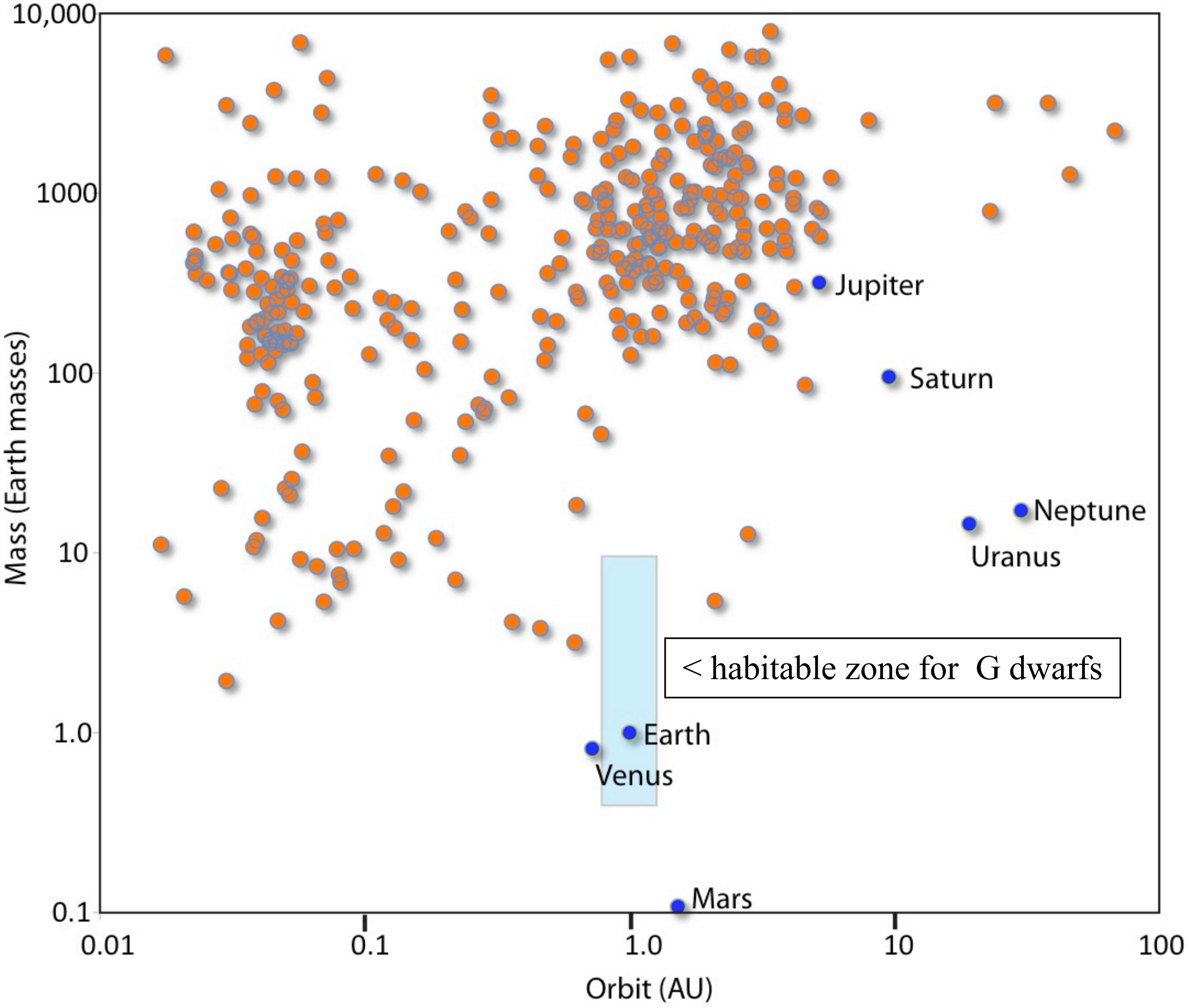
Planet Formation Theories and the Relevance of Microlensing Planets

Alan P. Boss
DTM, Carnegie Institution

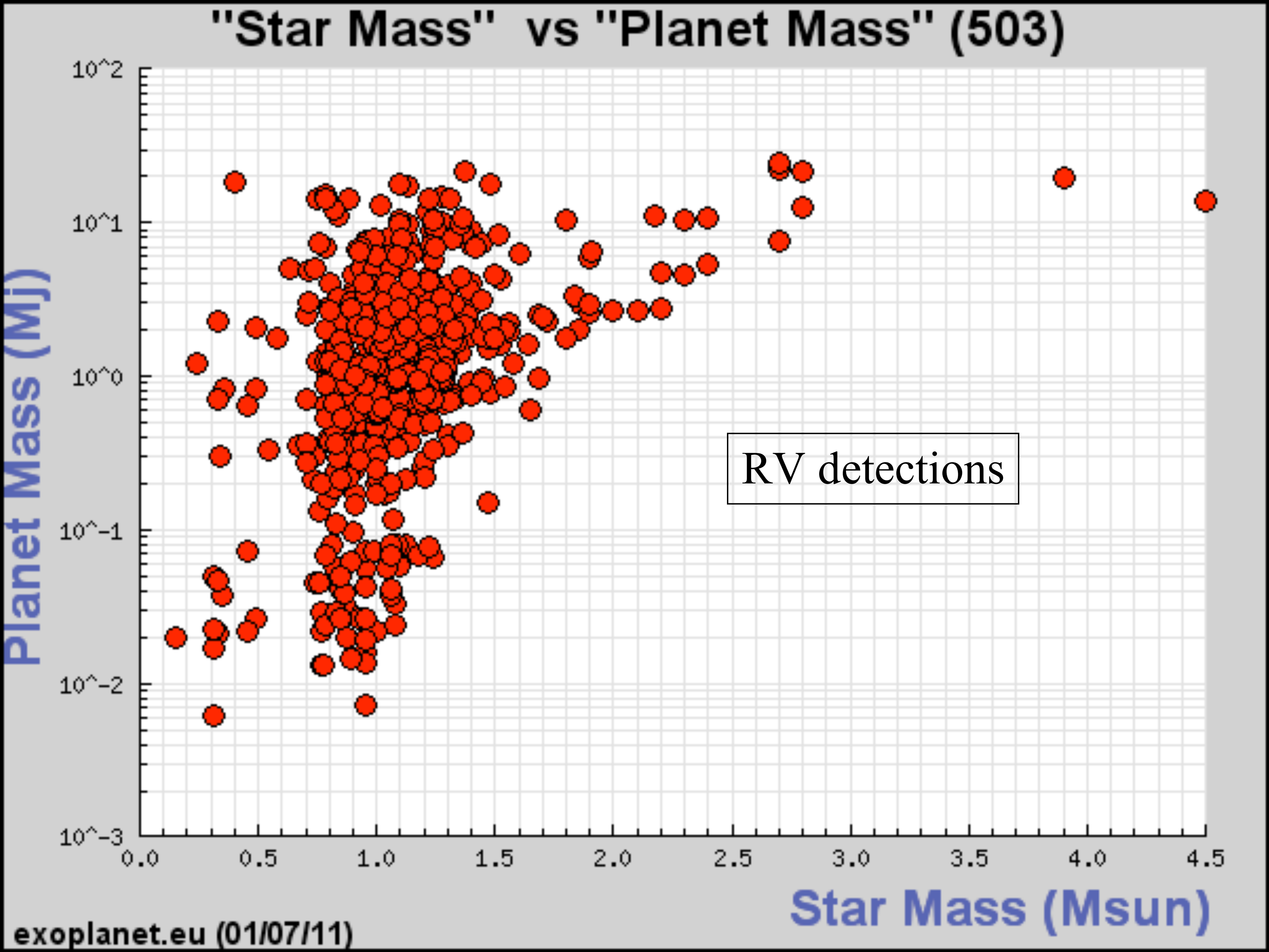
1902

2011 Sagan Exoplanet Summer Workshop
Exploring Exoplanets with Microlensing
Caltech, Pasadena, California
July 25, 2011

Discovery space circa 2010



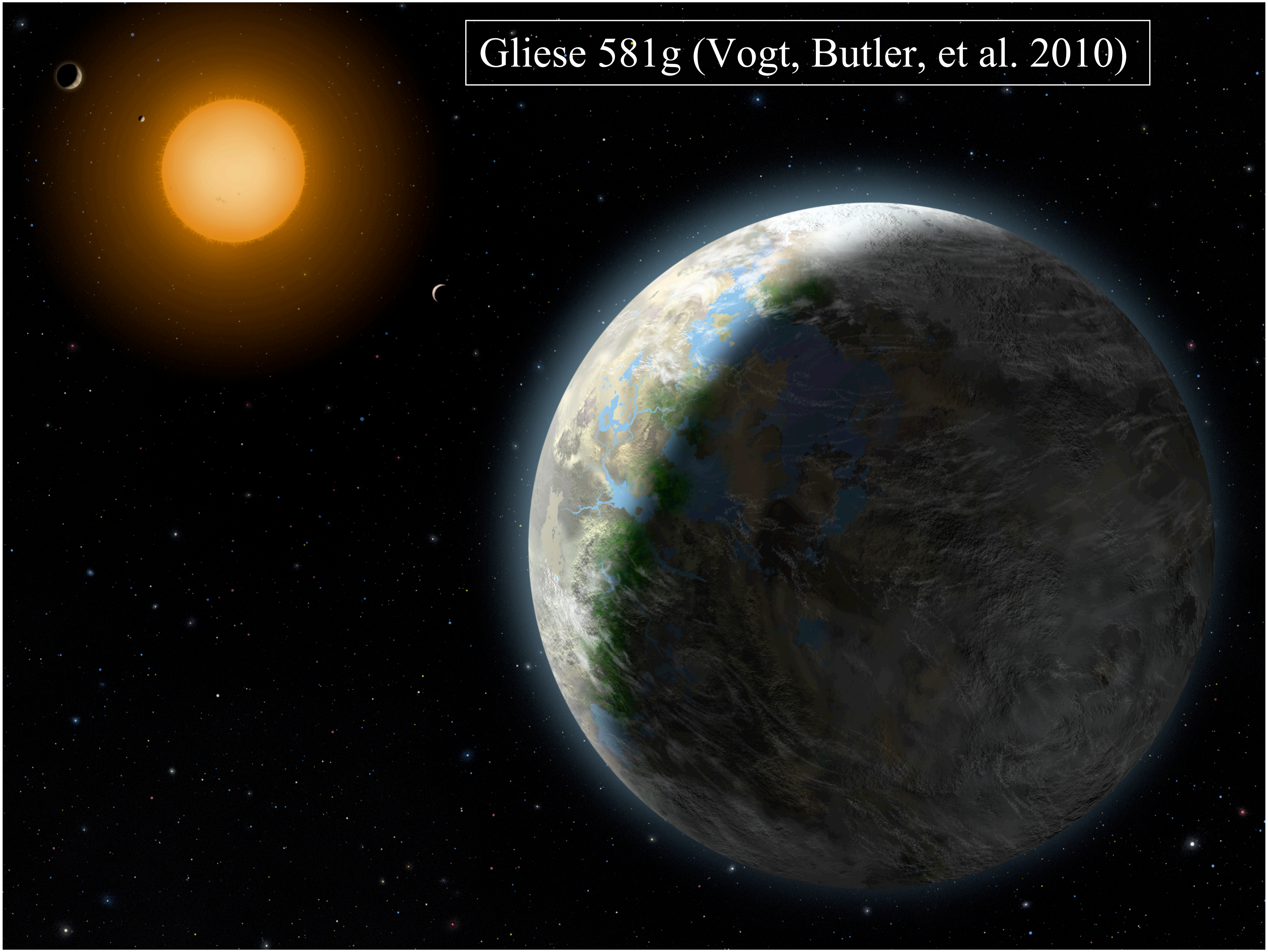
< habitable zone for G dwarfs


"Star Mass" vs "Planet Mass" (503)

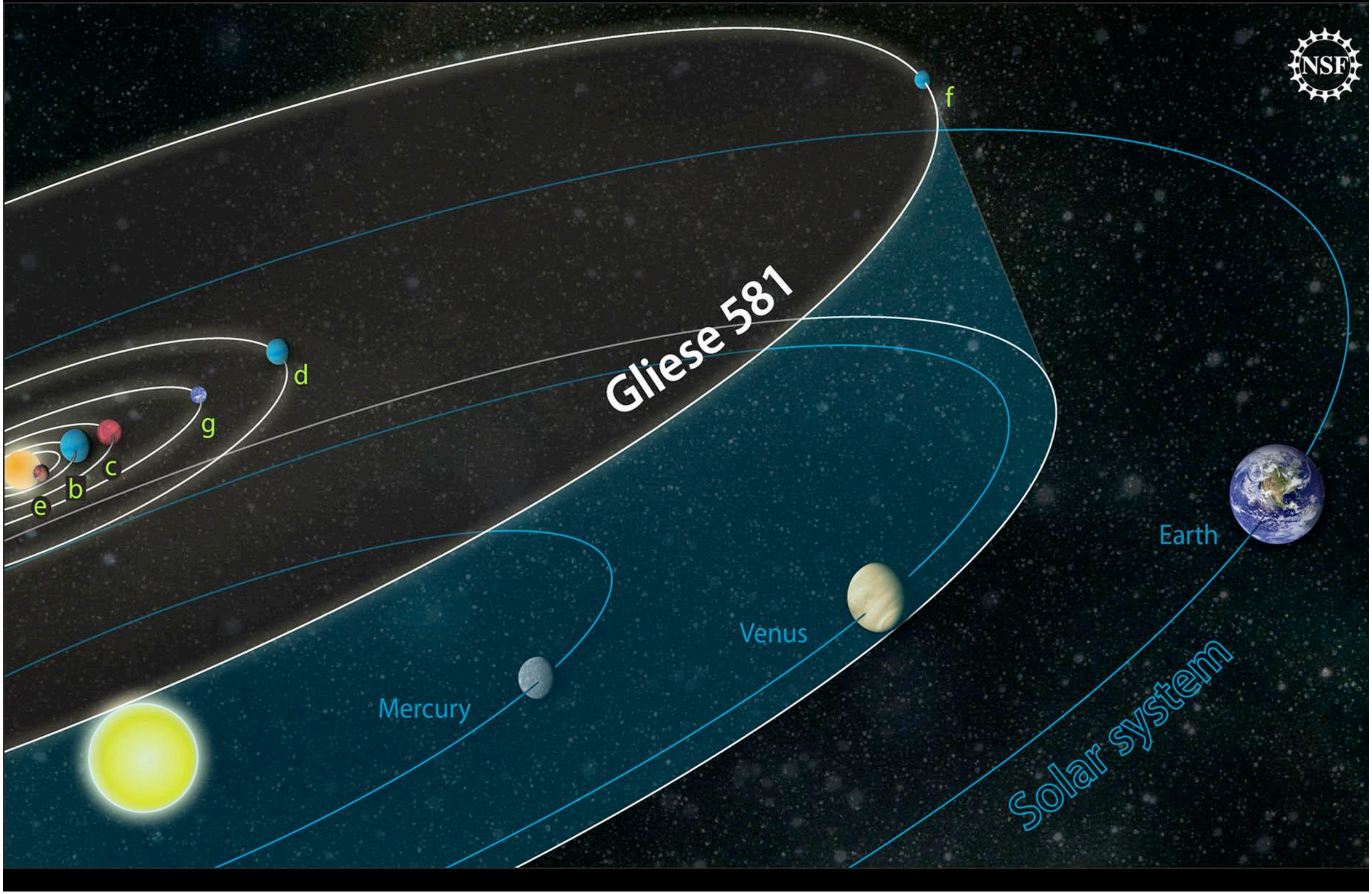
RV detections

exoplanet.eu (01/07/11)

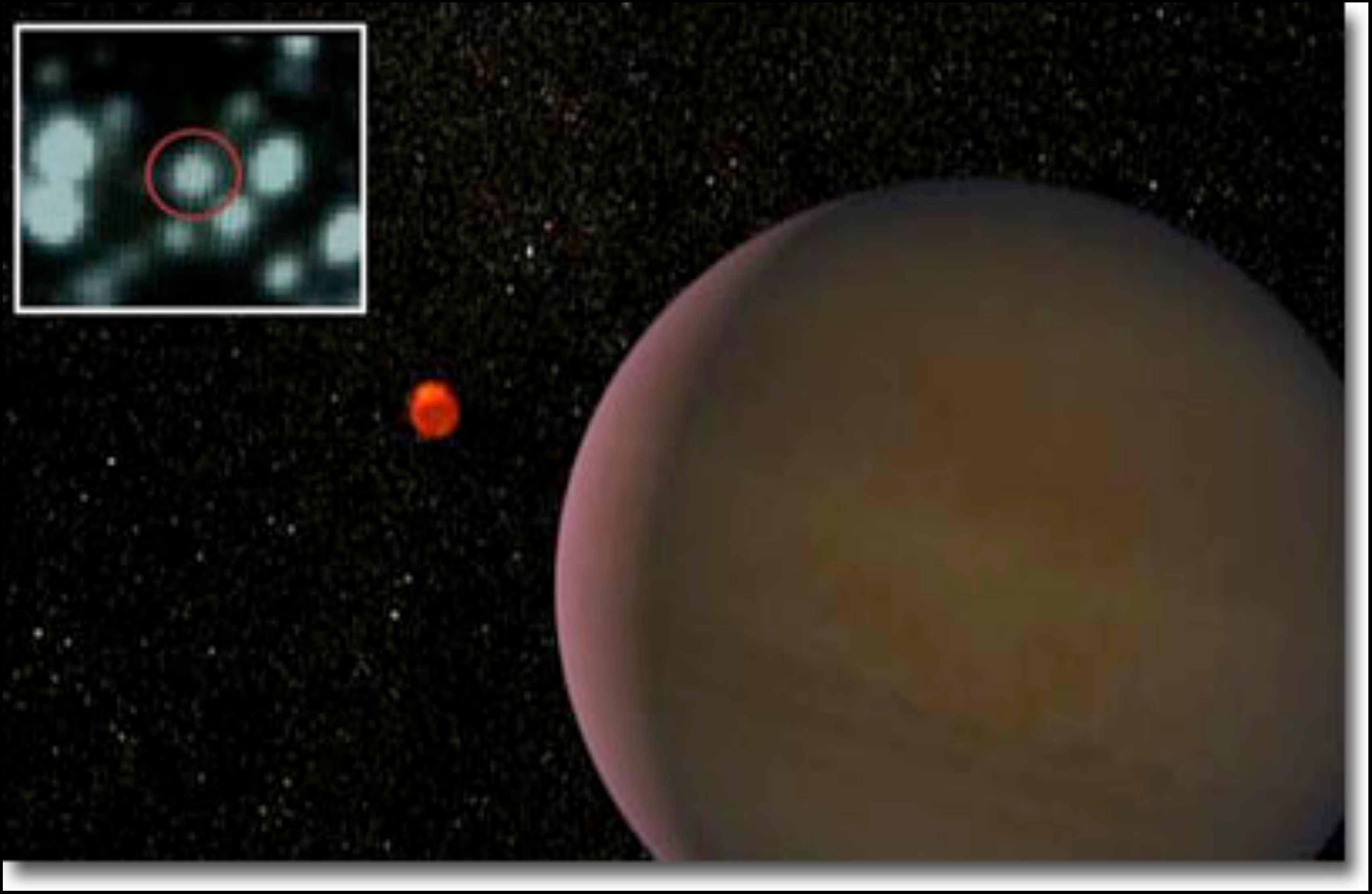
Gliese 581g (Vogt, Butler, et al. 2010)

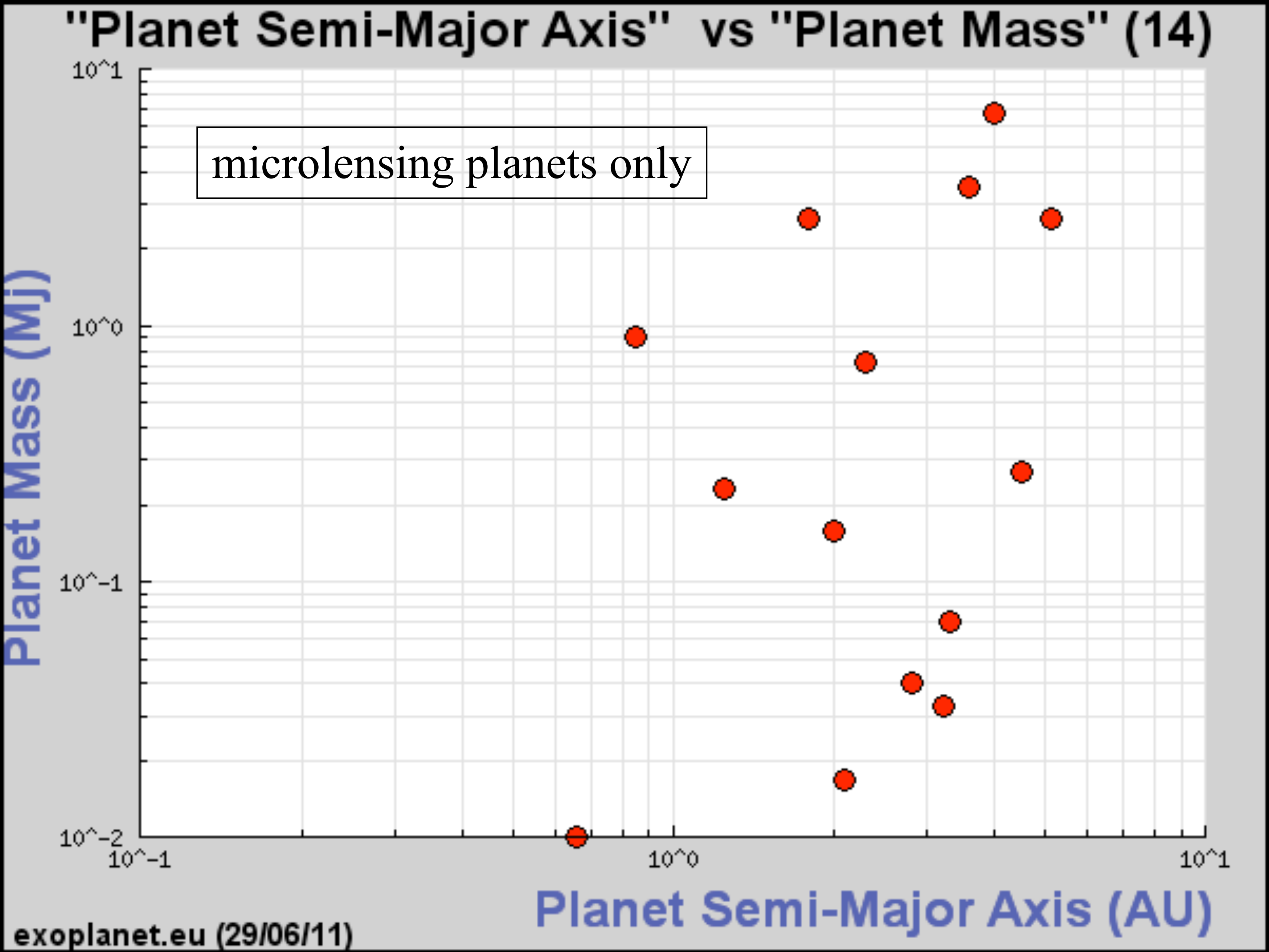


Gliese 581g (Vogt, Butler, et al. 2010)



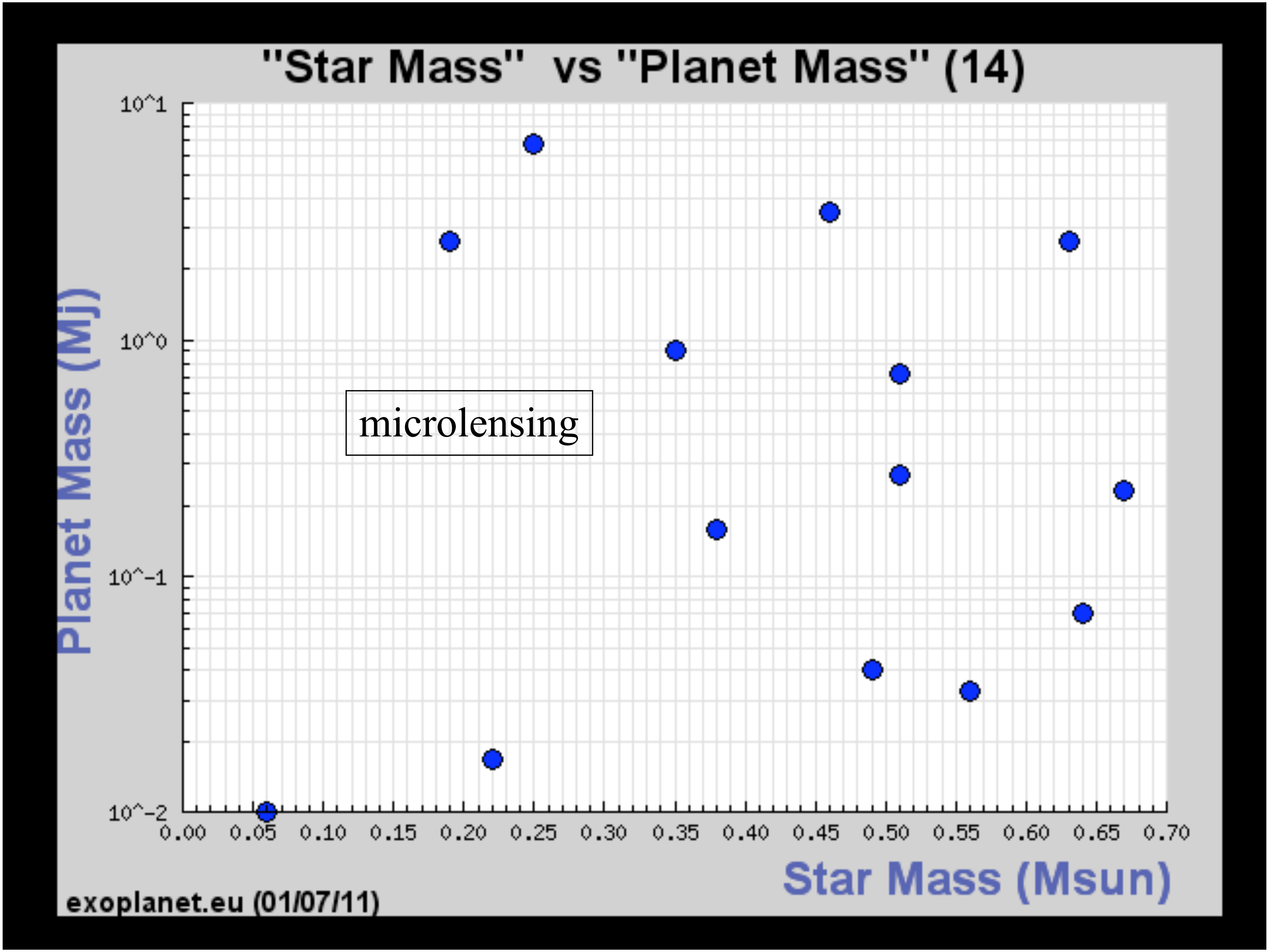
Microlensing detection with Warsaw 1.3m telescope, Las Campanas - 2004





microlensing planets only

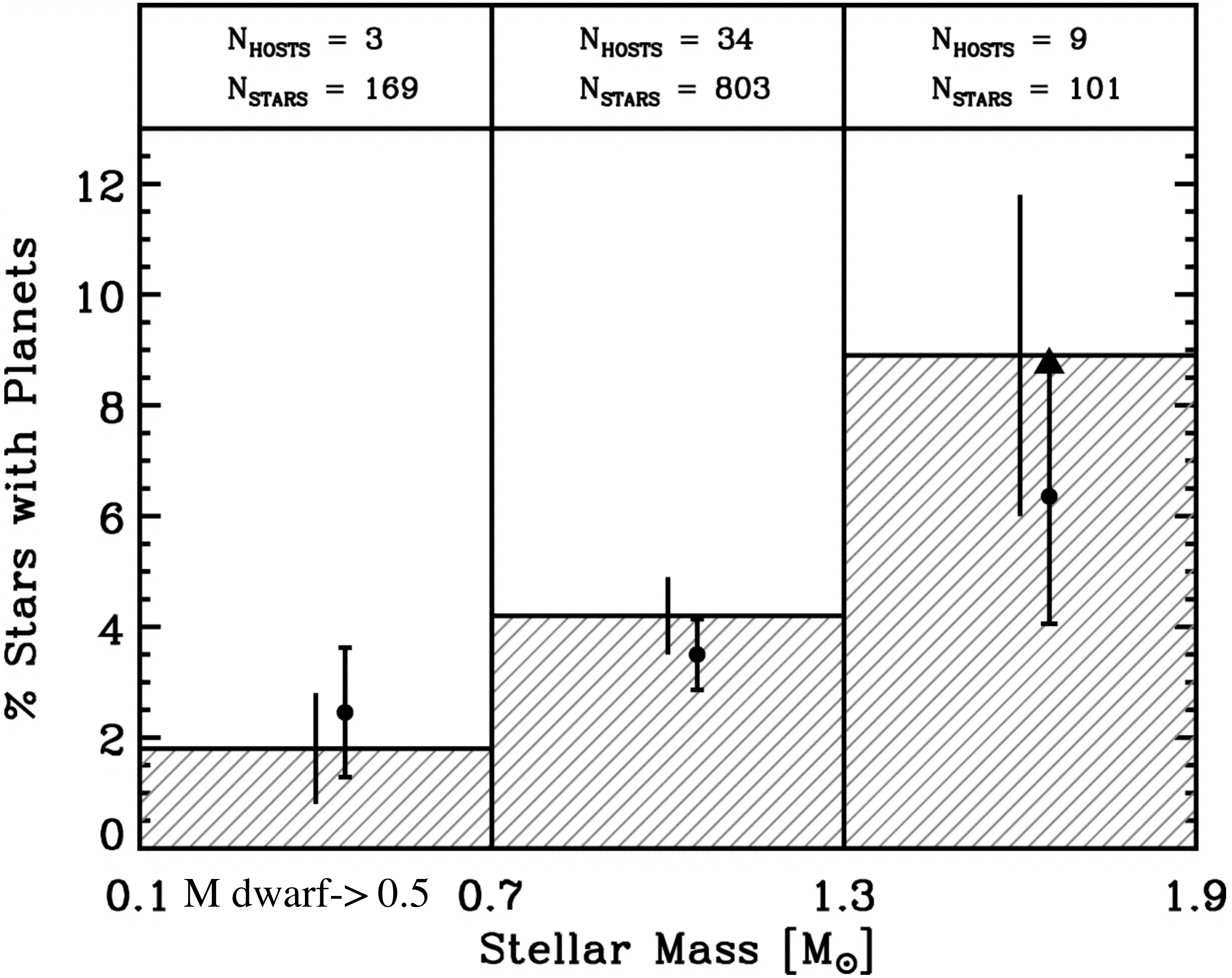
exoplanet.eu (29/06/11)



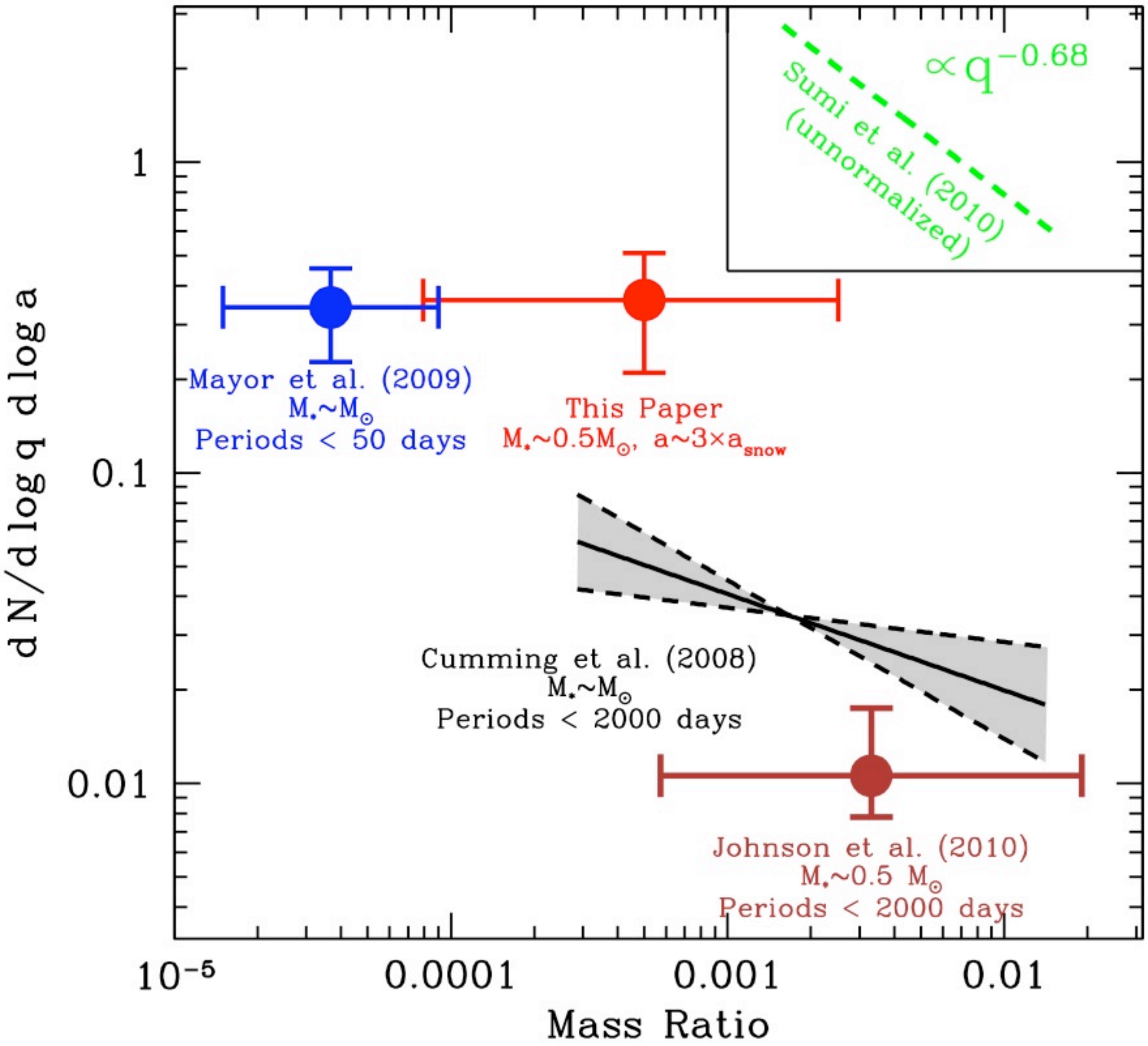
microlensing

exoplanet.eu (01/07/11)

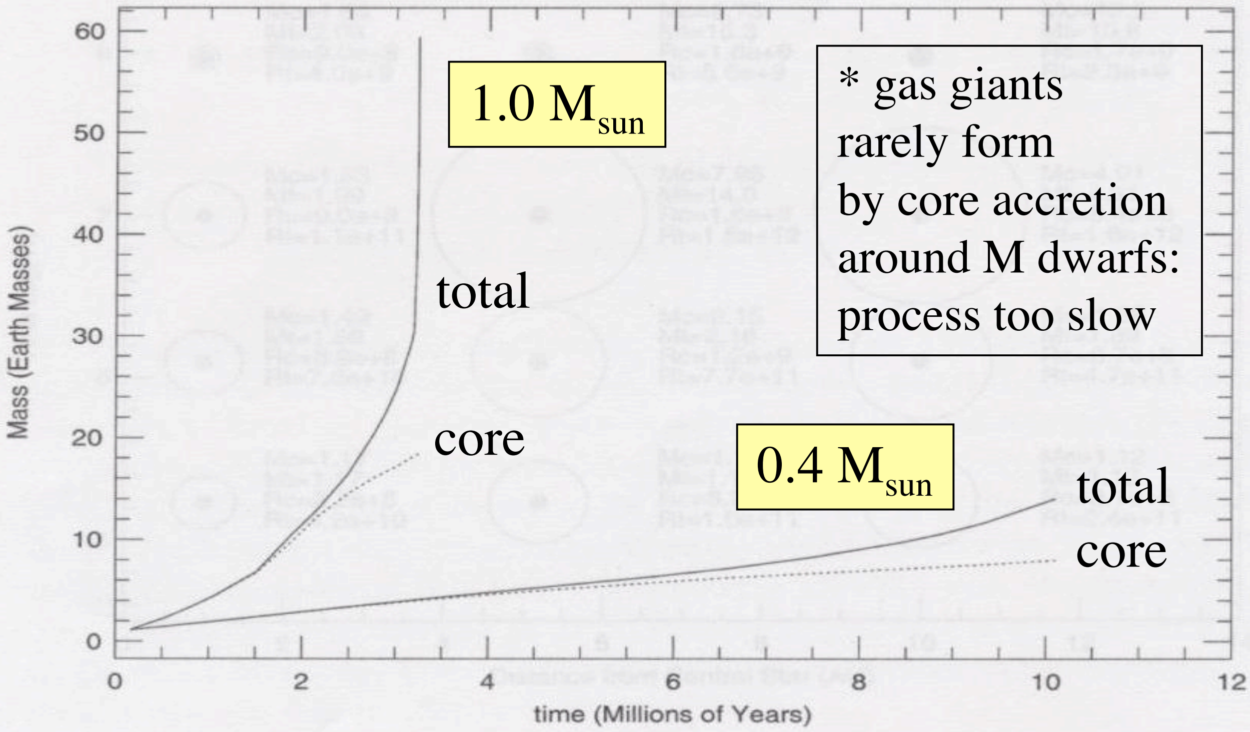
Johnson et al. (2007): Doppler surveys



Gould et al. (2010): gravitational microlensing surveys



Laughlin et al. (2004) core accretion models

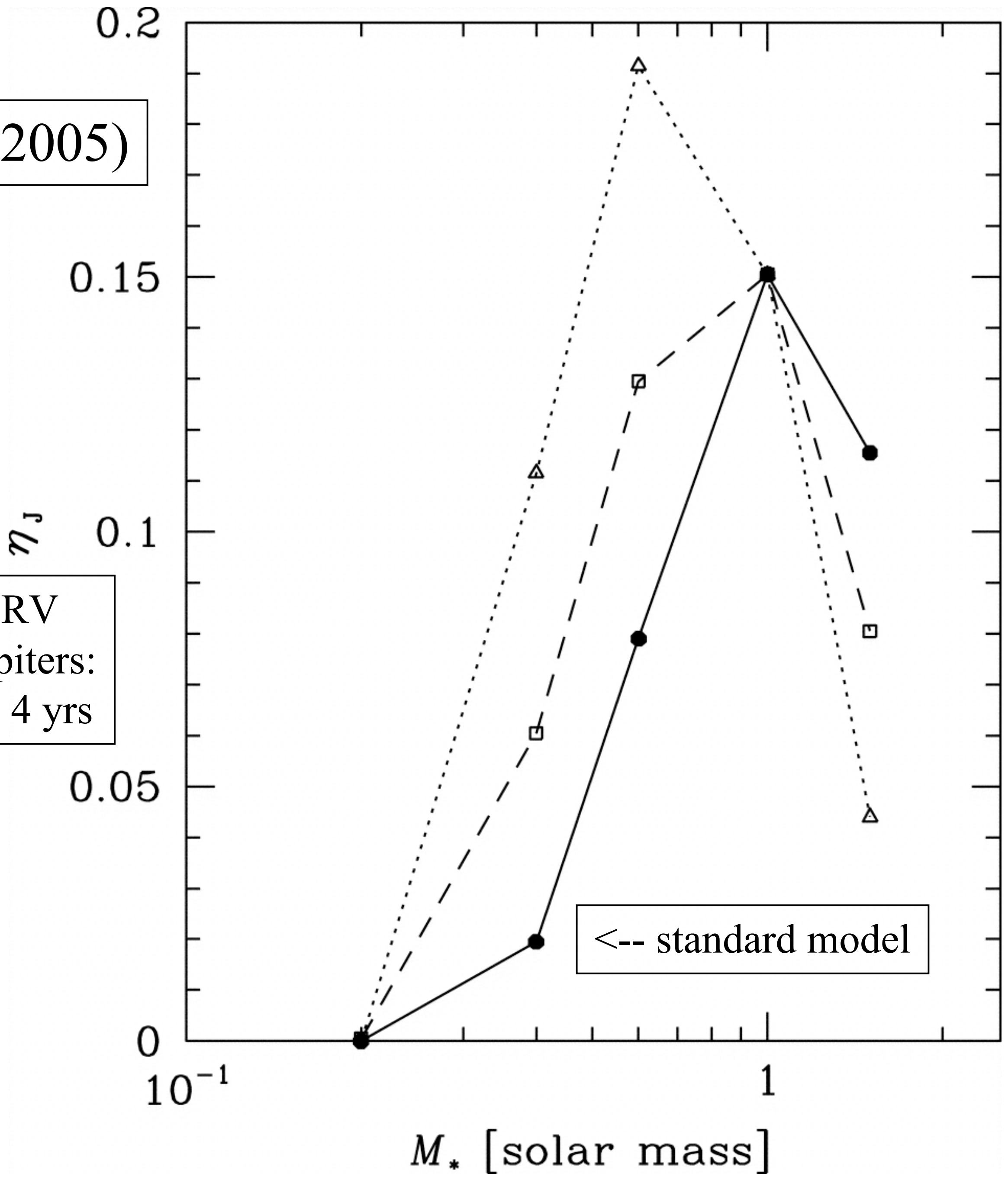


* gas giants rarely form by core accretion around M dwarfs: process too slow

Fig. 1.— Growth of the core and envelopes of planets at 5.2 AU in disks orbiting stars of two different masses. The upper curves show the time-dependent core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk surrounding a $1M_\odot$ star. The lower curves show the time dependence of the core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk around a $0.4M_\odot$ star. After 10 Myr, the disk masses become extremely low, which effectively halts further planetary growth. The planet orbiting the M star gains its mass more slowly and stops its growth at a relatively low mass $M \approx 14M_\oplus$.

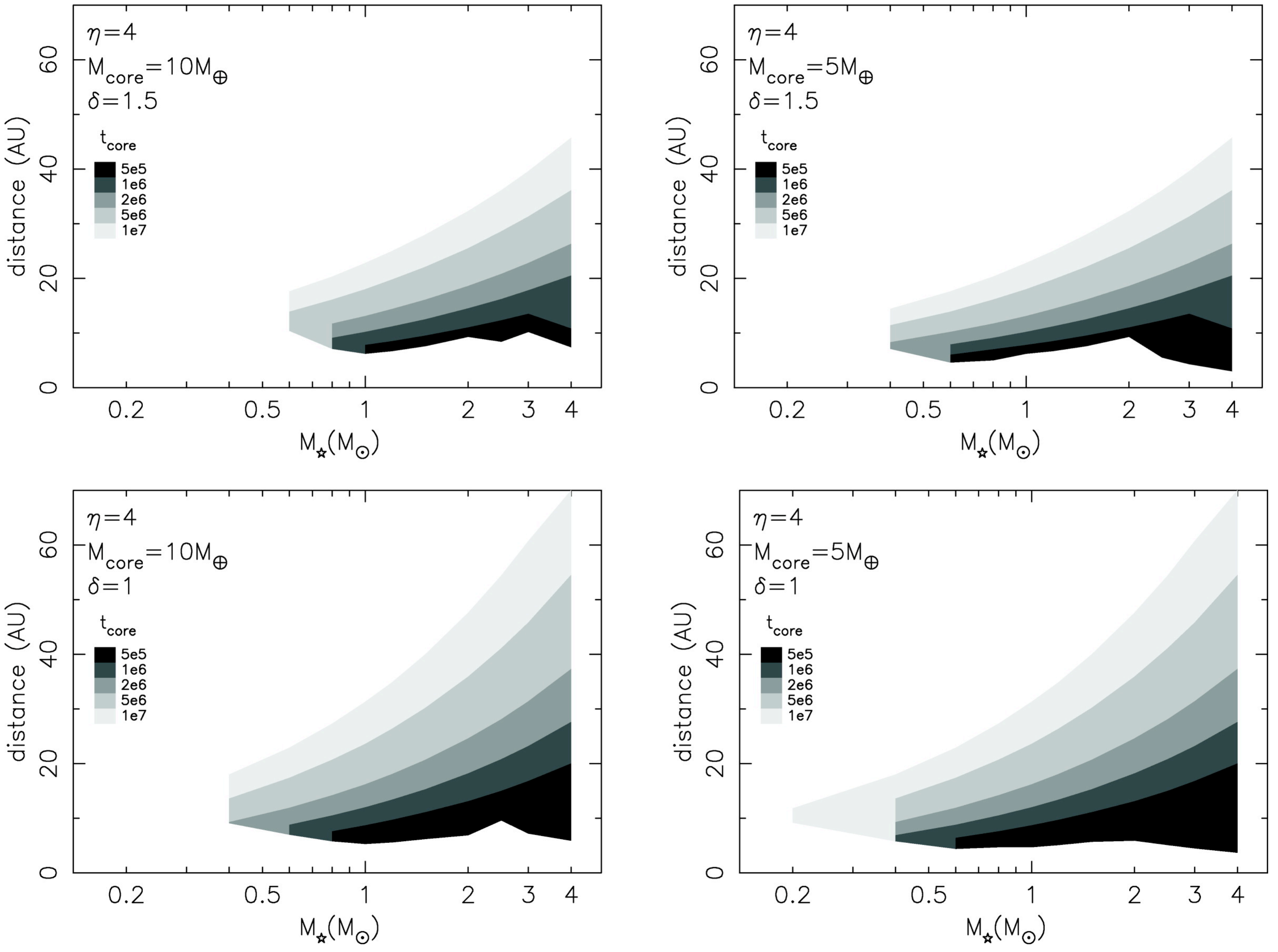
Ida & Lin (2005)

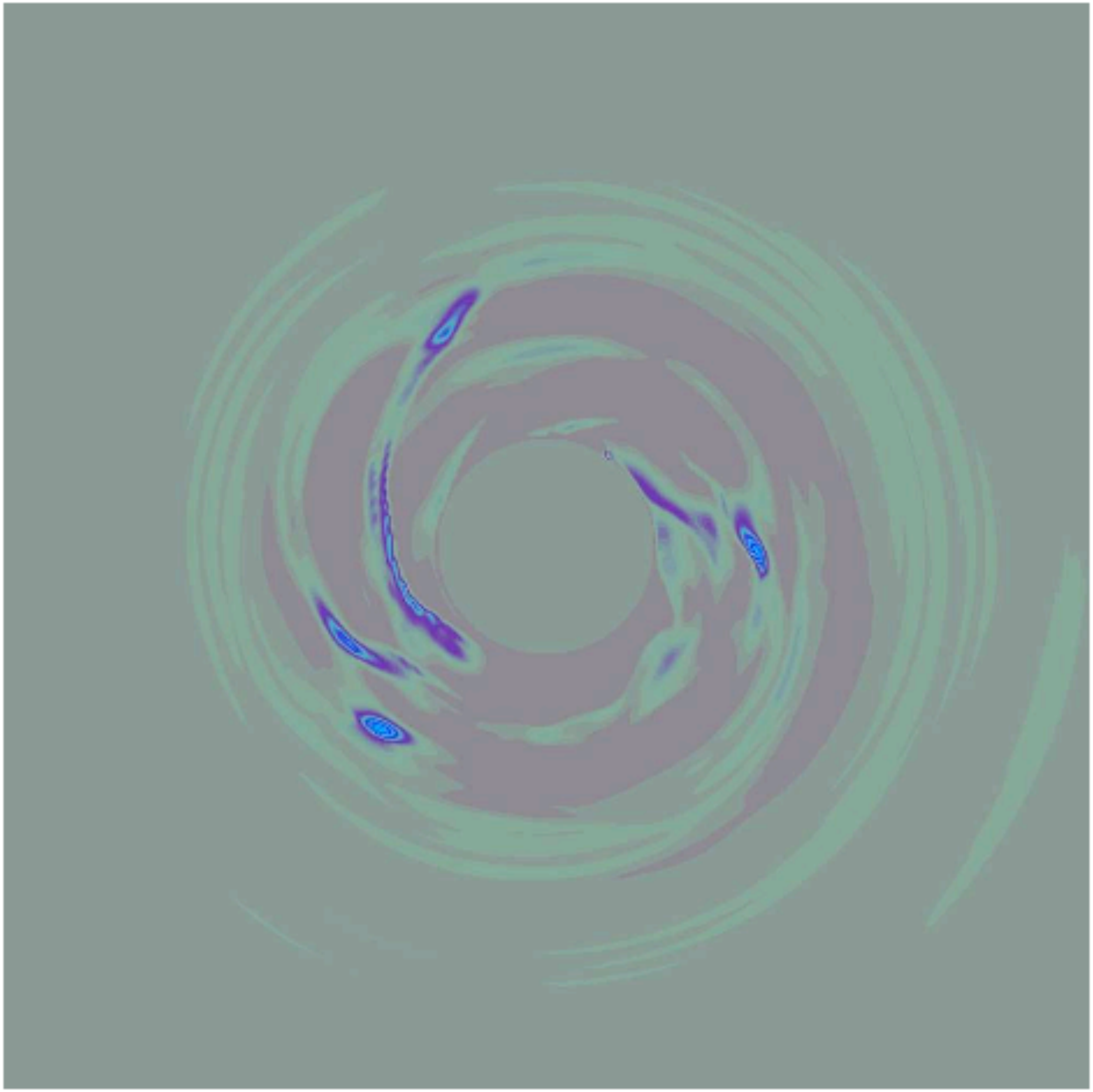
fraction with RV detectable Jupiters: > 10 m/s, P < 4 yrs



<-- standard model

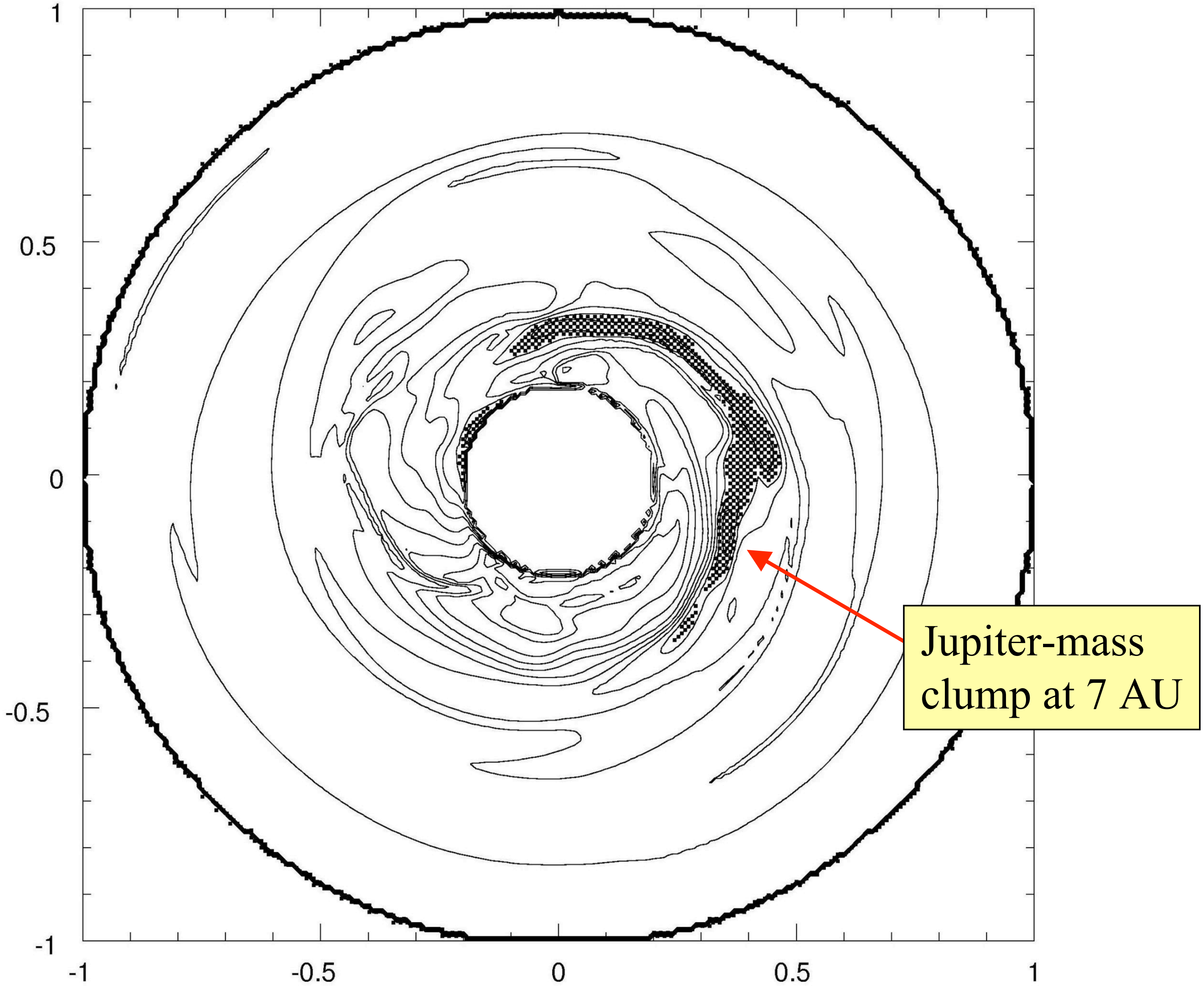
Kennedy & Kenyon (2008): varied disk surface density, mass, & lifetime





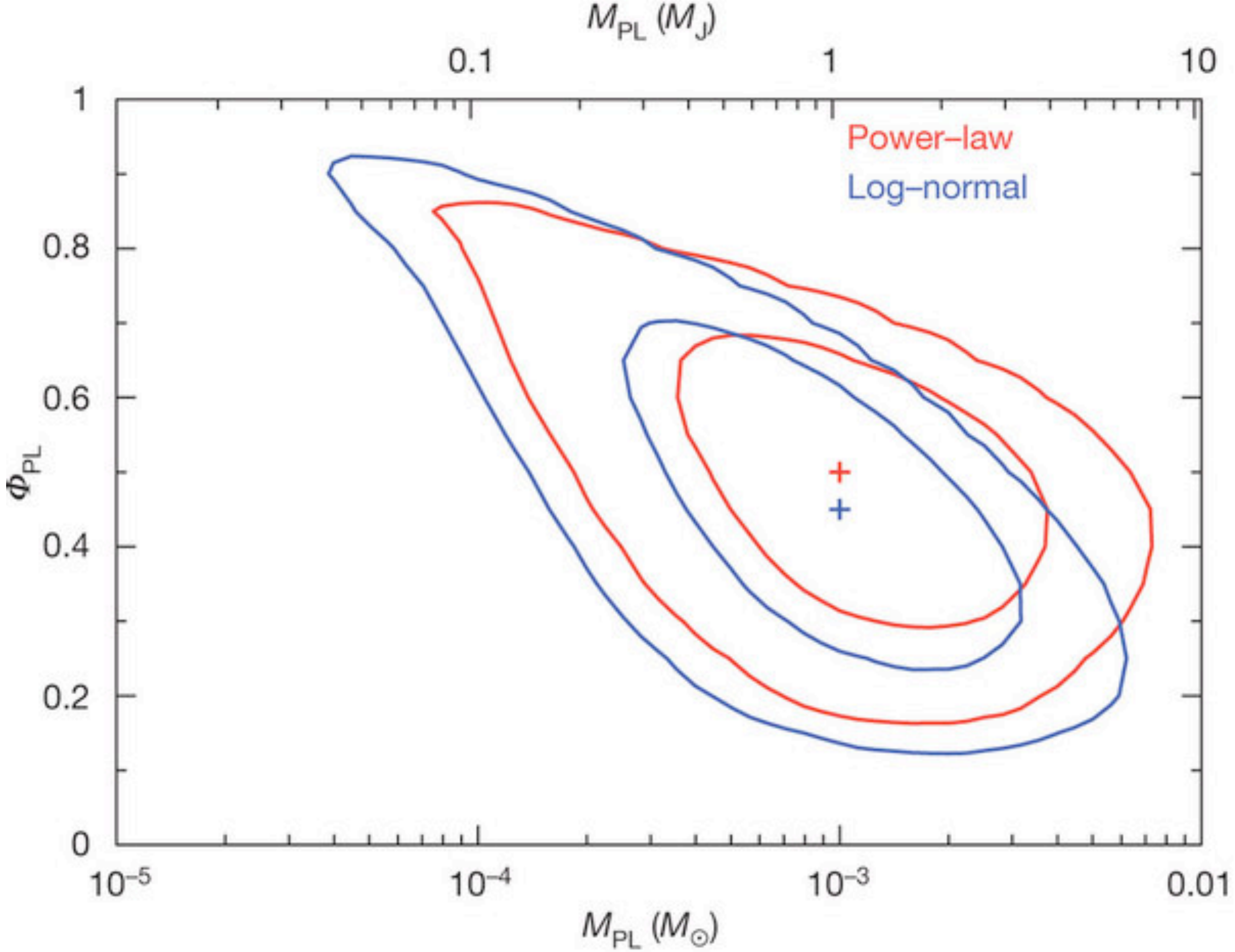
0.5 solar
mass star
with a 20
AU radius
disk after
215 yrs
(Boss 2006)

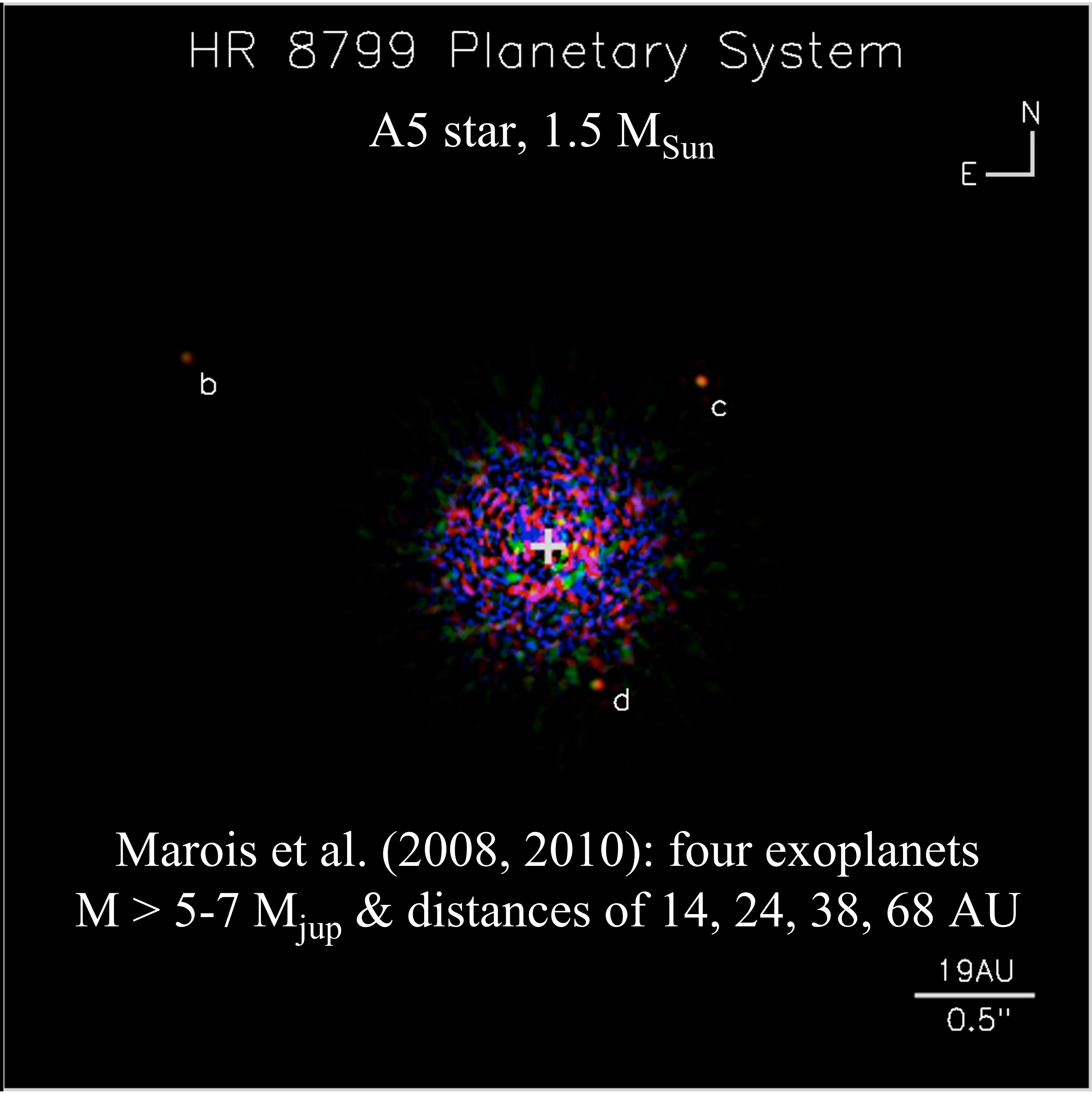
Clump formation by disk instability after 445 yrs in a 0.02 M_{sun} disk orbiting a 0.1 M_{sun} star (Boss 2006).



Jupiter-mass clump at 7 AU

Sumi et al. (2011): Jupiters beyond 10 AU ~1.8 as frequent as inside 10 AU



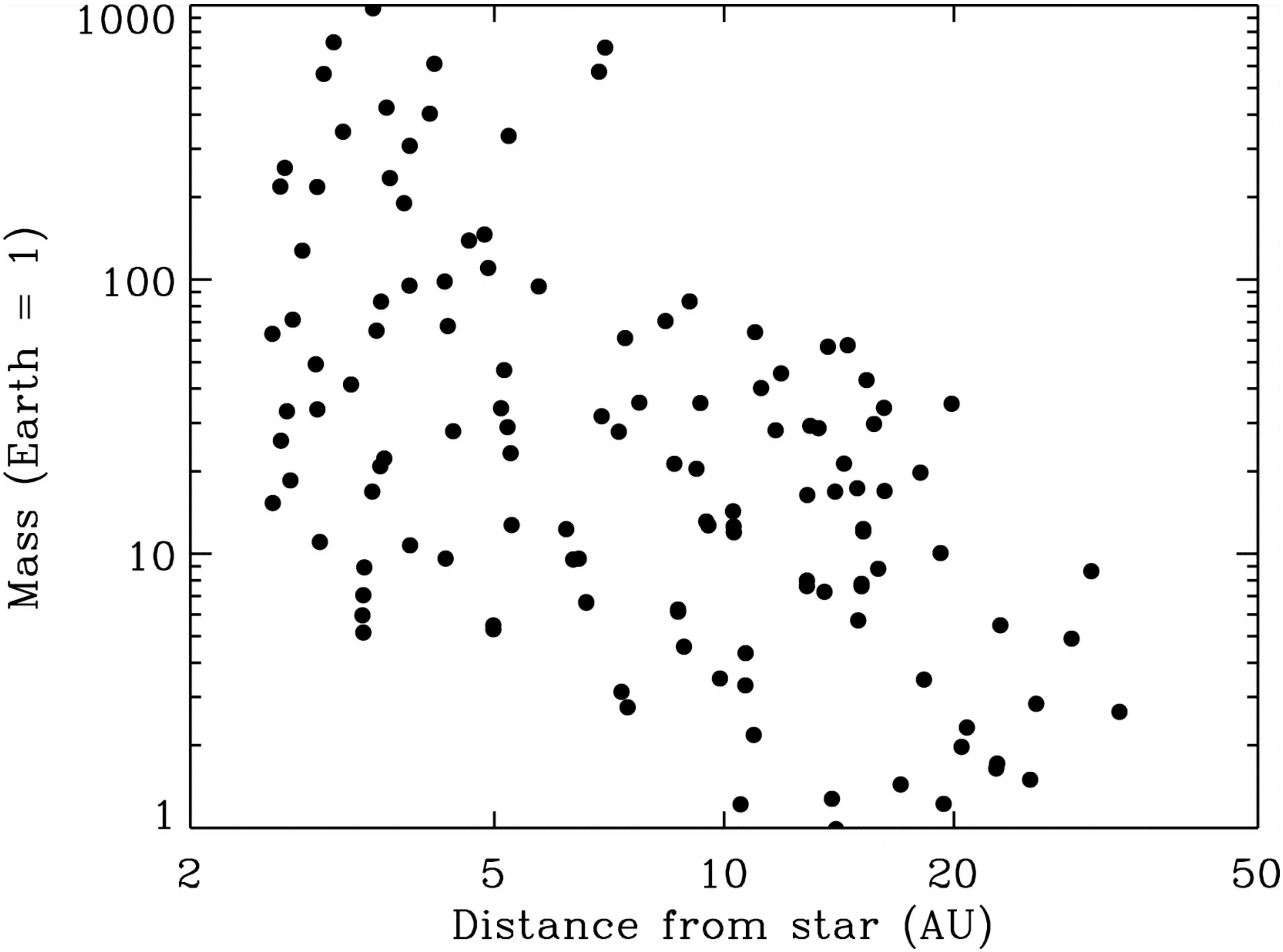


A5 star, 1.5 M_{Sun}

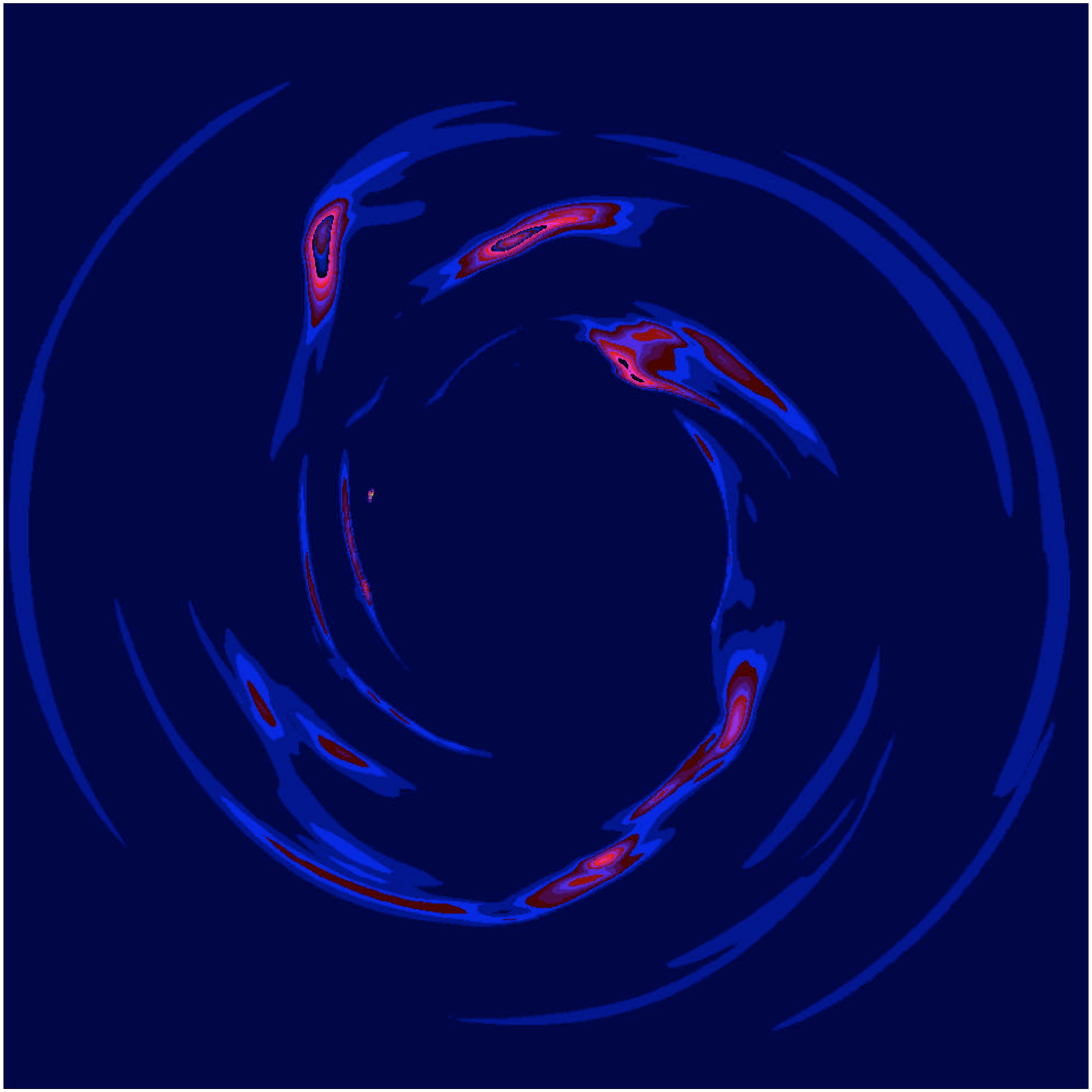
Marois et al. (2008, 2010): four exoplanets

M > 5-7 M_{jup} & distances of 14, 24, 38, 68 AU

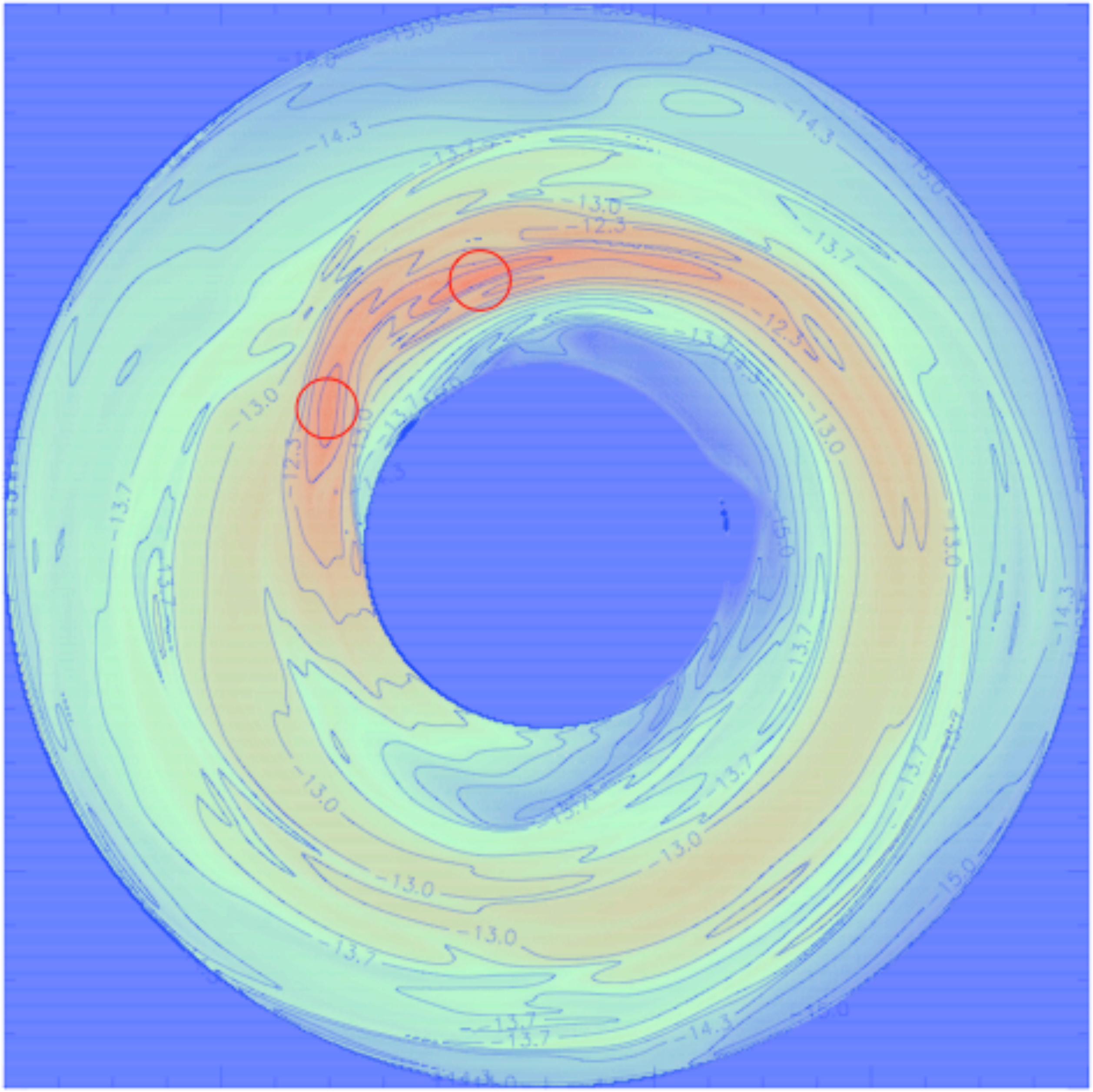
Chambers 2006



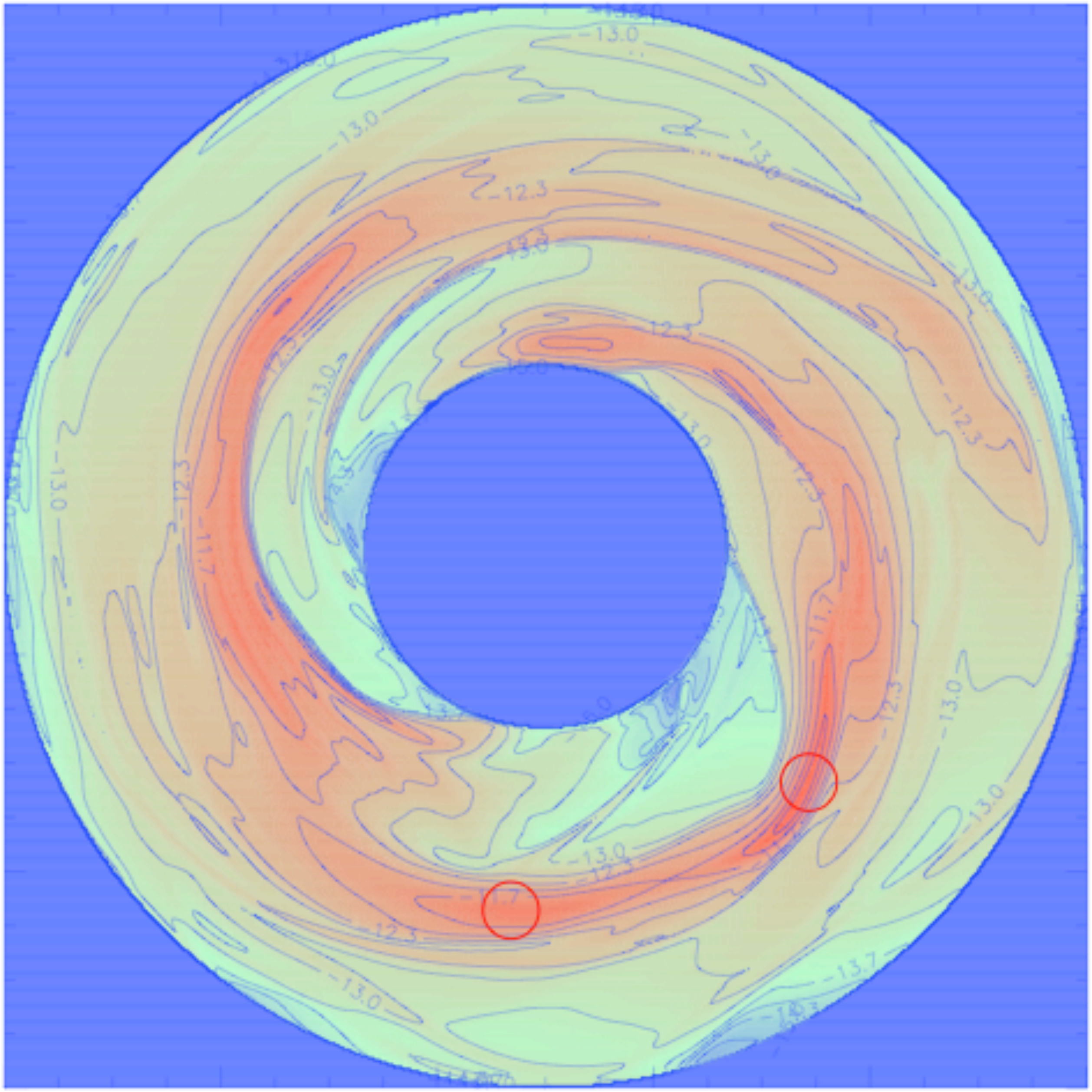
Boss (2003) - 30 AU radius disk around a 1M_{sun} protostar



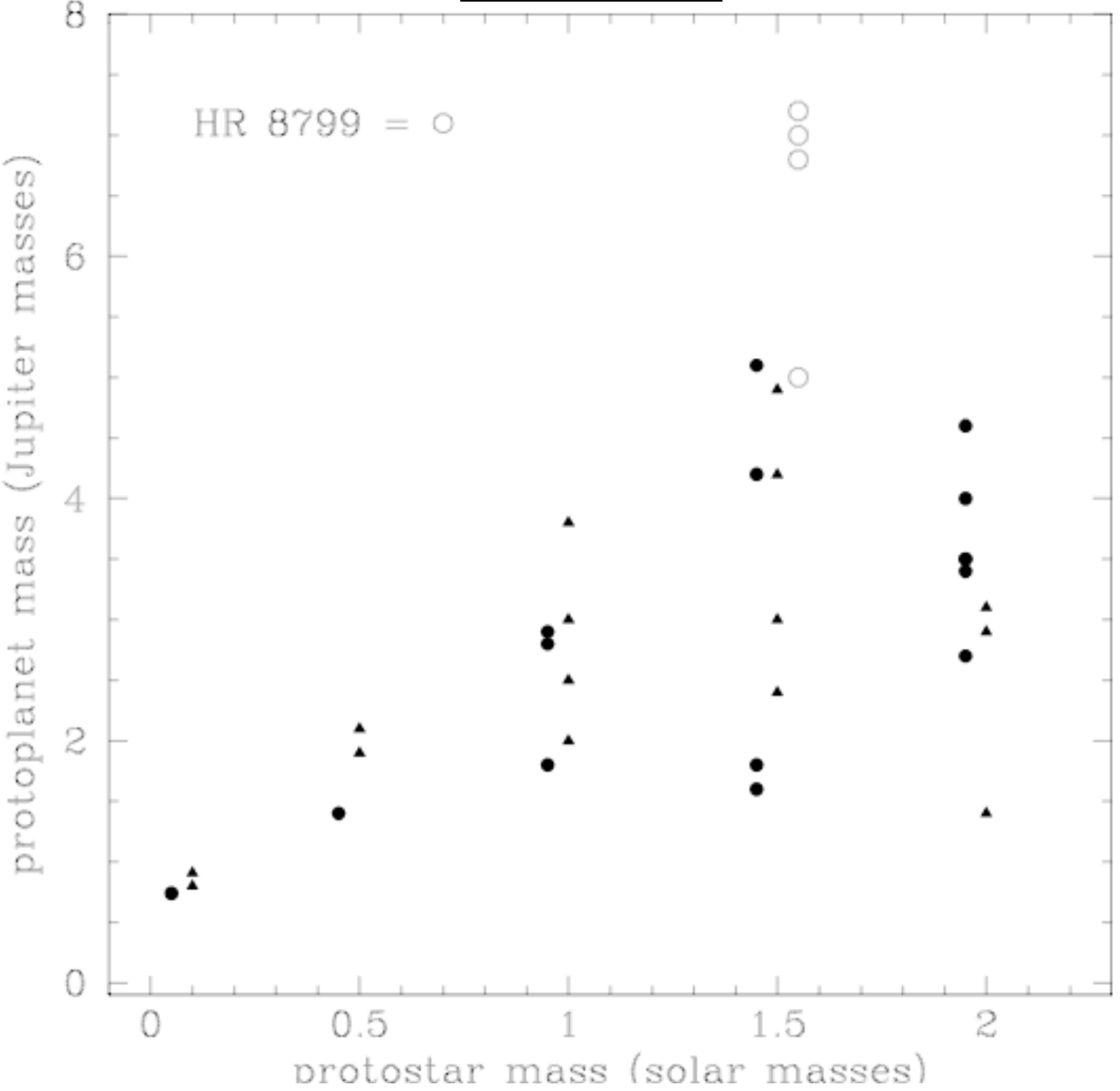
Boss (2011): 0.1 solar mass star, 60 AU radius disk



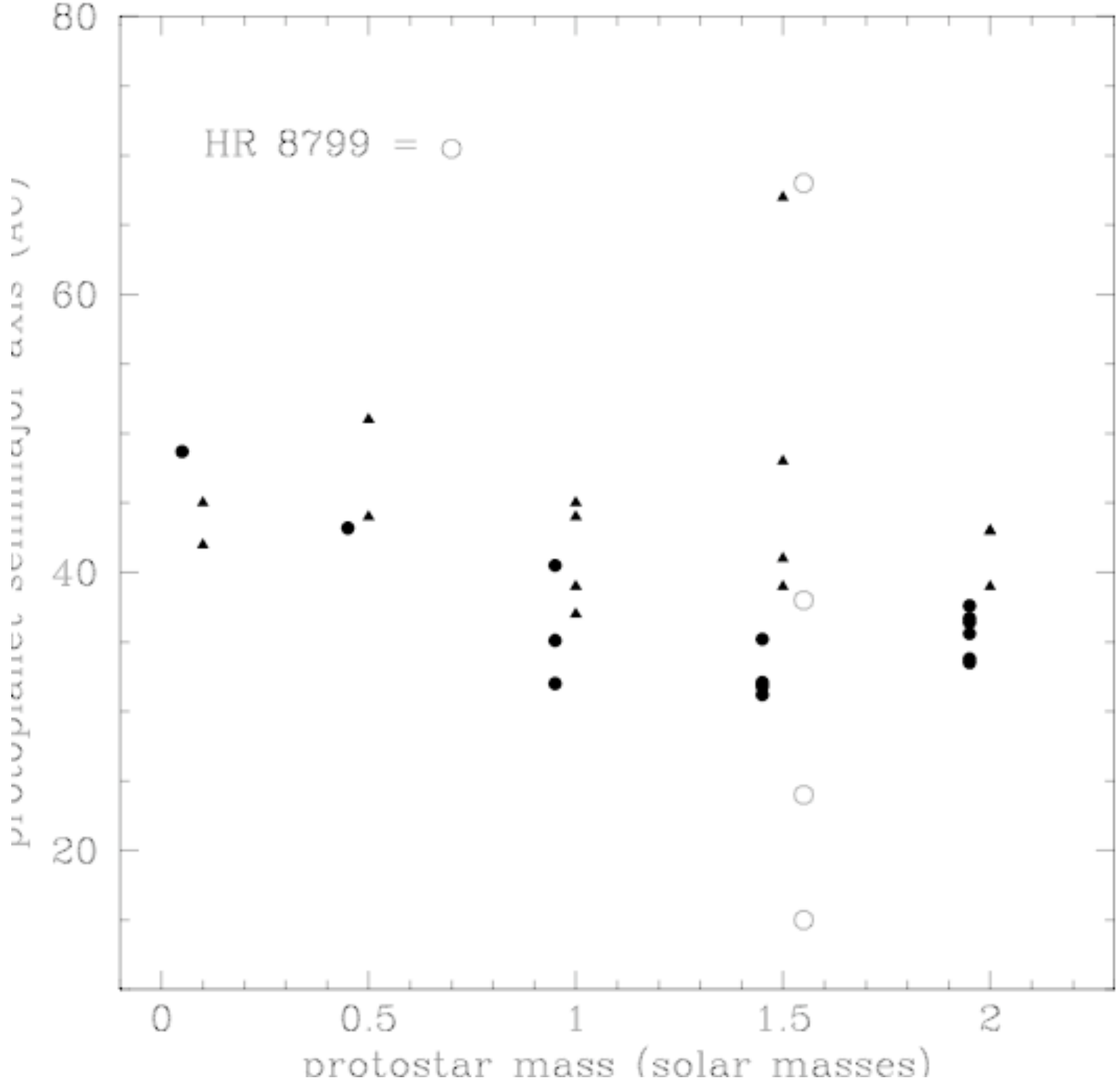
Boss (2011): 0.5 solar mass star, 60 AU radius disk



Boss (2011)

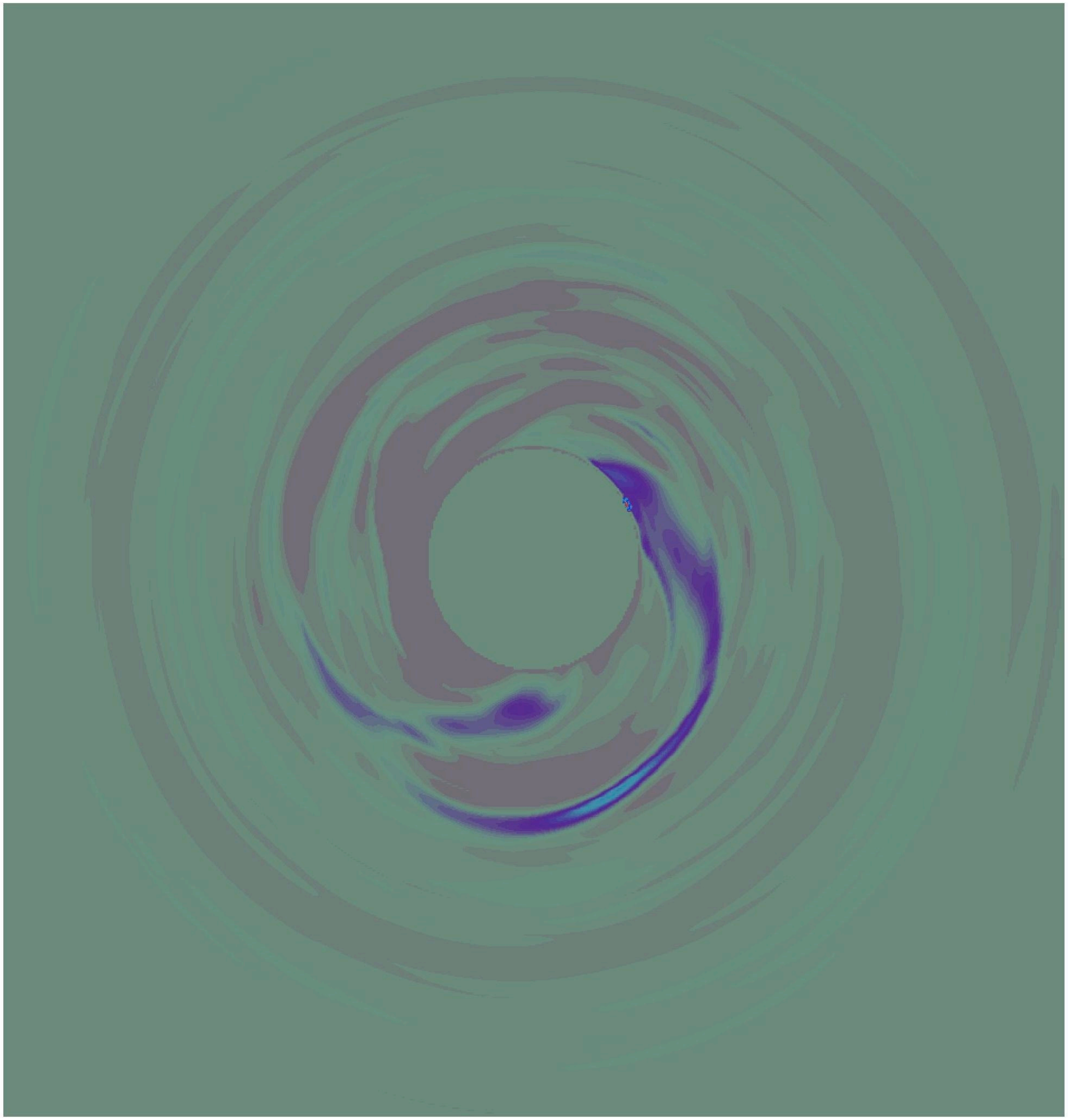

HR 8799 = ○
protoplanet mass (Jupiter masses)
protostar mass (solar masses)
0
2
4
6
8
0
0.5
1
1.5
2

Boss (2011)



a (AU)

Boss (2006)
20 AU
radius
disk

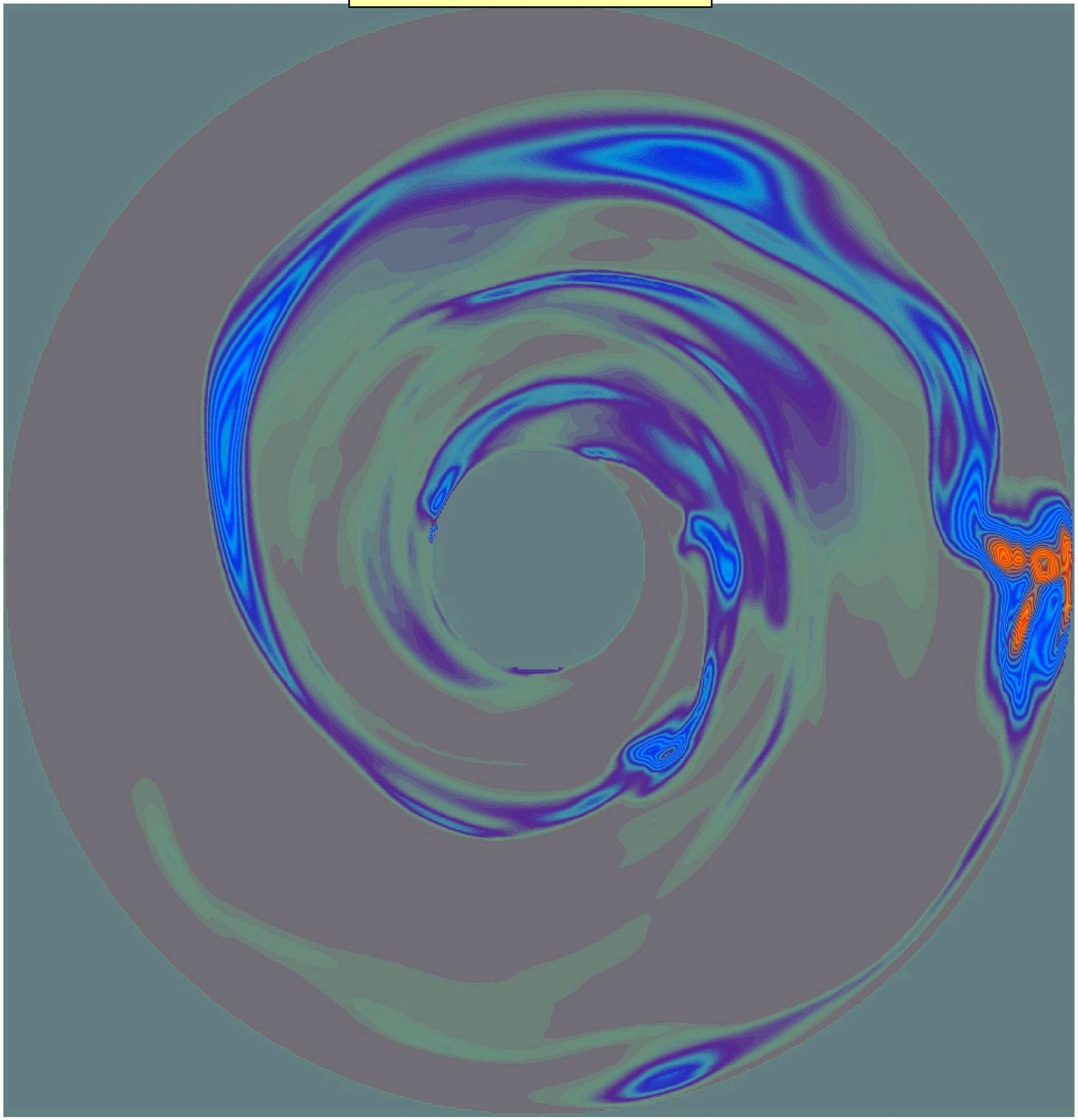


no binary
245 years

Boss (2006)
20 AU
radius
disk

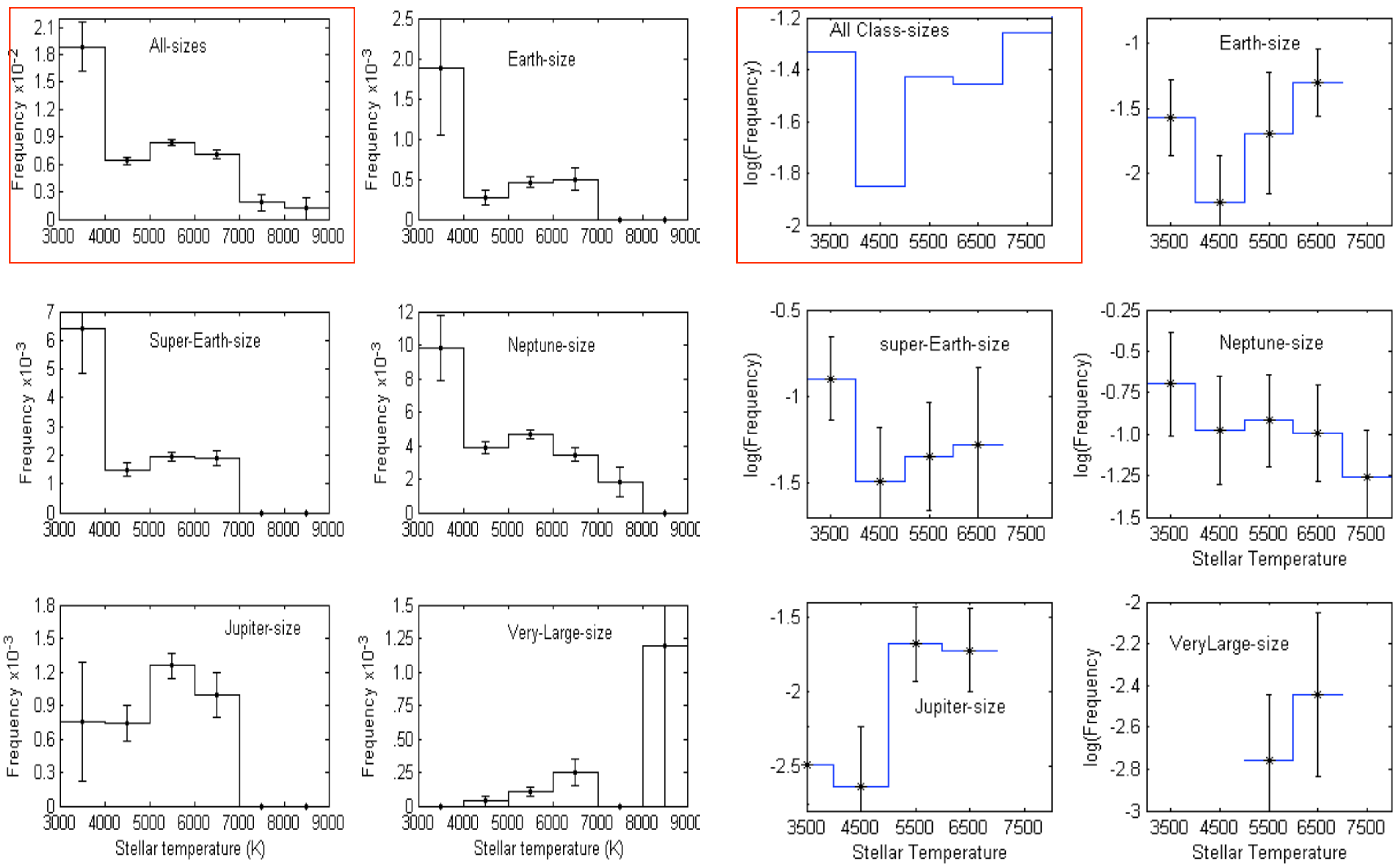
after one
binary
rotation
period:
239 years

$M_s = 1\ M_{sun}$
$M_d = 0.09\ M_{sun}$
$a = 50$ AU
$e = 0.5$



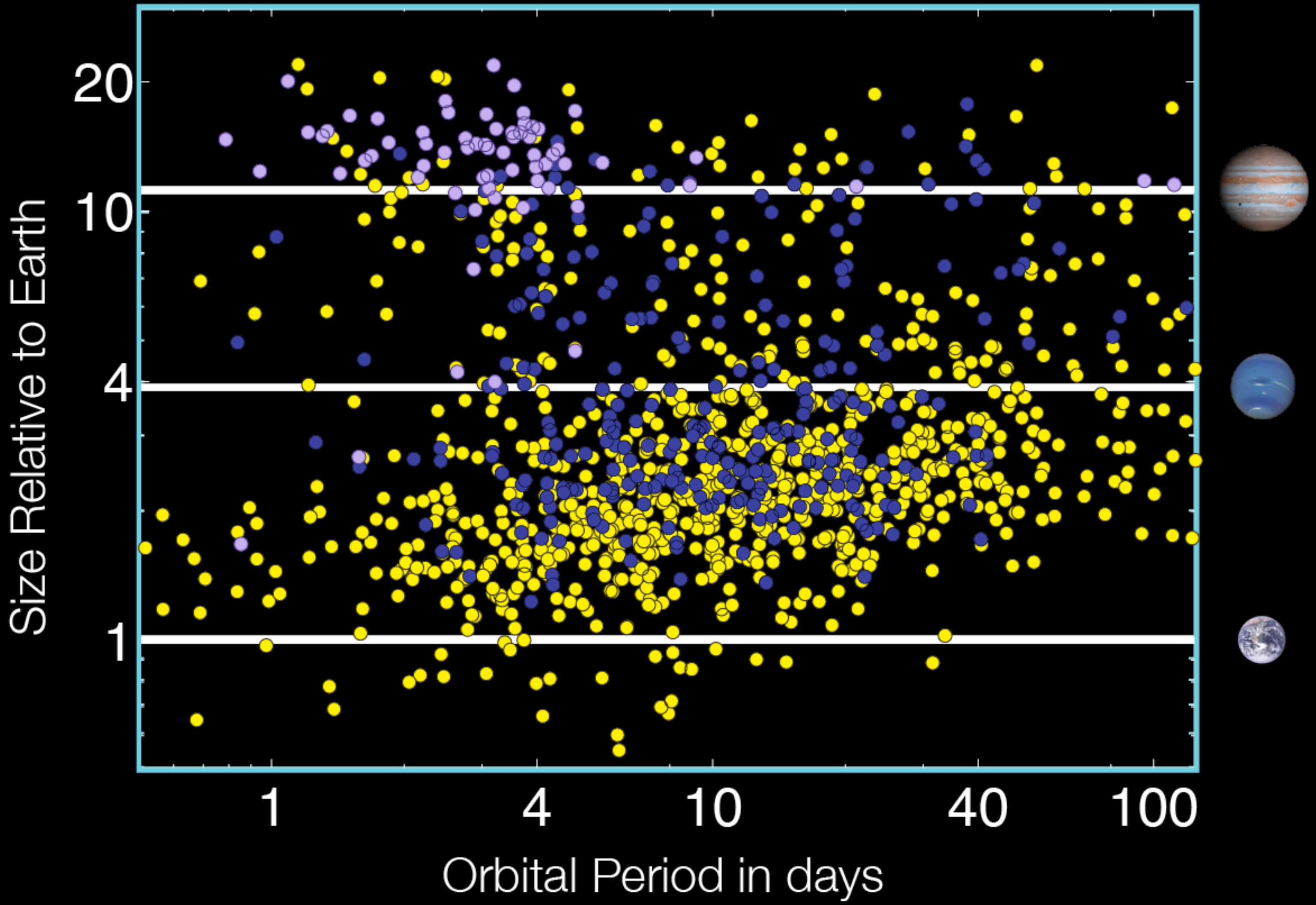
to binary ^ at apastron

Kepler: MEASURED [L] VS. INTRINSIC [R] DISTRIBUTIONS

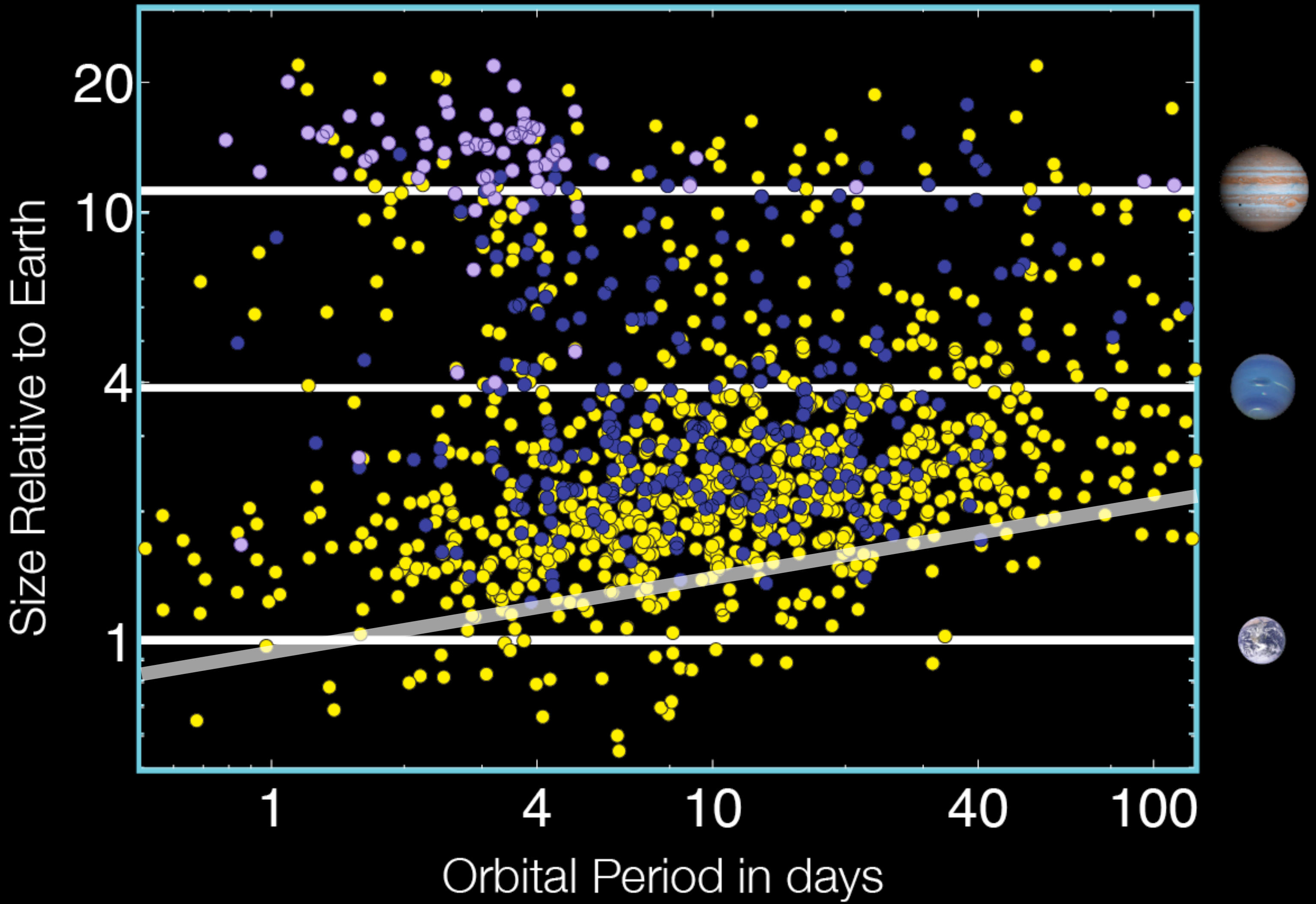


Correction for selection effects reduces the prominence of the coolest stars, resulting in a drop in frequency for K dwarfs and an enhanced frequency of Jupiter-size candidates in orbit around the hotter and more massive stars

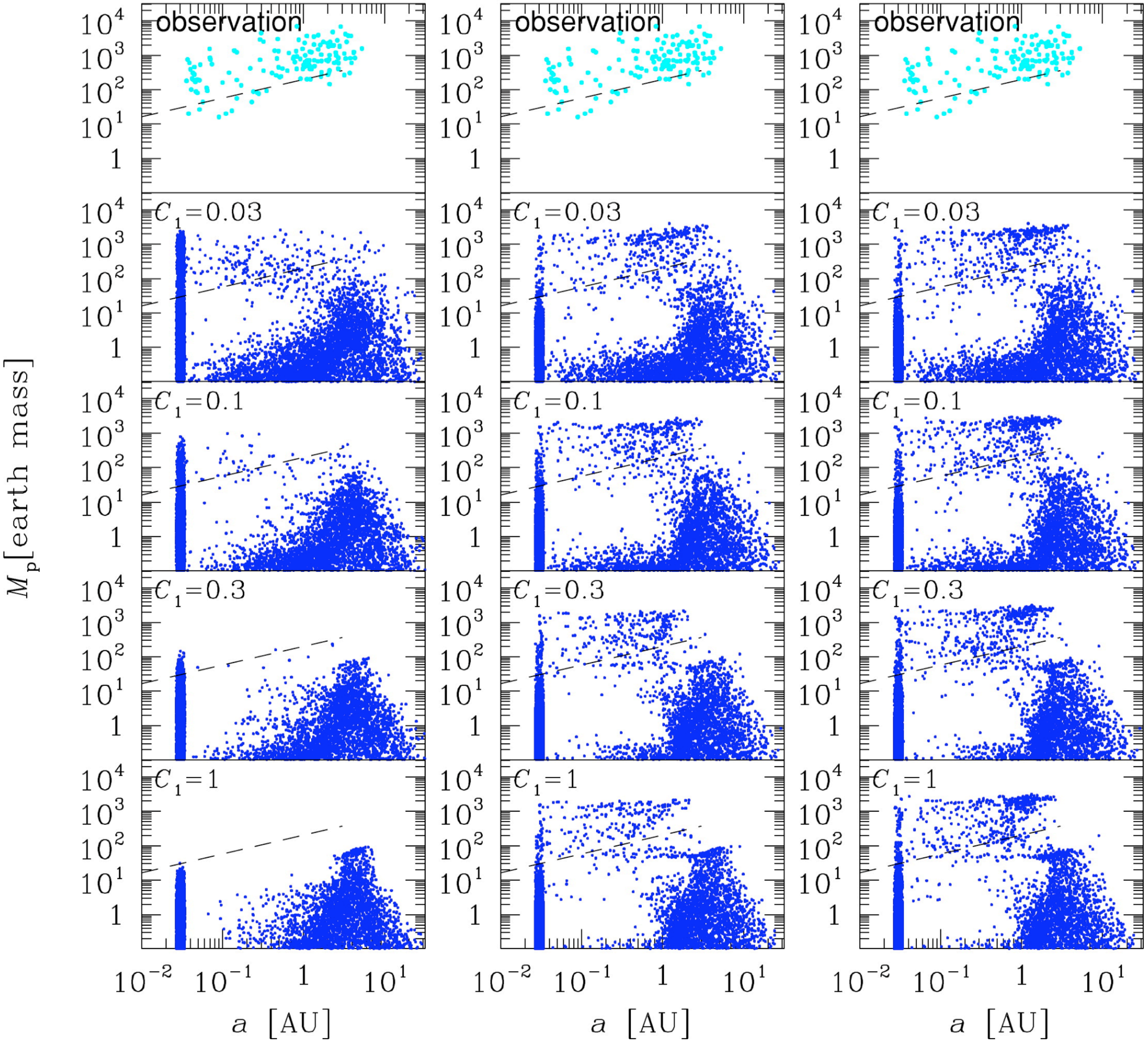
Kepler Candidates as of February 1, 2011



Kepler Candidates as of February 1, 2011

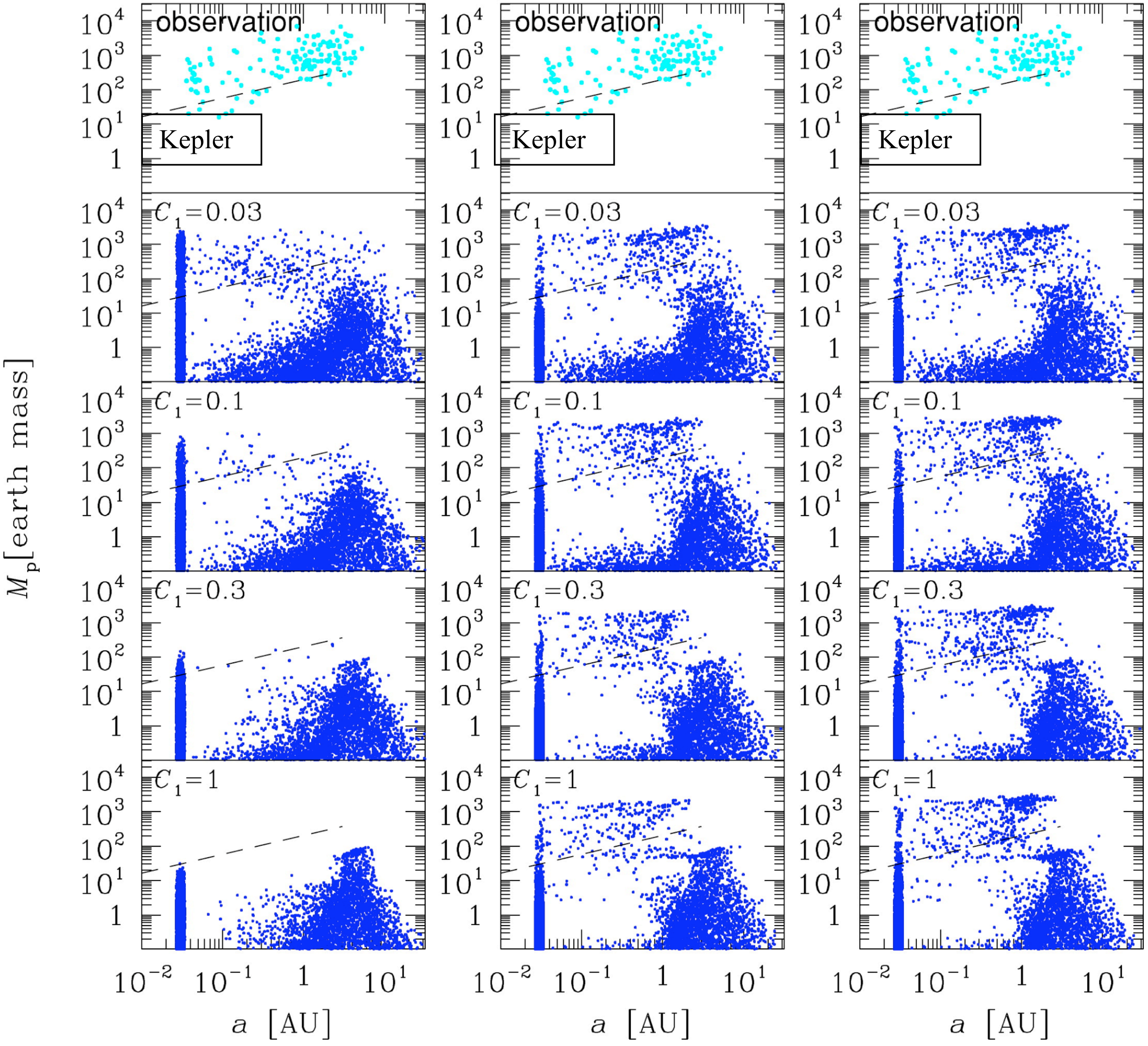


Ida & Lin (2008): no disk bumps (left) gas bump (middle) gas/dust bumps (right)



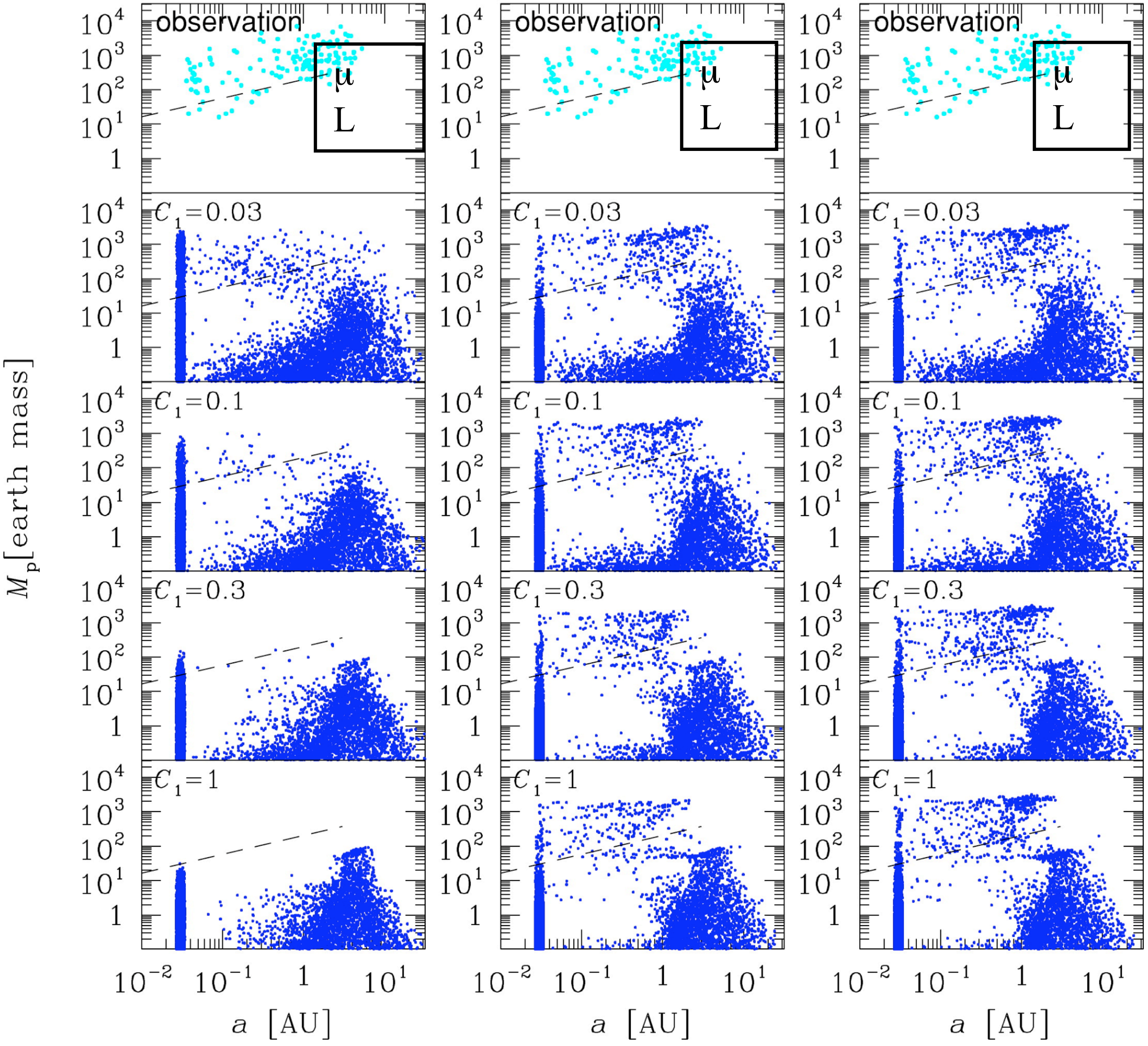
C_1~ dr/dt parameter for Type I migration; only solar mass stars

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



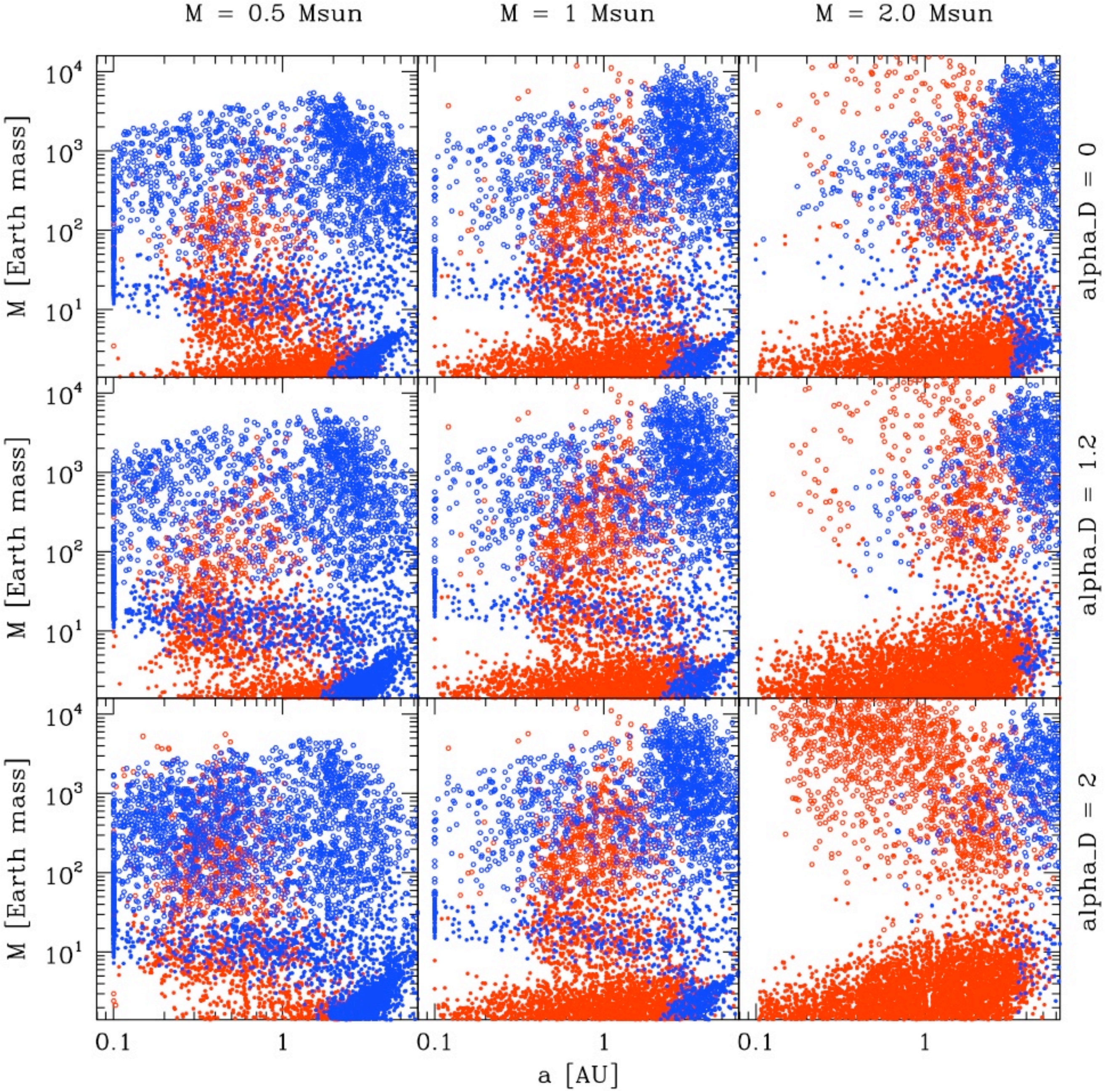
C_1~ dr/dt parameter for Type I migration; only solar mass stars

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



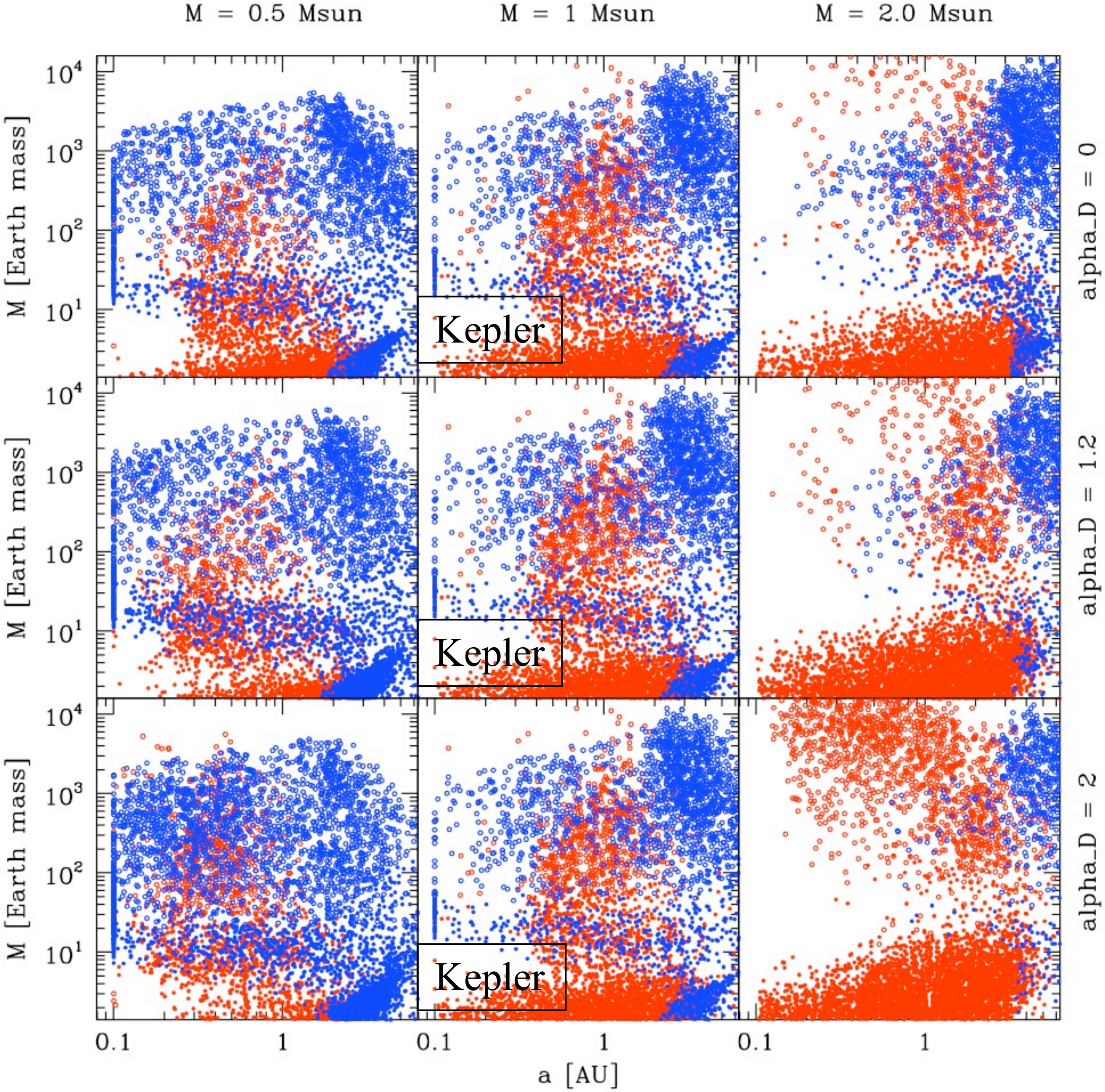
C_1~ dr/dt parameter for Type I migration; only solar mass stars

Alibert, Mordasini, & Benz (2011)



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

Alibert, Mordasini, & Benz (2011)



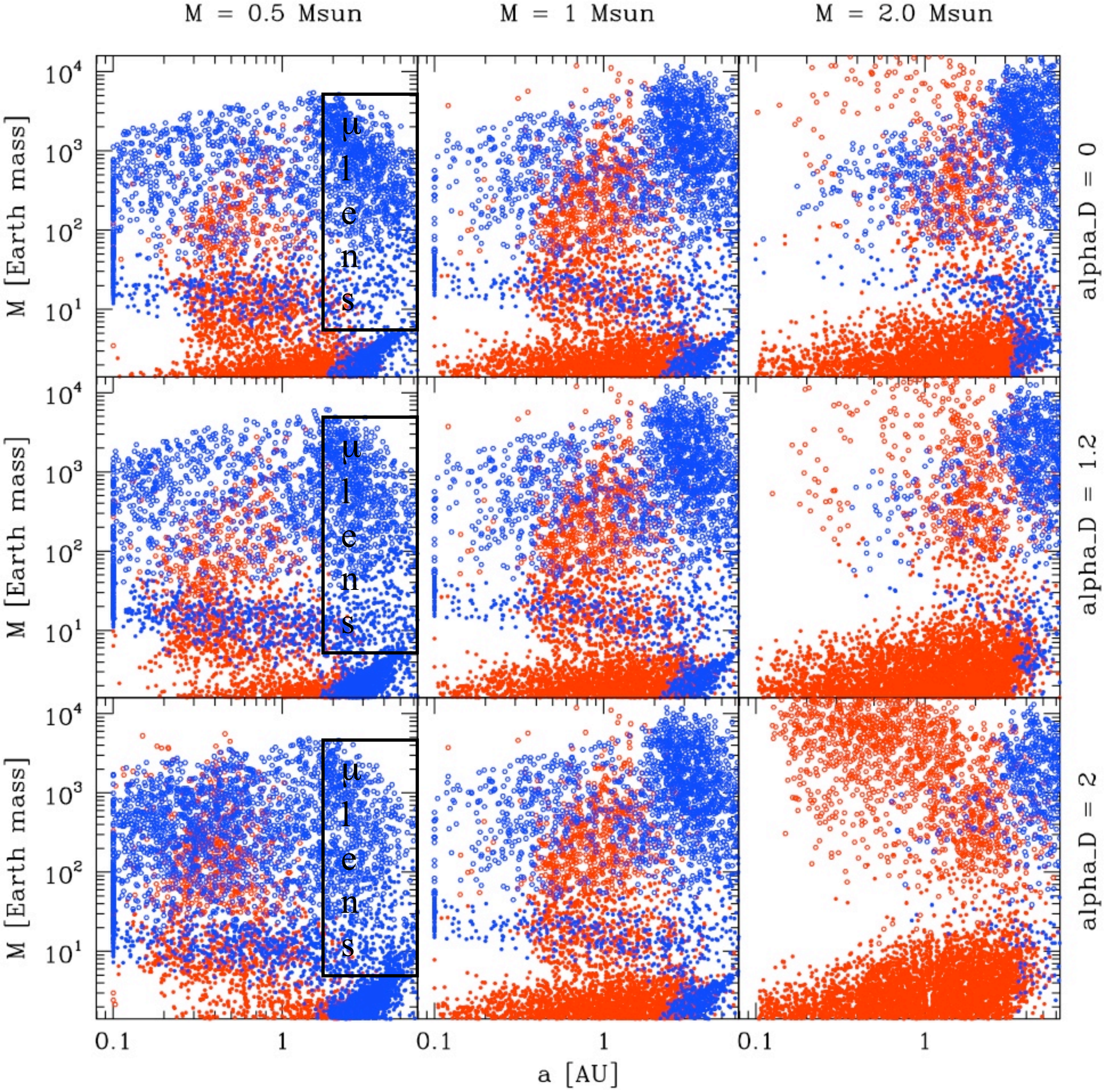
Kepler

Kepler

Kepler

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

Alibert, Mordasini, & Benz (2011)

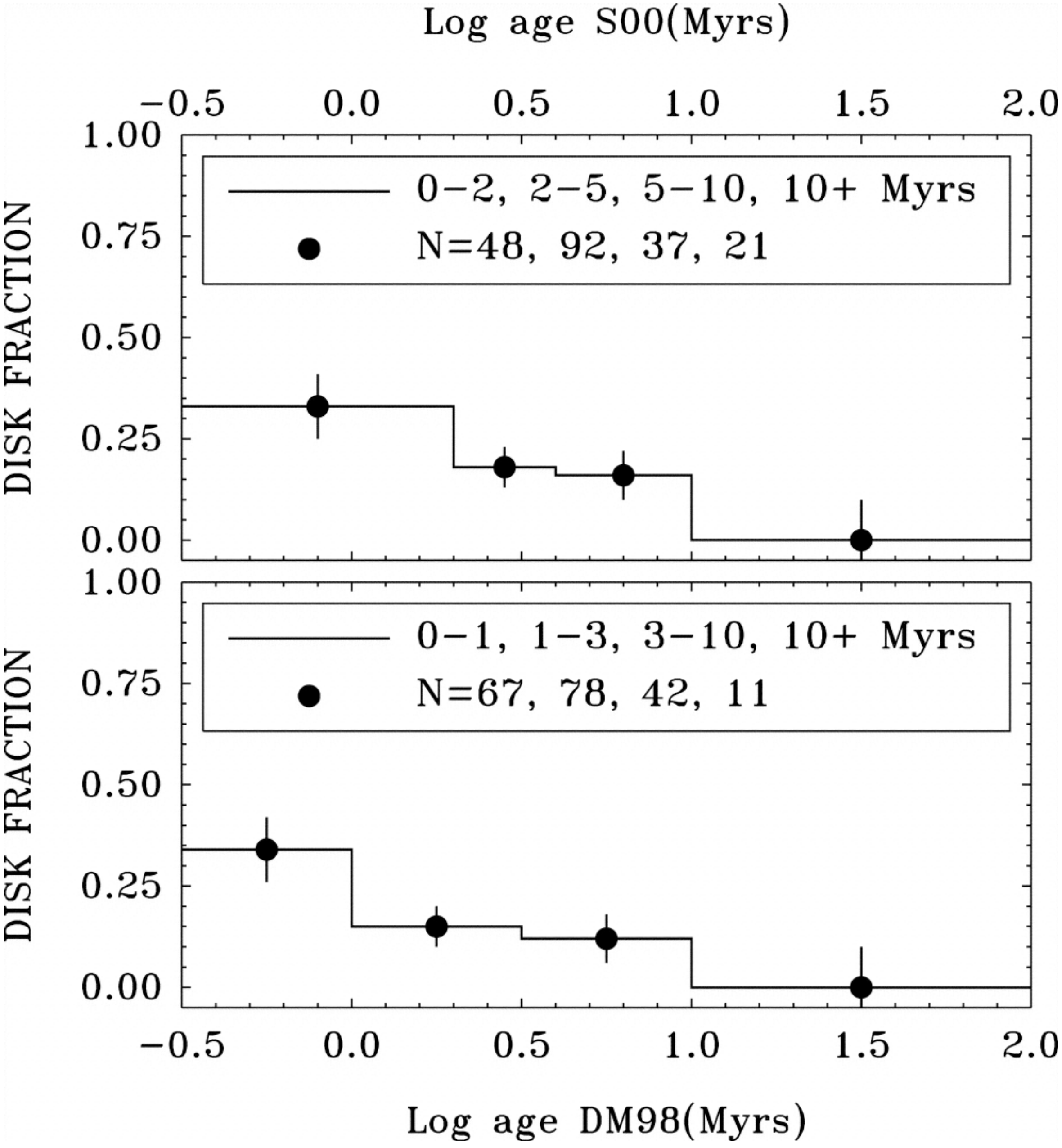


$M_d \sim M_s^{\alpha D}$

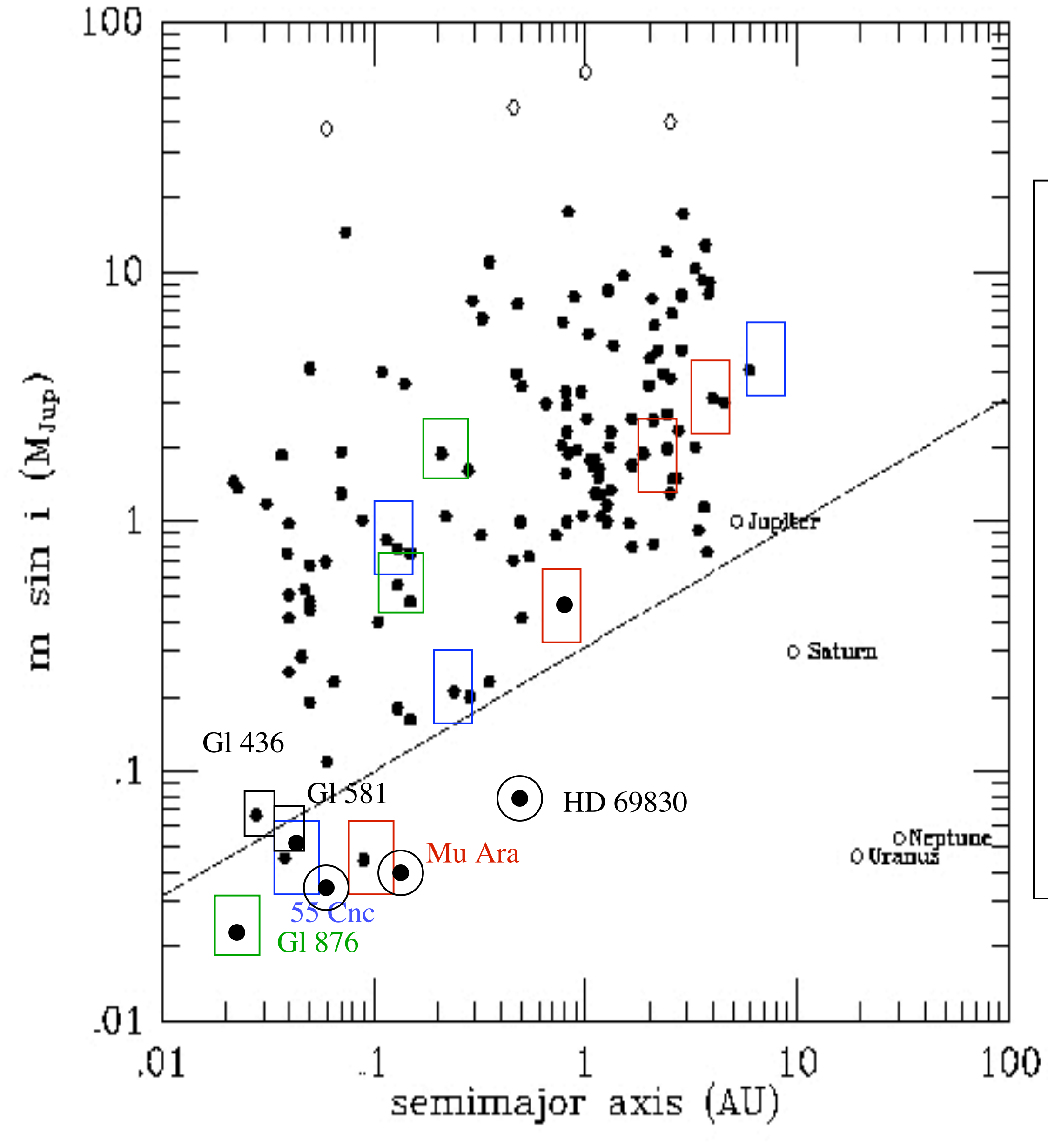
Exoplanet Population Synthesis Models

- 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



Discovery space with hot and warm super-Earths and their gas giant planet siblings

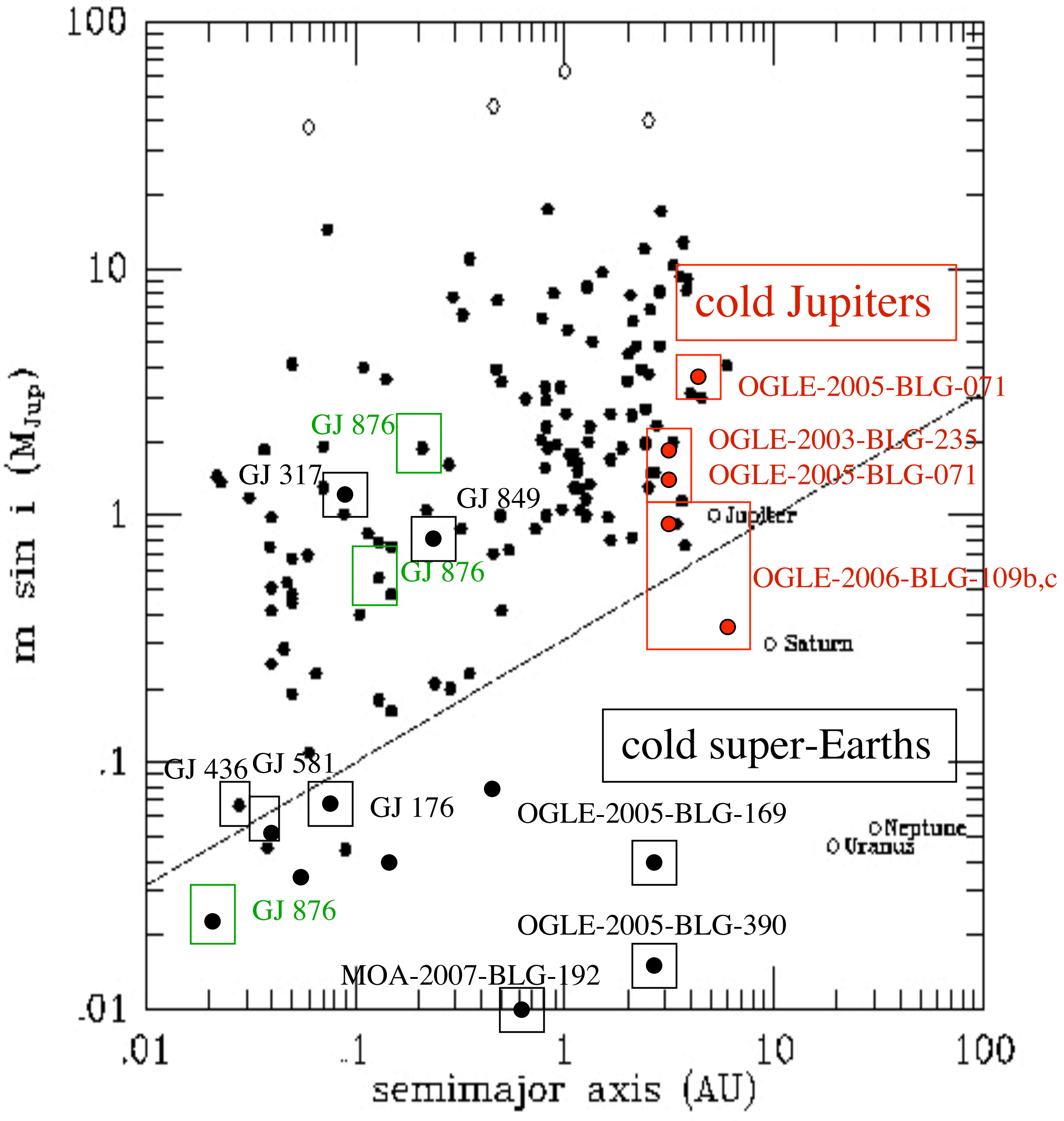


HD 181433: inner 7.5 Earth-mass and two outer Jupiters (Bouchy et al. 2009)

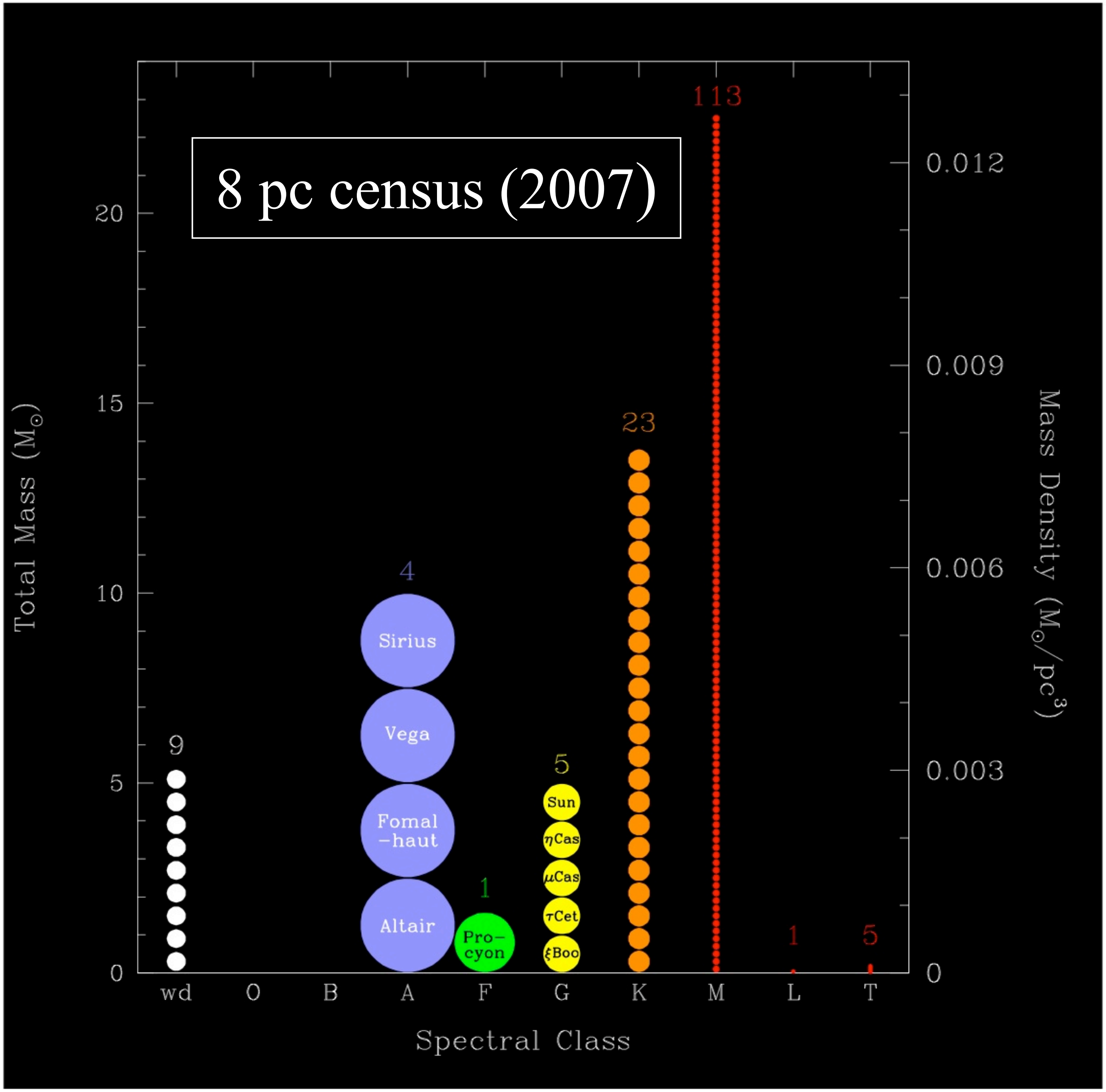
HD 47186: inner 22 Earth-mass and outer Saturn (Bouchy et al. 2009)

~30% of solar-type stars have super-Earths (Mayor et al. 2009)

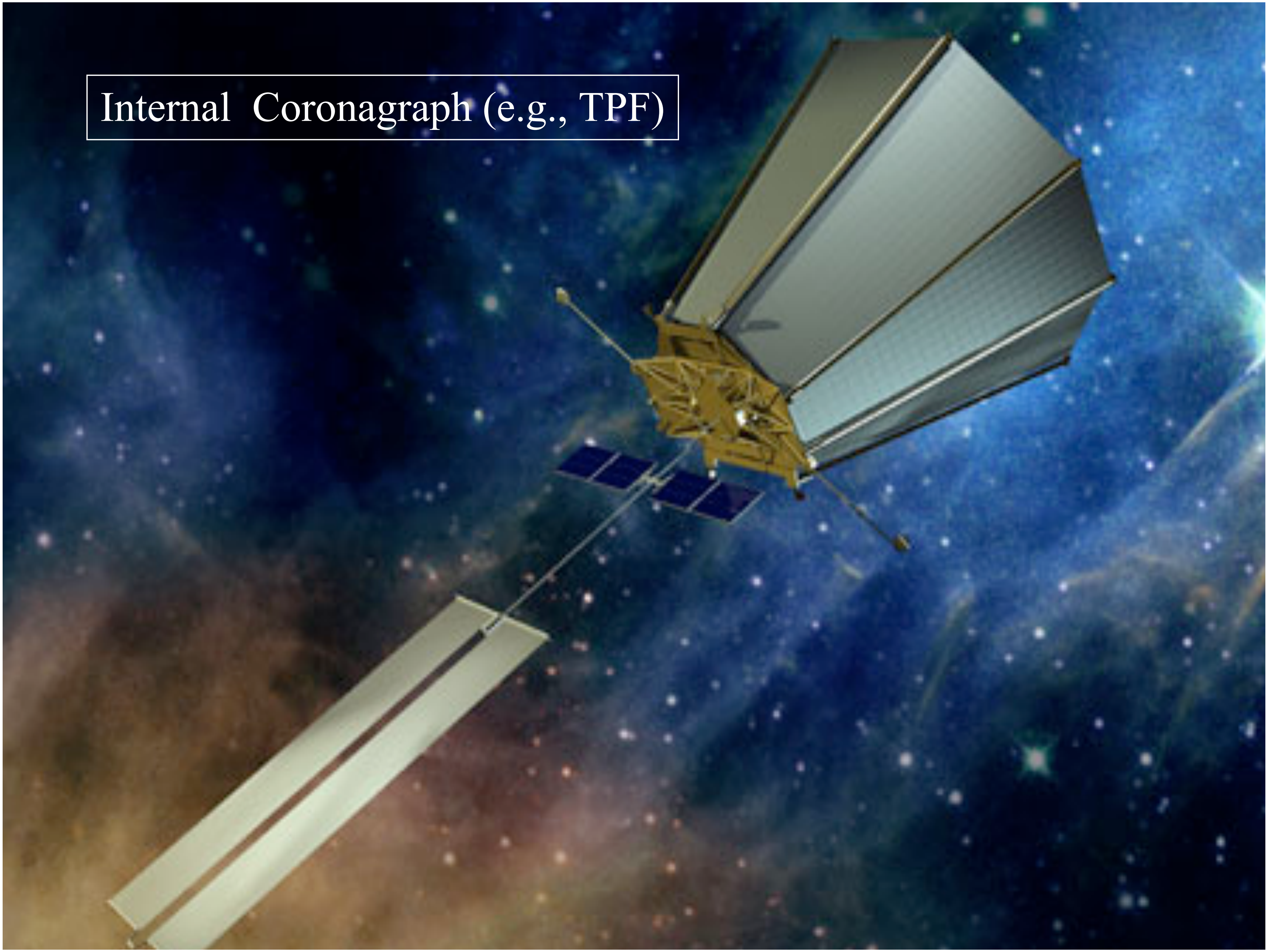
Discovery space with planets around M dwarf stars highlighted



8 pc census (2007)



Internal Coronagraph (e.g., TPF)



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

Planet Formation Theories and the Relevance of Microlensing Observations: Conclusions

- Doppler surveys show that ~30% of solar-type stars have hot or warm super-Earths (Mayor et al. 2009)
- Microlensing surveys imply that ~35% of M dwarfs have Jupiter-mass to super-Earth-mass planets (Gould et al. 2010)
- Microlensing probes preferentially lower mass stars than RV, and greater distances as well, putting important new constraints on planet formation theories (Boss 2006)
- Population synthesis models based on core accretion have problems accounting for the “planet oasis” and gas giants on wide or unbound orbits (Ida &Lin 2008)
- M dwarfs can host habitable worlds (Tarter et al. 2007)
- Microlensing can detect gas giants and cold super-Earths around typical M and K dwarfs in the galaxy (Gould et al. 2010)
- Long-period gas giants are frequent siblings to shorter-period super-Earths and habitable worlds (Lo Corto et al. 2010)
- Habitable Earths thus are expected to exist interior to the outer gas giants to be found by microlensing surveys
- Similar, but nearby M dwarfs should then be targets for future space telescopes capable of the direct detection of Earths