IPAC *WFIRST* Microlensing Primer Series III:

Results from and Future Directions for Ground-based Microlensing Surveys

Yossi Shvartzvald Calen B. Henderson
NPP Fellows @ JPL

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David Bennett
GSFC

JP Beaulieu
IAP

IPAC *WFIRST* Microlensing Primer Series

I. Basic Introduction to the Methodology and Theory of Microlensing Searches for Exoplanets

W, 21/Sept: Yossi Shvartzvald

II. Lens Companion Detection and Characterization

W, 28/Sept: Yossi Shvartzvald

III. Results from and Future Directions for Ground-based Microlensing Surveys

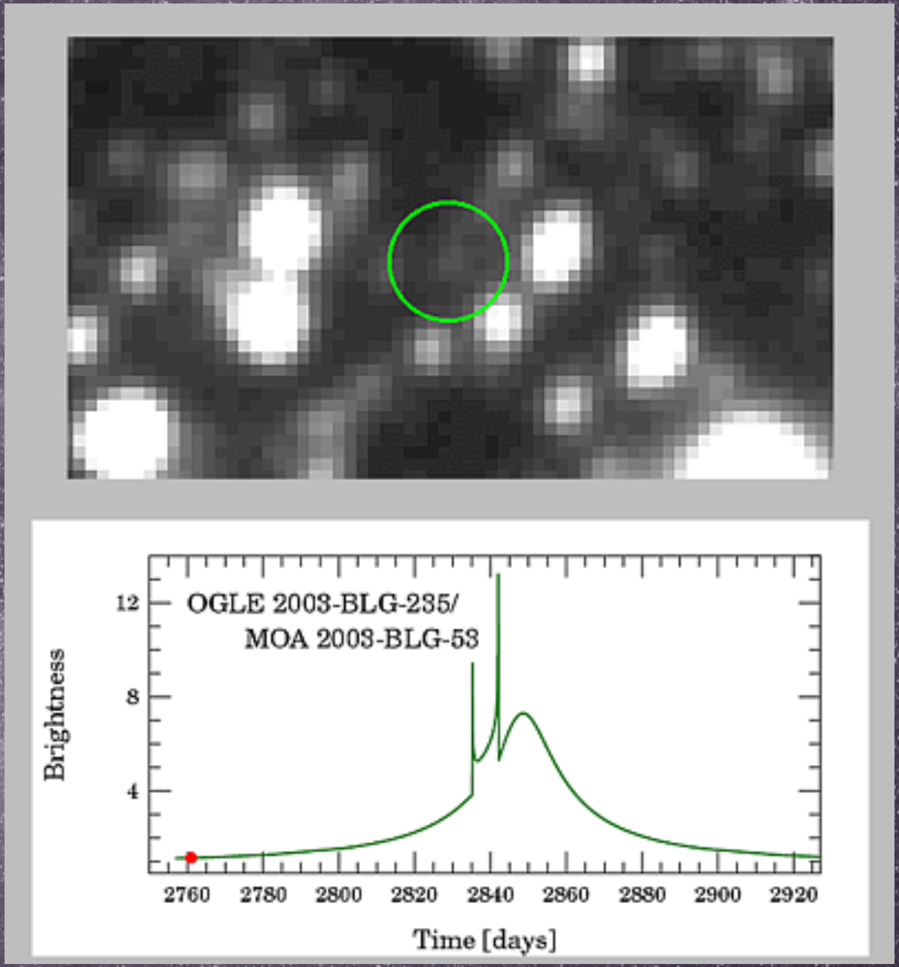
W, 12/Oct: Calen B. Henderson

IV. Results from and Future Directions for Space-based Microlensing Surveys

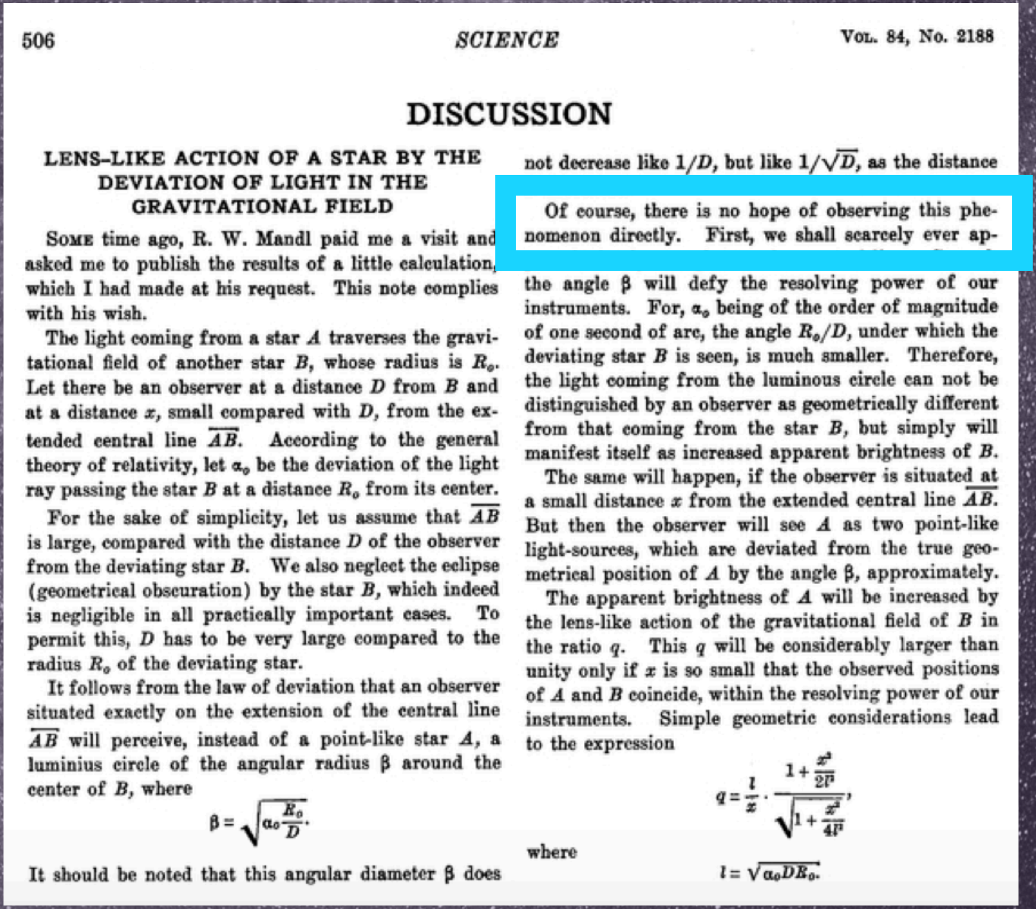
W, 2/Nov: Calen B. Henderson

Observational Microlensing

Observational Microlensing



A Brief History: Initial Derivation



DISCUSSION

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

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.

The light coming from a star A traverses the gravitational field of another star B, whose radius is R_o. Let there be an observer at a distance D from B and at a distance x, small compared with D, from the extended central line $\overline{AB}$. According to the general theory of relativity, let α_o be the deviation of the light ray passing the star B at a distance R_o from its center.

For the sake of simplicity, let us assume that $\overline{AB}$ is large, compared with the distance D of the observer from the deviating star B. We also neglect the eclipse (geometrical obscuration) by the star B, which indeed is negligible in all practically important cases. To permit this, D has to be very large compared to the radius R_o of the deviating star.

It follows from the law of deviation that an observer situated exactly on the extension of the central line $\overline{AB}$ will perceive, instead of a point-like star A, a luminius circle of the angular radius β around the center of B, where

$$\beta = \sqrt{\alpha_0 \frac{R_0}{D}}.$$

It should be noted that this angular diameter β does not decrease like $1/D$, but like $1/\sqrt{D}$, as the distance

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever ap-

the angle β will defy the resolving power of our instruments. For, α_o being of the order of magnitude of one second of arc, the angle R_o/D, under which the deviating star B is seen, is much smaller. Therefore, the light coming from the luminous circle can not be distinguished by an observer as geometrically different from that coming from the star B, but simply will manifest itself as increased apparent brightness of B.

The same will happen, if the observer is situated at a small distance x from the extended central line $\overline{AB}$. But then the observer will see A as two point-like light-sources, which are deviated from the true geometrical position of A by the angle β, approximately.

The apparent brightness of A will be increased by the lens-like action of the gravitational field of B in the ratio q. This q will be considerably larger than unity only if x is so small that the observed positions of A and B coincide, within the resolving power of our instruments. Simple geometric considerations lead to the expression

$$q = \frac{l}{x} \cdot \frac{1 + \frac{x^2}{2l^2}}{\sqrt{1 + \frac{x^2}{4l^2}}},$$

where

$$l = \sqrt{\alpha_0 D R_0}.$$

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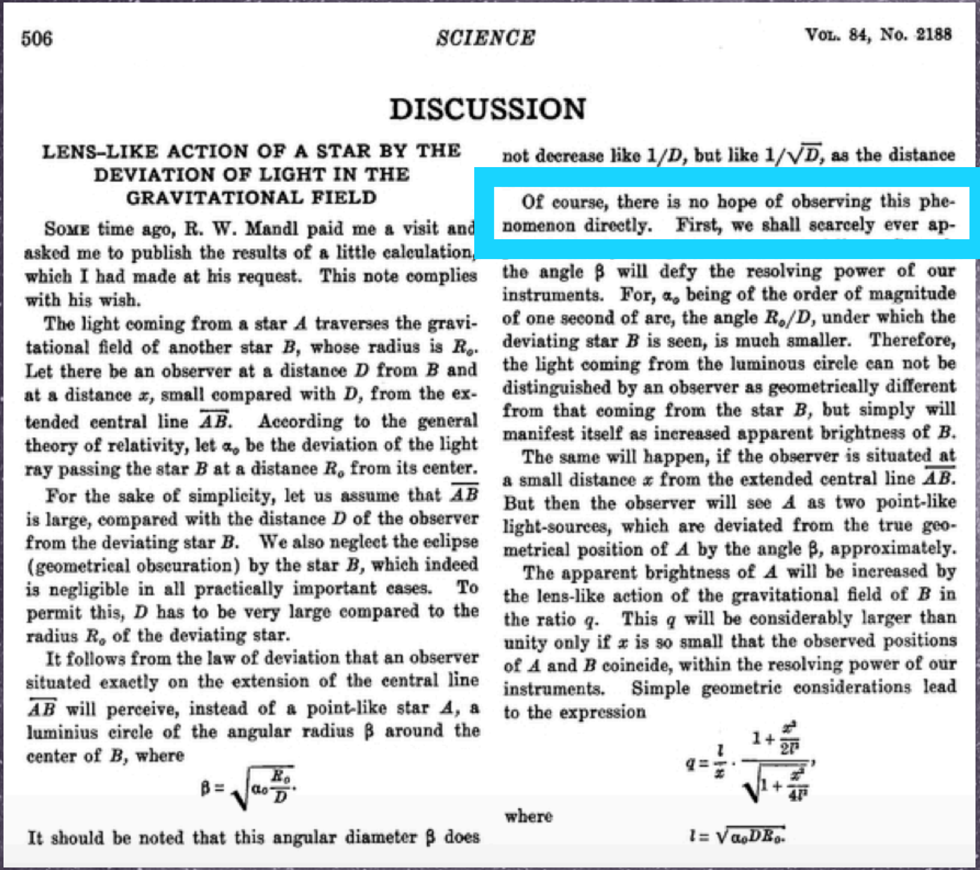

506 *SCIENCE* VOL. 84, No. 2188

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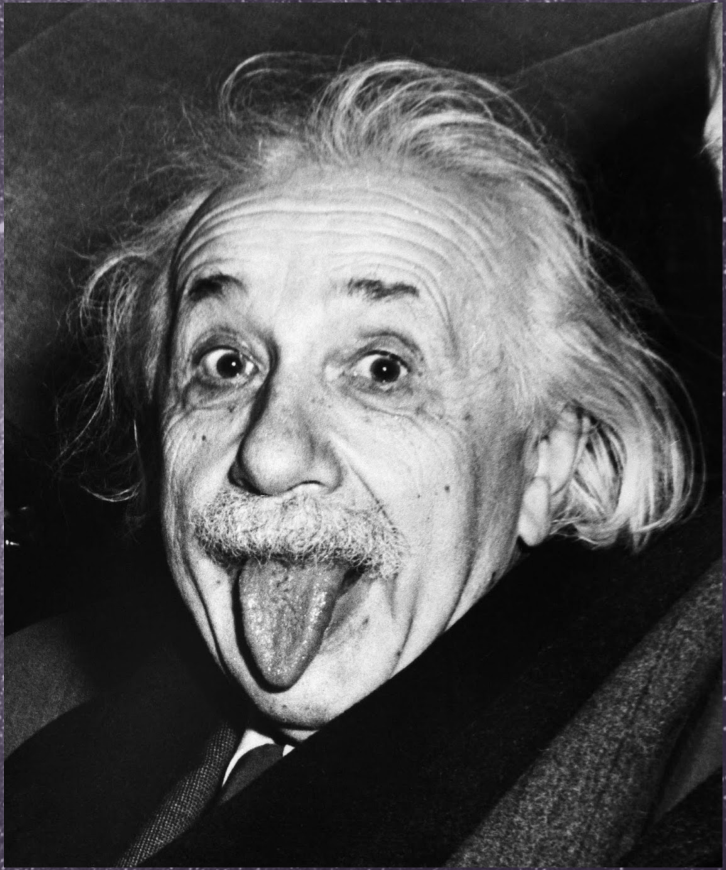
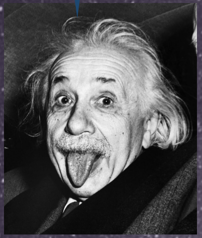


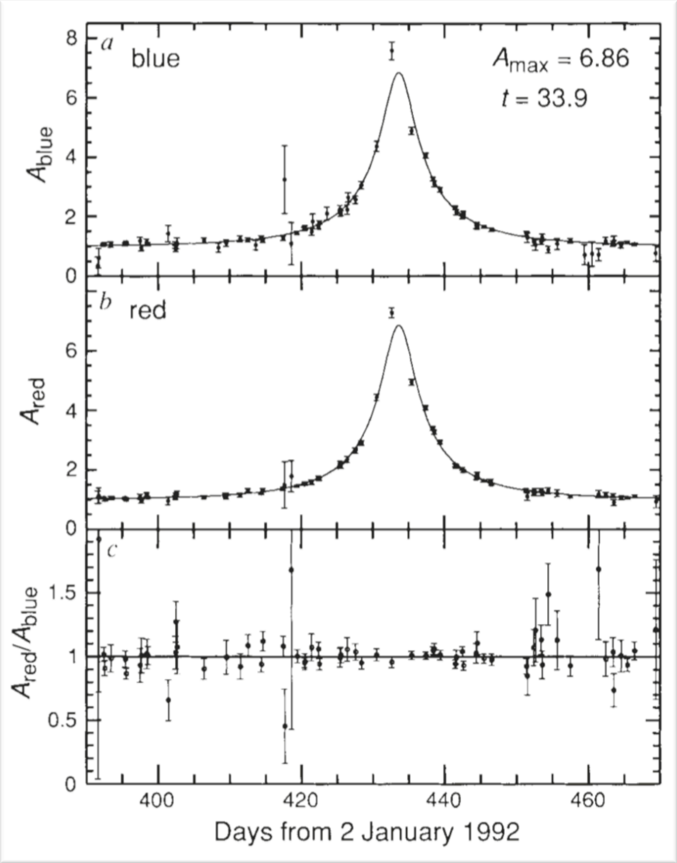
1936



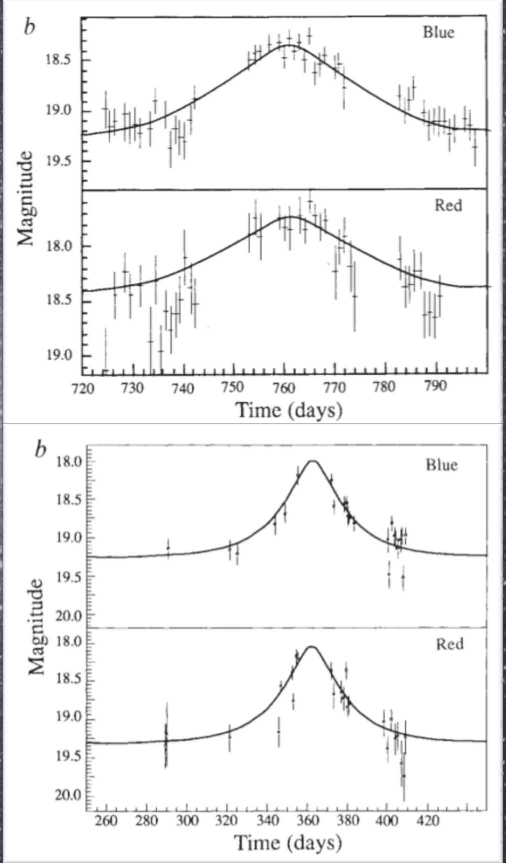
Derivation

A Brief History: First Candidate Event(s)

Toward LMC!



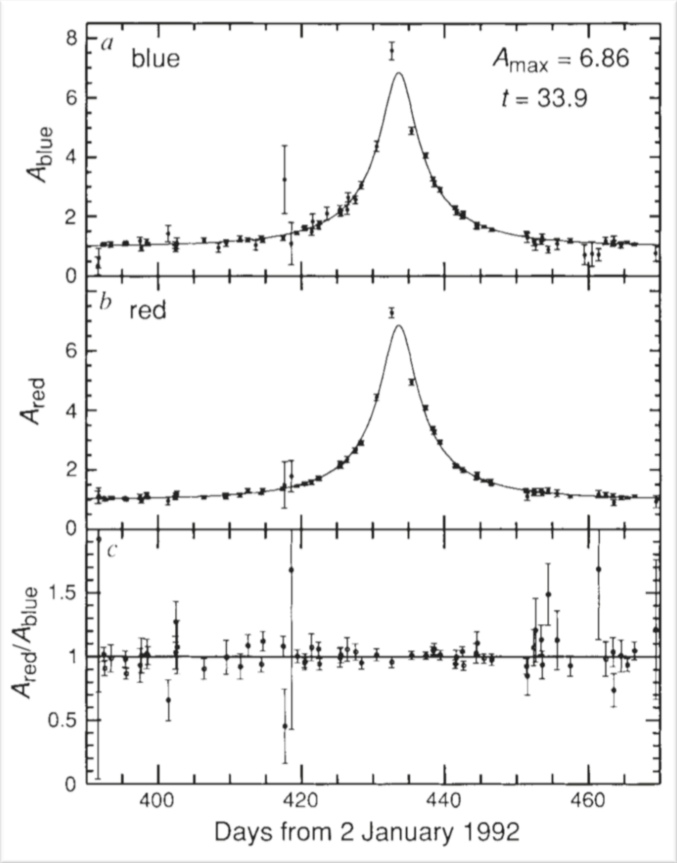
MACHO

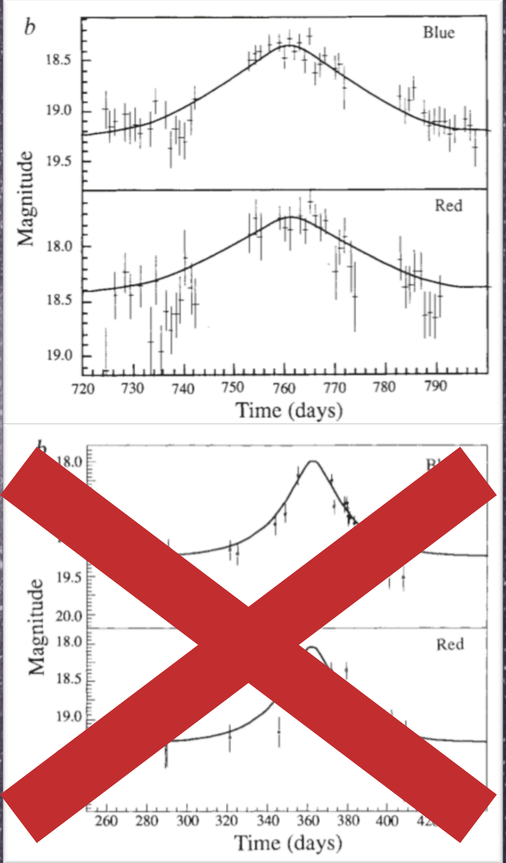


EROS

A Brief History: First Candidate Event(s)

Toward LMC!



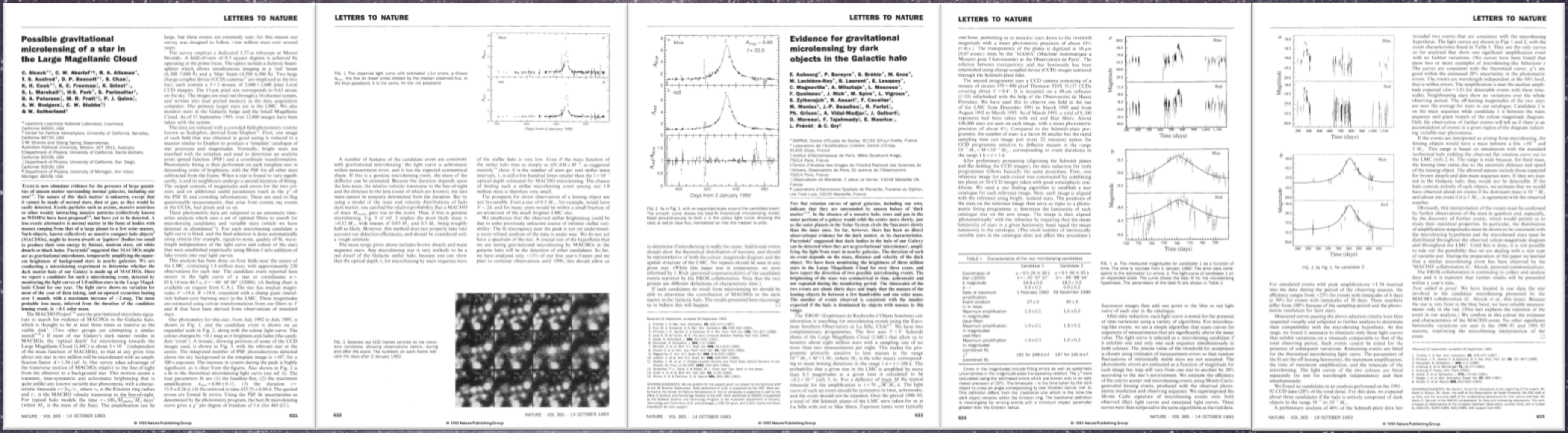


MACHO

EROS

A Brief History: First Candidate Event(s)

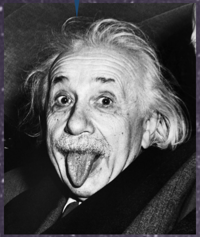
Same Issue of Nature!



Alcock+ (1993) Nature, 365, 621

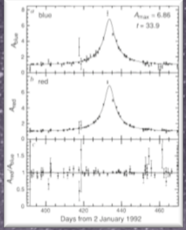
Aubourg+ (1993) Nature, 365, 623

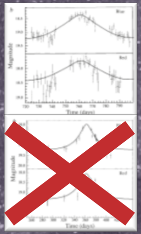
1936



Derivation

1993





First Events

Surveys

EROS

MACHO

Microlensing Surveys 1st Generation:
Alert and Follow-up

OGLE

MOA

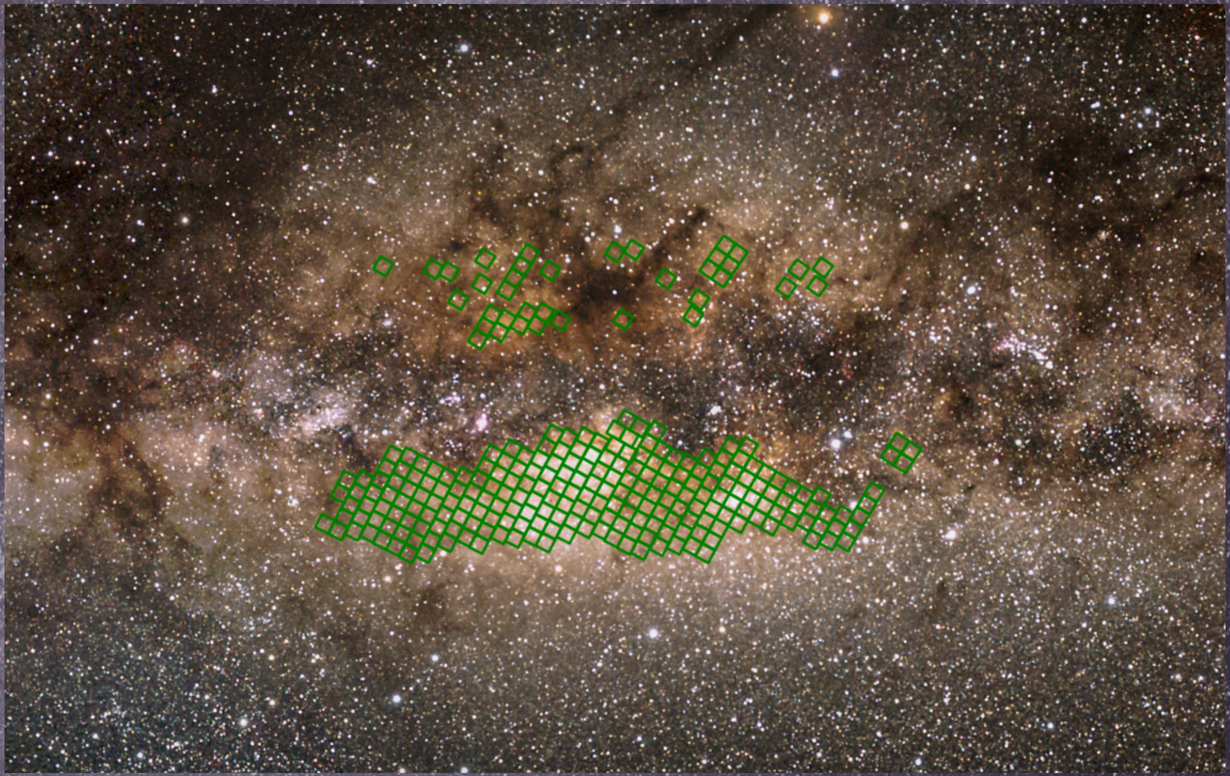
Microlensing Surveys 1st Generation:
Alert and Follow-up

OGLE

MOA

LCOGT (+PLANET+MicroFUN+RoboNet+MiNDSTEp)

Microlensing Surveys 1st Generation:
Alert and Follow-up

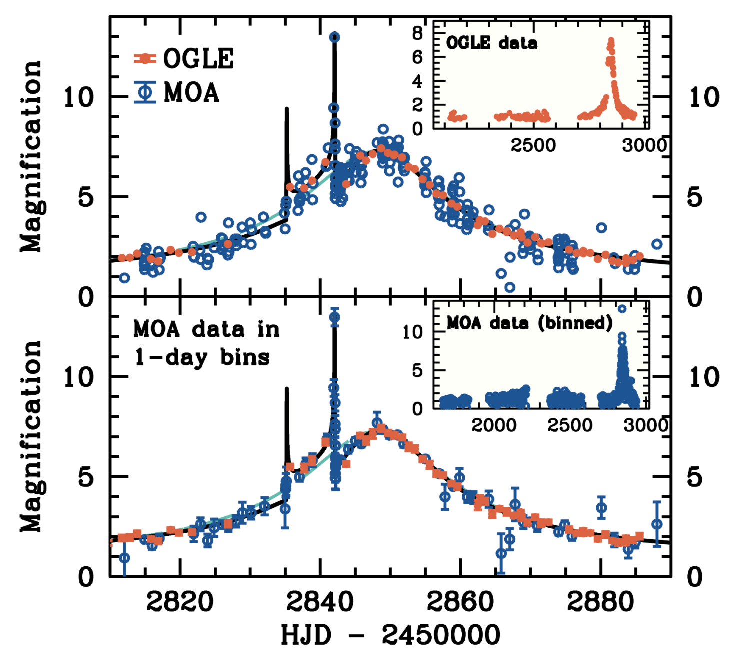


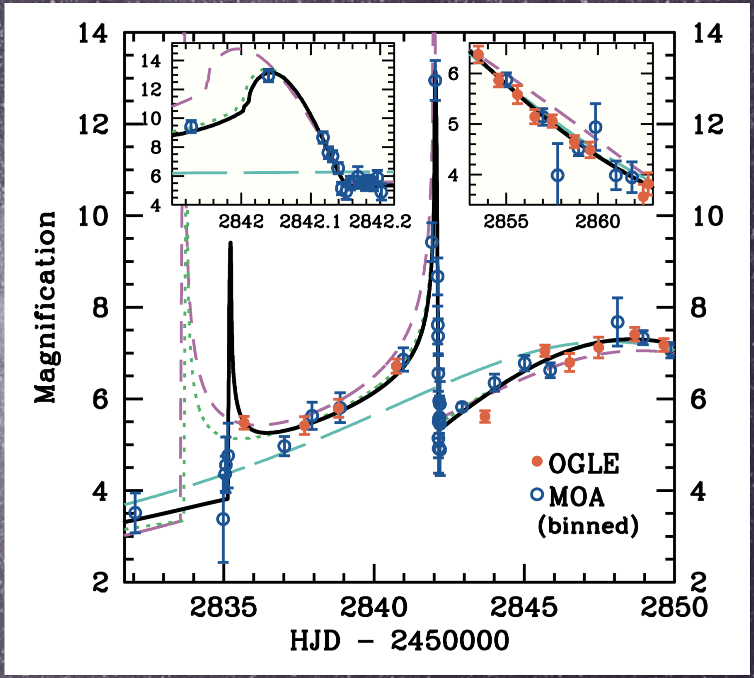
~650 events/year

Microlensing Surveys 1^{st} Generation:

First Planet!

OB03235/MB0353



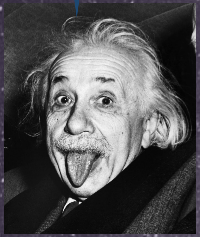


$q \sim 0.004$ / $M_* \sim 0.4\ M_\odot$ / $M_p \sim 1.5\ M_J$ / $a \sim 3$ AU

Bond+ (2004) ApJ, 606, 155

1936

1993



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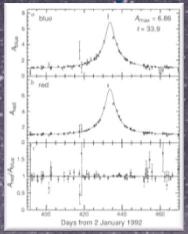
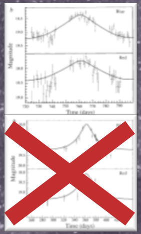




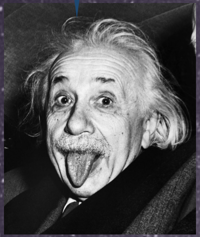
First Events

Surveys

EROS

MACHO

1936 1993 2004



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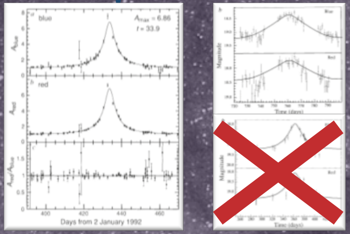
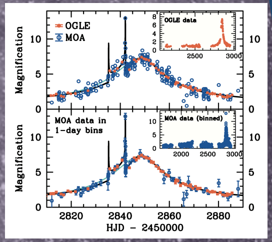


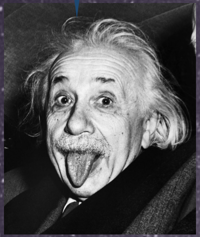
First Events



First Planet!

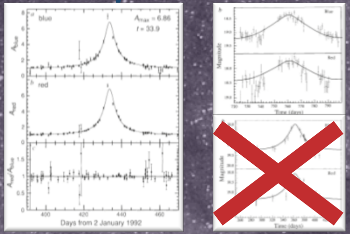
Surveys

1936



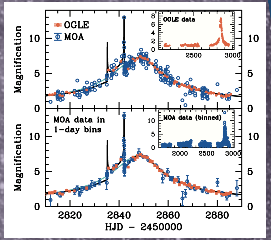
Derivation

1993



First Events

2004



First Planet!

Surveys

EROS

MACHO

OGLE

MOA

Follow-up Groups

PLANET

MicroFUN

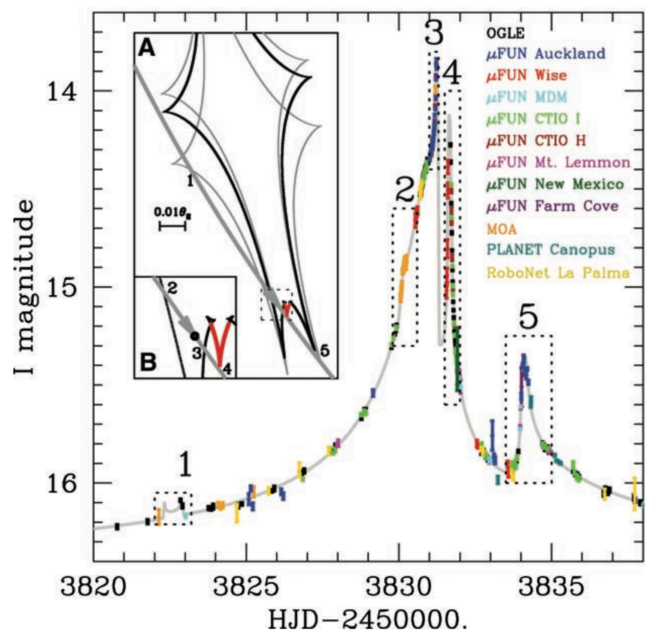
RoboNet

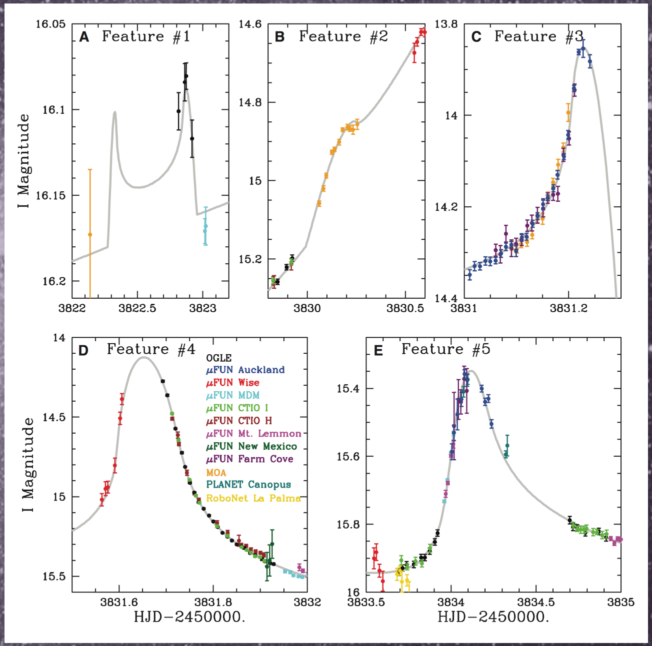
MiNDSTEp

Microlensing Surveys 1st Generation:

First Two-planet System!

OB06109

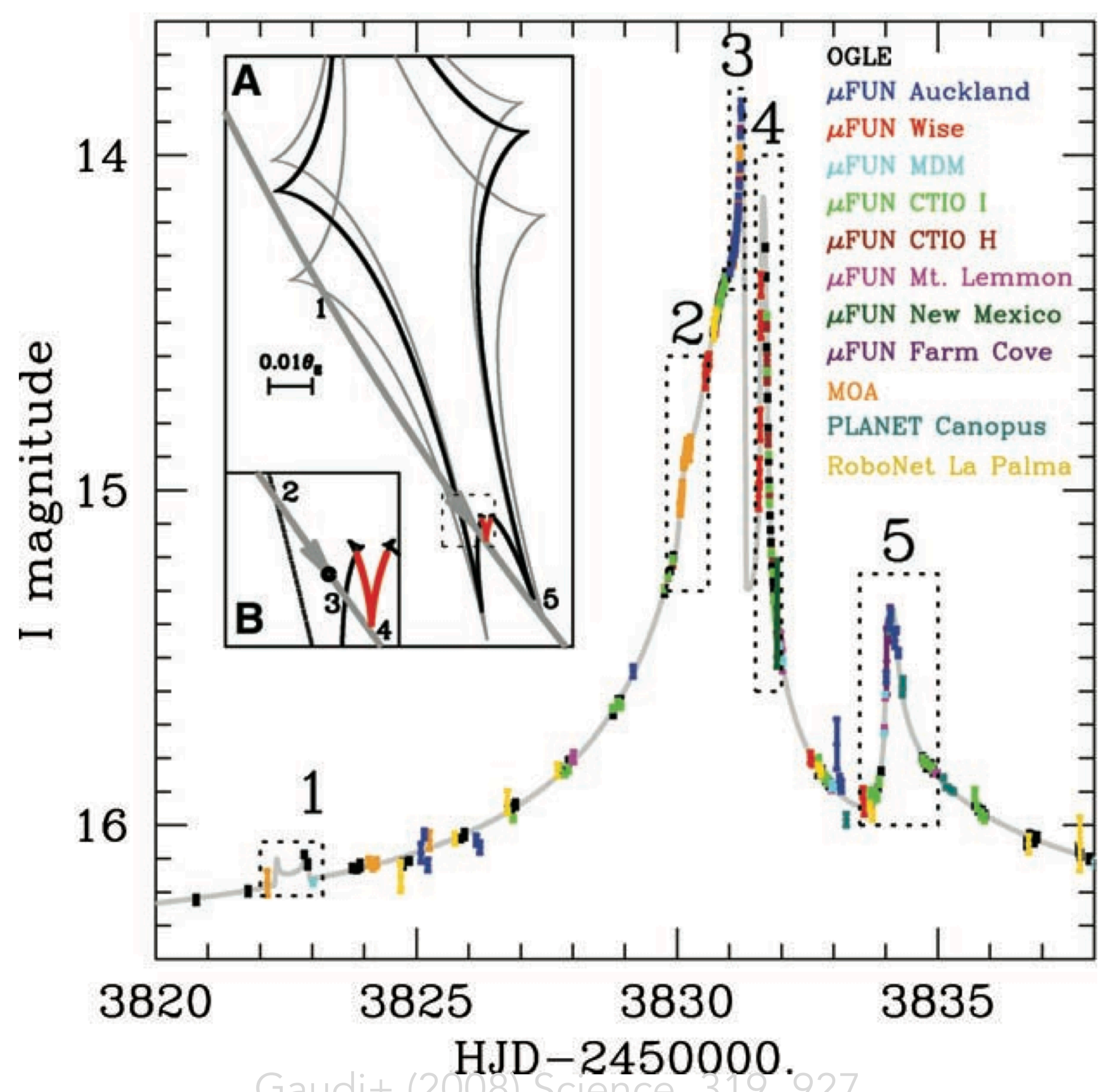




$M_1 \sim 0.71\ M_J$ / $M_2 \sim 0.27\ M_J$

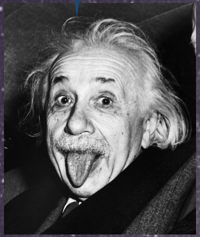
Gaudi+ (2008) Science, 319, 927

Microlensing Surveys 1st Generation:

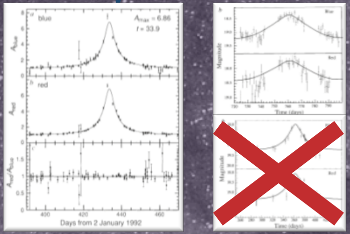


Gaudi+ (2008) Science, 319, 927

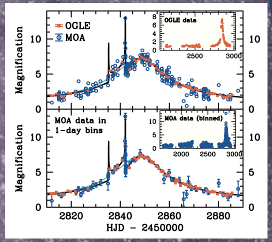
1936 1993 2004 2008



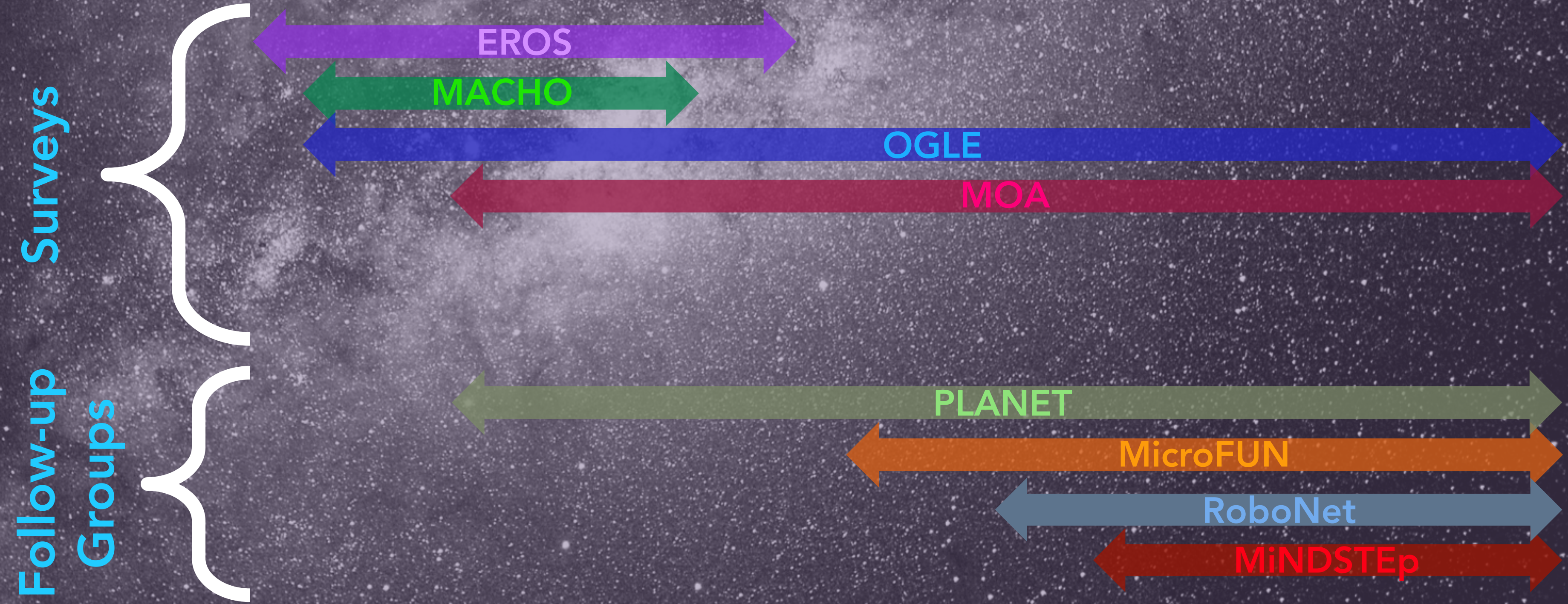
Derivation



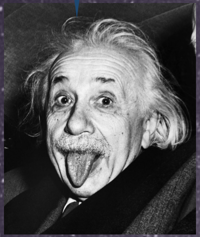
First Events



First Planet!



1936 1993 2004 2008



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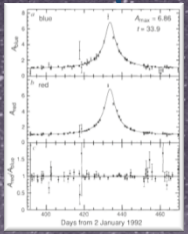
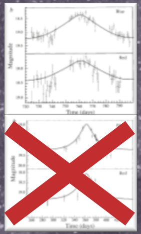
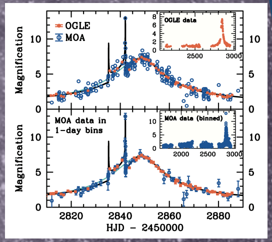




First Events



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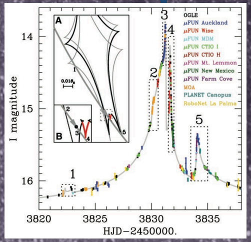
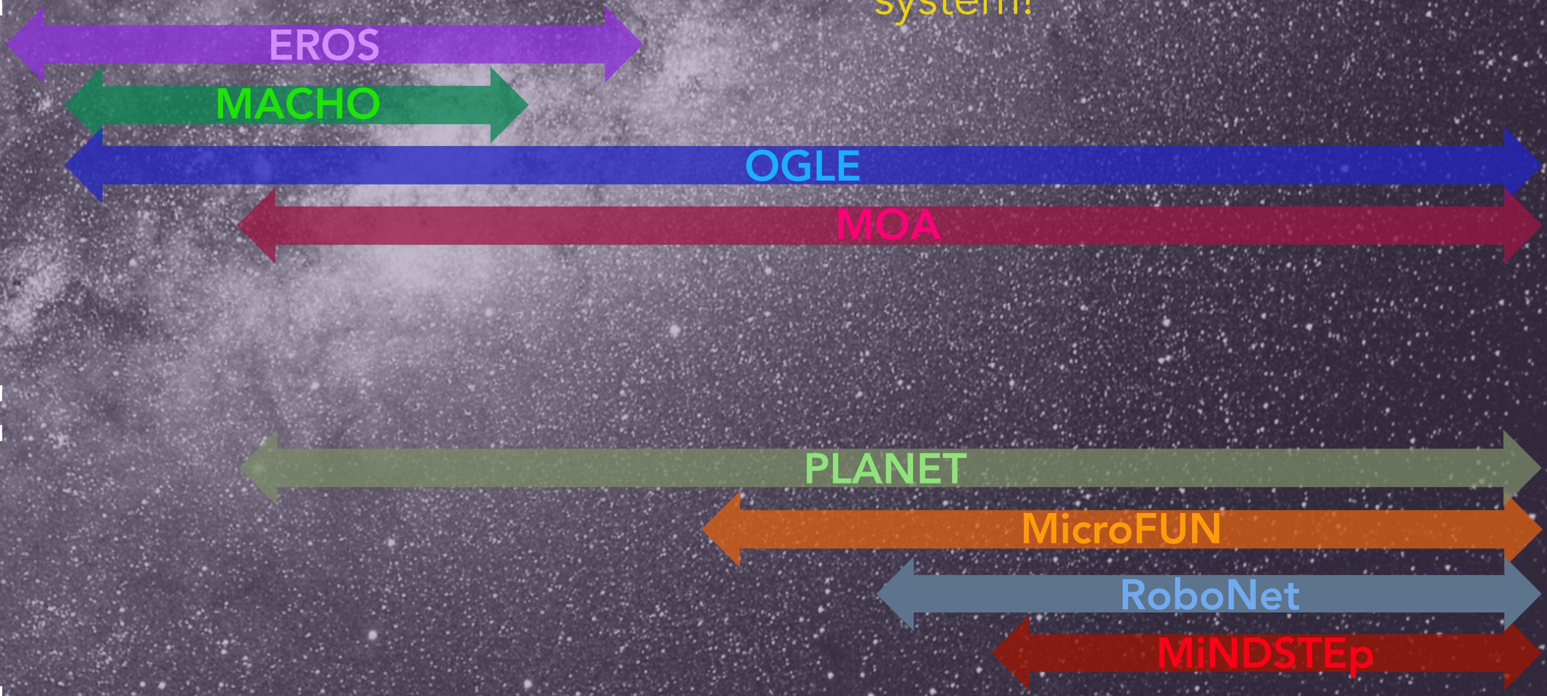


First two-planet system!

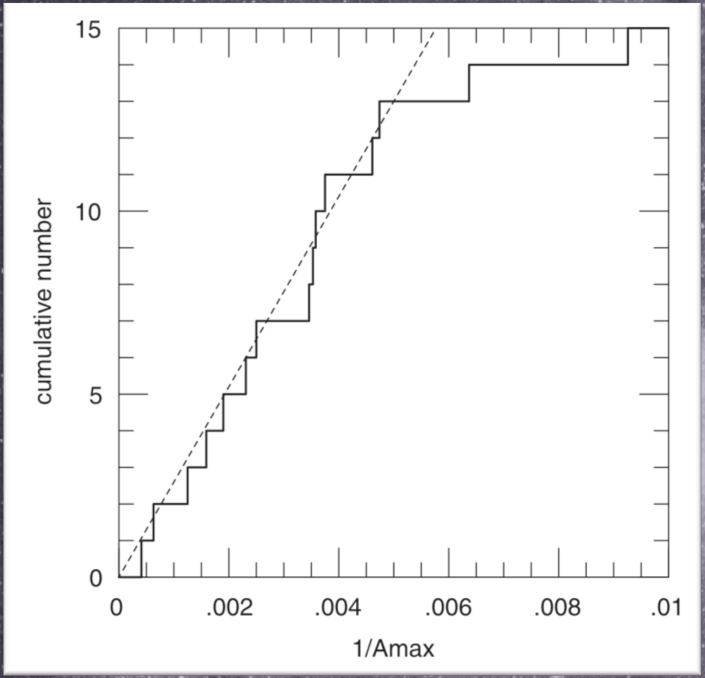
Surveys

Follow-up Groups

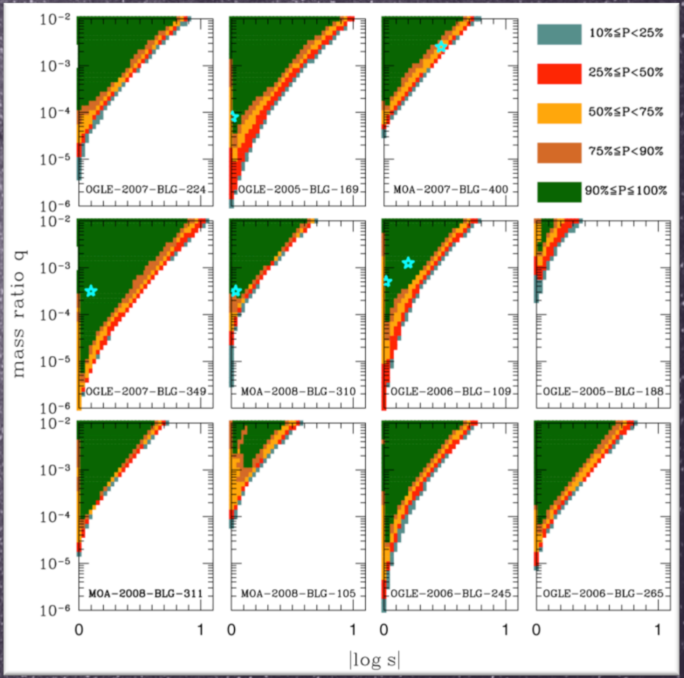


Microlensing Surveys 1st Generation:

Statistical Results I



- ✧ 13 Events
- ✧ 6 Planets
- ✧ $A_{max} > 200$

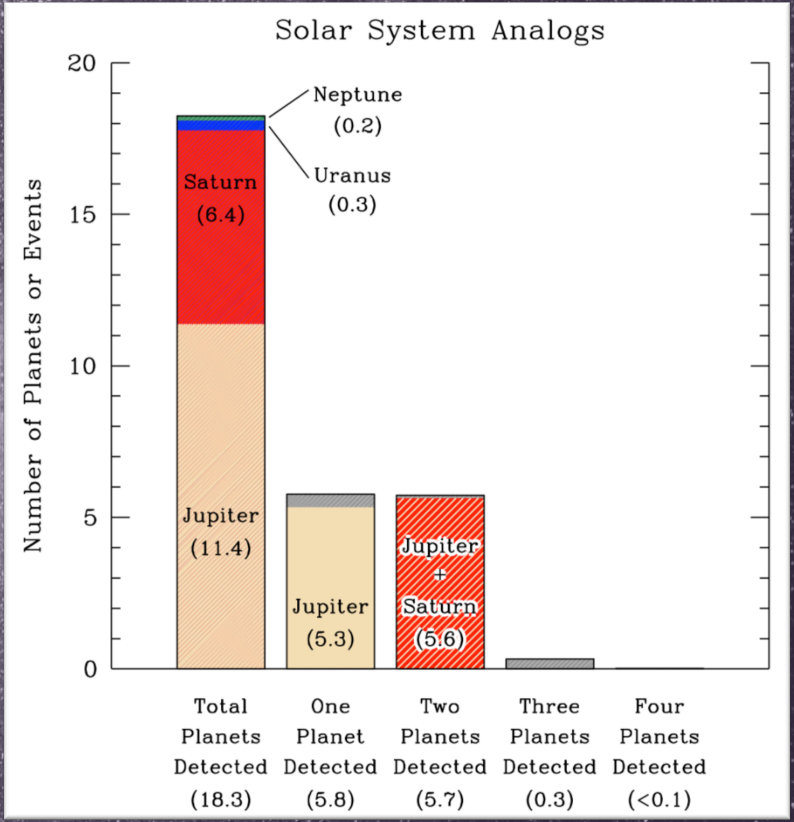


Gould+ (2010) ApJ, 720, 1073

Microlensing Surveys 1st Generation:
Statistical Results I

~1/3 of stars have snowline-region giant planets

~1/6 of stars have Solar-like Planetary systems



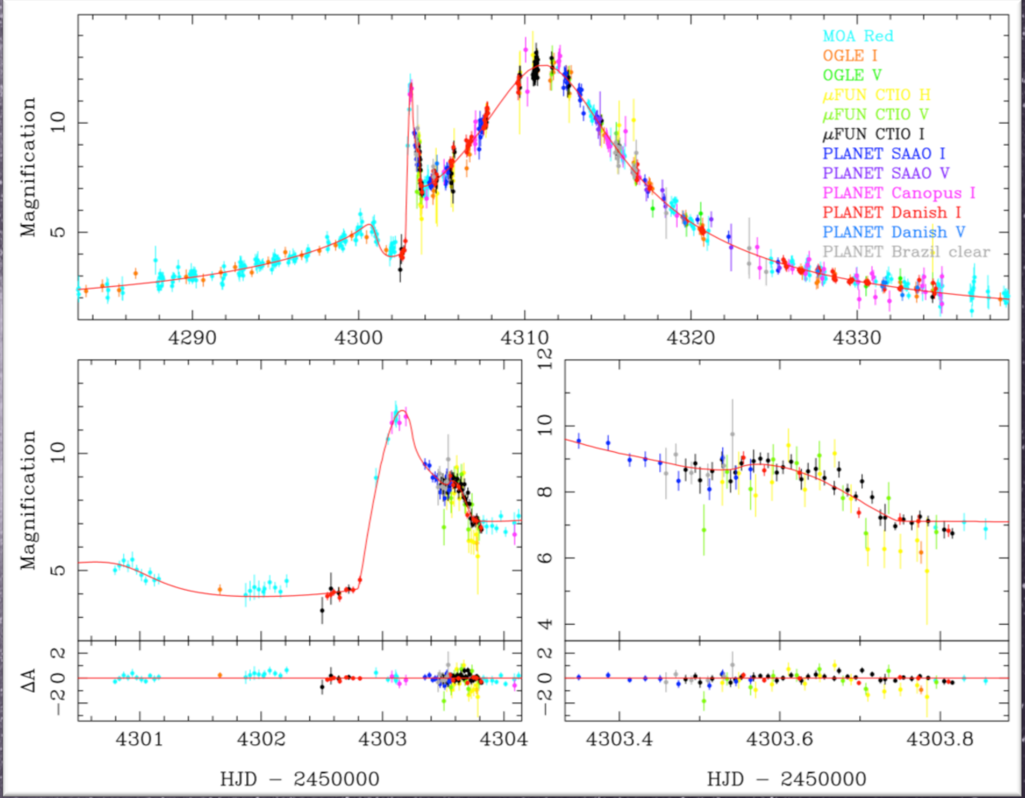
Gould+ (2010) ApJ, 720, 1073

Microlensing Surveys 1st Generation:

Statistical Results II

4 Planets +
Gould+ (2010)

Neptunes are ~3 times more common than Jupiters



Sumi+ (2010) ApJ, 710, 1641

Microlensing Surveys 1st Generation:

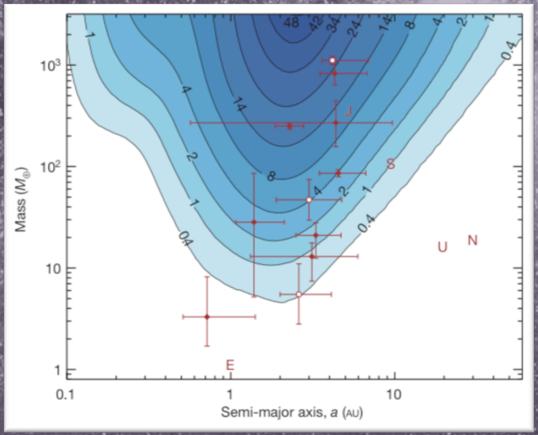
Statistical Results III

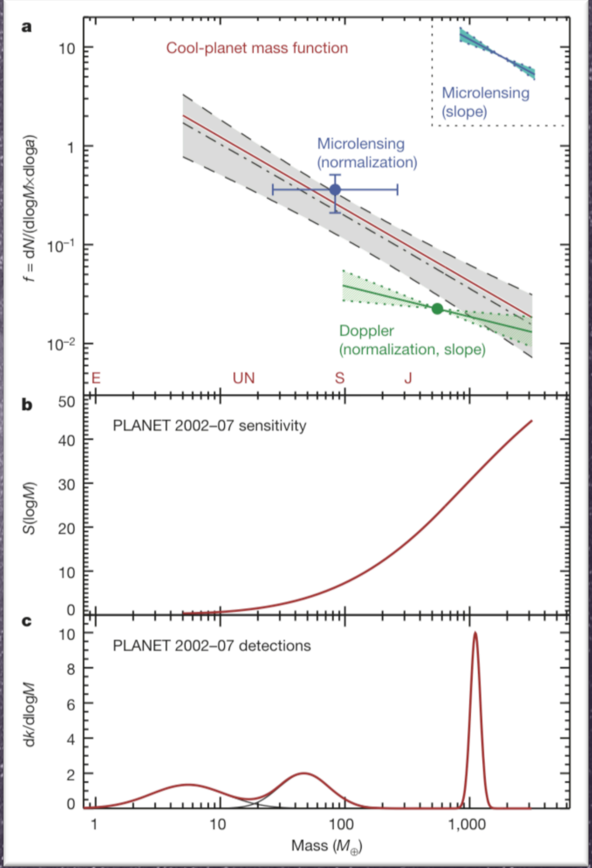
3 Planets +

~1/6 of stars host Jupiters

~1/2 of stars host Neptunes

~2/3 of stars host Super-Earths

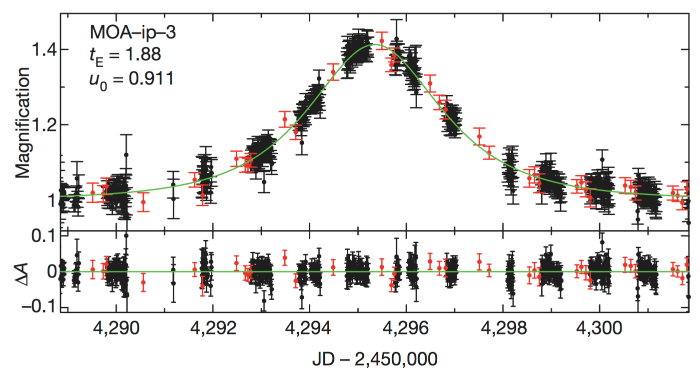




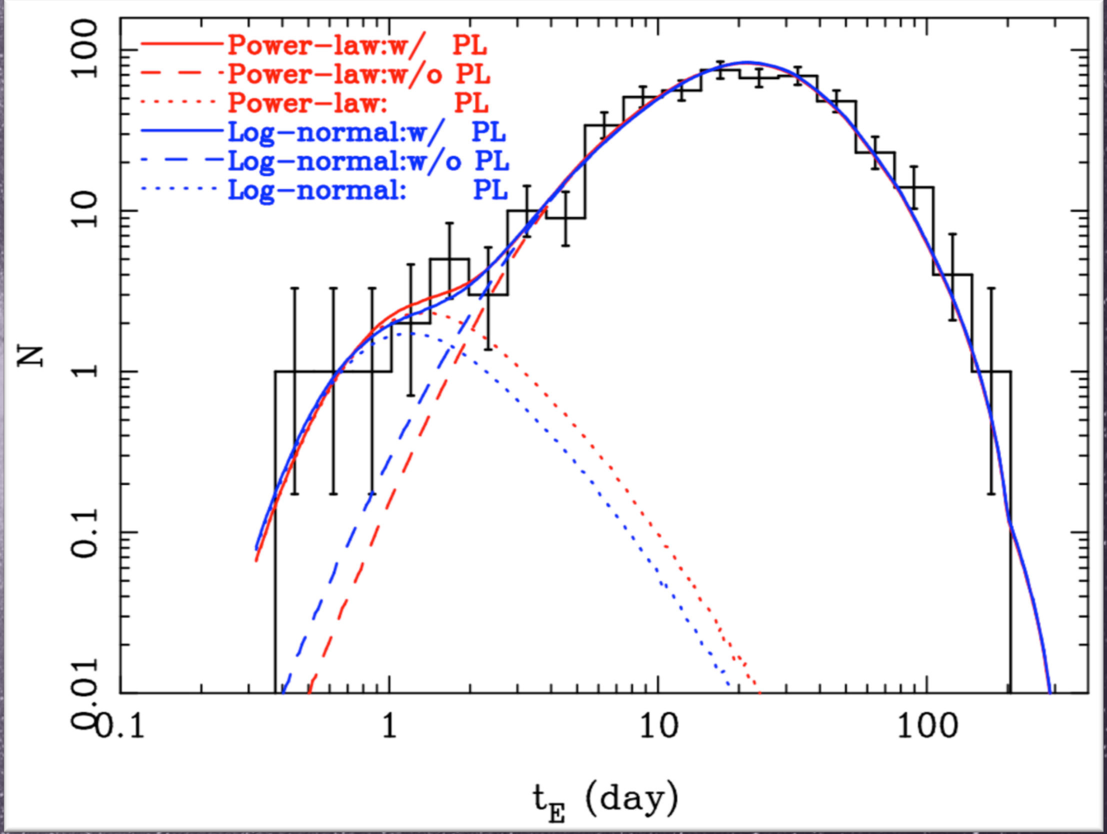
Cassan+ (2012) Nature, 481, 687

Microlensing Surveys 1st Generation:
Statistical Results IV

Short-timescale Microlensing Event

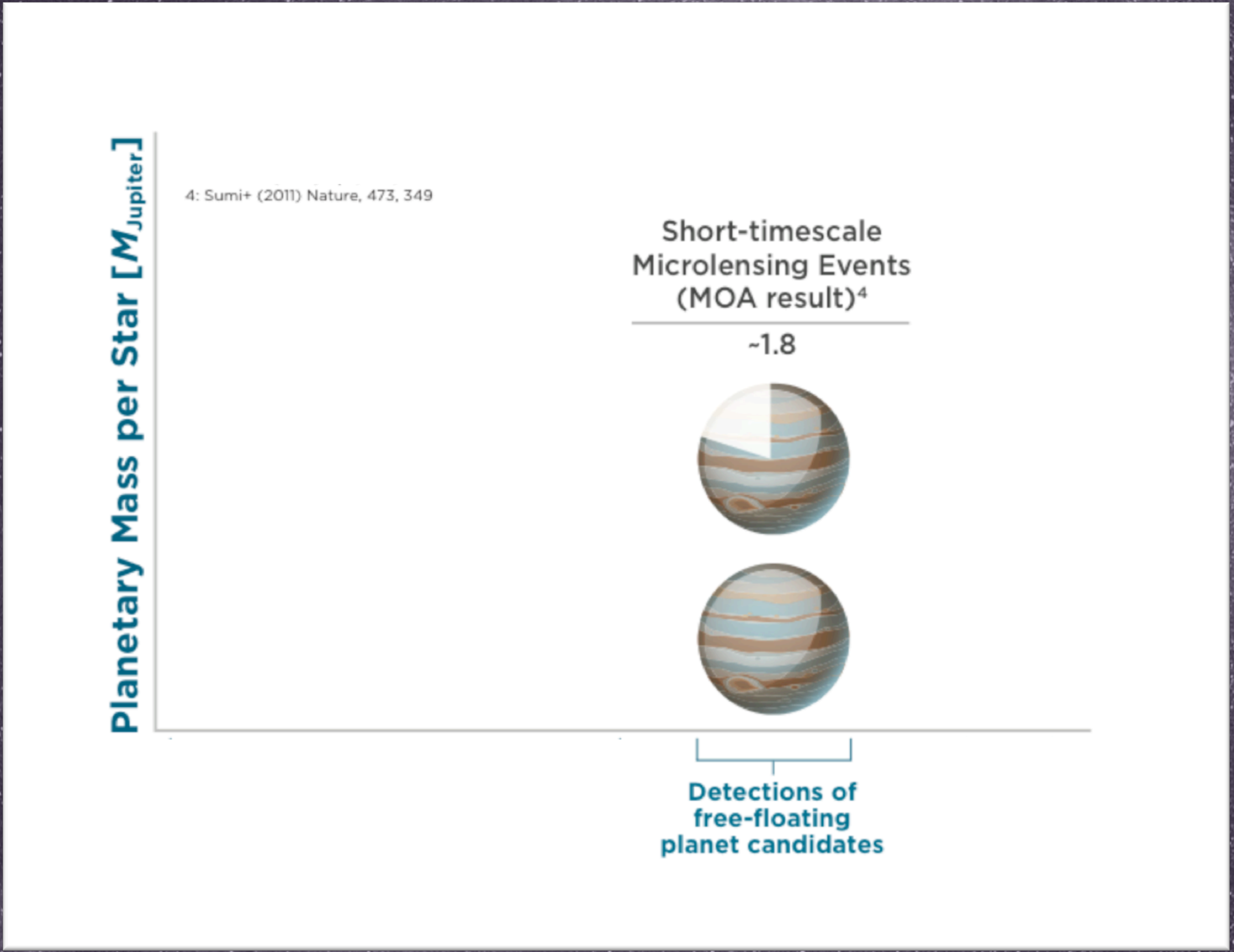


Overarching Timescale Distribution



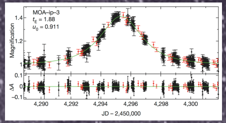
Sumi+ (2011) Nature, 473, 349

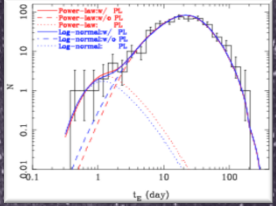
Planetary Mass Budget



Henderson+ (2015) arXiv:1512.09142

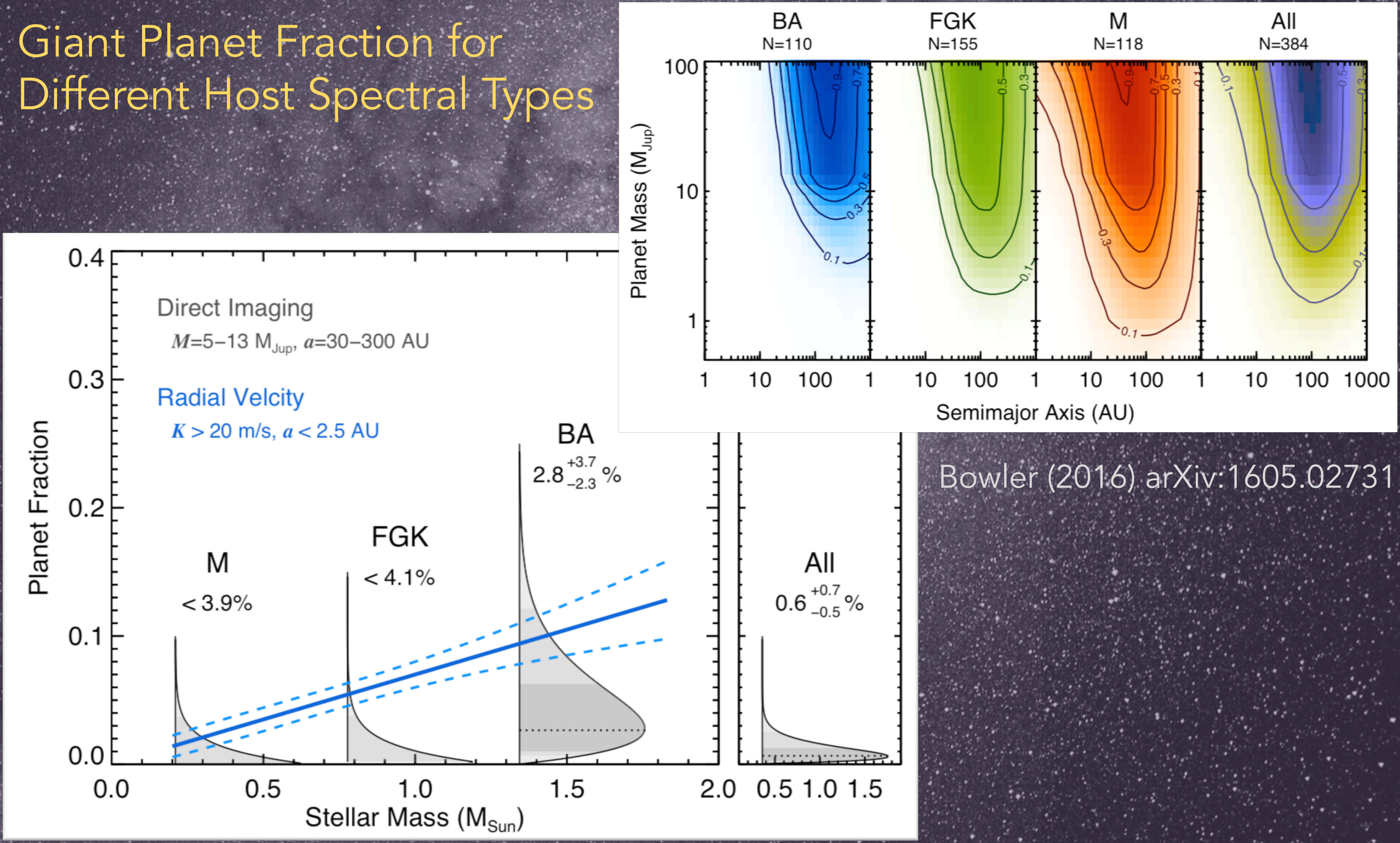
Microlensing (FFPs)





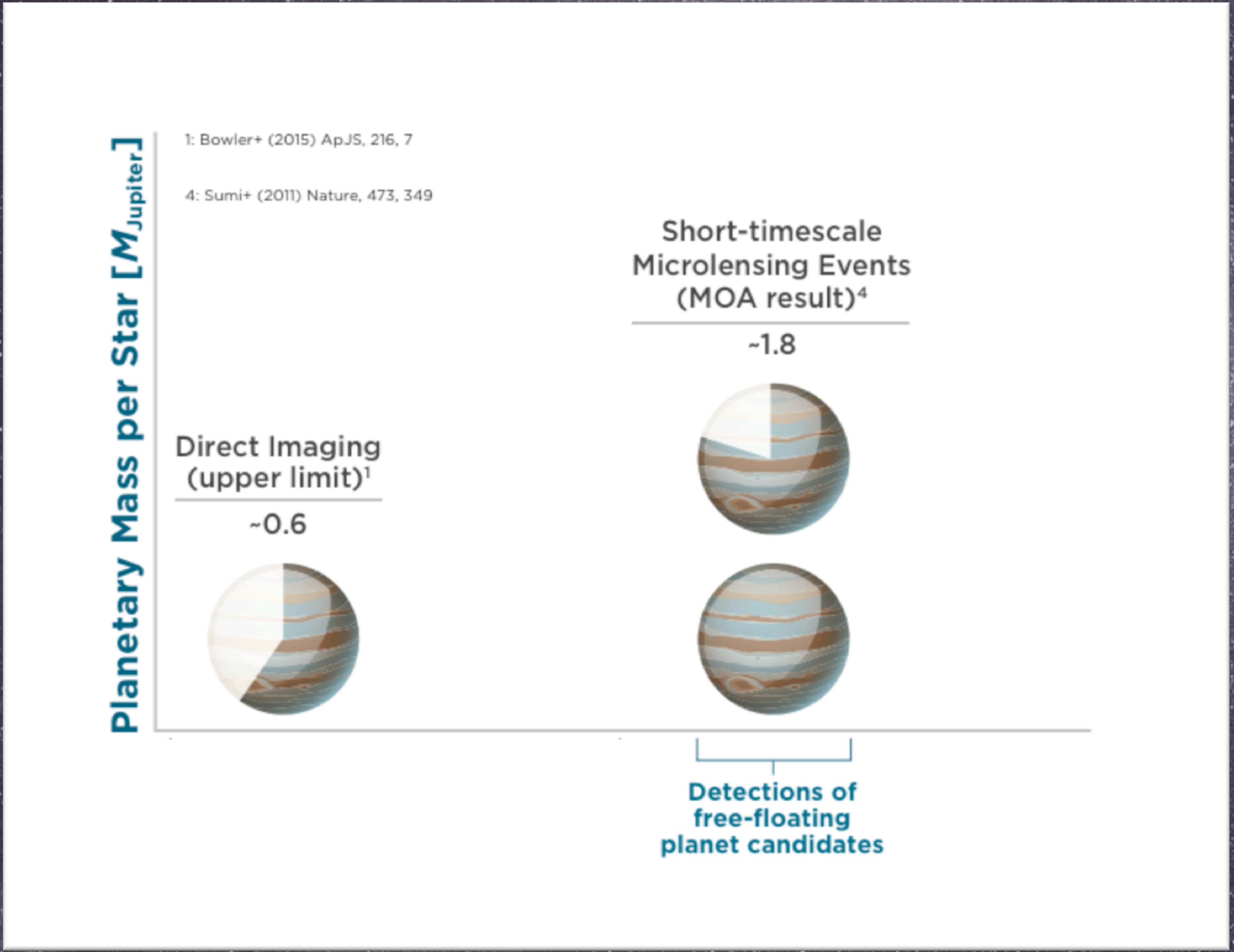
Direct Imaging Constraints

Giant Planet Fraction for Different Host Spectral Types



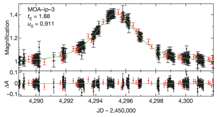
Bowler (2016) arXiv:1605.02731

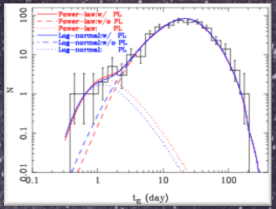
Planetary Mass Budget



Henderson+ (2015) arXiv:1512.09142

Microlensing (FFPs)





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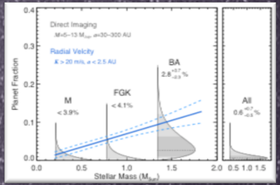
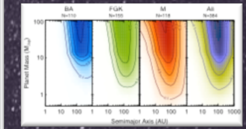
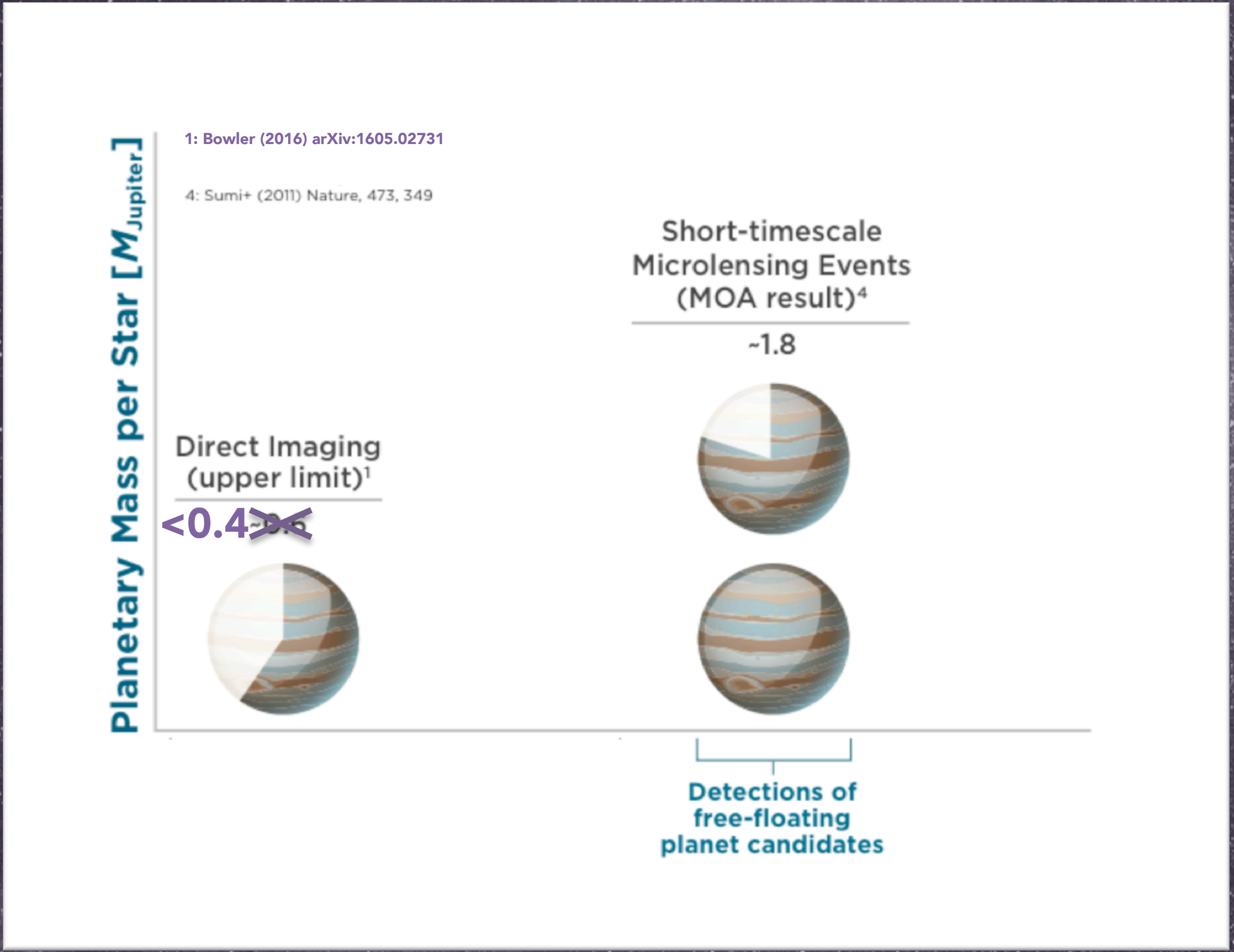




Jet Propulsion Laboratory
California Institute of Technology

Planetary Mass Budget

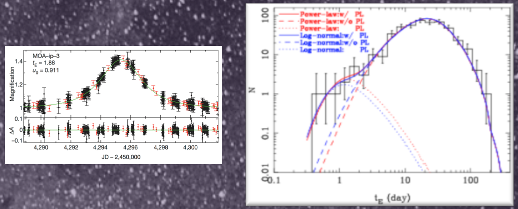


1: Bowler (2016) arXiv:1605.02731

4: Sumi+ (2011) Nature, 473, 349

Henderson+ (2015) arXiv:1512.09142

Microlensing (FFPs)



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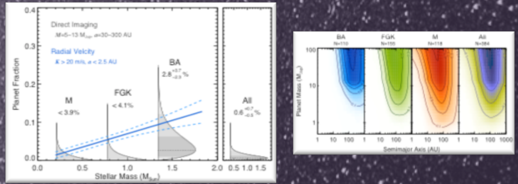


Transit + RV + Microlensing

Planet Frequency versus Orbital Period

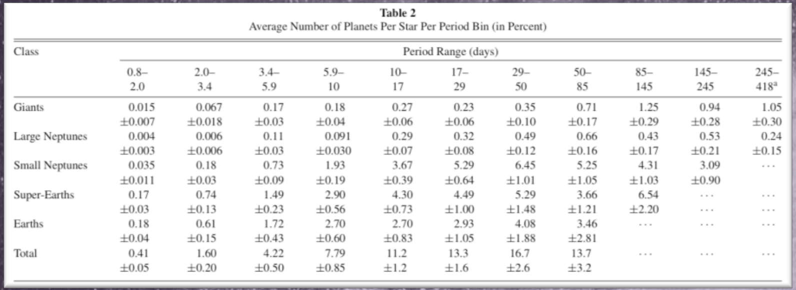
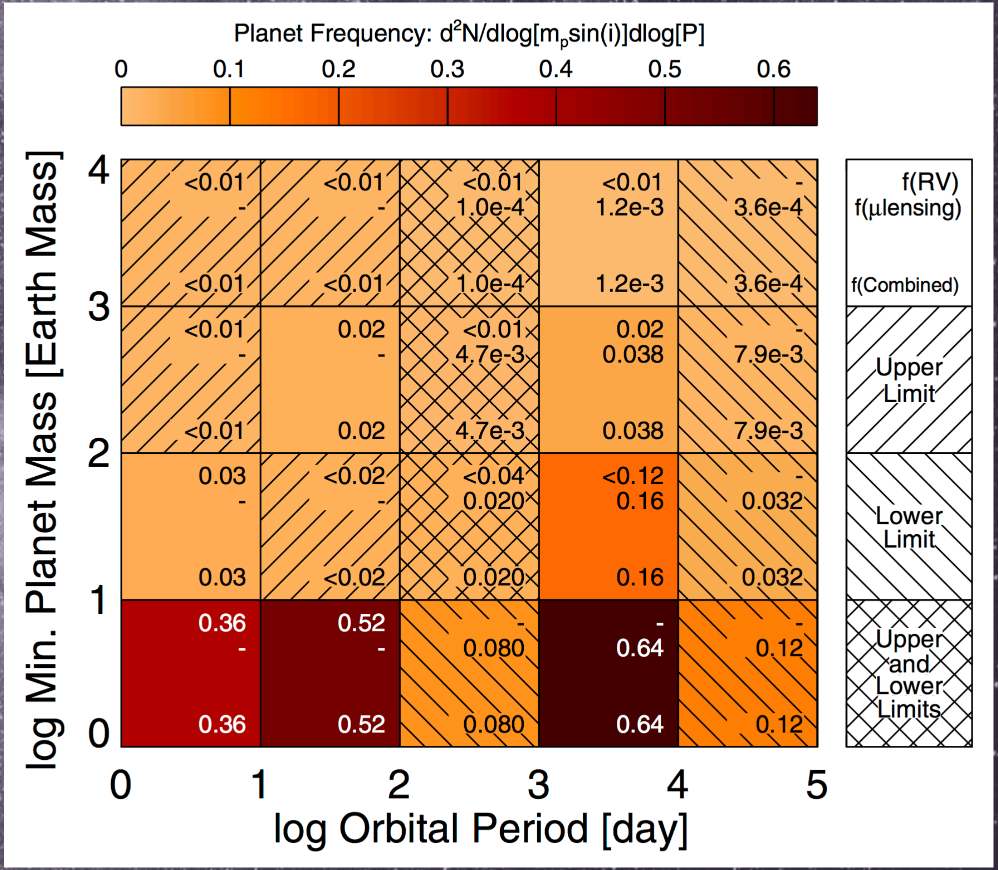


Table 2
Average Number of Planets Per Star Per Period Bin (in Percent)

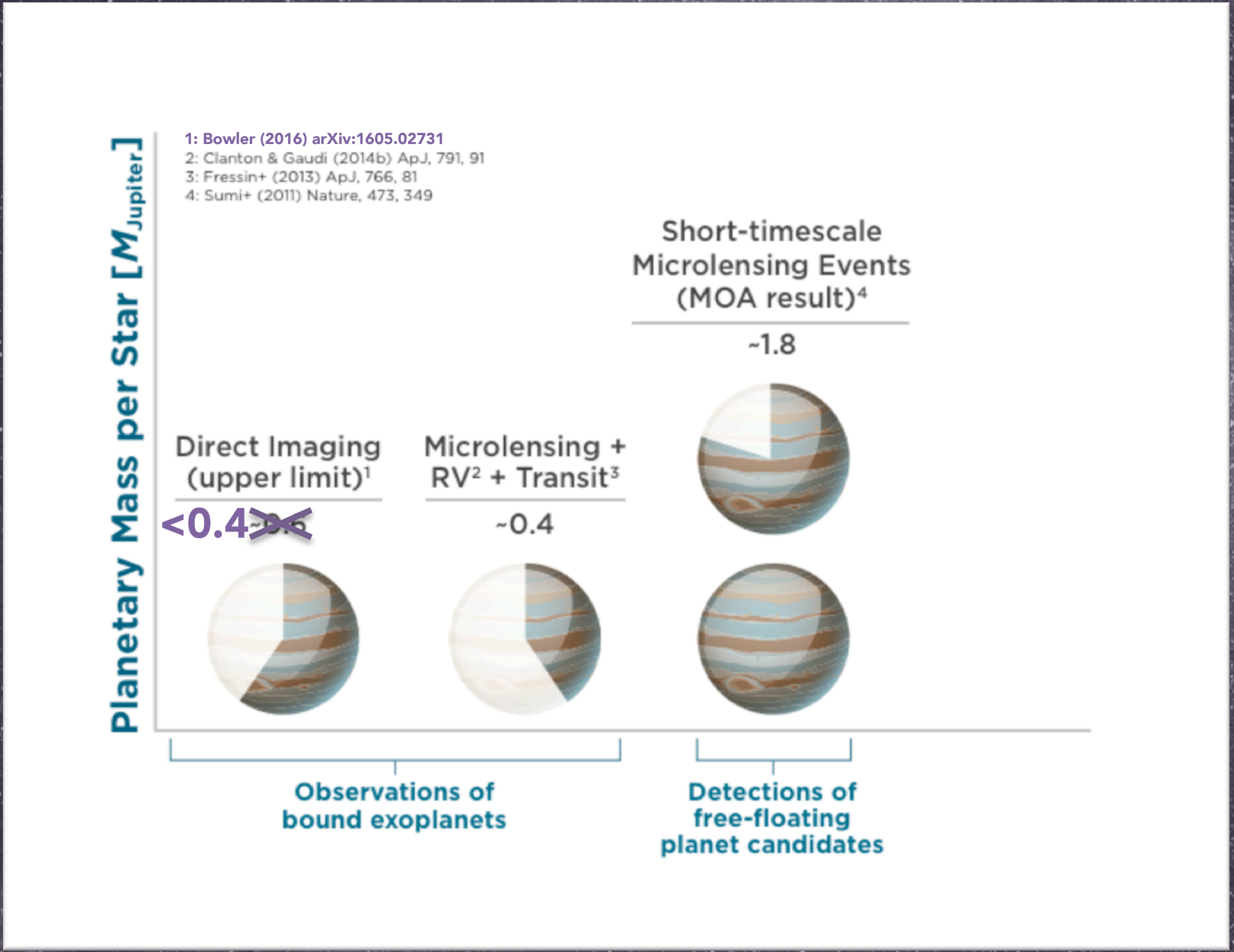
Class	Period Range (days)										
	0.8–2.0	2.0–3.4	3.4–5.9	5.9–10	10–17	17–29	29–50	50–85	85–145	145–245	245–418[a]
Giants	0.015 ±0.007	0.067 ±0.018	0.17 ±0.03	0.18 ±0.04	0.27 ±0.06	0.23 ±0.06	0.35 ±0.10	0.71 ±0.17	1.25 ±0.29	0.94 ±0.28	1.05 ±0.30
Large Neptunes	0.004 ±0.003	0.006 ±0.006	0.11 ±0.03	0.091 ±0.030	0.29 ±0.07	0.32 ±0.08	0.49 ±0.12	0.66 ±0.16	0.43 ±0.17	0.53 ±0.21	0.24 ±0.15
Small Neptunes	0.035 ±0.011	0.18 ±0.03	0.73 ±0.09	1.93 ±0.19	3.67 ±0.39	5.29 ±0.64	6.45 ±1.01	5.25 ±1.05	4.31 ±1.03	3.09 ±0.90	···
Super-Earths	0.17 ±0.03	0.74 ±0.13	1.49 ±0.23	2.90 ±0.56	4.30 ±0.73	4.49 ±1.00	5.29 ±1.48	3.66 ±1.21	6.54 ±2.20	··· ···	··· ···
Earths	0.18 ±0.04	0.61 ±0.15	1.72 ±0.43	2.70 ±0.60	2.70 ±0.83	2.93 ±1.05	4.08 ±1.88	3.46 ±2.81	···	···	···
Total	0.41 ±0.05	1.60 ±0.20	4.22 ±0.50	7.79 ±0.85	11.2 ±1.2	13.3 ±1.6	16.7 ±2.6	13.7 ±3.2	···	···	···

Fressin+ (2013) ApJ, 766, 81



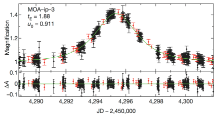
Clanton & Gaudi (2014b) ApJ, 791, 91

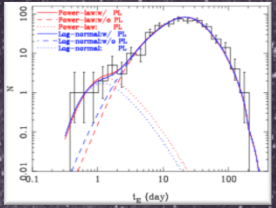
Planetary Mass Budget



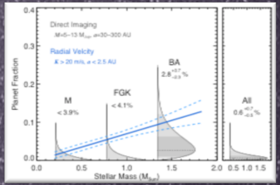
Henderson+ (2015) arXiv:1512.09142

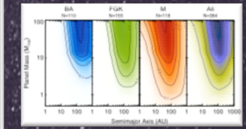
Microlensing (FFPs)



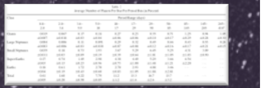


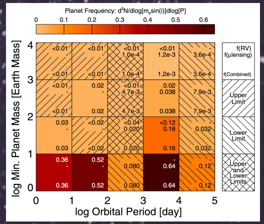
Direct Imaging



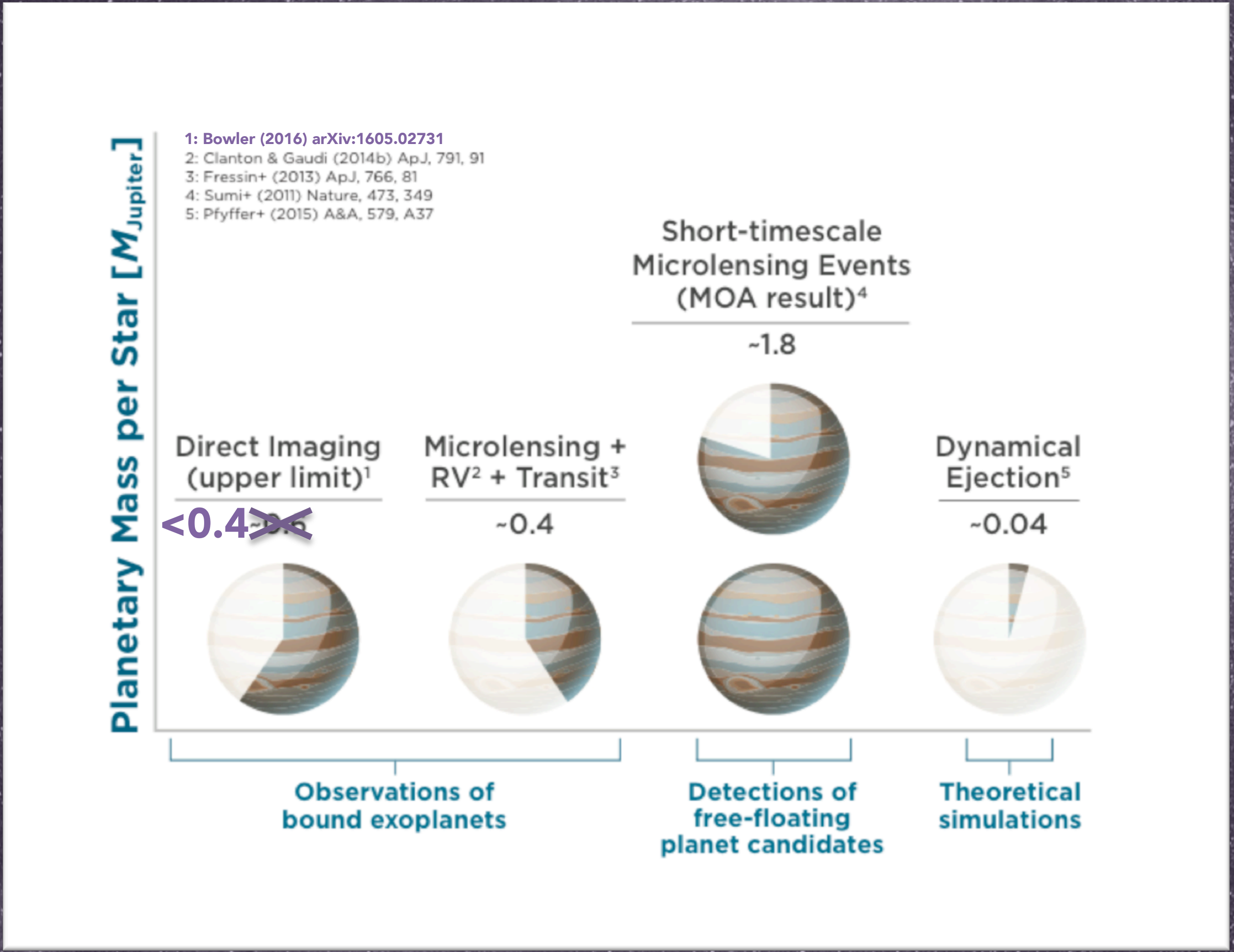


Transit + RV + Microlensing



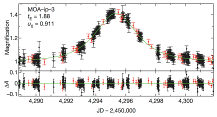


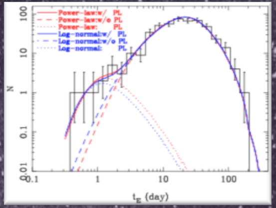
Planetary Mass Budget



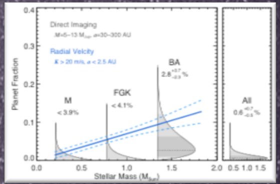
Henderson+ (2015) arXiv:1512.09142

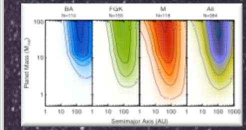
Microlensing (FFPs)



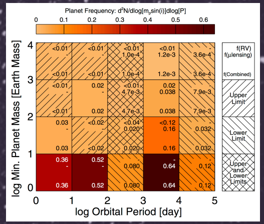


Direct Imaging





Transit + RV + Microlensing



Microlensing Surveys: 1st Generation

"Alert and Follow-up" strategy limitations:

High magnification events are rare events (~1%)

→~7 events/year → ~2 planets/year

Complex decision and communication process

→Bad statistical interpretation

Solution:

"Generation-II microlensing survey"

Microlensing Surveys: 2nd Generation

Controlled experiment:

- Untargeted survey, specific field (high mag + low mag)
- Continuous coverage, high cadence

Forward modeling for planet abundance:

- Simulate the experiment
- Define planetary anomaly detection threshold
- Compare data to simulation

Microlensing Surveys: 2nd Generation

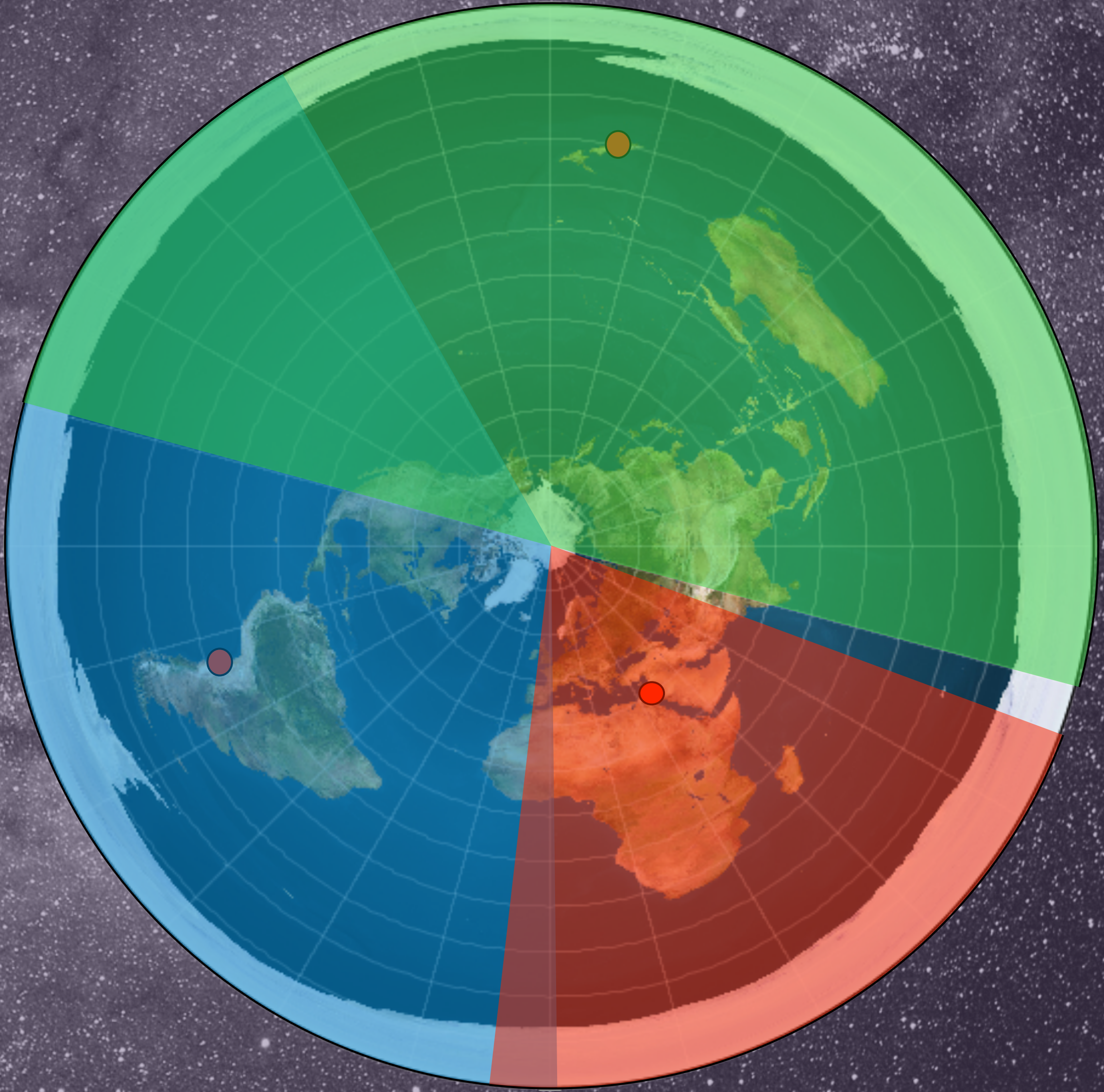
Wise, Israel, 1m

OGLE, Chile, 1.3m

MOA, NZ, 1.8m

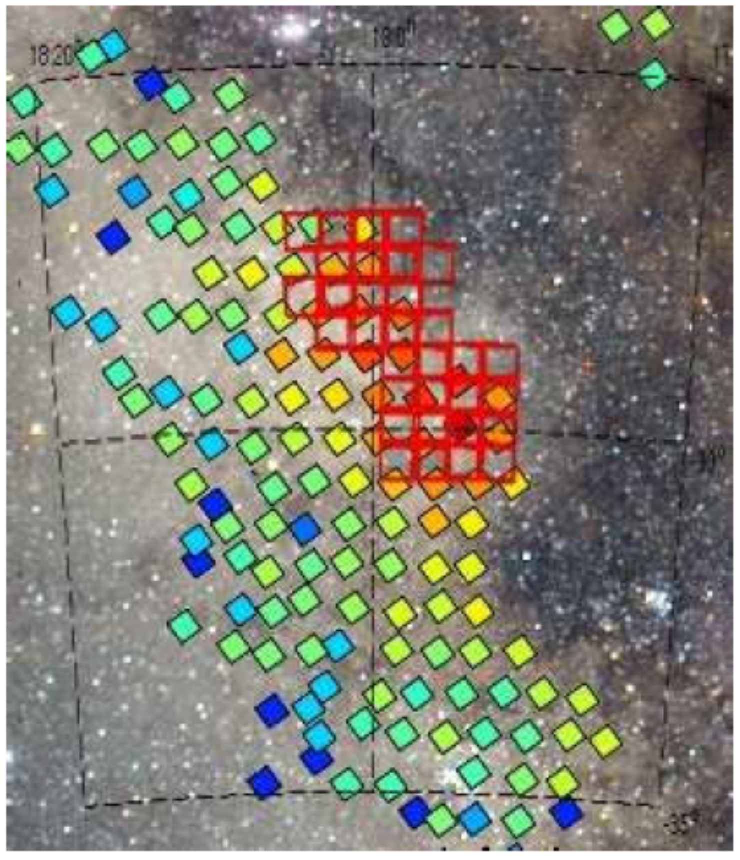
Microlensing Surveys: 2nd Generation

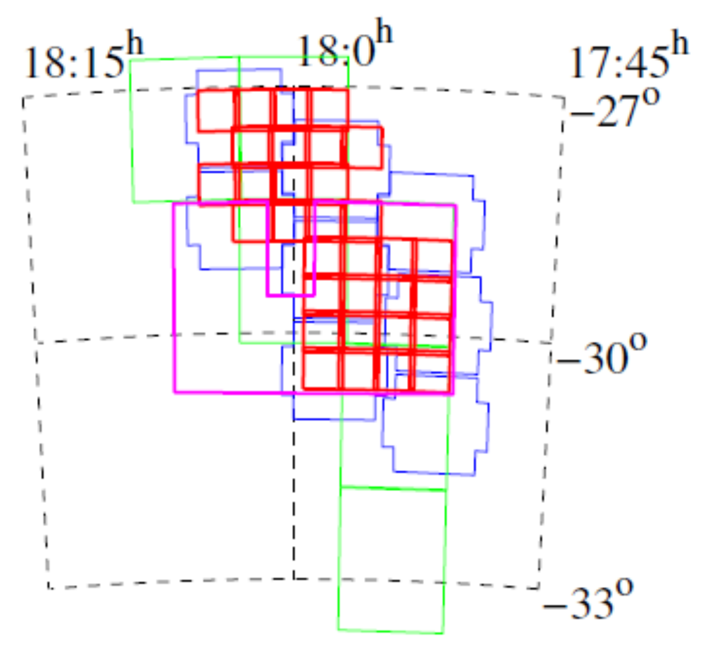
Group
OGLE
MOA
WISE



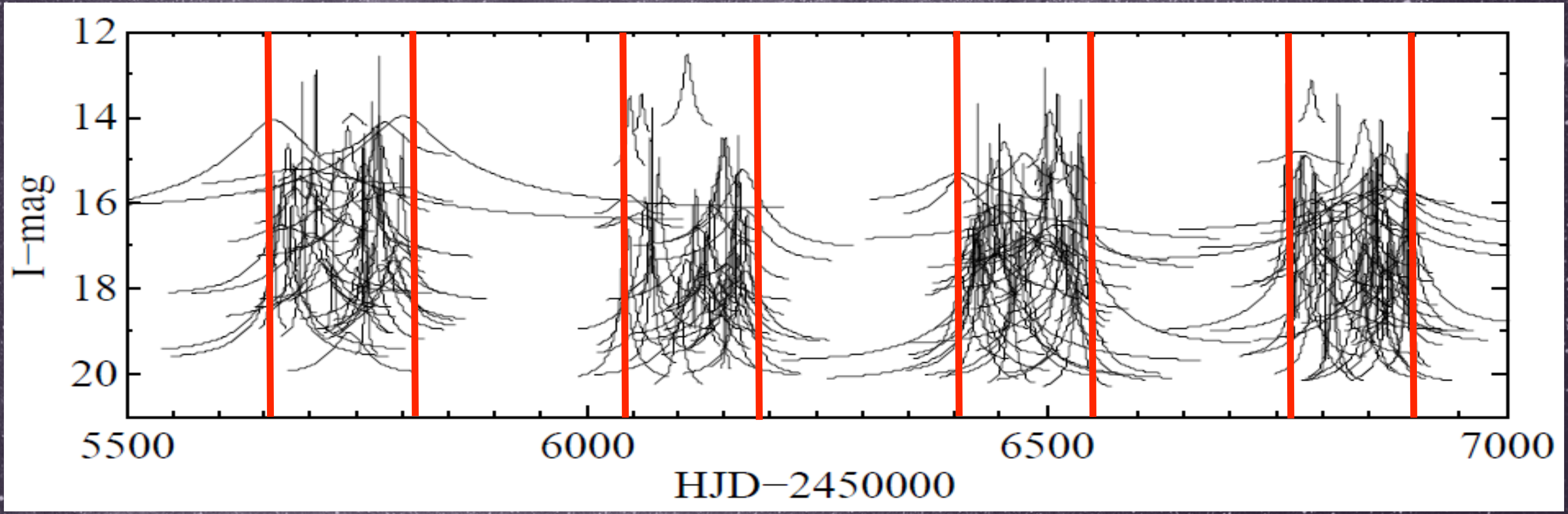
Microlensing Surveys: 2nd Generation

- 8 deg^2 of bulge with highest lensing rate
- covered quasi-continuously by all 3 telescopes
- cadences 20-40 min





Microlensing Surveys: 2nd Generation



Microlensing Surveys: 2nd Generation

- Frequency definition:

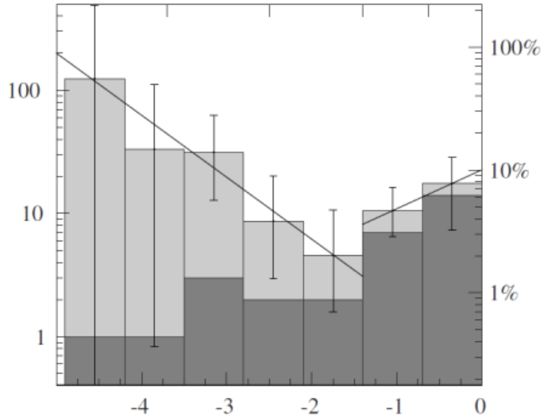
$$F(q) = \frac{N(q)}{\sum \eta(q)}$$

- "Jupiters":

$$f(10^{-2.8} < q < 10^{-1.4}) = 5.0^{+4.0}_{-2.4}\%$$

- "Neptunes":

$$f(10^{-4.9} < q < 10^{-2.8}) = 50^{+34}_{-22}\%$$



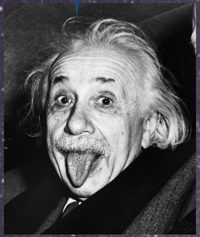
Snowline planet frequency:

$$f(10^{-4.9} < q < 10^{-1.4}) = 55^{+34}_{-22}\%$$

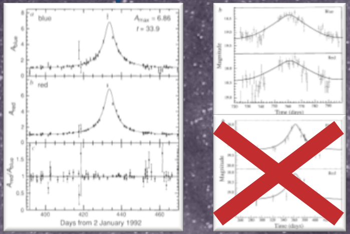
High occurrence of BD companions:
~4%

Shvartzvald et al. submitted

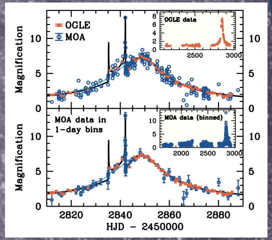
1936 1993 2004 2008 2016



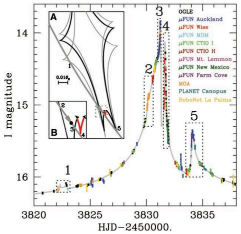
Derivation



First Events



First Planet!



First two-planet system!

Surveys

EROS

MACHO

OGLE

MOA

Wise

Follow-up Groups

PLANET

MicroFUN

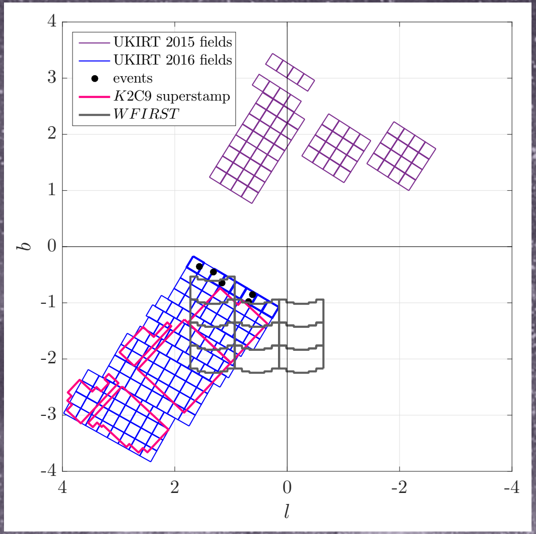
RoboNet

MiNDSTEp

UKIRT Pilot *H*-band Microlensing Surveys in 2015–2016

2015 Survey: *Spitzer*

- 3.4 square degrees
- 39 nights (120 hr)
- 5 epochs/night
- SNR ~ 10 at H ~ 16.5



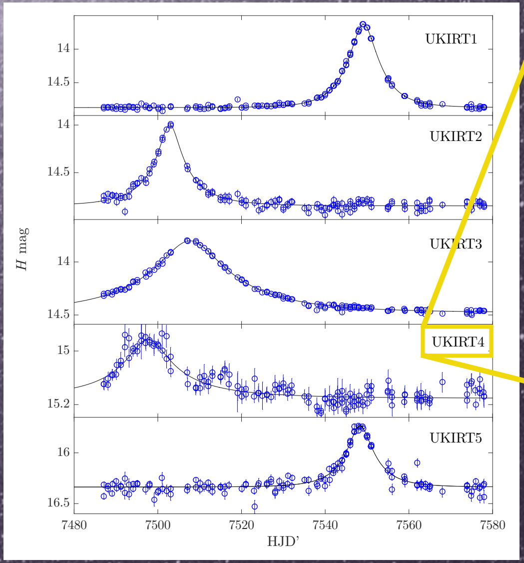
2016 Survey: *K2* Campaign 9

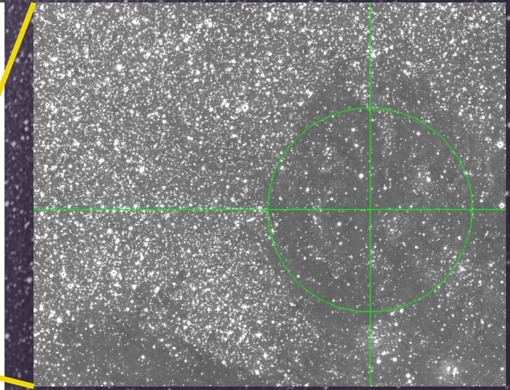
- 6 square degrees
- 91 nights (240 hr)
- 2—3 epochs/night
- SNR ~ 10 at H ~ 18.5
- Covered ~60% of proposed *WFIRST* target fields

Shvartzvald*, Bryden, Gould, Henderson*, Beichman, Howell (2016): submitted to *ApJL*

Non-systematic Analysis of 2016 Data

- Partial exploration of 7 out of 132 subfields
- 5 events discovered!
- High extinction: $0.81 \le A_H \le 1.97$
- Close to Galactic plane: $-0.98 \le b \le -0.36$
- All 5 covered by ground-based optical surveys, 4 with an hourly cadence, but none recovered!





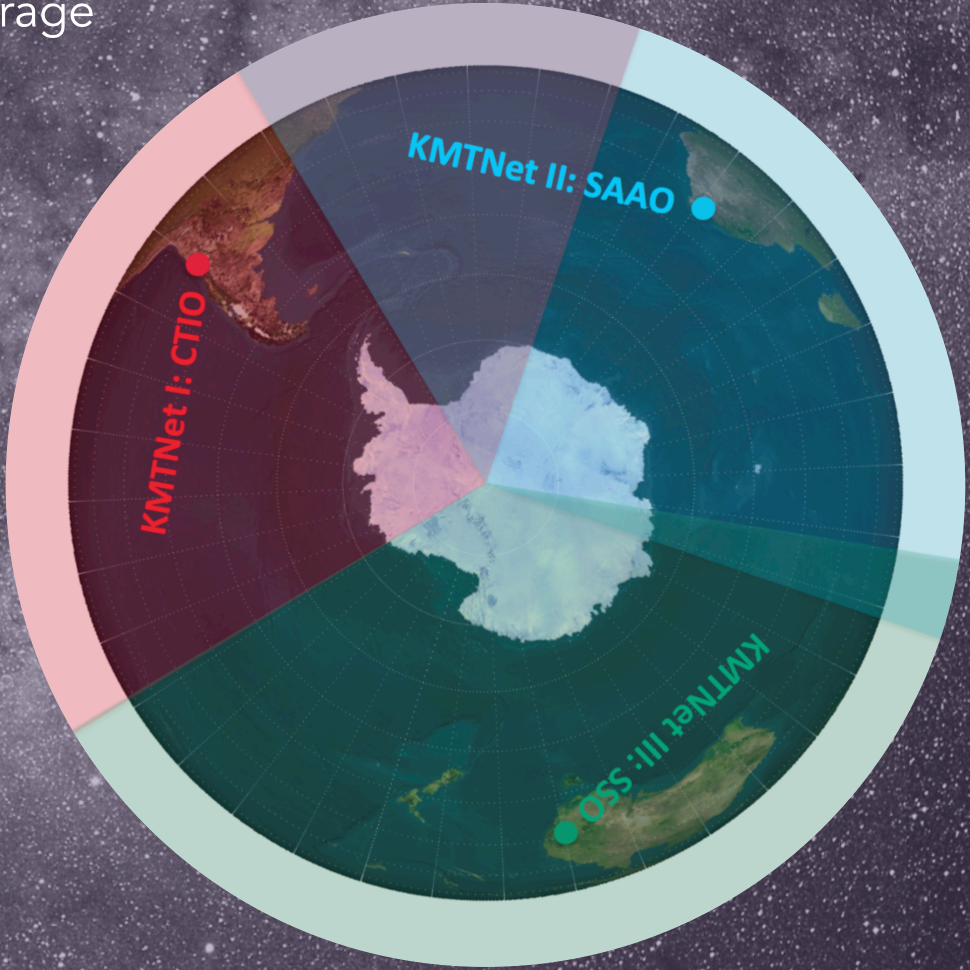
Left: light curves for five newly discovered UKIRT microlensing events.

Top: UKIRT image for UKIRT4, emphasizing the high degree of differential reddening across the *WFIRST* target field region.

*Co-leads for *WFIRST* MicroSIT Precursor Observations Group

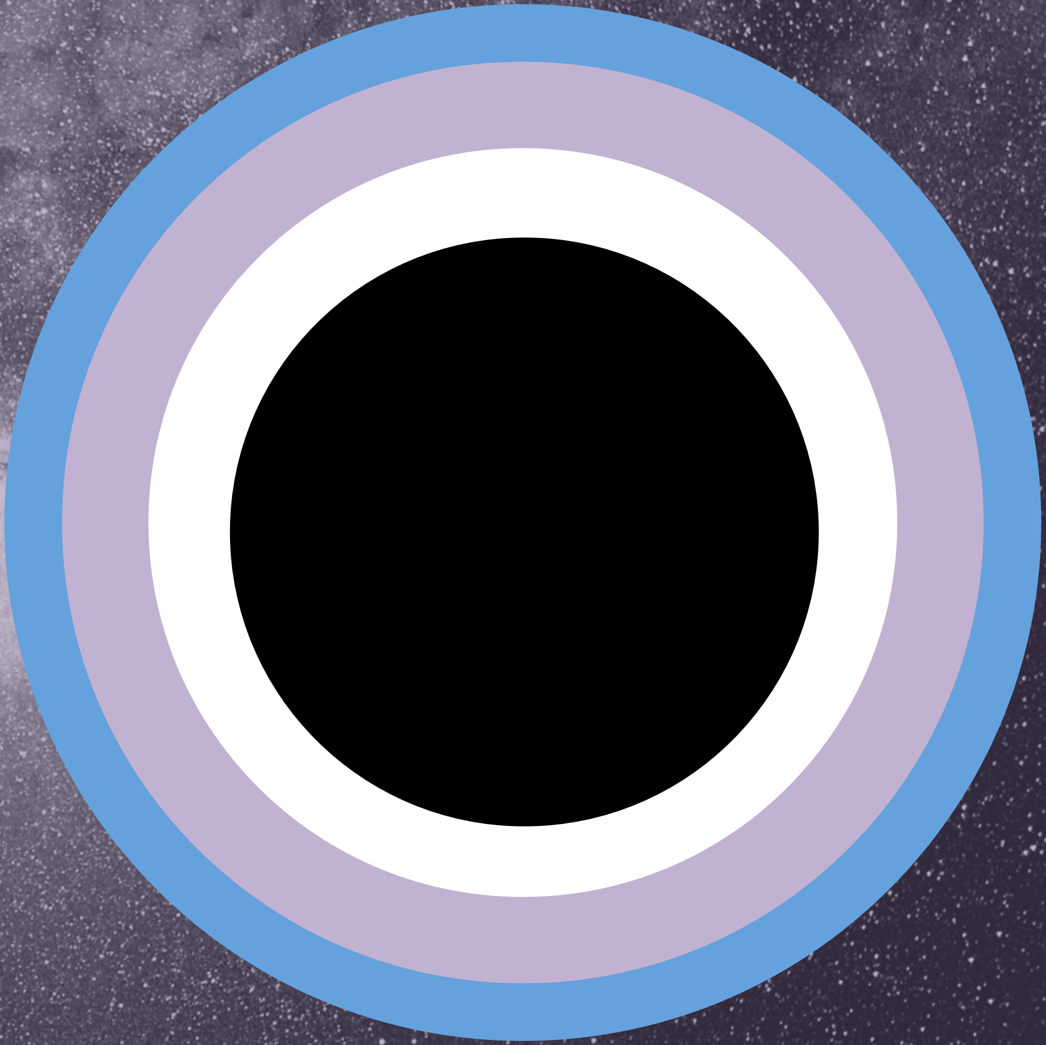
Microlensing Surveys: Next Generation

✓ Longitudinal Coverage



Microlensing Surveys: Next Generation

- ✓ Longitudinal Coverage
- ✓ Aperture



MOA-II: 1.8m

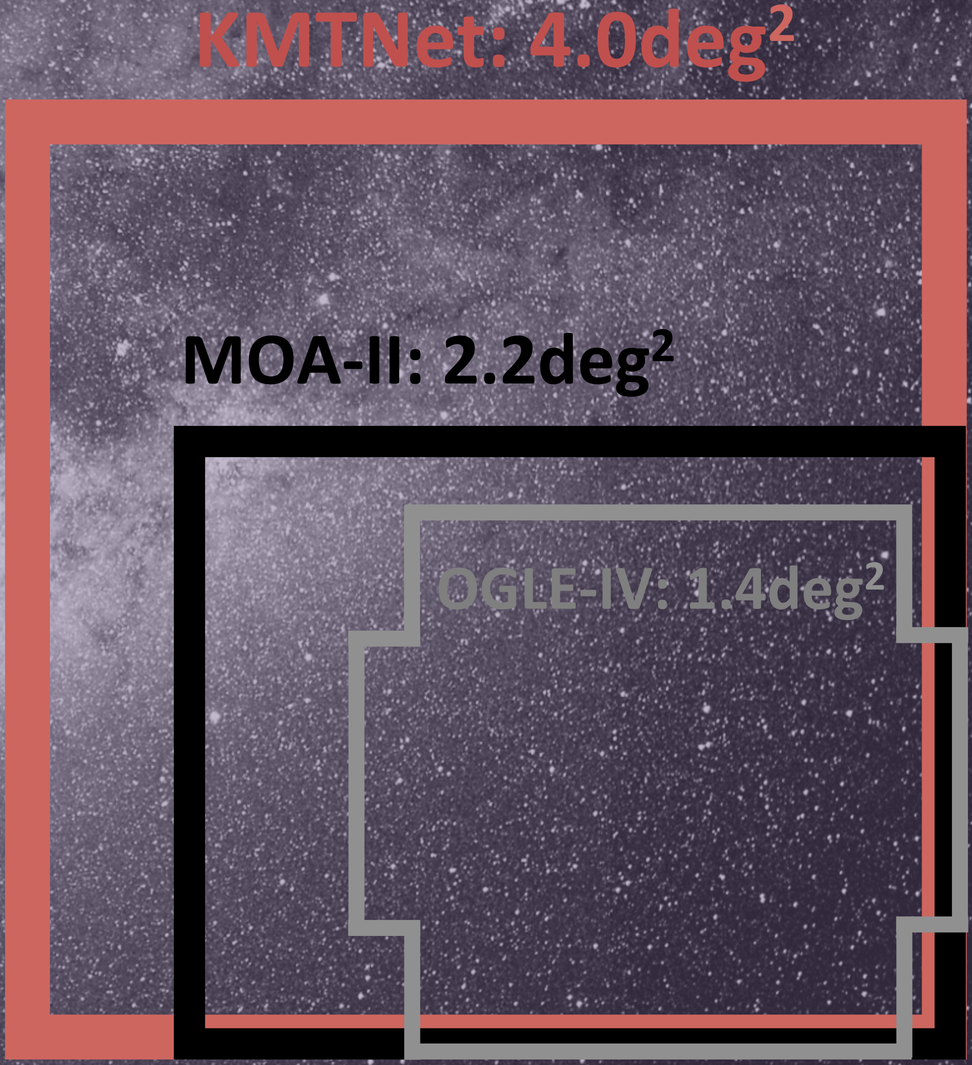
KMTNet: 1.6m

OGLE-IV: 1.3m

Wise: 1m

Microlensing Surveys: Next Generation

- ✓ Longitudinal Coverage
- ✓ Aperture
- ✓ Field of View

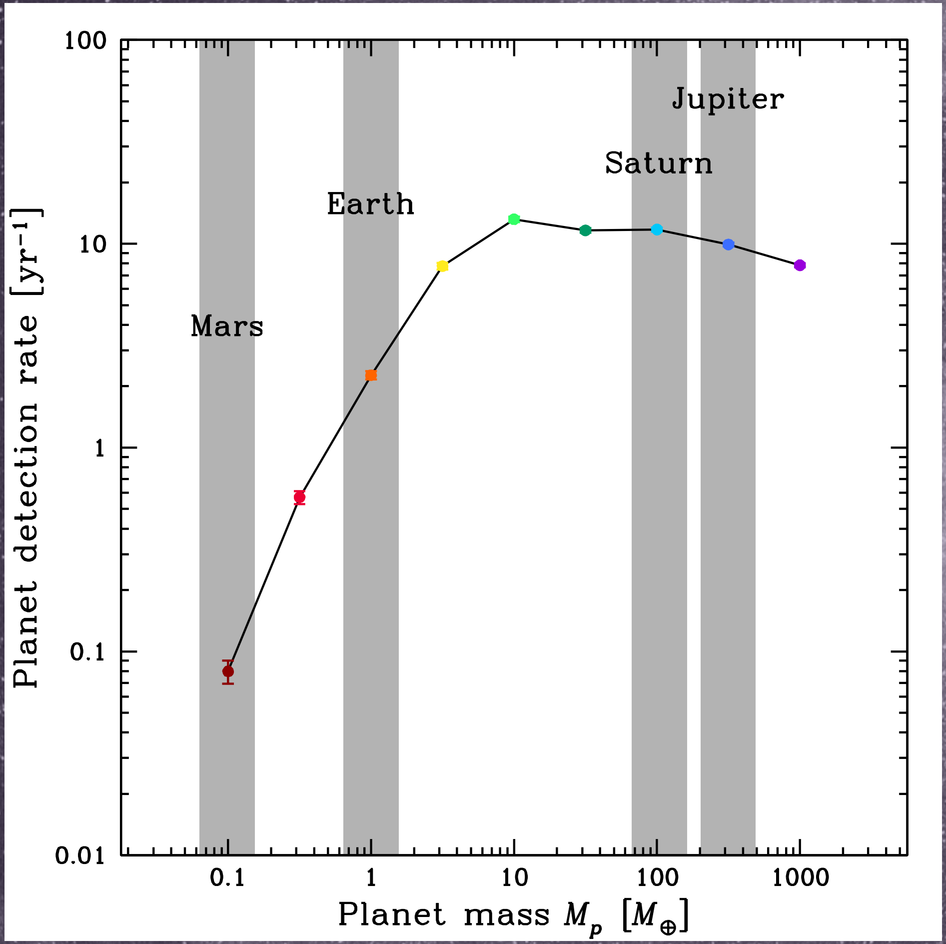


KMTNet: 4.0deg^2

MOA-II: 2.2deg^2

OGLE-IV: 1.4deg^2

Microlensing Surveys: Next Generation



Yours truly+ (2014) ApJ, 794, 52

Modified version of cool-planet mass function of Cassan+ (2012)

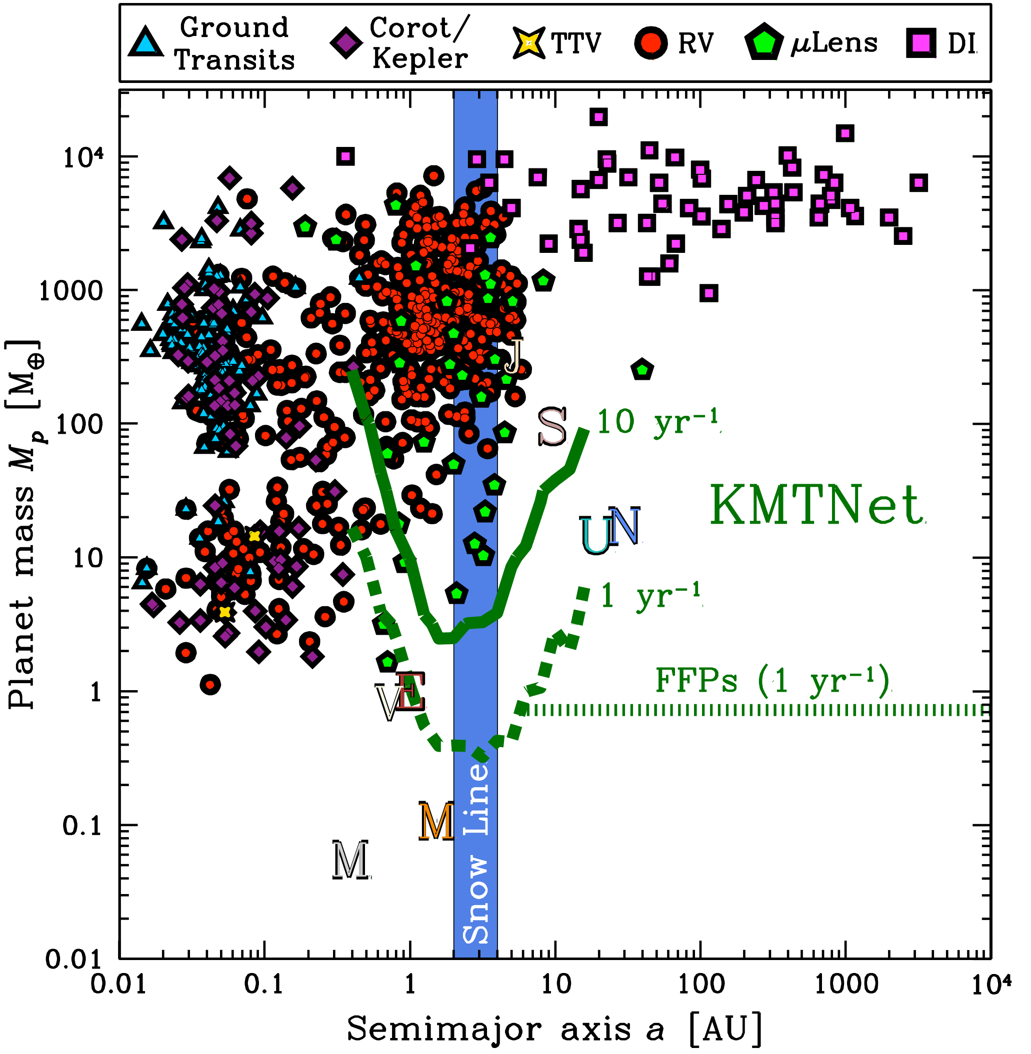
$M_p > 5\ M_{\mathrm{Earth}}$:

~20 planets/year
per dex in mass

$0.1M_{\mathrm{Earth}} < M_p < 5M_{\mathrm{Earth}}$:

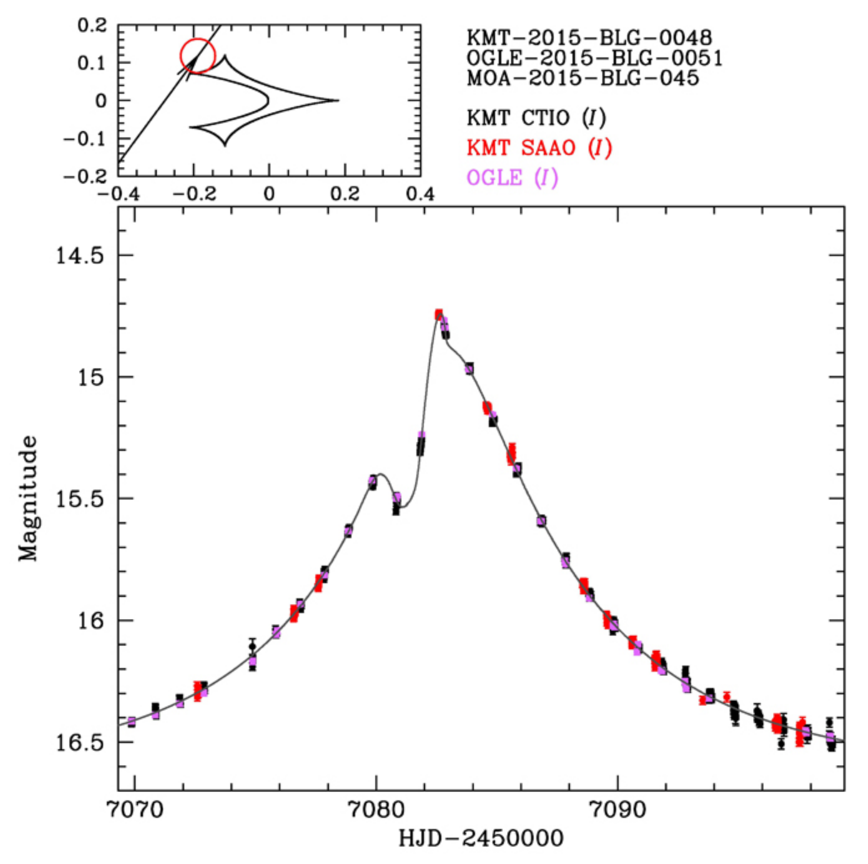
~10 planets/year

Microlensing Surveys: Next Generation



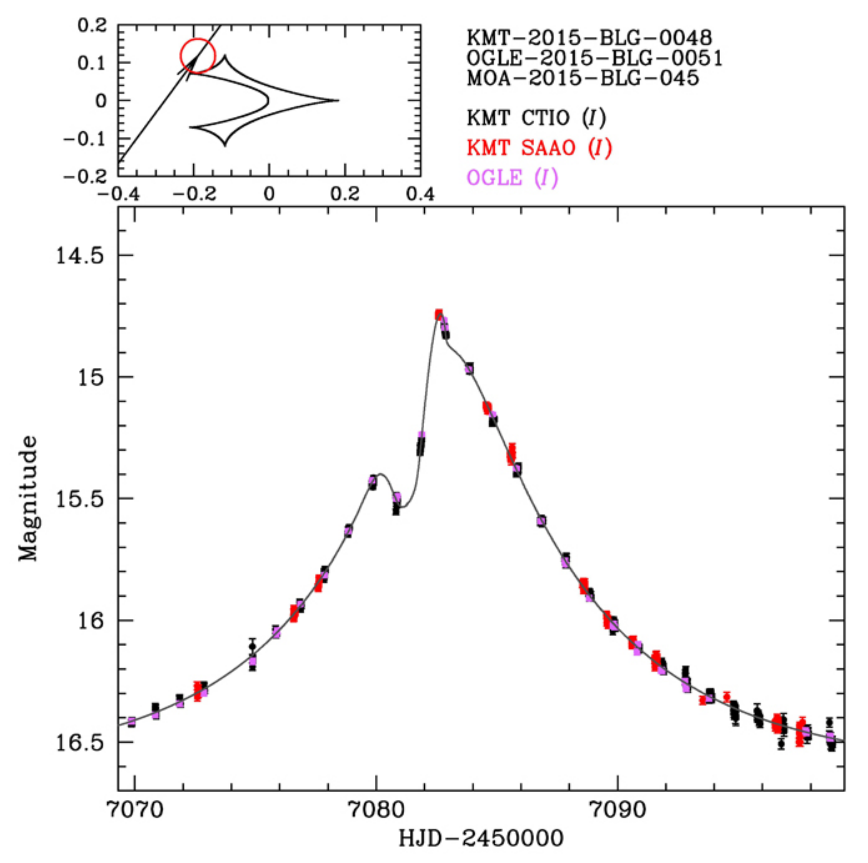
Yours truly+ (2014) ApJ, 794, 52

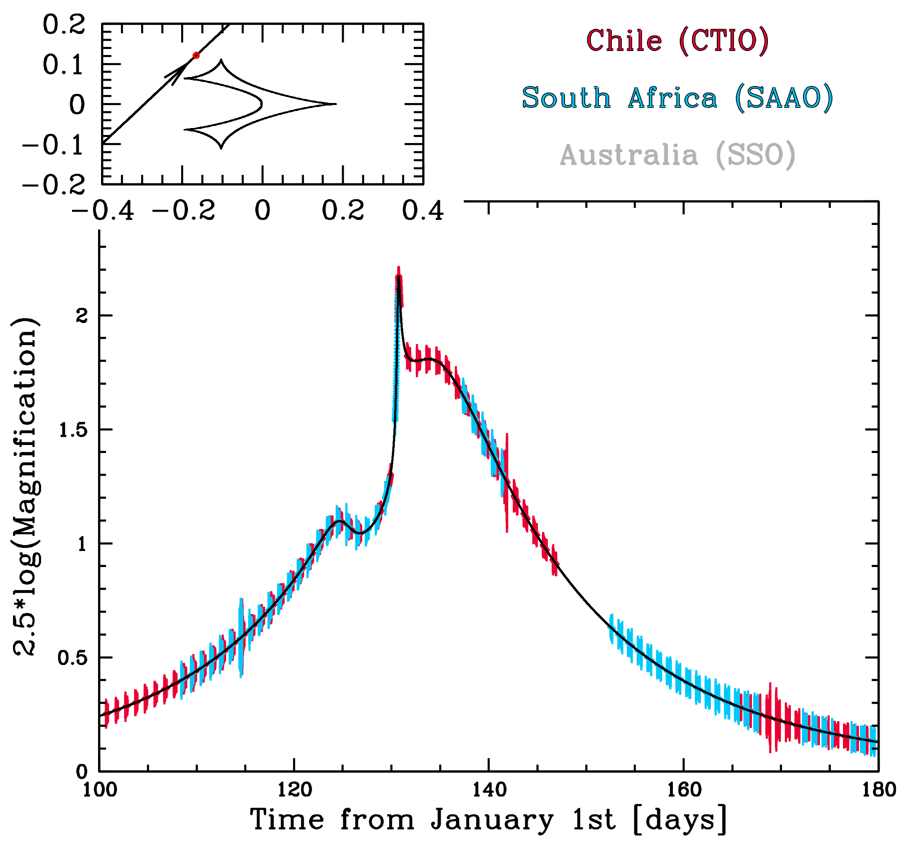
Microlensing Surveys: Next Generation



Hwang+ (2015)

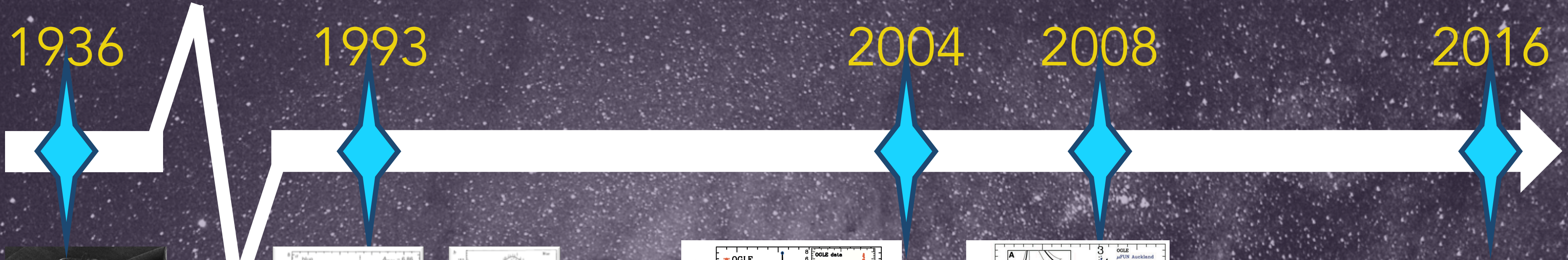
Microlensing Surveys: Next Generation

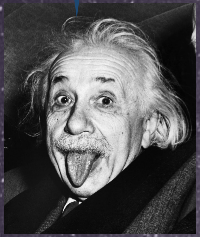




Hwang+ (2015)

Microlensing Surveys: Next Generation





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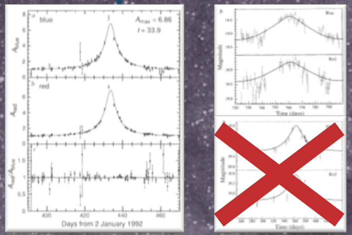

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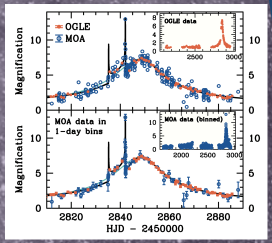
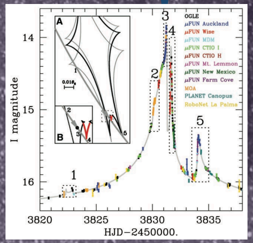


First Planet!



First two-planet system!

41 planets!!

Surveys

EROS

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Wise

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