Extrasolar planets from Gravitational microlensing

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Outline

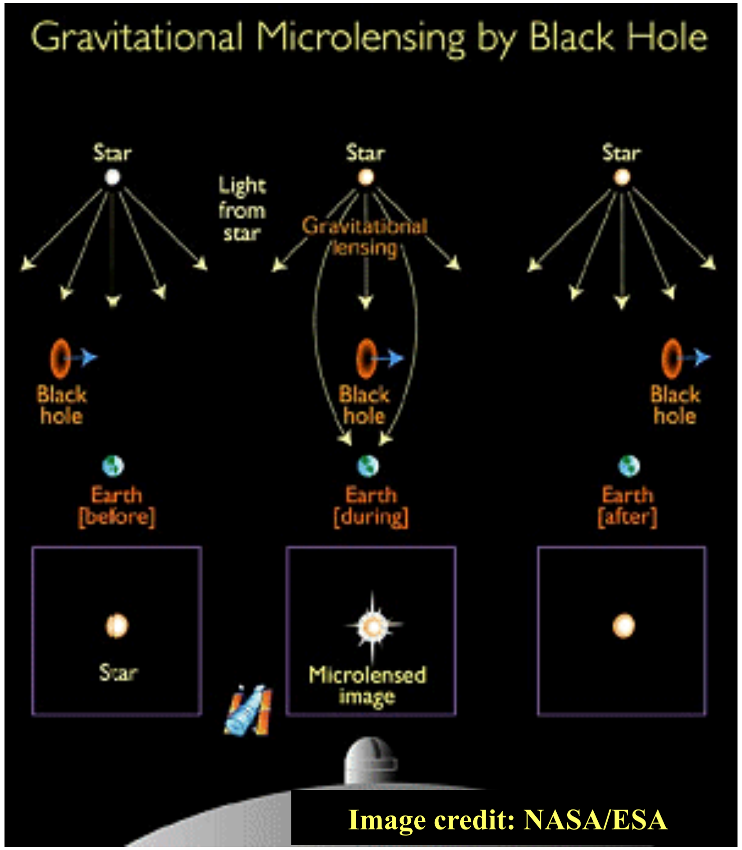
I. Introduction & current status

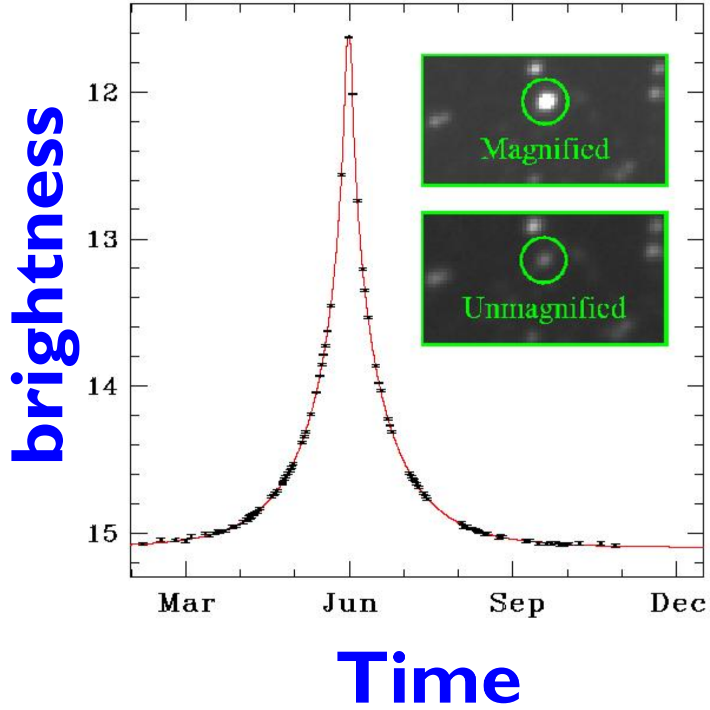
II. Principle of extrasolar planet detection with microlensing

III. Examples & statistics

IV. Future directions

What is near-field microlensing?

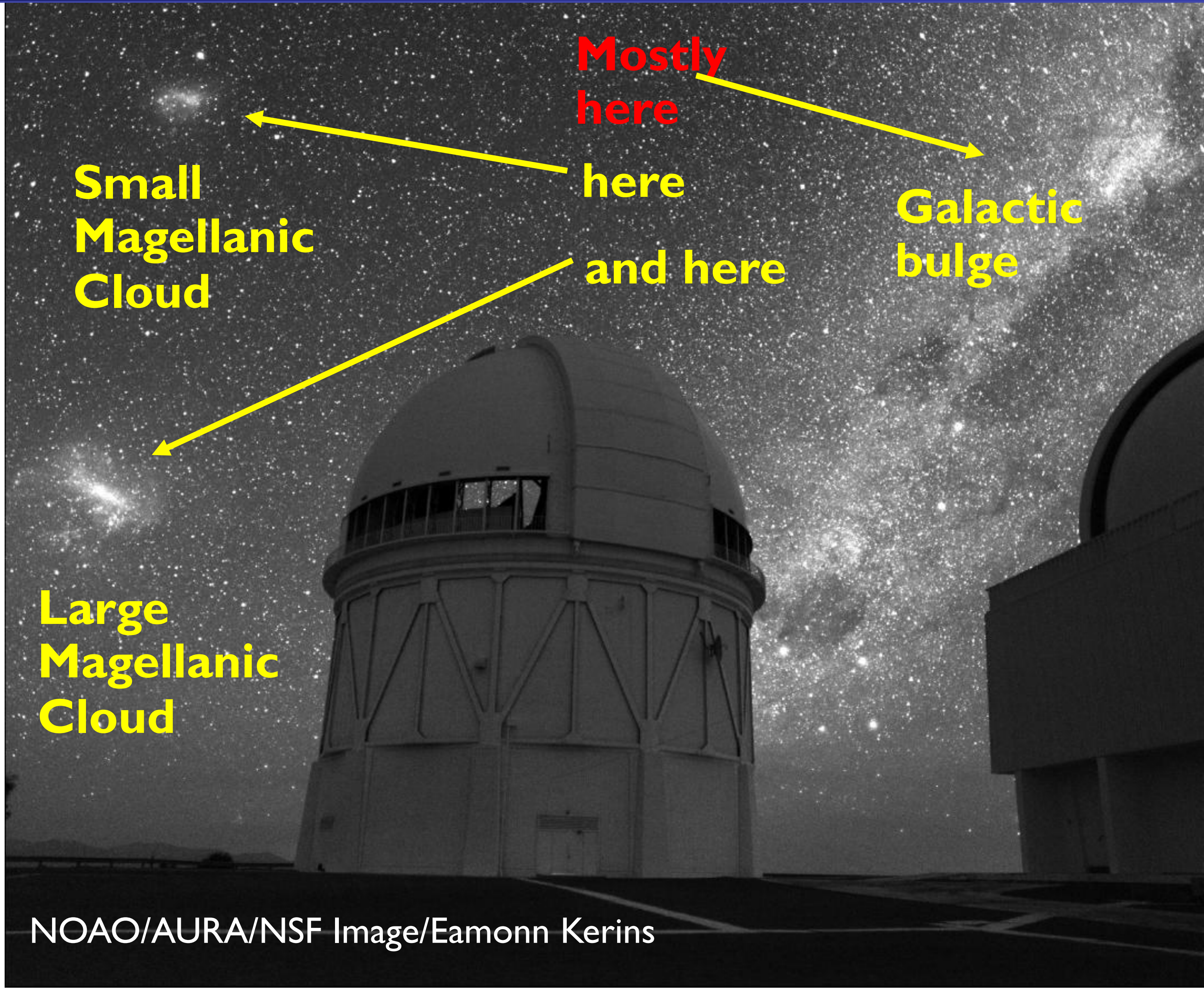




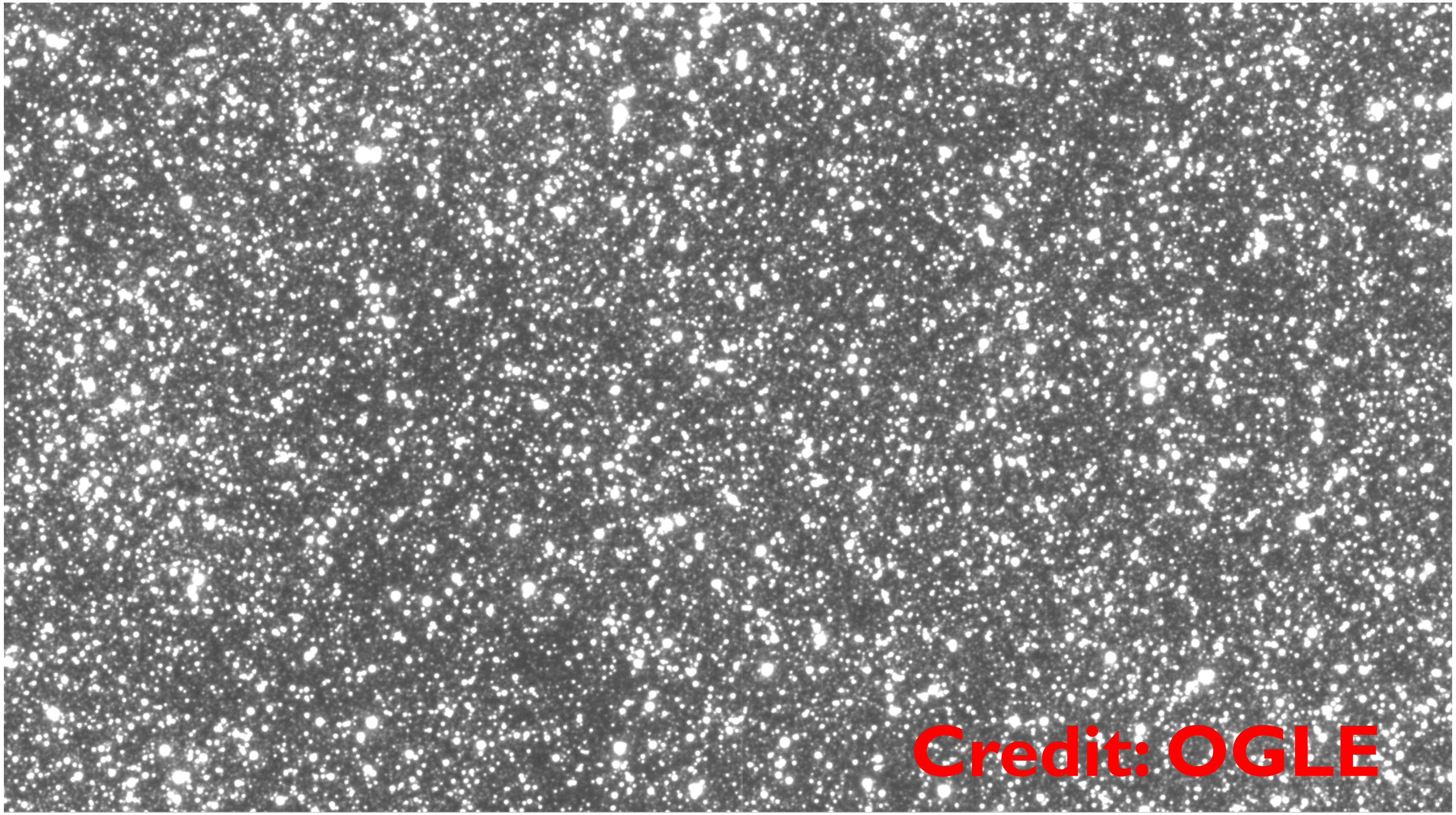
microlensing produces "symmetric", non-repeating & achromatic light curves

Small prob.: 10^{-6}

Where are we looking?



What do we see?



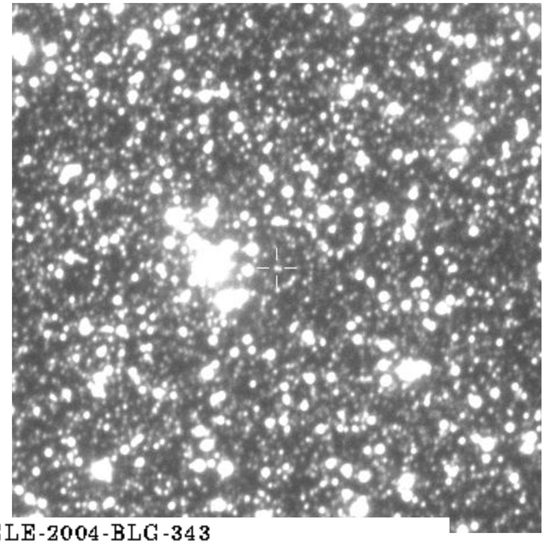
Challenges: **probability~10^{-6}, event rate ~ 10 events per year per 10^6 stars.**

Two decades of microlensing

- **OGLE, MOA, MACHO etc. assembled time series for hundreds of millions of stars toward GC, LMC, SMC, etc.**

- **To date ~ 15,000 events have been detected**
  - **The vast majority of events are detected towards the Galactic bulge**
  - **Current event rate by OGLE & MOA ~2000/yr, most in real-time**
  - **Durations: days to years, A=1 to thousands**

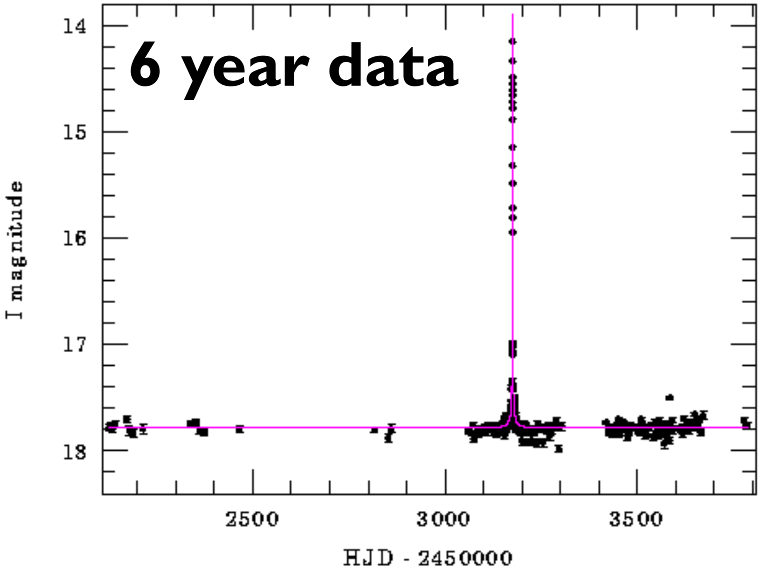
A high mag. standard light curve



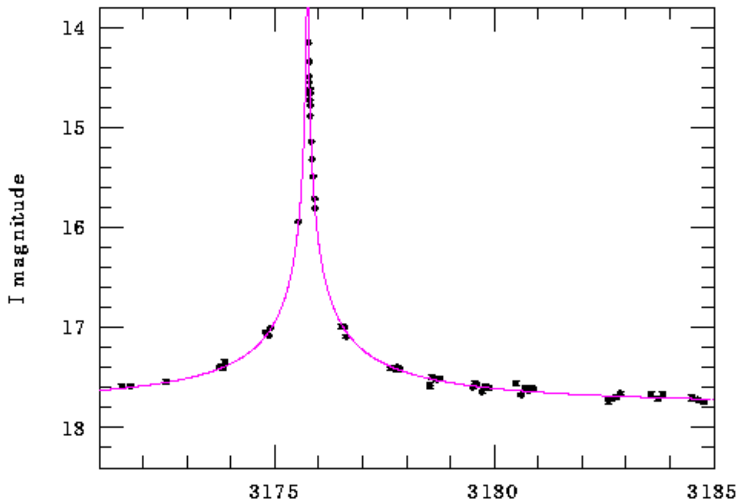
OGLE-2004-BLG-343

t_E~42 days, typical

μ_{max} ~3000

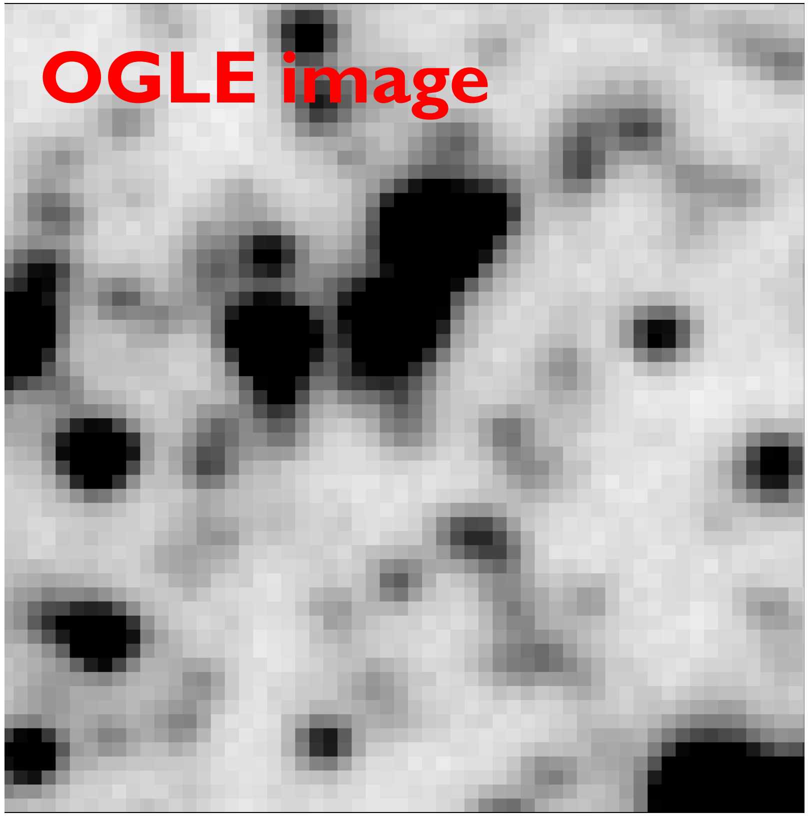


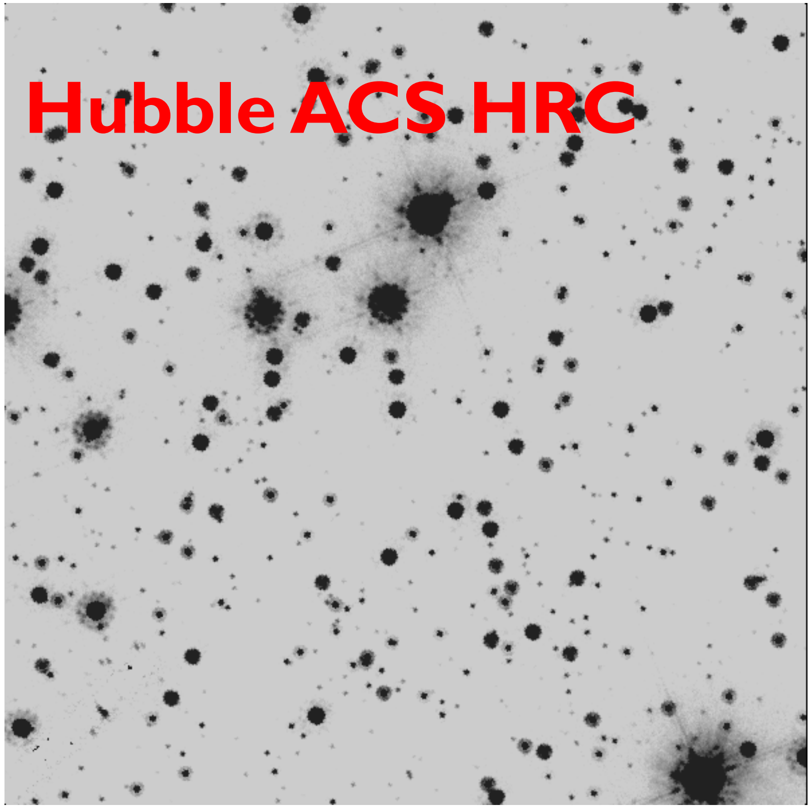
Obs. μ_{max} ~36



OGLE-2004-BLG-343

Blending in ground-based images

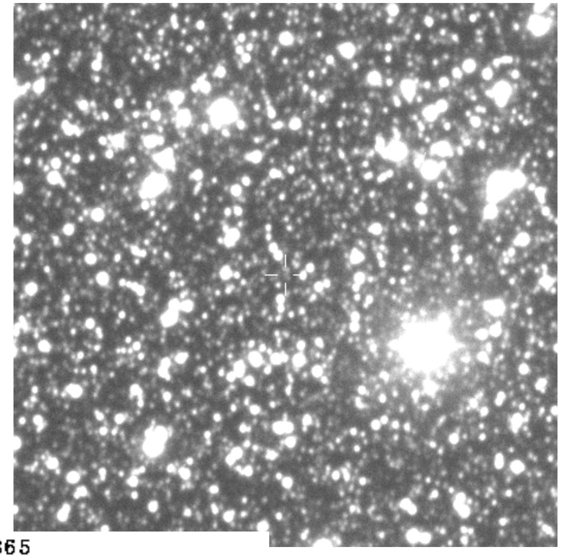




A star may be blended with other unrelated stars

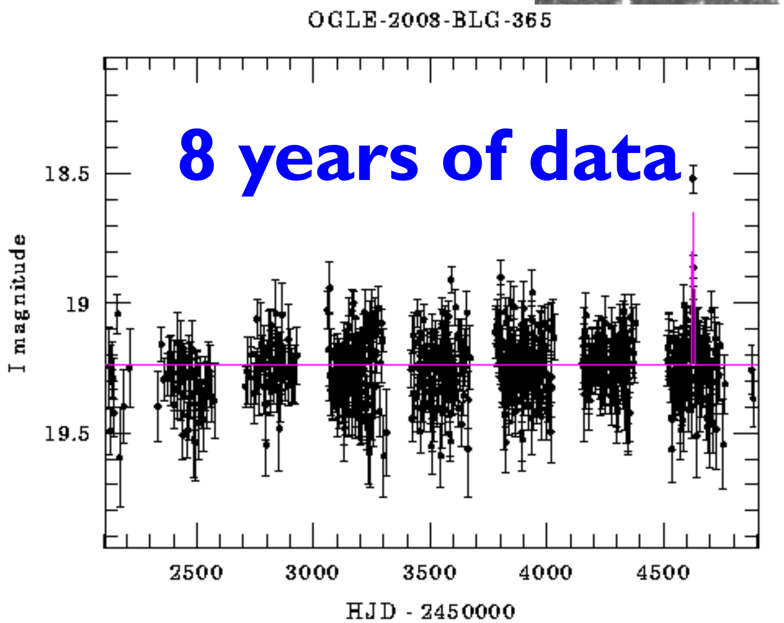
- ✓ **Reduces magnification**
- ✓ **Shortens the event duration ("iceberg" effect)**

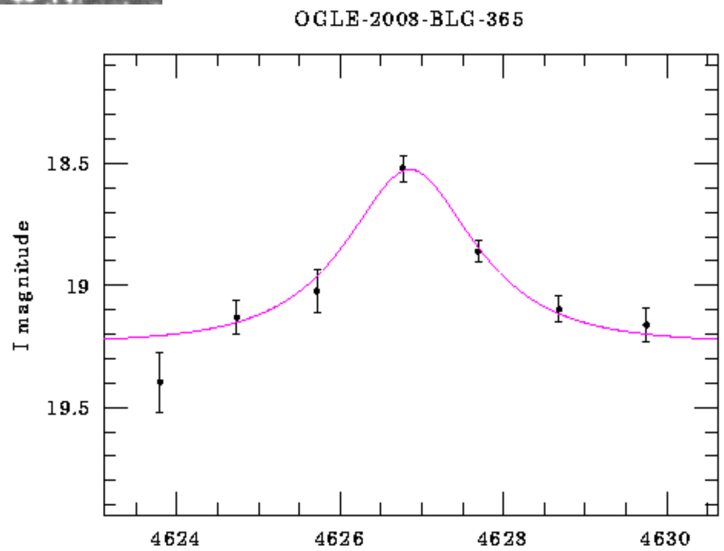
A short standard event



t_E=1.25 day

Free-floating planets? $t_E \sim M^{1/2}$



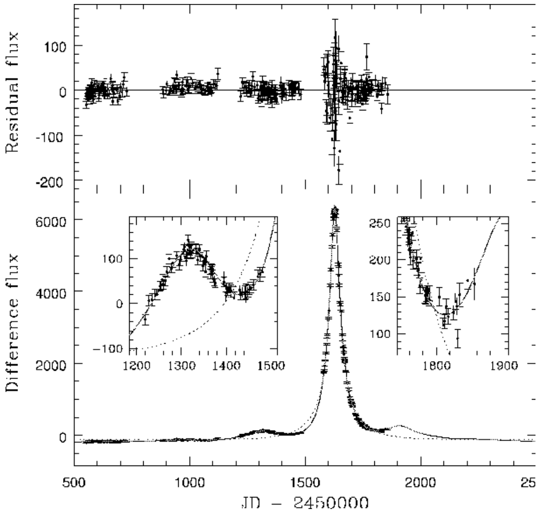


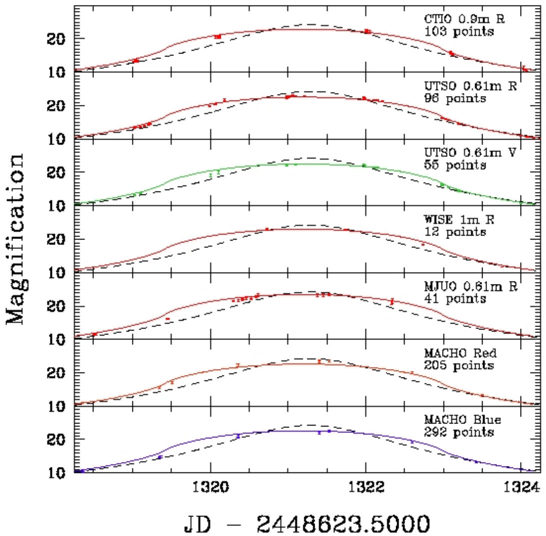
OGLE-2008-BLG-365

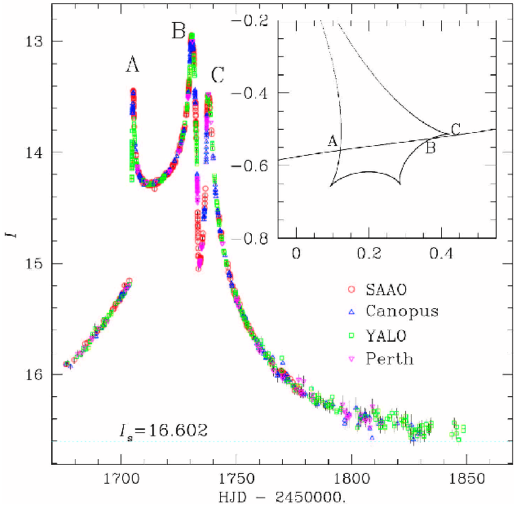
Exotic microlensing events

- **Standard light curve assumes single lens and point source with linear motions!**

parallax **finite source size** **binary lens**







Smith, Mao et al. (2002)

Alcock et al. (1997)

EROS-BLG-2000-5
An et al (2002)

- **Extra features in exotic light curves give additional constraints to break the microlens degeneracy**

Applications of microlensing

- Dark matter: MACHOS?
- Galactic structure/dynamics
  - CMDs, microlensing optical depth maps, proper motions (kinematics)
- High magnification events/caustic crossing events
  - Stellar atmosphere (limb-darkening)
  - Metallicity, surface gravity, ages of stars
- Binary mass function
- Stellar mass black holes
- Extrasolar planets (Beaulieu's talk)

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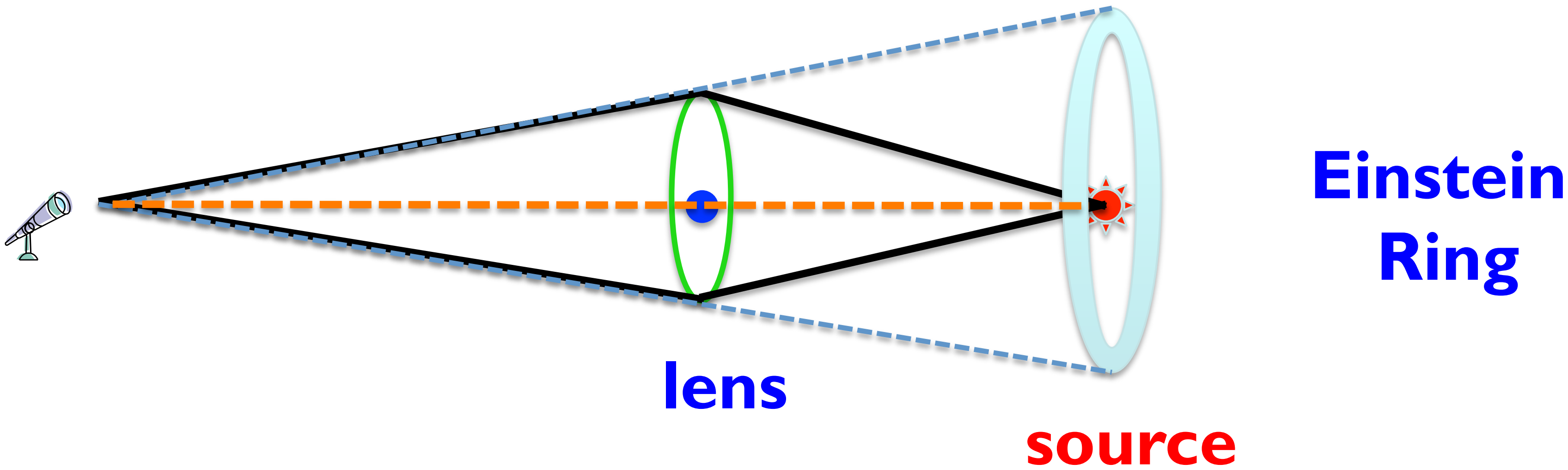
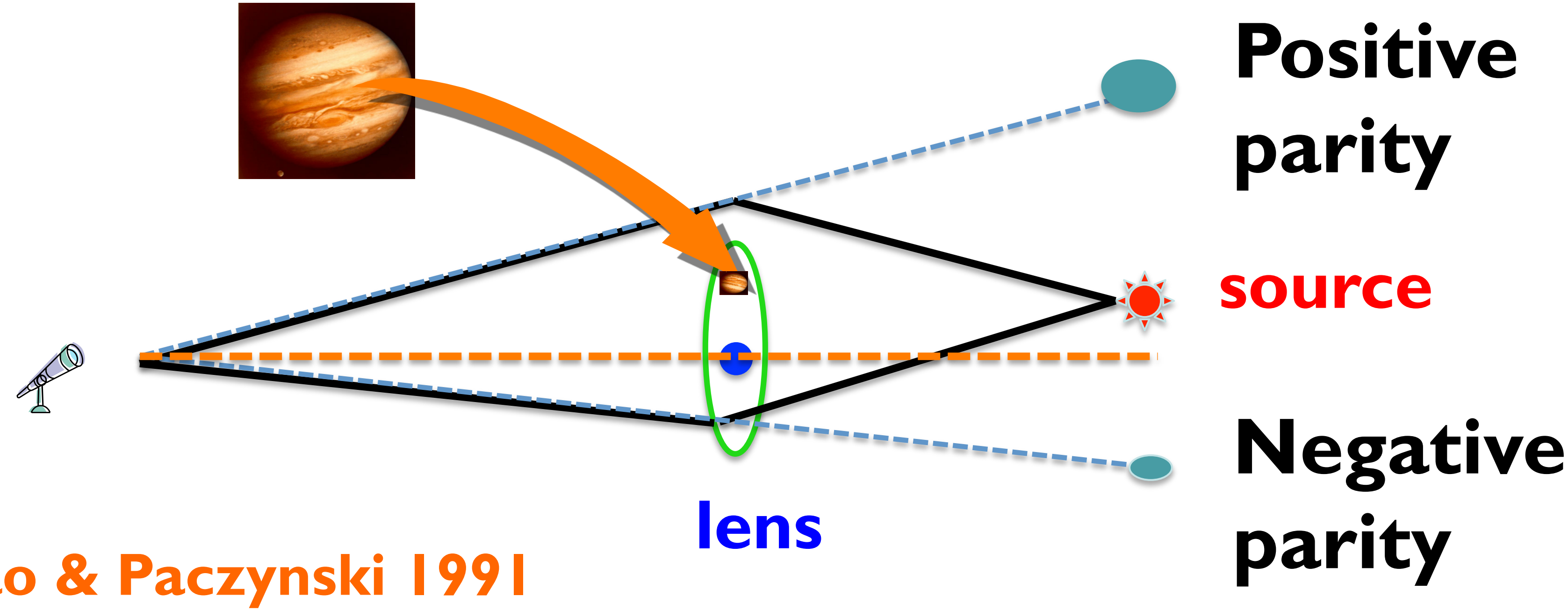
Microlensing: basic concepts



- Einstein radius $r_E \sim M^{1/2}$, ~ few AU, coincident with size of the solar system!

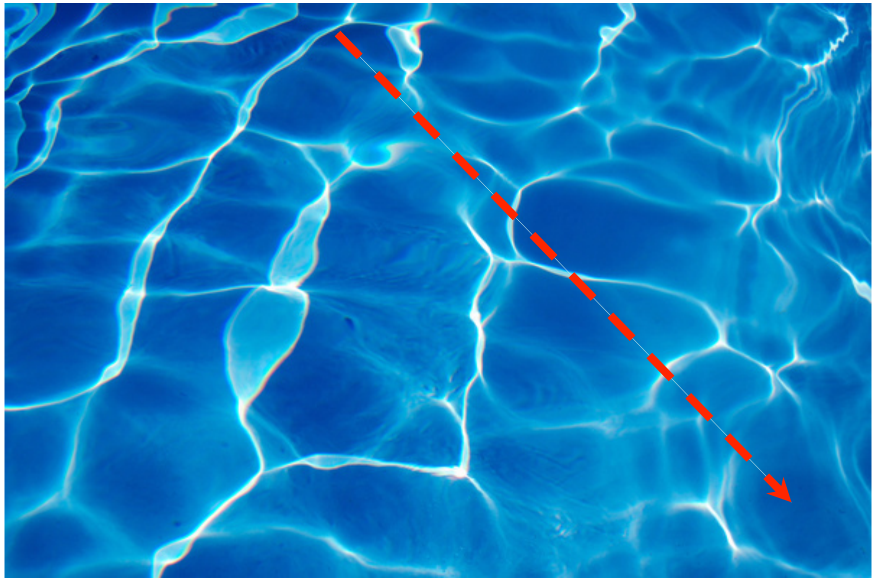
- Einstein radius crossing time $t_E \sim r_E/V$, lasting for days to years → degeneracy!

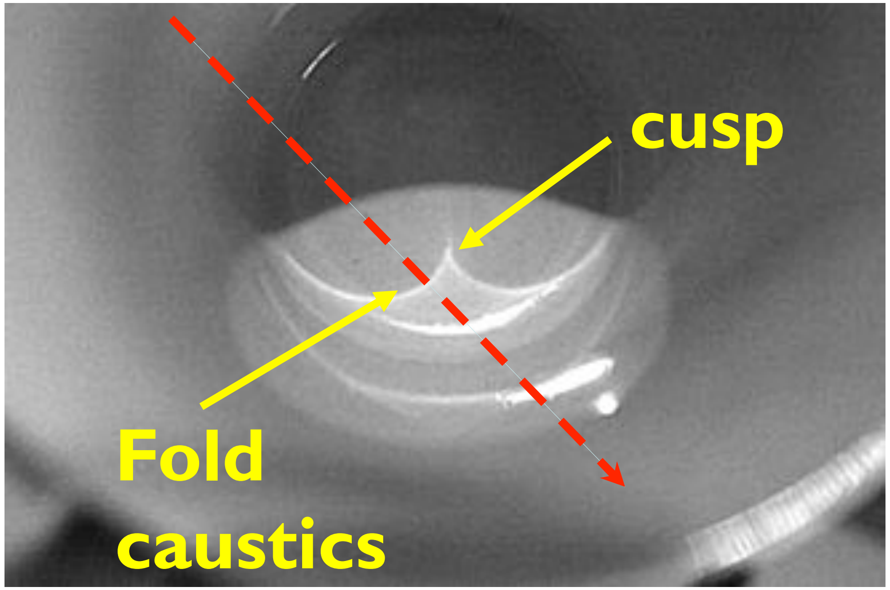
Principle of planet detection



- The presence of the planet perturbs the image positions and magnifications
- Duration $\delta t \sim 1$ day $(M/M_J)^{1/2}$
- In fact it can create one or three extra images! → caustics and critical curves

Caustics in the real world





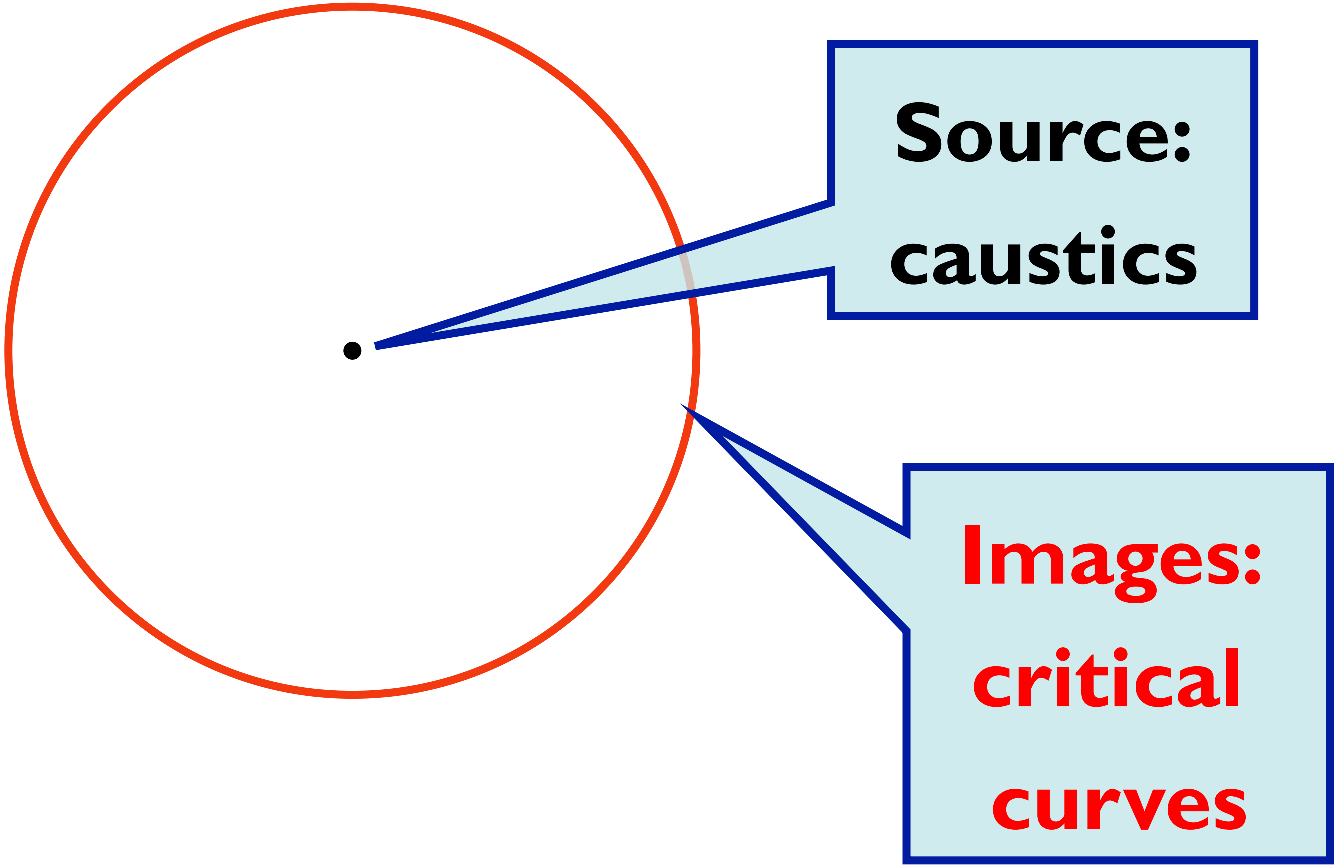
Parallel rays from the Sun are piled into **bright** optical caustics by waves

Wine glasses

In caustic crossing, a pair of images (dis)appears

critical curves and caustics for a point lens

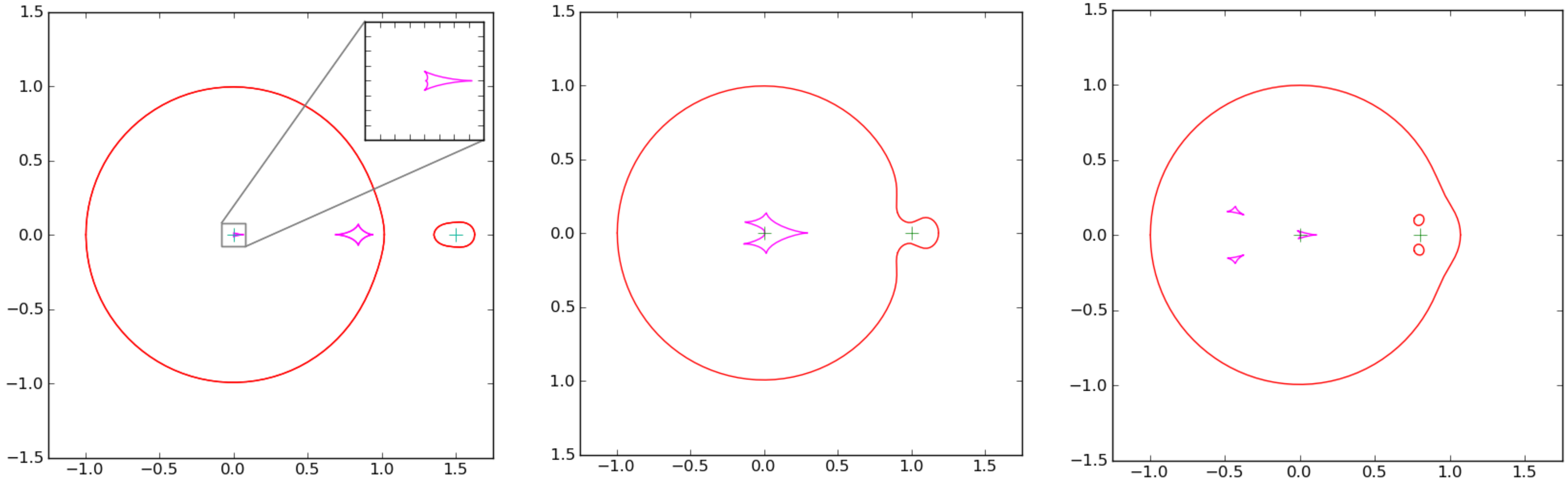
On the plane of sky



magnification=∞

Evolution of caustics & critical curves

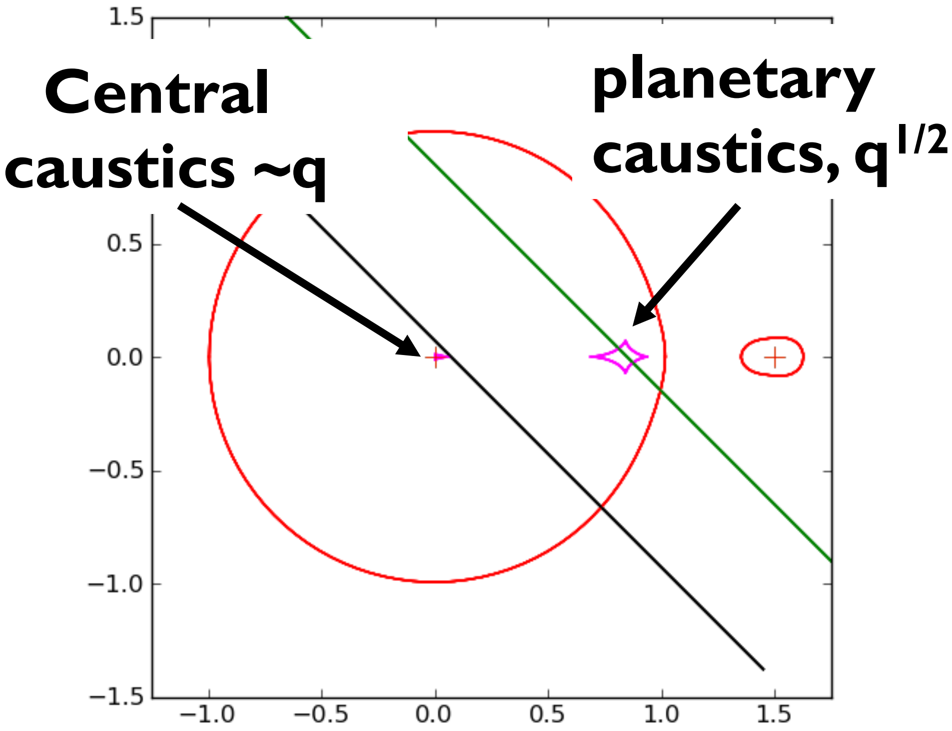
Binary mass ratio q=0.01

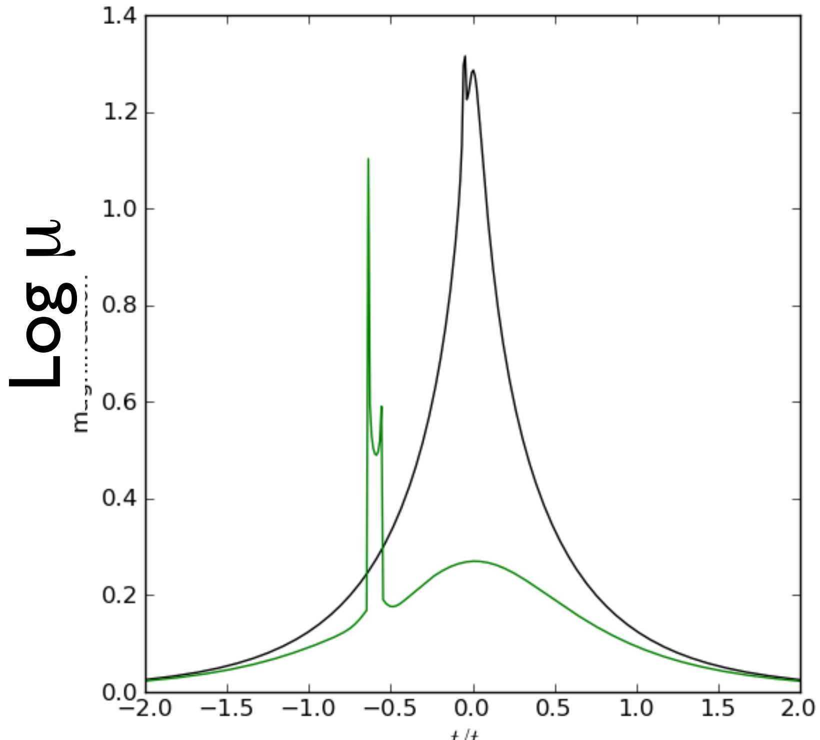


Far	Resonant	Near
a=1.5	a=1.0	a=0.8

Distance decreases

Light curves due to central & planetary caustics

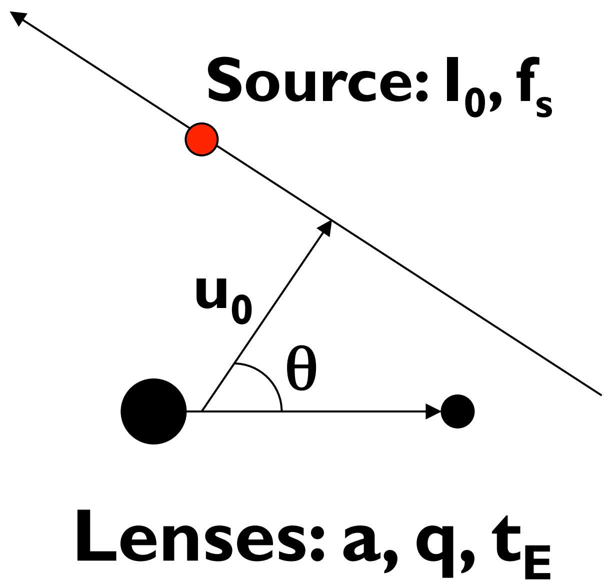




- Central caustic crossing: peak, high S/N, easier to predict and observe; sensitive to multiple planets!
- Planetary caustic crossing can occur any time, more difficult to predict and time followup observations!

Binary lens modelling

- **Number of parameters:**
  - ✓ **Lens (q, a, t_E); source I_0, f_s; trajectory: u_0, θ**
- **Modelling gives t_E, mass ratio q, and dimensionless separation a**
- **Combined with other information (finite source size, parallax, lens light)**
  - ✓ **Finite source size + parallax → lens mass unique**
  - ✓ **Otherwise Bayesian analysis**



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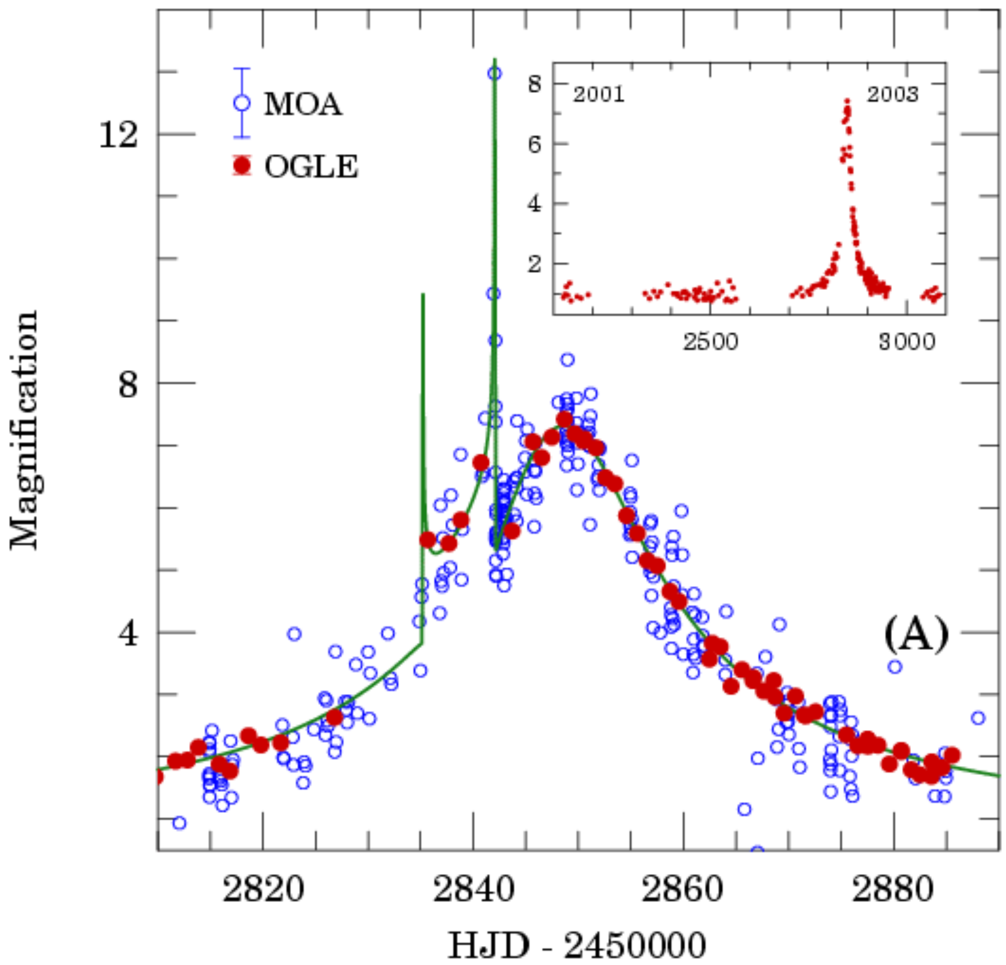
First Microlensing planet



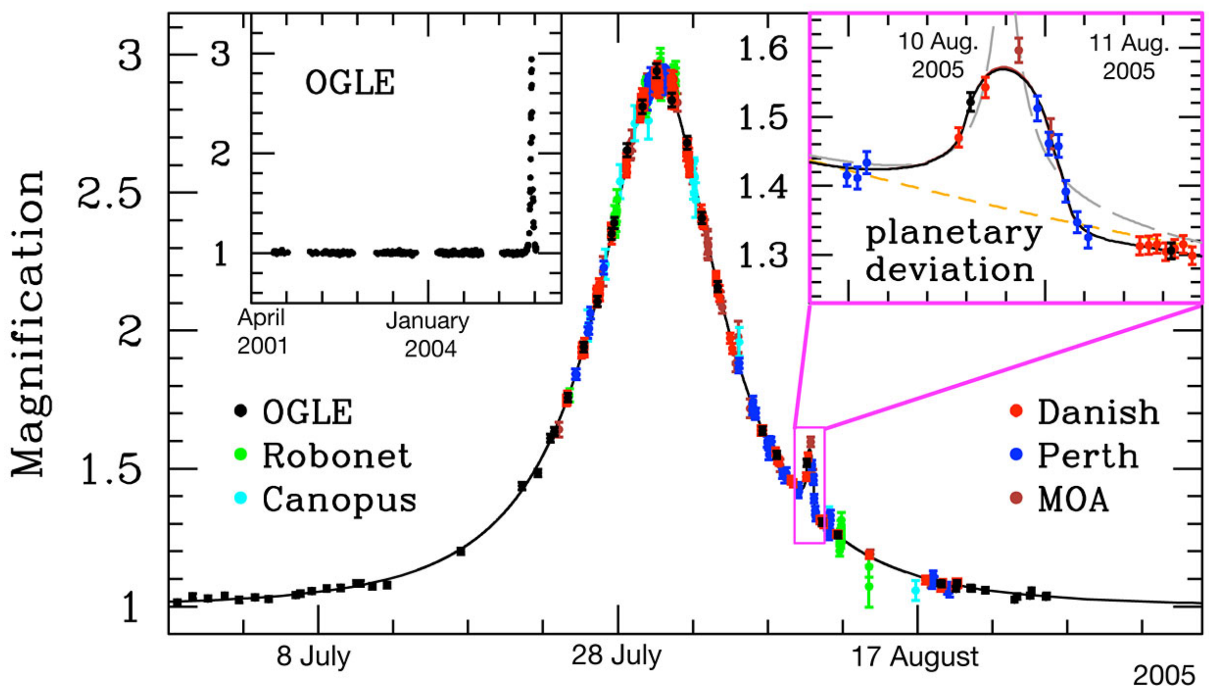
OGLE 2003-BLG-235/MOA 2003-BLG-53

- **Discovered by OGLE/MOA surveys**
- **7 day deviation!**

Bond et al. 2004

- **q=0.004**
- **If the lens is MS, M_{planet}(~1.5 M_J), d ~ 5kpc**

A cold, low-mass planet: OGLE-2005-BLG-390



Deviation lasting a day

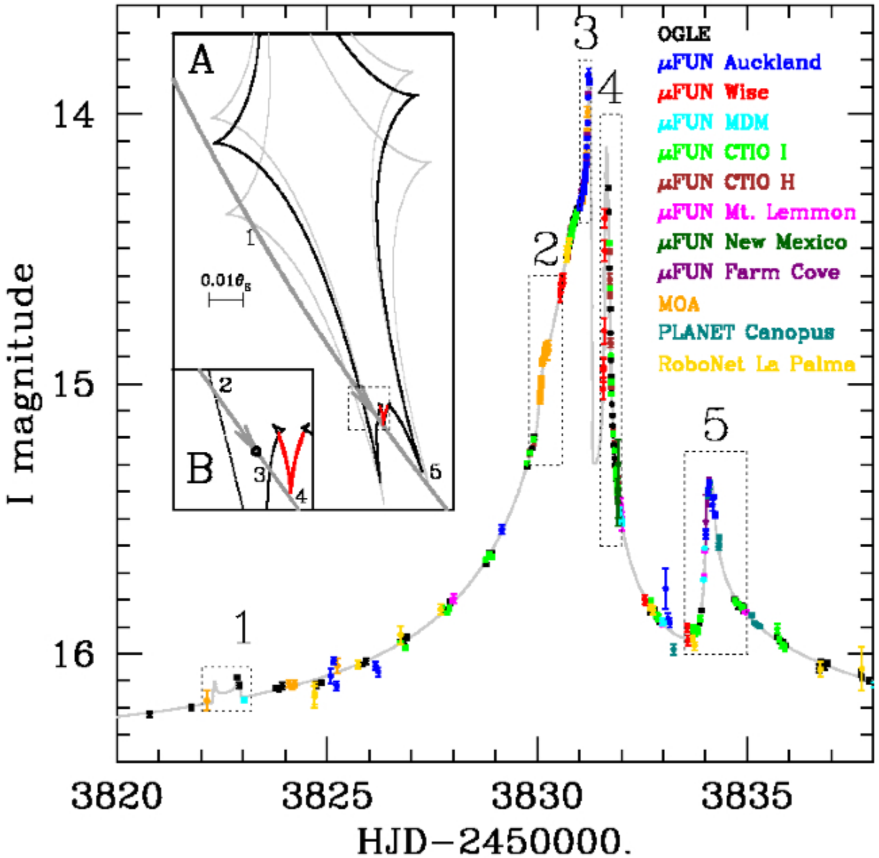
Population of cold, low-mass Neptunes and Super-Earths.

(Beaulieu et al. 2006; Gould et al. 2006; Bennett et al. 2009; Sumi et al. 2010; Muraki et al. 2011; Furusawa et al. 2013)

First multiple extrasolar planet: OGLE 2005-BLG-071

Gaudi et al. (2008);

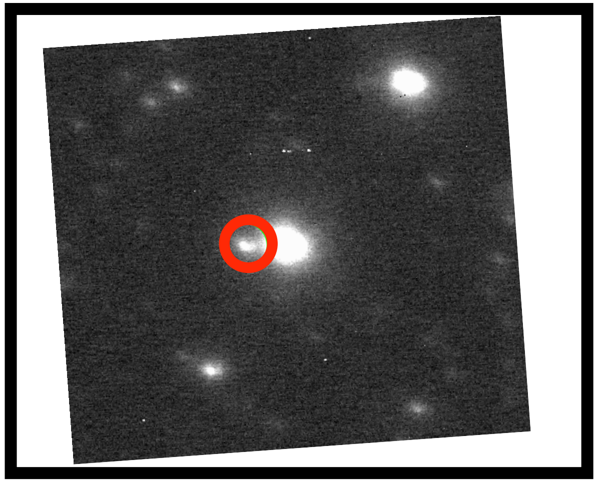
Bennett et al. (2010)



Rotation, parallax and finite source size effects are all seen.

Physical Properties

AO Imaging from Keck



Host:

Mass = 0.51 +/- 0.05 MSun

Luminosity ~ 5% LSun

Distance = 1510 +/- 120 pc

Planet b:

Mass = 0.73 +/- 0.06 MJup

Semimajor Axis = 2.3 +/- 0.5 AU

Planet c:

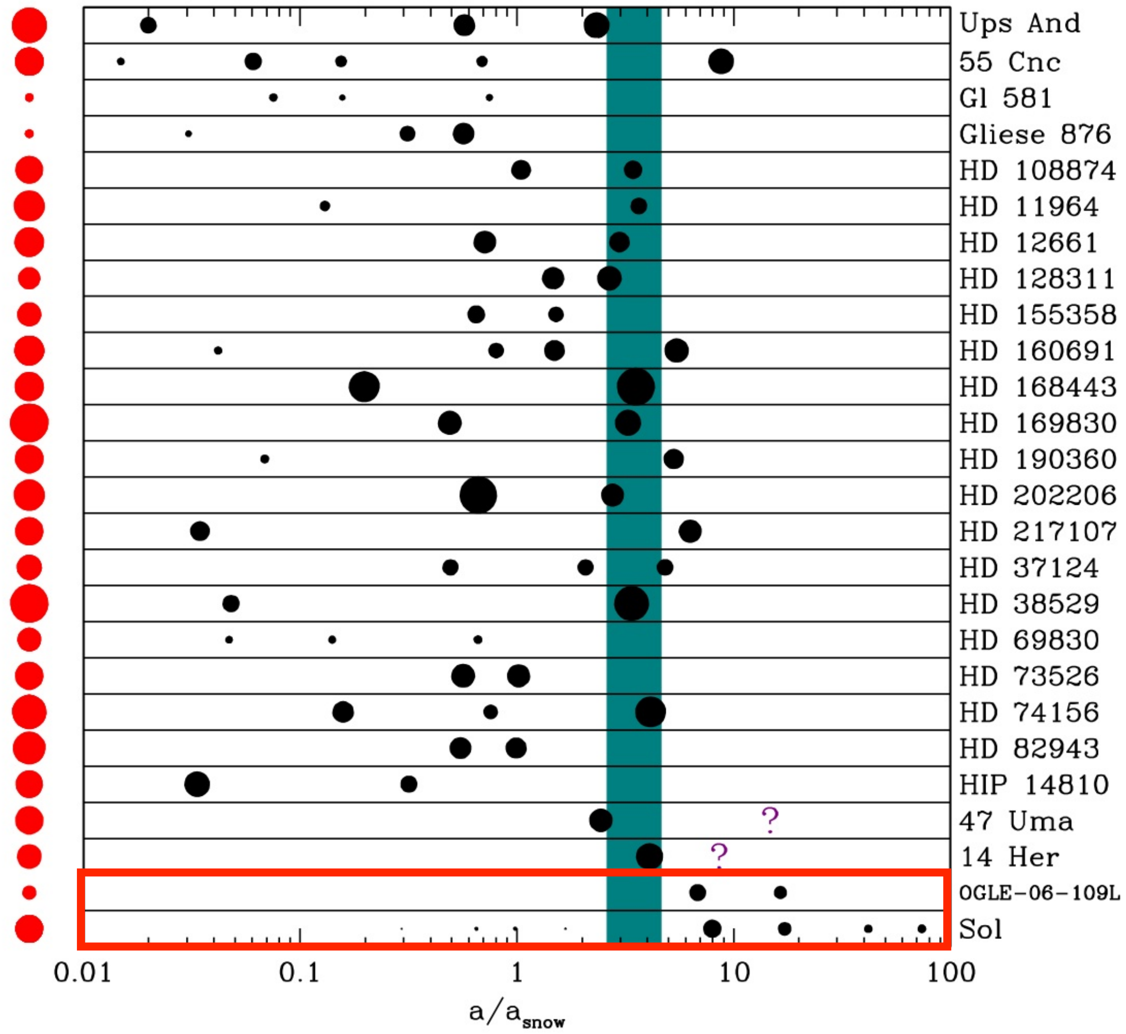
Mass = 0.27 +/- 0.02 MJup = 0.90

Semimajor Axis = 4.6 +/- 1.5 AU

Eccentricity = 0.15+0.17-0.10

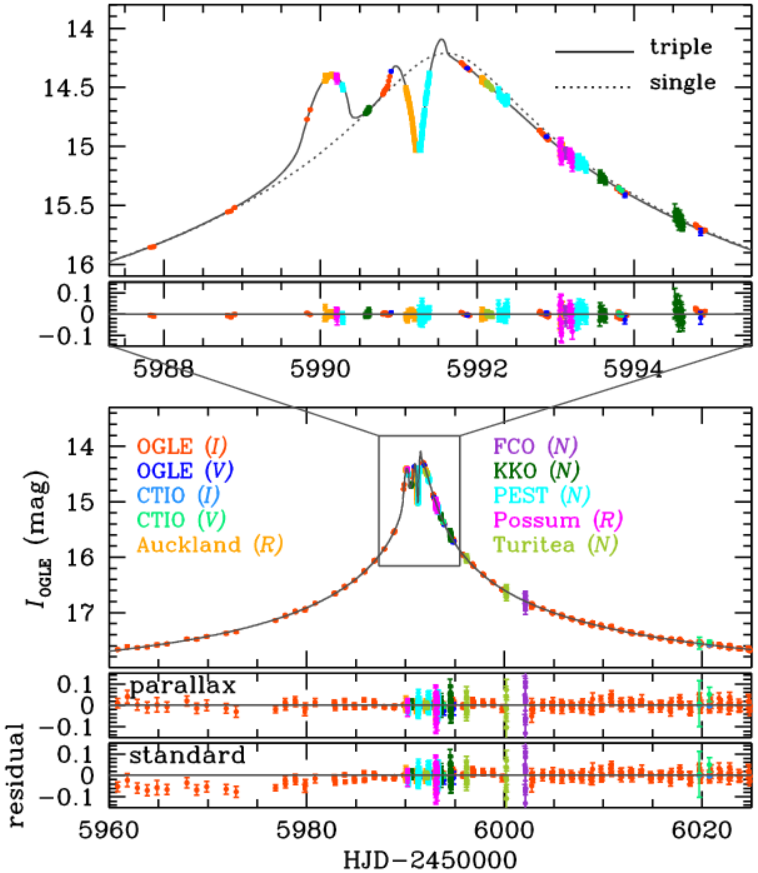
Inclination = 64+4-7 degrees

A Jupiter/Saturn Analog



Semi-major Axis Relative to Snow Line

Second multiple planets: OGLE-2012-BLG-0026

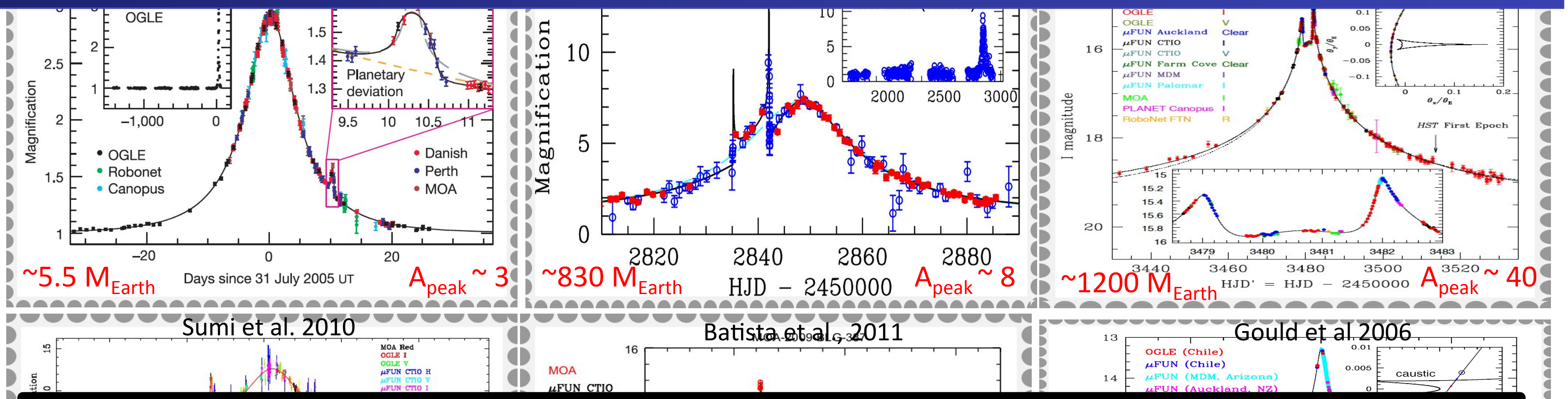


- 2 two-planets
- ~2 circumbinary planets
- **Modelling still a challenge!**

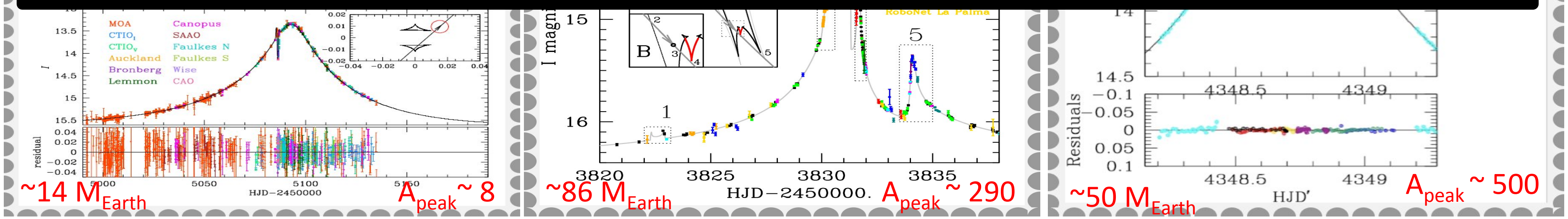
- $q_1 = 1.30 \times 10^{-4}$, $d_1 = 1.034$
- $q_2 = 7.84 \times 10^{-4}$, $d_2 = 1.304$
- $t_E = 93.92 \pm 0.58$ days

Han et al. (2013)

Family Album of Microlensing Planets



- ✓ **More than 50 microlensing planets discovered, but only 27 published, ~15/yr**
- ✓ **Needs faster publications and better communications with other fields**



Microlensing: pros & cons

Pros:

✓ **Wide range of host stars**

✓ **Disk/bulge/extragalactic (M31)**

✓ **Free-floating planets**

✓ **Good for providing statistics of cold rocky planets; complement other methods**

Cons:

✓ **Too distant to observe**

✓ **No repeated observations possible**

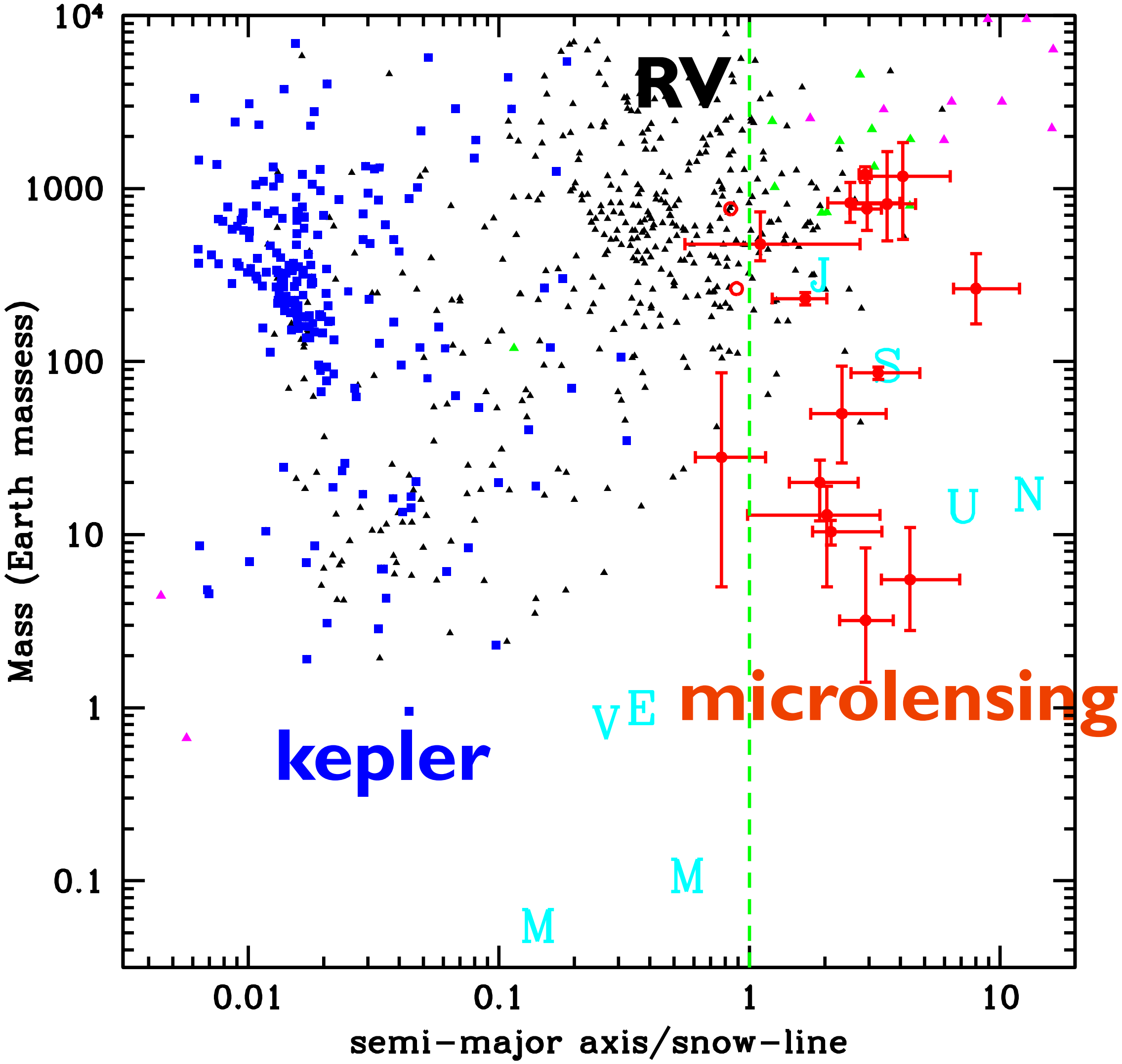
Distinguishing characteristics

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

Debra Fisher

- ✓ **Based on GR**
- ✓ **Caustic crossings always come in pairs**
- ✓ **Local light curves close to caustics follow simple asymptotic relations**
  - ❑ **In some cases, the parameters can be determined using local expansions**

Statistics in discovery space

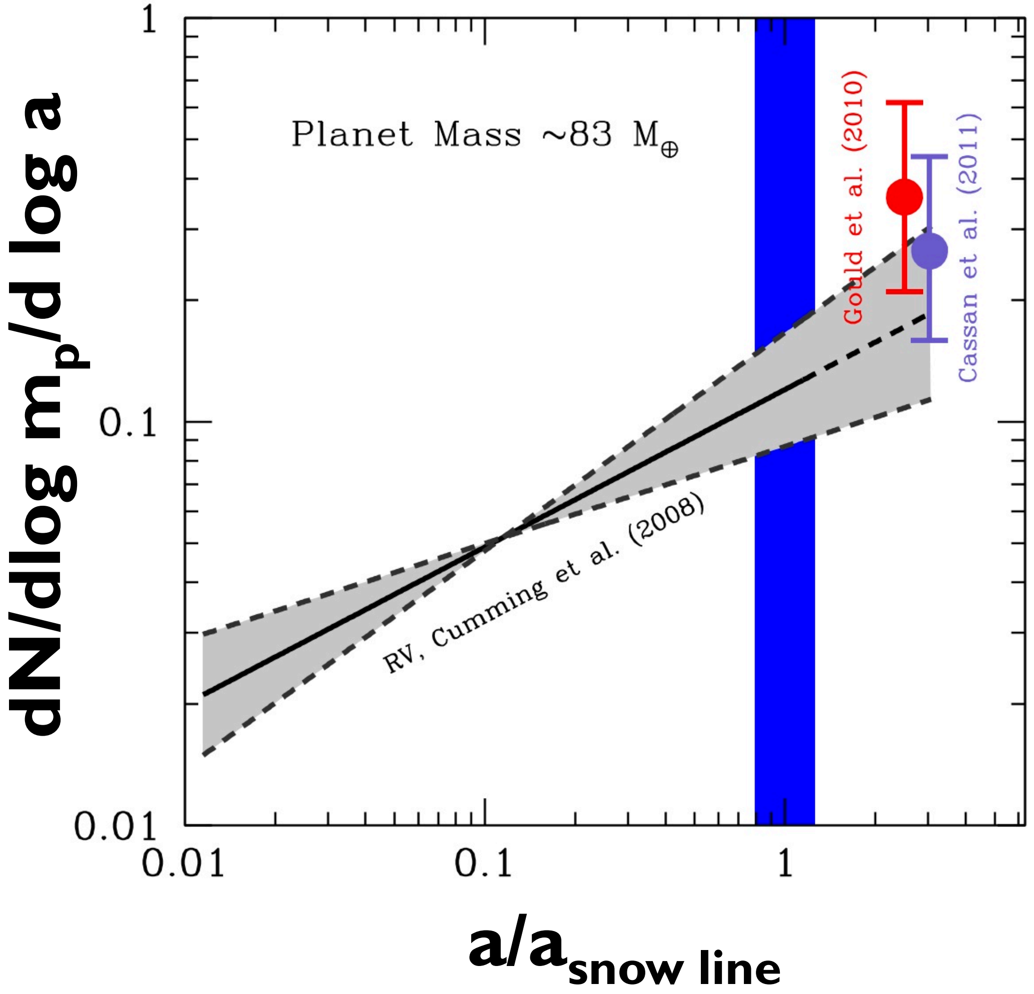


(Mao 2012)

- **Mostly beyond snow line**
- **Low mass planets are more common**
- **Between 0.5-10 AU - 17% have Jupiters, 50% Neptune and Super-Earths**

Cassan et al. (2012); Gould (2006, 2010)

Comparison with radial velocity



Microlensing gives ~ 0.36

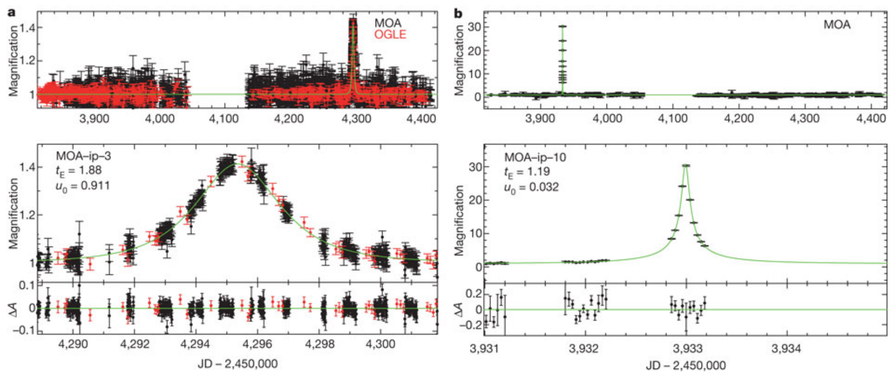
- **Smaller host masses**
- **Larger separation**

(Gould et al. 2010, Sumi et al. 2009, Cassan et al. 2012)

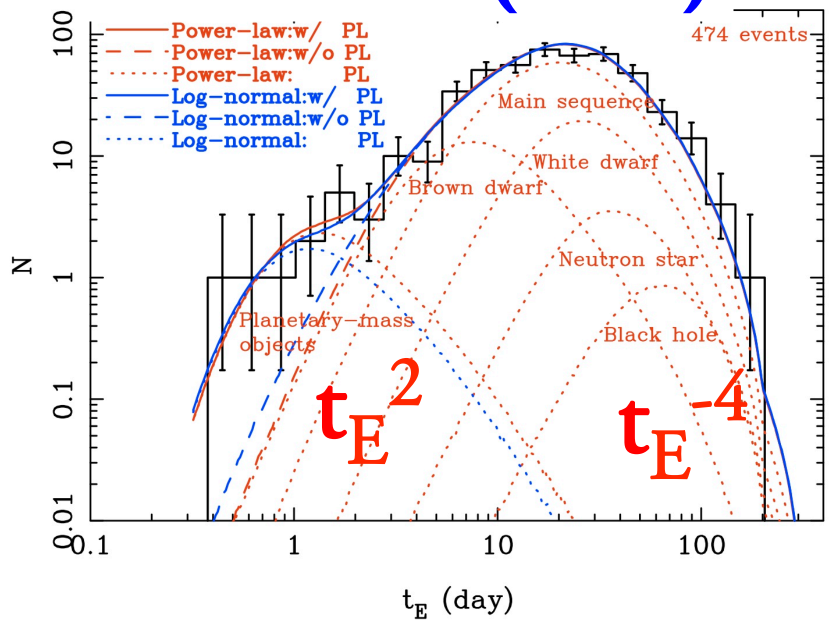
Free-floating planets

- **Excess of short time scale events due to unbound or wide-separation planets.**
- **Implies roughly 2 Jupiter-mass free-floating planets per star. Hard to explain?**

- **Blending? Correlated data points? (Albrow 2014, Santa Barabara)**



Sumi et al. (2011)



Mao & Paczynski (1996)

Frequency of multiple planets

Method	Number of planetary systems: Total	Multiple	fraction (%)	Total Number
RV or astrometry	419	98	23.4	558
Transit	615	350	56.9	1133
Microlensing	27	2	7.4	29
Imaging	43	2	4.7	47
Pulsar/timing	11	2	18.2	14
All	1105	460	41.6	1783

Are fractions in different methods consistent with each other? Selection effects and degeneracy (Song, Mao et al. 2014).

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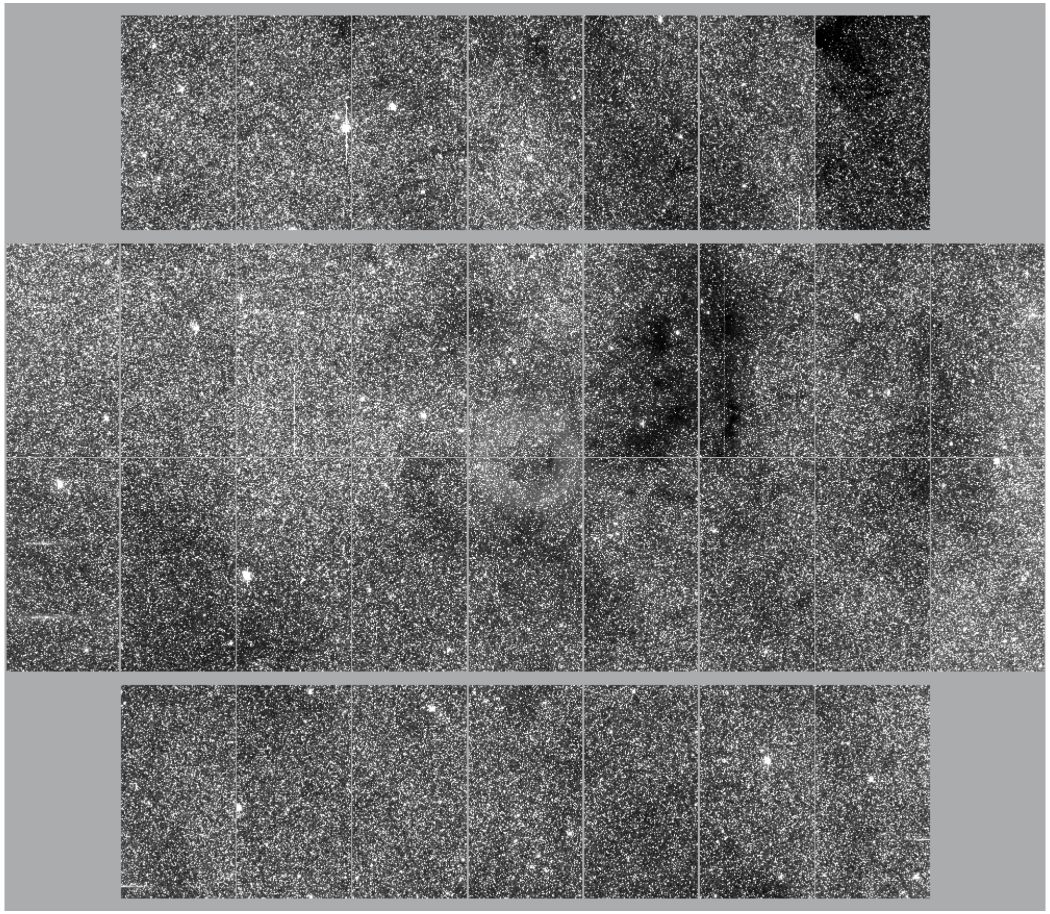
Current mode of discovery

Survey (MOA and OGLE collaborations) + follow-up (microFun/PLANET collaborations) *around the globe*

MicroFun - 24 hour relay

Near-Future: Upgraded Microlensing Experiments

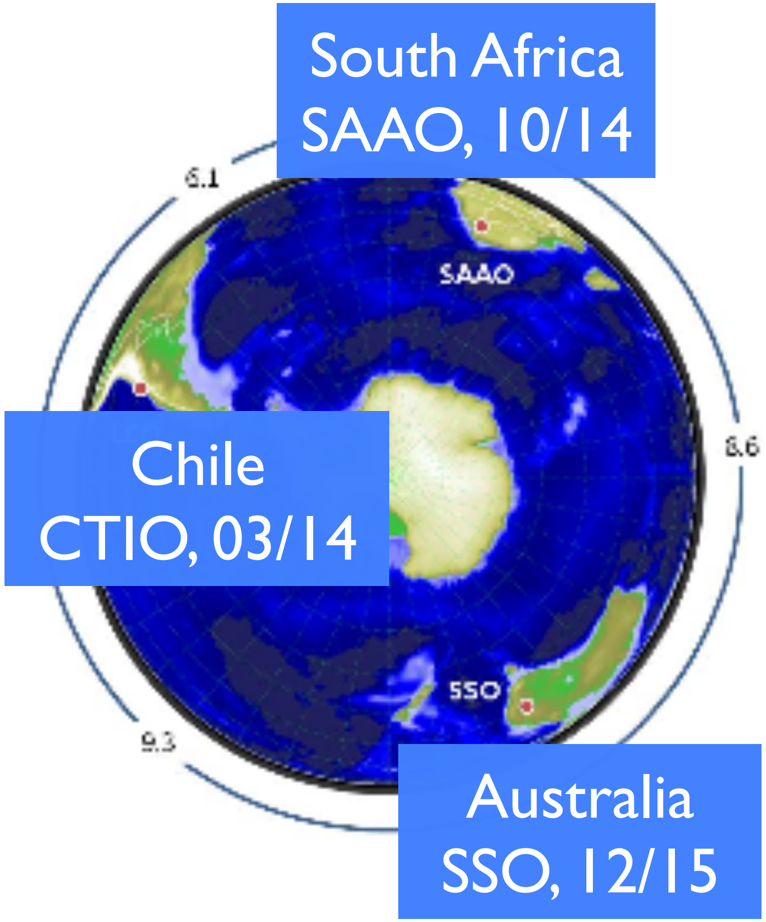


OGLE, 32 CCDs

- **OGLE IV is running in full power since 2011: 1.4 Deg^2 camera**
- **MOA-II: 1.8m telescope 2.2 Deg^2 camera**
- **Current survey + followup will likely continue**

Microlensing within ~5 years: KMTNet

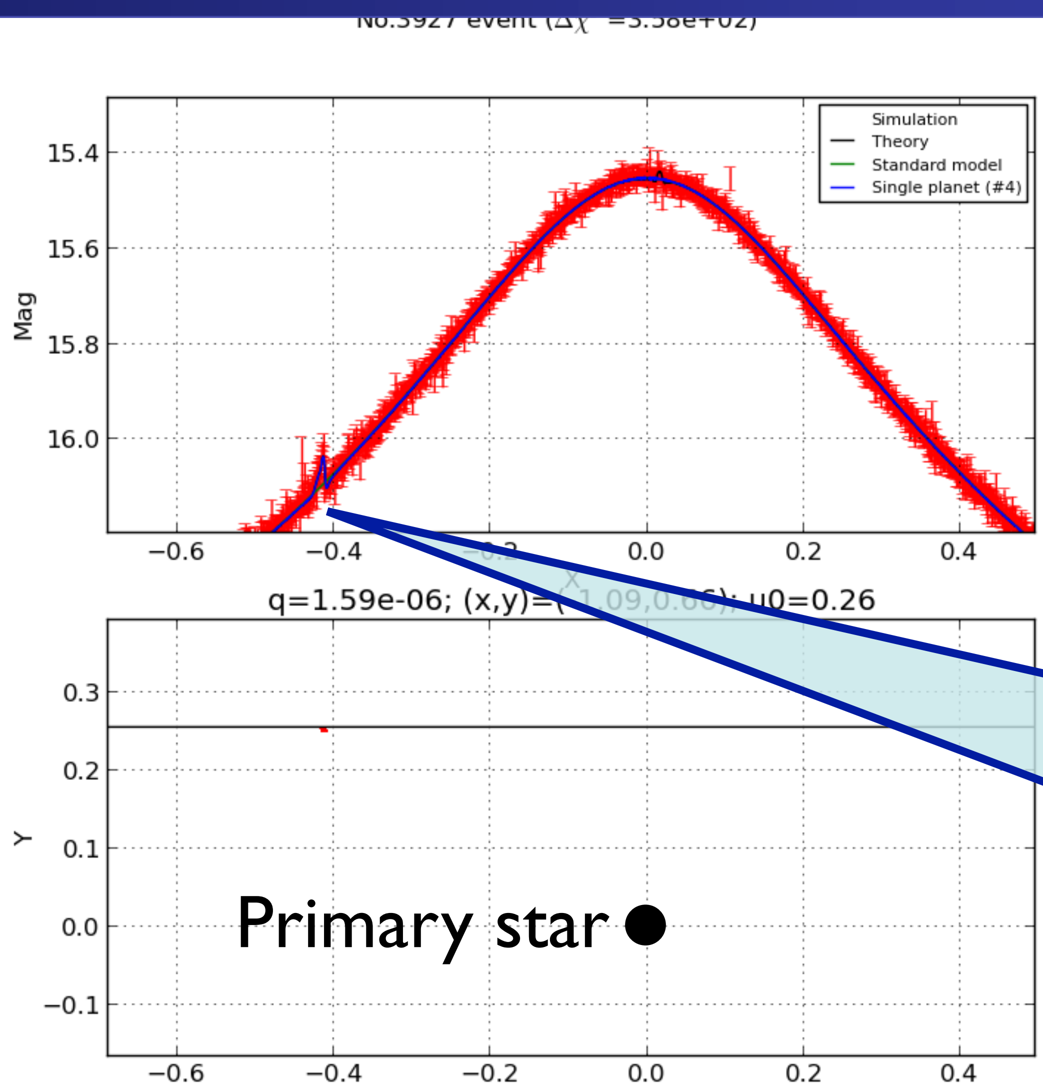
- **KMTNet**
  - **Three 1.6m telescope with ~4 deg^2 FoV, 10m cadence**
  - **~2000 events per year**
  - **~70 planets per year, depending on MF**



Monte Carlo simulations
(Zhu, Penny, Mao, Gould et al.)

- Planet population from Ida & Lin (2010)
- Choose primary star mass of 0.3 solar masses, and reasonable lens and source distances
- Orbital planes are randomly chosen
- all planets above 0.1 M_{earth} are retained
- Use rayshooting to generate light curves, with a cadence of 10min, as expected from KMTnet

A simulated light curve with an 1.6 Earth-mass planet

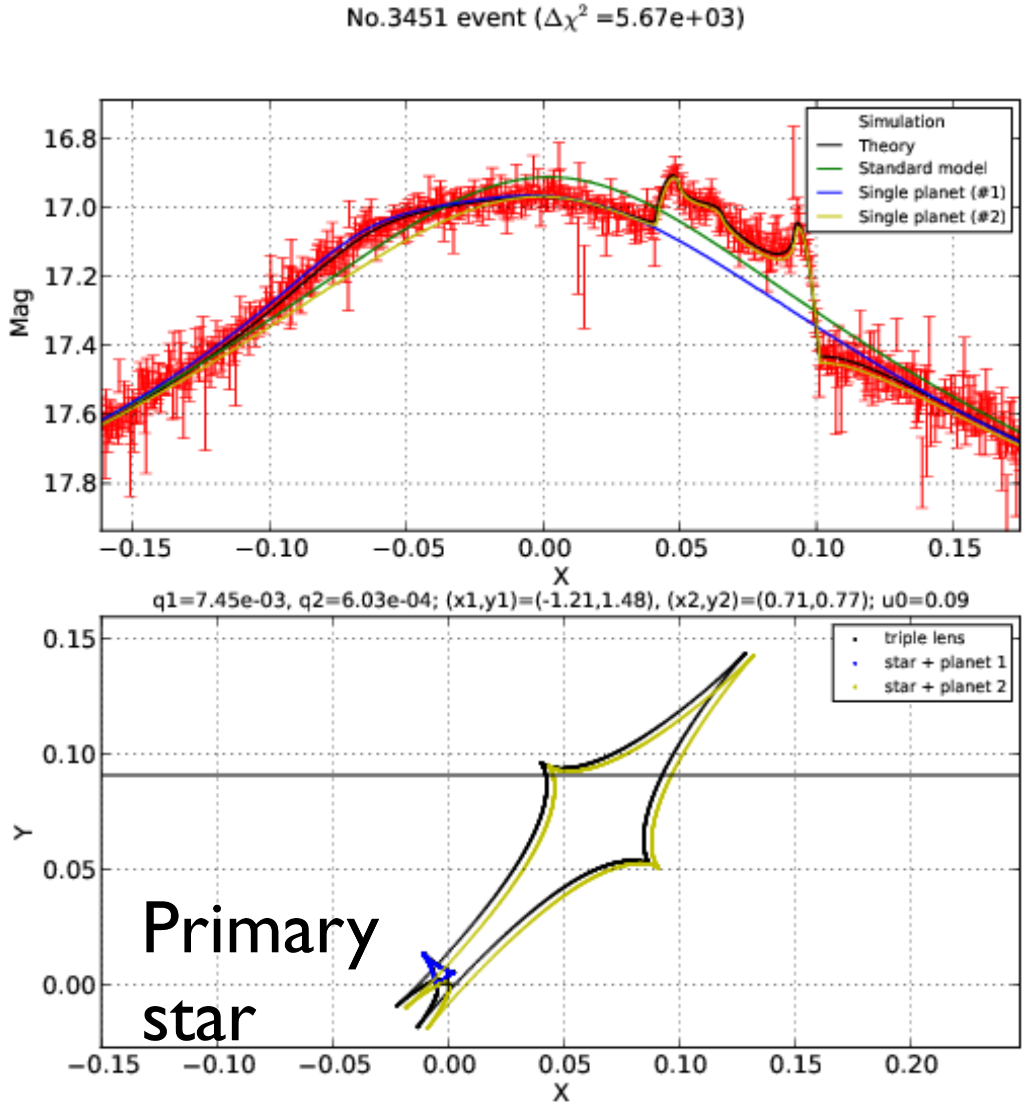


Separation (R_E=1.6

Single and double planets are selected by ΔX^2 (~ 300), and visual examination

- **q ~ 1.59x10^{-6}**
- **ΔX^2=358**
- **Planetary caustics**

A simulated light curve with two planets



- **double low-mass planets**

  $q_1 \sim 7.45 \times 10^{-3}$

  $q_2 \sim 6.03 \times 10^{-4}$

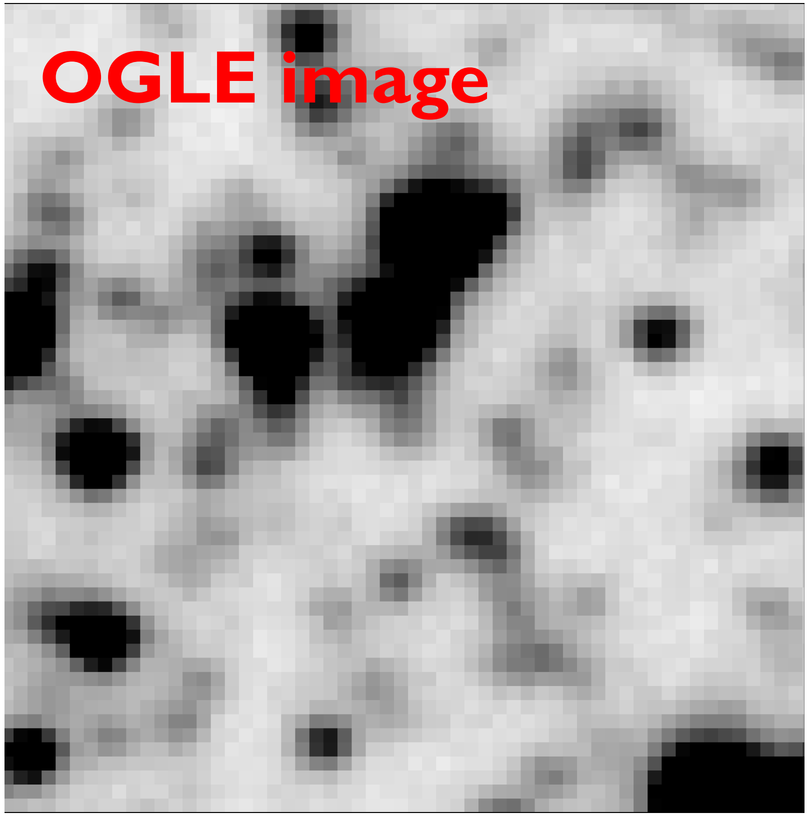
- **Central +resonant caustics**

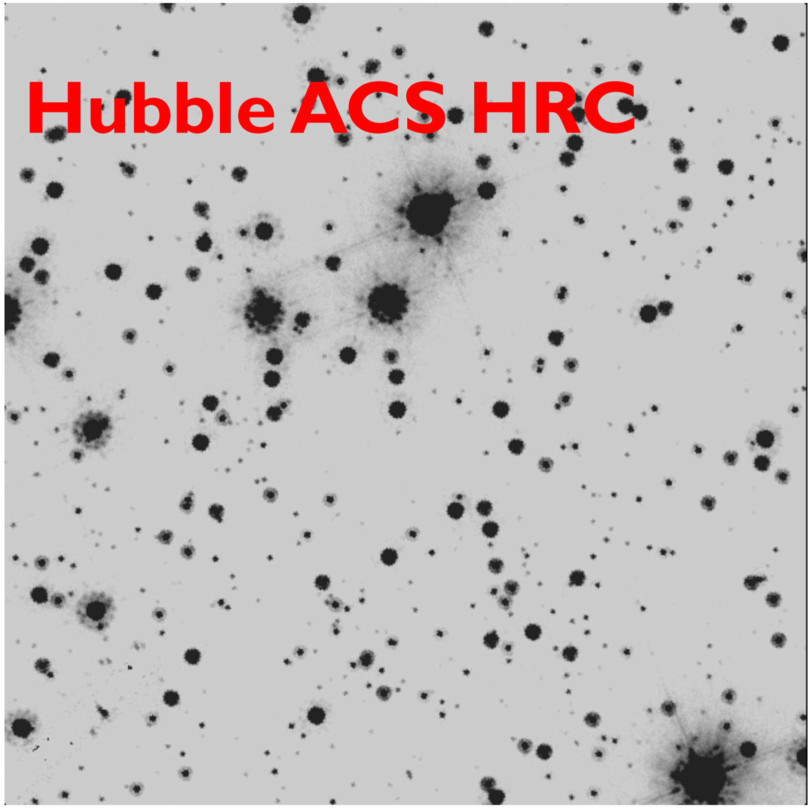
- **$\Delta X^2 = 5670$**

Statistical predictions

- Probability of planetary events is ~ 2.9%, out of which 5.5% is doubles
  - Central caustic crossing are more common for multiple-planet systems
- super-Earths:Neptunes:Jupiters ~1:1:1
  - Sensitive to Mars-mass planets close to the Einstein radius
- Planetary: central: resonant=107:128:78

Microlensing in ~10 years: space



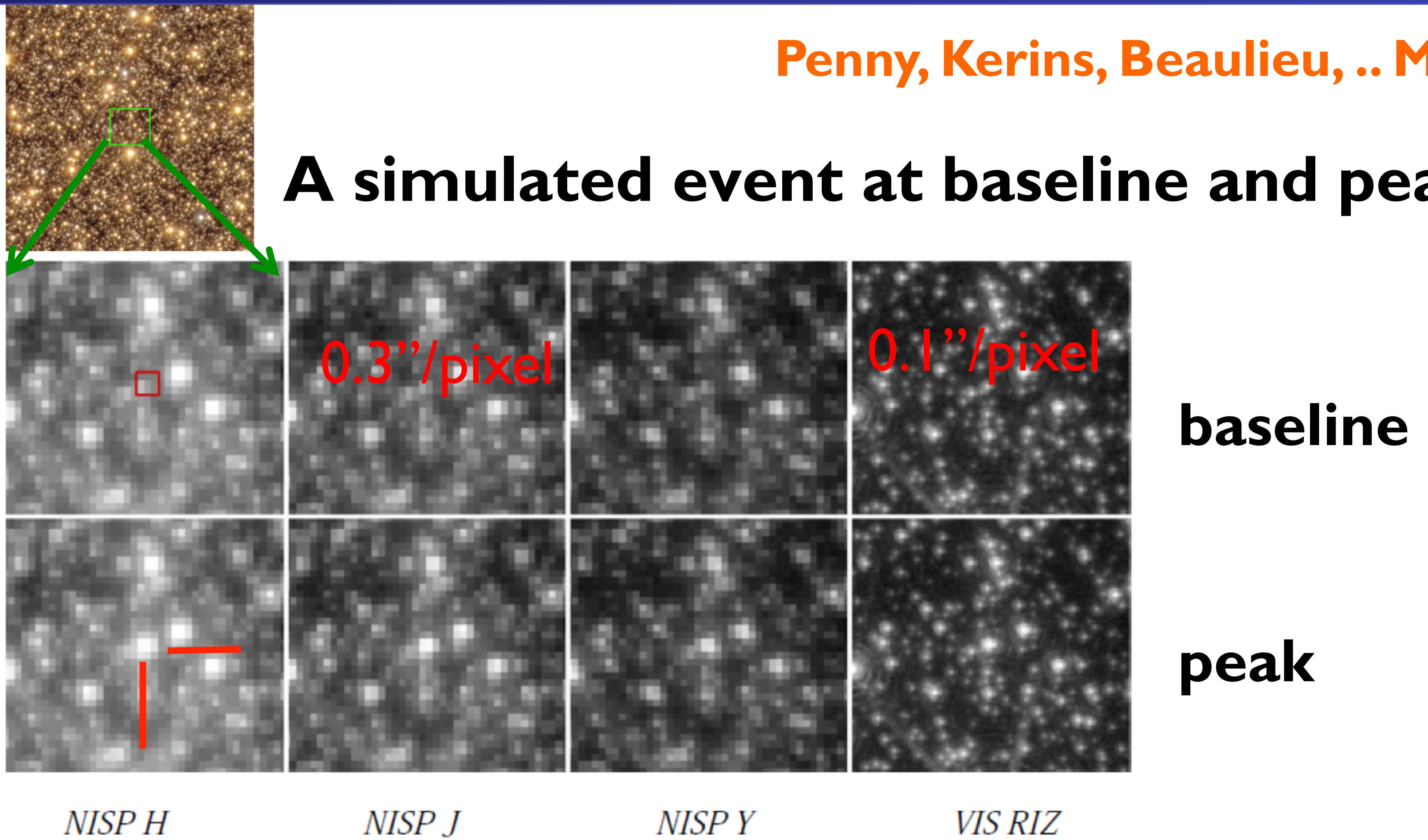


- **Space allows to observe in IR, and study fainter, smaller stars to discover very low-mass planets**
- **Direct lens-source separation partially/completely remove the degeneracies**

Microlensing from space: Euclid

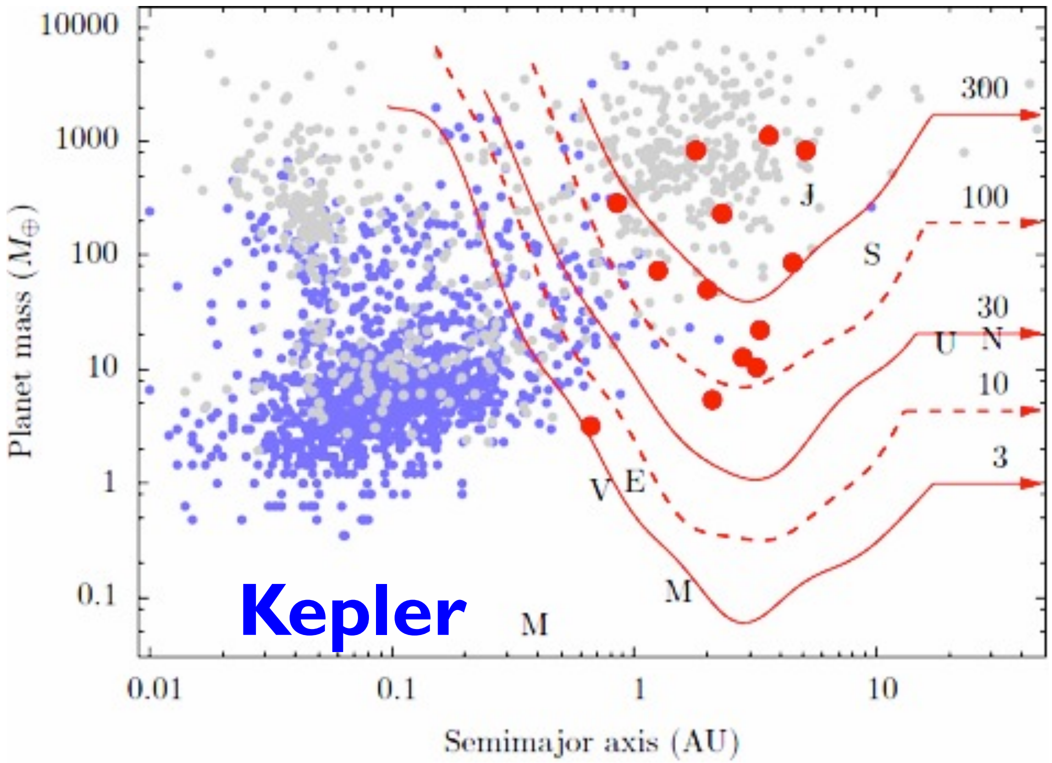
Penny, Kerins, Beaulieu, .. Mao

A simulated event at baseline and peak



Euclid (2020) focus on weak lensing and BAO, but may have a microlensing component

Euclid sensitivities and yields

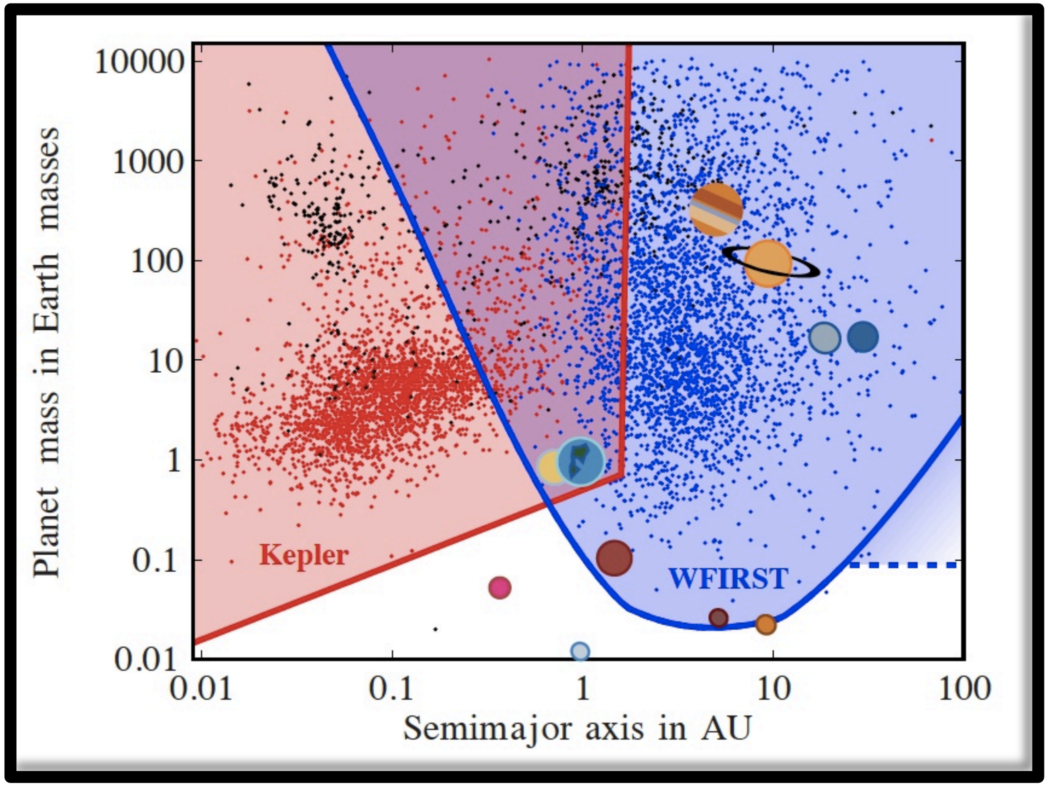


5 year mission,

two-month per year

- **Default MF: 1/3 per log m per log a, flat log mass dependence**
- **total detections (-1.5<log M/Me<3): ~400, 6 Earths (range: 6-100 in different models)**
- **Sensitivity to free floating planets**

A complete census of planets



WFIRST

- **Space microlensing, together with other can potentially provide a complete census of the planet population**

Summary

- Two decades of microlensing data have yielded large, still under-explored datasets
- Microlensing extrasolar planet detection complements other methods:
  - free-floating planets, planets in binaries, even extragalactic planets
  - Current planetary rate: ~15/yr
  - KMTNet: a factor 5-10 increase in rate
  - space another factor of 5-10 down to lower masses with better determinations