Extrasolar planets with gravitational microlensing

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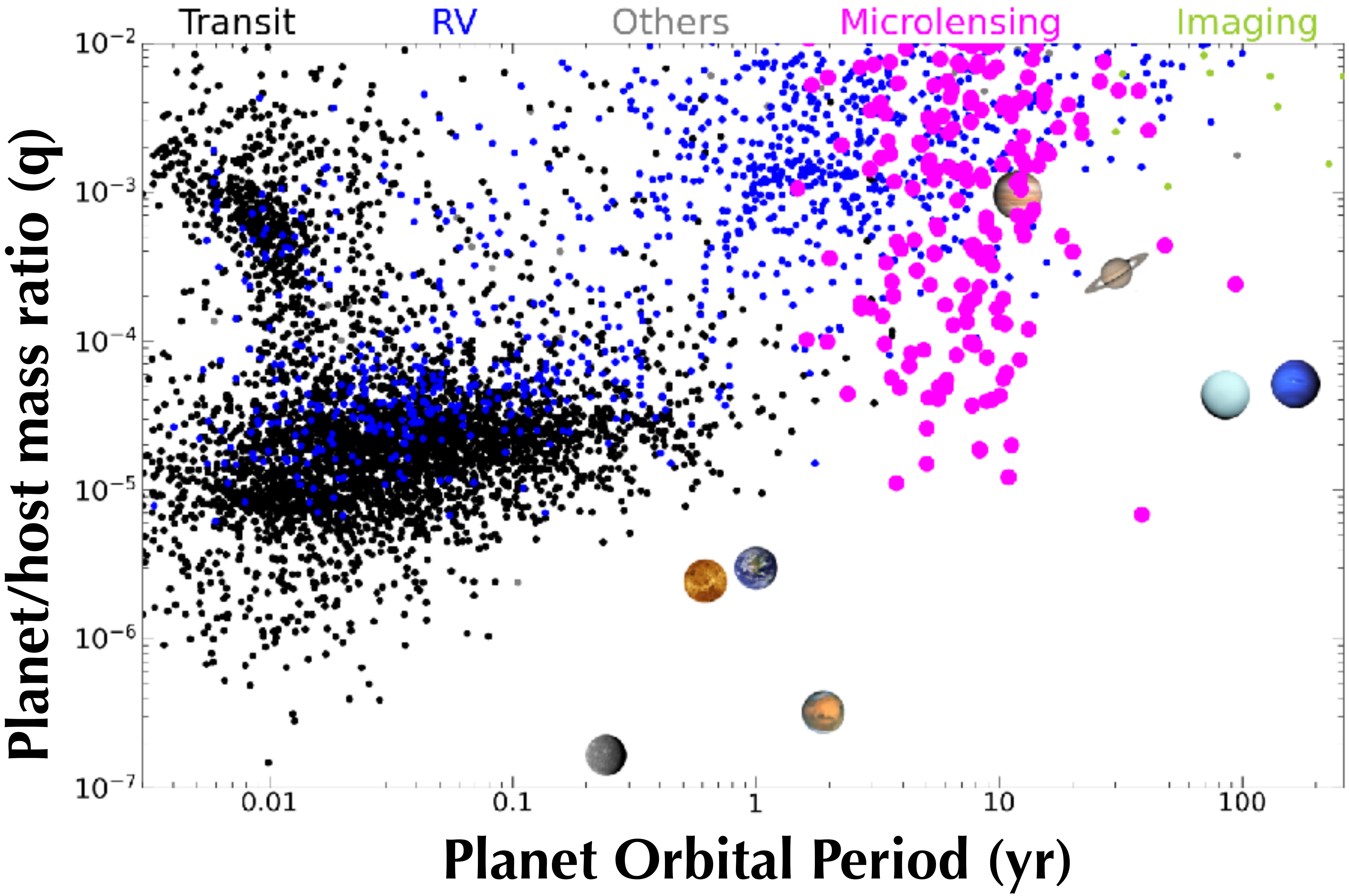
Hongjing Yang, Renkun Kuang, Jiyuan Zhang, Qiyue Qian (**Tsinghua**)
Chung-Uk Lee, Andy Gould, Jennifer Yee (**KMTNet**)

Exoplanet discovery space

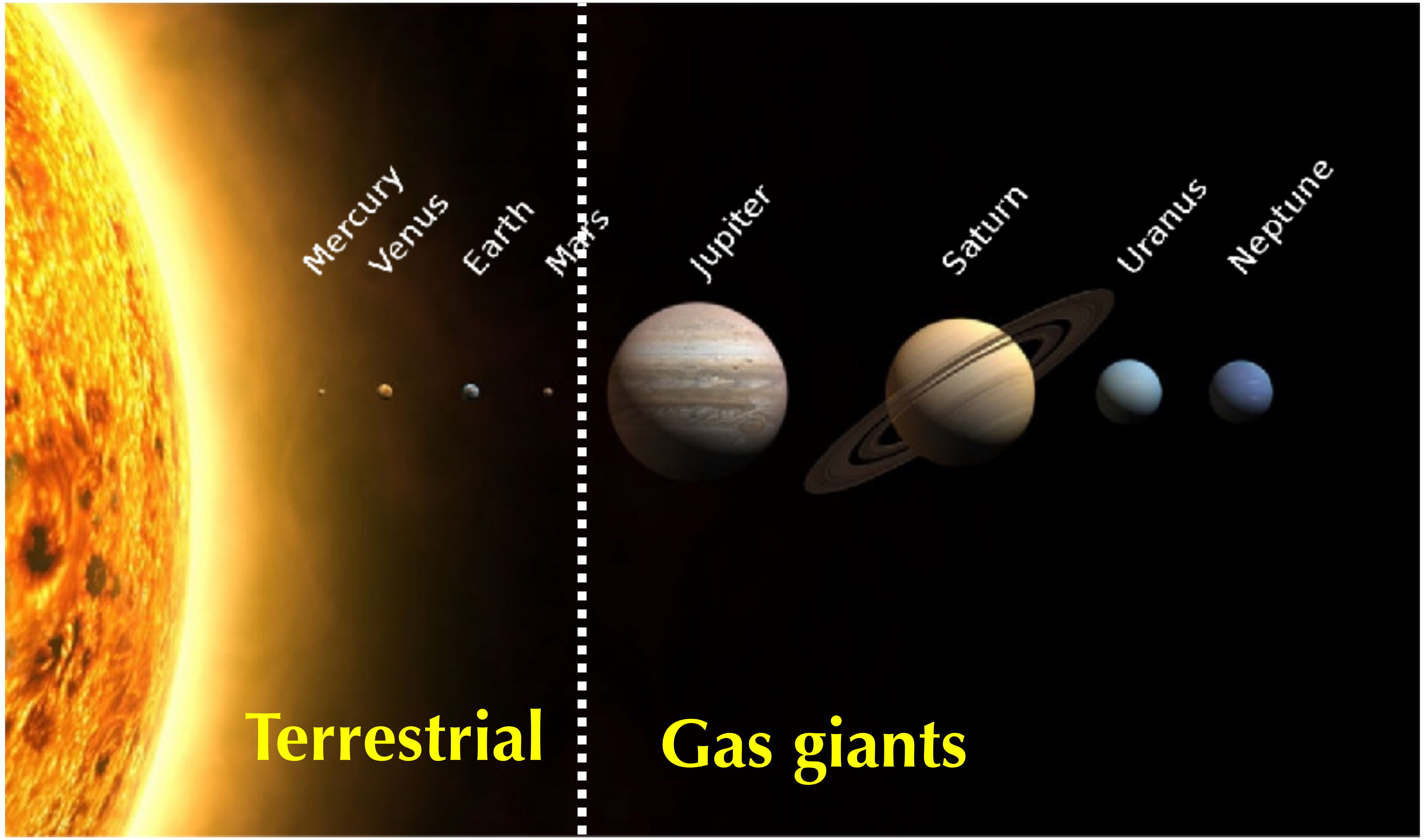


Total confirm planets:
>5000

Microlensing planets:
~200

Credit: NASA Exoplanet Archive

Cold planets are very important!



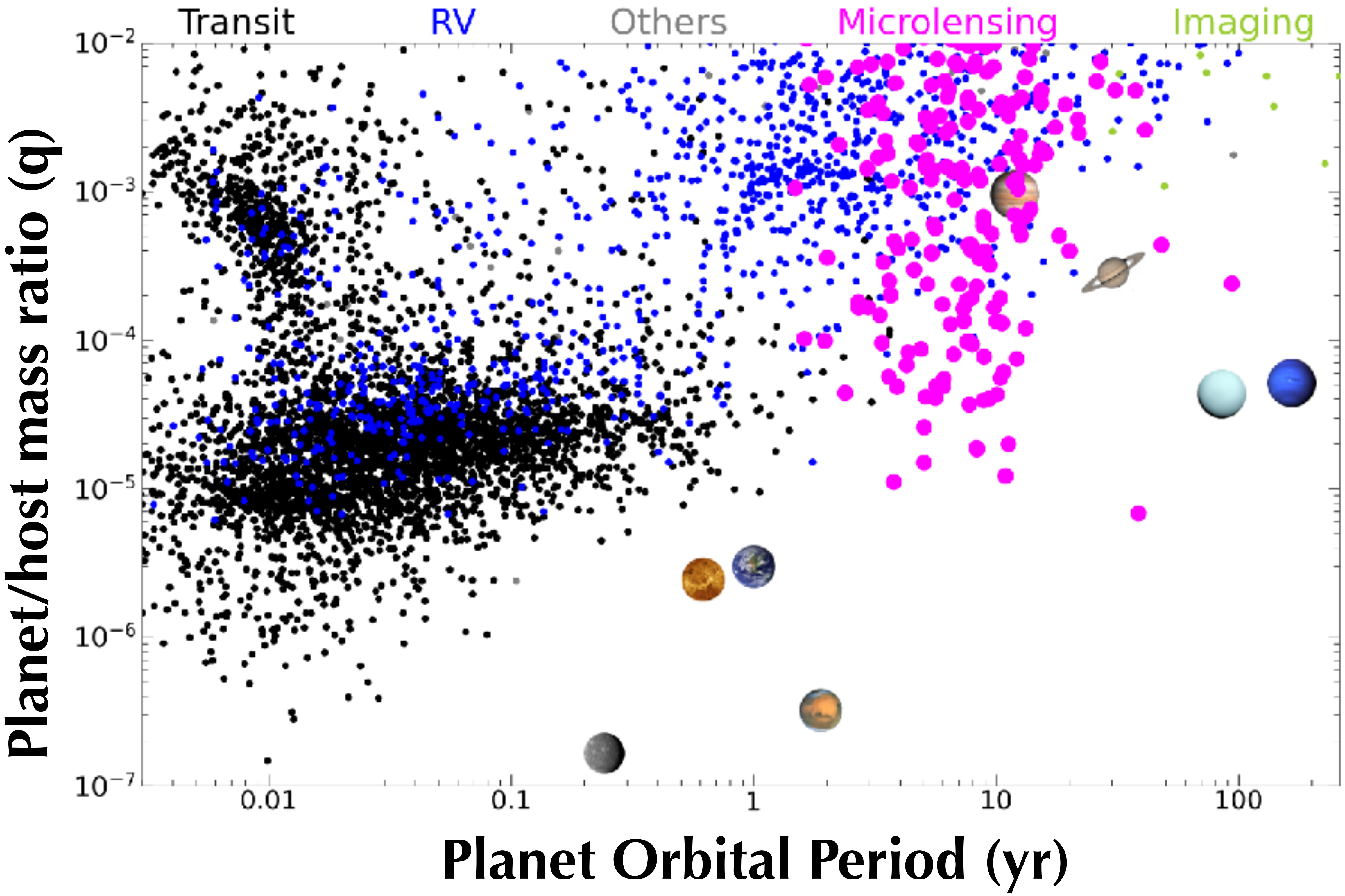
water snow line

Beyond which volatile elements turn into solid

In the solar system, they have >99% of

- planet mass
- angular momentum

Microlensing opens a unique window for cold planets

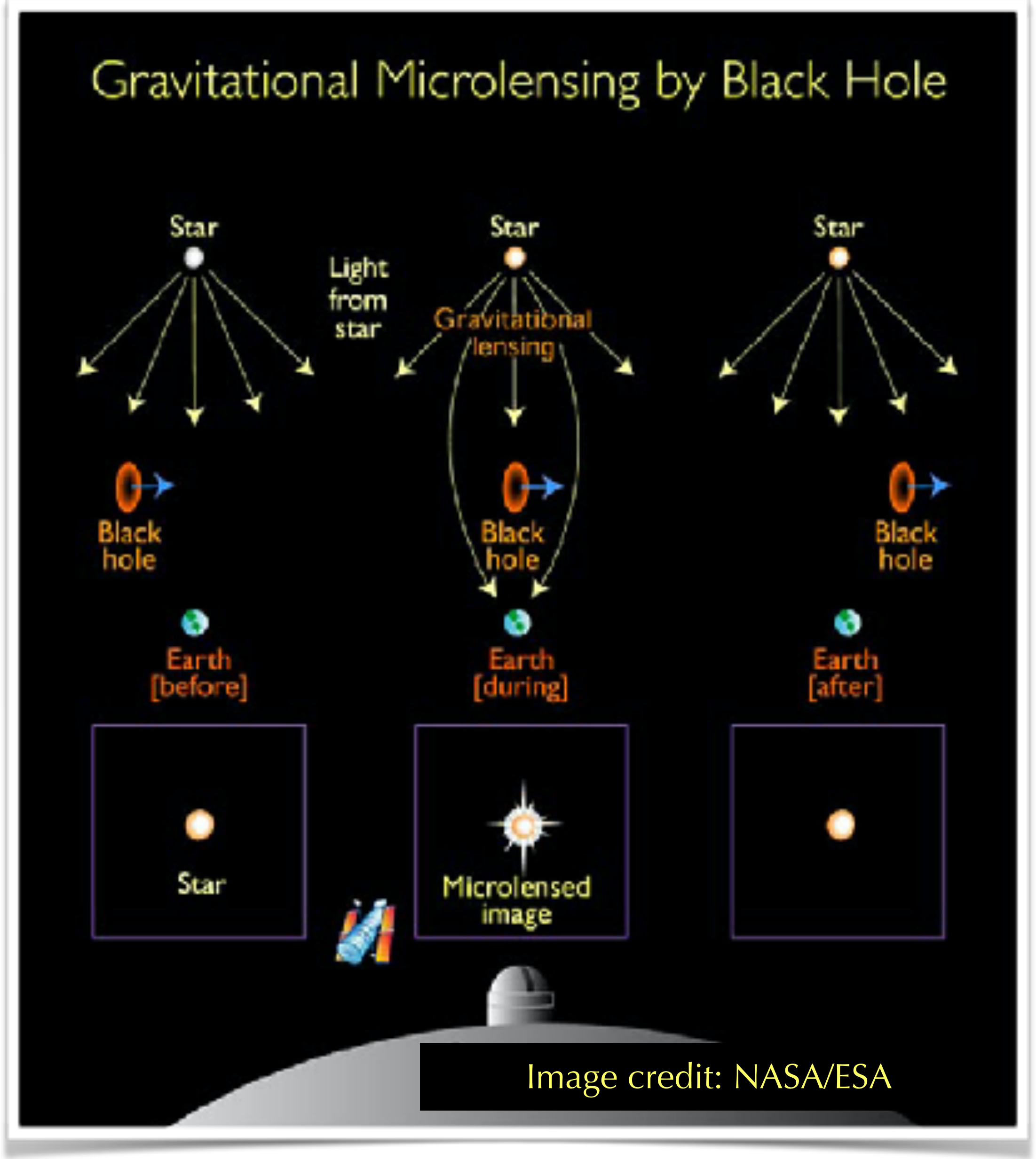


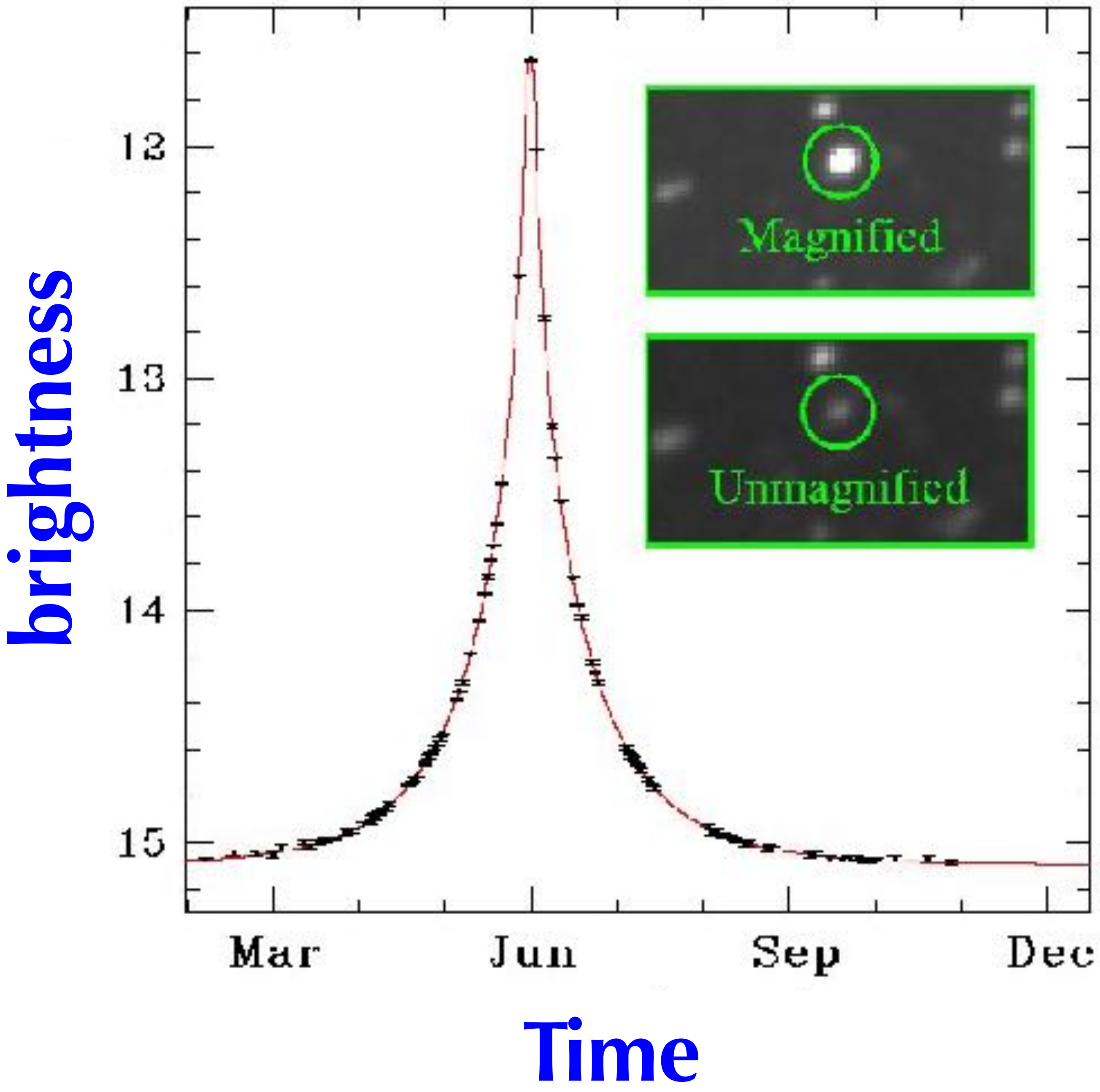
Total confirm planets:
>5000

Microlensing planets:
~200

Credit: NASA Exoplanet Archive

What is Galactic microlensing?

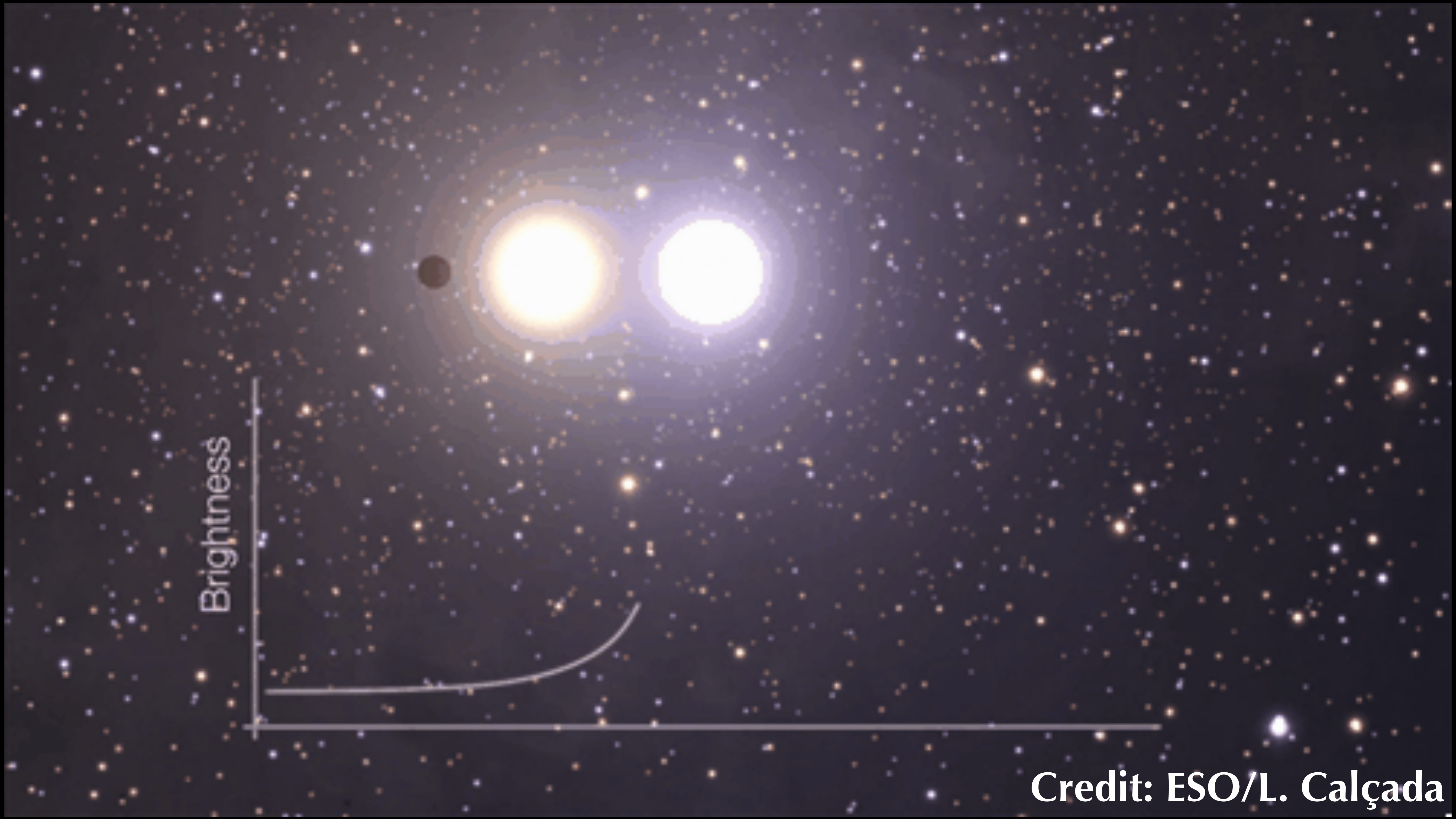




microlensing produces "symmetric", non-repeating & achromatic light curves

probability: 10^{-6}

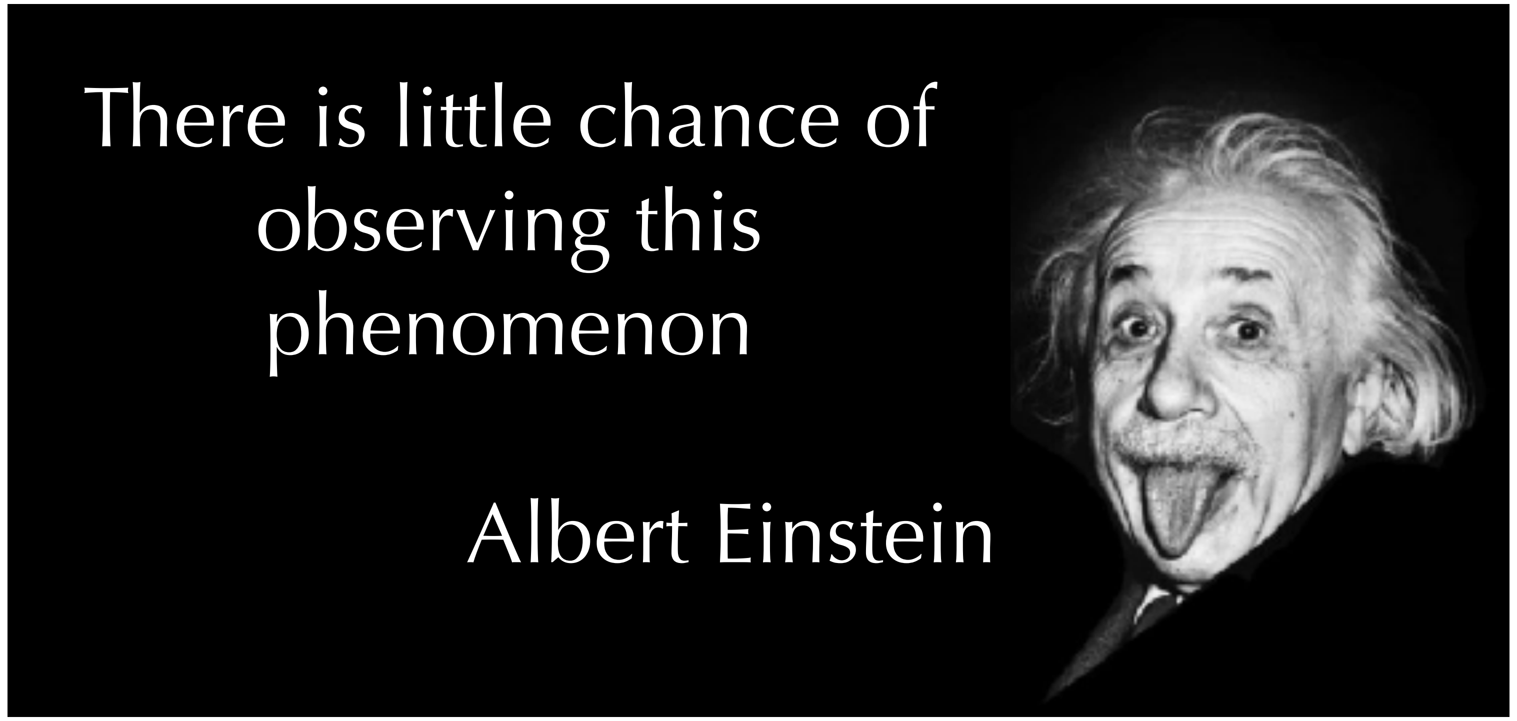
How can microlensing be used to detect planets?

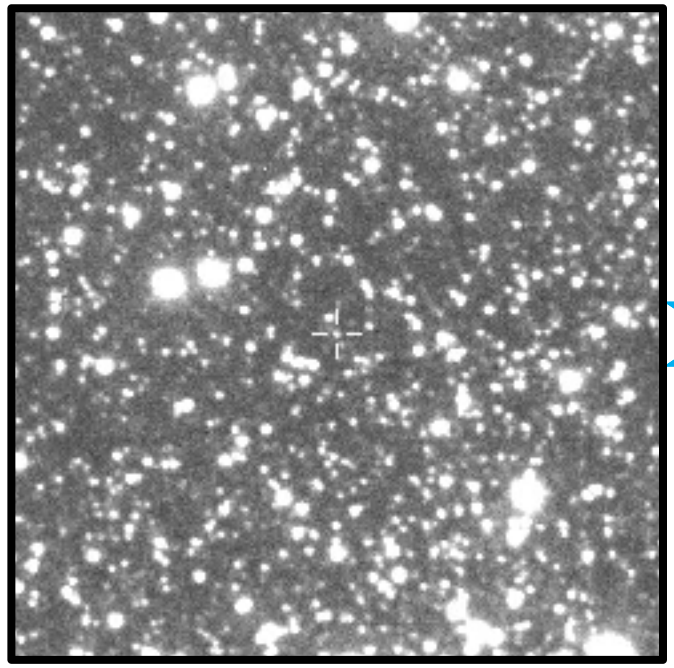


probability: 10^{-8}

Mao & Paczynski (1991)
Gould & Loeb (1992)

So in 1936 Einstein said...

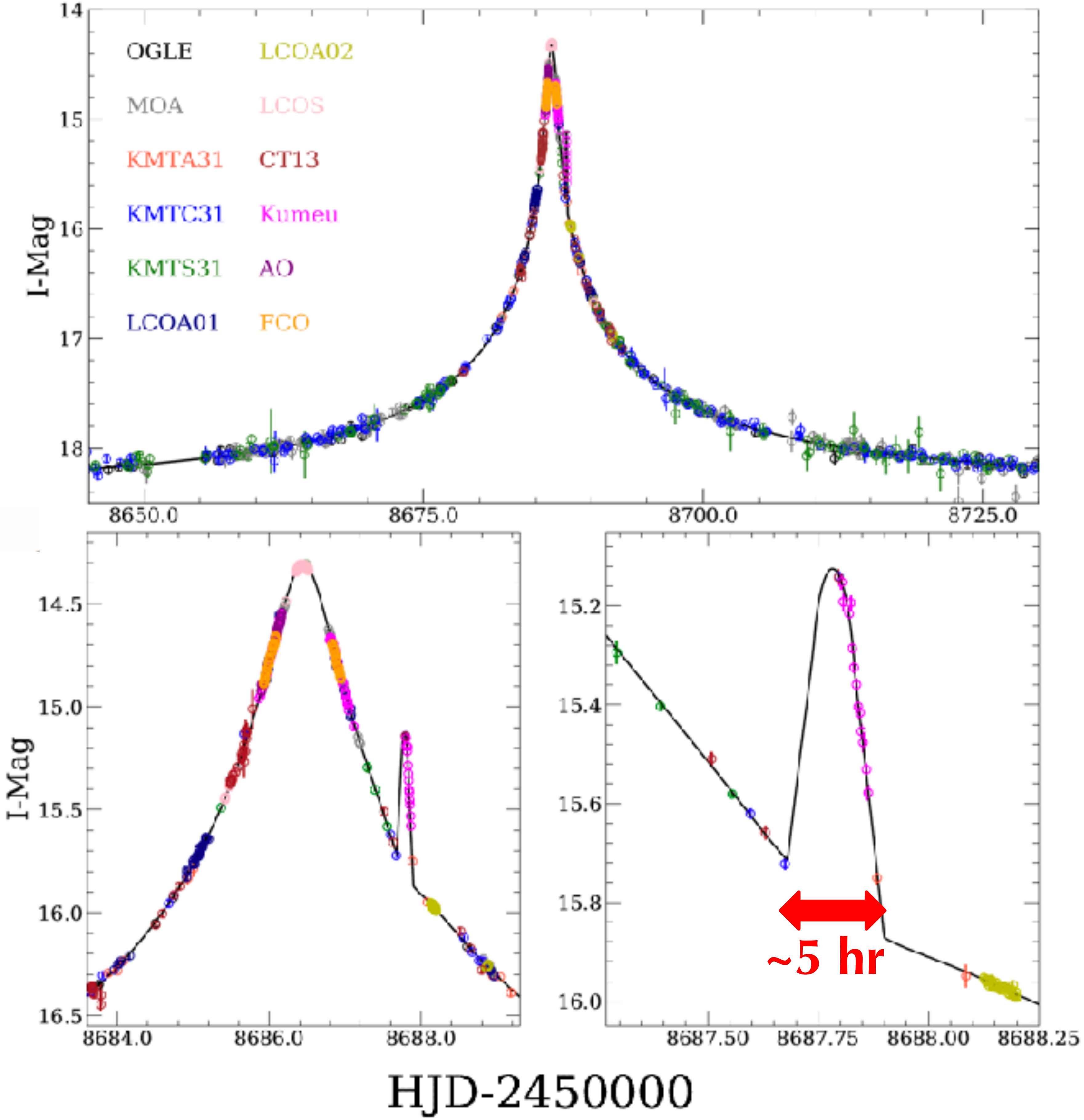




Total events
>30 000

Planets:
~200

A real example of 2 Earth mass microlensing planet



Mass ratio $q \sim 1.4 \times 10^{-5}$

Host mass = 0.5 $M_\odot$

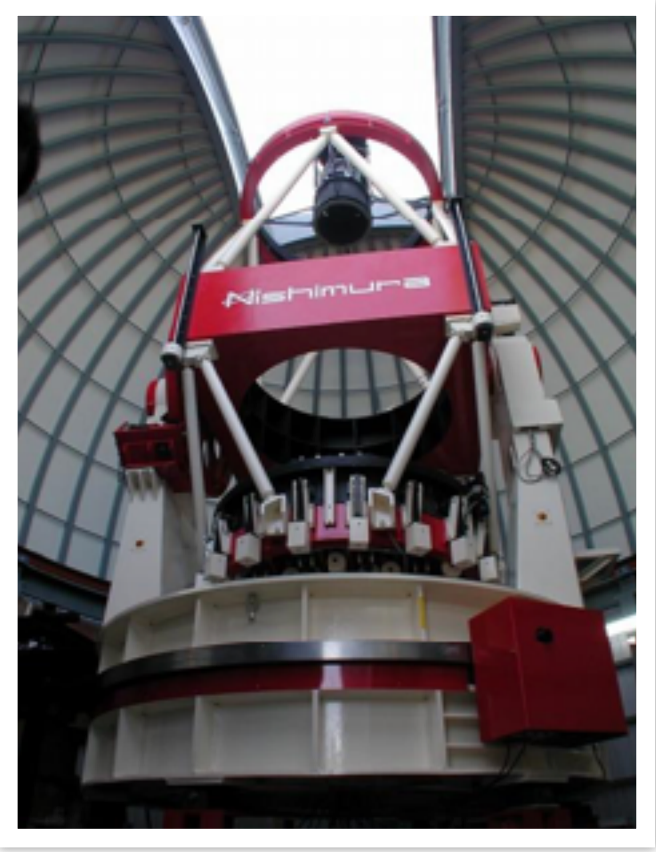
Planet mass = 2 $M_\oplus$

Yee, Zang et al. (2021)

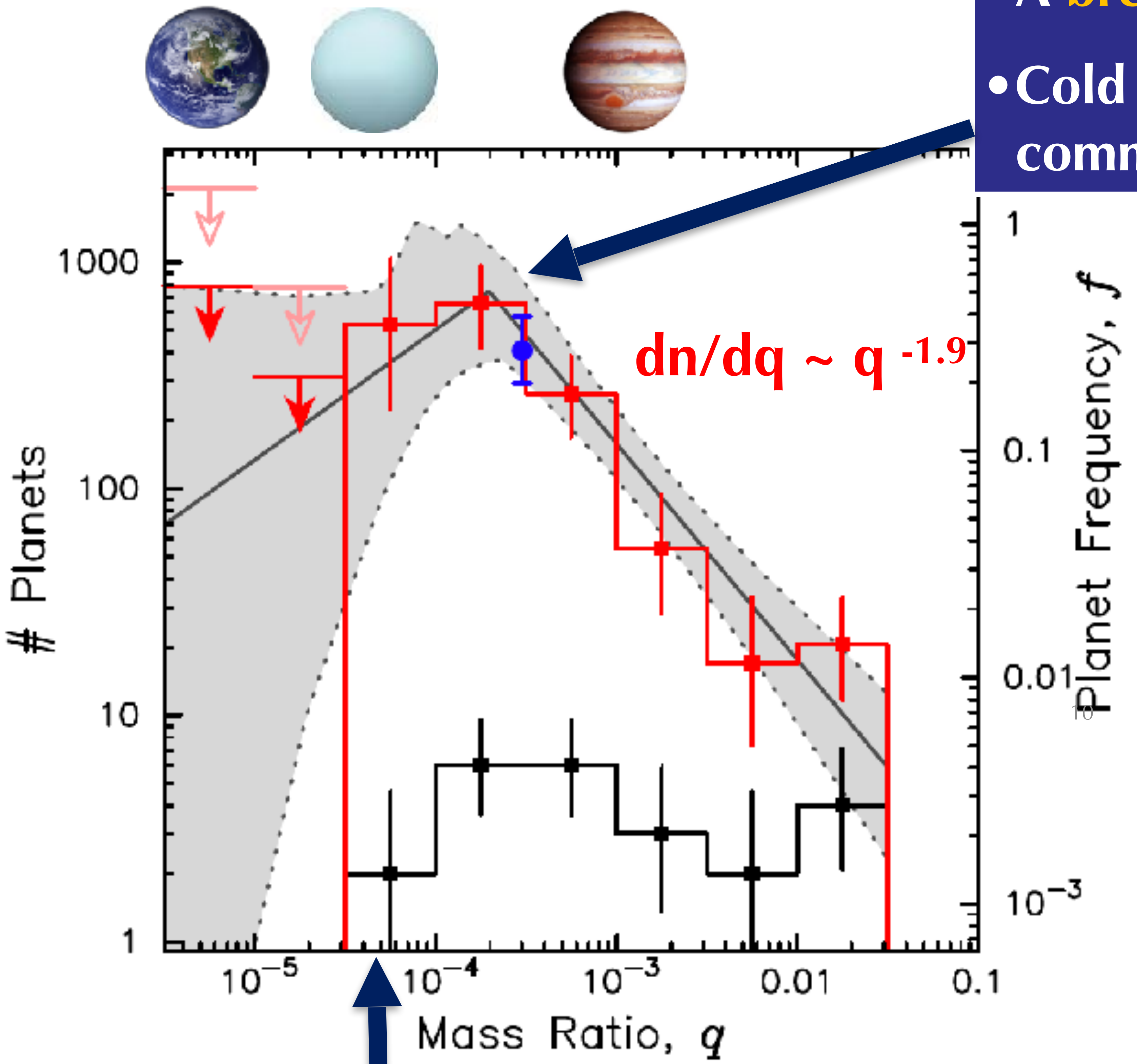
What we need to discover microlensing planets?

- **High-cadence**
- **Wide-field**
- **Bulge (dense stellar fields)**
- **Survey (+ follow-up)**

MOA-II Survey: 22 planets (6 yr, 2007-2012)



- MOA 1.8m
- FOV: 2.2 deg^2

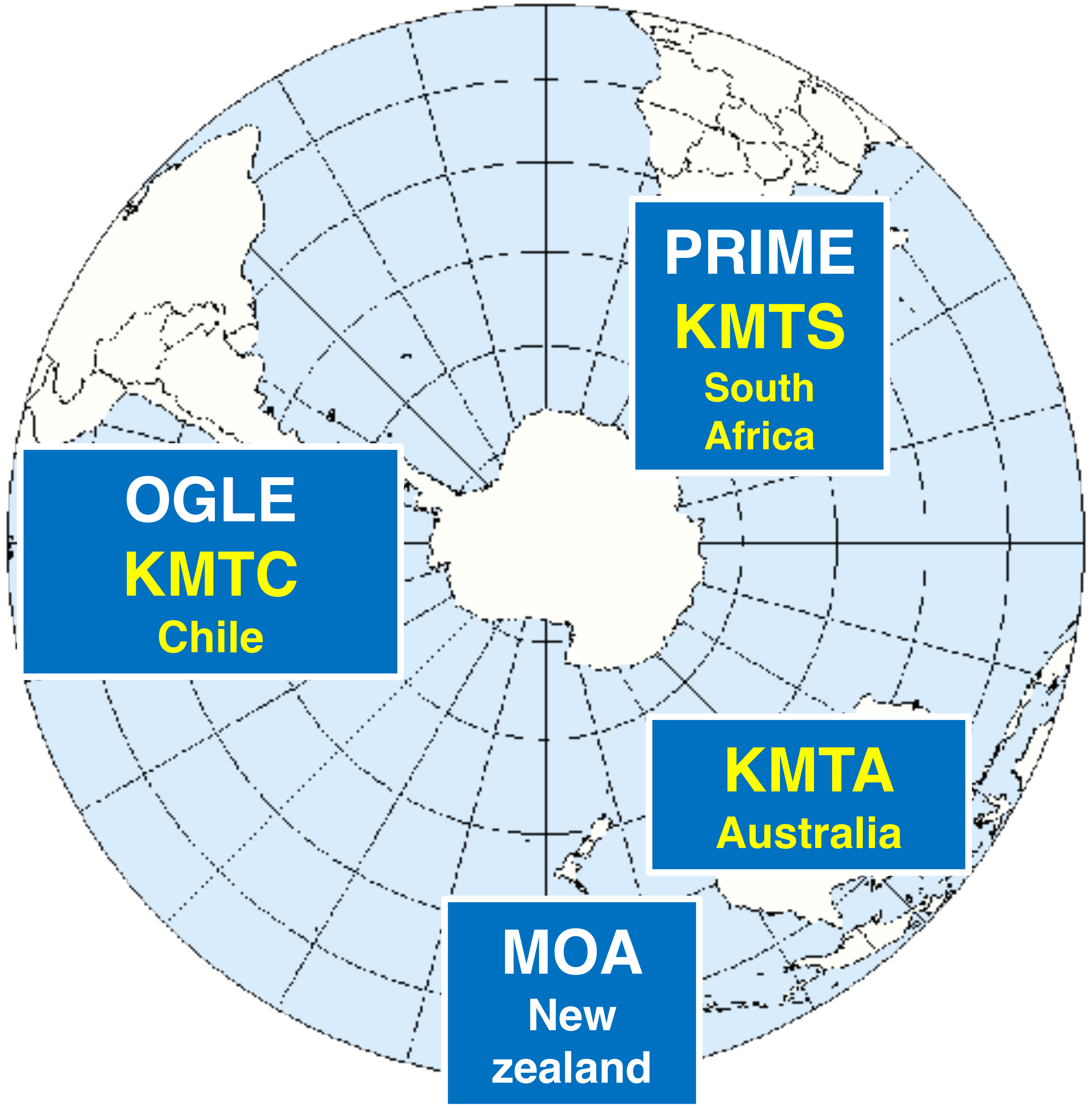


- A break at $q \sim 1.7 \times 10^{-4}$?
- Cold Neptunes are most common?

Only two $q < 10^{-4}$ planets

Suzuki et al. (2016)

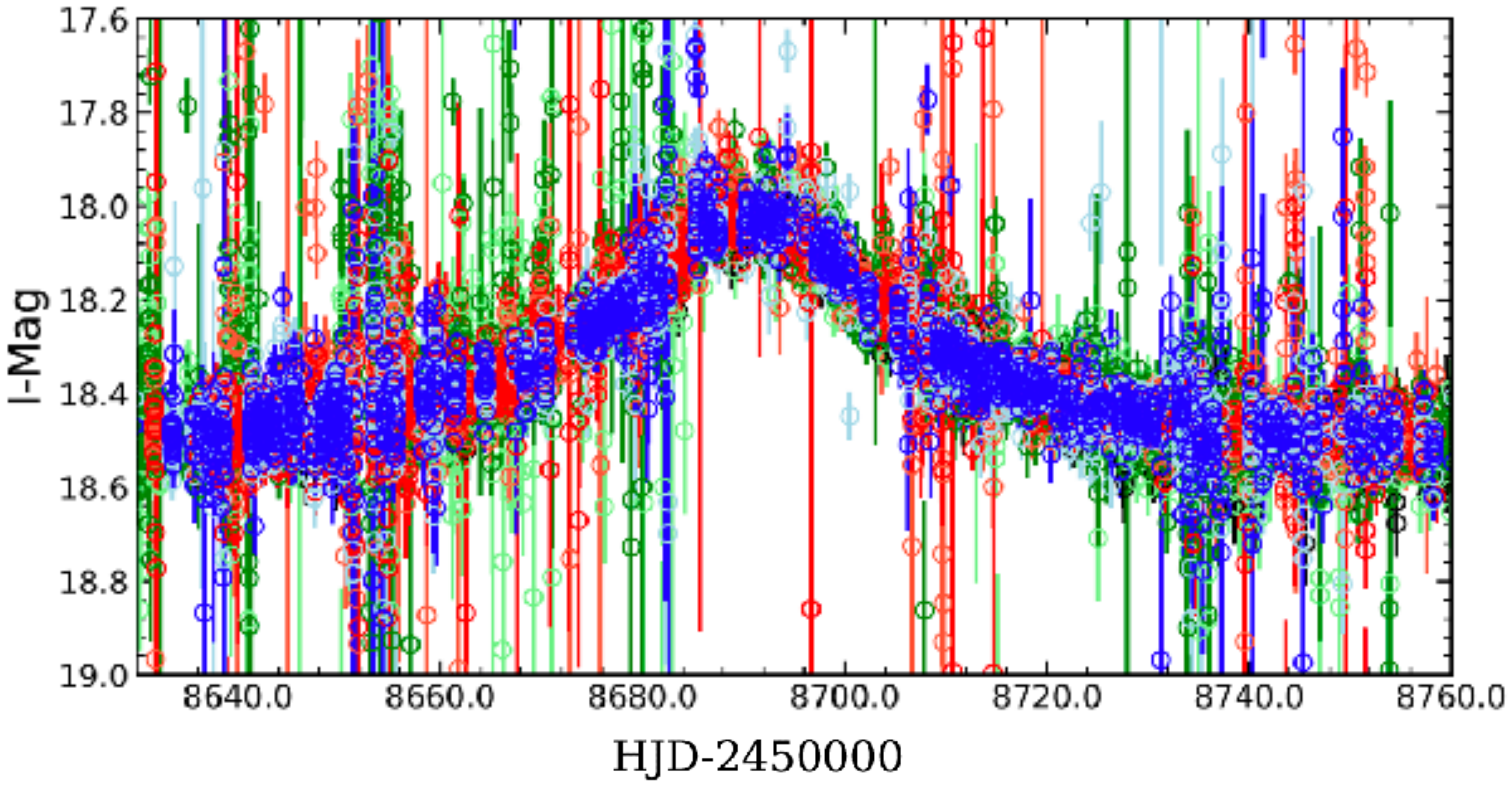
Korea Microlensing Telescope Network (KMTNet)



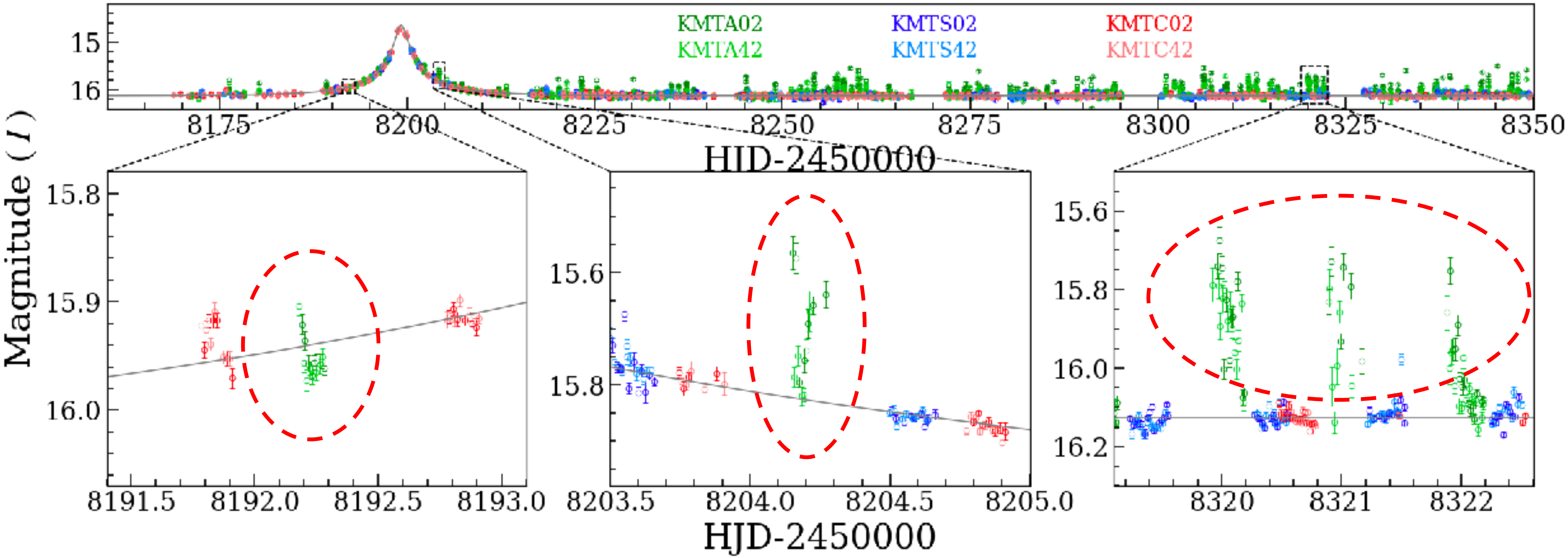
Survey	OGLE	MOA	PRIME	KMTNet
Location	Chile	New Zealand	South Africa	3 continents
Telescope number	1	1	1	3
FoV (deg^2)	1.4	2.2	1.3	4
Aperture (m)	1.3	1.8	1.8	1.6

Where is the planet signal (a bump)?

OGLE-2019-BLG-1053



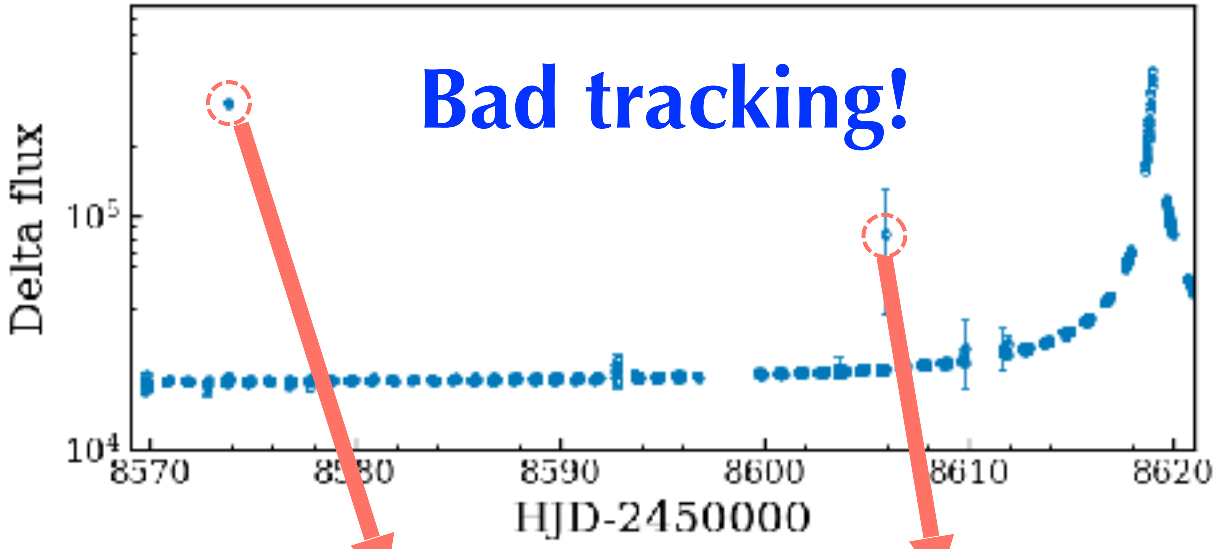
Photometry: outliers or planetary signals?

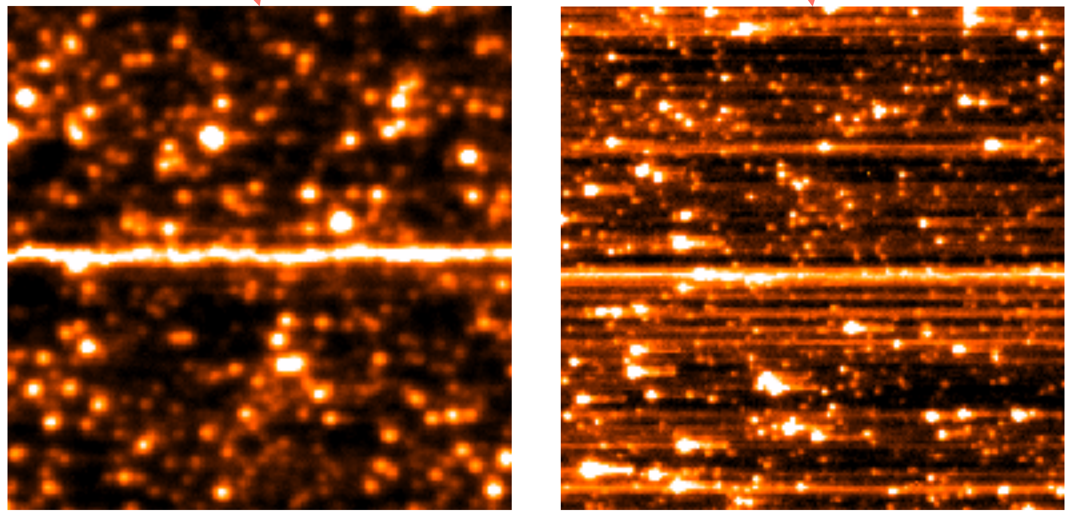


Bad weather/seeing? Full moons? Bad pixels? Satellites?
Bleeding effects of close bright stars?

Improving detection efficiency: a new pipeline

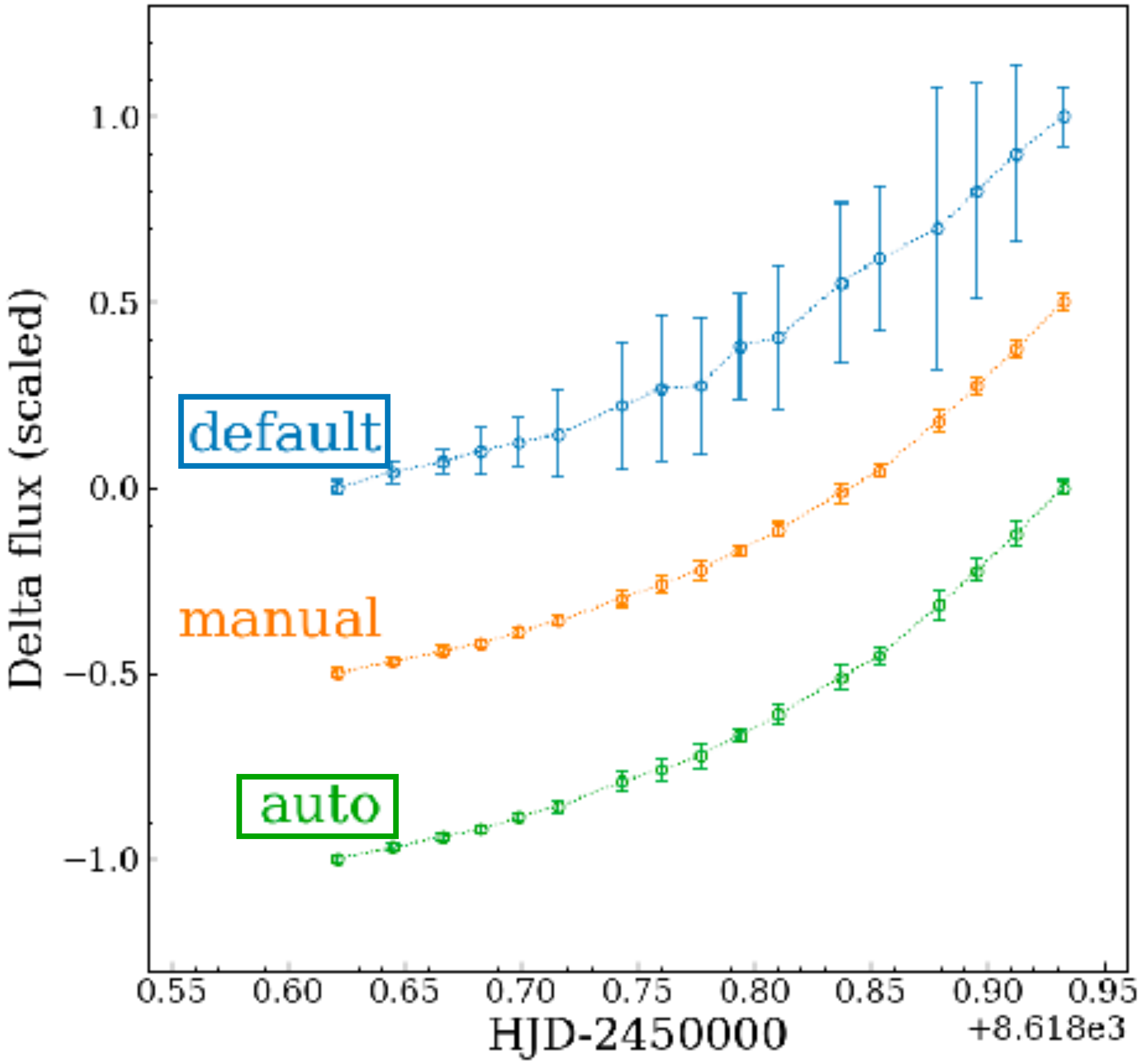
Hongjing Yang
(5th yr grad)





Add an indicator of bad images
Pick out outliers automatically

Yang et al. (2023)

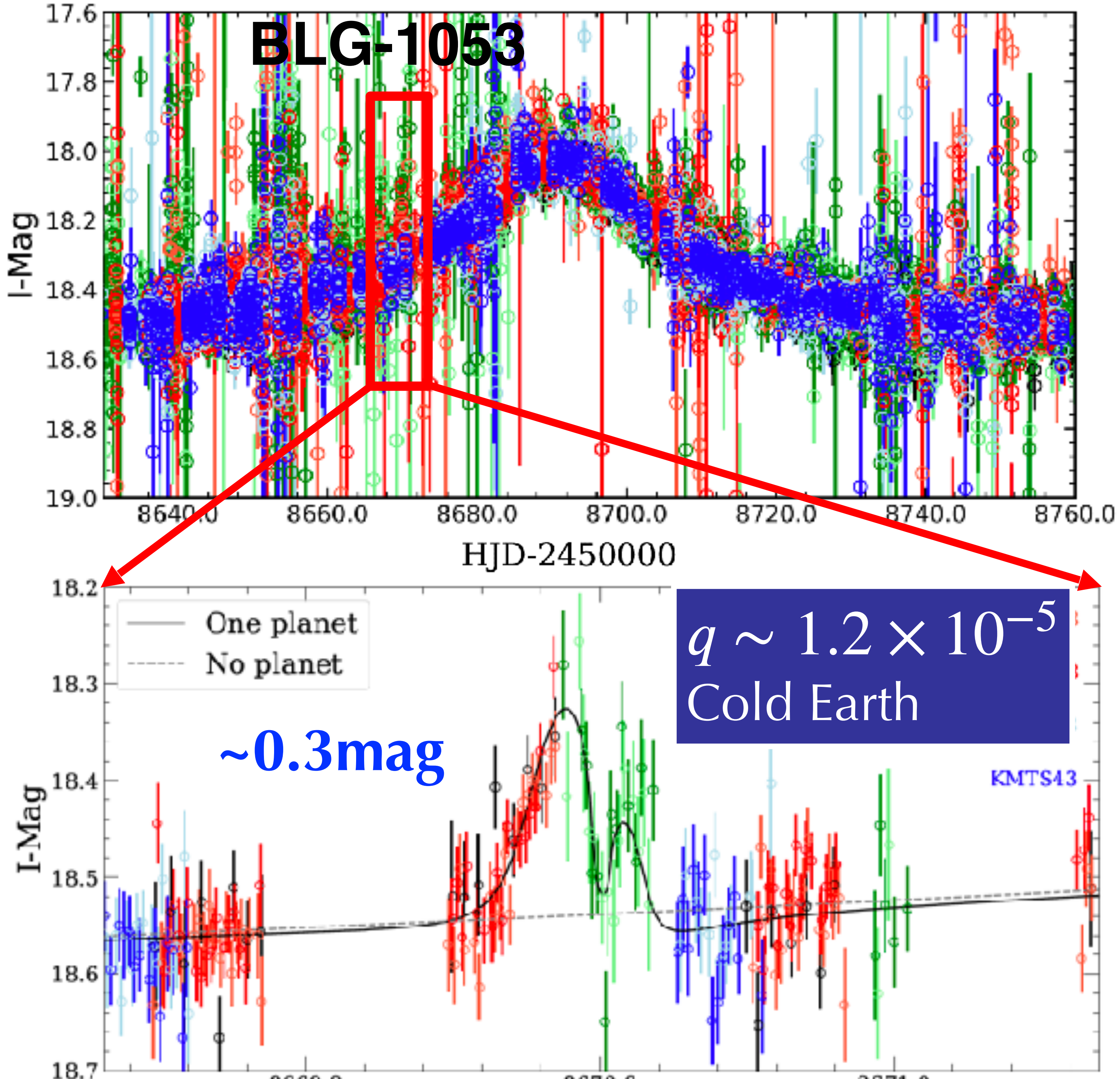


~12 hr → ~2 hr per event

Applied to ~500 events

KMTNet PlanetFinder

OGLE-2019-BLG-1053

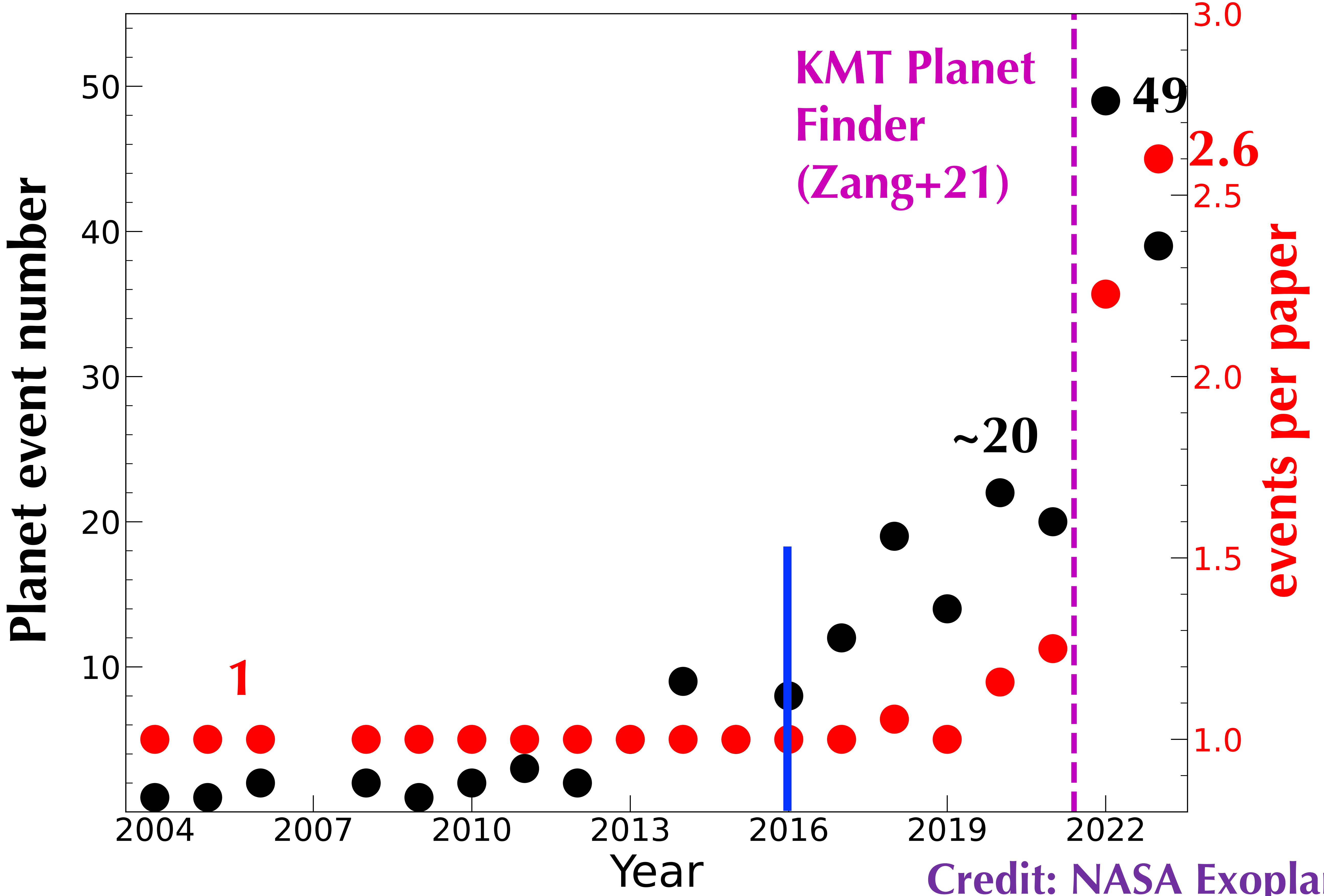


Zang et al. (2021), Zang et al. (2022)

Weicheng Zang
(CfA fellow)

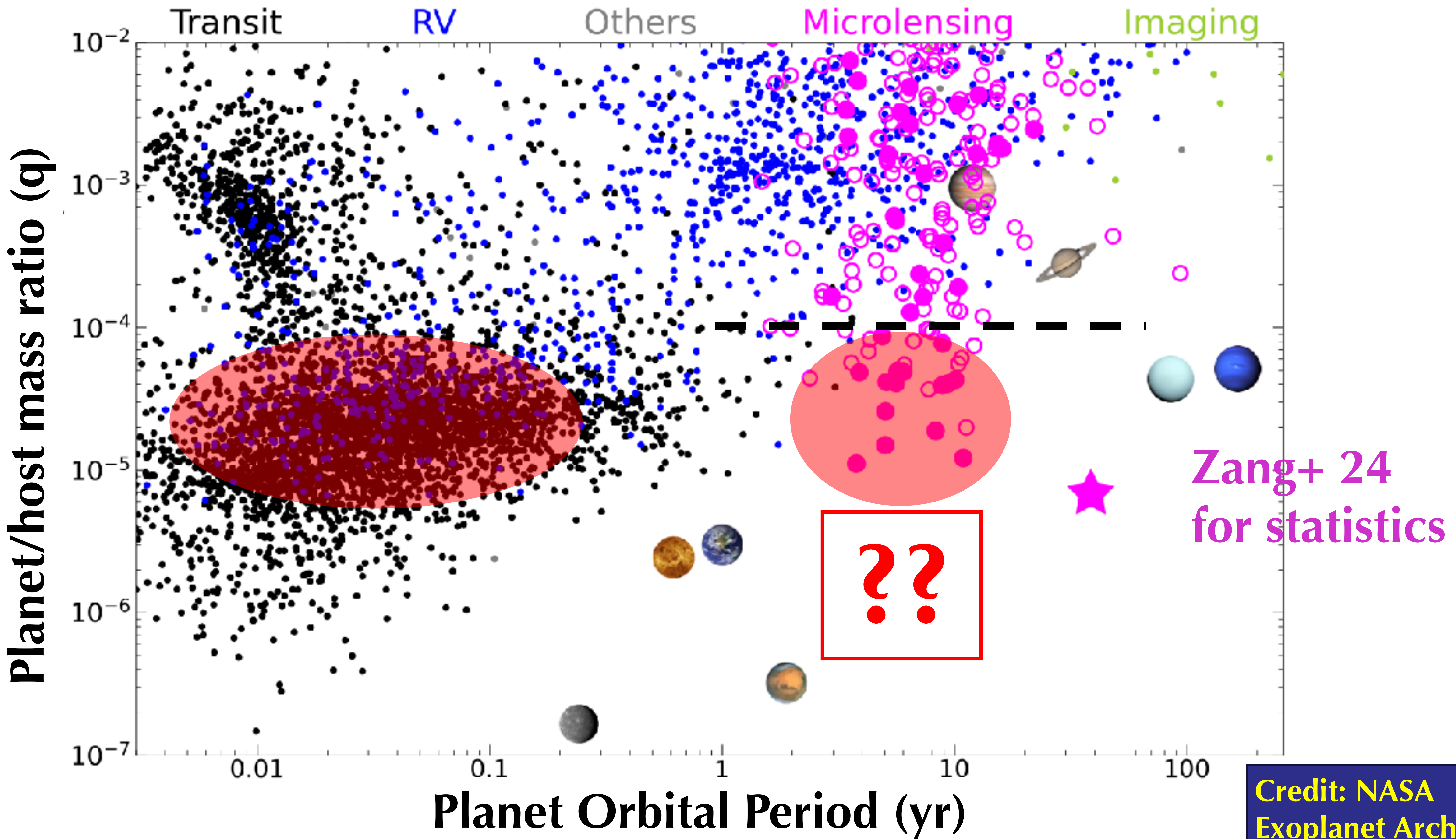
- **First semi-automated Microlensing Planet Finder**
- **One-year KMTNet: ~40 planets**

~"Mass" Production for Microlensing Planets



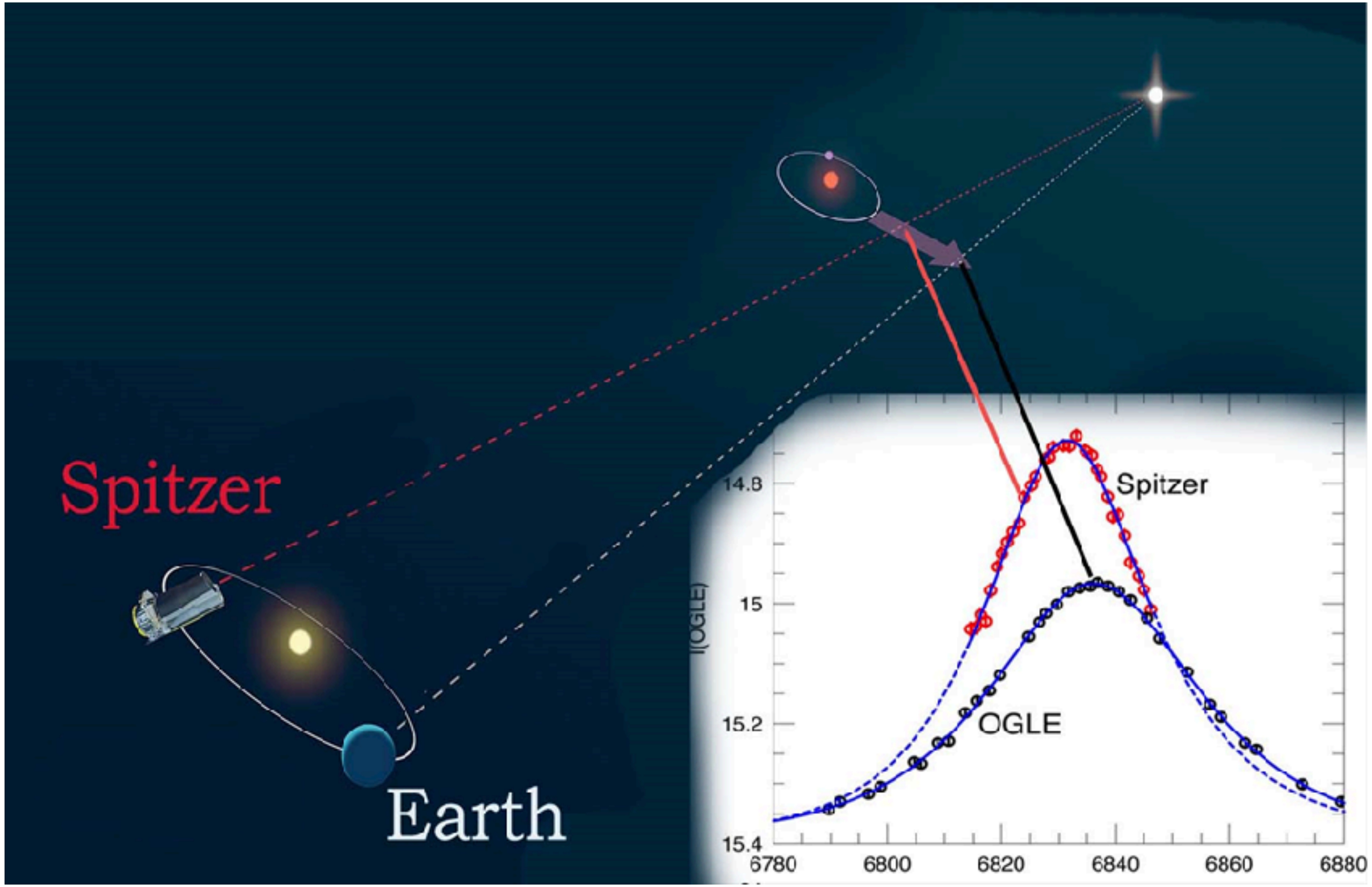
Credit: NASA Exoplanet Archive

Super Earths are Common in both Close and Wide Orbits



Credit: NASA Exoplanet Archive

Future outlook: Roman (2027+) & Earth 2.0 Satellites



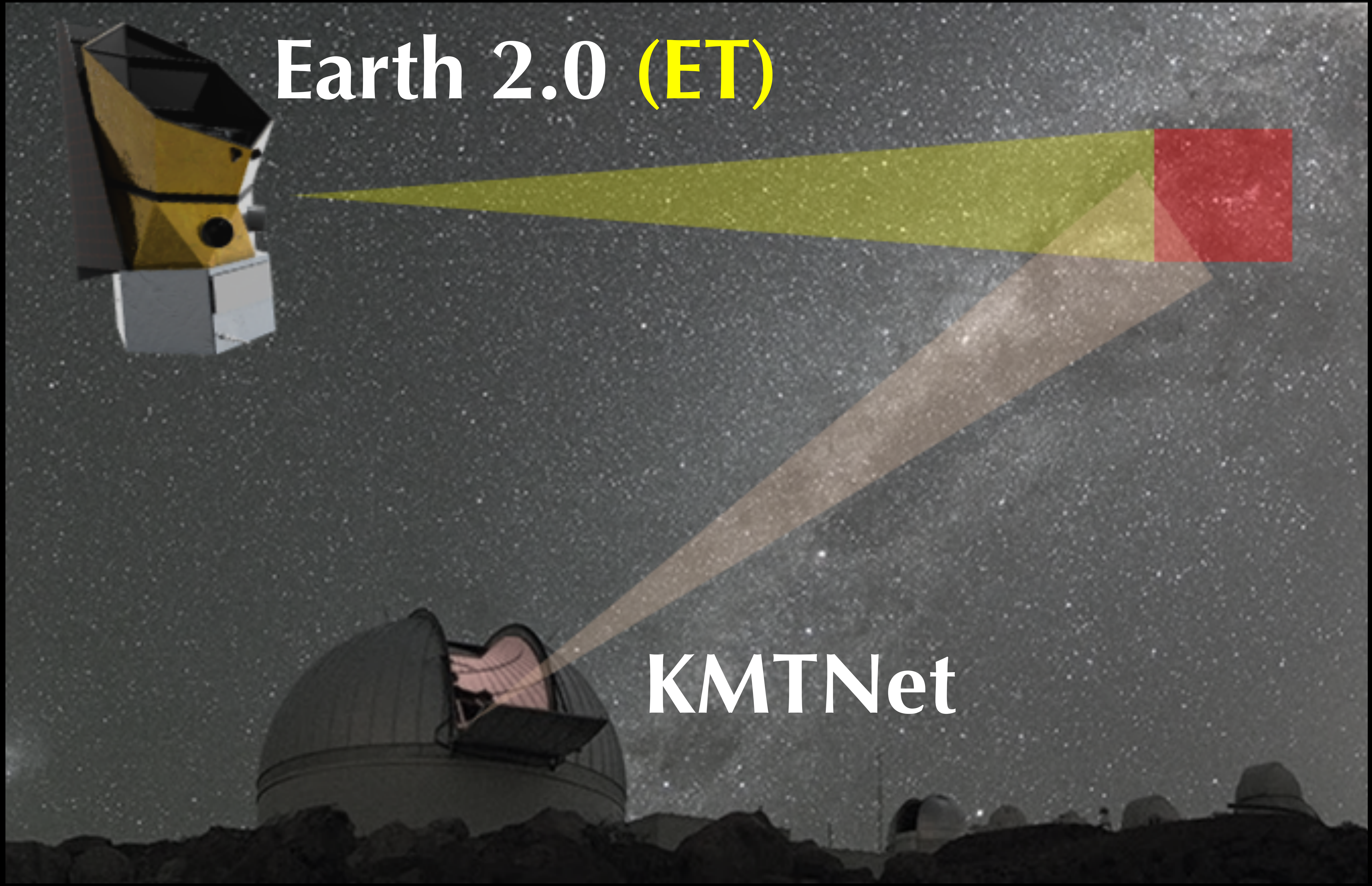
We can measure parallax to put further constraints on the lens properties.

Credit: JPL

Earth 2.0 (~2027, L2, PI: Jian Ge/SHAO)

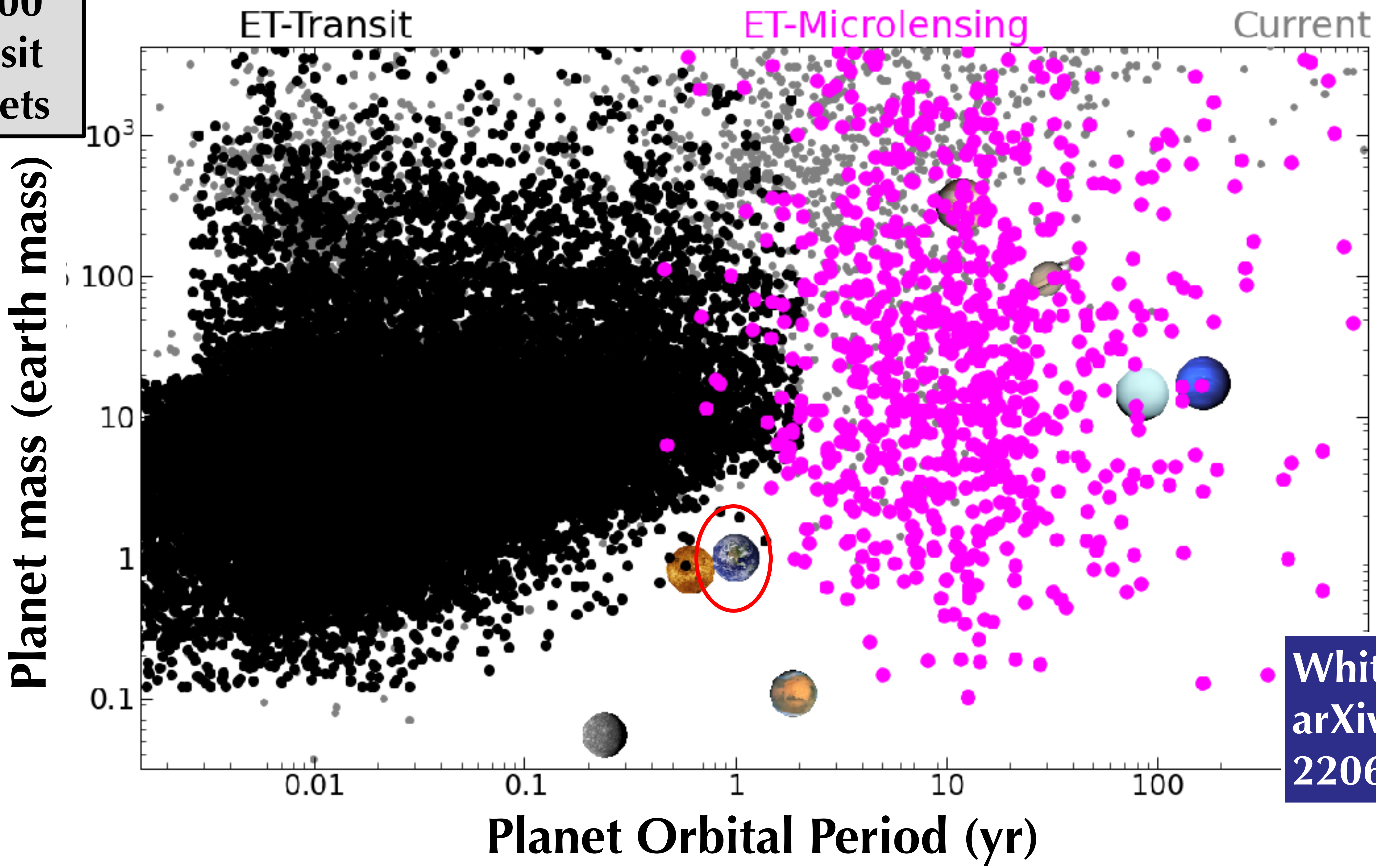
Microlensing co-PIs:
Weicheng Zang
Shude Mao

One telescope:
- 35cm, 4 sq. deg.
- Co-observing with KMTNet
- L2 (0.01 AU)
- ~300 planets with mass



Earth 2.0: Transit + Microlensing ~ All Orbits

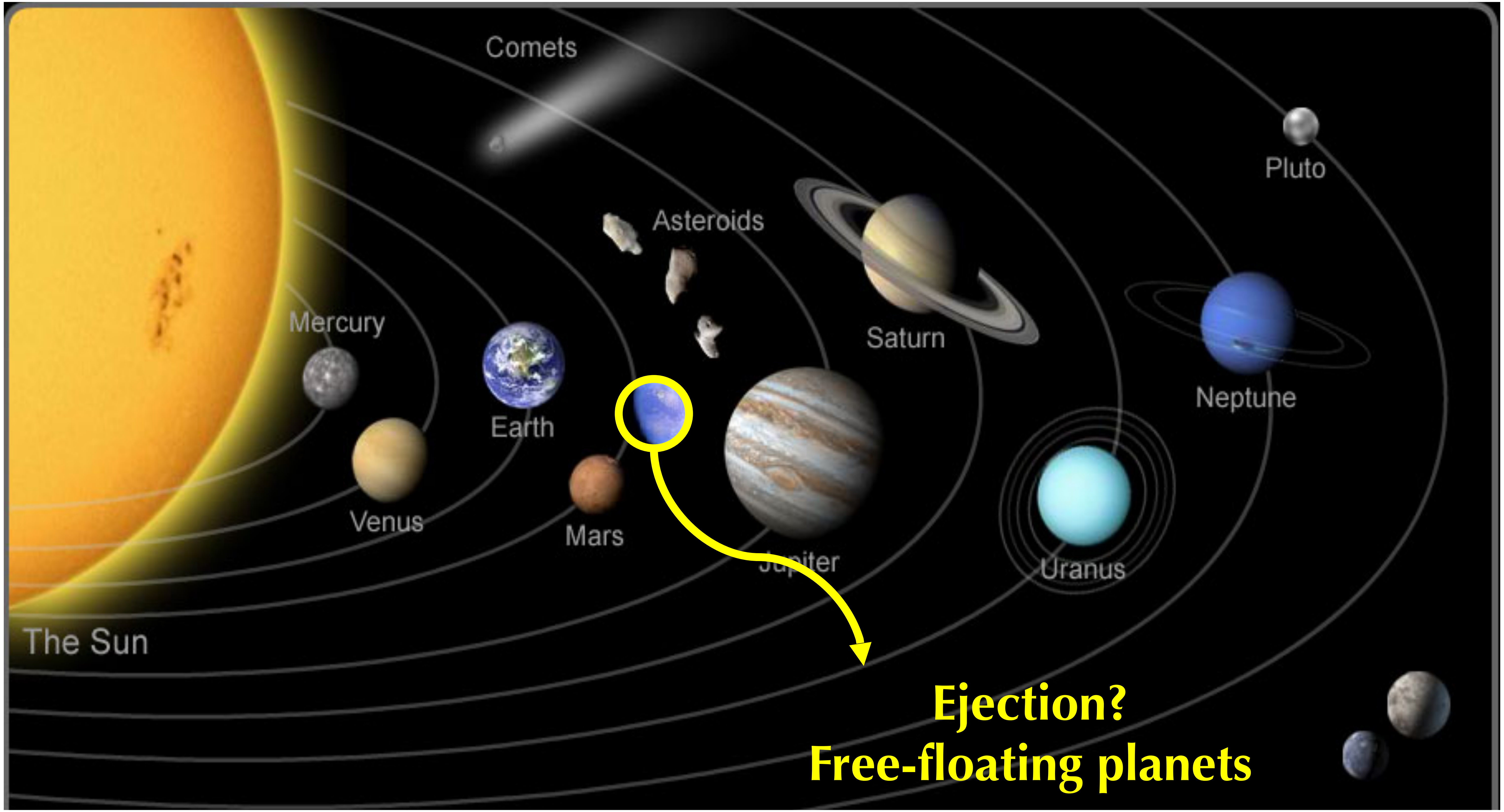
30000 transit planets



~1100 microlensing planets

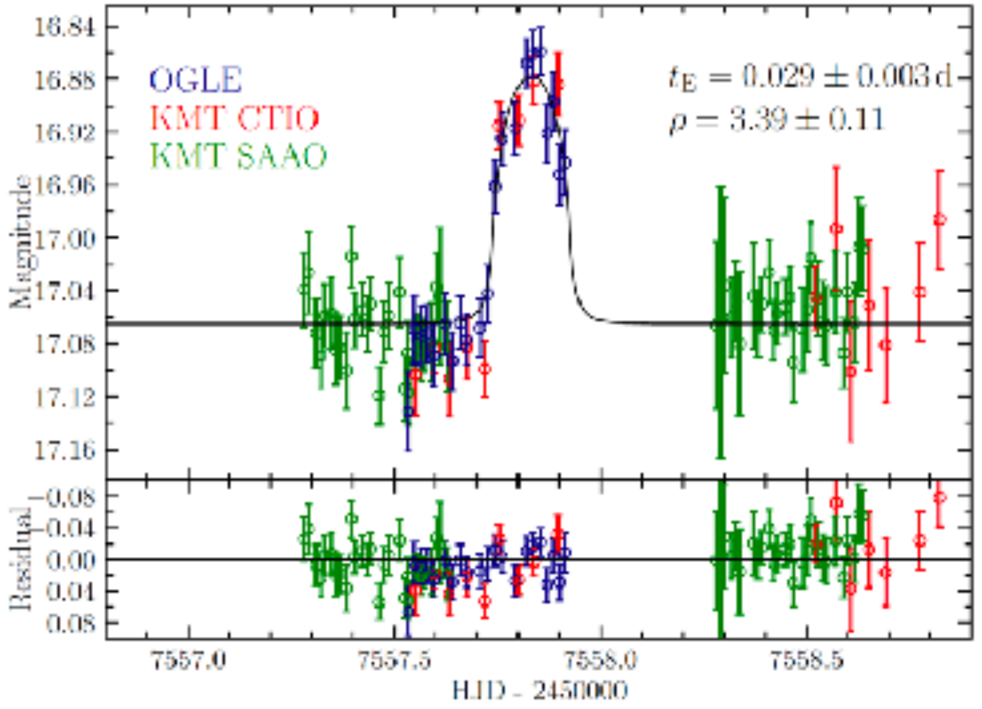
White Paper: arXiv: 2206.06693

Free-floating planets: dynamical/chaotic ejections

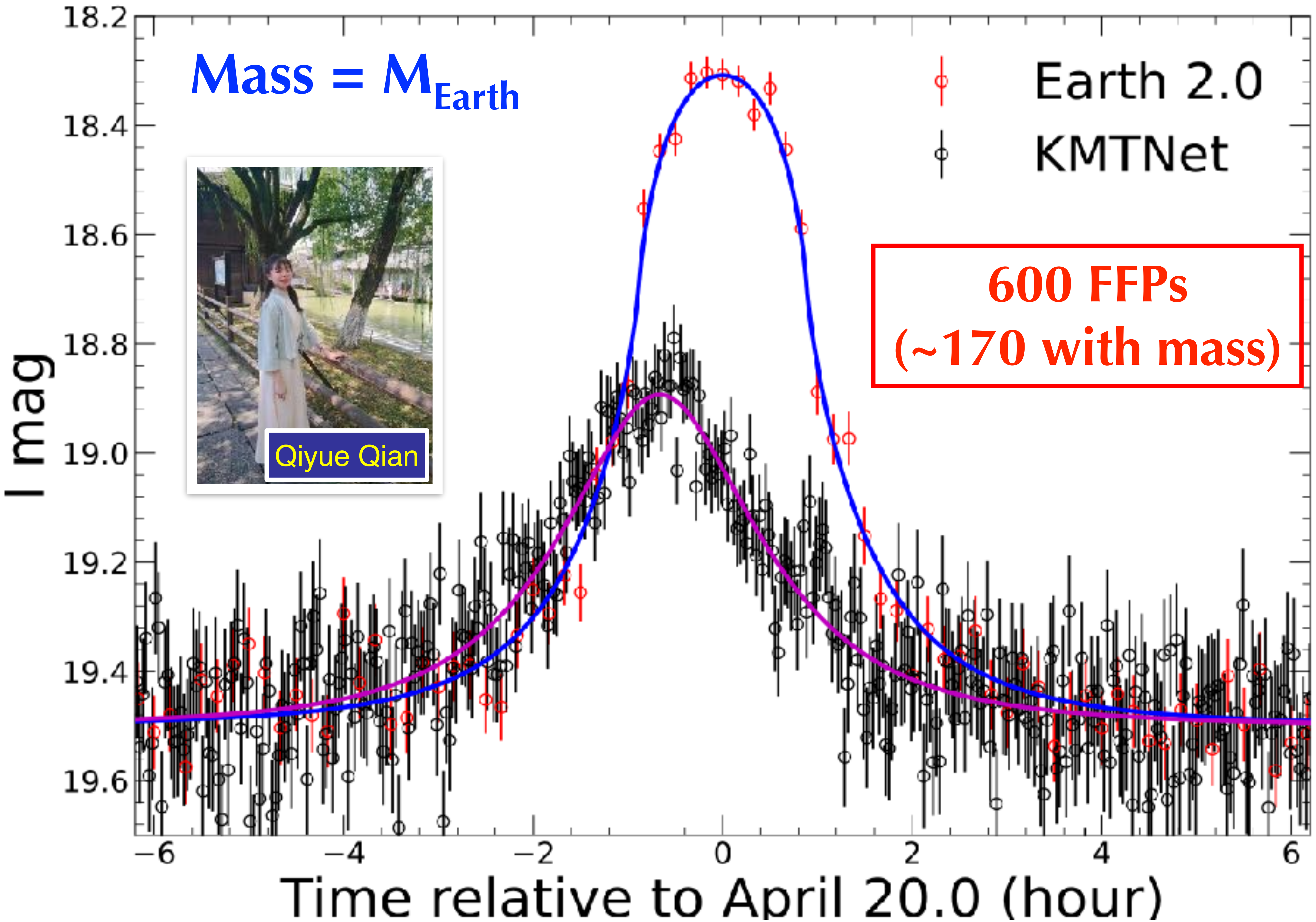


Free-floating planets from satellites

~20 FFPs/star?
(Gould+22; Sumi+23)



t_E =42min
Mars to Earth mass?
NO unique mass!



Gould, Zang, Mao, Dong 21

Summary

- **200+ microlensing planets have been discovered**

❖ **it is the best method to probe the cold planet population**

❖ **Cold Super-Earths are common, no break around mass ratio q ~ 10^{-4}**

- **Future for gravitational microlensing is bright:**

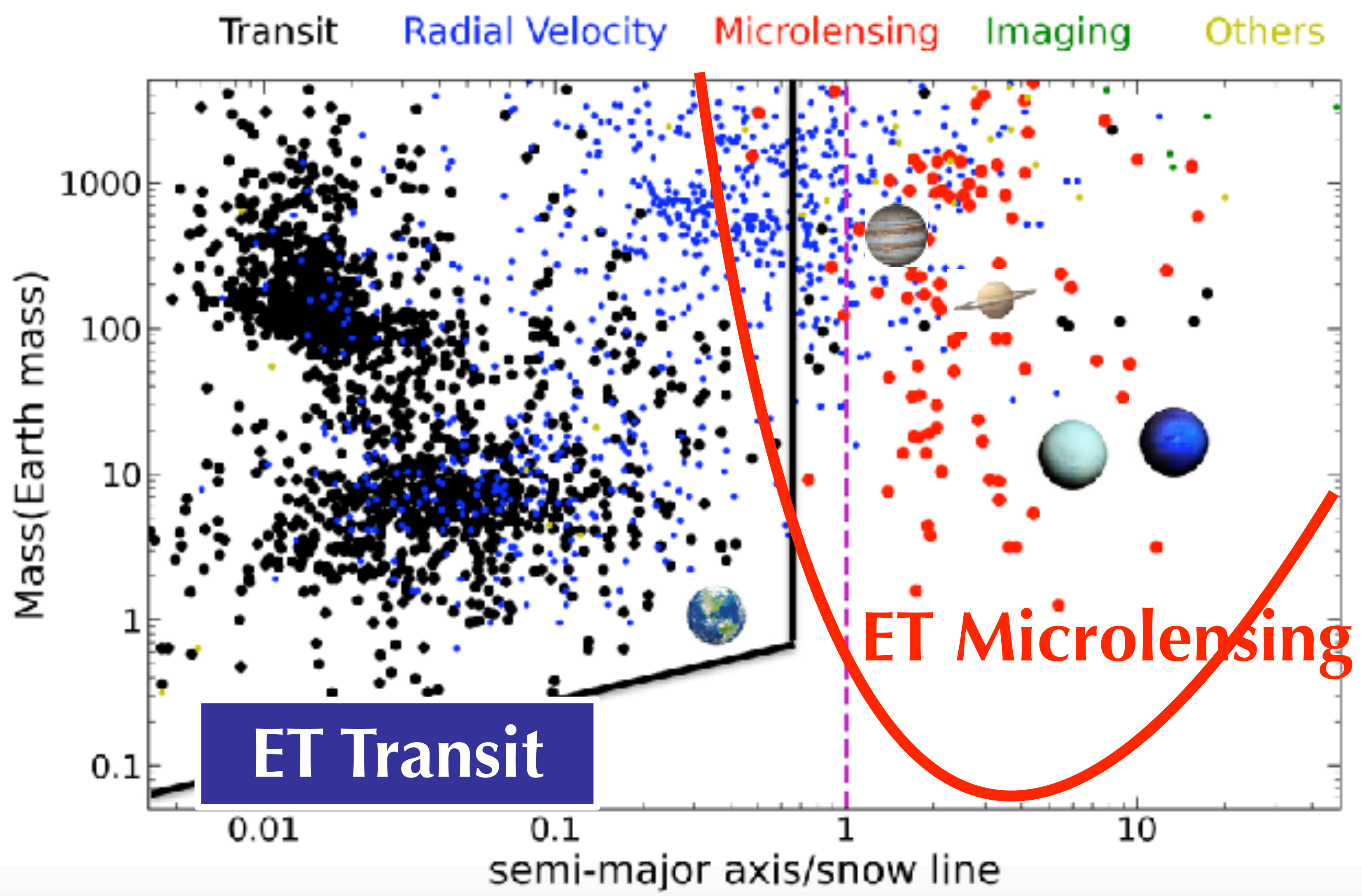
❖ ***Ground AO/ELTs can study many past events in great detail***

❖ **Roman/ET can discover more planets, including free-floating ones**

❖ **further constrain planet formation theories**

Thank you!

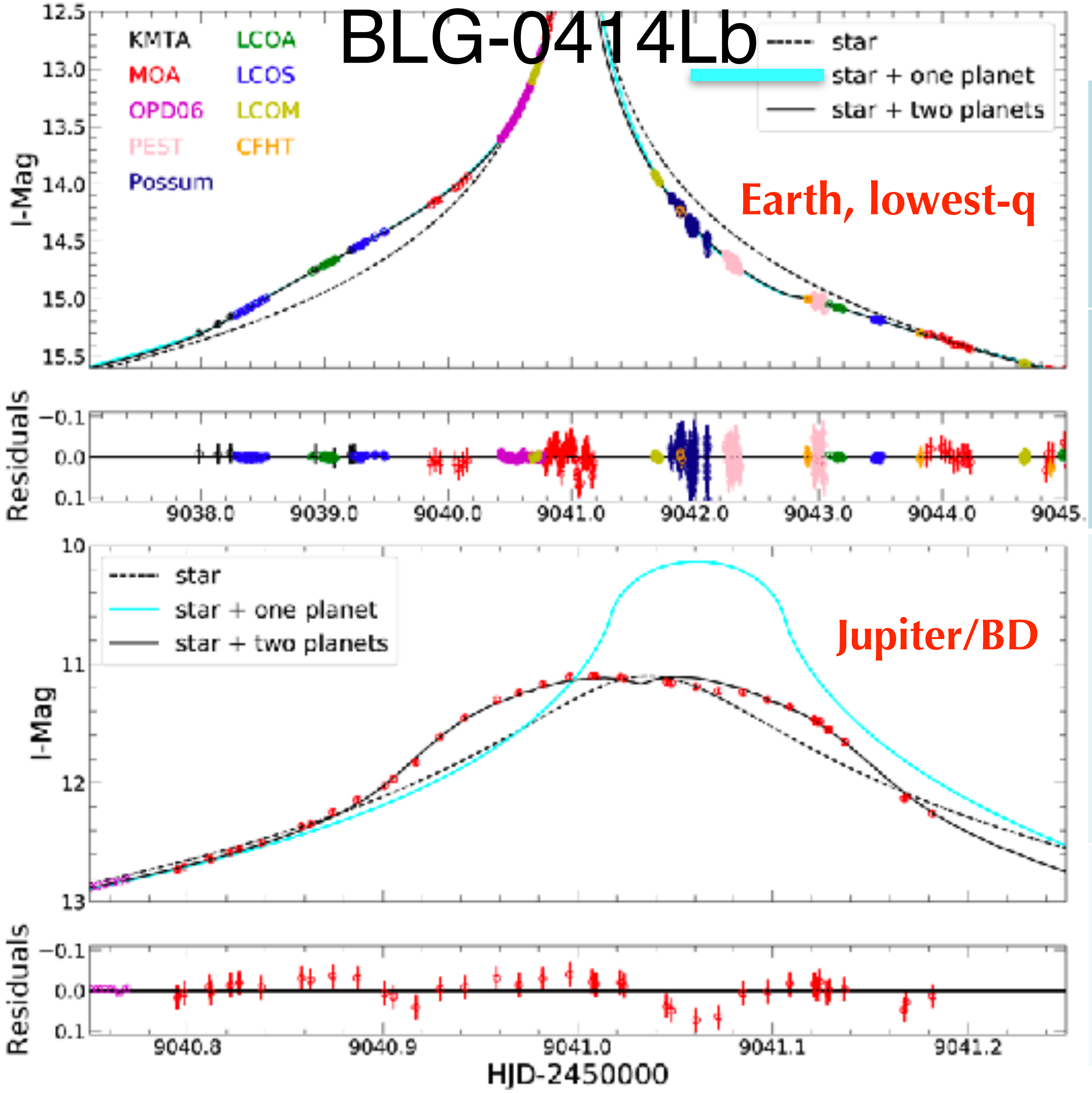
ET can cover the whole planet parameter space



	Cost (dollar)	Aperture (m)	FoV (deg^2)	Days	Band	Expected bound planets (with mass)	Expected free-floating planets (with mass)
ET+KMTNet	\$0.2B	0.35	4	720	I	450 (~130)	~600 (~170)
Roman	>\$3B?	2.36	0.282	360	H	~650 (~160)	~900 (~10)

Discovering two planet systems

KMT-2020-BLG-0414Lb



	Gould + 2010	Suzuki+ 2018	~20 yr microlensing	Our follow-up (2 yr)
Team	μFUN	MOA	All teams	KMTNet + LCO + μFUN
Two-planet system	1	1	5	2
Occurrence rate	~1/6	~6%	Non-homogeneous	A future paper

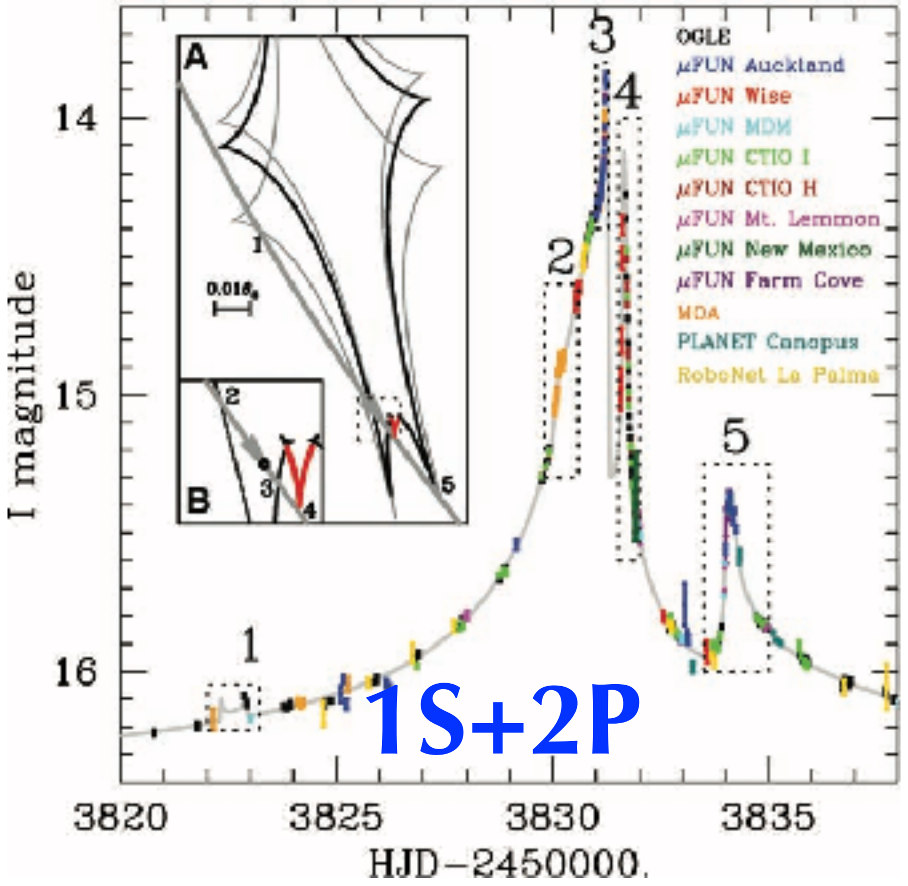
Zang et al. (2021a)

Multiple planets/circum-binary planets: triple lensing

1 Star
+2 planets

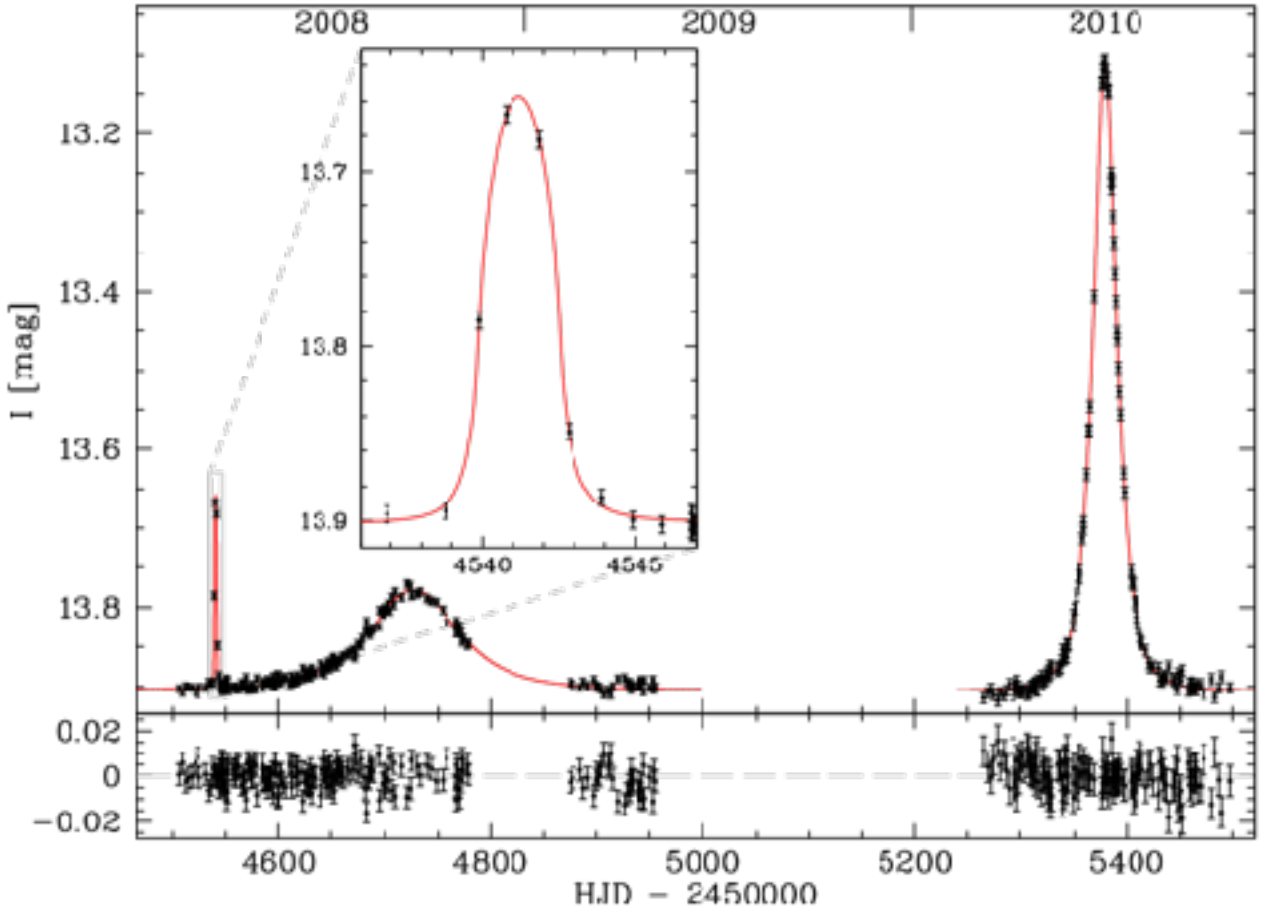
(J:S analogs)

OGLE-2006-BLG-109L



Gaudi et al. (2009)

OGLE-2008-BLG-092

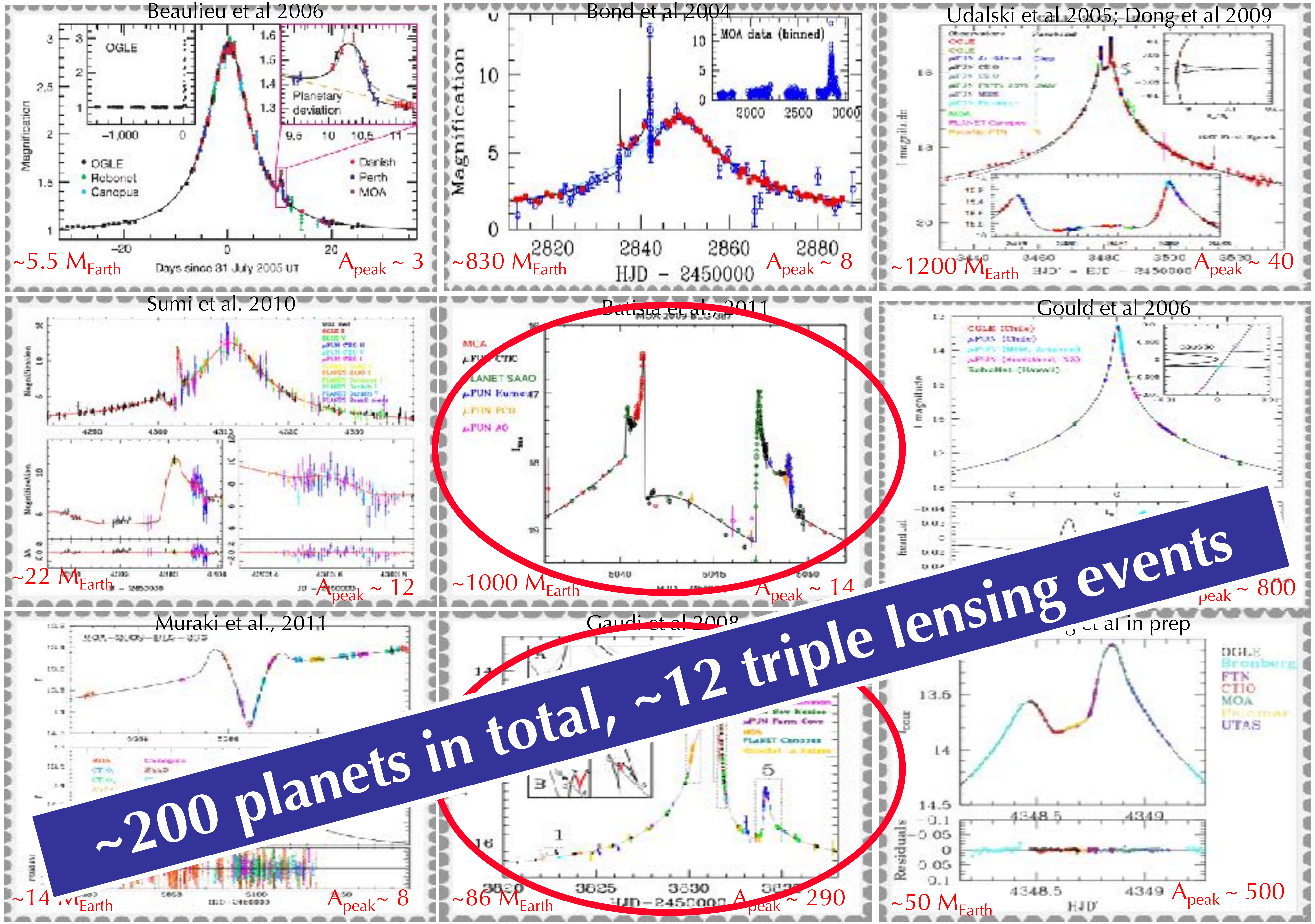


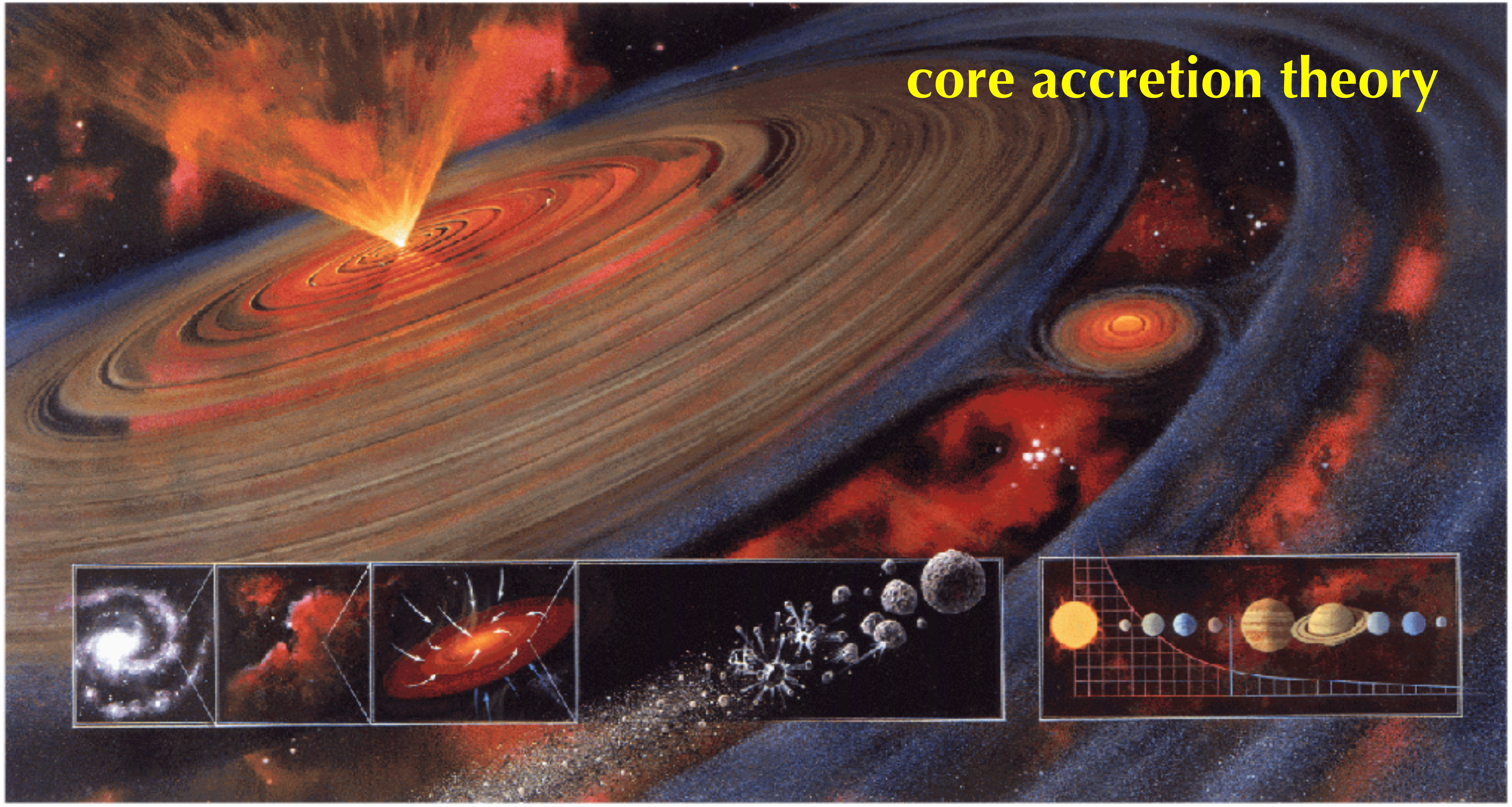
Poleski et al. (2014)

2 Stars
+1 planet
(~Uranus)

- Probe multiple planet population beyond the snow line
- Probe formation scenarios of planets around binary stars
- How to model them remains a challenge (Kuang, Mao et al. 2021)!

Examples of Microlensing Planets

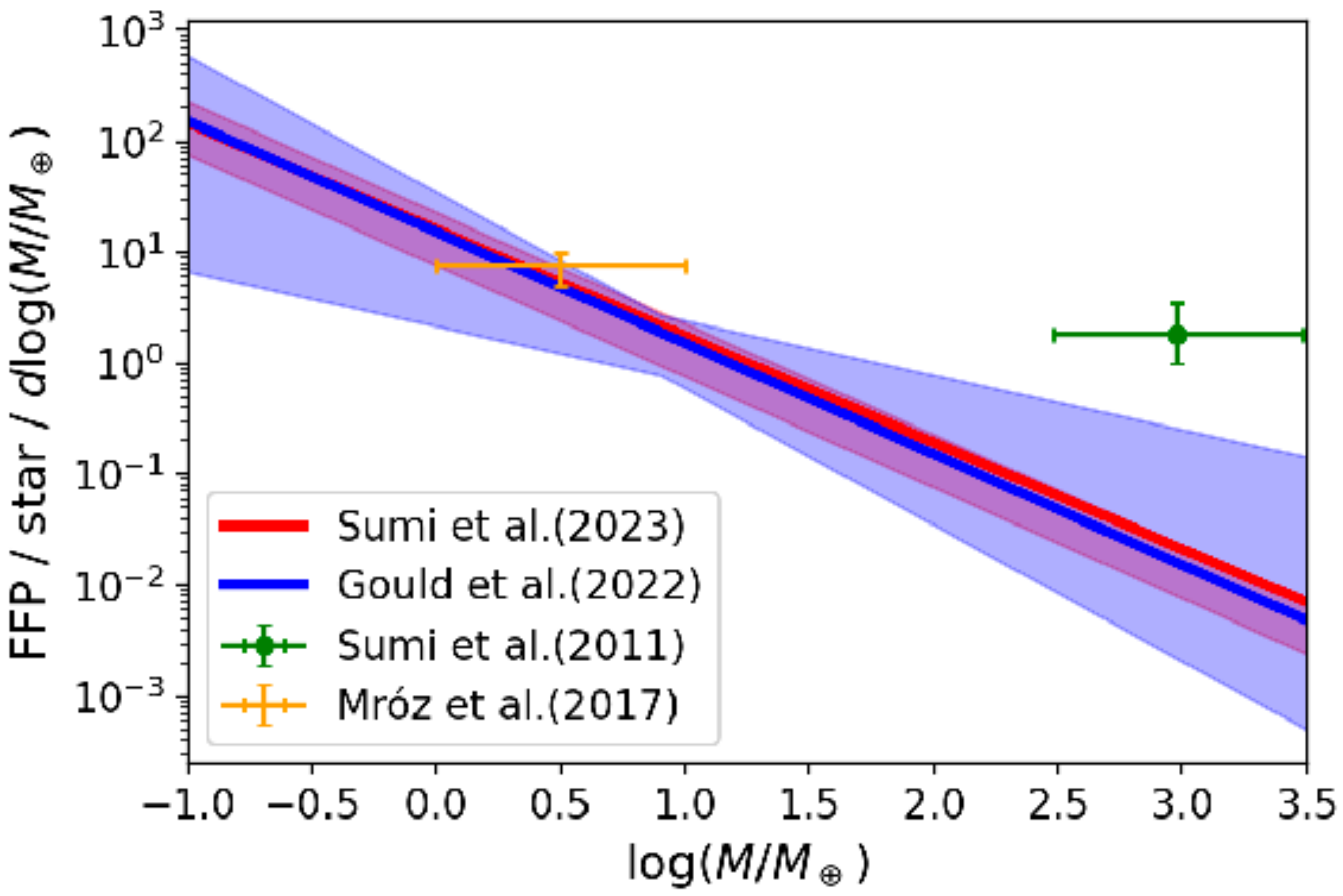




- How do planets form? How do giant planets around M dwarfs form?
- Is the solar system unusual?
- Are there differences in planet formation efficiency in different environments (e.g. thin, thick disks, bulge)?
- Planetary atmospheres (JWST)?

Free-floating planets

Mass function



More than 20 FFPs/star for $M > 0.3M_{\oplus}$!

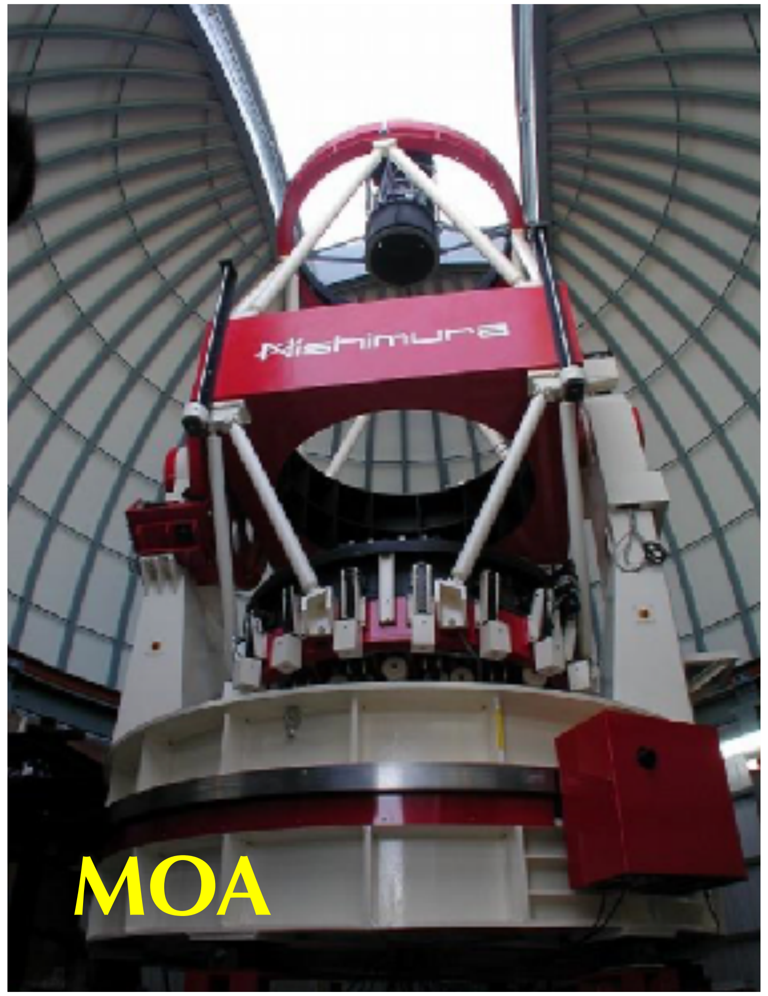
MOA in 9 years (Sumi et al. 2023): 7 candidates (t_E< 0.5 day)

KMTNet in 6 years: 4 candidates

- KMT-2017-BLG-2820
- KMT-2019-BLG-2073
- KMT-2019-BLG-0519 (OB190551)
- OB161540
- **And more?**

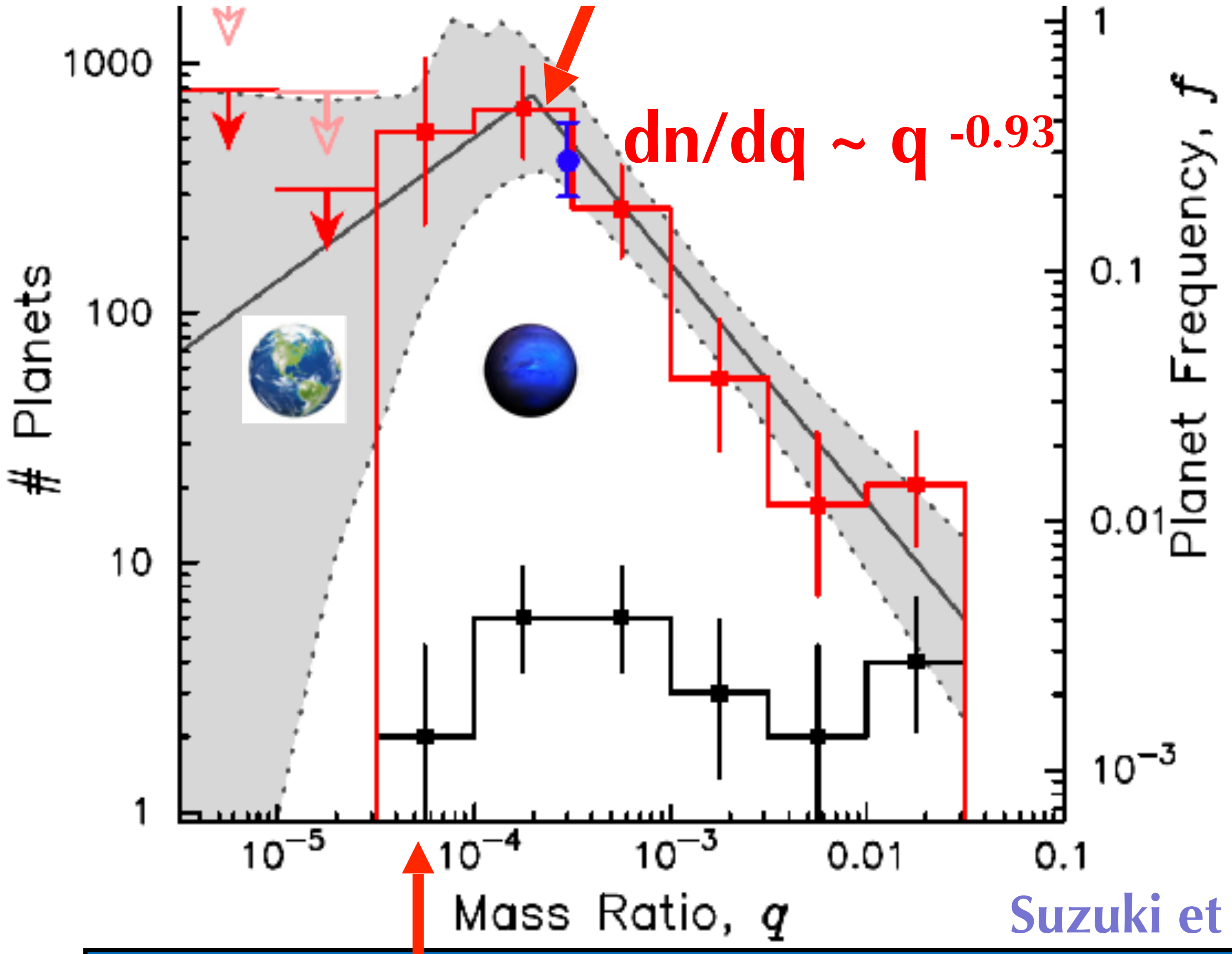
Statistical results: MOA/OGLE-IV (23 planets)

high-cadence wide-field microlensing surveys



- FOV: 2.2 $\deg^2$
- 15min cadence for 13 $\deg^2$
- ~600 events per year
- 23 planets during 2007-2012

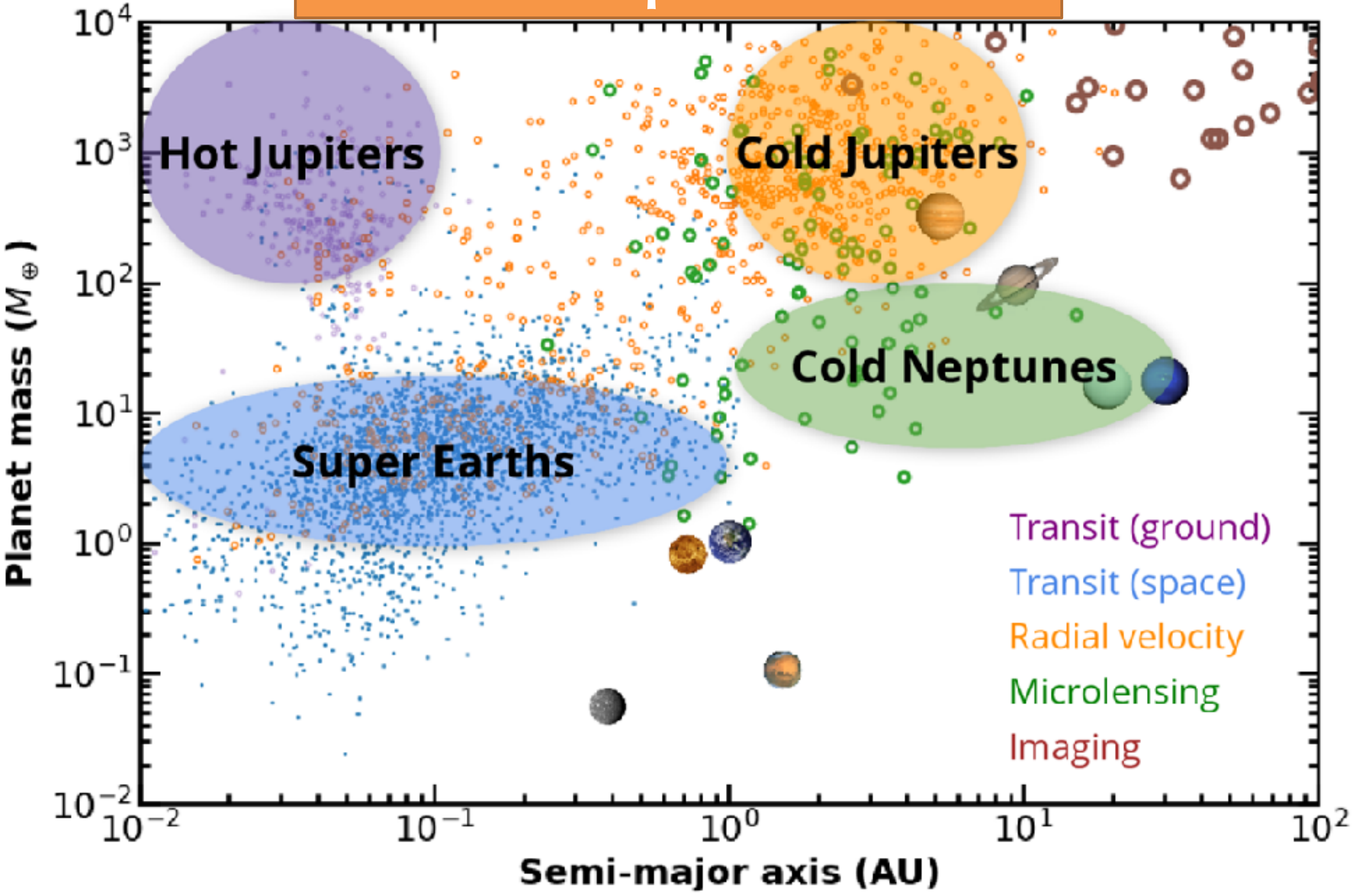
- A break at $q \sim 1.7 \times 10^{-4}$?
- Cold Neptunes are most common?



Suzuki et al. (2016)

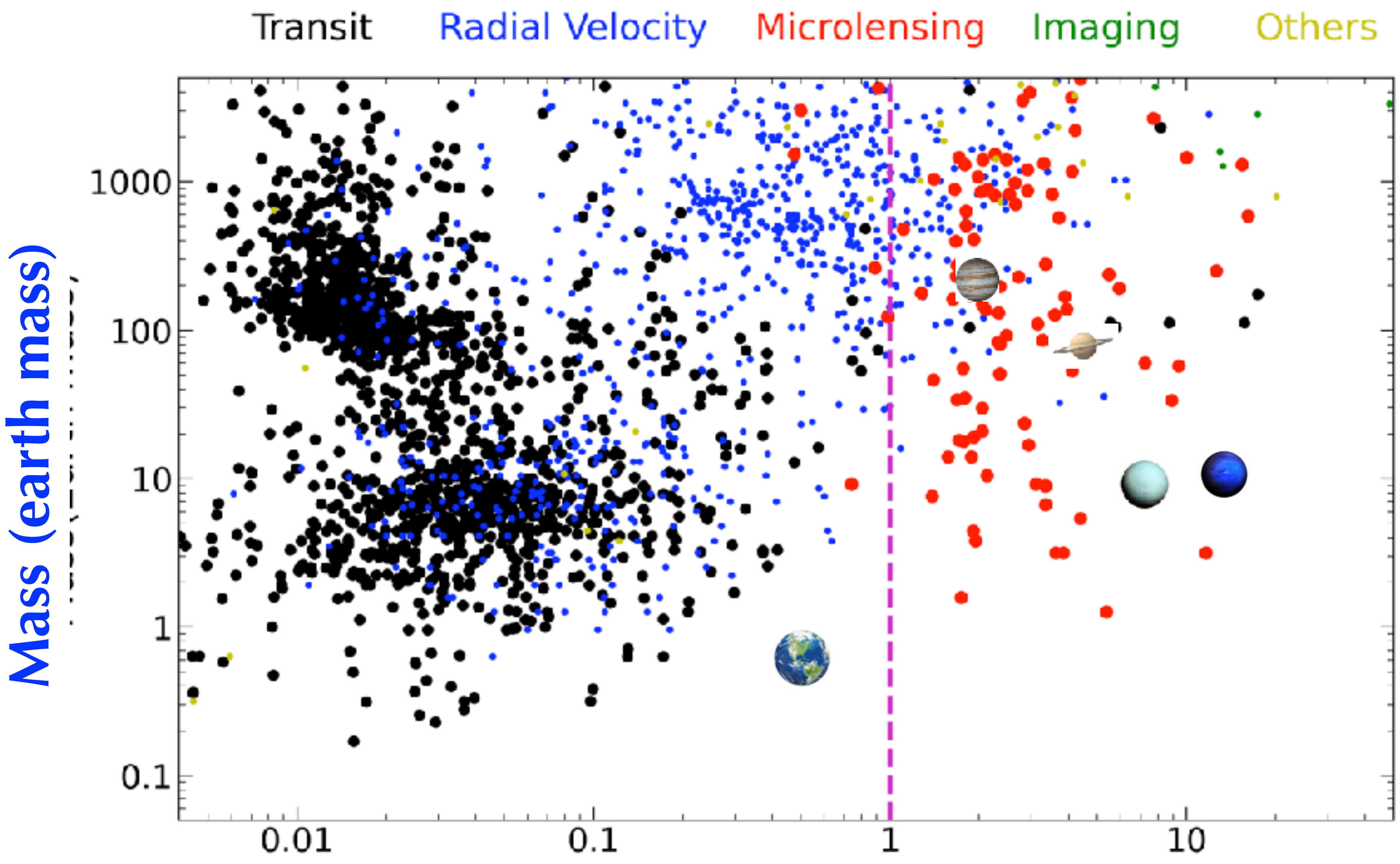
- Only two $q < 10^{-4}$ planets
- No detection of cold Earths ($q \sim 10^{-5}$)

Total confirm planets: >5000



Based on data from NASA Exoplanet Archive.

Microlensing opens a unique window for cold planets



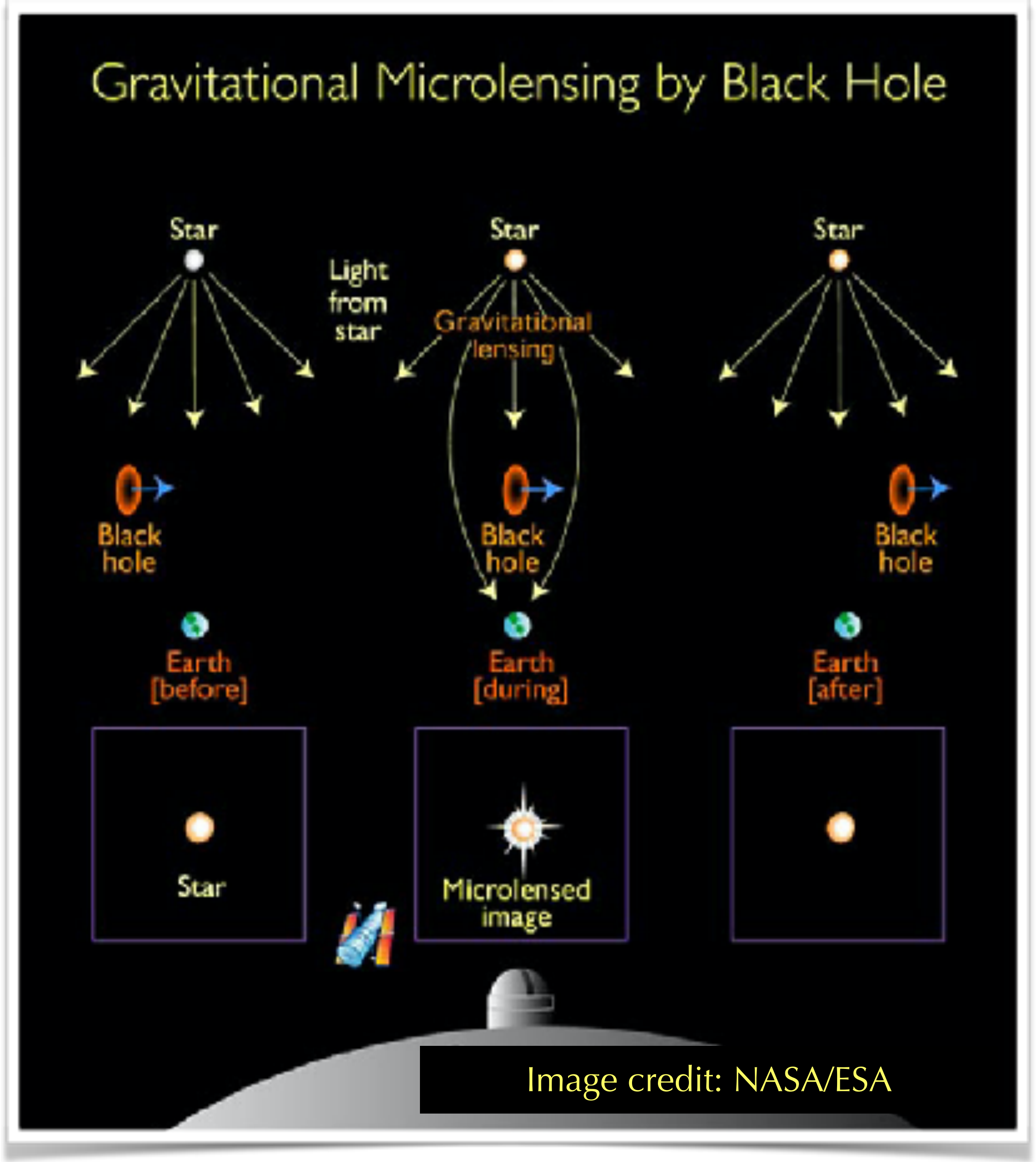
Semi-major axis/snow line

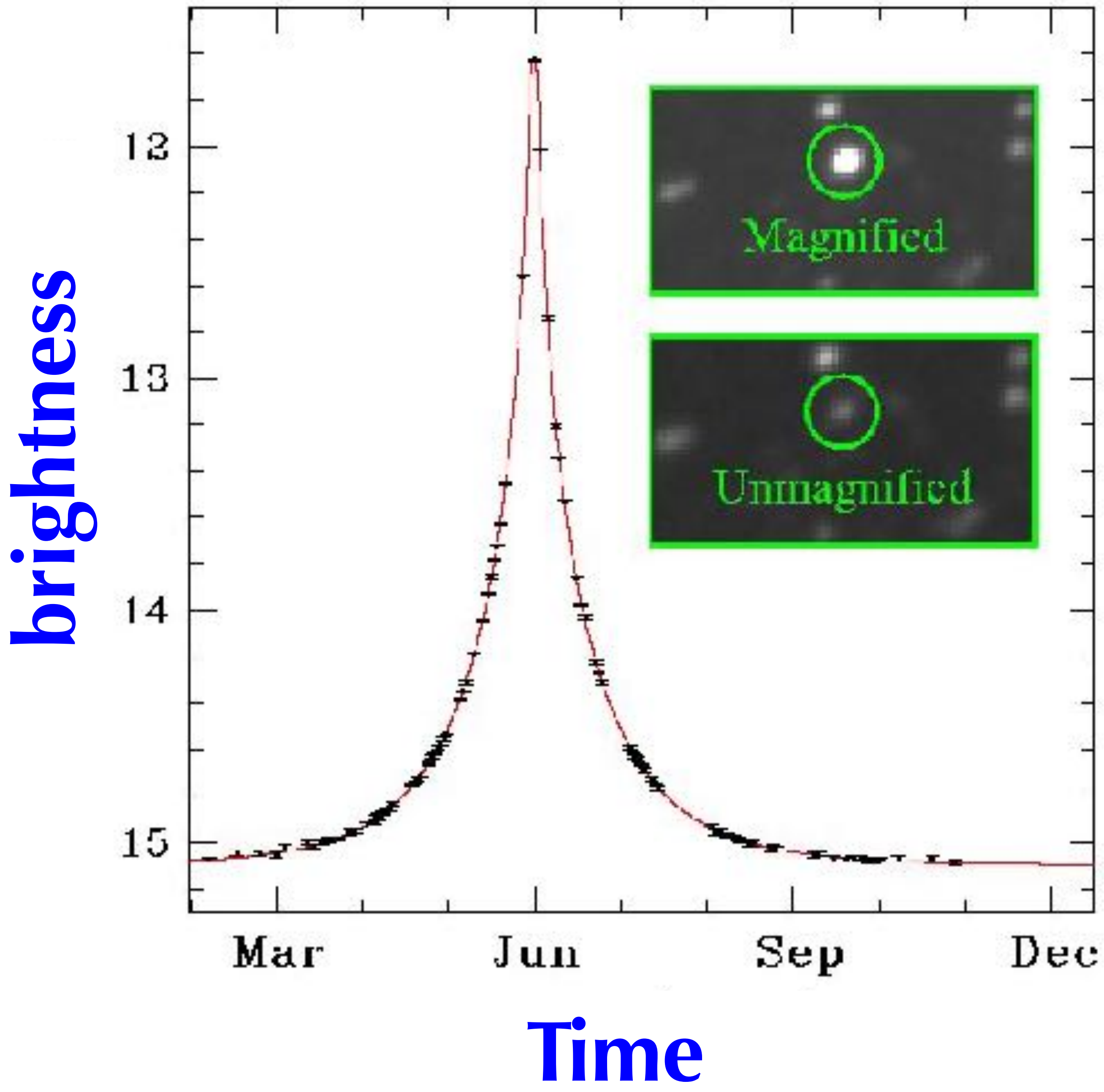
Snow line = $2.7(M_{host}/M_{\odot})$AU

Total confirm planets:
>5000

Microlensing planets:
~200

What is Galactic microlensing?

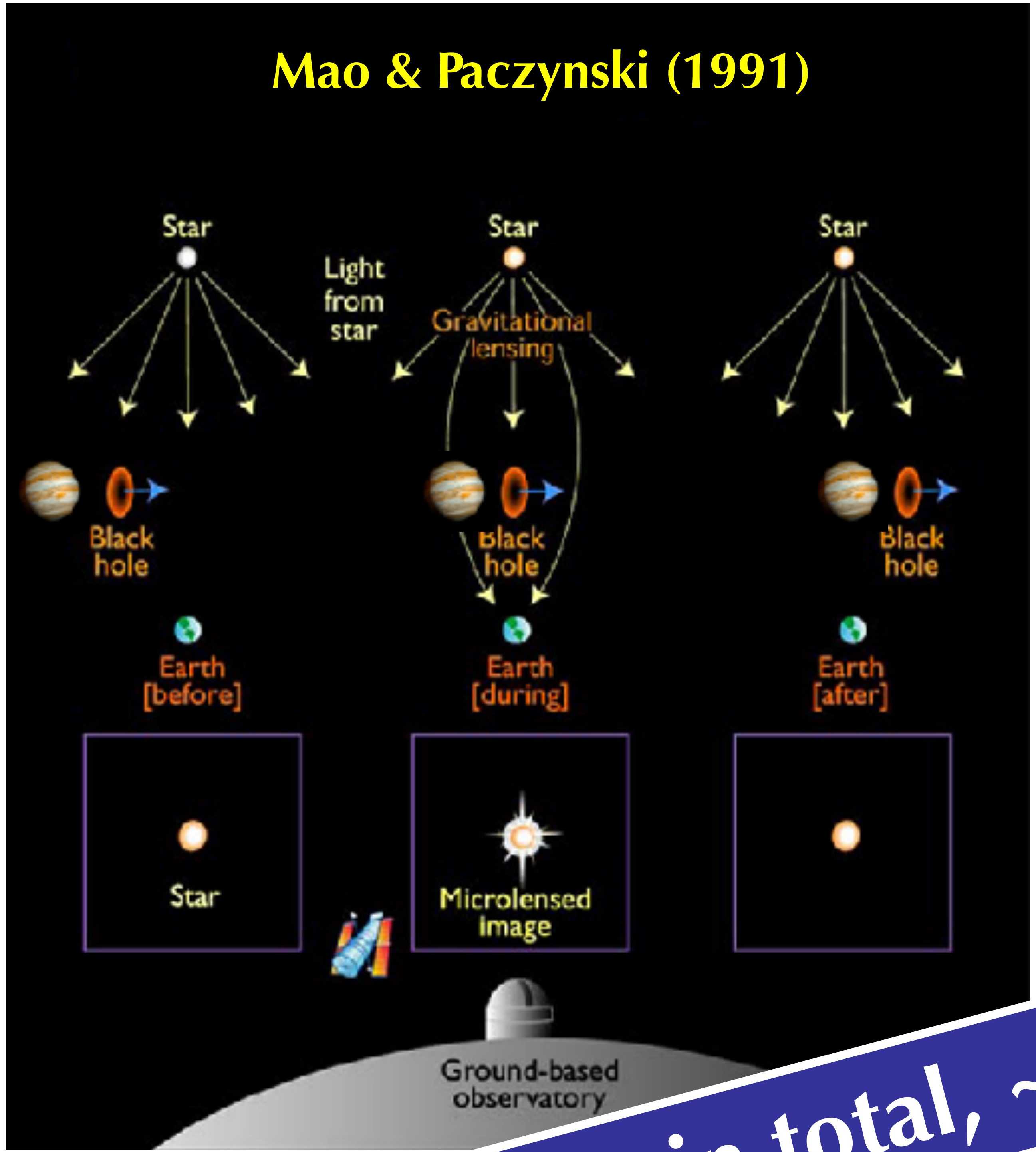




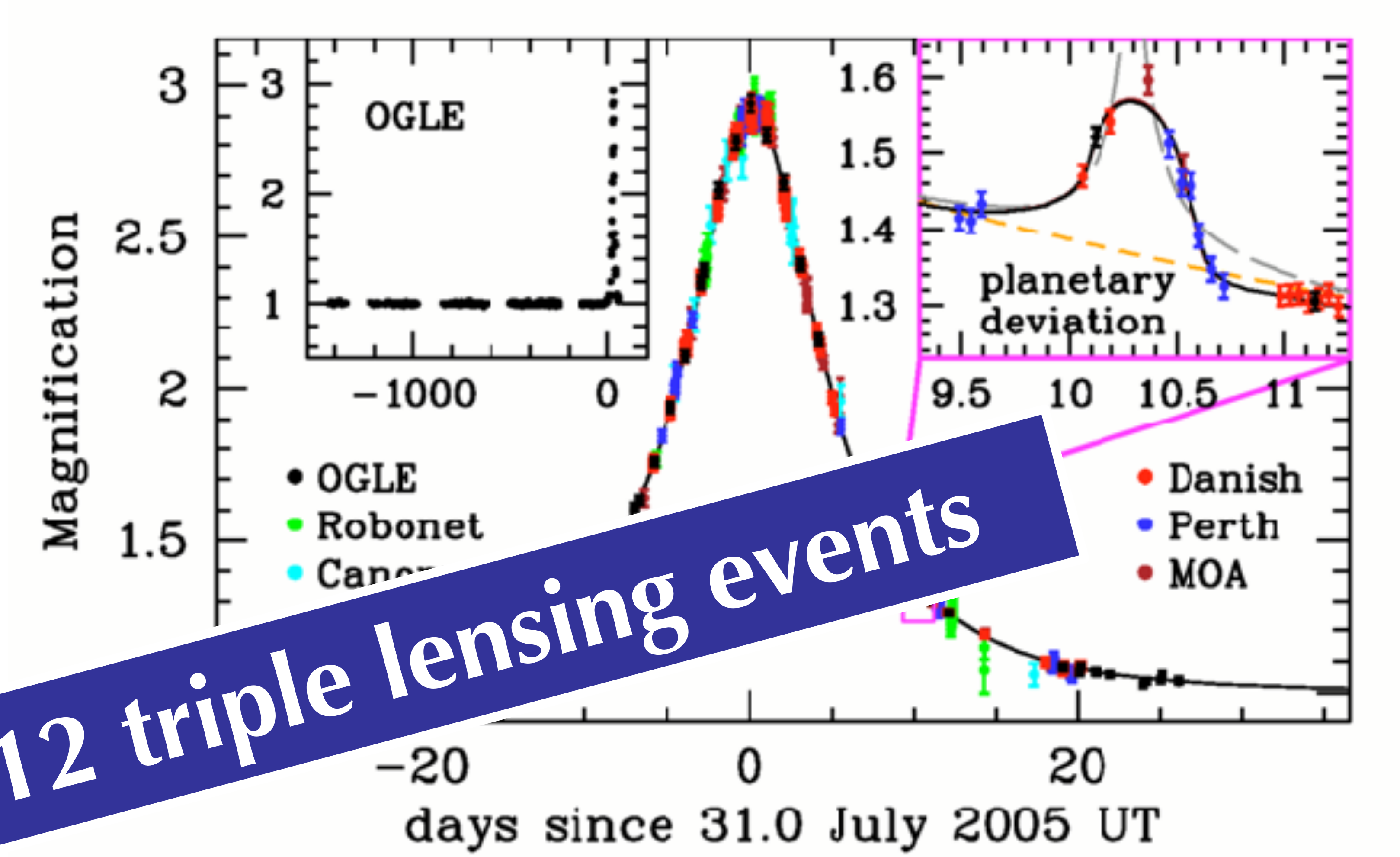
microlensing produces "symmetric", non-repeating & achromatic light curves

probability: 10^{-6}

Basic principle



Mass ratio q



Beaulieu et al. (2006)

~200 planets in total, ~12 triple lensing events

- An extr… produces …
- …plitude can be large!

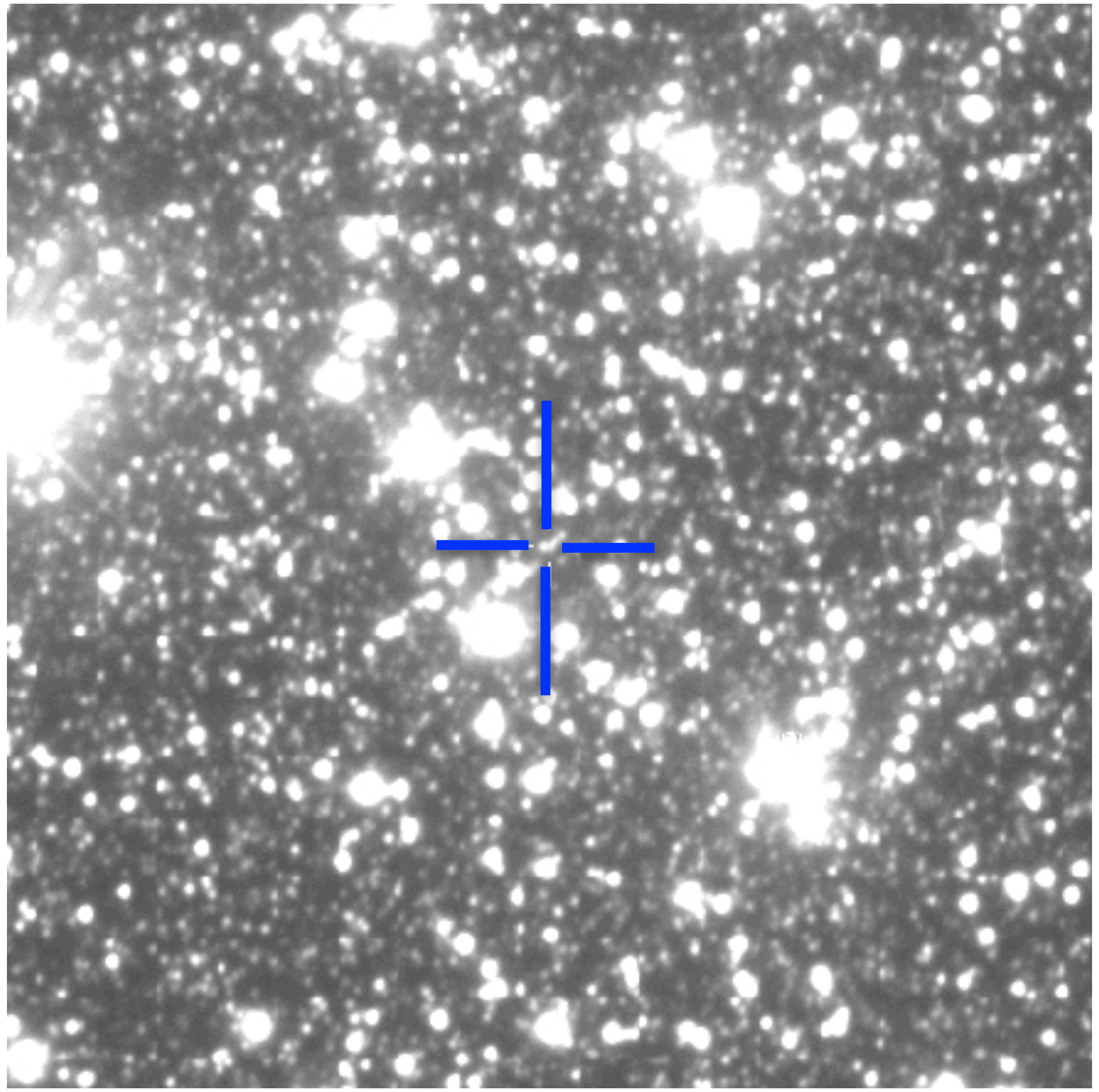
Challenges of planet search with microlensing

- Duration $\delta t \sim 1$ day $(M/M_J)^{1/2}$
- Probability: $\sim 10^{-8}$

- high-cadence, 24 hour monitoring
- wide-field microlensing surveys

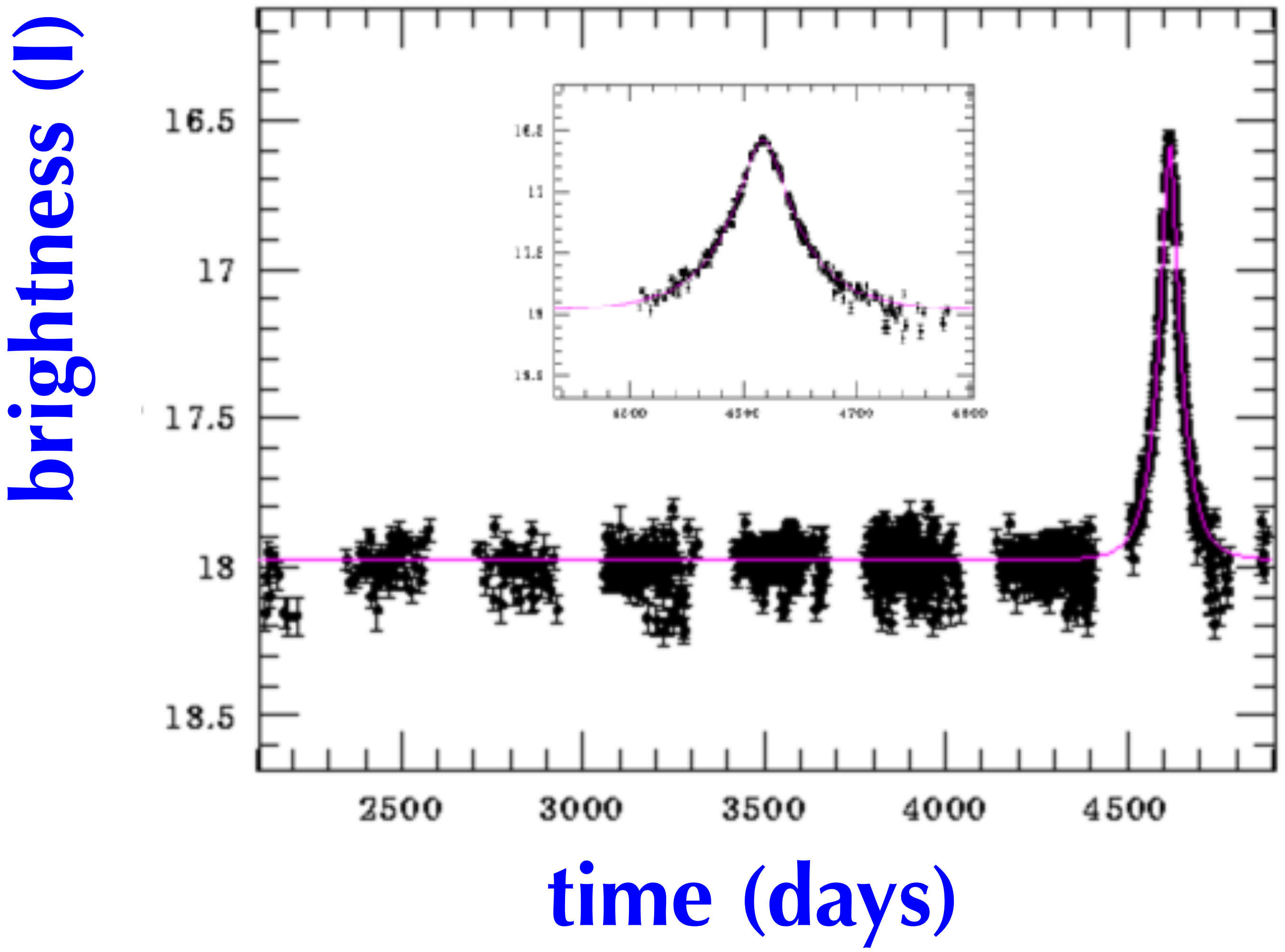
- Survey telescopes (~1/day)
- Follow-up telescopes (dense coverage)

Survey Telescopes: OGLE I-III



Most events are discovered in real time

OGLE-2008-BLG-BLG-102

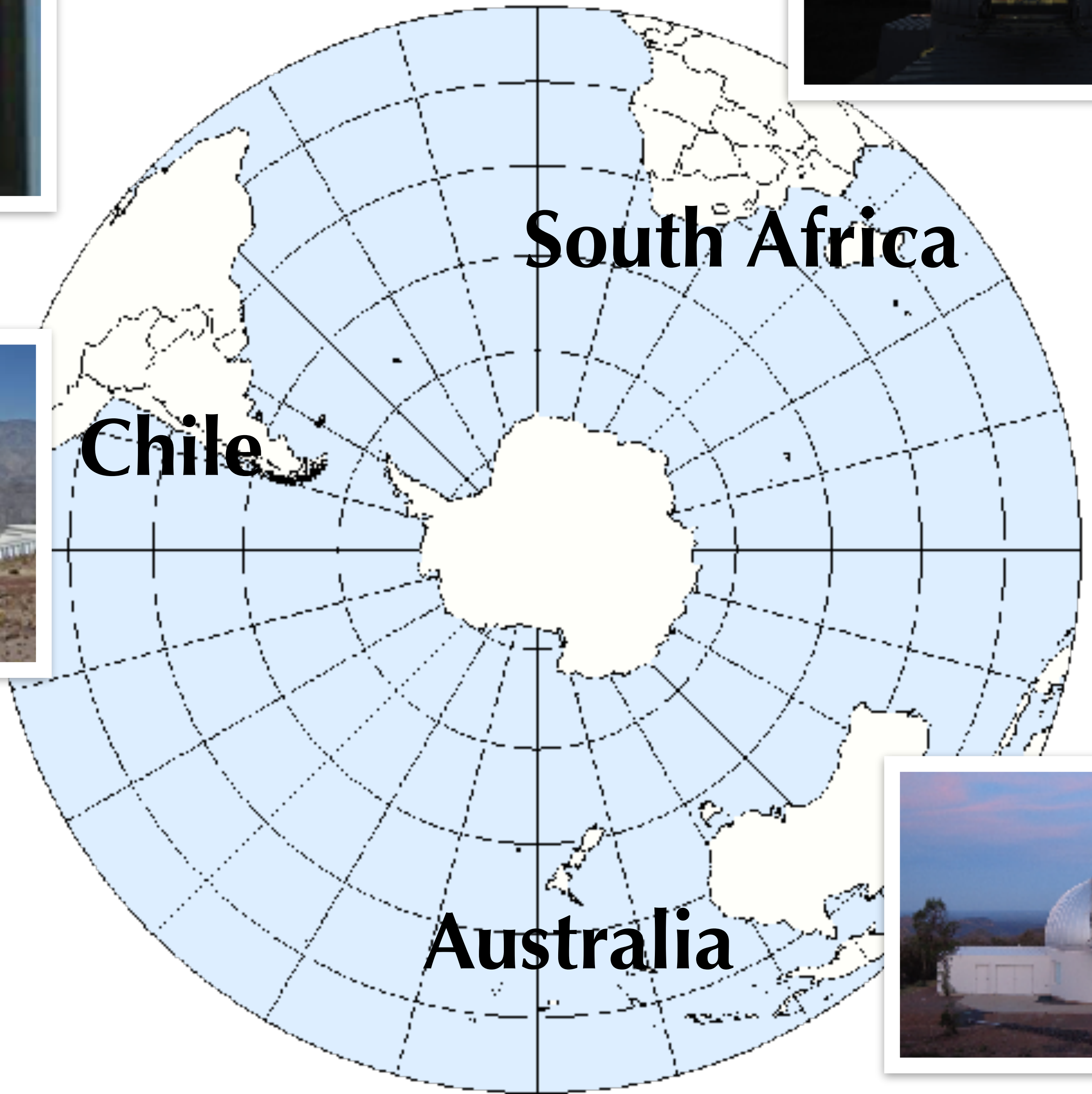


New world leader:

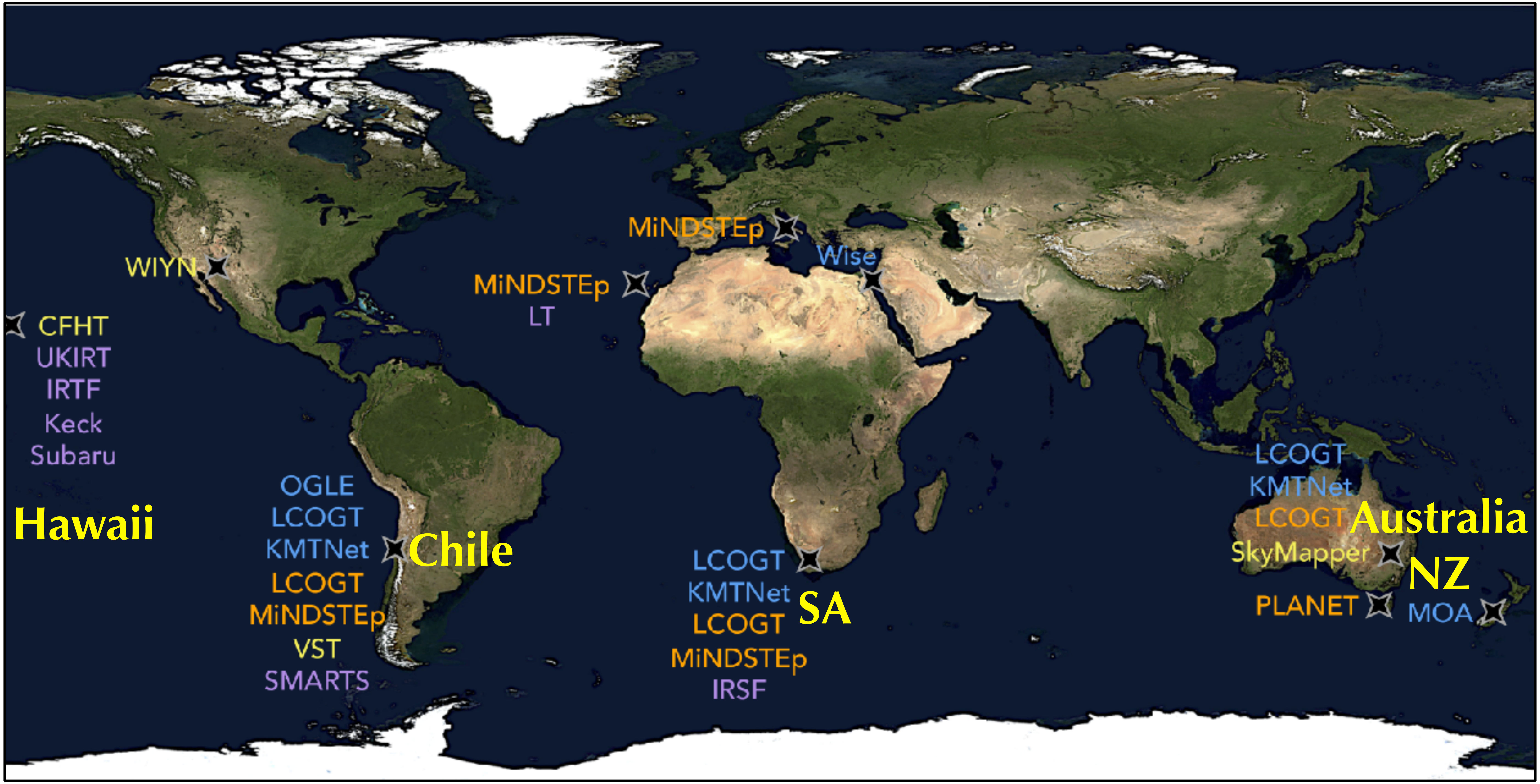
Korea Microlensing Telescope Network

- **MOA**
  - One 1.8m telescope
  - FoV: 2.2 deg^2
  - ~600 events per year
- **KMTNet**
  - Three 1.6m telescopes
  - FoV: 4 deg^2
  - ~3000 events per year

Chung-Uk Lee
(KASI)



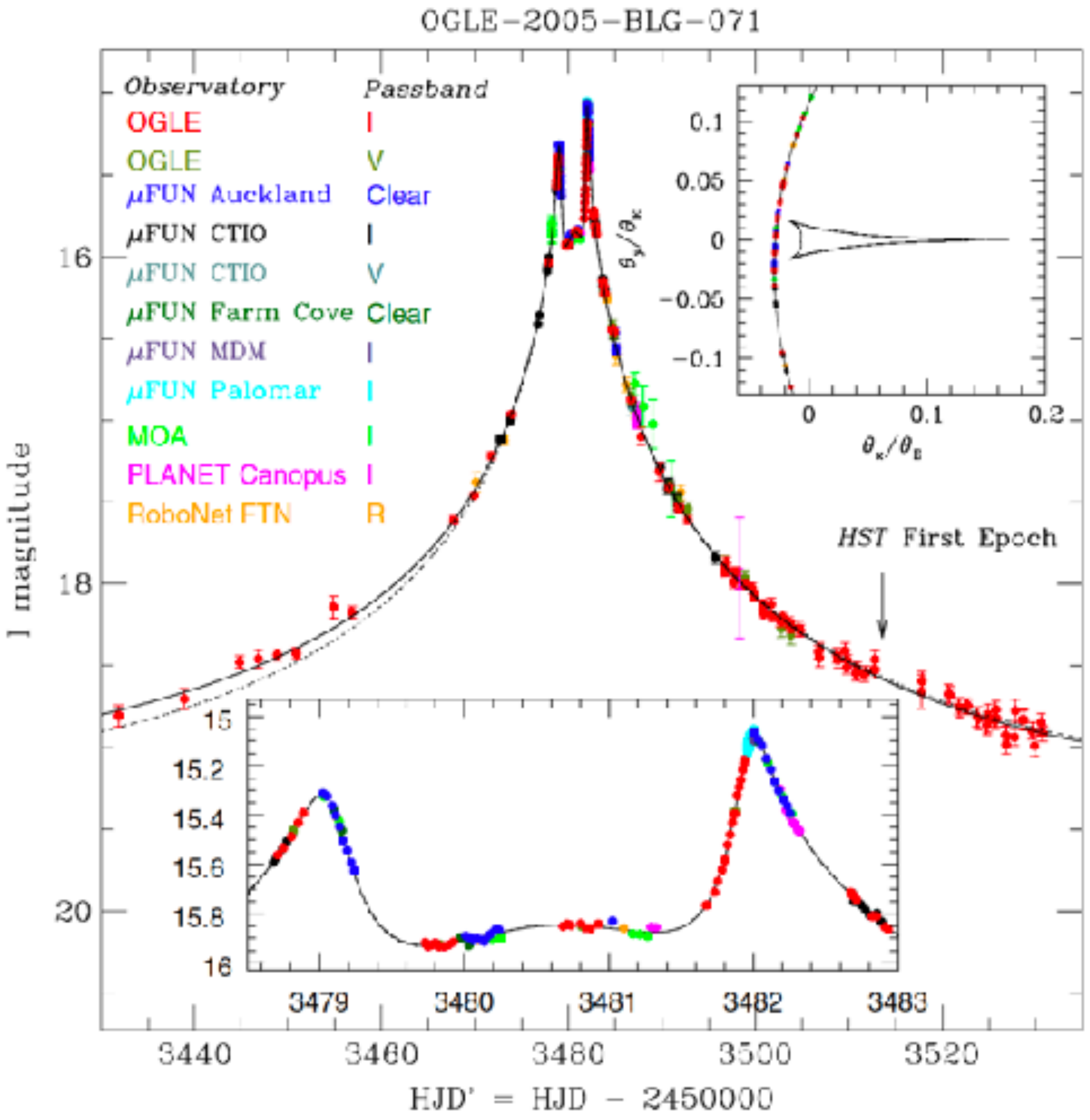
Follow-up telescopes: 24 hour relay network



First statistical result (Gould+ 2010, 6 planets)

Andrew Gould

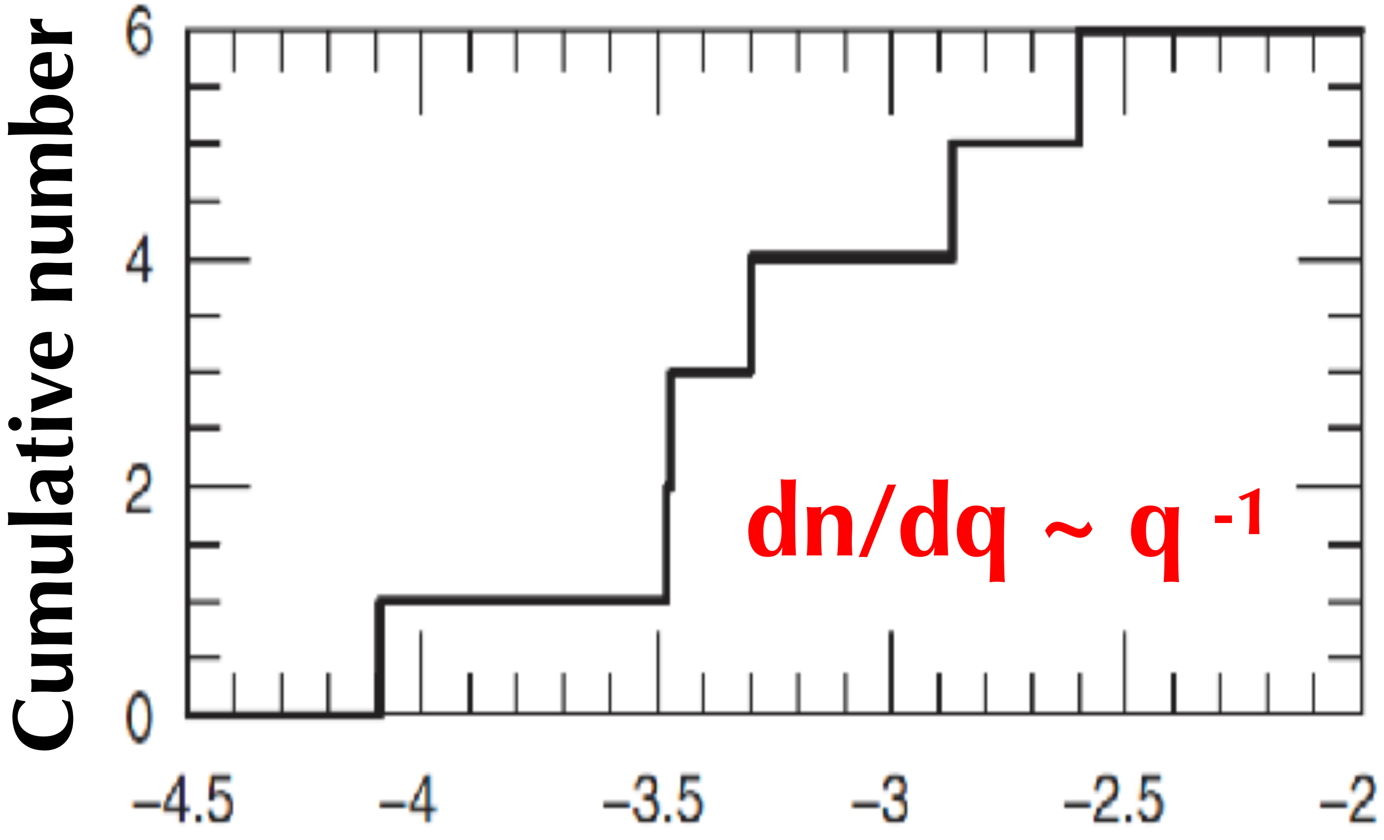
Subo Dong



Udalski et al. (2005)

Dong et al. (2009)

A uniform distribution in log mass ratio

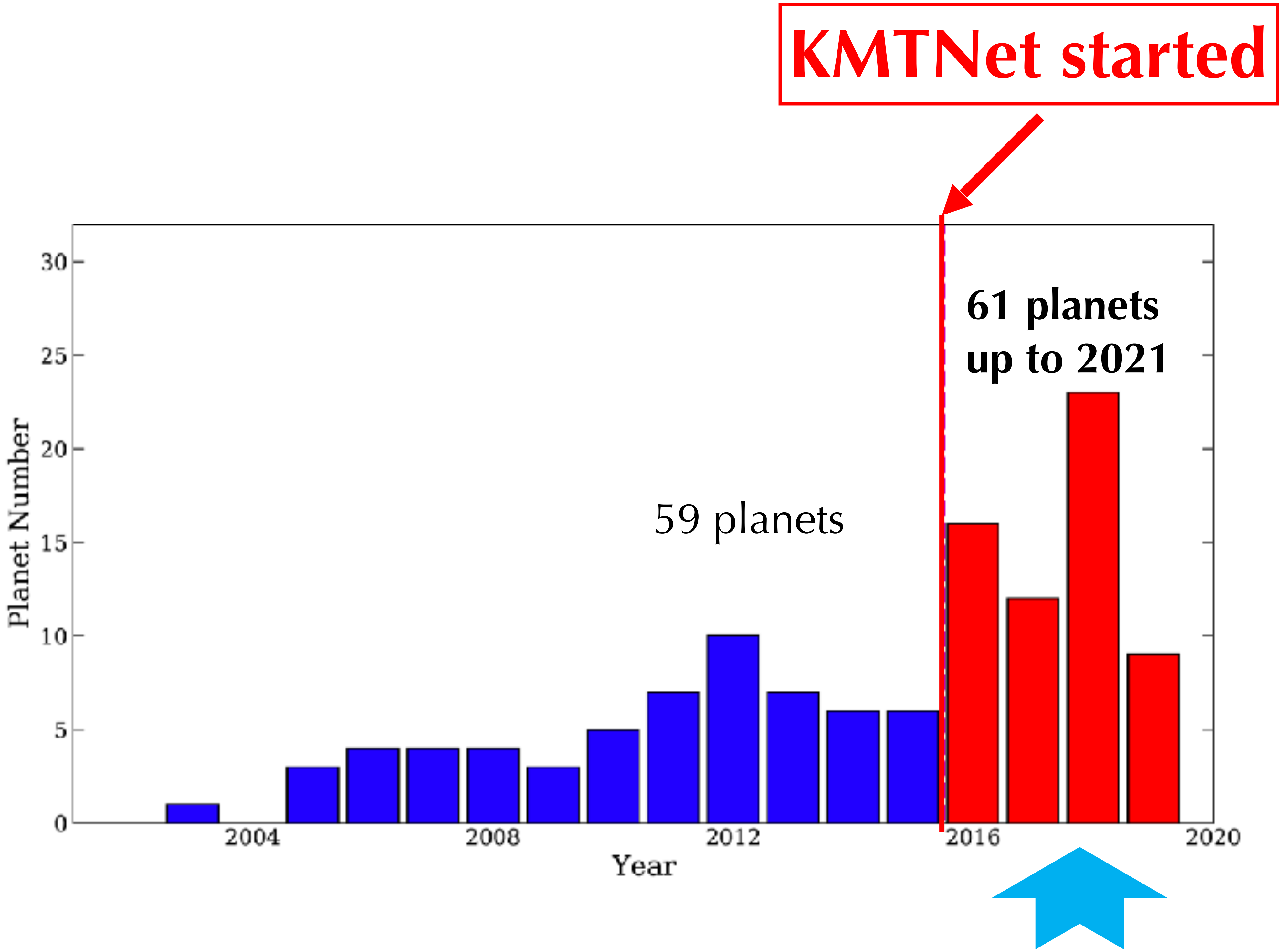


log q

q=planet/host mass ratio

Gould et al. (2010)

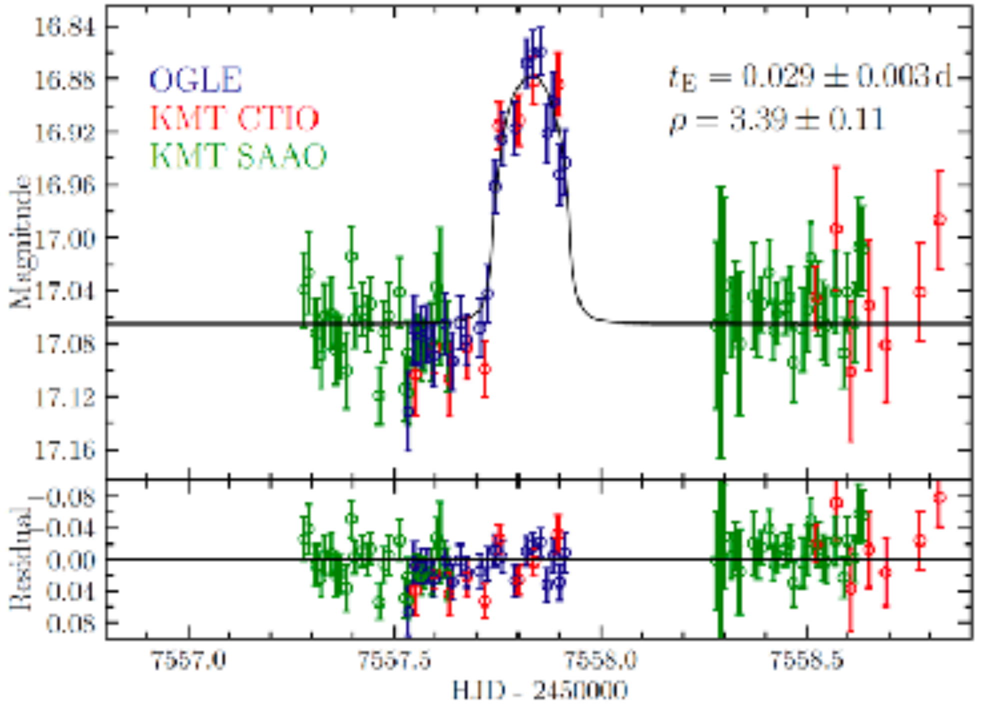
KMTNet greatly accelerated planet discoveries



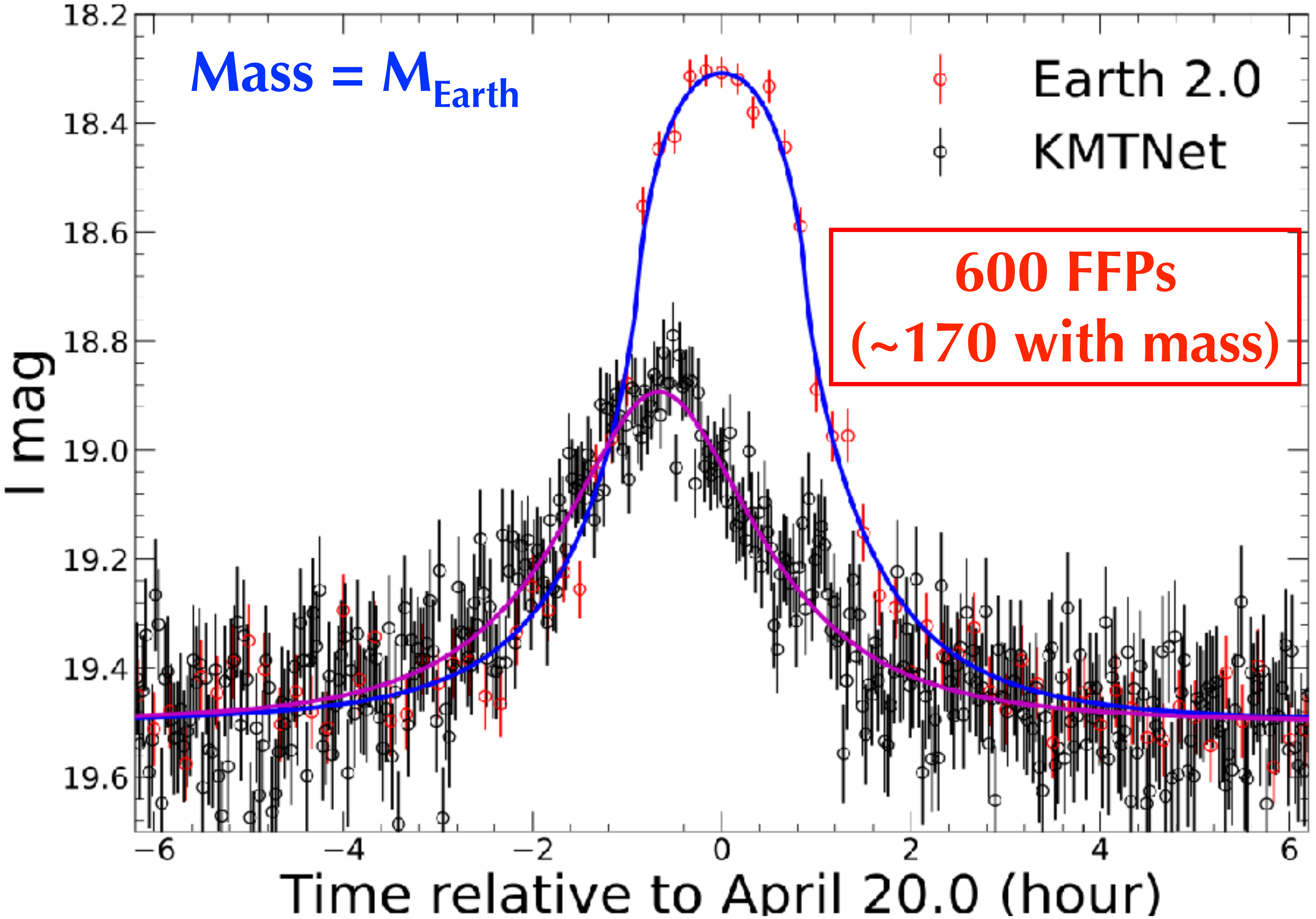
- Search for planet signals by eyes
- Only identified obvious signals

Free-floating planets: dynamical/chaotic ejections

~20 FFPs/star?
(Sumi+23; Gould+23)

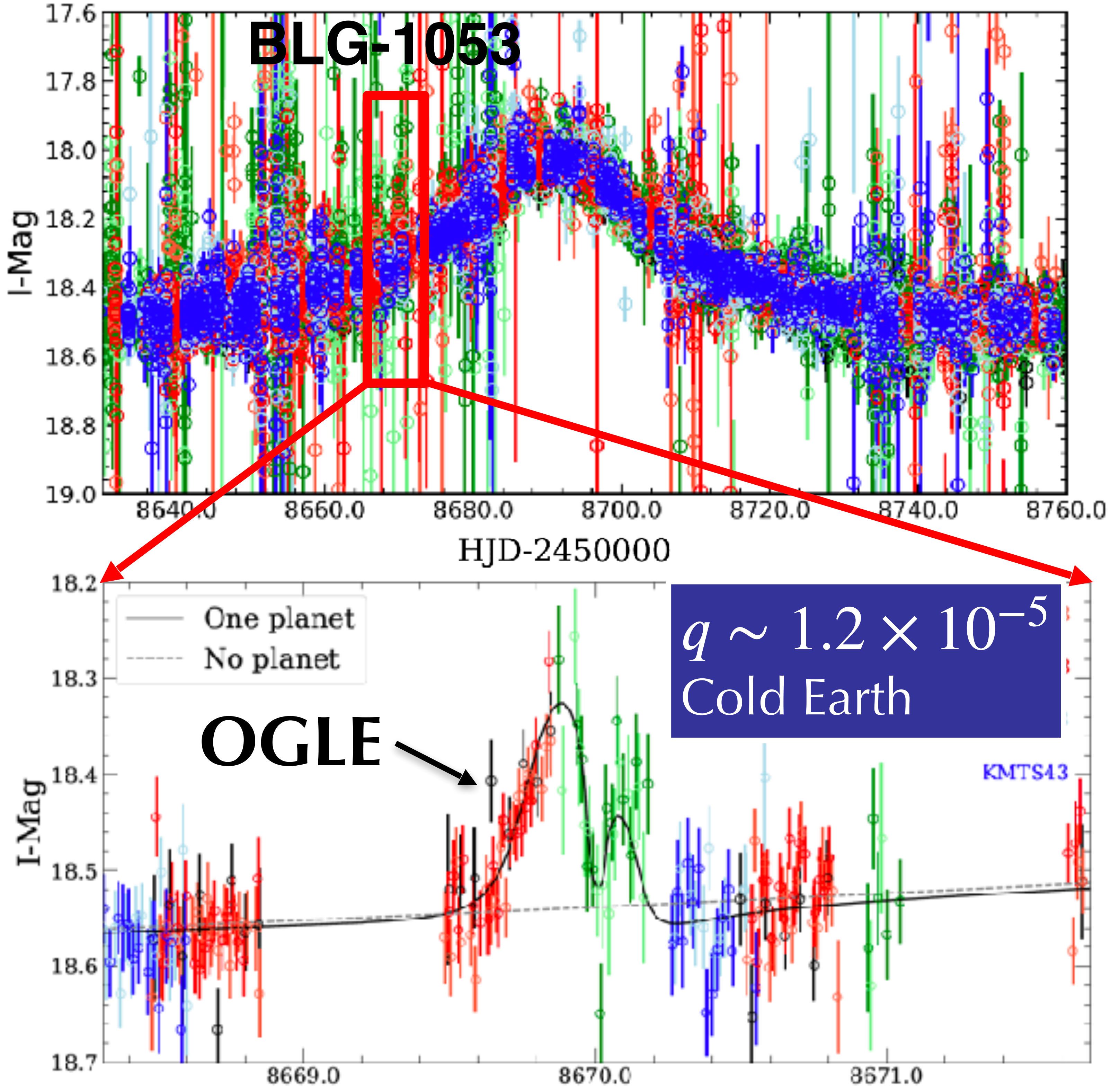


t_E =42min
Mars to Earth mass?
NO unique mass!



KMTNet PlanetFinder

OGLE-2019-BLG-1053

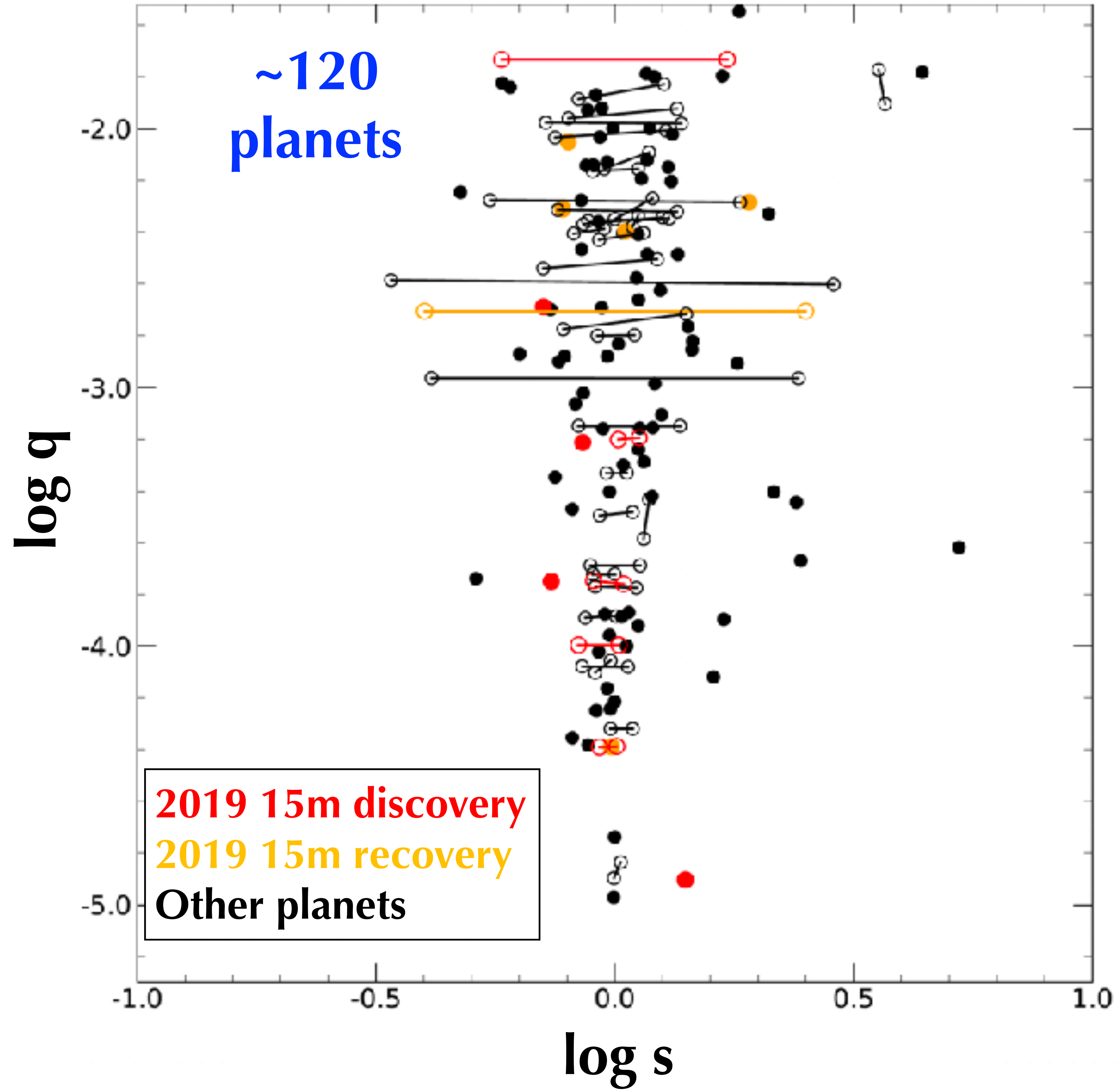


Zang et al. (2021b)

Weicheng Zang
(5th yr grad student
→ Harvard CfA)

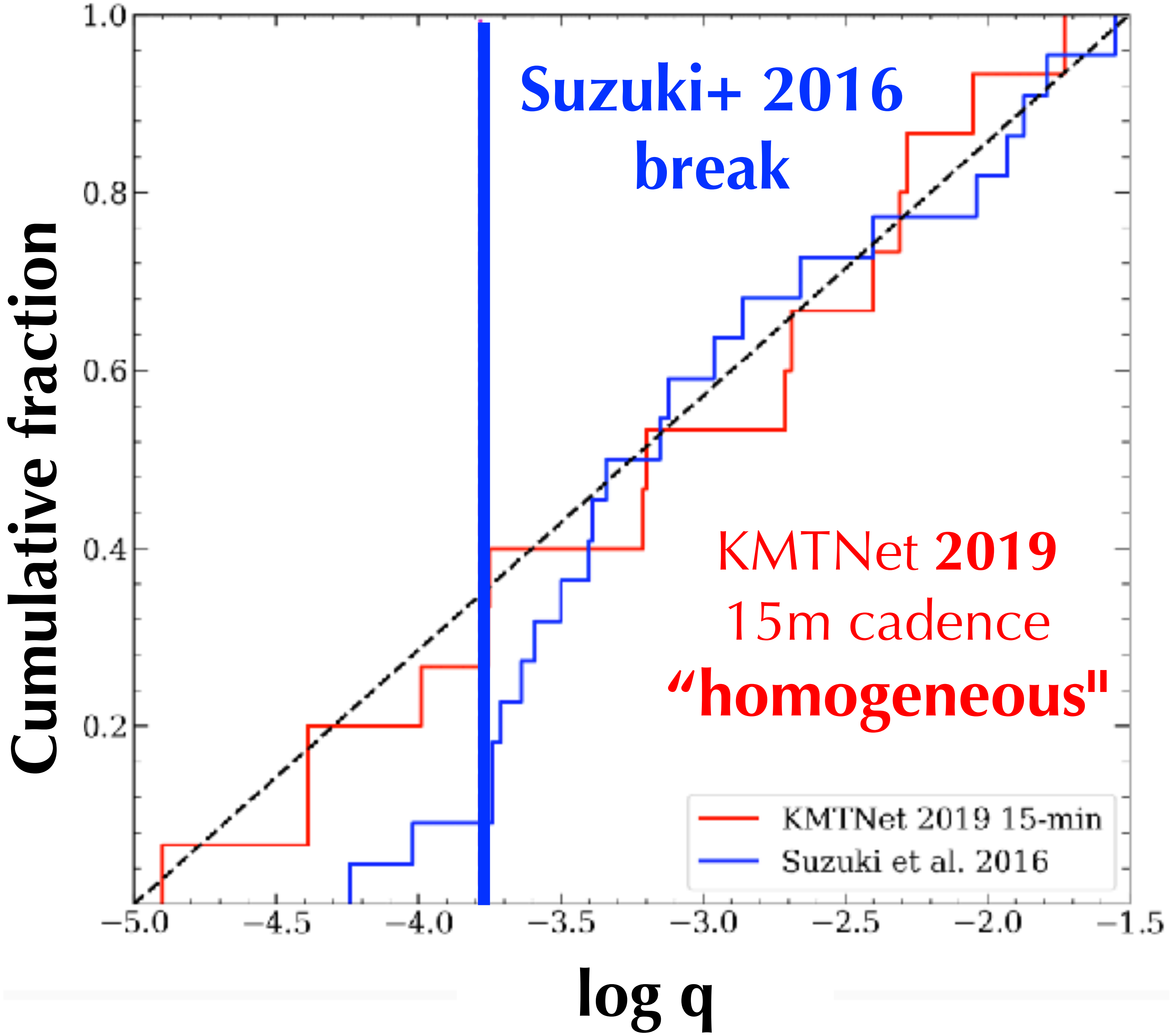
- **First semi-automated Microlensing Planet Finder**
- **One-year KMTNet: ~40 planets**

Reveal "buried" small planets



s: Planet-host separation scaled by Einstein radius

No evidence for a break in the mass ratio function



Zang et al. 2022

Zang et al. 2024, to be submitted

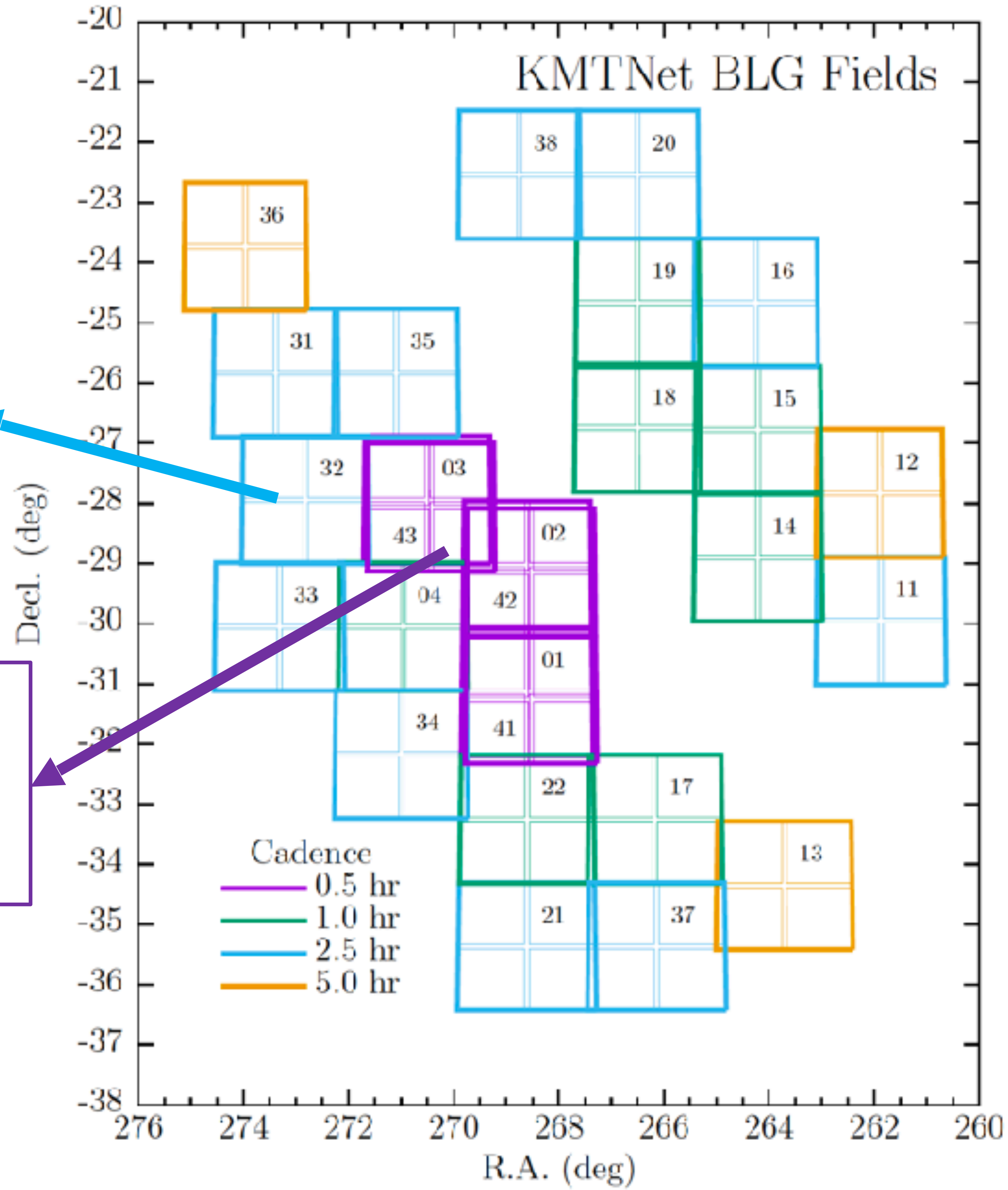
Detecting small planets with follow-ups

~84 sq. degree KMTNet low-cadence fields

Need follow-up observations

~ 12 sq. degree KMTNet high-cadence fields

Already sensitive to detect small planets



A global follow-up network

Leaders:

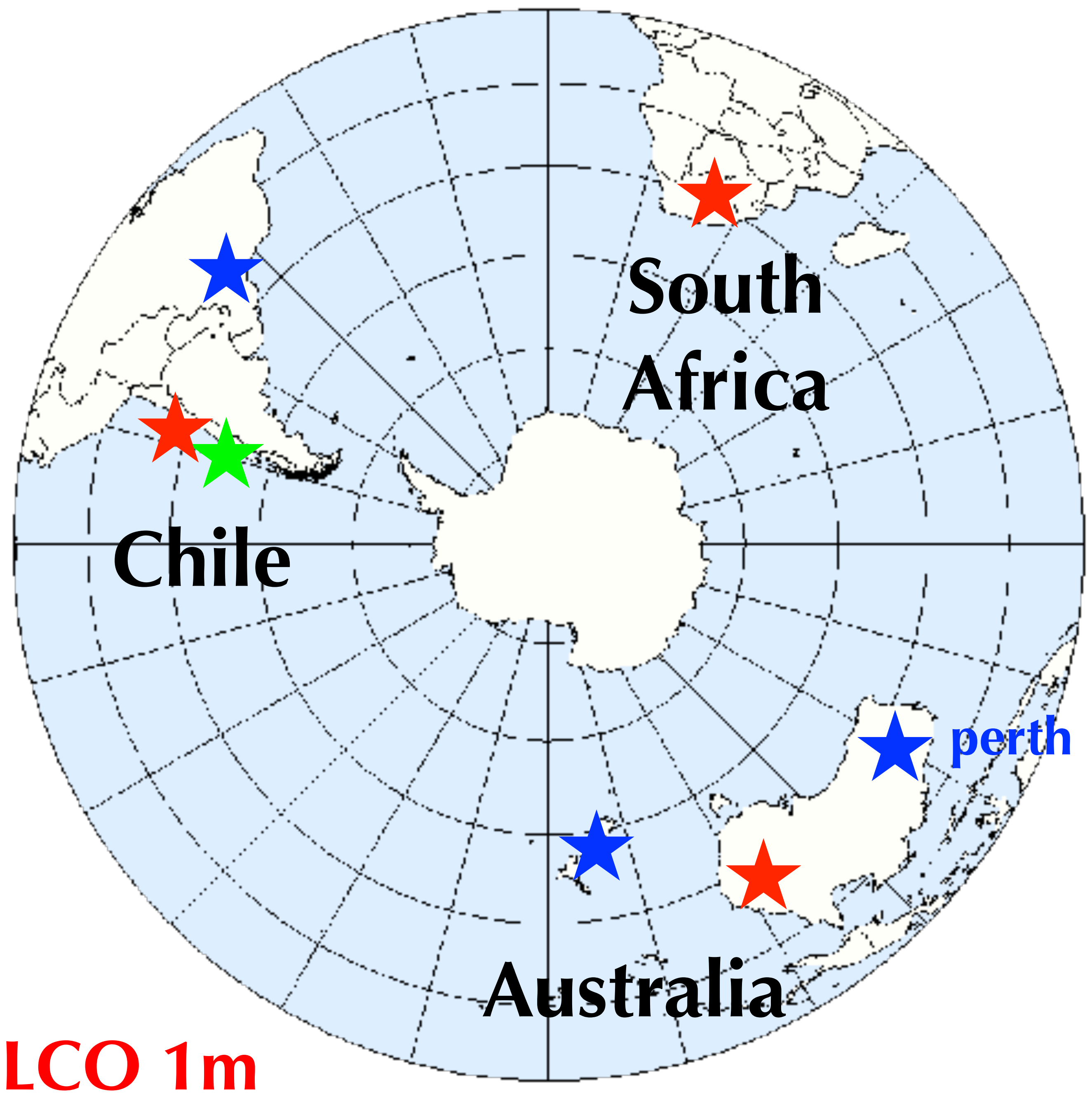
Weicheng Zang & Andrew Gould

Targets: high-magnification events

➢ **Sensitive to planets**

➢ **Bright**

- **Leading a LCO key project (PI: Zang and Mao) to discover low-mass and multiple planets! Stay tuned.**

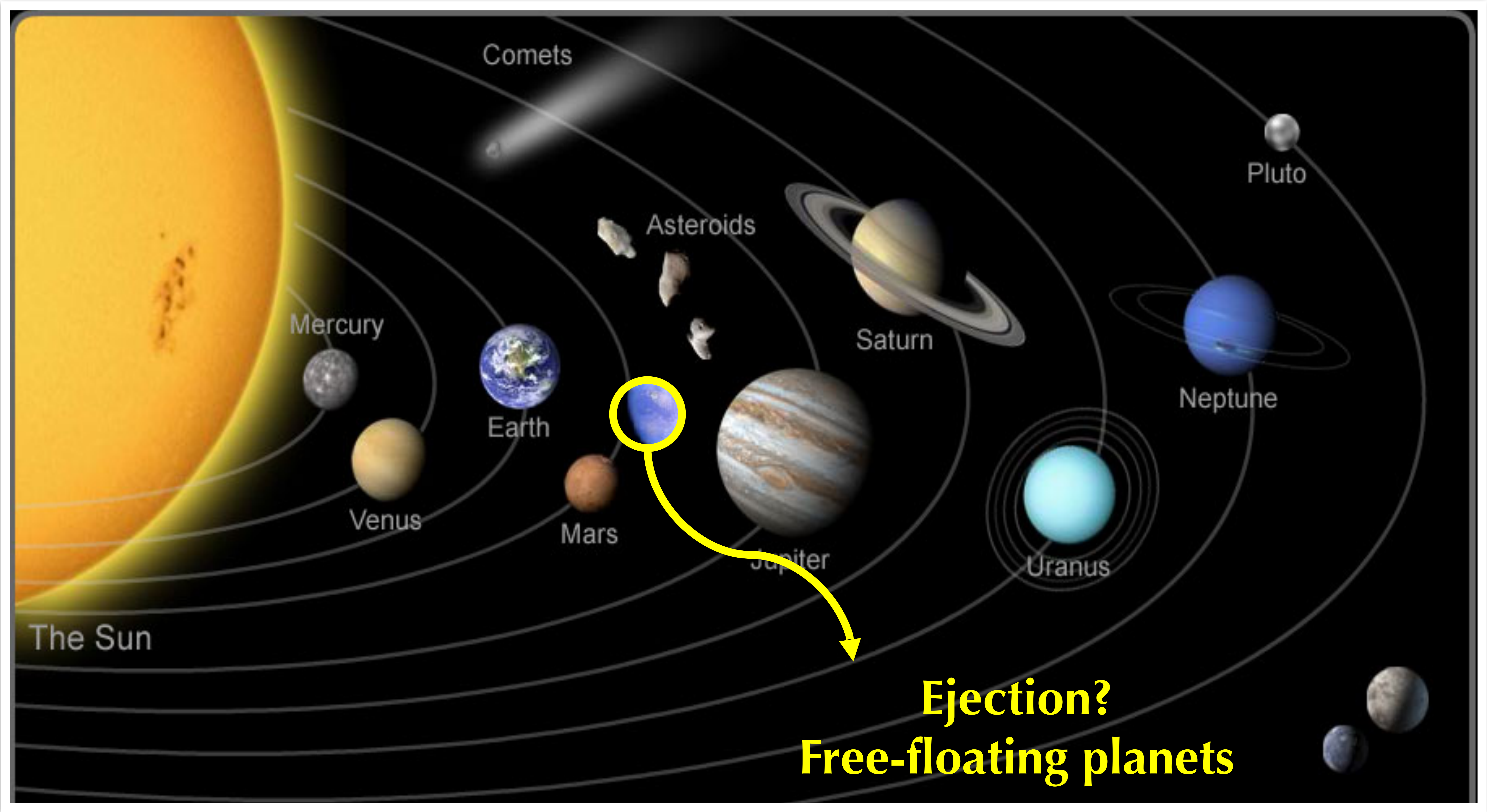


★ LCO 1m

★ MicroFUN

★ Chile 18, 50, 60cm

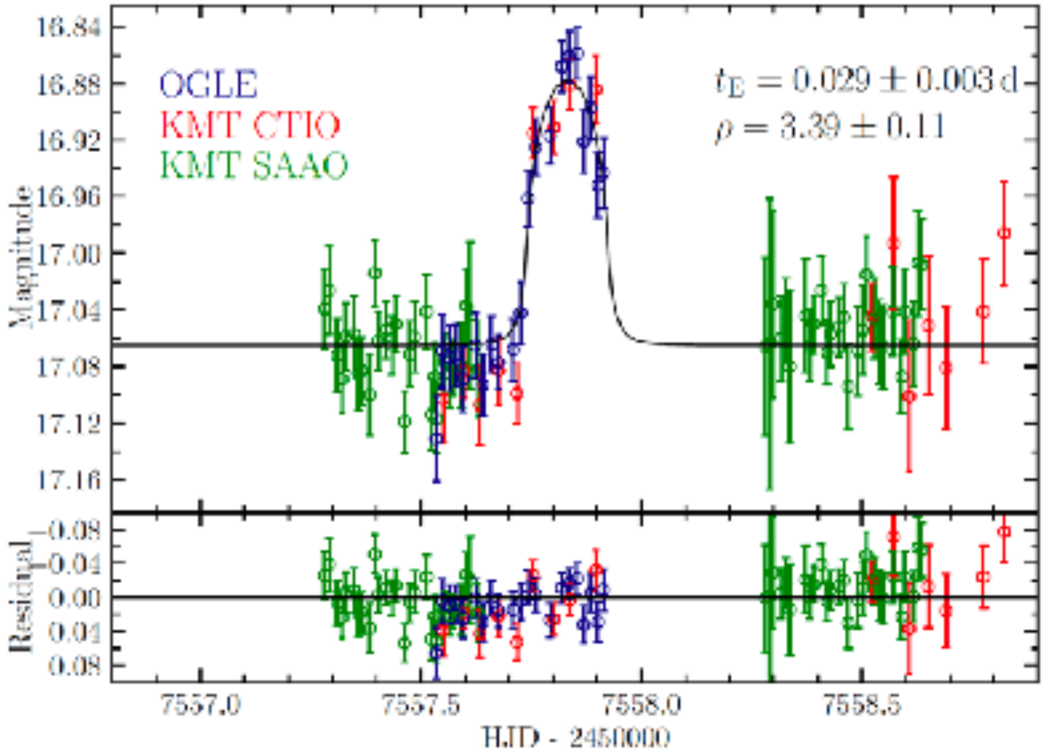
Dynamical evolution: free-floating planets



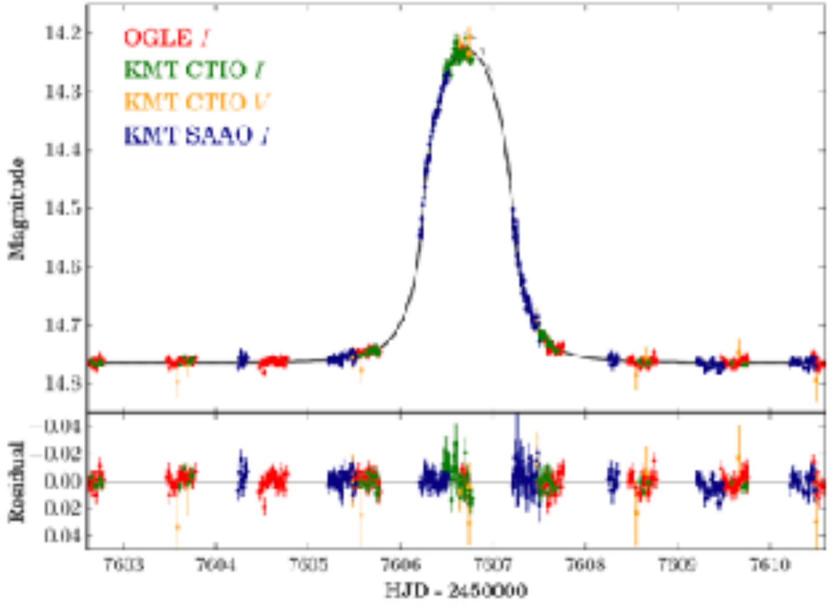
Free-floating planets?

Mroz+ 2020

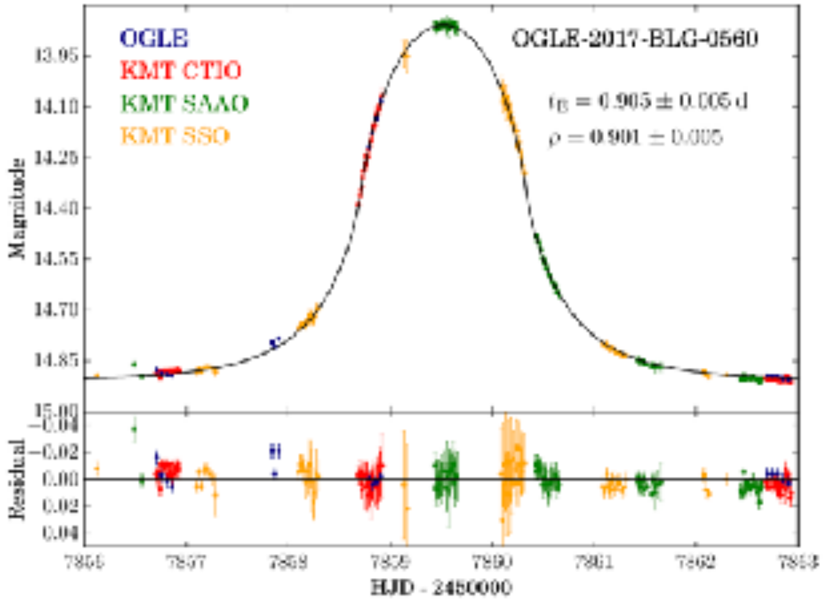
OGLE + KMTNet collaborations



t_E = 0.03d
= 42min
Mars to Earth!



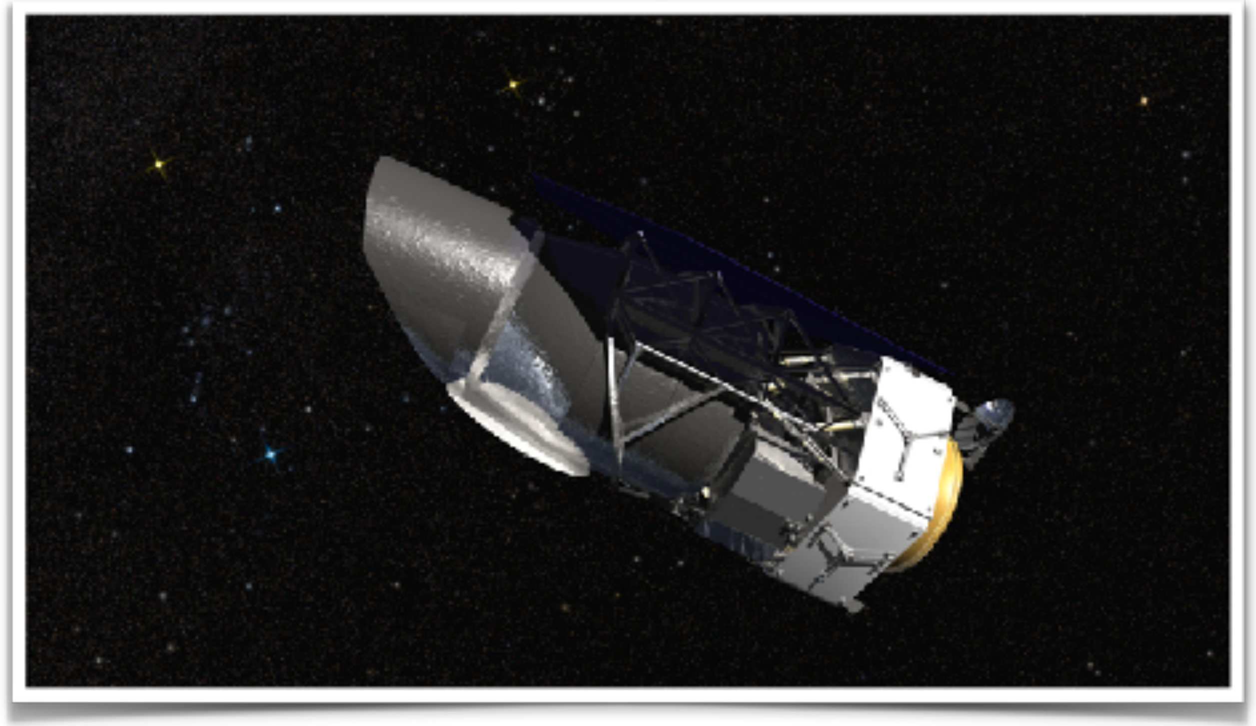
t_E = 0.32d
~Neptune mass



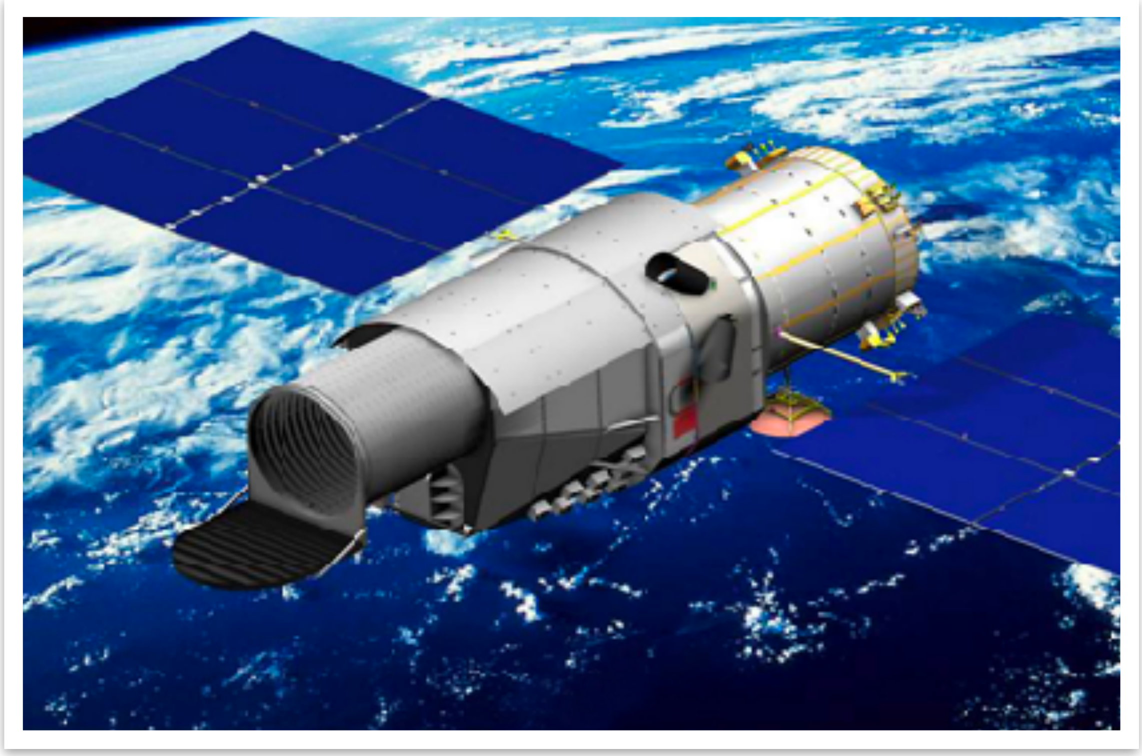
t_E = 0.91d
Jupiter mass

- 12 candidates found so far
- Free-Floating Earth ~ 5-10 per star? (see also Gould+ 2022)
- NO firm masses!

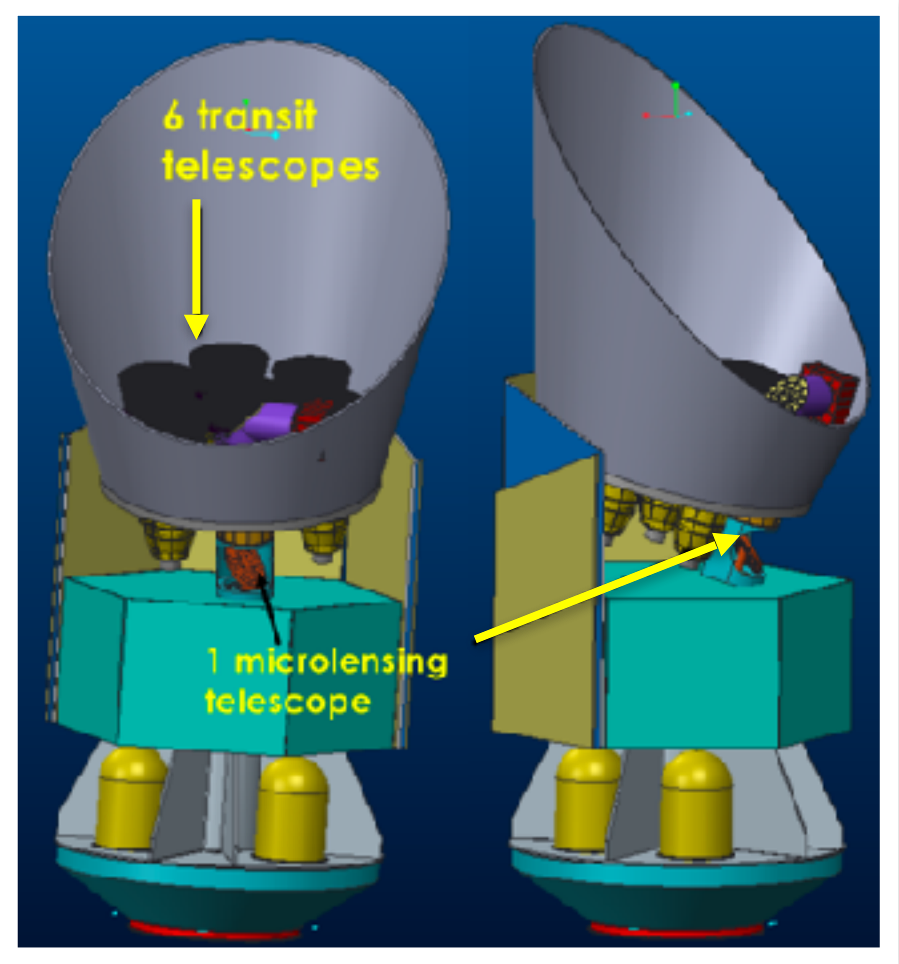
Microlensing from space



Roman
(2027+)
NASA



CSST
(2025+)
Zhu, Dong+

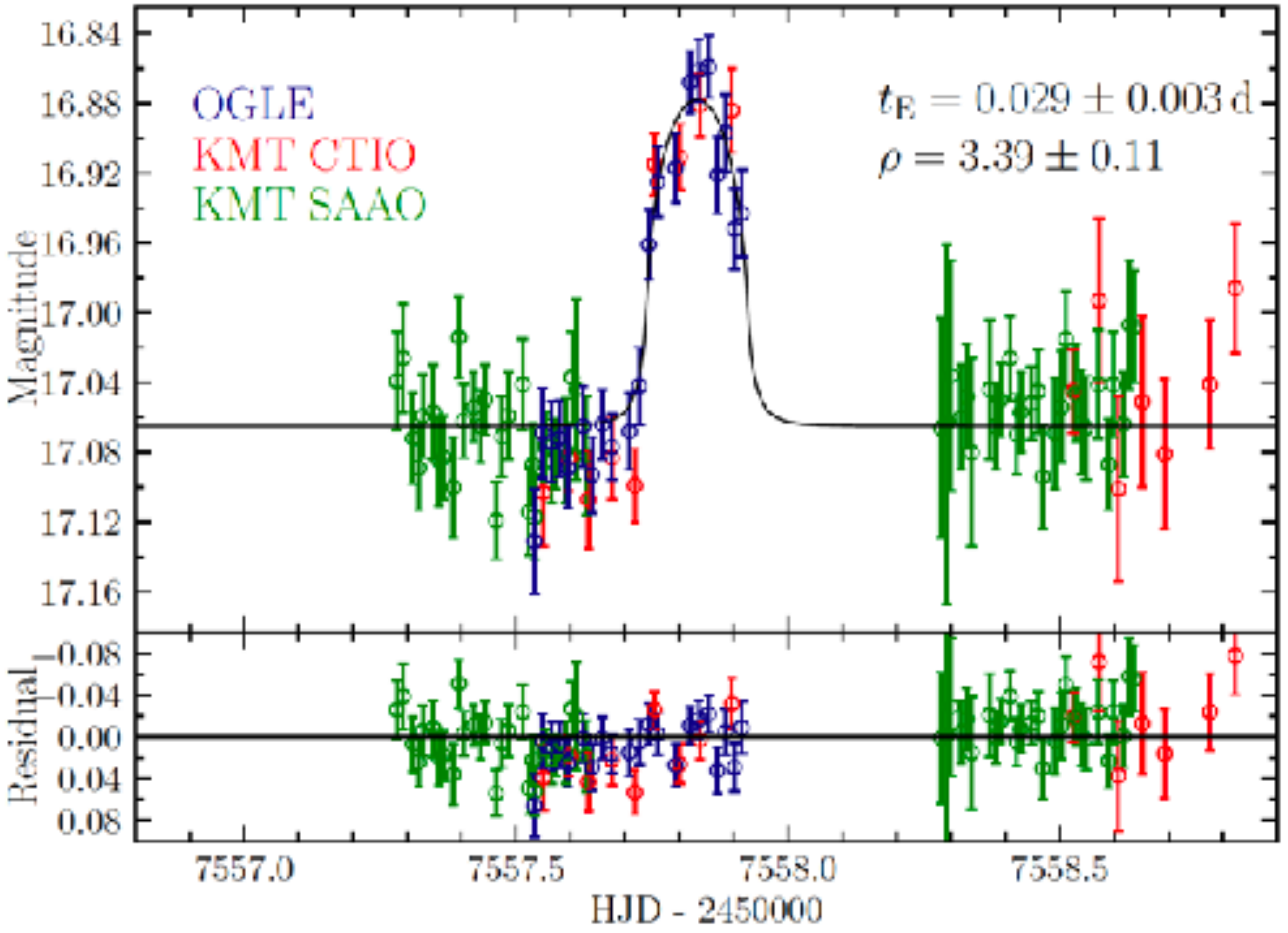


Earth 2.0 (ET)
2026+
Zang, Mao +

At L2, 0.01 AU
Ideal for measuring
free-floating planet
parallax

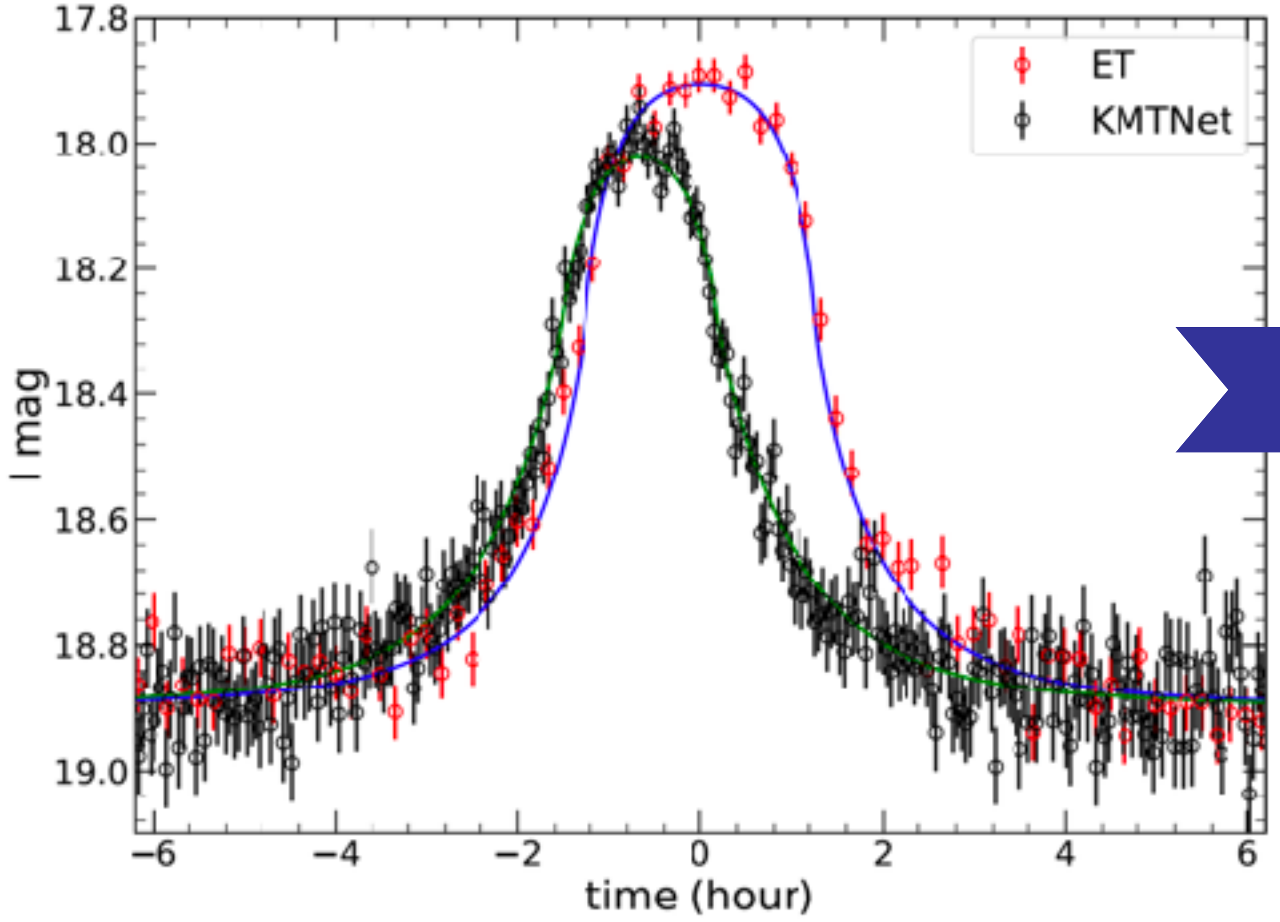
ET can determine FFP masses

Ground: candidates



Mroz et al. 2020

Ground/KMTNet+Space/ET: robust determination of mass



$\theta_E\ \pi_E$

Free-floating Earth

Gould, Zang, Mao et al. 2021

5. Summary

- **Many (200+) microlensing planets have been discovered**
- **Microlensing is the best method to probe the cold planet population**
- **Future for gravitational microlensing is bright:**

➢ Ground-based facilities can probe cold planets in multiple ways

➢ Satellites can discover a factor ~10 more planets, including free-floating ones

➢ **Significantly constrain planet formation theories**

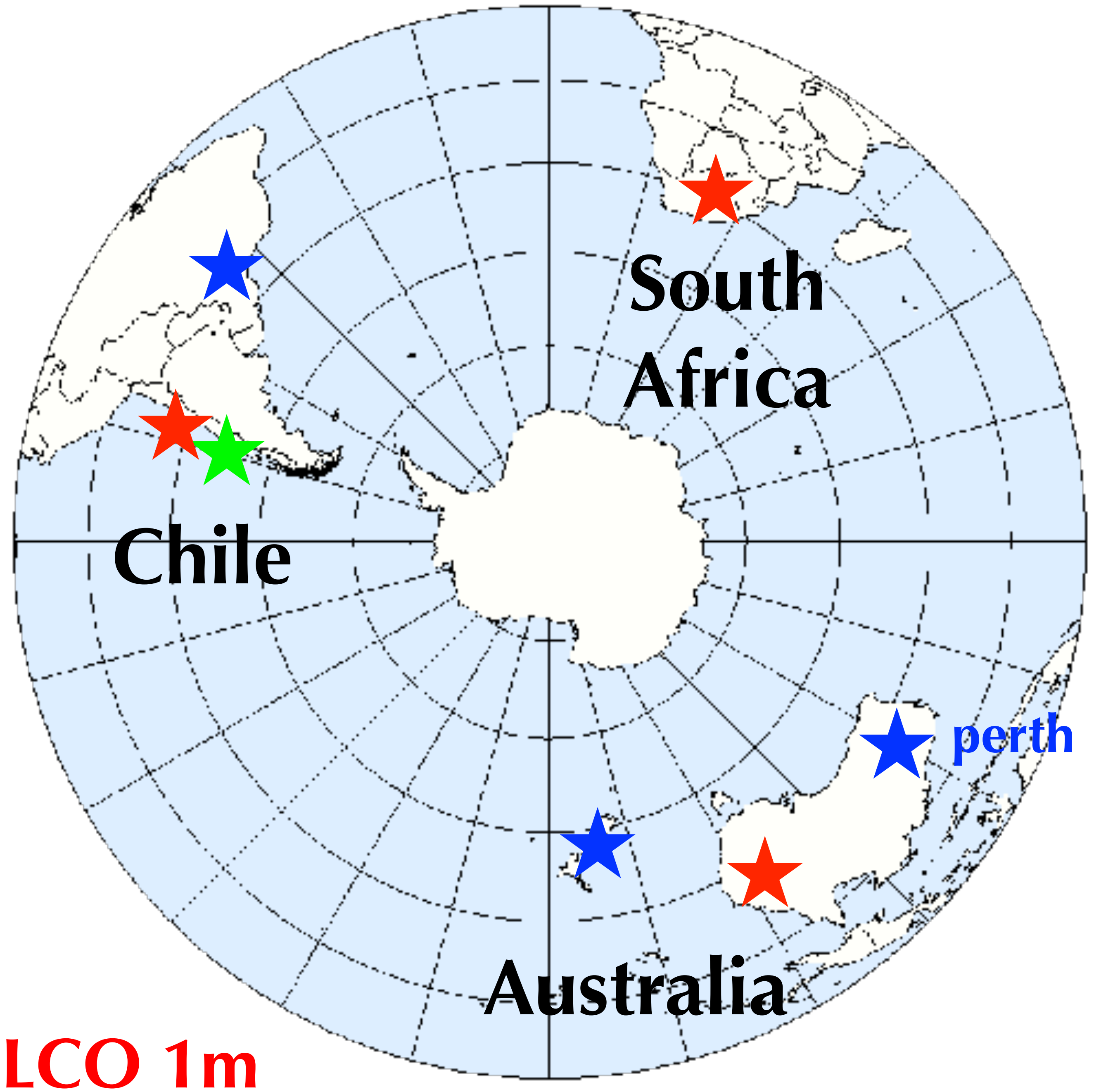
A global follow-up network

Leaders:

Weicheng Zang & Andrew Gould

Targets: high-magnification events

- ➢ Sensitive to planets
- ➢ Bright

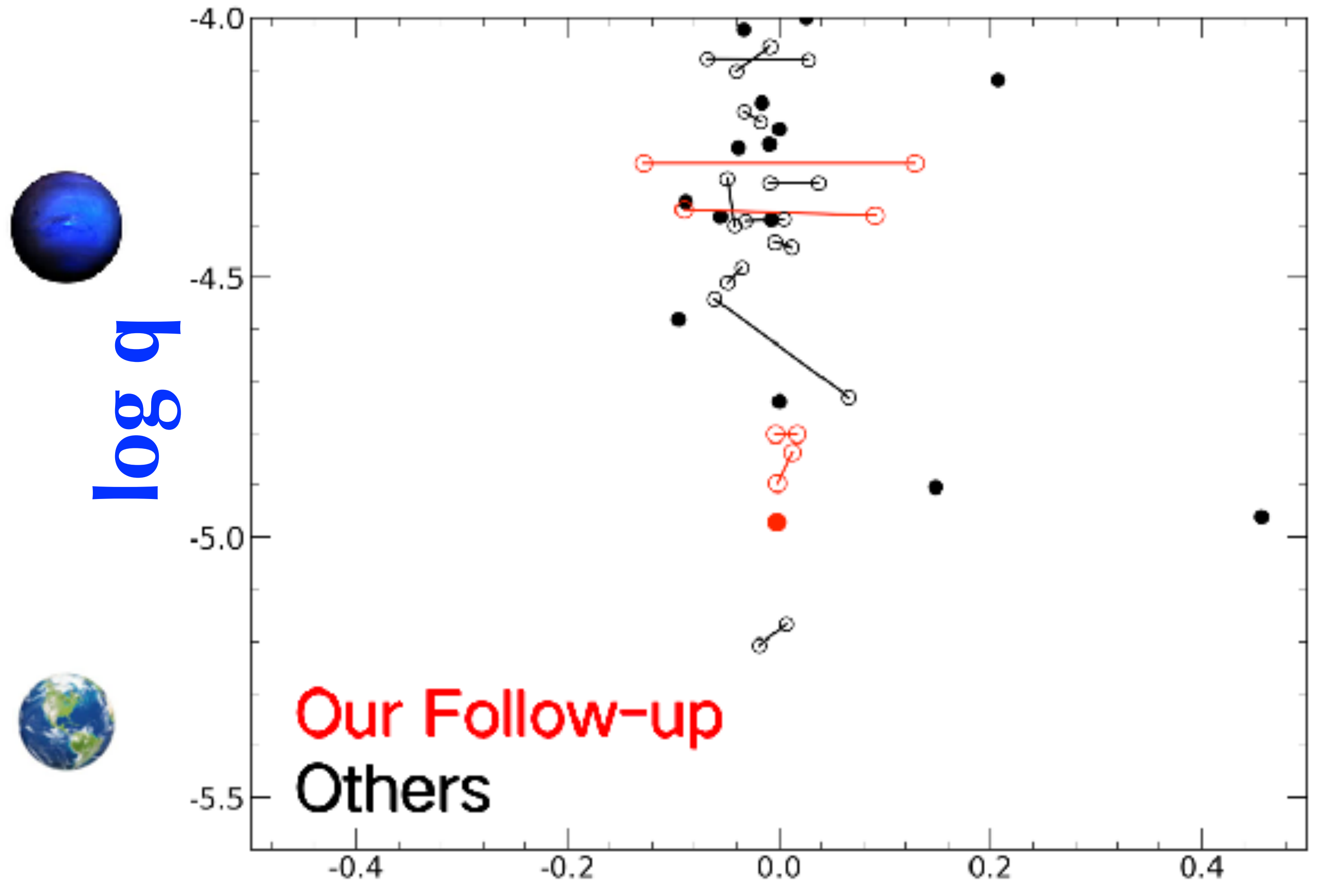


★ LCO 1m

★ MicroFUN

★ Chile 18, 50, 60cm

Detecting low mass-ratio planets

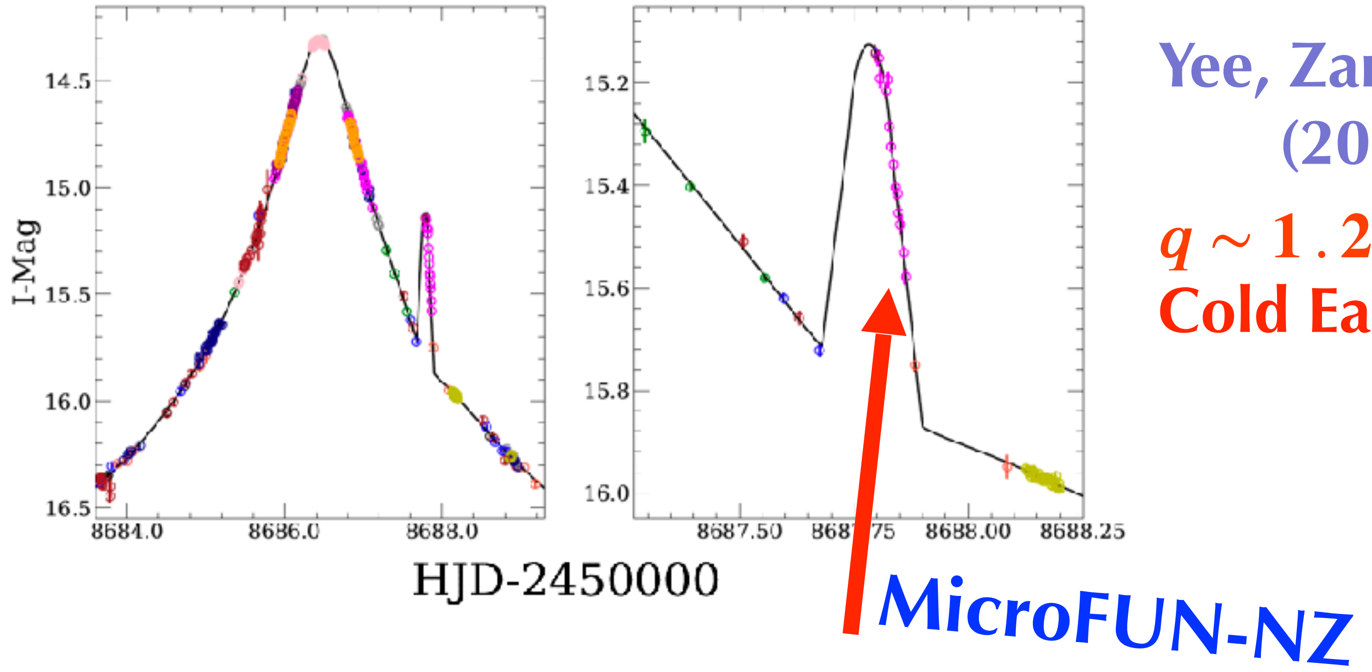


s: Planet-host separation scaled by Einstein radius

Zang et al. (2021a); Yee, Zang et al. (2021)

Yang, Zang et al; Zhang, Zang et al. in prep

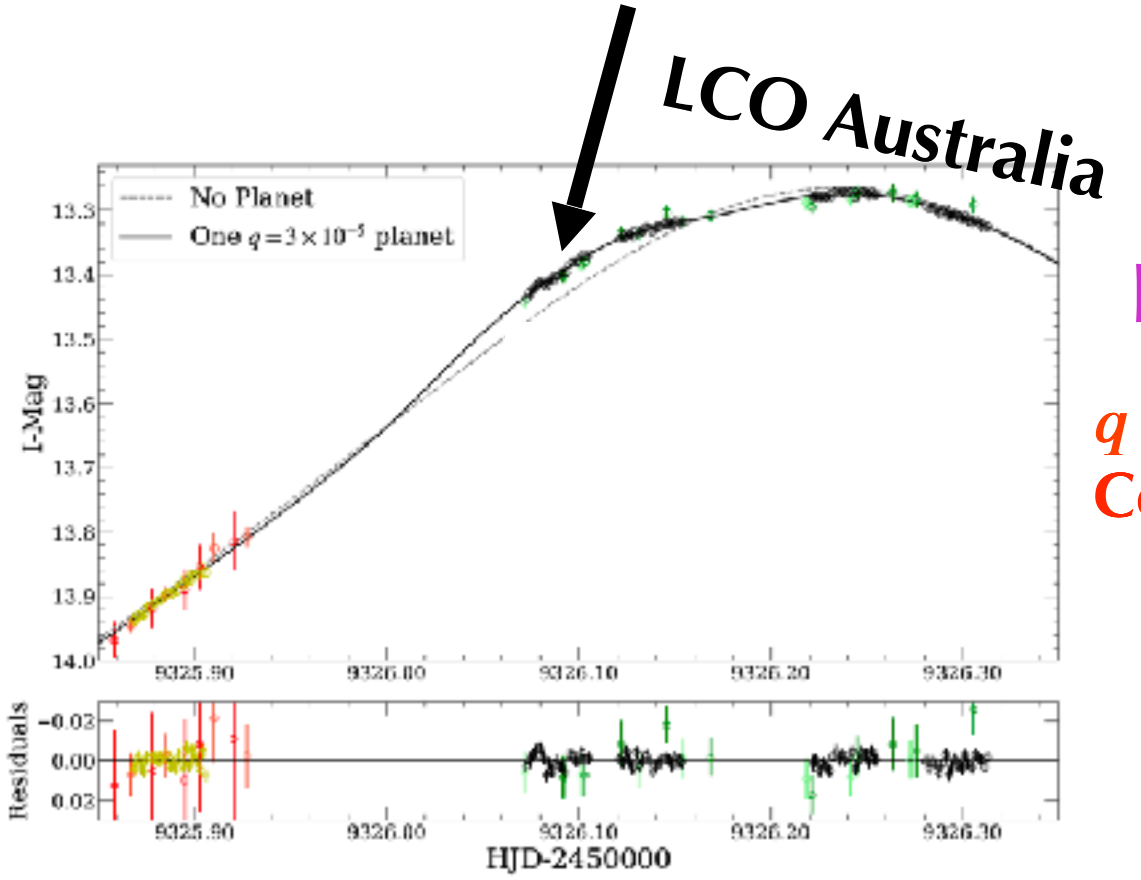
OGLE-2019-BLG-0960



Yee, Zang et al. (2021)

$q \sim 1.25 \times 10^{-5}$

Cold Earth



KB210171

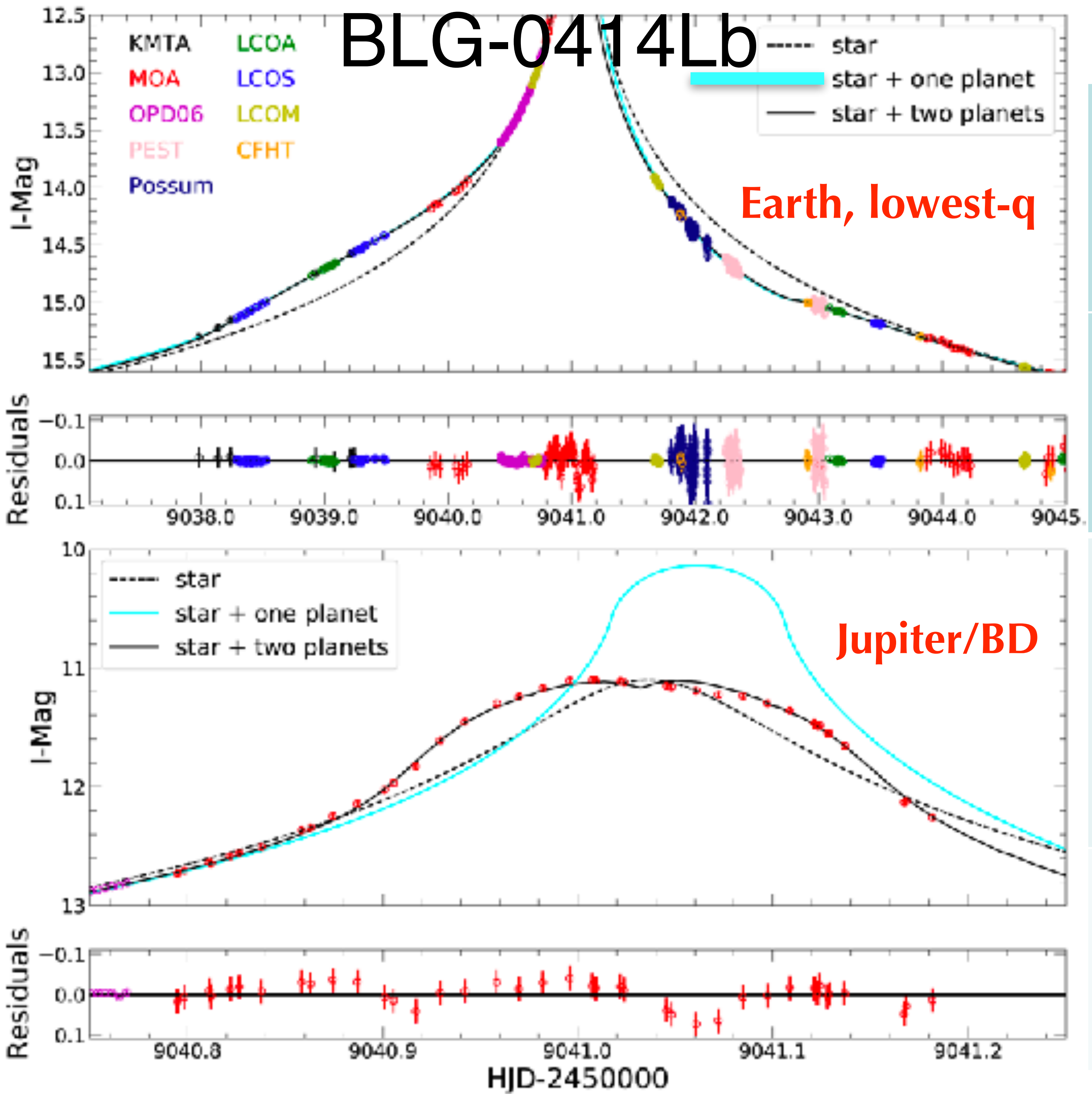
$q \sim 3 \times 10^{-5}$

Cold super-Earth

KB210171 Yang, Zang et al. 2022

Discovering two planet systems

KMT-2020-BLG-0414Lb



	Gould + 2010	Suzuki+ 2018	~20 yr microlensing	Our follow-up (2 yr)
Team	μFUN	MOA	All teams	KMTNet + LCO + μFUN
Two-planet system	1	1	5	2
Occurrence rate	~1/6	~6%	Non-homogeneous	A future paper

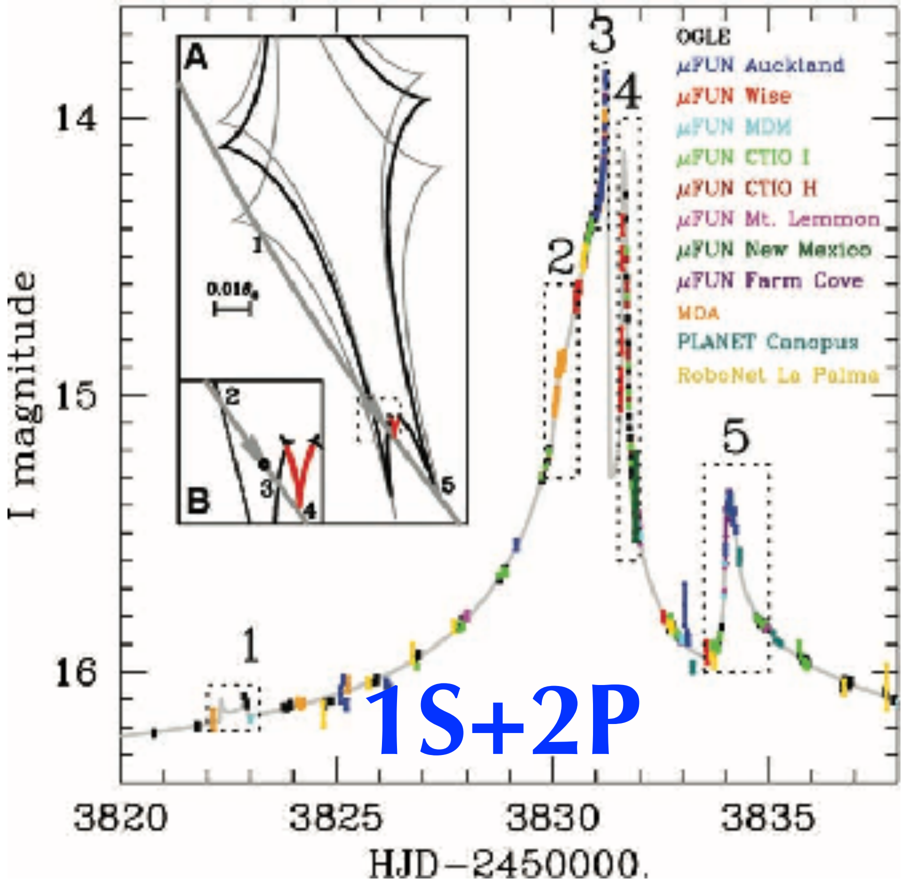
Zang et al. (2021a)

Multiple planets/circum-binary planets: triple lensing

OGLE-2006-BLG-109L

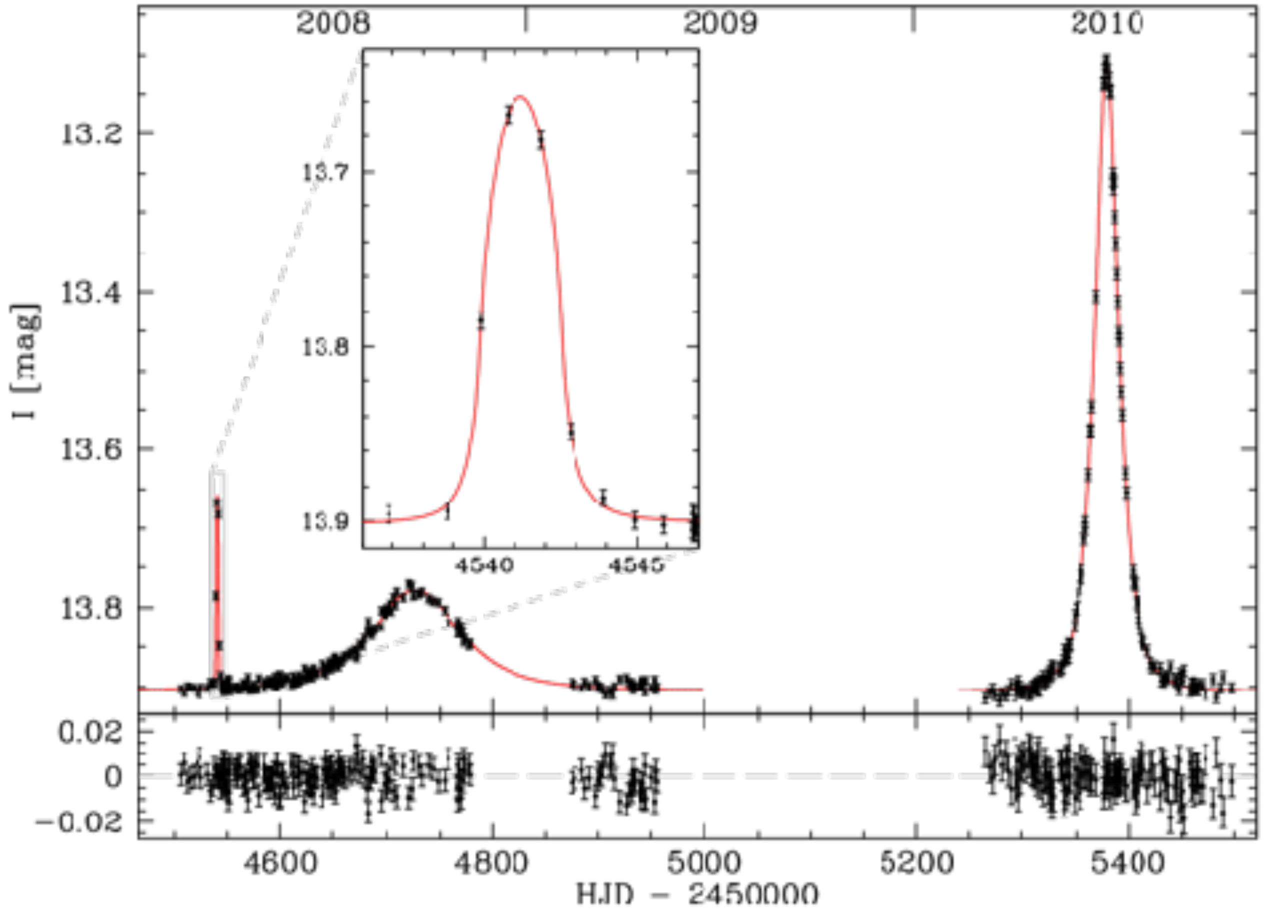
1 Star
+2 planets

(J:S analogs)



Gaudi et al. (2009)

OGLE-2008-BLG-092

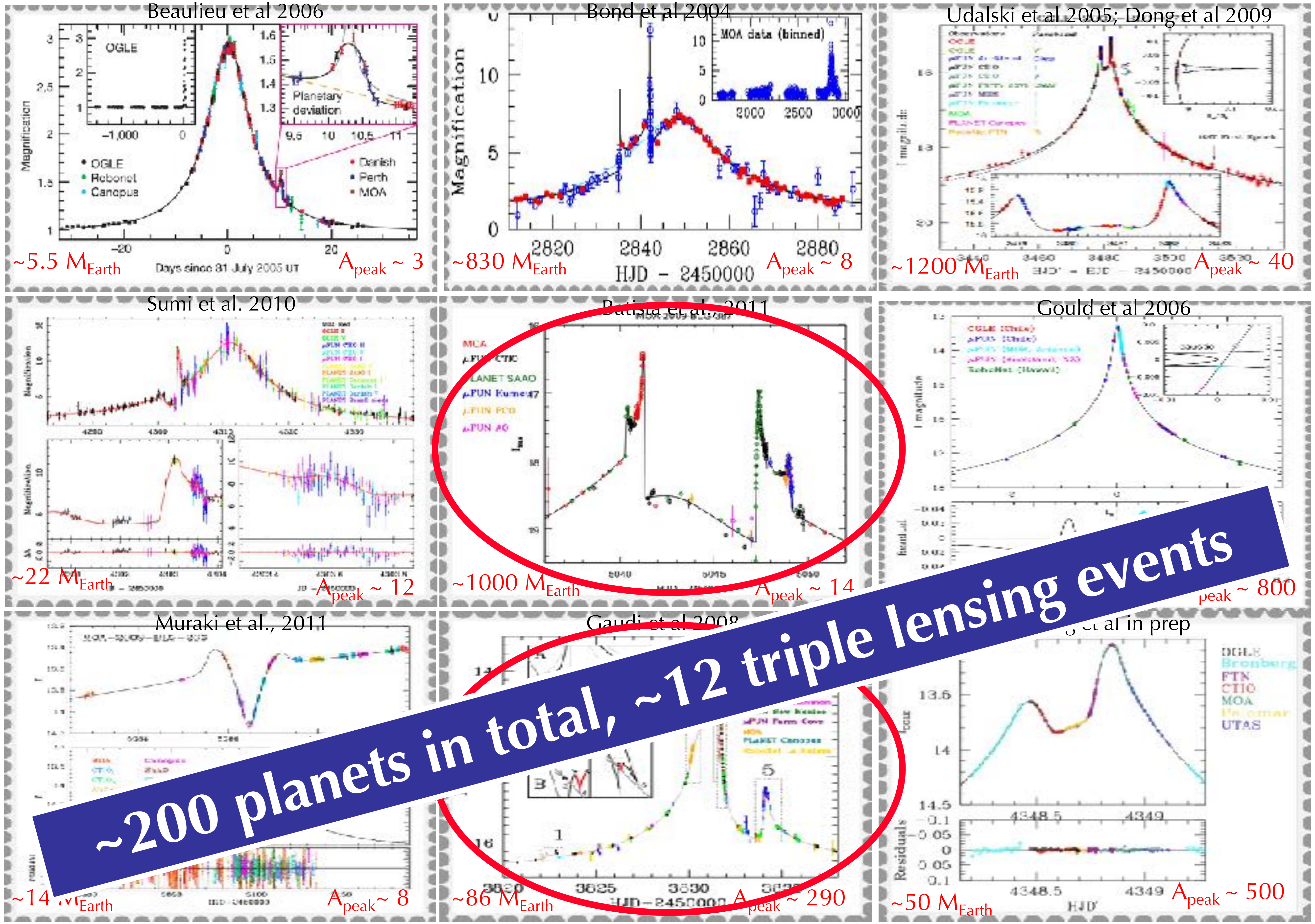


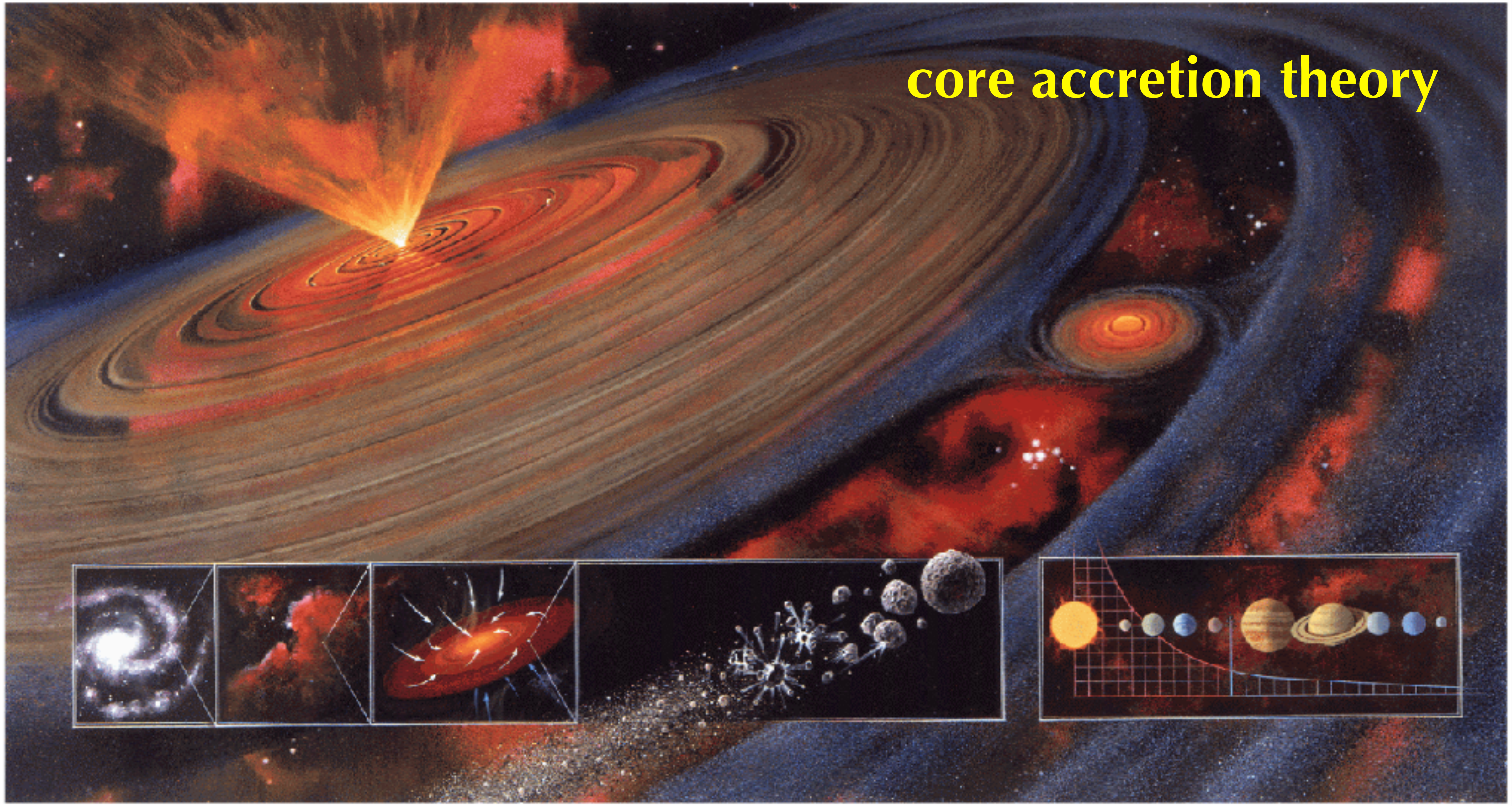
Poleski et al. (2014)

2 Stars
+1 planet
(~Uranus)

- Probe multiple planet population beyond the snow line
- Probe formation scenarios of planets around binary stars
- How to model them remains a challenge (Kuang, Mao et al. 2021)!

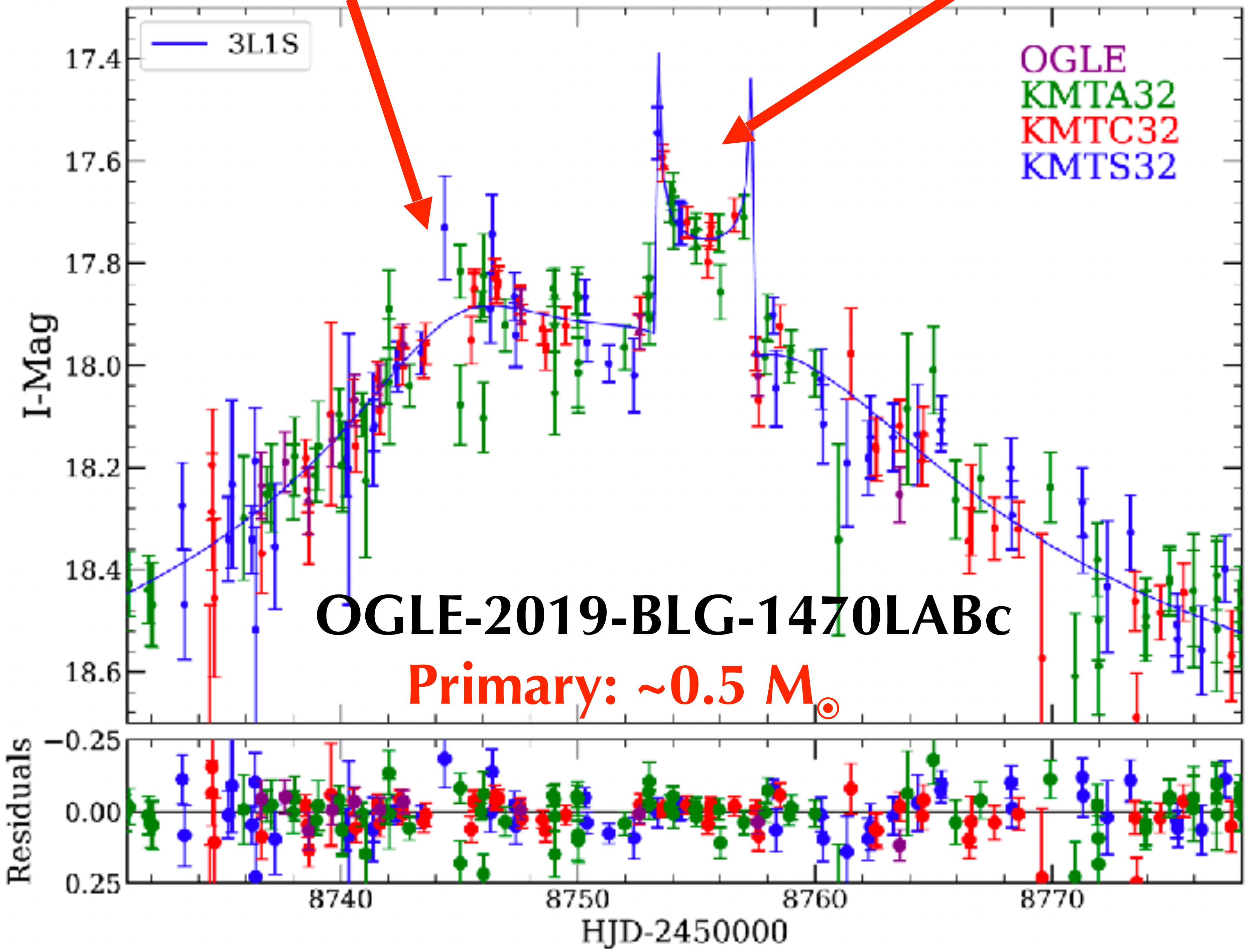
Examples of Microlensing Planets





- How do planets form? How do giant planets around M dwarfs form?
- Is the solar system unusual?
- Are there differences in planet formation efficiency in different environments (e.g. thin, thick disks, bulge)?
- Planetary atmospheres (JWST)?

First public triple-lens code

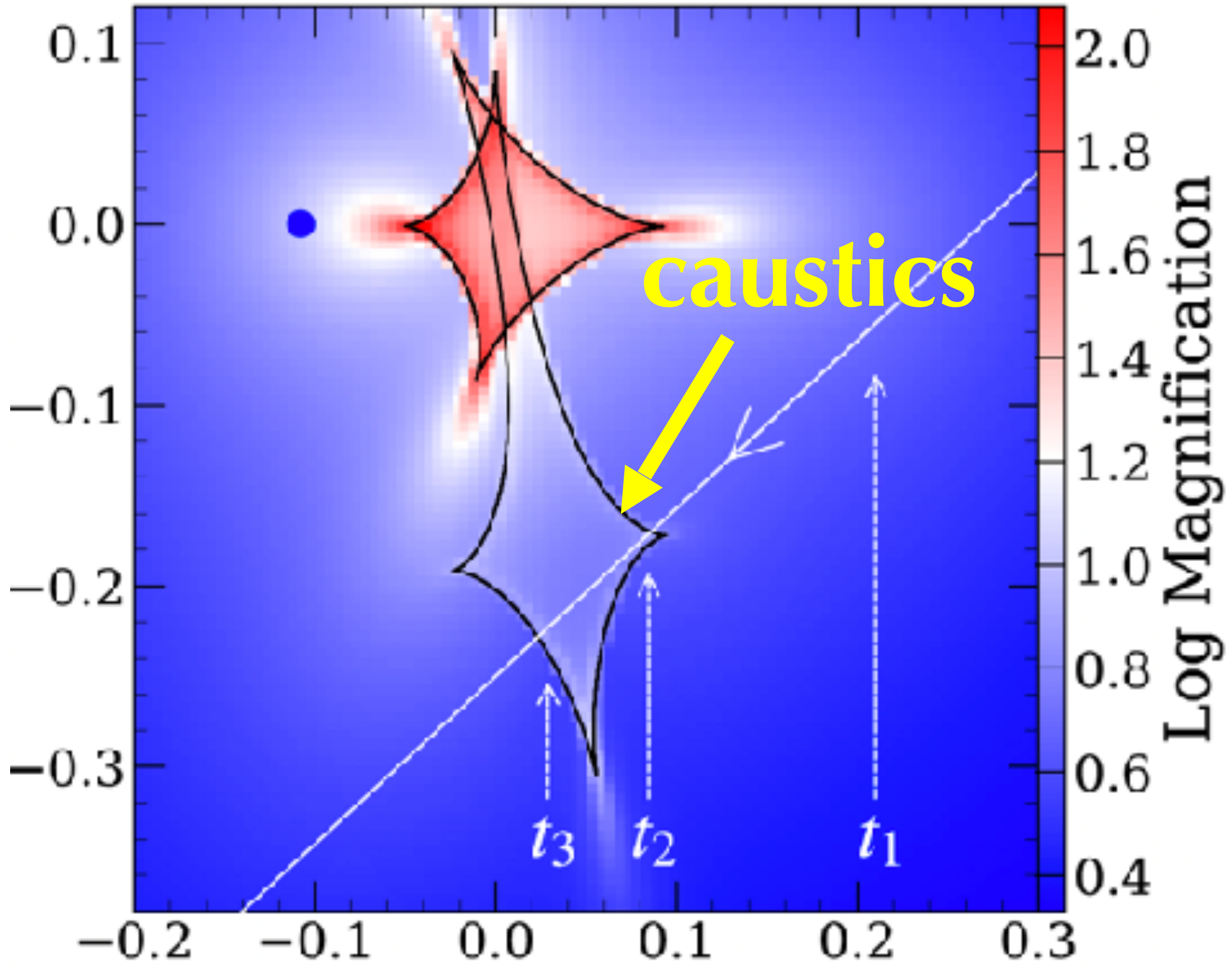


Kuang, Zang et al. (2022), submitted

Renkun Kuang
(4th yr grad student)

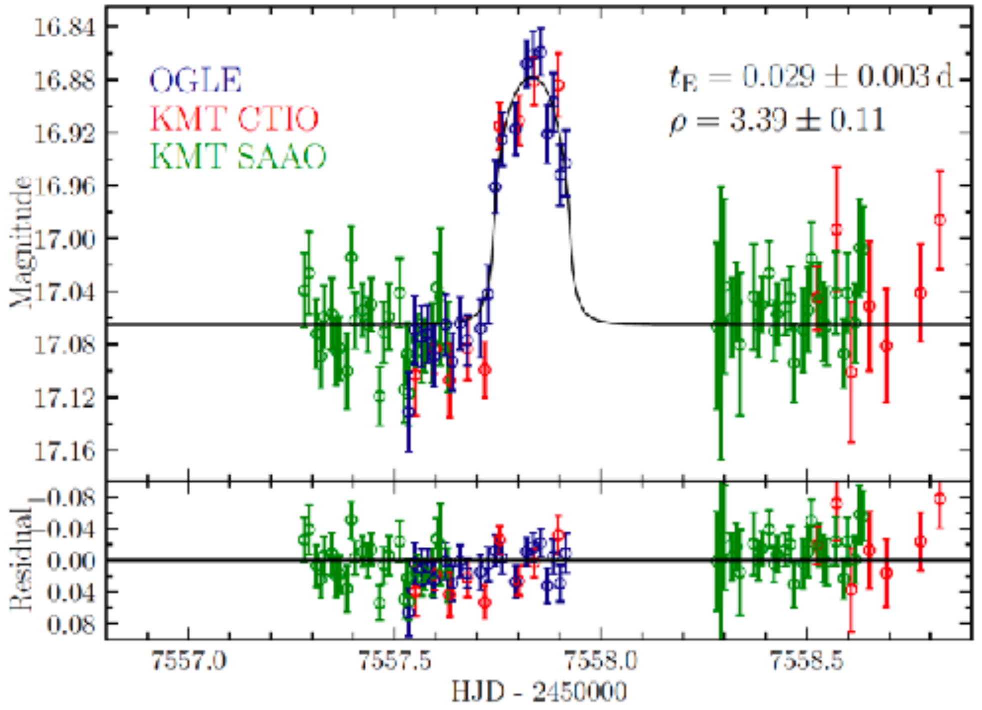
https://github.com/rkkuang/triplelens

Magnification pattern



Free-floating planets: dynamical/chaotic ejections

~20 FFPs/star?
(Sumi+23; Gould+23)



t_E =42min
Mars to Earth mass?
NO unique mass!