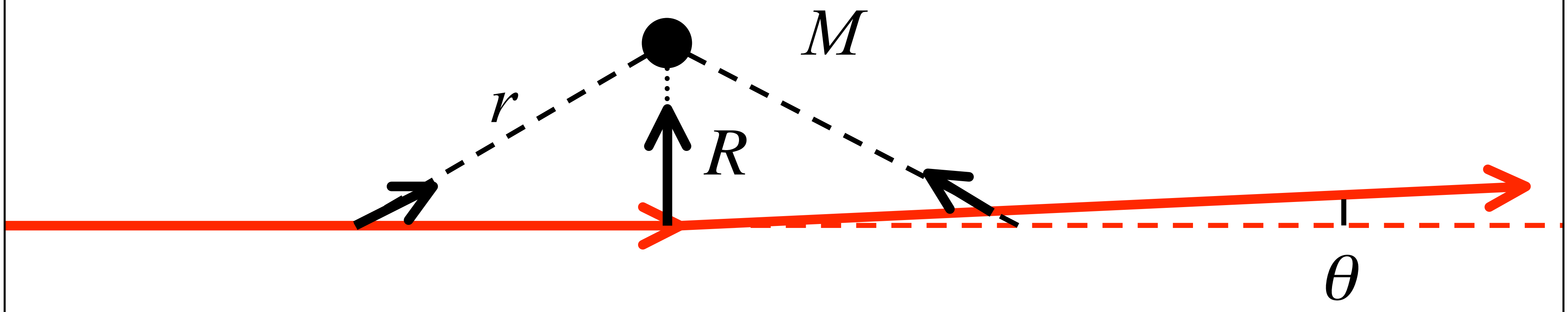


Einstein's bend angle $\theta = \frac{4\,G\,M}{R\;c^2}$

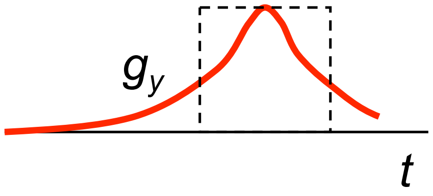
Predicts 1.7 arcsec for Sun-grazing ray.

Verified by Eddington during solar eclipse.

Newtonian Deflection Angle



vertical acceleration $g_y = \left(\frac{G\,M}{r^2}\right)\left(\frac{R}{r}\right) \le \frac{G\,M}{R^2} = g_{\max}$

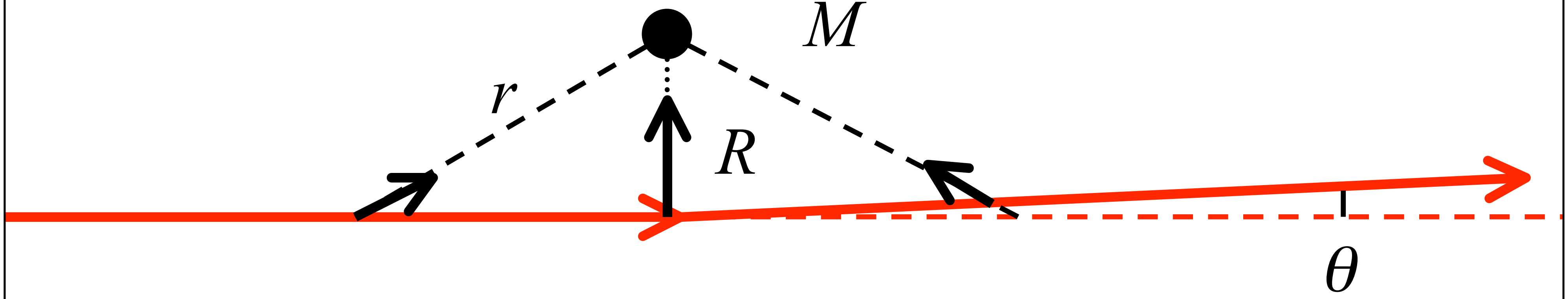


time to pass $\Delta t \approx 2\,R/V_x$

vertical velocity $V_y = \int g_y\,\mathrm{d}t \approx g_{\max}\Delta t \approx \left(\frac{G\,M}{R^2}\right)\left(\frac{2\,R}{V_x}\right) = \frac{2\,G\,M}{R V_x}$

bend angle $\theta \approx \frac{V_y}{V_x} \approx \frac{2\,G\,M}{R V_x^2} \Rightarrow \frac{2\,G\,M}{R c^2}$

Newtonian Deflection Angle

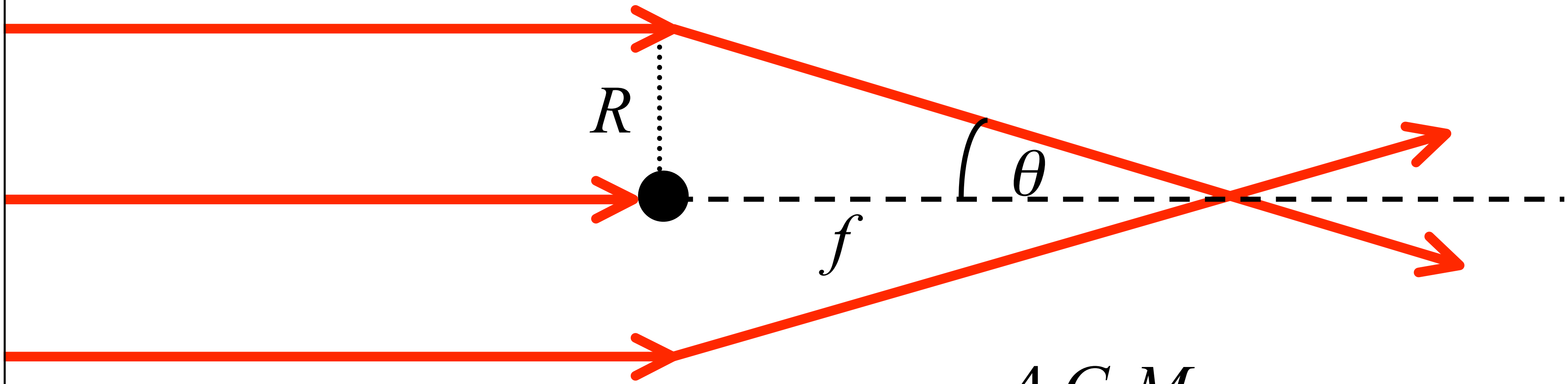


vertical acceleration $g_y = \left(\frac{G\,M}{r^2}\right)\left(\frac{R}{r}\right)$ $\quad r^2 = R^2 + x^2$

vertical velocity $V_y = \int g_y\,dt \approx \int \frac{G\,M\,R}{\left(R^2 + x^2\right)^{3/2}} \frac{dx}{V_x} = \frac{2\,G\,M}{R\,V_x}$

bend angle $\theta \approx \frac{V_y}{V_x} \approx \frac{2\,G\,M}{R\,V_x^2} \Rightarrow \frac{2\,G\,M}{R\,c^2}$

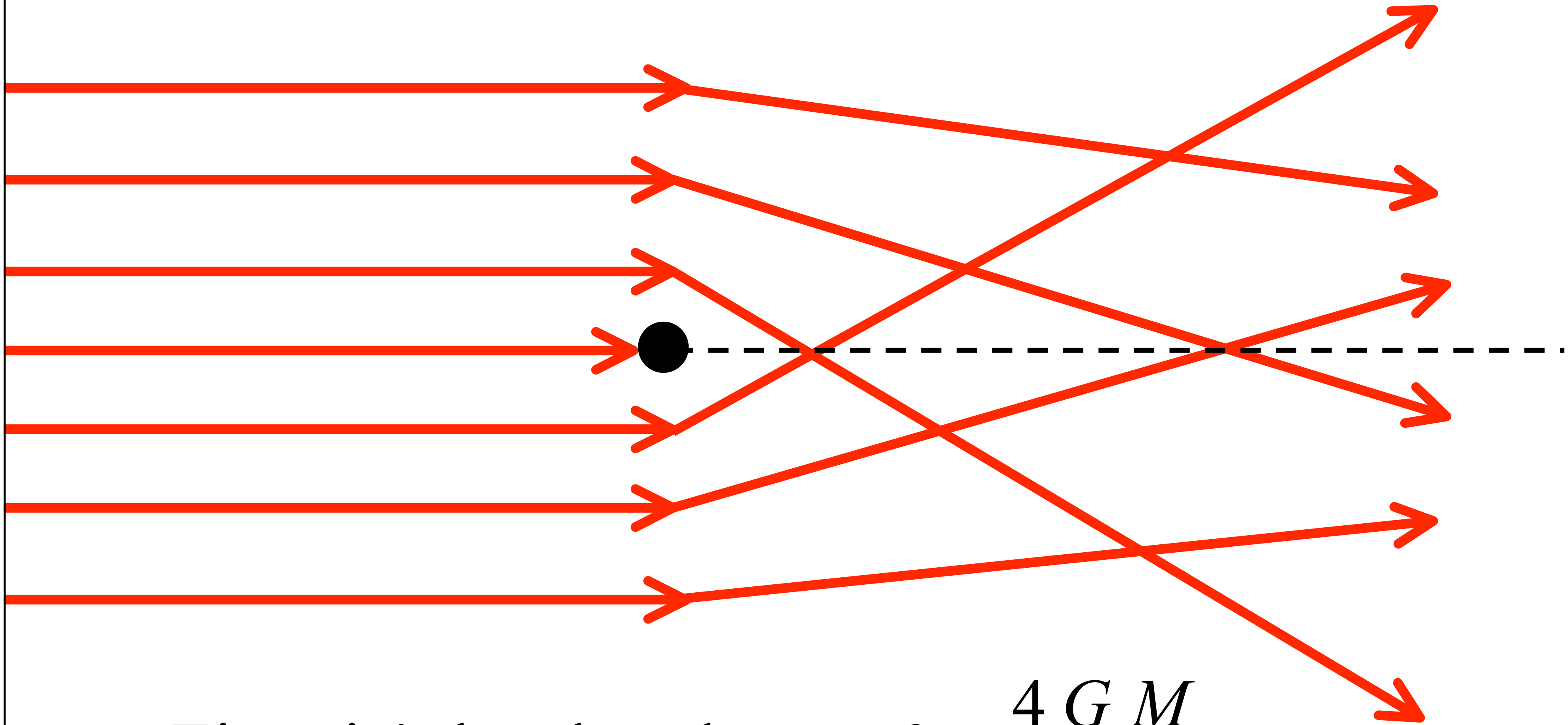
Focal Length of Gravitational Lens



Einstein's bend angle $\theta = \dfrac{4\,G\,M}{R\;c^2}$

Focal length : $f = \dfrac{R}{\theta} = \dfrac{R^2\,c^2}{4\,G\,M}$

Spherical Aberration

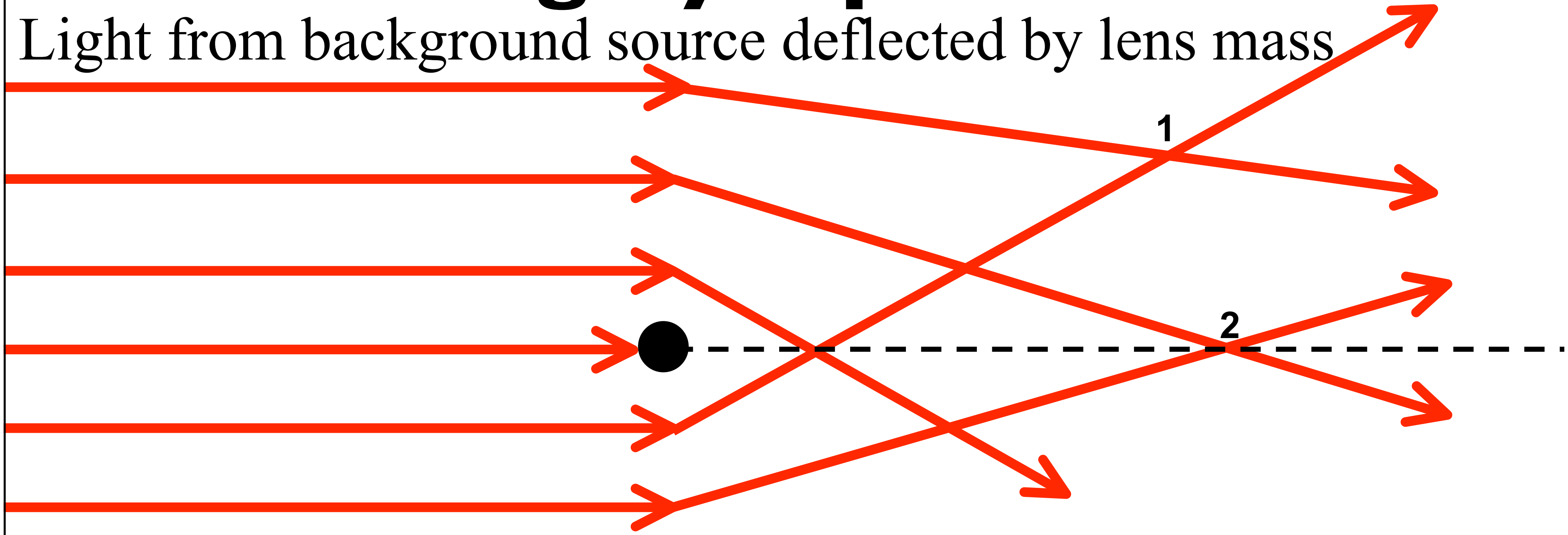


Einstein's bend angle $\theta = \frac{4\,G\,M}{R\,c^2}$

Focal length : $f = \frac{R}{\theta} = \frac{R^2\,c^2}{4\,G\,M}$

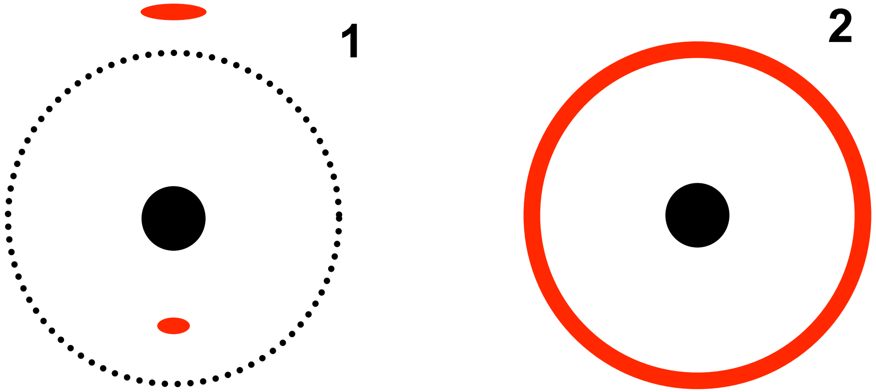
Lensing by a point mass

Light from background source deflected by lens mass



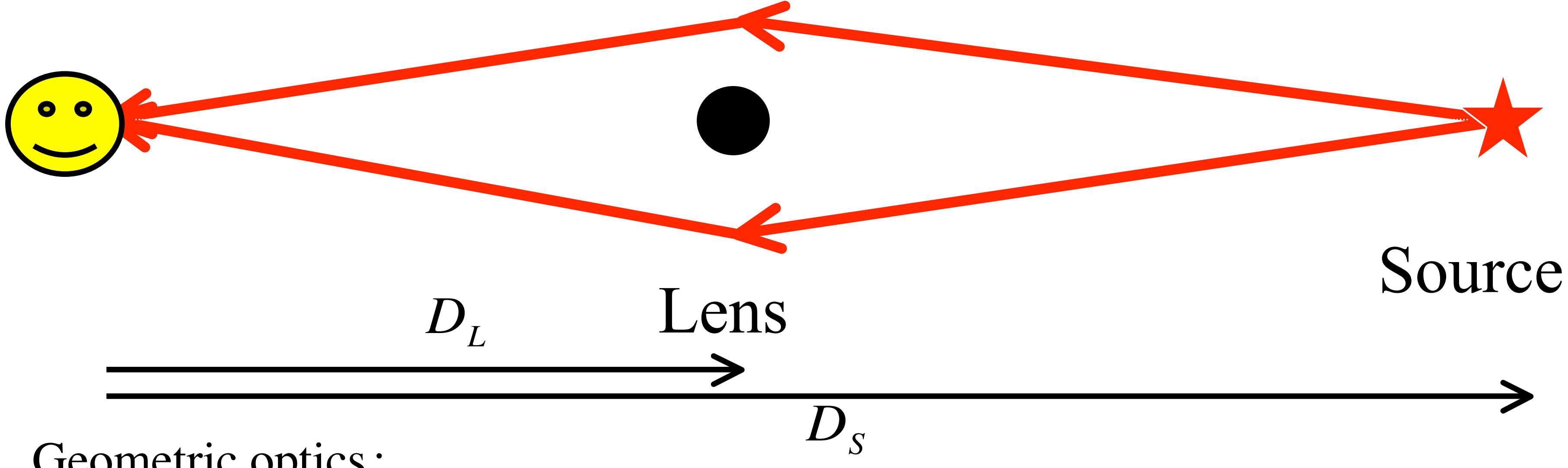
Two distorted/magnified images of background source

Observer's view:



Einstein ring

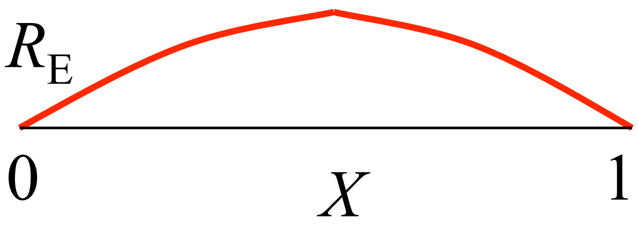
Einstein Ring Radius



Geometric optics:

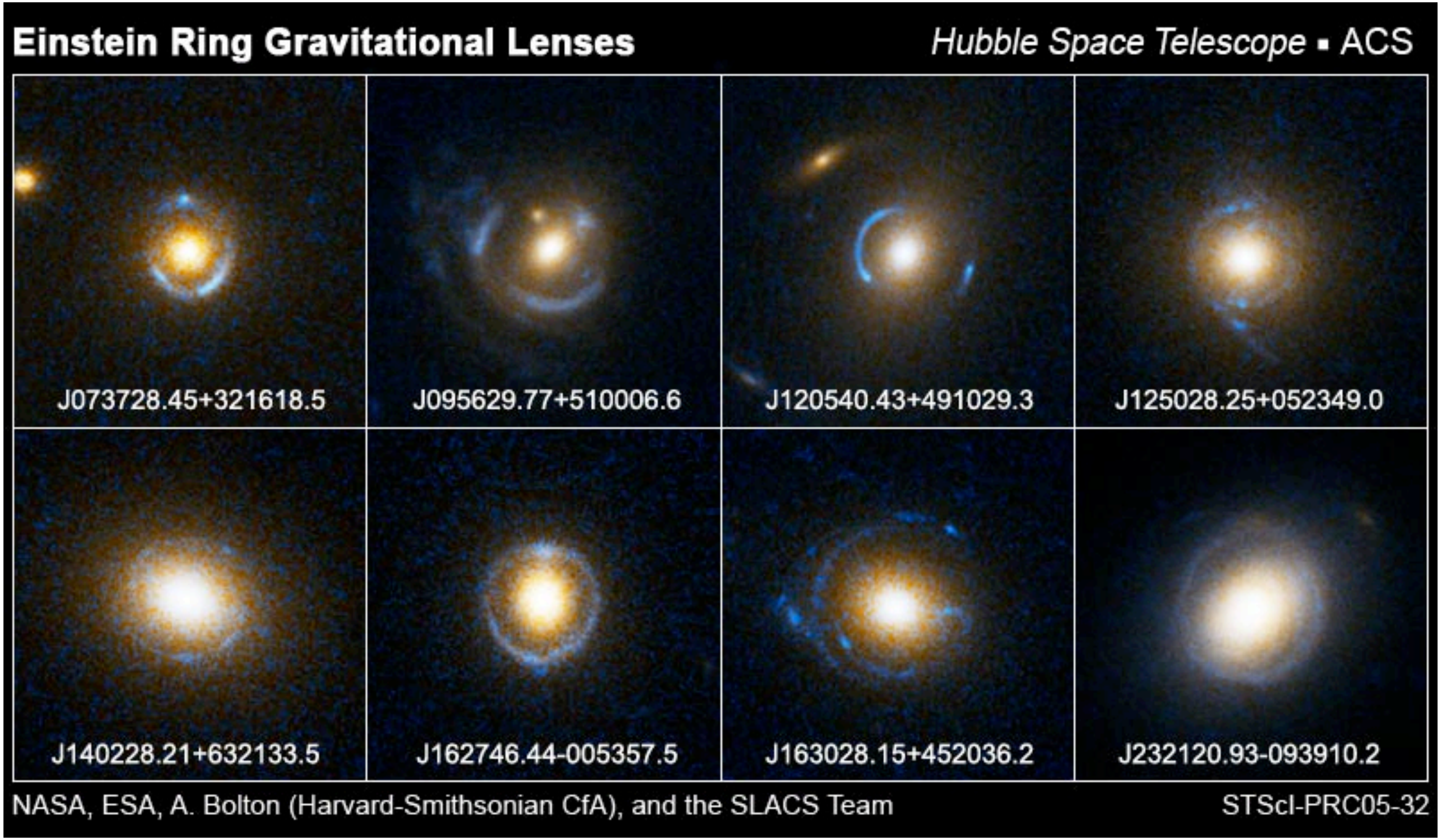
$$\frac{1}{D_S - D_L} + \frac{1}{D_L} = \frac{1}{f} = \frac{4\,G\,M}{c^2\,R^2}$$

Einstein Ring Radius: $X \equiv \frac{D_L}{D_S}$



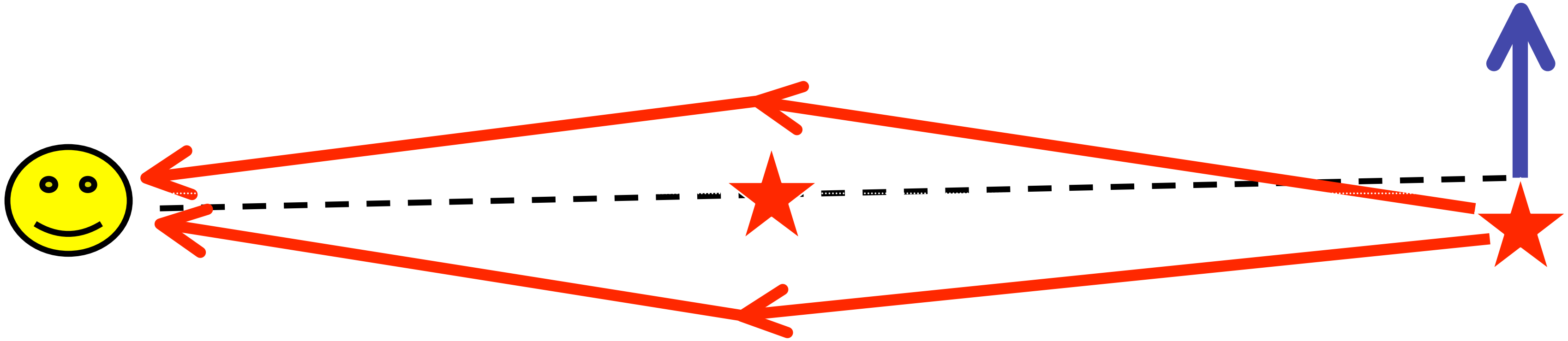
$$R_E = \left(\frac{4\,G\,M}{c^2}\right)^{1/2} D_S^{1/2} \sqrt{X(1-X)} = 8\,\text{AU} \left(\frac{M}{M_{SUN}}\right)^{1/2} \left(\frac{D_S}{8\,\text{kpc}}\right)^{1/2} \sqrt{X(1-X)}$$

$$\theta_E = \frac{R_E}{D_L} = \sqrt{\frac{4\,G\,M}{c^2}\left(\frac{1}{D_L} - \frac{1}{D_S}\right)} \sim 10^{-3}\,\text{arcsec} \left(\frac{M}{M_{SUN}}\right)^{1/2} \left(\frac{D_S}{8\ \text{kpc}}\right)^{-1/2} \sqrt{\frac{1-X}{X}}$$



Real images of Einstein Rings. The bright yellow object is the foreground “lens”. The blue arcs are images of the background “source”. The images of the source form in a ring around the lens.

Lensing of Stars by Stars



$V_{rel} \sim 200$ km/s

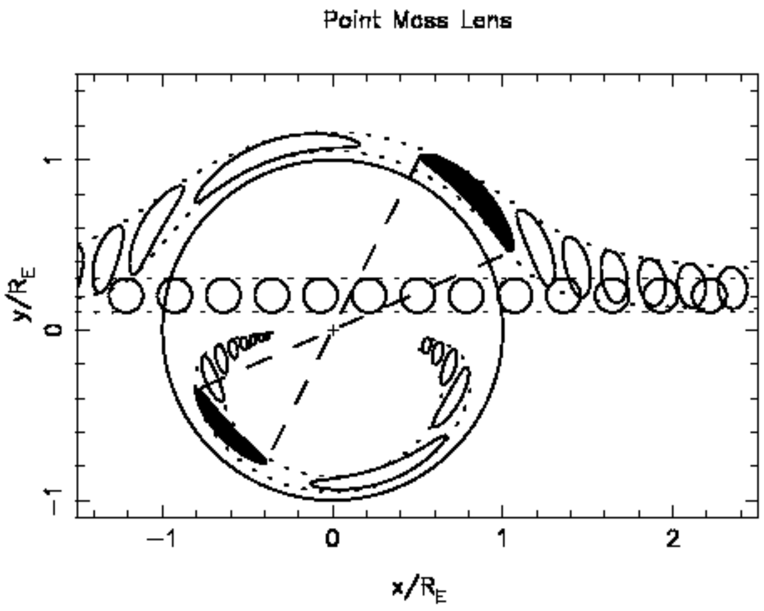
Lens star, possibly
with planets

Source star
near centre of
Milky Way

Bend angle ~ 1 milli-arcsec

~500 cases found every year

Lensing by a Point Mass

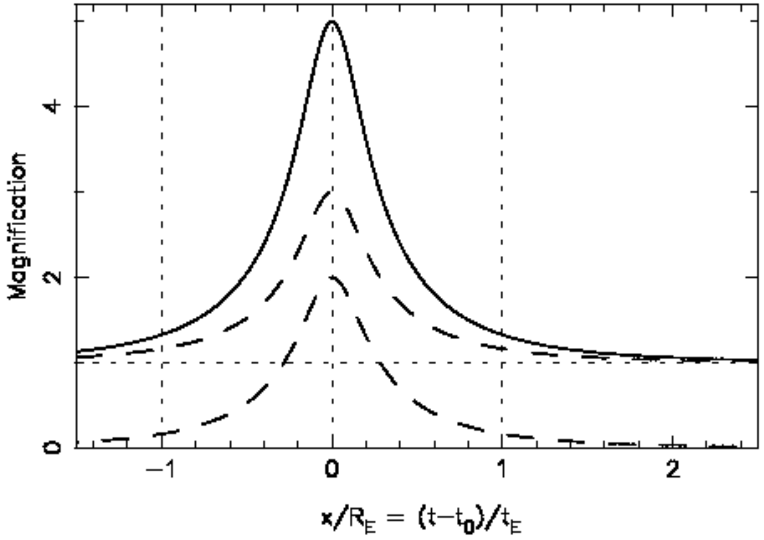


2 images

opposite sides of lens

major image outside ring

minor image inside ring



net magnification

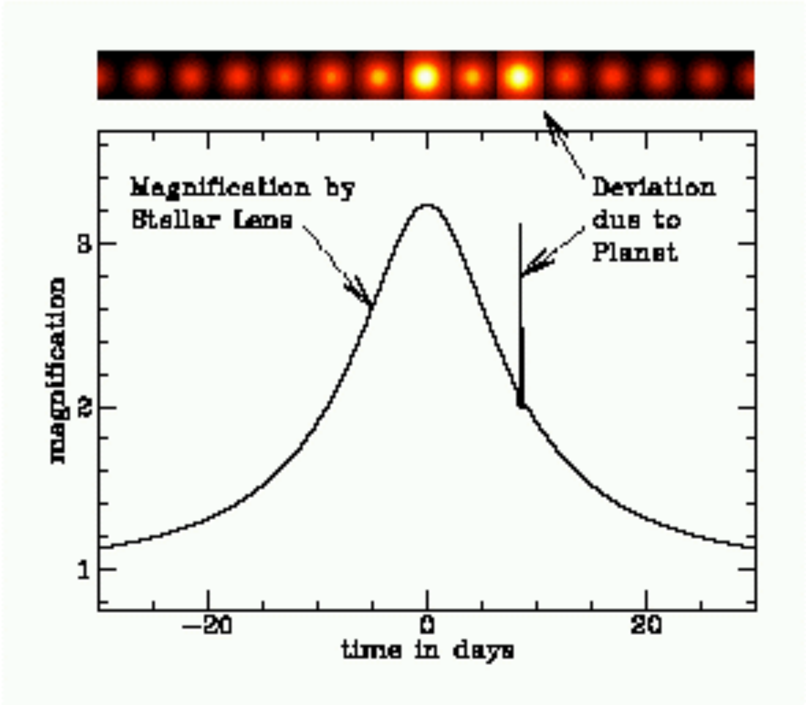
(sum of 2 images)

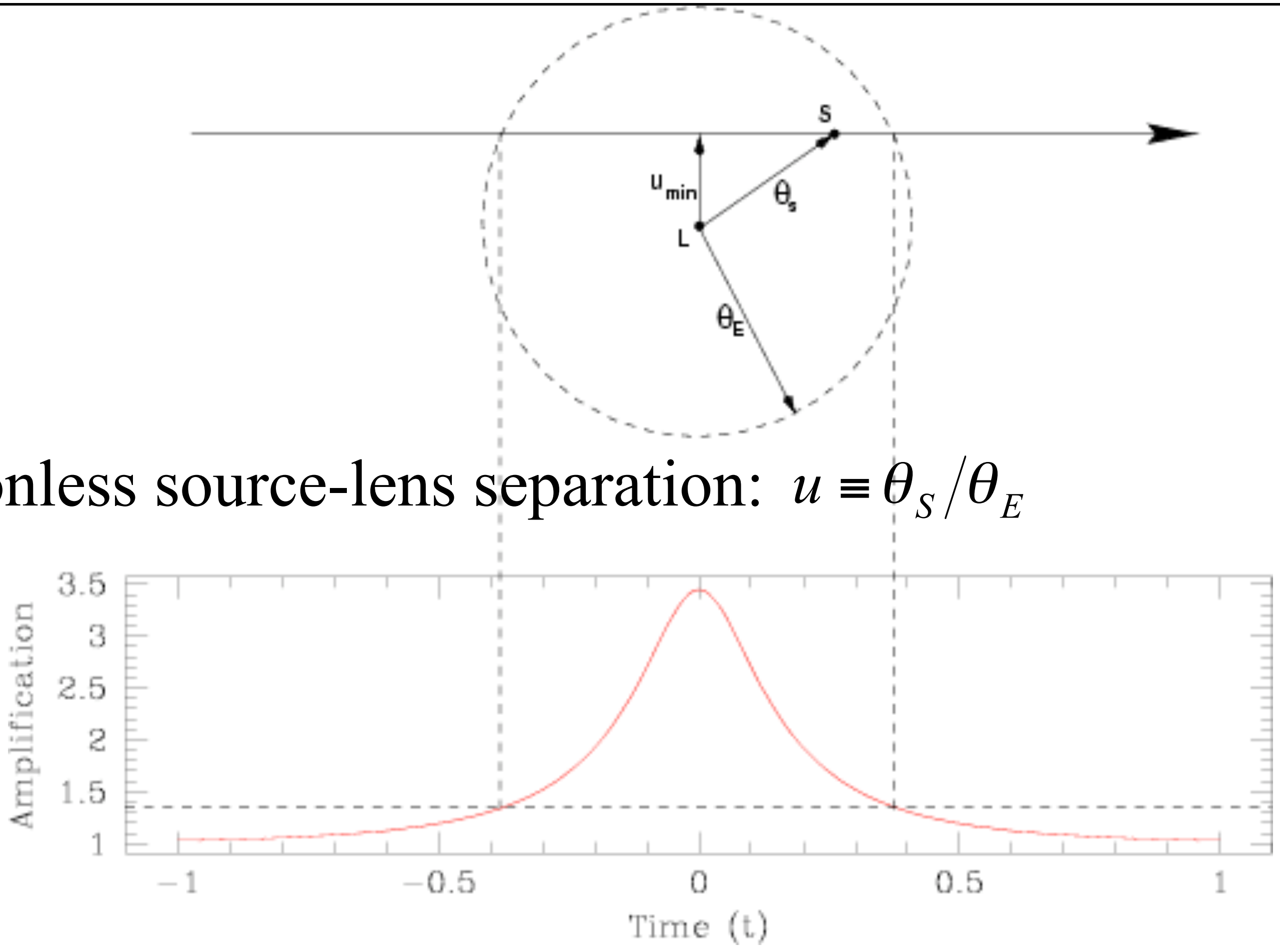
vs time

Mass of the Lens determines the type of Gravitational Lensing

Macrolensing: Very massive lenses, like galaxies or galaxy clusters, produce resolvable images of background objects.

Microlensing: A small lens, like a single star, produces unresolved images. We observe a time-dependent brightening of the source.





Dimensionless source-lens separation: $u \equiv \theta_S / \theta_E$

The total magnification (sum of both images) :

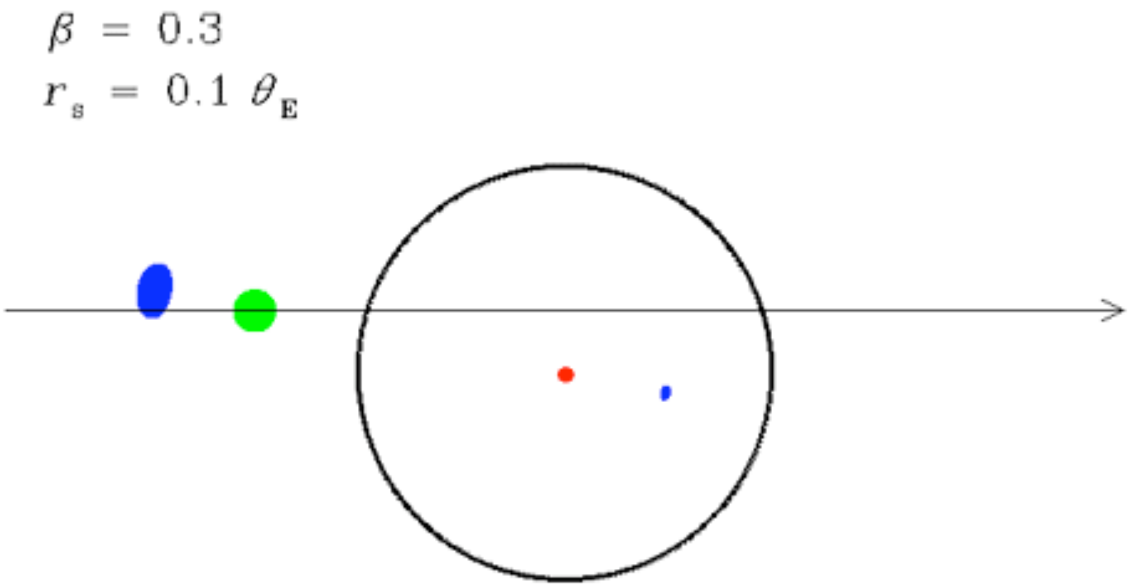
$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \qquad u(t) = \left(u_{\min}{}^2 + \left(\frac{t - t_0}{t_E} \right)^2 \right)^{1/2}$$

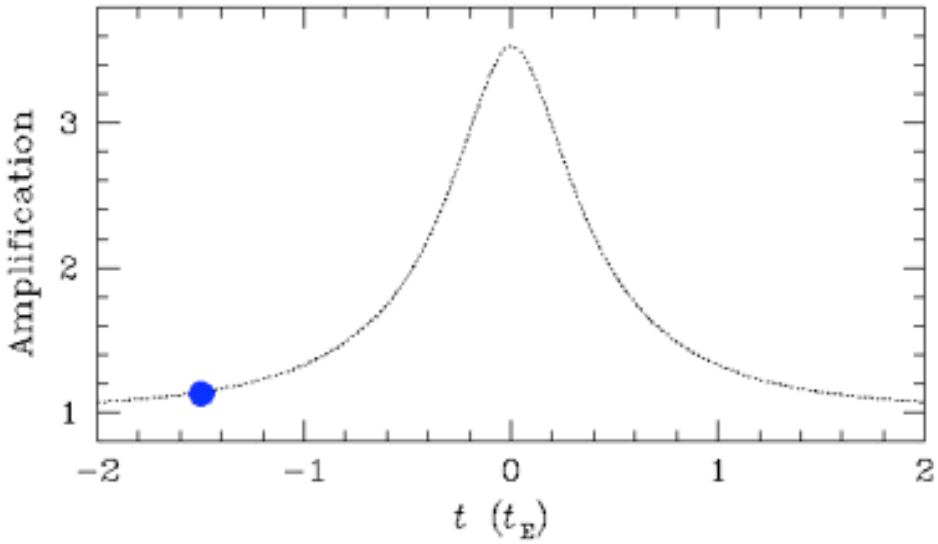
At closest approach, $t = t_0$, $u(t_0) = u_{\min}$

“***Einstein time scale***”, t_E, is the time for the source to move, with respect to the lens, by one Einstein ring radius

$$t_E \equiv \frac{R_E}{V_{rel}} \propto \sqrt{M}$$

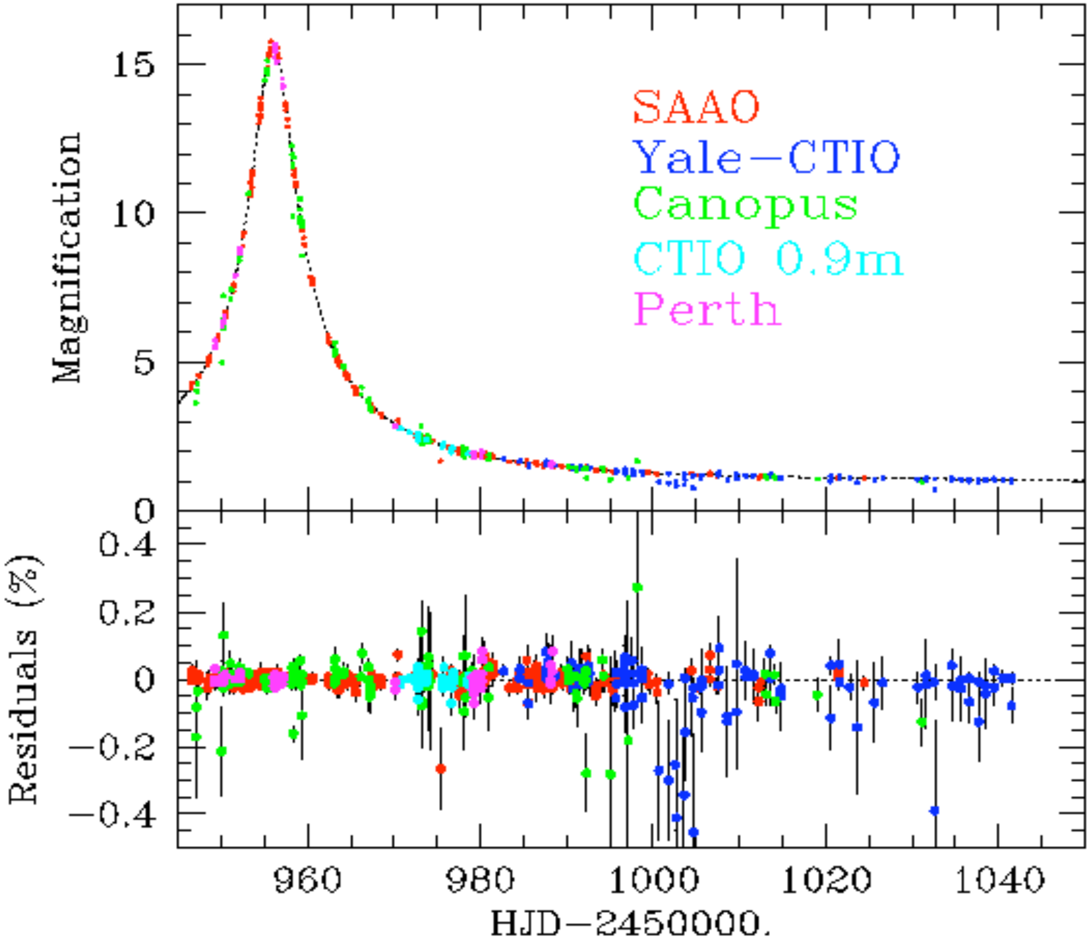
V_{rel} is the relative velocity between the source and lens in the plane of the sky.

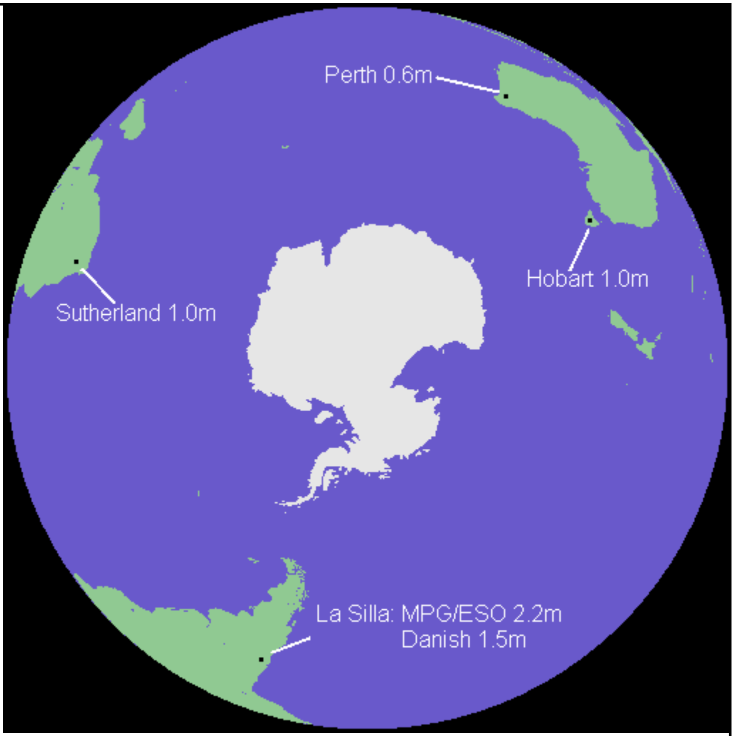




Microlens Follow-up Network:

OGLE, MOA, μFUN, PLANET / RoboNet





Global Telescope Network

=>24-hour coverage

1 day => Jupiters

1 hour => Earths

1990s, several groups monitored Galactic Bulge and the Magellanic Cloud starfields to detect lensing by foreground objects (*MACHO, EROS, MOA, OGLE*).
Original motivation was to search for Dark Matter in the form of massive compact halo objects (MACHOs).

Timescales $t_E \sim M^{1/2}$ for Galactic Bulge source stars:

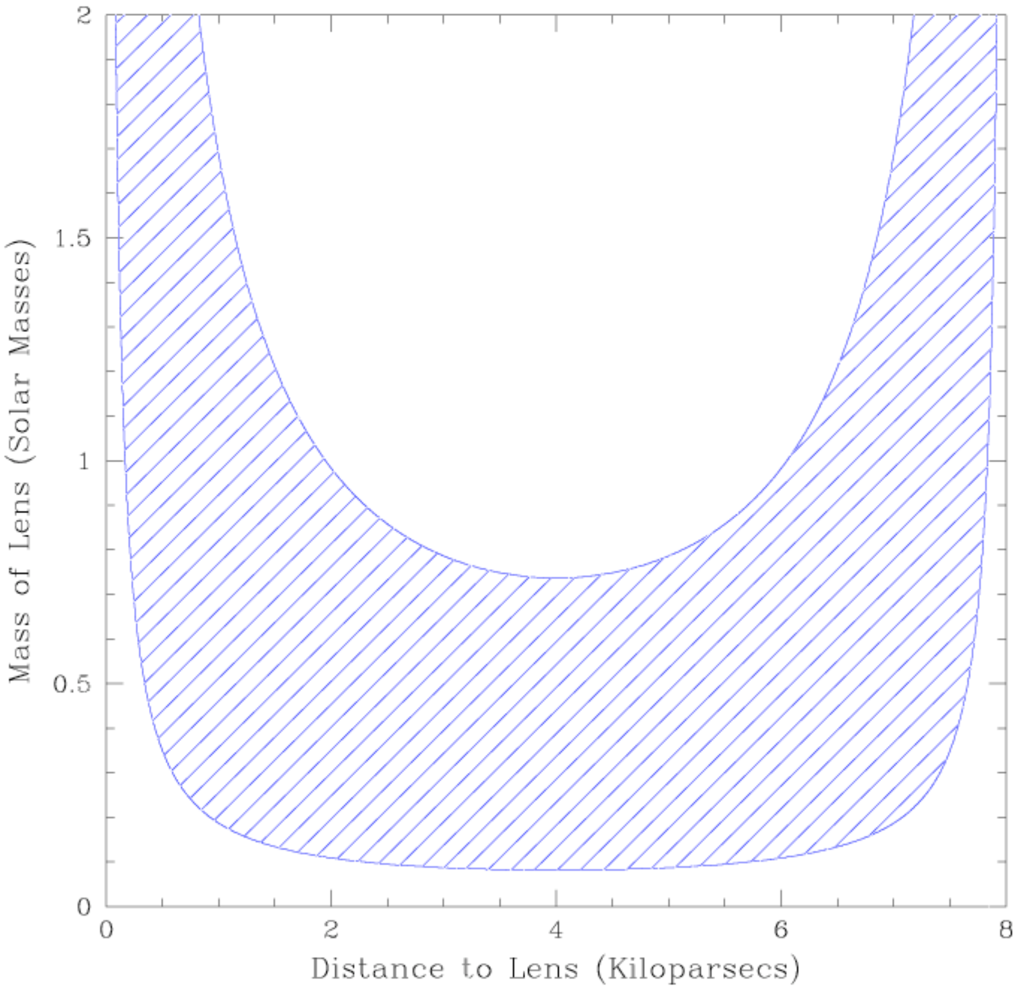
- Solar mass star ~ 1 month
- Jupiter mass planet ~ 1 day
- Earth mass planet ~ 1 hour

These timescales are observationally feasible.

Small bend angles => lensing is a very **rare event**.
Only 1 star in a million is lensed at any given time.

Galactic Bulge surveys (OGLE, MOA) find ~ 600 events/ year.

Degeneracy of Lens Parameters



- Event timescale t_E is a function of lens mass M_L, distance D_L, and relative velocity V_{rel}.

- A continuum of lens parameters can produce the same t_E

- For t_E = 40 d and V_{rel} = 100 - 300 km/s, M_L and D_L can be anywhere in the shaded region.

Notes:

(1) Peak magnification depends on the impact parameter, small impact parameter -> large magnification ($A \sim 1/u$).

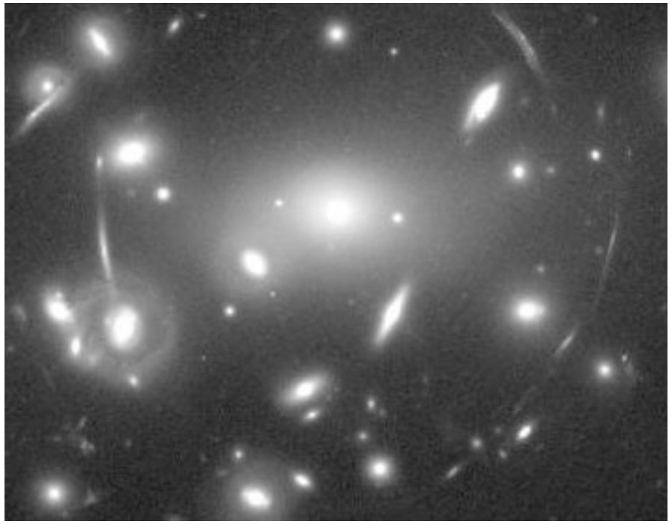
(2) For $u = 0$, apparently infinite magnification! In reality, finite size of source star limits the peak magnification.

(3) Significant magnification ($A>1.3$) requires alignment smaller than the Einstein ring radius ($u<1$).

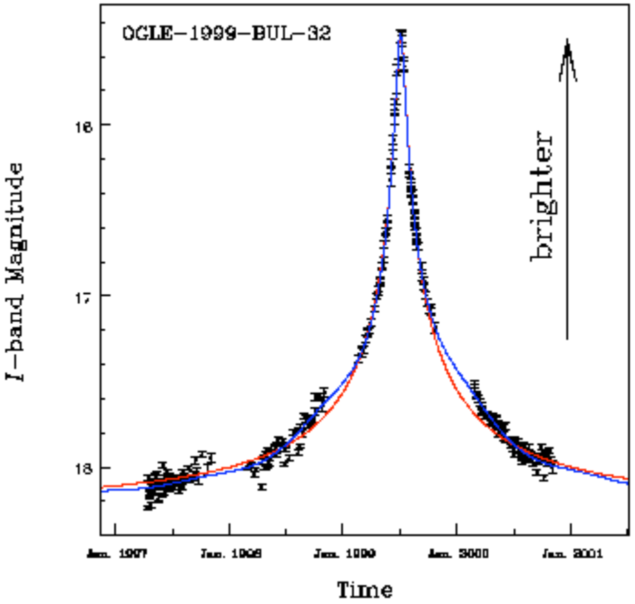
(4) Microlensing is achromatic – all wavelengths affected equally.

(5) Chances of microlensing occurring for a particular star is around 1 in a million – any given star lensed only once.

The Mass Profile of the Lens affects the structure of the source images (macrolensing) or shape of lightcurve (microlensing)

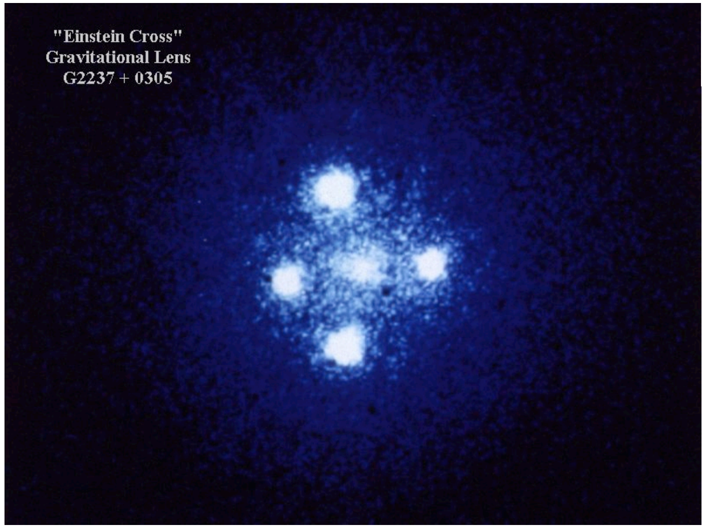


Lens = Galaxy Cluster



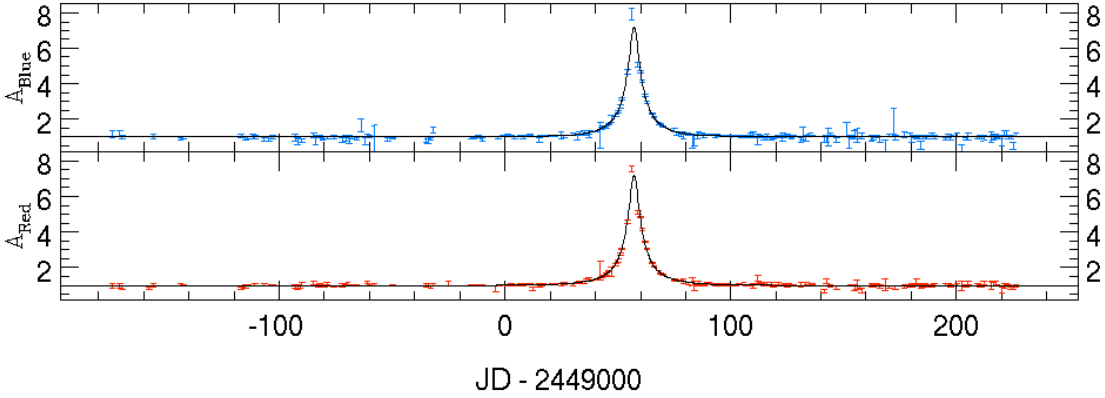
Lens = Black Hole?

Note wobble due to Earth’s annual orbit around the Sun.



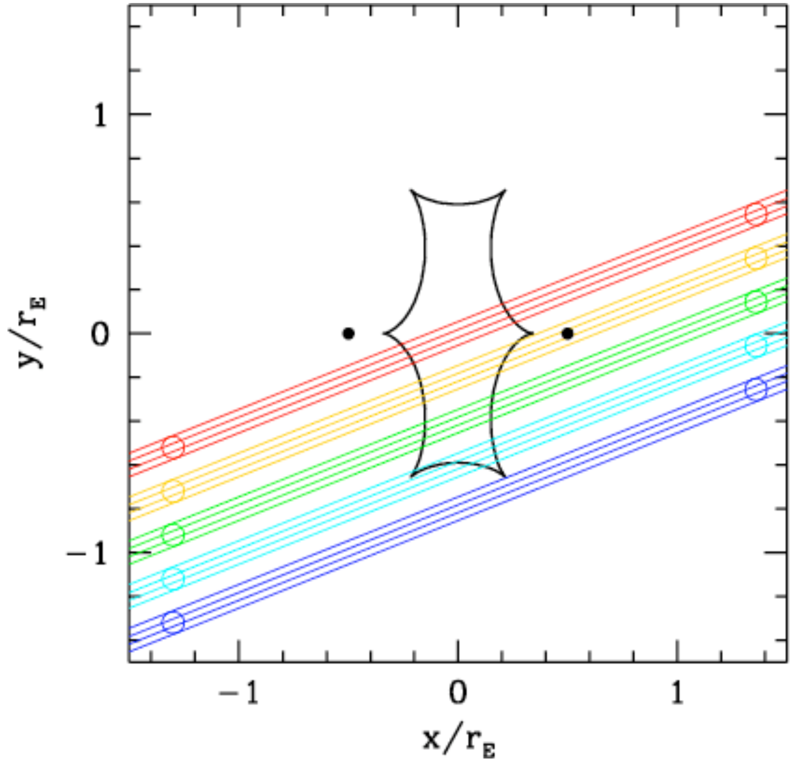
Lens = Single Galaxy

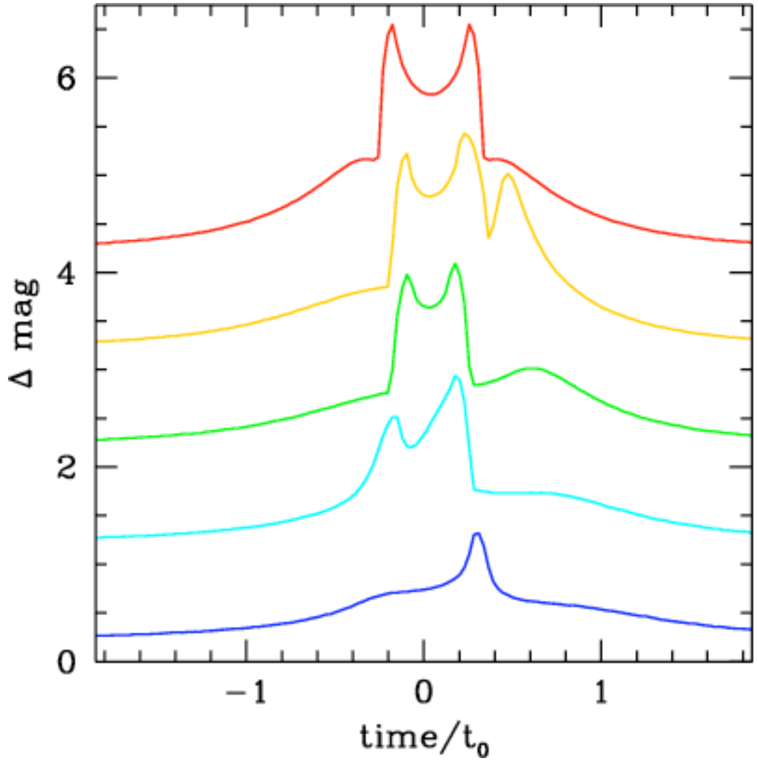
Lens = simple low mass star



Microlensing Anomalies

- Deviations from the standard point-lens point-source light curve are referred to as *microlensing anomalies*.
- The most interesting anomaly occurs in the case of a binary lens.
- Lightcurve shape depends on source trajectory relative to binary.

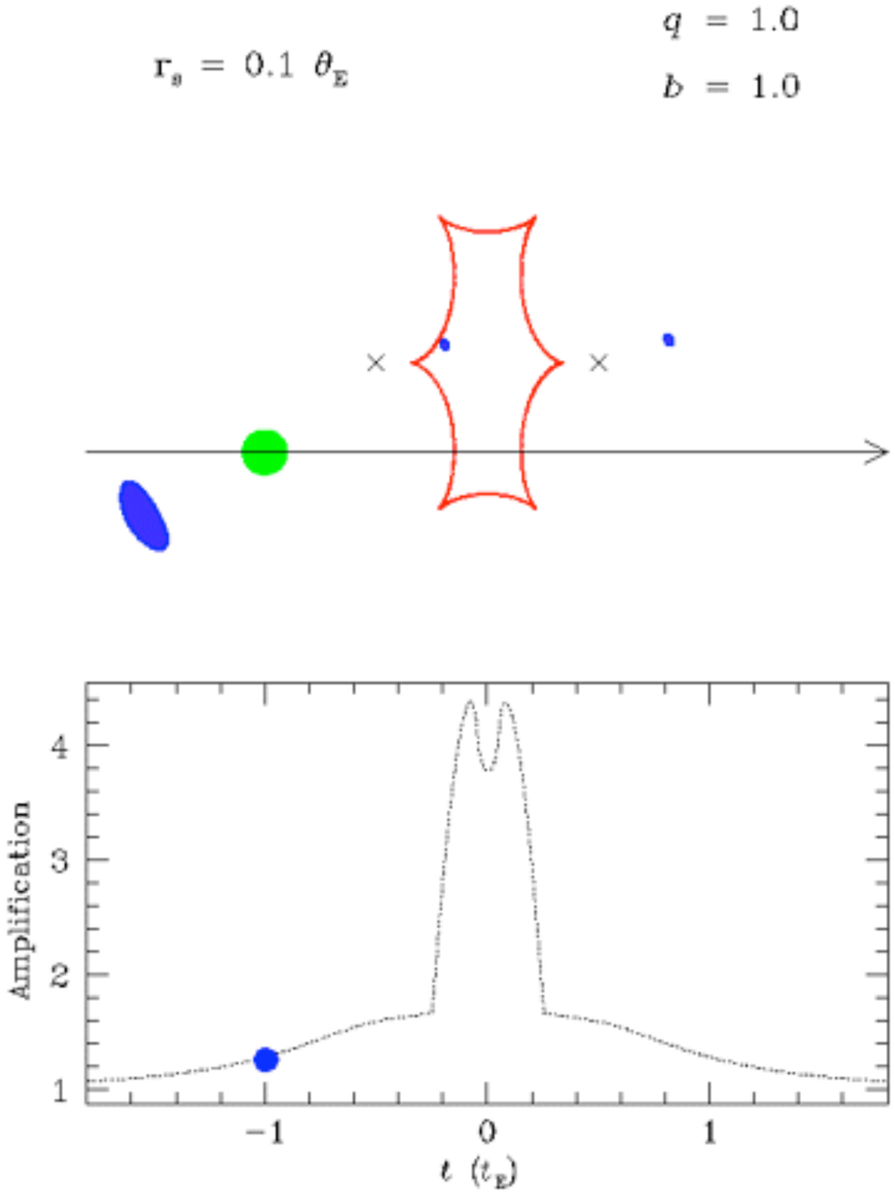




Caustic Crossings

Two new images appear (3->5) when source star enters a caustic curve.

Two images merge and disappear (5->3) when source exits a caustic curve.



How does microlensing find planets?

Light curve for a binary lens is complicated, but a characteristic is the presence of sharp spikes or **caustics**.
With good monitoring, parameters of the binary can be recovered.

Orbiting planet is just a binary with mass ratio $q = m_p / M_* << 1$

- Monitor known lensing events in real-time with dense, high precision photometry from several sites.
- Look for deviations from single star light curve due to planets
- Timescales ~ a day for Jupiter mass planets, ~ hour for Earths
- Most sensitive to planets at a ~ R_E, the Einstein ring radius
- Around 3-5 AU for typical parameters

Aug 2005

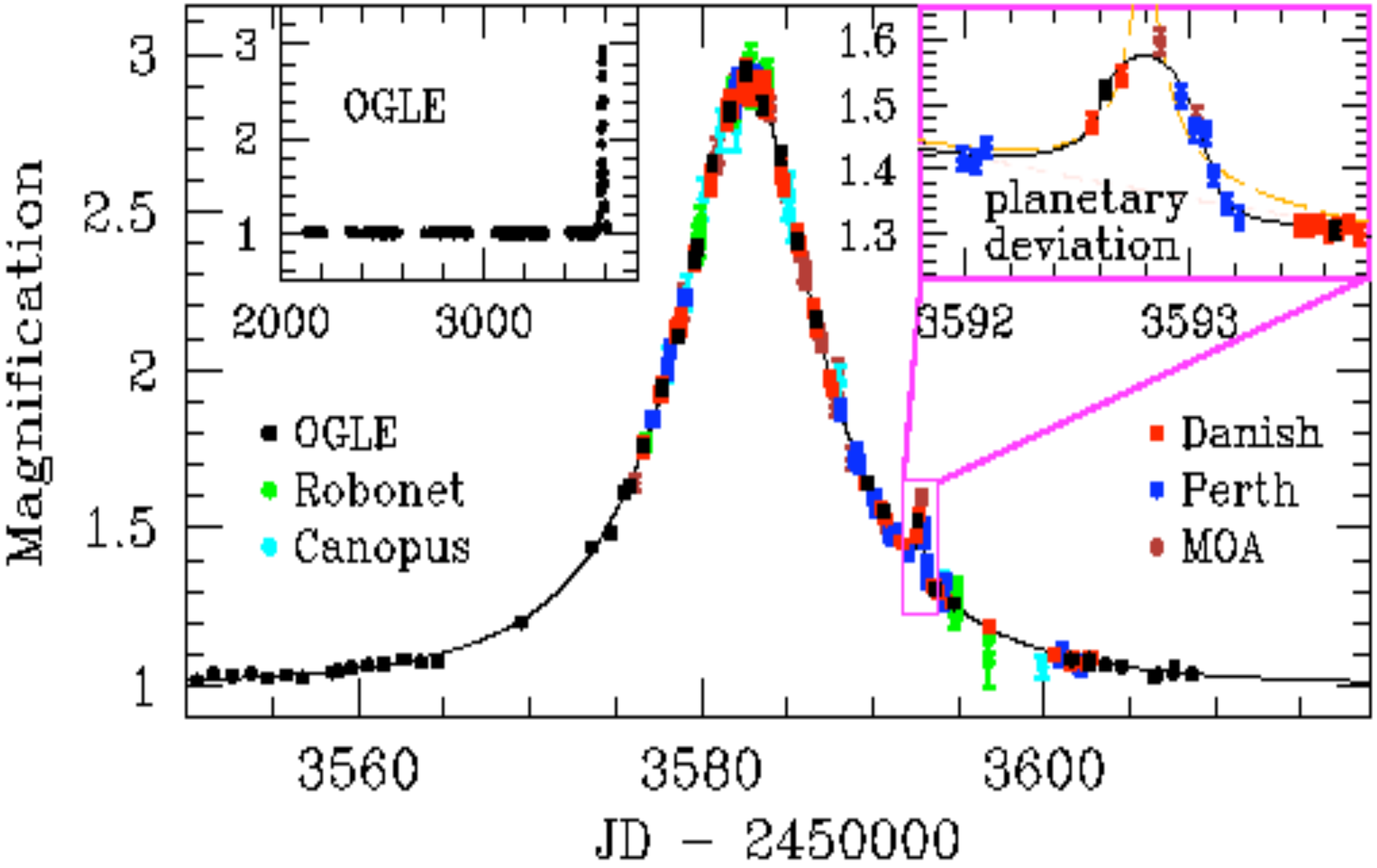
OB-05-390

smallest cool planet

$m \sim 5.5\, m_{\oplus}$

$a \sim 2.9$ AU

PLANET/
RoboNet
OGLE
MOA



Beaulieu et al. (2006).

OB-06-109

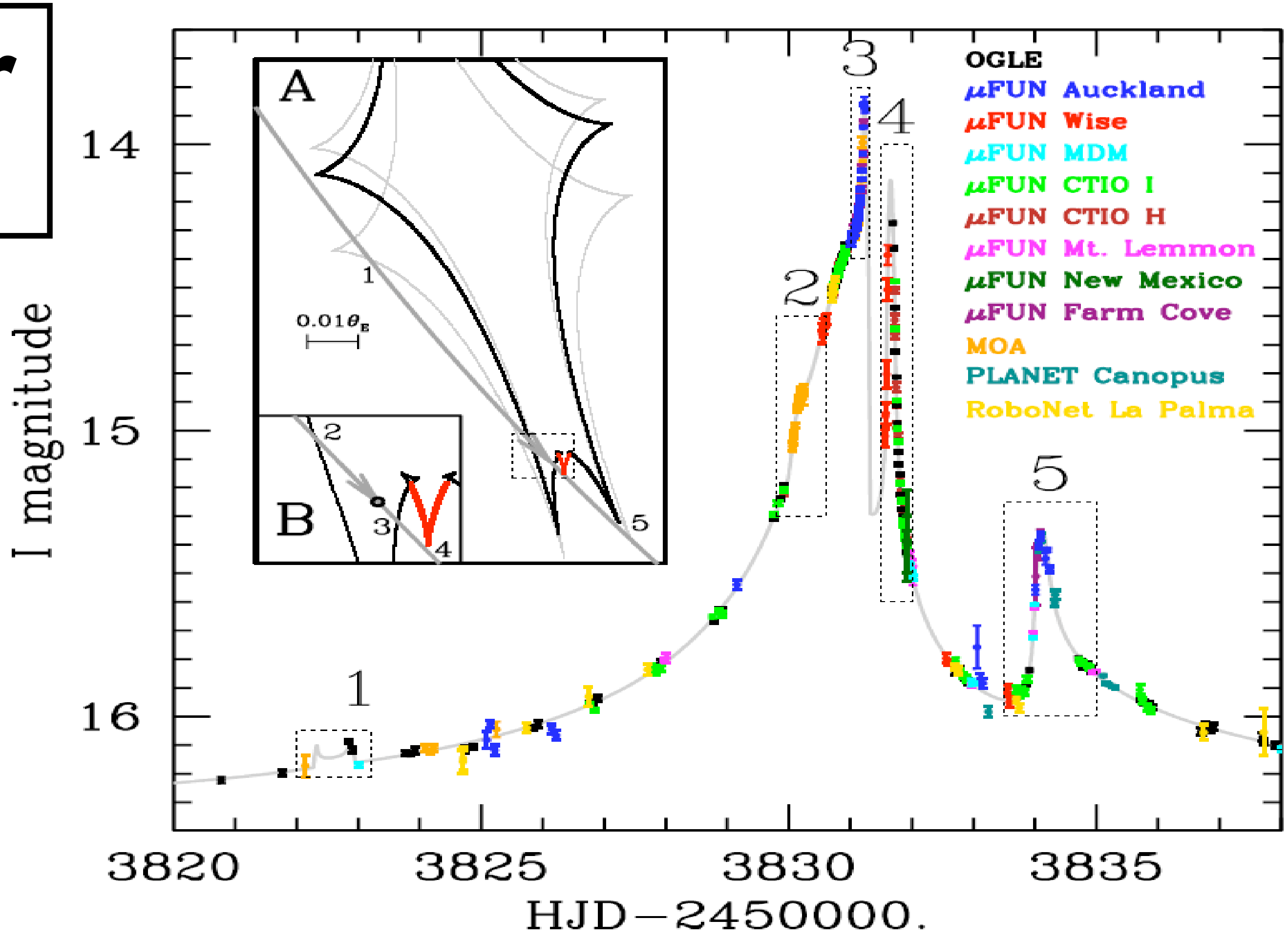
Apr 2006

2 planets detected !

m_b~jupiter
m_c~saturn

OGLE
microFUN

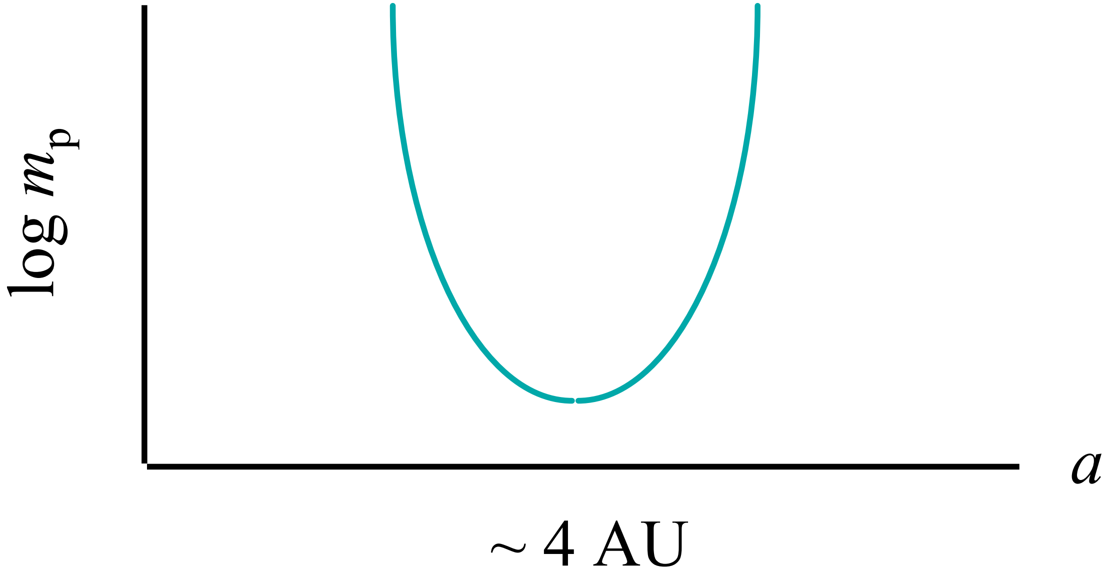
MOA
PLANET/
RoboNet



Gaudi et al. (2008)

Sensitivity to "Cool" Planets

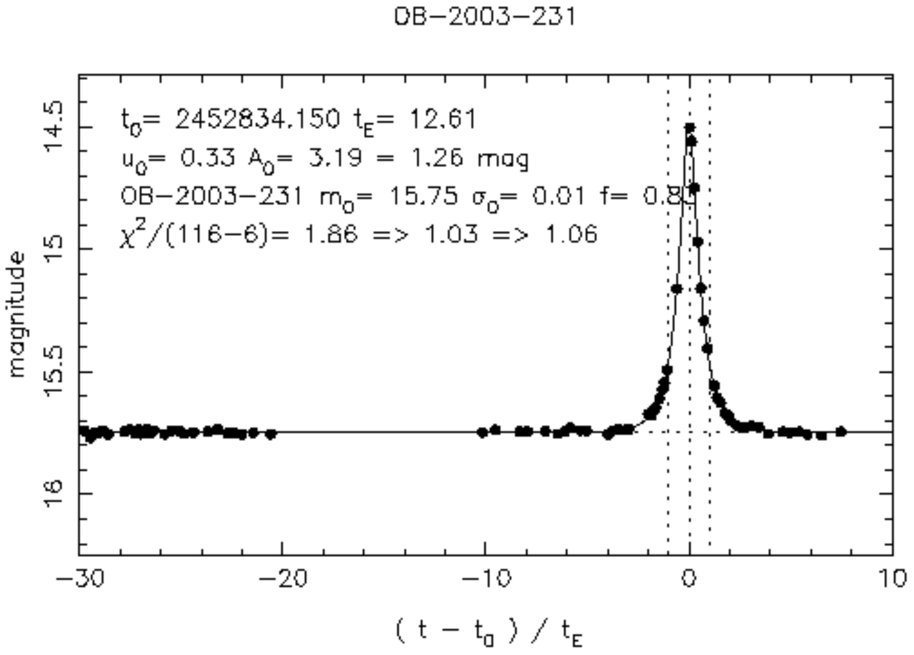
Complementary to other methods:

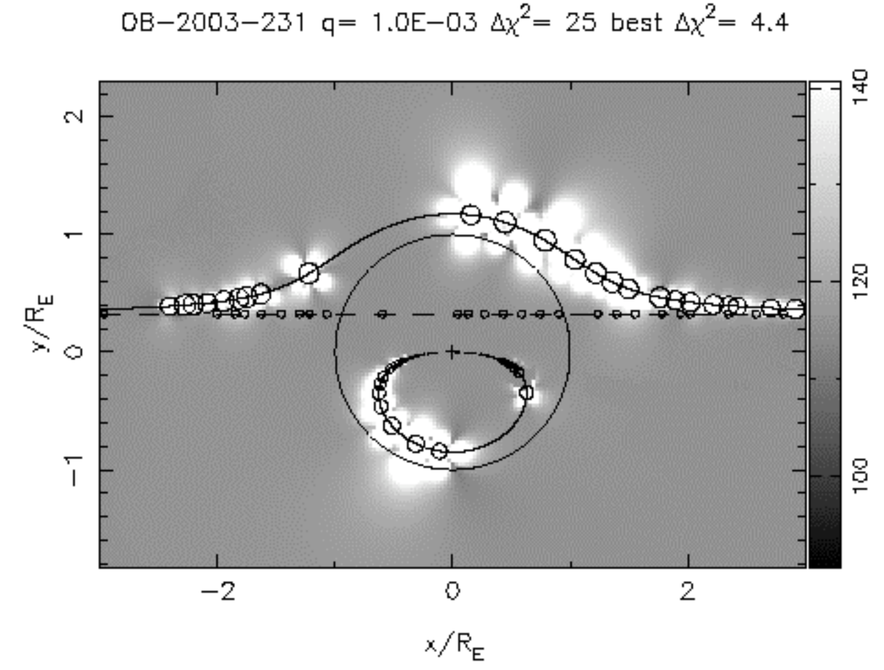


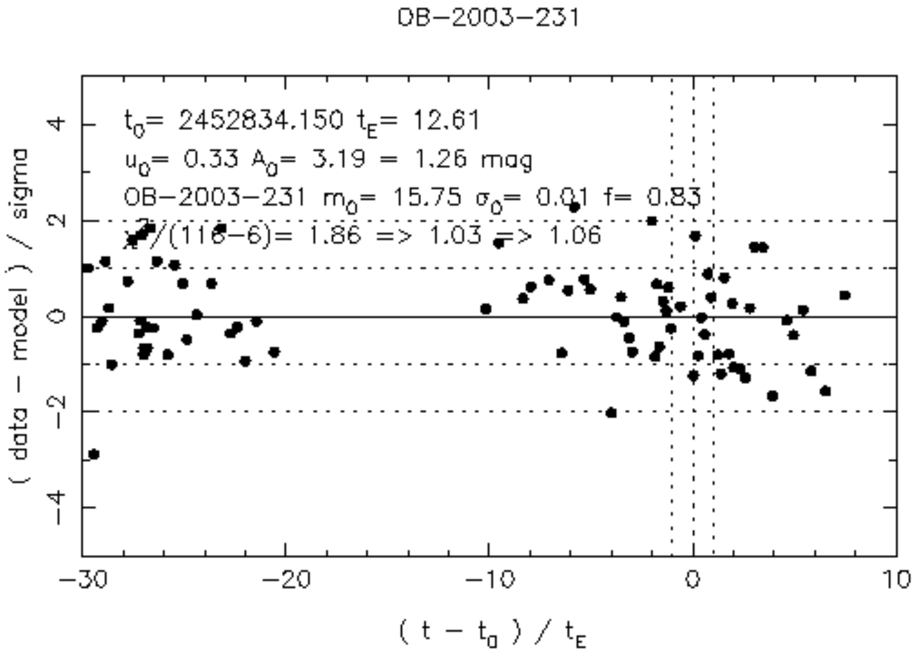
Sensitivity is hard to evaluate: depends on **cadence** of photometric monitoring (high cadence needed for lower masses), **accuracy** of photometry (planets produce weak deviations more often than strong ones)

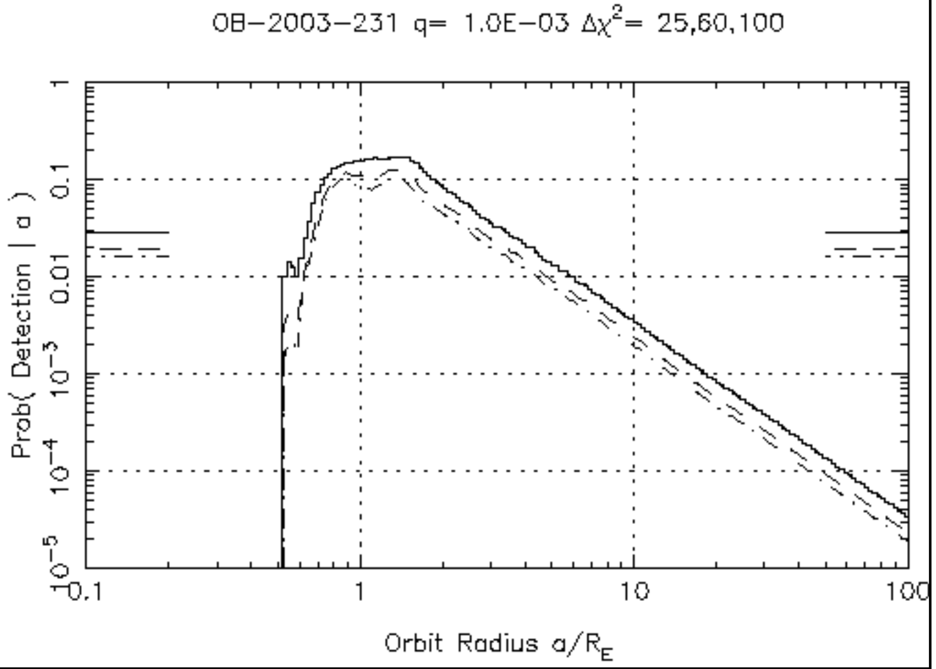
Very roughly: observe with 1-2% accuracy, once per night, detect Jupiters, if present, with 10% efficiency.
Once per hour, detect Earths, if present, with 1% efficiency.

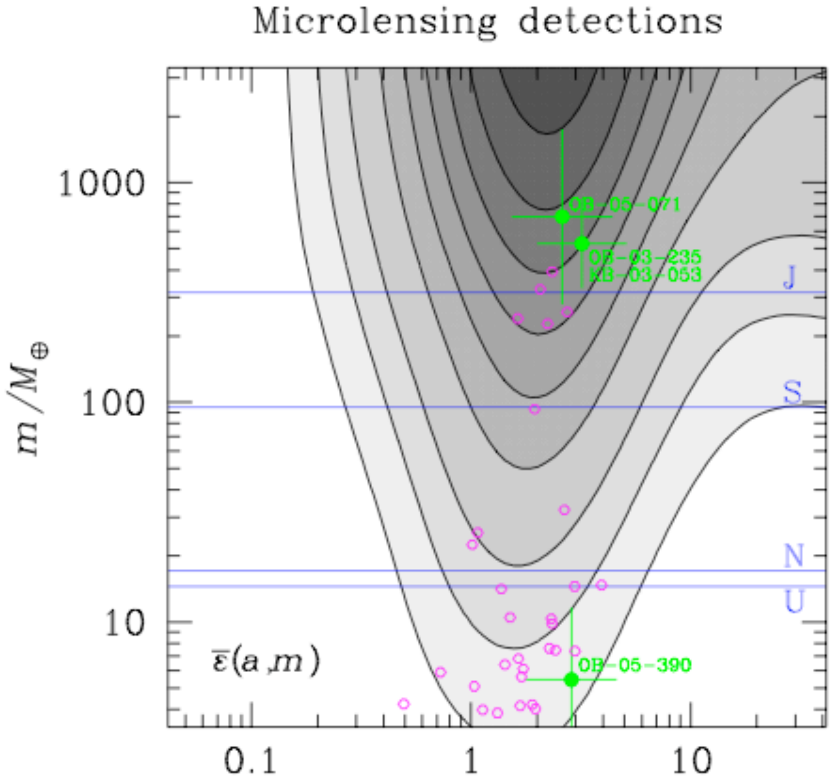
Planet Detection Zones


OB−2003−231

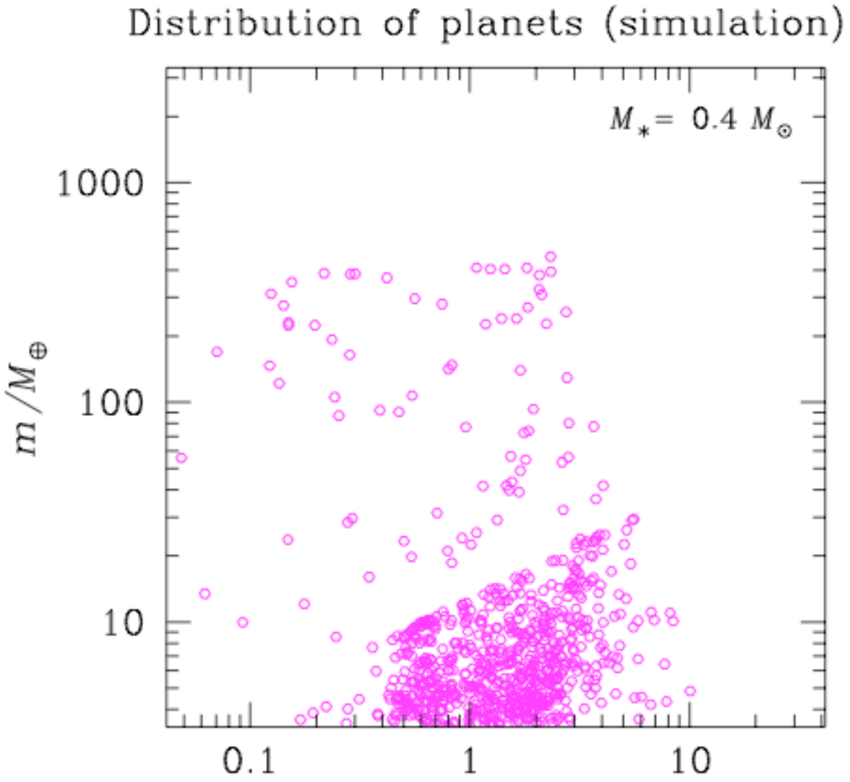

OB−2003−231 q= 1.0E−03 $\Delta\chi^2$= 25 best $\Delta\chi^2$= 4.4


OB−2003−231


OB−2003−231 q= 1.0E−03 $\Delta\chi^2$= 25,60,100



Microlensing detections



Distribution of planets (simulation)

More (Smaller) Cool Planets to Come!

Mass function of Cool Planets

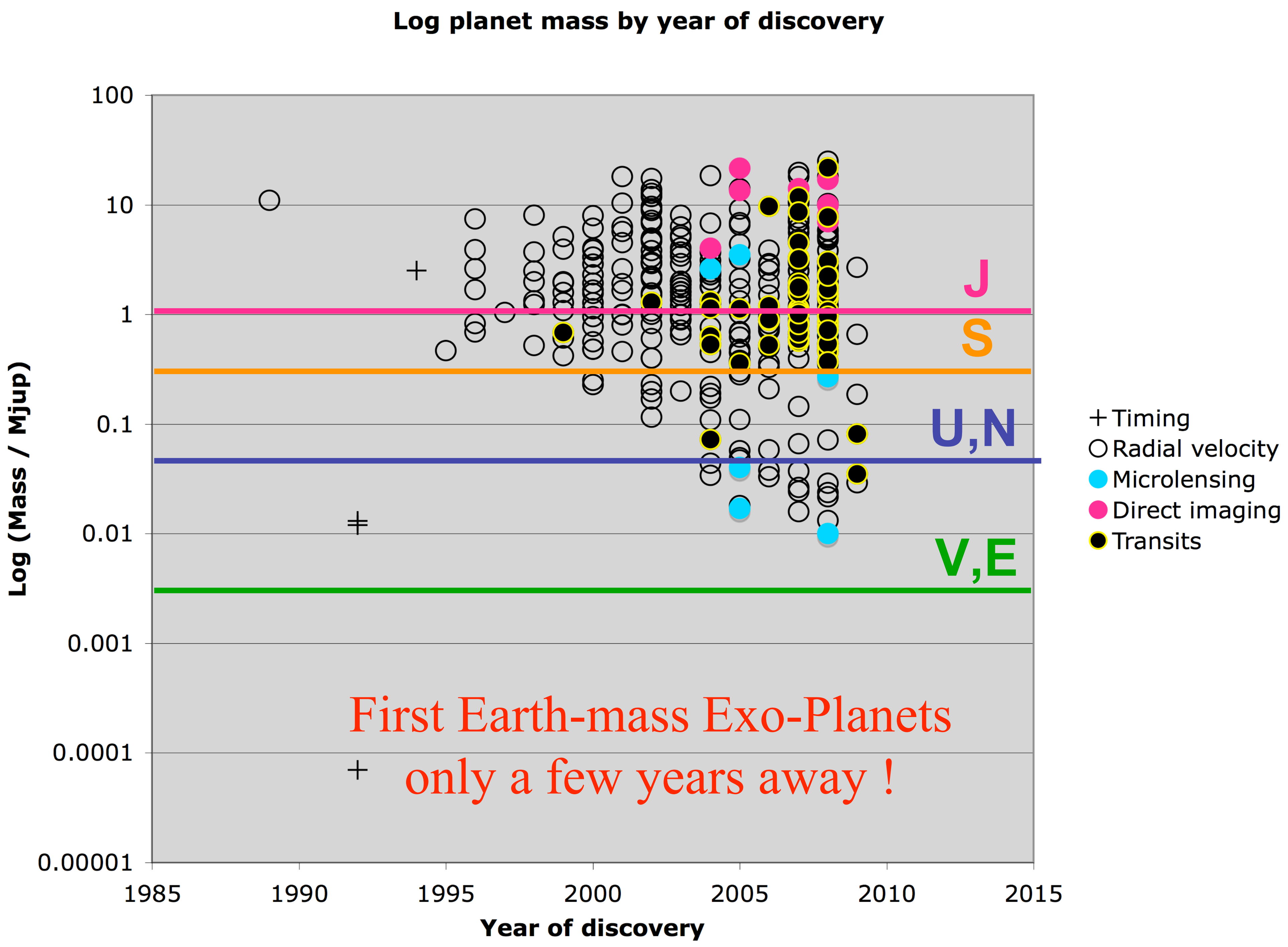
tests Planet Formation / Migration Theory

Microlensing Planets

- 10 planets have been found by microlensing,
including a 5.5 Earth-mass object and a multi-planet system.
- Typical lens stars are 0.3 M_{sun} (0.1 - 2 M_{sun})
- Sensitive to “cool” planets at ~ 4 AU, outside the “Snow Line”.
- Determine planet mass, orbit size, star mass, distance.
- **Earth-mass planets can be detected.**

- Monitoring microlensing events takes a lot of time on small telescopes around the world.

- Planet detections are made, but sometimes ambiguous.
- Degeneracy in microlensing light curves -- one lightcurve has several possible solutions for the properties of the source.
- No repeat observations. One time event. Get no more information about the planet-star system.



First Earth-mass Exo-Planets
only a few years away !