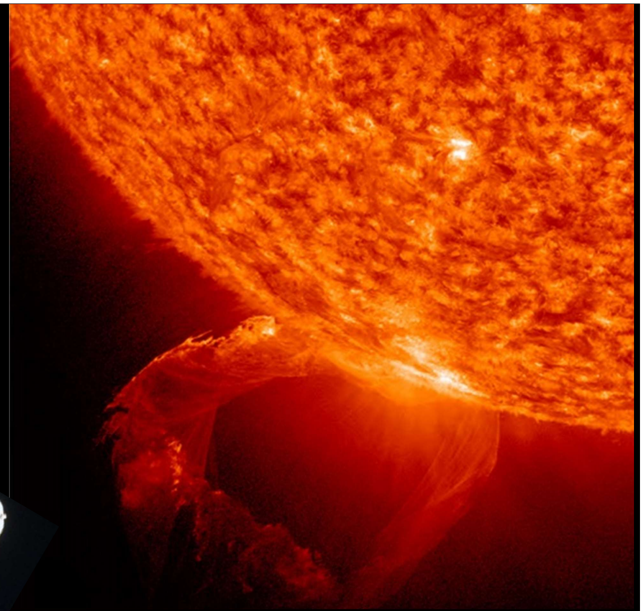
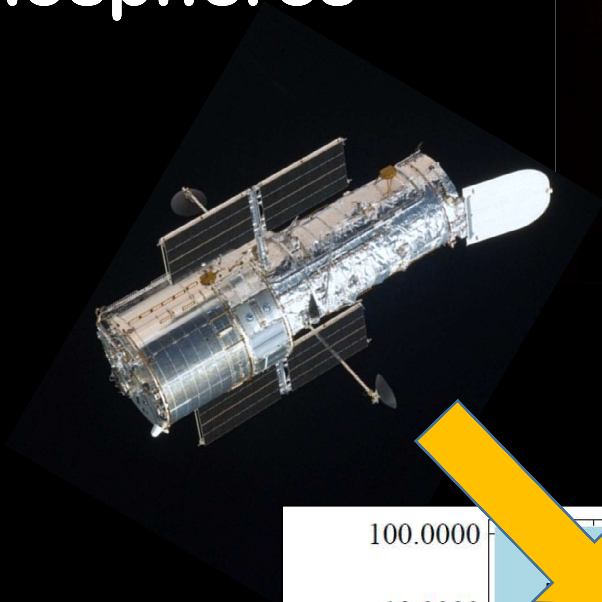
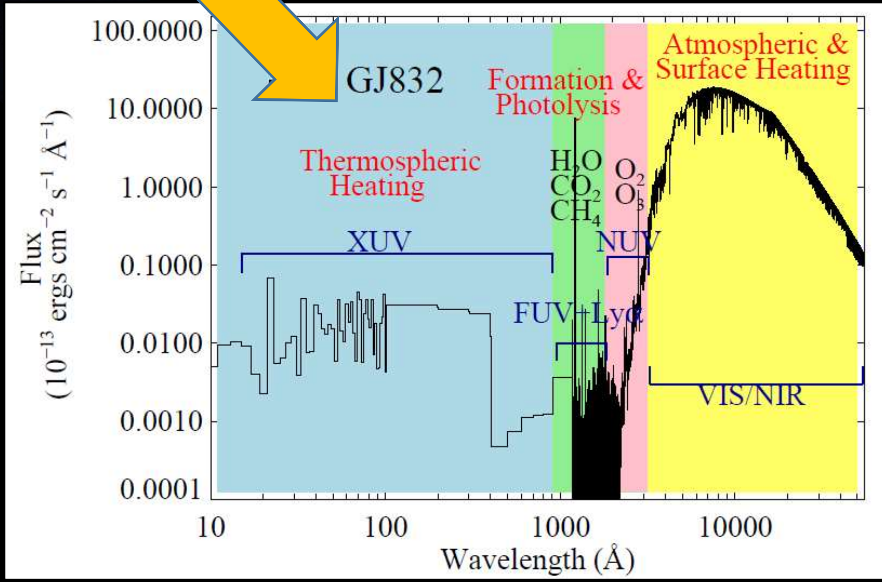
EUV Astronomy and Extreme Exoplanet Atmospheres





Kevin France
(University of Colorado)

New Horizons Science Team Meeting #54 - 27 Oct 2023



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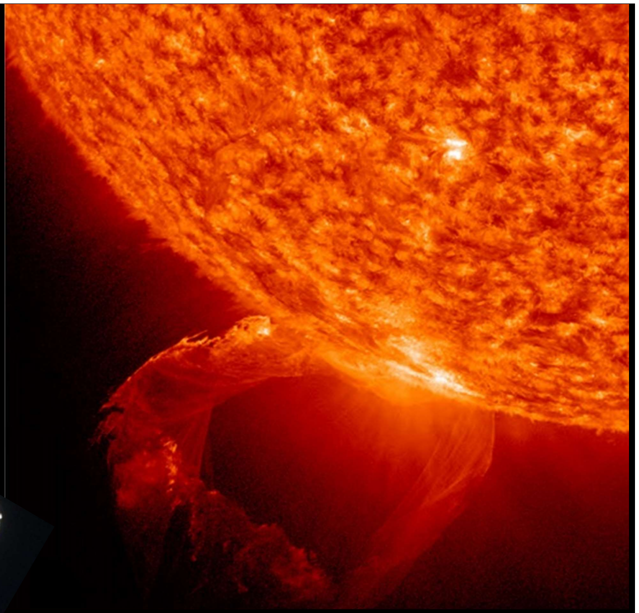
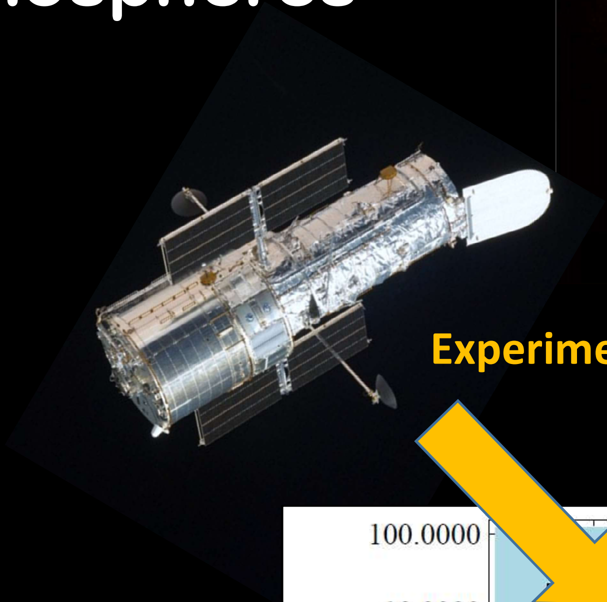
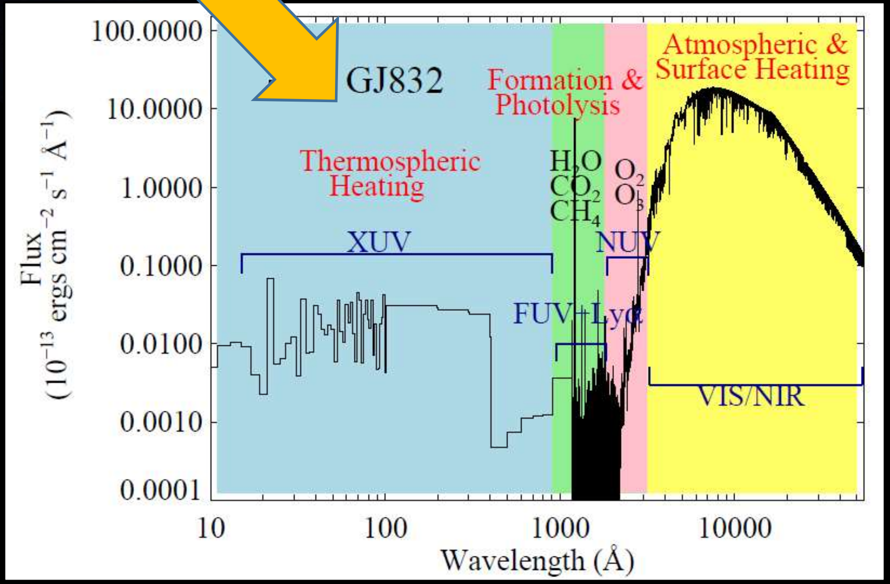




Experiment, observation, analysis



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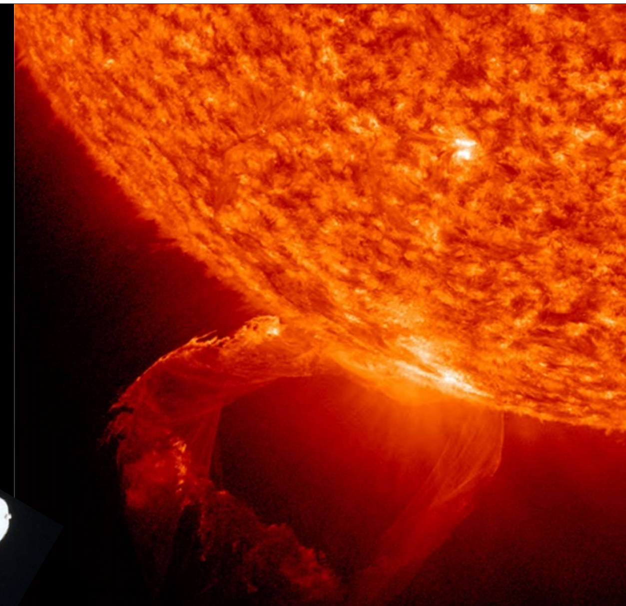

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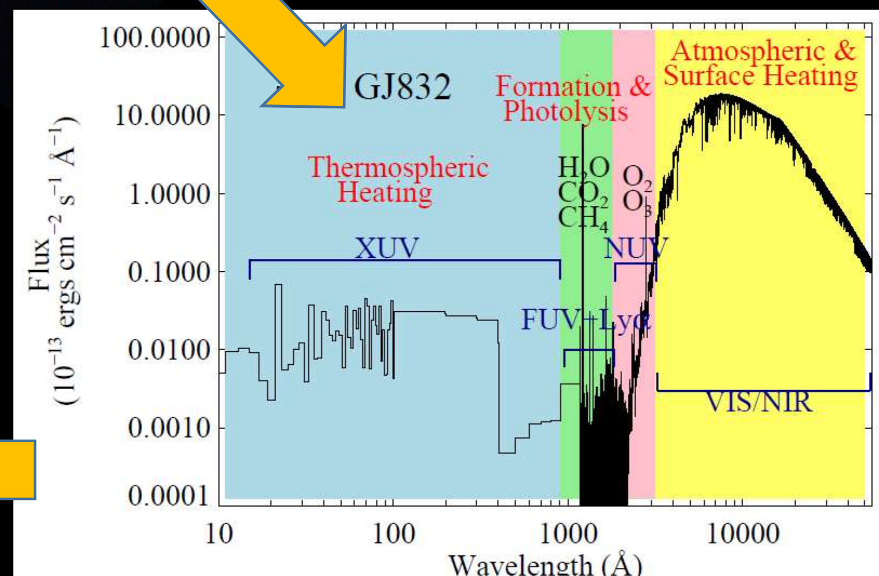
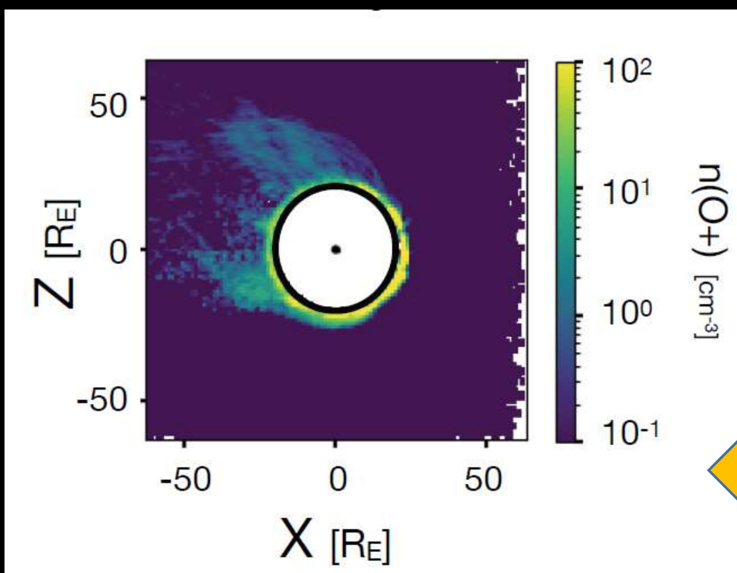
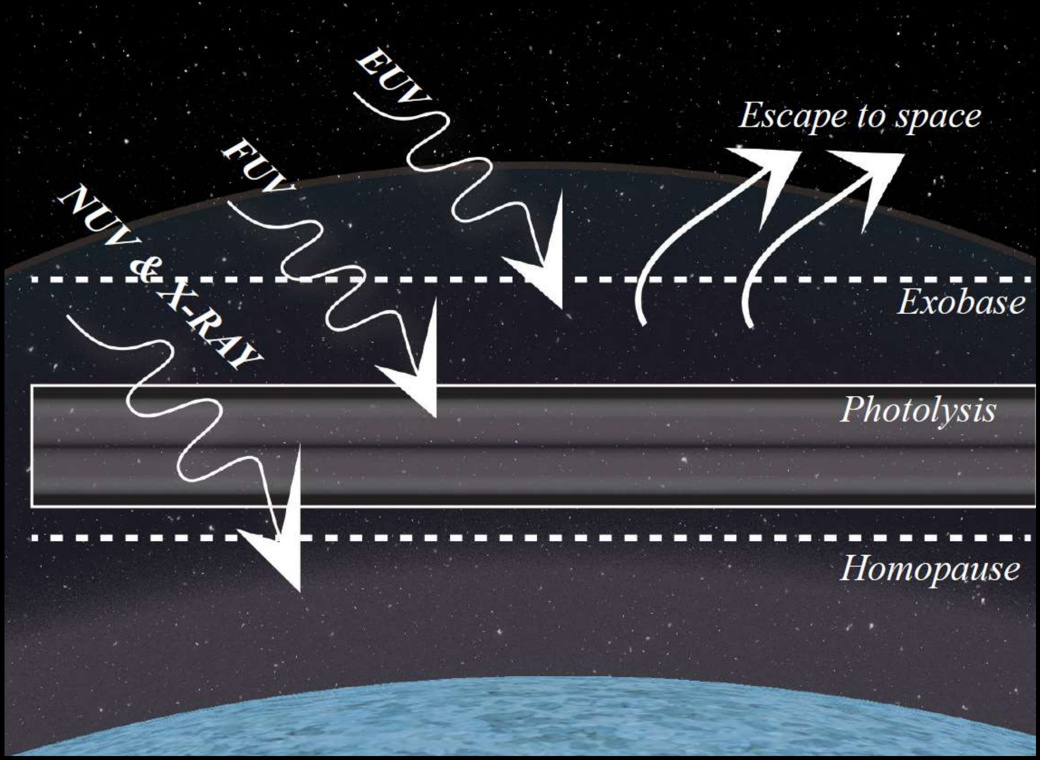


Modeling



Introduction: Stellar SED and Atmospheric Impacts



Adapted from France et al. 2019

- 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

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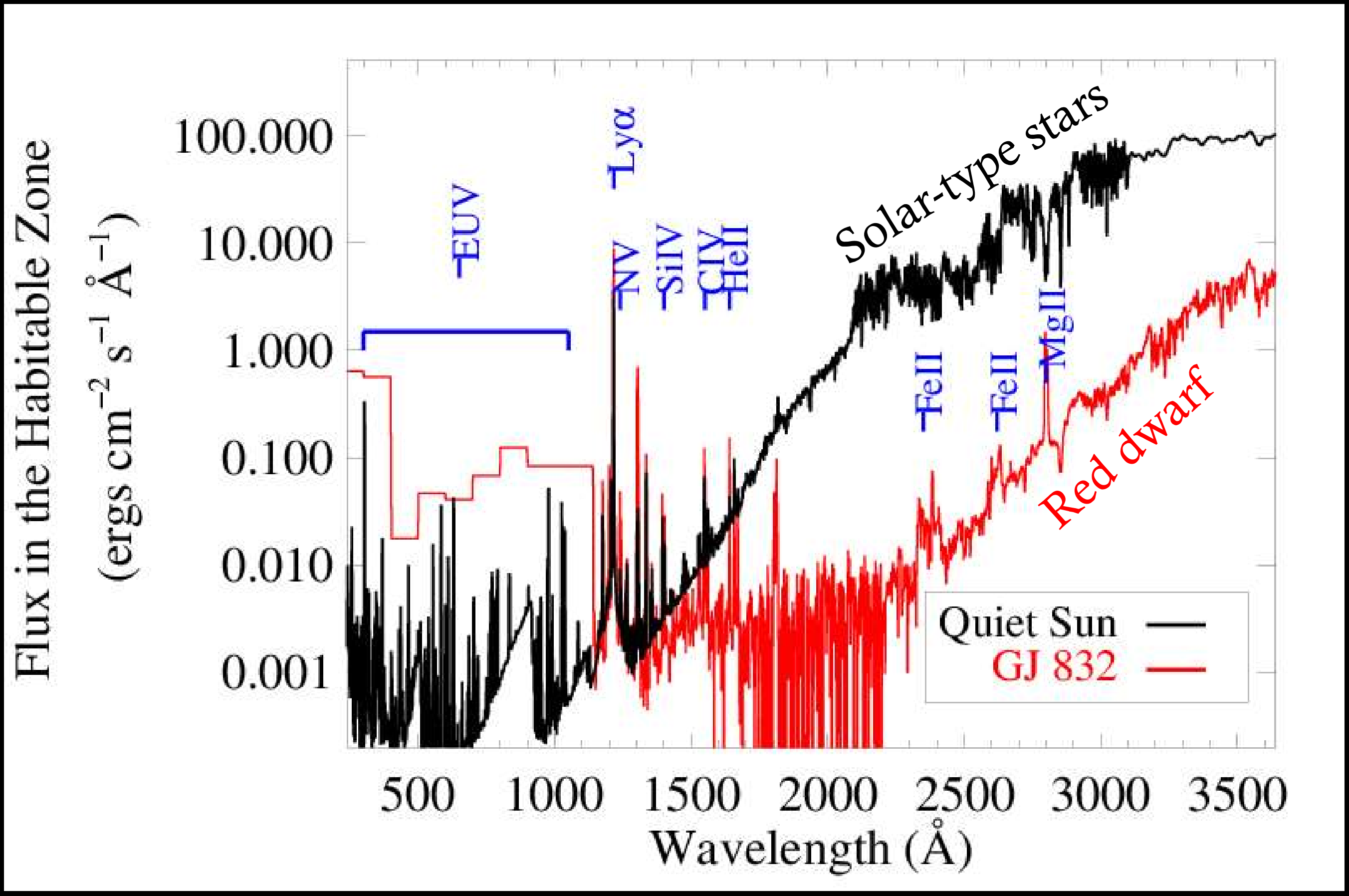
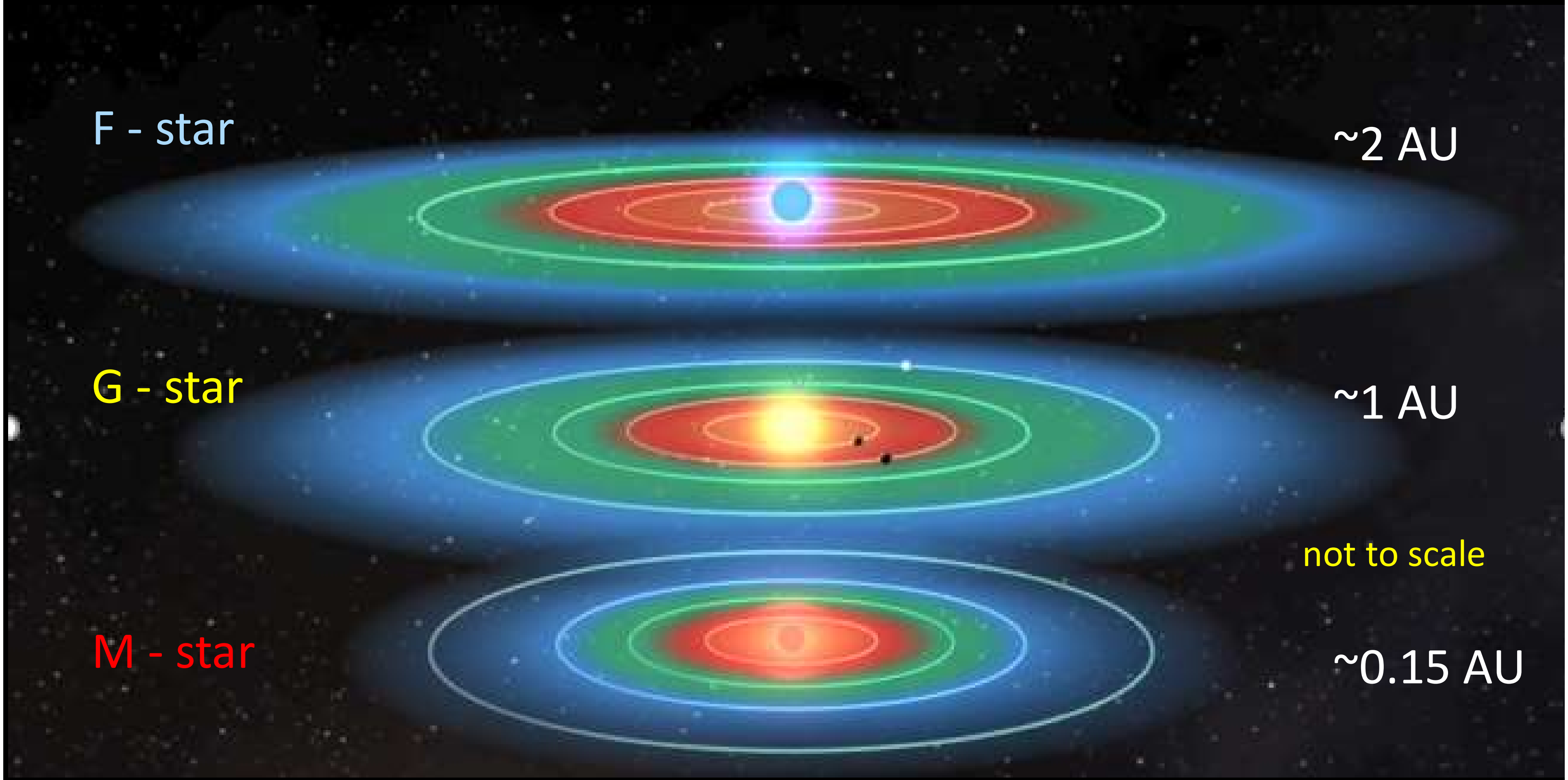


France et al. (ApJ-2012, 2016, 2020)

France et al. (ApJL-2012c, ApJ-2016)

The liquid water "Habitable Zone"



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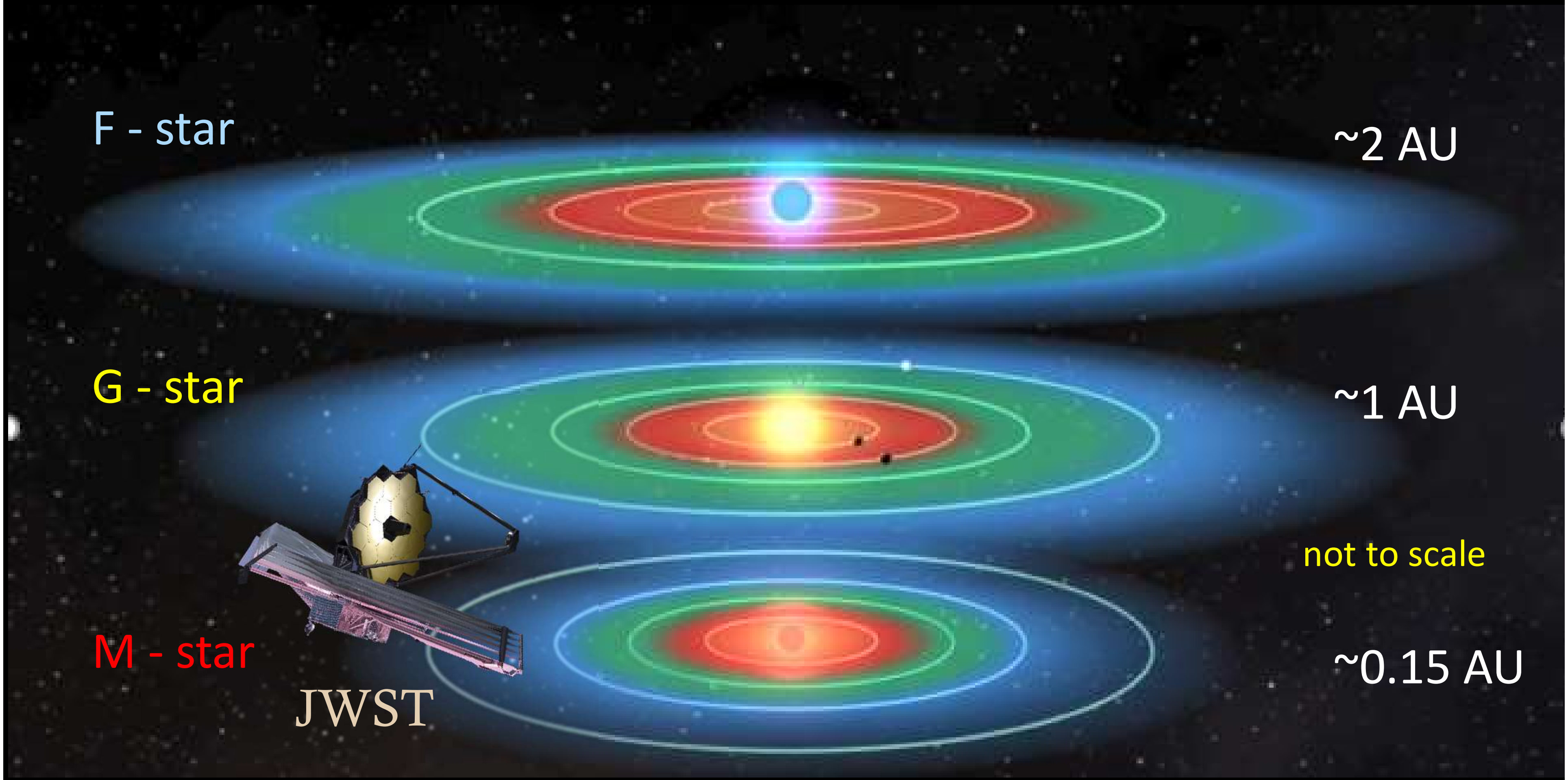

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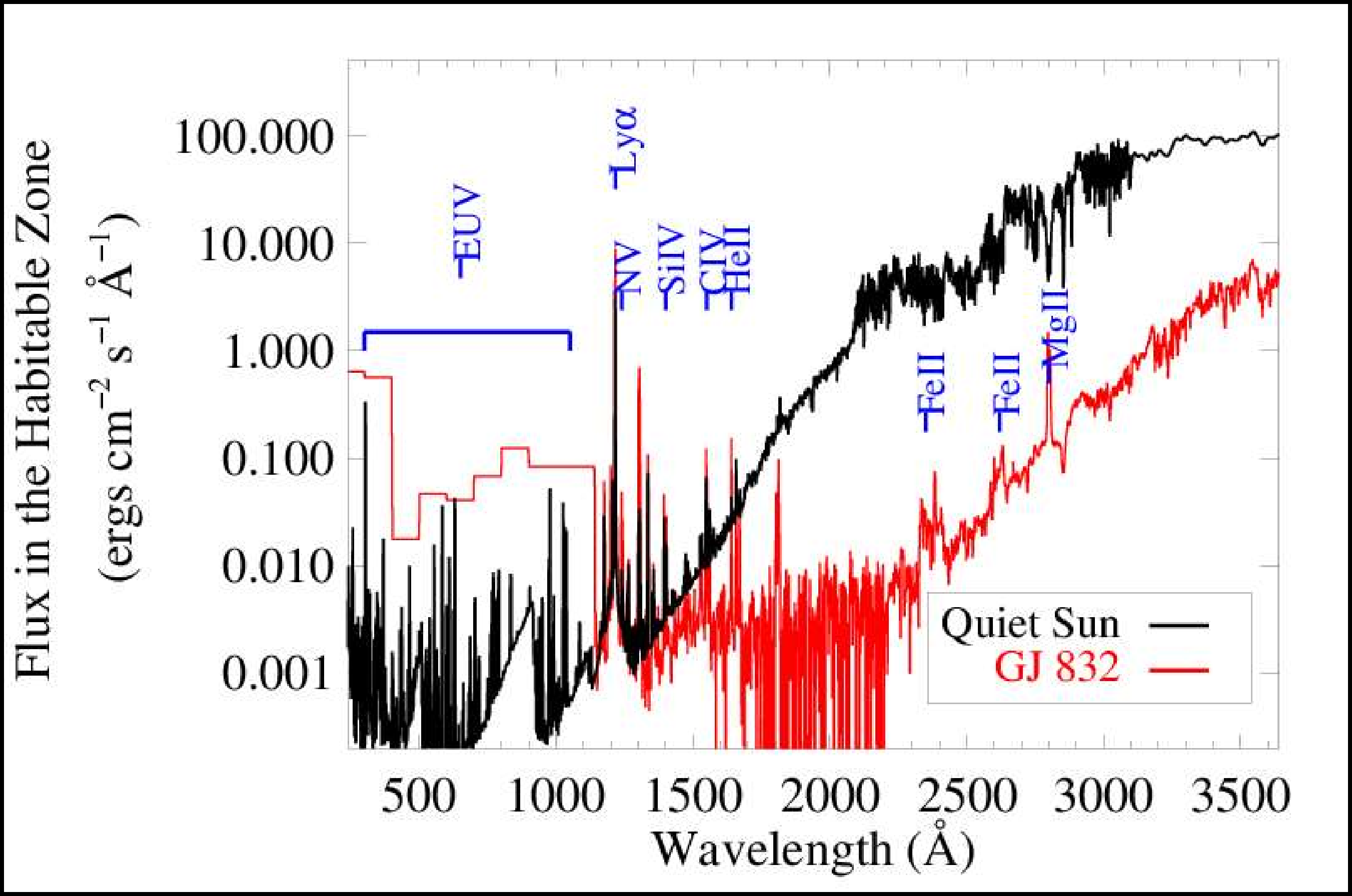

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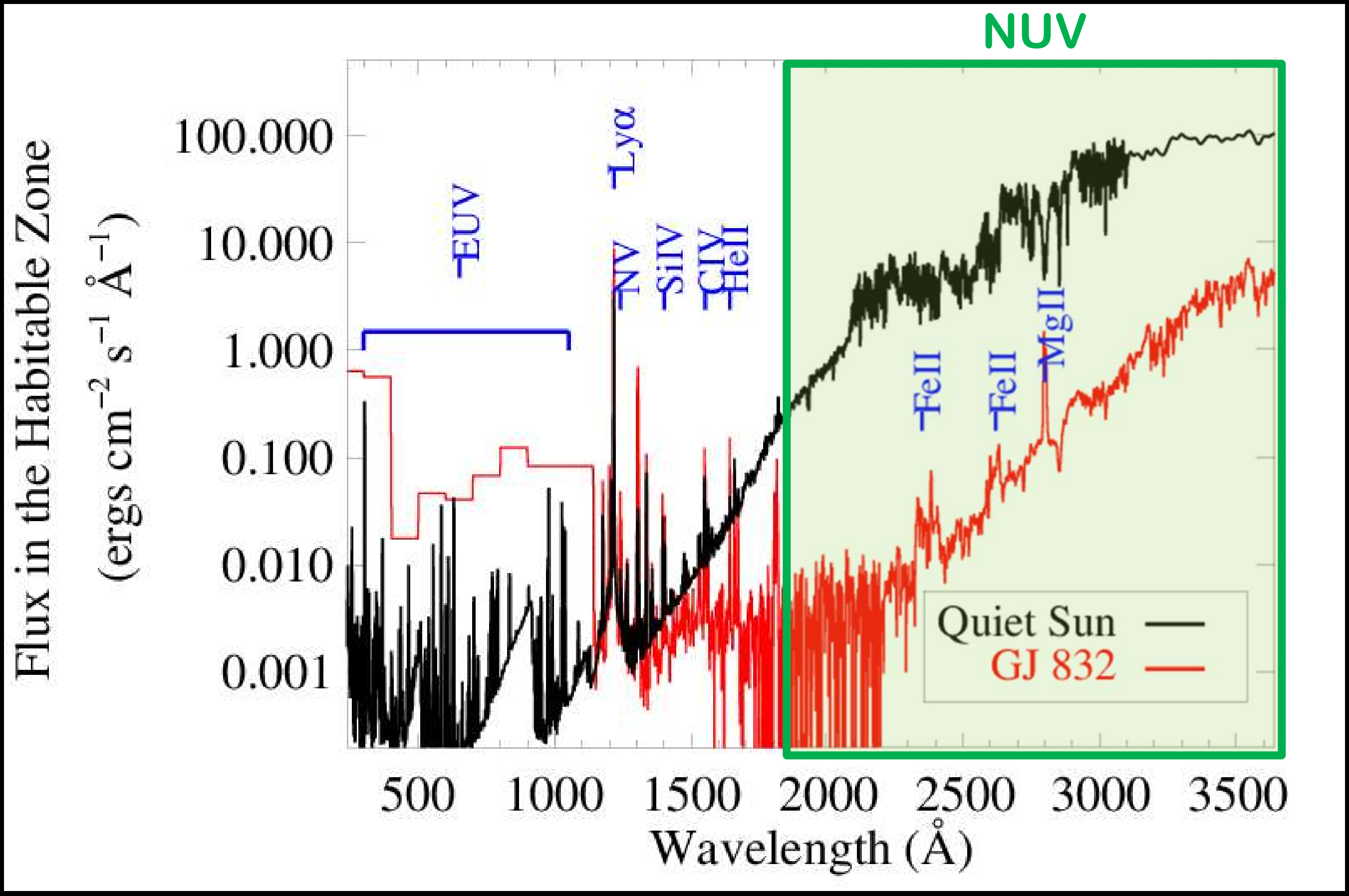

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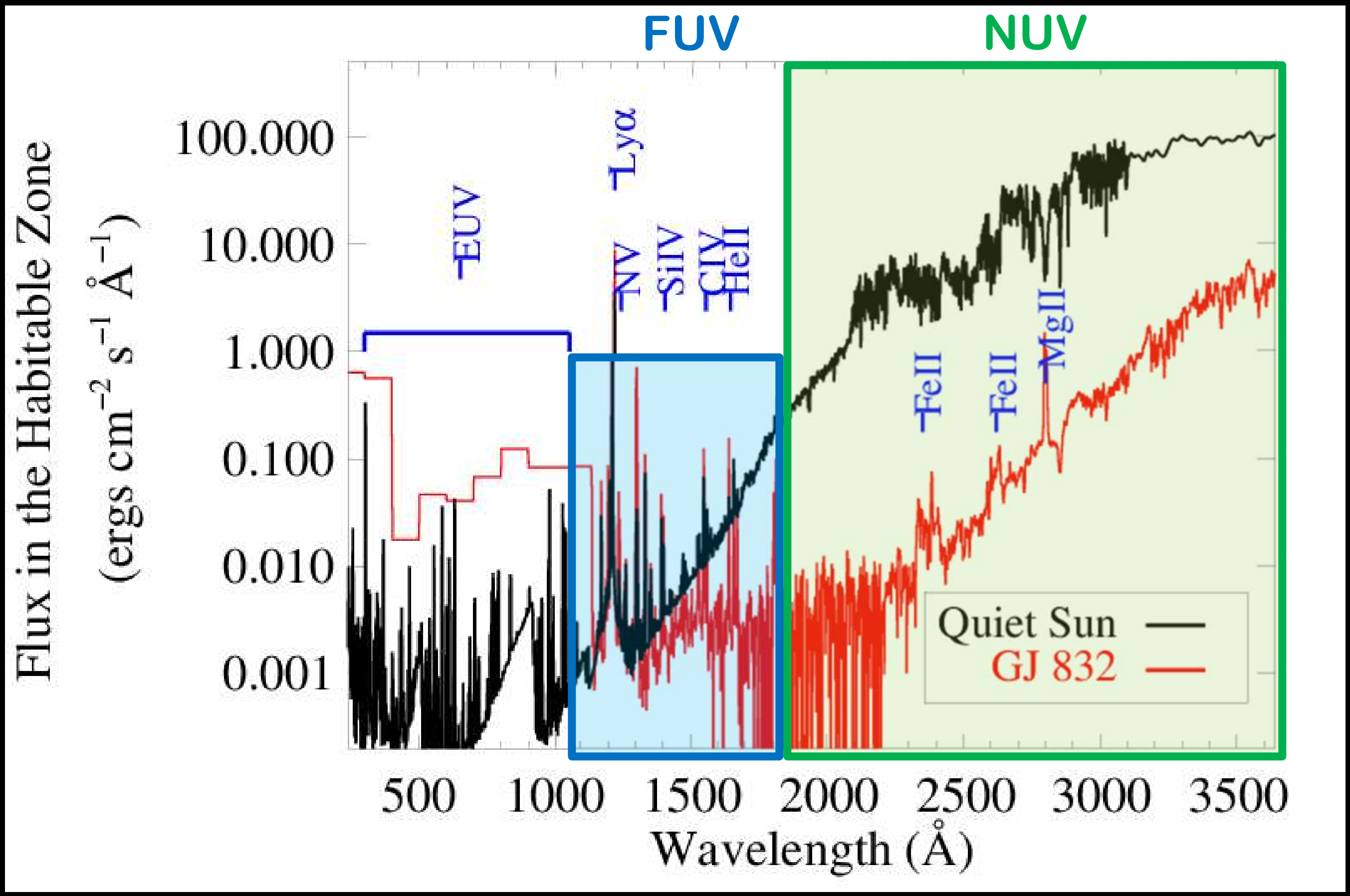

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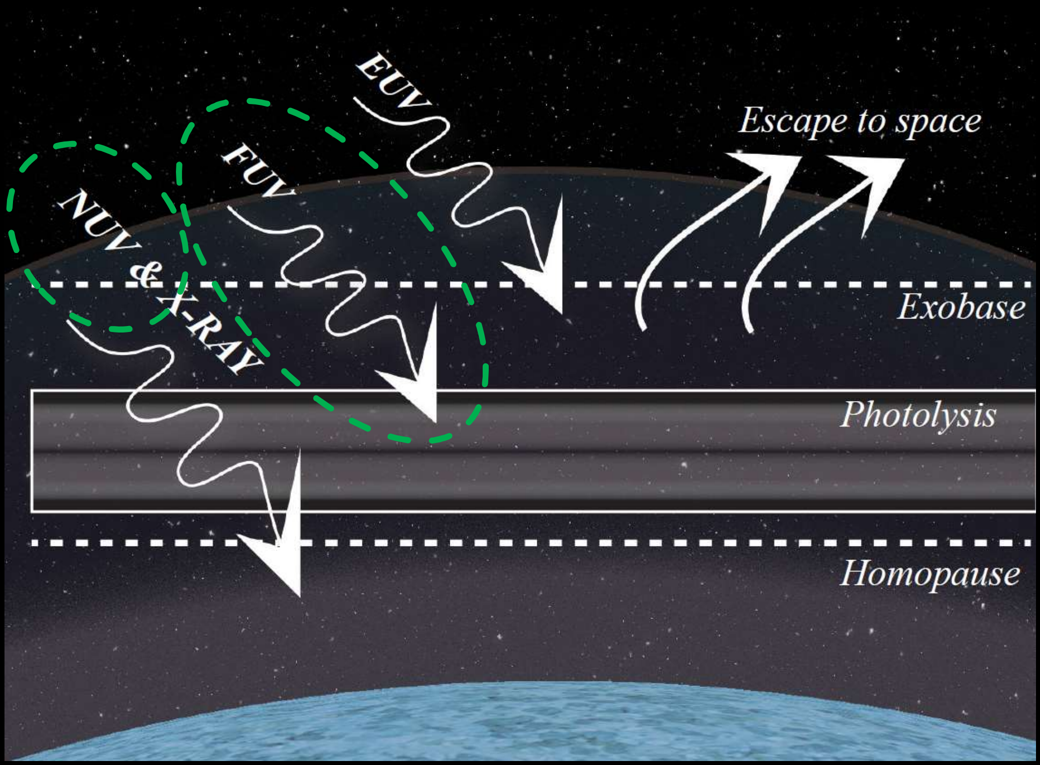

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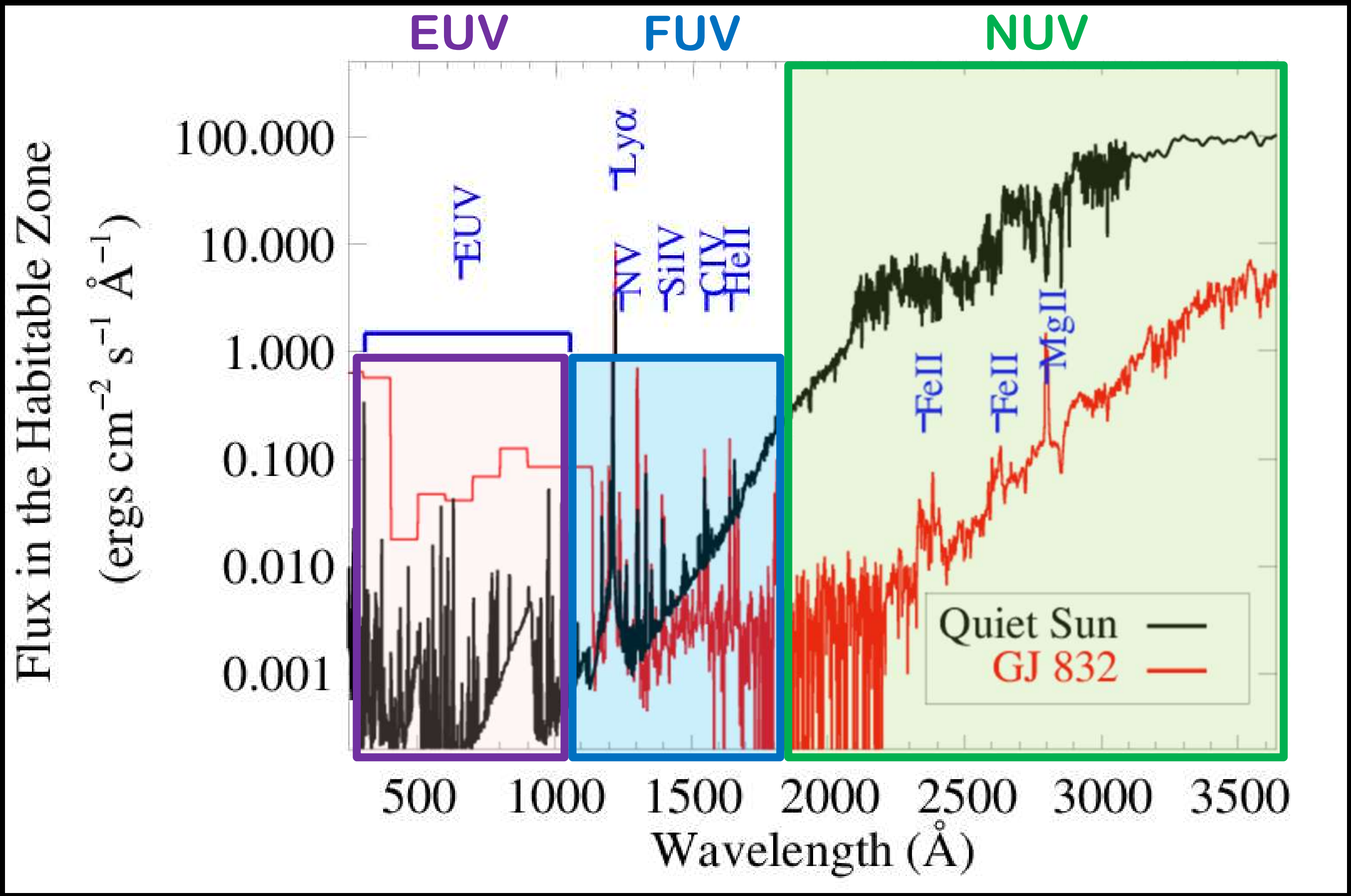
Introduction: Stellar SED and Atmospheric Impacts

EUV = 100 – 911 Å



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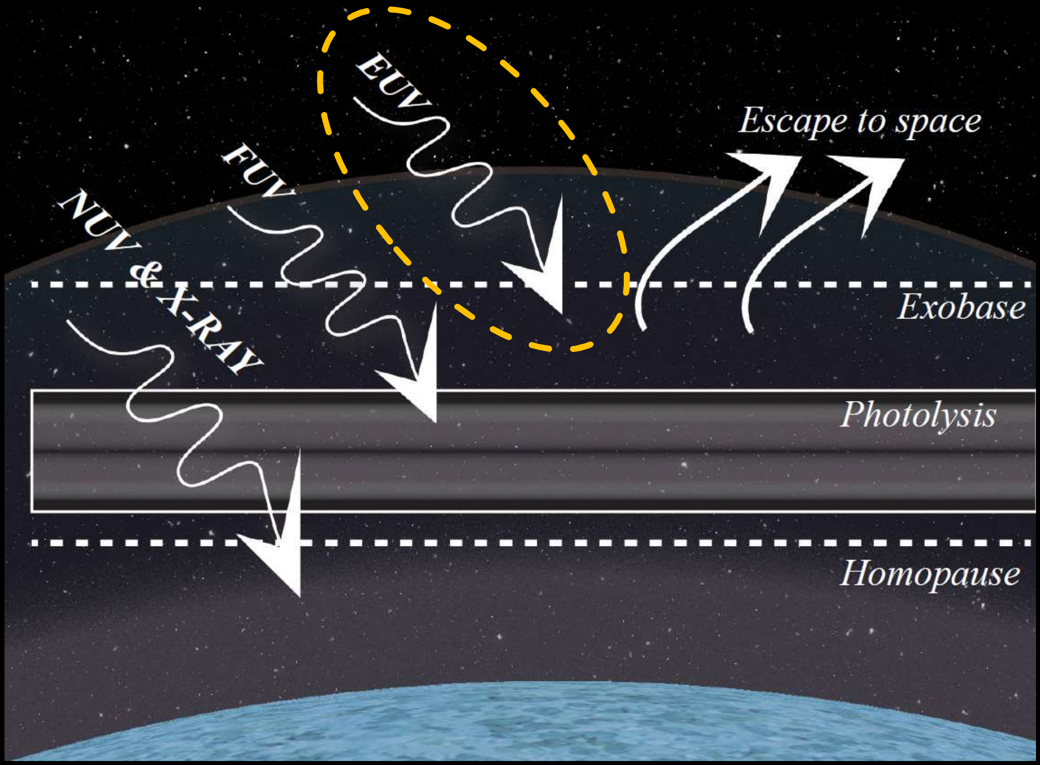

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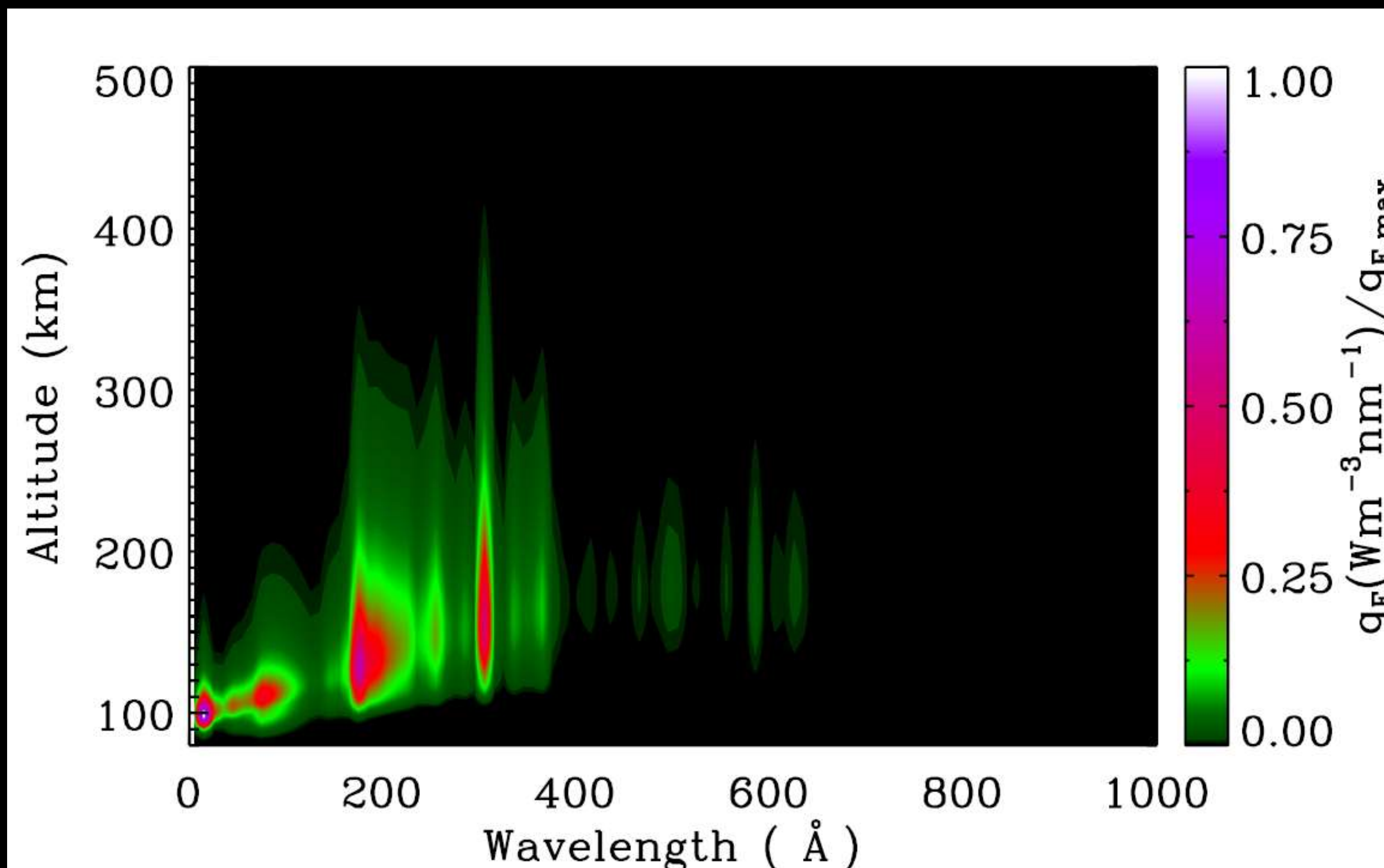
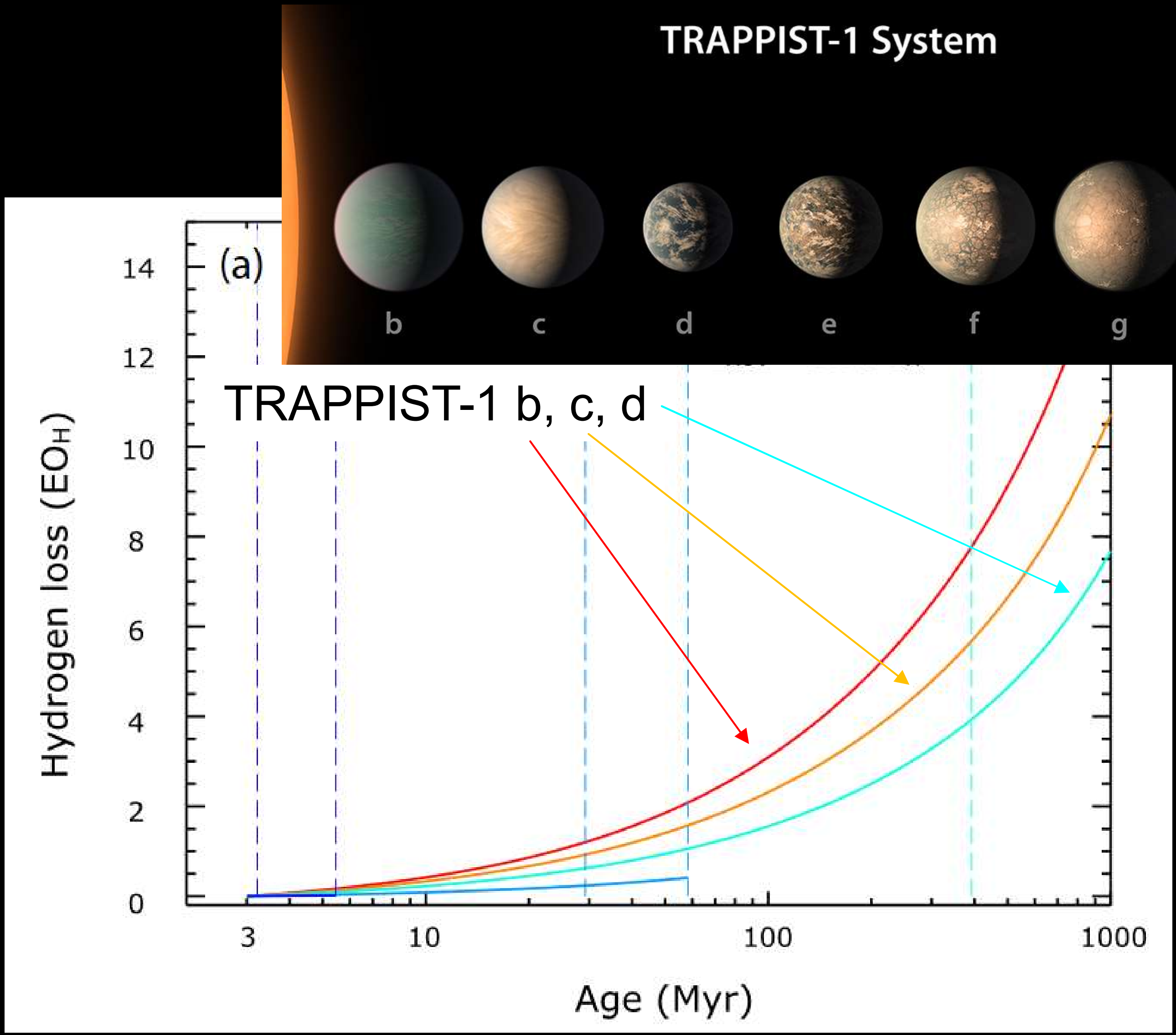
EUV photons dominate heating inputs to Earth-like exoplanets (nitrogen and oxygen dominated)



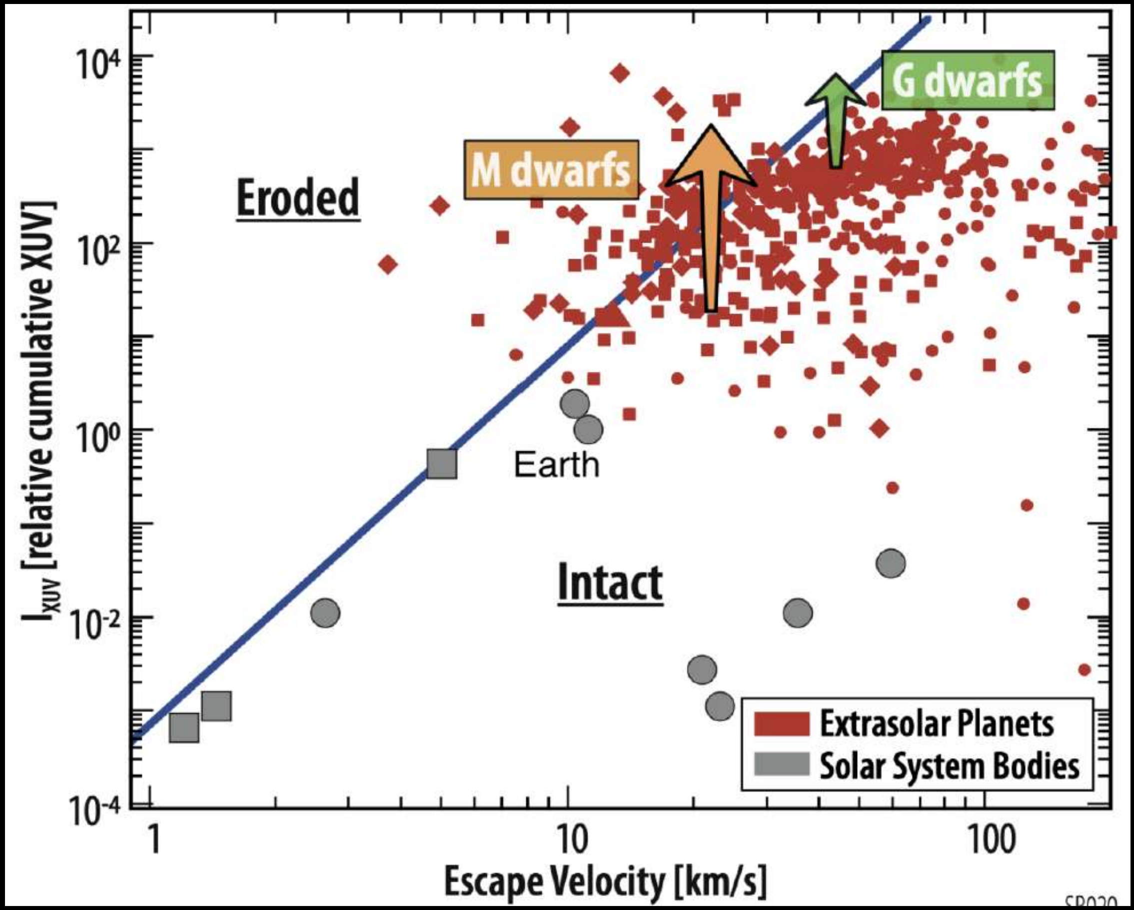
(Koskinen, Huang, et al. – in prep)

EUV photons may drive rapid water loss on rocky planet around M dwarfs



(Bolmont et al. 2017)

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



'The Cosmic Shoreline': Zahnle & Catling (2017) + STAR-X team 2023

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

The unobservable EUV (10-91nm)

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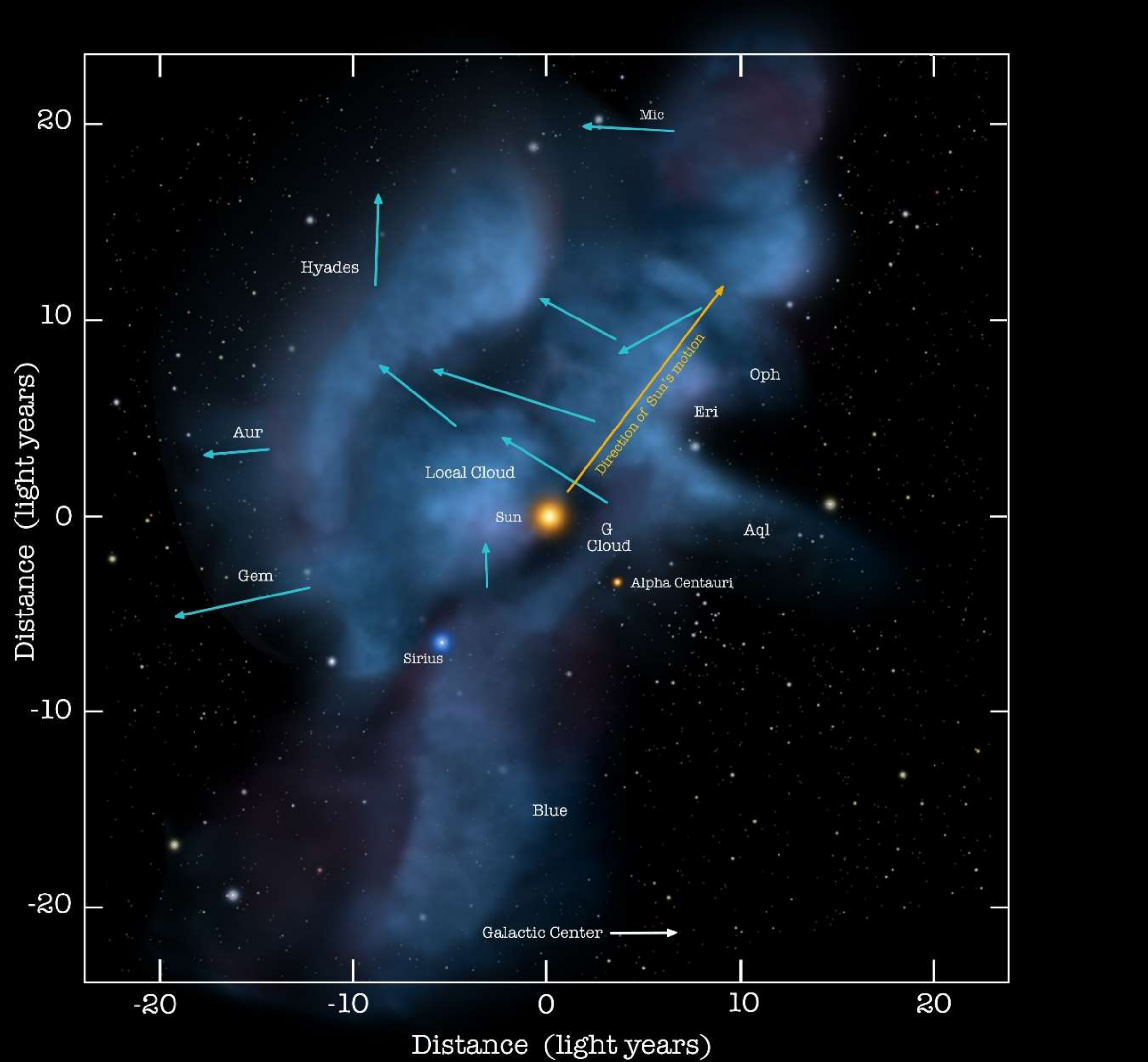
The Local Interstellar Medium



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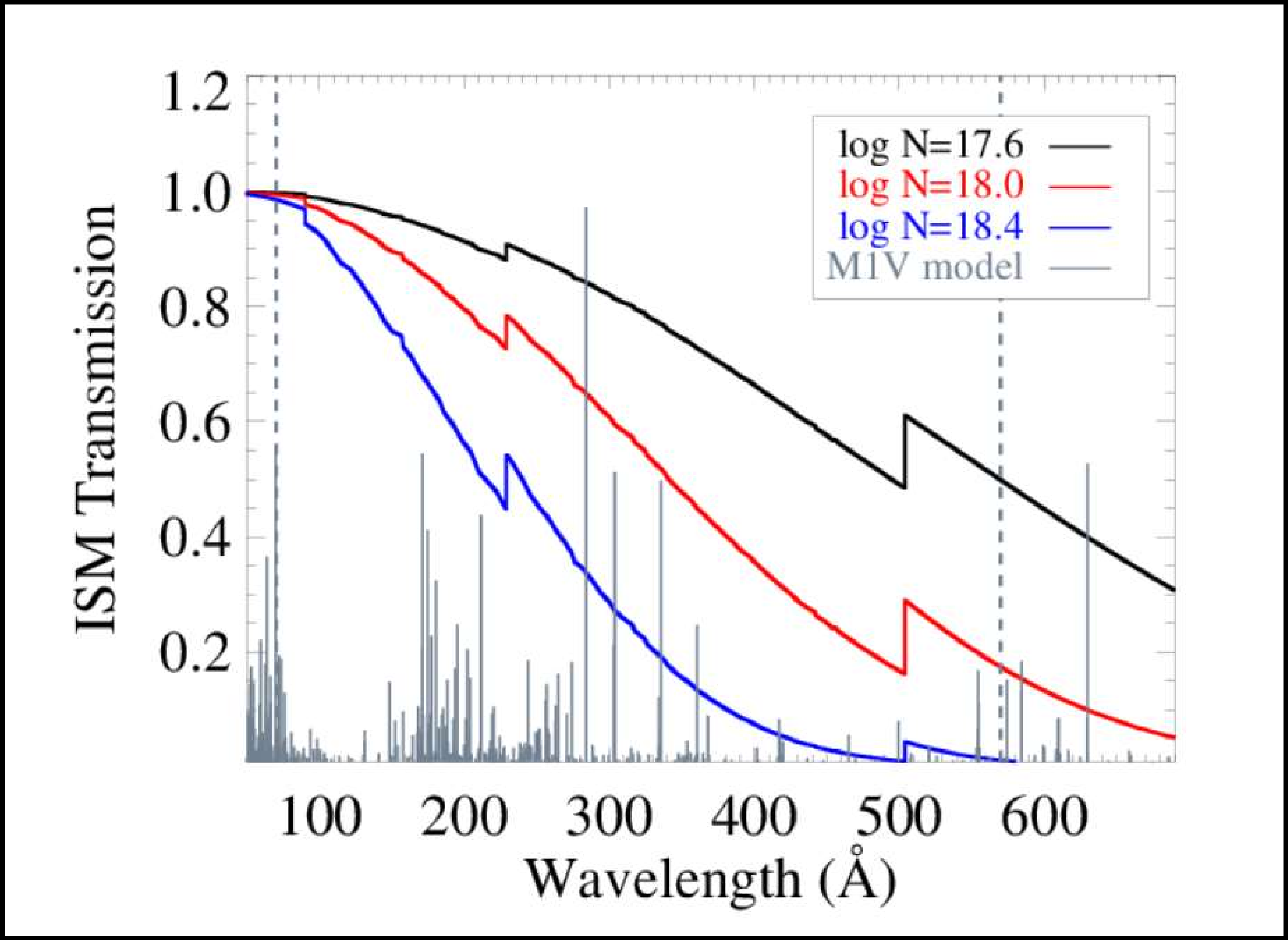

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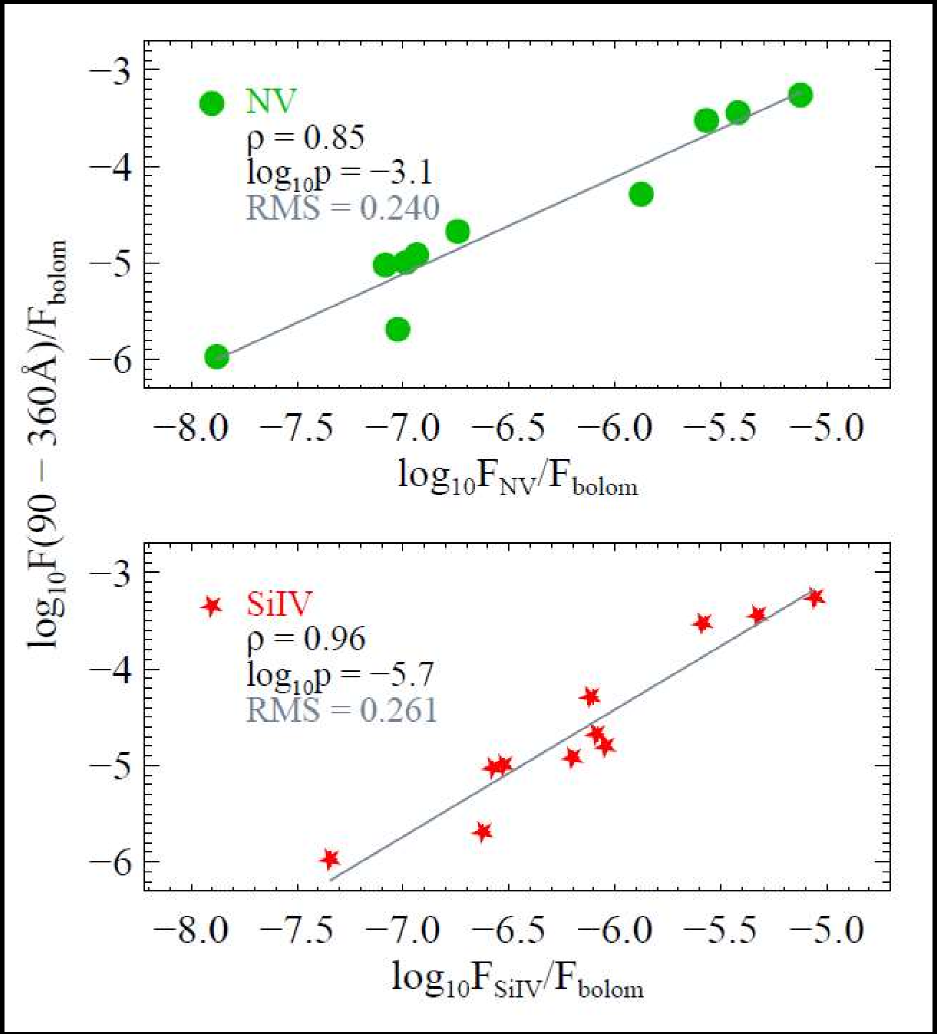
  - Astronomy has never had a high-sensitivity EUV mission
  - The interstellar medium is a large opacity source for even nearby stars (H and He ionization x-sec in EUV)

- How are we estimating the unobserved flux?
  - Scaling relations with other high-energy tracers (FUV, X-rays)
  - Semi-empirical stellar models or plasma calculations (e.g., differential emission measure, based on FUV/X-ray inputs)

EUV scaling relations: HST to EUVE



France et al. 2018

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

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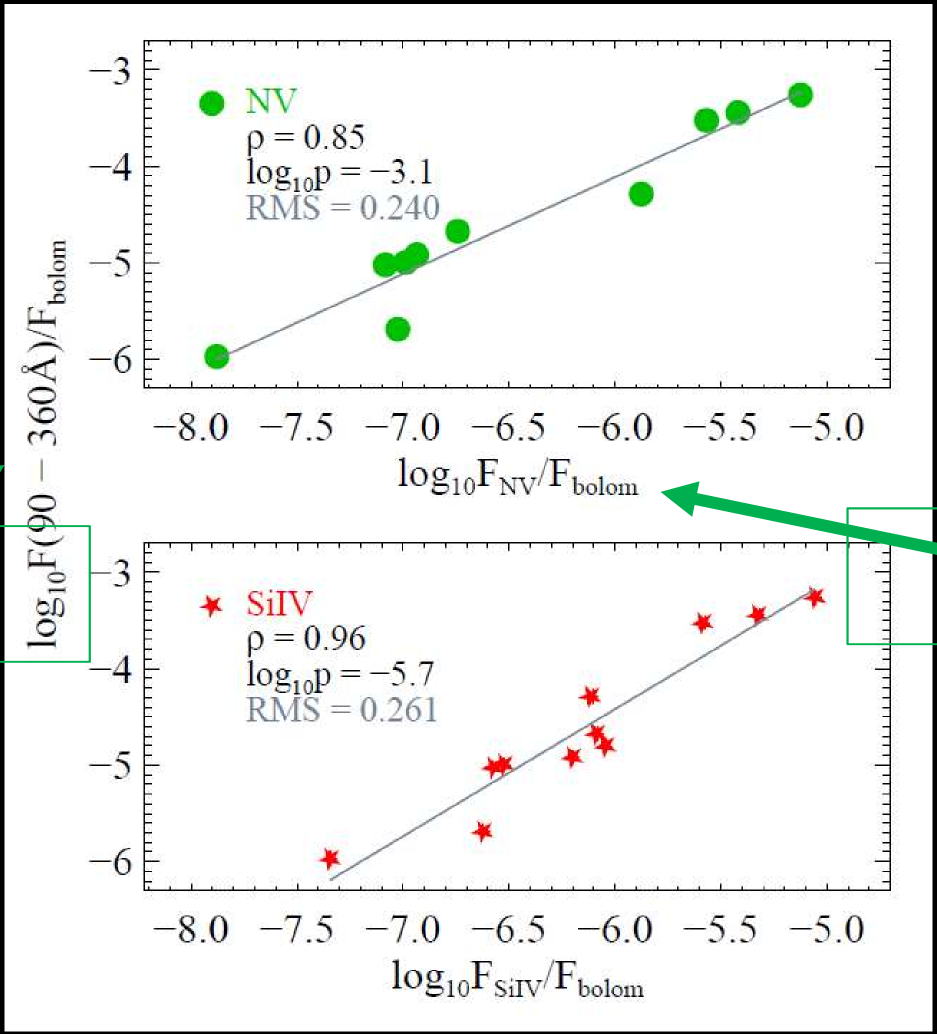
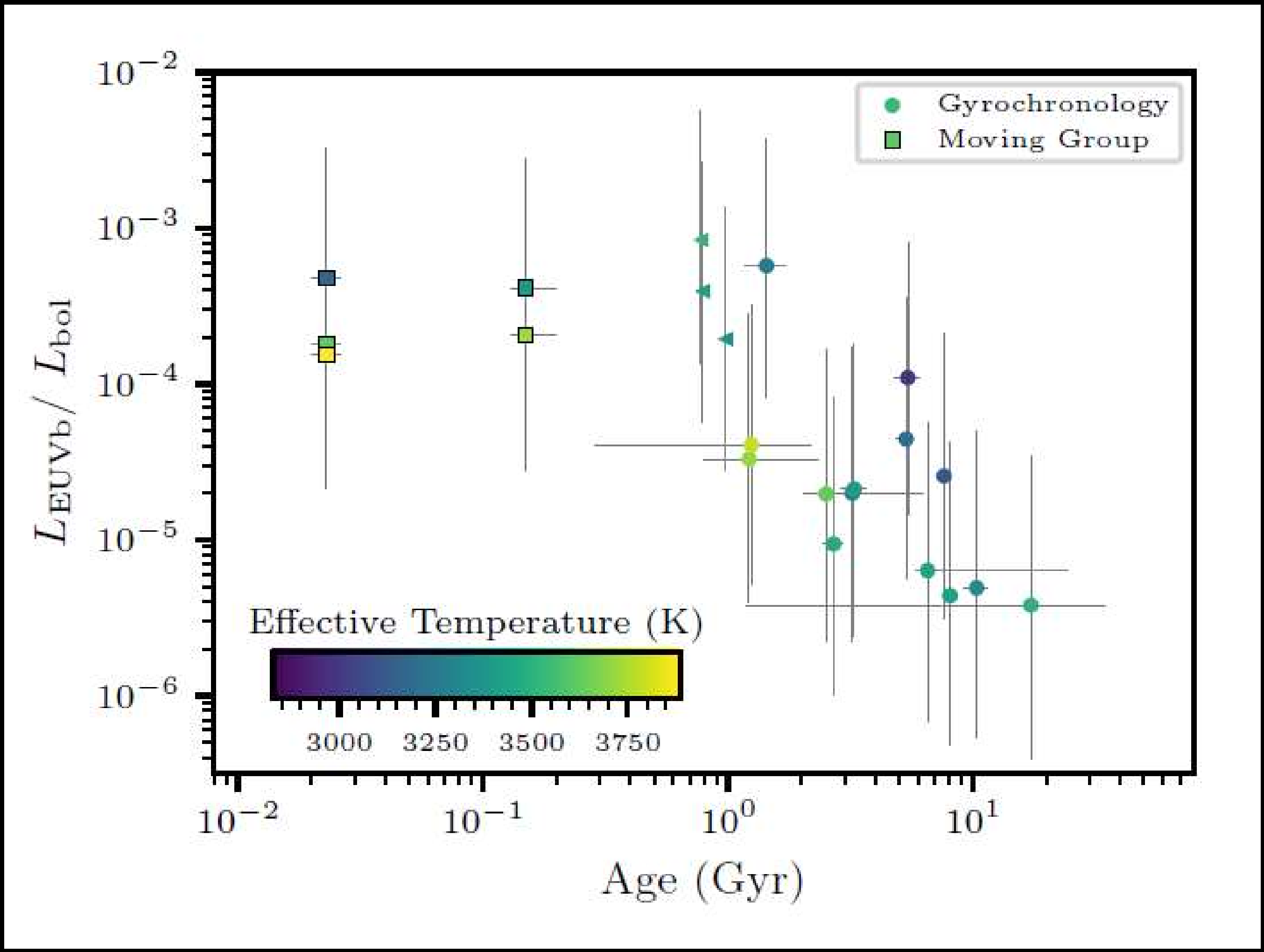


EUV: 9 – 36 nm
Mostly formed > 10^5 K

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)

Applying scaling relations: EUV evolution over lifetime of a planet



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

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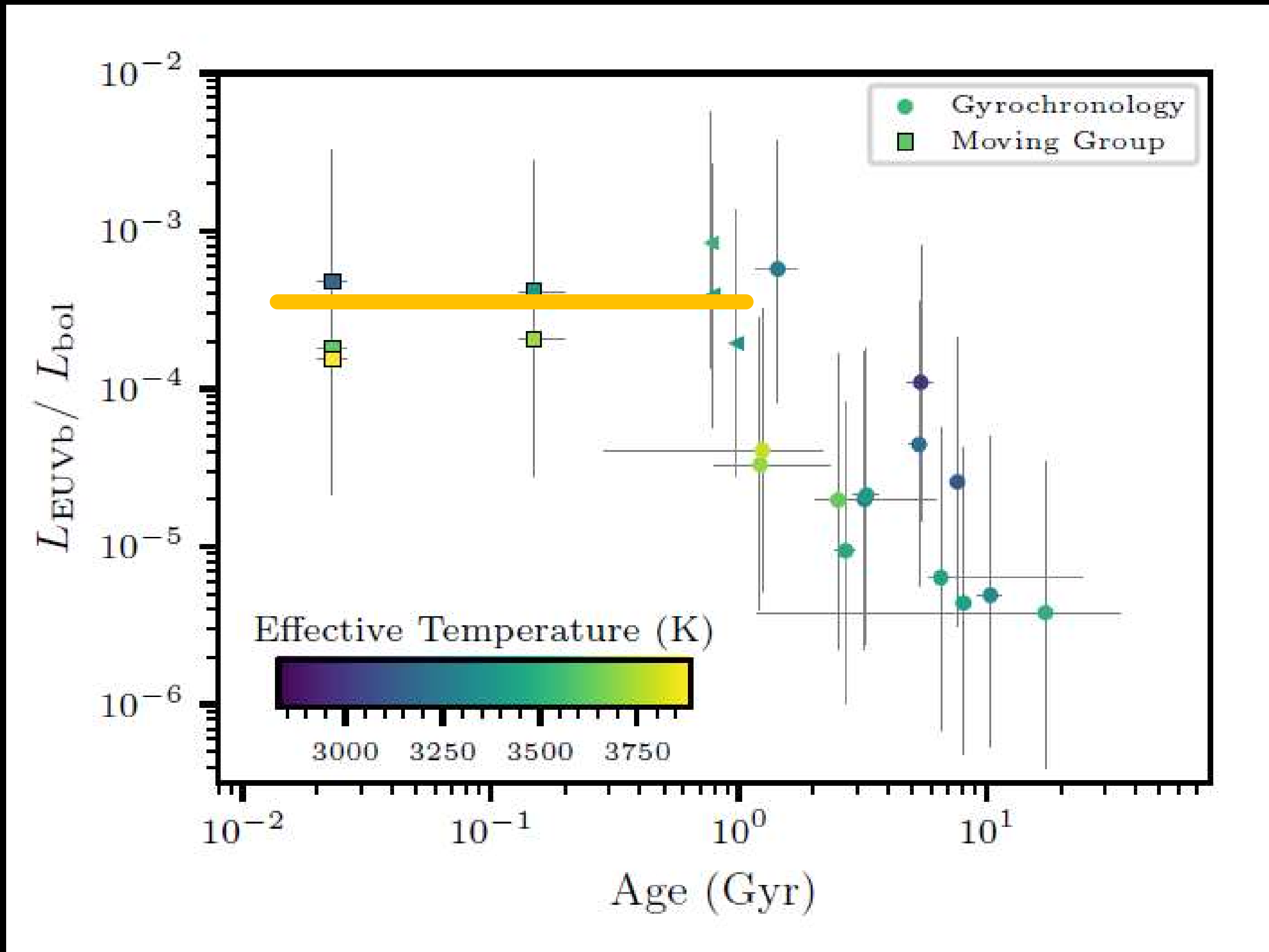

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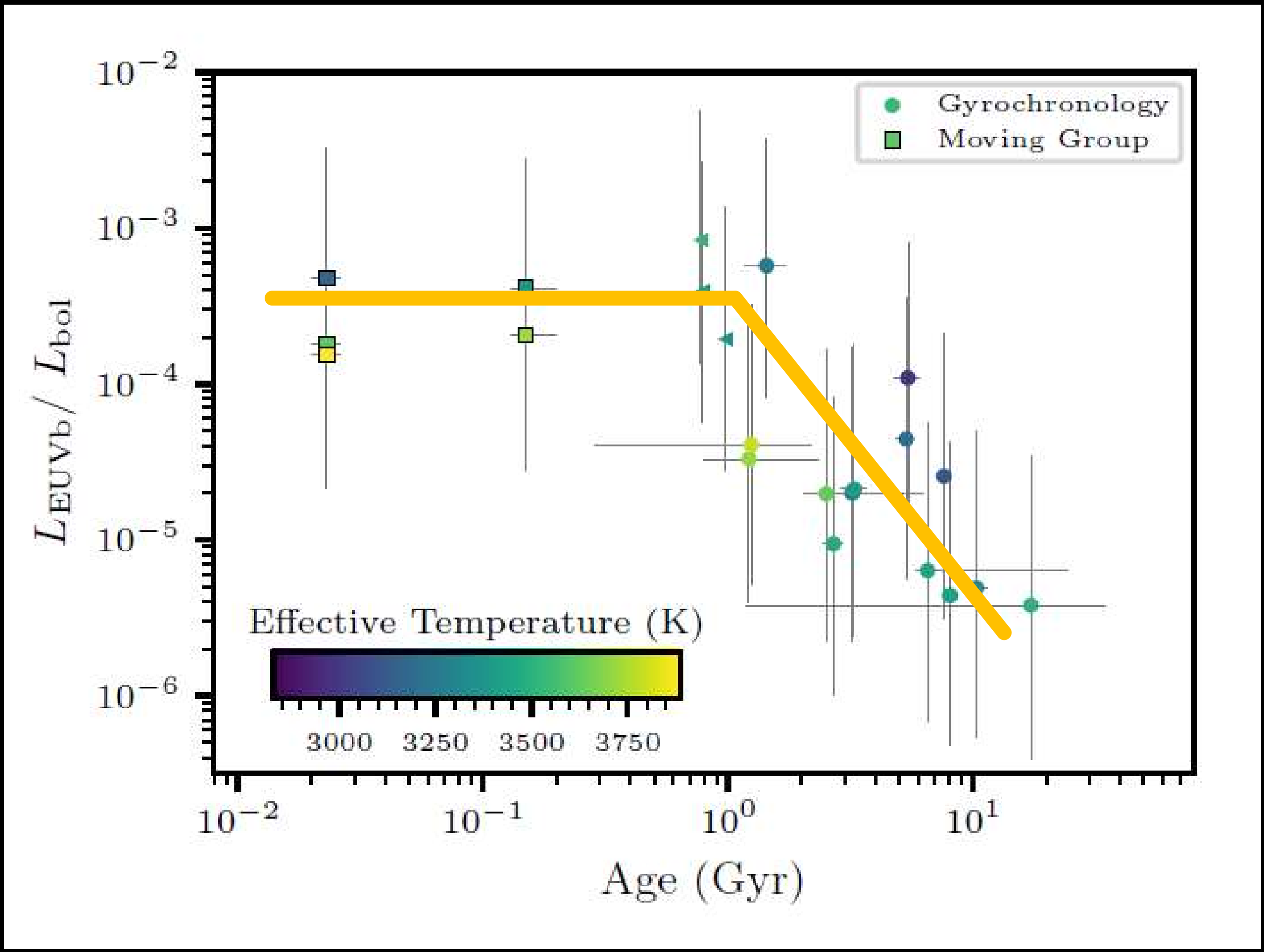

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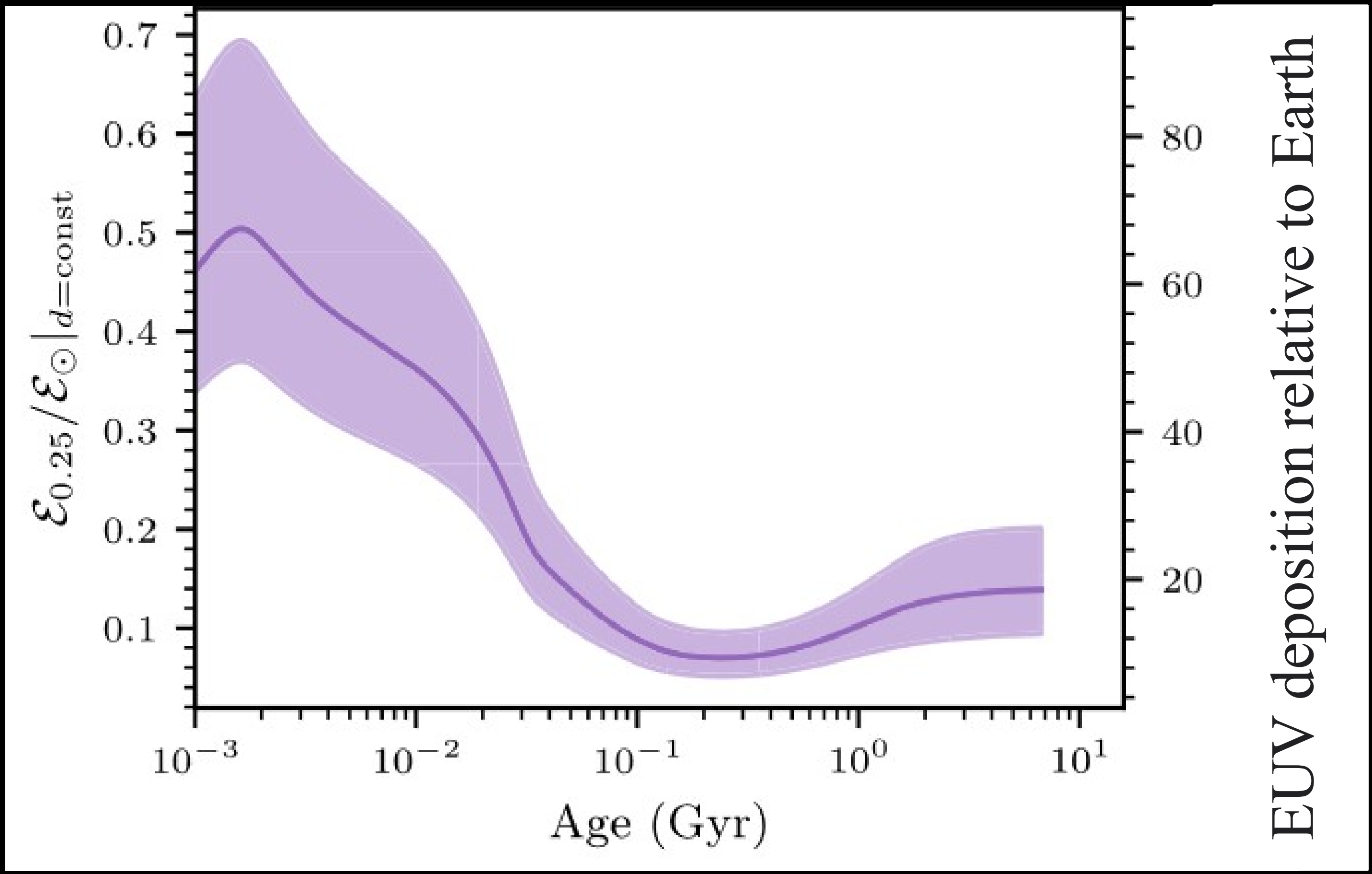

EUV irradiance deposition ratio in the Habitable Zone: mid-M dwarfs vs. solar-type stars

Pineda et al. (2021)

EUV and atmospheric stability:

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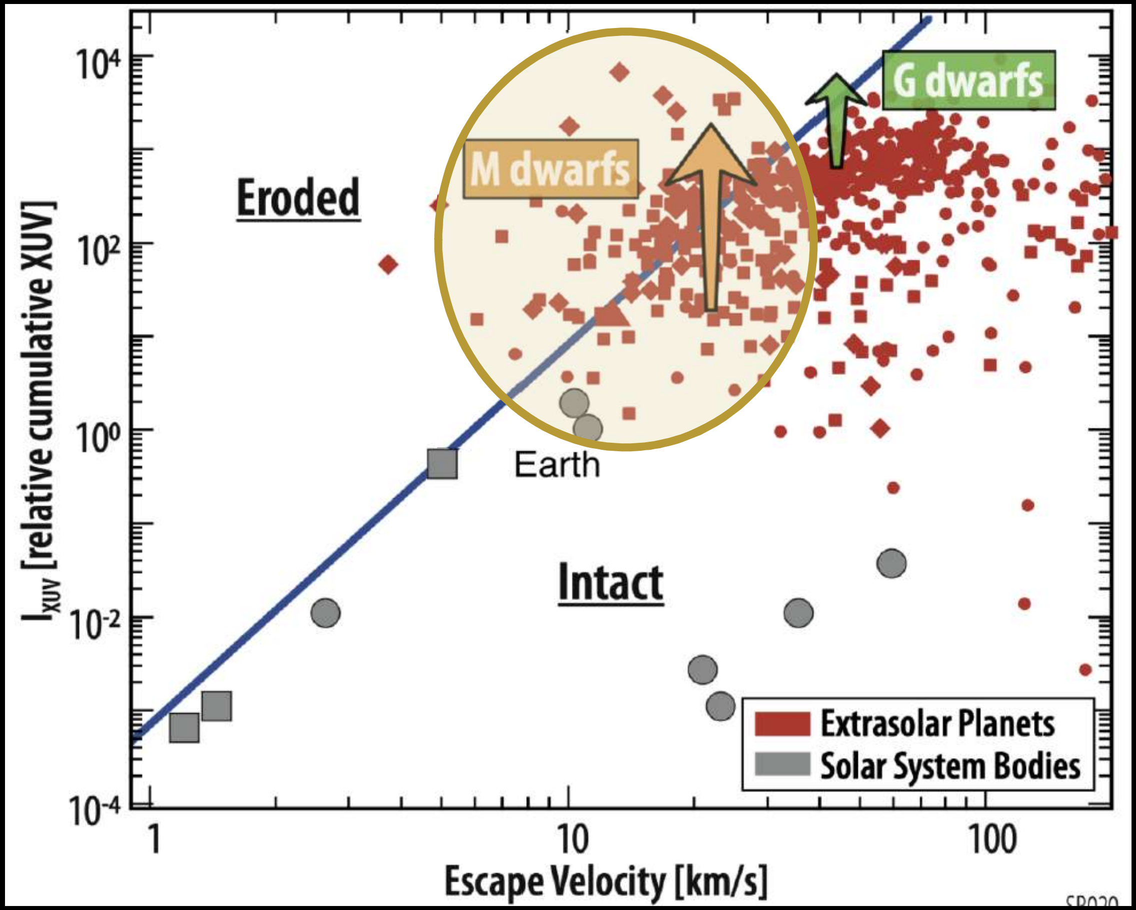

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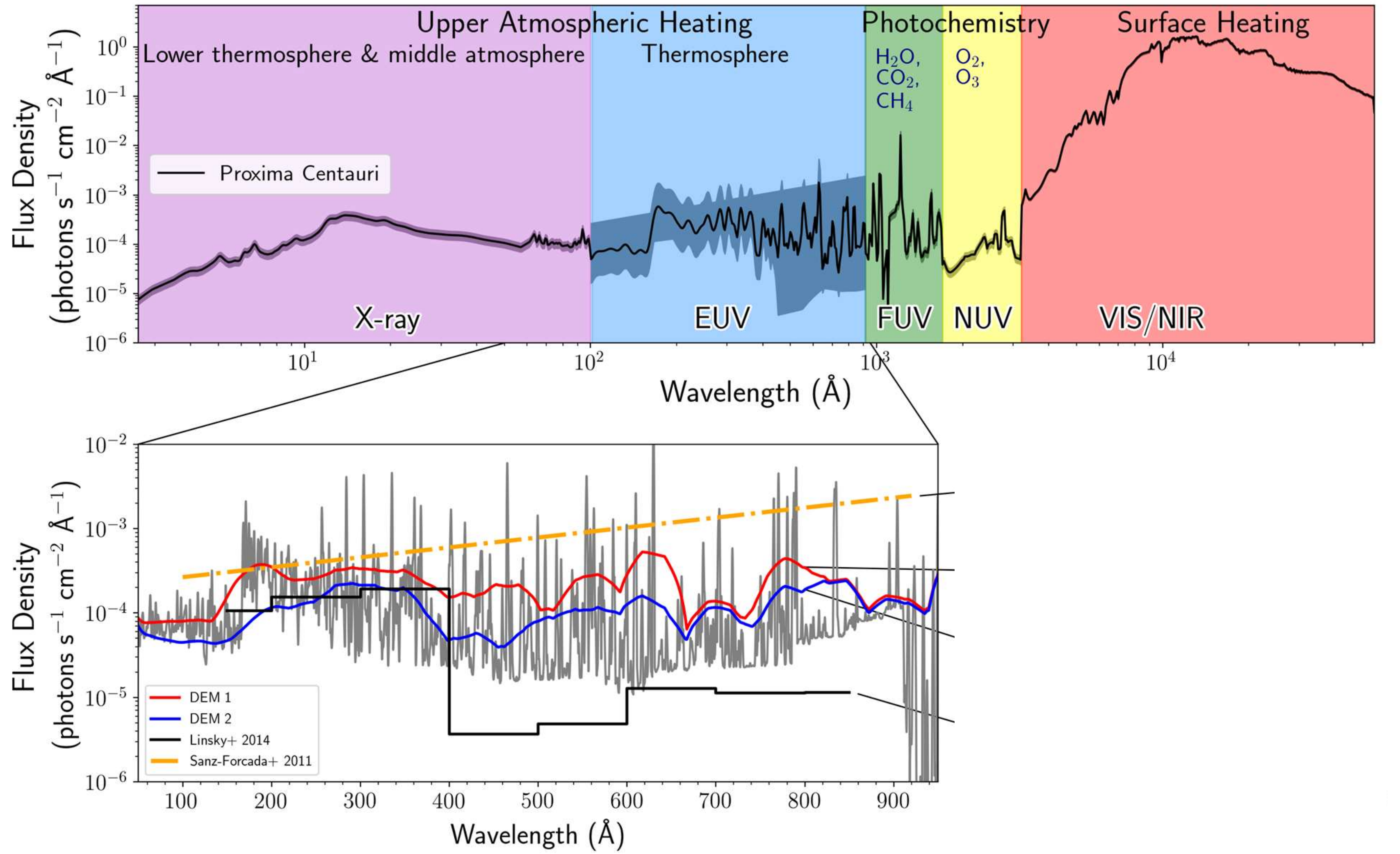
X-ray + EUV irradiance deposition ratio in the Habitable Zone: mid-M dwarfs vs. solar-type stars

EUV environment remains the key uncertainty for all F, G, K, M stars

Youngblood et al. (2019), France et al. (2022)



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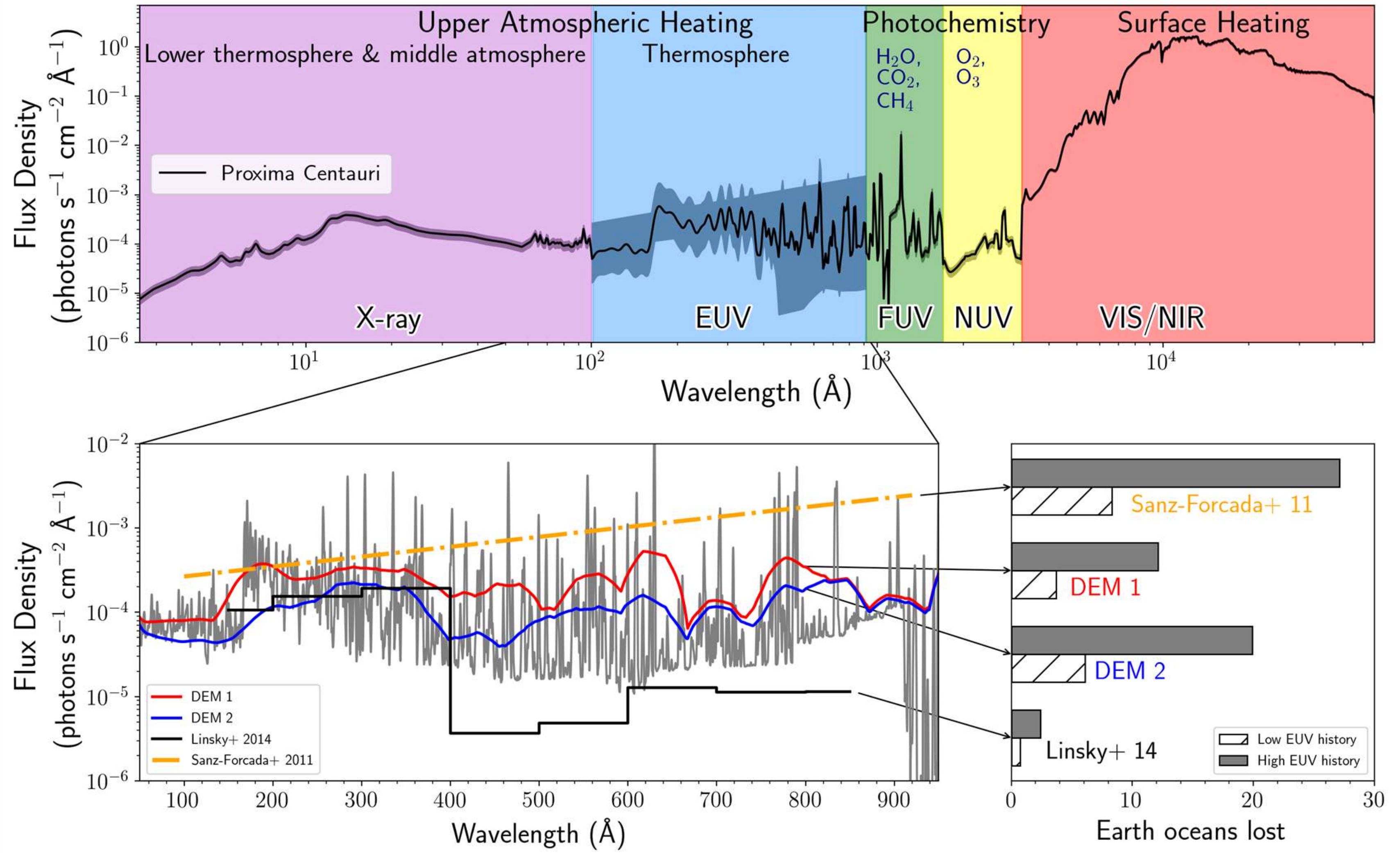
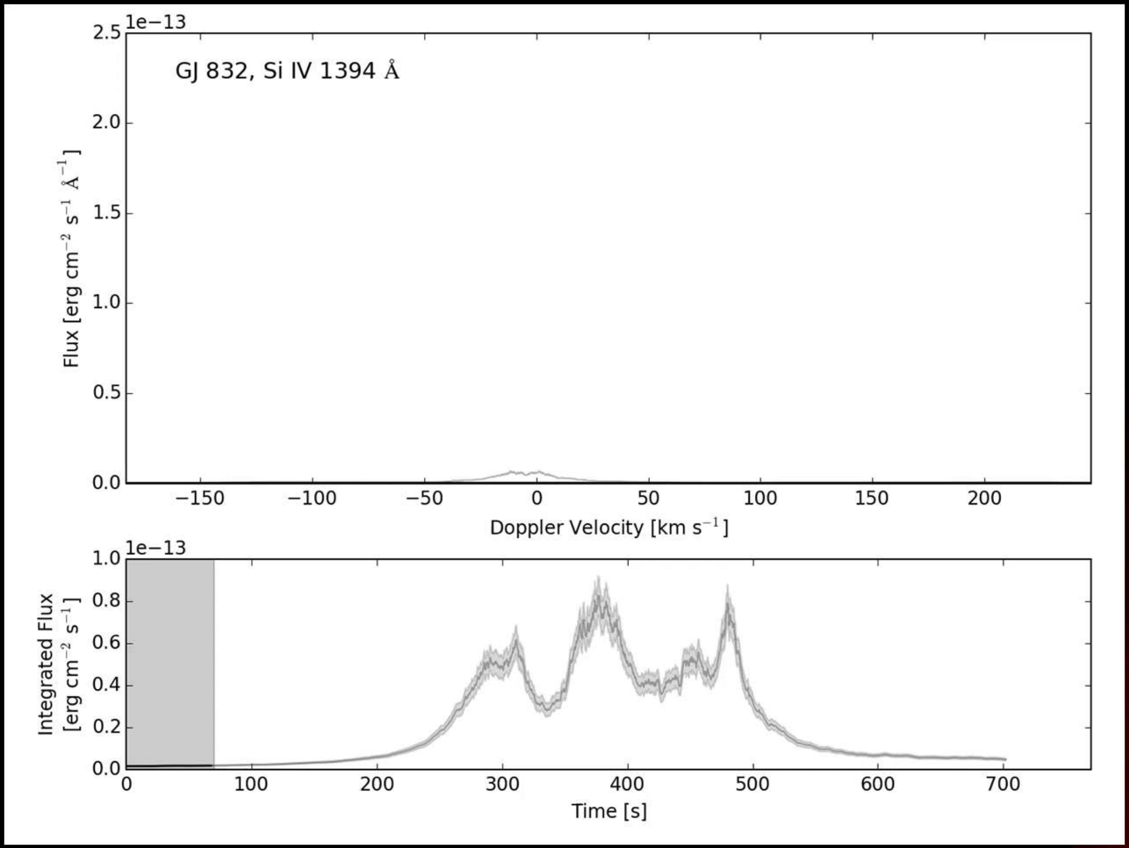
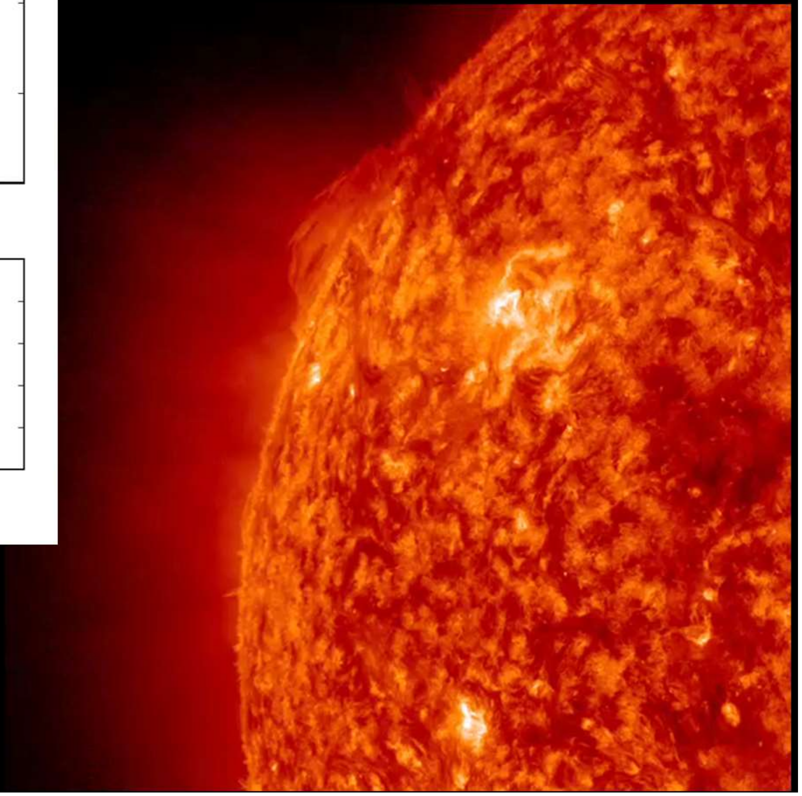


M dwarf EUV: Allison Youngblood - CU

UV variability on exoplanet host stars



Flares & CMEs



Loyd et al. (2018a)

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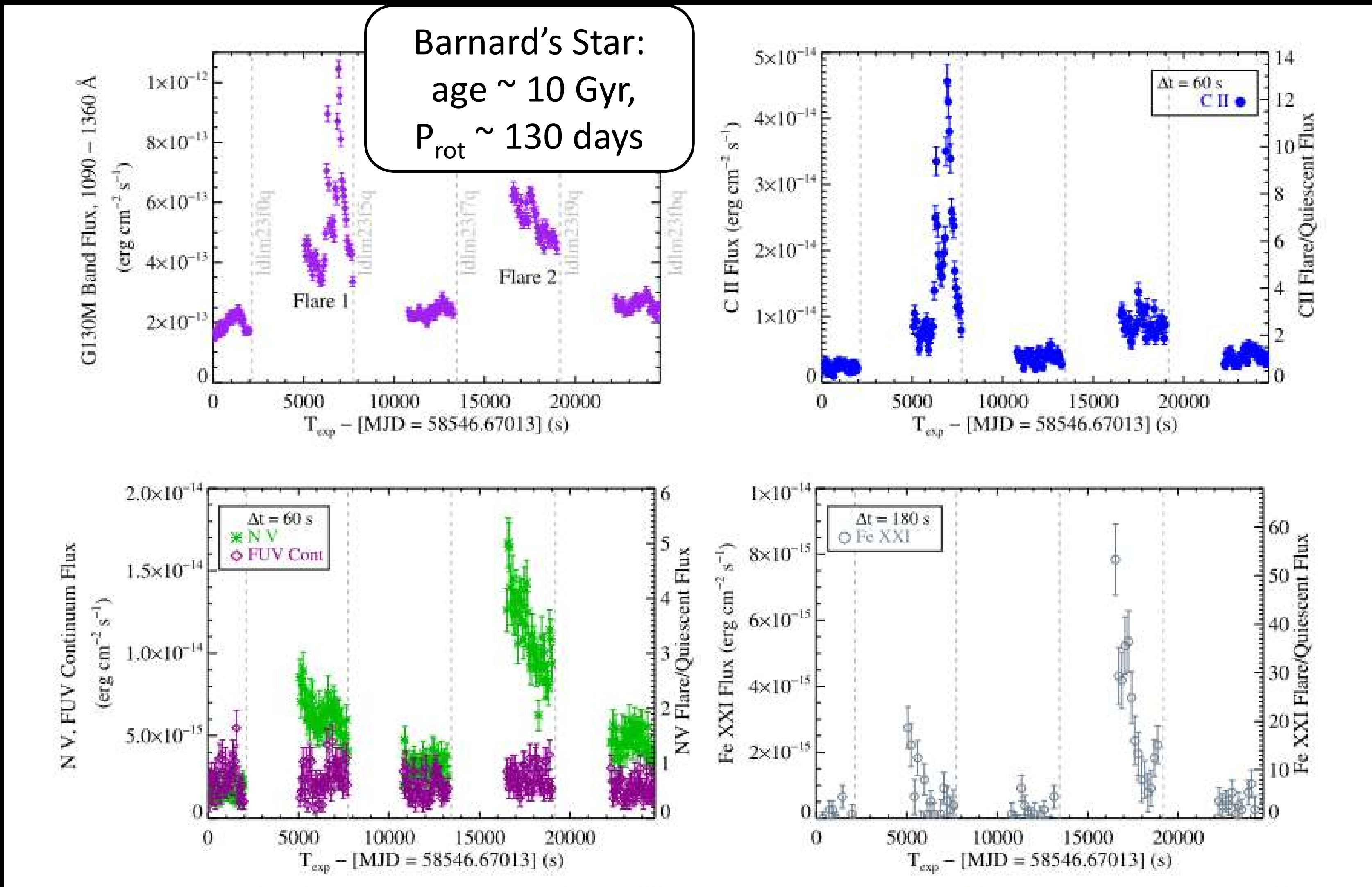
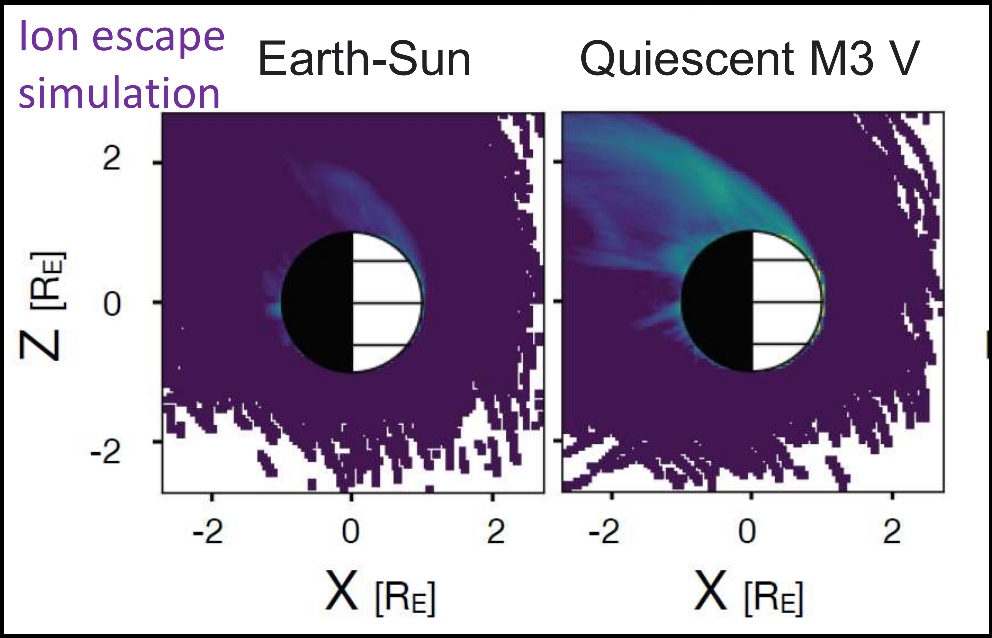


France et al. (2020)

Flare impacts on atmospheric escape



France et al. (2020)

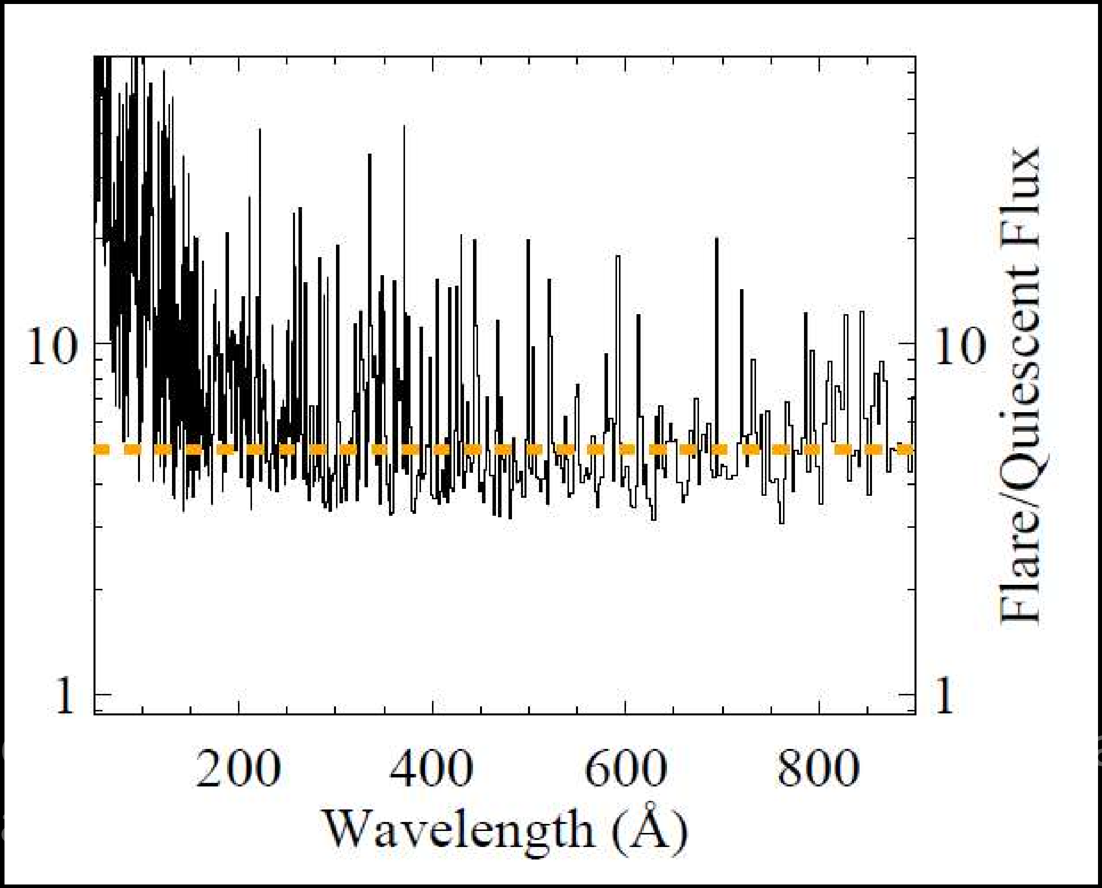
Consider an unmagnetized, but otherwise Earth-like planet, orbiting in the HZ (0.088 AU) of Barnard's Star (7 – 12 Gyr M3 star).

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

France et al. (2020)

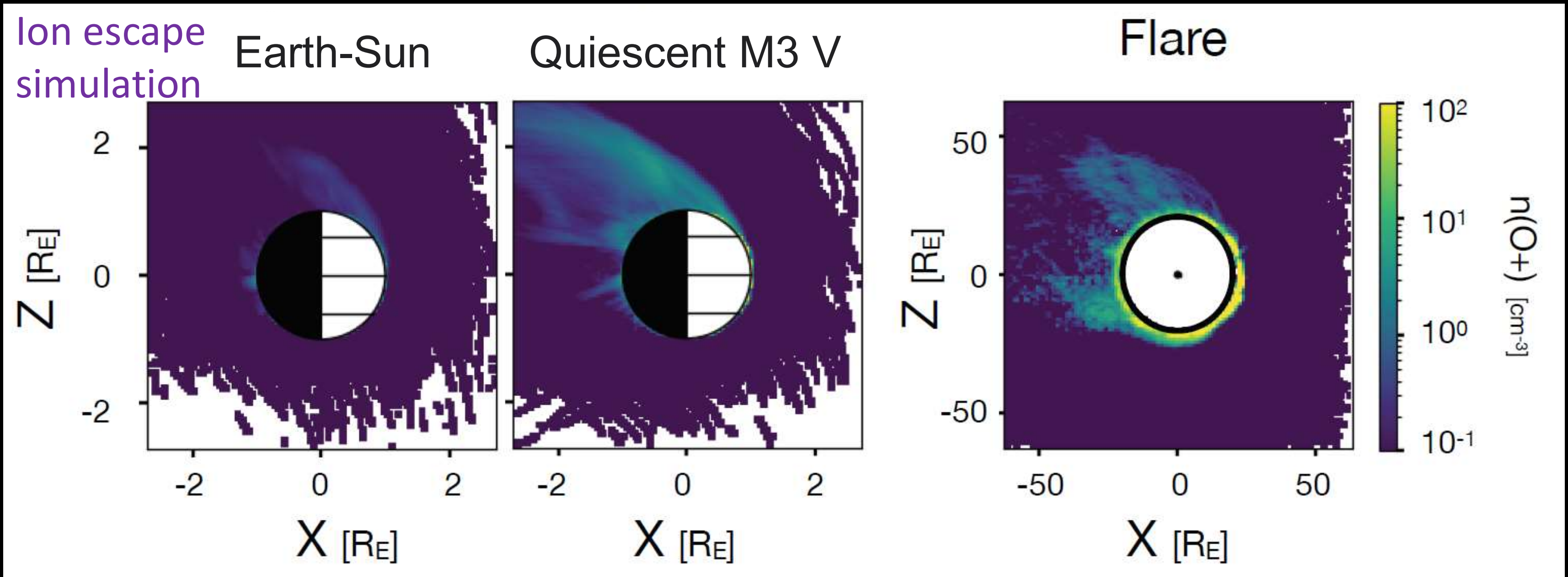


Atmosph… …anet at 1 AU equiv…

1. Quiescent high energy flux drives Earth-like escape rates
2. Computing the stellar EUV enhancement based on FUV and X-ray flare observations of Barnard's Star

Flare impacts on atmospheric escape

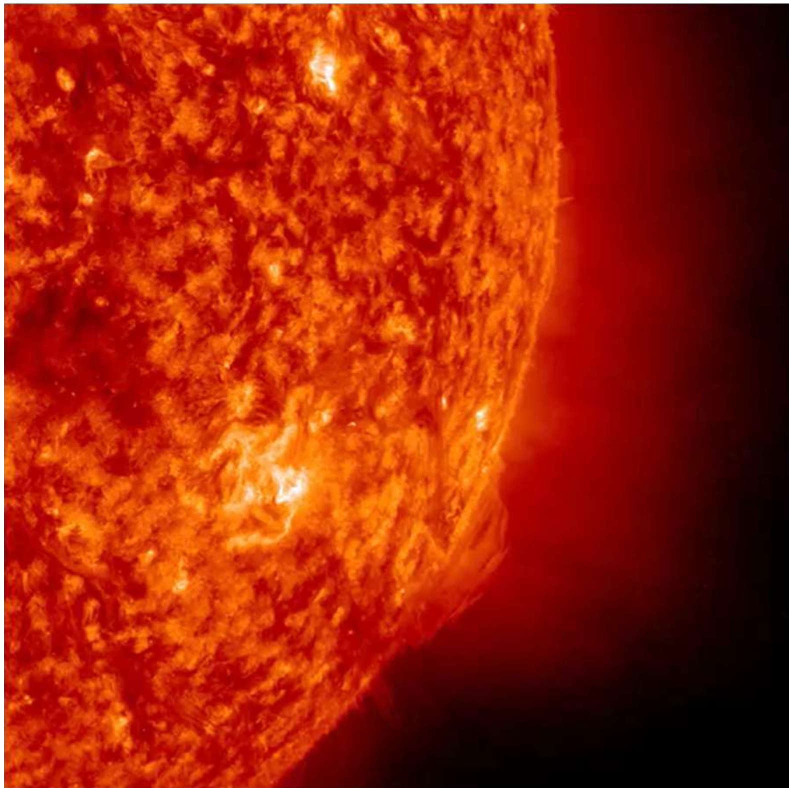
France et al. (2020)

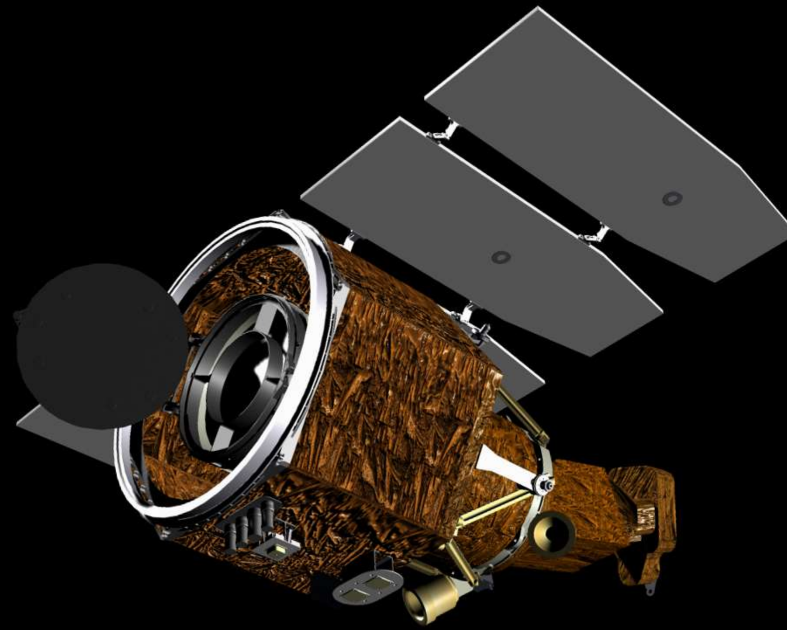


Atmospheric escape from hypothetical Earth-like planet at 1 AU equivalent from Barnard's Star:

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])



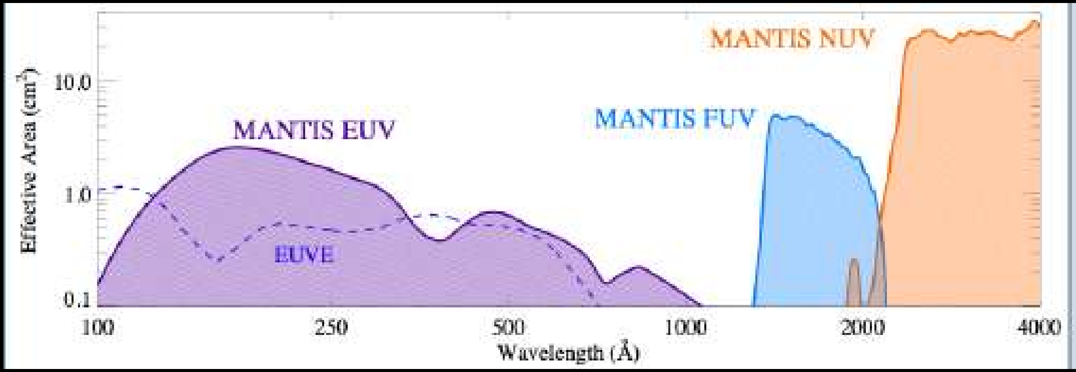


Future Observational Capabilities

Observing the unobserved EUV

The MANTIS SmallSat:

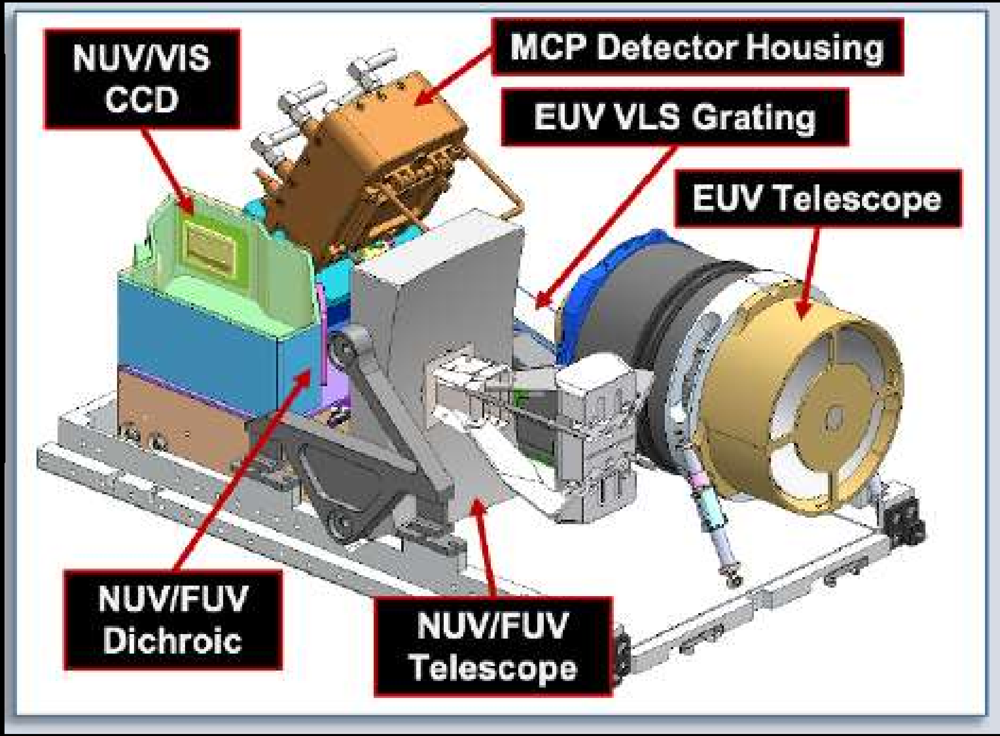
(Monitoring Activity of Nearby sTars with uv Imaging and Spectroscopy)



MANTIS includes 4 wavelength bands:

- -EUV spectroscopy (100 – 500 Å)
- -FUV photometry (1300 – 2000 Å)
- -NUV spectroscopy (2000 – 4000 Å)
- -Optical photometry (4000 – 9000 Å)

Selected by NASA,
project starts late-2023



The MANTIS SmallSat:

(Monitoring Activity of Nearby sTars with uv Imaging and Spectroscopy)

NASA 12U Cubesat (PI: Briana Indahl, CU/LASP):

Two science surveys:

1. Nearby star survey
2. JWST UV Monitoring Program

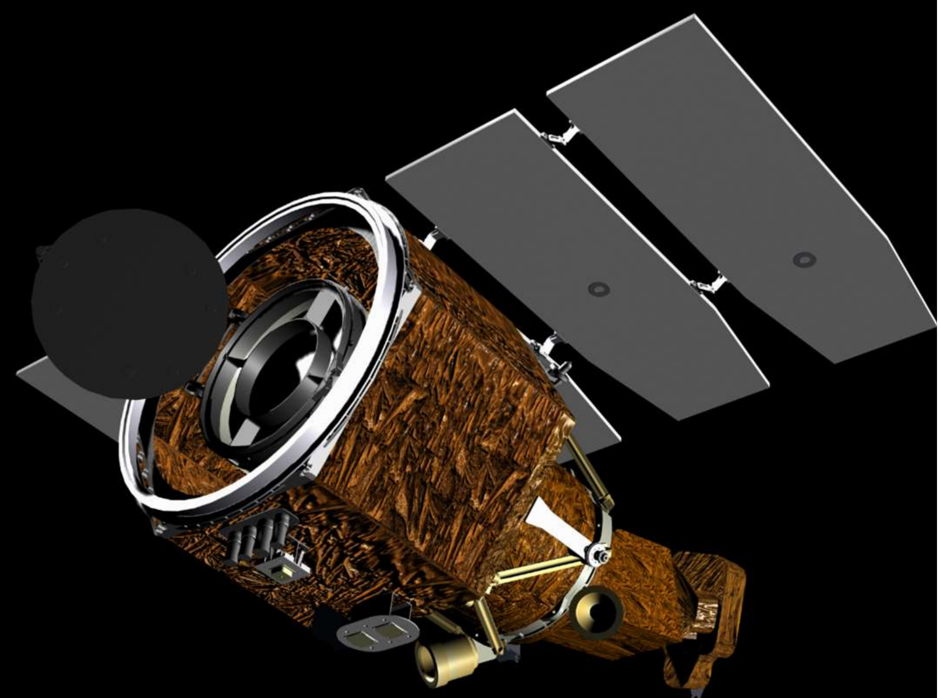
- Launch in 2026/2027 for a 12 month baseline mission

- Science team a collaboration between CU/LASP, INAF, STScI, GSFC, Univ Hamburg, Univ Leiden, Penn State, U of Arizona, U of Maryland

NASA Small Explorer mission
2020 Phase A selection

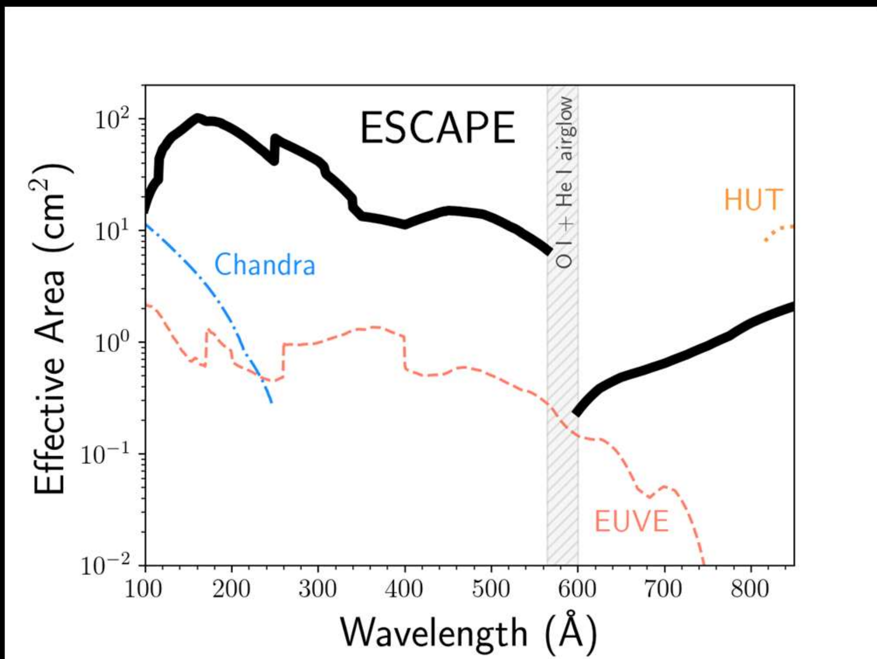
EUV & FUV (80 – 1650 Å) spectroscopy of > 200 stars, spectral types F - M

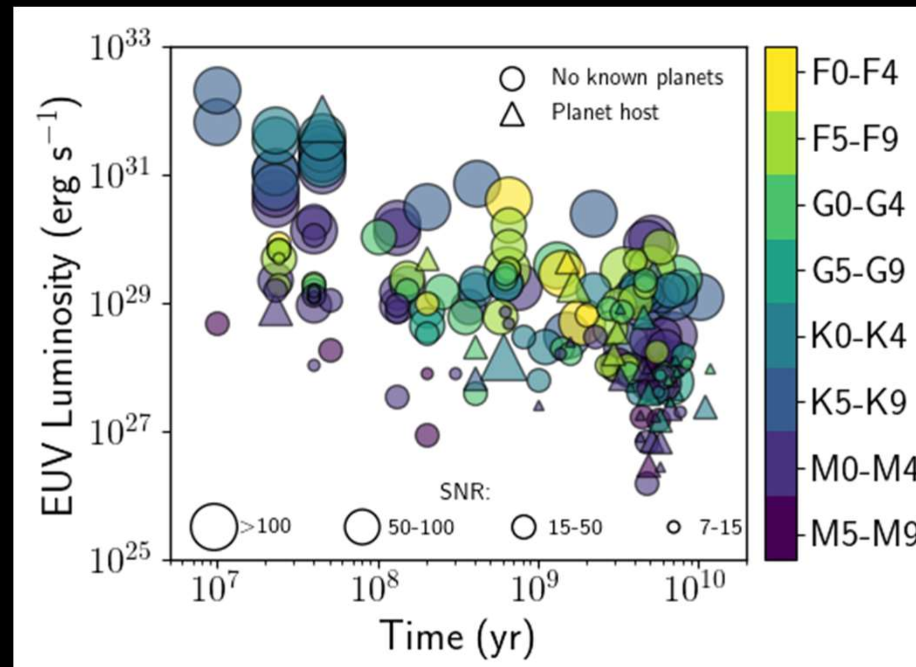
Deep monitoring observations of 30 targets of interest for flare and CME frequency distributions



The ESCAPE Small Explorer Mission

(Euv Stellar Characterization for Atmospheric Physics and Evolution)





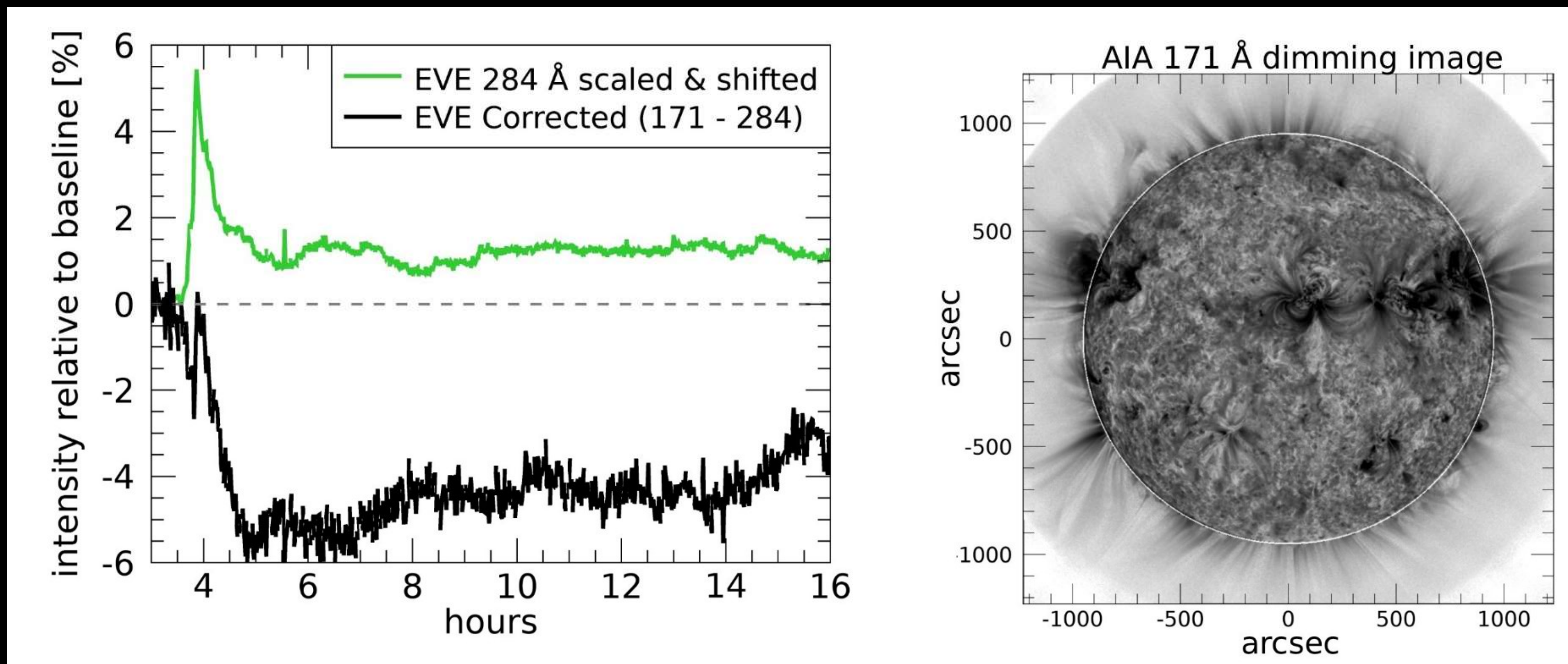
> 50 x EUV sensitivity vs. EUVE & Chandra enables:

- First statistical study of EUV irradiance on planet-hosting stars
- EUV variability on flare, rotational, and evolutionary timescales

France et al. (2019,2022)

The ESCAPE Small Explorer Mission

(Euv Stellar Characterization for Atmospheric Physics and Evolution)



> 50 x EUV sensitivity vs. EUVE & Chandra enables:

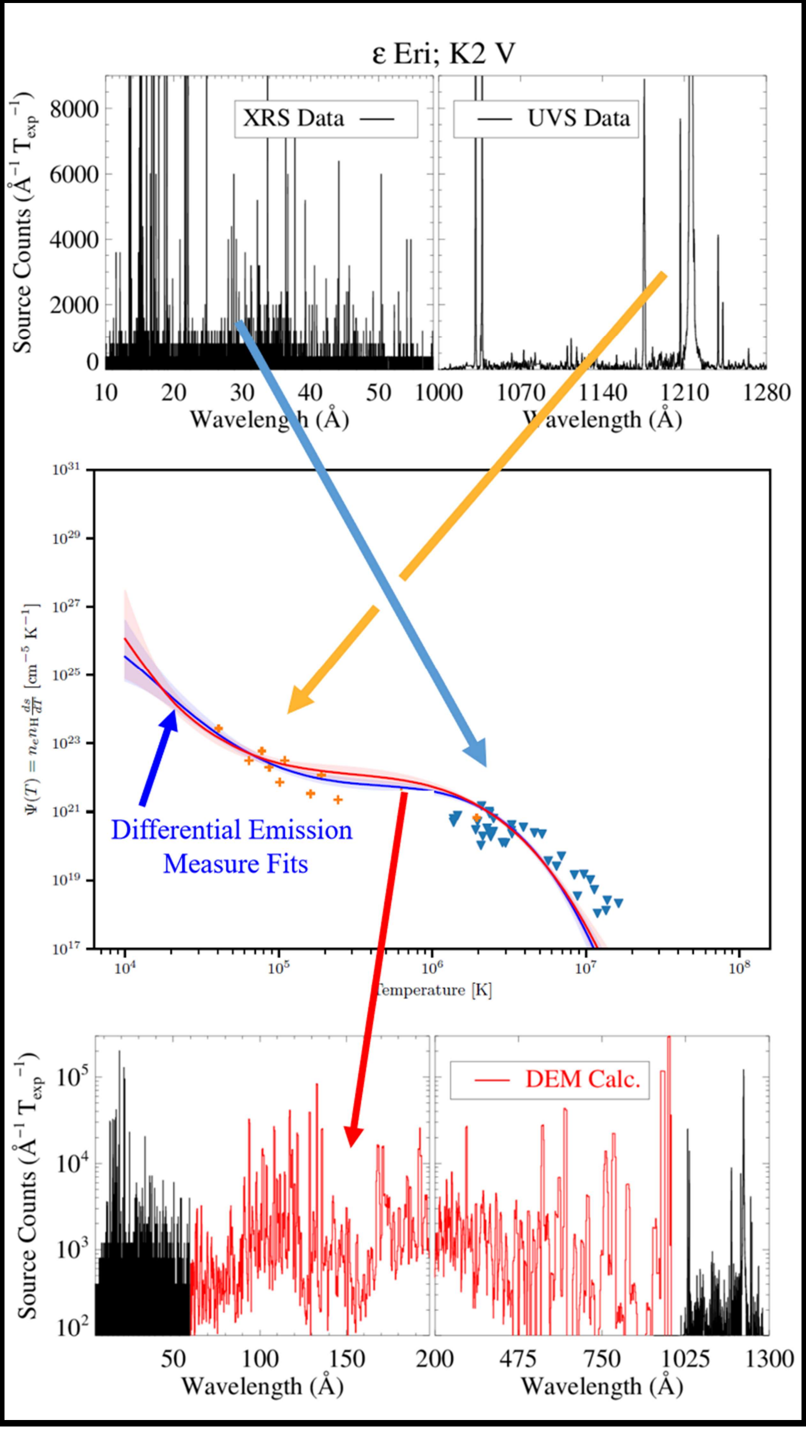
- CME frequency distribution via coronal dimming (10 – 15 F, G, K, and M stars)
- CME kinetic energy for brightest stars

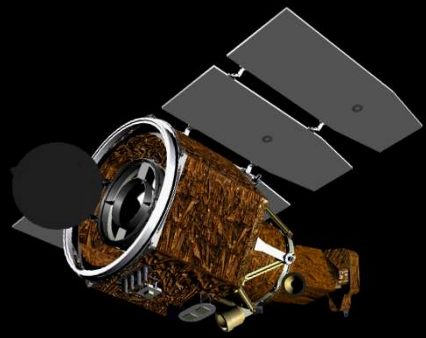
France et al. (2022; adapted from Mason et al. 2016)

Arcus Probe: Simultaneous X-ray + FUV spectroscopy

To be submitted to NASA Probe opportunity in November 2023
(PI – Randall Smith, CfA/SAO;
UV instrument, KF, CU/LASP)

- Simultaneous 10-60Å & 970-1580Å
- *Resolving Power* = 3500 & 24000
- High-sensitivity for high temporal cadence observations
- DEM calculations using high-S/N, high-resolution X-ray and FUV emission lines are likely our next best approach to stellar EUV fluxes





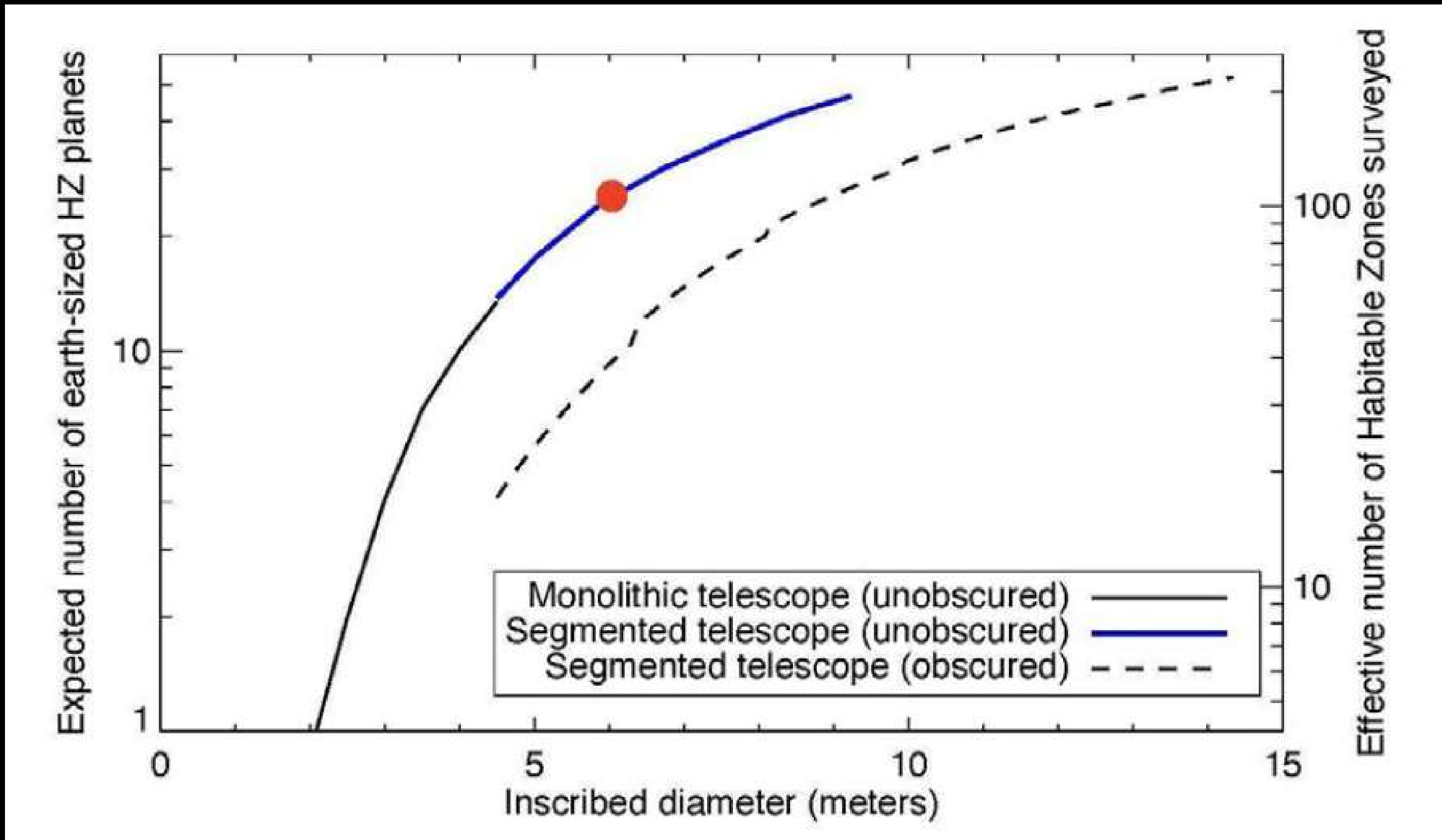
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**
kevin.france@colorado.edu

Summary:

1) EUV inputs drive atmospheric heating and evolution of (exo)planetary atmospheres
   - JWST sensitive to M dwarf planets. Habitable zones are close in.
   - Scaling relations for the EUV, some semi-empirical model work
   - Lack of observational constraints on EUV → greatest stellar input uncertainty

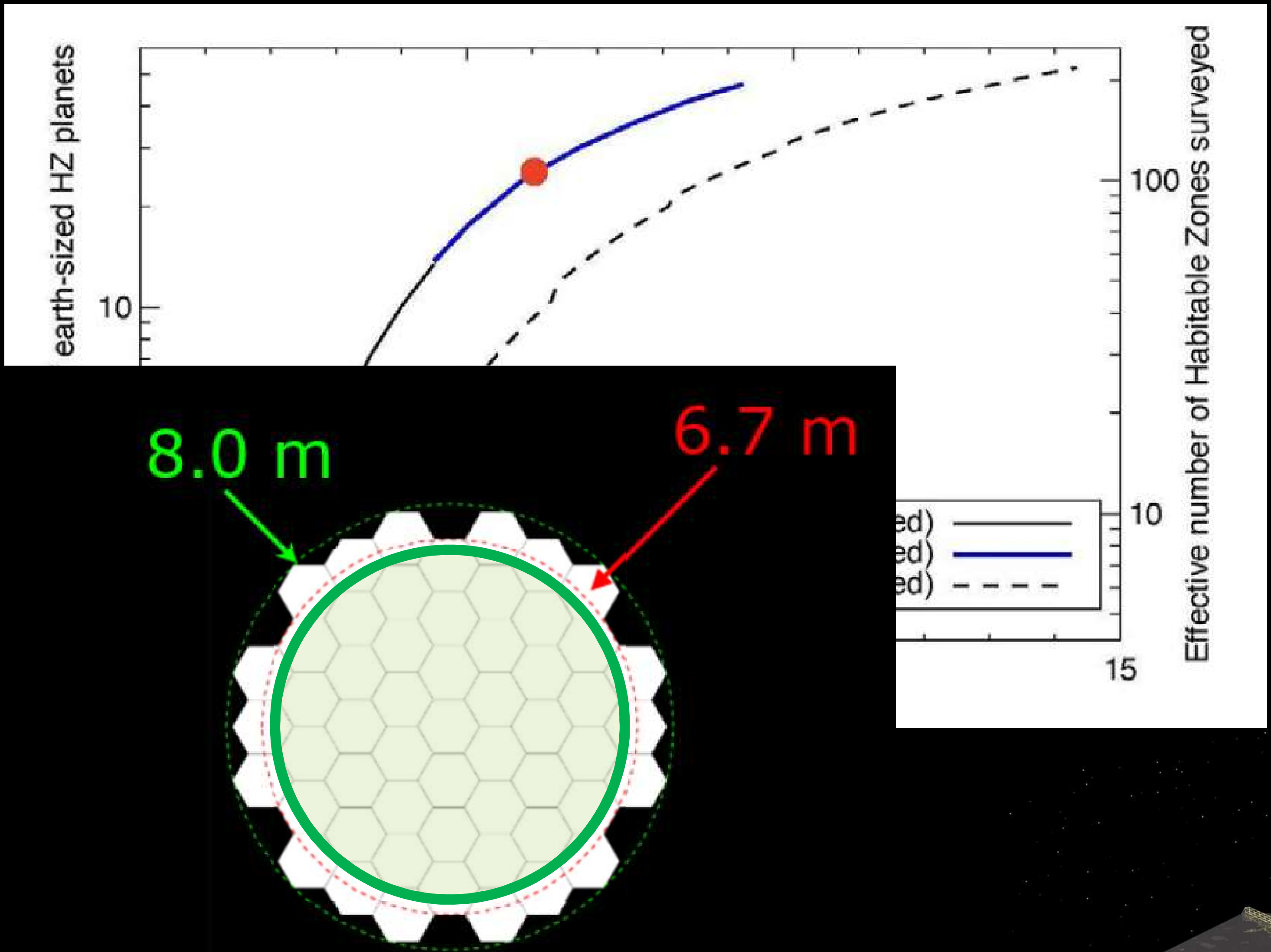
2) UV and X-ray flares are frequent, even on "inactive" M dwarfs;
   - Flares may push terrestrial planets into hydrodynamic escape regime around M dwarfs

3) Future observatories: Need to fill in the EUV gap in our electromagnetic understanding of stars

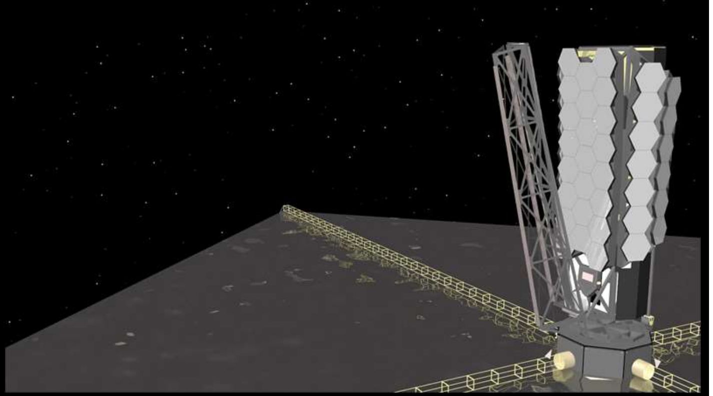


2020 DECADAL SURVEY REPORT: "THE SURVEY RECOMMENDS THAT THE FIRST MISSION TO ENTER THIS PROGRAM IS A LARGE (~6 M APERTURE) INFRARED/OPTICAL/ULTRAVIOLET (IR/O/UV) SPACE TELESCOPE."

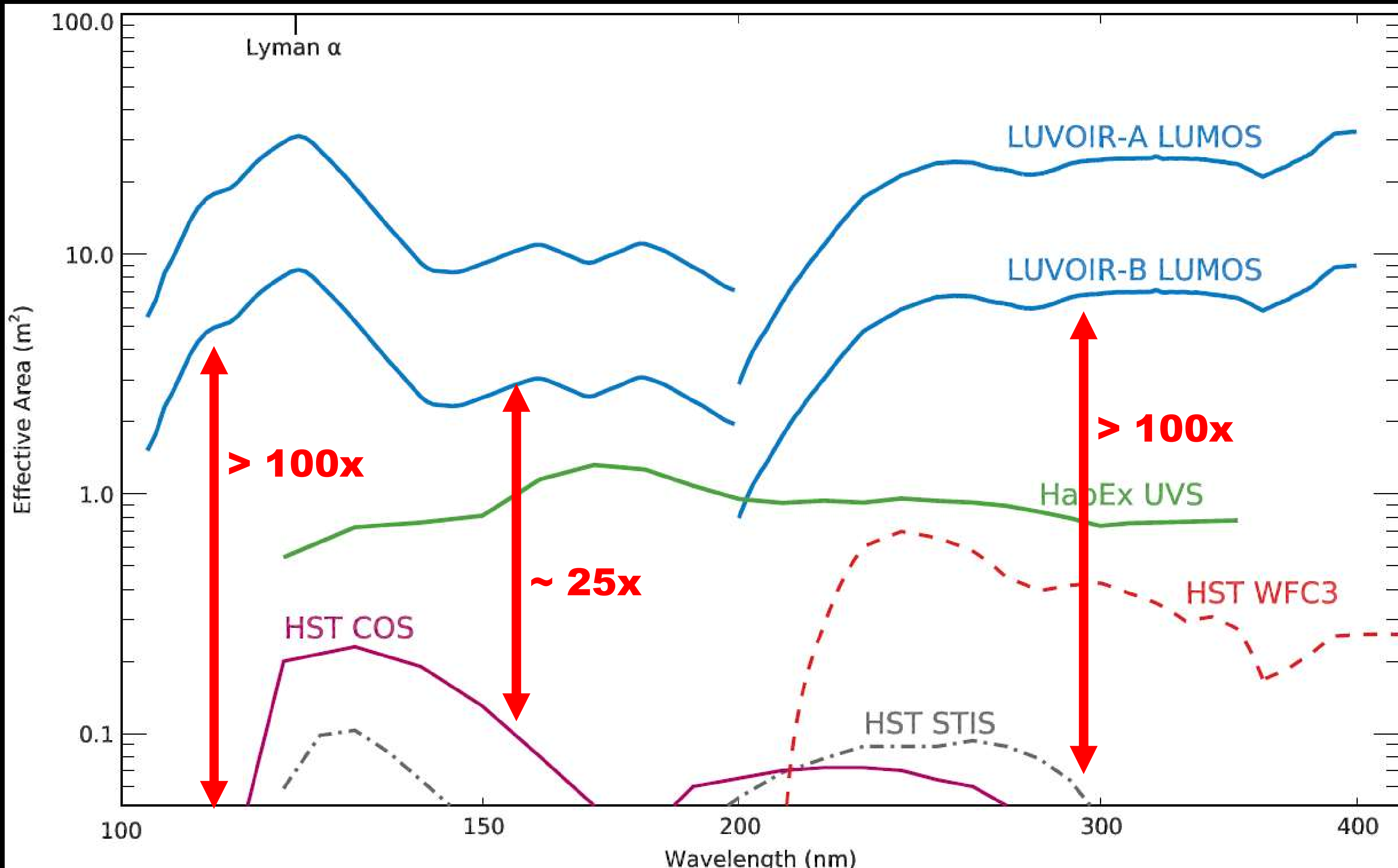
THE "L" IS FOR LARGE, ≥ 6 M INSCRIBED



LUVOIR-B

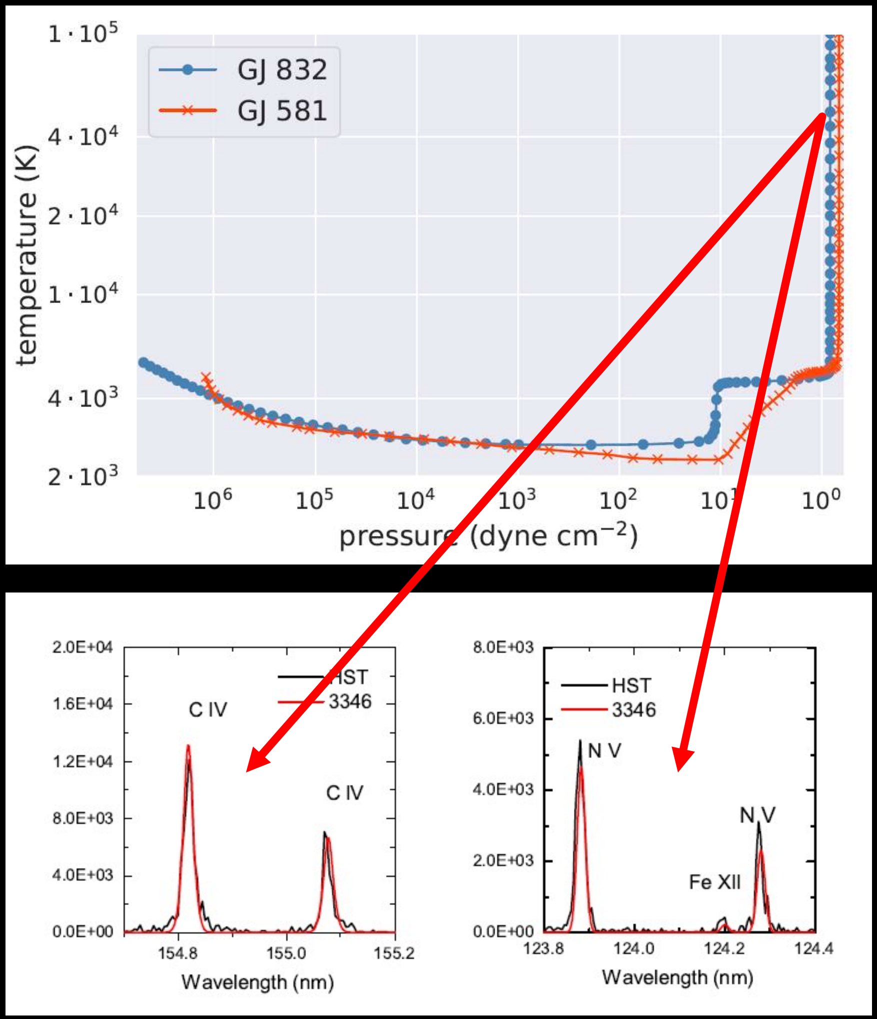


Approximate Habitable Worlds Observatory Performance



Courtesy of Eric Lopez, NASA/GSFC

Model Atmospheres: Spectral Synthesis Irradiance Codes for Full X-ray to IR



Fontenla et al. 2016, Peacock et al. 2019
(recent student papers - Tilipman et al. 2021; Duvvuri et al. 2021)

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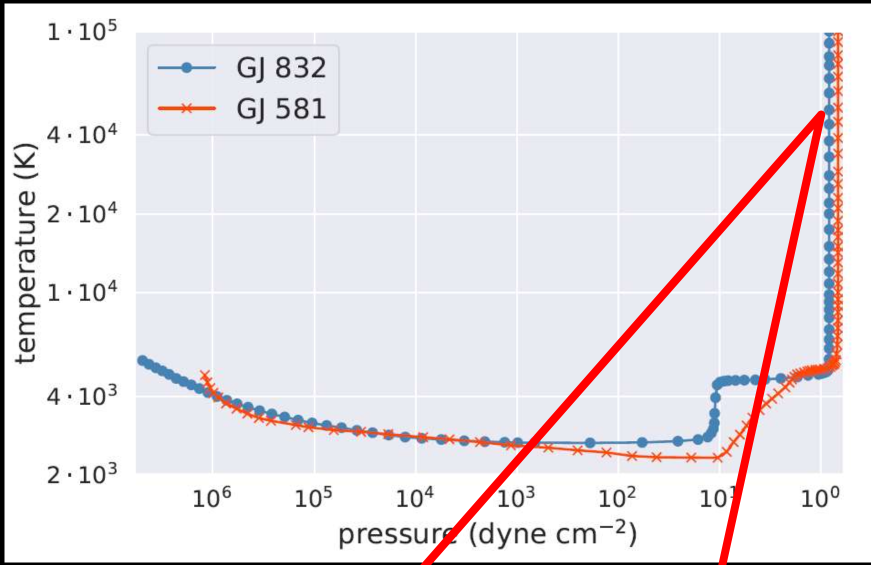
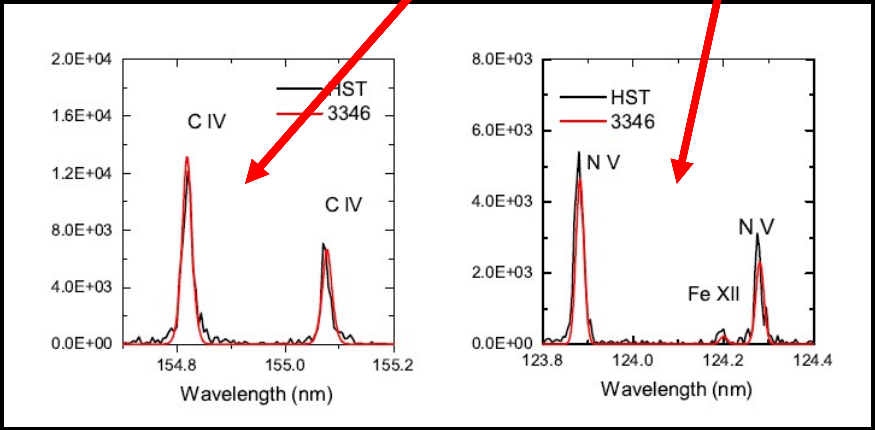
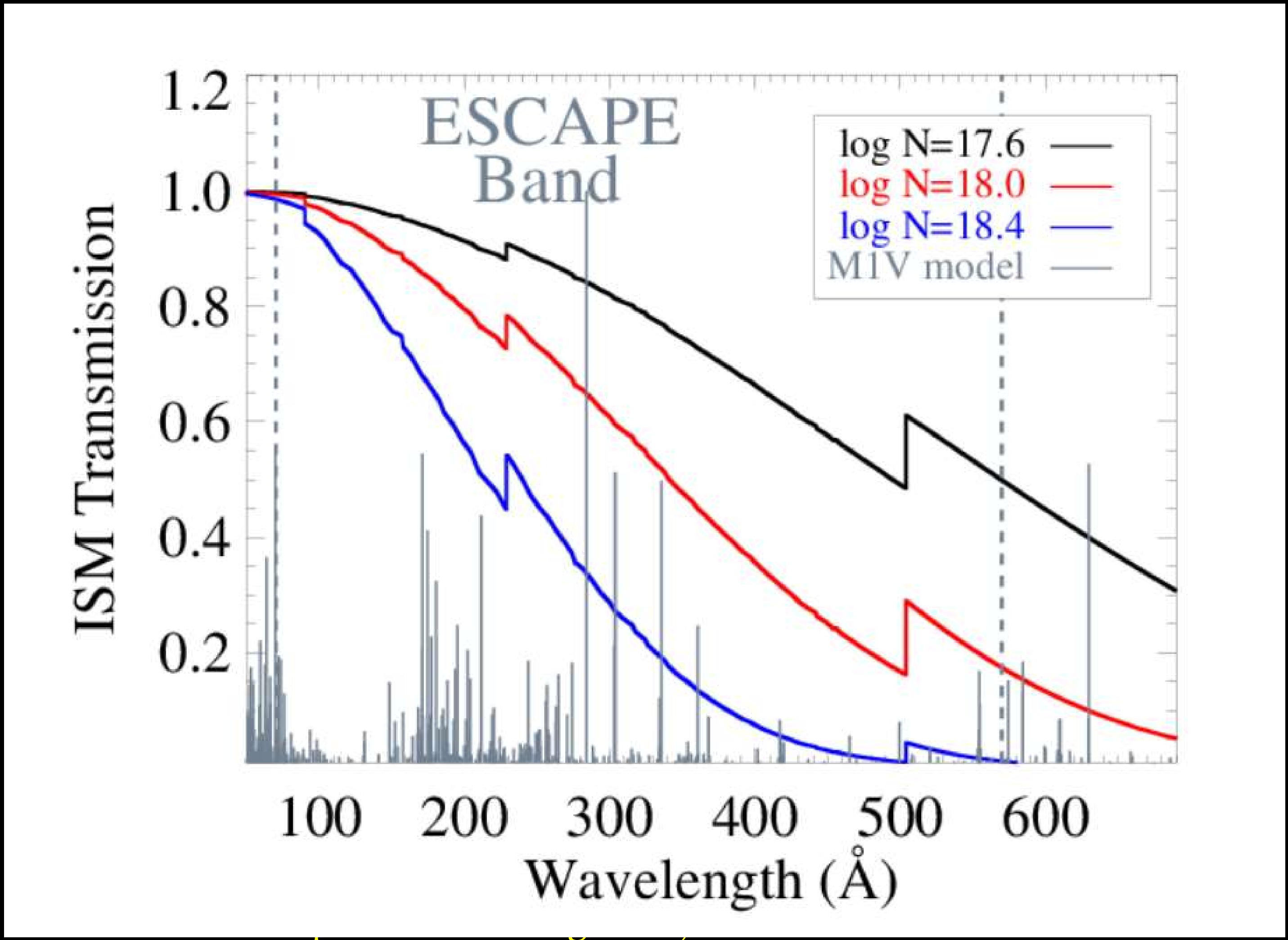




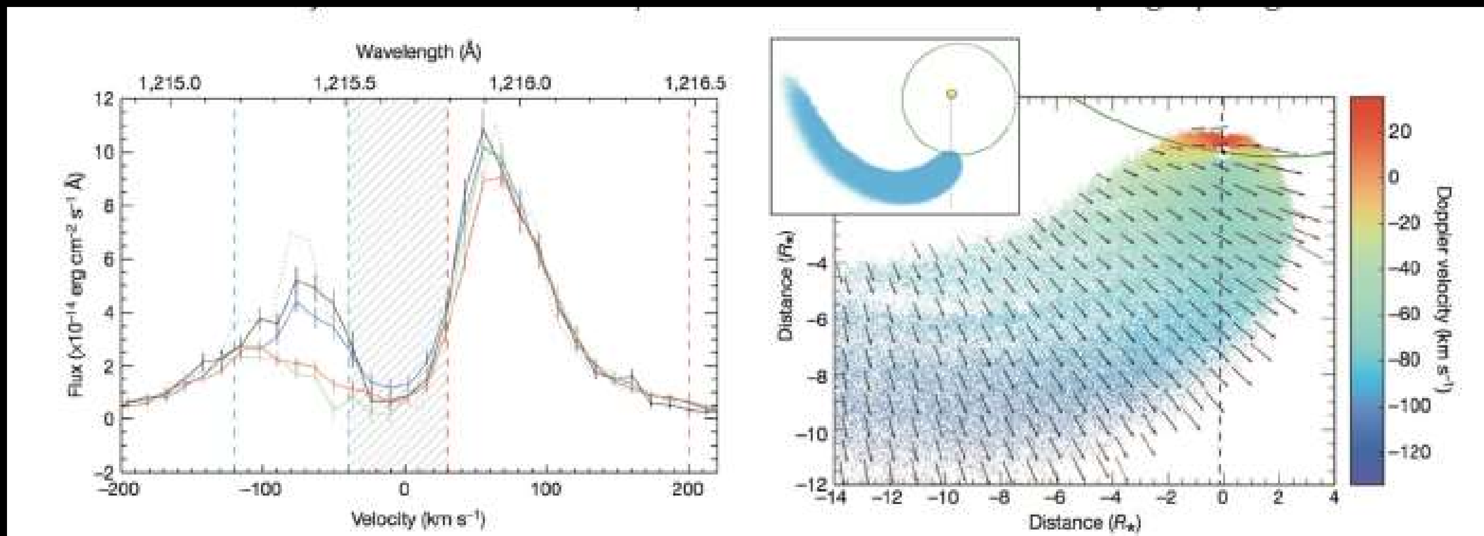
Important EUV calculations from Sanz-Forcada et al. papers, Vienna group (numerous Johnstone papers), and Warwick group (King et al. and Louden et al. papers).

Fontenla et al. 2016, Peacock et al. 2019
(recent student papers - Tilipman et al. 2021; Duvvuri et al. 2021)

Don't Fear the LISM

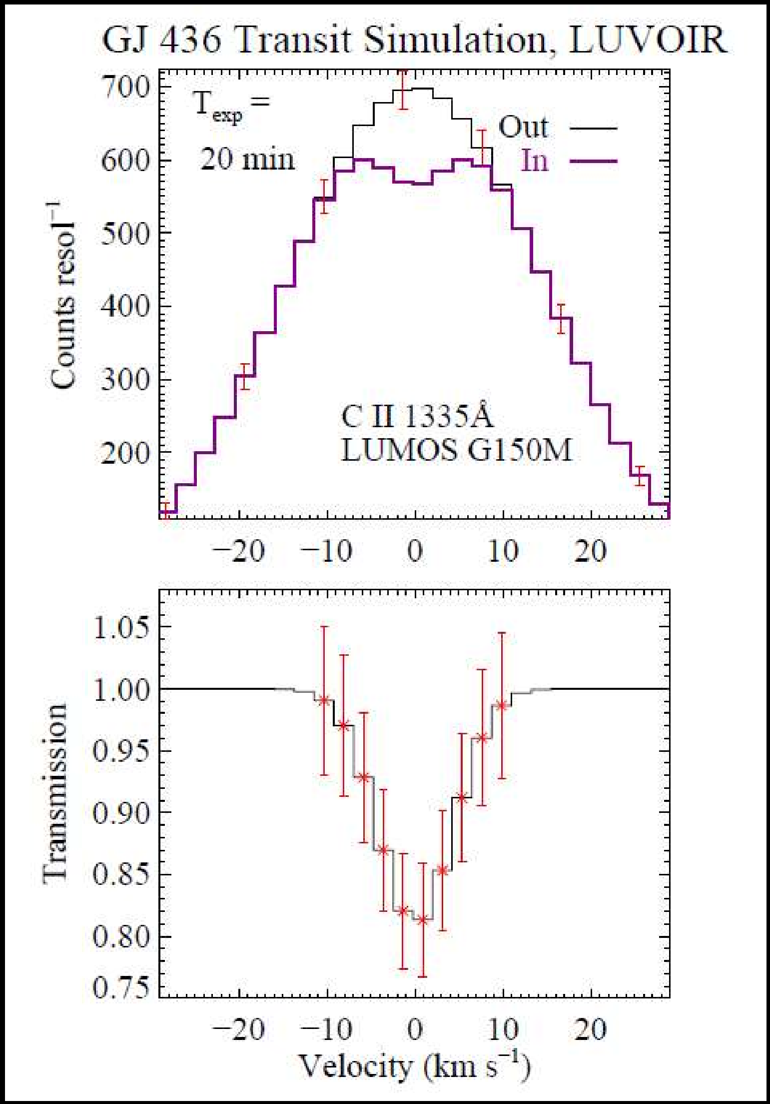


ATMOSPHERIC ESCAPE: FUV TRANSMISSION SPECTROSCOPY



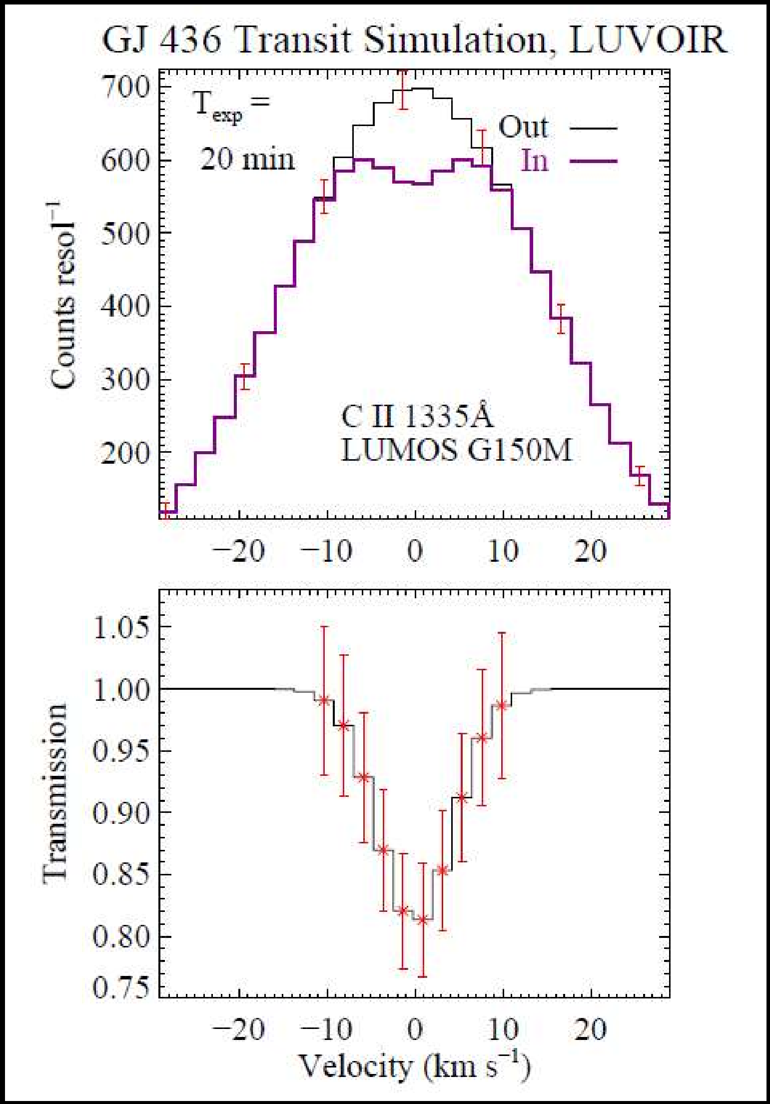
GJ 436b: ~50-60% transit depth in Lyα, no detection in metal species (Kulow et al. 2014; Ehrenreich et al. 2015; Loyd et al. 2017; dos Santos et al. 2019)

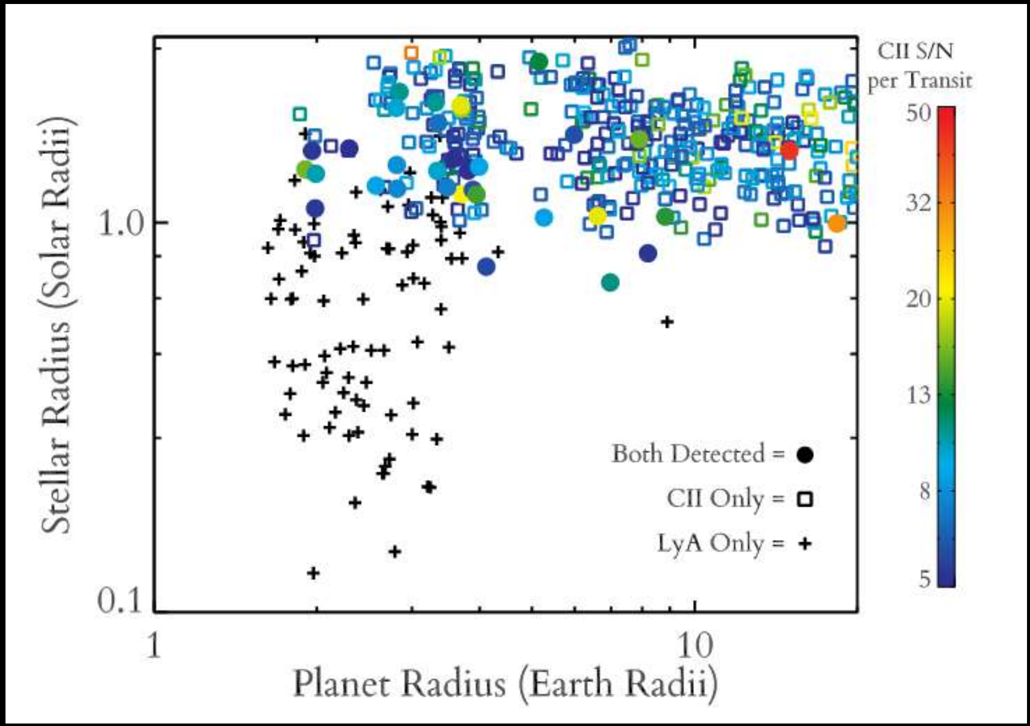
ATMOSPHERIC ESCAPE:
FUV TRANSMISSION SPECTROSCOPY



GJ 436b with LUMOS (Lopez & France, LUVOIR Final Report 2019)

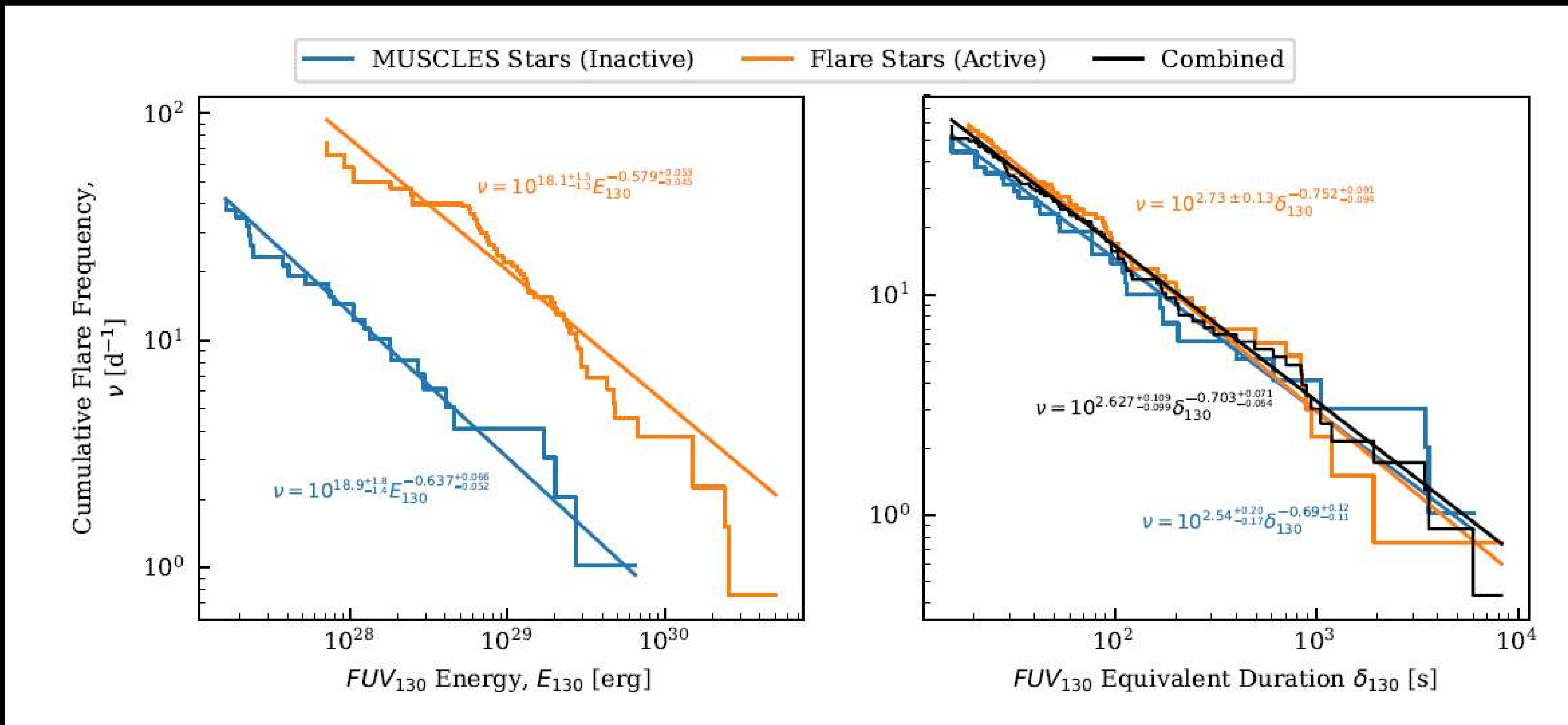
ATMOSPHERIC ESCAPE: FUV TRANSIT SPECTROSCOPY





H and C^+ atmospheric escape survey with LUMOS (Lopez & France, LUVOIR Final Report 2019)

UV flare distribution



$$E = 4\pi d^2 \int_{\text{flare}} (F - F_q)dt,$$

$$\delta = \int_{\text{flare}} \frac{F - F_q}{F_q} dt.$$

E_{UV}(30 – 170nm) > 10^{32} erg about 2/week

Loyd & France, ApJS 2014
Loyd et al. (2017)