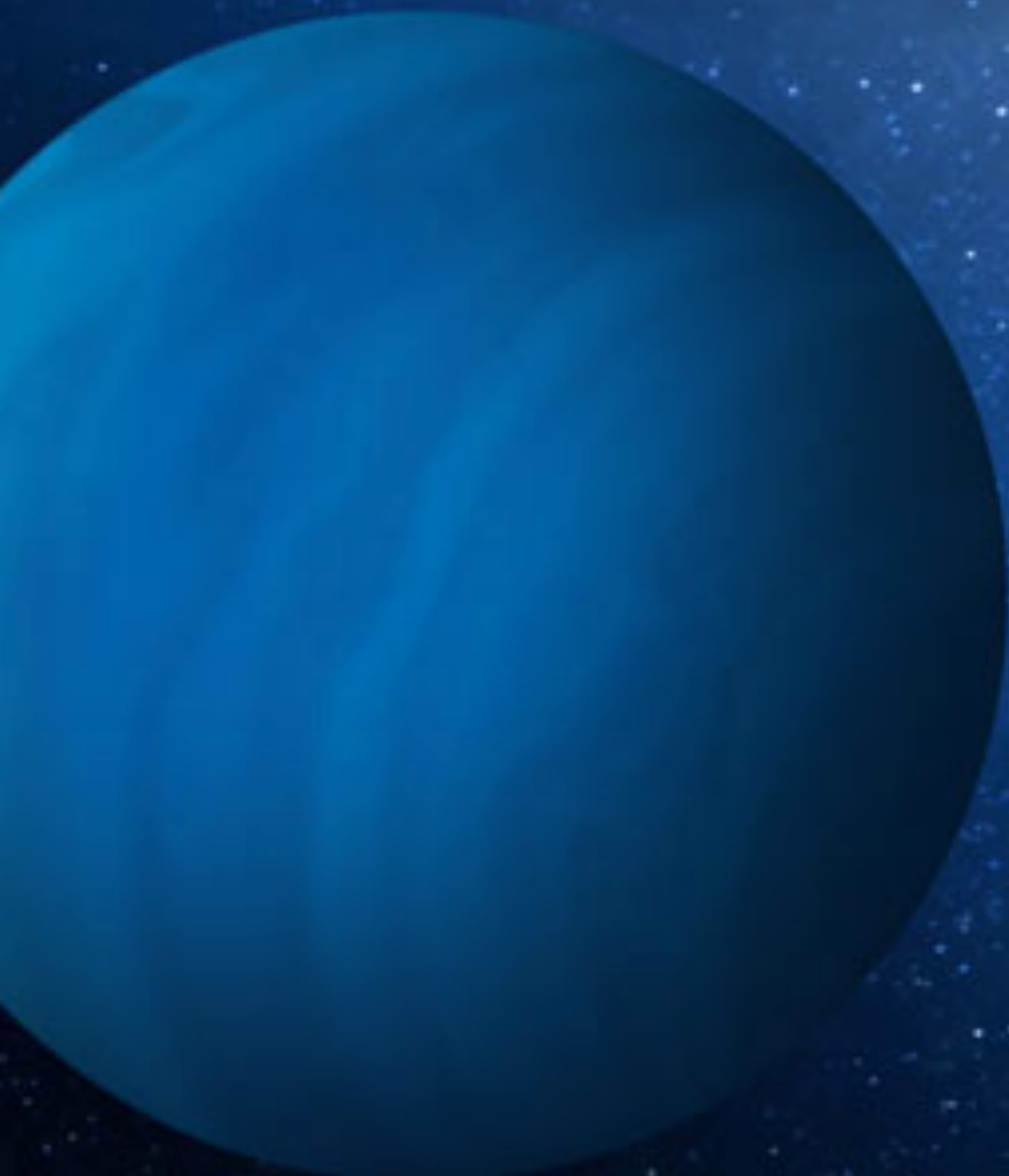
Formation of Free Floating Planets

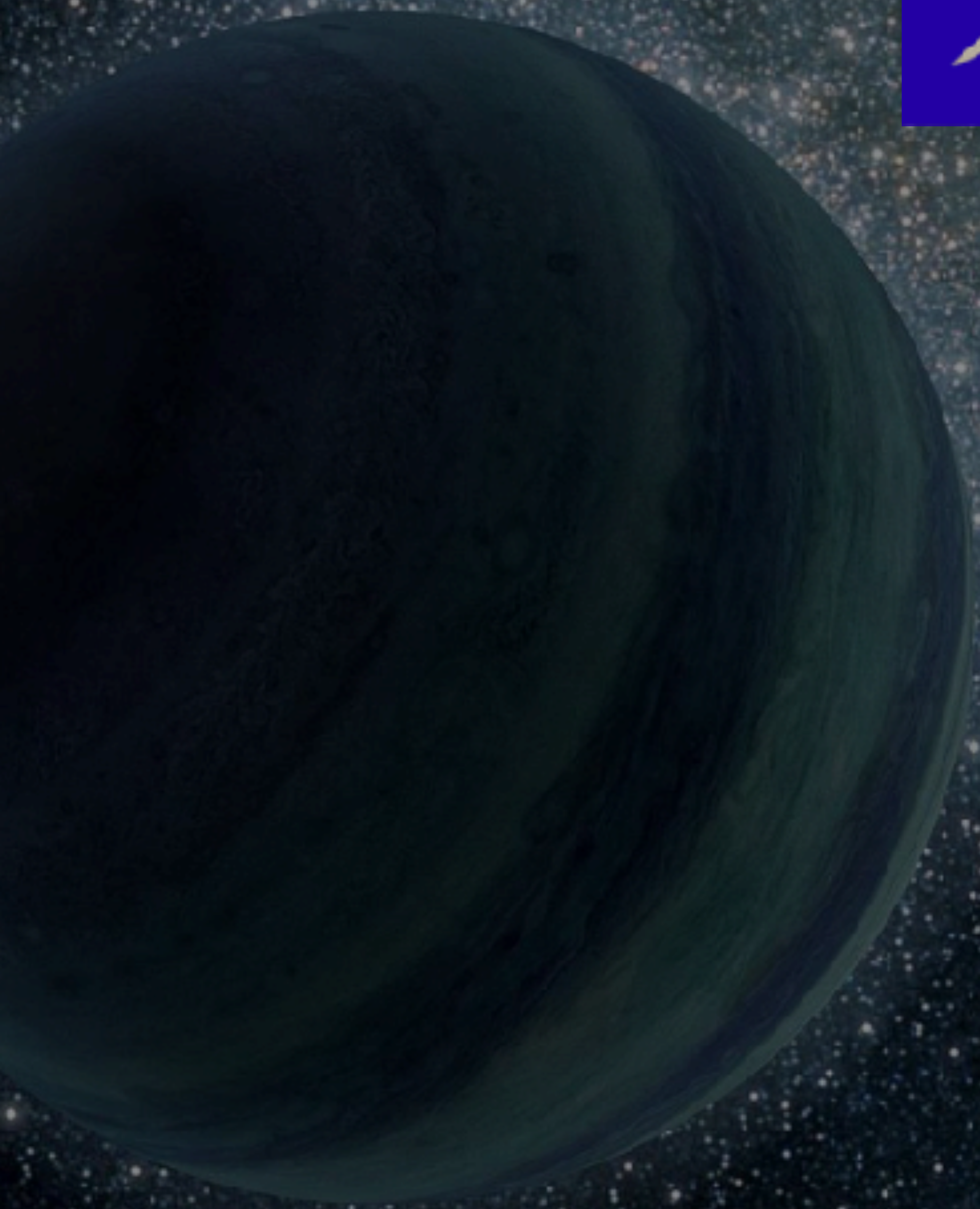


Elisa Quintana
NASA Goddard Space Flight Center

Sagan Workshop 2017

Overview

Exoplanet Population
Free Floating Planets
Formation Mechanisms
FFP yields via Ejection
- G stars
- M stars

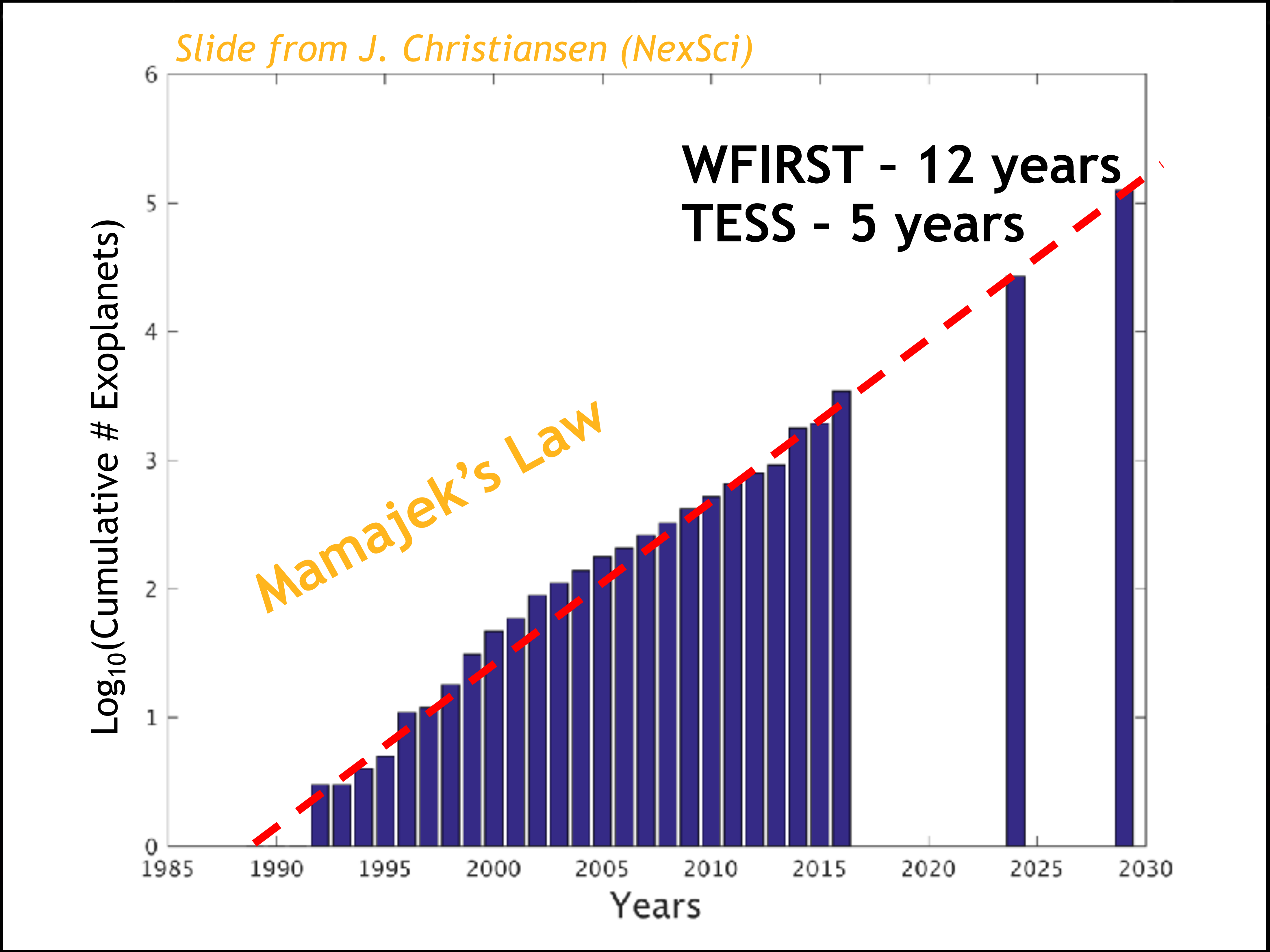


Confirmed Exoplanet Statistics

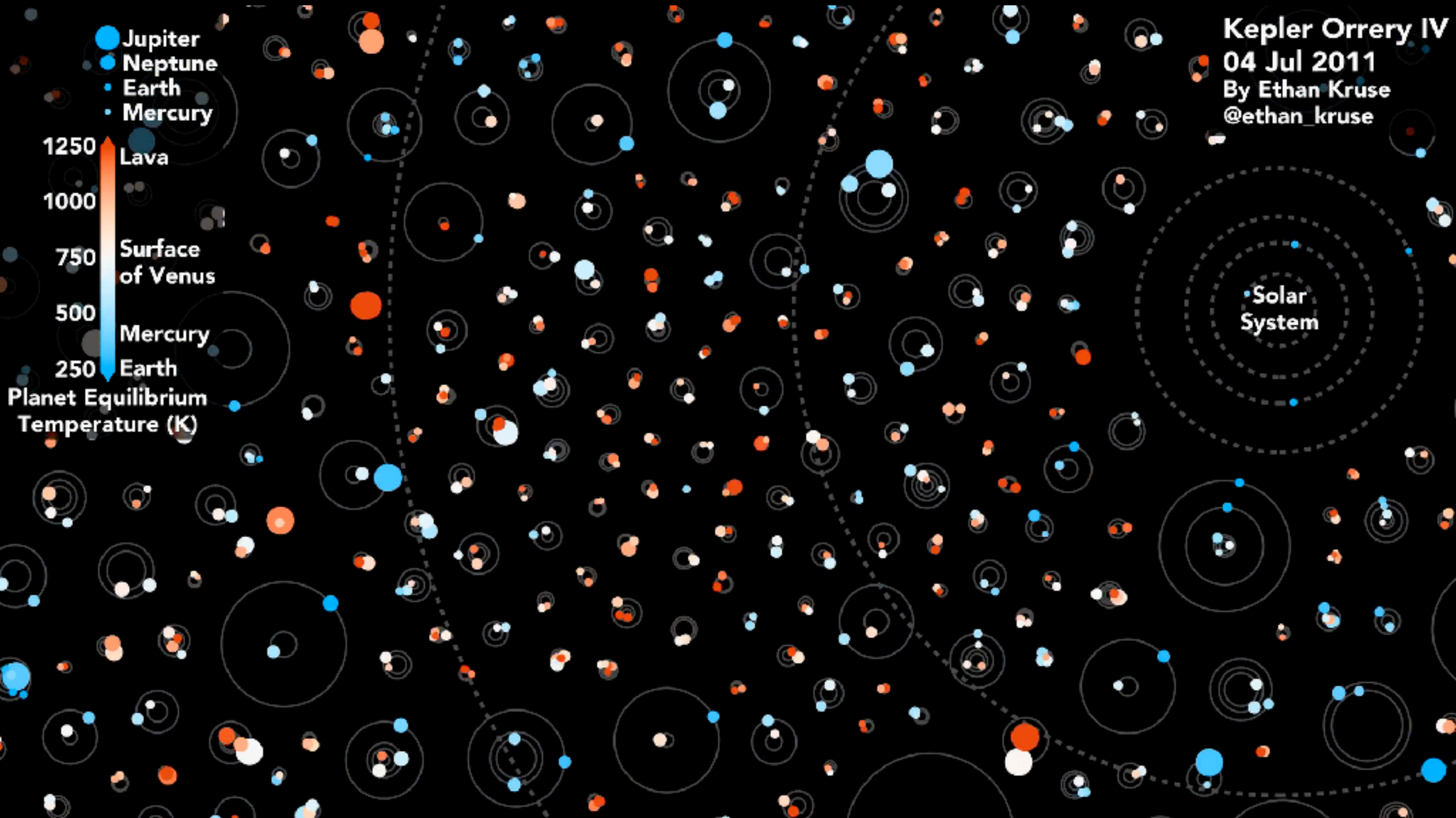
Discovery Method	Number of Planets
Astrometry	1
Imaging	44
Radial Velocity	639
Transit	2734
Transit timing variations	15
Eclipse timing variations	9
Microlensing	47
Pulsar timing variations	5
Pulsation timing variations	2
Orbital brightness modulations	6

NASA Exoplanet Archive
A service of NASA Exoplanet Science Institute

The number of known exoplanets has been increasing exponentially for 25 years…



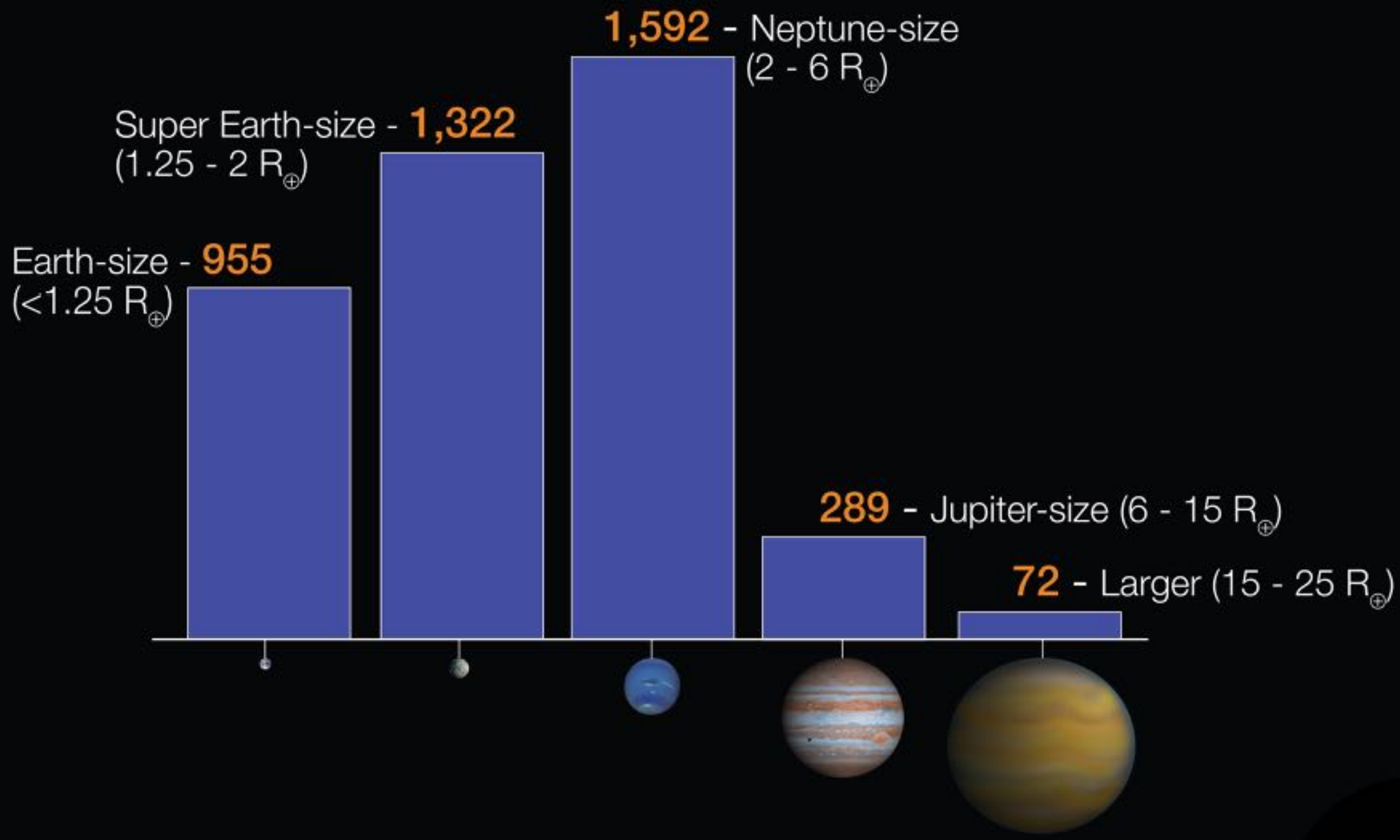
Exoplanet Population



> 3500 confirmed   > 580 Multis

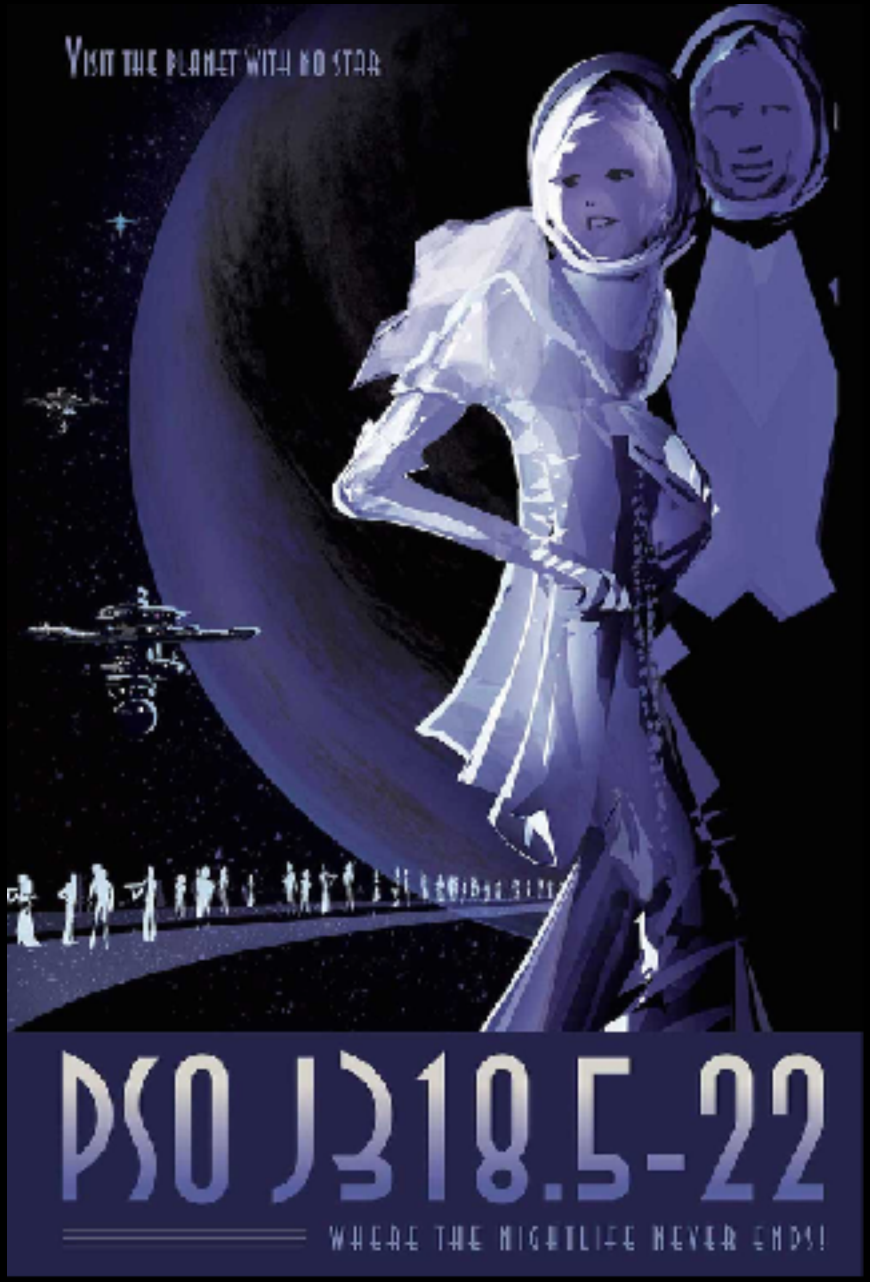
Sizes of Kepler Planet Candidates

As of July 23, 2015



What is a Free-Floating Planet?

free-floating planet
rogue planet
interstellar planet
nomad planet
orphan planet
wandering planet
starless planet
sunless planet
Planemo



FFP is a planetary-mass object that orbits the galaxy directly and does not appear to have a host star

Free-Floating Planet Population

Exoplanet	Mass (M_J)	Age (Myr)	Distance (ly)	Status	Discovery
OTS 44	~15	0.5–3	160	Likely a low-mass brown dwarf[19]	1998
S Ori 52	2–8	1–5	1150	Age and mass uncertain; may be a foreground brown dwarf	2000[20]
Cha 110913-773444	5–15	~2	163	Candidate	2004[21]
UGPS J072227.51-054031.2	5–40		13	Mass uncertain	2010
[MPK2010b] 4450	2–3		325	Candidate	2010[22]
CFBDSIR 2149-0403	4–7	110–130	117–143	Candidate	2012[23]
MOA-2011-BLG-262	~4			May be a red dwarf	2013
PSO J318.5-22	5.5–8	21–27	80	Confirmed	2013[24]
2MASS J2208+2921	11–13	21–27	115	Candidate; radial velocity needed	2014[25]
WISE J1741-4642	4–21	23–130		Candidate	2014[26]
WISE 0855–0714	3–10		7.1	Age uncertain; may be a brown dwarf	2014[27]
2MASS J12074836–3900043	11–13	7–13	200	Candidate; distance needed	2014[28]
SIMP J2154–1055	9–11	30–50	63	Age questioned[29]	2014[30]
SDSS J111010.01+011613.1	10–12	110–130	63	Confirmed	2015[31]
2MASS J1119–1137	4–8	7–13	94	Candidate; distance needed	2016[32]
WISEA 1147	5–13	7–13	94	Candidate; distance needed	2016[33]

*from wikipedia, likely not up-to-date

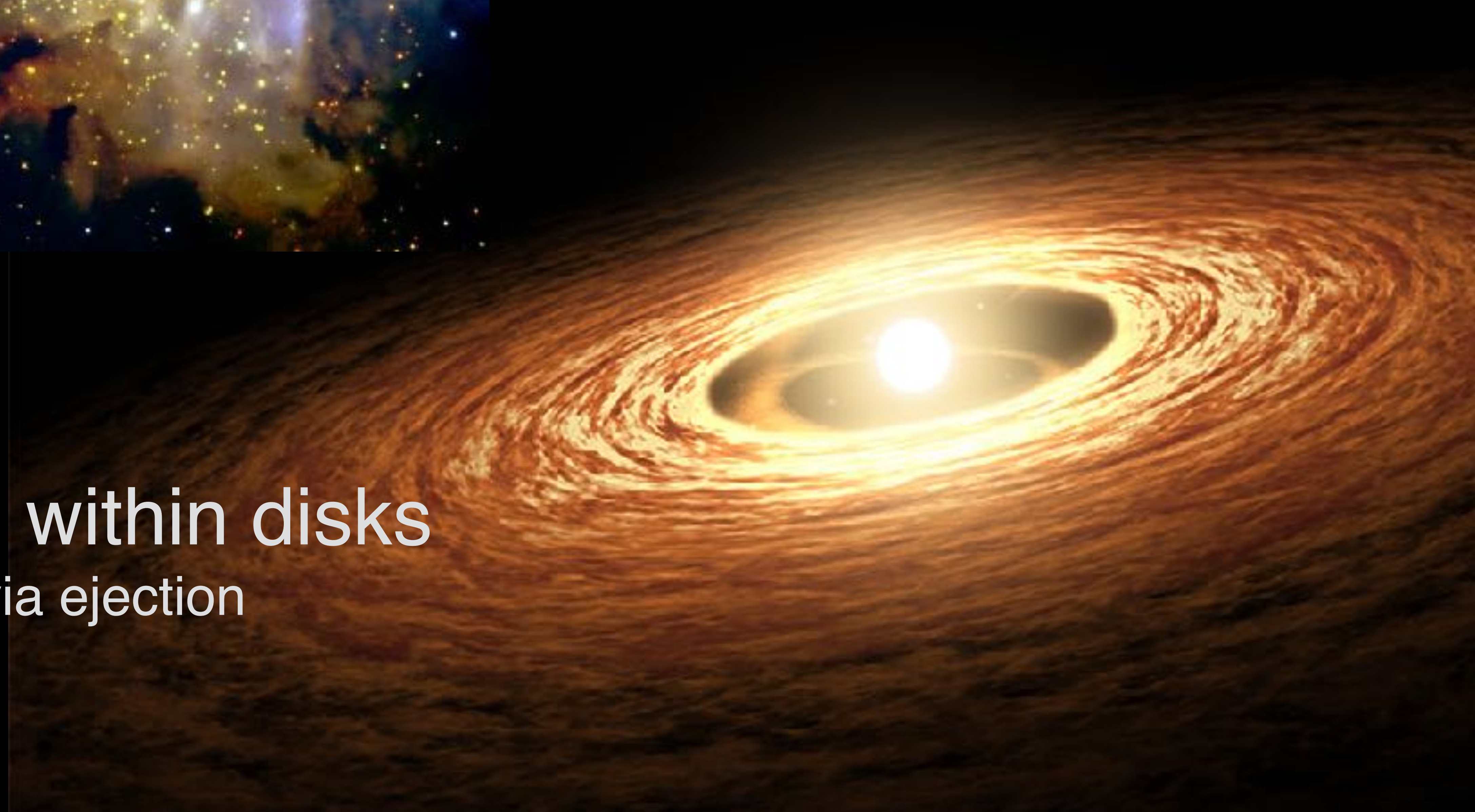
- FFP have been observed by microlensing surveys and optical and IR wide-field surveys
- The detected free-floating planets are mostly giant worlds that could represent the tail-end of the stellar mass distribution

FFP Formation Mechanisms

formation via collapse

planetary mass object

sub-brown dwarf



formation within disks

FFP via ejection

FFP Formation Mechanisms

Kant (1755) and Laplace (1796): planets form in disks

Core Accretion (Safronov 1969; Lissauer 1993)
Gravitational Instabilities (Kuiper 1951; Boss 2006)
Pebble Accretion (Levison; Chambers)

FFP Formation Mechanisms

Ejected material is a natural outcome of the planet formation process

- planet-planet interactions
- giant planet or stellar companion
- external forces (passing stars, galactic tides, clusters)

Lots of analytical, numerical models

Numerical N-body Models

Widely used tools to explore planet formation

- different stars
- different architectures

- explore where planets form and timescales
- fate of mass that falls into star (stellar pollution)
- fate of ejected mass (implications for FFPs)

Integration packages:
Mercury (Chambers 2001)
REBOUND (Rein 2011)

Planet-Planet Interactions

Veras and Raymond (2012) scattering simulations:

Observed frequency of FFPs (giants)

$$\frac{N_{FFP}}{N_{stars}} = f_{giant} \times f_{unstable} \times n_{ejected}$$

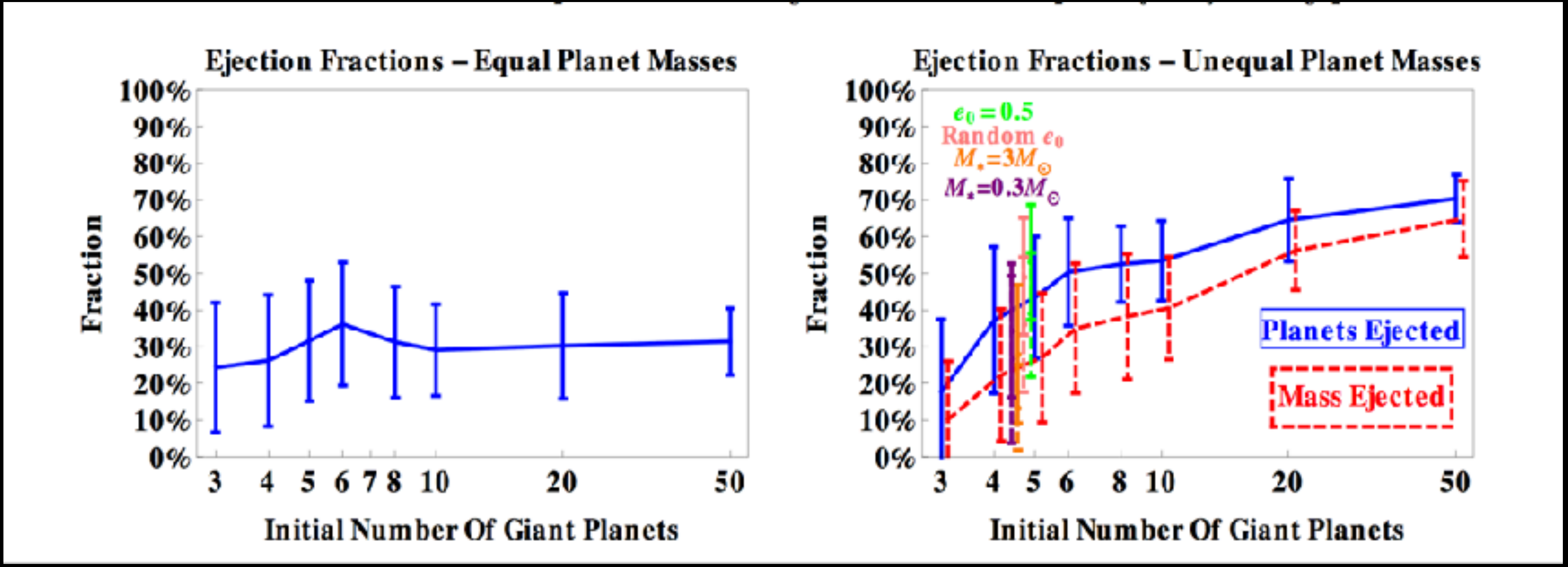
f_{giant} = fraction of stars with giant planets
$f_{unstable}$ = fractions of giant planet systems that become unstable
$n_{ejected}$ = mean # planets ejected via dynamical instability

Numerical simulations to estimate # of ejected planets ($n_{ejected}$) needed to match observations

Planet-Planet Interactions

Scattering simulations: Veras and Raymond 2012

3 - 50 giant planets
equal-mass Jupiters, or Saturn to 10 Jupiter-mass
3 AU — 200 AU, “ejection” if a > 10^5 AU



20 — 70% giant planets ejected

Planet-Planet Interactions

$$\frac{N_{FFP}}{N_{stars}} = f_{giant} \times f_{unstable} \times n_{ejected}$$

Assuming observationally motivated constraints

$$\frac{N_{FFP}}{N_{stars}} = 1.8$$

$f_{giant} = 0.2$

$f_{unstable} = 0.7$

$n_{ejected} = 12$

Sumi et al. 2011

Inconsistent with observational constraints, concluded planet-planet scattering cannot explain the FFP population

Veras and Raymond 2012

$$\frac{N_{FFP}}{N_{stars}} = 0.25$$

$n_{ejected} = 1.6$

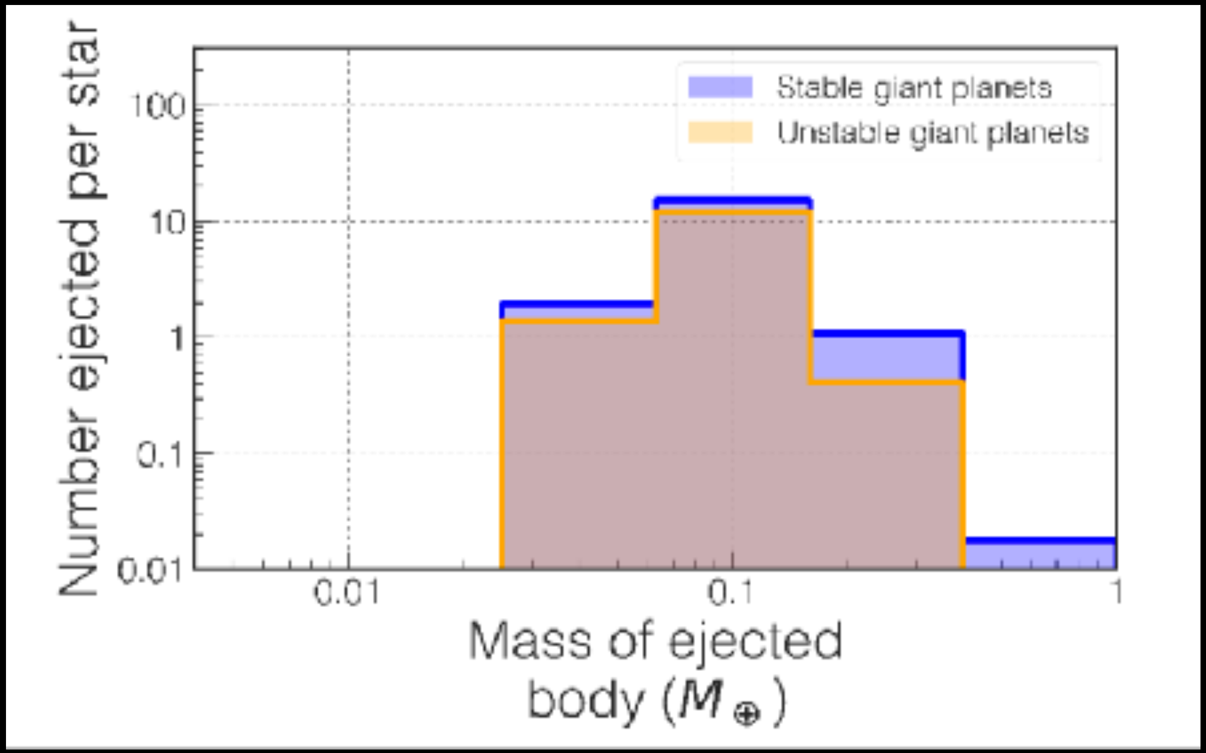
Mroz et al. 2017

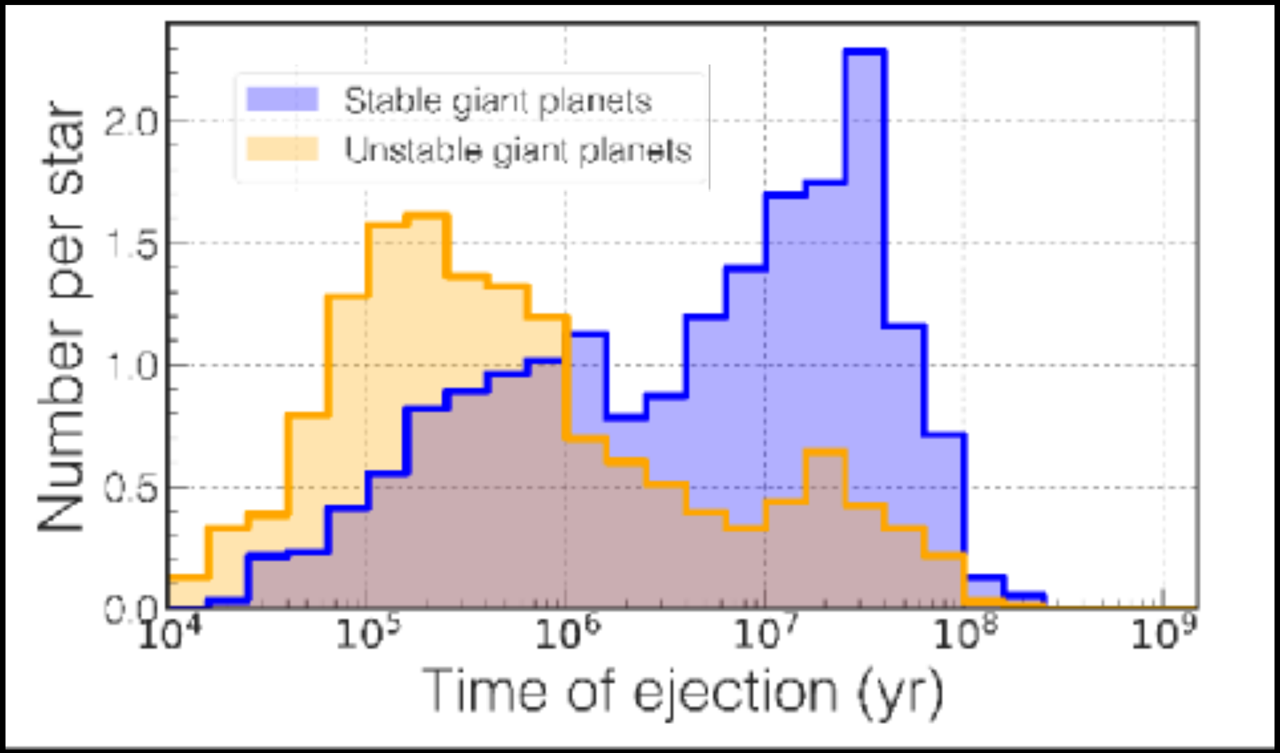
FFP Terrestrial Planets

Exploring gas giant instabilities on terrestrial FFPs

inner disk: 550 embryos/planetesimals
middle disk: 3 giant planets >=5.2 AU (Saturn - 3 Mjup)
outer disk: 1000 planetesimals

500 sims; giant planets unstable in ~2/3
Instabilities affected timescales, not mass





Raymond et al. 2011, 2012
Barclay et al. 2017

Jupiter analogs are likely scarce

Occurrence Rates of Jupiter (RV + Transits) ~ 6%

(Wittenmyer et al. 2016)

How do systems that lack giants affect terrestrial FFPs?

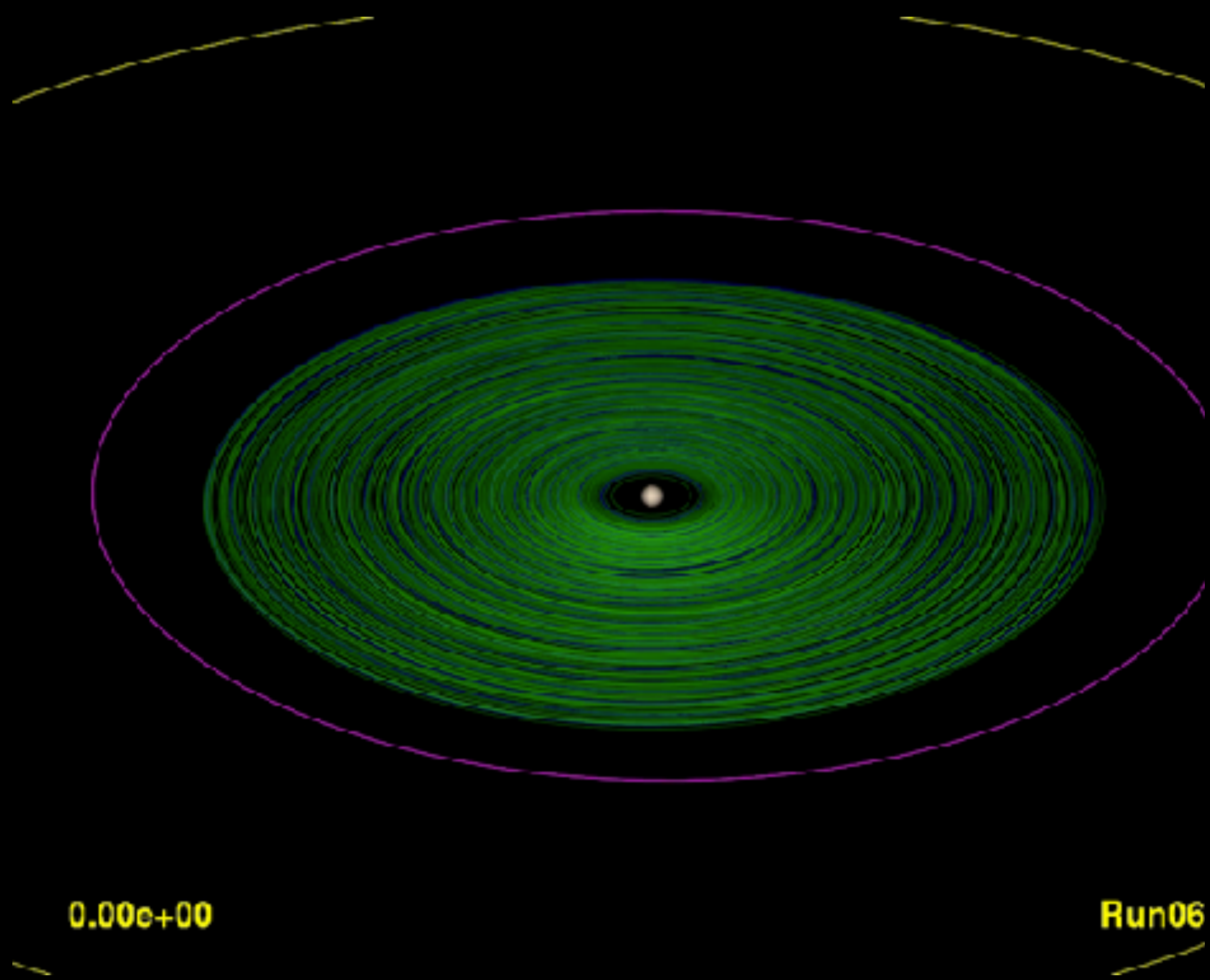
Solar System Test Case

Barclay et al. 2017

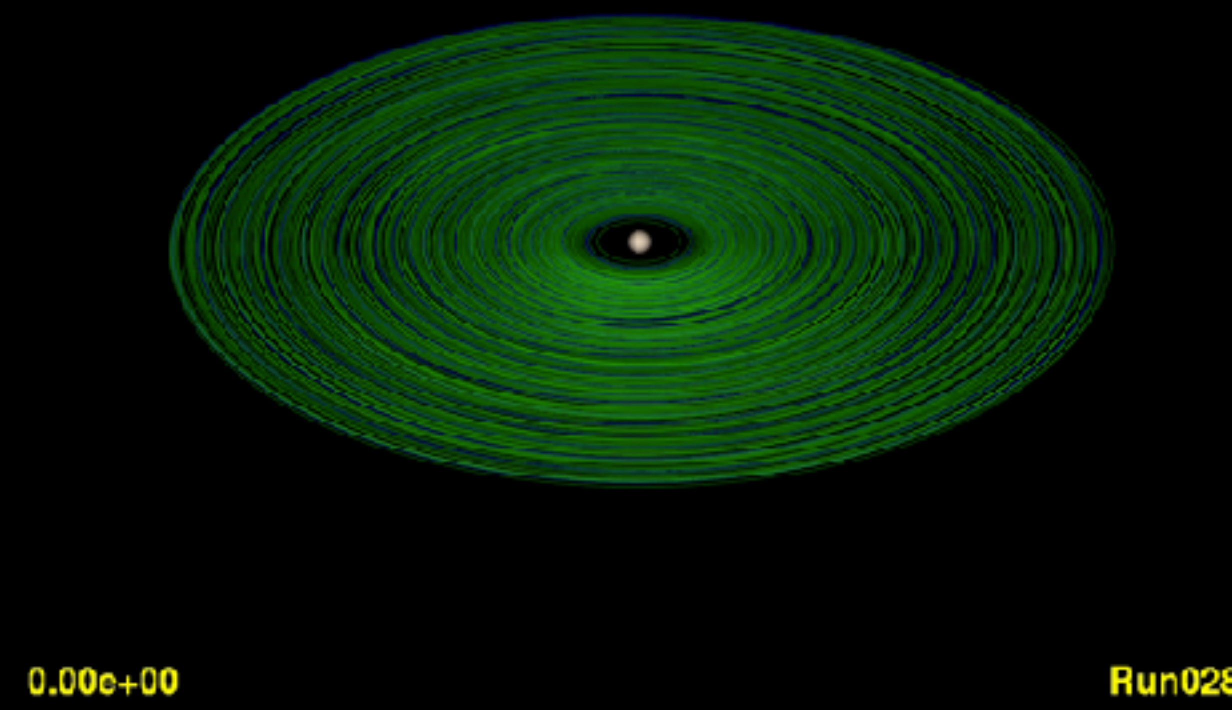
1) Sun + Jupiter + Saturn
2) Sun only

Moon-to-Mars-sized embryos in protoplanetary disk

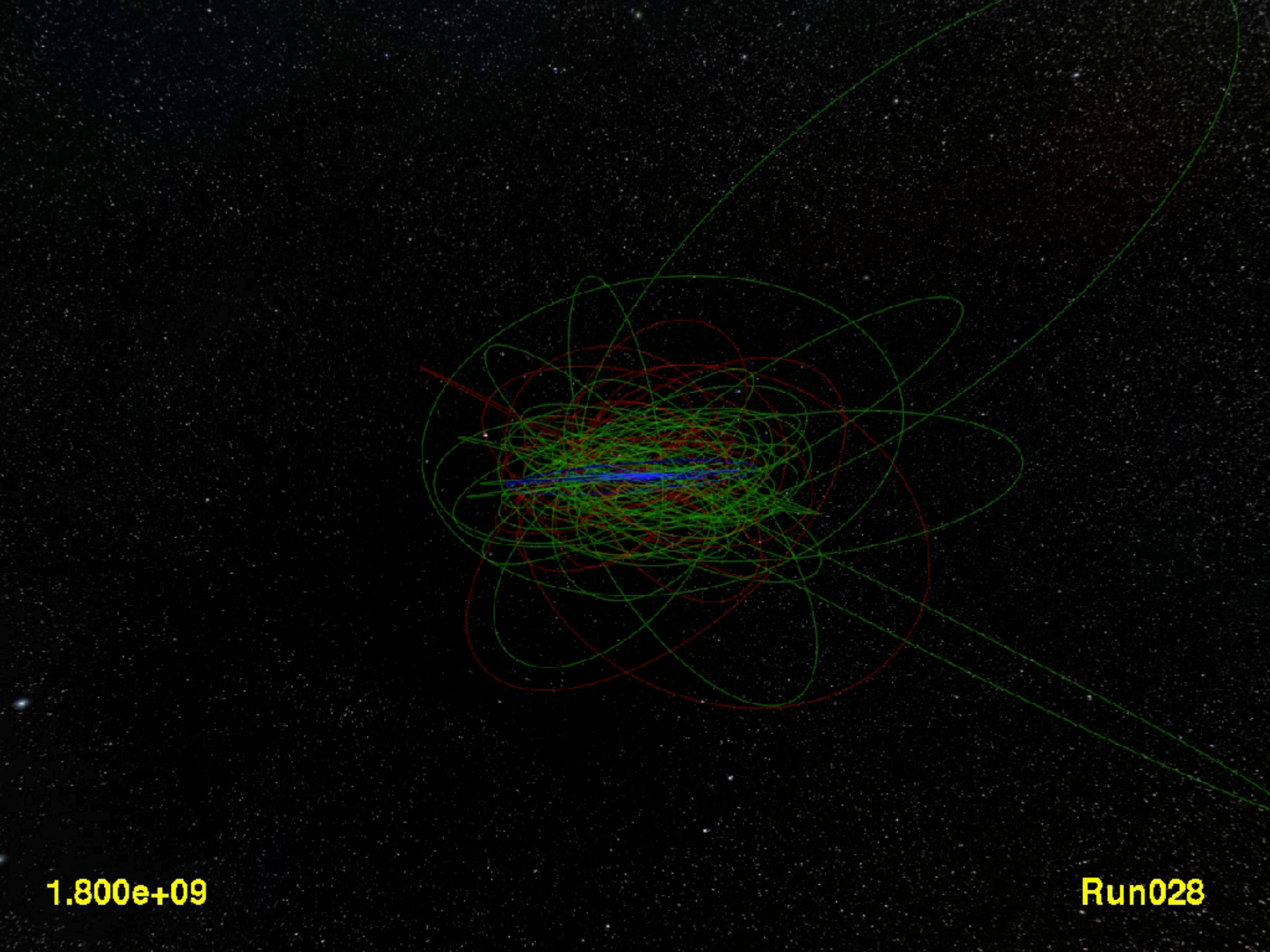
Fragmentation
5 Gyrs



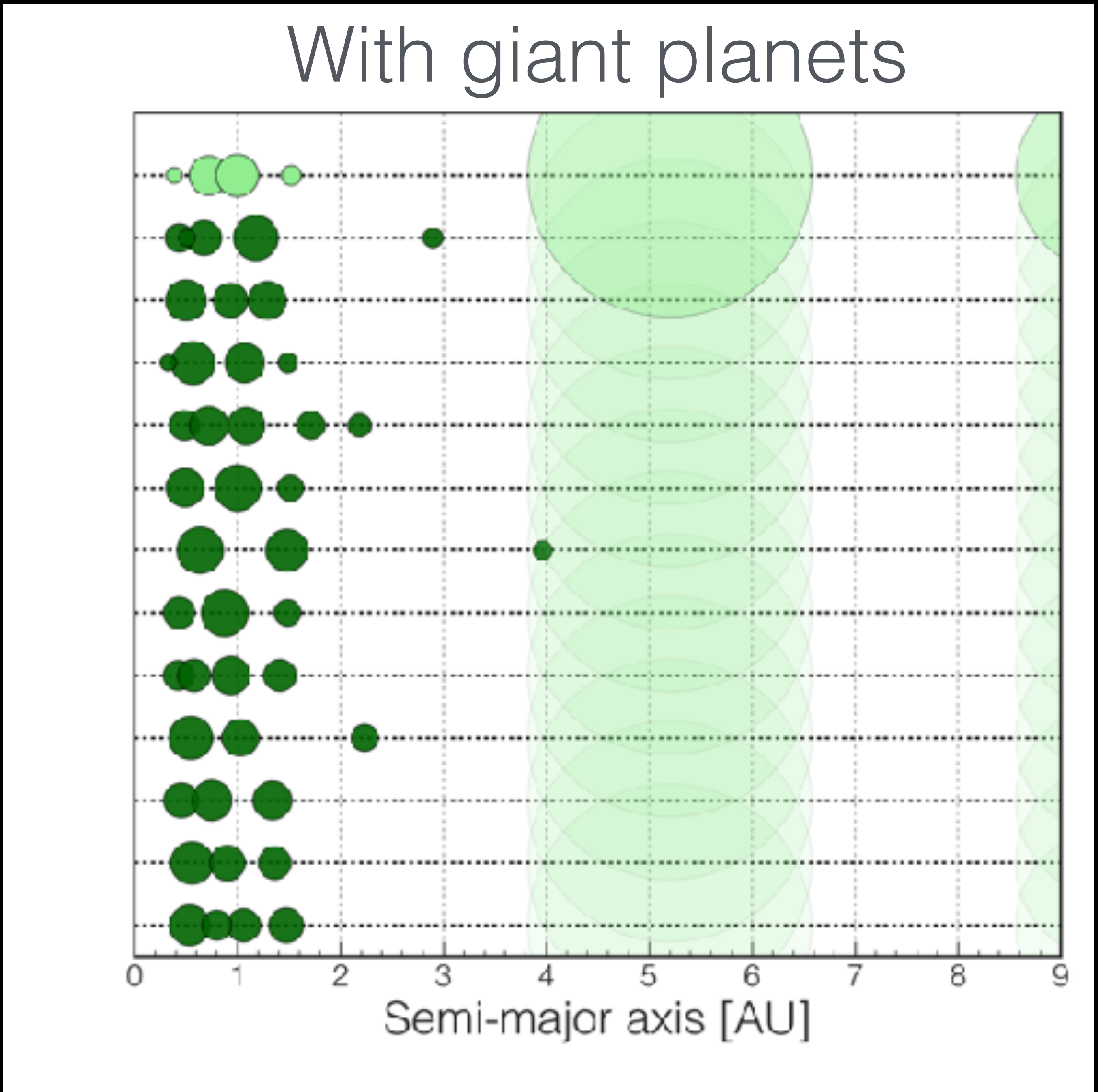
Jupiter+Saturn

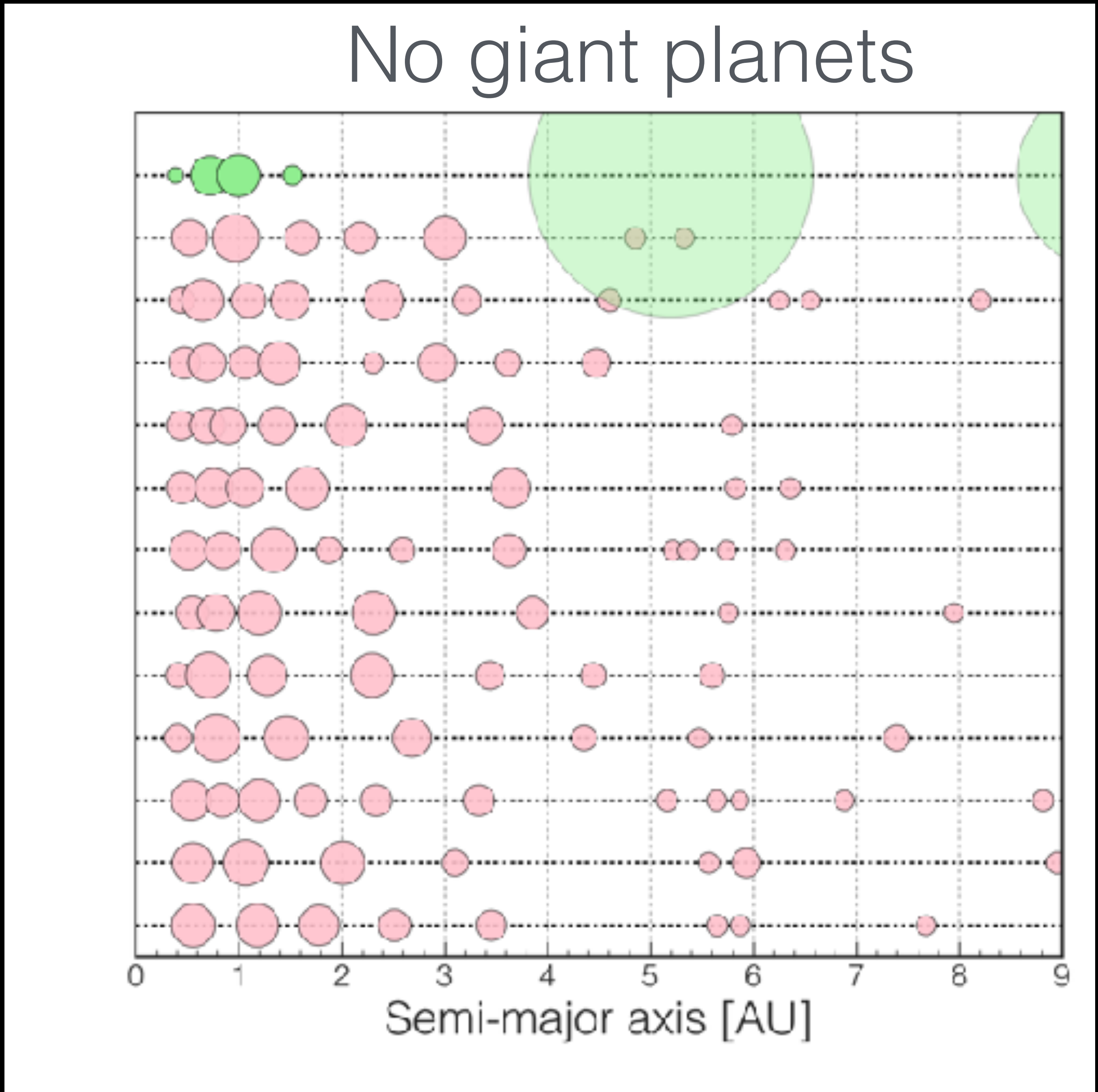


No giant planets

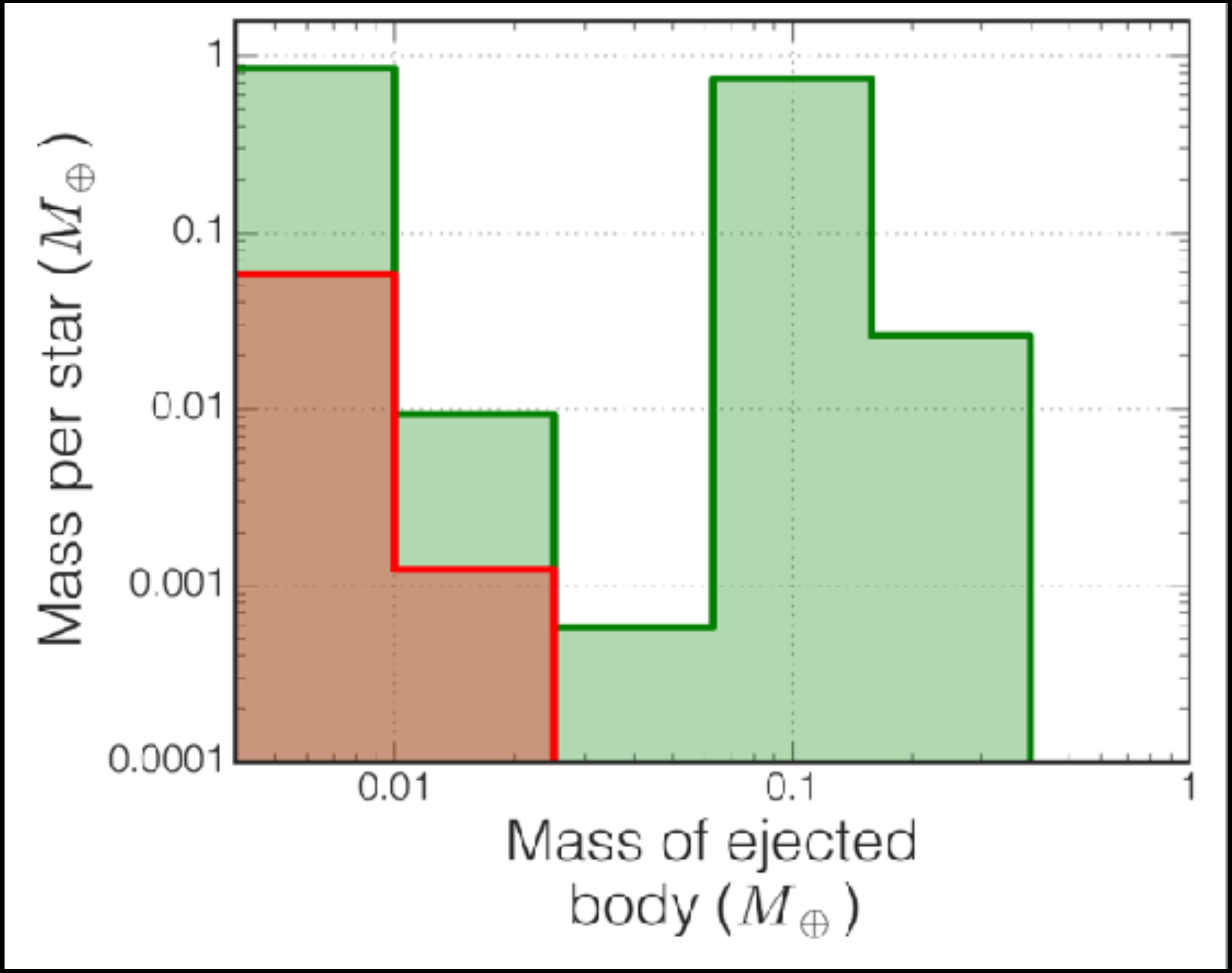

1.800e+09
Run028

Final Planetary Systems





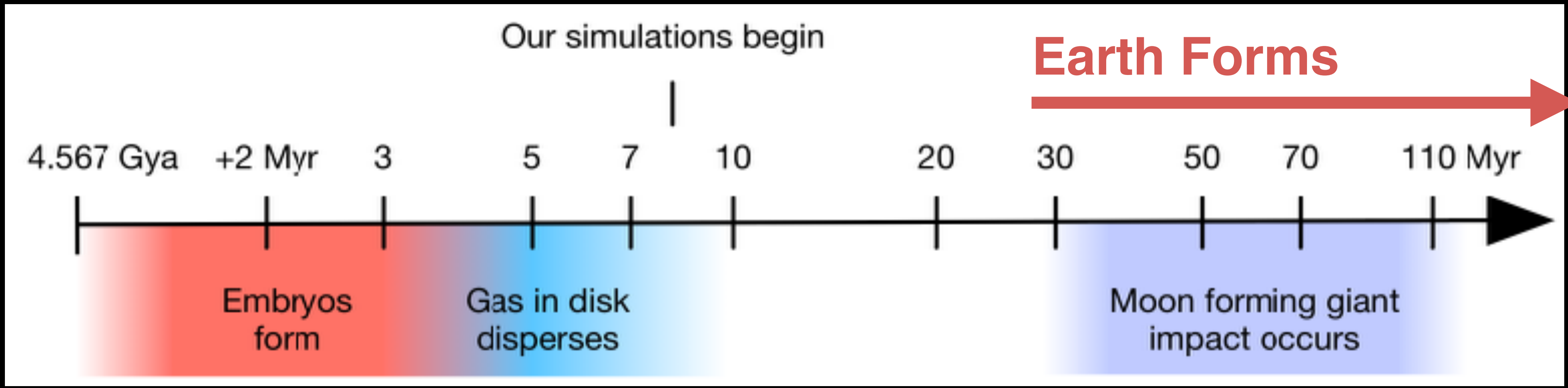
Mass in Ejected Material

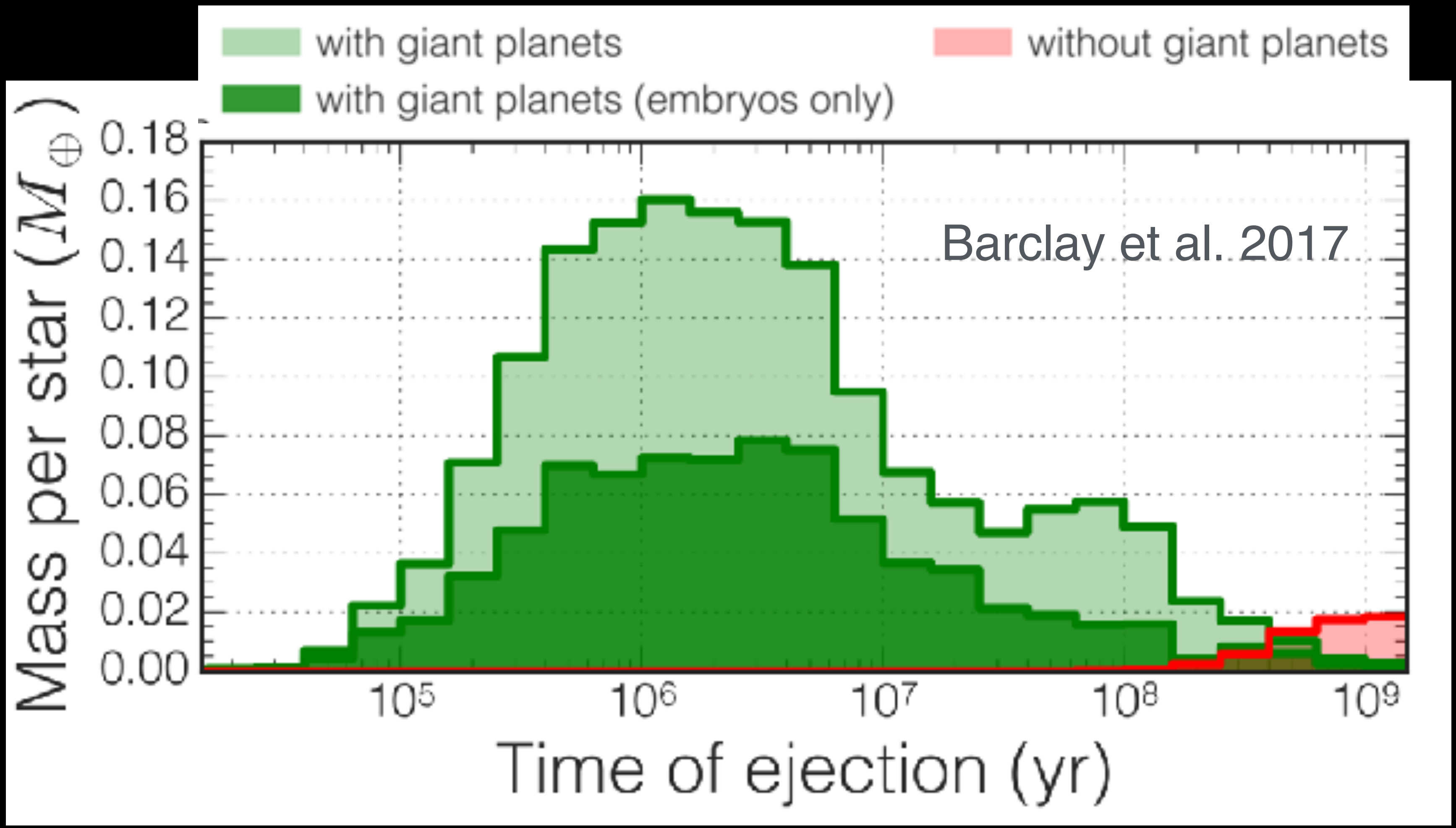


Barclay et al. 2017

No bodies larger than 0.3 $M_\oplus$ were ejected

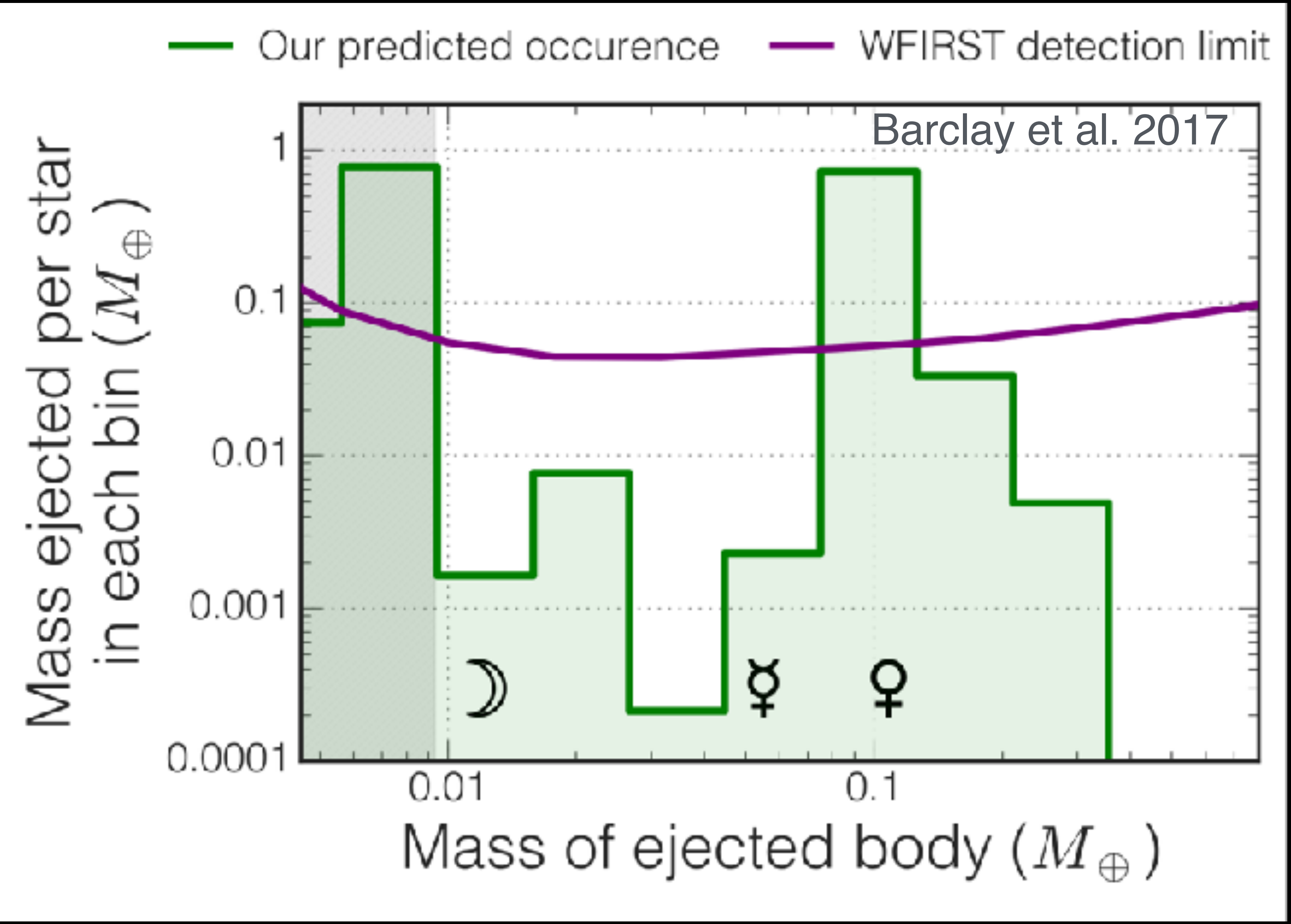
Ejection Timescales





With giant planets, ejections occur prior to epoch of Earth formation

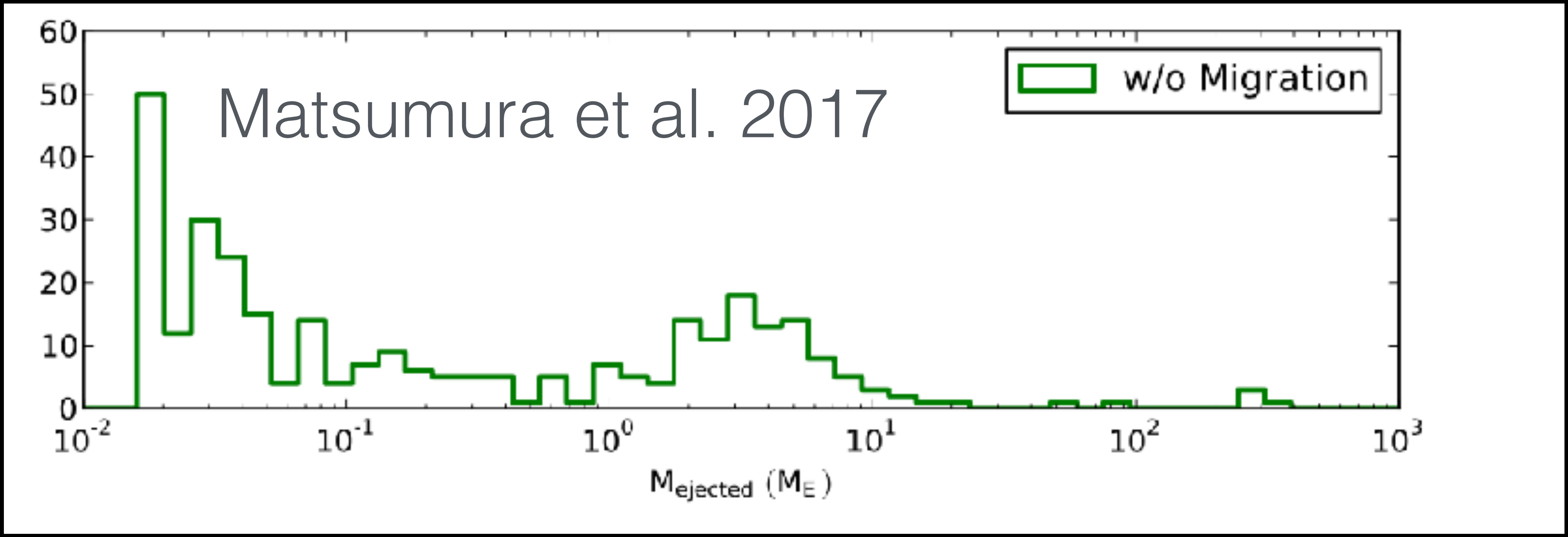
WFIRST Detections



Prediction: WFIRST will find plenty of Mars' but few *Earths

*if giant planets are common

Ejections in Pebble Accretion Regime

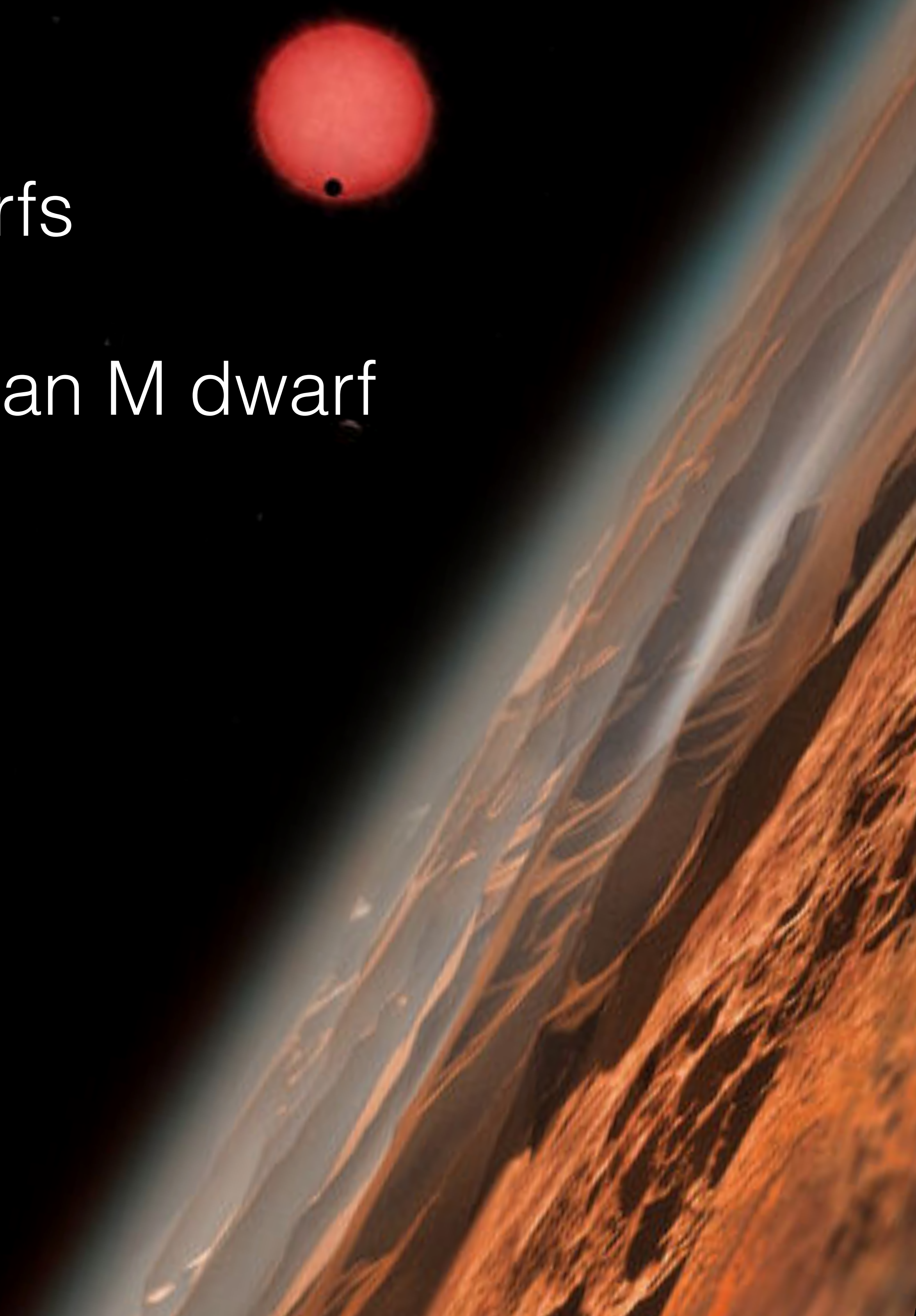


WFIRST prediction: at least one Earth or more massive FFP may be discovered for two Mars-like planets

Caveats:

- simulations with migration do not lead to any ejections due to early dynamical instability
- simulations do not reproduce the observed distributions well

What about M dwarfs??



>70% stars in galaxy are M dwarfs

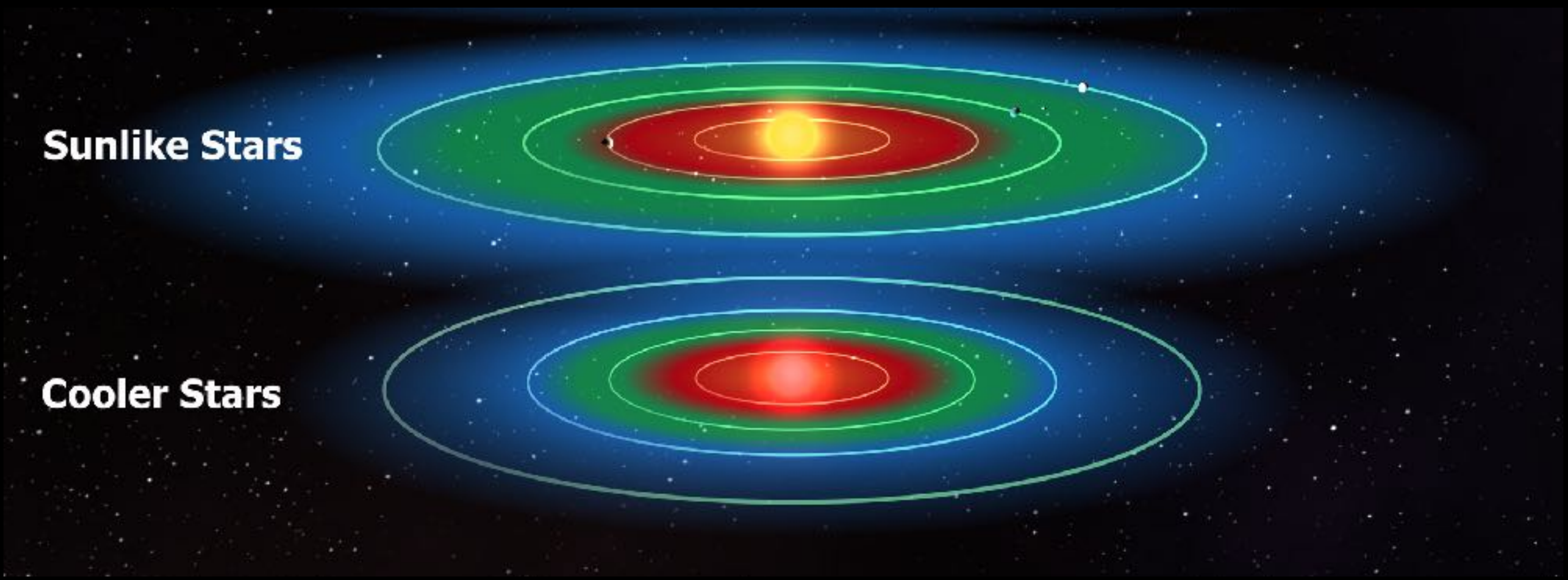
Typical microlensing host star is an M dwarf

M dwarfs Disks

Difficult to constrain

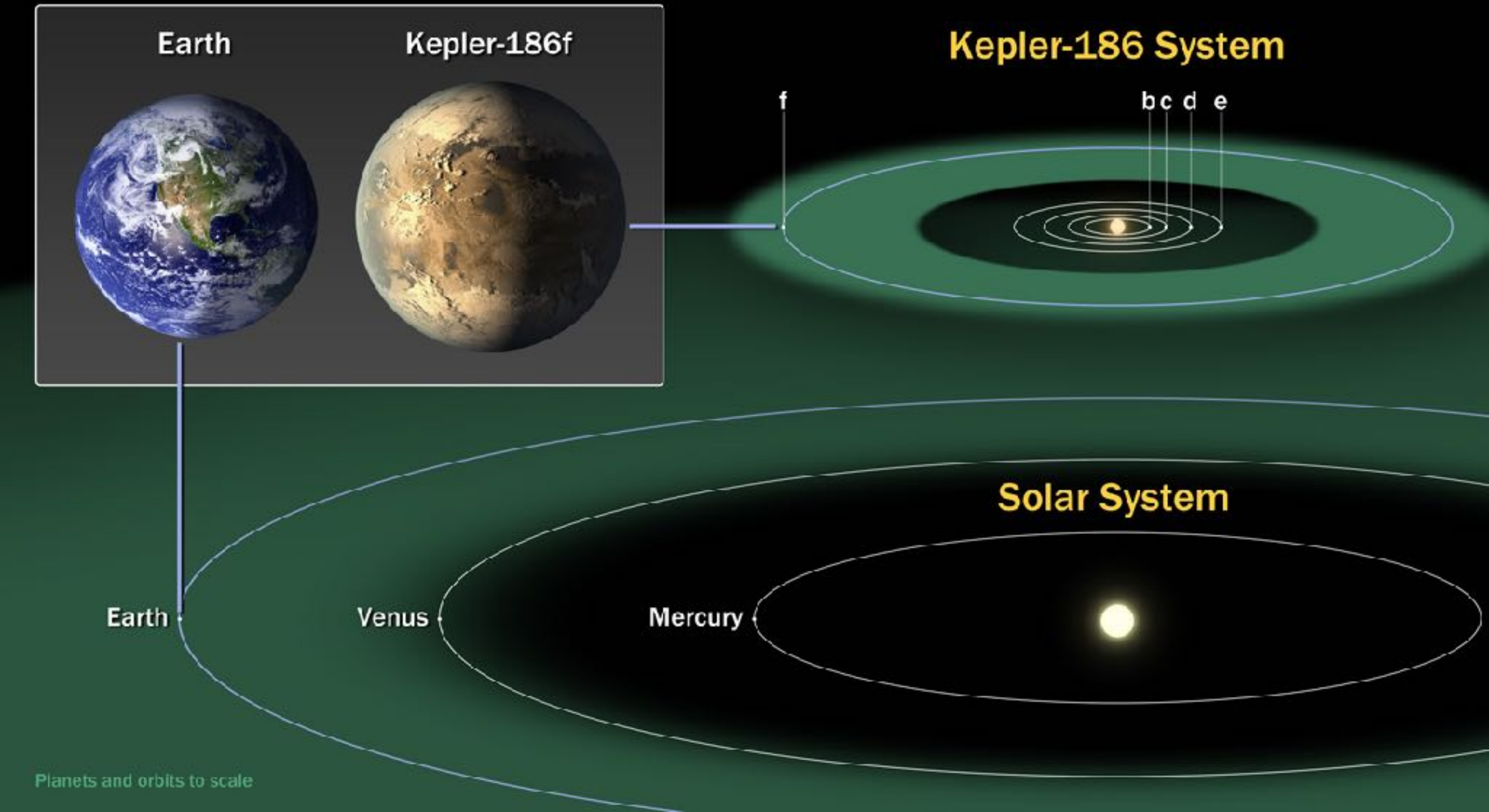
Surveys of disks at sub-mm wavelengths show an overall positive relation between stellar and disk mass, either linear or steeper

Andrews et al. 2013, Gaidos 2017

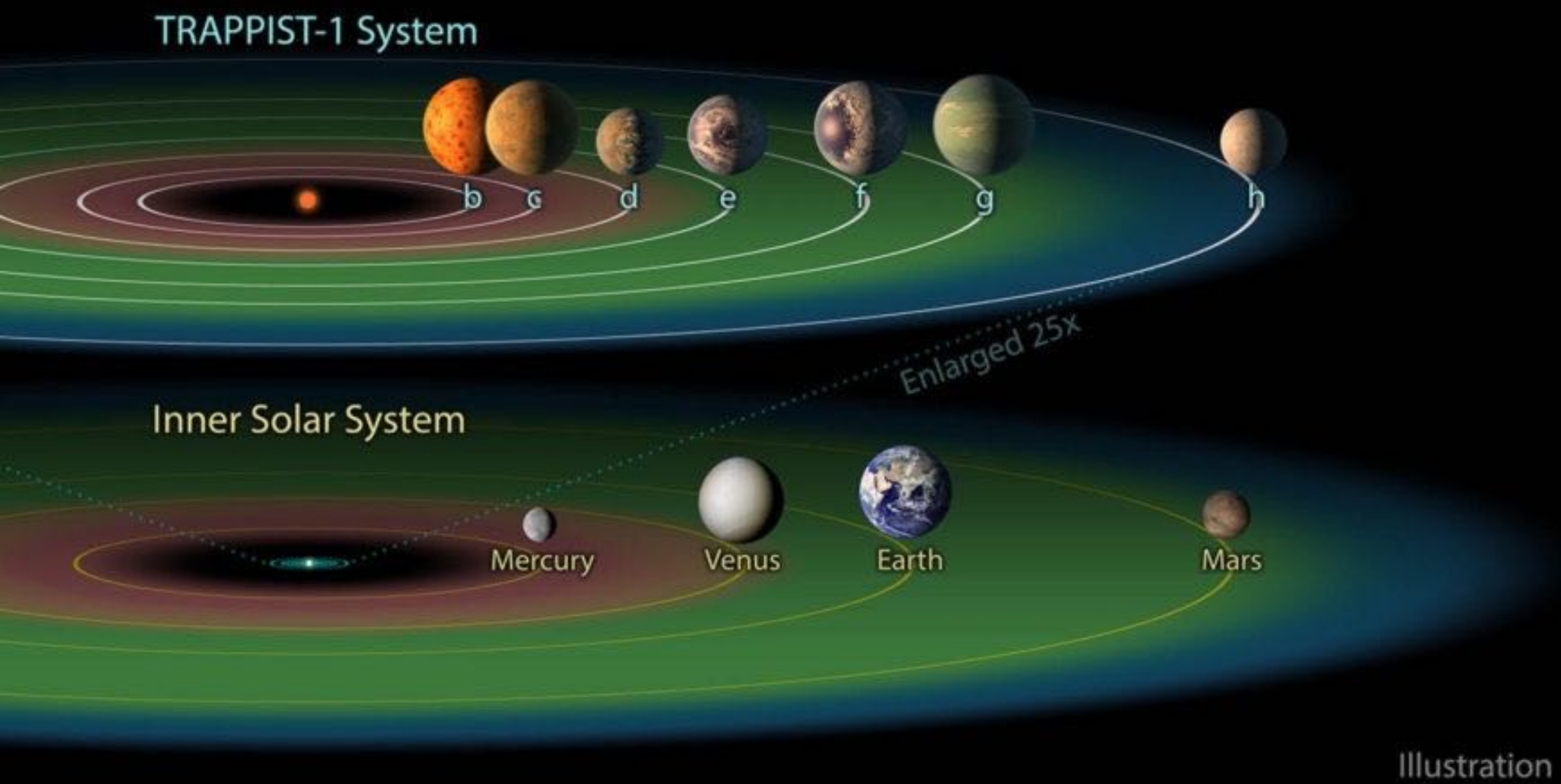


Scaling Solar Nebula to M <0.25 M_{sun} leaves < 1 M_{Earth} in disk

>5 Mearths around 0.5 Msun M dwarf



>7 Mearths around 0.08 Msun M dwarf



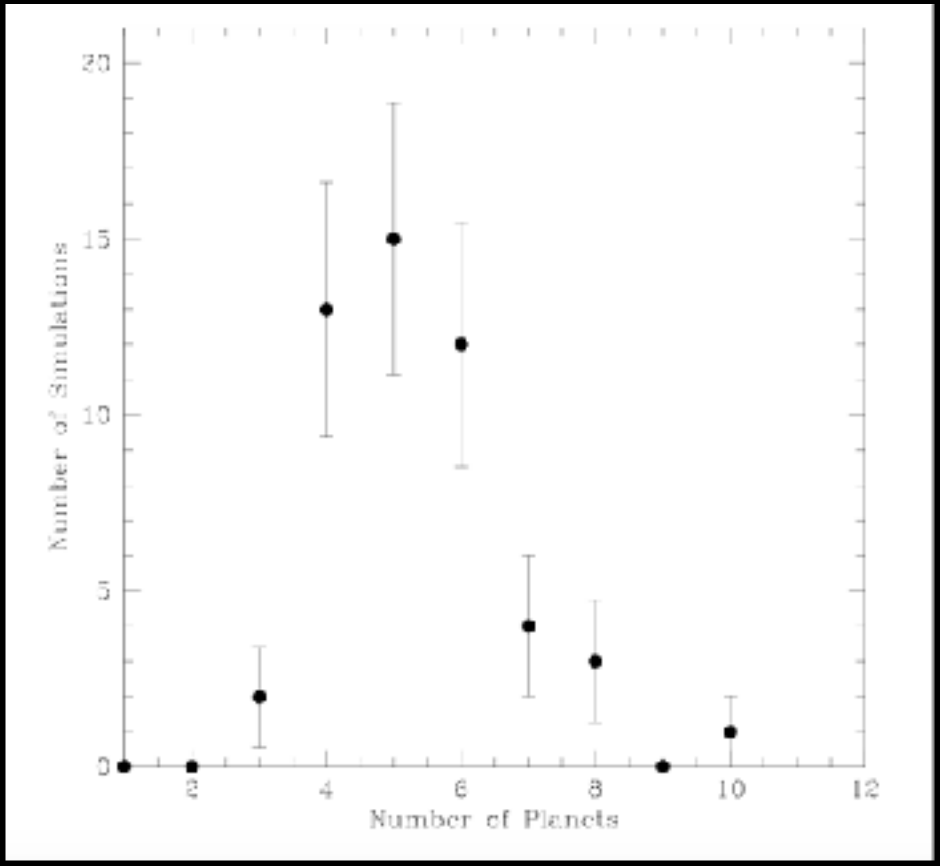
Studying planet formation around M dwarfs is hard!

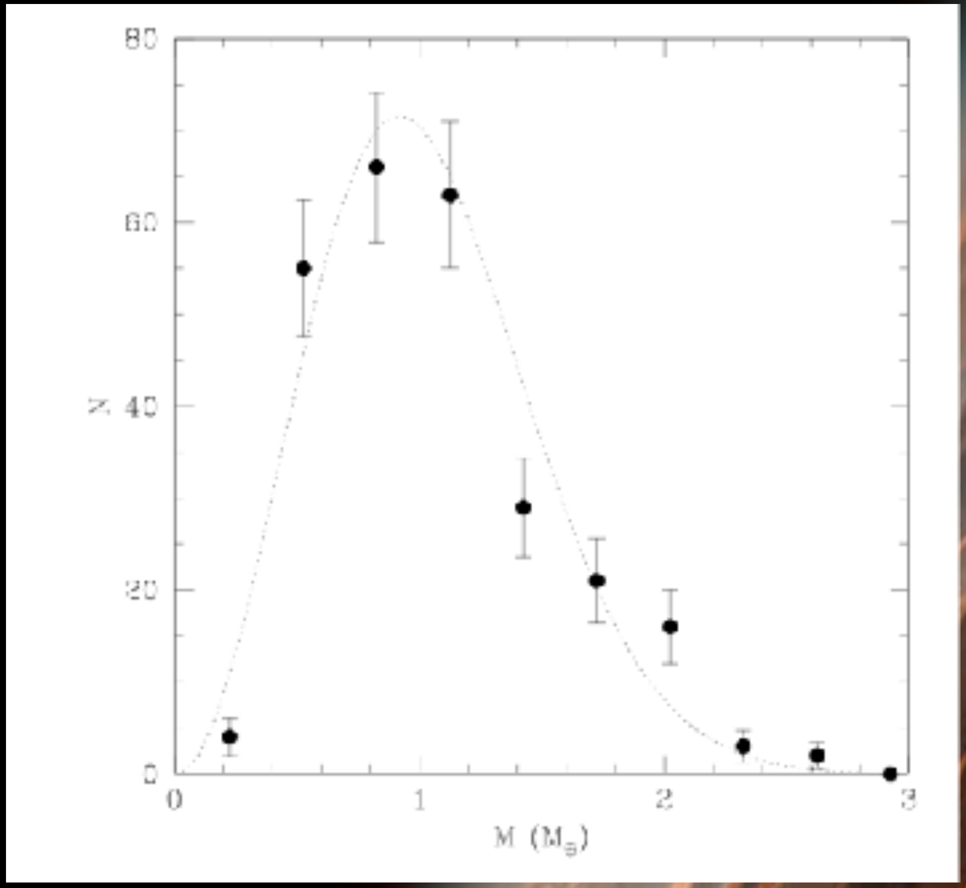
M dwarf In Situ Simulations

Hansen (2014)

0.5 Msun, no giant planets

a = 0.05 - 0.5 AU (6 M_{Earth})

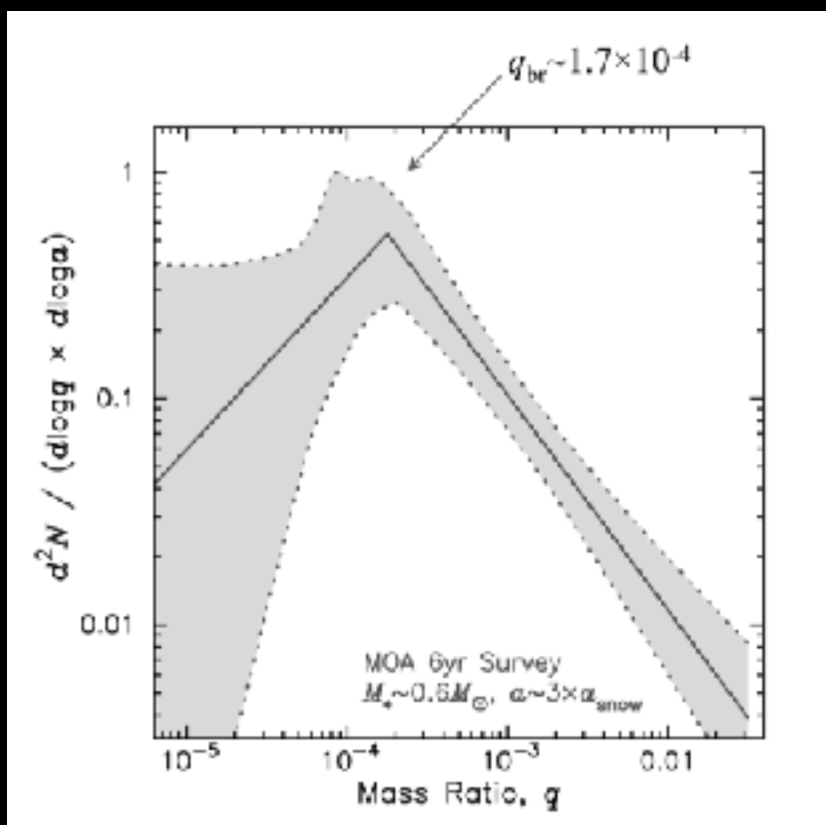




No ejected planets!

Jupiters are rare around M dwarfs,
… but Neptunes likely common

Microlensing



Suzuki et al. 2016

RVs (HARPS)

Astudillo-Defru et al. 2017

GJ 3138d (M0, 0.7 Msun)

P = 258 d

Msini = 10.5 Mearth

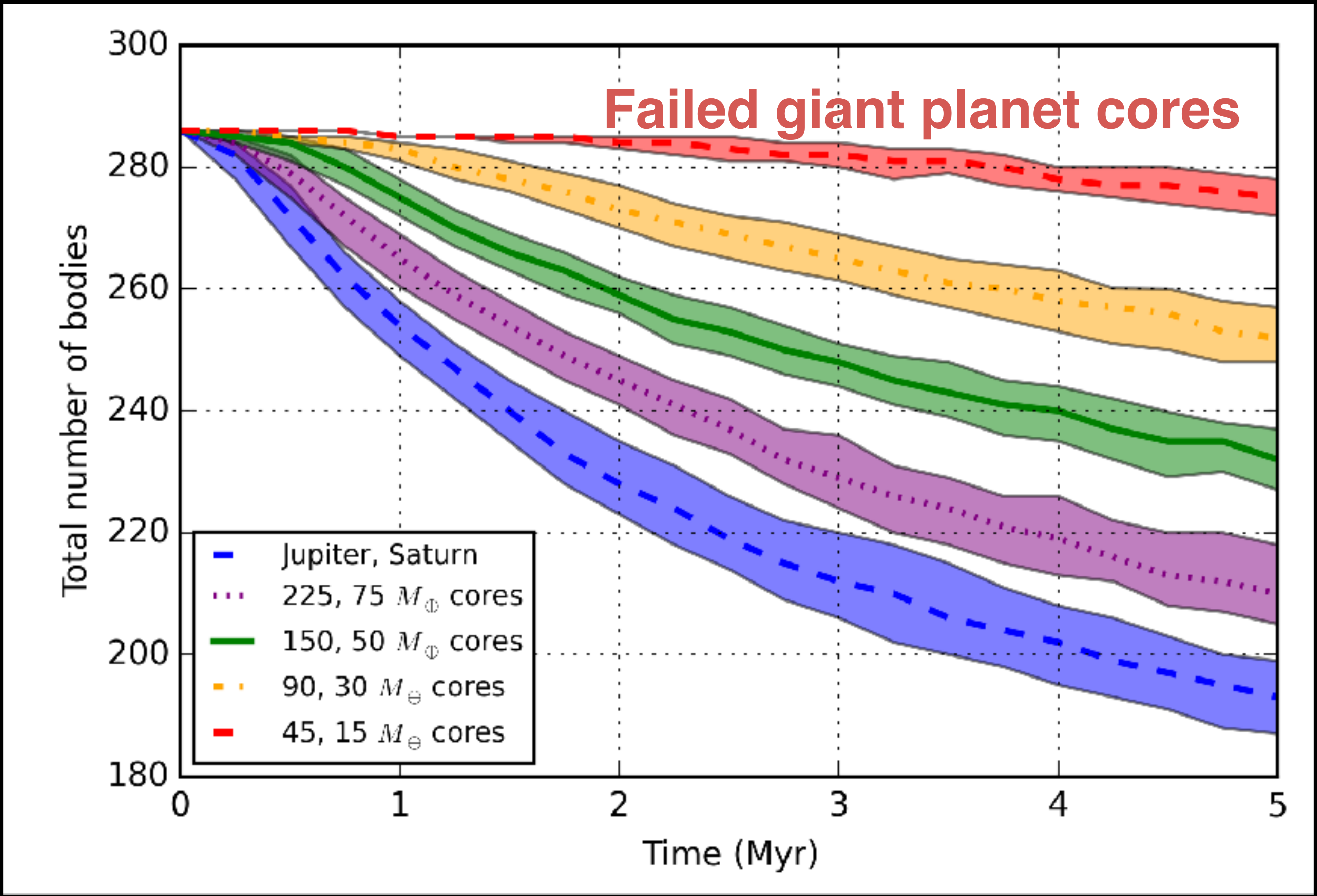
GJ 628d (M3.5, 0.3 Msun)

P = 217 d

Msini = 7.7 Mearth

Simulations in progress …

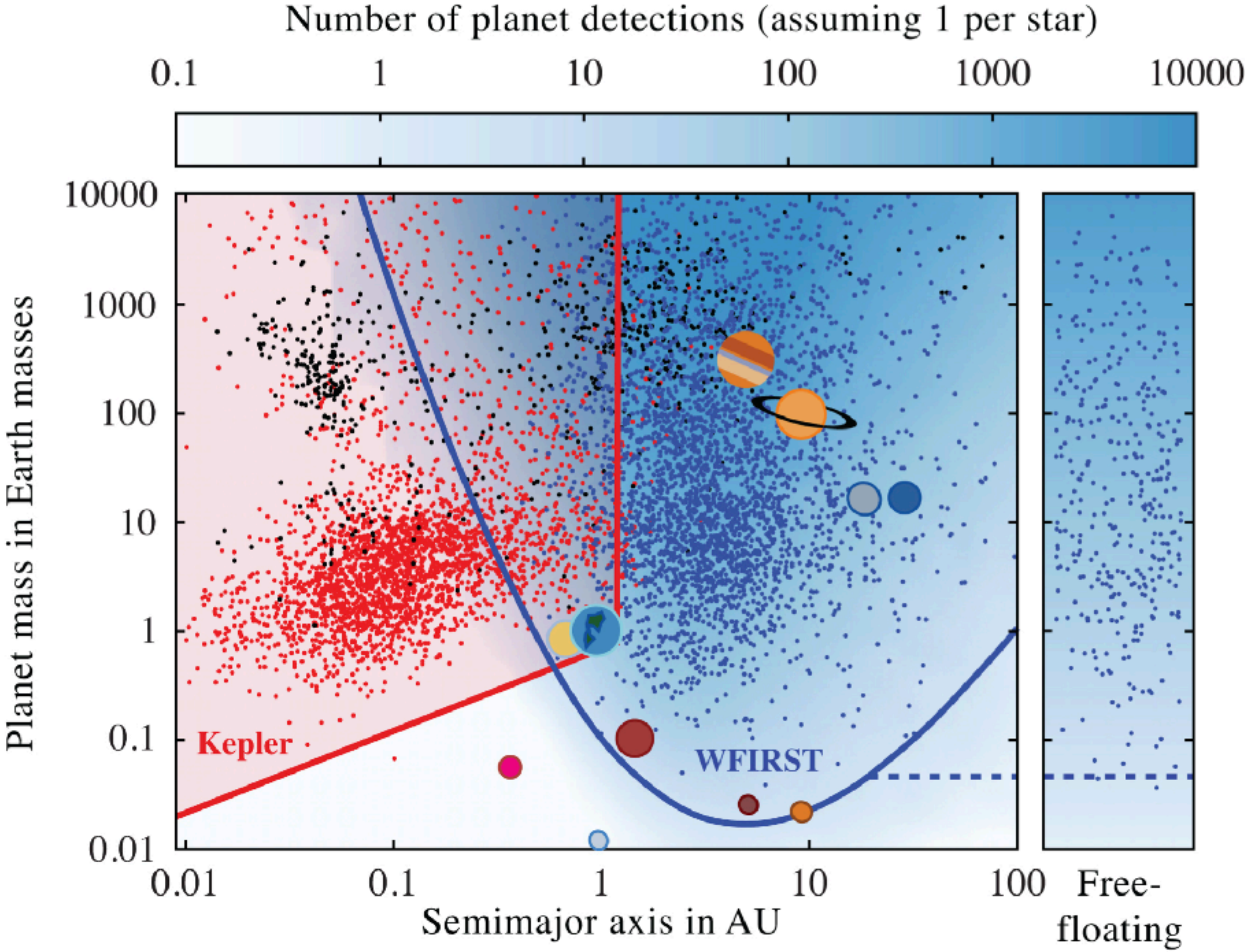
Pre-lim Results for Solar System



Demographics of outer giants will provide constraints on FFPs, formation mechanisms


The Amazing Story of the End of the World!
WHEN WORLDS COLLIDE
PRODUCED BY GEORGE PAL
MAKER OF 'DESTINATION MOON'
DIRECTED BY RUDOLPH MATÉ
SCREENPLAY BY SYDNEY BOEHM
BASED ON A NOVEL BY EDWIN BALMER and PHILIP WYLIE
COLOR BY Technicolor
A PARAMOUNT PICTURE

The End



Number of planet detections (assuming 1 per star)
0.1
1
10
100
1000
10000
Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
Kepler
WFIRST
0.01
0.1
1
10
100
Semimajor axis in AU
Free-
floating

Dana Berry/SwRI