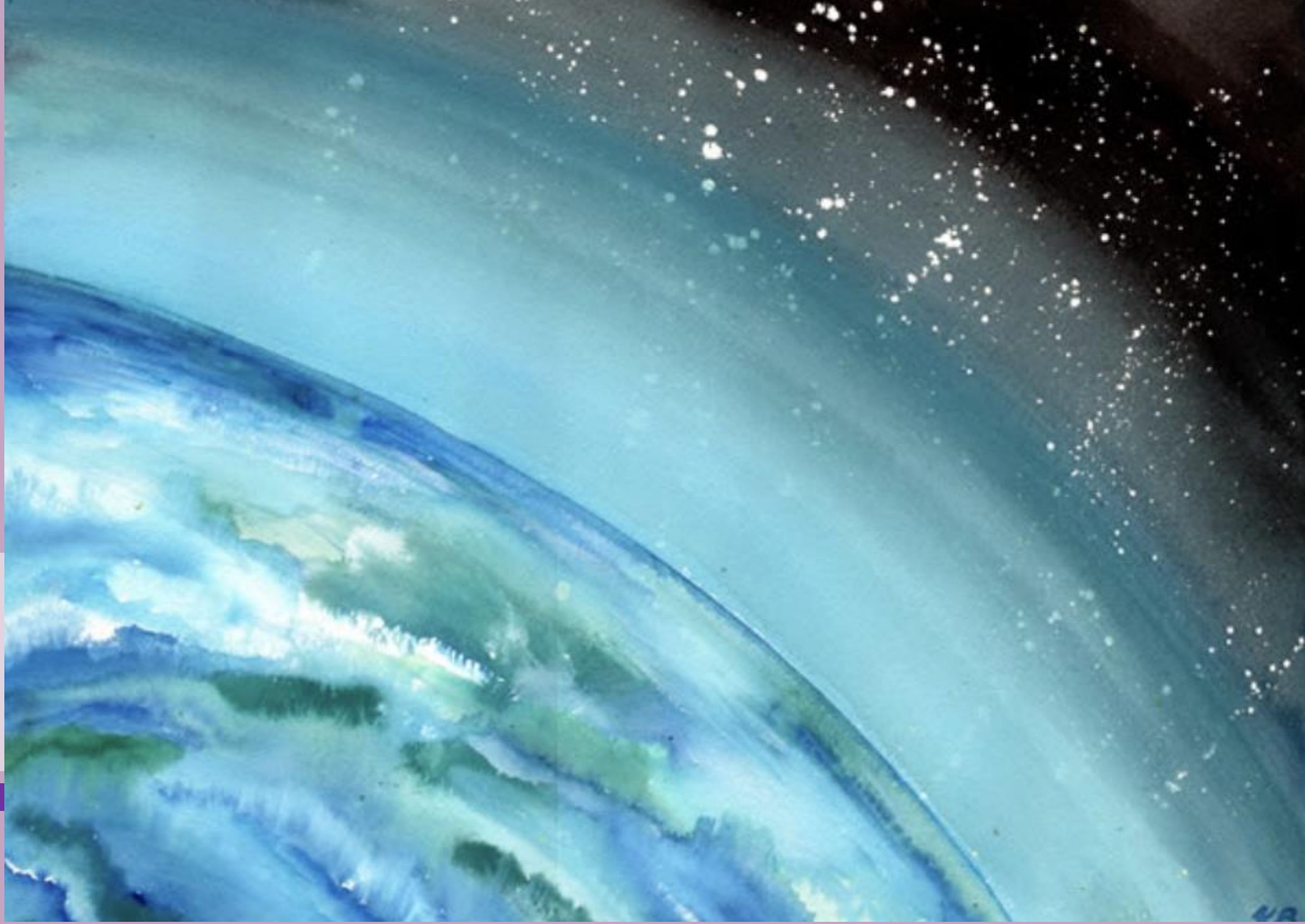
Keep it or Lose it: the Fate of Rocky Exoplanetary Atmospheres Under the Influence of their Host Star



Art Credit: Kirsten Bailey

Raissa Estrela

Contact: restrela@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

In collaboration with: Mark Swain (JPL), Adriana Valio (CRAAM/Mackenzie) and Viktor Sumida (CRAAM/Mackenzie).

Image credits: ESA

Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2023)

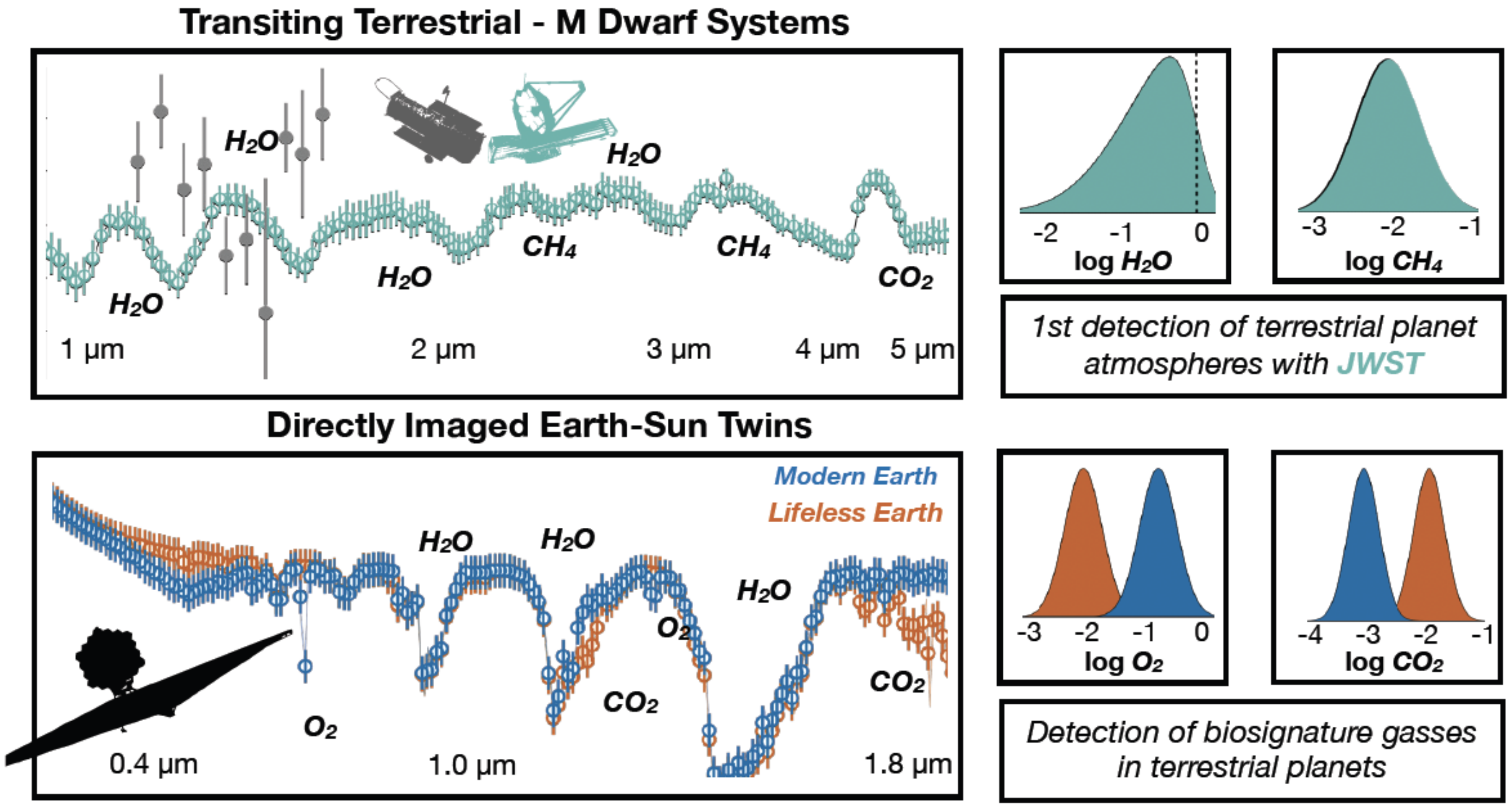
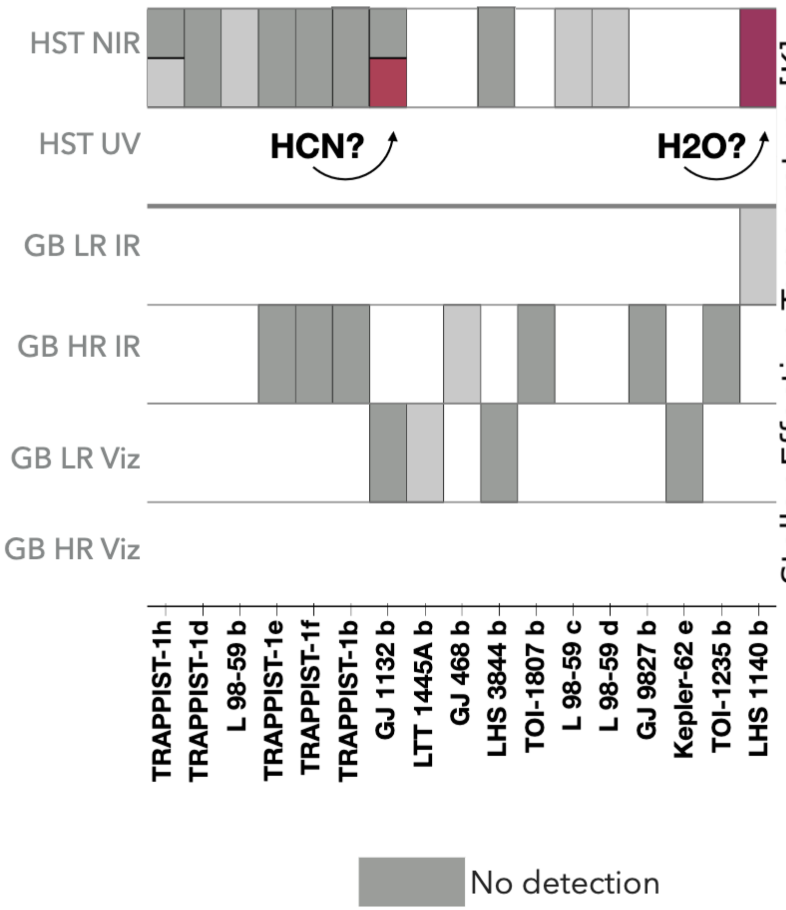
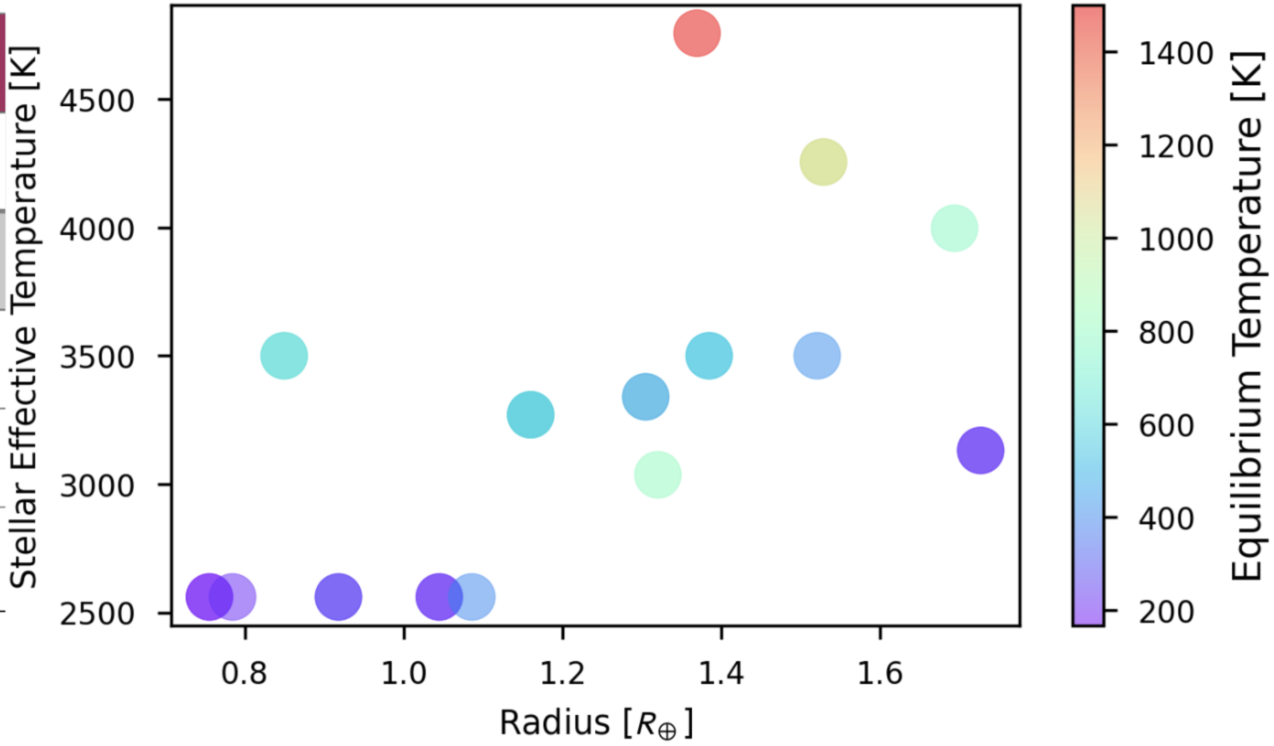


FIGURE 2.8 The 2020s and beyond will be an era of spectroscopy of exoplanet atmospheres. For giant planets such as transit-

Initial HST efforts to detect atmospheres in R < 1.8$R_\oplus$ planets





Credit: Natasha Batalha (2023 Sagan Summer Workshop)


National Aeronautics and Space Administration
NASA
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SPACE TELESCOPE


National Aeronautics and Space Administration
NASA esa
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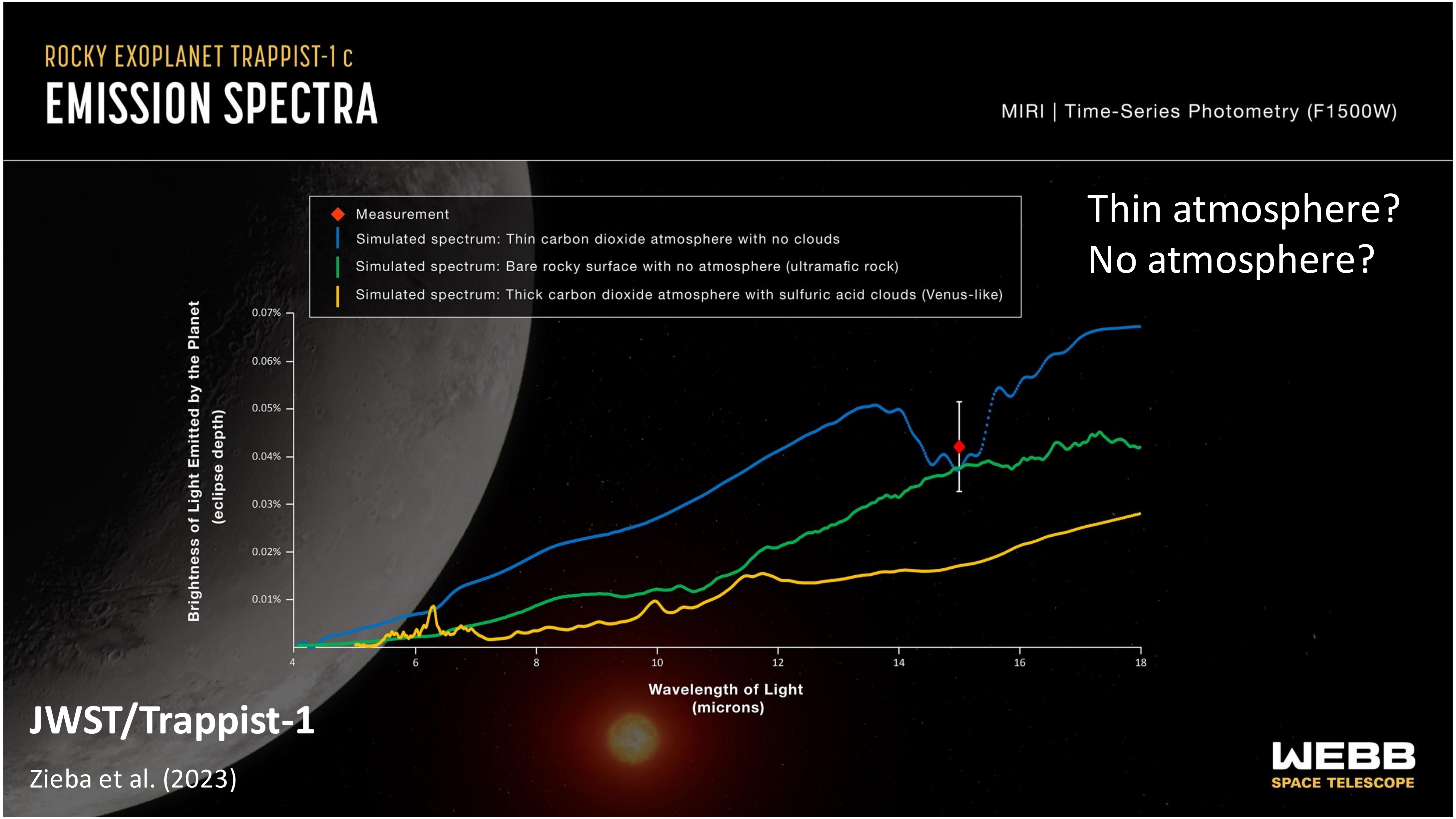
www.exoplanets.nasa.gov
www.nasa.gov

Transitioning to detect atmospheres in rocky planets with JWST

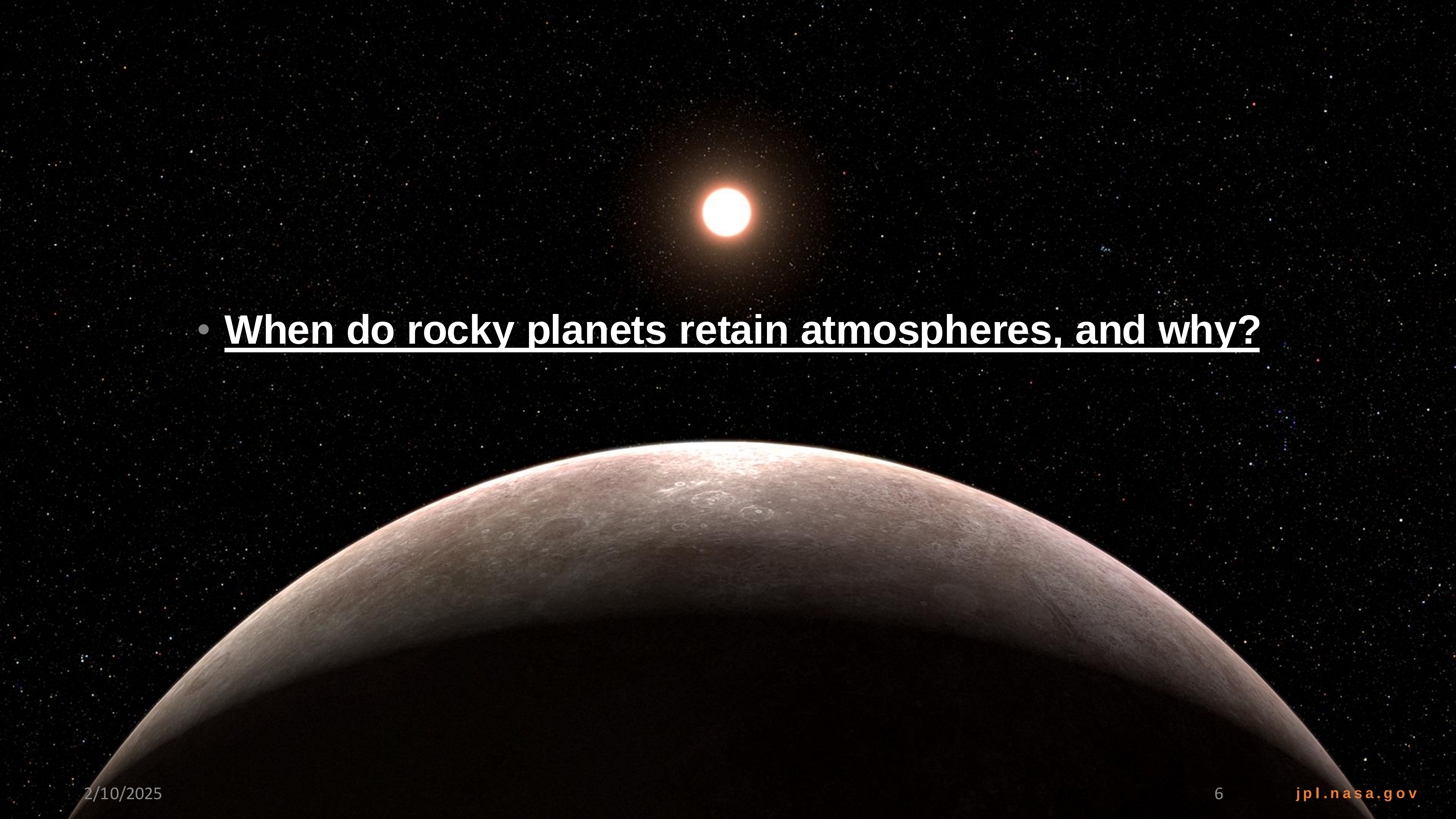


Thin atmosphere?

No atmosphere?

JWST/Trappist-1

Zieba et al. (2023)



- **When do rocky planets retain atmospheres, and why?**

Factors influencing planetary evolution

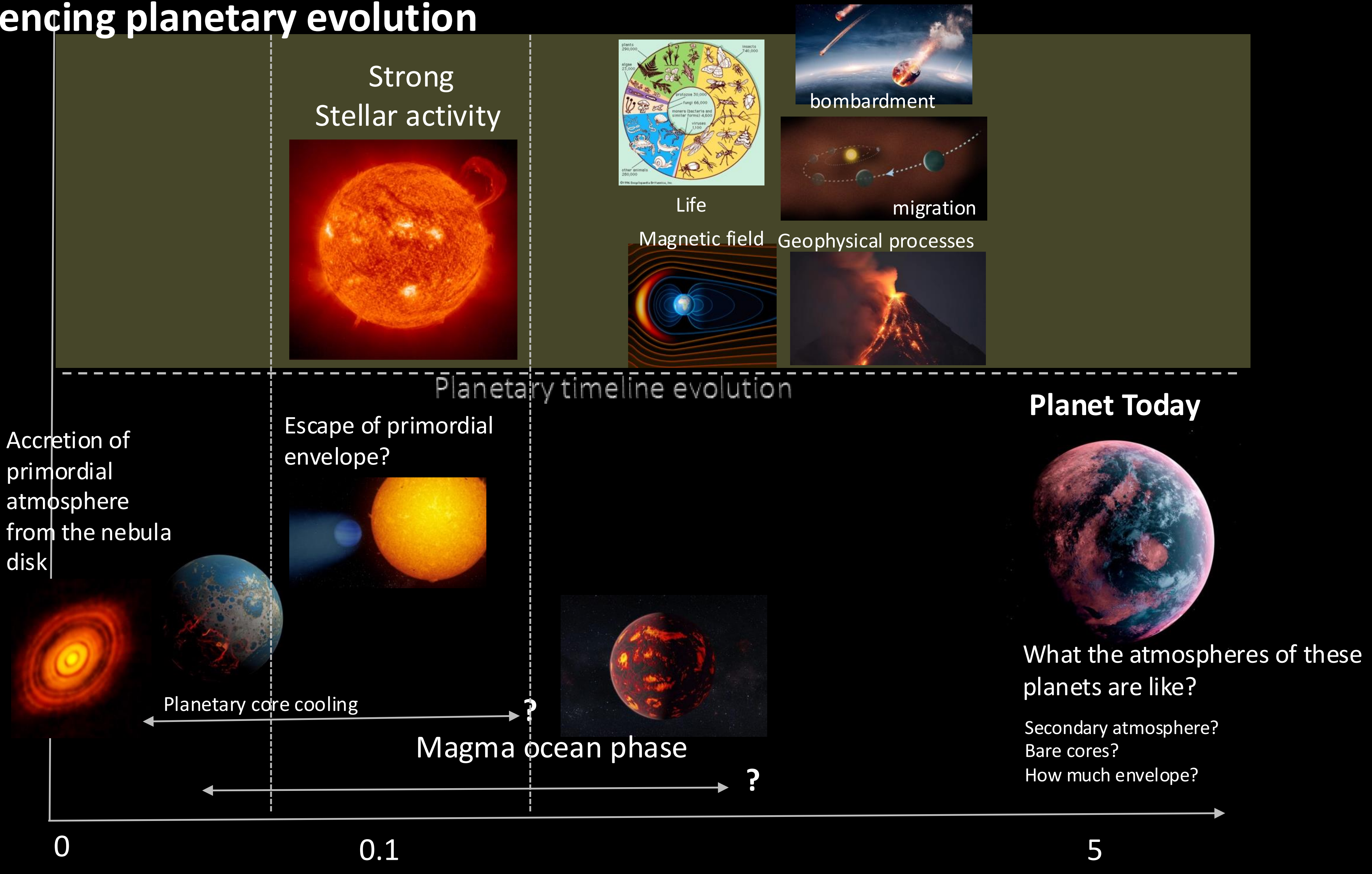


Figure credits: ДМИТРИЙ ЛАРИЧЕВ/ISTOCK.COM
NASA
CARNERGIE
ESA/HUBBLE

Factors influencing planetary evolution

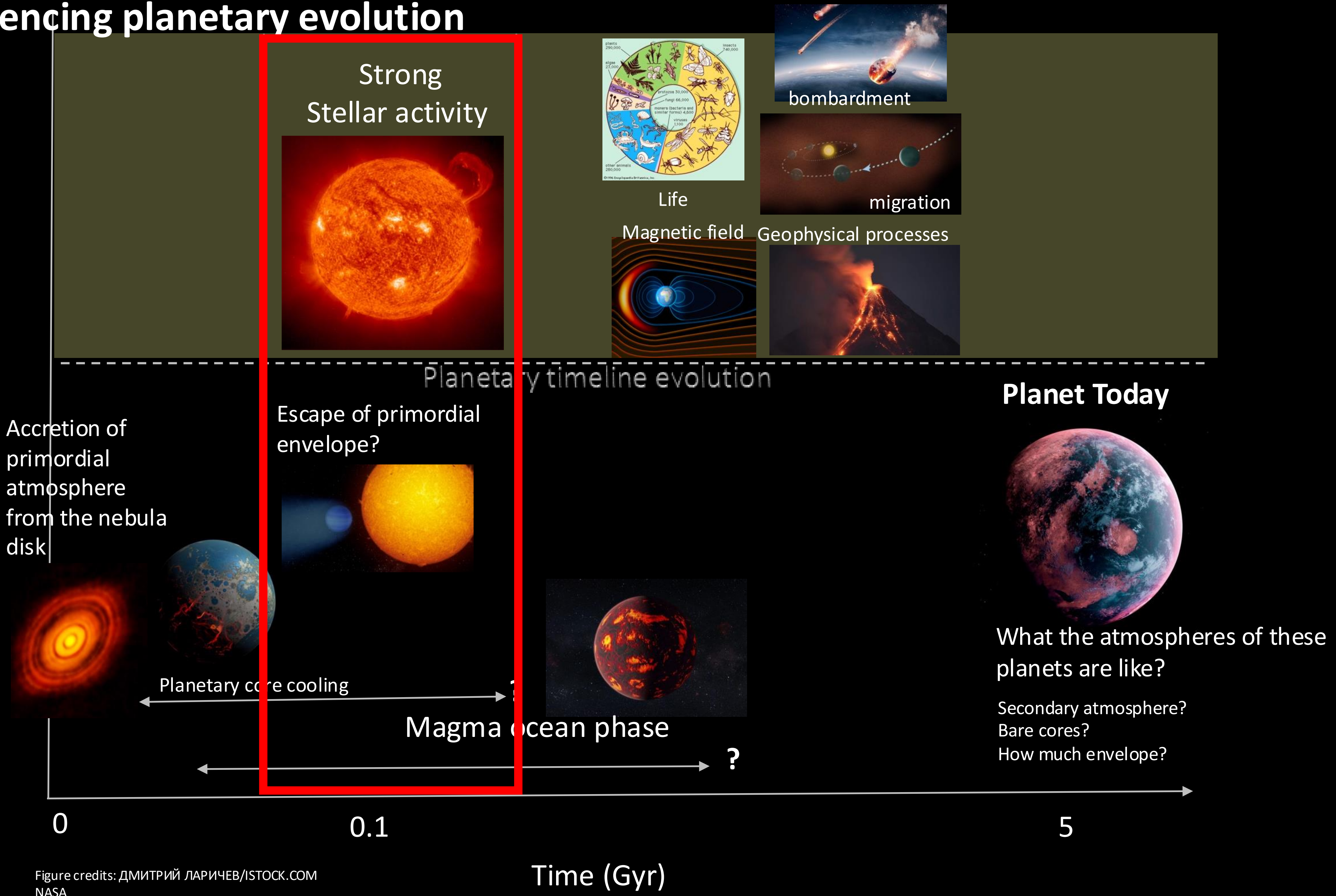


Figure credits: ДМИТРИЙ ЛАРИЧЕВ/ISTOCK.COM
NASA
CARNERGIE
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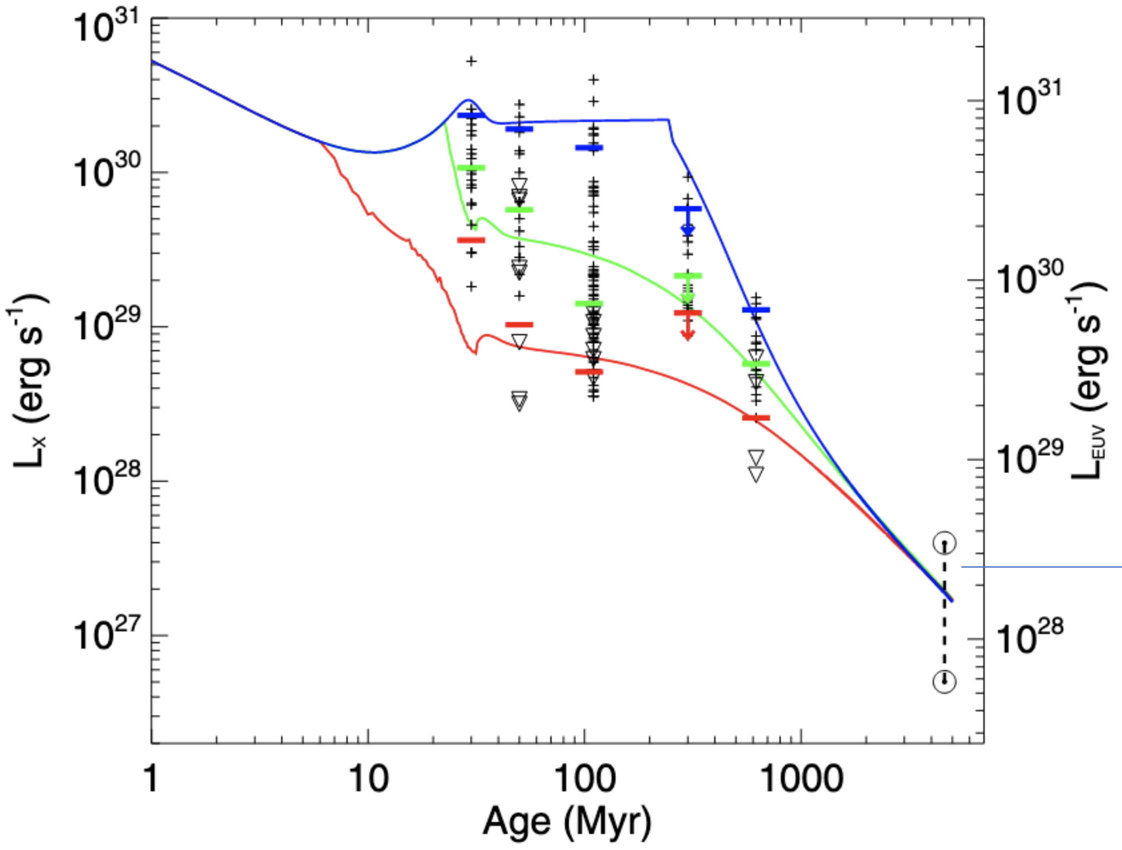
Stars change through time: the star luminosity evolves

Younger stars
More active, fast rotation

Age

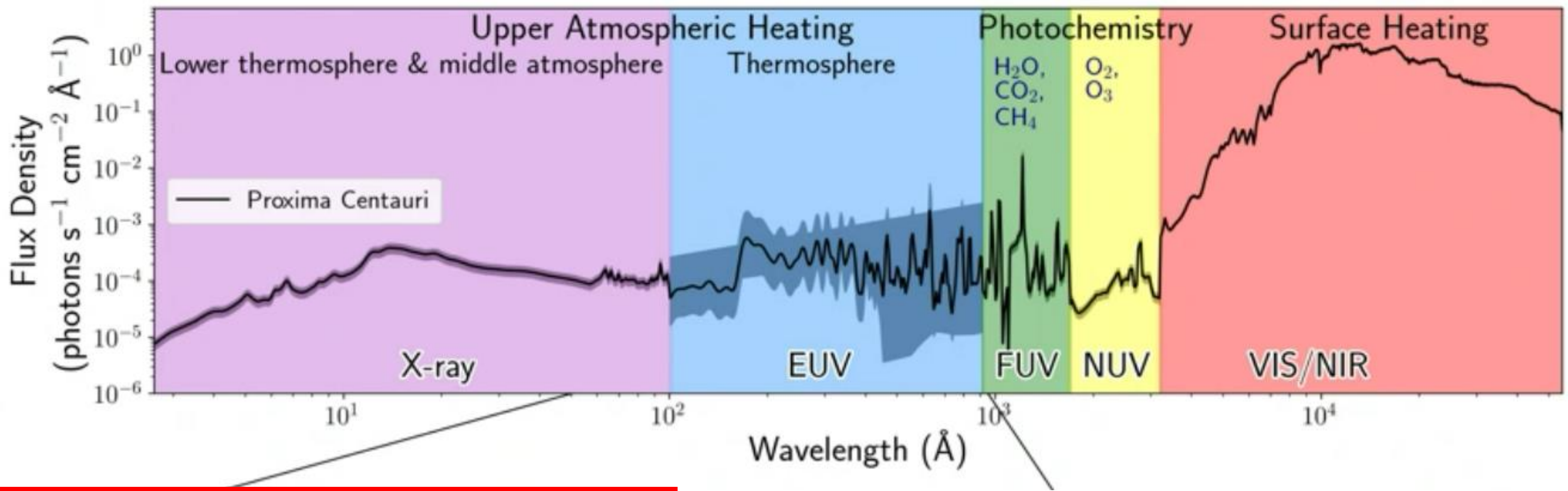
Older stars
Less active, lower rotation



Sun

Tu et al. (2015)

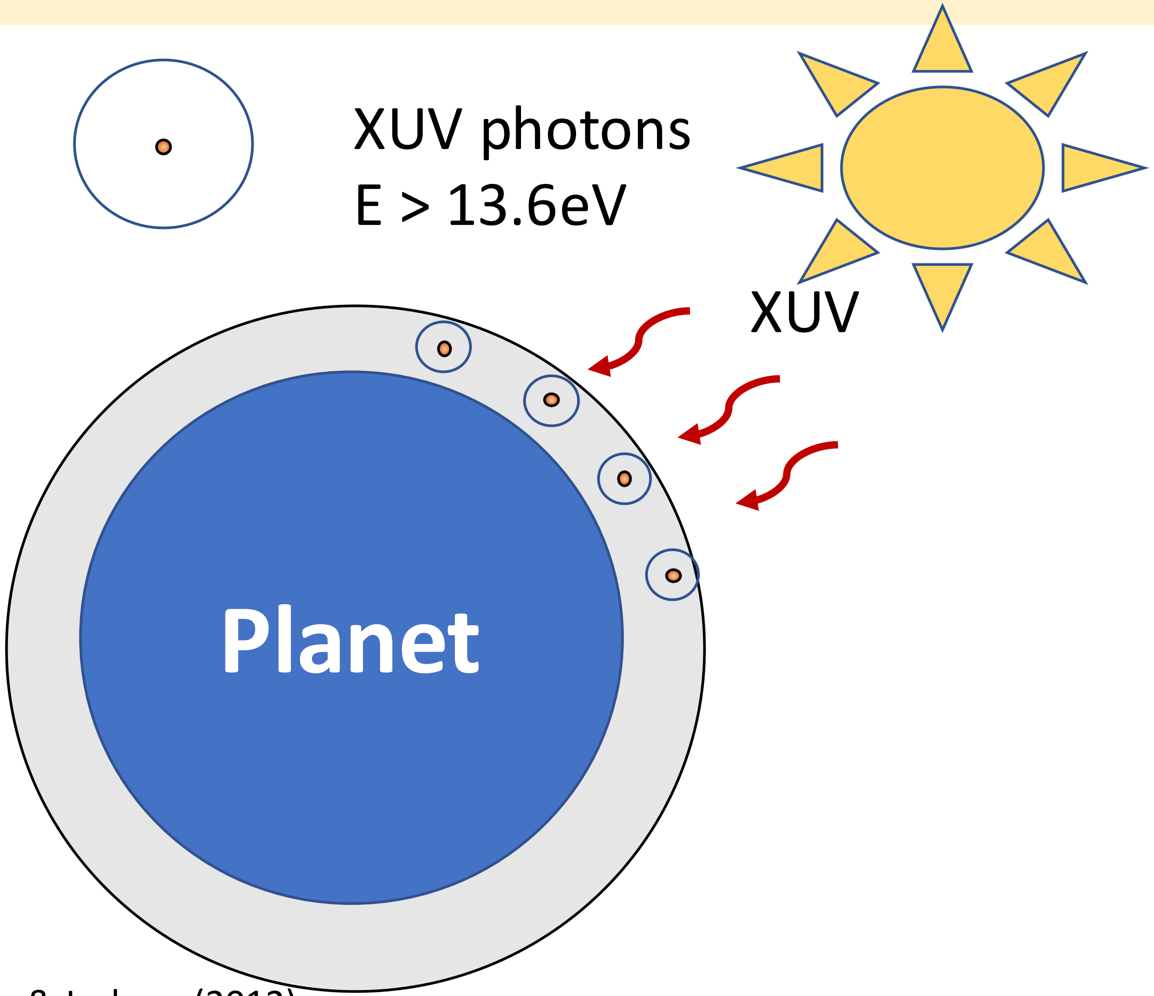
Influence of the host star according to the wavelength



Xray and EUV irradiance:
Drives atmospheric escape

FUV and NUV irradiance:
Origins of life
Drives photochemistry

Atmospheric escape processes shape exoplanets



Owen & Jackson (2012)
Lopez & Fortney (2013)
Owen & Wu (2013, 2017)
Jin et al. (2014)

Sub-Neptunes

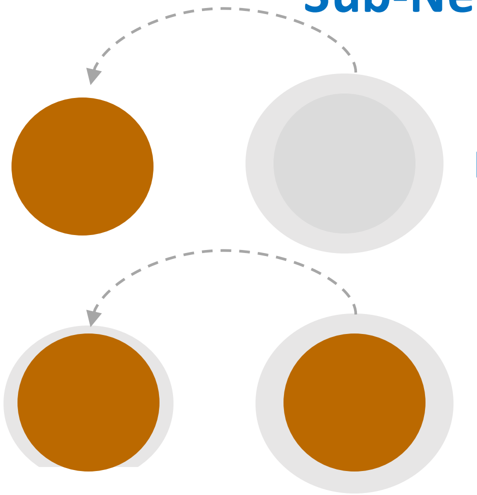
Rocky Planets

Bare rocks

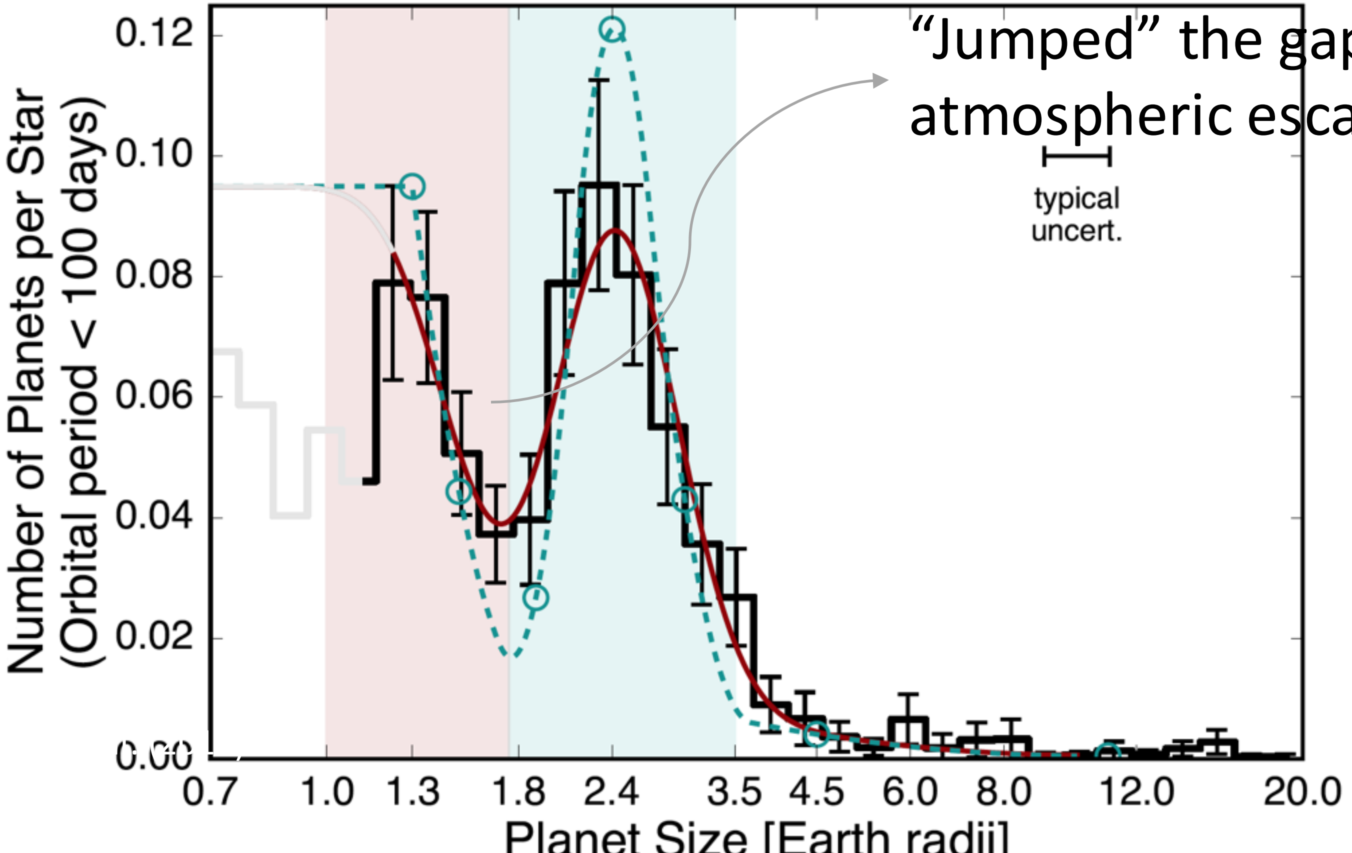
Liquid ocean and a thick H_2/He atmosphere

Rocky with thin atmospheres

Rocky with a thick H_2/He atmosphere



“Jumped” the gap due to atmospheric escape



Fulton et al. (2017)

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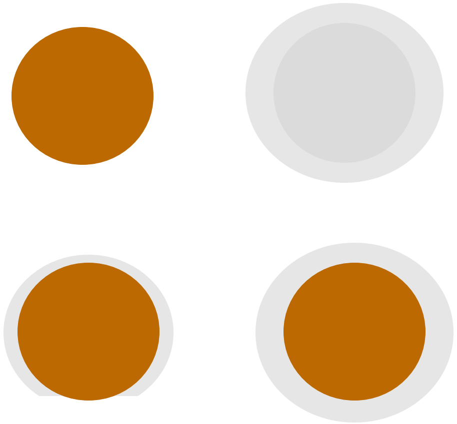
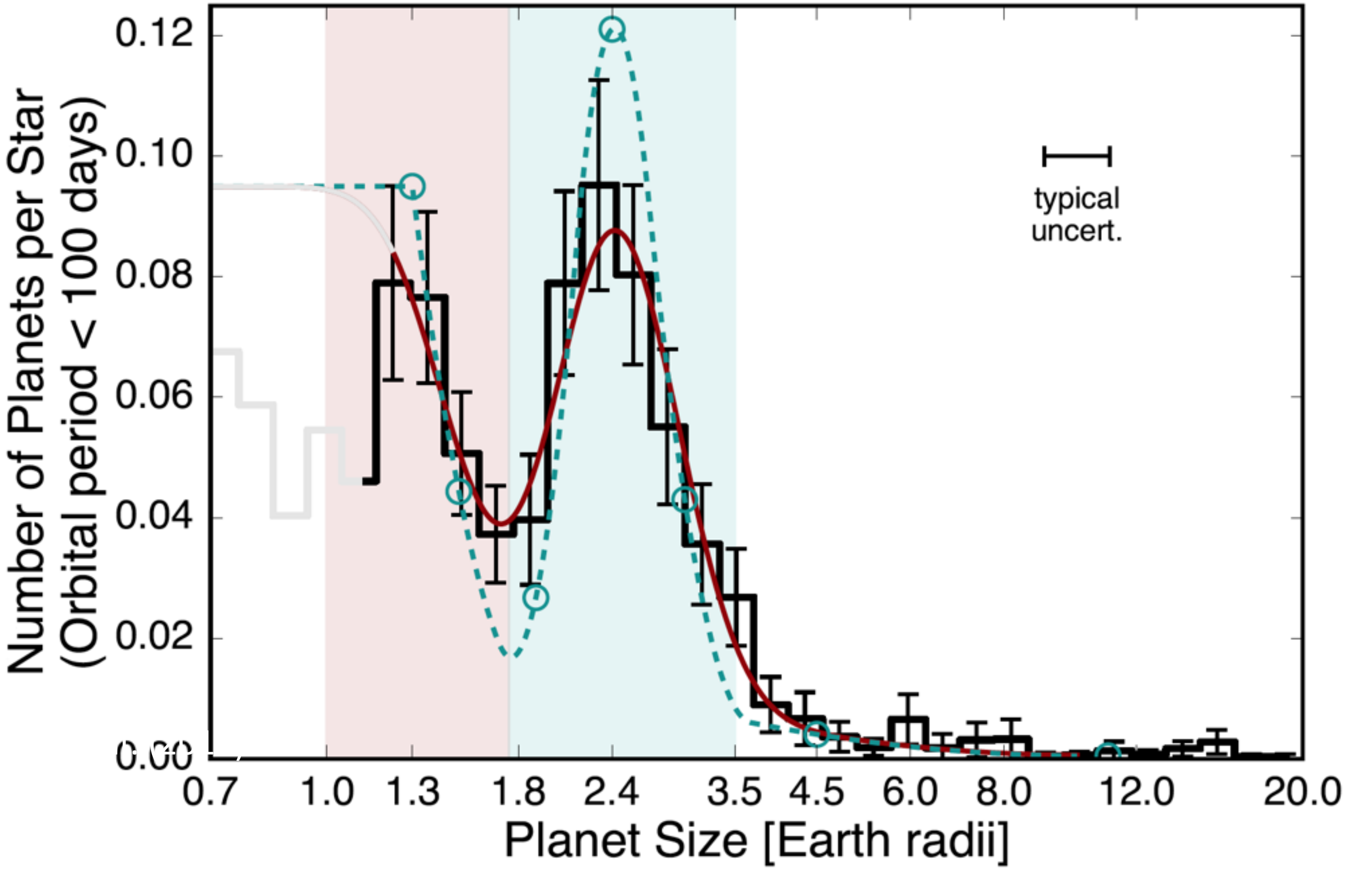
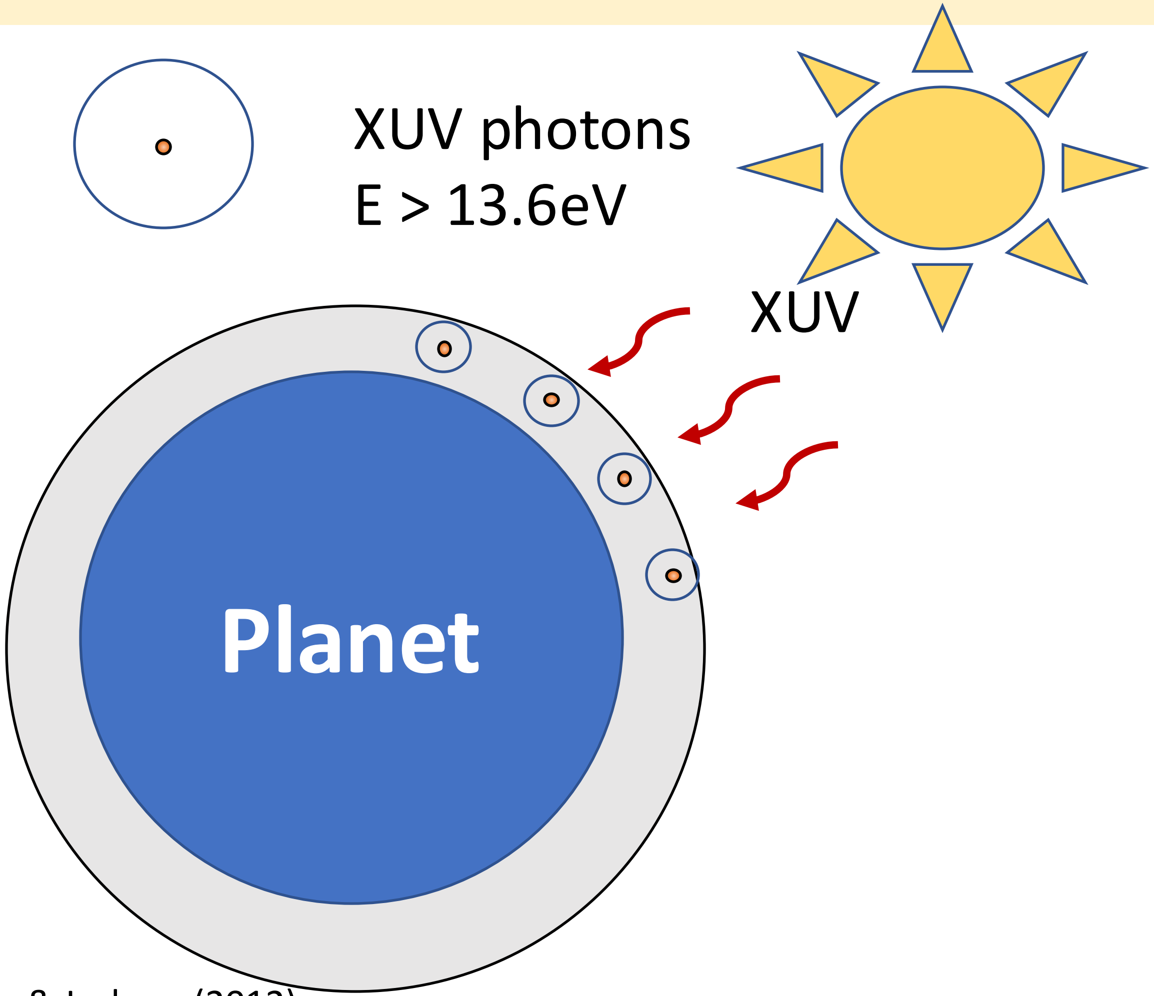
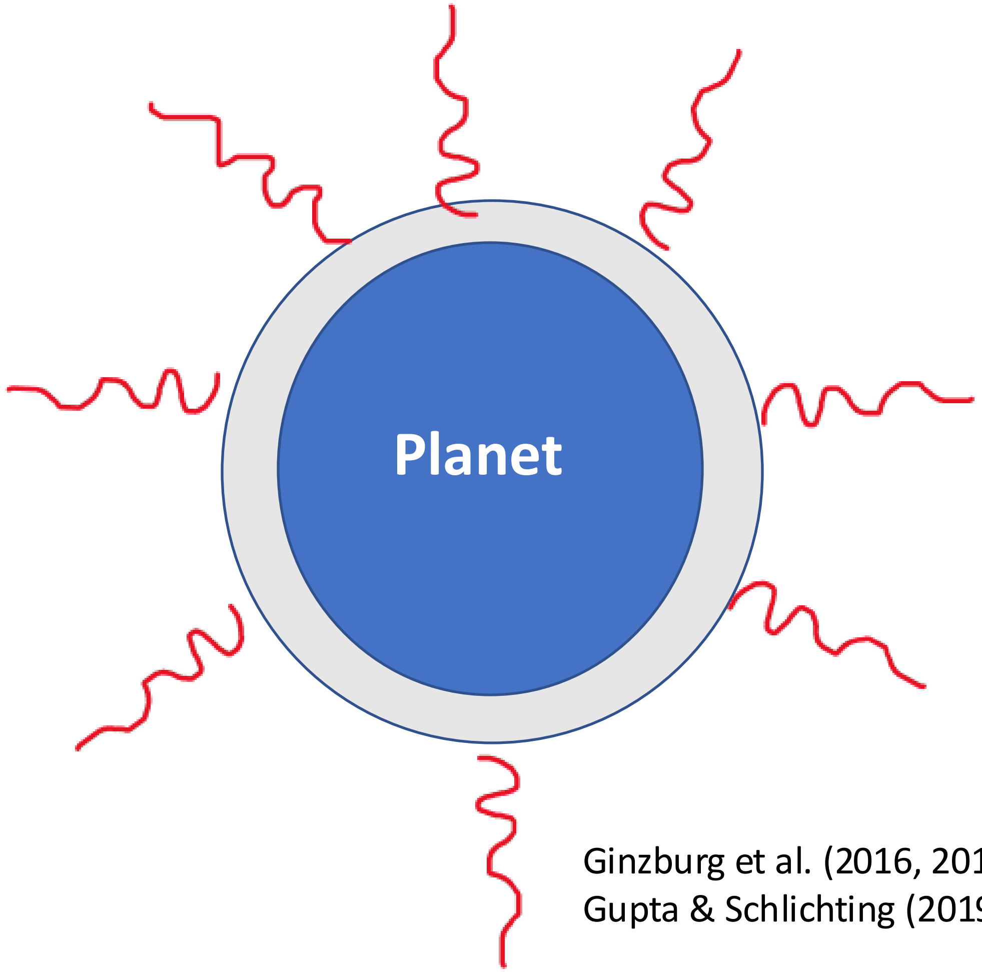




Fulton et al. (2017)

Atmospheric escape processes shape exoplanets





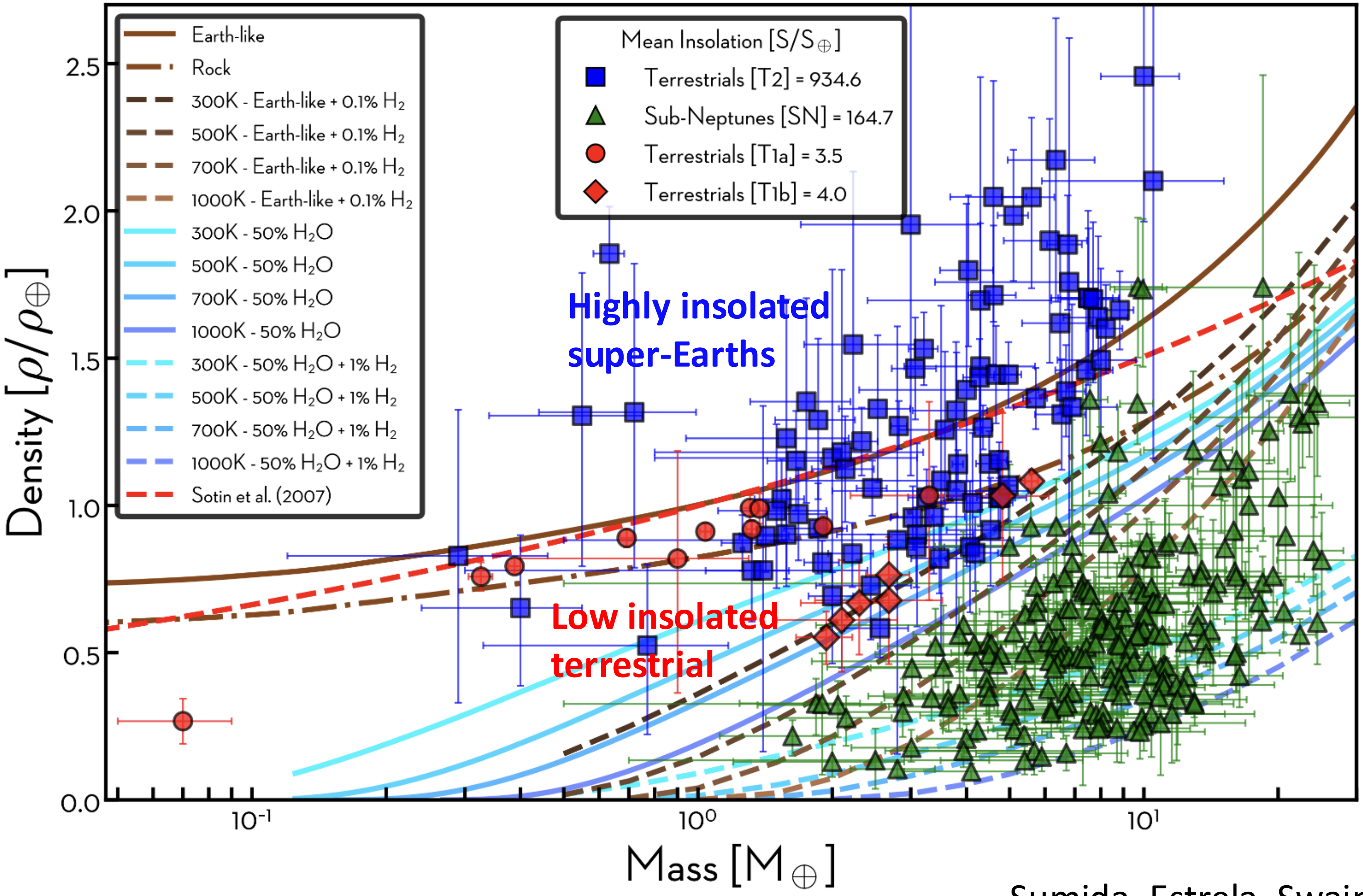
Owen & Jackson (2012)
Lopez & Fortney (2013)
Owen & Wu (2013, 2017)
Jin et al. (2014)

Ginzburg et al. (2016, 2018)
Gupta & Schlichting (2019,2020)

Understand how rocky planets evolve by looking into their planetary and stellar properties:

- Density
- Insolation
- XUV fluxes

Highly insolated rocky planets atmospheres were likely shaped by XUV radiation



Sumida, Estrela, Swain and Valio (in prep, 2024)

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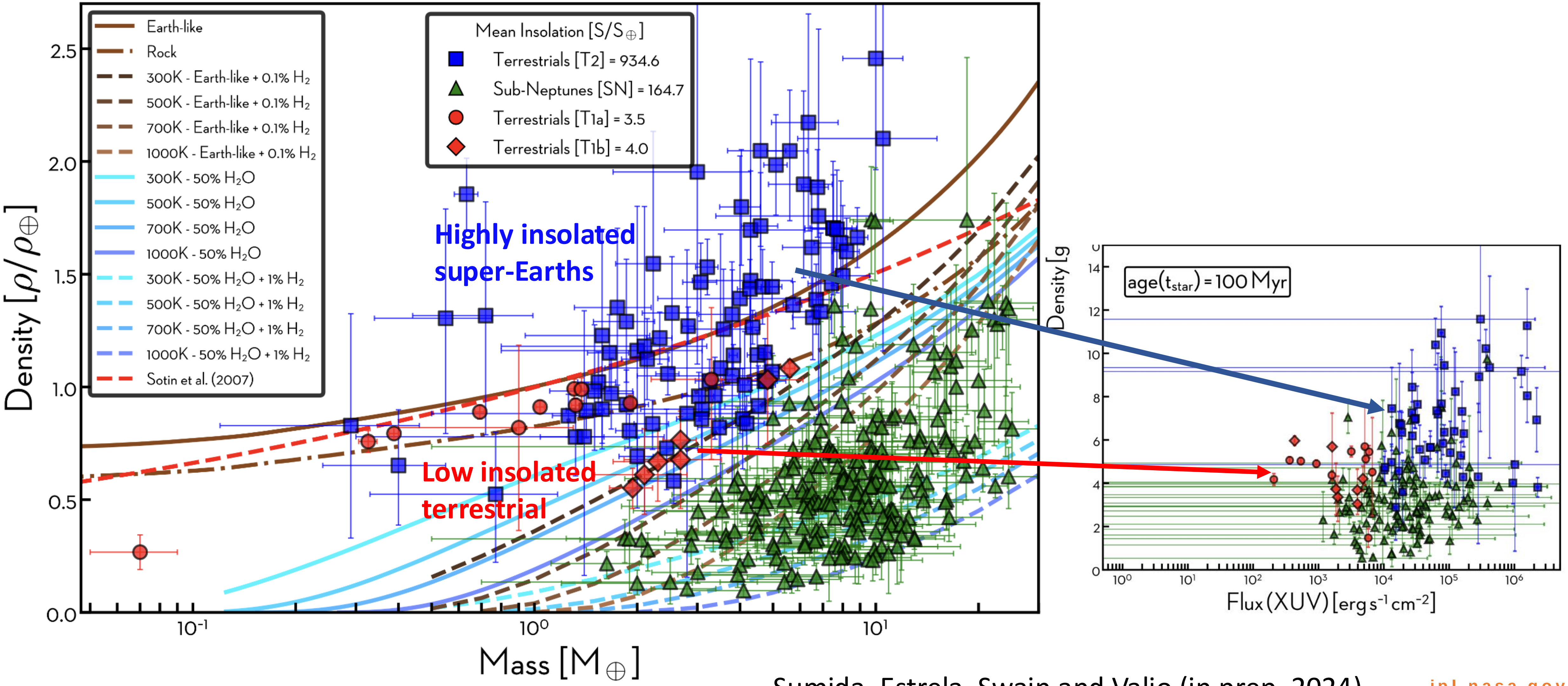
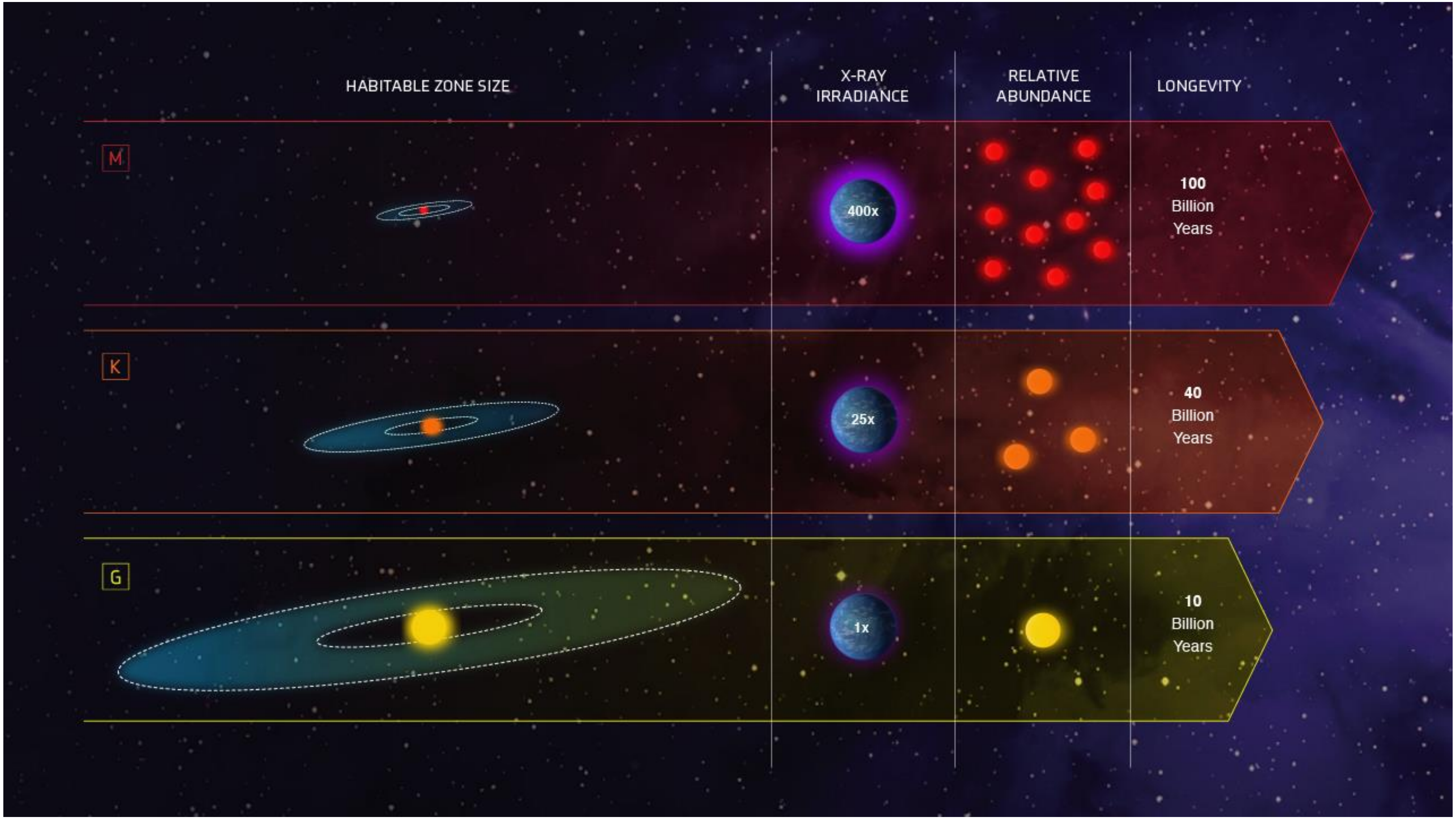


Sumida, Estrela, Swain and Valio (in prep, 2024)

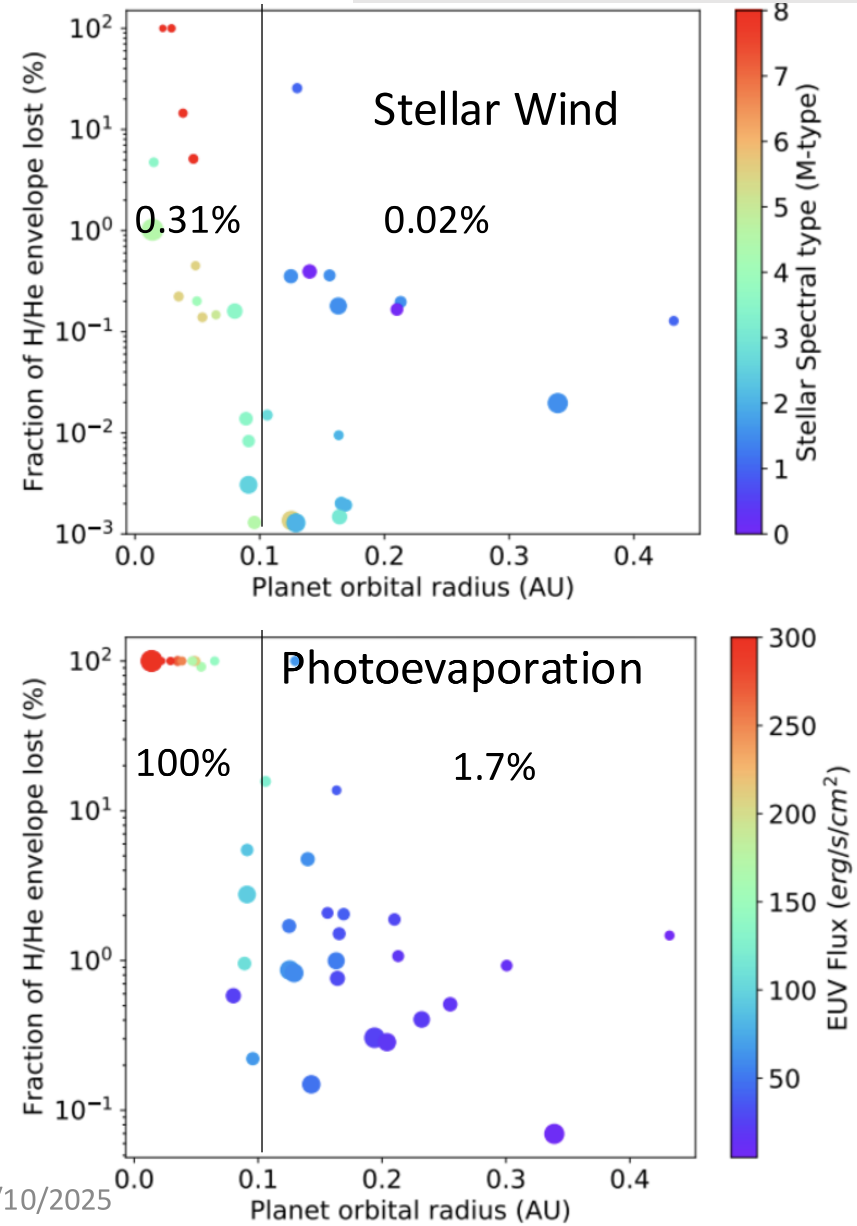
Planets orbiting M dwarfs are more susceptible to the host star radiation

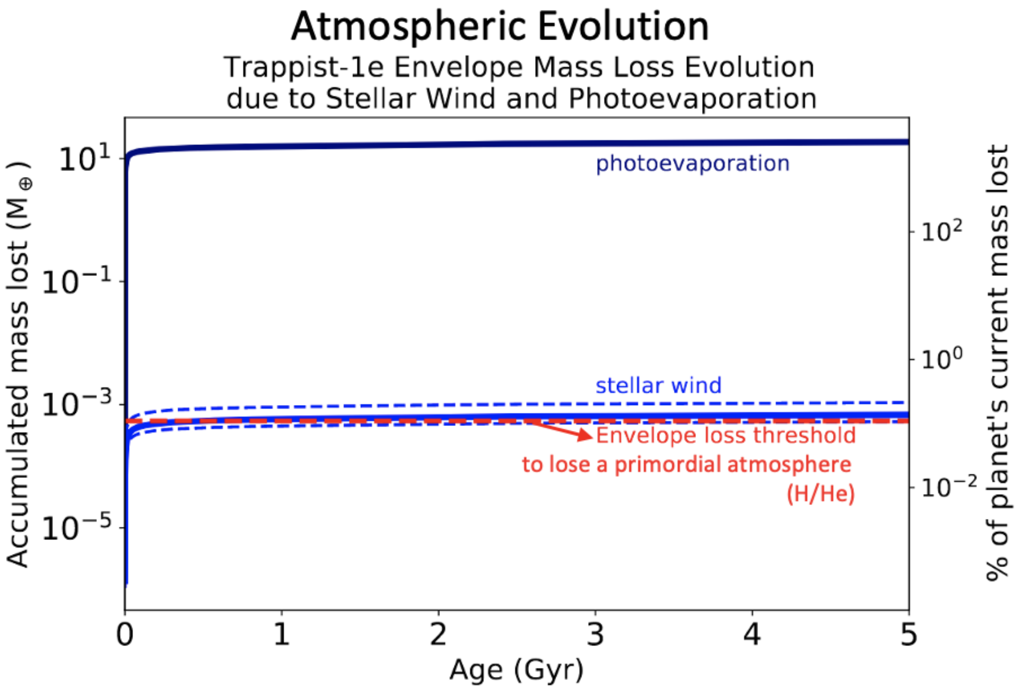


Credits: NASA, ESA, STScI

Do planets in the habitable zone of M dwarfs lost their primordial atmospheres?

Ashini Modi
Harvard University

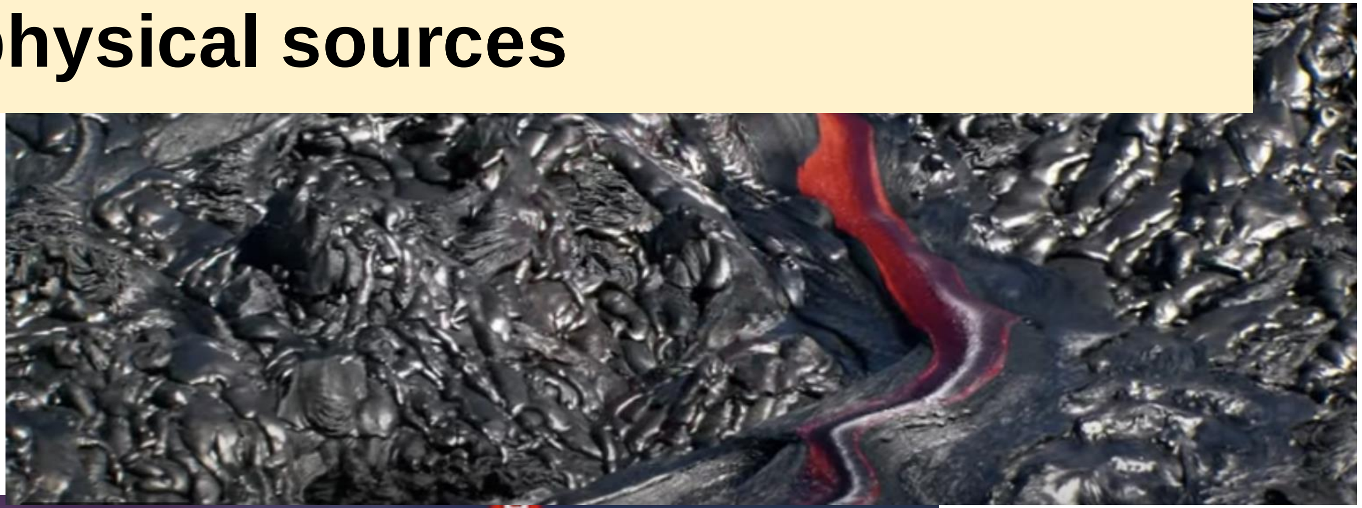




Modi, **Estrela** & Valio, MNRAS 2023

https://astrobites.org/2023/09/27/uh-oh-where-did-the-atmosphere-go-the-impact-of-host-stars-radiation-on-exoplanet-atmospheres/

Secondary atmospheres:
Replenishment through geophysical sources

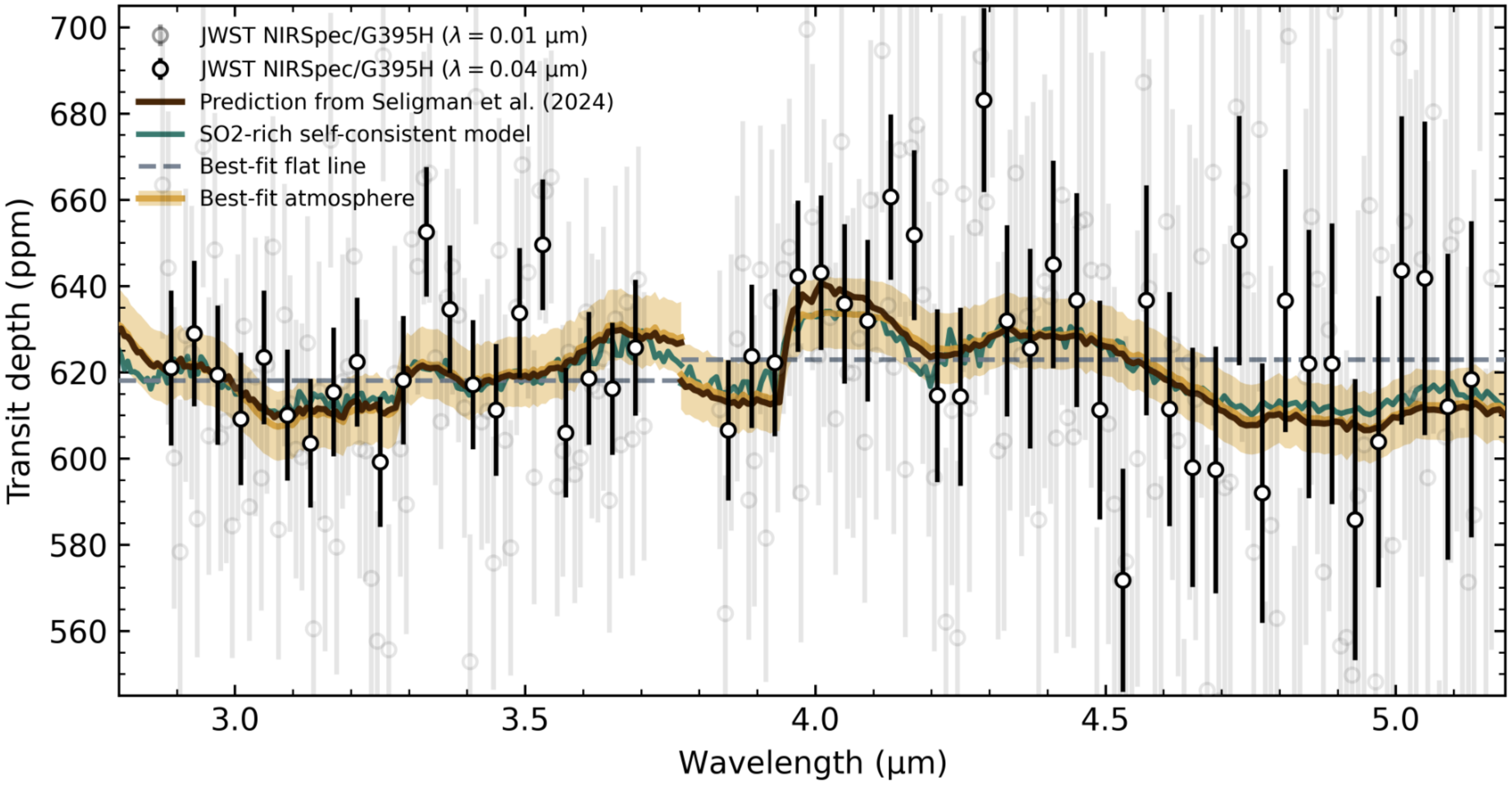


Outgassing through volcanism

Tidal heating keeps the mantle hot enough to remain liquid releasing gases that were originally dissolved in the primordial magma ocean during the planetary accretion phase.

Evidence for a volcanic atmosphere on the sub-Earth L 98-59 b

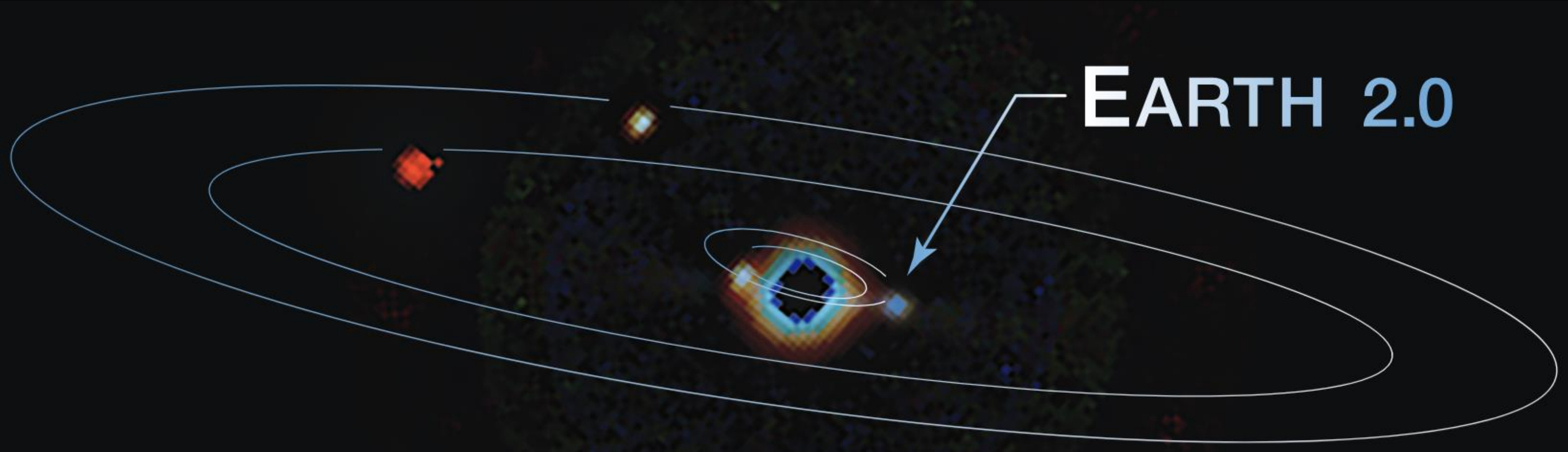
Aaron Bello-Arufe [1], Mario Damiano [1], Katherine A. Bennett [2], Renyu Hu [1,3], Luis Welbanks [4,*]
Ryan J. MacDonald [5,†], Darryl Z. Seligman [6,‡], David K. Sing [2,7], Armen Tokadjian [1], Apurva Oza [3,1] and
Jeehyun Yang [1]



Planetary spectra is consistent with a SO2-dominated atmosphere

LARGE ULTRAVIOLET/OPTICAL/INFRARED Space Telescope: Habitable Worlds Observatory

- identify and directly image at least 25 potentially habitable planets
- Search for chemical “biosignatures” in the atmospheres of these planets, including



Simulated image of a Solar System analog 30 light-years away, as captured by a large Infrared/Optical/Ultraviolet space telescope

What planets are suitable for follow-up observations?

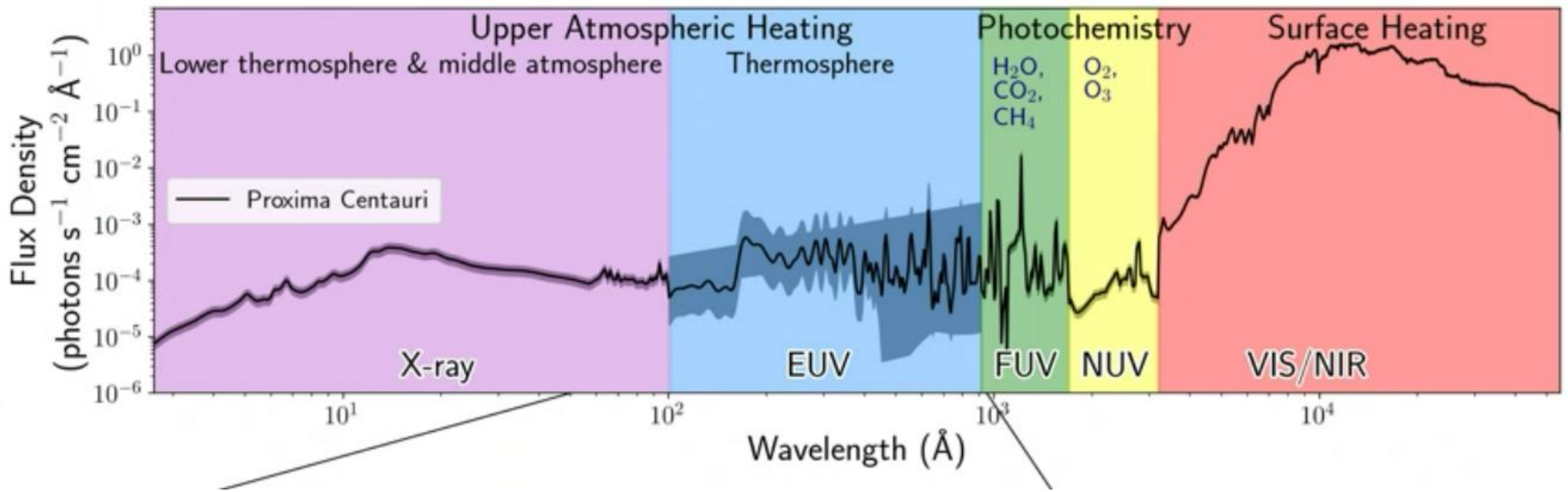
Atmospheric retention
(Do planets retain atmospheres?)

If yes..

Habitability
Are they habitable?

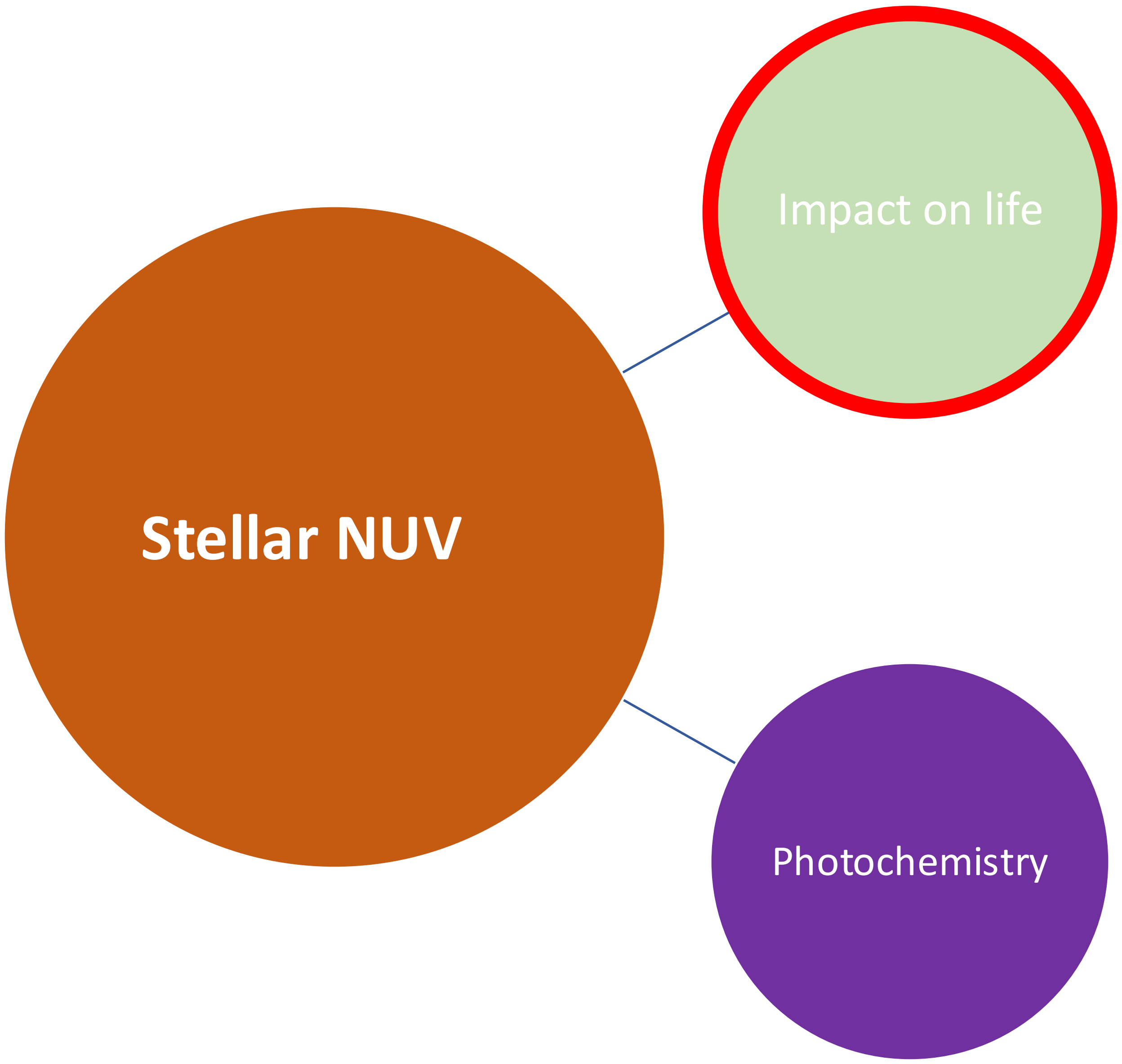
False positive biosignatures

Influence of the host star according to the wavelength



Xray and EUV irradiance:
Drives atmospheric escape

FUV and NUV irradiance:
Origins of life
Drives photochemistry



- Trigger prebiotic chemistry

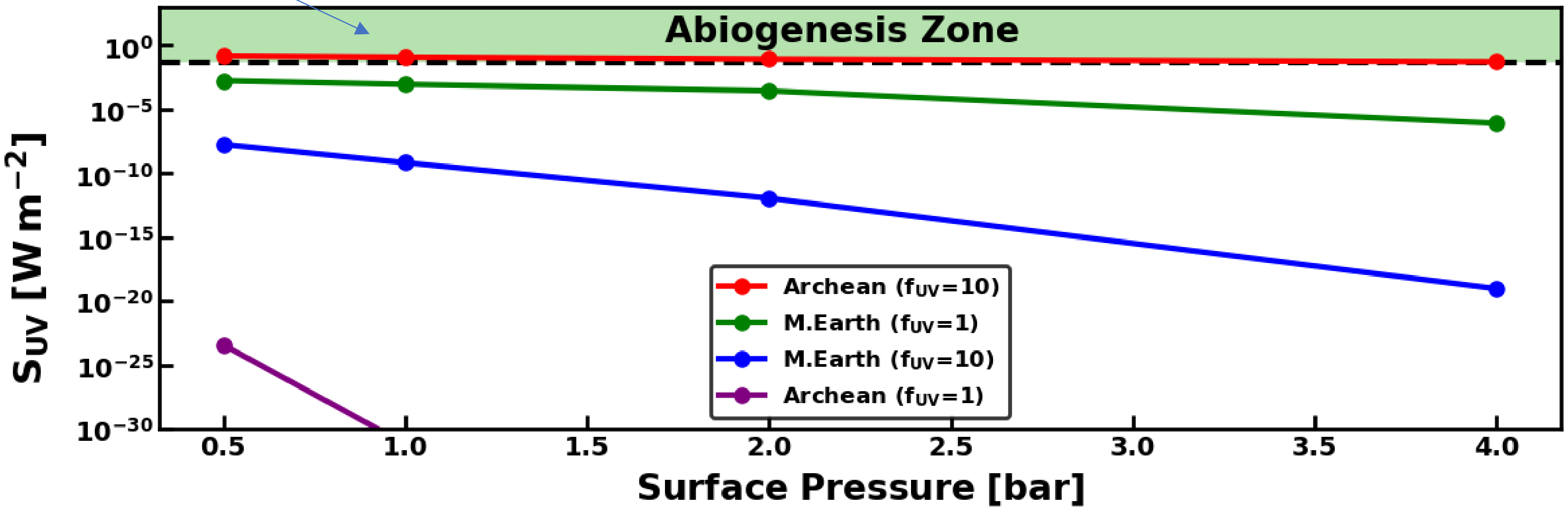
- Create False-positive biosignatures
- Deplete ozone layer

Flares augmented NUV may provide the UV flux required for formation of RNA precursors

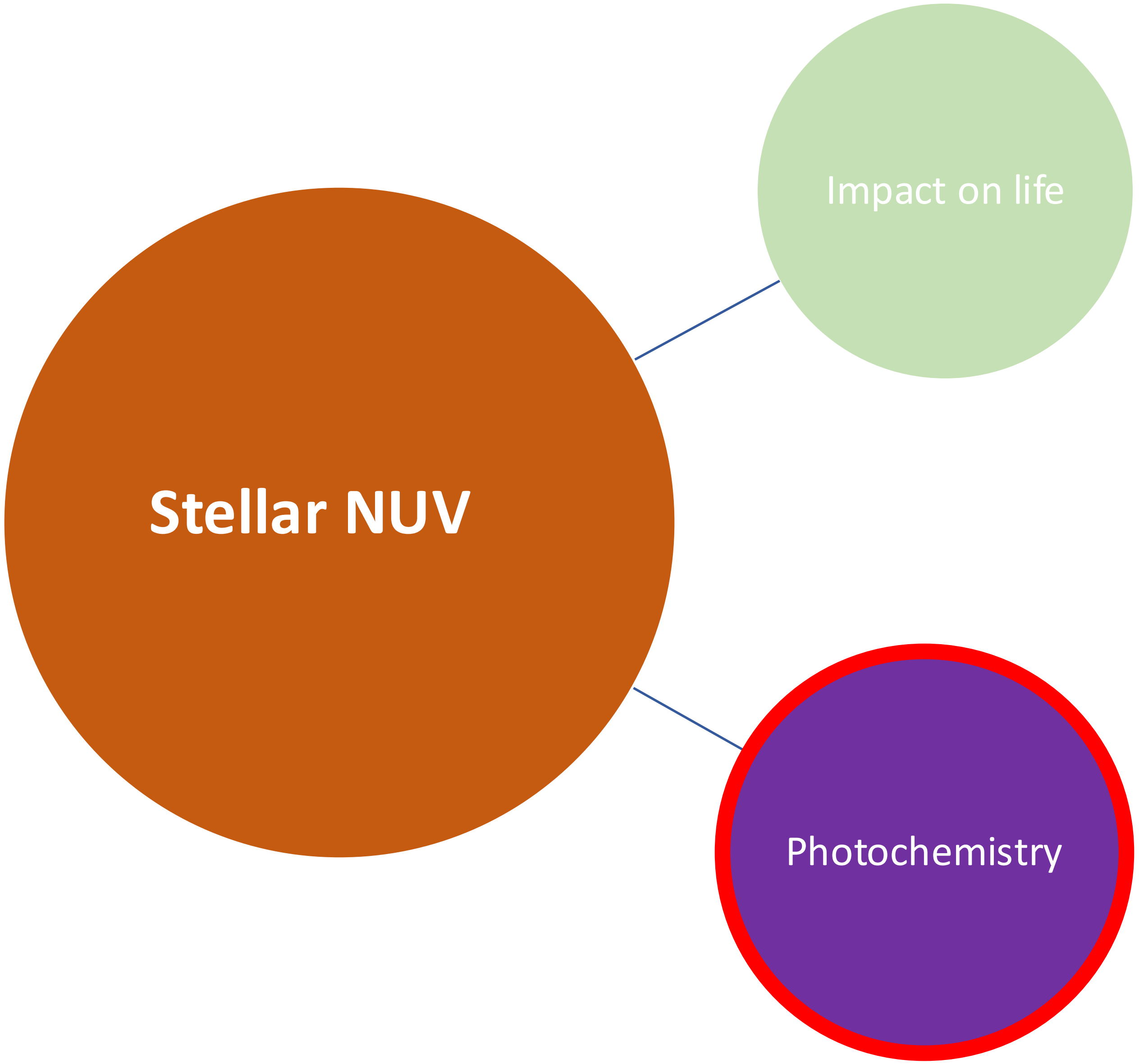
Viktor Sumida
(CRAAM/Mackenzie, Brazil)

FUV = 10x quiescent flux in TOI-700

Surface receives minimum UV flux required for the formation of RNA precursors.



Sumida, **Estrela** & Valio (in review by Astrobiology)



- Trigger prebiotic chemistry

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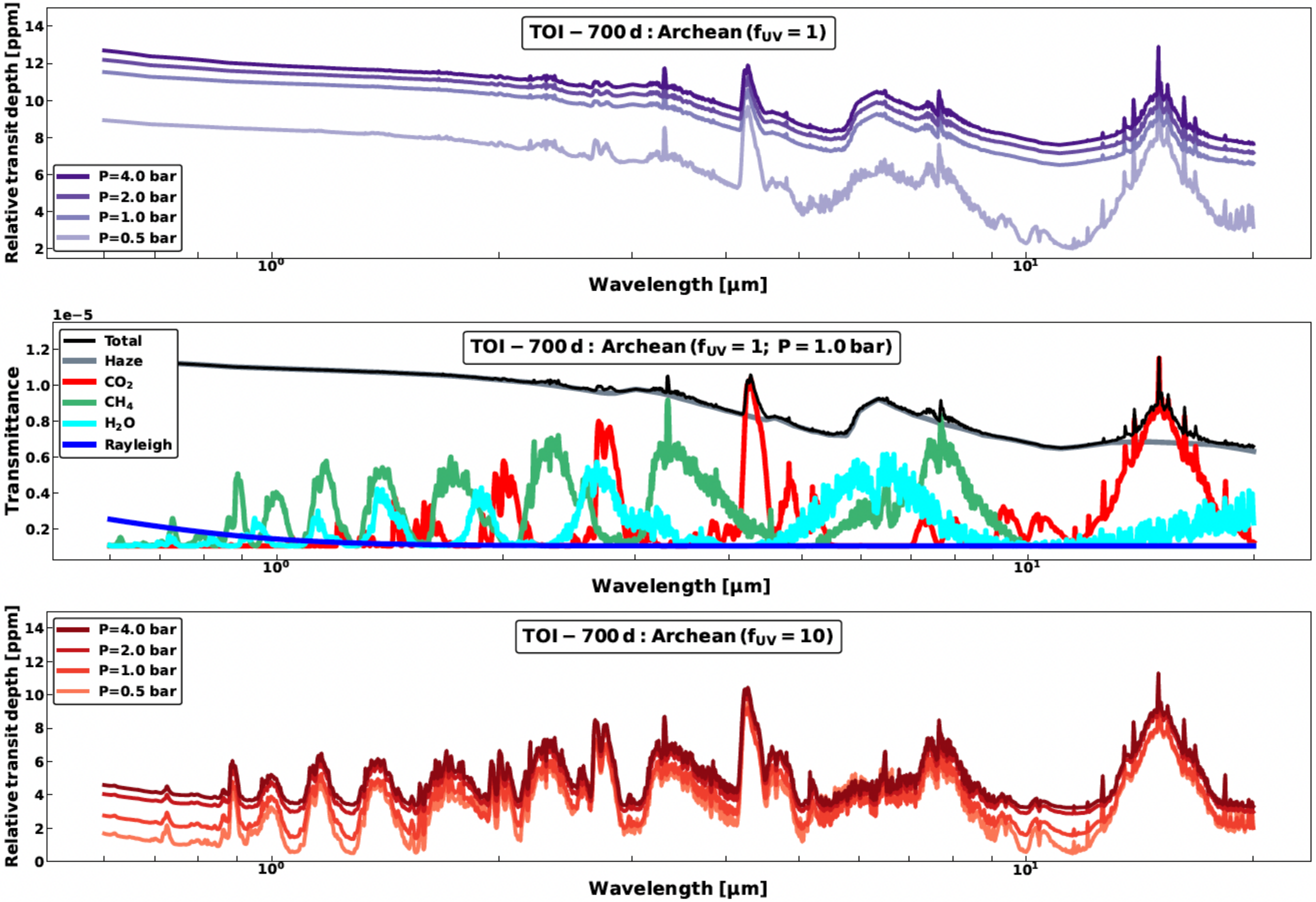
Stellar NUV photochemistry will influence the atmospheric signatures in the atmosphere

TOI-700 d

Viktor Sumida
(CRAAM/Mackenzie, Brazil)

Low FUV

High FUV



Sumida, Estrela & Valio 2024 (in review by Astrobiology)

See Poster 7.04!

Abstracts submissions deadline:
February 21

see https://www.stsci.edu

Science

- **Galaxy Growth:** Cosmic Web (Intergalactic & Circumgalactic Medium), Active Galactic Nuclei & Black Holes, Galaxy Evolution
- **Evolution of the Elements:** Stars & Stellar Populations, Star Formation & Interstellar Medium, Cosmic Explosions
- **Cosmology:** Nature of Dark Matter & Dark Energy, Distance Scale, Hubble Tension
- **Planetary Systems:** Formation, Evolution, Architectures, Our Solar System, Exoplanet Demographics
- **Search for Life:** Target Stars & Systems, Biosignatures, Habitability

Technology

- **Starlight Suppression:** Contrast Technology & Methods
- **Ultrastable Telescope and Observatory Technology**
- **Ultraviolet, Optical, & Near-Infrared Instrument Technologies:** mirror coatings, gratings, detectors, spectroscopic multiplexing technologies
- **L2 Servicing** technology and commercial synergies
- **Artificial Intelligence & Machine Learning** for mission development, engineering, science research

Key points

- With the arrival of the JWST, there is a renewed focus on characterizing the atmospheres of rocky planets. Alongside observational efforts, evolutionary models can provide valuable context.

- Planets around M dwarfs are susceptible to complete/partial erosion of a H2—dominated envelope due to photoevaporation.

- Planets can retain residuals atmospheres or replenish them through geophysical processes creating secondary atmospheres.

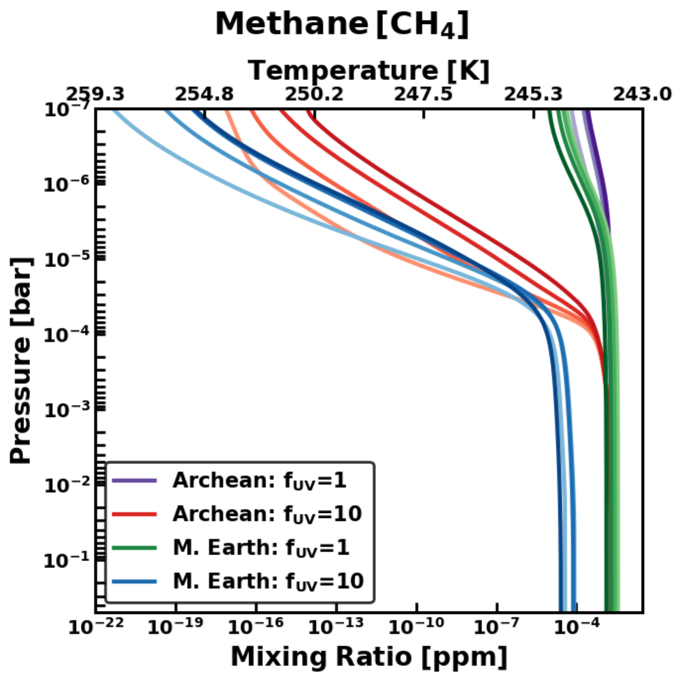
- Identifying planets if planets are habitable or could potentially have false positive biosignatures is essential for selecting the most promising targets for follow-up observations.

Image credit: Robert Lea

See Viktor's Sumida poster

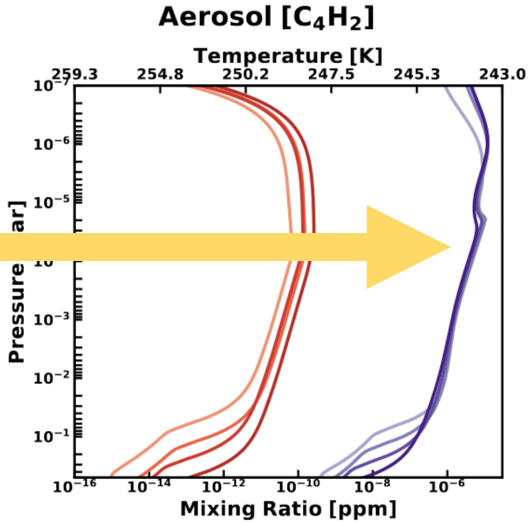
Viktor Sumida (CRAAM/Mackenzie, Brazil)

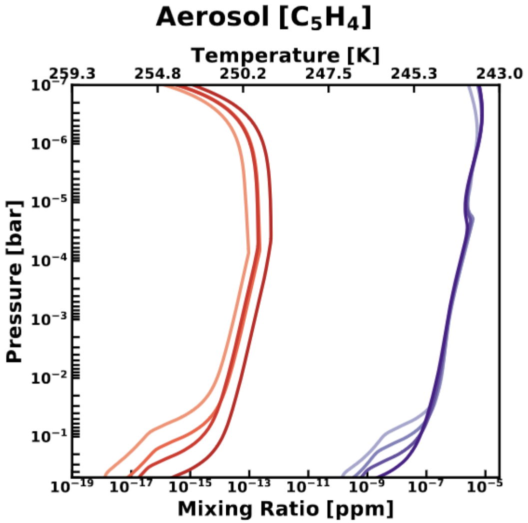
NUV drives photochemistry and production of false-positive biosignatures



Methane accumulates in the atmosphere

Haze accumulate particularly at atmospheres receiving lower FUV (FUV = 1)

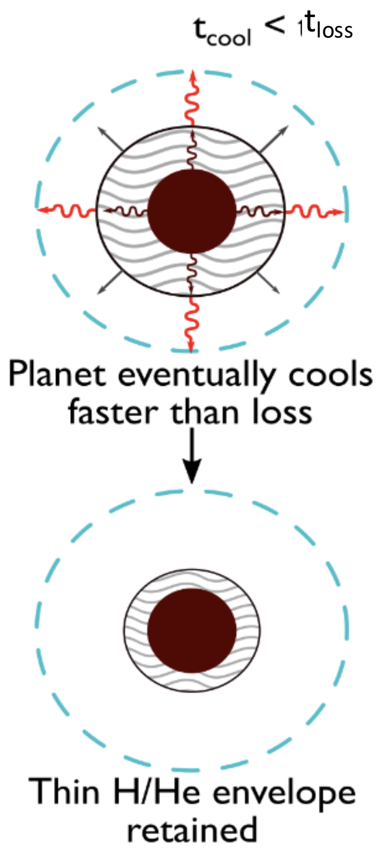


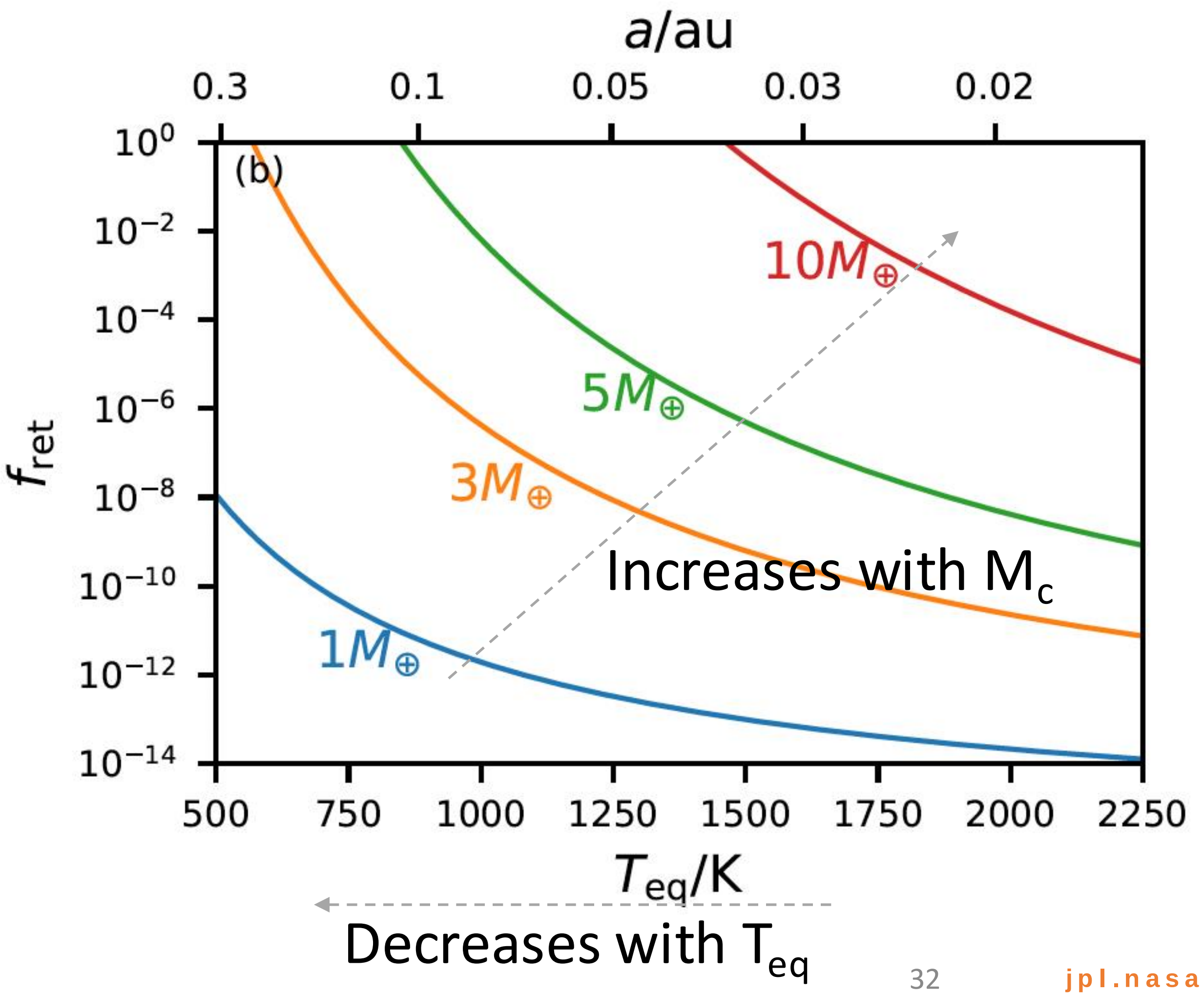


Sumida, **Estrela** & Valio (submitted to Astrobiology)

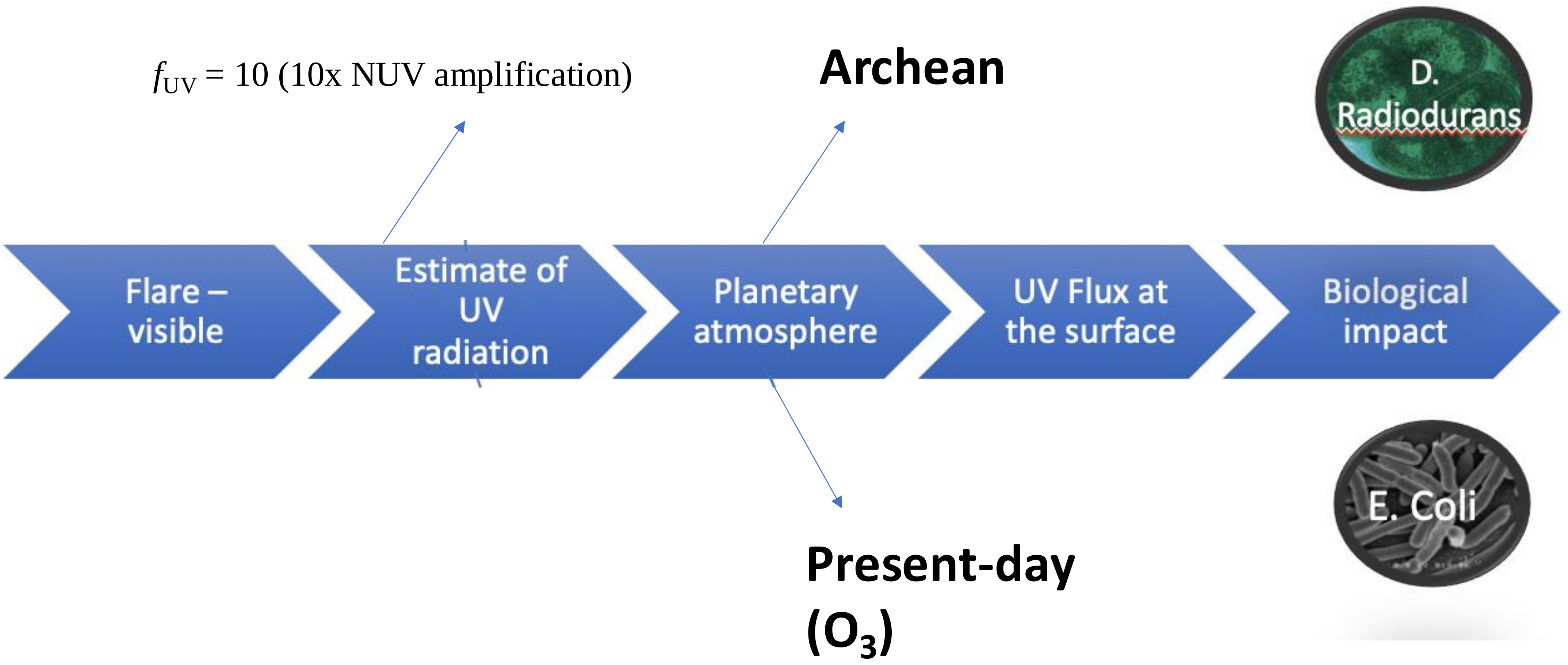
Residual atmospheres with core-powered mass-loss

After undergoing core-powered mass-loss, some super-Earths can retain small residual H/He envelopes





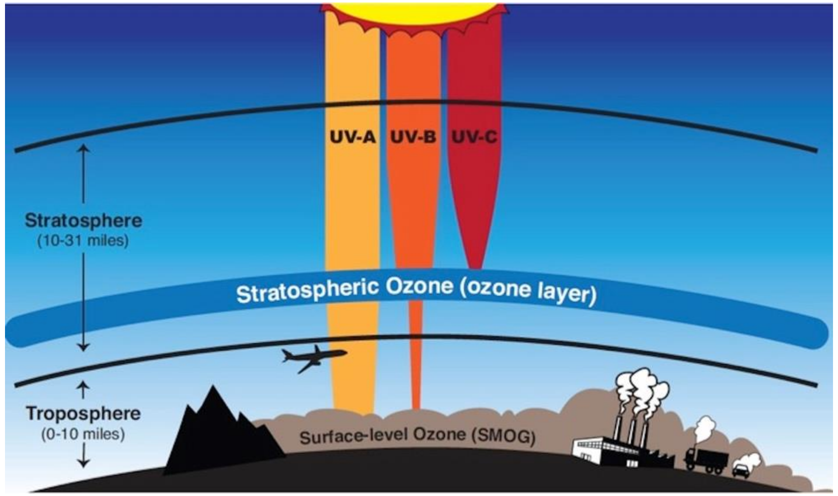
Misener & Schlichting (2021)

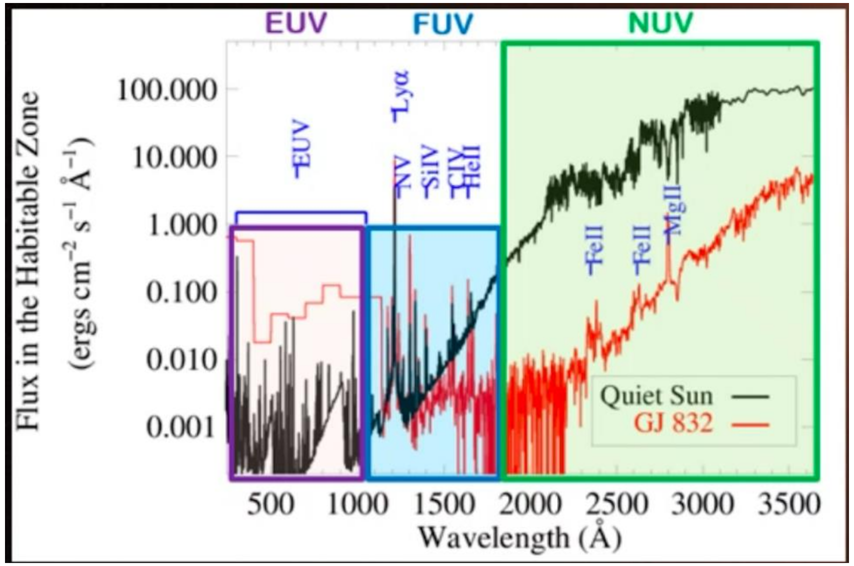


f_{UV} = 10 (10x NUV amplification)
Archean
D. Radiodurans
Flare – visible
Estimate of UV radiation
Planetary atmosphere
UV Flux at the surface
Biological impact
E. Coli
Present-day (O_3)

UV effects on habitability

Active stars can release significant amount of XUV, EUV, FUV and UV radiation





- UV can be harmful for life

+ UV can provide the energy for photochemical synthesis of molecules of interest in origins of life