Exoplanets: Composition & Characterization

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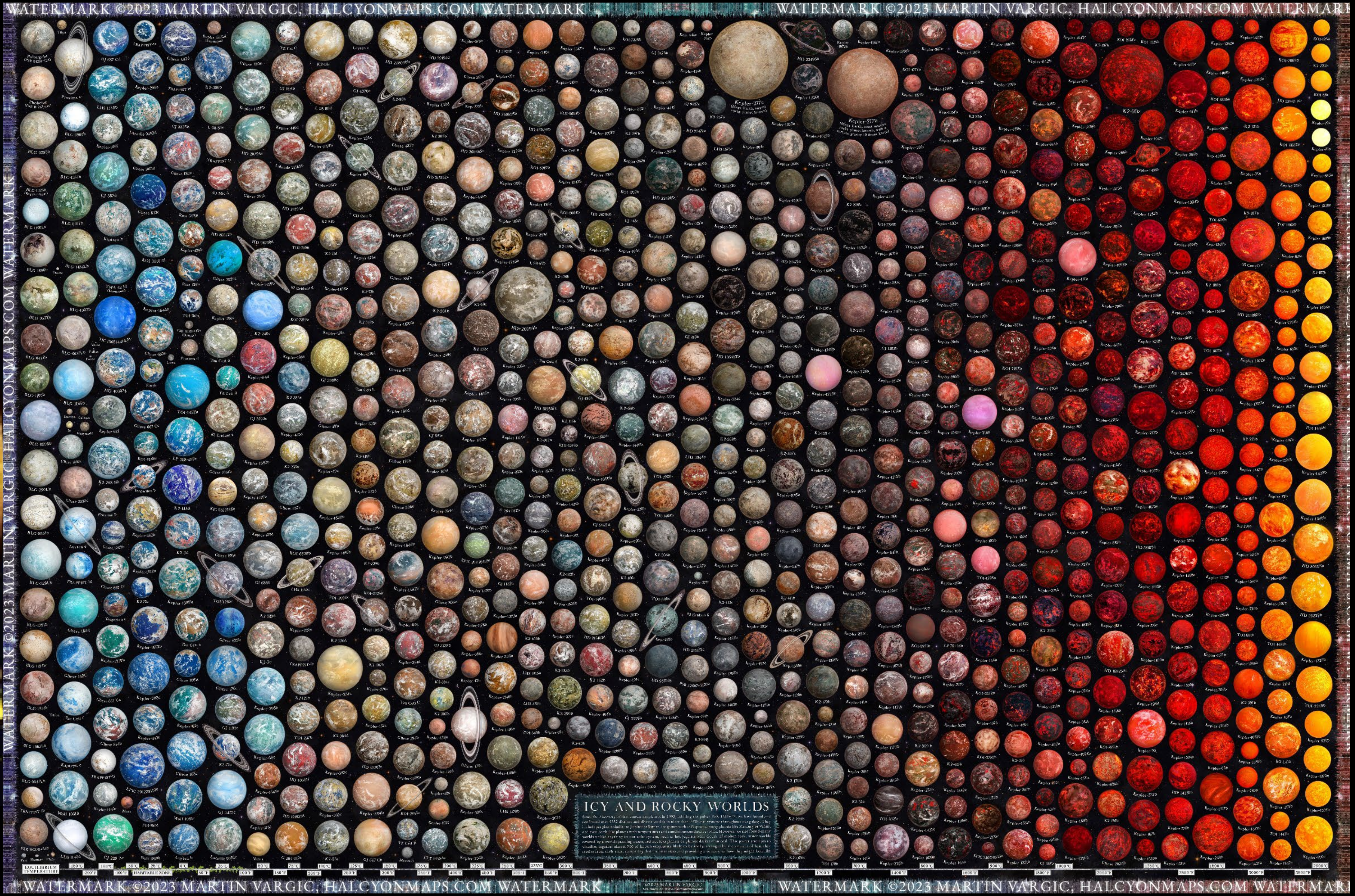
UNM PHYS 480/581 GUEST LECTURE
NOVEMBER 25, 2024

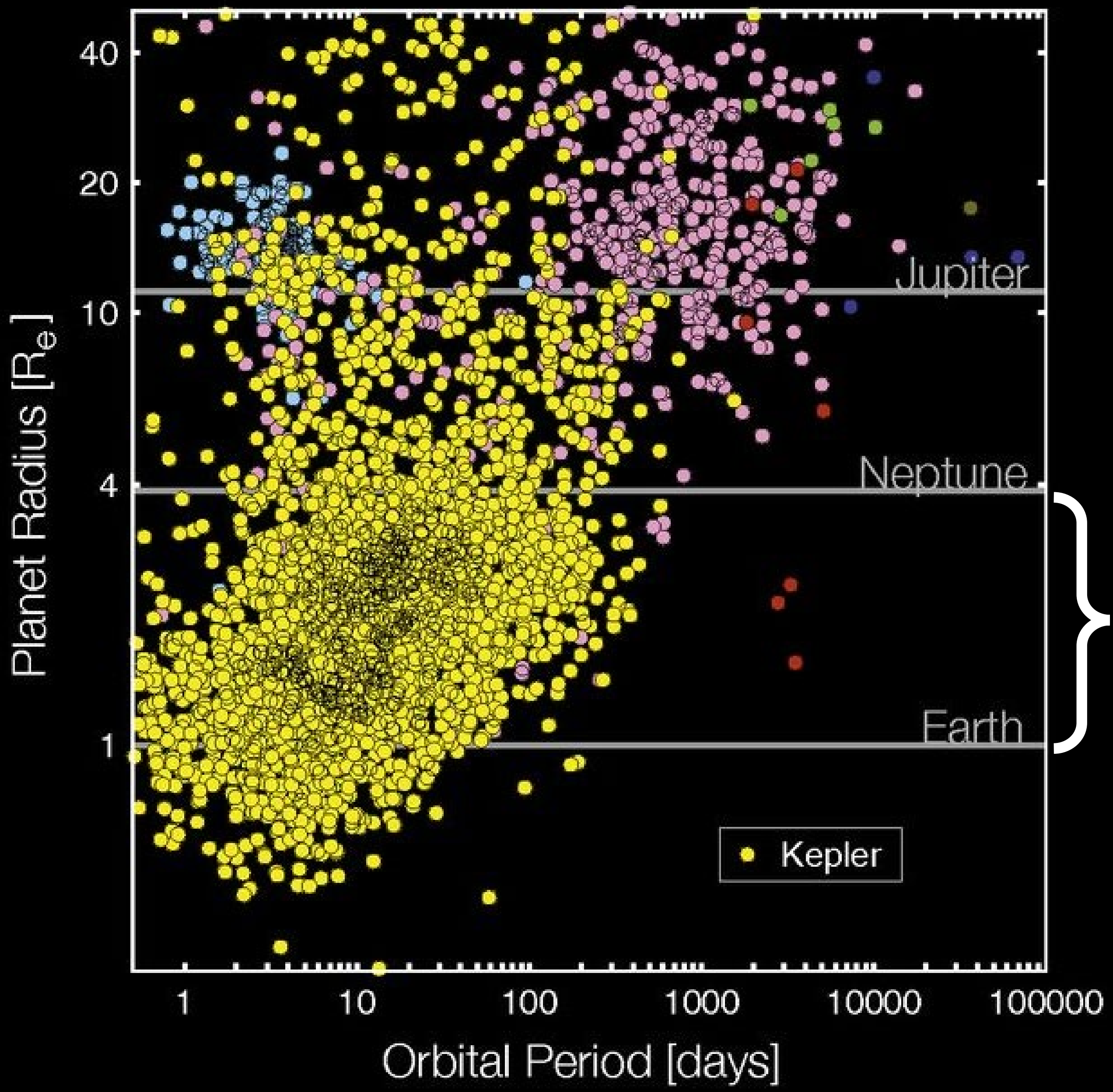
OUTLINE

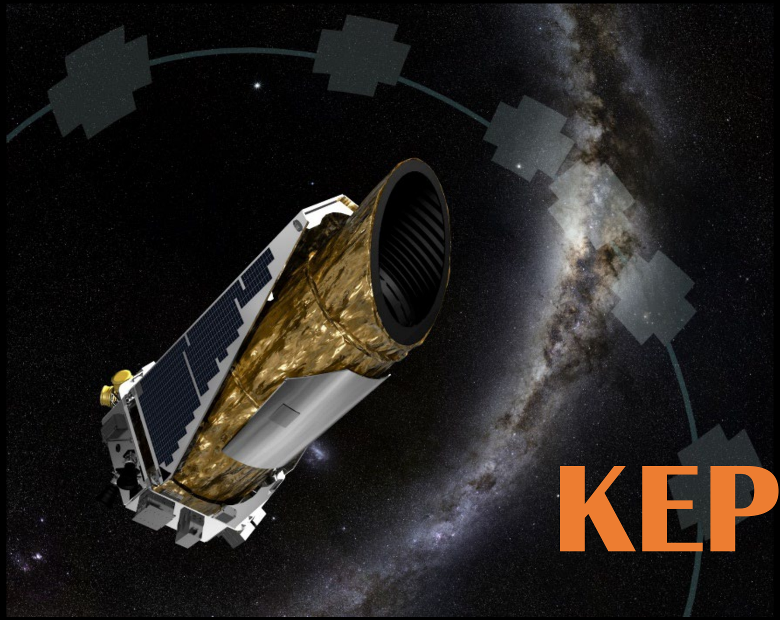
- **Exoplanet Detection Methods**
  - Transits
  - Radial Velocity
- **Planetary Interiors & Composition**
  - Mass-Radius Relations/Diagrams
  - Ternary Diagrams (+ interactive exercise)
  - Compressed vs. Uncompressed Densities
- **Hot Super-Earths Research**
  - Planet Detection: TOI-1075 b
  - Surface Characterization: Low-albedo Surfaces of Lava Worlds
  - Atmospheric Characterization: Sodium in Hot Super-Earths Atmospheres



**Credit: Getty Images;
Martin Vargic**

Credit: NASA; N. Batalha (2014)





KEPLER

The most common size of planet in the galaxy is between the size of Earth and Neptune (1-4 R_{Earth}).

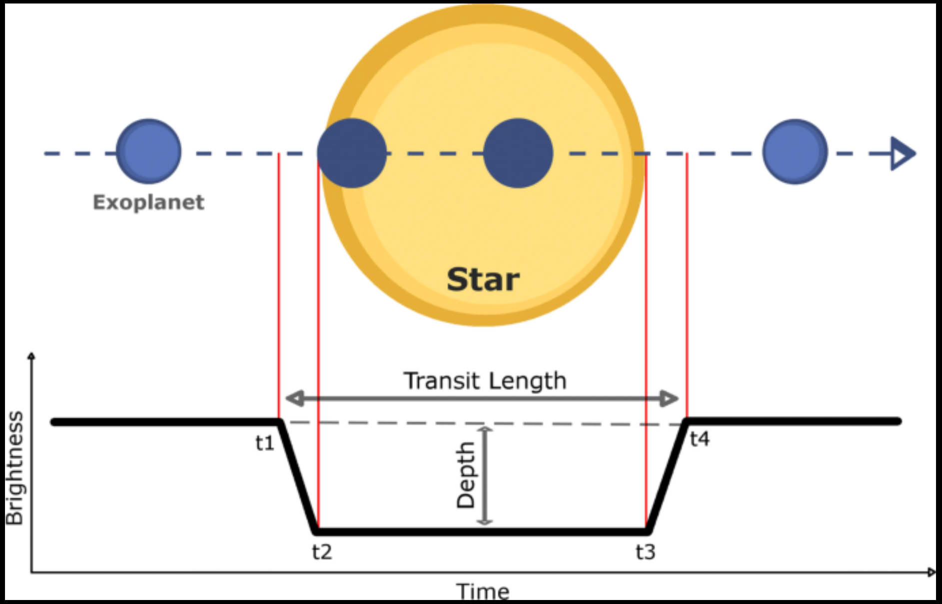
EXOPLANET DETECTION METHODS

THE TRANSIT METHOD

Credit: NASA

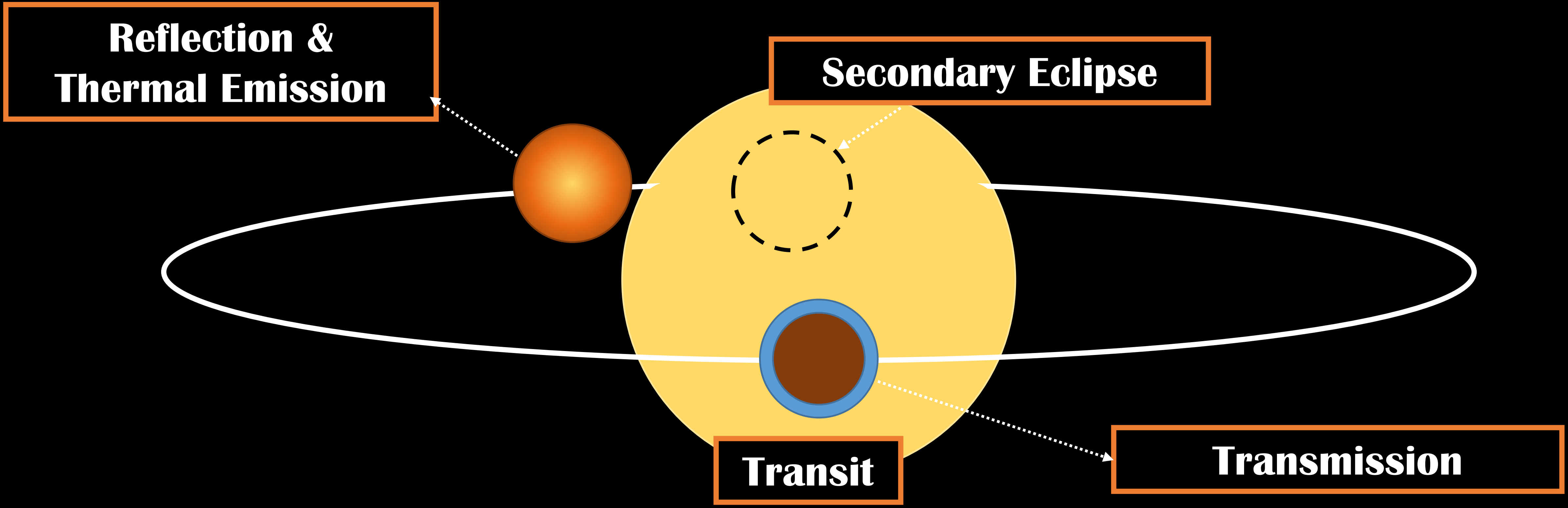
THE TRANSIT METHOD

- Measure change in flux of star as orbiting planet passes in front of the star, and between the star and observer.
- Transit depth (δ) measured from light curve.
  - Planet-to star-flux ratio → Planet-to-star area ratio
- **Yields planet radius.**
  - $\delta = \left(\frac{R_{planet}}{R_{star}}\right)^2$
  - $R_{planet} = \sqrt{\delta} \times R_{star}$



Credit: Jara-Maldonado et al. (2020)

CHARACTERIZATION TECHNIQUES



Reflection & Thermal Emission

Secondary Eclipse

Transit

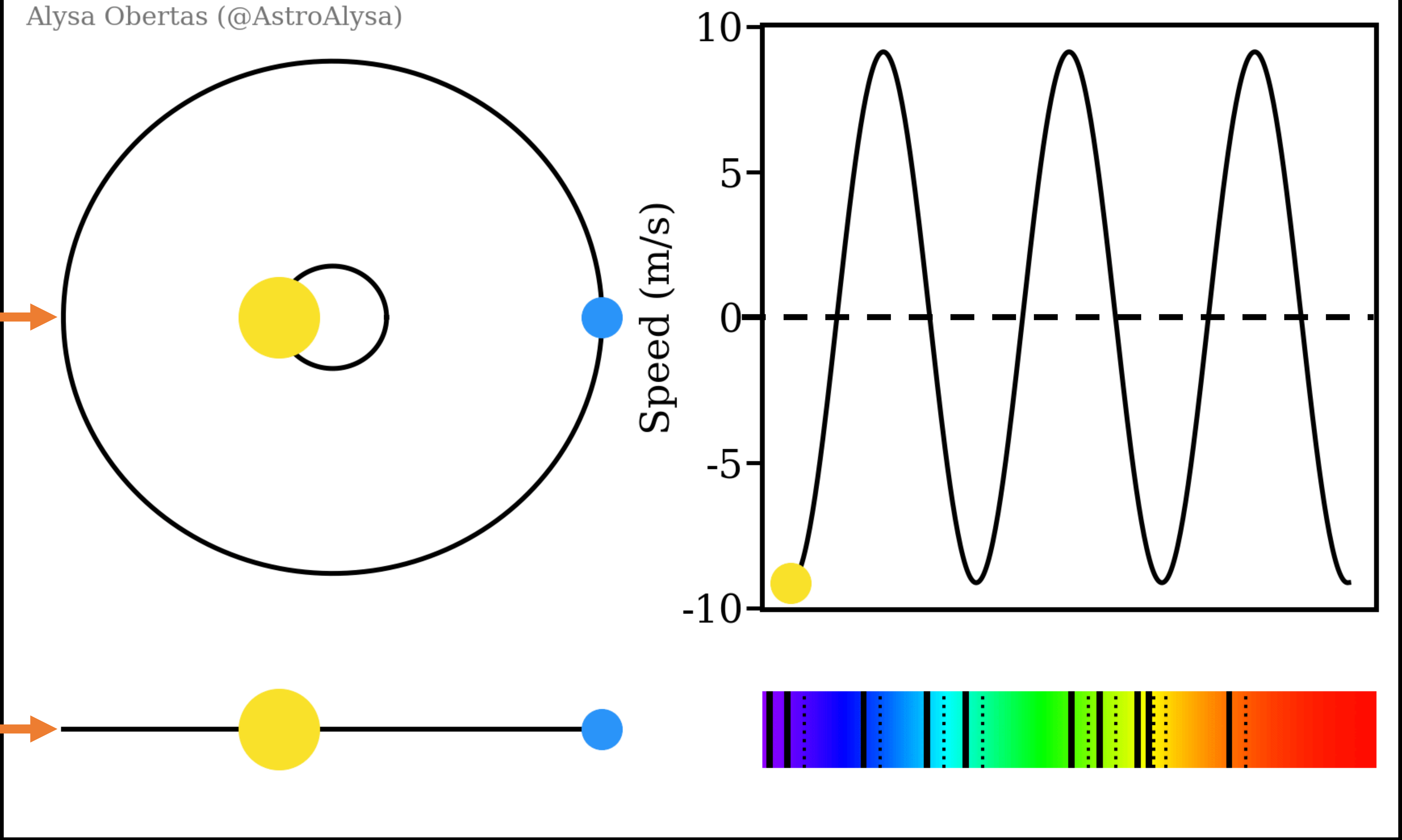
Transmission

Figure not to scale.

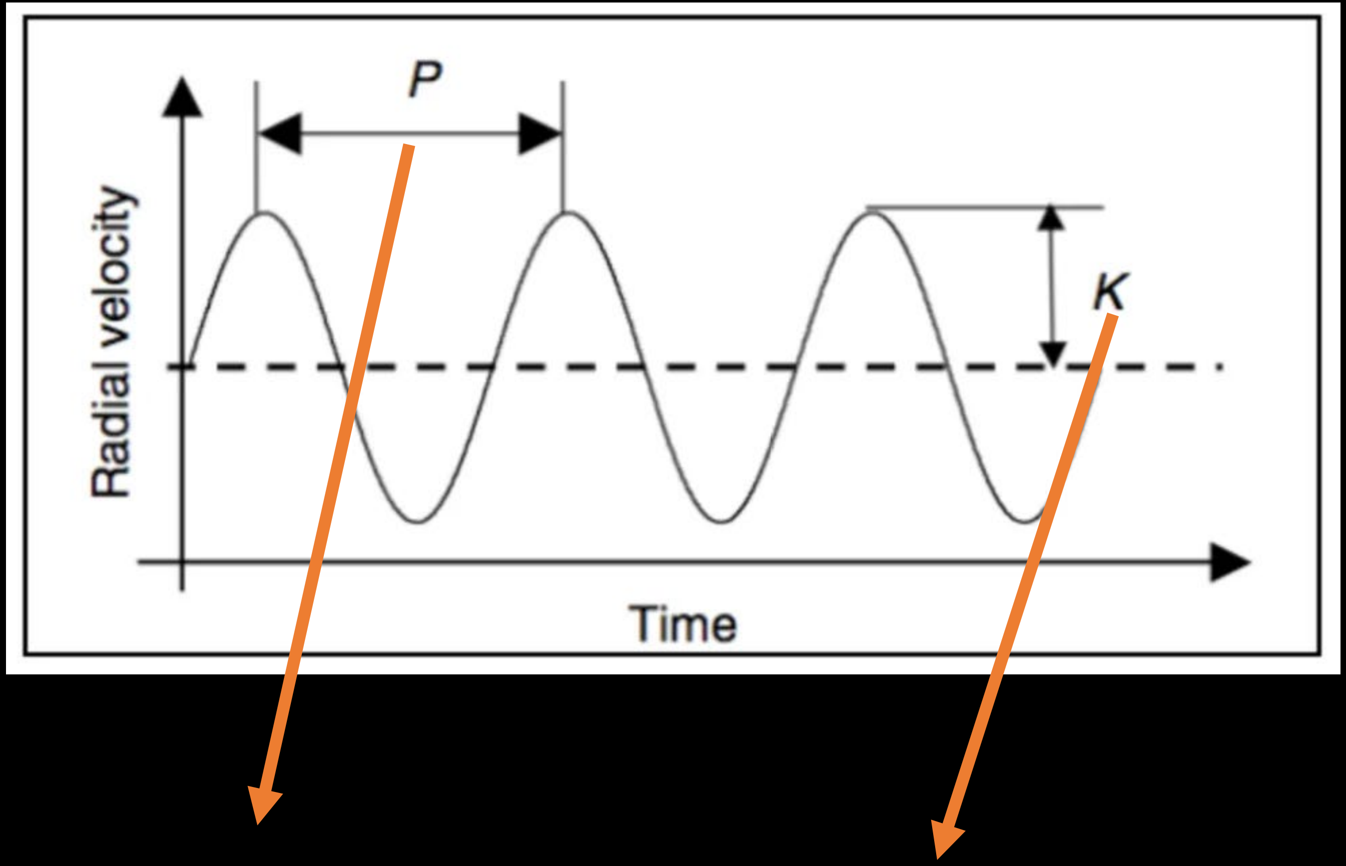
THE RADIAL VELOCITY METHOD

TOP VIEW

EDGE-ON VIEW

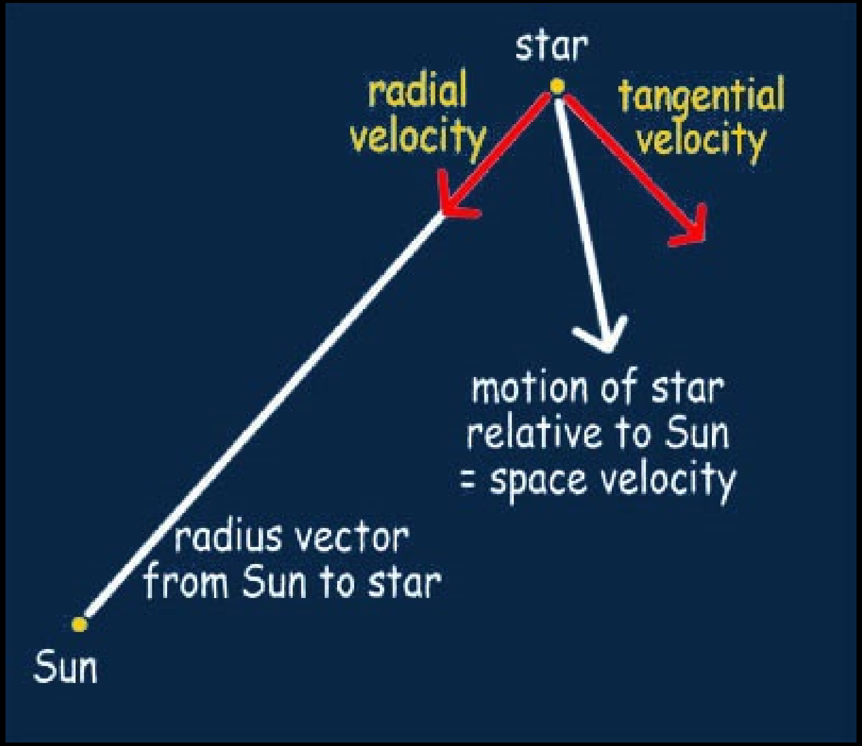


THE RADIAL VELOCITY METHOD



P = Orbital period of planet

K = RV semi-amplitude



Credit: Eklavya (2019); C. Seligman

THE RADIAL VELOCITY METHOD

Star velocity

$$K = \frac{2\pi a_{star}}{P}$$

Center of mass

$$m_{star}\, a_{star} = m_{planet}\, a_{planet}$$

Definition of orbit semi-major axis

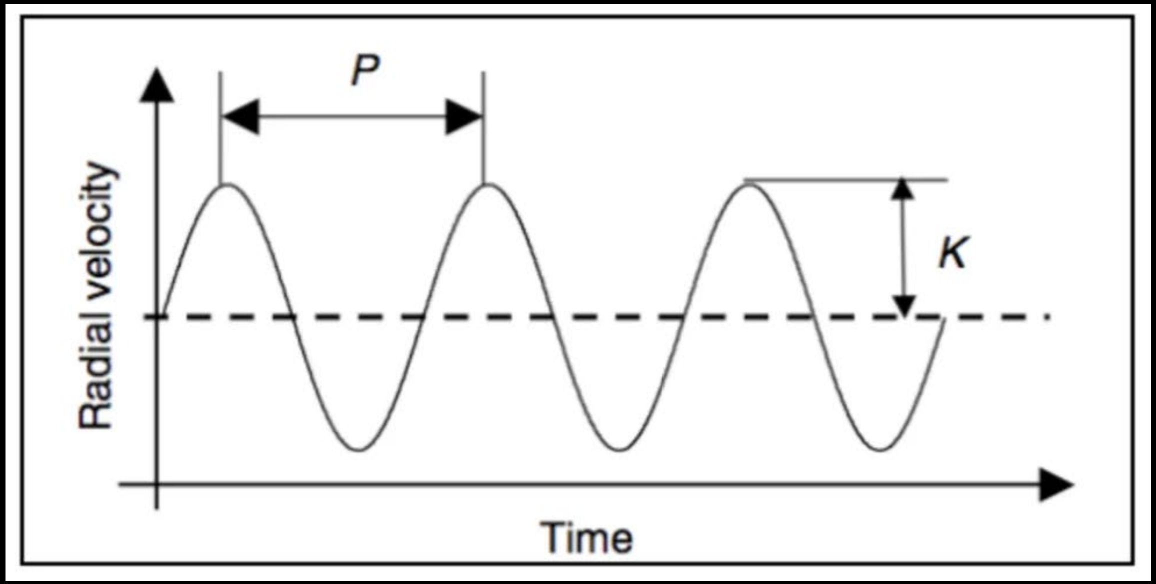
$$a_{star} + a_{planet} = a$$

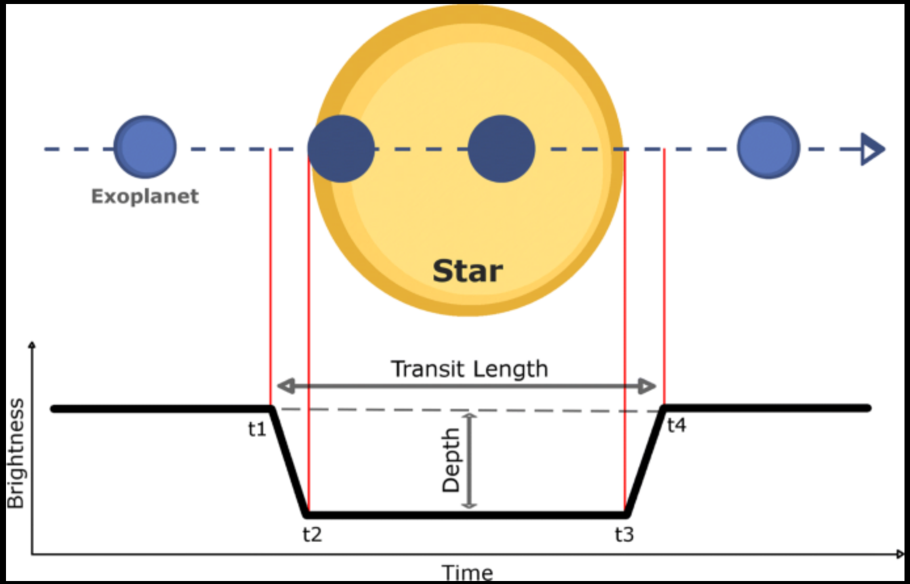
Kepler's Third Law

$$\frac{a^3}{(m_{star} + m_{planet})} = \frac{P^2 G}{4\pi^2}$$

$$\boxed{m_{planet} = K \left(\frac{P}{2\pi G}\right)^{1/3} m_{star}^{2/3} \quad *}$$

* Assuming i = 90˚ & e = 0





Planet Mass

Planet Radius

Planet Density

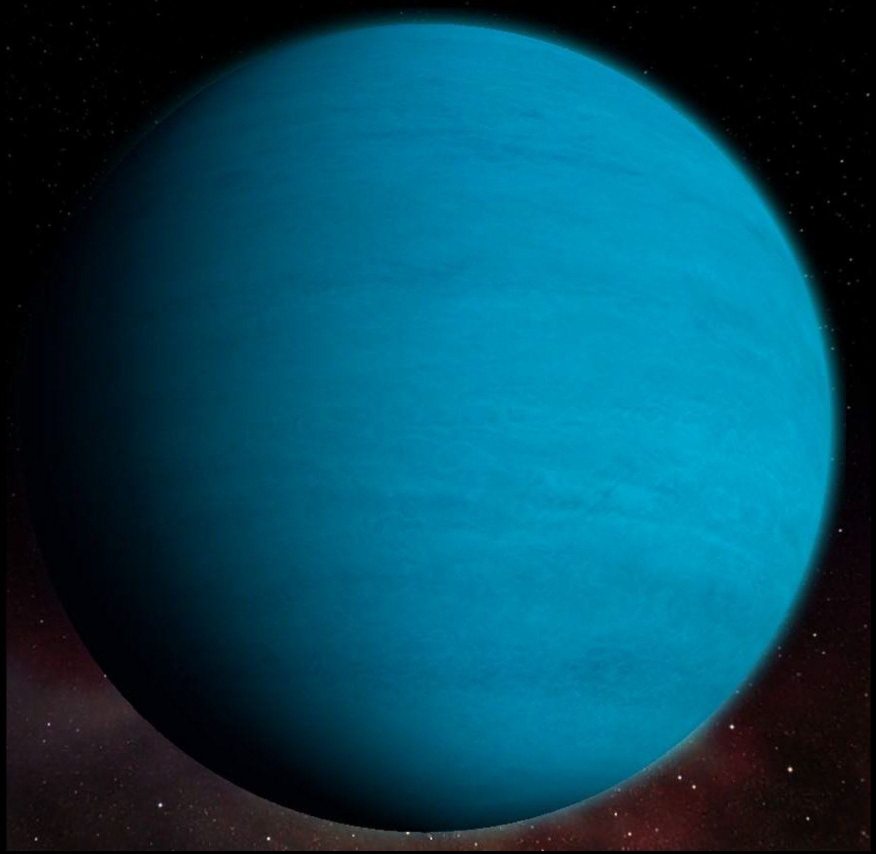
$$\rho = \frac{m}{V} = \frac{3m_{planet}}{4\pi R_{planet}^{3}}$$

Credit: S. Seager

PLANETARY INTERIORS & COMPOSITION

The most common size of planet in the galaxy is between the size of Earth and Neptune (1-4 R_{Earth}).

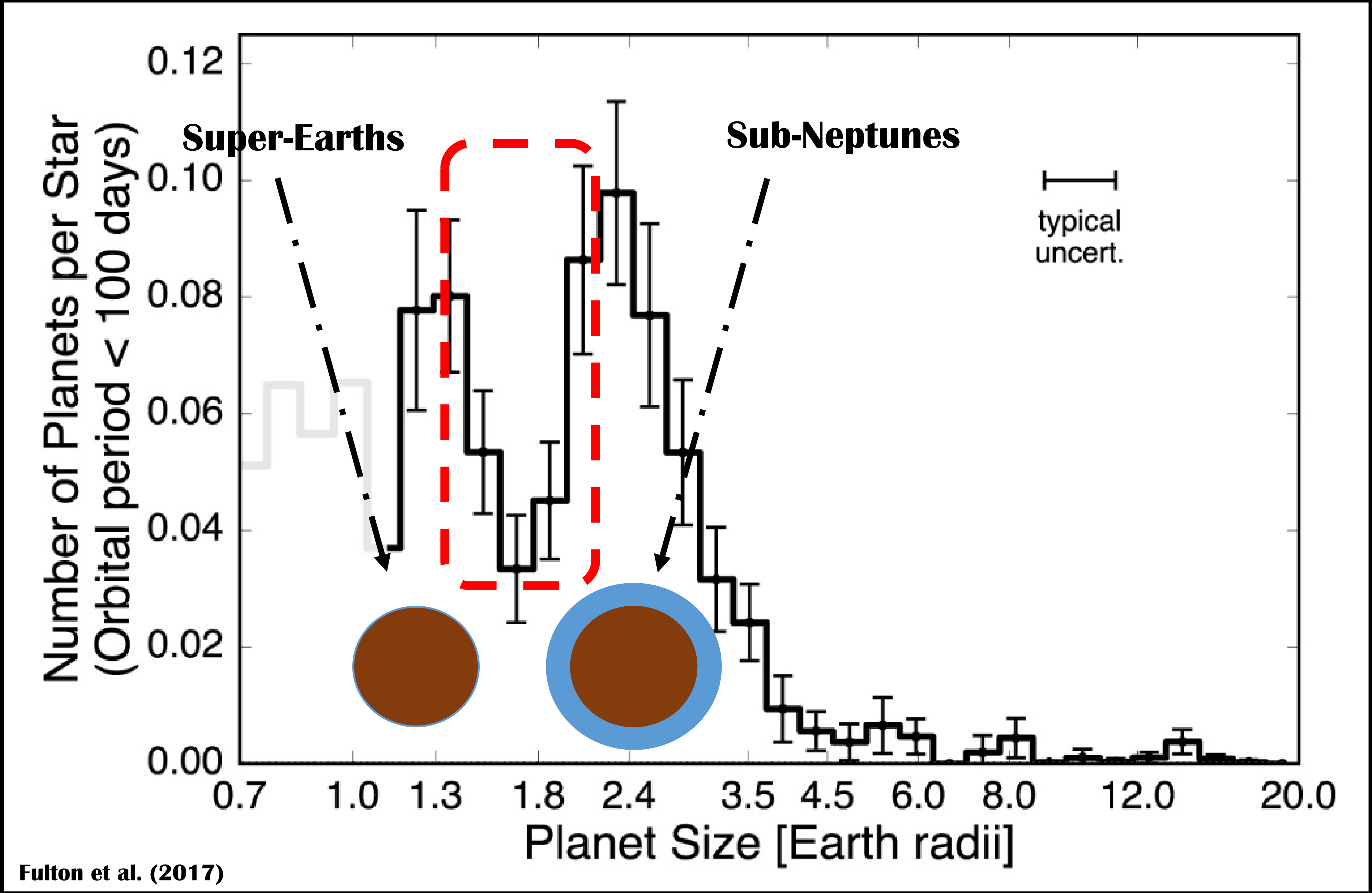
1-2 R_{Earth}



2-4 R_{Earth}

Credit: NASA; Christian Hart

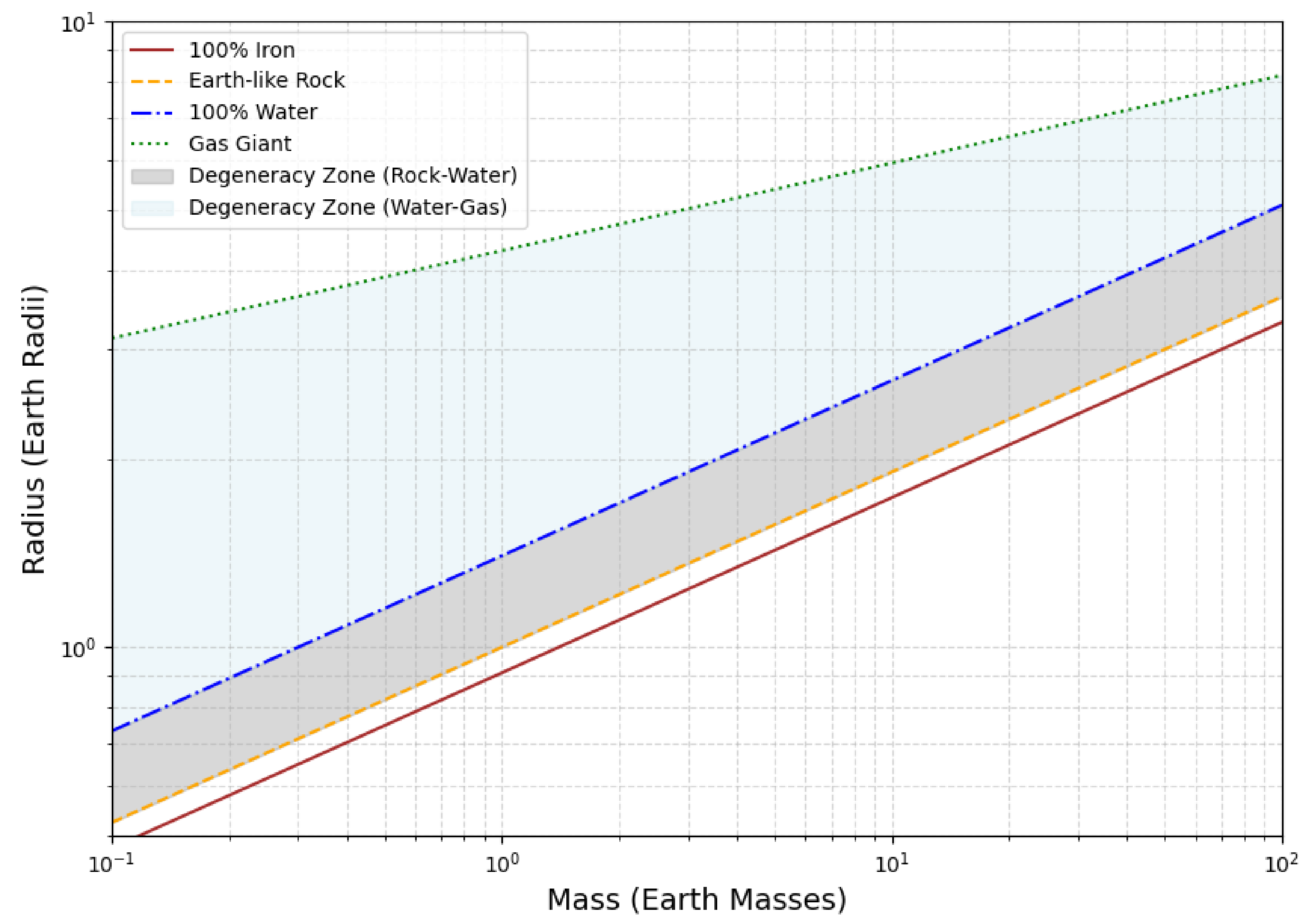
THE RADIUS VALLEY



Fulton et al. (2017)

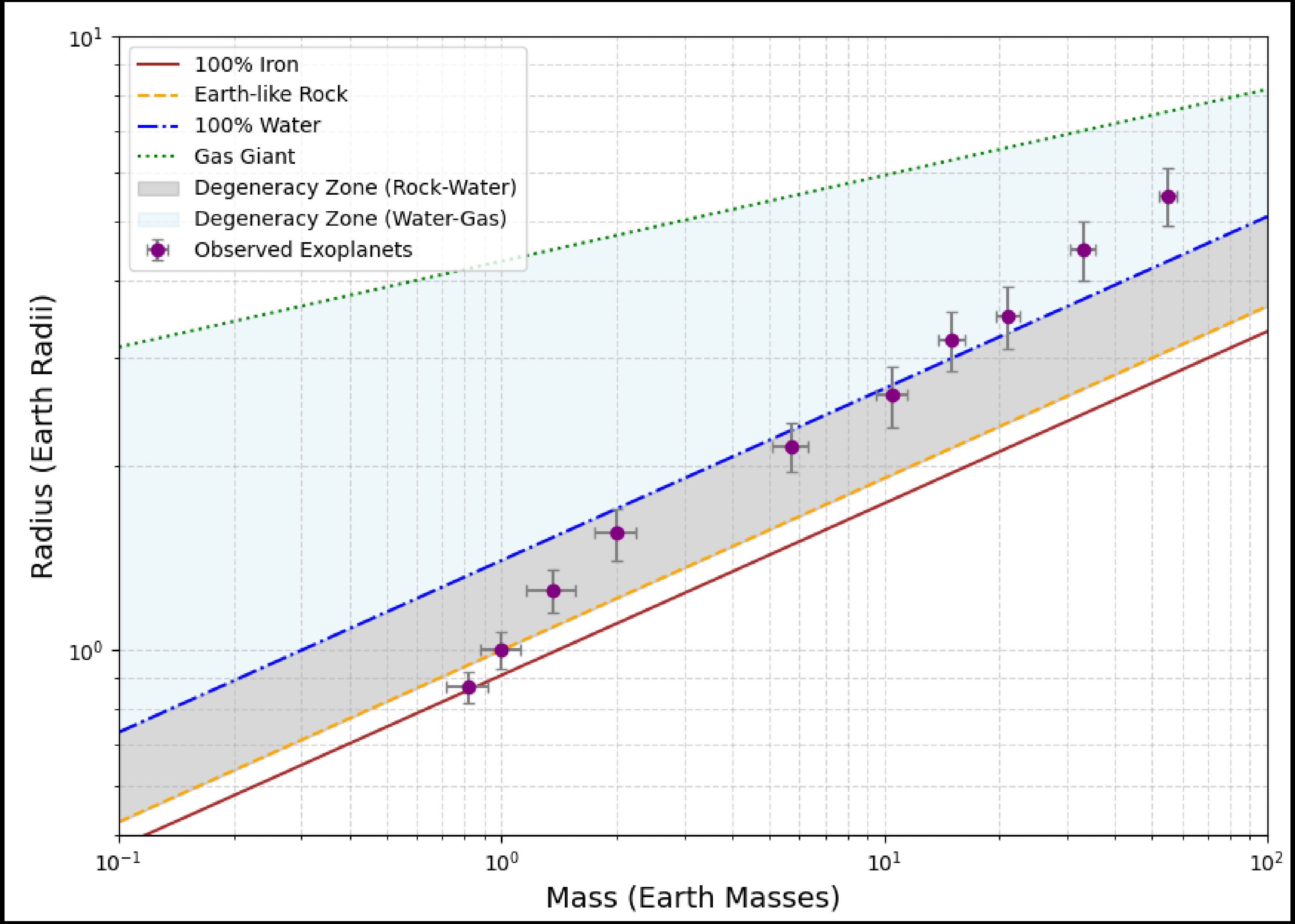
Local minimum in the radius distribution of small, close-in planets orbiting Sun-like stars (~1.75 R_{Earth})

MASS-RADIUS RELATIONS



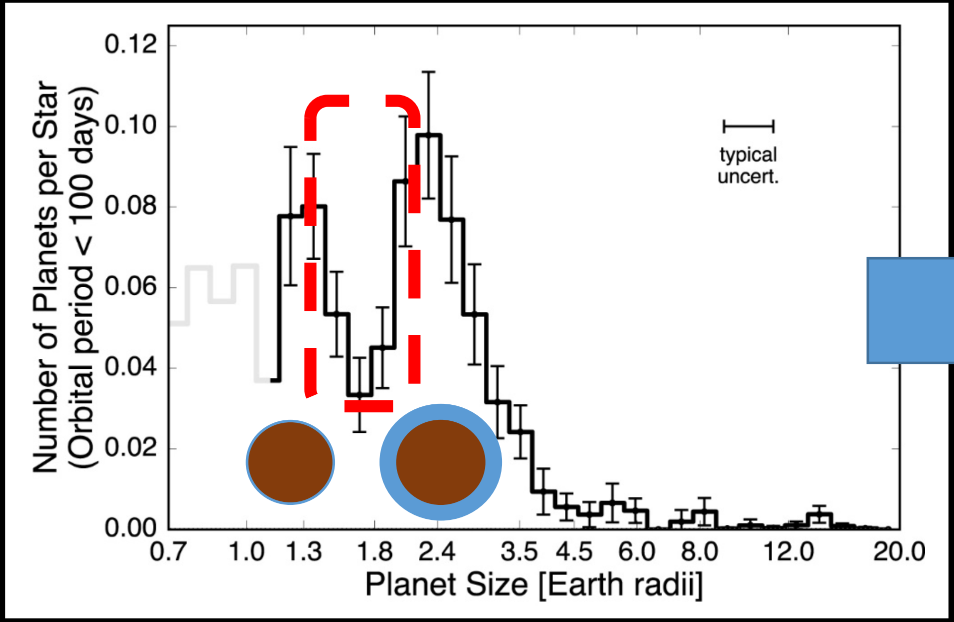
- **Lines of constant composition:**
  - **100% Iron (Fe)**
  - **Earth-like rocky (32.5% Fe + 67.5% $MgSiO_3$)**
  - **100% Water (H20)**
  - **Gas giant (10% H/He atmosphere)**

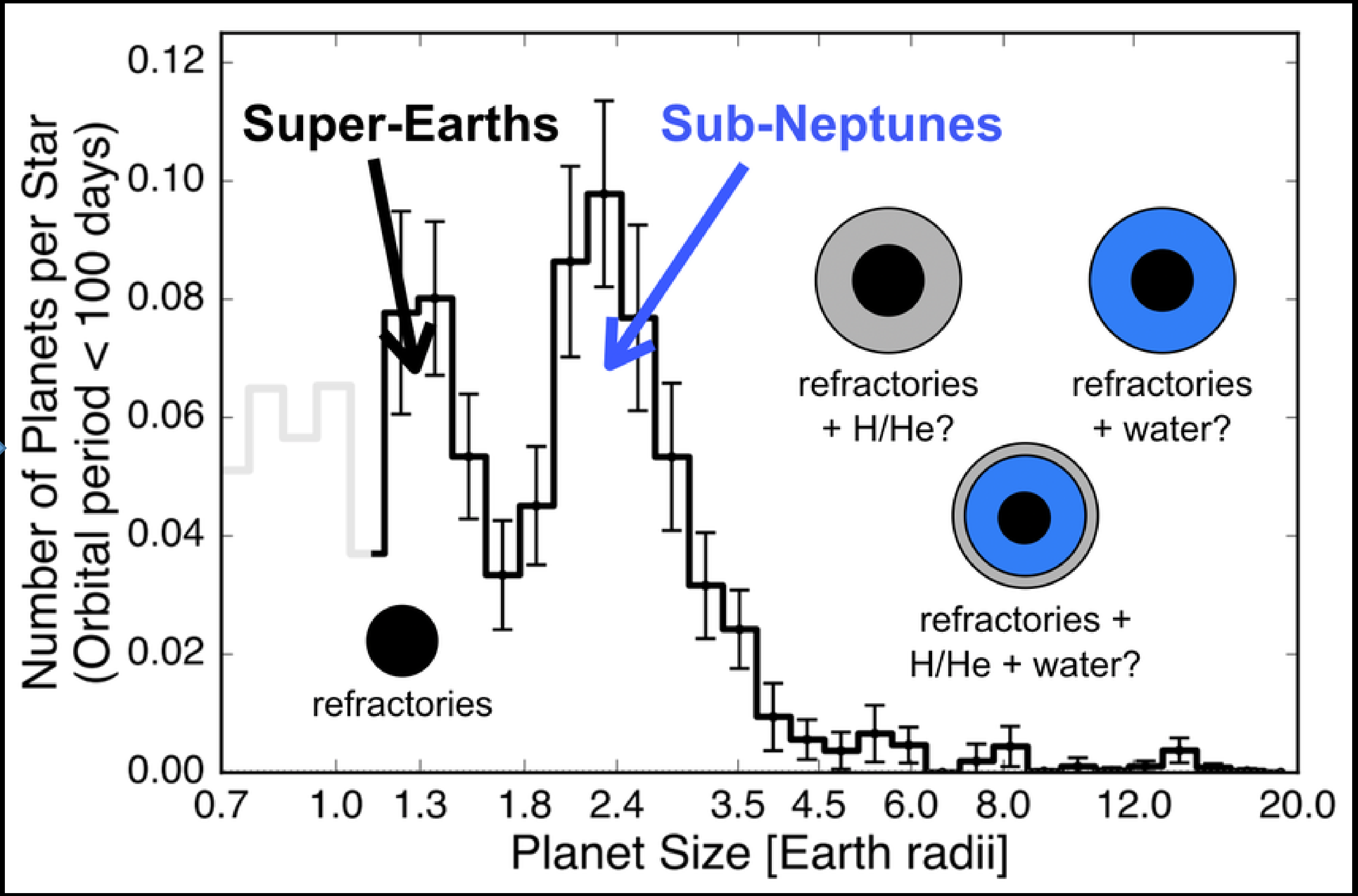
MASS-RADIUS RELATIONS



- **Different planetary compositions can overlap in mass-radius space.**
  - **Degeneracy!**
- **It is challenging to distinguish planet composition based solely on mass and radius.**

THE RADIUS VALLEY & COMPOSITIONAL DEGENERACY

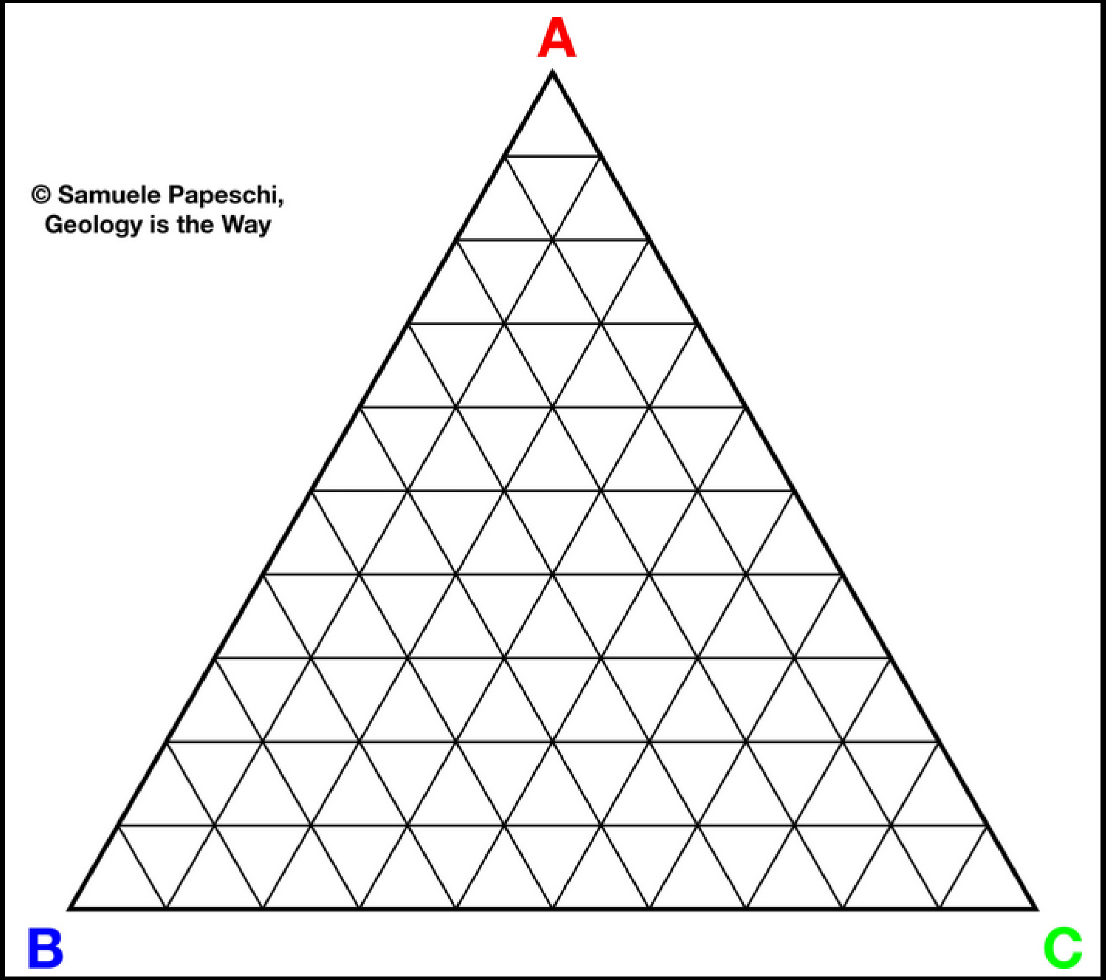




Fulton et al. (2017); Cloutier (2024)

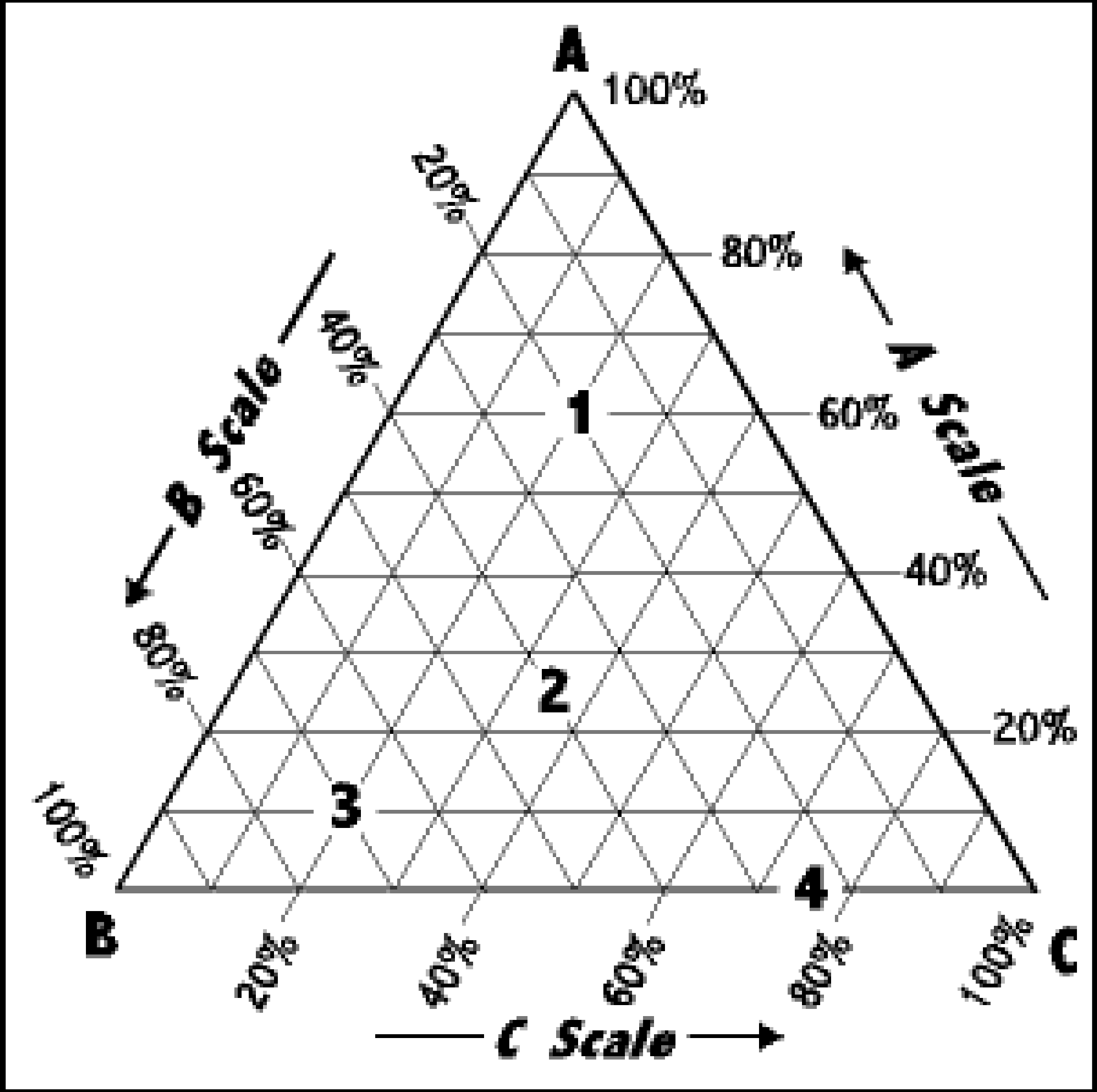
TERNARY DIAGRAMS

- **Definition:** A ternary diagram (or ternary plot) is a triangular graph used to represent the proportions of three variables that sum to a constant.
- Each point inside the triangle represents a mixture of three components (A, B, C) in varying proportions.
- Widely used in geology, materials science, and planetary science to visualize compositional data.



© Samuele Papeschi, Geology is the Way

HOW TO READ A TERNARY DIAGRAM



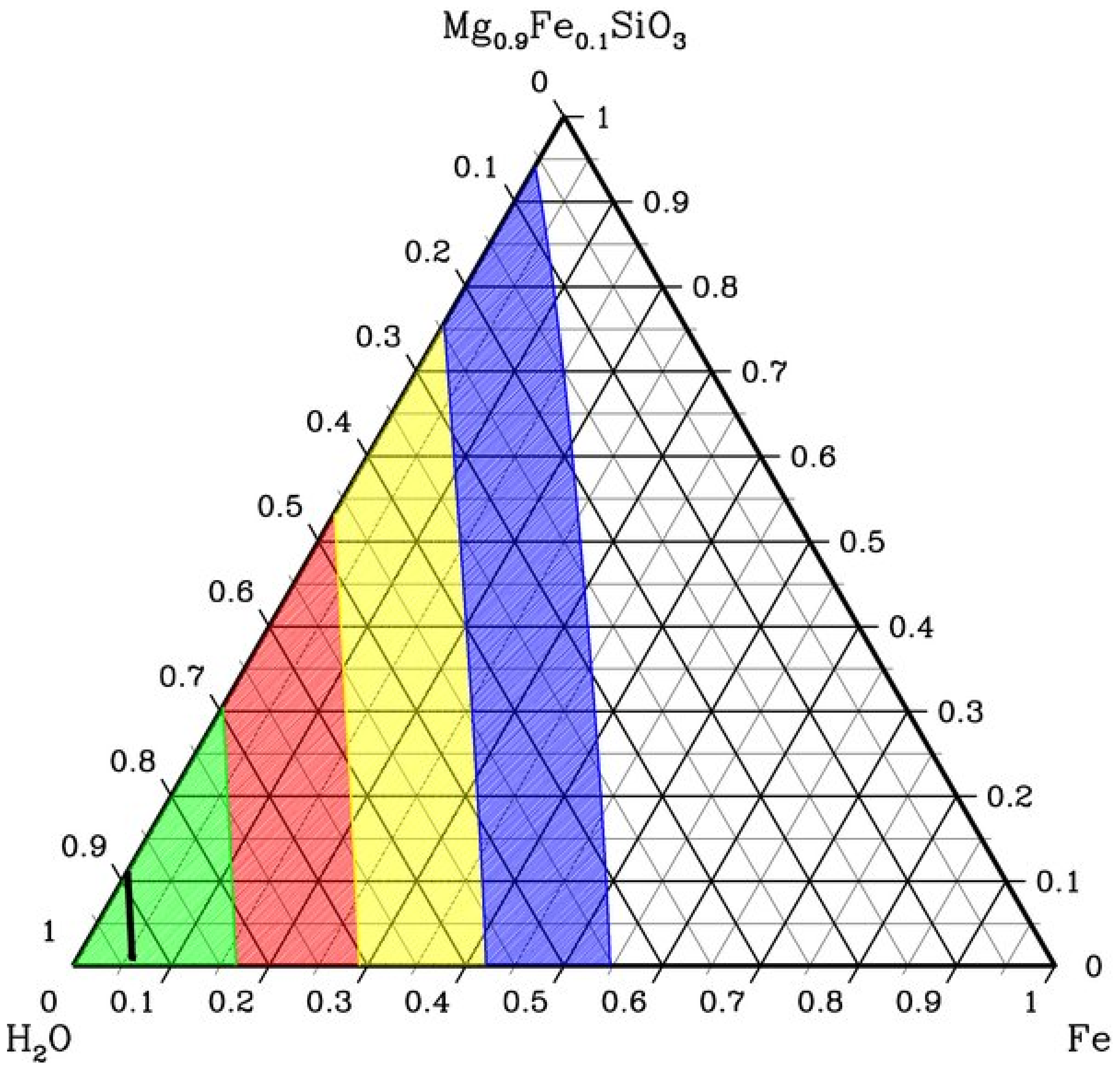
- Each corner represents 100% of one component (A, B, or C).
- Grid lines show constant proportions of each component.
- Values are normalized so that A + B + C = 1 (or 100%).

- What are the compositions of 1, 2, 3 & 4?


1. 60% A | 20% B | 20% C = 100%
2. 25% A | 40% B | 35% C = 100%
3. 10% A | 70% B | 20% C = 100%
4. 0.0% A | 25% B | 75% C = 100%

https://csmgeo.csm.jmu.edu/geollab/fichter/sedrx/readternary.html

TERNARY DIAGRAMS FOR EXOPLANETS



GJ 1214 b

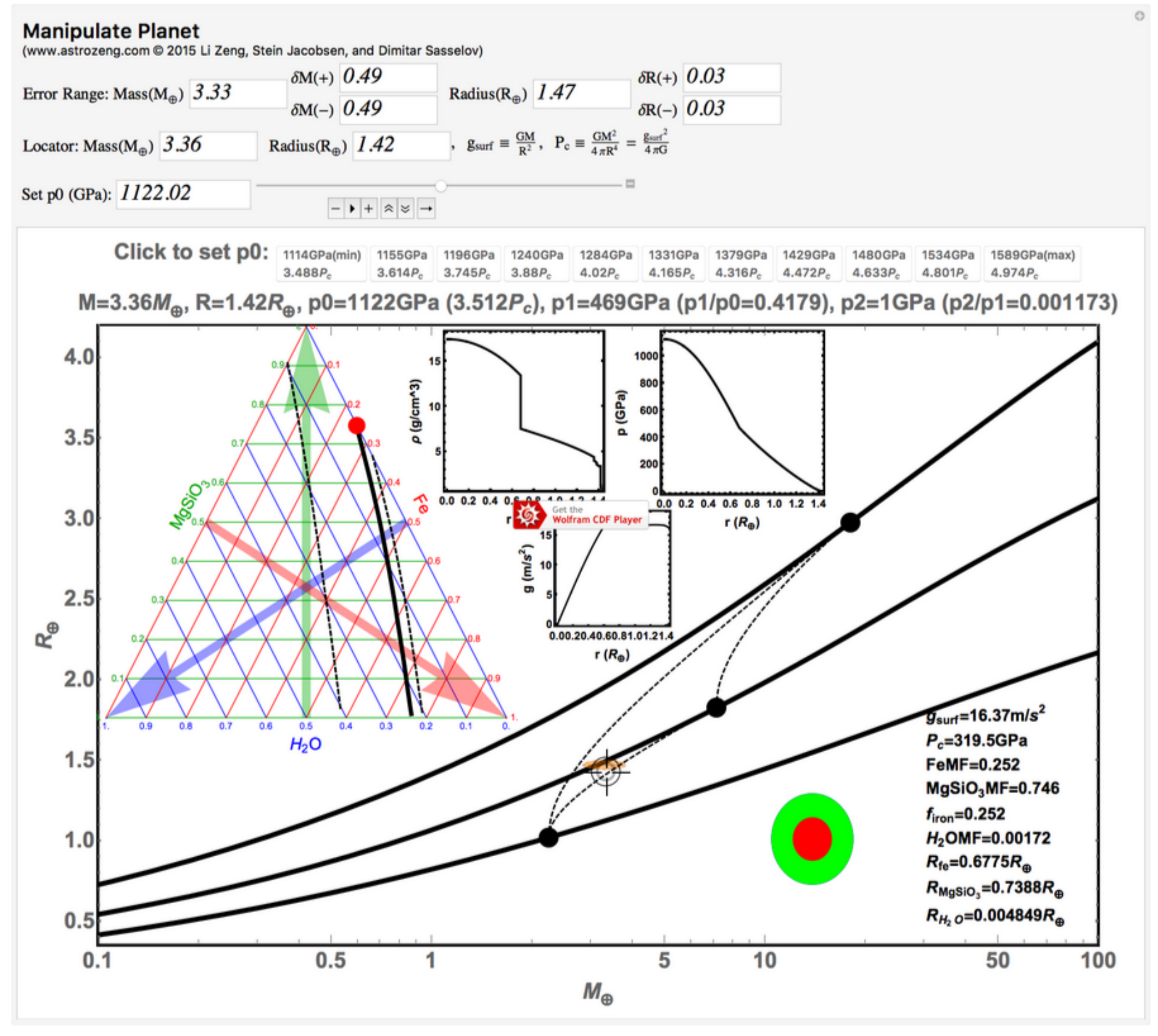
$M_{planet} = 6.55 \pm 0.98\, M_{Earth}$

$R_{planet} = 2.678 \pm 0.13\, R_{earth}$

- Fe core
- Silicate mantle
- Water vapor envelope

L. A. Rogers and S. Seager (2010) *ApJ* 716 1208

INTERACTIVE TERNARY DIAGRAM



Manipulate Planet

(www.astrozeng.com © 2015 Li Zeng, Stein Jacobsen, and Dimitar Sasselov)

Error Range: Mass($M_\oplus$) 3.33 δM(+) 0.49 δM(−) 0.49 Radius($R_\oplus$) 1.47 δR(+) 0.03 δR(−) 0.03

Locator: Mass($M_\oplus$) 3.36 Radius($R_\oplus$) 1.42 , $g_{surf} \equiv \frac{GM}{R^2}$, $P_c \equiv \frac{GM^2}{4\pi R^4} = \frac{g_{surf}^2}{4\pi G}$

Set p0 (GPa): 1122.02

M=3.36$M_\oplus$, R=1.42$R_\oplus$, p0=1122GPa (3.512P_c), p1=469GPa (p1/p0=0.4179), p2=1GPa (p2/p1=0.001173)

g_{surf}=16.37m/s^2
P_c=319.5GPa
FeMF=0.252
$MgSiO_3$MF=0.746
f_{iron}=0.252
H_2OMF=0.00172
R_{fe}=0.6775$R_\oplus$
R_{MgSiO_3}=0.7388$R_\oplus$
R_{H_2O}=0.004849$R_\oplus$

https://lweb.cfa.harvard.edu/~lzeng/planetmodels.html#planetinteriors

COMPRESSED VS. UNCOMPRESSED DENSITY

- **Compressed Density:** The density of a planet under its own gravity at its current size and mass.
  - Accounts for gravitational compression, which squeezes the material towards the center, especially in larger/more massive planets.

- **Uncompressed Density:** The density a planet would have if gravitational compression was removed.
  - Determined by the planet's composition, rather than its current size or gravitational effects.
  - Used to compare planets of different sizes in terms of differences in composition.

COMPRESSED VS UNCOMPRESSED DENSITY

Solar System Planets

Planet	Compressed Density (g/cm^3)	Uncompressed Density (g/cm^3)
Mercury	5.43	5.30
Venus	5.24	4.38
Earth	5.52	4.40
Mars	3.93	3.76
Jupiter	1.33	1.24
Saturn	0.69	0.63
Uranus	1.27	1.23
Neptune	1.64	1.56

Common Materials

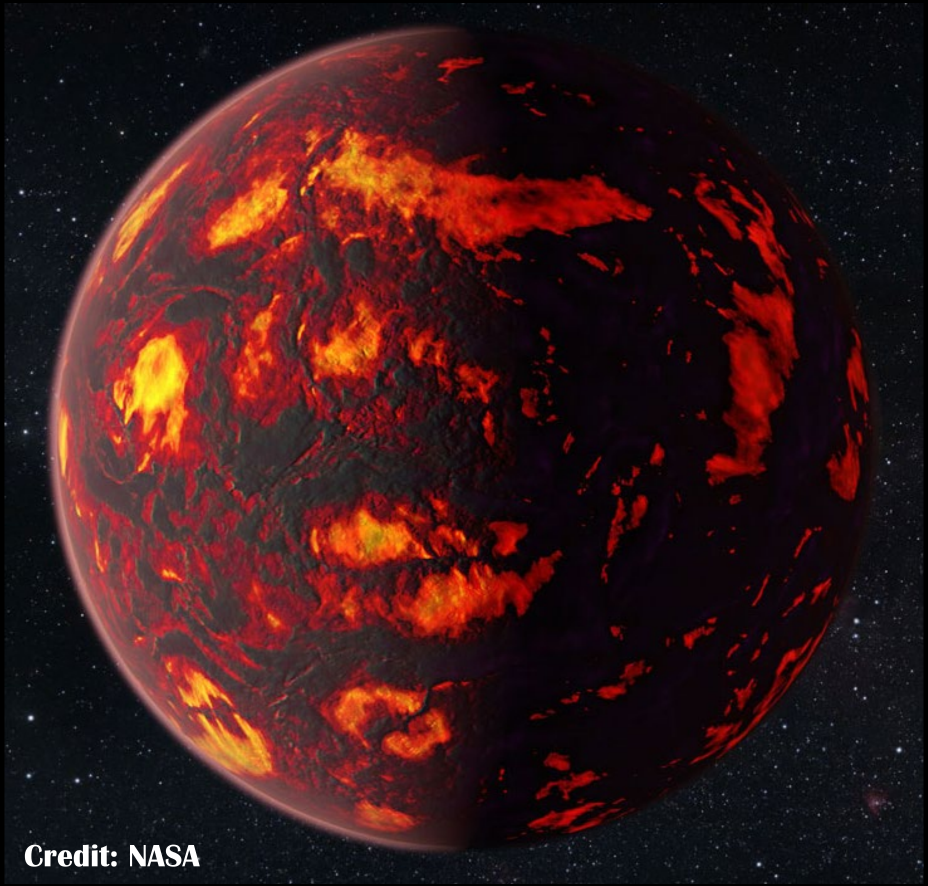
Material	Density (g/cm^3)
Iron (Fe)	7.87
Silicate rock	3.00
Water Ice (H_2O)	0.92
Liquid Water (H_2O)	1.00
Hydrogen (H_2)	0.00009
Helium (He)	0.00018

HOT SUPER-EARTHS RESEARCH

SUPER-EARTHS

↓

HOT SUPER-EARTHS


Credit: NASA

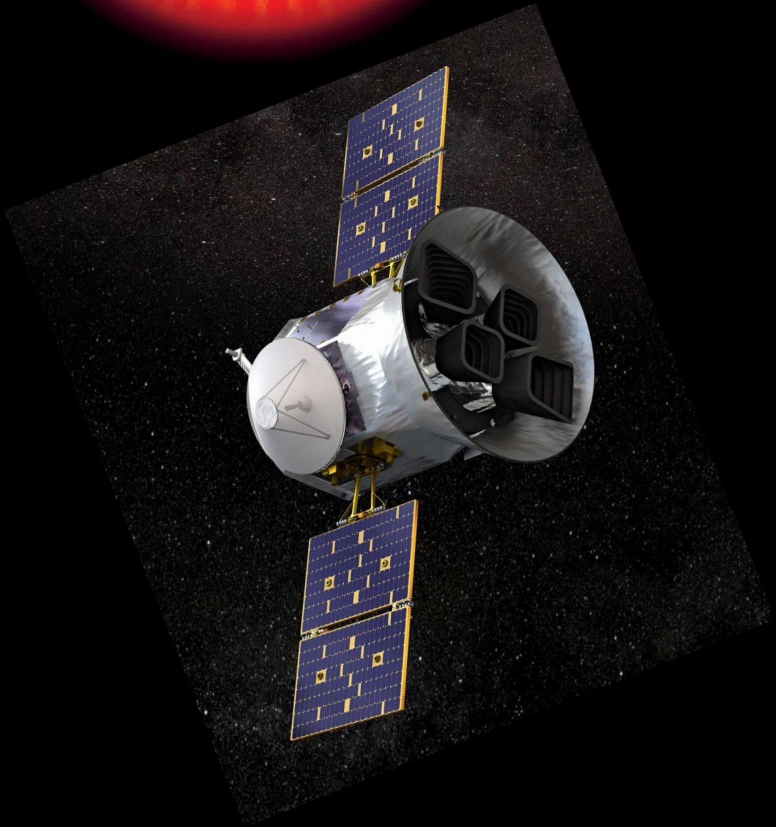
- $1\ R_{earth} < R_{planet} < 2\ R_{earth}$
- Orbital Period < 10 days
- Surface temperatures > 800 K
- Tidally locked
- Circular orbits
- No solar system analog

PLANET DETECTION

TOI-1075 b: A DENSE, ULTRA-SHORT PERIOD HOT SUPER-EARTH STRADDLING THE RADIUS GAP

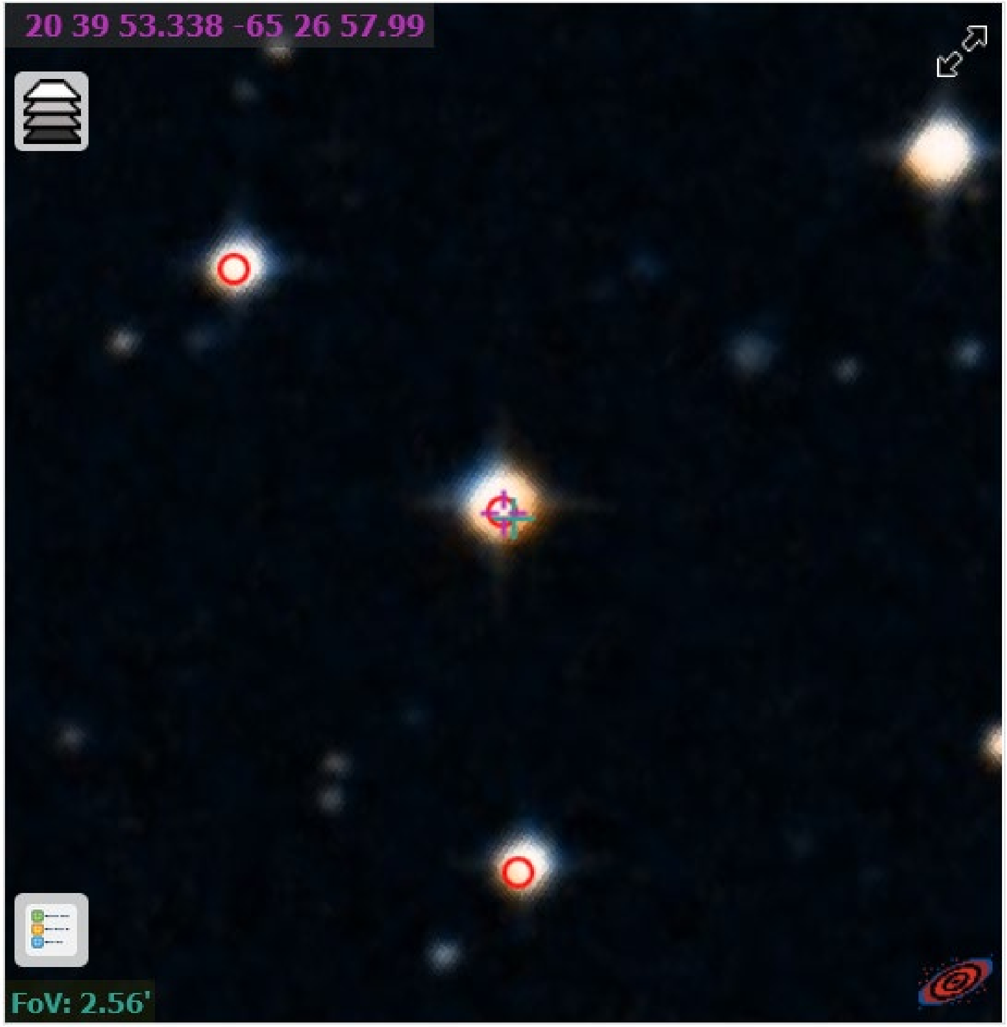
ESSACK ET AL. (2023), *THE ASTRONOMICAL JOURNAL, 165, 47.*

TESS



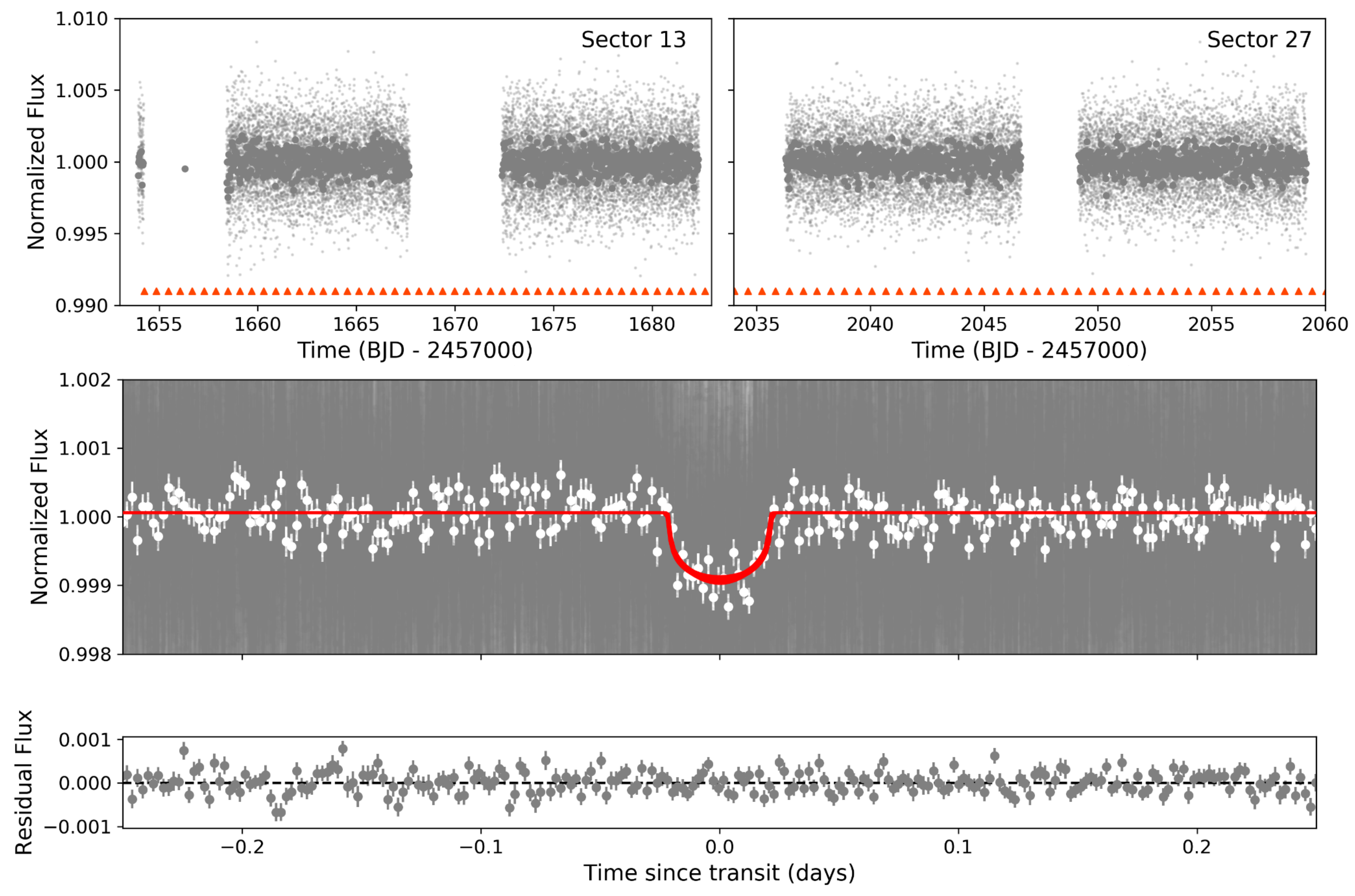
Credit: NASA/MIT/TESS

THE STAR: TOI-1075 (TIC 351601843)



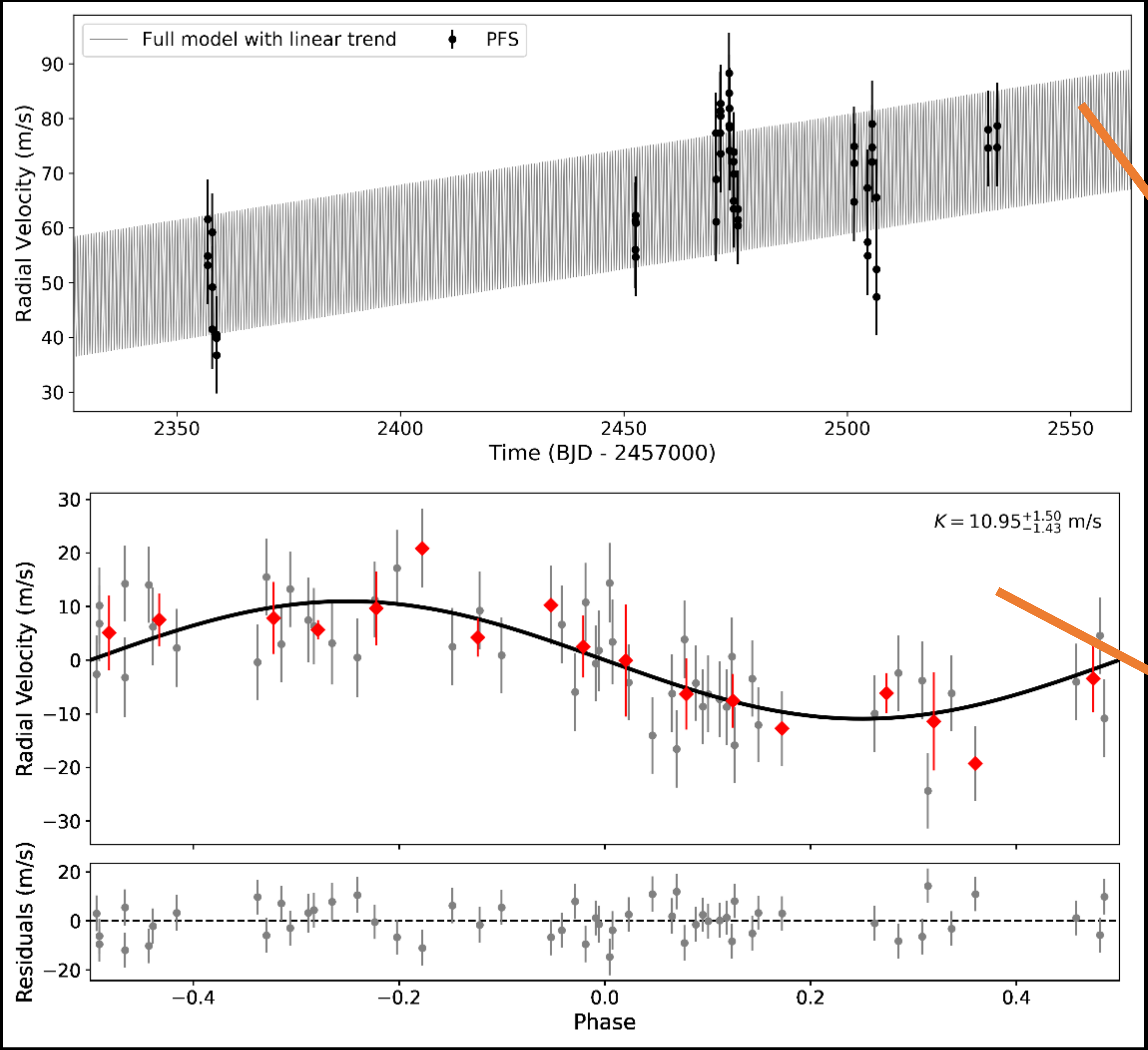
- K9V/M0V
- d = 200 ly
- T_{eff} = 3875 ± 75 K
- $R_\star$ = 0.581 ± 0.024 $R_\odot$
- $M_\star$ = 0.604 ± 0.030 $M_\odot$
- V = 12.75 mag
- Quiet, well-behaved

TESS PHOTOMETRY



- **Period = 0.605 days**
- **$R_p = 1.791^{+0.116}_{-0.081}\ R_\oplus$**
- **Transit Depth (δ) = ~900 ppm**

PFS RADIAL VELOCITIES



Linear long-term trend. Second planet in the system?

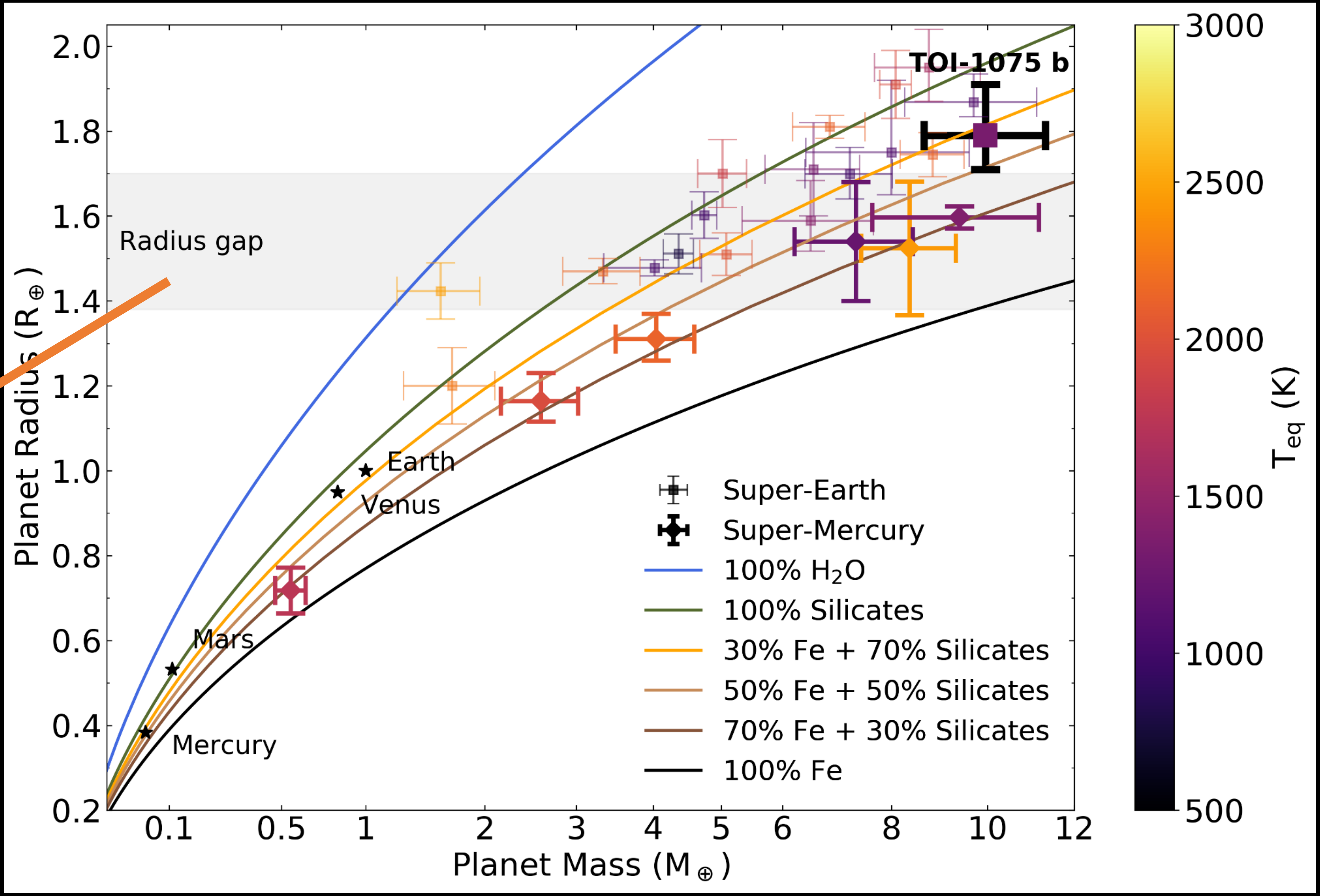
P > 353 days; M_{p2} > 87 $M_\oplus$

54 PFS RVs collected over 6 months.

$$M_p = 9.95^{+1.36}_{-1.30}\ M_\oplus$$

TOI-1075 b COMPOSITION

35% Fe + 65% Silicates



Radius valley around low-mass stars
1.54 ± 0.16 $R_\oplus$

Cloutier & Menou (2020)
Zeng et al. (2021)

UNCOMPRESSED DENSITY EXERCISE: TOI-1075 b

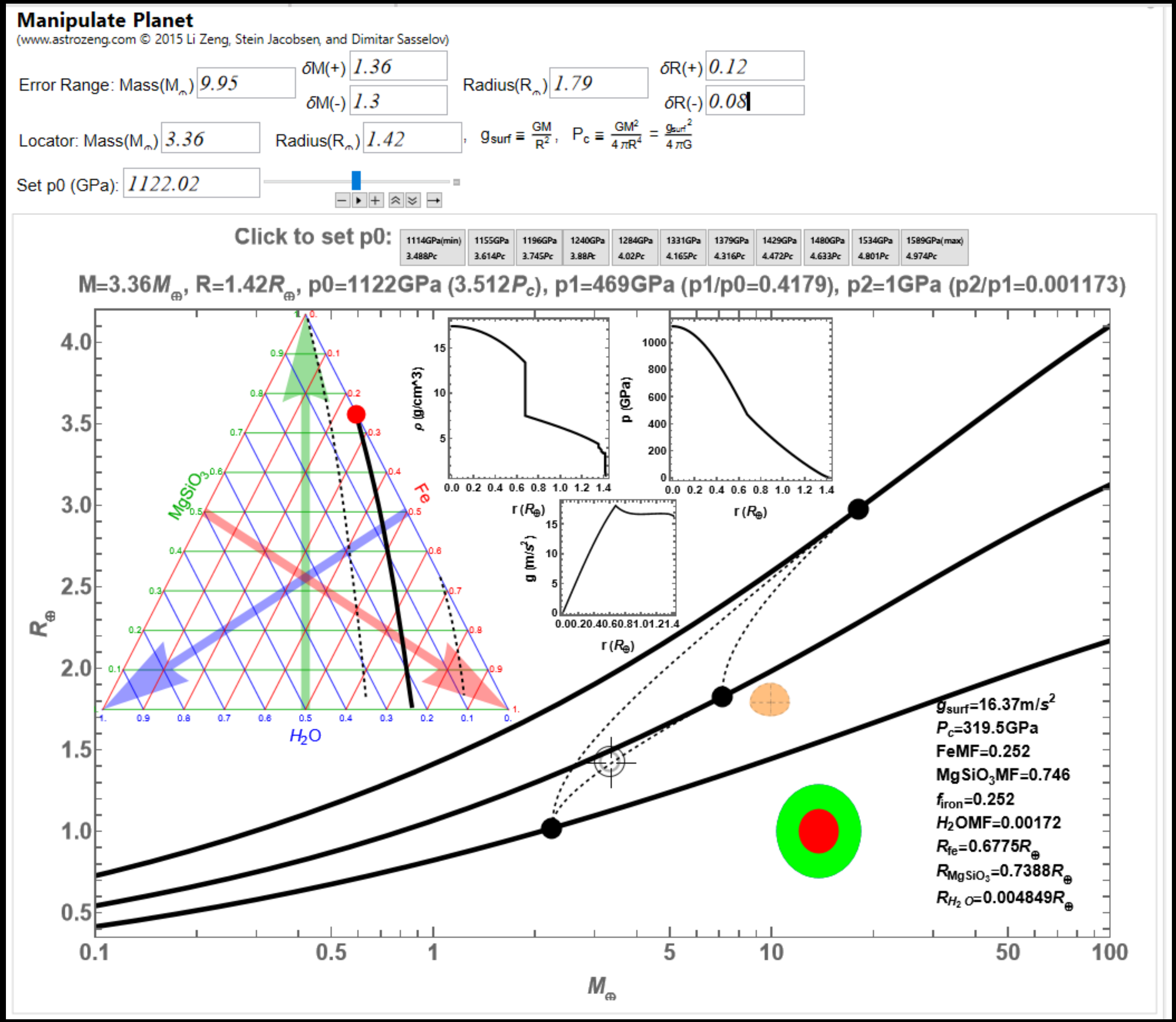
- TOI-1075 b's compressed (mean) density is 9.32 g/cm^3. Calculate its uncompressed density.
  - Planet composition: 35% Fe; 65% silicates
  - Answer: 4.7 g/cm^3

- Compare to Earth's density.
  - Compressed: 5.52 g/cm^3
  - Uncompressed: 4.40 g/cm^3

Material	Density (g/cm^3)
Iron (Fe)	7.87
Silicate rock	3.00
Water Ice (H_2O)	0.92
Liquid Water (H_2O)	1.00
Hydrogen (H_2)	0.00009
Helium (He)	0.00018

TERNARY DIAGRAM EXERCISE: TOI-1075 b

- **Insert TOI-1075 b's mass and radius into Manipulate Planet (interactive ternary diagram)**
  - $M_p = 9.95^{+1.36}_{-1.30}\ M_\oplus$
  - $R_p = 1.791^{+0.116}_{-0.081}\ R_\oplus$
- **What do you observe from the ternary diagram?**



Manipulate Planet

(www.astrozeng.com © 2015 Li Zeng, Stein Jacobsen, and Dimitar Sasselov)

Error Range: Mass($M_\oplus$) 9.95 δM(+) 1.36 δM(-) 1.3 Radius($R_\oplus$) 1.79 δR(+) 0.12 δR(-) 0.08

Locator: Mass($M_\oplus$) 3.36 Radius($R_\oplus$) 1.42, $g_{surf} \equiv \frac{GM}{R^2}$, $P_c \equiv \frac{GM^2}{4\pi R^4} = \frac{g_{surf}^2}{4\pi G}$

Set p0 (GPa): 1122.02

Click to set p0:

M=3.36$M_\oplus$, R=1.42$R_\oplus$, p0=1122GPa (3.512P_c), p1=469GPa (p1/p0=0.4179), p2=1GPa (p2/p1=0.001173)

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f_{iron}=0.252

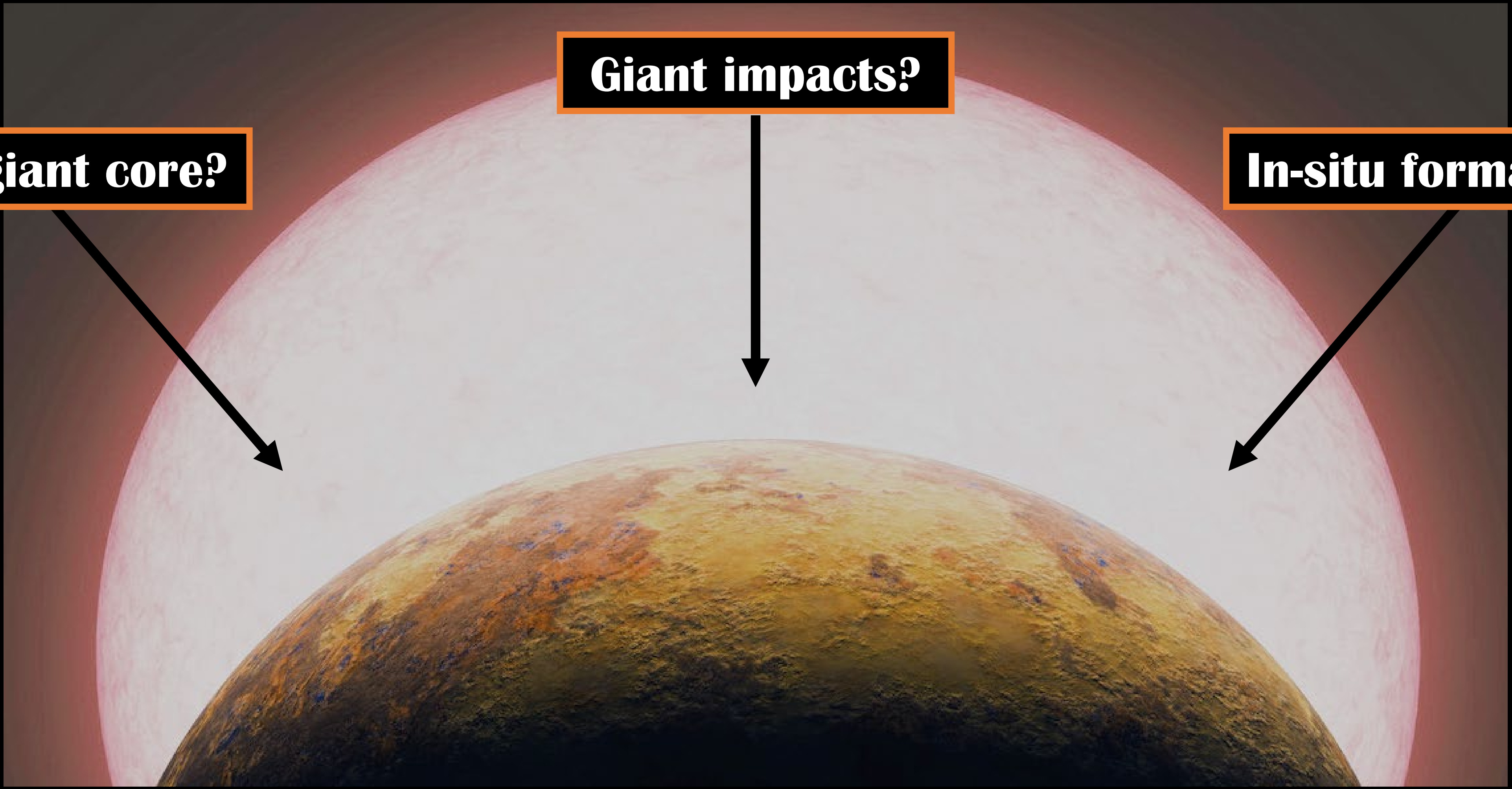
H_2OMF=0.00172

R_{fe}=0.6775$R_\oplus$

R_{MgSiO_3}=0.7388$R_\oplus$

R_{H_2O}=0.004849$R_\oplus$

PLANET FORMATION



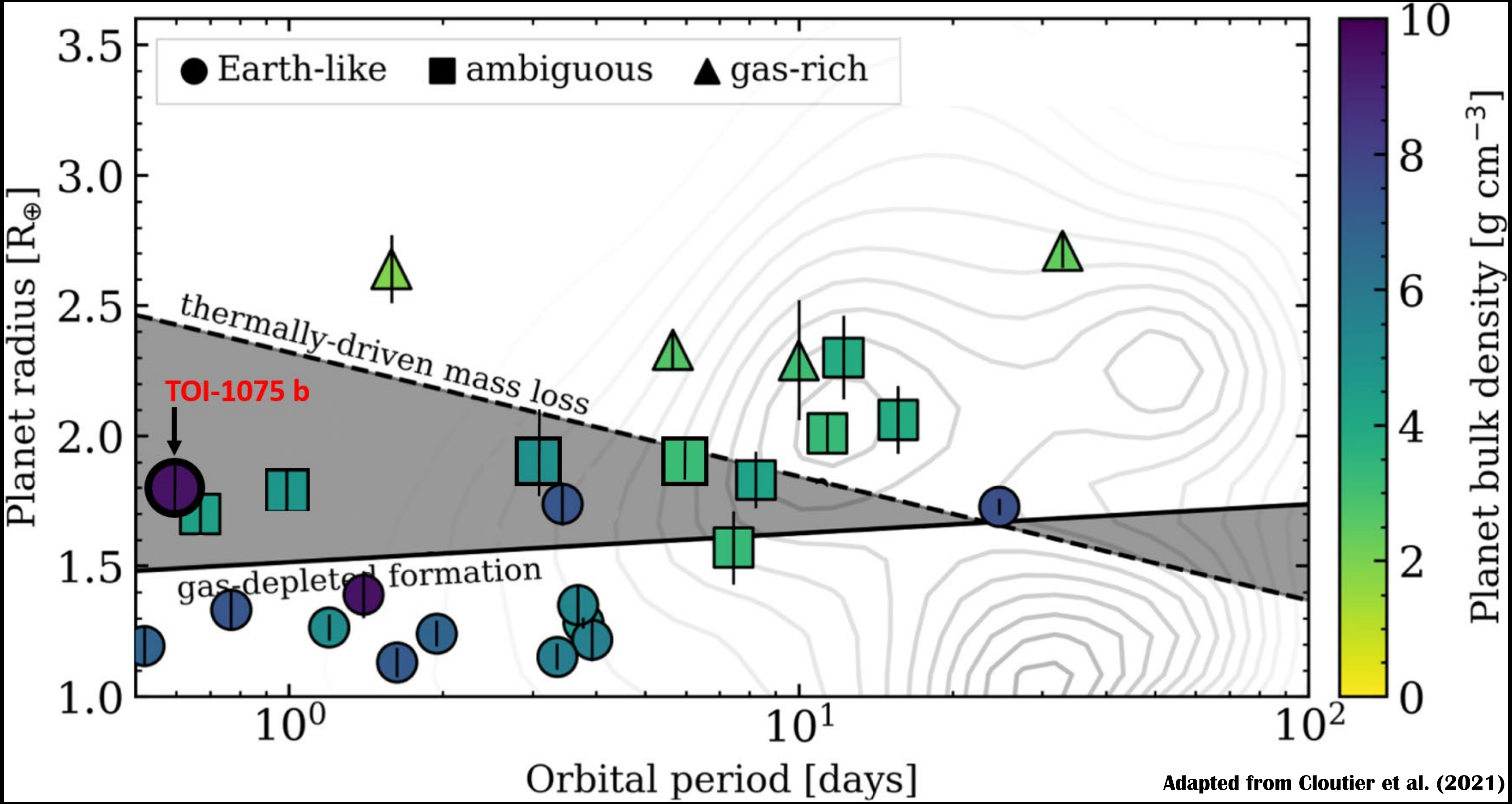
Gas giant core?

Giant impacts?

In-situ formation?

Illustration of TOI-1075 b (Credit: NASA/JPL-Caltech)

M DWARF RADIUS VALLEY



Adapted from Cloutier et al. (2021)

SUMMARY

- TOI-1075 b is one of the most massive hot super-Earths discovered, and is consistent with an Earth-like composition.
- Challenges our understanding of the radius valley – the planet is inconsistent with having a significant atmosphere, despite its mass and size.
- A "keystone planet" to help test competing radius valley emergence theories.
- PFS radial velocities reveal a potential long-period, massive companion in the system. Additional data are being collected for a future study on planet formation and orbital migration/system dynamical history.

ESSACK ET AL. (2023), *THE ASTRONOMICAL JOURNAL, 165, 47.*

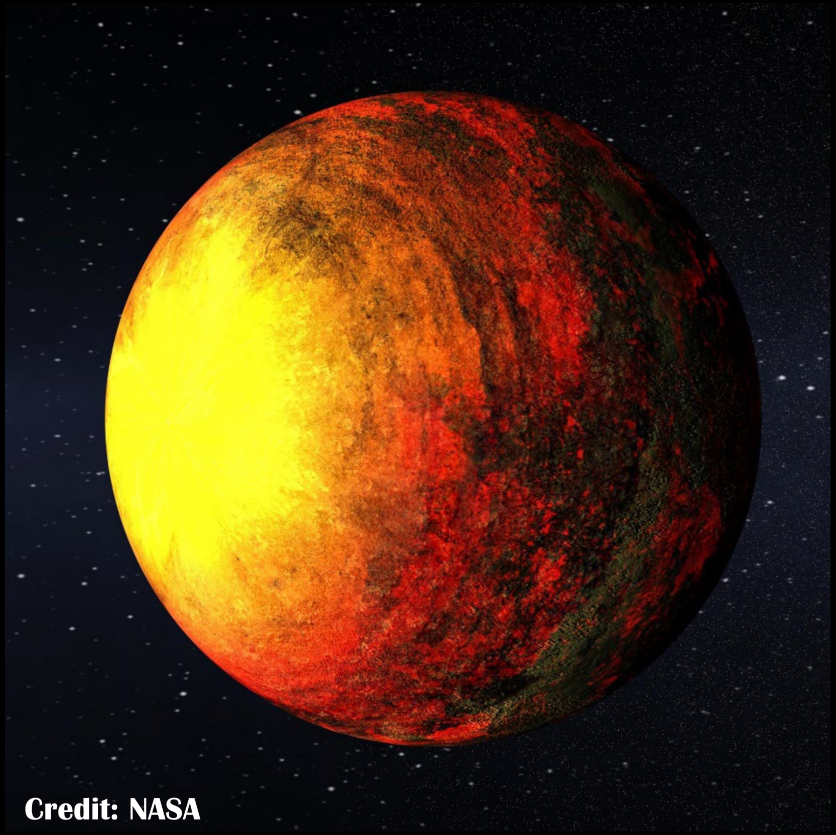
SURFACE CHARACTERIZATION

LOW-ALBEDO SURFACES OF LAVA WORLDS

ESSACK ET AL. (2020), *THE ASTROPHYSICAL JOURNAL, 898, 160.*

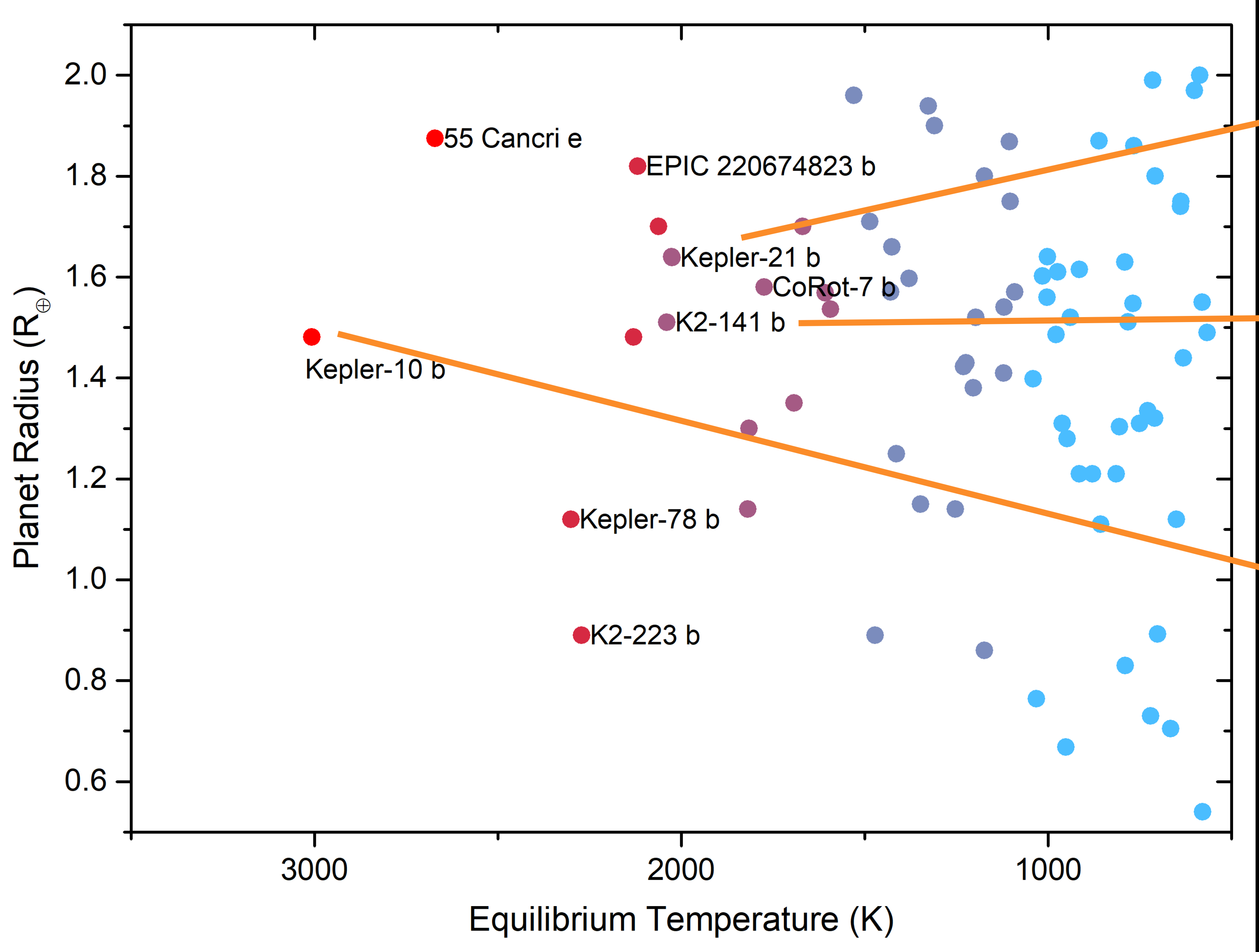
HOT SUPER-EARTHS
LAVA-OCEAN EXOPLANETS

What causes the high geometric albedos on some hot super-Earths?


Credit: NASA

- $R_{planet} < 1.6\ R_{earth}$
- Tidally locked
- Low pressure atmospheres (< 0.1 bar)
- Substellar temperature > 850 K
- Surface lava oceans due to intense stellar irradiation

LAVA-OCEAN EXOPLANET CANDIDATES



$0.4 < A_g < 0.5$

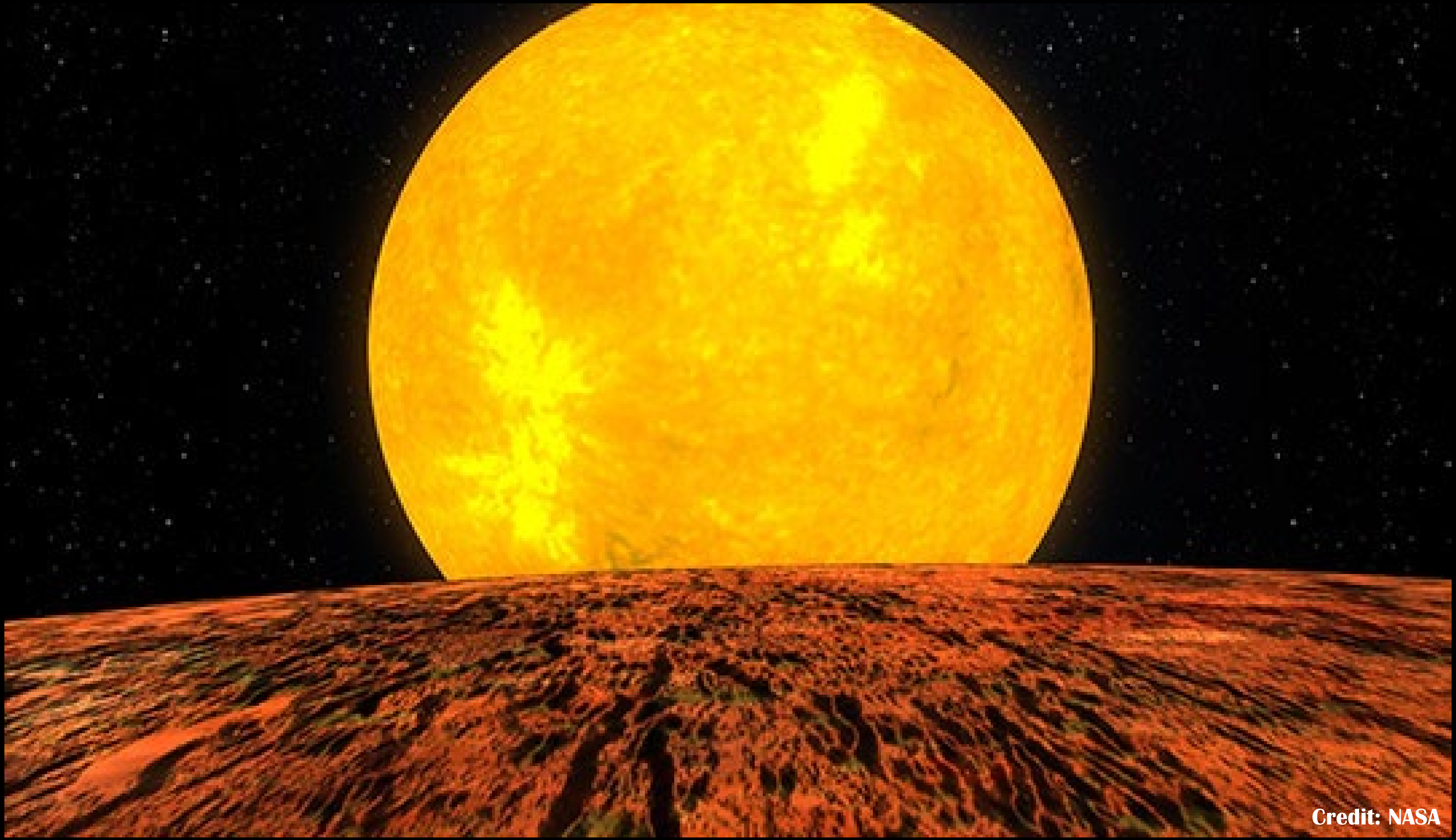
$0.2 < A_g < 0.4$

$0.4 < A_g < 0.5$

A_g = Geometric Albedo

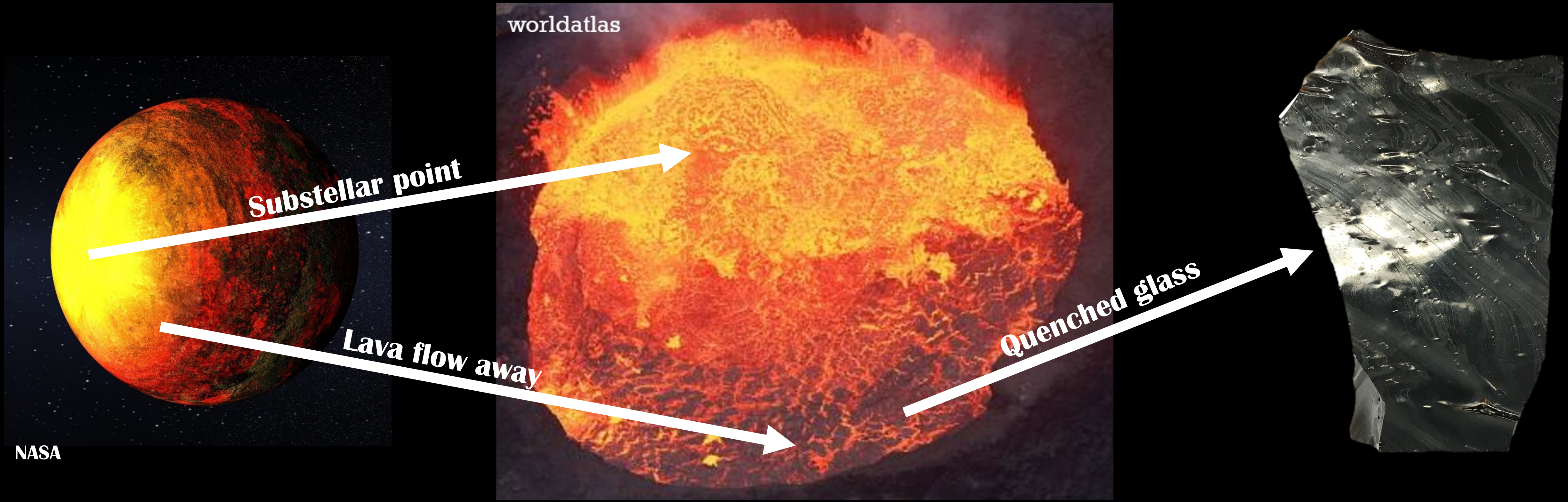
Demory (2014)
Malavolta et al. (2018)

SURFACES AS A SOURCE OF HIGH ALBEDOS



Credit: NASA

A (SIMPLE) THEORETICAL SURFACE OF A LAVA WORLD



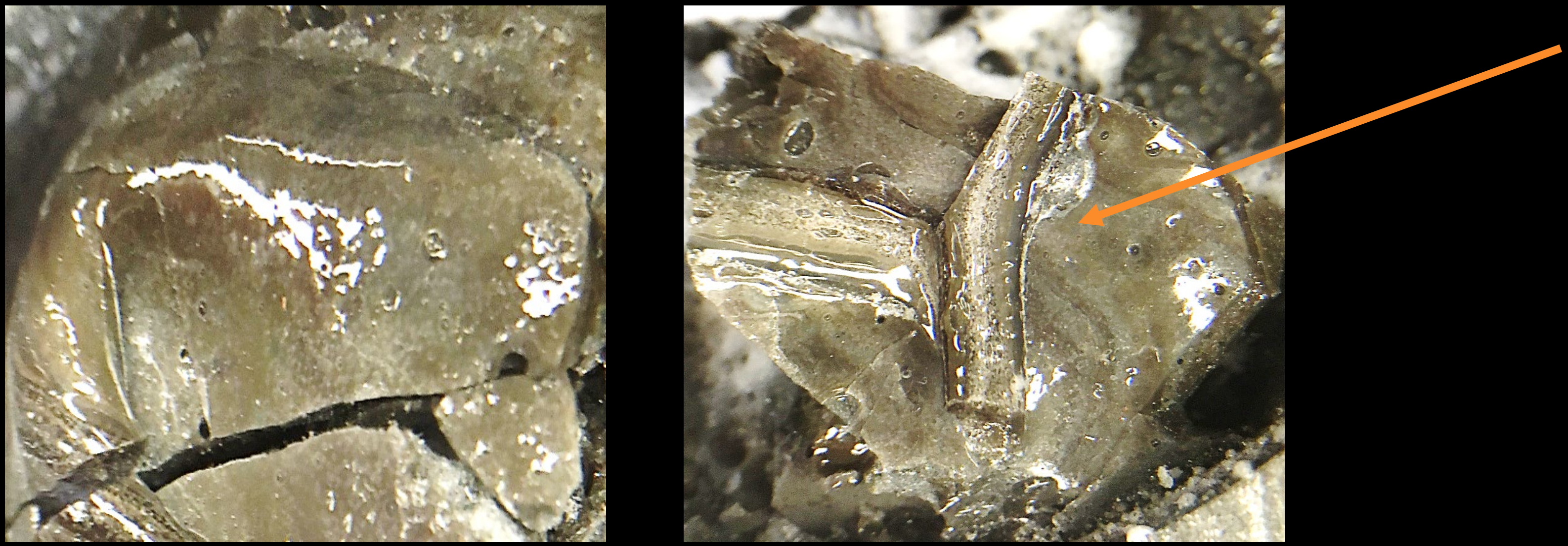
worldatlas

NASA

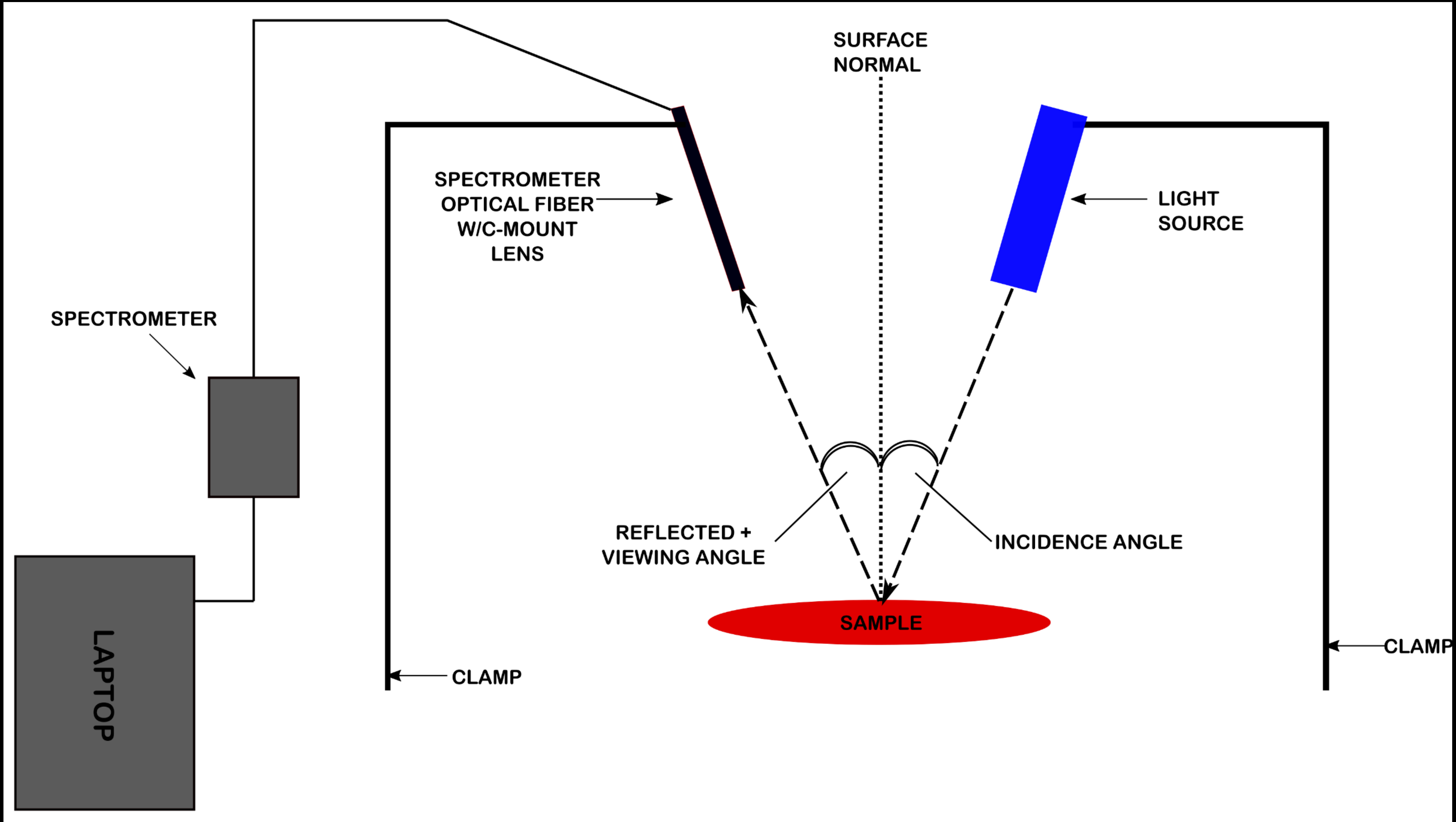
BASALT AND FELDSPAR QUENCHED GLASSES

Basalt

Feldspar



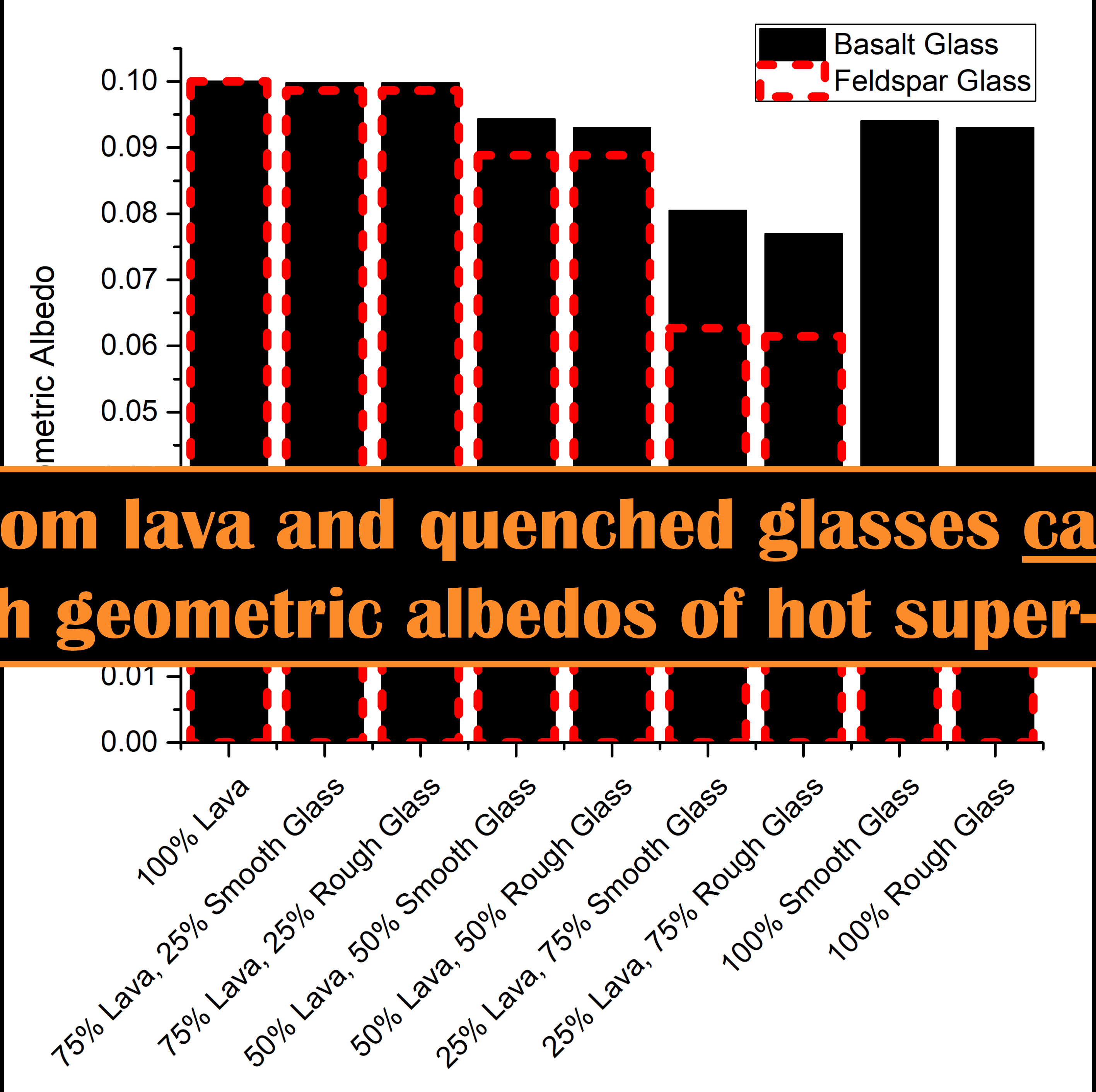
MEASURING REFLECTION FROM QUENCHED GLASSES



METHODS

- **Modeling:**
  - **Planet geometric albedo modeled as a function of the reflection coefficient function of lava/quenched glass, and the cosine of the reflected angle*.**
  - **Experimentally measured reflectance data integrated into the planet hemisphere albedo model.**
  - **Varied the amount of lava and quenched glass on the surface to determine the effect on albedo.**

* Adapted from Sobolev (1975).

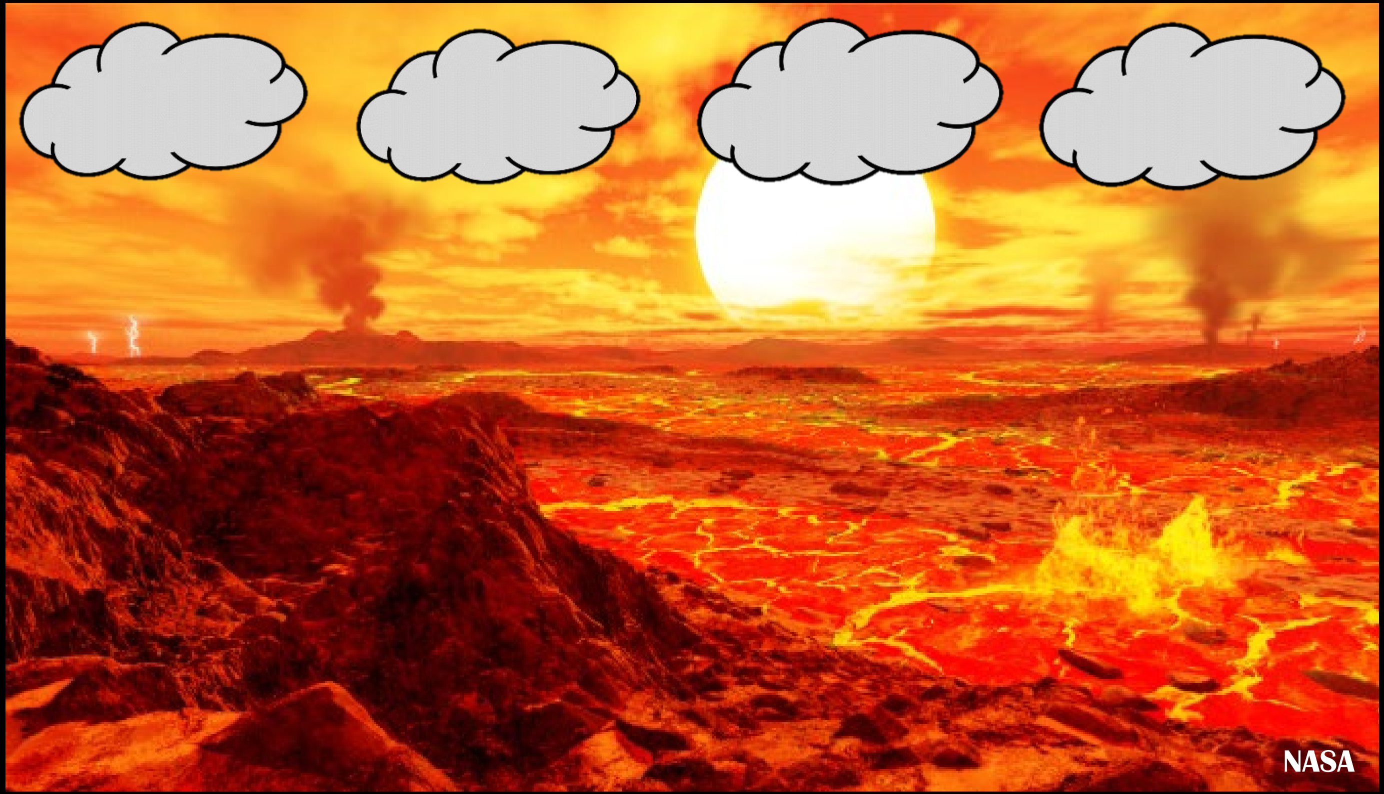


Reflection from lava and quenched glasses cannot explain the high geometric albedos of hot super-Earths.

Essack et al. 2020

OTHER SOURCES OF REFLECTION

ATMOSPHERES



EVOLVED HIGH ALBEDO SURFACES

Combining results from Zebger et al. (2005); Schaefer & Fegley (2009); Kite et al. (2016).

SUMMARY AND CONCLUSIONS

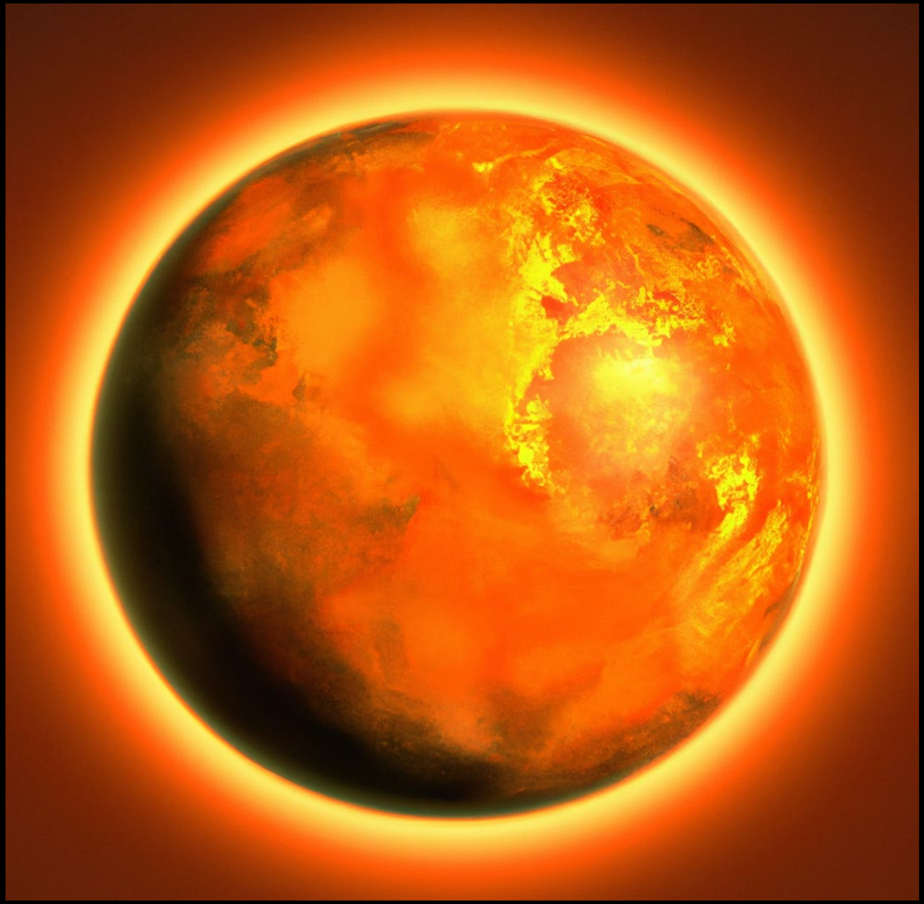
- Designed high-temperature lab experiments to help explain the observed brightness (high geometric albedos) of some hot super-Earths.
- **Main Result:** Lava worlds with solid (quenched glass) or liquid (lava) surfaces have low albedos (< 0.1), hence these surfaces have a negligible contribution to the high albedos of some hot super-Earths.
- **The high geometric albedos of hot super-Earths are likely explained by atmospheres with reflective clouds or evolved surfaces.** This allows us to narrow down the range of possible reflected light sources present on these planets.
- Validating lava planet candidates from TESS and characterizing them with JWST will allow us to better understand their atmospheres, surfaces, and other properties.

ESSACK ET AL. (2020), *THE ASTROPHYSICAL JOURNAL, 898, 160.*

ATMOSPHERIC CHARACTERIZATION

OBSERVING SODIUM IN HOT SUPER-EARTHS ATMOSPHERES

SODIUM IN PLANETARY ASTRONOMY

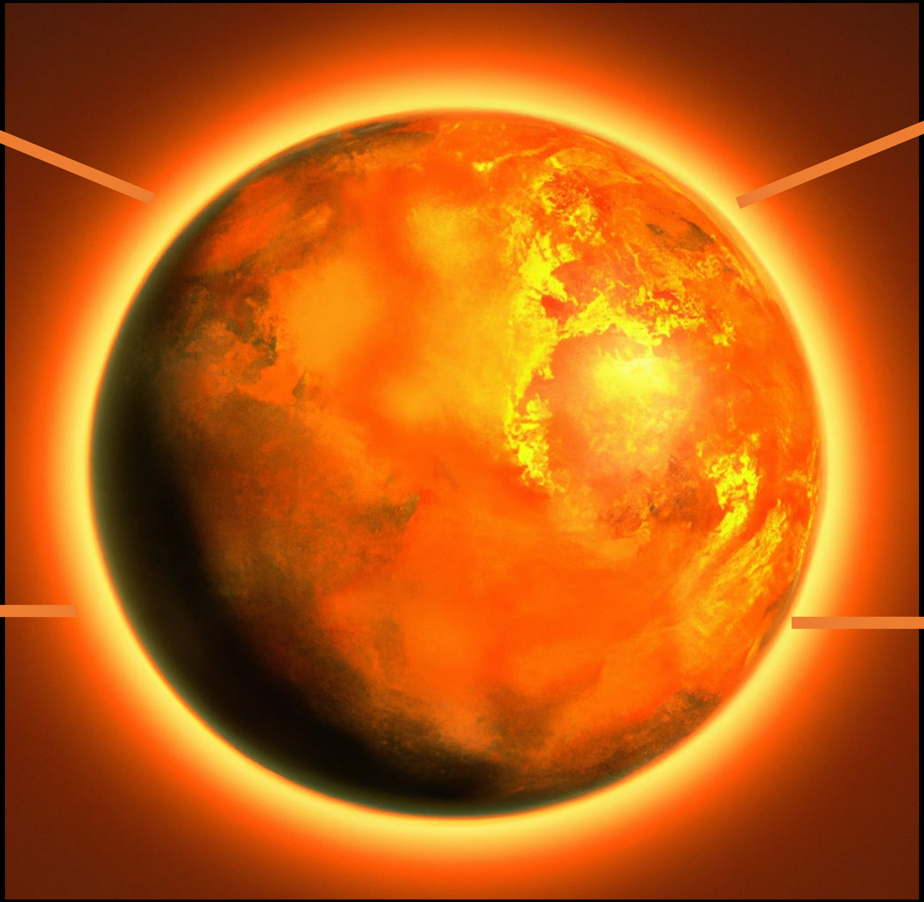


- Strong absorber at VIS wavelengths
- Observed in the solar system
  - Mercury exosphere
  - Io torus
- Detected in the first exoplanet atmosphere (transmission spectroscopy)

WHY STUDY SODIUM AROUND HOT SUPER-EARTHS?

- Identification of atmospheric species is key focus of the exoplanets field, especially since the launch of JWST.
- Sodium is expected to be major component of hot, rocky super-Earth atmospheres.
  - BUT: there has been no definitive detection of sodium around a rocky exoplanet to date.
  - Observations would validate existing models on surface and atmospheric evolution.

THE IMPORTANCE OF OBSERVING SODIUM AROUND ROCKY PLANETS



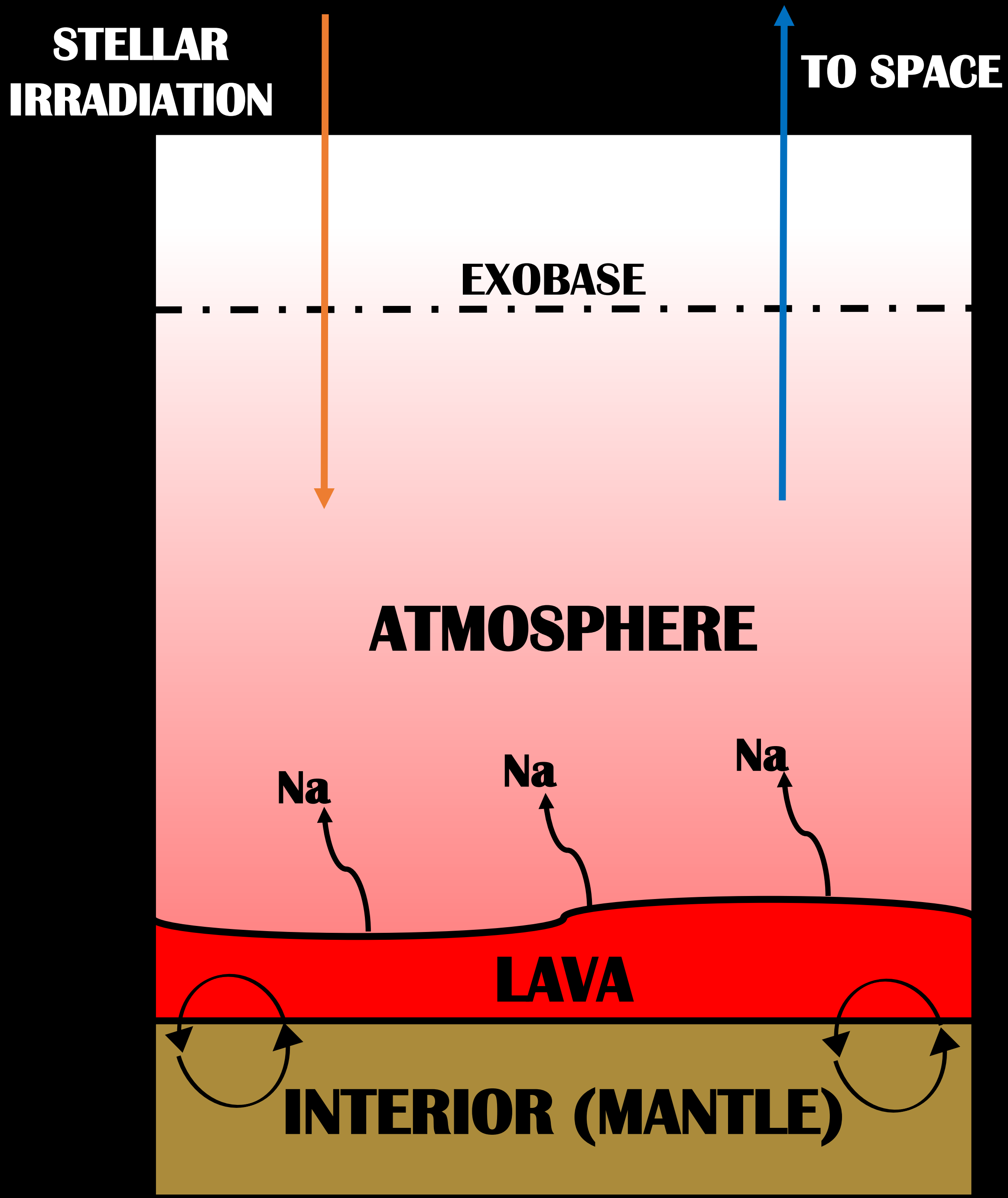
Composition

Surface-Interior Exchange

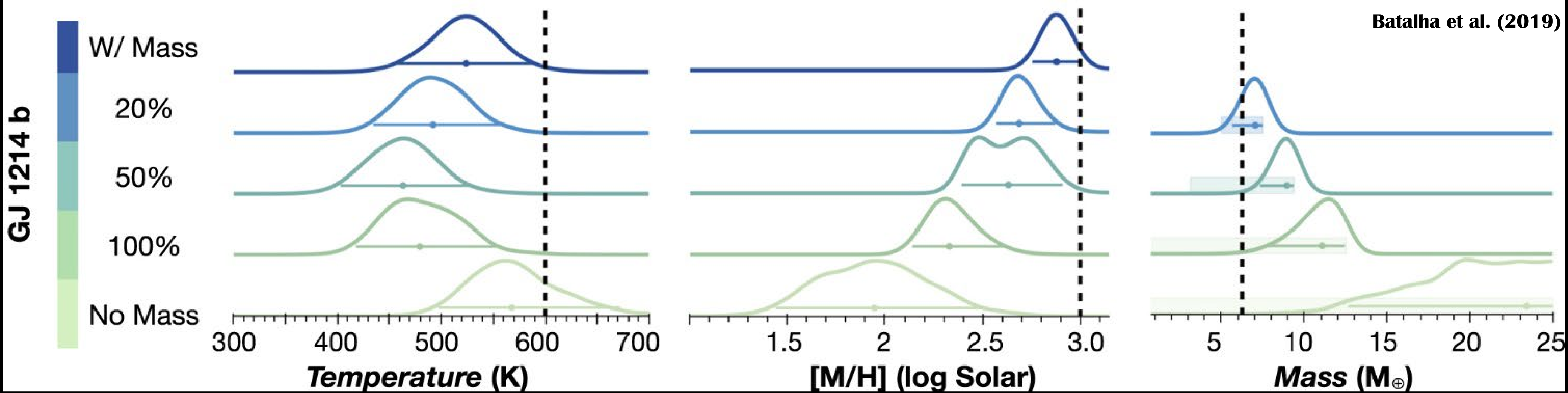
Formation & Migration History

Volcanic Activity

STRUCTURE & PROCESSES ON HOT, ROCKY SUPER-EARTHS



THE IMPORTANCE OF MASS MEASUREMENT PRECISION FOR ATMOSPHERIC CHARACTERIZATION



Batalha et al. (2019)

Obtaining precise masses for the planet population spanning the radius valley is crucial for determining the atmospheric composition and evolution of hot super-Earths.

PLANET SAMPLE

- **Identified potential targets for Na atmospheric observations.**
- **Selection Criteria:**
  - ***Planet mass (and radius) precision better than 20% (or 5σ)***
    - **To reduce degeneracy in determining atmospheric properties.**
  - ***Consistent with a rocky composition ($\rho_p > 5$ g/cm^3; $R_p < 1.75$ R_{earth})***
    - **Planets below the radius valley at 1.75 R_{earth} are expected to be rocky, without a H/He atmosphere.**
  - ***Surface temperature > 2000 K***
    - **Sufficient initial atmospheric pressure, and quantity of Na vaporized.**

Final sample: 12 planets

ENERGY LIMITED ESCAPE

- **Hydrodynamic escape drive by stellar XUV radiation.**

Heating efficiency
$\eta \sim 10^{-3}$
Ito & Ikoma (2021)

$$\dot{M} = \eta \frac{\pi R_p^3 L_{XUV}}{4\pi a^2 G M_p}$$

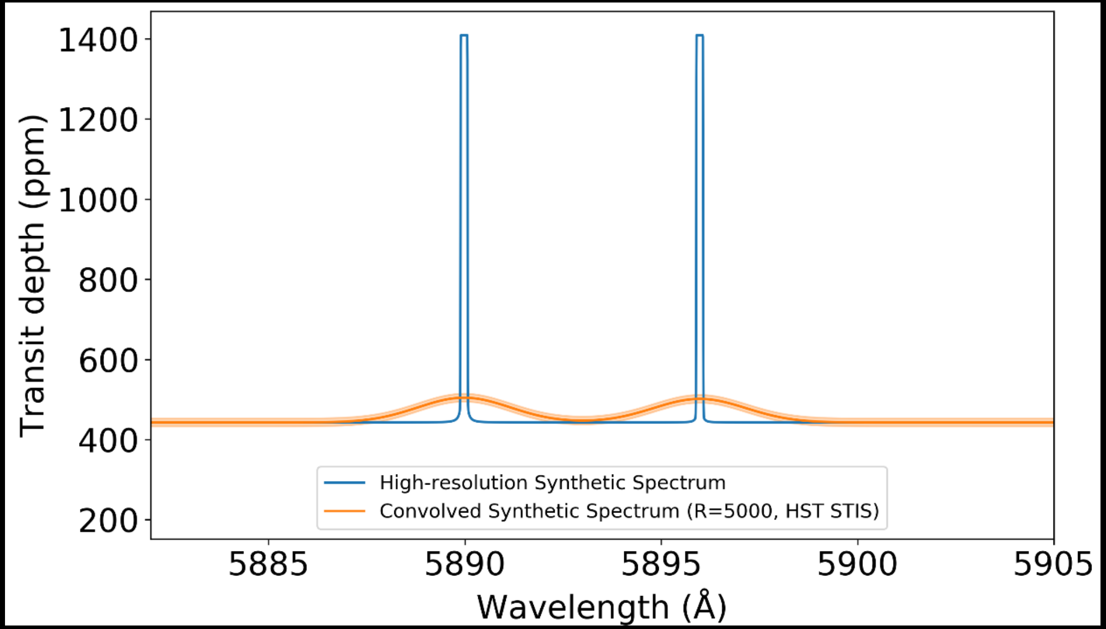
★ XUV luminosity
Empirical Relations
Sanz-Forcada et al. (2011)

→ Calculate mass loss timescale for Na, given a bulk silicate Earth composition.

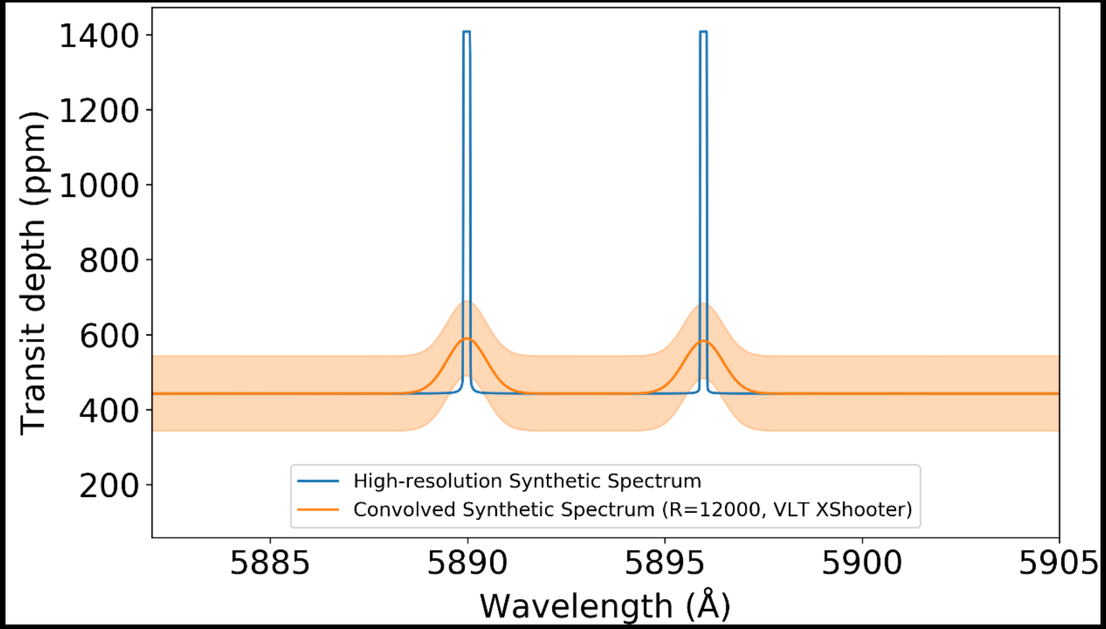
INSTRUMENT CAPABILITIES

- **What does the theoretical transmission spectrum look like when observed with currently available space-and ground-based spectrographs?**
  - **HST STIS (R = 5,000) – medium resolution**
  - **VLT X-shooter (R = 12,000) - intermediate resolution**
  - **VLT UVES (R = 100,000) - high resolution**

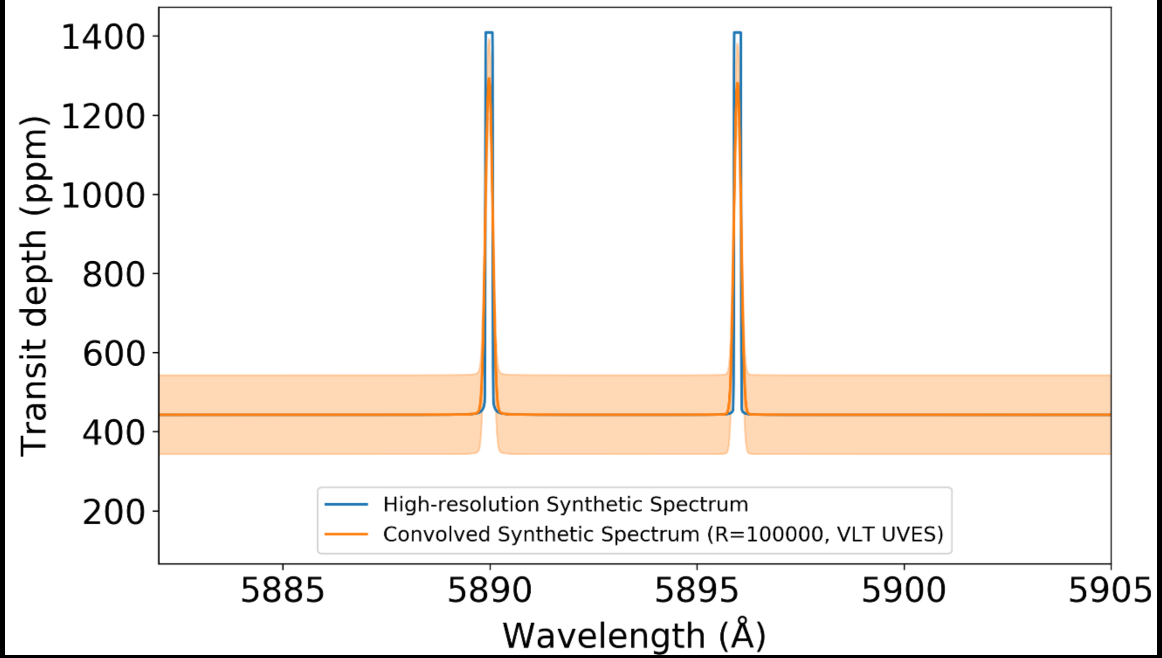
HST STIS



VLT X-SHOOTER



K2-141 b



VLT UVES

SUMMARY AND CONCLUSIONS

- **Motivation:** Sodium around hot, rocky planets can provide insights into their composition and formation & validate current surface and atmospheric evolution models.
- Modeled atmospheric escape and transmission spectra to determine if the Na absorption feature is observable.
- **Main Results:**
  - Ground-based high-resolution spectrographs have the best capabilities for detecting Na around the hot super-Earths in our sample.
  - Identified K2-141 b as the best planetary target for Na observations.
    - Future JWST IR observations of K2-141 b. Complementary Na detection/non-detection would be valuable