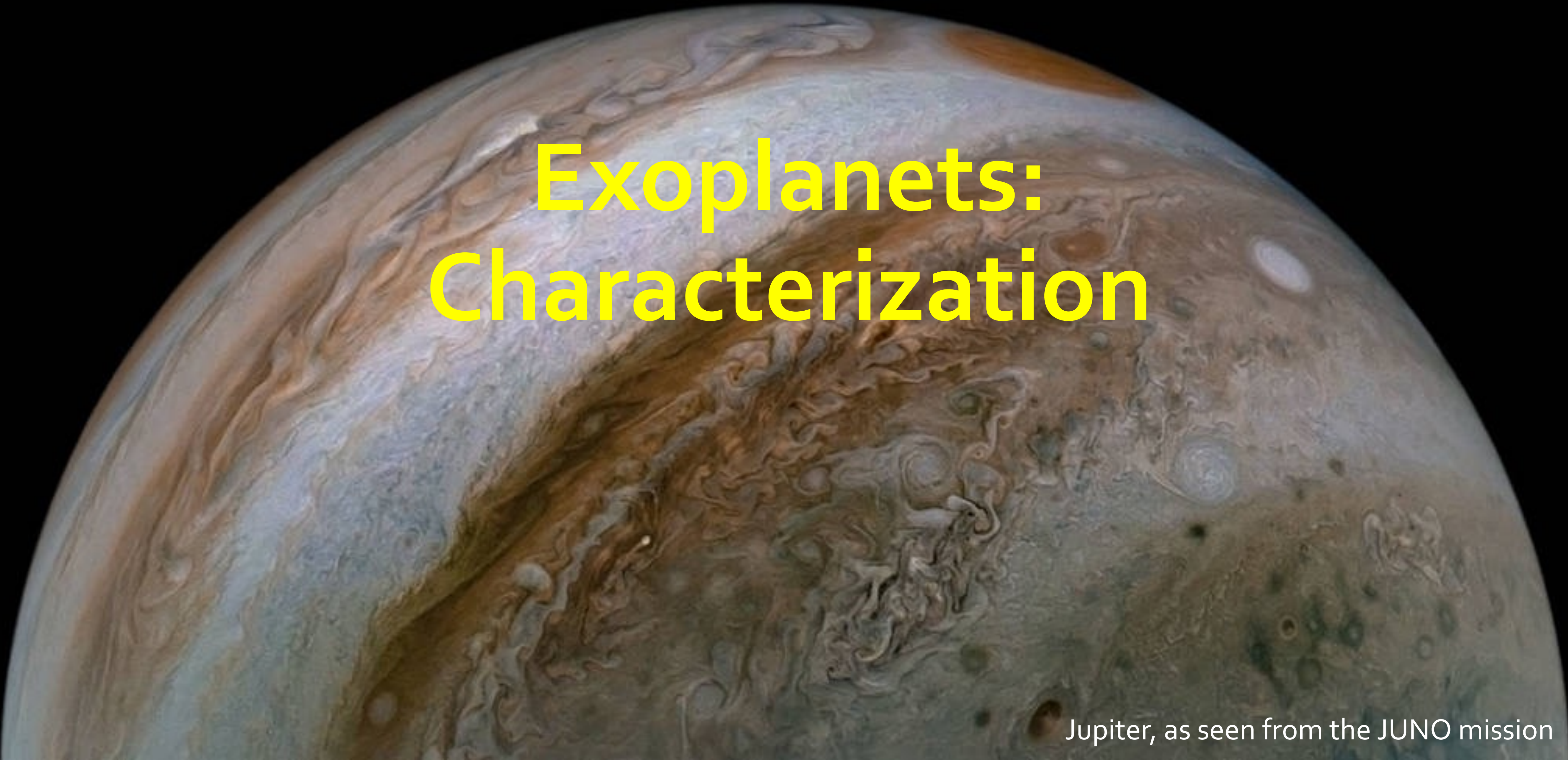
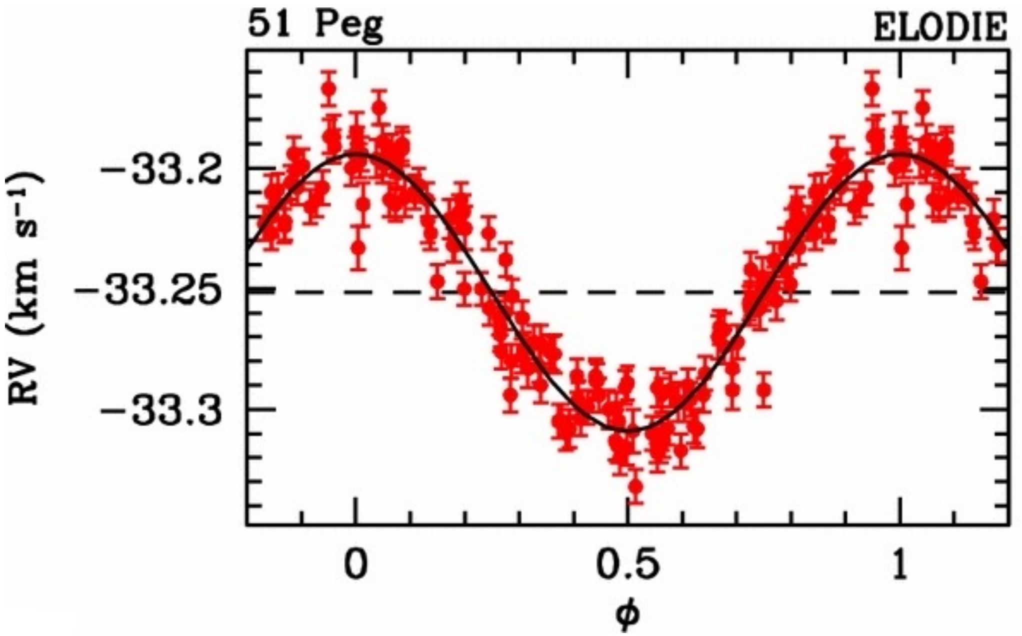
Exoplanets: Characterization

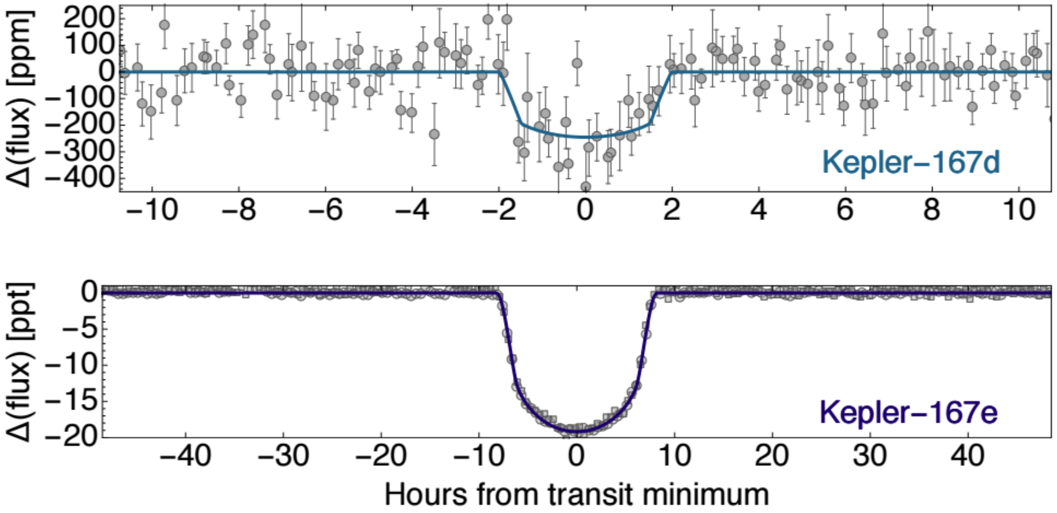


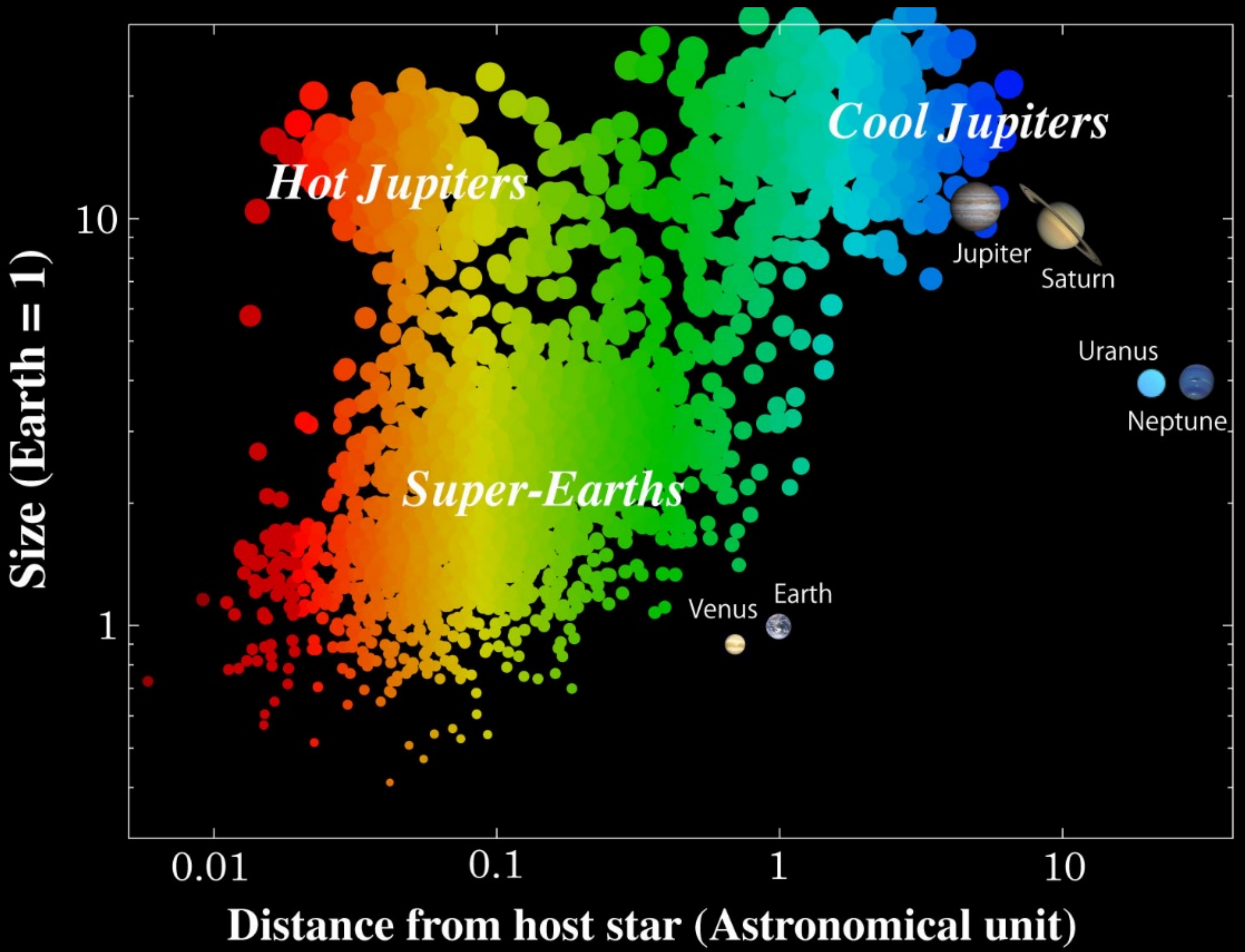
Jupiter, as seen from the JUNO mission

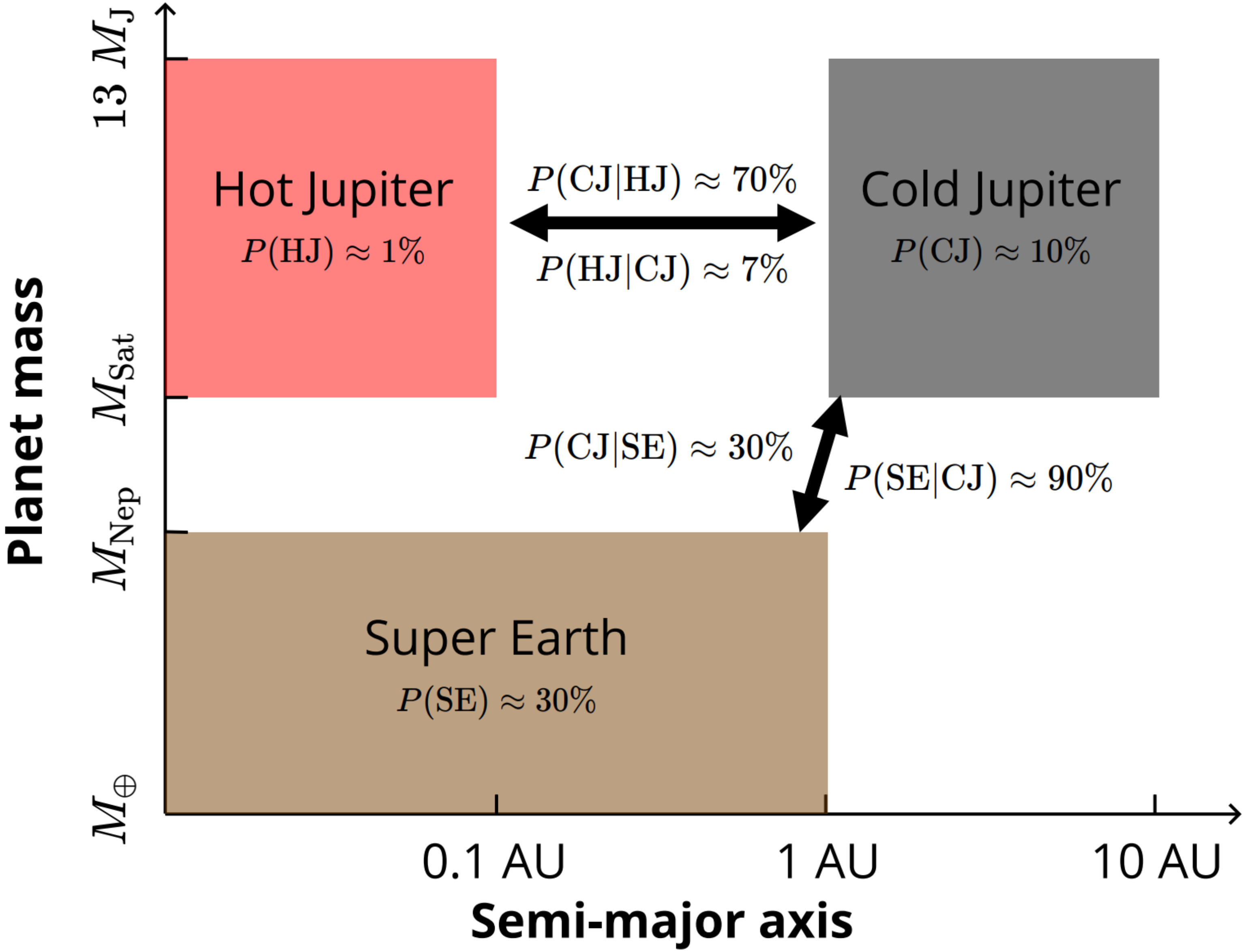
Methods to detect exoplanets

- Radial velocity
  - (motion of star in our line-of-sight)
- Transit photometry
- Direct imaging
- Astrometry (motion of star on sky)
- Microlensing
- Transit Timing Variation



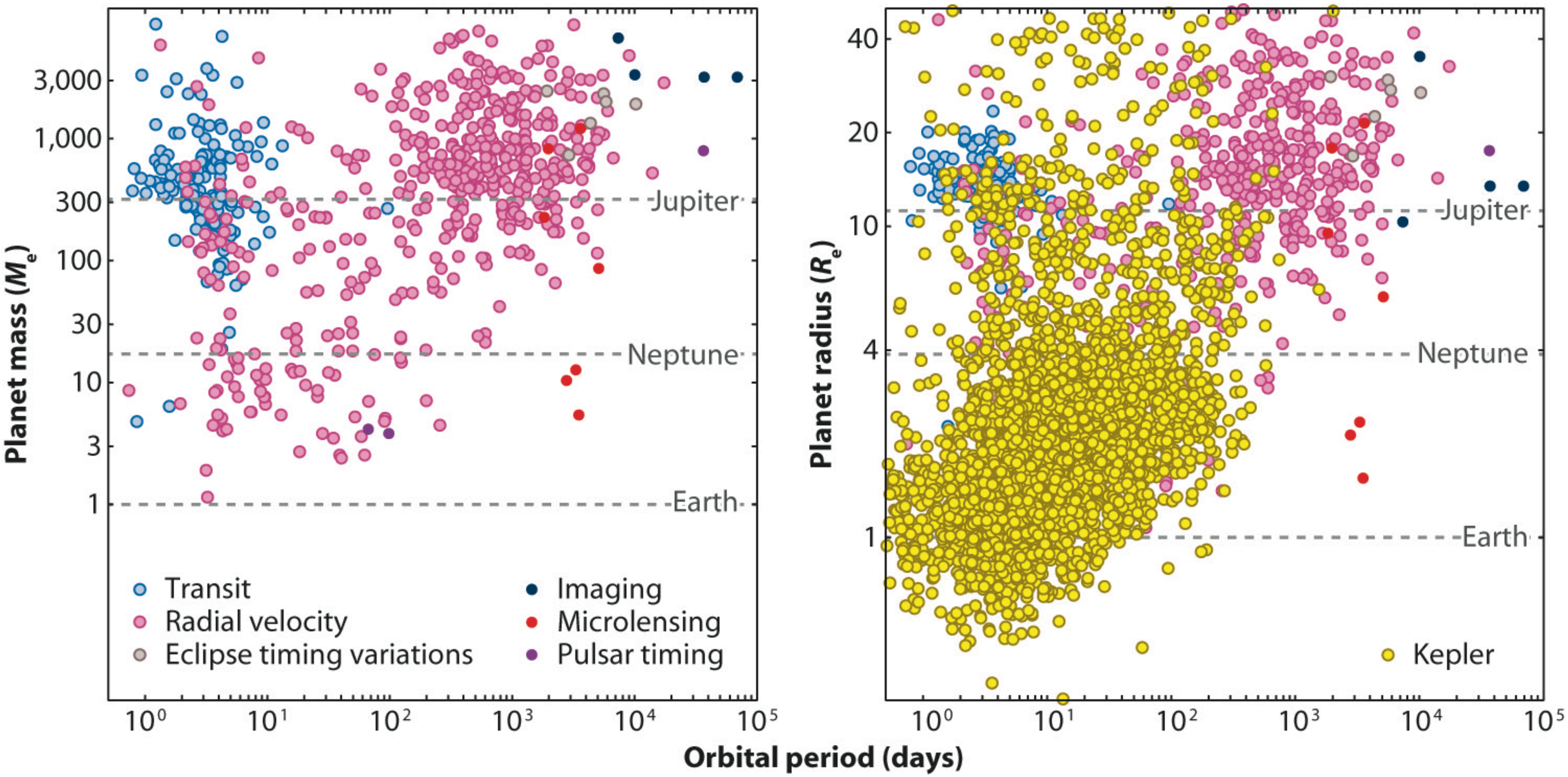



Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
10
1
Size (Earth = 1)
0.01
0.1
1
10
Distance from host star (Astronomical unit)



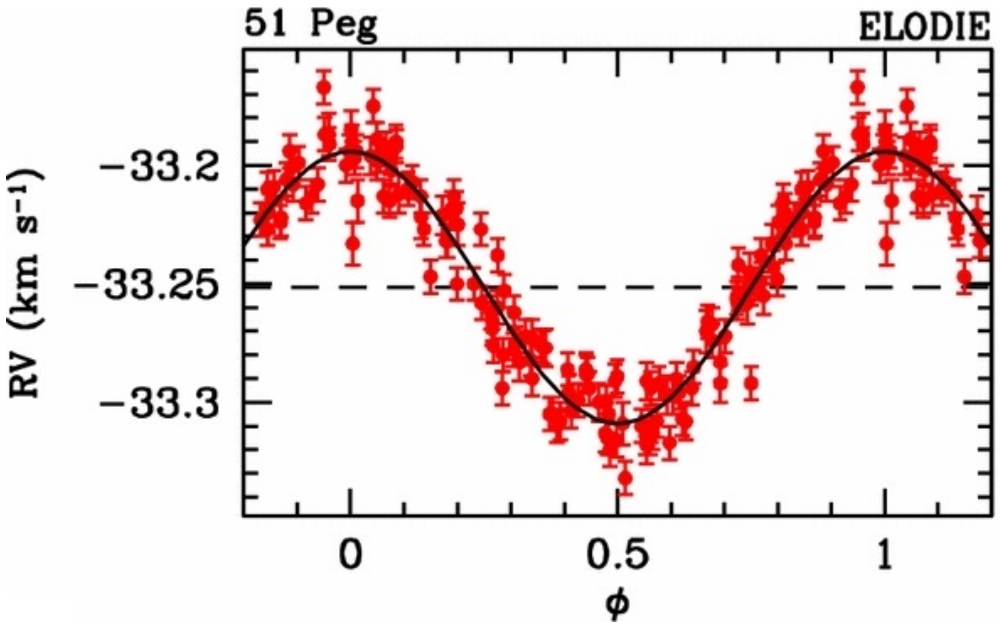
- Most common systems have Super-Earths
- Cold Jupiters (like solar system): not too unusual
- Hot Jupiters: rare but easy to detect

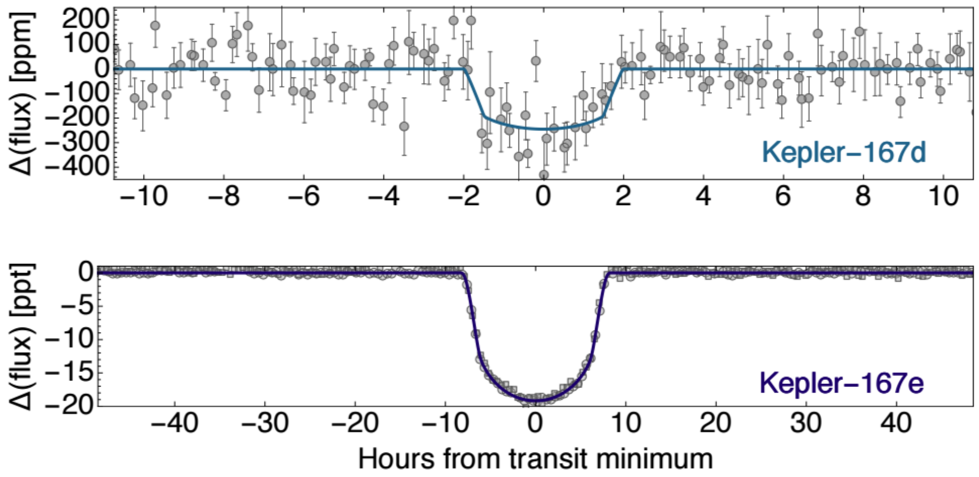
Exoplanets are common!



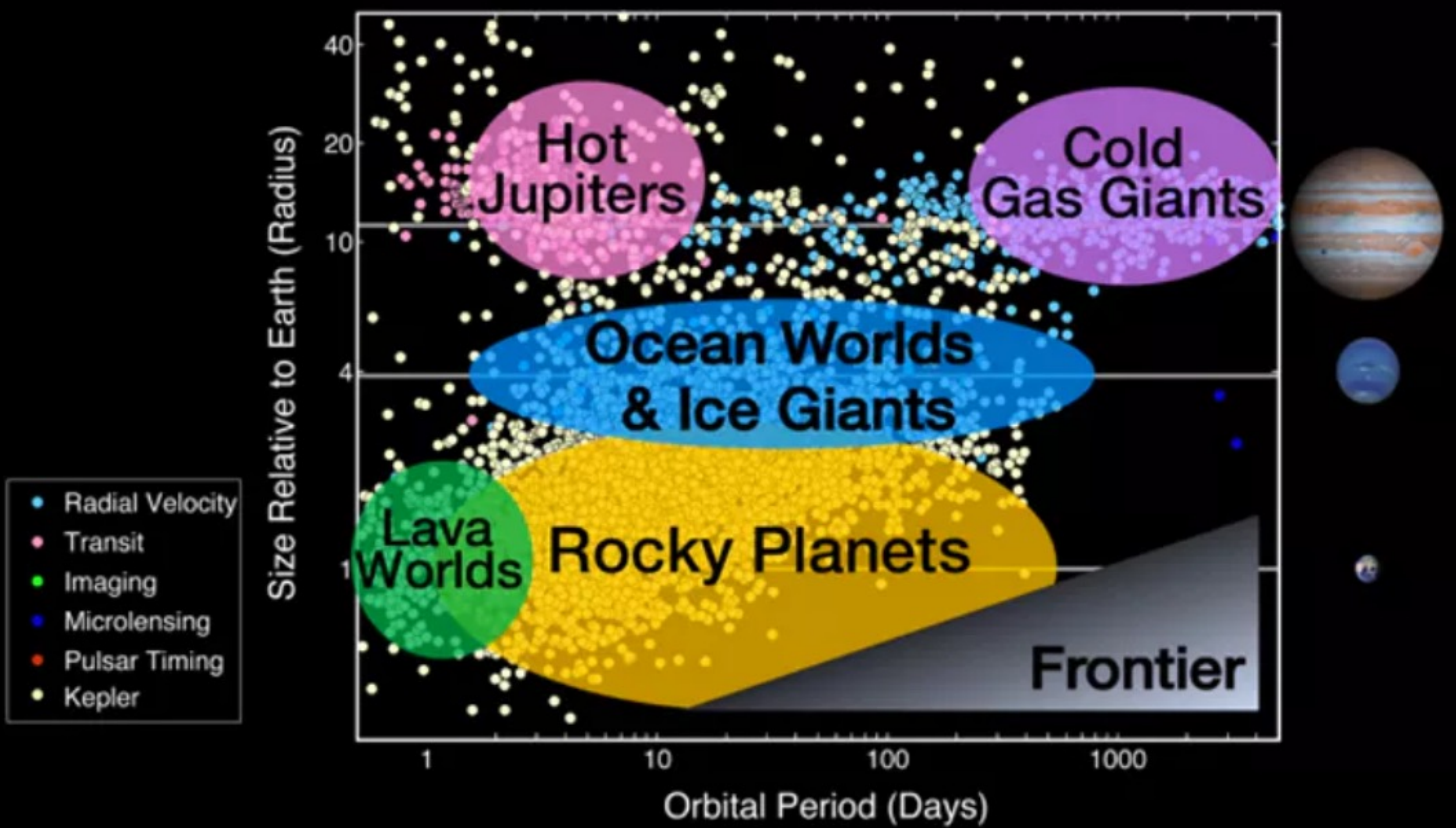
Methods to characterize exoplanets
(atmosphere+composition)

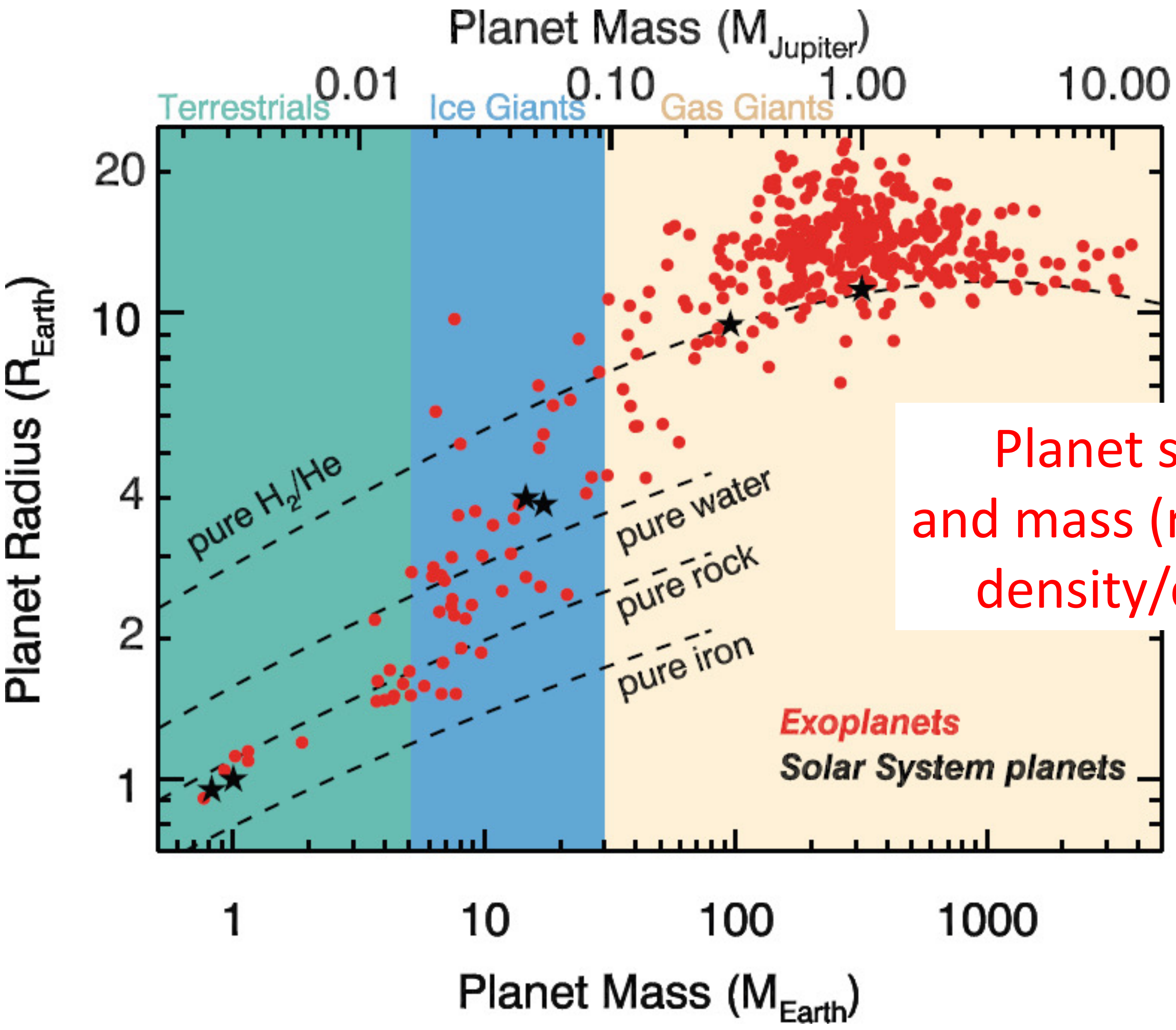
- **Density:** transit+radial velocity
- **Atmospheres:**
  - Primary or secondary transit
  - Direct imaging
  - Both cases: spectra or multi-band photometry
- Orbital line variations: challenging
  - beyond today's discussion
- Astrometry: very hard, unused to date
- Transit timing variations and Microlensing: useless





Exoplanet Populations





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

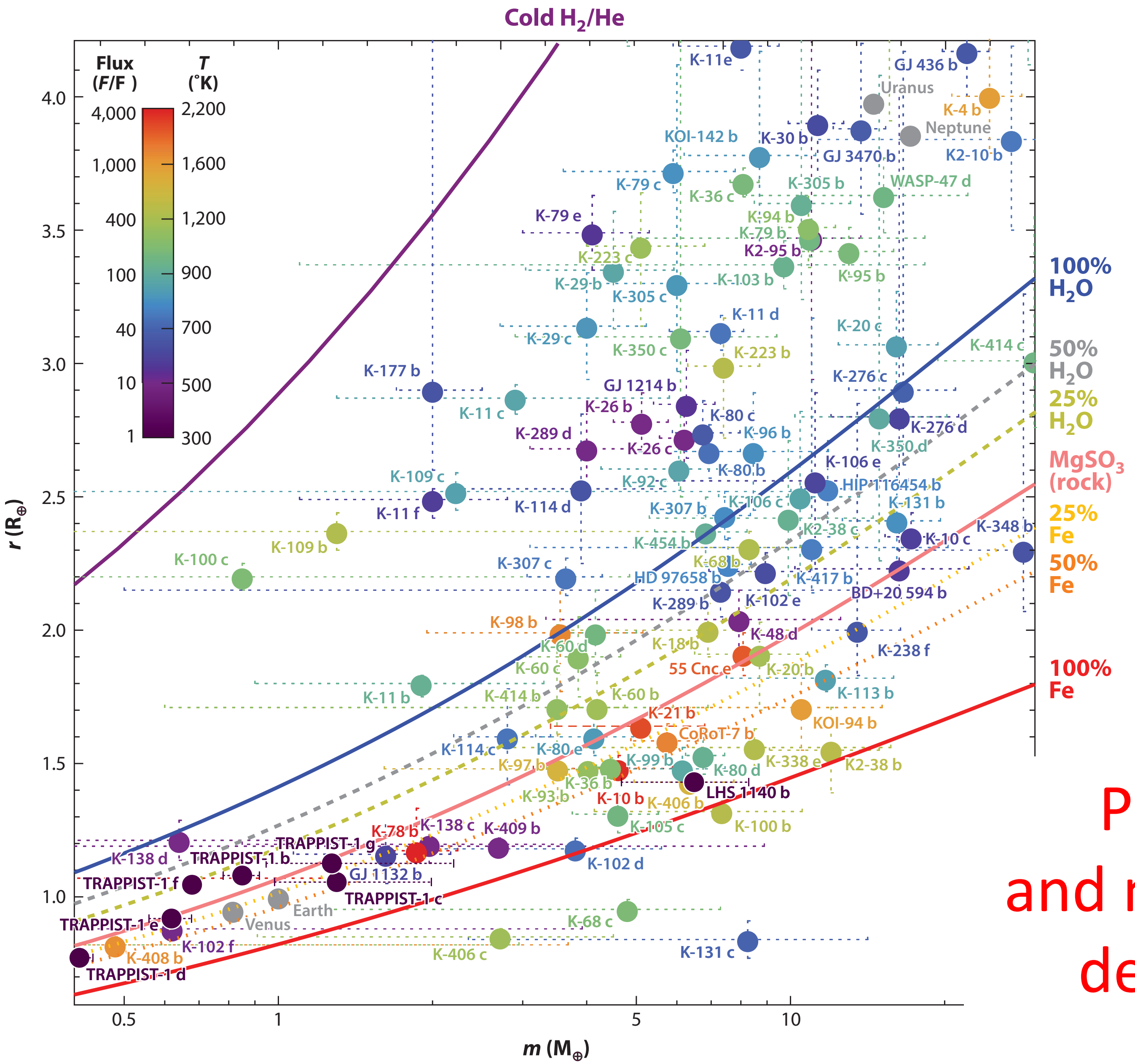
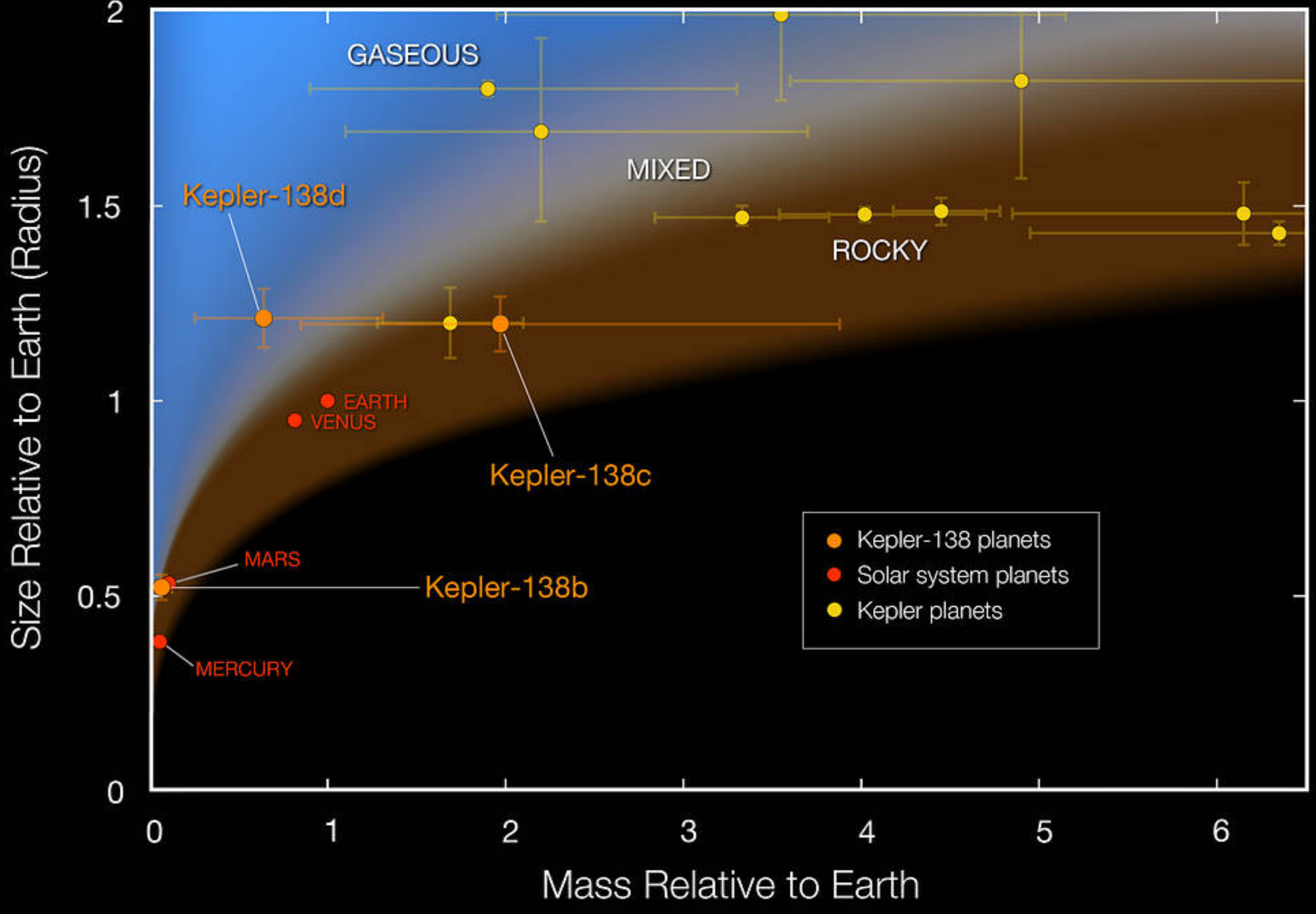


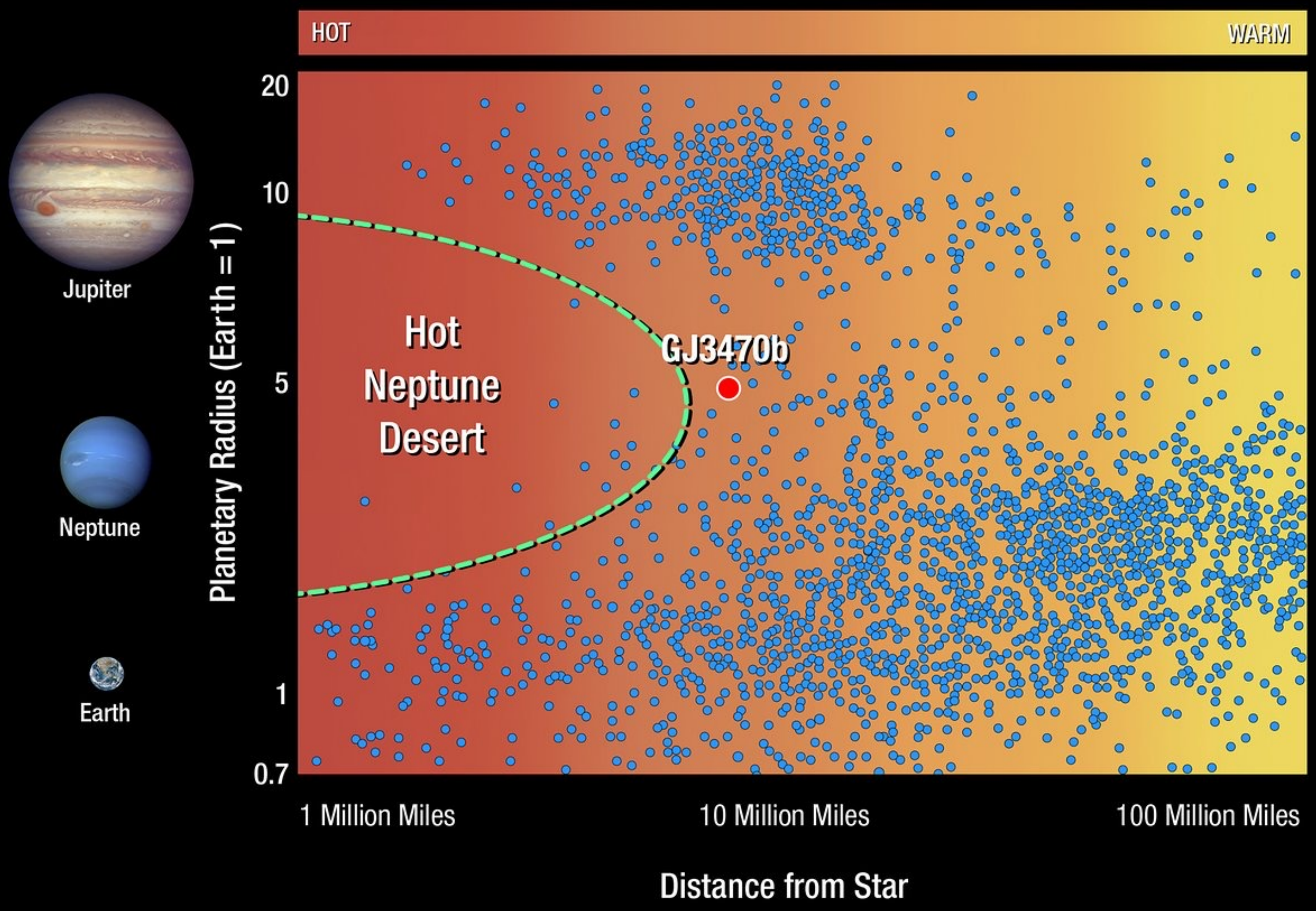
Figure 1

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

Mass and Radius of Kepler-138 Planets

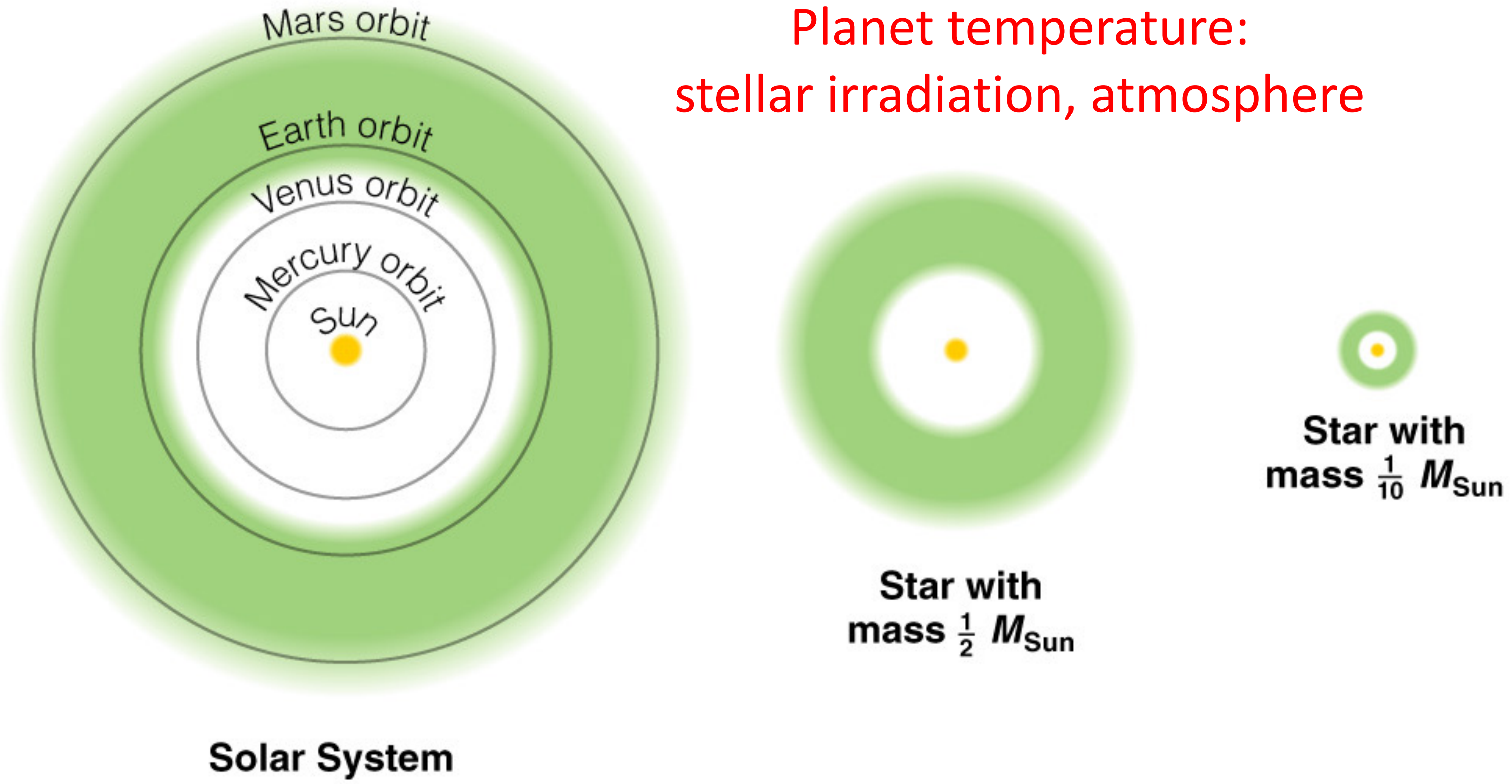


Exoplanet Radius vs. Distance from Star

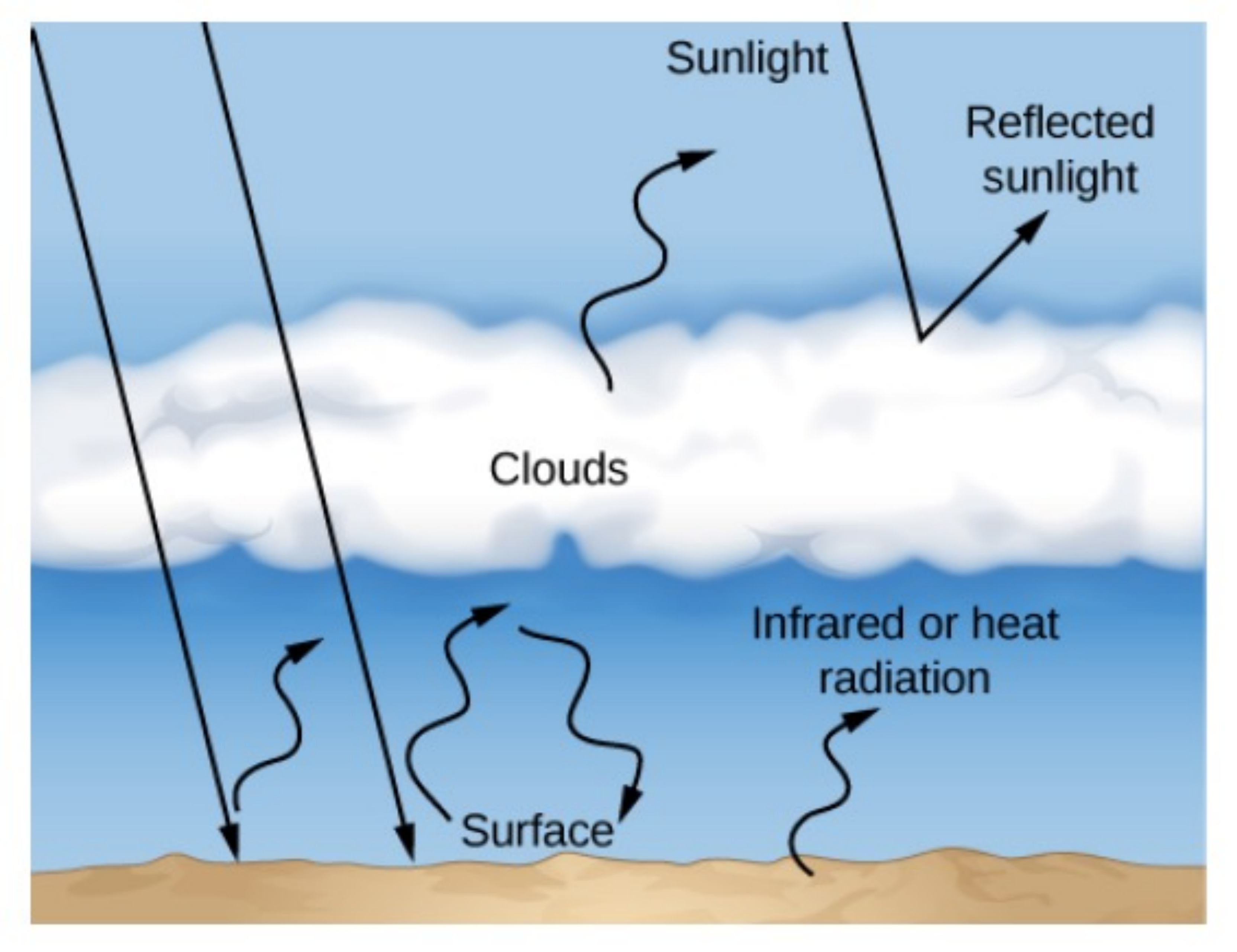


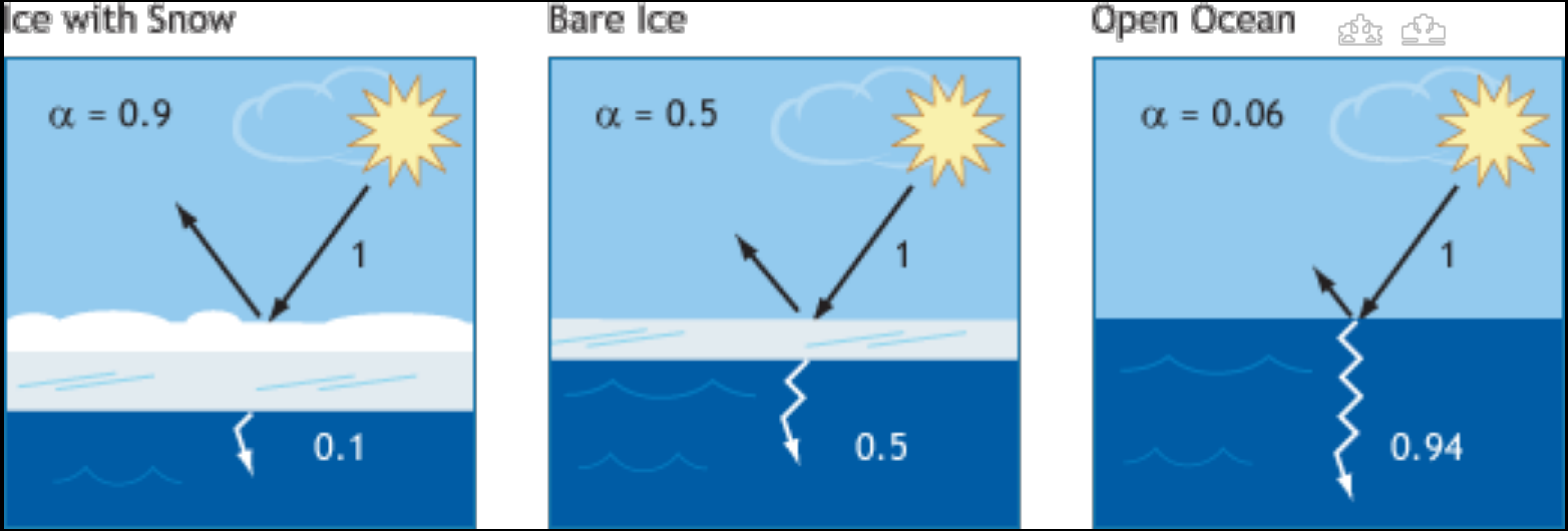
Are terrestrial planets habitable?

Planet temperature:
stellar irradiation, atmosphere



The greenhouse effect



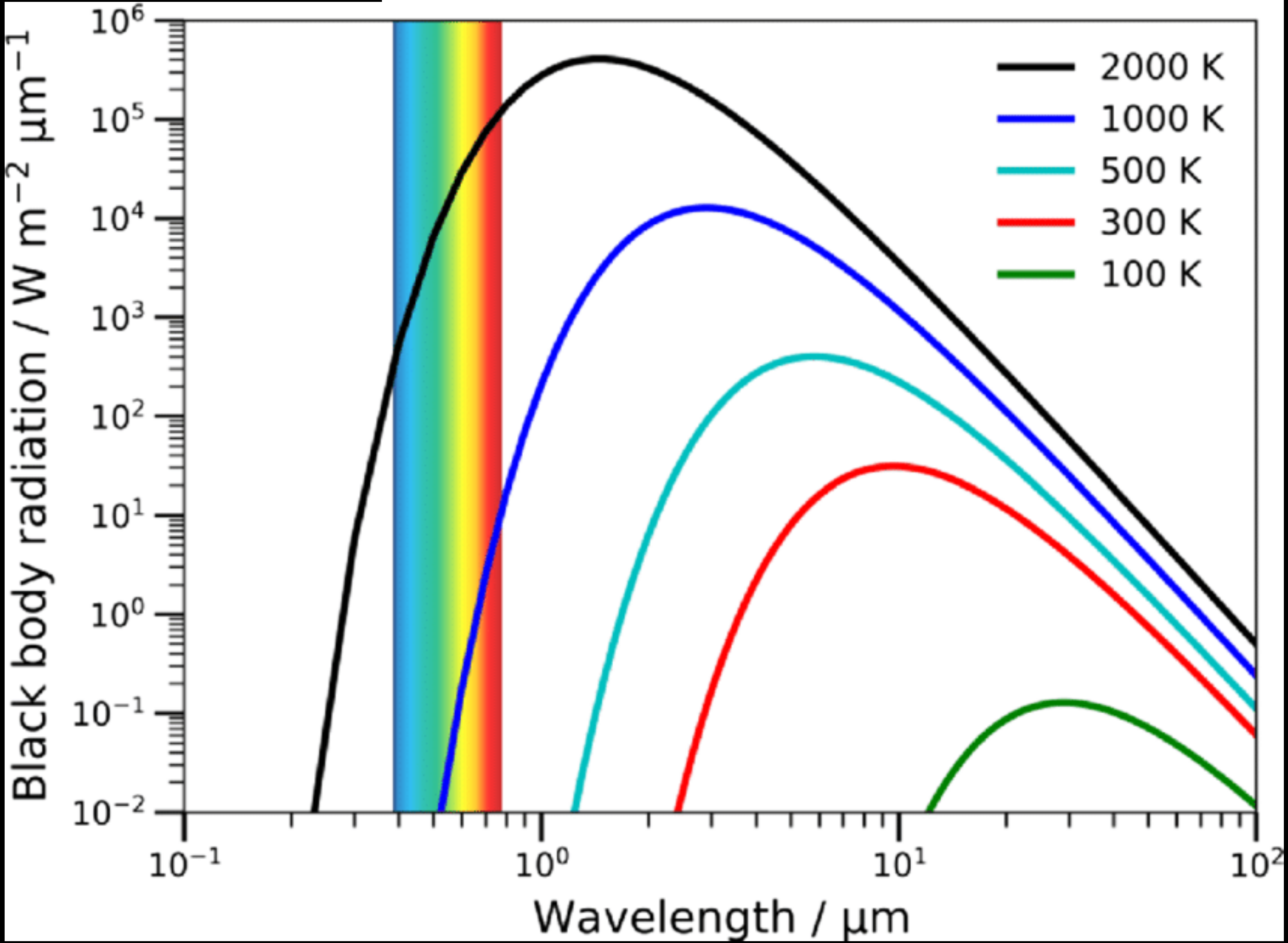


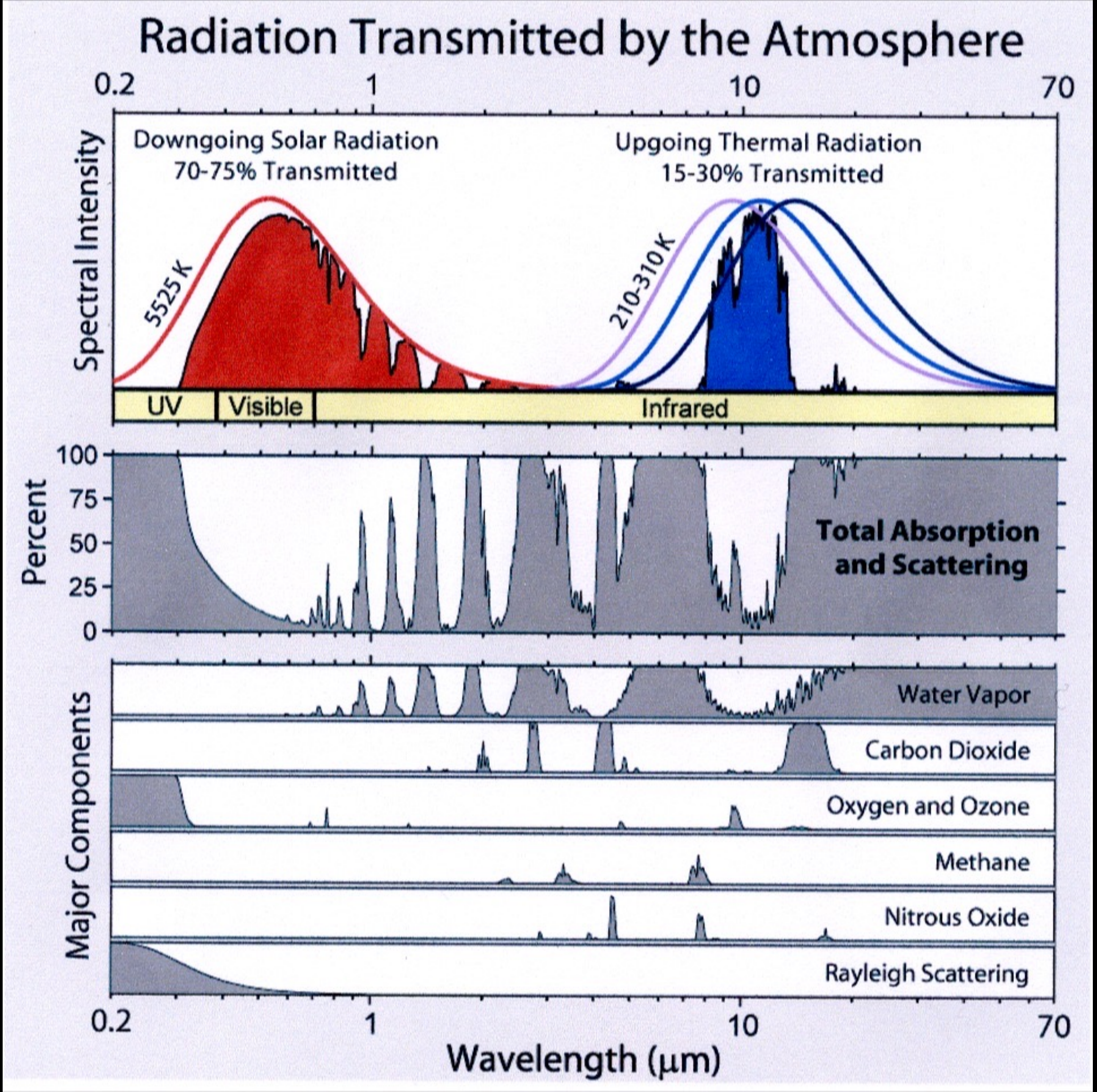
α: albedo = reflectance

Ice (and clouds) reflects energy = cooler planet

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

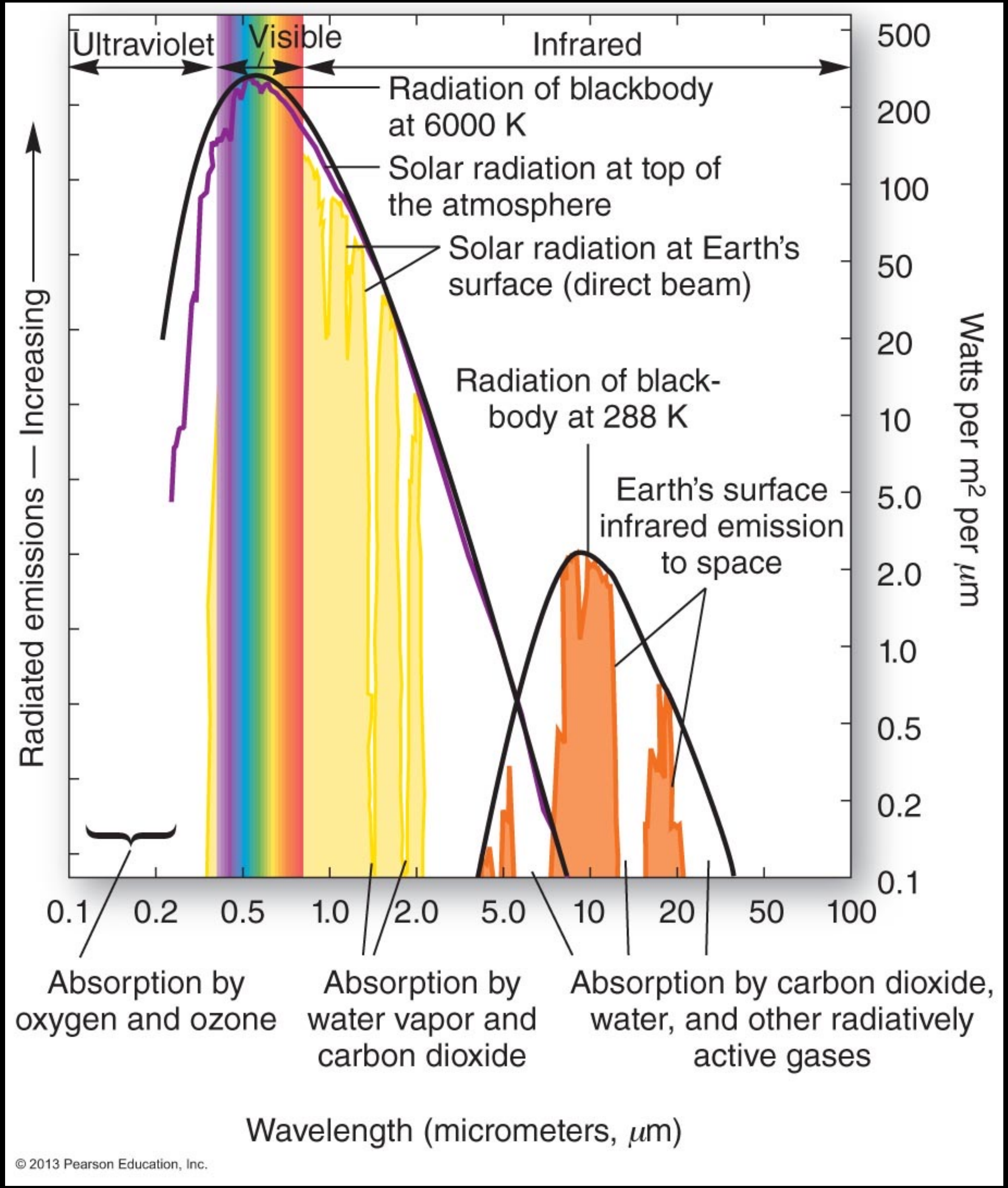
Peak of blackbody: $\lambda_{max} \cdot T = 0.288\ \text{cm} \cdot \text{K}$





- Molecules in Earth's atmosphere block detection of same molecules from exoplanet
  - "opposite" of greenhouse effect

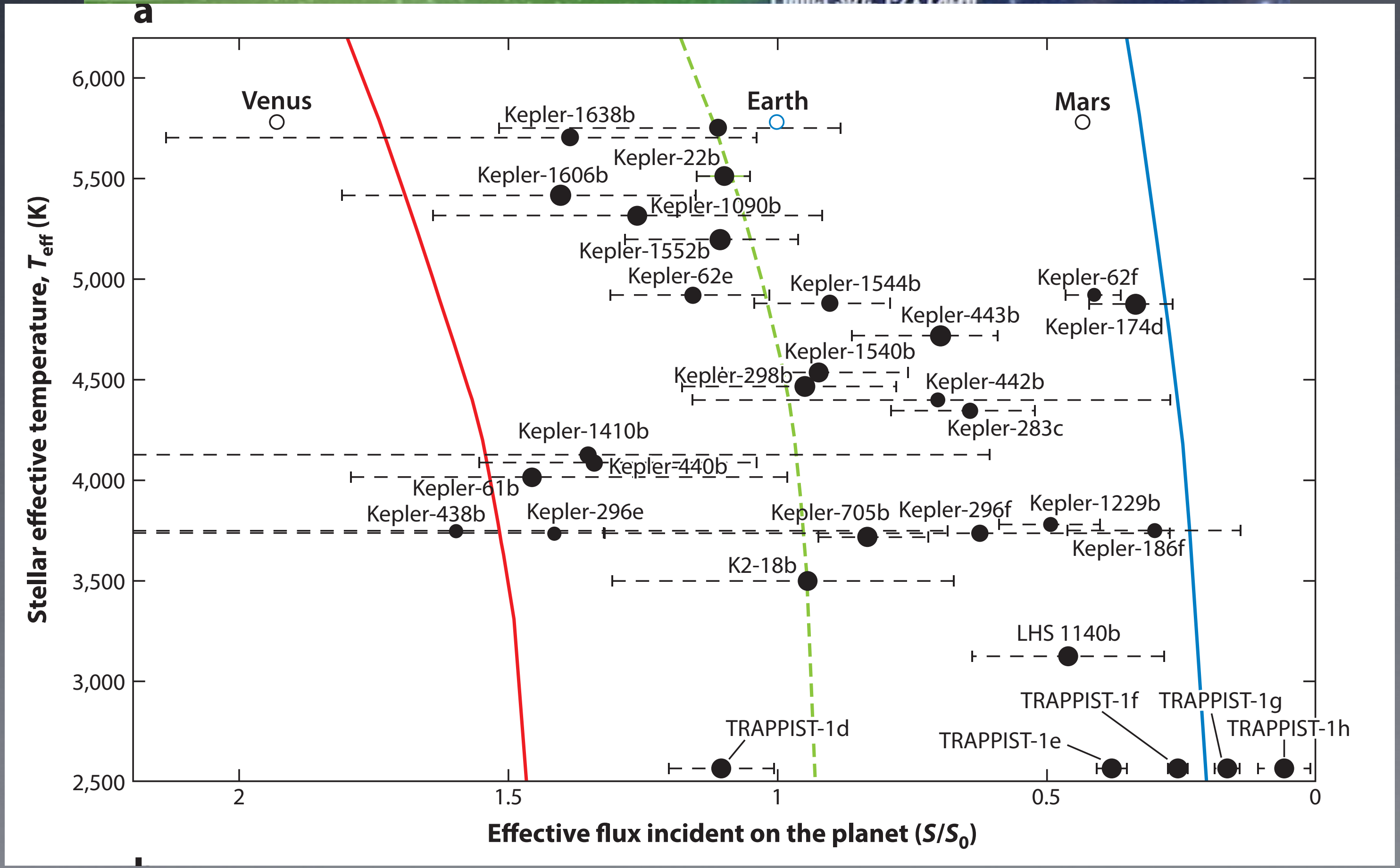
- Often need space observations!

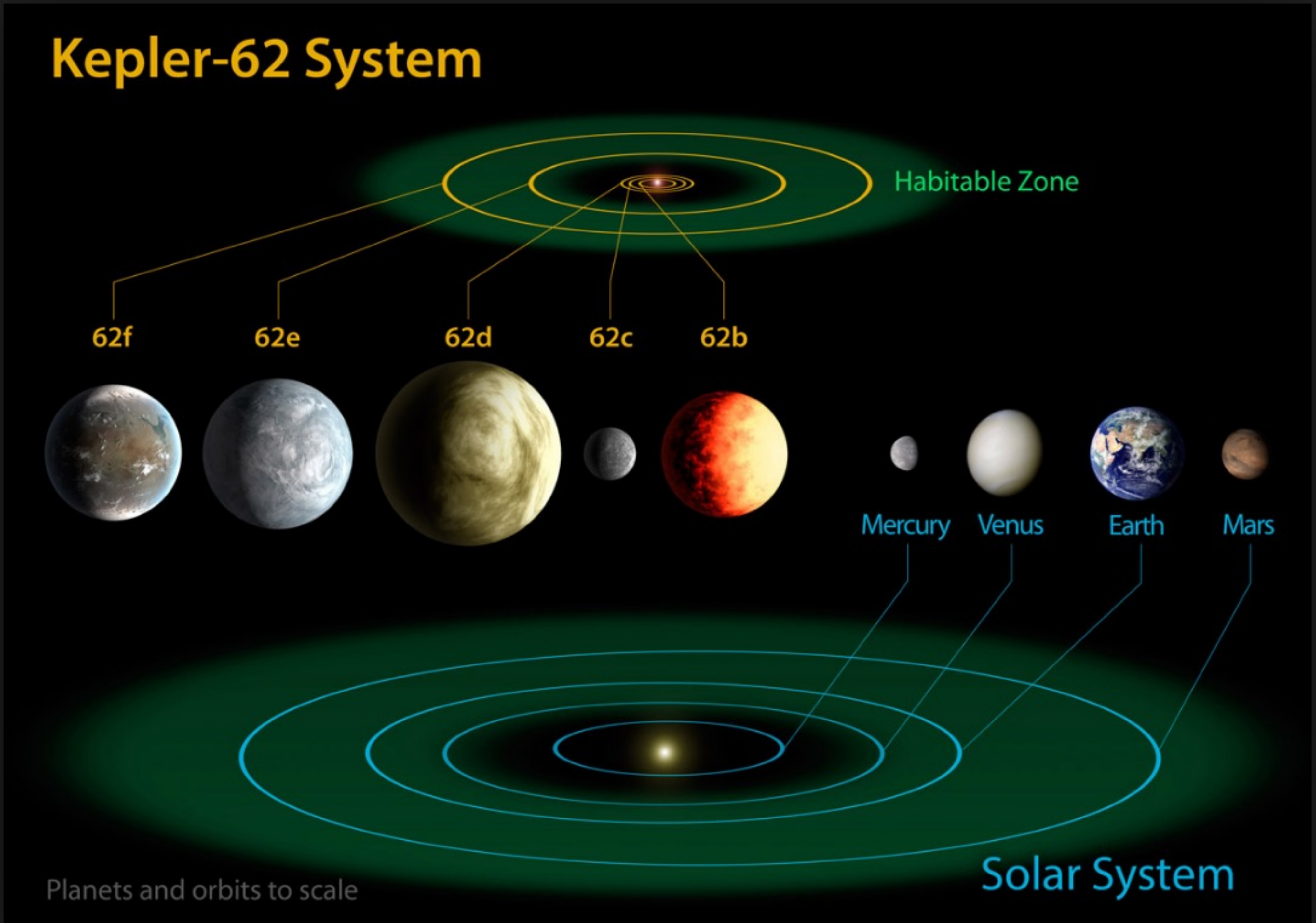


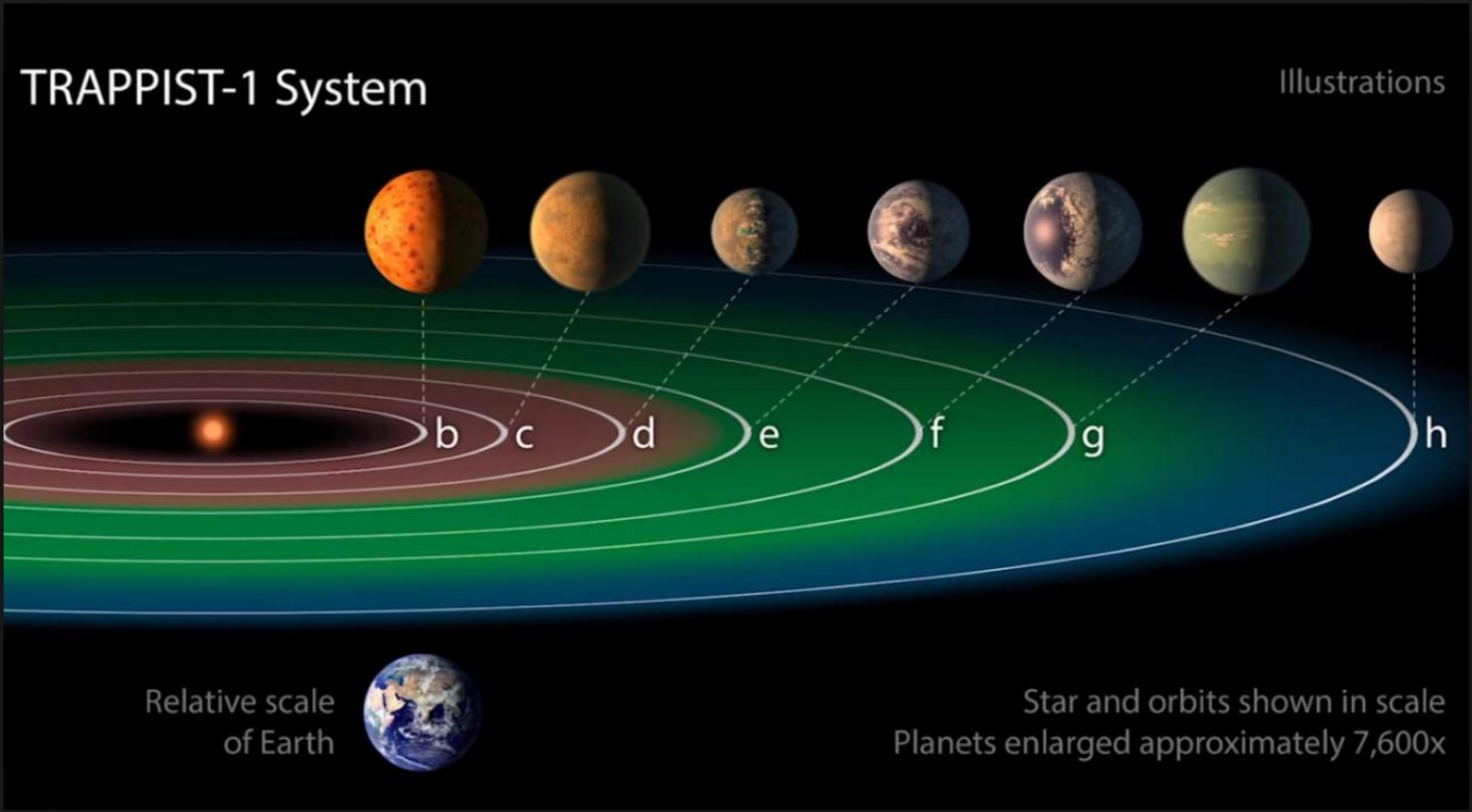
- Planets are cool
- Need infrared telescopes!

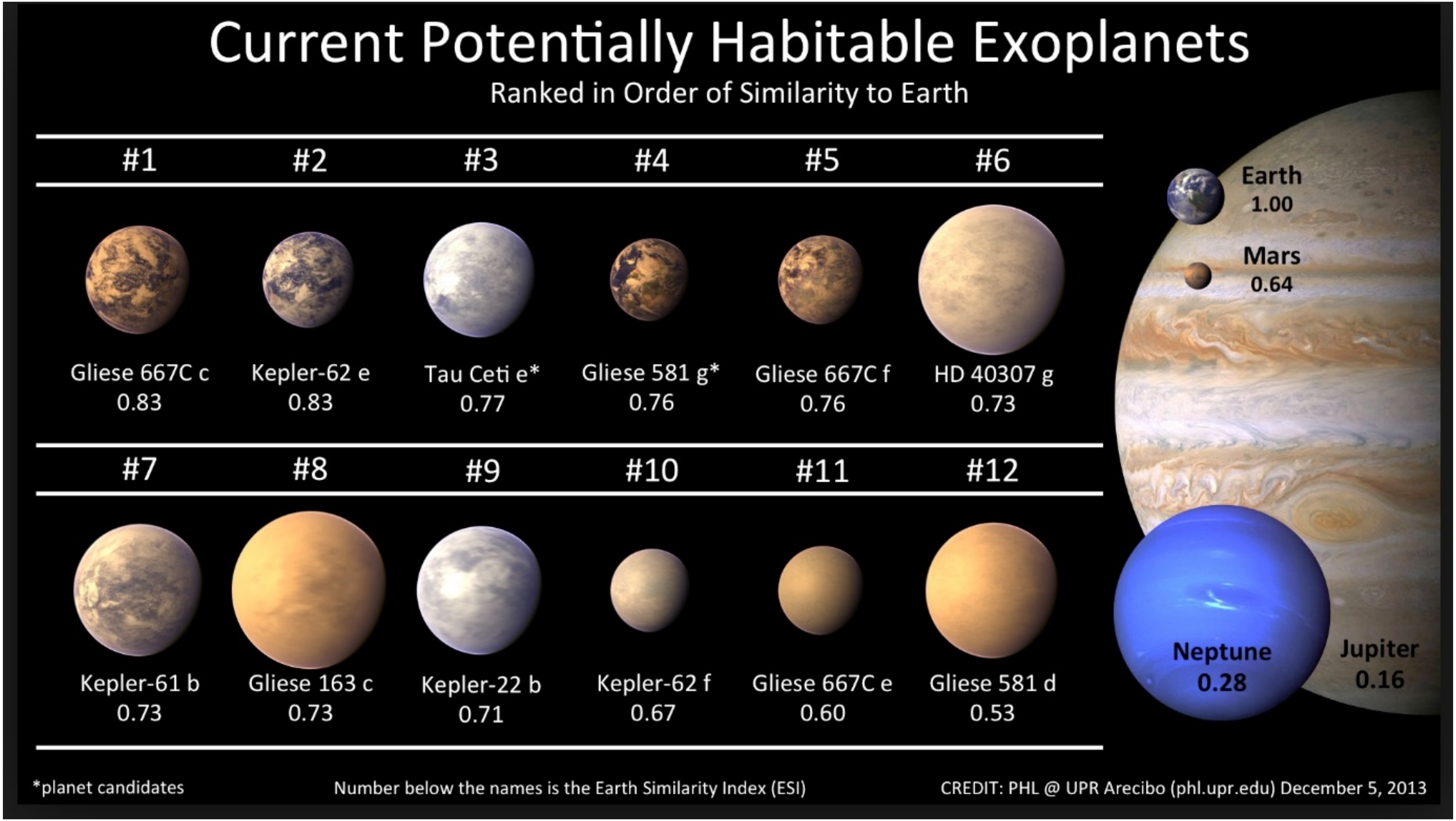
Habitable (liquid water) zone

Terrestrial exoplanets in habitable zones



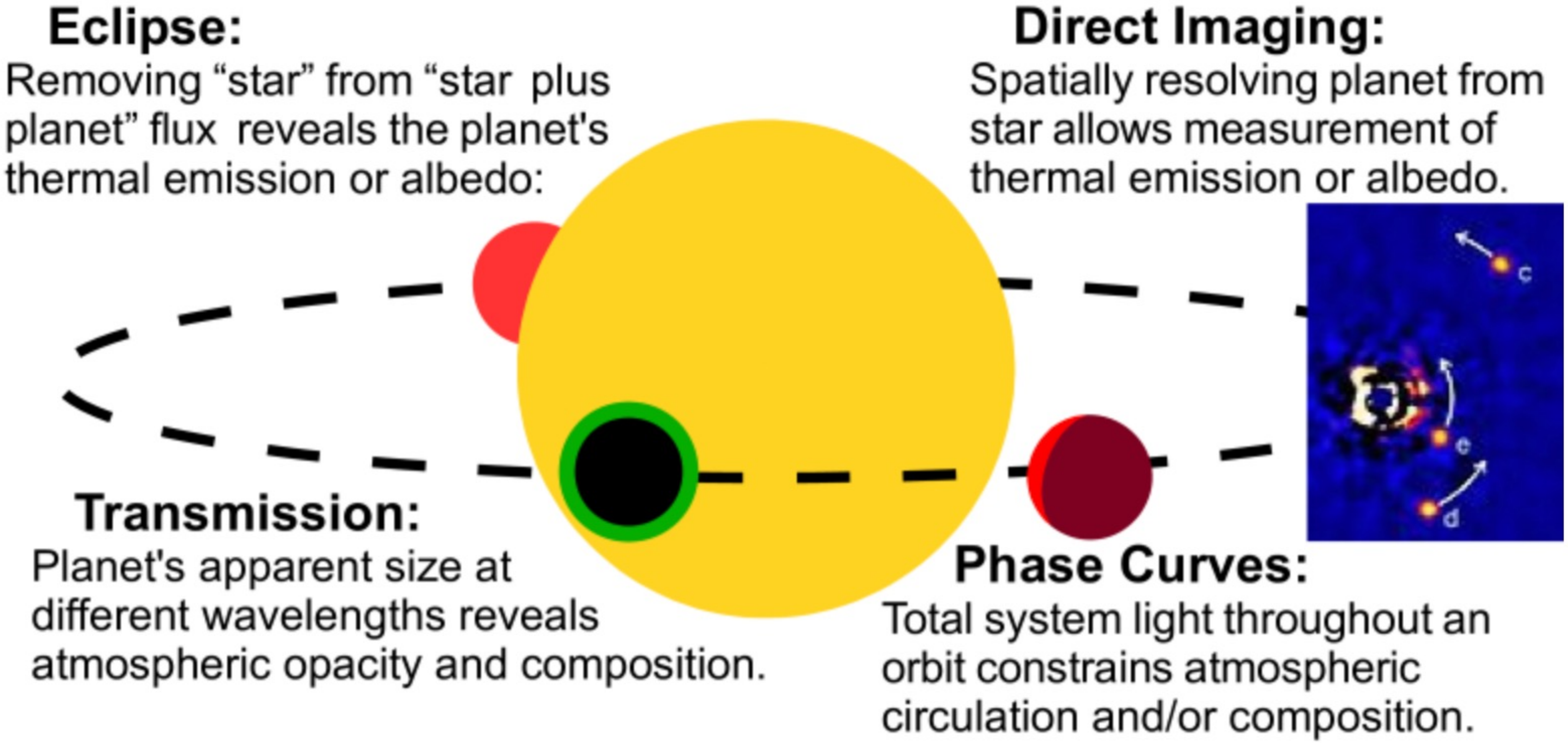

Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale


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

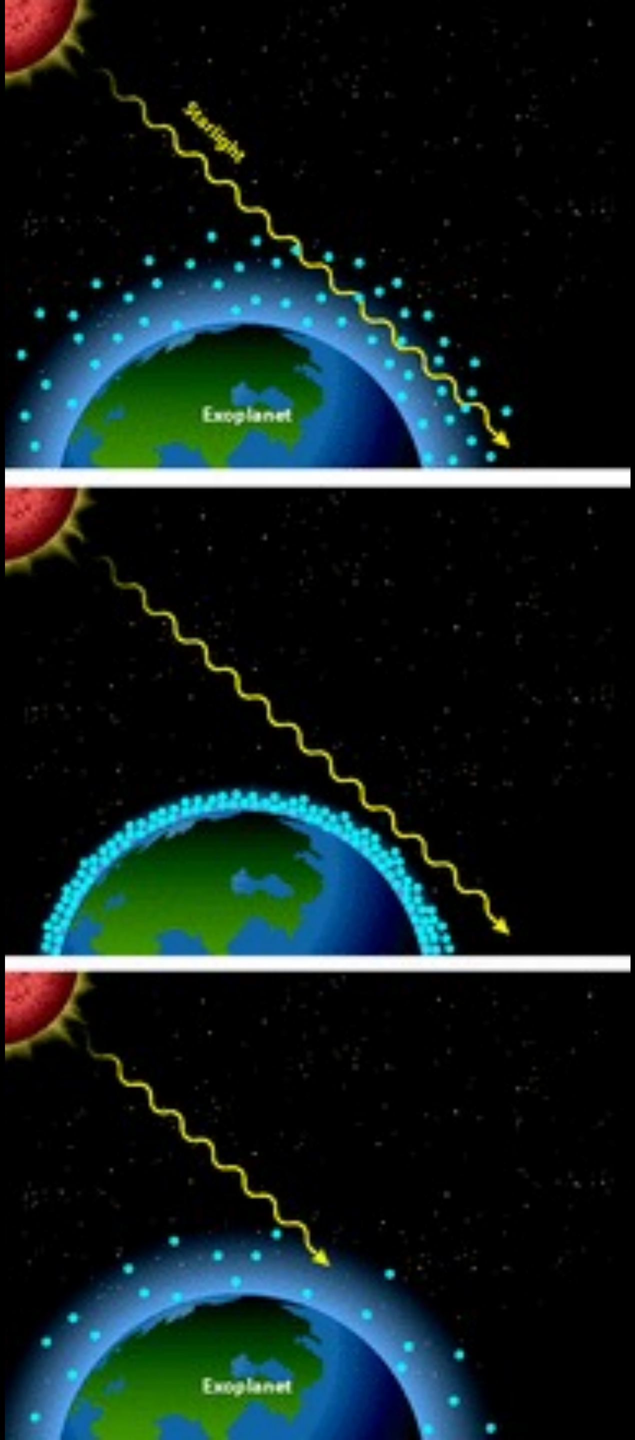


Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
#1
#2
#3
#4
#5
#6
Gliese 667C c
0.83
Kepler-62 e
0.83
Tau Ceti e*
0.77
Gliese 581 g*
0.76
Gliese 667C f
0.76
HD 40307 g
0.73
#7
#8
#9
#10
#11
#12
Kepler-61 b
0.73
Gliese 163 c
0.73
Kepler-22 b
0.71
Kepler-62 f
0.67
Gliese 667C e
0.60
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

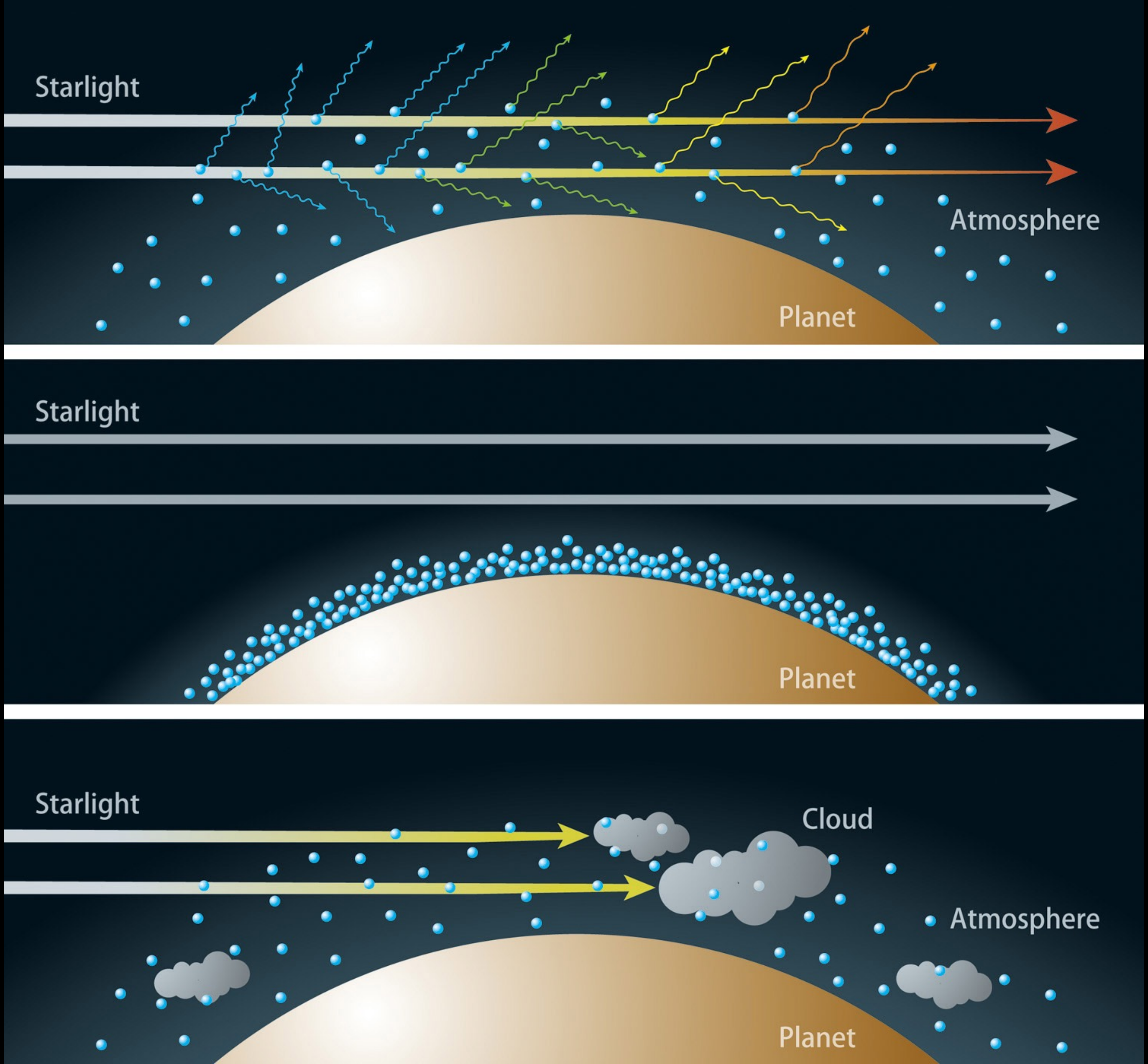
Atmosphere detection methods



Exoplanet atmospheres!



E^{o}	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	$H_2O \rightarrow O_2$	$O_2 \rightarrow H_2O$

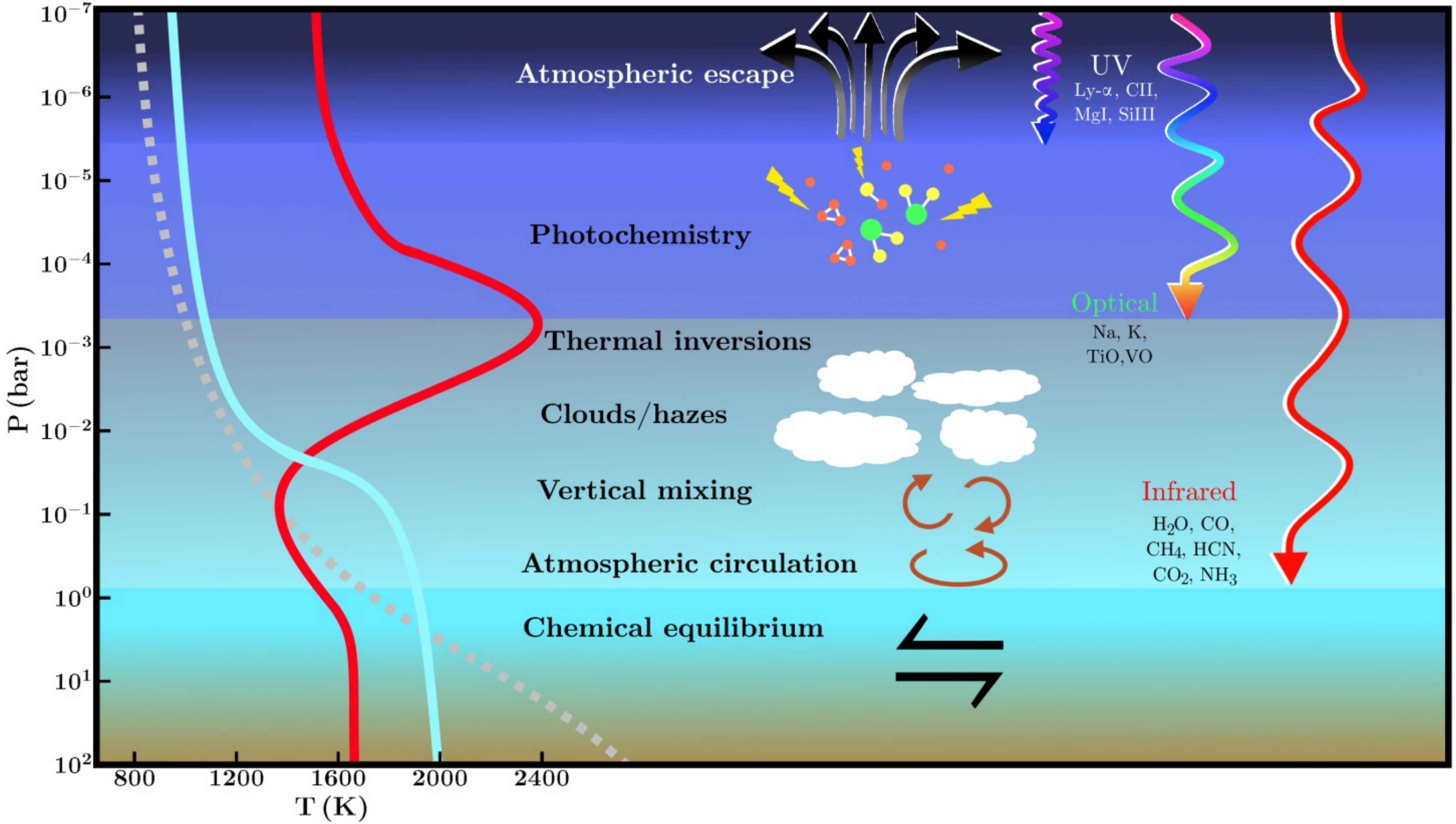


Transmission studies of atmospheres

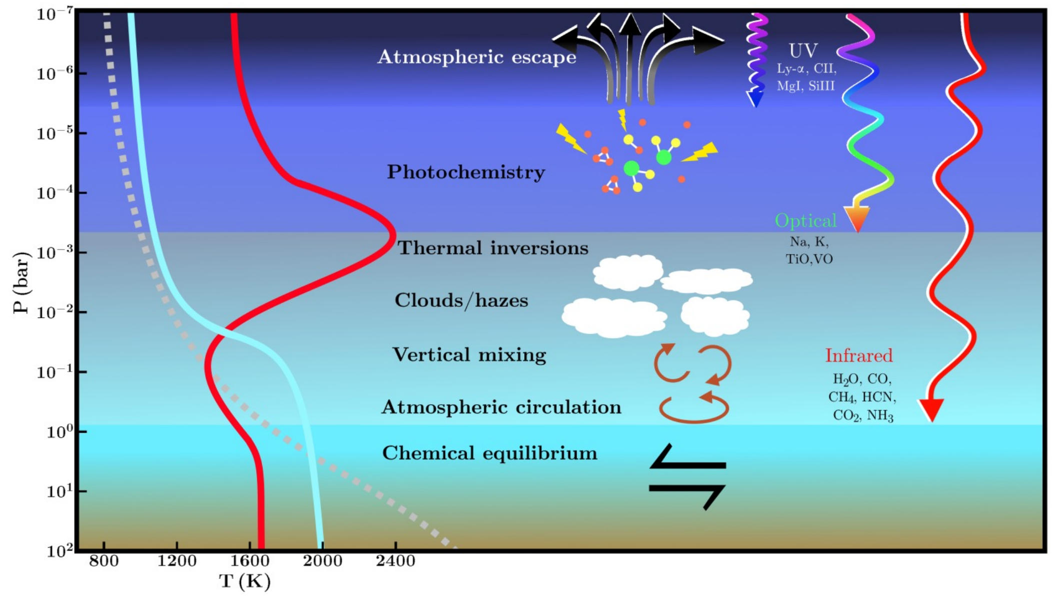
Earth: 6400 km radius, ~10-100 km atmosphere

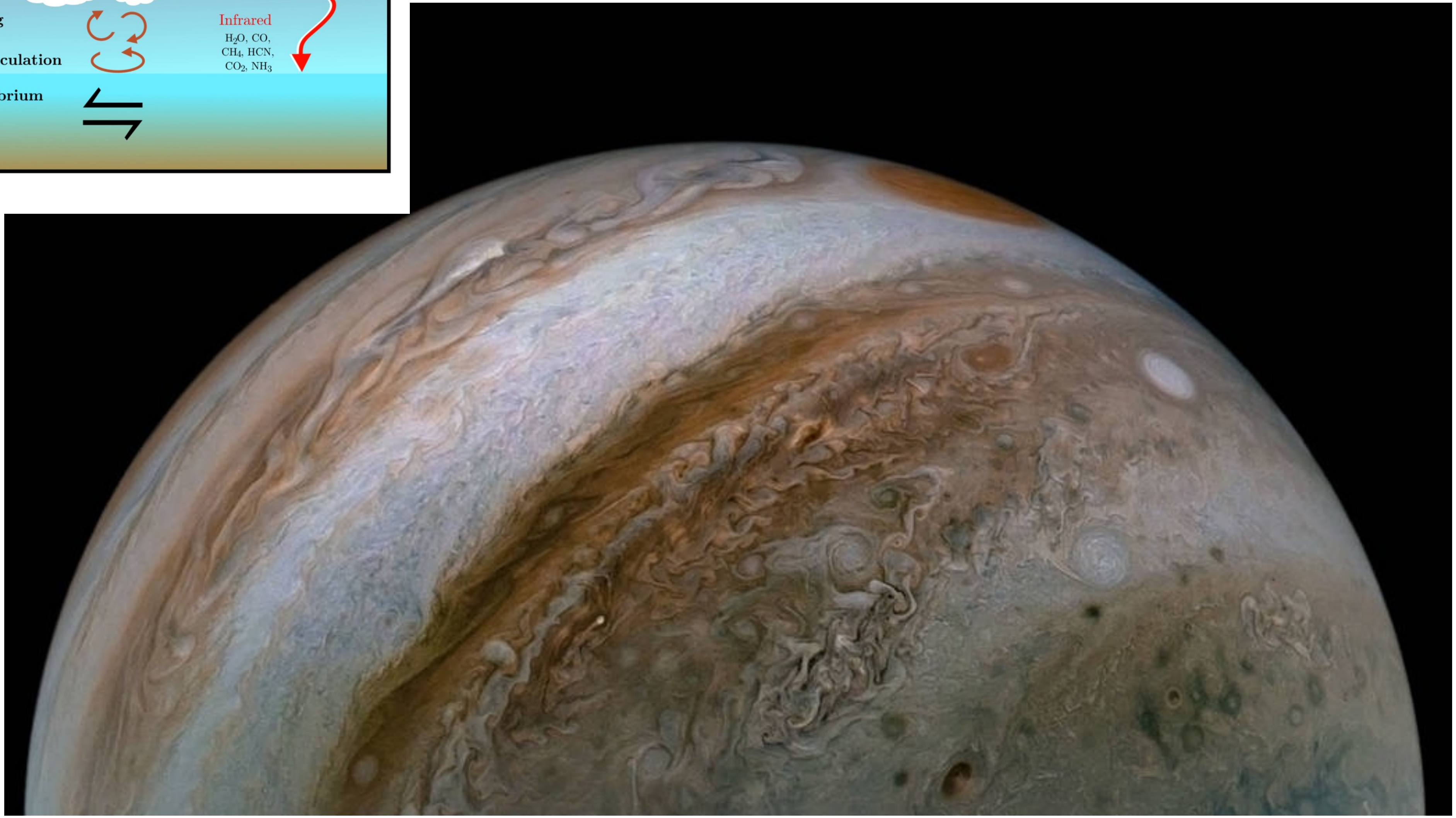
Tiny signal!

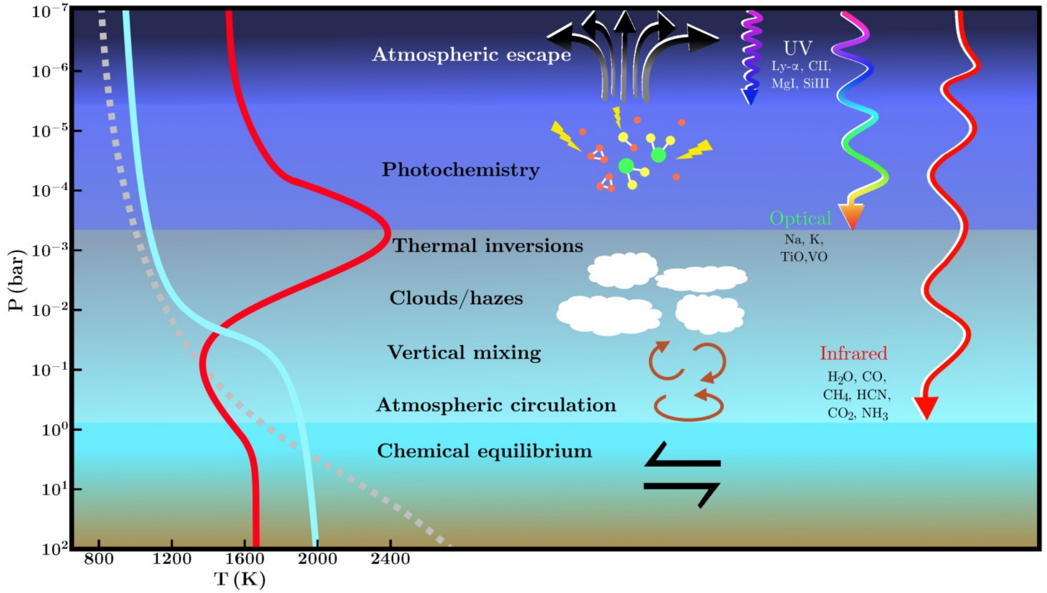
Atmosphere detection methods



Different wavelengths probe different layers in atmosphere

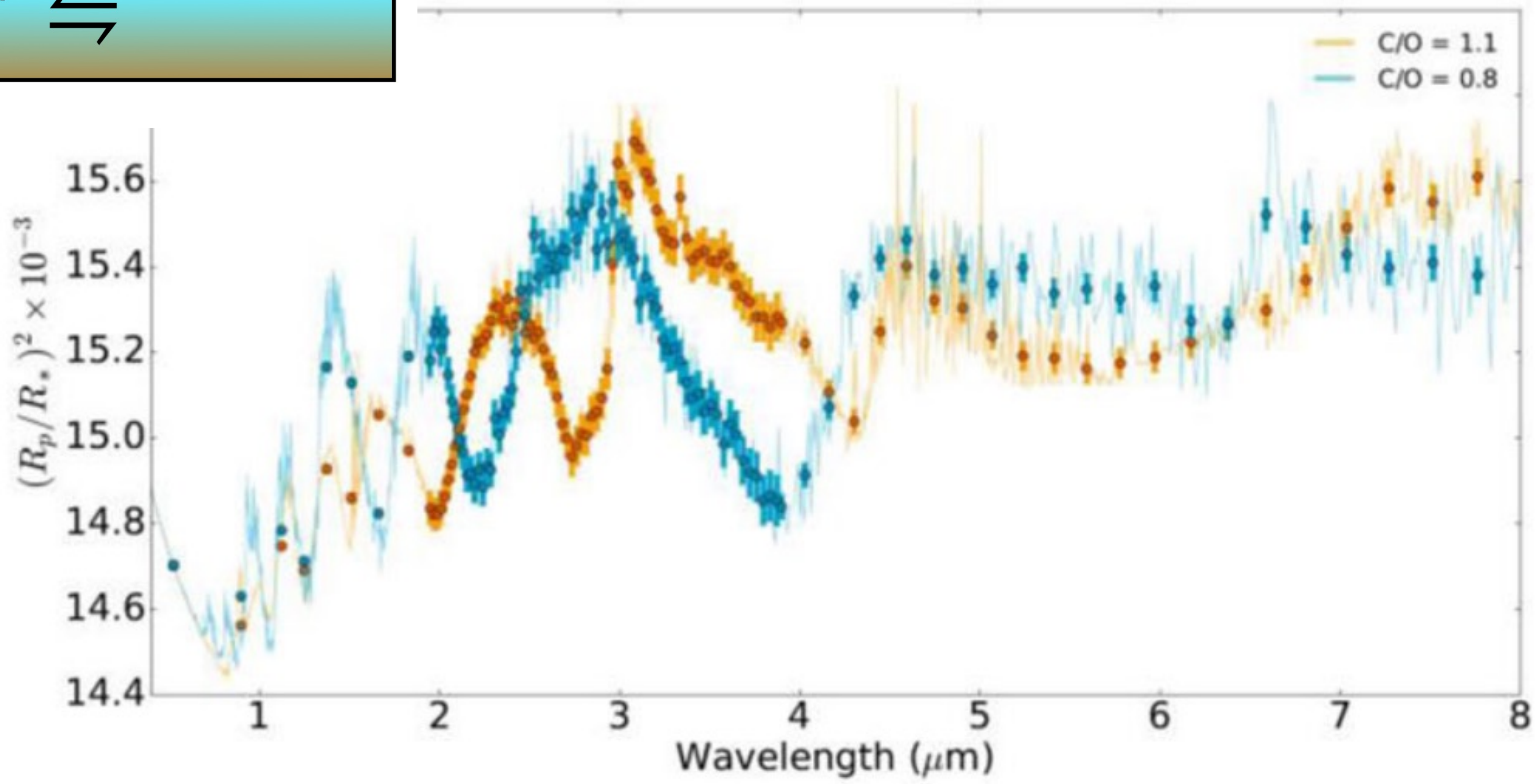


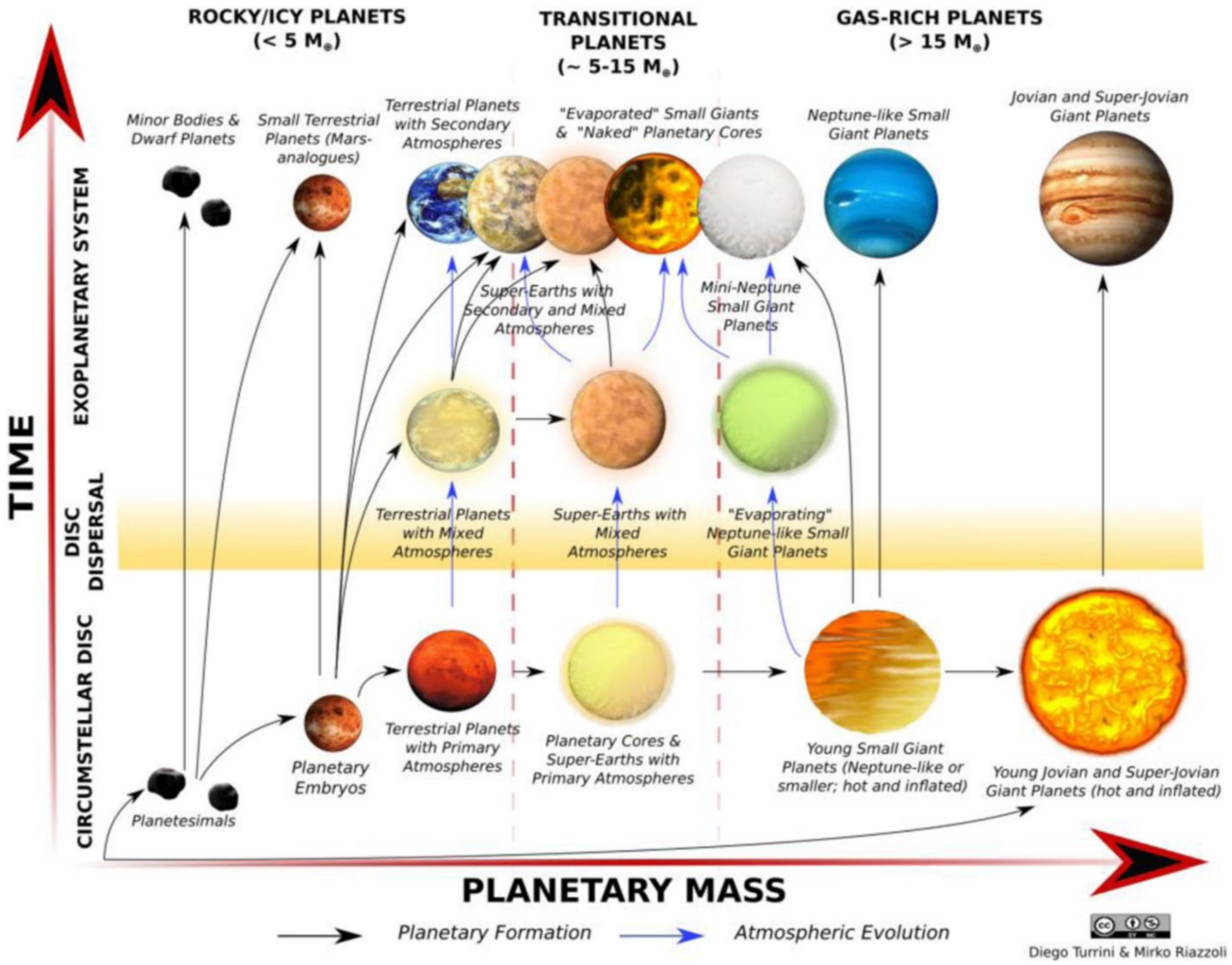




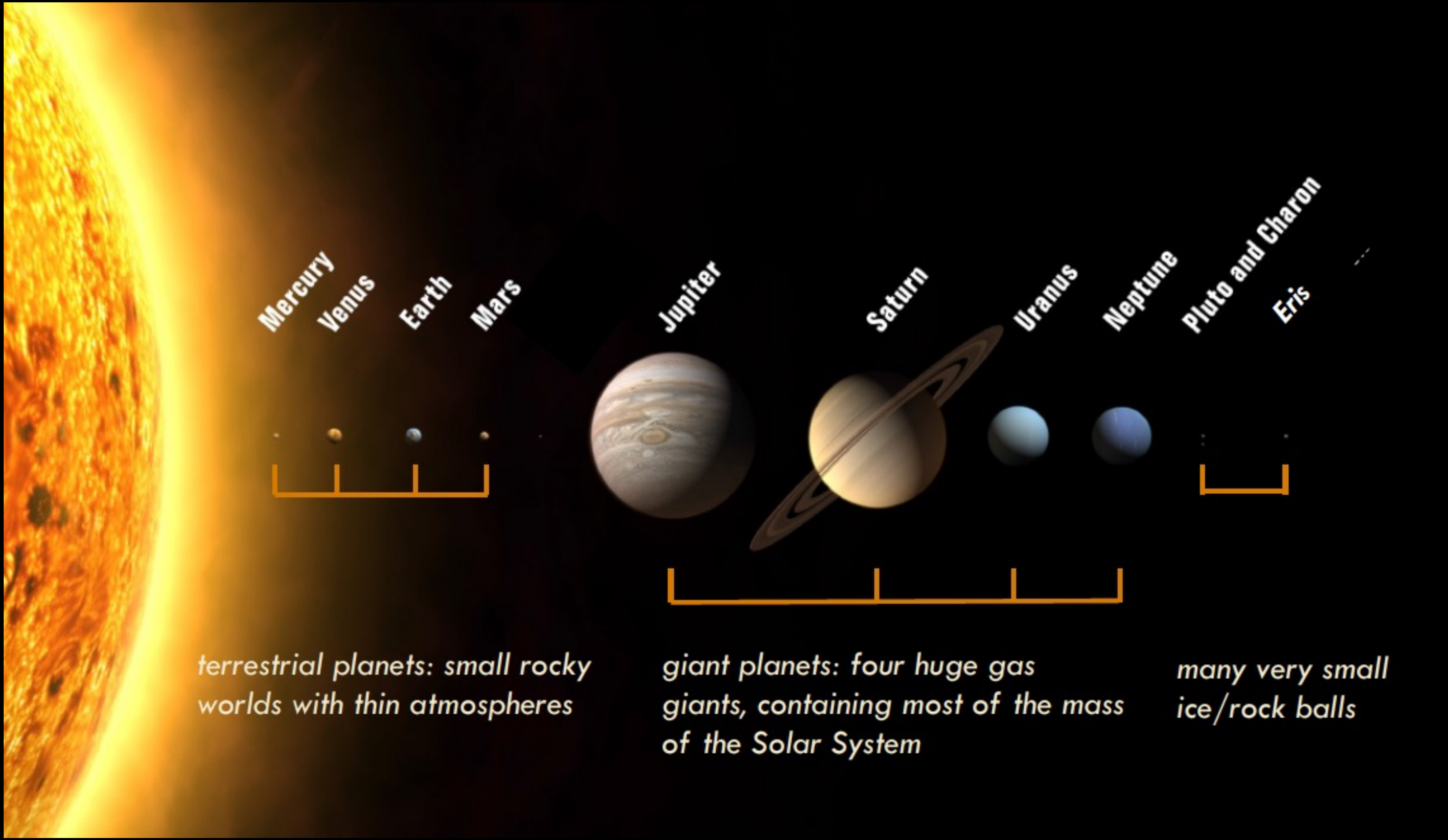
Complex atmospheric models:

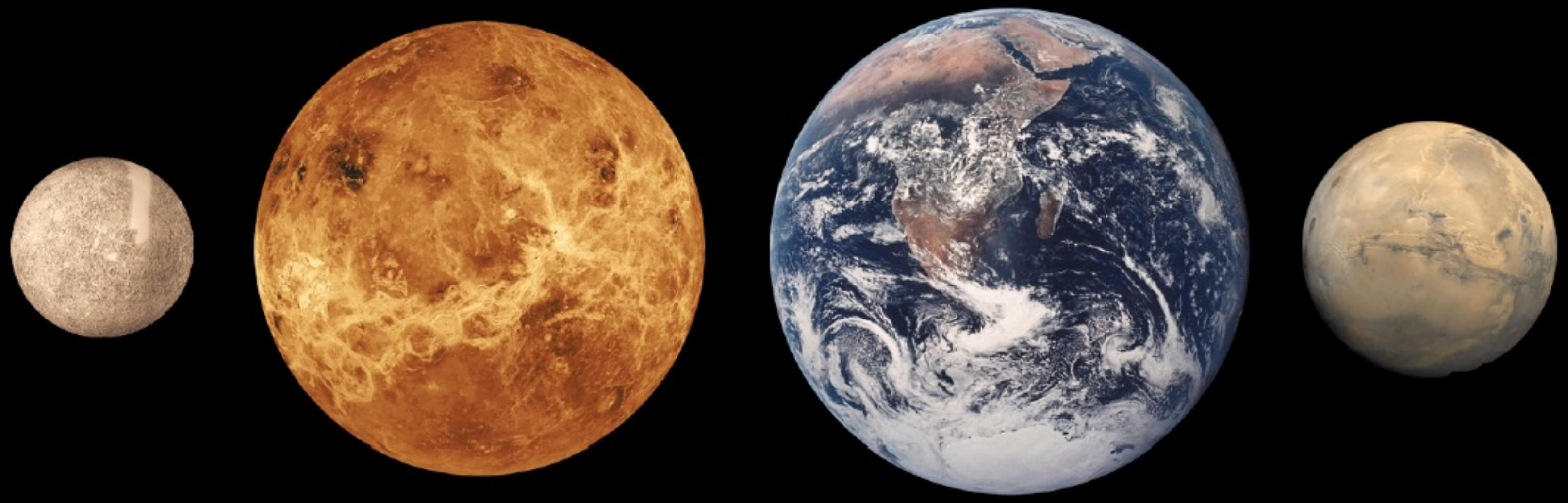
testable predictions for different abundances (C/O ratio) and atmospheric properties



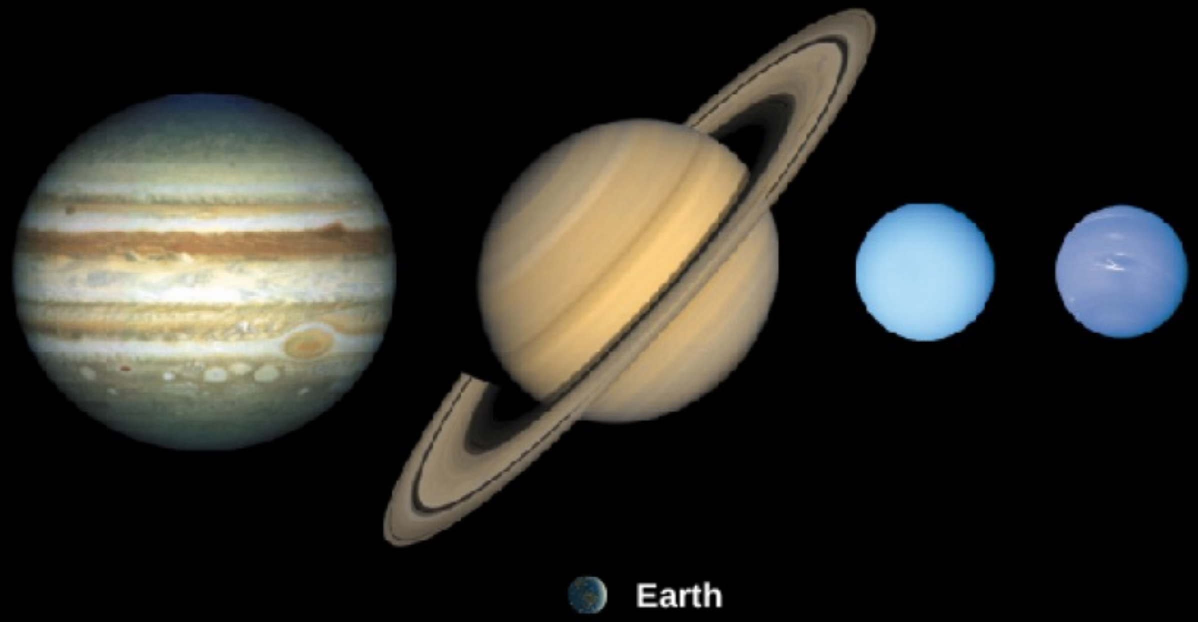


Atmospheres and types of planets

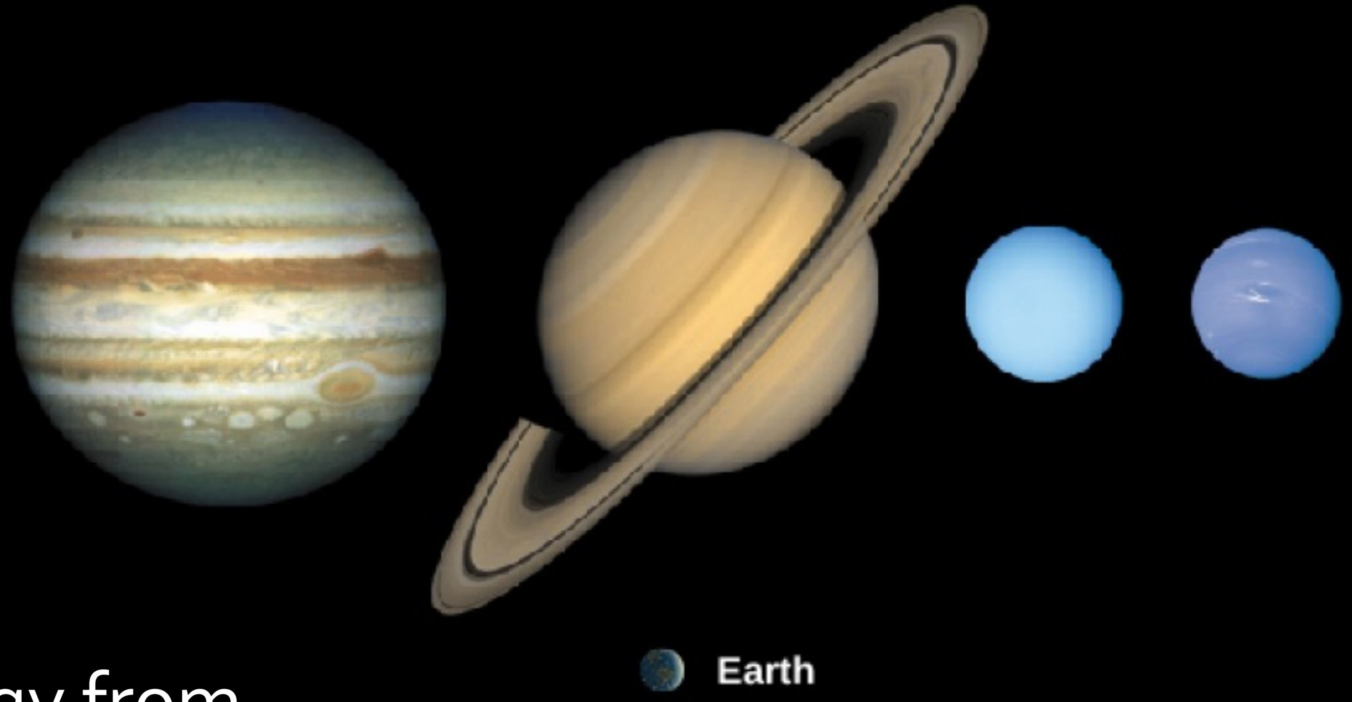

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto and Charon
Eris
terrestrial planets: small rocky worlds with thin atmospheres
giant planets: four huge gas giants, containing most of the mass of the Solar System
many very small ice/rock balls



Terrestrial planets



Giant planets



Gas giants

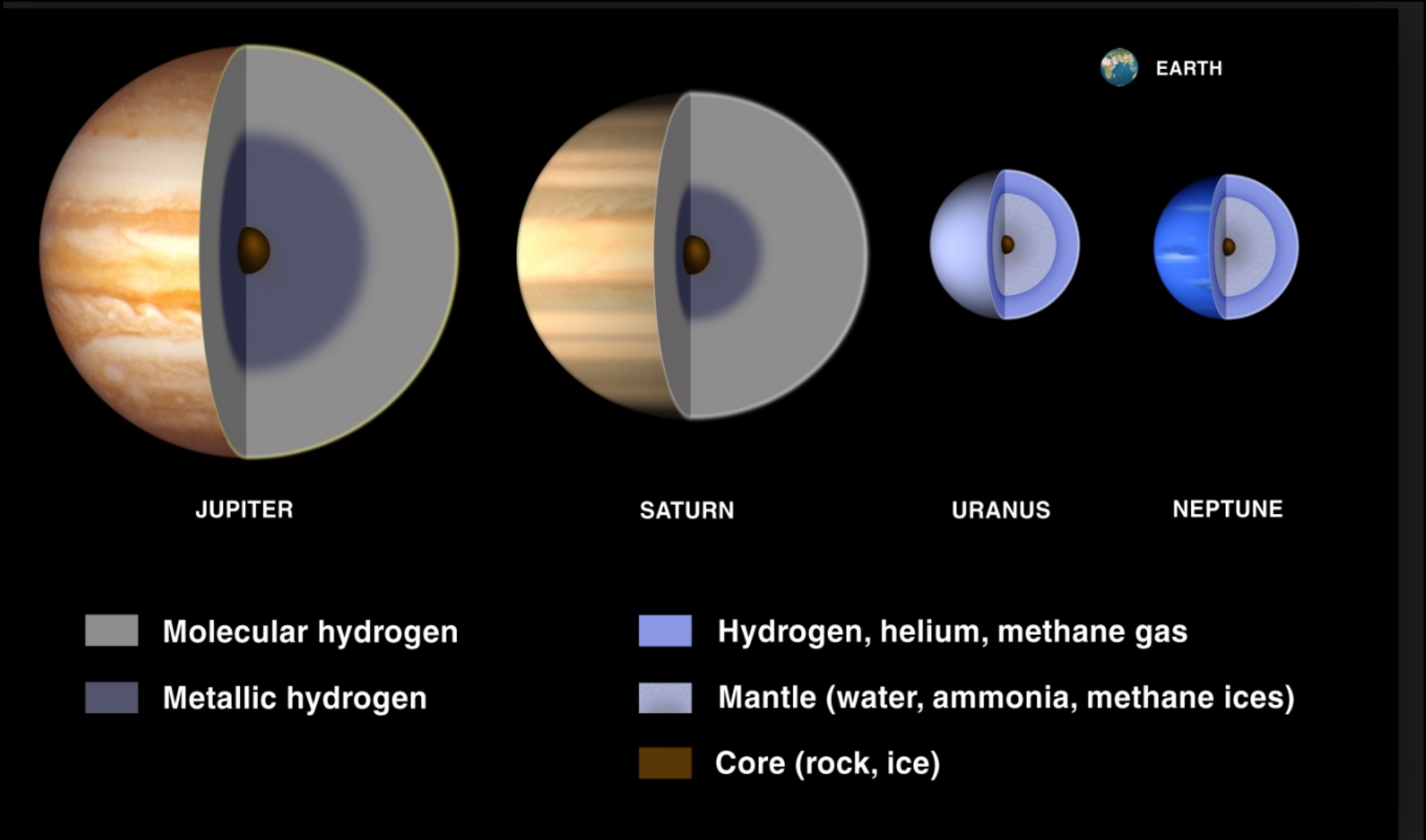
Jupiter: energy from contraction (2 cm/yr)

Saturn: energy from differentiation (heavier elements sink)

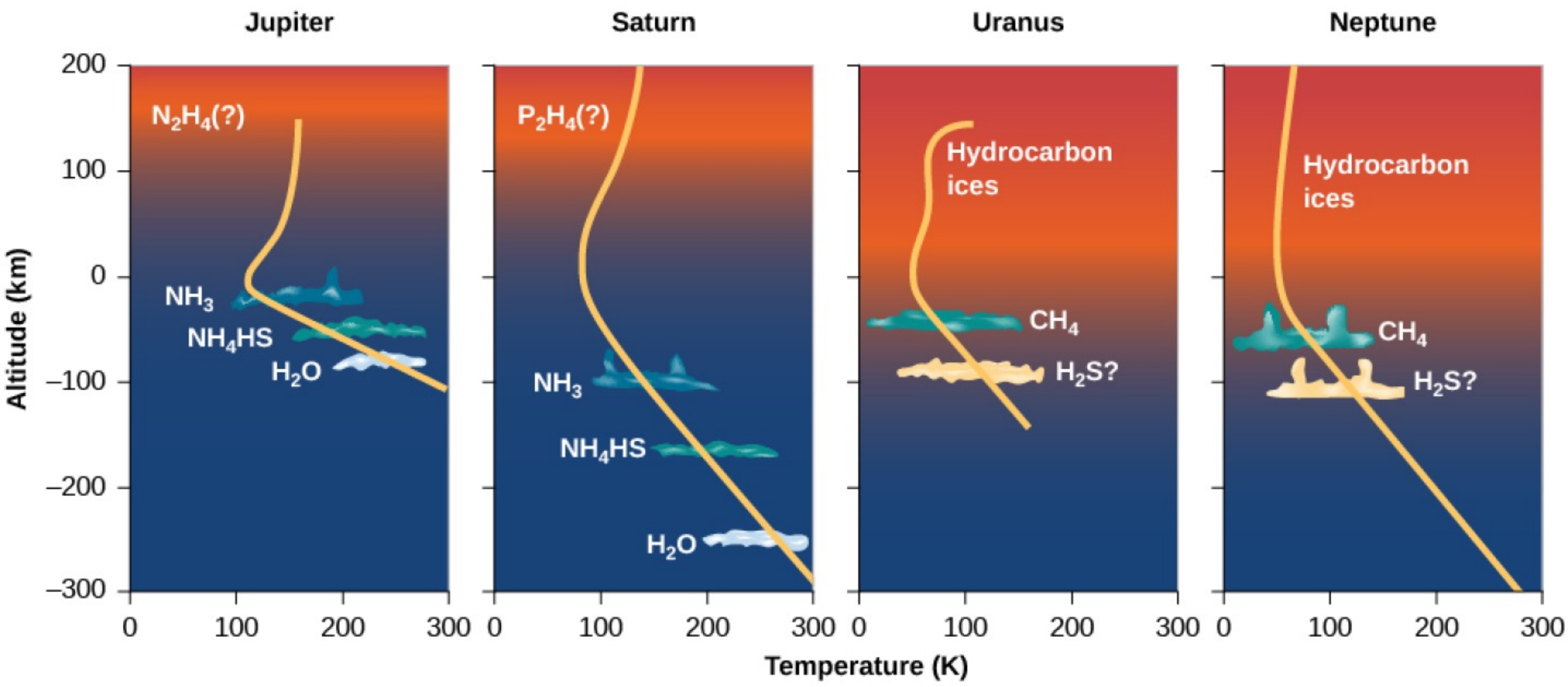
Ice Giants

Cold

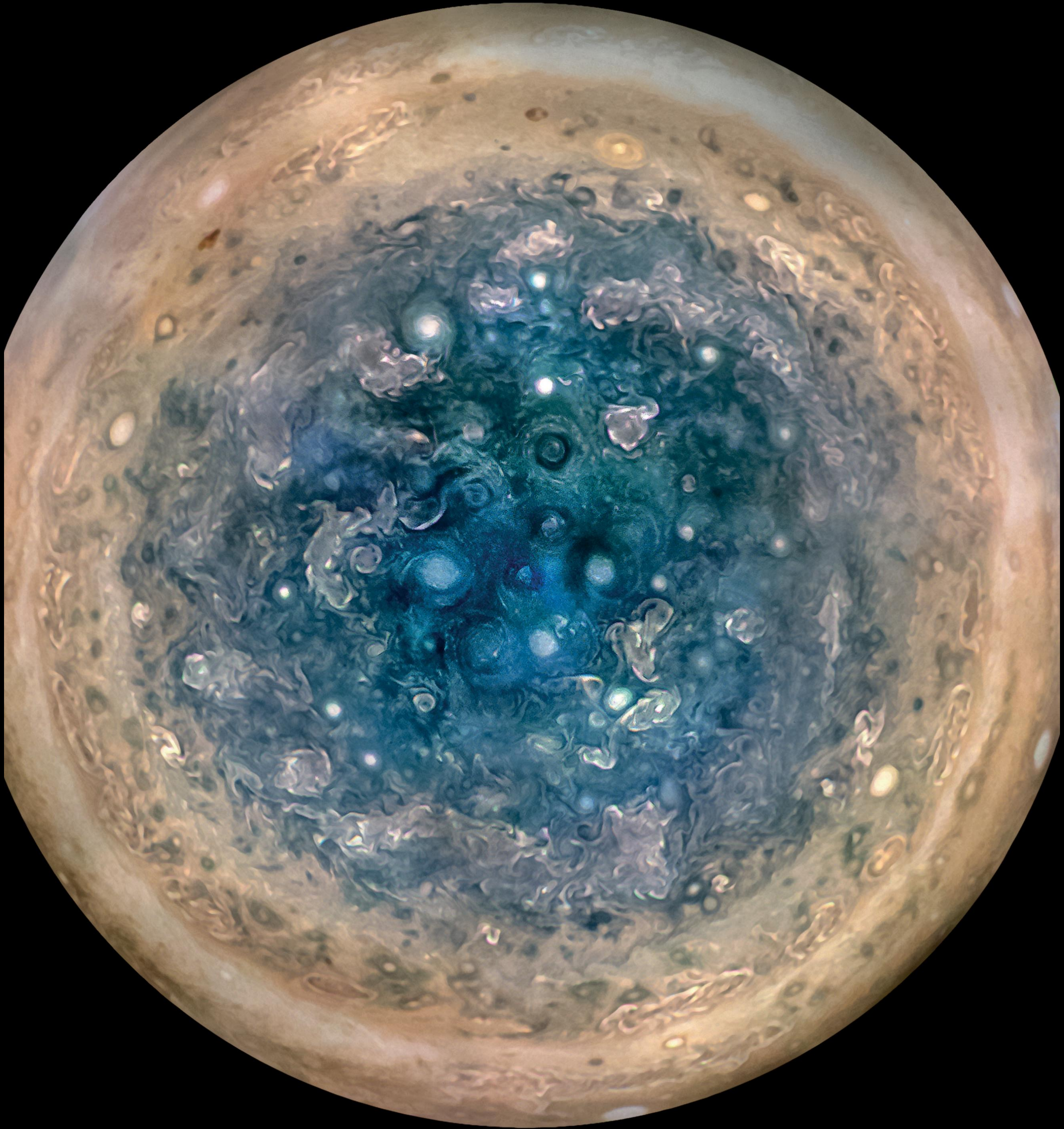
Large cores/small envelopes



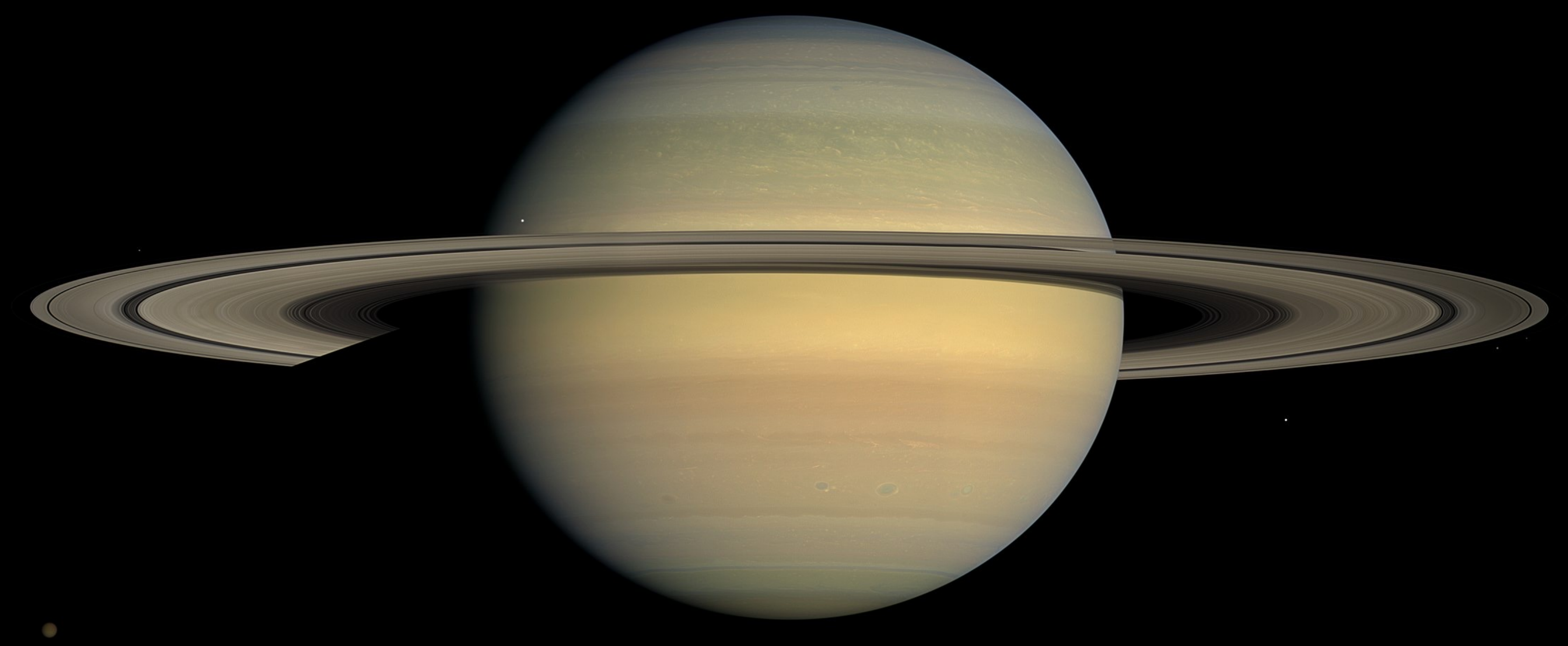
EARTH
JUPITER
SATURN
URANUS
NEPTUNE
Molecular hydrogen
Metallic hydrogen
Hydrogen, helium, methane gas
Mantle (water, ammonia, methane ices)
Core (rock, ice)

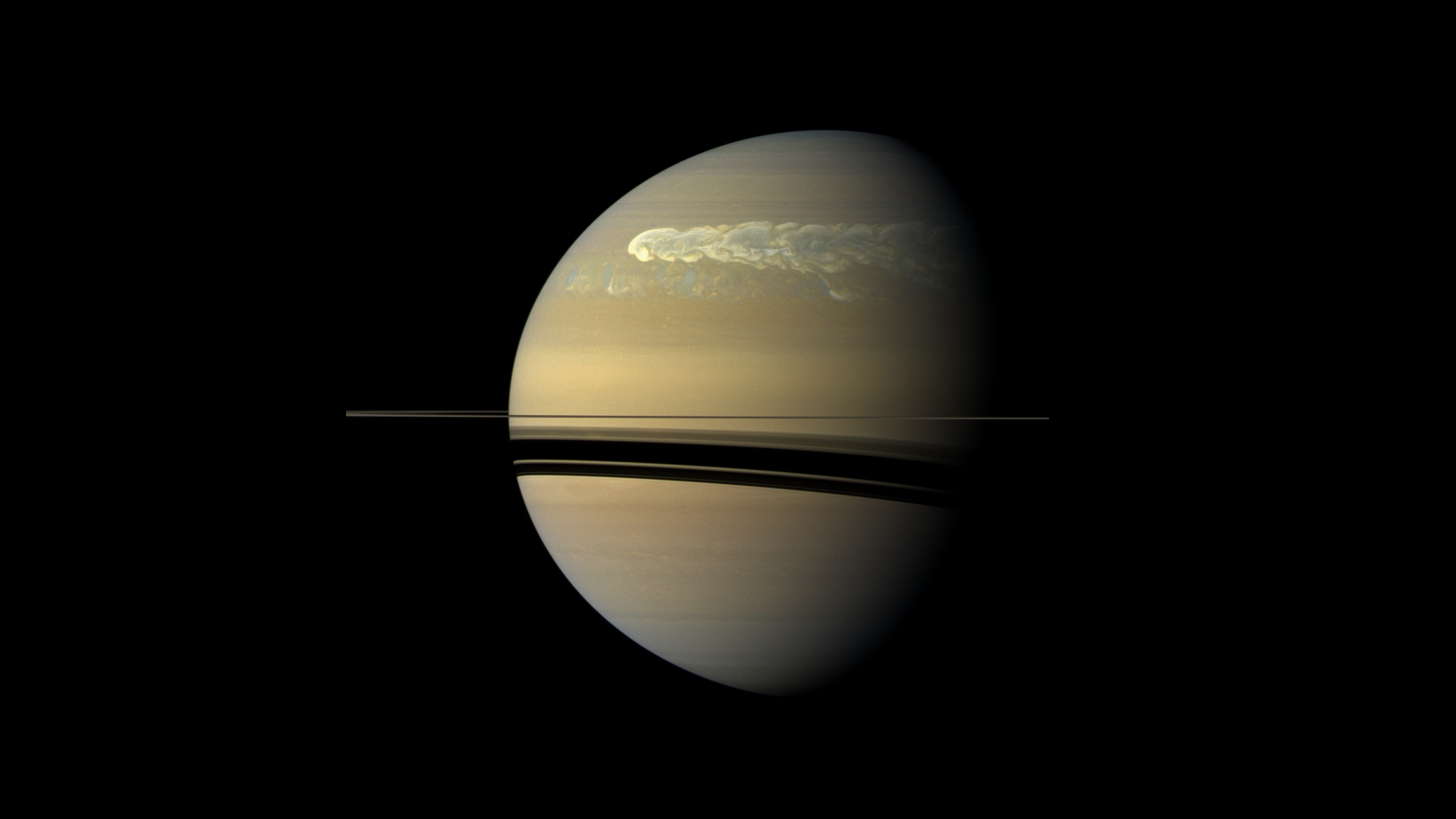


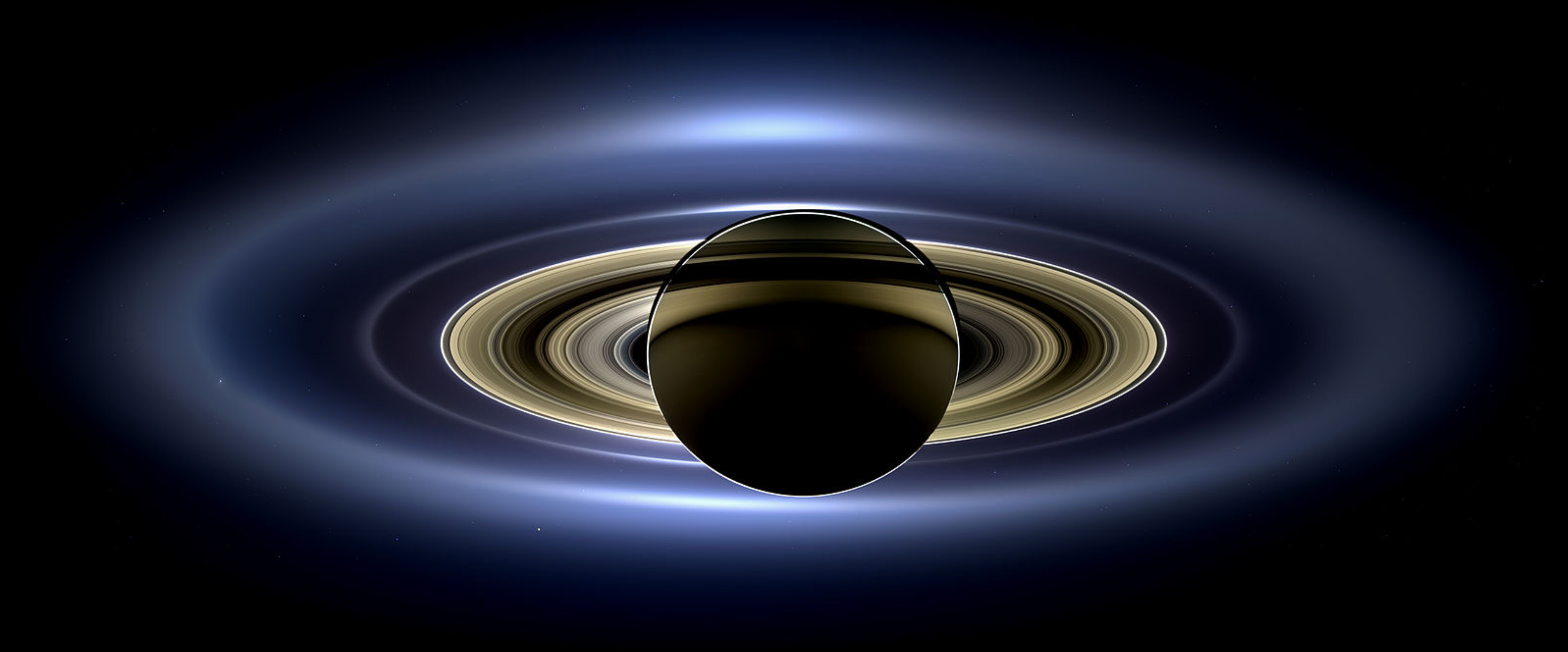
Jupiter
Saturn
Uranus
Neptune
Altitude (km)
200
100
0
–100
–200
–300
N2H4(?)
NH3
NH4HS
H2O
P2H4(?)
NH3
NH4HS
H2O
Hydrocarbon ices
CH4
H2S?
Hydrocarbon ices
CH4
H2S?
0 100 200 300
Temperature (K)



Saturn (and its rings)







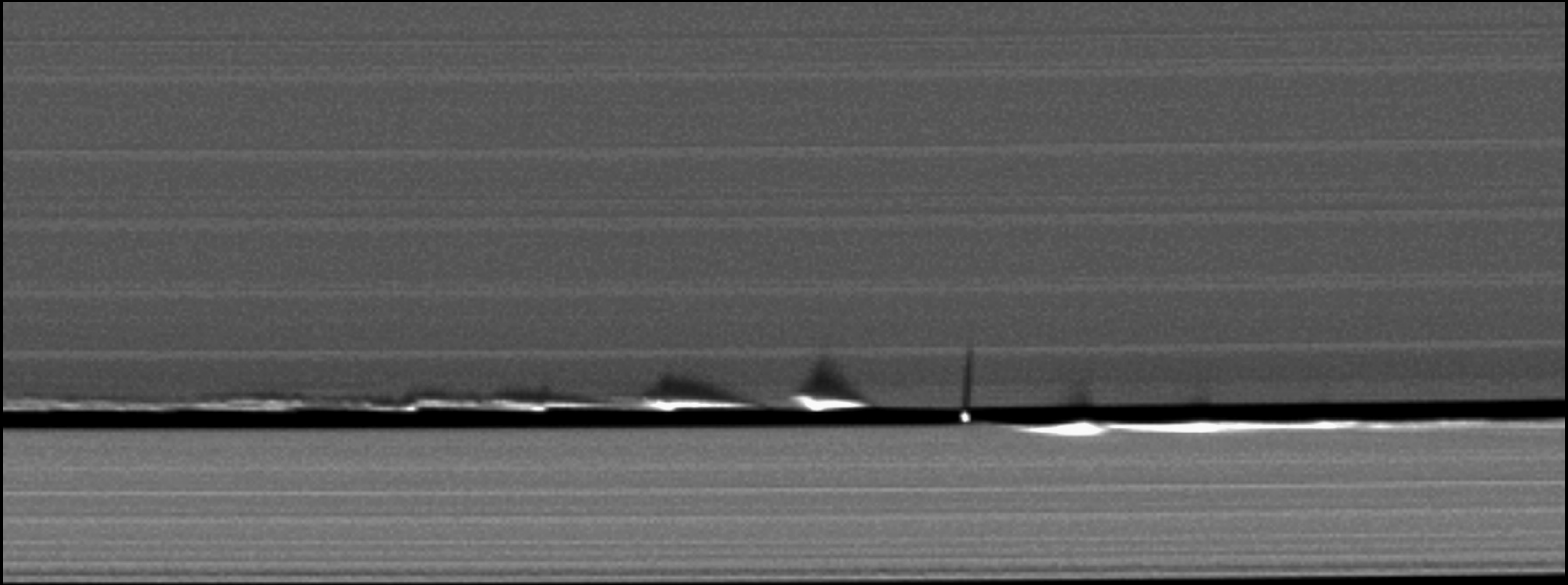
Rings: water ice a few m across

remnants of a moon

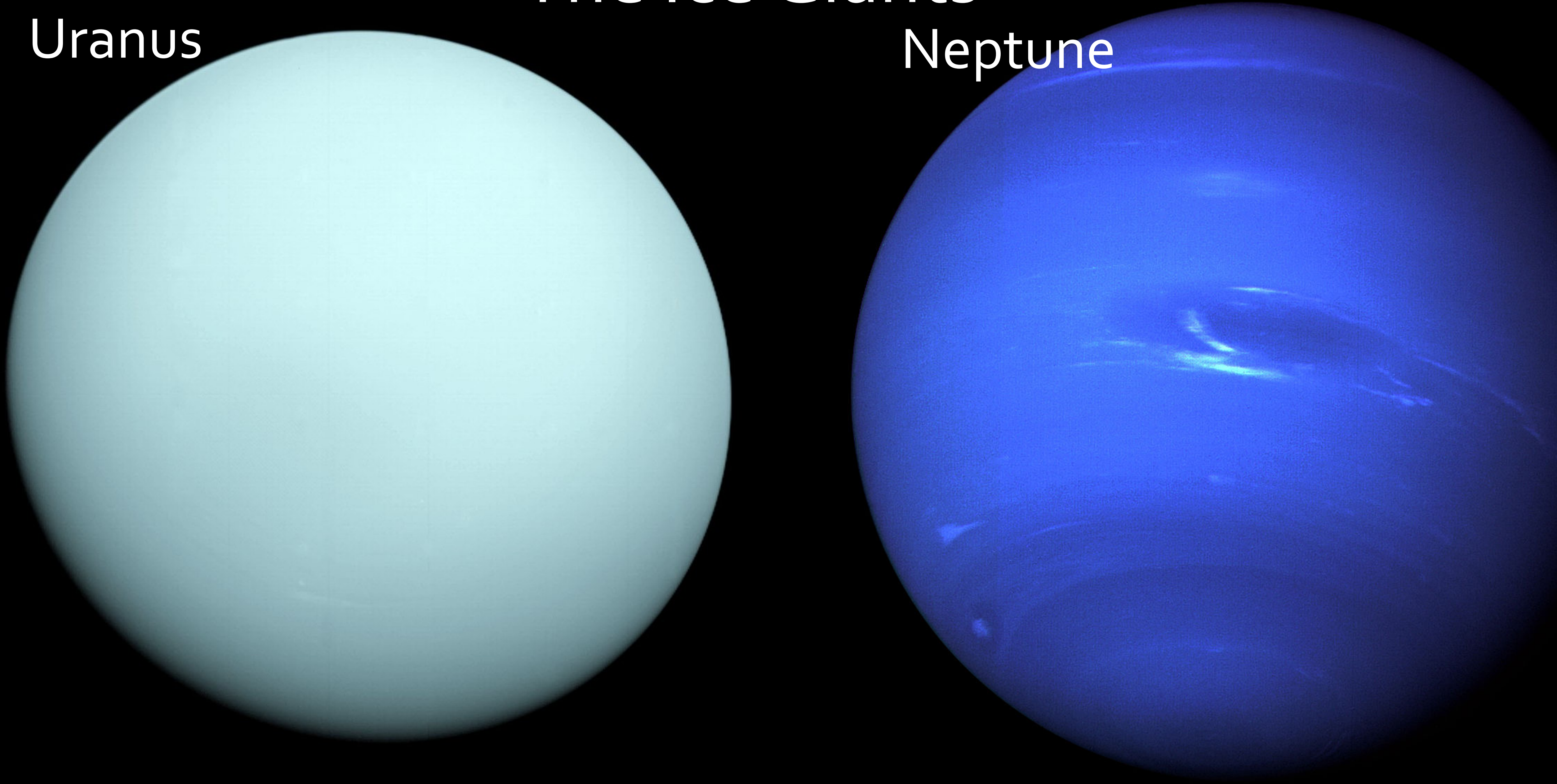
Thousands of km across; ~10 m thick!

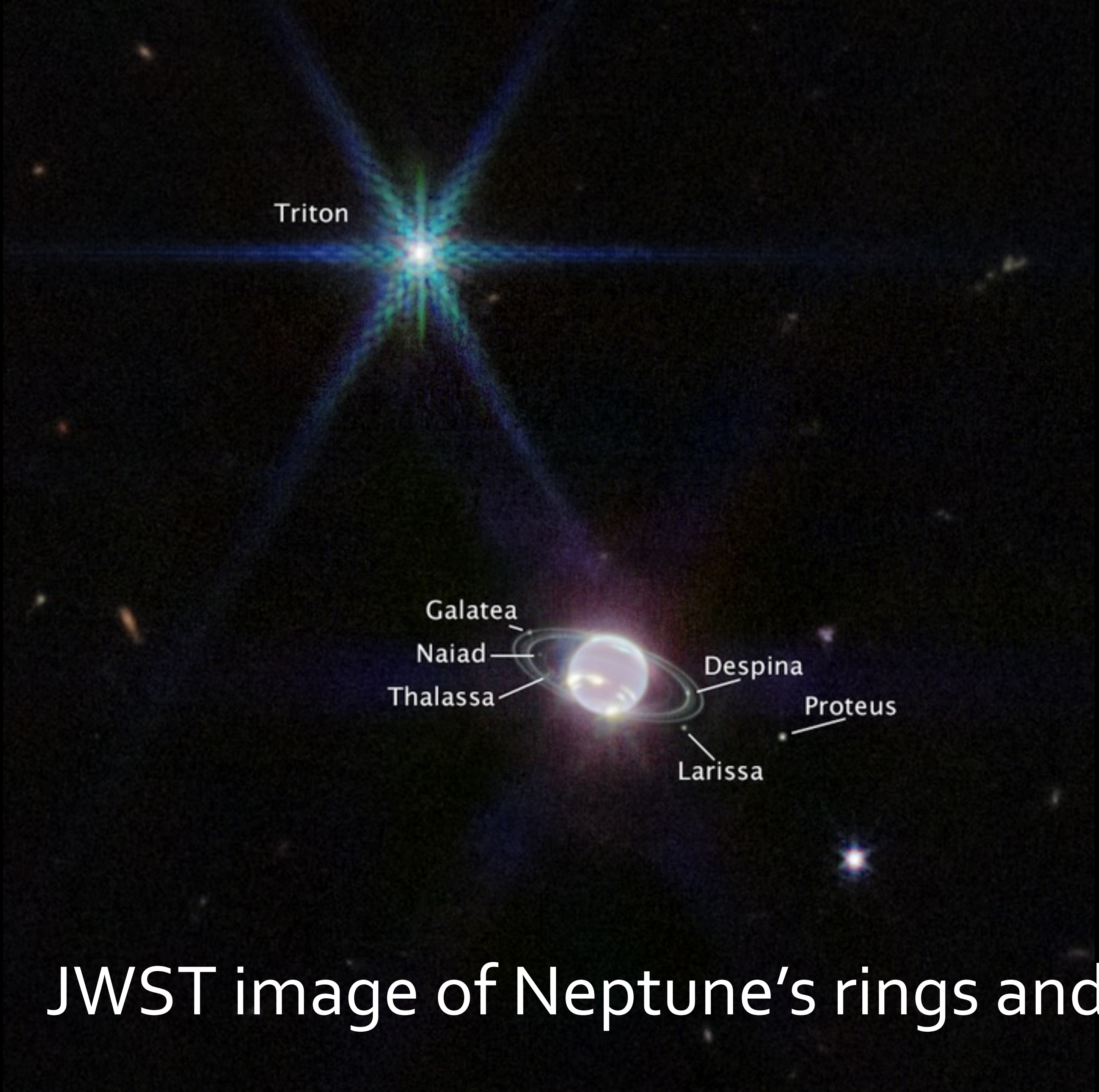
<100 million years old

Shepherd moons



The Ice Giants



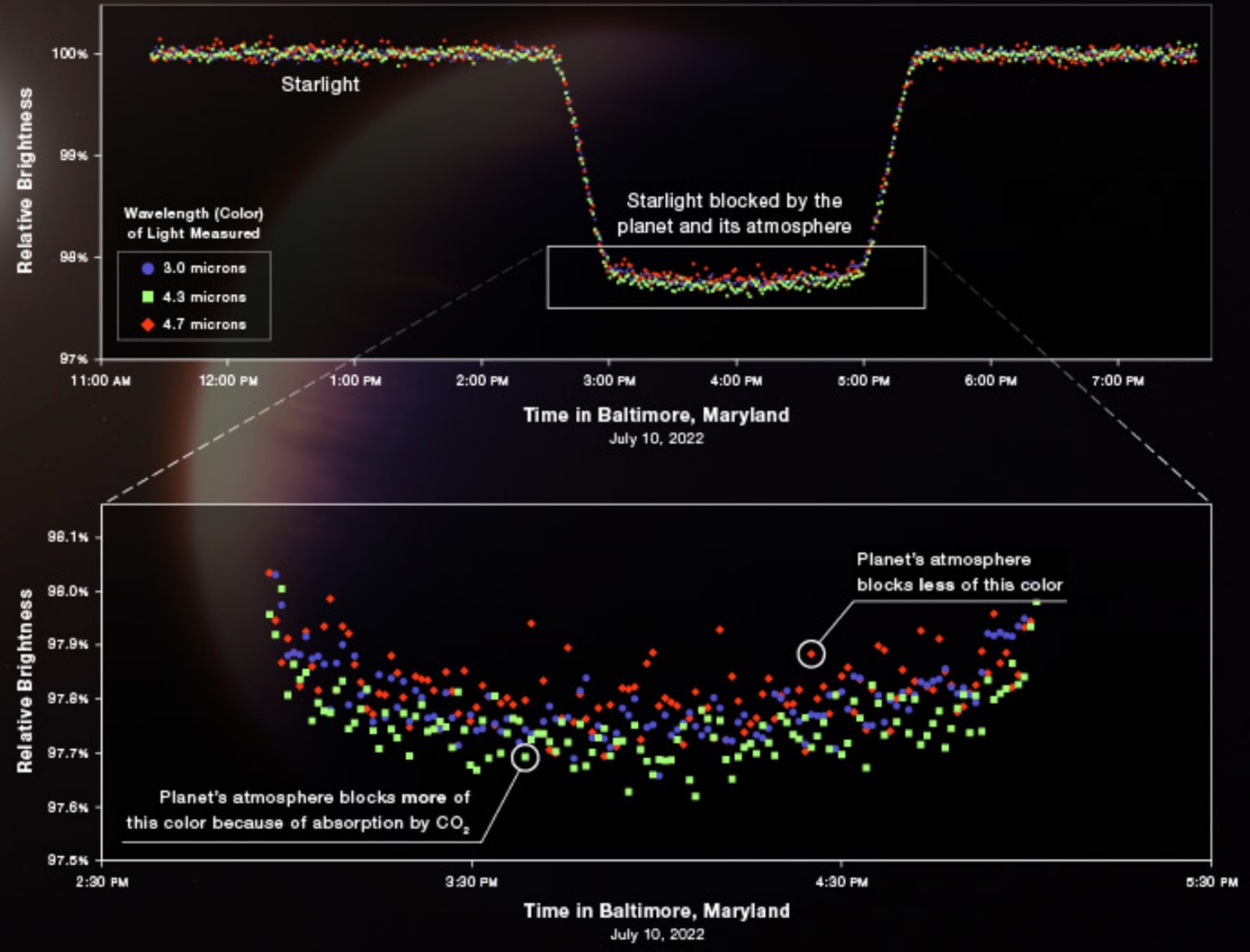


JWST image of Neptune’s rings and moons

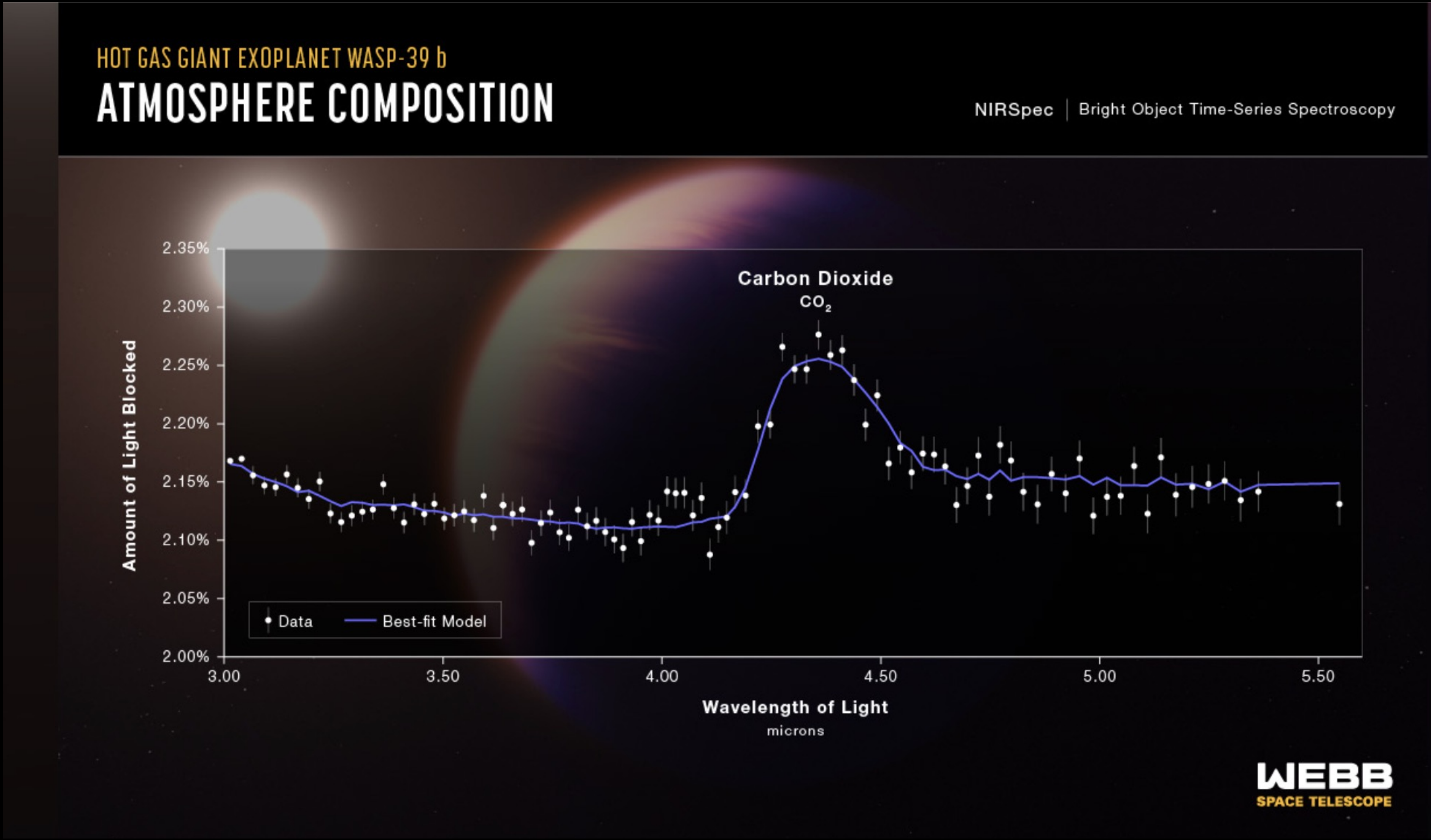
HOT GAS GIANT EXOPLANET WASP-39 b

TRANSIT LIGHT CURVE

NIRSpec | Bright Object Time-Series Spectroscopy

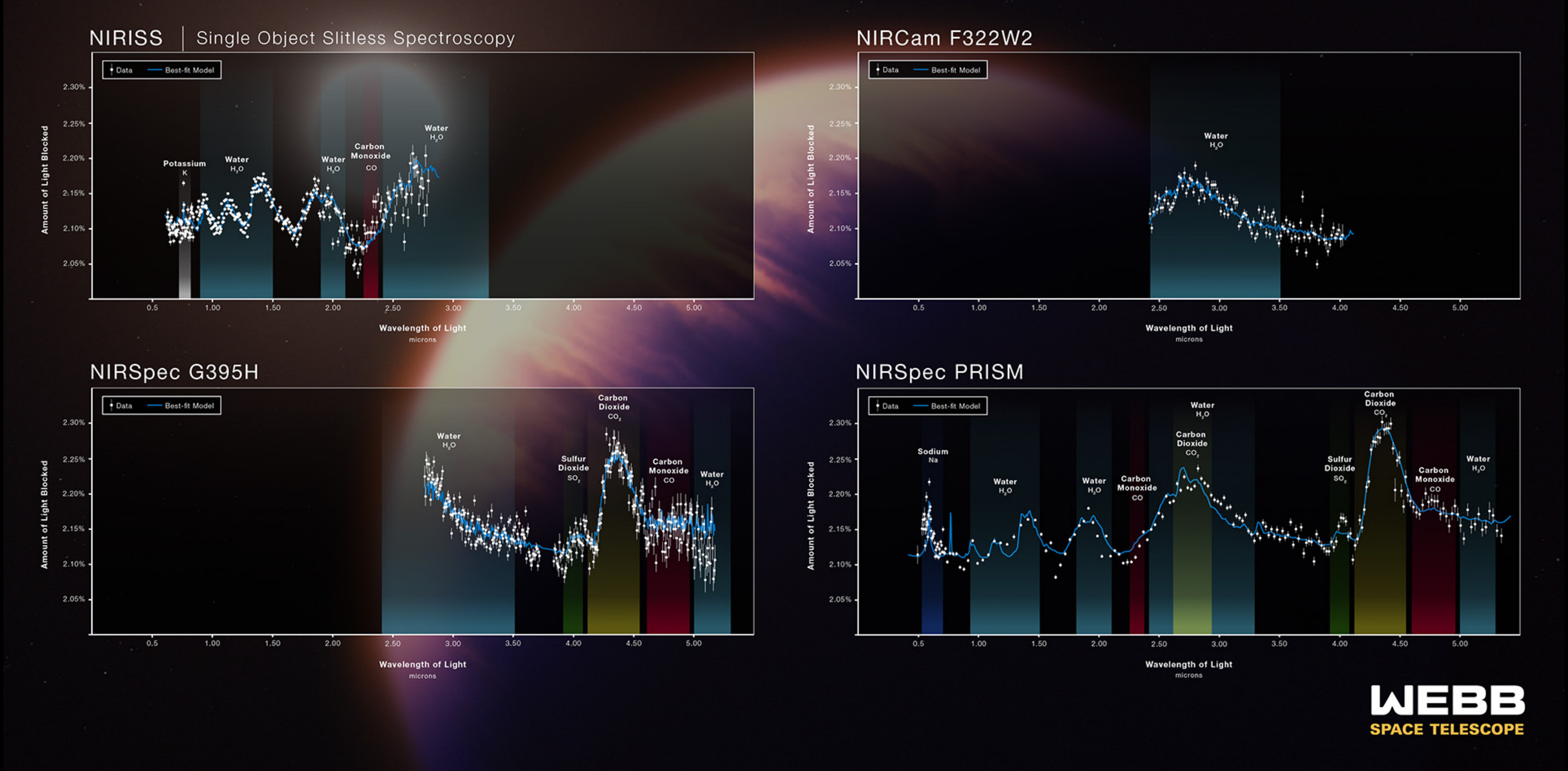


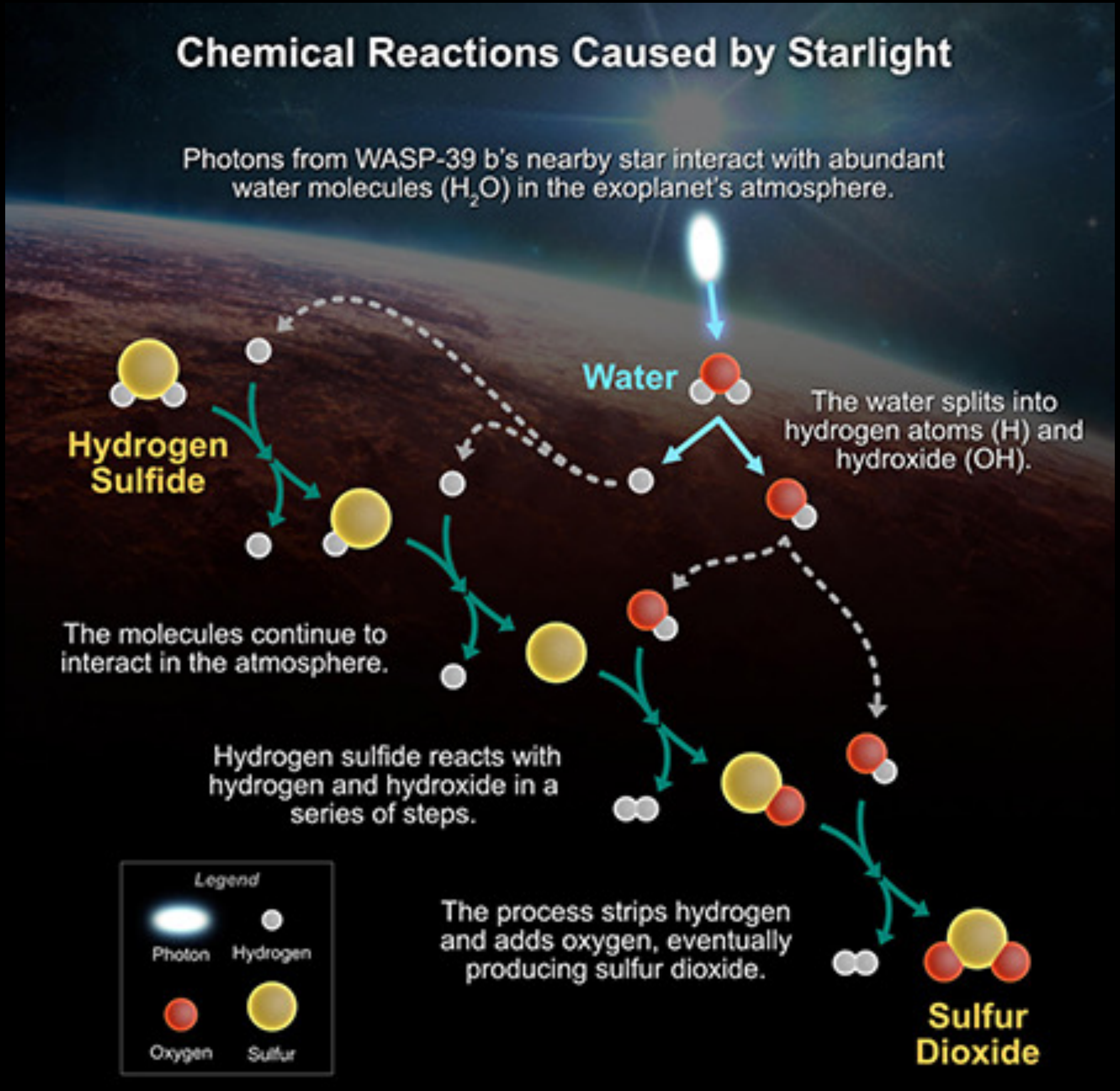
WEBB SPACE TELESCOPE


HOT GAS GIANT EXOPLANET WASP-39 b
ATMOSPHERE COMPOSITION
NIRSpec | Bright Object Time-Series Spectroscopy
Carbon Dioxide
CO_2
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

HOT GAS GIANT EXOPLANET WASP-39 b

ATMOSPHERE COMPOSITION

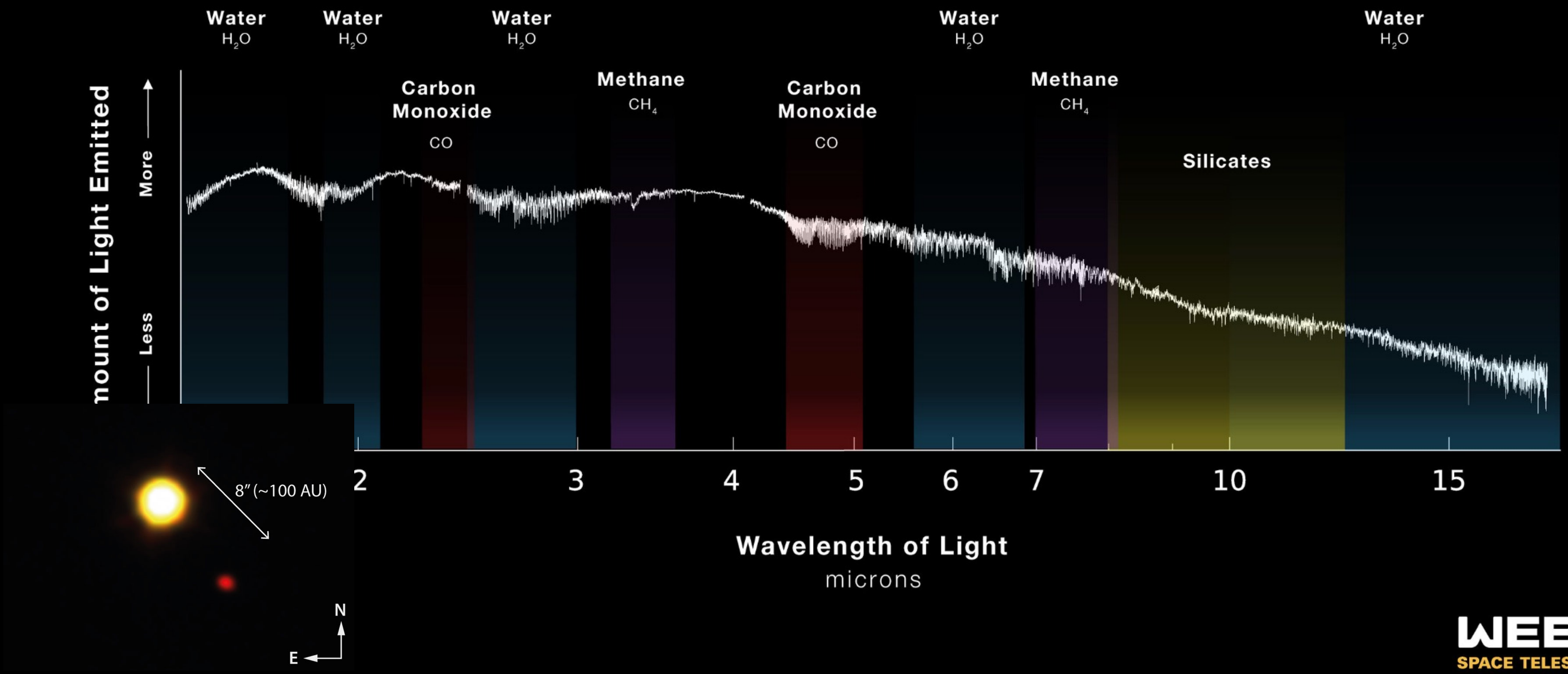



Chemical Reactions Caused by Starlight
Photons from WASP-39 b's nearby star interact with abundant water molecules (H_2O) in the exoplanet's atmosphere.
Water
The water splits into hydrogen atoms (H) and hydroxide (OH).
Hydrogen Sulfide
The molecules continue to interact in the atmosphere.
Hydrogen sulfide reacts with hydrogen and hydroxide in a series of steps.
The process strips hydrogen and adds oxygen, eventually producing sulfur dioxide.
Sulfur Dioxide
Legend
Photon
Hydrogen
Oxygen
Sulfur

EXOPLANET VHS 1256 b

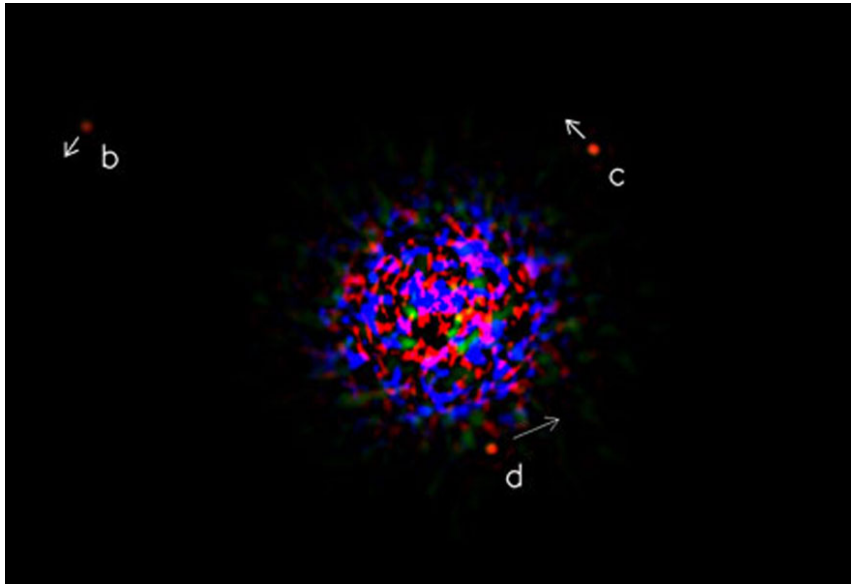
EMISSION SPECTRUM

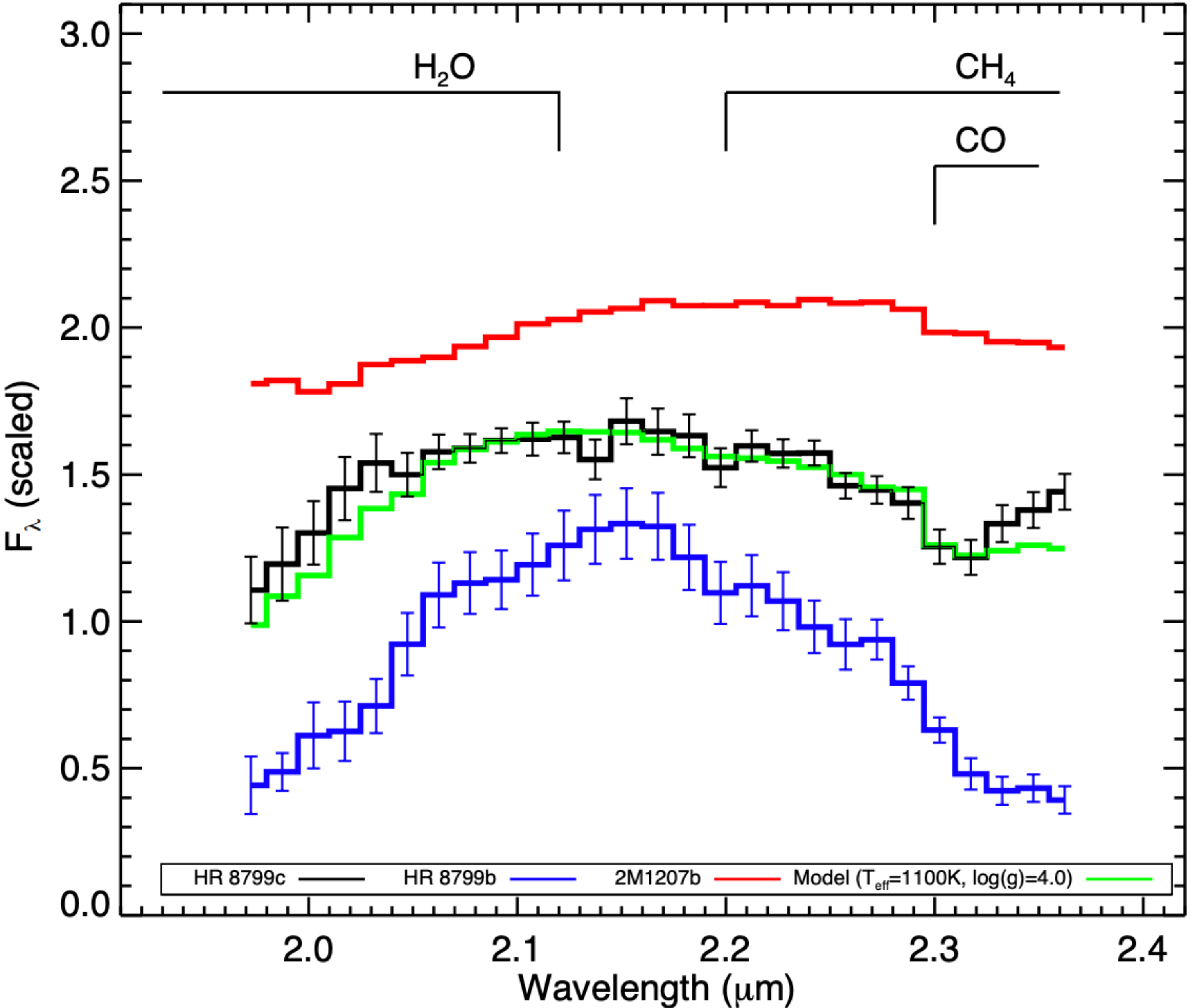
NIRSpec and MIRI | IFU Medium-Resolution Spectroscopy

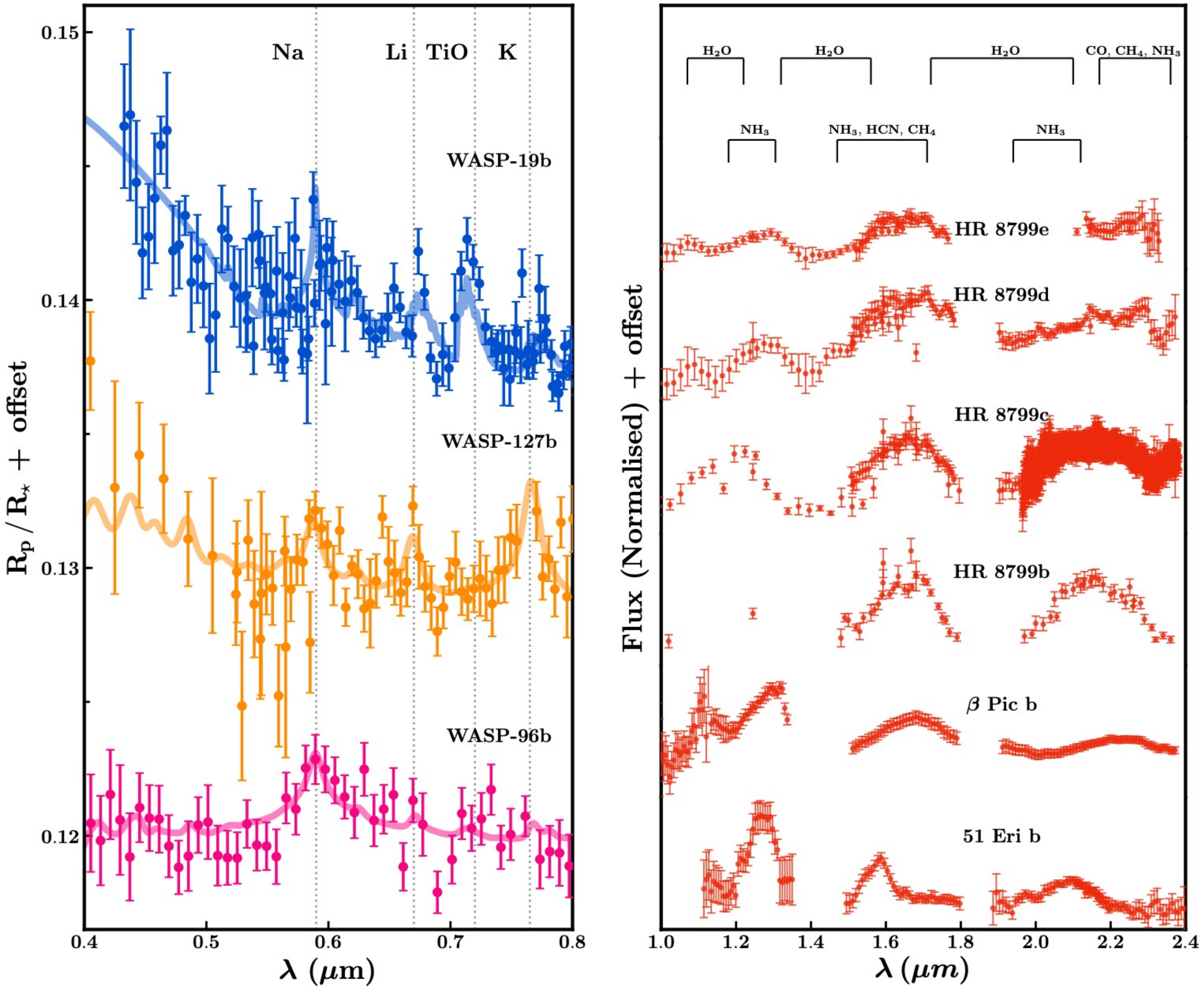


WEBB
SPACE TELESCOPE

Spectra of different directly imaged planets



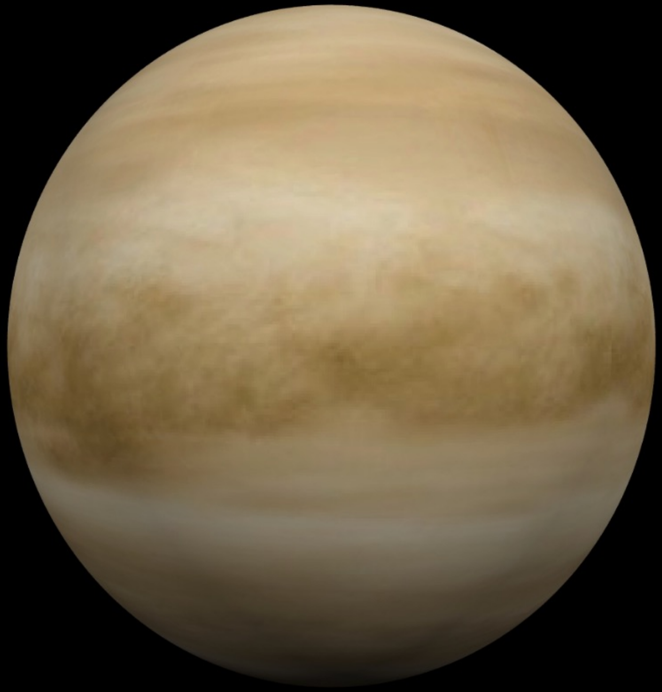




Range of spectra for directly imaged planets

Tomorrow: formation of exoplanets

Terrestrial worlds



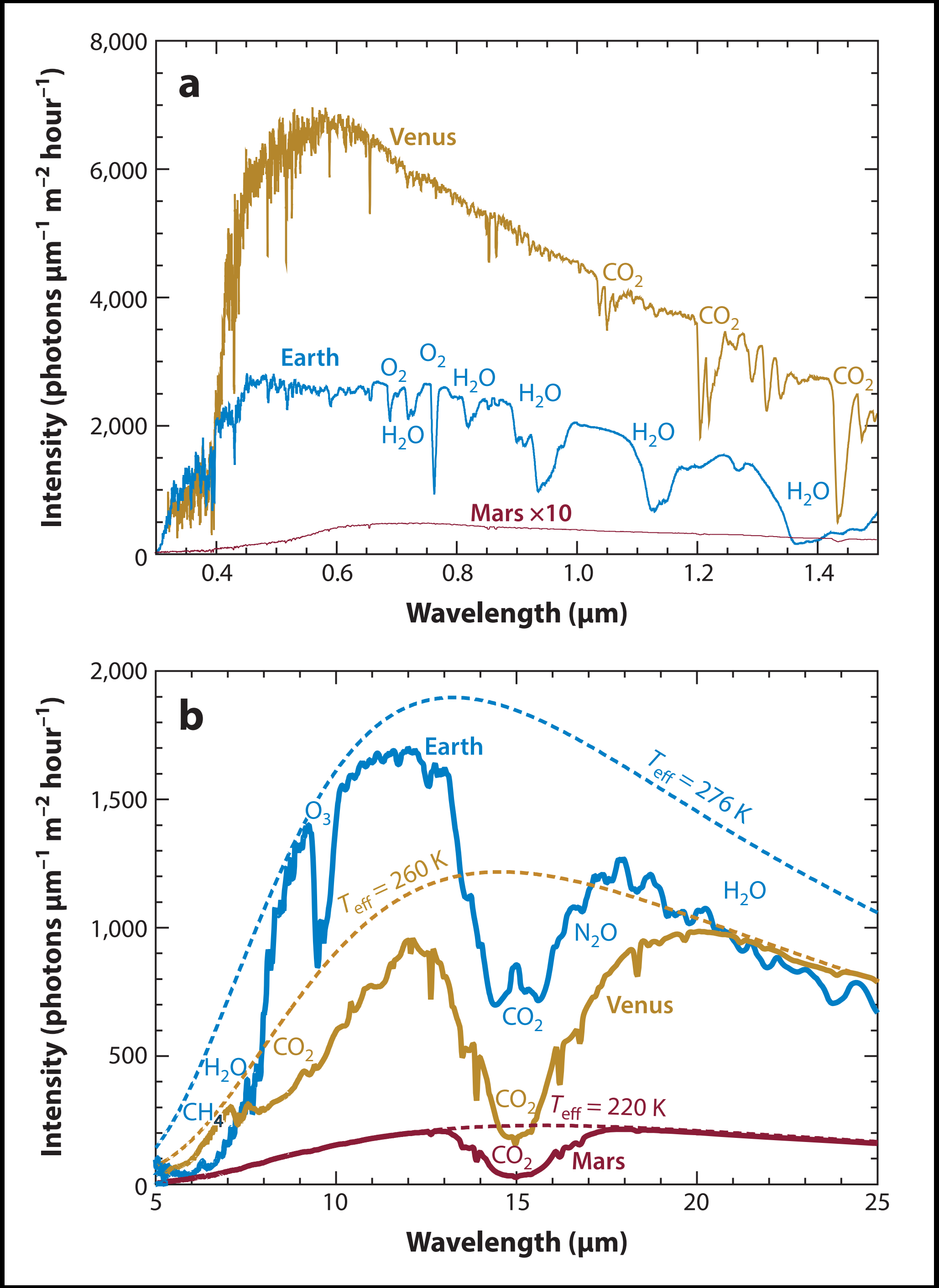
Venus:
thick atmosphere

Earth:
Very nice!

Mars:
Very little atmosphere

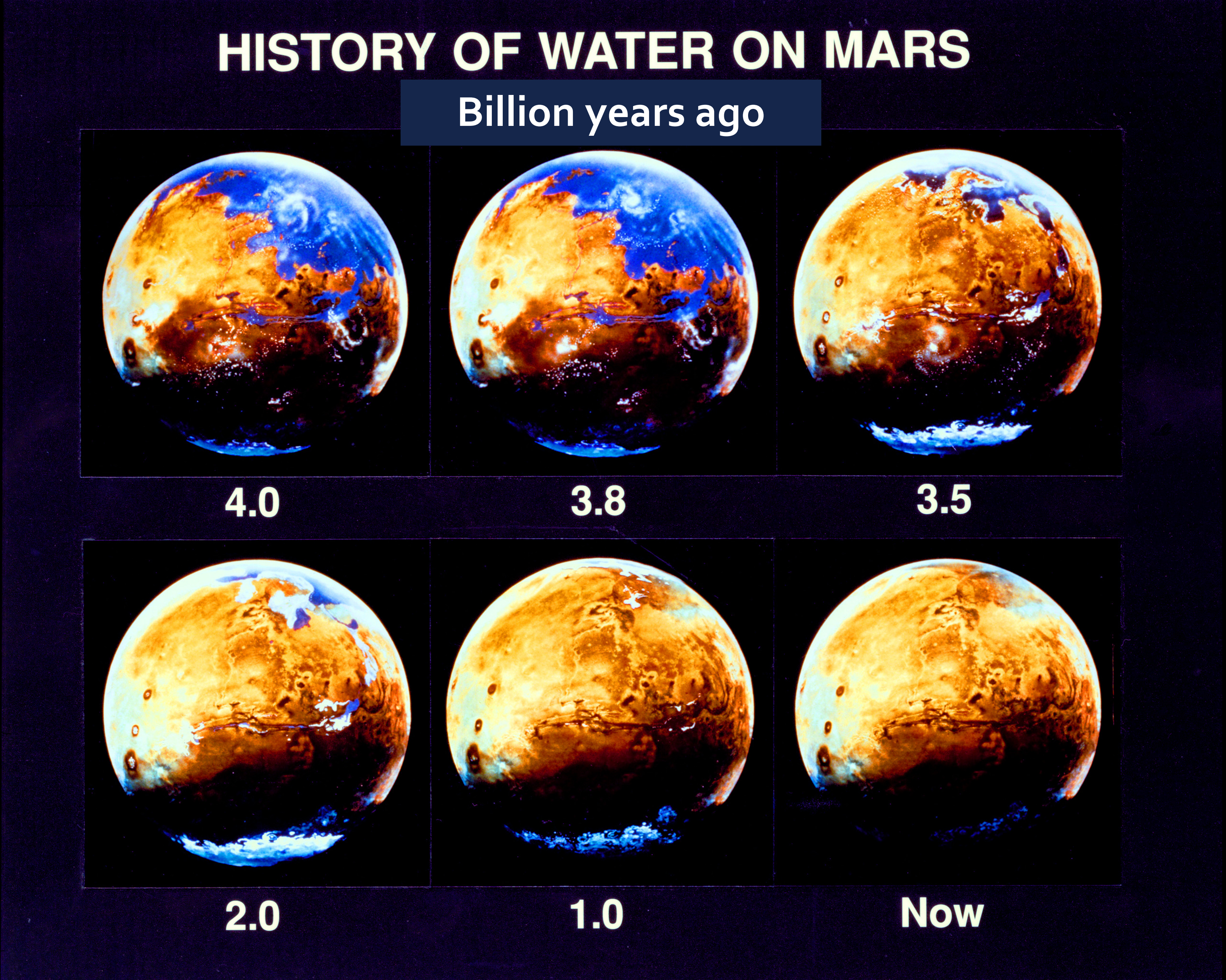
Properties of Earth, Venus, and Mars

Property	Earth	Venus	Mars
Semimajor axis (AU)	1.00	0.72	1.52
Period (year)	1.00	0.61	1.88
Mass (Earth = 1)	1.00	0.82	0.11
Diameter (km)	12,756	12,102	6,790
Density (g/cm^3)	5.5	5.3	3.9
Surface gravity (Earth = 1)	1.00	0.91	0.38
Escape velocity (km/s)	11.2	10.4	5.0
Rotation period (hours or days)	23.9 h	243 d	24.6 h
Surface area (Earth = 1)	1.00	0.90	0.28
Atmospheric pressure (bar)	1.00	90	0.007



With enough S/N, we can detect the differences between Venus, Earth, and Mars-like exoplanets!

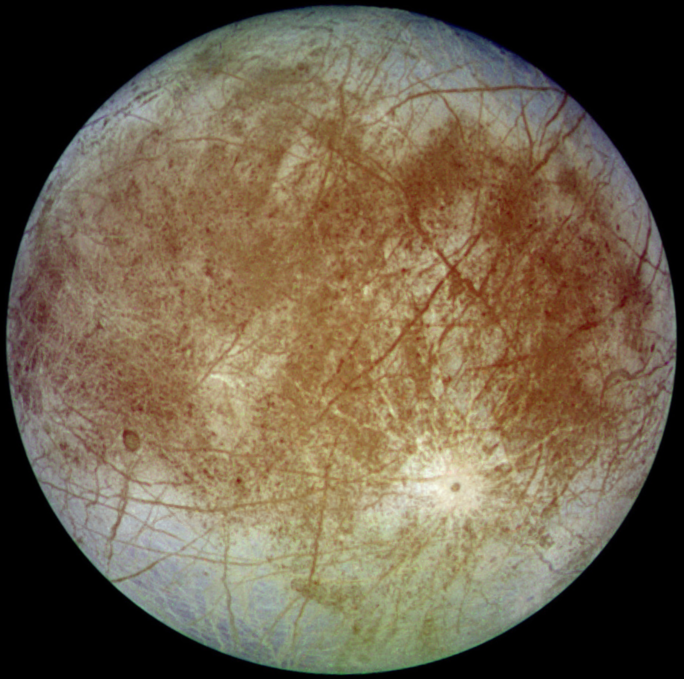
(but need high S/N in infrared)


HISTORY OF WATER ON MARS
Billion years ago
4.0
3.8
3.5
2.0
1.0
Now


Ganymede
5262 km
Titan
5150 km
Mercury
4880 km
Callisto
4806 km
Io
3642 km
Moon
3476 km
Europa
3138 km
Triton
2706 km
Pluto
2300 km
Titania
1580 km

NASA/Dragonfly Titan Mission
(artist image, planned for late 2020s)

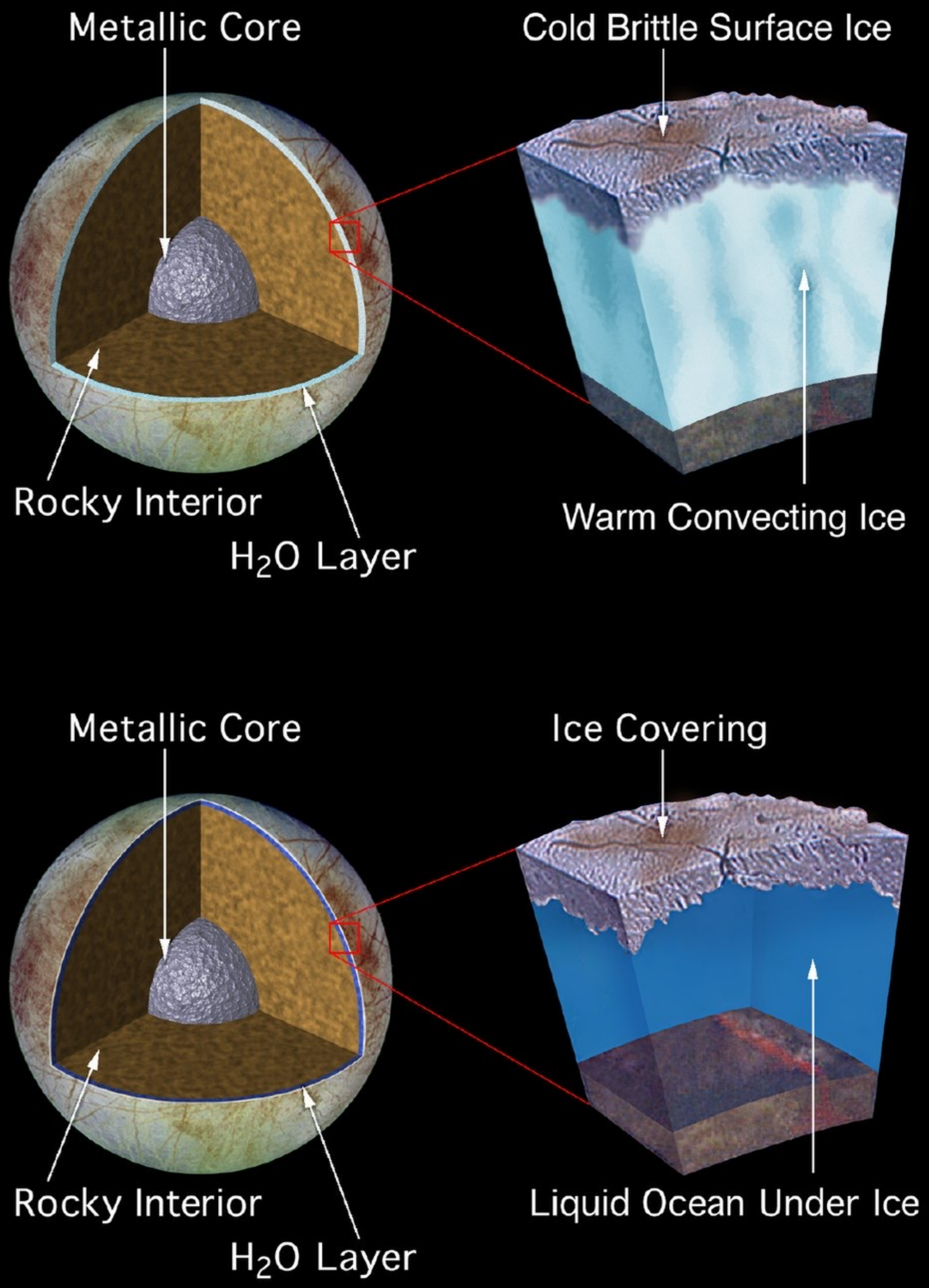
Ice worlds of Jupiter



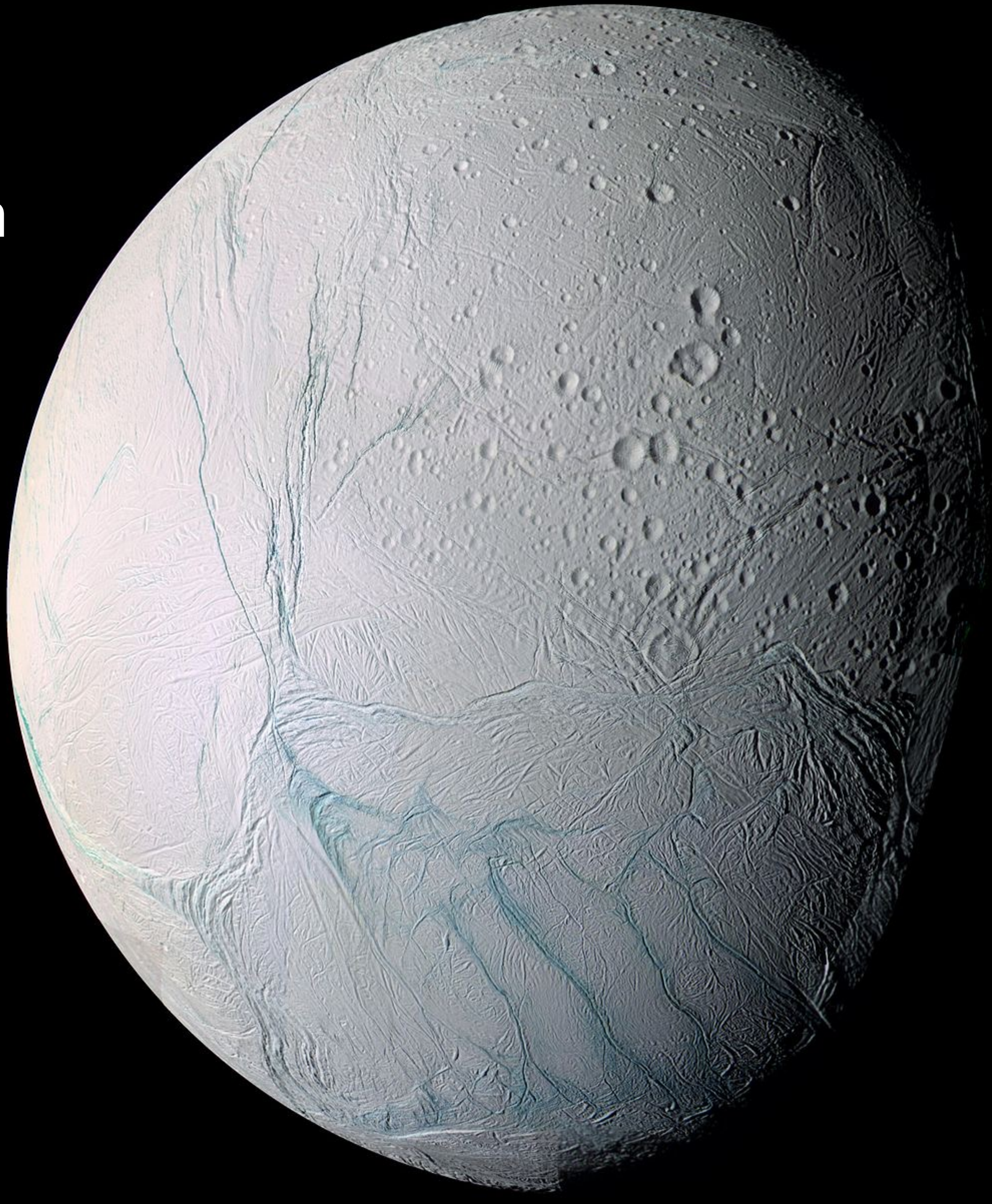
Europa

Ganymede

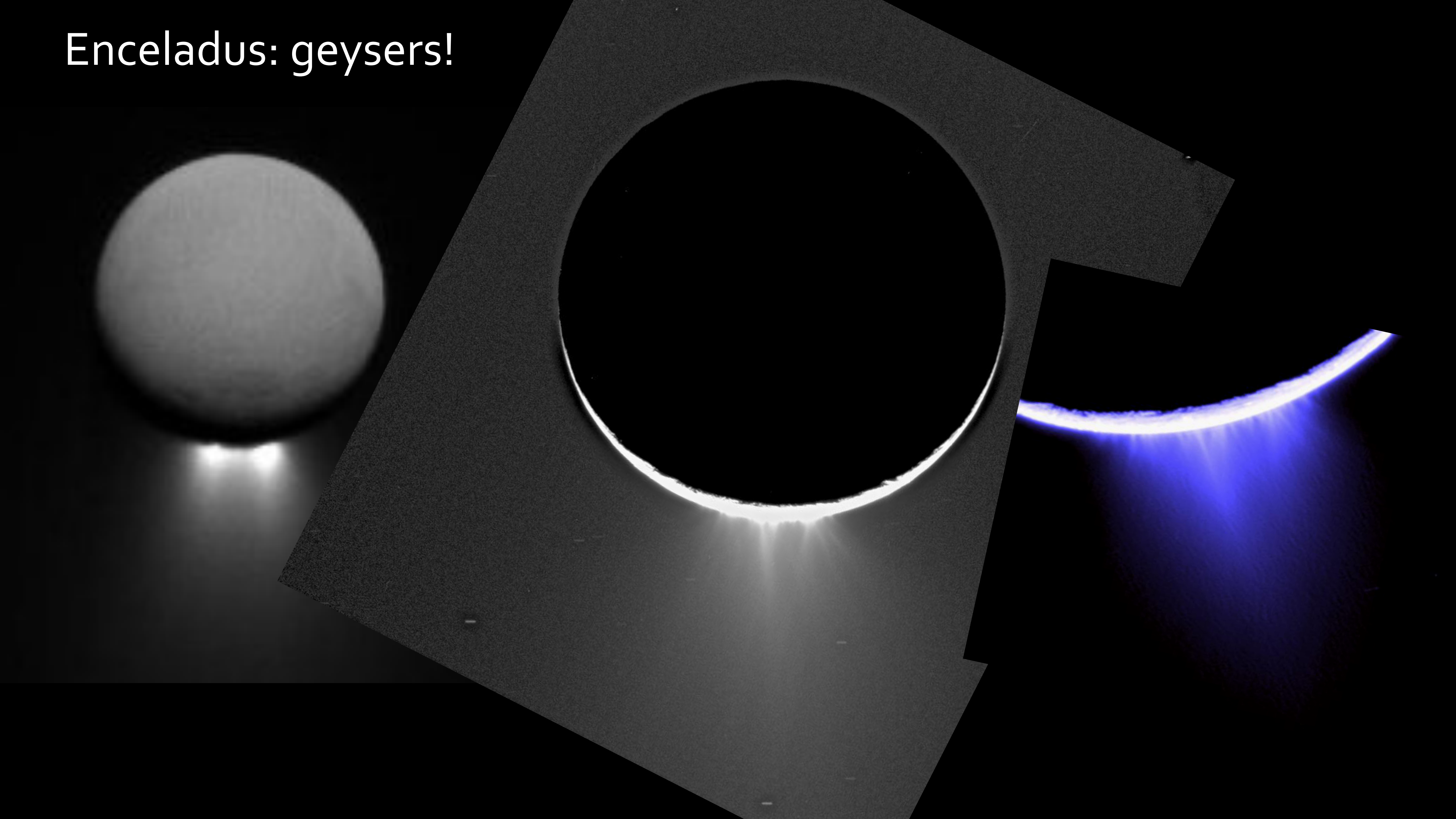
Callisto

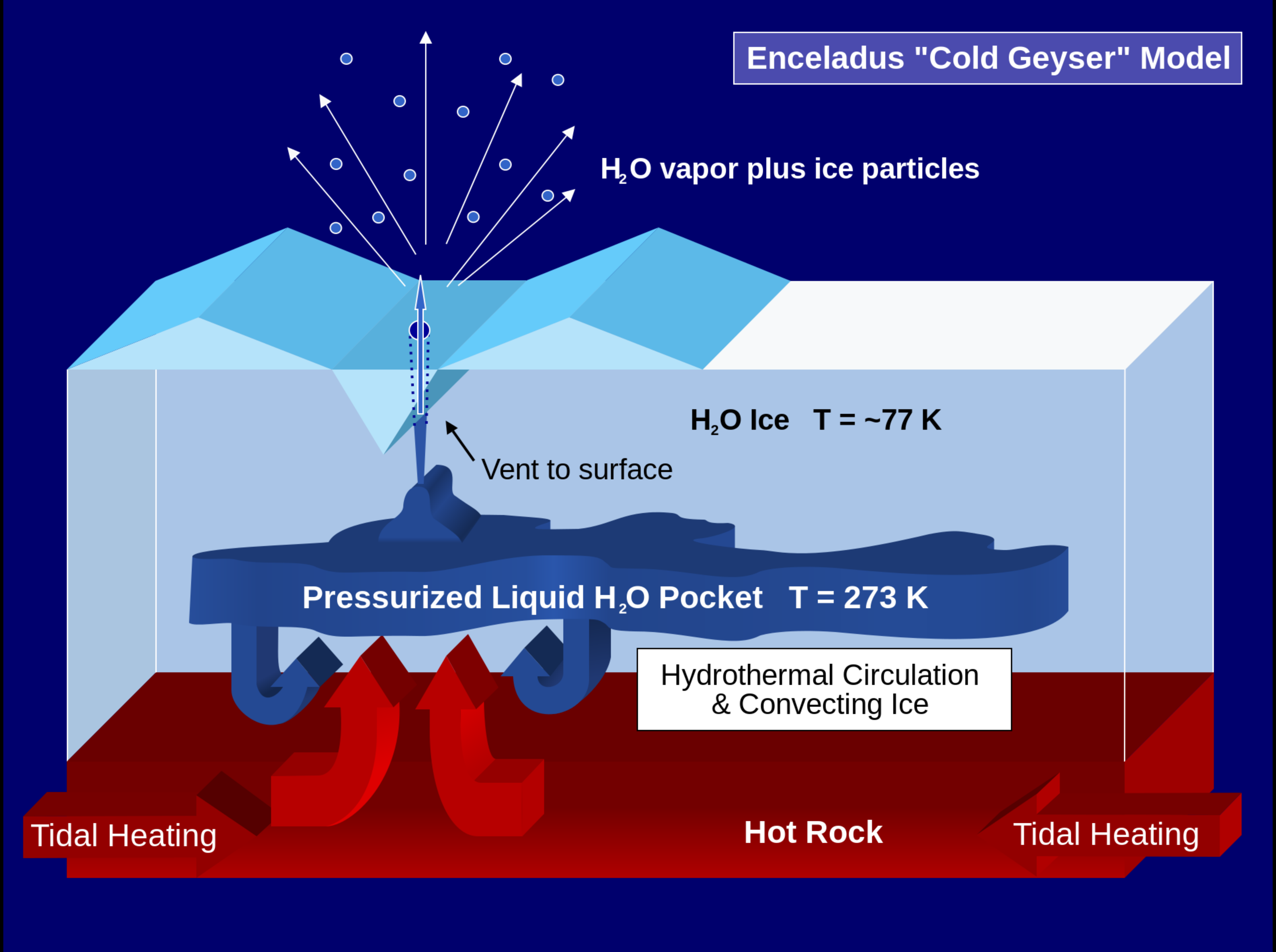

Metallic Core
Cold Brittle Surface Ice
Rocky Interior
Warm Convecting Ice
H_2O Layer
Metallic Core
Ice Covering
Rocky Interior
Liquid Ocean Under Ice
H_2O Layer

Enceladus: ice moon of Saturn

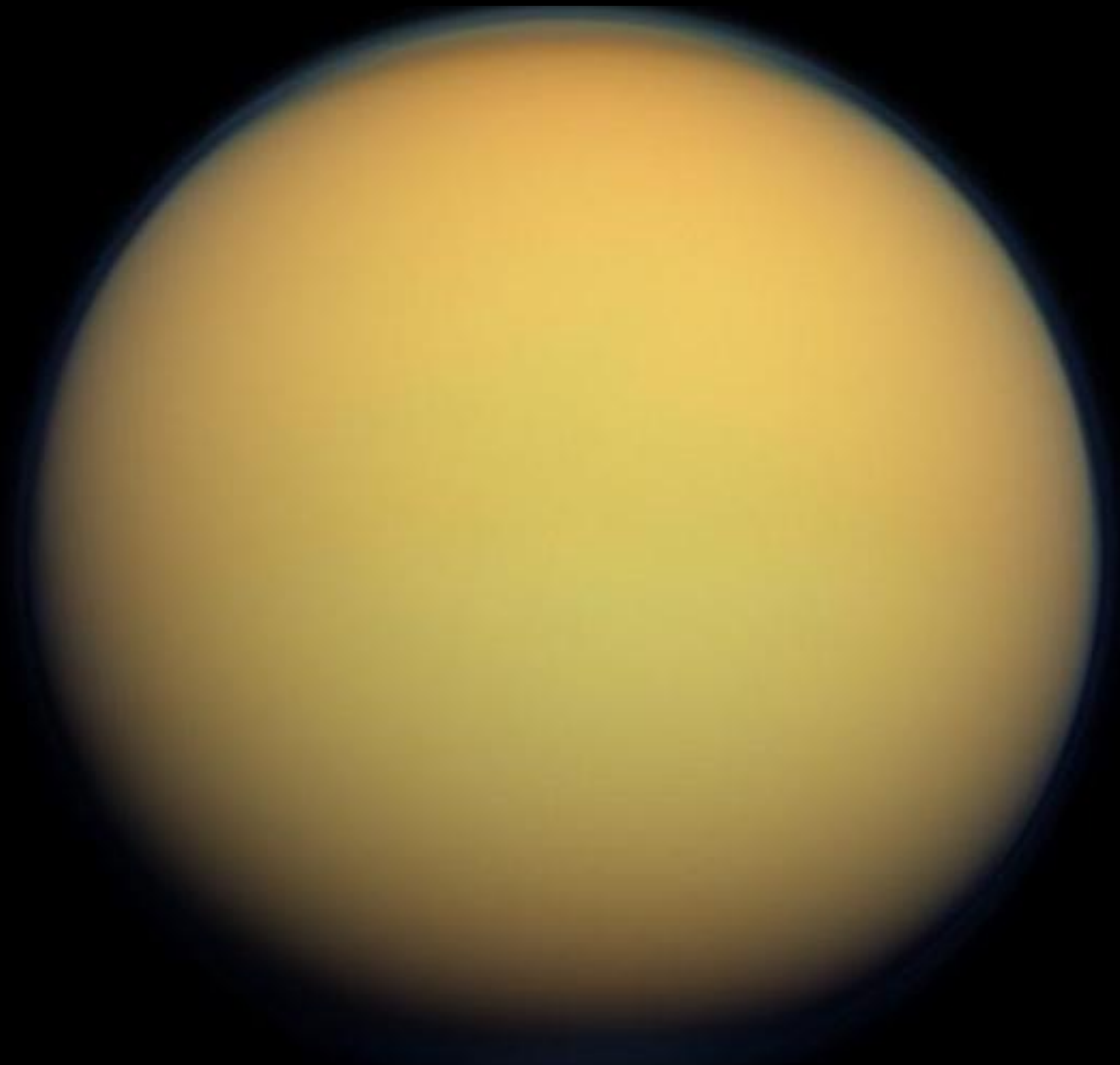


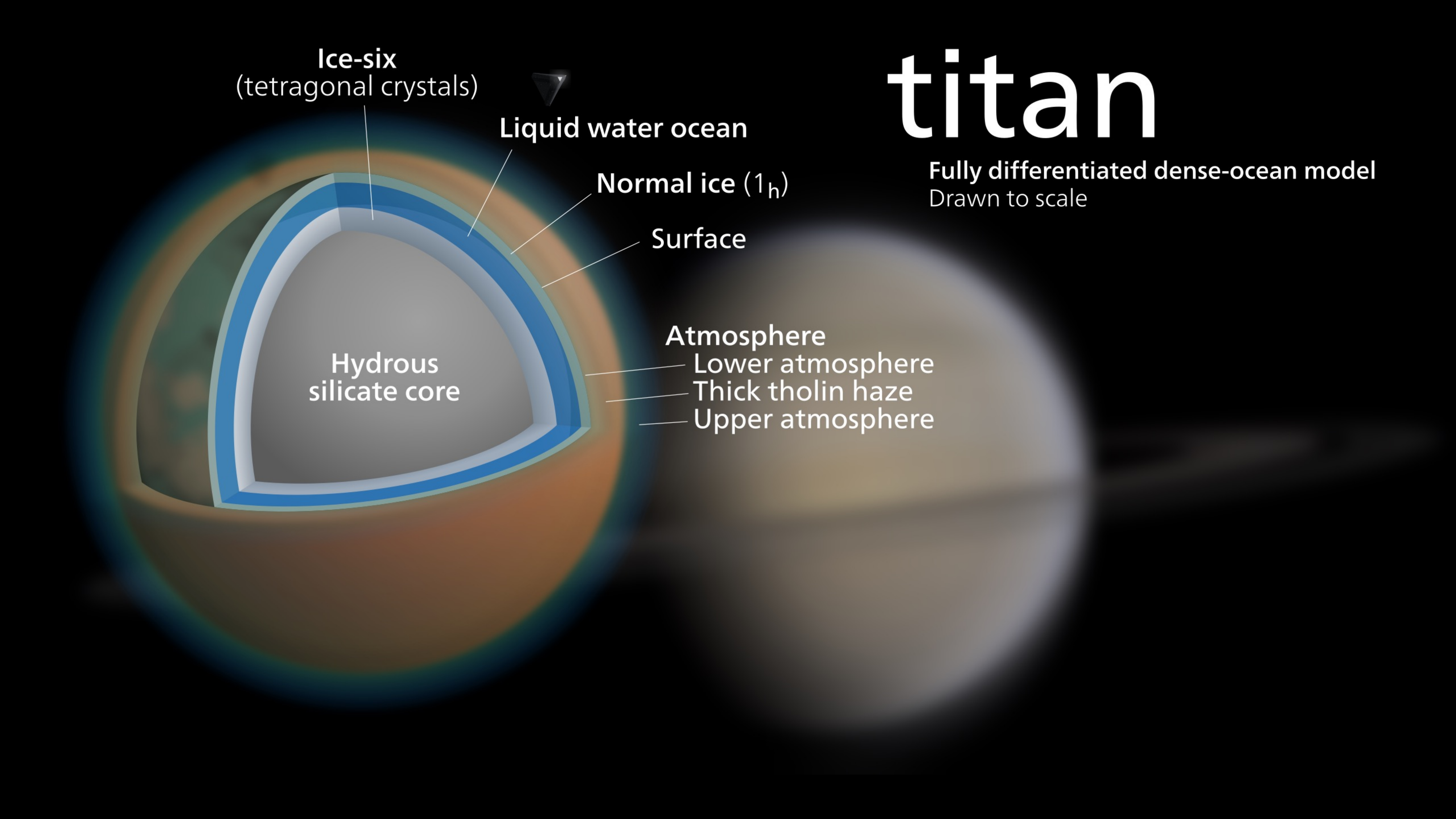
Enceladus: geysers!



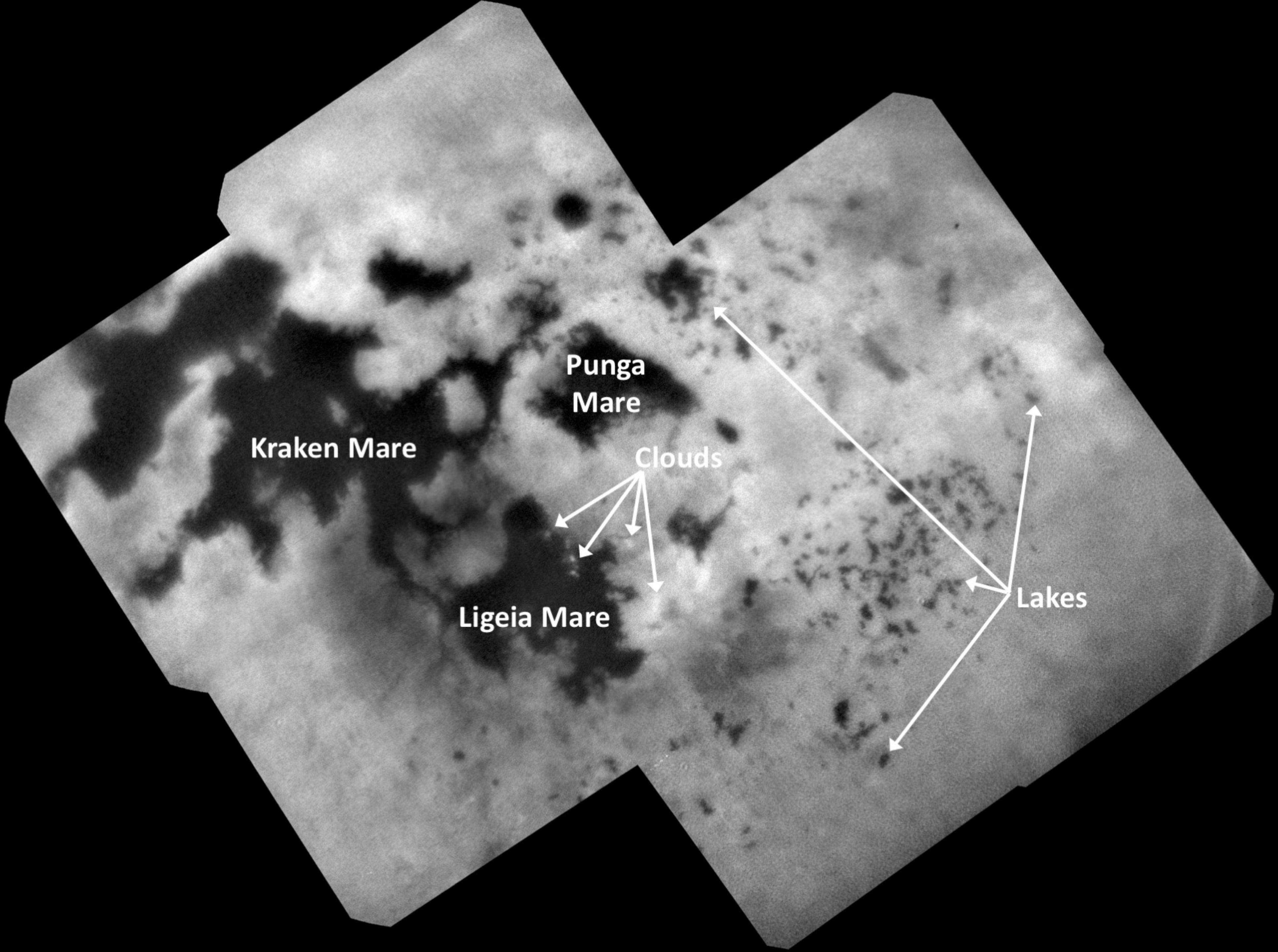

Enceladus "Cold Geyser" Model
H_2O vapor plus ice particles
H_2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H_2O Pocket T = 273 K
Hydrothermal Circulation & Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating

Titan: the main moon of Saturn

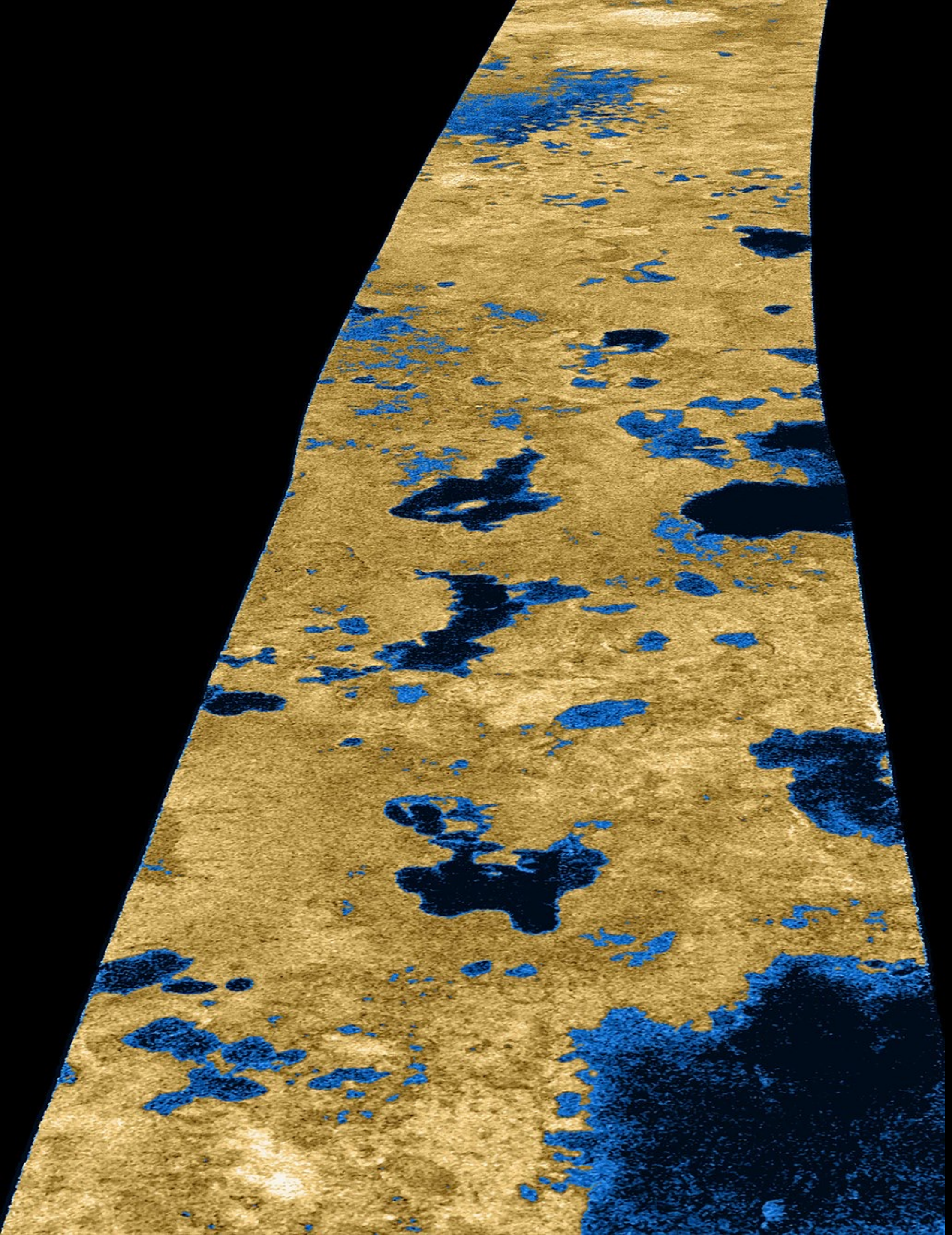


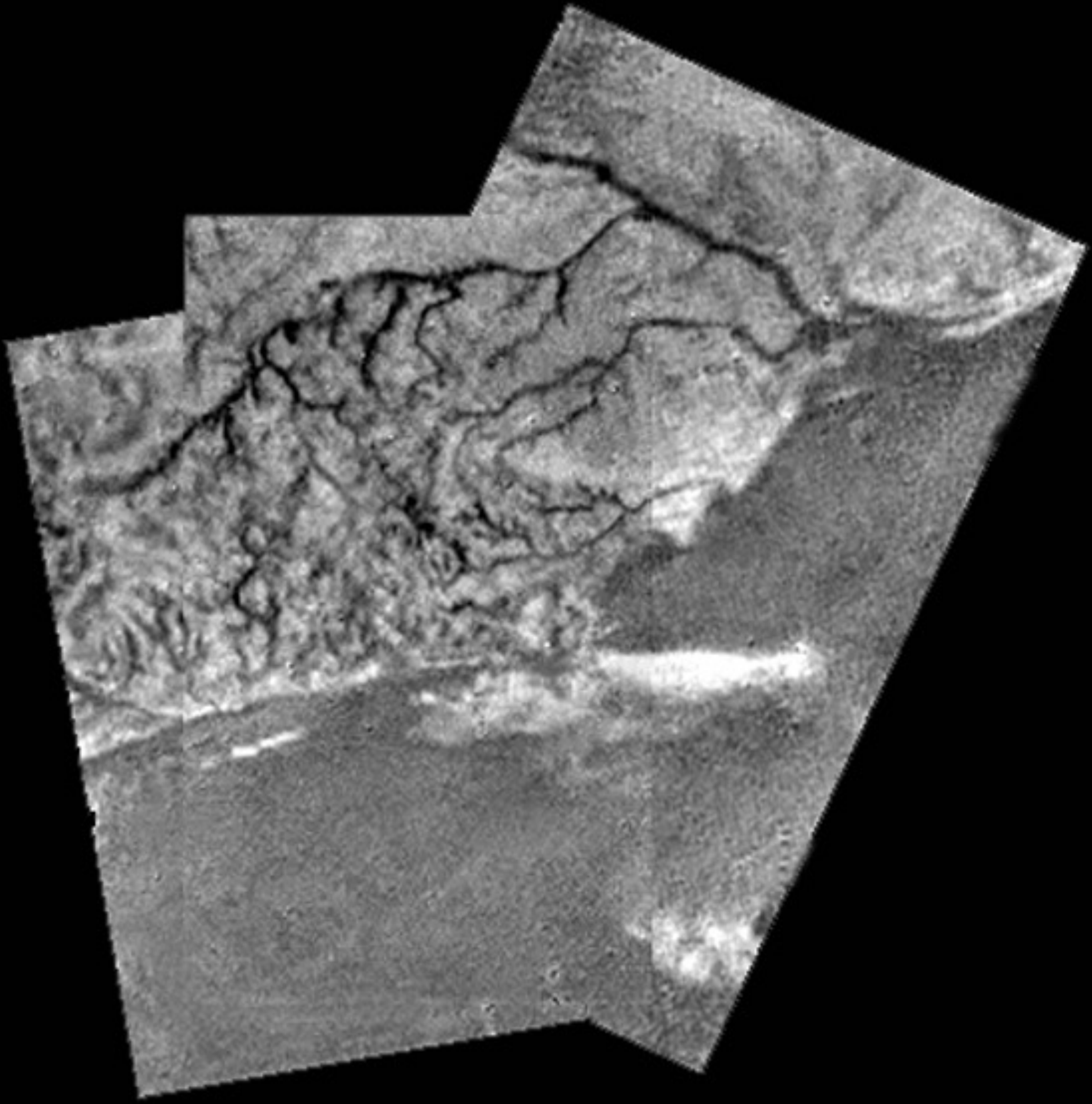


titan
Fully differentiated dense-ocean model
Drawn to scale
Ice-six
(tetragonal crystals)
Liquid water ocean
Normal ice (1h)
Surface
Atmosphere
Lower atmosphere
Thick tholin haze
Upper atmosphere
Hydrous silicate core



Punga Mare
Kraken Mare
Clouds
Ligeia Mare
Lakes

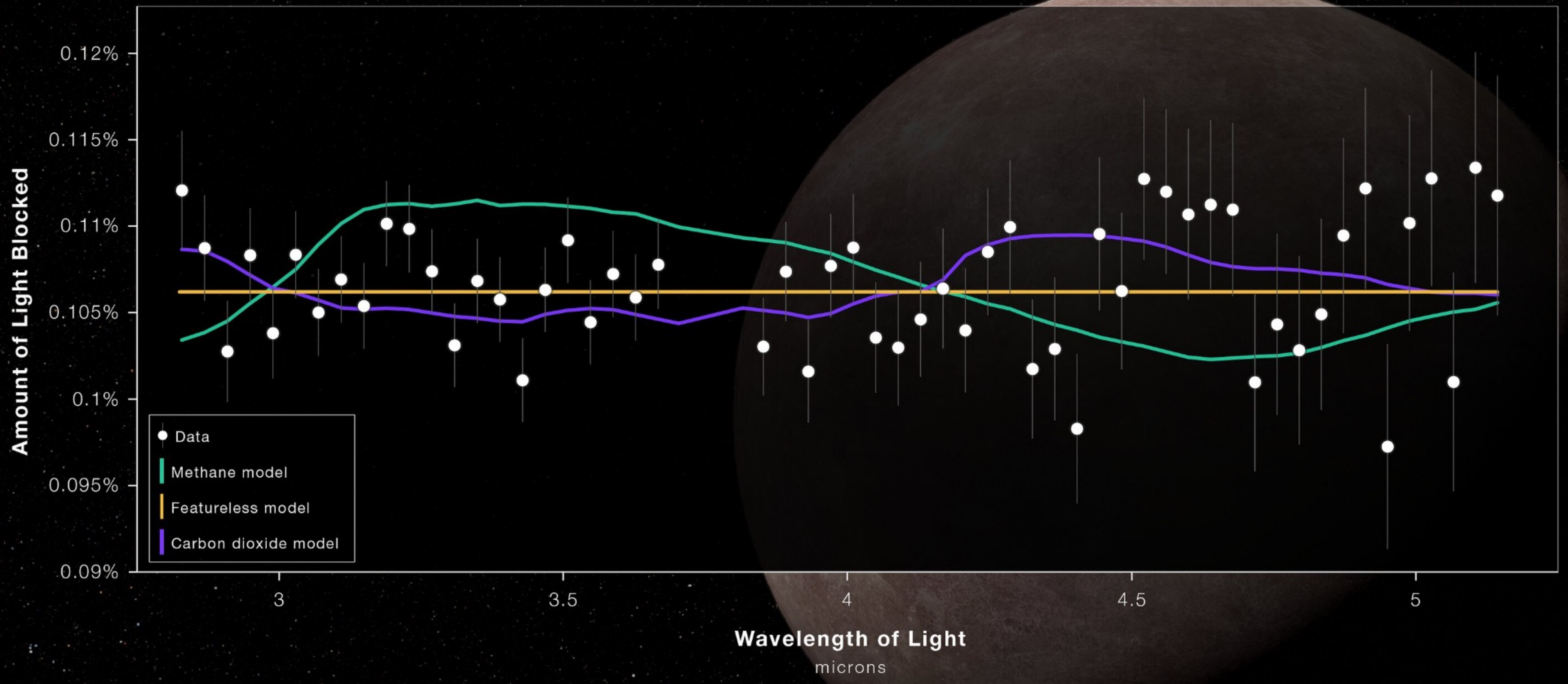




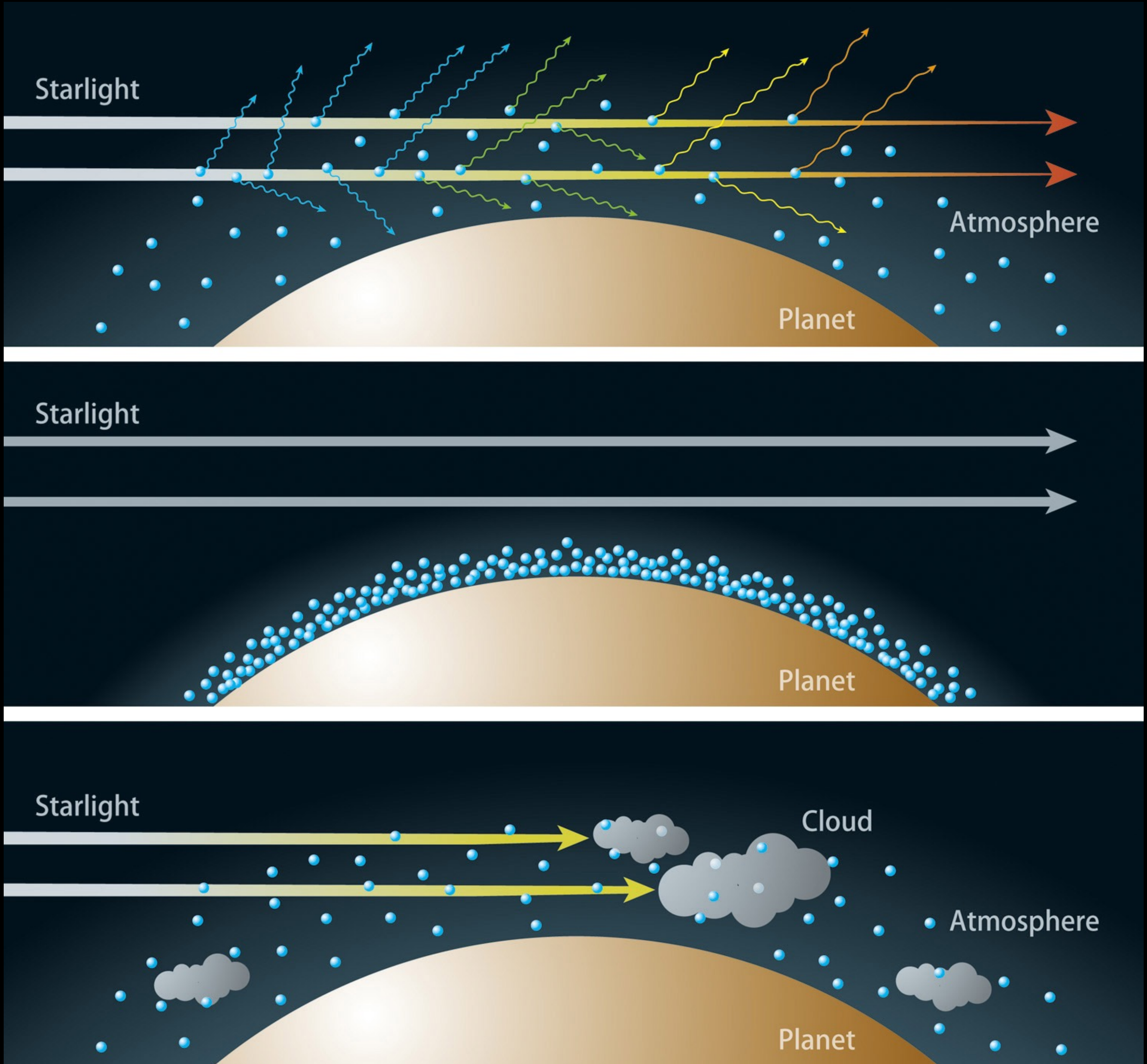
ROCKY EXOPLANET LHS 475 b

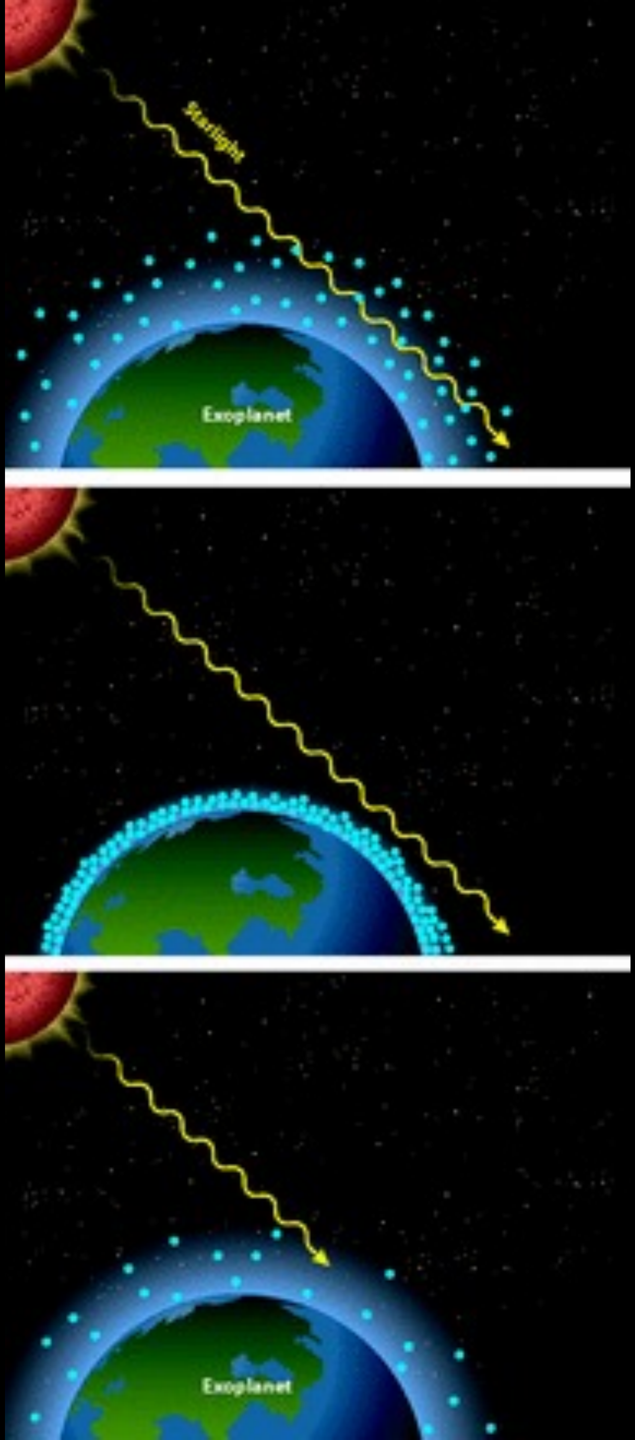
TRANSMISSION SPECTRUM

NIRSpec | Bright Object Time-Series Spectroscopy



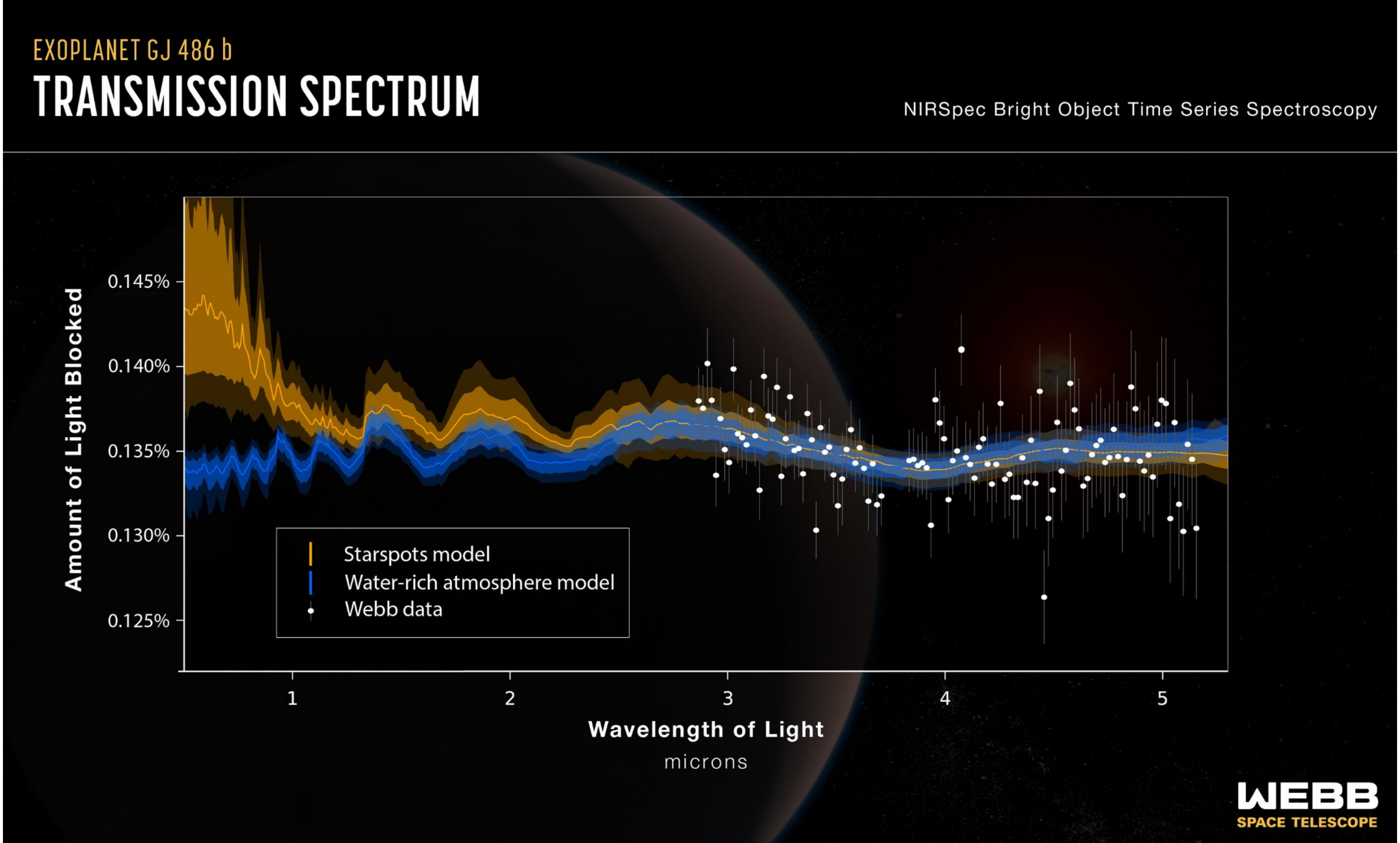
WEBB
SPACE TELESCOPE


Starlight
Atmosphere
Planet
Starlight
Planet
Starlight
Cloud
Atmosphere
Planet



Exoplanet atmospheres!

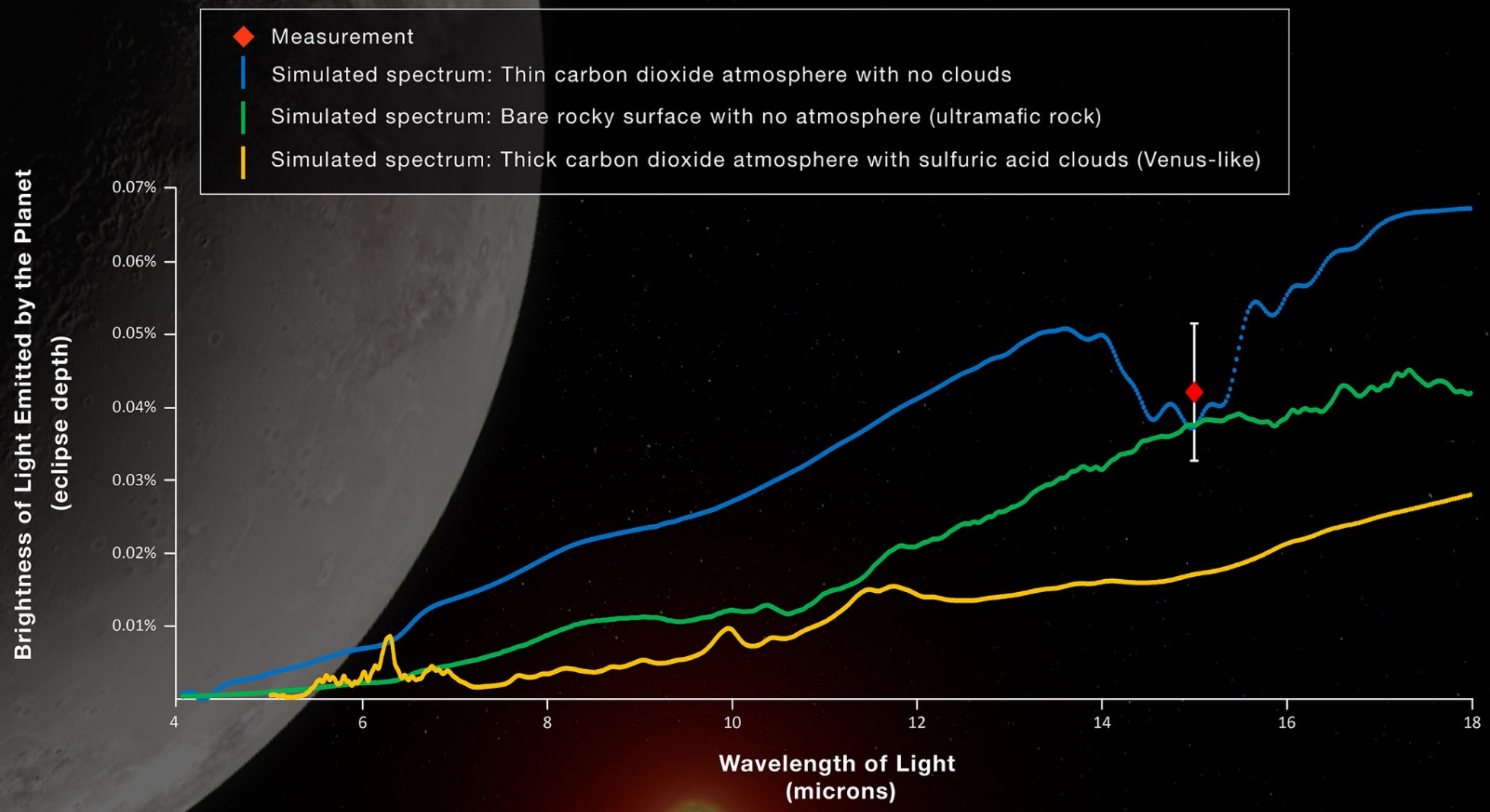
E^o	Oxidizing half-reaction	Reducing half-reaction
−0.535	$CO \rightarrow CO_2$	$CO_2 \rightarrow CO$
−0.482	$CH_2O \rightarrow CO_2$	$CO_2 \rightarrow CH_2O$
−0.431	$H_2 \rightarrow 2H^+$	$2H^+ \rightarrow H_2$
−0.375	$2NH_3 \rightarrow N_2$	$N_2 \rightarrow NH_3$
−0.280	$H_2S \rightarrow S$	$S \rightarrow H_2S$
−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	$H_2O \rightarrow O_2$	$O_2 \rightarrow H_2O$


EXOPLANET GJ 486 b
TRANSMISSION SPECTRUM
NIRSpec Bright Object Time Series Spectroscopy
Amount of Light Blocked
0.145%
0.140%
0.135%
0.130%
0.125%
1
2
3
4
5
Wavelength of Light
microns
Starspots model
Water-rich atmosphere model
Webb data
WEBB
SPACE TELESCOPE

ROCKY EXOPLANET TRAPPIST-1 c

EMISSION SPECTRA

MIRI | Time-Series Photometry (F1500W)



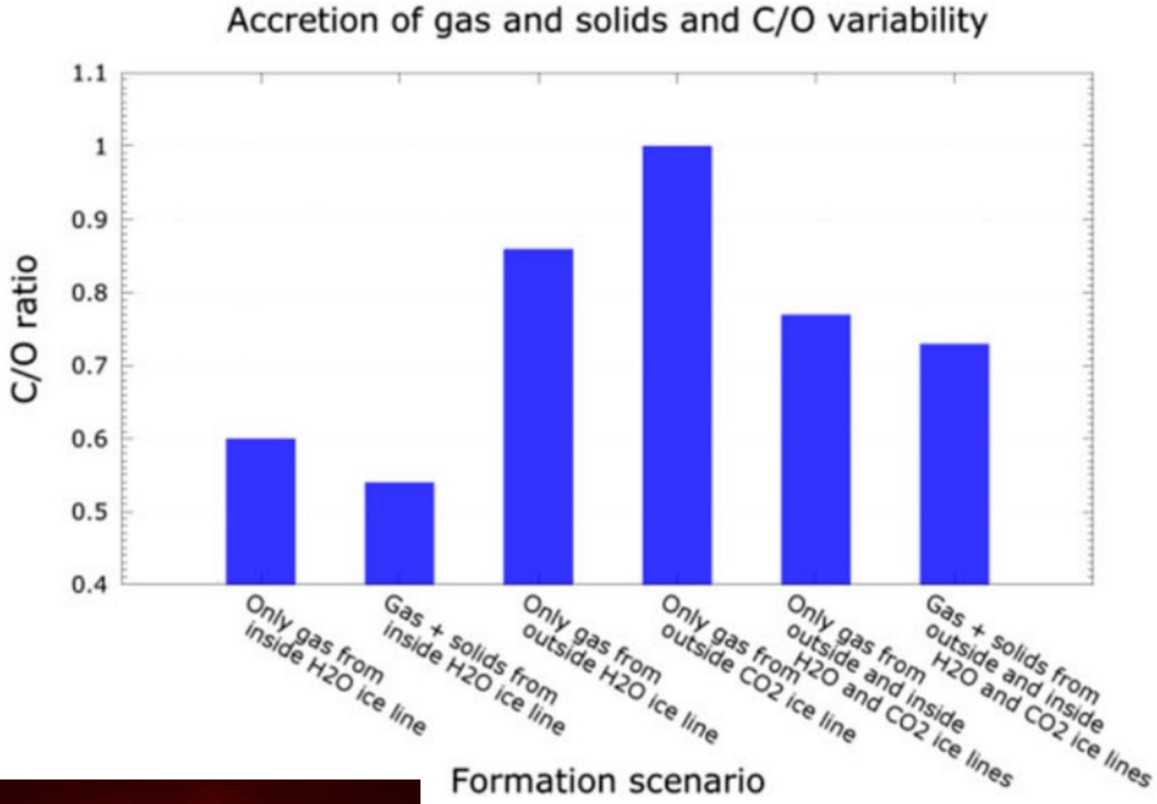
WEBB
SPACE TELESCOPE

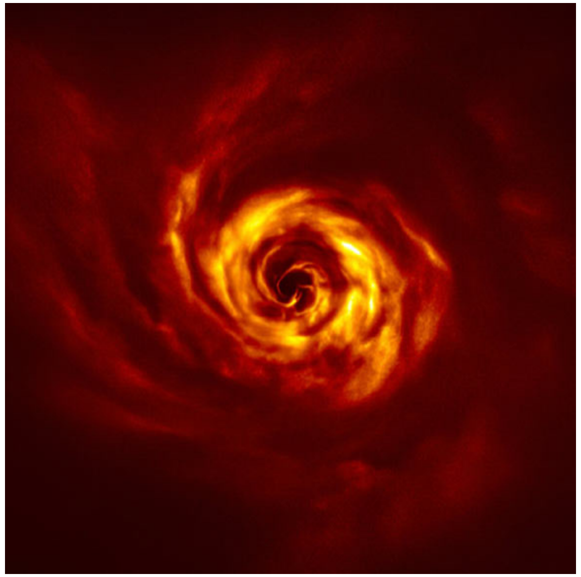
Futures of atmosphere studies

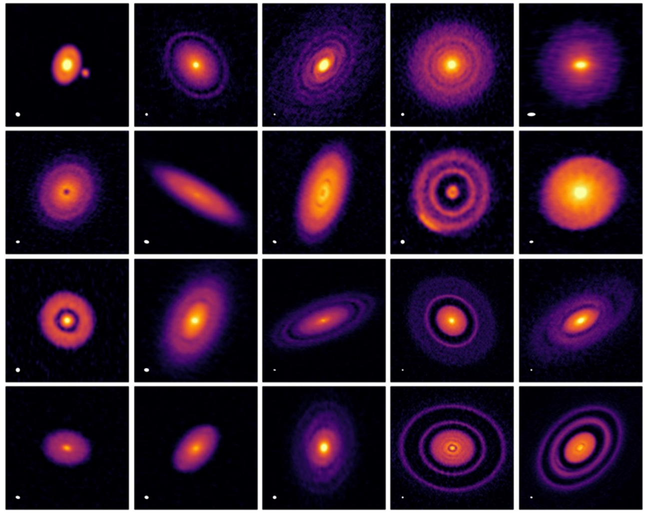
- JWST: mid-IR telescope, 10-20 years of discovery
  - $10 billion USD, led by NASA+Canada/ESA
  - Most powerful astronomy facility ever built
- ARIEL (ESA)
- ELTs (Extremely Large Telescopes): next generation…

Next class: formation of exoplanets

- Where and how do exoplanets form?
  - Protoplanetar disks!
- How do different formation scenarios affect planet chemistry and habitability?







Next class: planet formation