Introduction to exoplanets

Jovian population

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My career path

- 2018 Bc from Masaryk University, Brno, Czechia
- 2019 ERASMUS stay at IAC, La Palma, Spain
- 2020 MSc from Masaryk University, Brno, Czechia

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- Currently PostDoc at ASU
- Research interest: exoplanets, binaries, stellar parameters

Extrasolar planets

- Planets orbiting stars other than the Sun

What is a planet?

The definition of a planet adopted by the IAU says a planet must do three things:

1. It must orbit a star (in our cosmic neighborhood, the Sun).
2. It must be big enough to have enough gravity to force it into a spherical shape.
3. It must be big enough that its gravity has cleared away any other objects of a similar size near its orbit around the Sun.

What is an exoplanet?

- **IAU working definition**

The current working definition of an exoplanet is as follows:

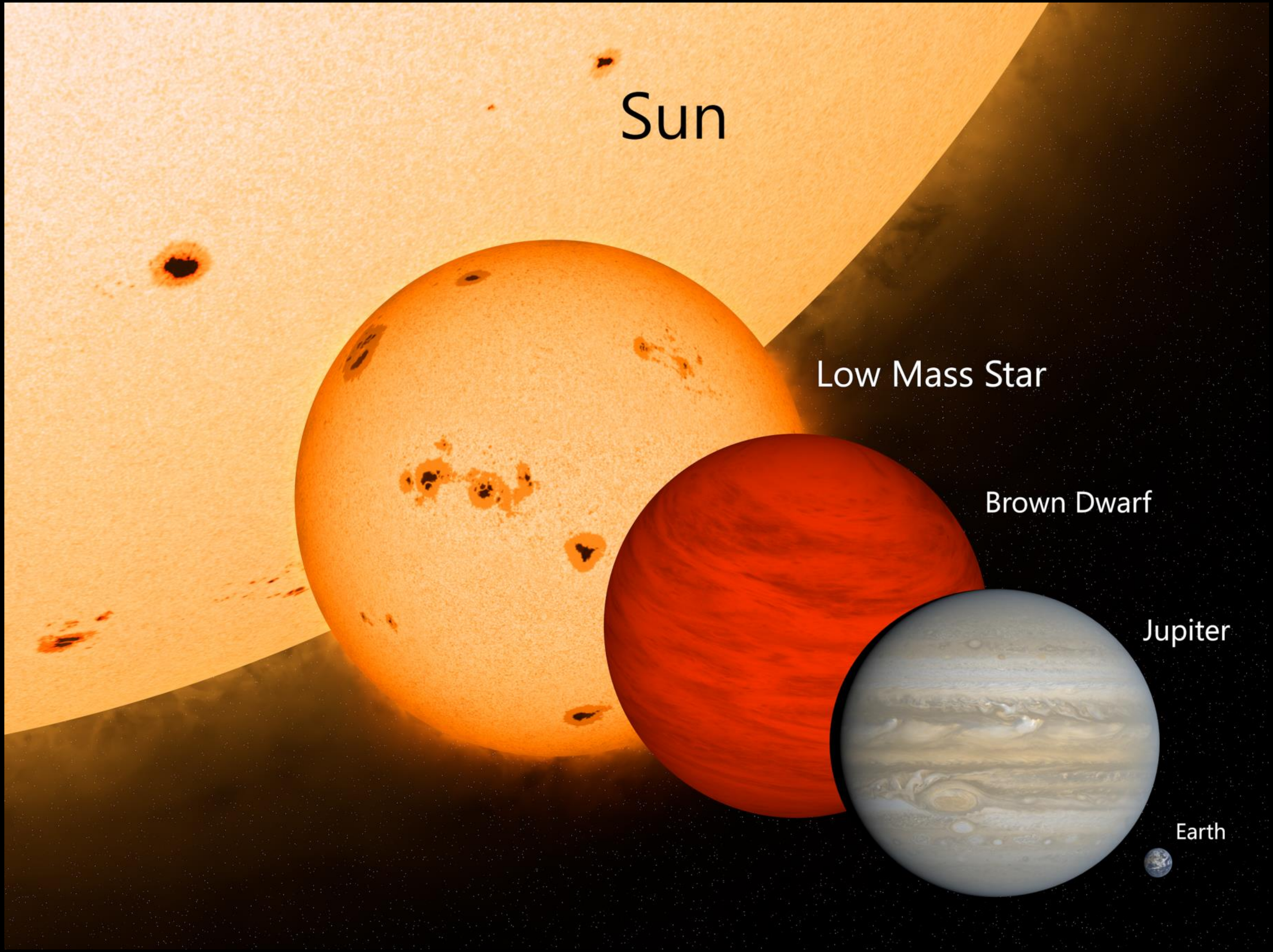
1. *Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars, brown dwarfs or stellar remnants and that have a mass ratio with the central object below the L_4/L_5 instability ($M/M_{\mathrm{central}} < 2/\left(25+\sqrt{621}\right) \approx 1/25$) are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.*

2. *Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.*

3. *Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).*

What is an exoplanet?

- **Planets**: Mass below the deuterium fusion limit (~13 Jupiter masses), distinguishing it from brown dwarfs
- **Brown dwarfs**: Below the mass of stars but above planets (~13 to ~ 75 Jupiter masses), cannot fuse hydrogen to helium but can fuse deuterium and in some cases lithium



NASA

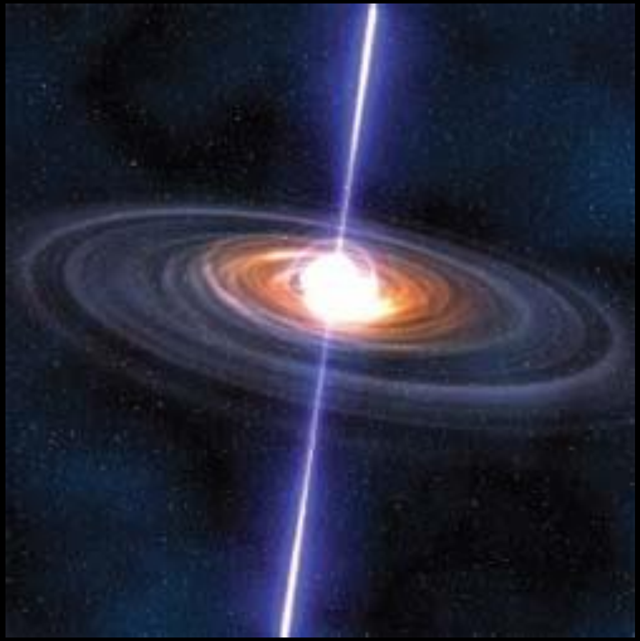
Extrasolar planets

- Planets orbiting stars other than the Sun
- Early modern ideas in the 1950s by Otto Struve

ESO

Extrasolar planets

- Planets orbiting stars other than the Sun
- Early modern ideas in the 1950s by Otto Struve
- First firm detection by Wolszczan et al. (1992) around a pulsar



C. Liu

Extrasolar planets

- Planets orbiting stars other than the Sun
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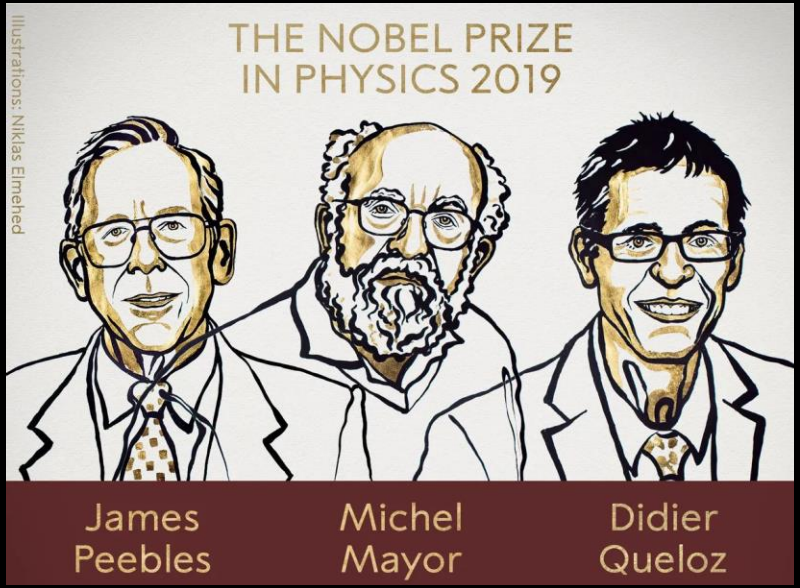
- First planet around a main sequence star (Mayor & Queloz, 1995)



N. Elmehed

Extrasolar planets

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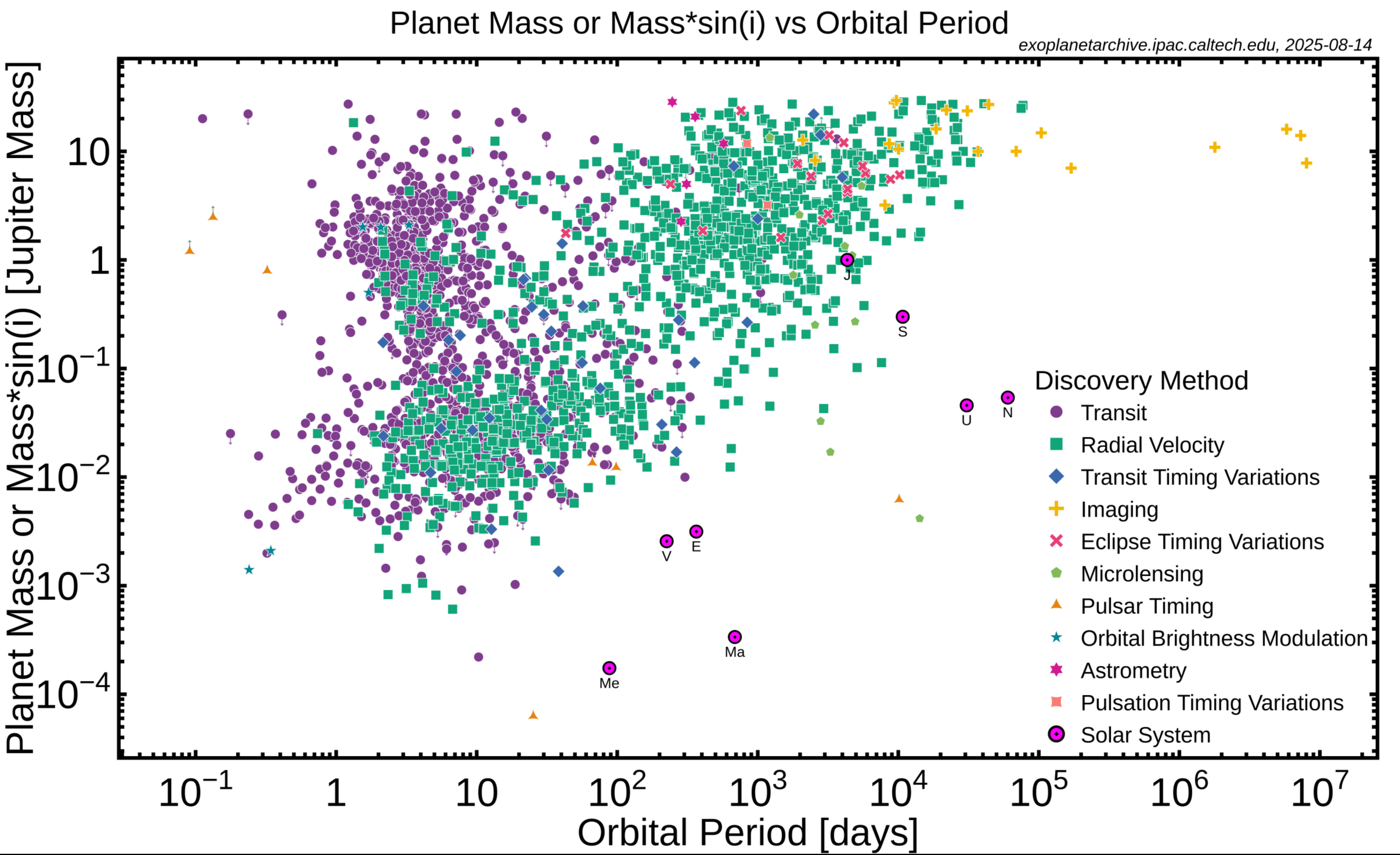
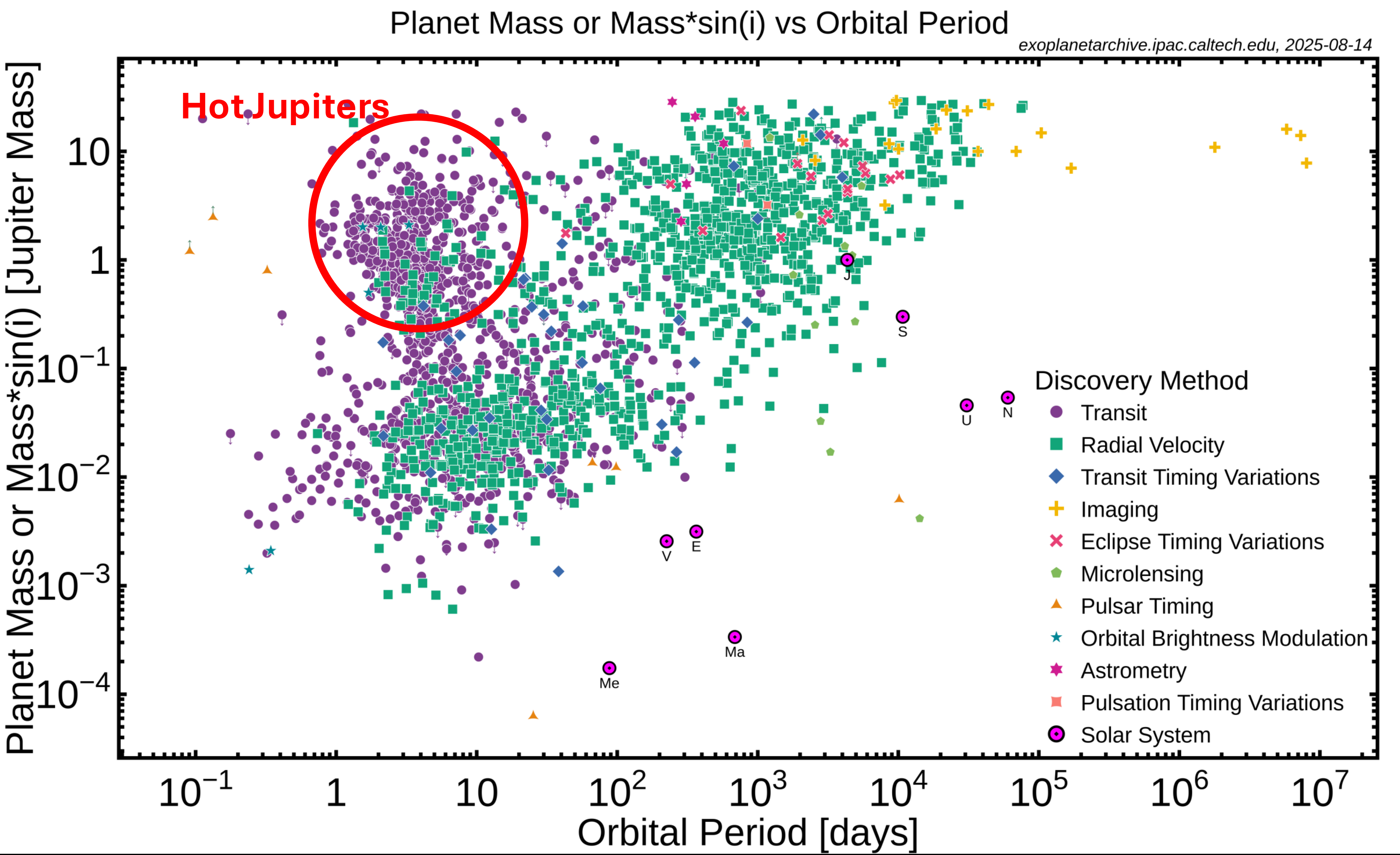
- Early modern ideas in the 1950s by Otto Struve
- First firm detection by Wolszczan et al. (1992) around a pulsar
- First planet around a main sequence star (Mayor & Queloz, 1995)

- Currently around 6000 confirmed planets and 1000 multi-planetary systems with a large diversity



Planet Mass or Mass*sin(i) vs Orbital Period
exoplanetarchive.ipac.caltech.edu, 2025-08-14
Planet Mass or Mass*sin(i) [Jupiter Mass]
Orbital Period [days]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
J
S
U
N
V
E
Ma
Me
Discovery Method
Transit
Radial Velocity
Transit Timing Variations
Imaging
Eclipse Timing Variations
Microlensing
Pulsar Timing
Orbital Brightness Modulation
Astrometry
Pulsation Timing Variations
Solar System



Planet Mass or Mass*sin(i) vs Orbital Period
exoplanetarchive.ipac.caltech.edu, 2025-08-14
Hot Jupiters
Planet Mass or Mass*sin(i) [Jupiter Mass]
Orbital Period [days]
Discovery Method
Transit
Radial Velocity
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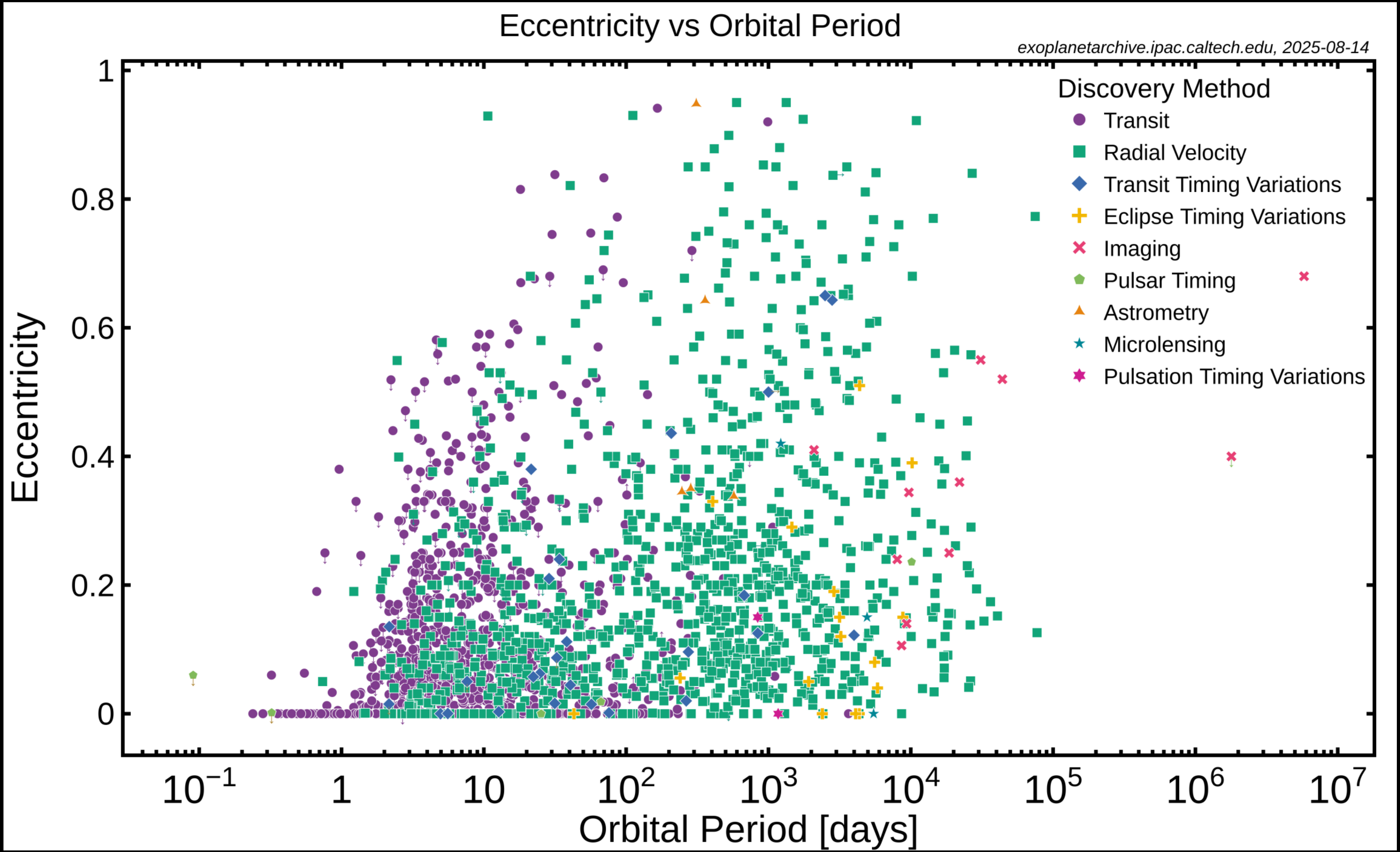
Solar System
Me
V
E
Ma
J
S
U
N

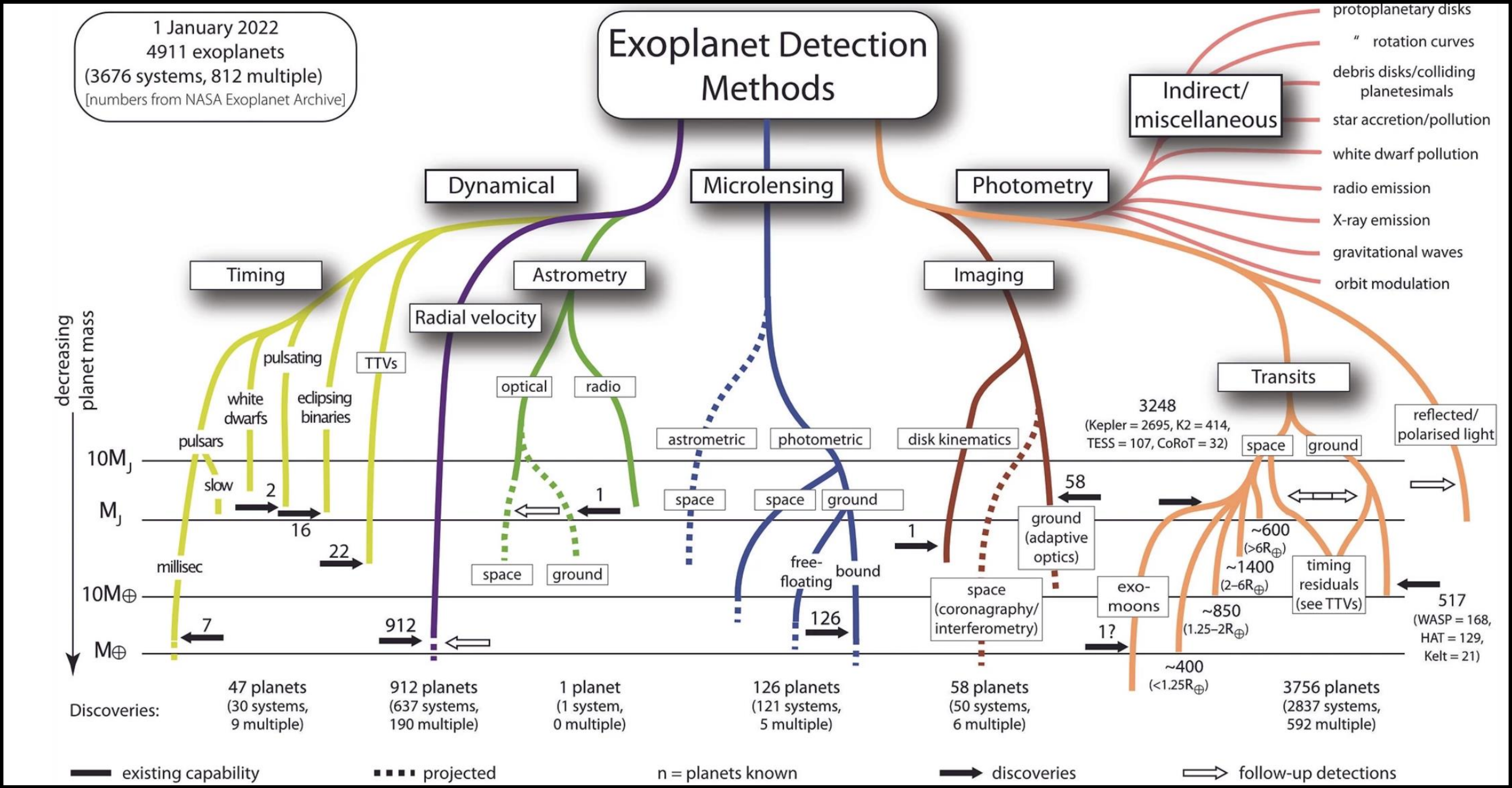


Eccentricity vs Orbital Period
exoplanetarchive.ipac.caltech.edu, 2025-08-14
Eccentricity
Orbital Period [days]
Discovery Method
Transit
Radial Velocity
Transit Timing Variations
Eclipse Timing Variations
Imaging
Pulsar Timing
Astrometry
Microlensing
Pulsation Timing Variations

Key questions

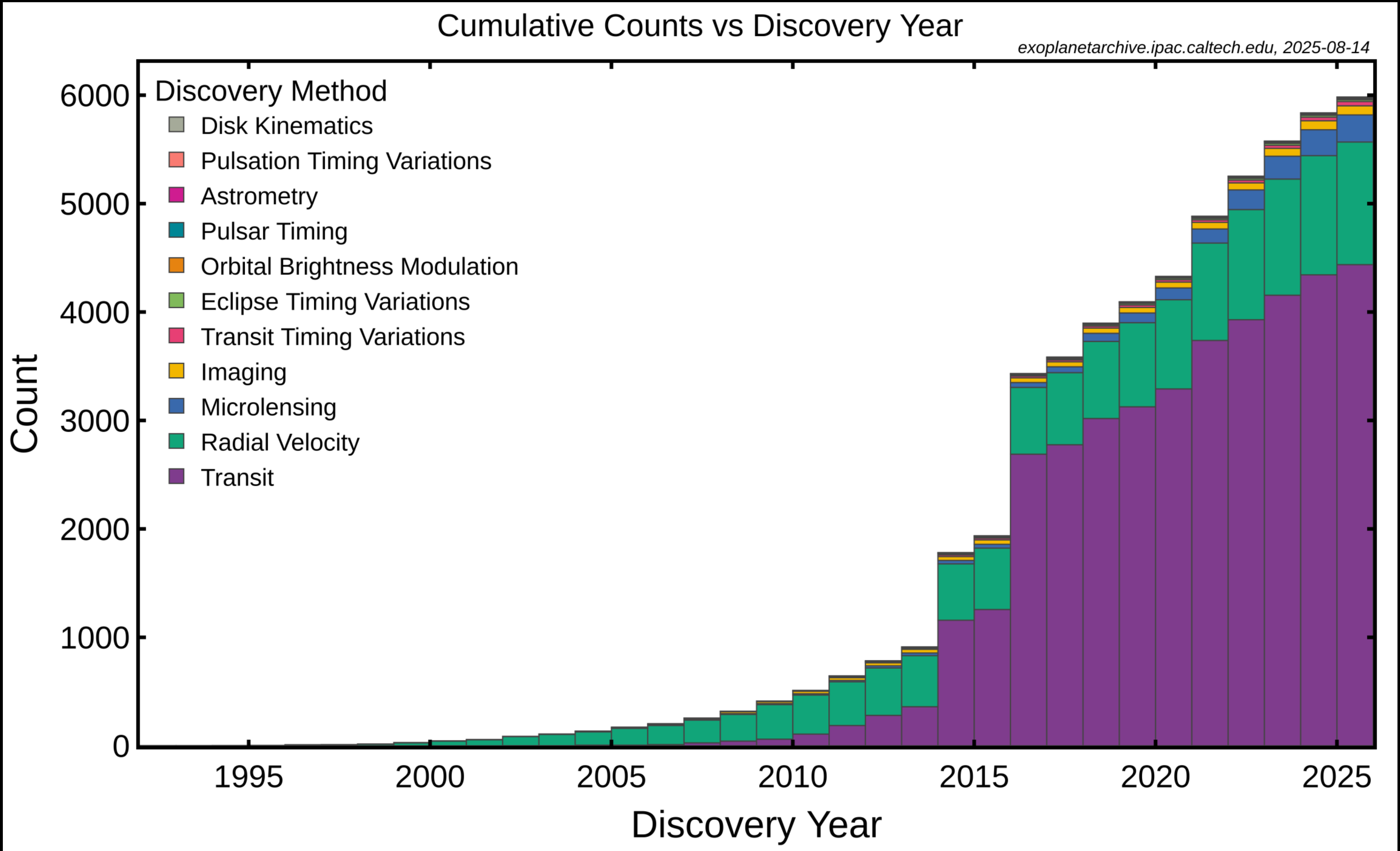
- How do planets form and evolve?
- Is our own Solar System unique?
- What are exoplanets made of?
- What are the physical processes shaping them?

Discovery methods


1 January 2022
4911 exoplanets
(3676 systems, 812 multiple)
[numbers from NASA Exoplanet Archive]
Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Indirect/ miscellaneous
protoplanetary disks
" rotation curves
debris disks/colliding planetesimals
star accretion/pollution
white dwarf pollution
radio emission
X-ray emission
gravitational waves
orbit modulation
Timing
Astrometry
Radial velocity
Imaging
Transits
decreasing planet mass
pulsating
TTVs
white dwarfs
eclipsing binaries
pulsars
slow
millisec
optical
radio
space
ground
astrometric
photometric
space
space
ground
free-floating
bound
disk kinematics
ground (adaptive optics)
space (coronagraphy/ interferometry)
3248
(Kepler = 2695, K2 = 414, TESS = 107, CoRoT = 32)
space
ground
reflected/ polarised light
exo-moons
timing residuals (see TTVs)
~600 (>6R⊕)
~1400 (2–6R⊕)
~850 (1.25–2R⊕)
~400 (<1.25R⊕)
517
(WASP = 168, HAT = 129, Kelt = 21)
10MJ
MJ
10M⊕
M⊕
2
16
22
7
912
1
126
1
58
1?
Discoveries:
47 planets (30 systems, 9 multiple)
912 planets (637 systems, 190 multiple)
1 planet (1 system, 0 multiple)
126 planets (121 systems, 5 multiple)
58 planets (50 systems, 6 multiple)
3756 planets (2837 systems, 592 multiple)
existing capability
projected
n = planets known
discoveries
follow-up detections

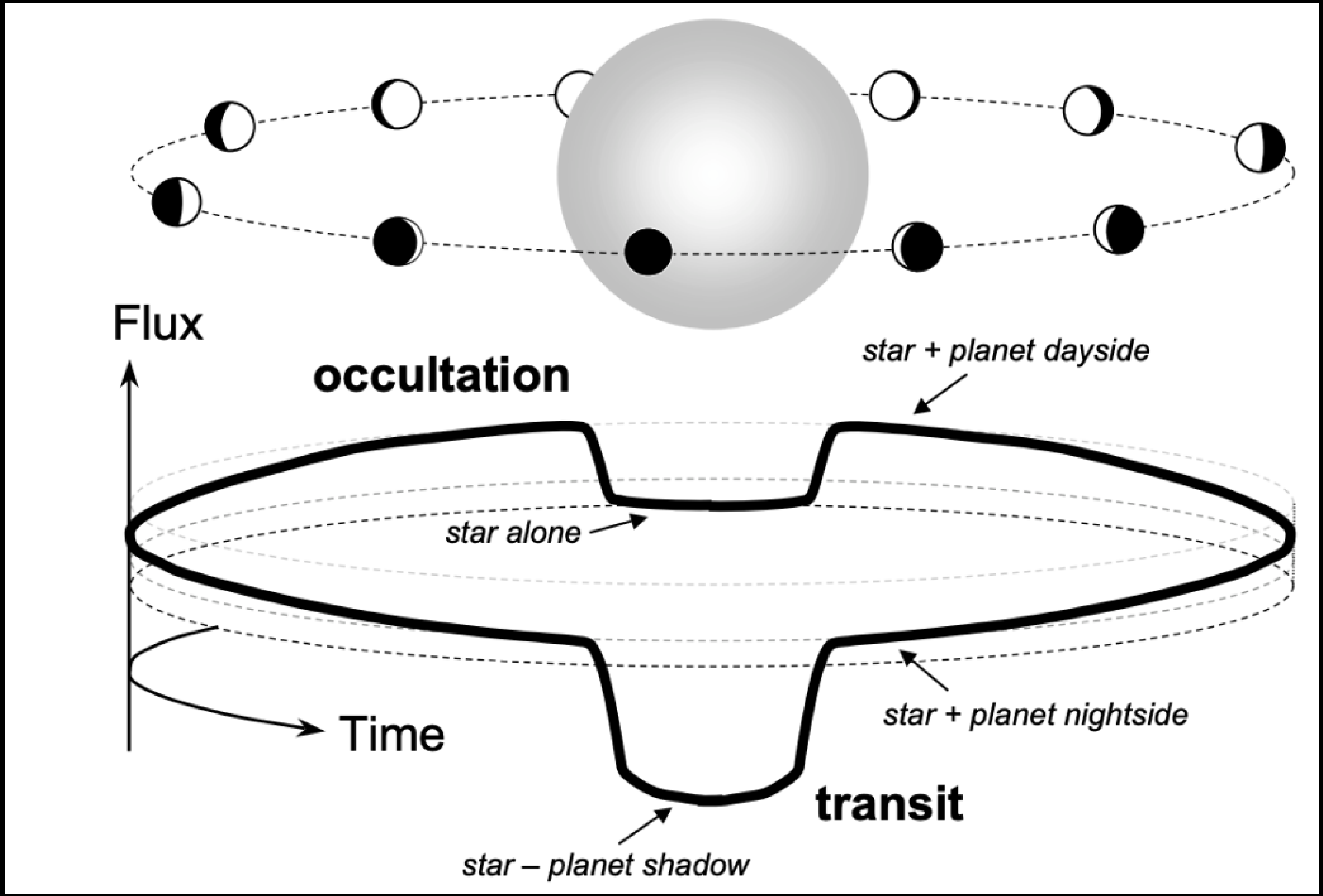
Discovery methods

- Transit
- Radial velocity
- Astrometry
- Microlensing
- Many others



Cumulative Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2025-08-14
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Count
0
1000
2000
3000
4000
5000
6000
1995
2000
2005
2010
2015
2020
2025
Discovery Year

Transit method



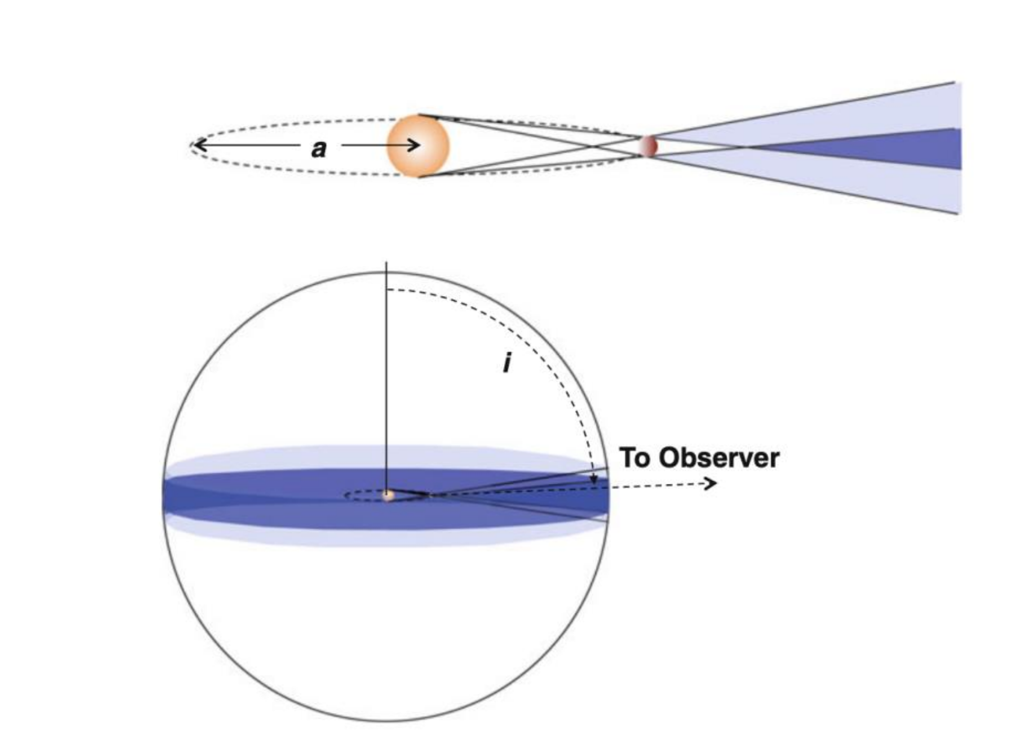
Transit method

- Most common
- HD 209458 b (Charbonneau and Henry) in 1999

Transit method

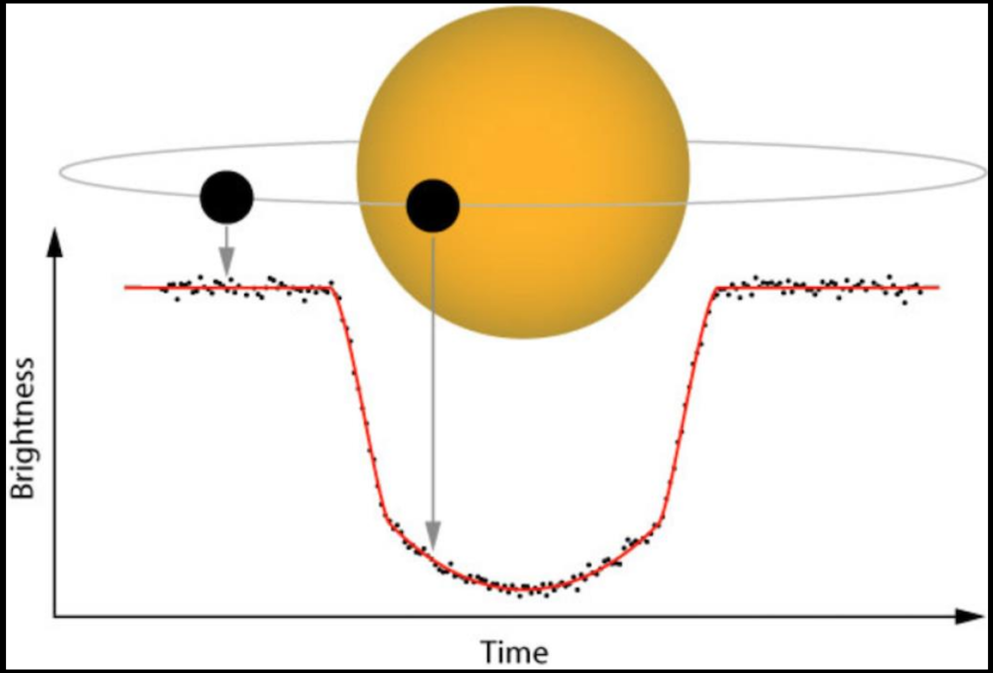
- Most common
- Bias towards large planets on short orbits

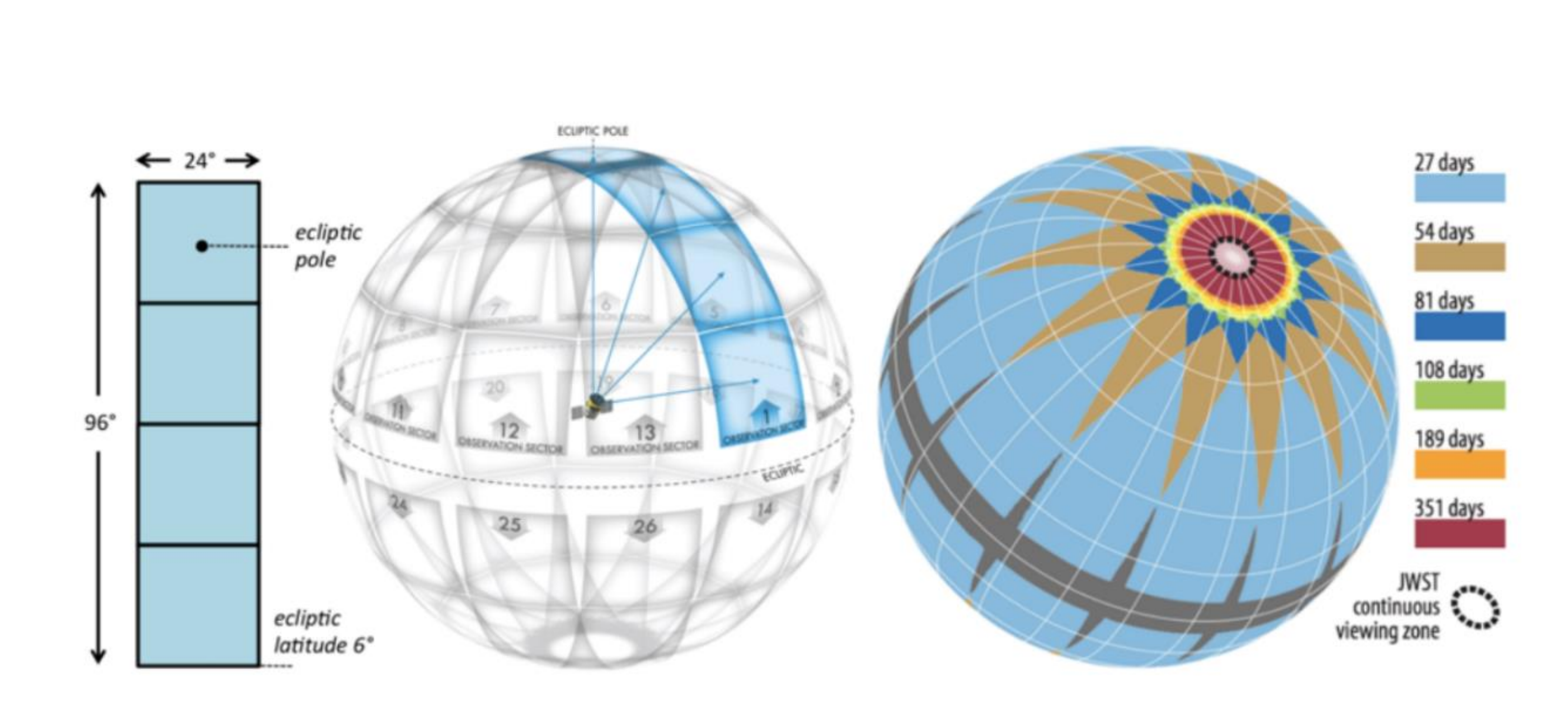
$$p = \frac{R_\star}{a} \simeq 0.005 \left(\frac{R_\star}{R_\odot}\right) \left(\frac{a}{1au}\right)^{-1}$$



Transit method

- Most common
- HD 209458 b (Charbonneau and Henry) in 1999
- Bias towards large planets on short orbits
- Kepler and TESS missions, soon PLATO




24°
96°
ecliptic pole
ecliptic latitude 6°
ECLIPTIC POLE
12
OBSERVATION SECTOR
13
OBSERVATION SECTOR
1
OBSERVATION SECTOR
ECLIPTIC
25
26
27 days
54 days
81 days
108 days
189 days
351 days
JWST continuous viewing zone

NASA

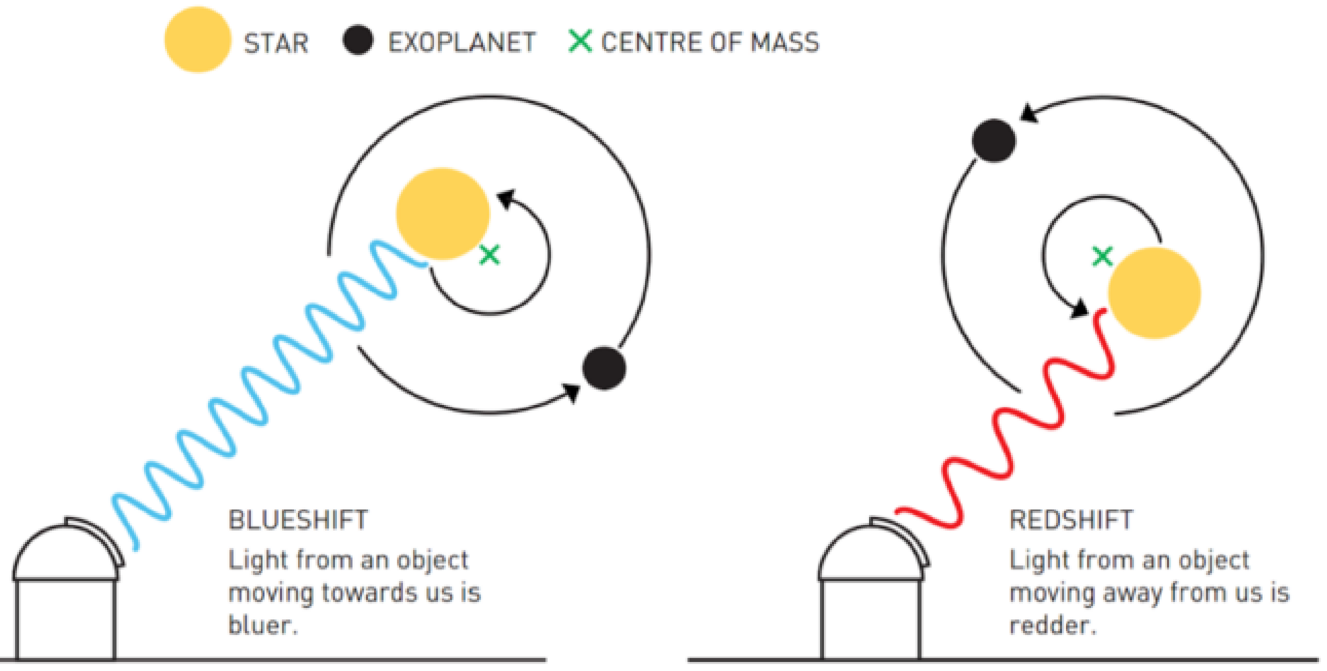
Transit method

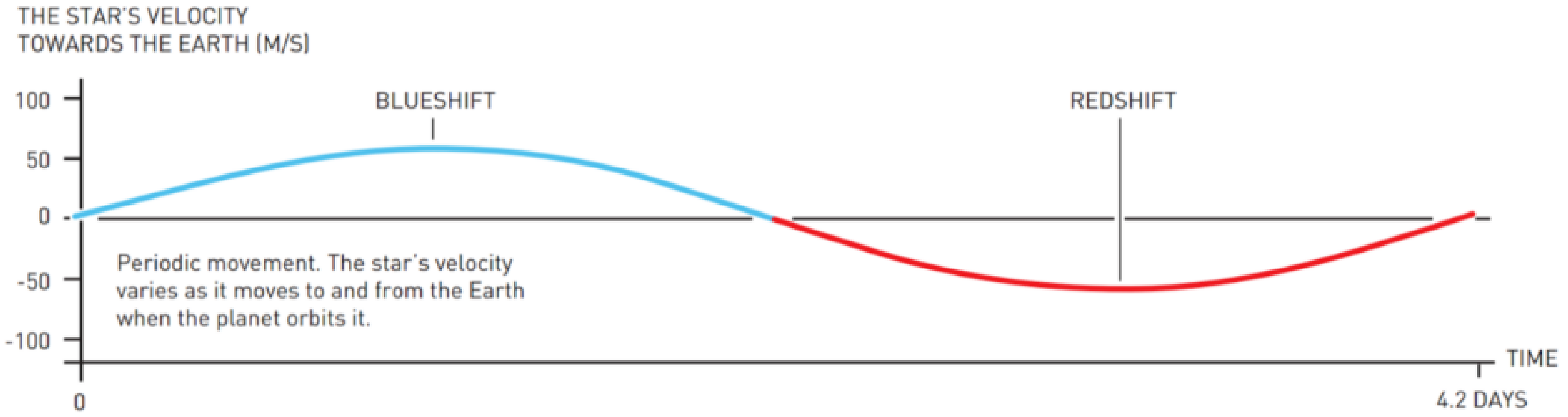
- Most common
- HD 209458 b (Charbonneau and Henry) 1999
- Bias towards large planets on short orbits
- Kepler and TESS missions, soon PLATO
- Only provides planetary radius, information on mass is missing

Radial velocity method

FINDING PLANETS USING THE RADIAL VELOCITY METHOD

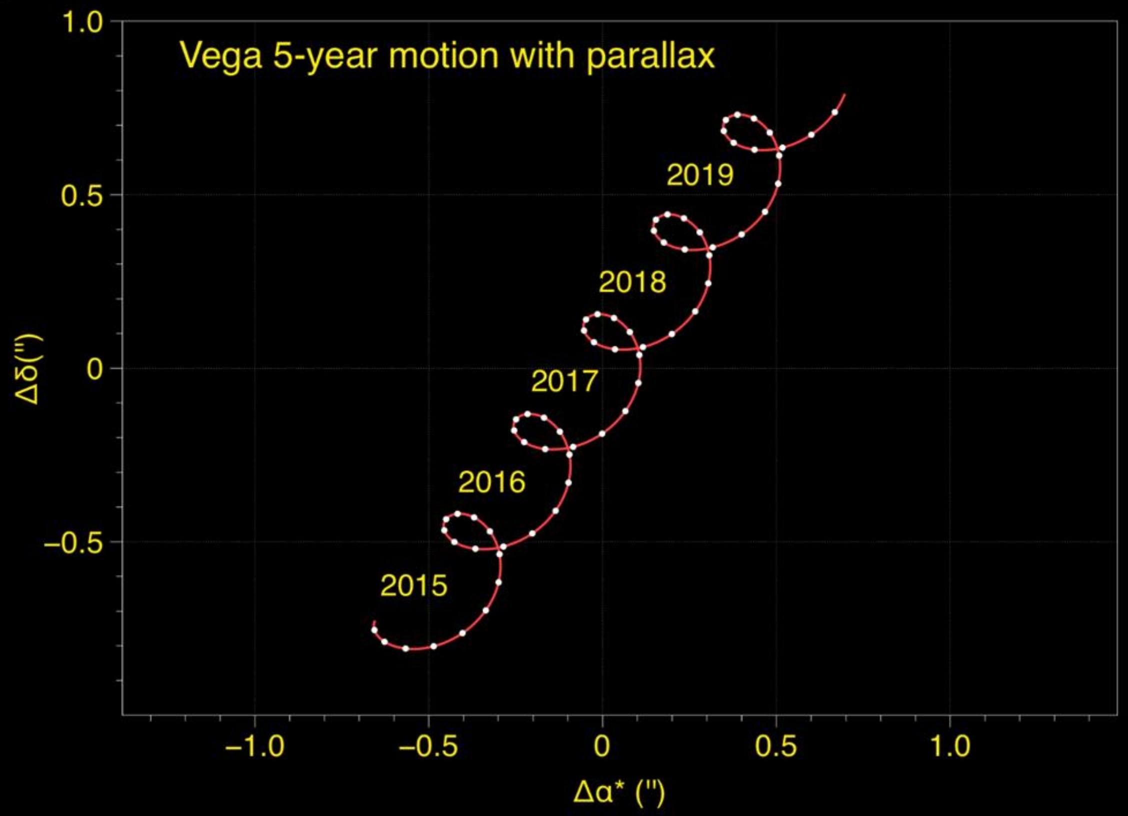
The star moves as it is affected by the gravity of its planet. Seen from the Earth, the star wobbles backwards and forwards in the line of sight. The speed of this movement, its radial velocity, can be determined using the Doppler effect, because the light from a moving object changes colour.





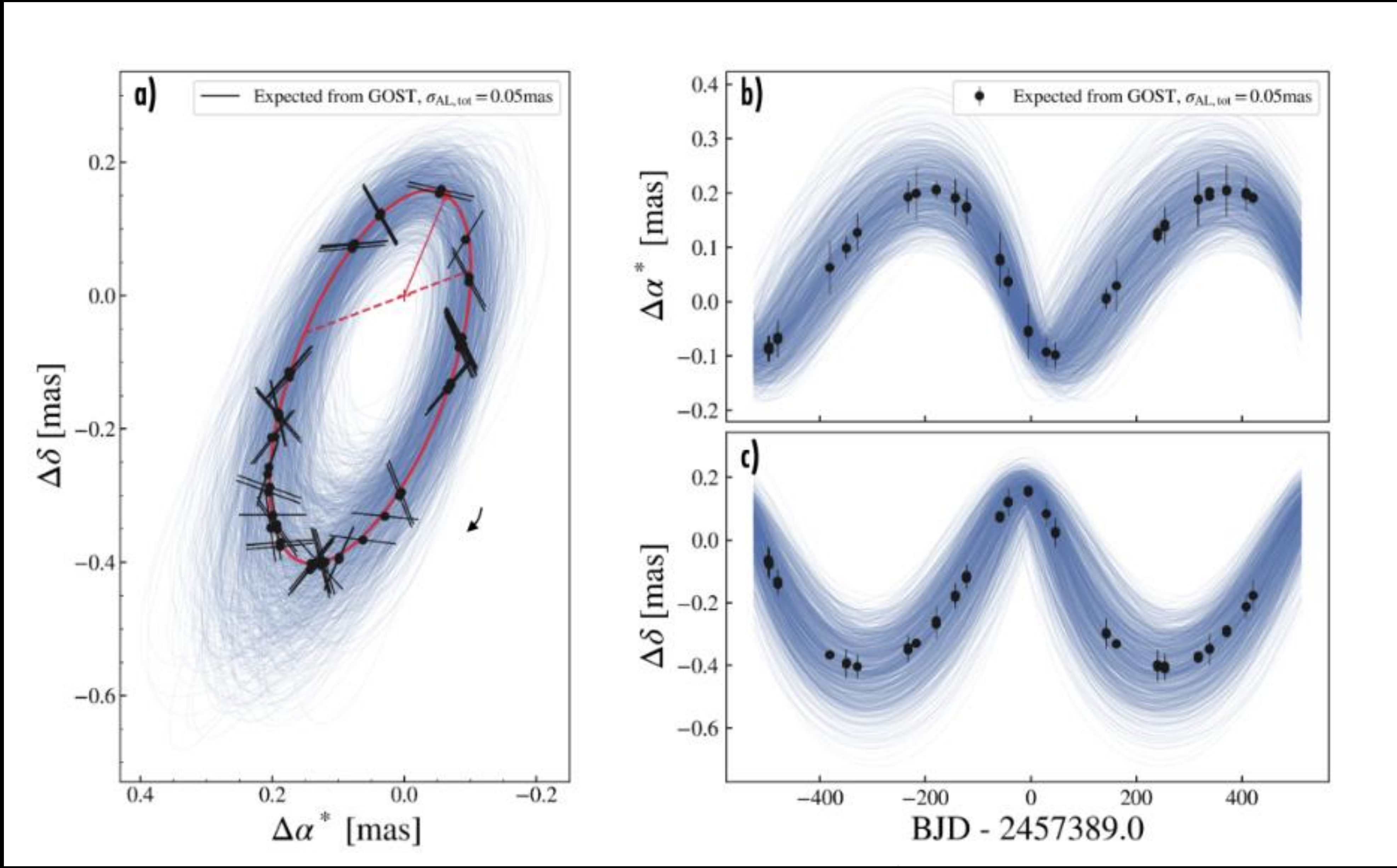
Astrometry

- Measure a star's position to find small, periodic wobbles caused by an orbiting planet's gravitational pull.
- Astrometry missions: Gaia



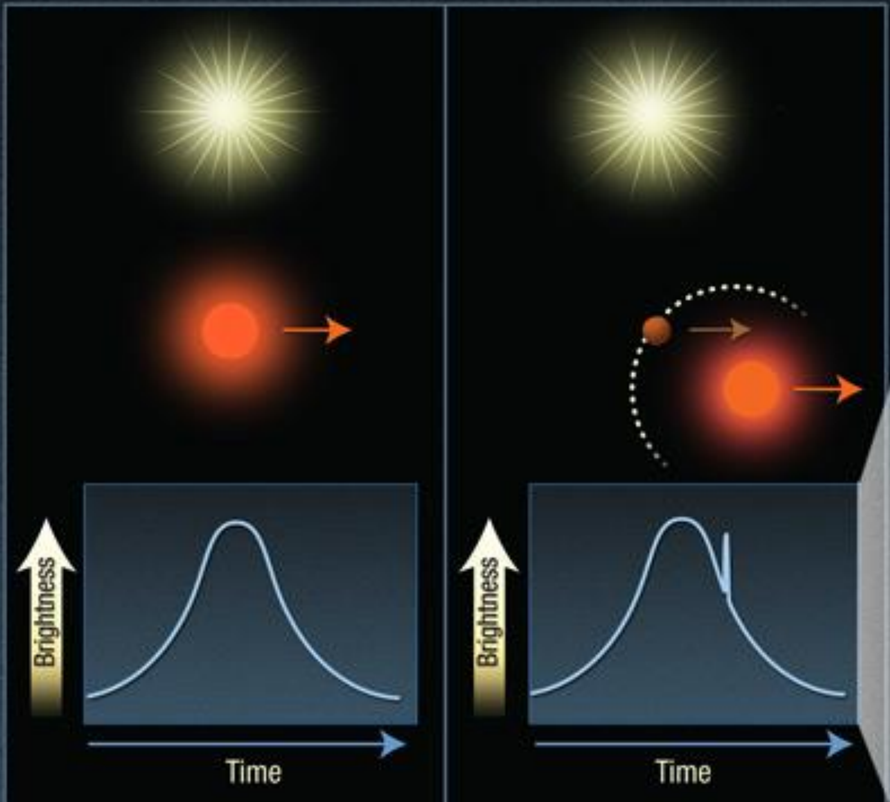
Astrometry

- Measure a star's position to find small, periodic wobbles caused by an orbiting planet's gravitational pull.
- Astrometry missions: Gaia
- Biases towards nearby star hosting massive planets at large separations


a)
Expected from GOST, $\sigma_{AL,tot} = 0.05$mas
0.2
0.0
−0.2
−0.4
−0.6
$\Delta\delta$ [mas]
0.4
0.2
0.0
−0.2
$\Delta\alpha^*$ [mas]
b)
Expected from GOST, $\sigma_{AL,tot} = 0.05$mas
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
$\Delta\alpha^*$ [mas]
c)
0.2
0.0
−0.2
−0.4
−0.6
$\Delta\delta$ [mas]
−400
−200
0
200
400
BJD - 2457389.0

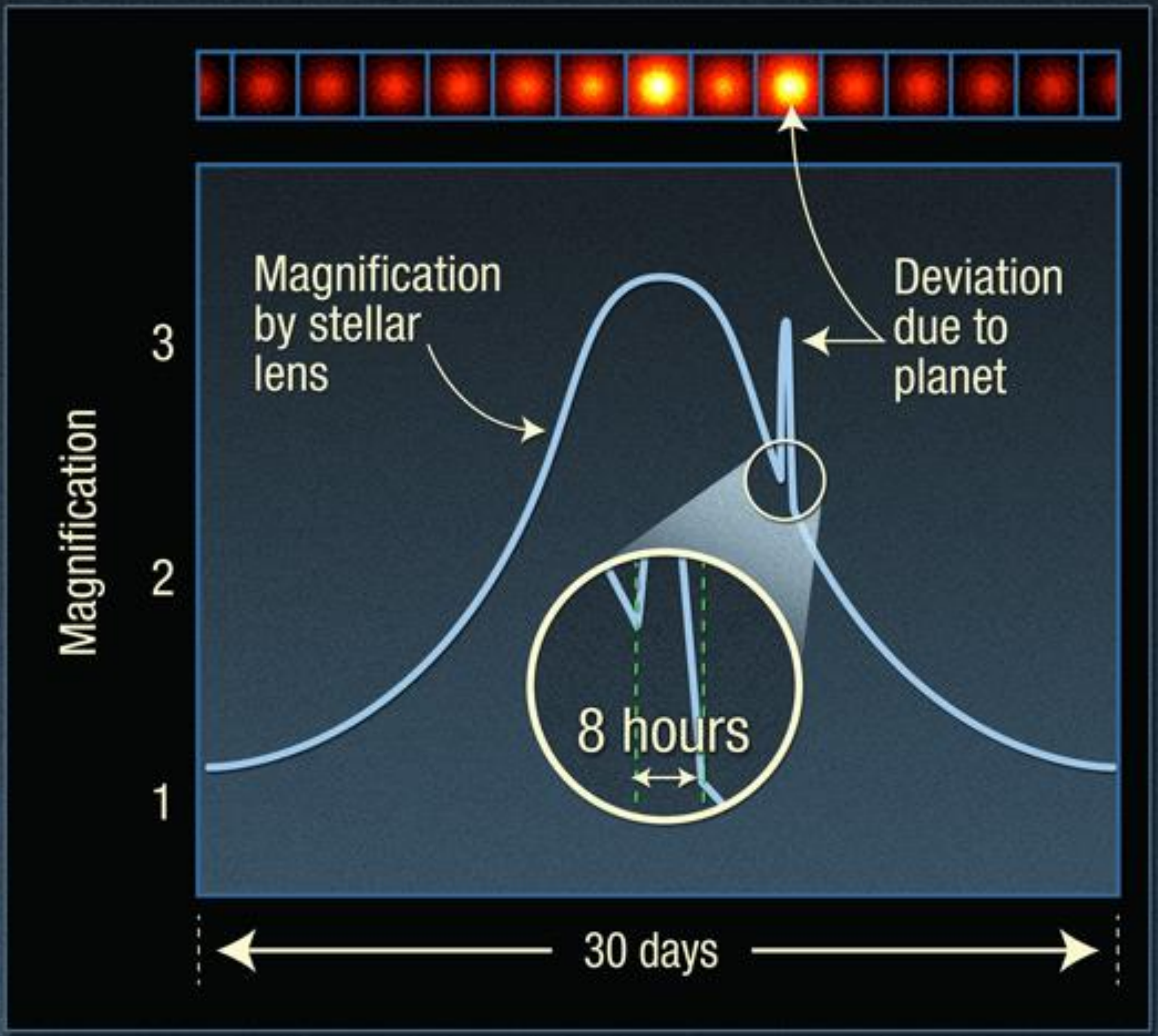
Stefansson

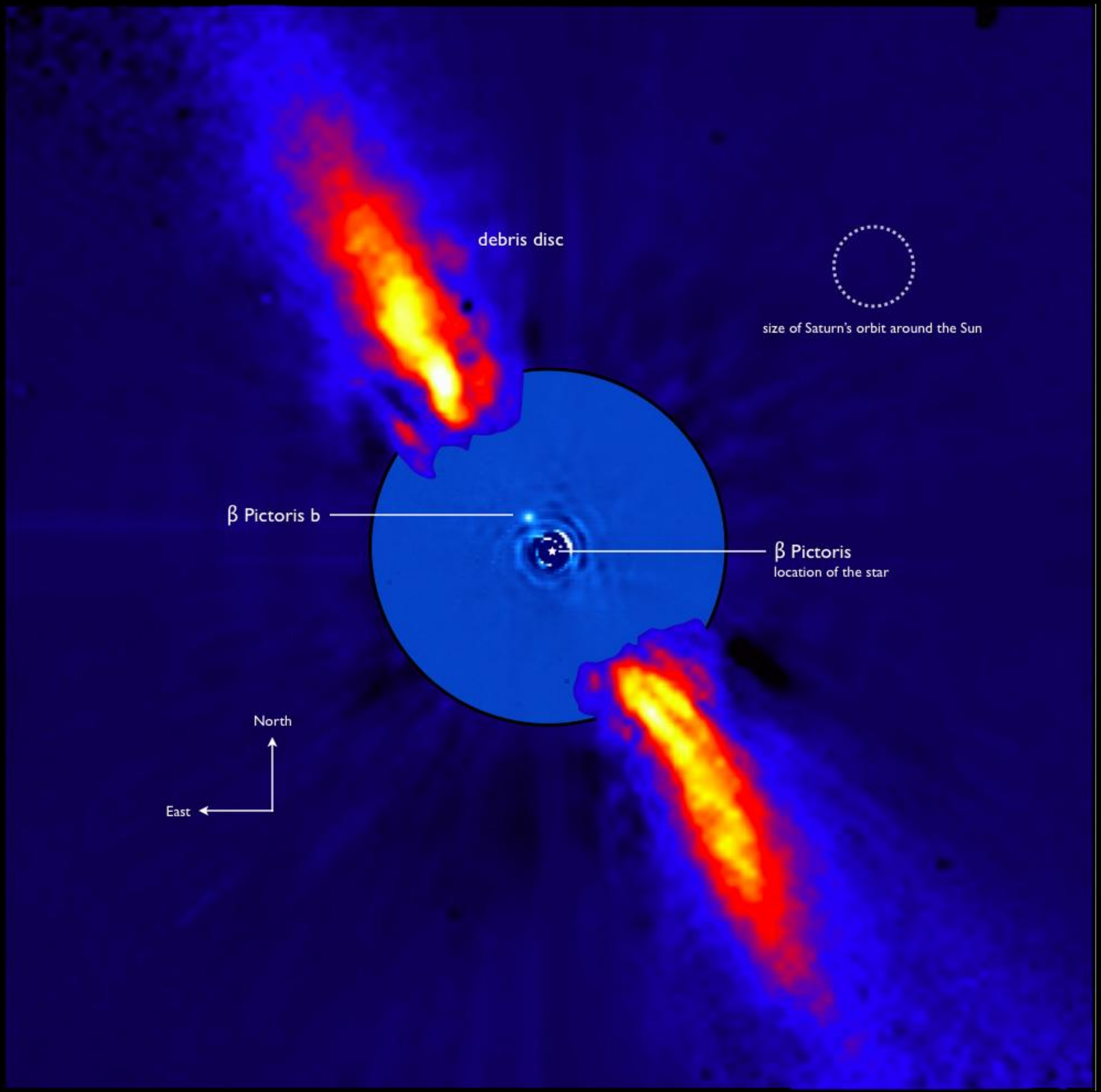
Extrasolar planet detected by gravitational microlensing

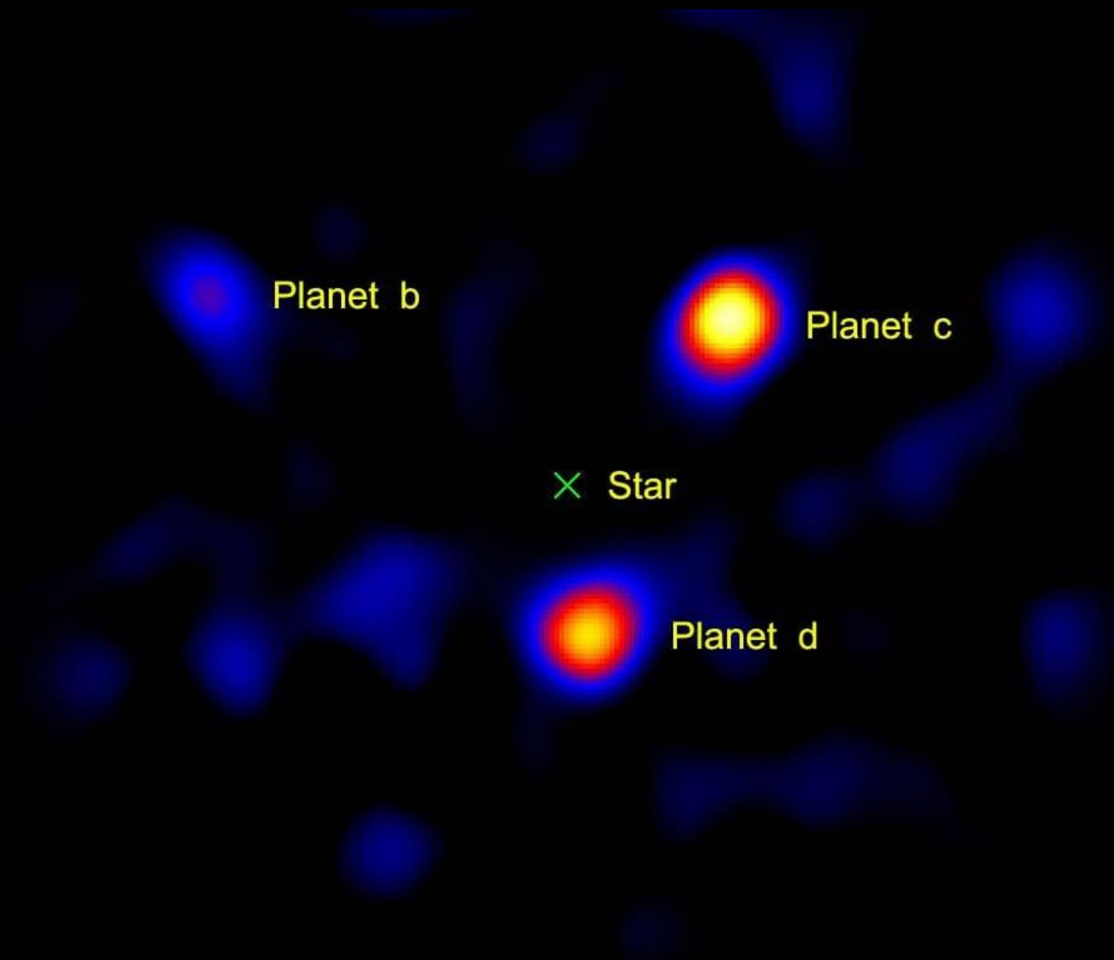


1 When a foreground star (red) passes in front of a background star, it brightens the light of the background star. The gravitational field of the foreground star warps space to create a gravitational lens that magnifies light.

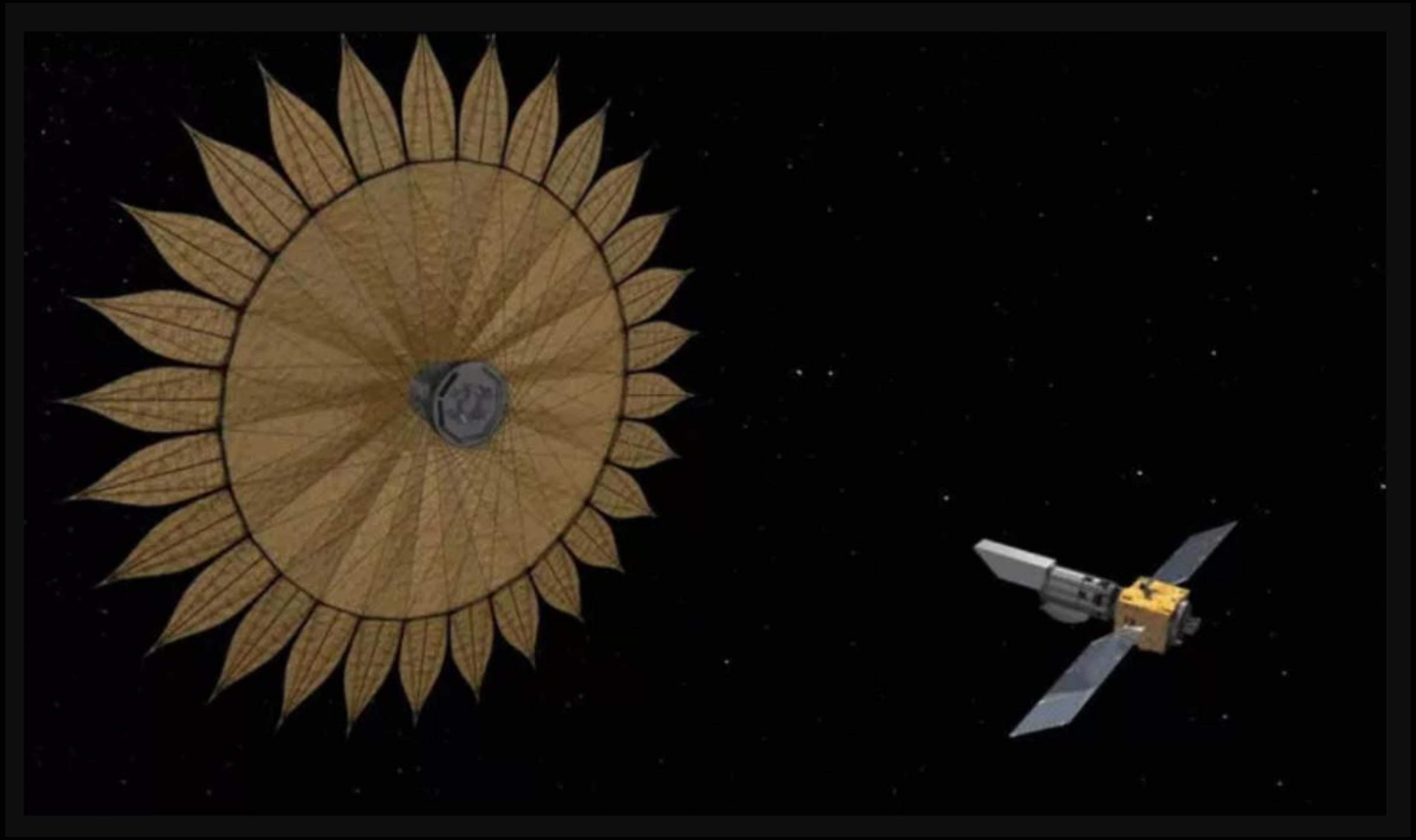
2 If a planet is orbiting the foreground star, it, too, will gravitationally lens the background star for a shorter duration.




debris disc
size of Saturn's orbit around the Sun
β Pictoris b
β Pictoris
location of the star
North
East

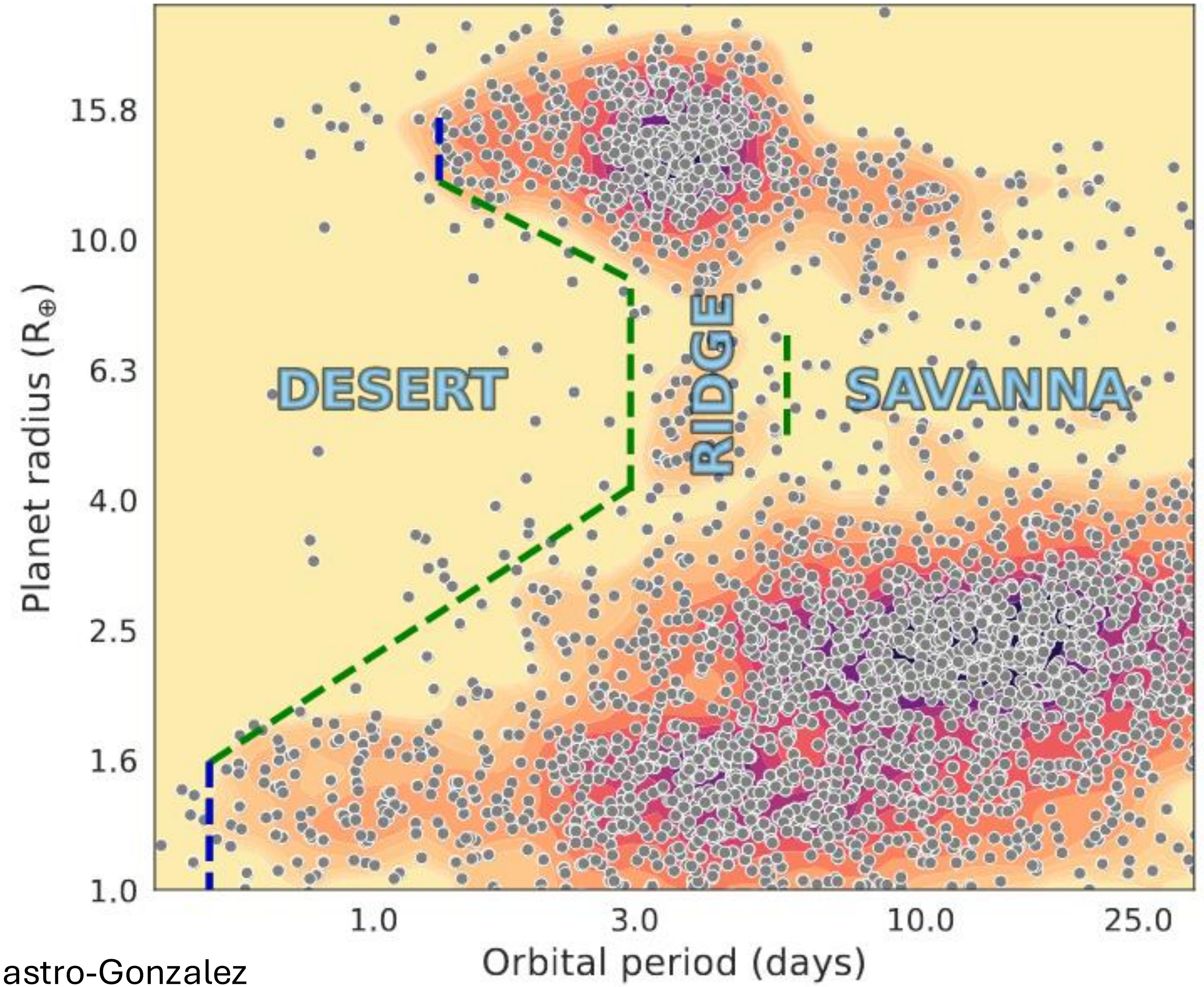

Planet b
Planet c
Star
Planet d

Lagrange

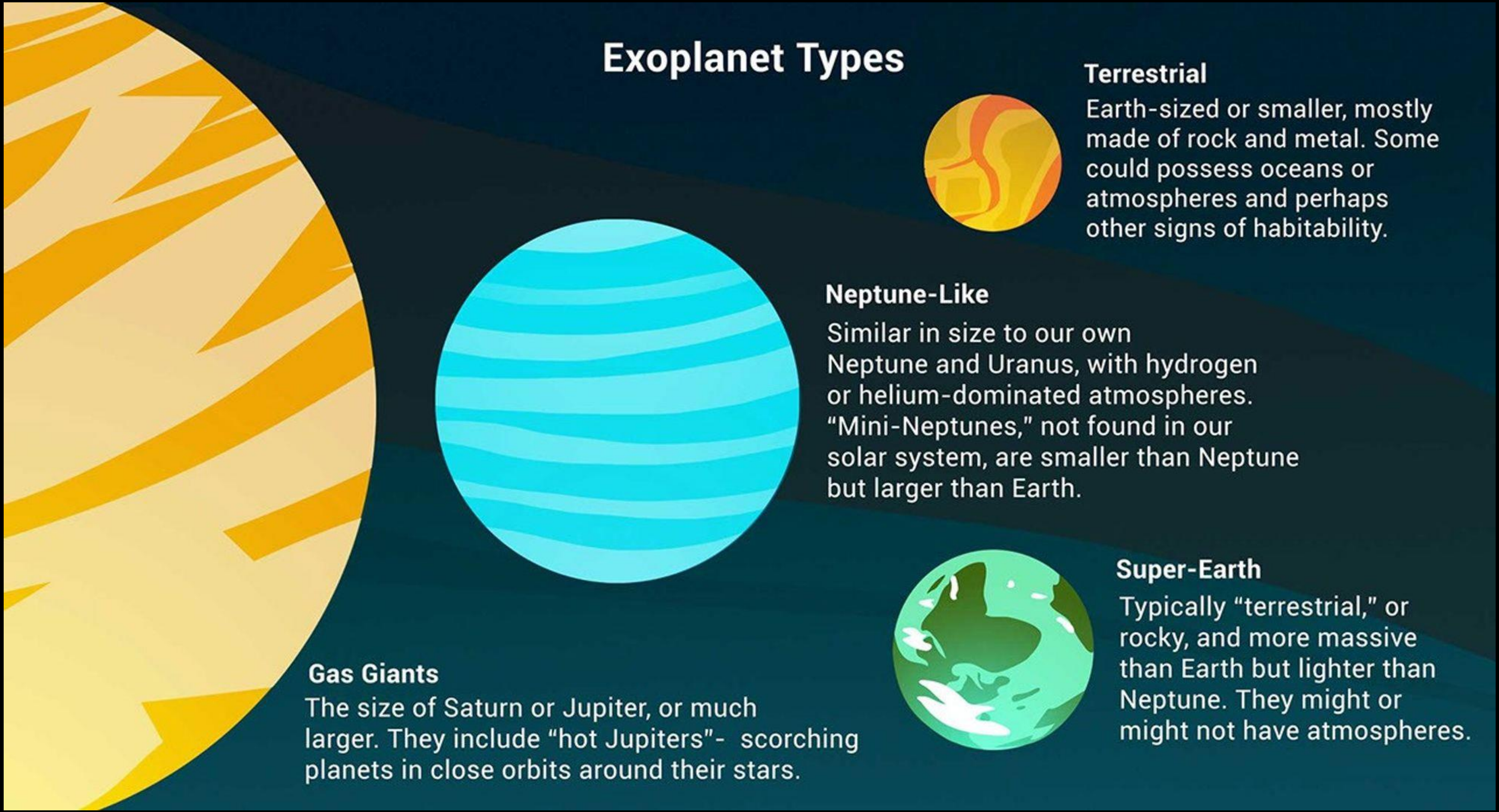


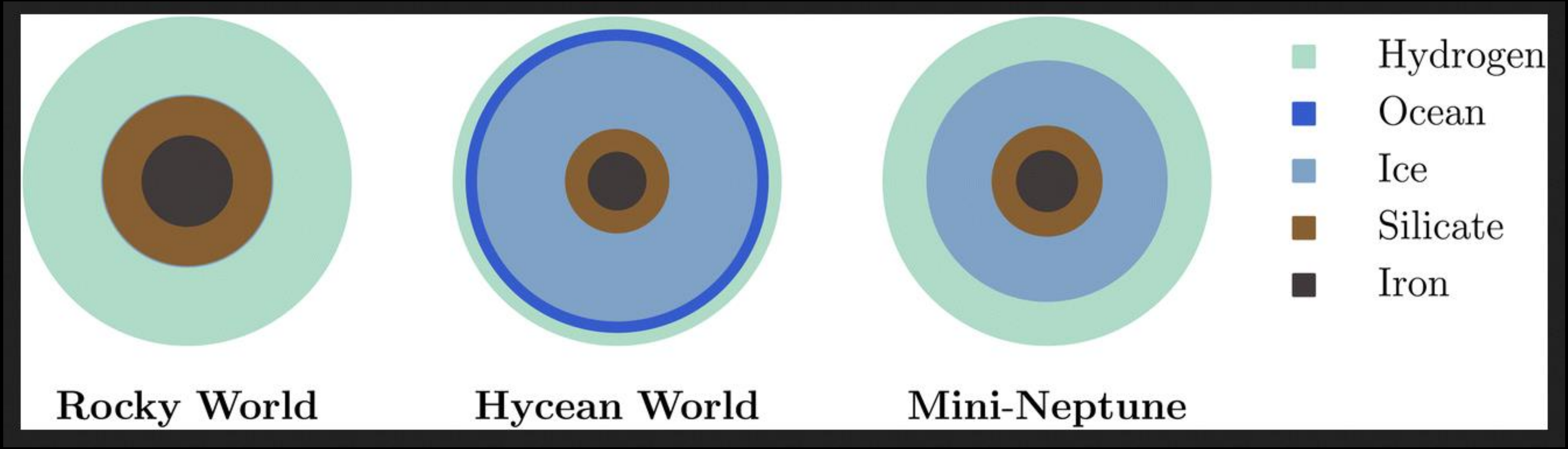
NASA

Demography

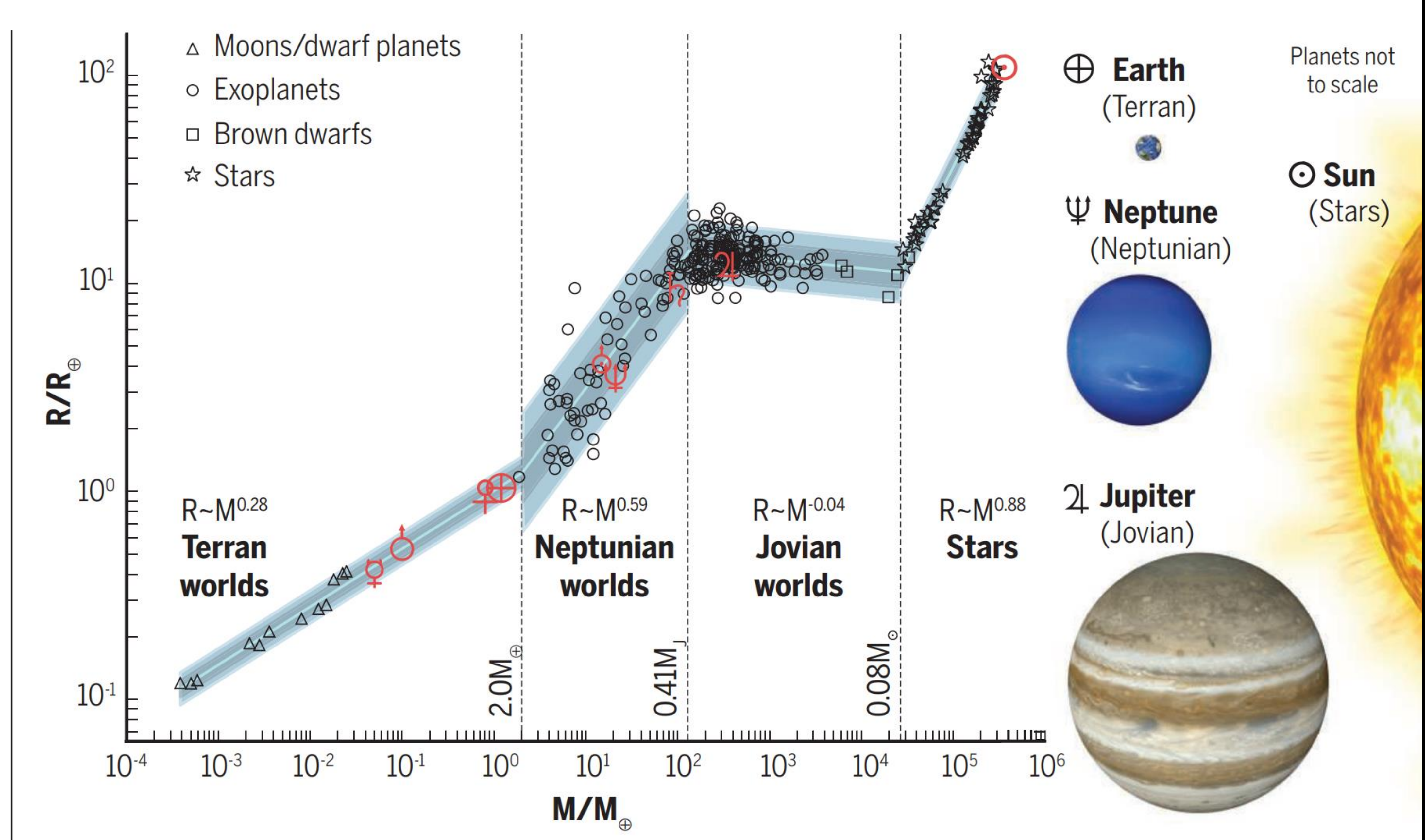


Castro-Gonzalez


Exoplanet Types
Terrestrial
Earth-sized or smaller, mostly made of rock and metal. Some could possess oceans or atmospheres and perhaps other signs of habitability.
Neptune-Like
Similar in size to our own Neptune and Uranus, with hydrogen or helium-dominated atmospheres. “Mini-Neptunes,” not found in our solar system, are smaller than Neptune but larger than Earth.
Super-Earth
Typically “terrestrial,” or rocky, and more massive than Earth but lighter than Neptune. They might or might not have atmospheres.
Gas Giants
The size of Saturn or Jupiter, or much larger. They include “hot Jupiters”- scorching planets in close orbits around their stars.



Madhusudhan



Moons/dwarf planets
Exoplanets
Brown dwarfs
Stars
R/R⊕
M/M⊕
R~M0.28
Terran worlds
R~M0.59
Neptunian worlds
R~M-0.04
Jovian worlds
R~M0.88
Stars
2.0M⊕
0.41MJ
0.08M⊙
Earth
(Terran)
Neptune
(Neptunian)
Jupiter
(Jovian)
Sun
(Stars)
Planets not to scale

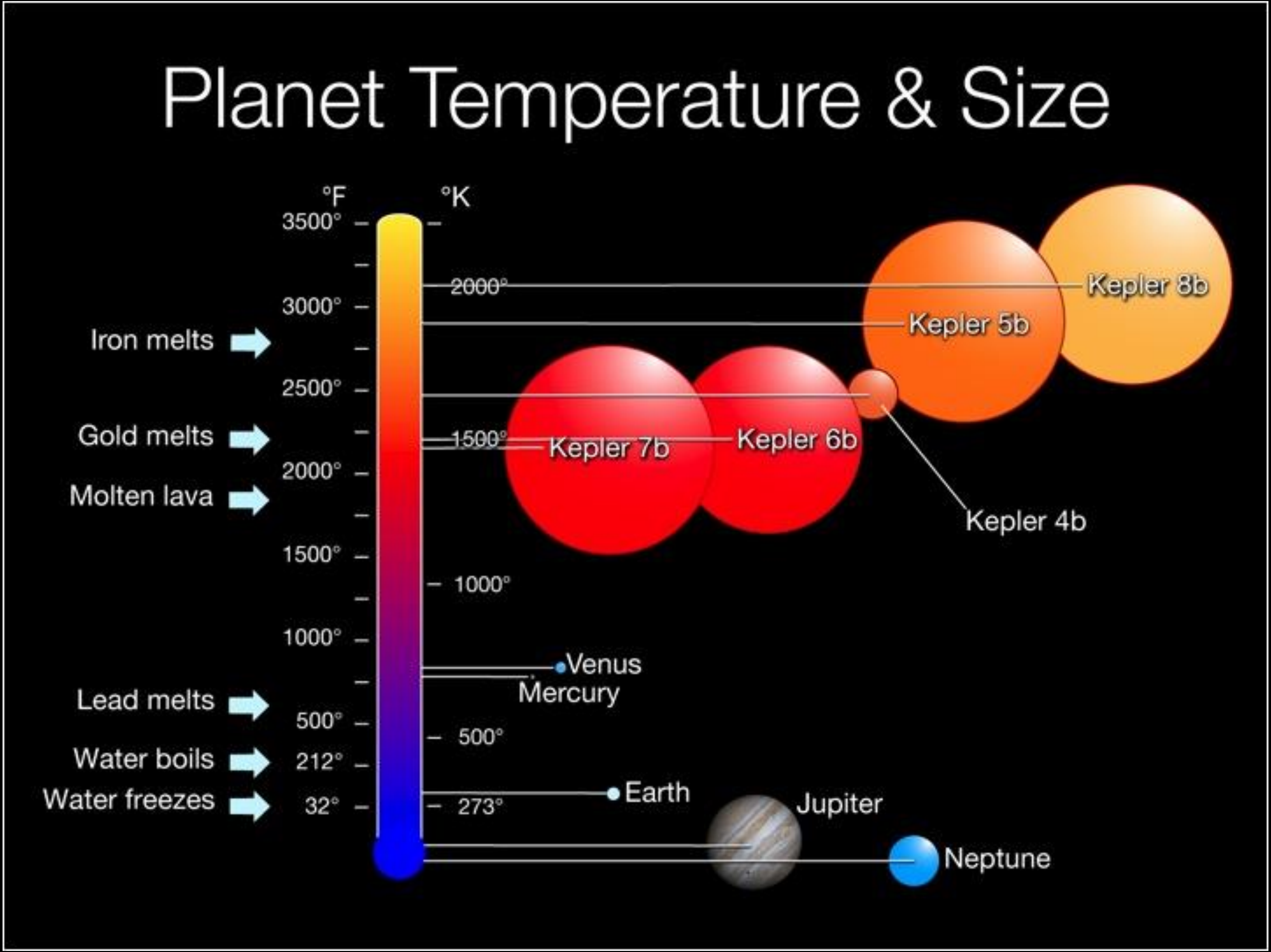
Planetary temperature

- Depends on the orbital distance, radius and temperature of the star

$$T_{\mathrm{eq}} = T_{\mathrm{star}} \sqrt{\frac{R}{2a}} (1 - A_B)^{1/4}$$

- Albedo: a fraction of the light that is diffusely reflected by a body.

- Atmosphere, tidal heating etc.

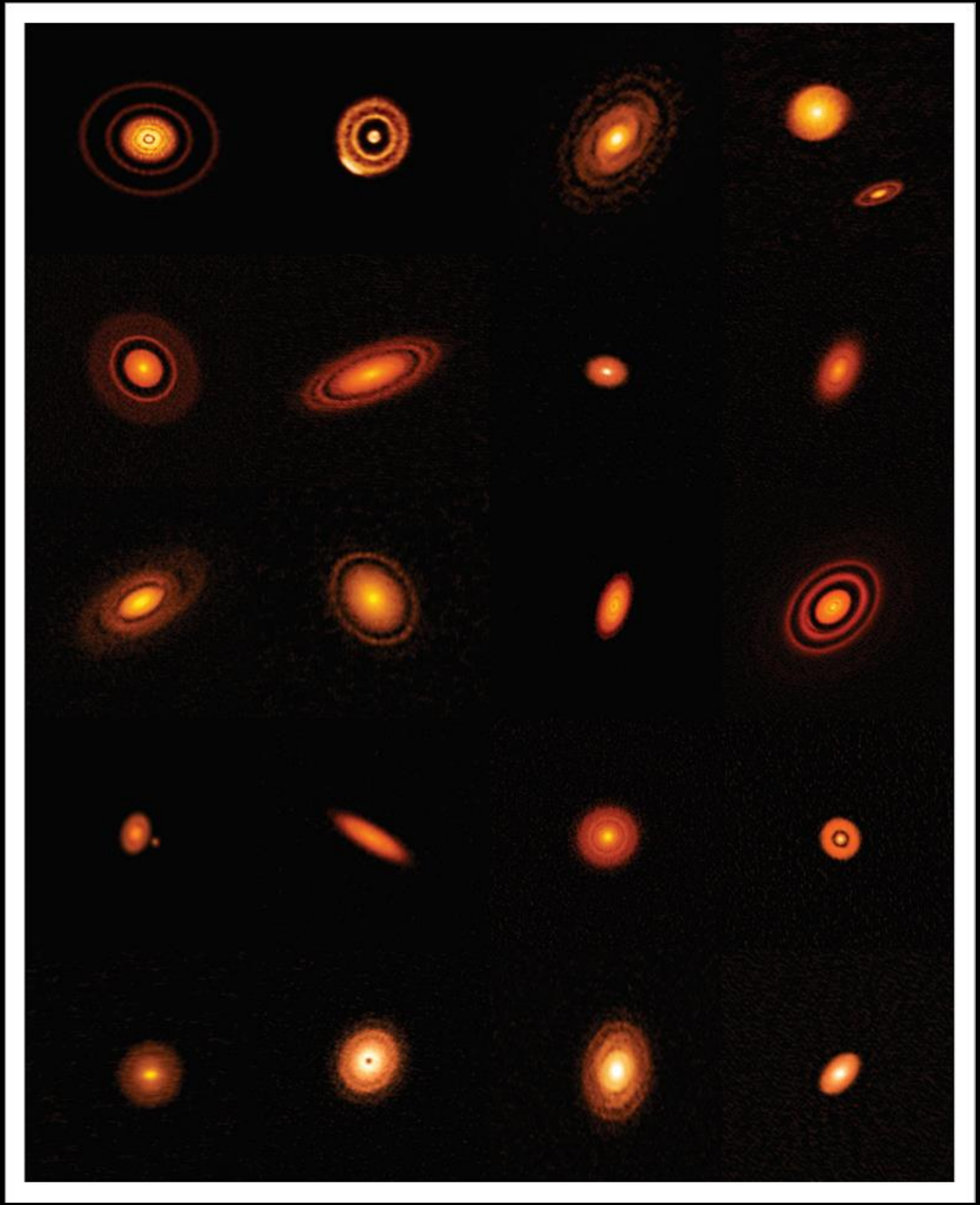


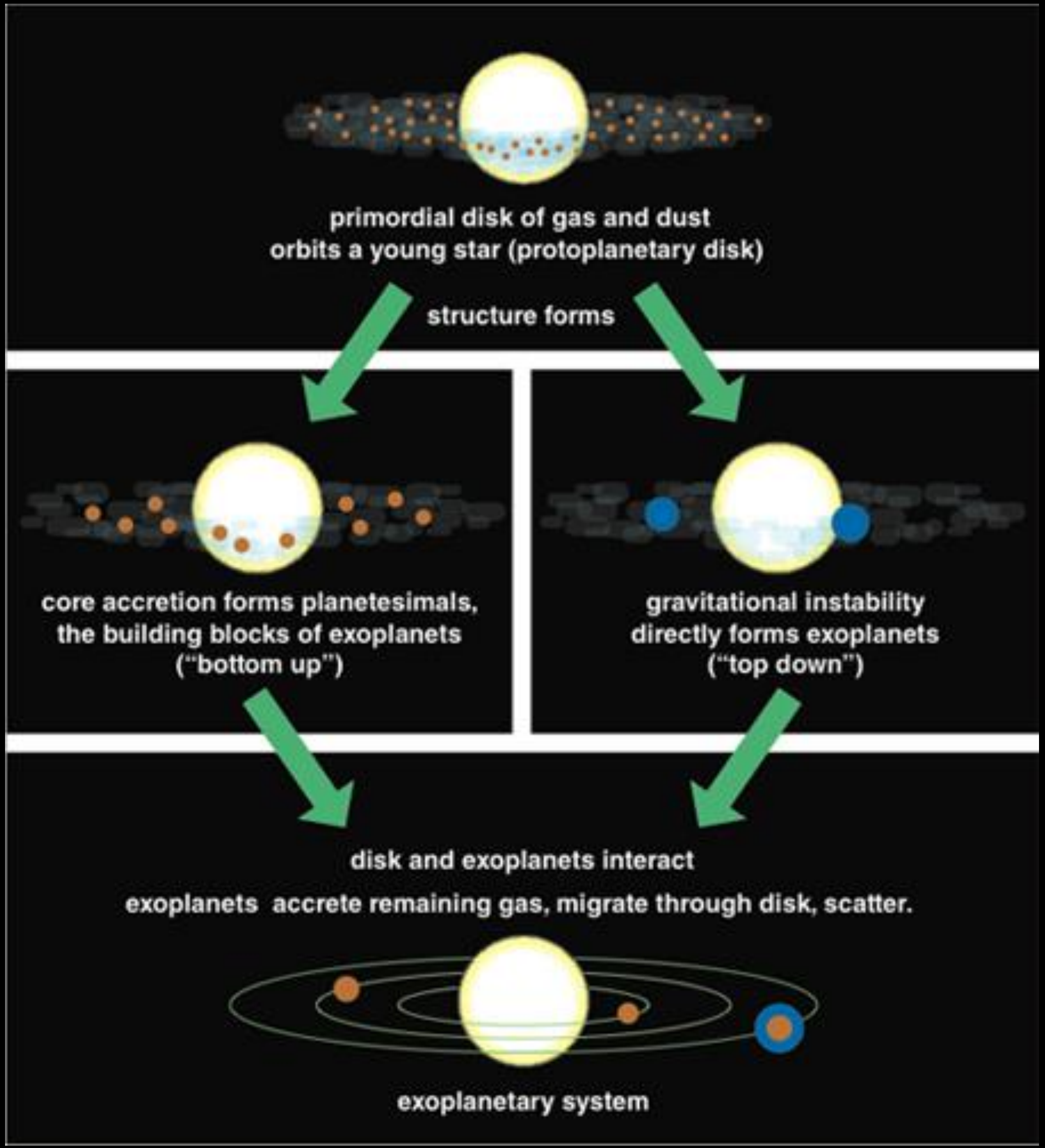
Planet Temperature & Size
°F
°K
3500°
3000°
2500°
2000°
1500°
1000°
500°
212°
32°
2000°
1500°
1000°
500°
273°
Iron melts
Gold melts
Molten lava
Lead melts
Water boils
Water freezes
Kepler 8b
Kepler 5b
Kepler 7b
Kepler 6b
Kepler 4b
Venus
Mercury
Earth
Jupiter
Neptune

NASA

Planet formation

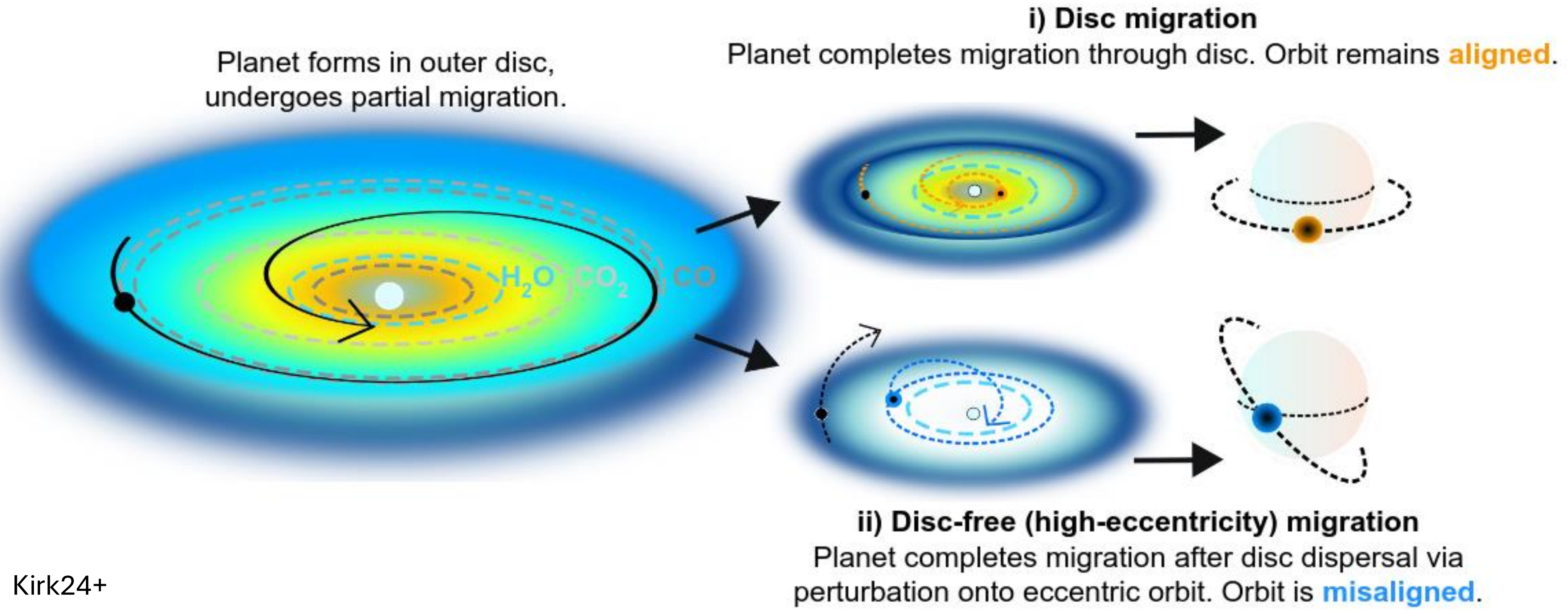
Andrews+




primordial disk of gas and dust
orbits a young star (protoplanetary disk)
structure forms
core accretion forms planetesimals,
the building blocks of exoplanets
("bottom up")
gravitational instability
directly forms exoplanets
("top down")
disk and exoplanets interact
exoplanets accrete remaining gas, migrate through disk, scatter.
exoplanetary system

NASA

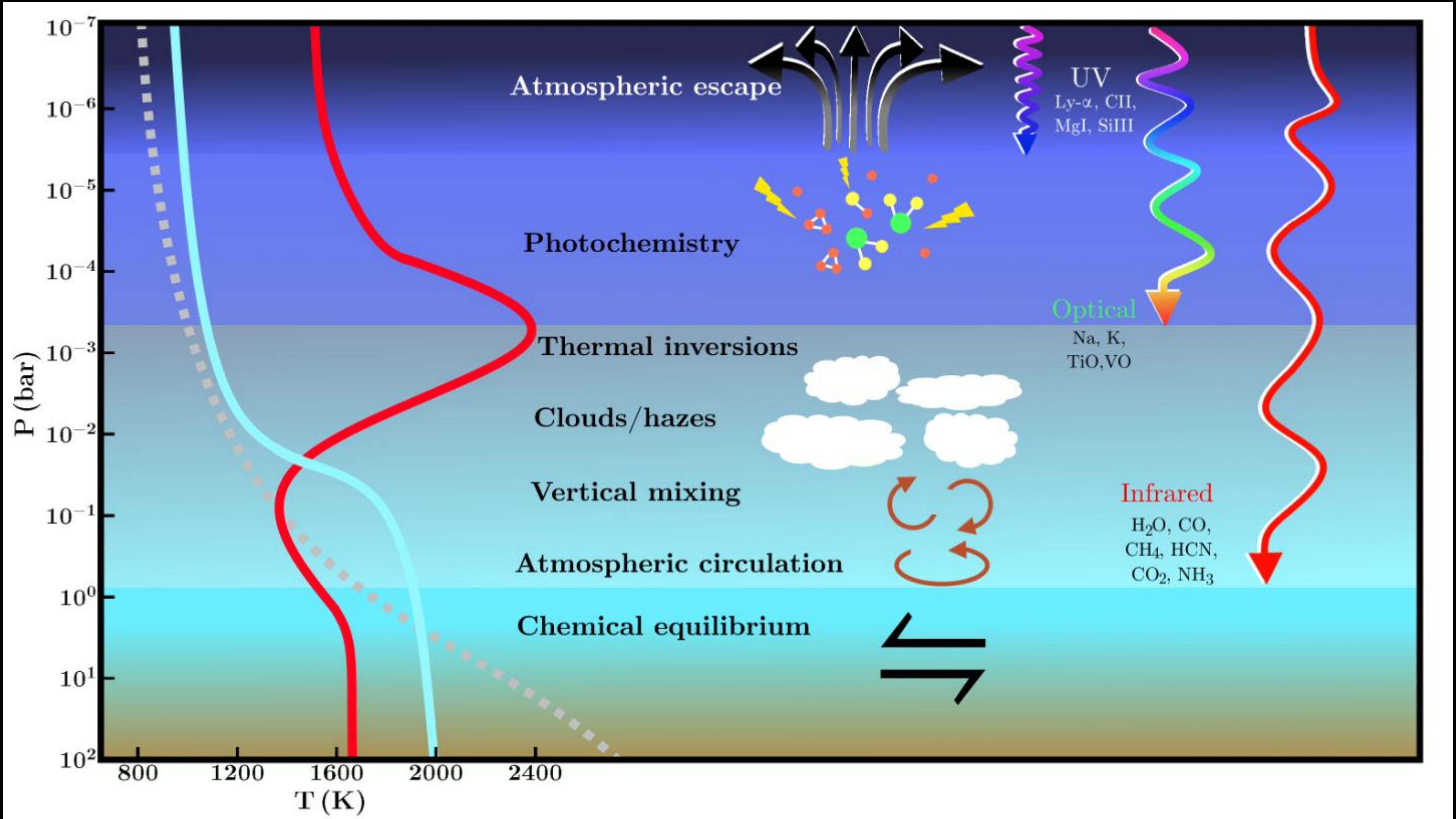
Evolutionary pathways of exoplanets



Kirk24+

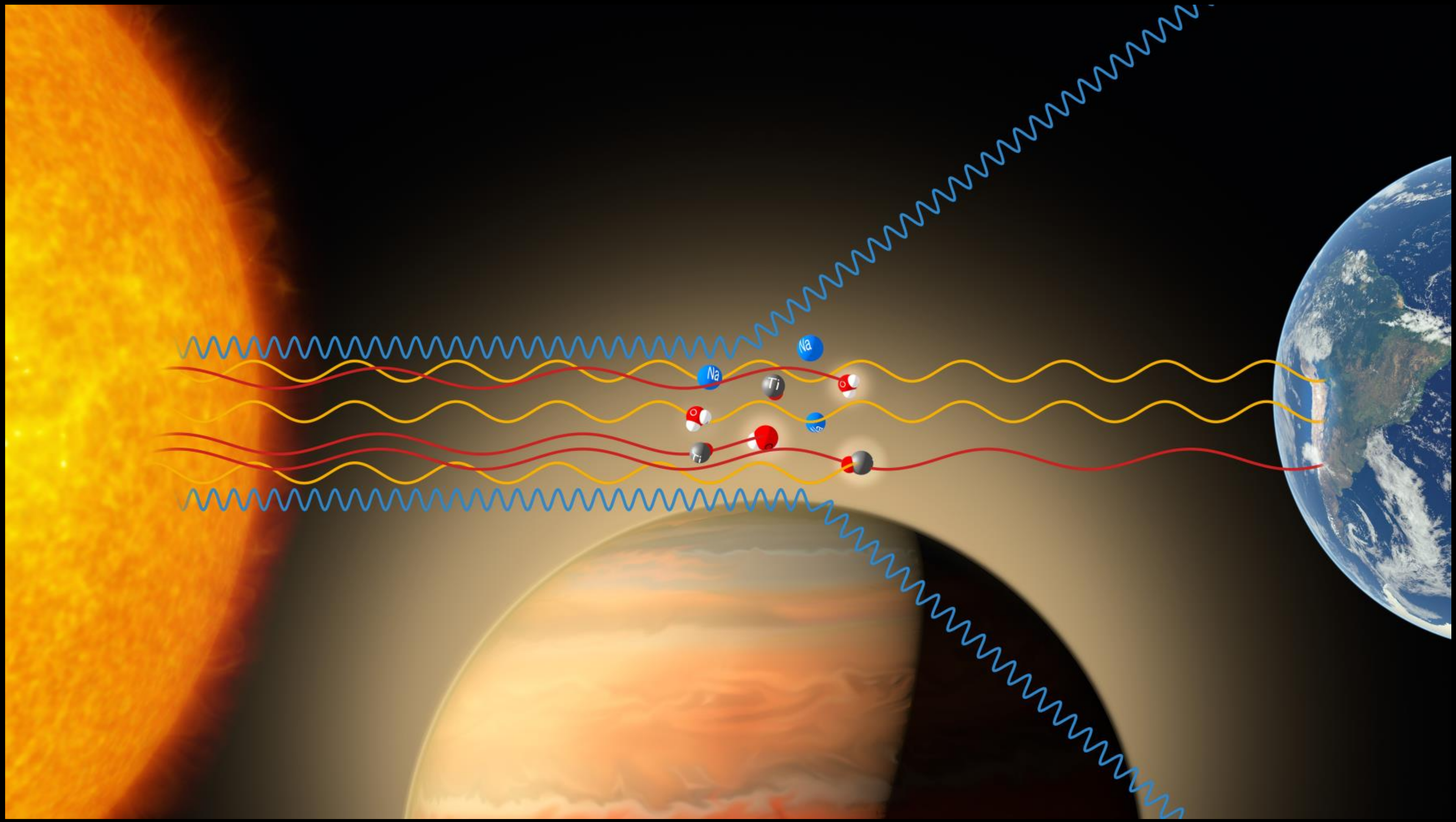
How to study fully formed exoplanets?

- Exoplanetary atmospheres

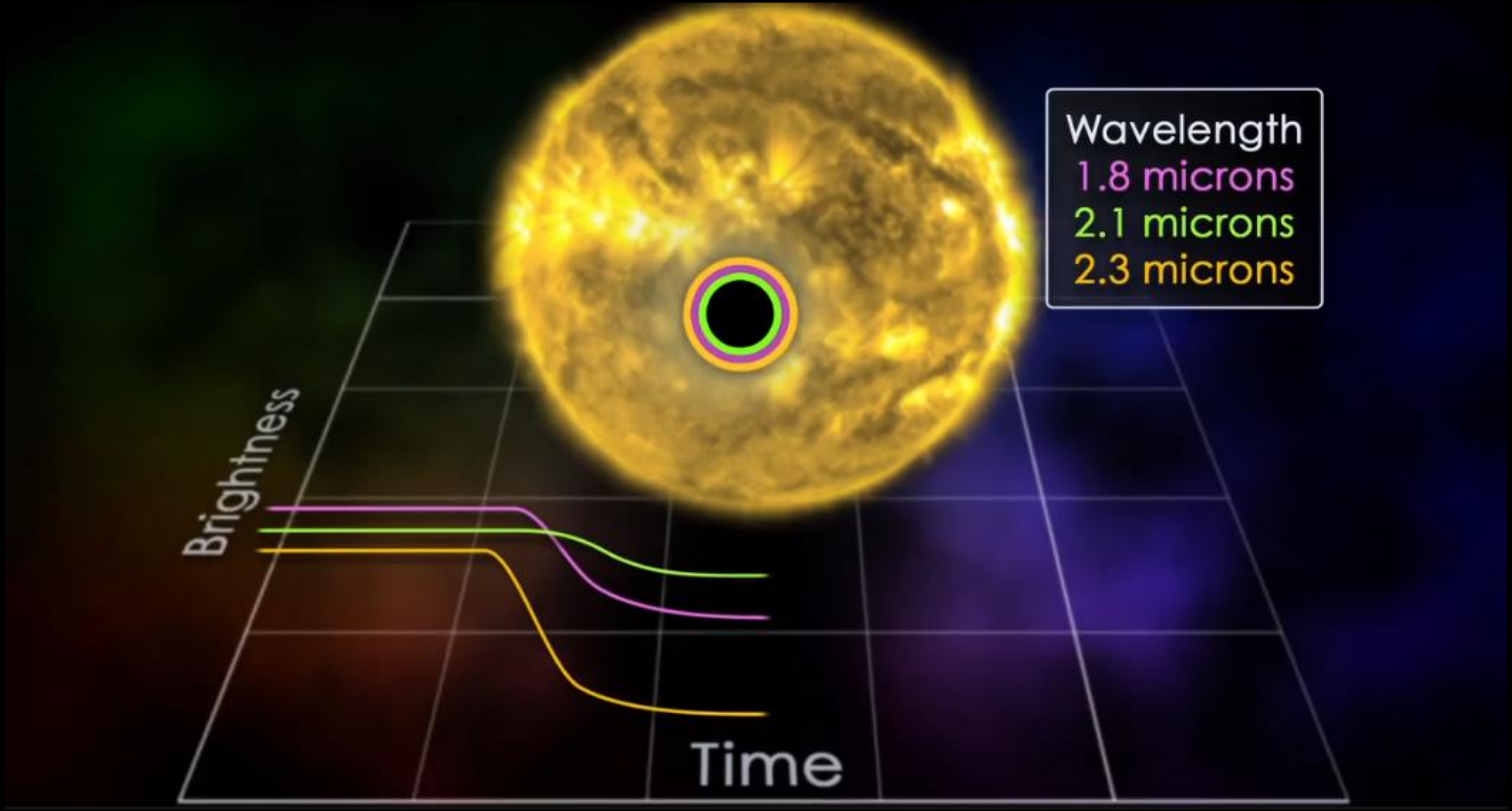


Madhusudhan

Transmission spectroscopy



ESO


Wavelength
1.8 microns
2.1 microns
2.3 microns
Brightness
Time

NASA

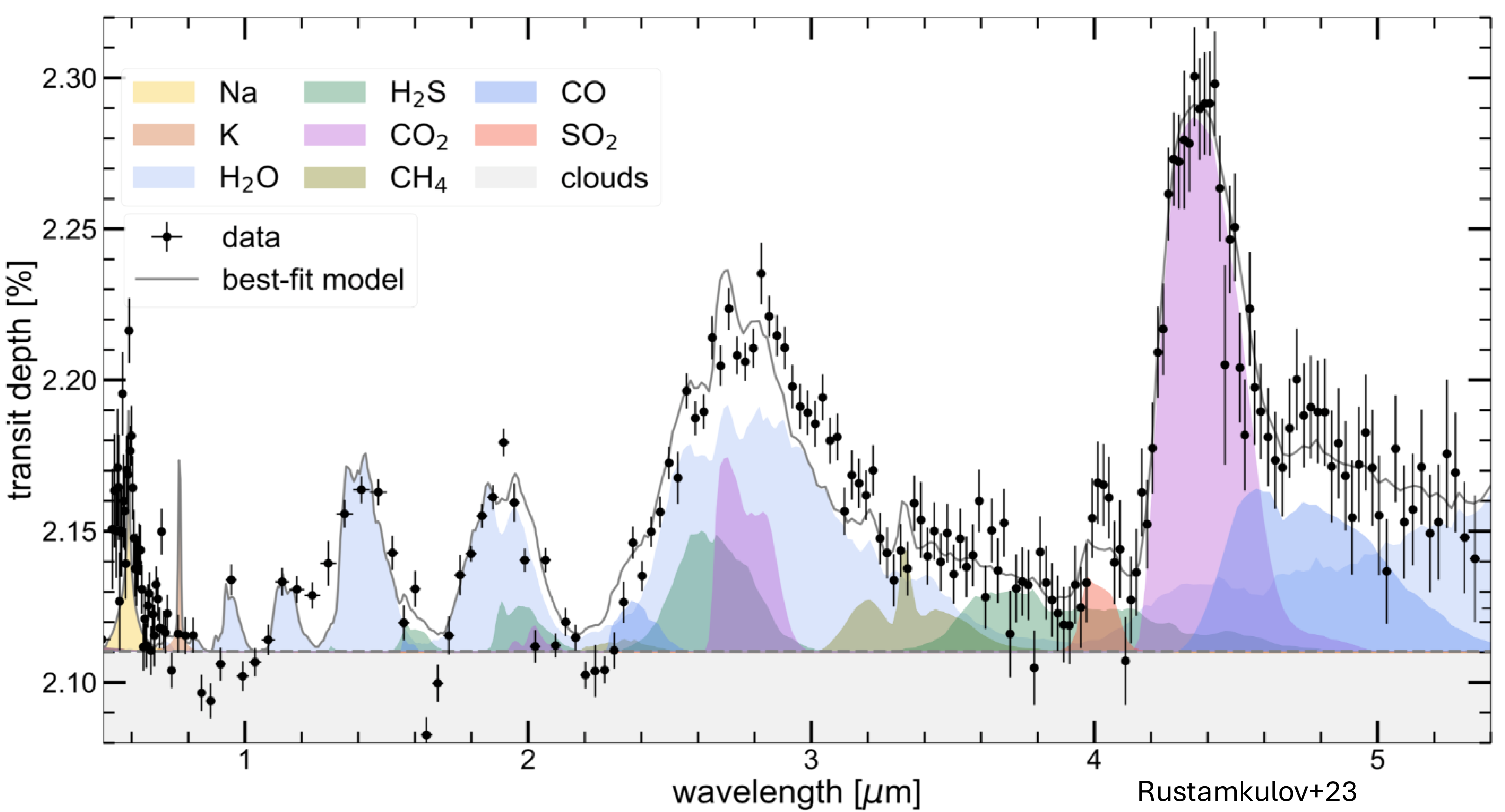
Atmospheric properties and detectability

- **Scale height:** increase in altitude for which the atmospheric pressure decreases by a factor of *e*

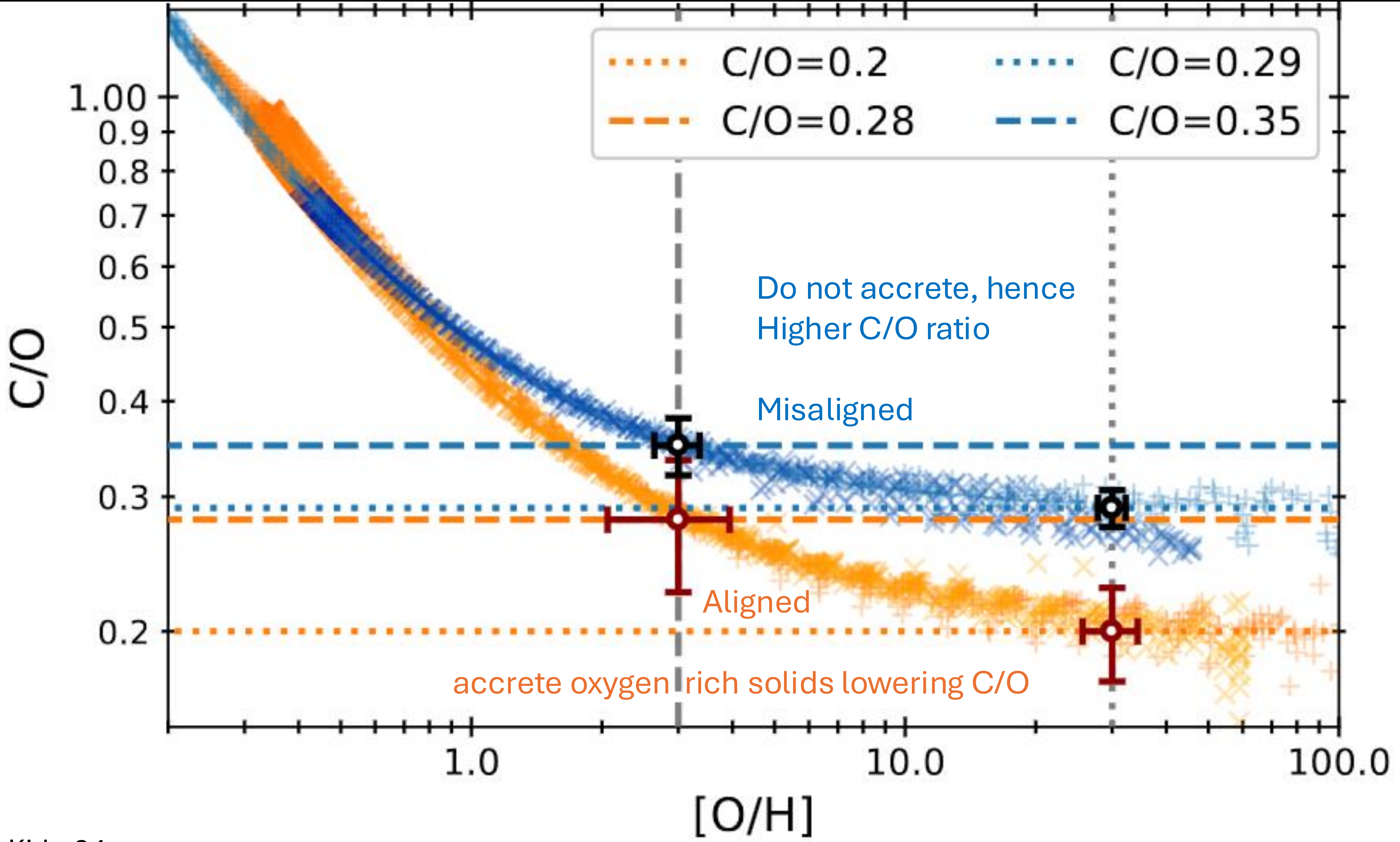
$$H = \frac{k_B T_p}{\mu_m g},$$

- Transmission Spectroscopy metric

$$\mathrm{TSM} = (\mathrm{Scale\ factor}) \times \frac{R_p^3\, T_{eq}}{M_p\, R_*^2} \times 10^{-m_J/5}$$



Rustamkulov+23



C/O=0.2
C/O=0.28
C/O=0.29
C/O=0.35
1.00
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
C/O
1.0
10.0
100.0
[O/H]
Do not accrete, hence
Higher C/O ratio
Misaligned
Aligned
accrete oxygen rich solids lowering C/O

Kirk+24

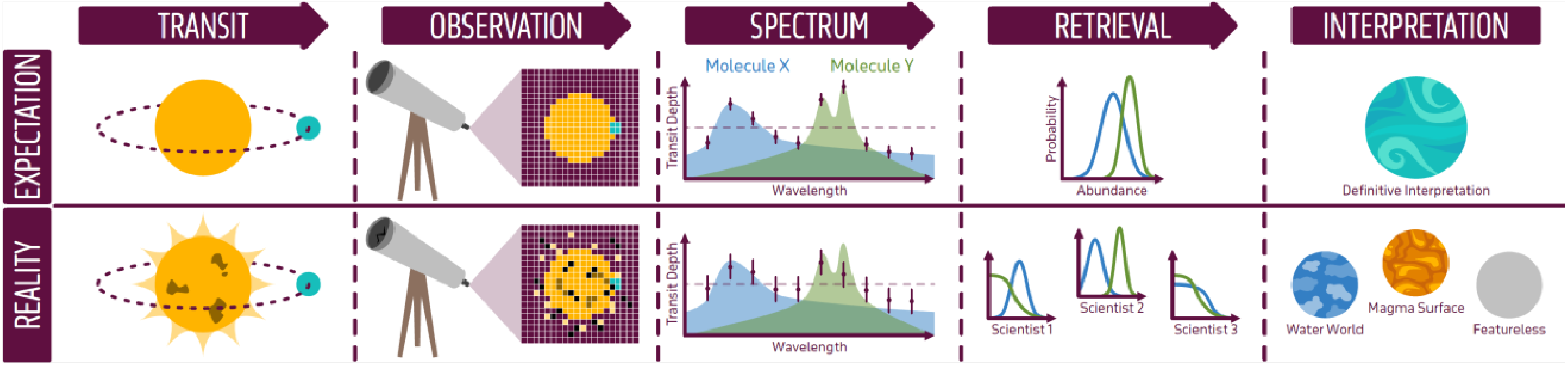
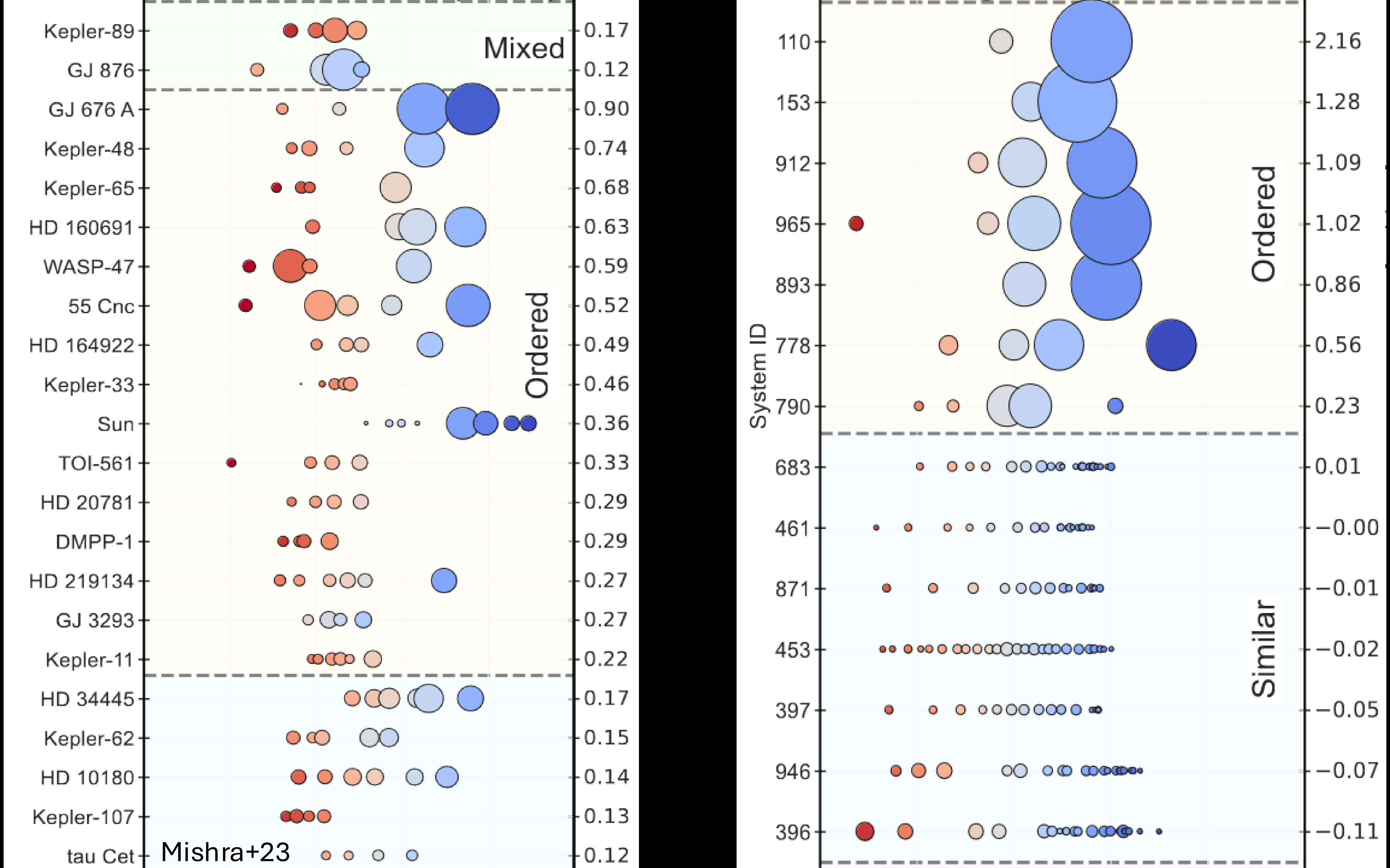


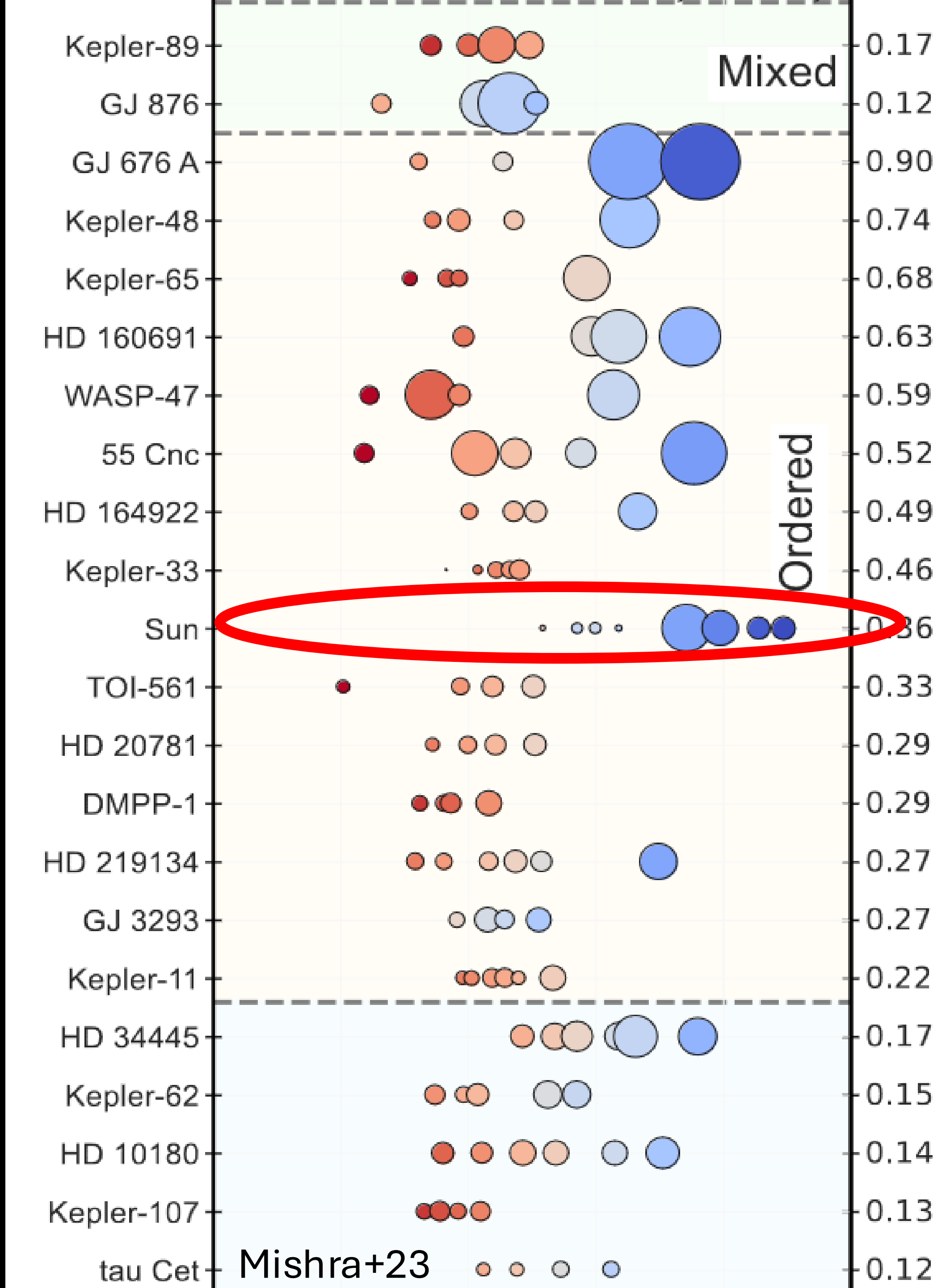
Figure 4. Illustrative schematic of the atmospheric data analysis and interpretation process, from observations through interpretation of an exoplanet's nature. The pathway involves four main steps: [1] taking observations; [2] processing the data from pixels to a spectrum; [3] interpreting the resulting spectrum with model fits to infer planetary properties such as gas abundances; and [4] drawing conclusions about the planet properties. The top row is inspired by WASP-107b (35) a relatively straightforward case, and the bottom row is motivated by TOI 270d ((29)), a disputed planetary nature. All panels are illustrative only. See text for details. Credit: Seager, Welbanks, Tilke.

How to study fully formed exoplanets?

- Exoplanetary atmosphere
- Orbital dynamics



Kepler-89
GJ 876
GJ 676 A
Kepler-48
Kepler-65
HD 160691
WASP-47
55 Cnc
HD 164922
Kepler-33
Sun
TOI-561
HD 20781
DMPP-1
HD 219134
GJ 3293
Kepler-11
HD 34445
Kepler-62
HD 10180
Kepler-107
tau Cet
Mixed
Ordered
Mishra+23
0.17
0.12
0.90
0.74
0.68
0.63
0.59
0.52
0.49
0.46
0.36
0.33
0.29
0.29
0.27
0.27
0.22
0.17
0.15
0.14
0.13
0.12
System ID
110
153
912
965
893
778
790
683
461
871
453
397
946
396
Ordered
Similar
2.16
1.28
1.09
1.02
0.86
0.56
0.23
0.01
−0.00
−0.01
−0.02
−0.05
−0.07
−0.11


Kepler-89
GJ 876
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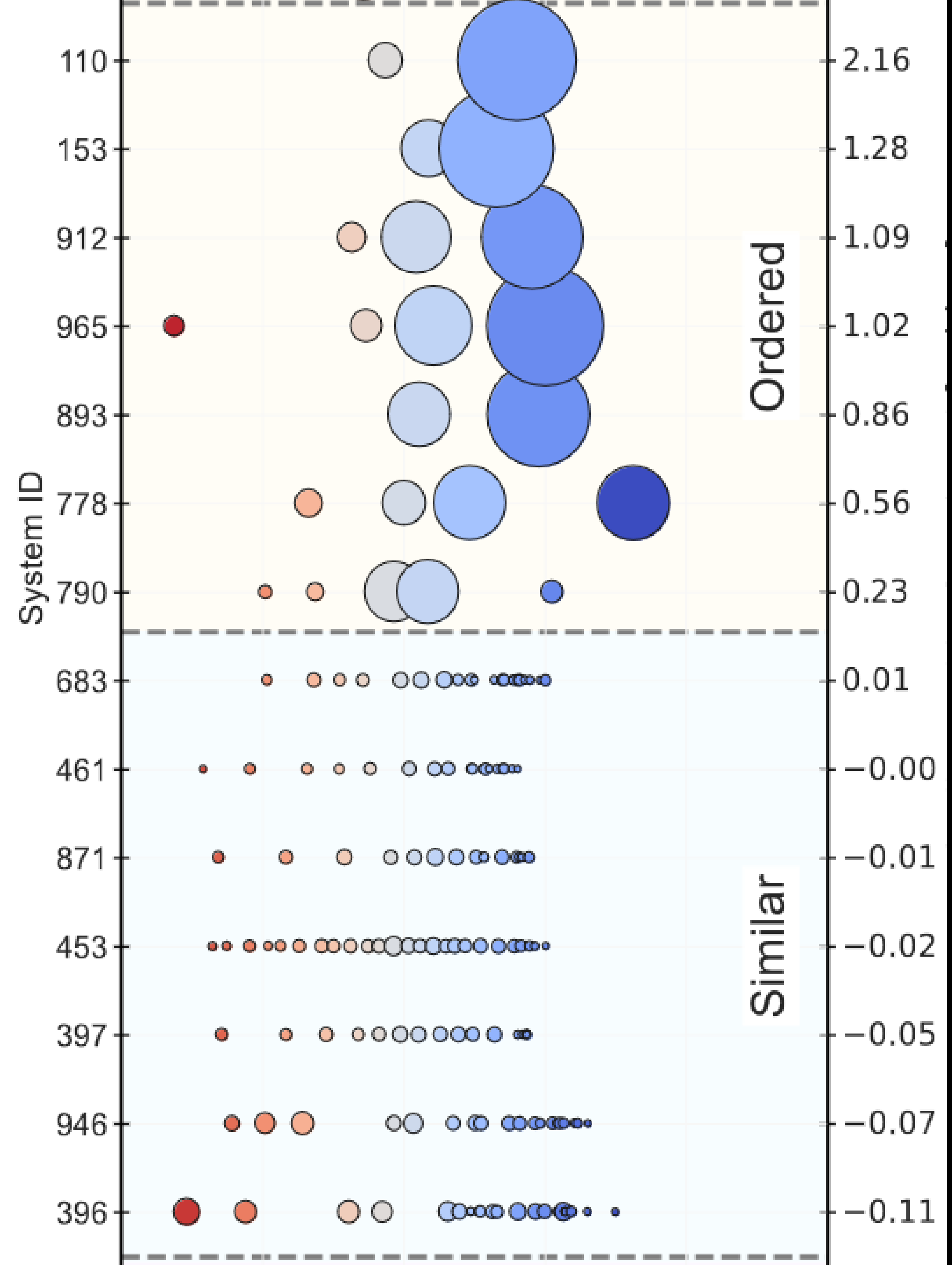
System ID
110
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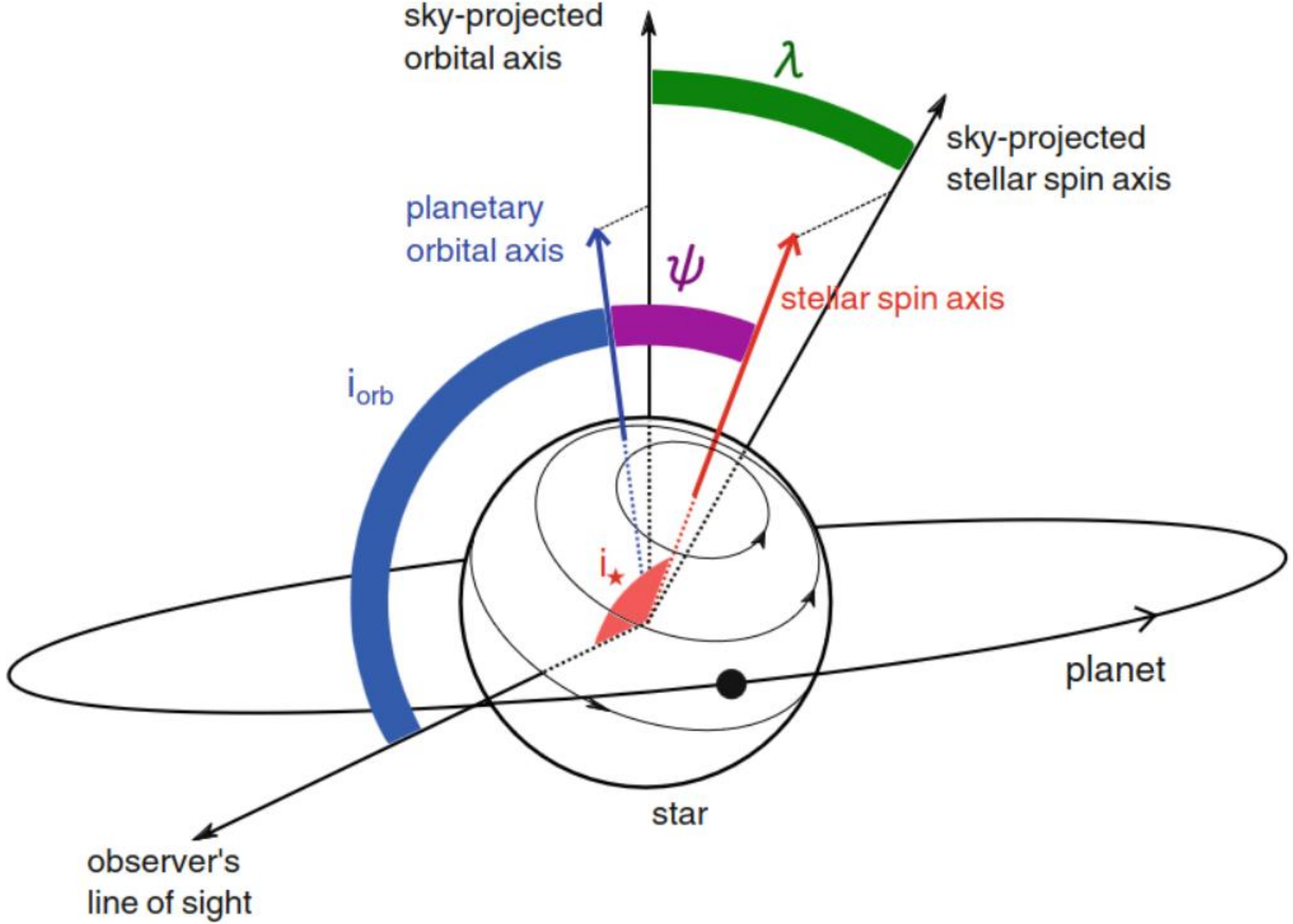

sky-projected orbital axis
λ
sky-projected stellar spin axis
planetary orbital axis
ψ
stellar spin axis
i_{orb}
$i_\star$
planet
star
observer's line of sight

Masuda

Rossiter-McLaughlin effect

- Spectroscopy phenomenon during transit

Rossiter-McLaughlin effect

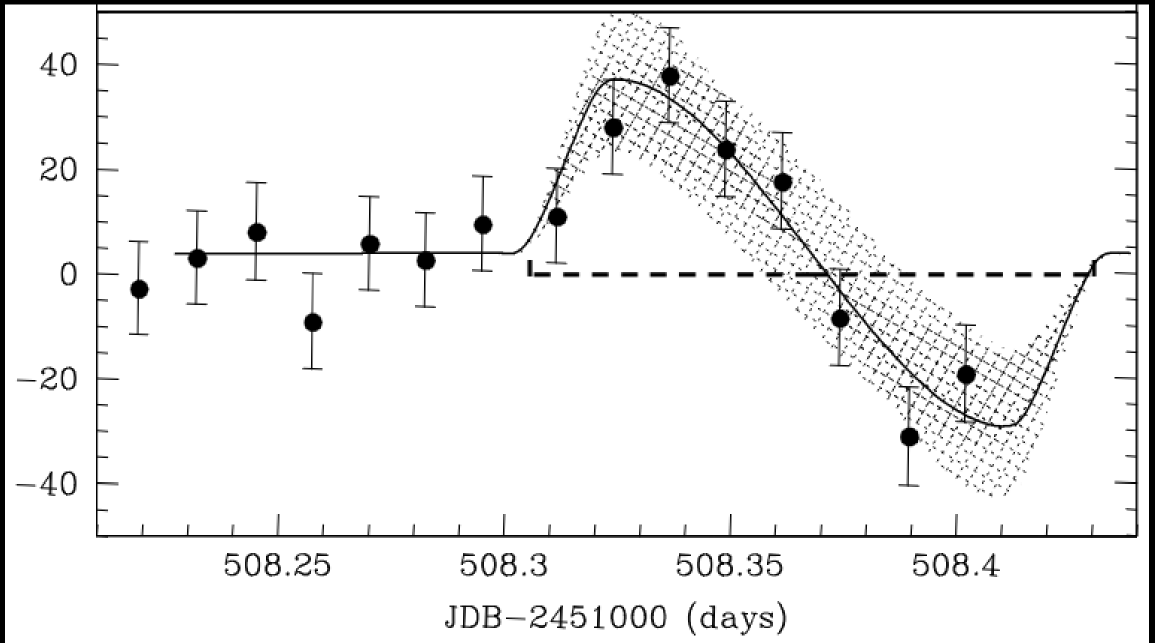
- Spectroscopy phenomenon during transit
- Predicted by Holt in 1893

> In fact, during the progress of the partial eclipse, there should be a shift in position of the lines; and although this shift is probably very small, it ought to be detected by a powerful instrument.
>
> J. R. HOLT.

Rossiter-McLaughlin effect

- Spectroscopy phenomenon during transit
- Binaries and exoplanets since 2000

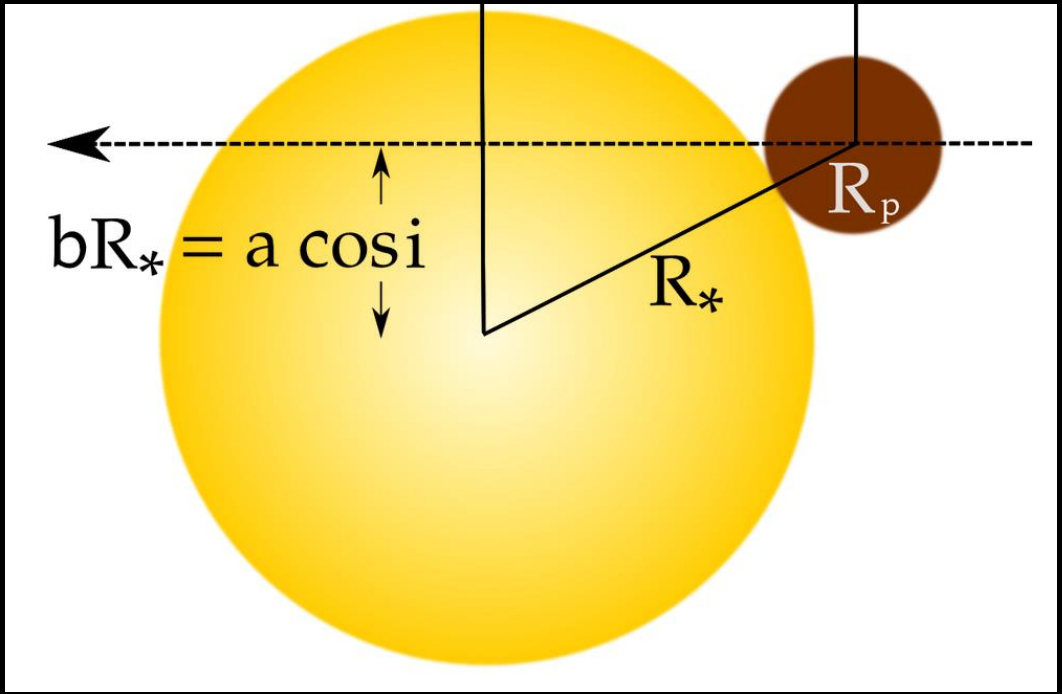
D. Queloz



Rossiter-McLaughlin effect

- Spectroscopy phenomenon during transit
- Binaries and exoplanets since 2000
- RV anomaly with an amplitude:

$$K_{\rm RM} \propto v \sin(i) \left(\frac{R_p}{R_\star}\right)^2 \sqrt{1-b^2}$$



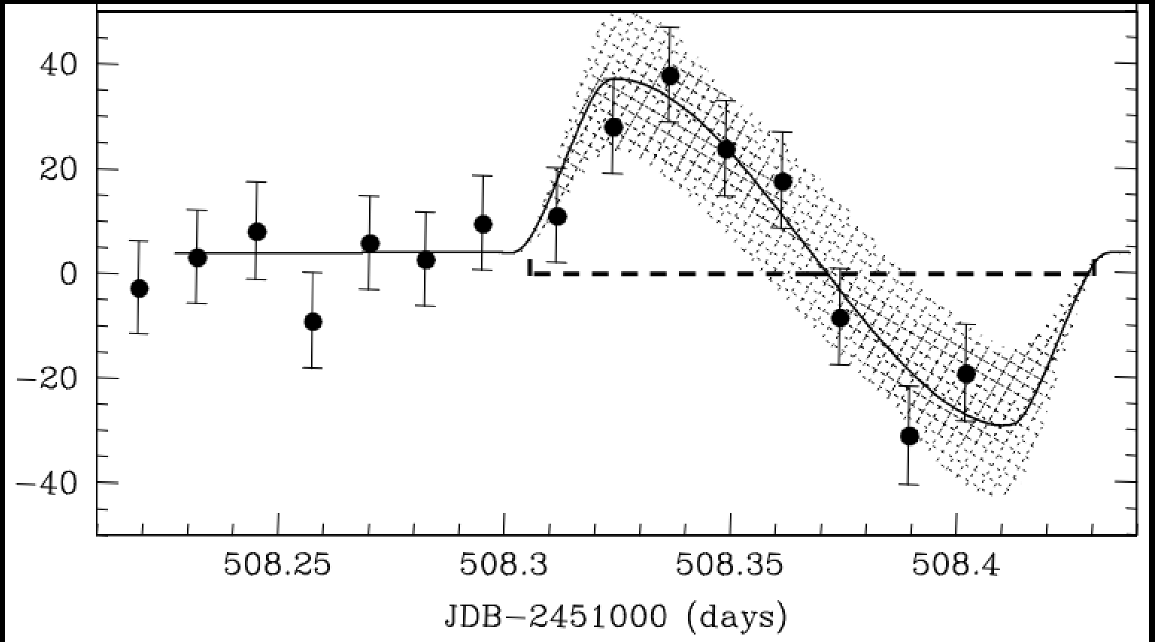
P. Wilson

Rossiter-McLaughlin effect

- Spectroscopy phenomenon during transit
- Binaries and exoplanets since 2000
- RV anomaly with an amplitude:

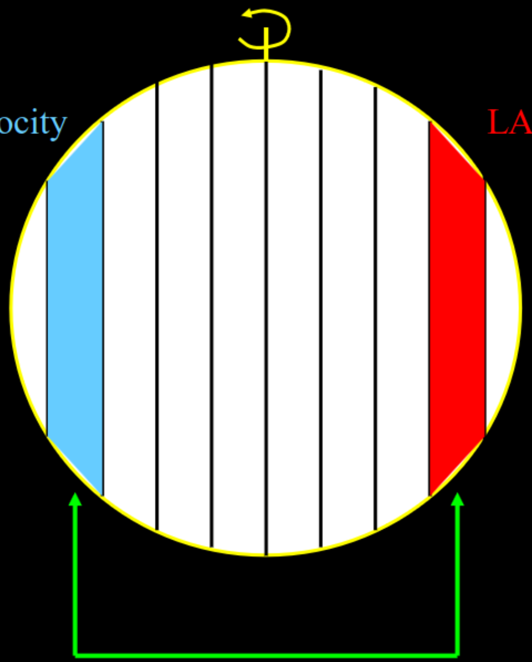
$$K_{\mathrm{RM}} \propto v \sin(i) \left(\frac{R_p}{R_\star}\right)^2 \sqrt{1-b^2}$$

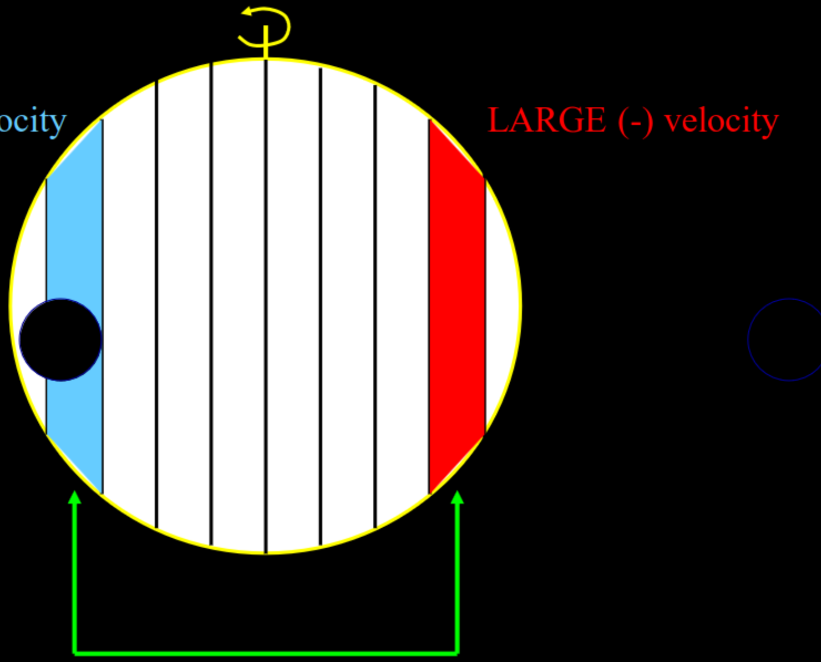
D. Queloz



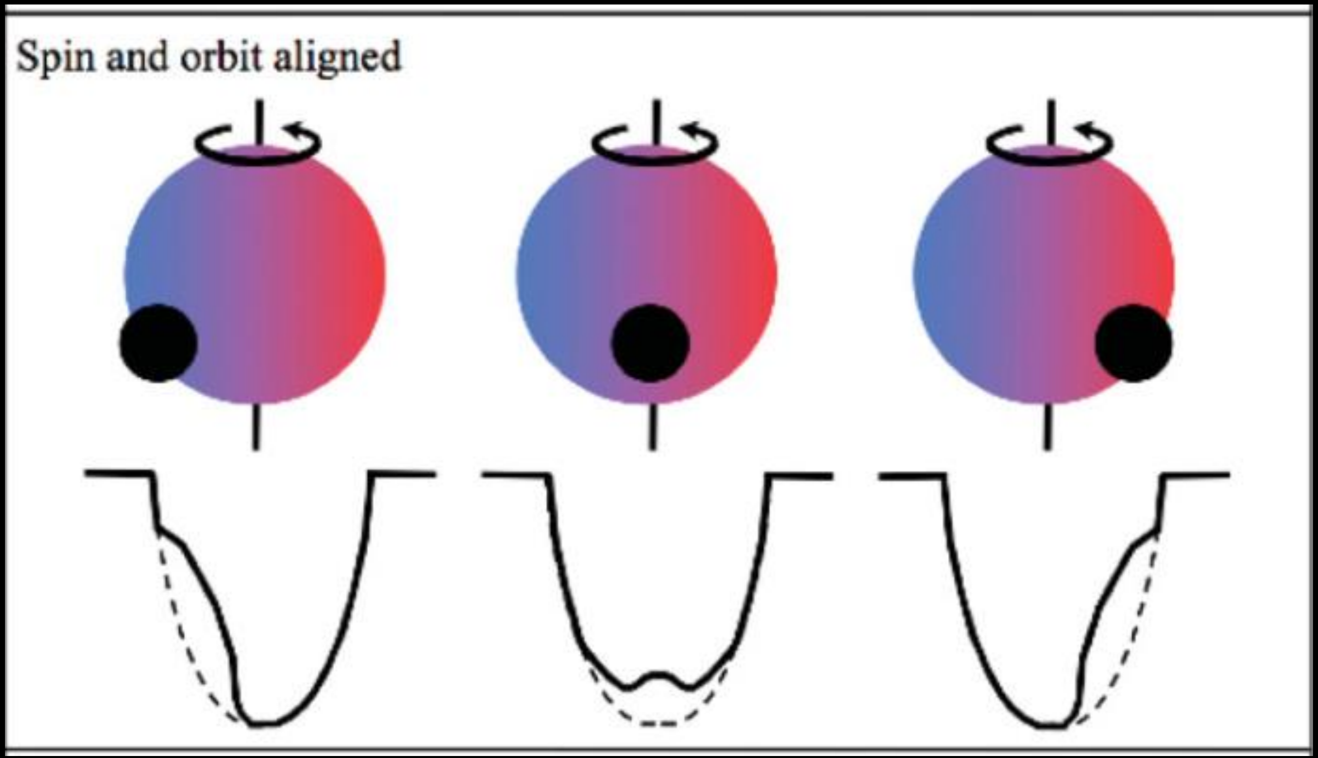
Rossiter-McLaughlin effect

W. Welsch



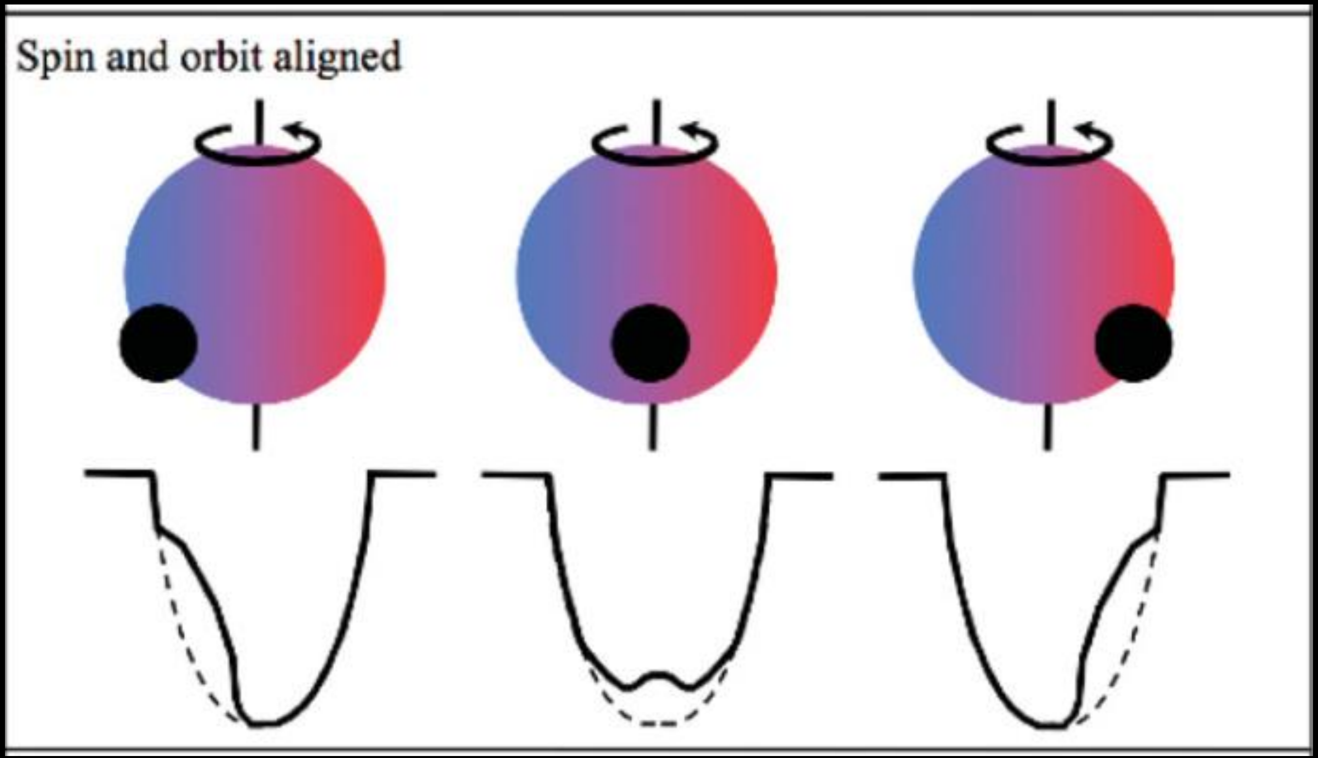


Rossiter-McLaughlin effect



Winn (2010)

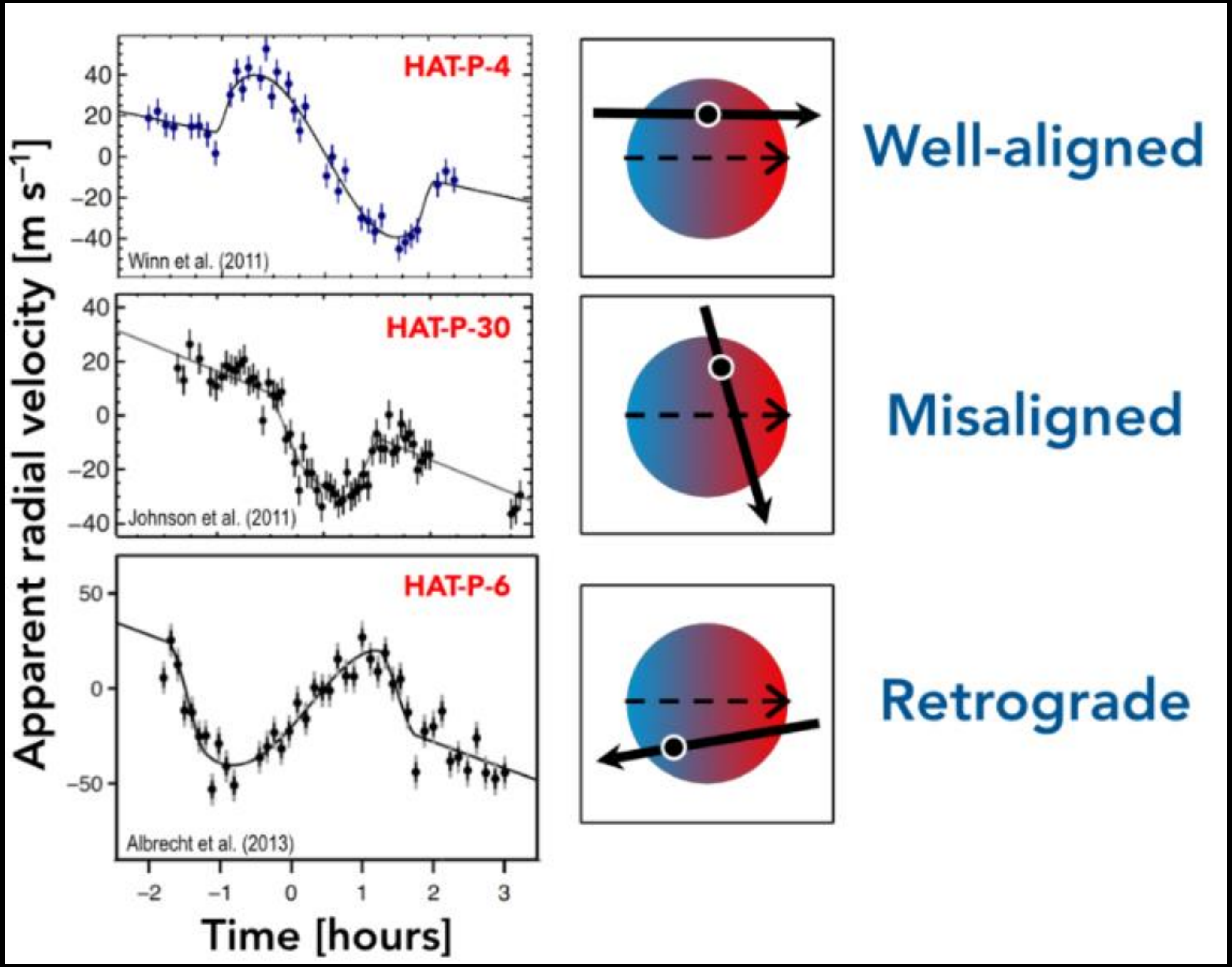
Rossiter-McLaughlin effect



Winn (2010)

- Allows for determination of the projected angle between the stellar spin axis and the orbital plane

Types of orbits

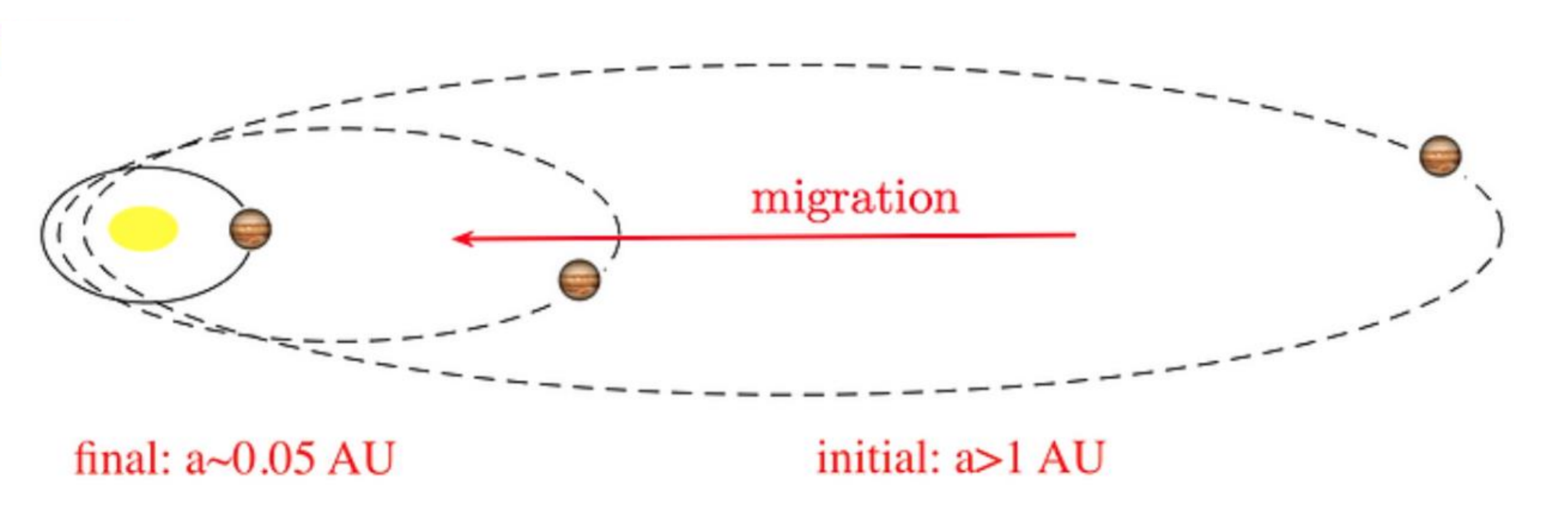


princeton.edu

Misaligned orbits

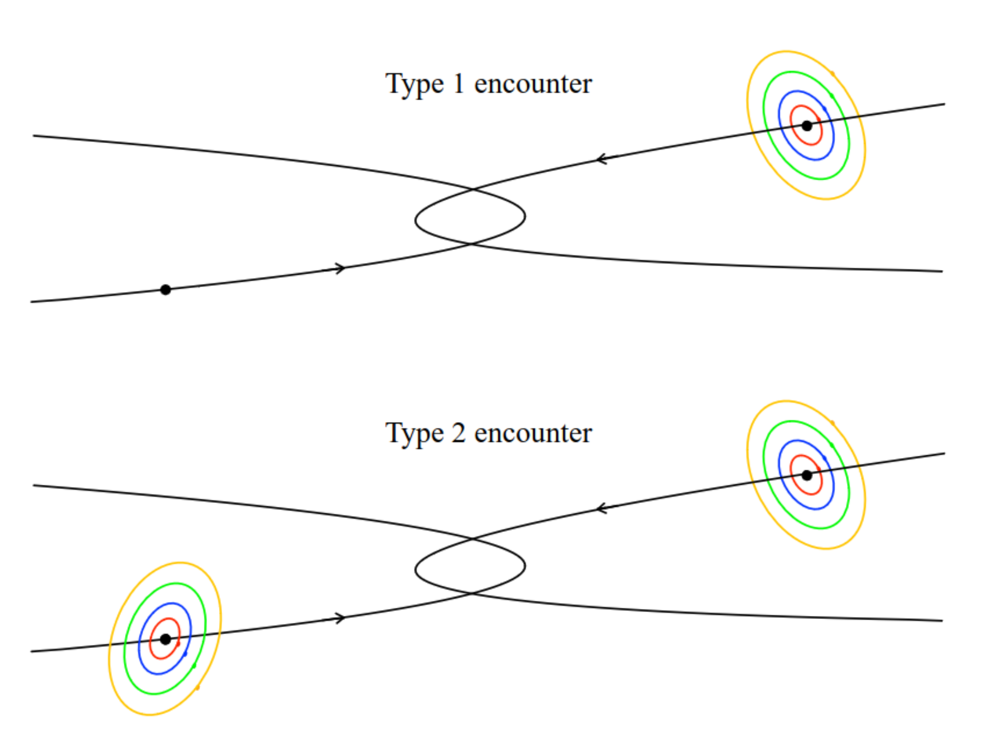
- High eccentricity migration
- Stellar or planetary companion

Petrovich



Misaligned orbits

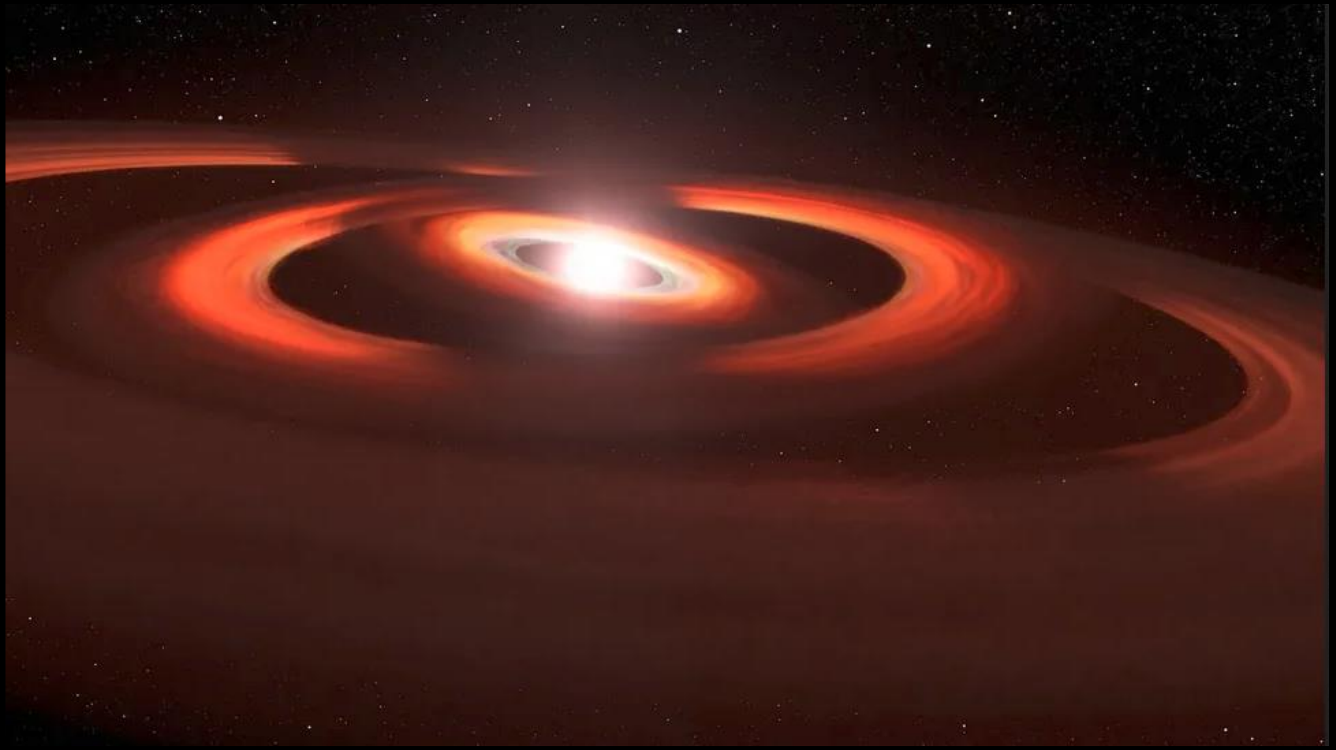
- High eccentricity migration
- Stellar or planetary companion
- Stellar fly-by



Li et al. (2019)

Misaligned orbits

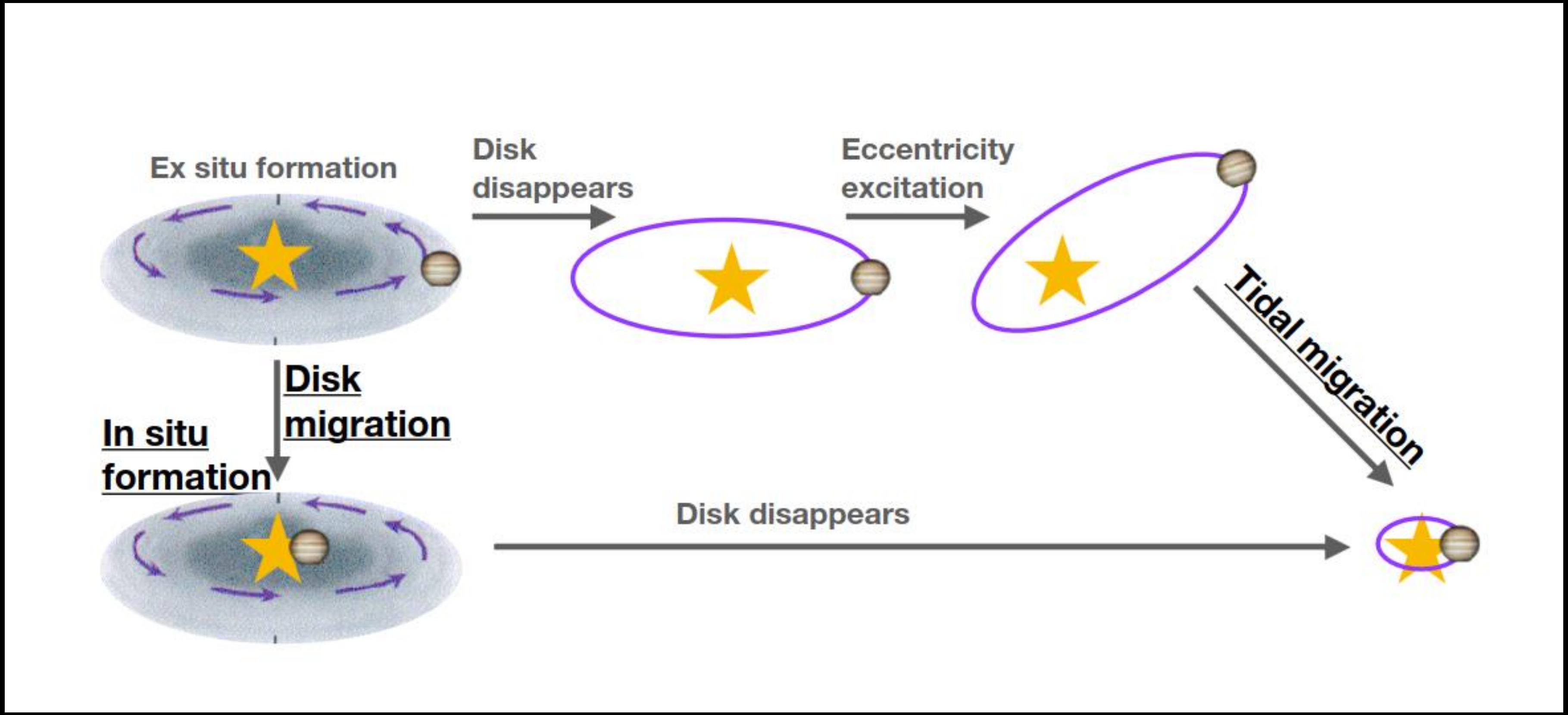
- High eccentricity migration
- Stellar or planetary companion
- Stellar fly-by
- Primordial misalignment



NASA

Formation mechanism

- R-M effect can be used to study the history of the system

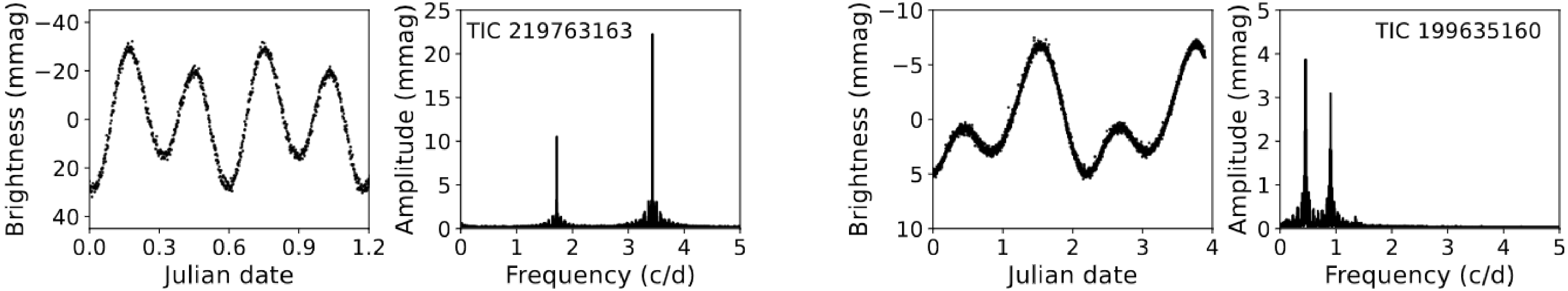


R. Dawson

Stellar variability

- Rotational modulation to derive stellar rotation

Type	Light curve	Frequency spectrum	Physical origin
ROTM	strictly repeating pattern, smooth variation without sharp features, maxima and minima generally different, superposition of two waves	one or two dominant peaks that are harmonics of the basic rotational frequency ($f_2 = 2f_1$), low-amplitude harmonics of f_1 may be present	rotation of a star with abundance anomaly spots



Skarka & Žák+22

Stellar variability

- Rotational modulation to derive stellar rotation and inclination

$$i = \sin^{-1}\left(\frac{v \sin i}{v}\right) = \sin^{-1}\left(\frac{v \sin i}{2\pi R/P}\right).$$

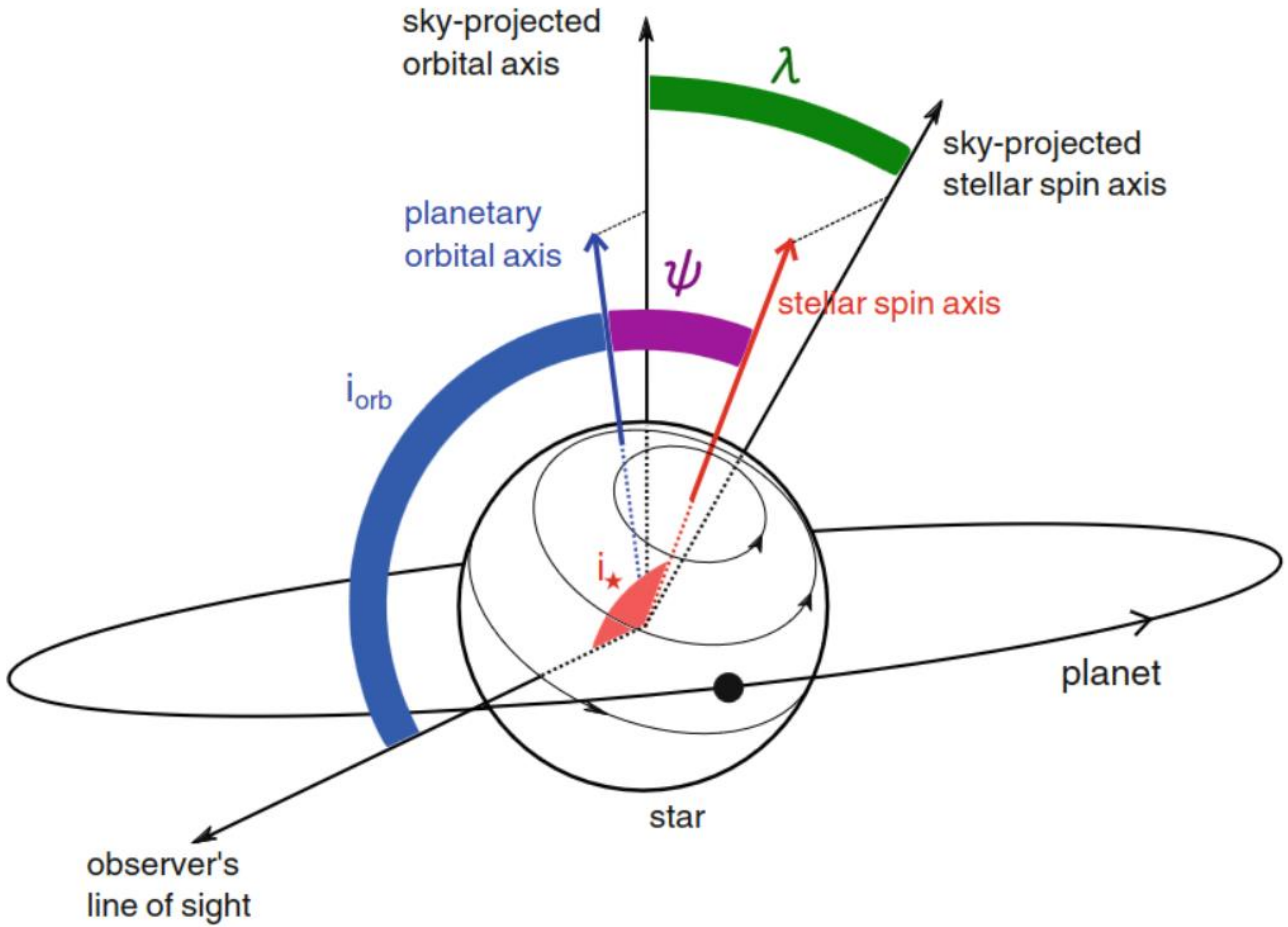
Stellar variability

- Rotational modulation to derive stellar rotation and inclination

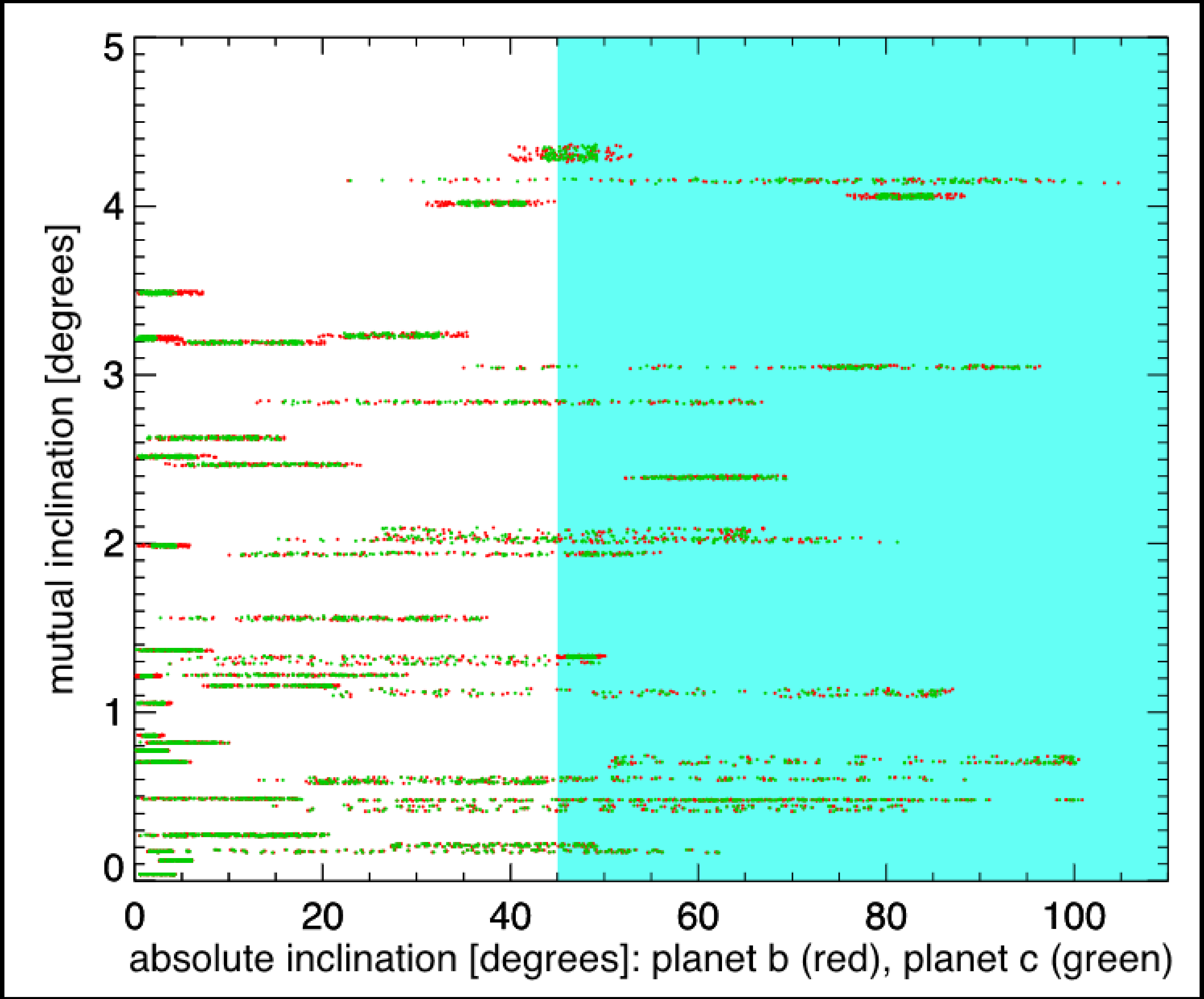
$$i = \sin^{-1}\left(\frac{v \sin i}{v}\right) = \sin^{-1}\left(\frac{v \sin i}{2\pi R/P}\right).$$

- This allows us to compute Ψ - True obliquity

$$\cos\psi = \cos i \cos i_{\rm o} + \sin i \sin i_{\rm o} \cos\lambda,$$

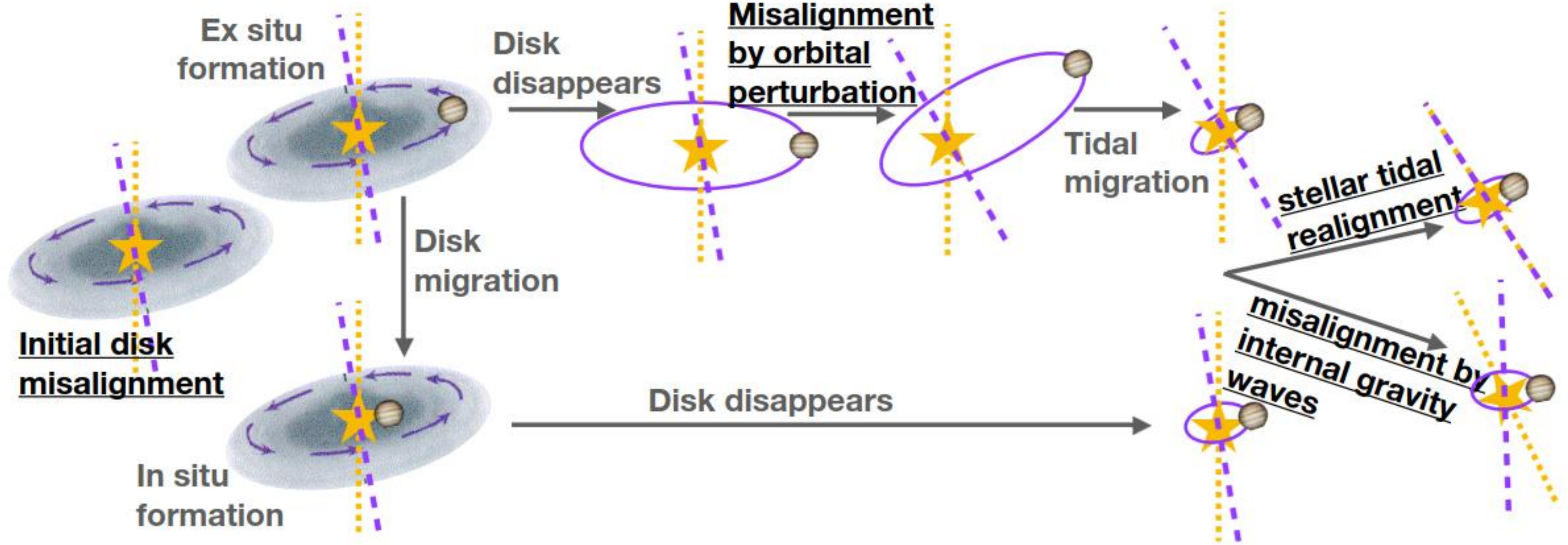

sky-projected
orbital axis
λ
sky-projected
stellar spin axis
planetary
orbital axis
ψ
stellar spin axis
i_orb
i★
planet
star
observer's
line of sight

Masuda

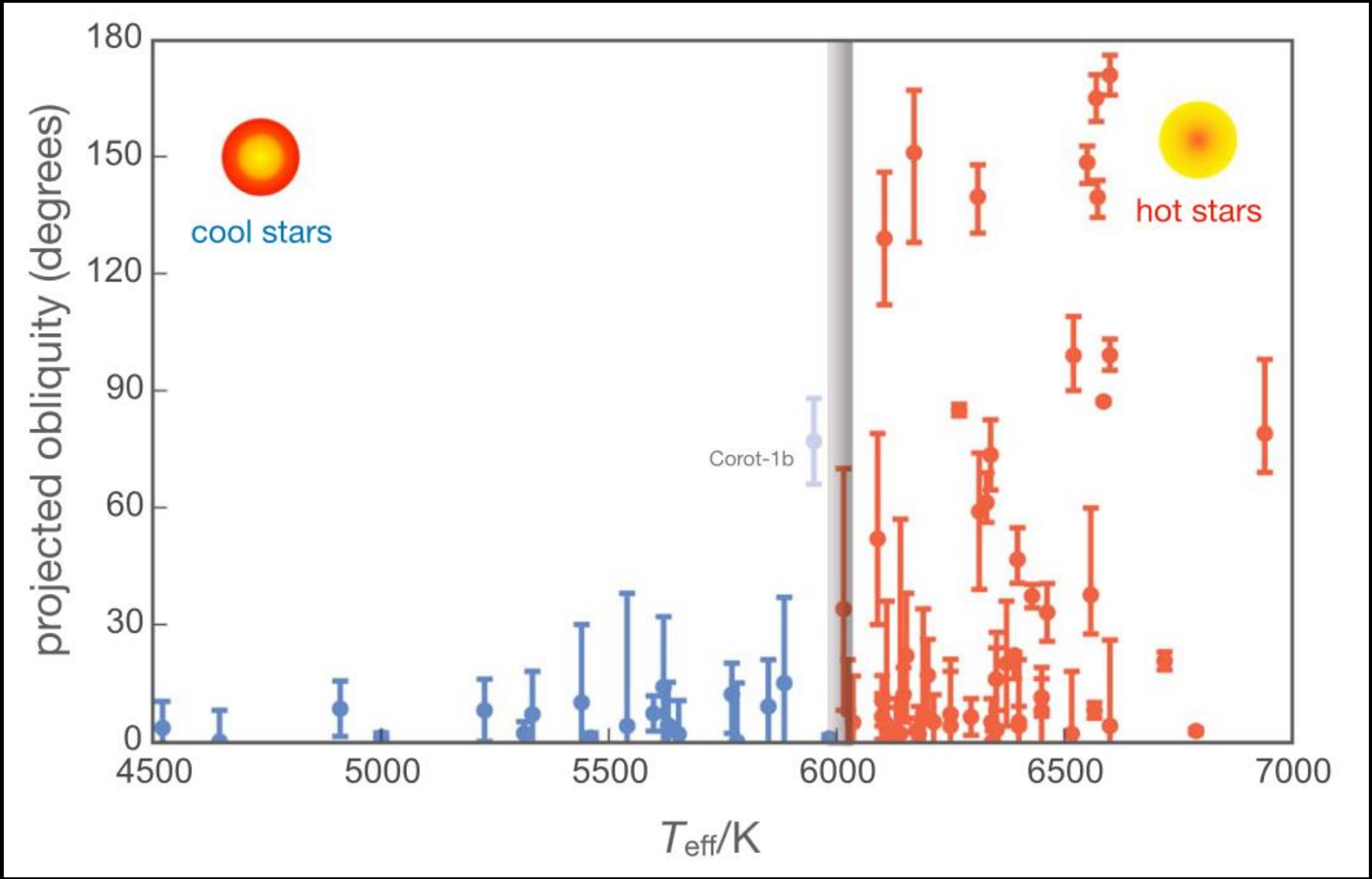


mutual inclination [degrees]
absolute inclination [degrees]: planet b (red), planet c (green)
0
1
2
3
4
5
0
20
40
60
80
100

Gratia+2017


Ex situ formation
Disk disappears
Misalignment by orbital perturbation
Tidal migration
stellar tidal realignment
Disk migration
Initial disk misalignment
misalignment by internal gravity waves
Disk disappears
In situ formation

R. Dawson

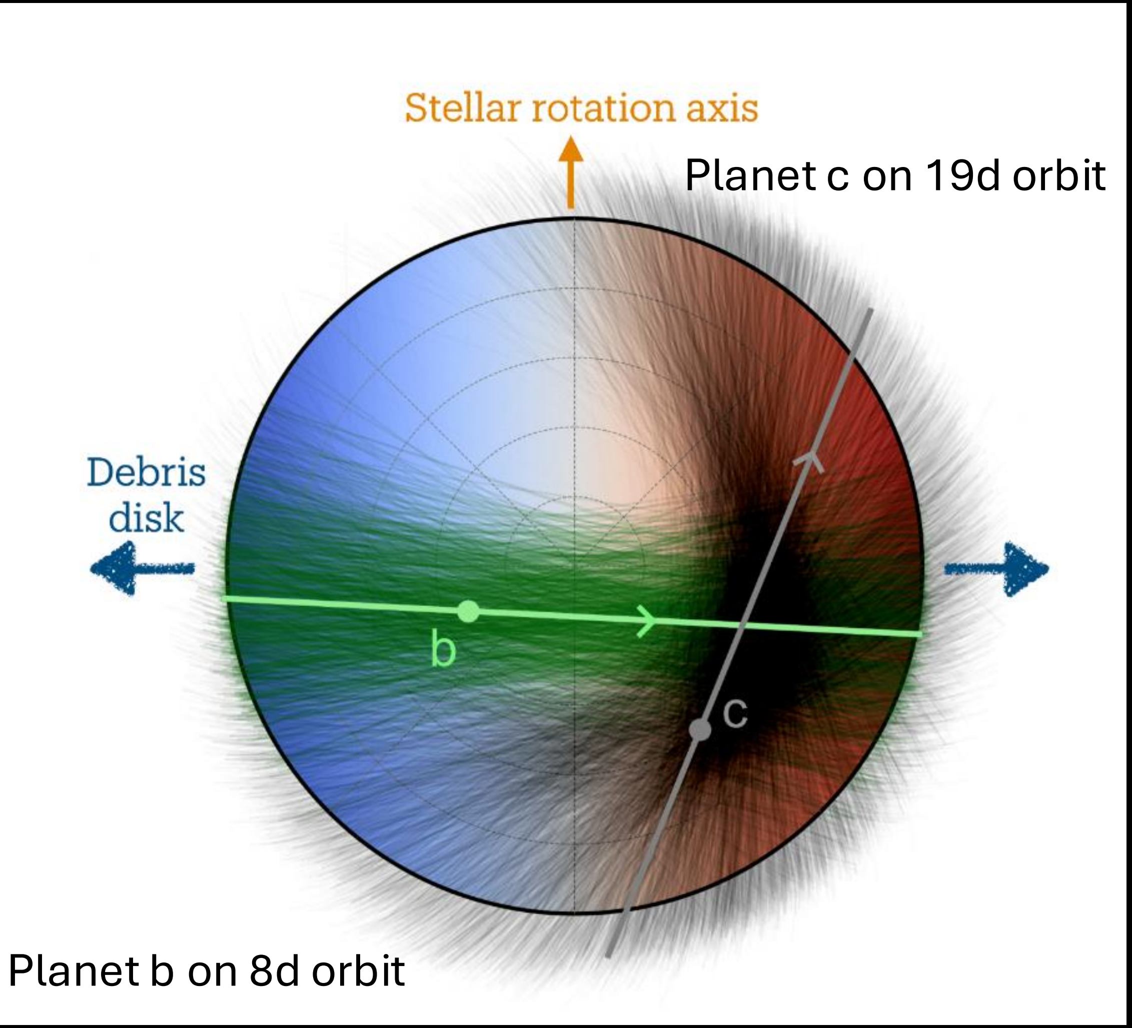


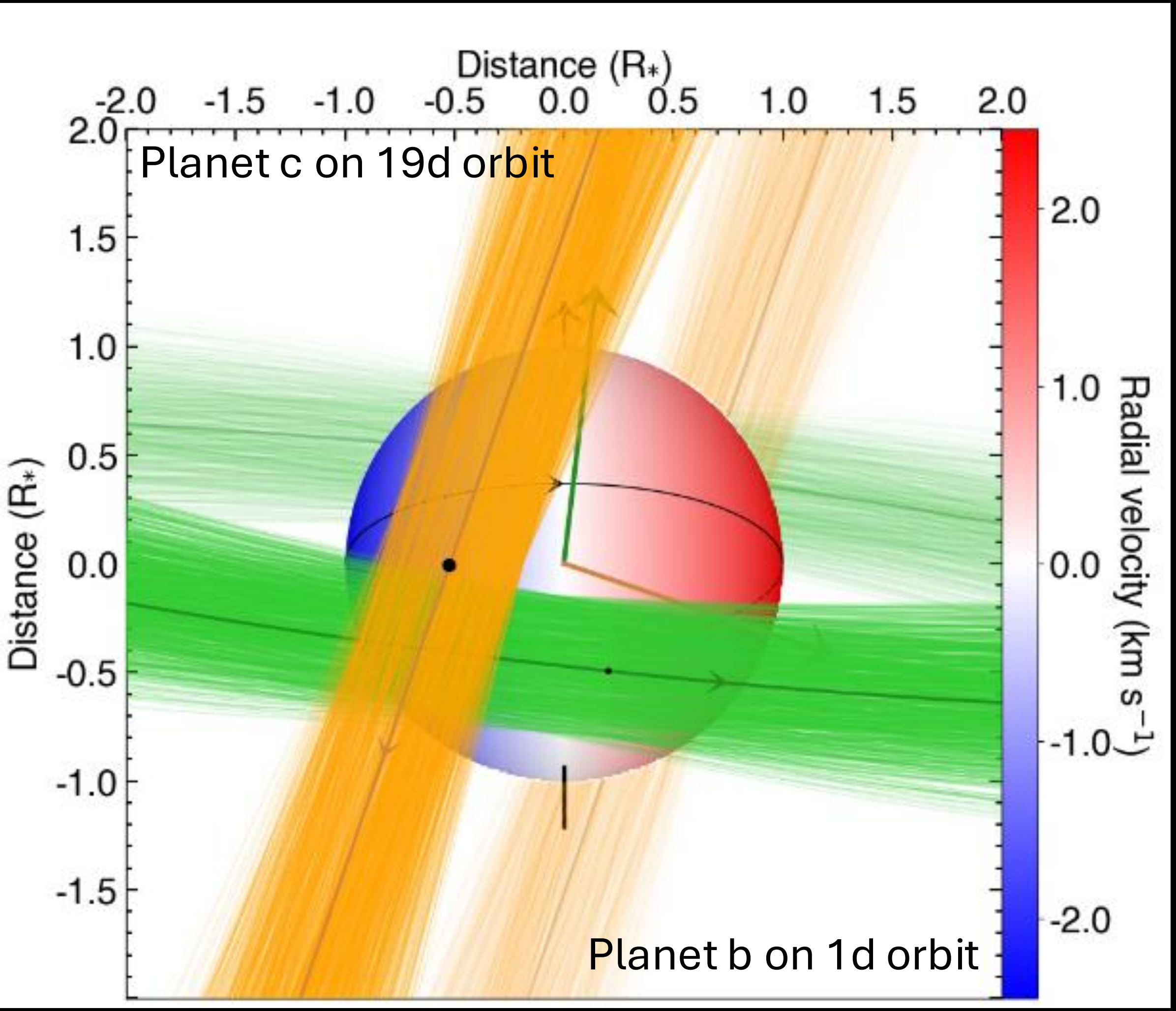
180
150
120
90
60
30
0
projected obliquity (degrees)
cool stars
hot stars
Corot-1b
4500
5000
5500
6000
6500
7000
T_{eff}/K

Spalding+22

AU Mic

HD 3167

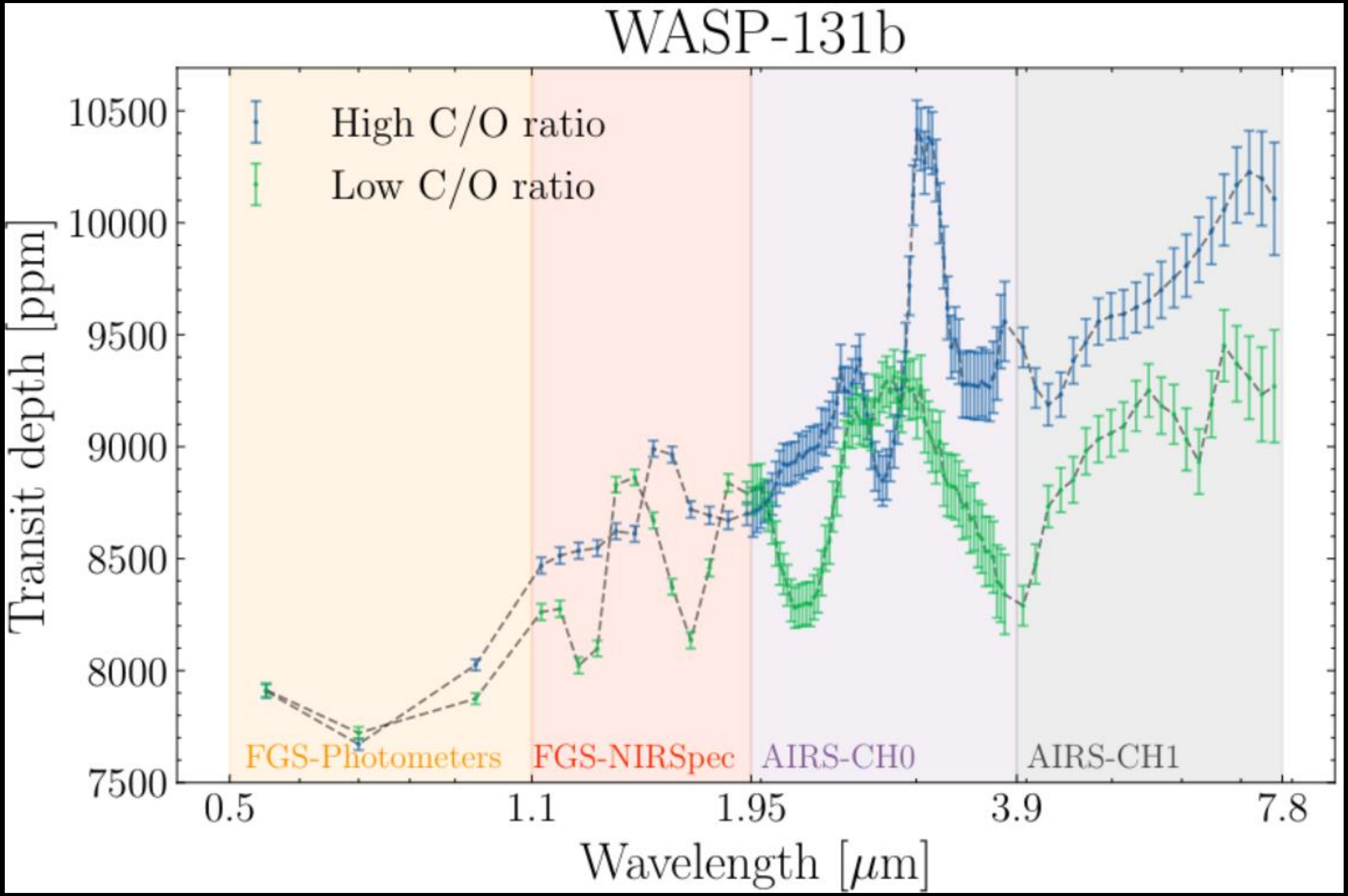




Yu+25

Bourrier+21

Transmission spectra



Žák+24

Questions?