Recent Microlensing Results from the Ground and from Space

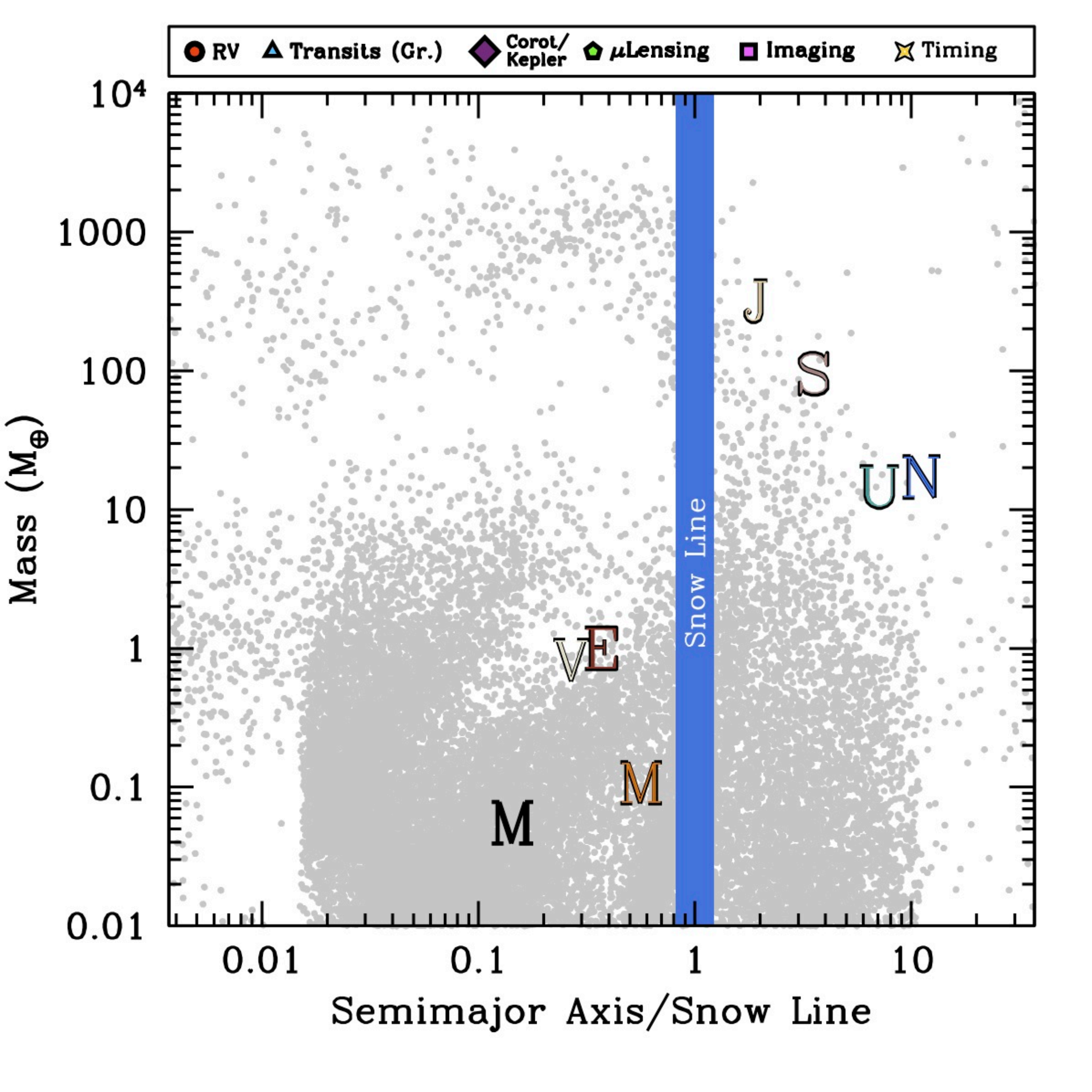
Wide-field InfraRed Surveys
November 17, 2014

Scott Gaudi
The Ohio State University

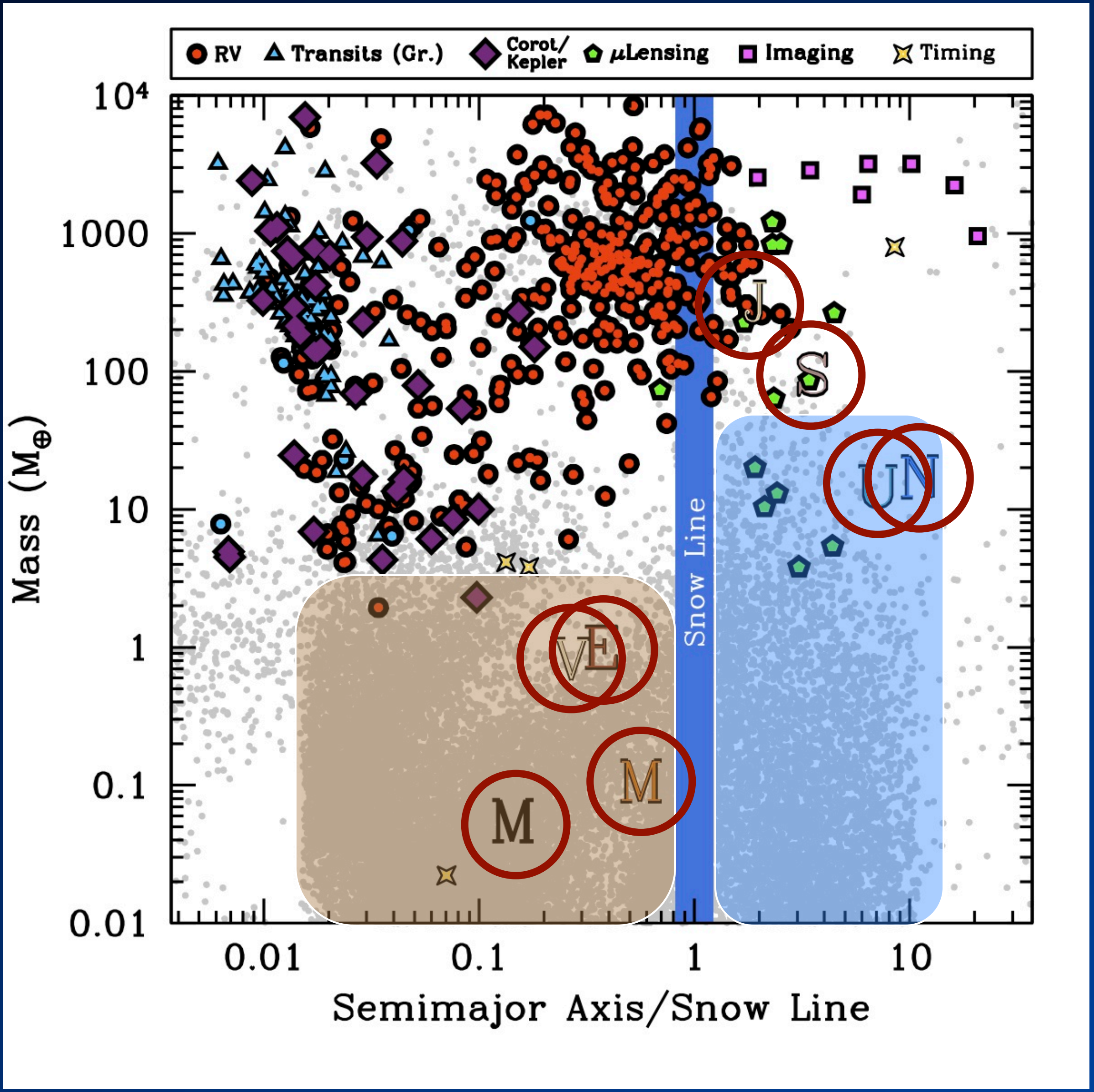
Planet Formation.

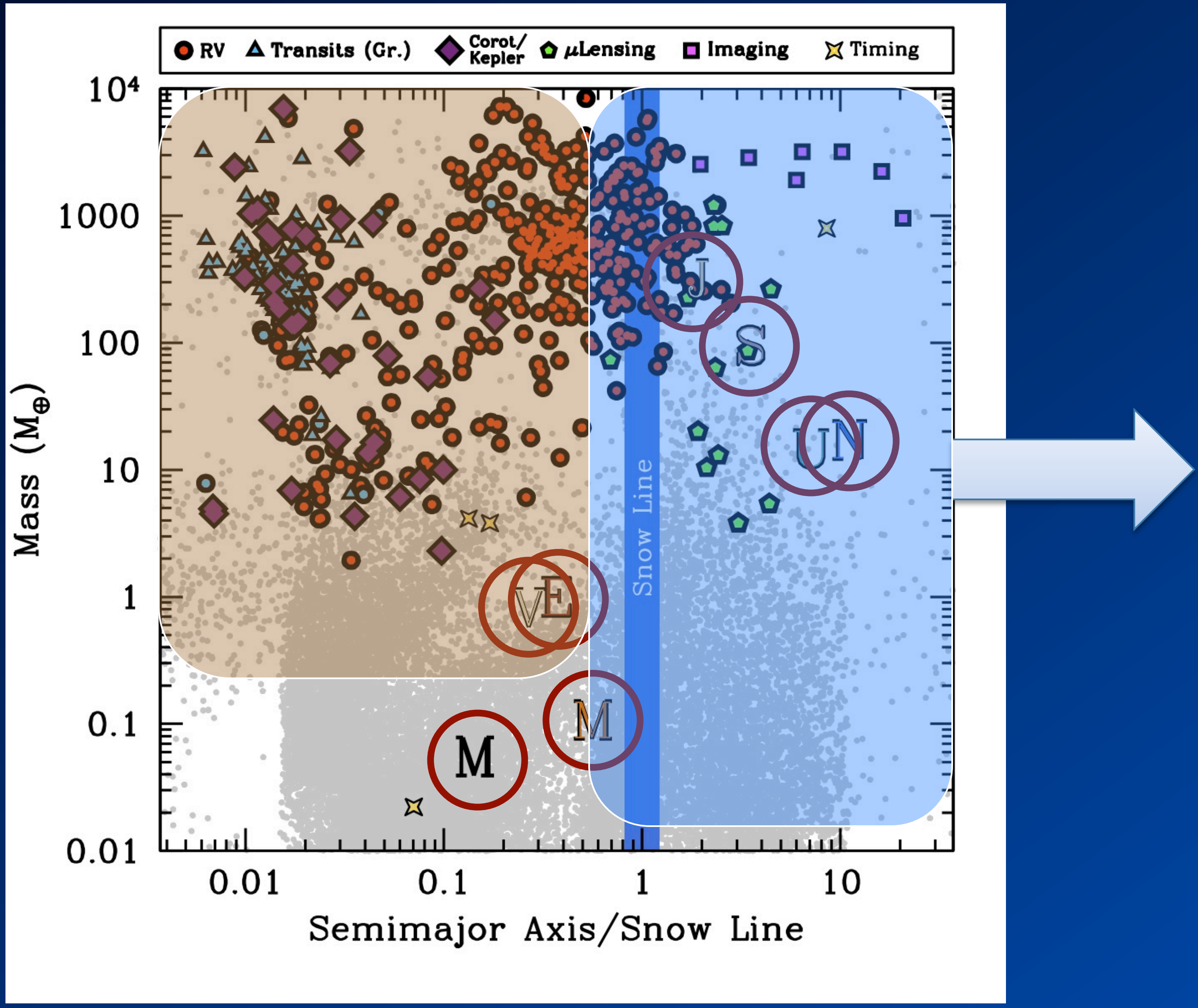
Must understand the physical processes by which micron-sized grains in protoplanetary disks grow by $10^{\sim 13\text{-}14}$ in size and $10^{\sim 38\text{-}41}$ in mass.

Hard!

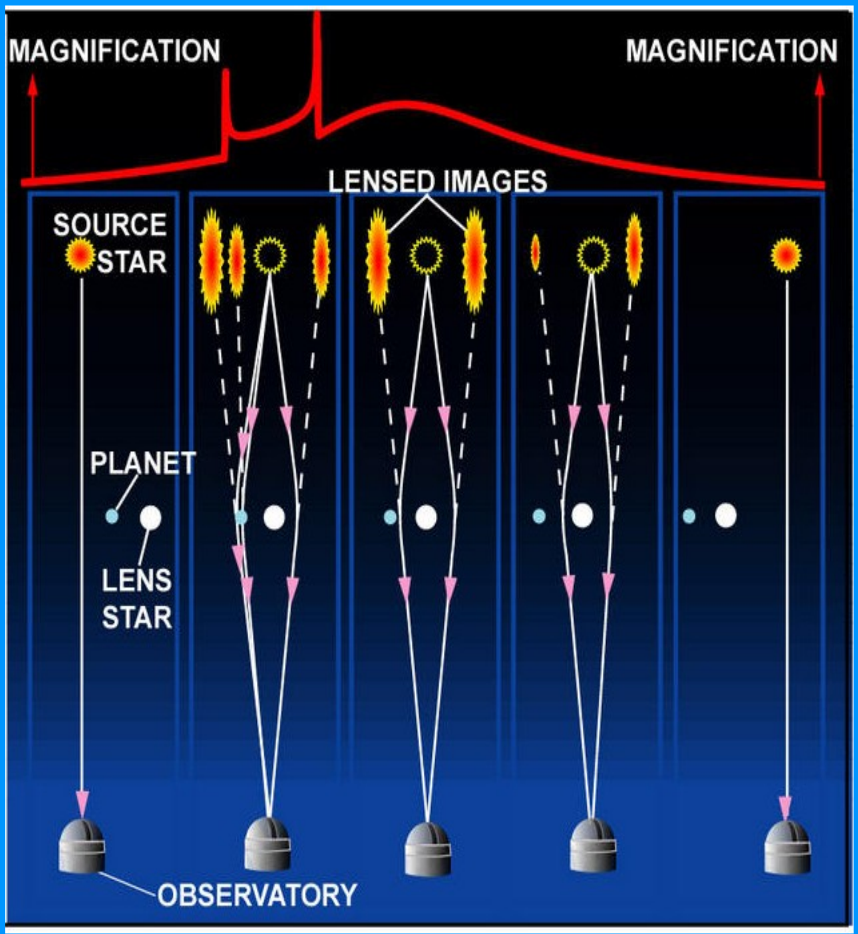

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass (M⊕)
Semimajor Axis/Snow Line
Snow Line
10⁴
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
J
S
U
N
V
E
M
M

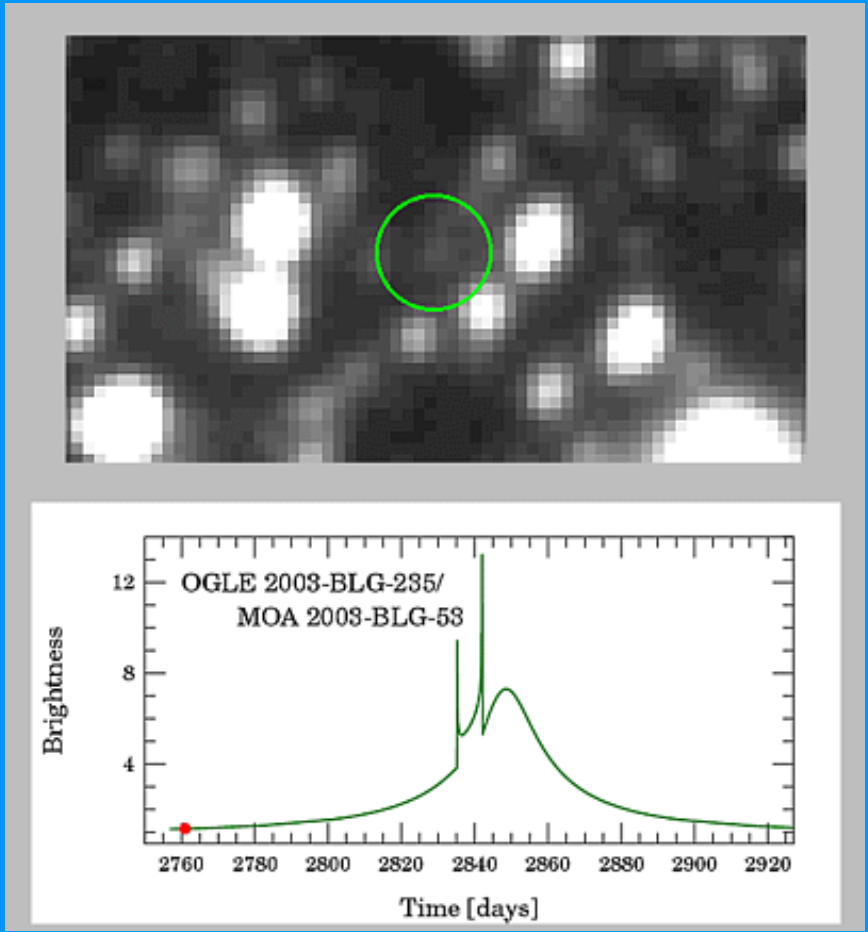
(Ida & Lin)


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
U
N
V
E
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
U
N
V
E
M
M

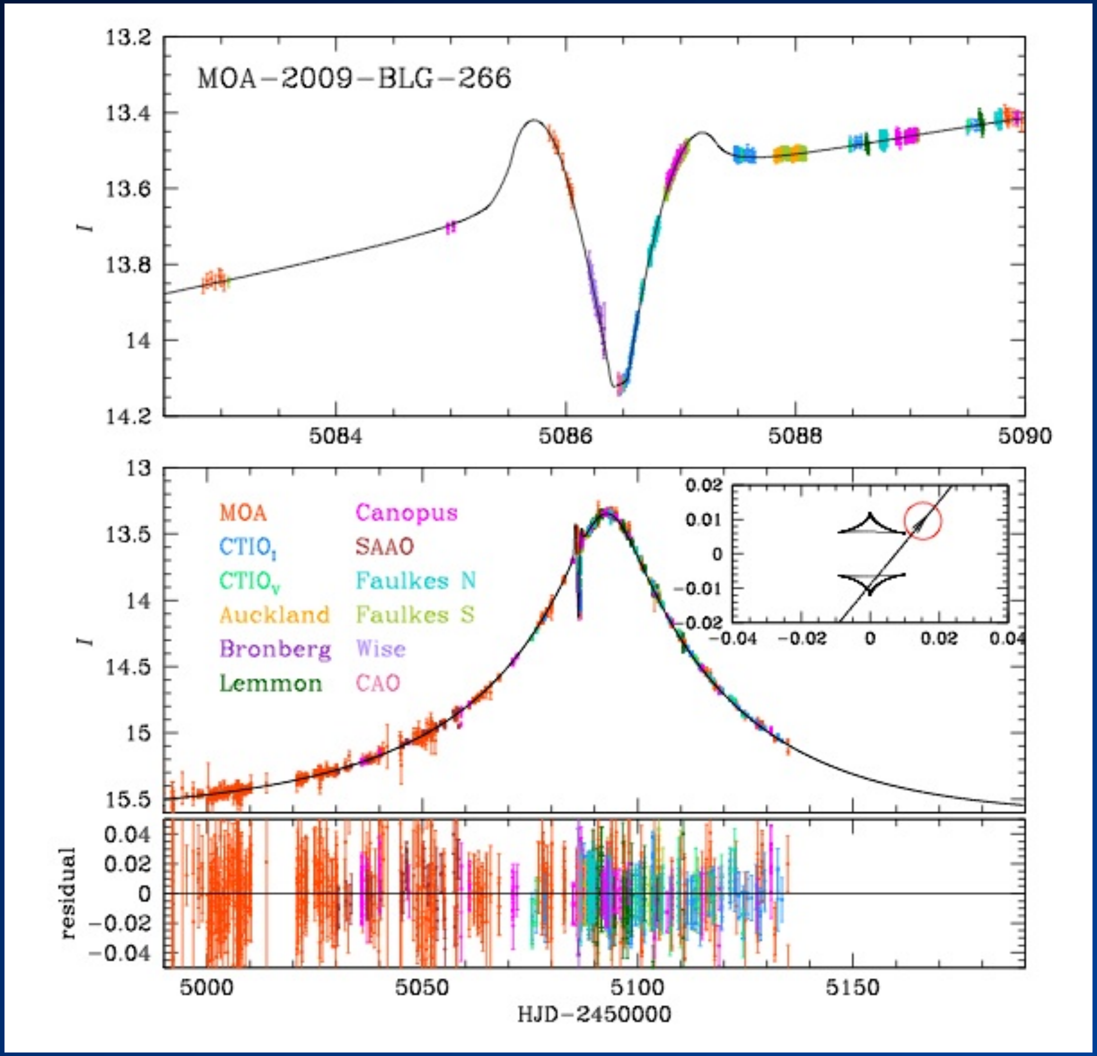
Cool, low-mass, and free-floating planets.





Results: Individual Systems.

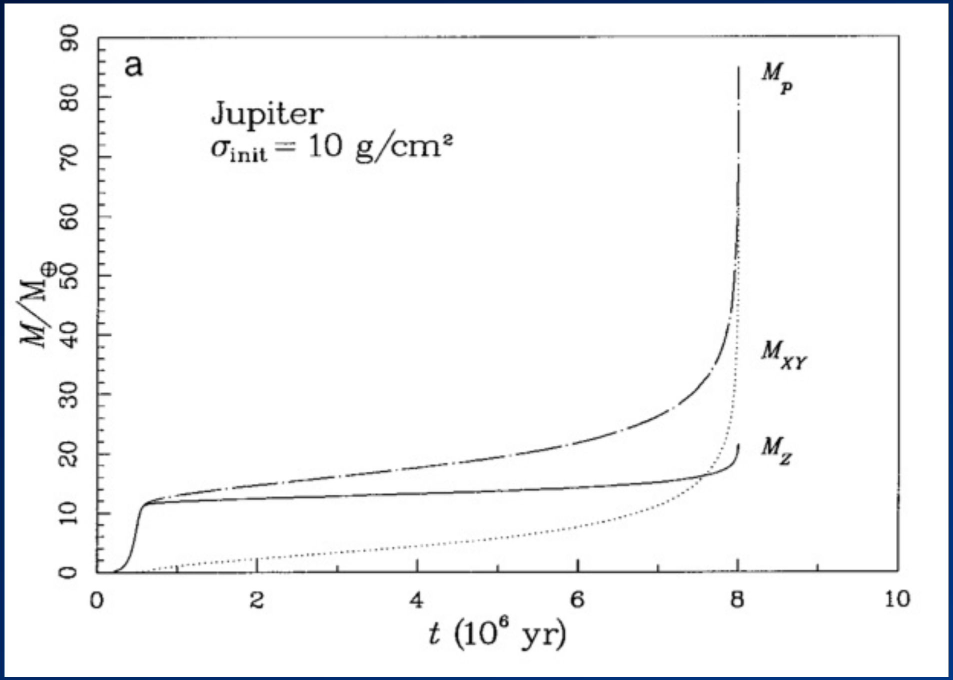
~10 M_{Earth} Planet.



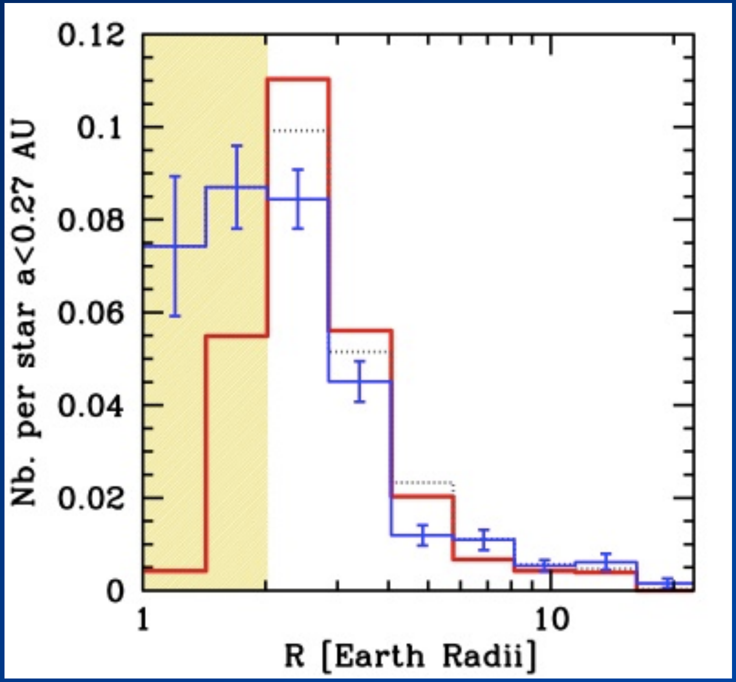
(MOA, μFUN, PLANET, RoboNET, Muraki et al. 2011)

Failed Jupiter Core?

$$\text{Planet mass} = 10.4 \pm 1.7\, M_{\text{Earth}}$$

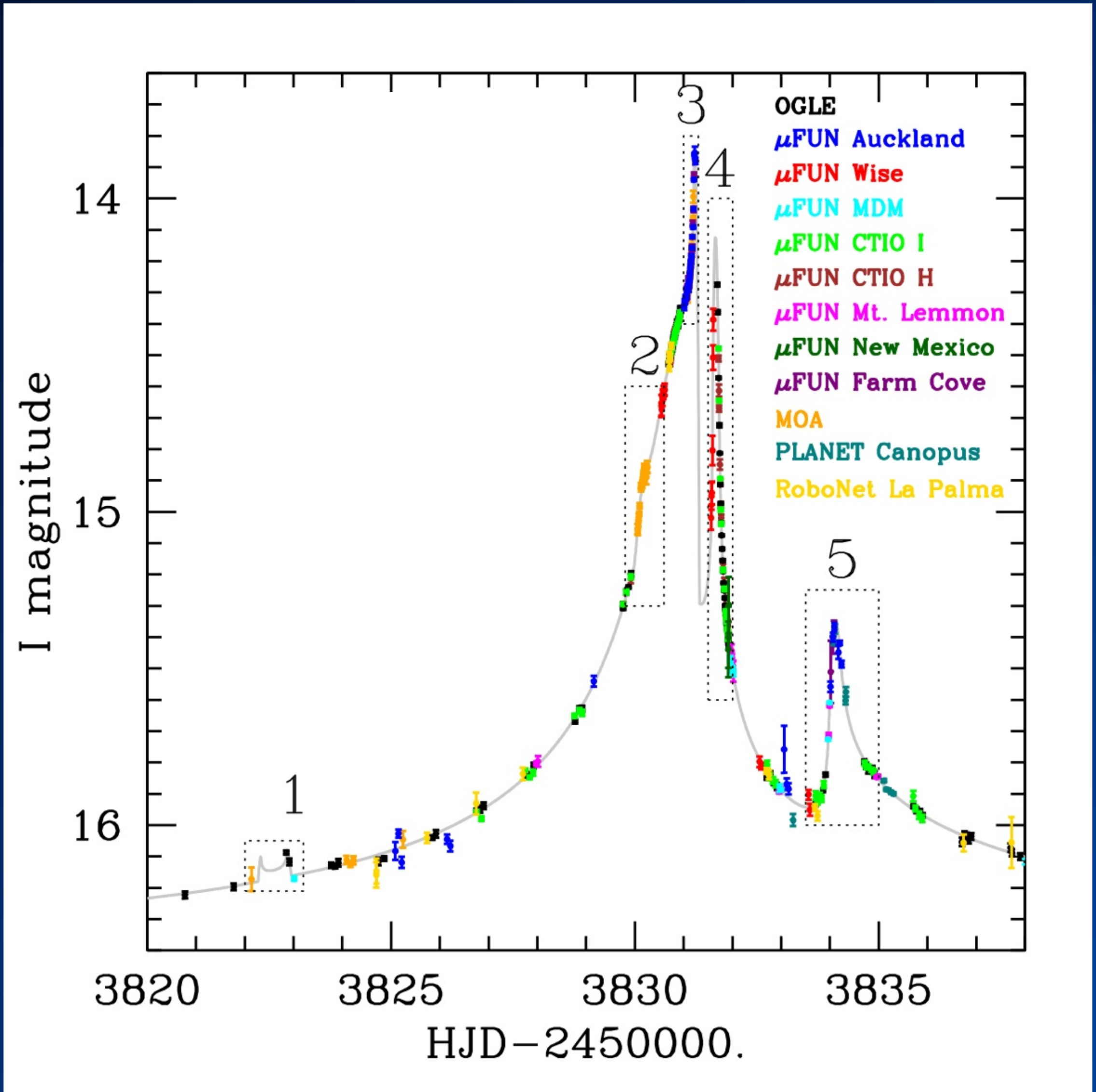


(Pollack et al. 1996)



(Mordasini et al. 2012)

A Multiple-Planet System.



(Gaudi et al 2008; Bennett et al 2010)

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:

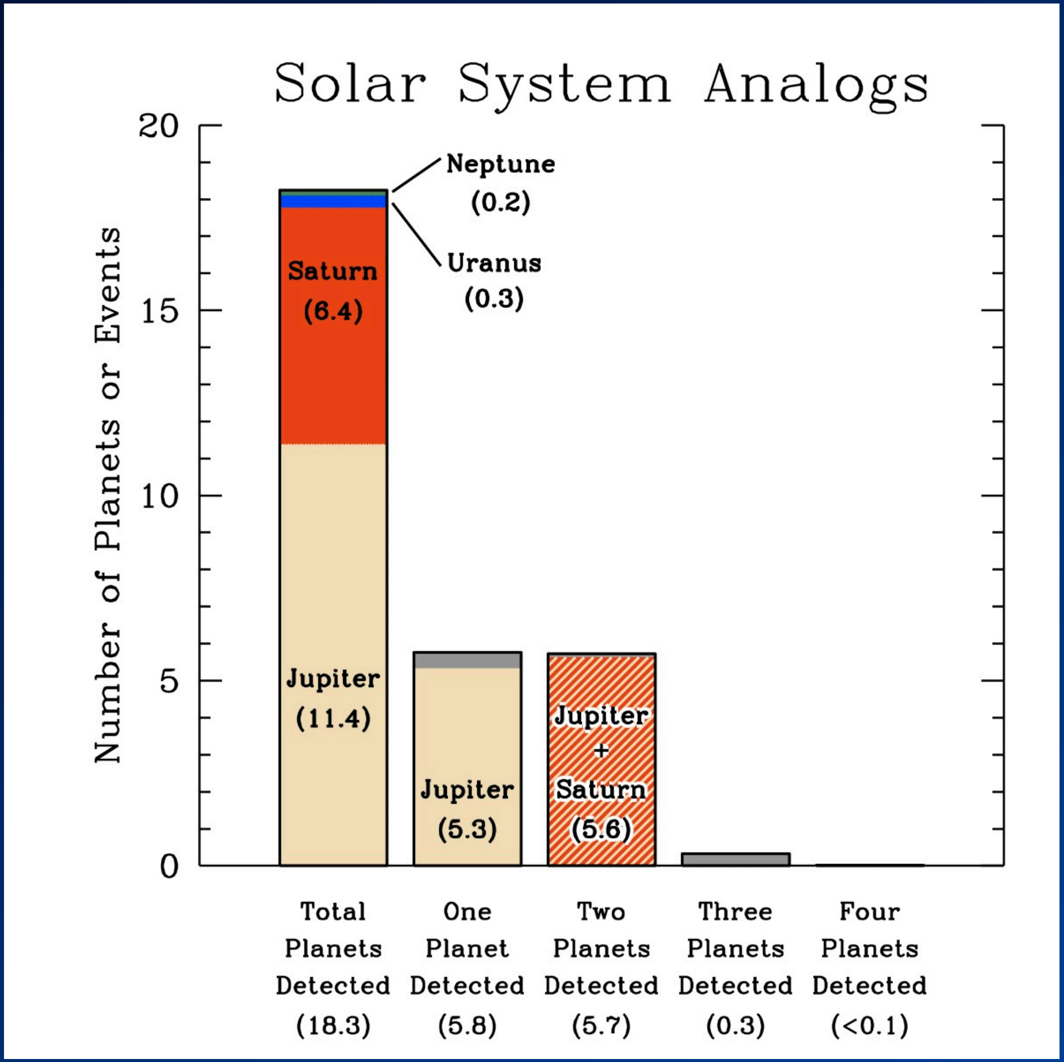
Mass = 0.27 +/- 0.02 M_{Jup} = 0.90 M_{Sat}

Semimajor Axis = 4.6 +/- 1.5 AU

Eccentricity = 0.15+0.17-0.10

Inclination = 64+4-7 degrees

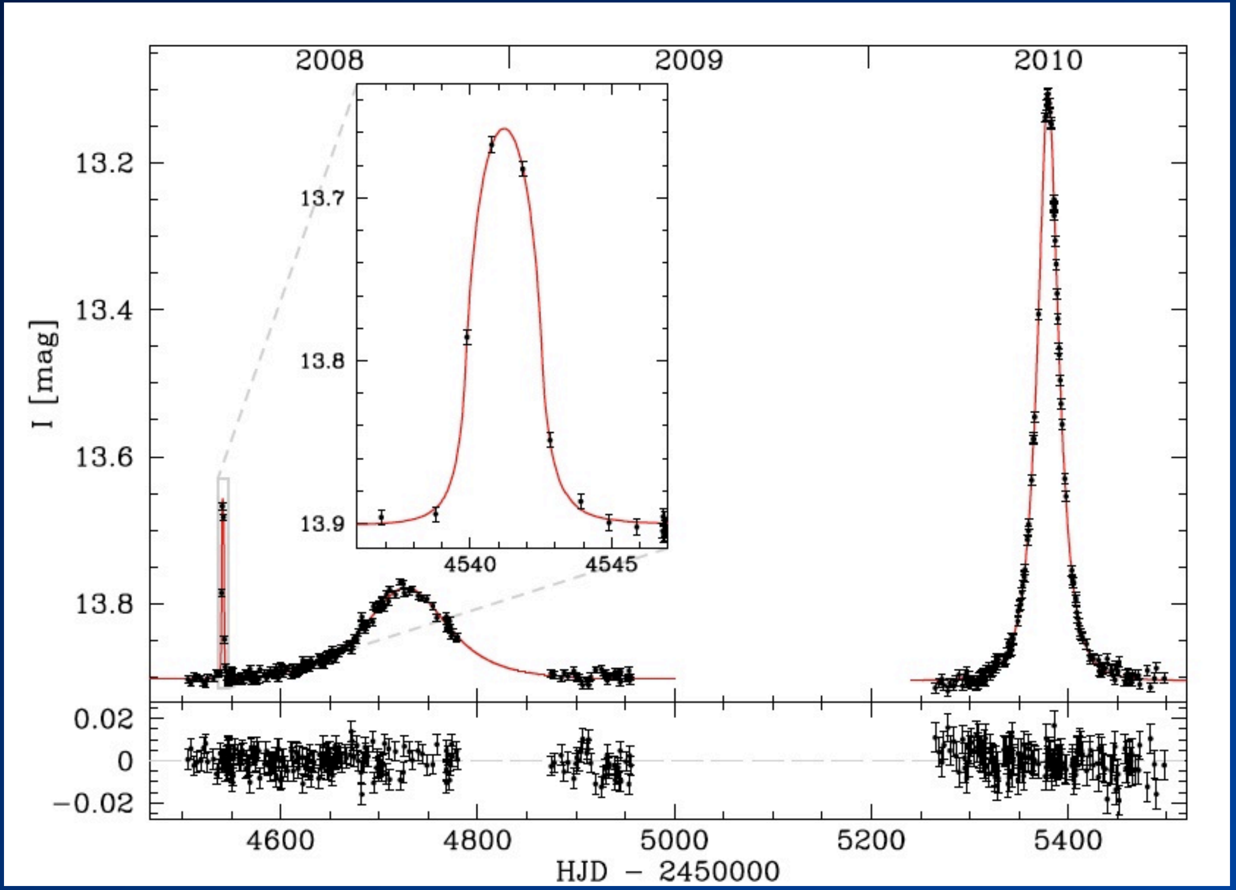
No Place Like Home?



Frequency of Solar System Analogs: ~15% (Gould et al. 2010)

First ice giant analog.

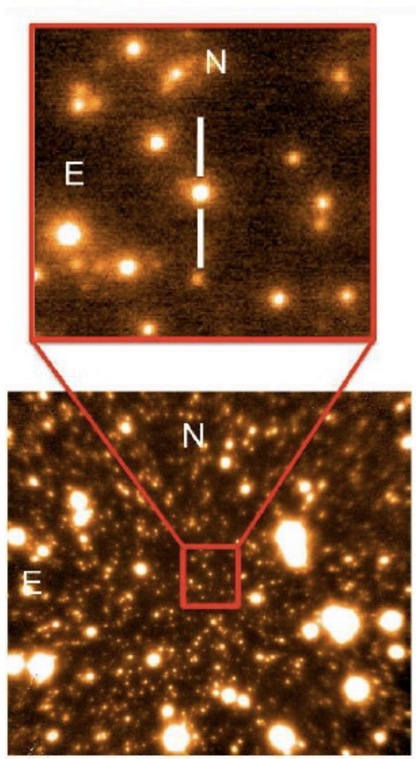
- Primary
  - ~0.71 M_{Sun}
- Planet
  - ~4 M_{Uranus}
  - ~18 AU.
- Secondary
  - ~0.15 M_{Sun}
  - ~58 AU

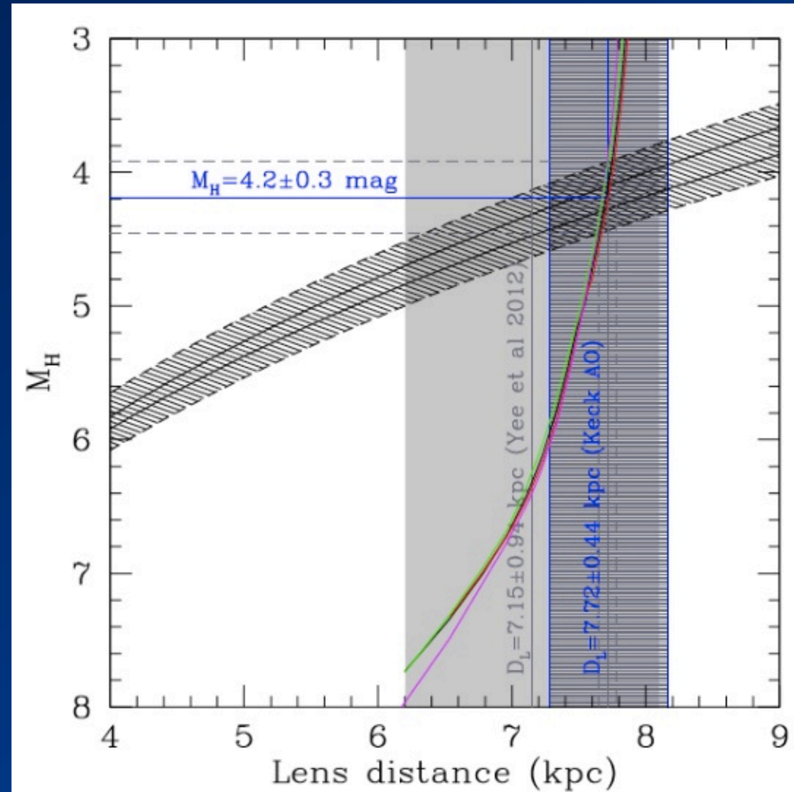


(Poleski et al. 2014)

Bulge/Habitable Zone Planet.

- Primary
  - ~0.86 M_{Sun}
  - ~7.7 kpc
- Planet
  - ~4.8 M_{Jup}
  - ~1.1 AU

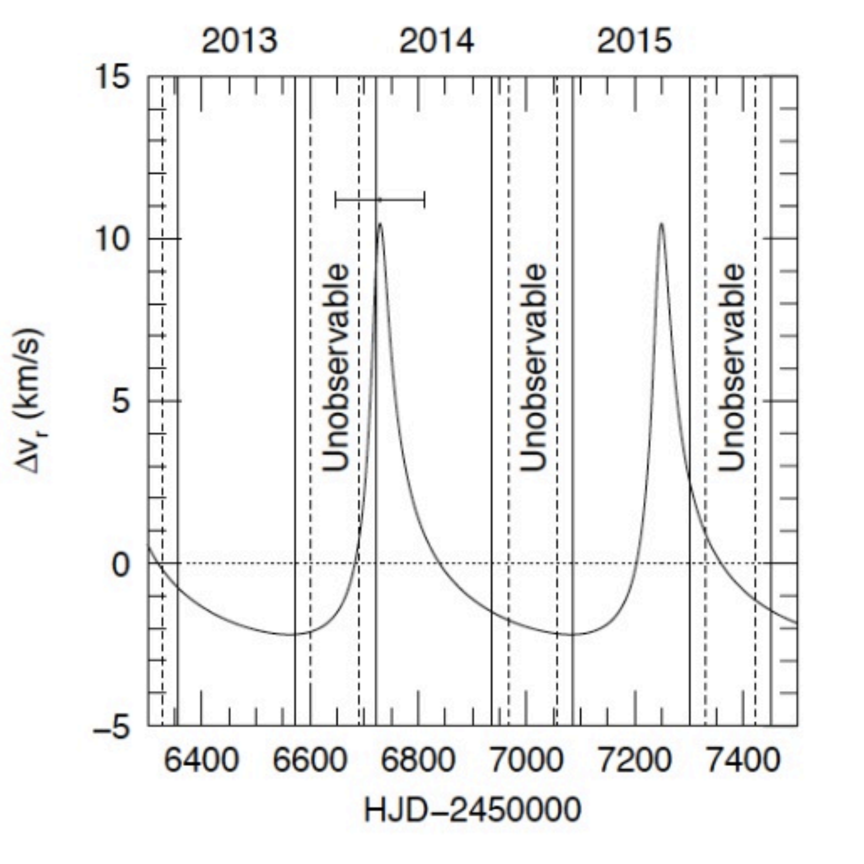




(Yee et al. 2012, Batista et al. 2014, see Thompson 2013)

Radial Velocity Confirmation.

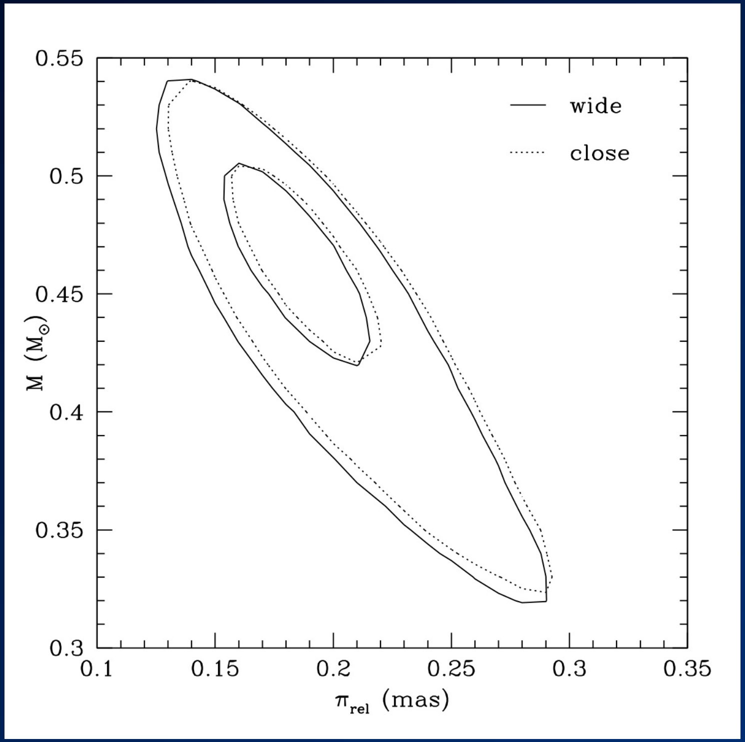
- Binary lens event OGLE-2011-BLG-0417
  - 8-parameter solution
  - Yields a precise prediction for the RV signal.
- Bright Lens
  - I=16.3
  - V=18.2
- Large Amplitude
  - K=6.4 km/s

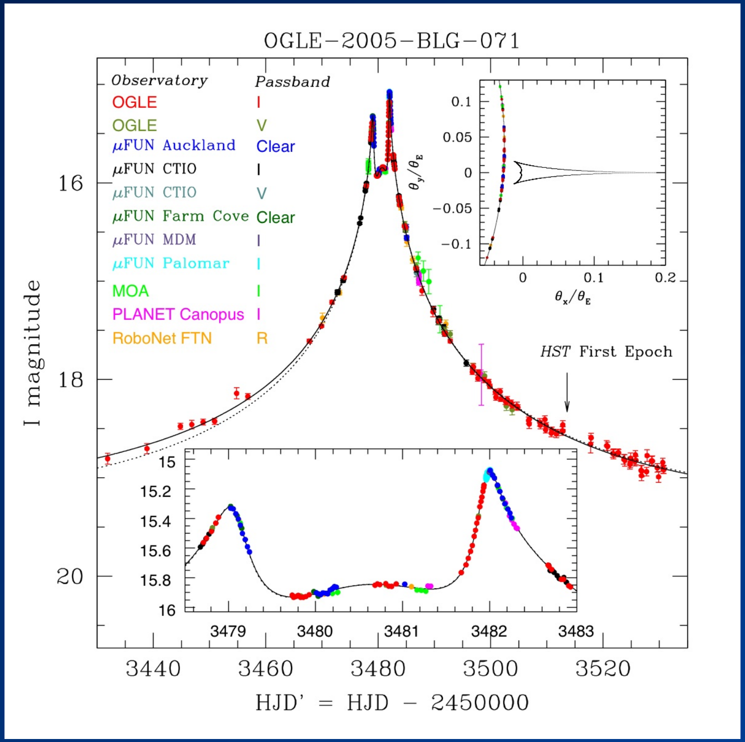


(Skowron et al. 2011, Gould et al. 2013)

Results: Demographics.

Massive M Dwarf Planets.





(Dong et al. 2008, Batista et al. 2011, Poleski et al. 2014, Tsapras et al. 2014)

$$M = 0.46 \pm 0.04 M_\odot$$

$$D_l = 3.2 \pm 0.4 \text{ kpc}$$

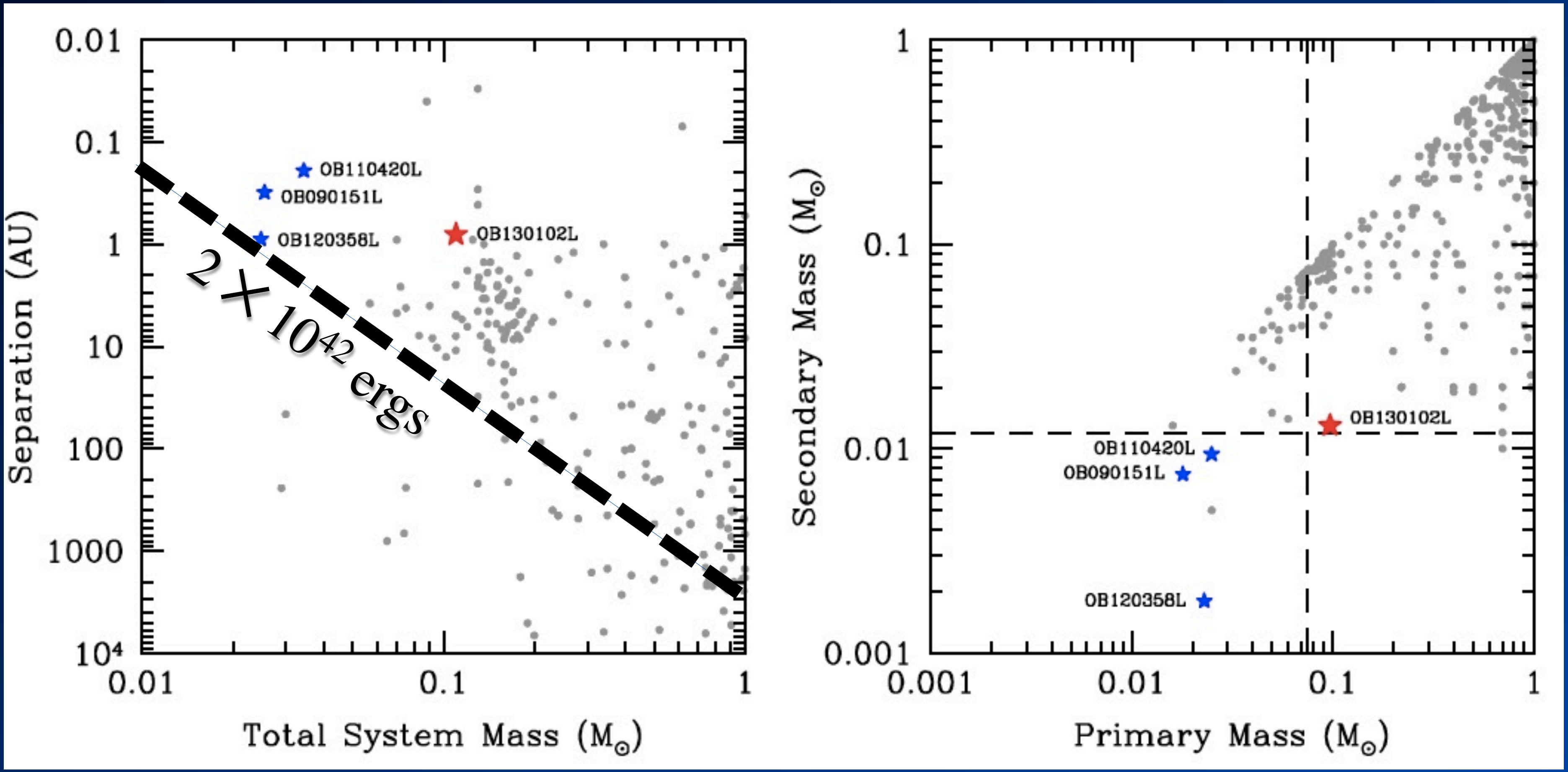
$$v_{\text{LSR}} = 103 \pm 15 \text{ km s}^{-1}$$

$$m = 3.8 \pm 0.4 M_{\text{Jup}}$$

$$r_\perp = 3.6 \pm 0.2 \text{ AU}$$

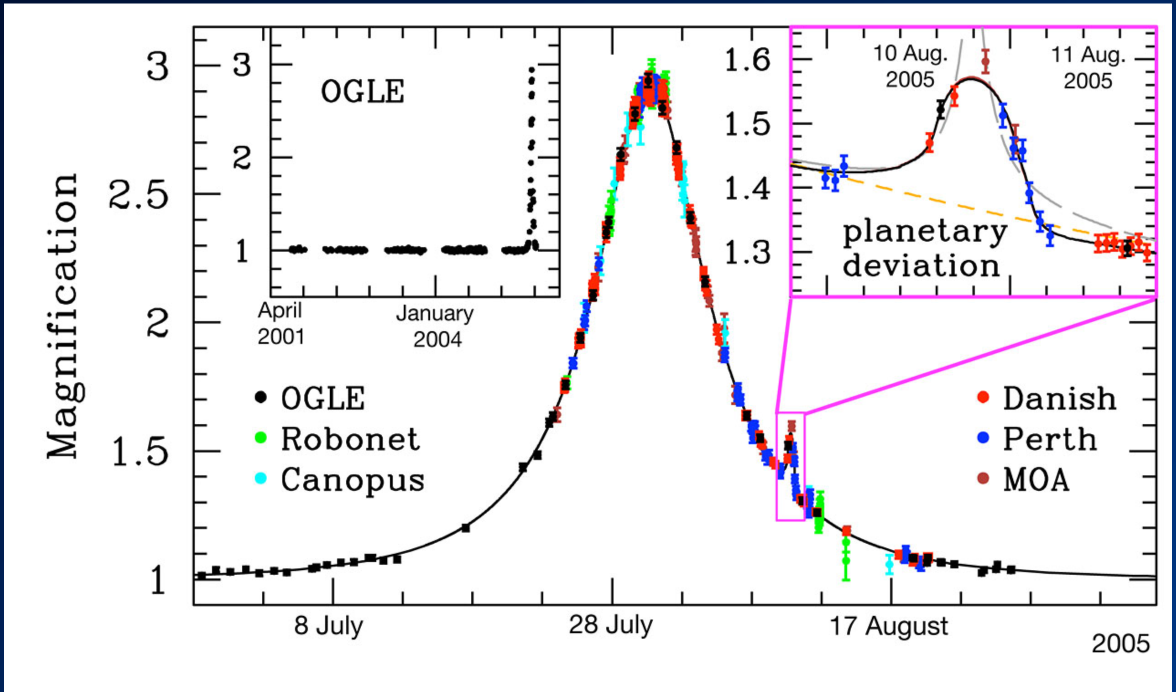
$$T_{eq} \sim 50 K$$

Low Mass Binaries.



(Choi et al. 2013, Han et al. 2013, Jung et al. 2013)

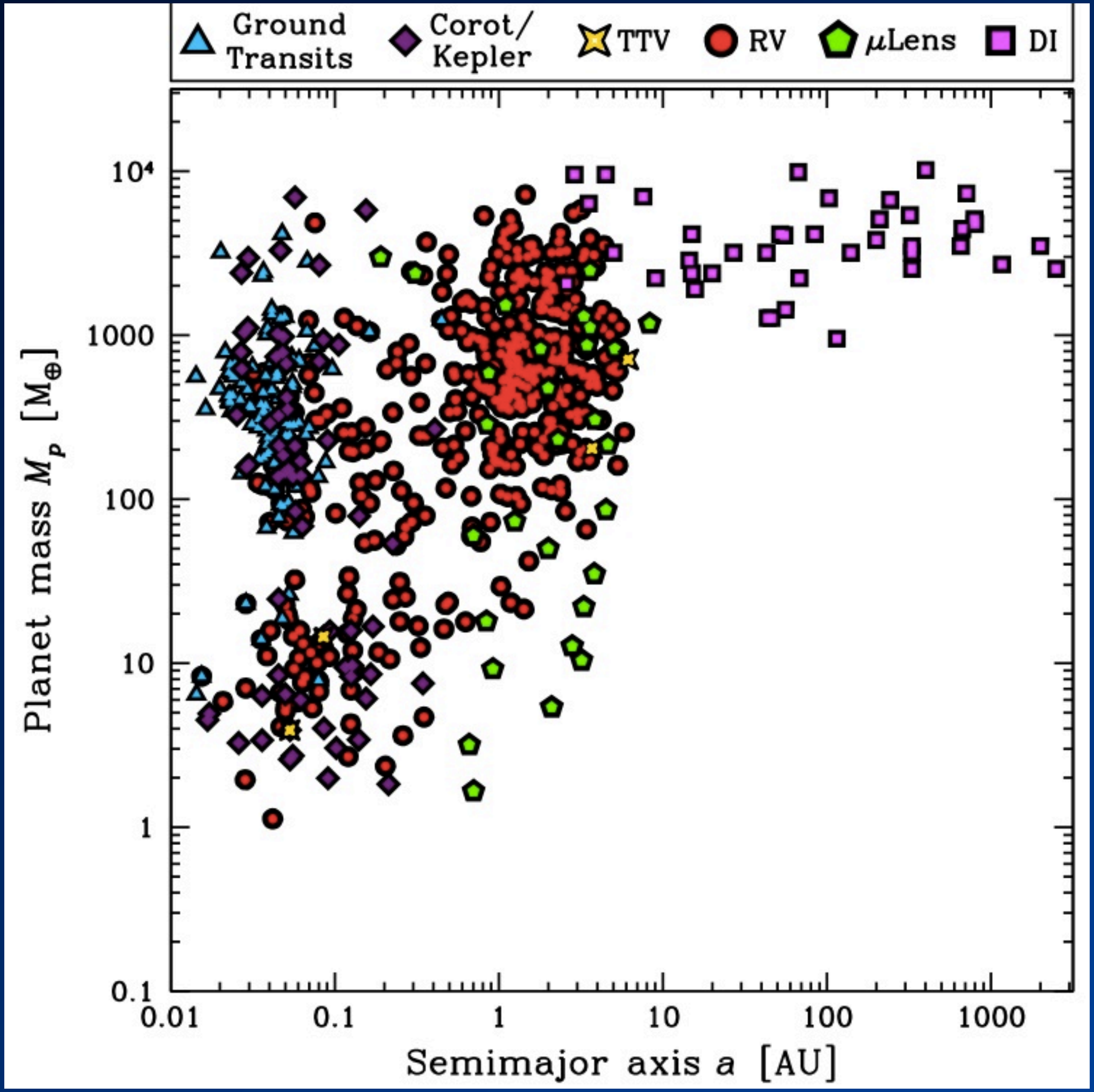
Cold, low-mass planets.



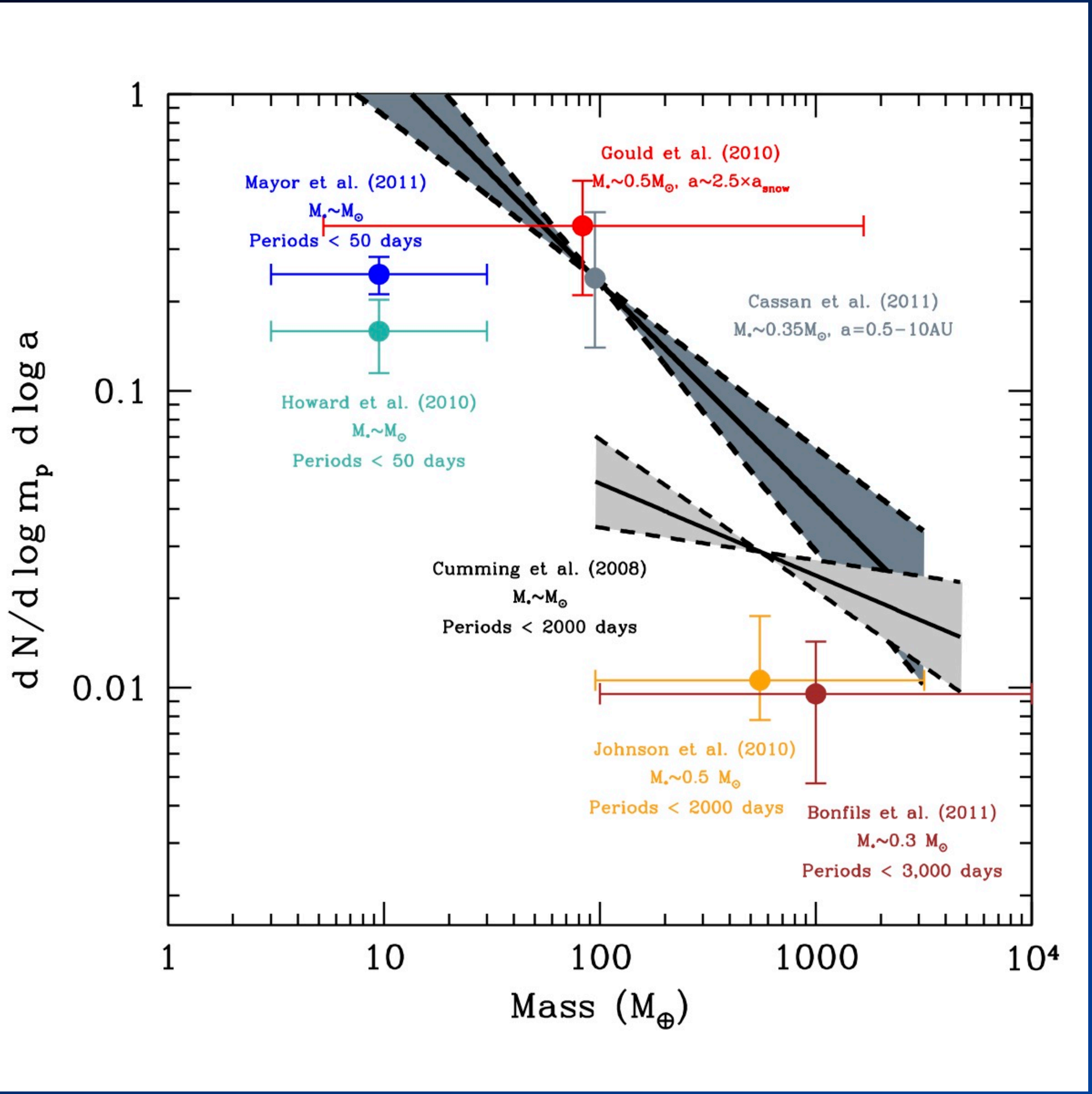
- Population of cold, low-mass Neptunes and Super-Earths.

(Beaulieu et al. 2006; Gould et al. 2006; Bennett et al. 2008; Sumi et al. 2010; Muraki et al. 2011; Furusawa et al. 2013)

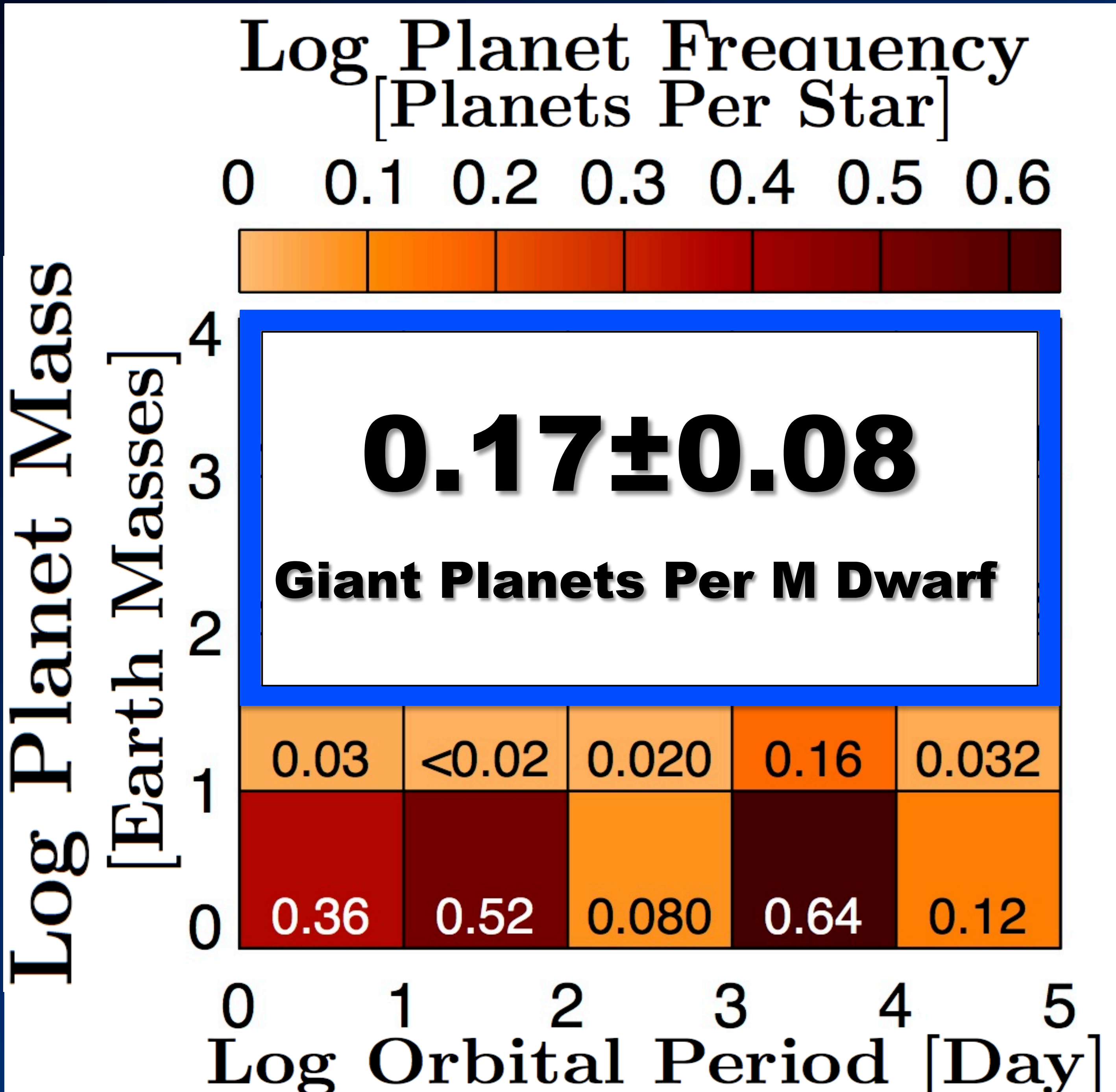
Low-mass planets are more common.



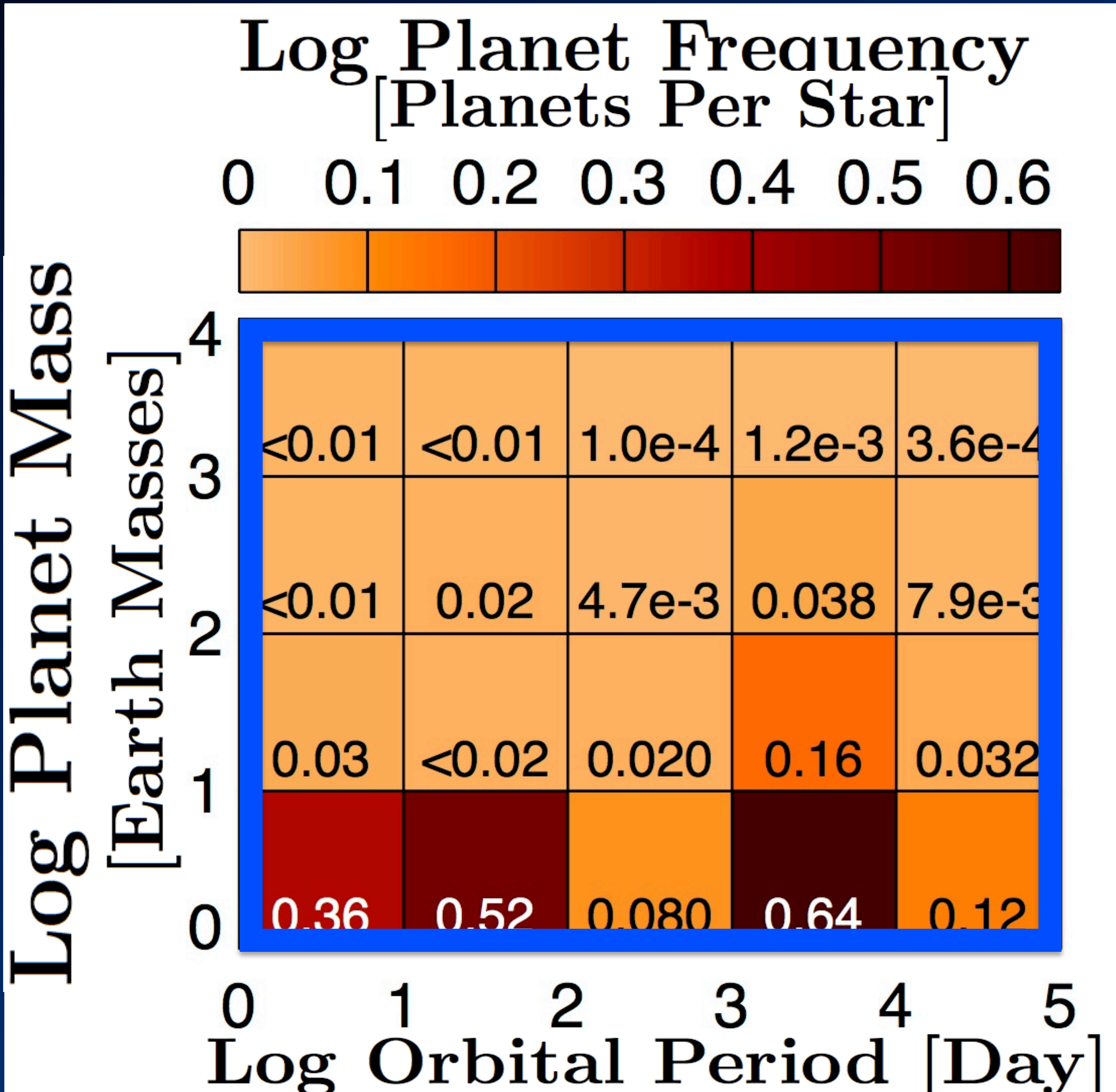
(Gould et al. 2006, Sumi et al. 2010, Cassan et al. 2012)



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



(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

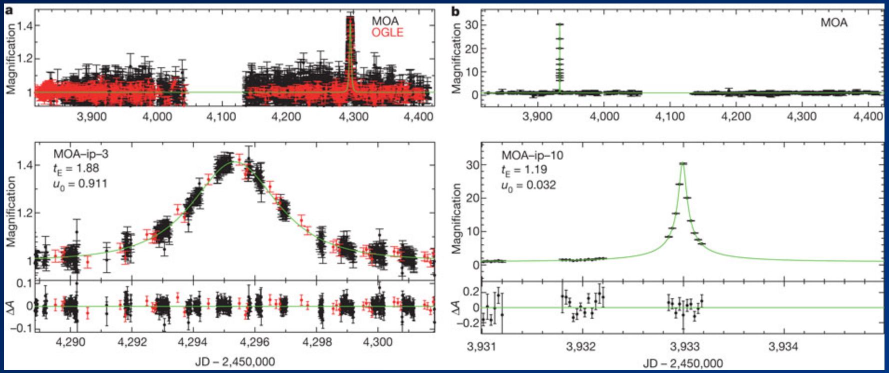
Giant Planets Per M Dwarf

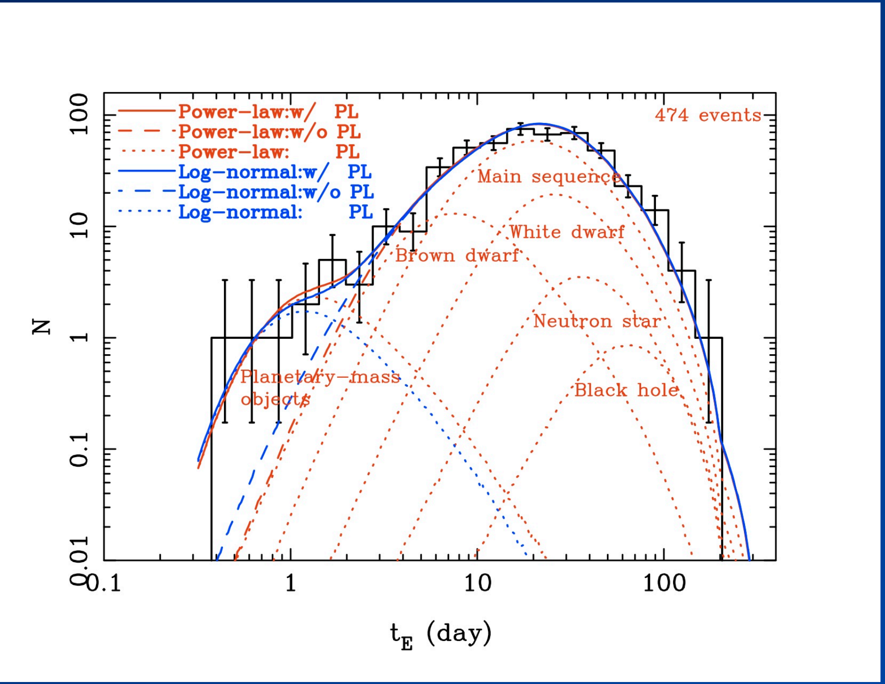
(mass>30×Earth, periods<10^4 days)

(Clanton & Gaudi 2014a,b)

Free Floating Planets.

- Excess of short time scale events relative to expected stellar/brown dwarf contribution.
- Unbound or wide-separation planets.
- Implies roughly 2 Jupiter-mass free-floating planets per star.
- If free-floating, hard to explain.

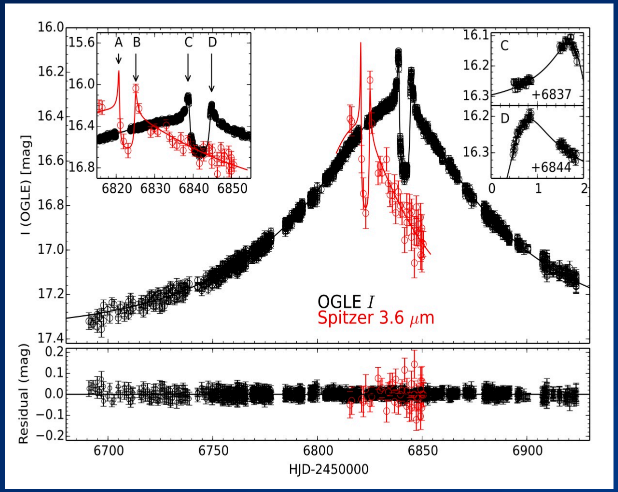


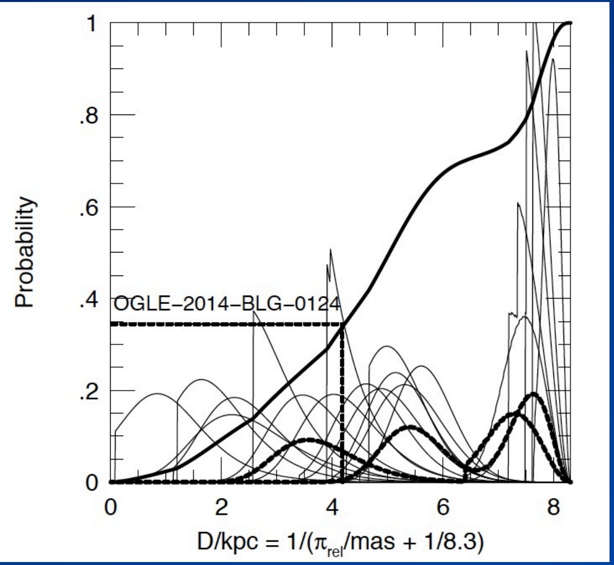


(Sumi et al. 2011; MOA + OGLE)

The Watershed.

- **Spitzer & K2.**
  - **Masses and distances.**
  - **Mass function and Galactic distribution of planets.**
- KMTNet
  - 60 detections/year.
- Euclid & WFIRST
  - Detections *en masse*.
  - Complete the census of exoplanets started by *Kepler*.
- See talks and posters by: Bennett, Calchi Novati, Gould, Henderson, Penny, Yee, Zhu

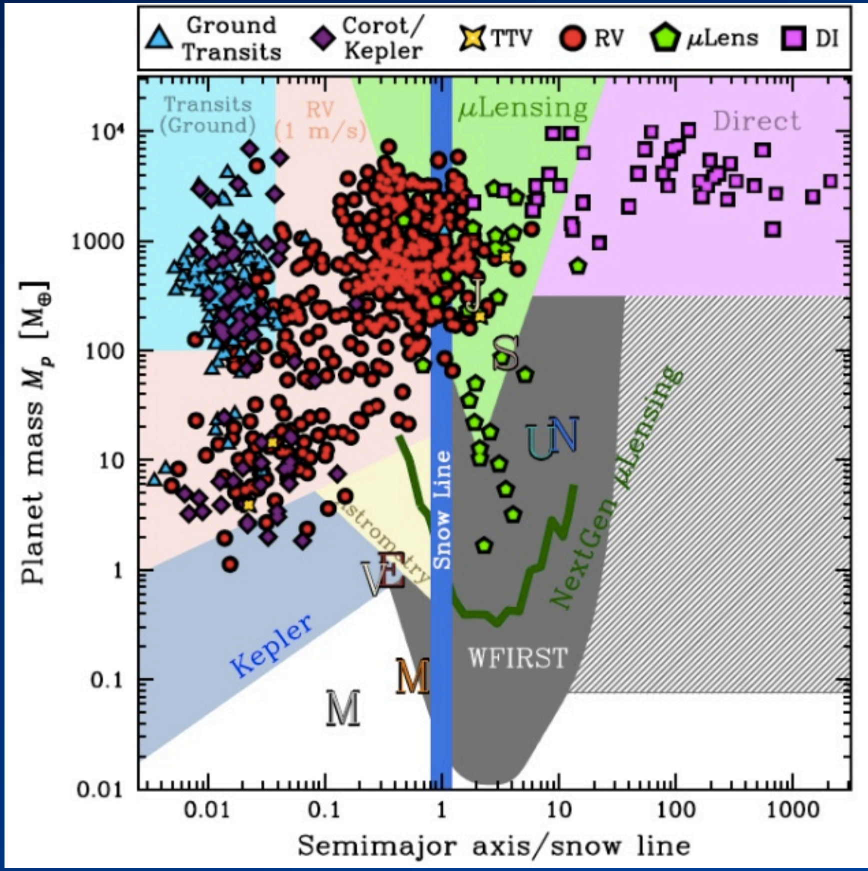




(Udalski et al. 2014, Yee et al. 2014, Calchi Novati et al. 2014)

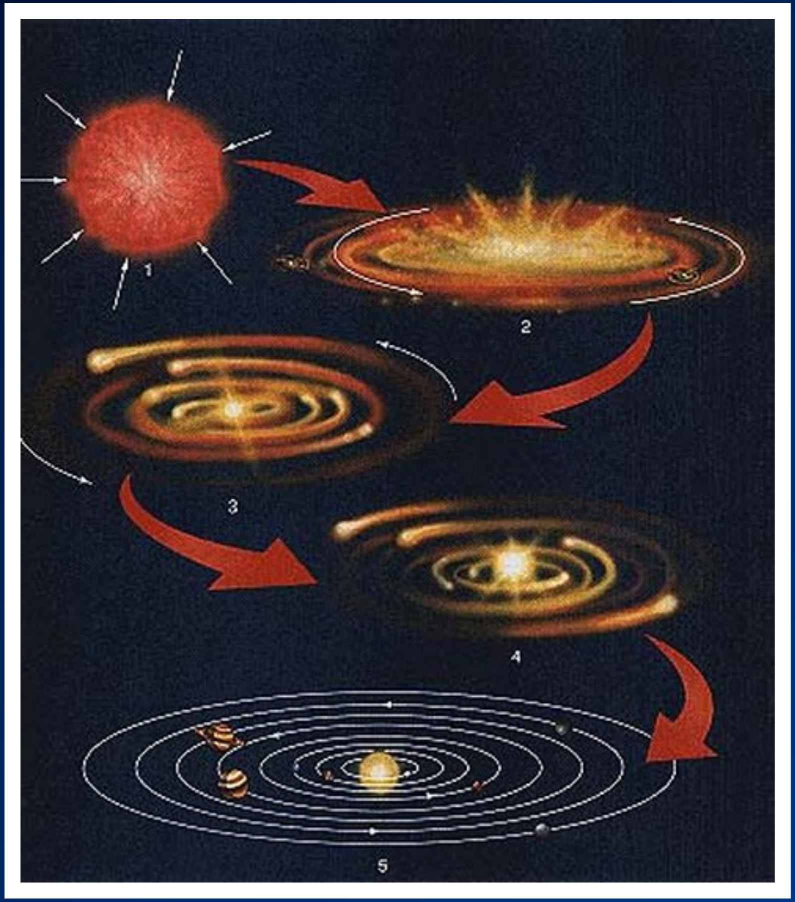
The Watershed.

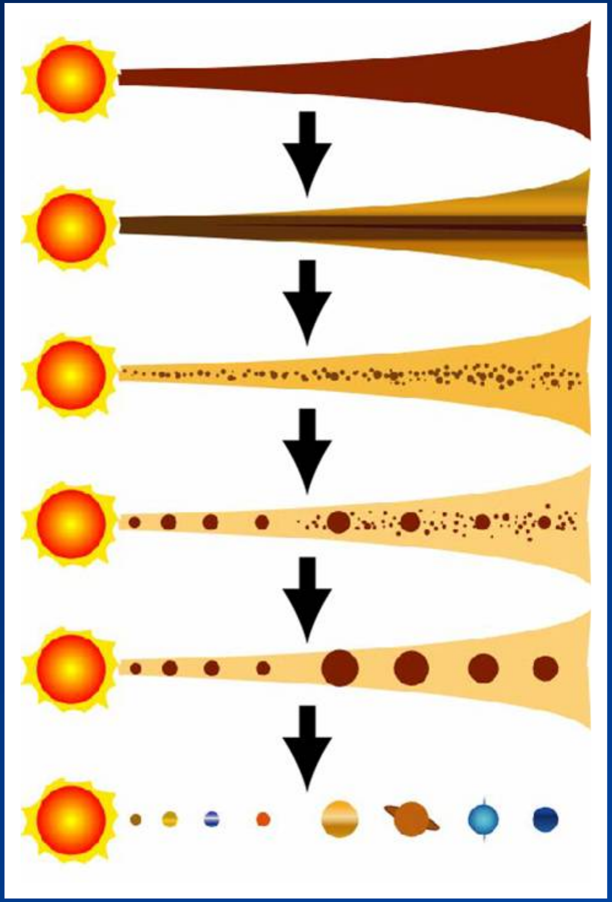
- **Spitzer & K2.**
  - **Masses and distances.**
  - **Mass function and Galactic distribution of planets.**
- KMTNet
  - 60 detections/year.
- Euclid & WFIRST
  - Detections *en masse*.
  - Complete the census of exoplanets started by *Kepler*.
- See talks and posters by: Bennett, Calchi Novati, Gould, Henderson, Penny, Yee, Zhu



(Henderson et al. 2014, Penny et al. 2013; Spergel et al. 2013)

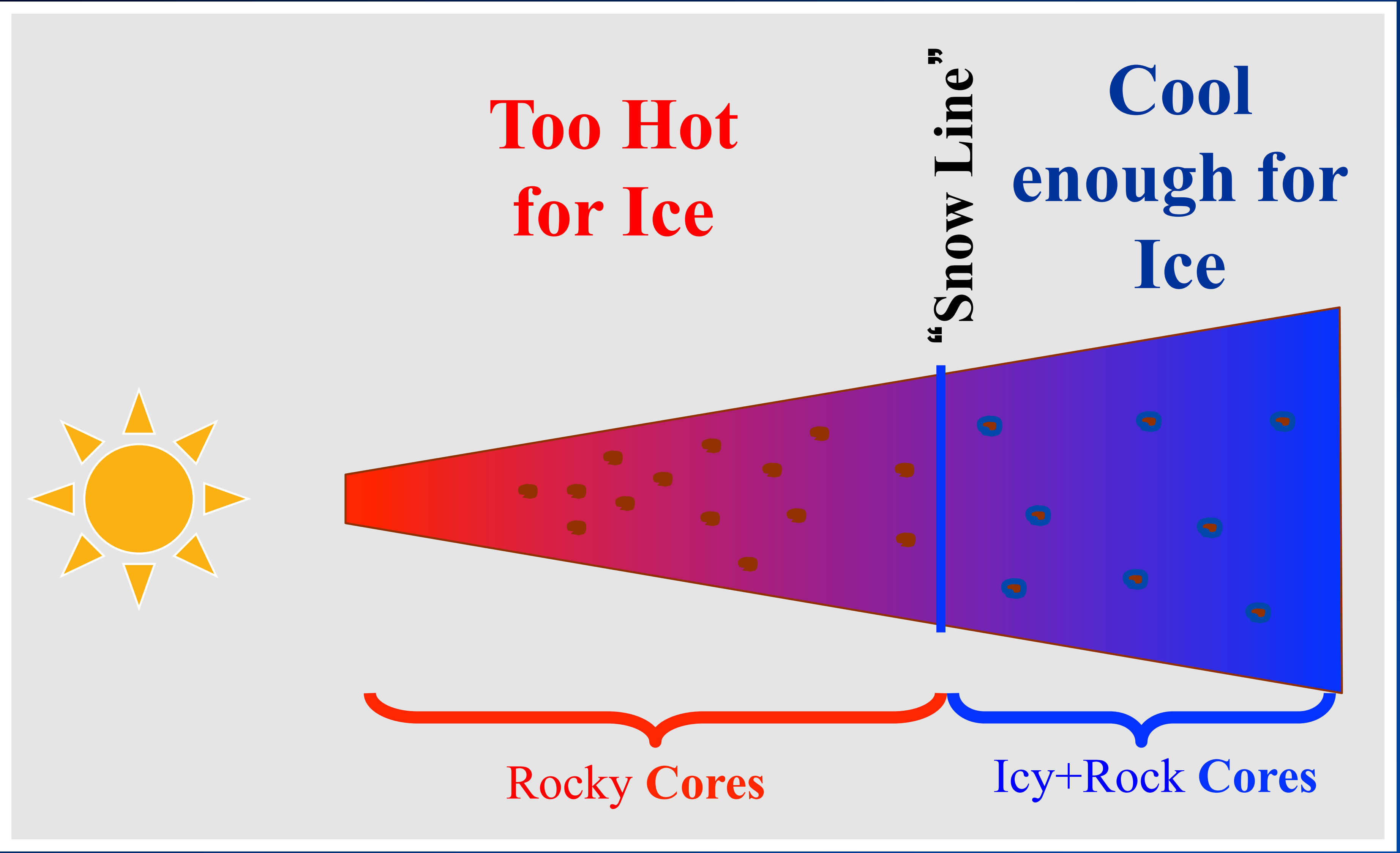
Bottom-Up Planet Formation.



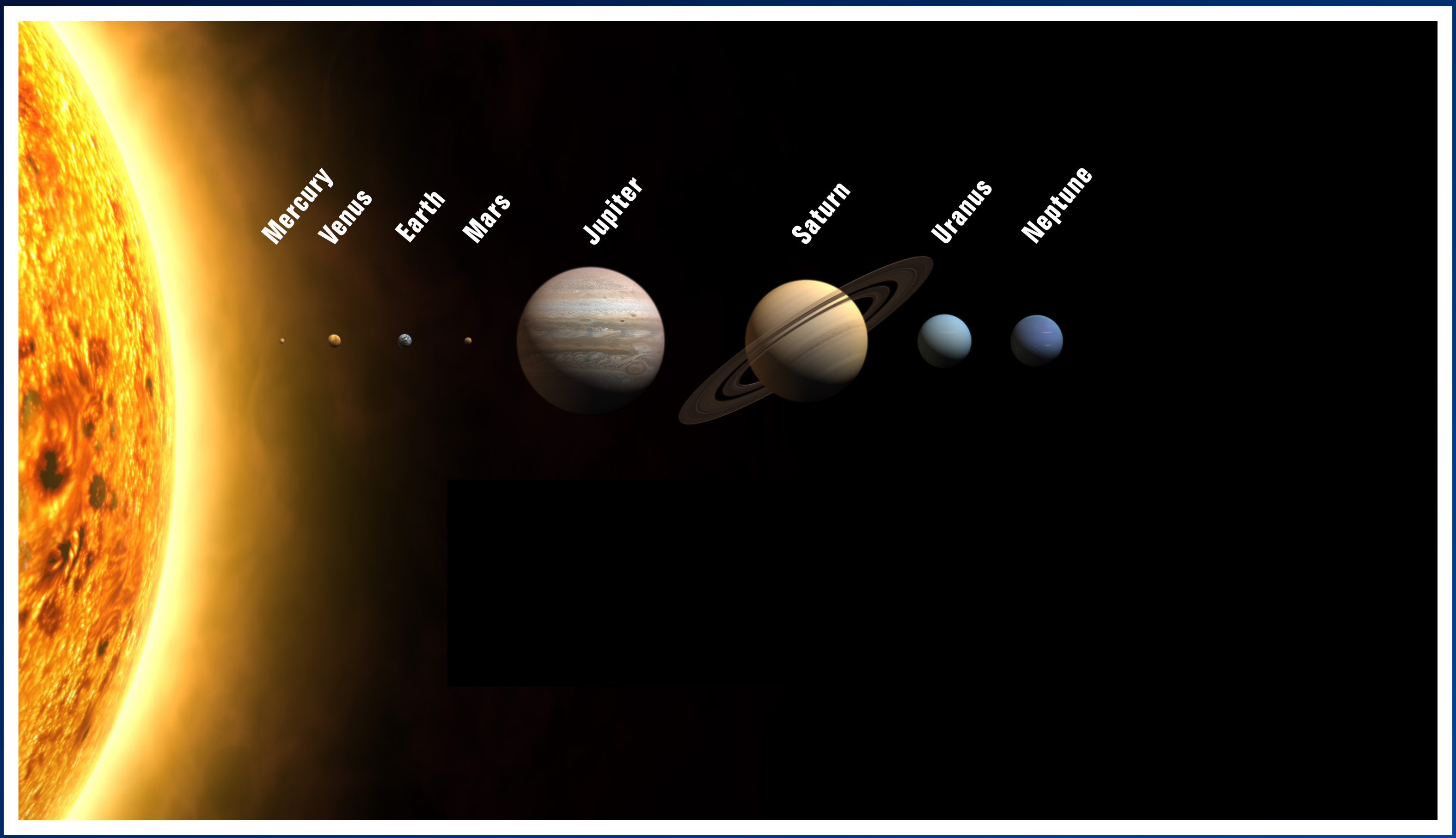


(e.g., Lissauer 1987; Ida & Lin 2004, 2005)

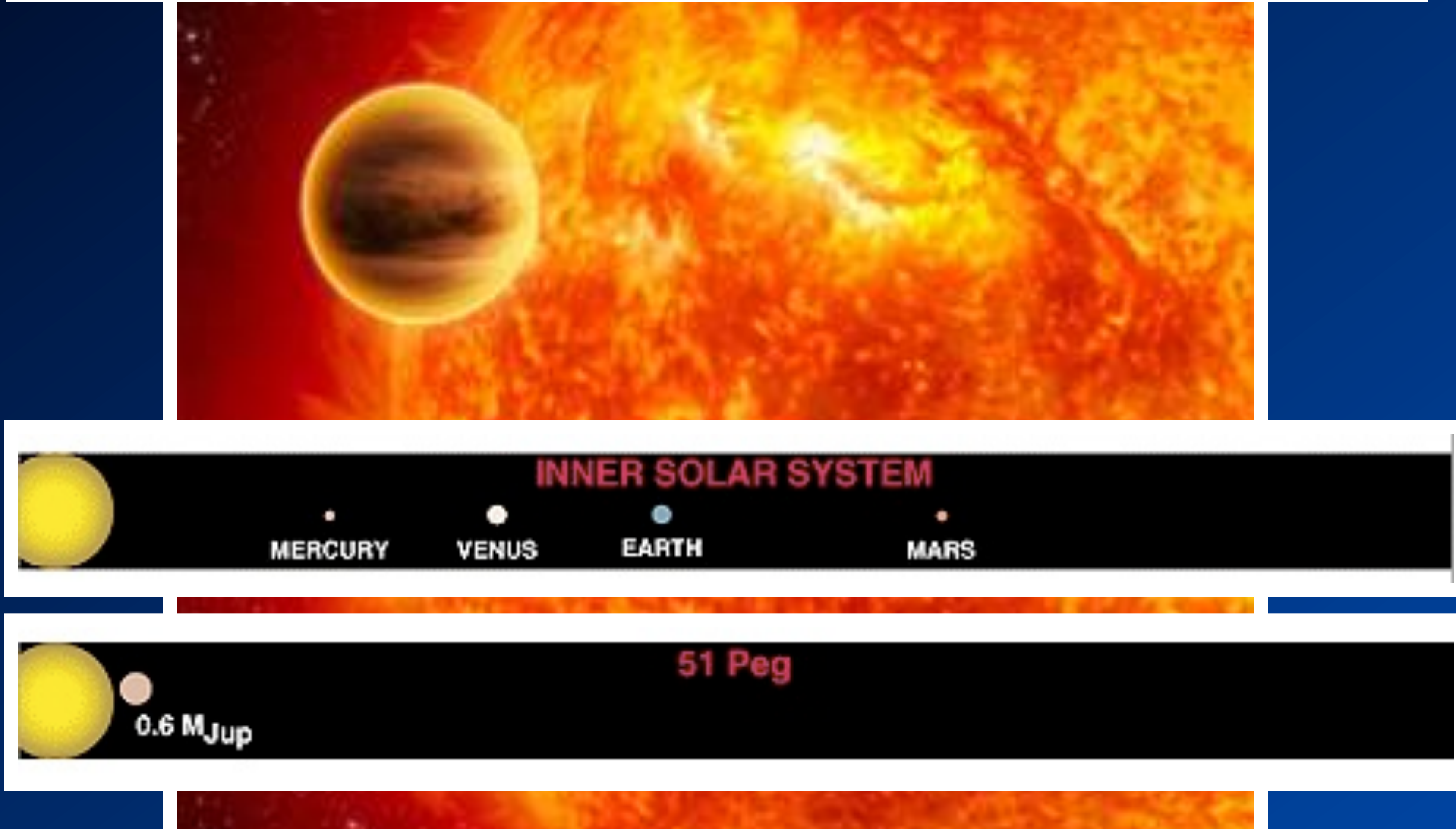
The Snow Line.



Matched Data Well.



1995: A Planetary Companion to 51 Peg



(Mayor & Queloz 1995)

Planet formation is *really* hard!

Additional physics, e.g.,

- Migration.
- Influence of host star mass, metallicity.
- Dynamical interactions.
- Tides.
- Disk properties.
- Other models! (e.g., disk instability)
- Etc.

Meanwhile…