# ASTROCHEMISTRY

## FROM THE BIG BANG TO LIFE

*Global Astrochemistry Lecture Series (GALS) 2024*

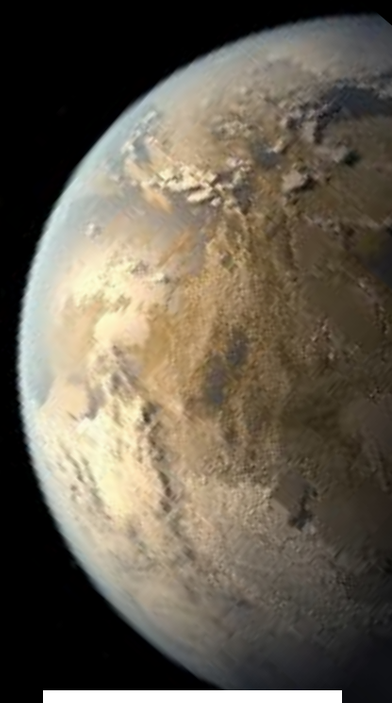
# EVOLUTION OF PLANETARY SYSTEMS

**Sean Raymond.** *University of Bordeaux, France*

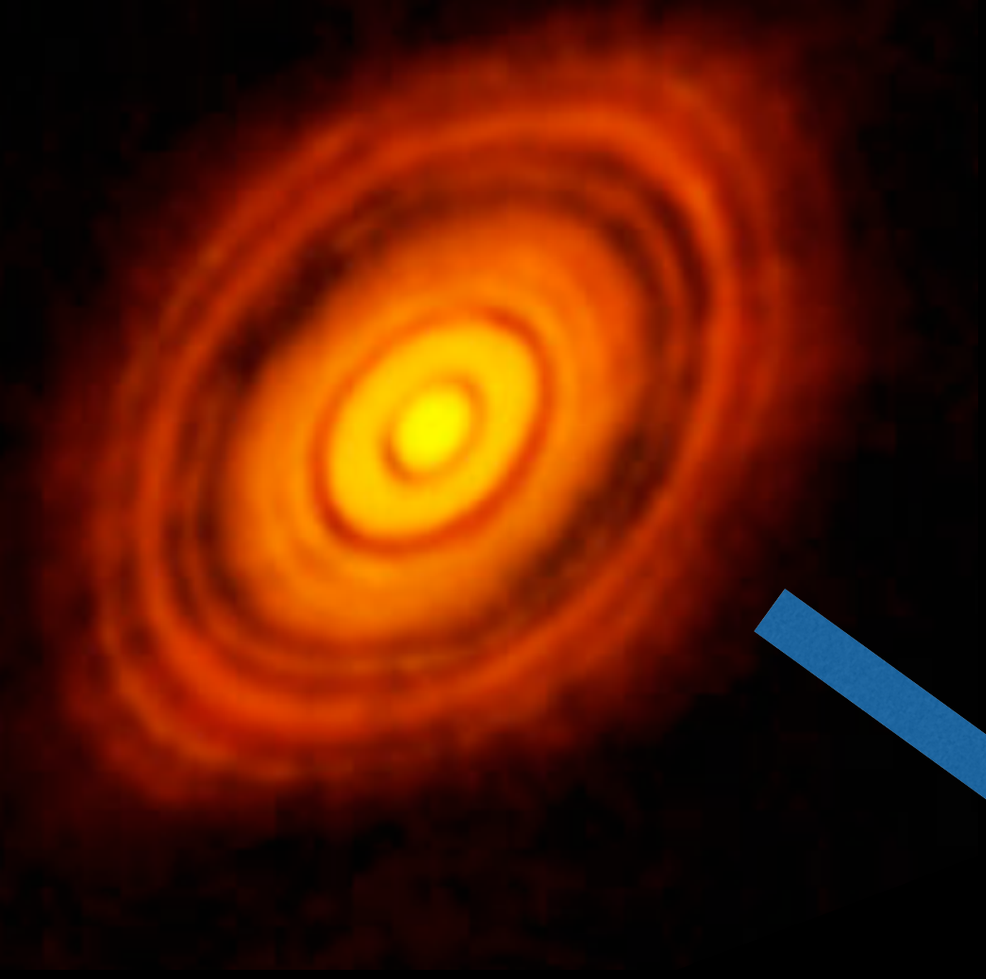
**14.03.2024 | 15:00 - 17:00 CET**

cost
NanoSpace
Funded by the European Union

# Formation and dynamical evolution of planetary systems

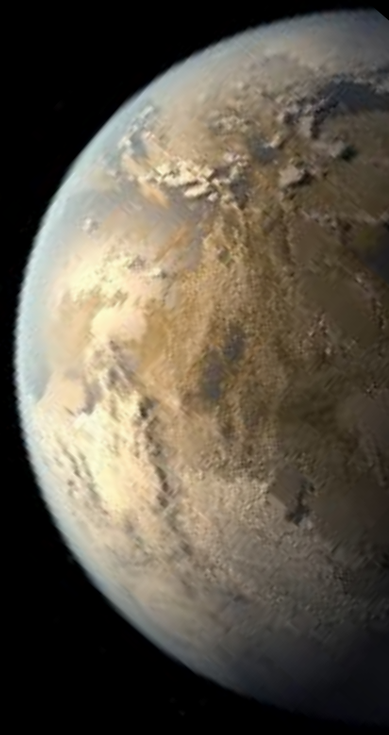


**Sean Raymond**
Laboratoire d'Astrophysique de Bordeaux
planetplanet.net





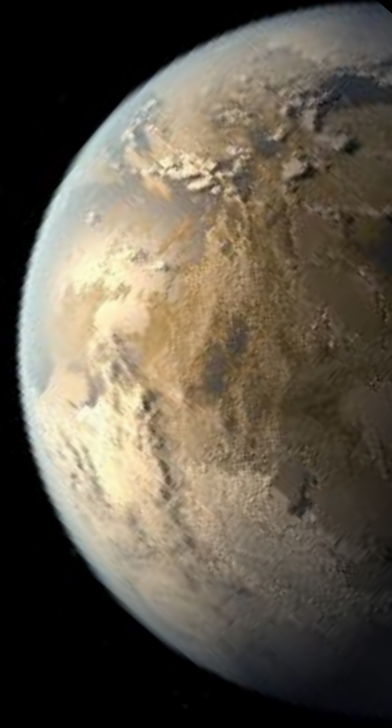

# “planet formation”





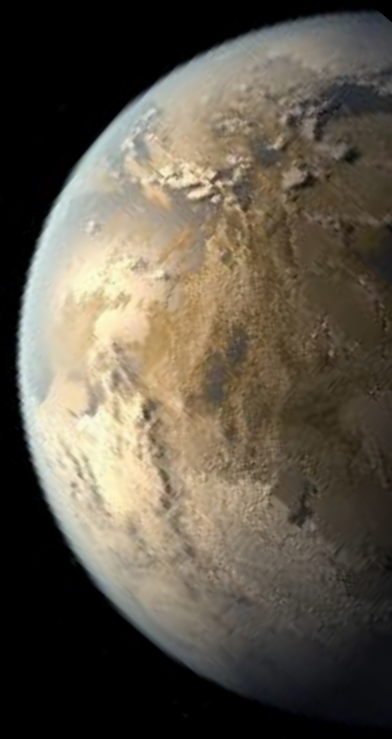
# Outline

1. Observational constraints (and the Solar System in context)
2. Stages of planet formation
3. Formation/evolution models for exoplanets:
   - ’Super-Earths’
   - Giant exoplanets



# 1. Observational constraints

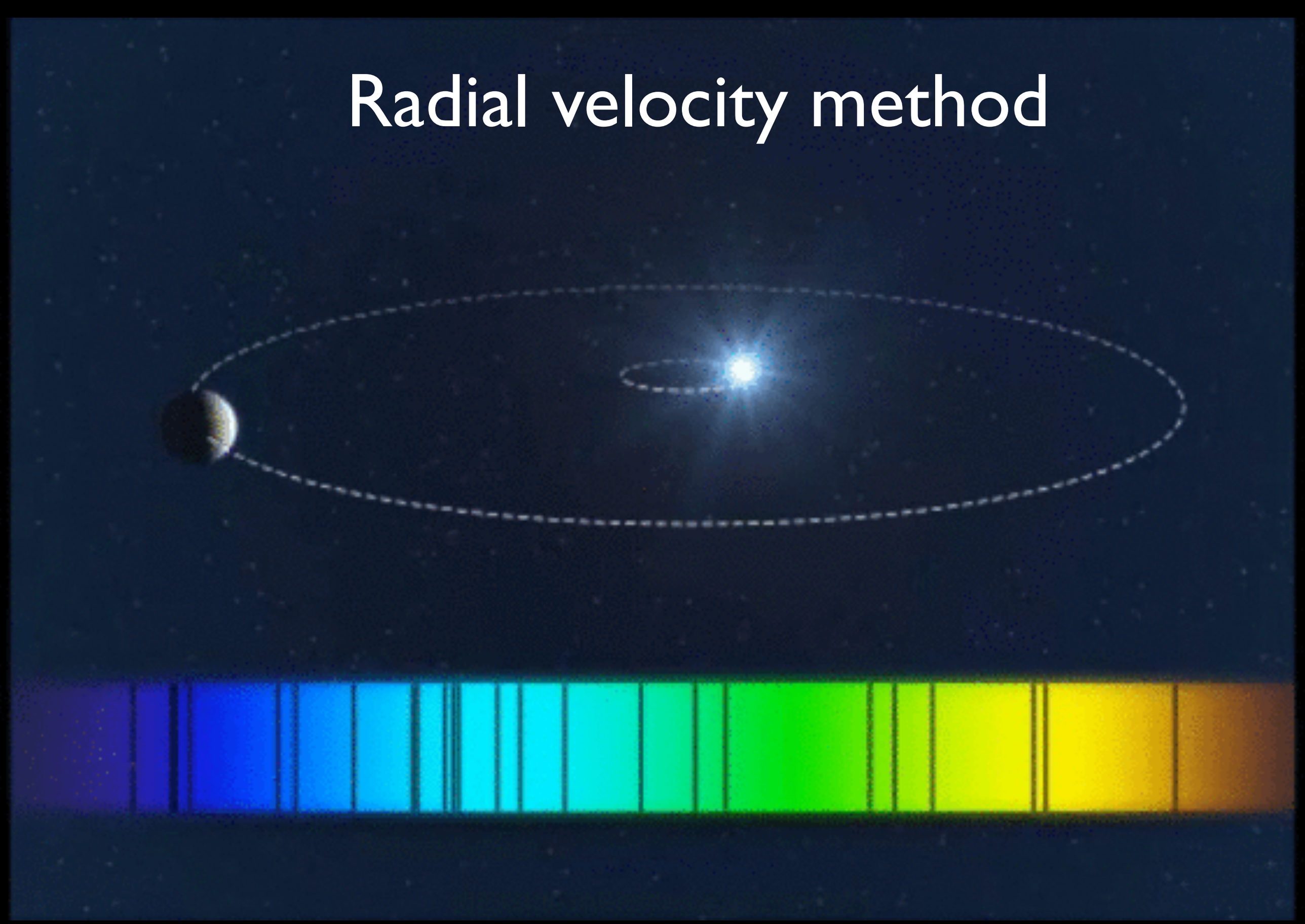
- Detection of exoplanets
- The Solar System in context
- Planet-forming disks



# Exoplanet detection techniques

# Radial velocity method

# Radial velocity method



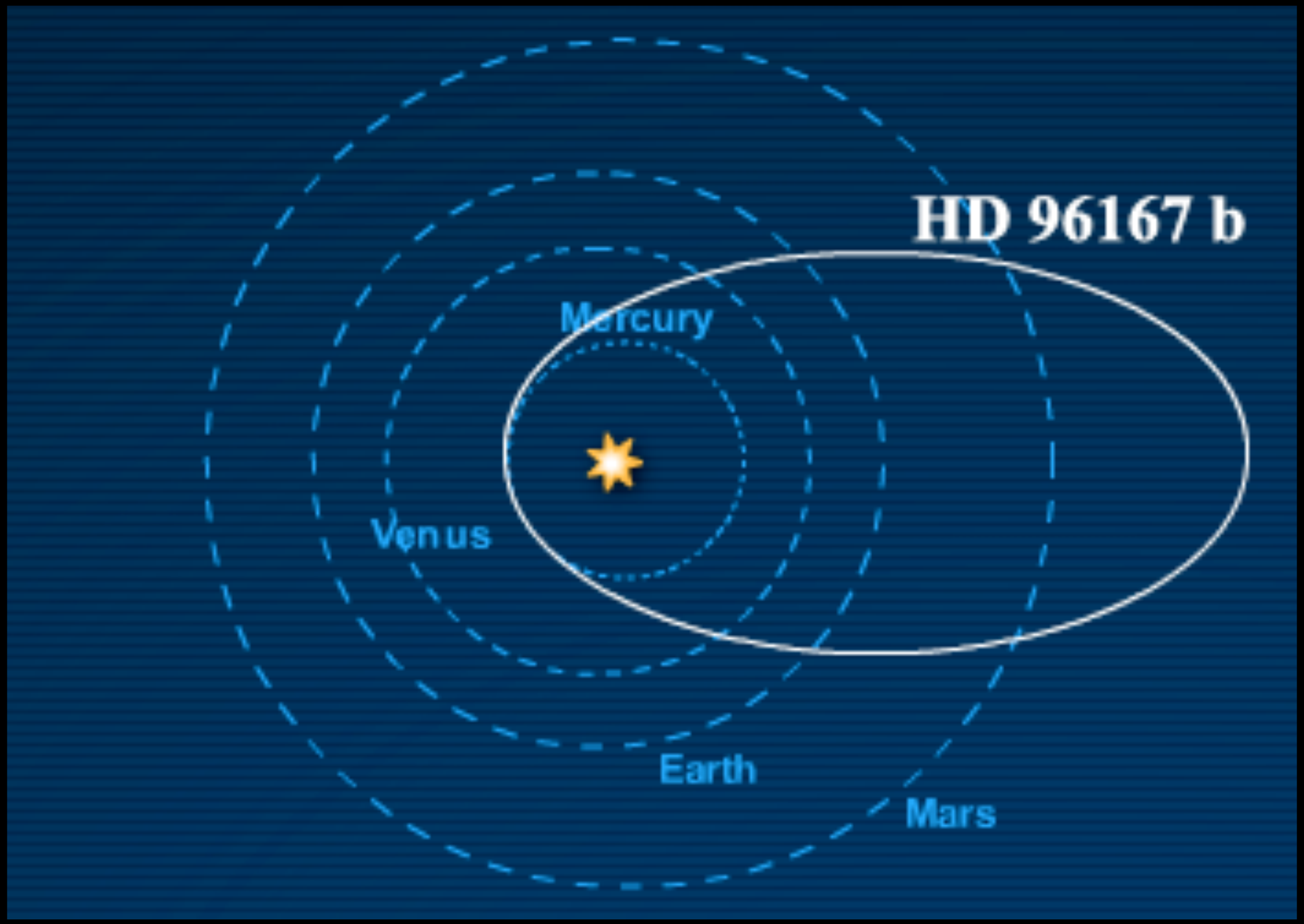


3.6-meter telescope at ESO, Chile

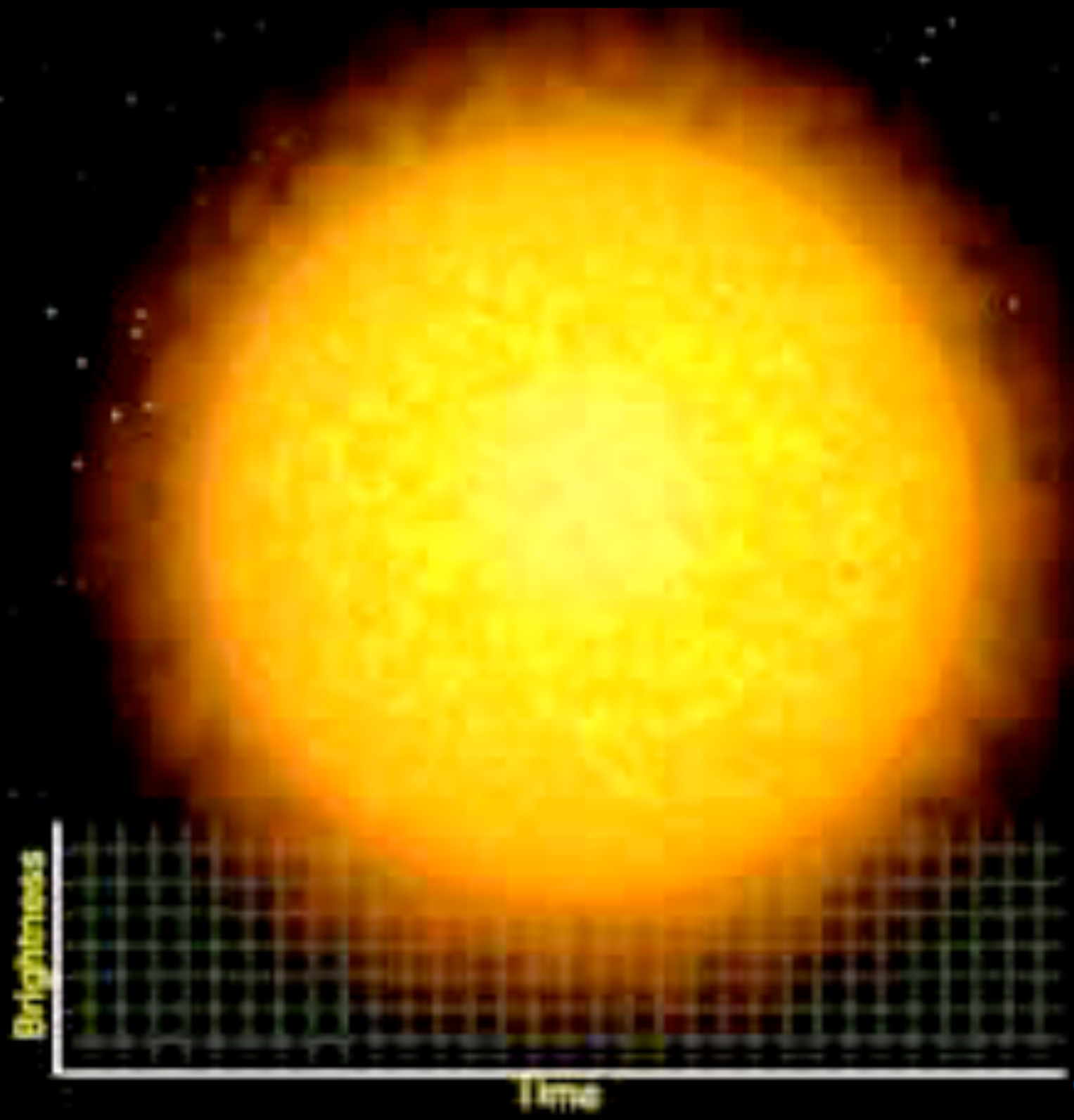
# 1995: the first "hot Jupiter"

(Nobel prize for Mayor and Queloz in 2019)

# Giant exoplanets often have eccentric orbits



# The transit method



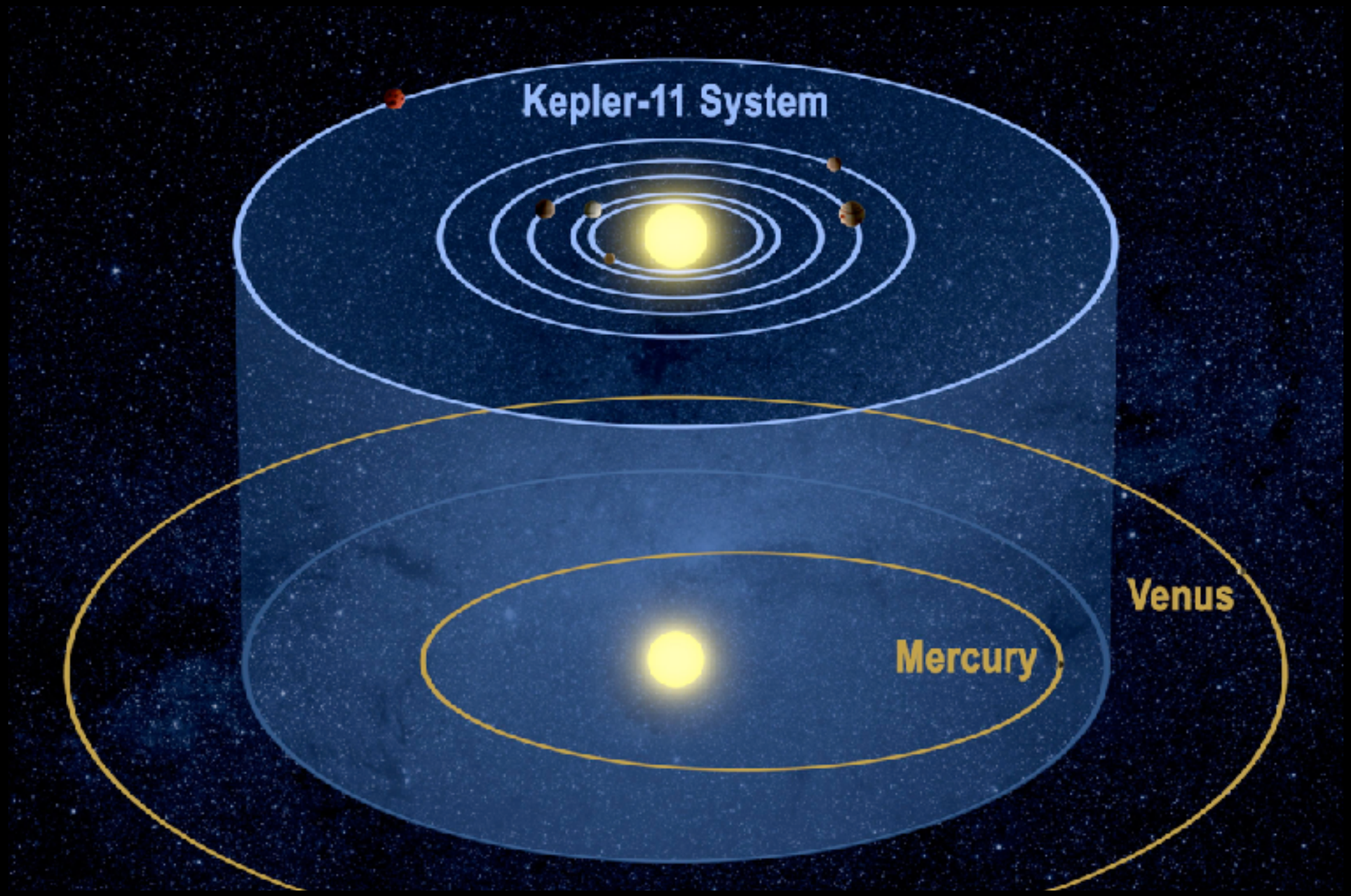

Credit: ESA



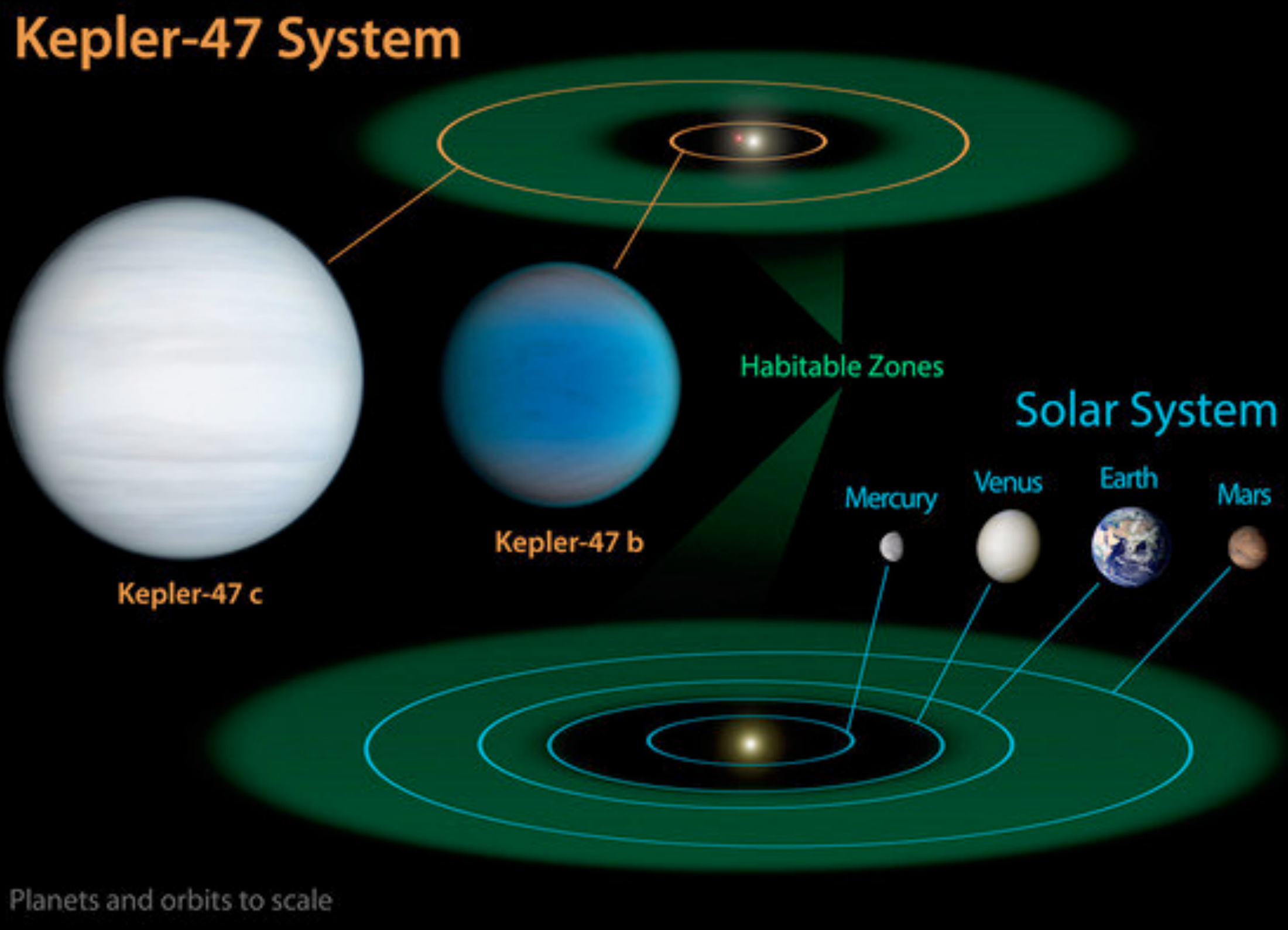



Kepler Space Telescope
(launched in 2009)

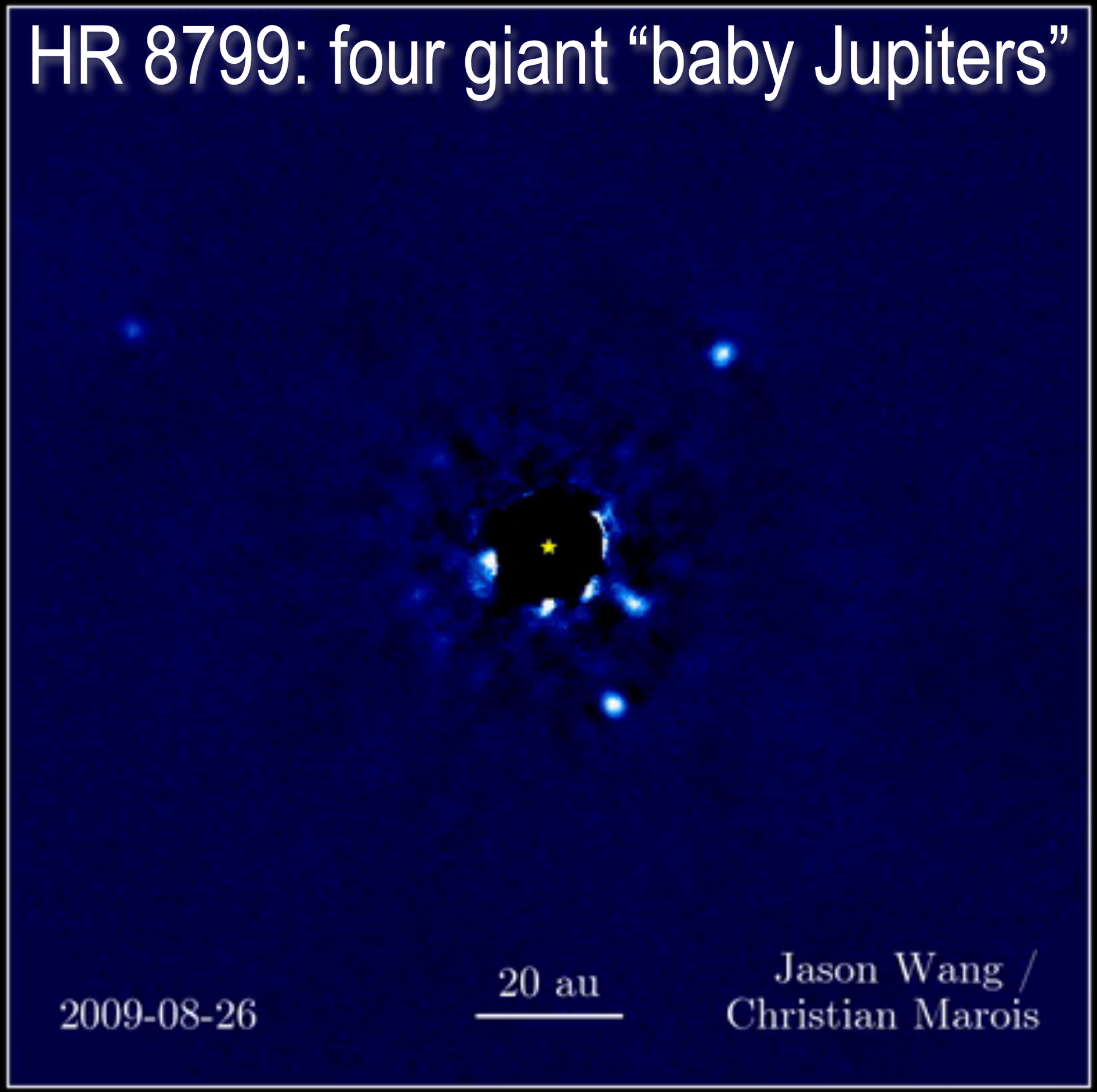
# “Super-Earths” (and “mini-Neptunes”) exist around ~half of all stars

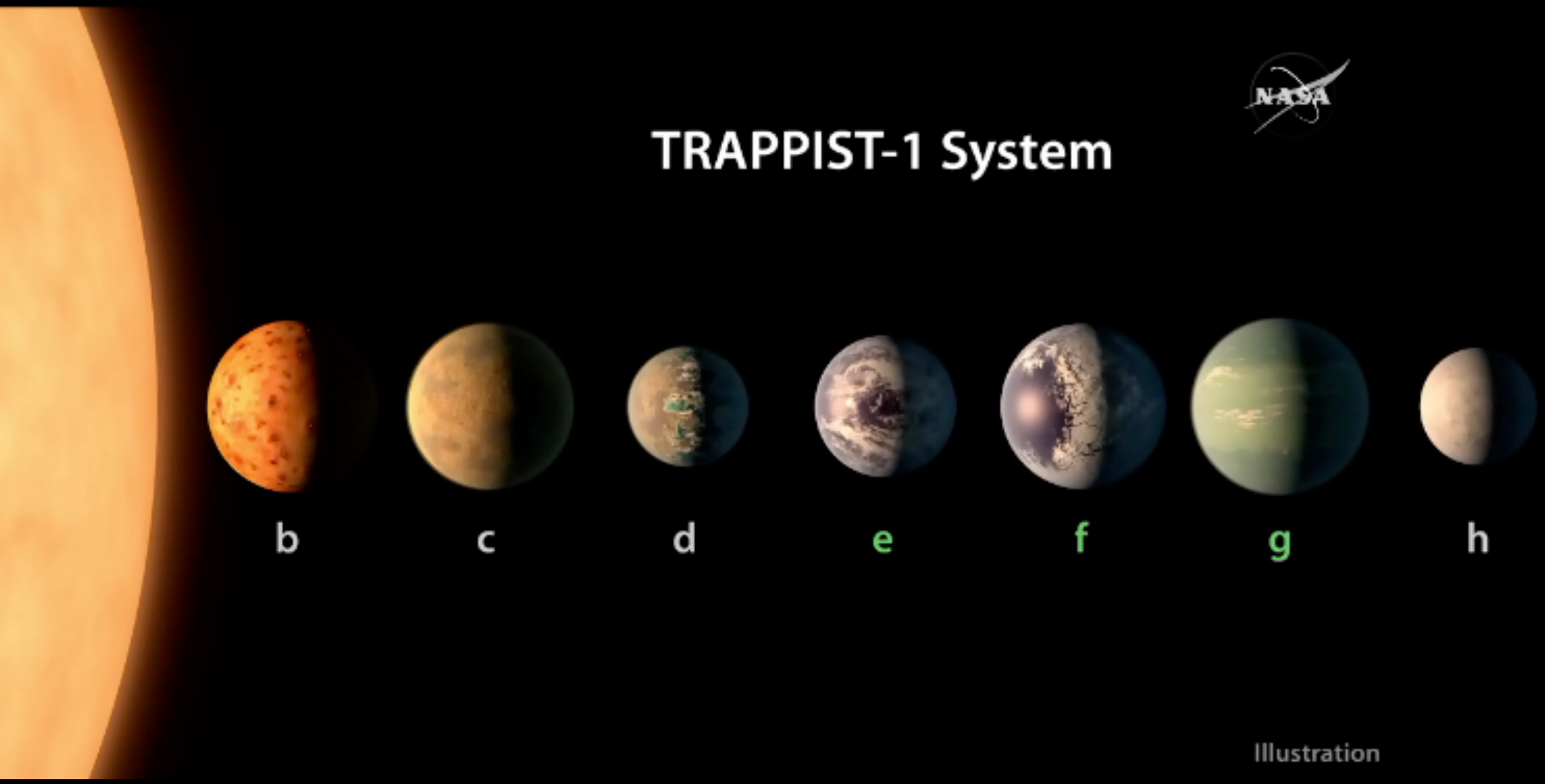


# “Tatooine” planets



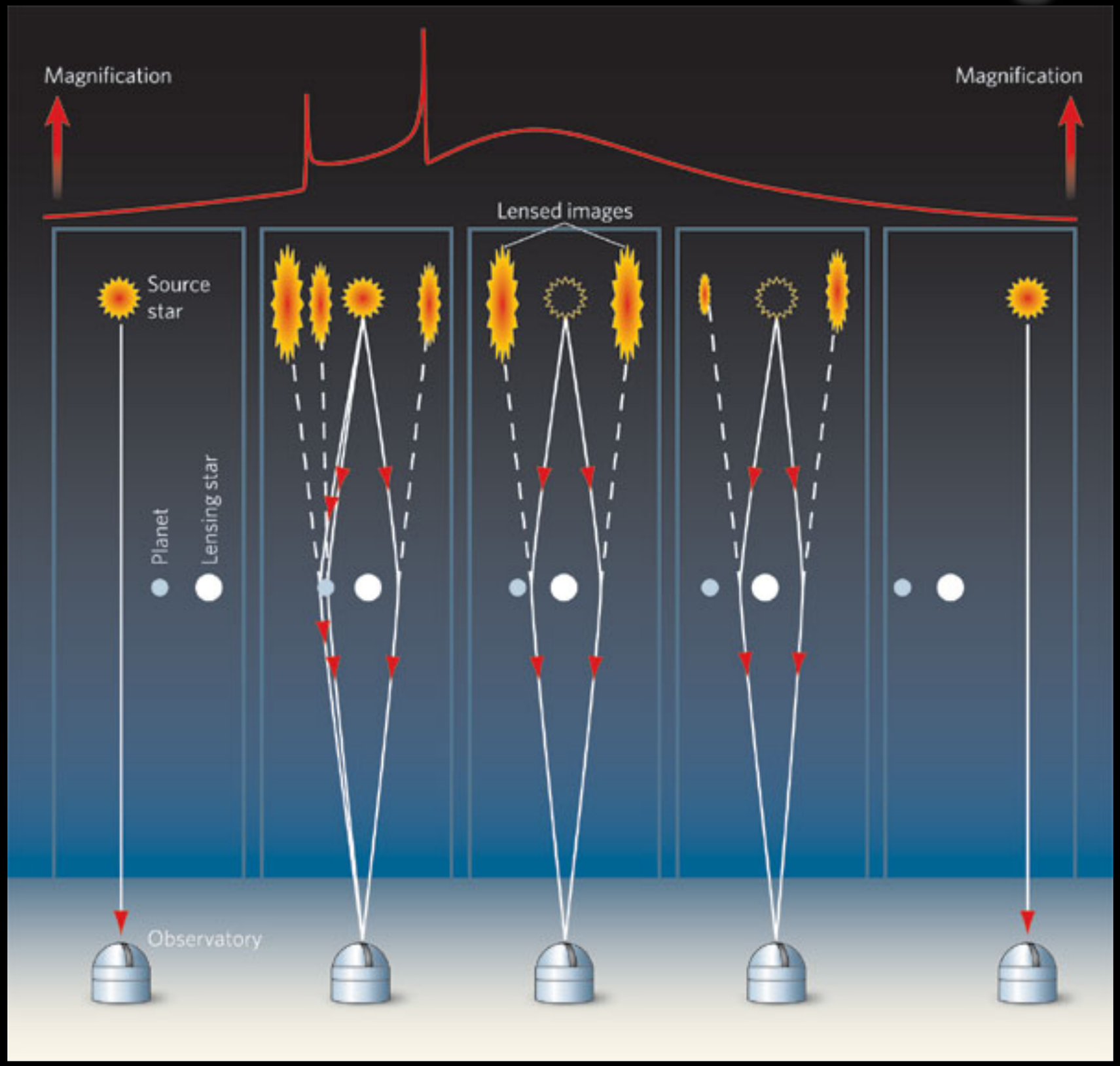
# HR 8799: four giant “baby Jupiters”






discovery: Gillon et al (2016, 2017)

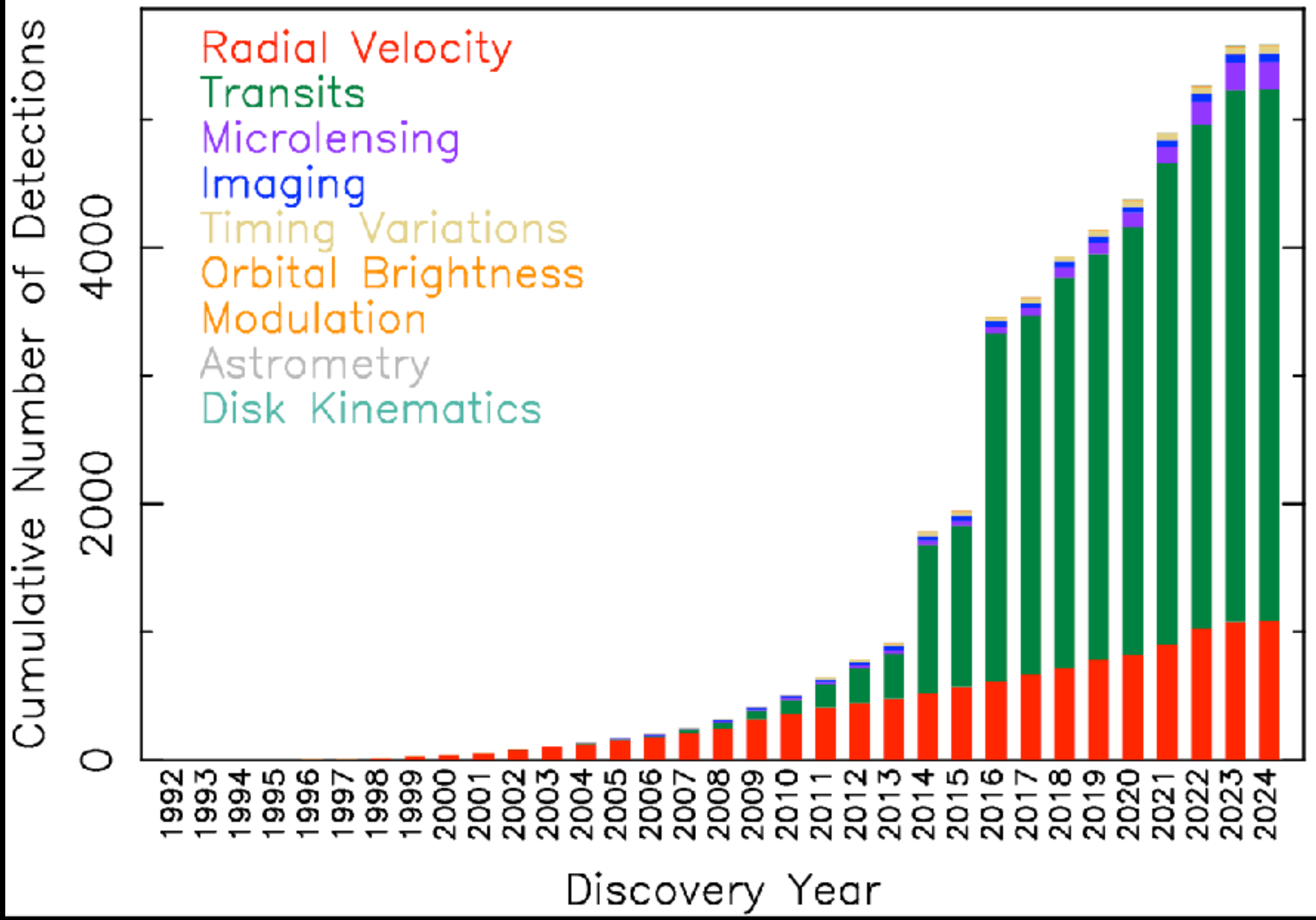
# Gravitational microlensing



# Exoplanet measurements

# Cumulative Detections Per Year

29 Feb 2024
exoplanetarchive.ipac.caltech.edu



exoplanets.org | 2/28/2015

Hot Jupiters

"Normal" Jupiters

Hot Super-Earths

Planet Mass [Jupiter Mass]

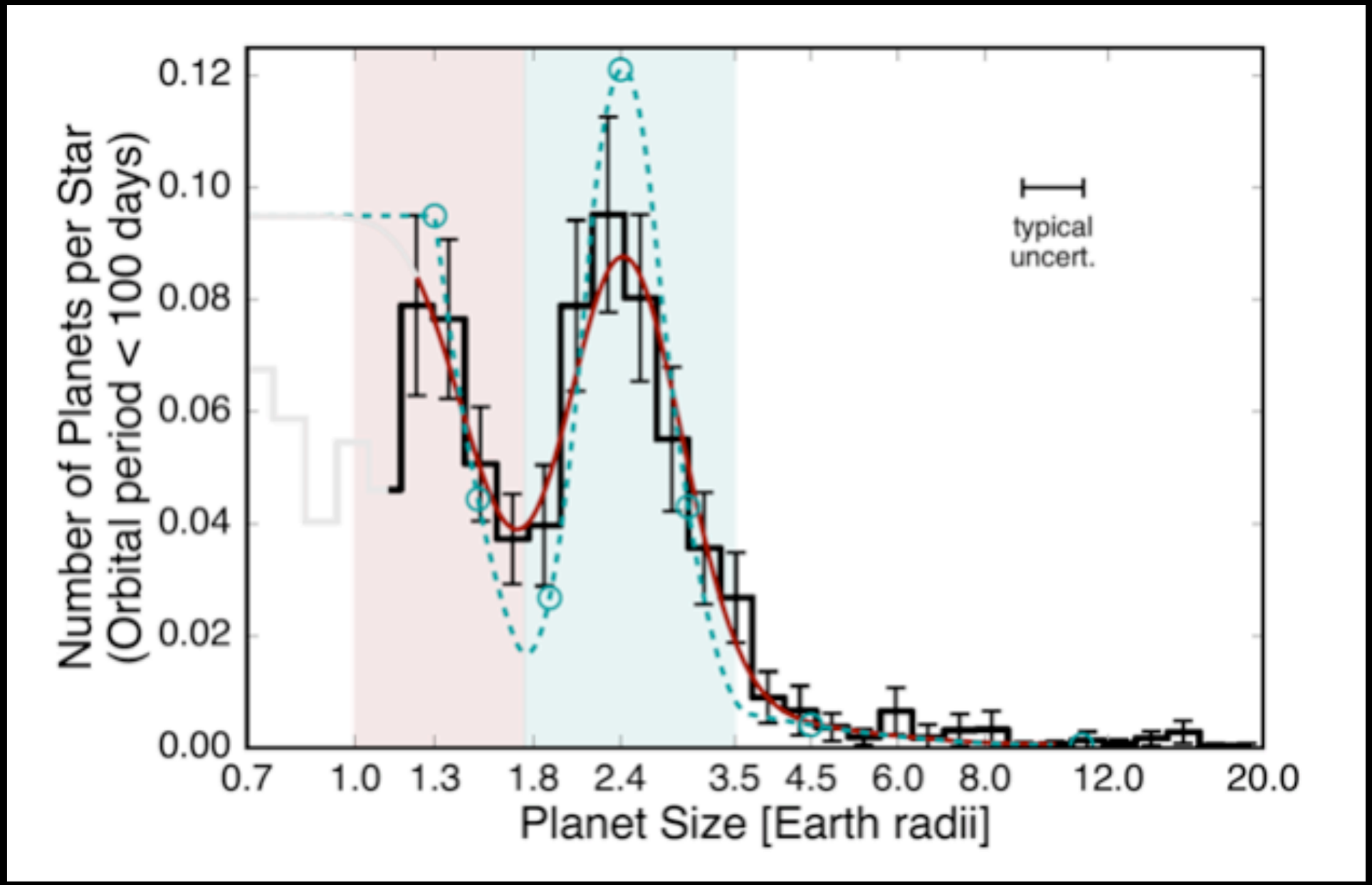
10
1
0.1
0.01
$10^{-3}$

0.01
0.1
1
10

Separation [Astronomical Units (AU)]

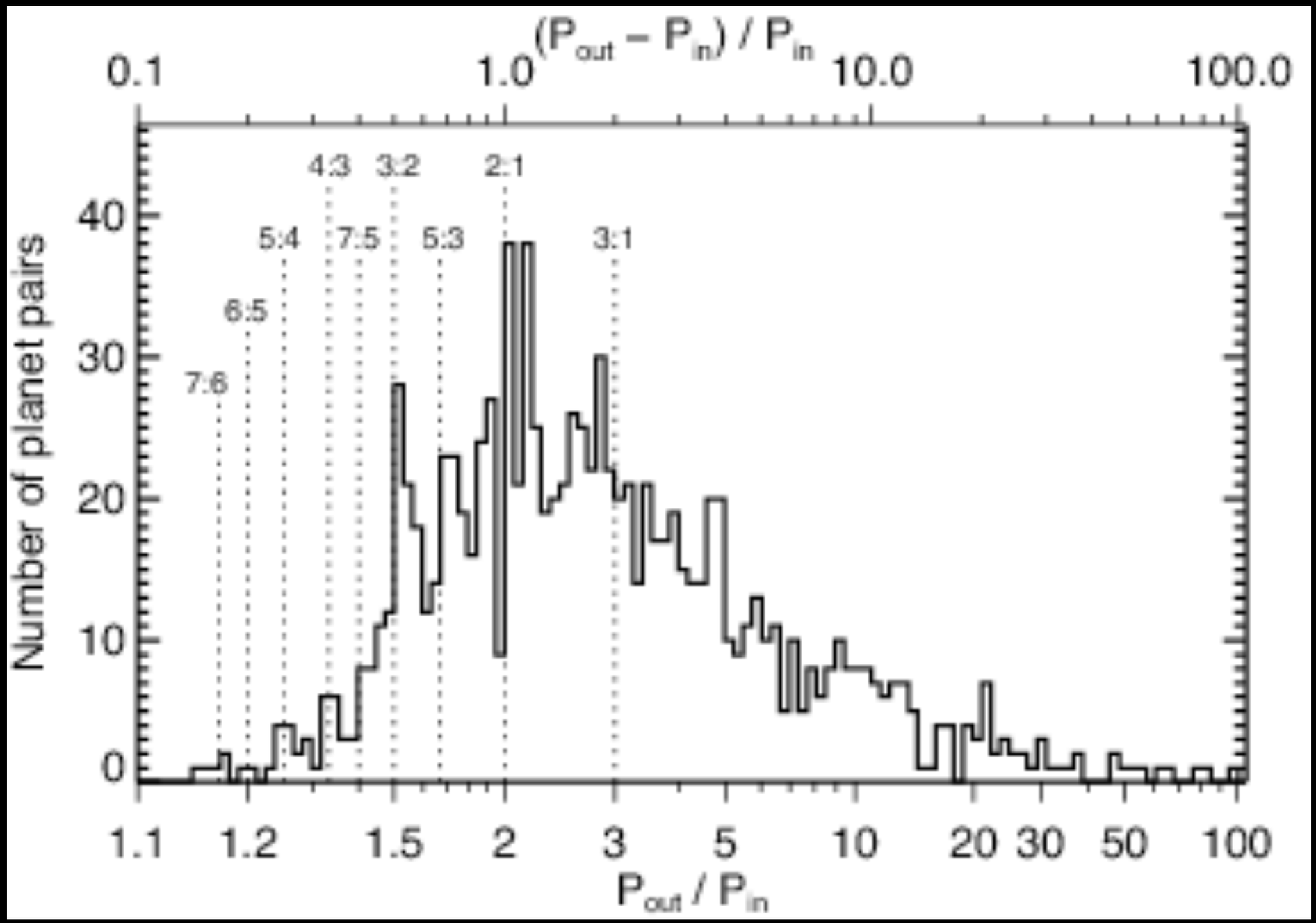
# Exoplanet size distribution

‘super-Earths’ ‘sub-Neptunes’



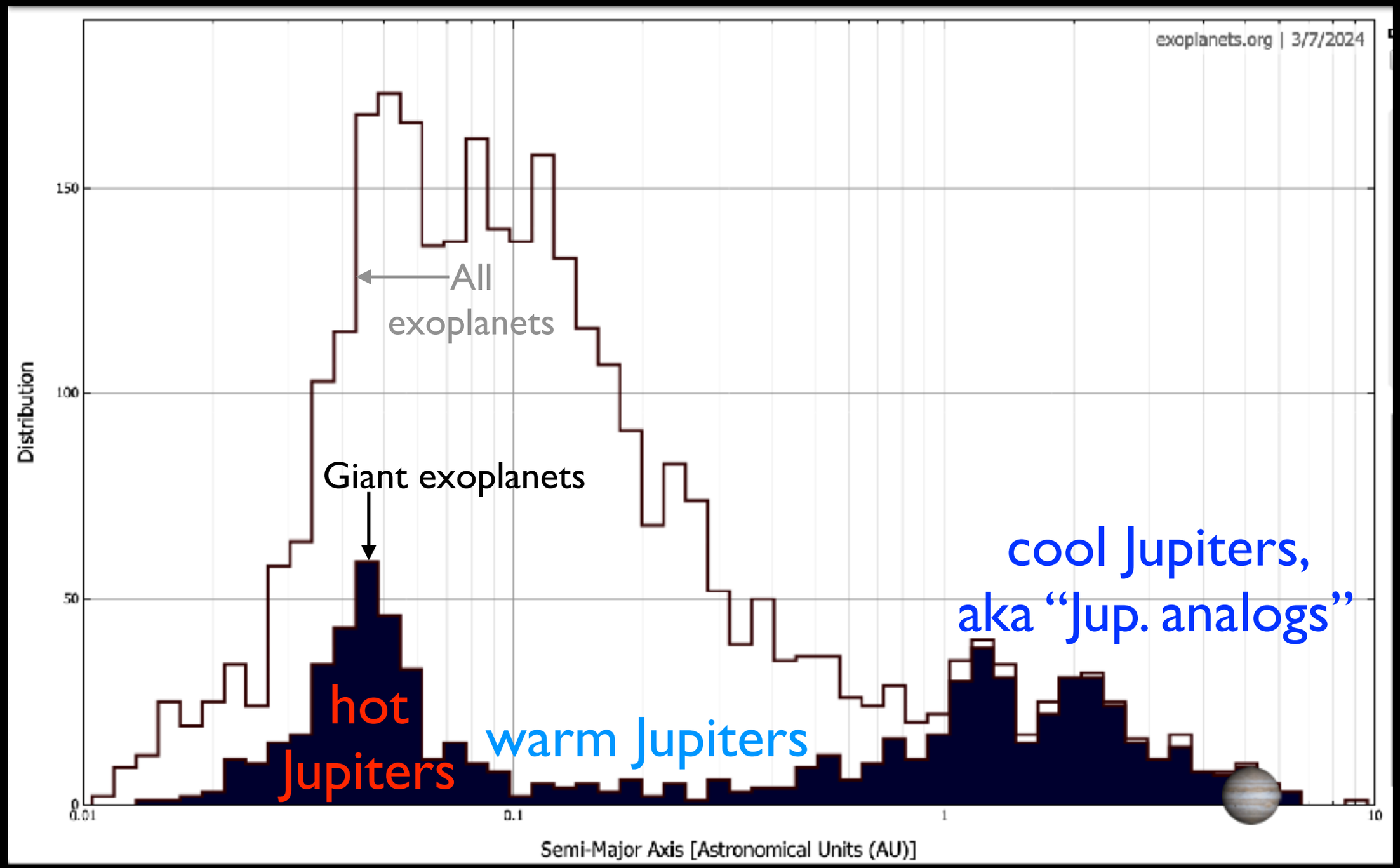

Fulton et al (2017); **Fulton & Petigura (2018)**; van Eylen et al (2018)

# Period Ratio distribution

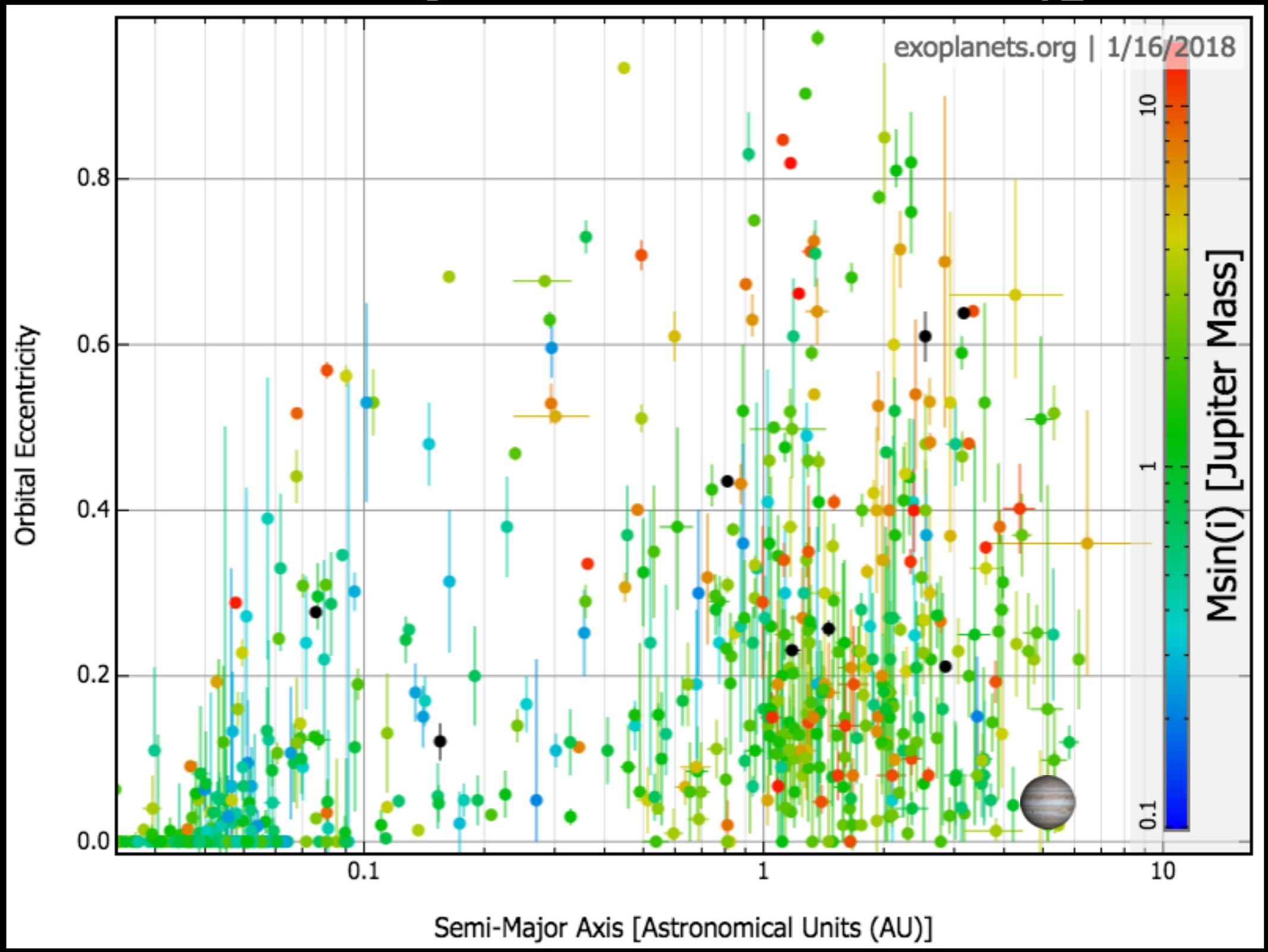



Winn & Fabrycky 2015

# Radial distribution of gas giants

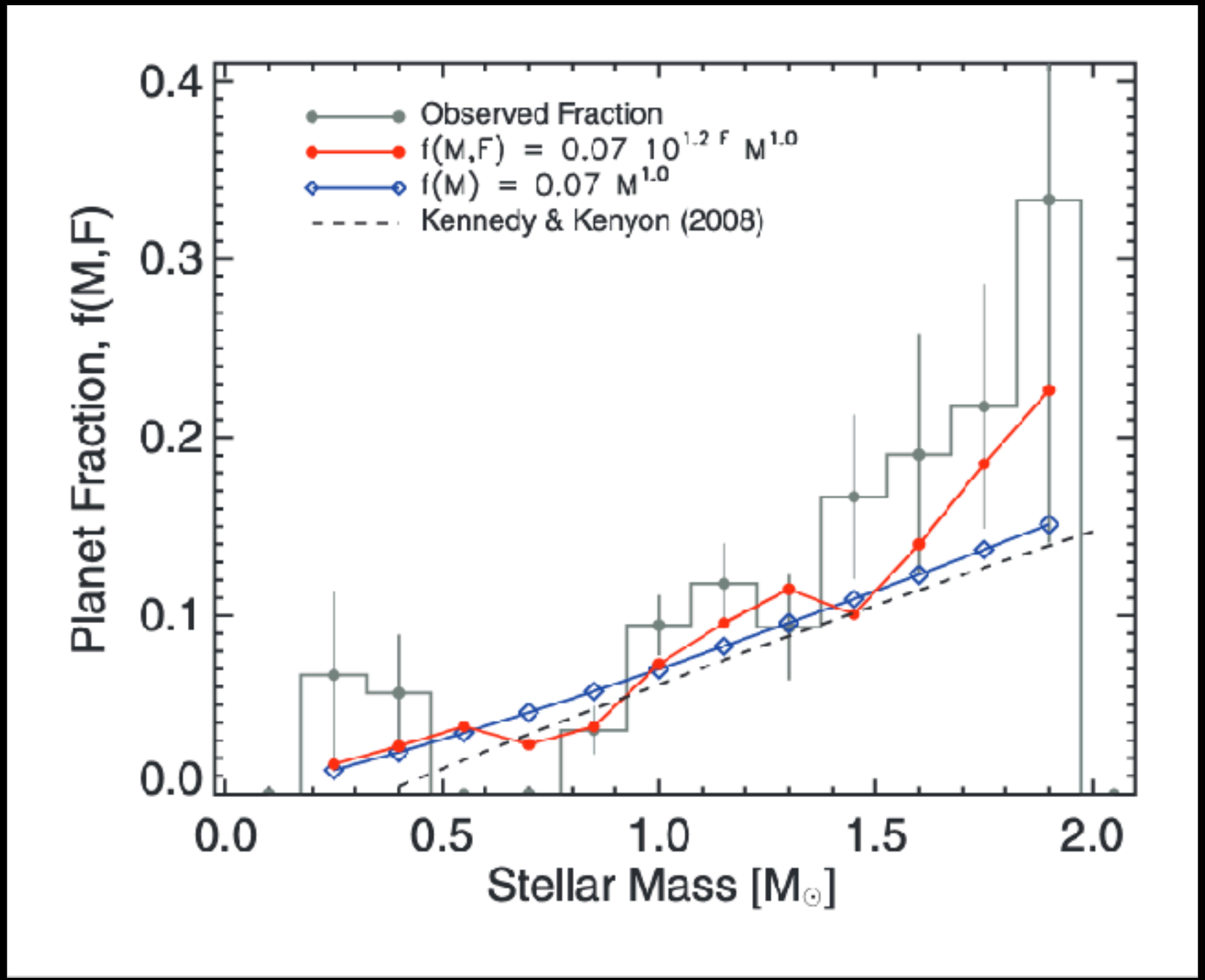


# Eccentricity distribution (giants)



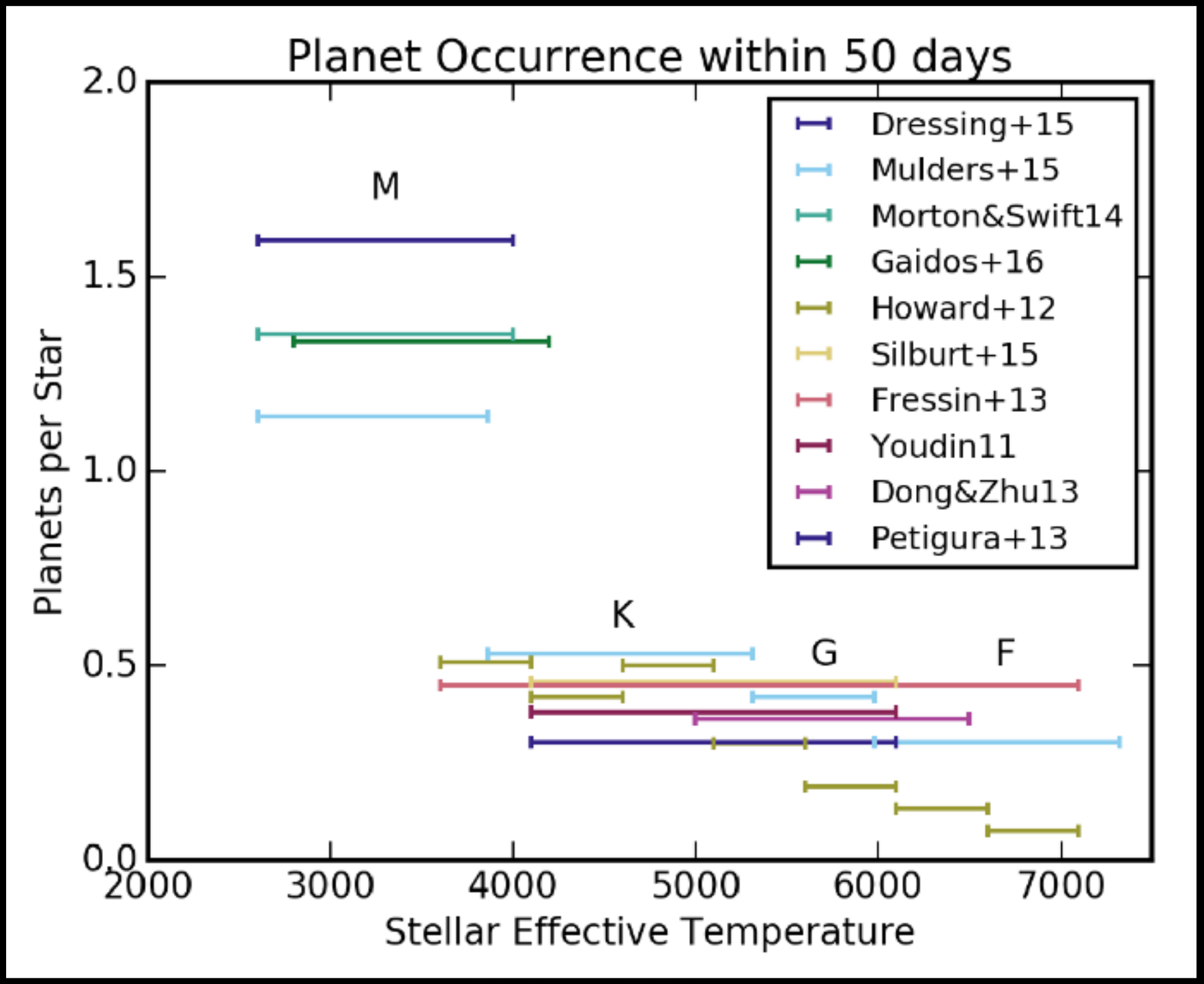

Wright et al 2011

# Higher-mass stars have more gas giants



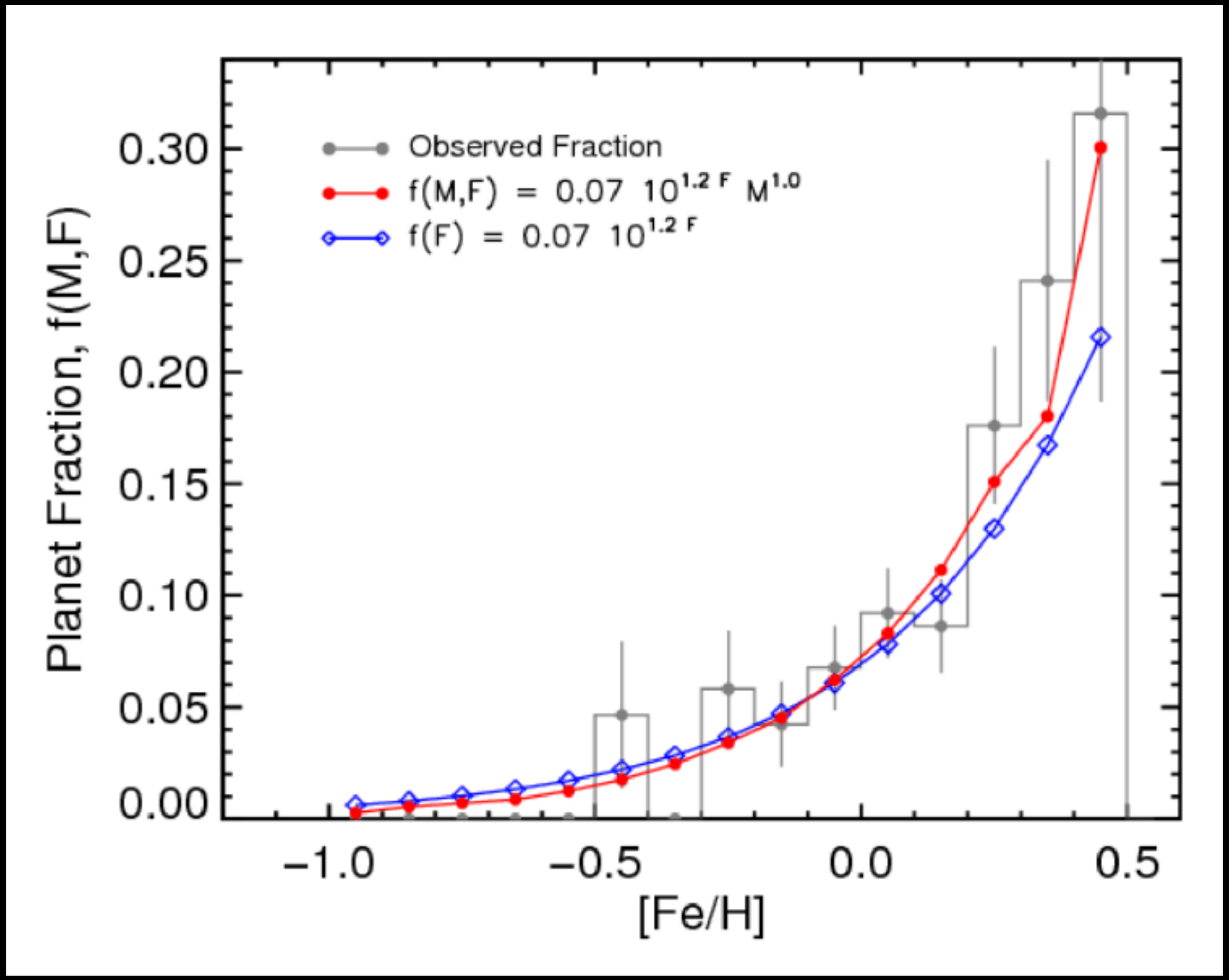

Johnson et al (2010)

# Low-mass stars have more close-in planets




Mulders (2018)

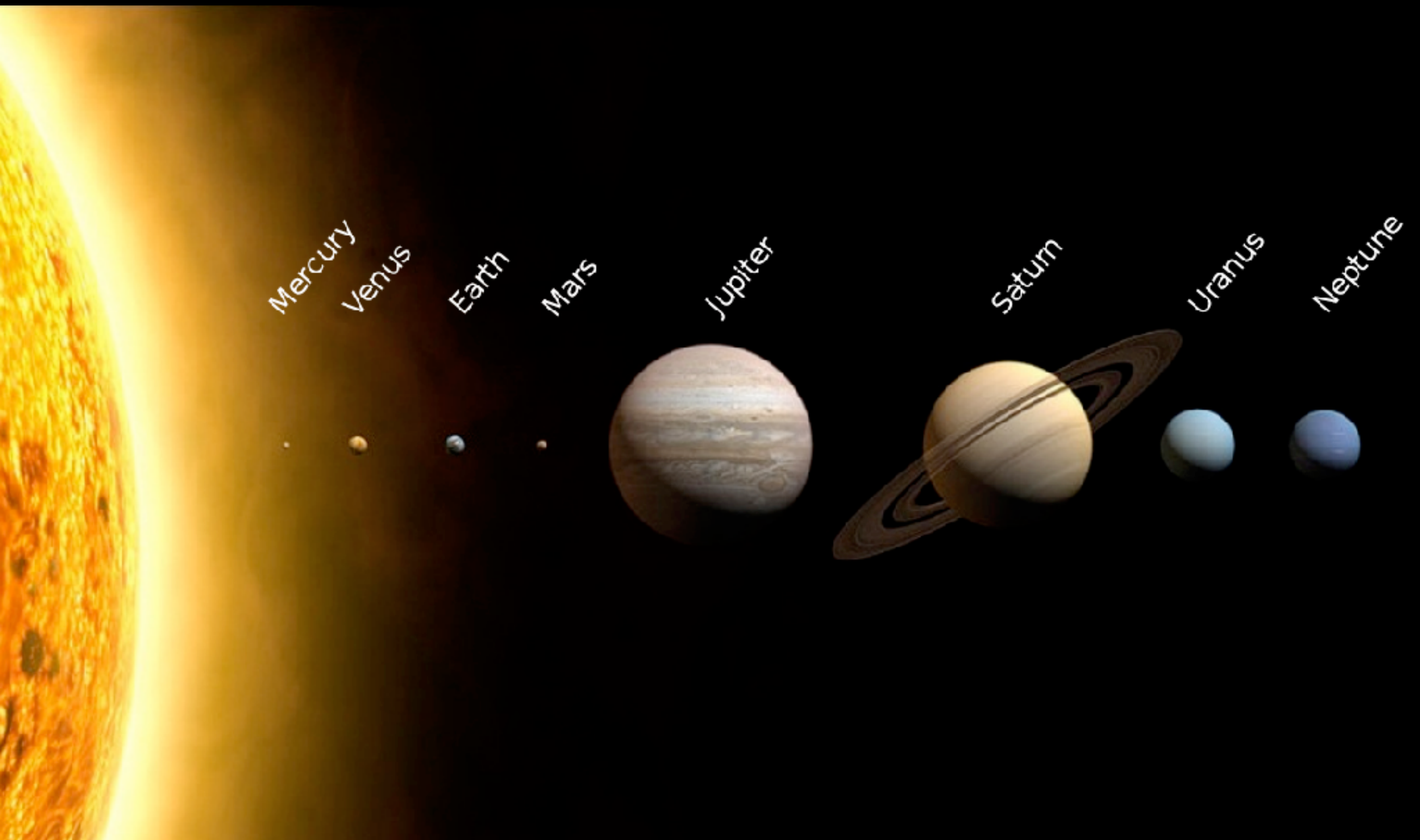
# Giant planet-metallicity correlation



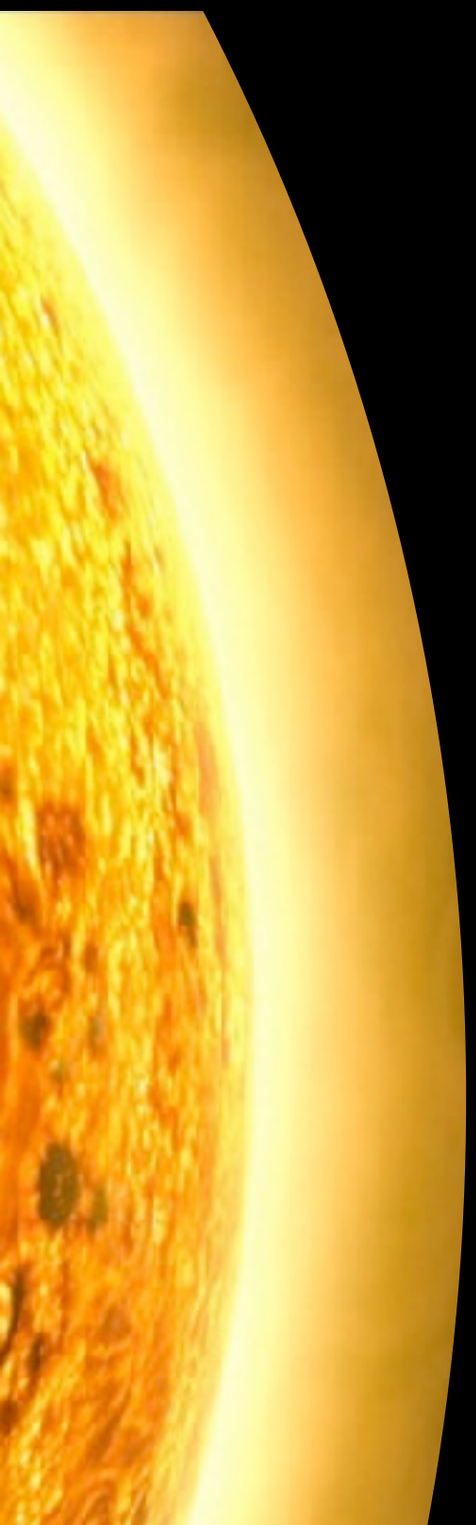

Johnson et al (2010)

also Gonzalez (1997); Santos et al (2003); Fischer & Valenti (2005)

# The Solar System



# The exo-Solar System

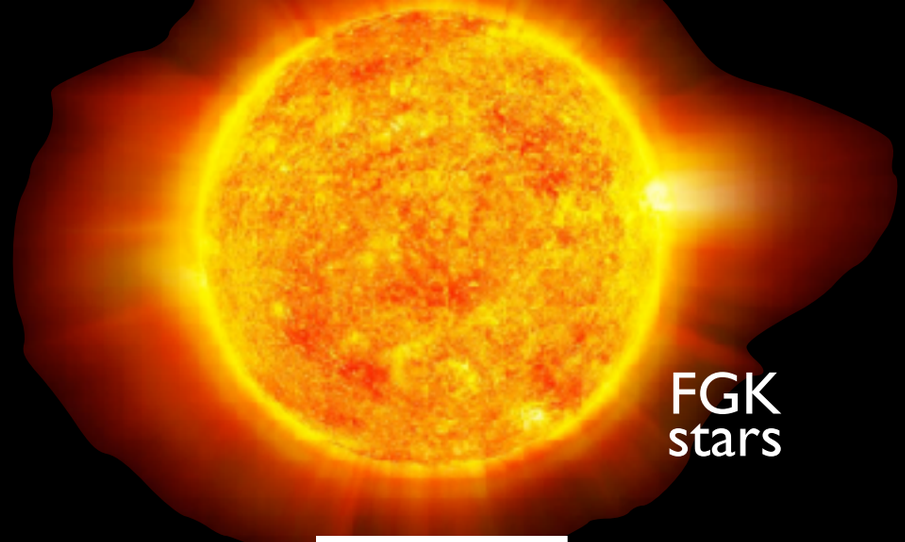


Measure:

- mass ($M_{Jup}$ sin i)
- orbital size
- orbital shape (eccentricity)



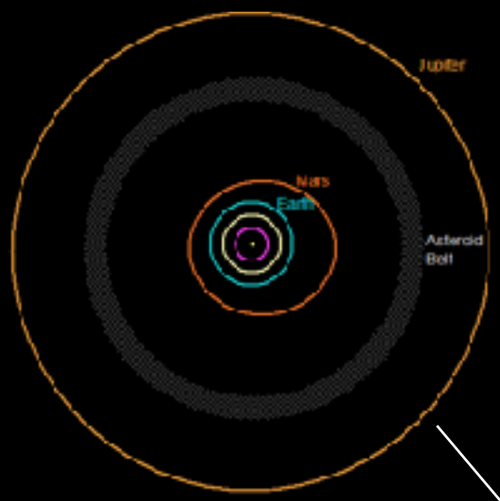

(Sun's radial velocity amplitude due to Jupiter ~12 m/s, P=12 yr)



FGK
stars

No planets
detected to date

Solar System-like
(~1% of total)

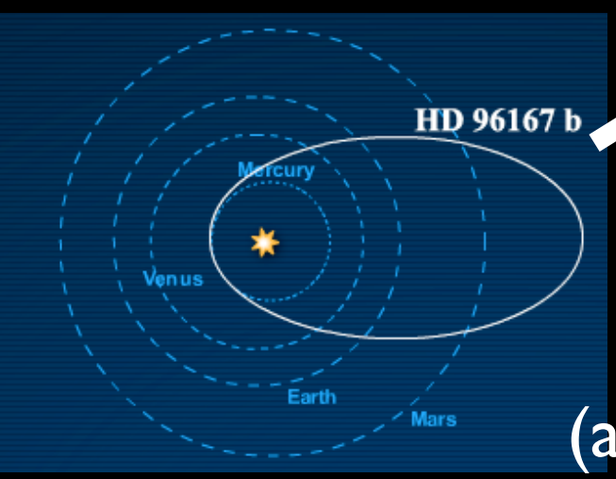



~10%

~10%

?

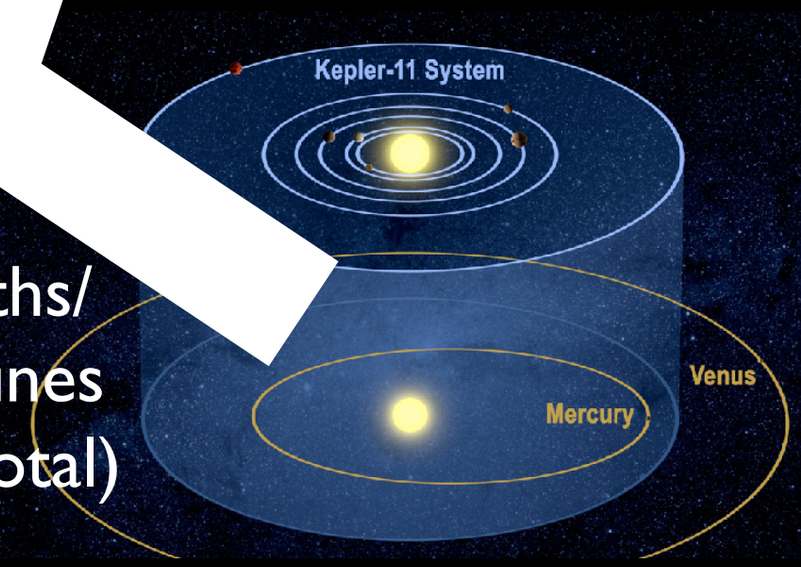
~90%



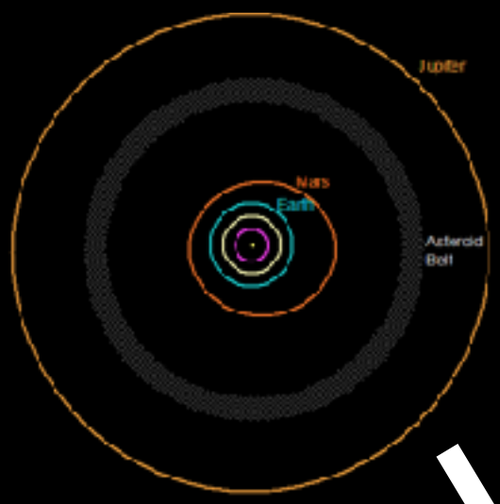

~90%

Eccentric giants
(and some hot Jupiters)

super-Earths/
sub-Neptunes
(~50% of total)



# Planet formation




Disk evolution



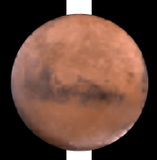
Planetesimal formation



Pebble/planetesimal accretion



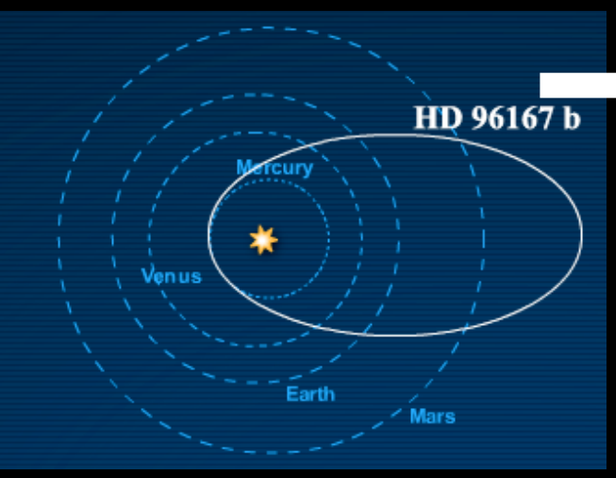
Giant impacts

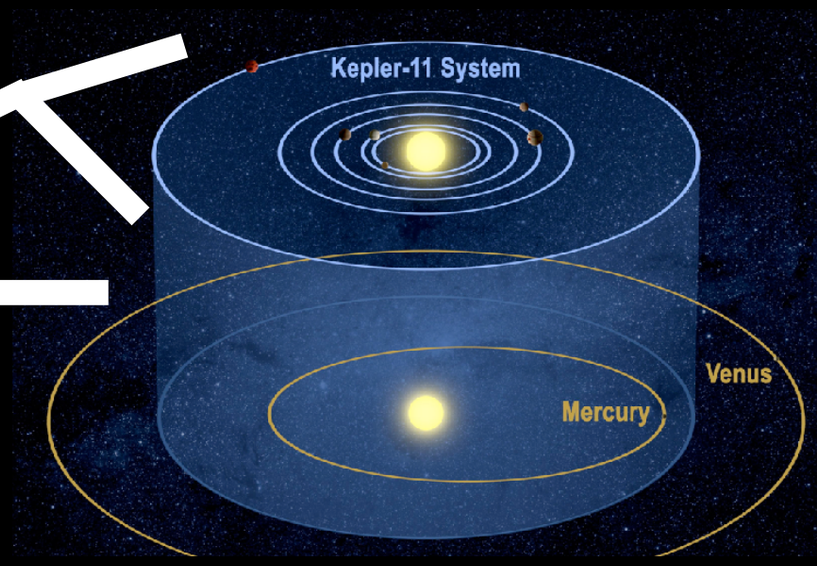


Orbital migration

Gas accretion



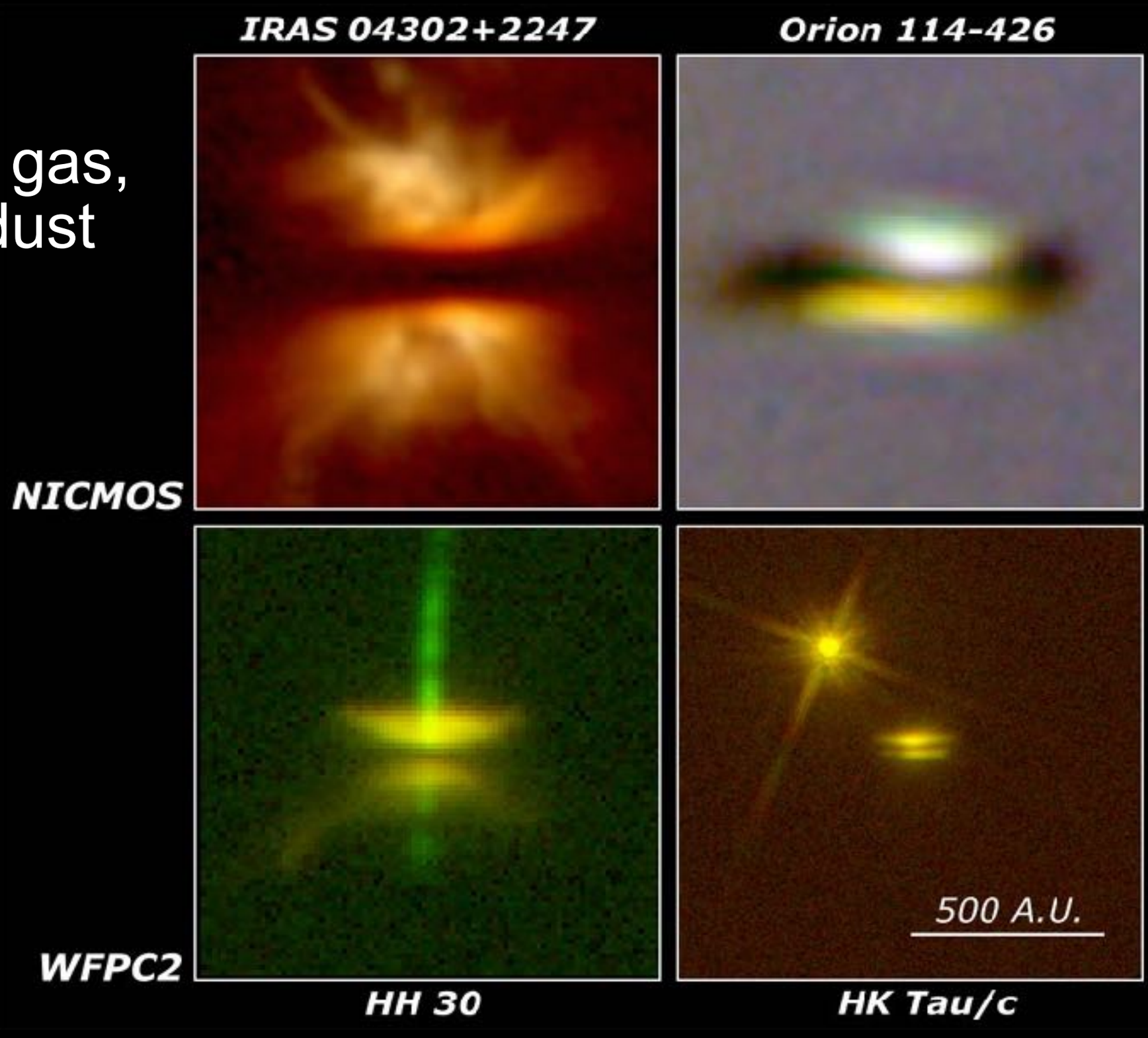



# Protoplanetary disks



# Disks around young stars: Hubble

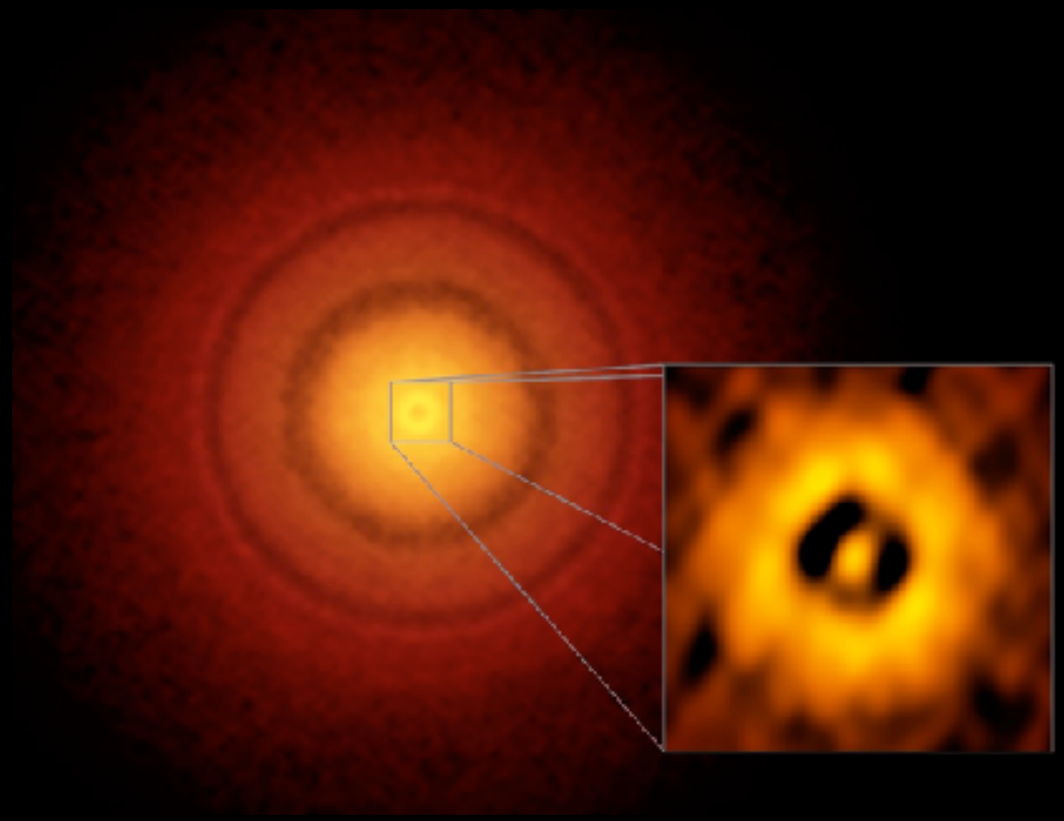
- 99% gas, 1% dust



# ALMA Images of young disks

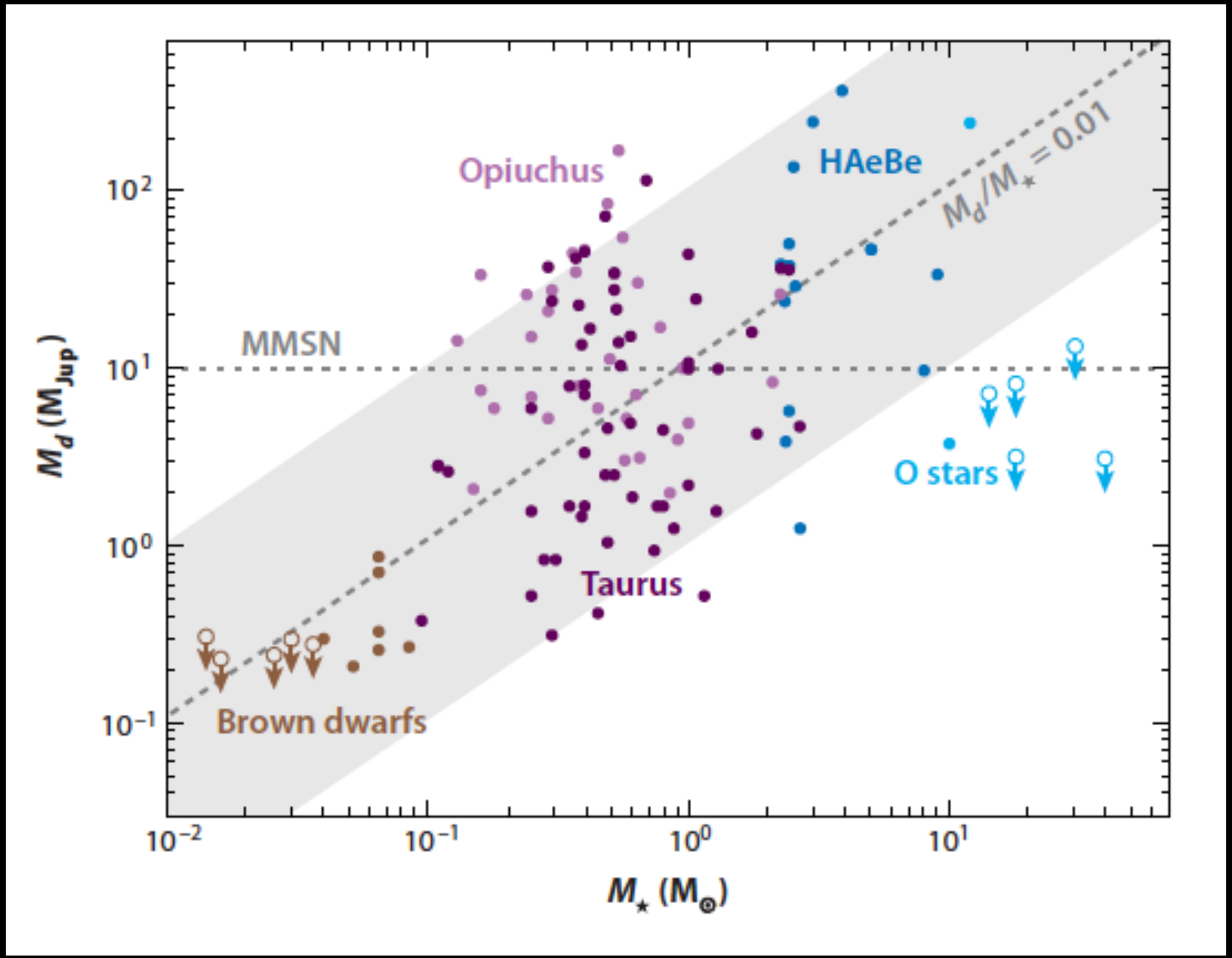


ALMA Partnership 2015



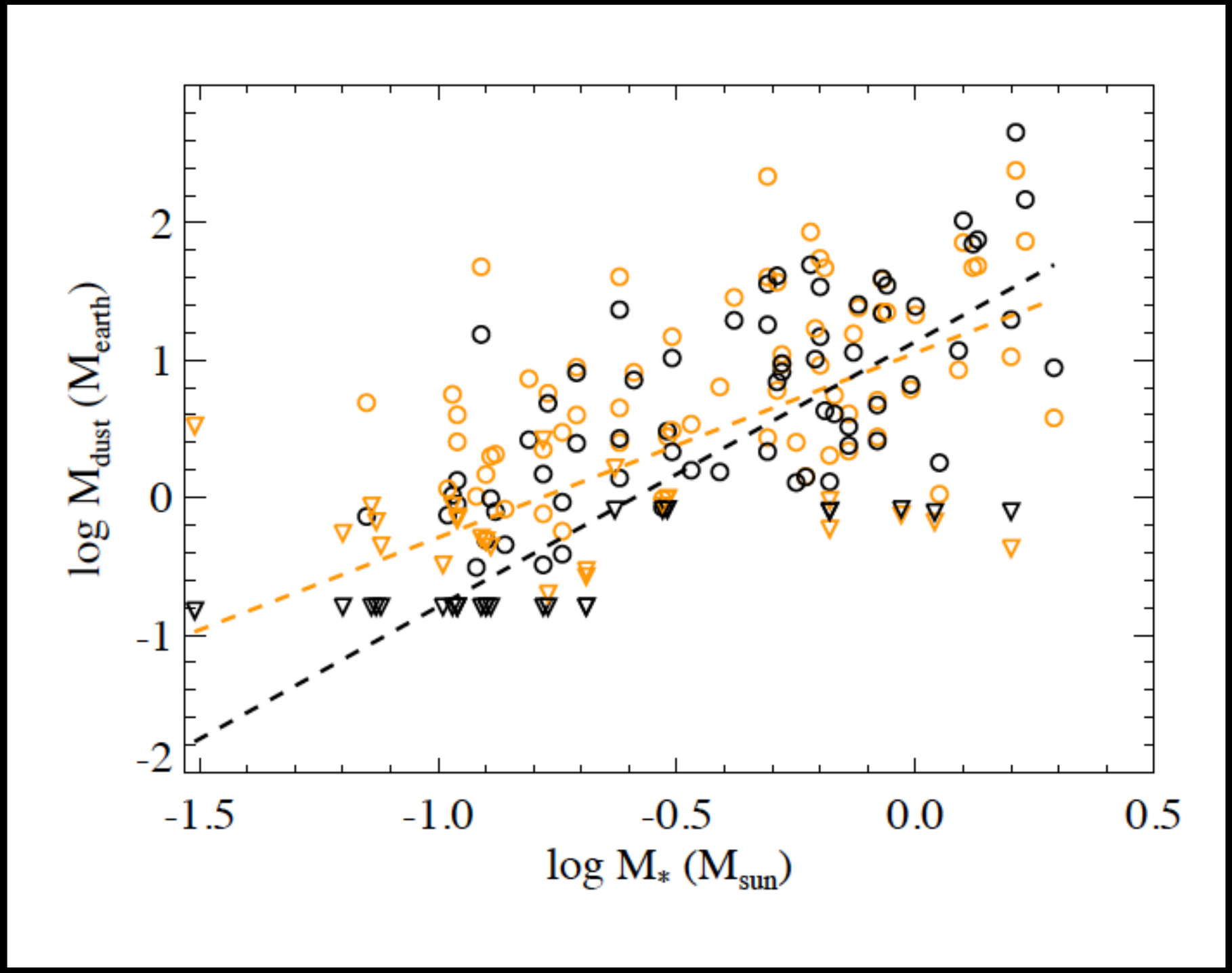
Andrews et al (2016)

# Disk masses




Williams & Cieza 2011

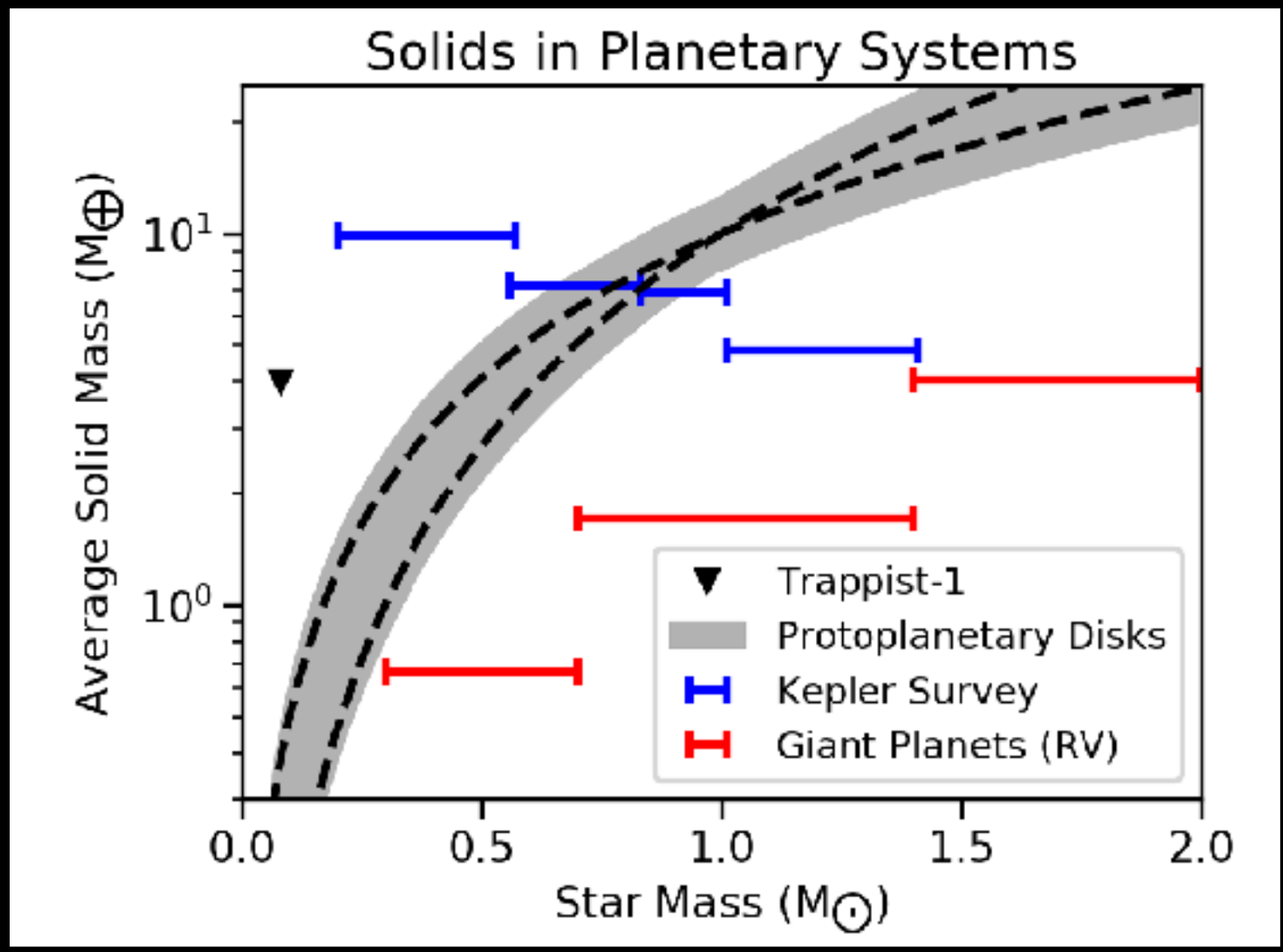
# Mdisk-Mstar correlation (Md~Mst$^{1.6}$) — but lots of scatter




Pascucci et al 2016

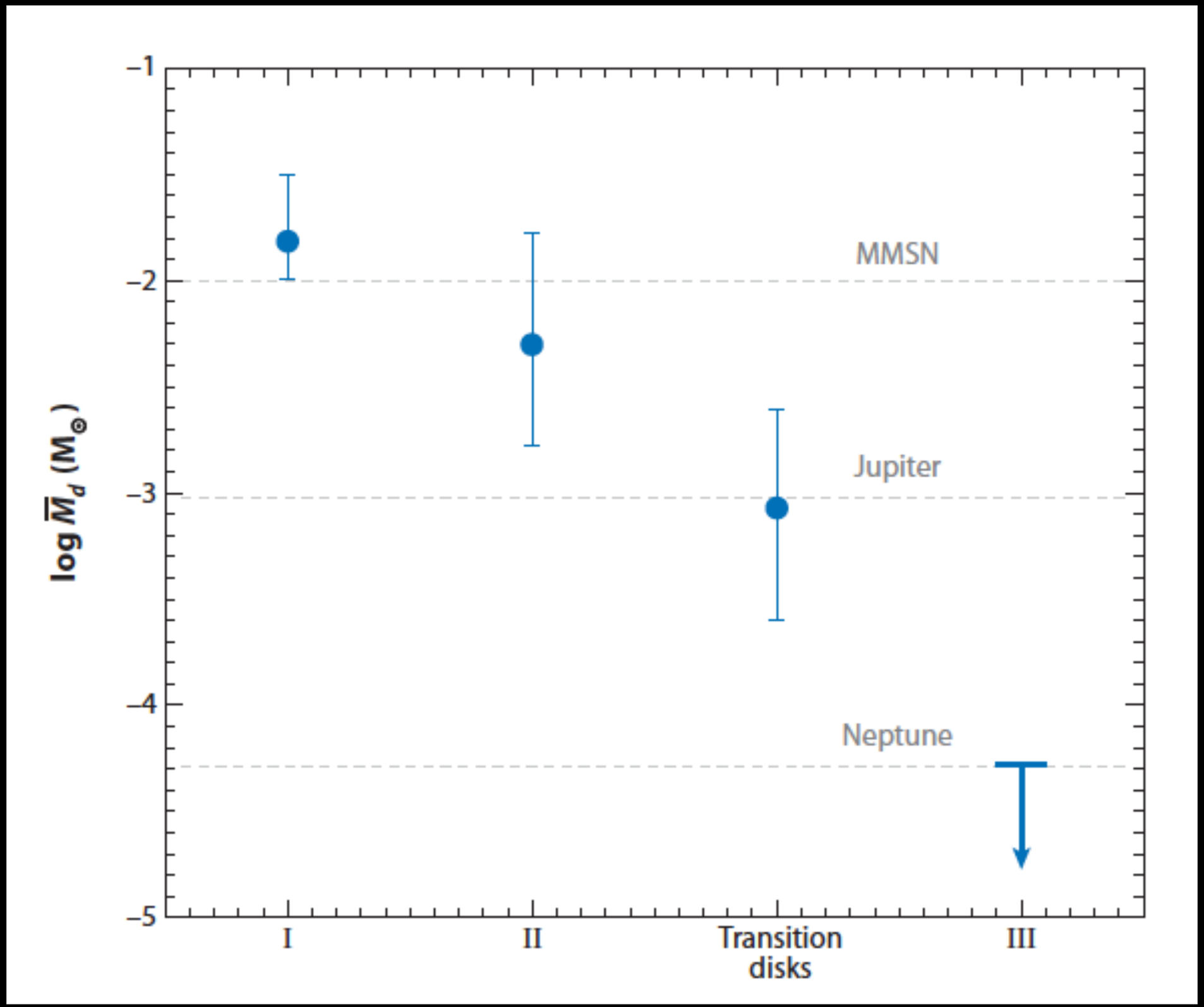
# Are disk masses underestimated?

Disk masses appear too small to explain the masses in observed planetary systems



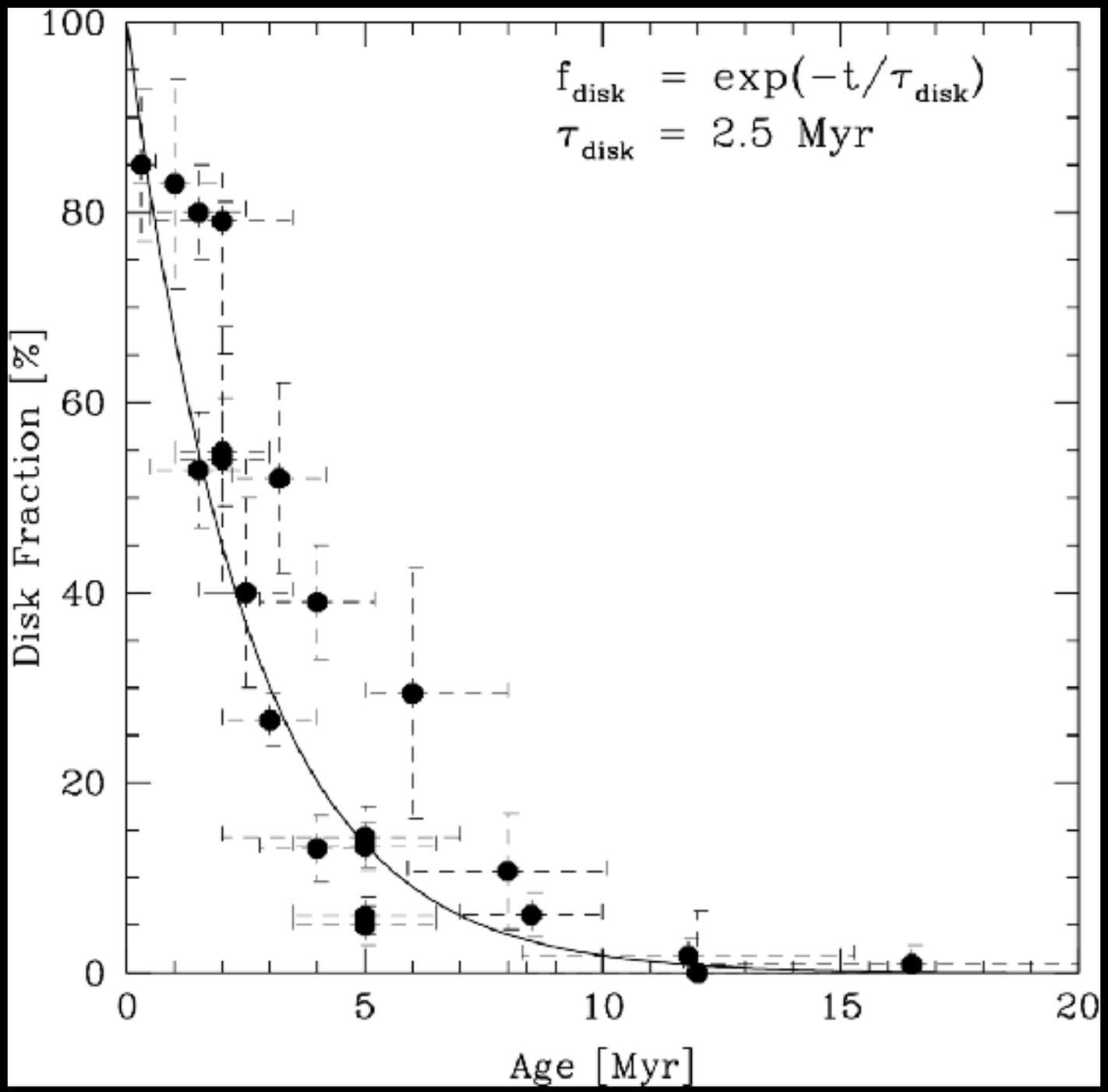

Mulders (2018)
[also Manara et al 2018]

# Disk masses



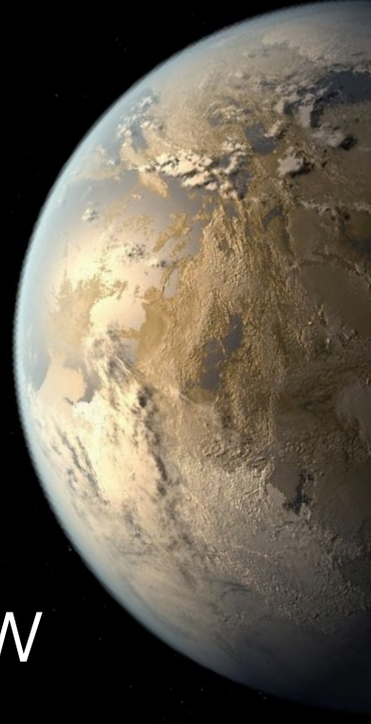

Williams & Cieza 2011

# Gas disks (inferred from hot dust) dissipate on a few Myr timescale




Mamajek 2009

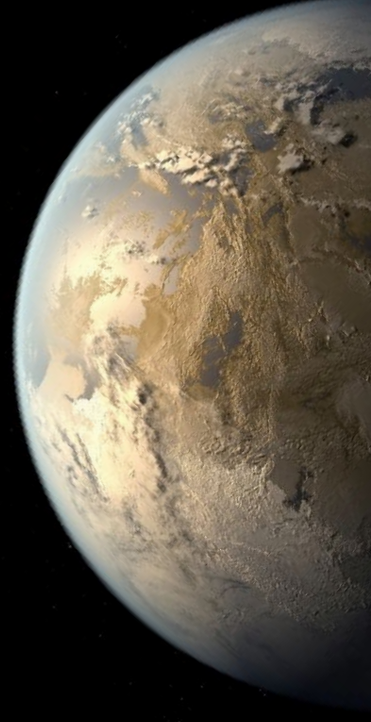
# Summary: Observational constraints



- Huge diversity of planetary systems
  - Solar System unusual at ~1% level
  - “Super-Earths” very common
- The window for most planet formation: the few million year lifetime of gaseous disks

# 2. Stages of planet formation

- planetesimal formation
- pebble/planetesimal accretion
- orbital migration
- giant impacts
- gas accretion
- giant planet scattering



Gas giants

~10 Earth-mass cores

1 $M_{Earth}$

Mars-mass embryos

Planete-simals (~100 km)

Dust (μm)

gas accretion (slow, then runaway)

pebble isolation

late accretion (planetesimal impacts)

pebble accretion

within snow line: rocky

giant impacts

beyond snow line: ice+rock

planetesimal/pebble accretion

Moon-forming impact

streaming instability

dust coagulation

gas disk lasts a few Myr

$10^4$ yrs

$10^5$ yrs

$10^6$ yrs

$10^7$ yrs

$10^8$ yrs

Gas giants

~10 Earth-mass cores

1 $M_{Earth}$

Mars-mass embryos

Planete-simals (~100 km)

Dust (μm)

gas accretion (slow, then runaway)

pebble isolation

Migration

pebble accretion

within snow line: rocky

beyond snow line: ice+rock

late accretion (planetesimal impacts)

giant impacts

Moon-forming impact

planetesimal/pebble accretion

streaming instability

dust coagulation

gas disk lasts a few Myr

$10^4$ yrs

$10^5$ yrs

$10^6$ yrs

$10^7$ yrs

$10^8$ yrs

# Planet formation: the cast of characters

*pebbles*:
~1mm-10cm





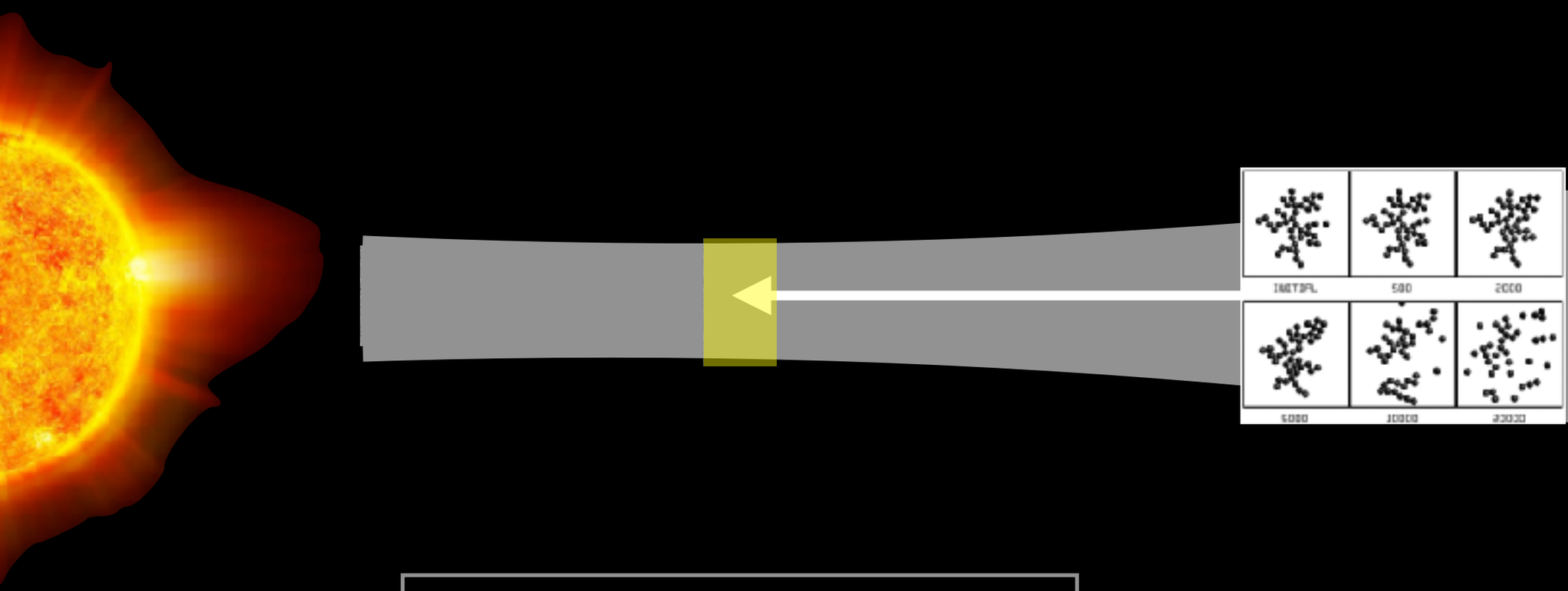
*planetesimals*:
~10-1000km

*terrestrial planetary embryos (=protoplanets)*:
~Moon-sized or larger



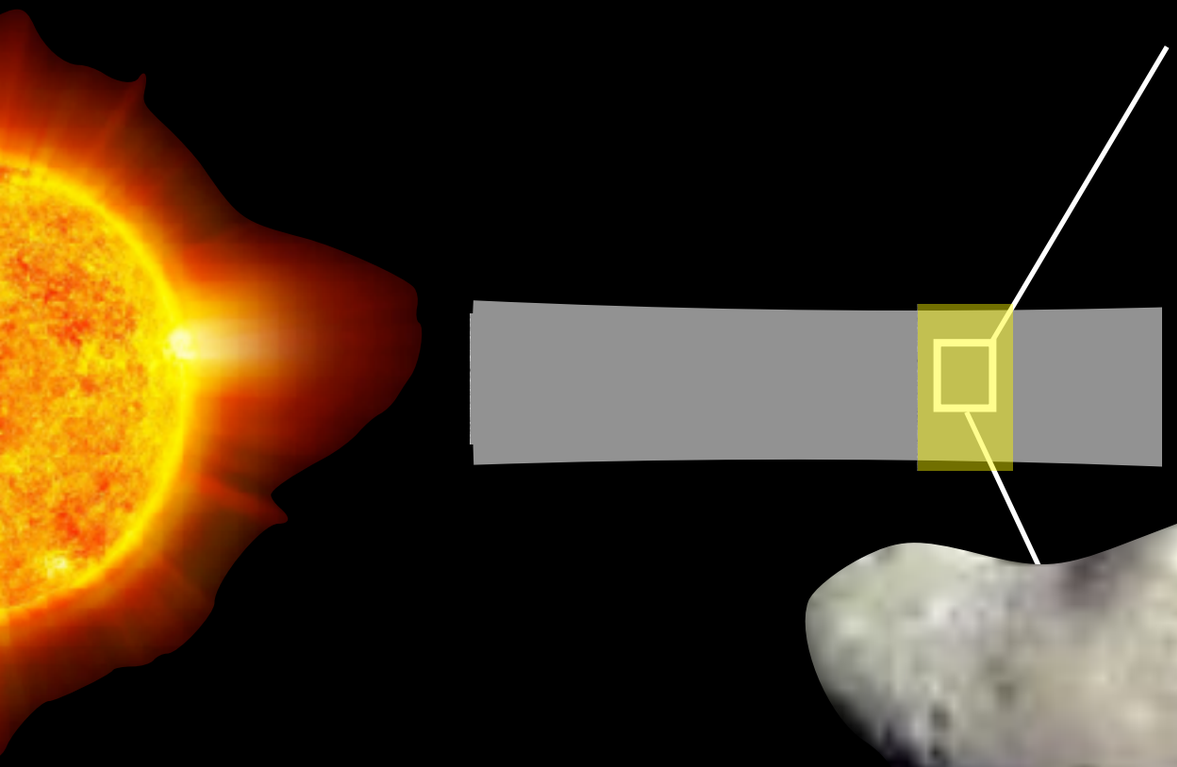
*giant planet "cores" or "embryos"*:
~Earth-sized or larger

# Planetesimal formation models: dust growth/drift with disk evolution




**Dust concentrated at “pressure bumps” possibly associated with condensation temperatures**

# Planetesimal formation models: dust growth/drift with disk evolution





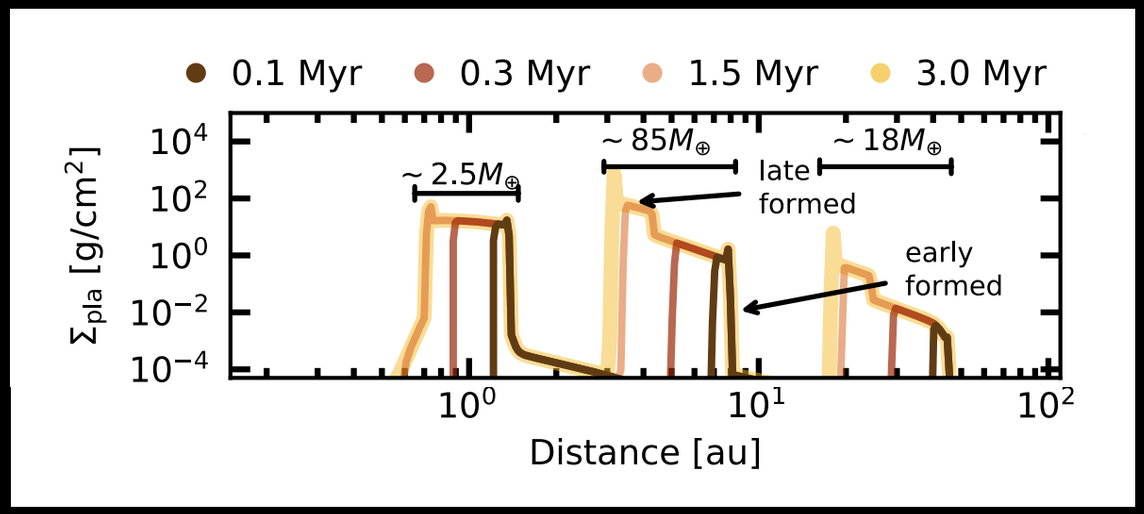


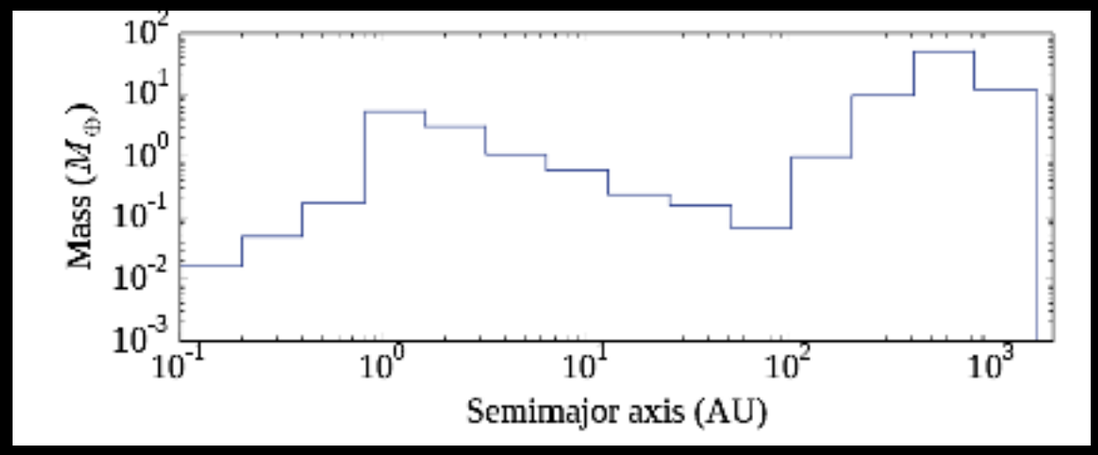



g (2011)

Planetesimals:
~100 km

# Where do planetesimals form?




Izidoro et al (2022): rings of planetesimals

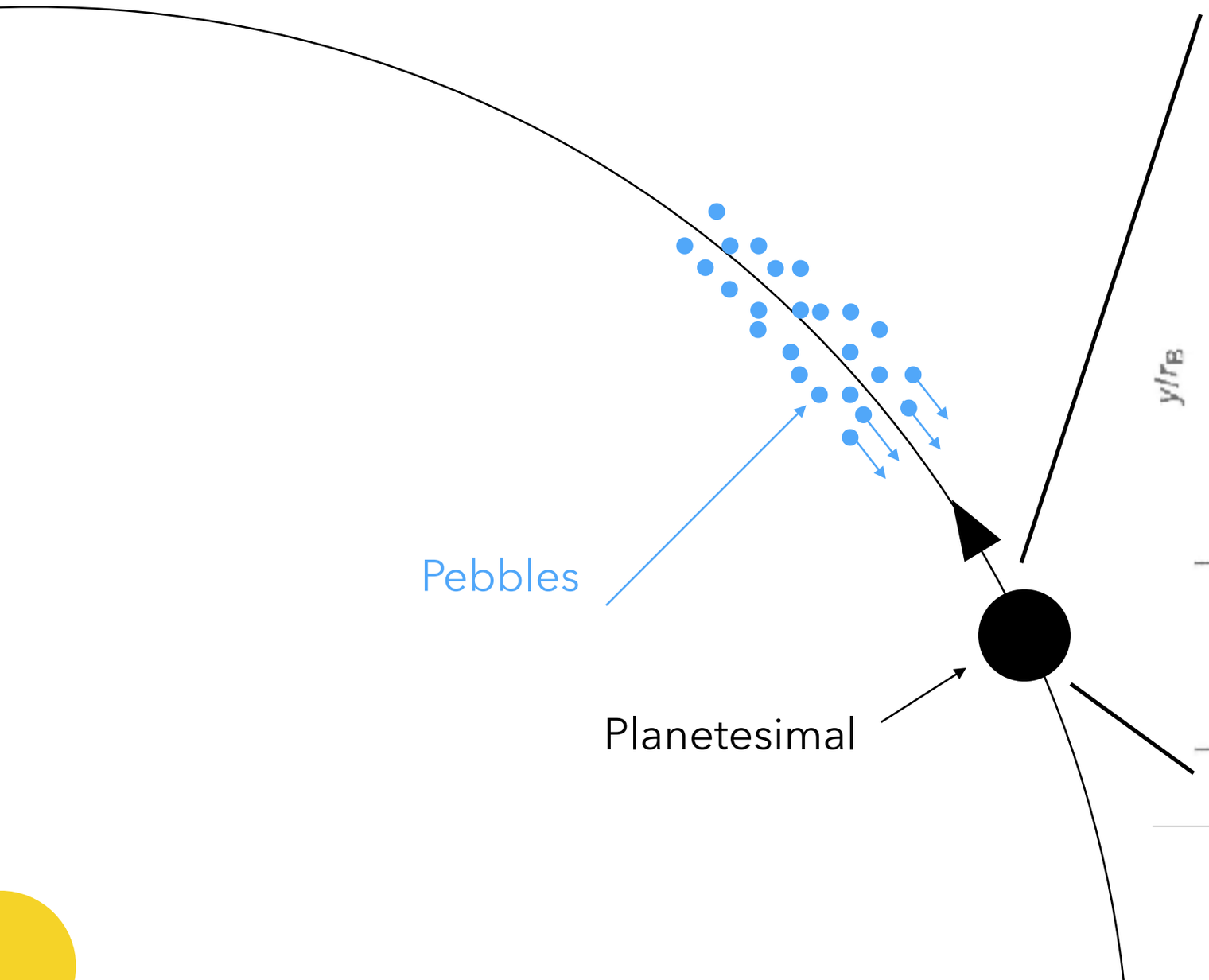
Carrera et al (2017): broad disk of planetesimals

(many other models exist)

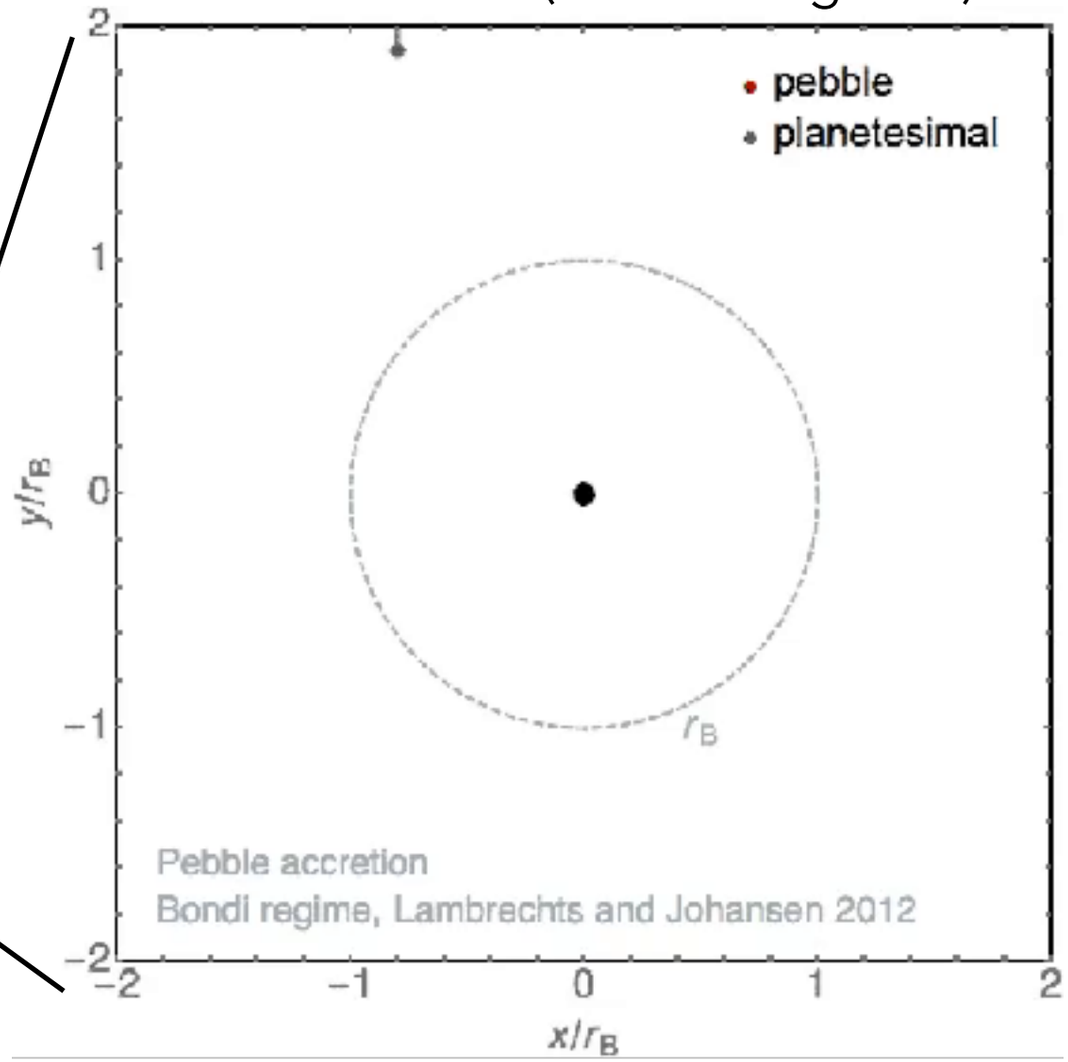
Slide credit: M. Lambrechts

# Pebble accretion

Ormel & Klahr 2010; Lambrechts & Johansen, 2012

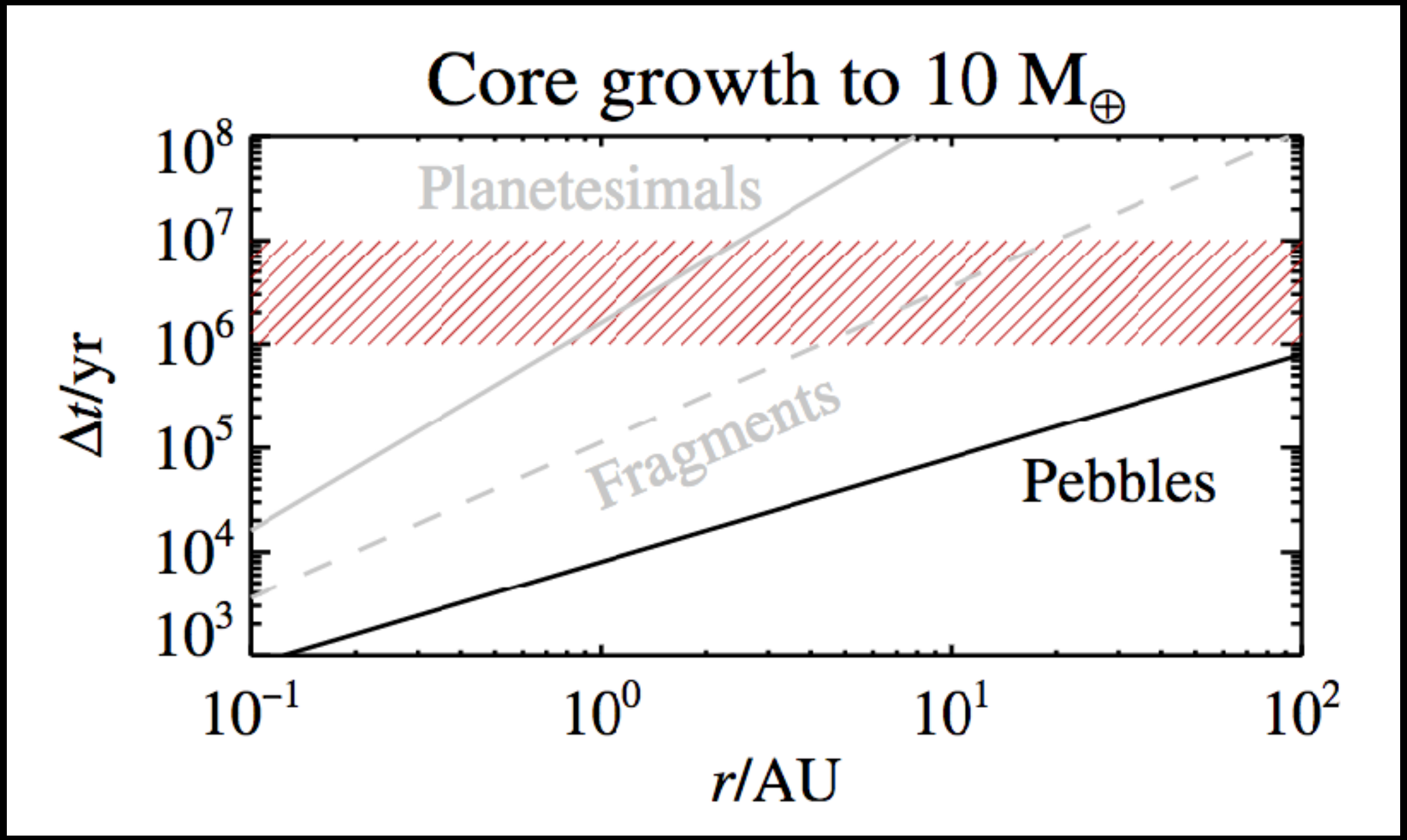



Pebble accretion ("Bondi regime")




$$r_{\mathrm{B}} = \frac{GM_c}{\Delta v^2}$$

# Pebble accretion is key for forming giant planet cores

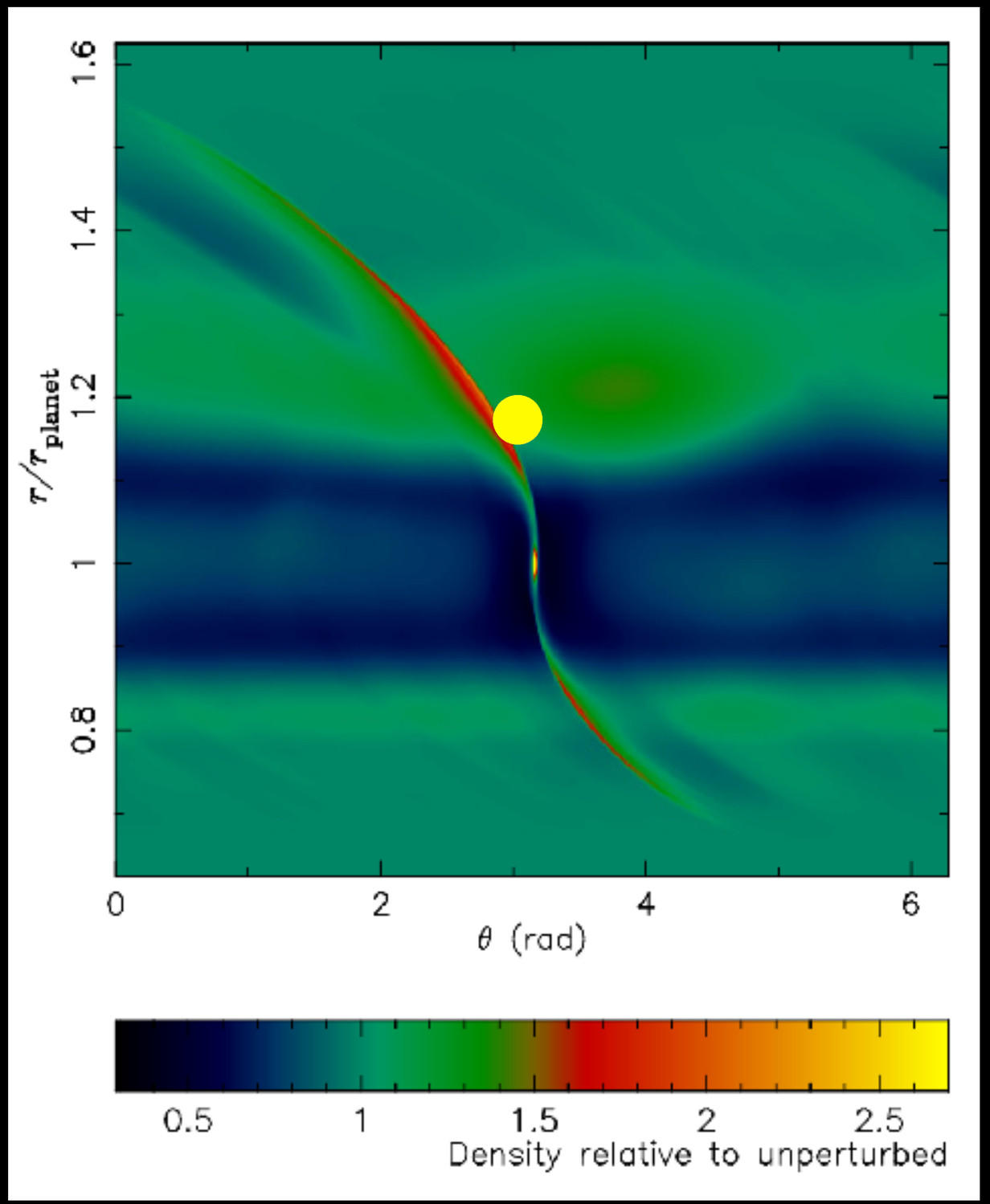



Lambrechts & Johansen (2012)

# Pebble accretion is self-limiting

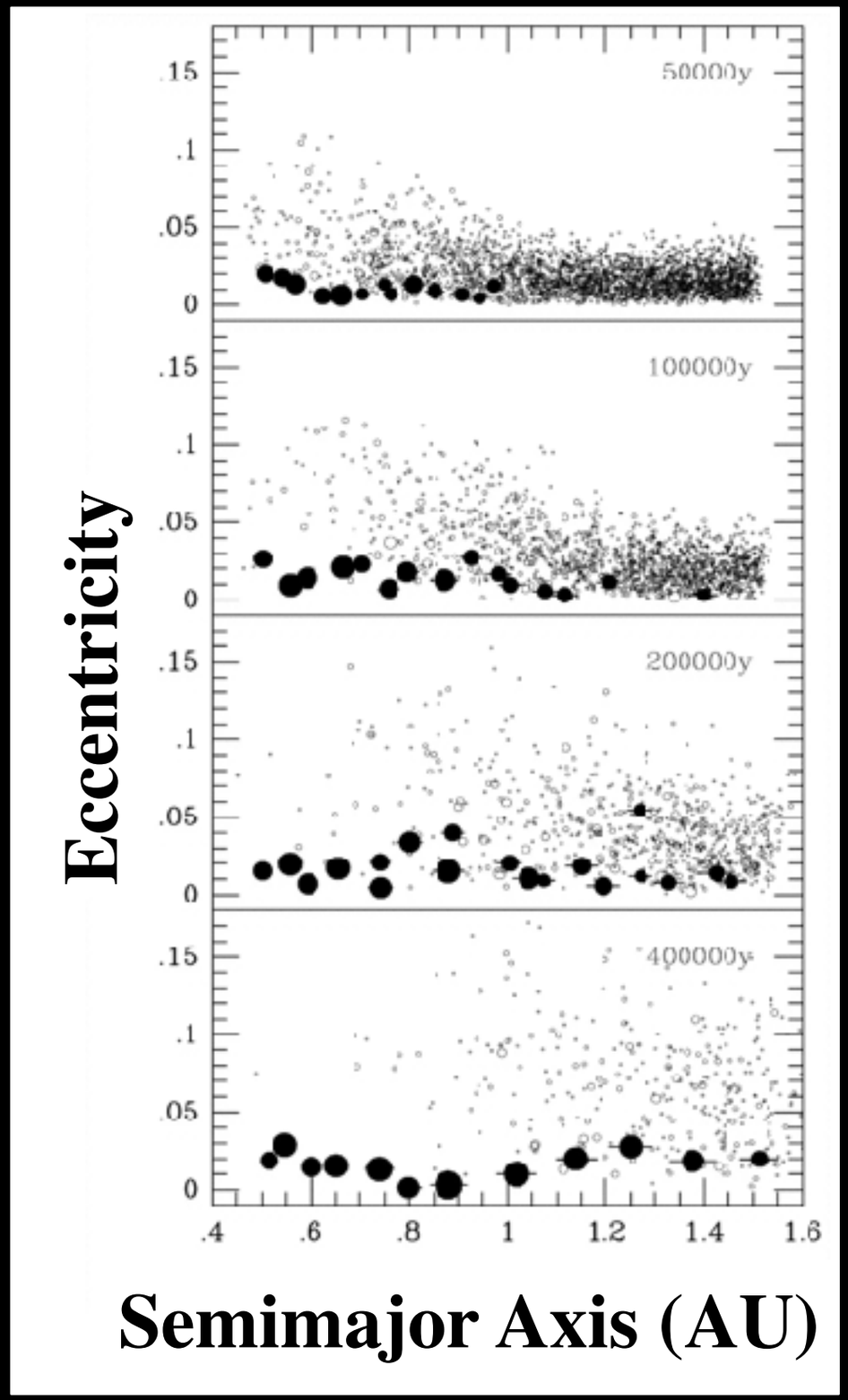
Above "pebble isolation mass", a planet creates an exterior pressure bump that traps pebbles

(~20 ME for typical disk at Jup's orbit)



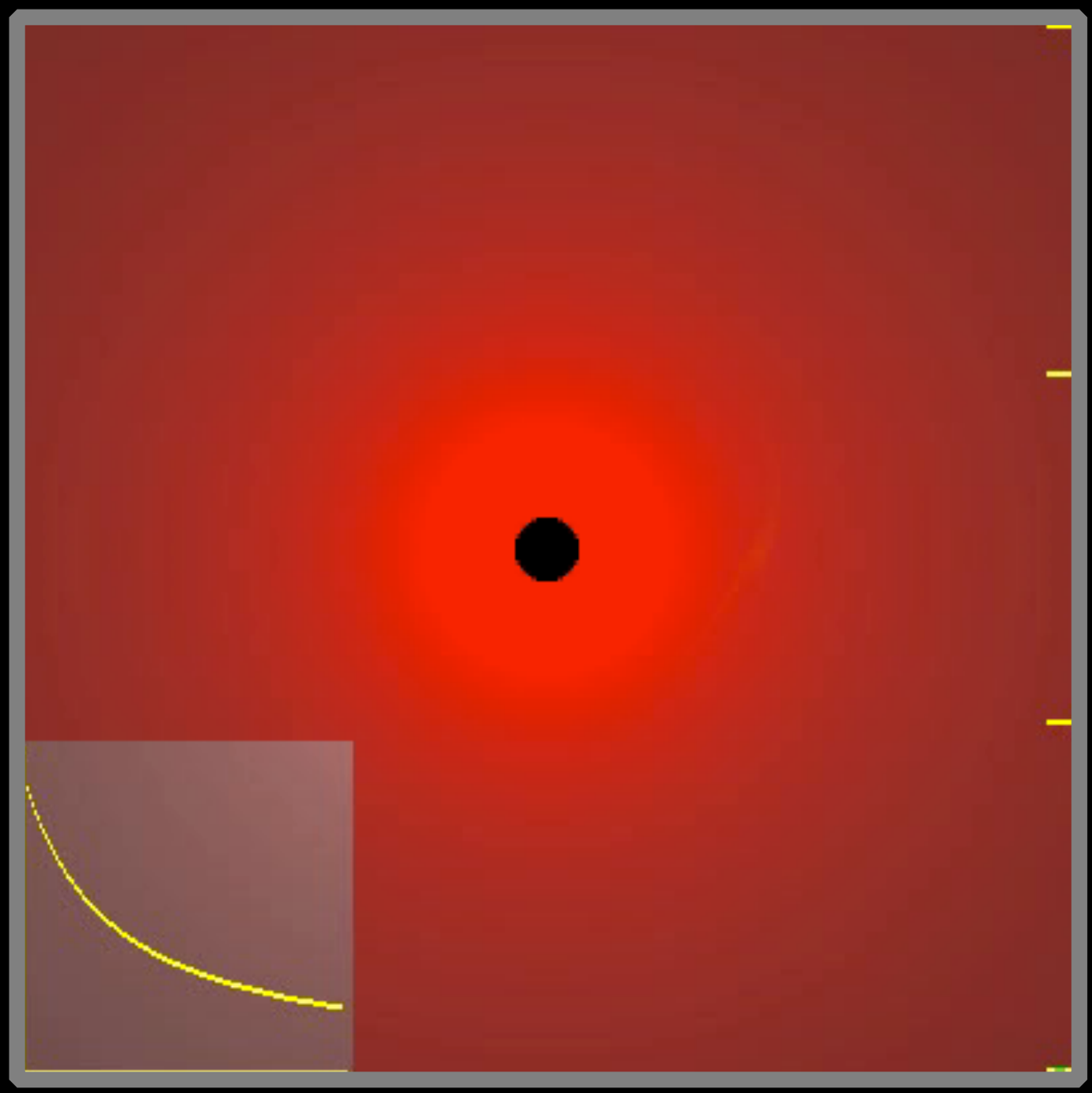

Lambrechts et al (2014)

# Embryos can grow from planetesimals in some cases (e.g. in terrestrial planet region)




Kokubo & Ida 2002

# Gravitational planet-disk interaction: orbital migration

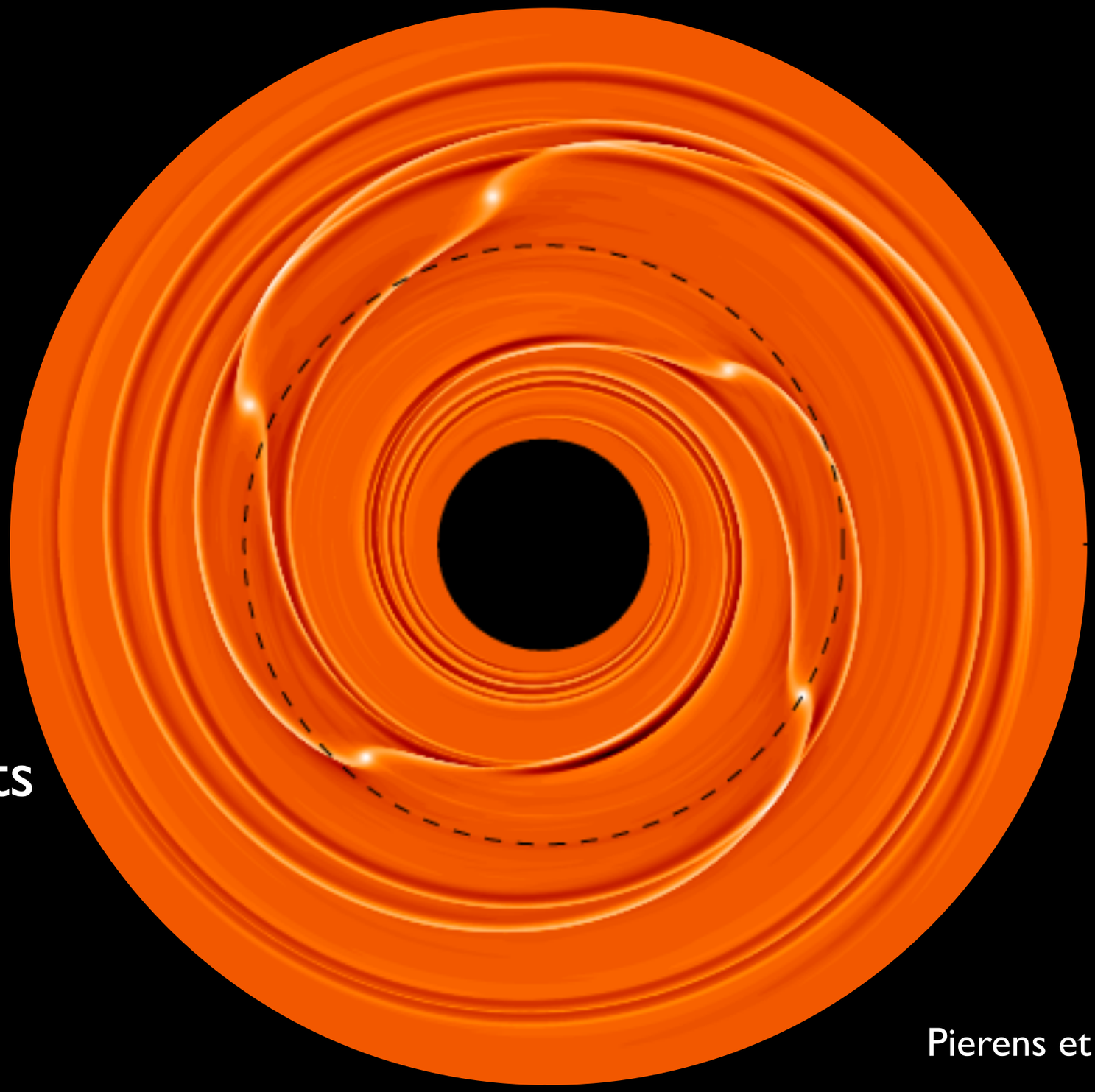


P. Armitage

# Type I migration

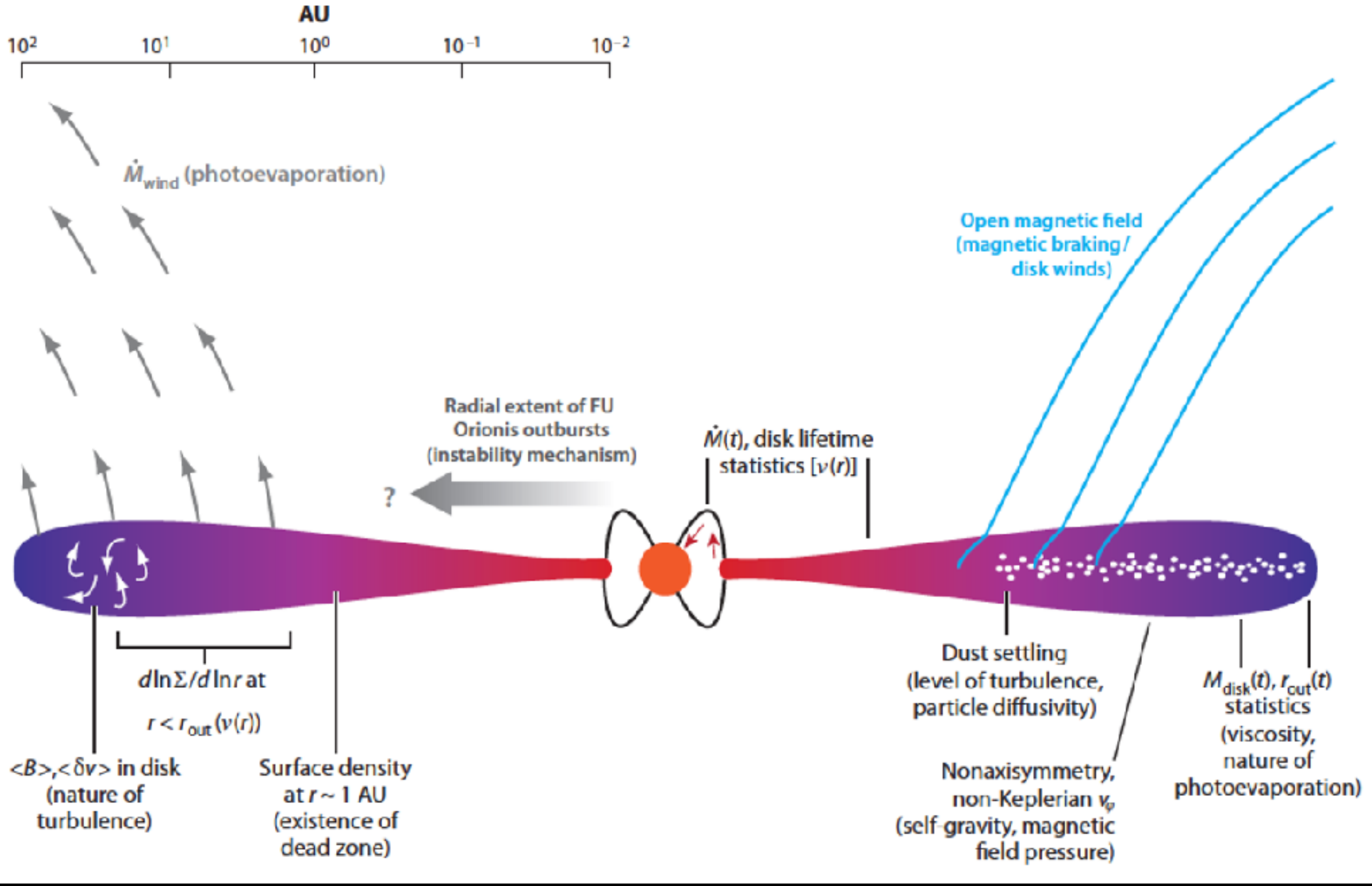
Matters for
Mp >~ MEarth

More massive planets
migrate faster



Pierens et al (2013)

Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014; Kley & Nelson 2014




Armitage 2011

# Migration stops at the inner edge of the disk

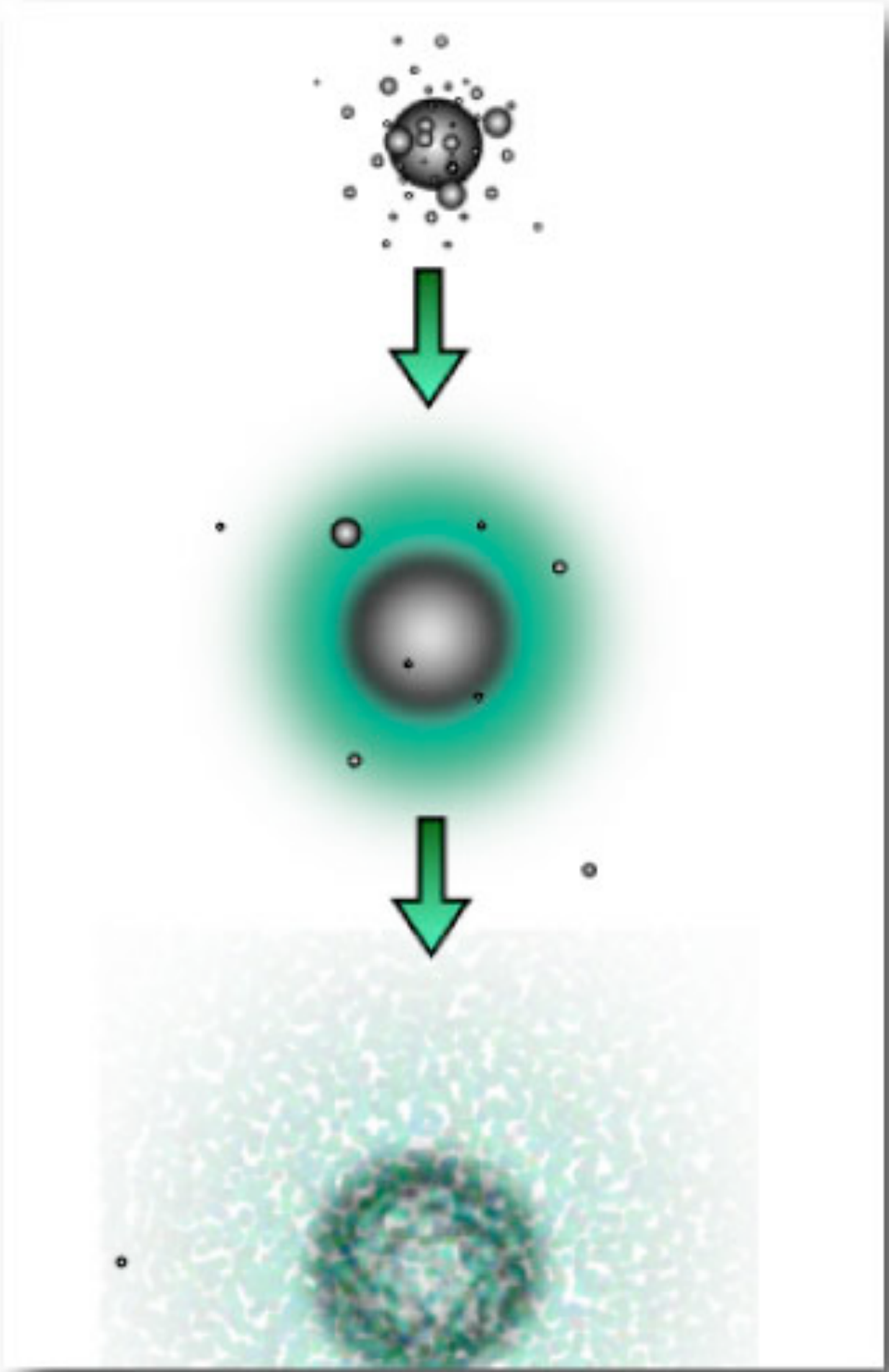


Masset et al (2006)

also Romanova & Lovelace (2006); Flock et al (2017)

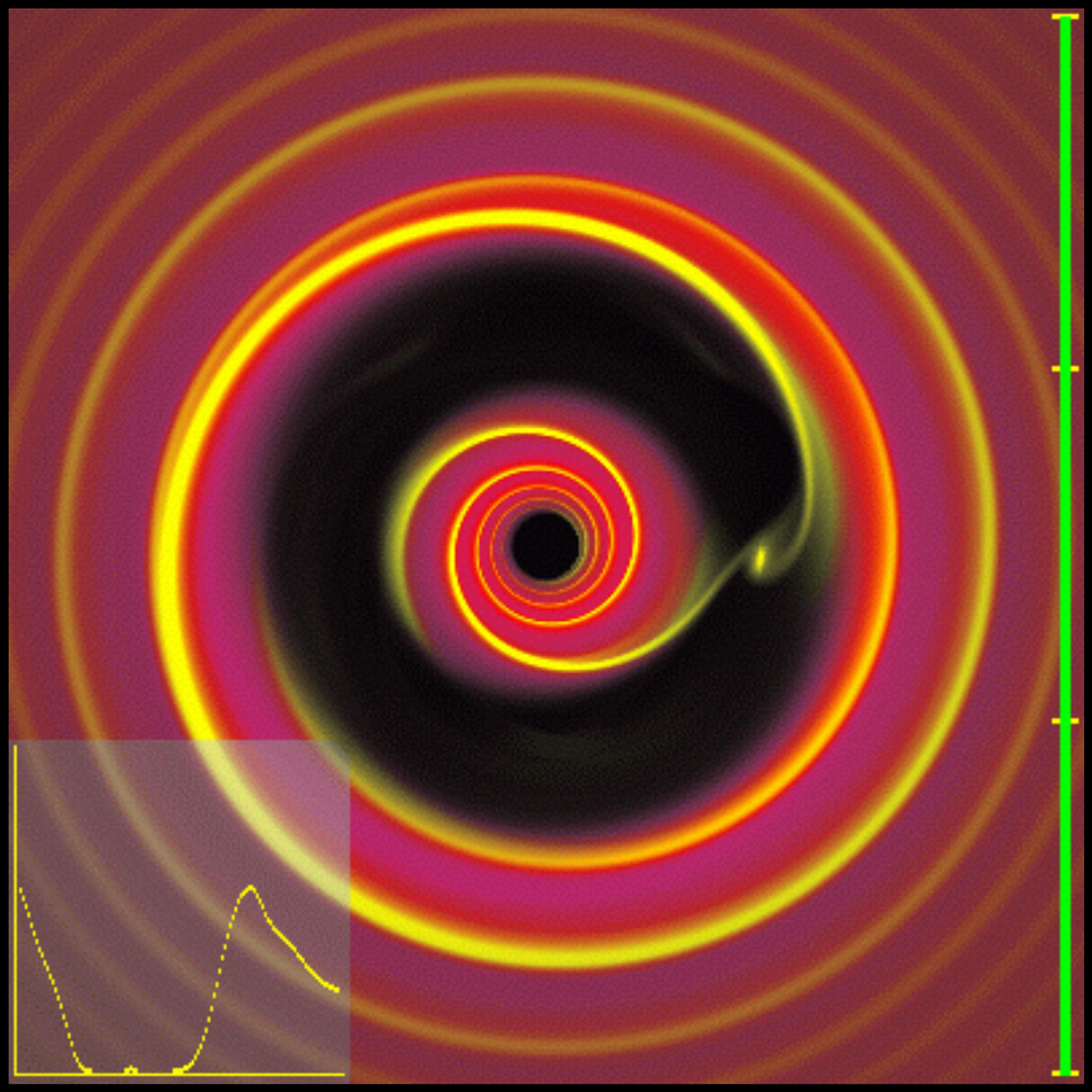
# Giant planet formation (core accretion)

- Growth of a 5-10 Earth-mass core
- Gravitational accumulation of gas from the disk



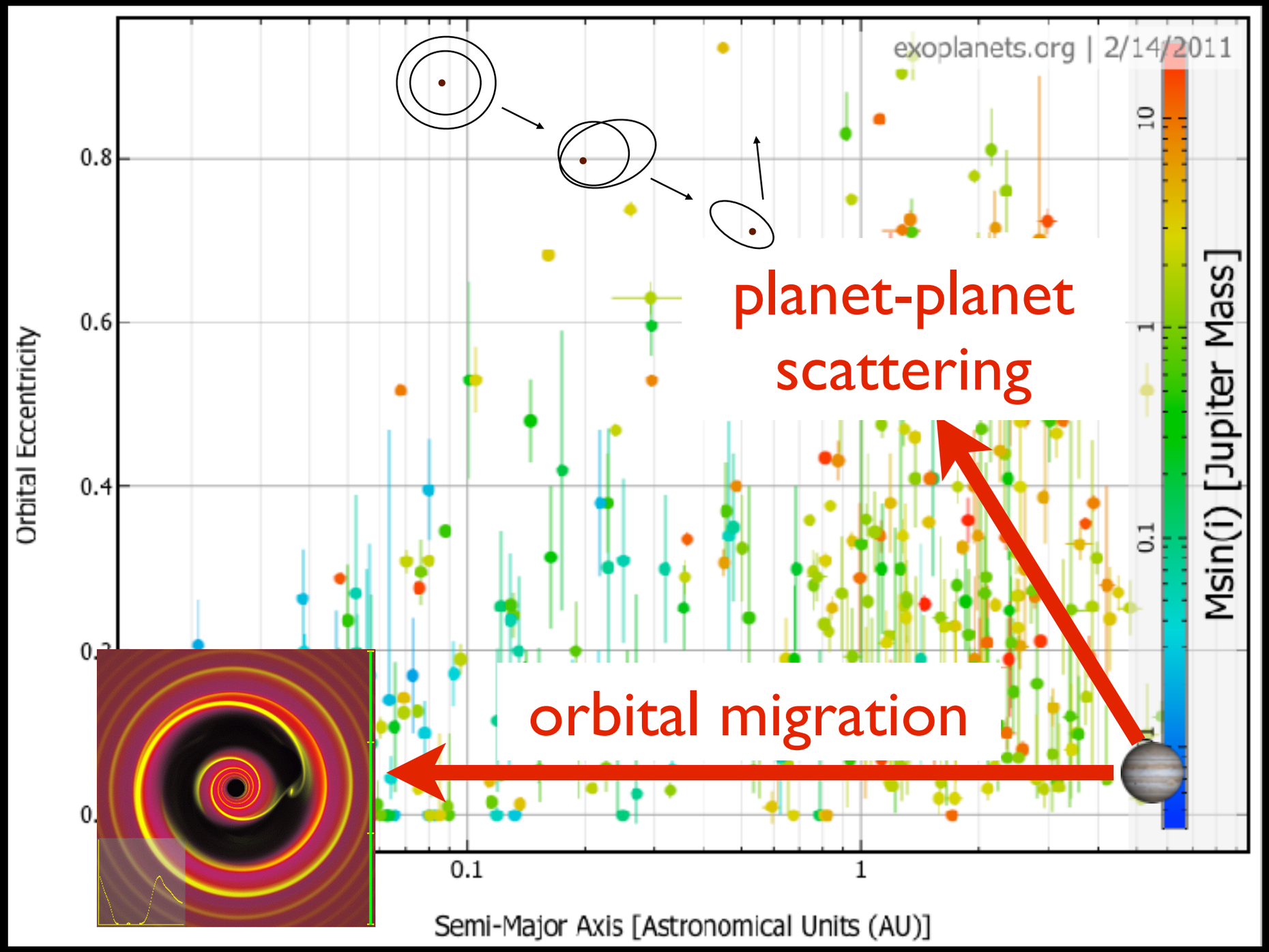
# Type 2 migration

- Carve gap in disk
- Migration almost always inward
- Special cases: 2+ planets can migrate outward (e.g., Grand Tack model)



P. Armitage

# Giant exoplanets



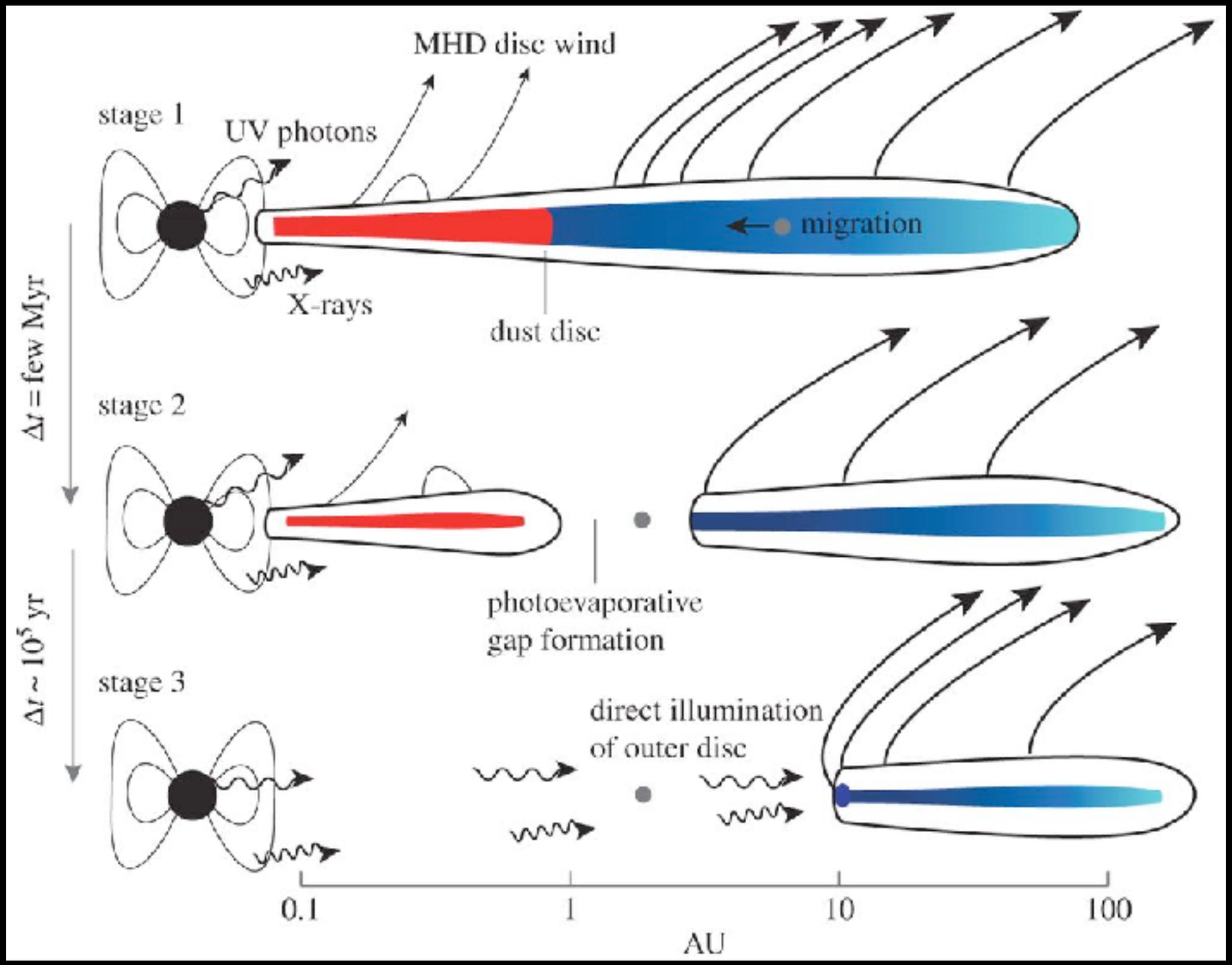

Wright et al 2011

# Planet-planet scattering




Credit: Eric Ford

# Inside-out photo-evaporation of gaseous disk



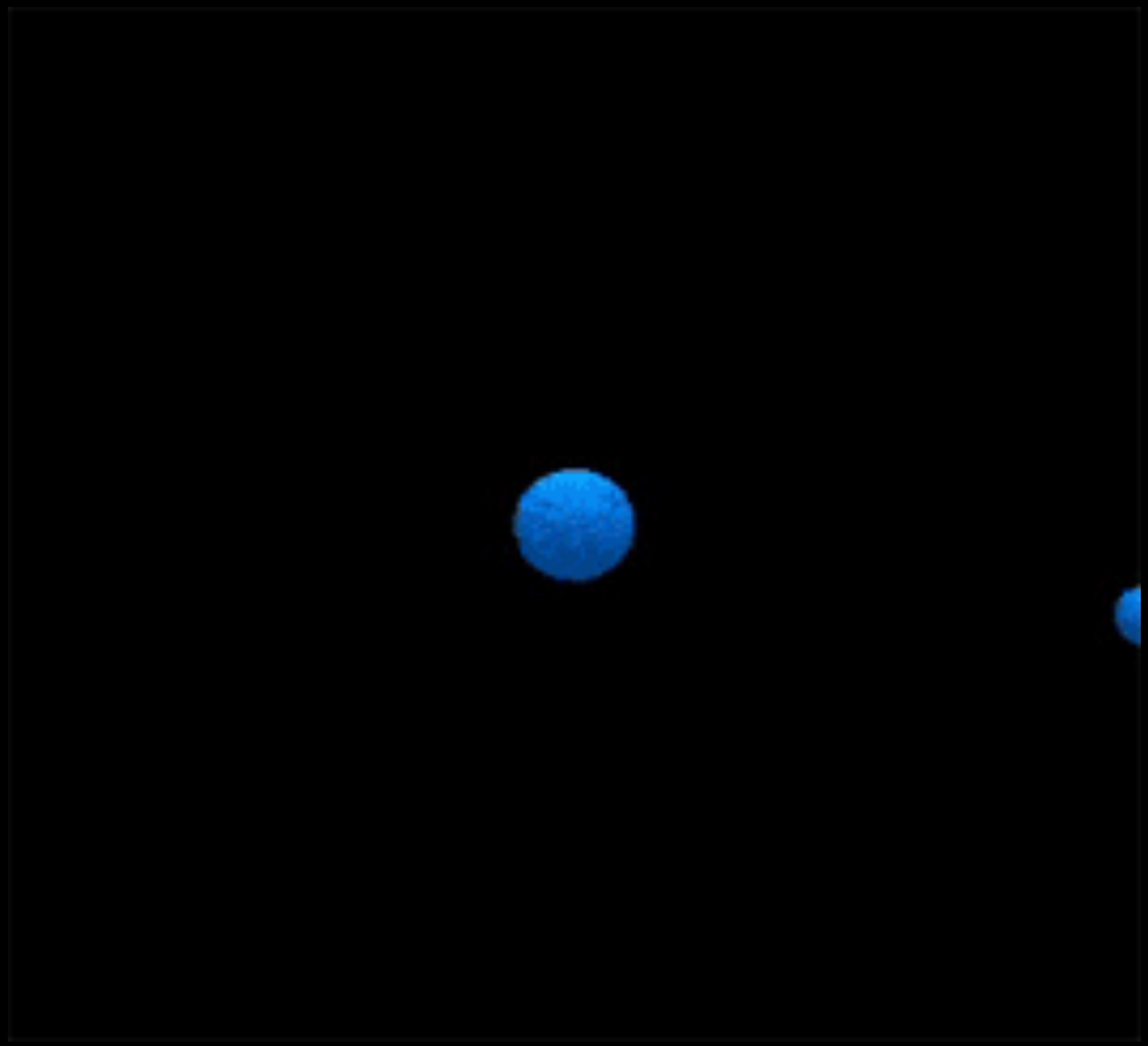

Armitage (2010)

# Late-stage accretion: final sweep-up of planetesimals and embryos into terrestrial planets



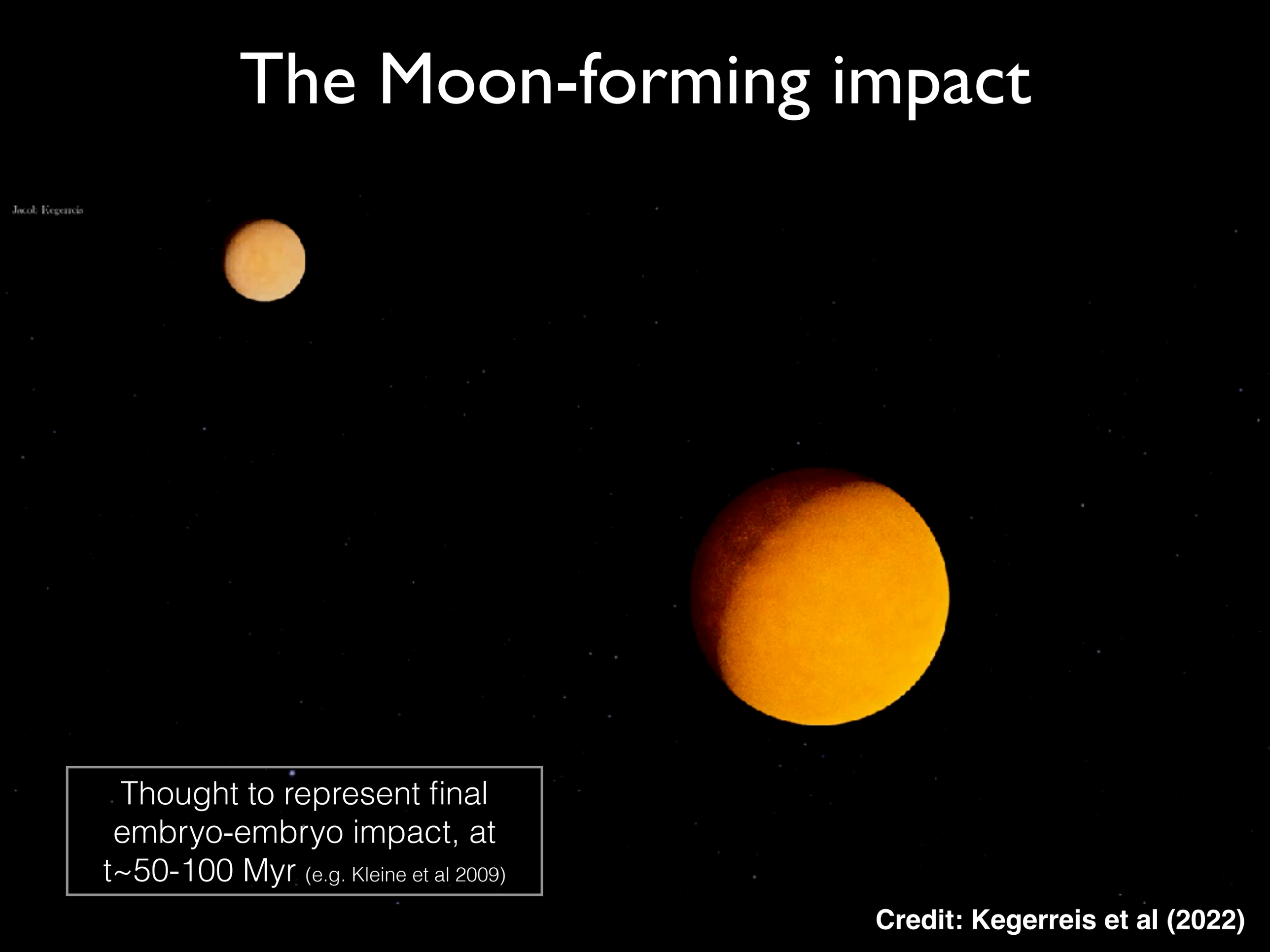
Credit: Hagai Perets

# Giant impacts between embryos



credit: Agnor & Asphaug

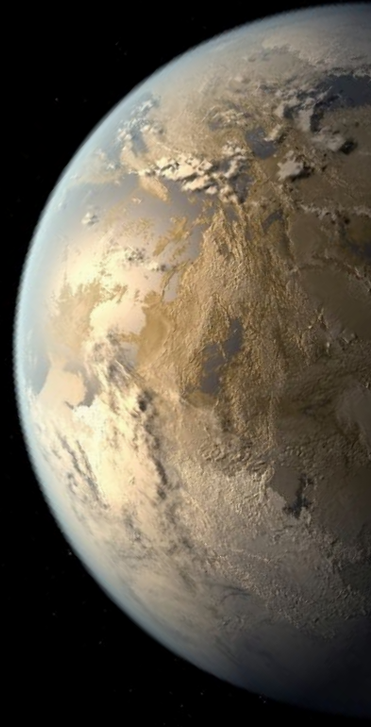
# The Moon-forming impact




Thought to represent final embryo-embryo impact, at t~50-100 Myr (e.g. Kleine et al 2009)

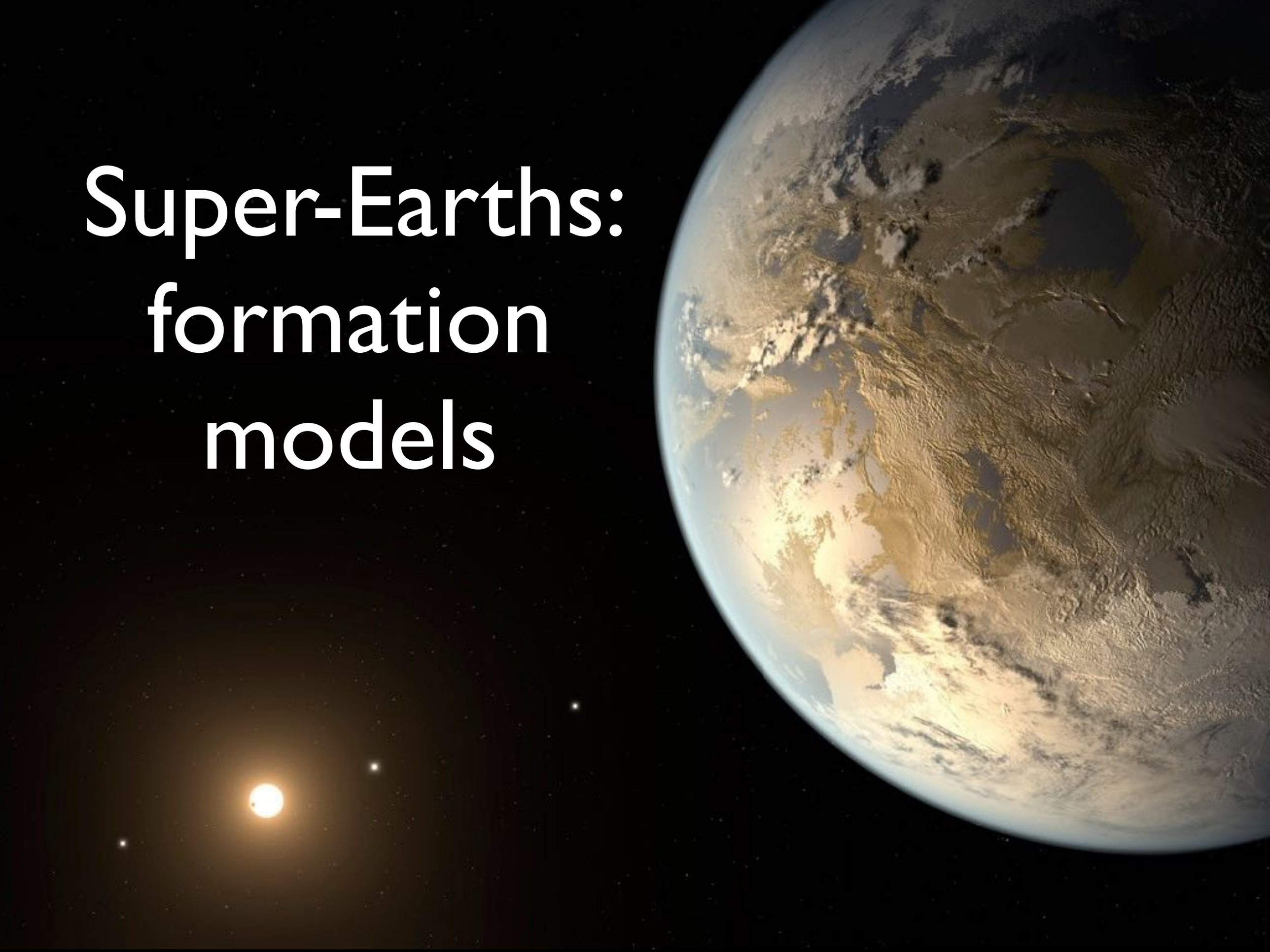
**Credit: Kegerreis et al (2022)**

# 3. Formation models: exoplanets



- Close-in “super-Earths”
- Gas giants
    - Hot Jupiters
    - “Cool” Jupiters

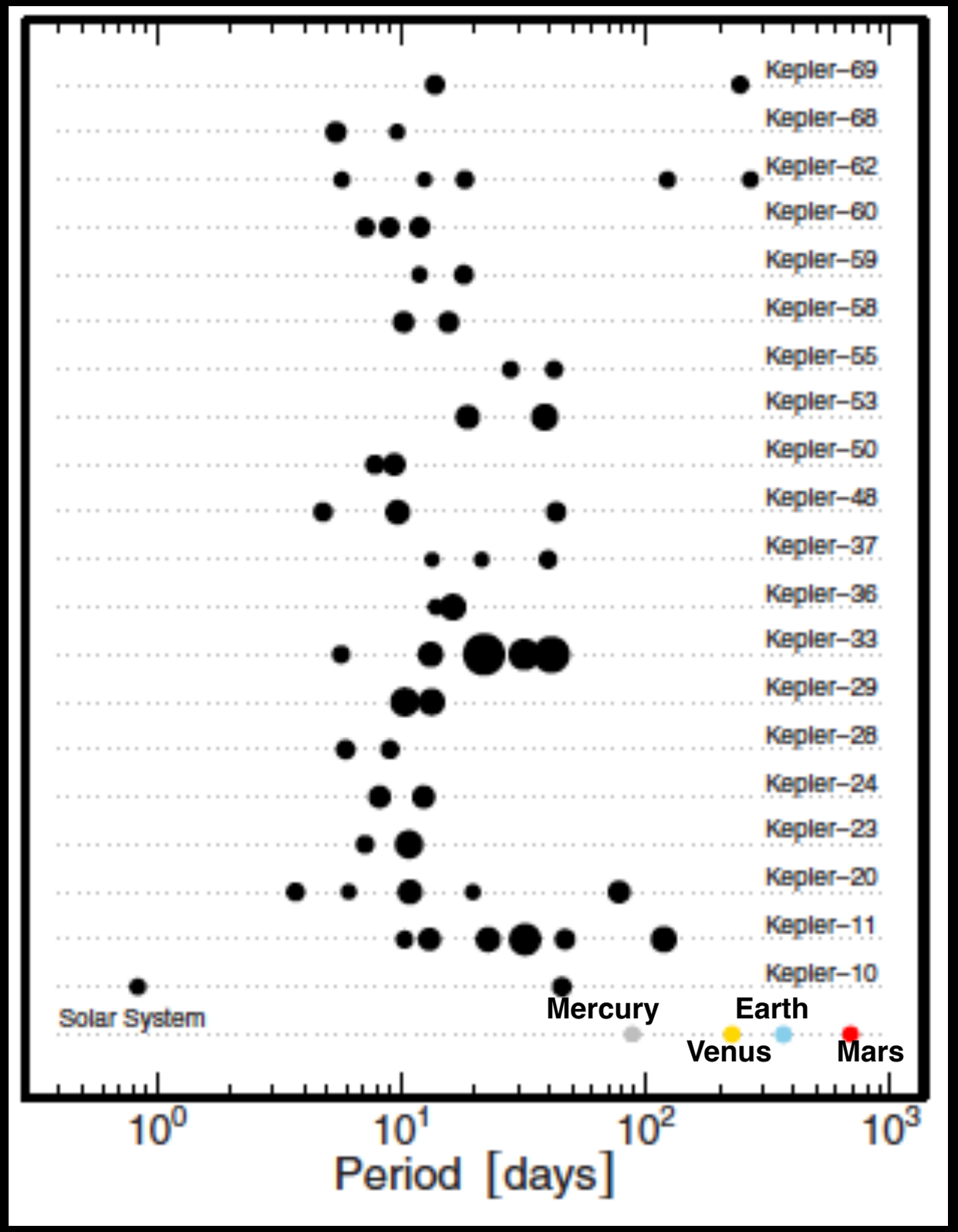
# Super-Earths: formation models



# Super-Earths and the Solar System

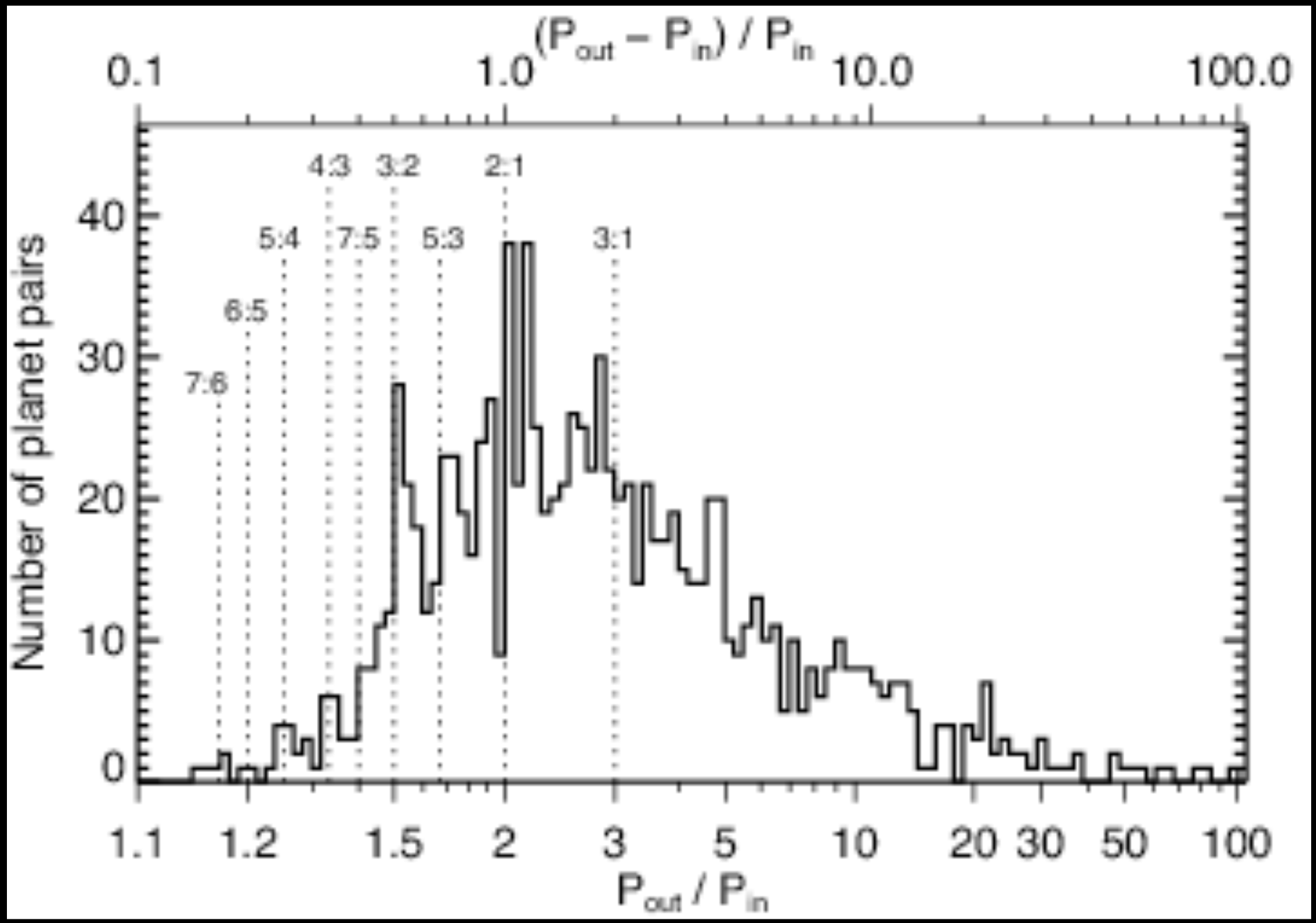
Occurrence rate:
~30-50%

(Mayor et al 2011; Howard et al 2012; Fressin et al 2013, Mulders et al 2018)



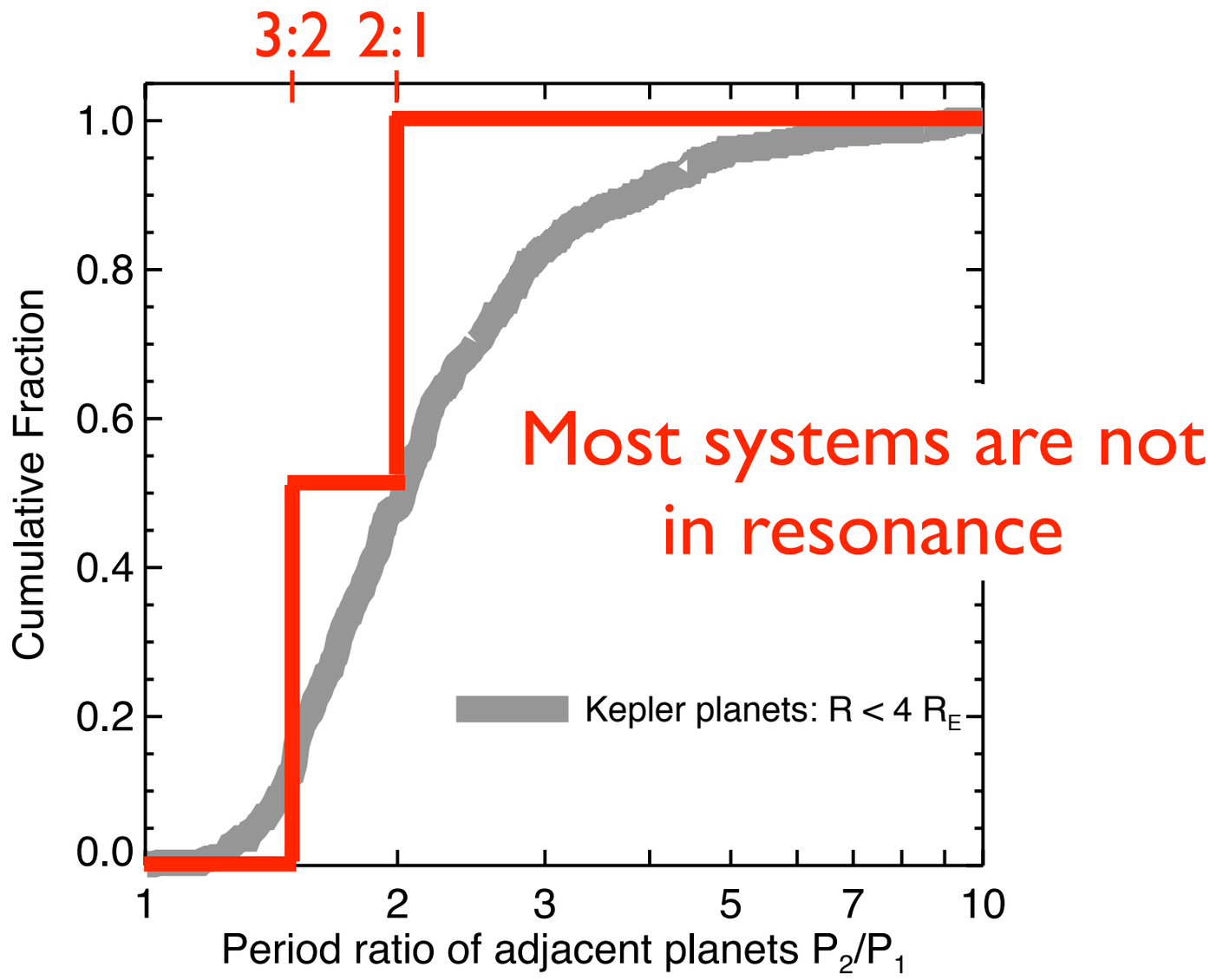

**Schlaufman (2014)**; Kepler data from Batalha et al (2013) and Rowe et al (2014)

# Period Ratio distribution




Winn & Fabrycky 2015

# Period ratio distribution




Lissauer et al (2011); Fabrycky et al (2014)

Size

1-4 $R_{Earth}$

Hot super-Earths

Orbital distance

Size

1-4 $R_{Earth}$

Hot super-Earths

1. In-situ accretion

Orbital distance

Raymond et al (2008), Chiang & Laughlin (2013)

Size

1-4 $R_{Earth}$

Hot super-Earths

1. In-situ accretion

2. Radial (aerodynamic) drift

Orbital distance

Chatterjee & Tan (2014, 2015), Boley et al (2014), Hansen & Murray (2012, 2013), Dawson et al (2015, 2016), Lee et al (2016)

Size

1-4 $R_{Earth}$

Hot super-Earths

3. Inward (type I) migration

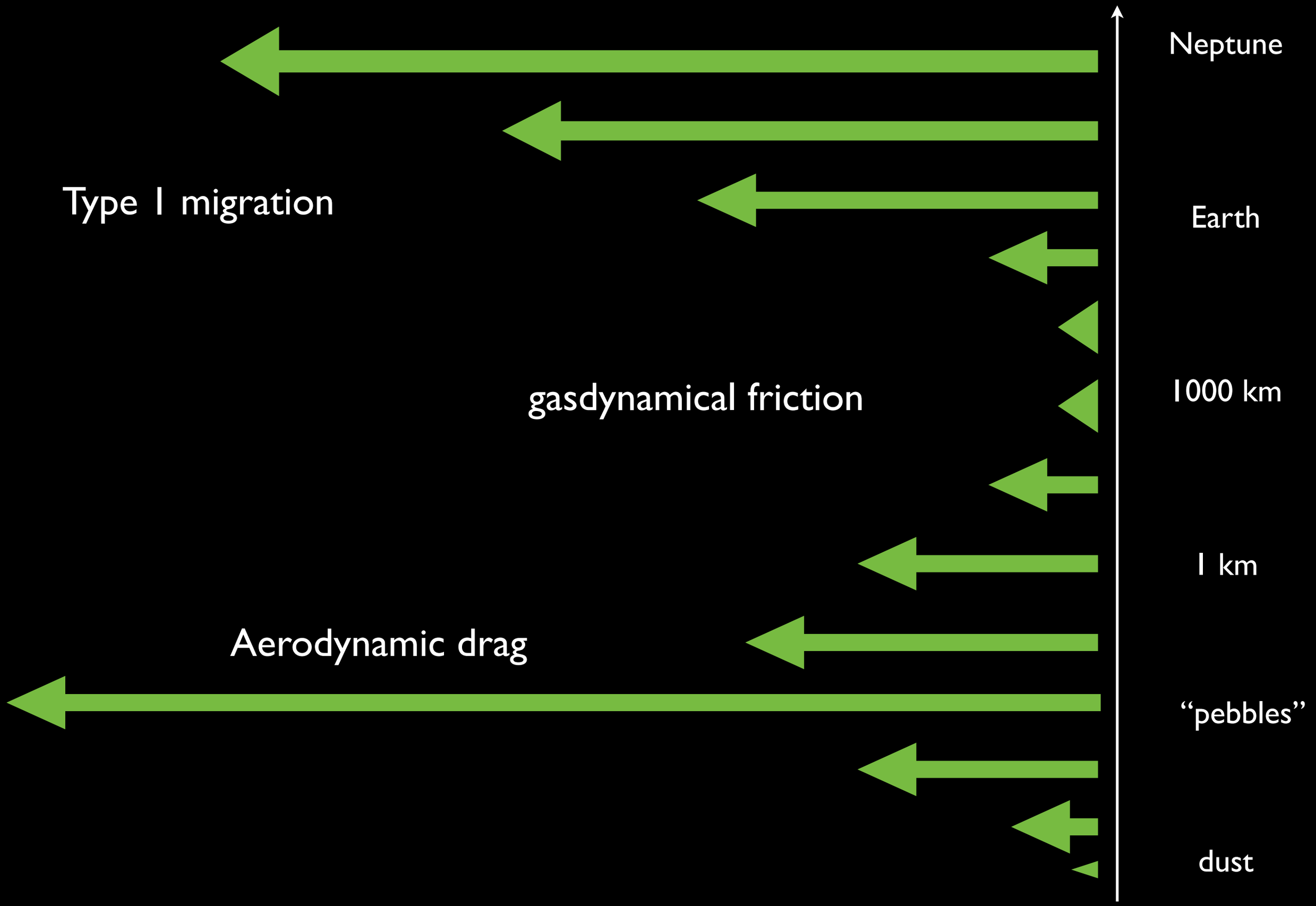
1. In-situ accretion

2. Radial (aerodynamic) drift

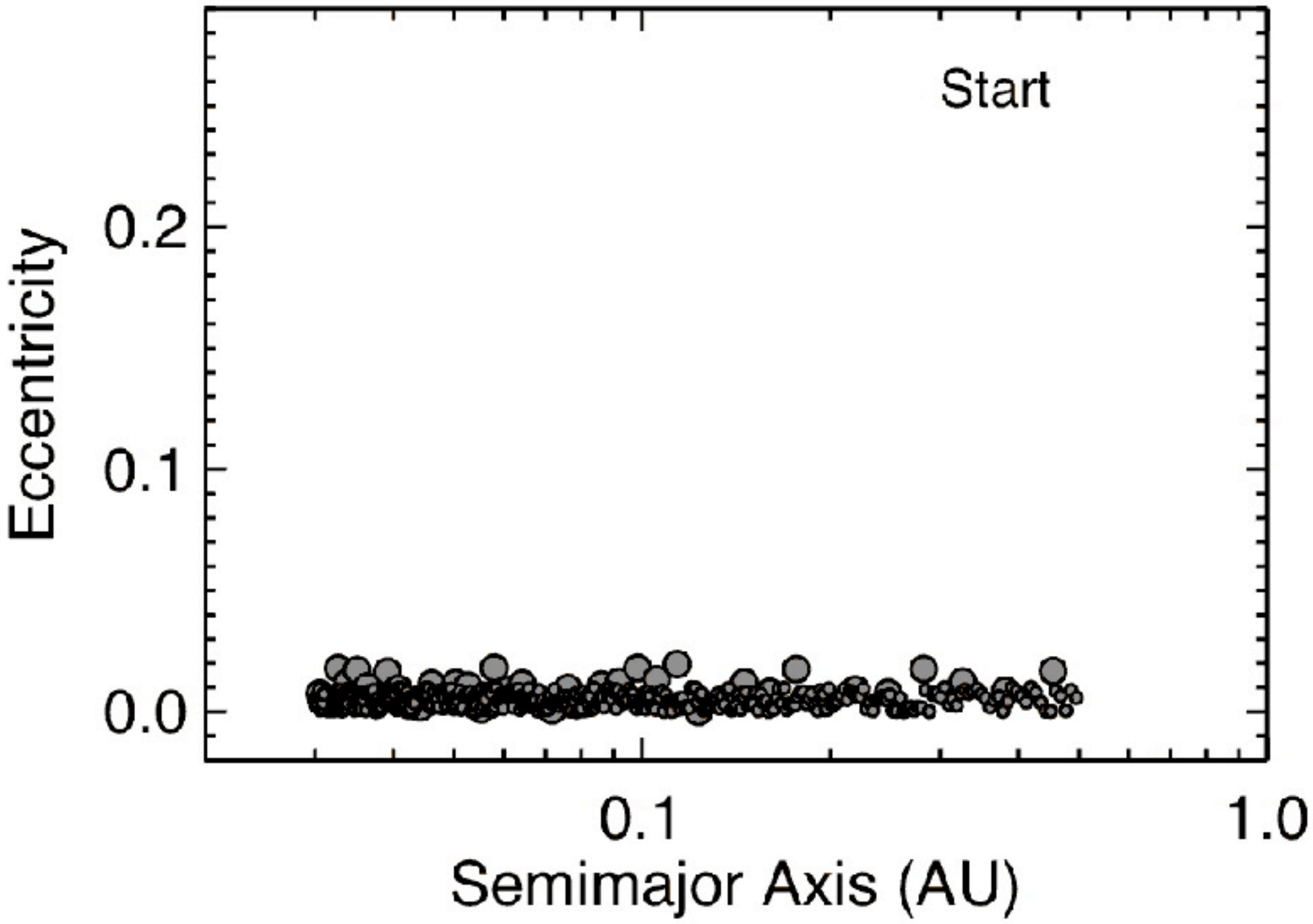
Orbital distance

Terquem & Papaloizou (2007), McNeil & Nelson (2010), Rogers et al (2011), Swift et al (2013), Cossou et al (2014), Ogihara et al (2015), **Izidoro et al (2017)**

# Gaseous disk causes orbital decay

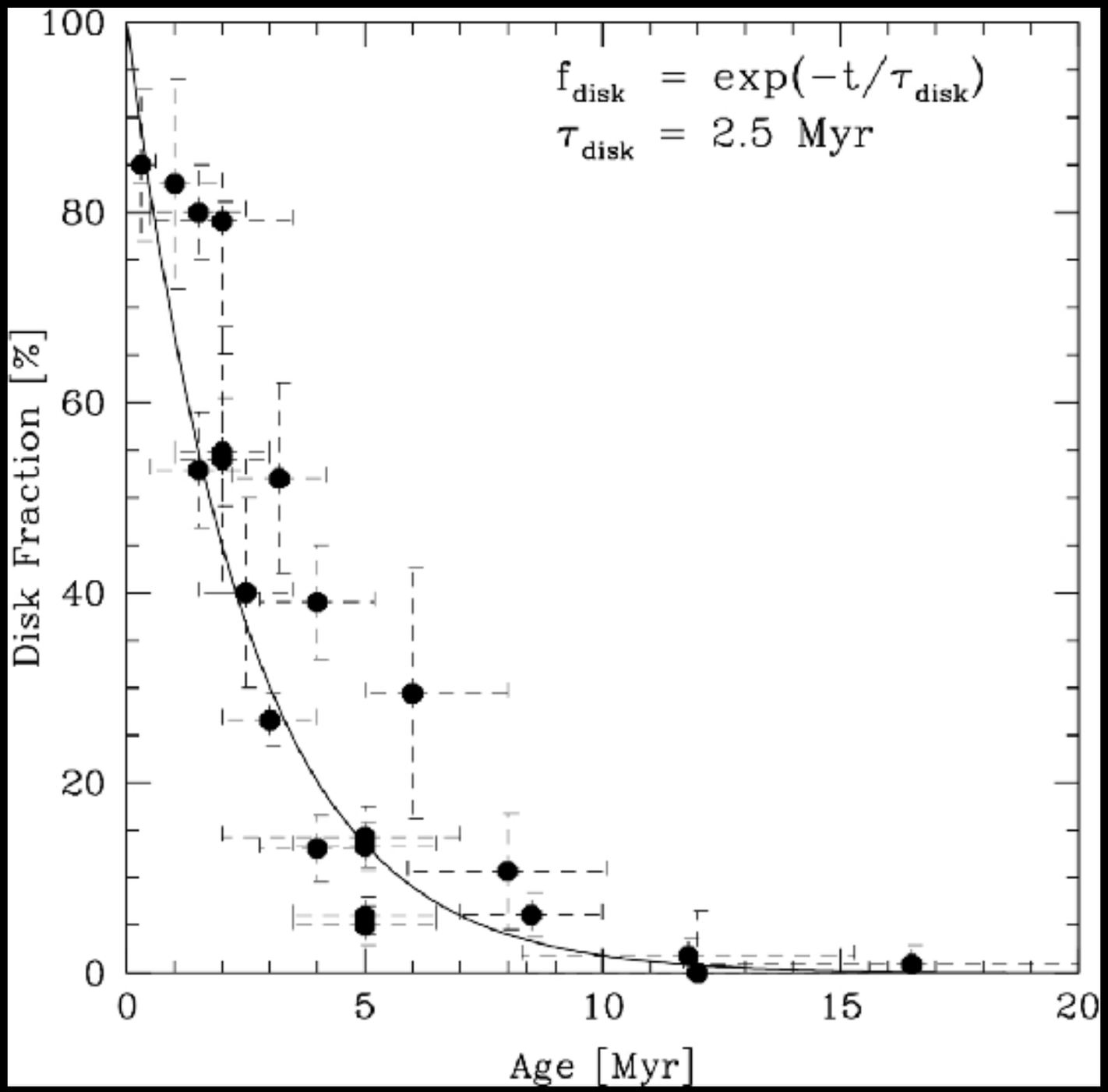


# Growth timescales are very short



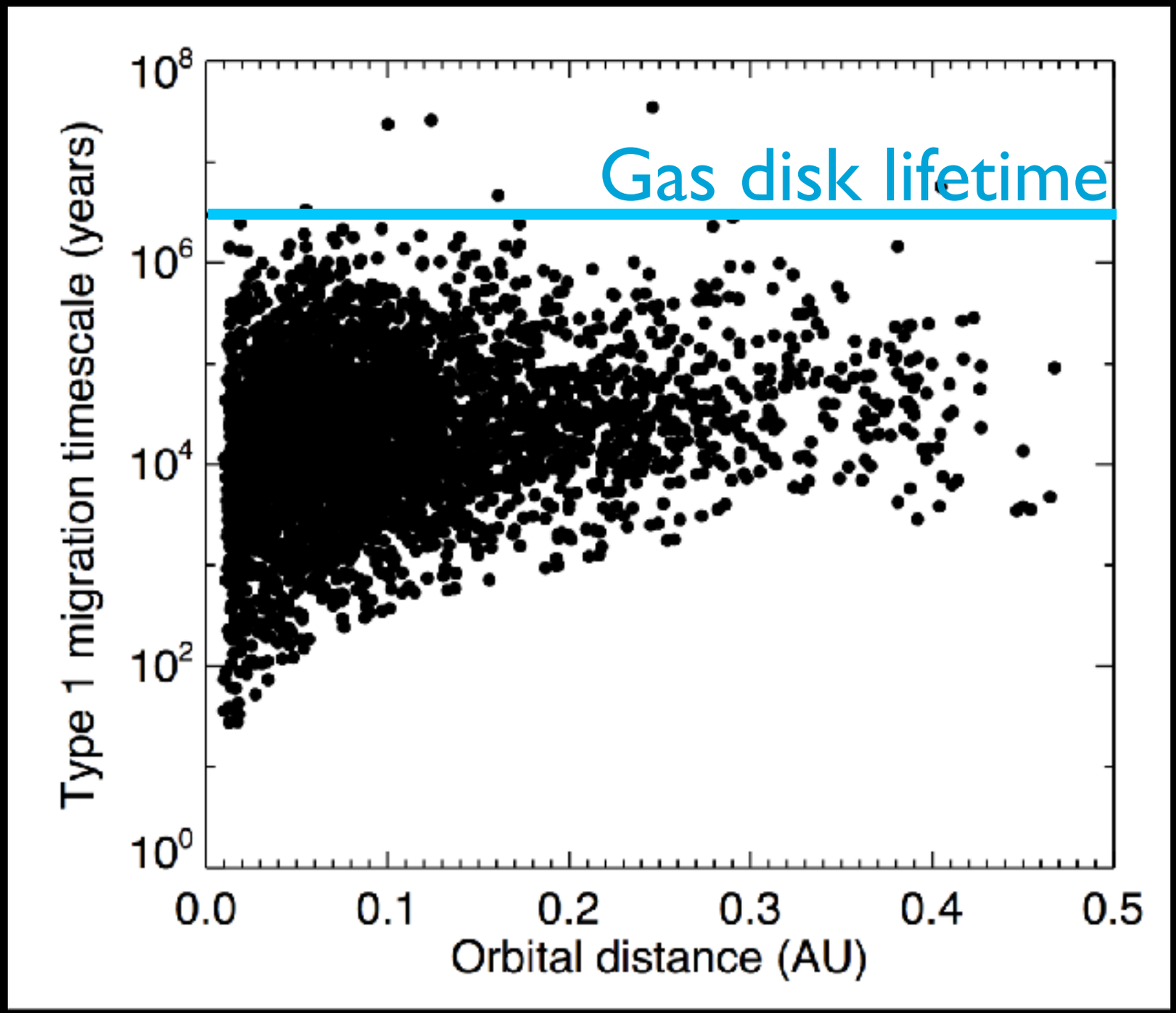

Bolmont et al 2014

# Gas disks (inferred from hot dust) dissipate on a few Myr timescale



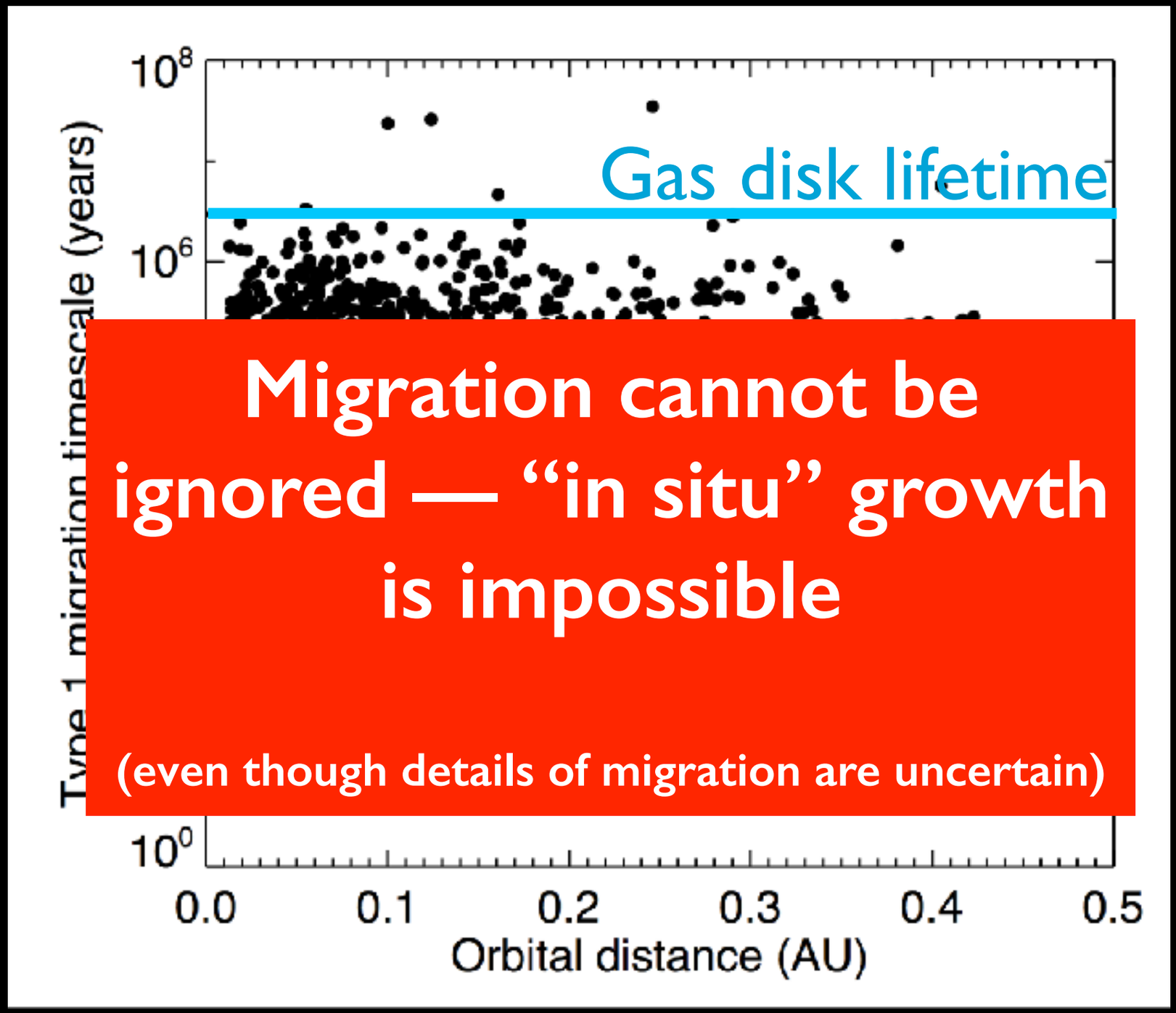

Mamajek 2009

# Migration timescales are very short: "in-situ" accretion is impossible

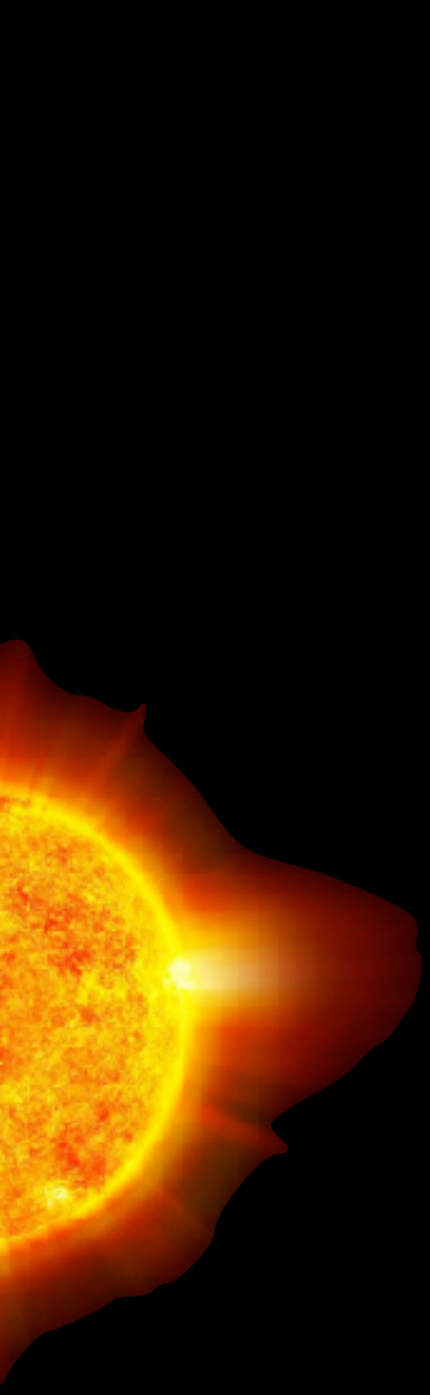



See Inamdar & Schlichting 2015, Schlichting 2014; Ogihara et al 2015; Grishin & Perets 2015

# Migration timescales are very short: "in-situ" accretion is impossible




See Inamdar & Schlichting 2015, Schlichting 2014; Ogihara et al 2015; Grishin & Perets 2015





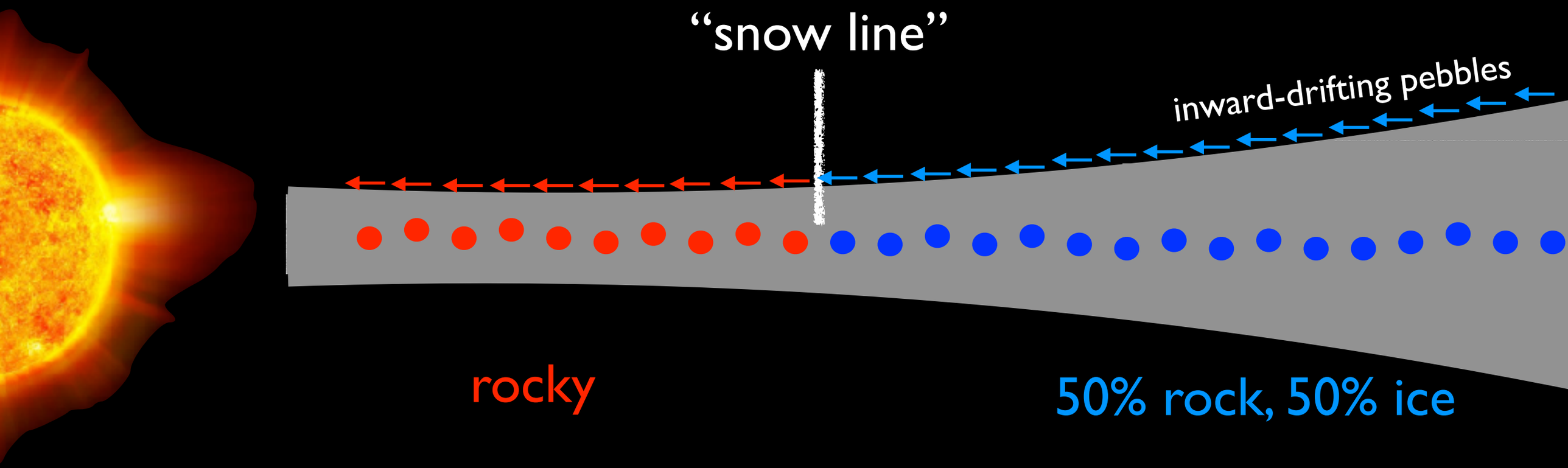




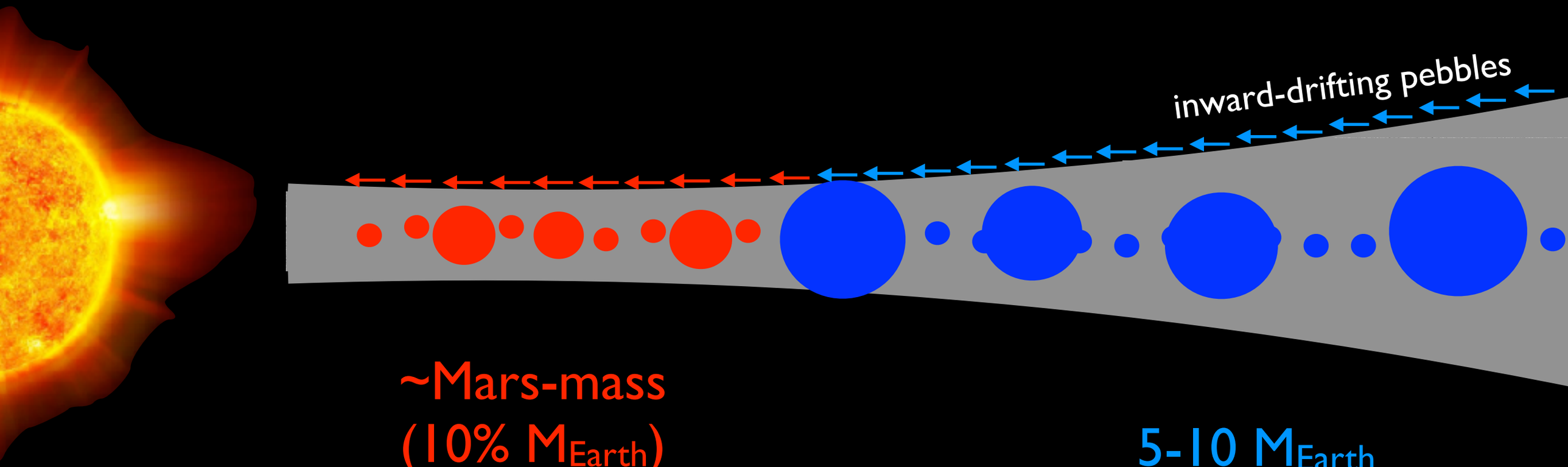

g (2011)

Planetesimals:
~100 km

# Planetesimals



# Planetary embryos



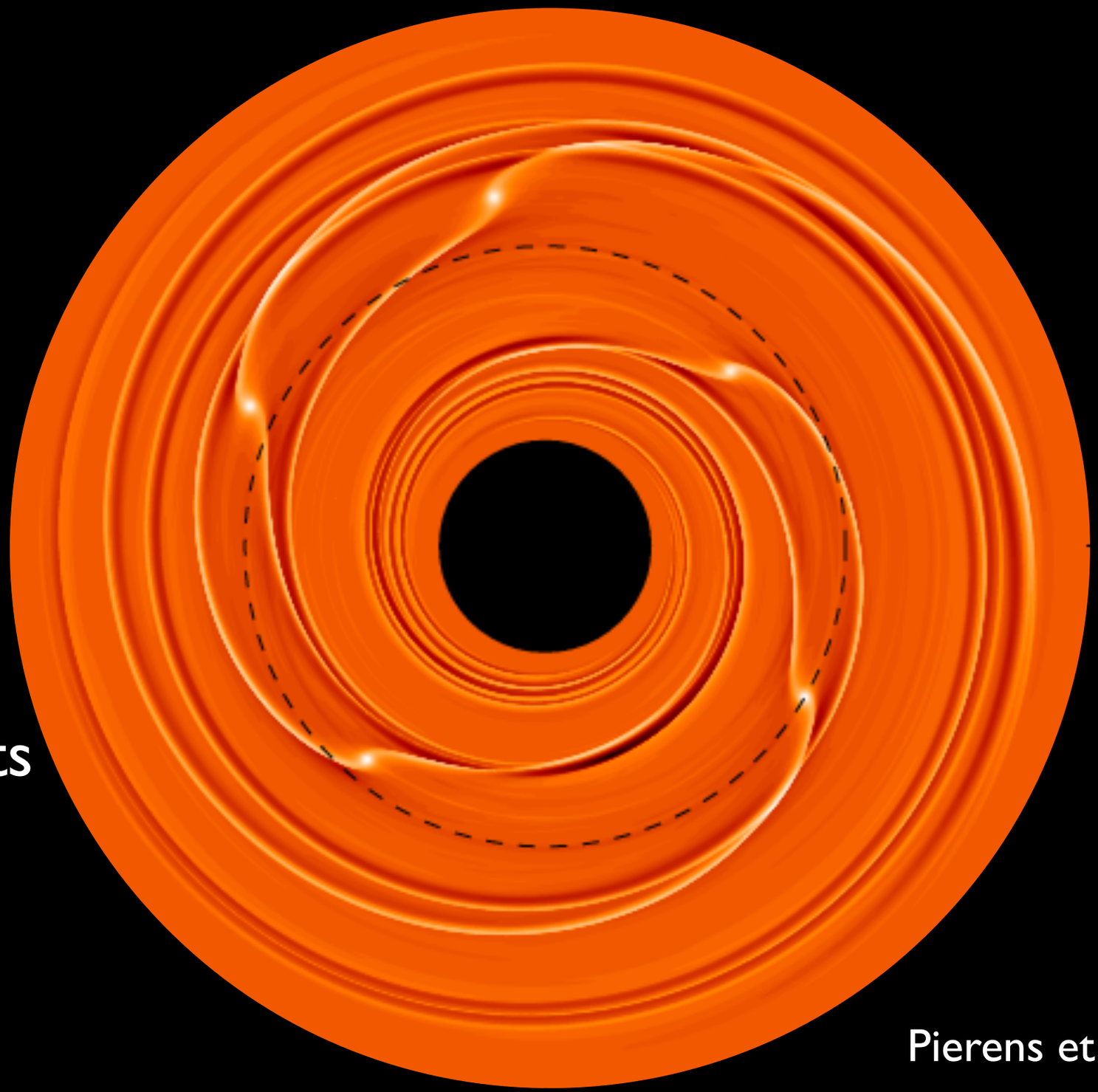

Pebble accretion is far more efficient past the snowline

(Lambrechts et al 2014; Morbidelli et al 2015; Ormel 2017)

# Orbital migration

Matters for
Mp >~ MEarth

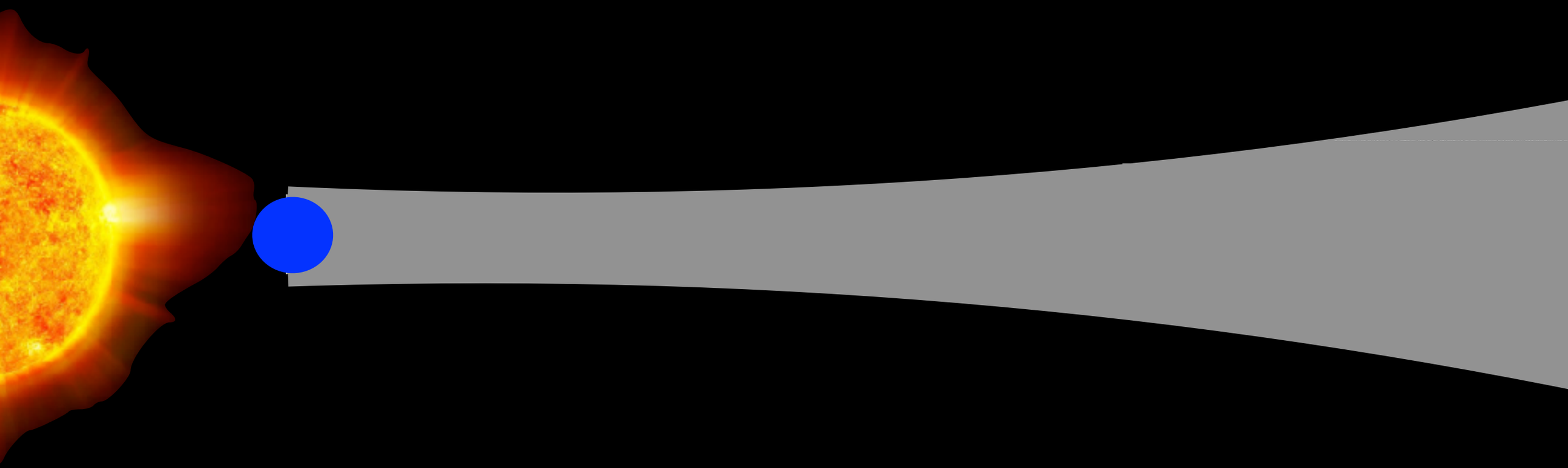
More massive planets
migrate faster



Pierens et al (2013)

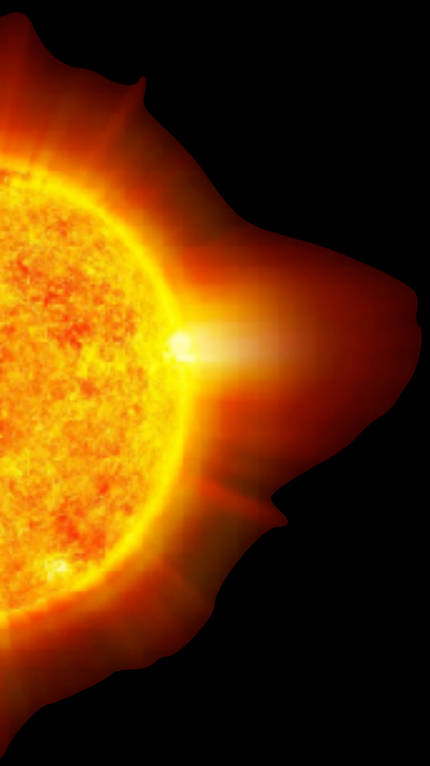
Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014; Kley & Nelson 2014

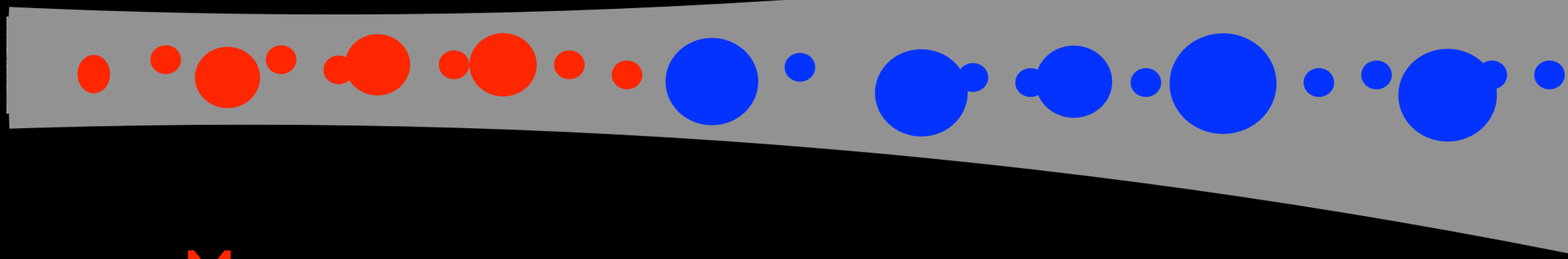
# Migrating planets are trapped at the inner edge of the disk



Masset et al (2006); Romanova & Lovelace (2006)

# Planetary embryos

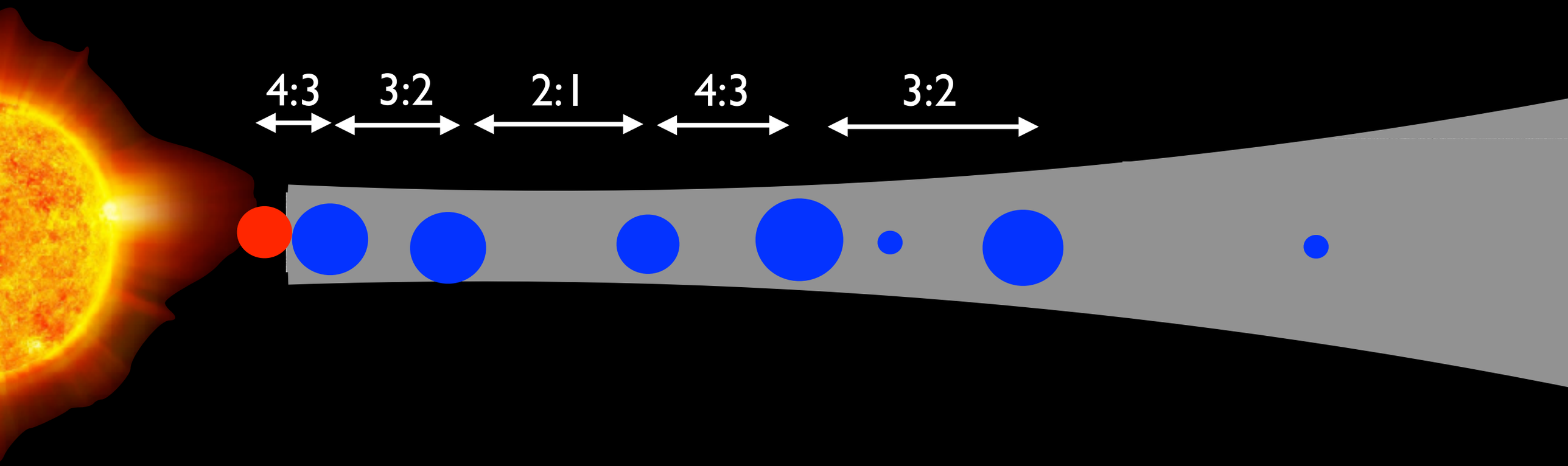




~Mars-mass
(10% $M_{Earth}$)

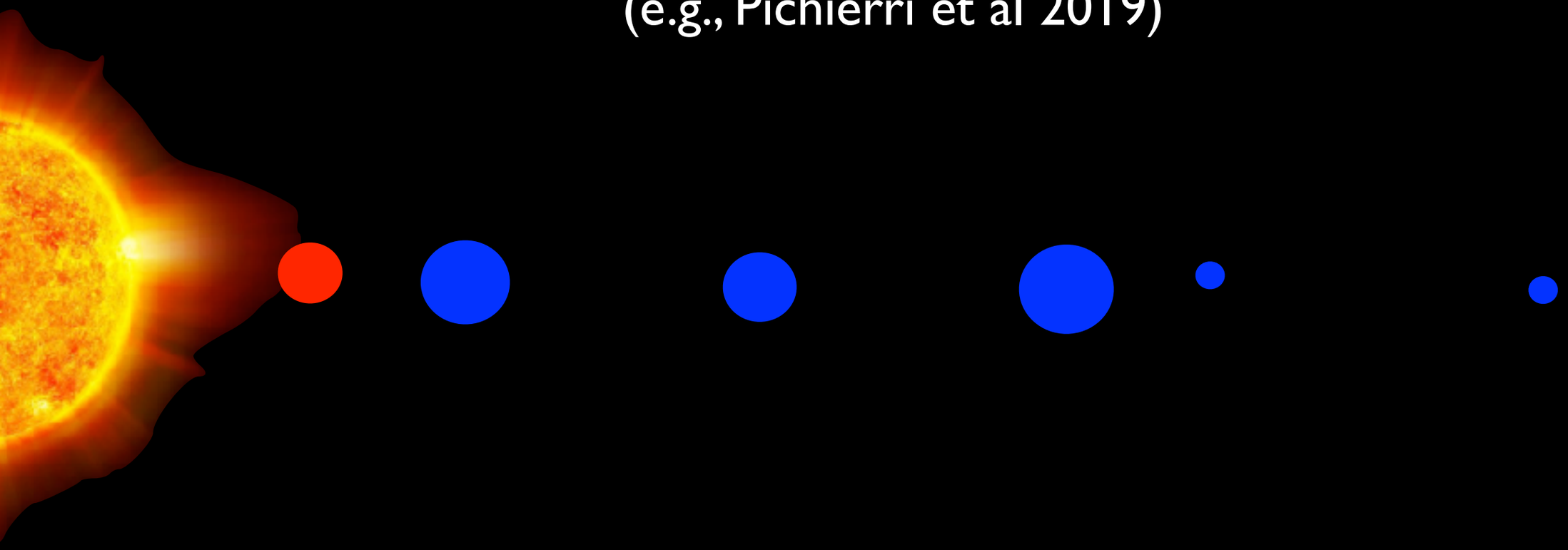
5-10 $M_{Earth}$

# Resonant chain

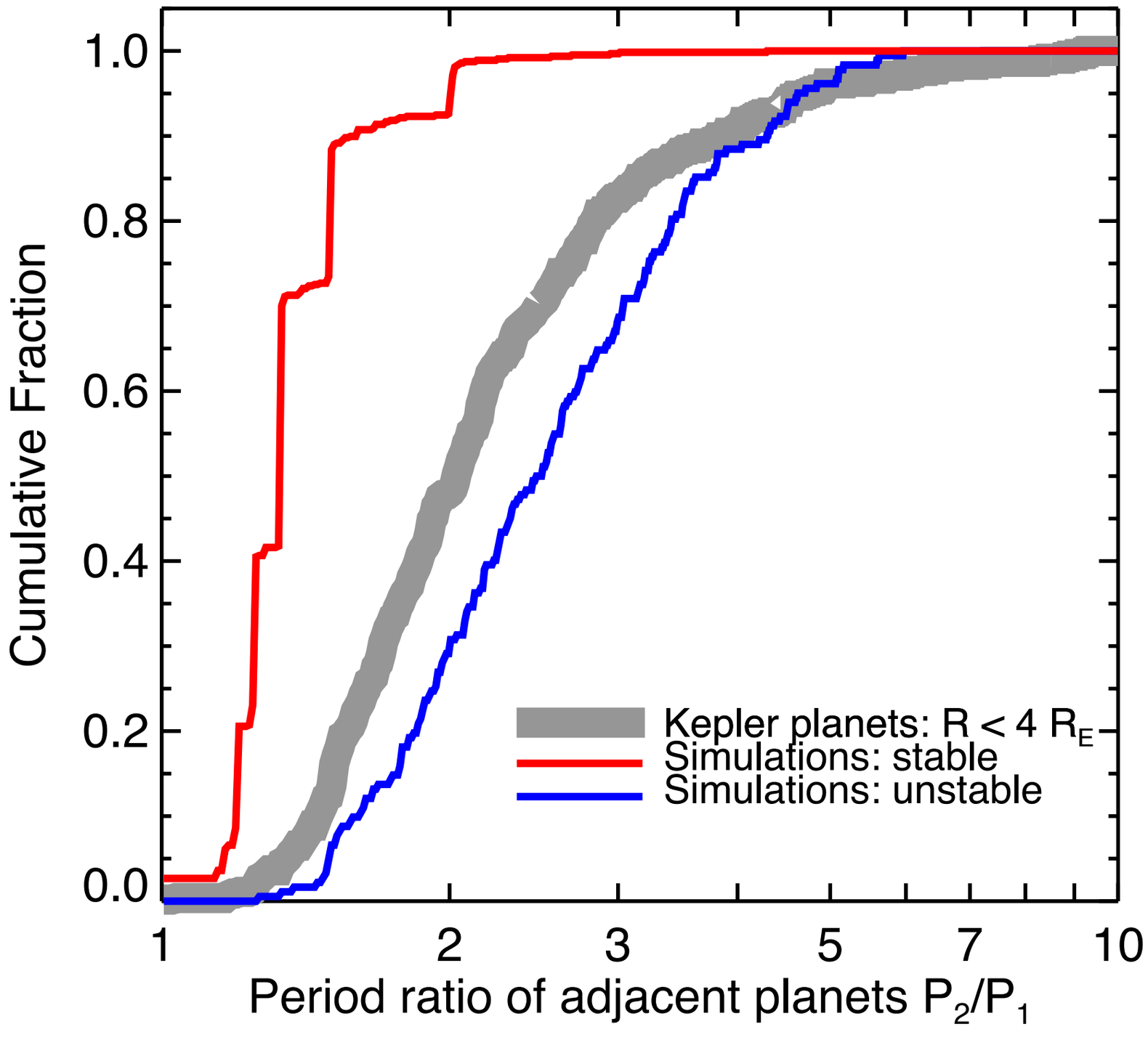


# Instability spreads planets out and destroys resonances

(e.g., Pichierri et al 2019)

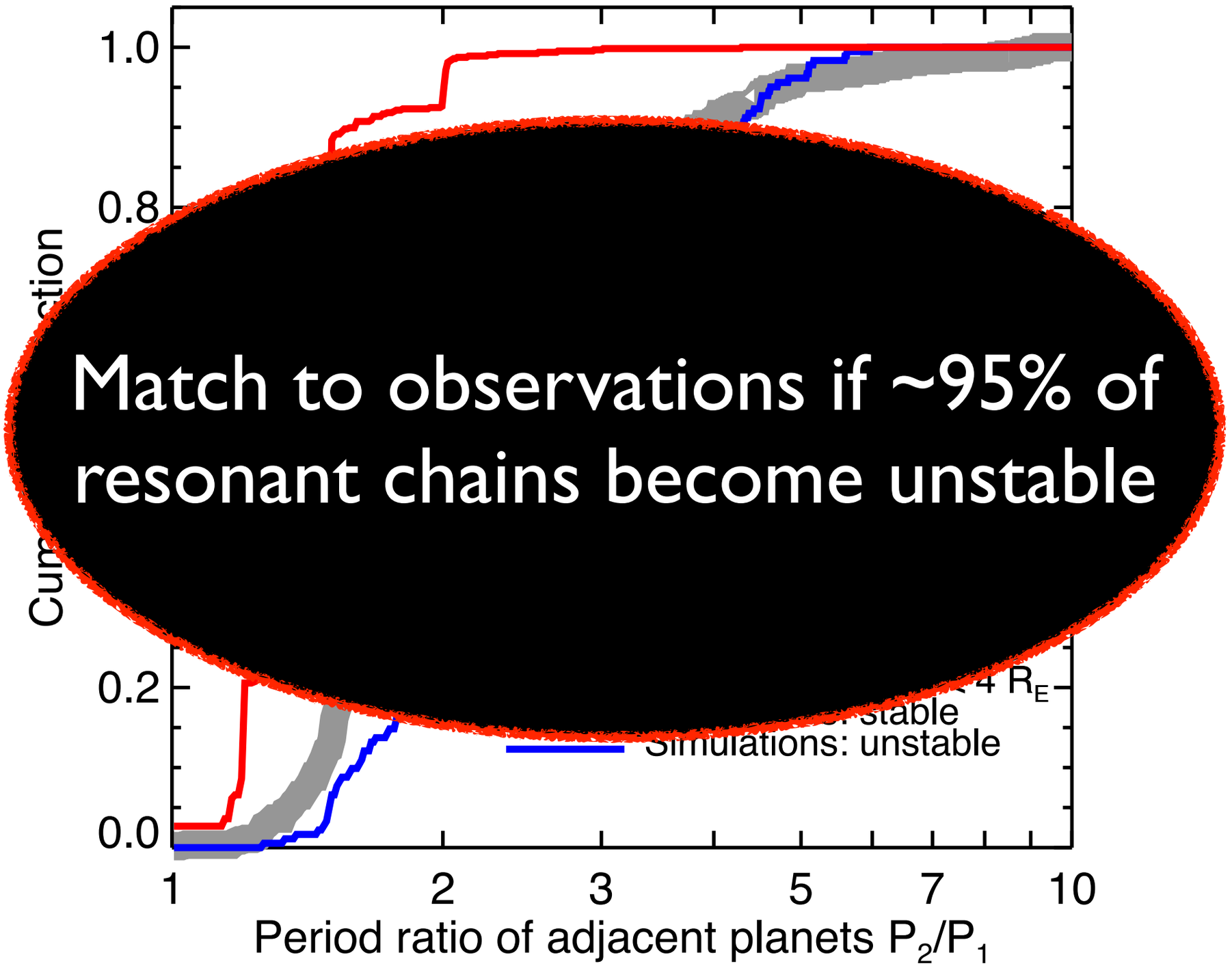


# The period ratio distribution

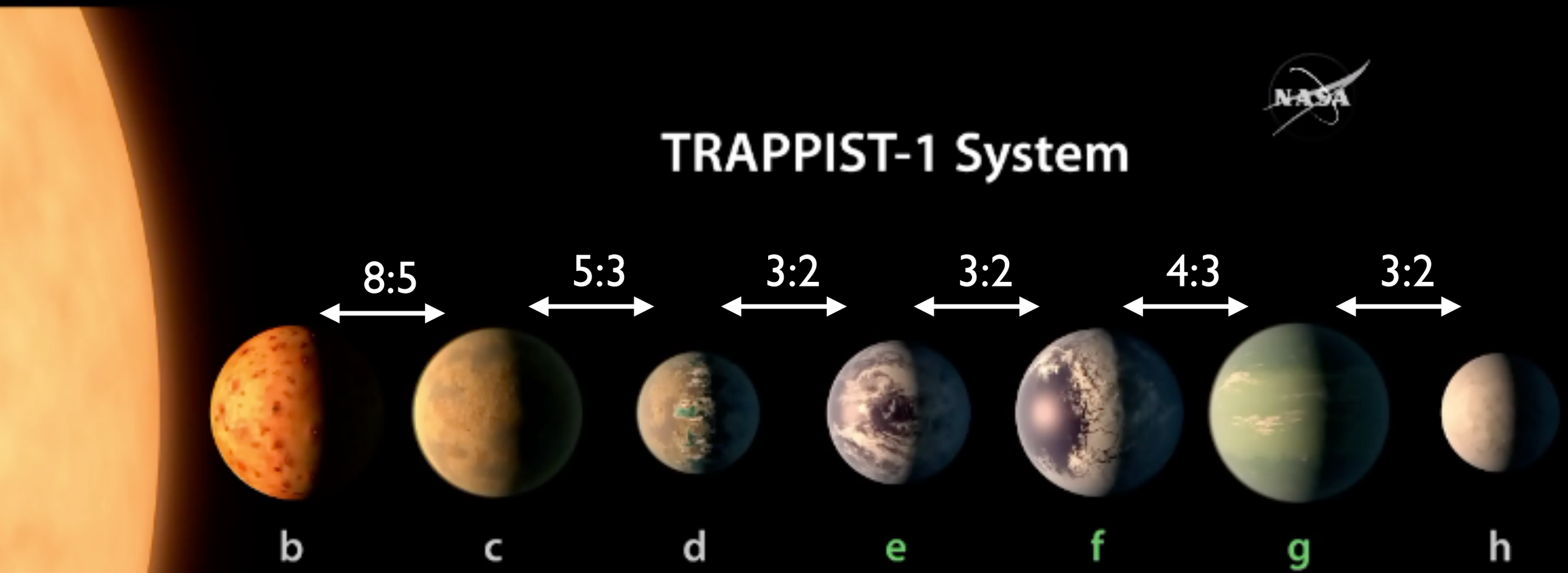



Izidoro et al (2017, 2021), Goldberg & Batygin (2022)

# The period ratio distribution




Izidoro et al (2017, 2021), Goldberg & Batygin (2022)



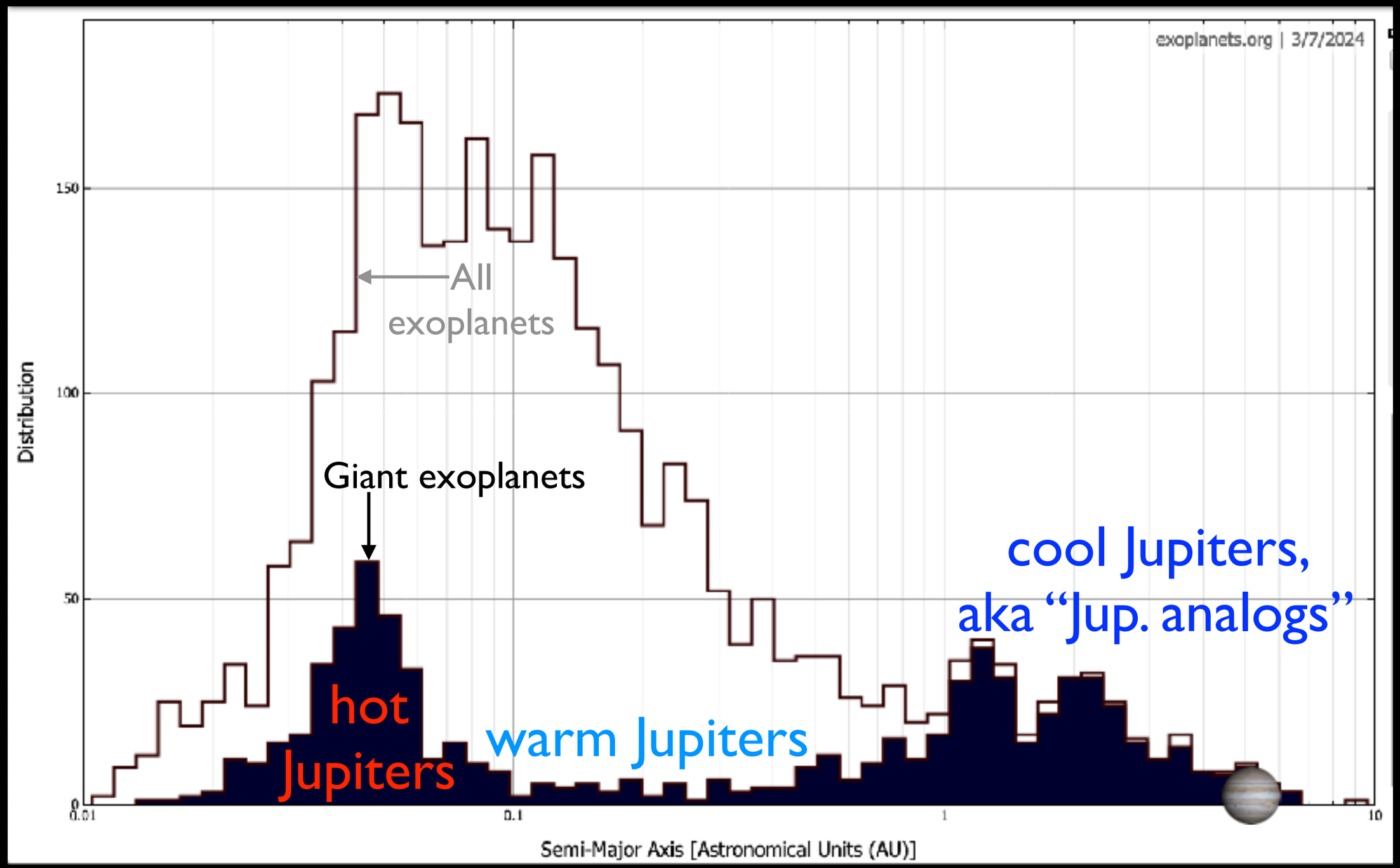

**Multi-resonant systems: ideal for**

- Transit-timing variations analysis to measure planet masses (e.g. Agol et al 2021)
- Understanding planets' detailed migration histories (e.g. Papaloizou et al 2018)
- Constraining planets' bombardment histories (Raymond et al 2022)

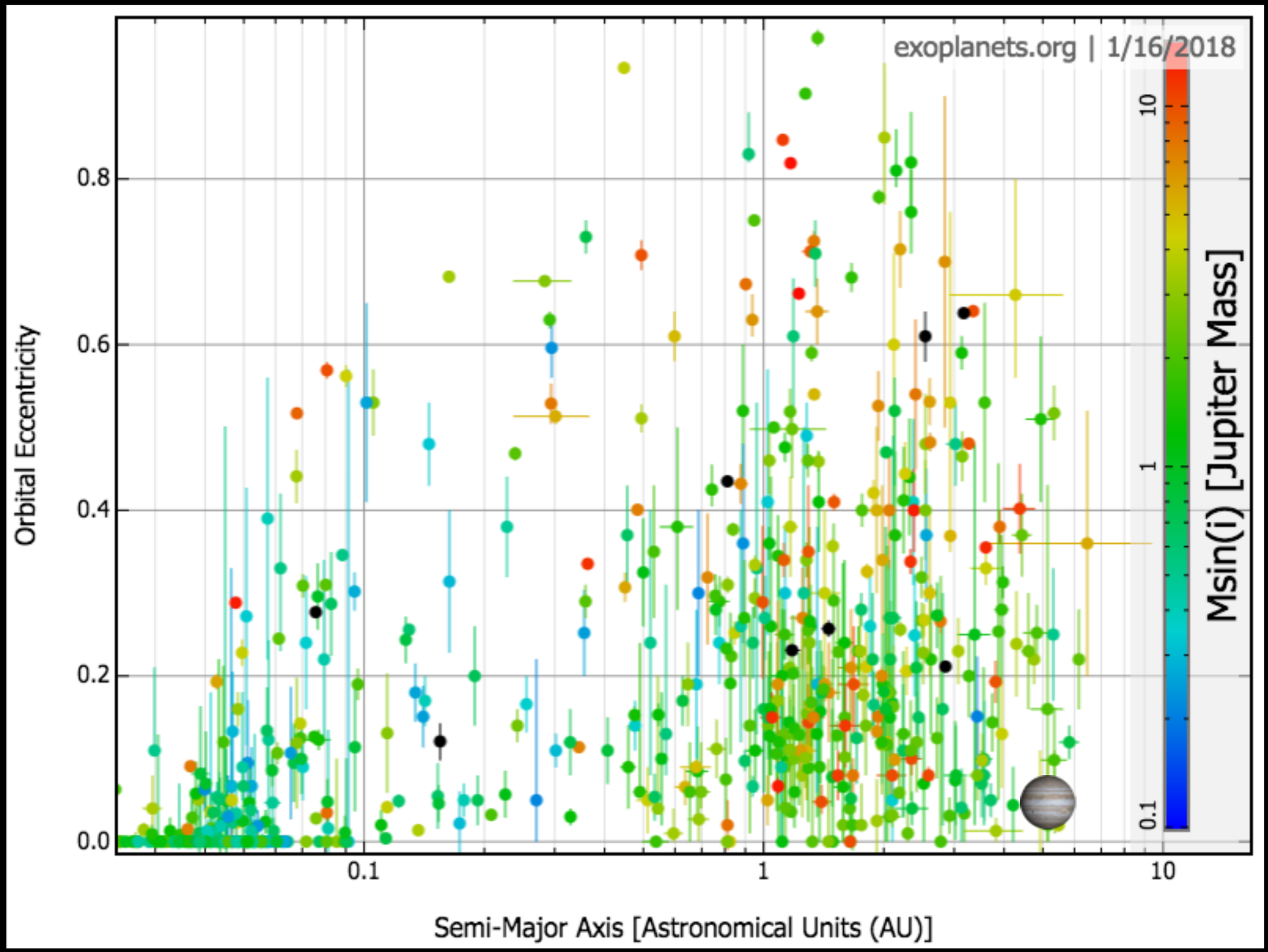
# Giant (exo)planets



# Radial distribution of gas giants

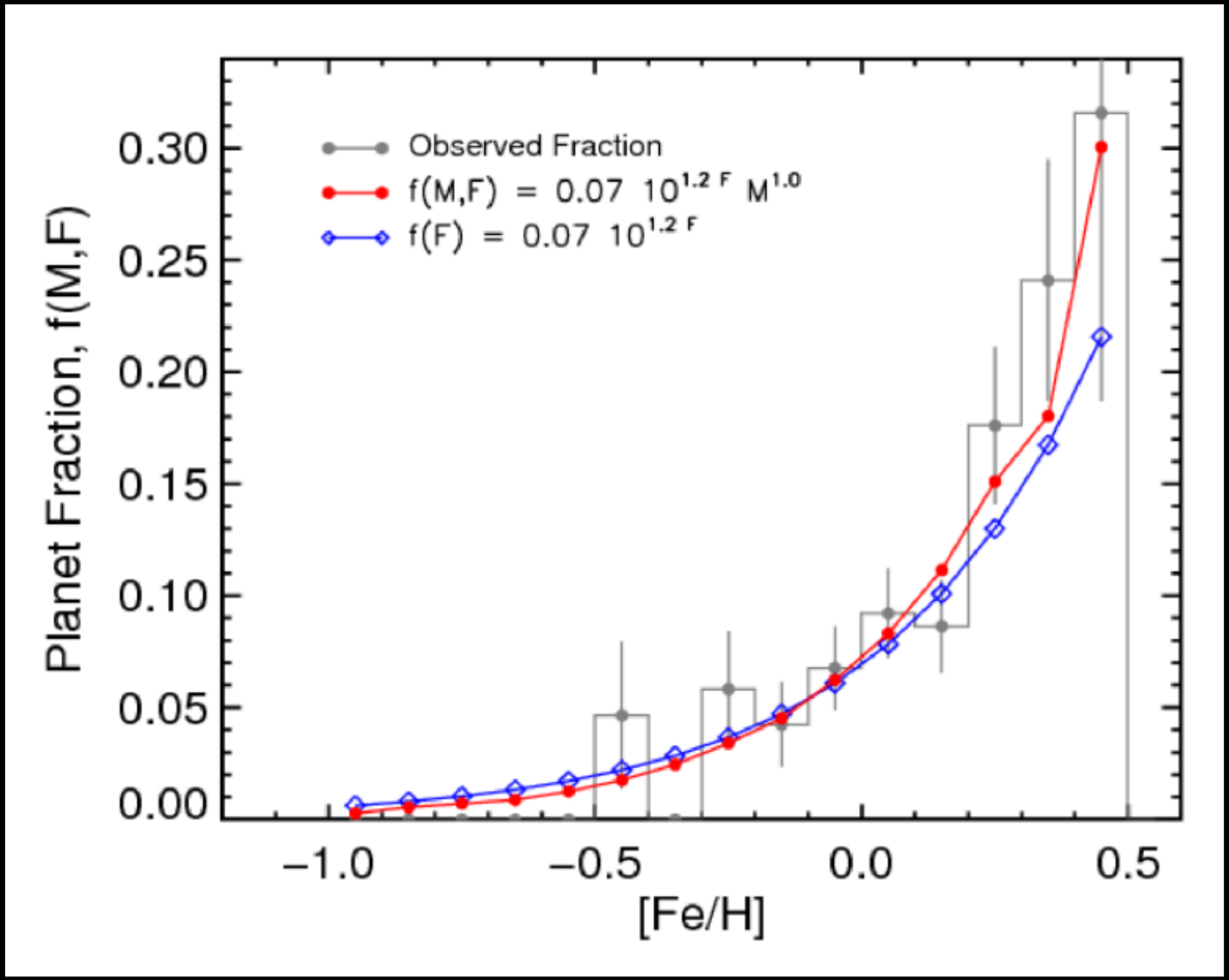


# Eccentricity distribution (giants)




Wright et al 2011

# Giant planet-metallicity correlation




Johnson et al (2010); also Gonzalez (1997); Santos et al (2003); Fischer & Valenti (2005)

# Formation models for giant planets

- Disk instability
- Core accretion



# Disk instability

- Requires a region in the disk to be Toomre unstable

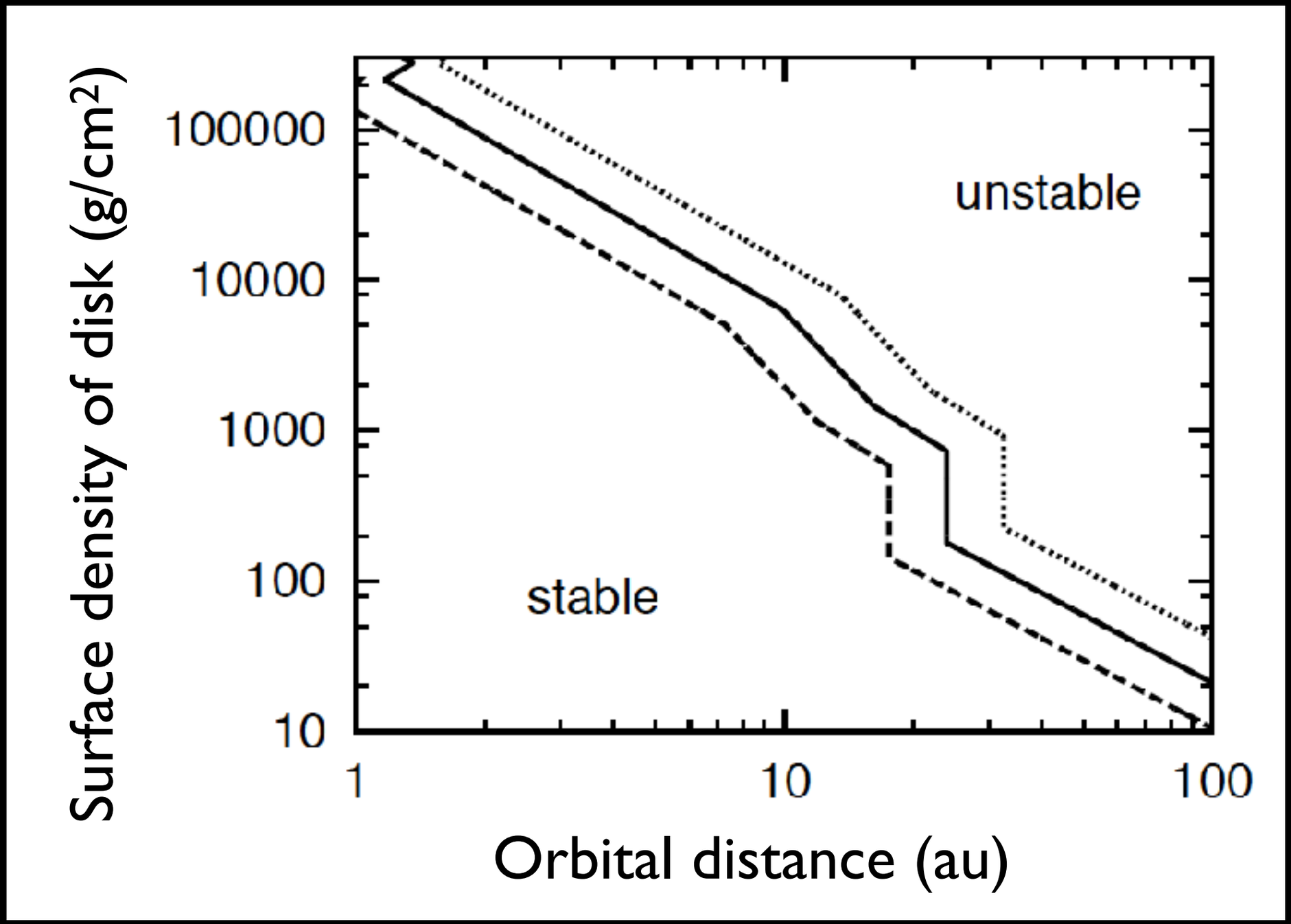
sound speed

orbital frequency

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\rm crit} \simeq 1$$

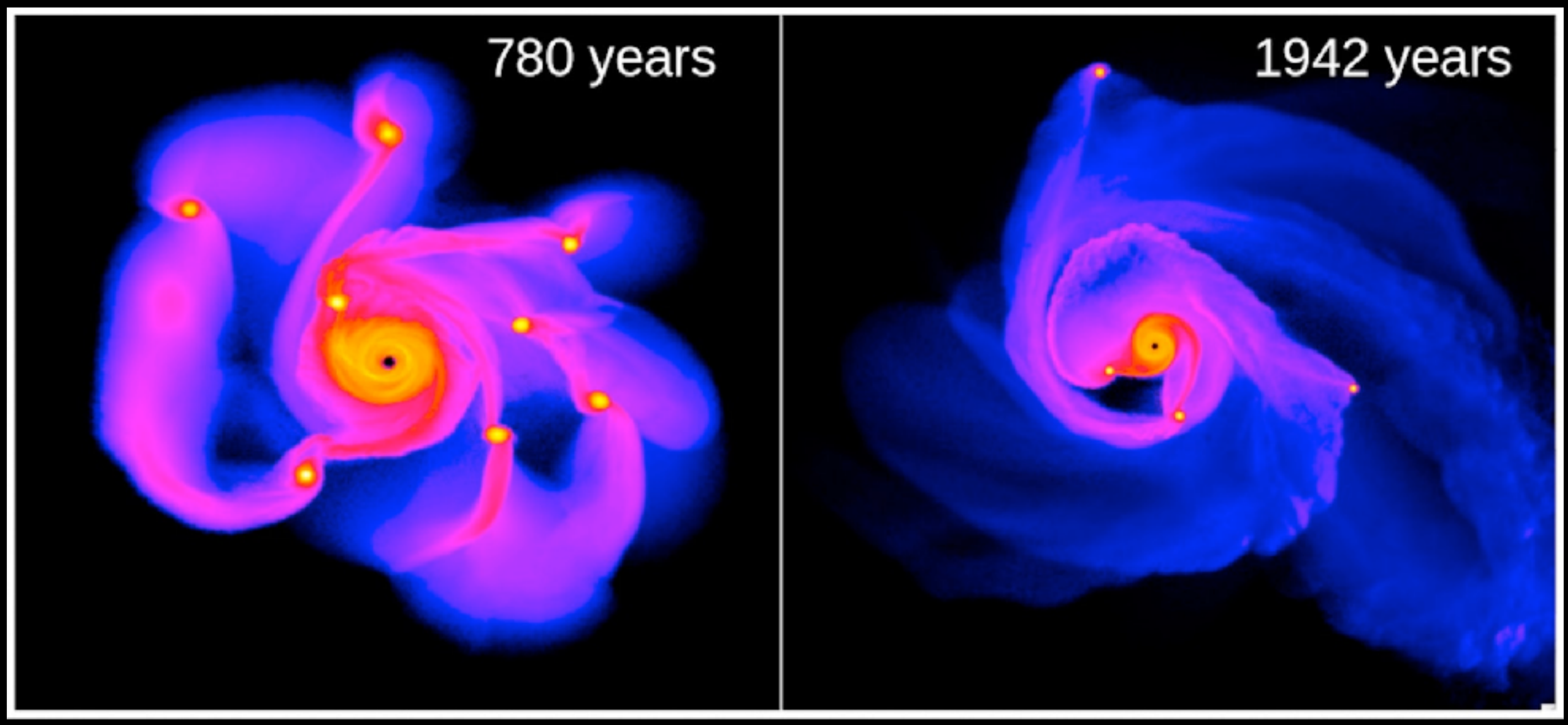
surface density

# Gravitational instability: only important for massive wide-orbit planets



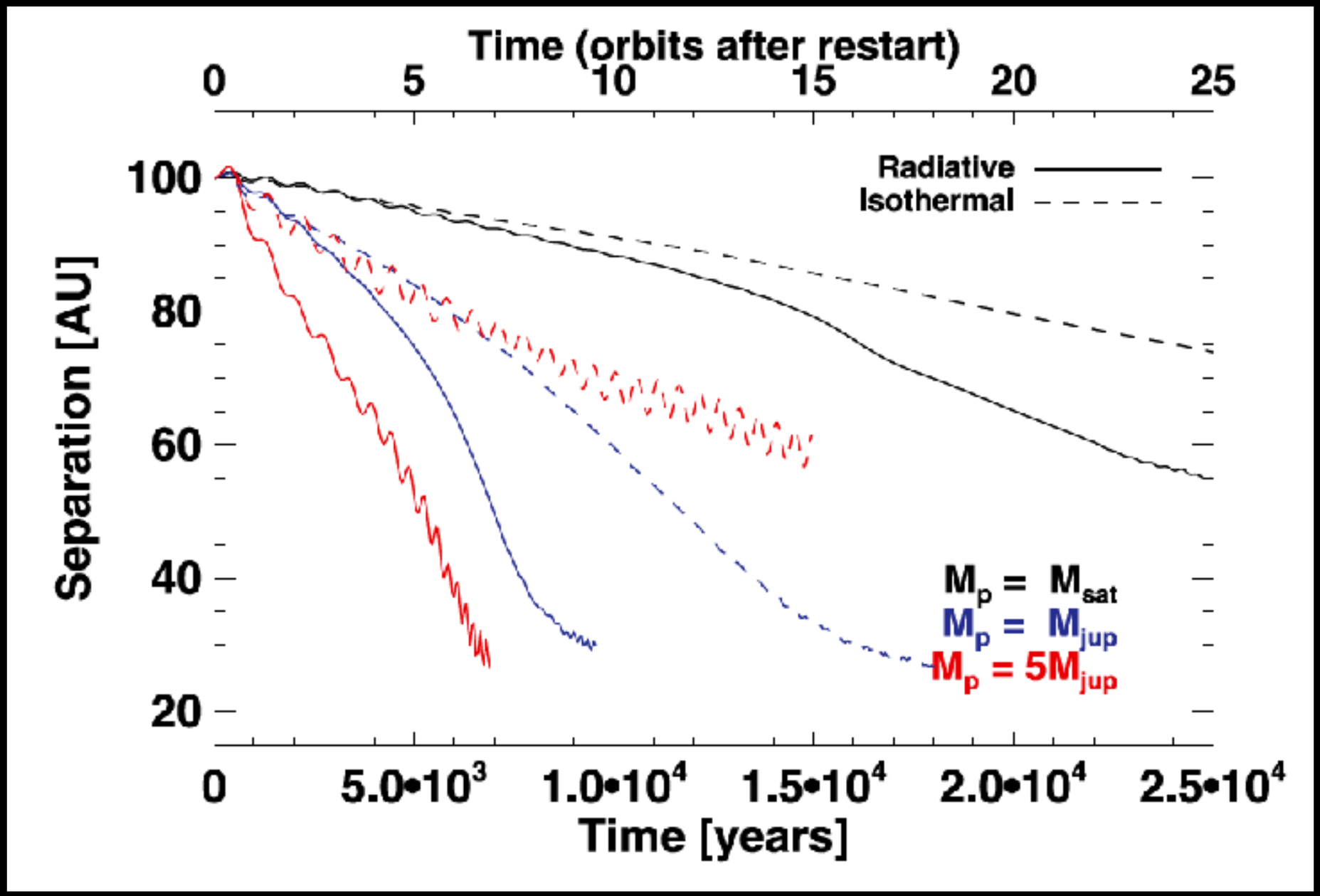

Kimura & Tsuribe (2012)

# Disk instability




Mayer & Quinn (2016)

# Clumps formed by disk instability migrate inward rapidly

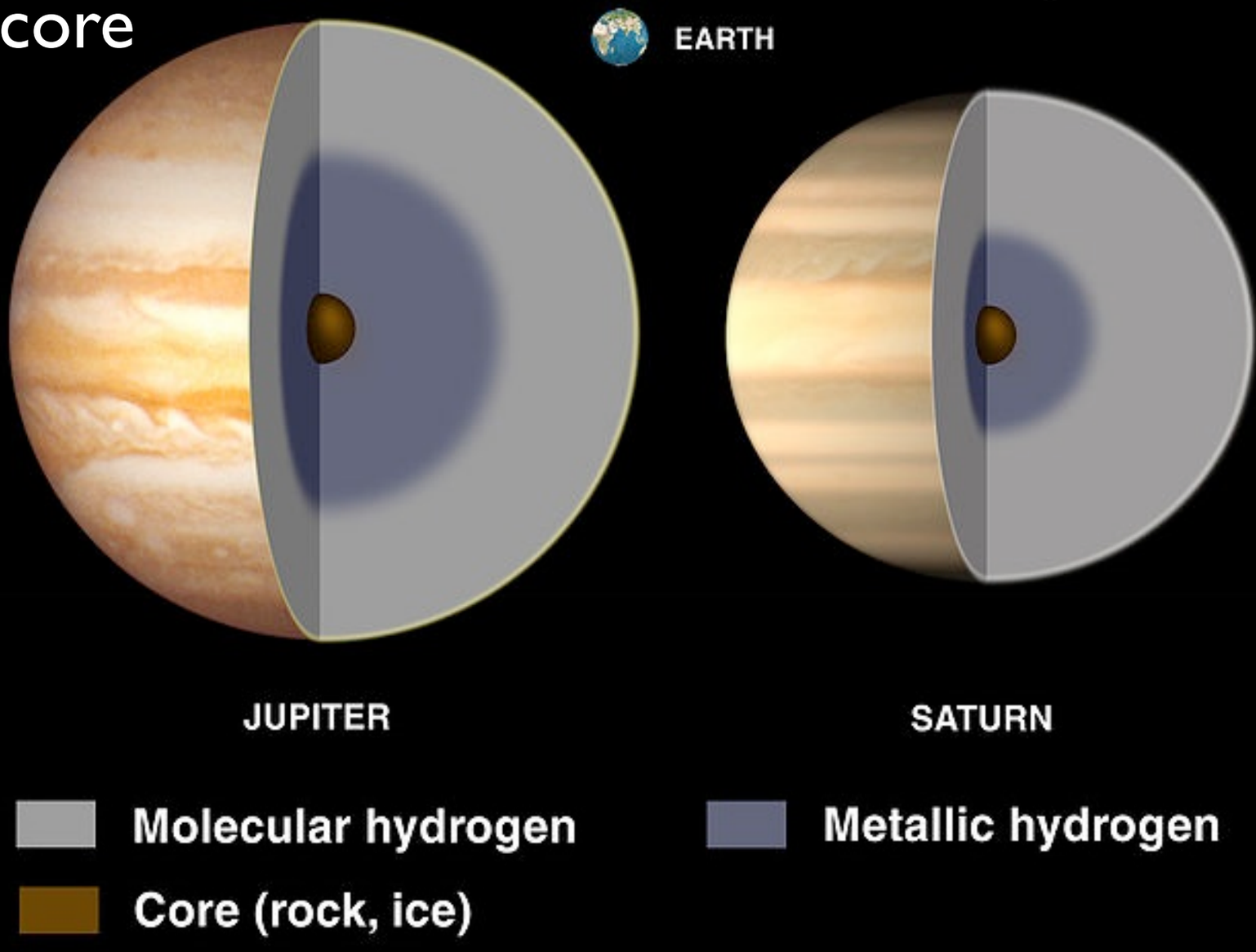



Baruteau et al (2012);
"tidal downsizing hypothesis" by Nayakshin (2010)

# Core accretion

growth of a large solid core

gas accretion

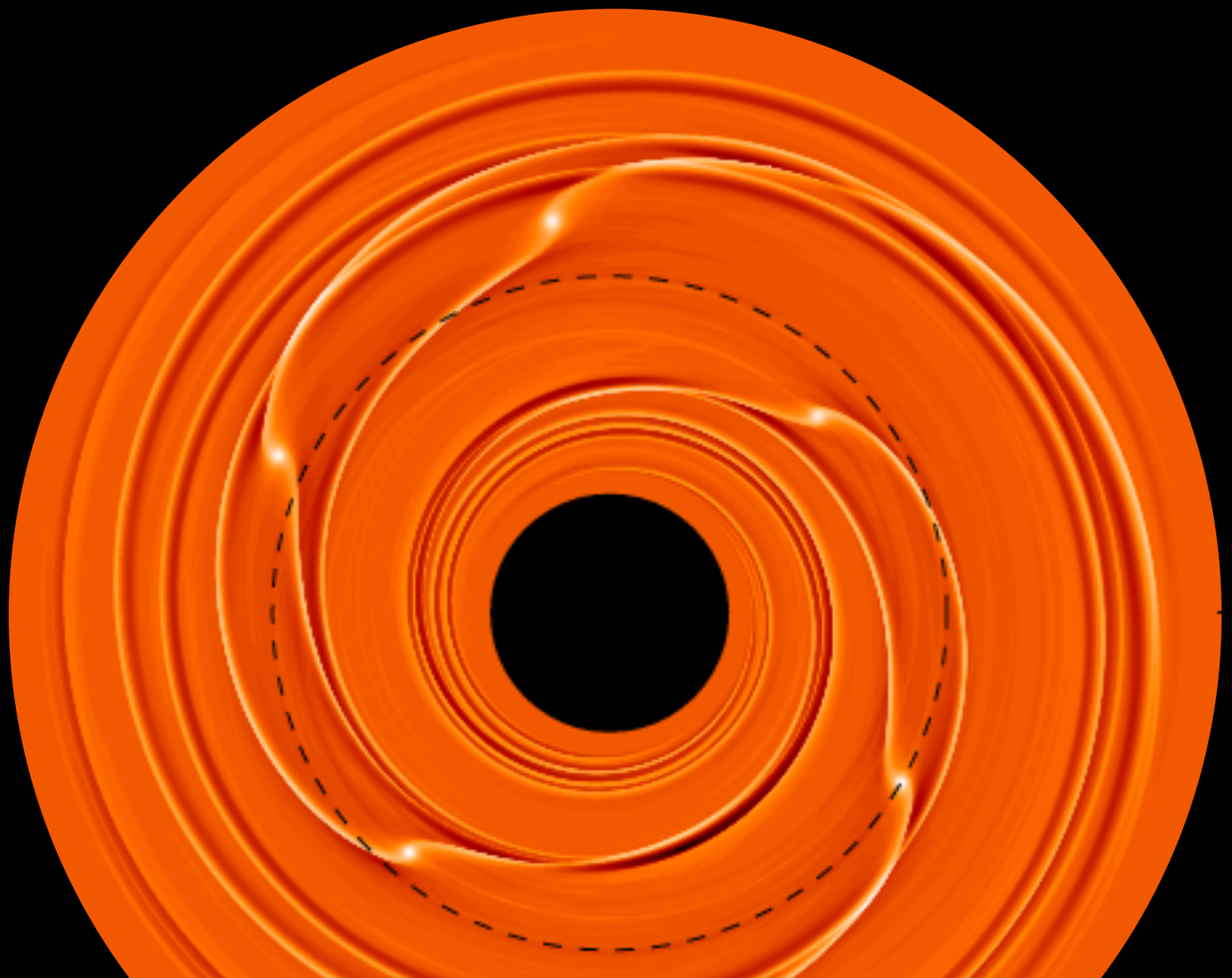


# Core migration accretion

growth of a large solid core

gas-driven migration

gas accretion

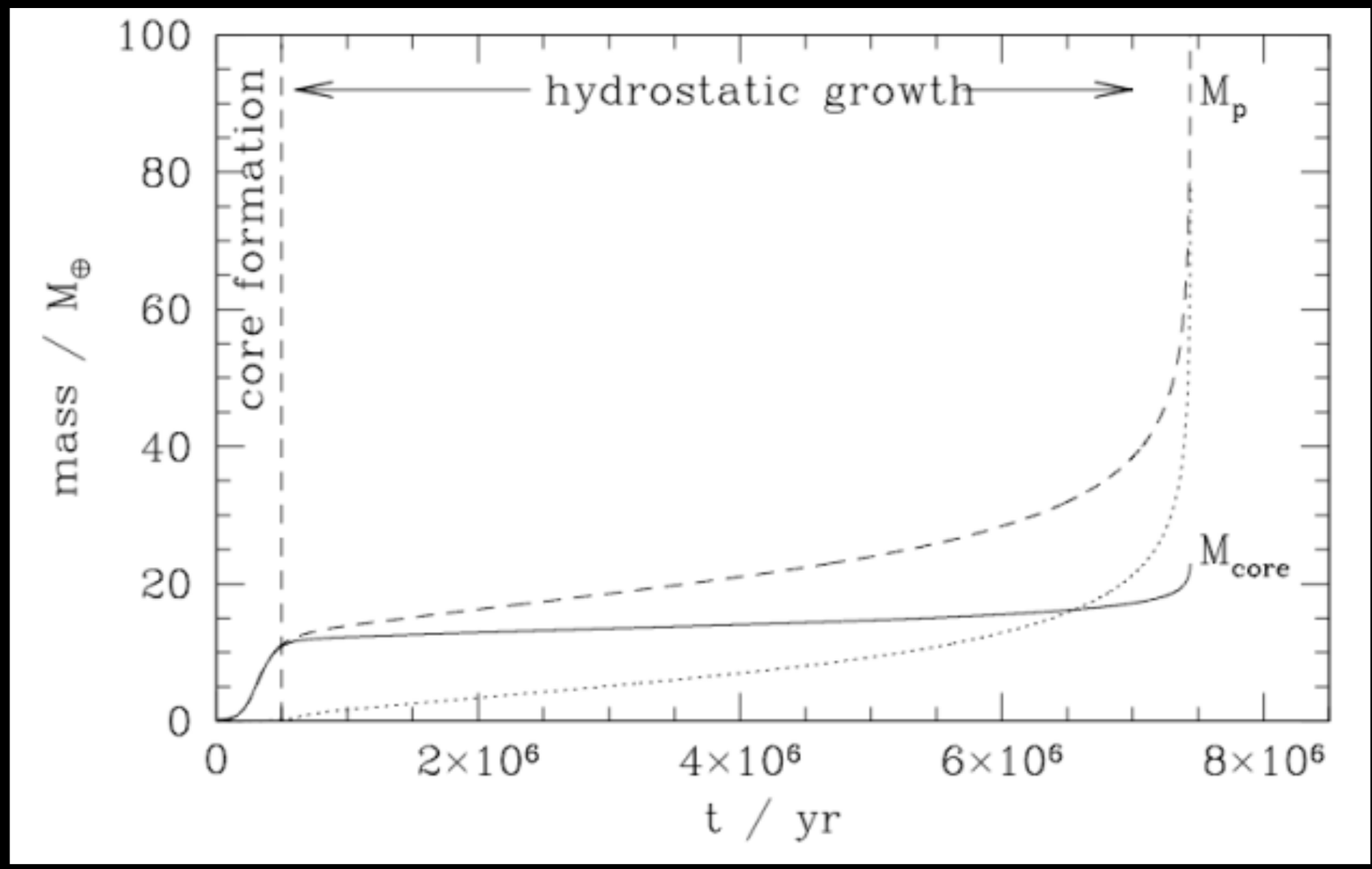


# Core migration accretion

growth of a large solid core

gas-driven migration

gas accretion



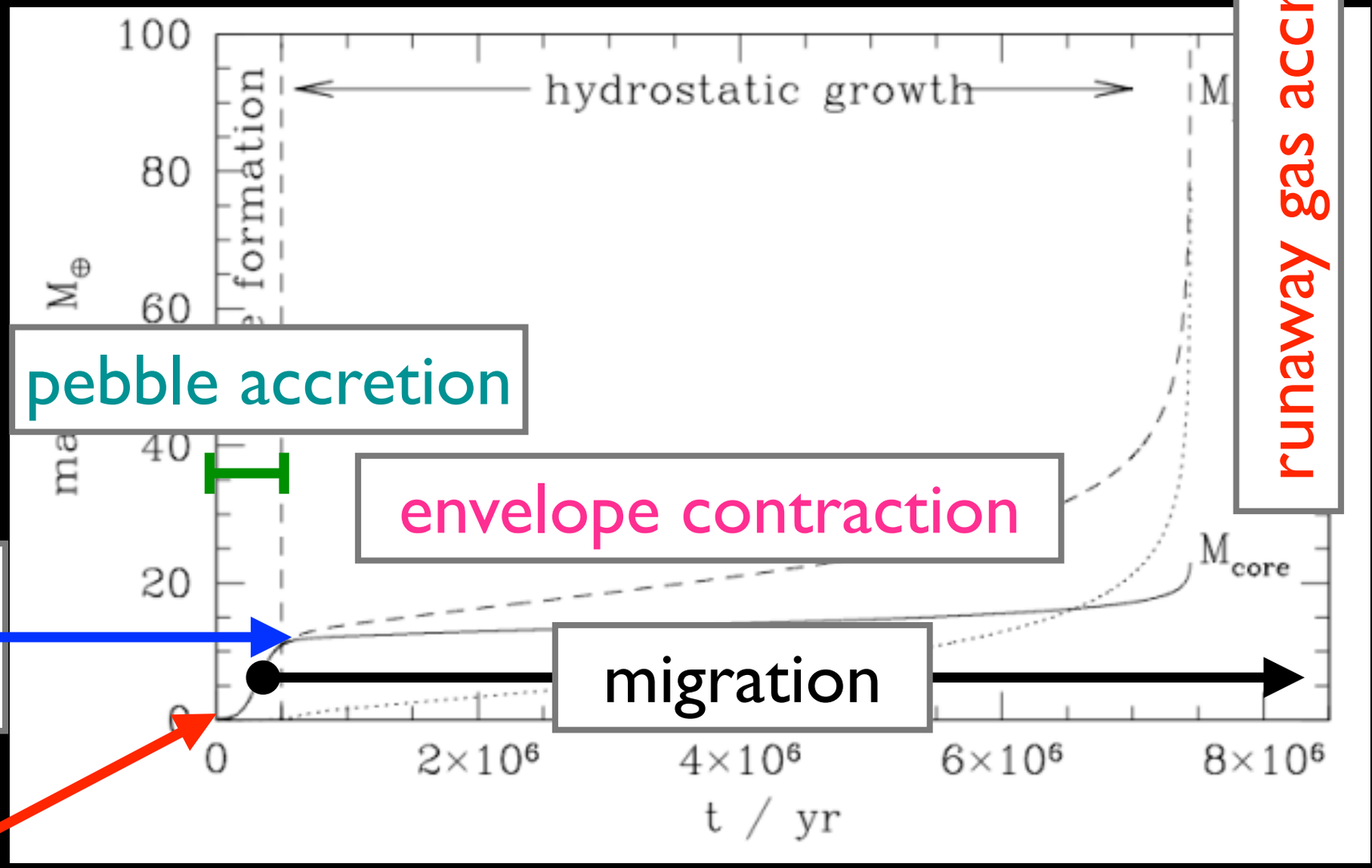

P. Armitage; after Pollack et al (1996)

# Core migration accretion

growth of a large solid core

gas-driven migration

gas accretion

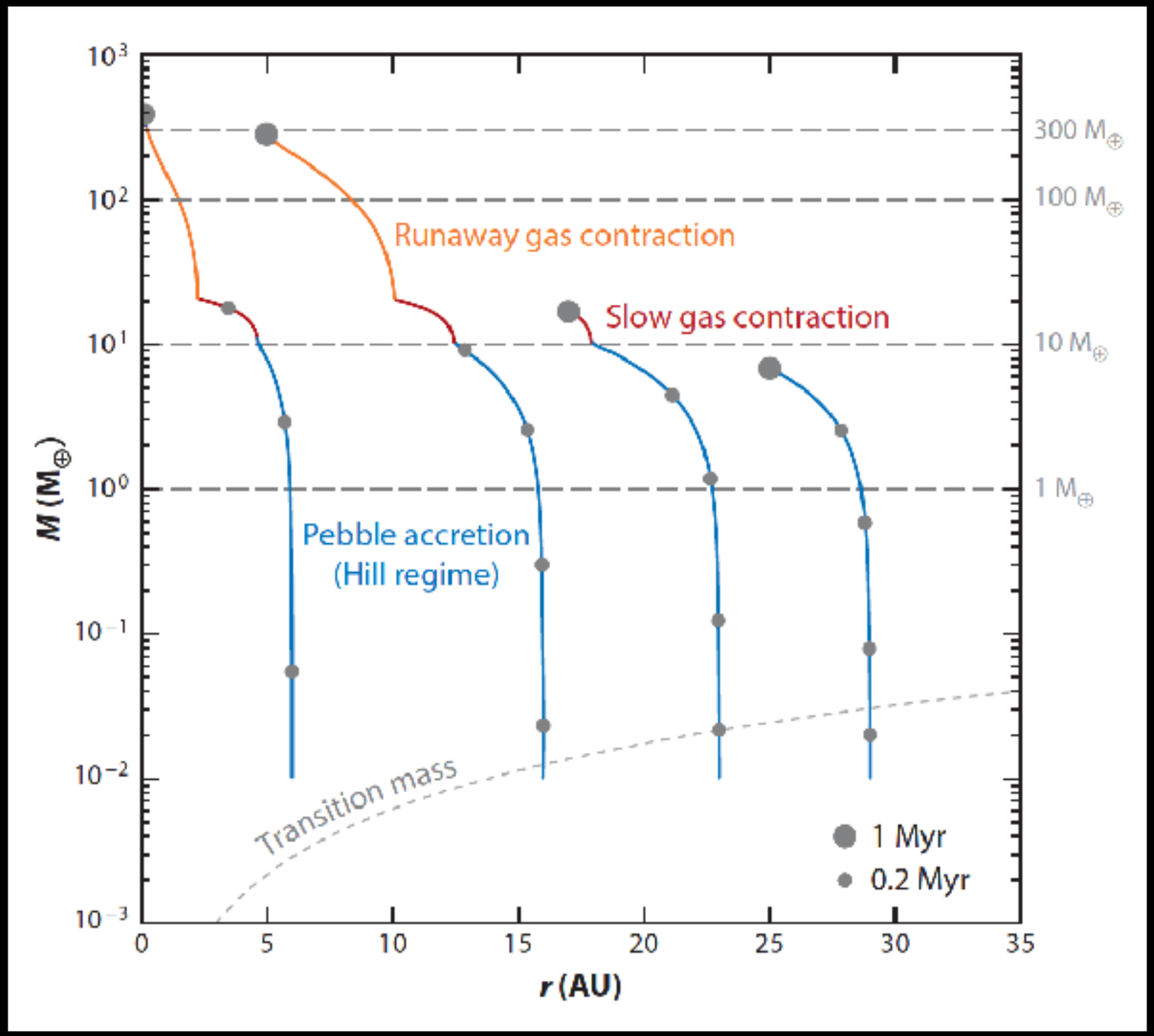



pebble "isolation mass"

planetesimal formation

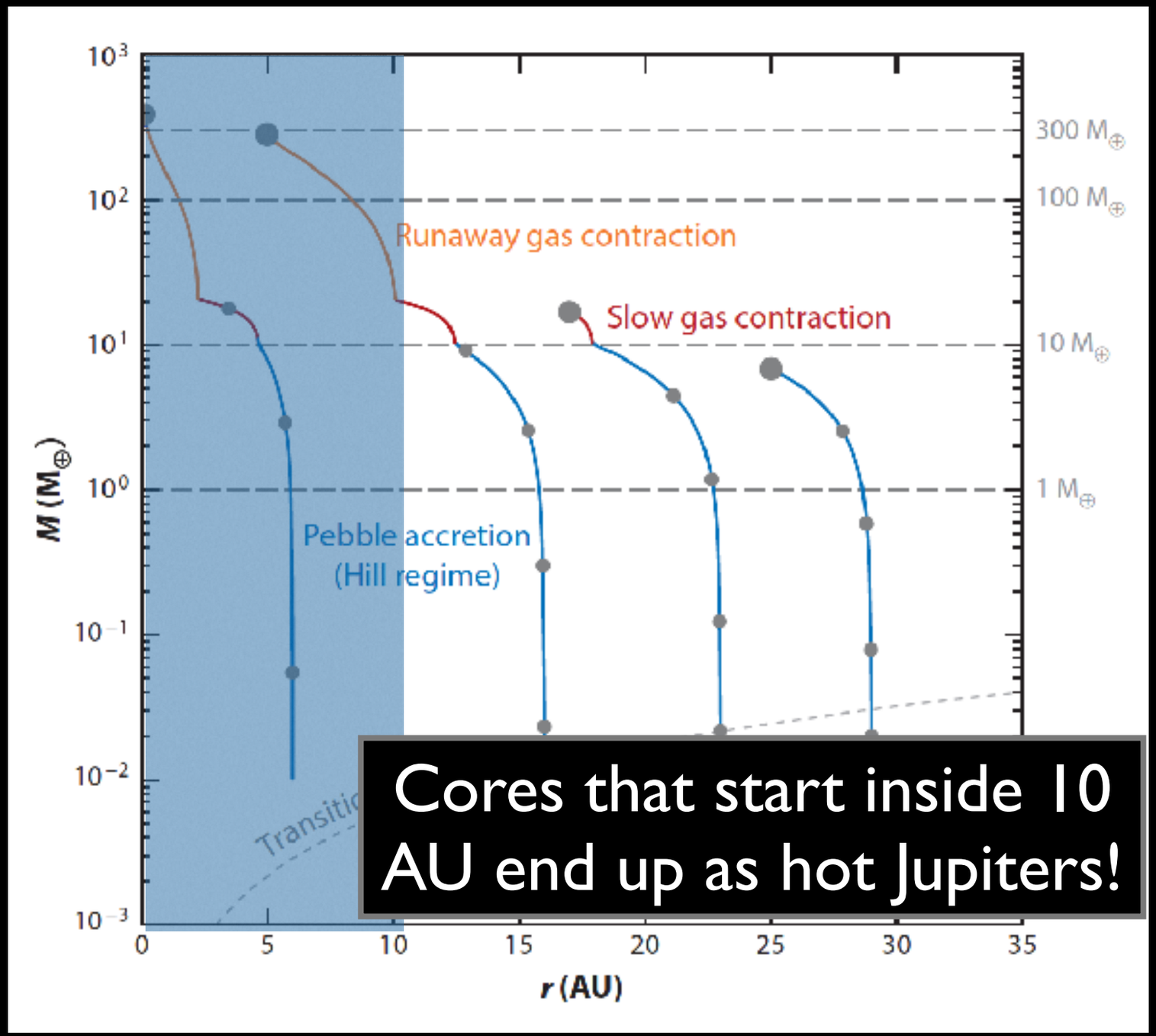
P. Armitage; after Pollack et al (1996)

# Growth/migration tracks with pebble accretion




Johansen & Lambrechts (2017); after Bitsch et al (2015)

# Growth/migration tracks with pebble accretion

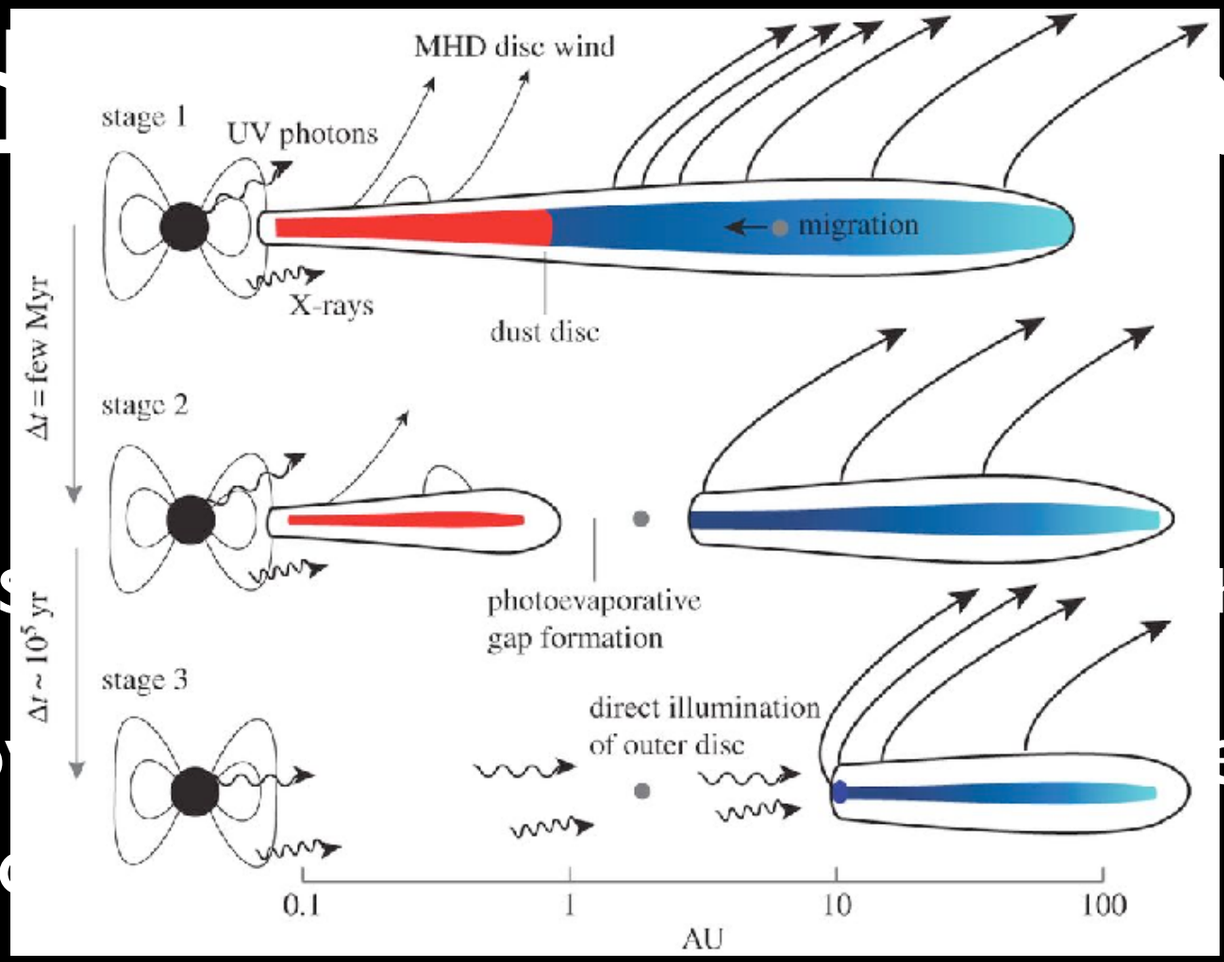



Johansen & Lambrechts (2017); after Bitsch et al (2015)

# How did Jupiter end up at 5 AU?

- Jupiter's core formed at 15-20 AU (Bitsch et al 2015)
- Very low viscosity disks: very slow type 2 migration (e.g., Bitsch et al 2019)

# How dic…t 5 AU?

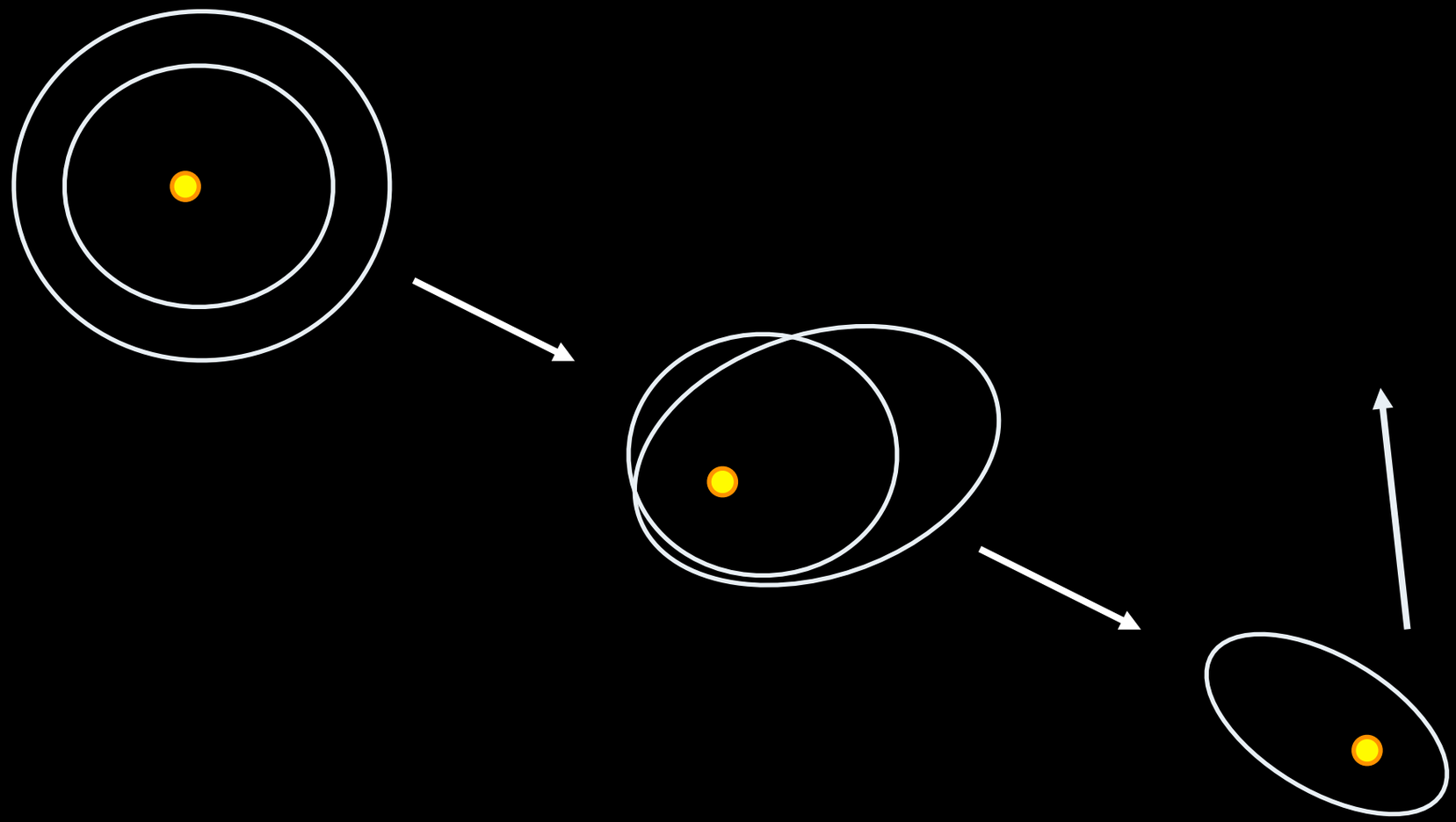



- Jupiter's …h et al 2015)
- Very lo… 2 migrati…
- Inner disk evaporated away, planets can't migrate closer than ~1 AU (Alexander & Pascucci 2012)

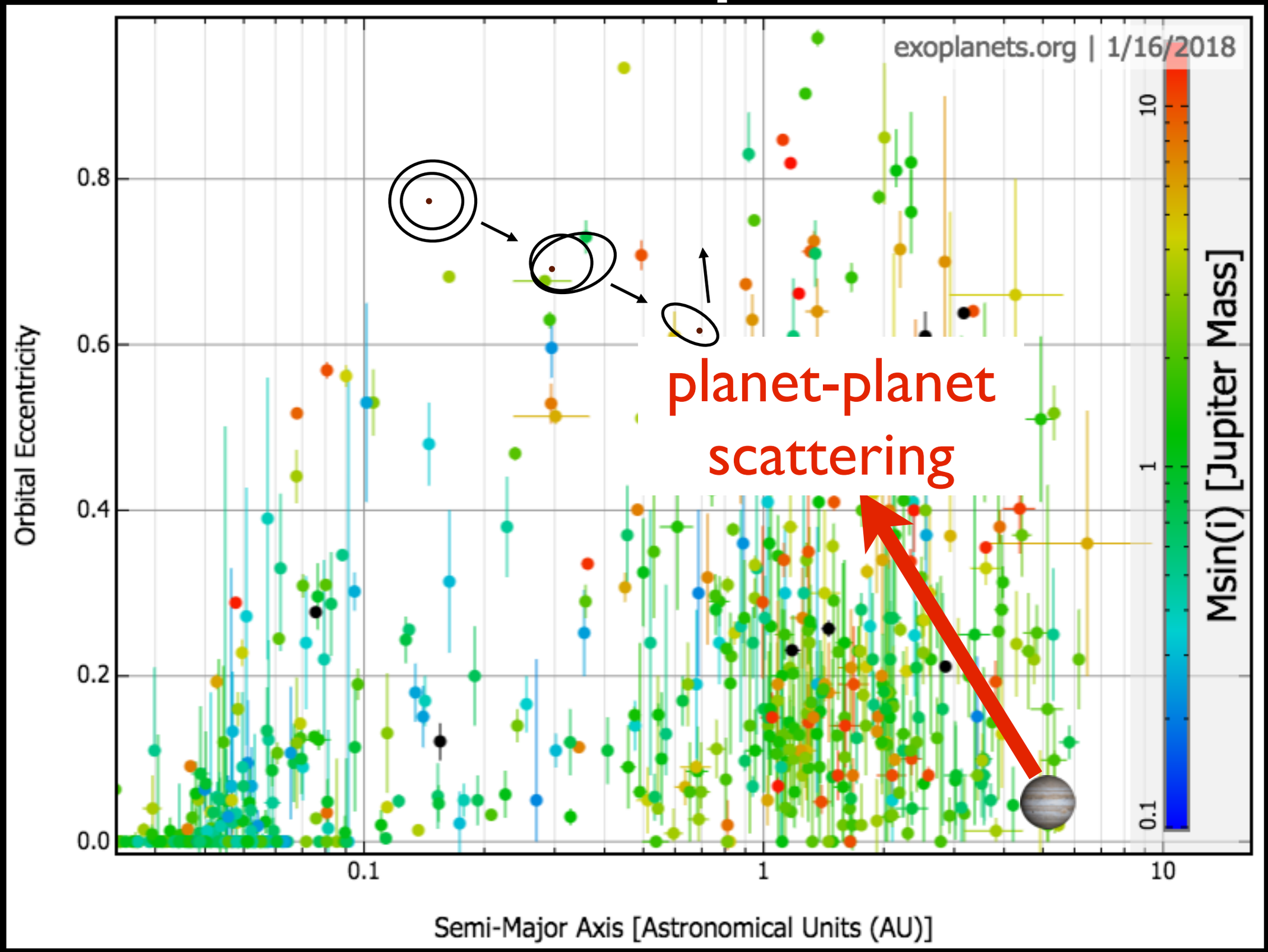
# How did Jupiter end up at 5 AU?

- Jupiter's core formed at 15-20 AU (Bitsch et al 2015)
- Very low viscosity disks: very slow type 2 migration (e.g., Bitsch et al 2019)
- Inner disk evaporated away, planets can't migrate closer than ~1 AU (Alexander & Pascucci 2012)
- Saturn stops or reverses Jupiter's migration (Masset & Snellgrove 2001; Grand Tack model)

# The giant exoplanet eccentricity distribution: planet-planet scattering



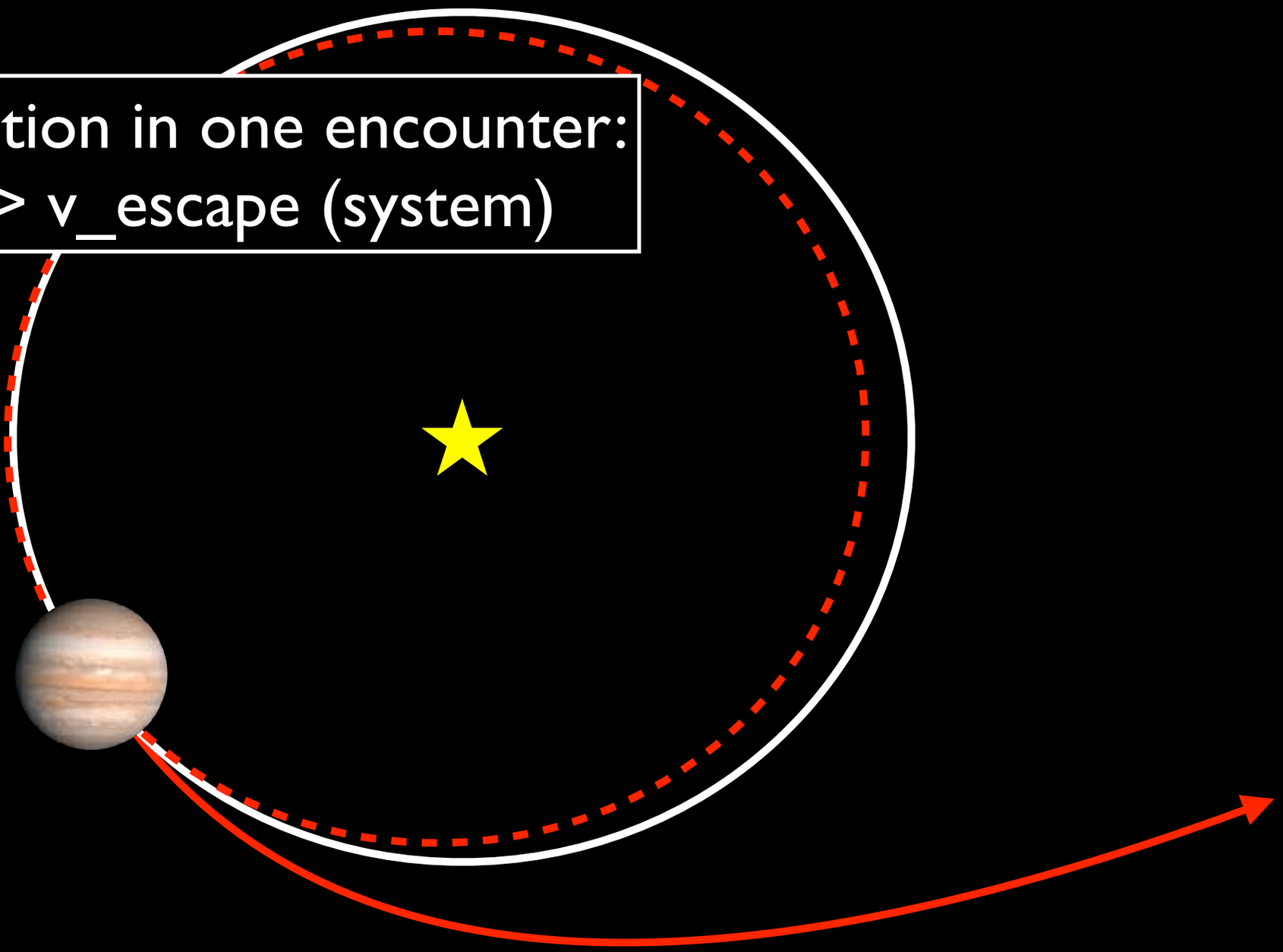
# Giant exoplanets




Wright et al 2011

# Scattering vs accretion

Requirement for ejection in one encounter:
v_escape (planet) > v_escape (system)



# The "Safronov number": scattering vs accretion

- Ratio of escape speed from planet's surface to escape speed from system at planet's orbital radius

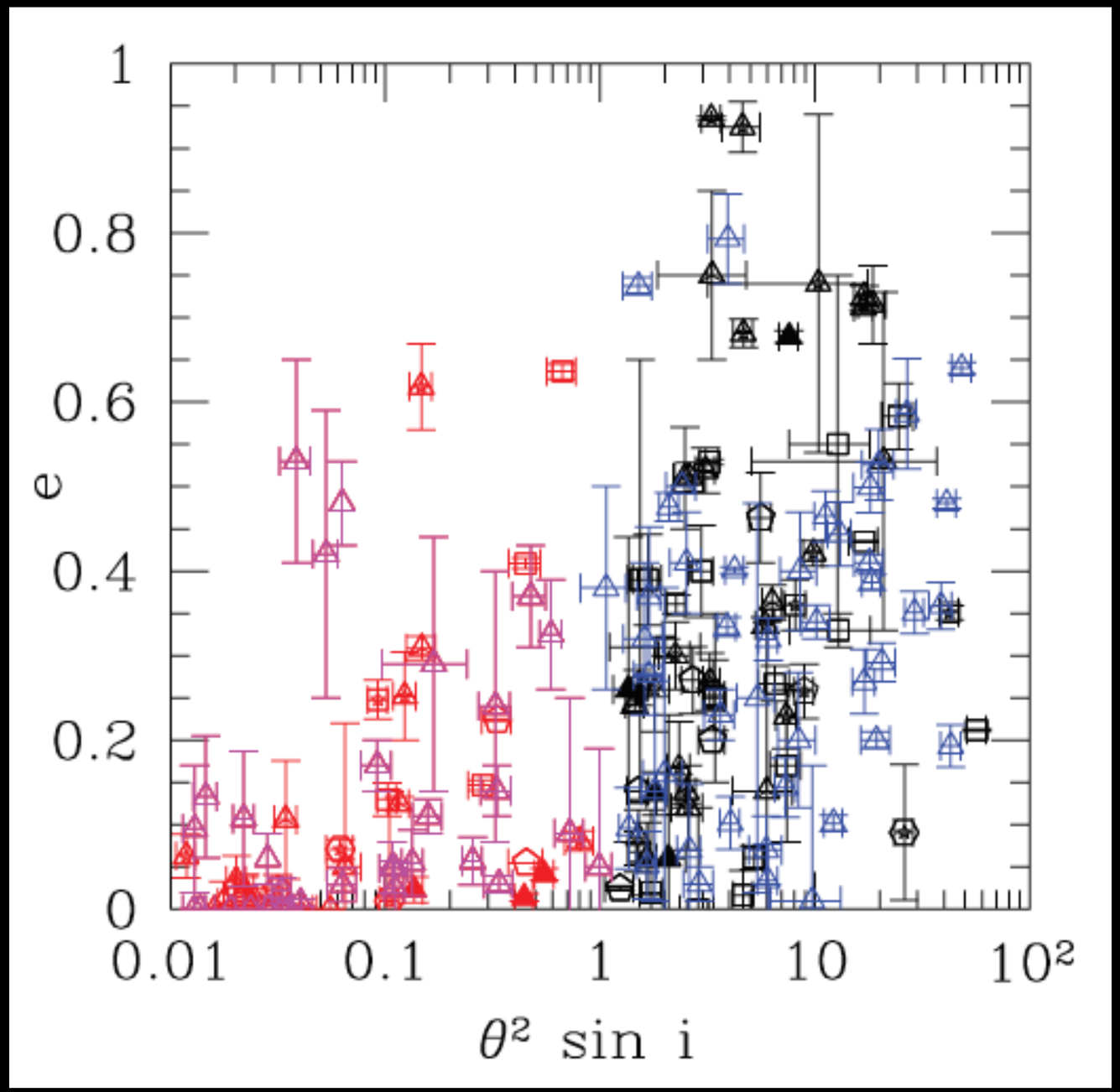
$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right)$$
$$= 10\left(\frac{m}{M_\mathrm{J}}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_\mathrm{J}}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right)$$

# The “Safronov number”: scattering vs accretion

- Saf> 1: high-mass or distant planets — **scattering**
- Saf< 1: low-mass or close-in planets — **accretion**

$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right)$$
$$= 10\left(\frac{m}{M_\mathrm{J}}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_\mathrm{J}}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right)$$

# Giant planet eccentricities correlate with Safronov#




Ford & Rasio (2008)

# Planet-planet scattering

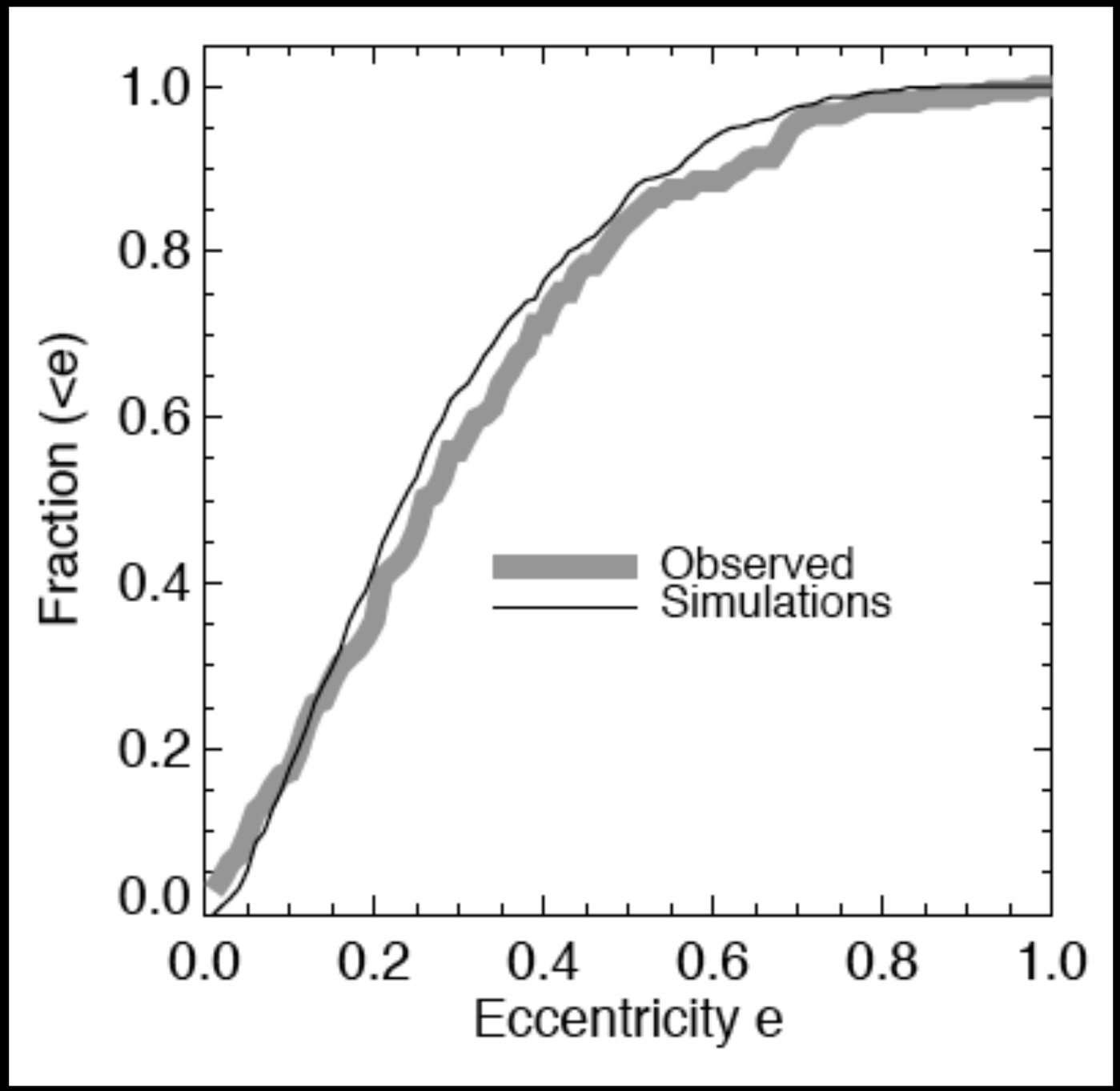



Credit: Eric Ford

# Survivors of planet-planet scattering match the eccentricity distribution

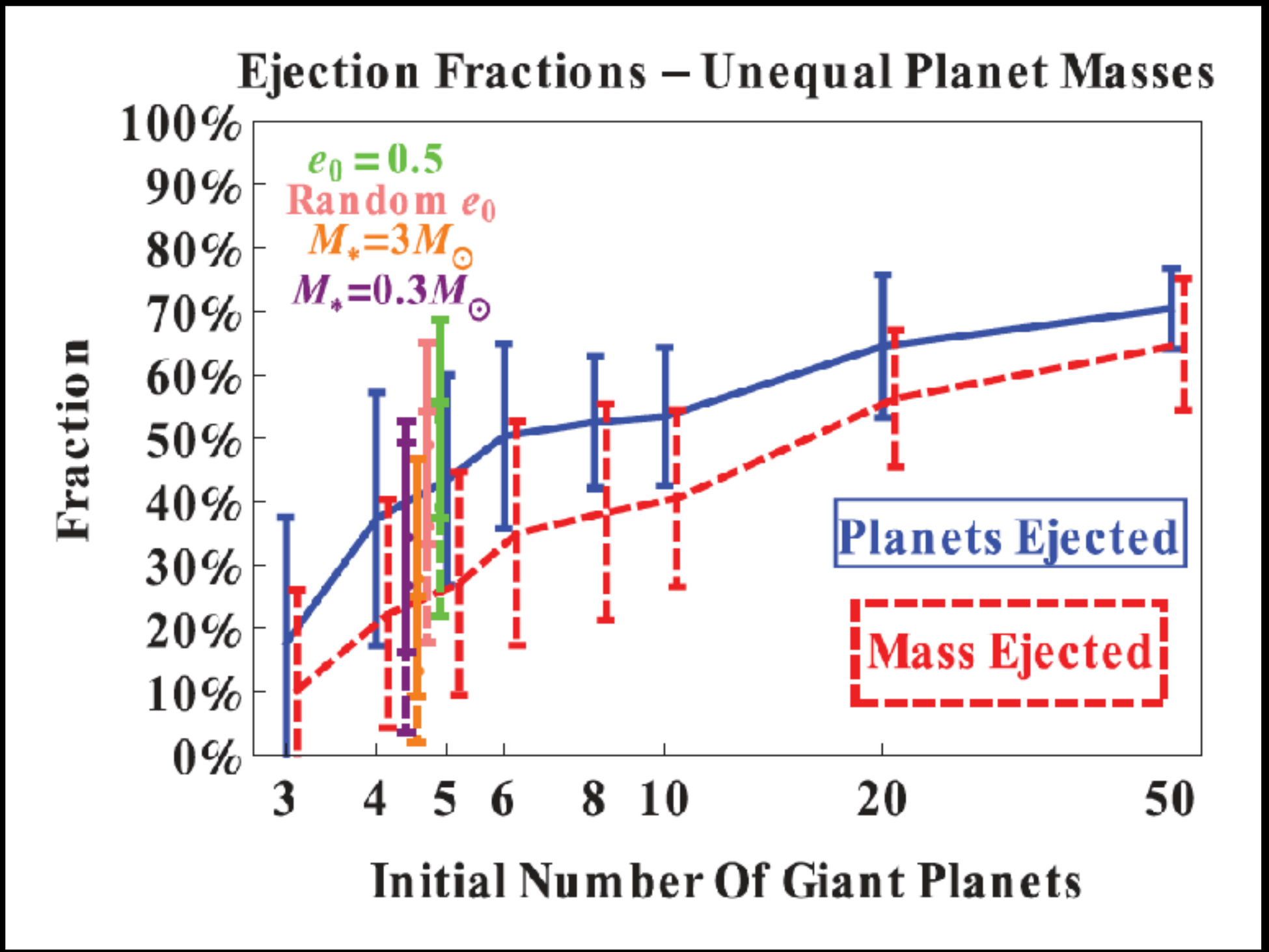
To fit eccentricity distribution, 75-95% of giant exoplanet systems must be survivors of instability

(Juric & Tremaine 2008; Chatterjee et al 2008; Raymond et al 2010)




**Raymond et al (2009)**

# Planet-planet scattering generates free-floating planets




Veras & Raymond (2012)

# ~100 free-floating planets found in Upper Scorpius

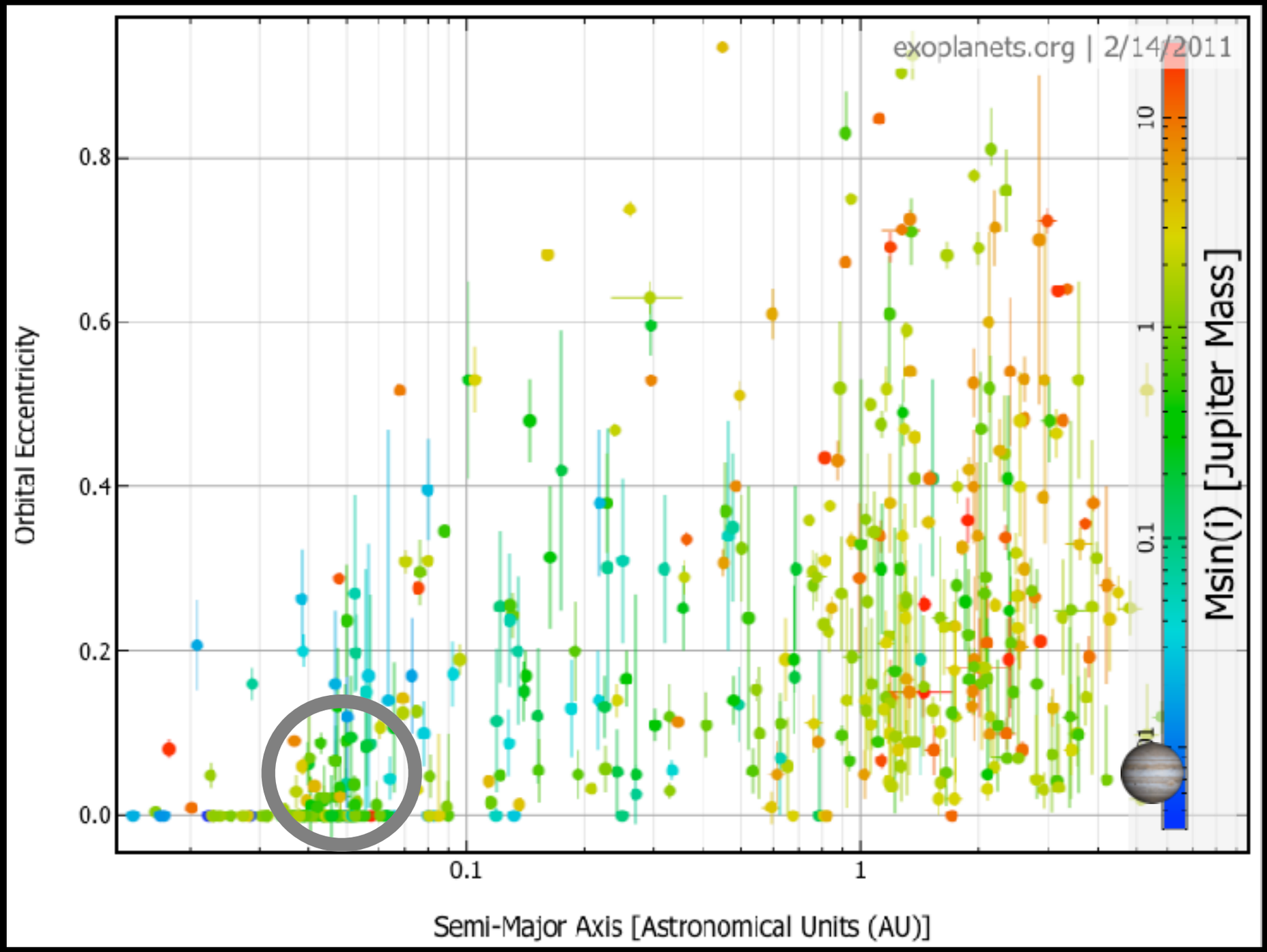
(plus hundreds in Orion with JWST)

Large enough sample to constrain origins: balance between ejected planets and tiny stars (bottom of IMF)

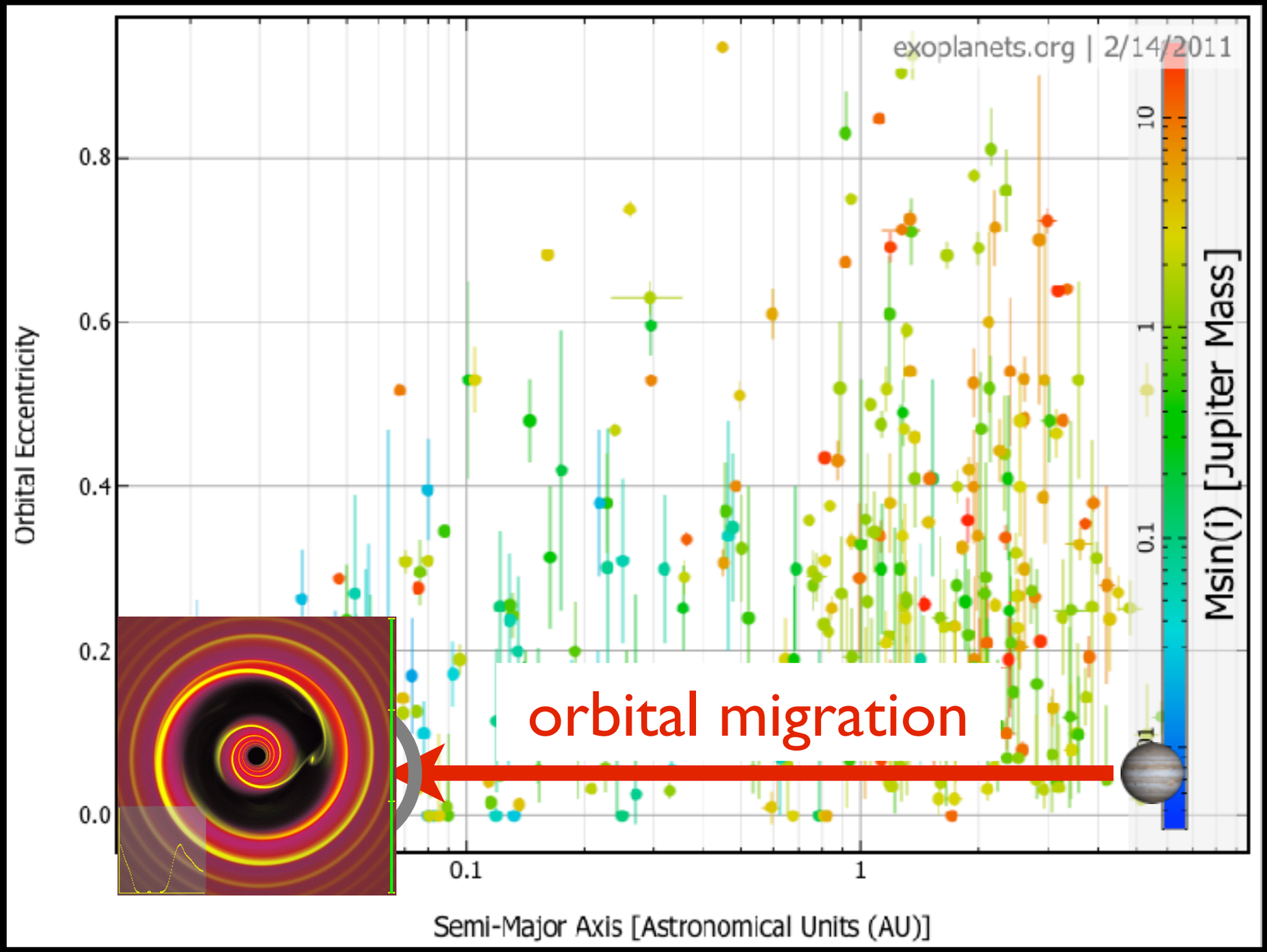


Miret-Roig et al (2022)

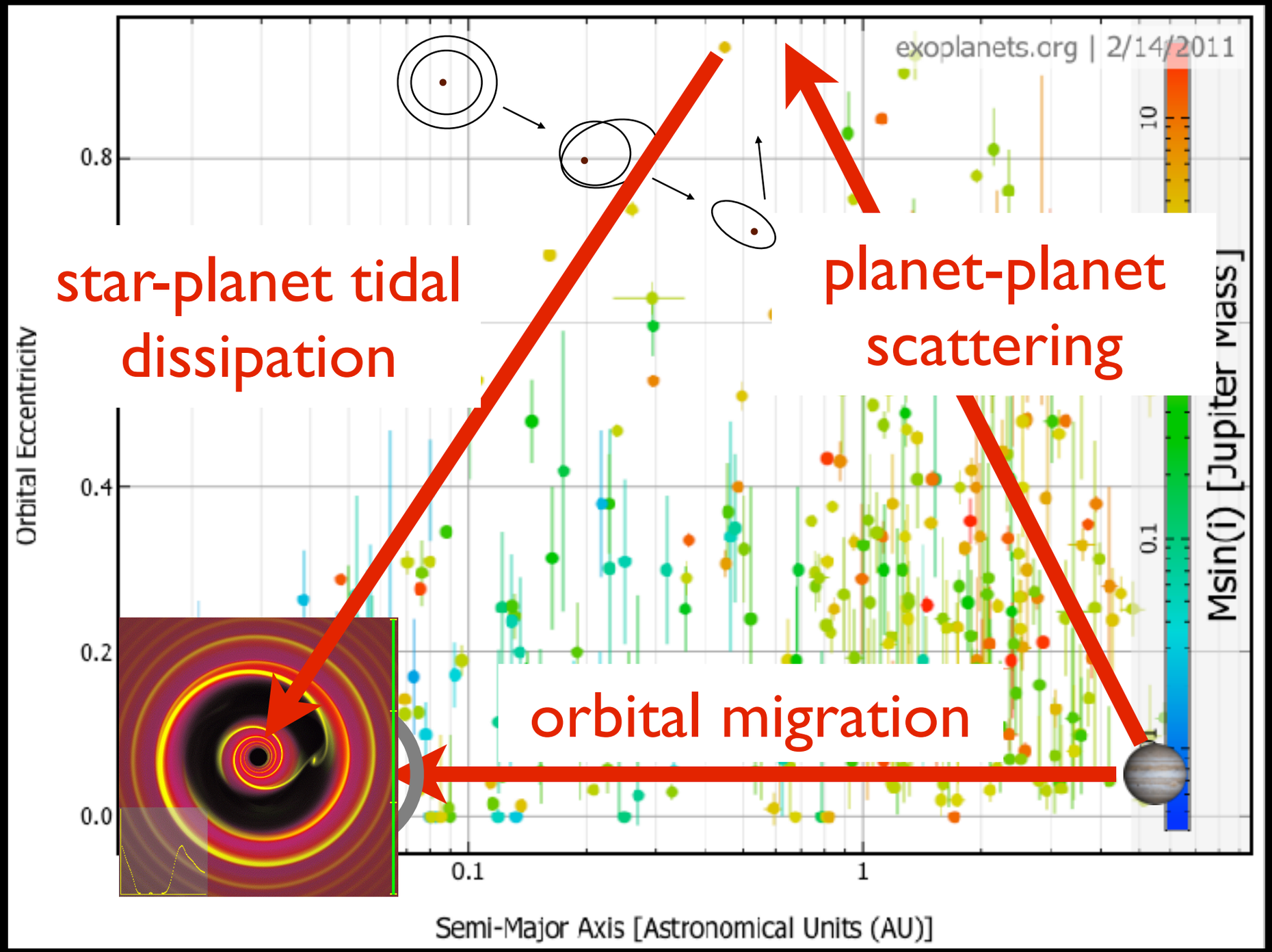
# Hot Jupiters



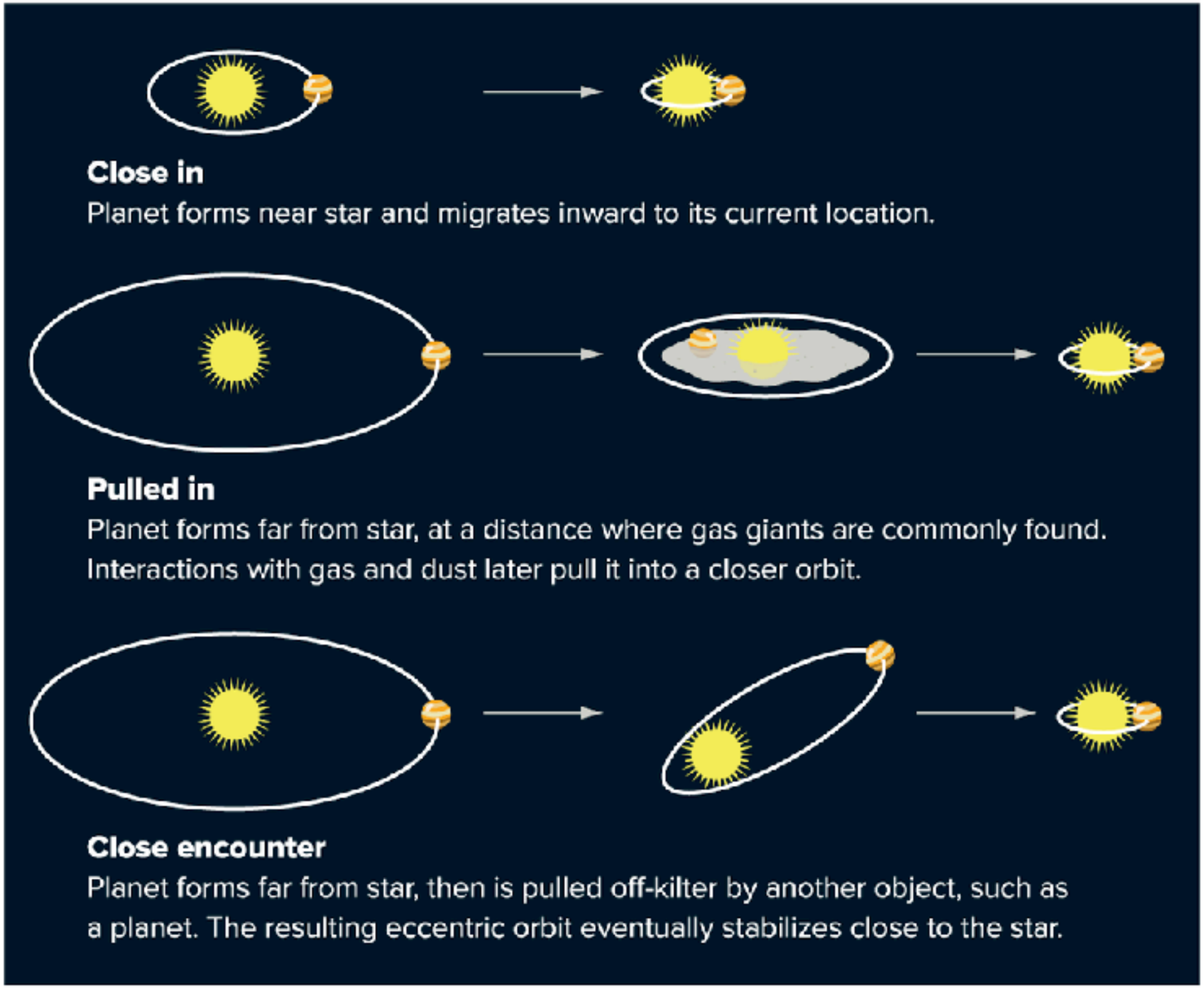
# Hot Jupiters



# Hot Jupiters



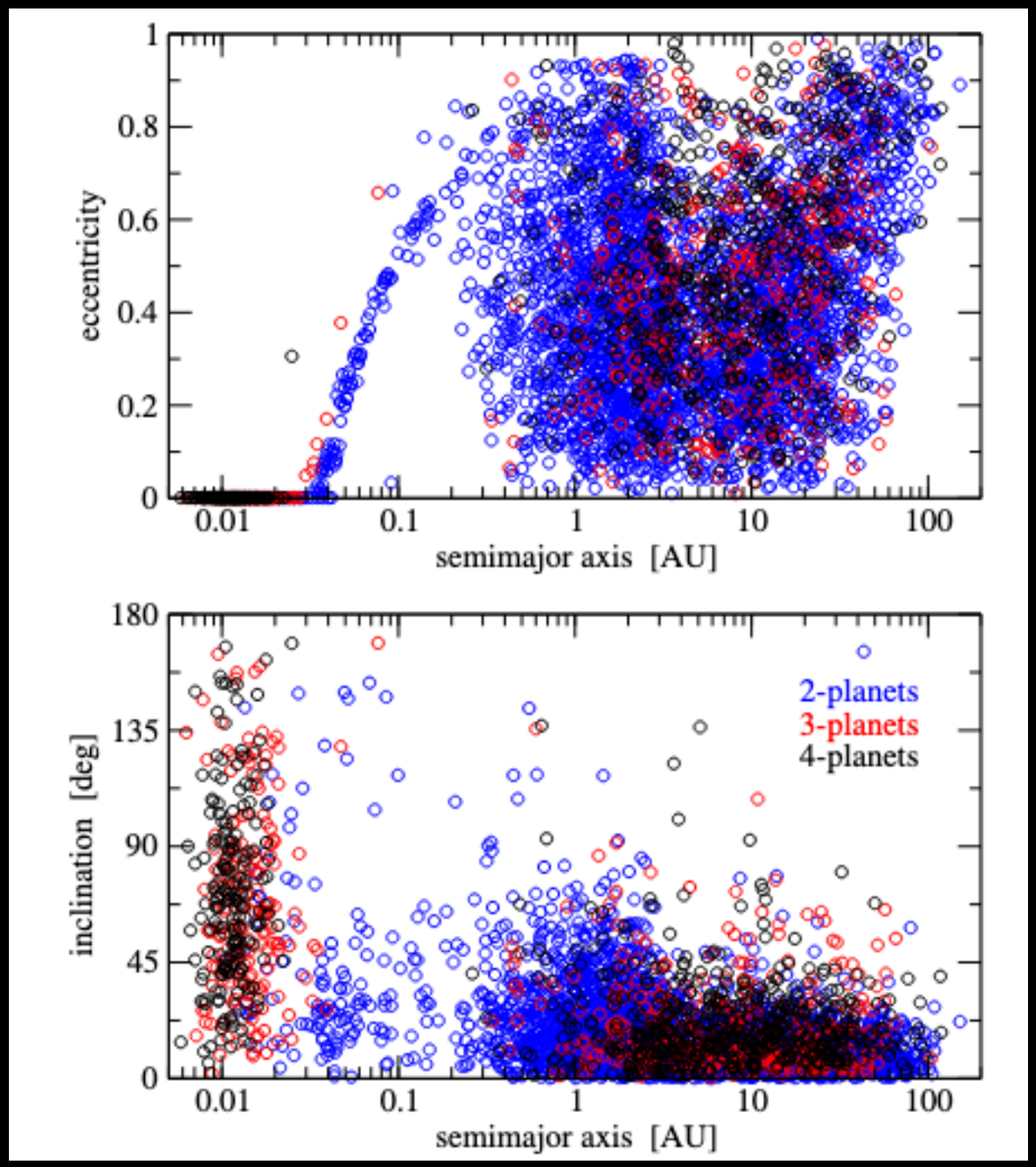
## Three origin theories for hot Jupiters




SOURCE: R.I. DAWSON AND J.A. JOHNSON / *AR ASTRONOMY AND ASTROPHYSICS* 2018 KNOWABLE MAGAZINE

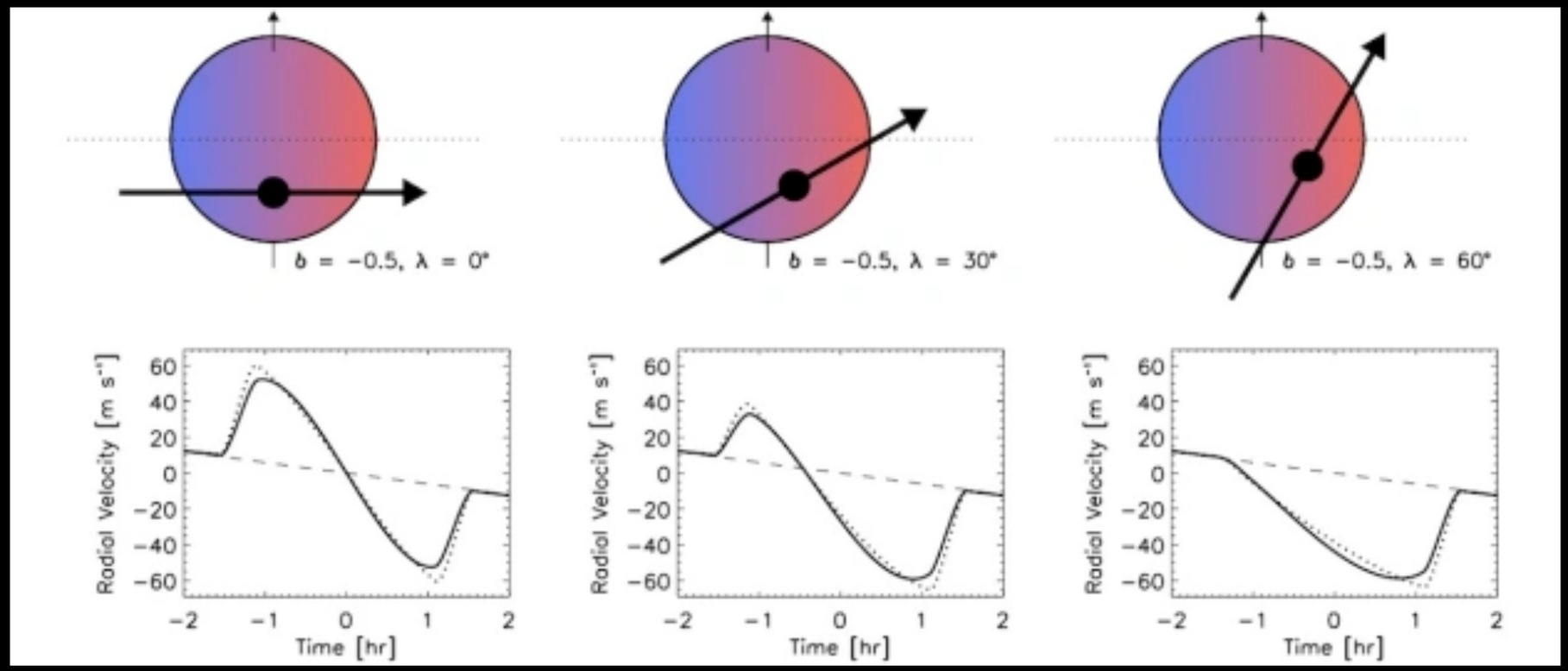
Dawson & Johnson (2018)

# Hot Jupiter formation from scattering + tides




Beaugé & Nesvorny (2012)

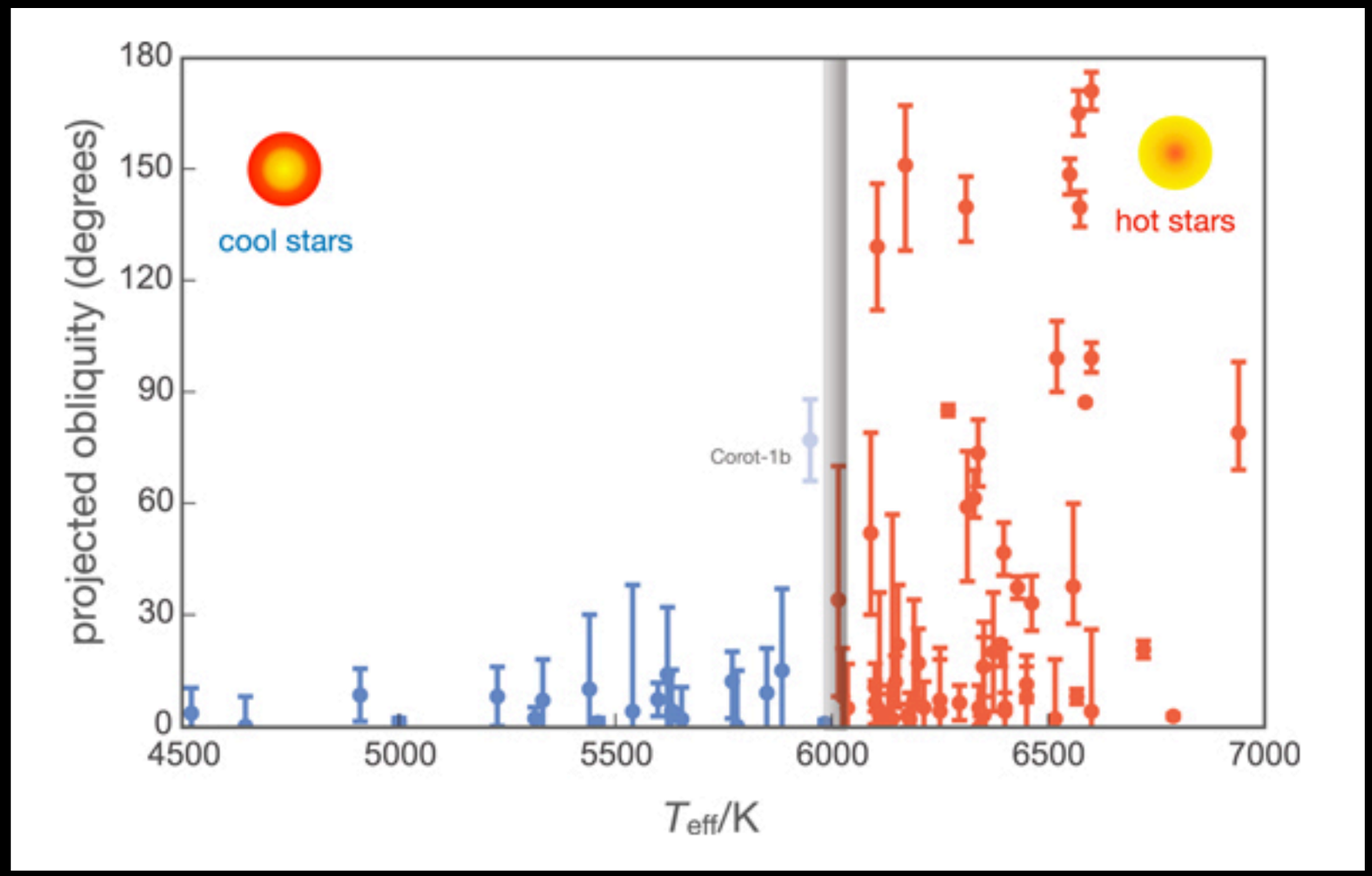
# How to tell hot Jupiter formation models apart?




source: wasp-planets.net

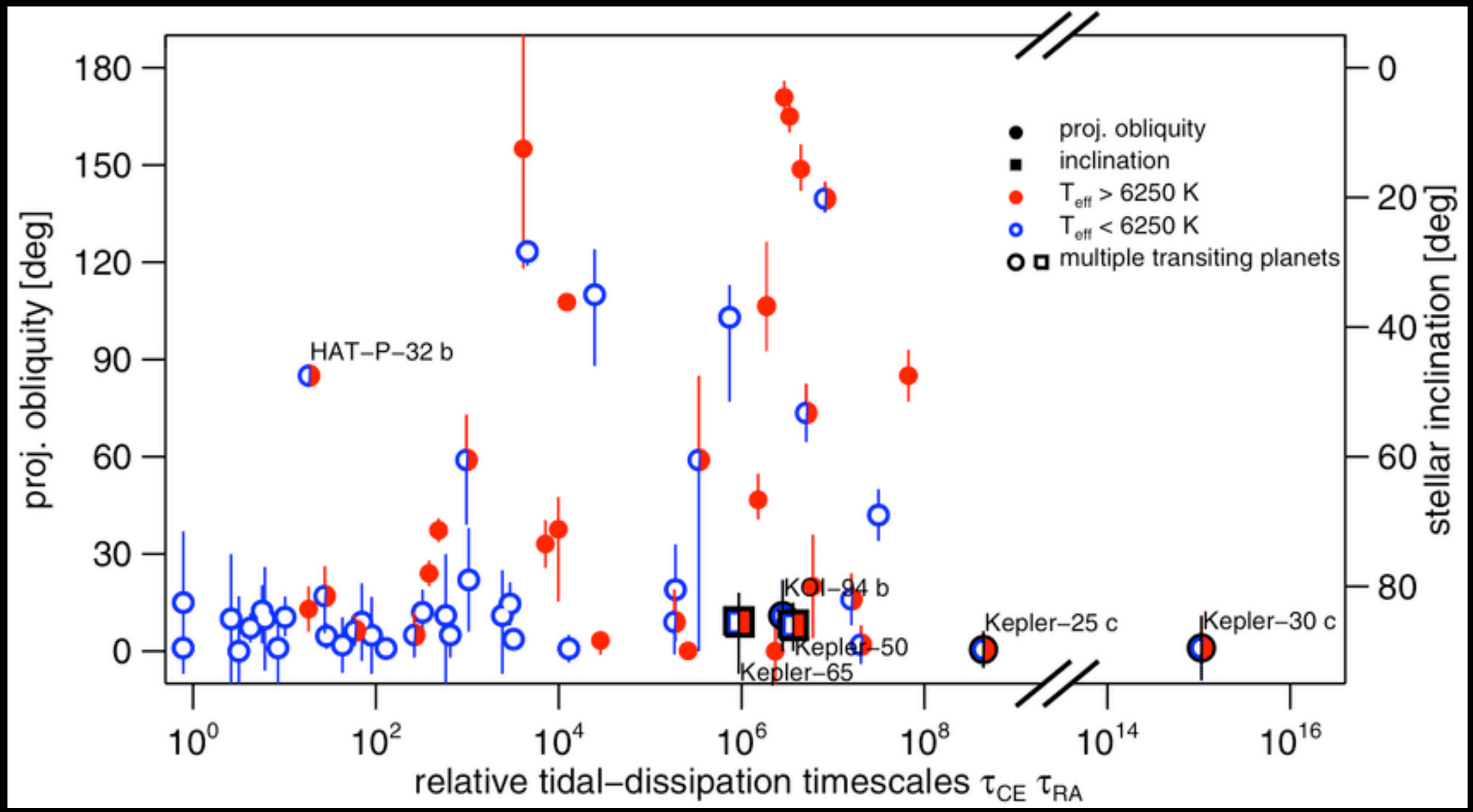
**Rossiter-McLaughlin effect**

# How to tell hot Jupiter formation models apart?




Spalding & Winn (2022)

# How to tell hot Jupiter formation models apart?




Addison et al (2014), after Albrecht et al (2012)

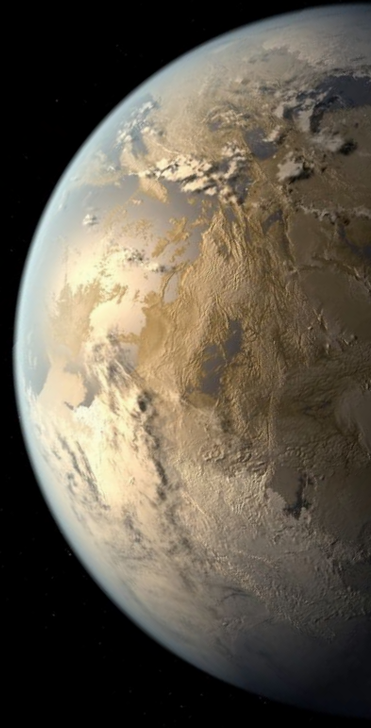
# Key processes in (exo)planet formation

## Super-Earths

- Planetesimal formation
- Embryo growth (pebble or planetesimal accretion)
- Migration
- Dynamical instability (leading to collisions)

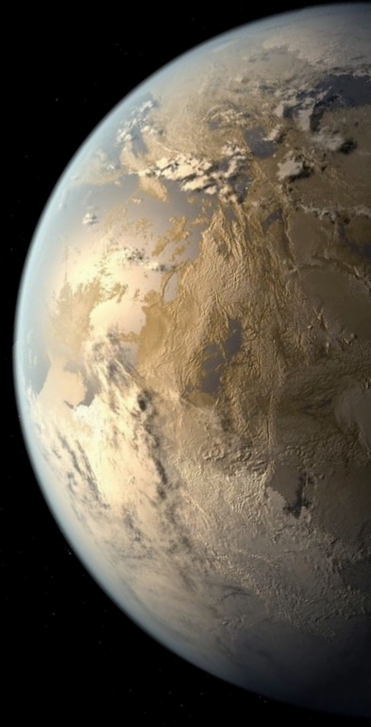
## Giant exoplanets

- Planetesimal formation
- Core growth (pebble accretion)
- Migration
- Dynamical instability (leading to ejection and eccentric orbits)



# Uncertainties

- Underlying structure of protoplanetary disks
- Planetesimal formation: where, when?
- Pebble vs. planetesimal accretion
- Influence of external perturbations



# Additional Resources

- Astrophysics of planet formation (excellent book by Phil Armitage)
- Planet Formation: key processes and global models (Raymond and Morbidelli, arXiv:2002.05756)
- The MOJO videos (with Morbidelli; YouTube)
- Protostars & Planets 7 chapters
- My blog (planetplanet.net)

