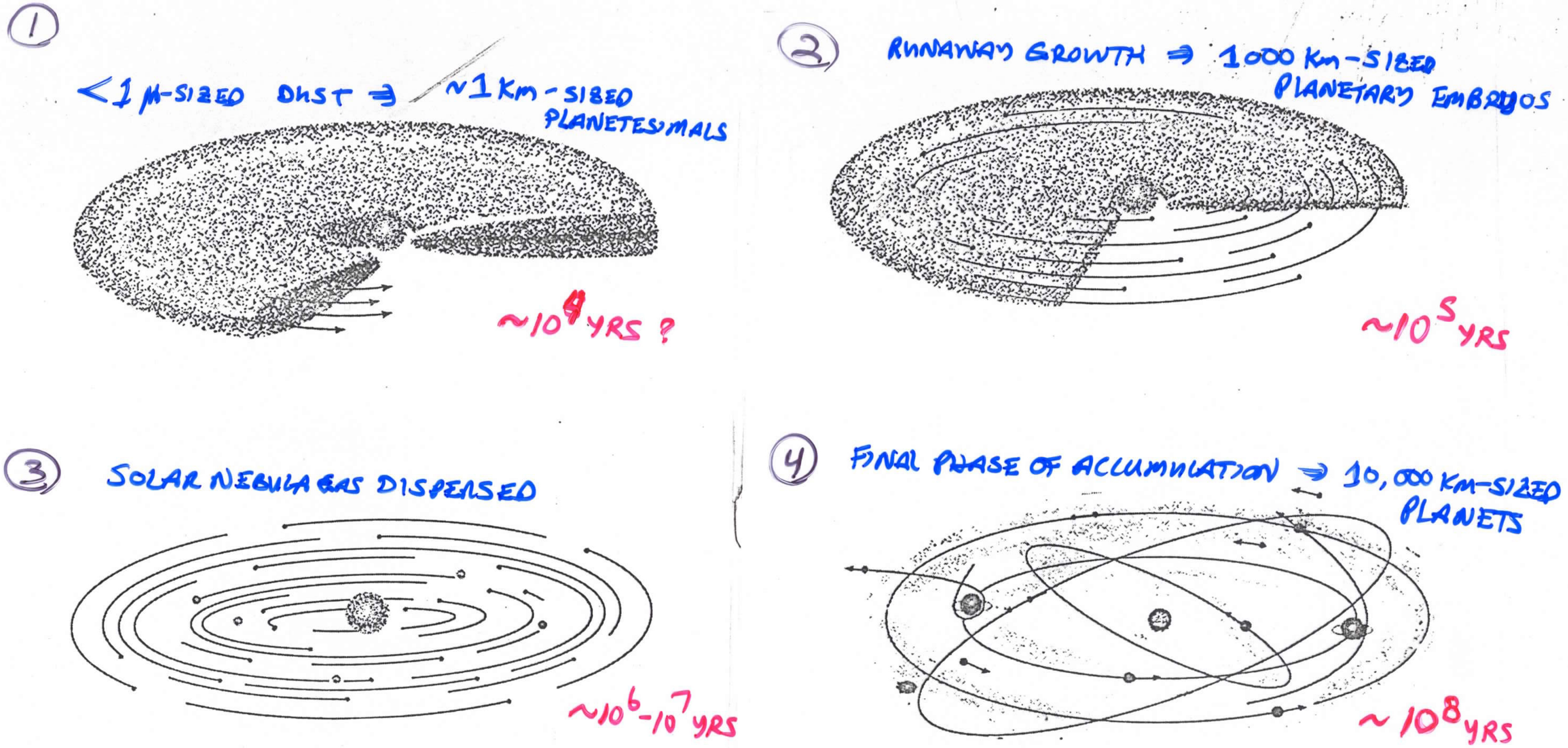
# WFIRST/AFTA: Exoplanet Science

Alan P. Boss
DTM, Carnegie Institution

Wide-Field InfraRed Surveys: Science and Techniques
Pasadena, California
November 17, 2014

# Solar System formation theory circa 1994



①

<1 μ-SIZED DUST ⇒ ~1 Km-SIZED PLANETESIMALS

$\sim 10^4$ YRS ?

②

RUNAWAY GROWTH ⇒ 1000 Km-SIZED PLANETARY EMBRYOS

$\sim 10^5$ YRS

③

SOLAR NEBULA GAS DISPERSED

$\sim 10^6 - 10^7$ YRS

④

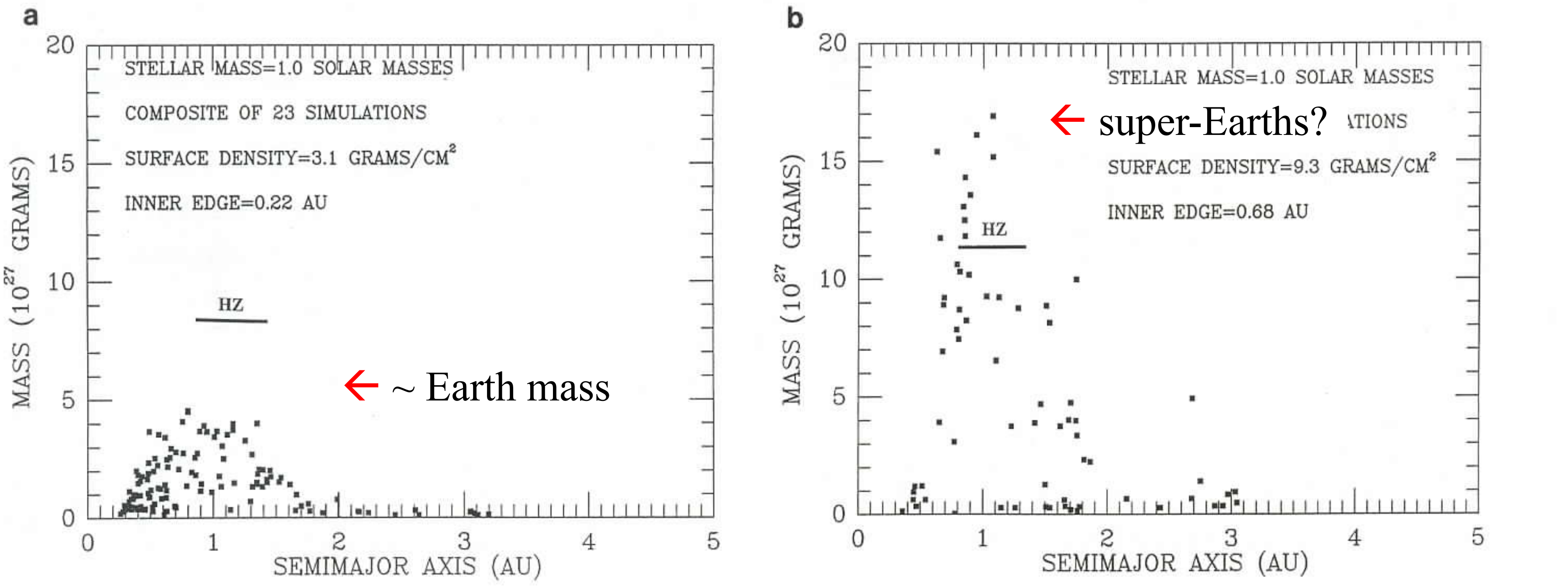
FINAL PHASE OF ACCUMULATION ⇒ 10,000 Km-SIZED PLANETS

$\sim 10^8$ YRS

FIGURE 3.2 Possible sequence of events in the terrestrial planet region. (top left) Growth of dust grains into ~10-km-diameter "planetesimals" through nongravitational forces (sticking). (top right) Runaway growth of planetesimals, moving in nearly circular, coplanar orbits, to form ~2000-km-diameter "planetary embryos" on a $10^5$-year time scale. (bottom left) Removal of gas from the inner solar system on a $10^6$- to $10^7$-year time scale. (bottom right) Mutual perturbation of planetary embryos into eccentric orbits and their merger to form the present planets on a $10^8$-year time scale. Asteroids are relics of similar processes in the present asteroidal region that failed to complete the runaway growth stage (top right) as a consequence of either gravitational or collisional removal of most of the other bodies in that region. Jupiter's perturbations, beginning at about $5 \times 10^6$ years, were primarily responsible for this clearing of the asteroid belt.

Wetherill (1996)

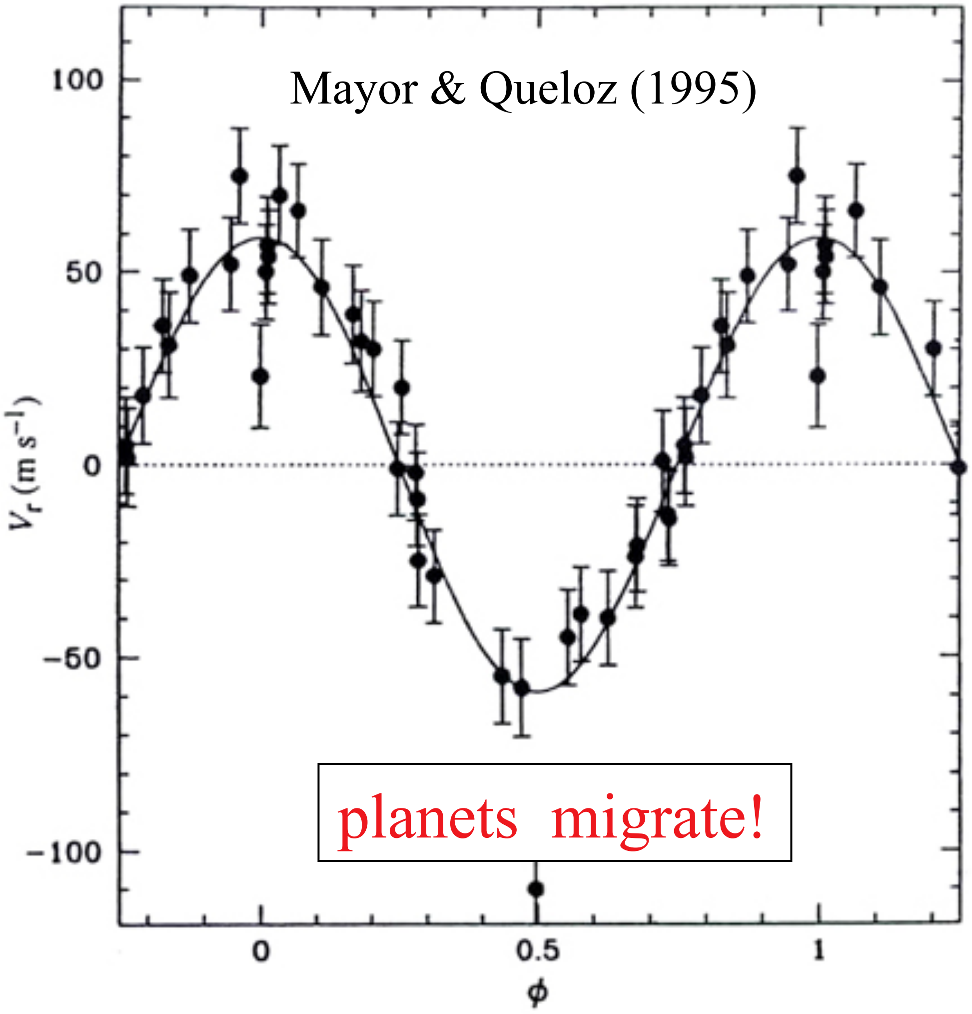
EXTRA-SOLAR PLANETS



← ~ Earth mass

← super-Earths?

**FIG. 4.** Effect of varying surface density with constant stellar mass. The positions of the final planets remain similar. Their mass is dependent on the surface density, particularly for lower surface densities. The nominal case is again Fig. 1a. (a) Stellar mass, 1.0 $M_\odot$. Surface density half the nominal value. (b) Stellar mass, 1.0 $M_\odot$. Surface density 3/2 the nominal value.

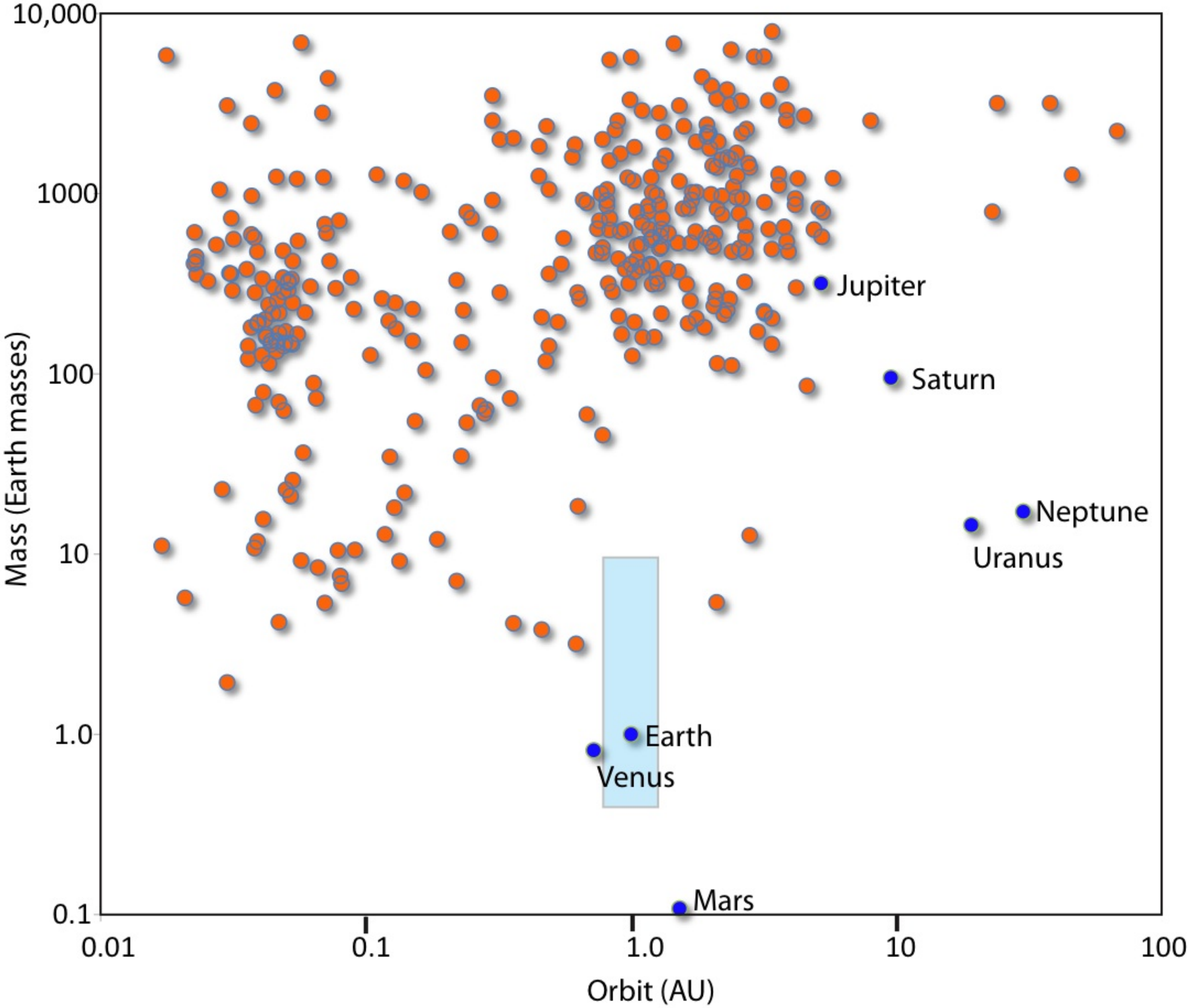


Mayor & Queloz (1995)

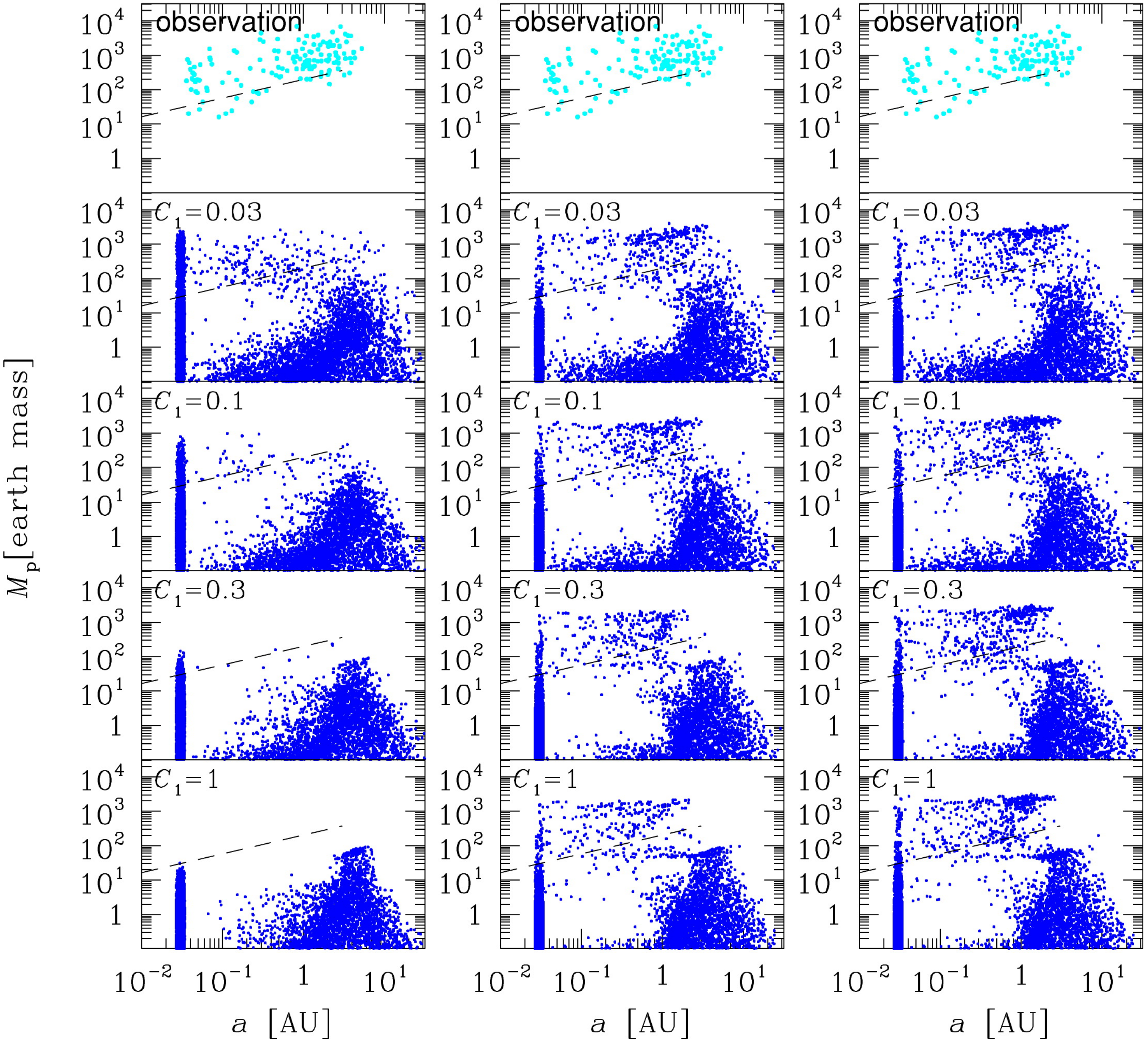
planets migrate!

FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the $\gamma$-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

# Discovery space circa 2010 – mostly Doppler exoplanets

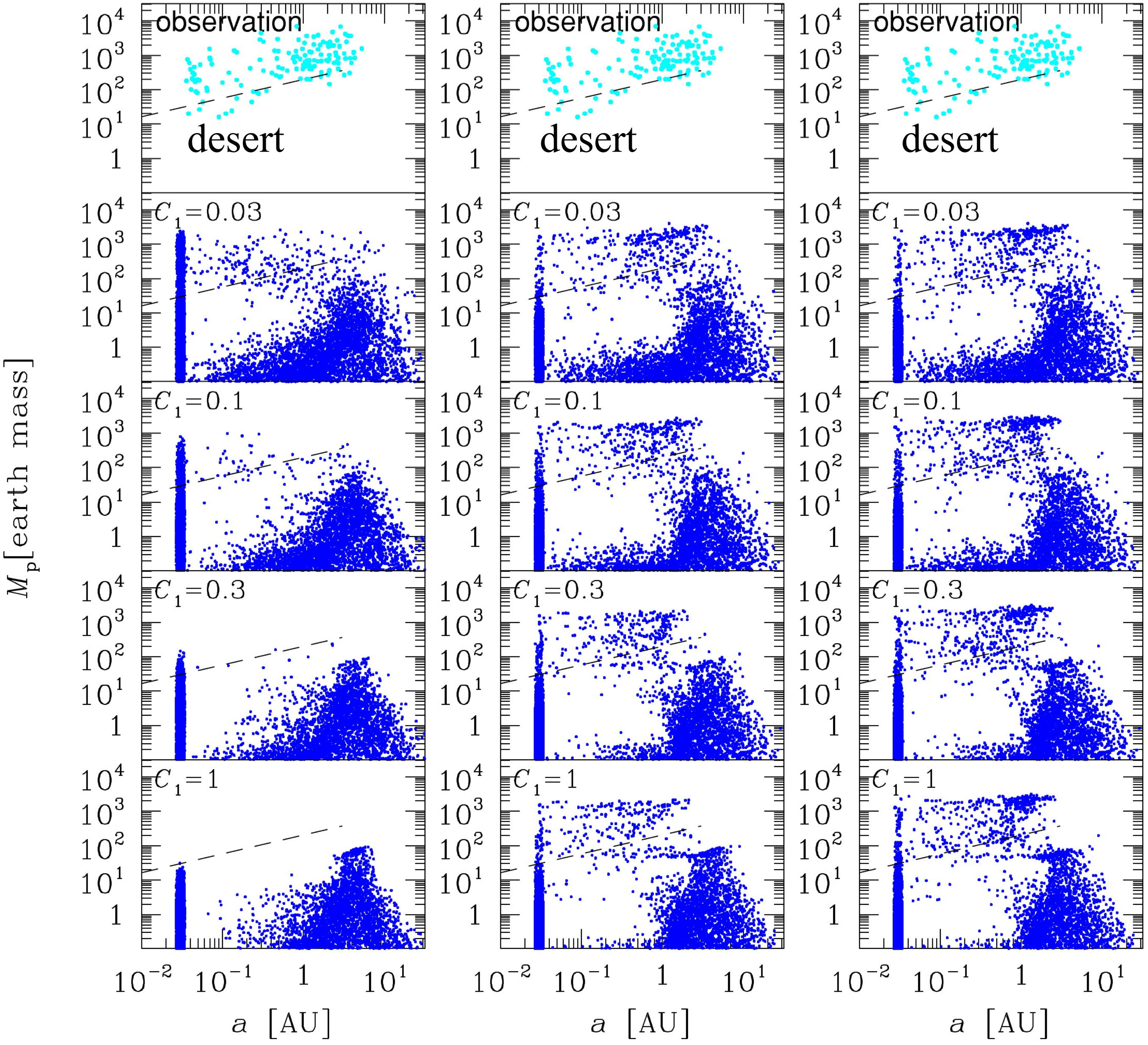


# Ida & Lin (2008): no disk bumps (left) gas bump (middle) gas/dust bumps (right)



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

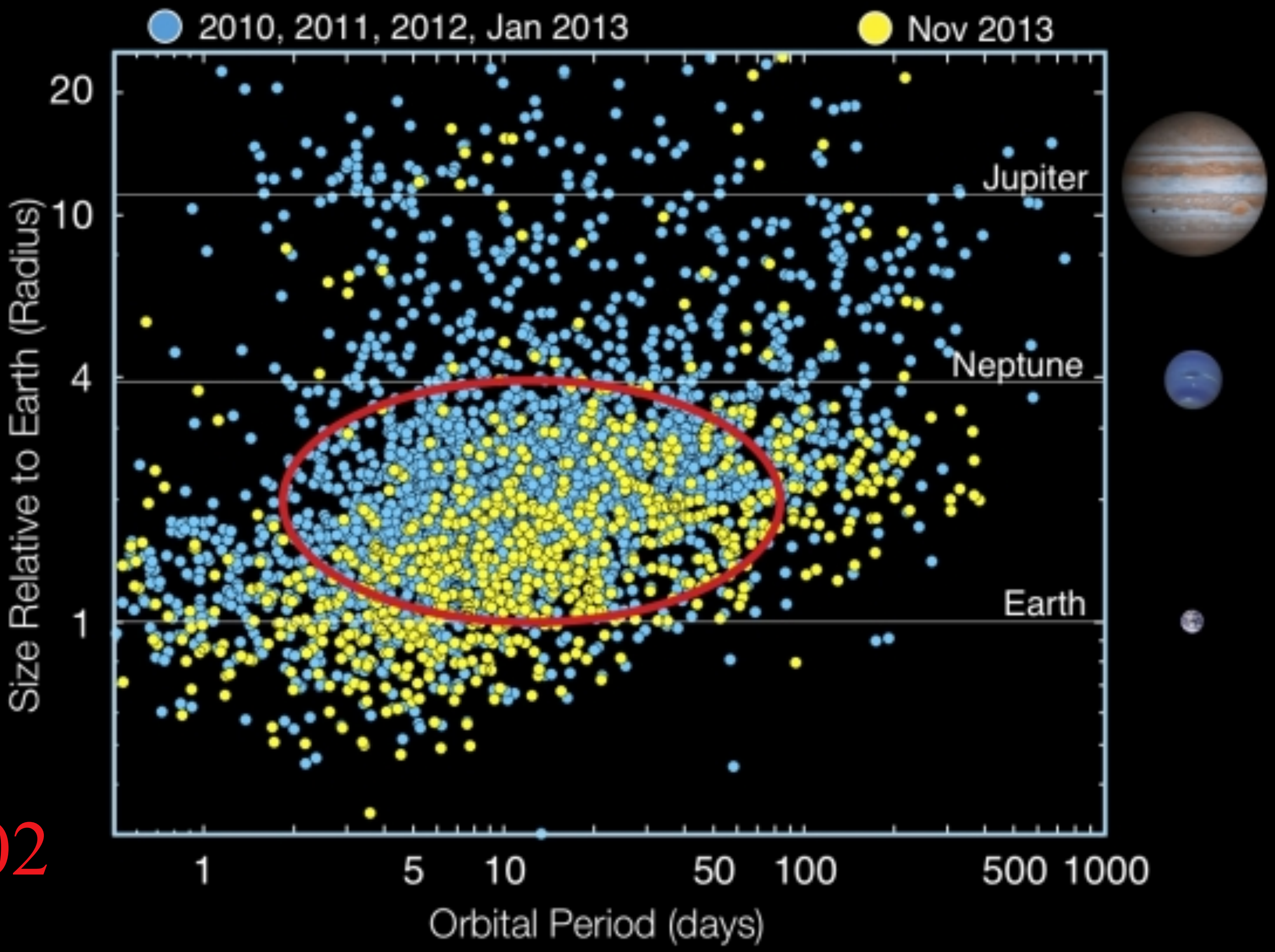
Ida & Lin (2008): no disk bumps (left) gas bump (middle) gas/dust bumps (right)



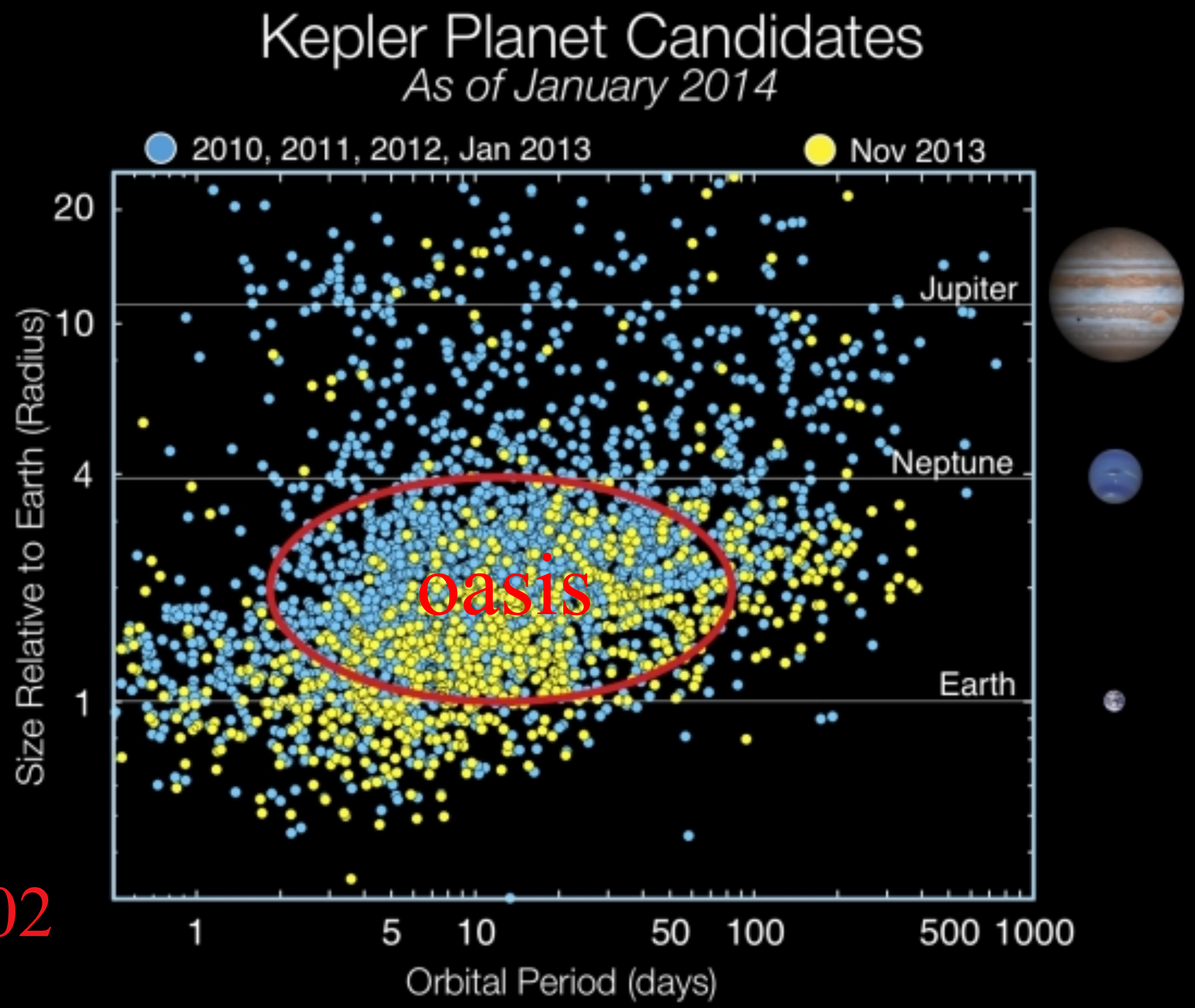
$C_1$~ dr/dt parameter for Type I migration; only solar mass stars

# Kepler Planet Candidates

*As of January 2014*



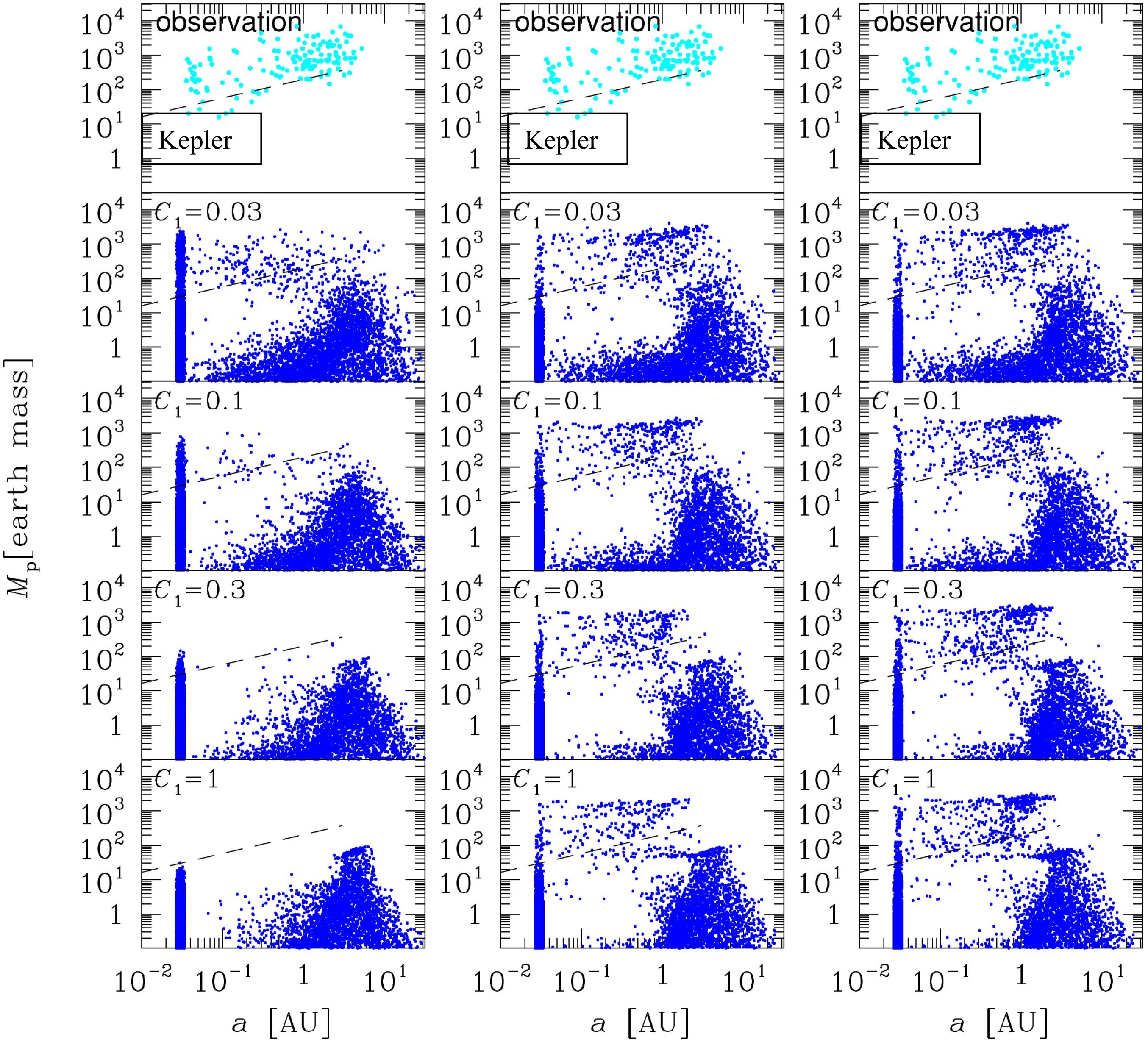
3602


Kepler Planet Candidates
As of January 2014
2010, 2011, 2012, Jan 2013
Nov 2013
20
10
4
1
Size Relative to Earth (Radius)
Jupiter
Neptune
Earth
1
5
10
50
100
500
1000
Orbital Period (days)

oasis

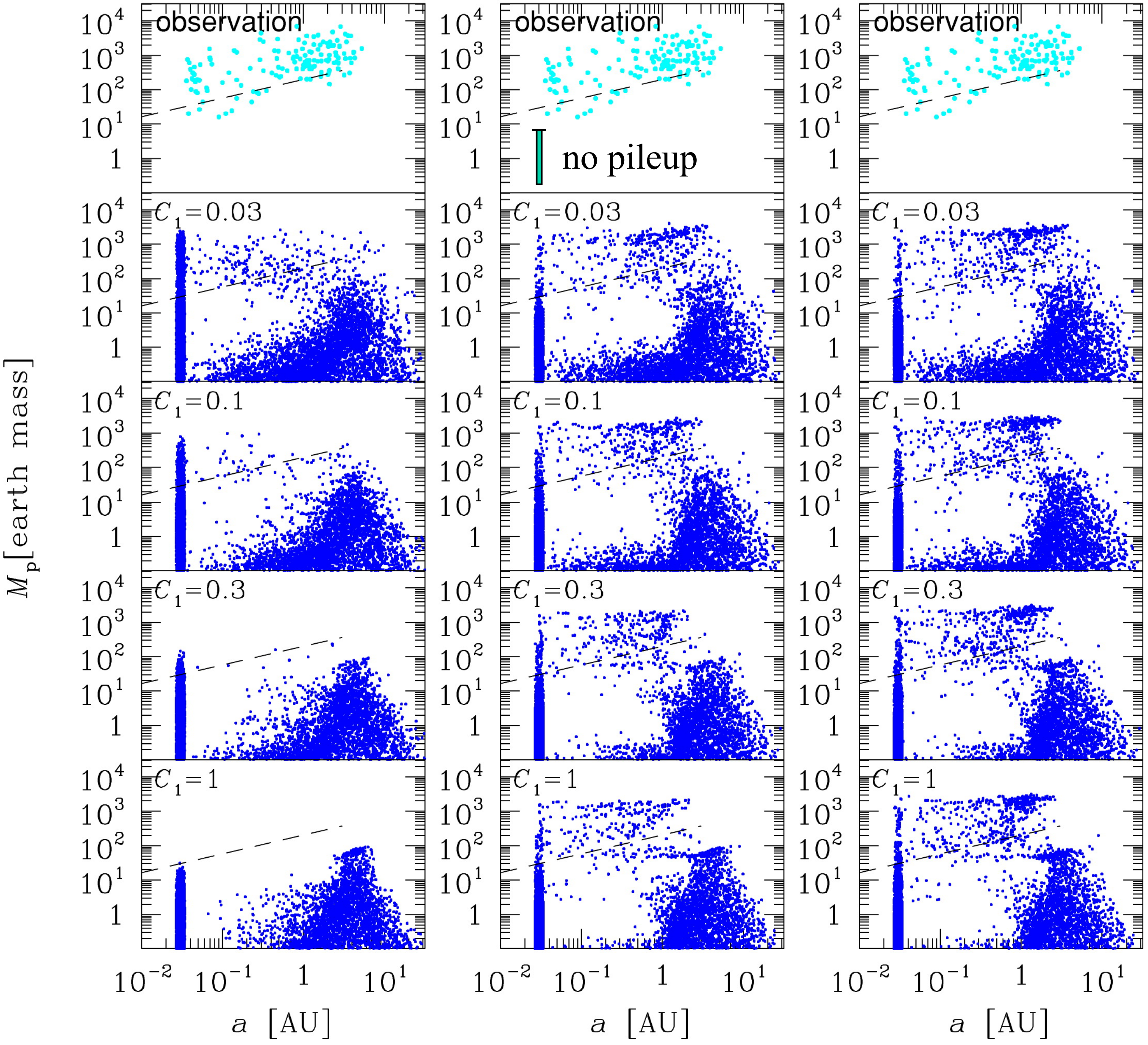
3602

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



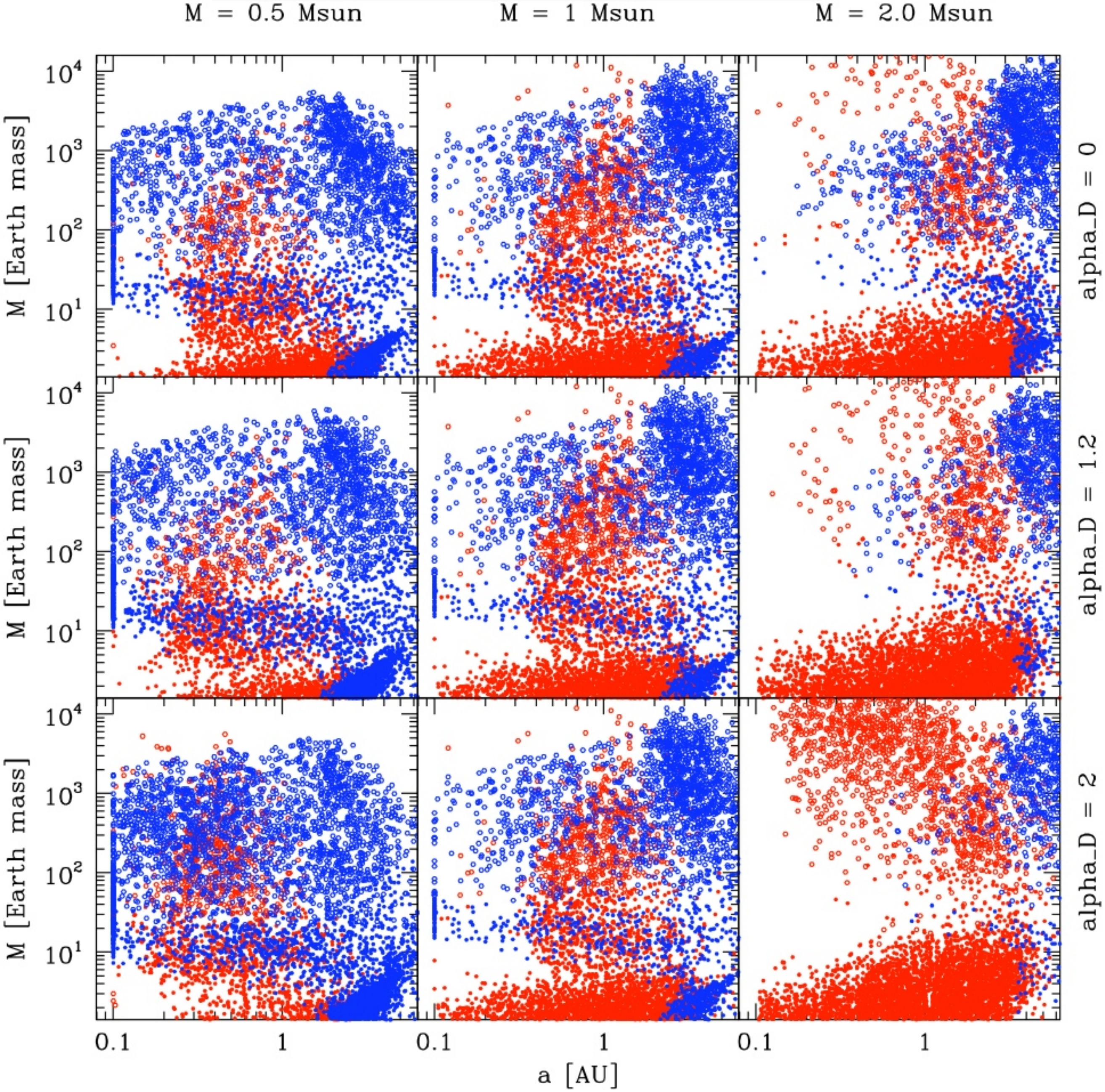
$C_1$~ dr/dt parameter for Type I migration; only solar mass stars

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



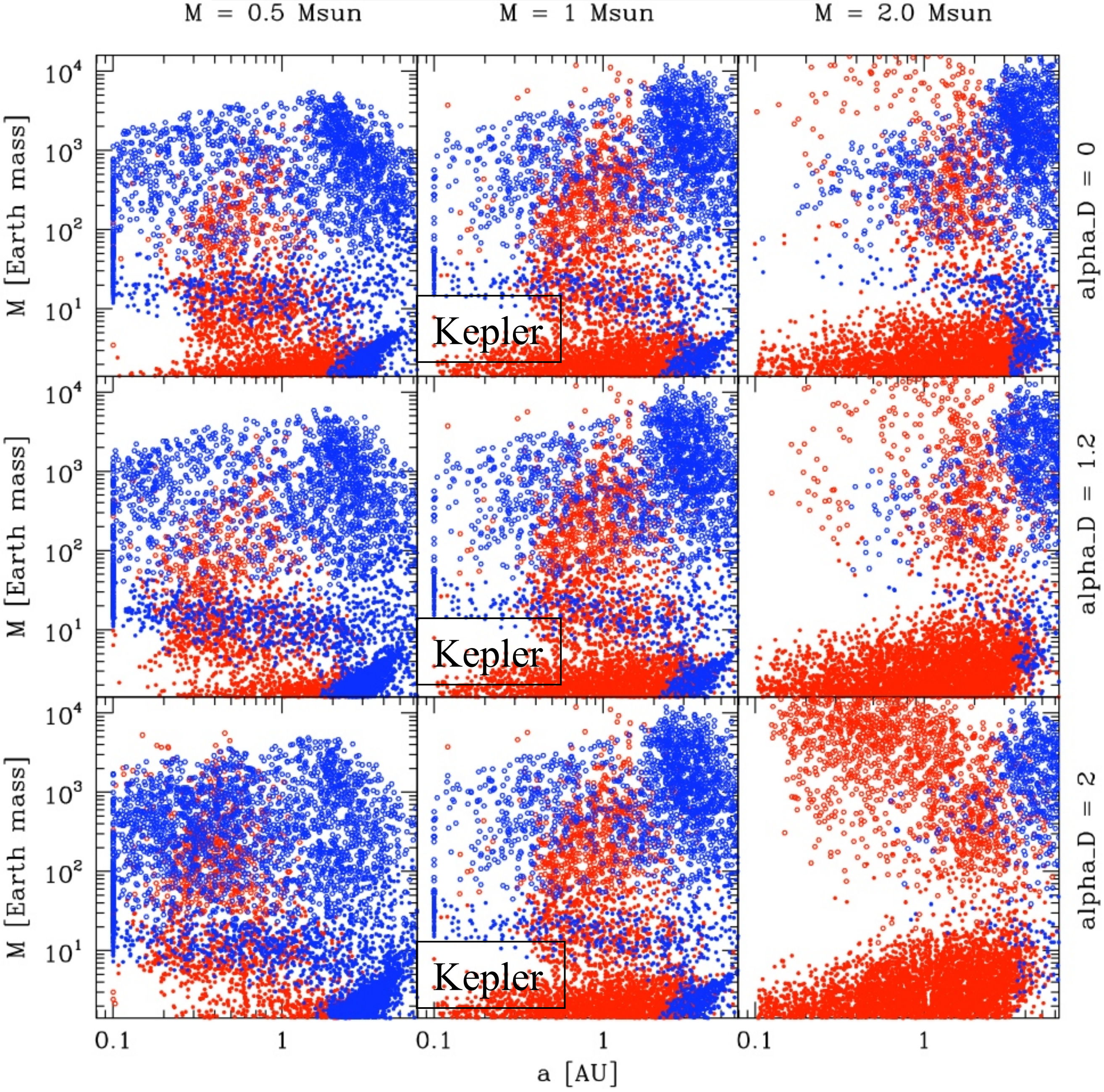
$C_1$~ dr/dt parameter for Type I migration; only solar mass stars

Alibert, Mordasini, & Benz (2011)



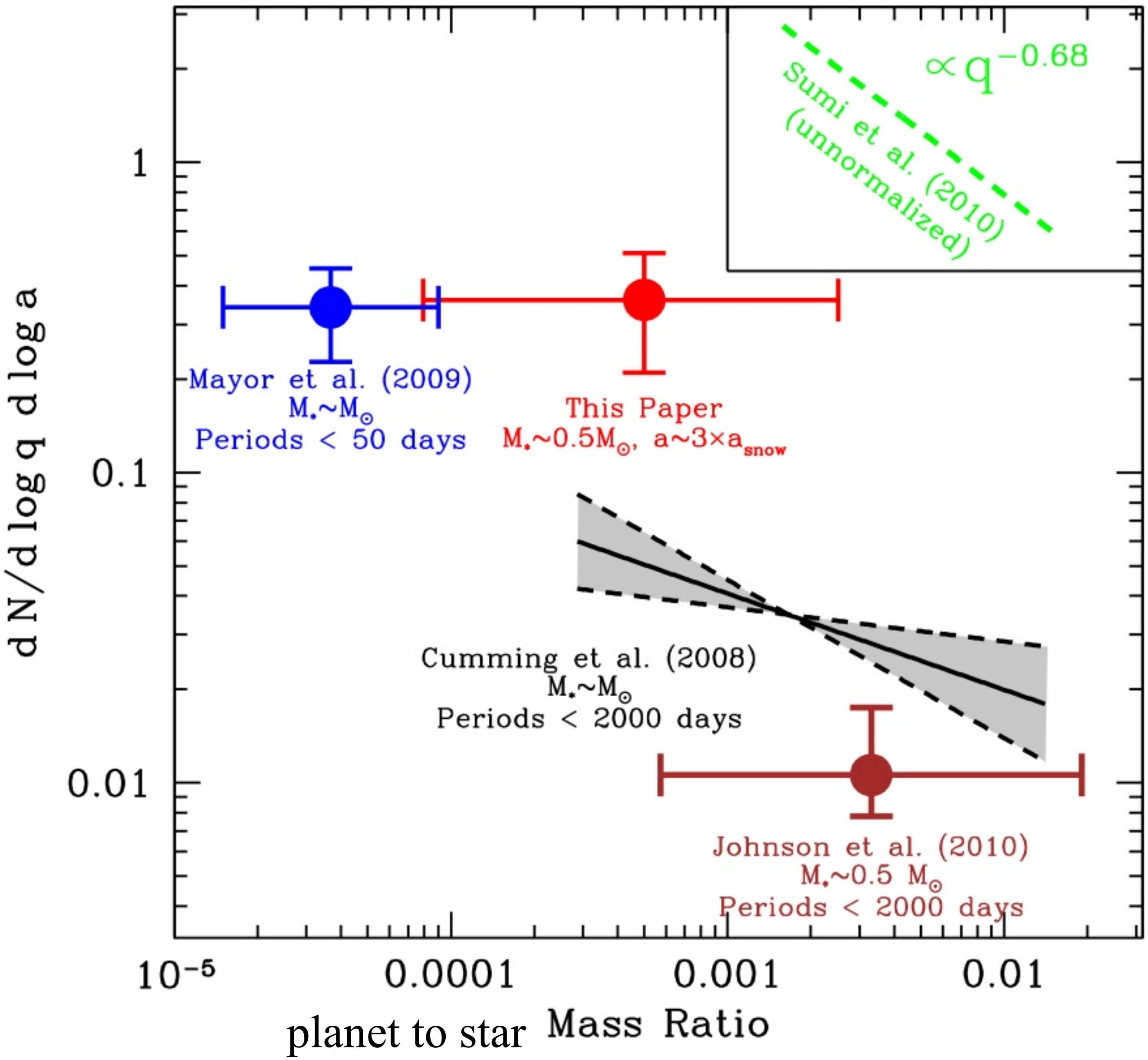
$M_d \sim M_s^{\alpha D}$

# Alibert, Mordasini, & Benz (2011)



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

# Gould et al. (2010): gravitational microlensing surveys



planet to star

## Cassan et al. (2012)

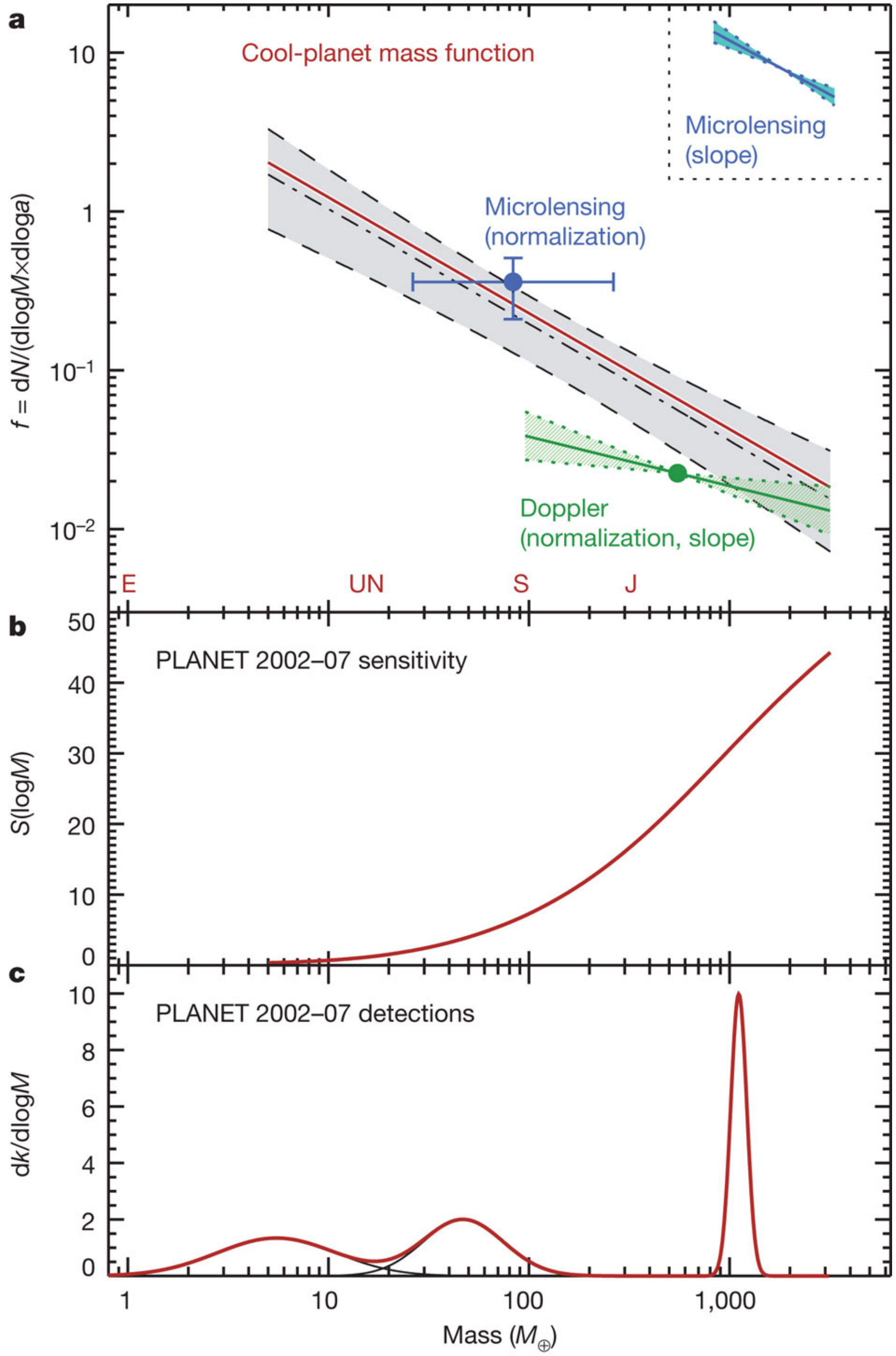
0.5 AU to 10 AU:
17% - 0.3 to 10 $M_{Jup}$
52% - 10 to 30 $M_{Earth}$
62% - 5 to 10 $M_{Earth}$

red dwarf K,M stars

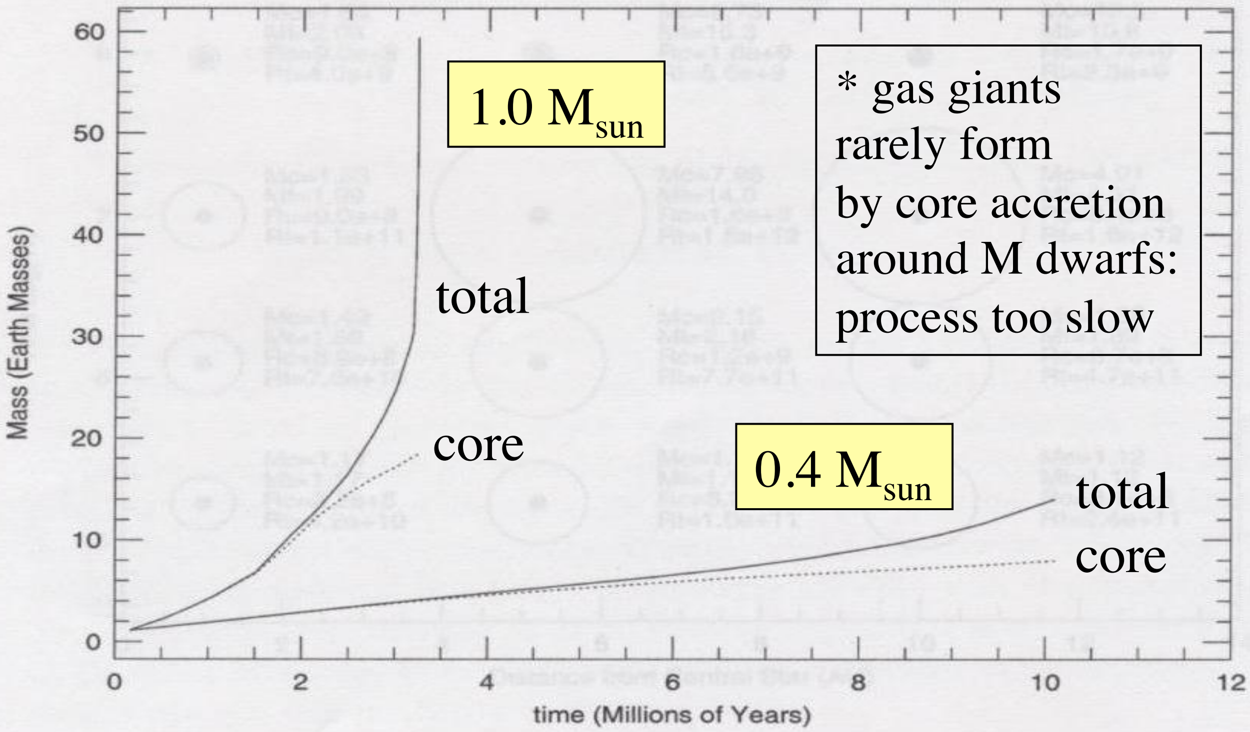
## Clanton & Gaudi (2014)

microlensing prediction for RV on M dwarfs

1 to $10^4$ day periods:
2.9% - 1 to 13 $M_{Jup}$
15% - 30 to $10^4$ $M_{Earth}$
190% - 1 to $10^4$ $M_{Earth}$



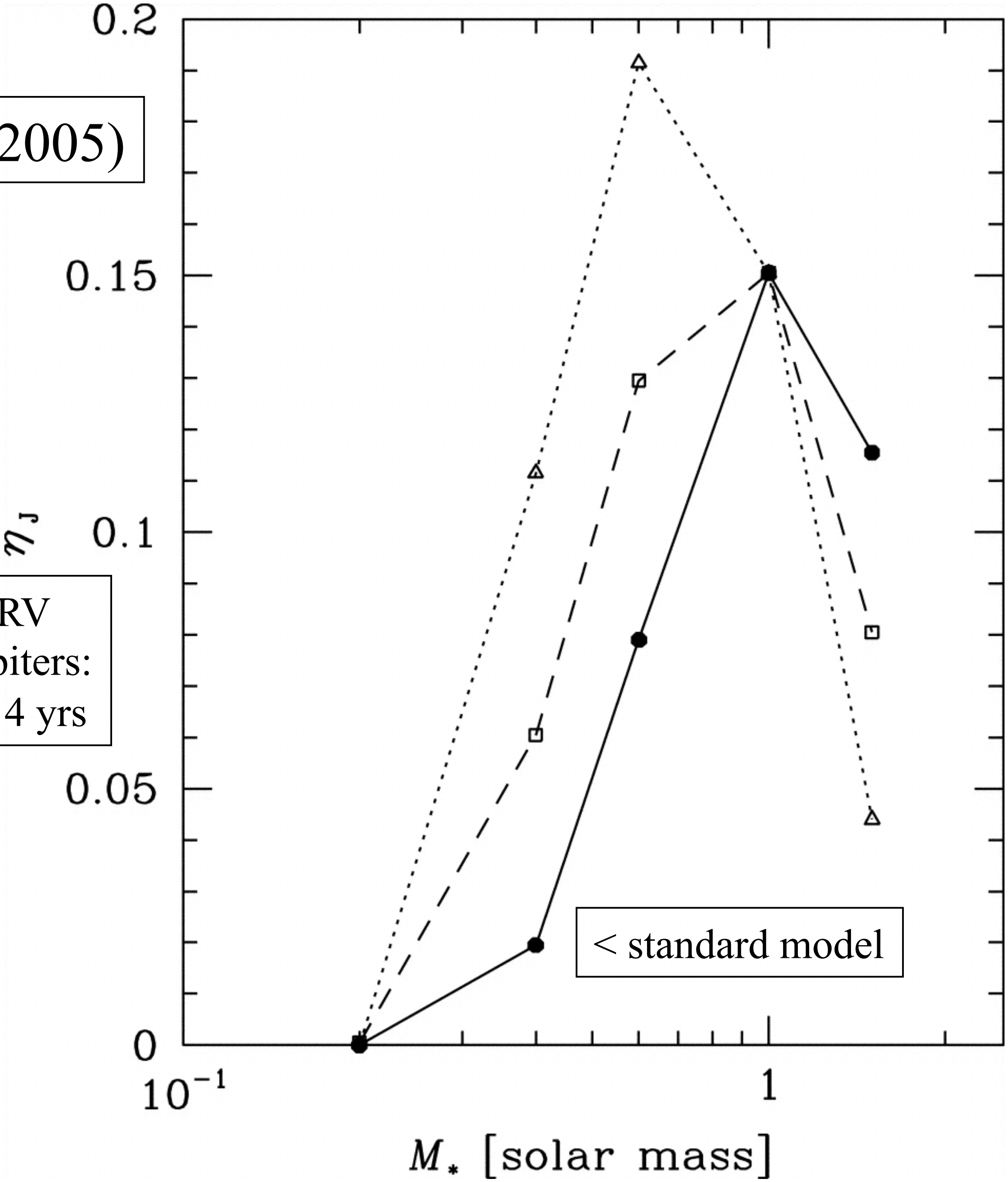
# Laughlin et al. (2004) core accretion models



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

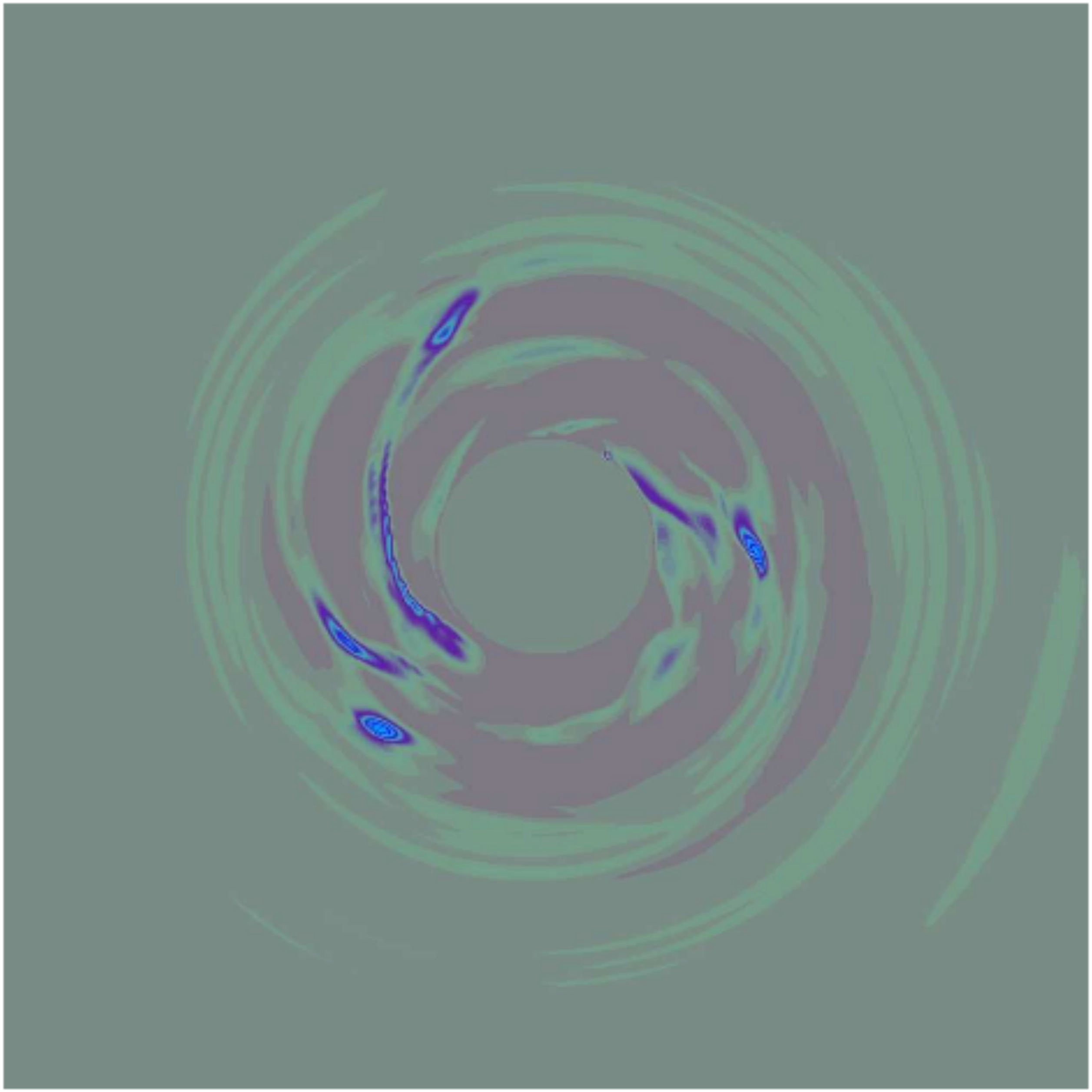
Fig. 1.— Growth of the core and envelopes of planets at 5.2 AU in disks orbiting stars of two different masses. The upper curves show the time-dependent core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk surrounding a $1M_{\odot}$ star. The lower curves show the time 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)



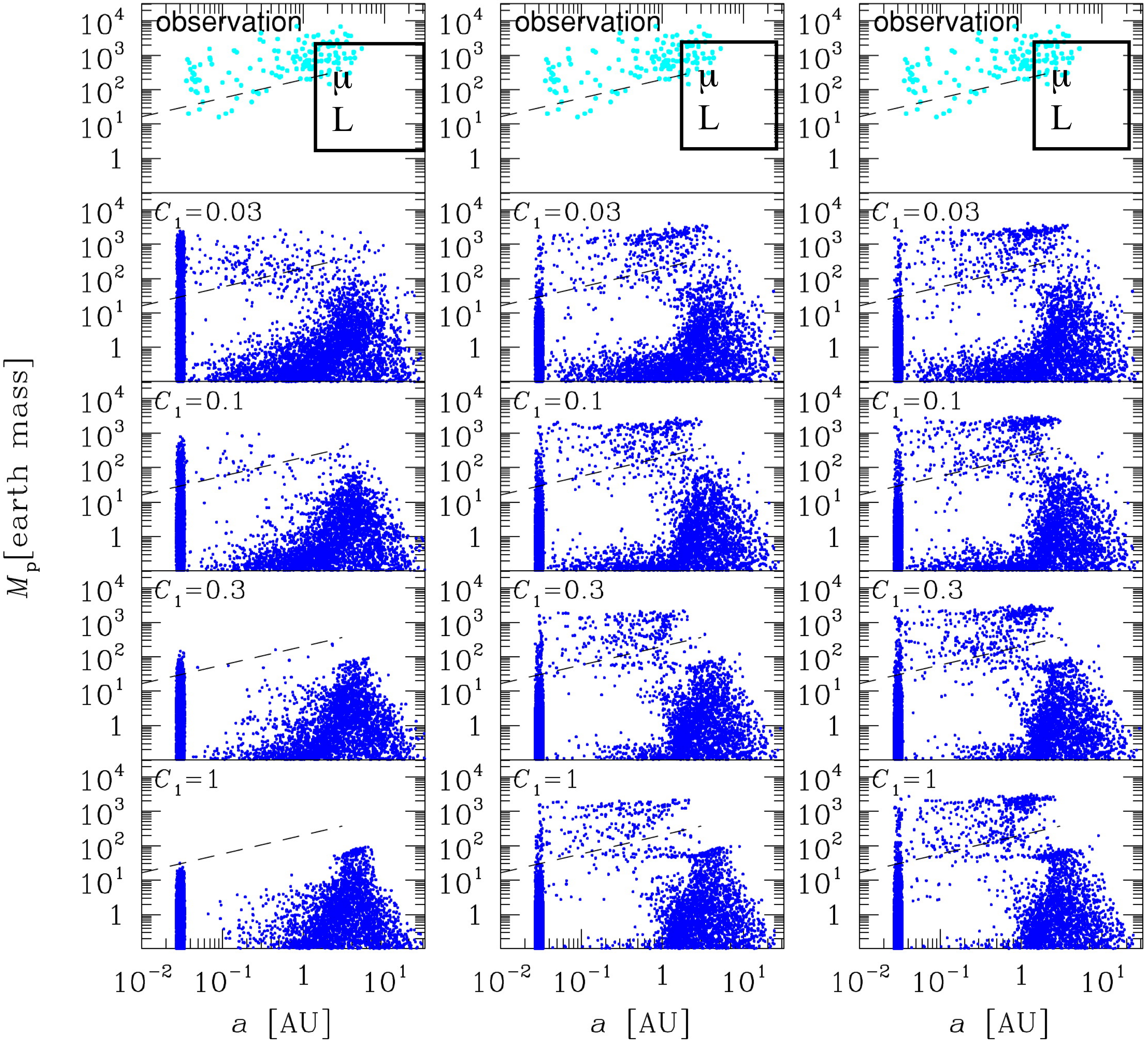
fraction with RV detectable Jupiters: > 10 m/s, P < 4 yrs

< standard model



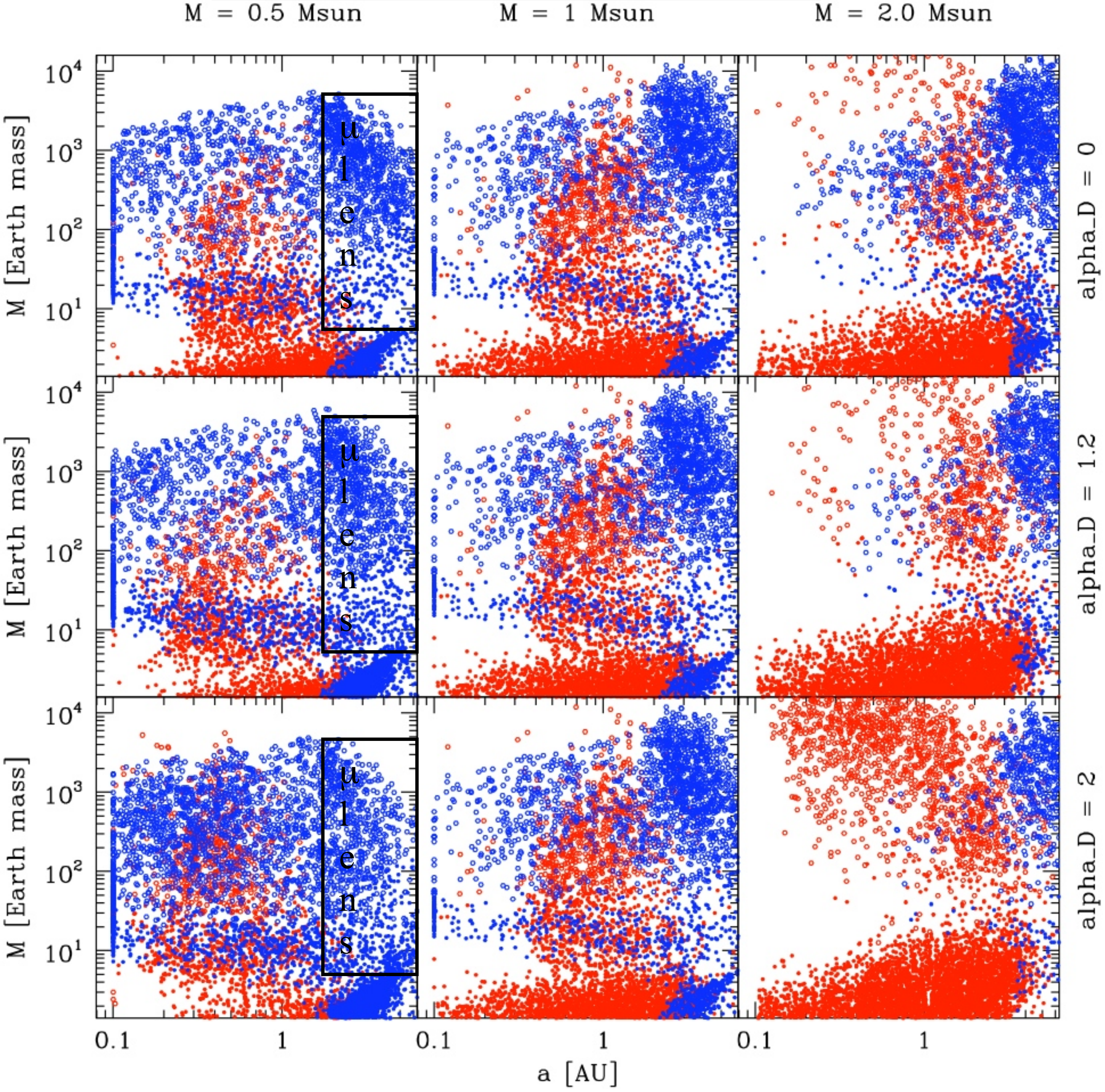
0.5 solar mass star with a 20 AU radius disk of 0.04 solar masses after 215 yrs (Boss 2006)

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



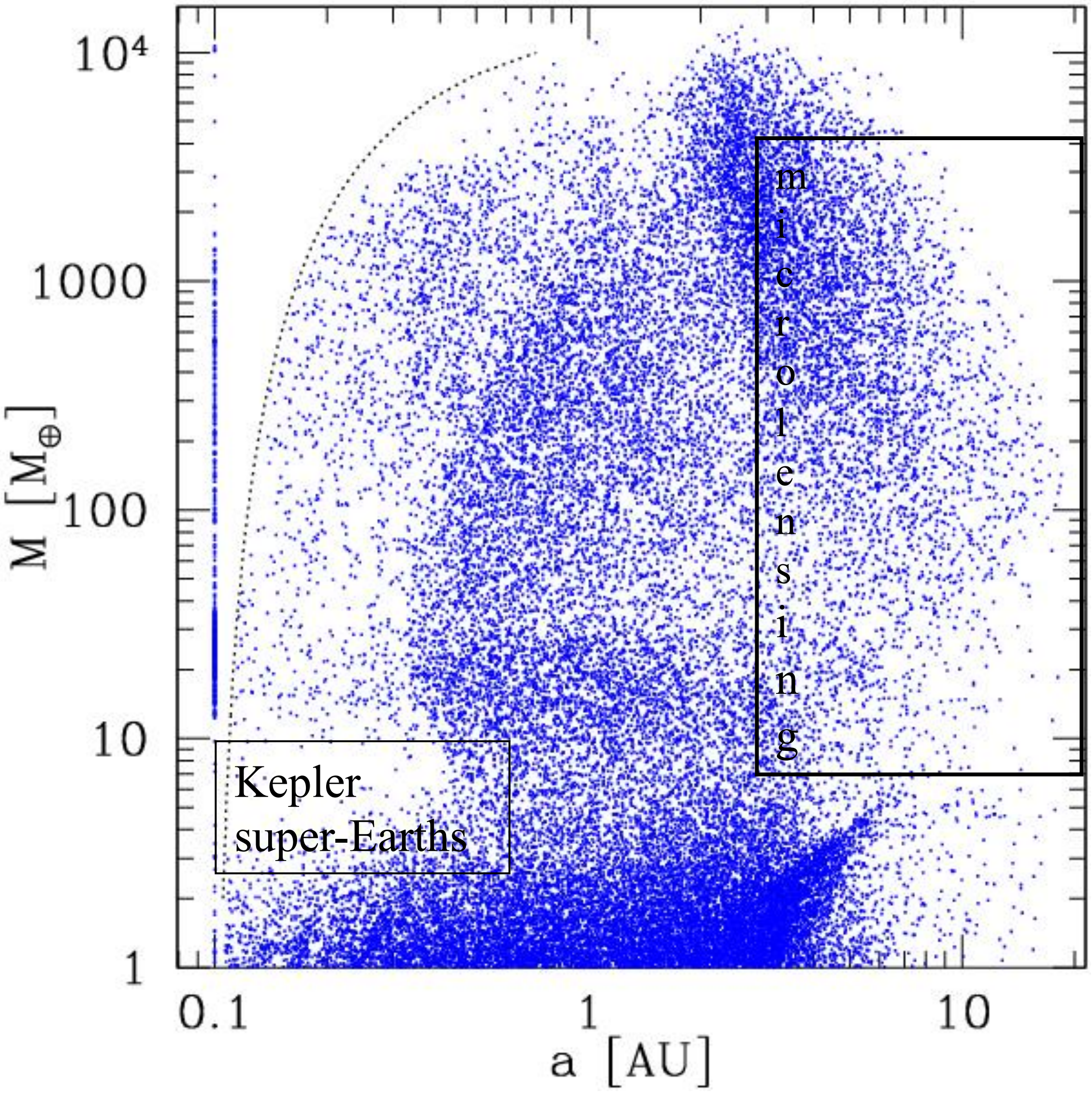
$C_1$~ dr/dt parameter for Type I migration; only solar mass stars

Alibert, Mordasini, & Benz (2011)

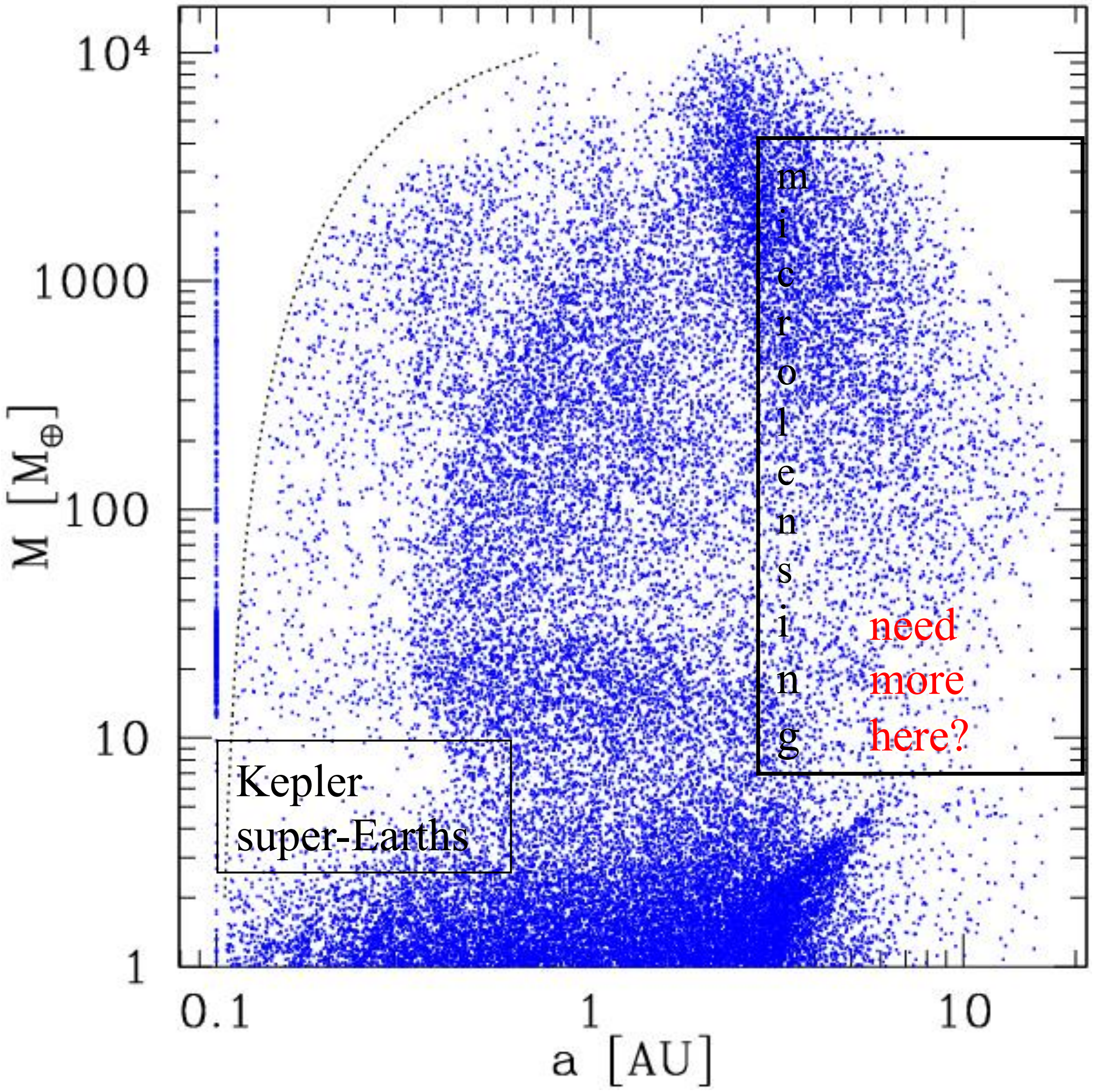


$M_d \sim M_s^{\alpha D}$

# Mordasini et al. (2012): 1 $M_{sun}$ , $f_I = 0.001$



# Mordasini et al. (2012): 1 $M_{sun}$ , $f_I = 0.001$

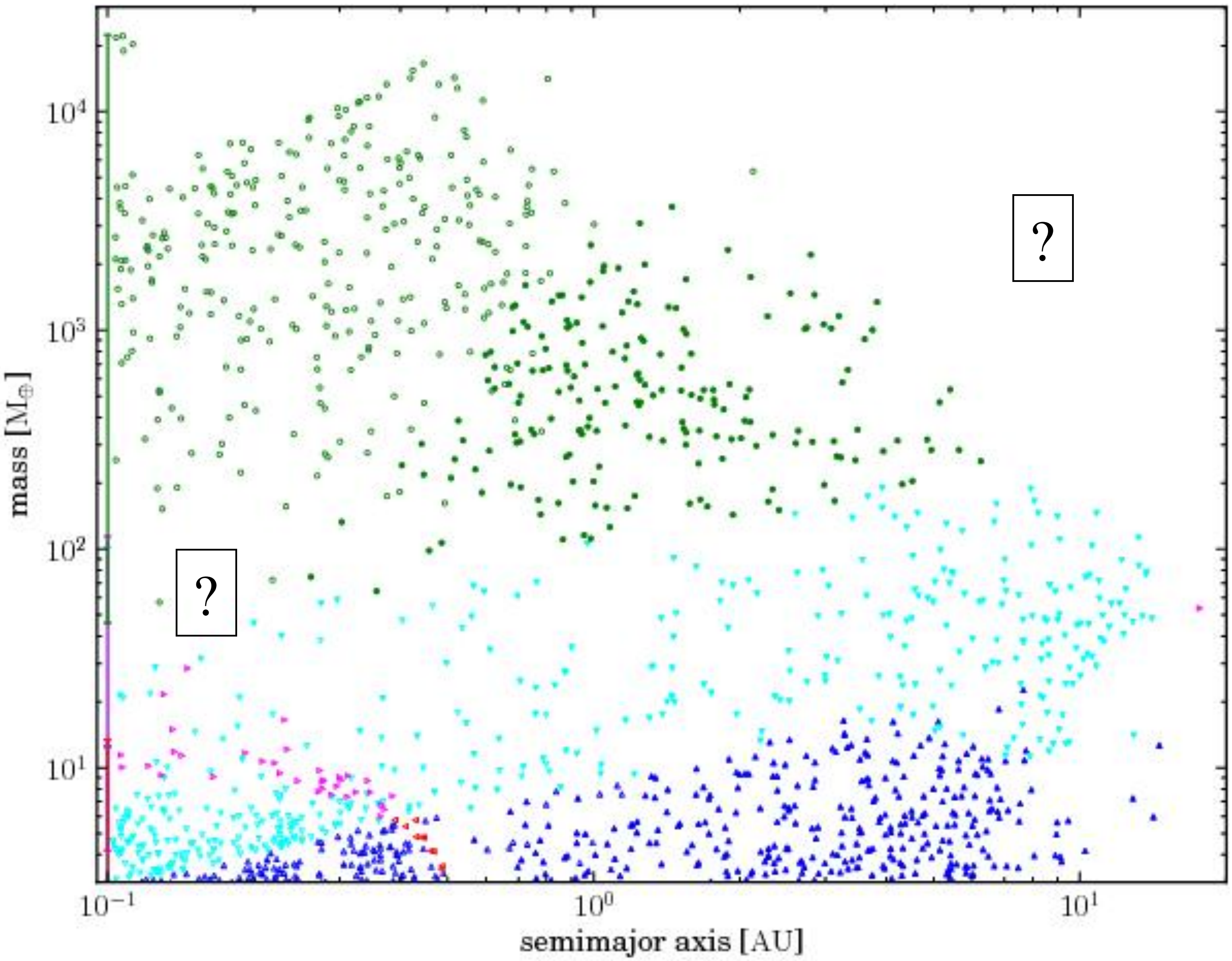


microlensing

need more here?

Kepler super-Earths

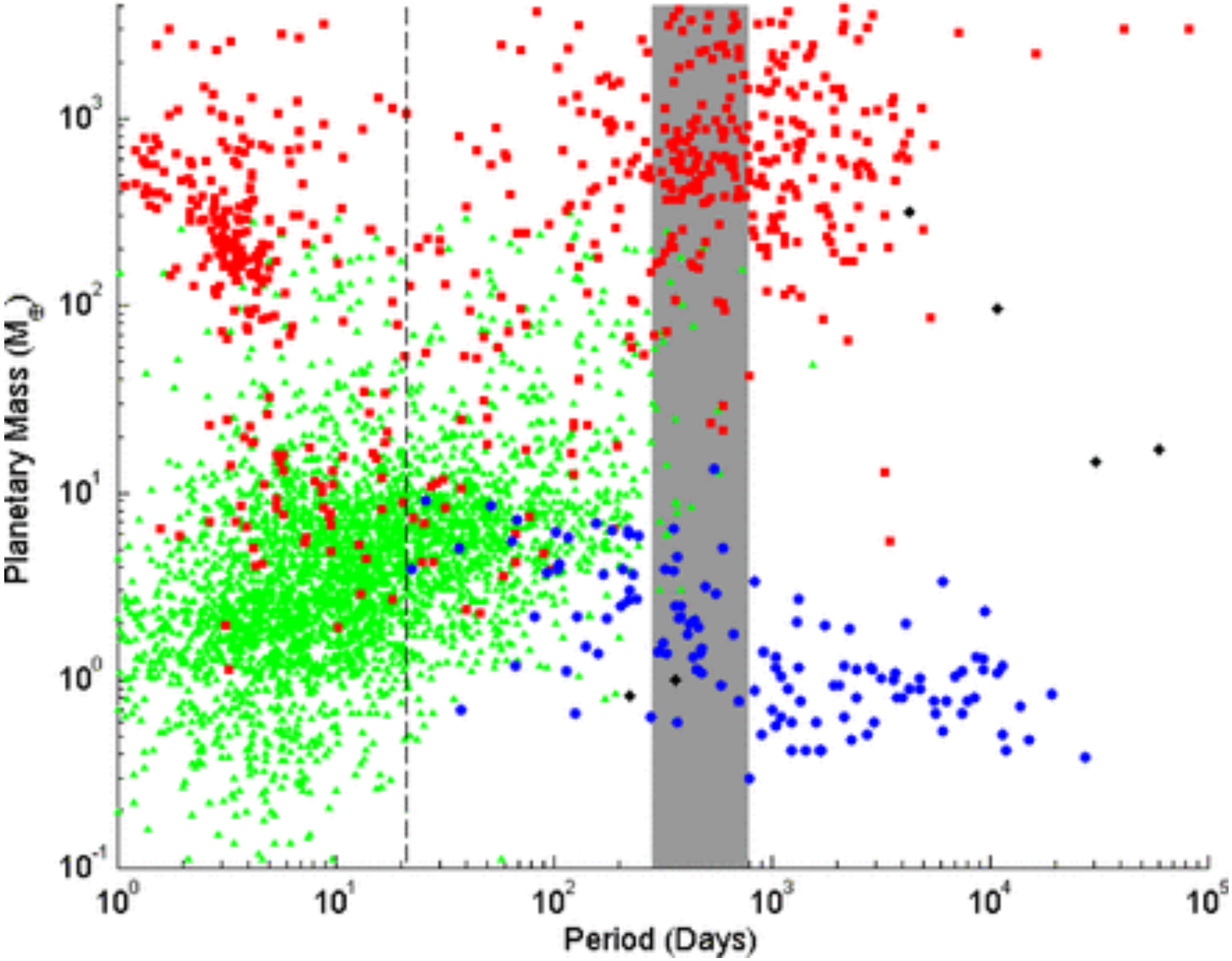
# Dittkrist, Mordasini et al. (2014): new migration model & stellar irradiation of disk

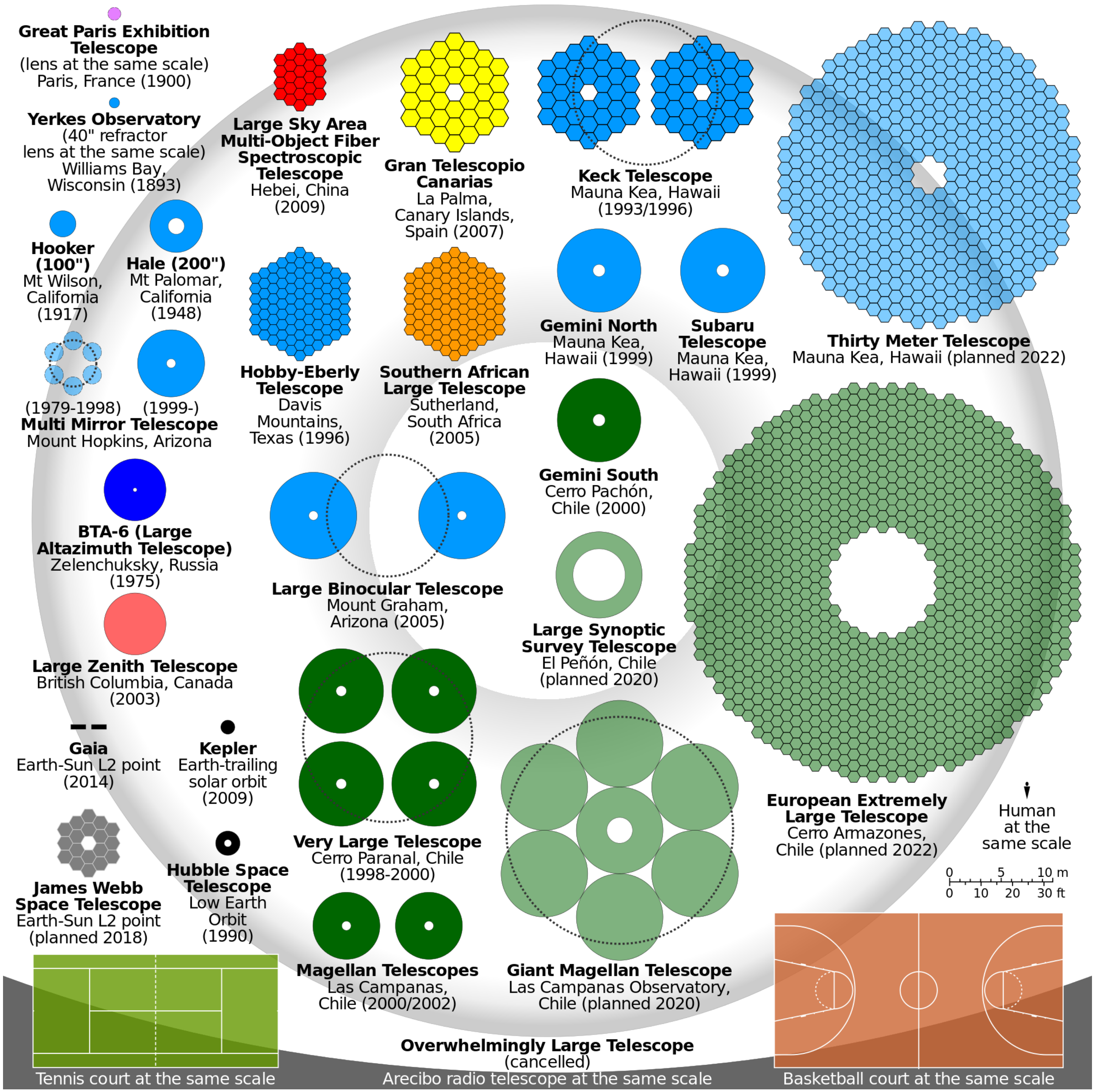


?

?

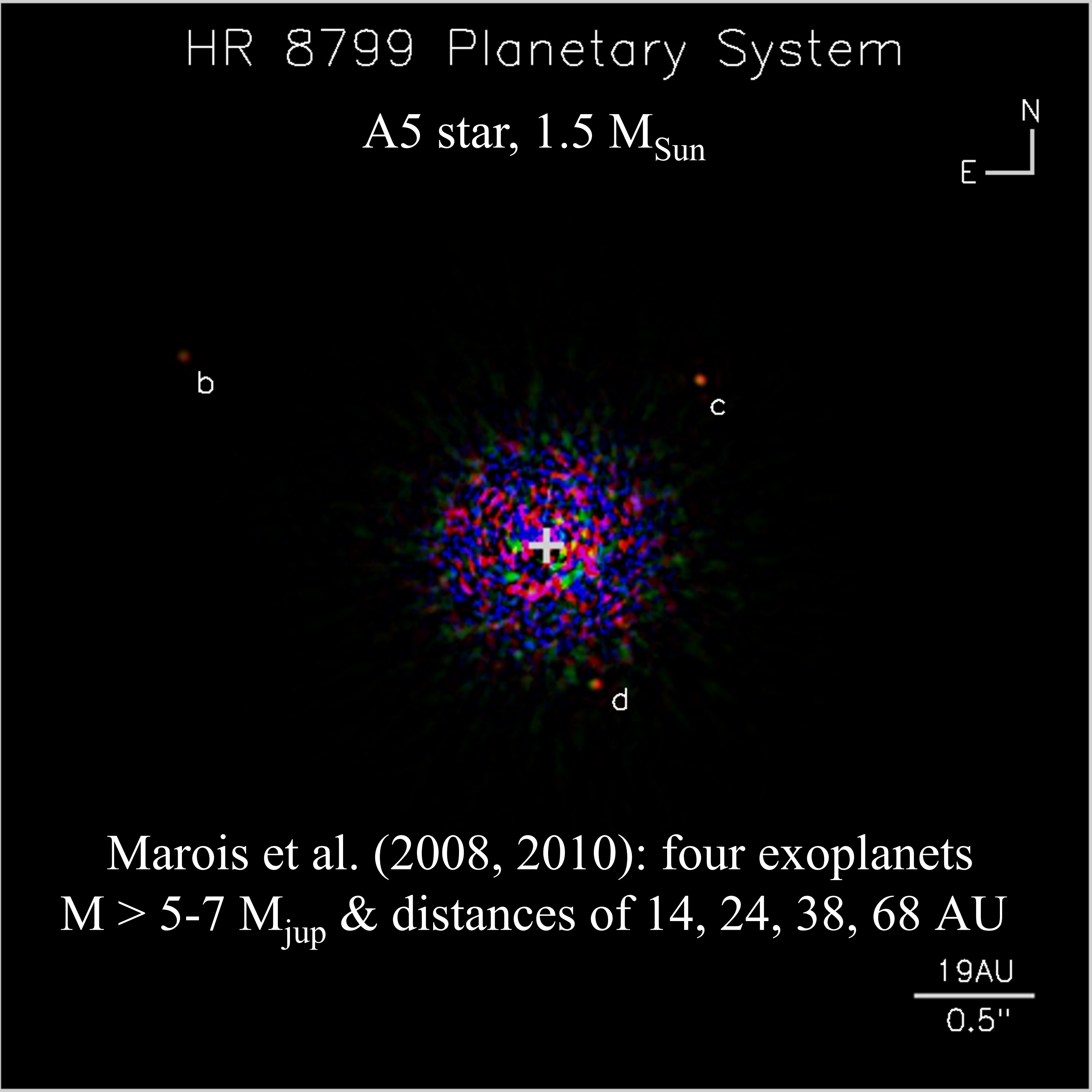
# Coleman & Nelson (2014): blue dots = detailed oligarchic growth & migration model




Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

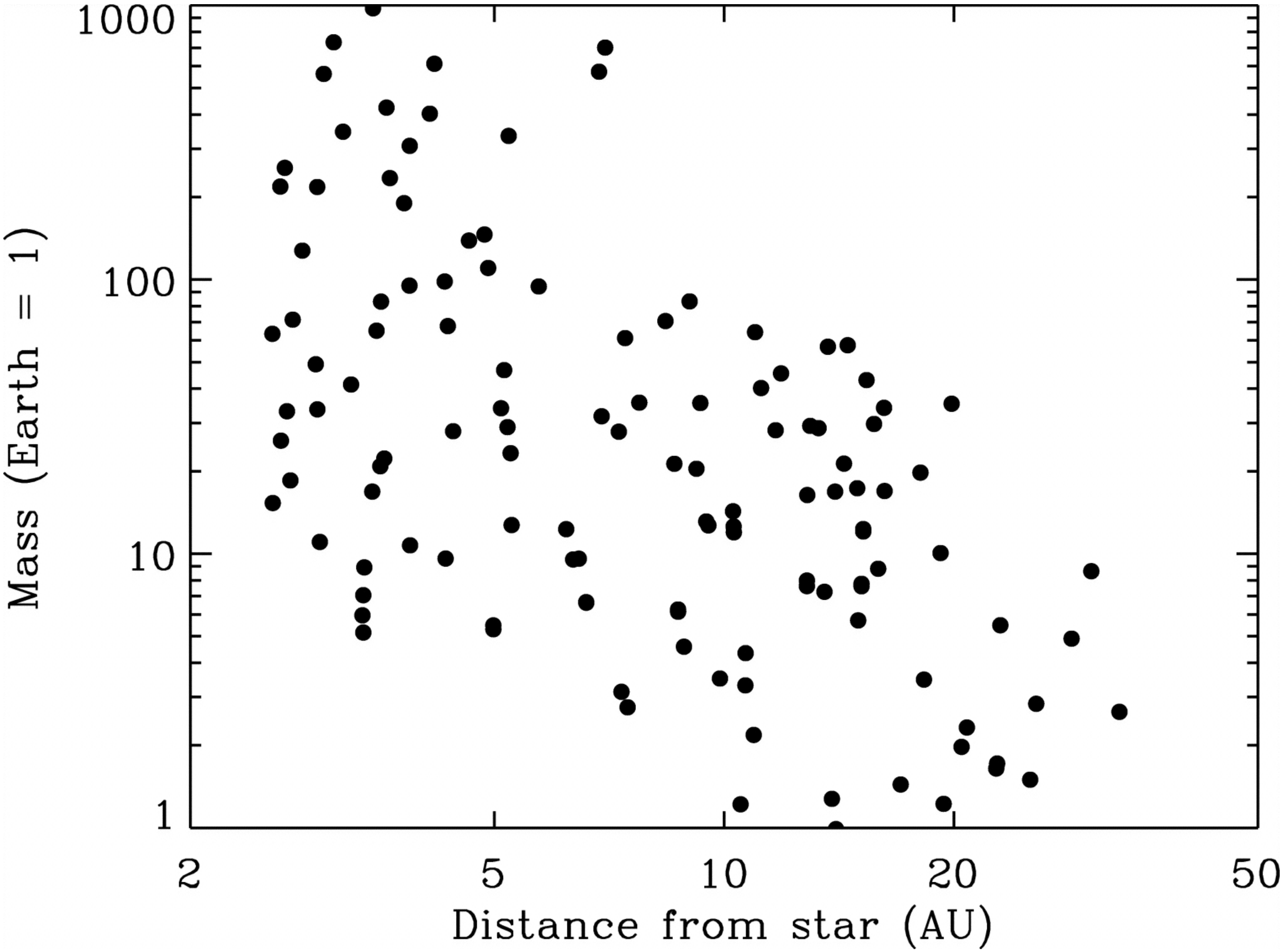
# HR 8799 Planetary System

A5 star, 1.5 $M_{Sun}$

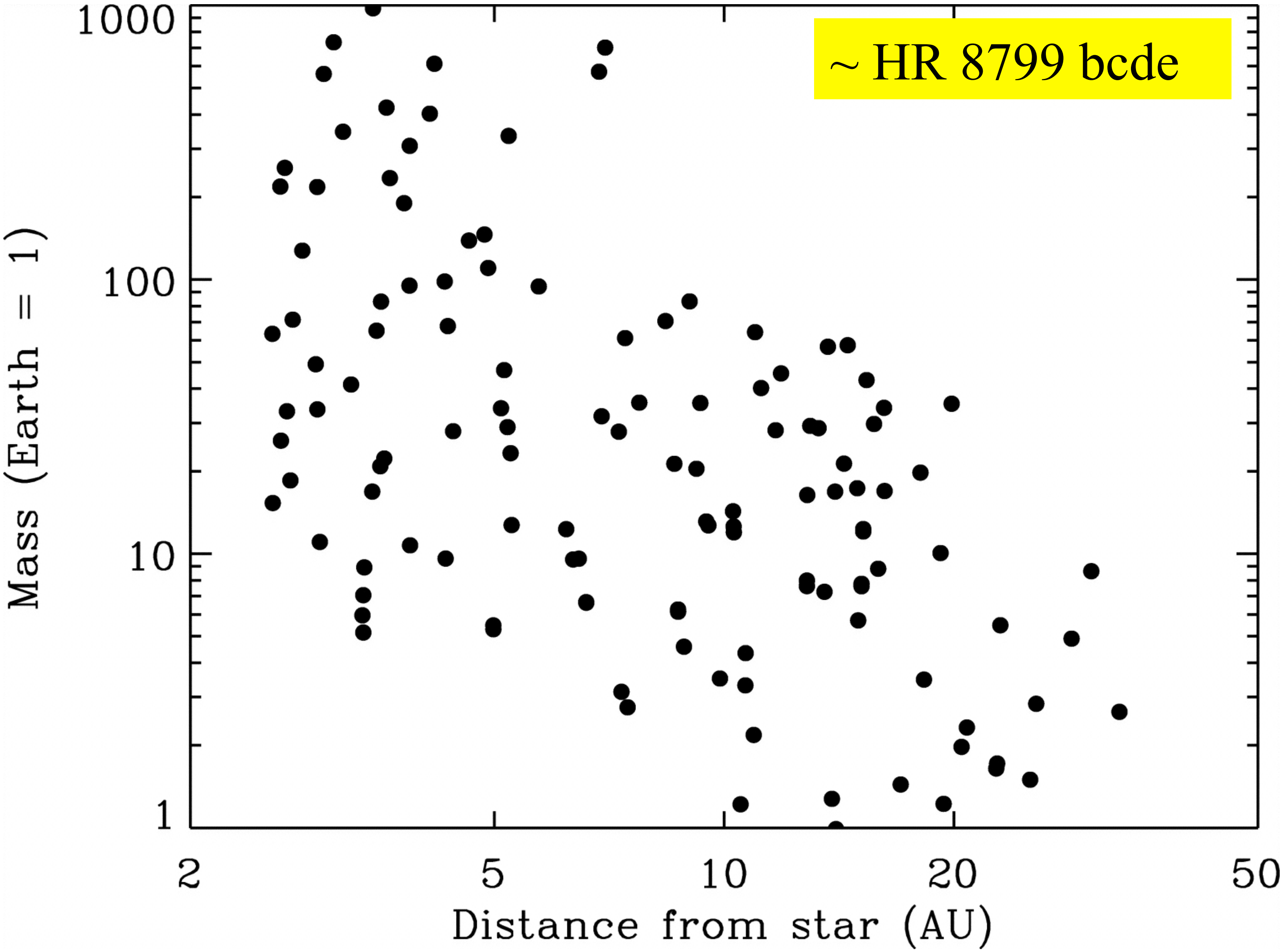


Marois et al. (2008, 2010): four exoplanets
$M > 5\text{-}7\ M_{jup}$ & distances of 14, 24, 38, 68 AU

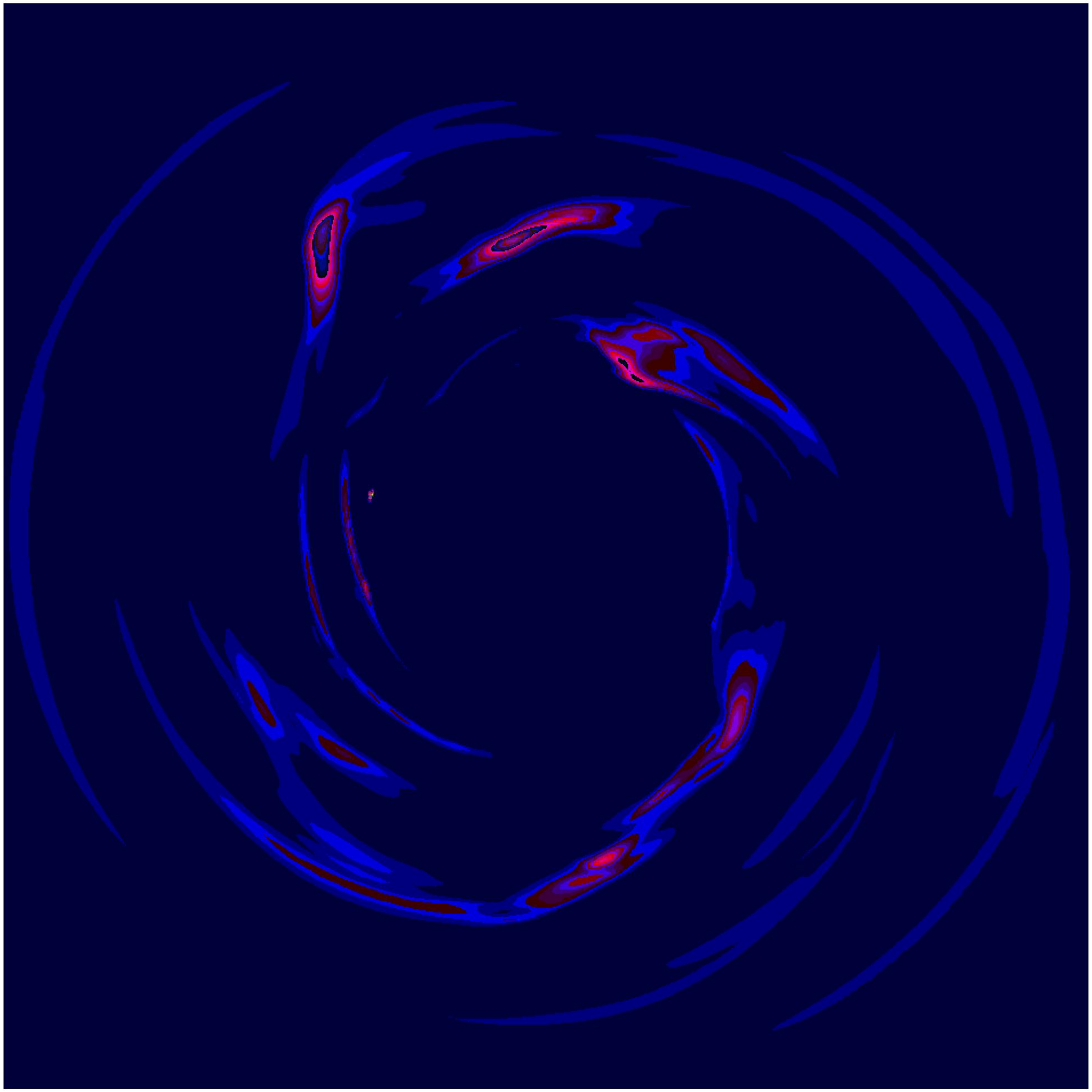
Chambers (2006) – core accretion in a 50 AU radius disk, 1 solar mass star



Chambers (2006) – core accretion in a 50 AU radius disk, 1 solar mass star

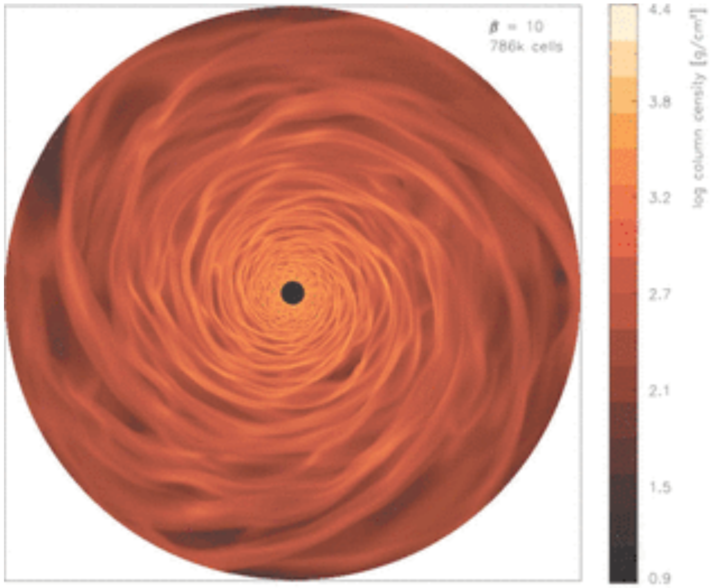


# Boss (2003): 1 $M_o$ star, 0.1 $M_o$ disk with 30 AU radius, DA-RT

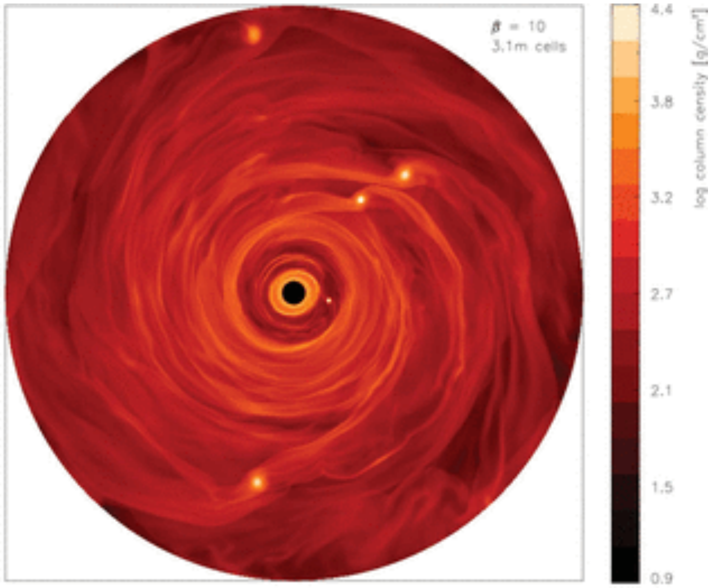


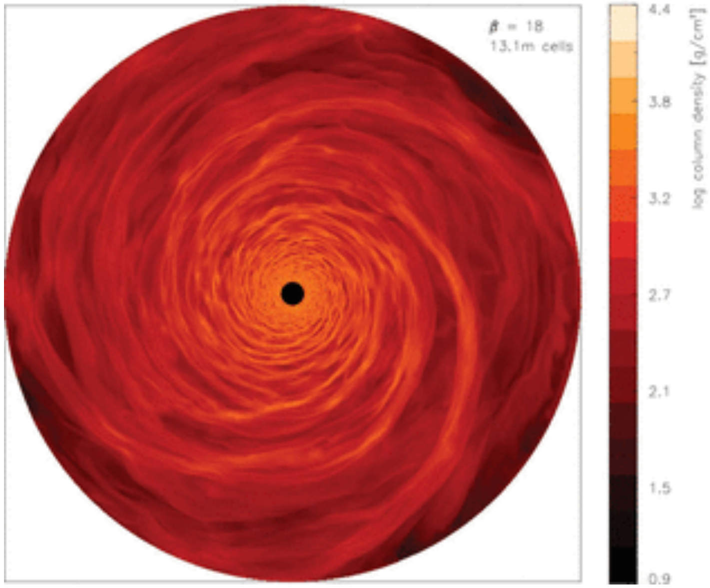
Meru & Bate (2011): 1 $M_o$ star, 0.1 $M_o$ disk with 25 AU radius

faster cooling →

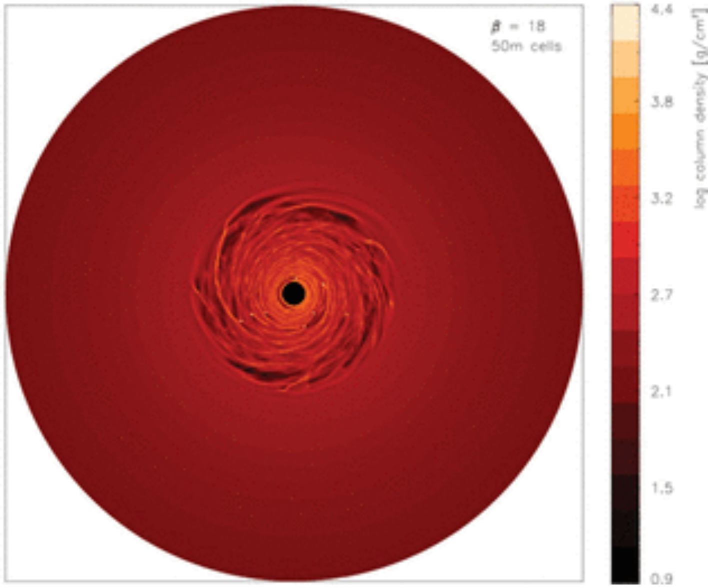


more
grid
cells
→

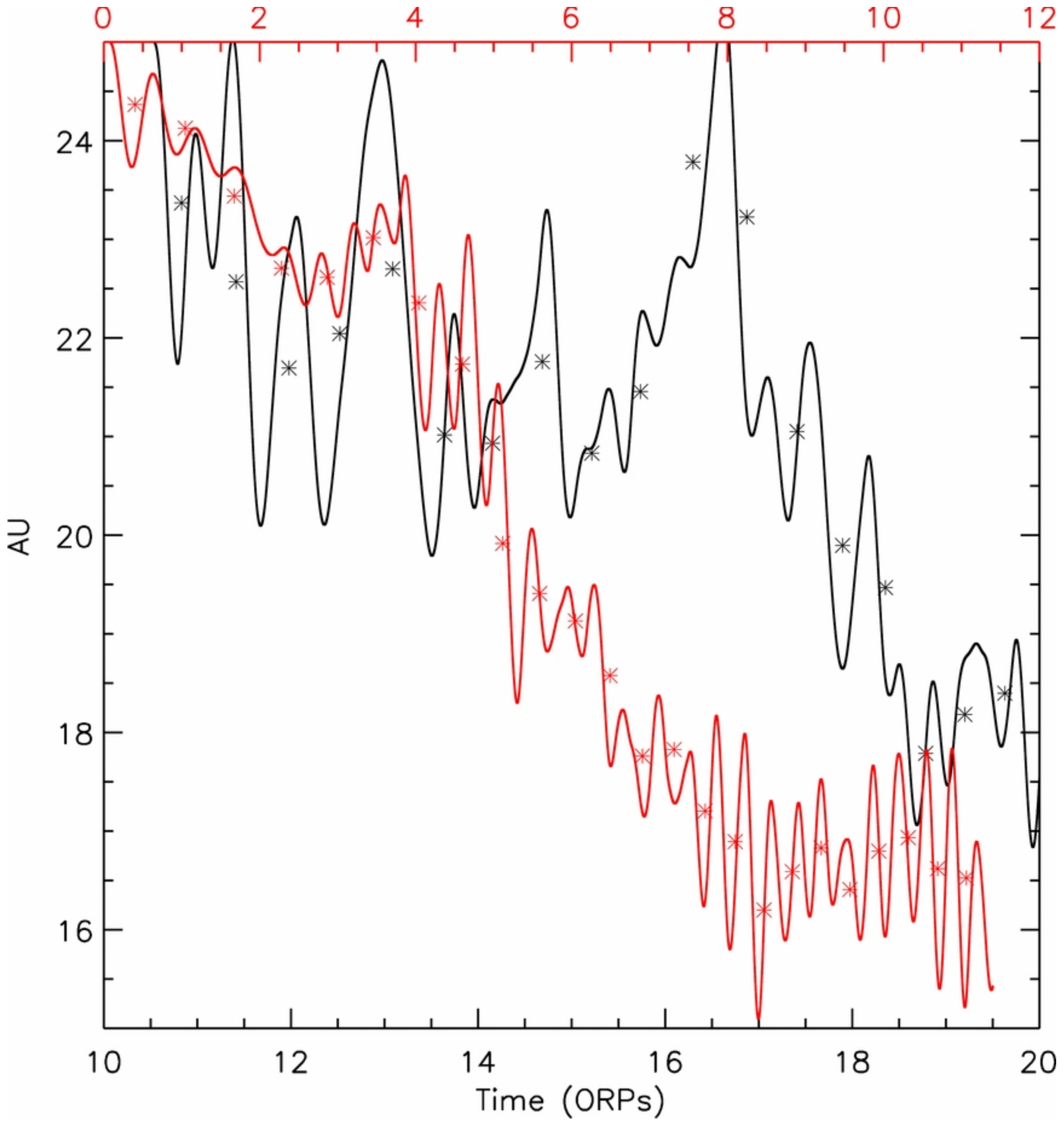




more
grid
cells
→



# Michael et al. (2011): 1 $M_o$ star, 0.14 $M_o$ disk with 40 AU radius, FLD



# Quanz et al. (2012): Gemini Deep Planet Survey

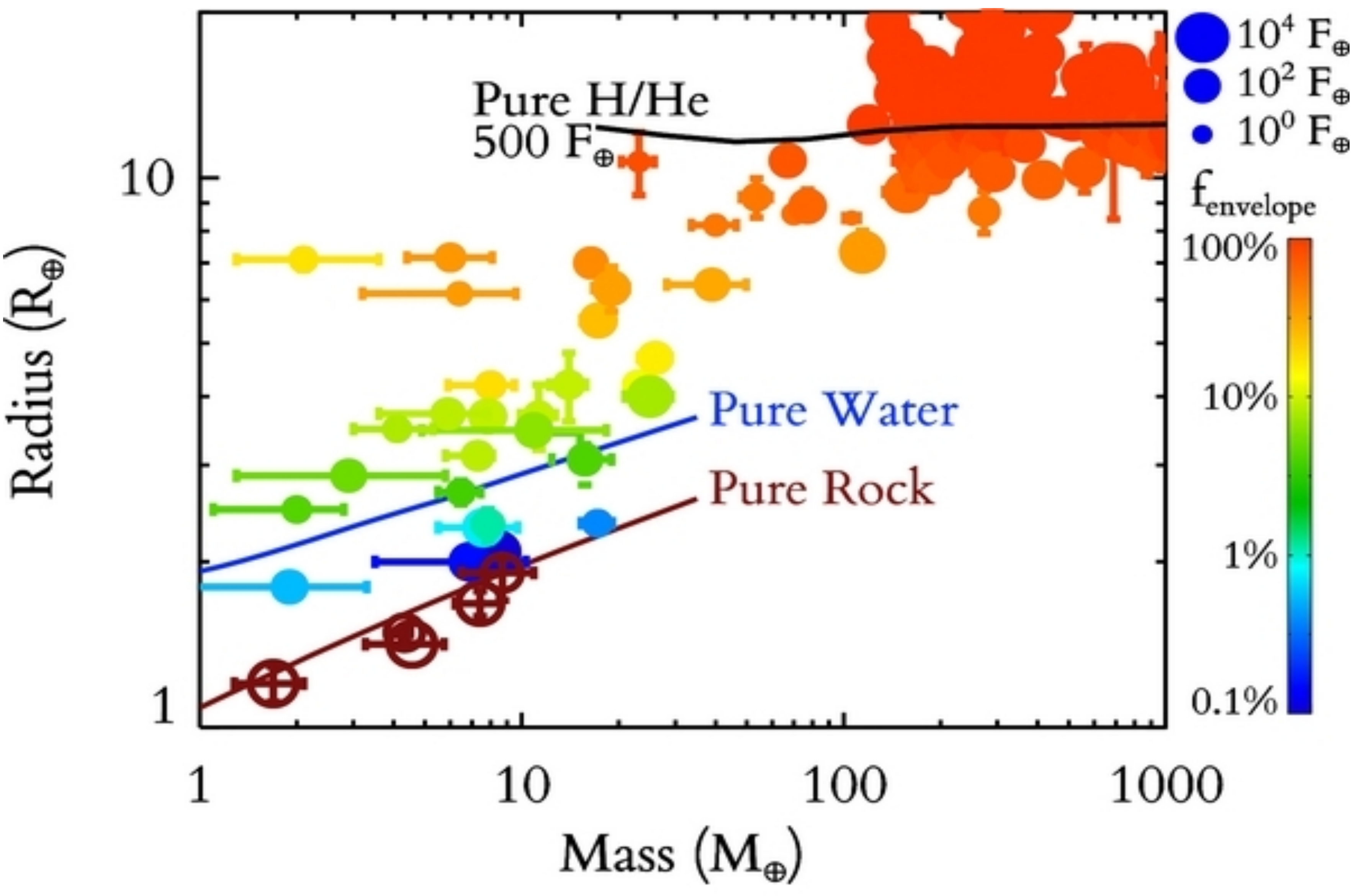
Table 1

Upper limit of stars having at least one planet (with 95% confidence) for different combinations of assumed planetary masses and semi-major axes.

| | $1\ M_{\mathrm{Jupiter}}$ | $0.5–3\ M_{\mathrm{Jupiter}}$ |
|---|---|---|
| $a = a_{\mathrm{min}}$ | 78% | 59 % |
| $a = 2a_{\mathrm{min}}$ | 49% | 29% |

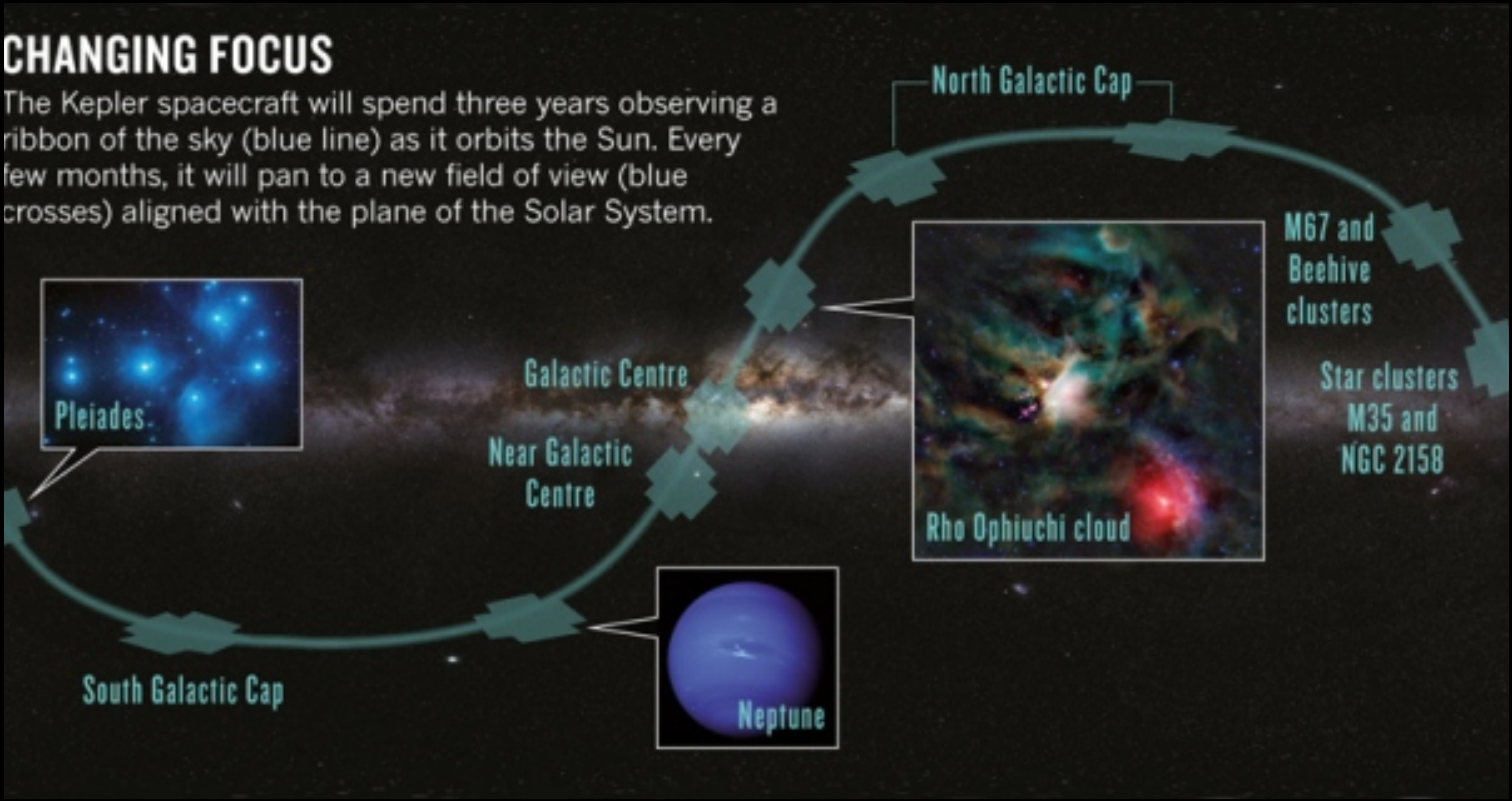
[$a_{\mathrm{min}} \sim 16$ AU (Sumi et al. 2011)]

# Lopez & Fortney (2014): M, R for 200 exoplanets



# Exoplanet
## Missions

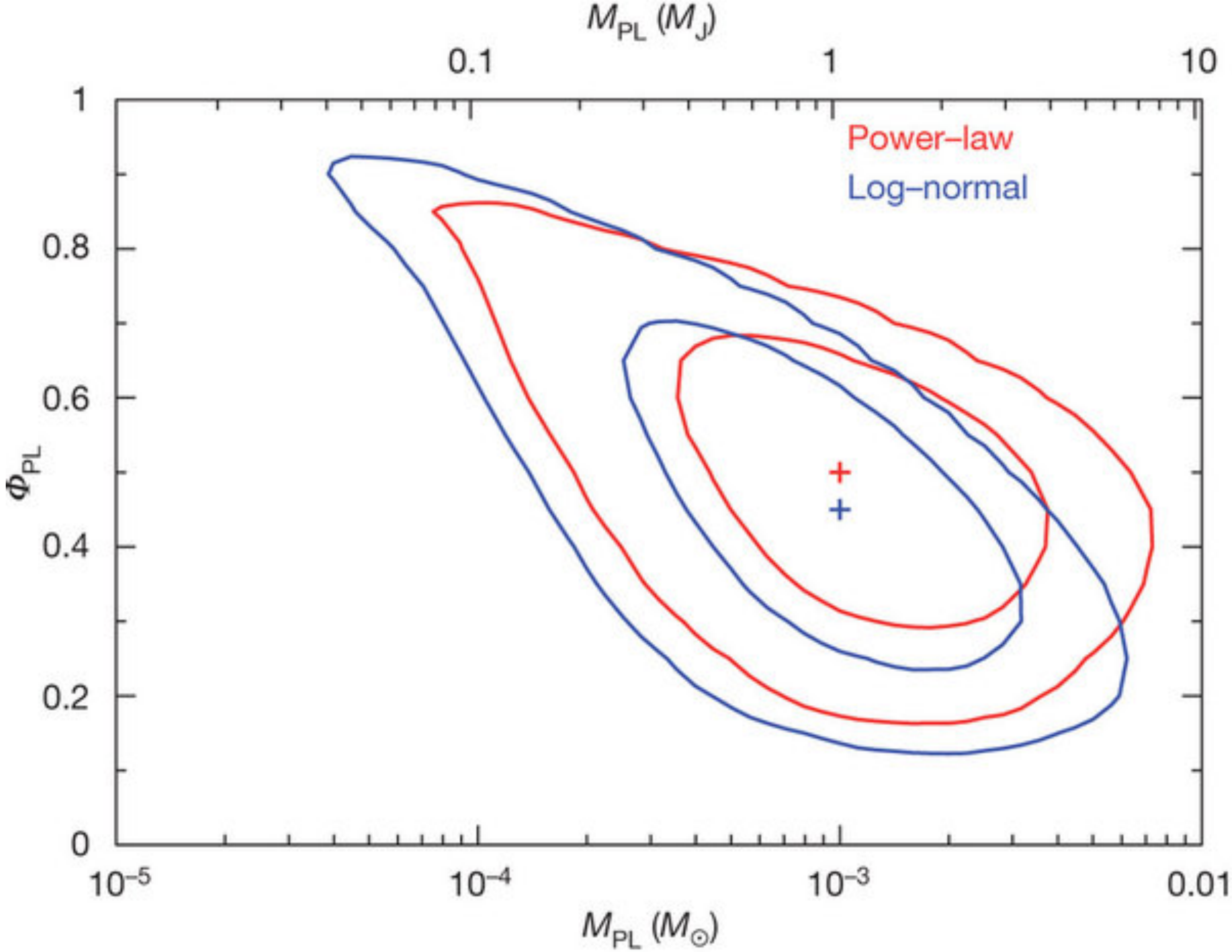
# Kepler K2 Mission



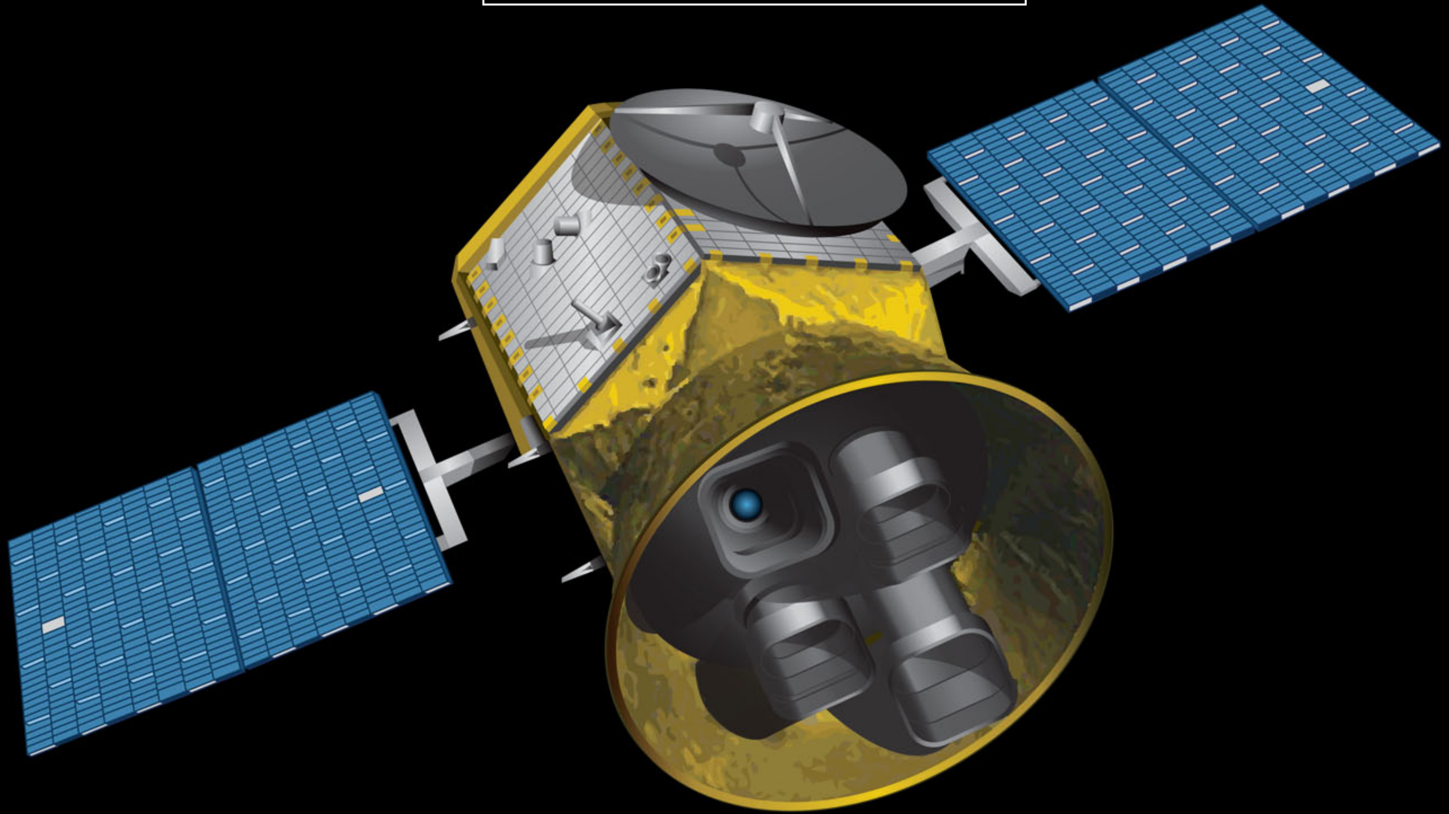
**CHANGING FOCUS**

The Kepler spacecraft will spend three years observing a ribbon of the sky (blue line) as it orbits the Sun. Every few months, it will pan to a new field of view (blue crosses) aligned with the plane of the Solar System.

Sumi et al. (2011) microlensing: Jupiters > 10 AU ~1.8 as frequent as MS stars



TESS: 2017 launch

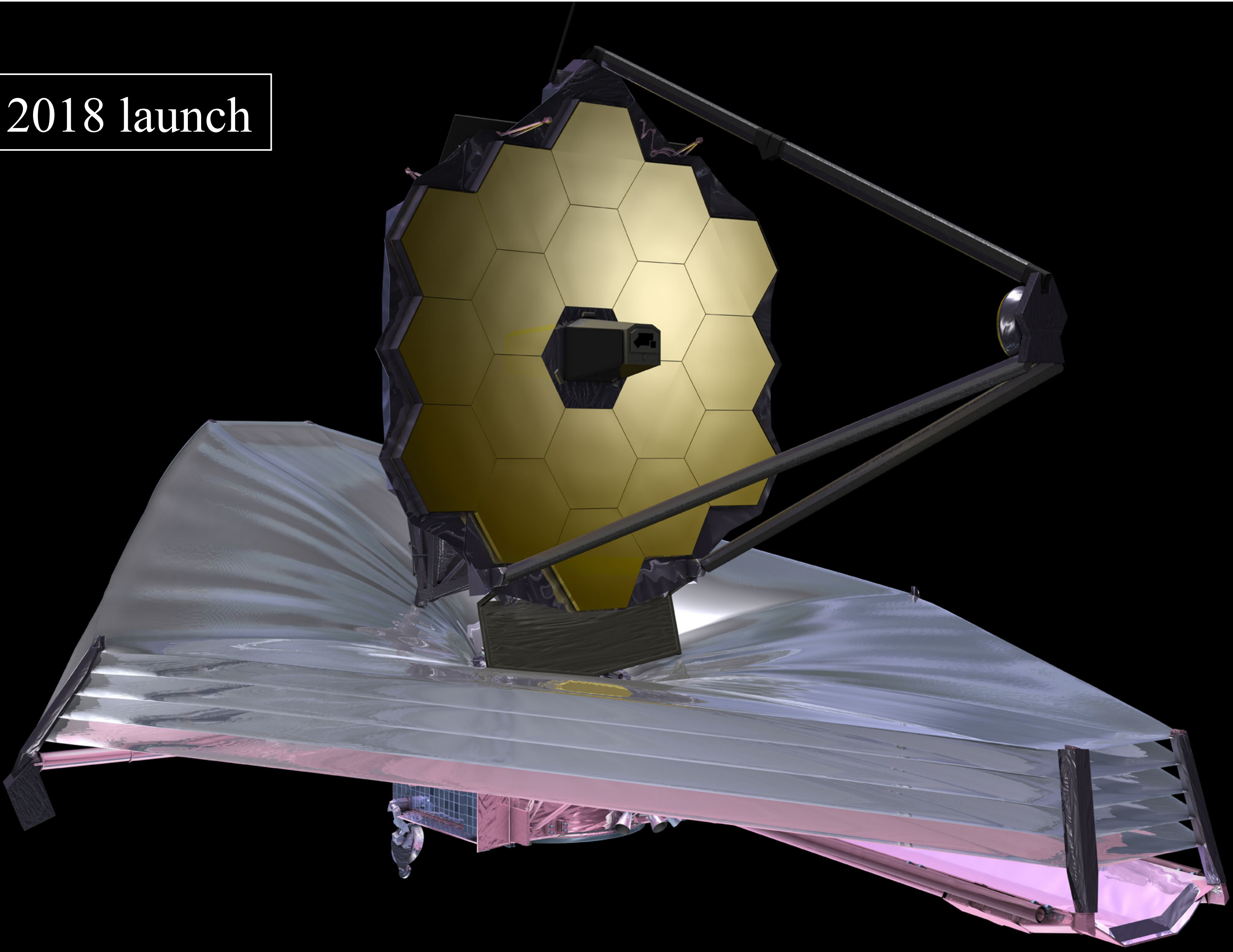


# TRANSITING EXOPLANET SURVEY SATELLITE

*DISCOVERING NEW EARTHS AND SUPER-EARTHS*
*IN THE SOLAR NEIGHBORHOOD*

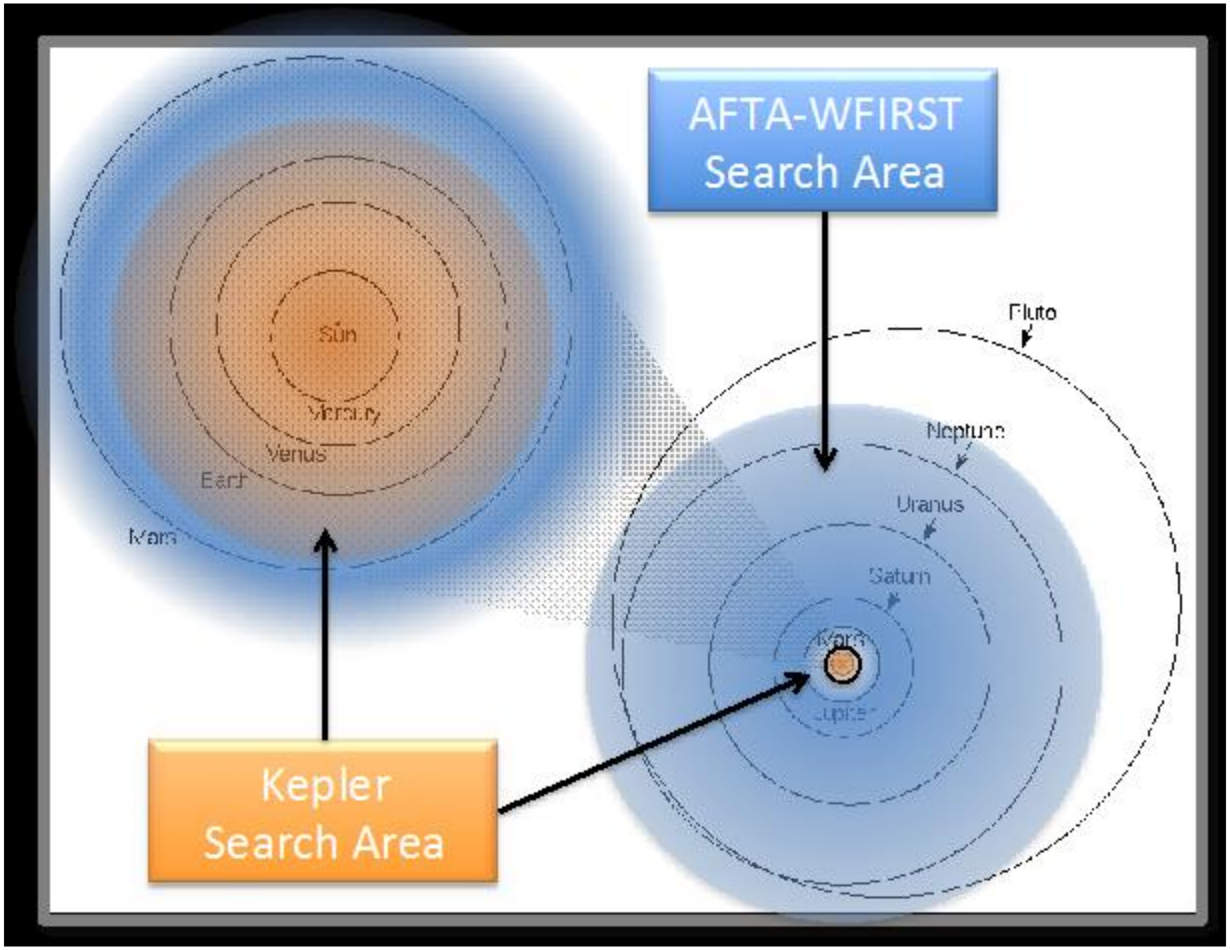
TESS and JWST (Deming et al. 2009): 1 to 4 habitable super-Earths?

JWST: 2018 launch

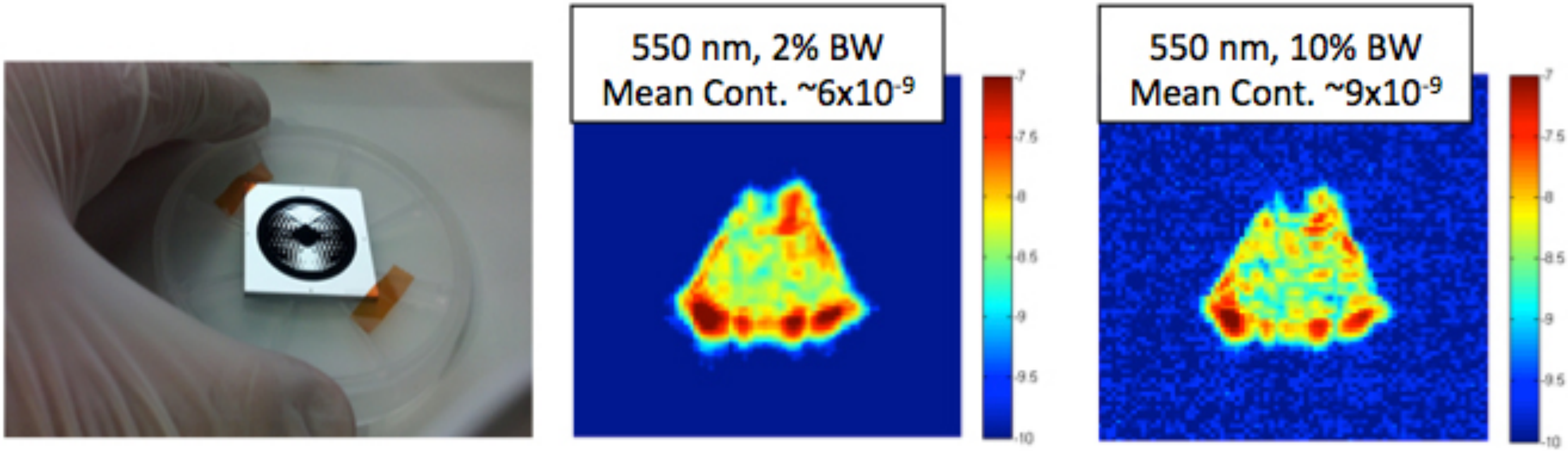


# 2.4-m NRO telescope = WFIRST/AFTA: 2023 launch?

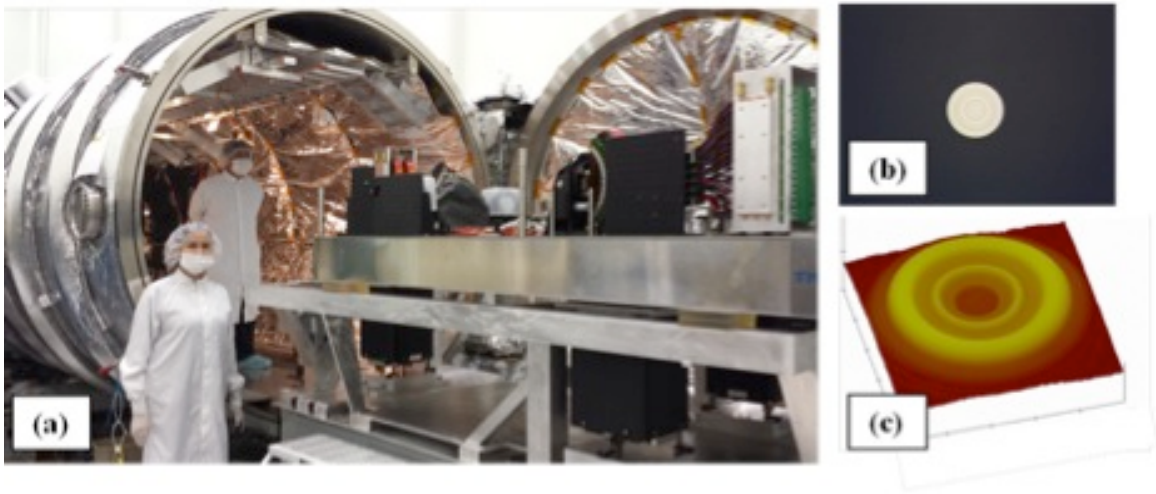
# WFIRST/AFTA gravitational microlensing (> 1AU): planet census complementary to Kepler (< 1 AU)



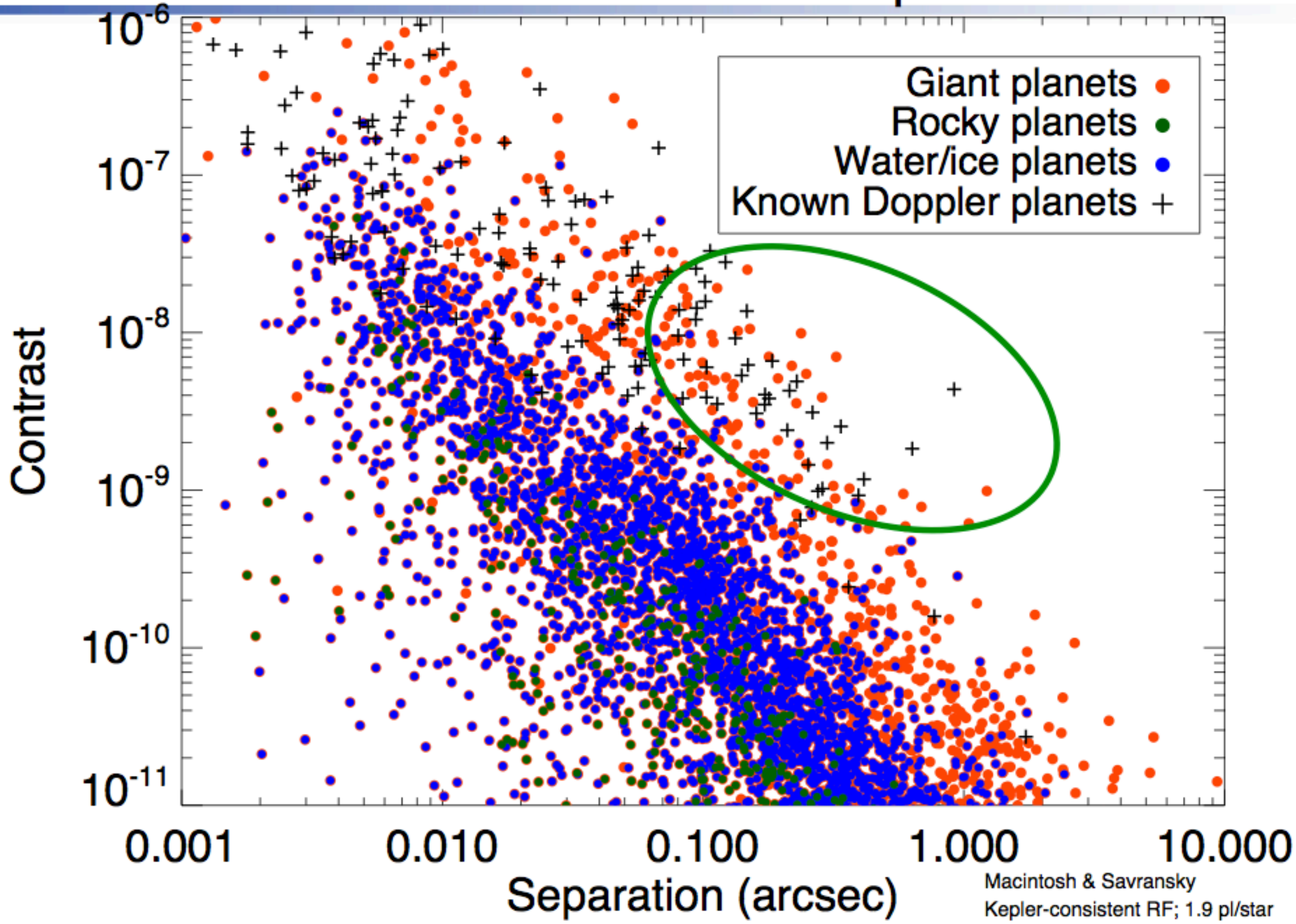
Reflective shaped pupil mask: one-sided dark hole generated by the shaped pupil coronagraph in narrowband (2%) light and broadband (10%) light:



Hybrid Lyot coronagraph testbed in vacuum tank and circular hybrid Lyot coronagraph mask imaged under optical and atomic force microscopes:



# Planets within 30 pc

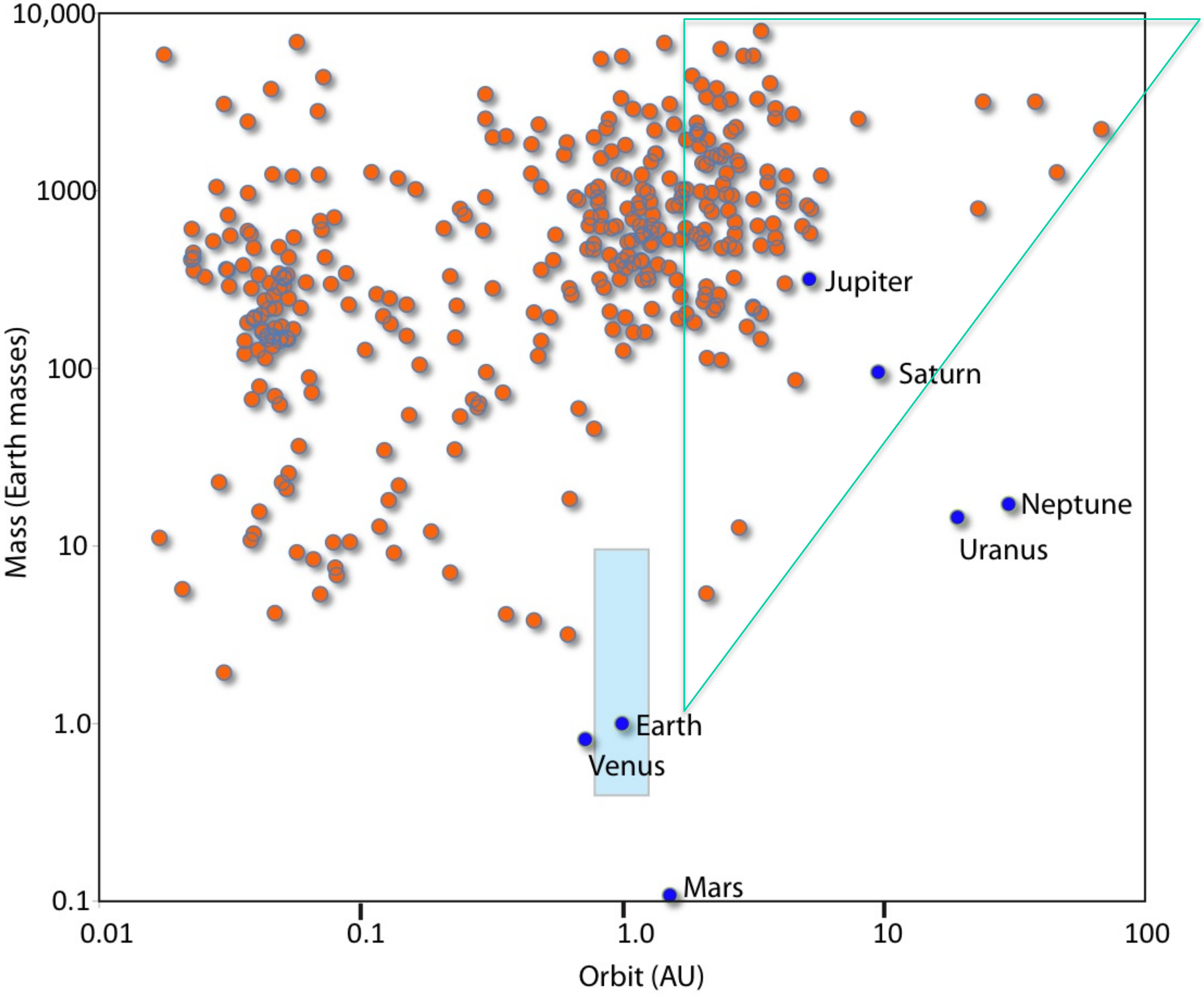


Macintosh & Savransky

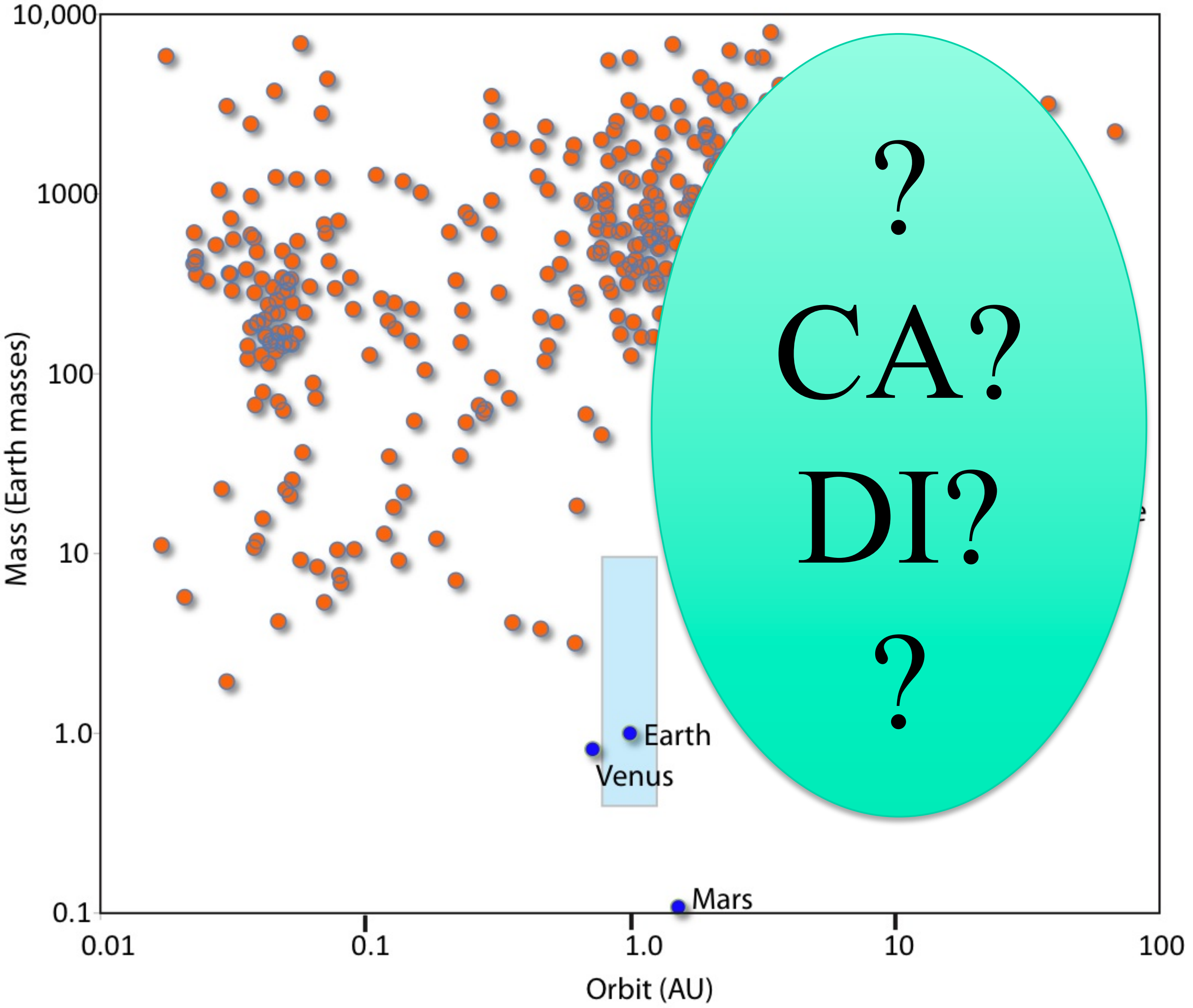
Kepler-consistent RF; 1.9 pl/star

Main sequence non binary stars

# Outer region of discovery space circa 2010 – microlensing and direct-imaging



# Discovery space circa 2025: WFIRST/AFTA detections



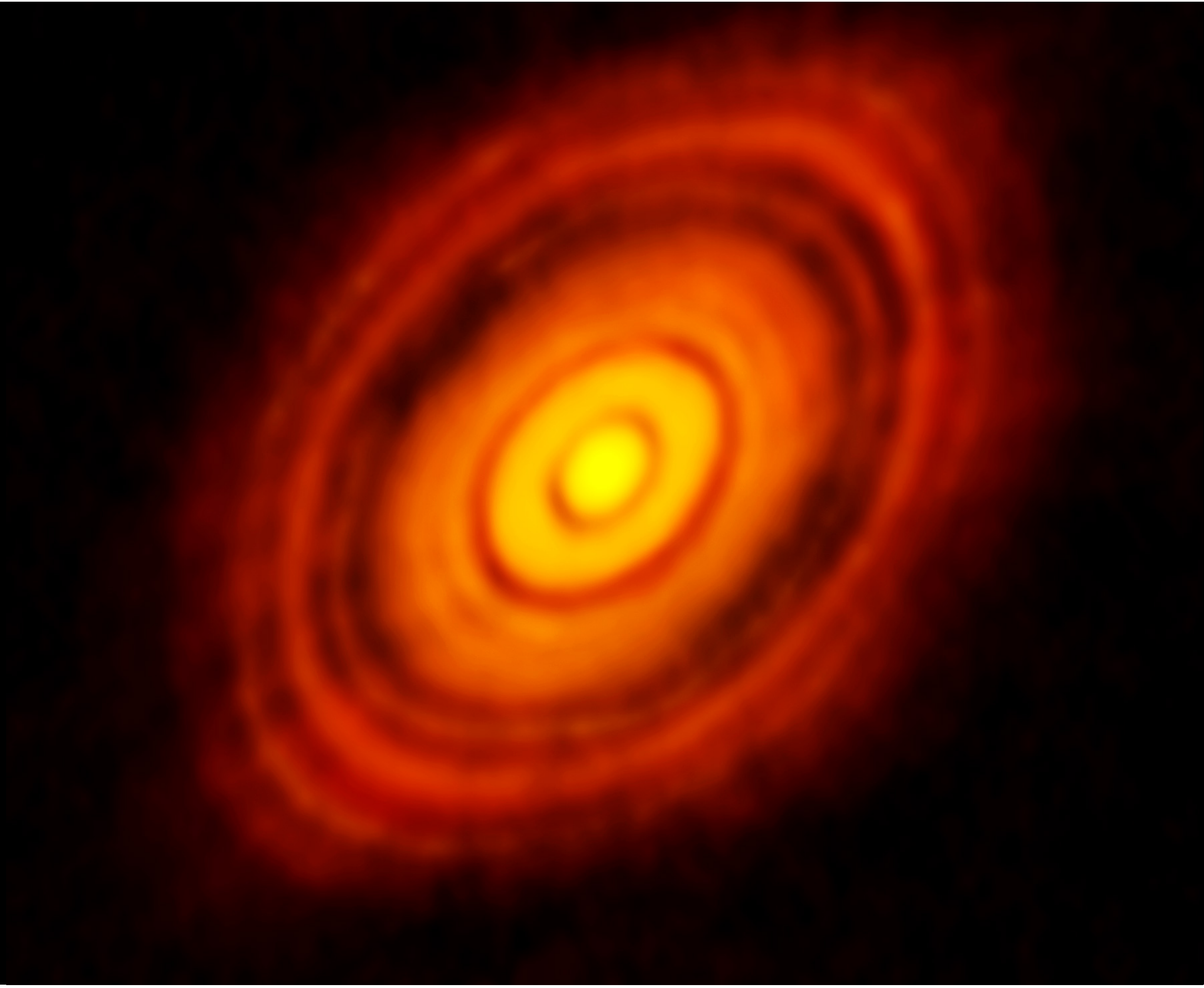
?

CA?

DI?

?

# HL Tauri - K9 - ~0.5 $M_{sun}$- ~1 Myr - ~100 AU - ALMA



## QUICK & EASY DIRECTIONS

**MIX SOUP + 1 OCEAN WATER**

**RADIATION : HEAT,** UNCOVERED IN MICROWAVABLE OCEAN ON HIGH ABOUT 100 MILLION YEARS. CAREFULLY LEAVE IN OCEAN FOR 3 BILLION YEARS, ALLOWING OXYGEN TO ACCUMULATE.

**SMOKER: HEAT,** CIRCULATING OCCASIONALLY

REG. U.S. PAT. & TM. OFF.

PROMPTLY REFRIGERATE UNUSED PORTION ON A SEPARATE PLANET.
RECOMMEND USE BY DATE ON END OF CAN.
STORE UNOPENED CAN IN INTERSTELLAR SPACE.

### Nutrition Facts

Serv. Size 1 mole serves one planet

**Calories** 0.0

Fat Calories 0.0

Serving size based on a 99% chance of a successful Origin of Life.

| Amount/serving | %DV | Amount/serving | %DV |
|---|---|---|---|
| Protein | 0% | Metal sulfides | 100% |
| Fat | 0% | Hydrogen | 100% |
| Carbohydrate | 0% | Ammonia | 100% |
| Fiber | 0% | Methane | 100% |
| Vitamins | 0% | Carbon monoxide | 100% |
| L-amino acids | 1% | Formaldehyde | 100% |
| D-amino acids | 1% | High MW PAHs | 100% |
| Nucleic acid | 0% | NP-40 | 100% |

Rich in reducing power, low in toxic oxygen and reactive oxygen products. High in heavy and transition metals. Great for the hottest, most radioactive watery planets!

Satisfaction guaranteed. For questions or comments,
please email arthur_dent@zz9.plural.z.alpha
Allow 5-6 x 10^24 years for refund or reply.

0 51000 01251 7

1251-108-10

CARBON
Please RECYCLE
WHERE ENZYMES AVAILABLE

# Campbell's®

CONDENSED

PARIS INTERNATIONAL EXPOSITION 1900

# Primordial

# SOUP

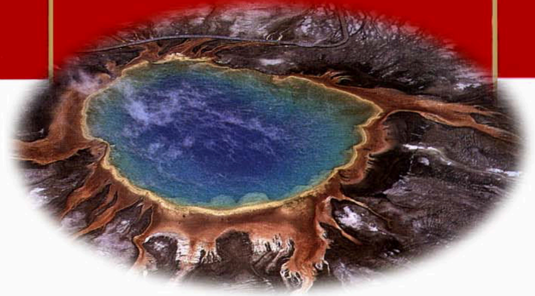
NET WT.
10 3/4 OZ.
(305g)

INSPECTED FOR WHOLESOMENESS BY U.S. DEPARTMENT OF CHEMISTRY

**A QUICK MEAL IN 4.5 BILLION YEARS!**

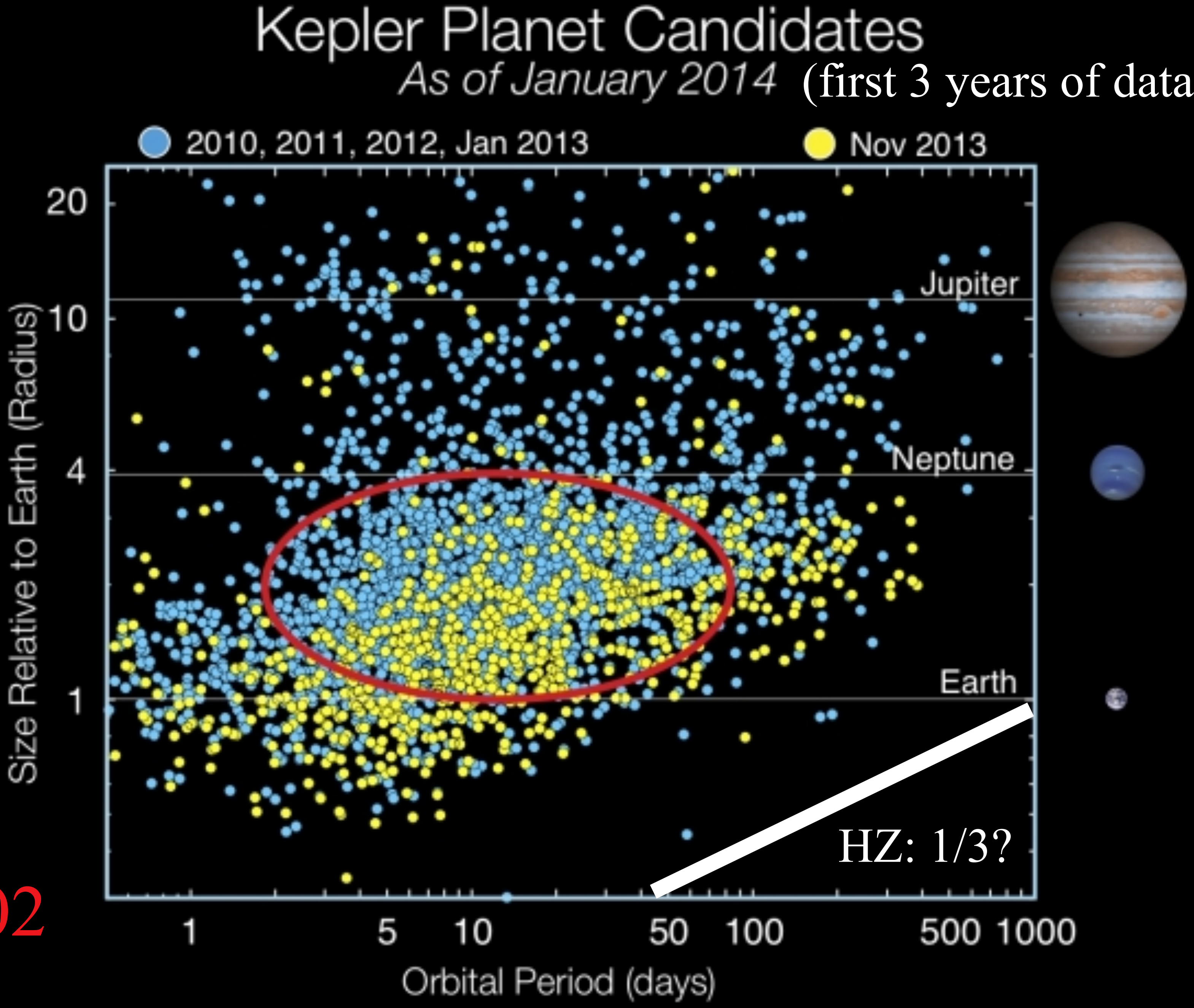
**PRIMORDIAL SOUP; FOR THE PRIMITIVE... AND THE PRIMITIVE AT HEART!**

A SIMPLE, SELF-ORGANIZING MEAL WITH EVERYTHING YOU NEED TO GET YOUR LIFE STARTED BEFORE THE ARCHAEAN PASSES BY. GREAT FOR ALL WATERY PLANETS, SERVE HOT WITH LOTS OF REDUCING POWER AND A GOOD DOSE OF IONIZING RADIATION FOR THAT UNIQUE MICROBIAL FLAVOR!



INGREDIENTS: WATER, SILICA, IRON SULFIDE, HYDROGEN SULFIDE, CARBON DIOXIDE, HYDROGEN, POTASSIUM CYANIDE, POTASSIUM ACETATE, FORMALDEHYDE, ADENINE, PROLINE, ALANINE, METHANE, CARBON MONOXIDE, AMMONIA, SODIUM ARSENITE, GLYCEROL PHOSPHATE, ACETYLENE, ACETALDEHYDE, HIGH MOLECULAR-WEIGHT PAH'S, PYRENE, MAGNETITE, PHOSPHORIC ACID, WOLF'S TRACE MINERALS. AND NP-40.

JWB MOCK SOUP COMPANY, RALEIGH, NORTH CAROLINA JAMES_W_BROWN@EARTHLINK.NET



Kepler Planet Candidates

*As of January 2014* (first 3 years of data)

HZ: 1/3?

3602

New Worlds Telescope?
~ TPF Coronagraph?
~ NWO Star Shade?