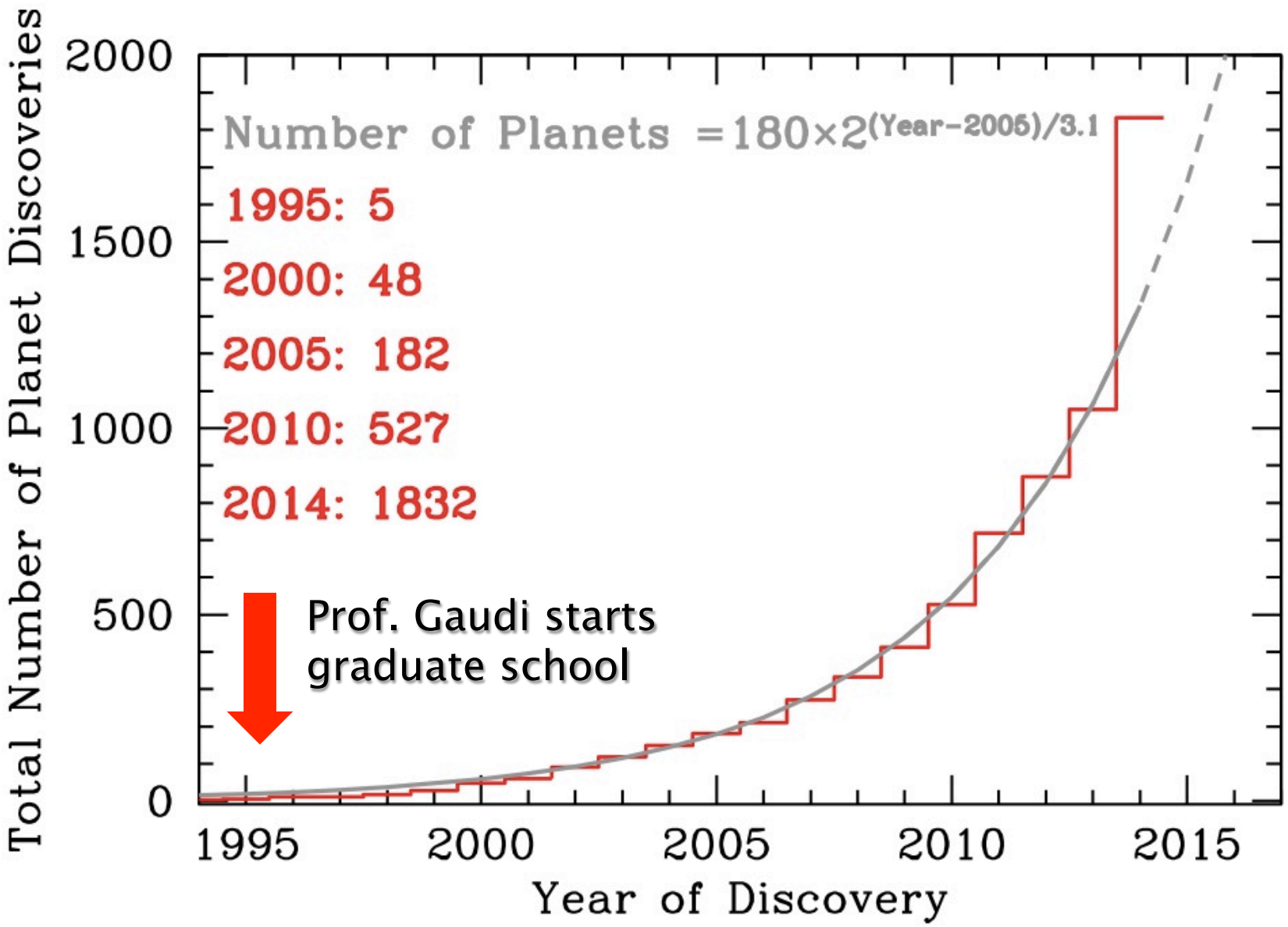
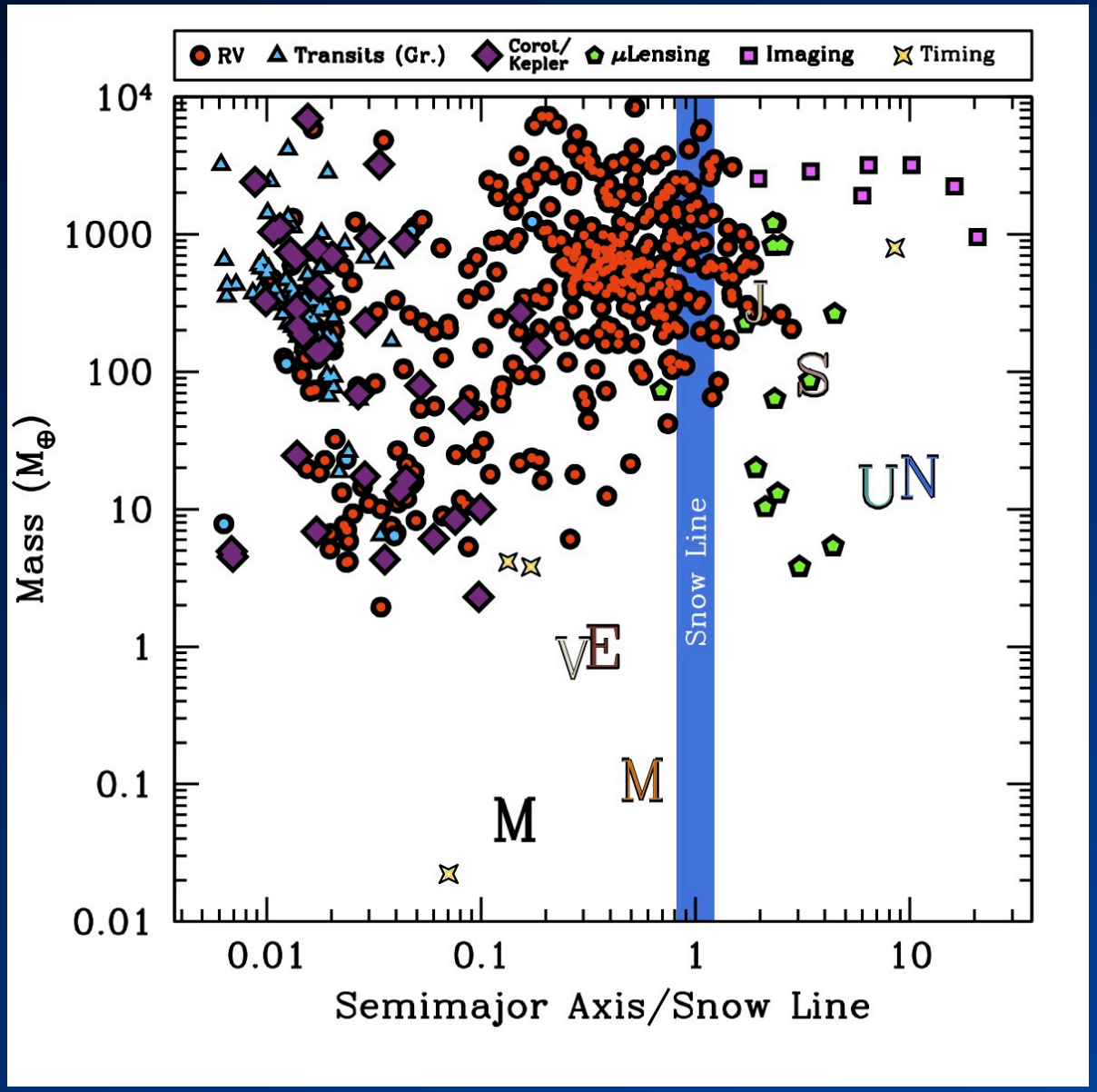
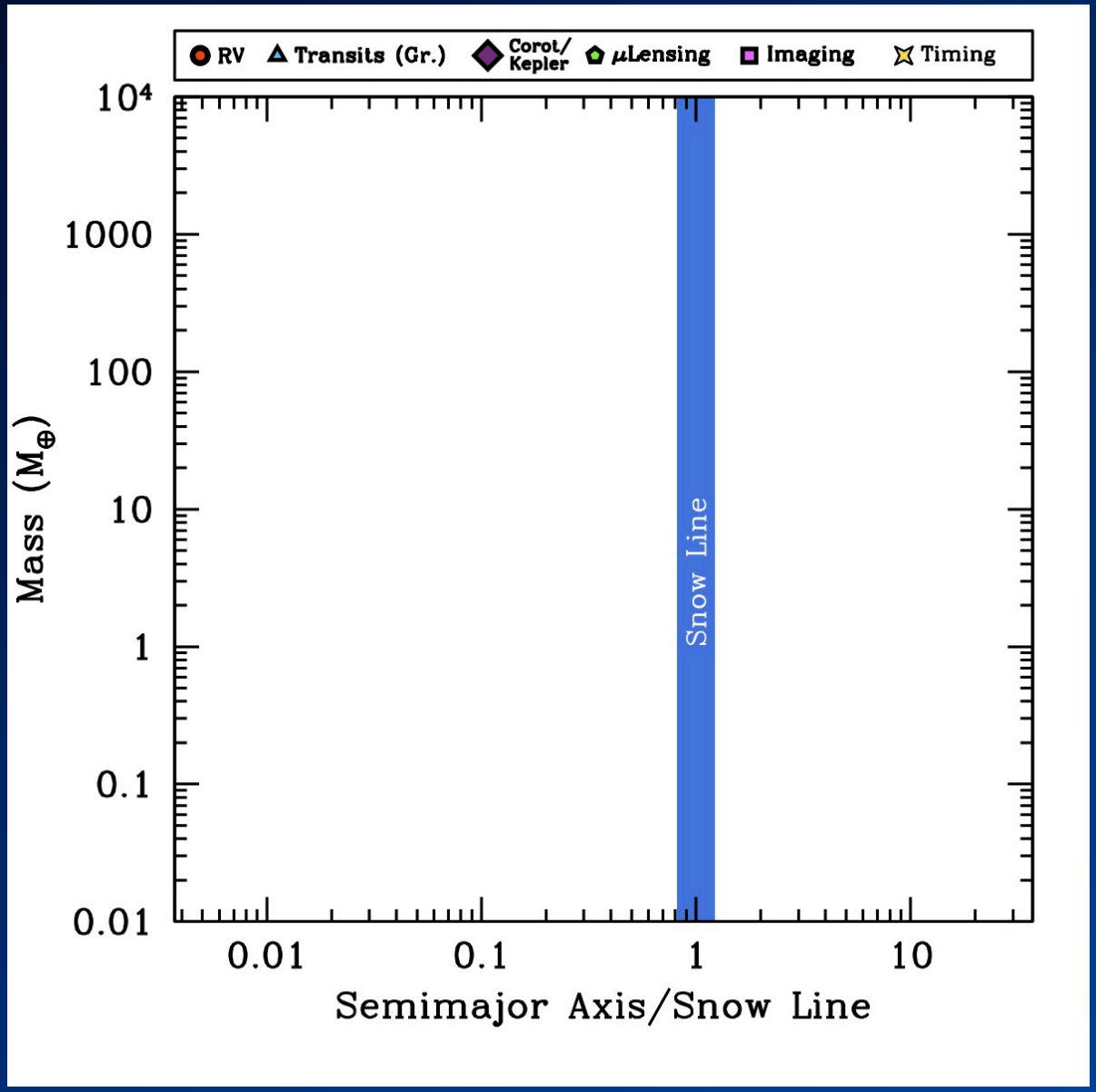
Detection Methods.

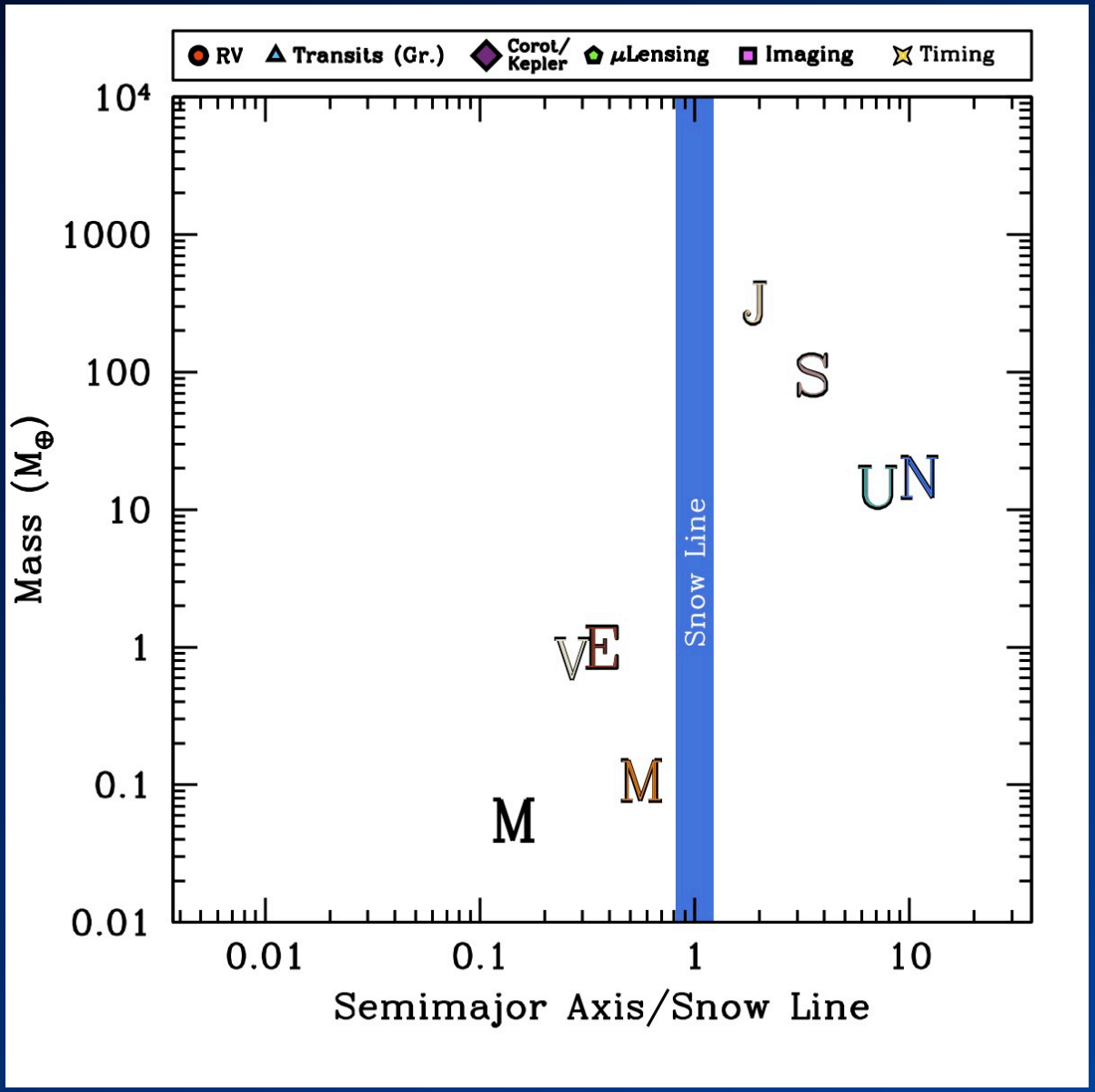
- Direct Imaging.
- Radial velocities.
- Astrometry.
- Timing.
- Transits.
- Microlensing.

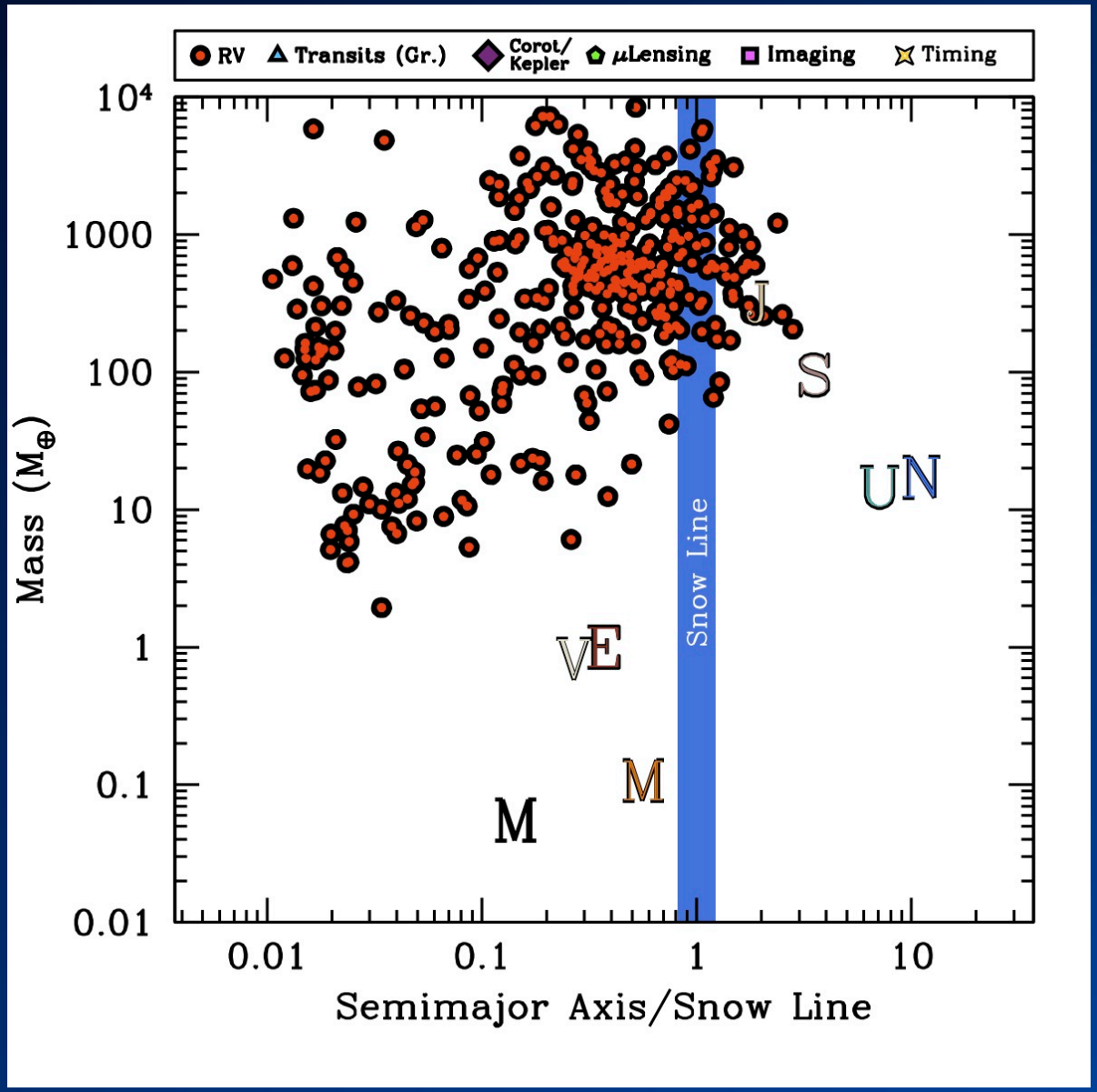
Underlying physics of all of these methods is relatively simple; this physics dictates their sensitivity.

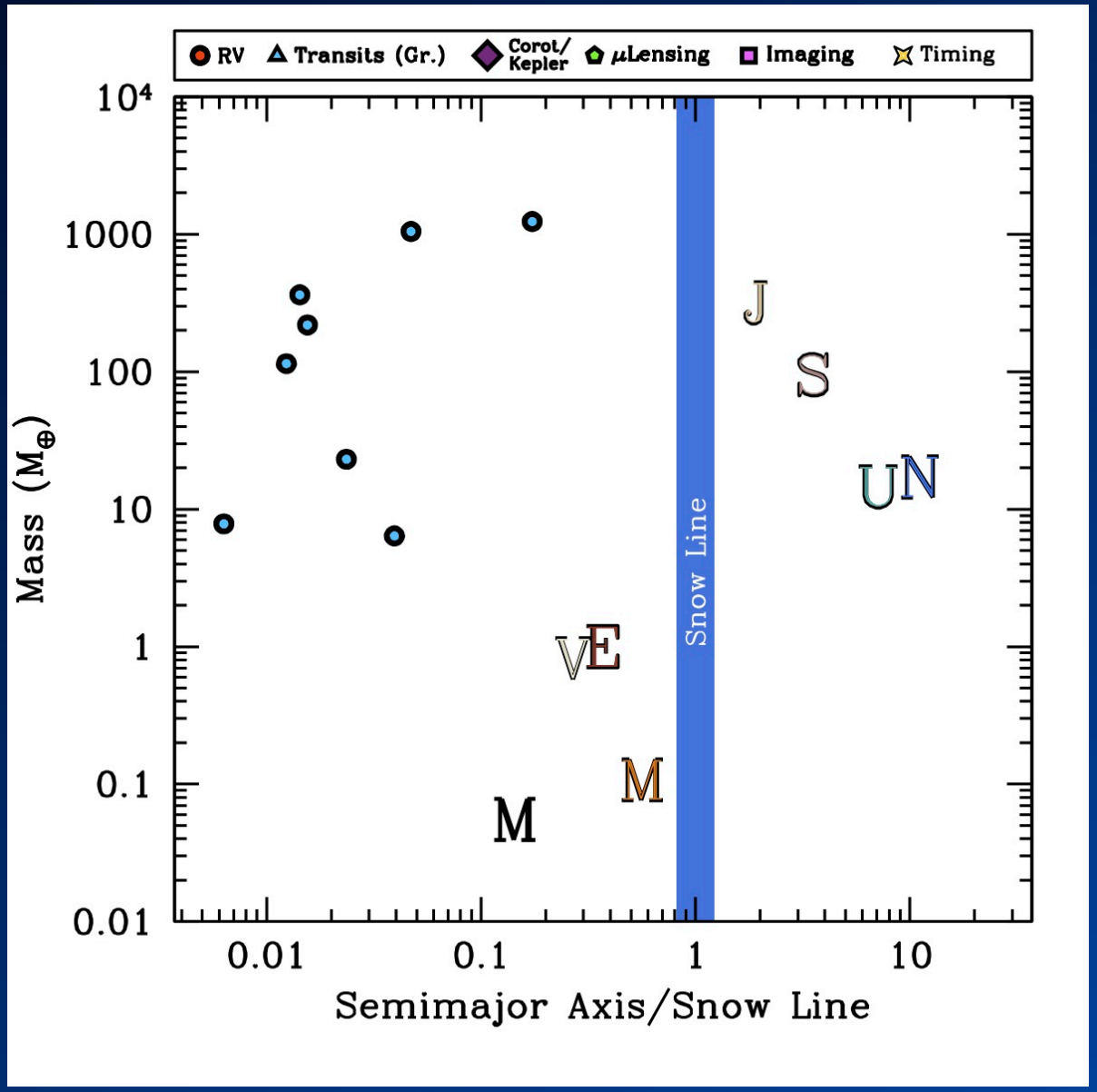

Total Number of Planet Discoveries
2000
1500
1000
500
0
Number of Planets =180×2(Year−2005)/3.1
1995: 5
2000: 48
2005: 182
2010: 527
2014: 1832
Prof. Gaudi starts graduate school
1995
2000
2005
2010
2015
Year of Discovery

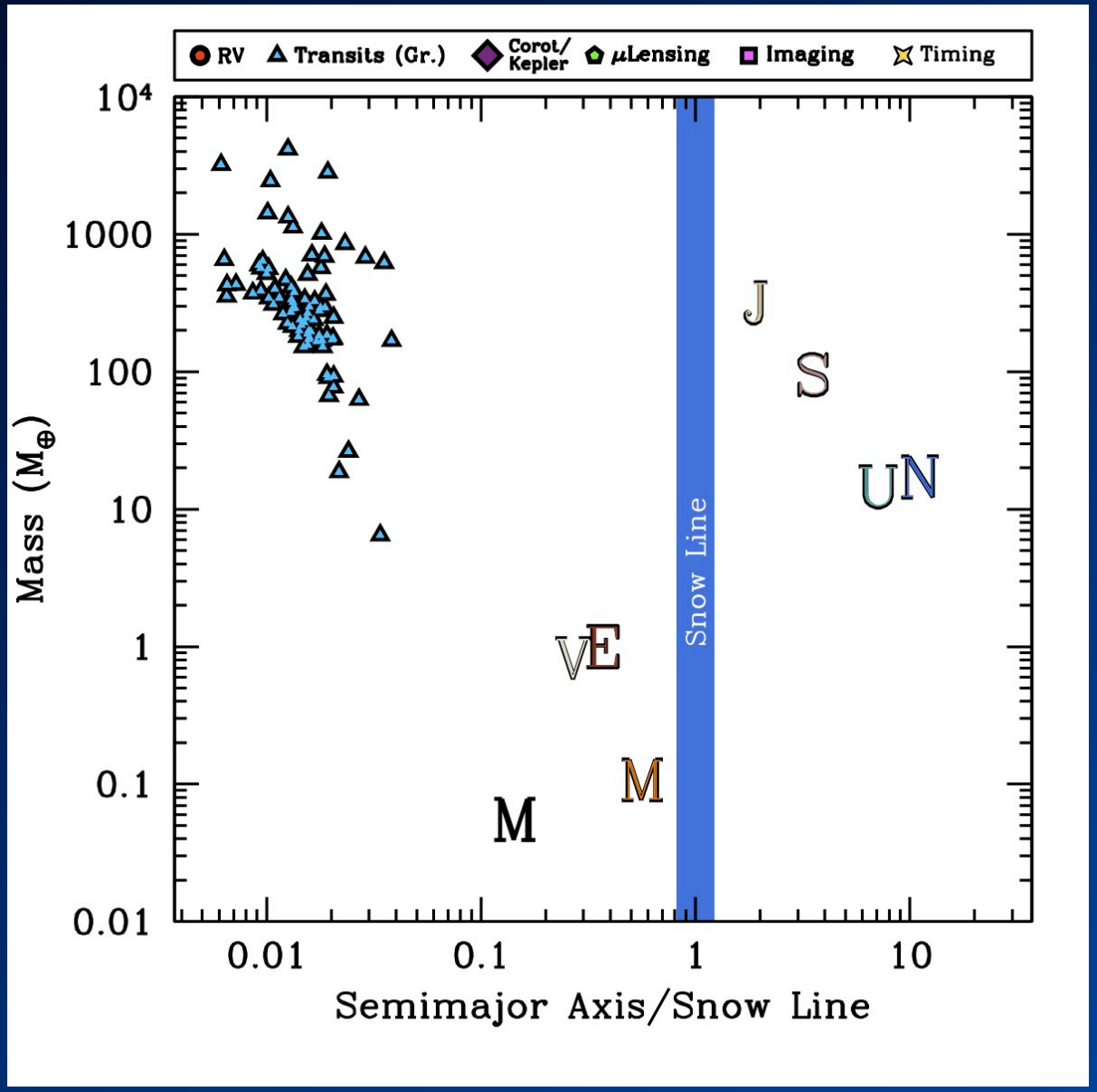

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M

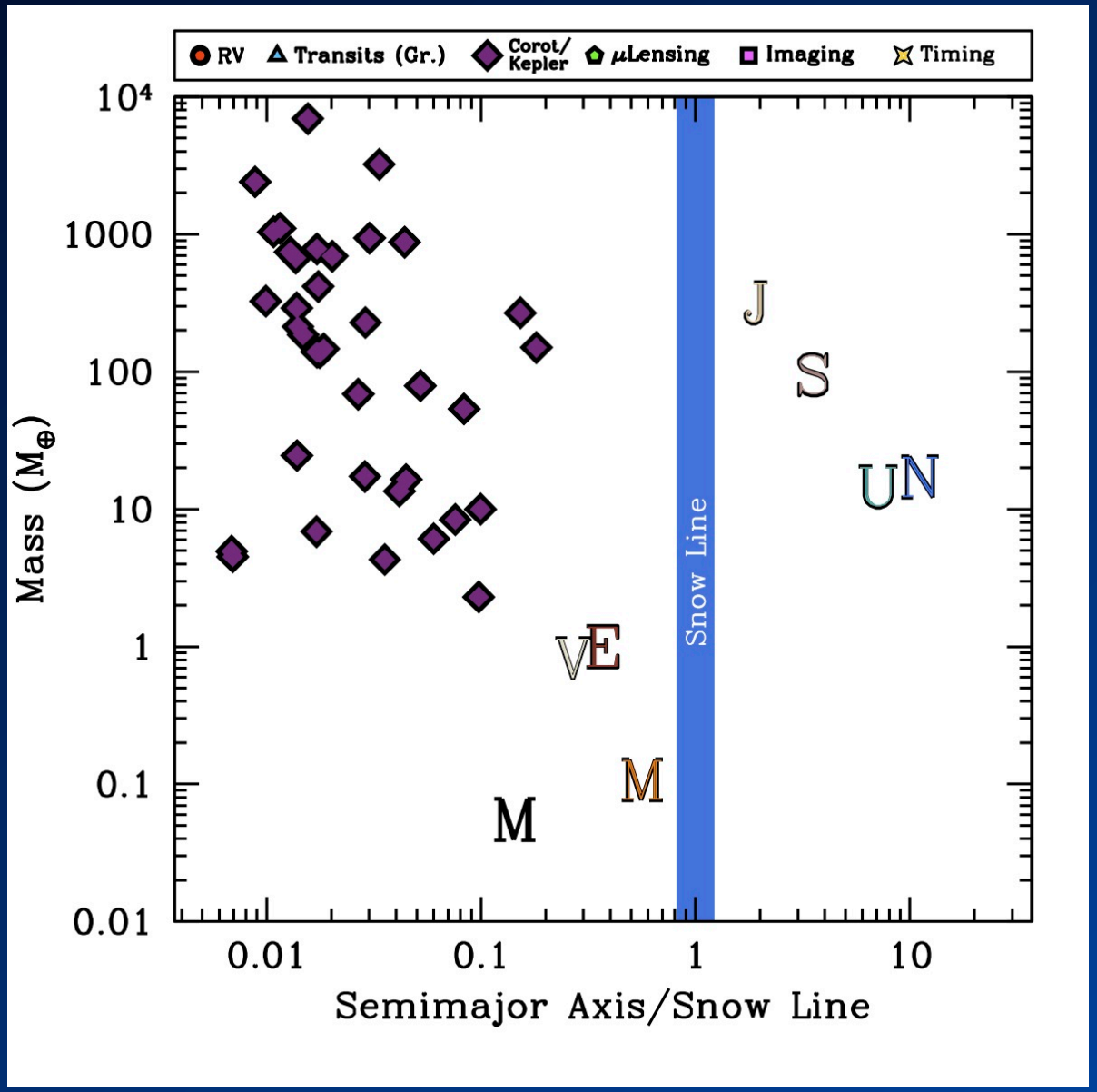

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
10⁴
1000
100
10
1
0.1
0.01
Mass (M⊕)
Snow Line
0.01
0.1
1
10
Semimajor Axis/Snow Line

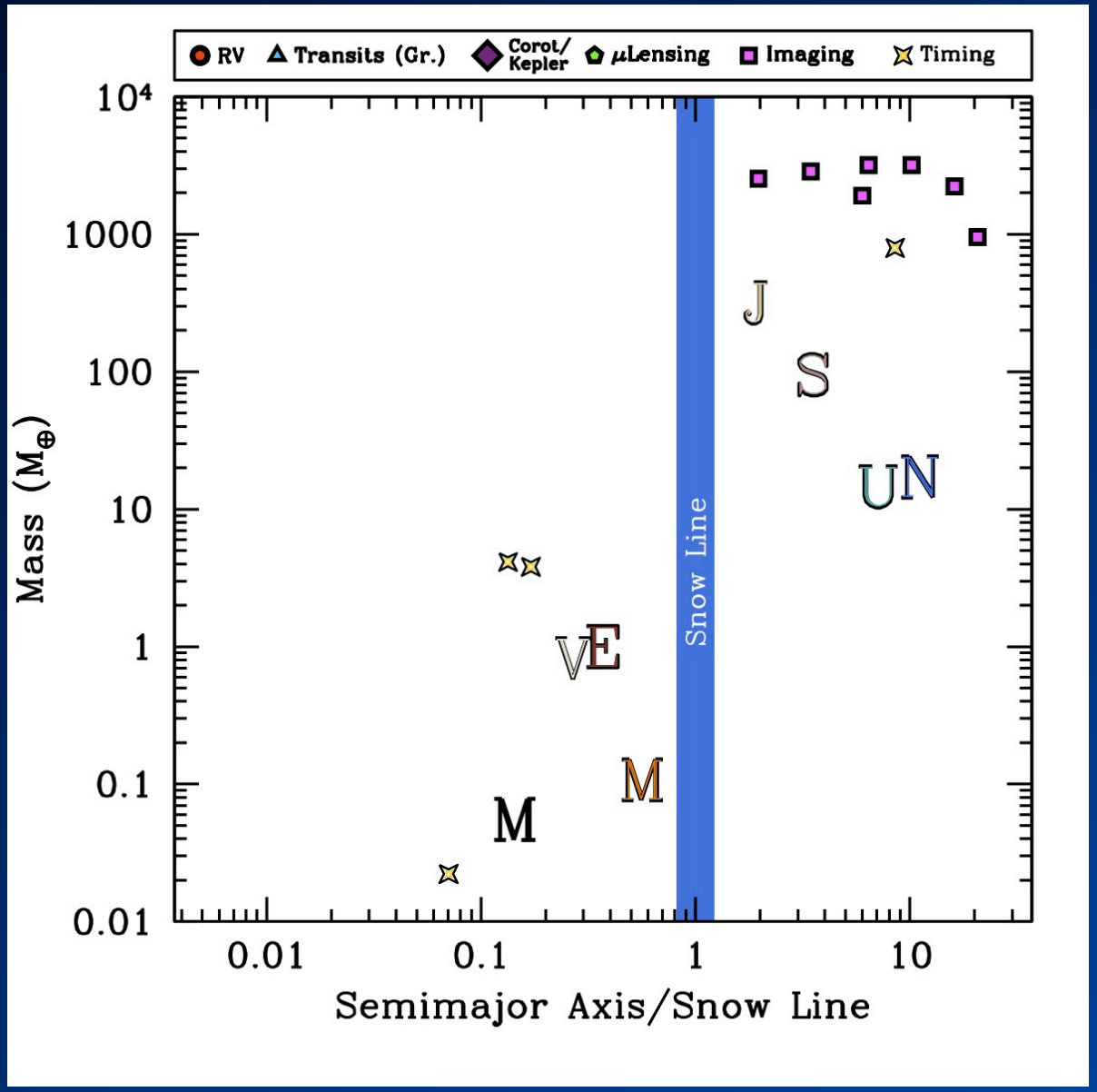

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
10⁴
1000
100
10
1
0.1
0.01
Mass (M⊕)
Snow Line
J
S
UN
VE
M
M
0.01
0.1
1
10
Semimajor Axis/Snow Line

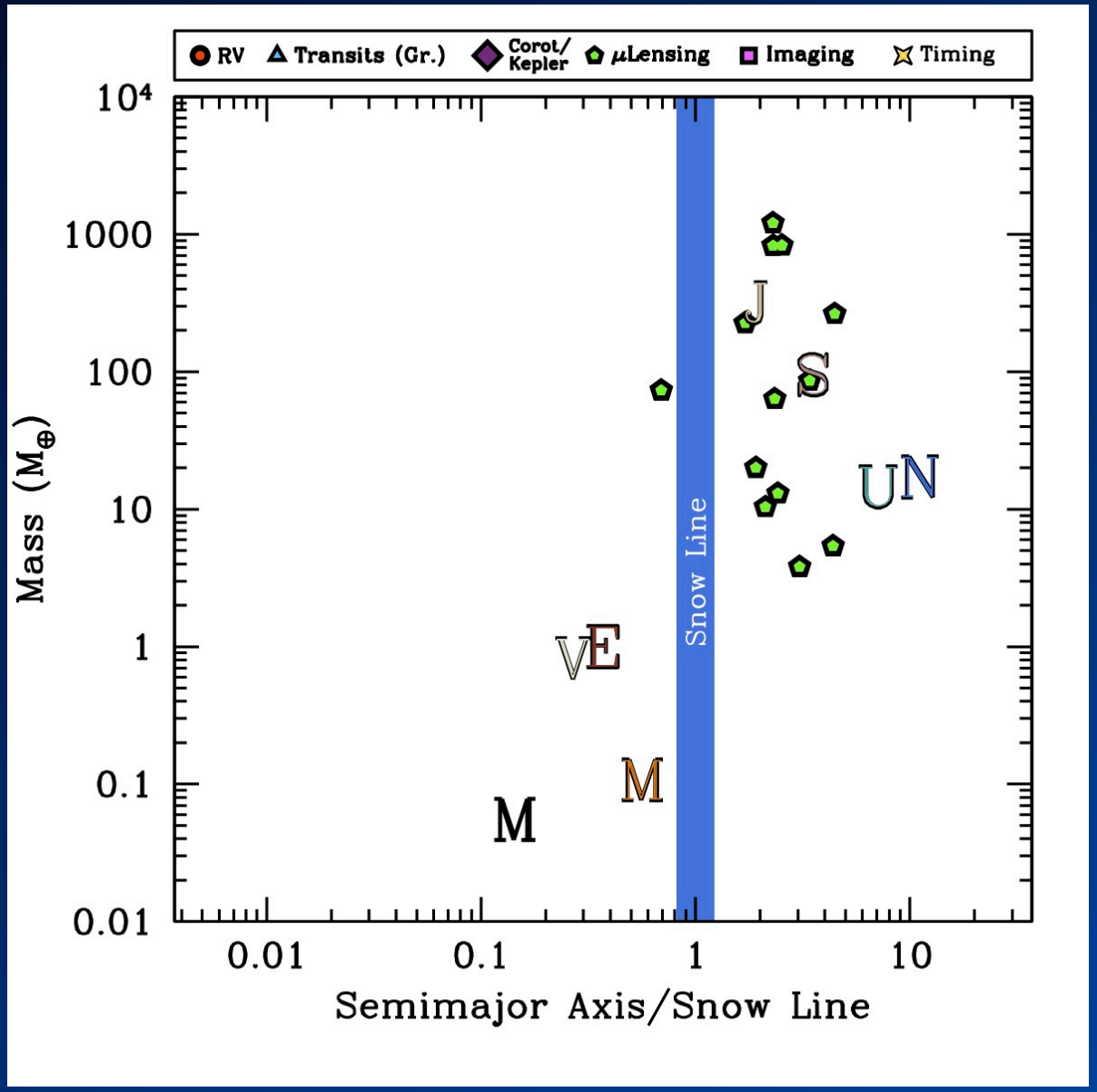

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M

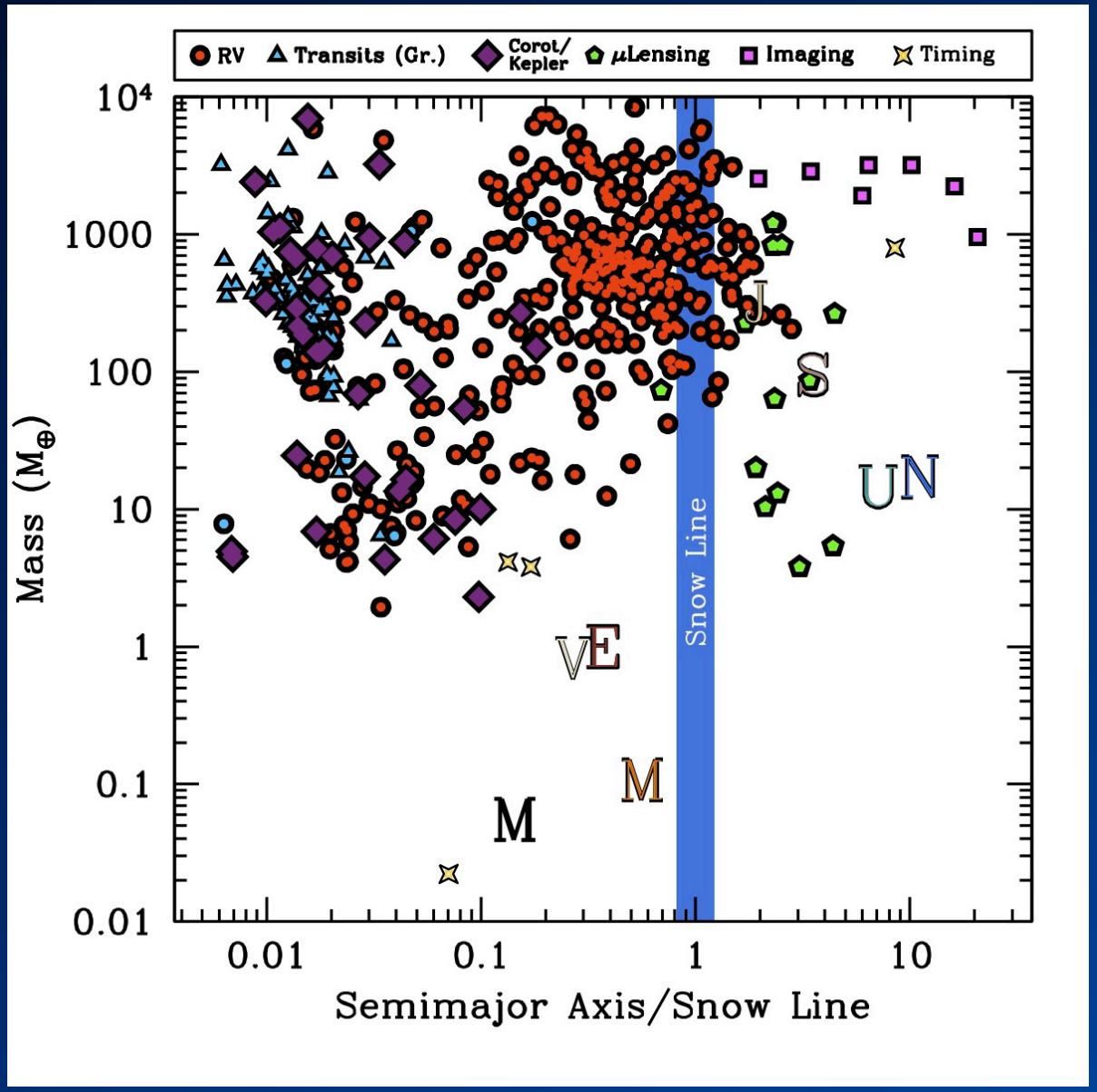

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M


RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
10⁴
1000
100
10
1
0.1
0.01
Mass (M⊕)
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M


RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M

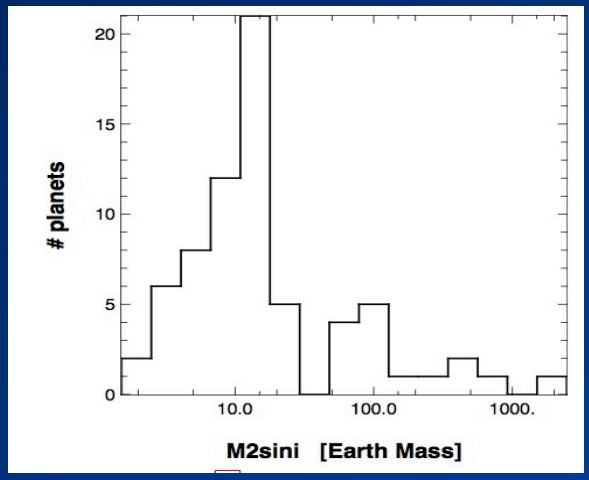

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M

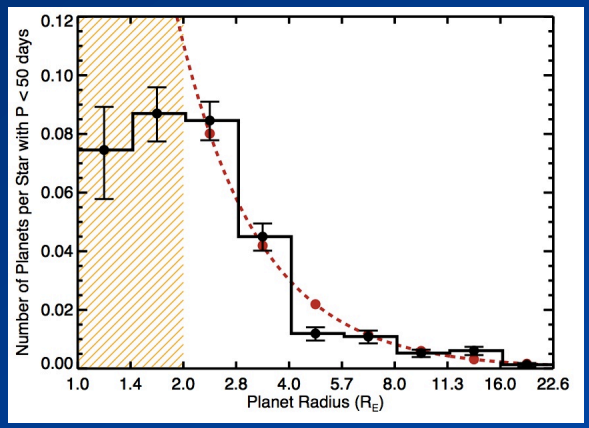

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M


RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass ($M_\oplus$)
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Semimajor Axis/Snow Line
Snow Line
J
S
UN
VE
M
M

Results from various methods.

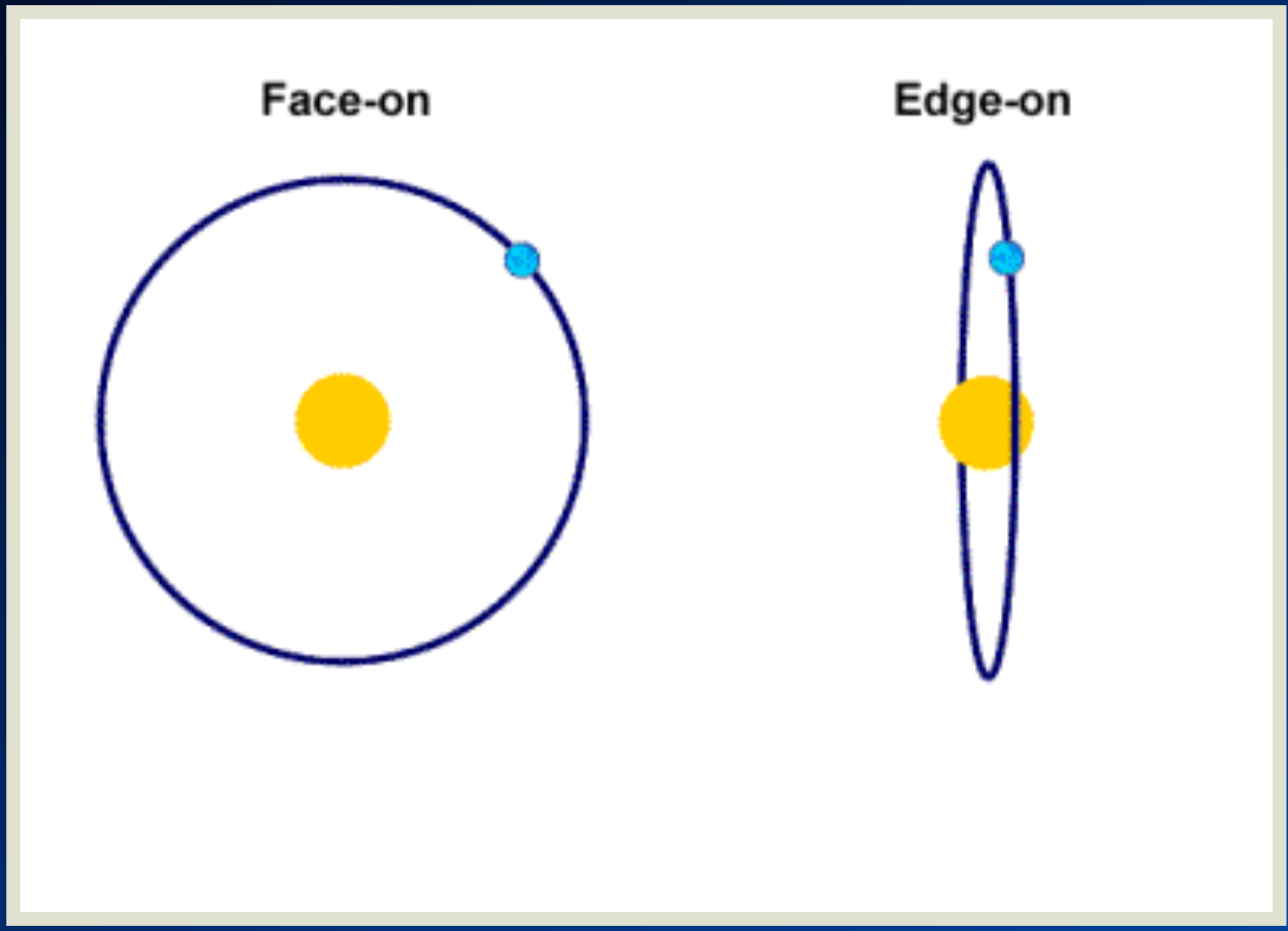
- Over 1600 confirmed planets with 5 techniques.
- Clear evidence for substantial dynamical evolution.
- Low-mass planets are much more common than high-mass planets
- Giant planet abundance scales with host star mass and heavy element abundance.
- Almost all results are for planets interior to the snow line, or relatively massive planets.

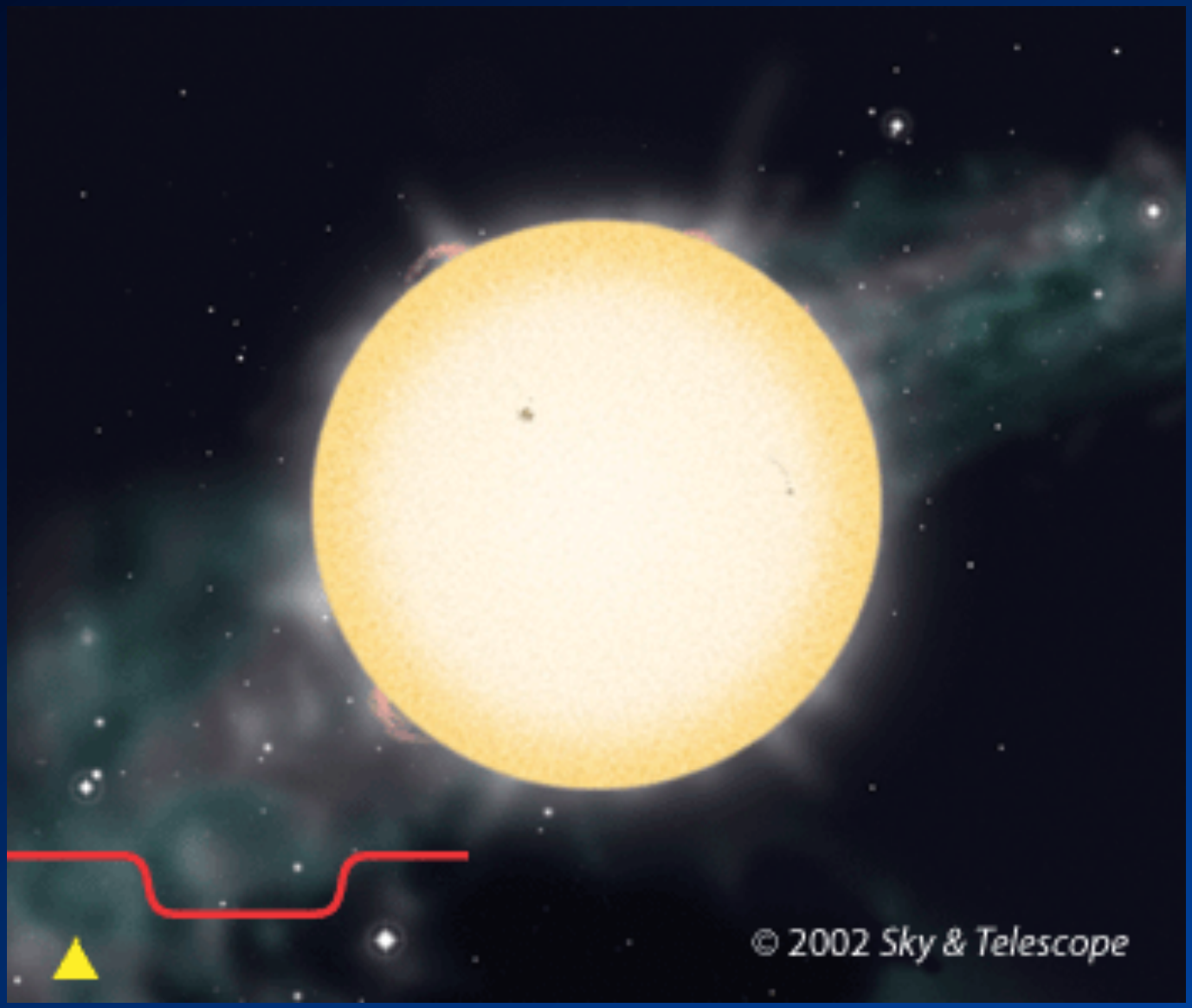




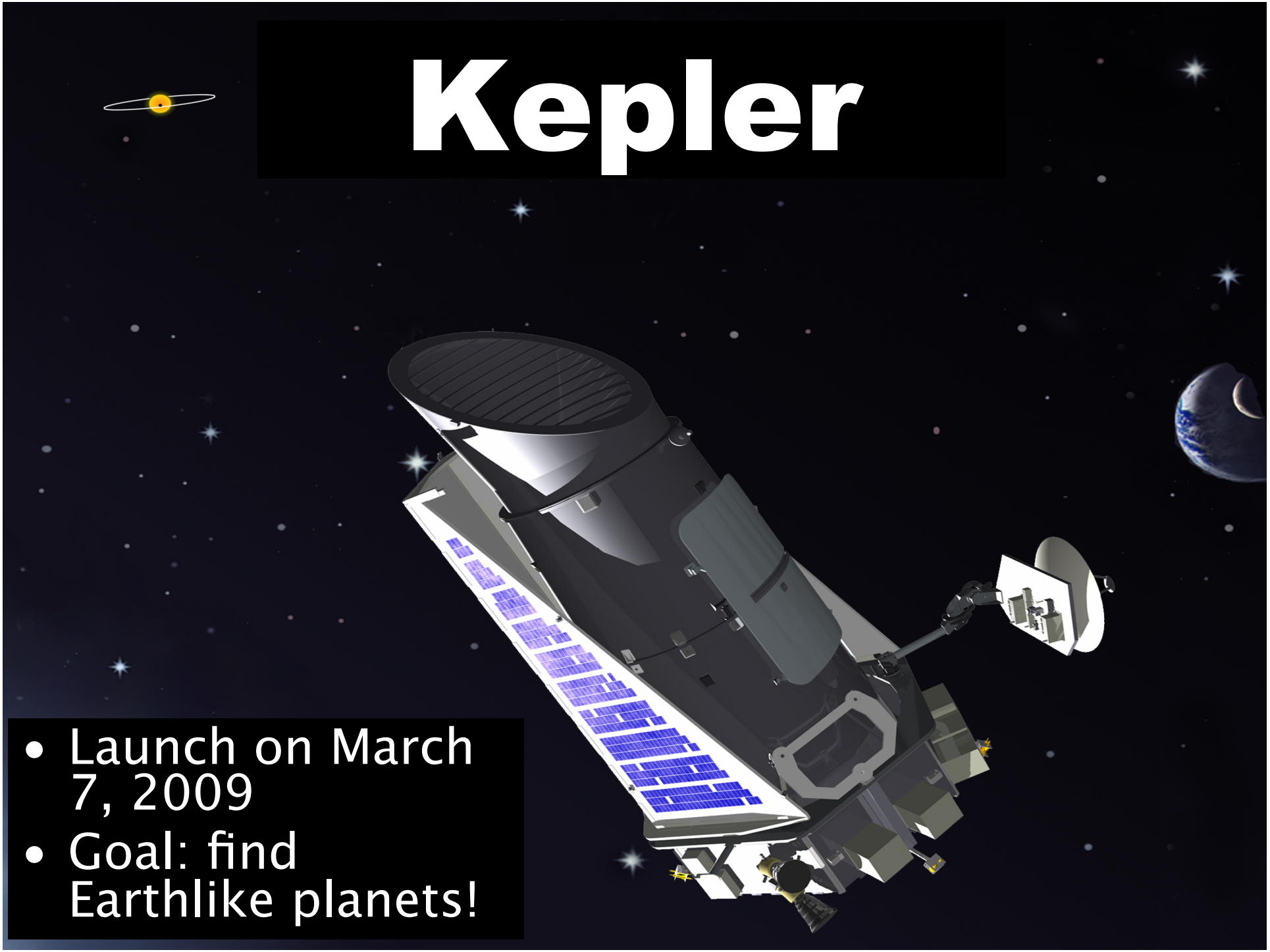
(Howard et al. 2012, Mayor et al. 2012)


Kepler.

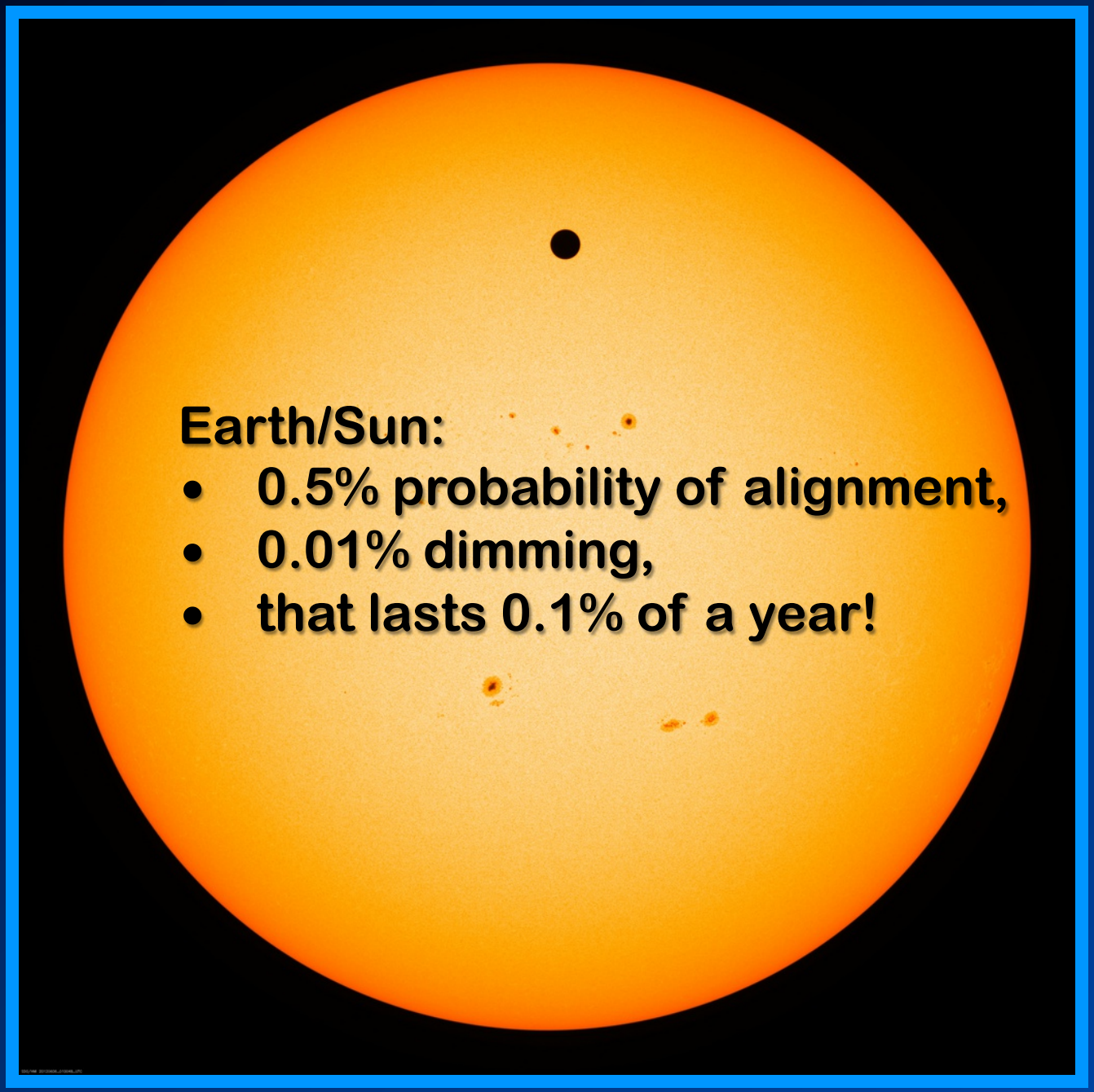

Face-on
Edge-on


© 2002 Sky & Telescope

Kepler

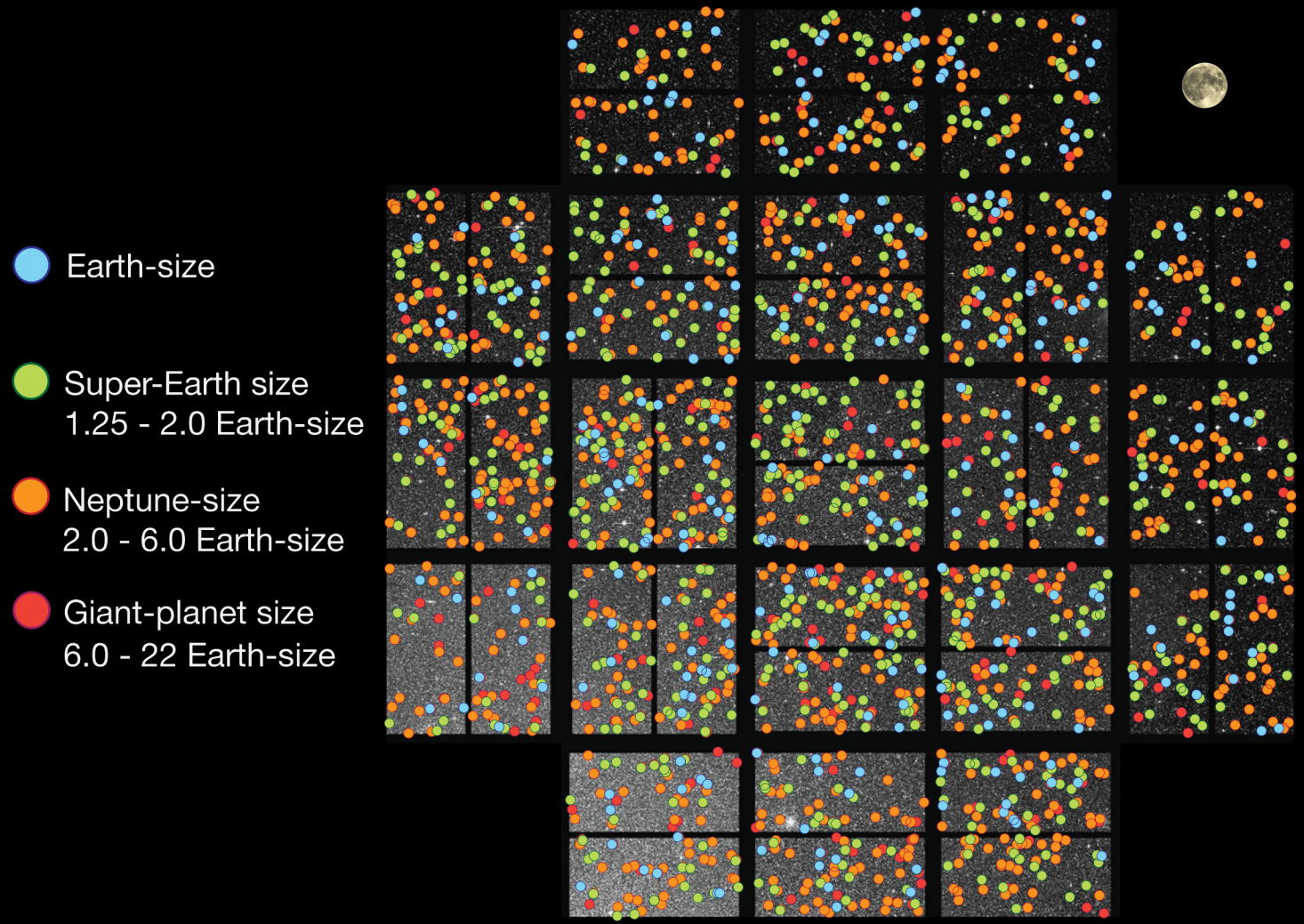


- Launch on March 7, 2009
- Goal: find Earthlike planets!

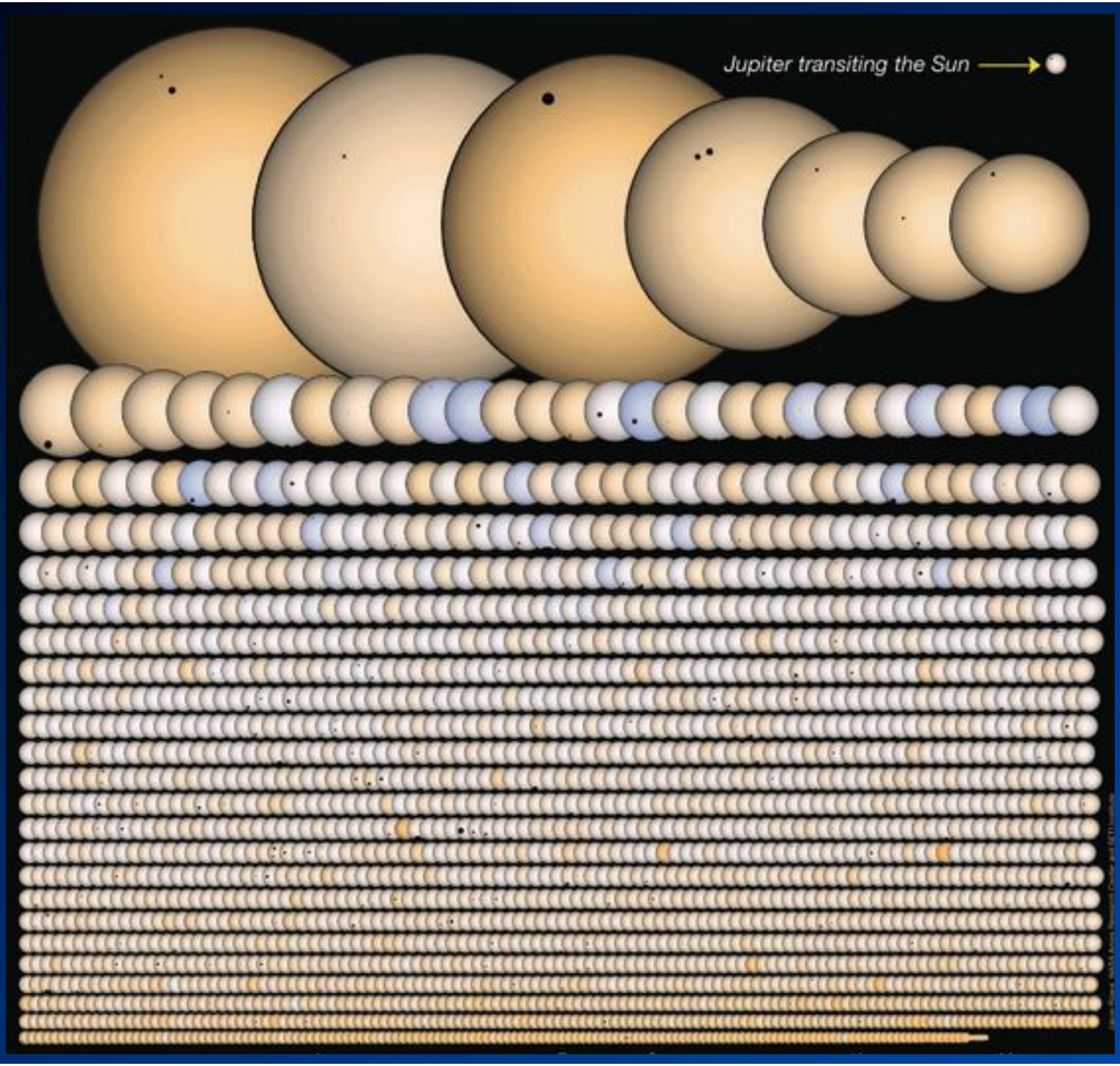

Earth/Sun:
• 0.5% probability of alignment,
• 0.01% dimming,
• that lasts 0.1% of a year!

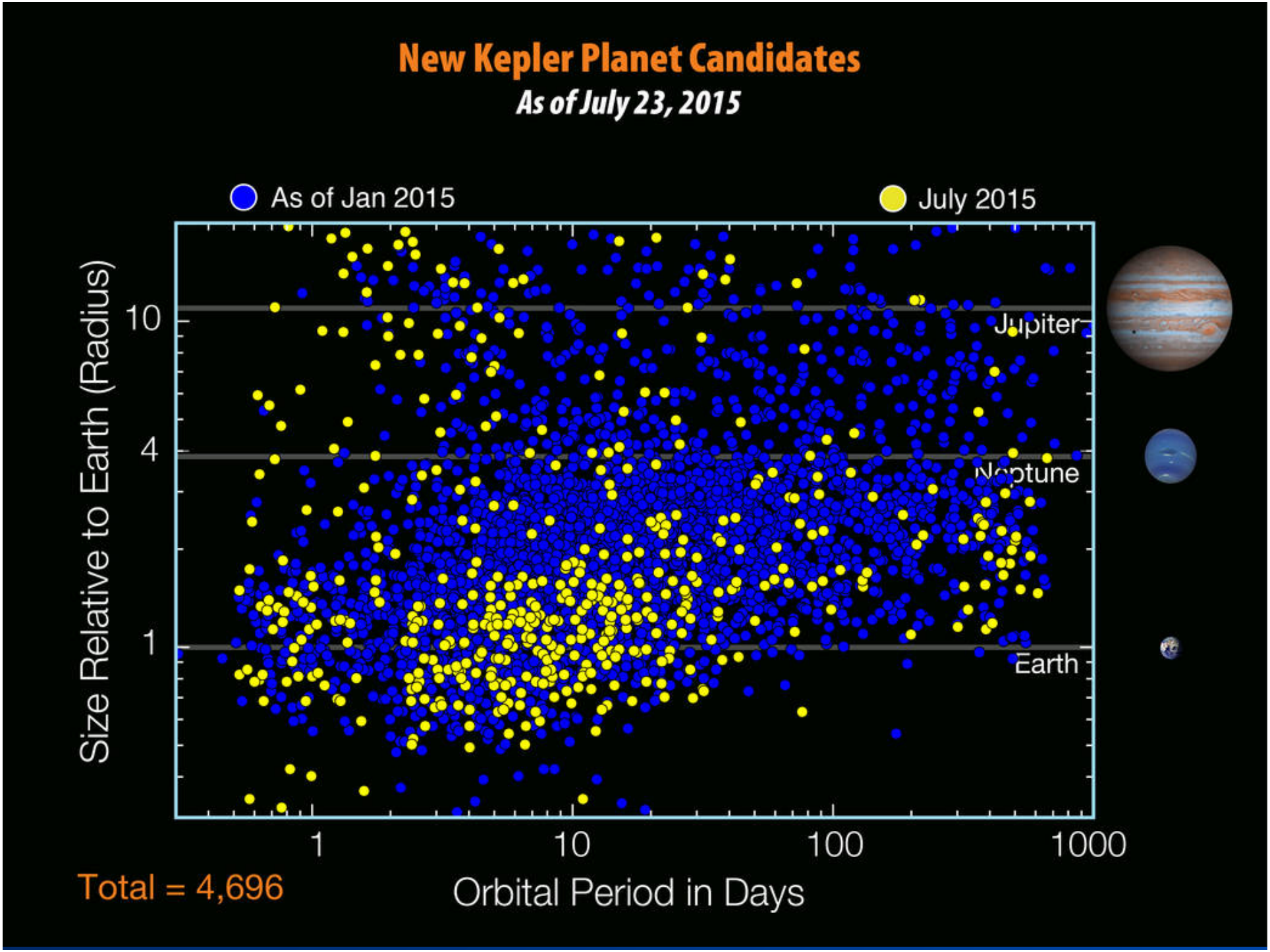
Locations of Kepler Planet Candidates

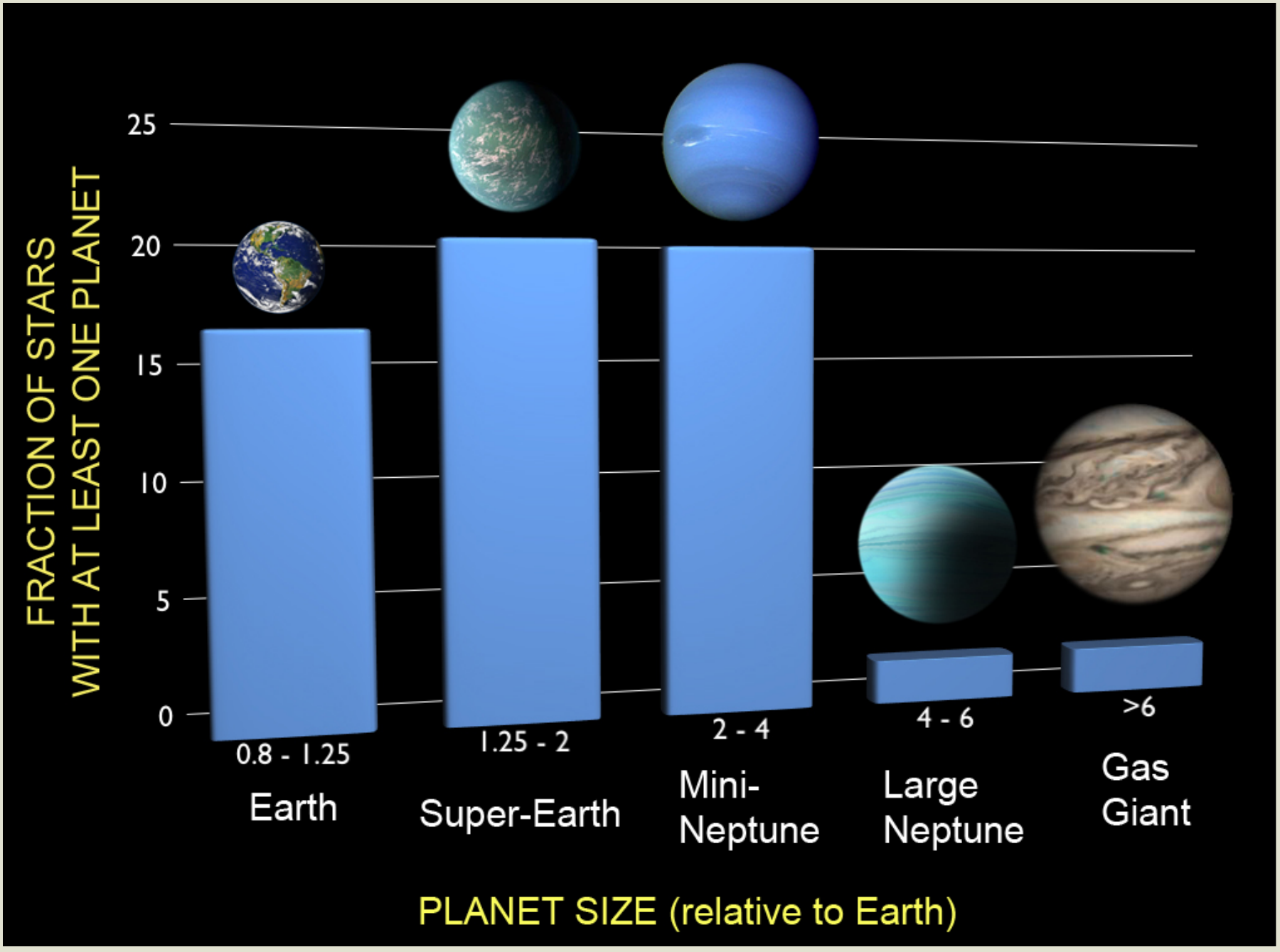
As of January 7, 2013



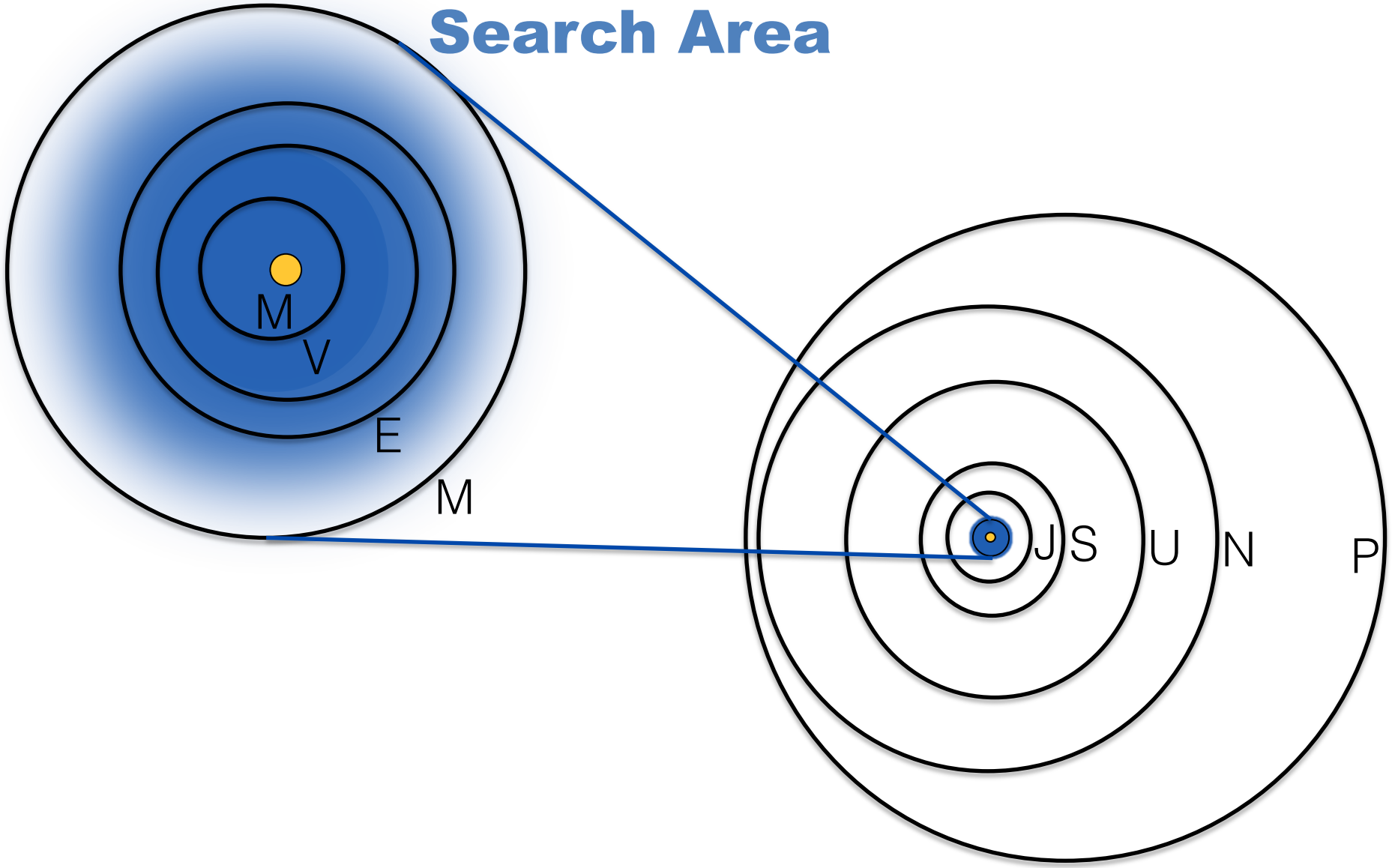
Over 4000 planet candidates found!


Jupiter transiting the Sun


New Kepler Planet Candidates
As of July 23, 2015
As of Jan 2015
July 2015
Size Relative to Earth (Radius)
10
4
1
Jupiter
Neptune
Earth
1
10
100
1000
Orbital Period in Days
Total = 4,696

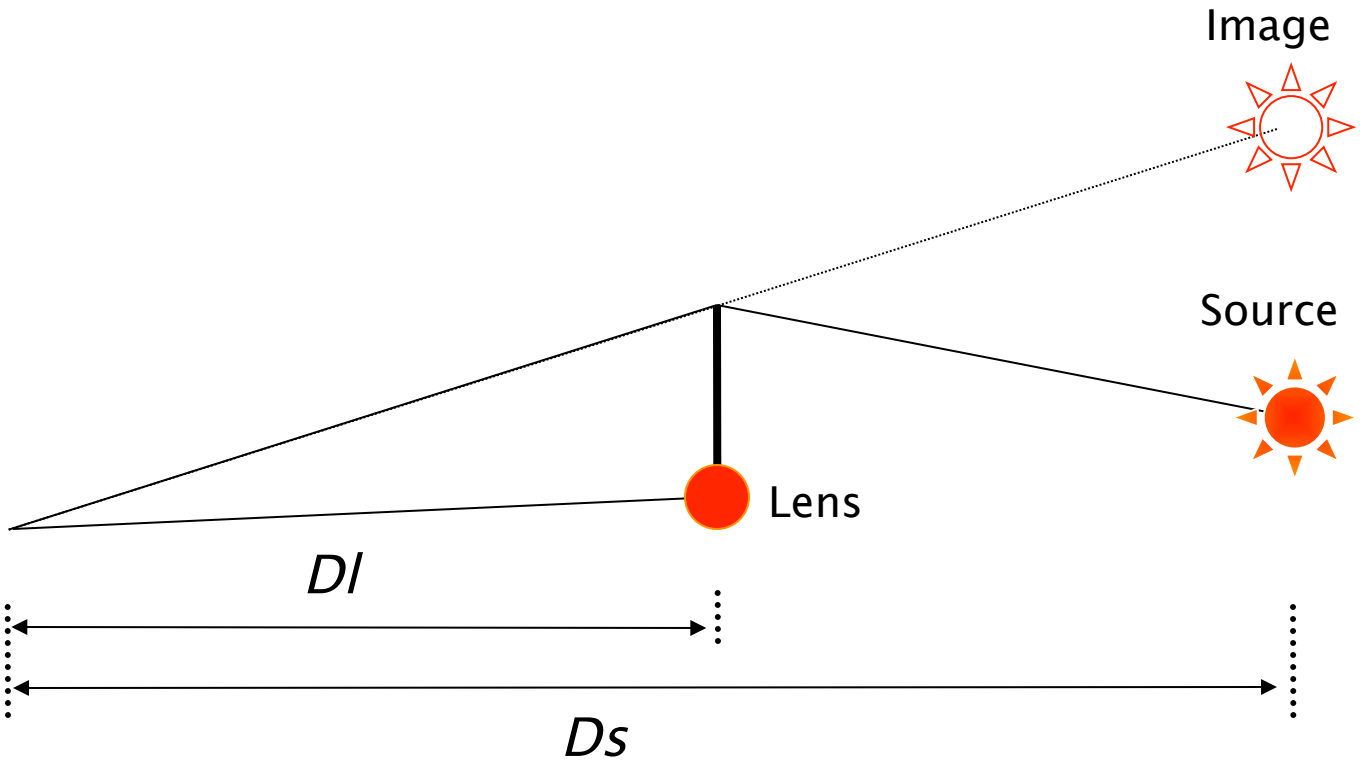

FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
1.25 - 2
2 - 4
4 - 6
>6
Earth
Super-Earth
Mini-
Neptune
Large
Neptune
Gas
Giant
PLANET SIZE (relative to Earth)

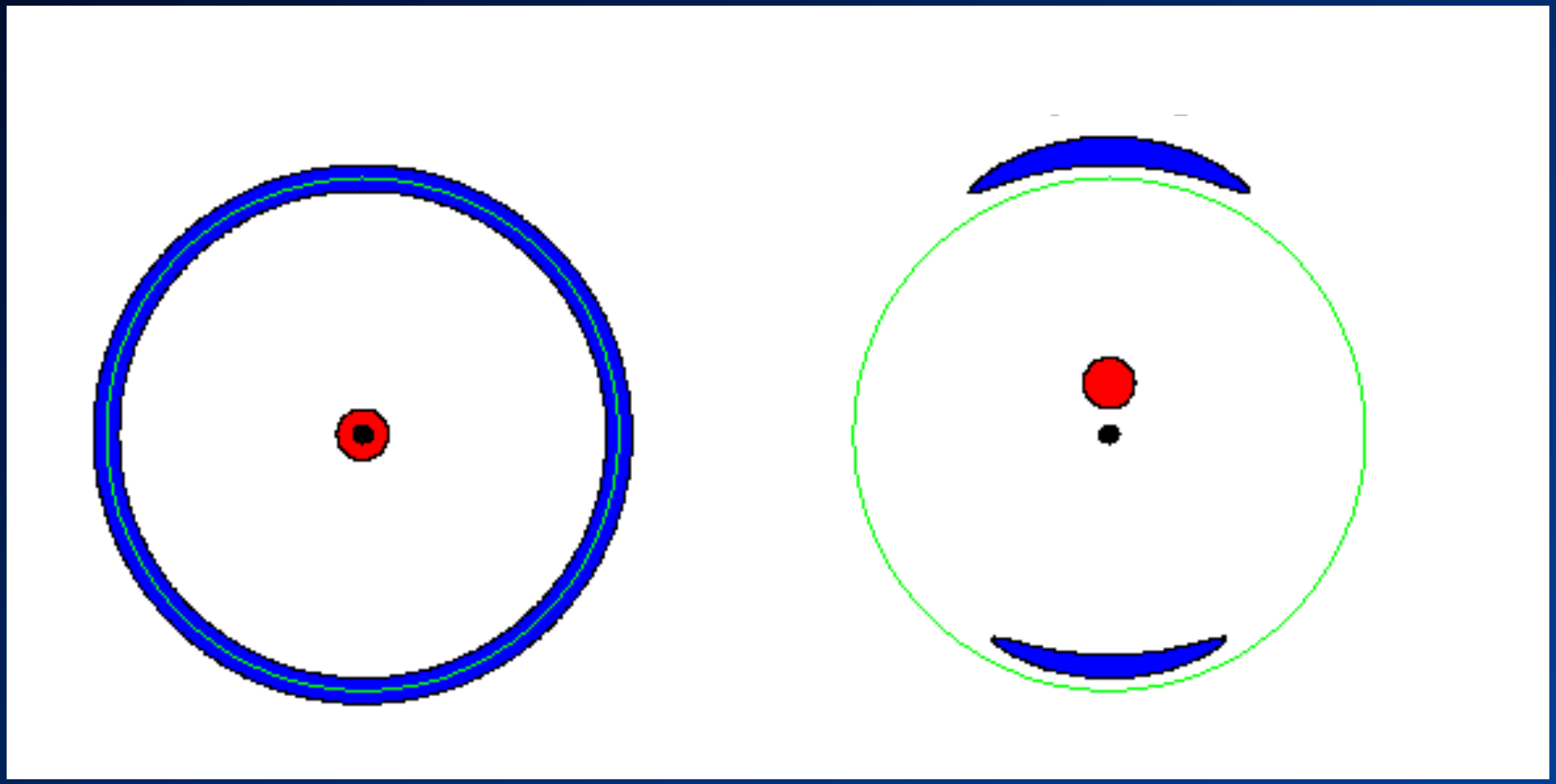
Kepler's Search Area



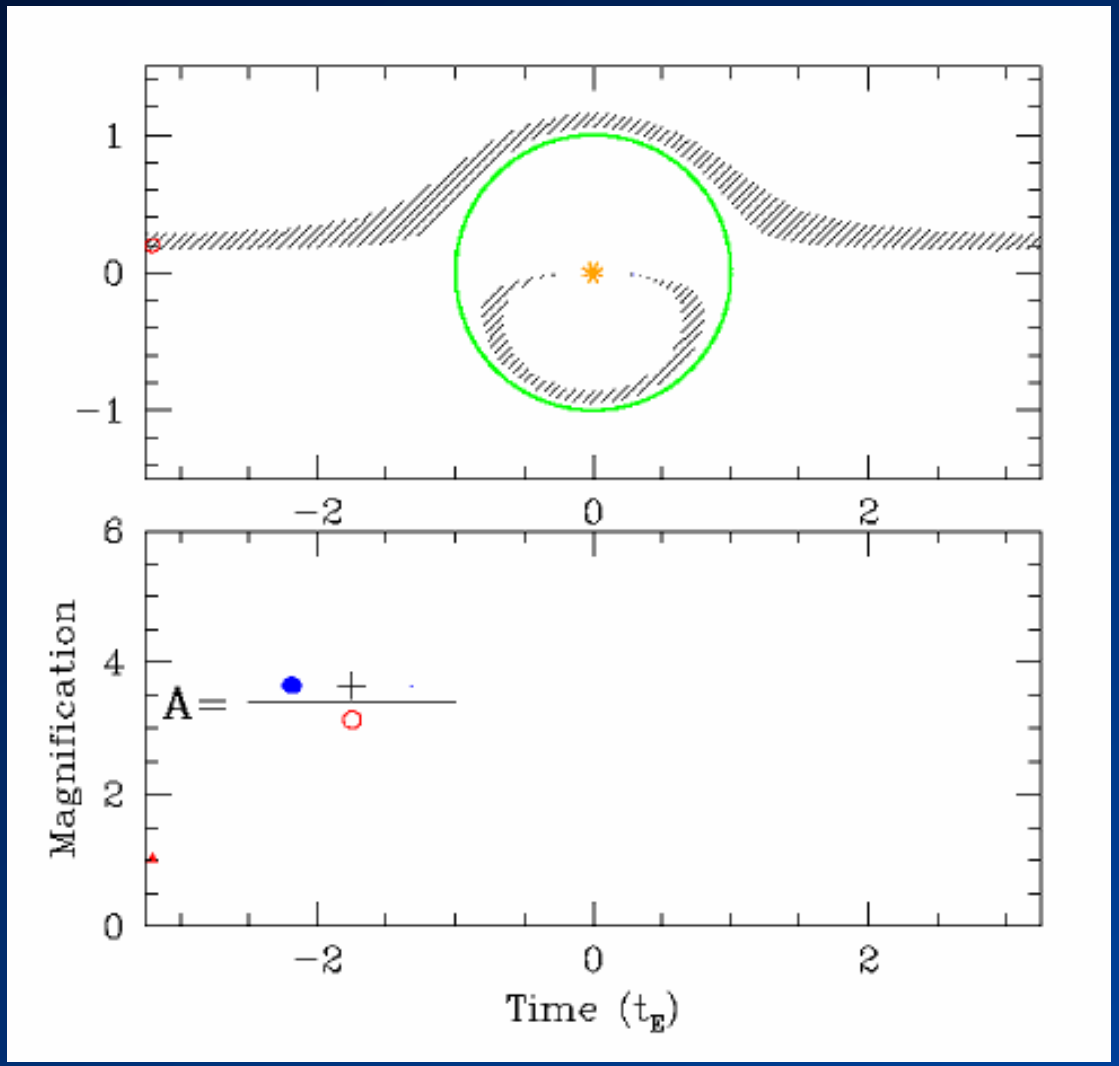
Microlensing.

Microlensing Basics.

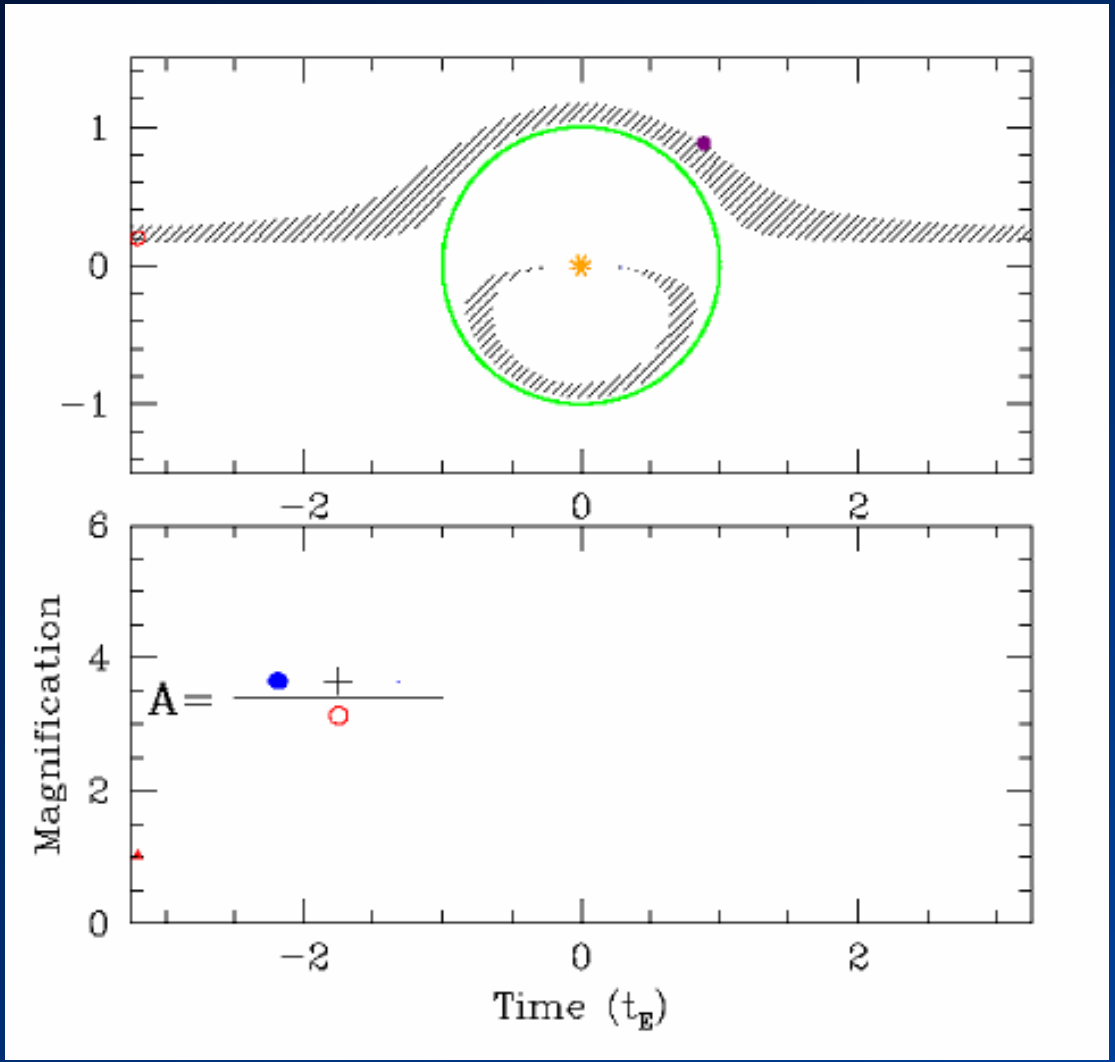


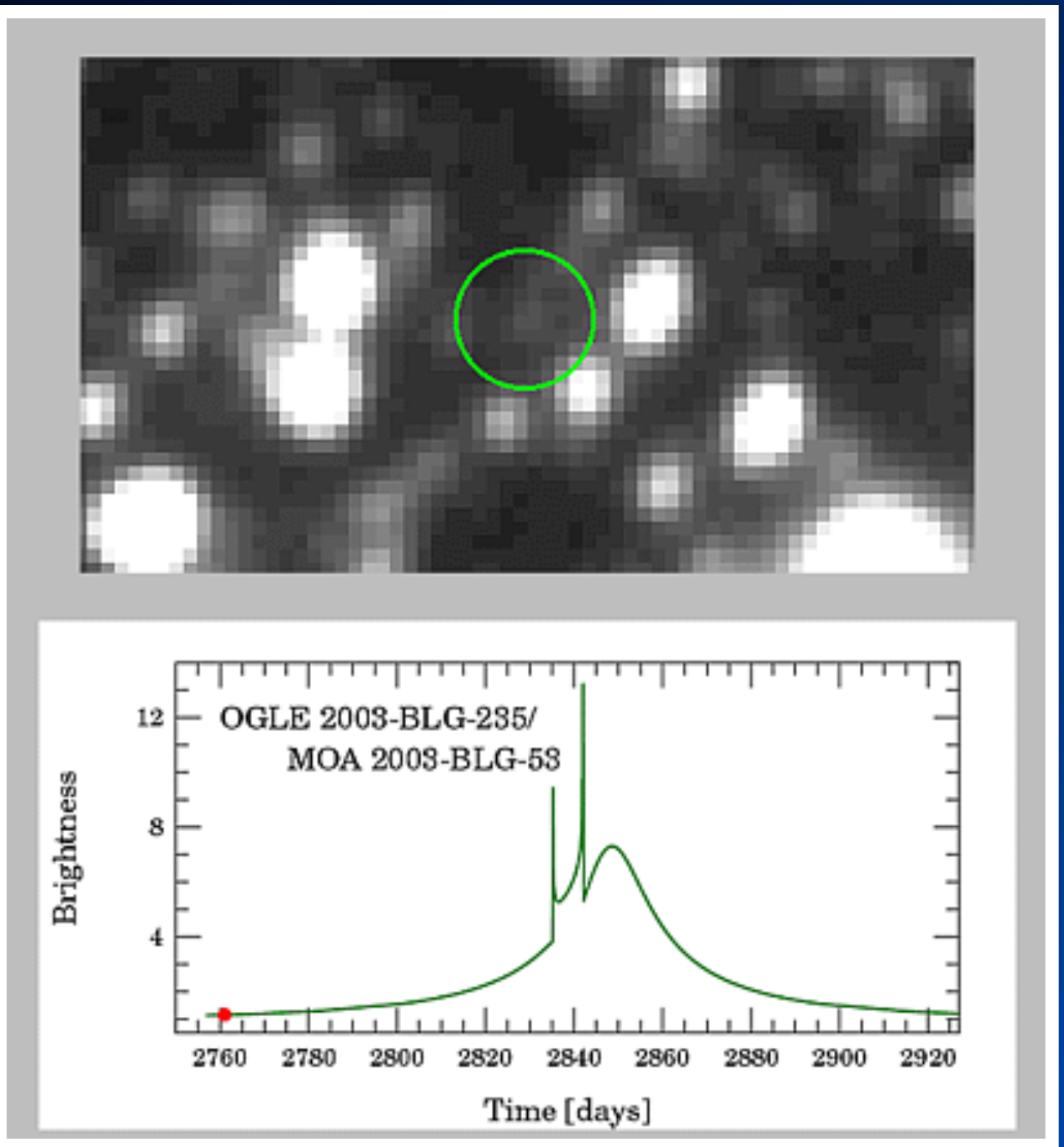


Microlensing Events.



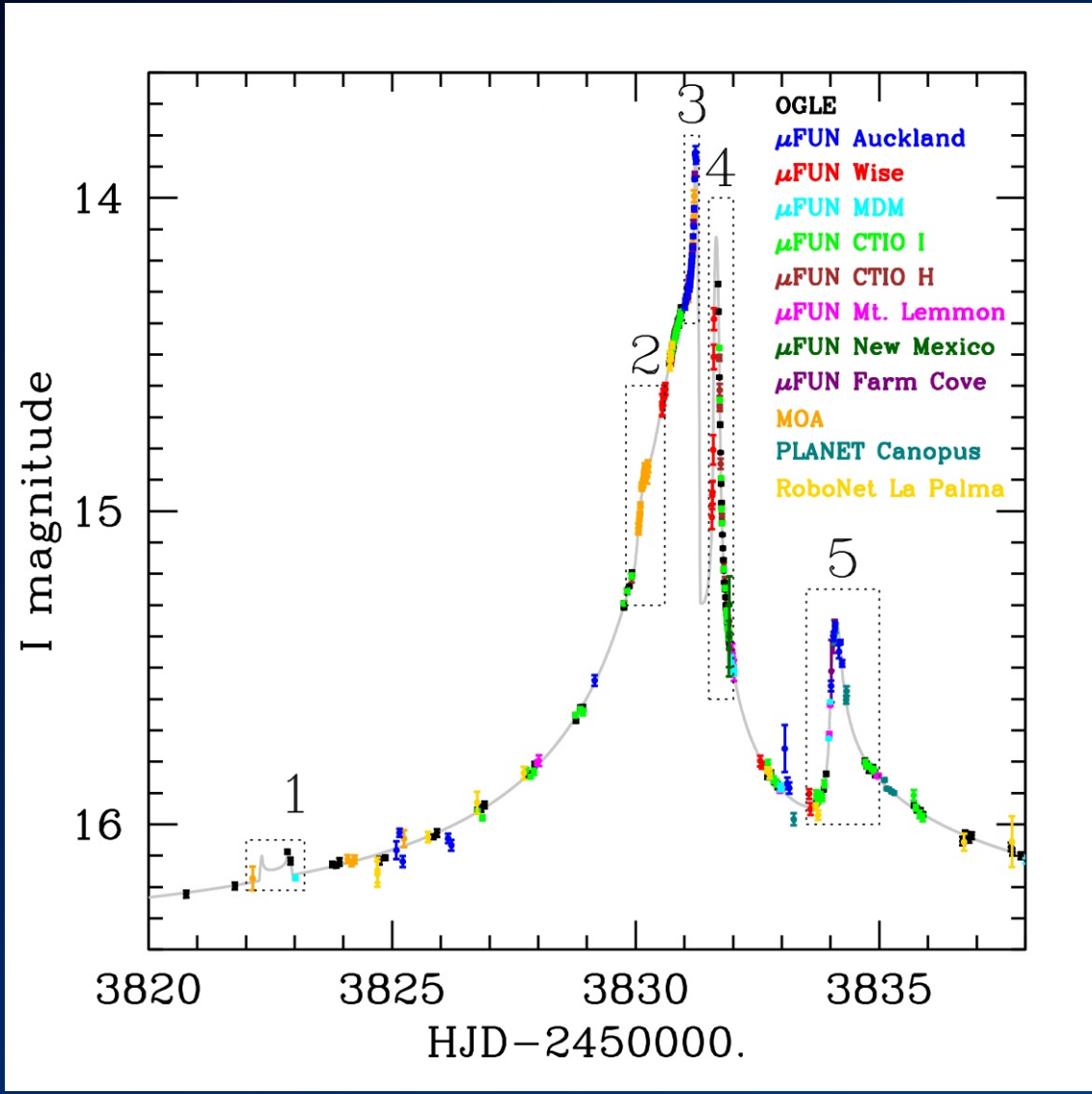
Detecting Planets.





(Bond et al. 2004)

A Multiple-Planet System.



(Gaudi et al 2008; Bennett et al 2010)

- Single planet models fail.
- Two planets models work well.
- First multiple-planet system detected by microlensing.

A Jupiter/Saturn Analog.

Host:

Mass = 0.51 +/- 0.05 M_{Sun}

Luminosity ~ 5% L_{Sun}

Distance = 1510 +/- 120 pc

Planet b:

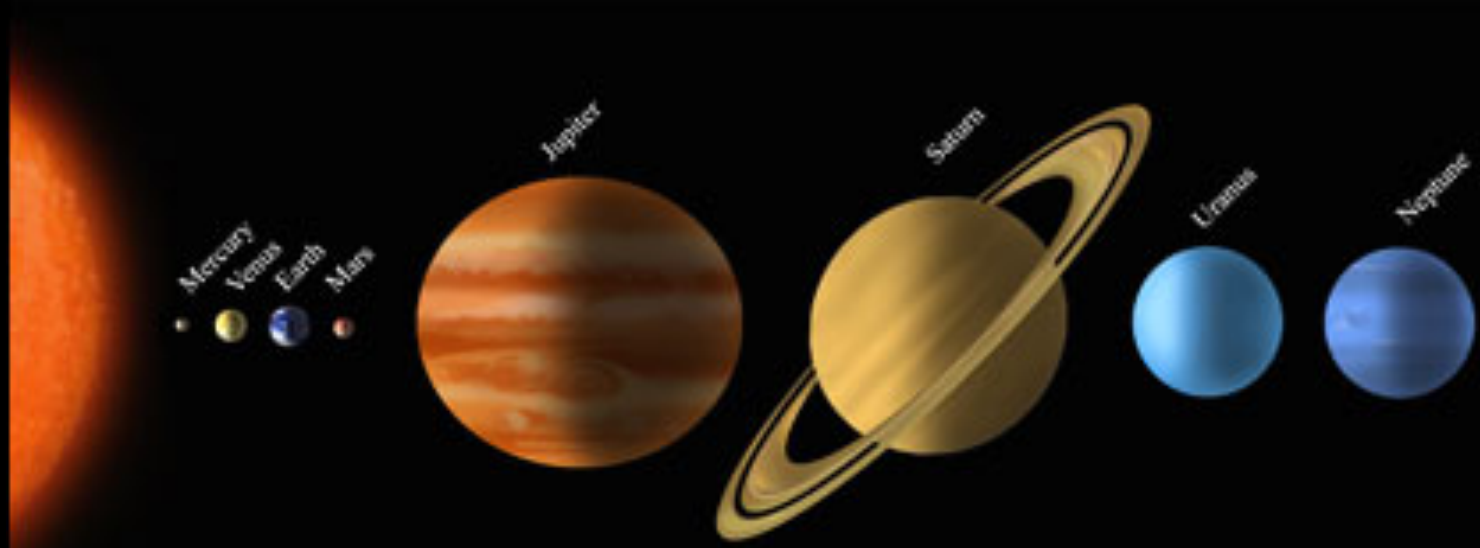
Mass = 0.73 +/- 0.06 M_{Jup}

Semimajor Axis = 2.3 +/- 0.5 AU

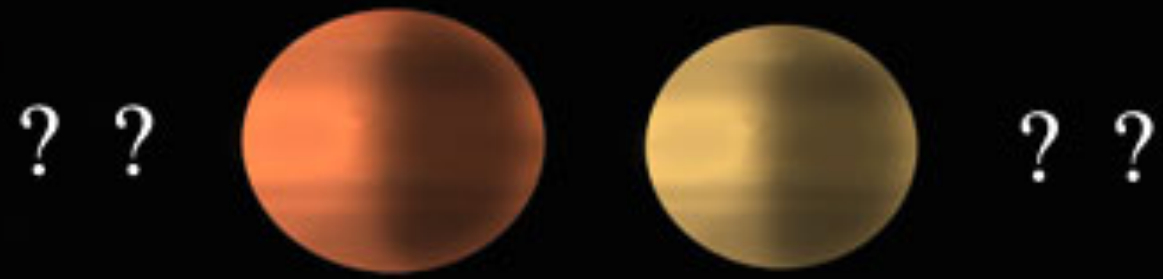
Planet c:

Mass = 0.27 +/- 0.02 M_{Jup} = 0.90 M_{Sat}

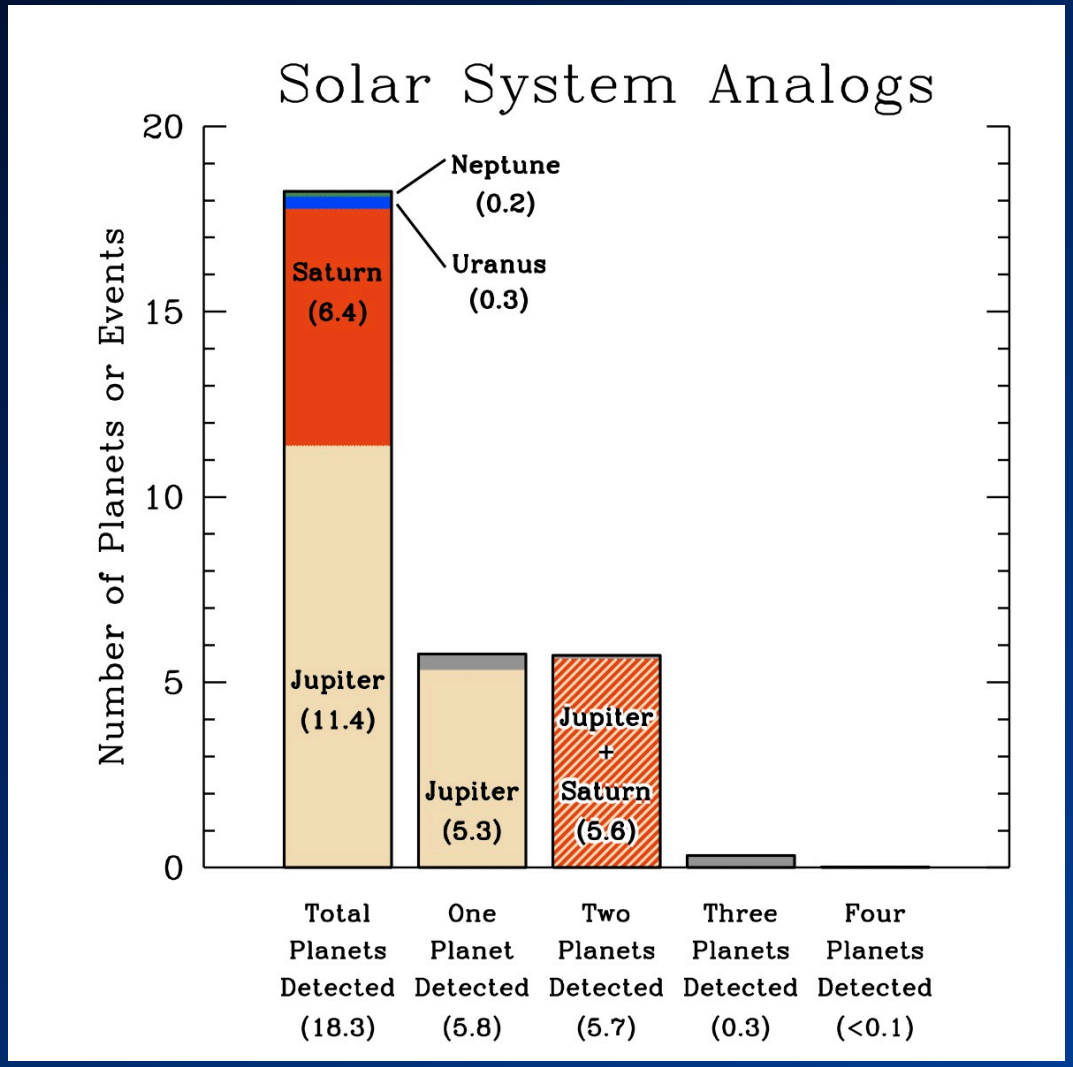
Semimajor Axis = 4.6 +/- 1.5 AU



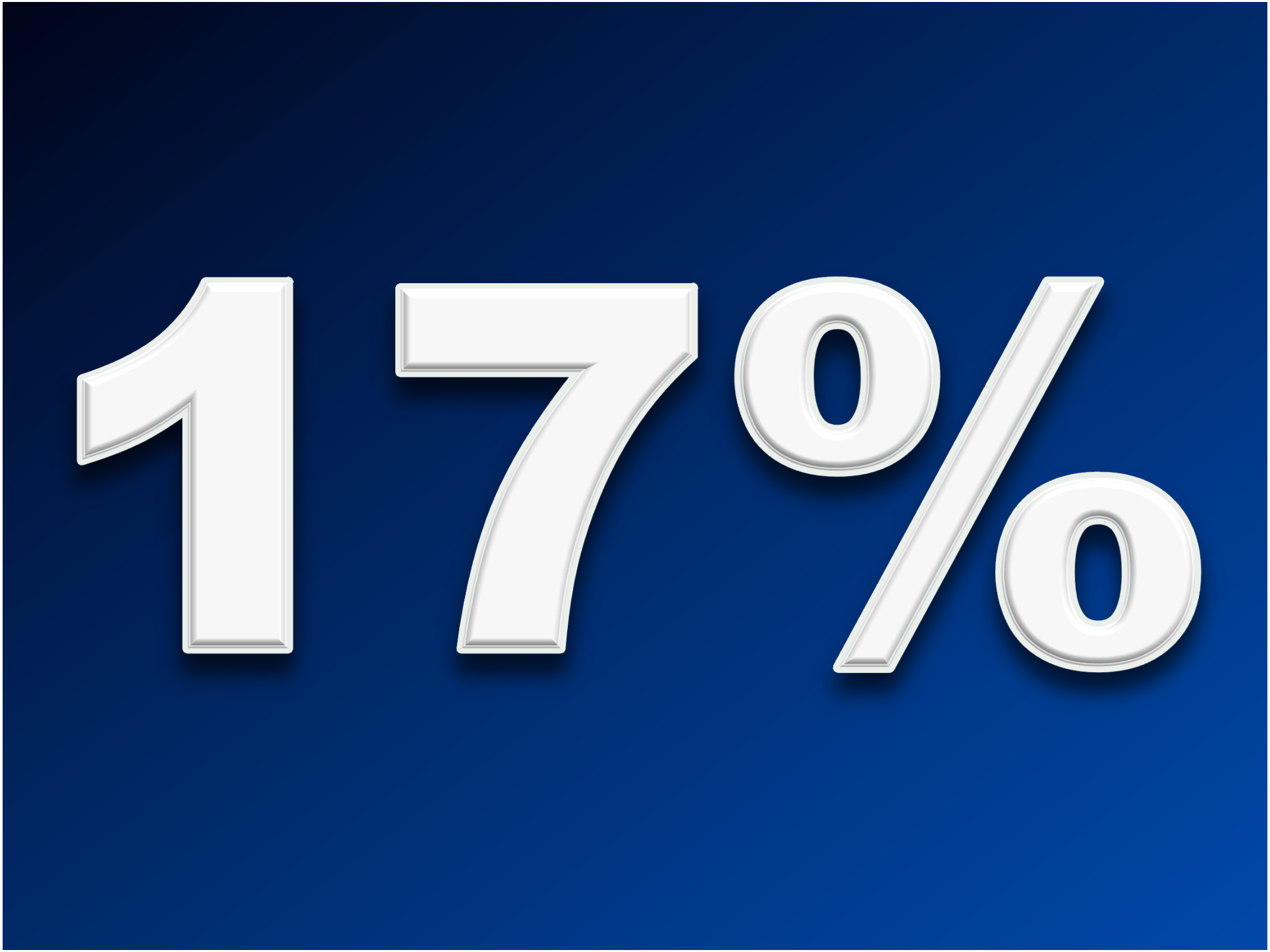
Our Solar System



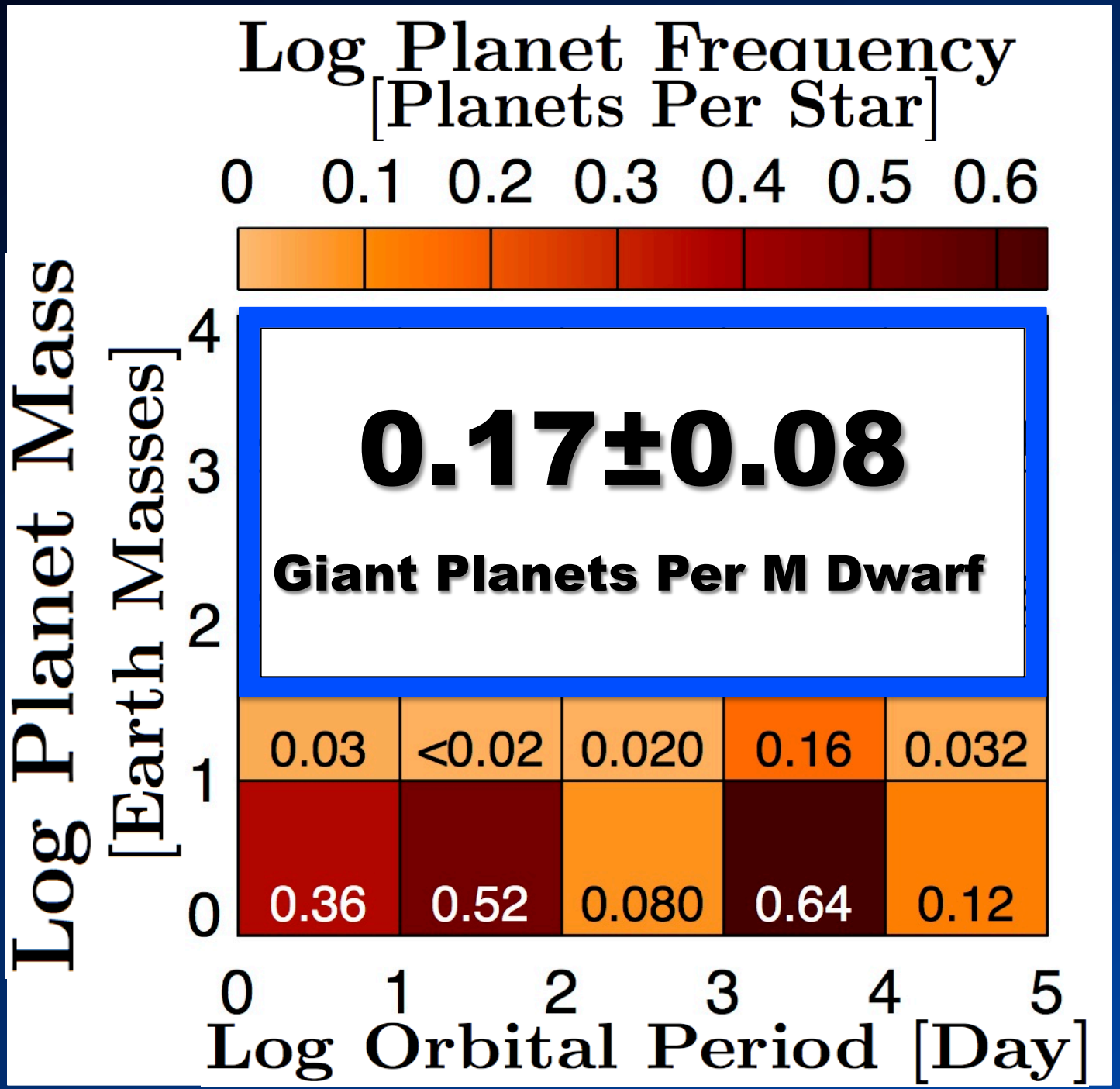
OGLE-2006-BLG-109Lb,c



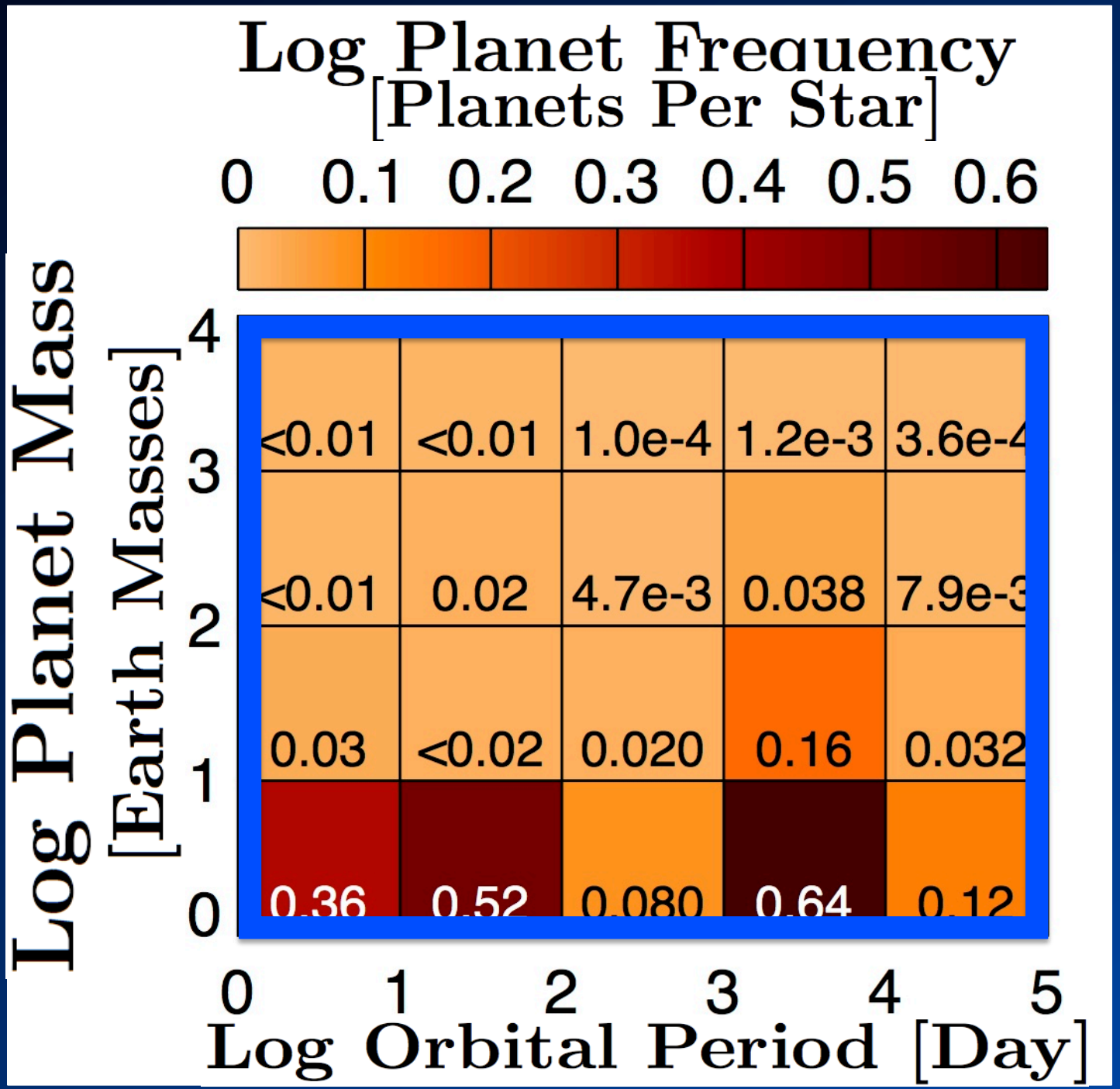
(Gould et al. 2010)


17%

Exoplanet Demographic Synthesis.



(Clanton & Gaudi 2014a,b)



(Clanton & Gaudi 2014a,b)

2.0 ± 0.5

Planets per M Dwarf

(mass>Earth, periods<10^4 days)

0.17 ± 0.08

Giant Planets Per M Dwarf

(mass>30×Earth, periods<10^4 days)

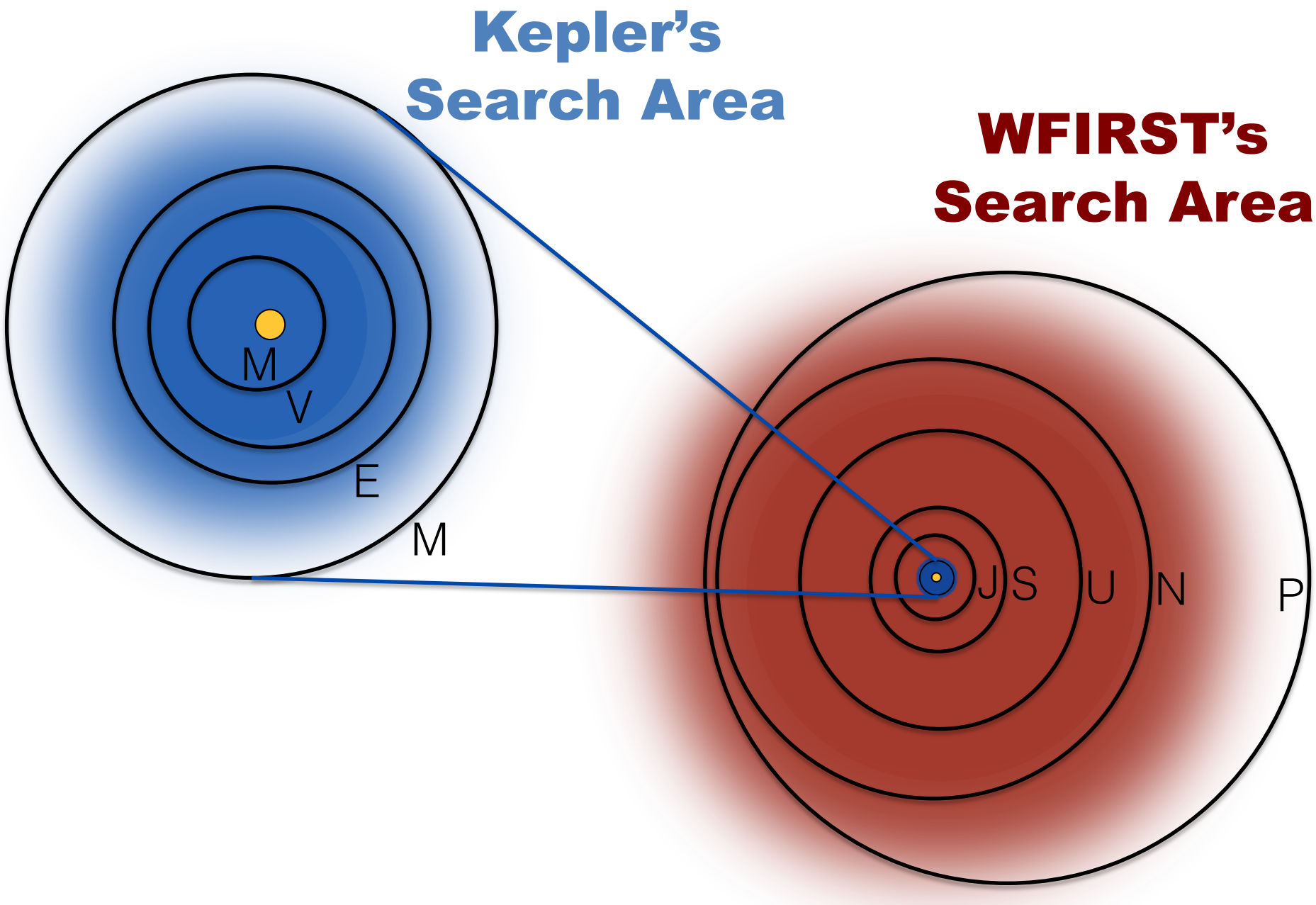
(Clanton & Gaudi 2014a,b)

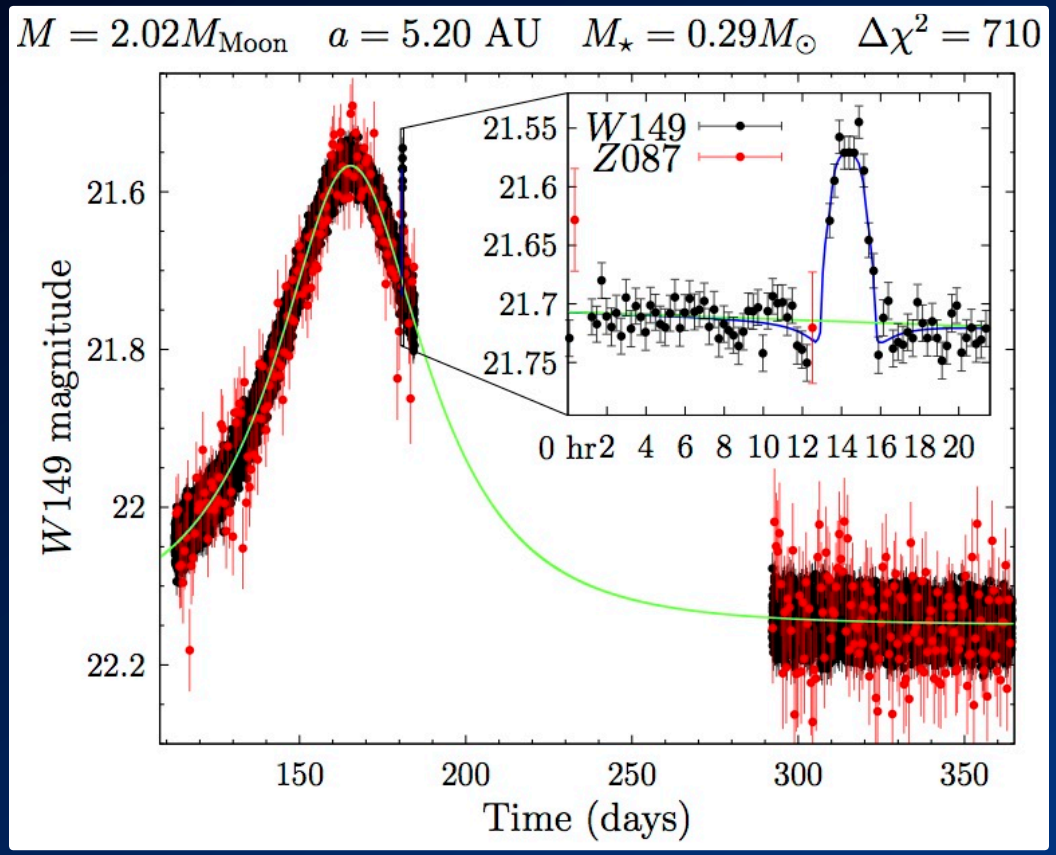
Future.

WFIRST.

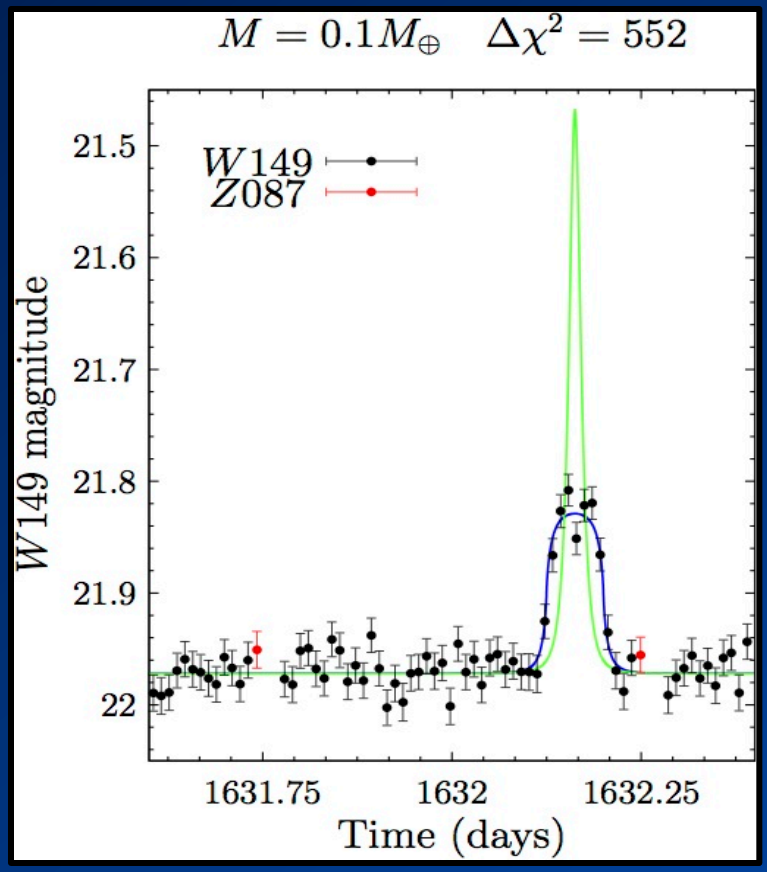
Wide-Field Infrared Survey Telescope, (WFIRST).

- Next large space telescope being planned by NASA.
  - Planned launch in 2023 (roughly).
- Think: Hubble Space Telescope, with a wide-angle lens.
- Will use one of two telescopes donated by the National Reconnaissance Office (NRO).
  - Two 2.4m space-qualified telescopes, donated to NASA.

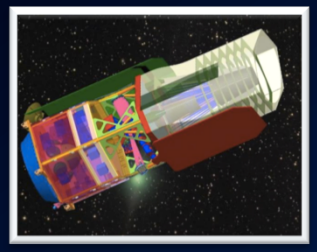

Kepler's
Search Area
WFIRST's
Search Area
M
V
E
M
J
S
U
N
P



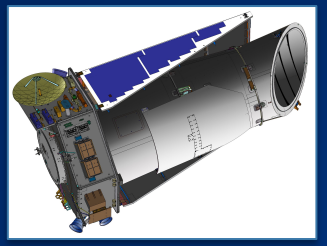
2 × Mass of the Moon @ 5.2 AU (~27 sigma)



Free floating Mars (~23 sigma)



Together, Kepler and WFIRST complete the statistical census of planetary systems in the Galaxy.



- ~3000 detections.
- Sensitive to analogs of all the solar systems planets except Mercury.
- Hundreds of free-floating planets.
- Galactic distribution of planets.
- Sensitive to lunar-mass satellites.