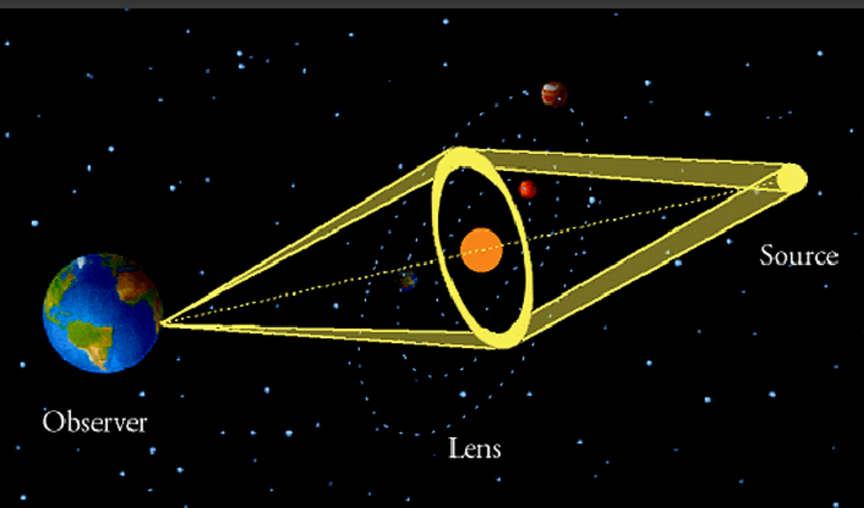
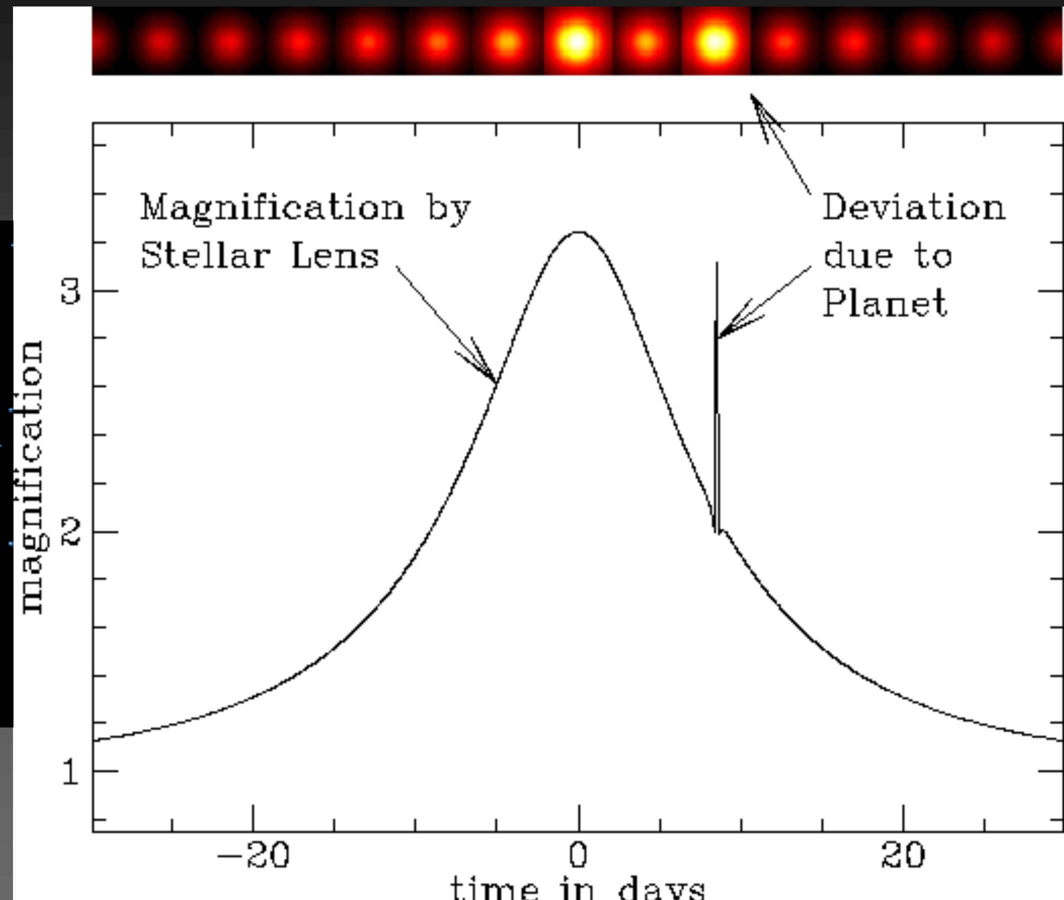
Jean-Philippe Beaulieu

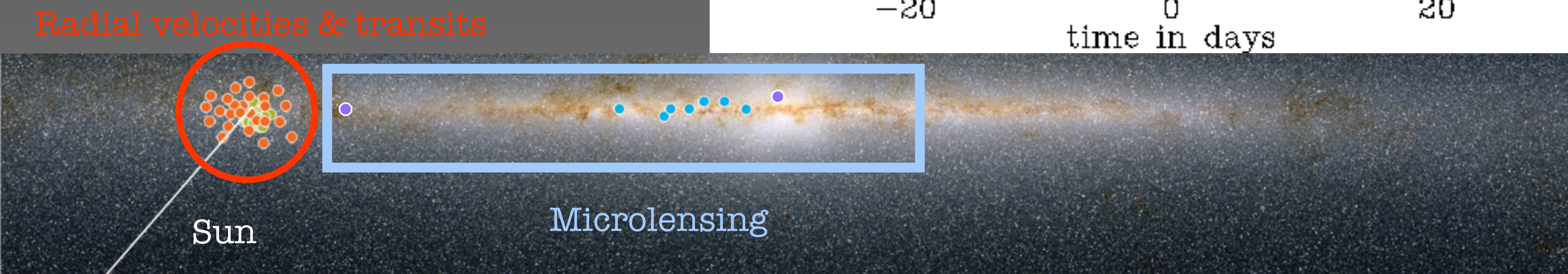
Microlensing surveys and exoplanets

University of Tasmania, Institut d'Astrophysique de Paris

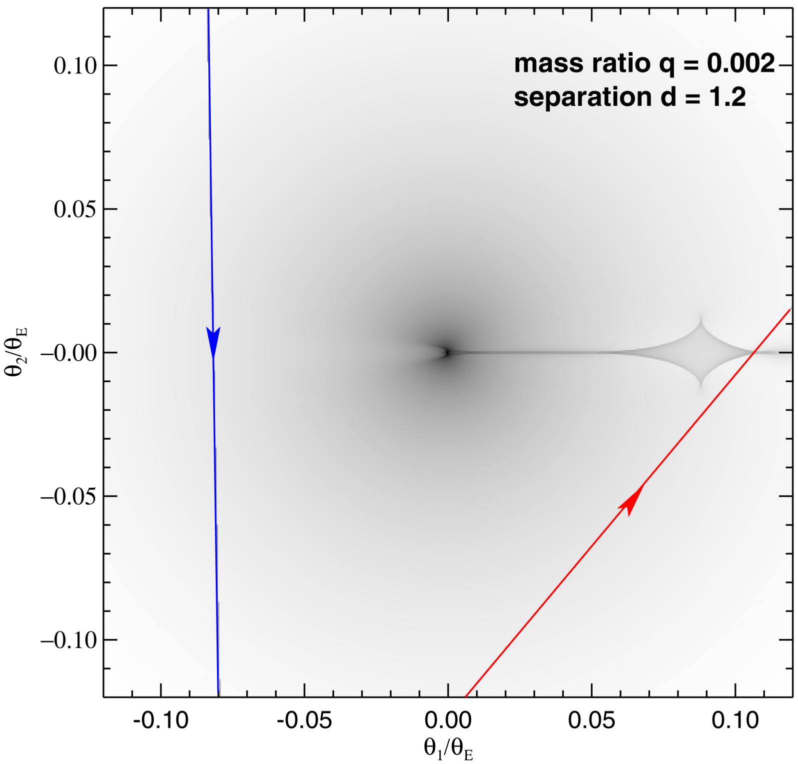
Detecting a planet via microlensing

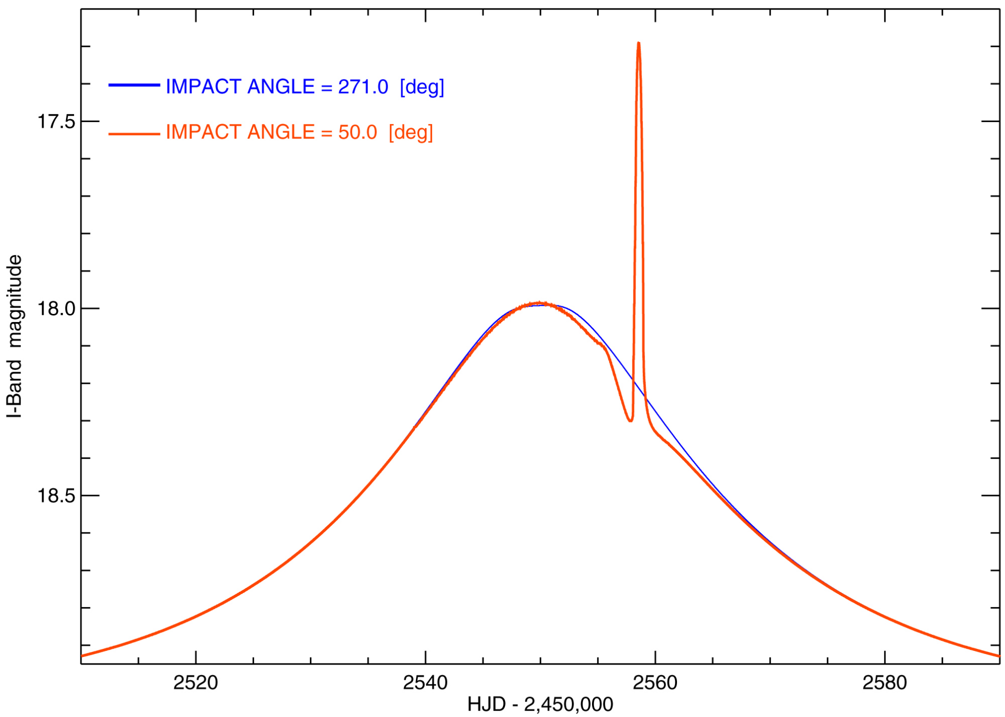






Catching a planetary companion





$$t_{\mathrm{E}} = 20\,\mathrm{d}, M = 0.3\,M_{\mathrm{sun}}:$$

$$t_{\mathrm{p}} = \sqrt{q}\; t_{\mathrm{E}}$$

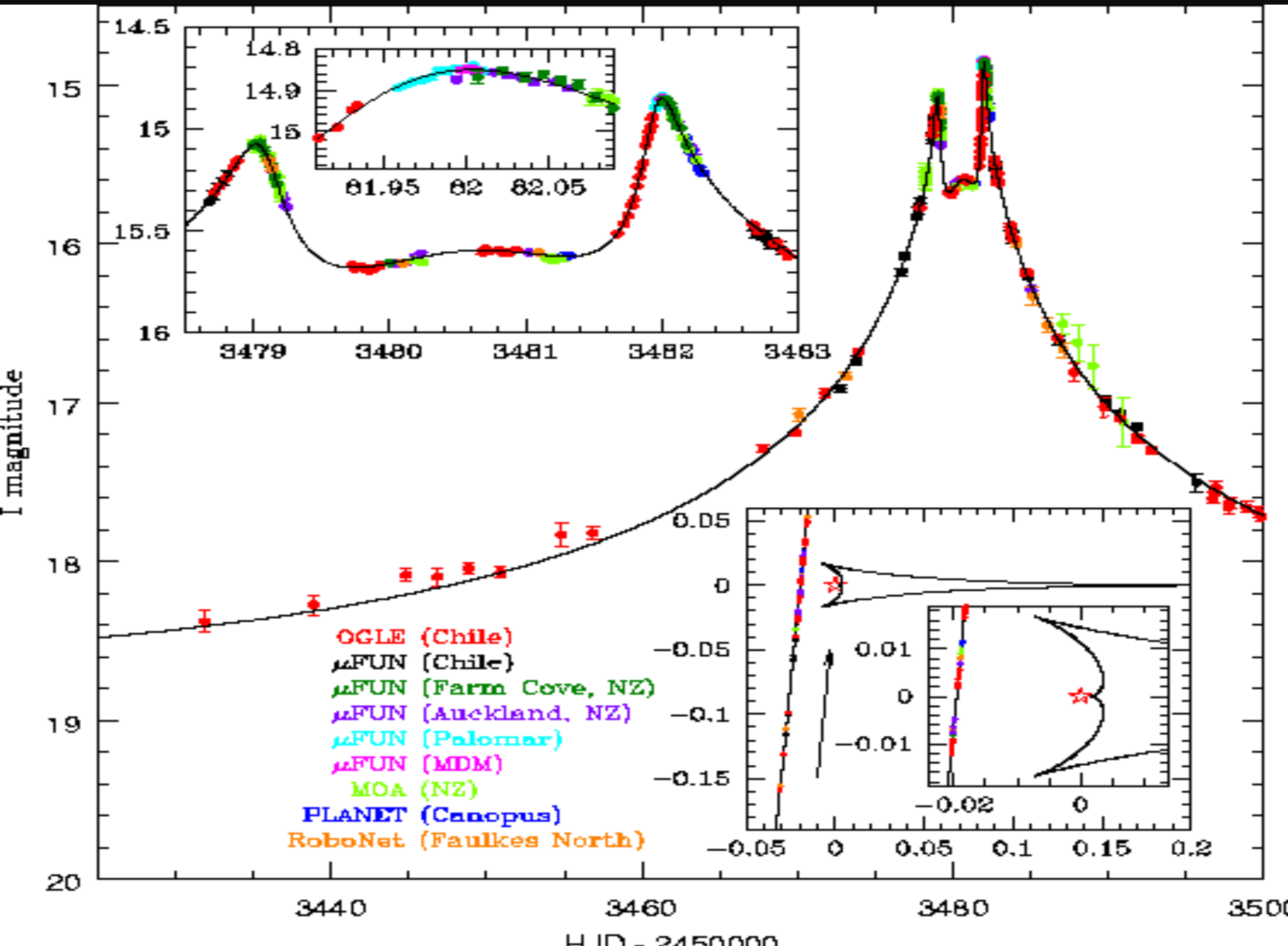
$$\text{Jupiter}: \; q = 3\;10^{-3} \Rightarrow t_{\mathrm{p}} = 1\ \mathrm{d}$$

$$\text{Earth}: \; q = 10^{-5} \Rightarrow t_{\mathrm{p}} = 2\ \mathrm{h}$$





A massive gazeous planet, OGLE-2005-BLG-071



Close binary :
d=0.758
q=6.7 10^{-3}

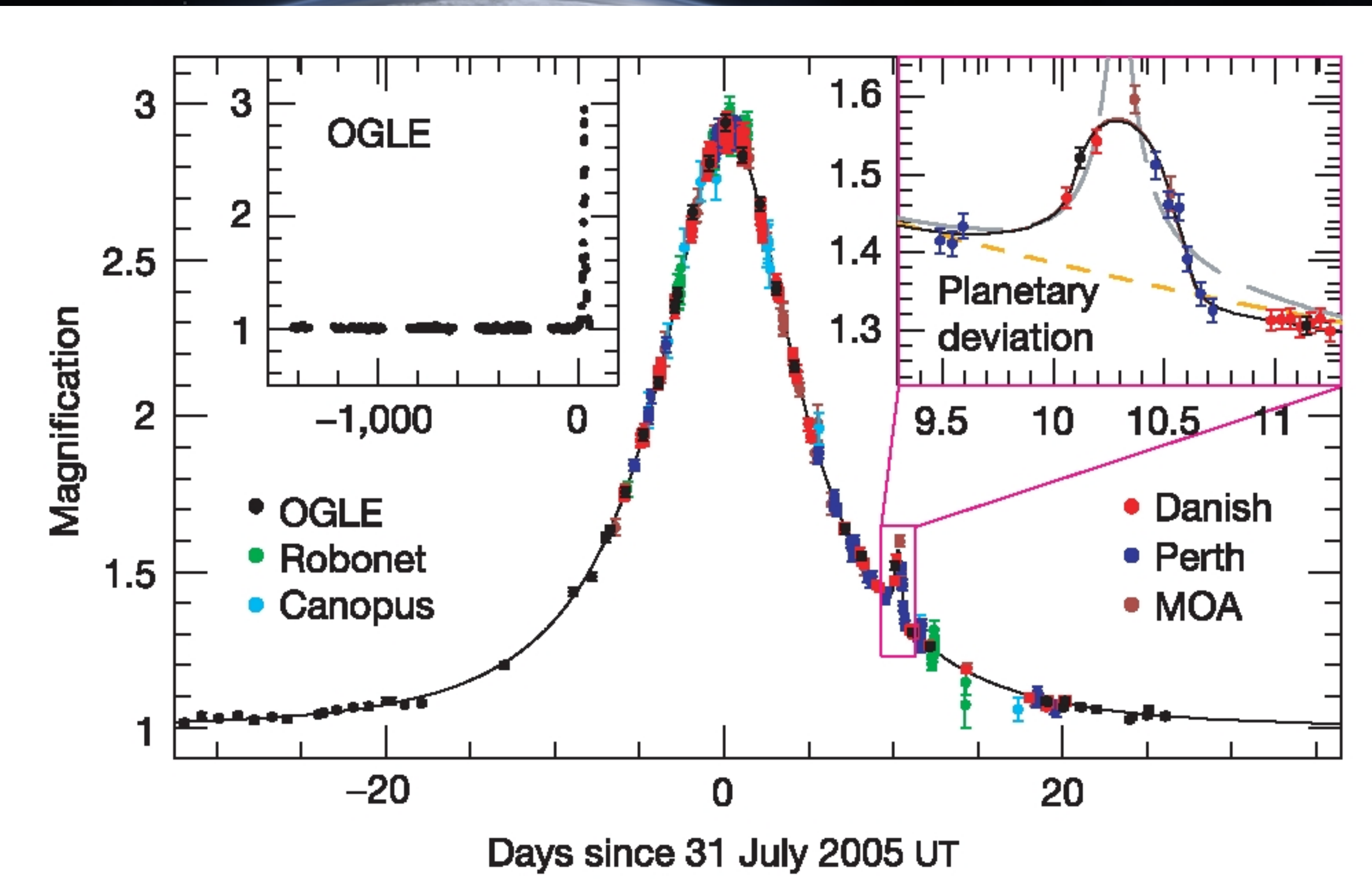
Wide binary :
d=1.294
q=7.1 10^{-3}

M* ~ 0.45 Mo
5.2 ± 1.8 kpc
2.7 MJupiter
a ~ 2.2 AU or3.7 AU

Udalski et al. 2005,
including Beaulieu, Dieters, Greenhill, Hill, Kubas (PLANET)

A first frozen super Earth

Gas giants are rare, super Earth-Neptunes are common
Same direction as the core accretion model predictions



$$M_* = 0.22^{+0.21}_{-0.11}\ M_{\text{SUN}}$$

$$M_{\text{p}} = 5.5^{+5.5}_{-2.7}\ M_{\text{EARTH}}$$

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

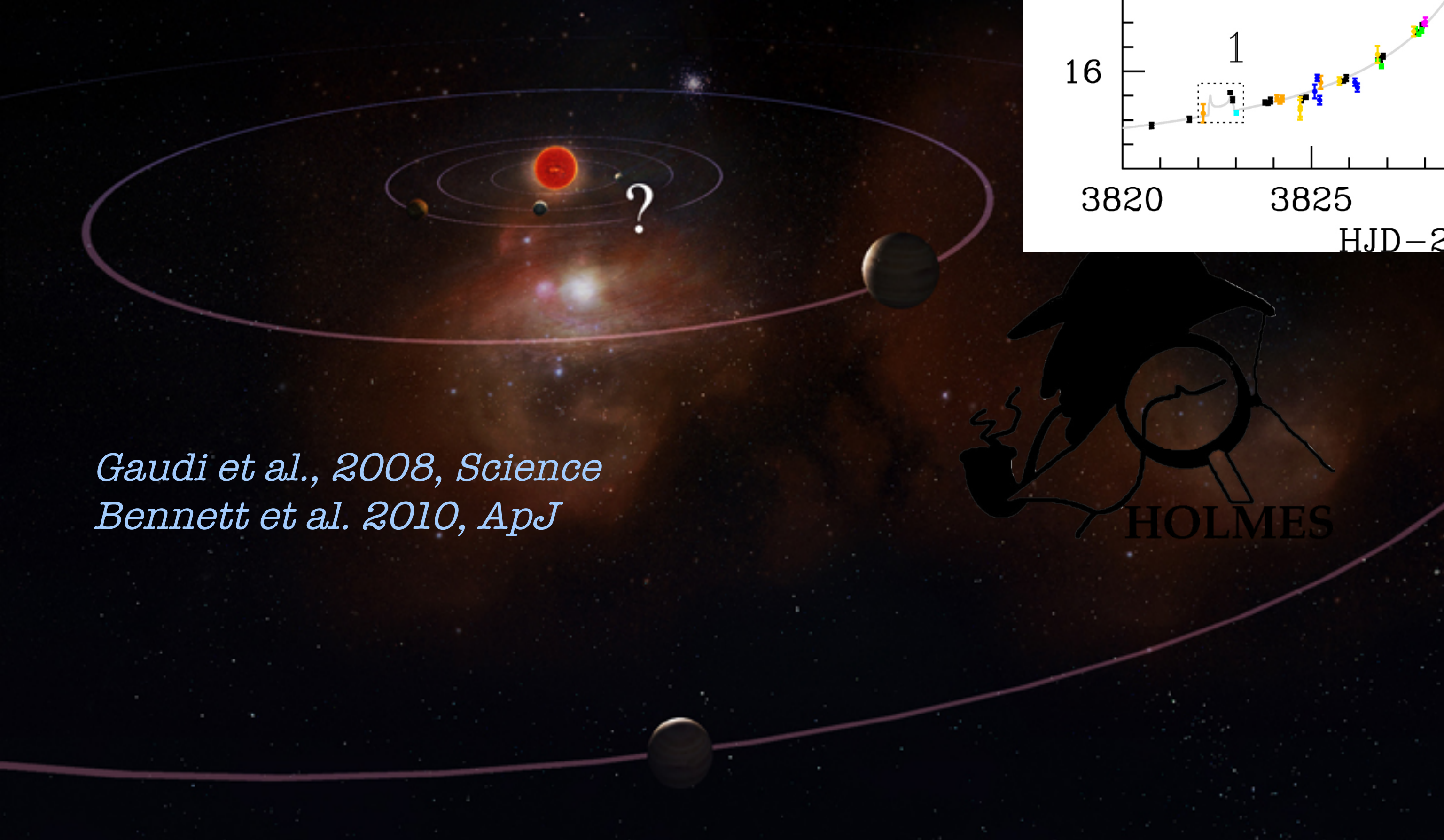
Beaulieu et al., 2006, Nature (PLANET, OGLE, MOA)

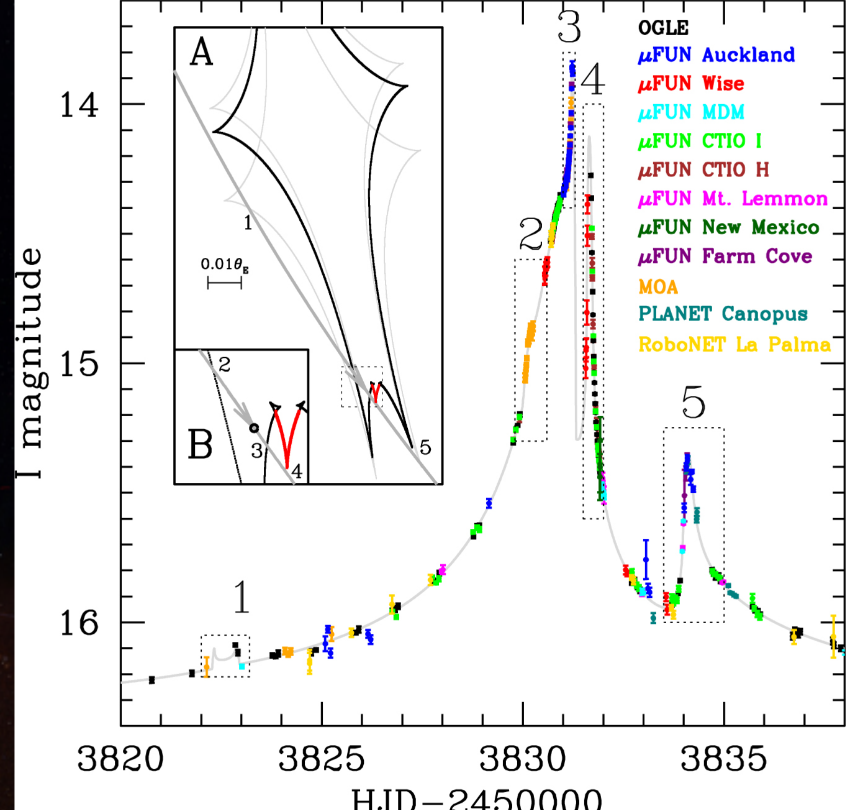
Similar to Hoth planet from Star-wars

A scale ½ solar system

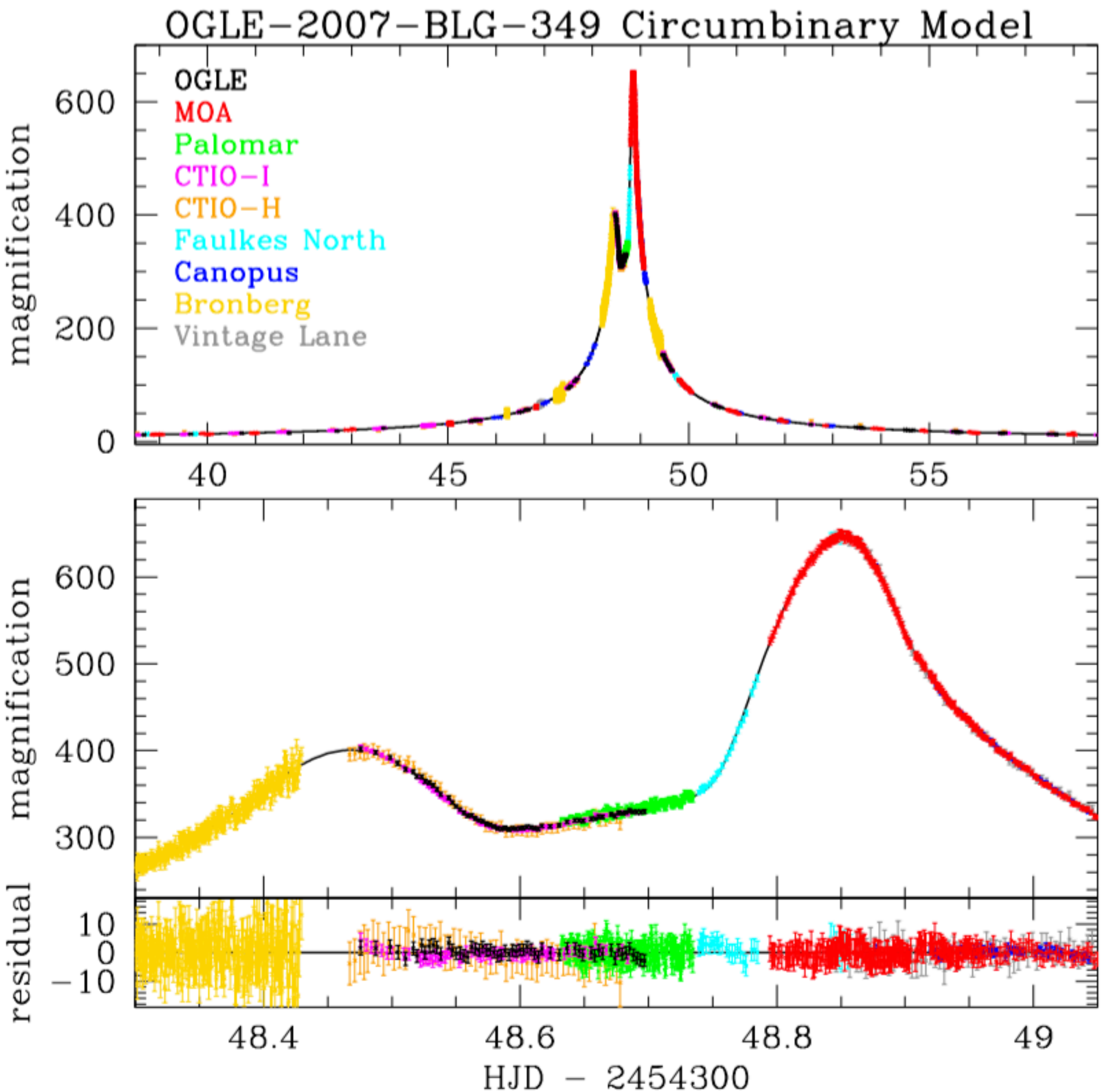
A small star (1/2 sun)

Two gazeous planets like Jupiter and Saturn
Big planet is 0.7 Jupiter at 2.3 AU
Second planet is 0.3 Jupiter at 4.6 AU





Gaudi et al., 2008, Science
Bennett et al. 2010, ApJ

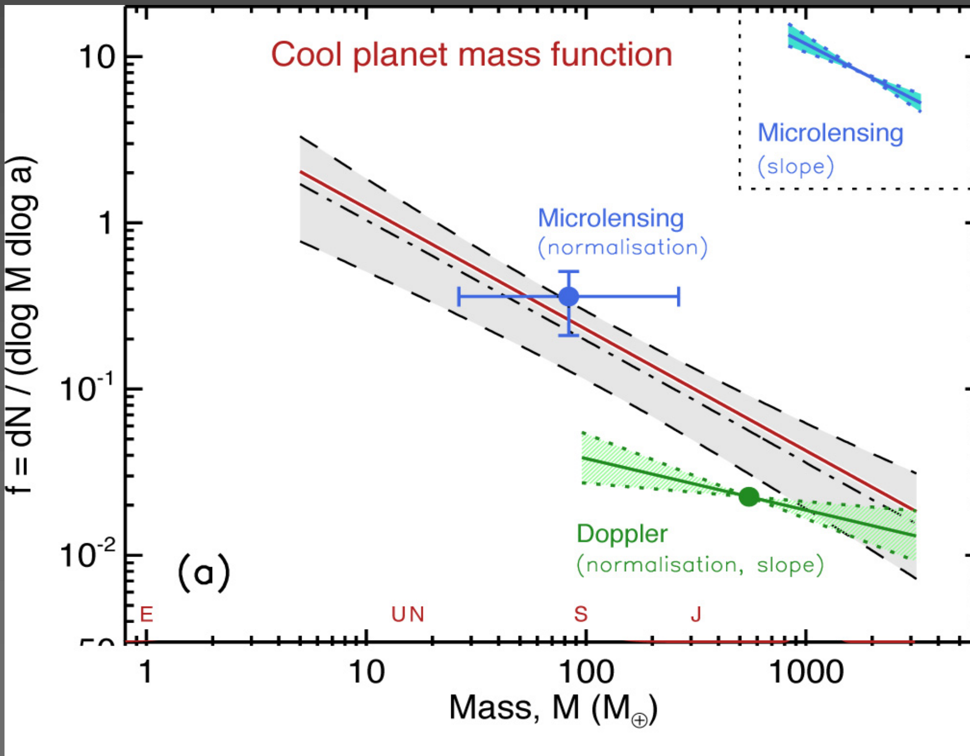

OGLE-2007-BLG-349 Circumbinary Model
OGLE
MOA
Palomar
CTIO-I
CTIO-H
Faulkes North
Canopus
Bronberg
Vintage Lane
magnification
magnification
residual
HJD − 2454300

Tatooine

Having a planet is the rule for stars in our galaxy.

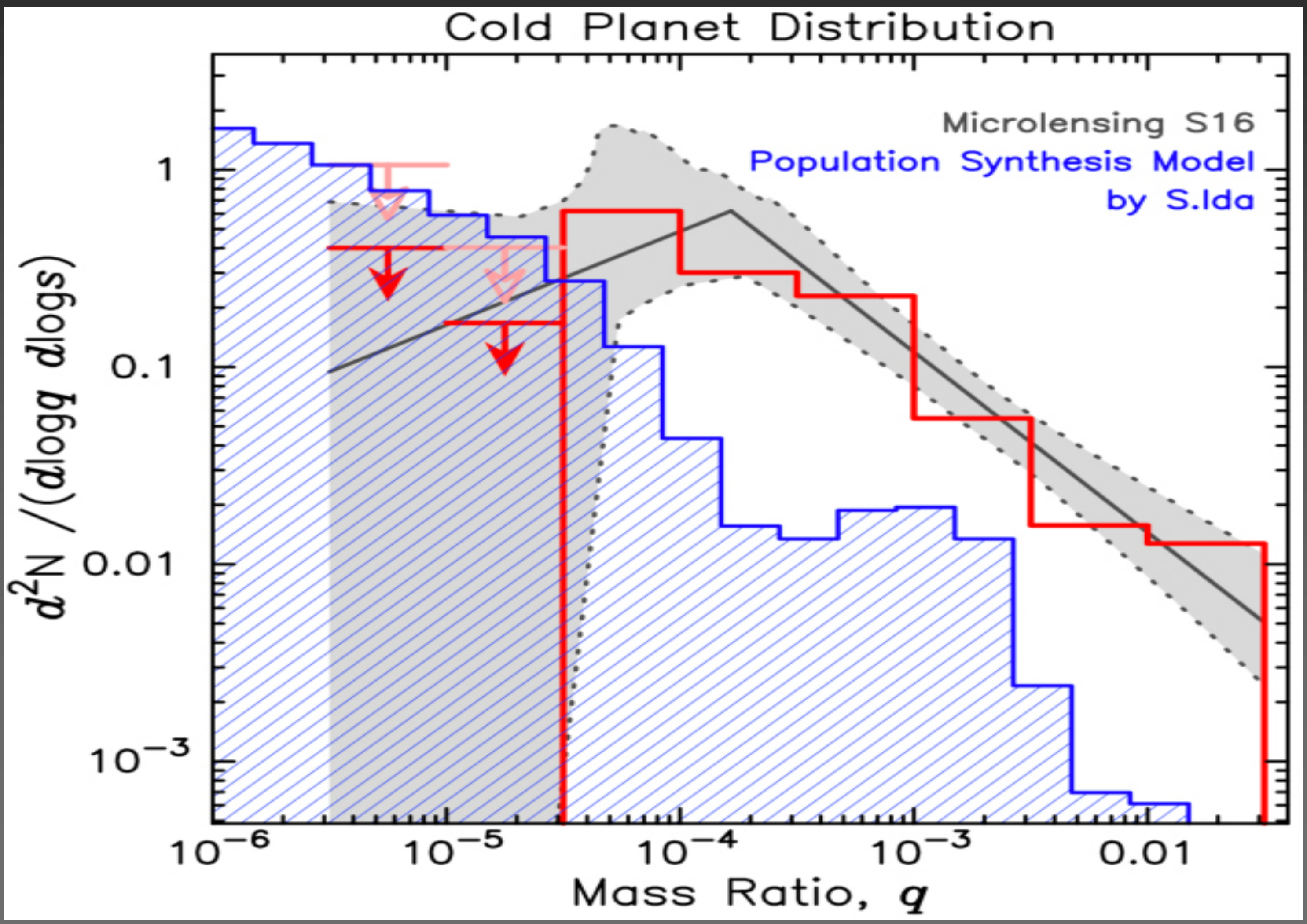
- About 17^{+6}_{-9} per cent of stars host Jupiter-mass planets (0.3-10 MJ).
- Cool Neptunes (10-30 $M_\oplus$) and super-Earths (5-10 $M_\oplus$), however, are even more common: Their respective abundances per star are 52^{+22}_{-29}% and 62^{+35}_{-37}% per cent.

Cassan A., J. et al., 2012, Nature PLANET, including J. Greenhill, A. Cole, S. Dieters, K. Hill, B. Watson

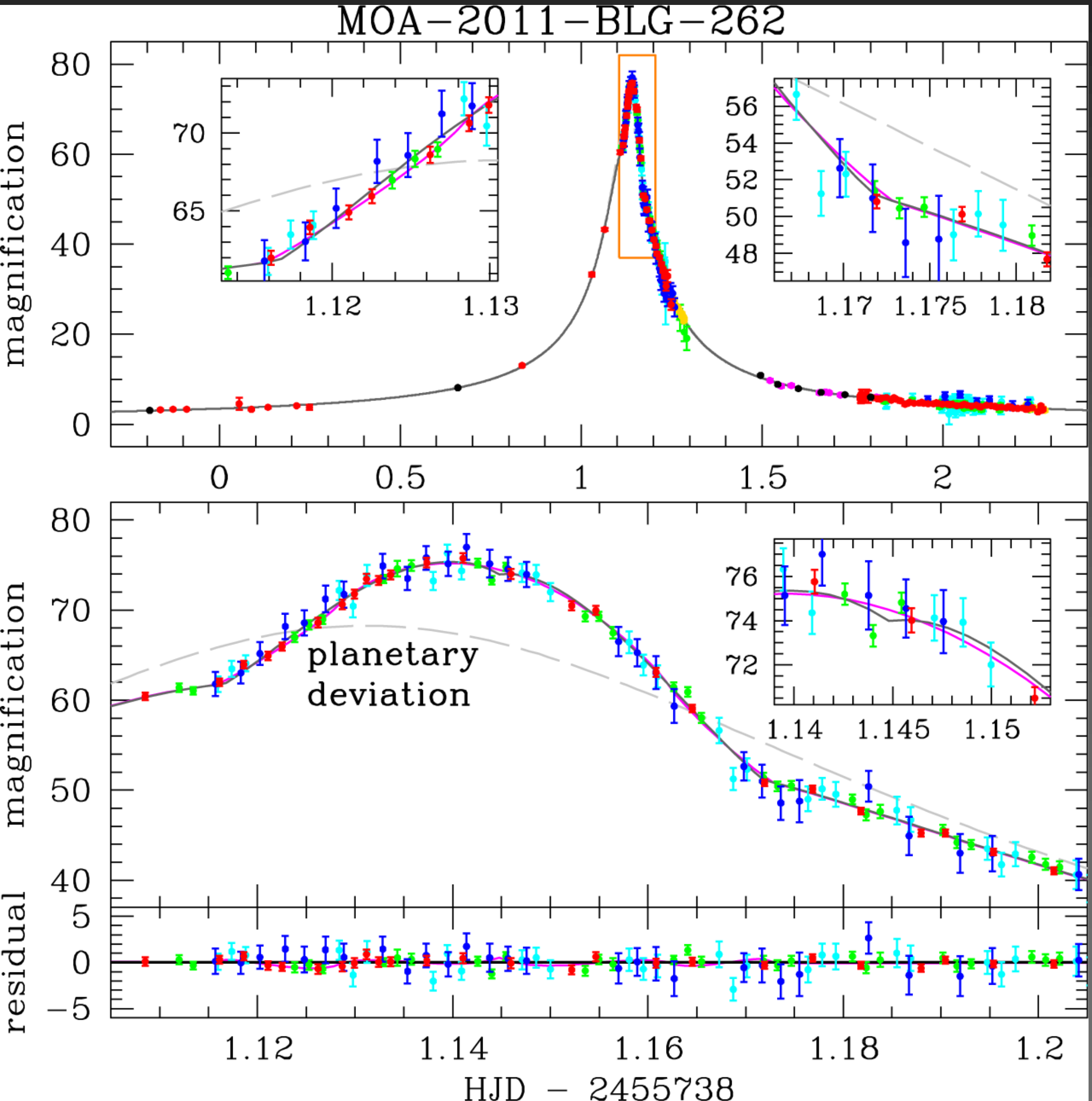


Cold planet mass function

Suzuki et al., 2016



A first exomoon ?



2 different solutions with ΔXi2 ≈ 3

Mass ratio of q = 4.7 10^{-4}, t_E= 3.8 days

A ~5 Jupiter with a sub Earth exomoon at 500 pc

An M/brown dwarf with a Neptune in the Bulge, at very high velocity

Bennett et al., 2014

Getting accurate physical parameters

Mass ratios & projected separations are well known

- Mass ratio $q = M_p/M_*$
- Planet/star separation in Einstein Ring radius units
- Timescale t_E

We need mass-distance relations to get physical parameters:

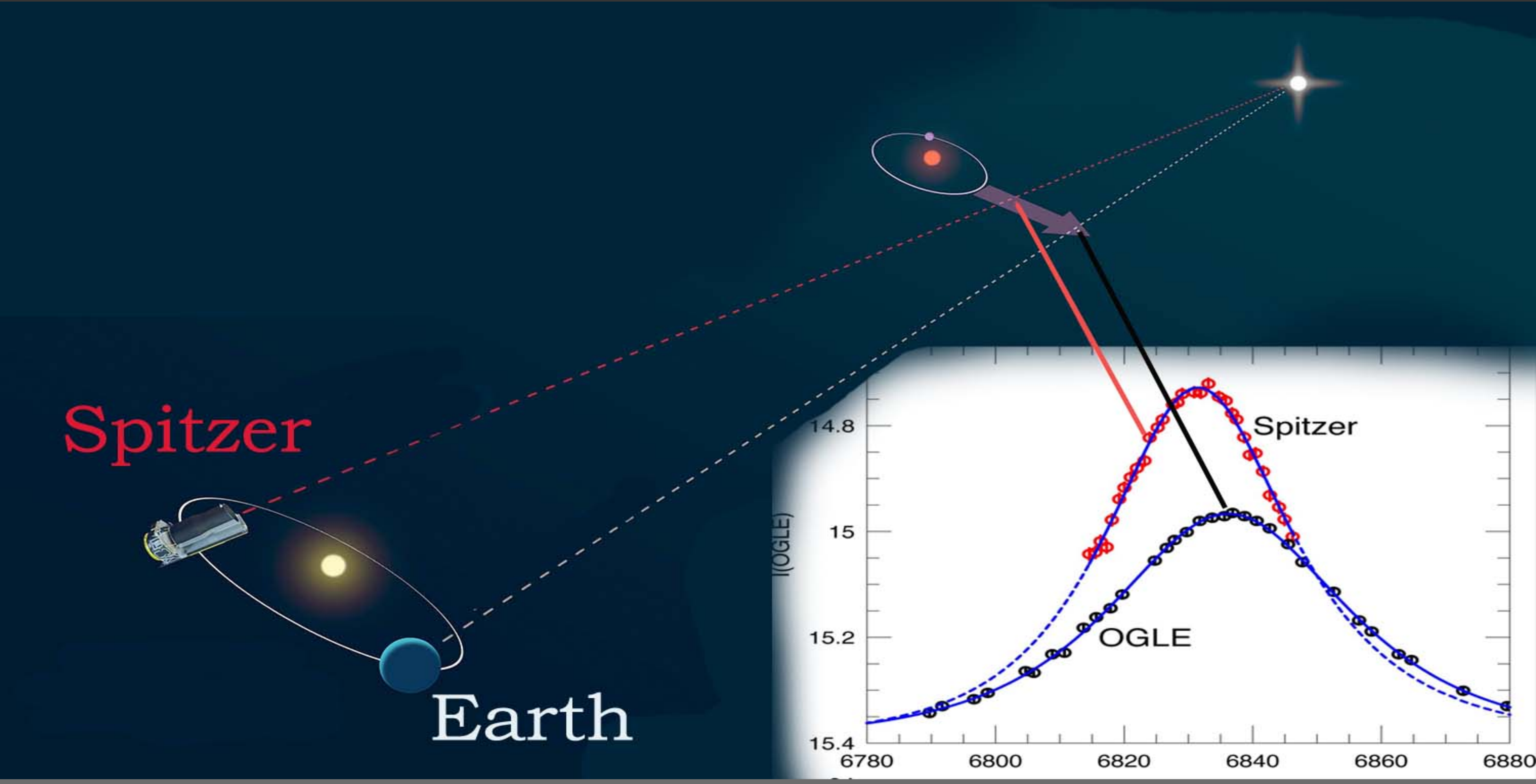
- Masse-distance relation from Einstein ring radius measurements

  Easy to get, when you have caustic crossings

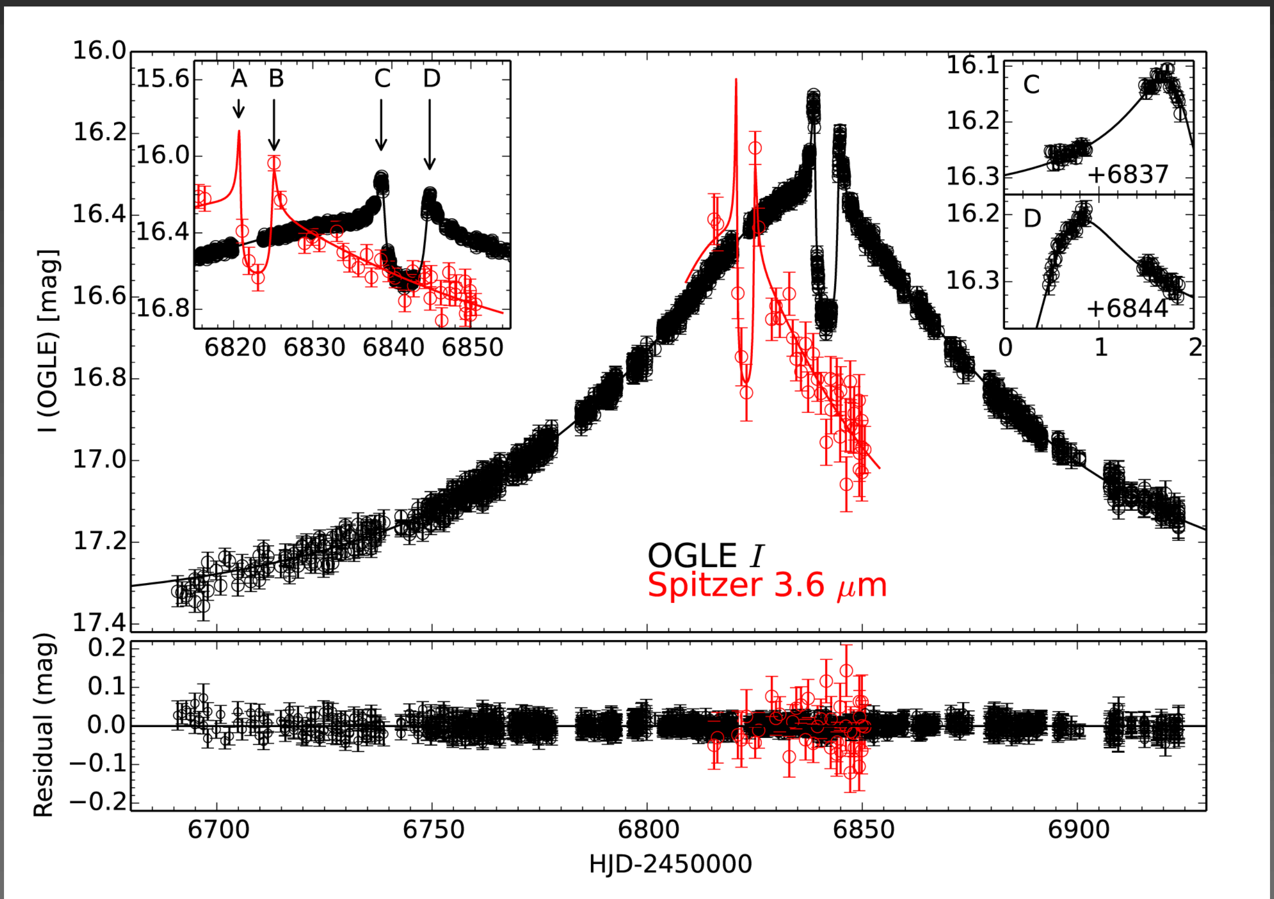
- Masse-distance relation from Parallax measurements

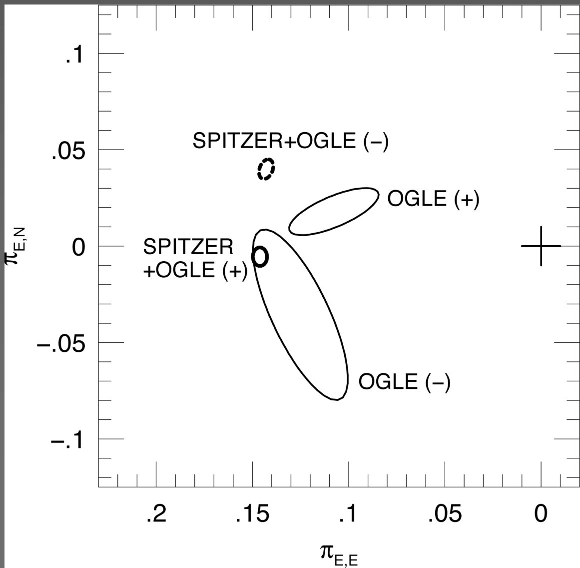
  Ground only is often problematic. Ideal with good-old-Spitzer /K2 !

Ground-space parrallax
Spitzer, Kepler-K2

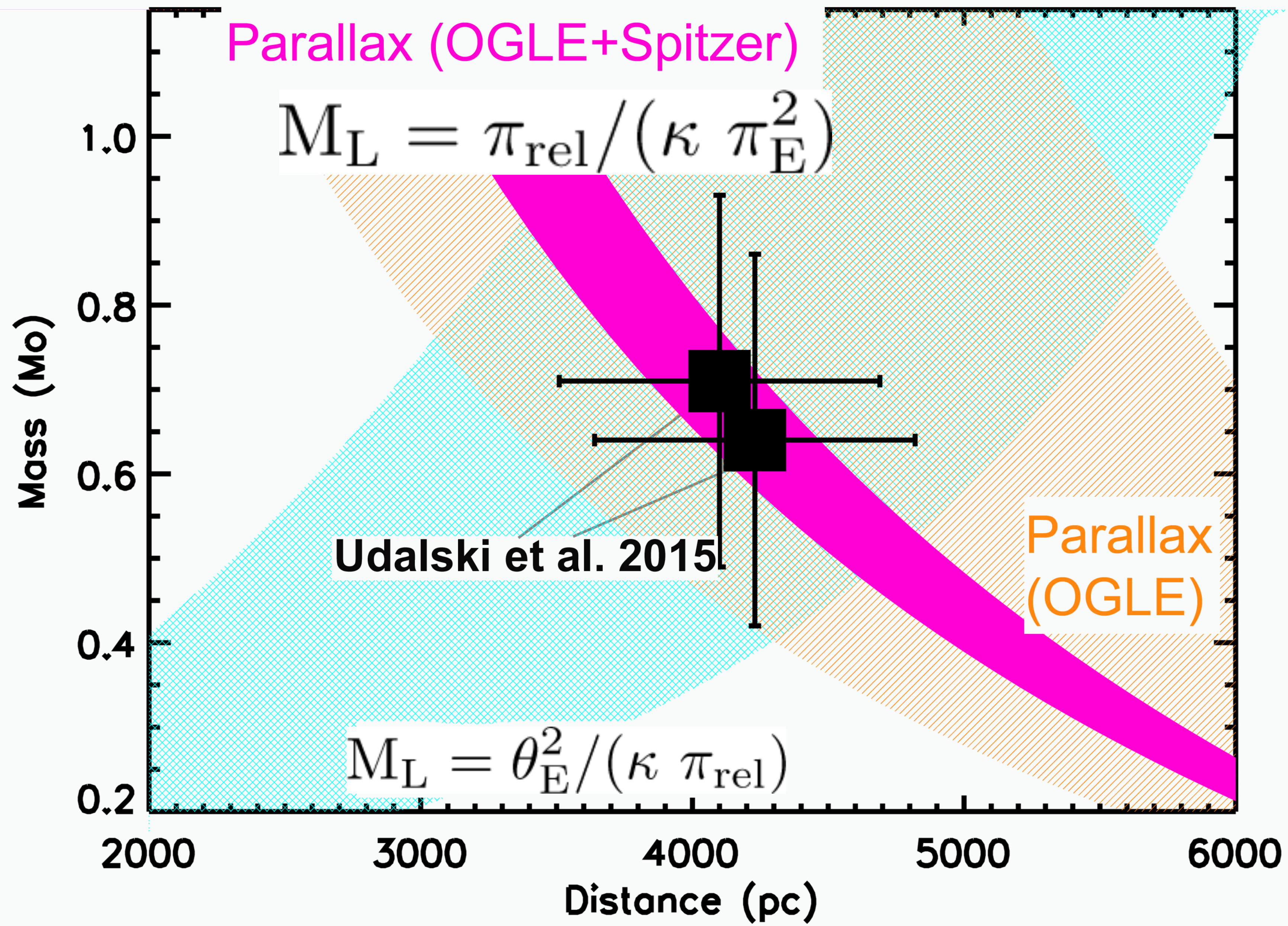


Ogle 2014-BLG-124: ground- Spitzer parallax





Udalski et al. 2015, Yee et al. 2016



$$\pi_{rel} = (AU)(D_S - D_L)/(D_S\ D_L)$$

Getting physical parameters

Mass ratios & projected separations are well known

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- Masse-distance relation from Parallax measurements

  Ground only is often problematic. Ideal with good-old-Spitzer /K2 !

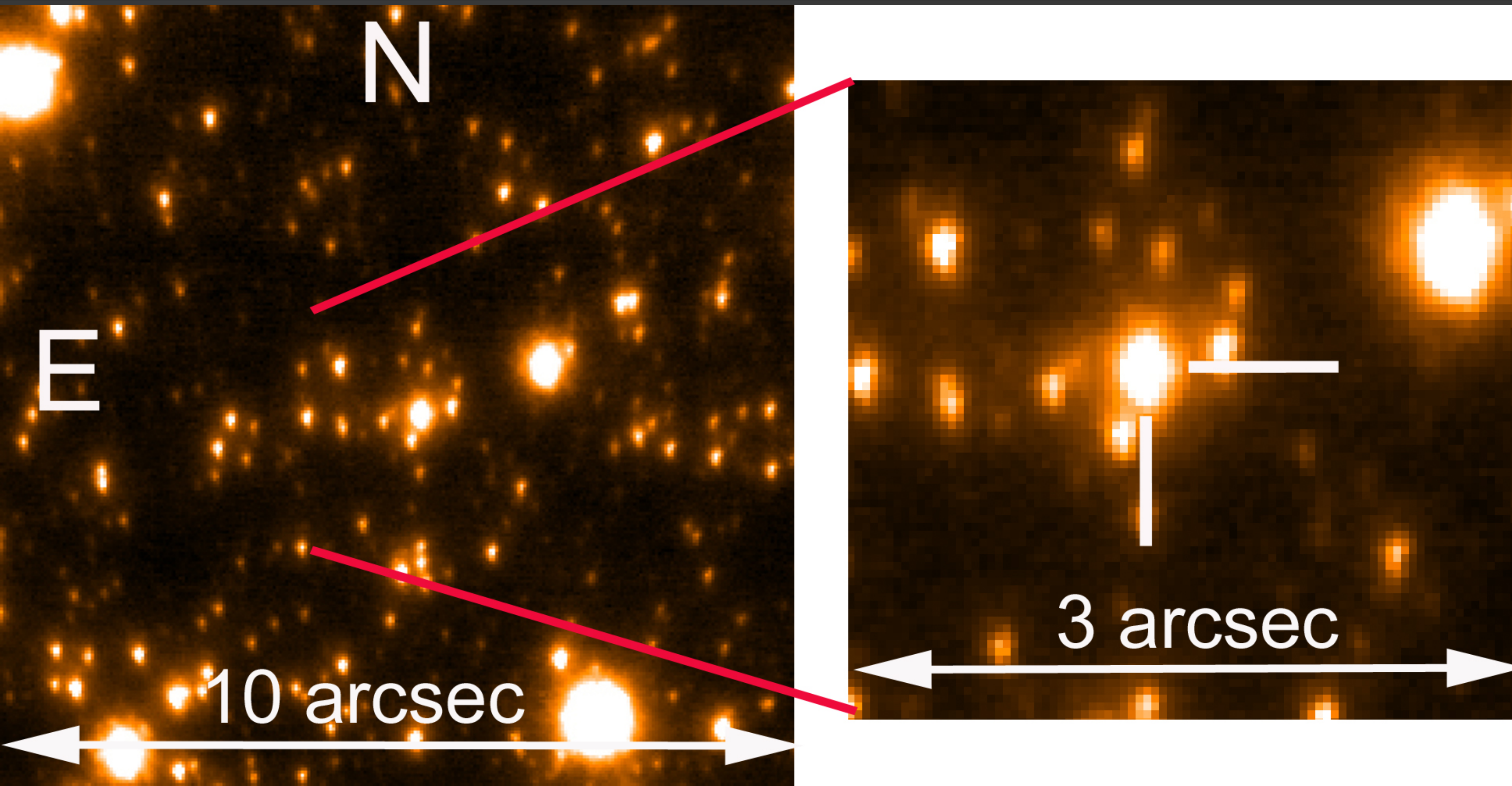
- Masse-distance relation from high angular resolution observations

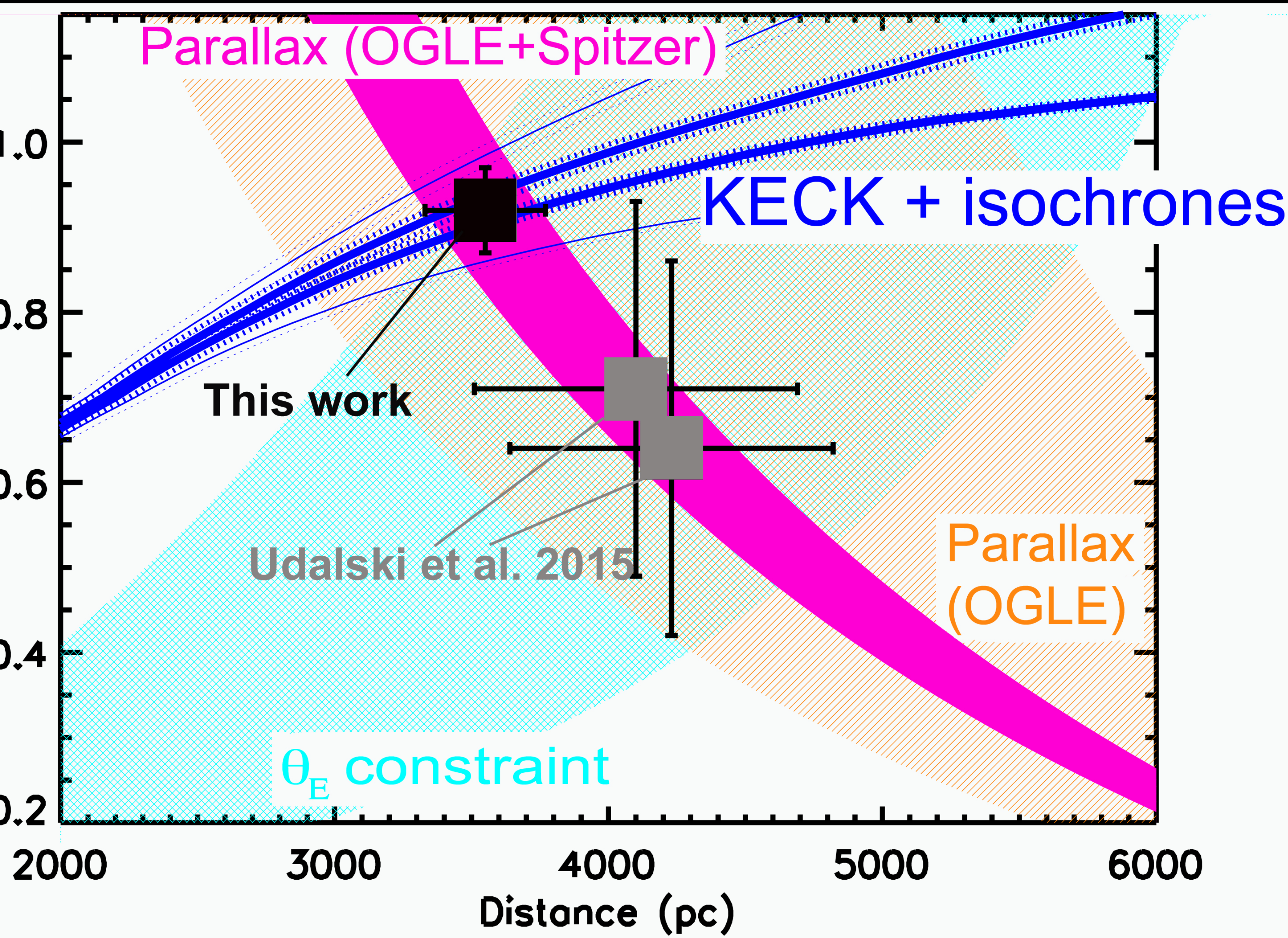
  With KECK AO: it is cheap (15-30 min) to constraint light from lens.
  Resolving source/lens is more tricky (~60 mas)

Source & lens are aligned

Source predicted H=17.04 ±0.05

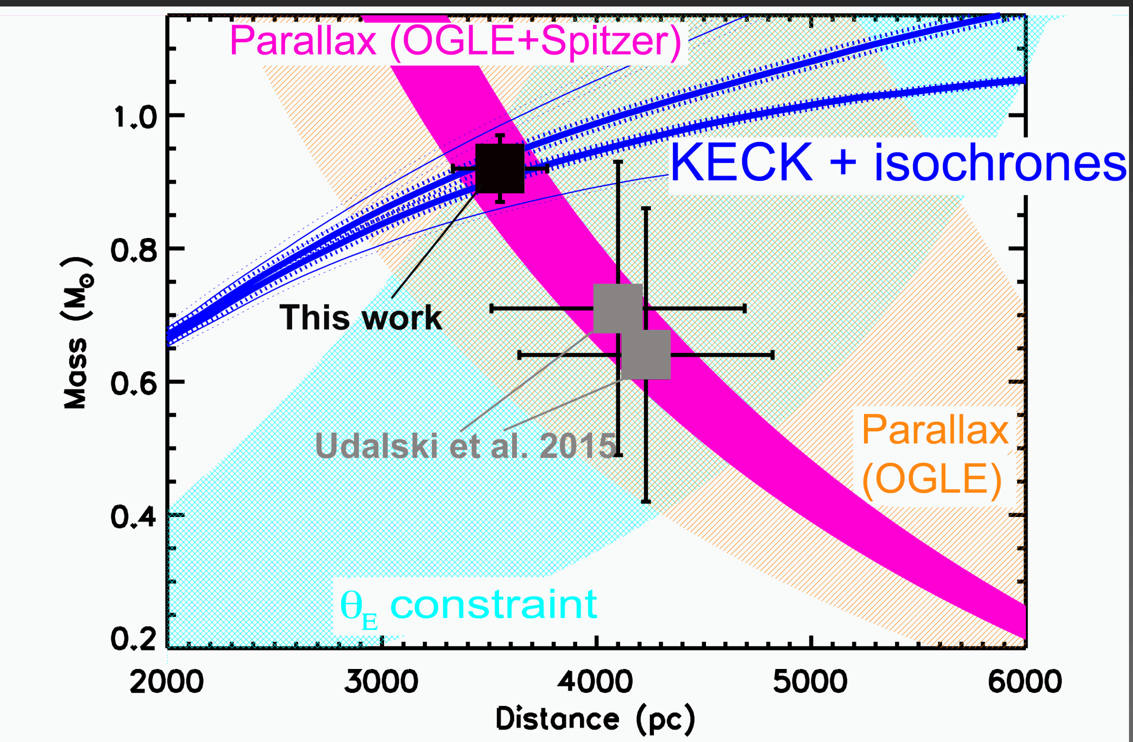
Source +blend measured at H=15.95 ±0.03, So the blend is H=16.46 ±0.06





Parallax (OGLE+Spitzer)
KECK + isochrones
This work
Udalski et al. 2015
Parallax (OGLE)
θ_E constraint
1.0
0.8
0.6
0.4
0.2
2000
3000
4000
5000
6000
Distance (pc)

Cold gazeous planet orbiting a sun like



Udalski et al. 2015

Host star mass: 0.80 ± 0.20 $M_\odot$

0.74 ± 0.20 $M_\odot$

Planet mass: 0.63 ± 0.18 $M_{Jupiter}$

0.53 ± 0.16 $M_{Jupiter}$

Distance D_L: 4.92 ± 0.69 kpc

4.25 ± 0.72 kpc

Proj. Separation: 3.16 ± 0.46 AU

3.13 ± 0.47 AU

Beaulieu et al. 2017 ApJ

Host star mass: 0.89 ± 0.06 $M_\odot$

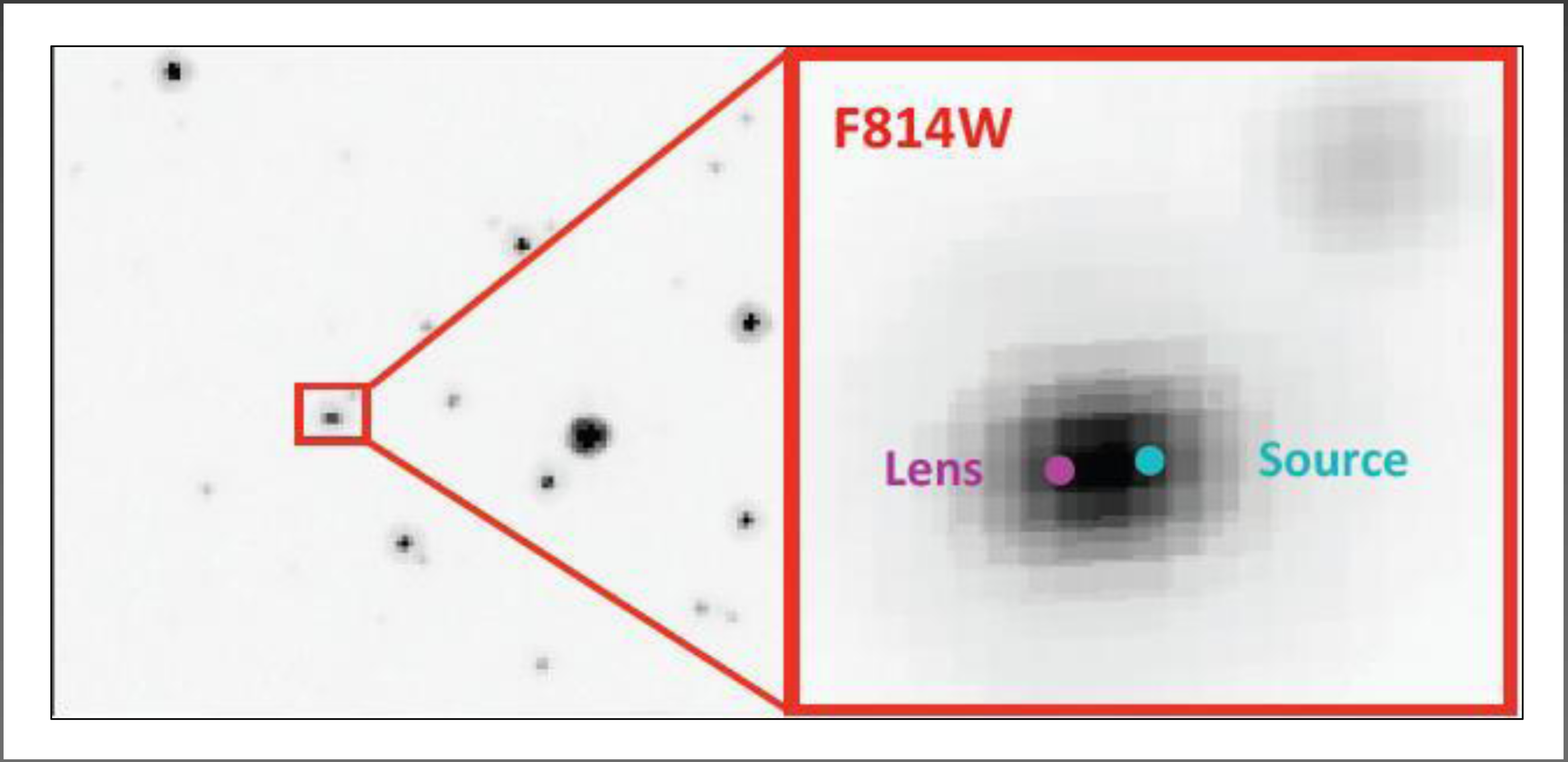
Planet mass: 0.64 ± 0.04 $M_{Jupiter}$

Orbit: 3.48 ± 0.22 AU

Distance: 3.6 ± 0.2 kpc

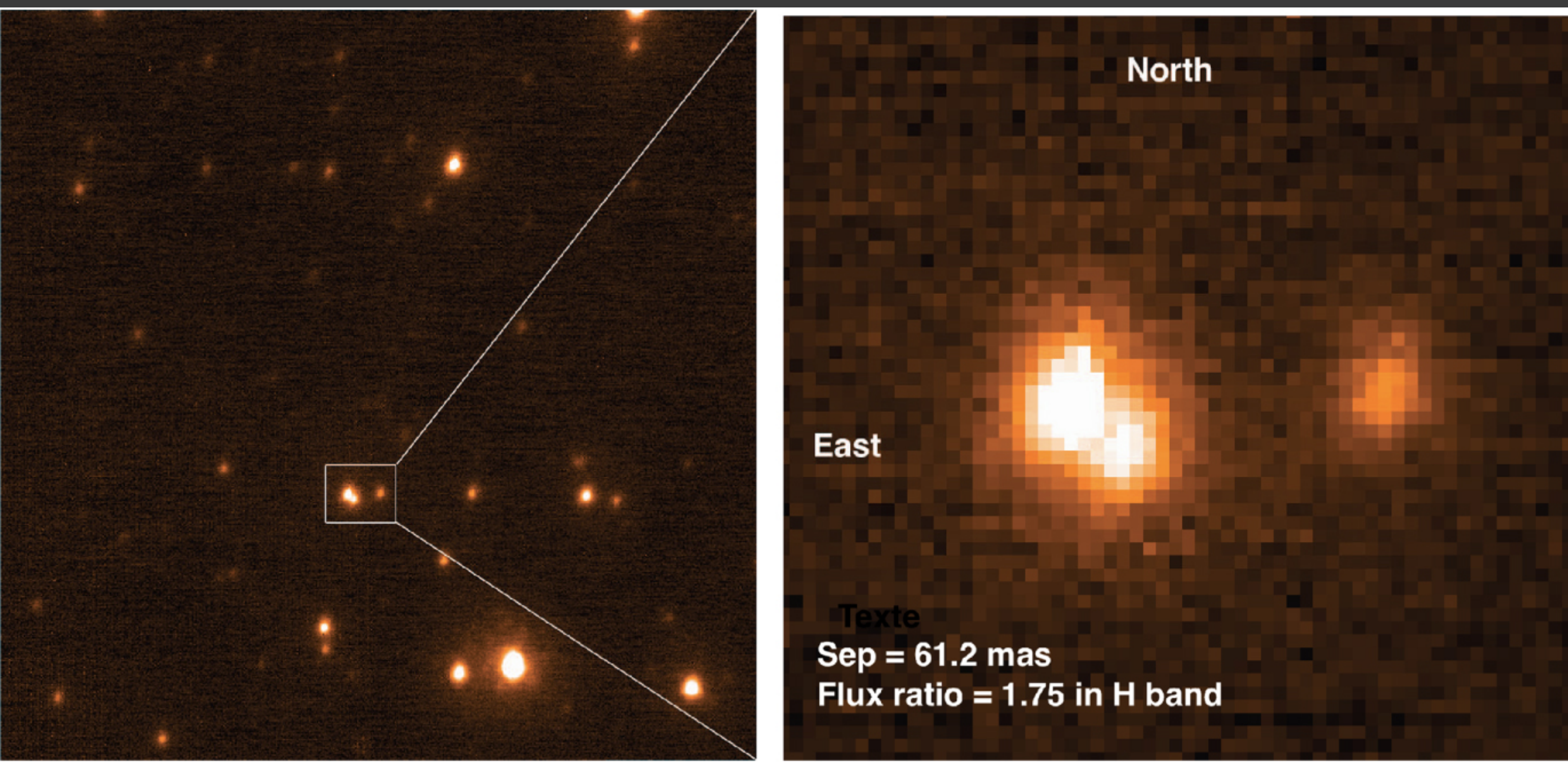
Neptune mass planet orbiting a 0.6 Mo
Resolving source & lens 6.5 years later with HST

Bennett et al., 2015



Neptune mass planet orbiting a 0.6 Mo
Resolving source & lens 8 years later with KECK

Batista et al., 2015



Detecting source & lens, measuring proper motion

Gould et al. 2006

Initial paper & preductions

Relative proper motion ~ 7-9 mas/yr
Host star mass 0.5 $\pm$0.3 $M_\odot$
Planet mass ~ 13 $M_{jupiter}$
Distance D_L=2.7 $\pm$ 1.6 kpc
Projected separation ~ 2.7 AU

HST Bennett et al. 2015

μ_{rel_l} = 7.39 $\pm$ 0.2 mas/yr
μ_{rel_b}= 1.33 $\pm$ 0.23 mas/yr

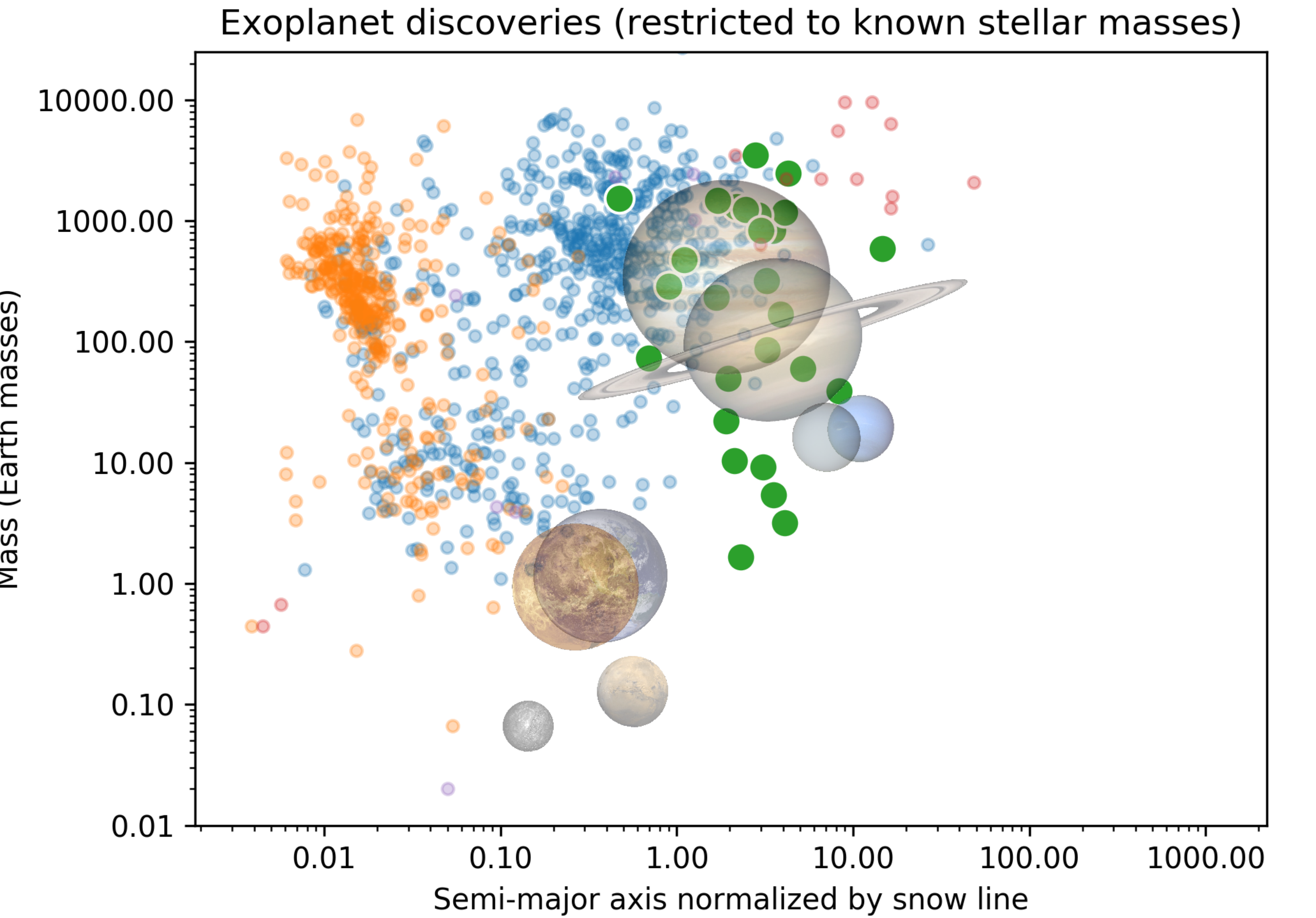
Host star mass: 0.69 $\pm$ 0.02 $M_\odot$
Planet mass: 14.1 $\pm$ 0.9 M_{earth}
Distance D_L = 4.1$\pm$ 0.4 kpc
Projected separation 3.5 $\pm$ 0.3 AU

KECK Batista et al. 2015

μ_{rel_l} = 7.28 $\pm$ 0.12 mas/yr
μ_{rel_b}= 1.54 $\pm$ 0.12 mas/yr

Host star mass: 0.65 $\pm$ 0.05 $M_\odot$
Planet mass: 13.2 $\pm$ 1.5 M_{earth}
Distance D_L = 4.0$\pm$ 0.4 kpc
Projected separation 3.4 $\pm$ 0.3 AU

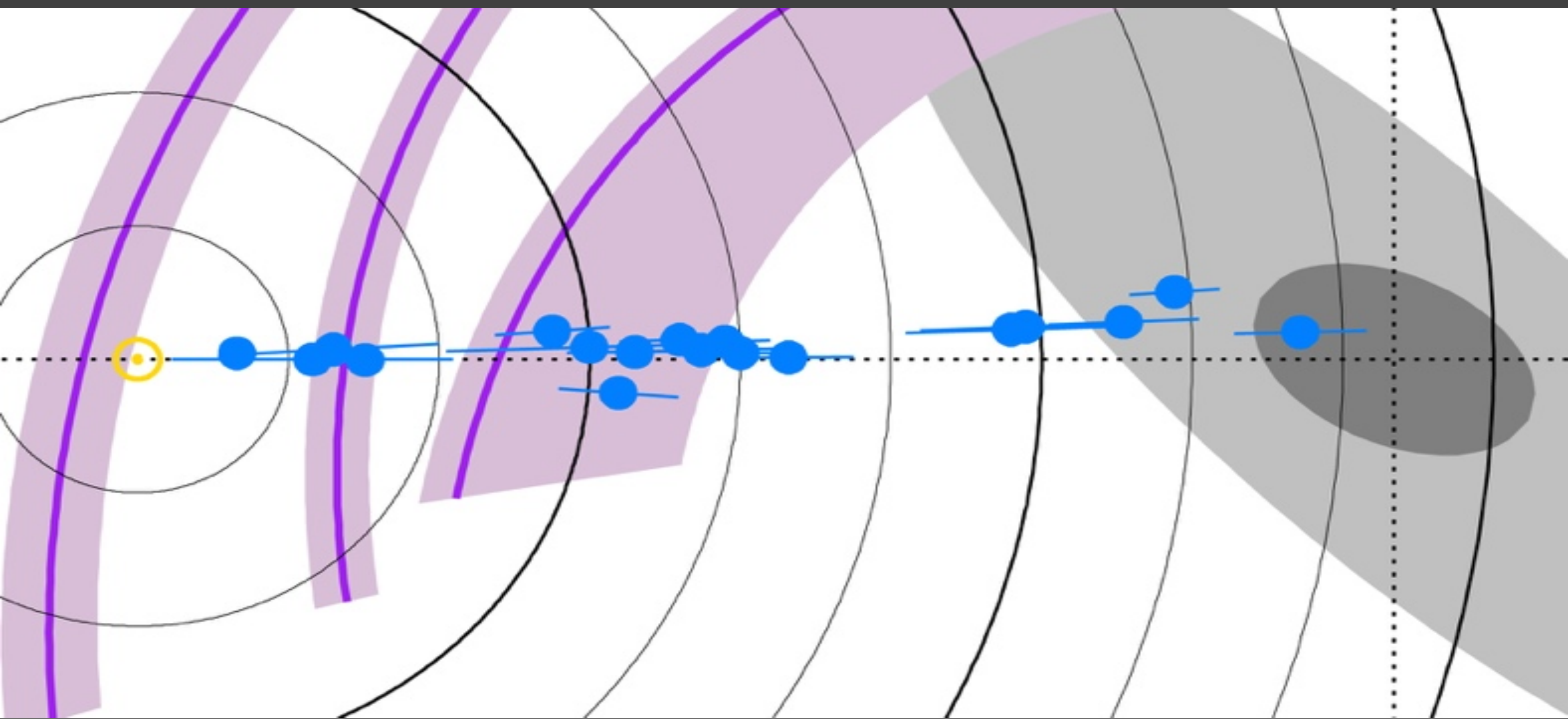
In agreement with Gould et al., 2006, but more accurate results.



Exoplanet discoveries (restricted to known stellar masses)
Mass (Earth masses)
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00
Semi-major axis normalized by snow line

Spatial distribution of planets

Beaulieu et al., 2018 in prep



One free-floating Jupiter per star in our galaxy ?

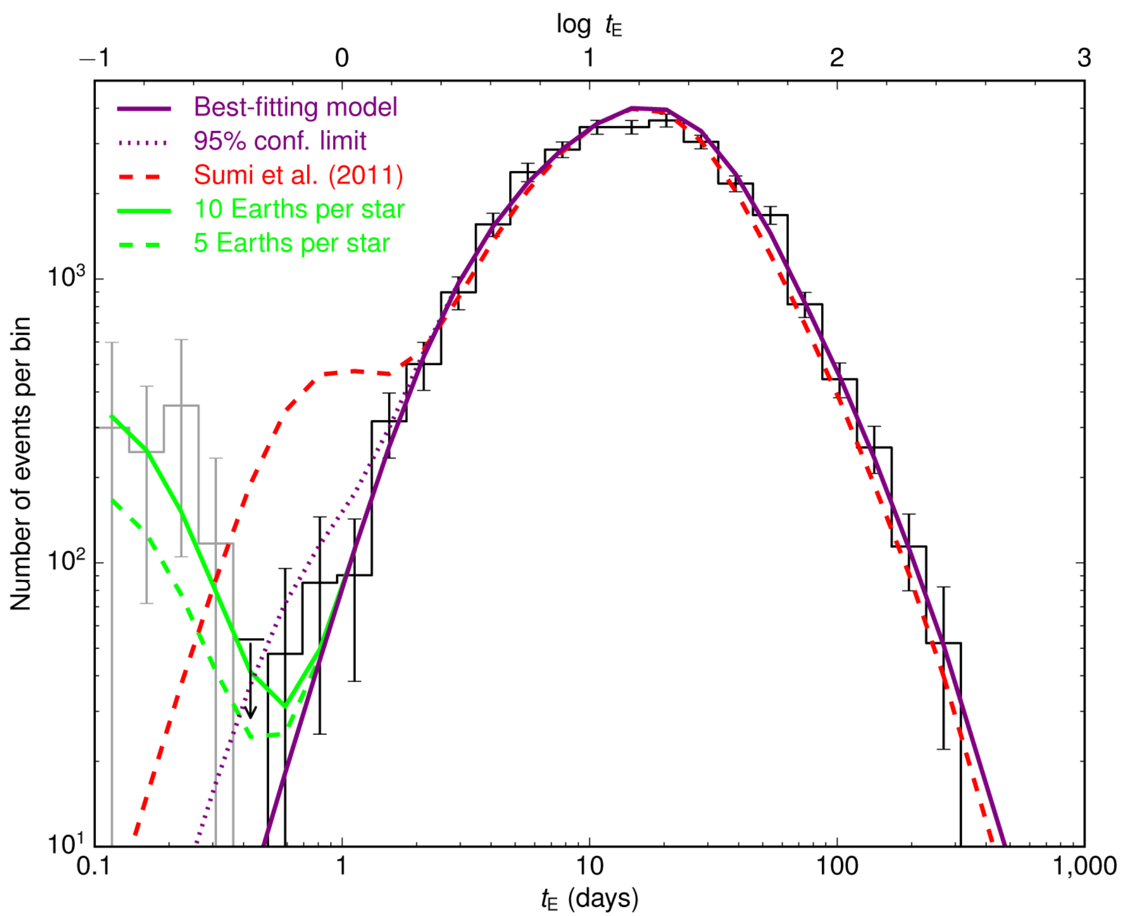


Figure 2 Distribution of event timescales corrected for the detection efficiency.

A new free-floating planet candidate ?

Mroz et al., 2017 astroph (KMT & OGLE)

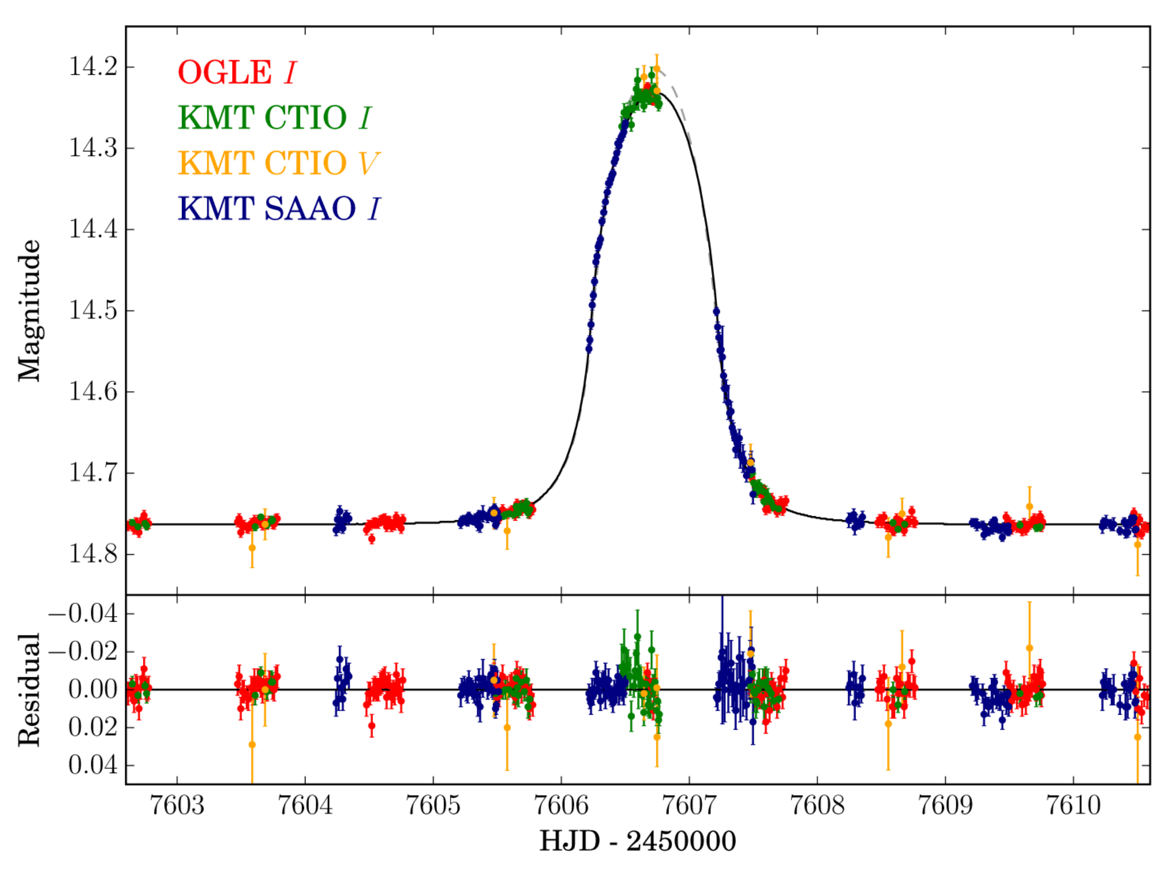


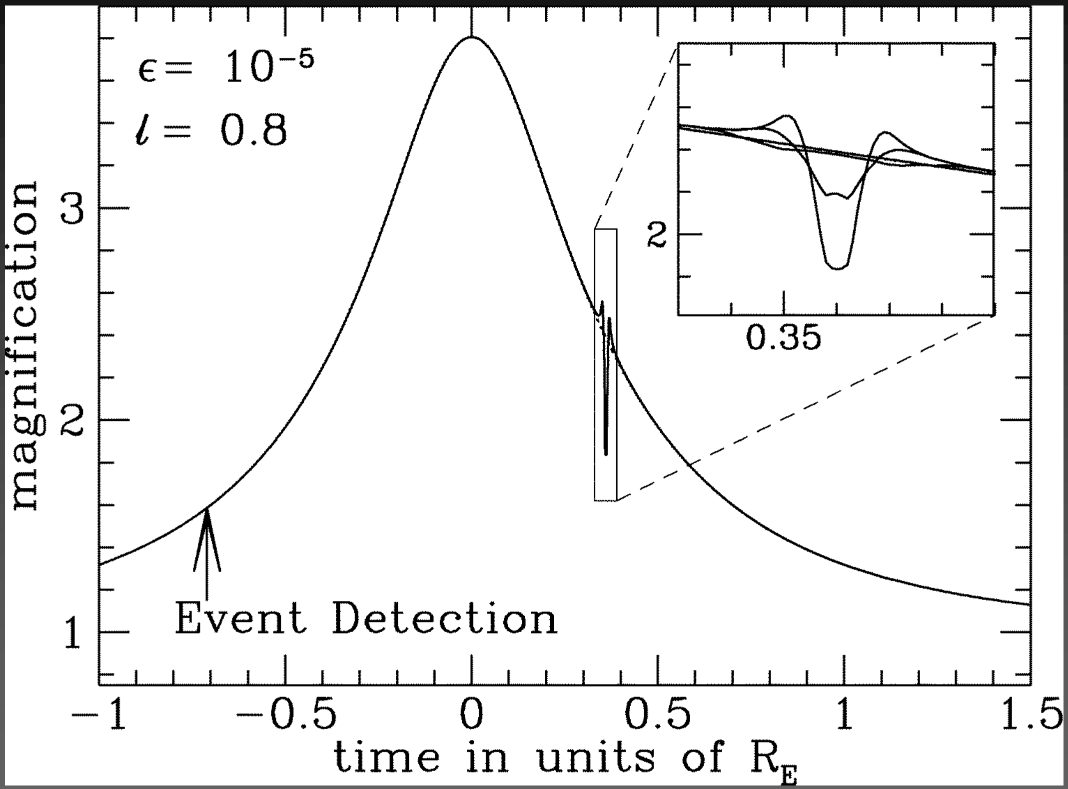
TABLE 1
BEST-FITTING MODEL PARAMETERS

Parameter	Value	Uncertainty
t_0 (HJD′)	7606.598	0.002
t_E (days)	0.320	0.003
u_0	0.70	0.04
ρ	1.65	0.01
I_s	14.76	0.05
f_s	1.00	(fixed)
χ^2/d.o.f.	2160.1/2153	

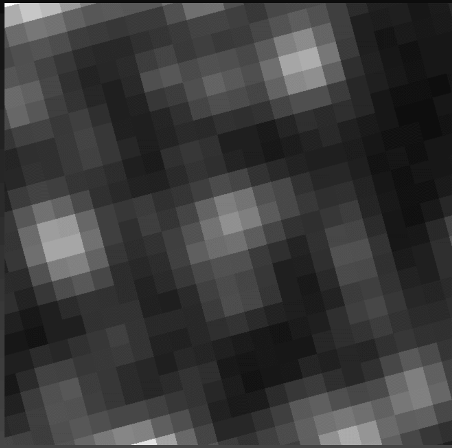
Note: HJD′=HJD-2450000. $f_s = F_s/(F_s + F_b)$ is the blending parameter.

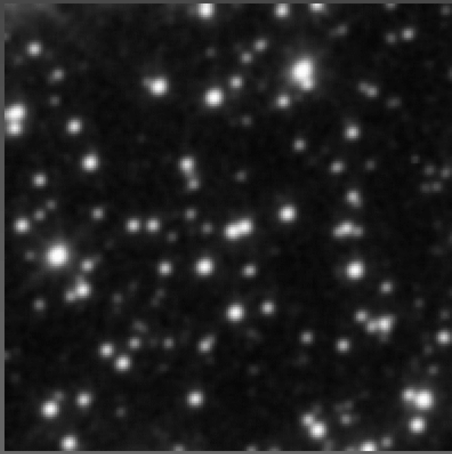
Down to the mass of Mars and in the habitable zone ?

To get small planet, you need small sources and higher angular resolution

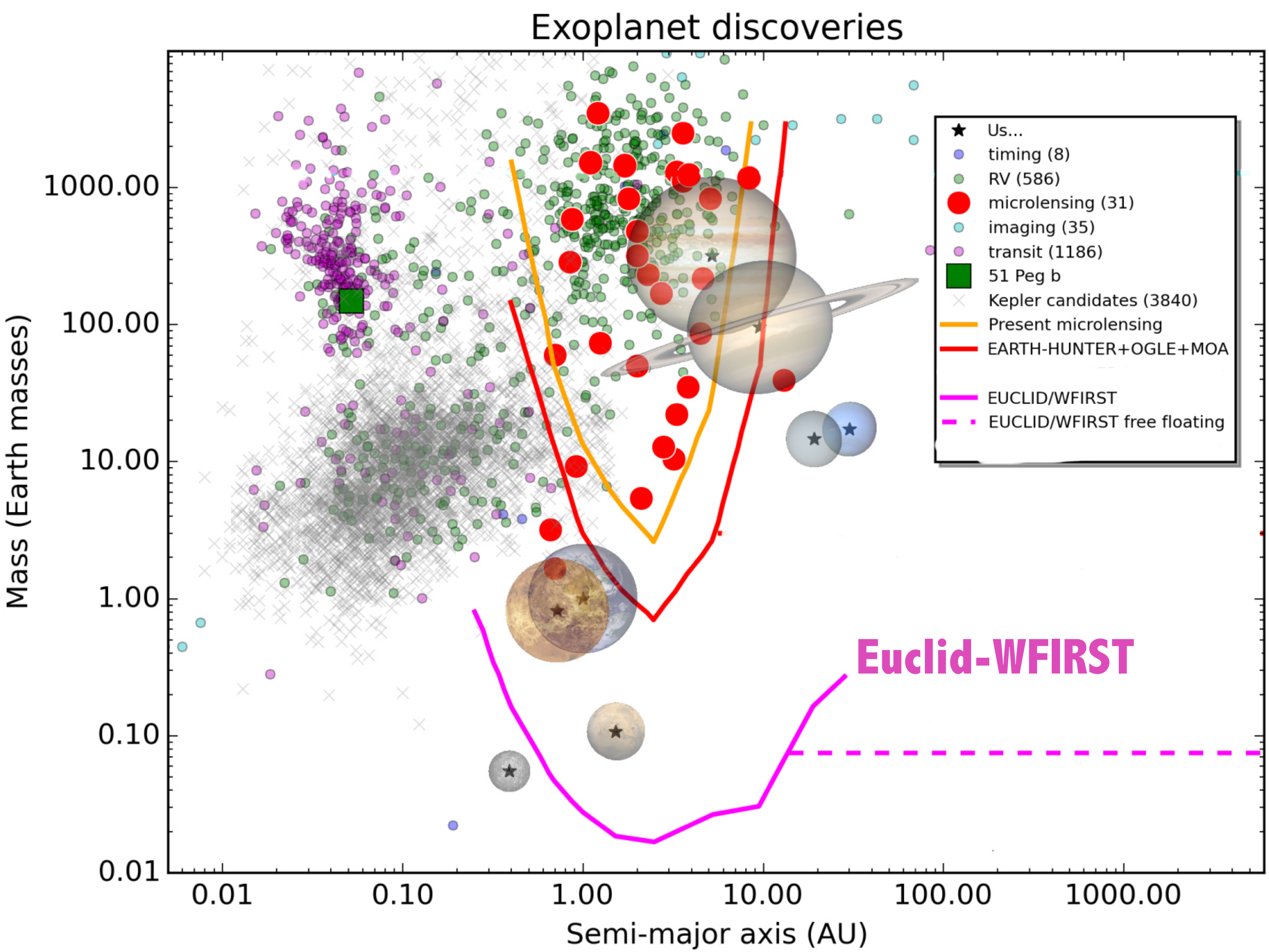


Bennett & Rhie 1996





High Resolution + large field + 24hr duty cycle



Exoplanet discoveries
Mass (Earth masses)
Semi-major axis (AU)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00
Us...
timing (8)
RV (586)
microlensing (31)
imaging (35)
transit (1186)
51 Peg b
Kepler candidates (3840)
Present microlensing
EARTH-HUNTER+OGLE+MOA
EUCLID/WFIRST
EUCLID/WFIRST free floating
Euclid-WFIRST

Dark Energy & microlensing

- 2002 Bennett & Rhie space based microlensing
- 2004-2005 : Cosmic shear and microlensing from Dome C ?

  (Mellier/ Beaulieu -> after all, not a good idea, so no papers about it)
- Bennett, Gaudi et al. advocating for space based microlensing

- 2007 DUNE proposal (3 months of microlensing)

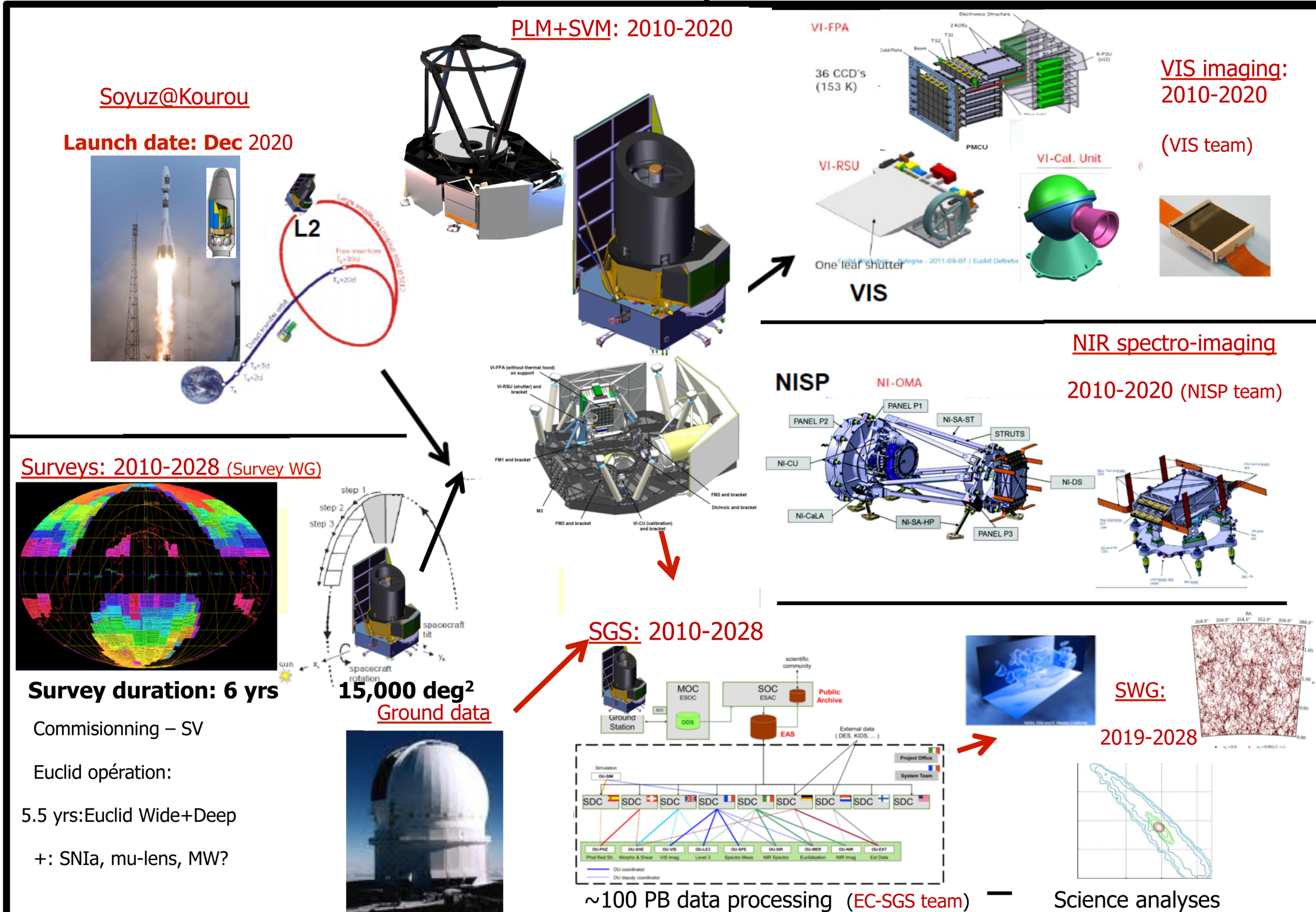
« Everything that is good for cosmic shear is good for microlensing »

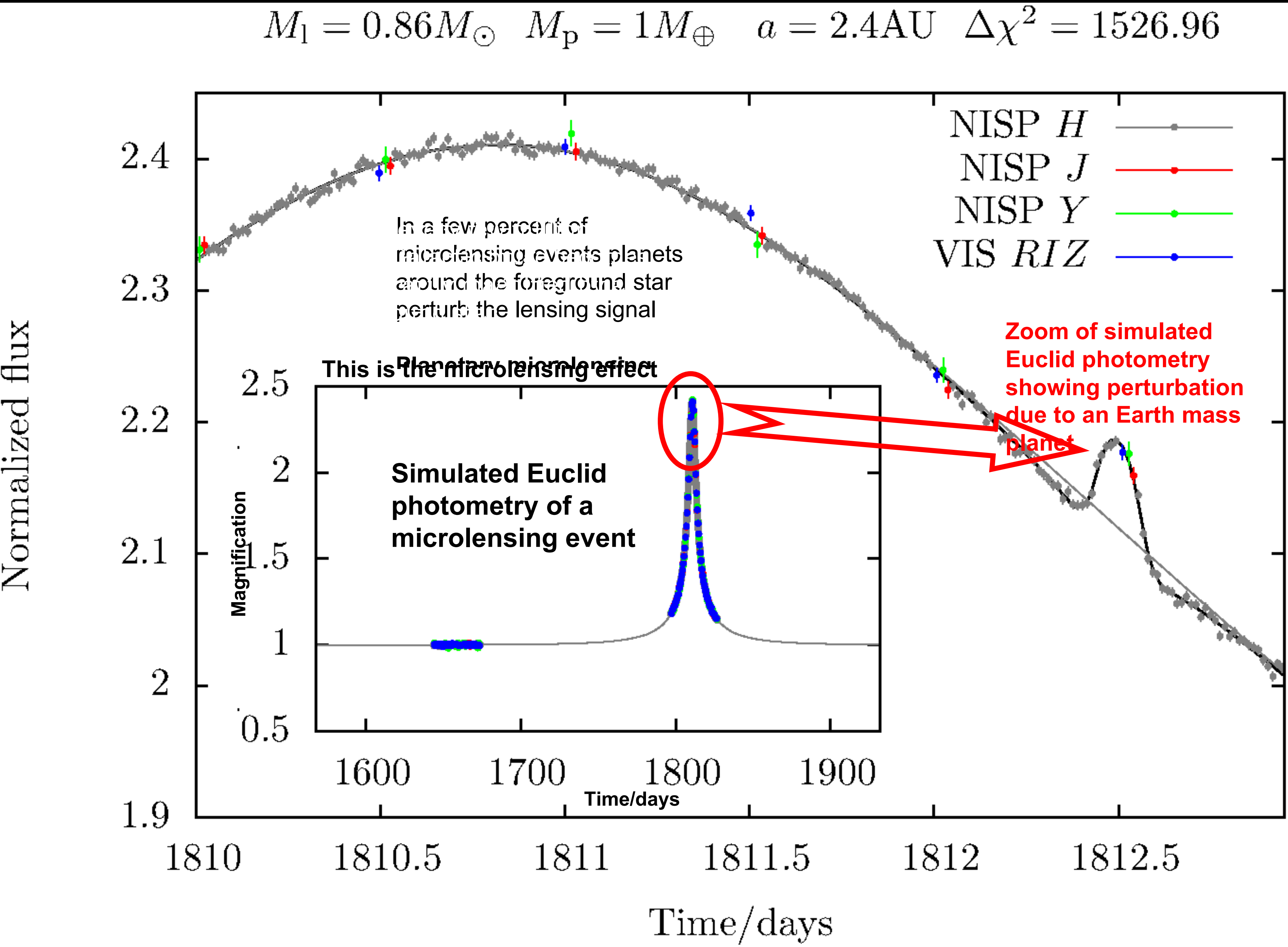
Beaulieu, Kerins, Mao, Bennett, Dieters, Gaudi, Gould, Batista et al., 2008, « Towards A Census of Earth-mass Exo-planets with Gravitational Microlensing", arXiv:0808.0005

- Microlensing program on board EUCLID (proposed 4 months)
- 2010 Decadal survey with WFIRST

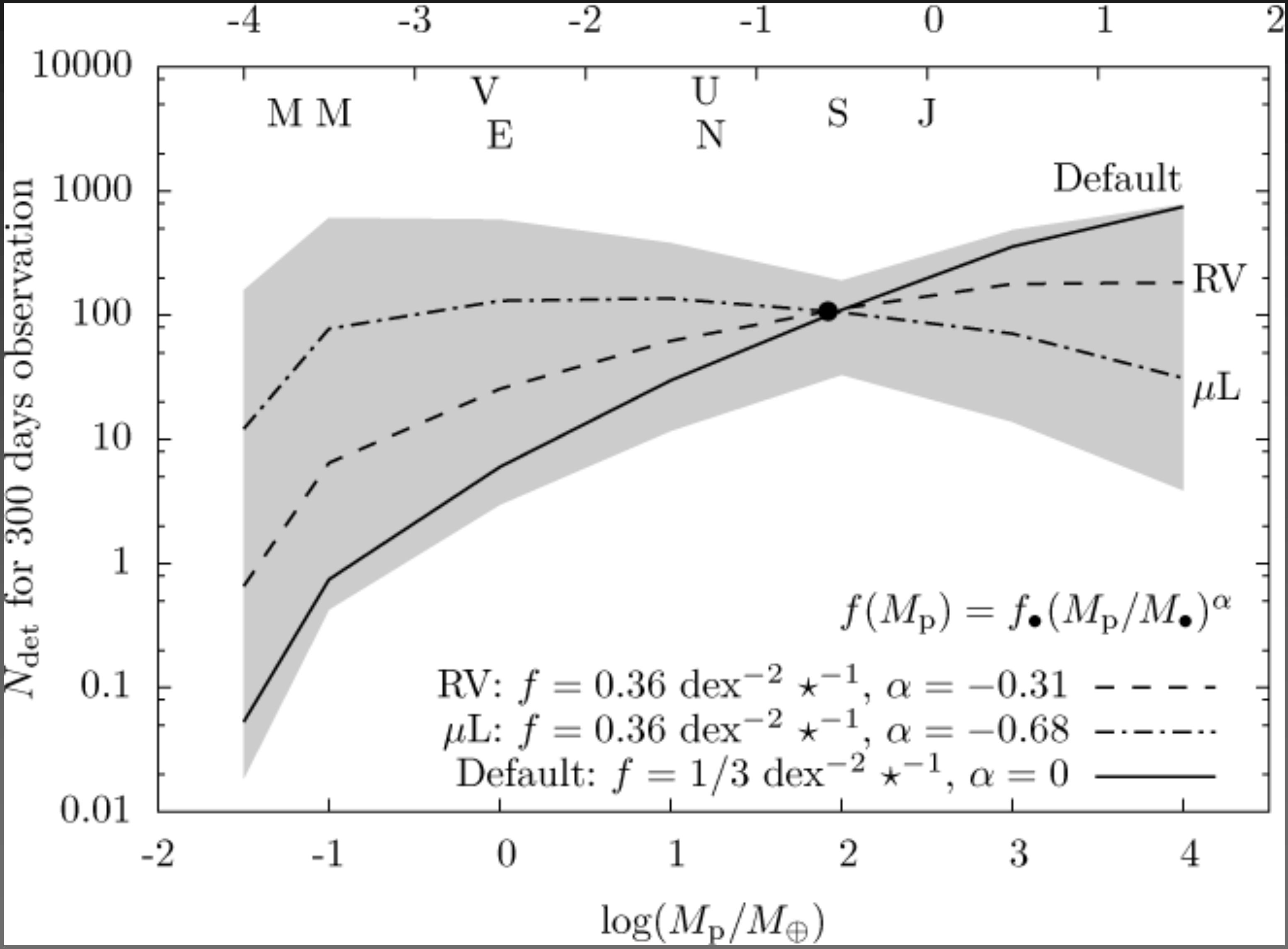
- Thesis of Matthew Penny: simulations for EUCLID & WFIRST.

The ESA Euclid space mission

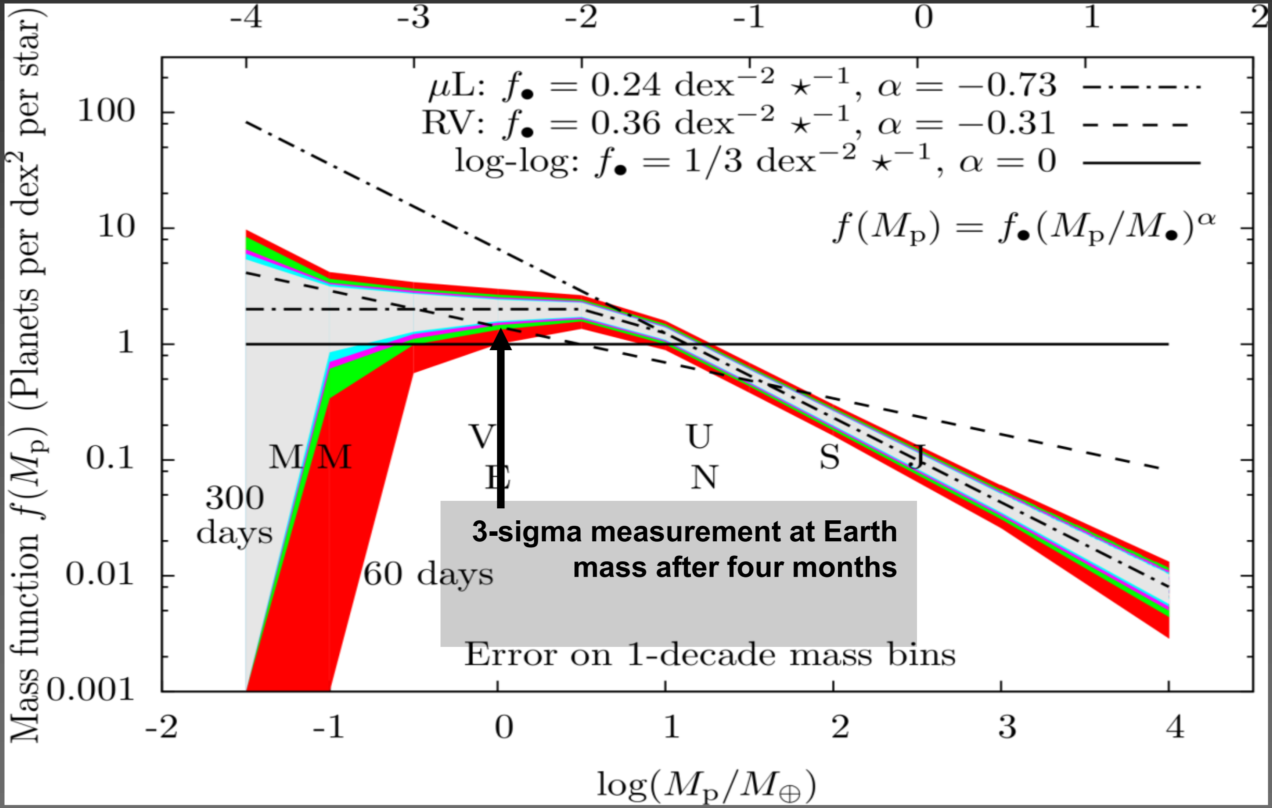



$M_l = 0.86 M_\odot \quad M_p = 1 M_\oplus \quad a = 2.4\text{AU} \quad \Delta\chi^2 = 1526.96$
Normalized flux
Time/days
NISP H
NISP J
NISP Y
VIS RIZ
In a few percent of microlensing events planets around the foreground star perturb the lensing signal
Planetary microlensing
This is the microlensing effect
Simulated Euclid photometry of a microlensing event
Magnification
Time/days
Zoom of simulated Euclid photometry showing perturbation due to an Earth mass planet

Measuring the planet mass function



Getting abundance of cold Earth in 4 months with Euclid



Abundance measurement sensitivity versus planet mass for different extrapolations of measured exoplanet mass functions and survey lifetimes

Euclid Microlensing survey

Beaulieu, Kerins, et al.

3 fields observed every 17 min in H, every 12 hours in VIS, J, Y.
Mini-survey during commissionning (24h), then 4 x 1 months survey

- Measuring cold Earth abundance and mass function

  ~35 planets / month (5 Earth / month, 15 Neptune / month)

- Getting constraints on free floating planets

  ~15 free-floating planets / month

- EUCLID/ML complements parameter space probed by RV and KEPLER

Measuring the cold planet mass function below 1 Earth mass.

- Possibility of simultaneous EUCLID-WFIRST in the extended mission 2026+
  (parallax between EUCLID and WFIRST to measure masses of Earth mass free floaters)

Penny et al., 2013 MNRAS 434, 2

Conclusion : Microlensing gives statistics !

- World wide network of ground-based telescopes
- OGLE, MOA, PLANET, RoboNET, KMTNeT
- Having a planet is the rule for stars of our galaxy
- Cold planets around any stars, down to ~1 Earth mass
- Combining, Spitzer, K2, AO to get masses to 10 % or better

- Planets in multiple systems, tatooine, exomoons
- Habitable zone is reachable
- Massive population of free-floating Jupiters :claimed then refuted

- Euclid with 4 months can measure cold planet mass function down to the mass of Mars.
- WFIRST will have a 400+ day survey : 1000 planets, from free-floating to habitable zone, all masses.