Overview of Kepler Results: Borucki et al. (2011)

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DTM, Carnegie Institution

Exploring Strange New Worlds: From Gas Giants to Super Earths
High Country Conference Center, Flagstaff, Arizona
May 3, 2011

FEBRUARY 5, 1996 $2.95

TIME

Dole Drops, Clinton Rises

IS ANYBODY OUT THERE?

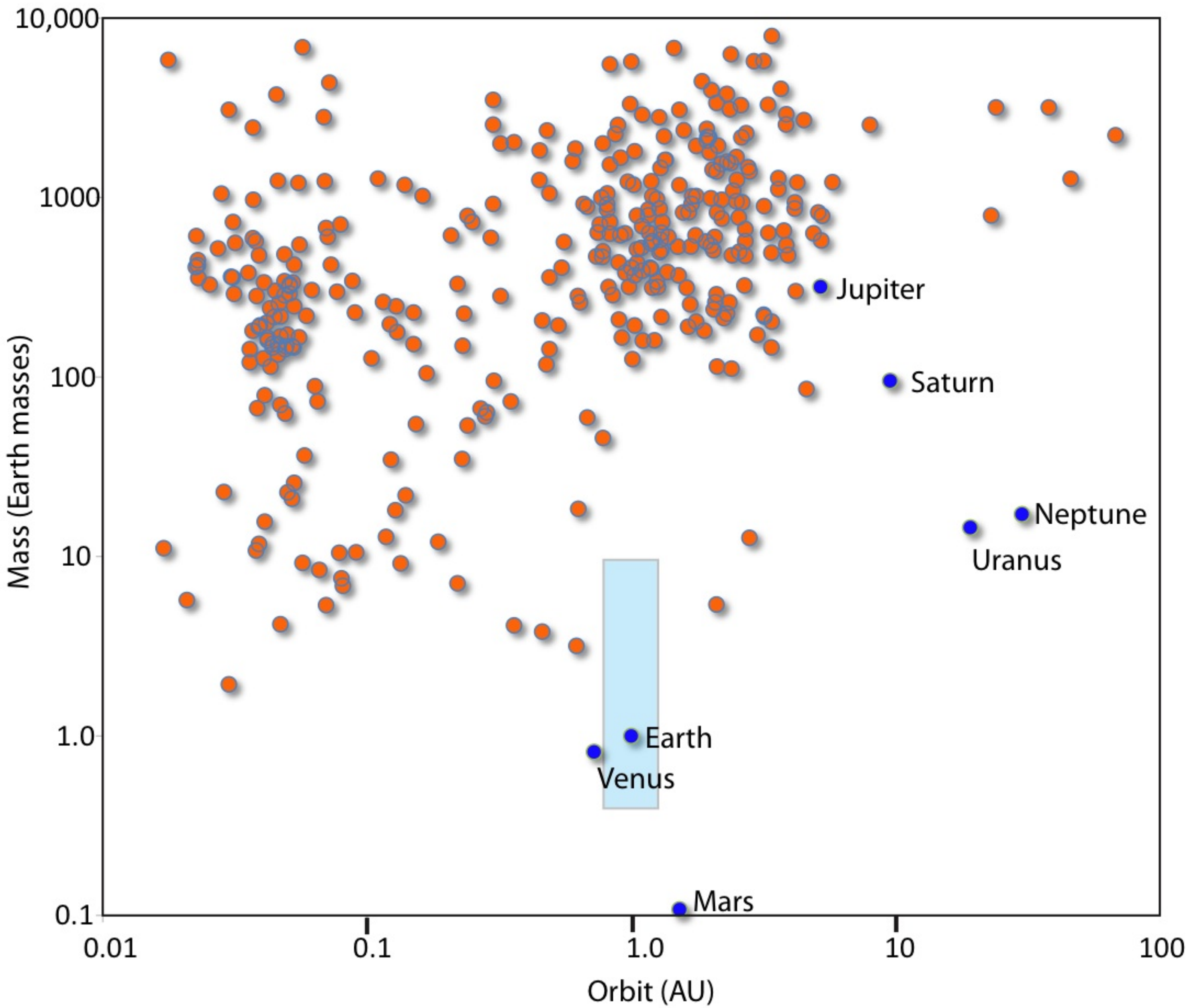
How the discovery of two planets brings us closer to solving the most profound mystery in the cosmos

06

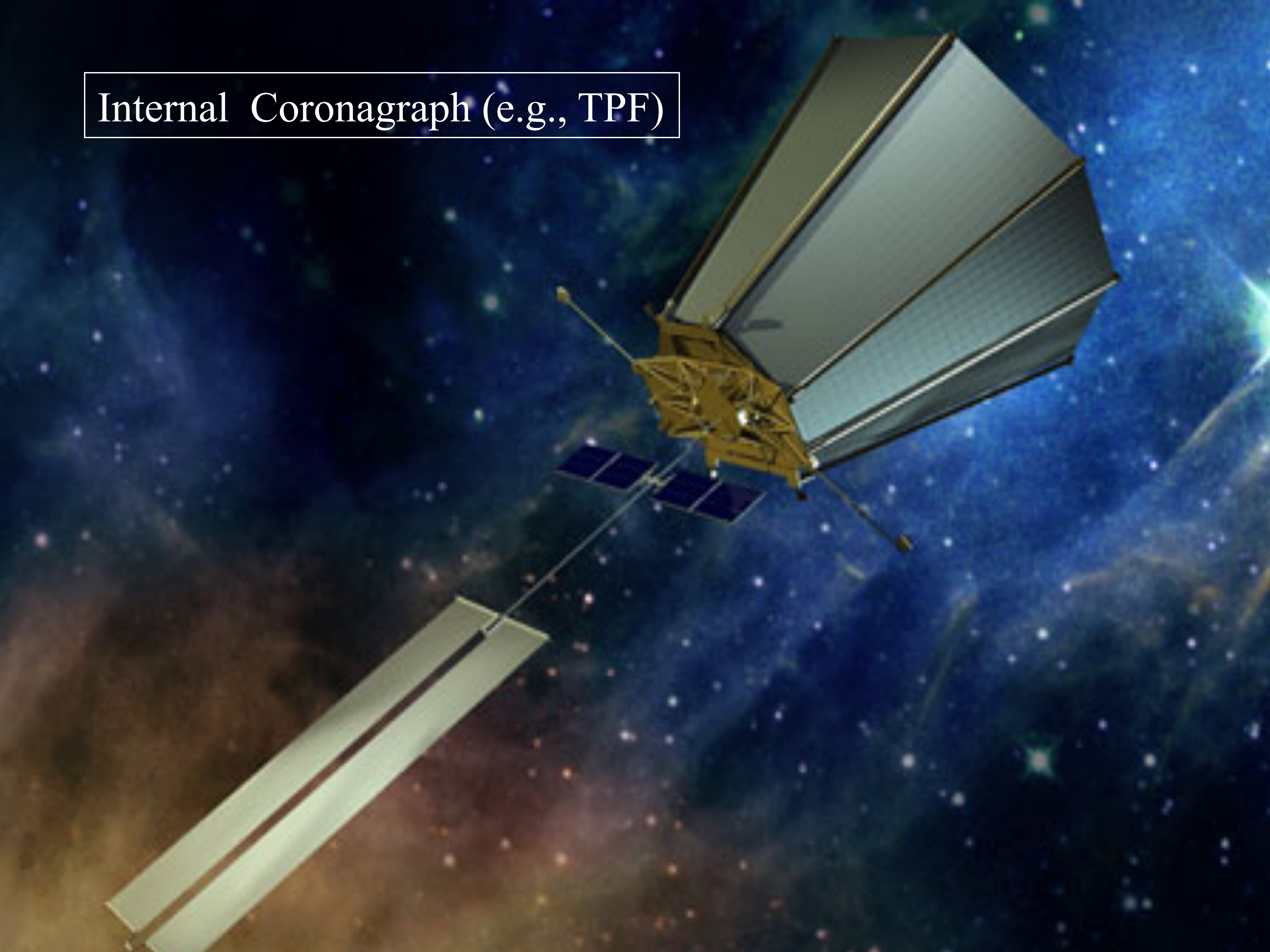
10090

724404 1 0

Discovery space circa 2011: ~ 535 exoplanets



Internal Coronagraph (e.g., TPF)

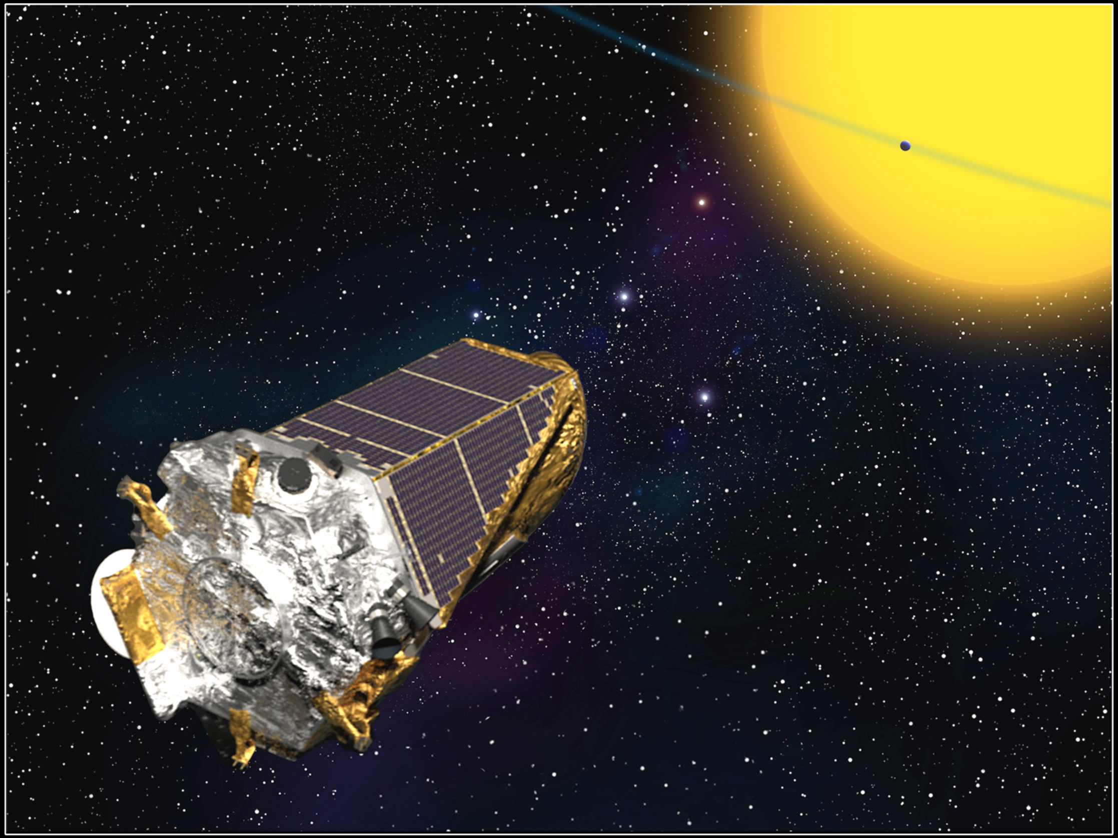


External Occulter (e.g., New Worlds Observer)

NASA's Kepler Mission

"TPF-T"

- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets



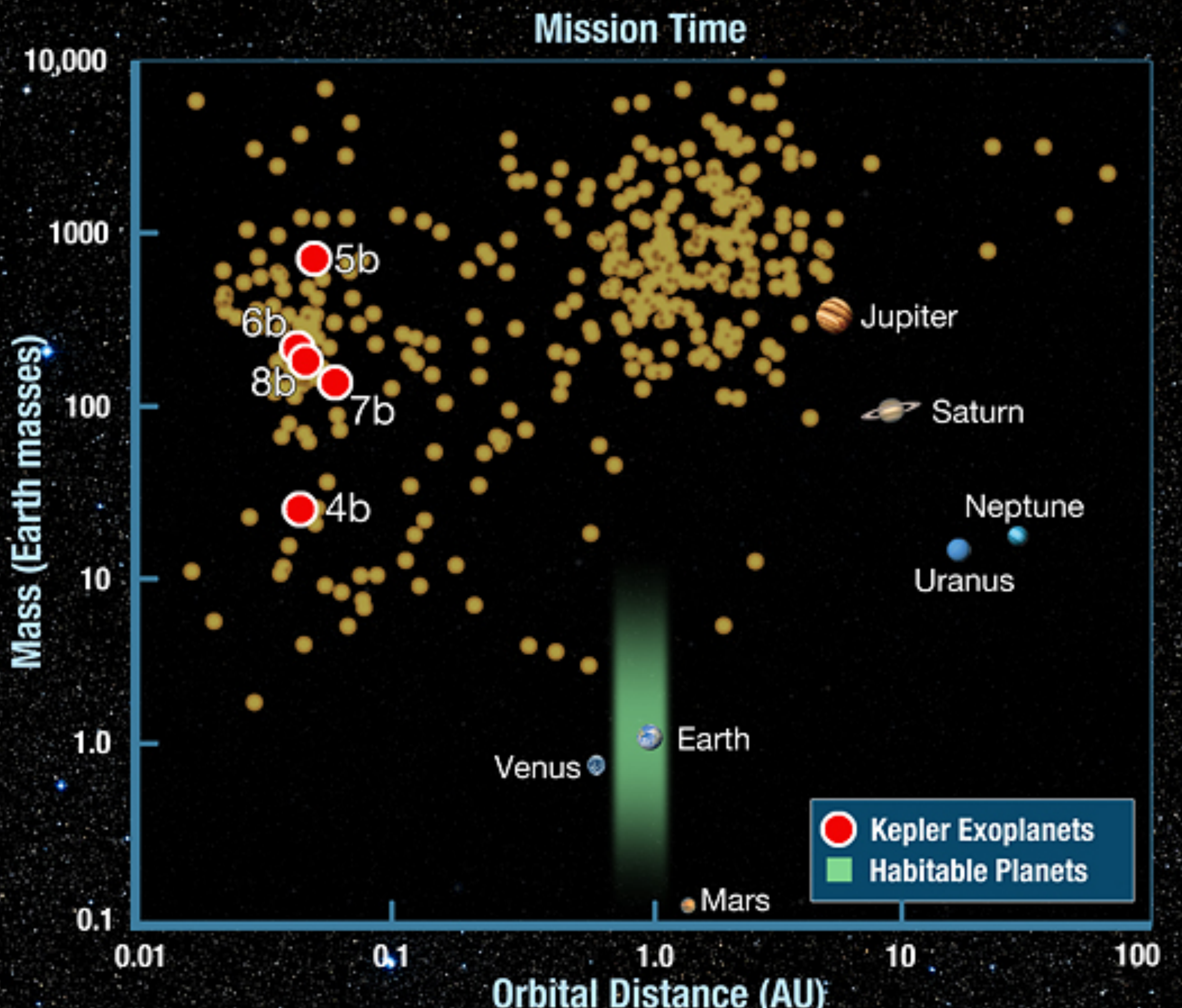
Venus transiting the Sun on June 8, 2004 (Robert Traube image)

William J. Borucki, Kepler Mission PI

Kepler Mission launch - March 6, 2009

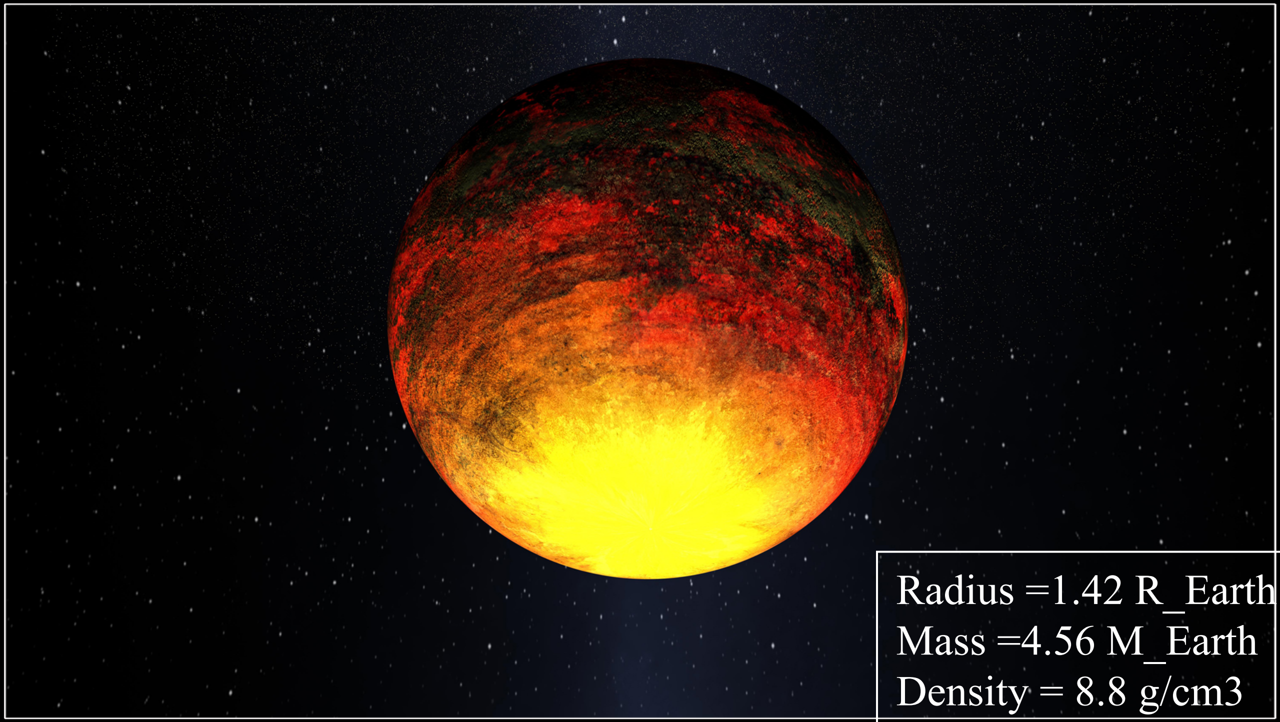
First Five Planet Discoveries

Made with First 43 Days of Data



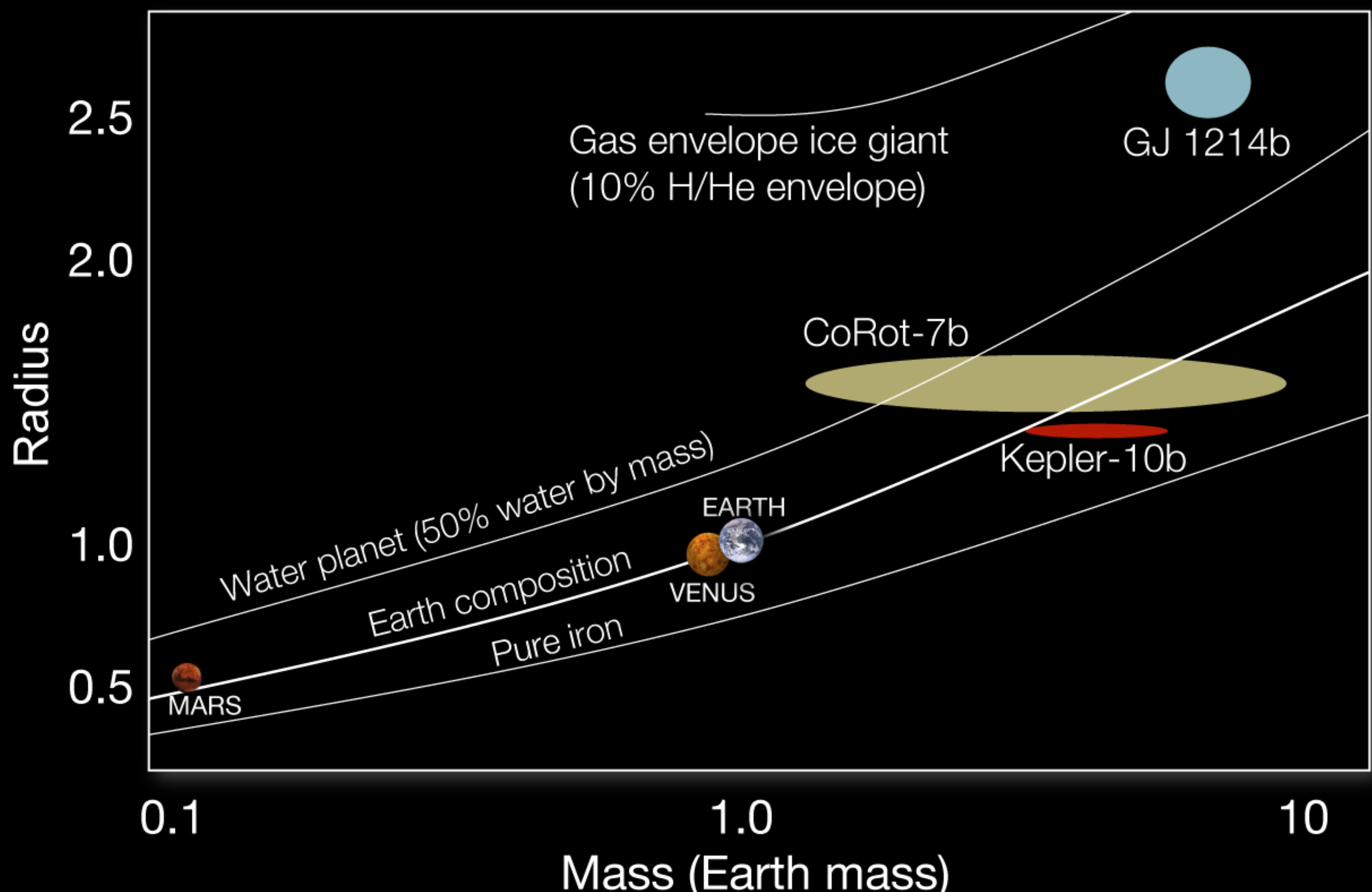
Kepler's First Rocky Planet: Kepler 10b

Kepler is giving us new knowledge about the frequency of planetary candidates in the habitable zone.

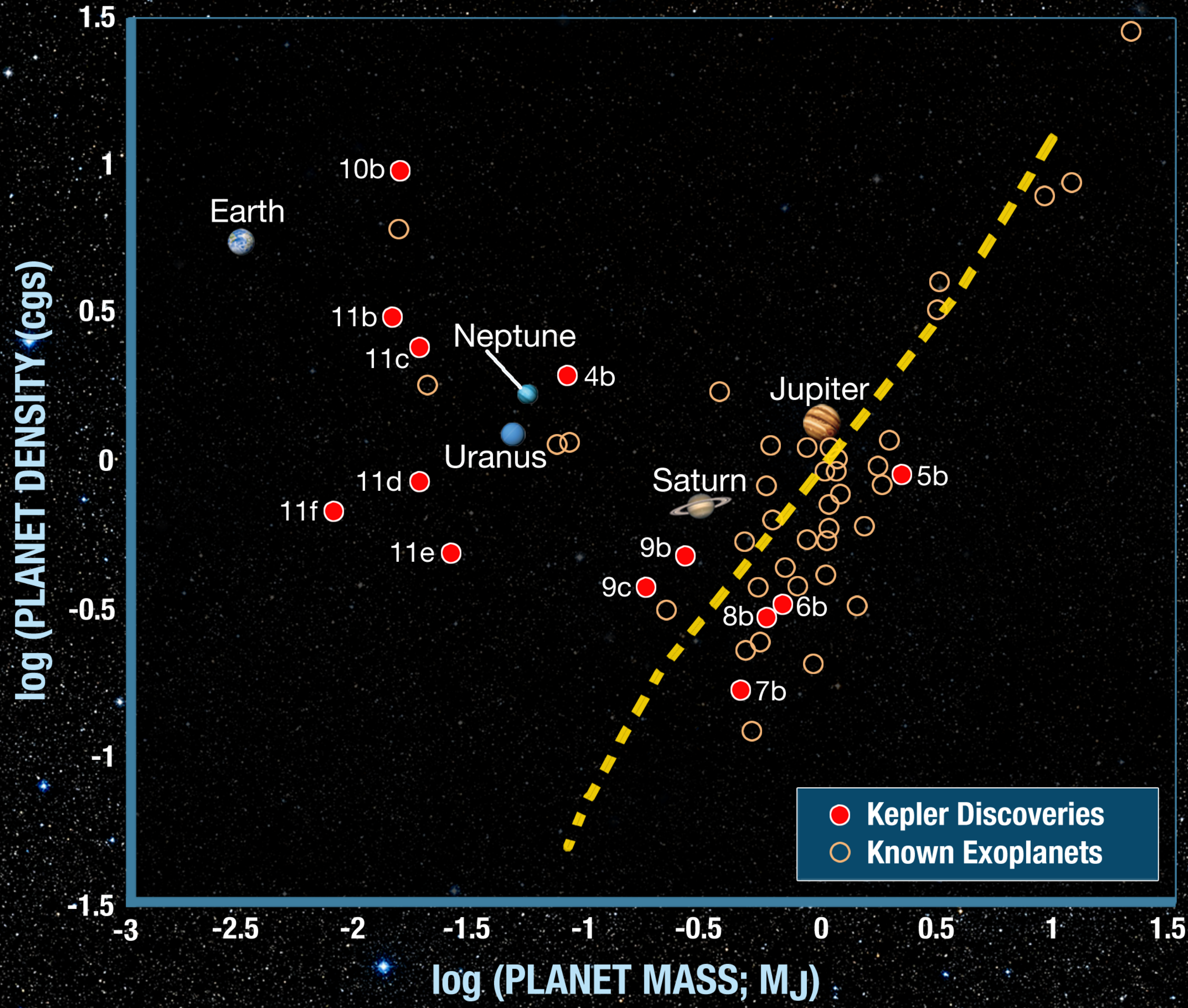


Radius =1.42 R_Earth
Mass =4.56 M_Earth
Density = 8.8 g/cm3
Semi-major axis = 0.0167 AU
Orbital Period = 0.84 days
Equilibrium Temperature = 1833 K

Composition of Kepler-10b

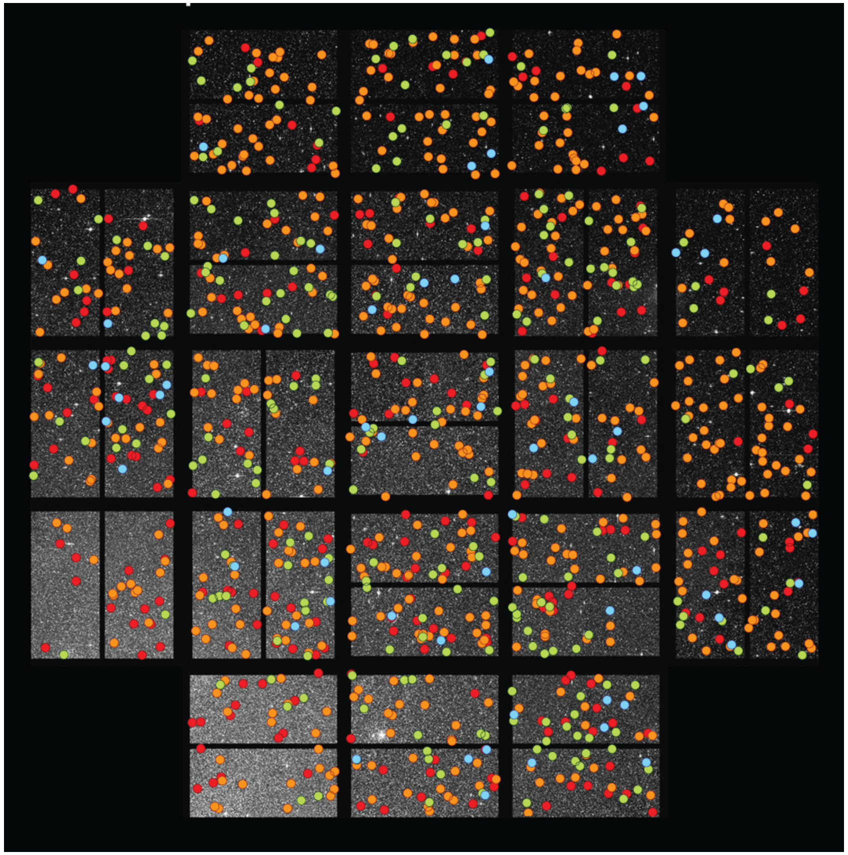


Variation of Planet Density with Mass



LATEST *KEPLER* DATA RELEASE

Candidates in the Kepler FOV



On 1 Feb 2011, Kepler released the data on 155,453 stars and the 1235 planetary candidates around 997 host stars discovered during the first 4 months of science operations.

The planetary candidates include:
68 of Earth size,
288 of super-Earth size,
662 of Neptune size, and
165 of Jupiter size.

54 candidates are in the habitable zone of their host stars.

170 stars show the presence of systems of transiting planetary candidates; 54 have 3 or more candidates

Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

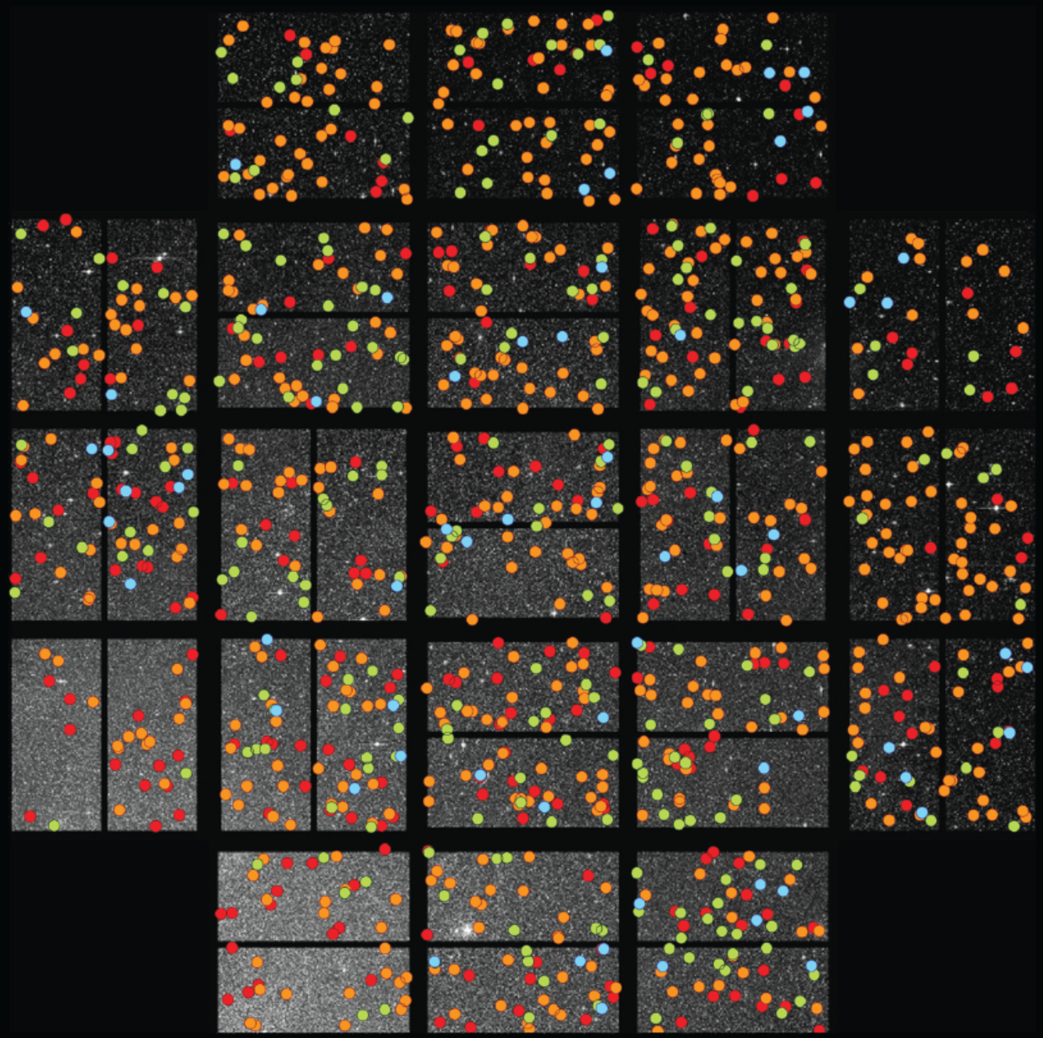
Locations of Kepler Planet Candidates

Earth-size

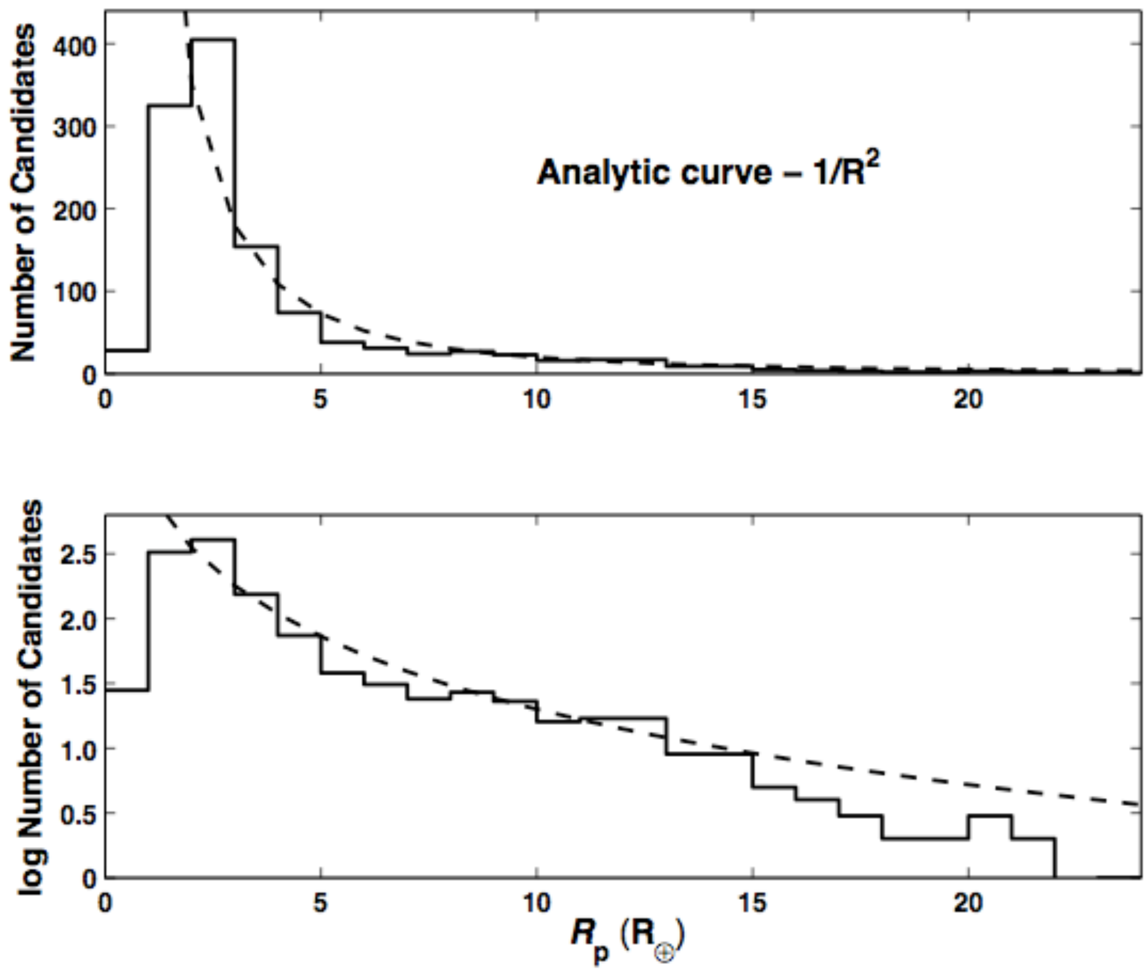
Super-Earth size
1.25 - 2.0 Earth-size

Neptune-size
2.0 - 6.0 Earth-size

Giant-planet size
6.0 - 22 Earth-size

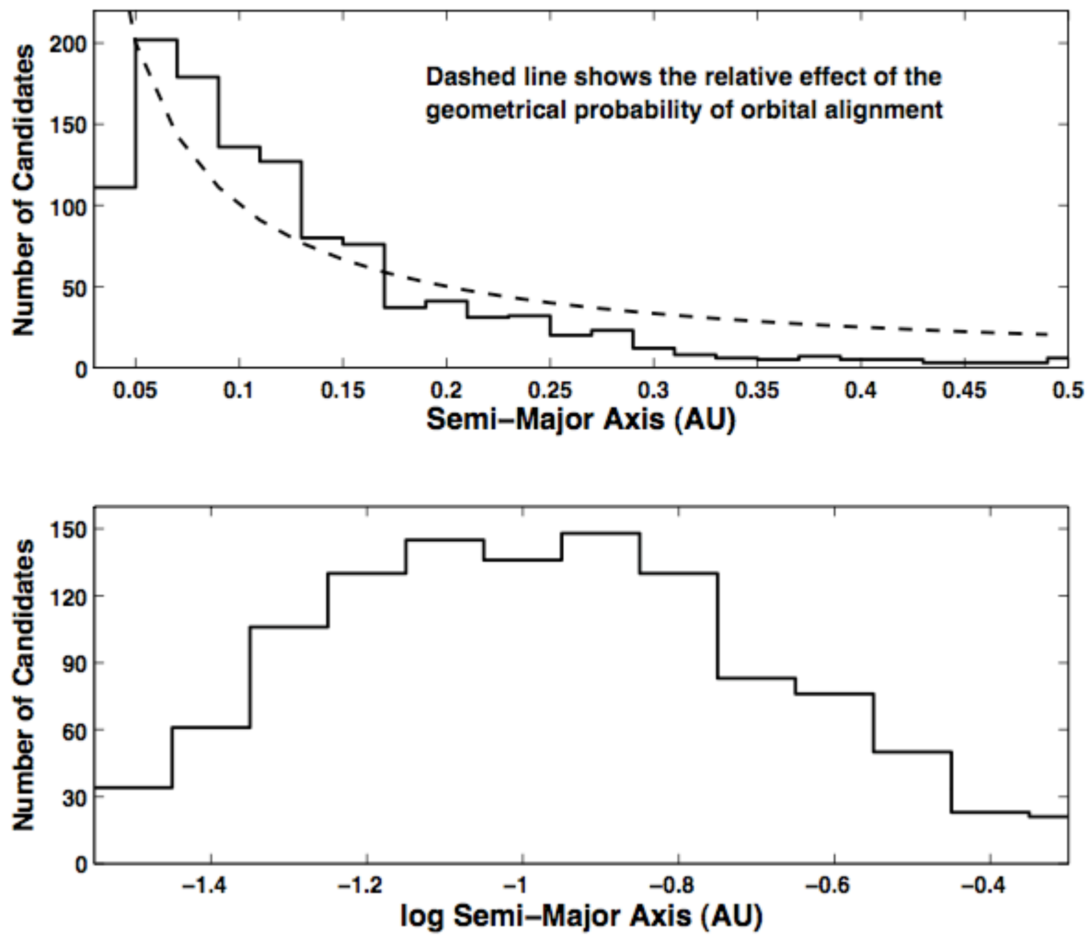


PLANETARY CANDIDATE SIZE DISTRIBUTION



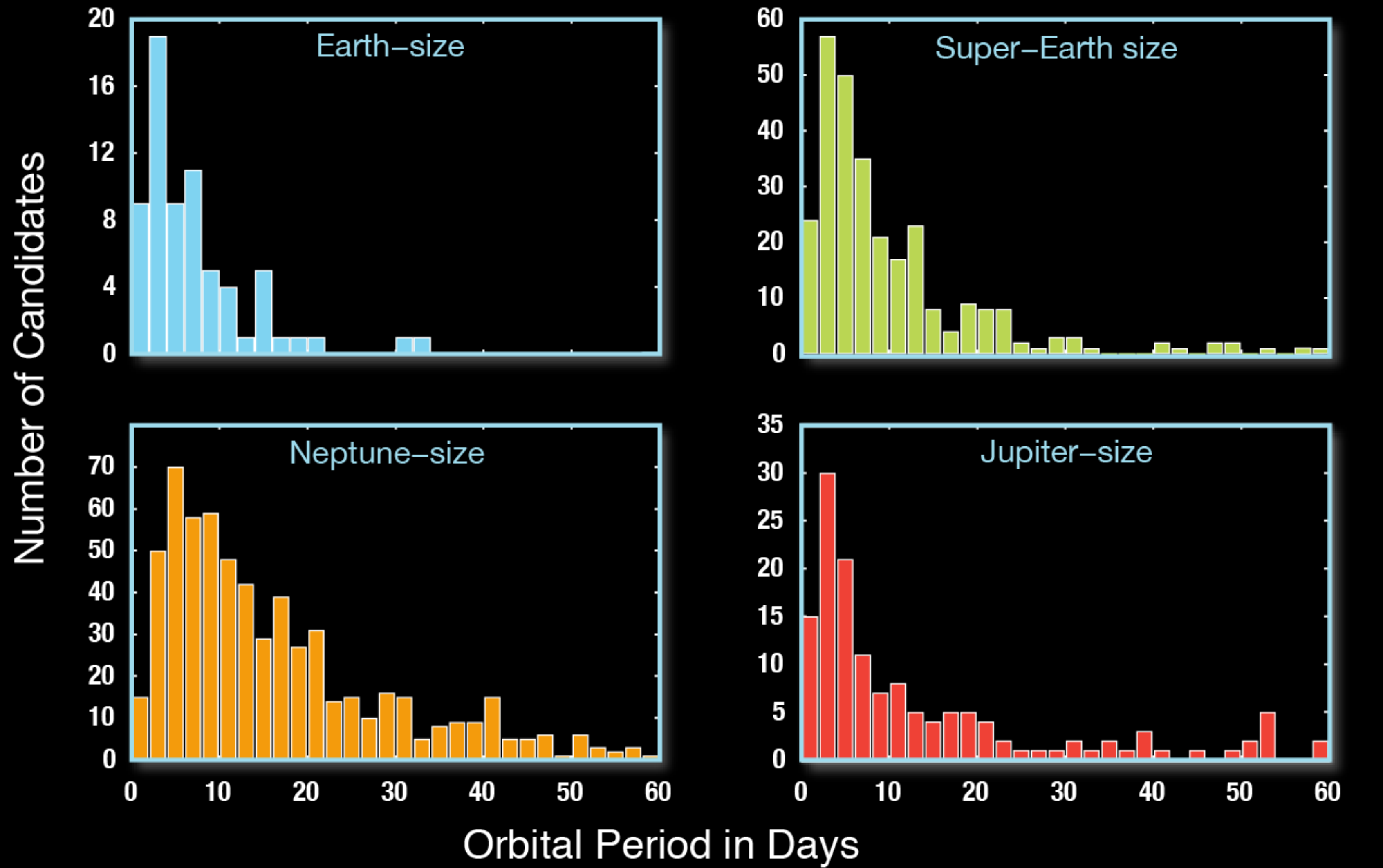
For 2 $R_\oplus$ < R_p < 15 $R_\oplus$, the sizes are well represented by a $1/(R_p)^2$ relation

NUMBER OF CANDIDATES VS SEMI-MAJOR AXIS

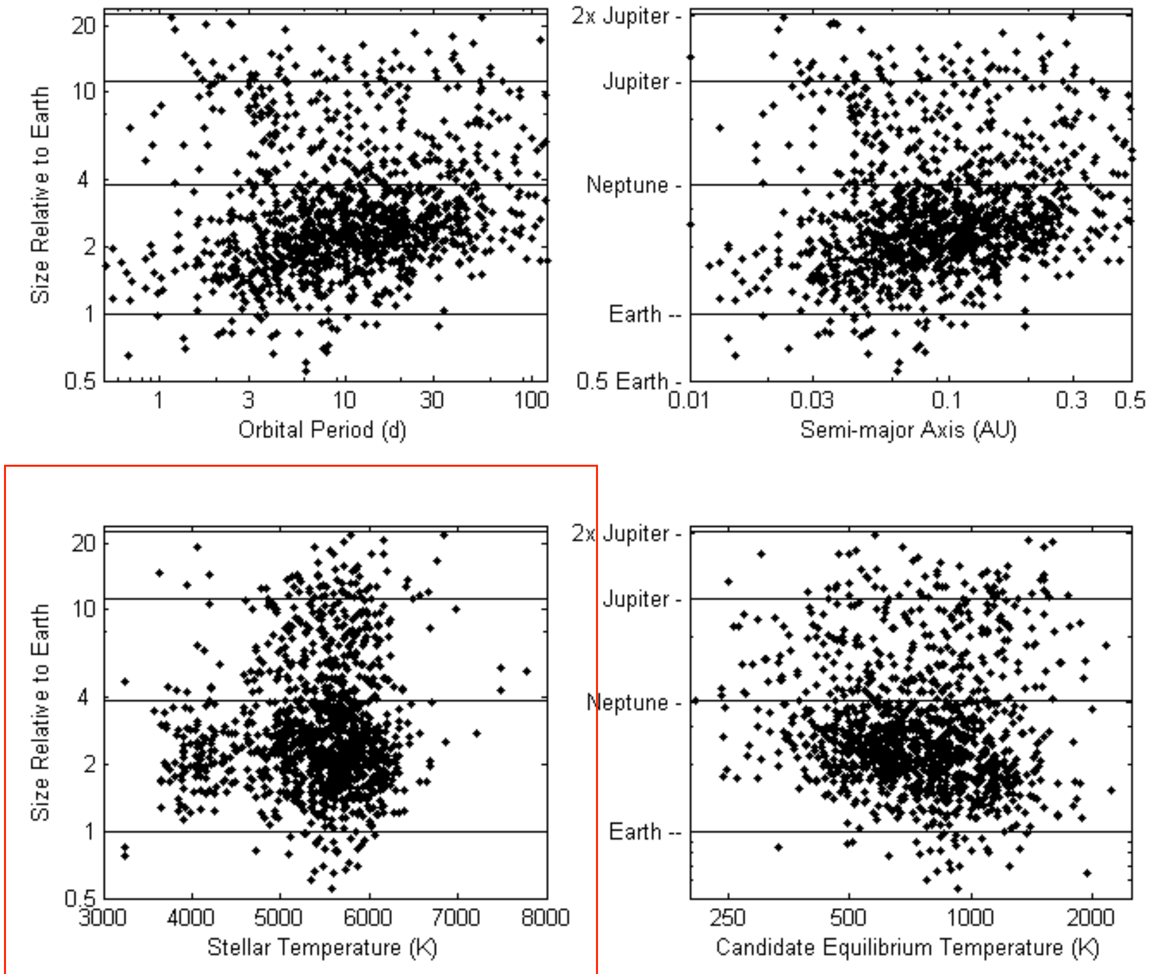


A relationship of the form of 1/*a* fits poorly, indicating that the correction for orbital alignment is not sufficient to account for the decrease in number with *a*.

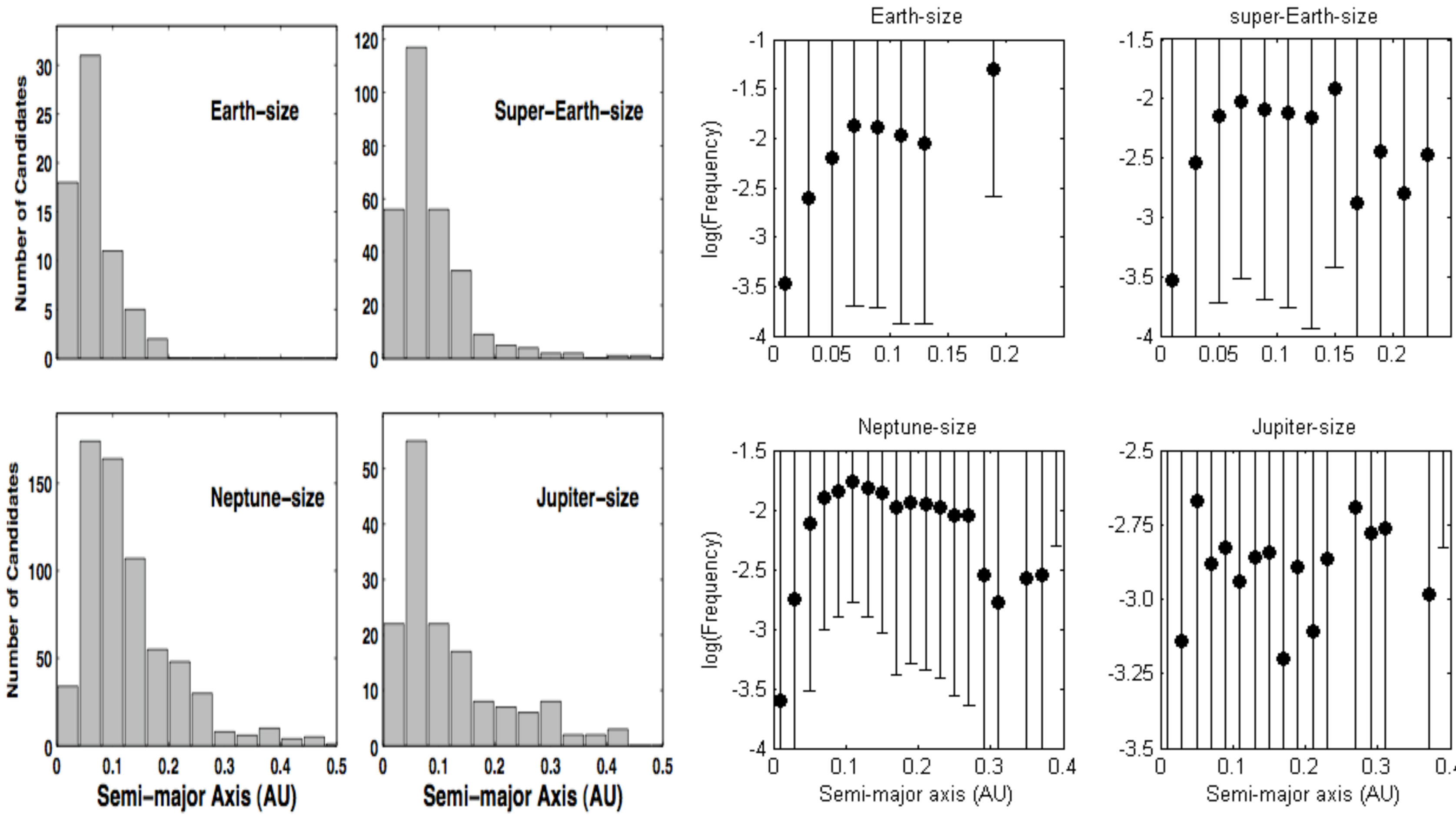
Candidates Show Drop Off for Shortest Orbital Periods



CANDIDATE SIZE VS. ORBITAL PERIOD, SEMI-MAJOR AXIS, STELLAR TEMPERATURE, & CANDIDATE EQUILIBRIUM TEMPERATURE

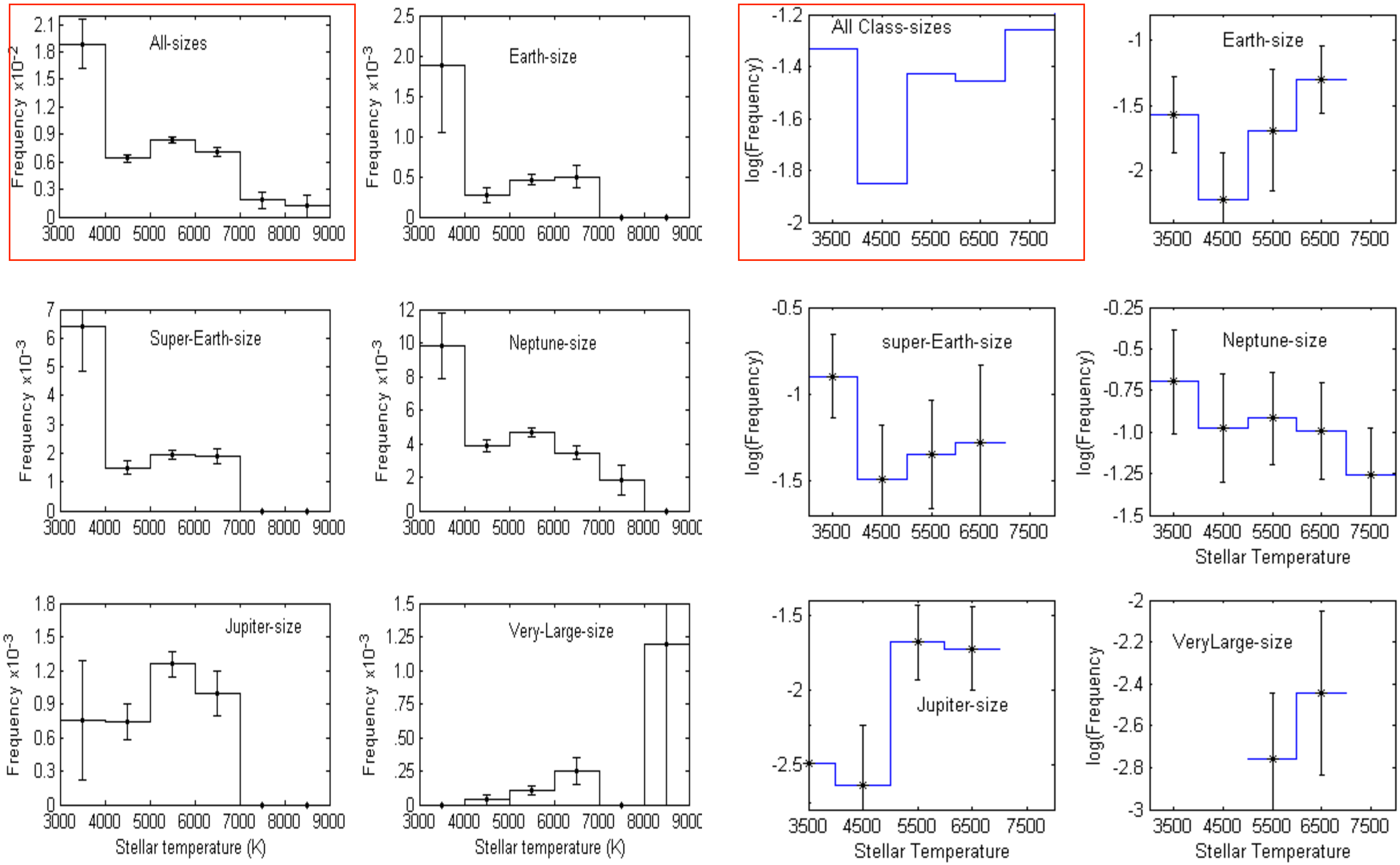


MEASURED [L] VS. INTRINSIC [R] DISTRIBUTIONS



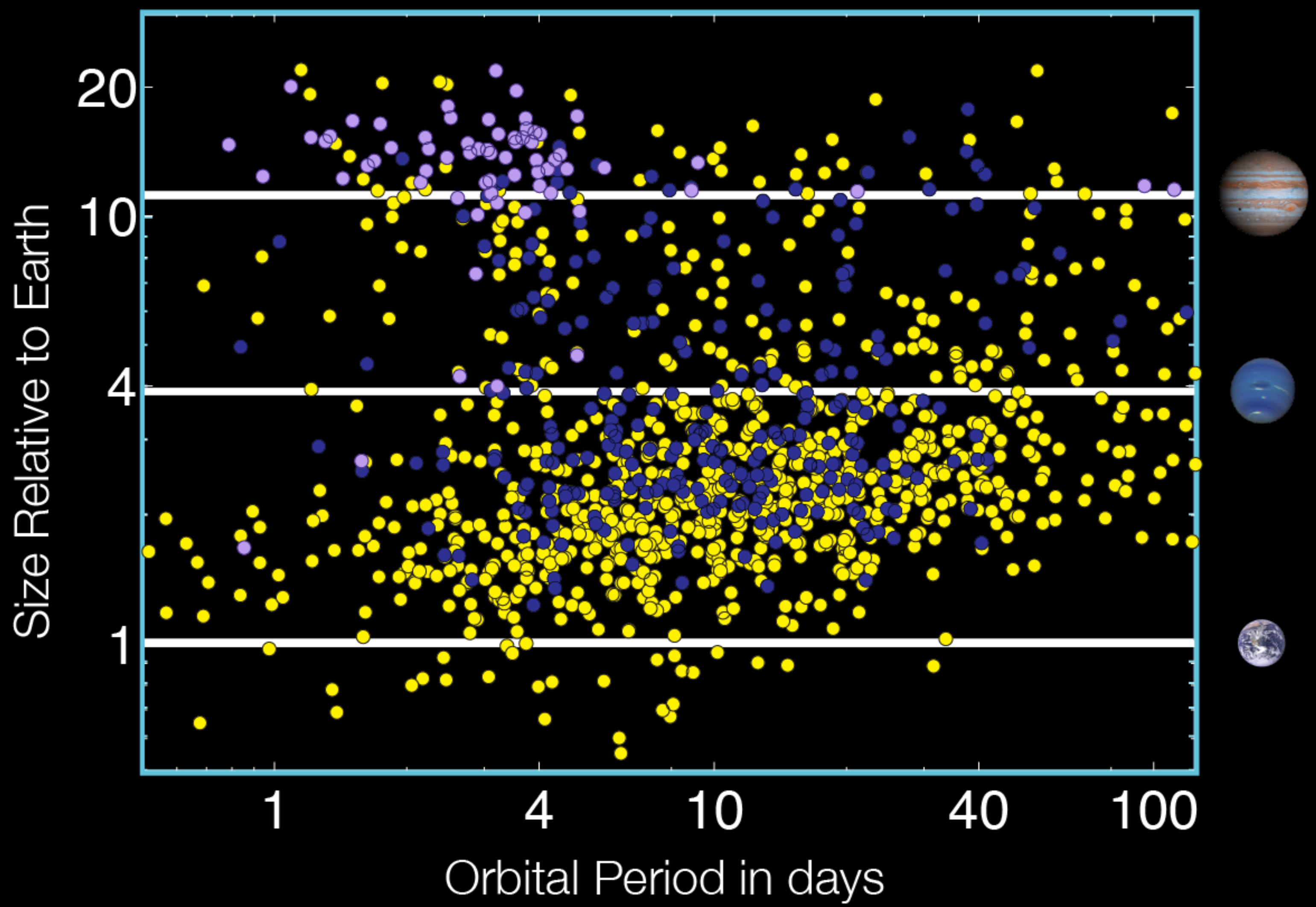
Intrinsic distribution estimation per target star in the Kepler sample:
5.4% Earth size, 6.8% super-Earth size, 19.3% Neptune size, and 2.4% for Jupiter size
→ Implies ~ 0.34 planet candidates per star for orbital periods ≤ 60 days

MEASURED [L] VS. INTRINSIC [R] DISTRIBUTIONS

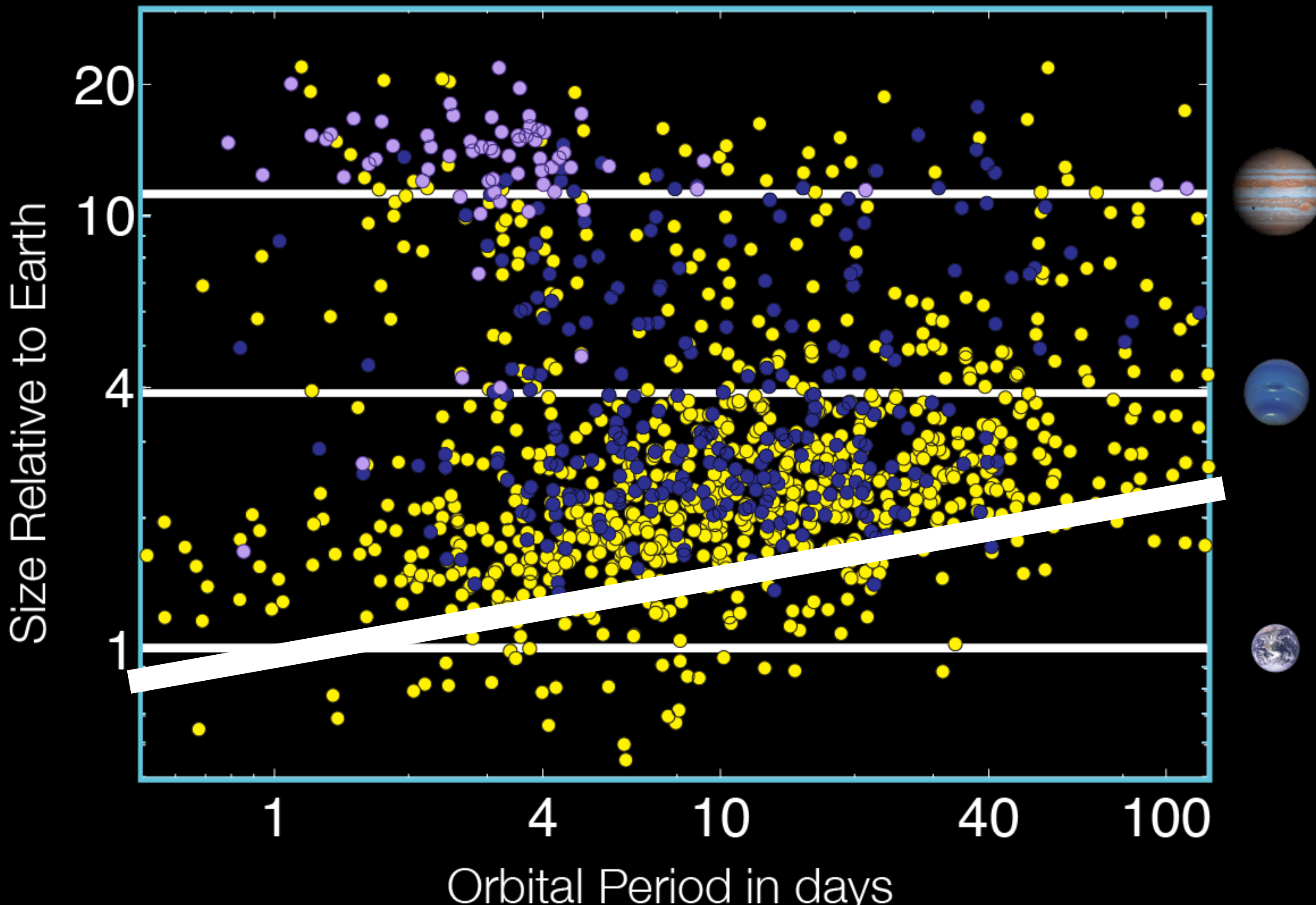


Correction for selection effects reduces the prominence of the coolest stars, resulting in a drop in frequency for K dwarfs and an enhanced frequency of Jupiter-size candidates in orbit around the hotter and more massive stars

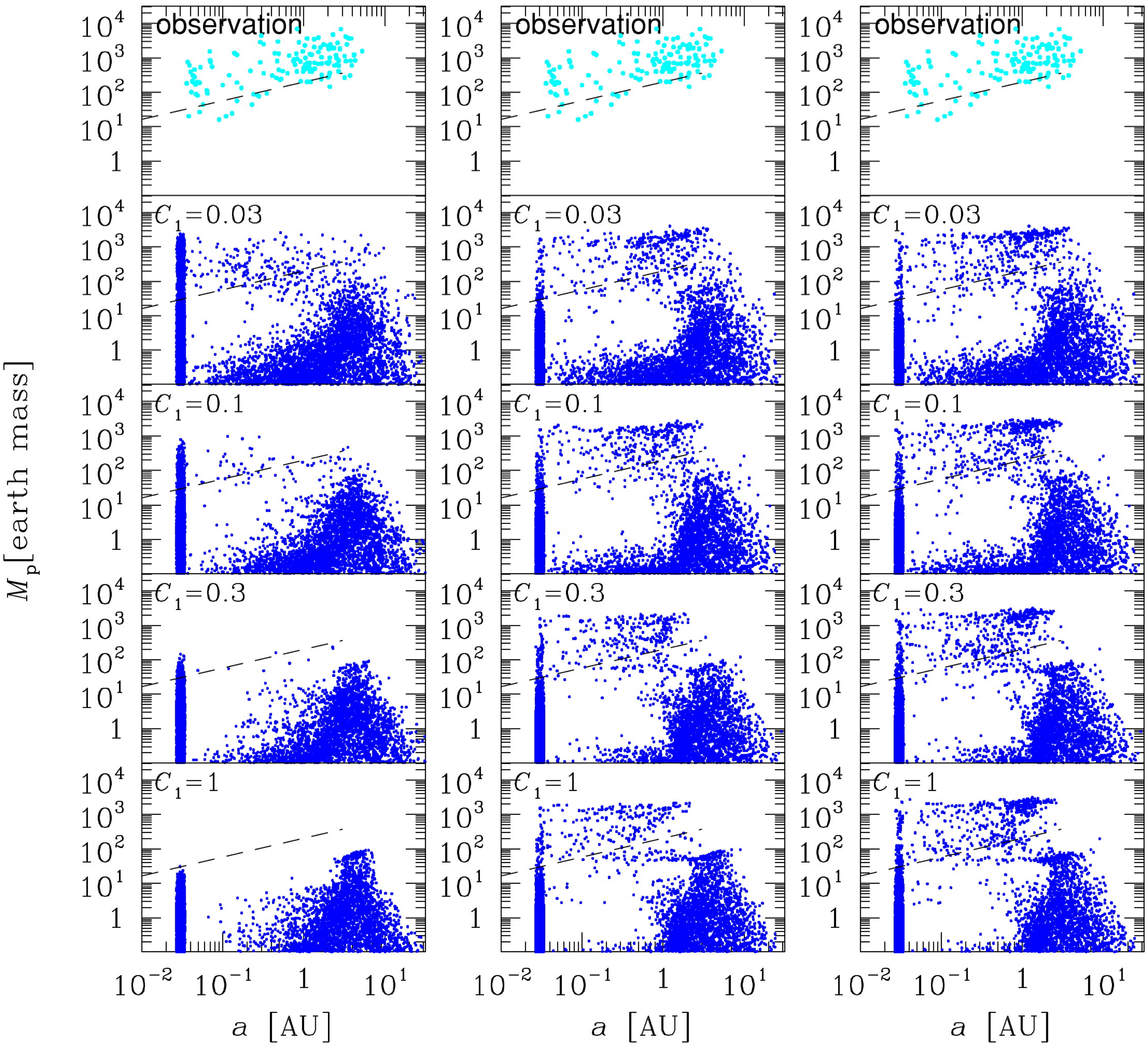
Kepler Candidates as of February 1, 2011



Kepler Candidates as of February 1, 2011



Ida & Lin (2008): no disk bumps (left) gas bump (middle) gas/dust bumps (right)



C_1~ dr/dt parameter for Type I migration

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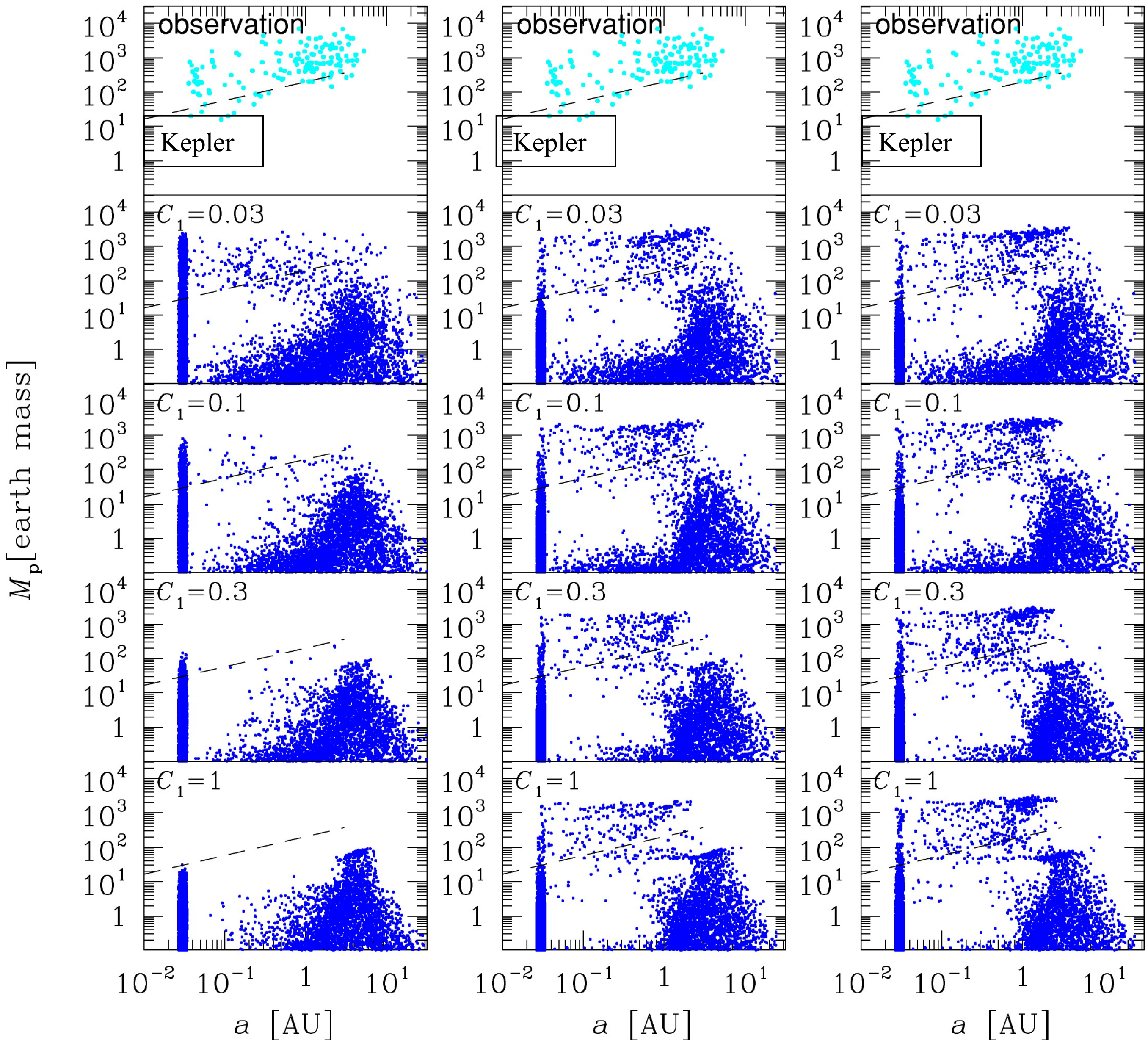
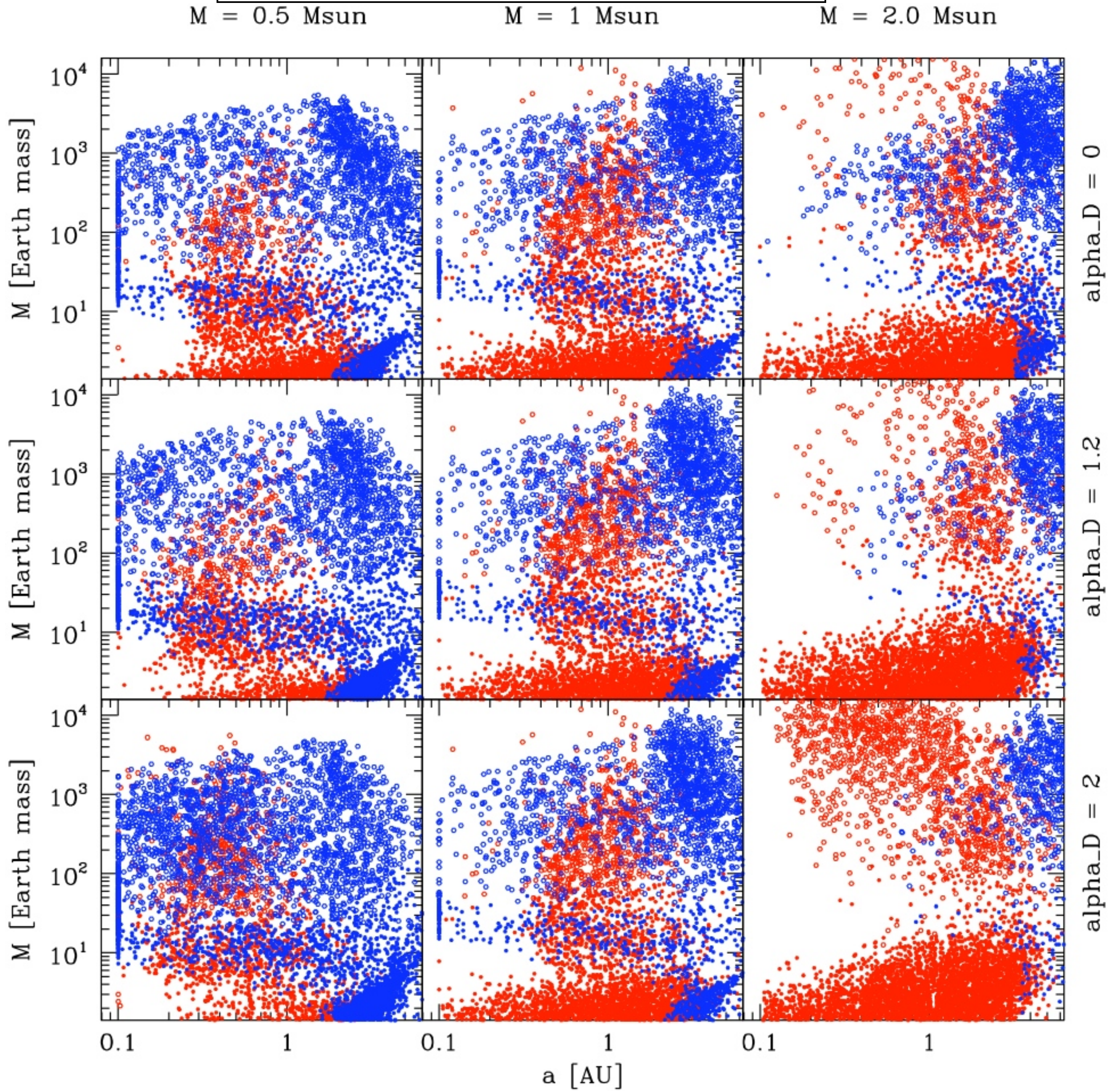


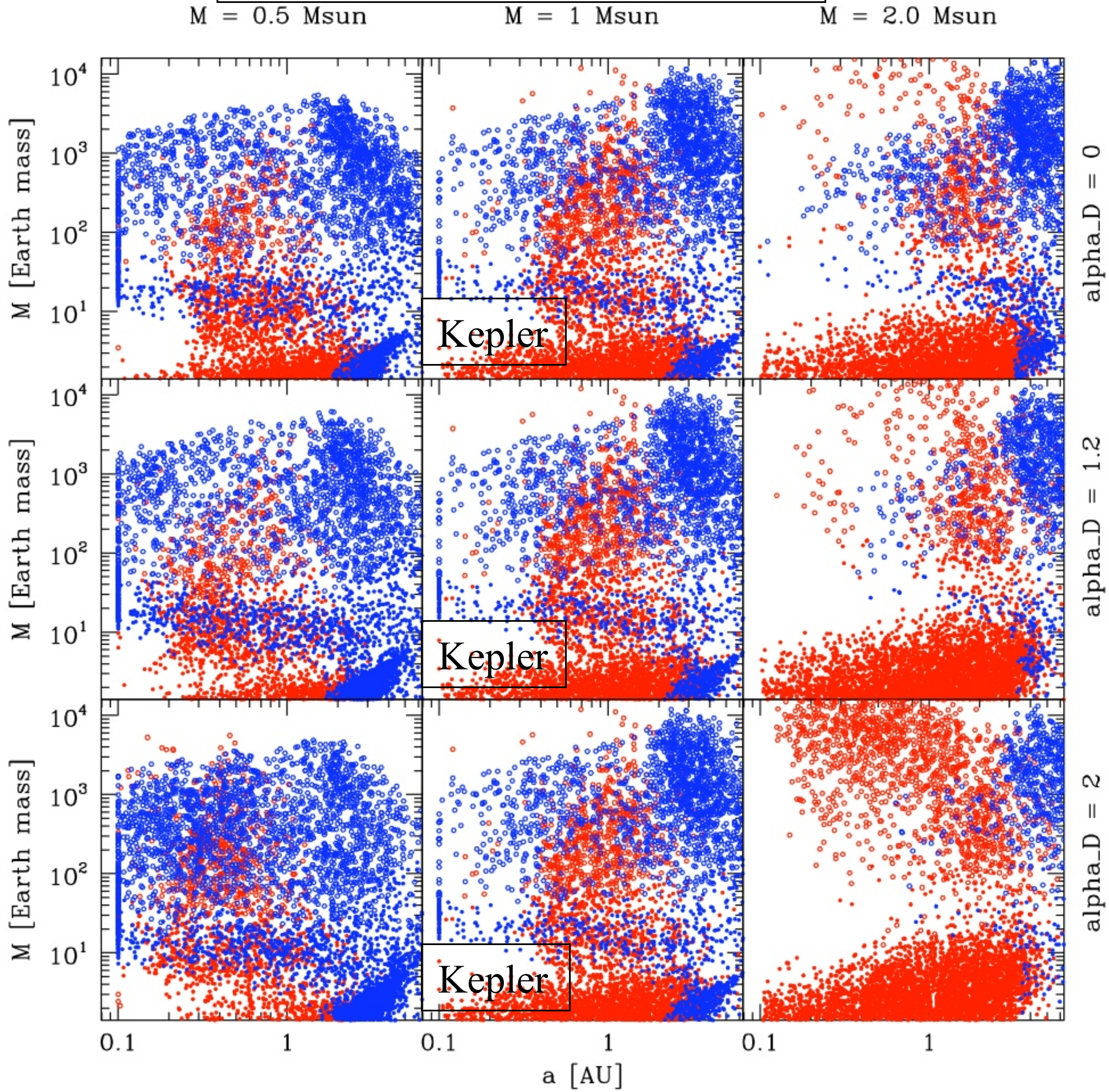
C_1~ dr/dt parameter for Type I migration

Alibert, Mordasini, & Benz (2011)



$M_d \sim M_s^{\alpha D}$

Alibert, Mordasini, & Benz (2011)

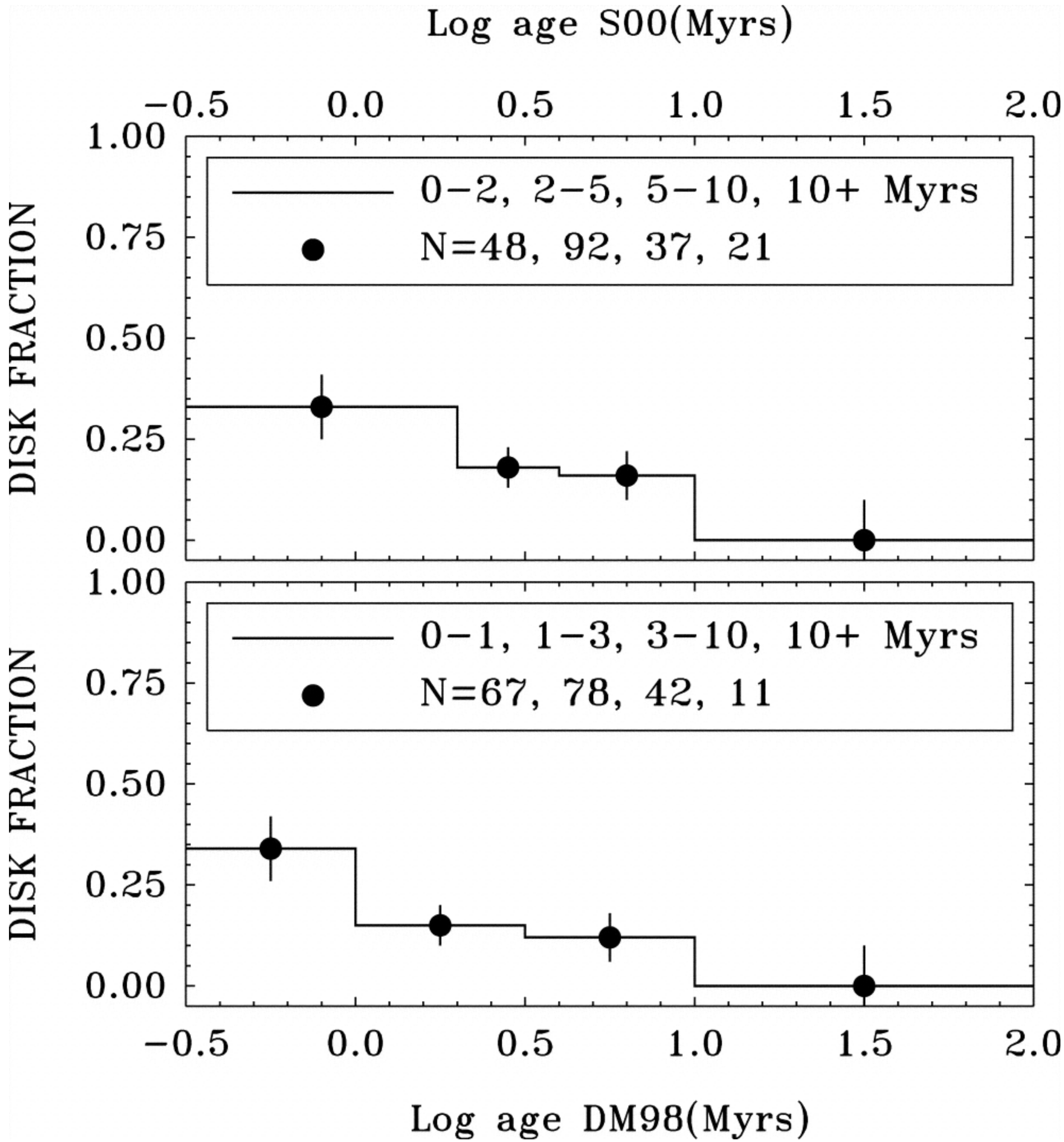


$M_d \sim M_s^{\alpha D}$

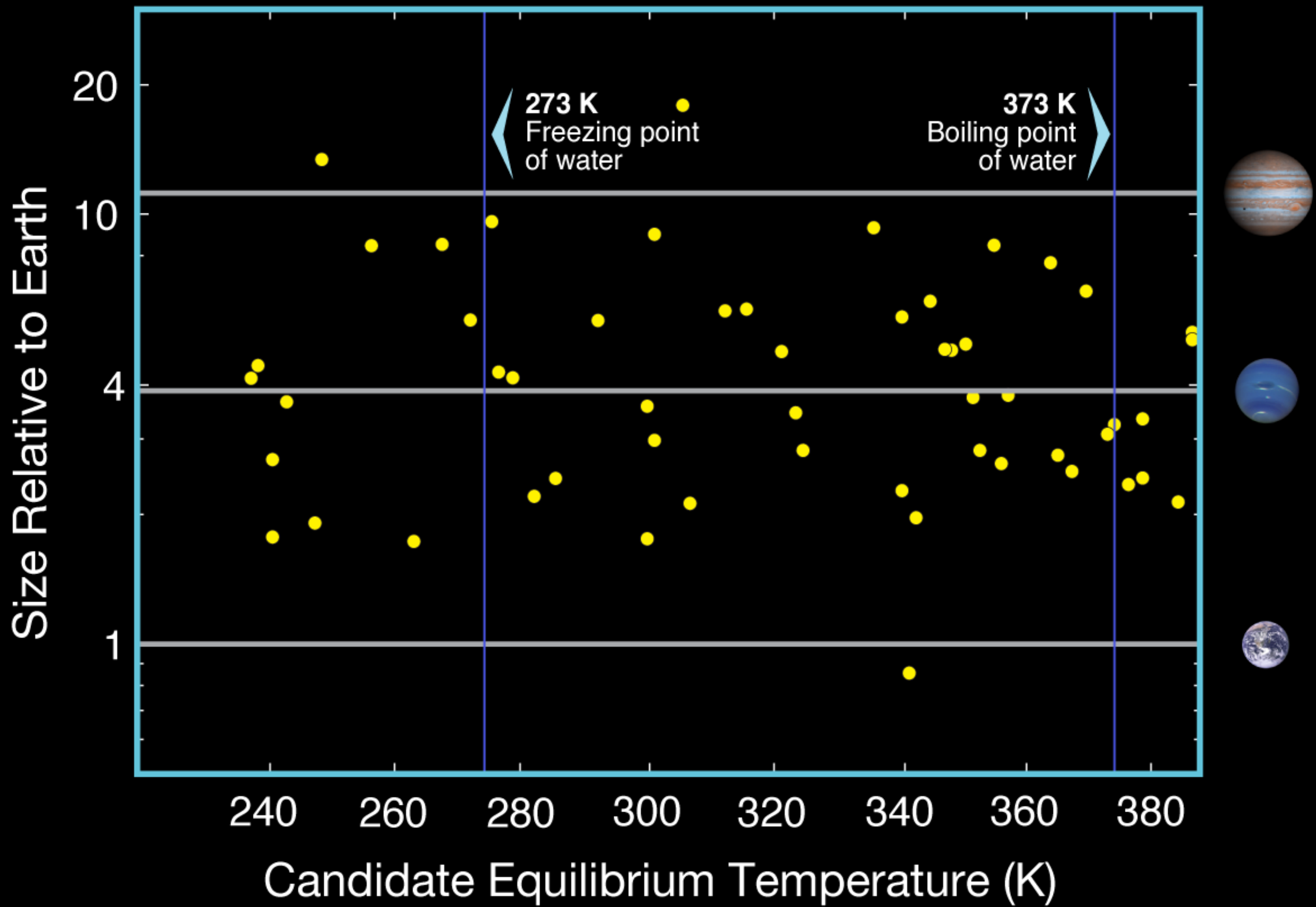
Exoplanet Population Synthesis Models

- The “planet desert” predicted by recent population synthesis models does not exist: in reality this mass range is observed to be a “planet oasis”
- Models also predict a pile-up of planets at small orbits, which is not seen
- The models necessarily rely on a large number of free (or poorly constrained) model parameters (e.g., assumed orbital migration rates, disk lifetimes)
- Prediction of a “planet desert” in particular appears to be caused by the rapid inward orbital migration (Type I) assumed in these models and by the runaway gas accretion of rocky/icy protoplanets, resulting in gas giant planet formation rather than super-Earth and Neptune formation
- As a result, models based on the classic core accretion mechanism for planetary system formation apparently require serious modifications to match the observed planetary distributions for super-Earths and Neptunes
- Perhaps hybrid models need to be considered, with much shorter disk lifetimes (e.g., < 1 Myr vs. ~ 5 Myr), minimizing Type I migration losses and preventing the growth of super-Earths into gas giants, while the needed gas giants are formed rapidly prior to disk dispersal by disk instability

Cieza et al. (2007) SST survey: ~ 65% of disks gone in < 1 Myr



Kepler Planet Candidates In the Habitable Zone



SUMMARY OF RESULTS TO DATE (Borucki et al. 2011)

- Preliminary calculation of the intrinsic frequency of planetary candidates per star is 5.4% for Earth- size, 6.8% for super-Earth size, 19.3% for Neptune-size candidates, and 2.4% for Jupiter-size -- small planets occur more frequently than large planets.
- Total number of planet candidates per star on short period orbits (< 60 days) is then approximately 0.34 -- at least 34% of solar-type stars have planetary systems.
- A large population of super-Earth-size to Neptune-size candidates exists in the "planet desert" predicted by exoplanet population synthesis models -- evidently these models are in need of serious revision.
- Multi-candidate, transiting systems are frequent: 17% of the host stars have multi-candidate systems, and 33.9% of all the candidates are part of multi-candidate systems -- planetary systems are often co-planar (e.g., Kepler 11bcdefg system).
- Kepler is making excellent progress toward its goals of determining the frequency of Earth-like planets and of characterizing the orbital and size distributions of small planets around solar-like stars -- Kepler will determine η_{Earth} by ~ 2013.