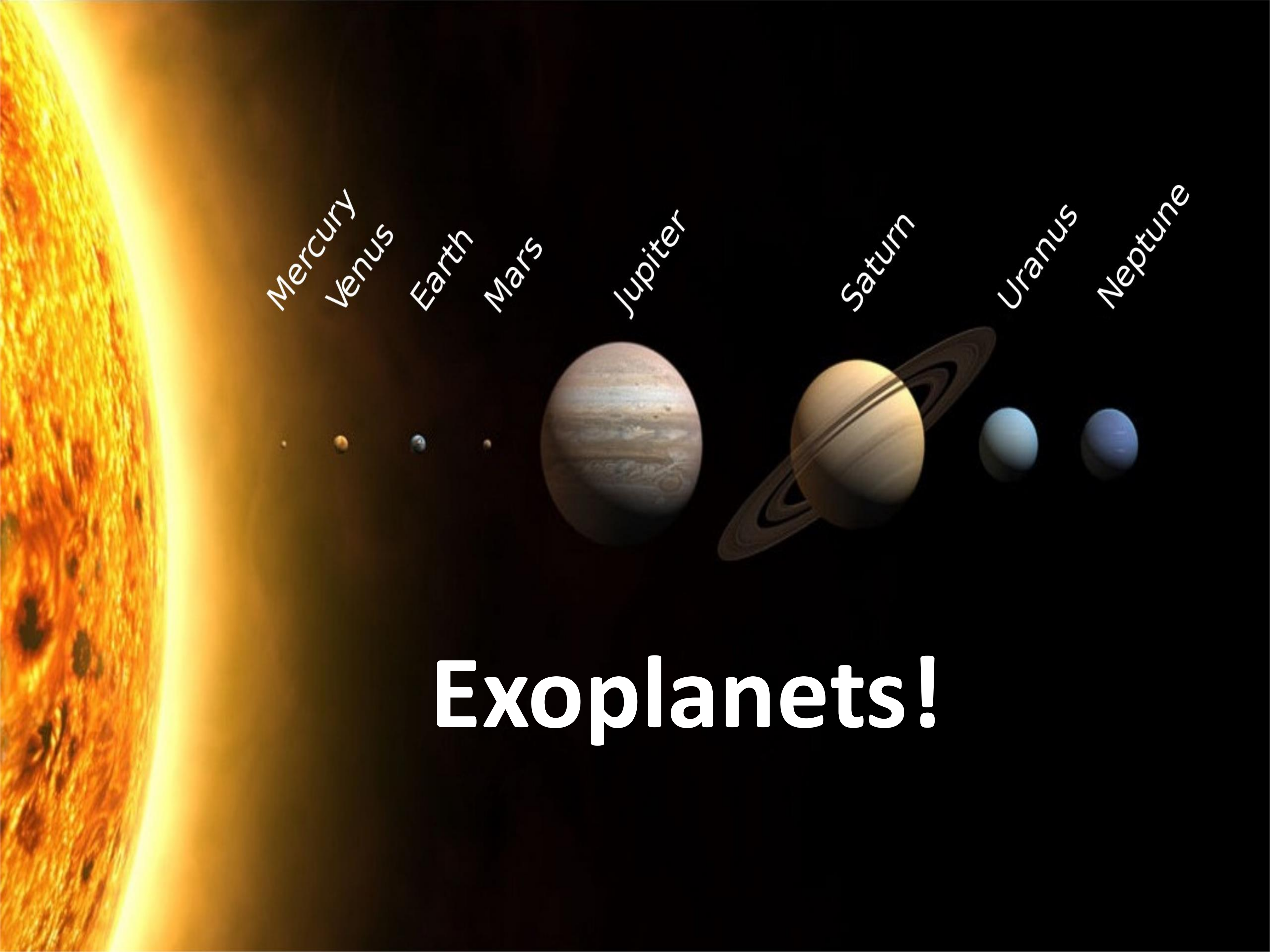

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Exoplanets!

Homework: due now!

Probably a 2-week turnaround for grades

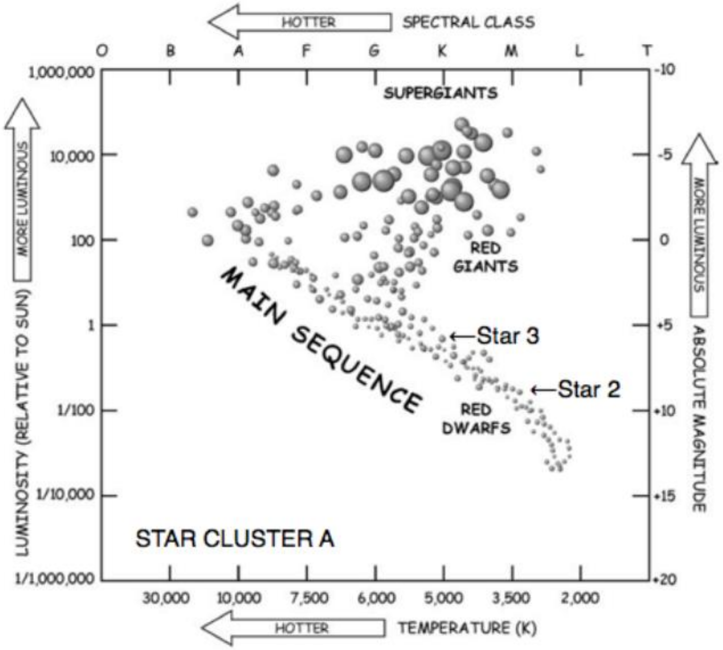
Class next week, then no class (Qing Ming)

Project 1: due on 4.13

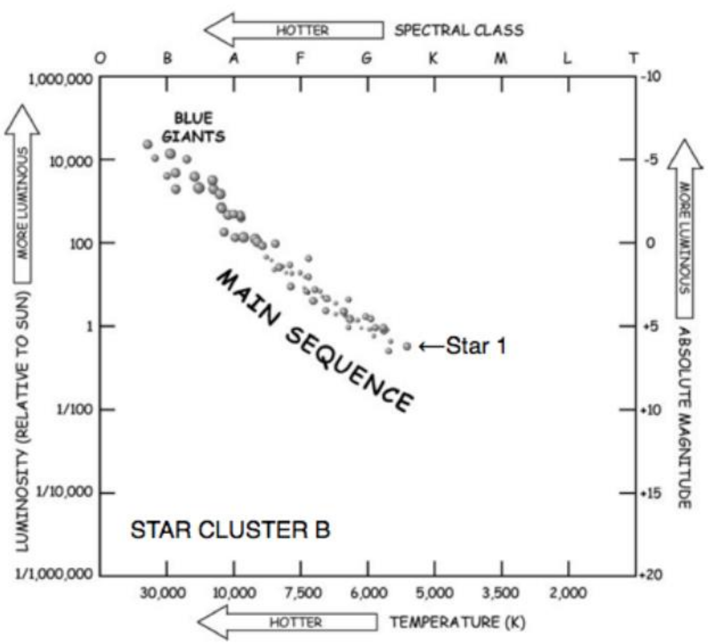
- Due before class on April 13
- Oral report
  - 6 min (don't go over)
  - Max 7 slides (including intro slide)
- Choose any astronomy-related topic
- Make it interesting!
- Upload video to PKU server
- Will circulate assignment to wechat group tomorrow

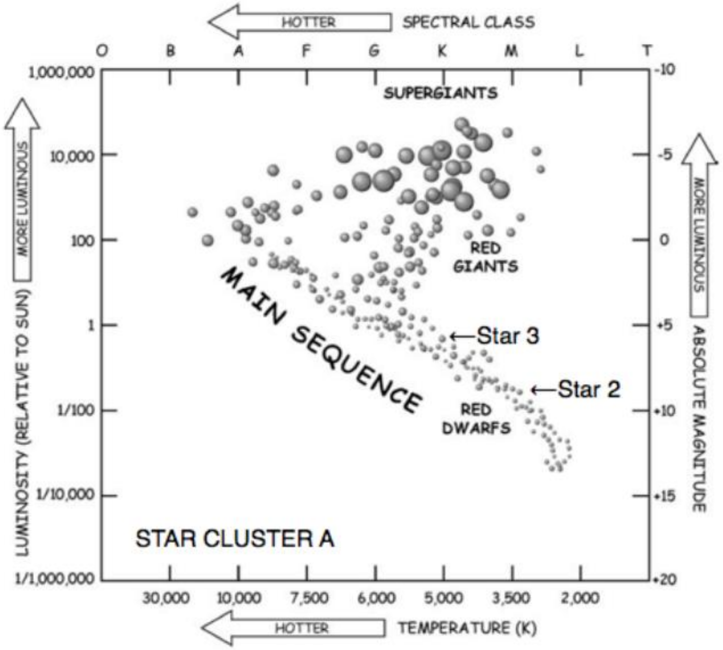
Homework

- Distances! If the sun is the size of a soccer ball (0.1 m radius):
  - Earth is 20 m away (other side of room)
  - Nearest star is 6000 km away (Europe)!
  - Nearest (large) galaxy is at location of Uranus!
  - Distance between Mars, Earth changes with time

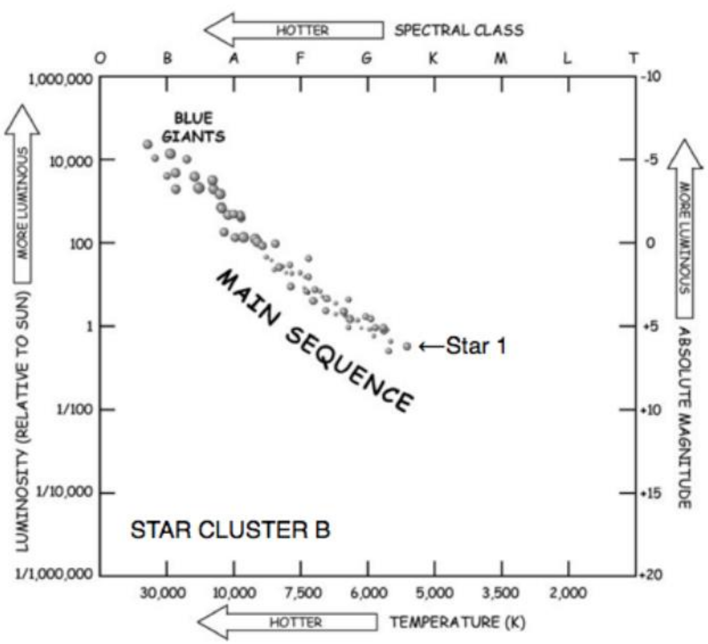


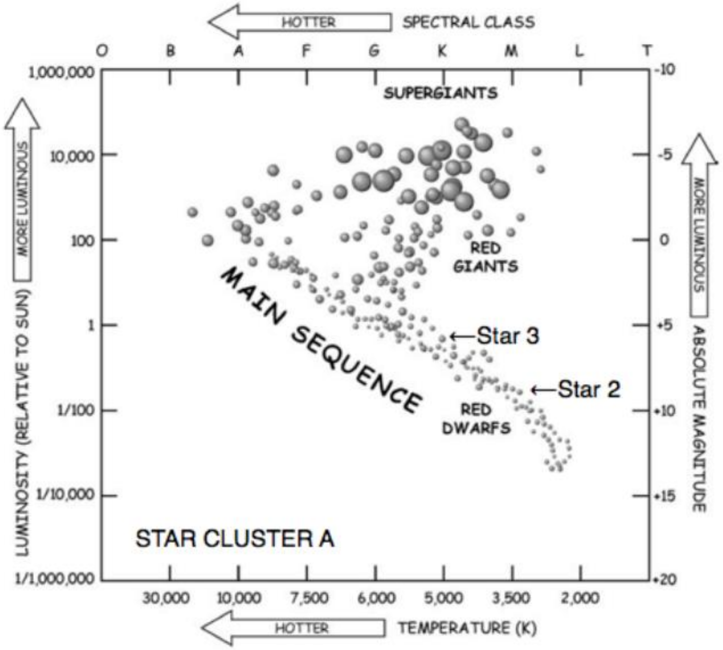
- Star 2: very faint! Any planet would be very cold! (more today and in a future homework)





- Binary: if two stars, the total brightness needs to add to observed luminosity
  - Both stars fainter
  - Color (temperature) should cancel, so one hotter, other is cooler

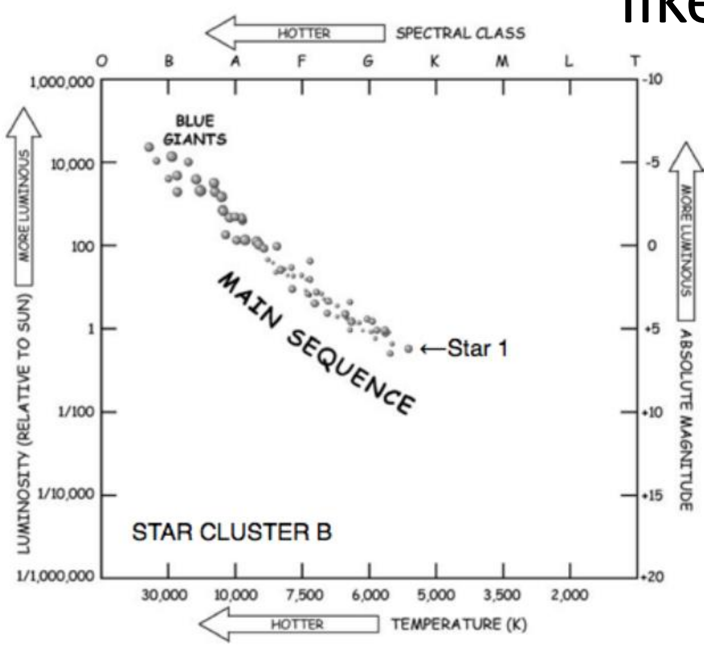




Which is more distant?

Same y-axes (absolute luminosity/magnitude).

One has fewer faint points, so likely further away

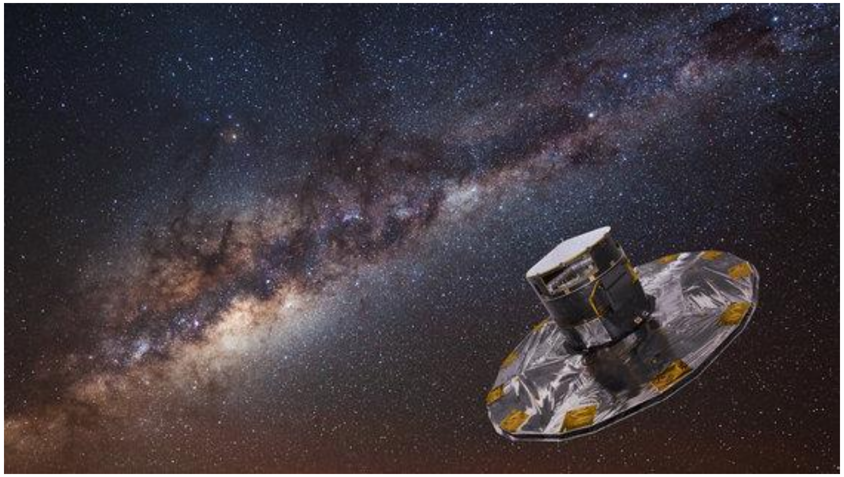


Gaia satellite and the Pleiades!

Stars that are born together travel together

--large clusters stay together

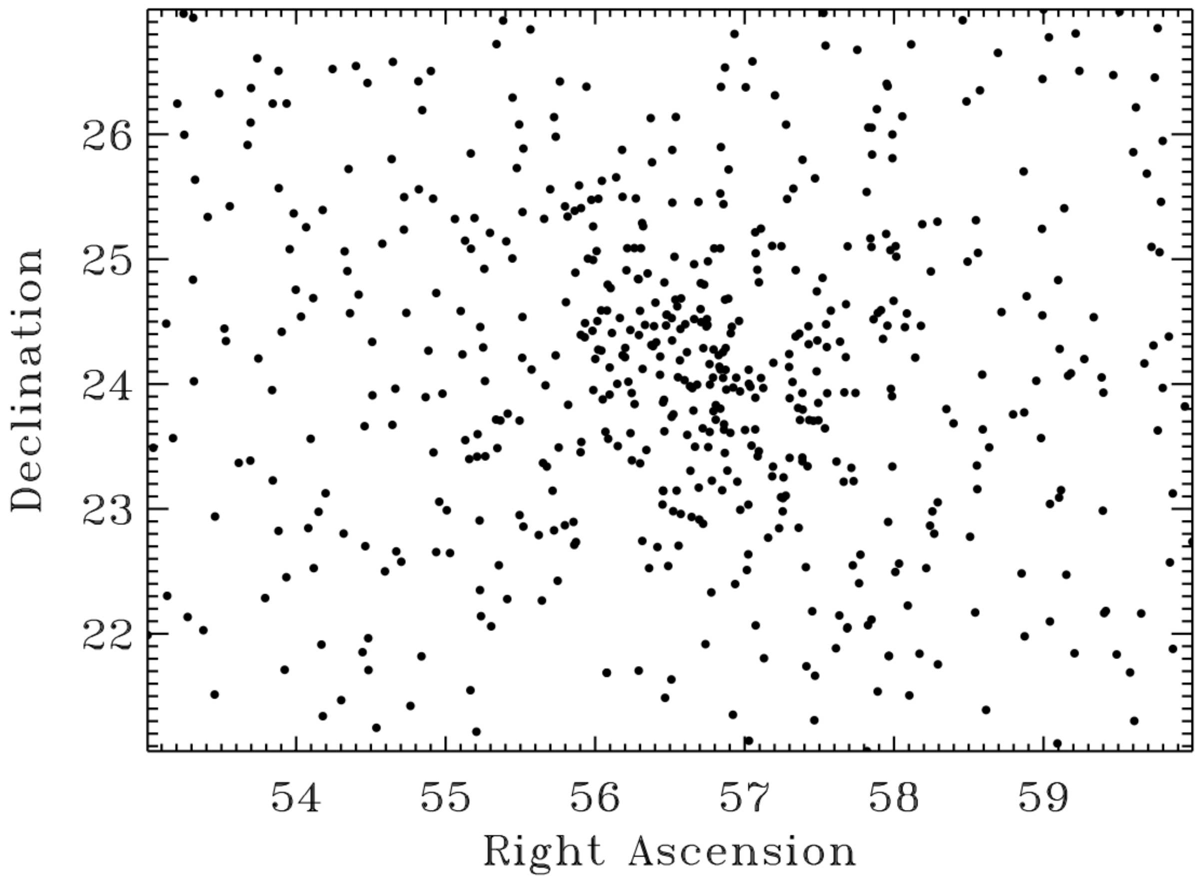
--smaller clusters disperse with time



Gaia satellite and the Pleiades!

Dataset: positions on the sky, motions on the sky, brightness in 3 bands

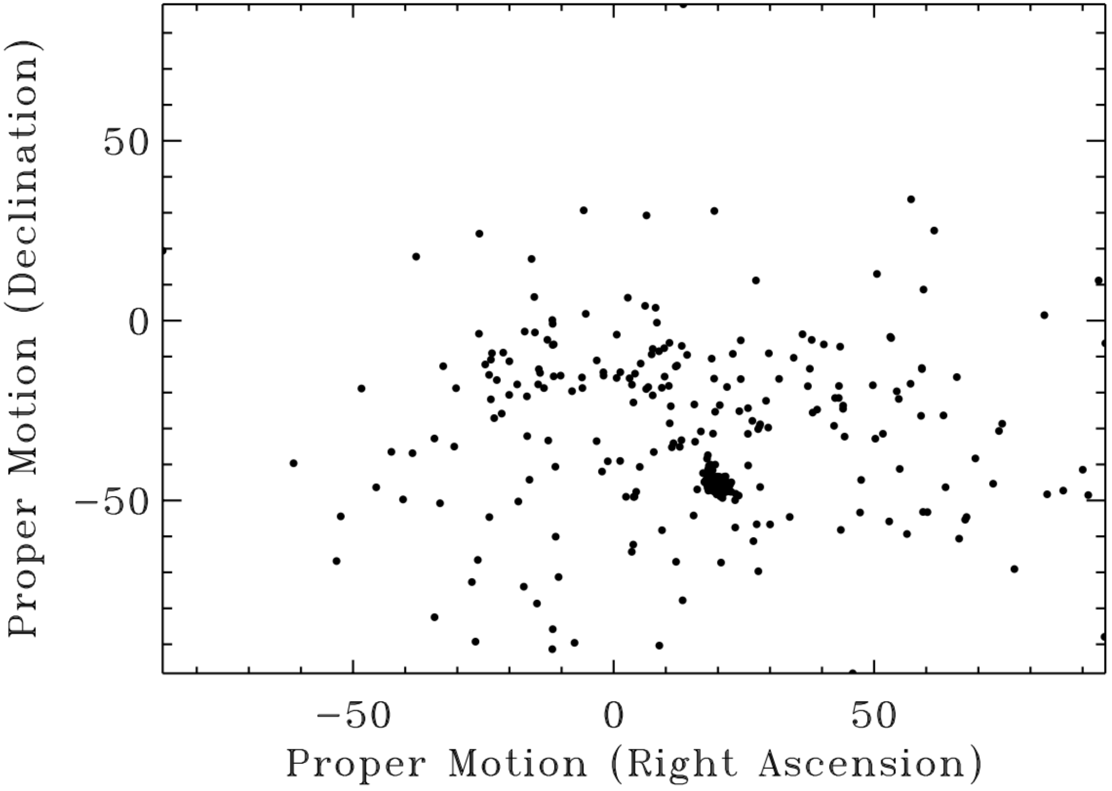
Plot: Positions



Gaia satellite and the Pleiades!

Dataset: positions on the sky, motions on the sky, brightness in 3 bands

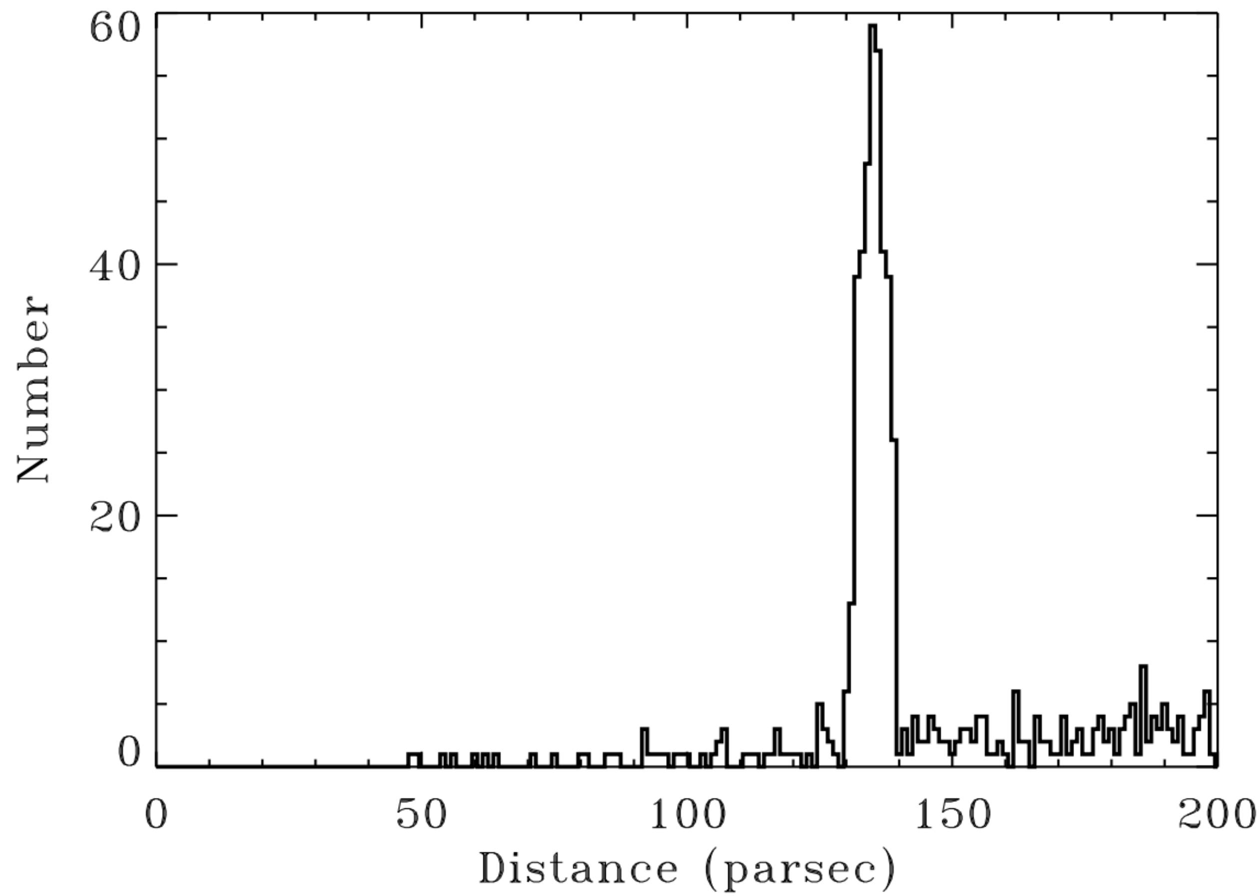
Plot: Proper motions (movement along sky



Gaia satellite and the Pleiades!

Dataset: positions on the sky, motions on the sky, brightness in 3 bands

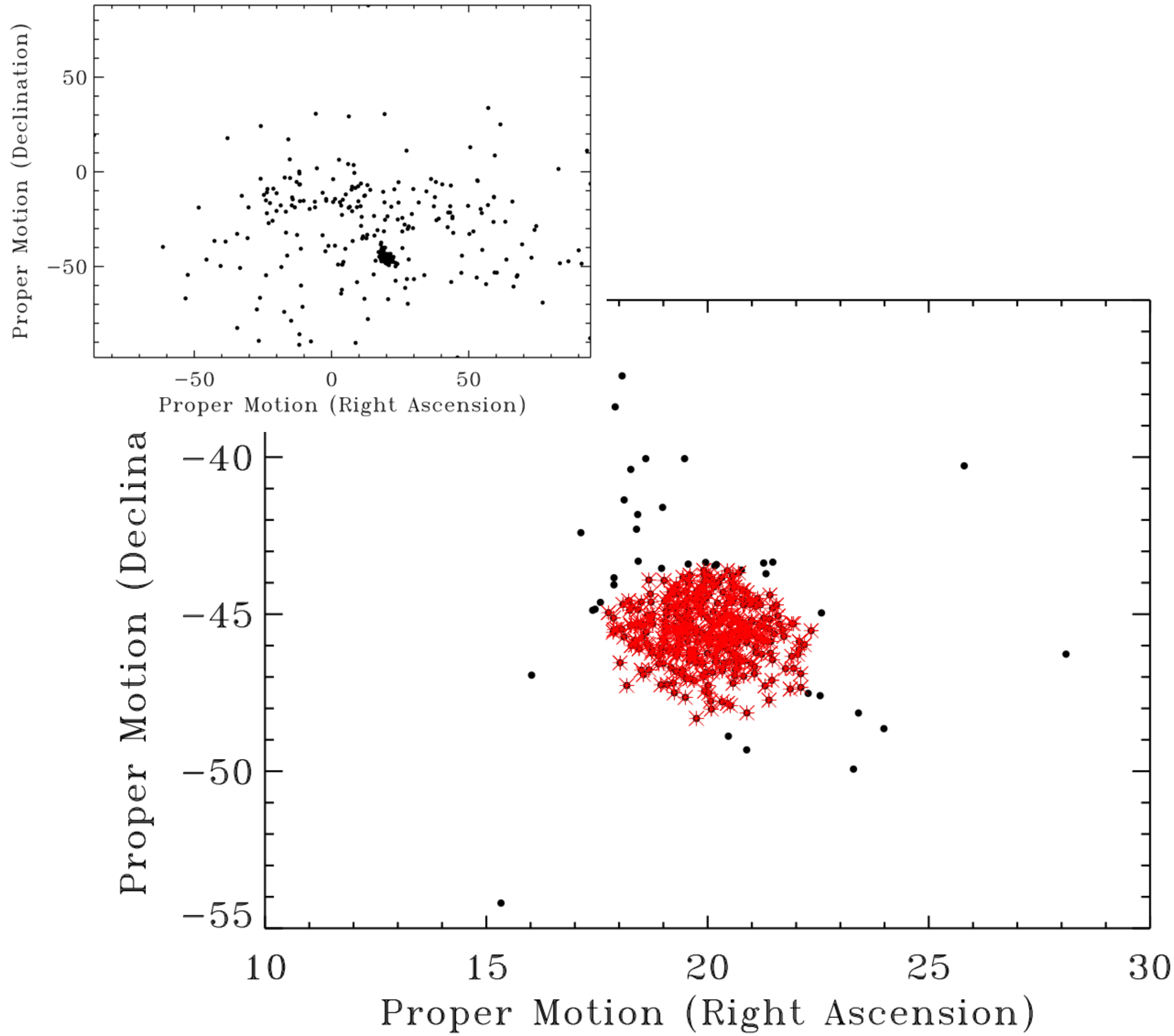
Histogram of distances



Gaia satellite and the Pleiades!

Plot: Proper motions (movement along sky)

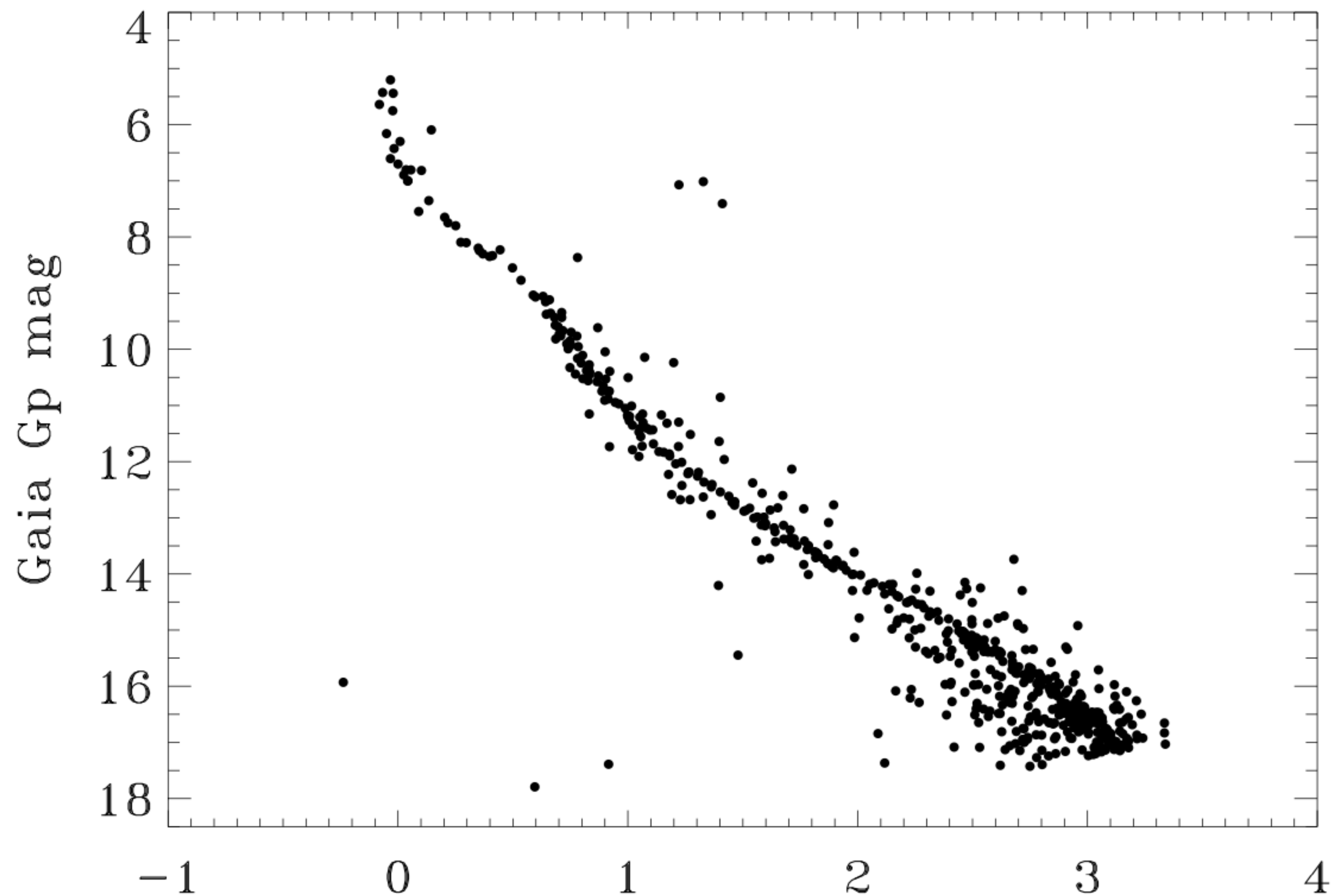
Selected for Pleiades distance (130-140 parsecs)



Gaia satellite and the Pleiades!

Dataset: positions on the sky, motions on the sky, brightness in 3 bands

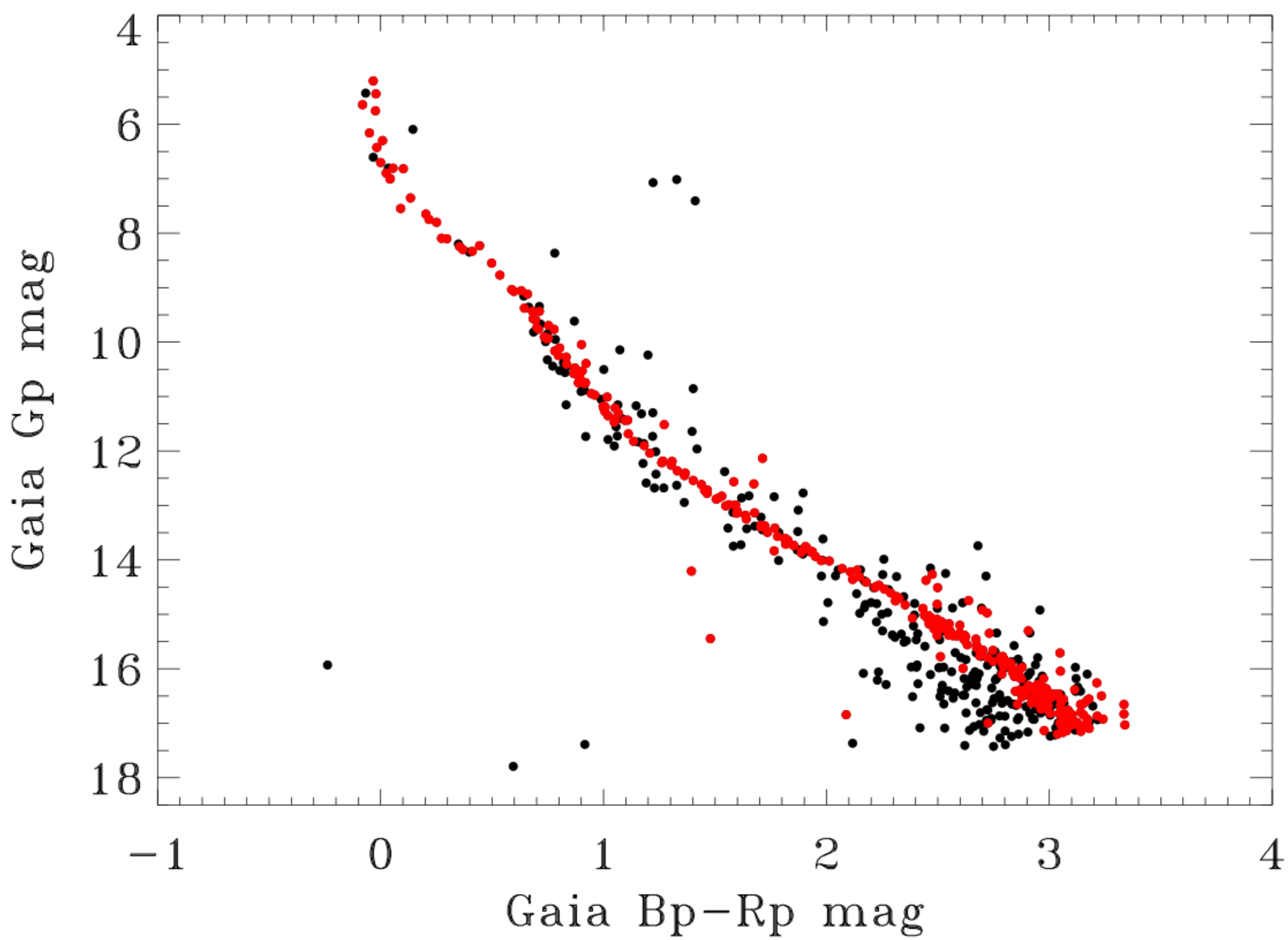
All stars



Gaia satellite and the Pleiades!

Dataset: positions on the sky, motions on the sky, brightness in 3 bands

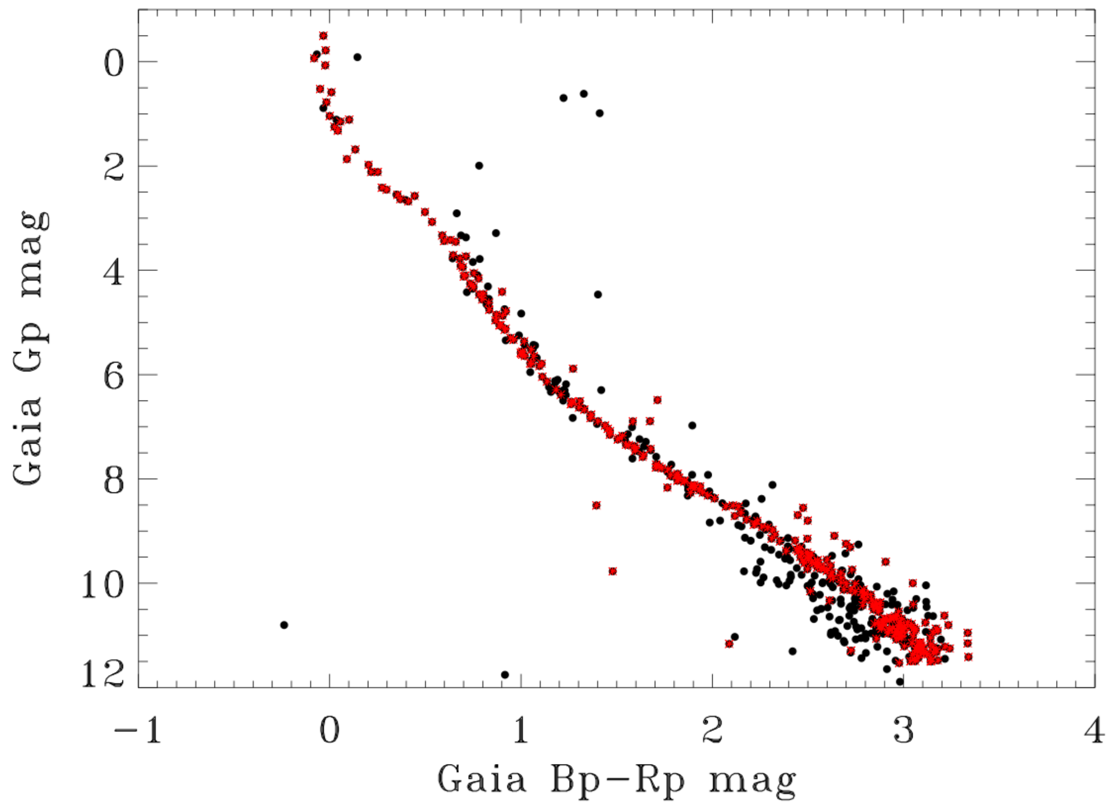
Red: cut in distance and proper motion



Gaia satellite and the Pleiades!

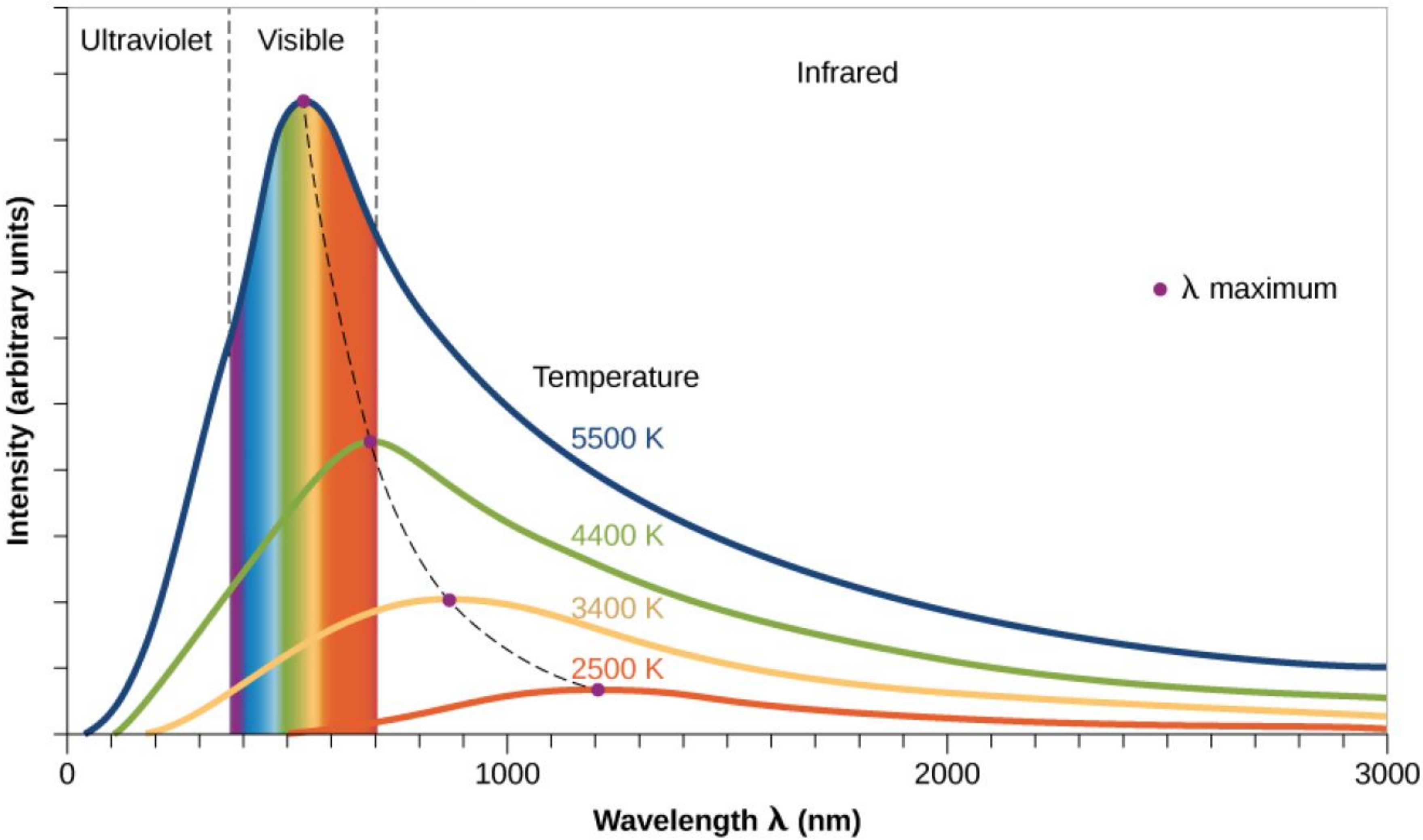
Dataset: positions on the sky, motions on the sky, brightness in 3 bands

Corrected for distance

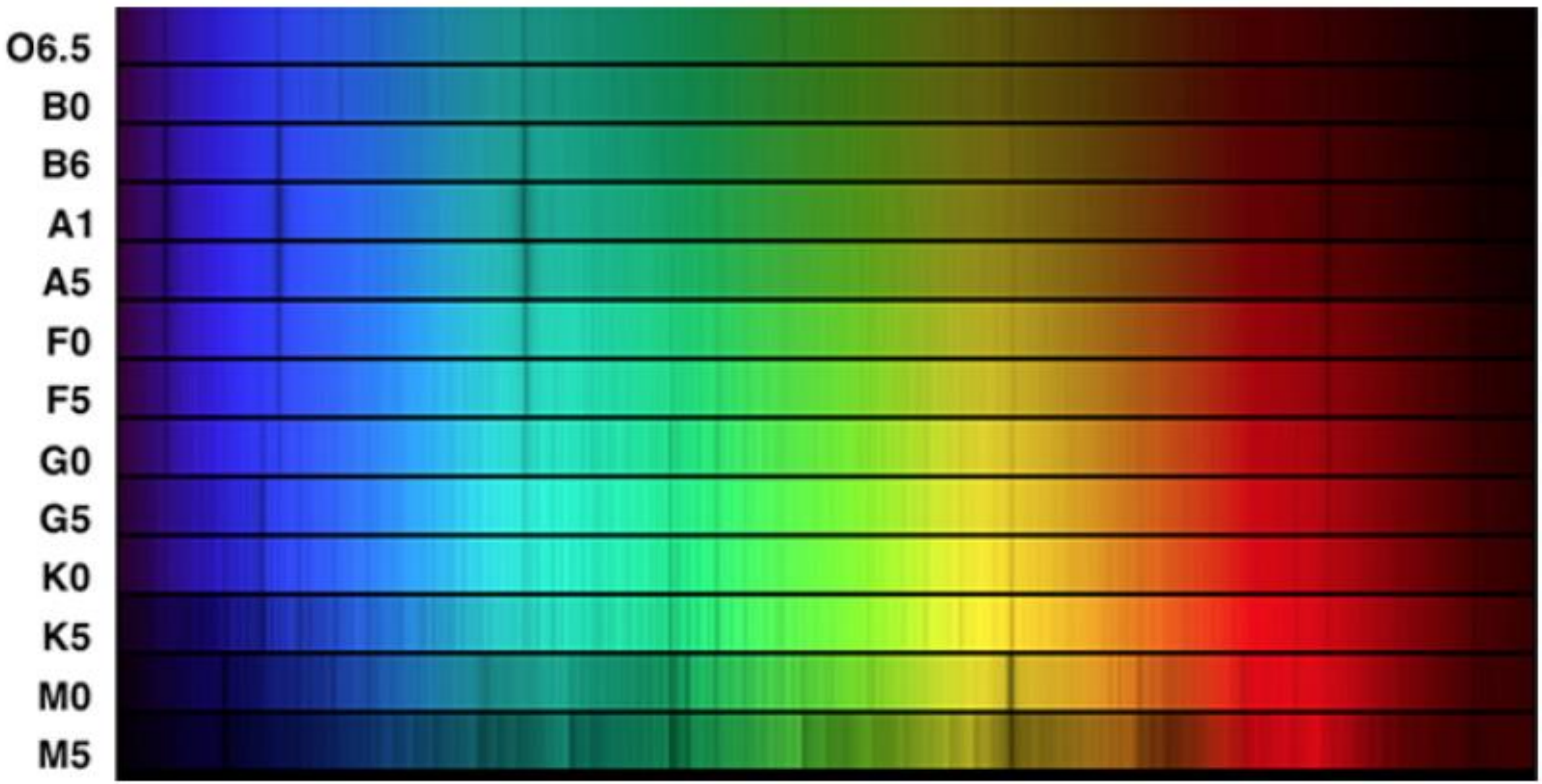


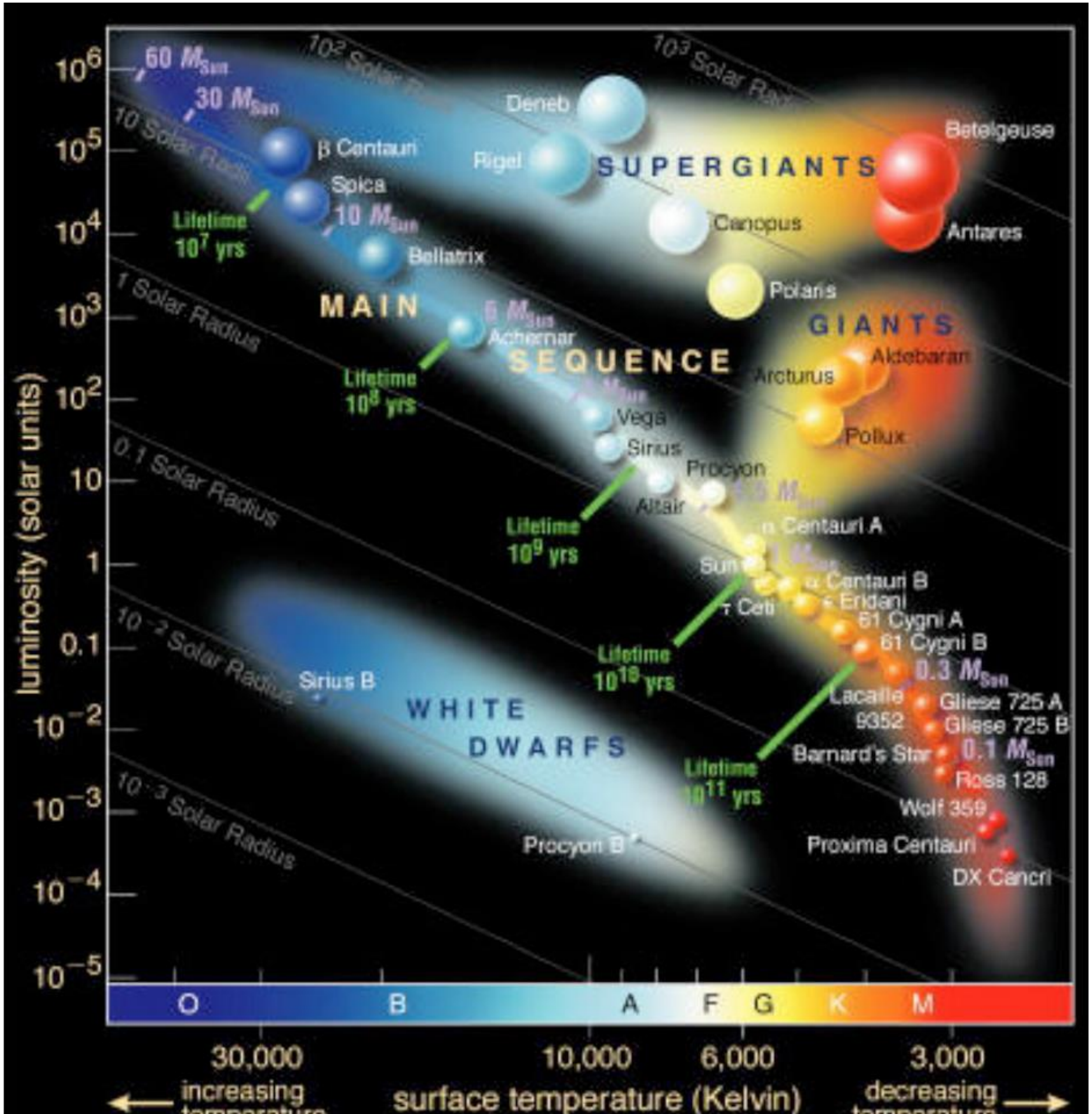
Blackbody emission: hotter things emit at higher energies (=shorter wavelengths)

Peak of blackobody: $\lambda_{\mathrm{max}} \cdot T = 0.288 \text{ cm} \cdot \text{K}$



Spectral type = temperature squence

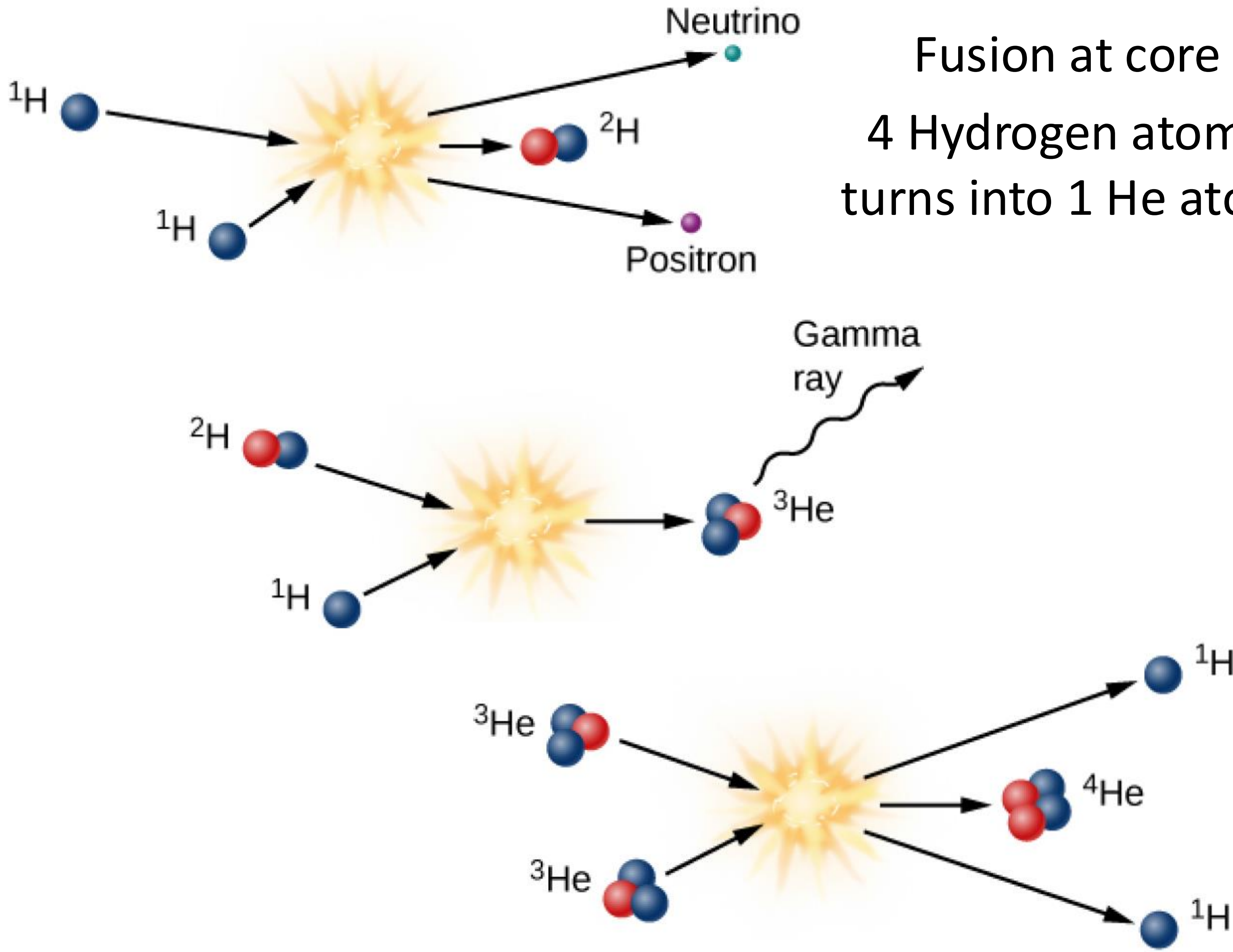




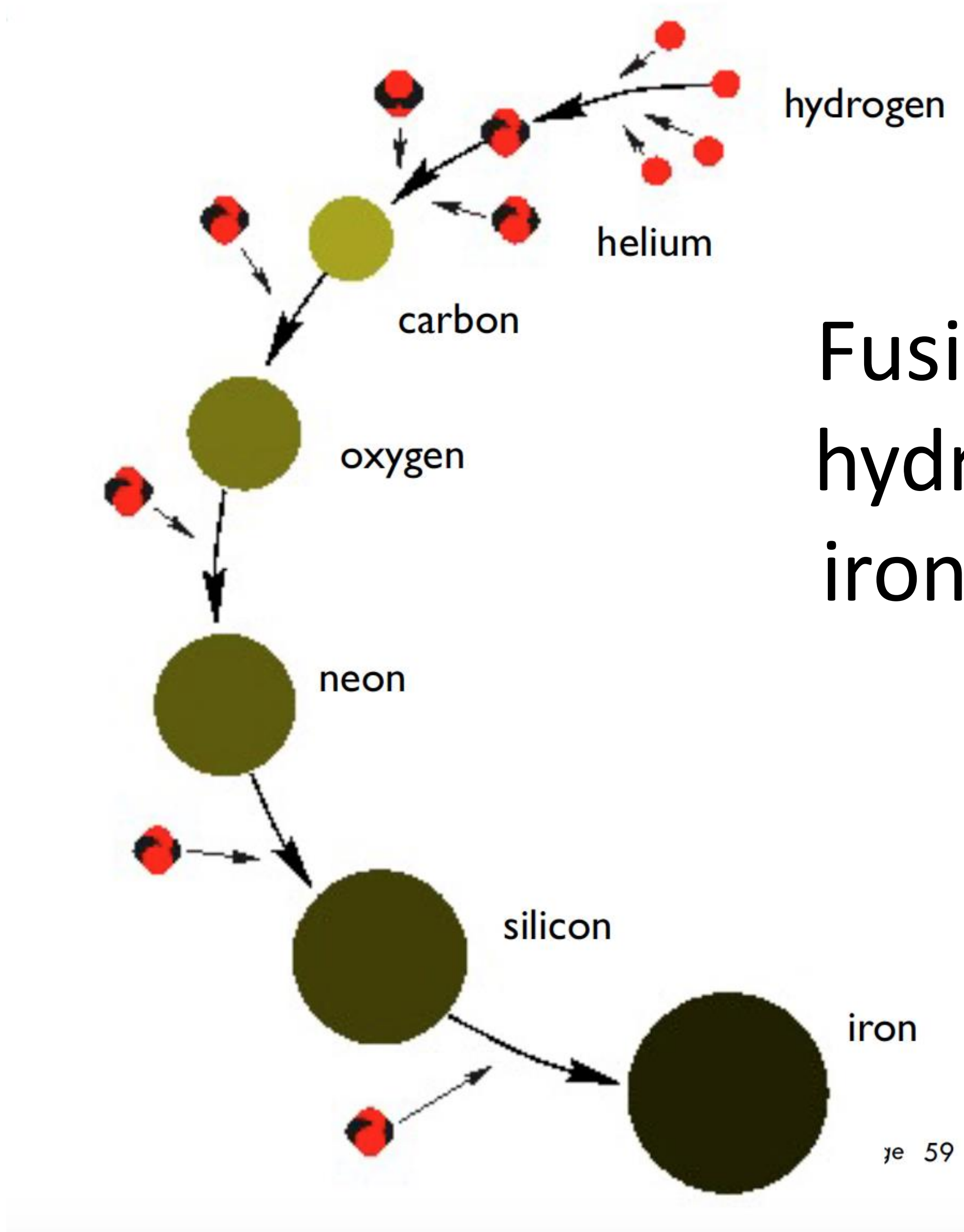
luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
MAIN SEQUENCE
SUPERGIANTS
GIANTS
WHITE DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}

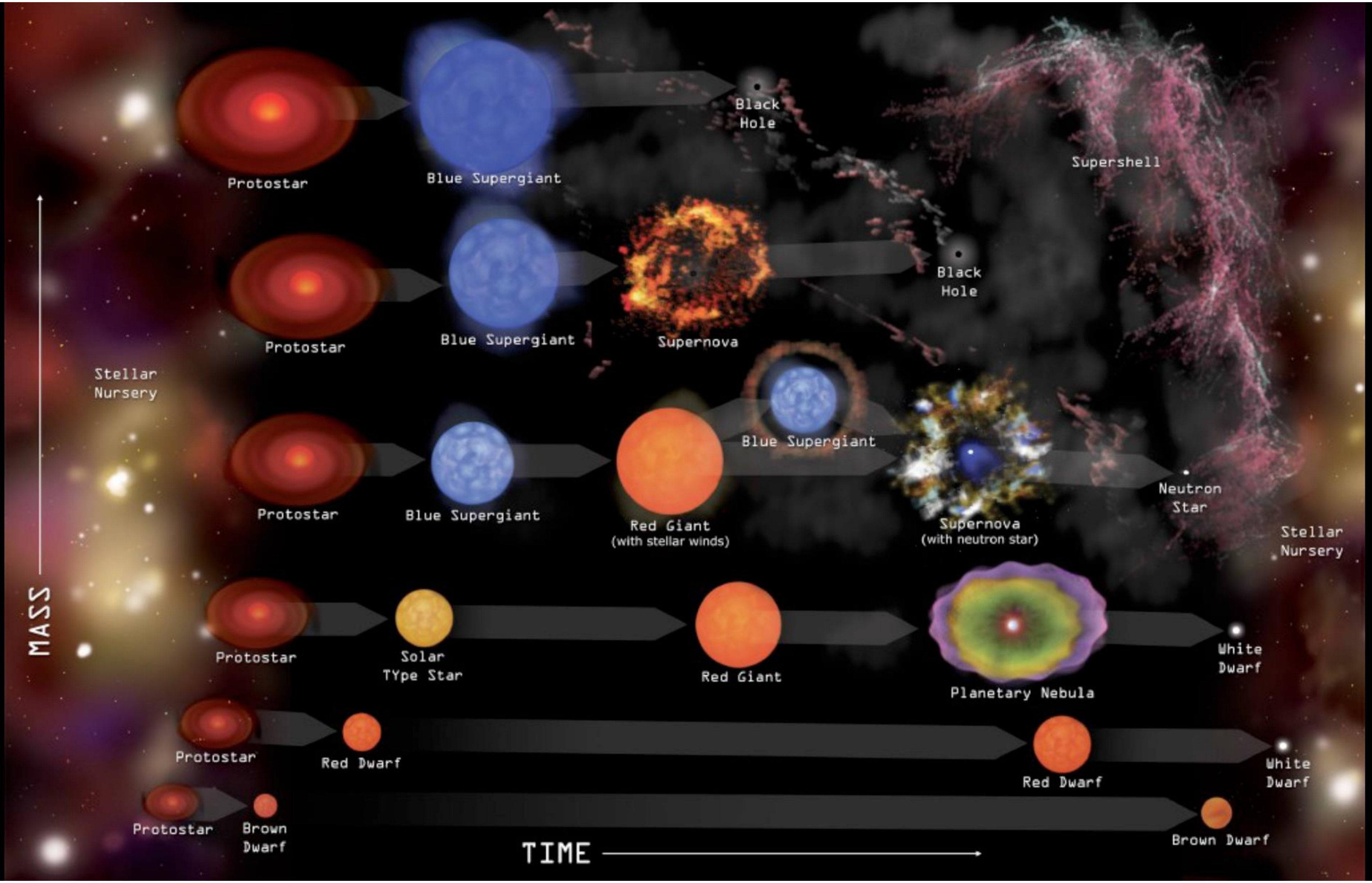
Fusion at core

4 Hydrogen atoms turns into 1 He atom



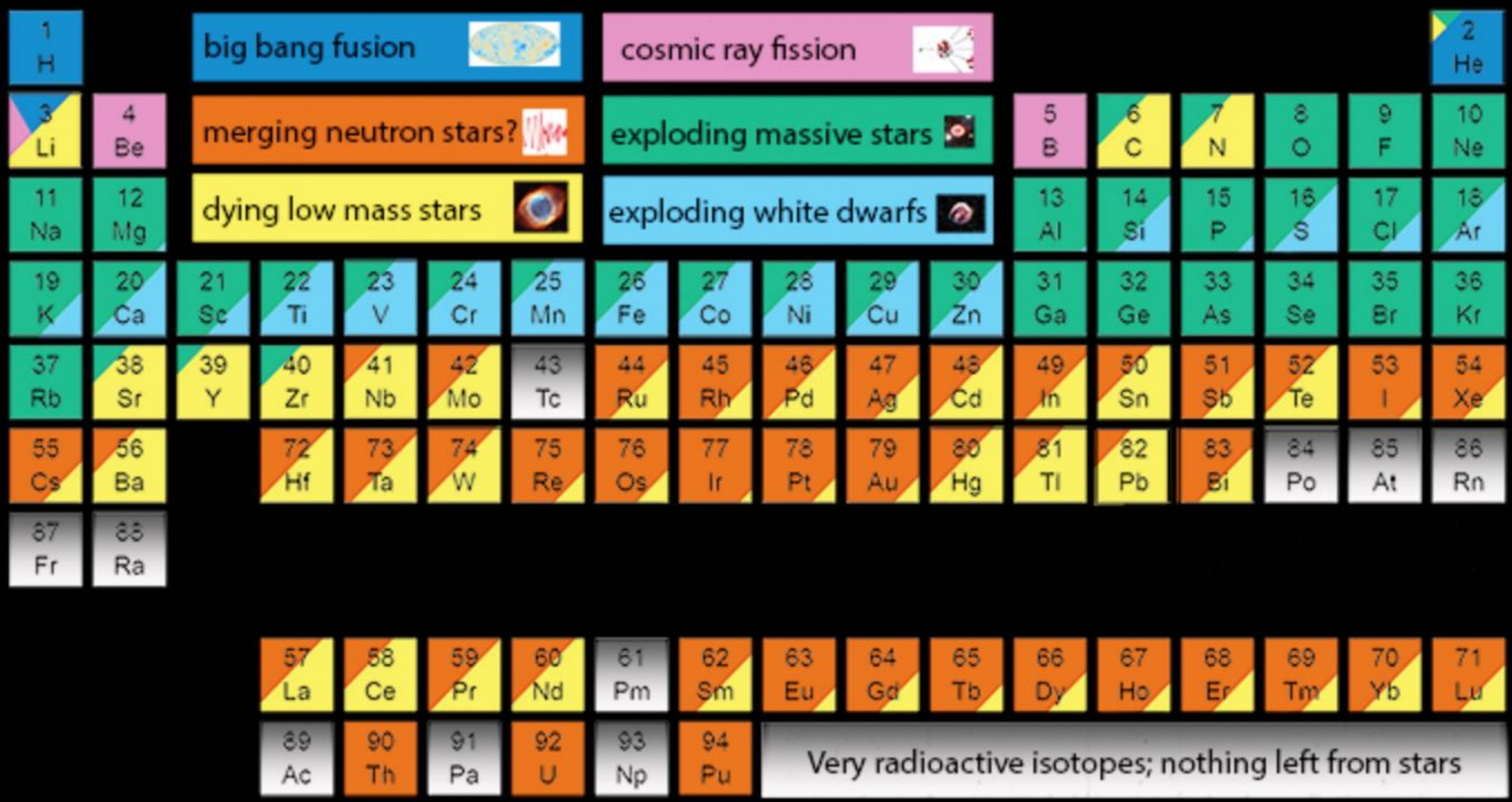
Fusion from hydrogen to iron in stars





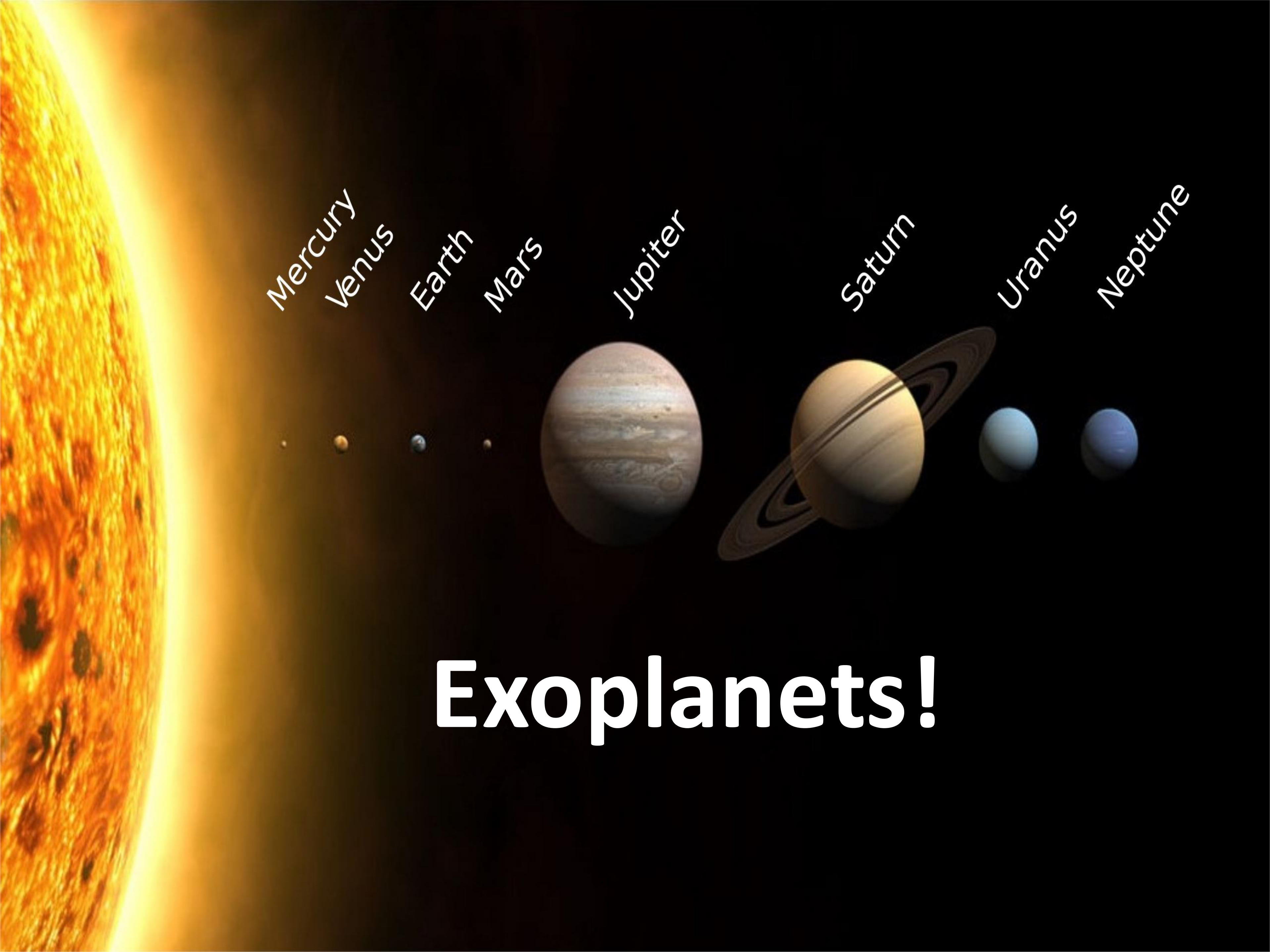
Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME

The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova



Exoplanets!

Exoplanets!!!

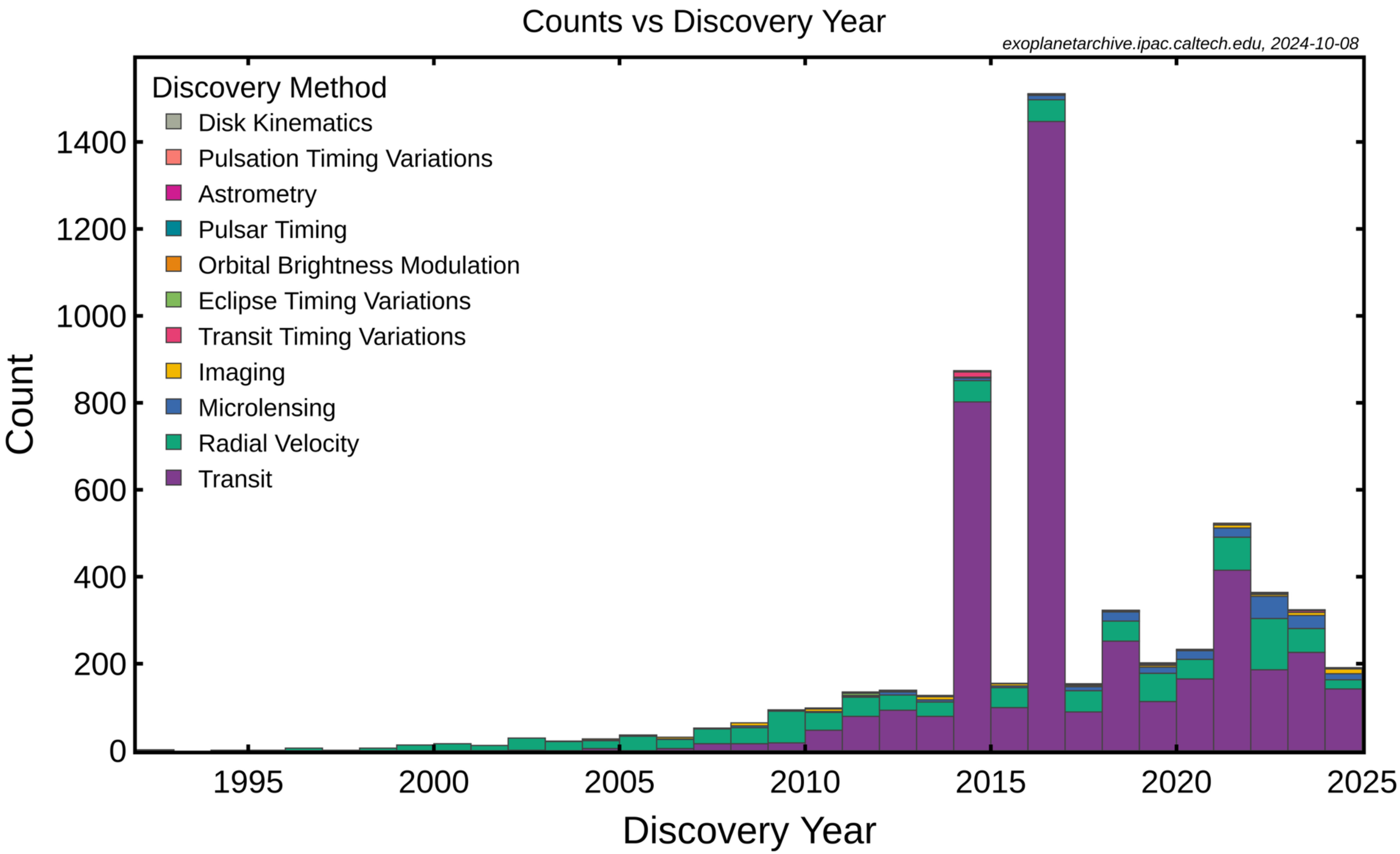
(planets outside of our solar system)

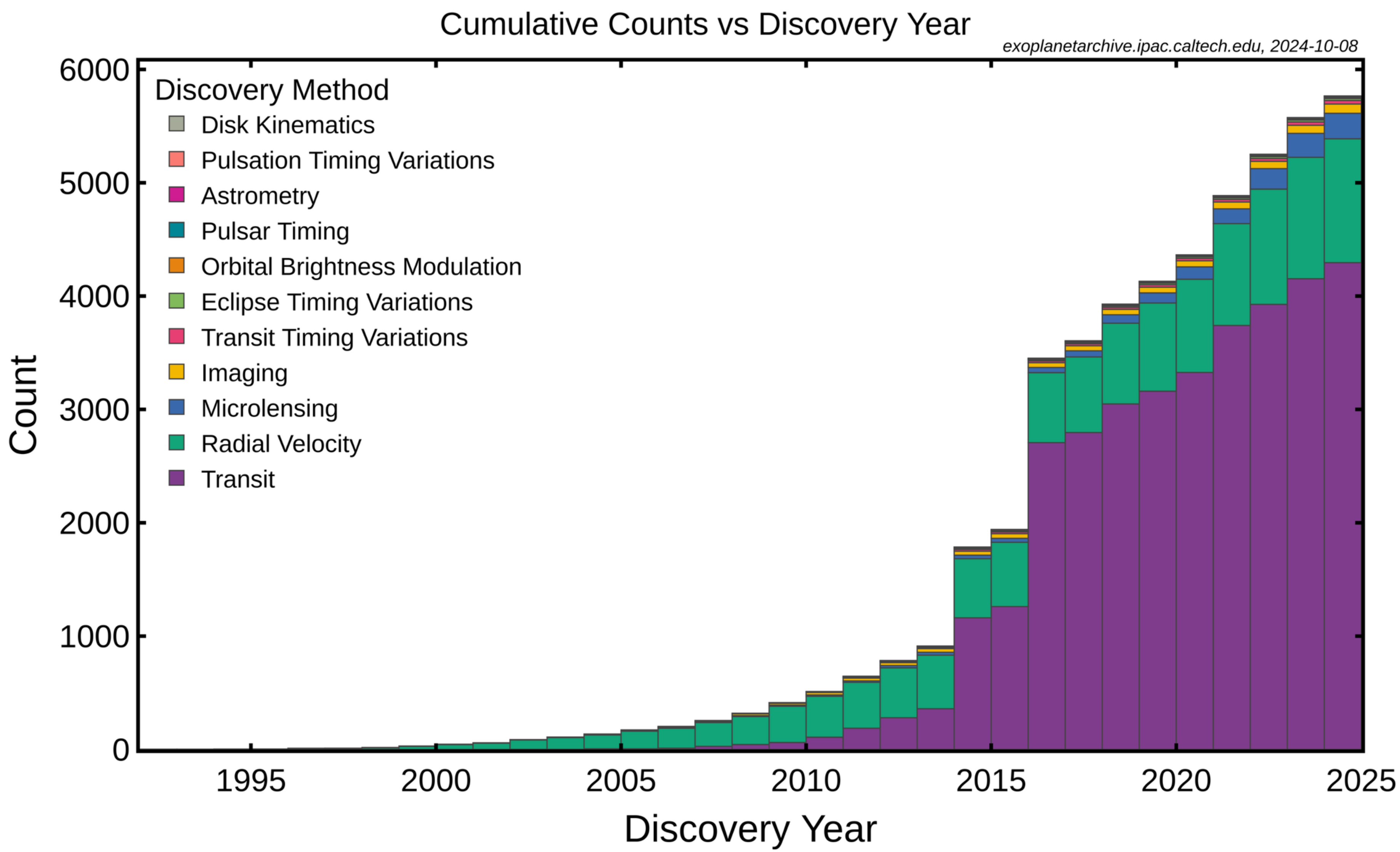
6,150 confirmed exoplanets!

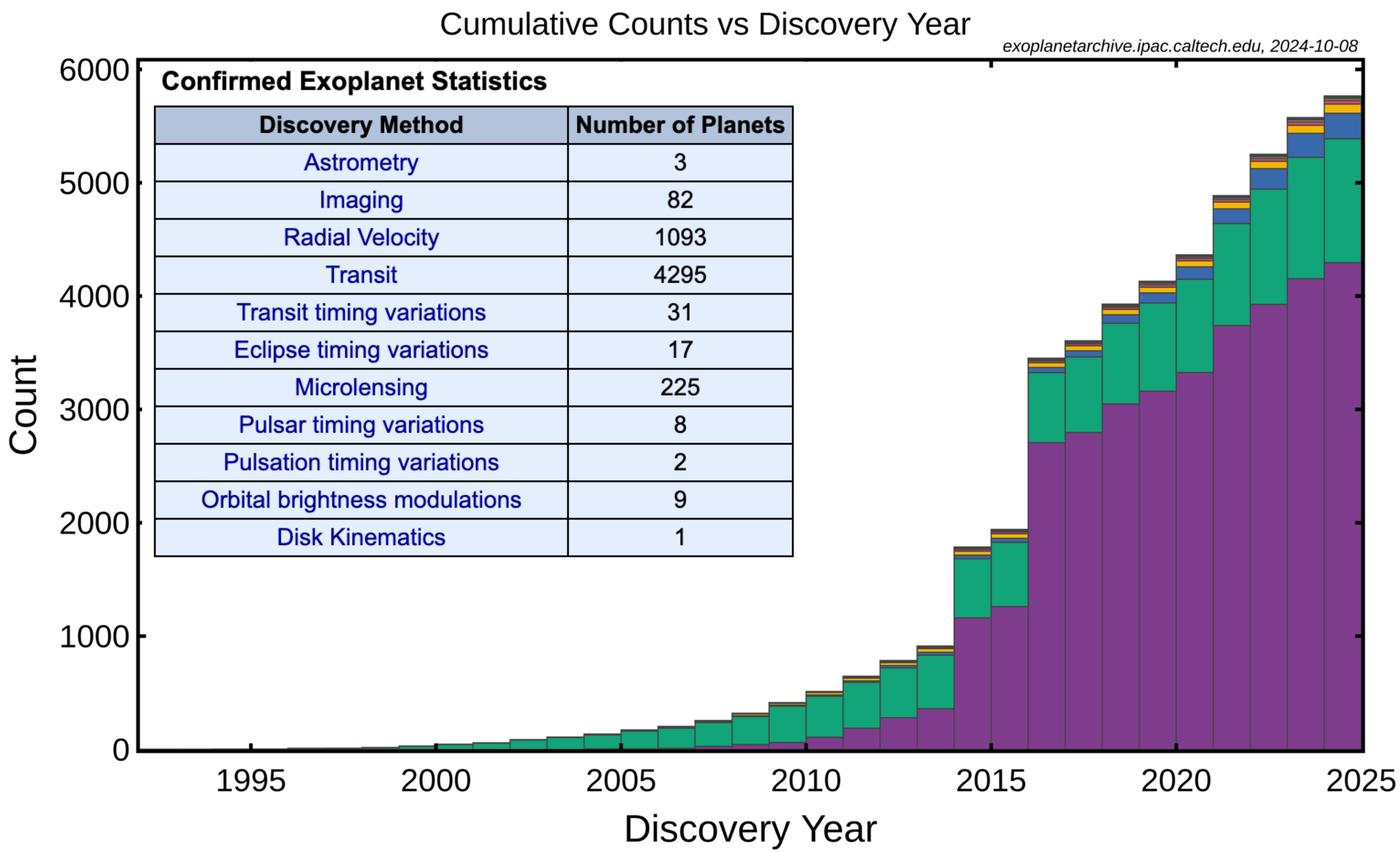
first detection around normal star: 1995

~10,000 more likely planets

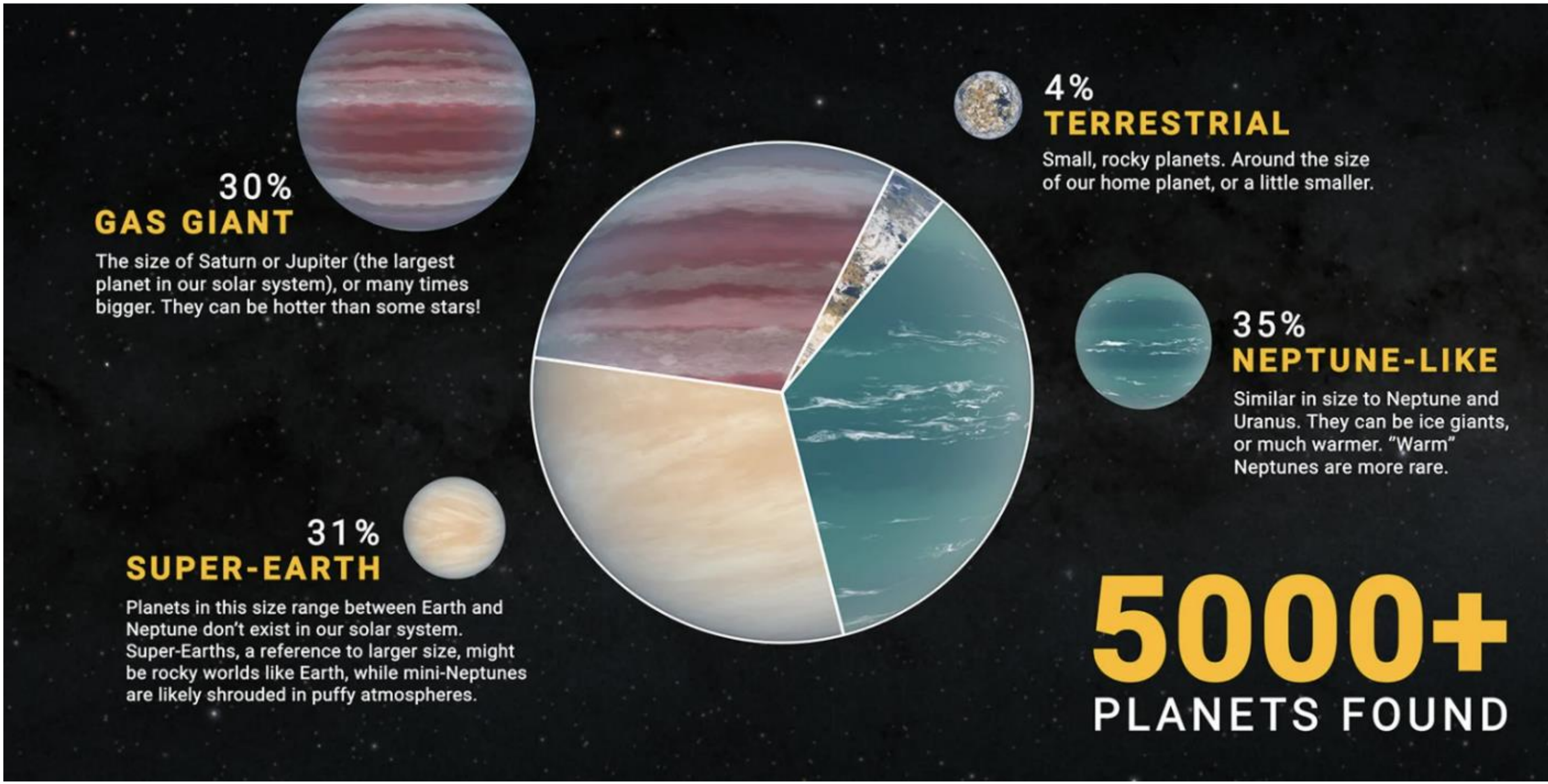
This is amazing!


Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-10-08
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
200
400
600
800
1000
1200
1400
1995
2000
2005
2010
2015
2020
2025
Discovery Year


Cumulative Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-10-08
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

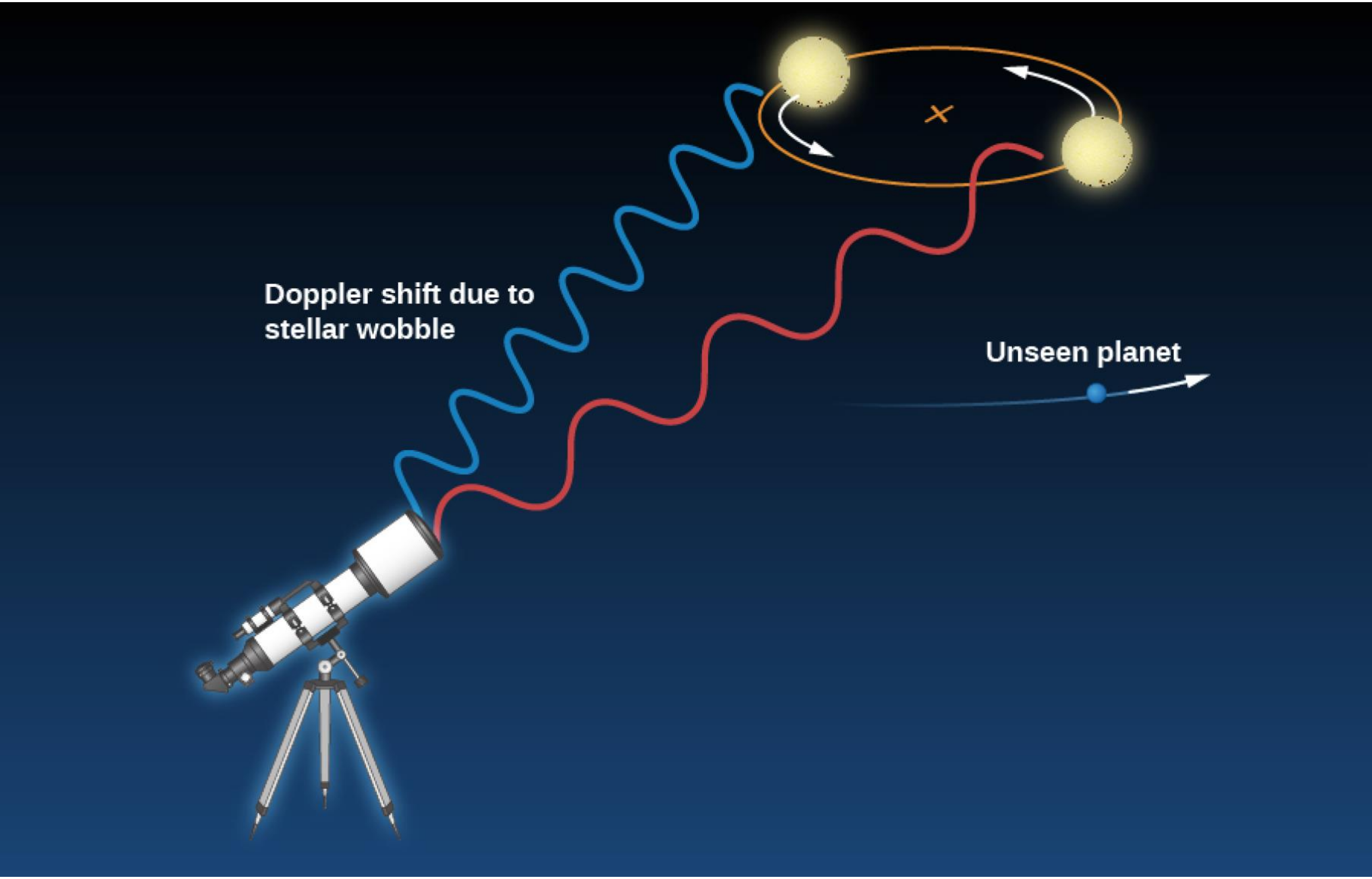


Discovery Method	Number of Planets
Astrometry	3
Imaging	82
Radial Velocity	1093
Transit	4295
Transit timing variations	31
Eclipse timing variations	17
Microlensing	225
Pulsar timing variations	8
Pulsation timing variations	2
Orbital brightness modulations	9
Disk Kinematics	1

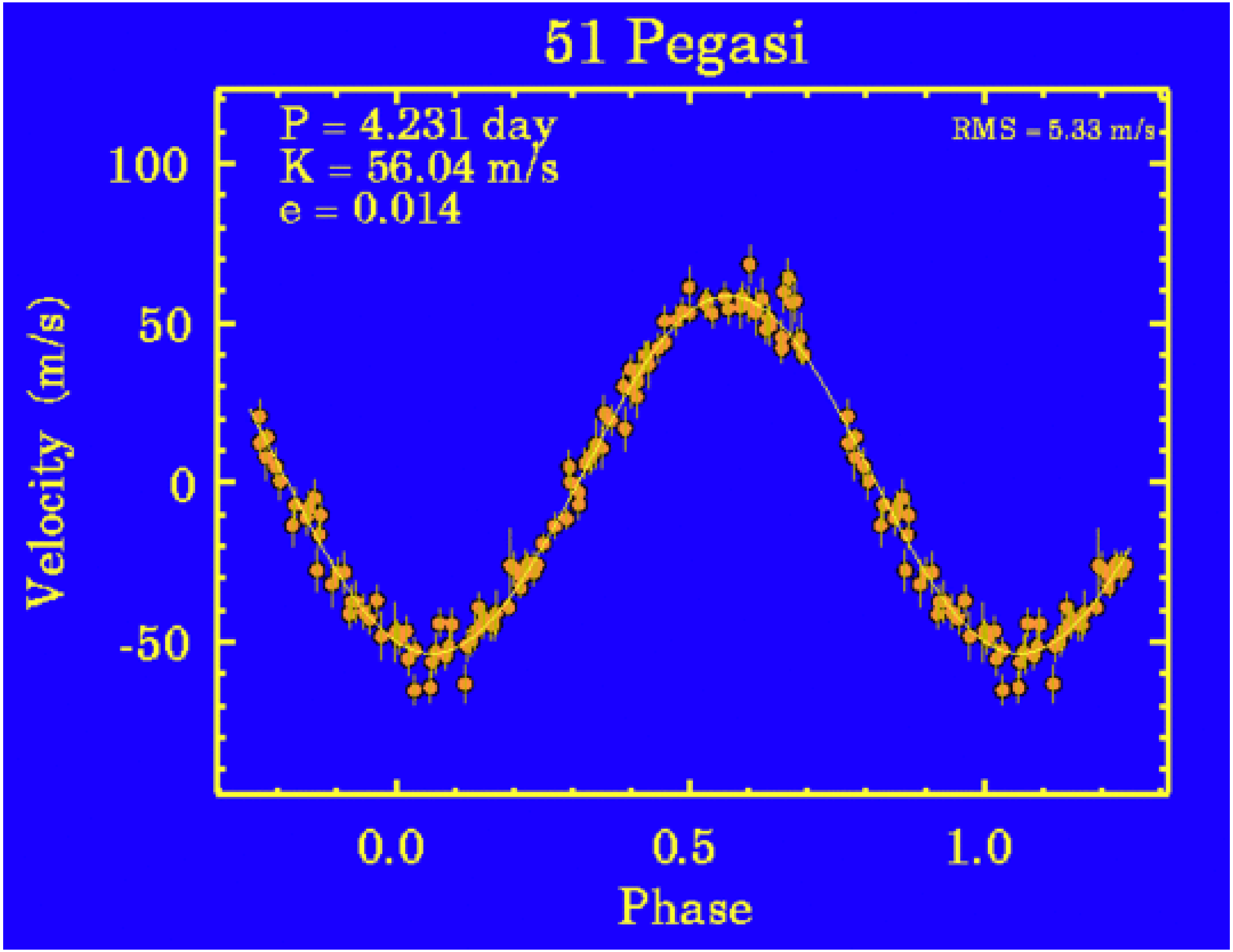

30%
GAS GIANT
The size of Saturn or Jupiter (the largest planet in our solar system), or many times bigger. They can be hotter than some stars!
4%
TERRESTRIAL
Small, rocky planets. Around the size of our home planet, or a little smaller.
35%
NEPTUNE-LIKE
Similar in size to Neptune and Uranus. They can be ice giants, or much warmer. "Warm" Neptunes are more rare.
31%
SUPER-EARTH
Planets in this size range between Earth and Neptune don't exist in our solar system. Super-Earths, a reference to larger size, might be rocky worlds like Earth, while mini-Neptunes are likely shrouded in puffy atmospheres.
5000+
PLANETS FOUND

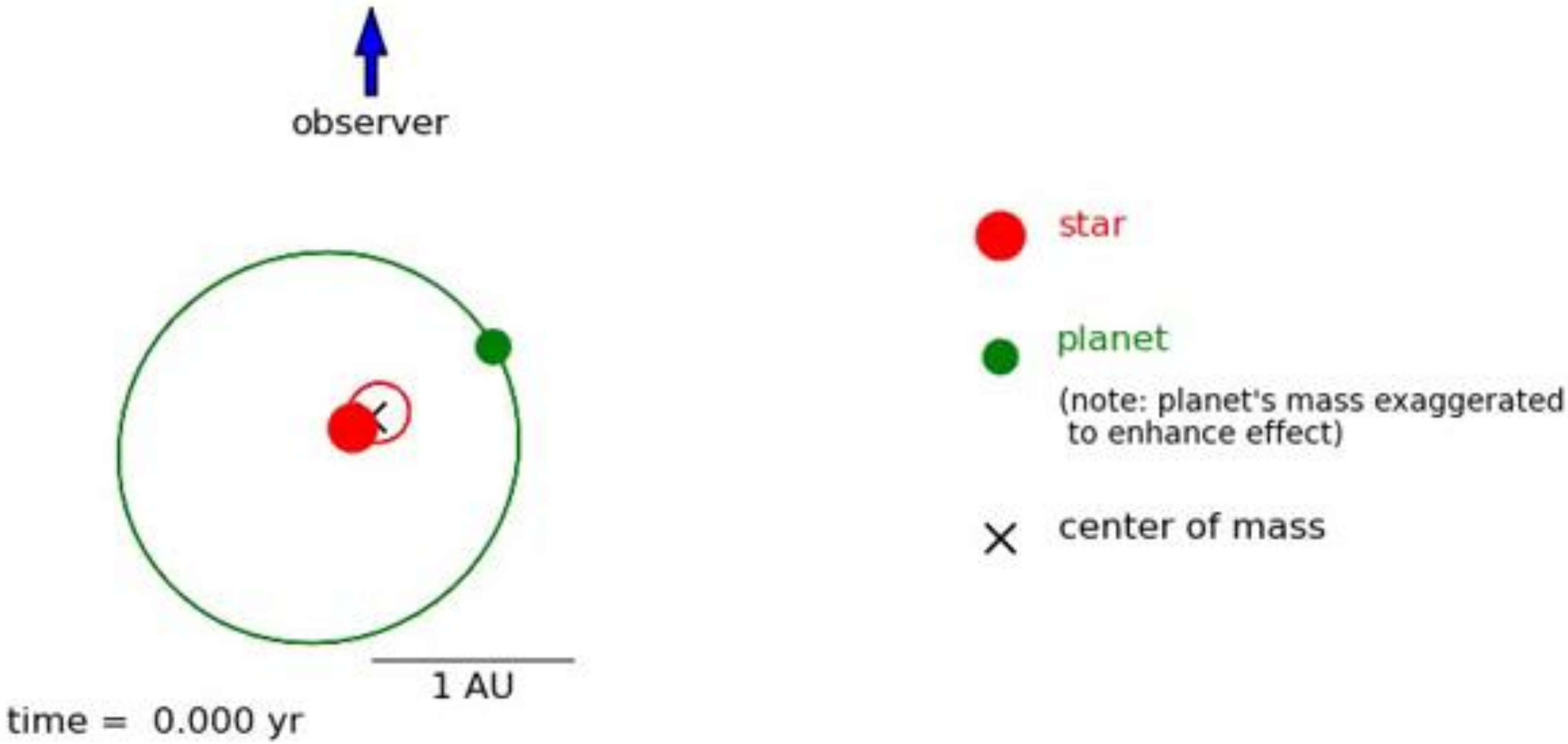
Keywords for Lecture 4

- Exoplanet: a planet around a different star
- Detection techniques: how exoplanets are detected?
  - Radial Velocity
  - Transits
  - Direct Imaging
- Atmospheres
- Protoplanetary disks
- Habitability
- Biases


Doppler shift due to
stellar wobble
Unseen planet

The first planet: a hot Jupiter




observer
star
planet
(note: planet's mass exaggerated
to enhance effect)
center of mass
1 AU
time = 0.000 yr

Bias of radial velocity

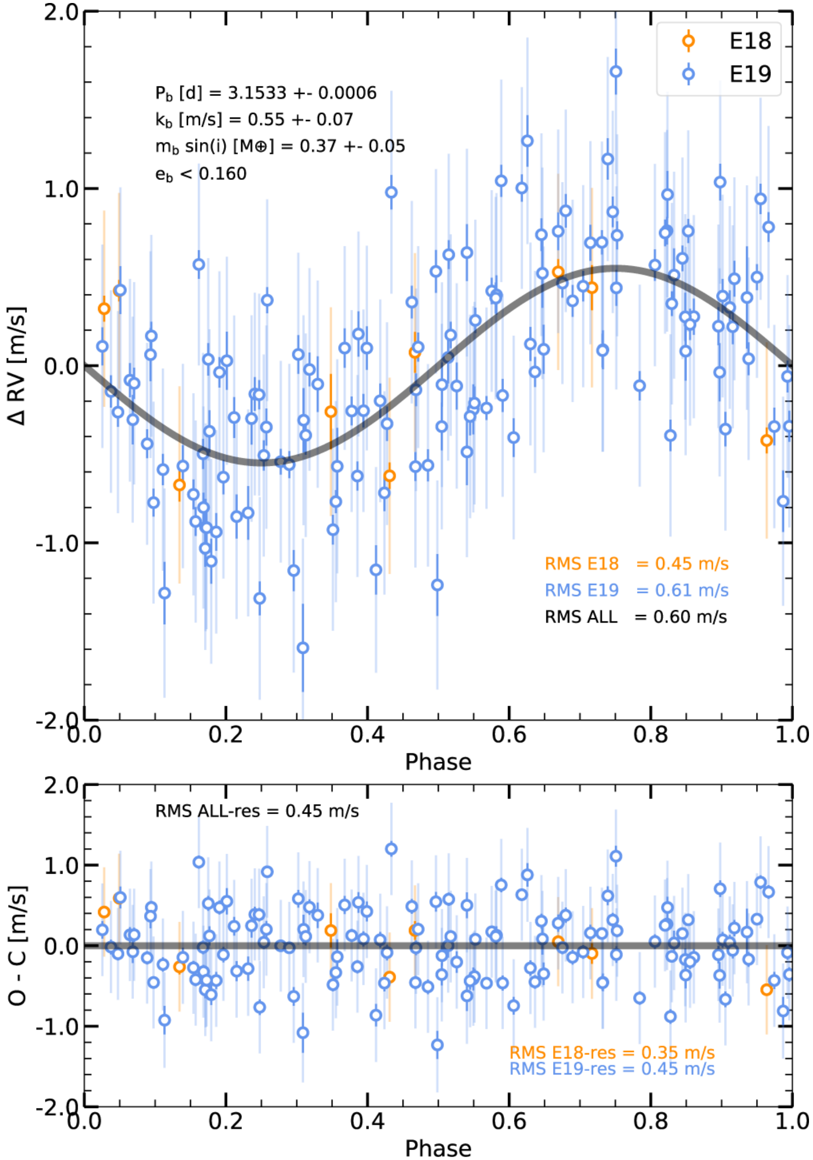
- What kinds of planets are easiest to detect?
  - Higher mass
  - Closer to the star
- Motion of star

$$v_{\rm obs} = 28.4 \frac{M_P \sin i}{P_{\rm orb}^{1/3} M_*^{2/3}}$$

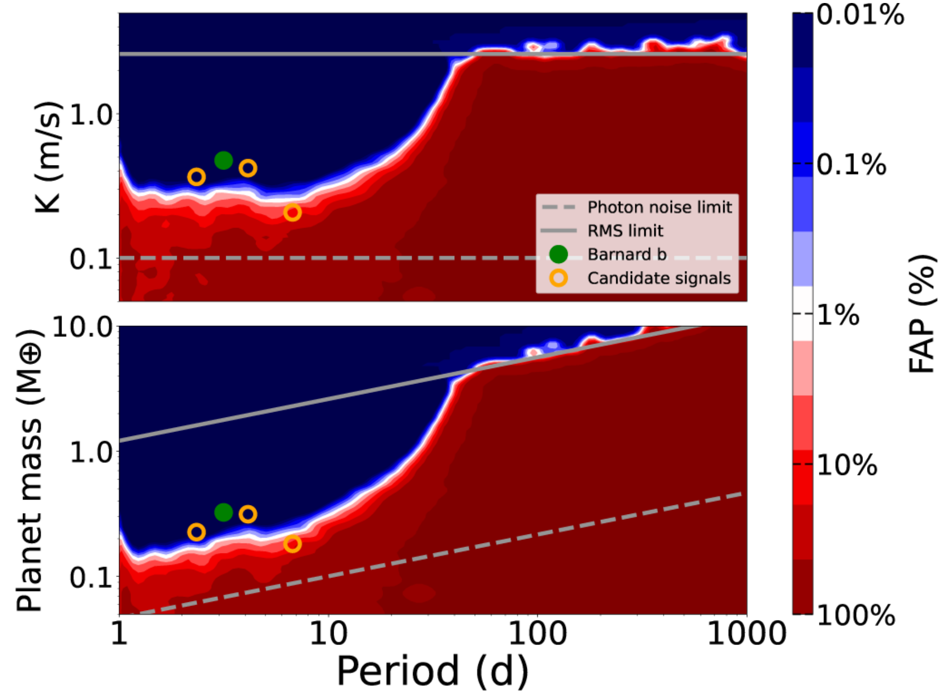
- M_P in Jupiter masses
- $P_{\rm orb}$ in years
- M_* in solar masses

Barnard star planet:

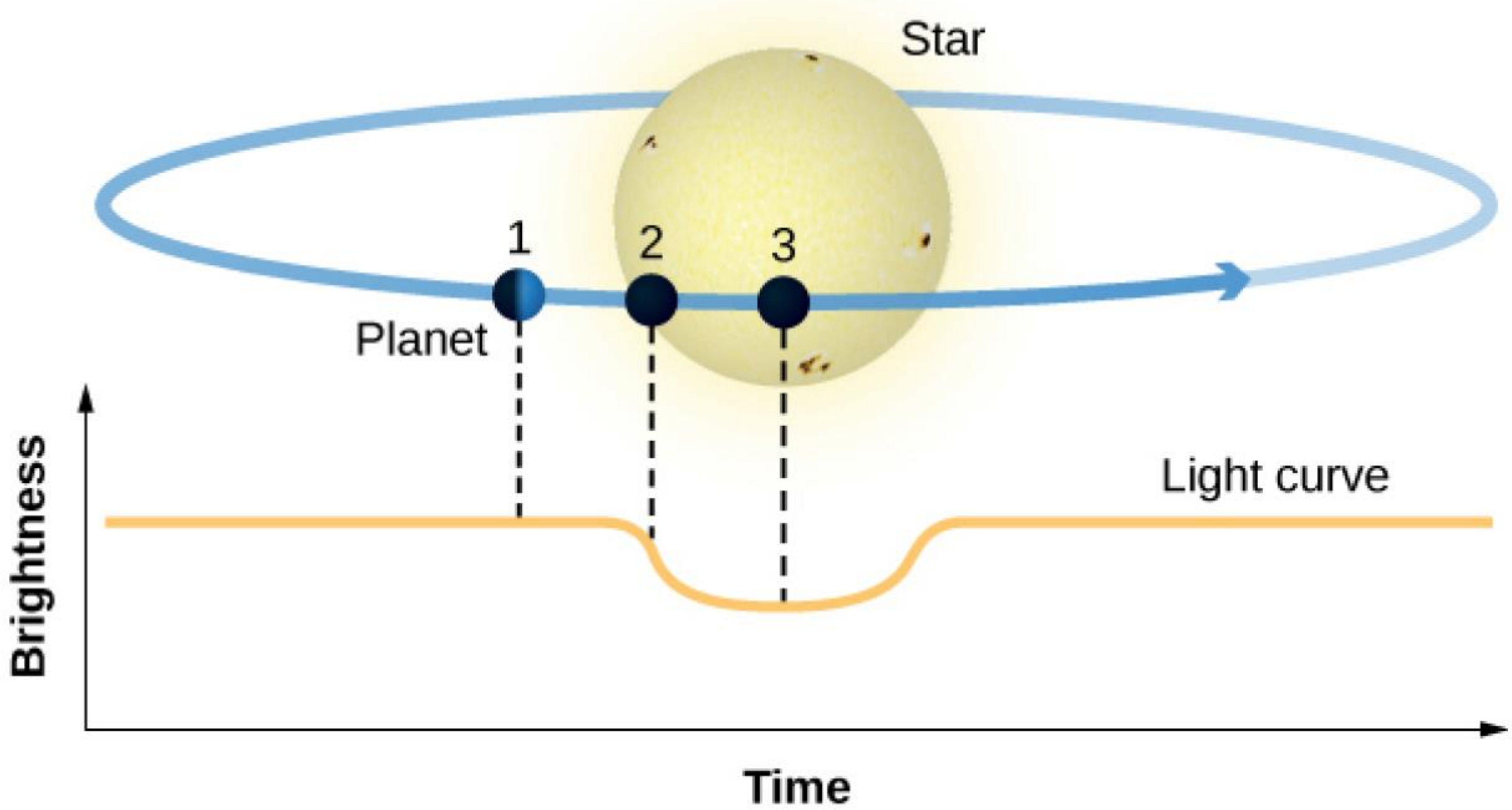
3-day period,
0.37 M_{earth}



Radial velocity signal+residual



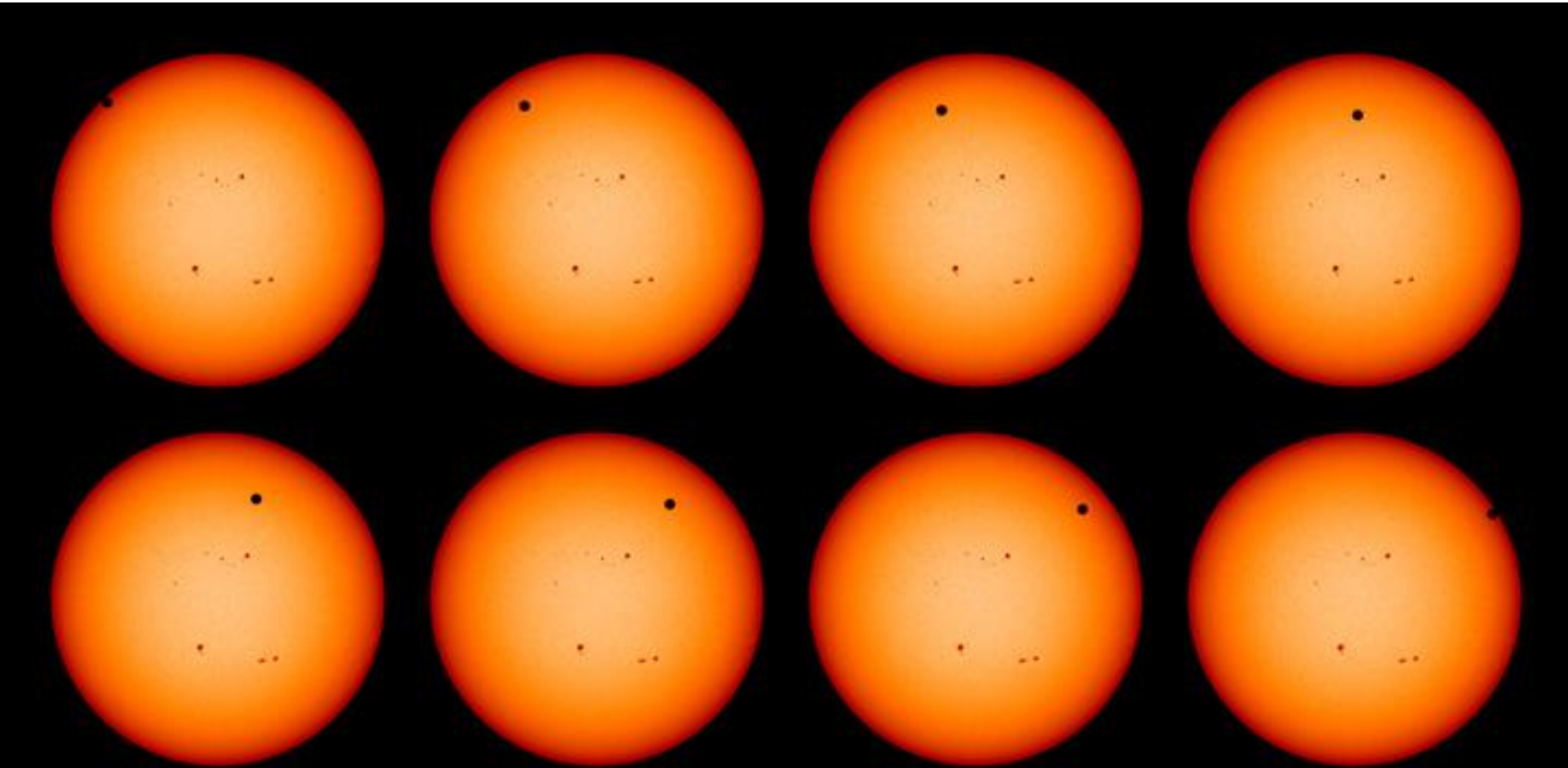
Bias: sensitivity to planet mass/radius


Star
1
2
3
Planet
Light curve
Brightness
Time

Venus transit

Every 112 years: (two times, separated by 8 years)

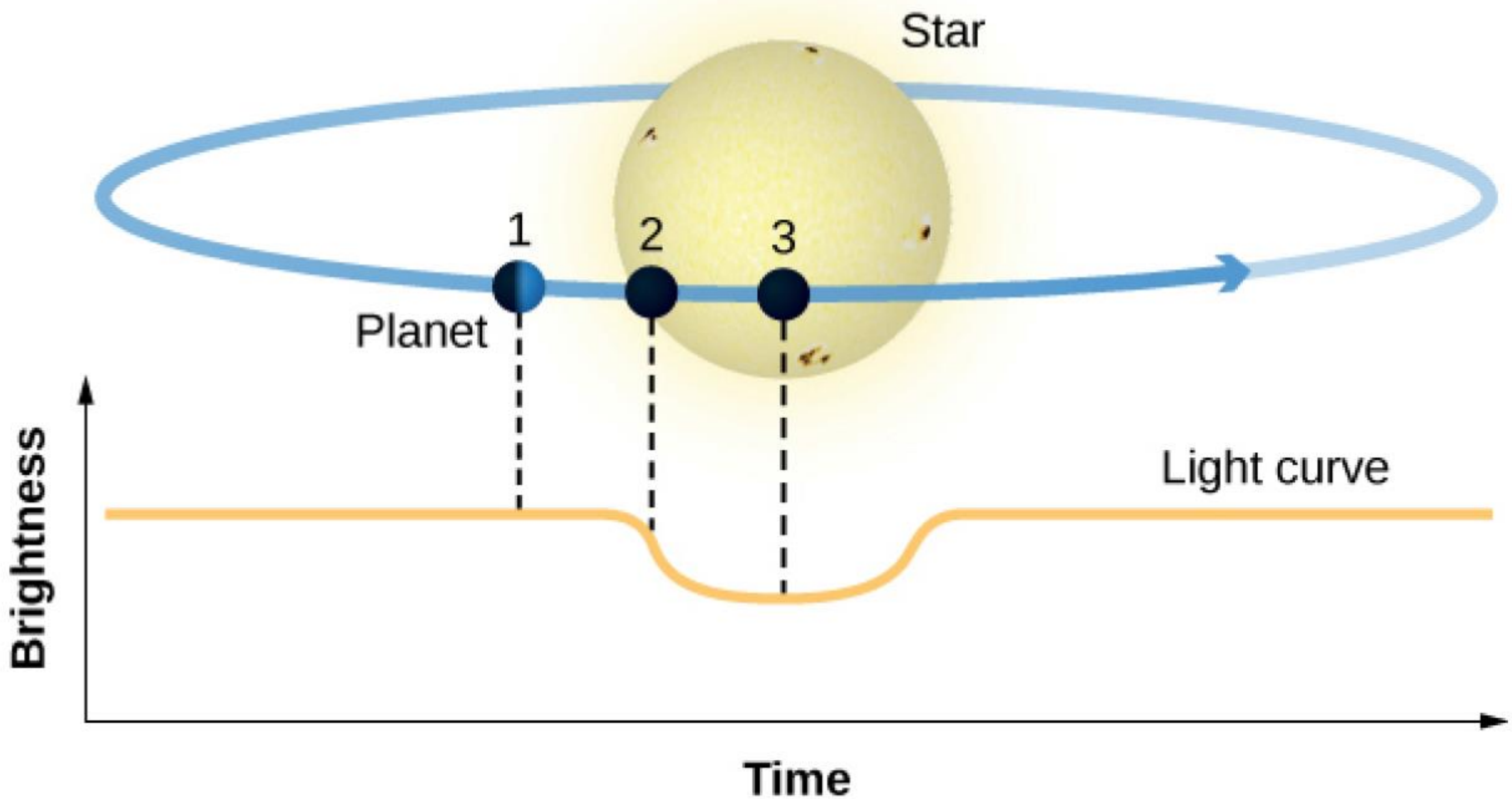
last time in 2004/2012

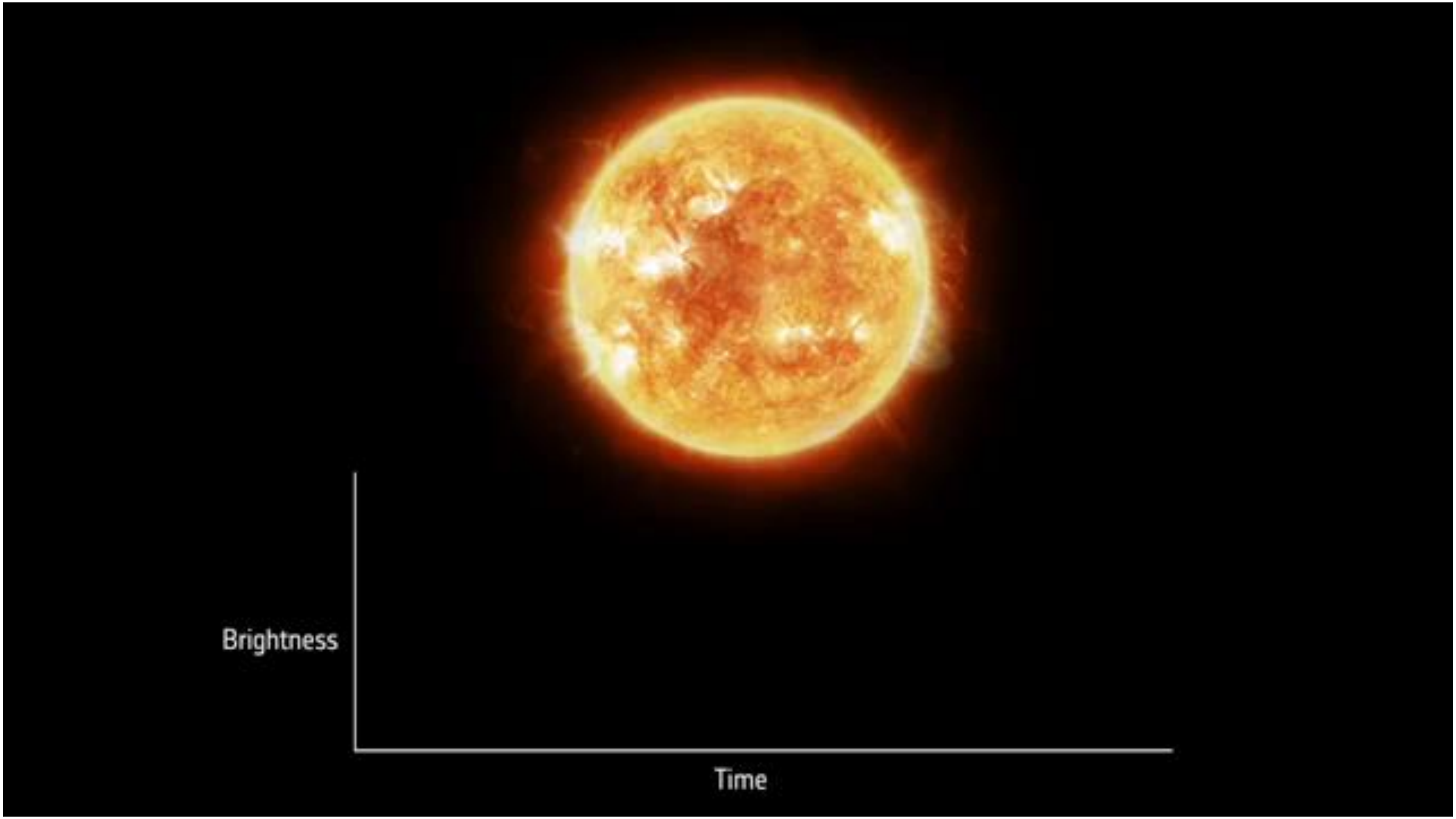


Venus transit

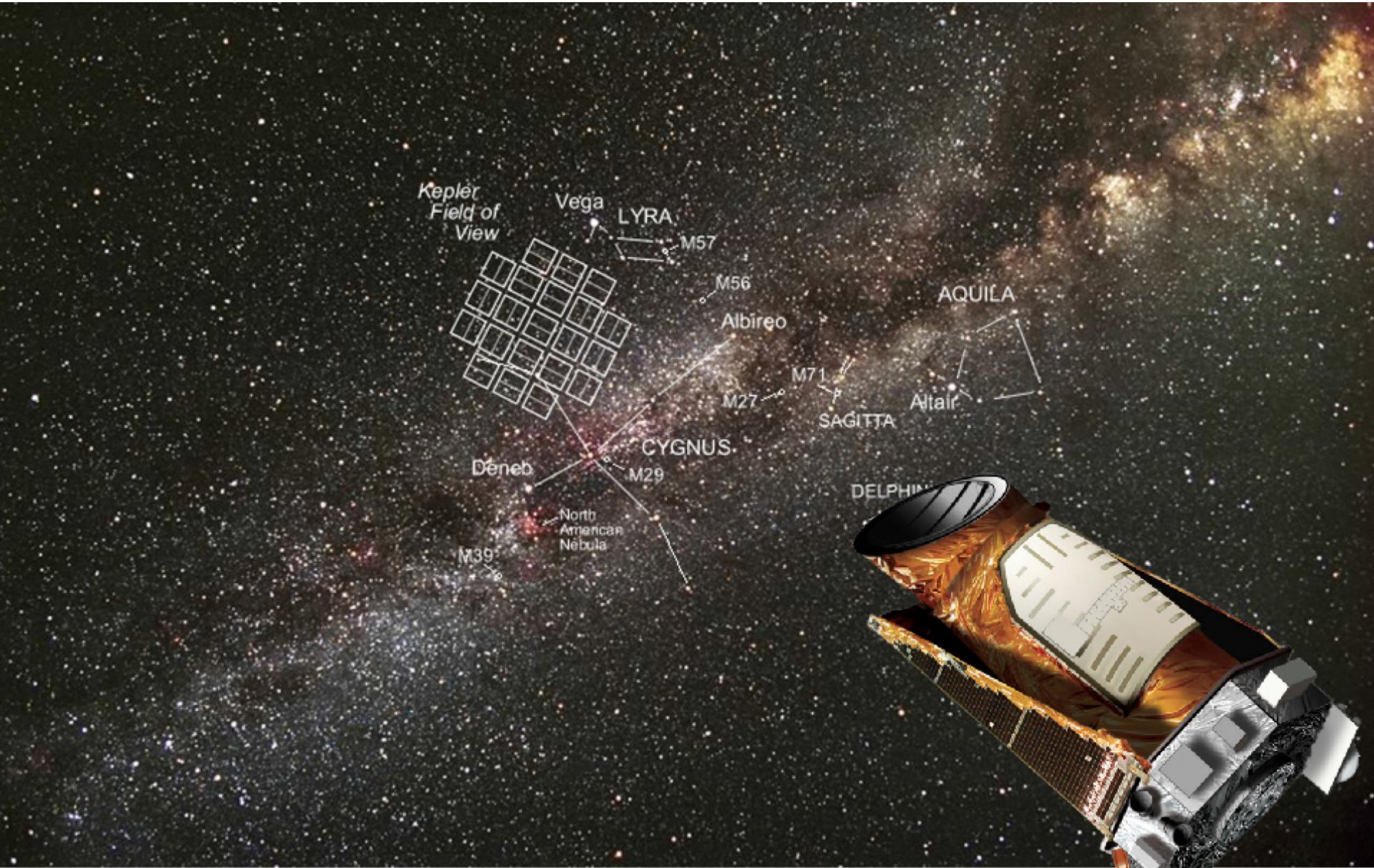
Guillaume Le Gentil: the unluckiest astronomer

1761/1769 transits from India?


Star
1
2
3
Planet
Light curve
Brightness
Time

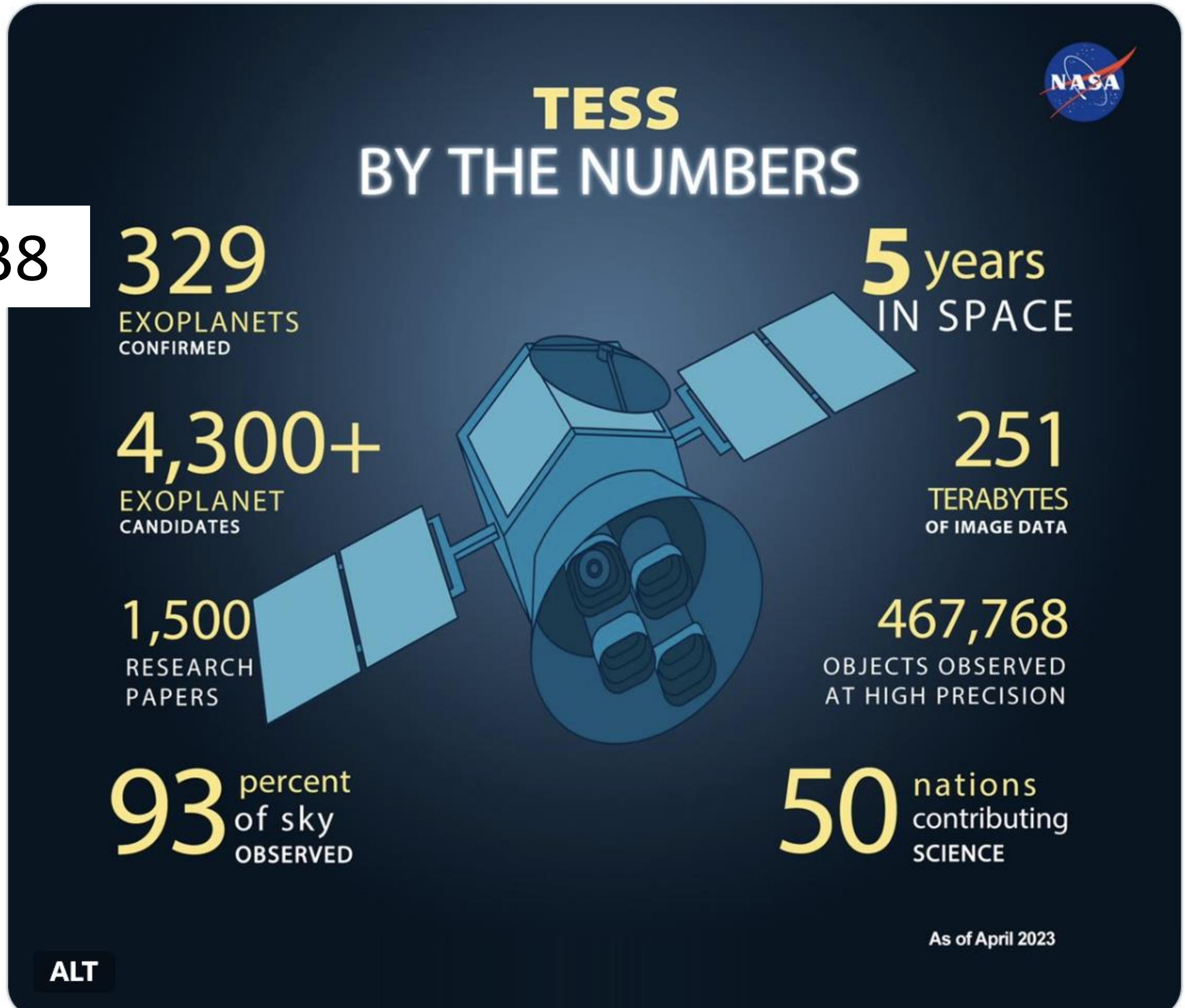

Brightness
Time

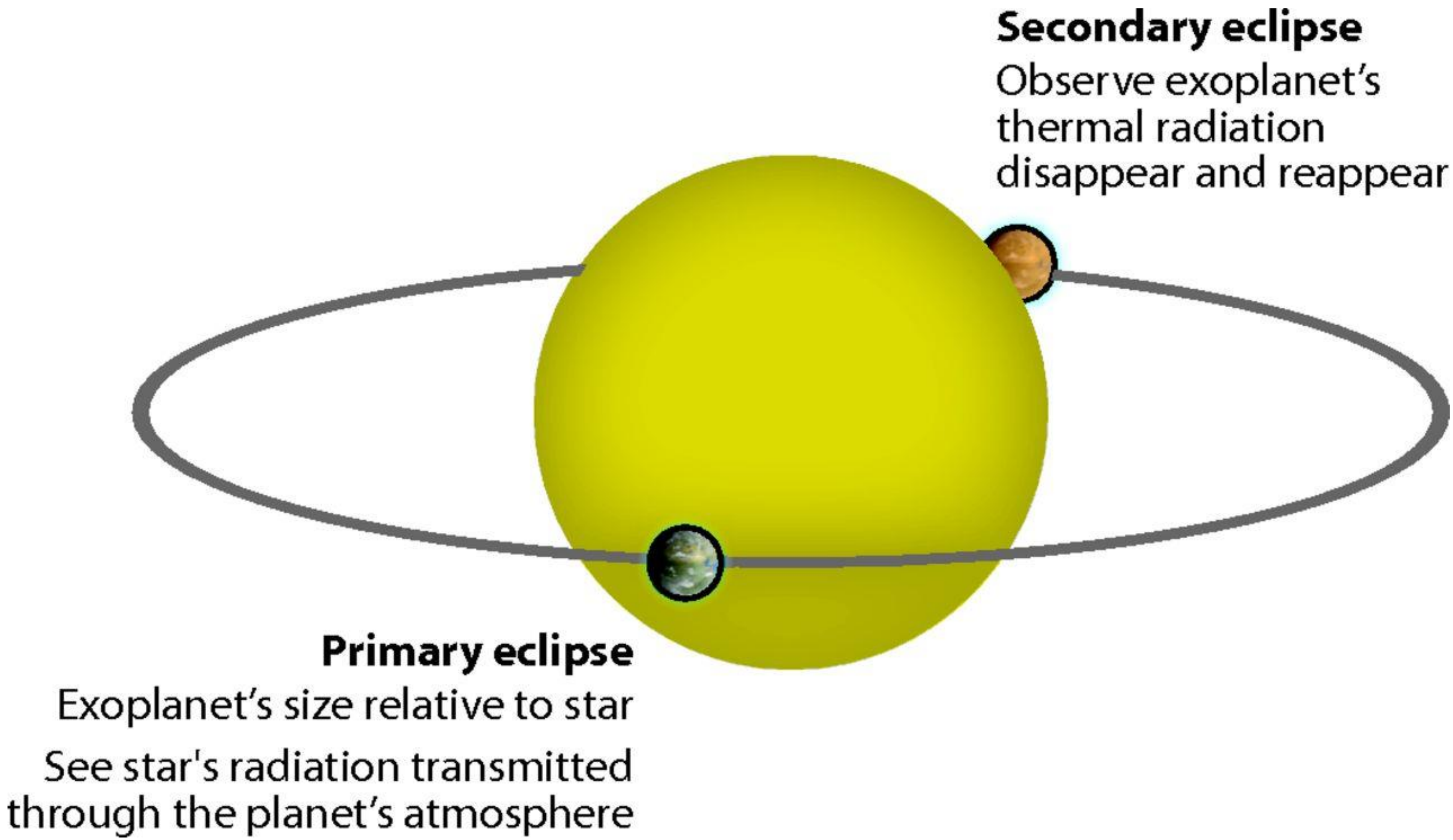
Kepler Observatory: thousands of planets

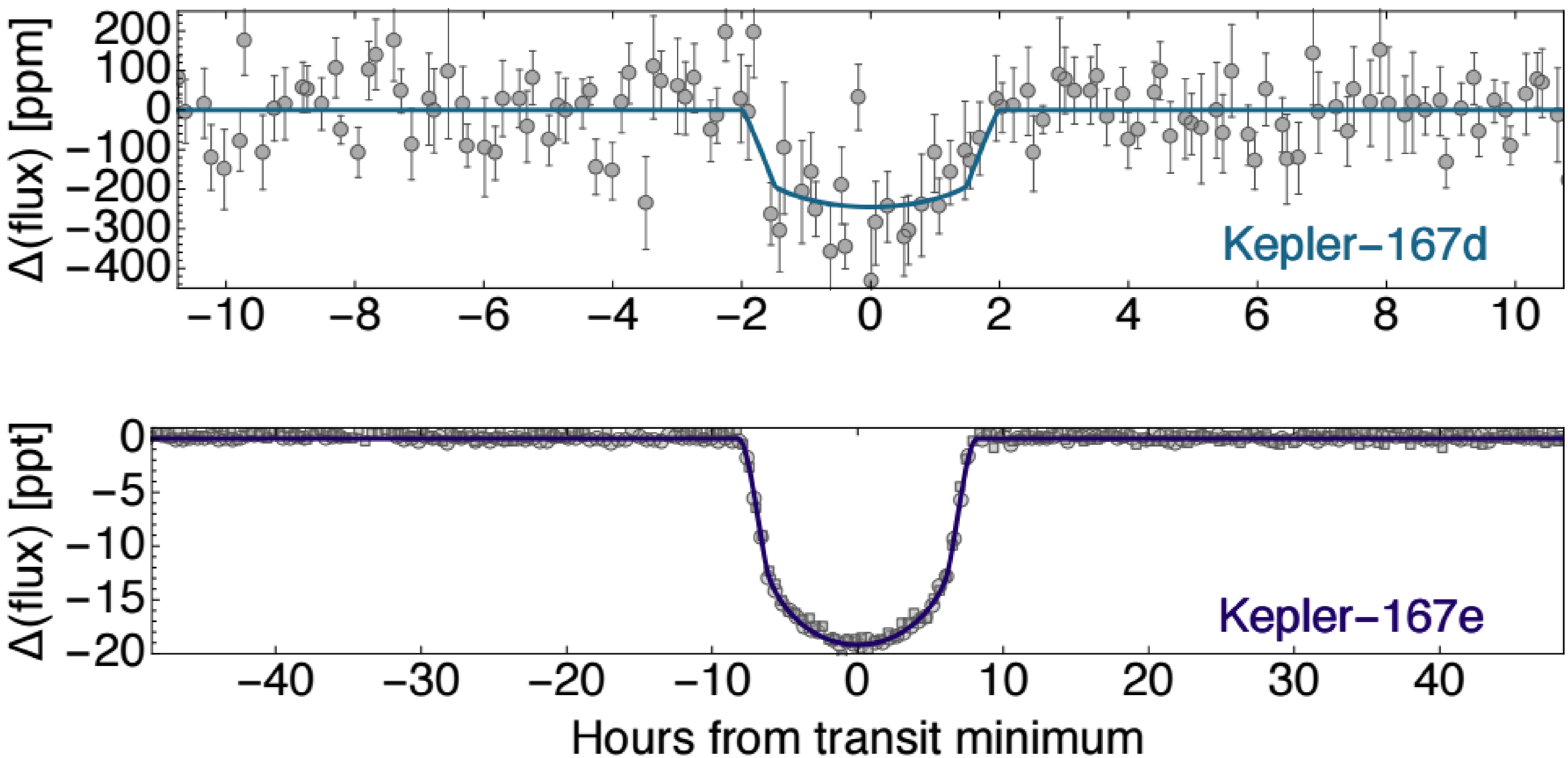


TESS Observatory: all-sky, bright stars

Now 638




Secondary eclipse
Observe exoplanet's thermal radiation disappear and reappear
Primary eclipse
Exoplanet's size relative to star
See star's radiation transmitted through the planet's atmosphere



Δ(flux) [ppm]
200
100
0
−100
−200
−300
−400
Kepler−167d
−10
−8
−6
−4
−2
0
2
4
6
8
10
Δ(flux) [ppt]
0
−5
−10
−15
−20
Kepler−167e
−40
−30
−20
−10
0
10
20
30
40
Hours from transit minimum

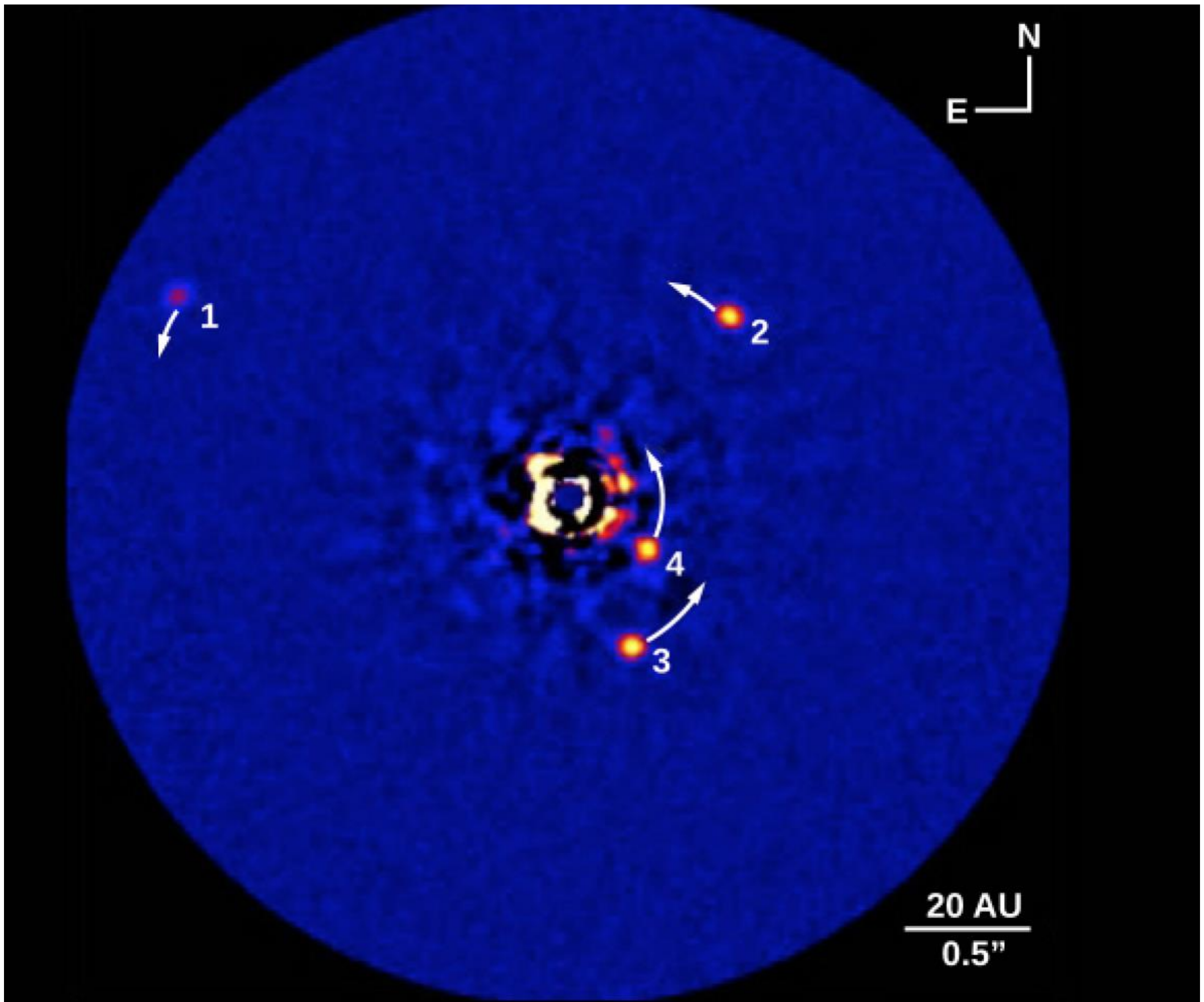
Bias of transits

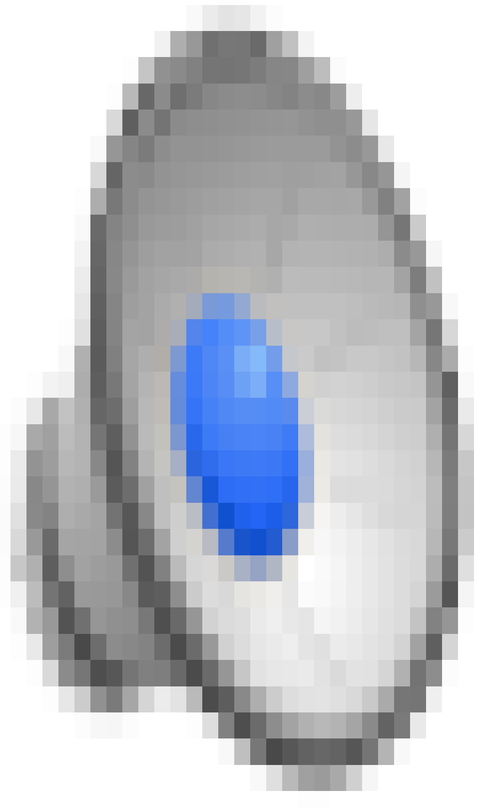
- What kinds of planets are easiest to detect?

- Close to star
- Large radius

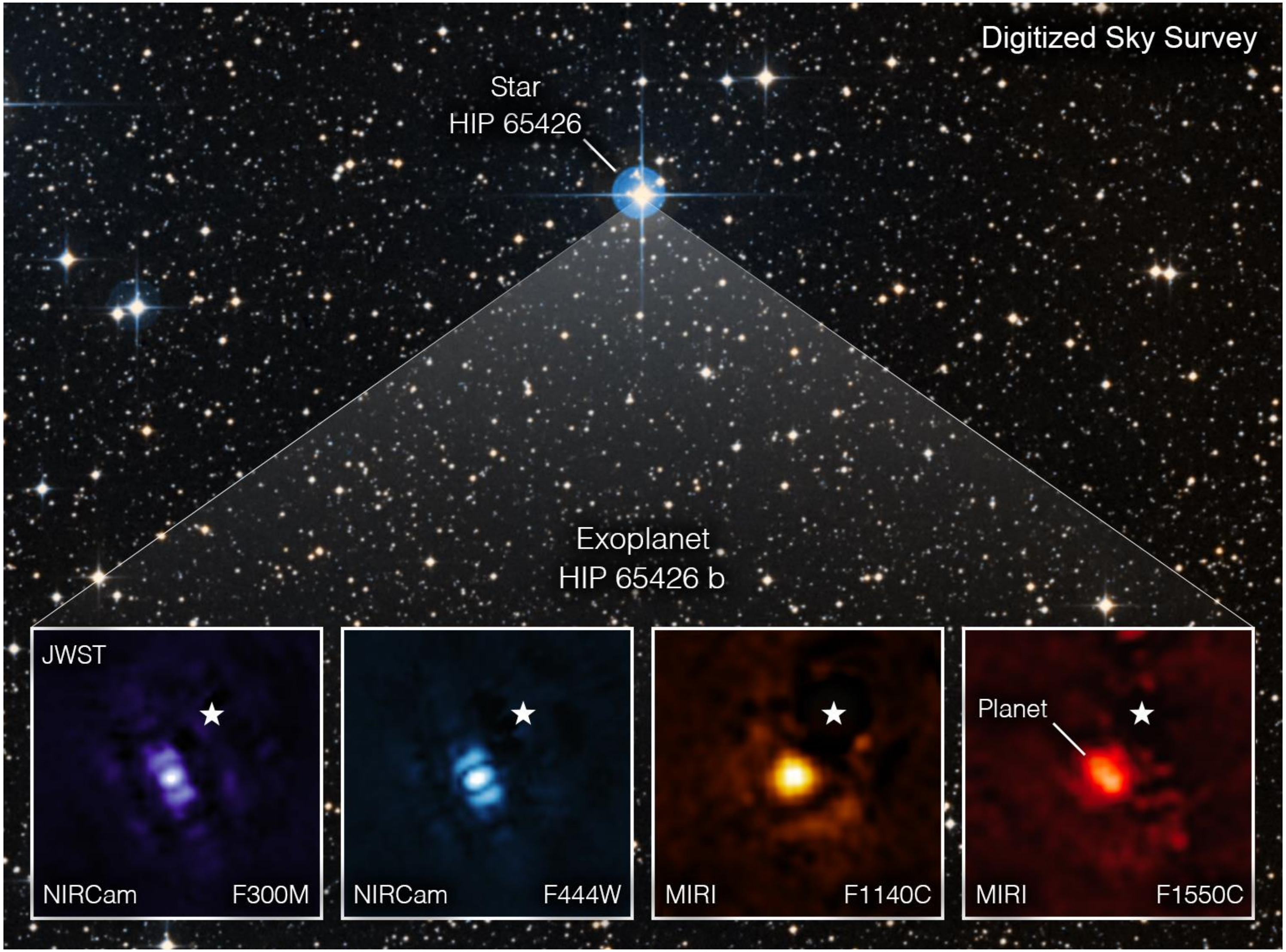
$$R_p = R_\star \sqrt{\mathrm{Depth}}$$

Direct Imaging: requires coronagraph to block out the star (similar to eclipse)



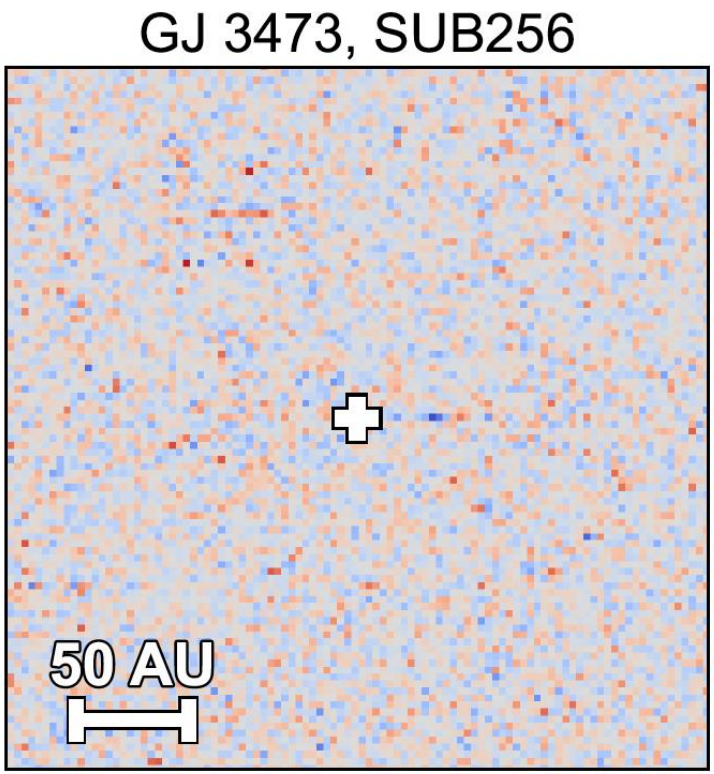


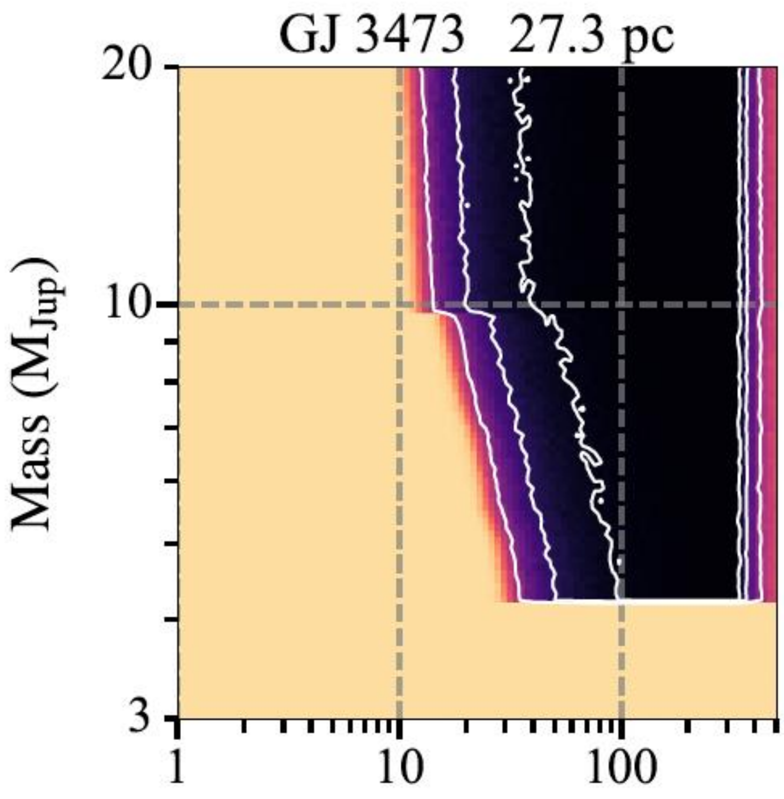
First JWST image of a planet



JWST:
Powerful new infrared telescope

Searching for cool planets with JWST
(new method from Yihan Li et al 2026)





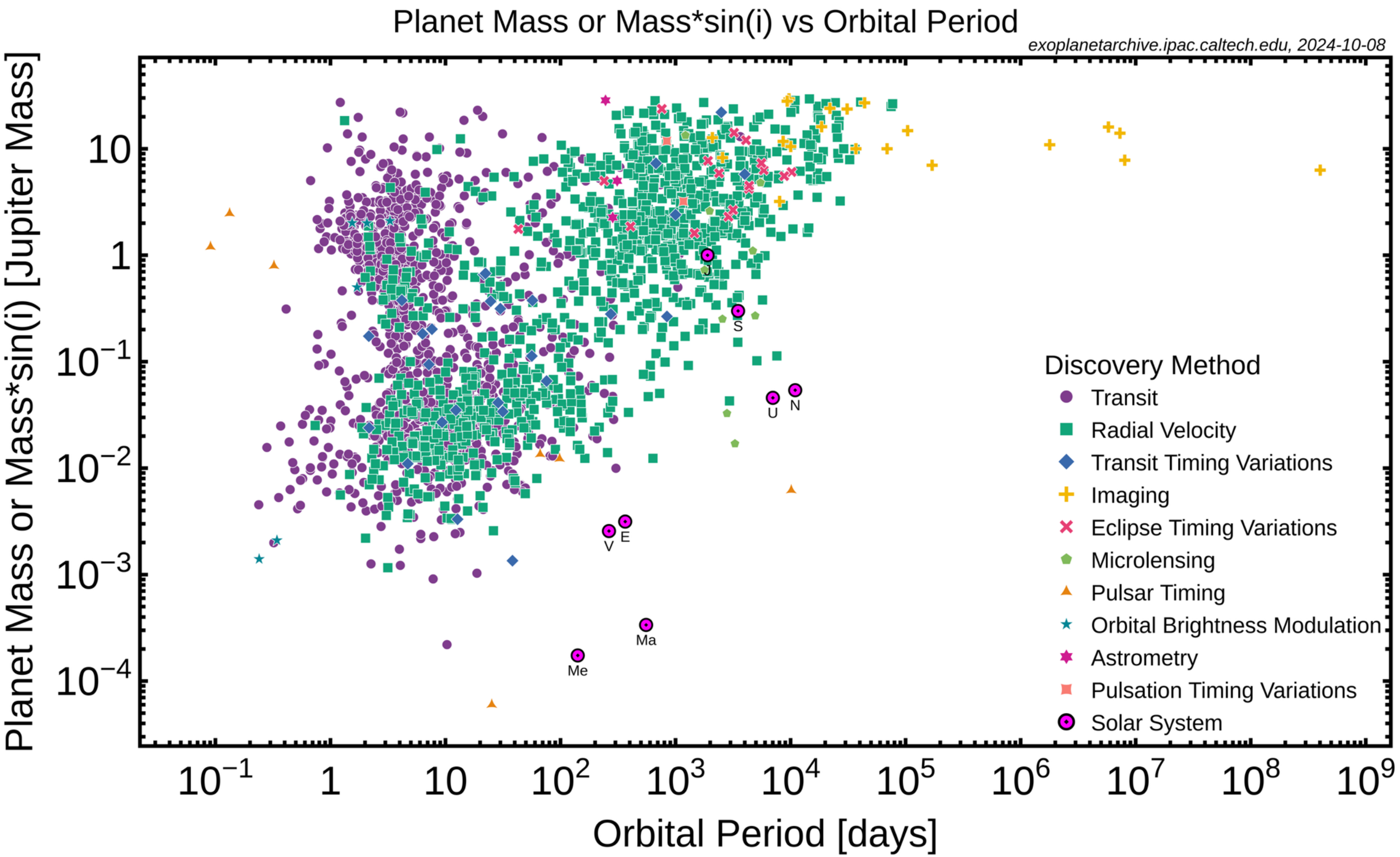
Bias of direct imaging

- What kinds of planets are easiest to detect?

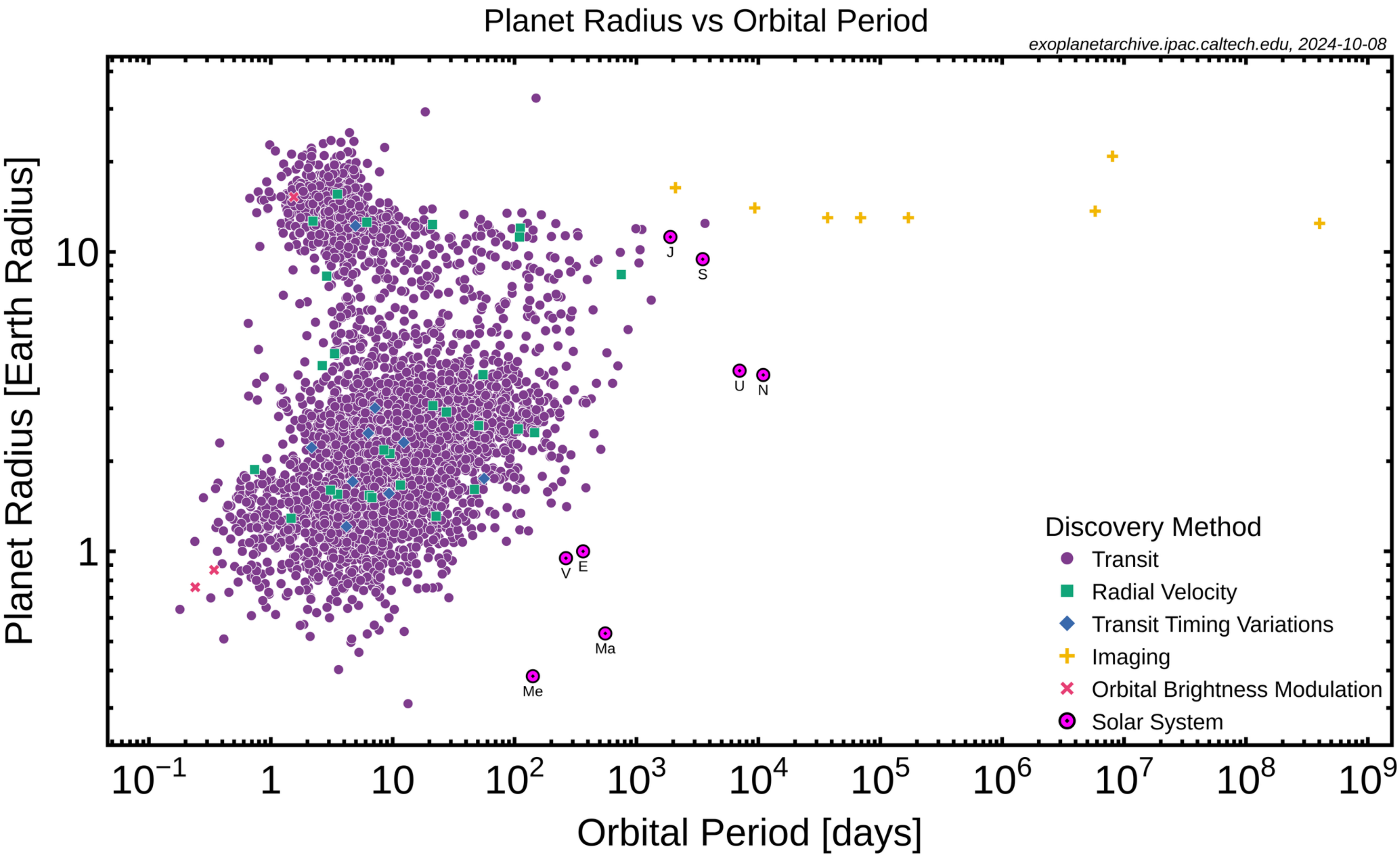
- Very bright (higher mass)
- Far from the star!

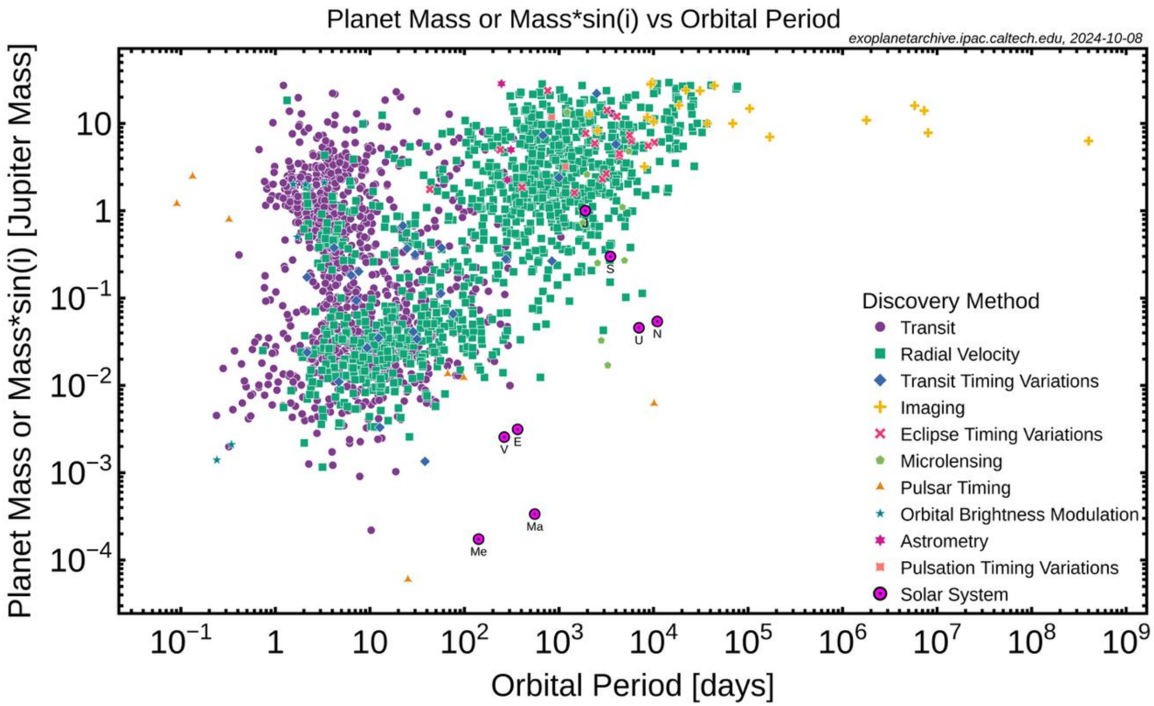
[also this is very hard]

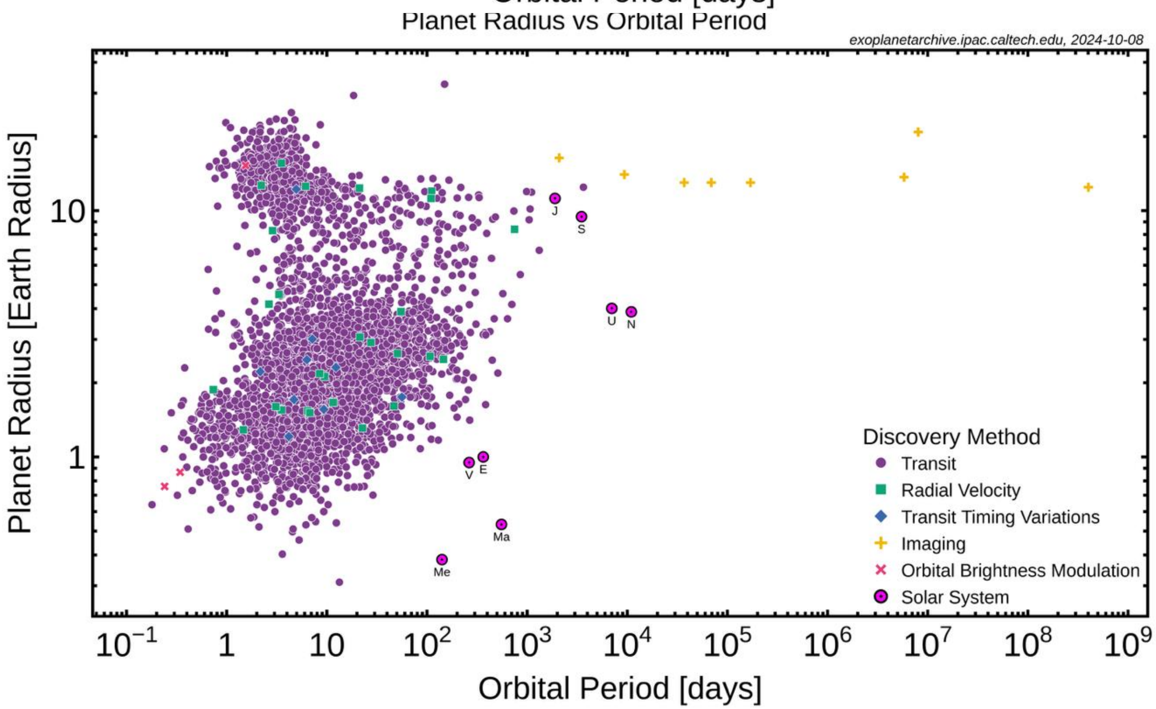
Exoplanets are common!



Exoplanets are common!





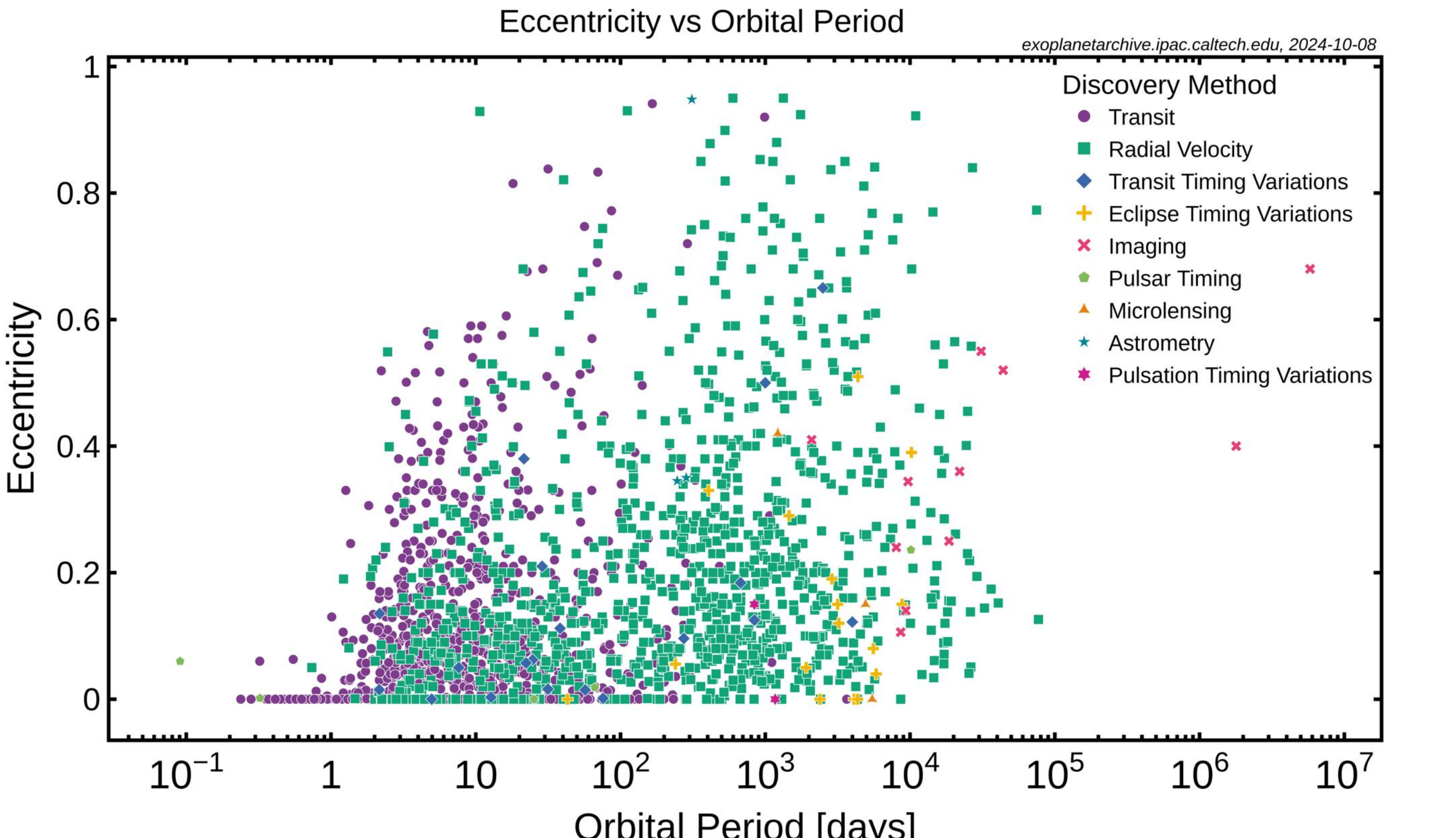


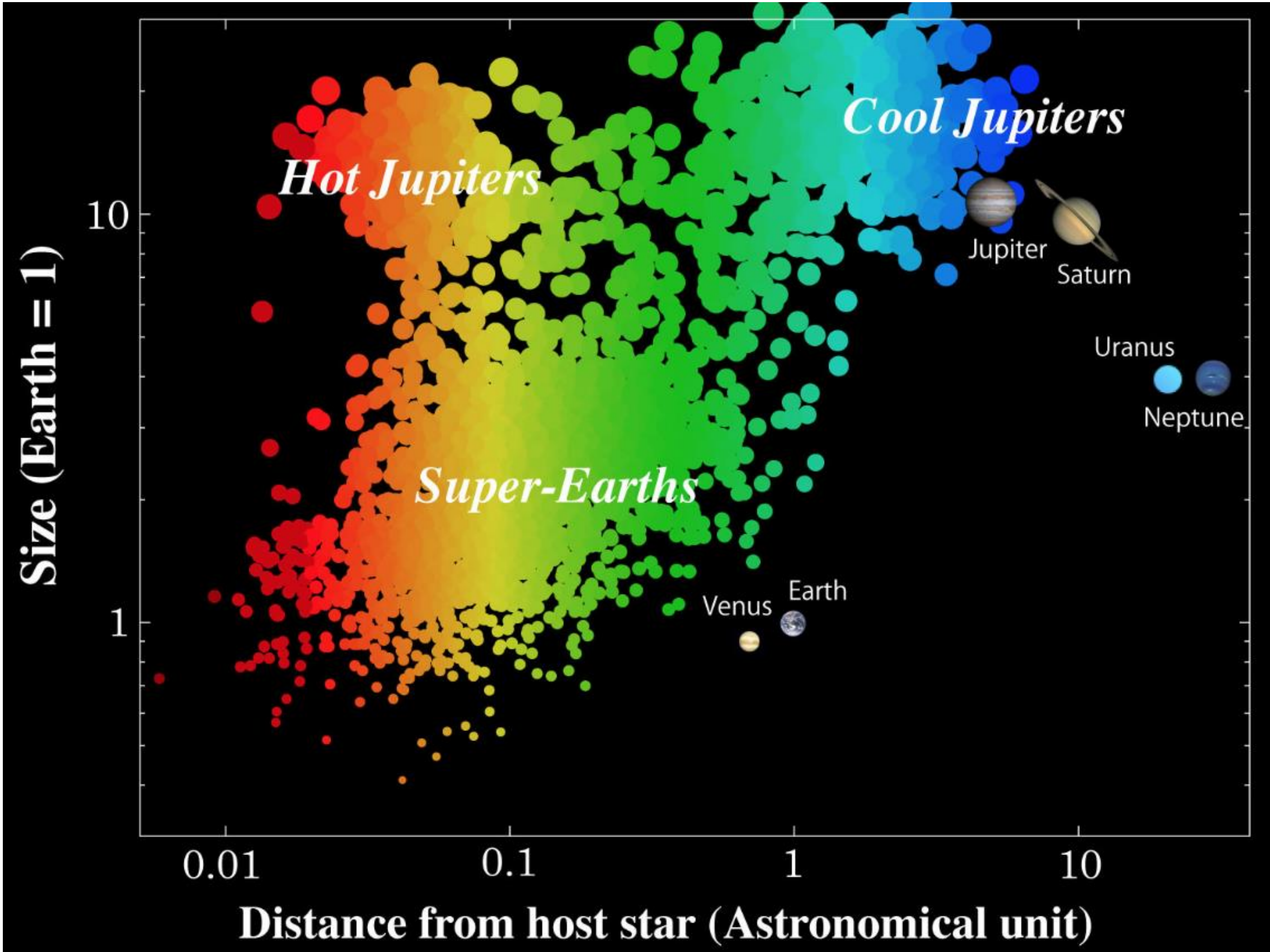
Differences in methods:

measuring mass or radius?

(ideally both)

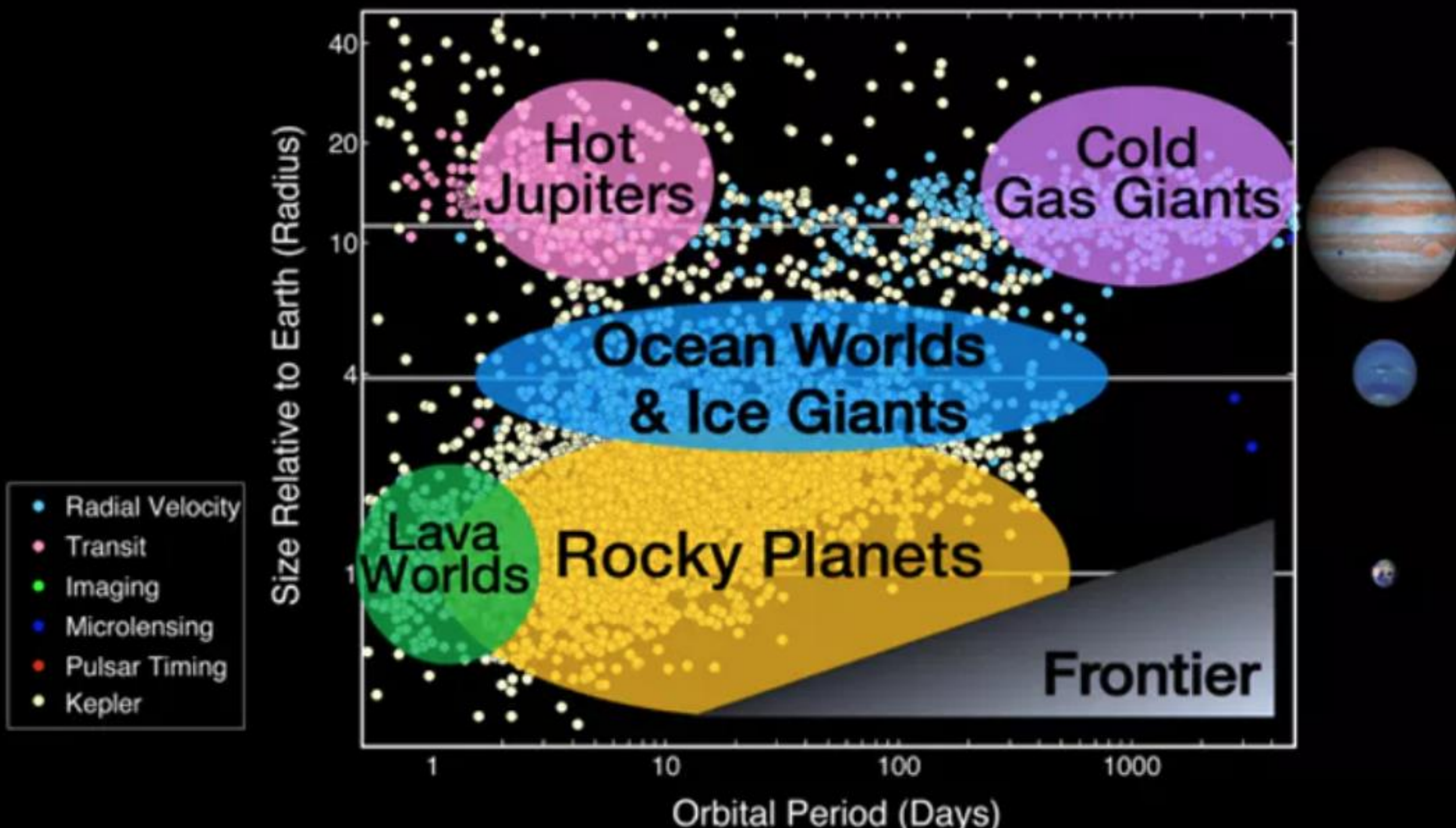
Most orbits are circular (but some eccentric)



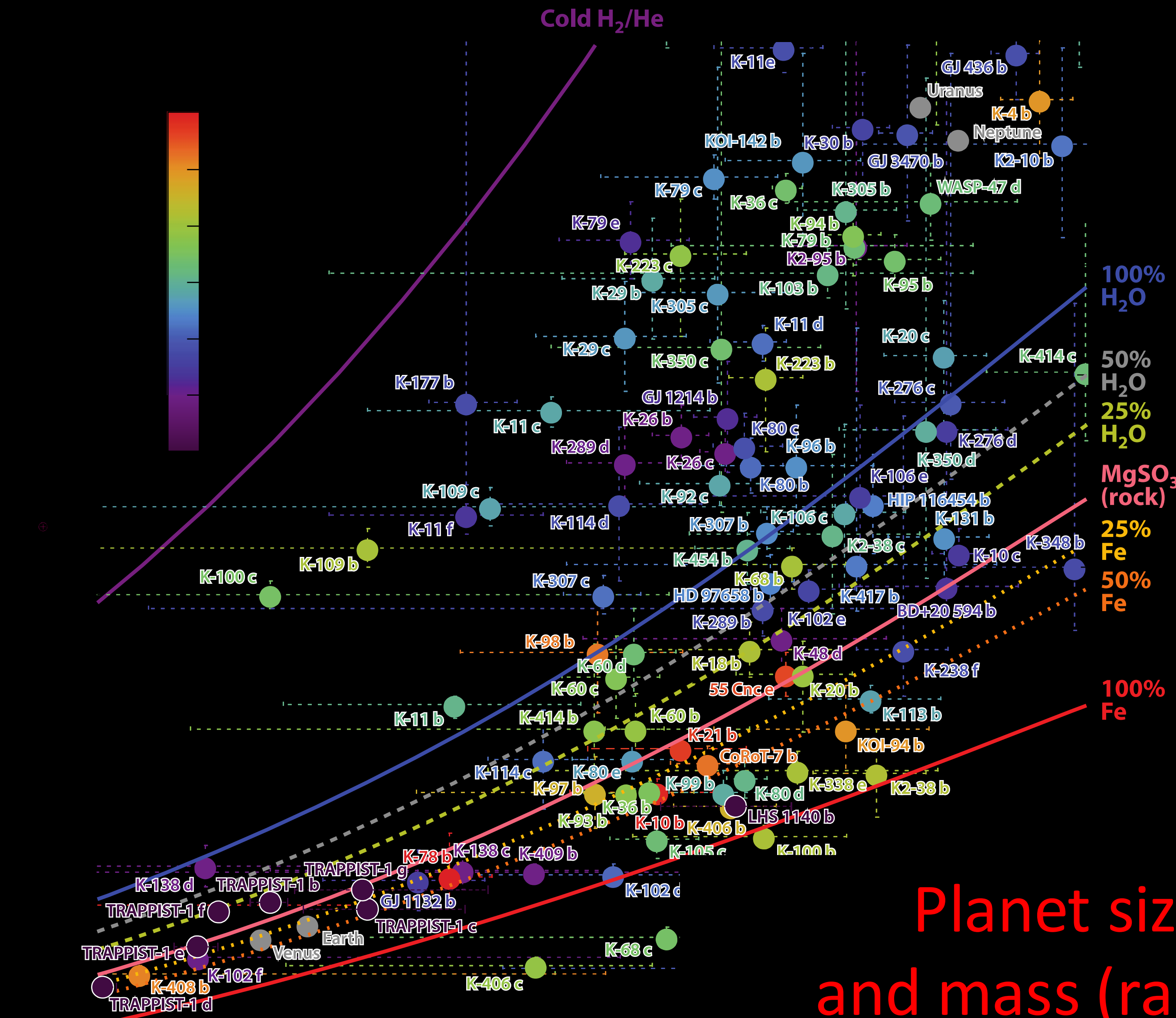


Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
10
1
0.01
0.1
1
10
Size (Earth = 1)
Distance from host star (Astronomical unit)

Exoplanet Populations



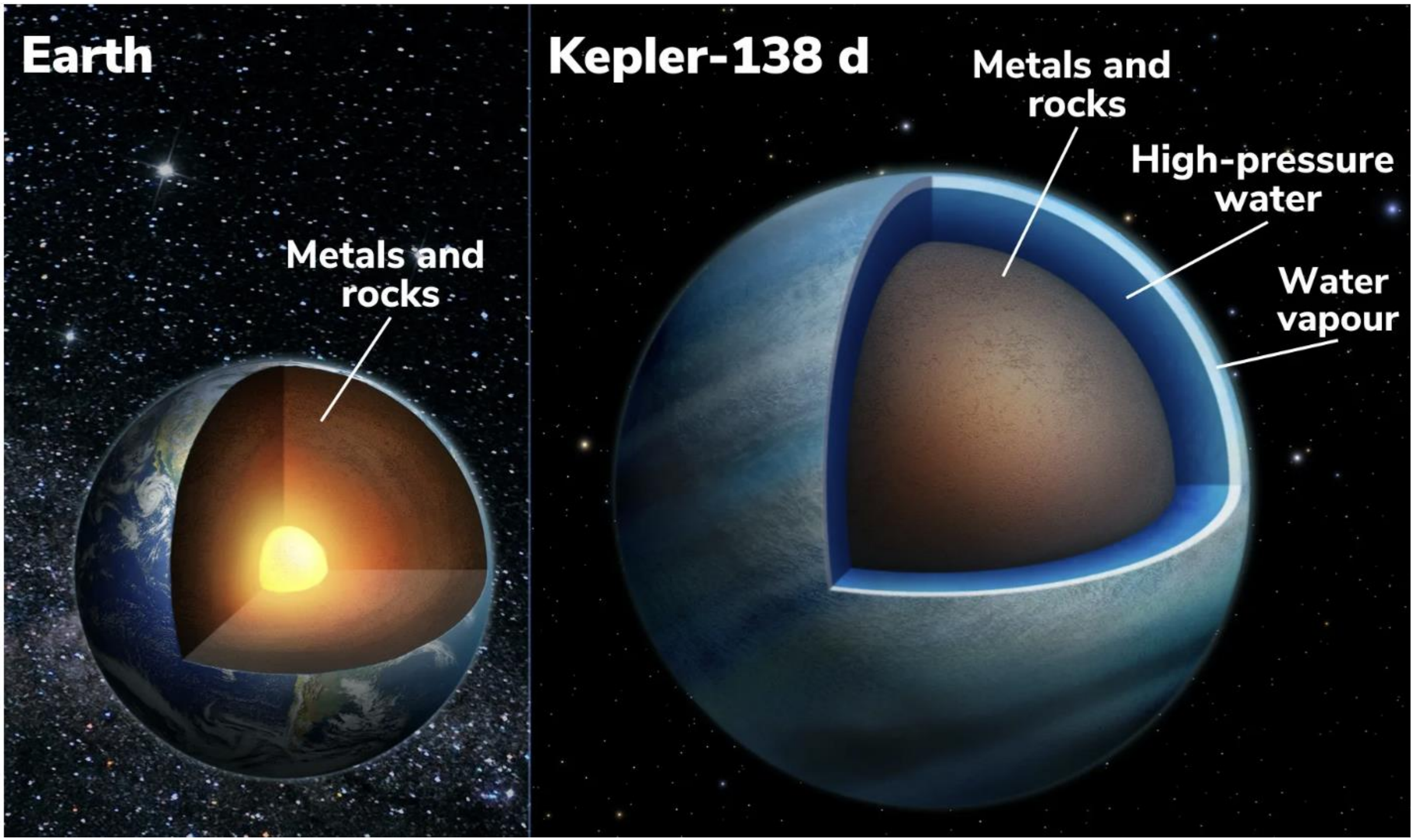
Planetary Systems by Number of Known Planets



Planet size (transit)
and mass (radial velocity):
density/composition

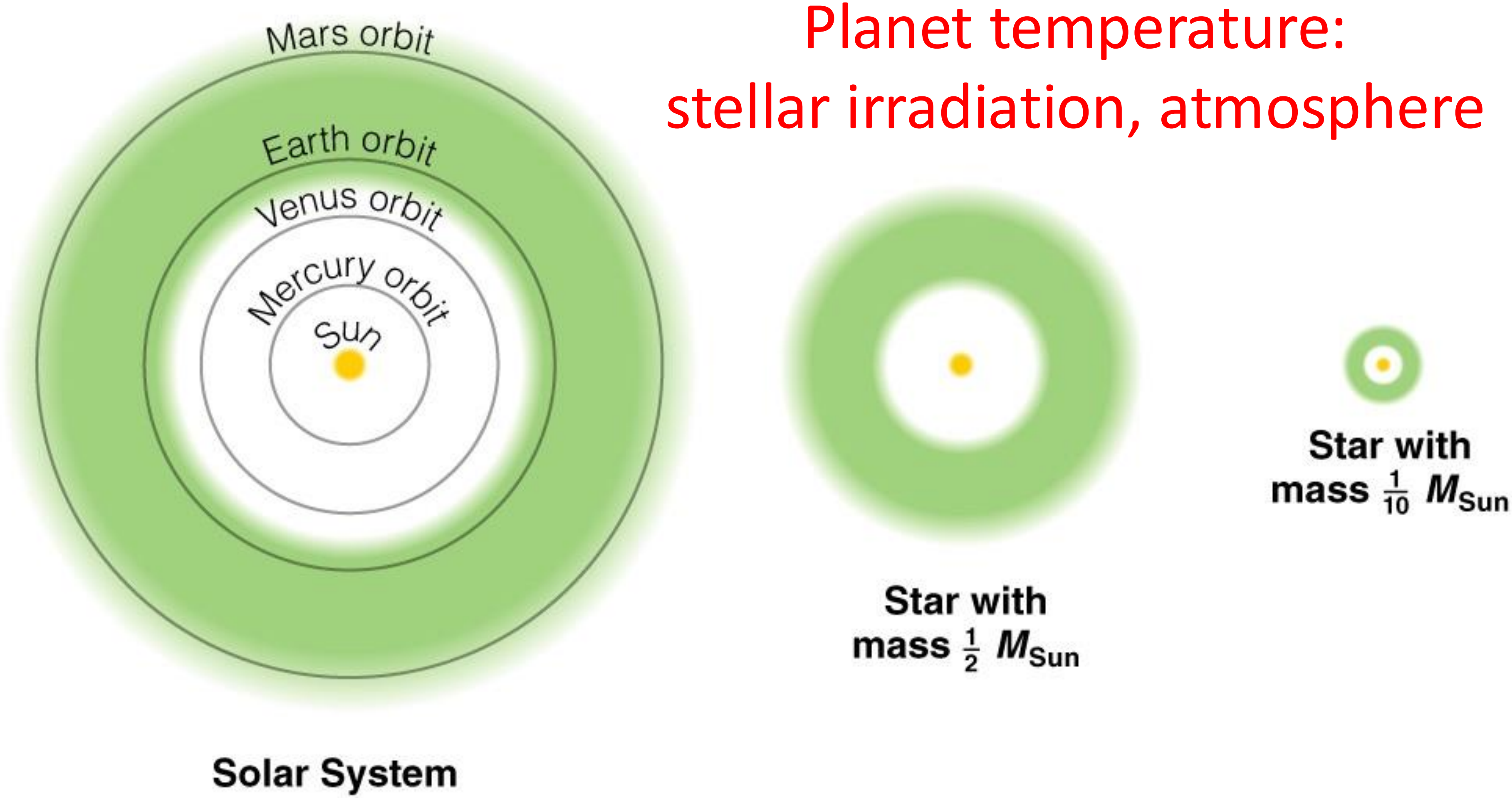
Figure 1

Water worlds?
Perhaps common for "super-earths"

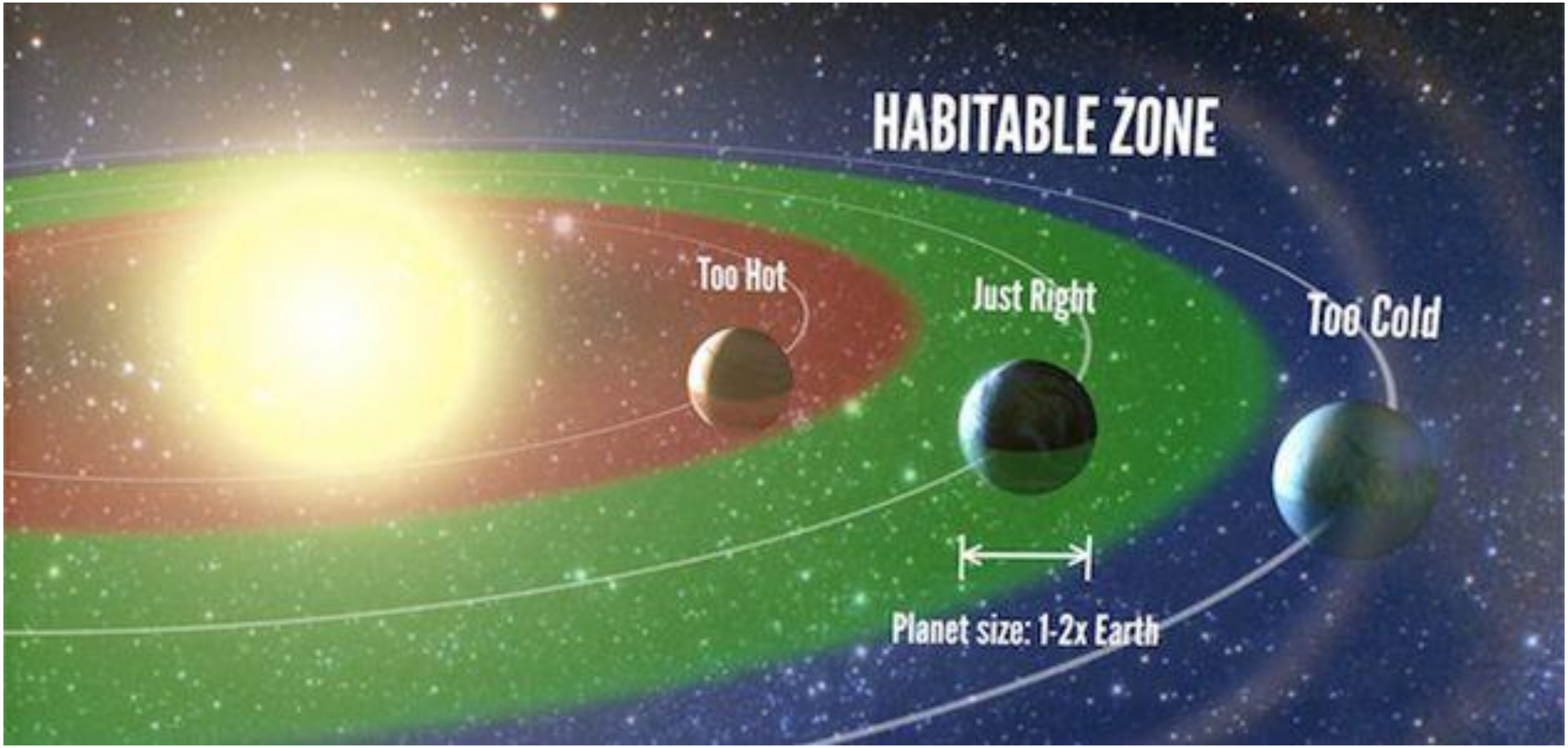


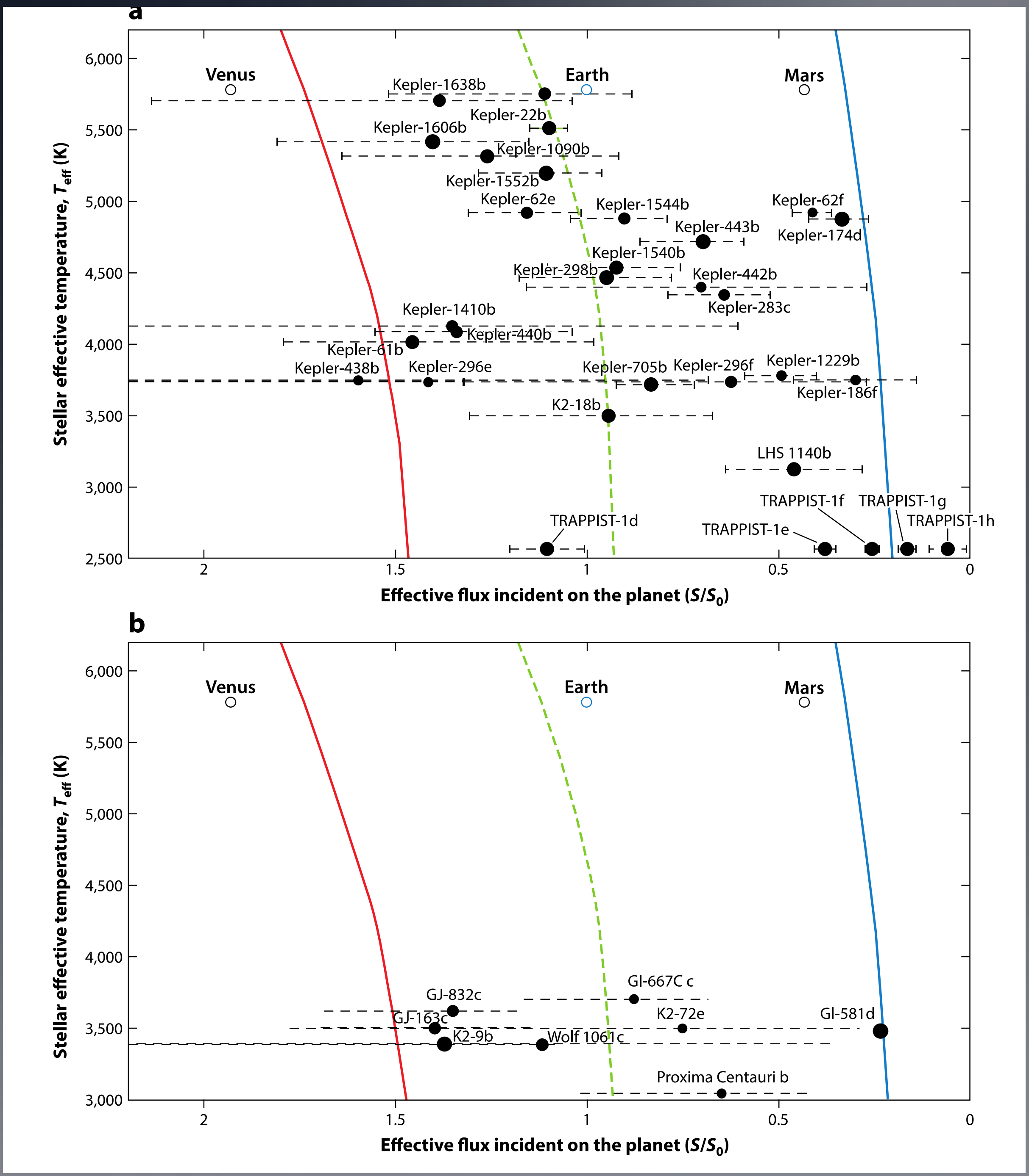
Are habitable planets likely?

Planet temperature:
stellar irradiation, atmosphere

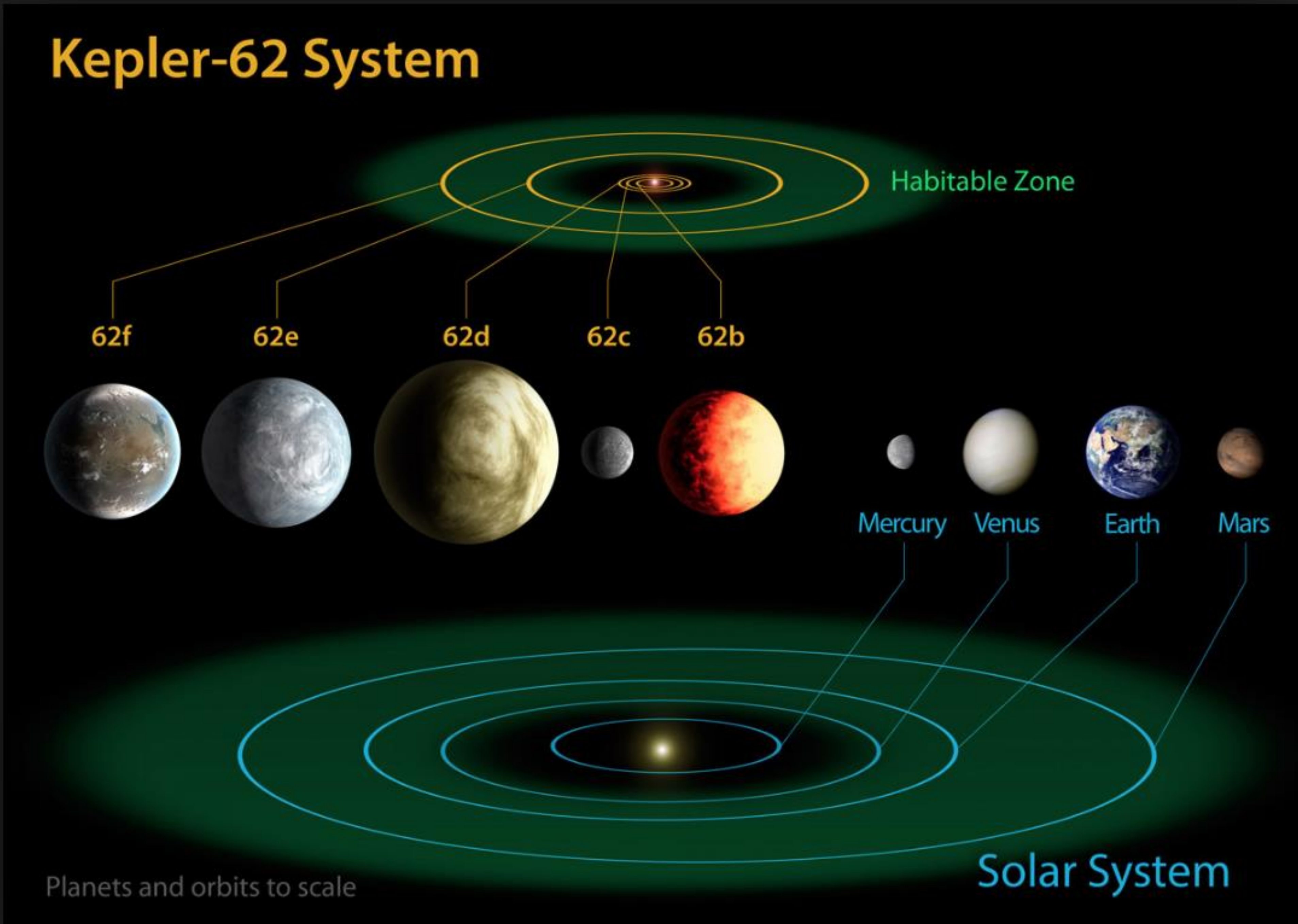


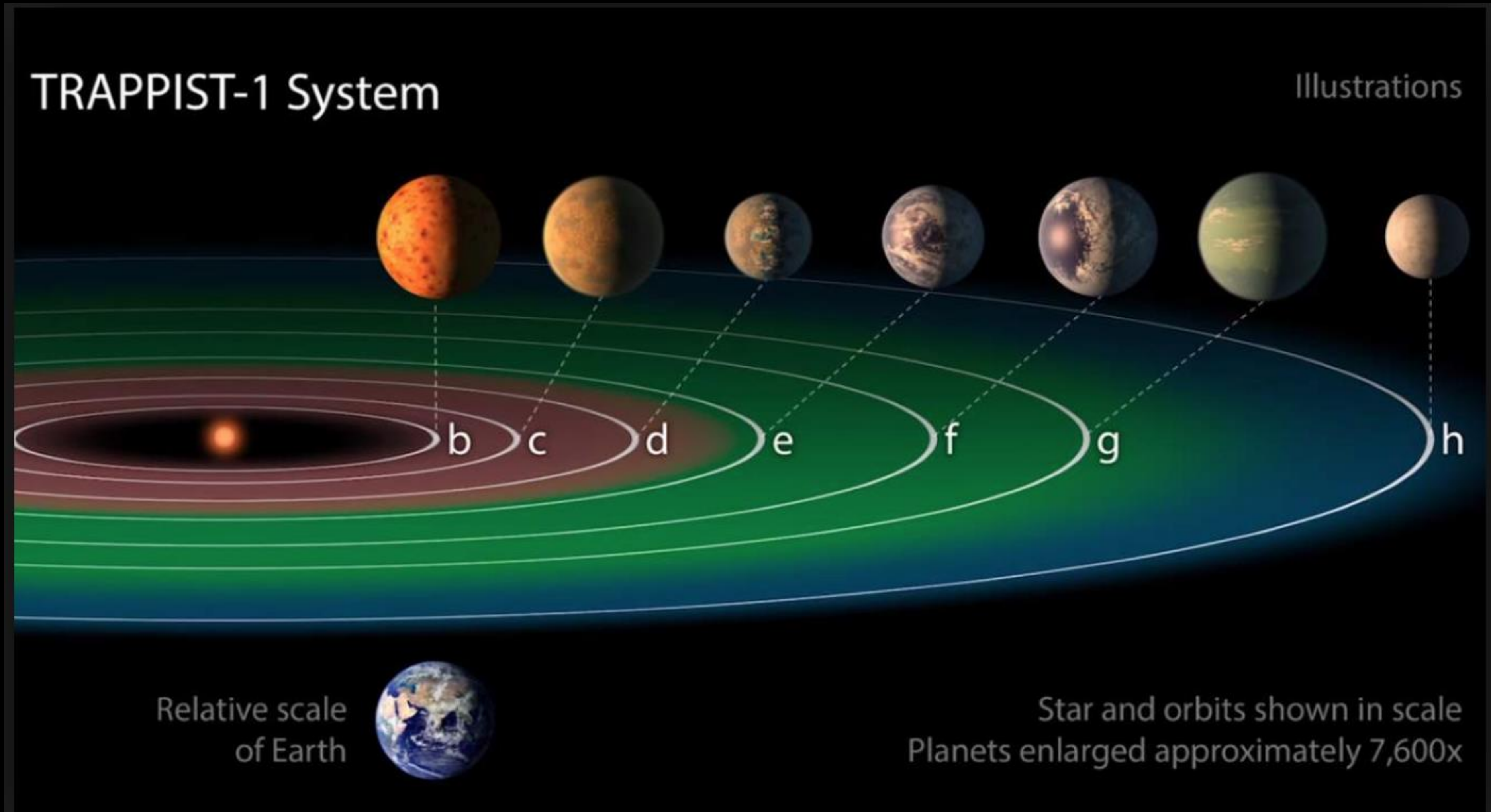
Habitable: liquid water

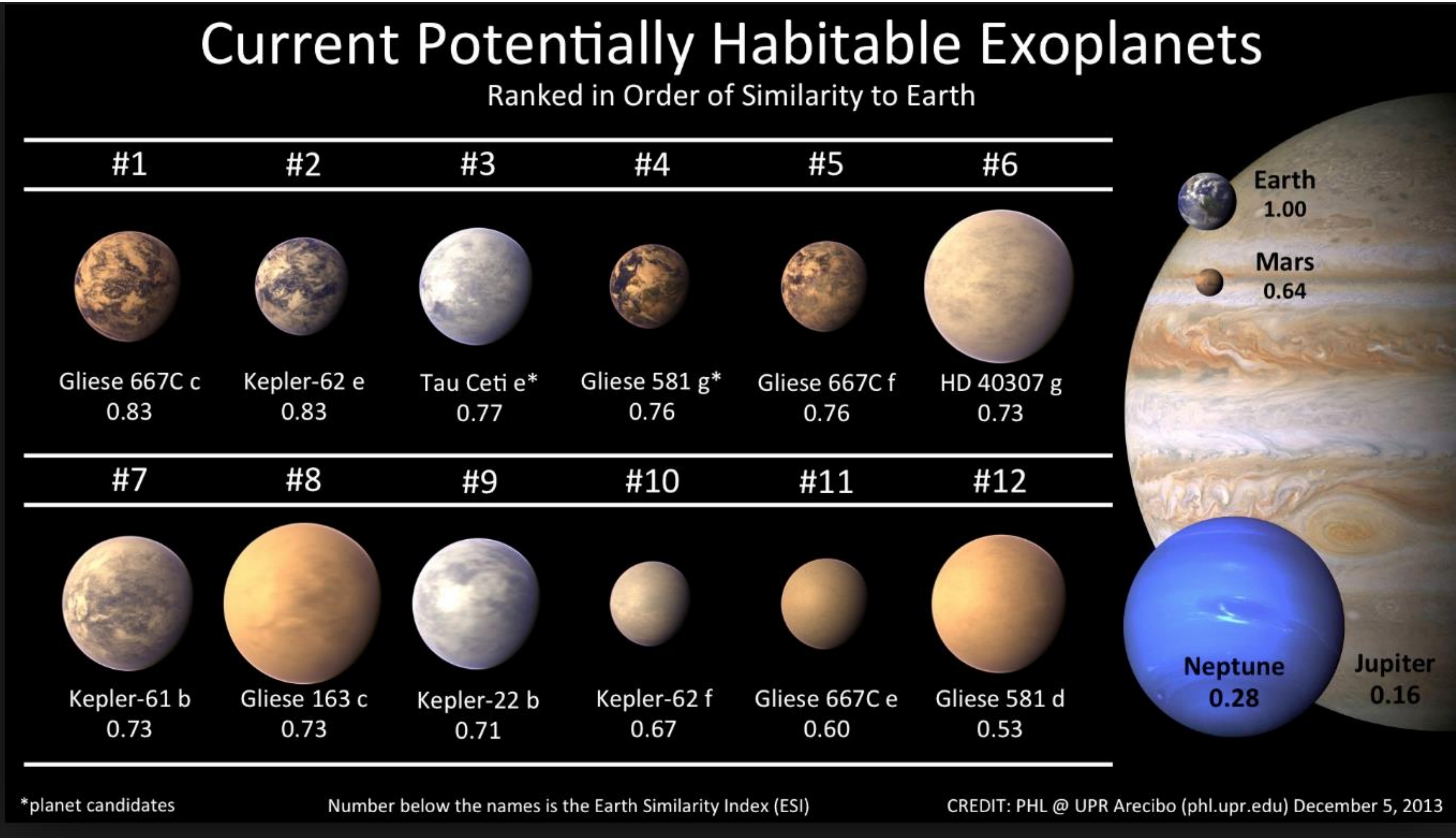

HABITABLE ZONE
Too Hot
Just Right
Too Cold
Planet size: 1-2x Earth



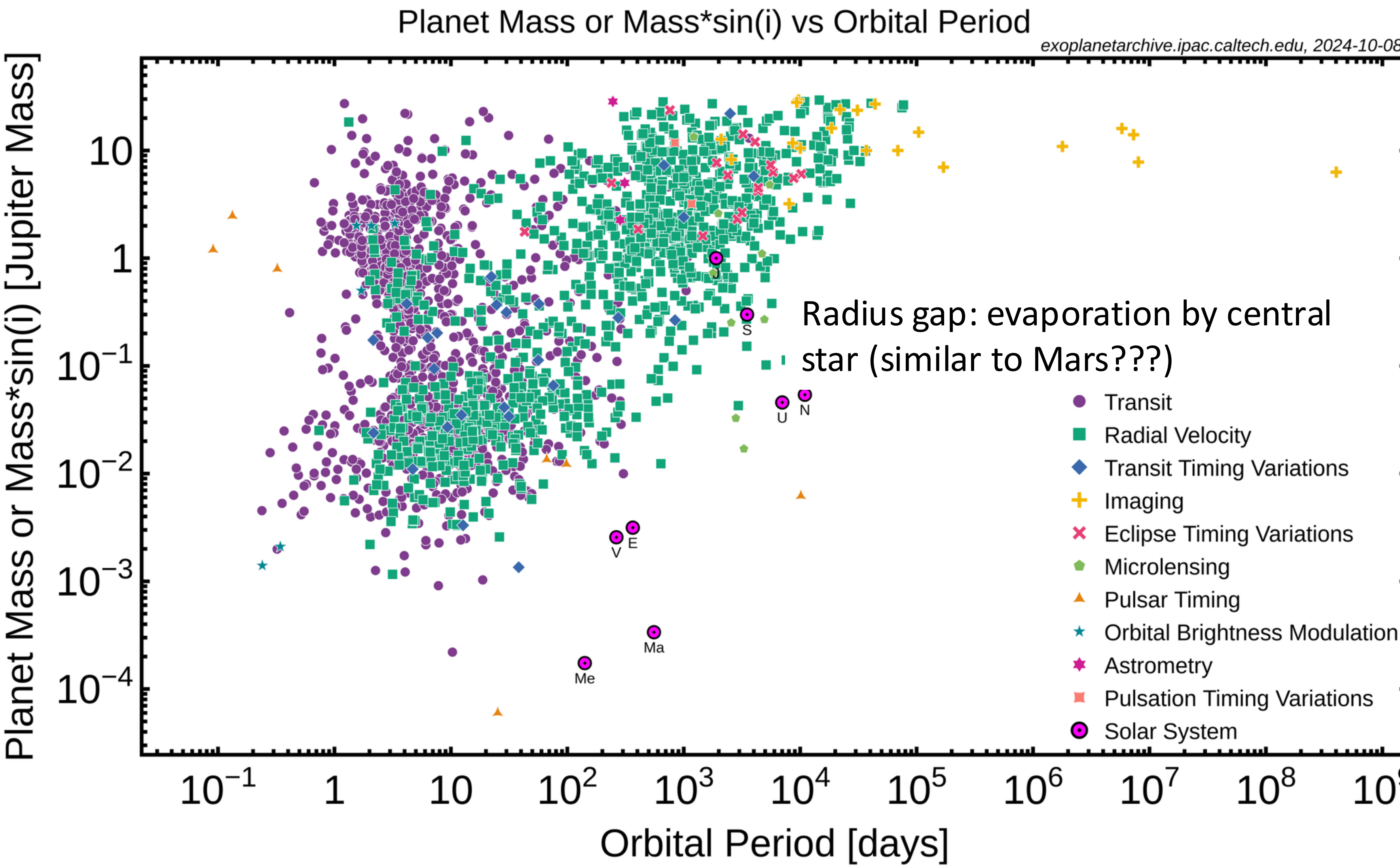
Exoplanets in habitable zone


Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

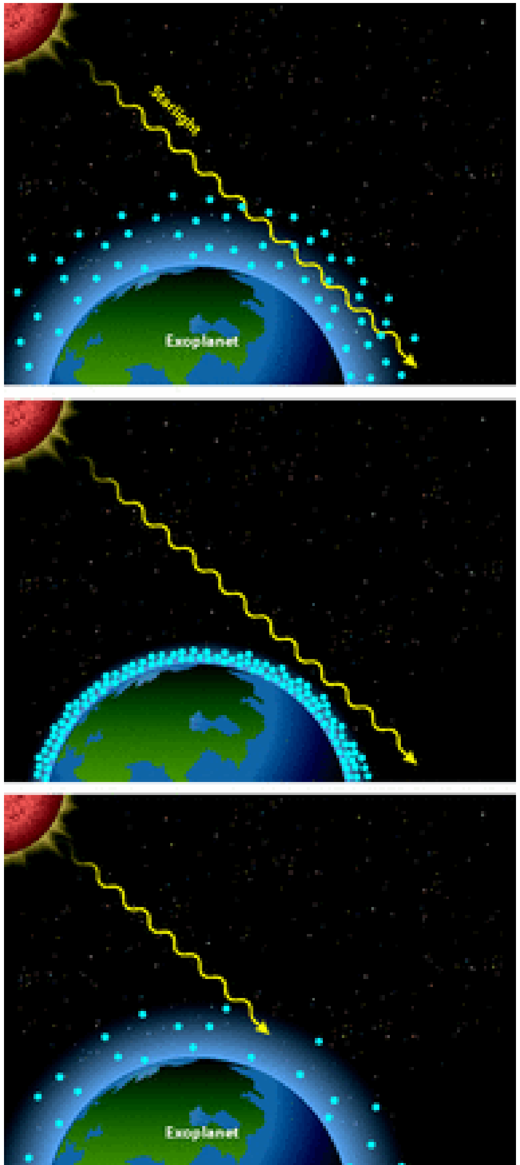

TRAPPIST-1 System
Illustrations
b
c
d
e
f
g
h
Relative scale of Earth
Star and orbits shown in scale
Planets enlarged approximately 7,600x

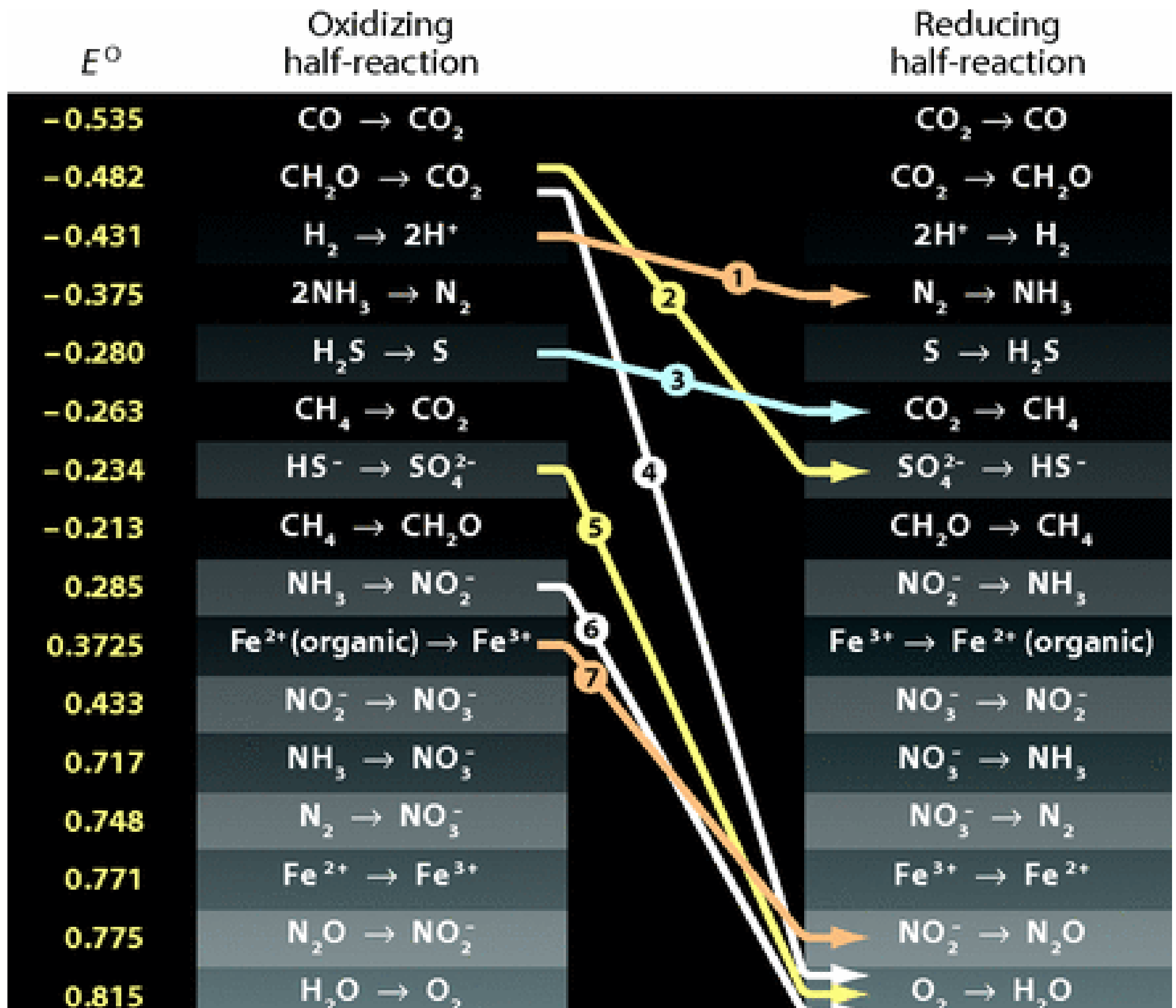

Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
#1
Gliese 667C c
0.83
#2
Kepler-62 e
0.83
#3
Tau Ceti e*
0.77
#4
Gliese 581 g*
0.76
#5
Gliese 667C f
0.76
#6
HD 40307 g
0.73
#7
Kepler-61 b
0.73
#8
Gliese 163 c
0.73
#9
Kepler-22 b
0.71
#10
Kepler-62 f
0.67
#11
Gliese 667C e
0.60
#12
Gliese 581 d
0.53
Earth
1.00
Mars
0.64
Neptune
0.28
Jupiter
0.16
*planet candidates
Number below the names is the Earth Similarity Index (ESI)
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) December 5, 2013

Searching for earth-like planets



Exoplanet atmospheres!



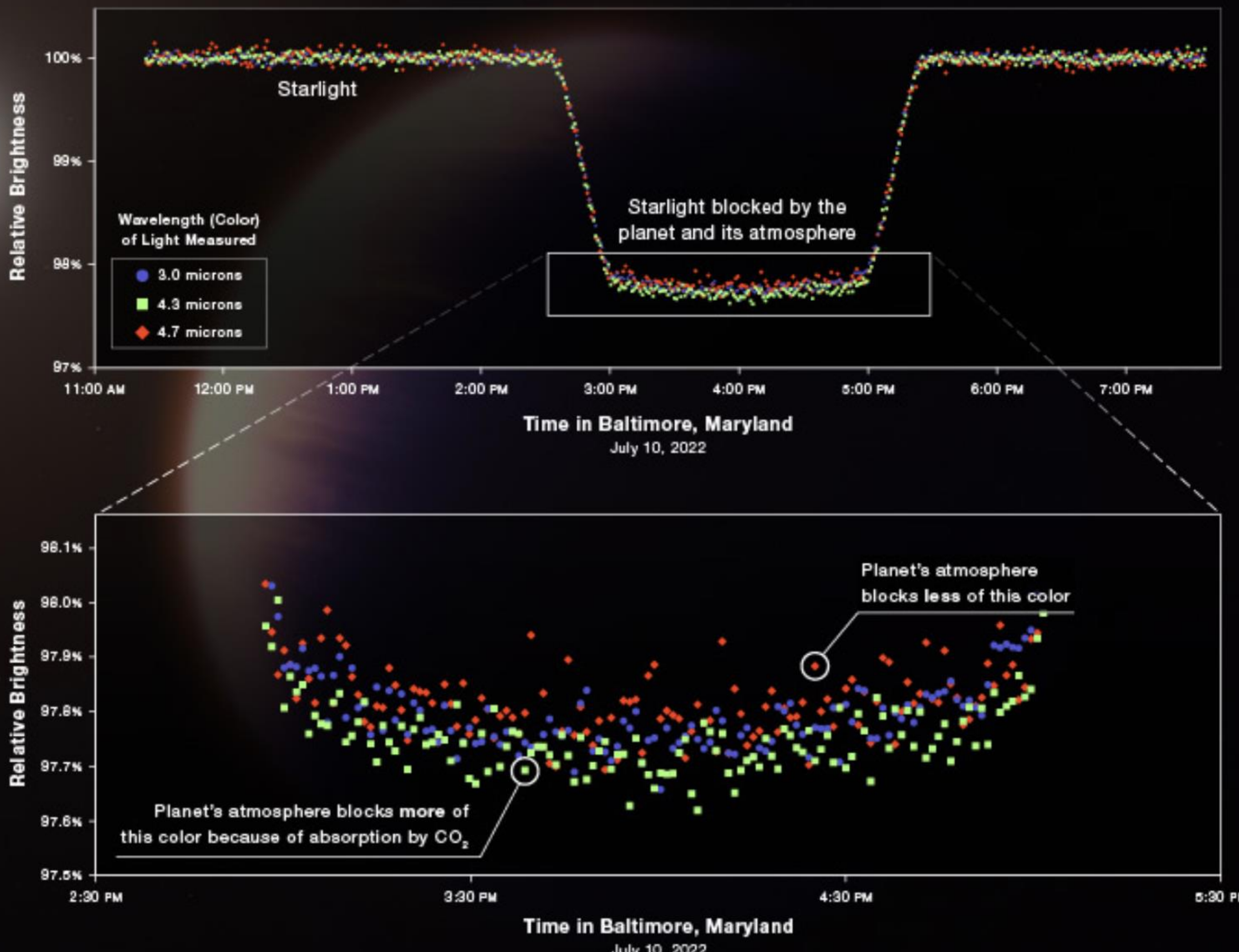


E°	Oxidizing half-reaction	Reducing half-reaction
−0.535	$CO \rightarrow CO_2$	$CO_2 \rightarrow CO$
−0.482	$CH_2O \rightarrow CO_2$	$CO_2 \rightarrow CH_2O$
−0.431	$H_2 \rightarrow 2H^+$	$2H^+ \rightarrow H_2$
−0.375	$2NH_3 \rightarrow N_2$	$N_2 \rightarrow NH_3$
−0.280	$H_2S \rightarrow S$	$S \rightarrow H_2S$
−0.263	$CH_4 \rightarrow CO_2$	$CO_2 \rightarrow CH_4$
−0.234	$HS^- \rightarrow SO_4^{2-}$	$SO_4^{2-} \rightarrow HS^-$
−0.213	$CH_4 \rightarrow CH_2O$	$CH_2O \rightarrow CH_4$
0.285	$NH_3 \rightarrow NO_2^-$	$NO_2^- \rightarrow NH_3$
0.3725	Fe^{2+}(organic) $\rightarrow Fe^{3+}$	$Fe^{3+} \rightarrow Fe^{2+}$(organic)
0.433	$NO_2^- \rightarrow NO_3^-$	$NO_3^- \rightarrow NO_2^-$
0.717	$NH_3 \rightarrow NO_3^-$	$NO_3^- \rightarrow NH_3$
0.748	$N_2 \rightarrow NO_3^-$	$NO_3^- \rightarrow N_2$
0.771	$Fe^{2+} \rightarrow Fe^{3+}$	$Fe^{3+} \rightarrow Fe^{2+}$
0.775	$N_2O \rightarrow NO_2^-$	$NO_2^- \rightarrow N_2O$
0.815	$H_2O \rightarrow O_2$	$O_2 \rightarrow H_2O$

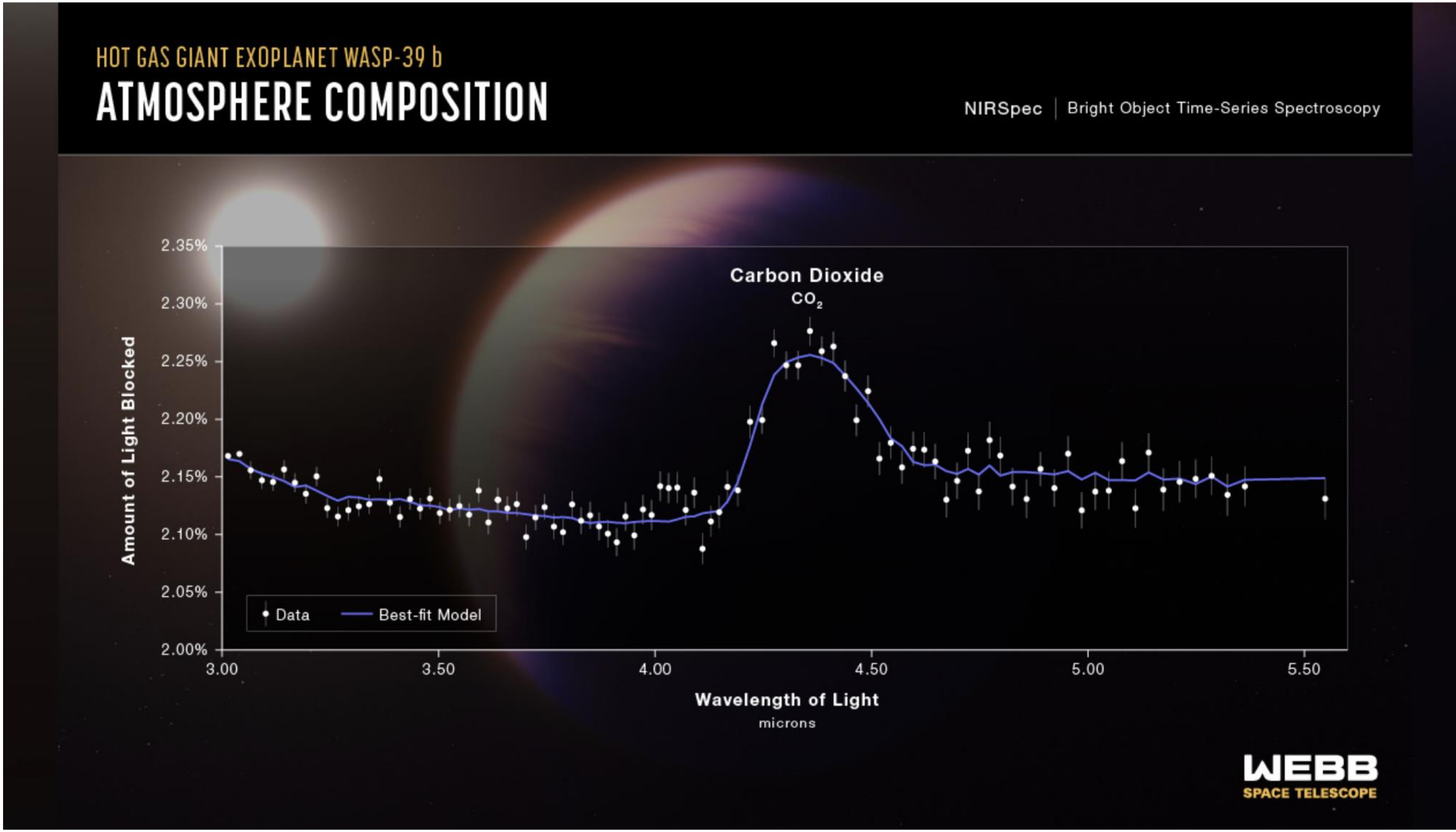
HOT GAS GIANT EXOPLANET WASP-39 b

TRANSIT LIGHT CURVE

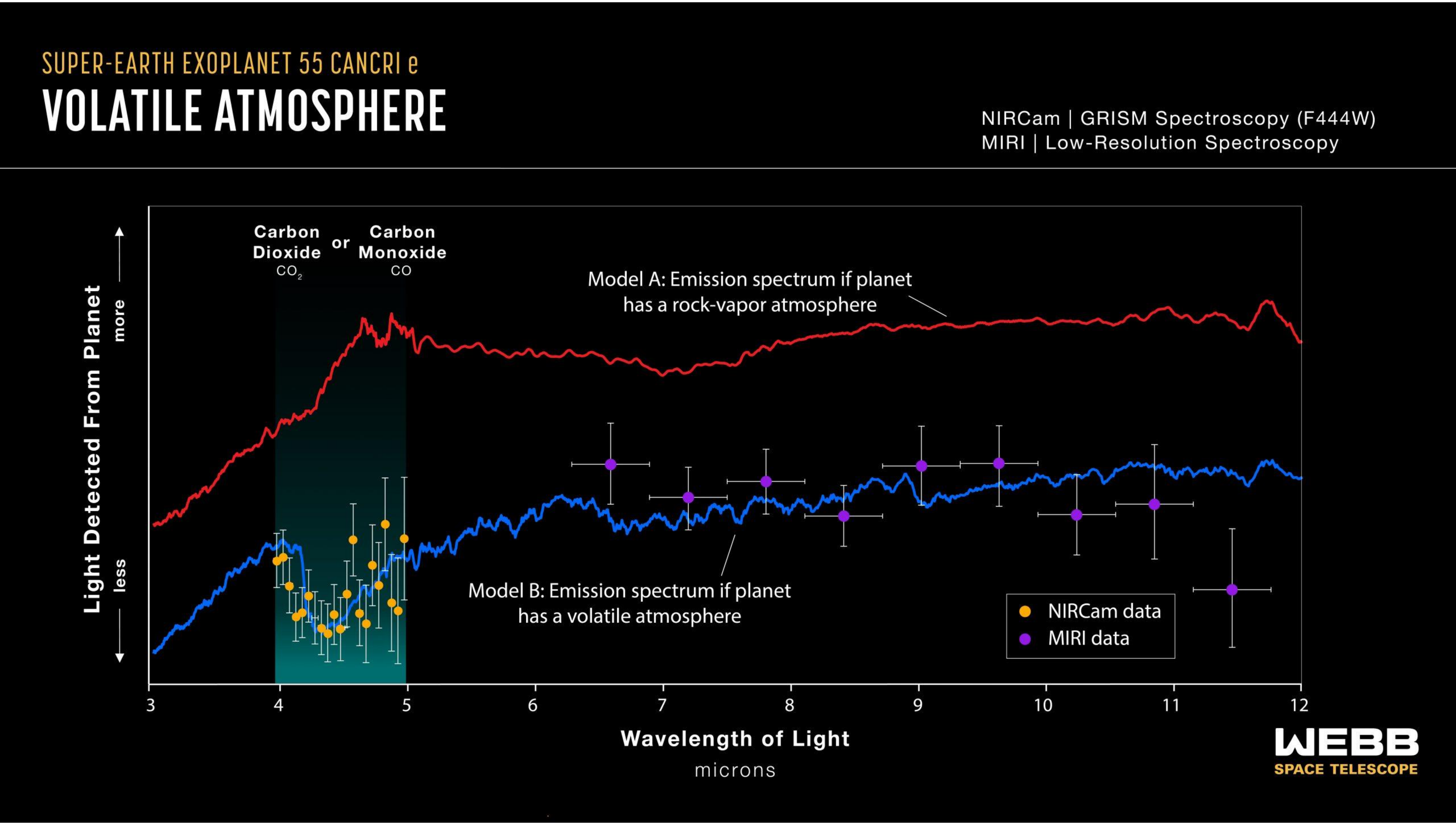
NIRSpec | Bright Object Time-Series Spectroscopy



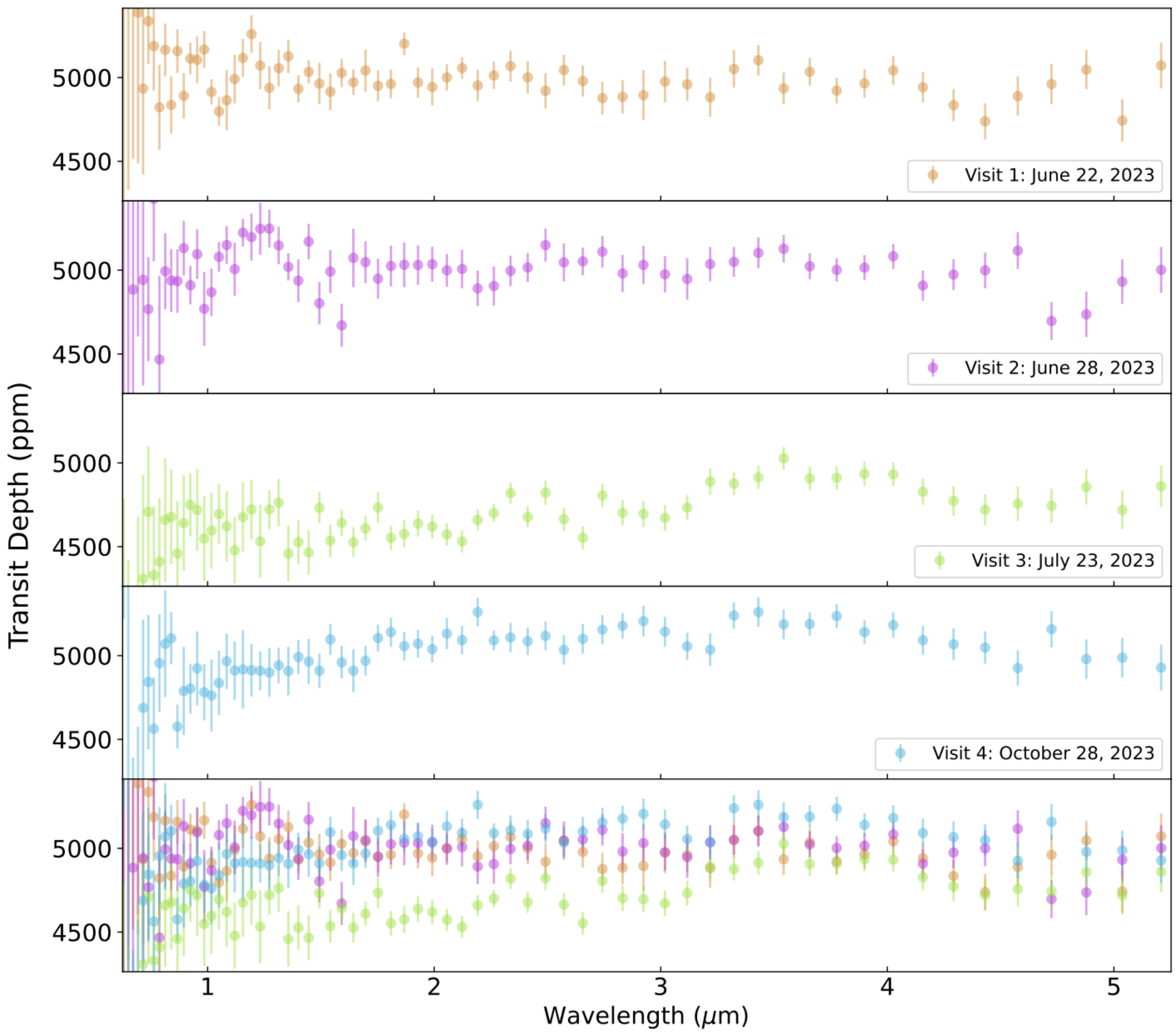
WEBB SPACE TELESCOPE


HOT GAS GIANT EXOPLANET WASP-39 b
ATMOSPHERE COMPOSITION
NIRSpec | Bright Object Time-Series Spectroscopy
Carbon Dioxide
CO2
Amount of Light Blocked
2.35%
2.30%
2.25%
2.20%
2.15%
2.10%
2.05%
2.00%
Data
Best-fit Model
3.00
3.50
4.00
4.50
5.00
5.50
Wavelength of Light
microns
WEBB
SPACE TELESCOPE

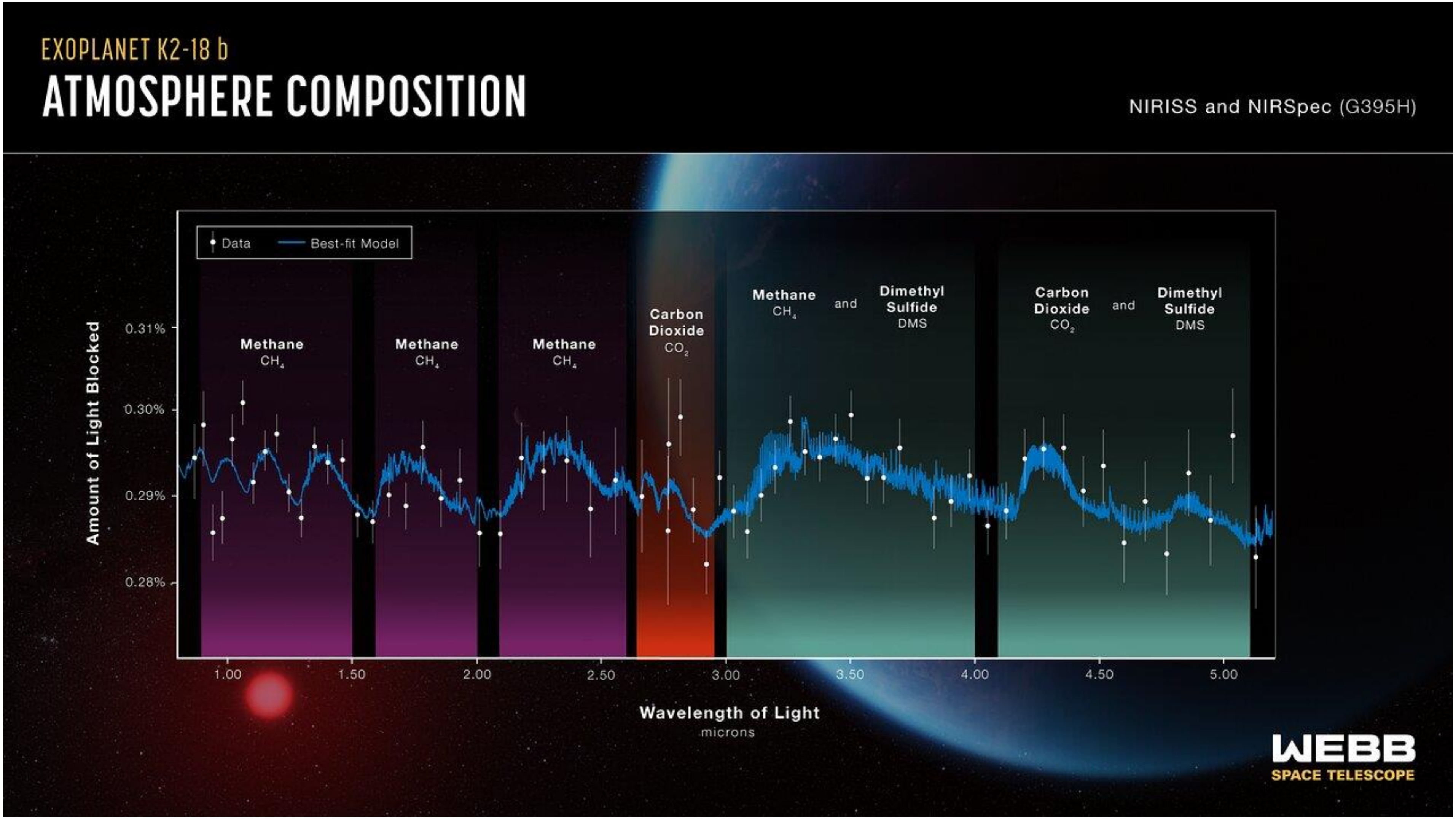
First atmosphere around a terrestrial exoplanet

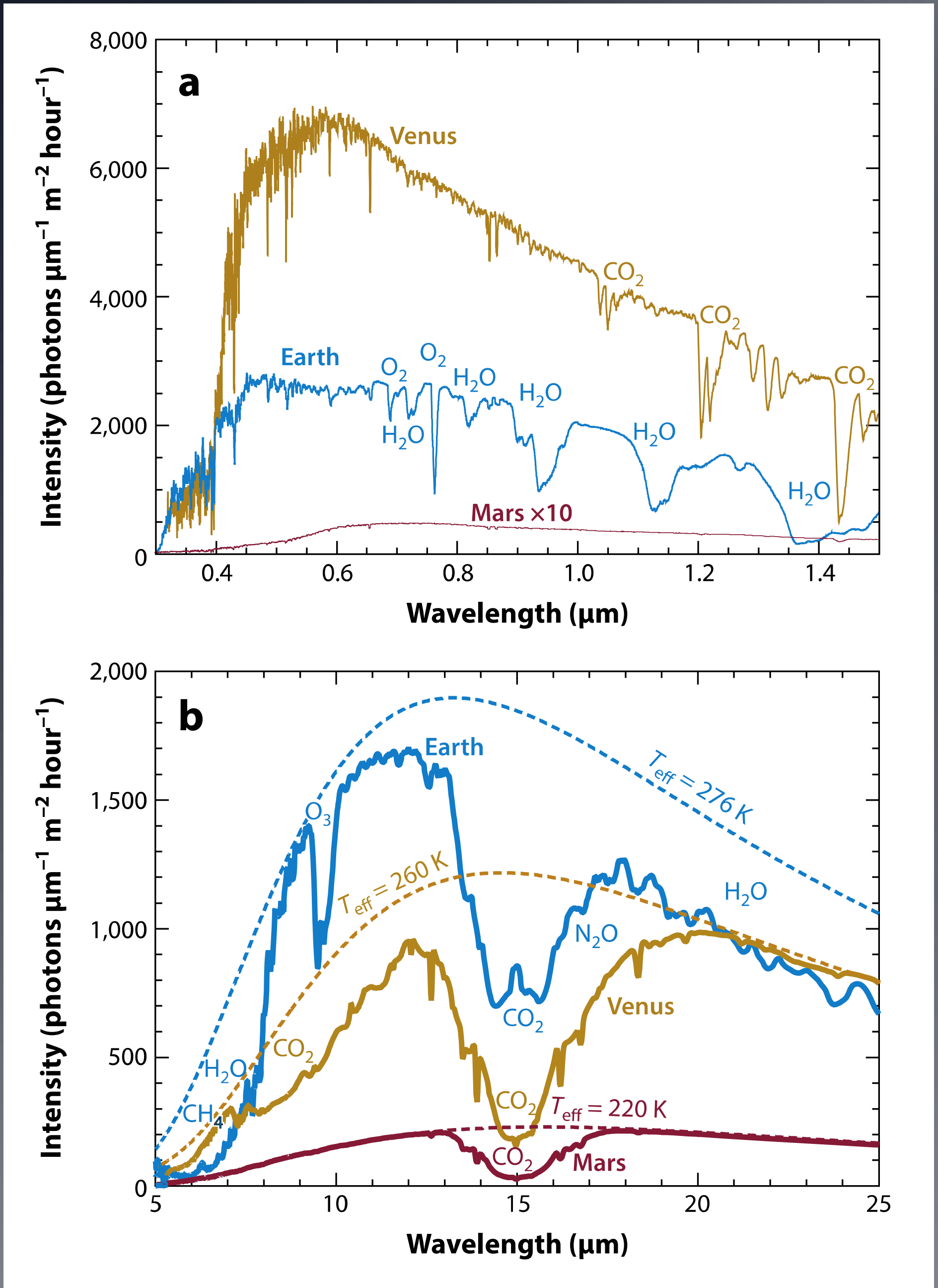


Searching for terrestrial planet atmospheres is difficult!



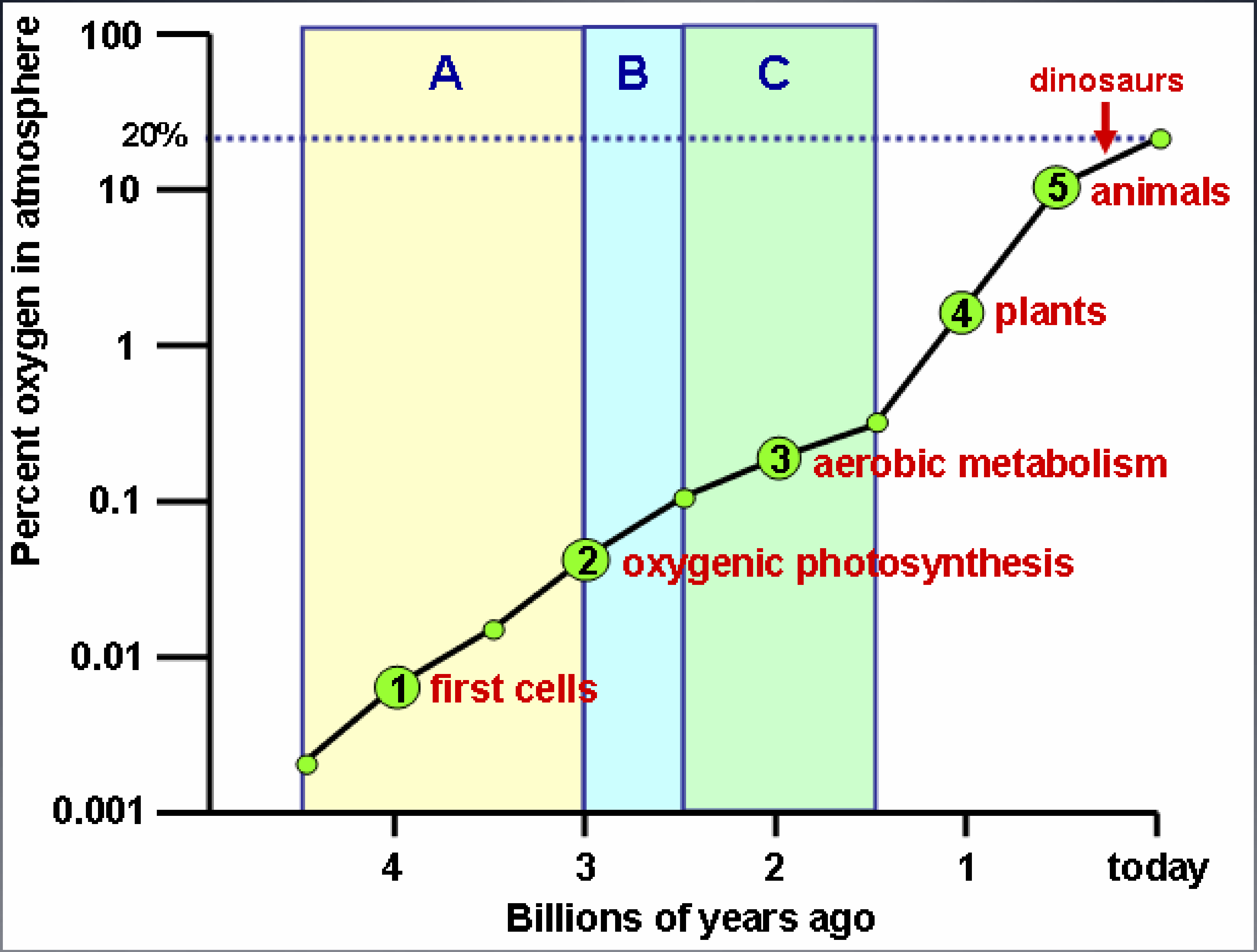
Biosignatures from a super-earth???





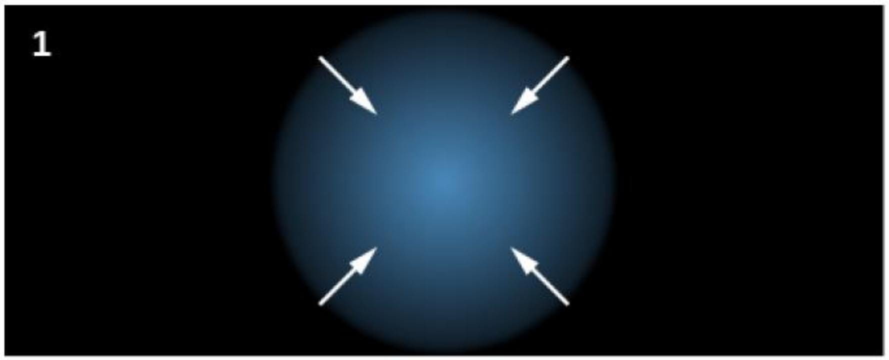
Life changes its environment

- Life needs a suitable environment to flourish.
- Feedback on environment and atmosphere
- Changes: biosignature, a sign of the presence of life
- Oxygen: a biosignature of life. Looking from afar, we cannot see plants and bacteria directly, but we can infer the presence of photosynthetic life if there is atmospheric oxygen.

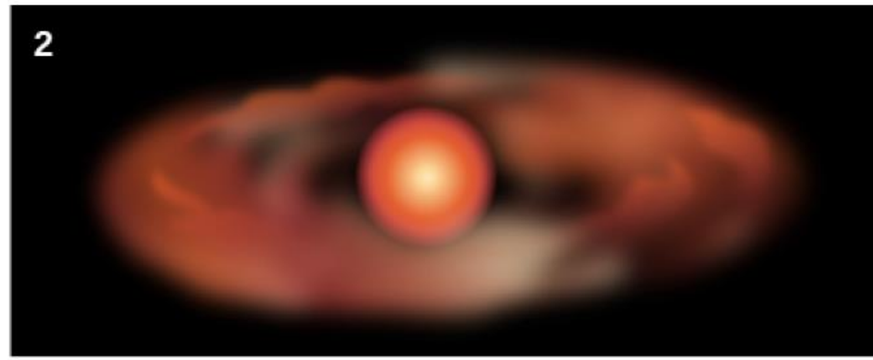


Percent oxygen in atmosphere
100
20%
10
1
0.1
0.01
0.001
A
B
C
dinosaurs
5 animals
4 plants
3 aerobic metabolism
2 oxygenic photosynthesis
1 first cells
4
3
2
1
today
Billions of years ago

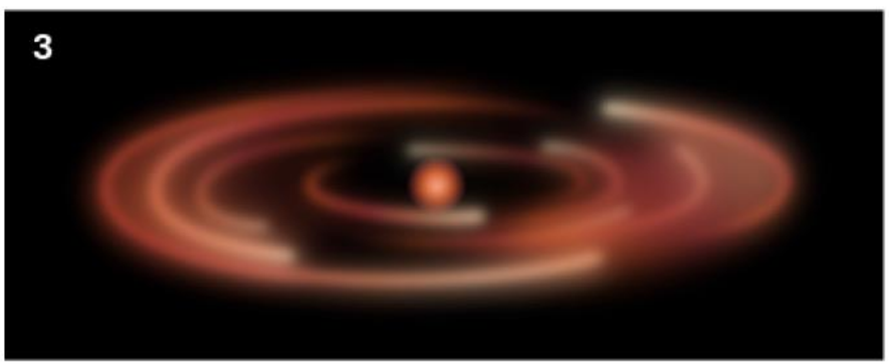
Planet Formation



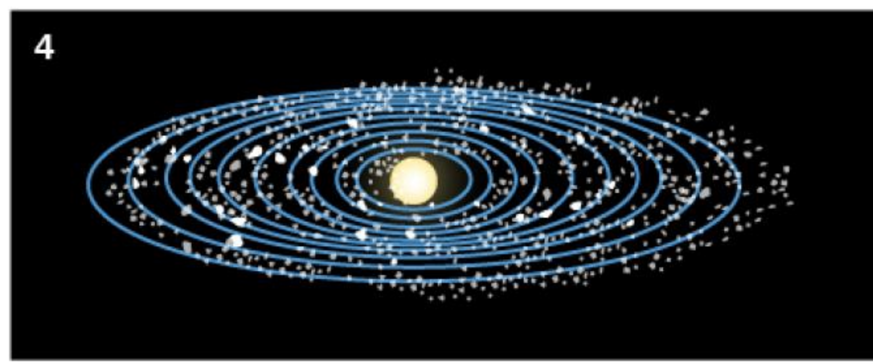
The solar nebula contracts.



As the nebula shrinks, its motion causes it to flatten.



The nebula is a disk of matter with a concentration near the center.



Formation of the protosun. Solid particles condense as the nebula cools, giving rise to the planetesimals, which are the building blocks of the planets.

Interstellar medium

- Space is not quite empty
  - Hot interstellar medium: 10^{-4} ions per cm^3
  - In this room: 10^{19} molecules/cm^3
  - Best vacuum in lab: 10^{10} molecules/cm^3

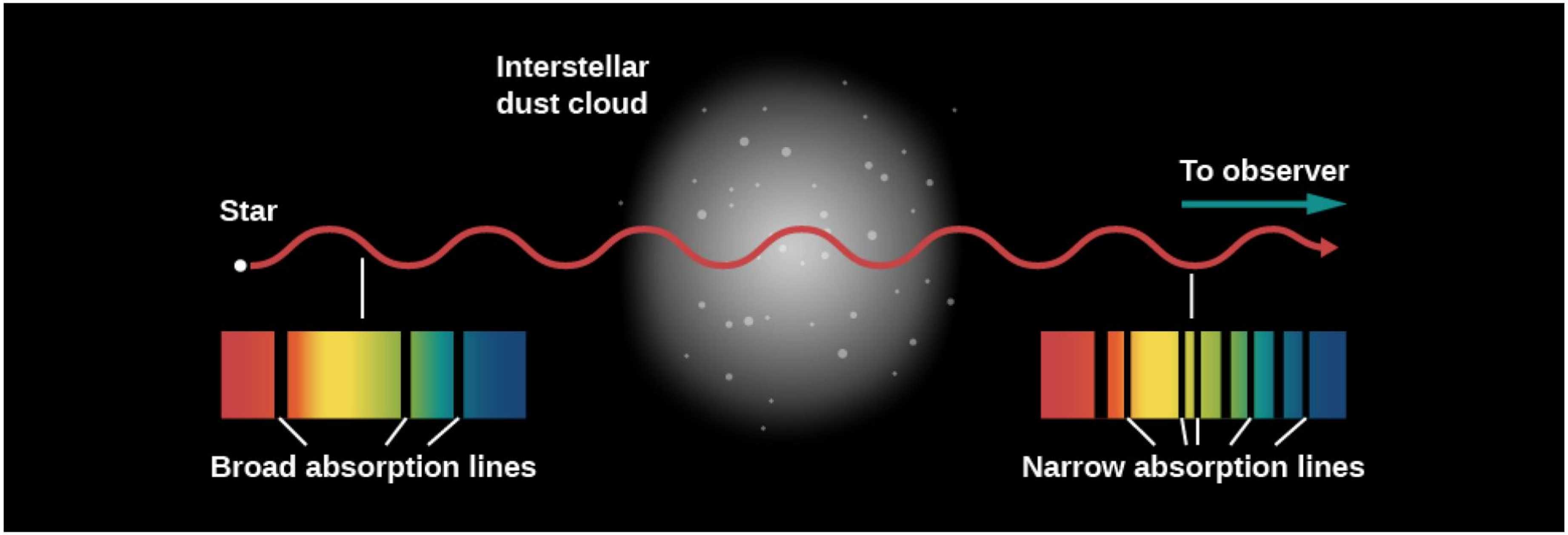
- Some places are denser and colder
  - **Molecular clouds**, where stars form
  - Densities of 10^2-10^6 molecules/cm^3

Interstellar medium, supernova remnants

Intestellar medium: how to detect?

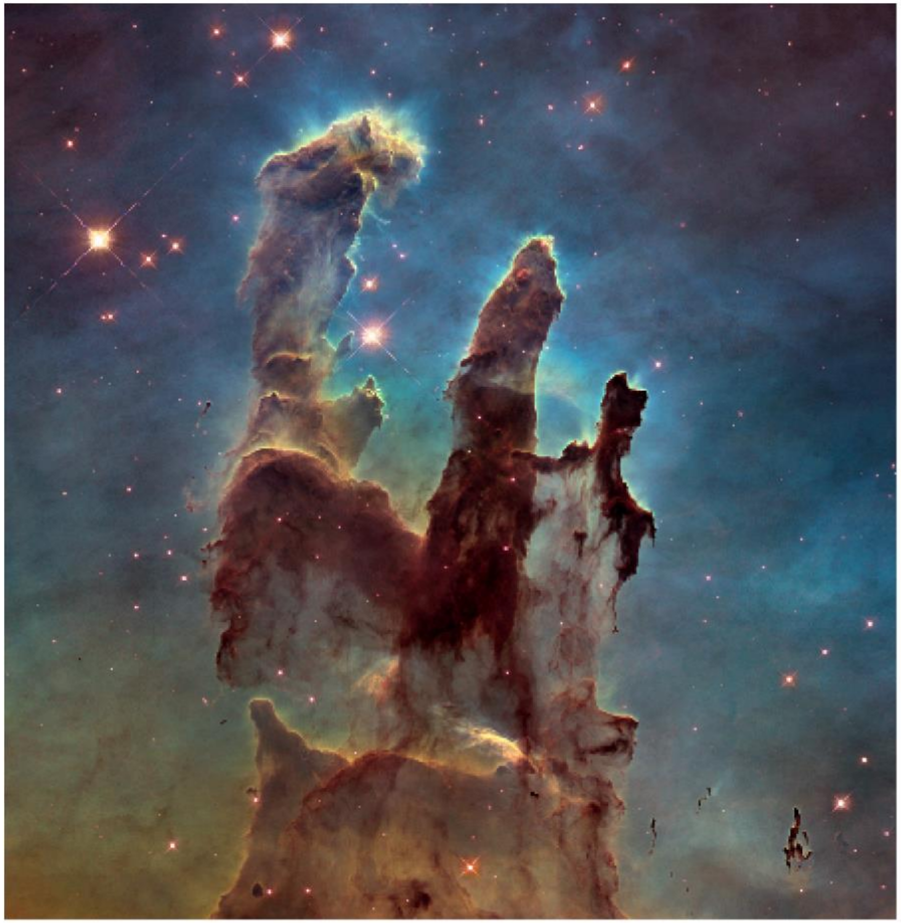
Absorption of photons by gas

Emission from gas/dust

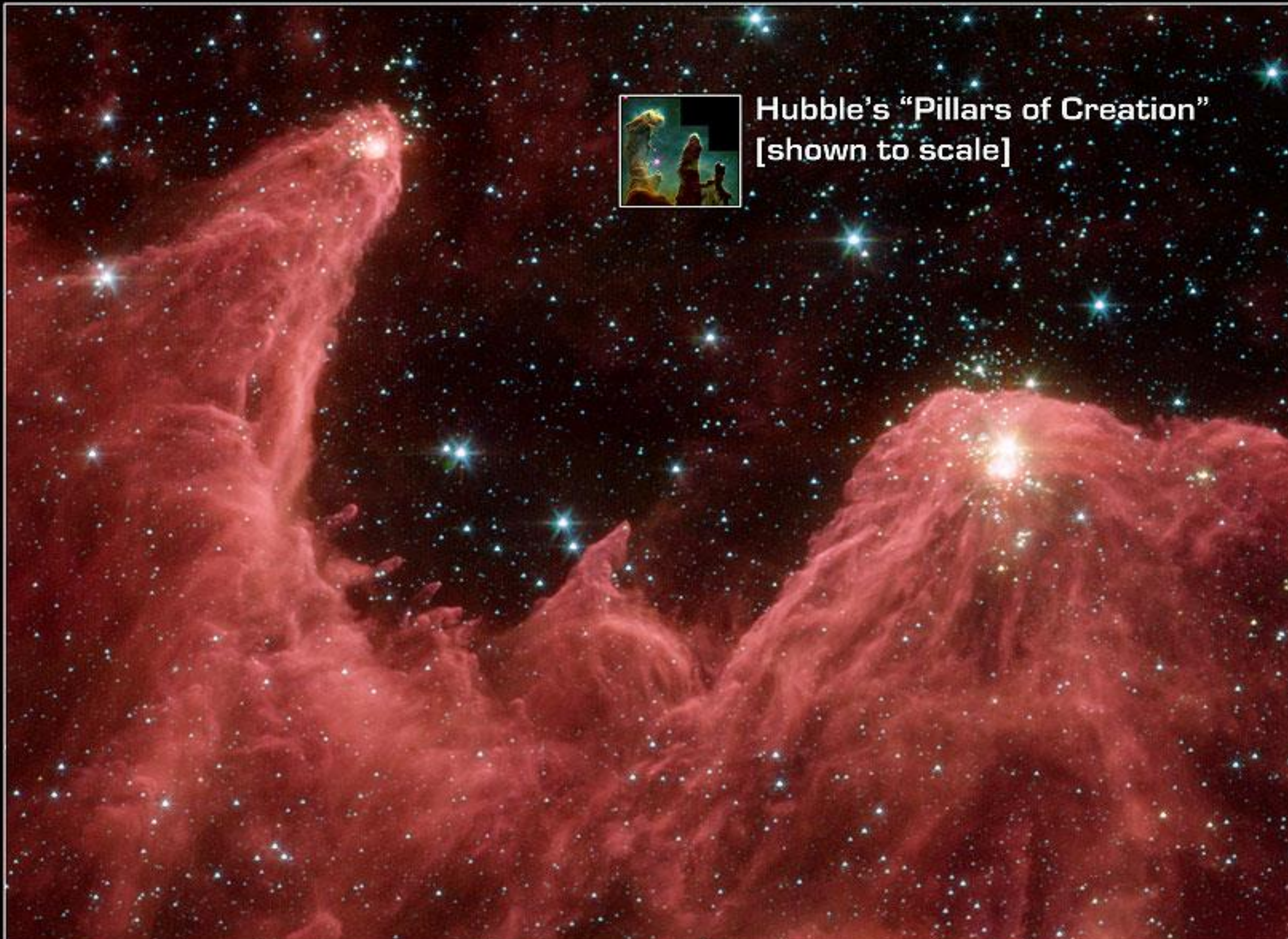



Orion Nebula
Largest nearby star-forming region

Eta Carina Cluster,
Hubble Space Telescope
Much larger than Orion Nebula



Pillars of Creation:
Hubble Space Telescope (optical) on left
JWST (infrared) on right



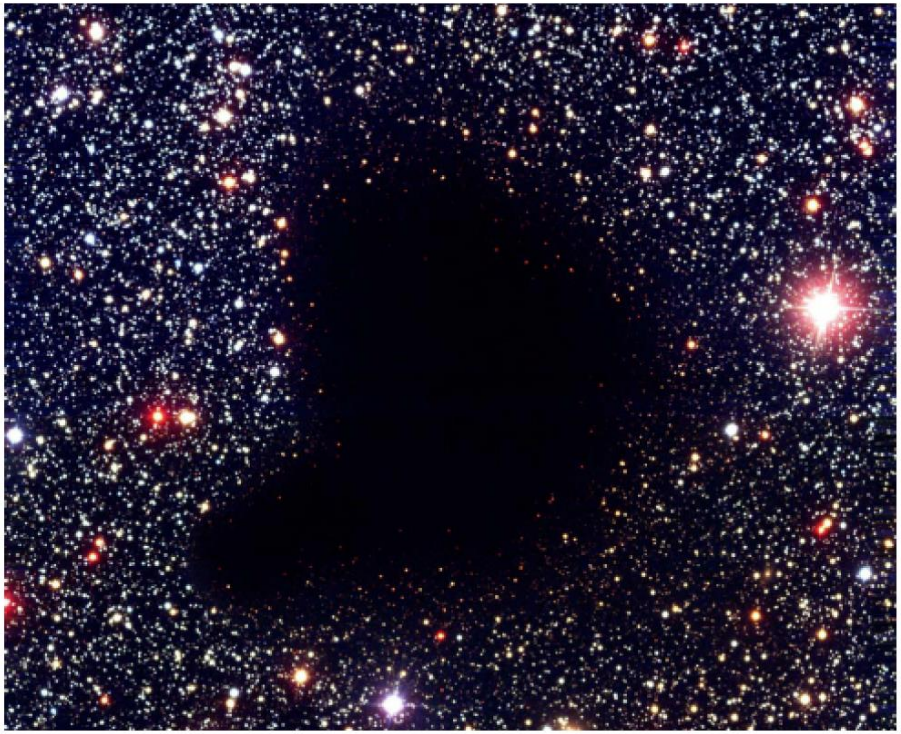
"Pillars" and "Mountains" of Star Formation

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

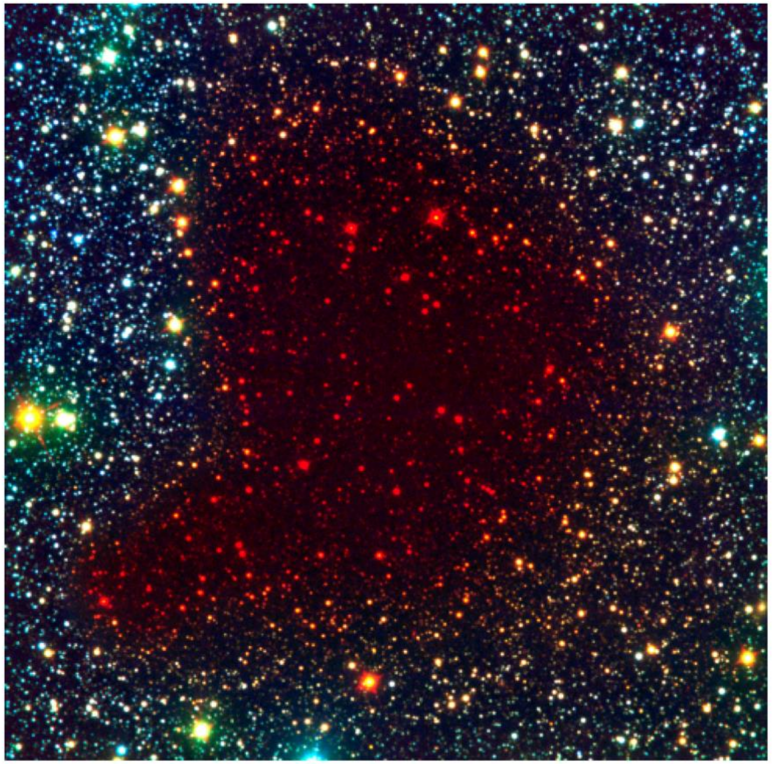
Spitzer Space Telescope • IRAC

Inset: Hubble Space Telescope

ssc2005-23b



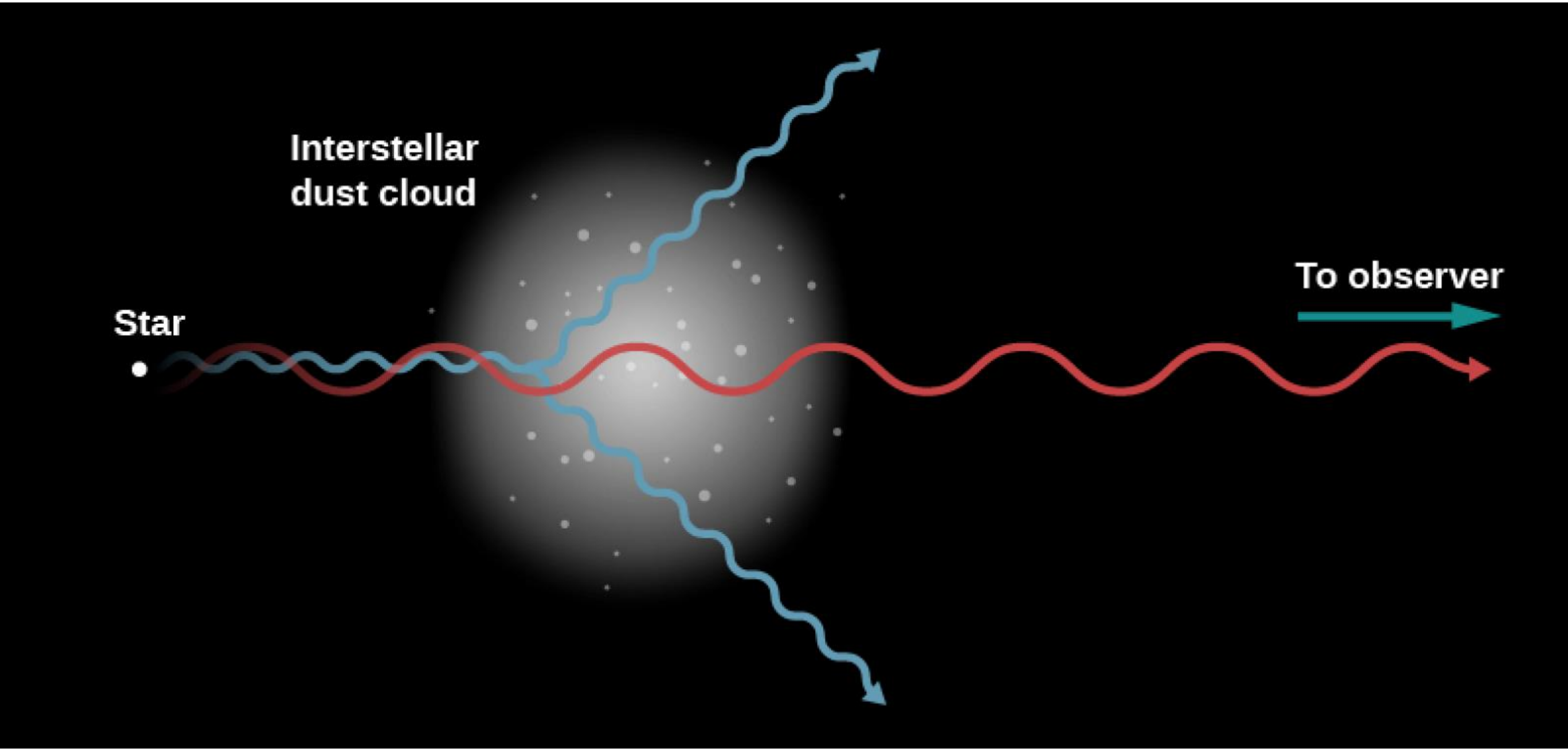
Optical



Near-infrared

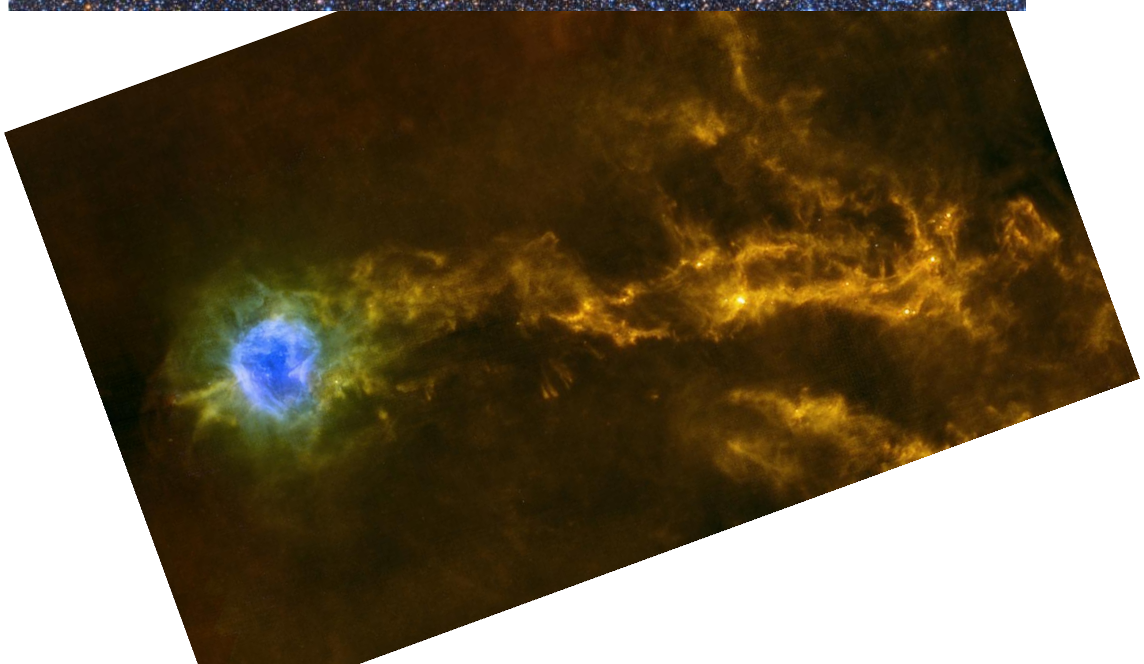
Barnard 68: very dusty!

Longer wavelengths look through dust (red objects on right)



Blue wavelengths: absorbed/scattered by dust
Red wavelengths: pass through dust


Rosette Nebula
Far-infrared: dust in emission

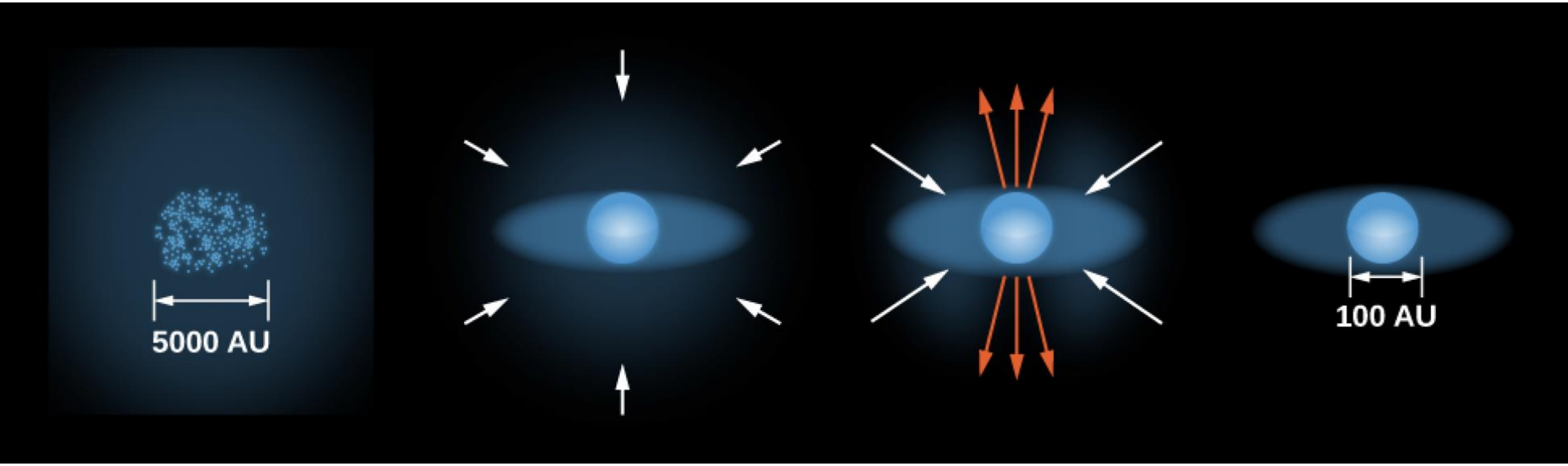


The same nebula can appear in both emission at short wavelengths and absorption at long wavelength

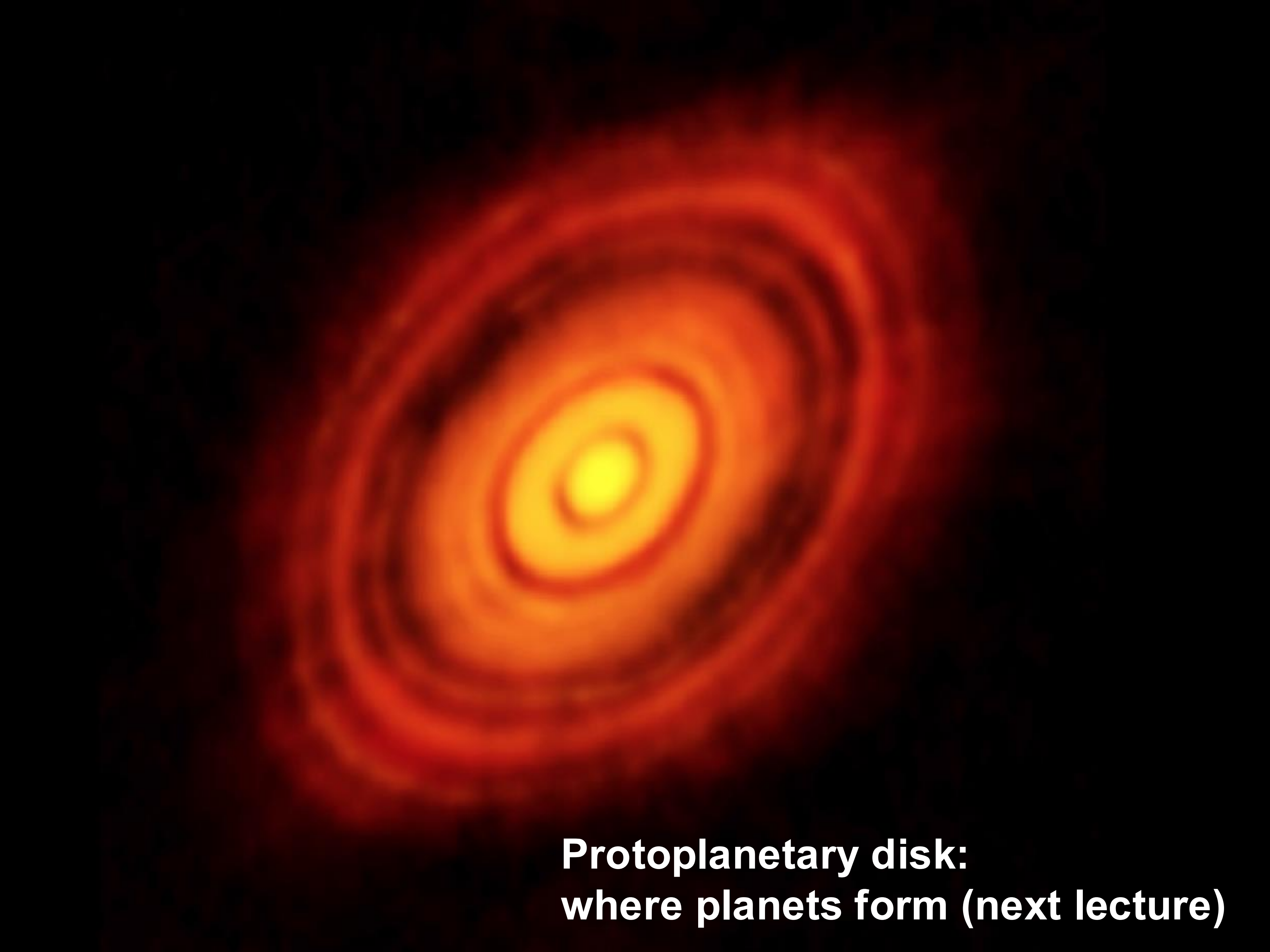
JWST image of Carina Nebula: hot stars ionize gas

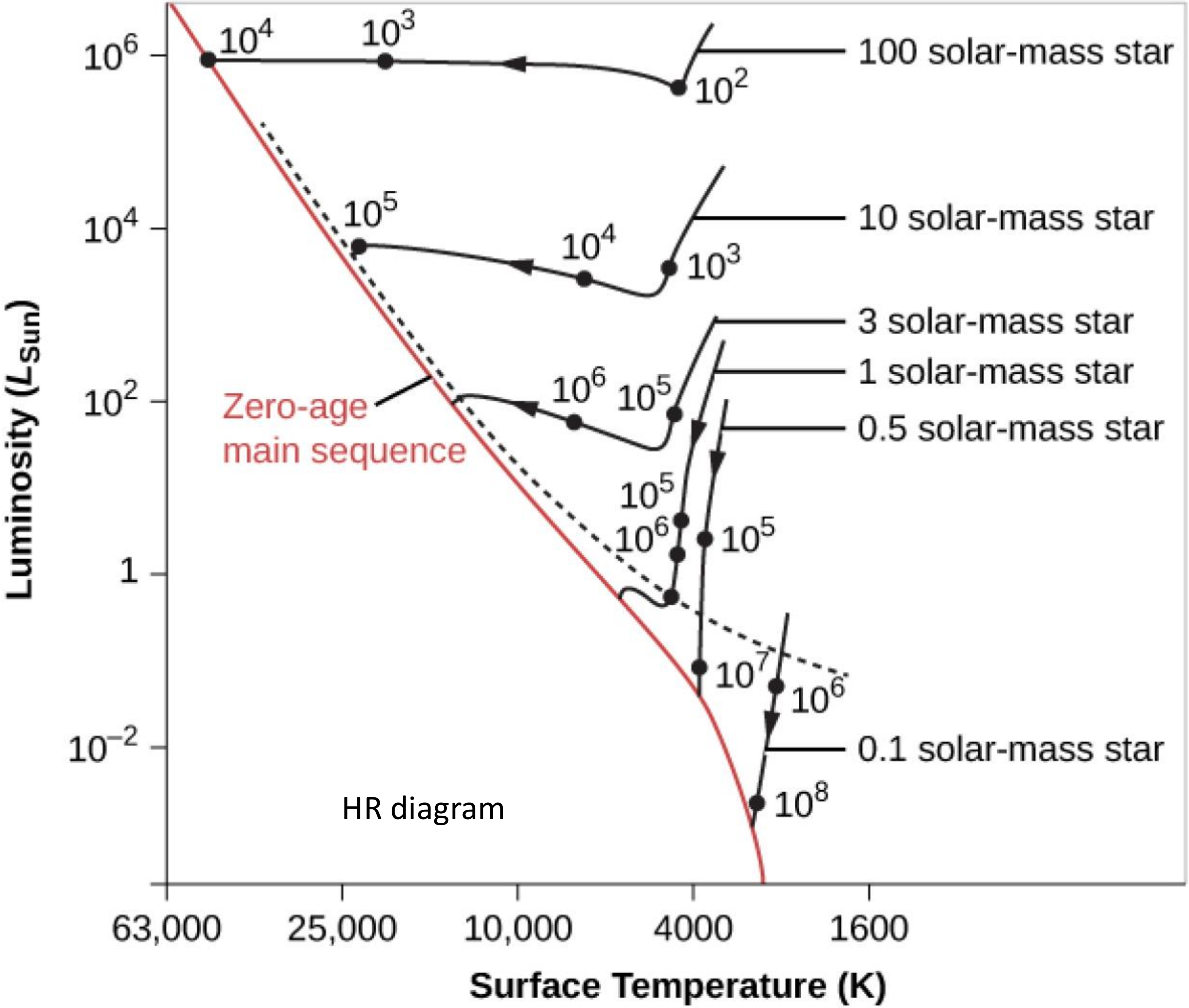
Steps of star formation:

1) Region is dense enough to be gravitationally unstable and collapse
2) Protostar forms, with envelope and disk
3) Star grows, leads to jets and outflows
4) Envelope and disk disappear, leaving behind planets+star



JWST Image of a Protostar:
Disk, bipolar outflow, and envelope

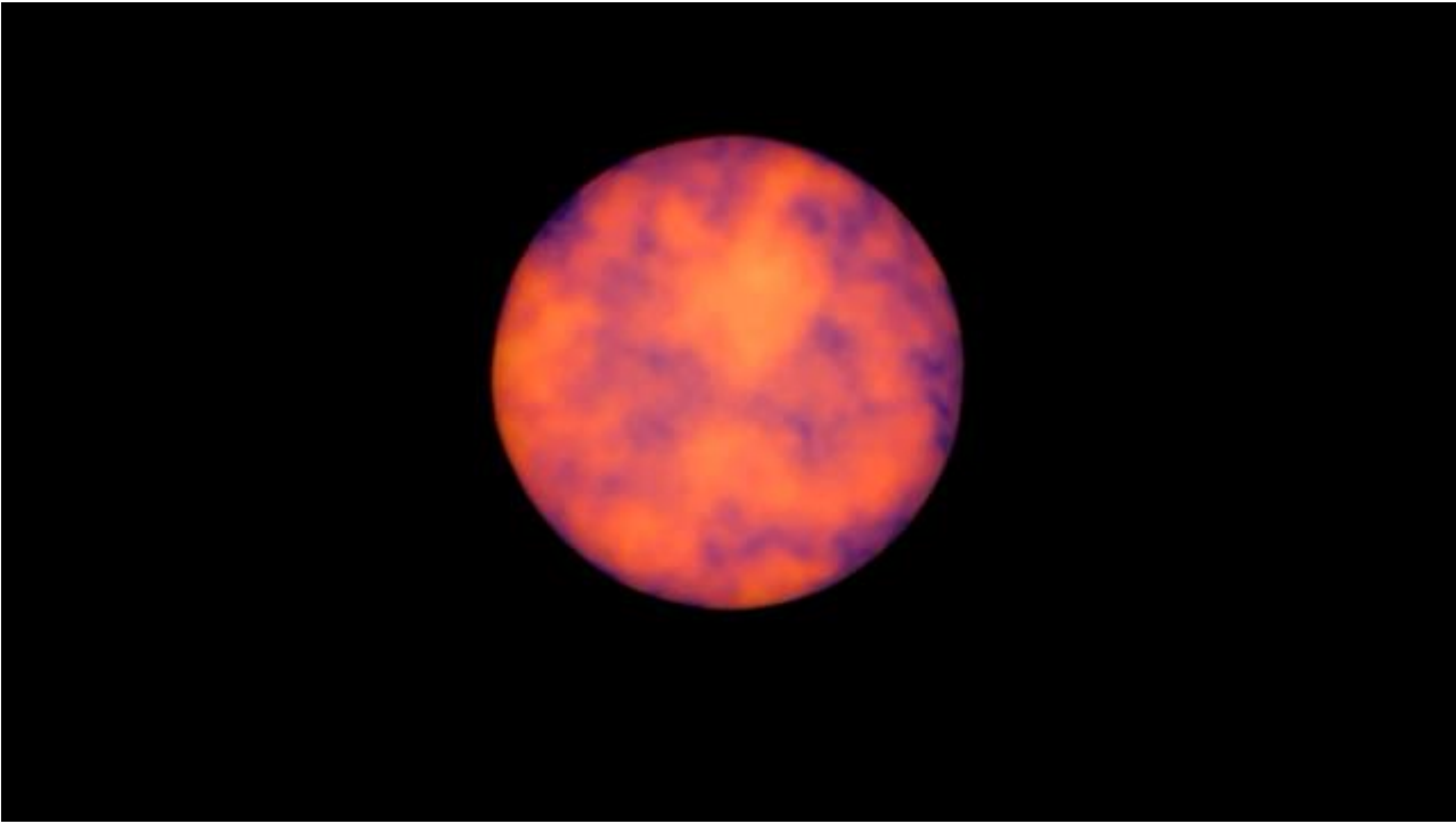

Protoplanetary disk:
where planets form (next lecture)



Luminosity (L_{Sun})
10^6
10^4
10^2
1
10^{-2}
Surface Temperature (K)
63,000
25,000
10,000
4000
1600
100 solar-mass star
10 solar-mass star
3 solar-mass star
1 solar-mass star
0.5 solar-mass star
0.1 solar-mass star
Zero-age main sequence
10^4
10^3
10^2
10^5
10^4
10^3
10^6
10^5
10^5
10^6
10^5
10^7
10^6
10^8

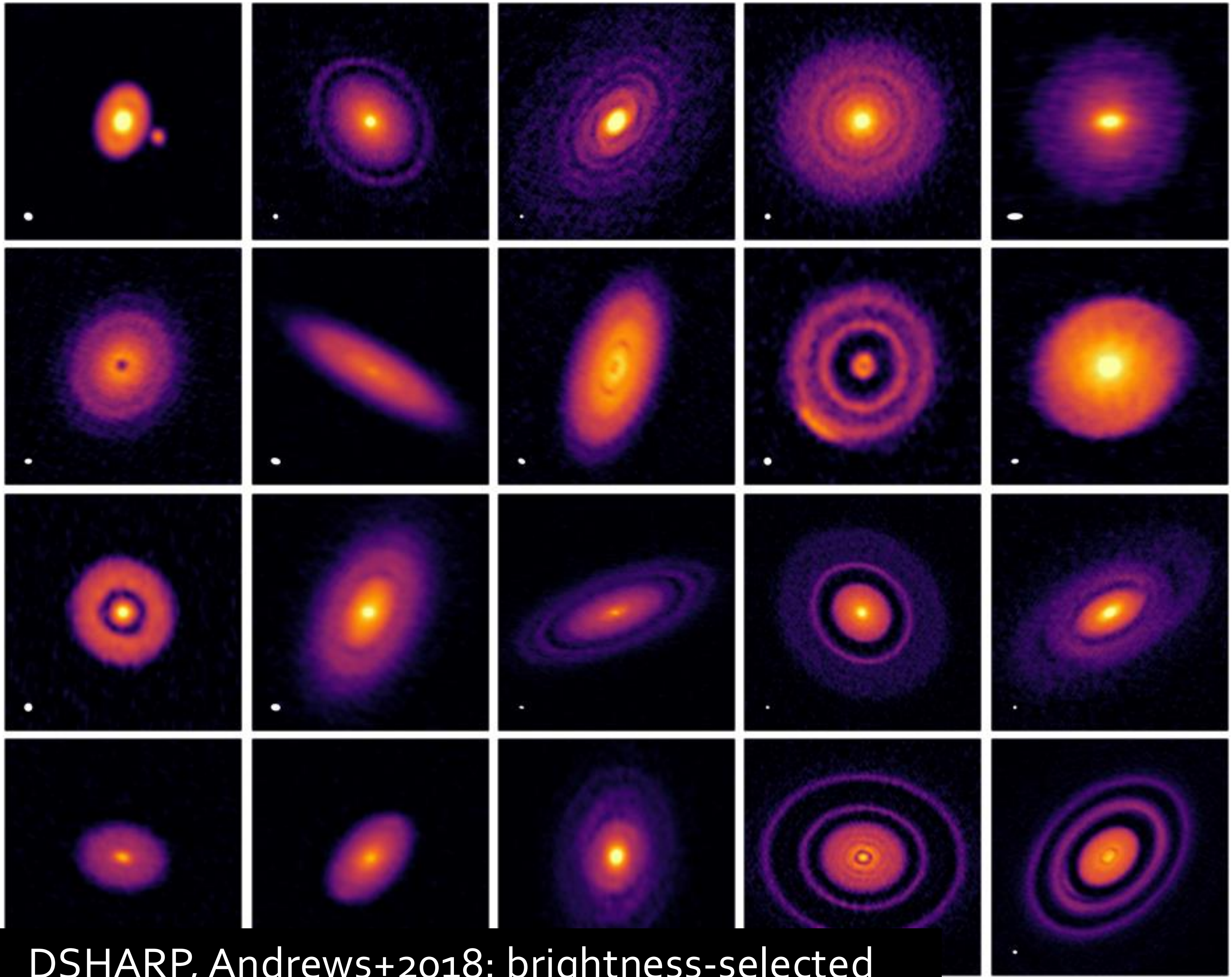
HR diagram

Simulation of a star-forming region: STARFORGE (Michael Grudic)



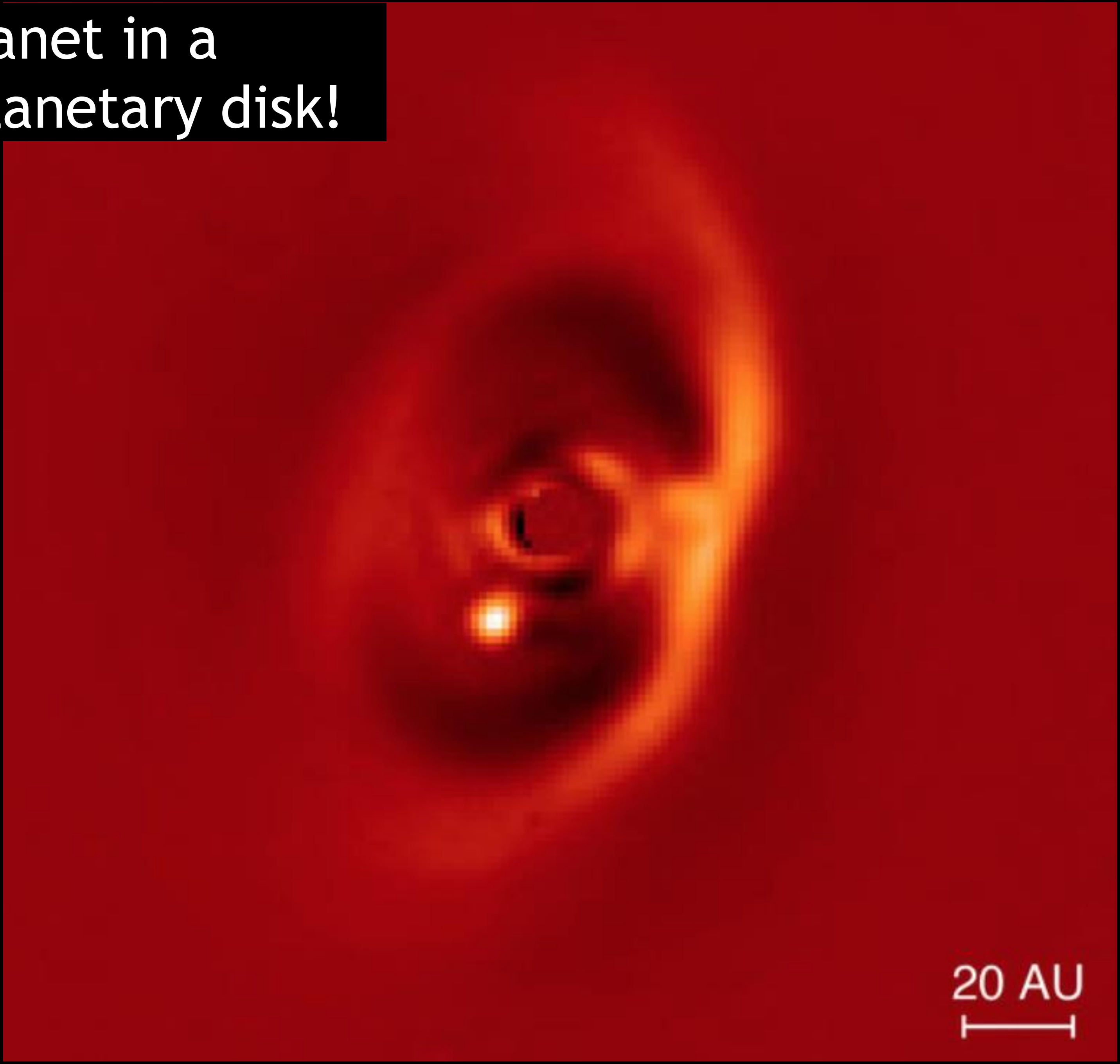
Planets should form in disk and carve a gap

Image of a protoplanetary disk

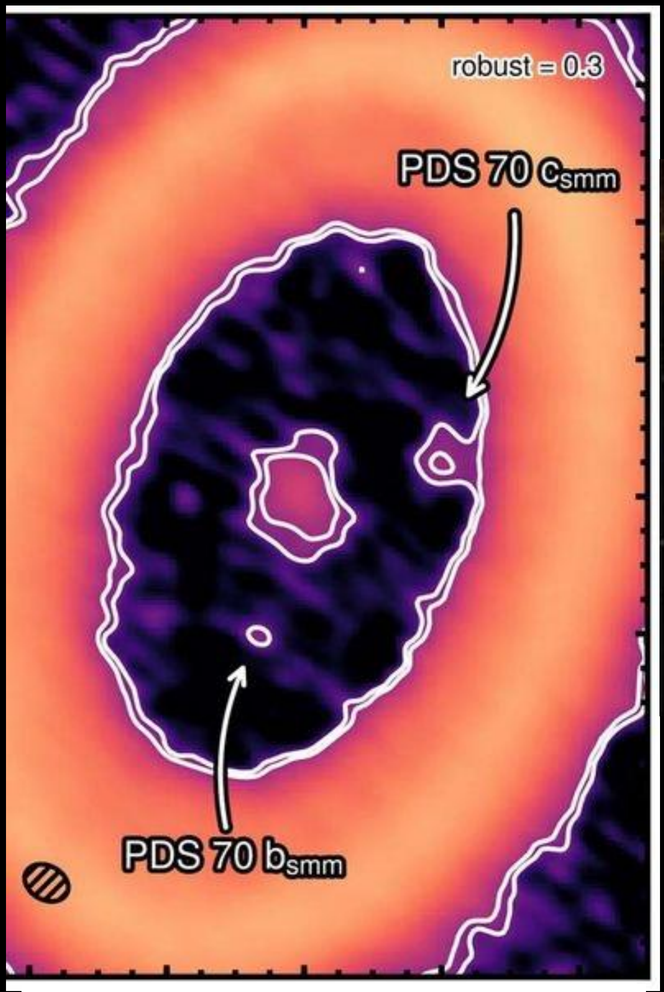


DSHARP, Andrews+2018: brightness-selected

Planet in a protoplanetary disk!



Proto-lunar disks around PDS 70bc?

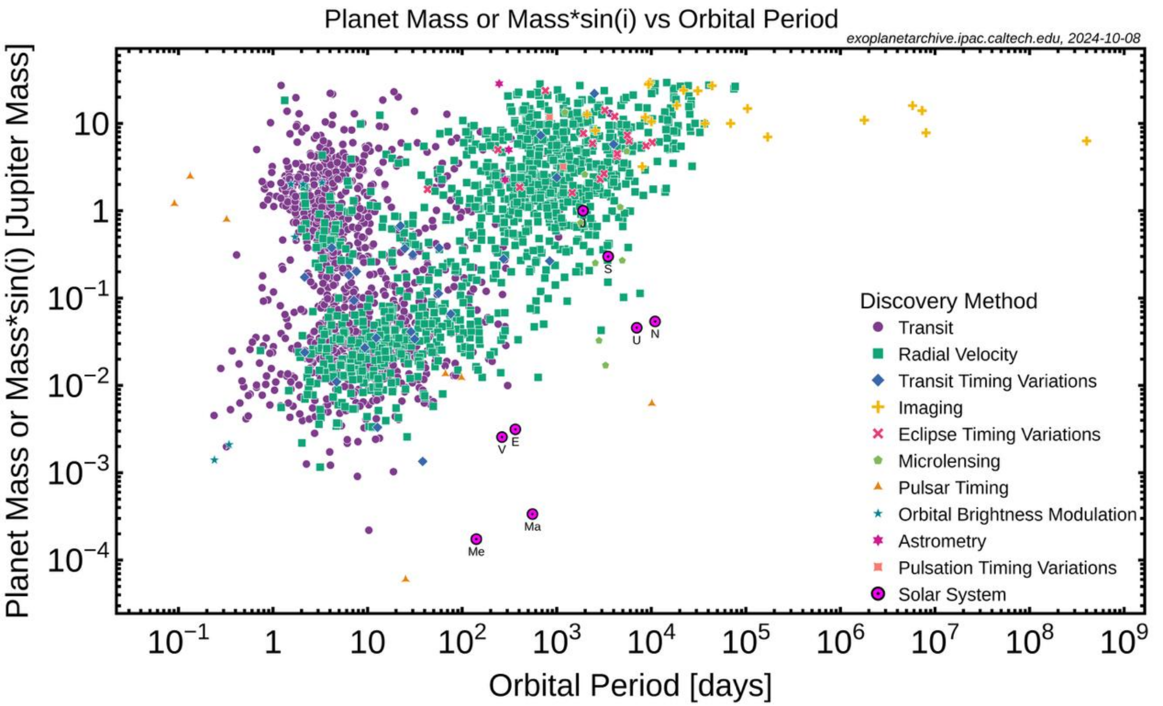


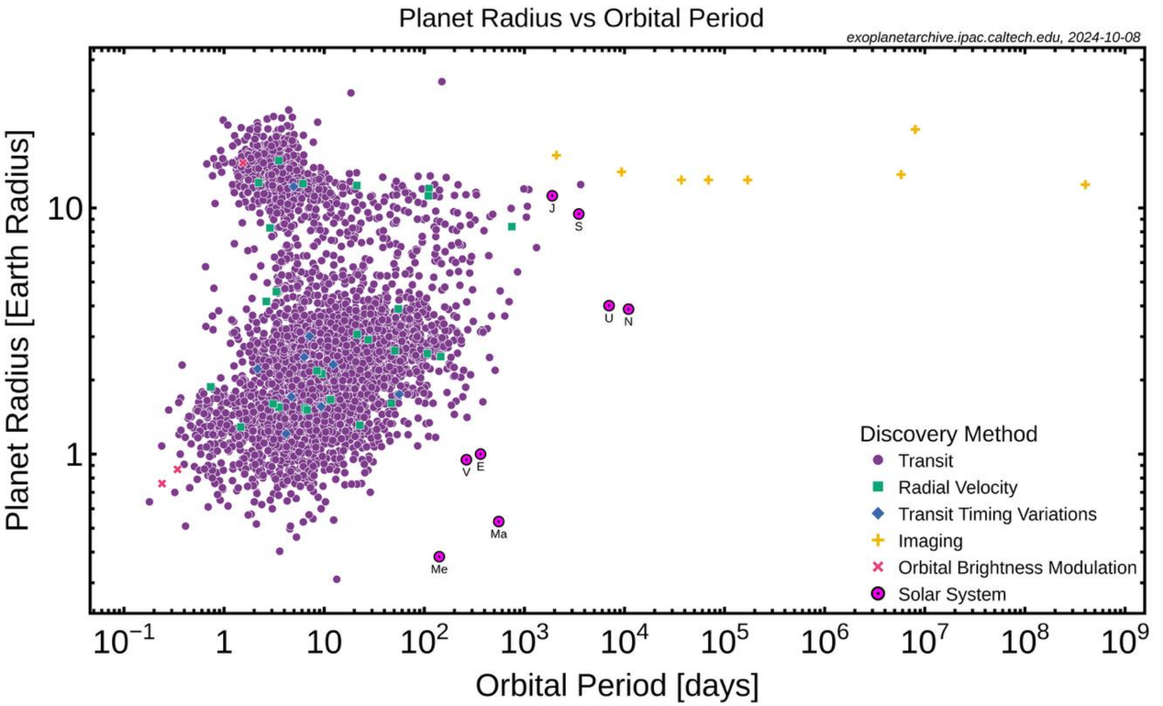
ALMA/dust, Isella+2019

Planets are everywhere!

- Many different detection techniques
  - Most common planet: "Super Earth"
  - Earths still challenging
  - Atmospheres very challenging
  - Many biases to larger planets, closer objects

- Planet Formation
  - Observational evidence for unseen planets
  - Challenge: Microscopic interactions on tiny scales lead to planets
  - Requires simulations+observations





Planets are everywhere!

Next lecture: the Milky Way!