The Demographics of Exoplanets: Theory vs. Observations

2015 Sagan Summer Workshop
July 27, 2015

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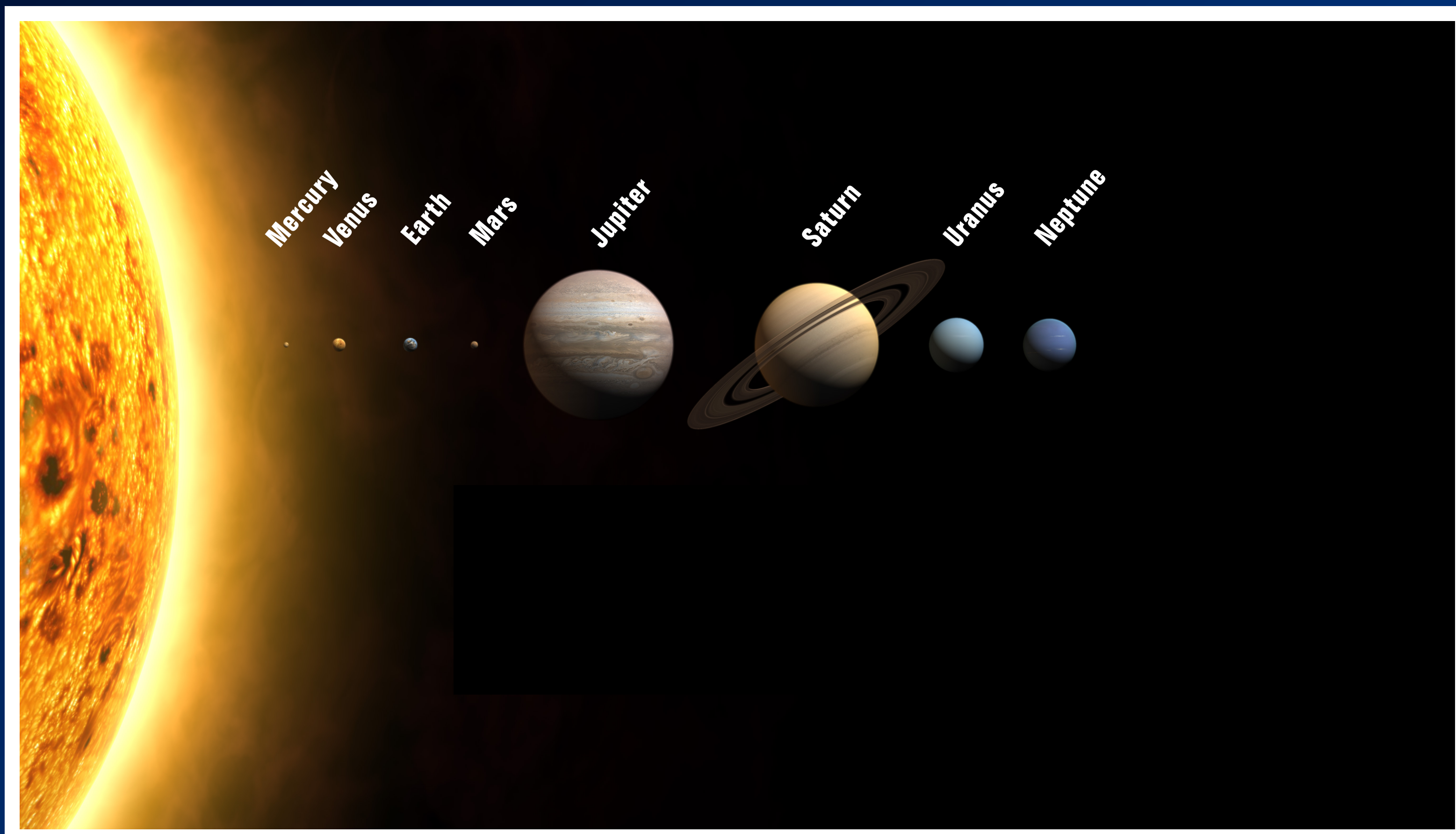
Backstory. Before 1995...



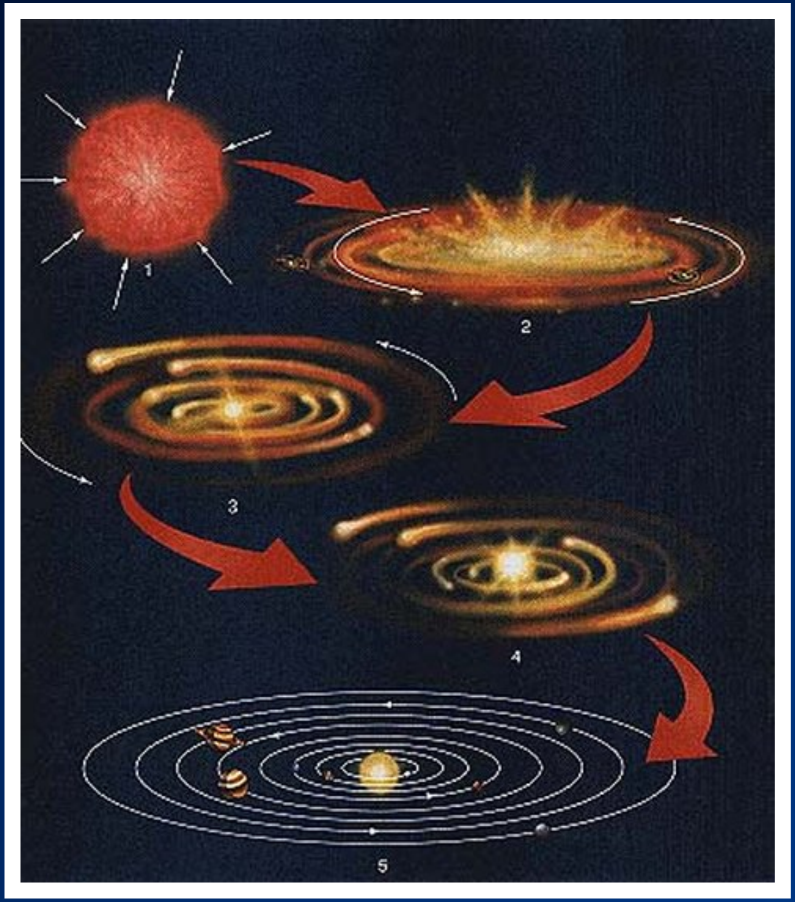
Planet Formation.

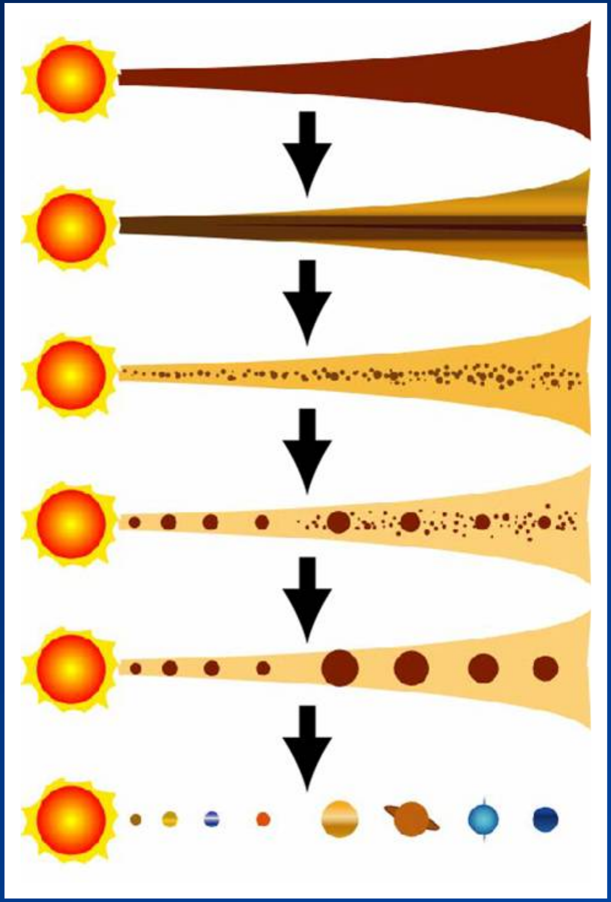
Must understand the physical processes by which micron-sized grains in protoplanetary disks grow by $10^{\sim 13-14}$ in size and $10^{\sim 38-41}$ in mass.

Hard!

A Fairy Tale.

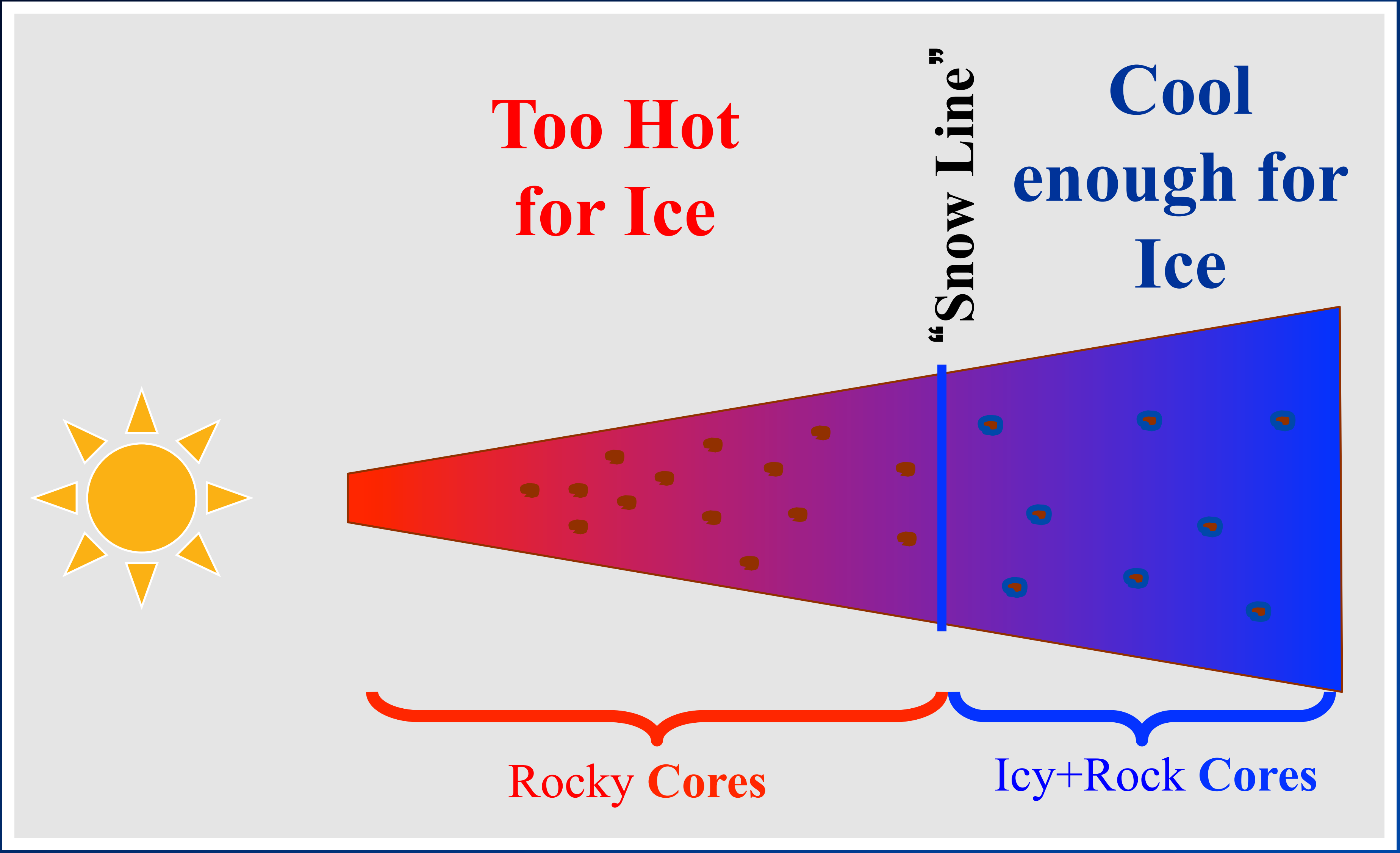
Bottom-Up Planet Formation.



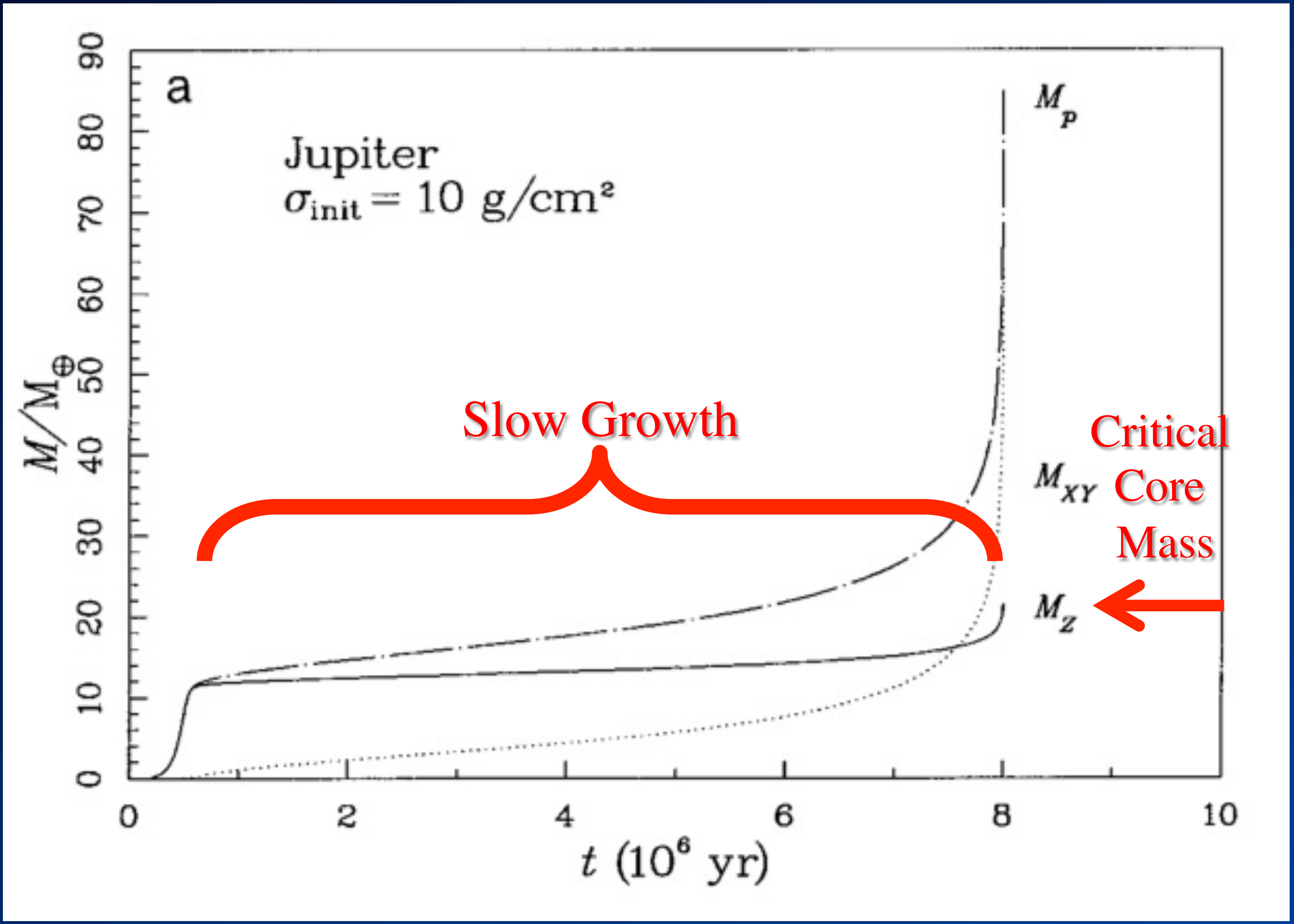


(e.g., Lissauer 1987; Ida & Lin 2004, 2005)

The Snow Line.

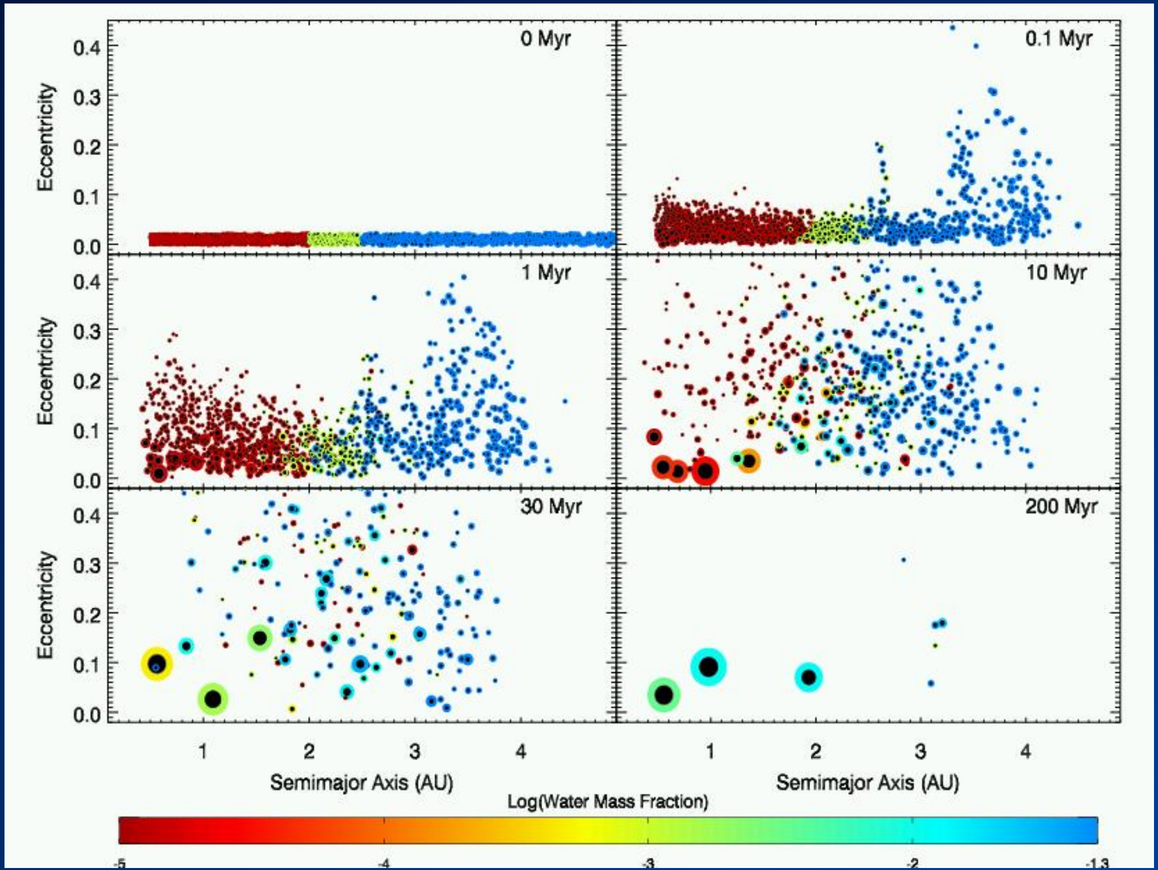


Core Accretion.



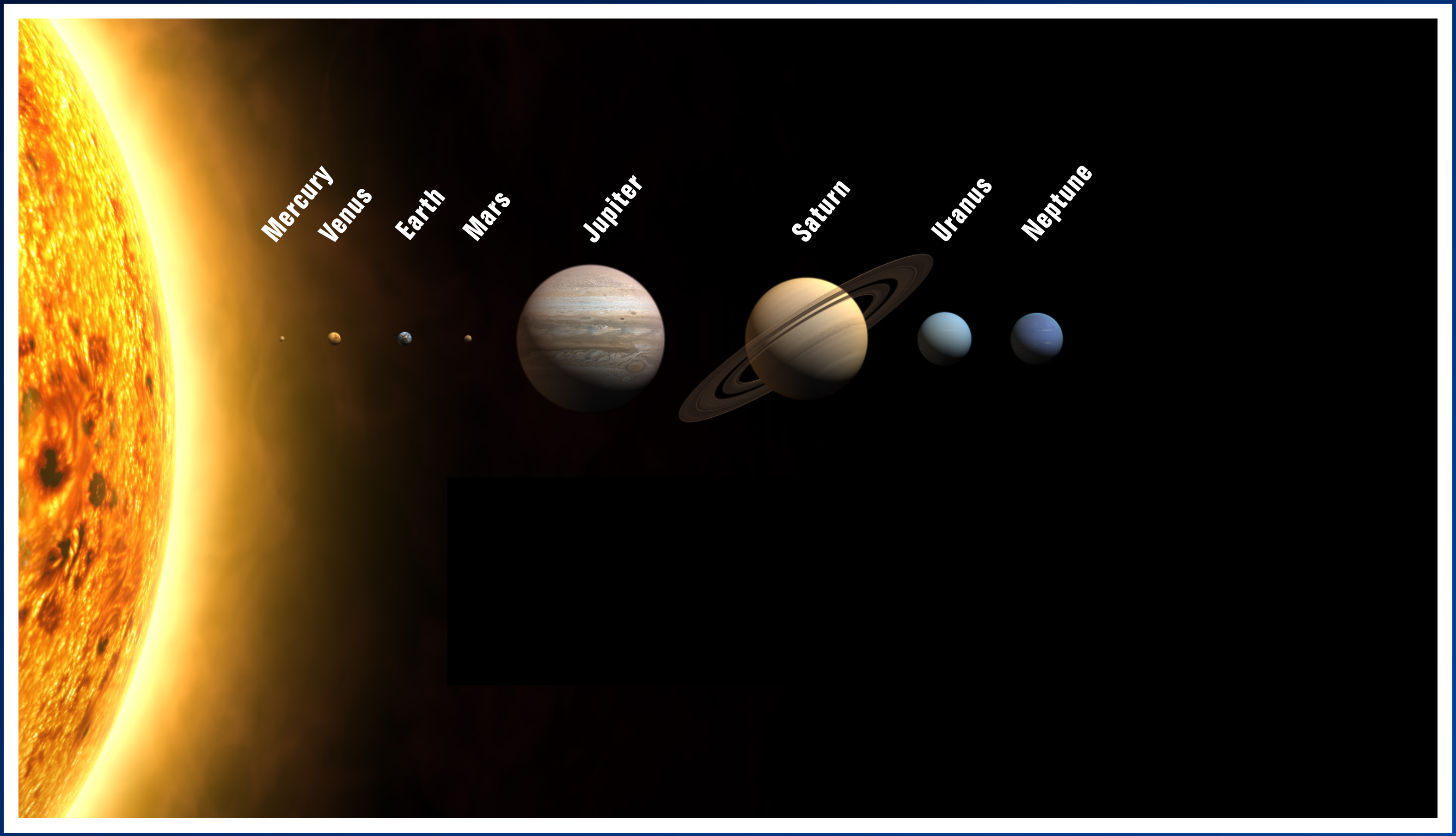
(Pollack et al. 1996)

Terrestrial Planet Formation.

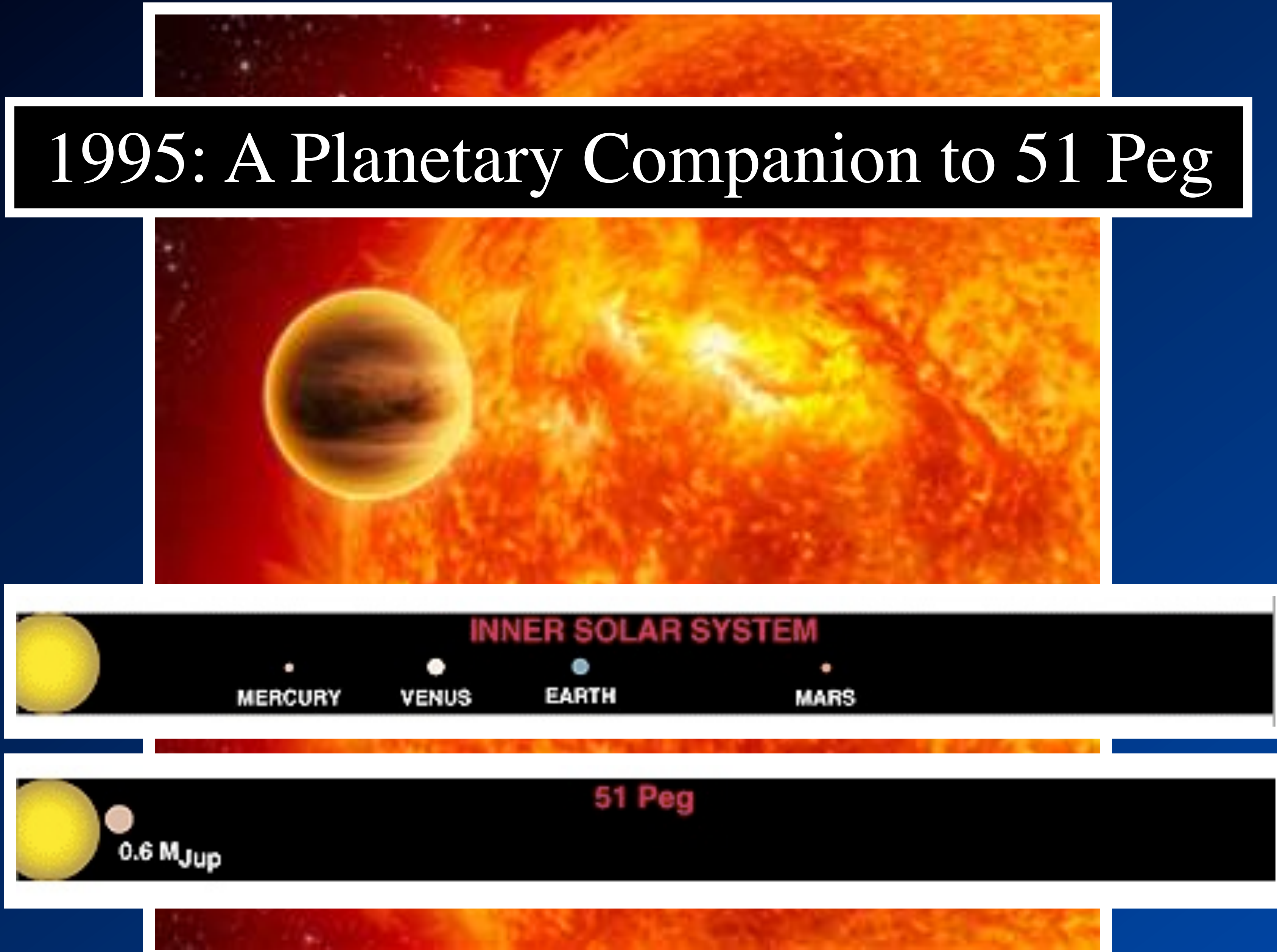


(Kokubo & Ida 2002, Raymond et al. 2006)

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.

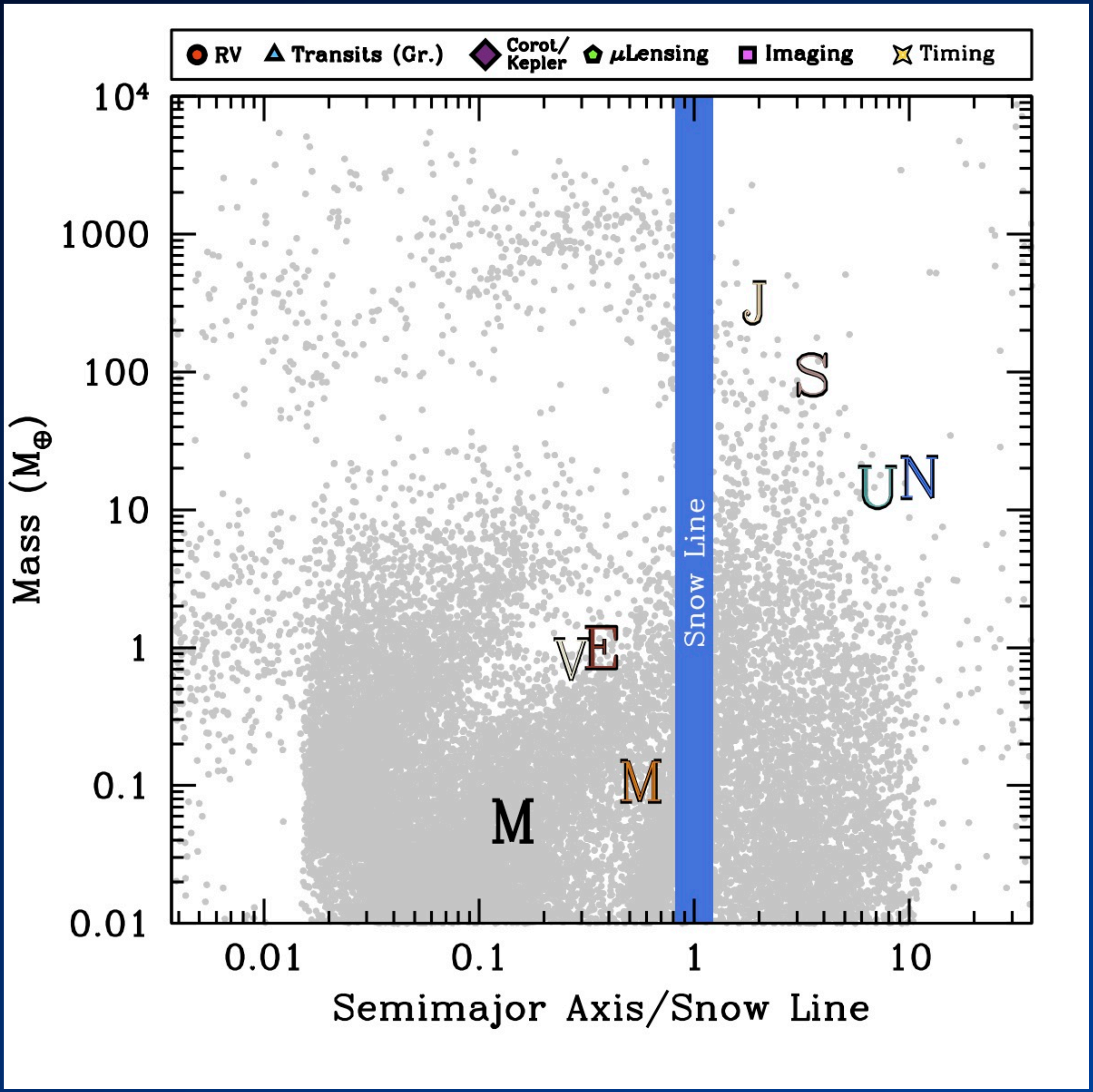
Testing and Refining Theories.

- Physical processes at work during planet formation and evolution are imprinted in planet distributions.
- Examples:
  - Feature in mass function near ~10 Earth masses.
  - Paucity of giant planets around low-mass stars
  - Free-floating planets
- By determining the **demographics** of exoplanets, we can test and refine theories of planet formation and evolution.

Meanwhile…

Semi-analytic planet formation.

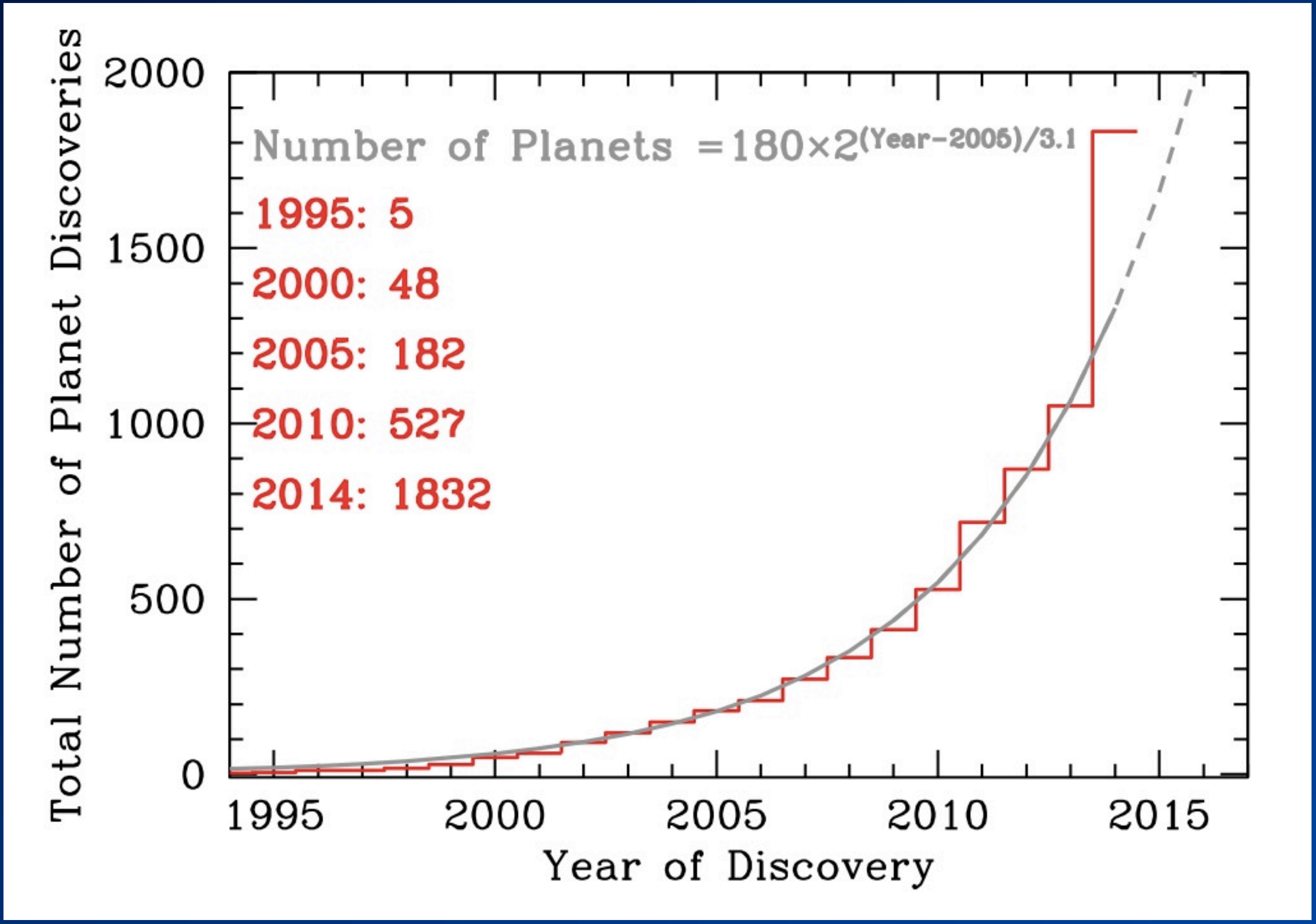
(Mordasani et al. 2009)


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

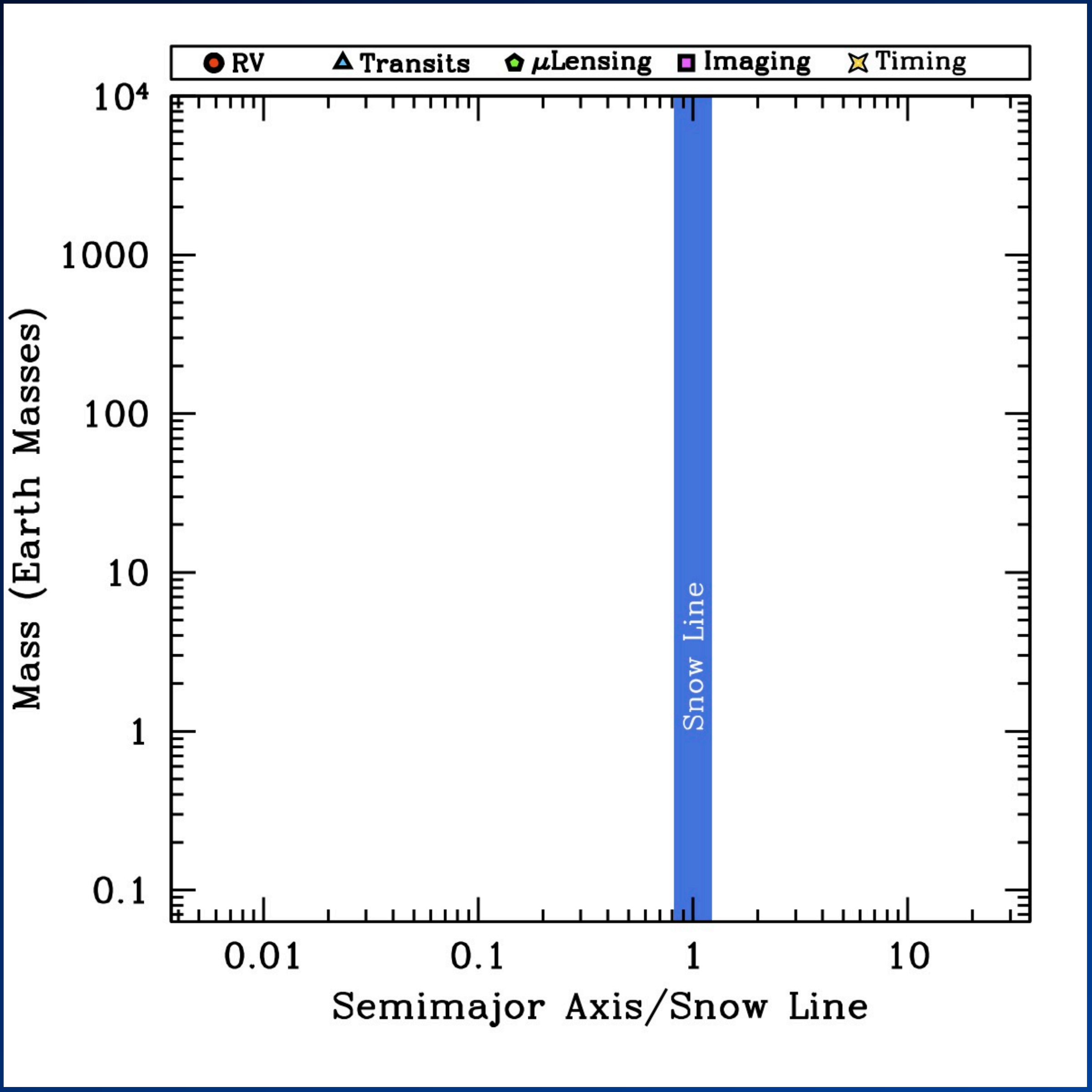
(Ida & Lin)

Meanwhile…

20+ Years of Exoplanets.



Strange New Worlds.



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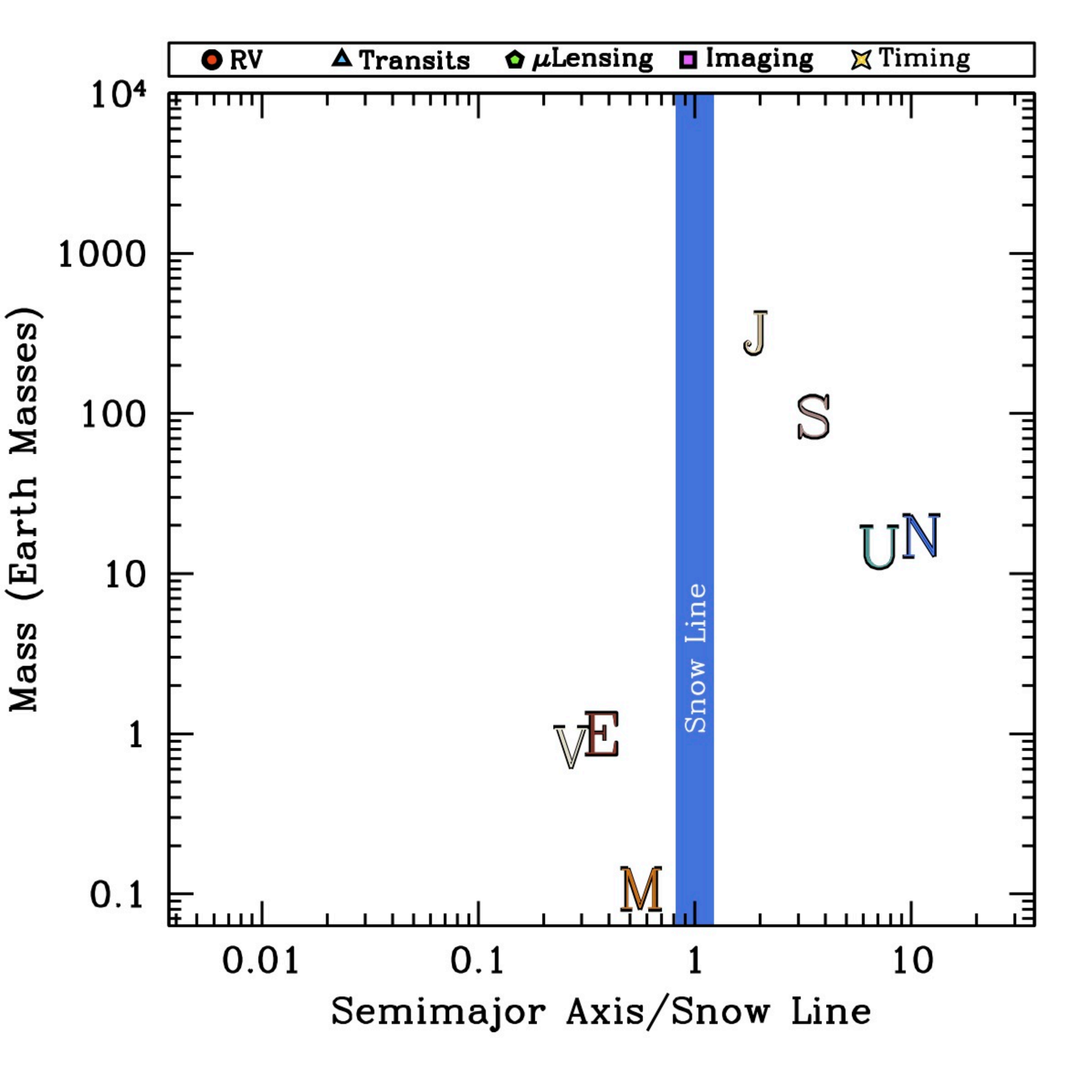
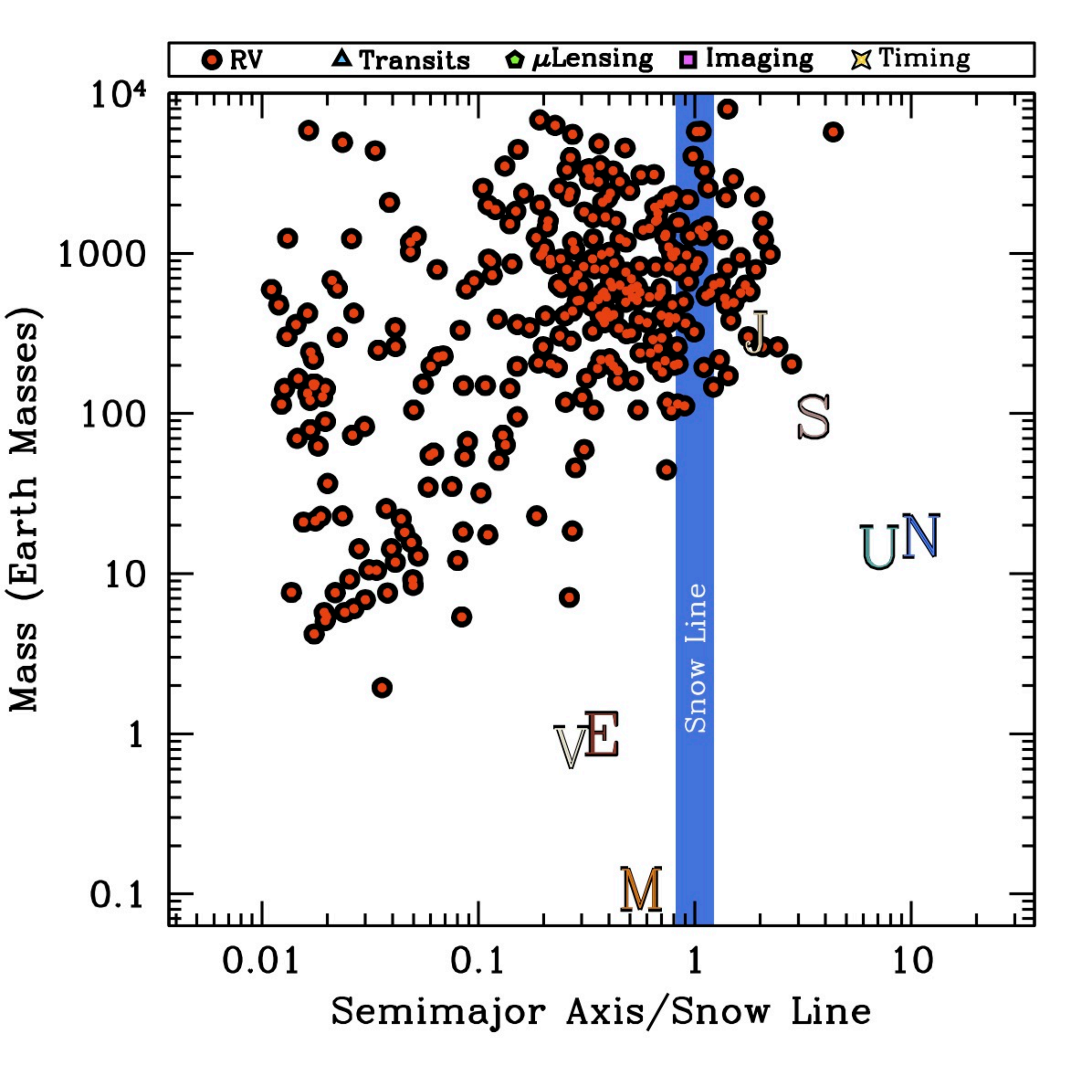
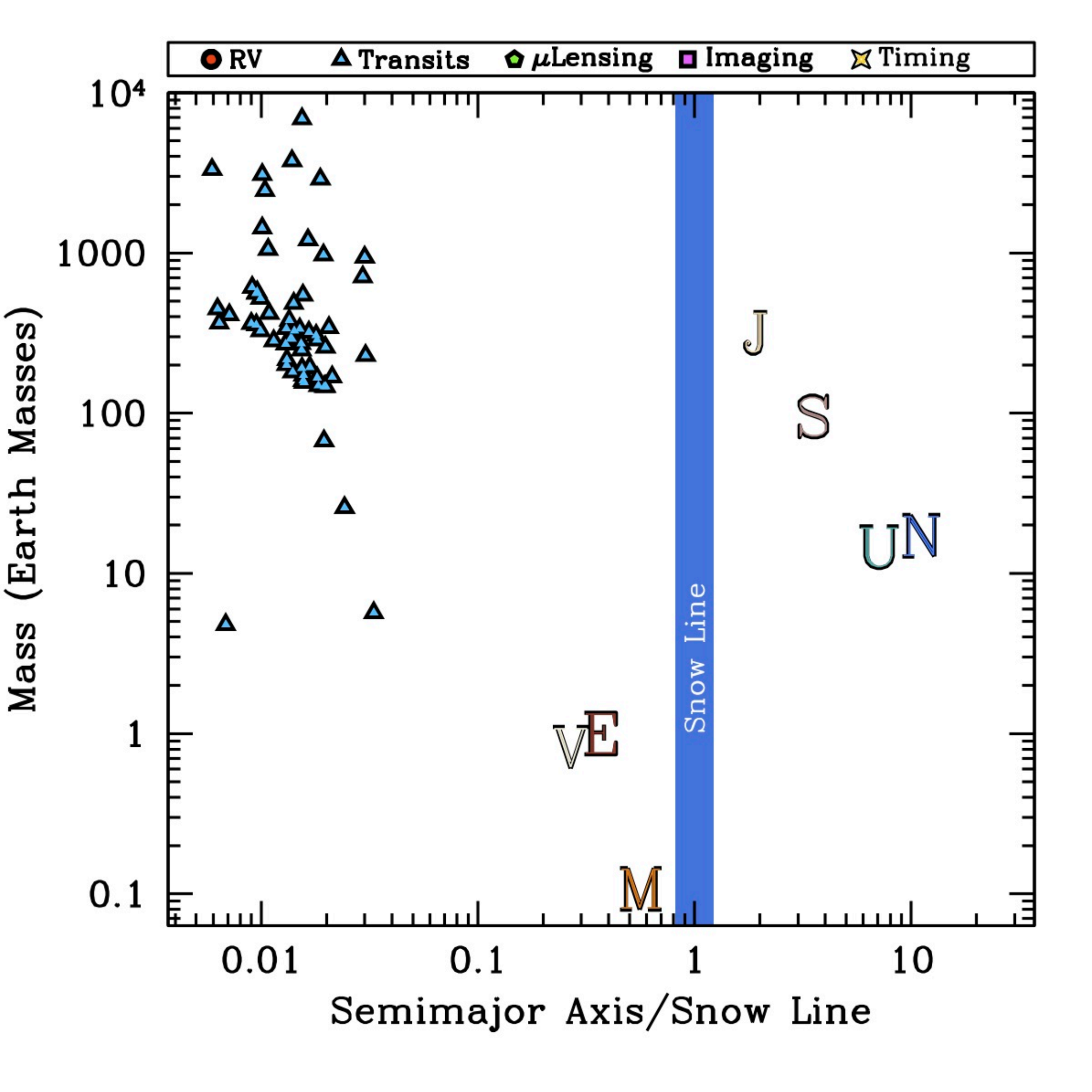


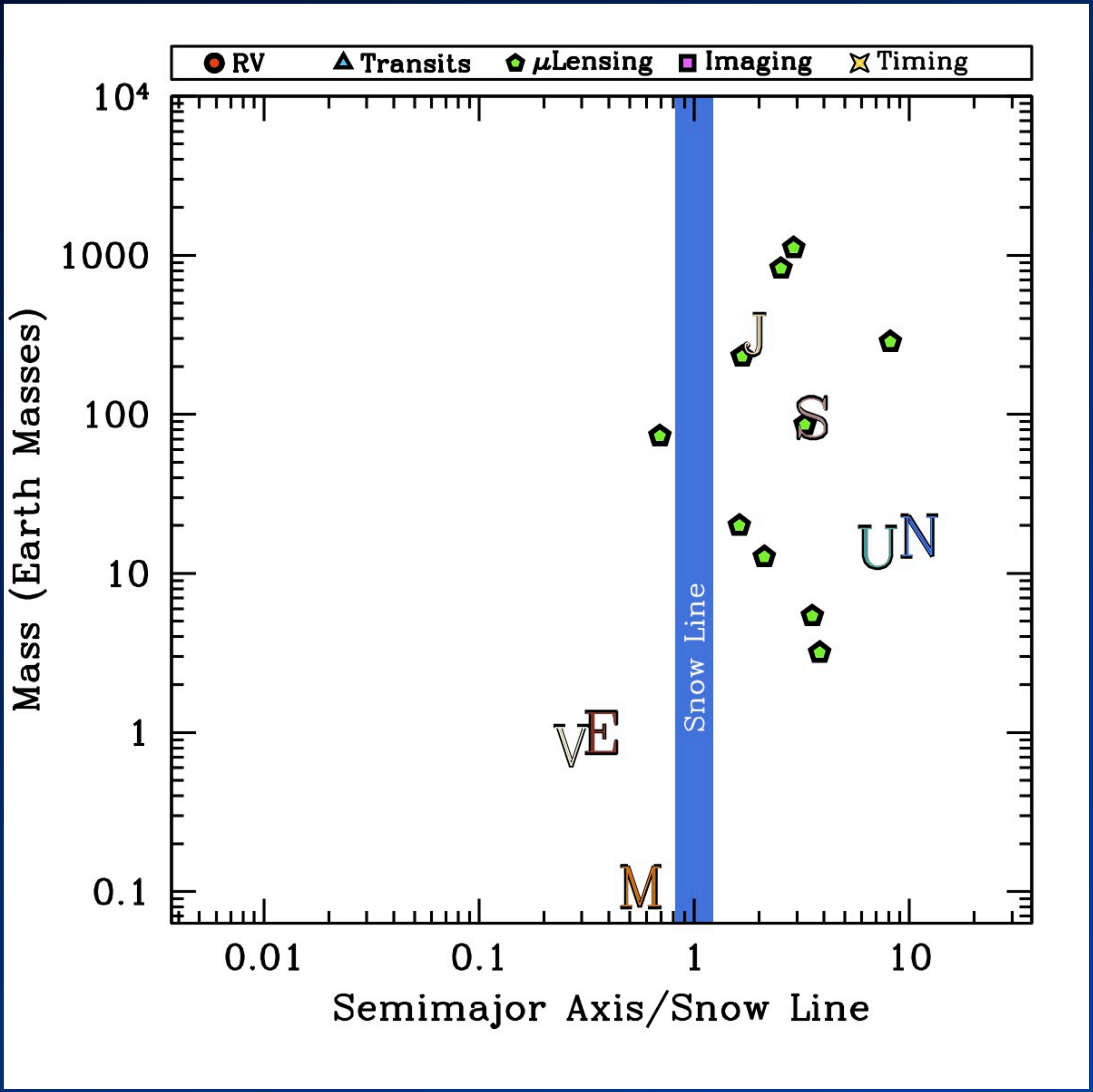
Strange New Worlds.



Strange New Worlds.



Strange New Worlds.



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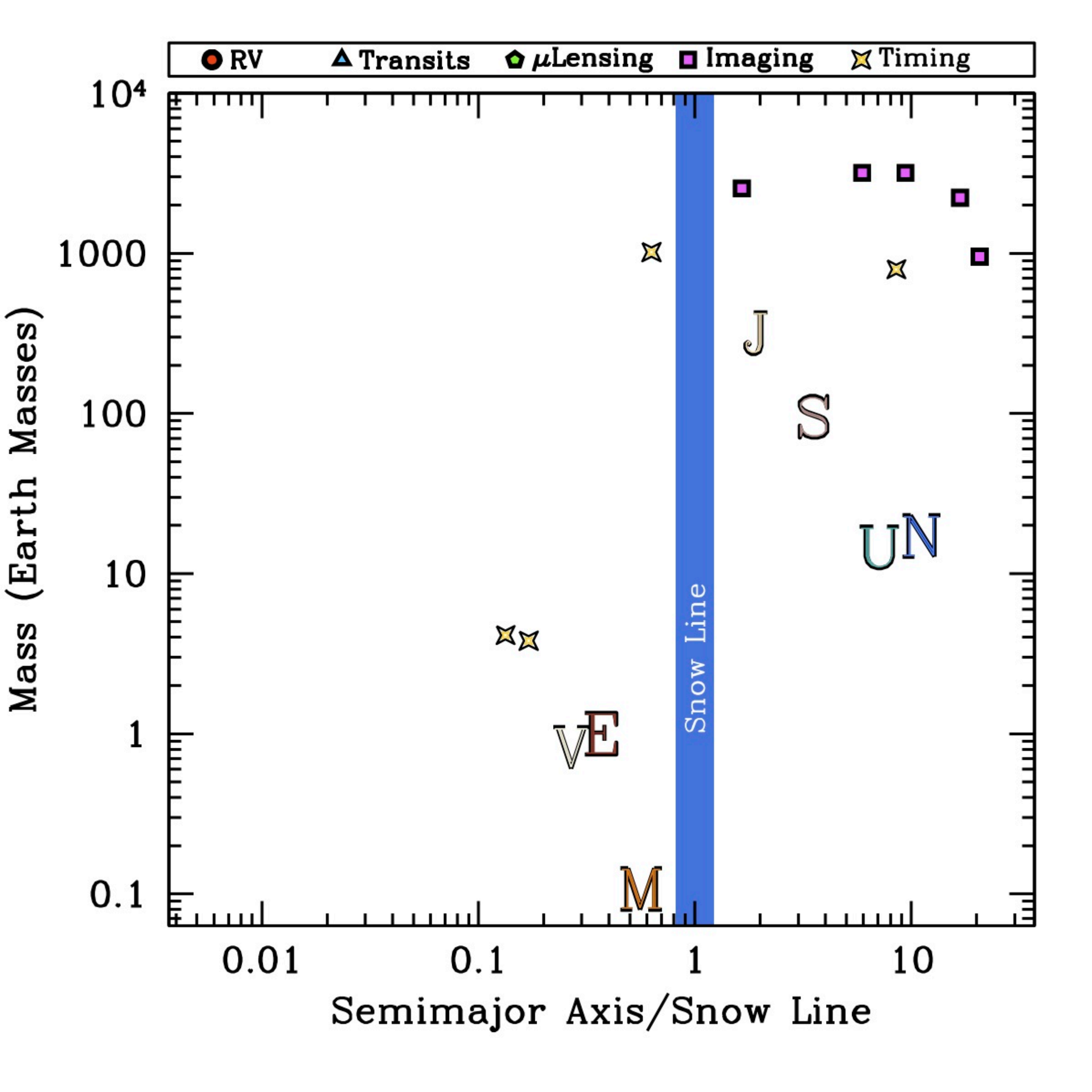
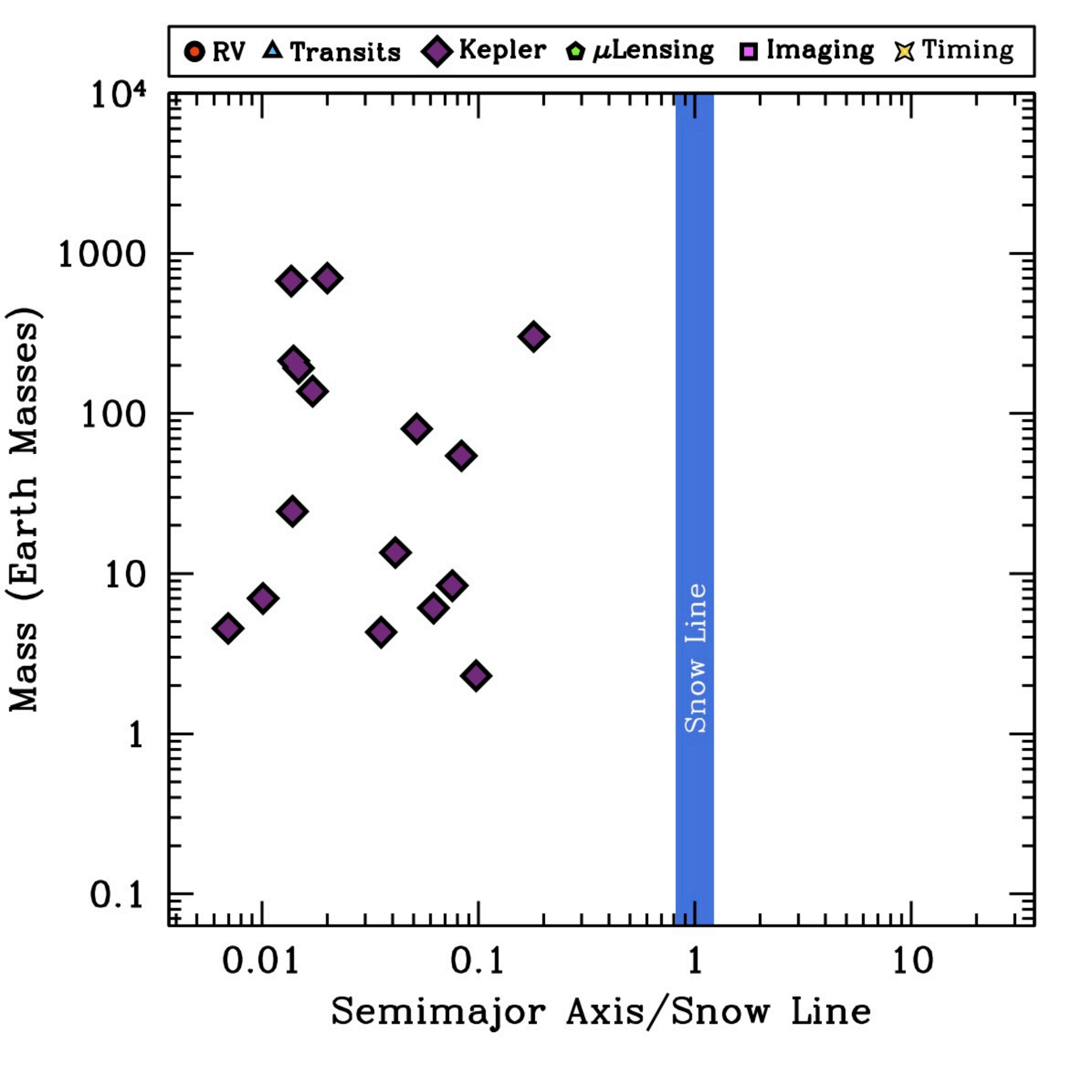
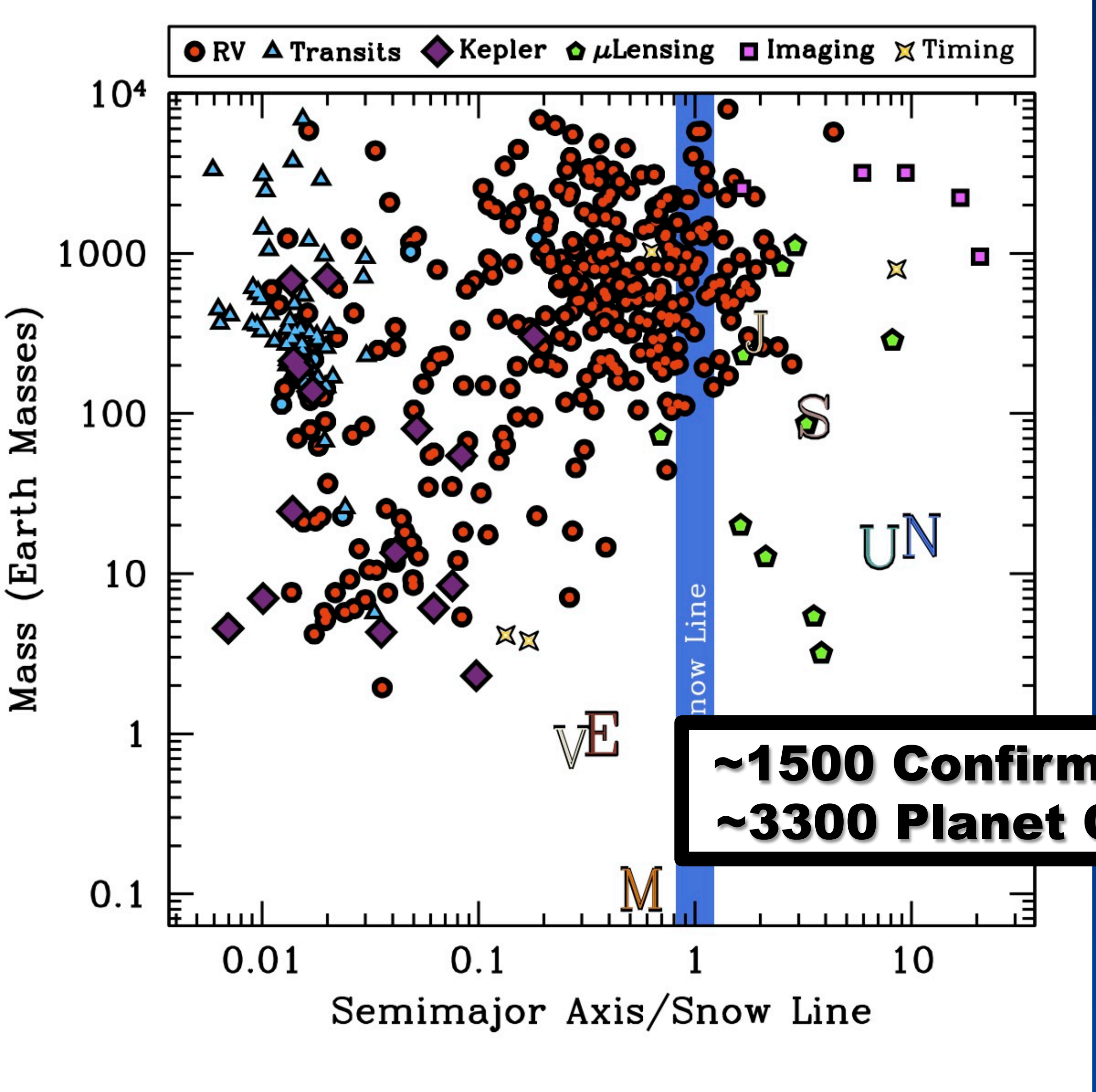


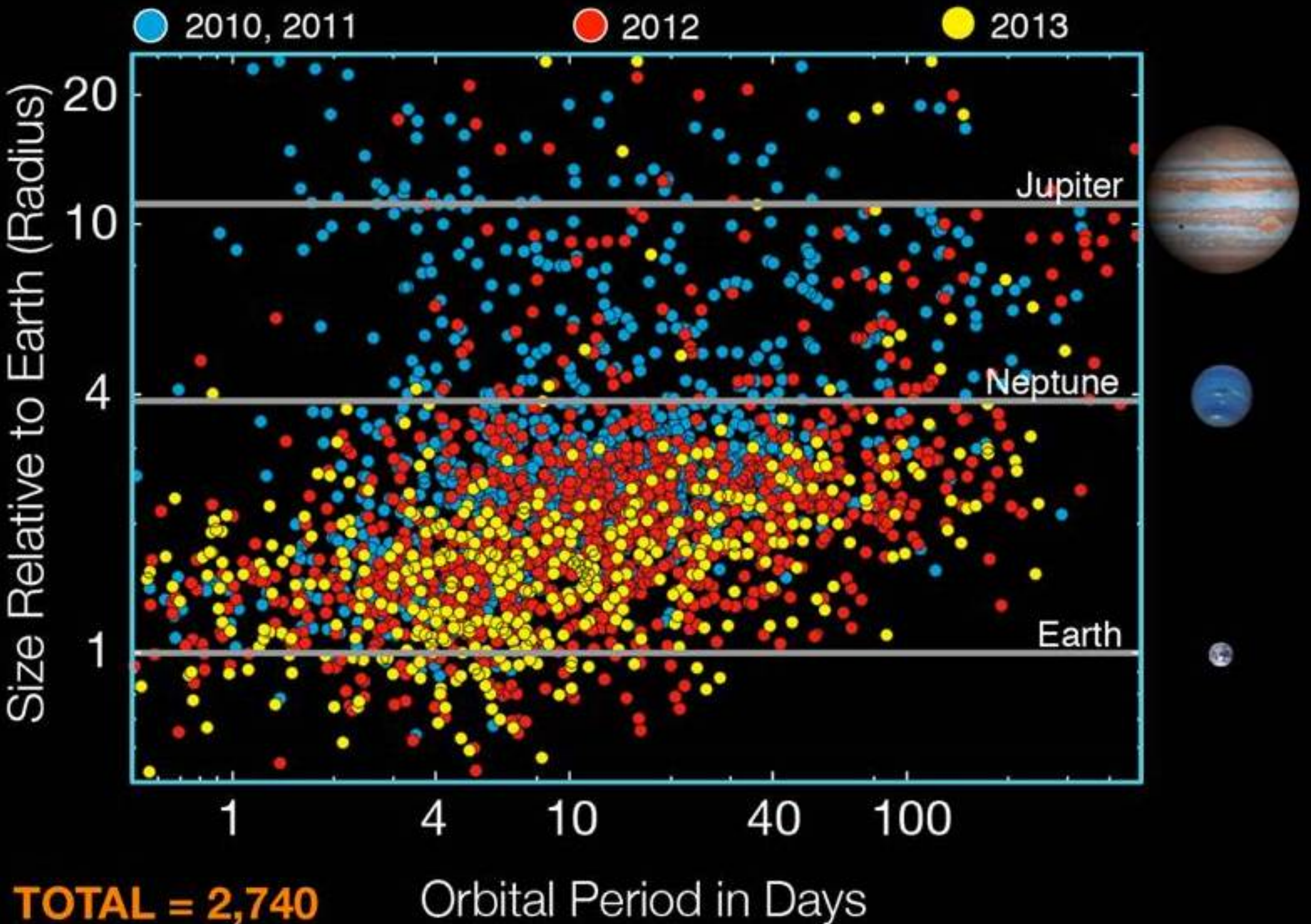
Strange New Worlds.



Strange New Worlds.



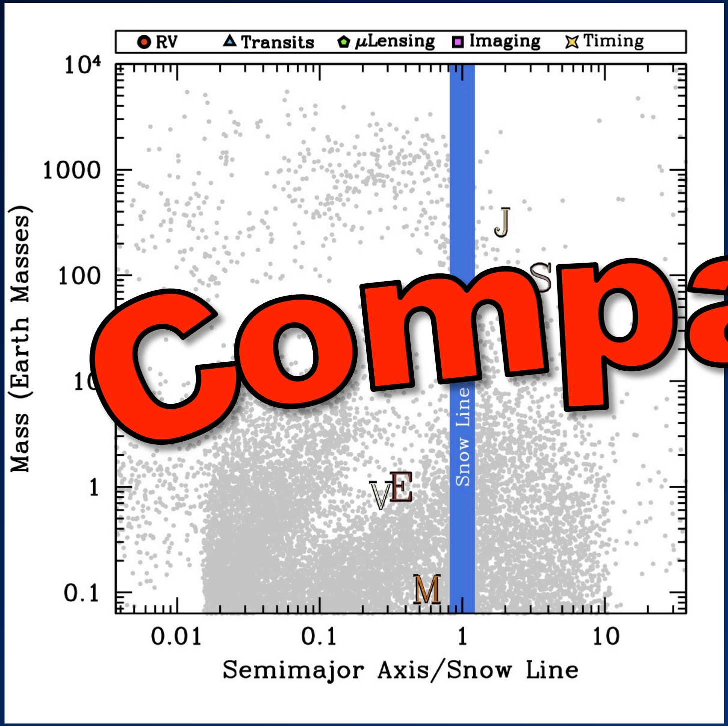
~1500 Confirmed Planets
~3300 Planet Candidates



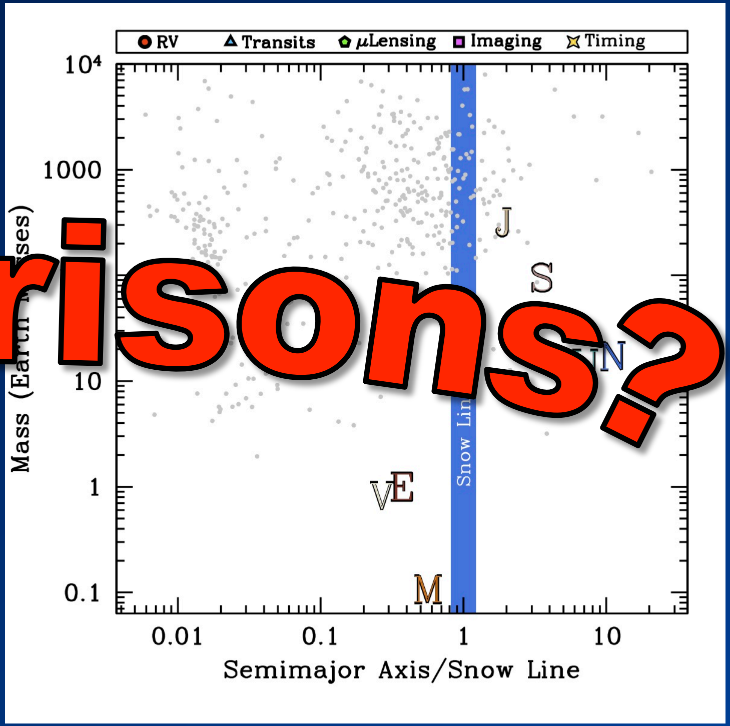
2010, 2011
2012
2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
Orbital Period in Days

TOTAL = 2,740

Detailed Predictions.



Comparisons?



- Detailed predictions for the demographics:
- (e.g., Ida & Lin 04,05,08; Alibert et al. 2005; Thommes et al. 2008, Mordasini et al. 2009, many others)
- Alternative models for giant planets formation (e.g., Boss 1997, Durisen et al. 2007, many others)

No!*

Why not?

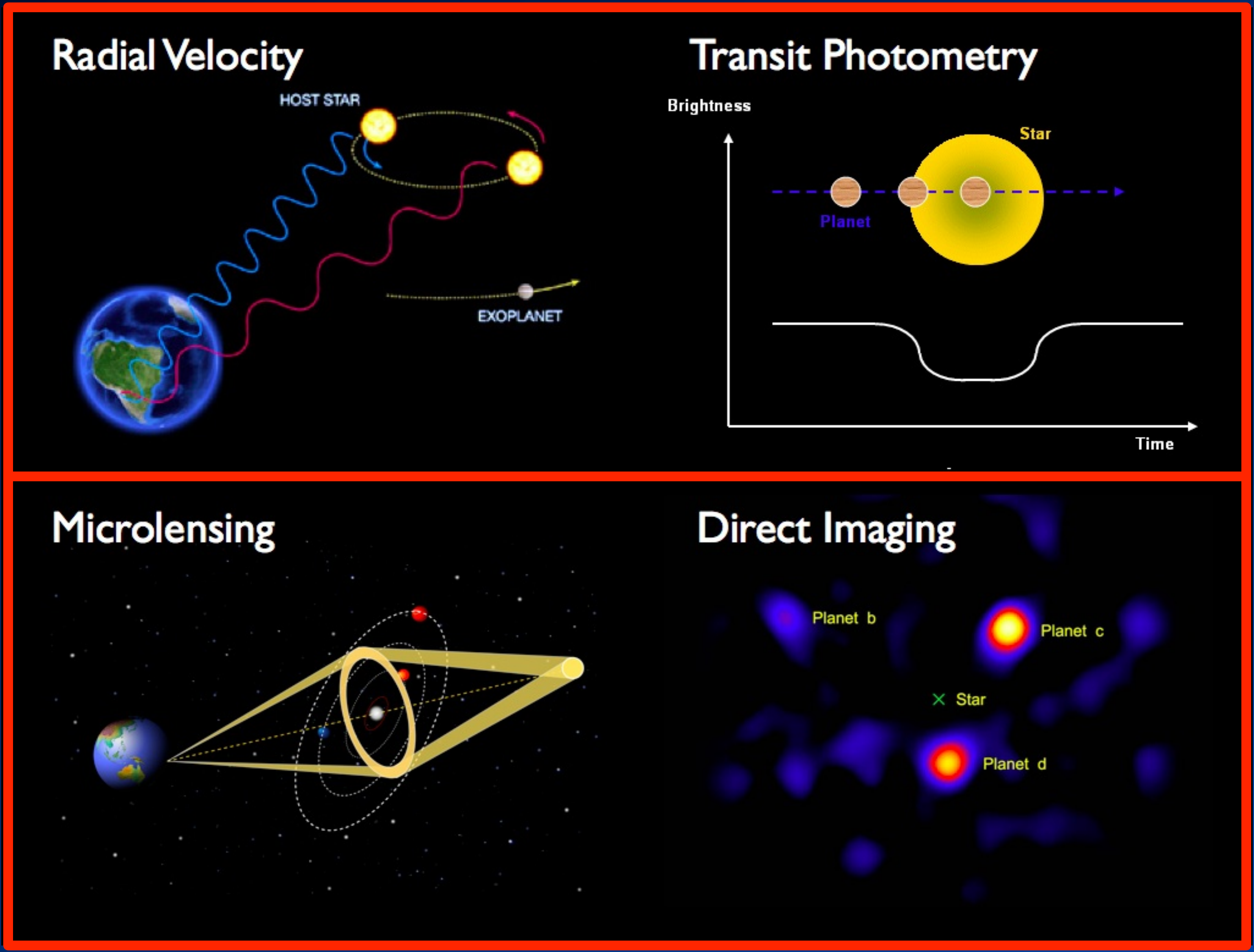
*well, a few.

So What is the Problem?

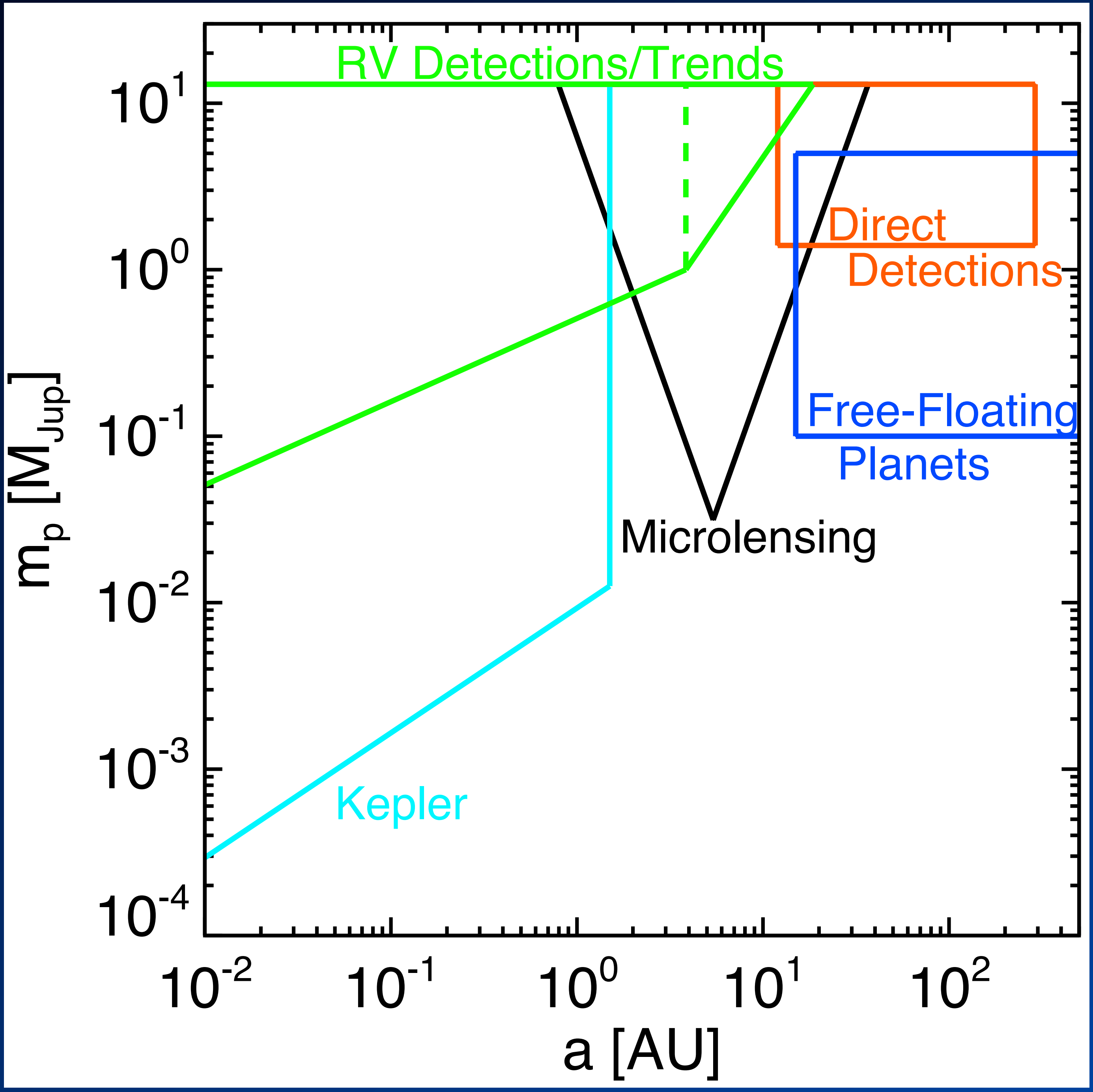
Challenges of Comparing Data to Models.

- Limited (and sometimes non-overlapping) ranges of sensitivity of different methods.
- Current experiments not sensitive to the “full” range of parameter space.
- Different methods measure different planet properties.
- Many surveys do not determine, or do not provide, their: sample selection, detection efficiencies, non-detections, etc.

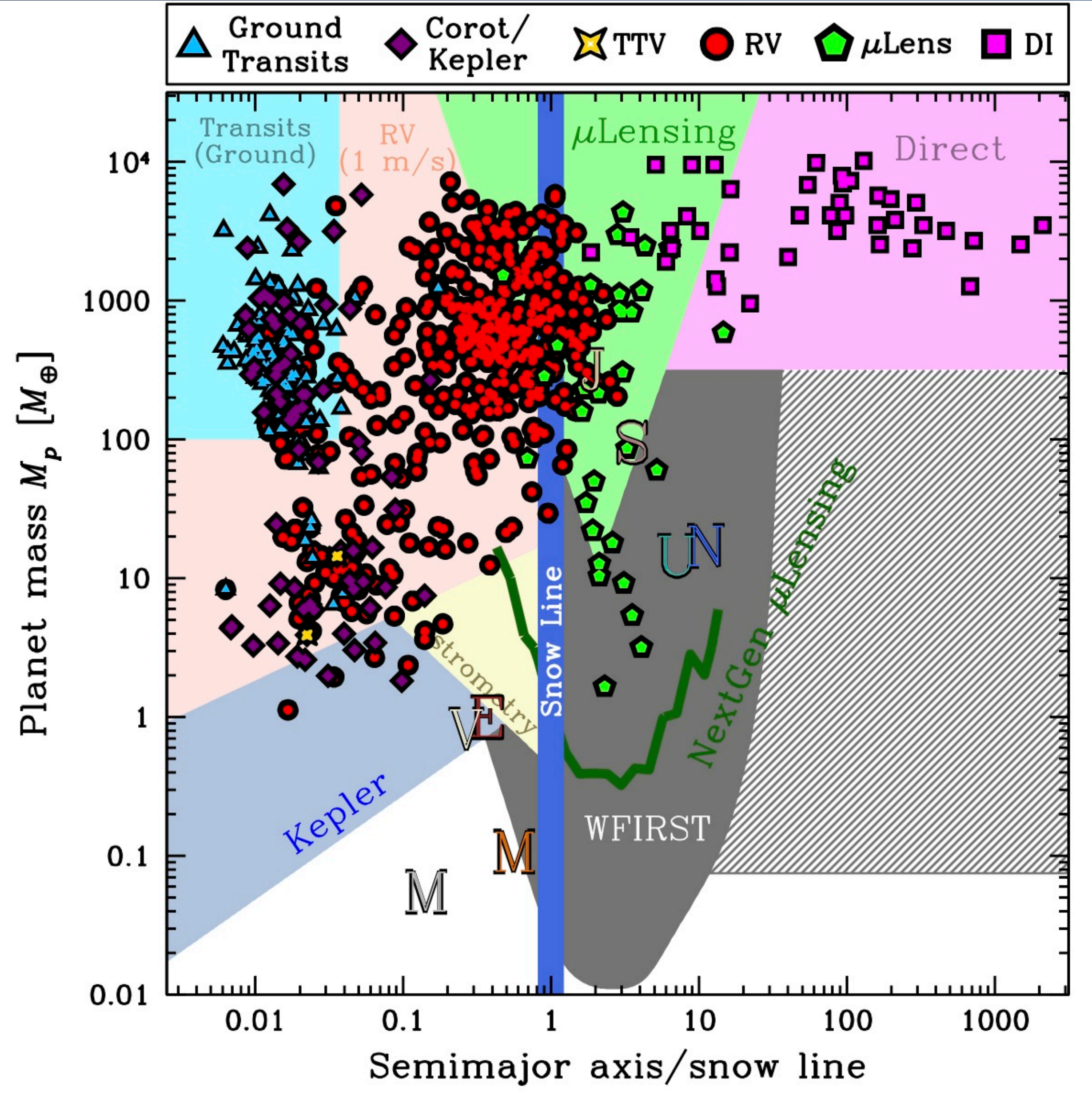
“Big Four”


Radial Velocity
HOST STAR
EXOPLANET
Transit Photometry
Brightness
Star
Planet
Time
Microlensing
Direct Imaging
Planet b
Planet c
Star
Planet d

Limited range of sensitivity.



RV Detections/Trends
Direct
Detections
Free-Floating
Planets
Microlensing
Kepler
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
m_p [M_{Jup}]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
a [AU]



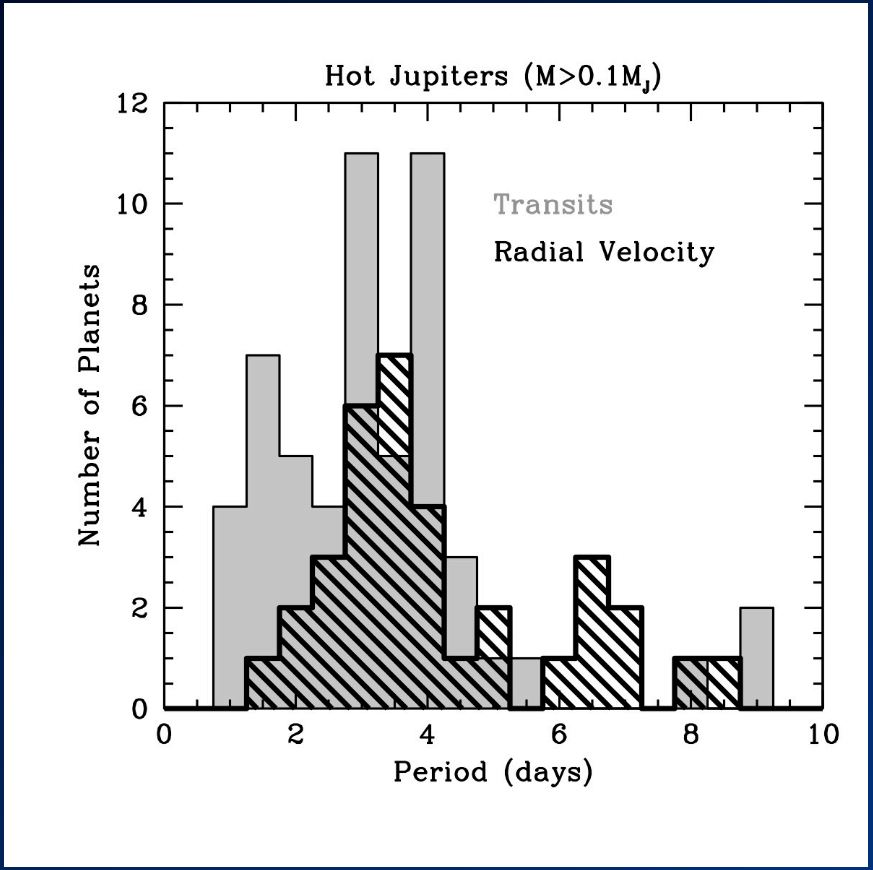
Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Transits (Ground)
RV (1 m/s)
μLensing
Direct
Snow Line
Kepler
Astrometry
NextGen μLensing
WFIRST
J
S
U
N
V
E
M
M
Planet mass M_p [$M_\oplus$]
Semimajor axis/snow line
0.01
0.1
1
10
100
1000
10^4

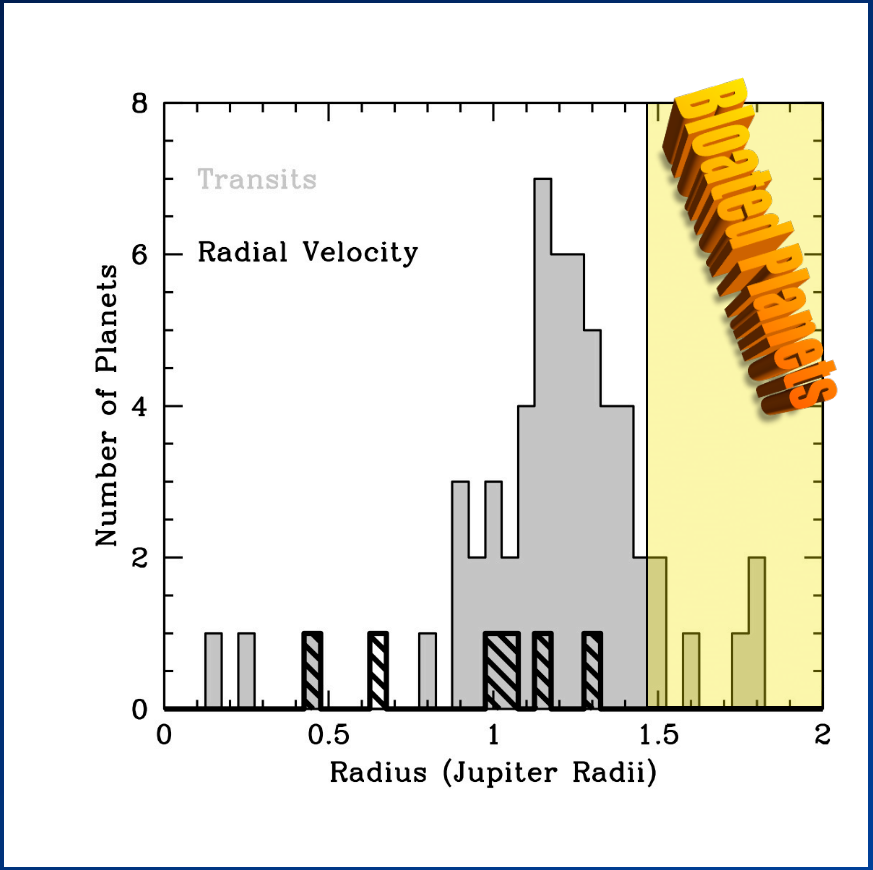
Sensitive to different parameters.

Observables.

- RV: minimum mass, period, eccentricity
- Direct detection: flux or luminosity, spectra, projected separation, age (?)
- Transits: radius ratio, period, mass (with RV follow-up).
- Microlensing: mass ratio, projected separation in units of R_E
- Astrometry: angular orbital radius, mass ratio, eccentricity, inclination.

Intrinsic biases.

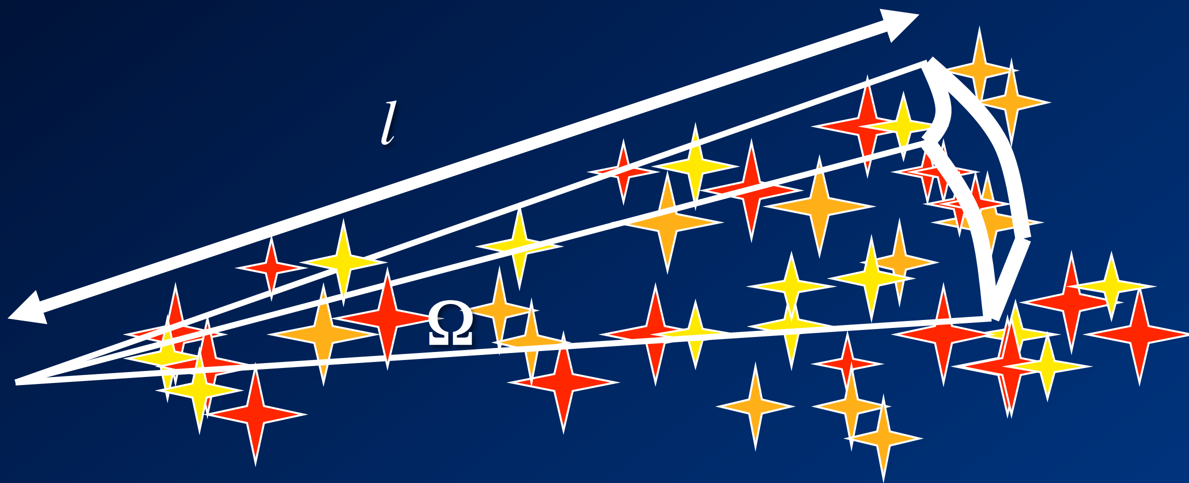




(Jackson et al 2008; Miller et al. 2009; Ibgui & Burrows 2009)

Observed distributions ≠ intrinsic distributions

Transit "Malmquist Bias"



$$\langle N \rangle \approx \frac{\Omega}{3} l_{\max}^3 \, n P_{transit}$$

- Can detect deeper transits around fainter stars
- Can detect shorter-period planets around fainter stars

Sensitive function of S/N

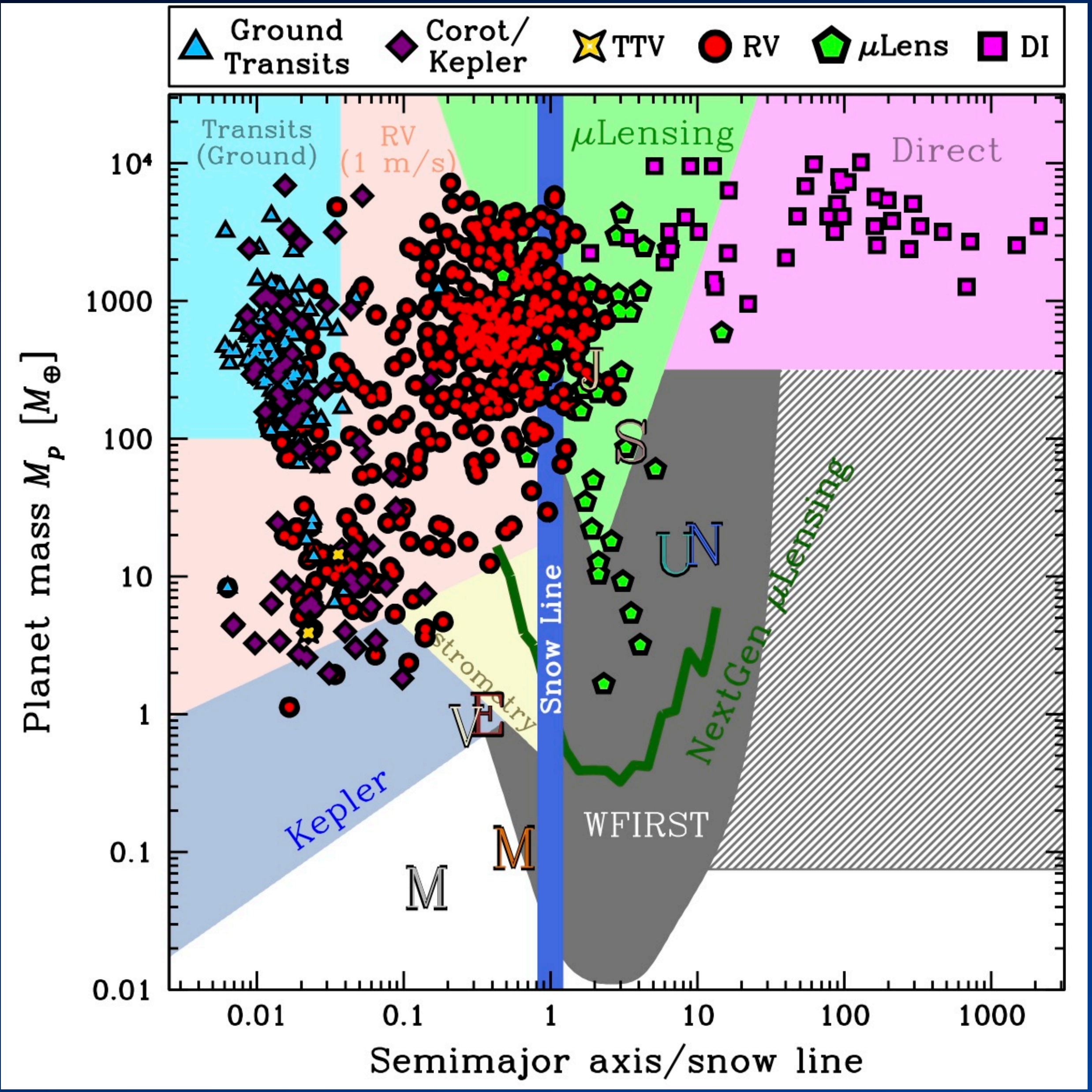
$$\langle N \rangle \propto P^{-5/3} r^{6} \left(\frac{S}{N} \right)_{\min}^{-3}$$

Favors shorter periods

Strongly favors bigger planets

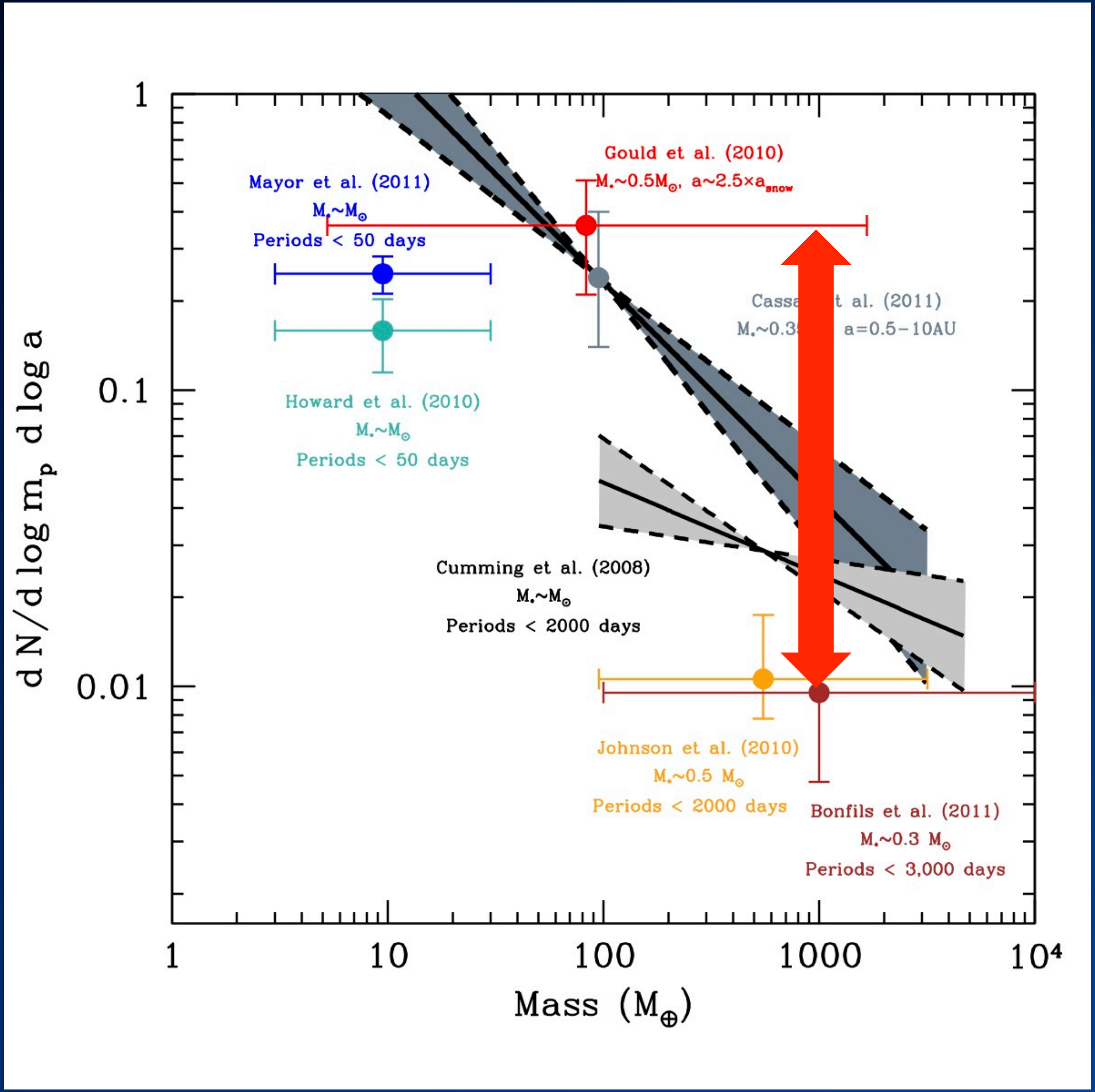
(Gaudi et al. 2003, Gaudi 2005, Gould et al. 2006)

⇒ Selection of candidates must be done carefully, objectively, and automatically.

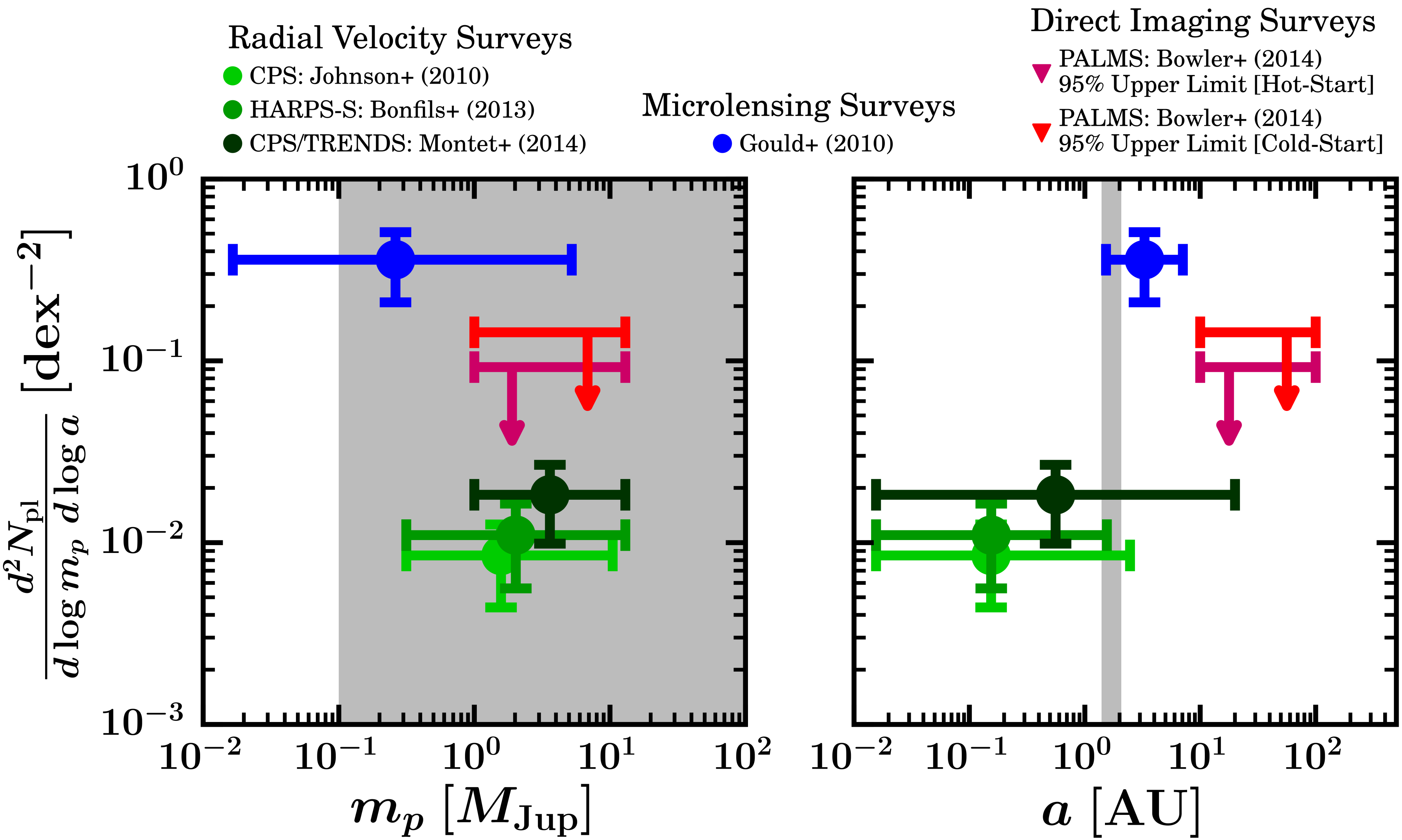


Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Transits (Ground)
RV (1 m/s)
μLensing
Direct
Snow Line
Kepler
Astrometry
NextGen μLensing
WFIRST
J
S
U
N
V
E
M
M
Planet mass M_p [$M_\oplus$]
Semimajor axis/snow line
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000

Synthesis.



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



(Clanton & Gaudi, in prep)

The ultimate goal of any exoplanet demographics survey is to obtain the distribution function $d^n N_{pl}/d\{\alpha\}$, where $\{\alpha\}$ is the set of all n intrinsic, physical parameters on which planet frequency fundamentally depends. These parameters include, but are not necessarily limited to, host star mass, stellar metallicity, distance to host star, planet mass, semi-major axis, and eccentricity: $\{M_l, [\mathrm{Fe/H}], D_l, m_p, a, e\}$. The total number of planets covered by the domain $\{\alpha\}$, obtained by marginalizing this distribution function over all parameters, is given by

$$N_{pl} = \int_{\alpha_0} d\alpha_0 \int_{\alpha_1} d\alpha_1 \cdots \int_{\alpha_n} d\alpha_n \frac{d^n N_{pl}}{d\{\alpha\}} . \qquad (8)$$

This distribution function is the most general, fundamental quantity related to the properties and demographics of exoplanets. If we were able to detect every planet and measure these properties, we could in principal derive this distribution function. However, the number of planets we can actually detect depends on many observable parameters affecting detectability, some of which belong to the set $\{\alpha\}$ or are functions of the parameters in the set $\{\alpha\}$. We group these observable parameters affecting detectability into the set $\{\beta\}$, containing k elements including (for RV surveys), but not necessarily limited to, velocity semi-amplitude, orbital period, stellar radius, inclination, mean anomaly, and argument of periastron: $\{K, P, R_*, i, M_0, \omega\}$.

(Clanton & Gaudi, 2014a)

In reality, the number of planets actually found in any exoplanet survey, be it RV, microlensing or other, is

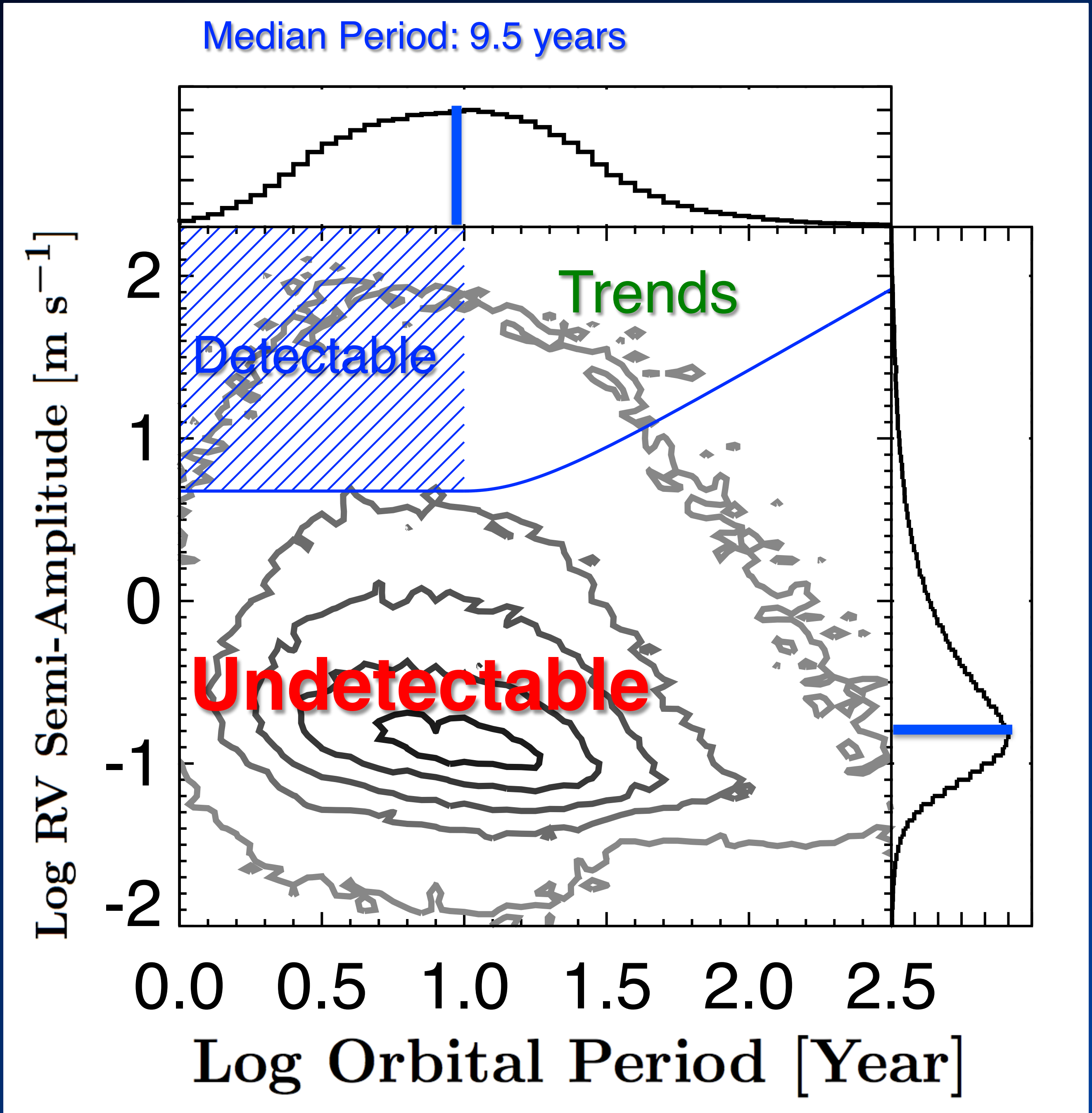
$$\mathrm{N}_{\mathrm{pl,obs}} = \int_{\beta_0} d\beta_0 \int_{\beta_1} d\beta_1 \cdots \int_{\beta_k} d\beta_k \frac{d^k \mathrm{N}_{\mathrm{pl}}}{d\{\beta\}} \times \prod_{j=0}^{k} \Phi(\beta_j) \ , \tag{9}$$

where $\Phi(\{\beta\})$ is the set of "efficiency" functions for each parameter in $\{\beta\}$ that a particular survey suffers. The distribution function $\frac{d^k \mathrm{N}_{\mathrm{pl}}}{d\{\beta\}}$ describes the properties of planets in terms of detectability parameters and is given by

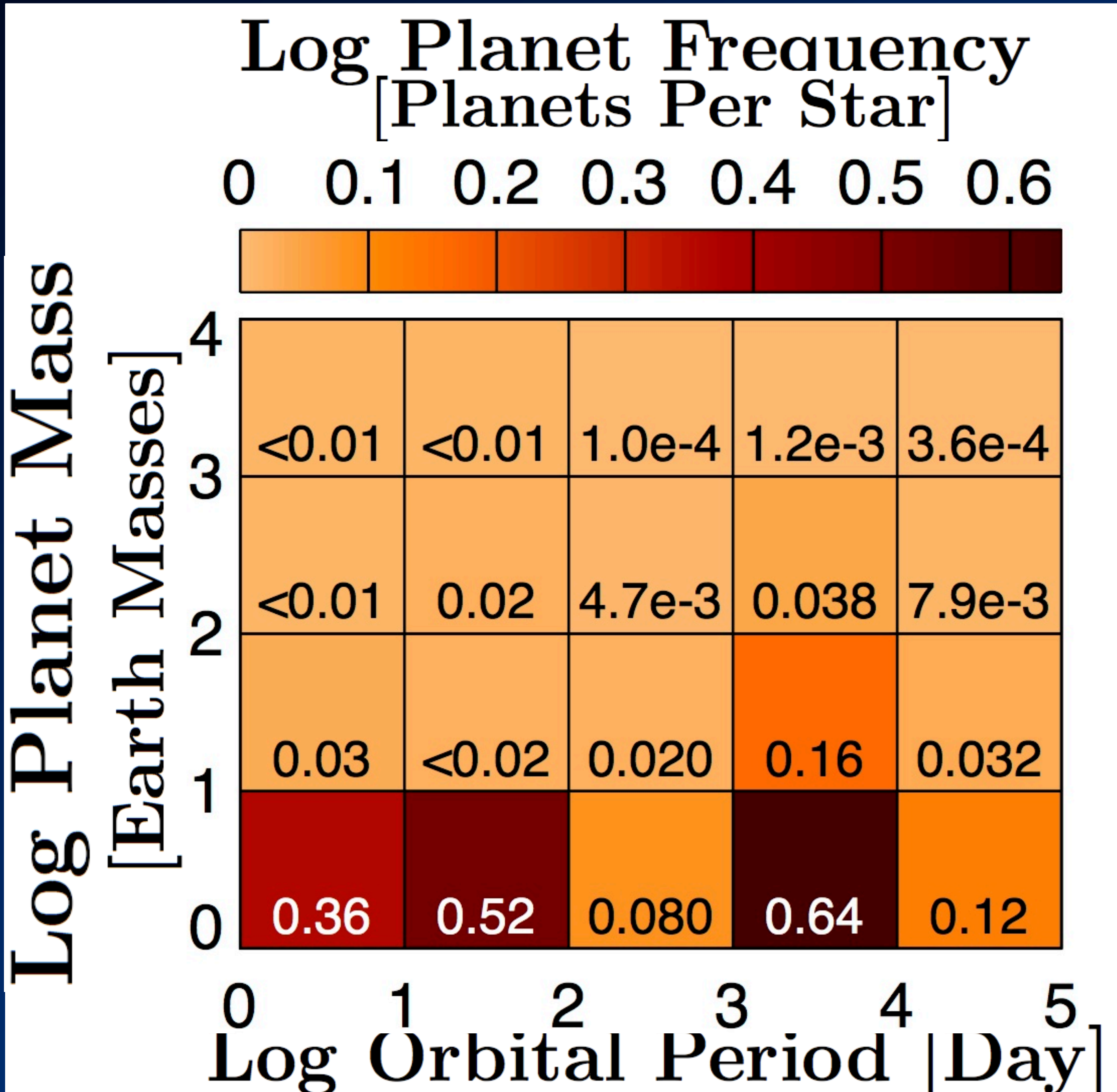
$$\frac{d^k \mathrm{N}_{\mathrm{pl}}}{d\{\beta\}} = \int_{\alpha_0} d\alpha_0 \int_{\alpha_1} d\alpha_1 \cdots \int_{\alpha_n} d\alpha_n \frac{d^n \mathrm{N}_{\mathrm{pl}}}{d\{\alpha\}} \times \prod_{j=0}^{k} \delta(\beta_j(\{\alpha\}) - \beta') \ . \tag{10}$$

Thus, even if we knew the exact form of our "efficiency" functions, $\Phi(\{\beta\})$, we are still unable to derive the true distribution function of planets in terms of *only* the intrinsic parameters affecting planet frequency, $\{\alpha\}$, because any given survey is not sensitive to the full parameter space spanned by all observable parameters $\{\beta\}$. Indeed, the parameters we can partially marginalize out depends on the type of survey, and presents a great challenge when trying to synthesize exoplanet demographics from multiple different surveys. Regardless, comparing and synthesizing data from multiple exoplanet detection data methods is the *only* way to cover a maximal amount of observable space and thus get as close to we can to obtaining the true distribution function, $d^n \mathrm{N}_{\mathrm{pl}}/d\{\alpha\}$, ultimately providing key empirical constraints necessary to learn about planet formation. This study is a step in that direction, as we aim to describe a comparison between microlensing and RV surveys.

(Clanton & Gaudi, 2014a)



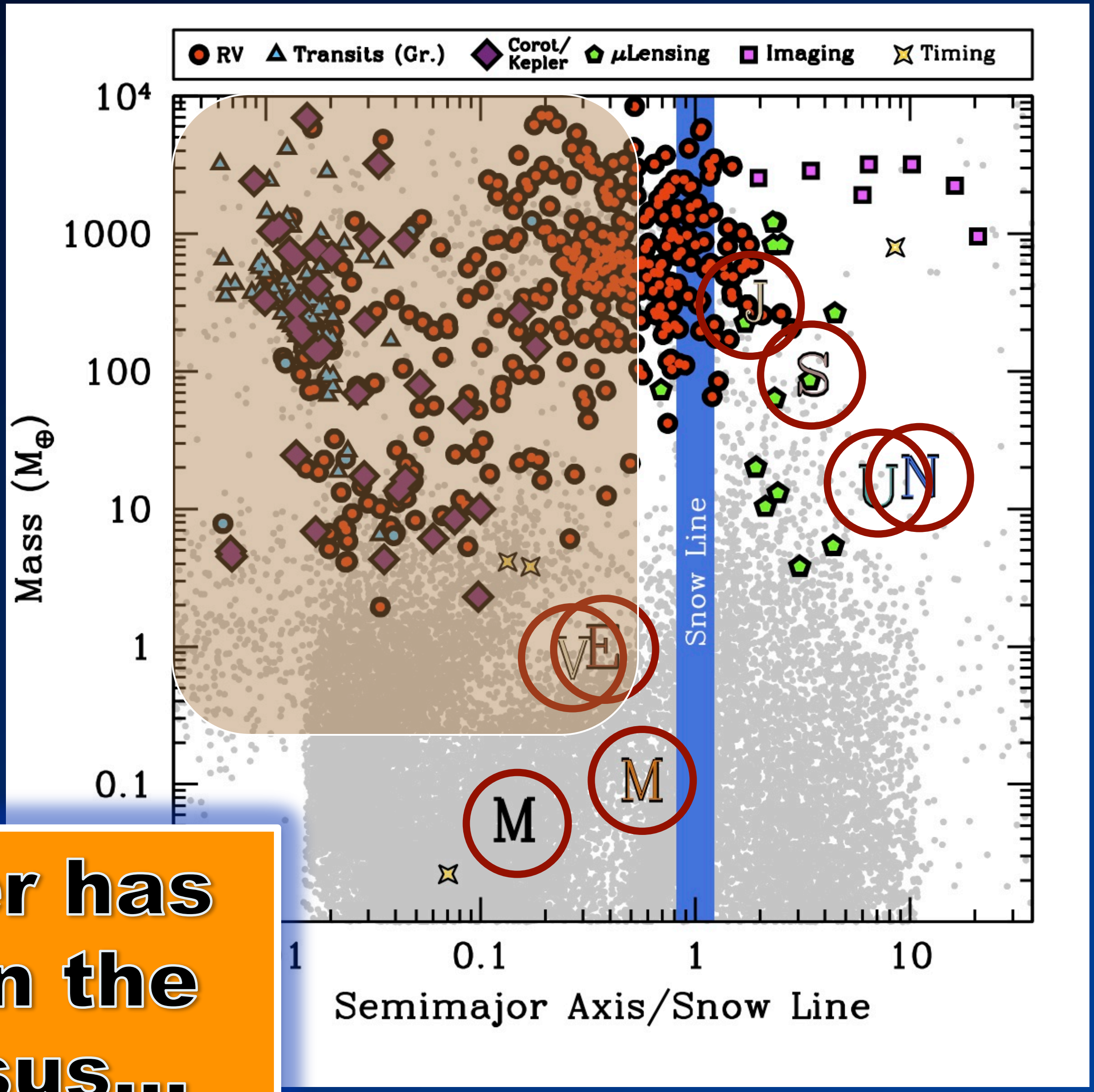
(Clanton & Gaudi 2014a,b)



(Clanton & Gaudi 2014)

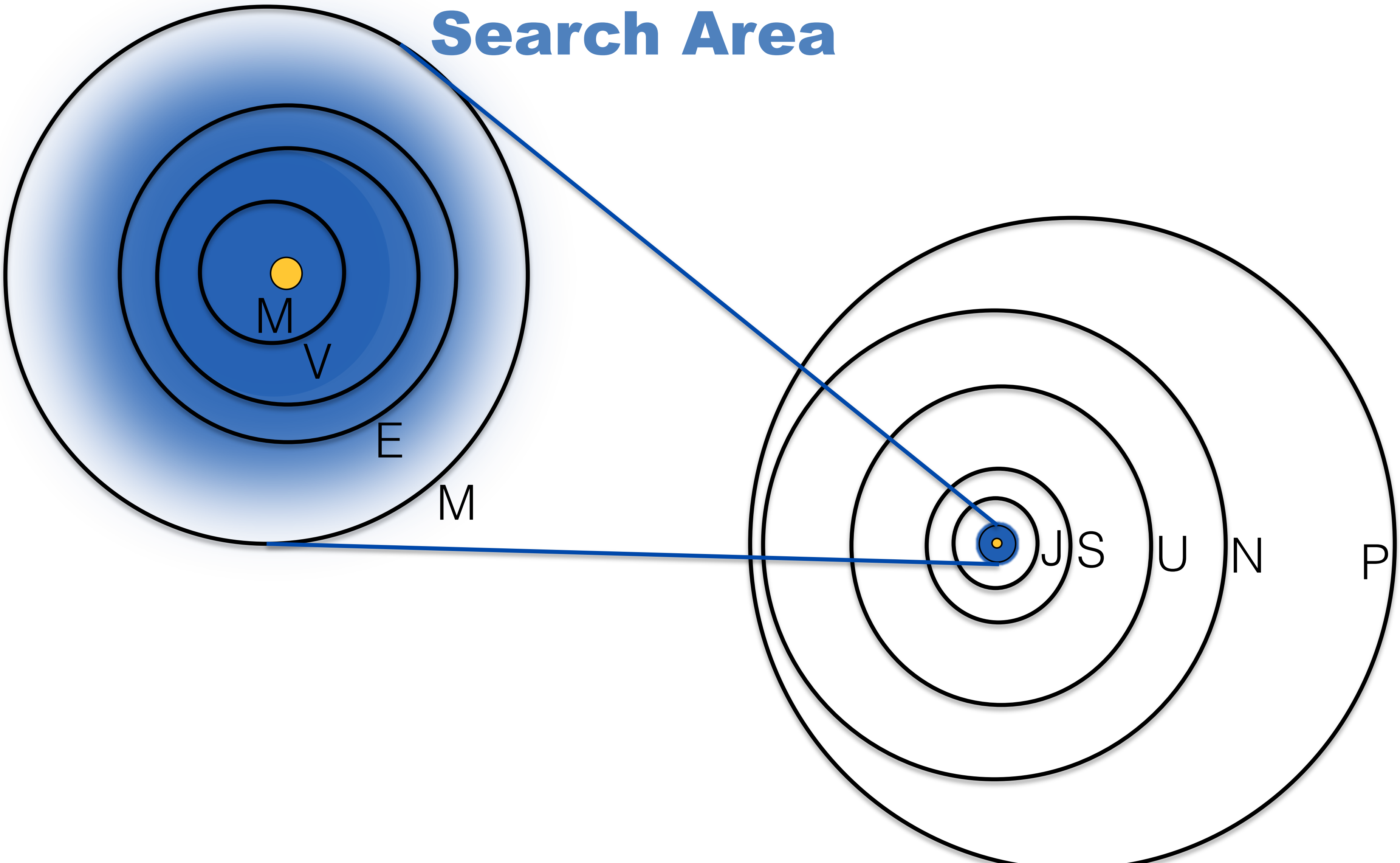
Future.

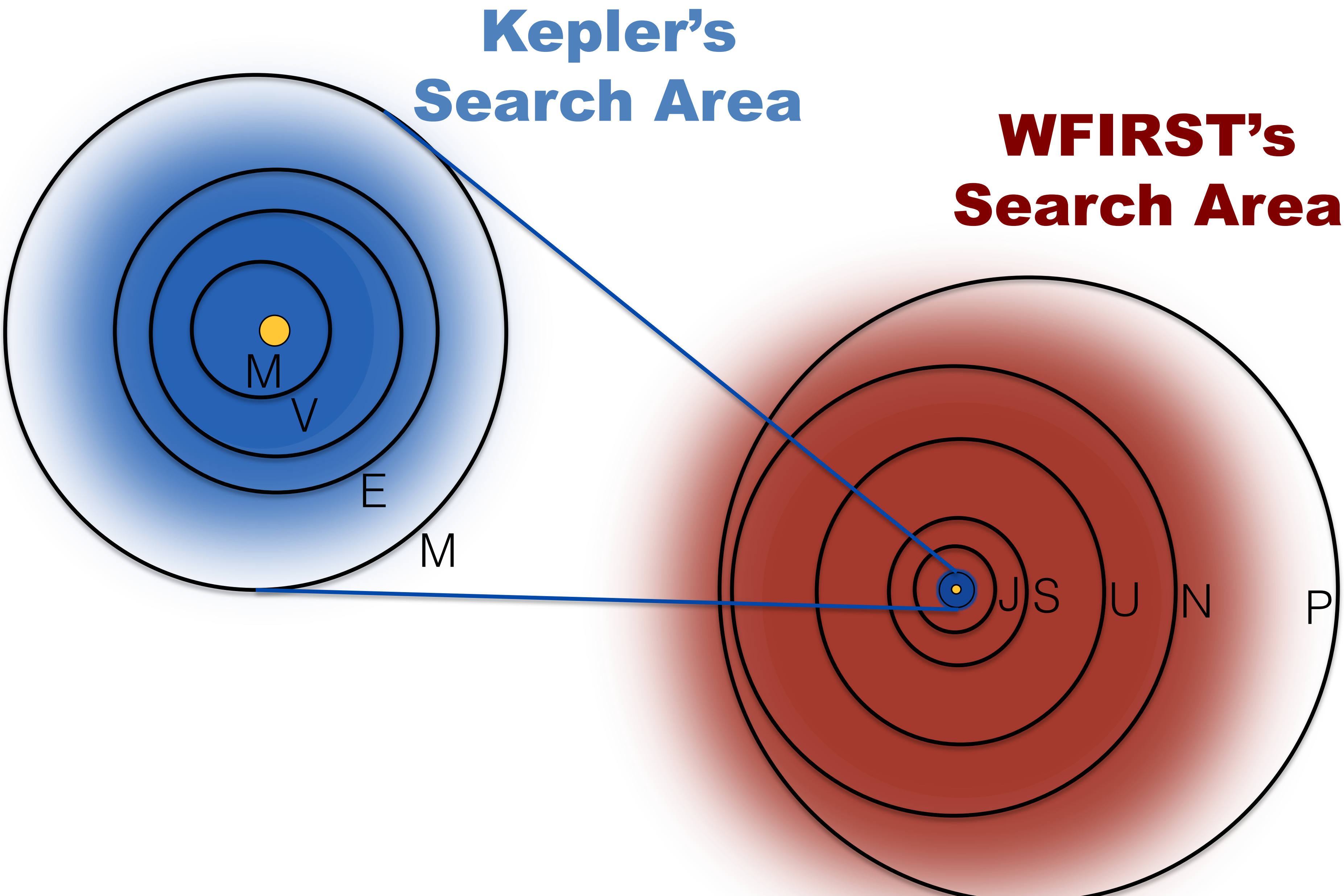
Toward a statistical census of exoplanets.

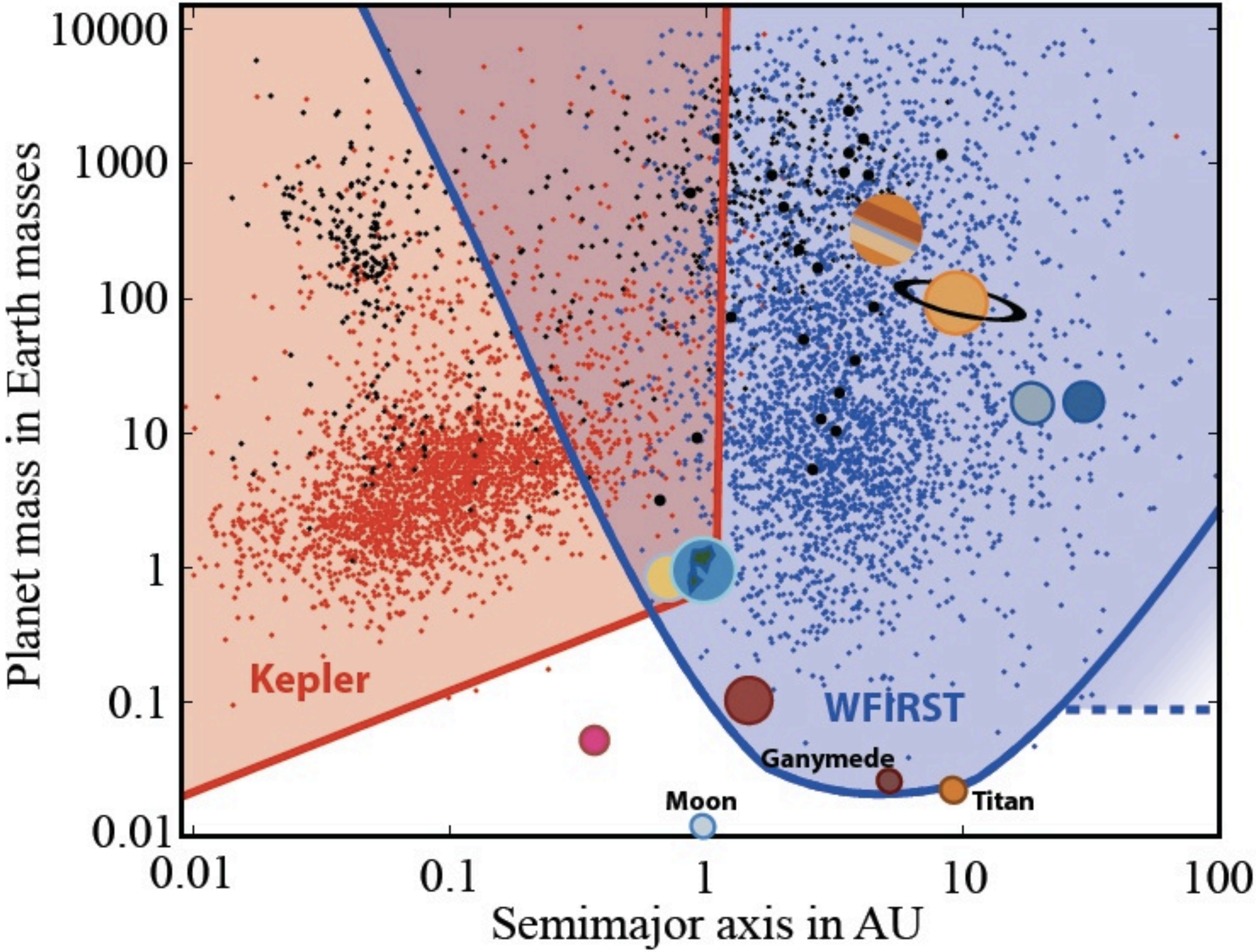


Kepler has begun the census...

Kepler's Search Area




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



Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
Kepler
WFIRST
Ganymede
Moon
Titan
0.01
0.1
1
10
100
Semimajor axis in AU

Summary.

- Many challenges to synthesizing results from different surveys and different methods.
- The time has come to face these challenges: theoretical models have developed to the point of making a priori predictions for exoplanet demographics.