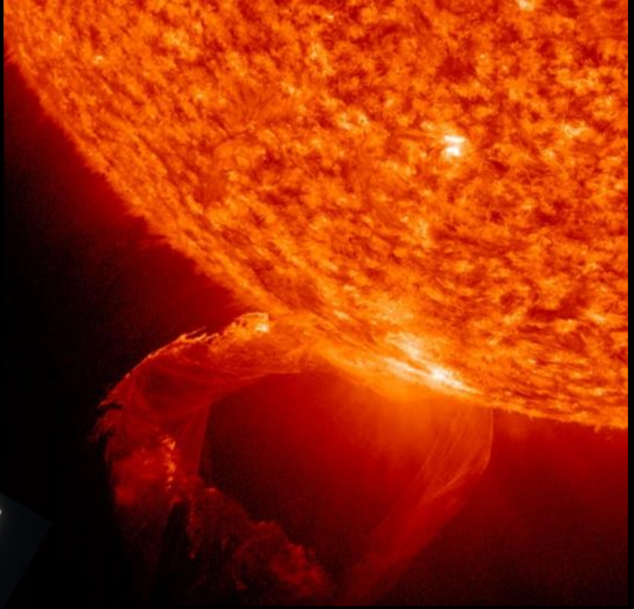
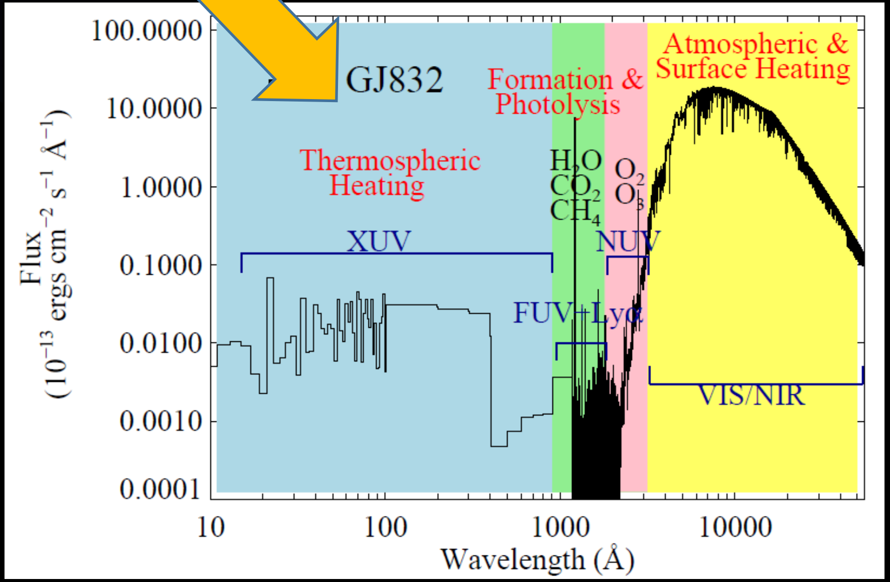
UV and X-ray Observations of Rocky Planet M Dwarf Host Stars: Inputs for Atmospheric Photochemistry and Escape Calculations

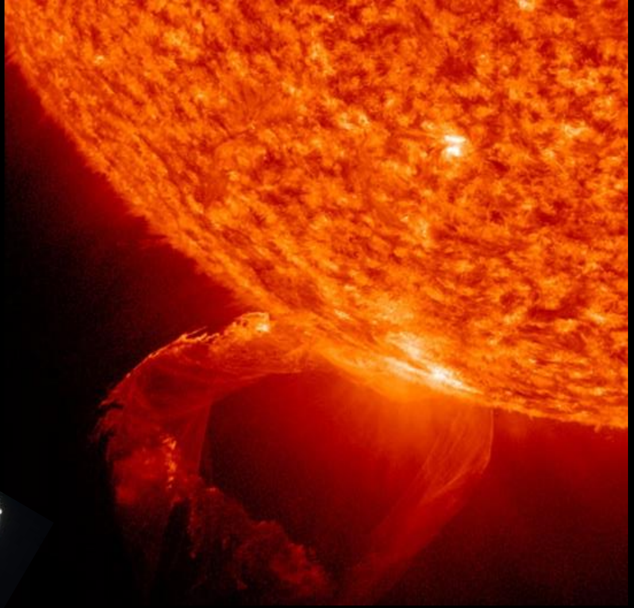


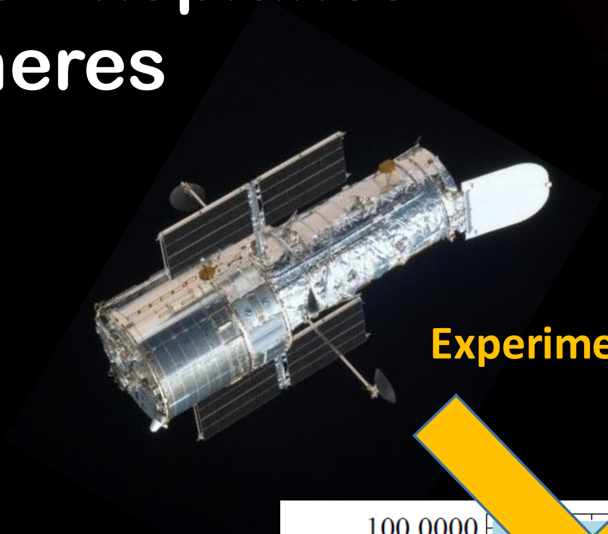
Kevin France (Univ of Colorado) &
Allison Youngblood (NASA/GSFC)

Know Thy Star Know Thy Planet 2
February 7th 2025

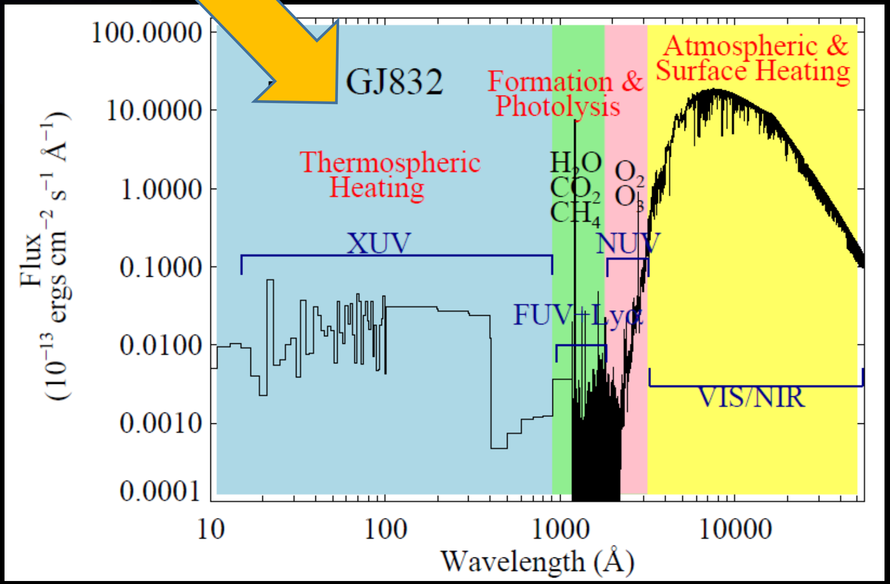


Connecting High-Energy Stellar Observations to Exoplanet Atmospheres





Experiment, observation, analysis



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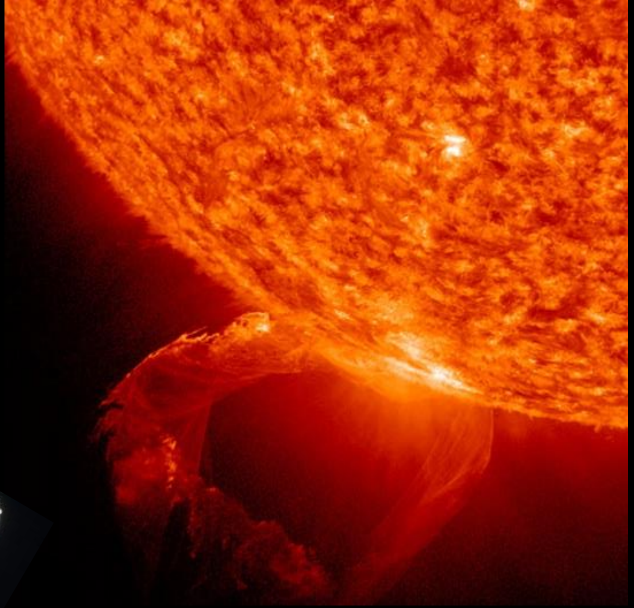

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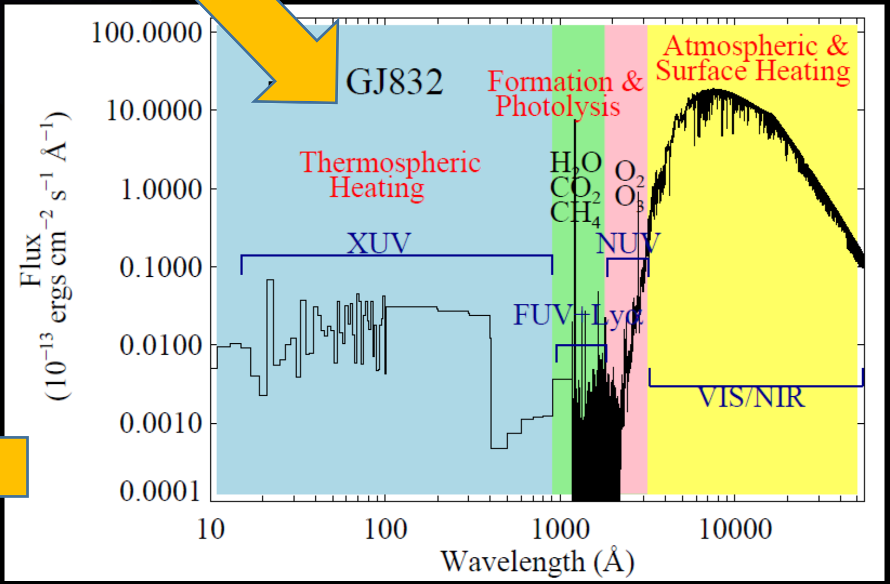
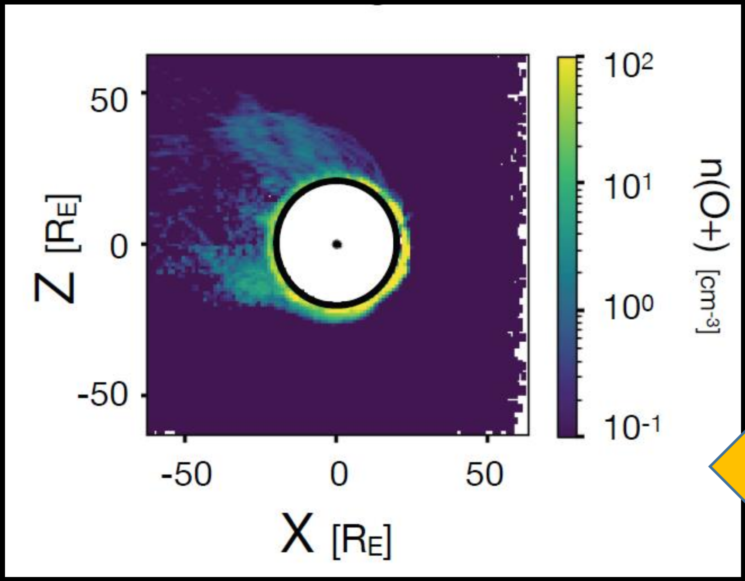
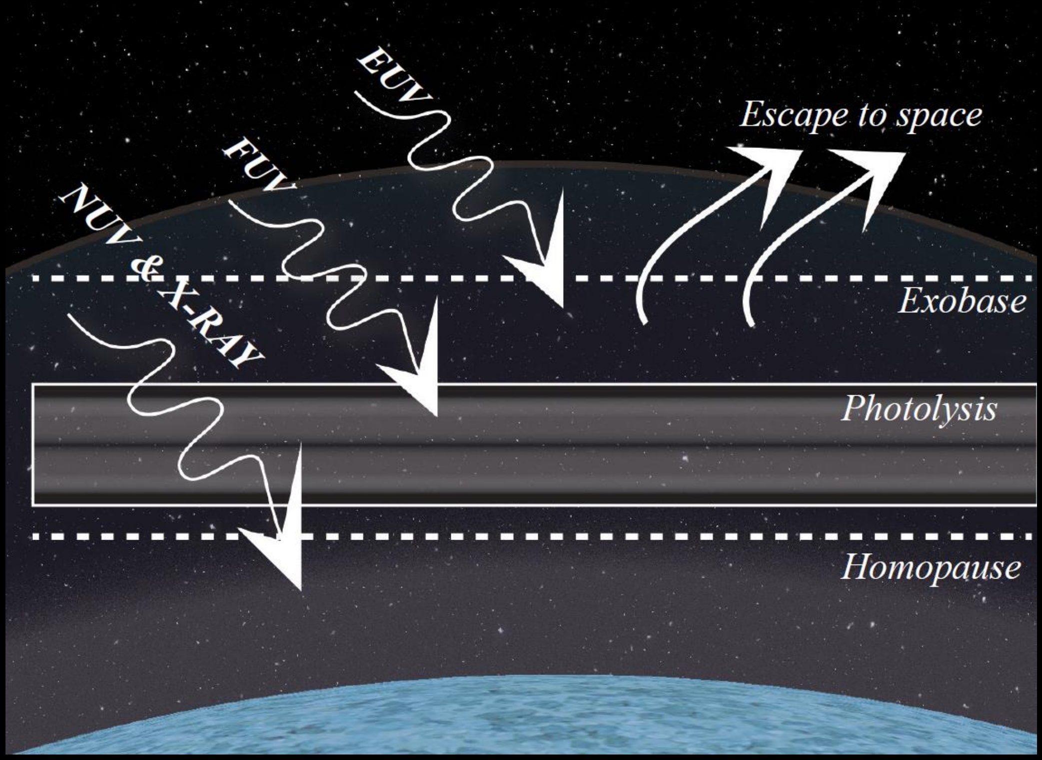


Modeling



Introduction: Stellar SED and Atmospheric Impacts

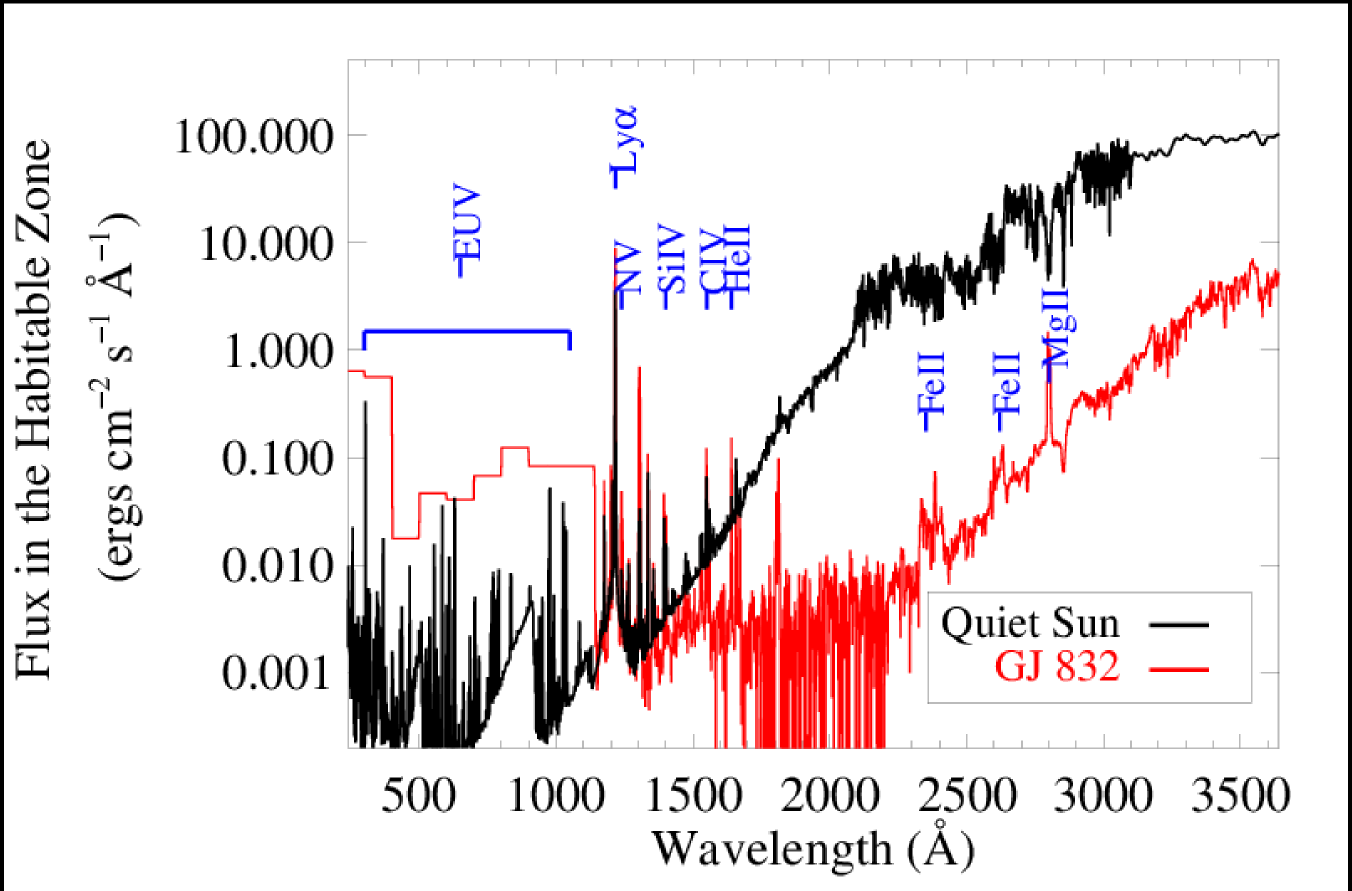


Adapted from France et al. (2019), see also Tuttle et al. (2024).

- Photons of different energy play distinct roles, and all contribute to the observable signatures of the atmosphere

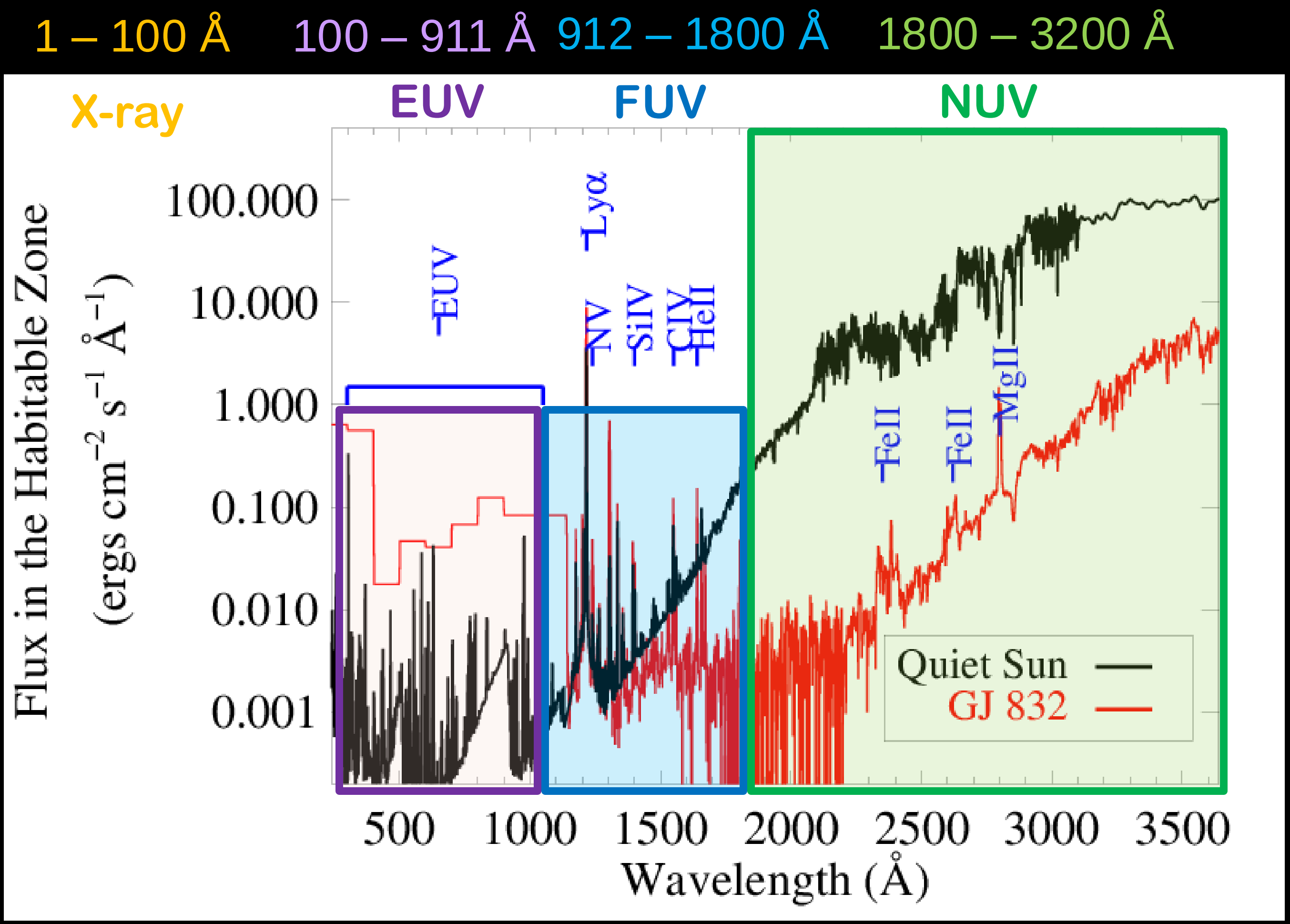
- The high-energy stellar emission dominates atmospheric photochemistry, ionization, and heating

Introduction: Stellar SED and Atmospheric Impacts



France et al. (2012, 2016, 2020)

Introduction: Stellar SED and Atmospheric Impacts



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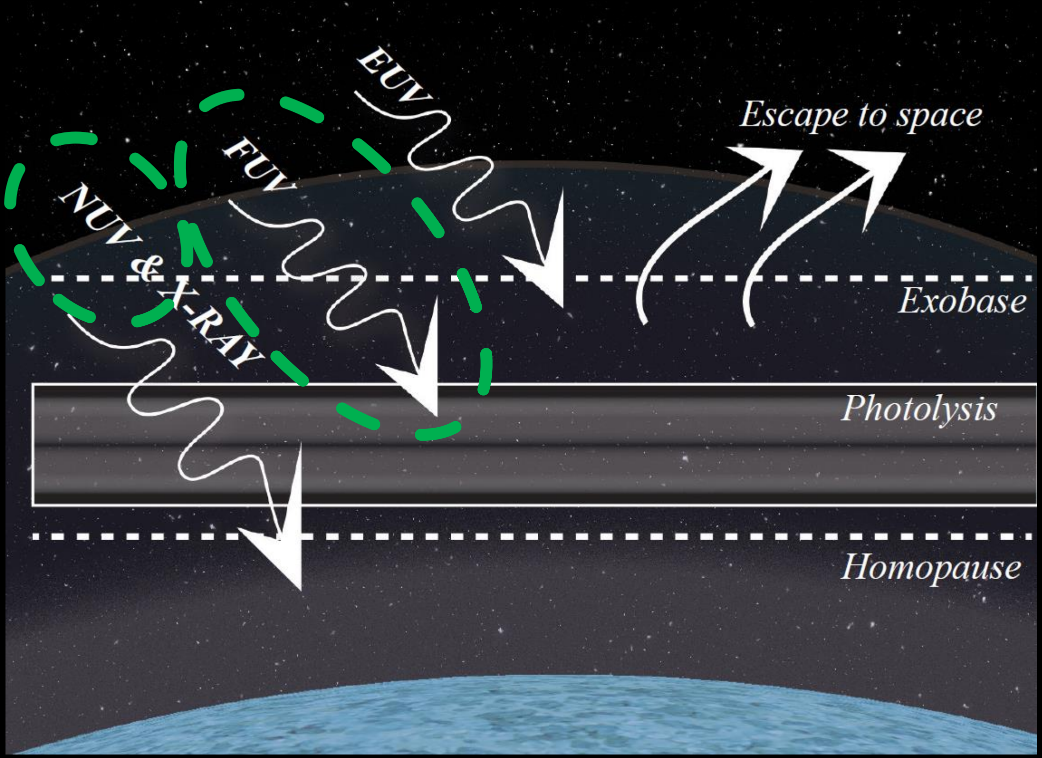
Introduction: Stellar SED and Atmospheric Impacts



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- Photons of different energy play distinct roles, and all contribute to the observable signatures of that atmosphere

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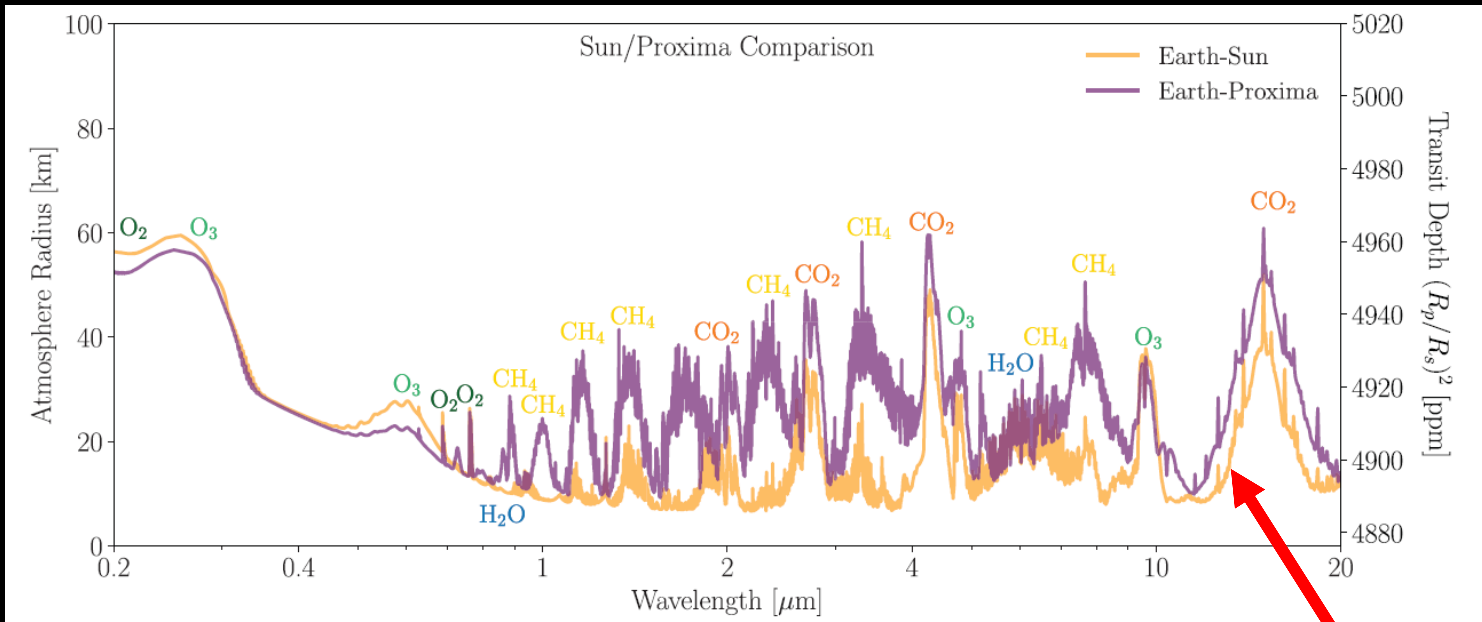
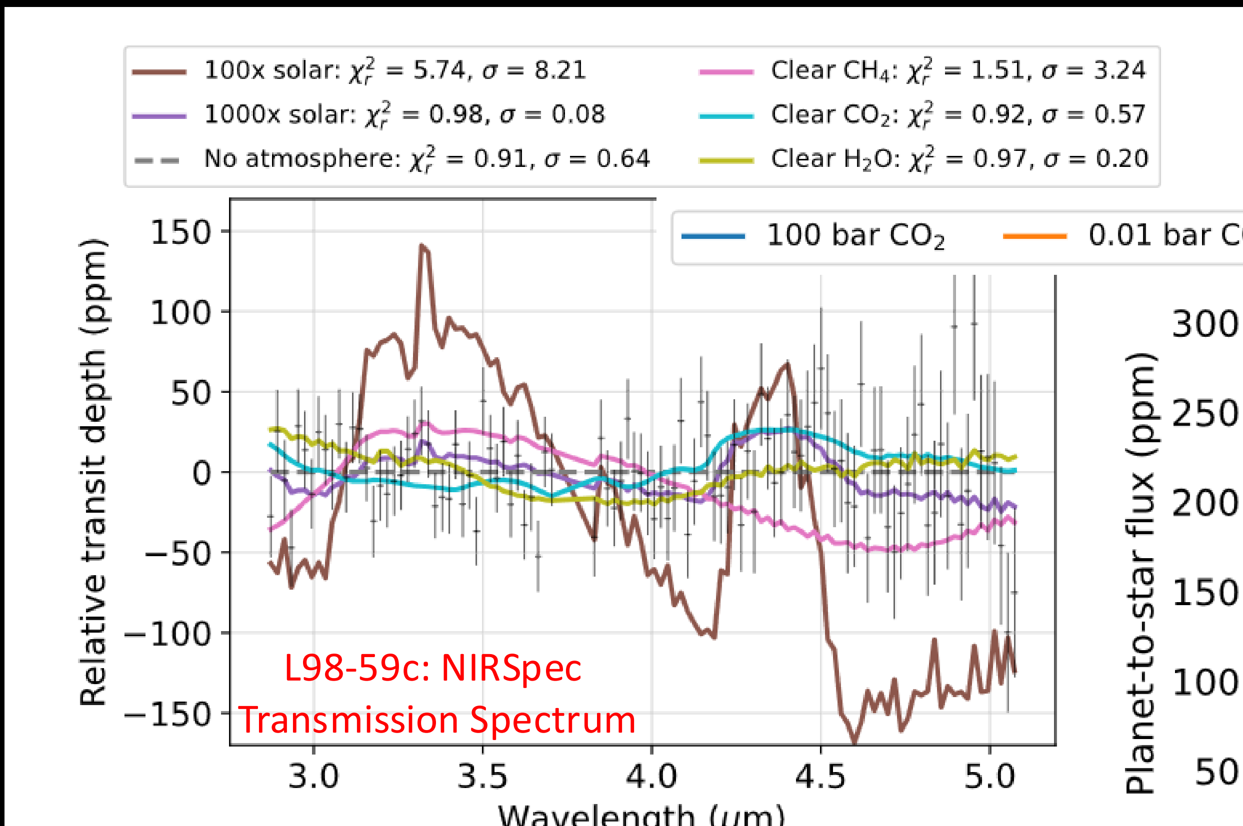
FUV and NUV inputs drive the observed composition of a planet’s atmosphere



Meadows et al. (2018)

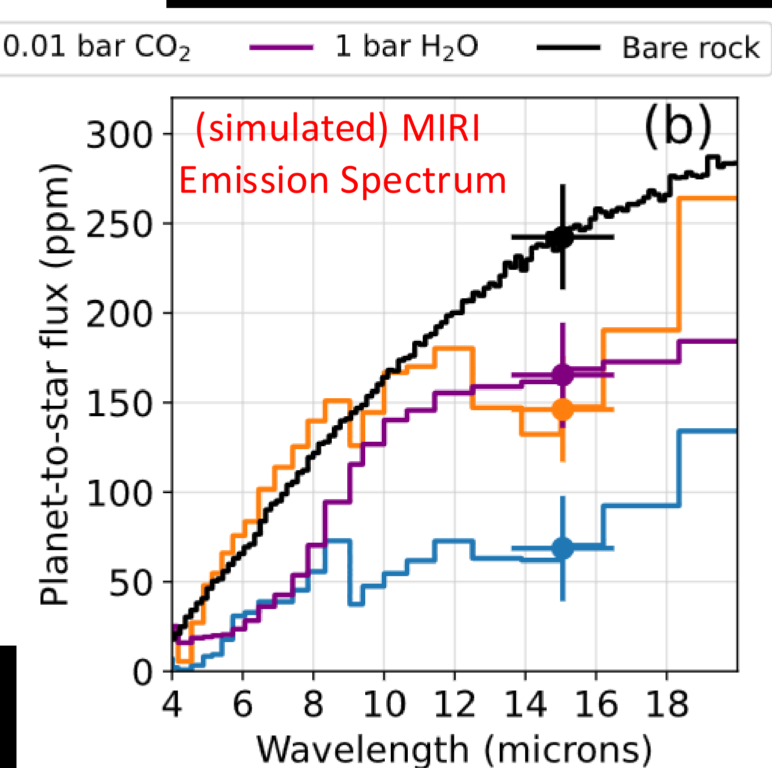
- The transmission and reflection spectra of ‘Earth-twin’ planets, including the absolute and relative abundances of ‘biomarkers’ (e.g., O_2, O_3, CO_2, CH_4) and potential false positives (Hu et al. 2012; Domagal-Goldman et al. 2014; Tian et al. 2014; Harman et al. 2015)

Stellar environment and atmospheric stability:
Initial JWST results are consistent with complete atmospheric loss



(Scarsdale et al. 2024)

Stay tuned for results of the Hot Rocks Survey (PI – H. Diamond-Lowe), being led by Dr. Jegug Ih



(Kreidberg et al. 2019; Crossfield et al. 2022; Greene et al. 2023; Zieba et al. 2023; Wachiraphan et al. 2024 Lustig-Yaeger et al. 2023; Moran et al. 2023; May et al. 2023; Lim et al. 2023; Mansfield et al. 2024; Xue et al. 2024)

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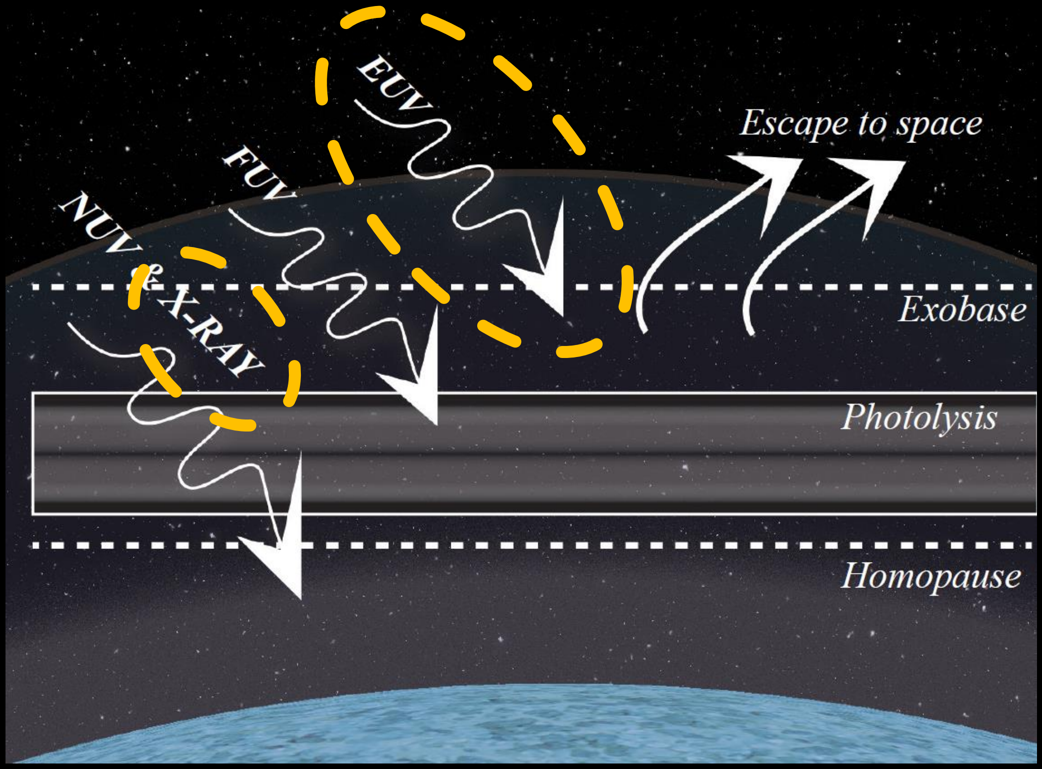

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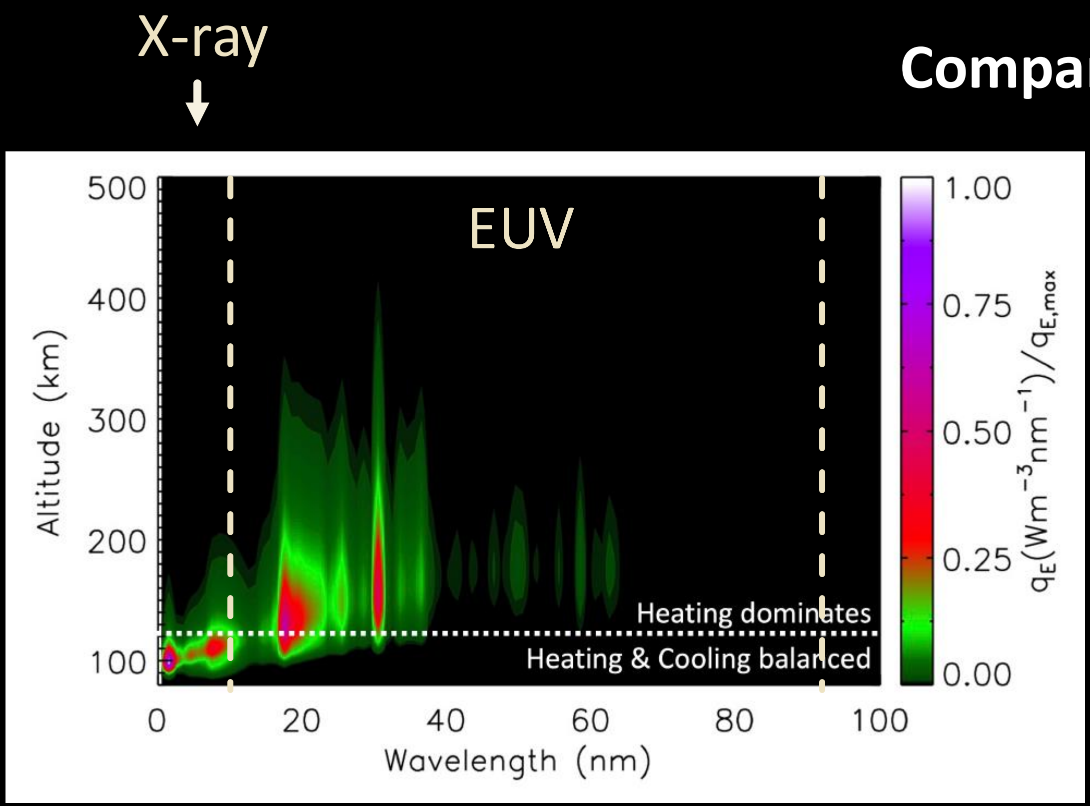
- Photons of different energy play distinct roles, and all contribute to the observable signatures of that atmosphere

- The high-energy stellar emission dominates atmospheric photochemistry, **ionization, and heating**

EUV photons dominate heating inputs to Earth-like exoplanets (nitrogen and oxygen dominated)



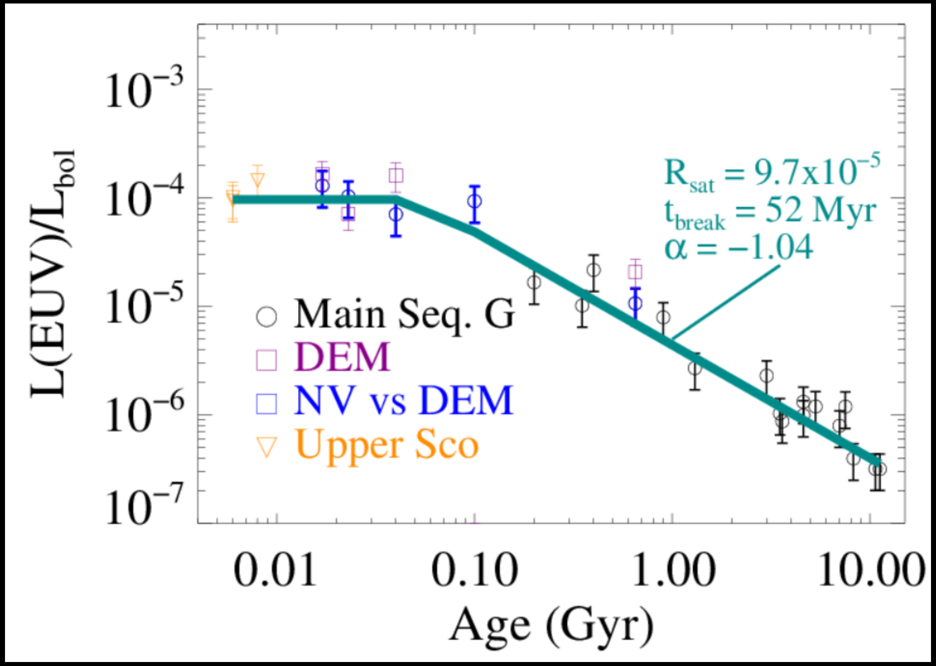
(Youngblood et al. 2025 – under review)

Comparing EUV and X-ray Influences

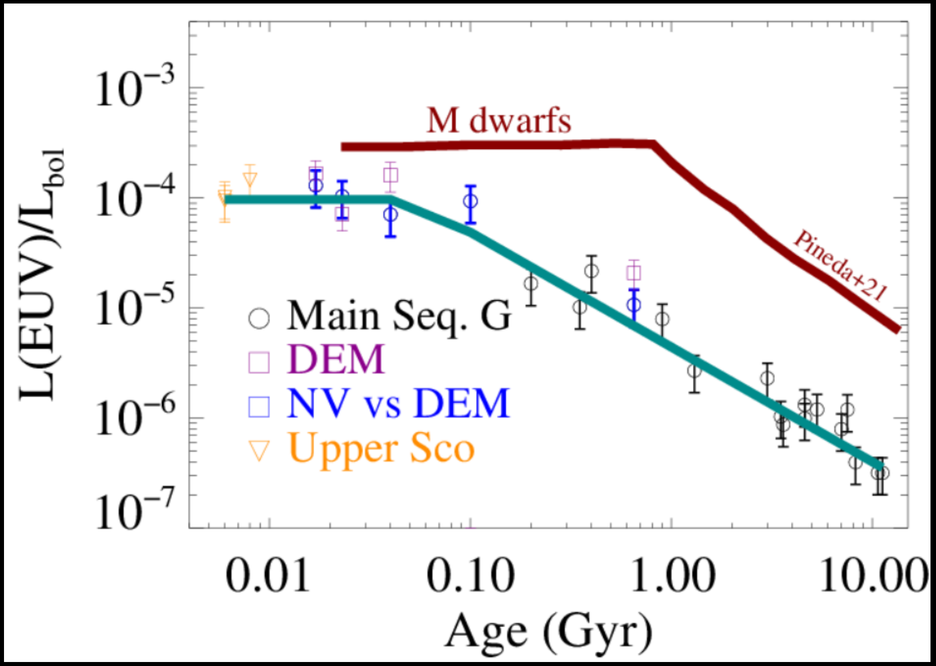
- Photo-absorption cross-sections are higher in EUV than X-ray
- EUV photons are absorbed in the highest (lowest density) layers of the atmosphere where radiative losses are minor and the heating efficiency is highest
- There are more EUV photons for all stars (noting X-ray luminosity is higher for the most active stars)

Solomon & Qian (2005)
Van Looveren et al. (2024)

Differences in the EUV History of Solar-type stars vs M dwarfs



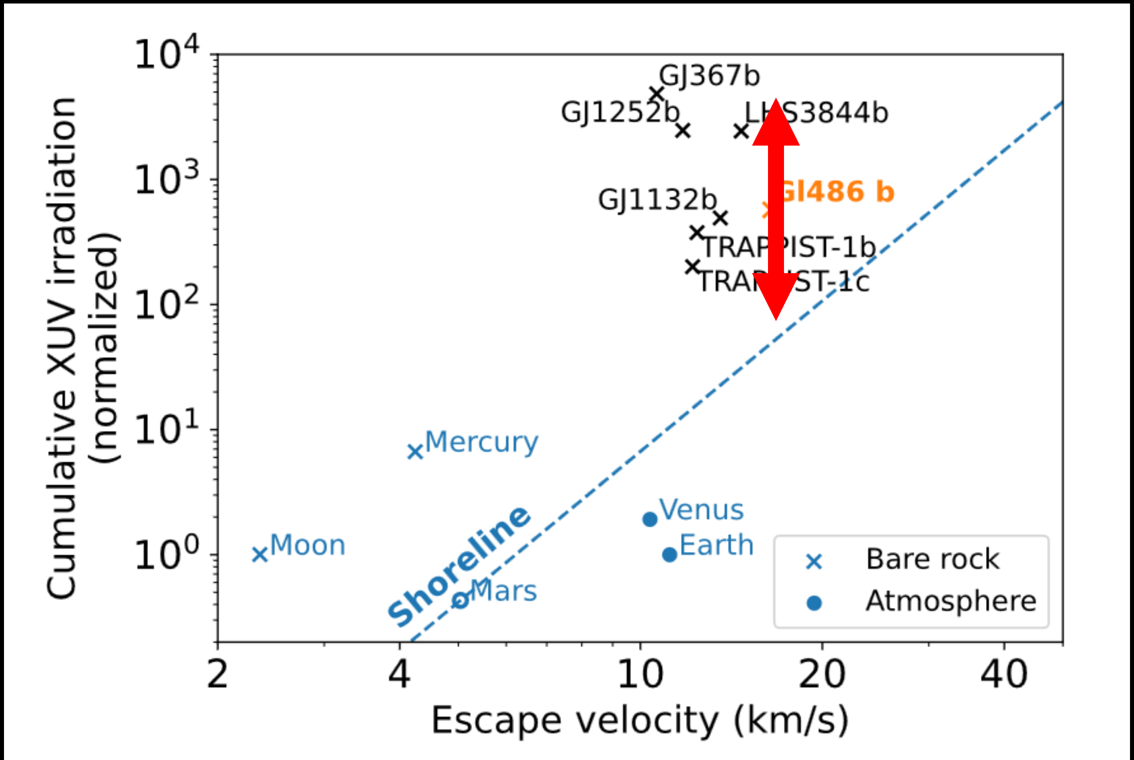
France et al. (2025 – in prep)



Pineda et al. (2021); see also Loyd et al. (2021)

1. M dwarfs spend ~10-20 times longer in the saturated phase
2. Different saturation level (with respect to bolometric luminosity) and different decline thereafter

EUV and atmospheric stability:
Long-term EUV deposition and effects of variability



'The Cosmic Shoreline':
Zahnle & Catling (2017) +
Barclay et al. (2023) +
Mansfield et al. (2024)

EUV and atmospheric stability:
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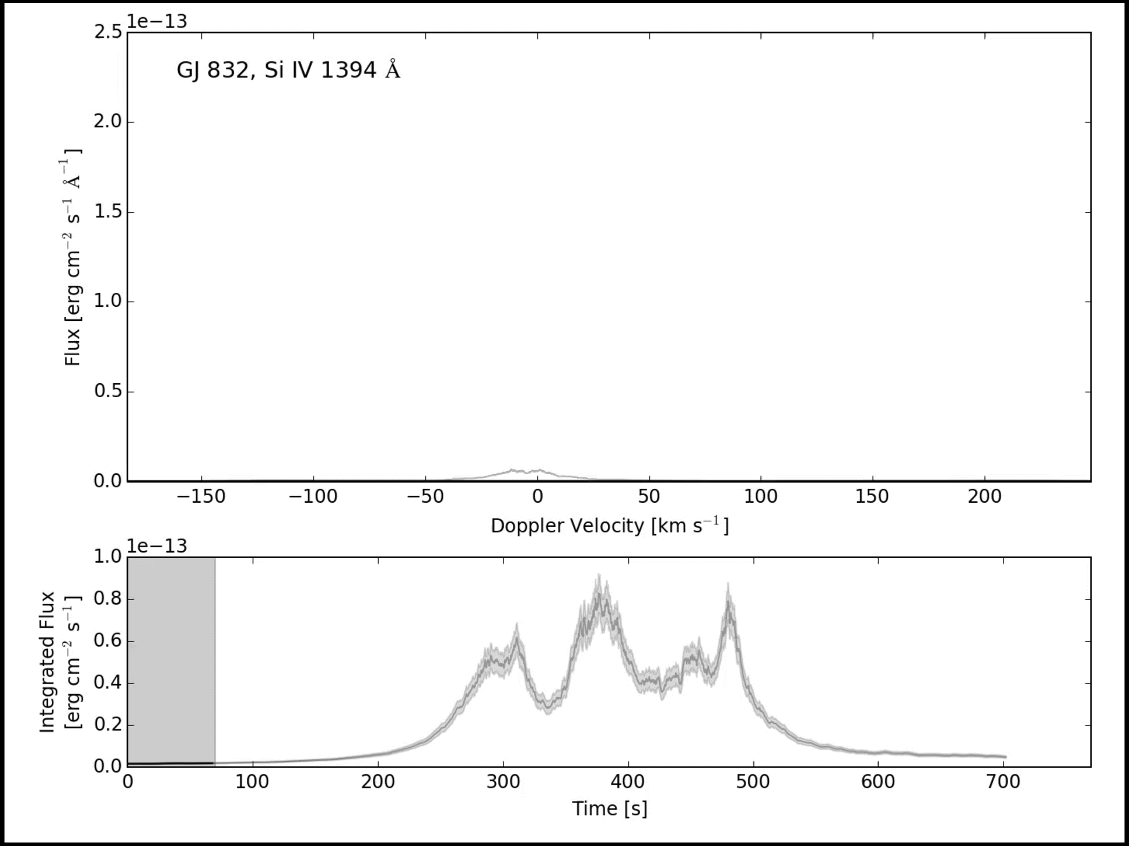
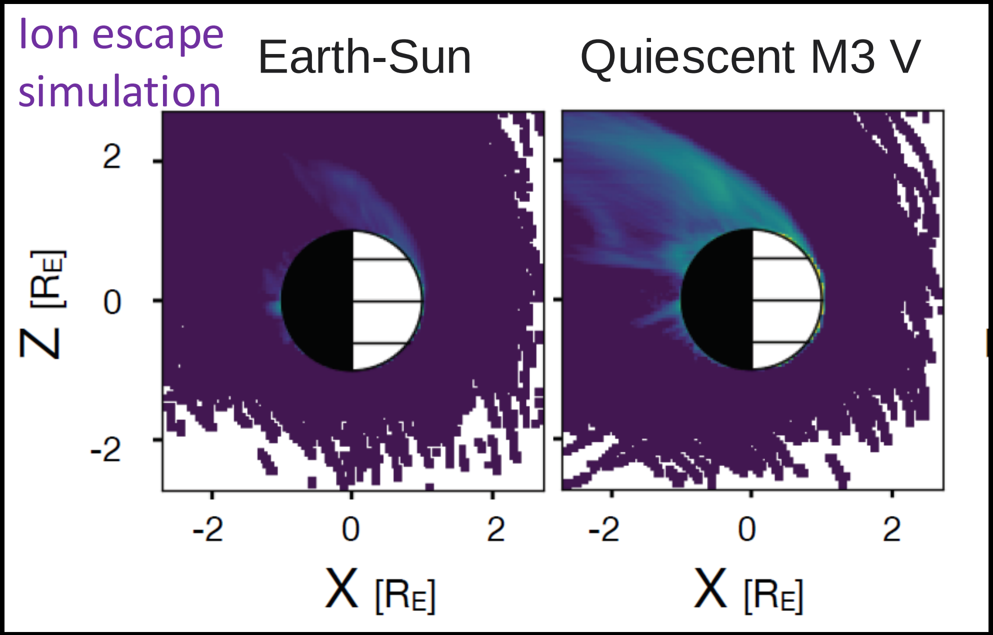


Loyd et al. (2018a,b);
Froning et al. (2019);
Feinstein et al. 2022;
Tristan et al. (2023)

Flare impacts on atmospheric escape

France et al. (2020)



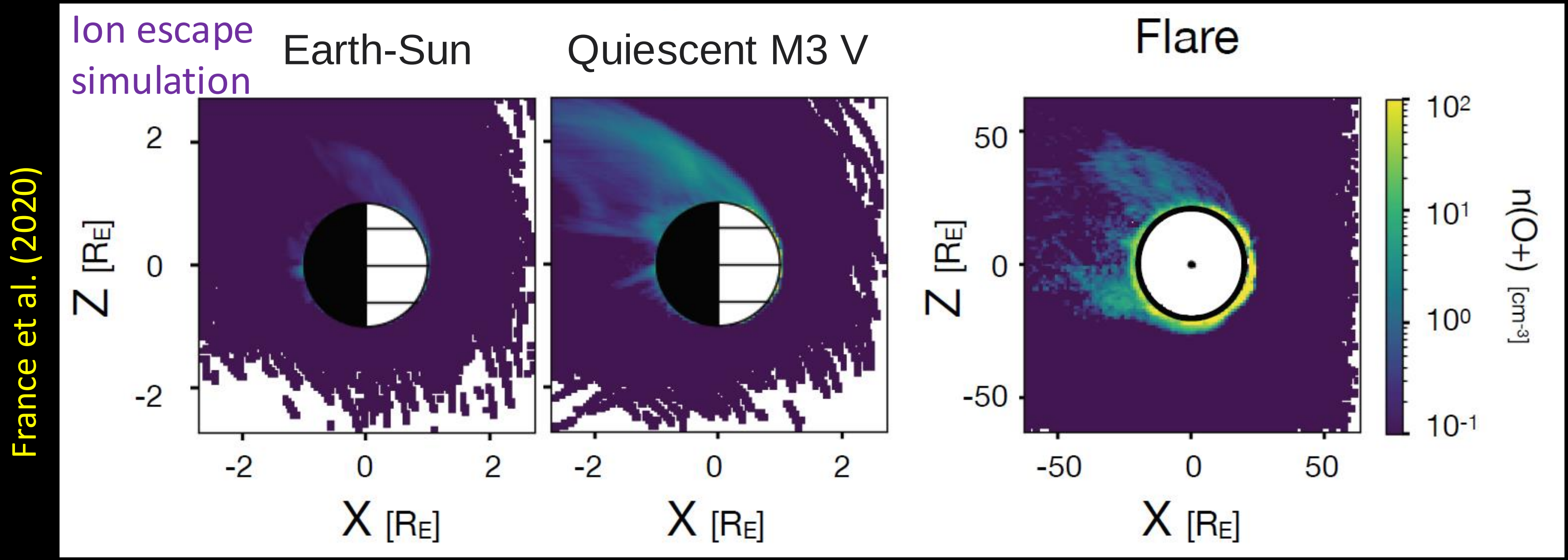
Consider an unmagnetized, but otherwise Earth-like planet, orbiting in the HZ (0.088 AU) of **Barnard's Star** (7 – 12 Gyr M3 star).

Atmospheric escape from hypothetical Earth-like planet at 1 AU equivalent from Barnard's Star:

1. Quiescent high energy flux drives Earth-like escape rates

Flare impacts on atmospheric escape

See also Amaral et al. (2022)



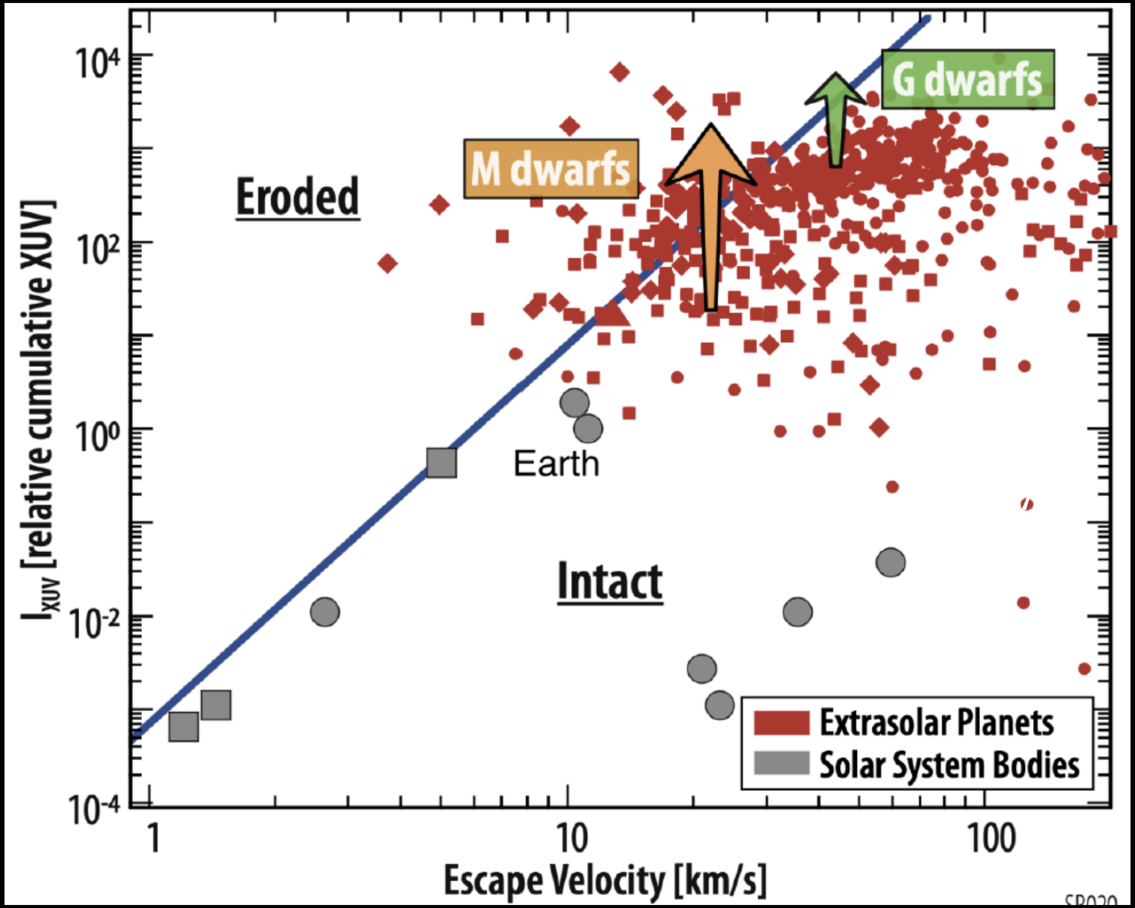
Atmospheric escape from hypothetical Earth-like planet at 1 AU equivalent from Barnard's Star:

1. Quiescent high energy flux drives Earth-like escape rates

2. Empirically-derived flare flux enhancement drives escape **~90 Earth atmospheres per Gyr** (thermal [87] + ion loss [3])

EUV and atmospheric stability:

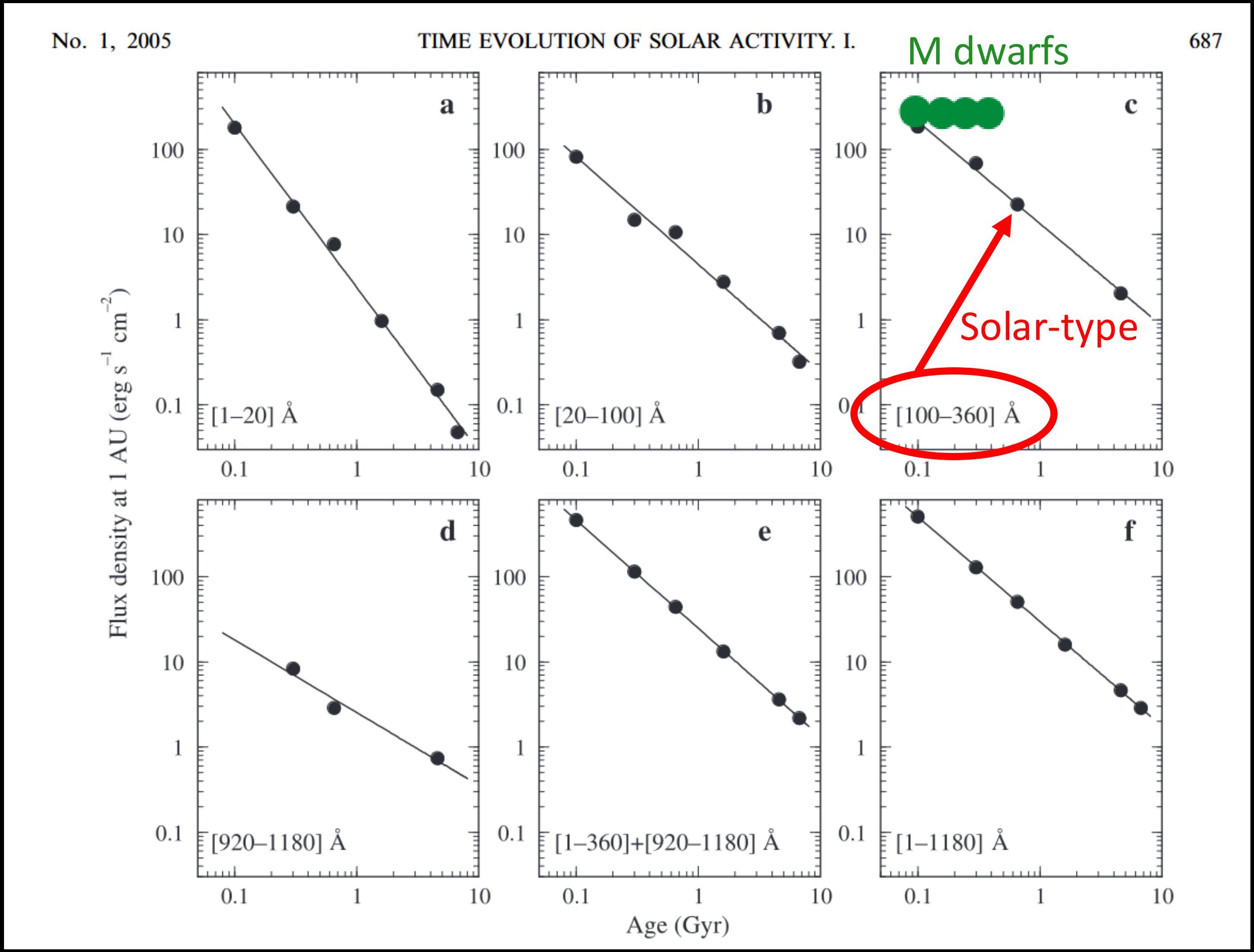
Long-term EUV deposition and effects of variability



'The Cosmic Shoreline': Zahnle & Catling (2017) + Sebastian Pineda (Colorado)

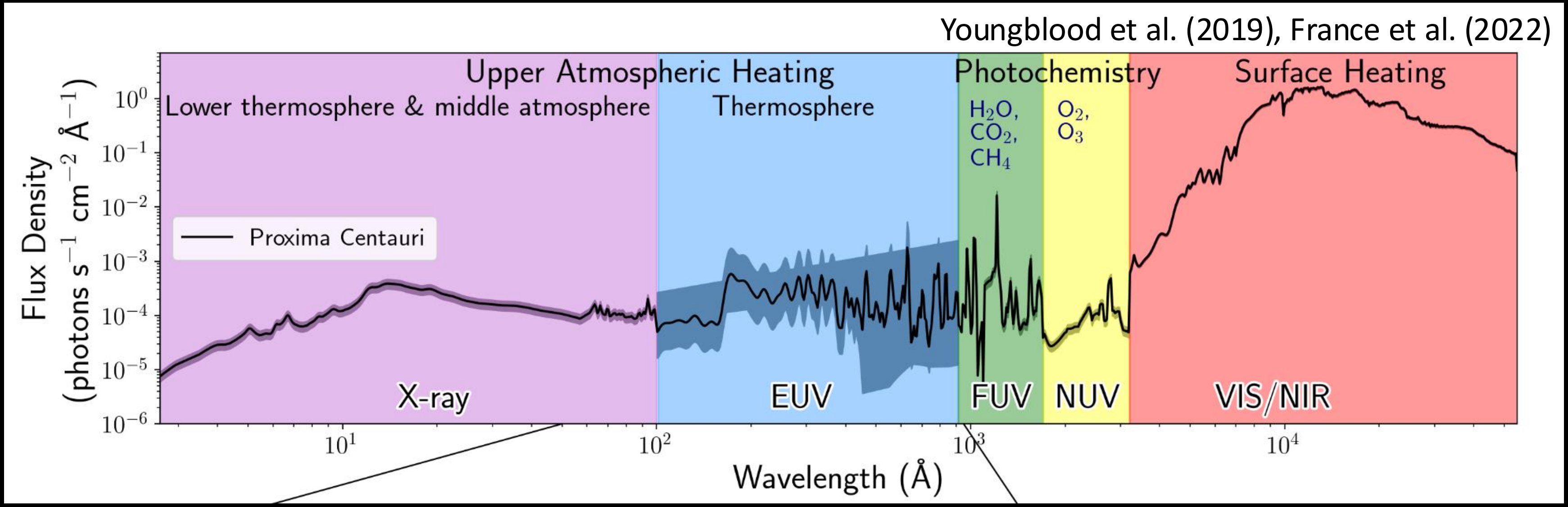
X-ray + EUV irradiance deposition ratio in the Habitable Zone: mid-M dwarfs vs. solar-type stars

Empirical EUV History of Solar-type stars vs M dwarfs



Ribas et al. (2005), "Sun in Time"

EUV environment remains a (the?) key uncertainty for all F, G, K, M stars



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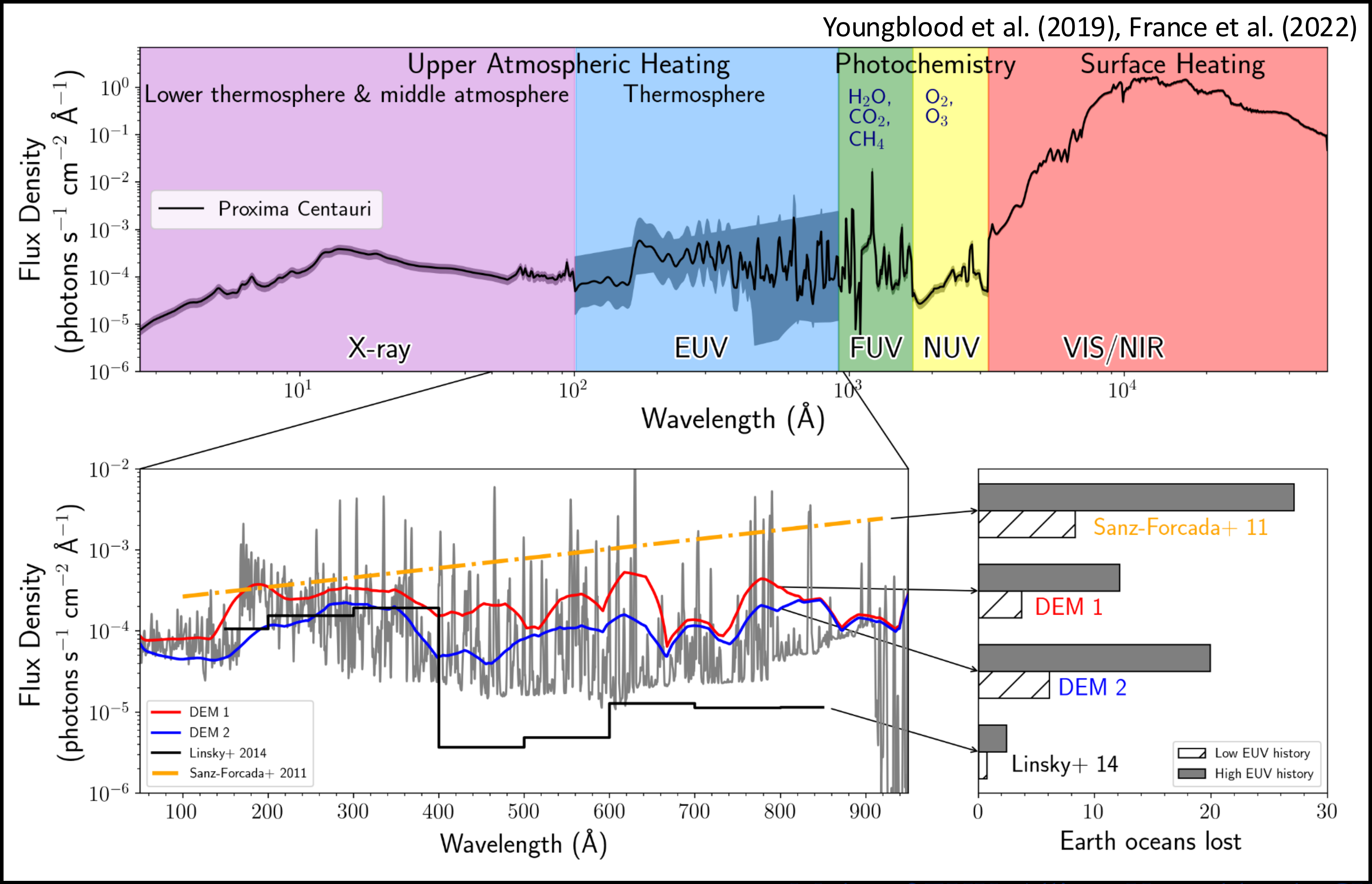
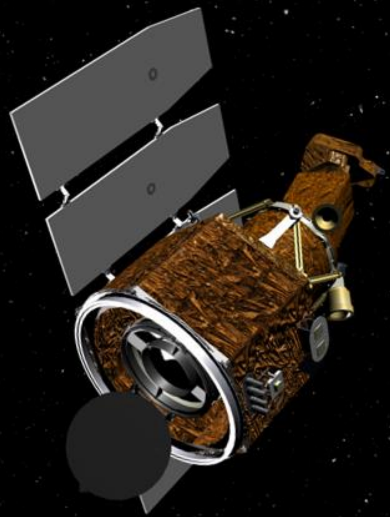




ESCAPE

NASA 2025 Small Explorer mission concept

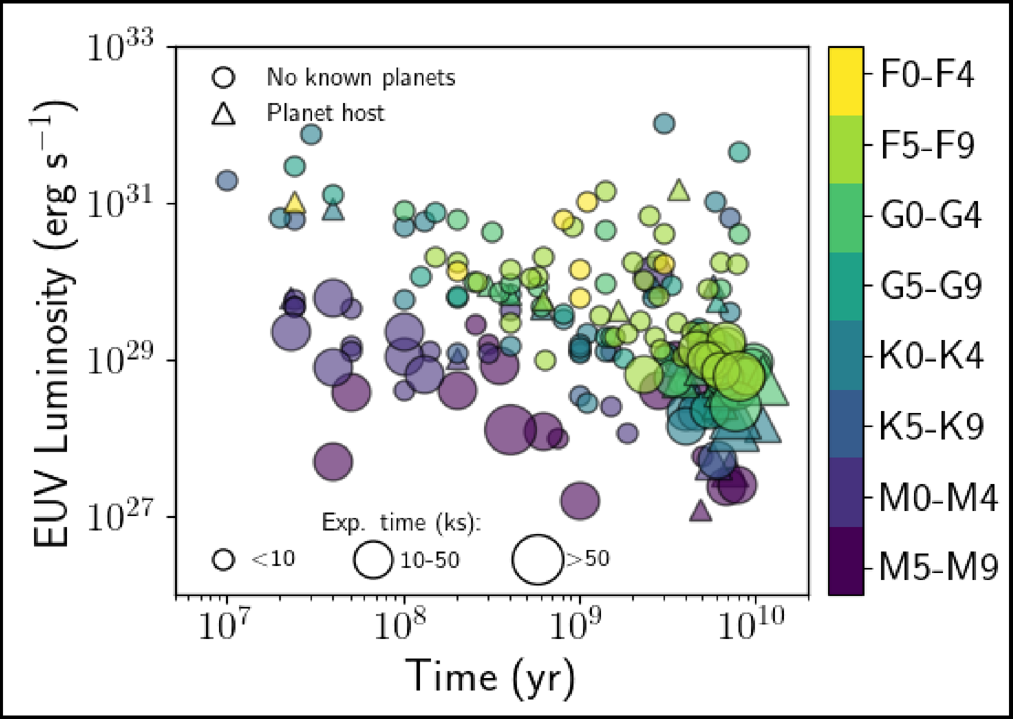
ESCAPE

Extreme-ultraviolet **S**tellar **C**haracterization for **A**tmospheric **P**hysics and **E**volution

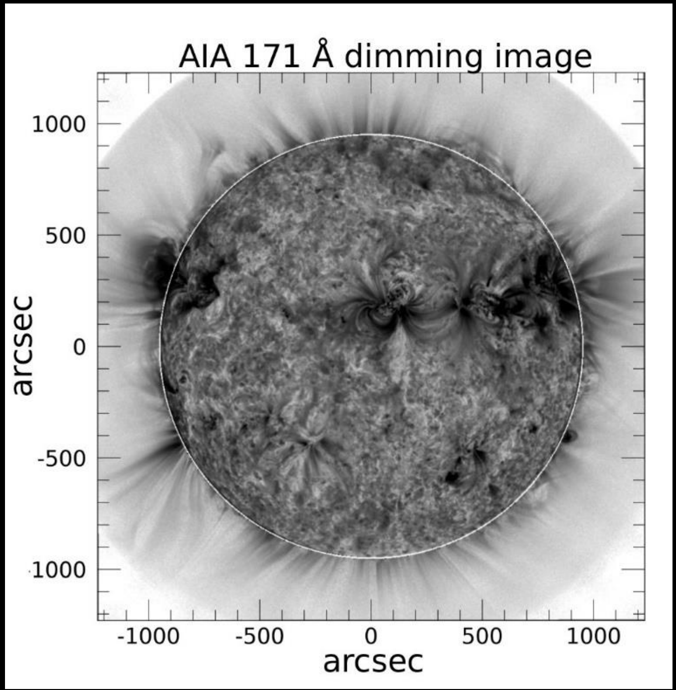
Exploring the Physics and Evolution of Potentially Habitable Worlds

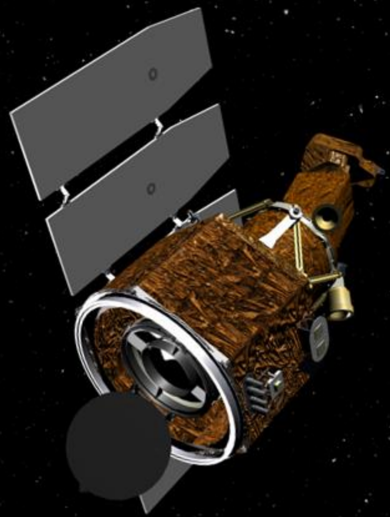
EUV & FUV (80 – 1650 Å) spectroscopy of > 300 stars, spectral types F - M

Deep monitoring observations of 24 targets of interest for flare and CME frequency distributions



Coronal dimming to detect and characterize CMEs





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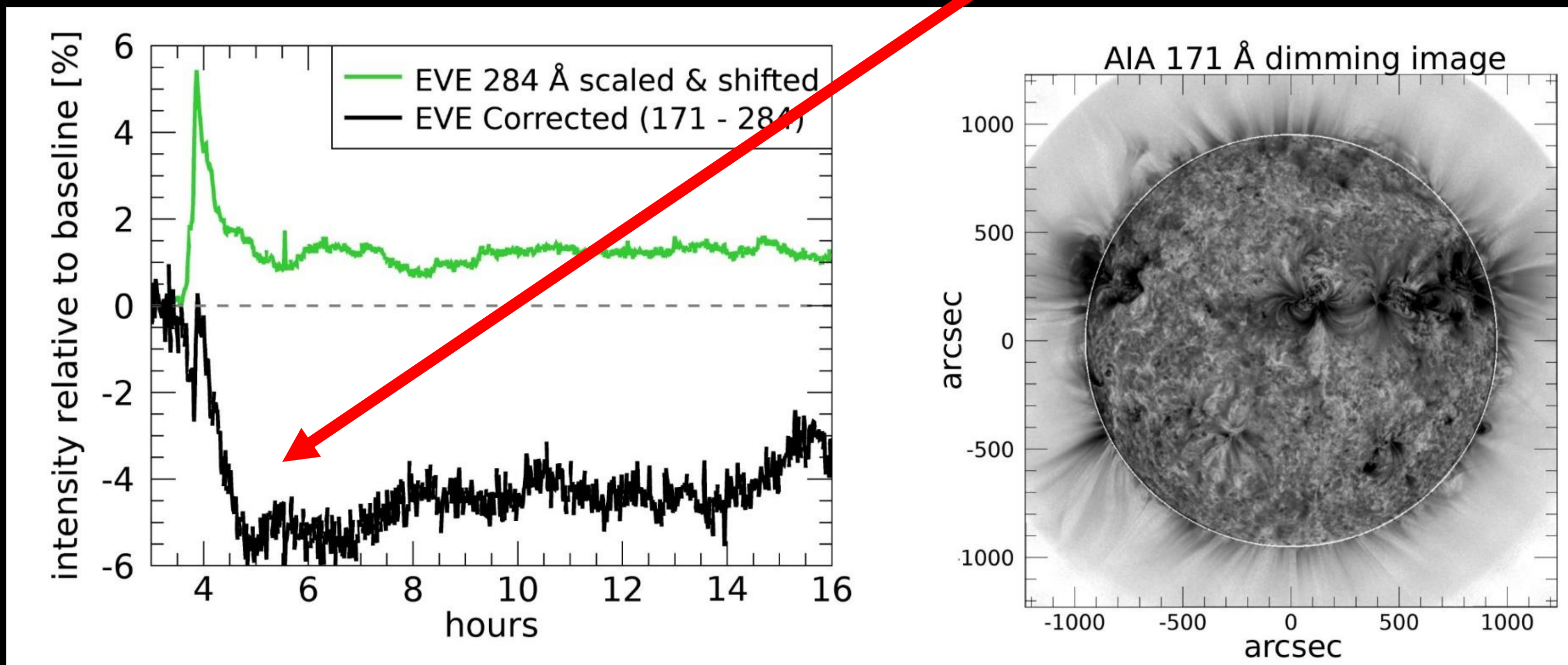
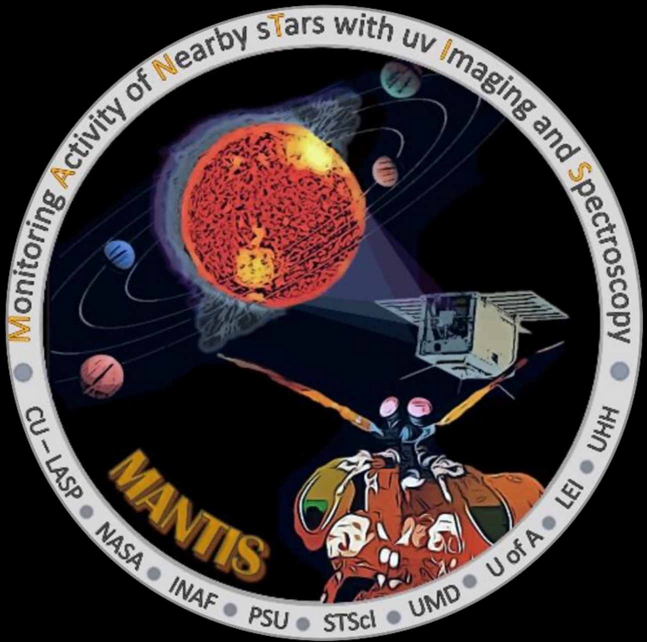
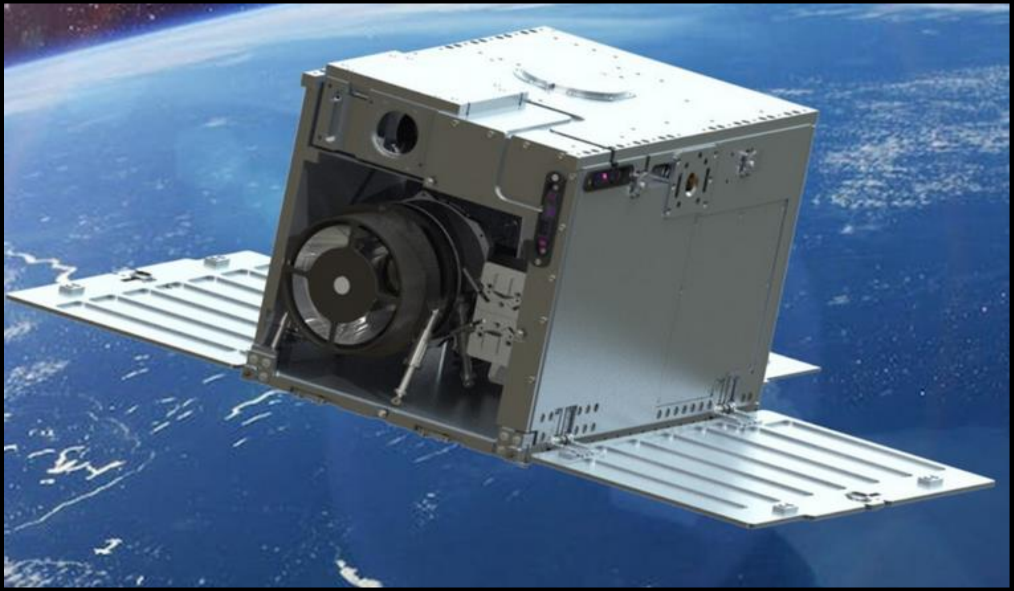




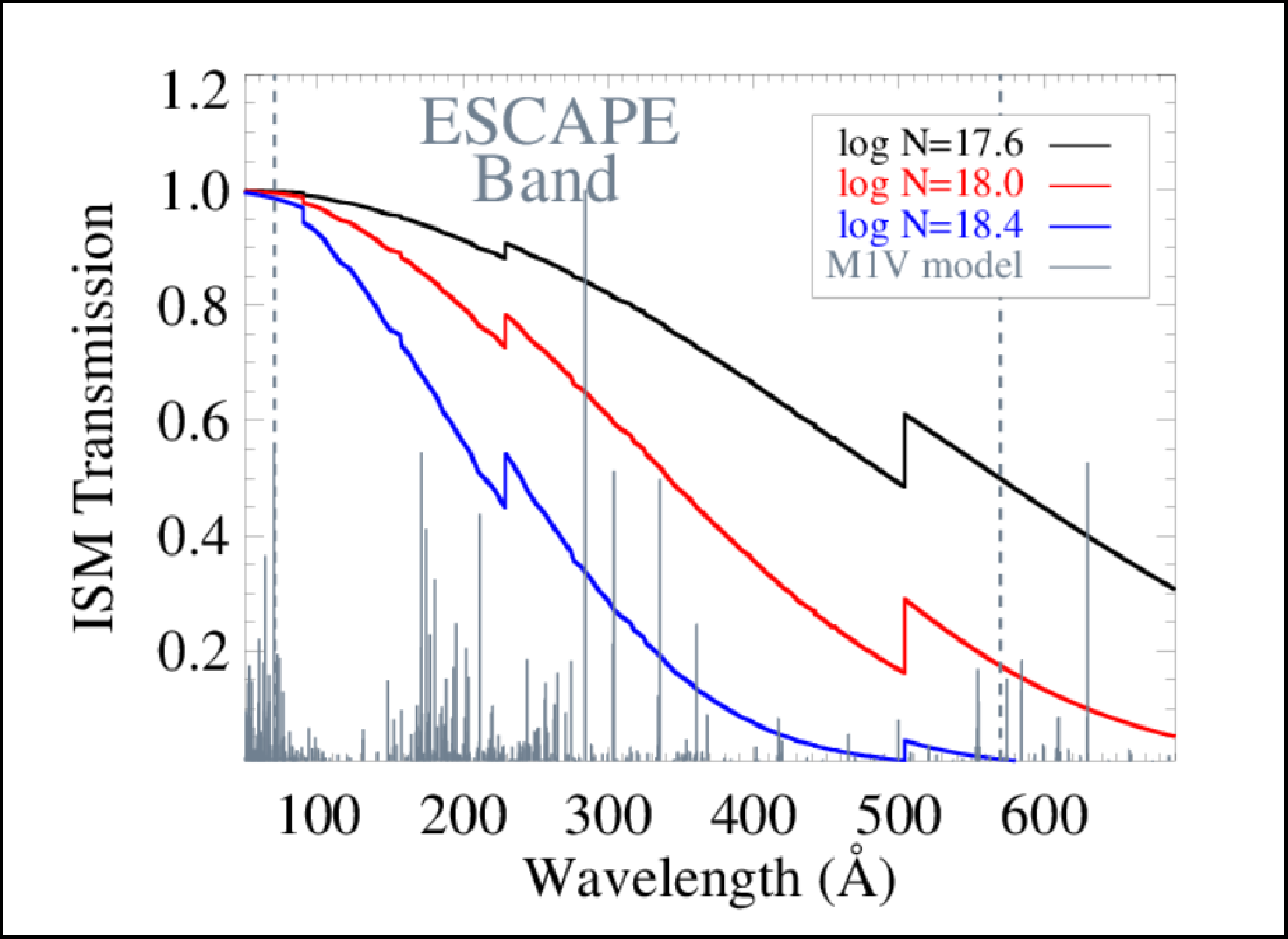
MANTIS technology and science demonstration mission – 2027 launch



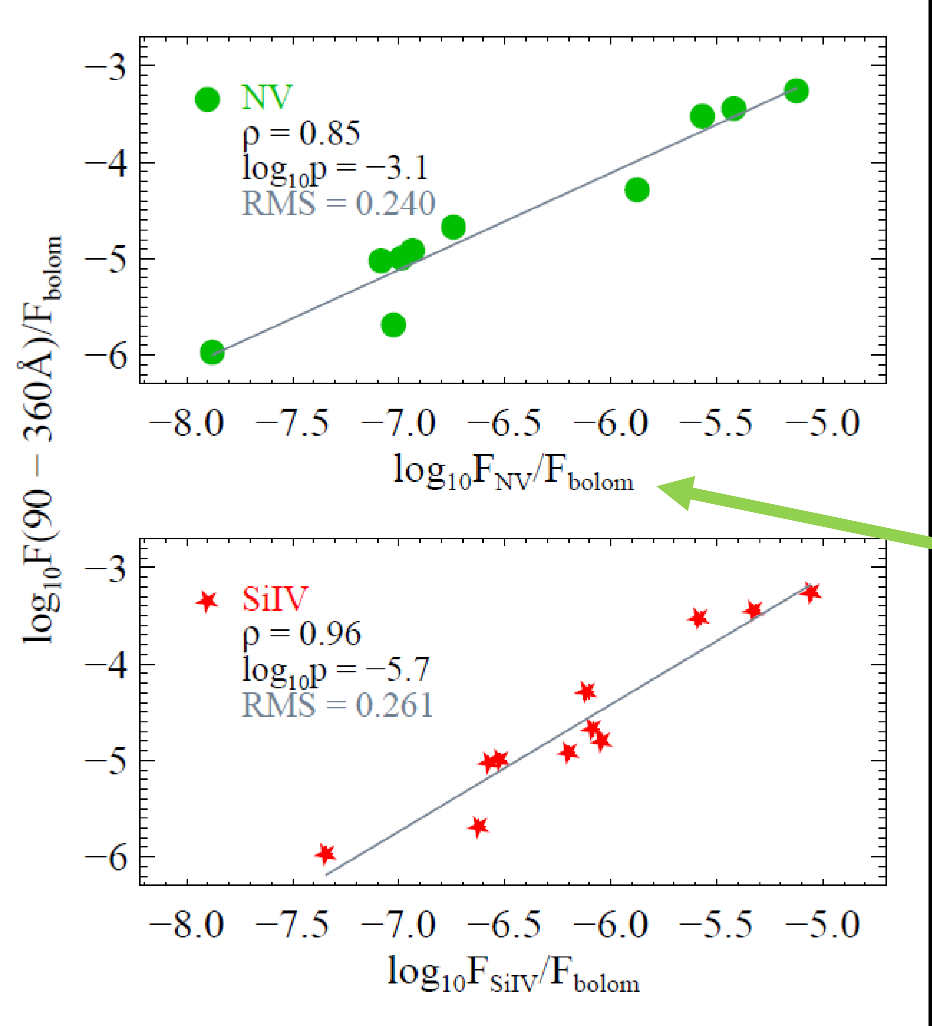
UV and X-ray Observations of Rocky Planet M Dwarf Host Stars: Inputs for Atmospheric Photochemistry and Escape Calculations

Additional Information

The unobserv~~able~~ed EUV (10-91nm)



EUV scaling relations: HST to EUVE

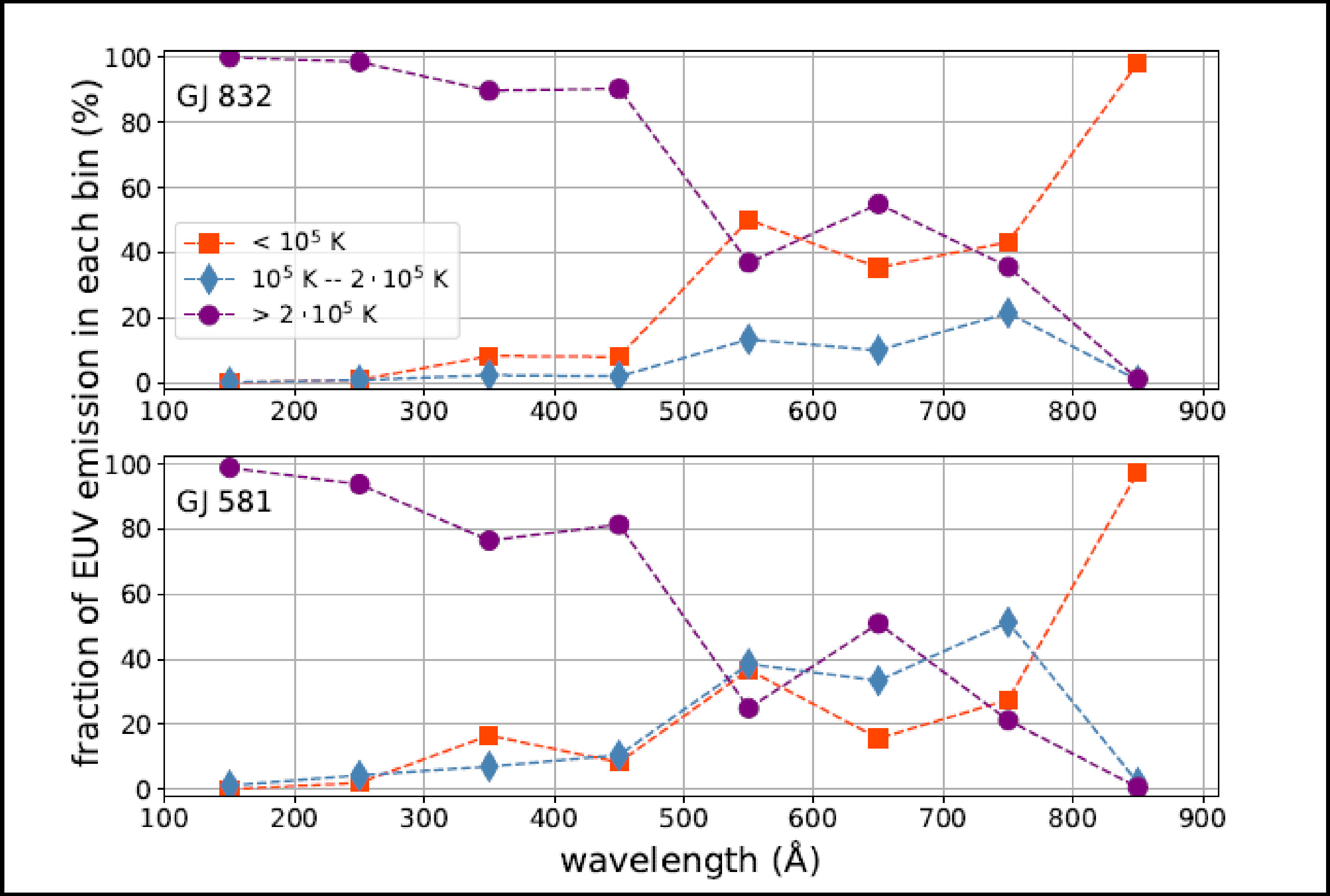


EUV: 9 – 36 nm
Mostly formed > 10^5 K

N V (124nm),
T_{form} ~ 2 x 10^5 K

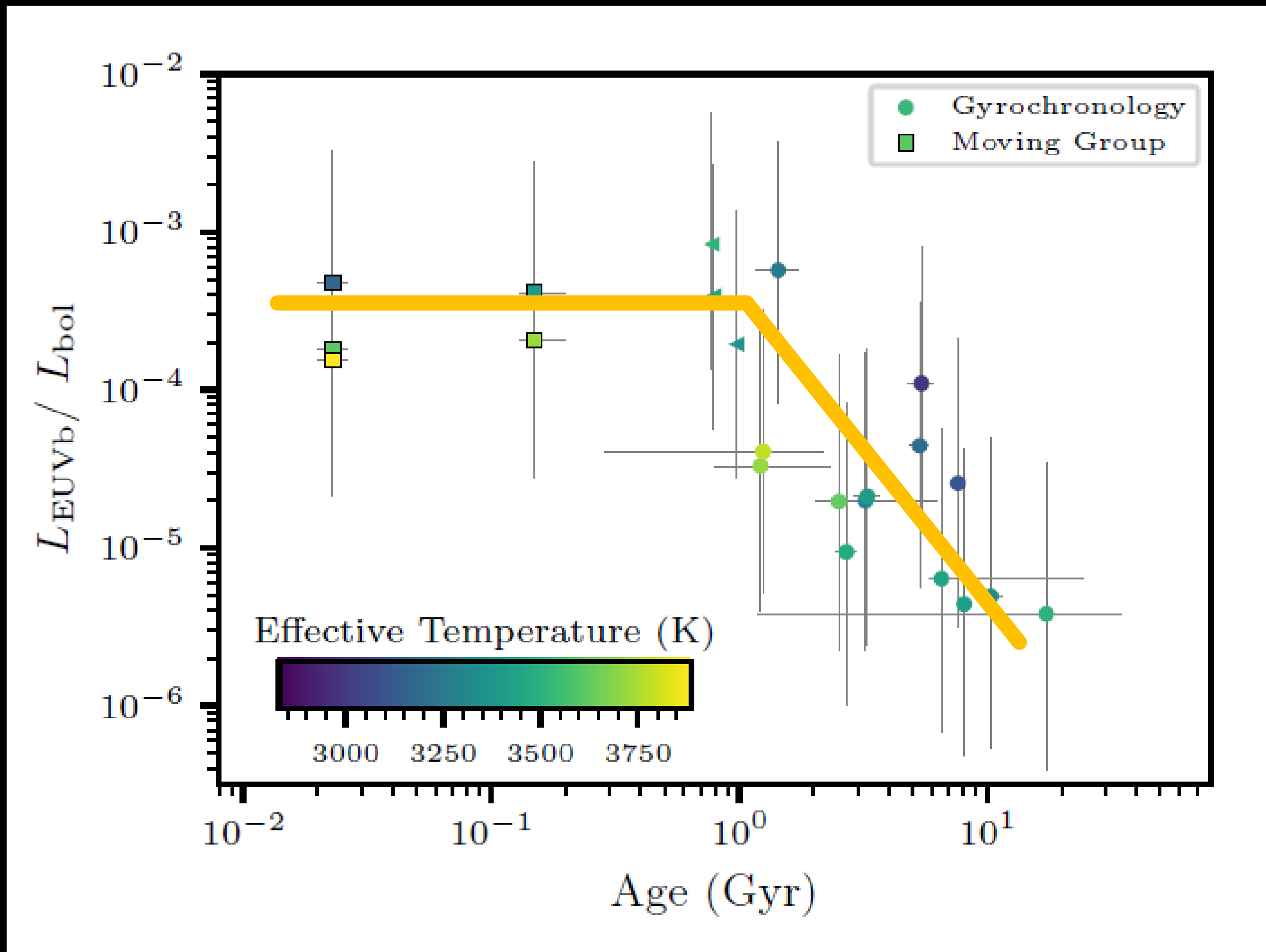
France et al. 2018
(see also, Sanz-Forcada et al. 2011; Linsky et al. 2014; Sreejith et al. 2020)

M dwarf Model Atmospheres: The corona dominates the EUV flux



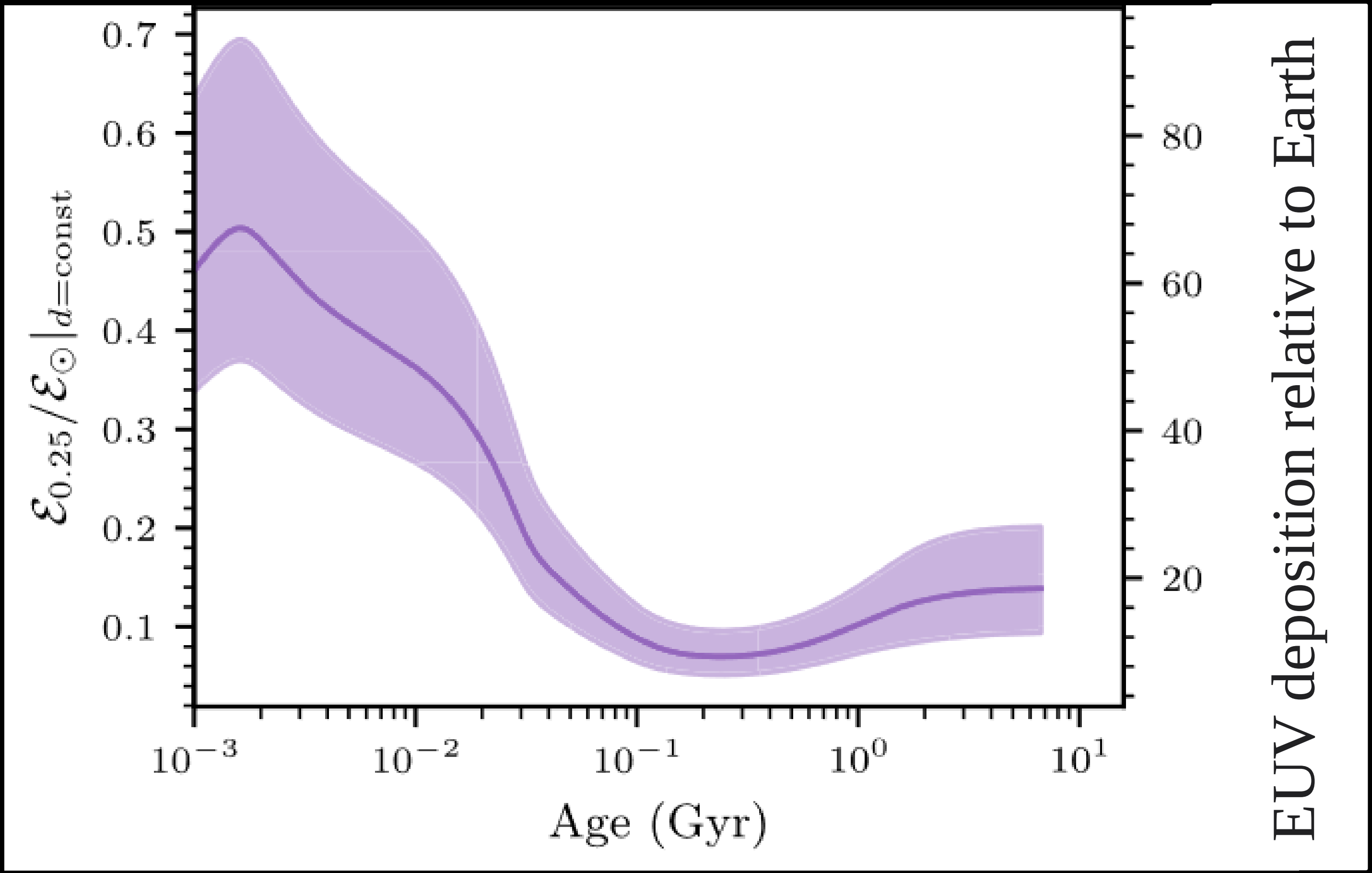
(Tilipman et al. 2021; Duvvuri et al. 2021)

Applying scaling relations: EUV evolution over lifetime of planet



Pineda et al. 2021
(see also, France et al. 2018, Loyd et al. 2020)

EUV and atmospheric stability: EUV evolution over lifetime of planet



EUV irradiance deposition ratio in the Habitable Zone: mid-M dwarfs vs. solar-type stars

Pineda et al. (2021)