# GRAVITATIONAL LENSING

## LECTURE 13

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*AA 2015-2016*

# TODAY'S LECTURE

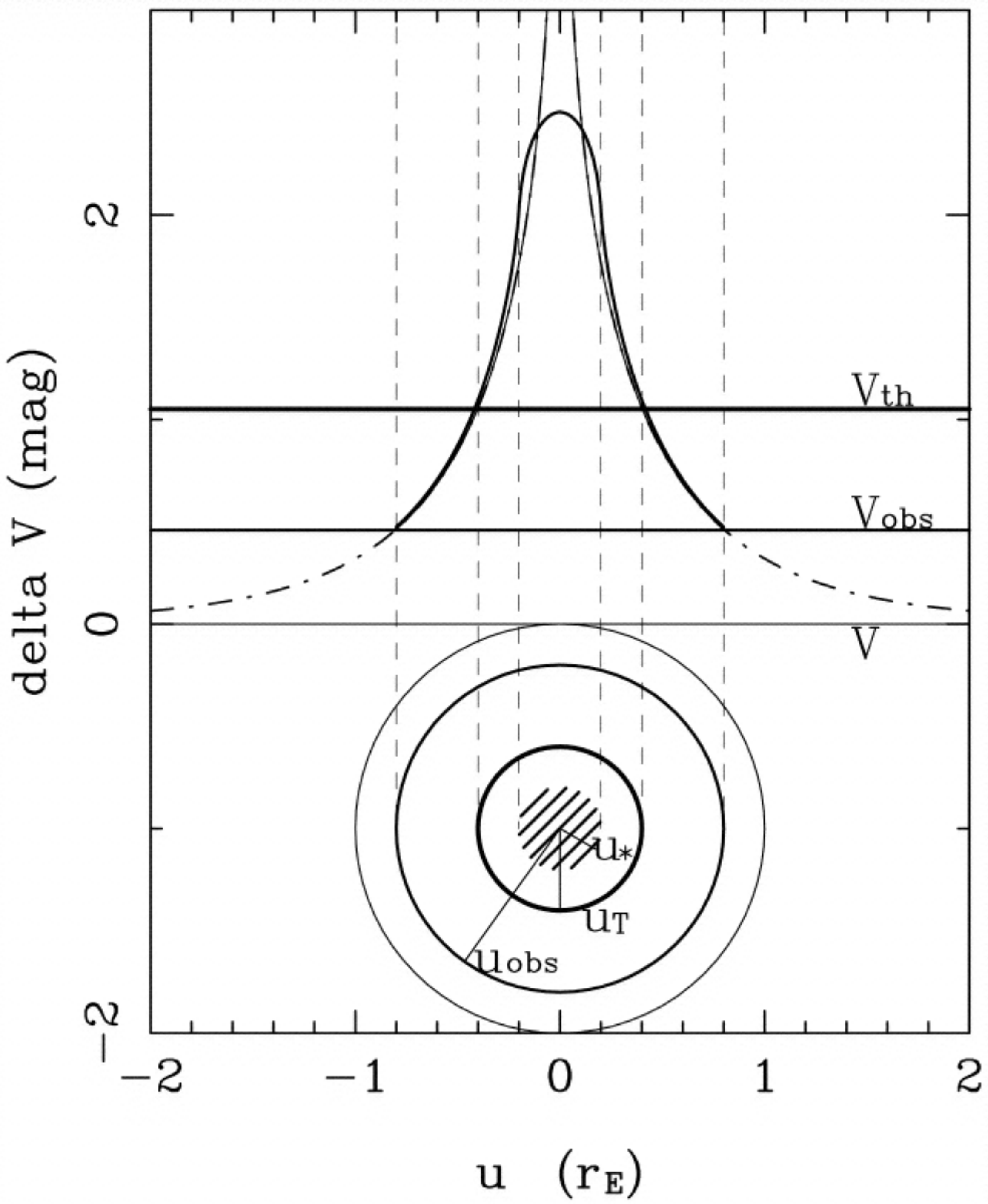
- Second order effects in the microlensing light curves
- Relevant results of microlensing
- The future of microlensing

# SECOND ORDER EFFECTS IN THE MICROLENSING LIGHT CURVES

- finite source size
- light from the lens
- direct measurement of the proper motion
- microlens parallax

# FINITE SOURCE SIZE

- microlensing events are detectable when the source passes close or onto the caustics of the lens
- if the source is not point-like, the effect of magnification will be smeared out
- this effect can be used to infer the angular size of the source in units of the Einstein ring radius
- it is often possible to measure the size of the source via its intrinsic color and magnitude using empirical color-surface brightness relations (Kervella et al. 2004)
- in these cases, it is possible to measure the Einstein radius!
- combining with the Einstein cr. time we can measure the proper motion



$$\rho = \frac{\theta_\star}{\theta_E} \qquad \theta_E = \theta_\star \frac{t_E}{t_\star}$$

$$\frac{M}{D_{rel}} = \frac{c^2}{4G}\theta_E^2 \qquad \mu_{rel} = \frac{v}{D_L} = \frac{\theta_E}{t_E}$$

# LIGHT FROM THE LENSES

- When the light of the lens is observable, additional information can be derived

$$F(t) = F_s \mu(t) + F_b$$

- combining the lens flux with a model for extinction as a function of distance and a mass luminosity relation yields a mass distance relationship for the lens

$$A_\lambda = f(D_L)$$

$$M \propto L^\alpha$$

$$\Downarrow$$

$$M \propto D_L$$

- if multi-band observations are available: color-mass empirical relation

$$C_\lambda = g(M)$$

$$\Downarrow$$

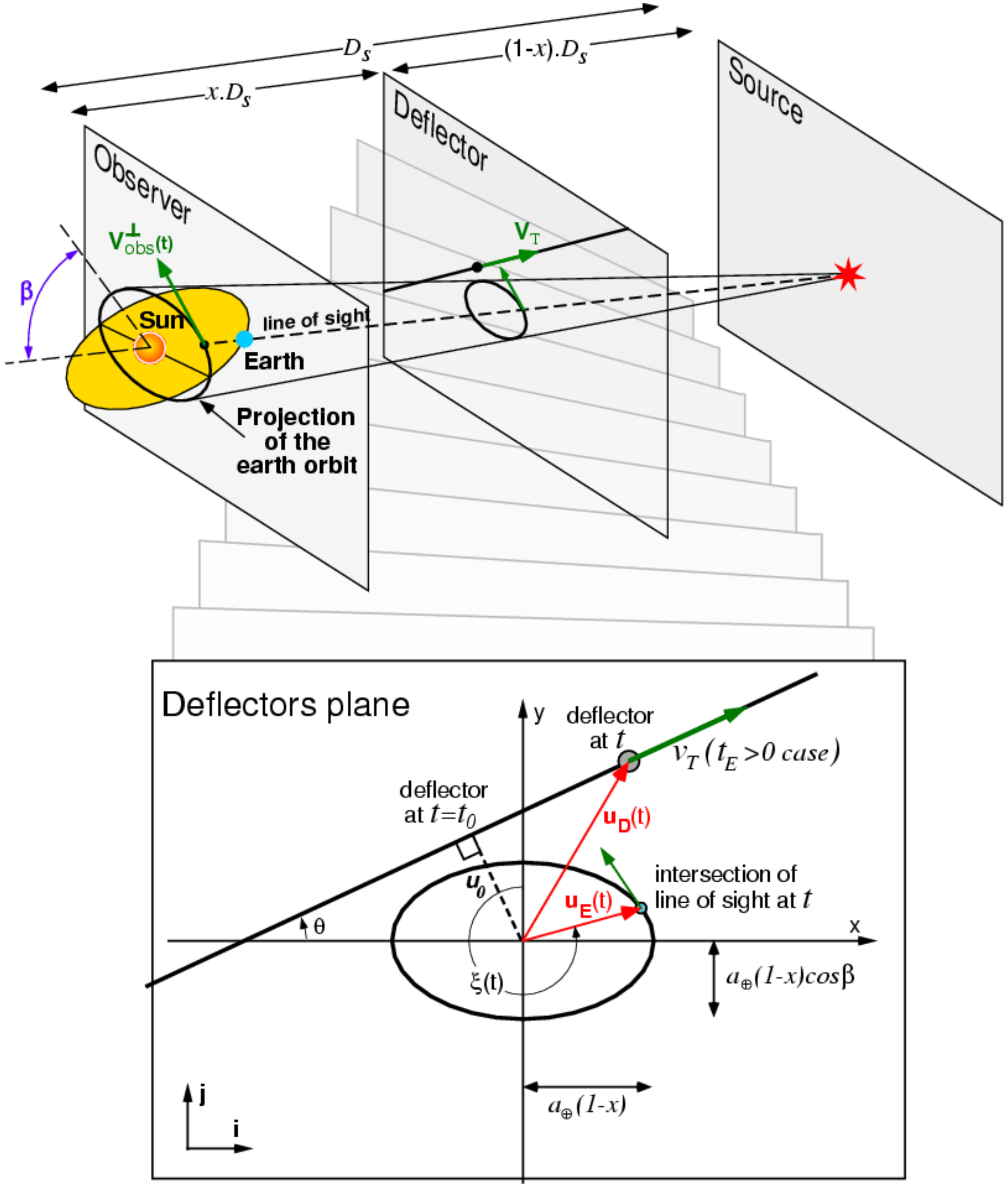
$$M, D_L$$

# DIRECT MEASUREMENT OF THE PROPER MOTION

- When the lens and the source can be resolved (e.g. using AO or HST), then it is possible to measure directly the proper motion
- For example, typical $\mu_{rel} \sim 5\text{-}10$ mas/year.
- after a few years from the event, the displacement will be ~0.01 arcsec
- proper motion+Einstein cr. time=Einstein radius

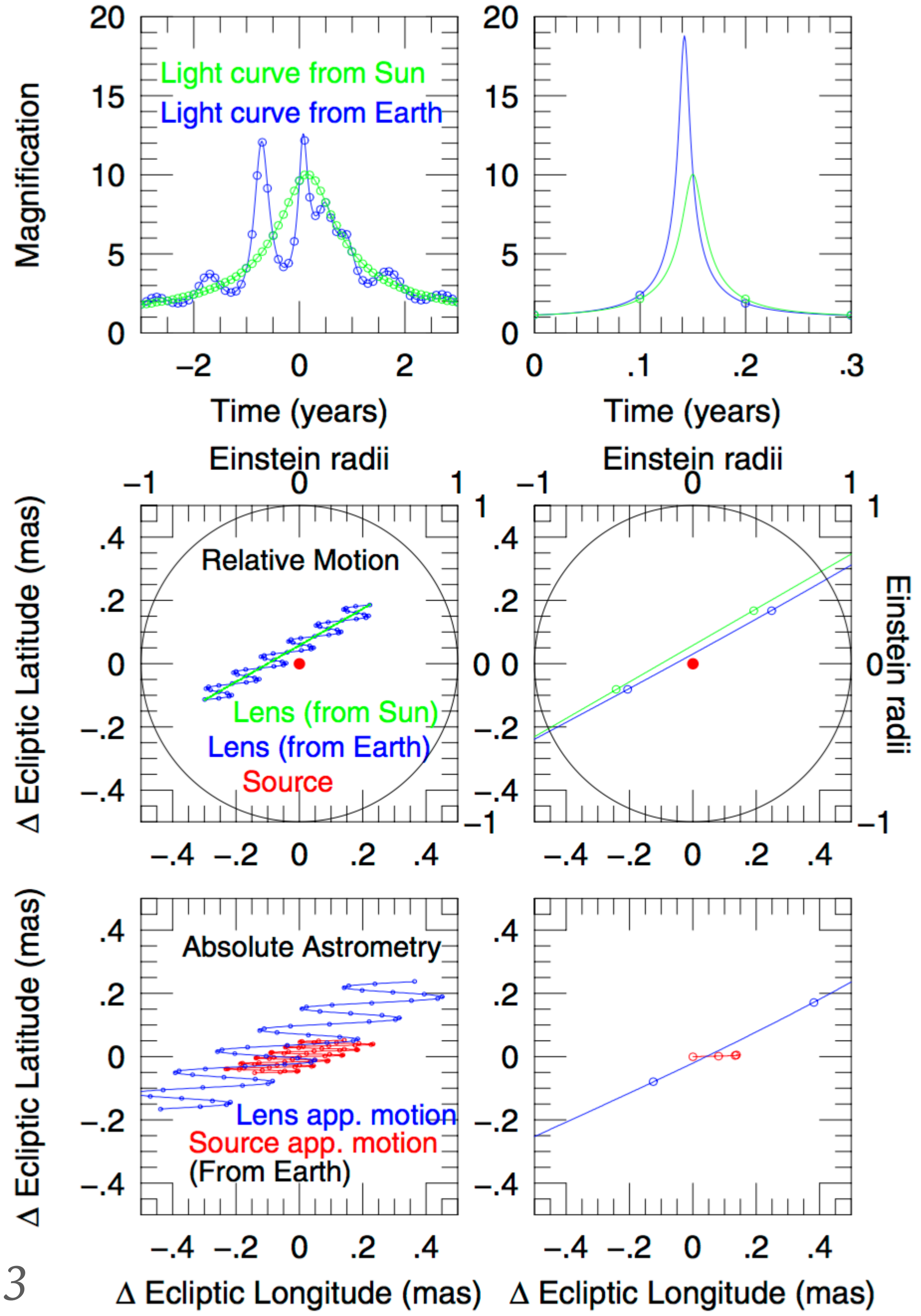
# MICROLENS PARALLAX

- Microlens parallax induces variations of the shape of the (classical) microlensing light curve, because the source trajectory is no longer rectilinear
- it can be due e.g. to the orbital motion of the earth around the sun…



# MICROLENS PARALLAX

- on the left: what we would see if the $\mu_{hel}=0.1$ mas/year
- on the right: the typical $\mu_{hel}=5$ mas/year
- the effect is relevant if the change in baseline is a significant fraction of the projected Einstein radius

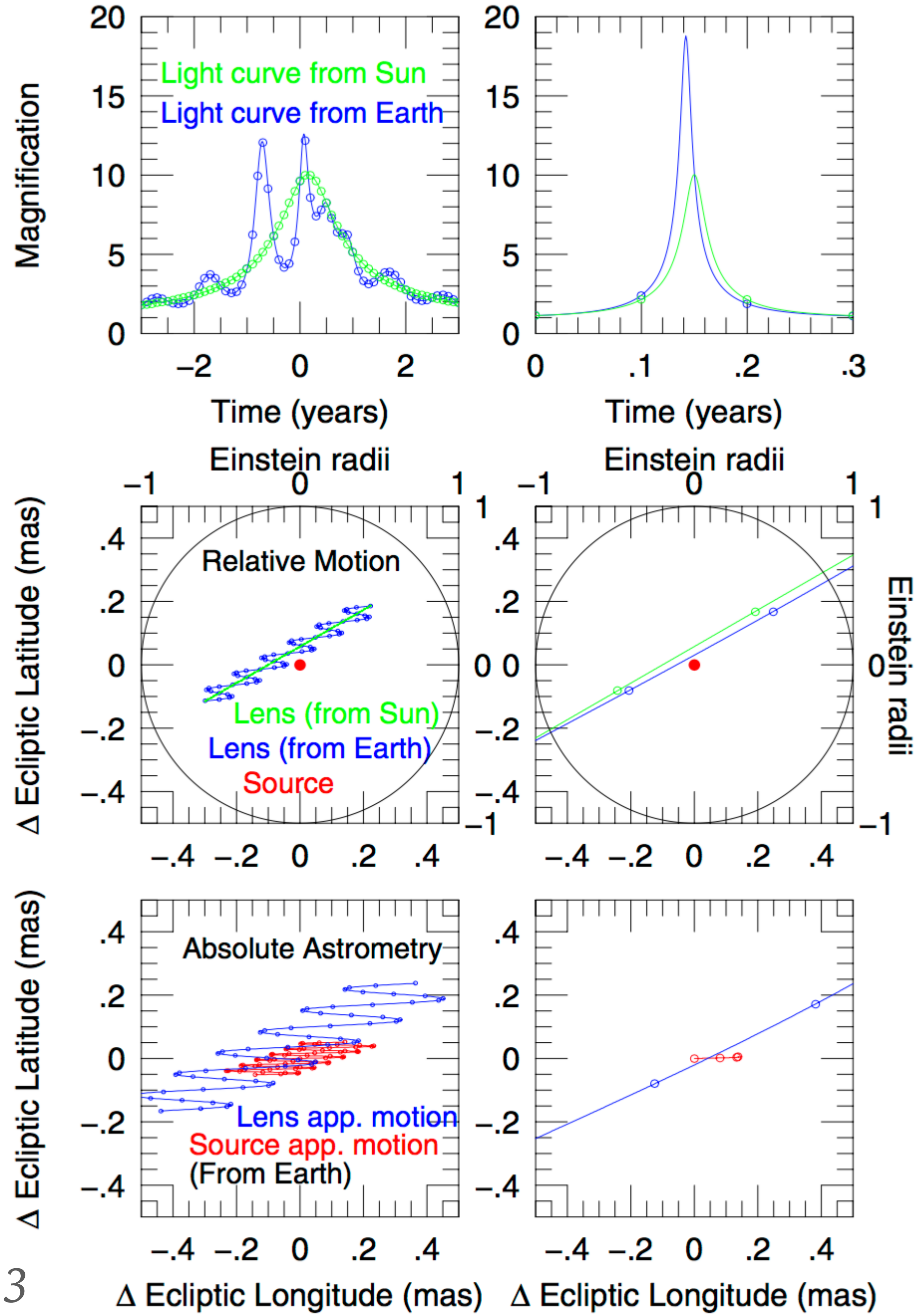


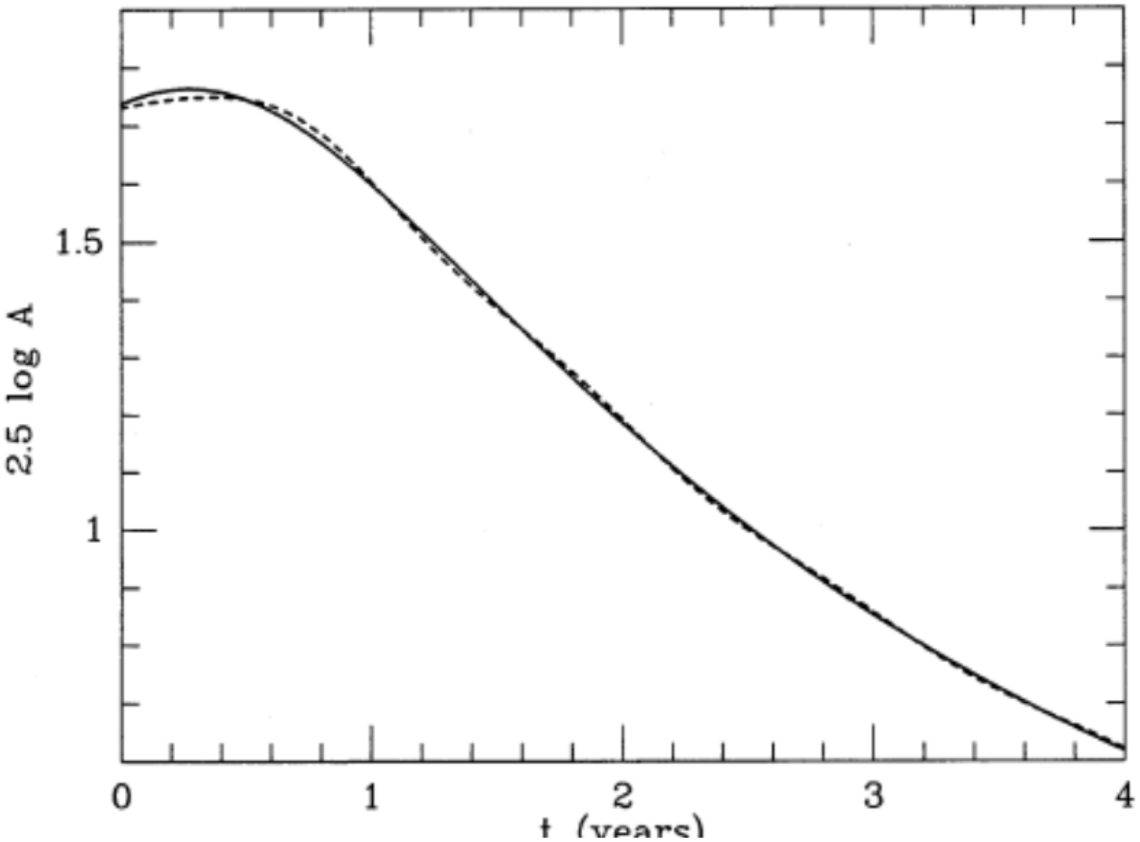
*Gould & Horne, 2013*

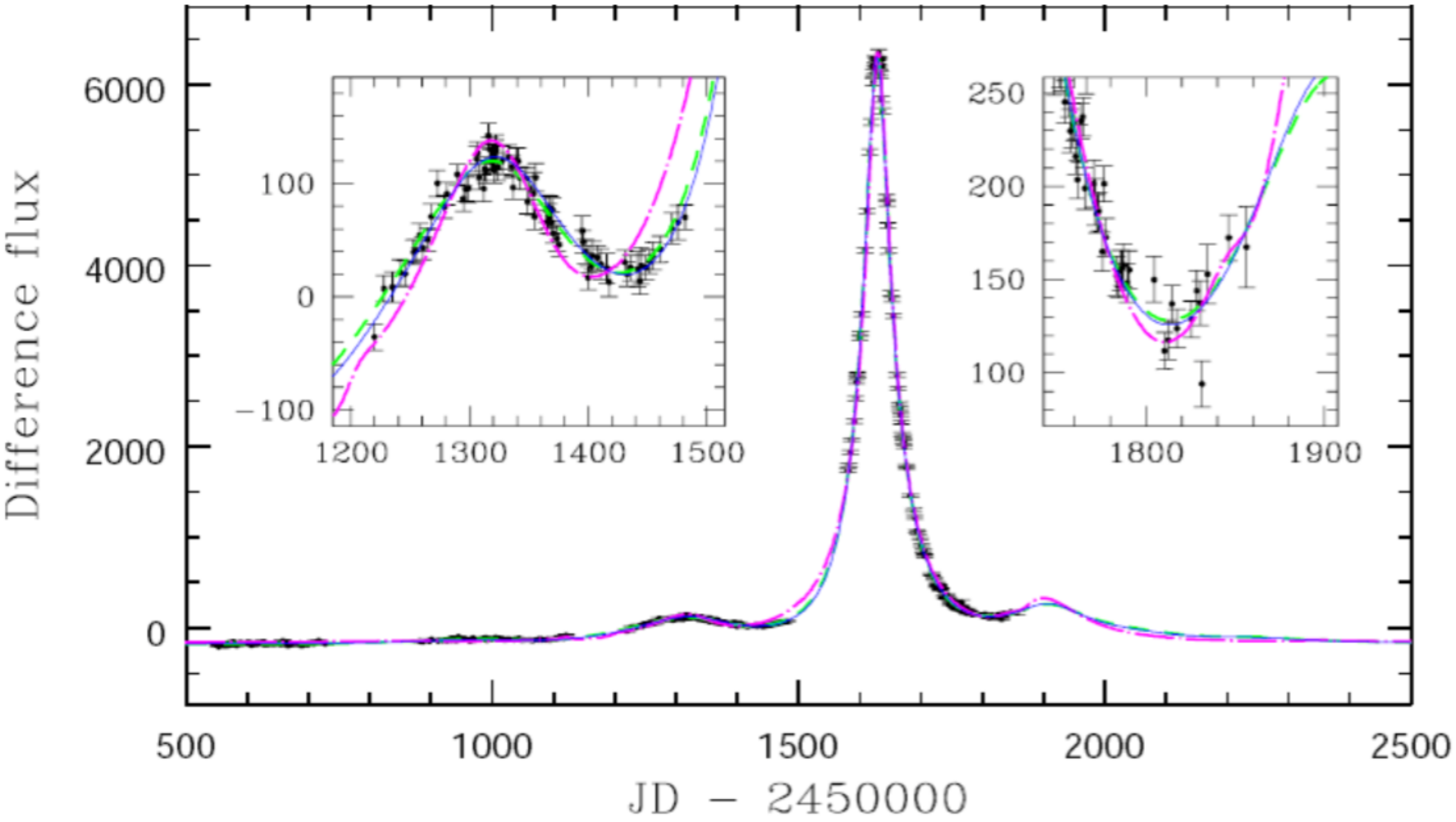
# MICROLENS PARALLAX

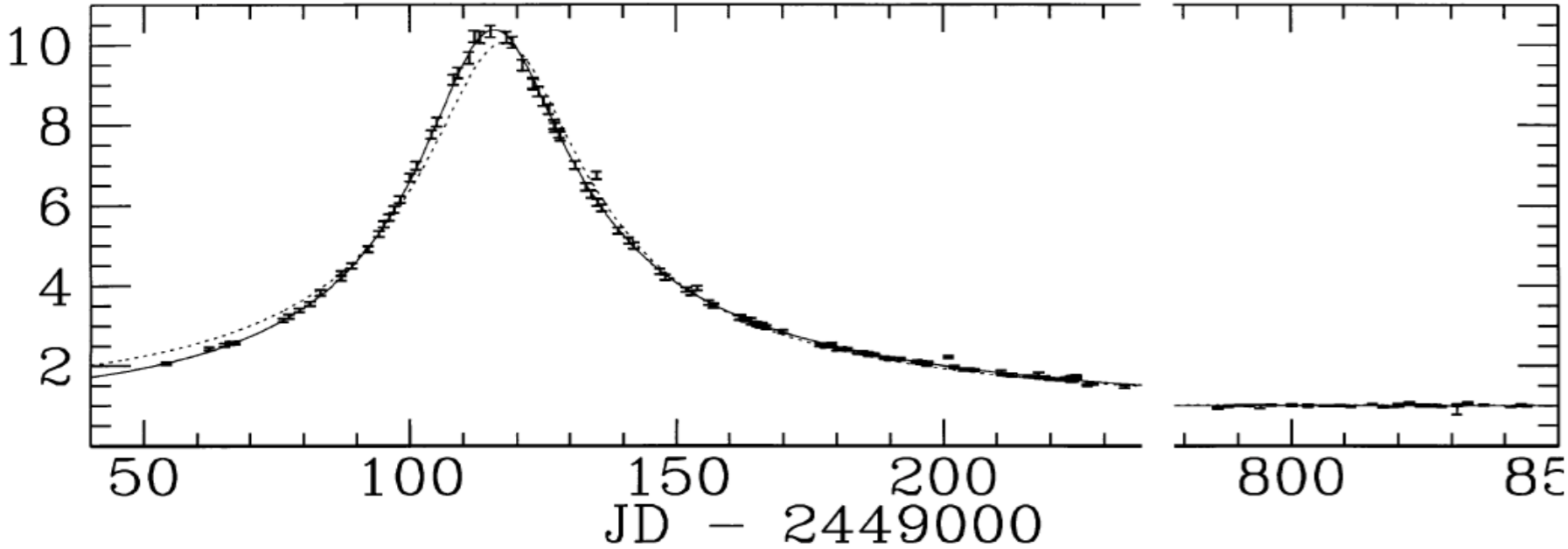
- on the left: what we would see if the $\mu_{hel}=0.1$ mas/year
- on the right: the typical $\mu_{hel}=5$ mas/year
- the effect is relevant if the change in baseline is a significant fraction of the projected Einstein radius
- can be used to measure the ER!

*Gould & Horne, 2013*




2.5 log A
1.5
1
0
1
2
3
4
t (years)

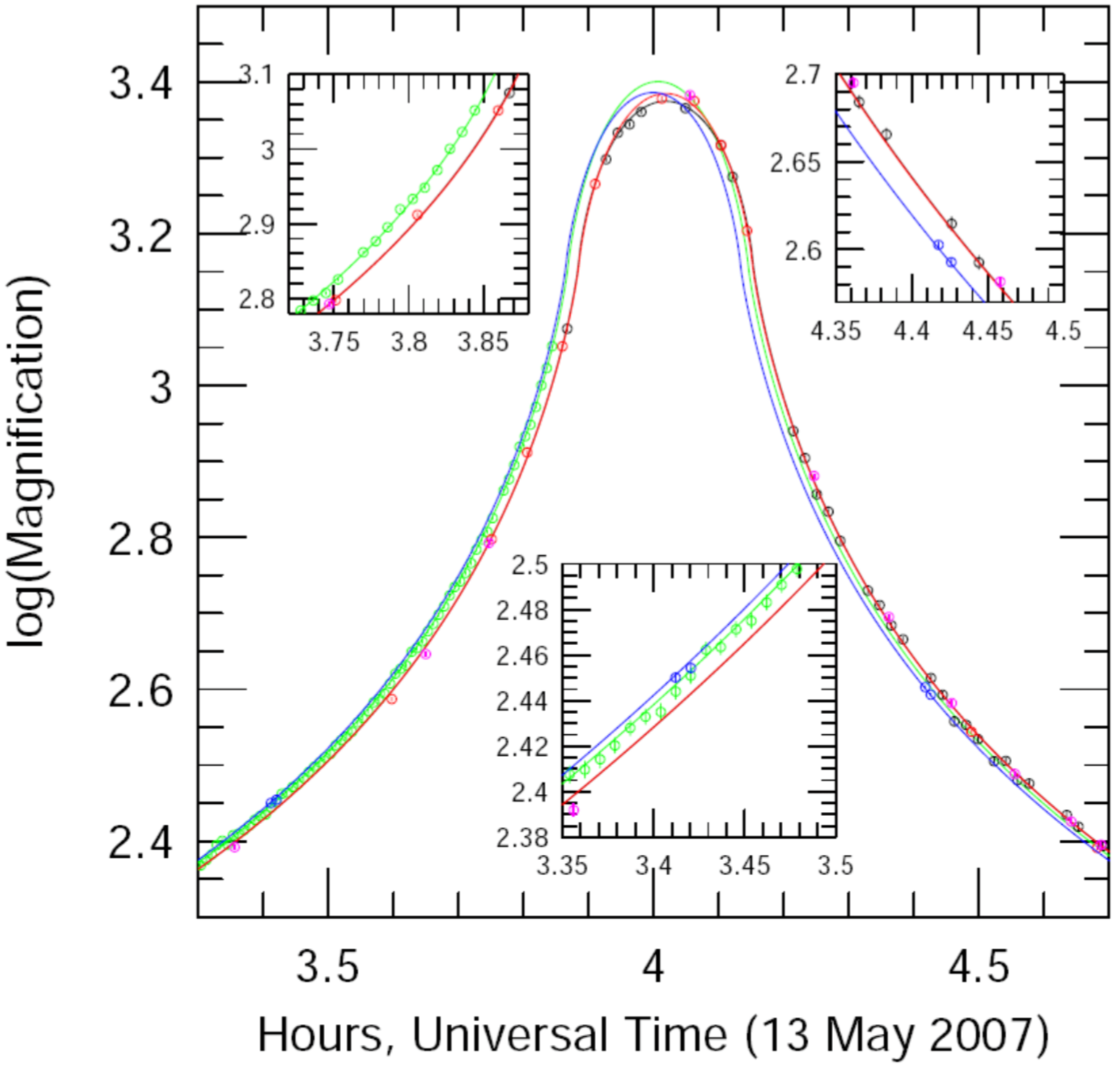

Difference flux
6000
4000
2000
0
500
1000
1500
2000
2500
JD − 2450000
100
0
−100
1200
1300
1400
1500
250
200
150
100
1800
1900

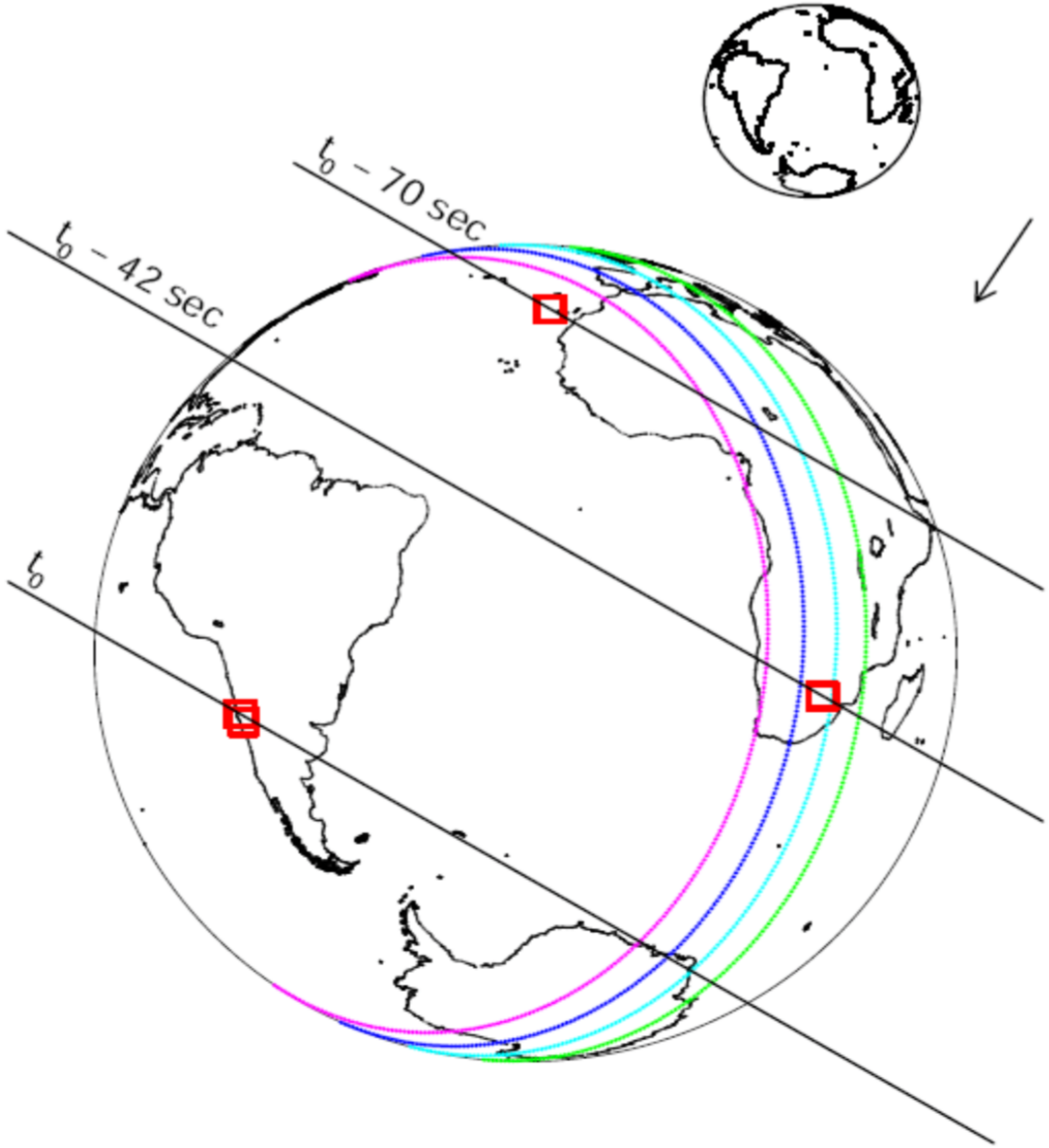

10
8
6
4
2
50
100
150
200
800
85
JD − 2449000

# MICROLENS PARALLAX (TERRESTRIAL)

OGLE-2007-BLG-224

Canaries South Africa Chile

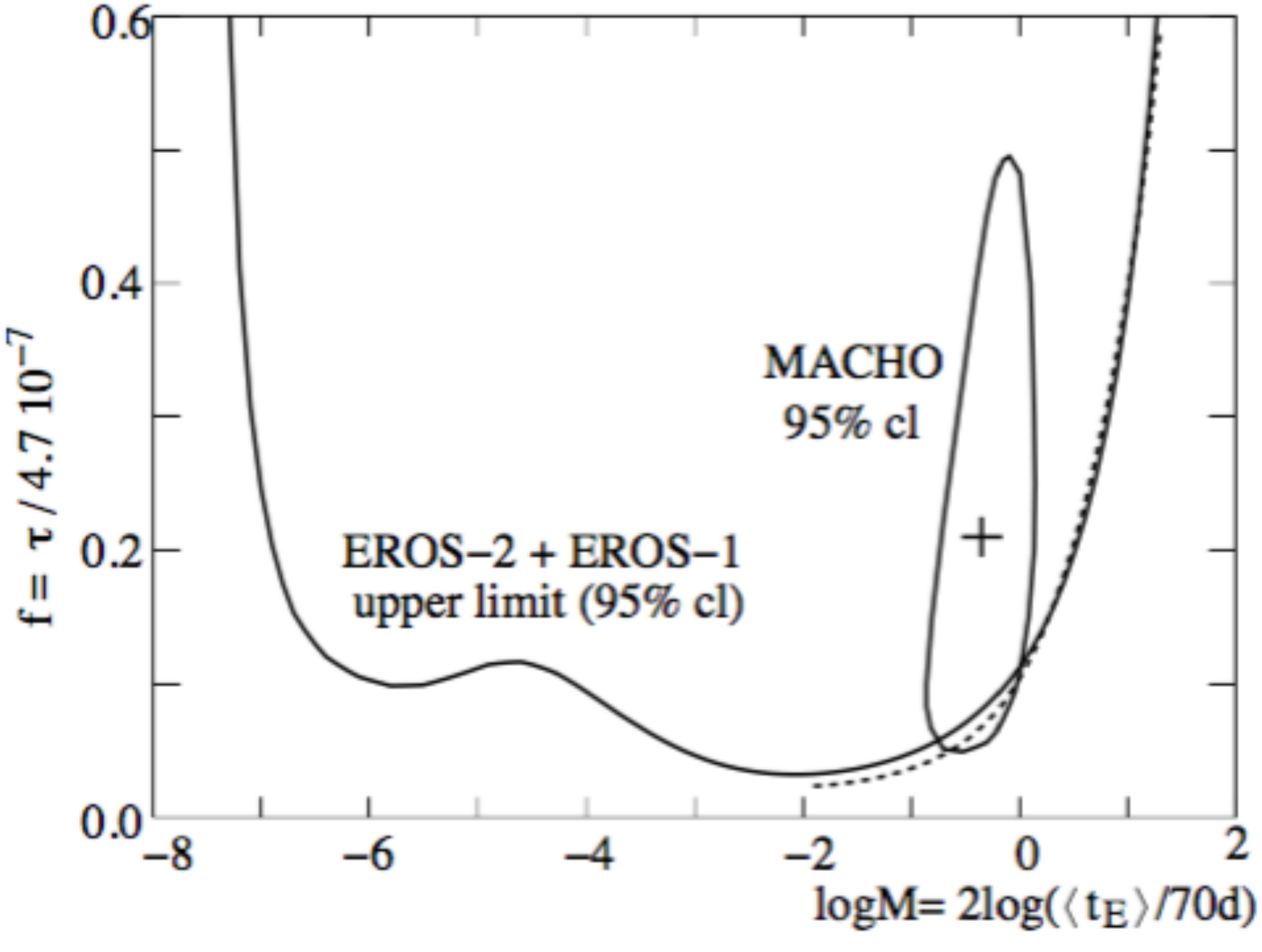




*Gould & Horne, 2013*

# PAST RESULTS IN MICROLENSING RESEARCH

- searches for MACHOs (<20% of the halo)
- galactic structure (essentially, the known stellar populations in the galaxy and in the LMC/SMC can explain all the microlensing signal)



# ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- planets are most easily identified when they are at a distance ∼ER
- example: 1 mas at ∼5kpc=5AU
- peak sensitivity beyond the snow line
- the snow line marks a very important region for planet formation! Giant planets can form only beyond the snow line.

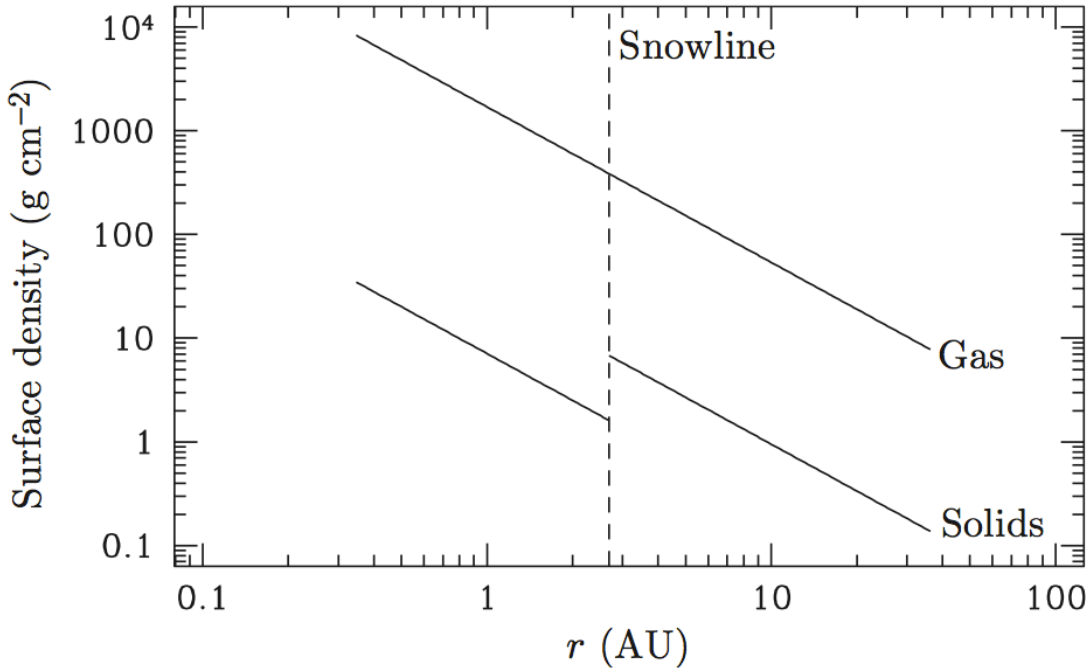
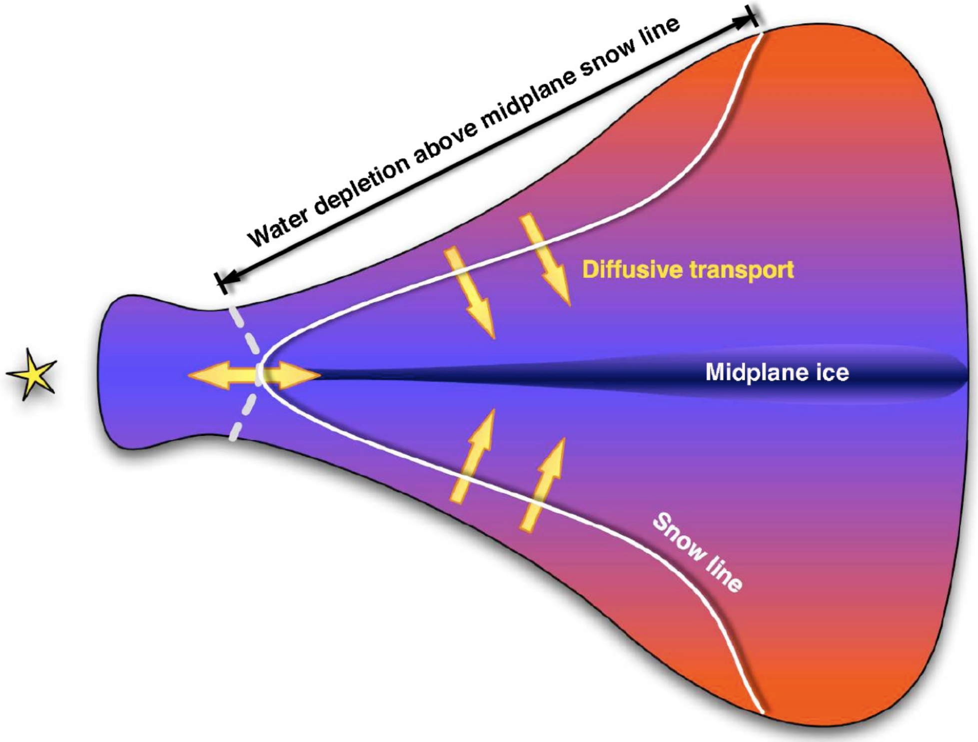
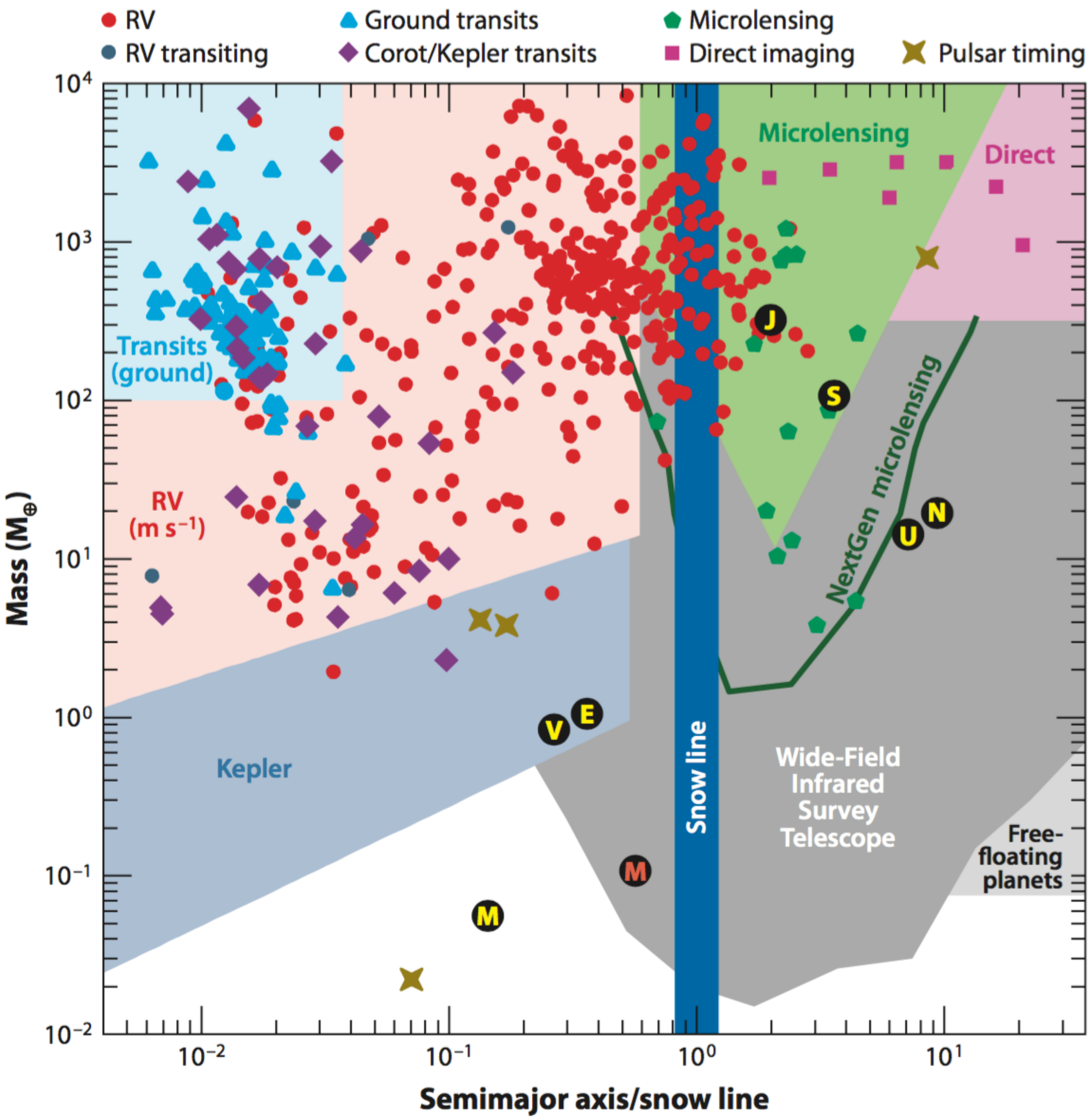


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.



# ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- ~35 planets discovered via microlensing so far
- $d_{min}$=0.66 AU
- bulk of planets at d~3 AU
- wide range of masses
- complementary technique to others that are most sensitive to planets near their host stars (transits, radial velocity)

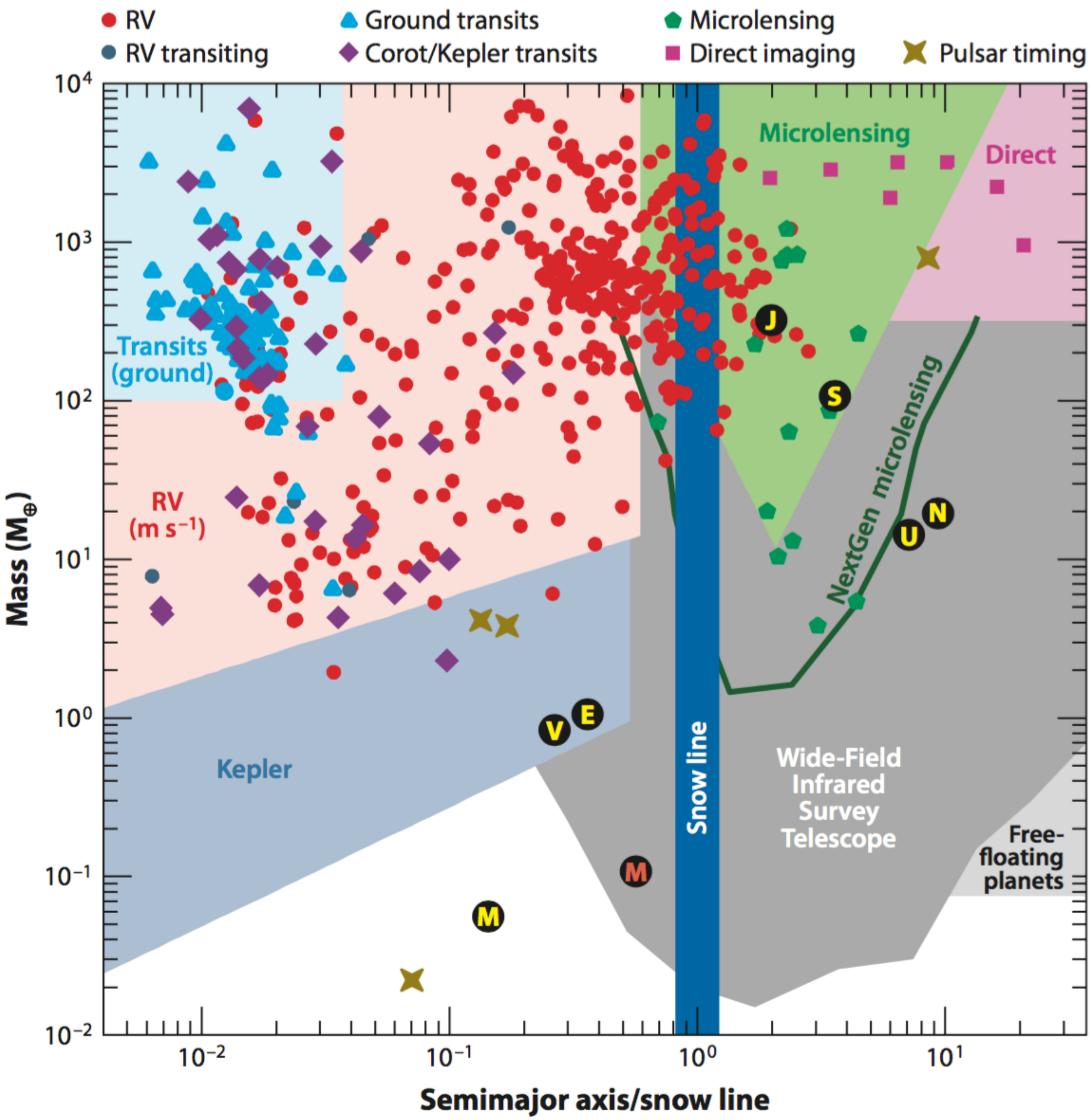


# OTHER ADVANTAGES…

- sensitivity to low-mass planets
- sensitivity to long period and free-floating planets
- sensitivity to a wide range of host stars over a wide range of galactocentric distances
- sensitivity to multiple planets

# …AND DISADVANTAGES

- small numbers compared to other methods (~2000 exoplanets confirmed to date)
- little sensitivity to the habitable zone
- faint and distant hosts
- limited information about the host and the planet



# HOW ARE PLANETS SEARCHED FOR?

- first generation of surveys: from MACHO searches to planets
- alert and follow-up
- survey teams (Optical Gravitational Lensing Experiment, OGLE; Microlensing Observations in Astrophysics, MOA) use medium size telescopes with relatively wide cameras to monitor the bulge or the MC with a cadence of few observations per day
- real-time data reduction and alerting in case of promising events
- follow-up teams (Probing Lensing Anomalies NETwork, PLANET; RoboNet; Microlensing Network for the Detection of Small Terrestrial planets, MiNDSTEp; Microlensing Follow-up Network, μFun) monitor on timescales of hours
- this strategy privileges intermediate-high-magnification events.
- likely to yield many central or resonant caustic events

# LIST OF MICROLENSING PLANETS (BEFORE 2013)

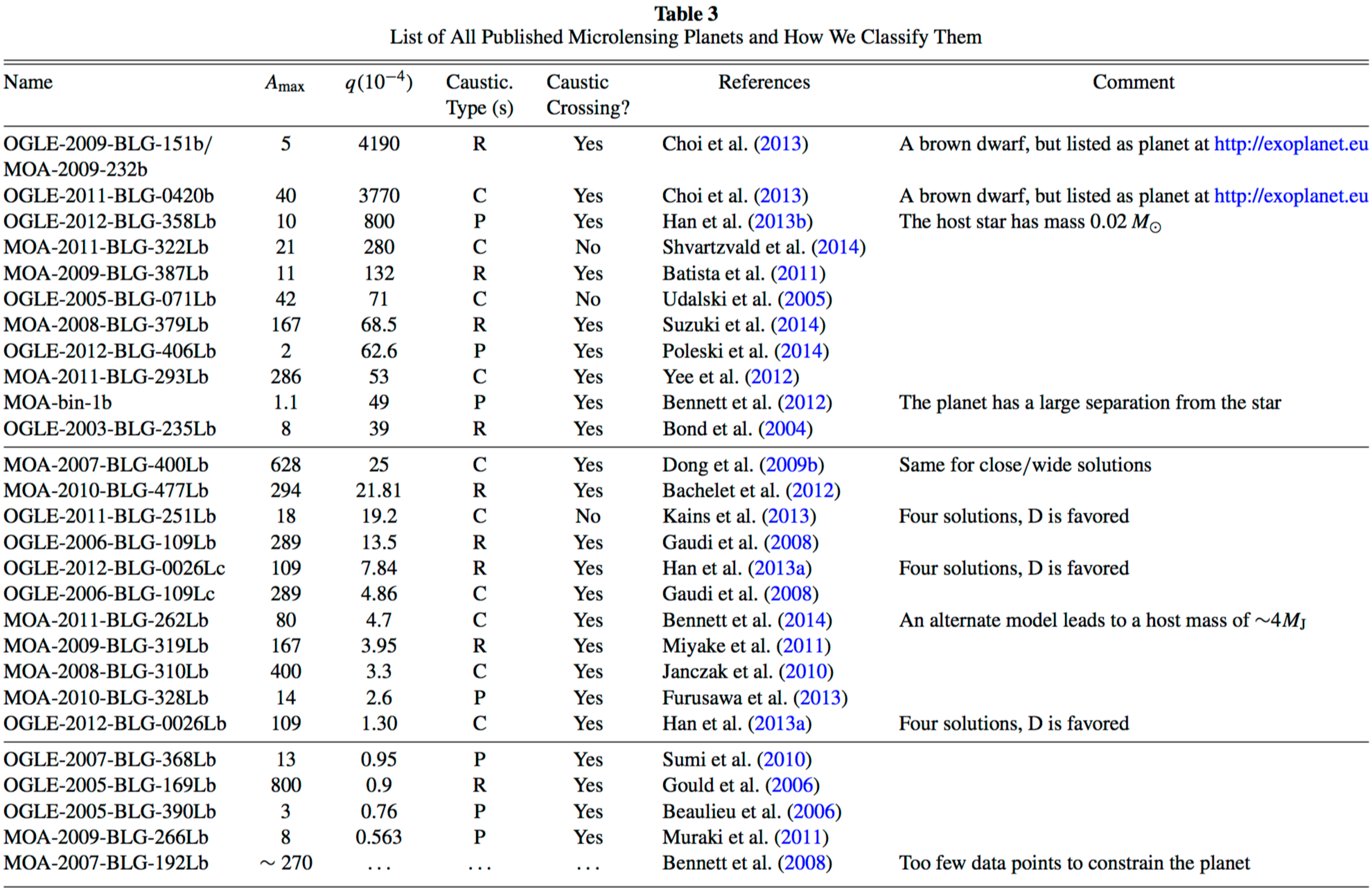


**Table 3**

List of All Published Microlensing Planets and How We Classify Them

| Name | $A_{\max}$ | $q(10^{-4})$ | Caustic. Type (s) | Caustic Crossing? | References | Comment |
|---|---|---|---|---|---|---|
| OGLE-2009-BLG-151b/ MOA-2009-232b | 5 | 4190 | R | Yes | Choi et al. (2013) | A brown dwarf, but listed as planet at http://exoplanet.eu |
| OGLE-2011-BLG-0420b | 40 | 3770 | C | Yes | Choi et al. (2013) | A brown dwarf, but listed as planet at http://exoplanet.eu |
| OGLE-2012-BLG-358Lb | 10 | 800 | P | Yes | Han et al. (2013b) | The host star has mass 0.02 $M_\odot$ |
| MOA-2011-BLG-322Lb | 21 | 280 | C | No | Shvartzvald et al. (2014) | |
| MOA-2009-BLG-387Lb | 11 | 132 | R | Yes | Batista et al. (2011) | |
| OGLE-2005-BLG-071Lb | 42 | 71 | C | No | Udalski et al. (2005) | |
| MOA-2008-BLG-379Lb | 167 | 68.5 | R | Yes | Suzuki et al. (2014) | |
| OGLE-2012-BLG-406Lb | 2 | 62.6 | P | Yes | Poleski et al. (2014) | |
| MOA-2011-BLG-293Lb | 286 | 53 | C | Yes | Yee et al. (2012) | |
| MOA-bin-1b | 1.1 | 49 | P | Yes | Bennett et al. (2012) | The planet has a large separation from the star |
| OGLE-2003-BLG-235Lb | 8 | 39 | R | Yes | Bond et al. (2004) | |
| MOA-2007-BLG-400Lb | 628 | 25 | C | Yes | Dong et al. (2009b) | Same for close/wide solutions |
| MOA-2010-BLG-477Lb | 294 | 21.81 | R | Yes | Bachelet et al. (2012) | |
| OGLE-2011-BLG-251Lb | 18 | 19.2 | C | No | Kains et al. (2013) | Four solutions, D is favored |
| OGLE-2006-BLG-109Lb | 289 | 13.5 | R | Yes | Gaudi et al. (2008) | |
| OGLE-2012-BLG-0026Lc | 109 | 7.84 | R | Yes | Han et al. (2013a) | Four solutions, D is favored |
| OGLE-2006-BLG-109Lc | 289 | 4.86 | C | Yes | Gaudi et al. (2008) | |
| MOA-2011-BLG-262Lb | 80 | 4.7 | C | Yes | Bennett et al. (2014) | An alternate model leads to a host mass of $\sim 4 M_{\rm J}$ |
| MOA-2009-BLG-319Lb | 167 | 3.95 | R | Yes | Miyake et al. (2011) | |
| MOA-2008-BLG-310Lb | 400 | 3.3 | C | Yes | Janczak et al. (2010) | |
| MOA-2010-BLG-328Lb | 14 | 2.6 | P | Yes | Furusawa et al. (2013) | |
| OGLE-2012-BLG-0026Lb | 109 | 1.30 | C | Yes | Han et al. (2013a) | Four solutions, D is favored |
| OGLE-2007-BLG-368Lb | 13 | 0.95 | P | Yes | Sumi et al. (2010) | |
| OGLE-2005-BLG-169Lb | 800 | 0.9 | R | Yes | Gould et al. (2006) | |
| OGLE-2005-BLG-390Lb | 3 | 0.76 | P | Yes | Beaulieu et al. (2006) | |
| MOA-2009-BLG-266Lb | 8 | 0.563 | P | Yes | Muraki et al. (2011) | |
| MOA-2007-BLG-192Lb | $\sim 270$ | ... | ... | ... | Bennett et al. (2008) | Too few data points to constrain the planet |

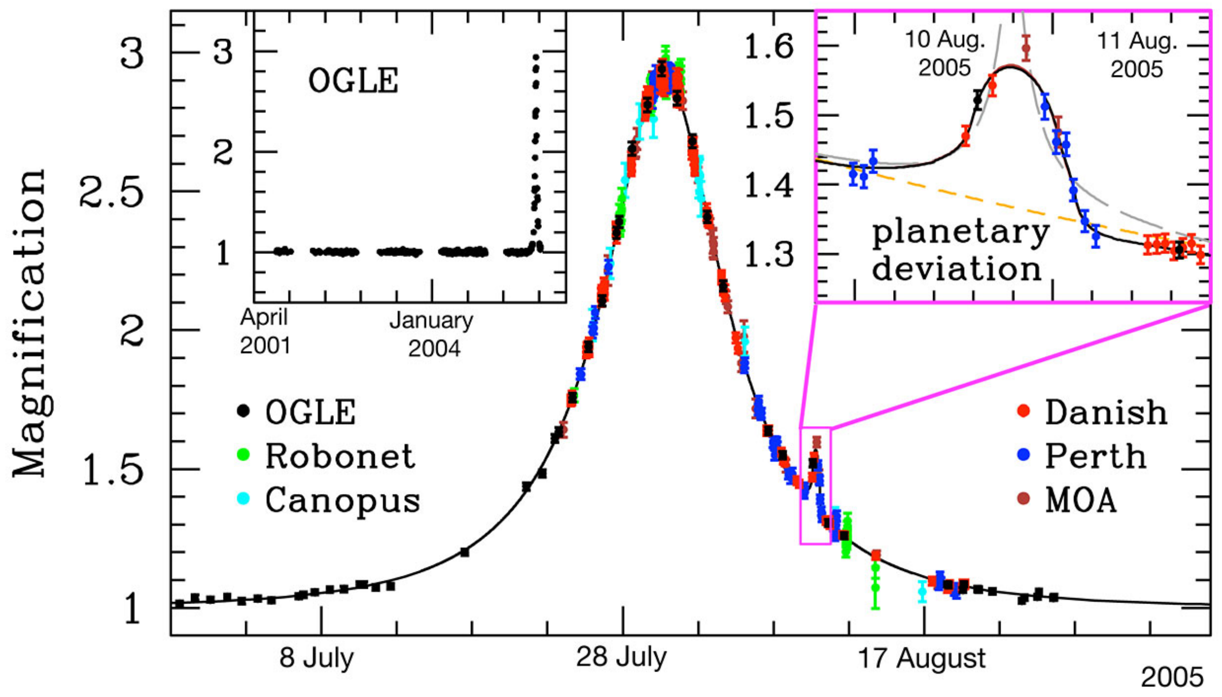
# CURRENT PLANET SEARCHES

- next generation surveys (after 2010)
- dedicated medium-small size telescopes (~1.5 m) observing with wide field cameras (FOV ~2 sq. degs.) large areas with a cadence of ~20 mins
- greater ability to observe planetary caustic events, in particular wide separation planets
- free-floating planets
- MOA-II (New Zealand, 1.8m, 2.2 sq. deg.), OGLE-IV (Chile, 1.3m, 1.4 sq. deg.), WISE Observatory (Israel, 1 m, 1 sq. deg)
- currently monitoring a common area of 8 sq. deg in the bulge

# INTERESTING CASES: COLD SUPER-EARTHS

*Beaulieu et al. 2005*

- OGLE-2005-BLG-390Lb: the first icy super-earth just beyond the snow line discovered via microlensing



$$M_\star = 0.22^{+0.21}_{-0.11} M_\odot$$

$$q \sim 8 \times 10^{-5} \quad M_p = 5.5^{+5.5}_{-2.7} M_\oplus$$

$$a = 2.6^{+1.5}_{-0.6} AU$$

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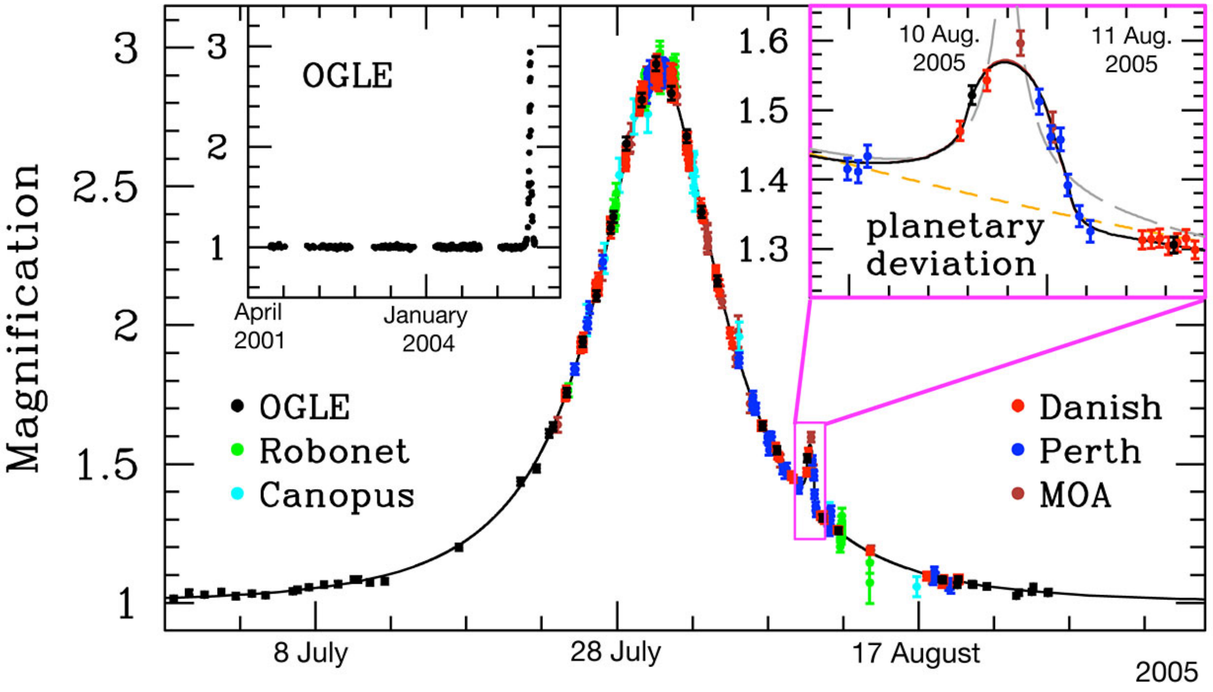

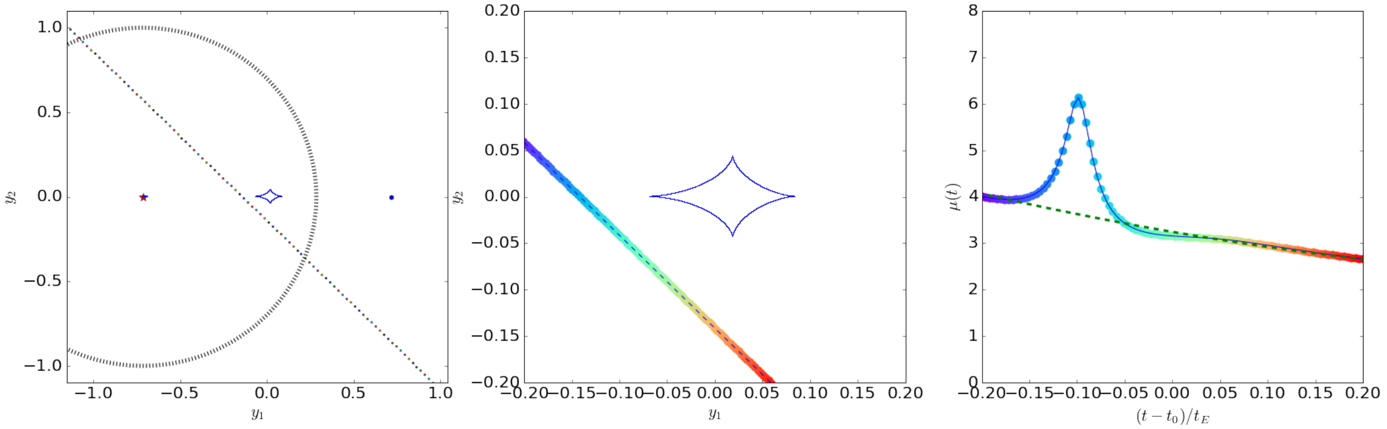

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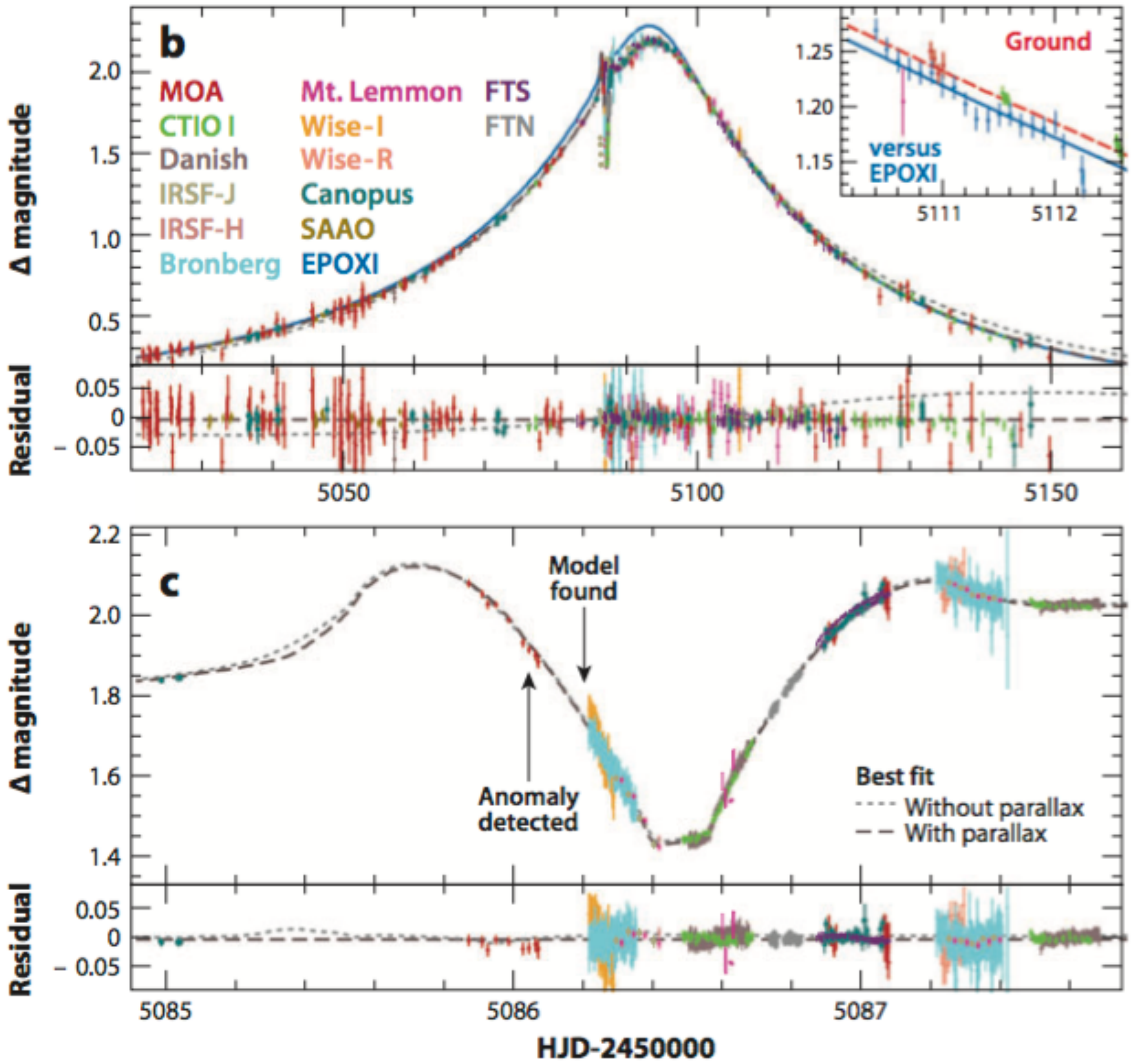
# INTERESTING CASES: COLD SUPER-EARTHS

- OGLE-2005-BLG-390Lb: the first icy super-earth just beyond the snow line discovered via microlensing
- other cases: MOA-2007-BLG-192Lb and, in particular, MOA-2009-BLG-266Lb



*Mouraki et al. 2011*

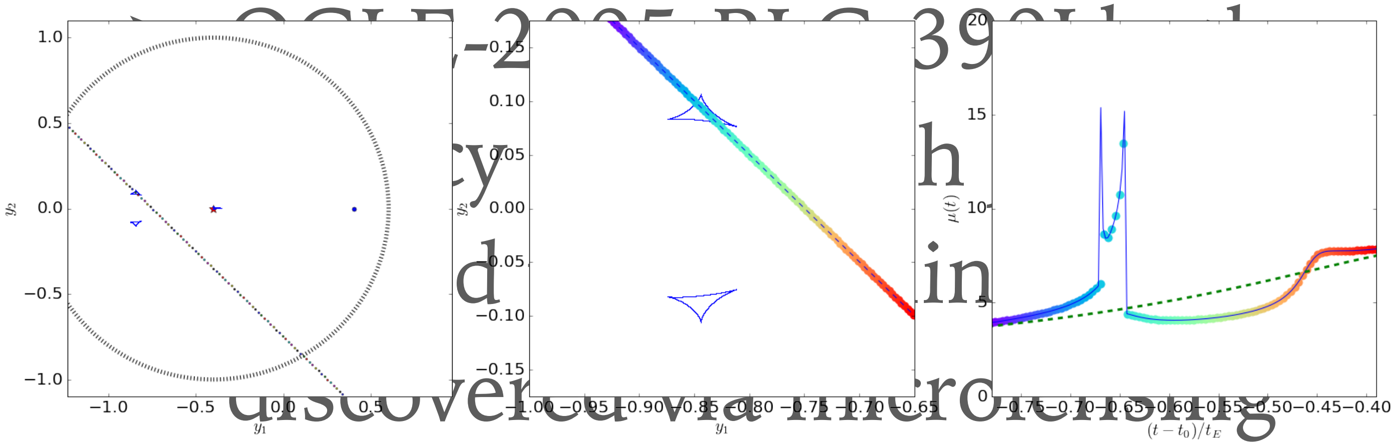
$$M_\star = 0.56^{+0.09}_{-0.09} M_\odot$$

$$M_p = 10.4^{+1.7}_{-1.7} M_\oplus$$

$$q = 5.63 \pm 0.25 \times 10^{-4}$$

$$a = 3.2^{+1.9}_{-0.6} AU$$

# INTERESTING CASES: COLD SUPER-EARTHS



discovered via microlensing

- ➤ other cases: MOA-2007-BLG-192Lb and, in particular, MOA-2009-BLG-266Lb

$$M_\star = 0.56^{+0.09}_{-0.09} M_\odot$$

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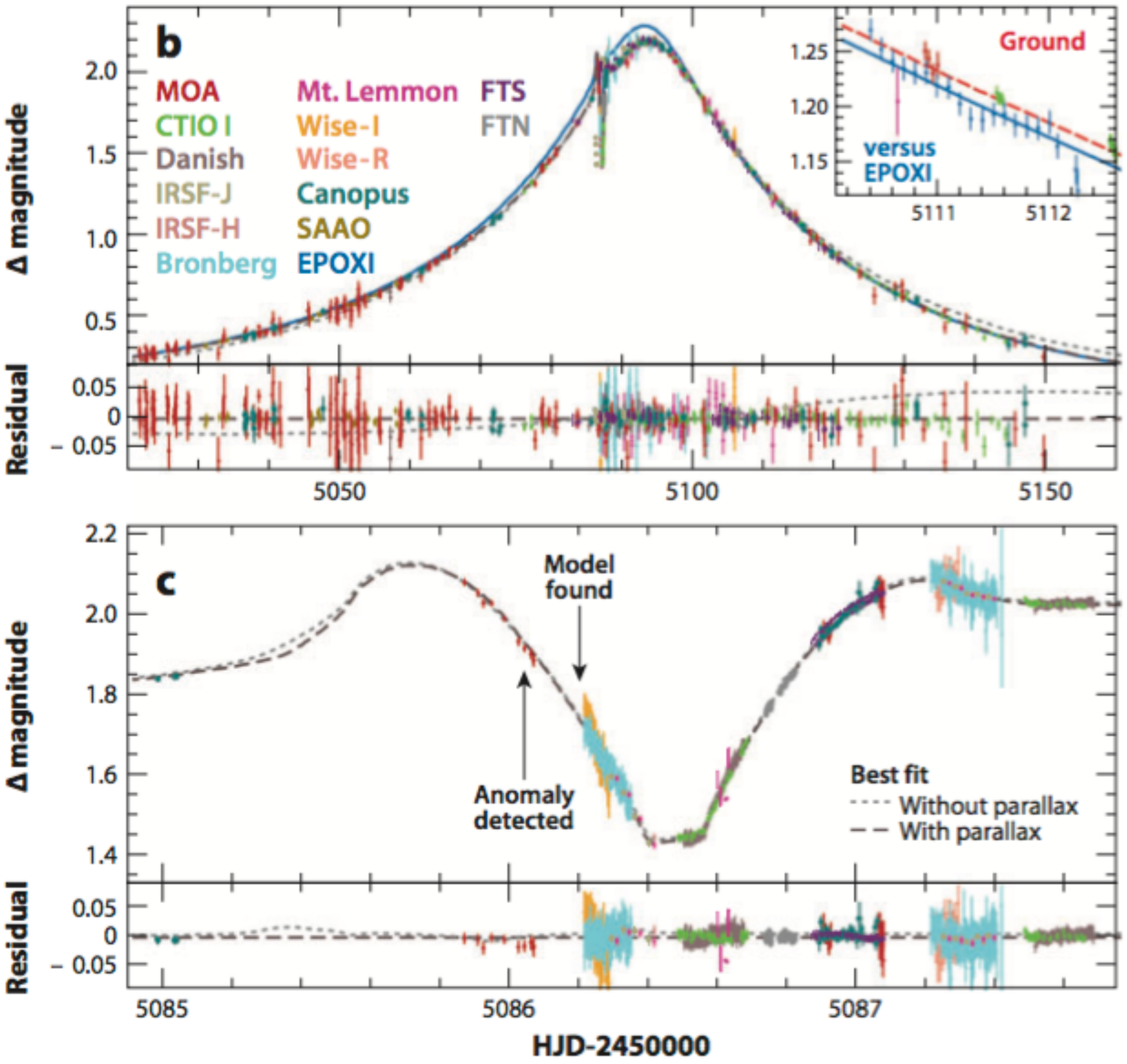
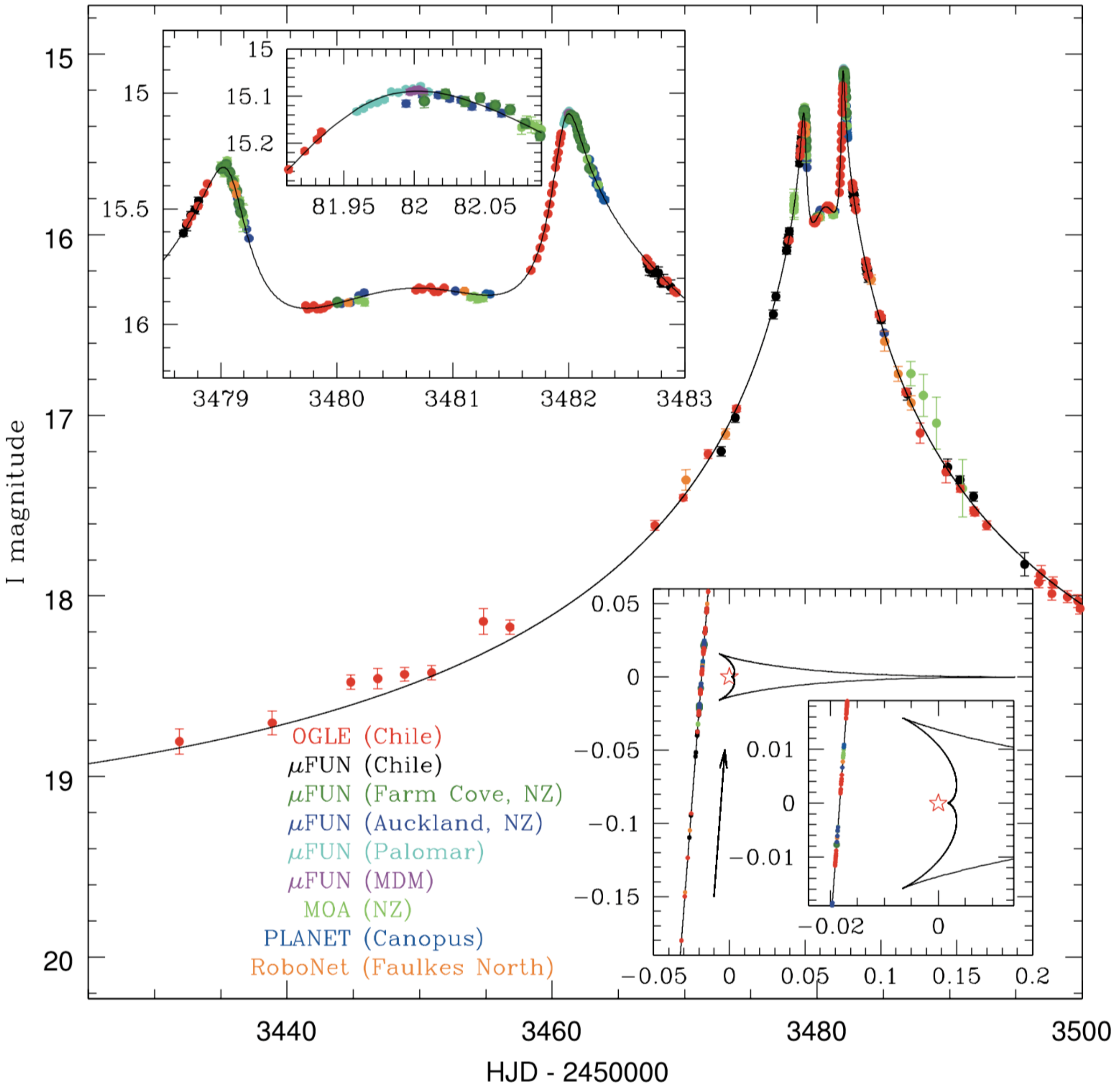


*Mouraki et al. 2011*

$$a = 3.2^{+1.9}_{-0.6} AU$$

# INTERESTING CASES: MASSIVE COMPANIONS TO M-DWARFS

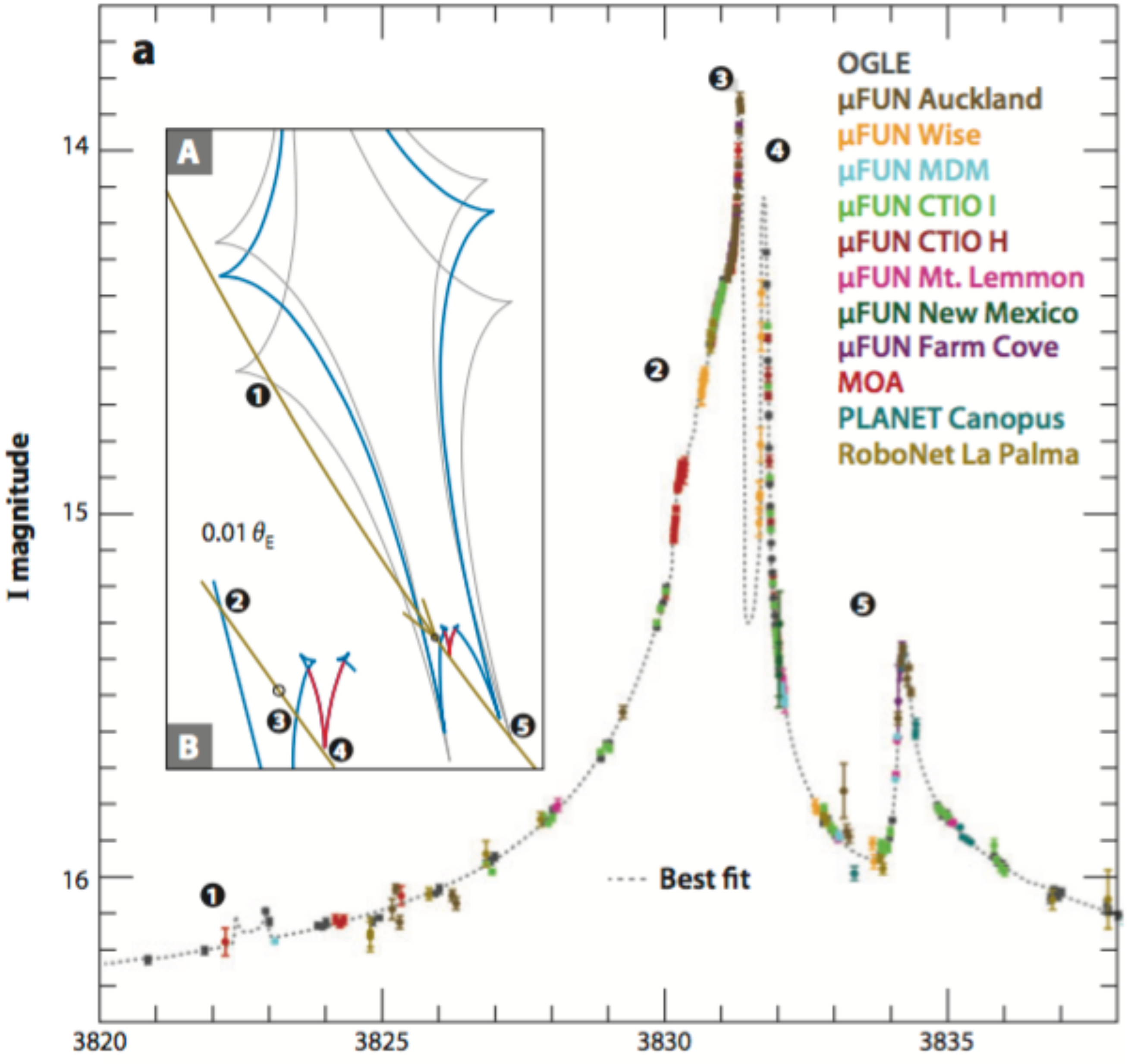
- OGLE-2005-BLG-071Lb: a Jovian-mass planet around a relatively small star
- Other cases: MOA-2009-BLG-387Lb, MOA-2011-BLG-293Lb
- At 2013: 3 out of 14 planets are Jovian companions of M-dwarf stars.
- they seem common, contrary to expectations



*Udalski et al. (2005)*

# INTERESTING CASES: MULTIPLE PLANETS AND EVOLVING CAUSTIC

- OGLE-2006-BLG-109Lb,c: the first detection of a multiple planet system via microlensing
- M-dwarf star host star
- A Saturn-like planet generating a resonant caustic
- A Jupiter-like planet generating a small perturbation (central caustic)
- **There are indications for an evolution of the caustic of the Saturn-like planet due to its orbital motion**



*Gaudi et al. (2008), Bennet et al. (2010)*

# SOME MORE RESULTS

- relatively uniform distribution of masses, although detection efficiency decreases with q. This suggests that there are many small planets!
- 40% of stars are likely to host cold super-earths
- high frequency of saturn-like planets
- but not all planetary systems host giant planets, otherwise we would have detected more multi planet systems
- Cassan et al. (2012) derived a power-law mass function of planets

$$\frac{d^2 N_{\mathrm{pl}}}{d\log a\; d\log m_{\mathrm{p}}} = 10^{-0.62\pm0.22}\left(\frac{m_{\mathrm{p}}}{M_{\mathrm{Saturn}}}\right)^{-0.73\pm0.17}$$

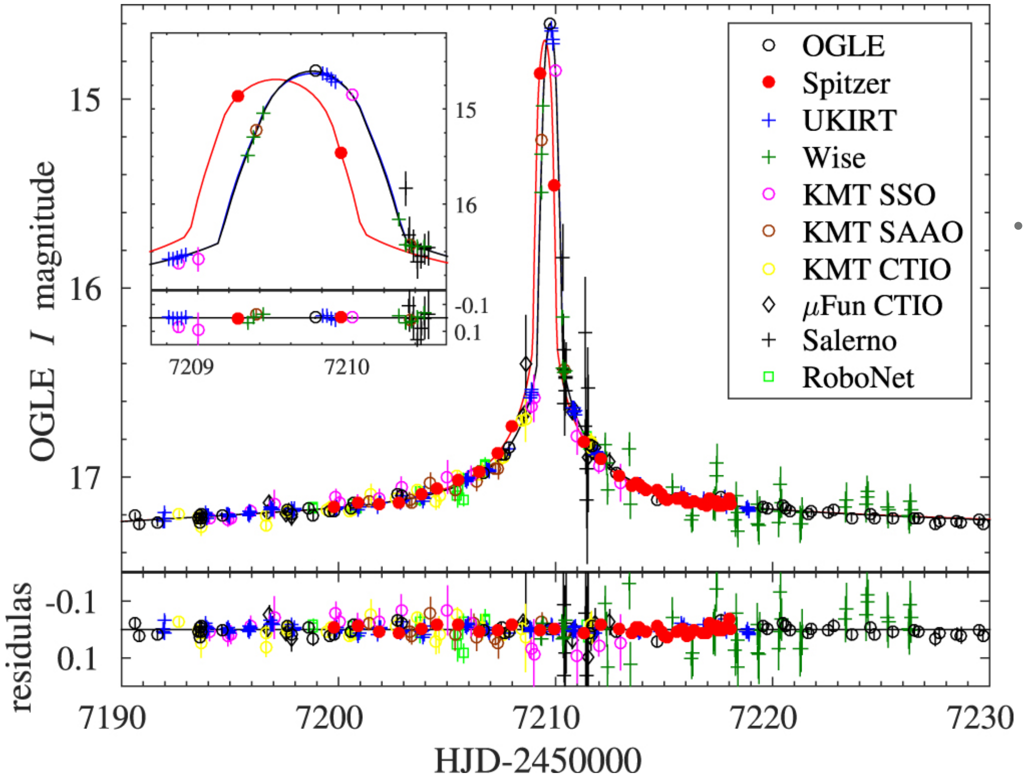
$$\langle N_{\mathrm{pl}}\rangle = 1.6^{+0.7}_{-0.9}$$

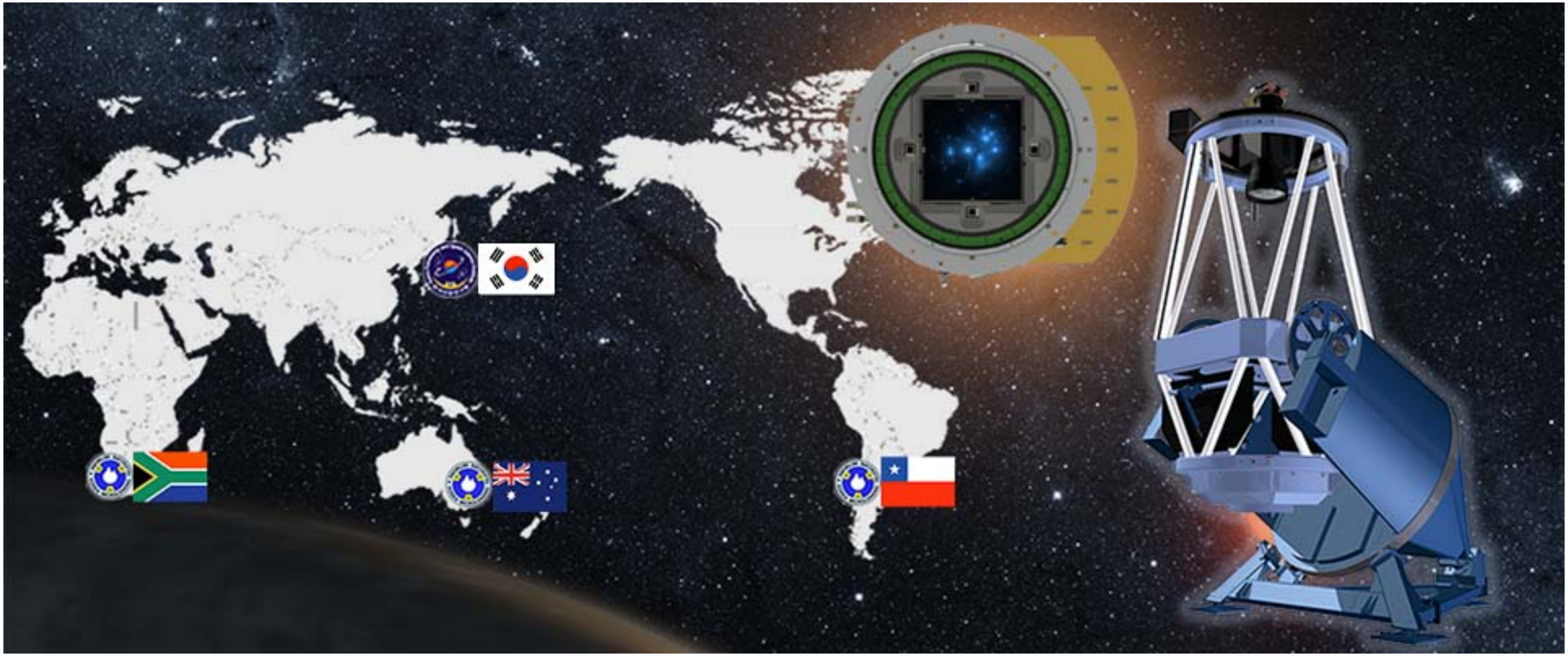
*in the range 0.5-10 AU*

# THE FUTURE OF MICROLENSING

- Korean Microlensing Telescope Network (KMTNet, South Africa, South America, Australia, 3x1.6m, 4 sq. deg. )

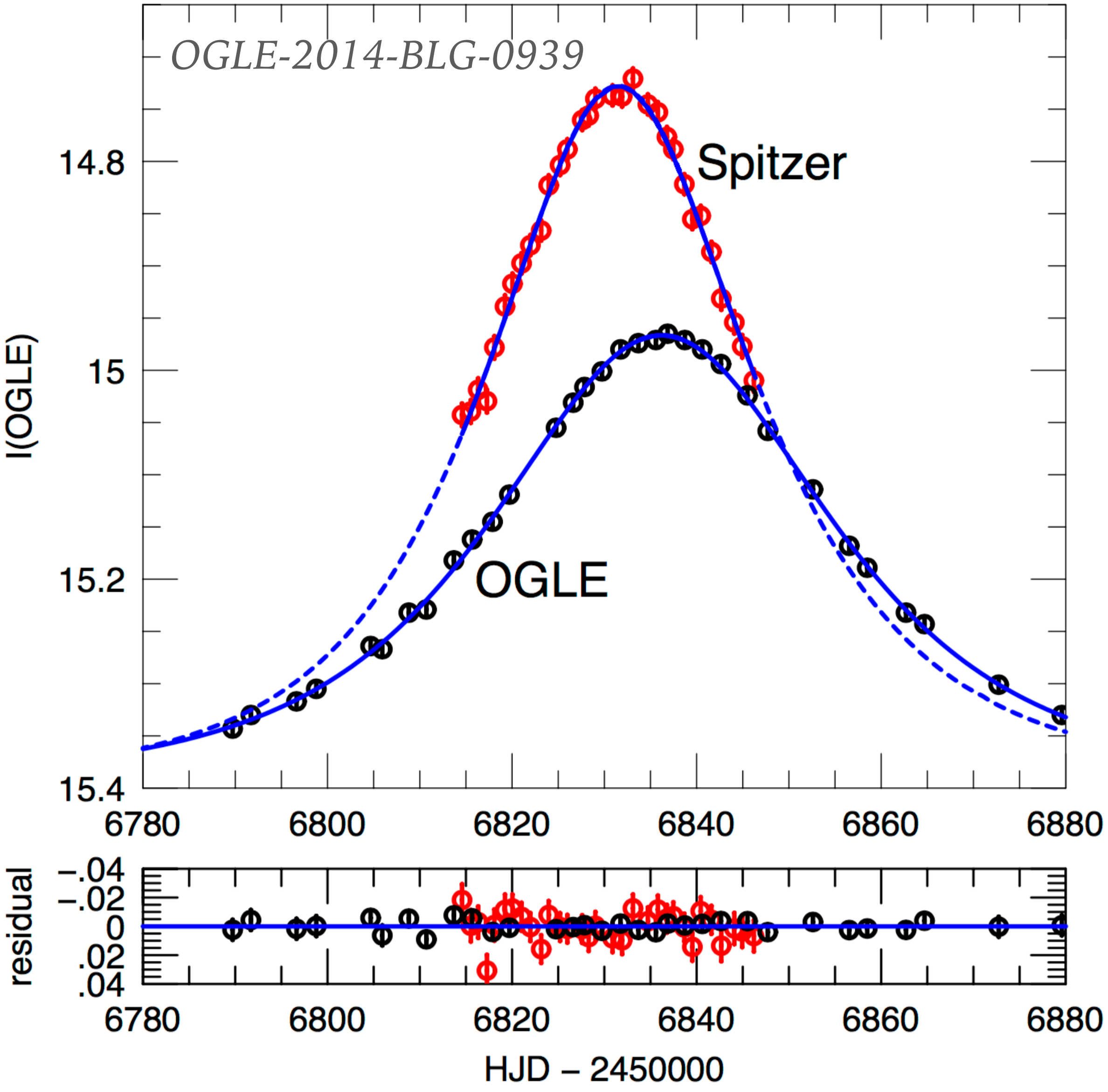
*Shvartzvald et al. 2015*





# THE FUTURE OF MICROLENSING

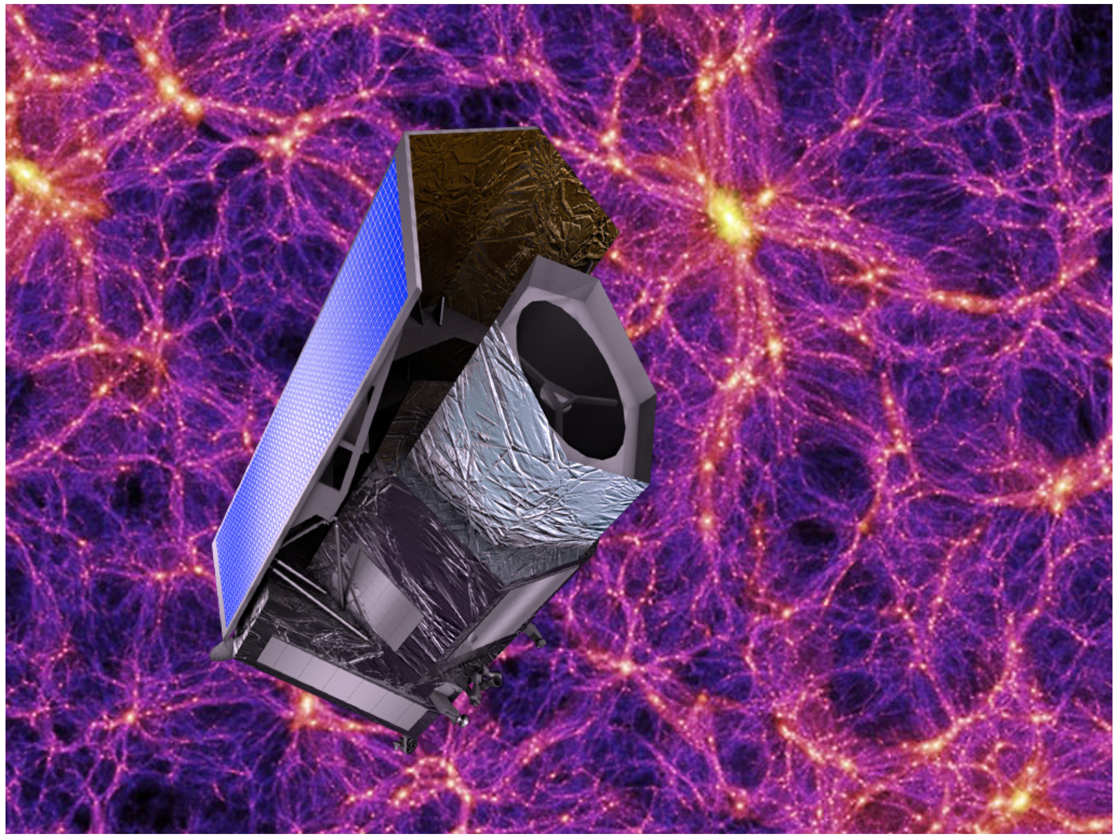
- microlensing searches from space
- possibility to resolve main sequence star lenses
- continuity of observations
- possibility to observe in the NIR-IR where several lenses are brighter
- satellite microlensing parallax
- currently: Spitzer (parallax measurements of 21 single-lens events)
- in 5-10 years: WFIRST, Euclid



*Yee et al. 2014*

# THE FUTURE OF MICROLENSING: EUCLID

- Euclid expected in 2020: 1.2m telescope with 0.5 sq. deg FOV; riz (VIS, 0.1”), Y, J,H (NIR, 0.3”)
- primary science: cosmology (growth of the cosmic structures, dark energy)
- likely, it will perform secondary surveys for other science goals: planet searches via microlensing
- limited view over the galactic bulge: can observe for about a month twice a year



- expected performance:
  - Cold earths and neptunes: 35 planets/month
  - Free-floating planets: 15 planets/month

# THE FUTURE OF MICROLENSING: WFIRST

- WFIRST expected in 2025: 2.4m telescope with 0.28 sq. deg FOV; NIR, 0.76-2.0 mum, ~0.2” res.
- primary science: cosmology and planets
- NIR imaging for microlensing
- Chronograph for characterizing the planets and their atmospheres (via direct imaging)
- more flexible telescope: will perform several surveys and will host a GO program

- expected performance (5 years survey)
  - 3250 bound exoplanets in the range 0.1-1000 Earth mass, 0.1-40 AU
  - 2080 free-floating planets