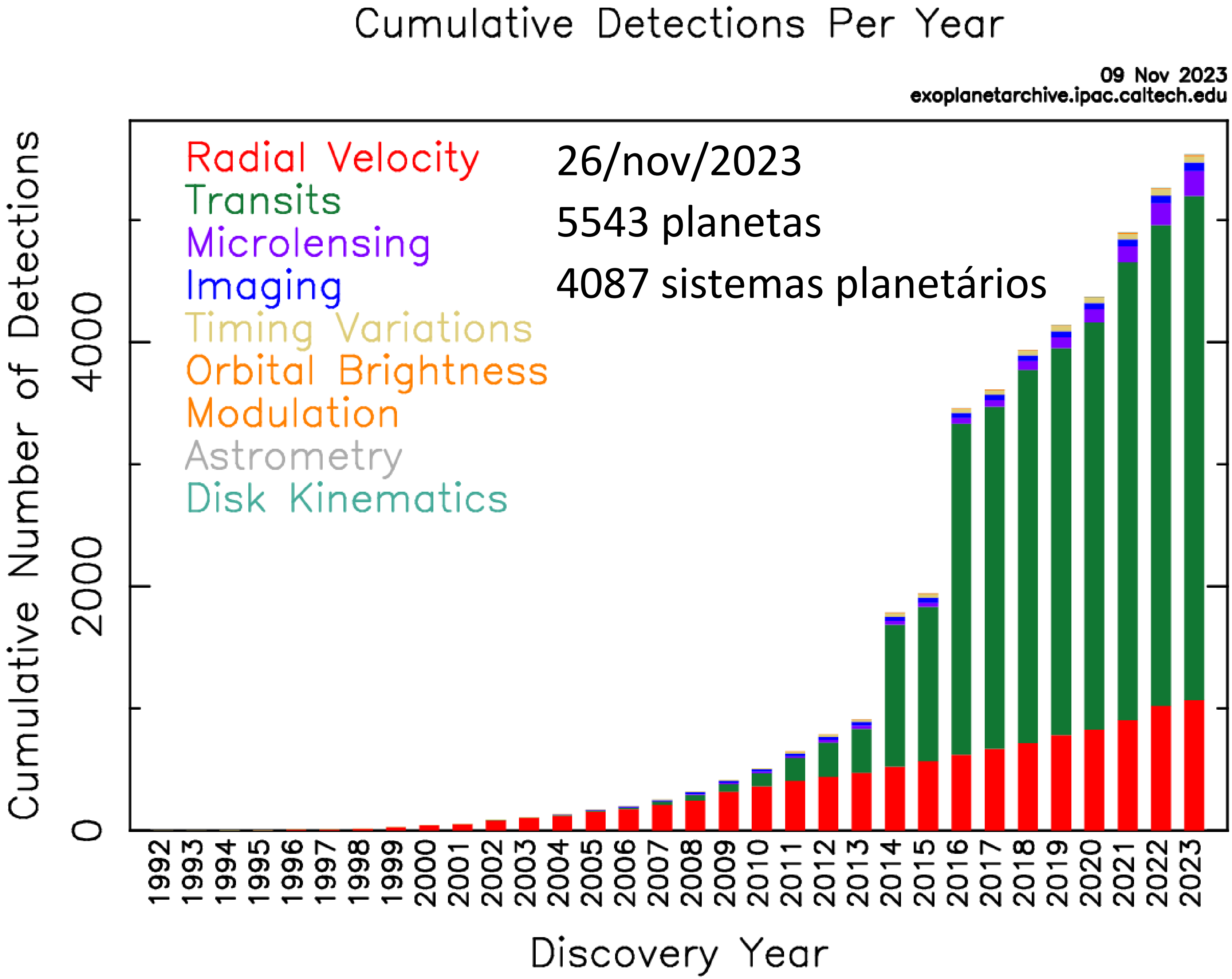
15. Diversidade de Sistemas Planetários

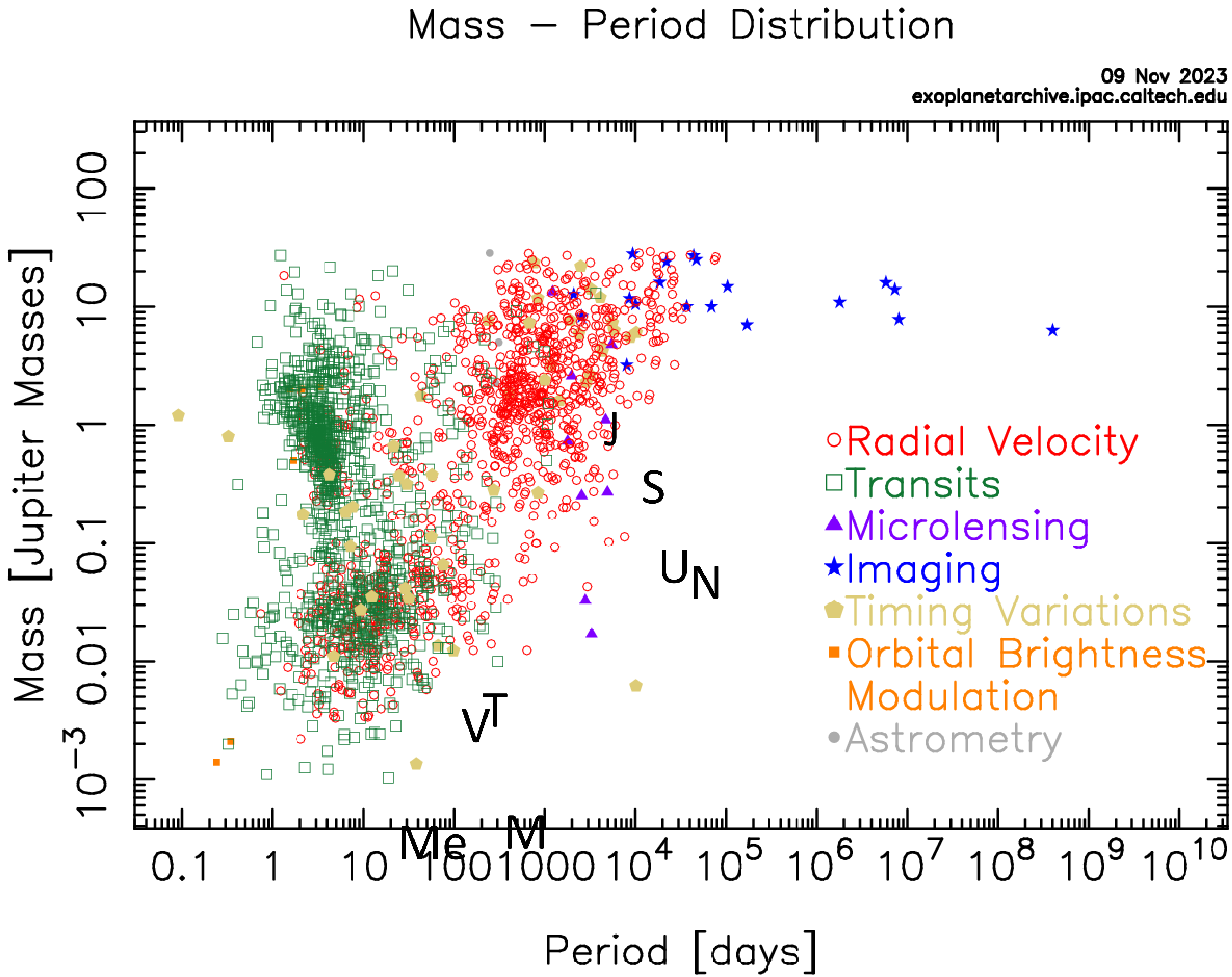
https://exoplanets.nasa.gov/news/1581/discovery-alert-a-record-haul-planet-count-hits-4000/

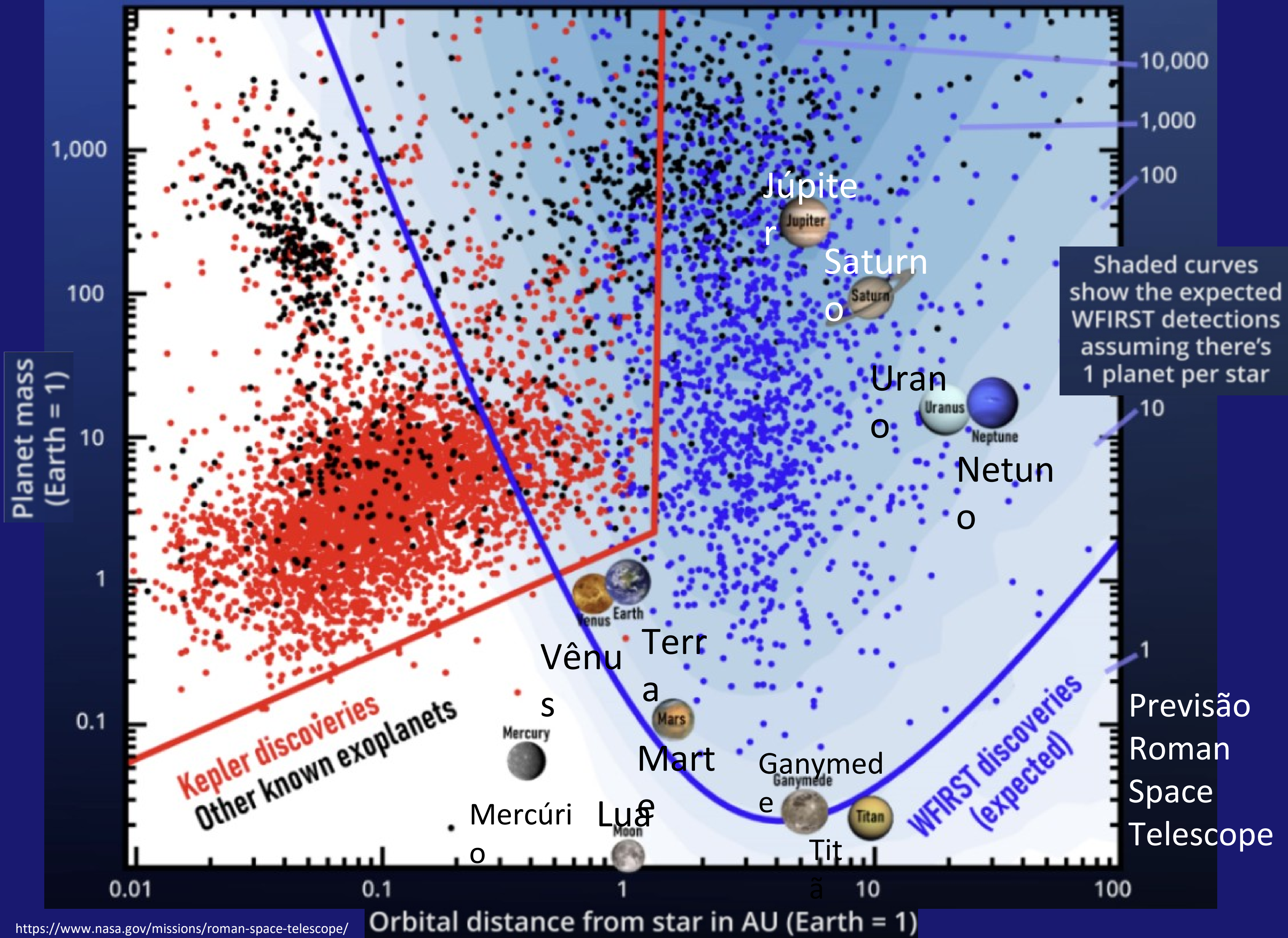
Prof. Jorge Meléndez

AGA0502, Planetas e Sistemas Planetários, IAG-USP

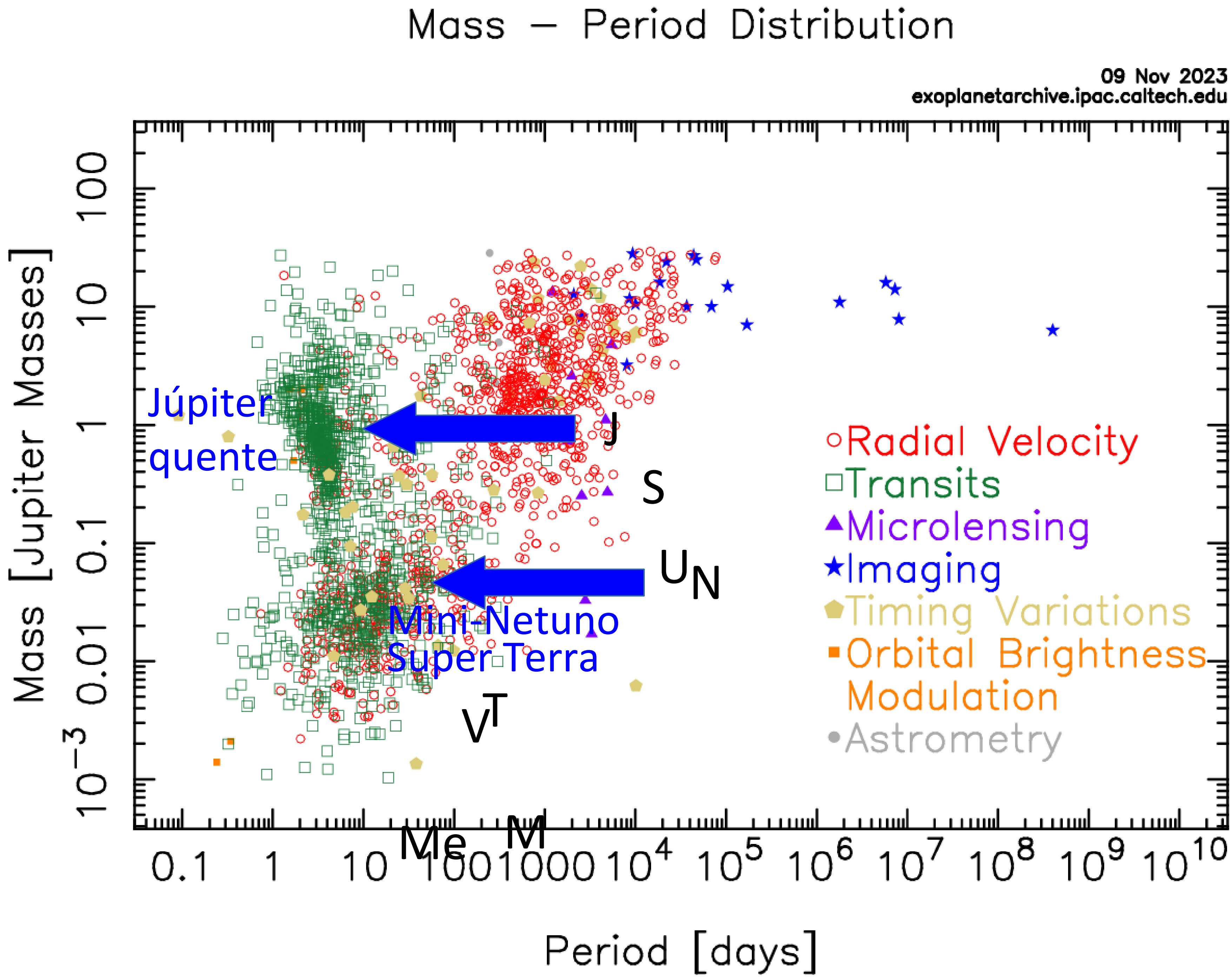


Cumulative Detections Per Year
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
26/nov/2023
5543 planetas
4087 sistemas planetários
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year

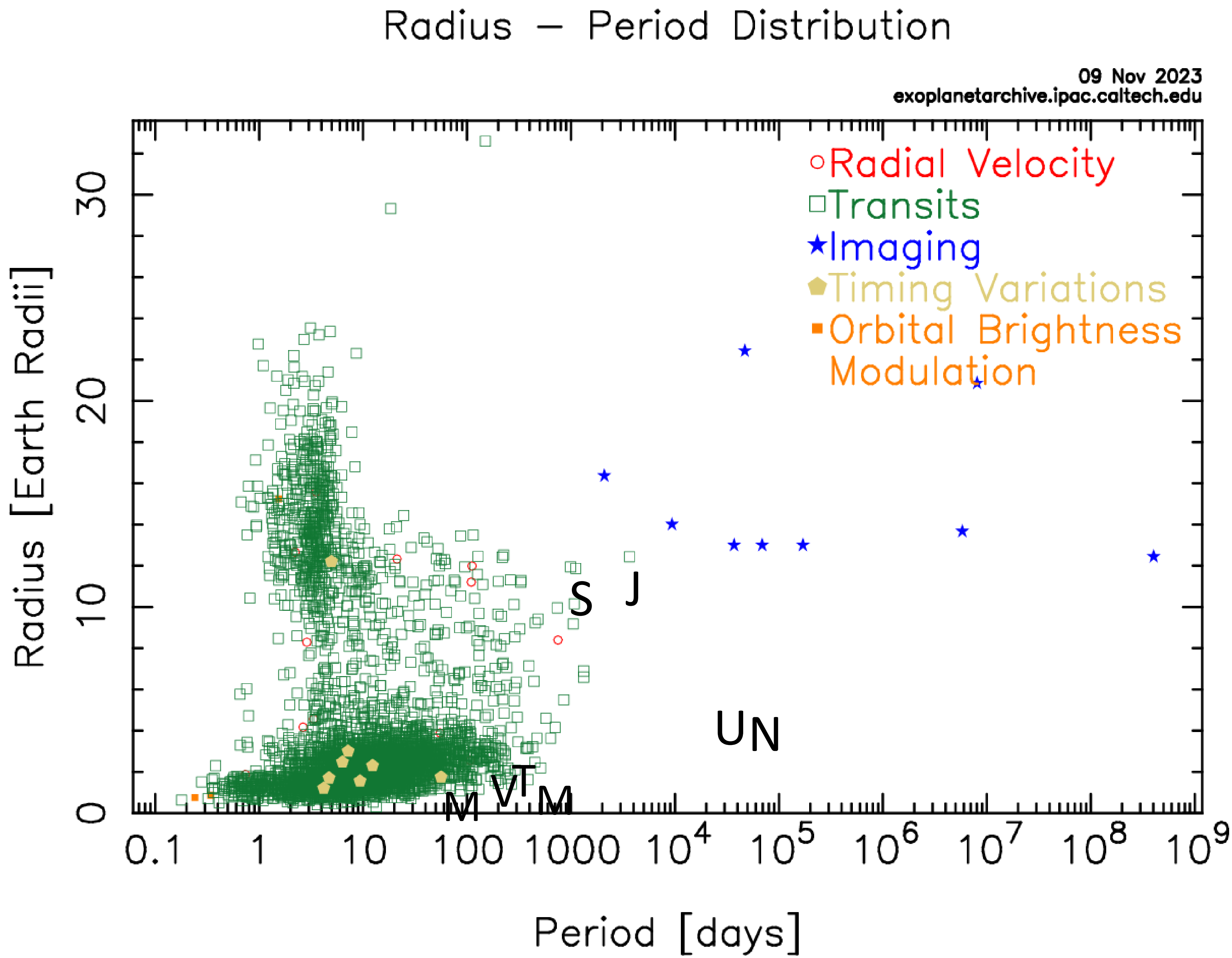

Mass – Period Distribution
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
Period [days]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry
J
S
U
N
V
T
Me
M



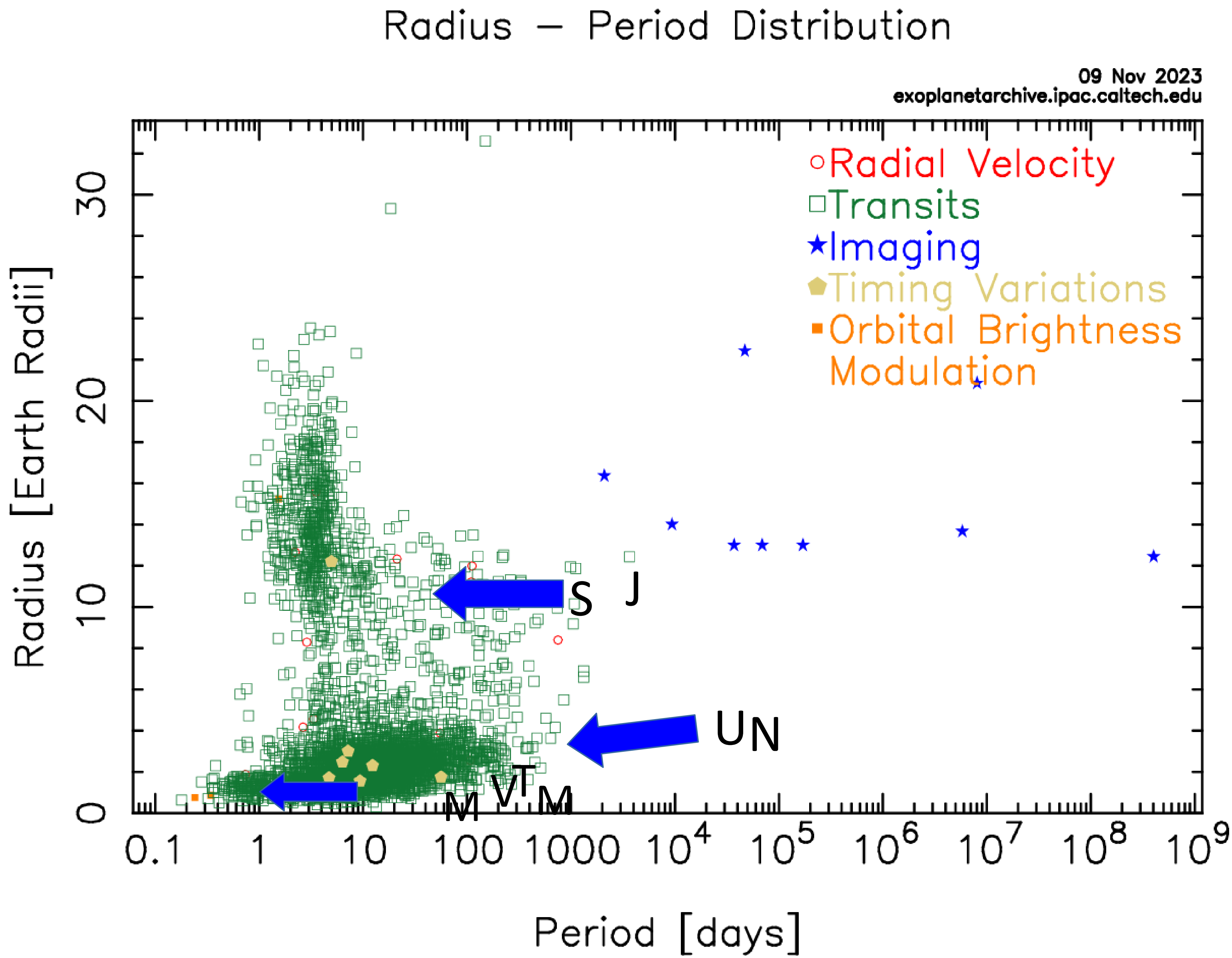
https://www.nasa.gov/missions/roman-space-telescope/warped-space-time-to-help-wfirst-find-exoplanets/



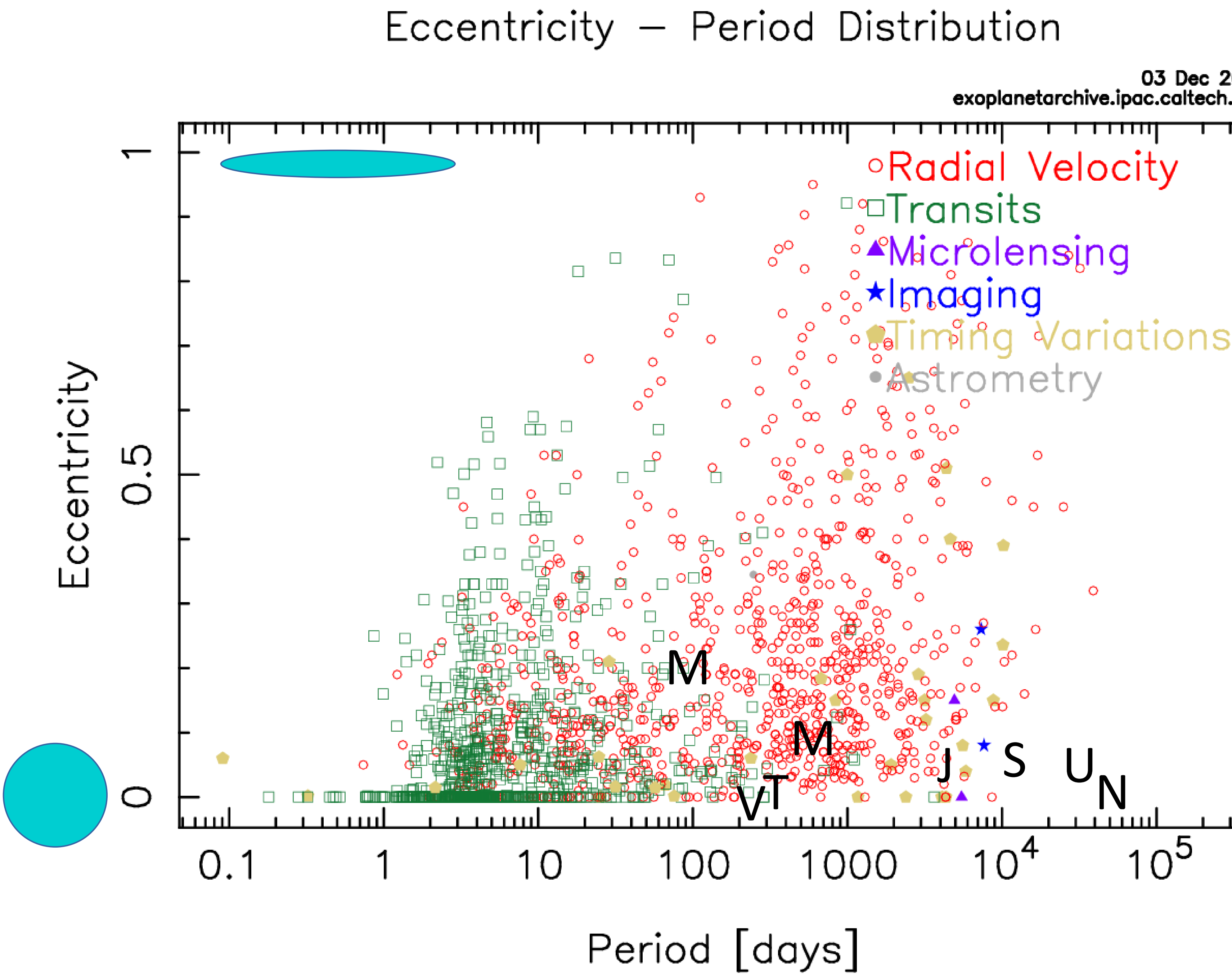
Mass – Period Distribution
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
Período
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]
Júpiter quente
Mini-Netuno
Super Terra
J
S
U
N
V
T
Me
M
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry



Radius – Period Distribution
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Imaging
Timing Variations
Orbital Brightness Modulation
Radius [Earth Radii]
0
10
20
30
Period [days]
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
M
V
T
M
S
J
U
N

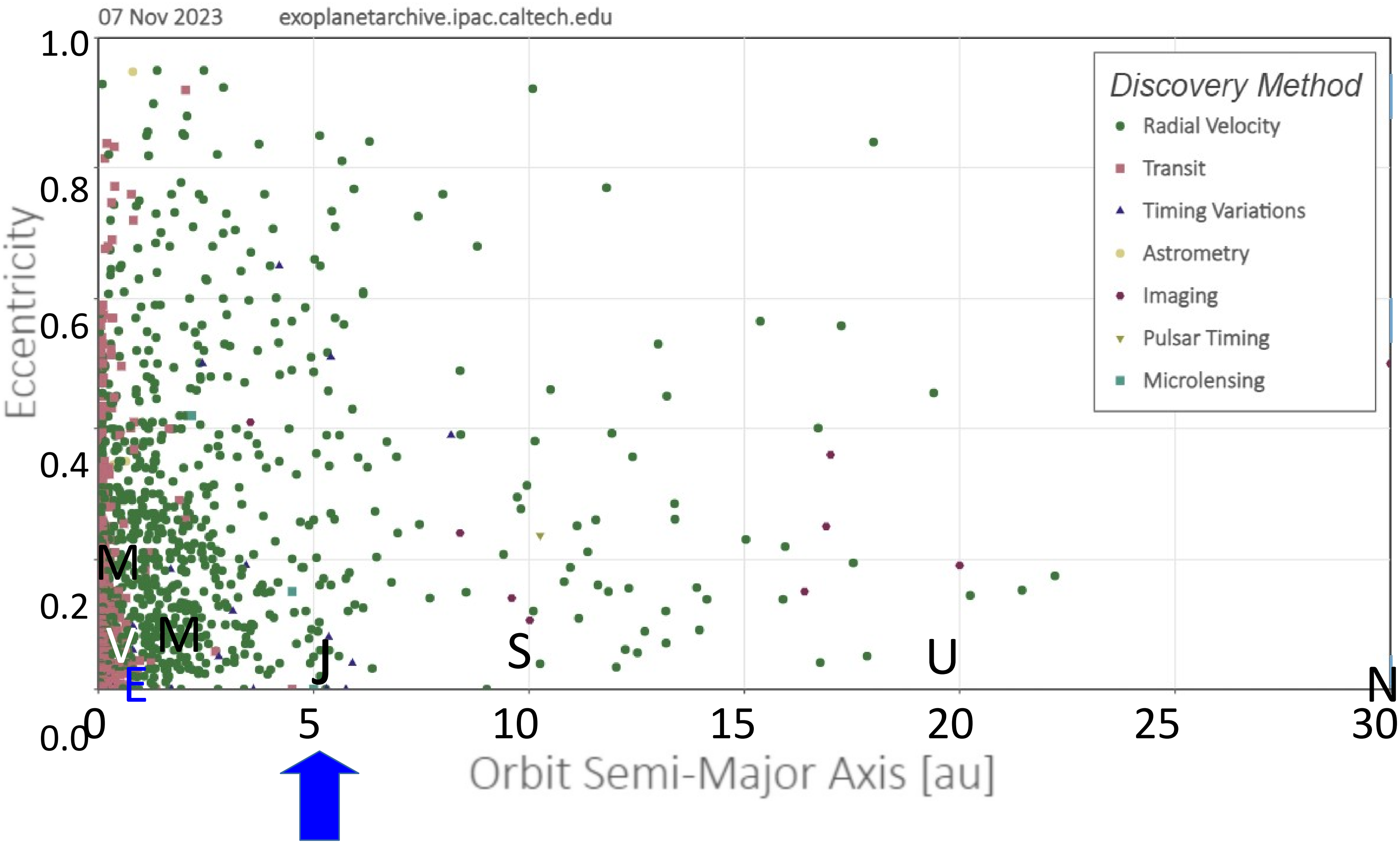


Radius – Period Distribution
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Imaging
Timing Variations
Orbital Brightness Modulation
Radius [Earth Radii]
0
10
20
30
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
Period [days]
S
J
U
N
M
V
T
M



Eccentricity – Period Distribution
03 Dec 2021
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Astrometry
Eccentricity
0
0.5
1
Period [days]
0.1
1
10
100
1000
10^4
10^5
M
M
V
T
J
S
U
N

Eccentricity – Semi-Major Axis distribution

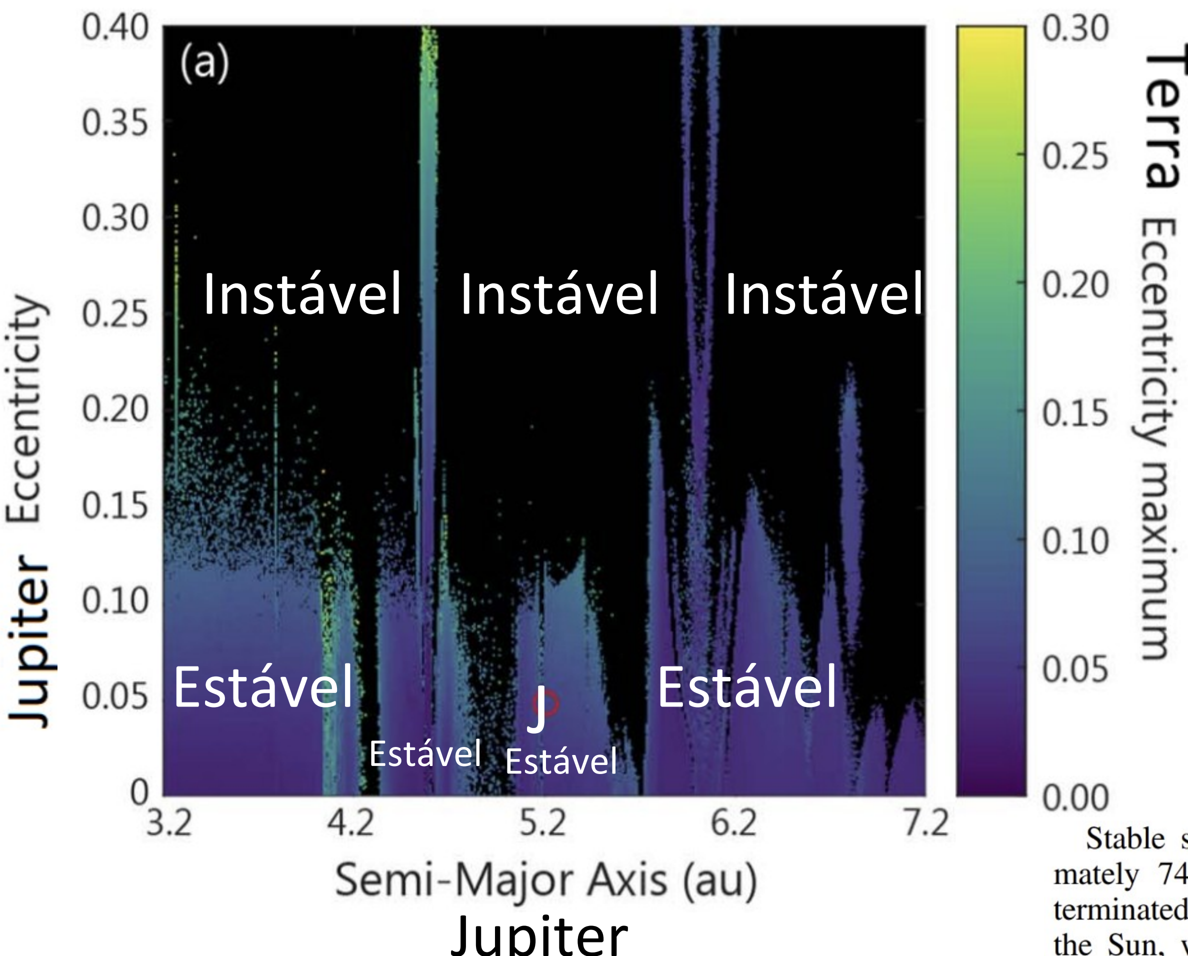


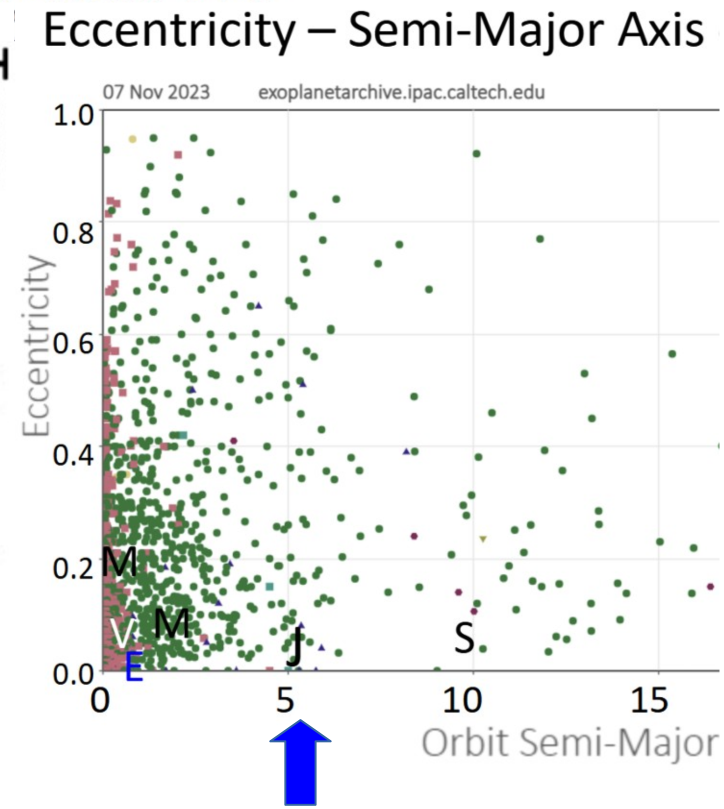
Qual o futuro da Terra se Júpiter tivesse outros valores de *a* e *e*?

THE ASTRONOMICAL JOURNAL, 164:130 (15pp), 2022 October https://doi.org/10.3847/1538-3881/ac87fd

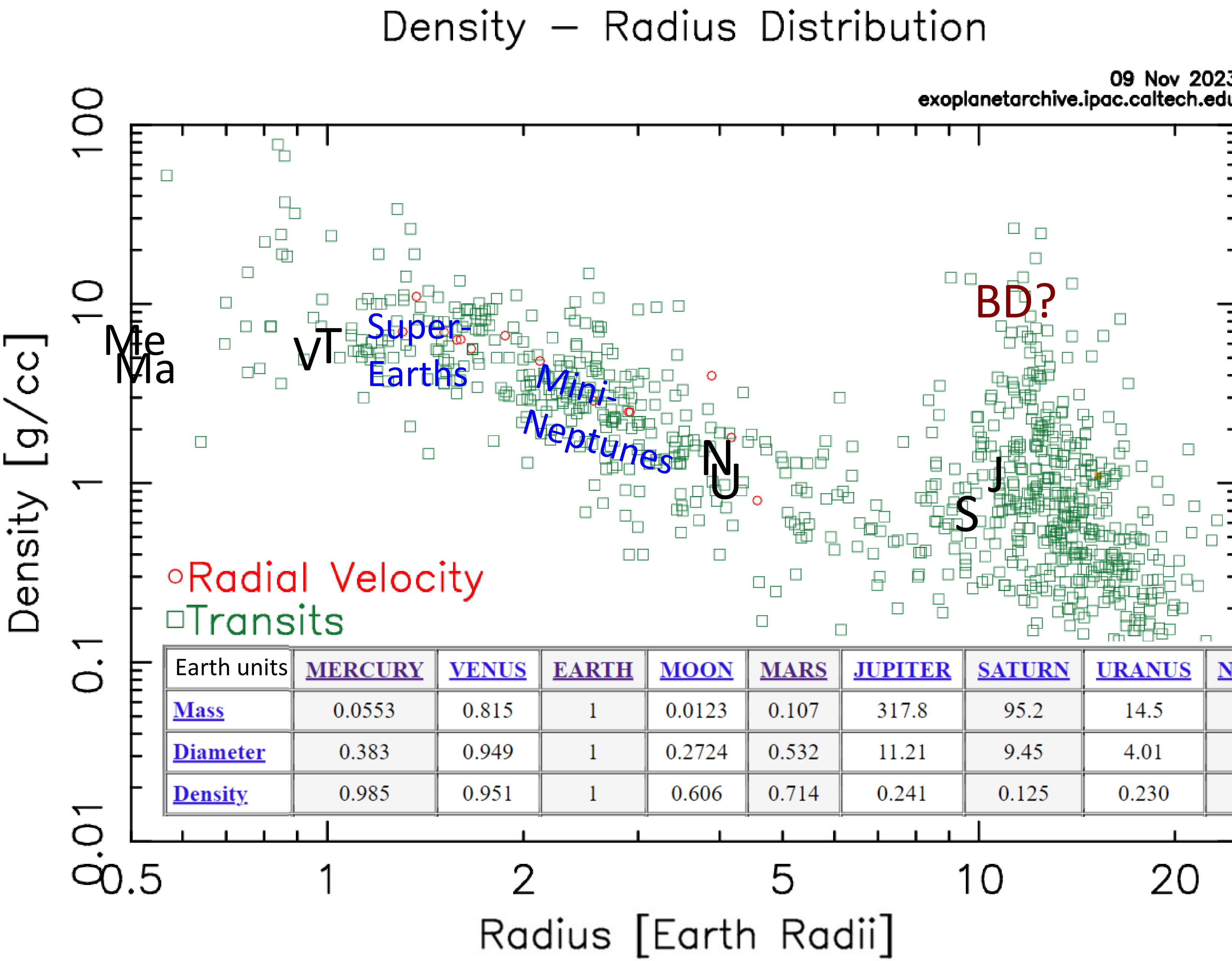
System Architecture and Planetary Obliquity: Implications for Long-term Habitability

Pam Vervoort[1], Jonathan Horner[2], Stephen R. Kane[1], Sandra Kirtland Turner[1], and James B. Gilmore[3]
[1] Department of Earth and Planetary Sciences, University of California, Riverside, CA, 92521, USA; pam.vervoort@email.ucr.edu

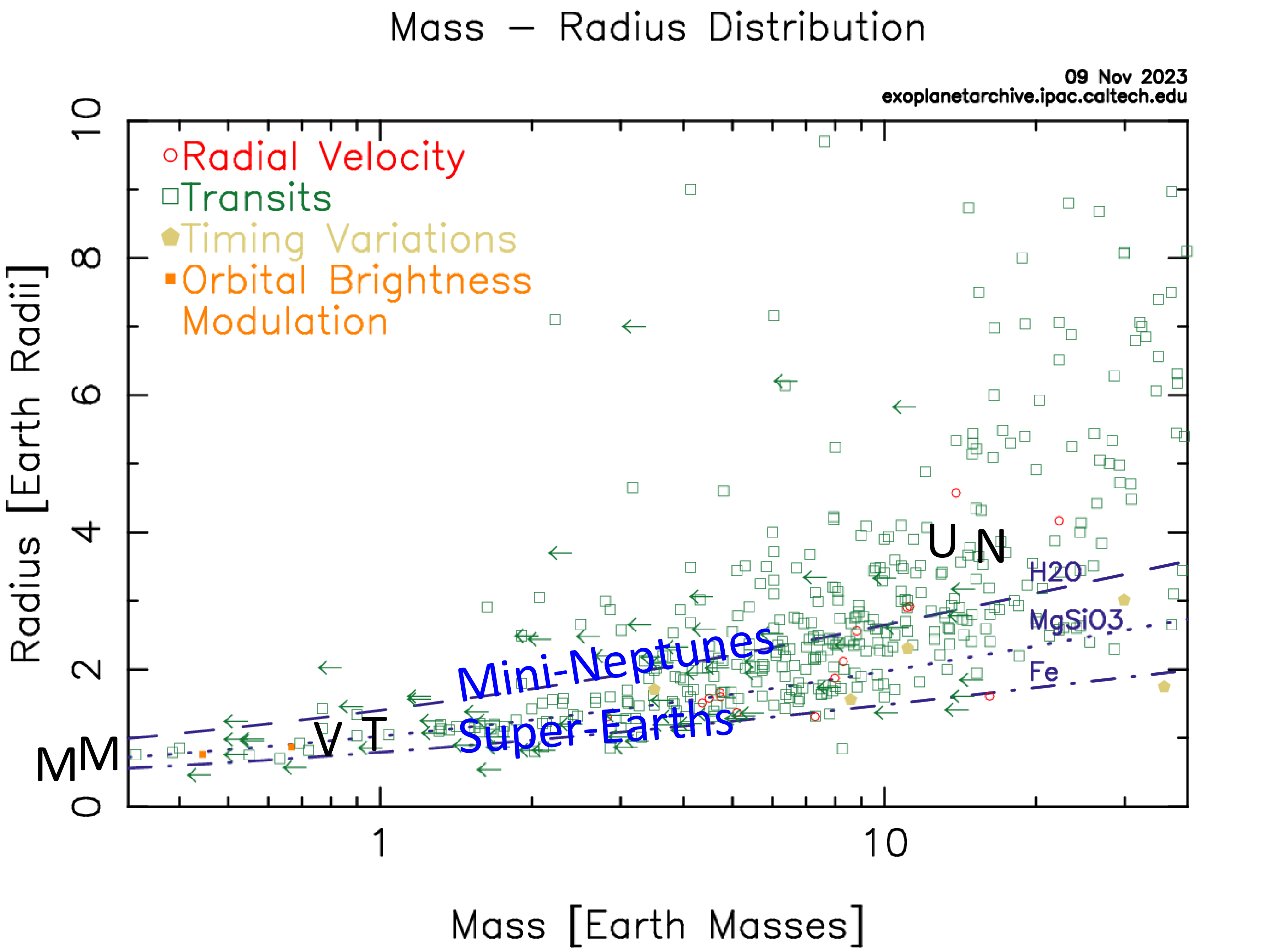


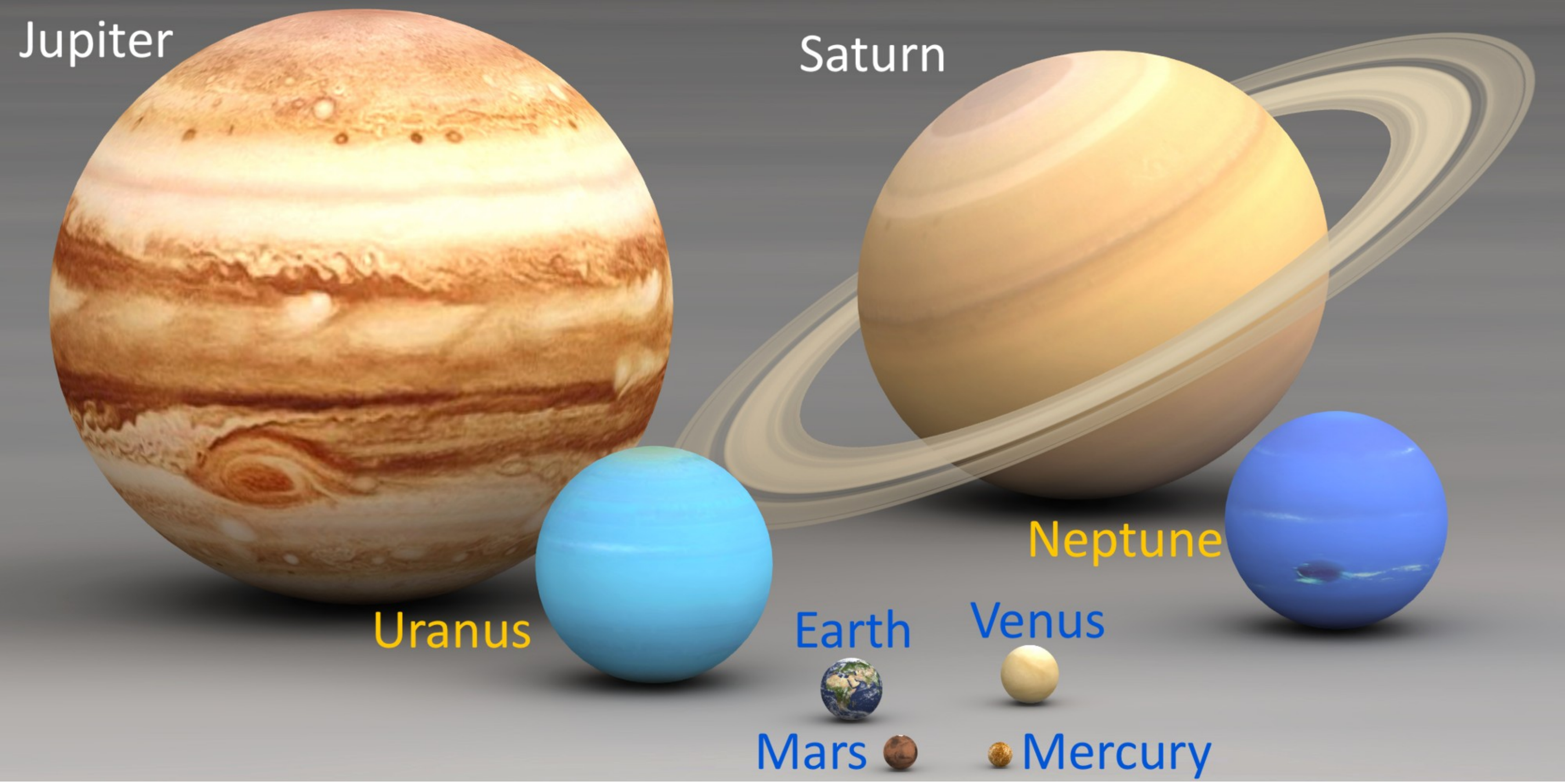


Stable simulations were integrated over 10 Myr. Approximately 74% of the simulations were deemed unstable and terminated prematurely when any of the planets collided with the Sun, with each other, or reached a heliocentric distance of 40 au.



Earth units	MERCURY	VENUS	EARTH	MOON	MARS	JUPITER	SATURN	URANUS	NEPTUNE
Mass	0.0553	0.815	1	0.0123	0.107	317.8	95.2	14.5	17.1
Diameter	0.383	0.949	1	0.2724	0.532	11.21	9.45	4.01	3.88
Density	0.985	0.951	1	0.606	0.714	0.241	0.125	0.230	0.297


Mass – Radius Distribution
09 Nov 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Timing Variations
Orbital Brightness Modulation
Radius [Earth Radii]
Mass [Earth Masses]
0
2
4
6
8
10
1
10
H2O
MgSiO3
Fe
U
N
V
T
M
M
Mini-Neptunes
Super-Earths



Solar system:

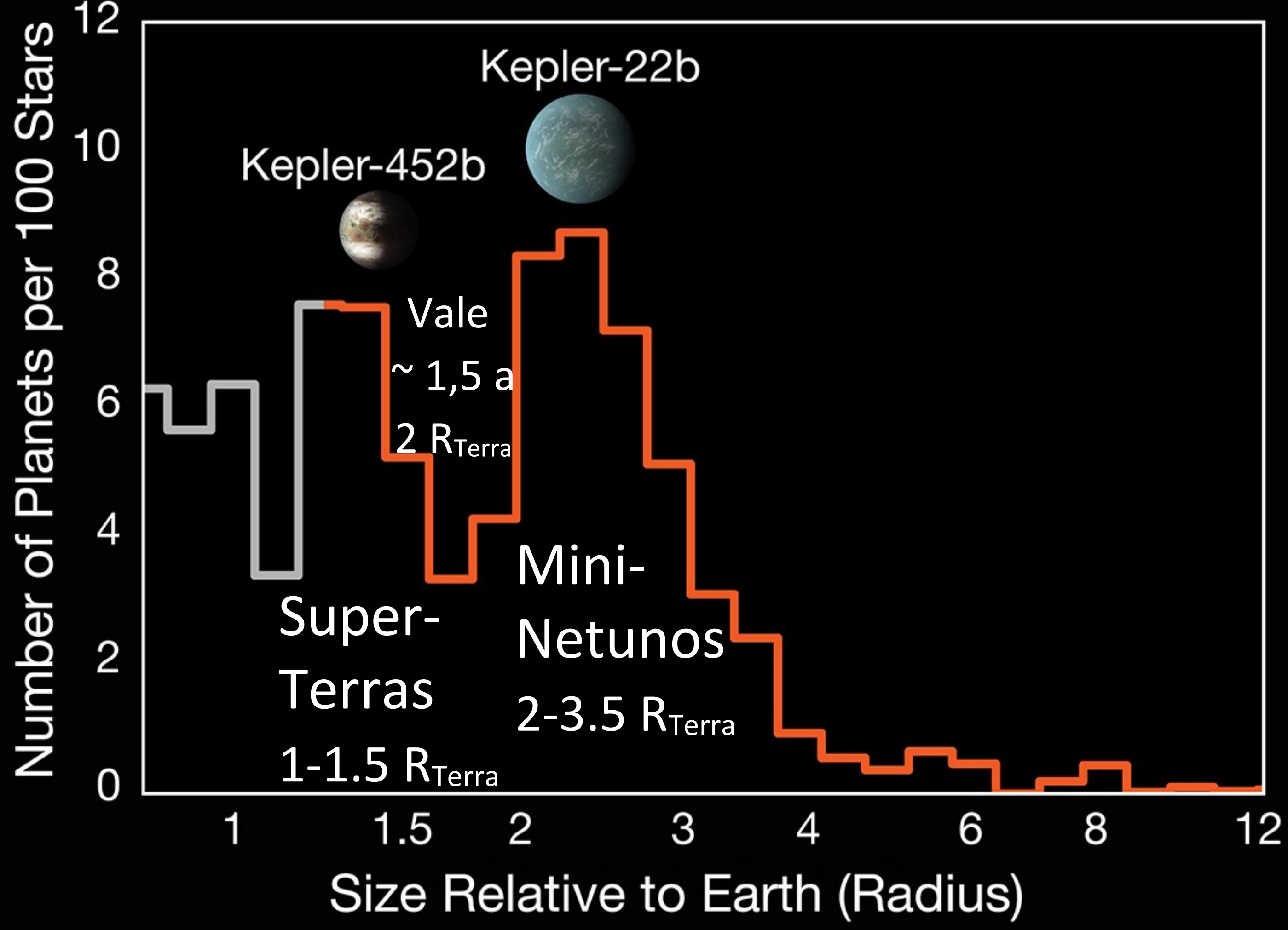
- Jupiters
- Neptunes
- Earths

Other systems may host:

- Hot-Jupiters
- Mini-Neptunes/Water worlds
- Super-Earths

http://www.lesud.com/lesud-astronomy_pageid81.html

Small Planets Come in Two Sizes

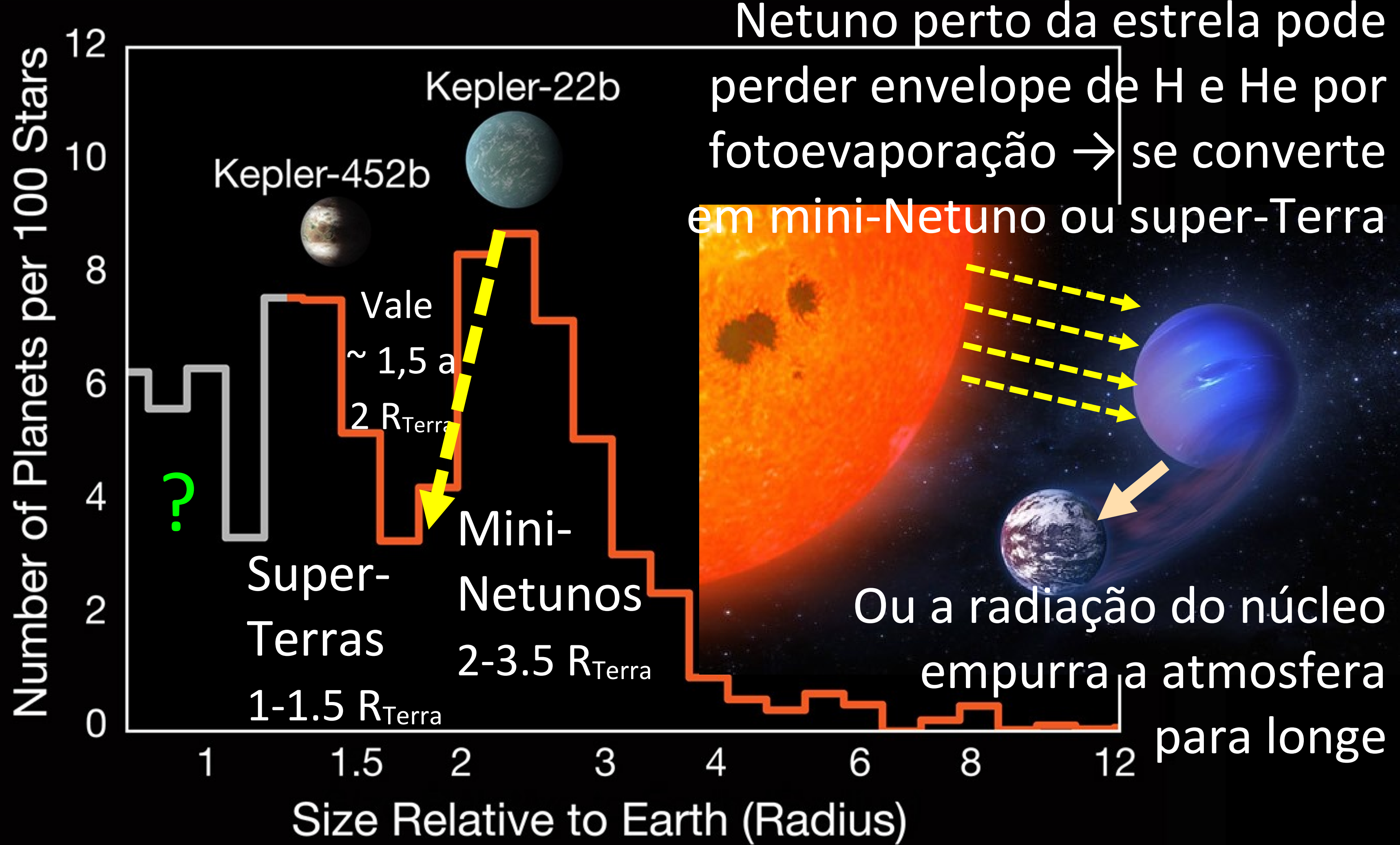


Benjamin Fulton et al. 2017

https://www.nasa.gov/image-feature/ames/small-planets-come-in-two-sizes

Small Planets Come in Two Sizes

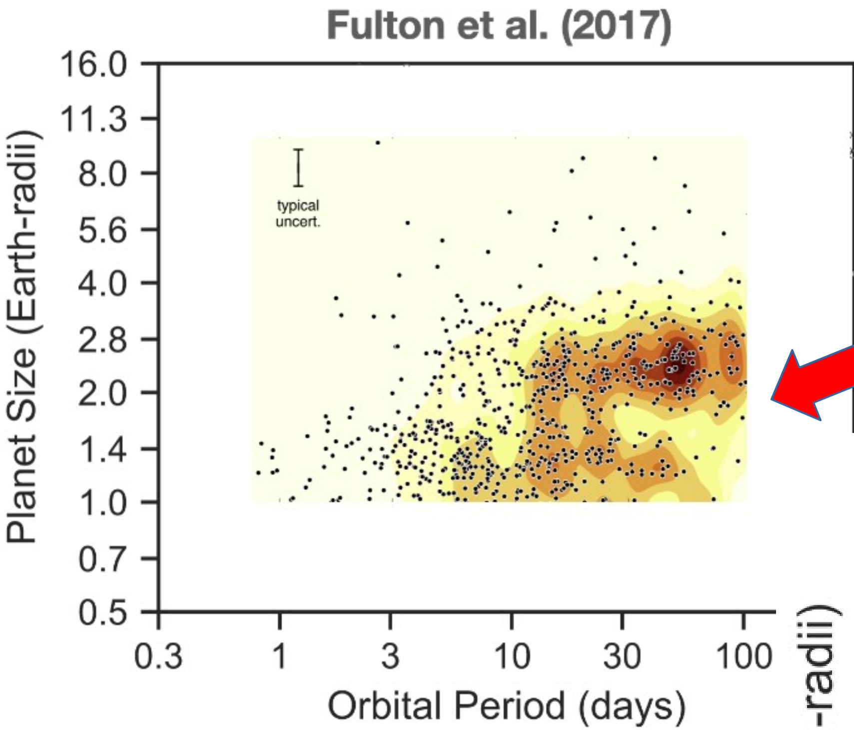
Netuno perto da estrela pode perder envelope de H e He por fotoevaporação → se converte em mini-Netuno ou super-Terra



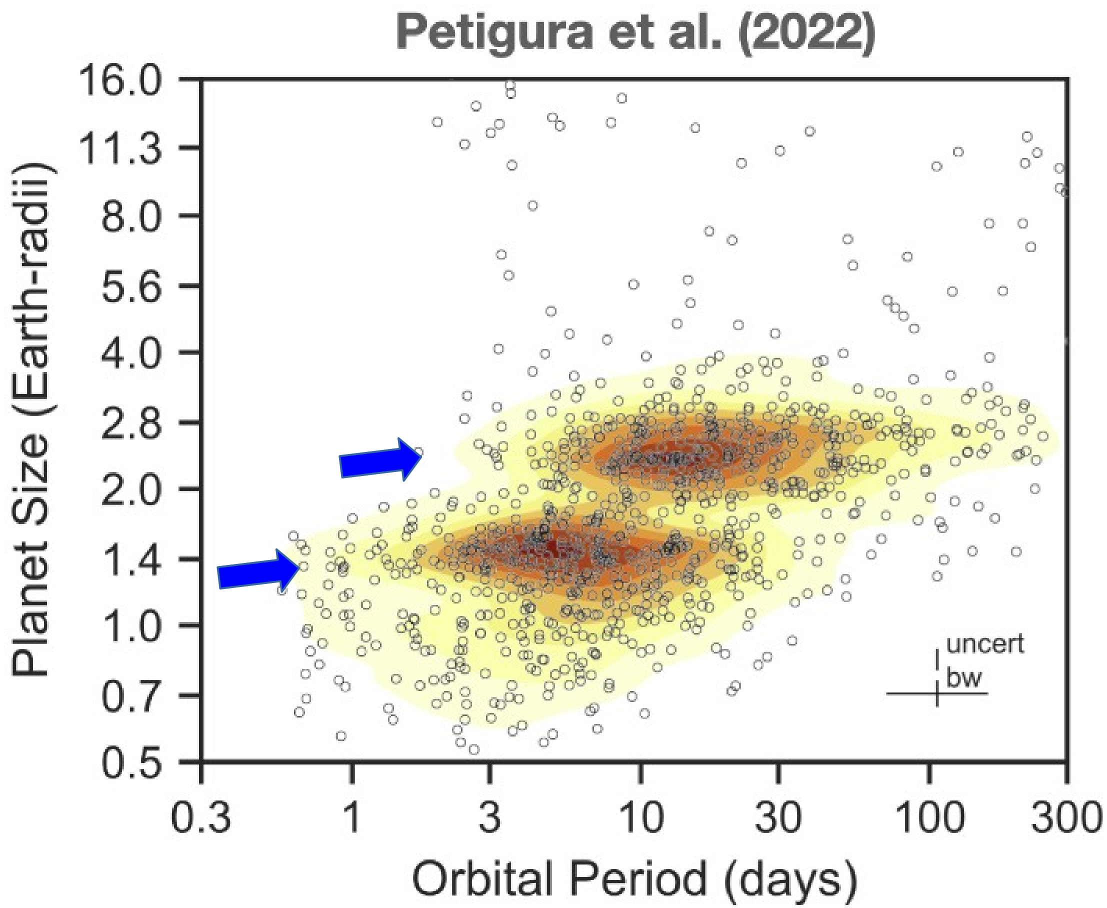
Ou a radiação do núcleo empurra a atmosfera para longe

Benjamin Fulton et al. 2017

https://www.nasa.gov/image-feature/ames/small-planets-come-in-two-sizes



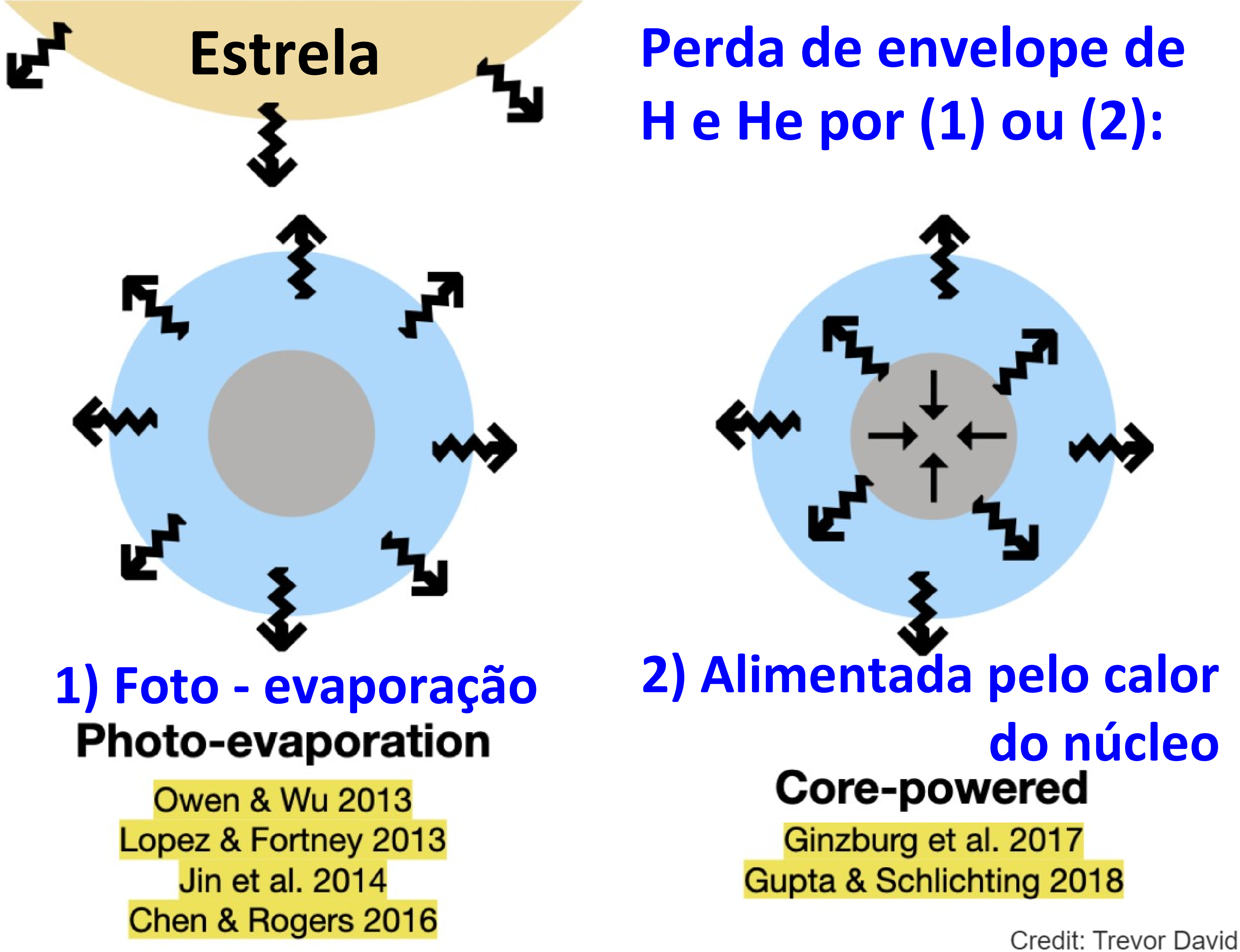
Em 2017, dados insuficientes, especialmente para super-Terras



Melhora nos dados em 2022 permite ver mais claramente a separação entre **mini-Netunos** e **super-Terras**

https://www.erikpetigura.com/post/how-stars-sculpt-the-super-earth-sub-neptune-dichotomy

Perda de envelope de H e He por (1) ou (2):

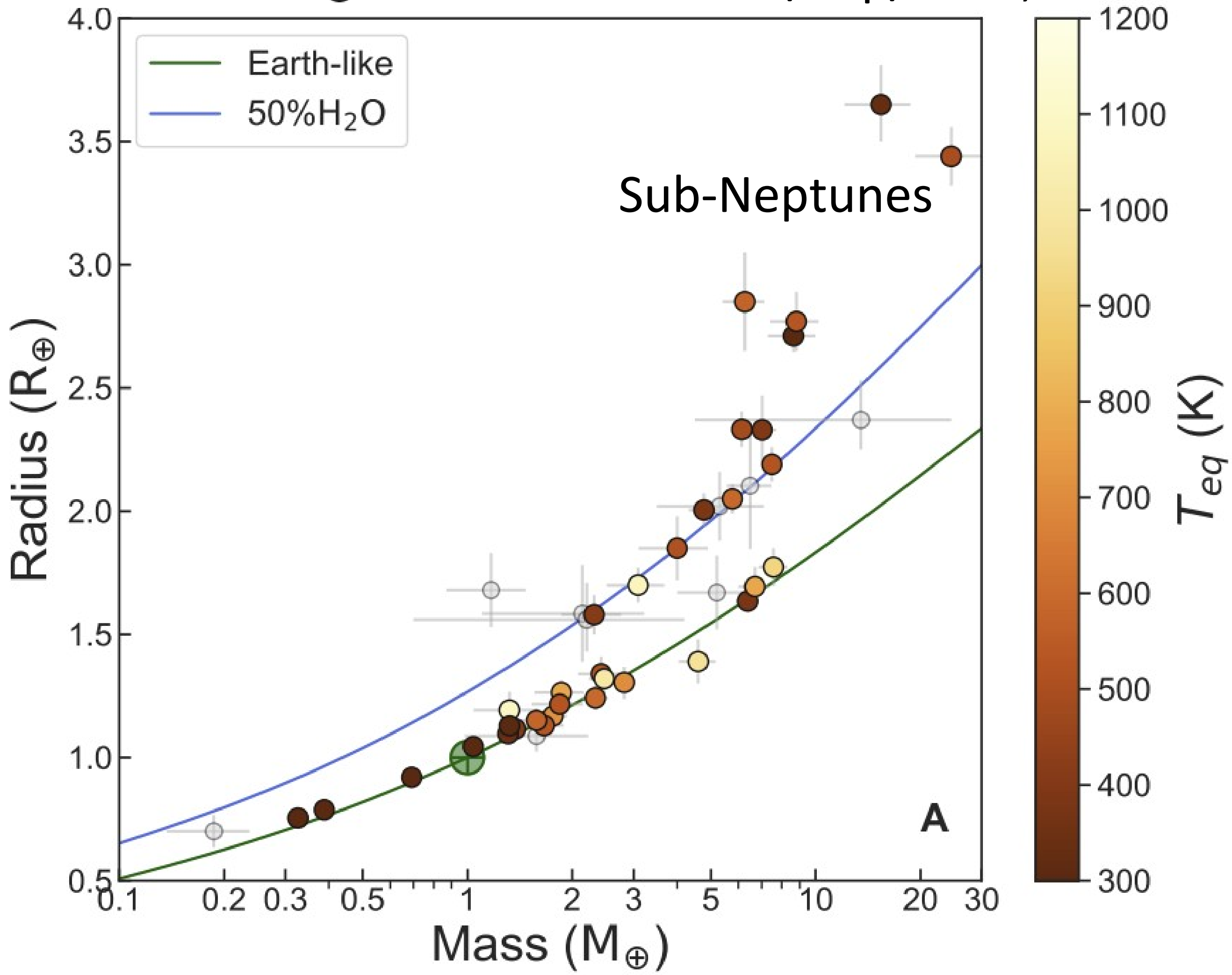


https://www.erikpetigura.com/post/how-stars-sculpt-the-super-earth-sub-neptune-dichotomy

Outros planetas: **mundos aquáticos** em estrelas M

Density, not radius, separates rocky and water-rich small planets orbiting M dwarf stars

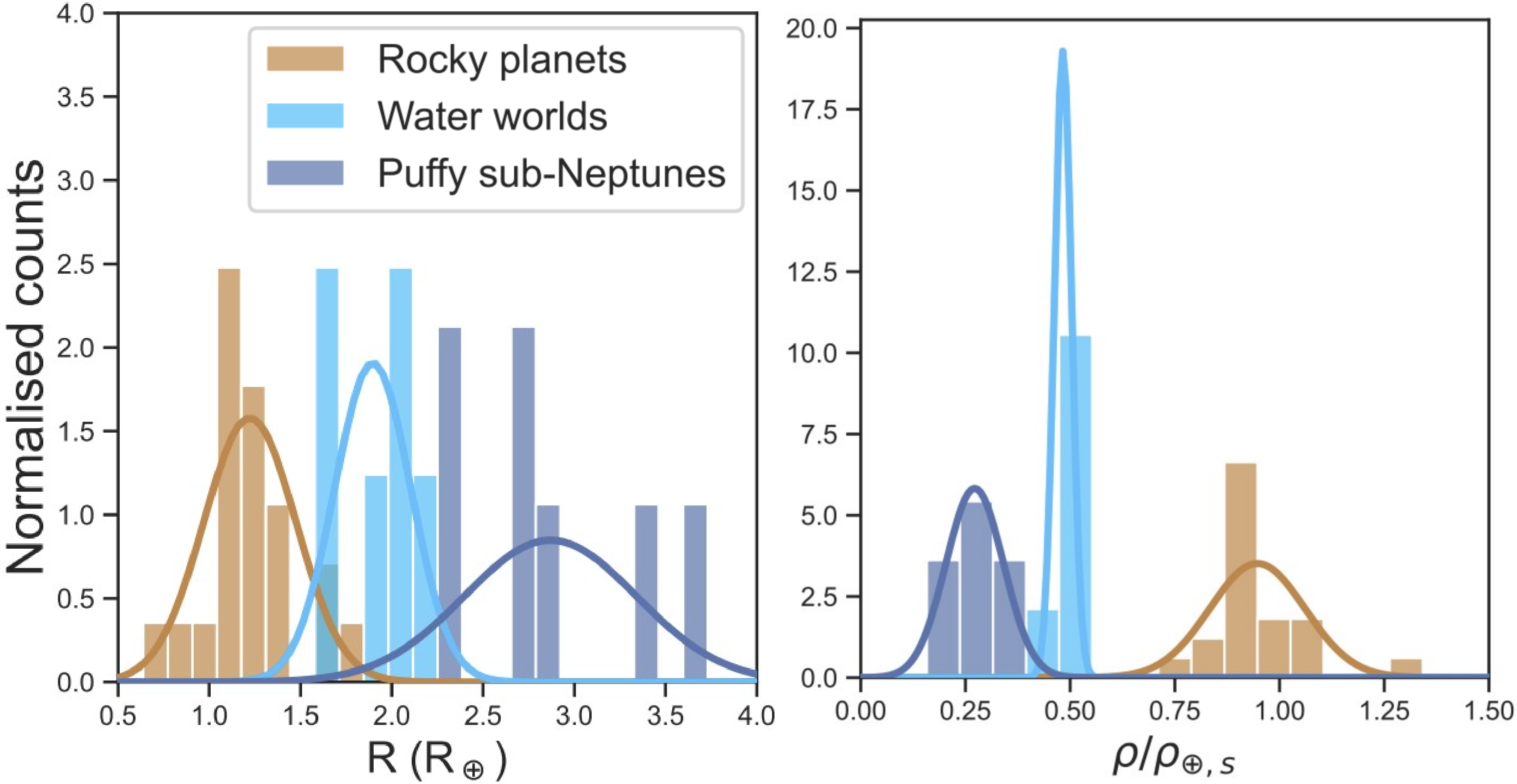
8/Sep/2022, Science 377, 1211



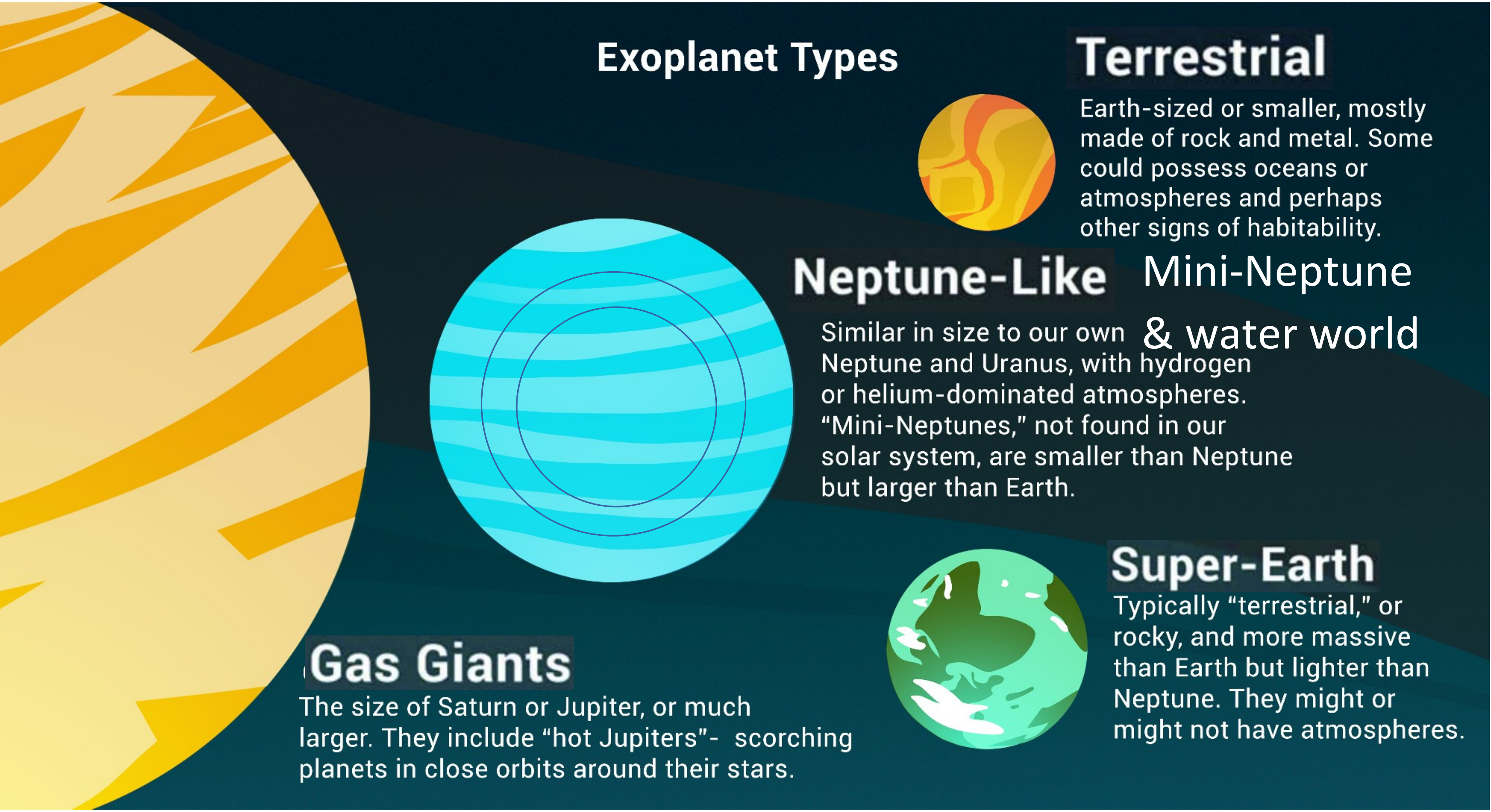
Mundos aquáticos em estrelas M podem ser comuns

Density, not radius, separates rocky and water-rich small planets orbiting M dwarf stars Science

8/Sep/2022, Science 377, 1211

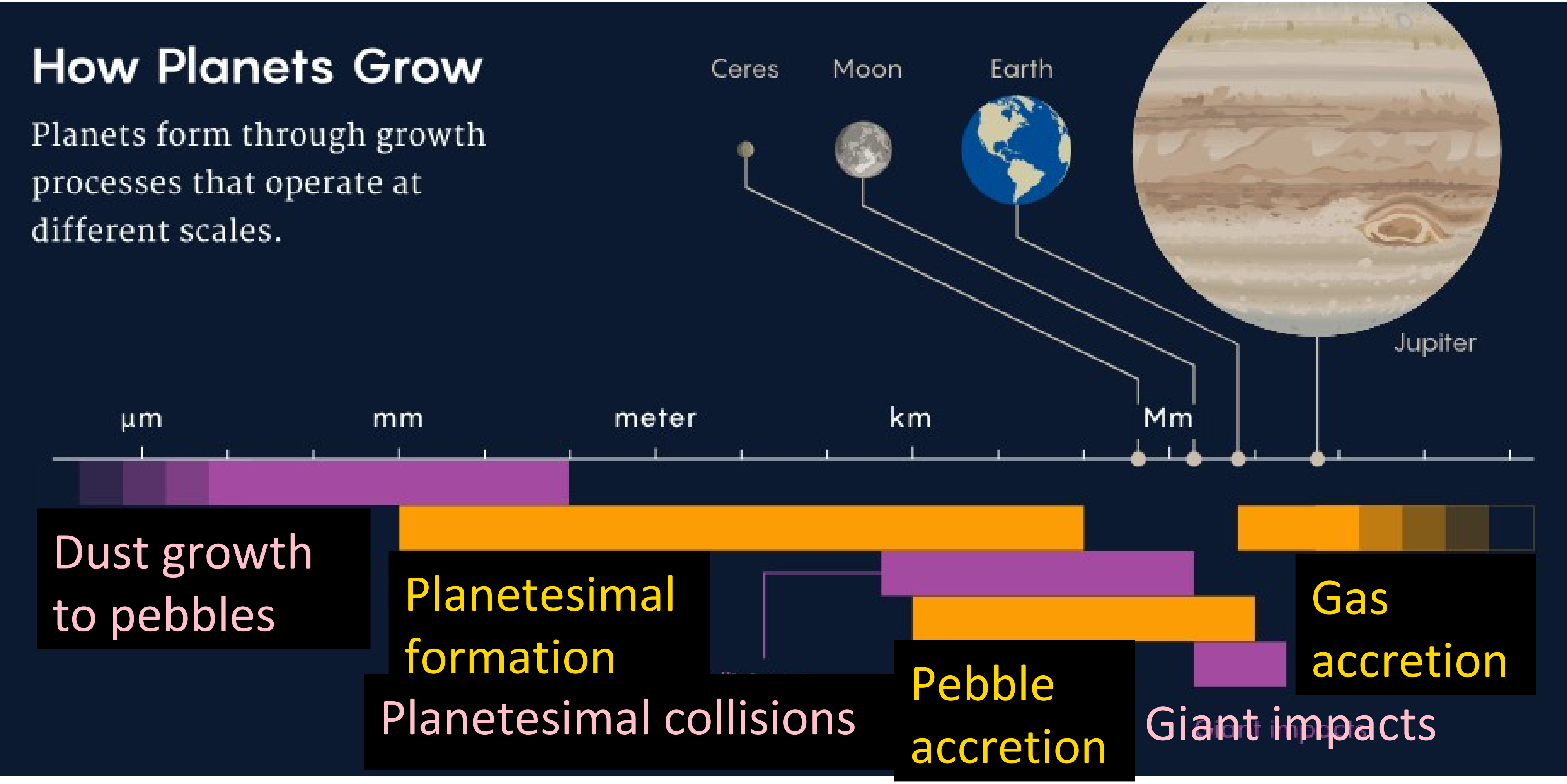


Como explicar a diversidade de exoplanetas e de Arquiteturas Planetárias?



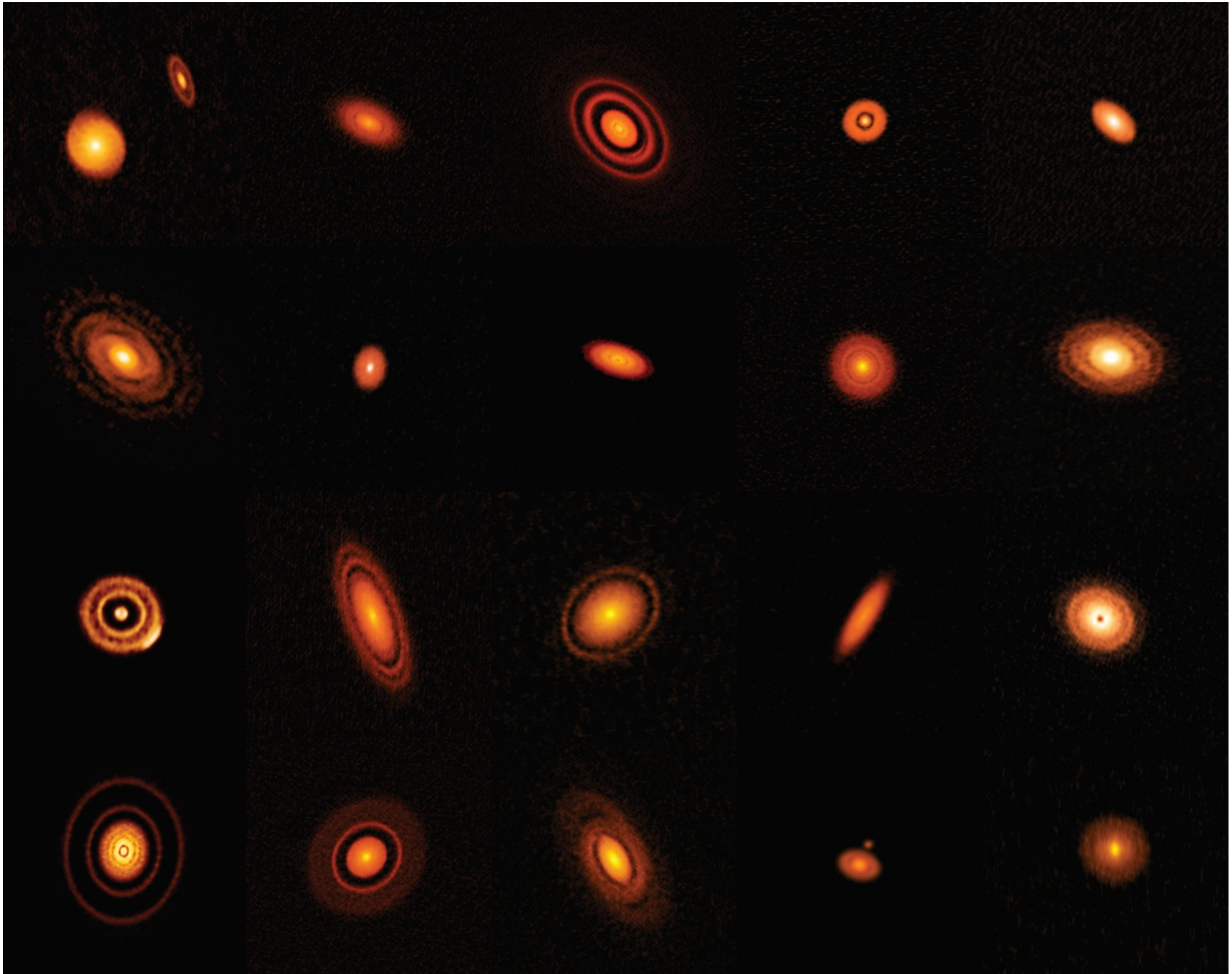
https://exoplanets.nasa.gov/resources/2253/exoplanet-types-graphic/

A formação de planetas acontece em diversas escalas e com diferentes tipos de ingredientes (poeira na região interna e poeira+gelo na região externa)



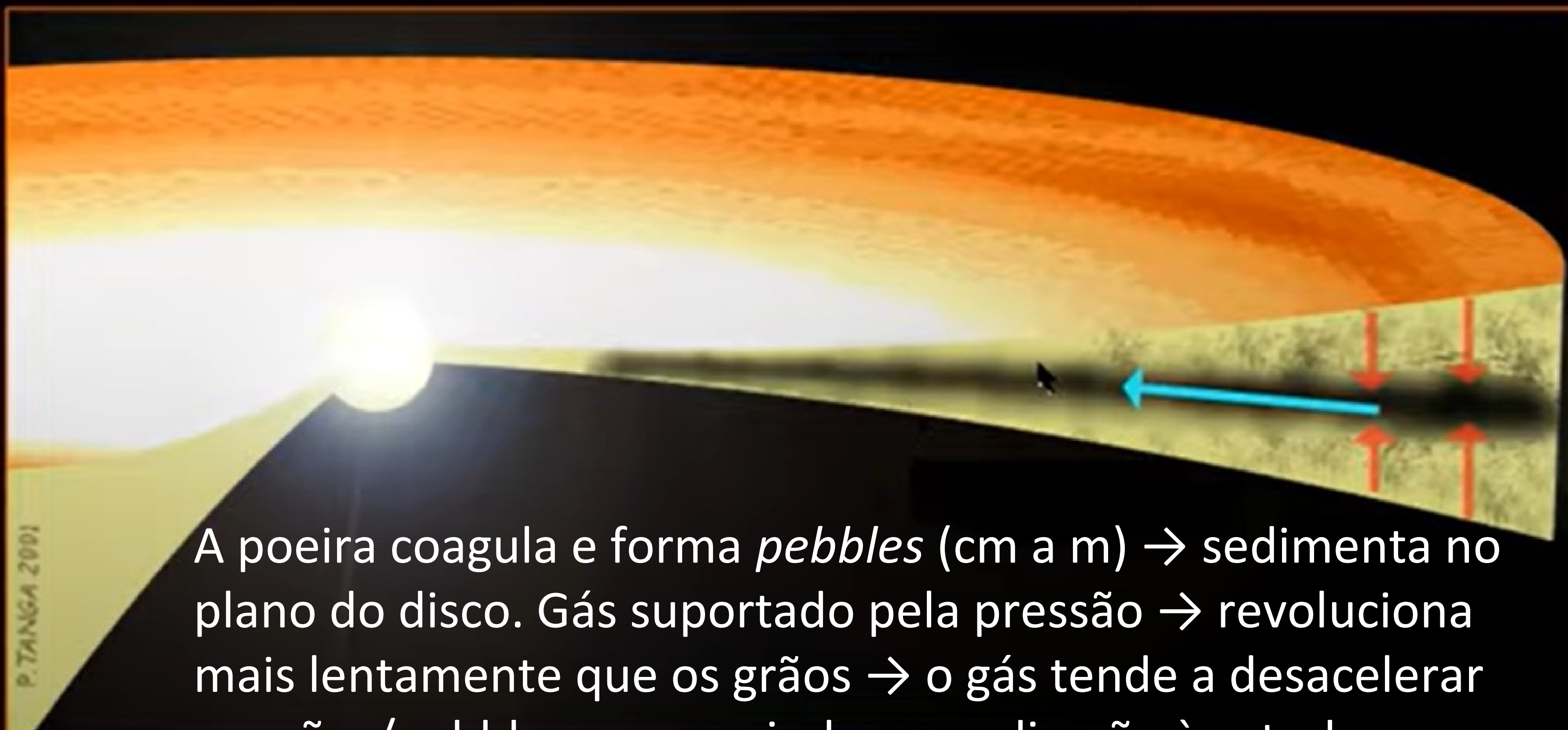
For icy particles, better sticking properties -> cm-dm.

Twenty Protoplanetary Disks Imaged by ALMA: diversity

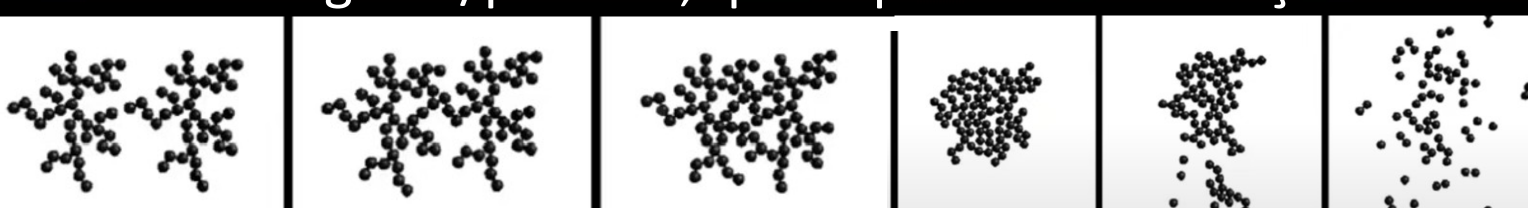


https://public.nrao.edu/gallery/twenty-protoplanetary-disks-imaged-by-alma/

TWO STEPS TO PLANET ACCRETION: 1) PLANETESIMAL FORMATION



A poeira coagula e forma *pebbles* (cm a m) → sedimenta no plano do disco. Gás suportado pela pressão → revoluciona mais lentamente que os grãos → o gás tende a desacelerar os grãos/pebbles, que espiralam em direção à estrela



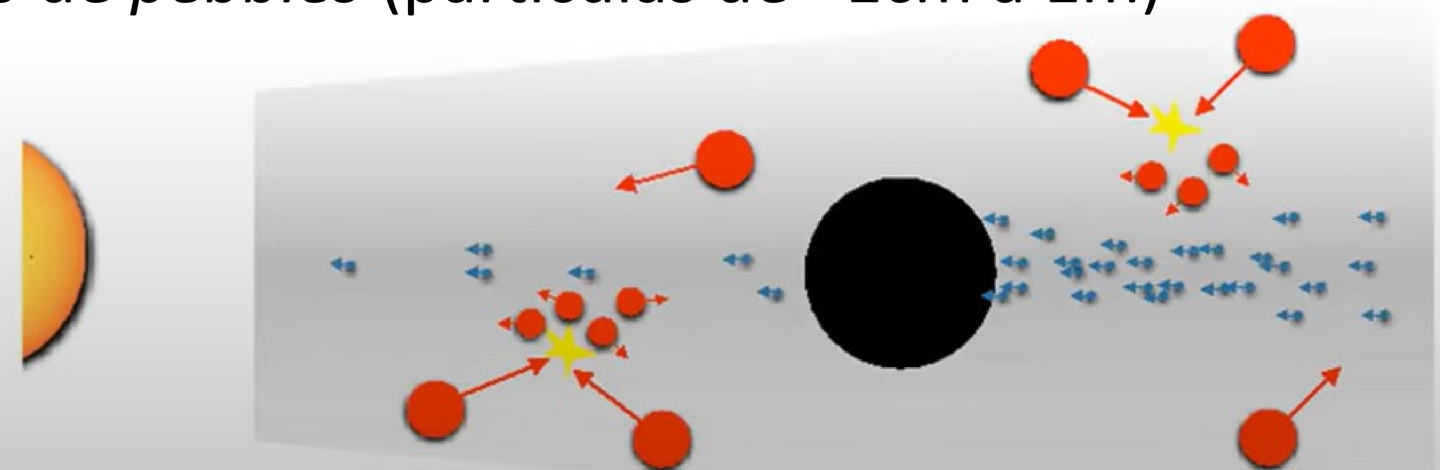
Gelo é “grudento”

(c) A.Morbidelli

Two-steps to planet formation:
2) from planetesimals to proto-planets

- **Planetesimals can collide with each other building protoplanets** (Kokubo and Ida, 1996, 1998)
- **The largest planetesimals keep growing by accreting individual dust particles as they drift in the gas (*pebble accretion*:** Johansen and Lacerda, 2010; Ormel and Klahr, 2010; Murray-Clay et al., 2011; Lambrechts and Johansen, 2012; Ida et al., 2016)

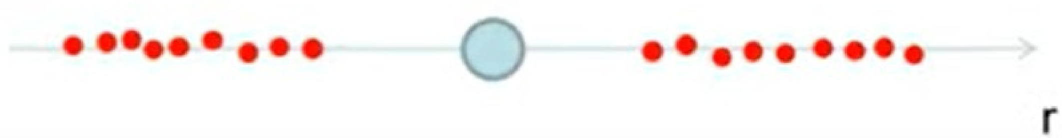
Os maiores planetesimais podem continuar crescendo pela acresção de *pebbles* (partículas de ~1cm a 1m)



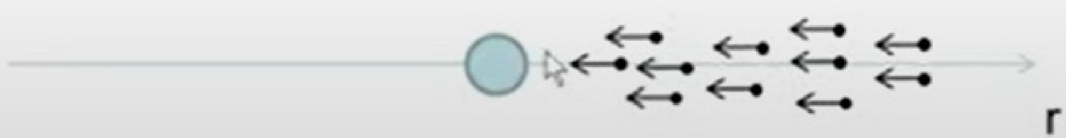
(c) A.Morbidelli

Two big advantages of pebble-accretion over planetesimal-planetesimal accretion:
I) No isolation

Vantagem de crescimento via acresção de pebbles: planetesimais orbitam isoladamente e é mais difícil se encontrarem para crescer:



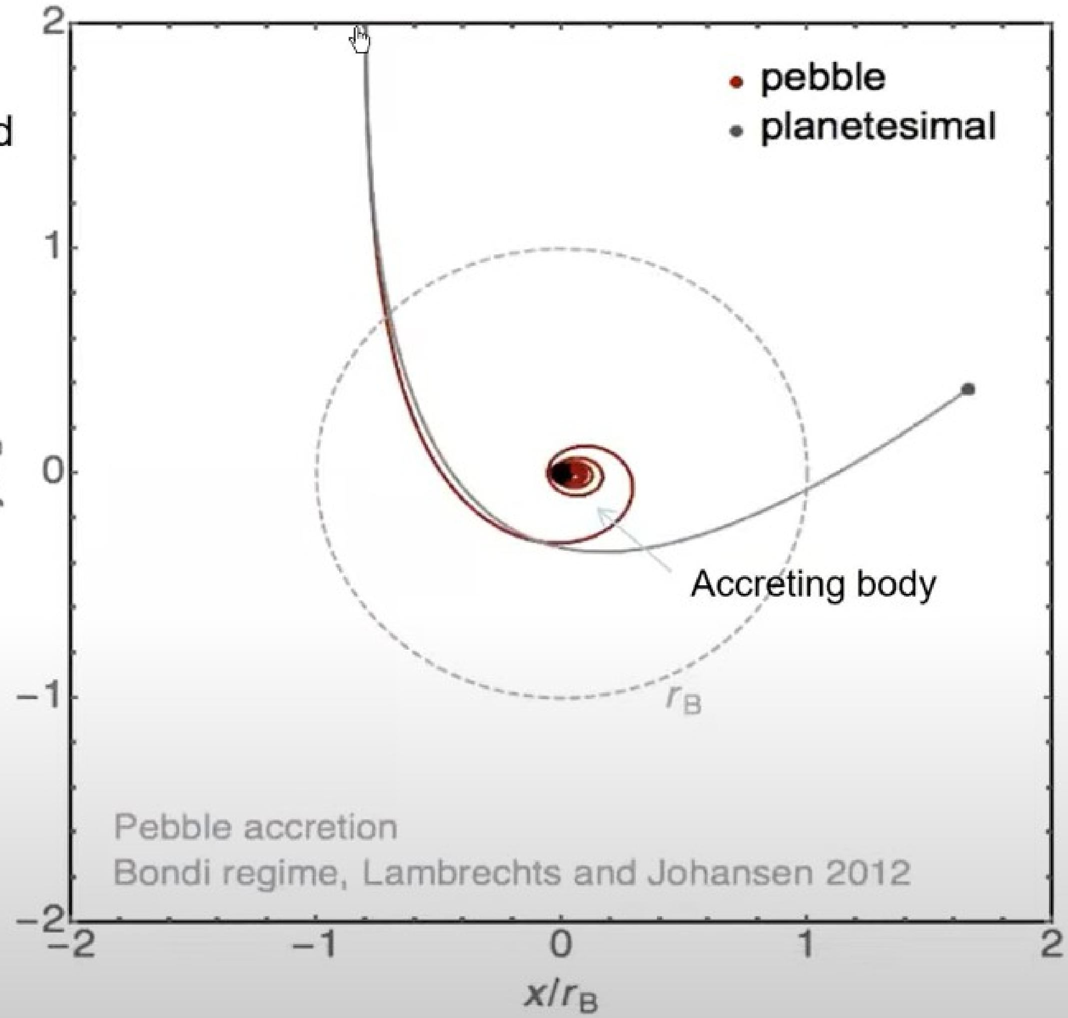
Já as *pebbles* migram e o corpo continua crescendo:



(c) A.Morbidelli

Two big advantages of pebble-accretion over planetesimal-planetesimal accretion :
II) Larger accretion cross-section

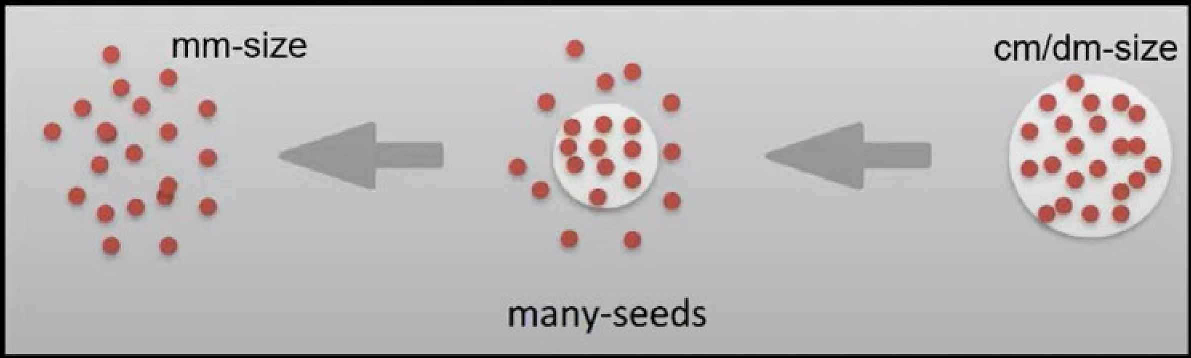
$$r_B = \frac{GM_c}{\Delta v^2}$$ ← relative speed

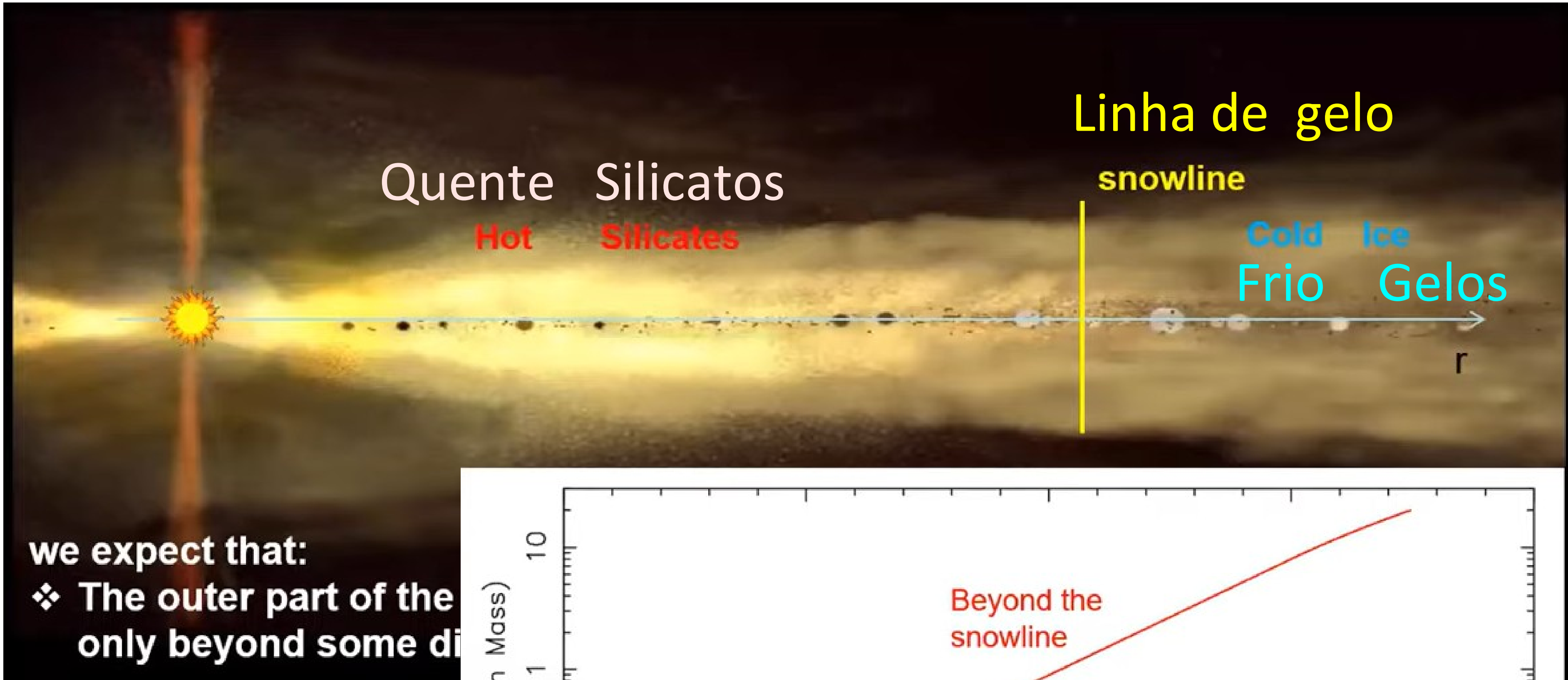


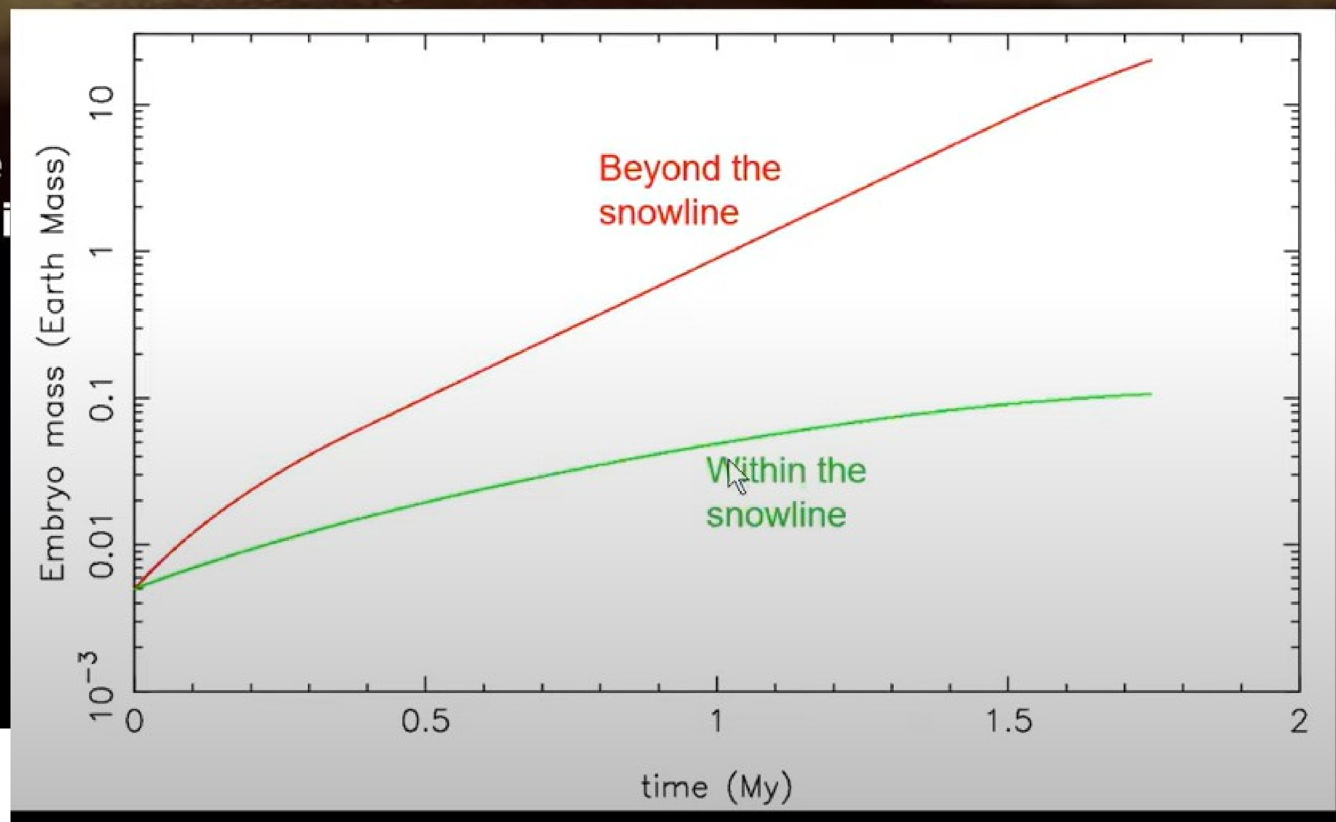
Acresção de *pebbles* é mais eficiente que acresção de corpos maiores (planetesimais)

(c) A.Morbidelli

As *pebbles* que migram para a região interna, perdem o gelo e ficam menores → mais fácil formar planetas além da linha de gelo







Planetesimais crescem lentamente (rapidamente) dentro (além) da linha de gelo

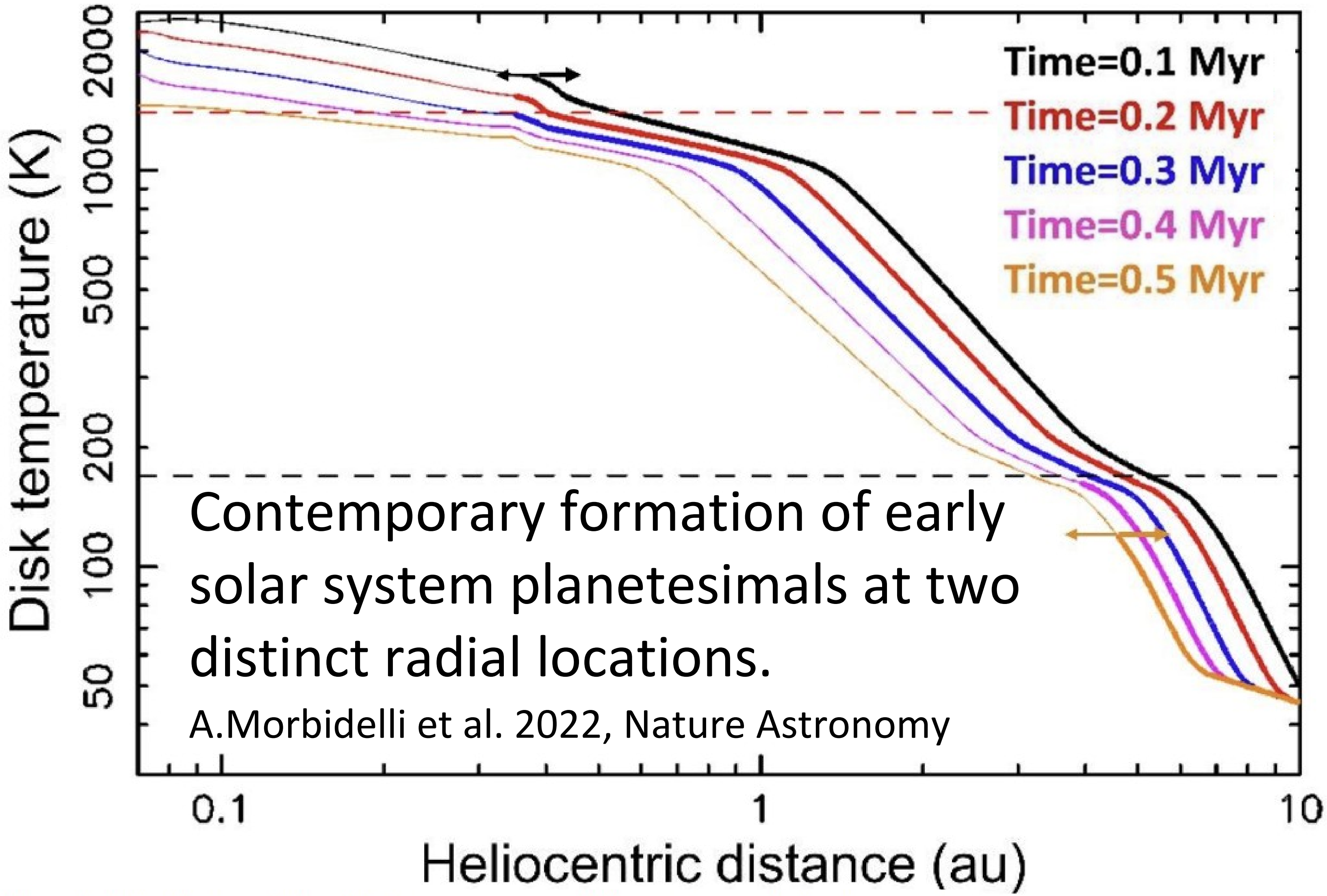


Fig.1 The radial distribution of the disk's temperature at different times, obtained assuming R_c=0.35au/[$M_{sun}(t)$]$^{0.5}$. The thick part of each curve shows the region where the radial velocity of the gas is positive (outward), whereas the thin part depicts the accretion part of the disk (negative radial velocity), as also indicated by the black and orange arrows. The horizontal dashed lines mark the condensation temperature of water (T=170K, black), and rocks (T=1,400K, red). The intersection of these lines with the various colored curves identify the location of the condensation/sublimation fronts of these elements as a function of time.

Contemporary formation of early solar system planetesimals at two distinct radial locations.

A.Morbidelli et al. 2022, Nature Astronomy

Pebbles (partículas de ~1cm a 1m) além da linha de gelo podem crescer mais facilmente ("*sticky*") e formar planetesimais

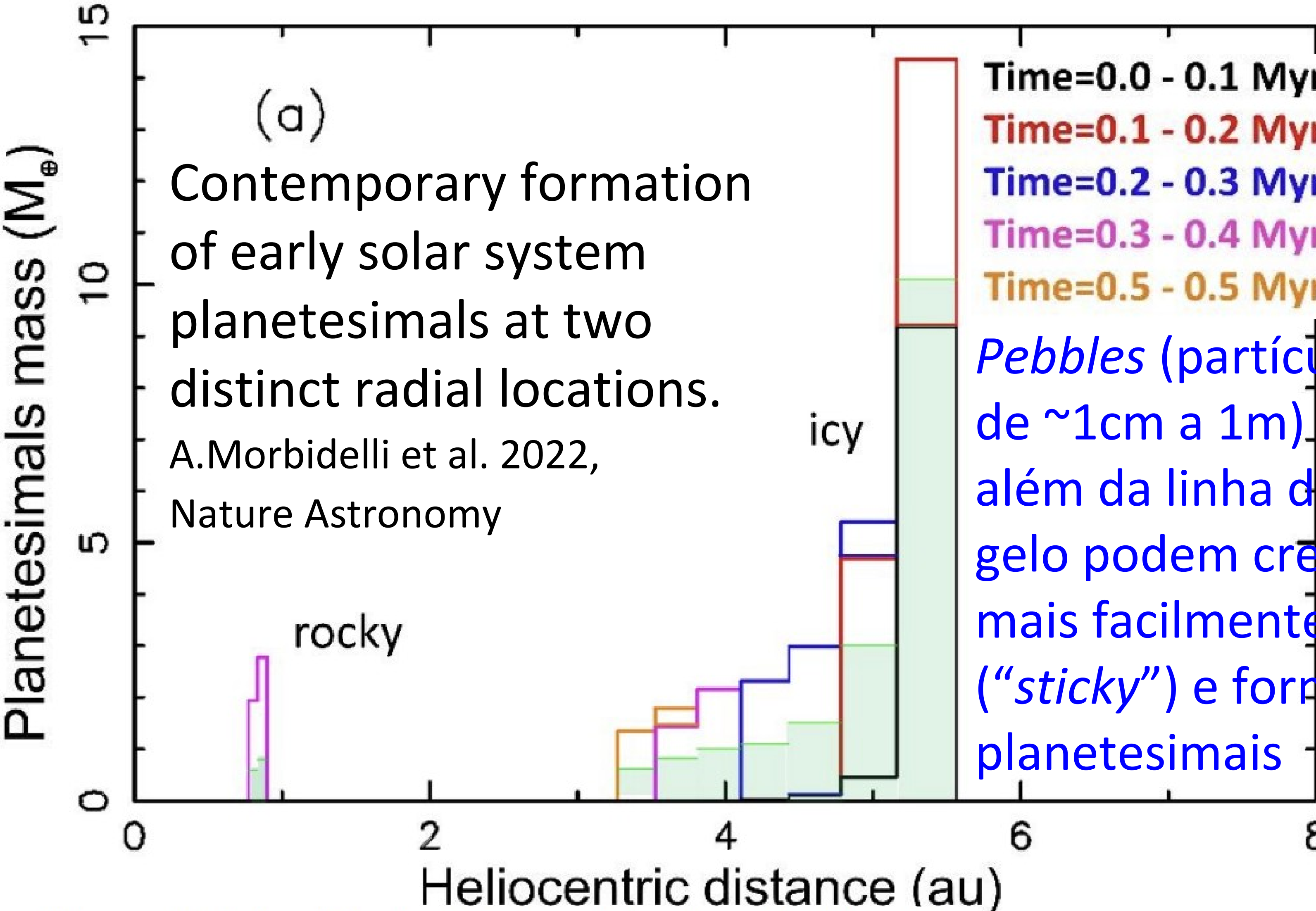
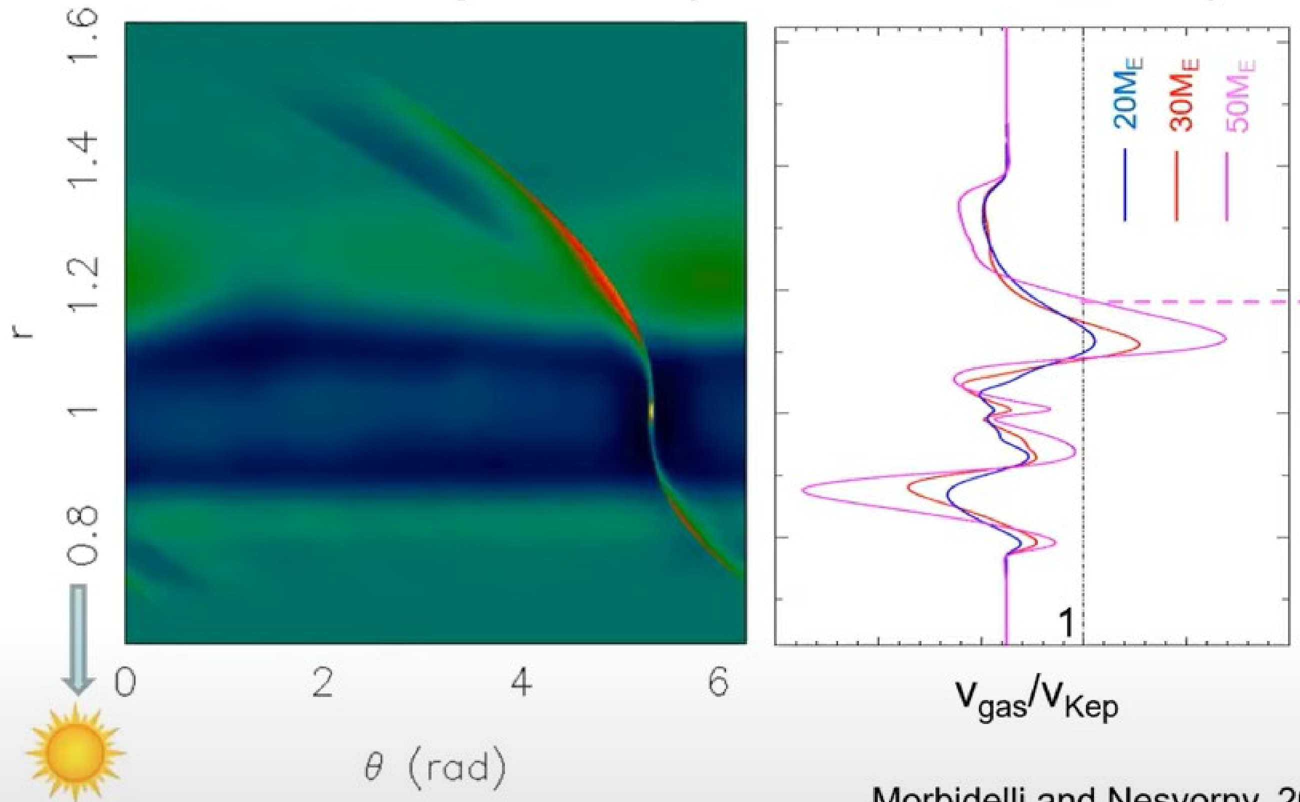


Fig.3 The radial mass distribution of the planetesimal populations formed in different time intervals (color-coded as indicated by the labels). Planetesimal masses formed in the same radial bin at subsequent time intervals are plotted on top of each other, so that the upper border of the histogram represents the total mass ever produced. The light green shaded area shows the fraction of this mass derived from early infalling material (the material accreted onto the disk before 20 Kyr). This fraction is 46-70% for the icy planetesimals between 3.1 and 5 au and increasing from inside-out (the mass-weighted average is 60%), and 28-30% for the rocky planetesimals, just inward of 1 au.

Effects of giant planet growth

When a protoplanet reaches a mass of ~ 20 Earth masses, it cuts off the flow of condensed particles (of size > 100microns) towards the inner disk

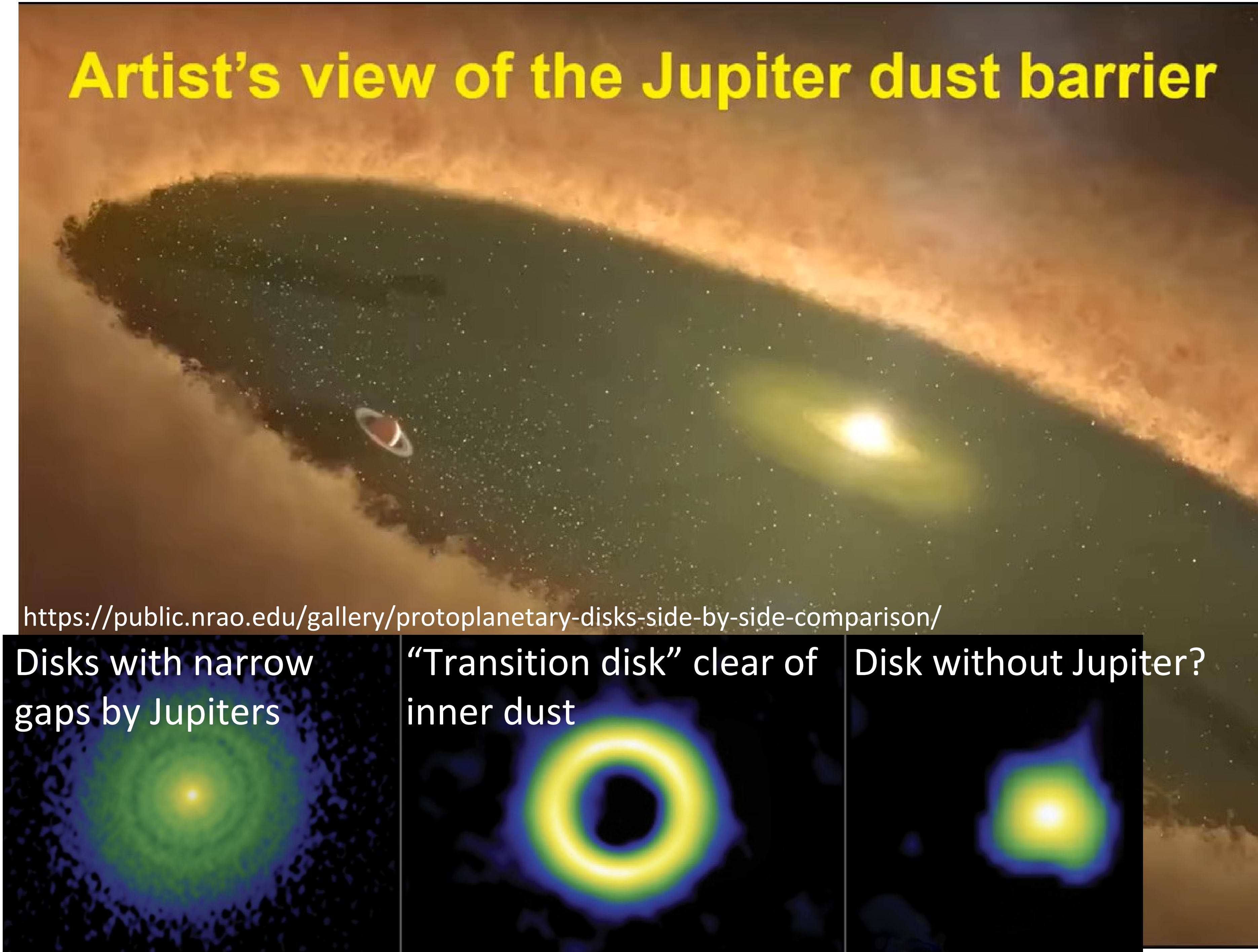


Protoplaneta ~$20M_{Earth}$
→ barreira para a migração de *pebbles*

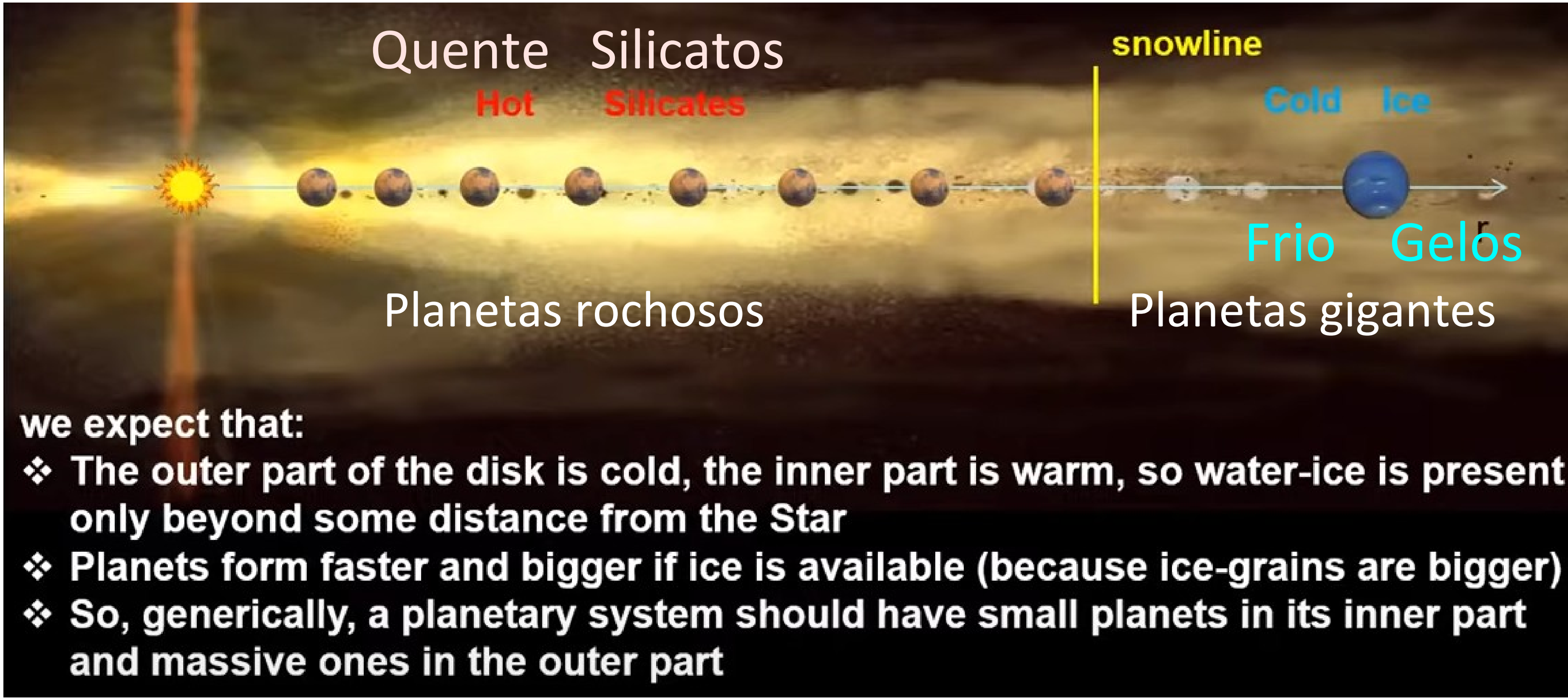
→ limita o crescimento de planetas rochosos por acresção de *pebbles*

Morbidelli and Nesvorny, 2012
Lambrechts, Johansen and Morbidelli, 2014
Weber et al., 2018

The growth of proto-Jupiter is the key to understand the separation of distinct reservoirs in the Solar System (Morbidelli et al., 2016, Kruijer et al., 2017)
Prevented the terrestrial planets from growing by pebble accretion

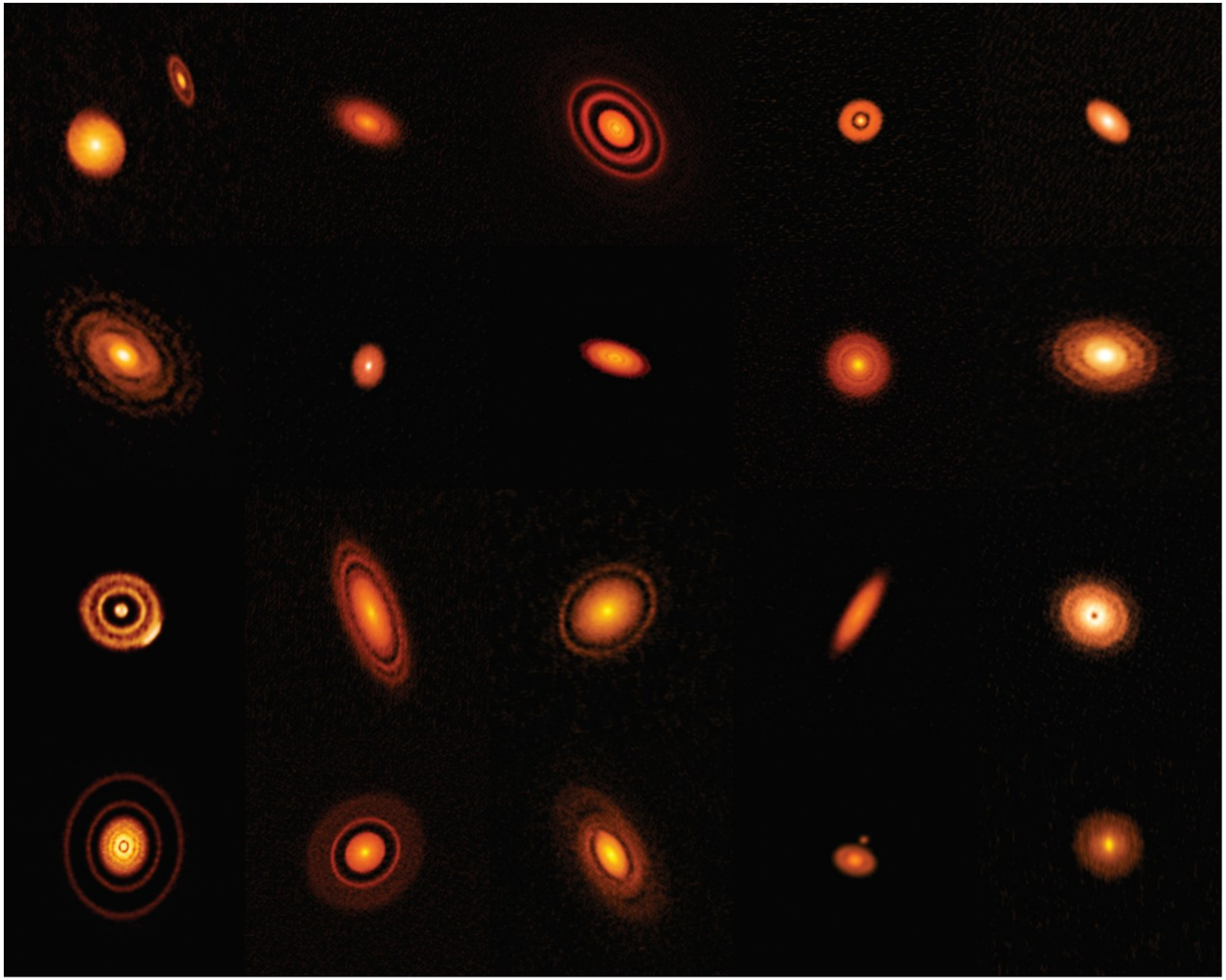

Artist's view of the Jupiter dust barrier
https://public.nrao.edu/gallery/protoplanetary-disks-side-by-side-comparison/
Disks with narrow gaps by Jupiters
"Transition disk" clear of inner dust
Disk without Jupiter?

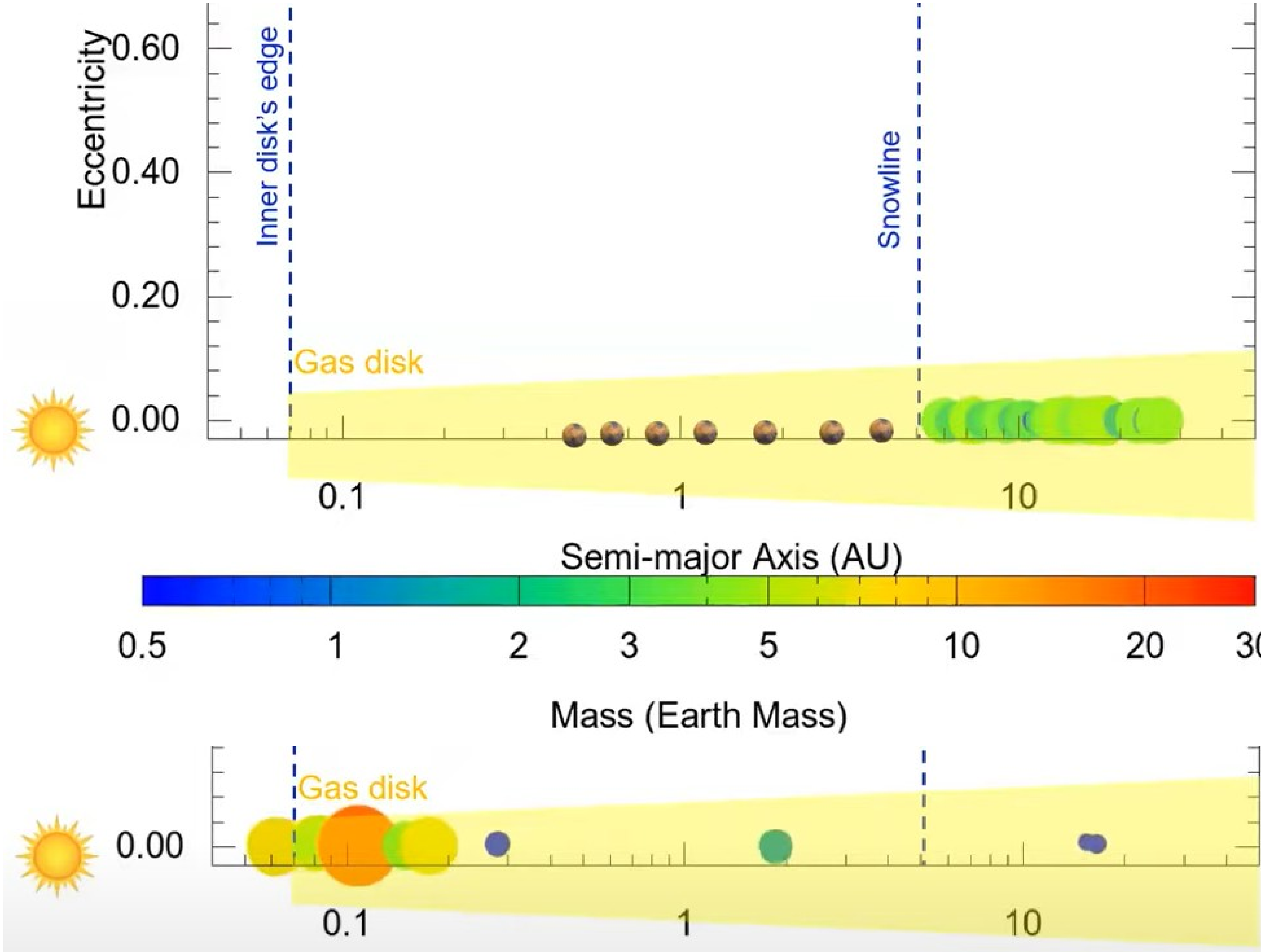
Inicialmente: planetas rochosos internos e gigantes externos



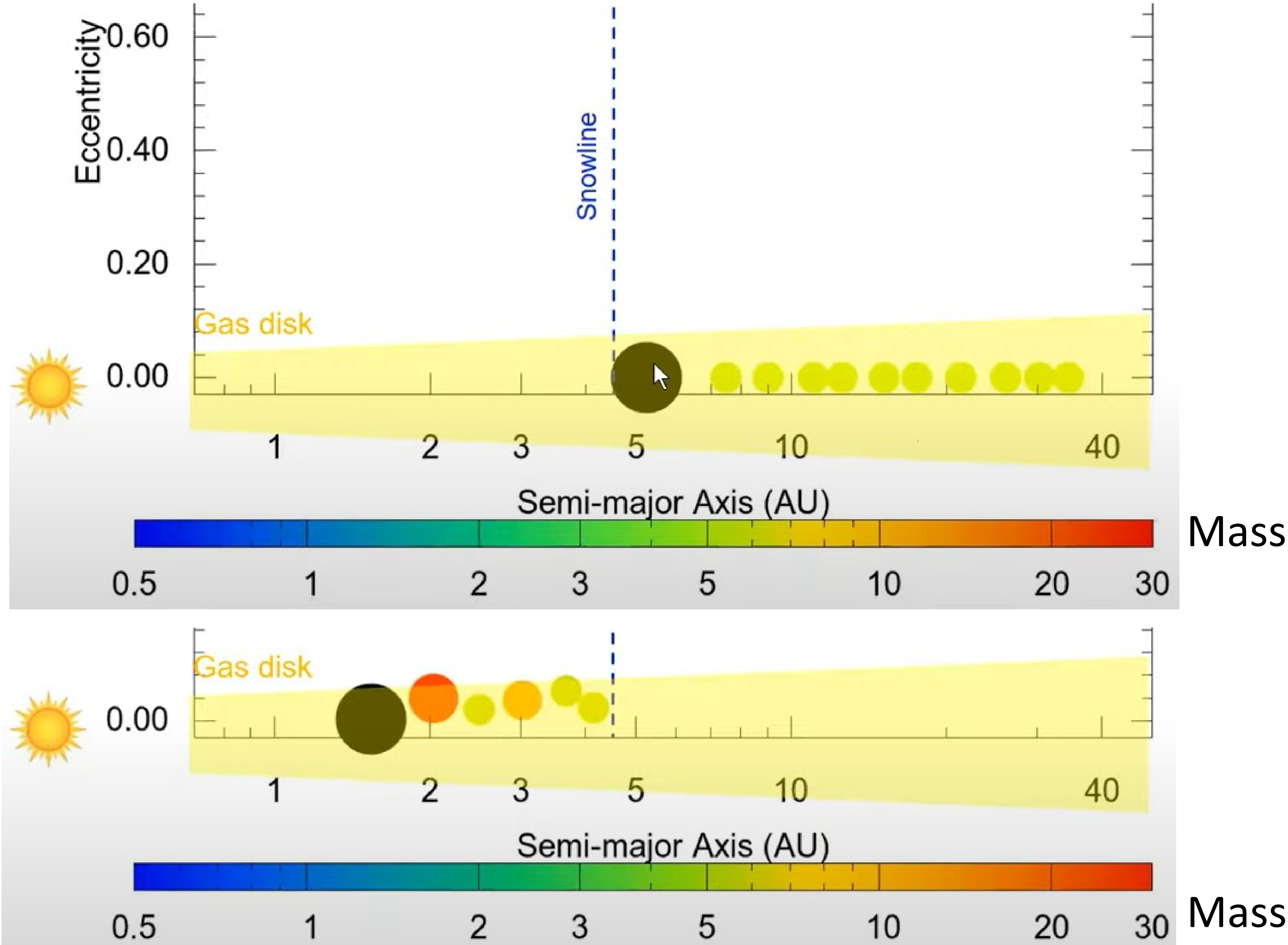
Migração de planeta gigante → caos no Sistema Planetário

Quando temos um processo **caótico**, uma pequena mudança nas condições iniciais pode ter um efeito importante no resultado final. Diferentes discos → diversidade de sistemas planetários

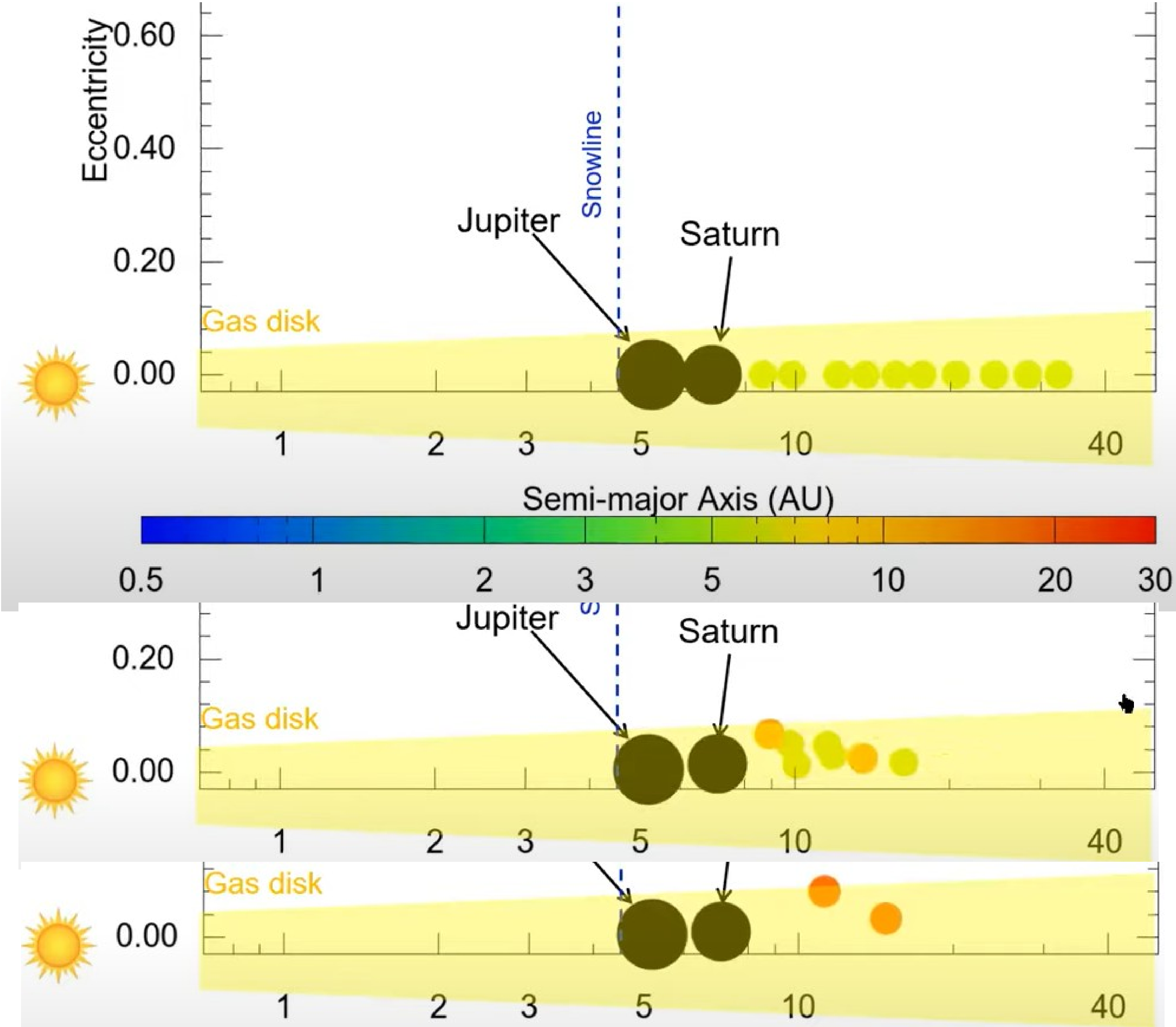




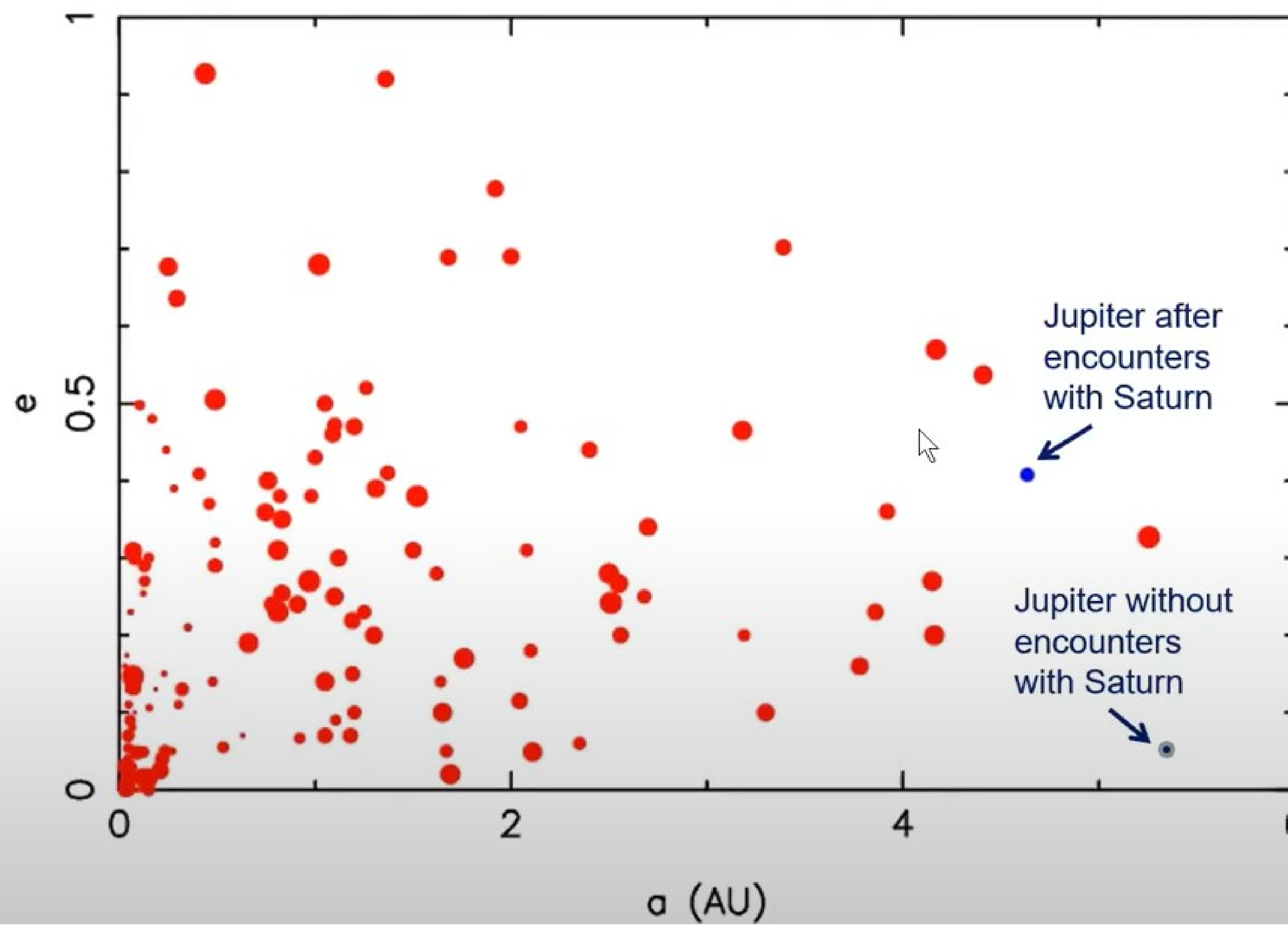
(c) A.Morbidelli



(c) A.Morbidelli


Eccentricity
0.60
0.40
0.20
0.00
Snowline
Jupiter
Saturn
Gas disk
1
2
3
5
10
40
Semi-major Axis (AU)
0.5
1
2
3
5
10
20
30

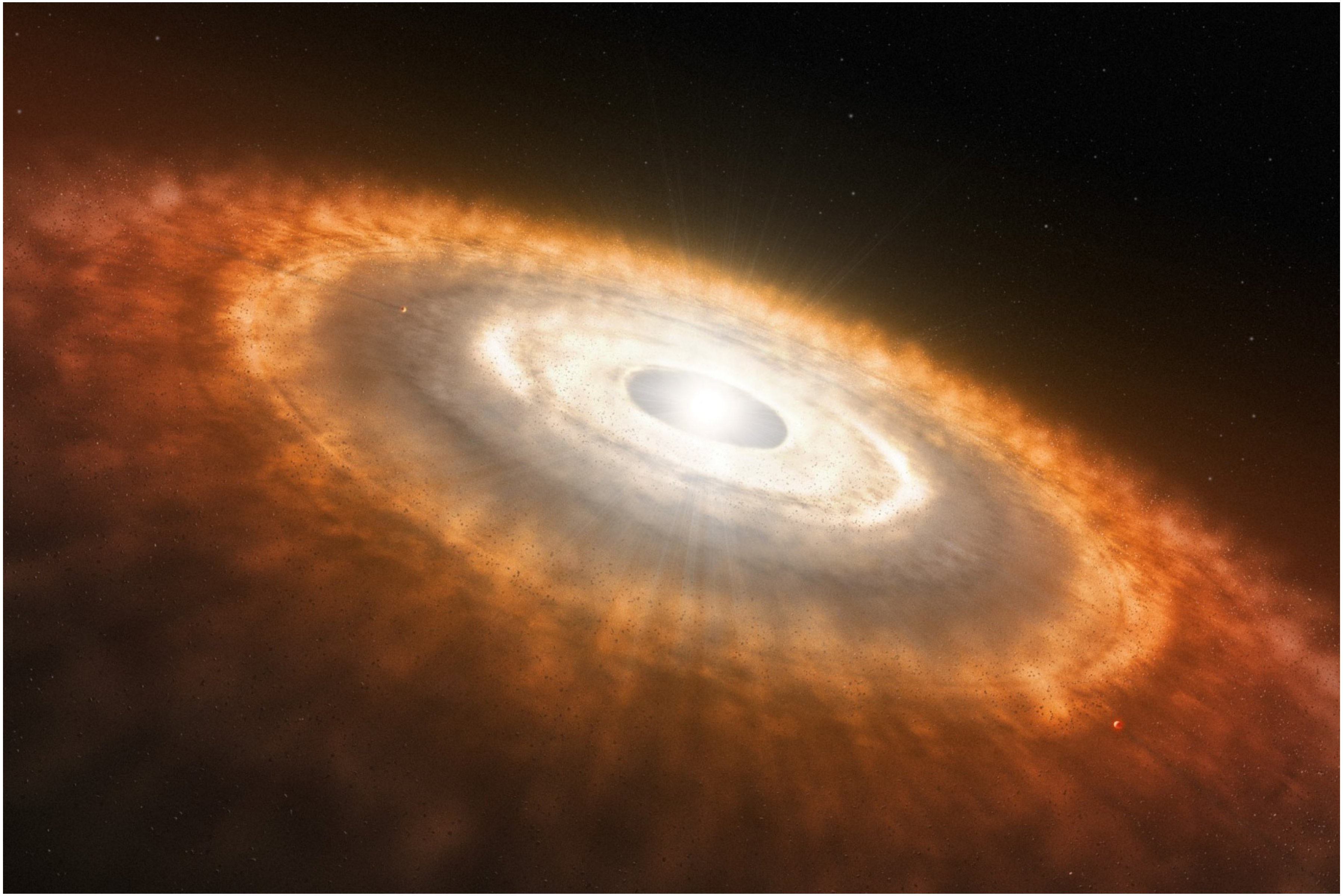
The small eccentricities of the giant planets of the Solar System are due to the fact that during the instability Jupiter and Saturn, fortuitously, avoided mutual close encounters
In simulations where these encounters happen, the final eccentricity of Jupiter is similar to typical of those at of extrasolar giant planets.



Apenas uma pequena fração das simulações resulta em Júpiter com baixa excentricidade

A relação planeta – composição química da estrela

Estrela e planetas se formam a partir da mesma nuvem



Notação

- A abundância química A_X do elemento X é:
  $A_X = \log(N_X/N_H) + 12 \rightarrow$ hidrogênio: $A_H = 12$

- $[X/H] = A_X^{estrela} - A_X^{Sol}$

  - [Fe/H] = 0.0: abundância de ferro igual ao Sol
  - [Fe/H] = +0.3: ferro 2 vezes (= $10^{+0.3}$) maior ao Sol
  - [Fe/H] = -1.0: 1/10 (= 10^{-1}) de Fe em relação ao Sol

Conexão metalicidade – planeta gigante

Mon. Not. R. Astron. Soc. **285**, 403–412 (1997)

The stellar metallicity–giant planet connection

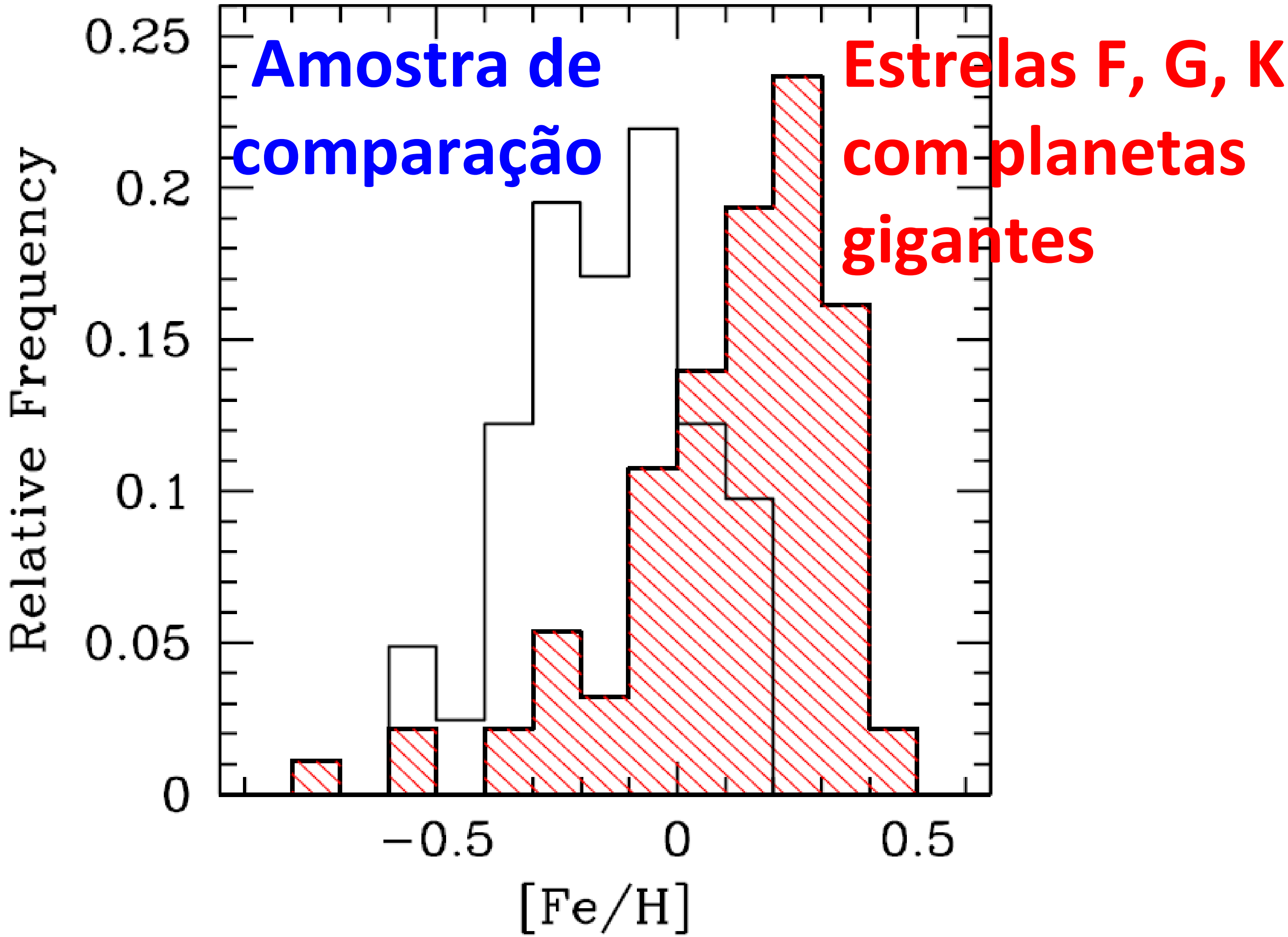
Guillermo Gonzalez★

Department of Astronomy, University of Texas, Austin, TX 78712, USA

Accepted 1996 September 24. Received 1996 September 23; in original form 1996 August 1

Conexão metalicidade – planeta gigante

N. C. Santos[1,2], G. Israelian[3], and M. Mayor[2]
A&A 415, 1153–1166 (2004)

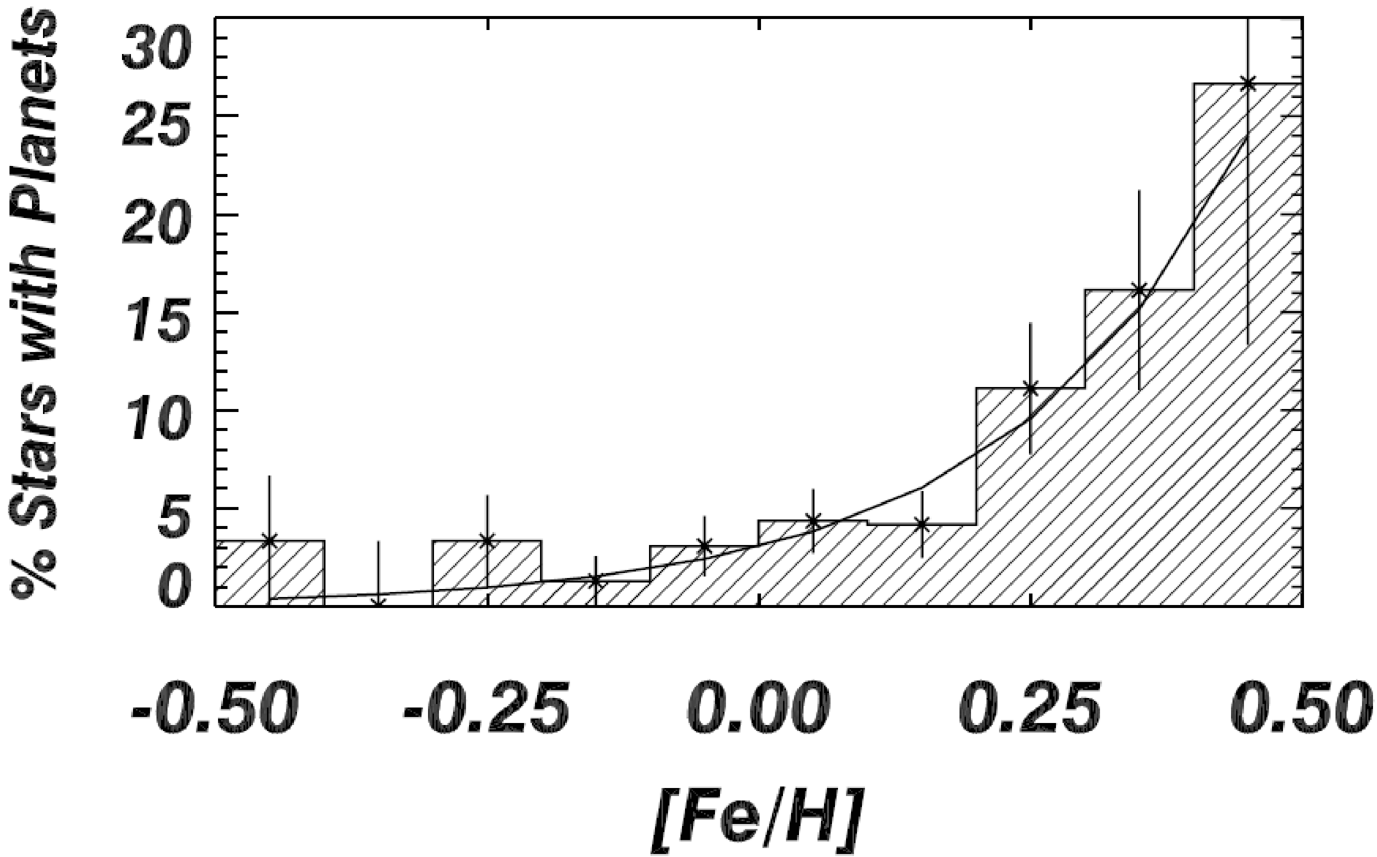


Conexão metalicidade – planeta gigante

THE ASTROPHYSICAL JOURNAL, 622:1102–1117, 2005 April 1

THE PLANET-METALLICITY CORRELATION

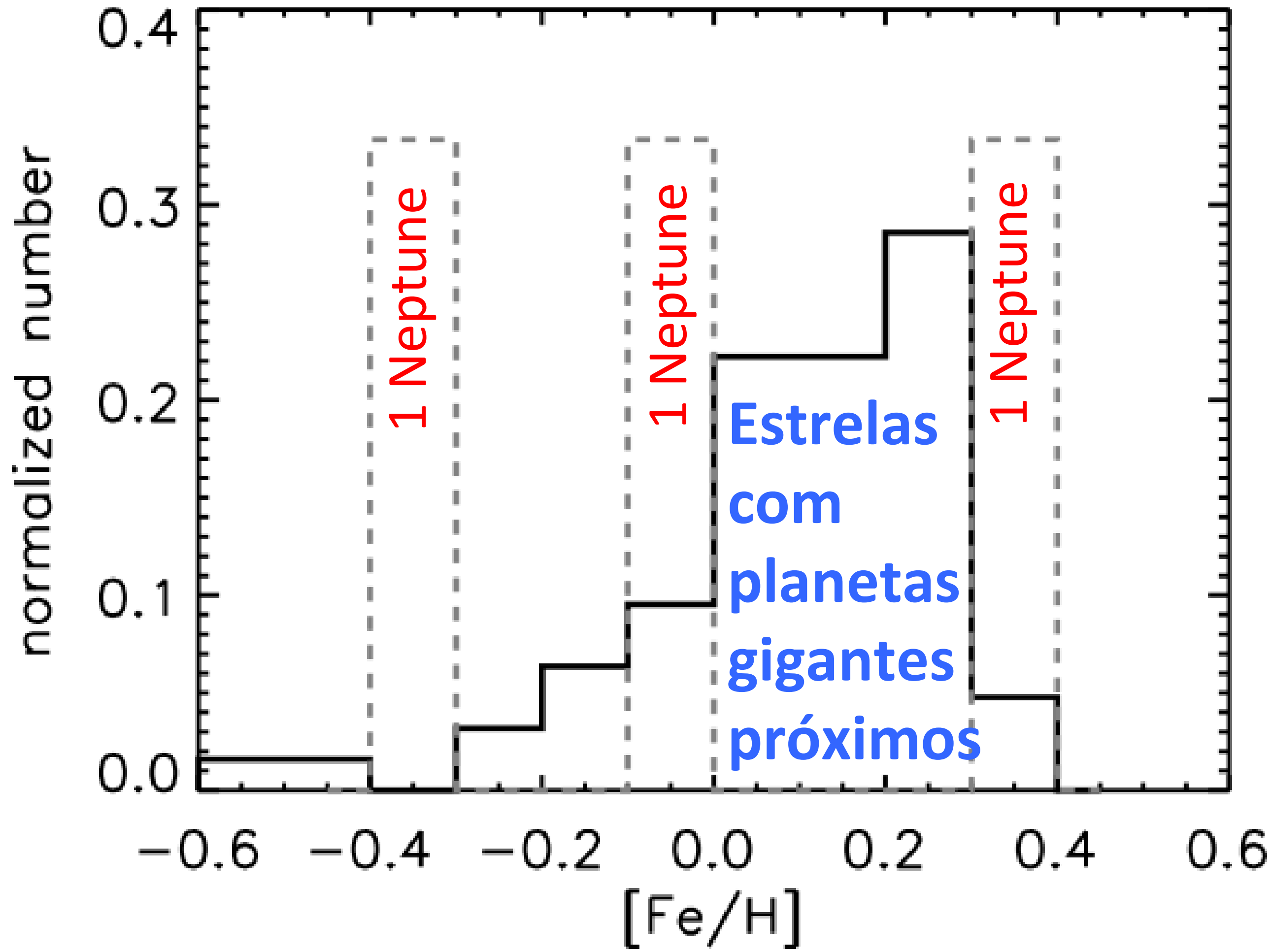
DEBRA A. FISCHER[2] AND JEFF VALENTI[3]



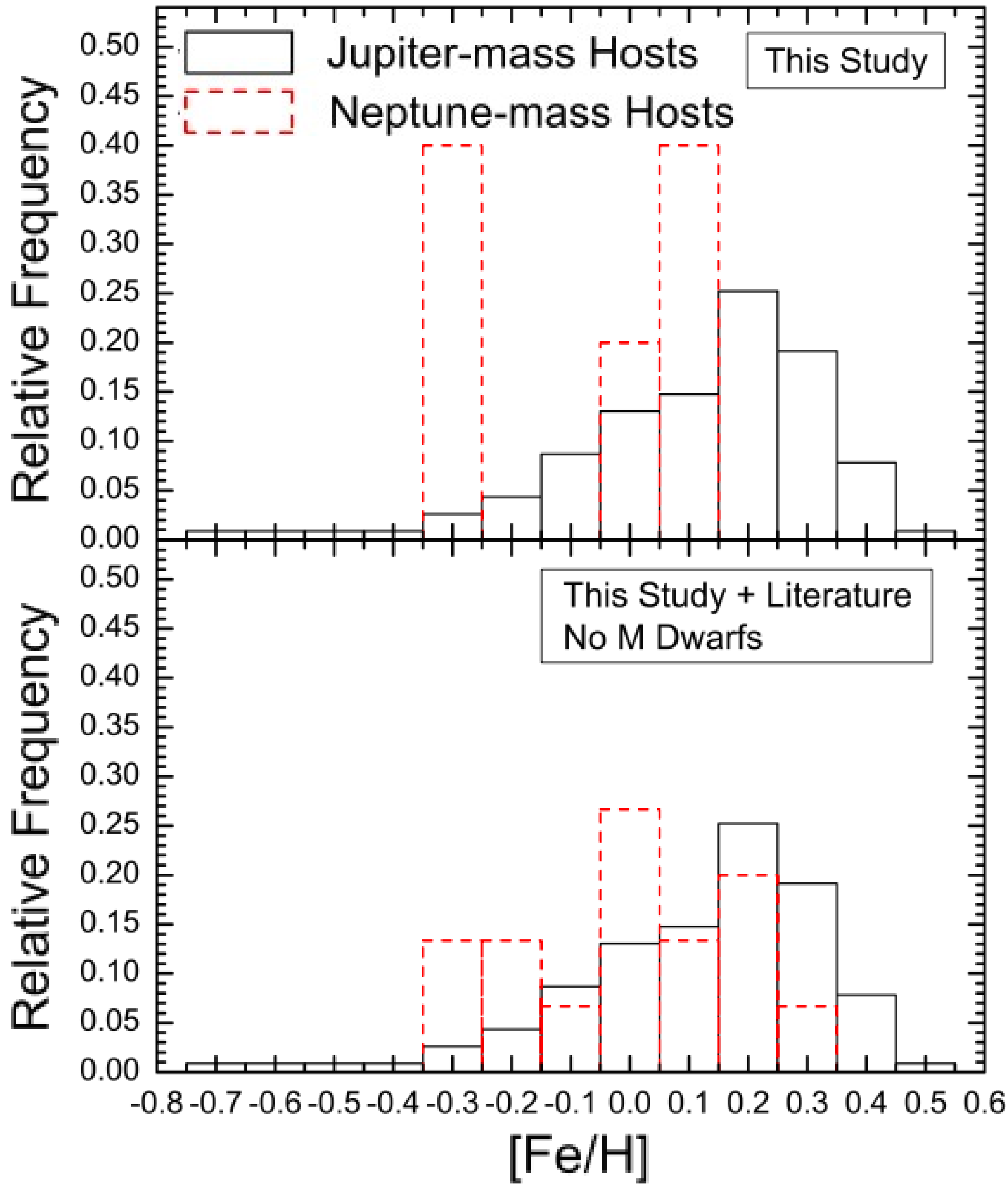
1040 estrelas de tipo FGK

Conexão metalicidade – planeta: **Netunos podem ser formados em qualquer metalicidade**

Sousa et al. 2008, A&A 487, 373

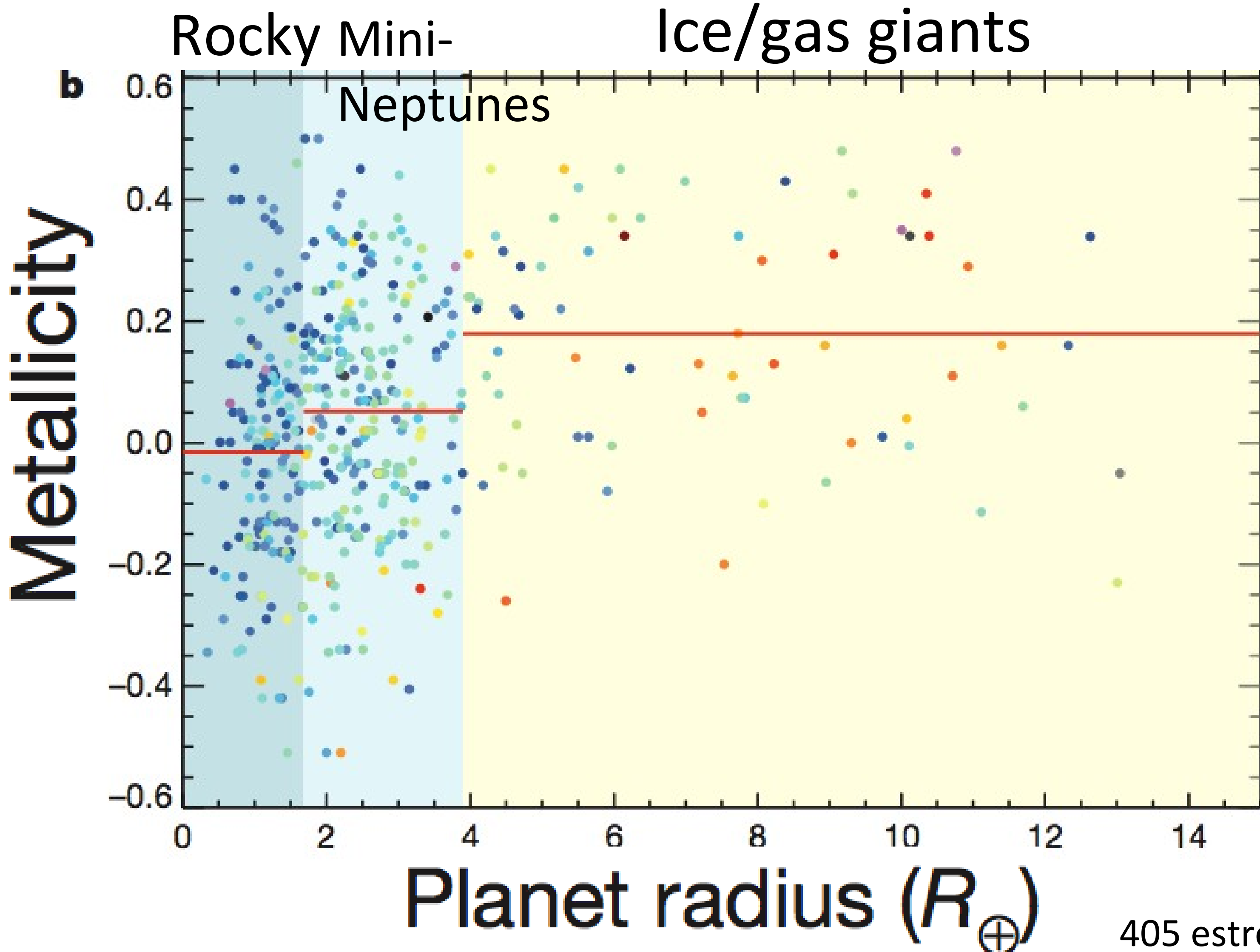


Conexão metalicidade – planeta **Netunos podem ser formados em qualquer metalicidade**



Ghezzi et al. 2010
ApJ 720, 1290

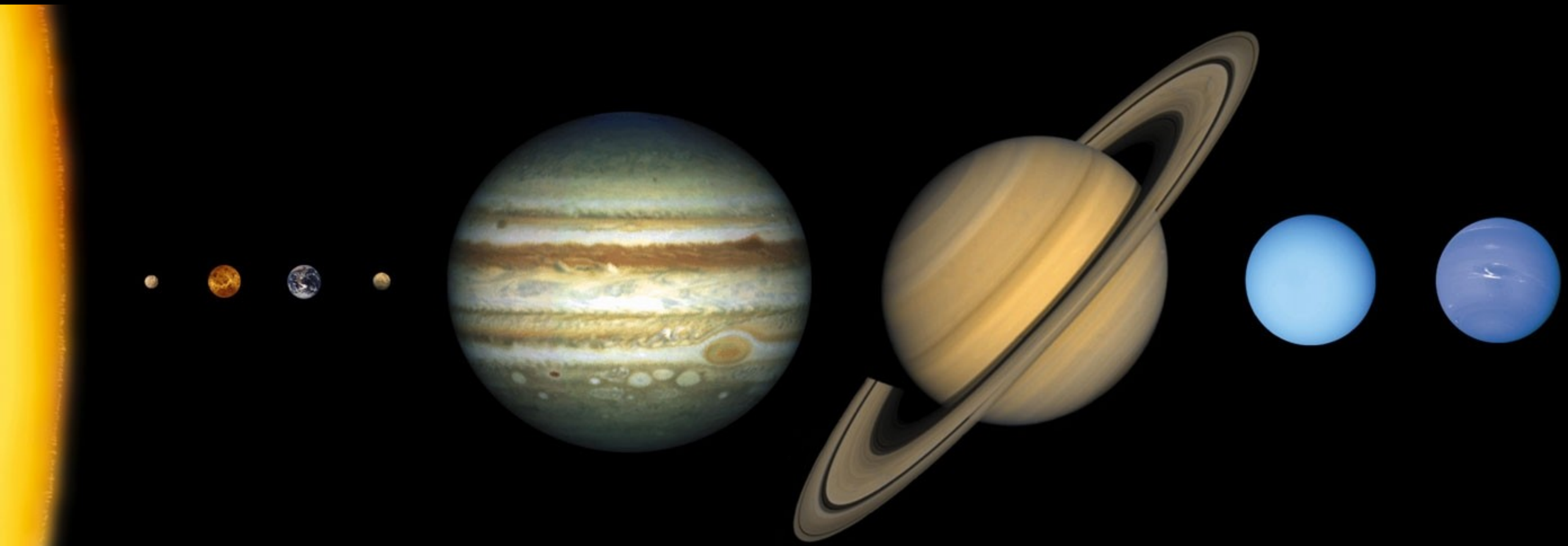
Conexão metalicidade – planeta em estrelas FGK: Planetas rochosos podem ser formados *at any* **[Fe/H]**



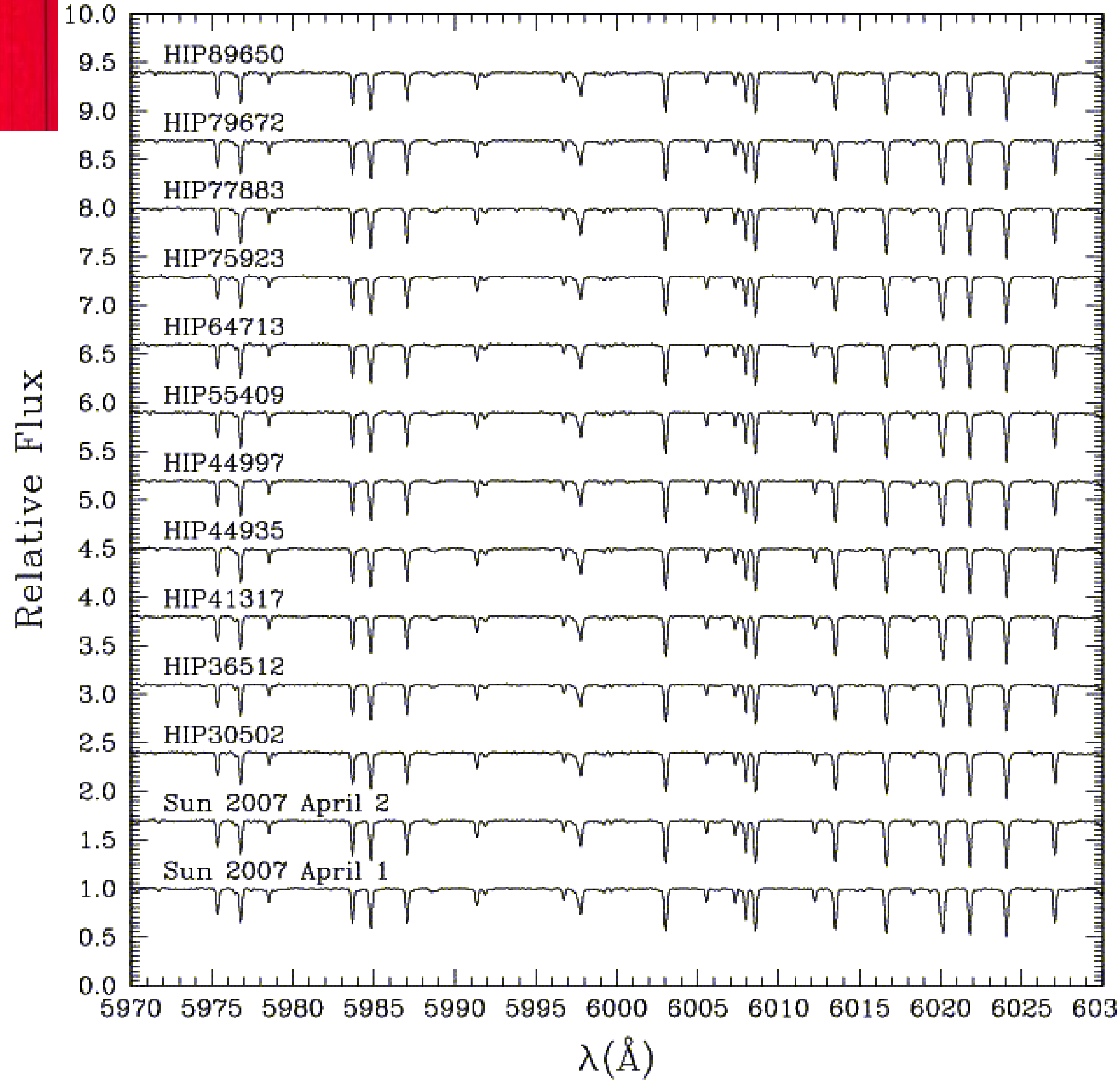
Buchhave et al. 2014 Nature 509, 593

405 estrelas com 600 exoplanet candidates

Existe alguma assinatura química da formação de planetas no Sistema Solar?



Exemplo de espectros de 11 gêmeas solares e o Sol



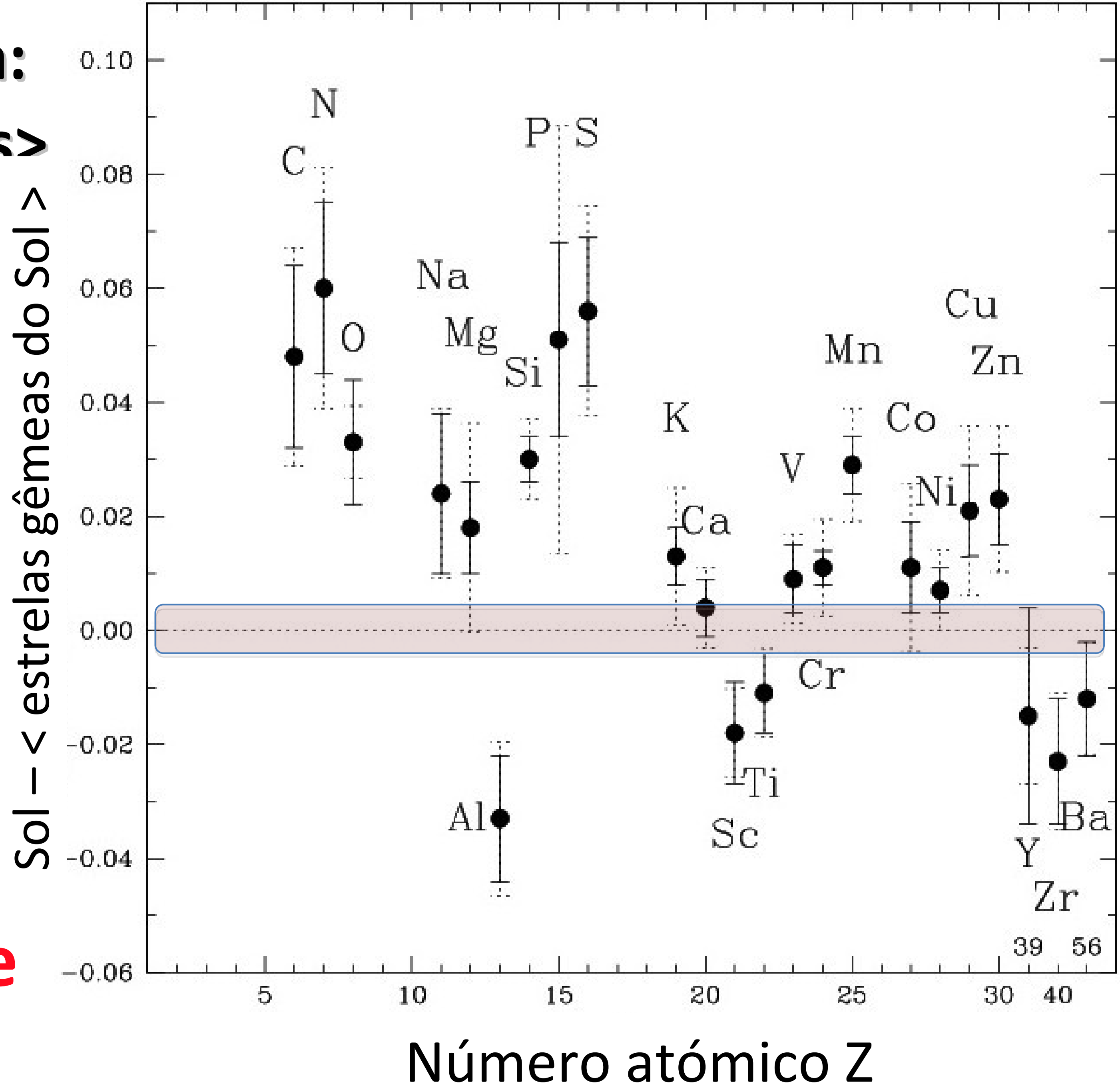
Meléndez et al. 2009, ApJ, 704, L66

Δ abundância: Sol - <gêmeas> vs. Número atómico Z

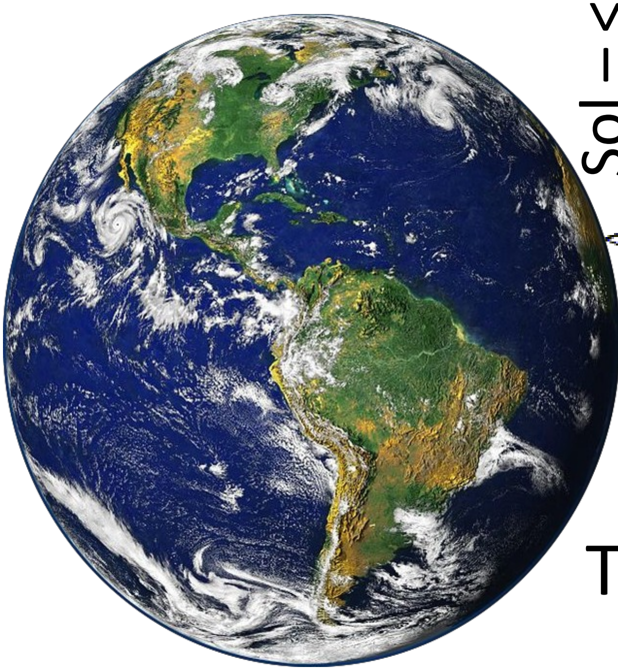
Sol normal : Δ = 0

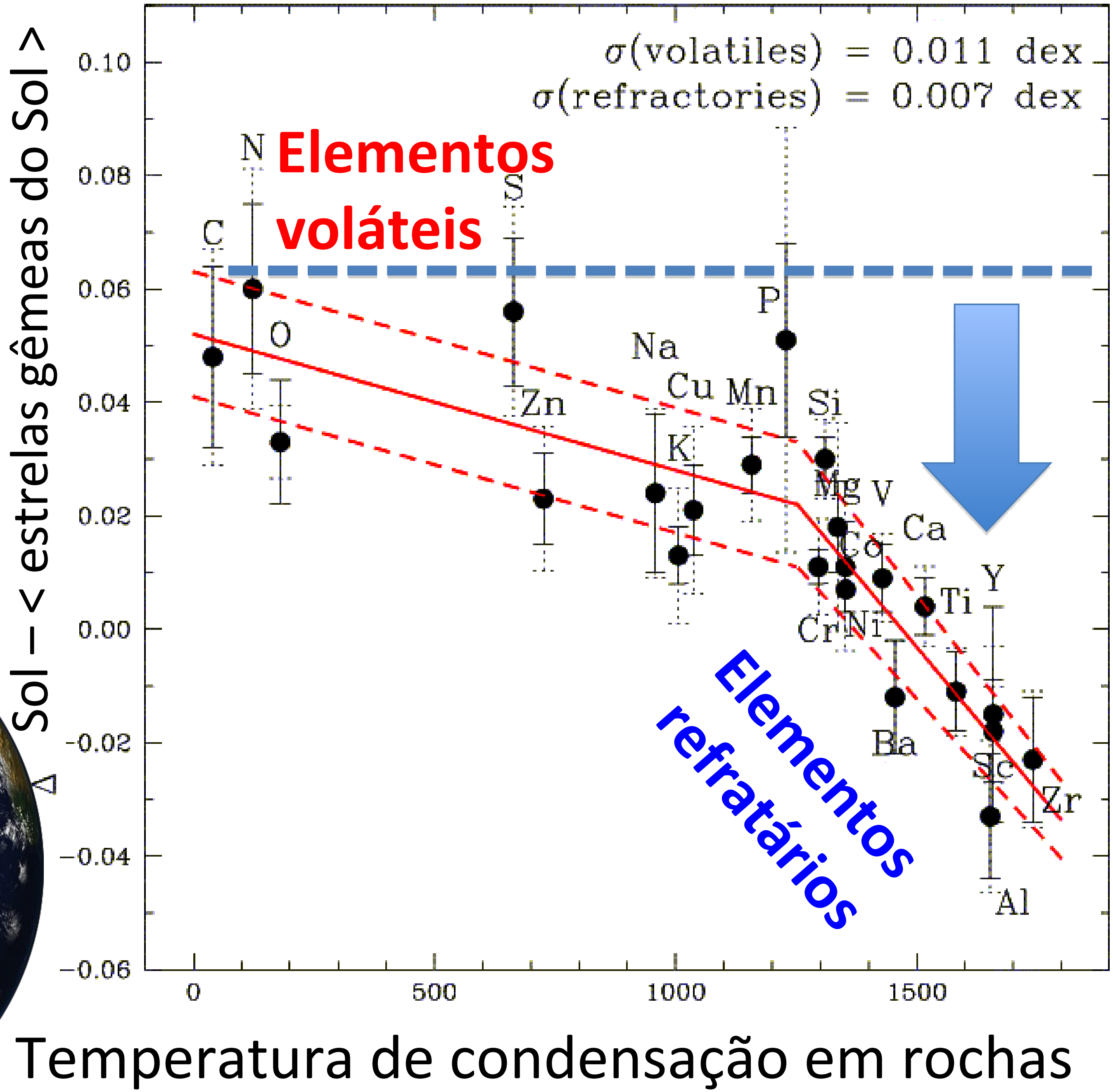
Sol anormal: Δ ≠ 0

Nossa estrela mãe é anómala



Elementos químicos que formam a Terra são mais deficientes no Sol !!!

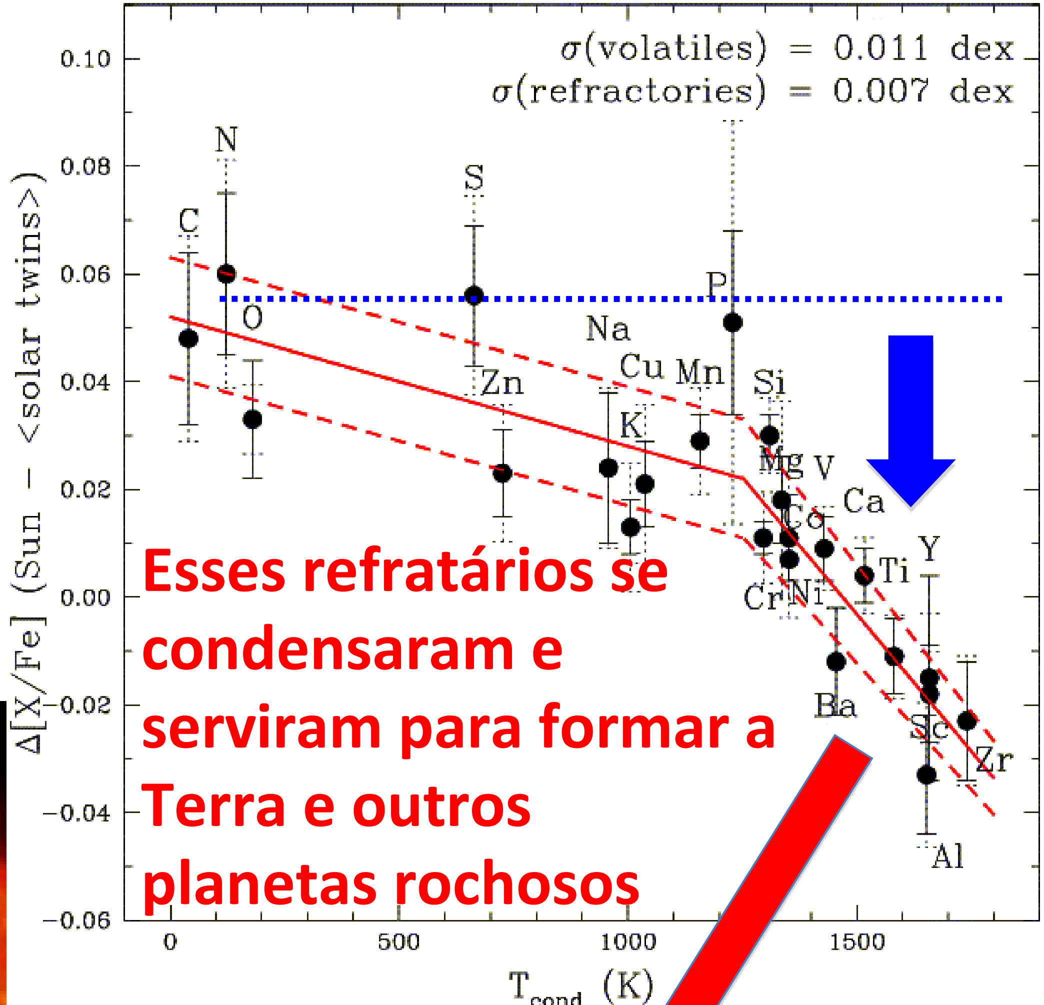




Meléndez, Asplund, Gustafsson, Yong 2009, ApJ Letters

Meléndez et al. 2009

Na região interna do Sistema Solar a temperatura é muito alta, permitindo a condensação de apenas elementos refratários



Esses refratários se condensaram e serviram para formar a Terra e outros planetas rochosos

https://arxiv.org/abs/2211.01800

Conexão estrela - planeta

Plausible constraints on the range of bulk terrestrial exoplanet compositions in the Solar neighbourhood

Rob J. Spaargaren et al., submitted to ApJ, Nov 3, 2022

- We circumscribe probable rocky exoplanet compositions based on a population analysis of stellar chemical abundances.

- Strong correlation between stellar Fe/Mg and metallic core sizes.

- Stellar Mg/Si gives a first-order indication of mantle mineralogy.

- The element Na, which modulates crustal buoyancy and mantle clinopyroxene fraction, is affected by devolatilization the most.

- Planetary mantles mostly consist of Fe/Mg-silicates

Composição química do Sol e de estrelas dos catálogos Hypatia e Galah

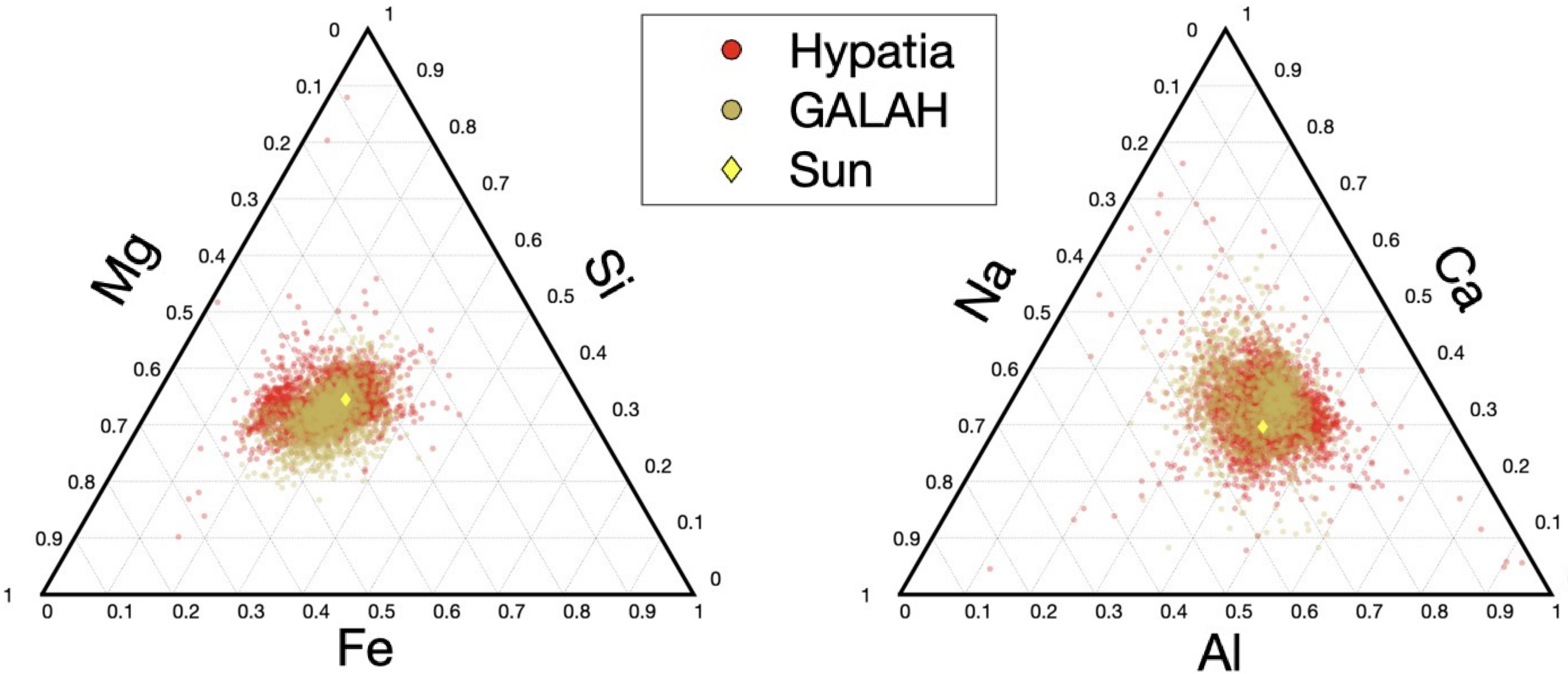


Figure 1. Stellar abundances documented in the Hypatia (red, 4236 stars) and GALAH (gold, 1971 stars) catalogues used in this study. Solar composition from Lodders et al. (2009) is plotted for comparison.

Composição química do Sol, estrelas, Terra e exoplanetas resultantes da composição química estelar

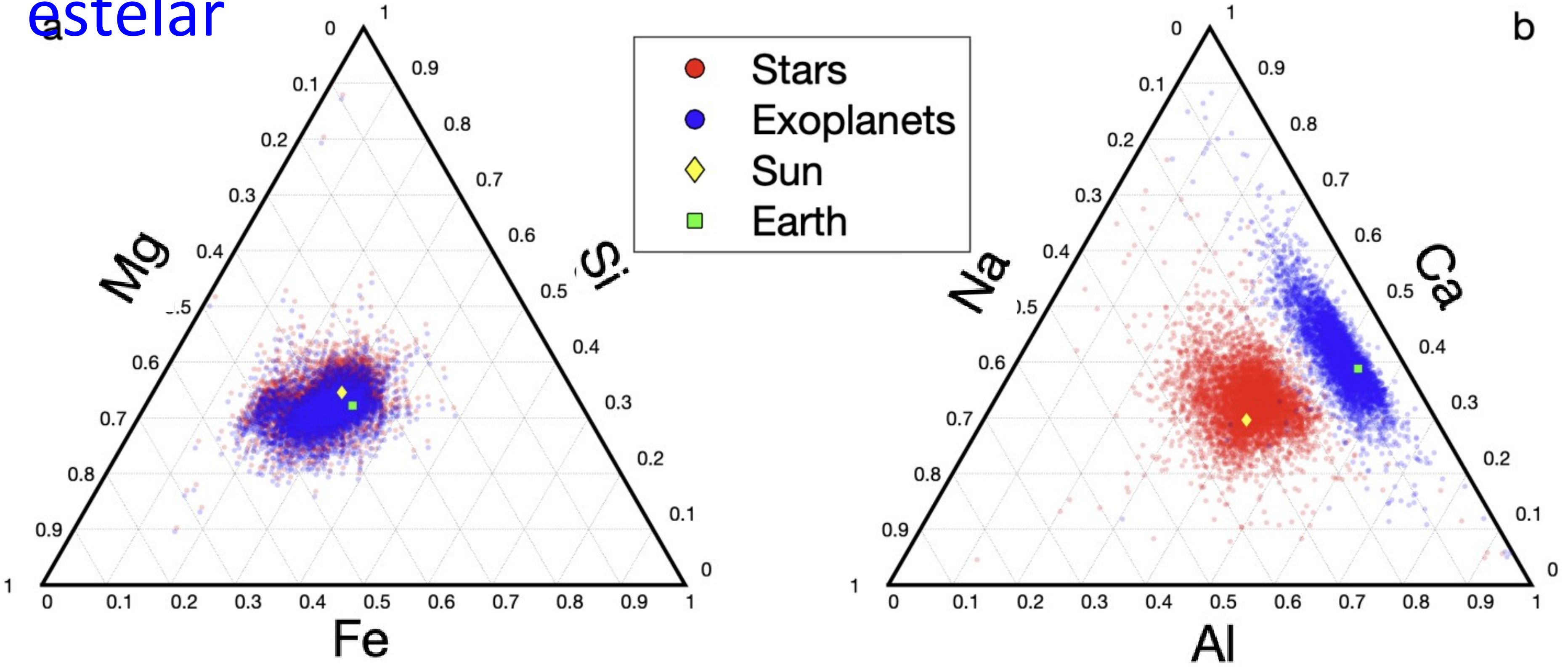


Figure 2. Bulk compositions of stars in the Solar neighbourhood (red; Hinkel et al. 2014; Buder et al. 2018), planet compositions calculated in this work (blue), Solar composition (yellow diamond; Lodders et al. 2009), and Earth composition (green square; McDonough 2003) molar compositions, in the Fe-Mg-Si (left) and Ca-Al-Na (right) systems.

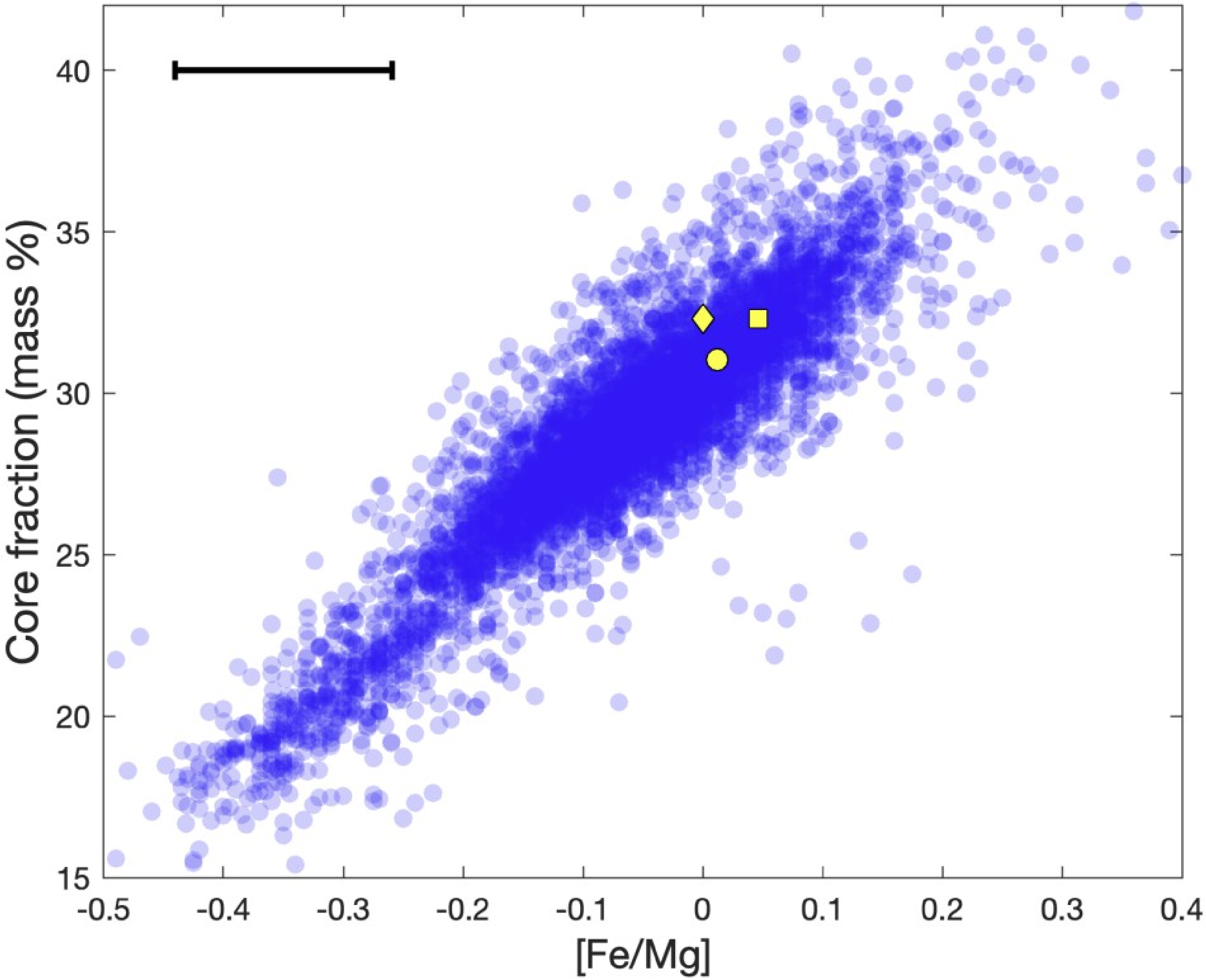


Figure 3. Core sizes of terrestrial-type exoplanets (mass fraction) as a function of stellar [Fe/Mg] (in dex, left)

Evolução química da Galáxia e interior de planetas

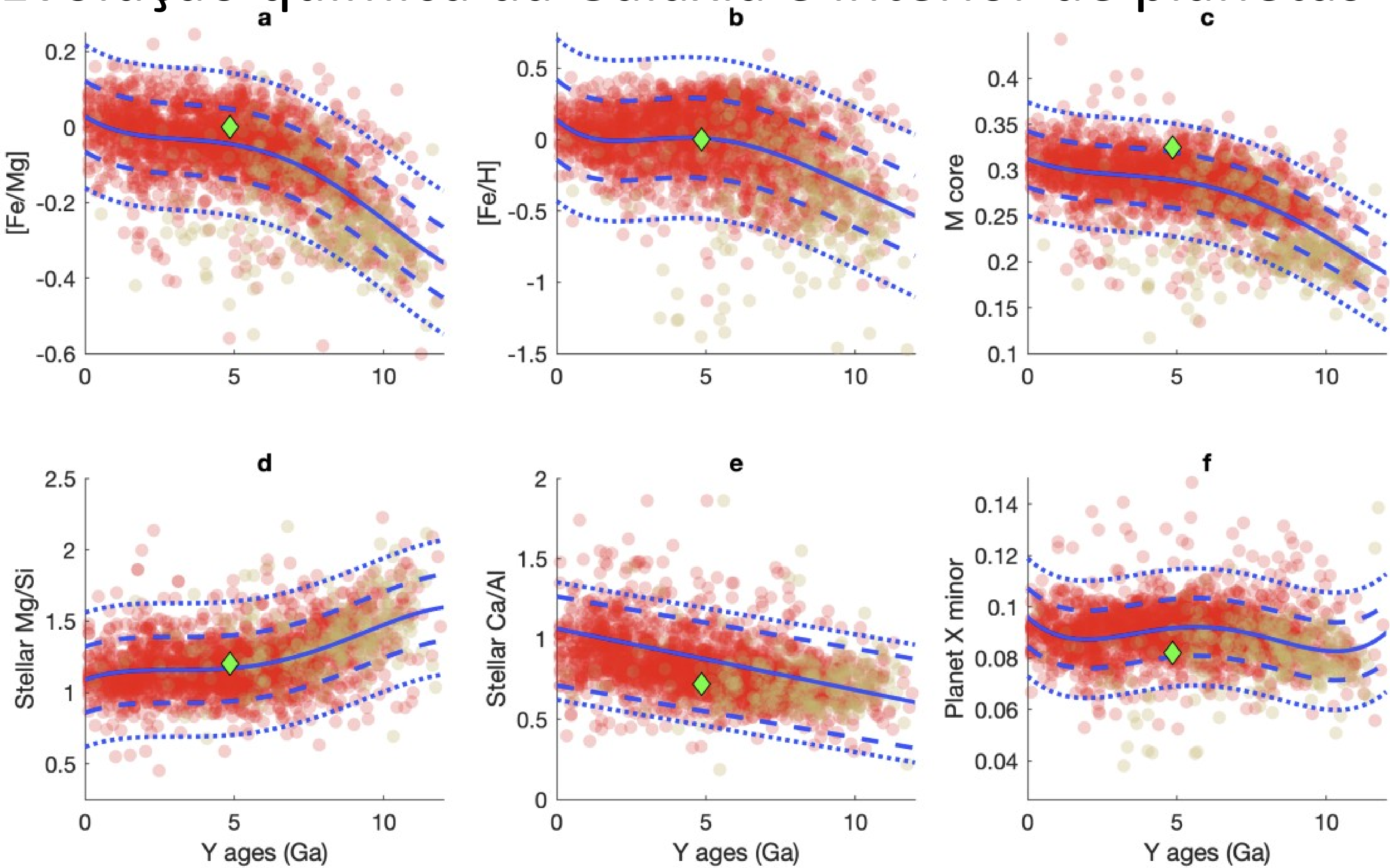


Figure S6. Stellar [Fe/Mg] (a), stellar [Fe/H] (b), core mass fraction (c), stellar molar Mg/Si (d), stellar Ca/Al (e), and planet mantle minor element fraction (f) as a function of stellar age (in Ga), estimated as a function of Y/Mg and Y/Al, based on equations 6 and 7 from Spina et al. (2018). Stellar compositions are from Hinkel et al. (2014), colour-coded for the thin disc (red) and thick disc (gold) populations of the Milky Way.

Não existe acordo sobre a influência da massa planetária na tectônica de placas

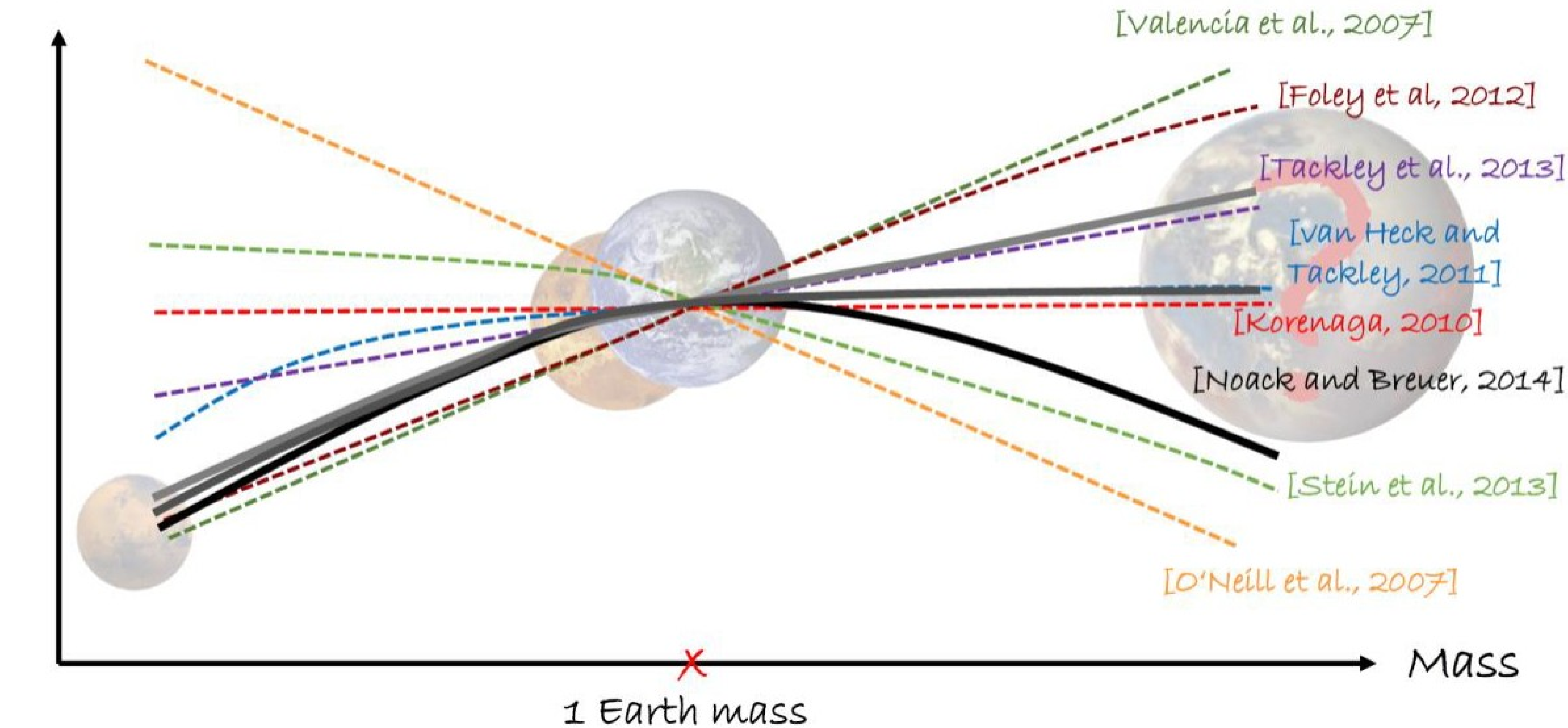
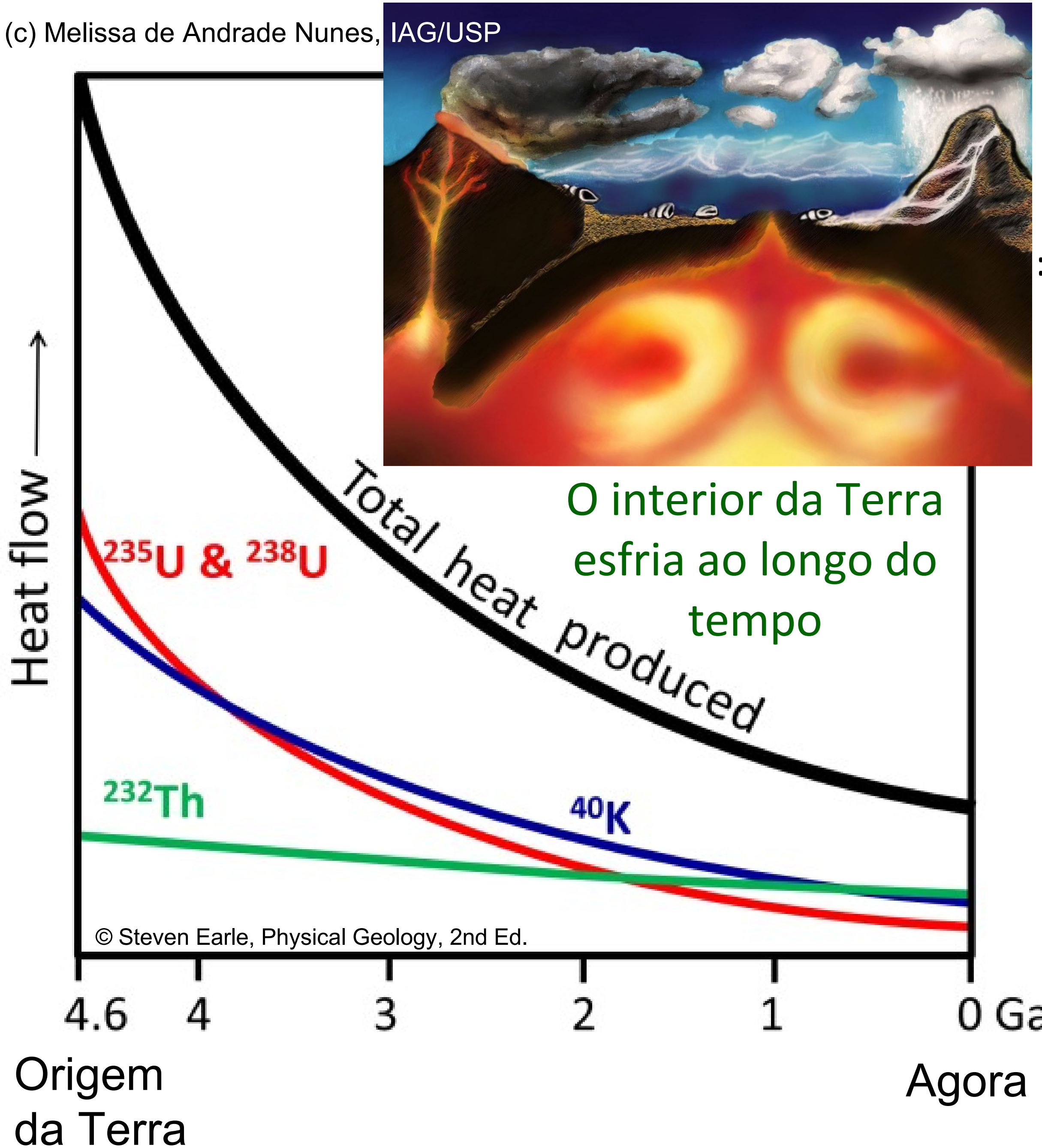


FIGURE 3 Sketch summarizing different predictions for the likelihood of plate tectonics as a function of planet mass, scaled to the same likelihood at one Earth mass (as a reference point). The grey-to-black lines indicate different trends as a function of initial mantle temperature (grey = hot; black = cold) after planet formation as found in Noack and Breuer (2014). The dashed colored lines refer to previous studies as cited in Noack and Breuer (2014).

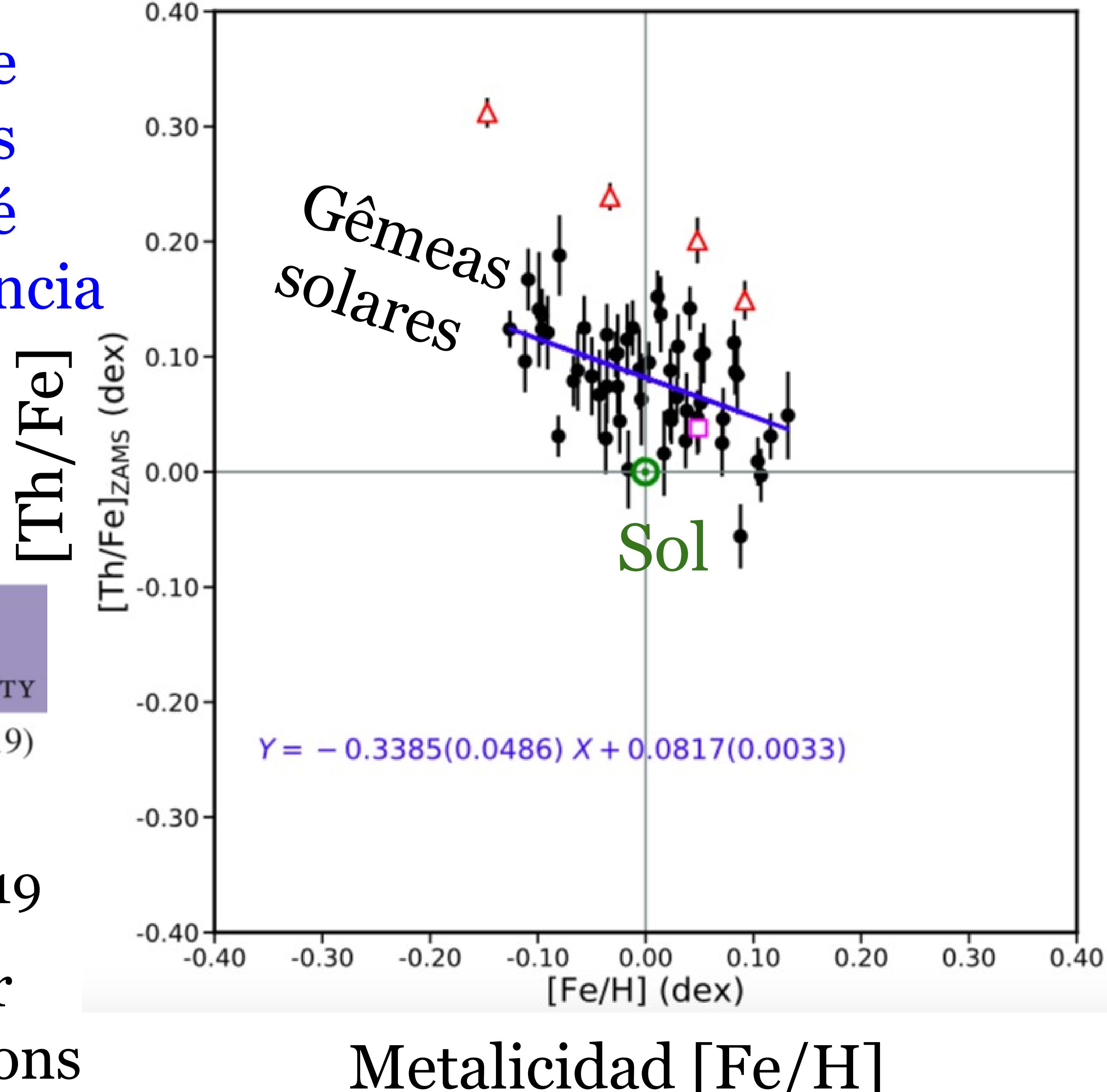


Fluxo de calor na superfície da Terra = 47 TW (Davies & Davies 2010)

Energia do decaimento radioativo ~24 TW (Die 2012)

→ ~50% do calor observado é residual da formação da Terra

A abundância de tório em estrelas gêmeas solares é maior à abundância de Th no Sol



Monthly Notices *of the* ROYAL ASTRONOMICAL SOCIETY

MNRAS **482,** 1690–1700 (2019)

Botelho, Milone, Meléndez et al. 2019

Thorium in Solar Twins: implications for habitability

Outras estrelas com planetas rochosos podem ter planetas ativos!

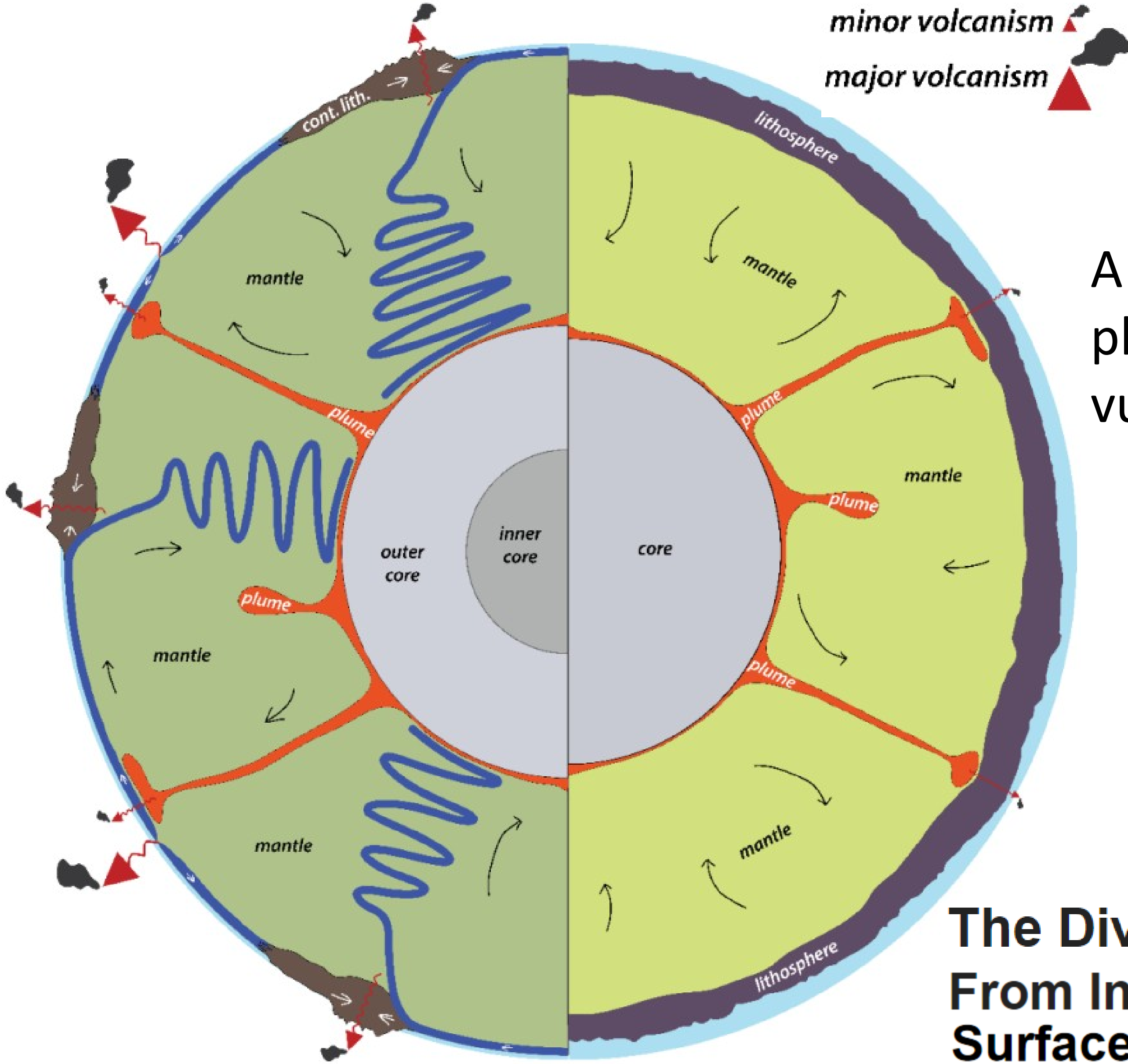


FIGURE 1 (LEFT) Dynamics of a plate-tectonic planet. (RIGHT) Dynamics of a stagnant-lid planet. Respective halves of composite planet not to scale. Continental lithosphere in dark brown; oceanic lithosphere in dark blue; stagnant lid in purplish brown; mantle in green. White arrows denote plate motion; black arrows denote mantle convection patterns. Hot upwelling plumes are orange. Triangles mark sites of more-or-less vigorous volcanism. Liquid outer core is light grey; solid inner core is dark grey. Potential oceans in light blue. The size of each planetary hemisphere is arbitrary.

A espessura da crosta planetária pode afetar o vulcanismo

The Diversity of Exoplanets: From Interior Dynamics to Surface Expressions

Maxim D. Ballmer[1,2] and Lena Noack[3]