Constraining Exoplanet Atmospheres with Multi-wavelength Flare Campaigns

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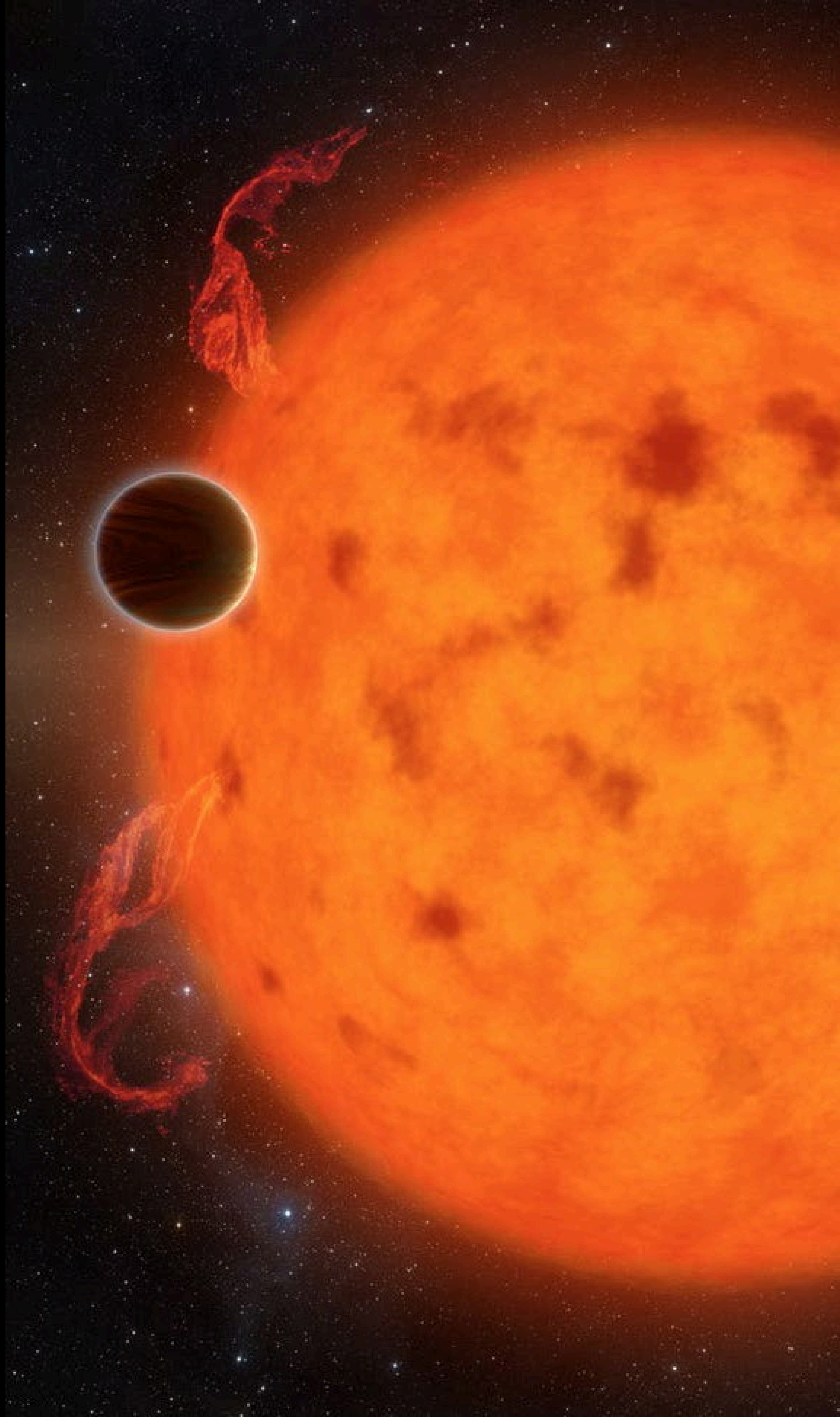
2023 Sun Climate Symposium, Tuesday Oct 17th 2023

Observing the atmospheres of rocky exoplanets

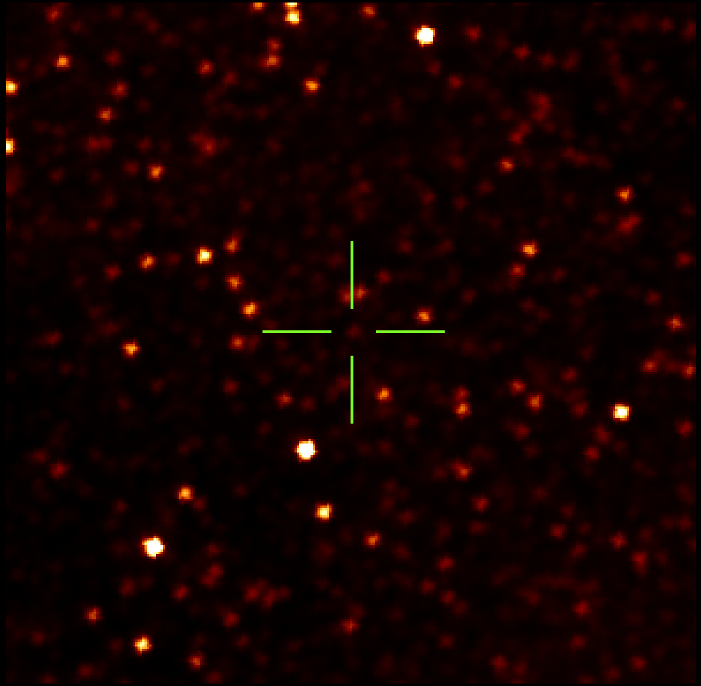
JWST is beginning to characterize the atmospheres of terrestrial exoplanets for the first time.

These terrestrial planet targets each orbit a nearby M-dwarf due to signal-to-noise constraints

M-dwarfs are also known for high levels of stellar activity, which impact the characterization and habitability of these worlds

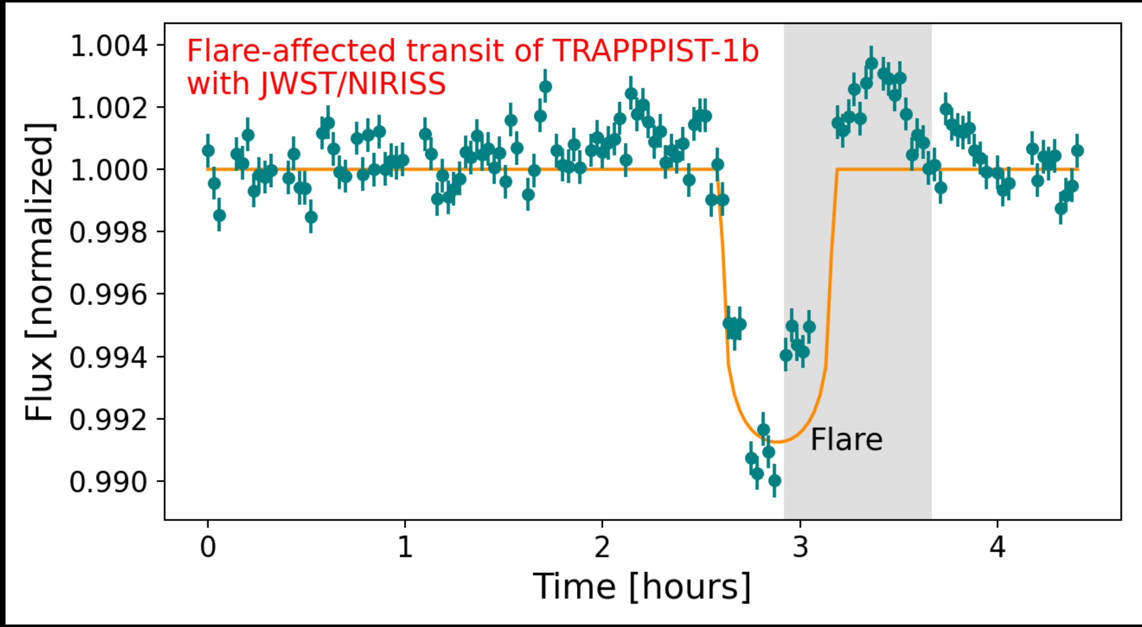


Observing the atmospheres of rocky exoplanets



Large flare from M5.5 dwarf, Proxima Cen, Evryscope (Law+ 2015, Howard+ 2018)

The largest stellar flares increase the brightness of the star by 100X, driving disequilibrium chemistry in terrestrial atmospheres

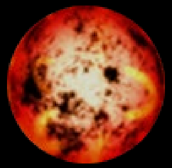


JWST Cycle 1 GO 2589 / PI: Olivia Lim

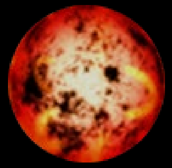
The smallest flares contaminate JWST observations of terrestrial atmospheres, potentially inducing false positives

Research overview

We will explore the multi-wavelength emission of stellar flares and their impact on exoplanet habitability and characterization through:



(1) Carrying out the first population-level survey of M-dwarf flare stars with ALMA, *Chandra*, Swift, and TESS to explore flare-induced photochemistry in terrestrial atmospheres



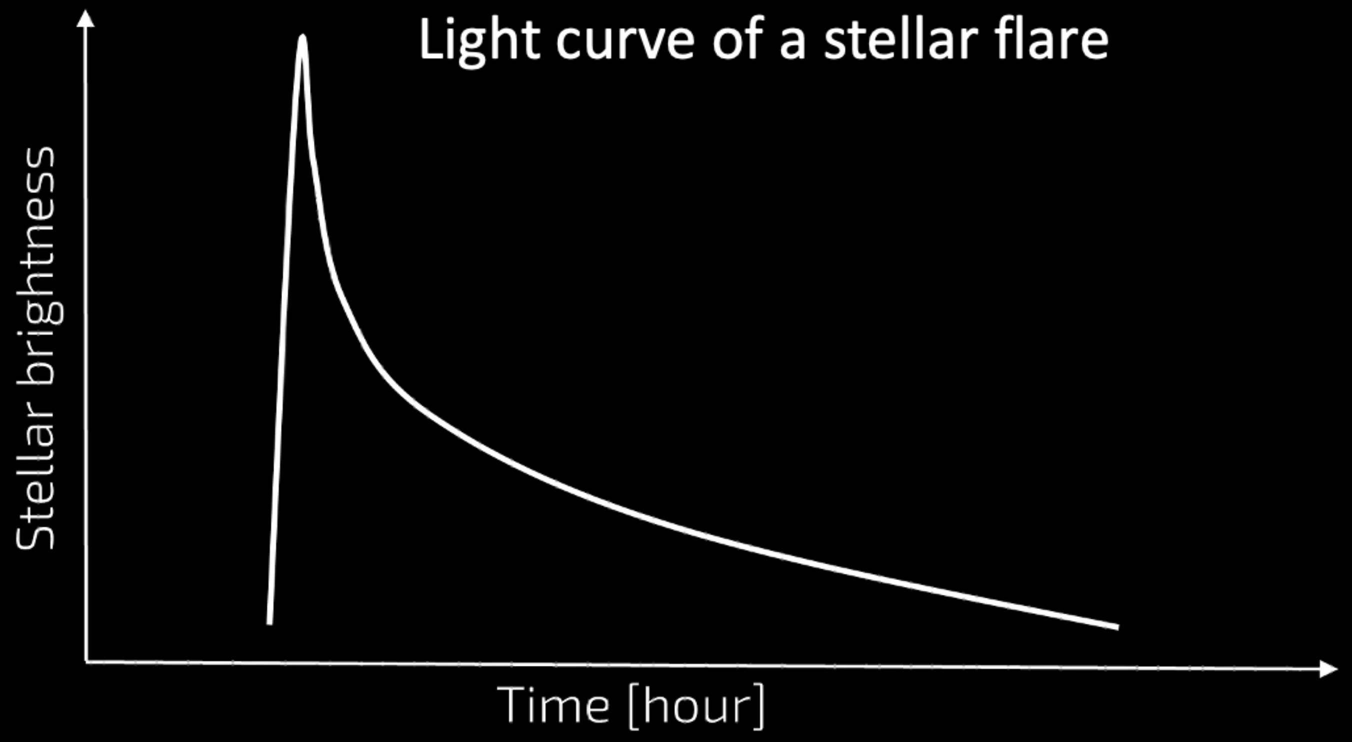
(2) Using flare spectroscopy to determine the challenges stellar activity creates for transmission spectroscopy of terrestrial planets

Research question (1)

Carrying out the first population-level survey of M-dwarf flare stars with ALMA, *Chandra*, Swift, and TESS

What is a solar or stellar flare?

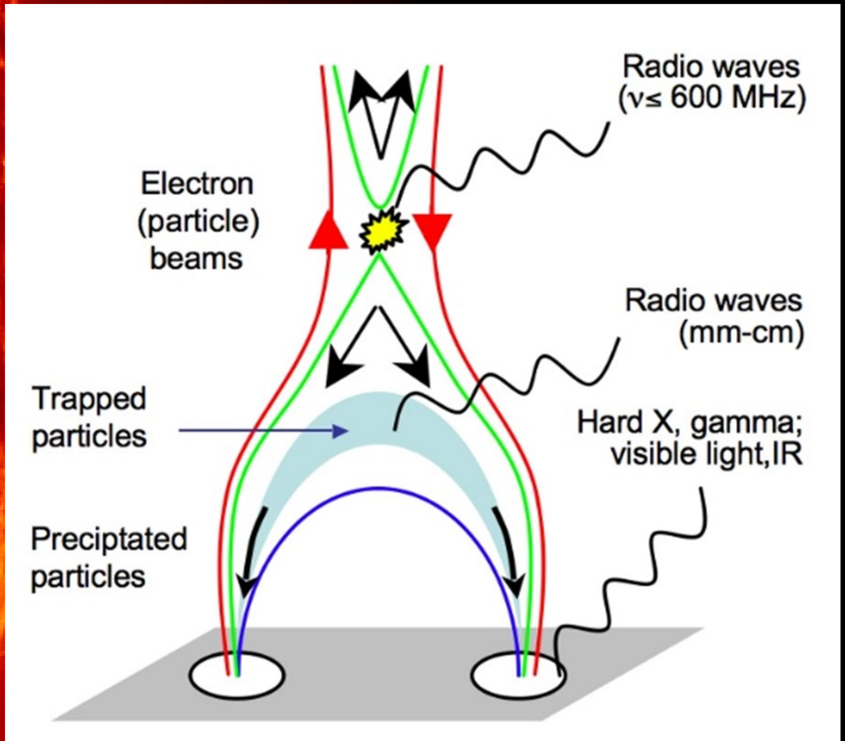
Flares occur when magnetic reconnection accelerates charged particles down field lines toward the star, heating the plasma



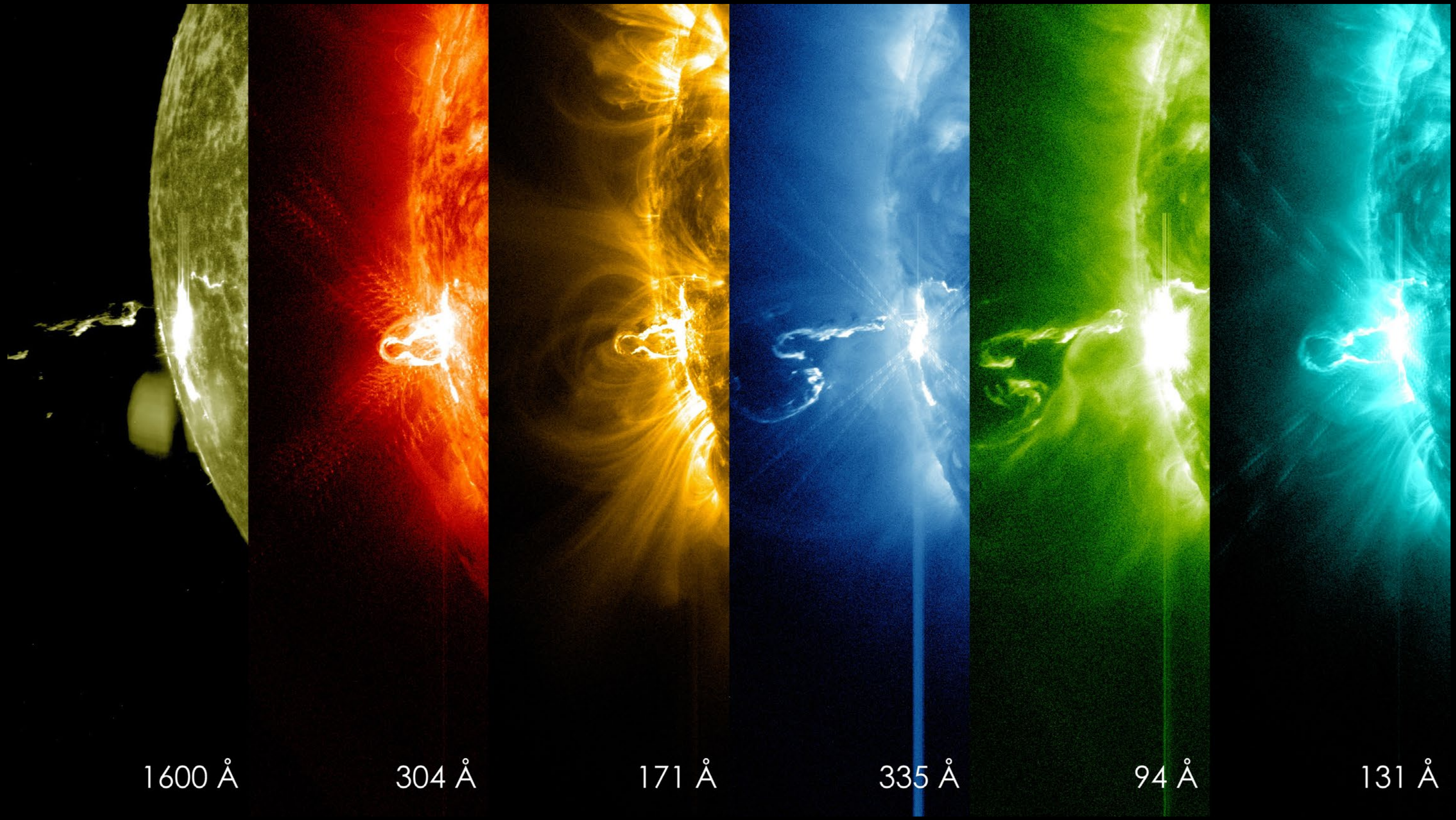
Stars flare across the electromagnetic spectrum

No single observation (at any wavelength) can give us a complete picture of the physics at work or the energies produced during a flare

We need multiwavelength observations to better understand stellar flares!

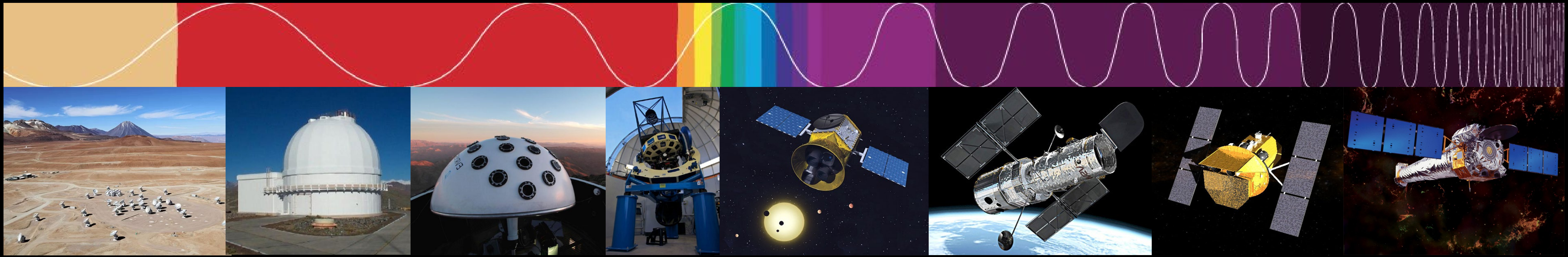


Klein & Dalla (2017), SSR 212, 1107



Simultaneous X-ray to millimeter flare observations of Proxima Cen for 40 hours

Coordinating PI: Meredith MacGregor, Johns Hopkins



ALMA
millimeter

Evryscope
optical photometry

TESS
optical (space)

Swift
UV, X-ray (space)

du Pont
optical spectroscopy

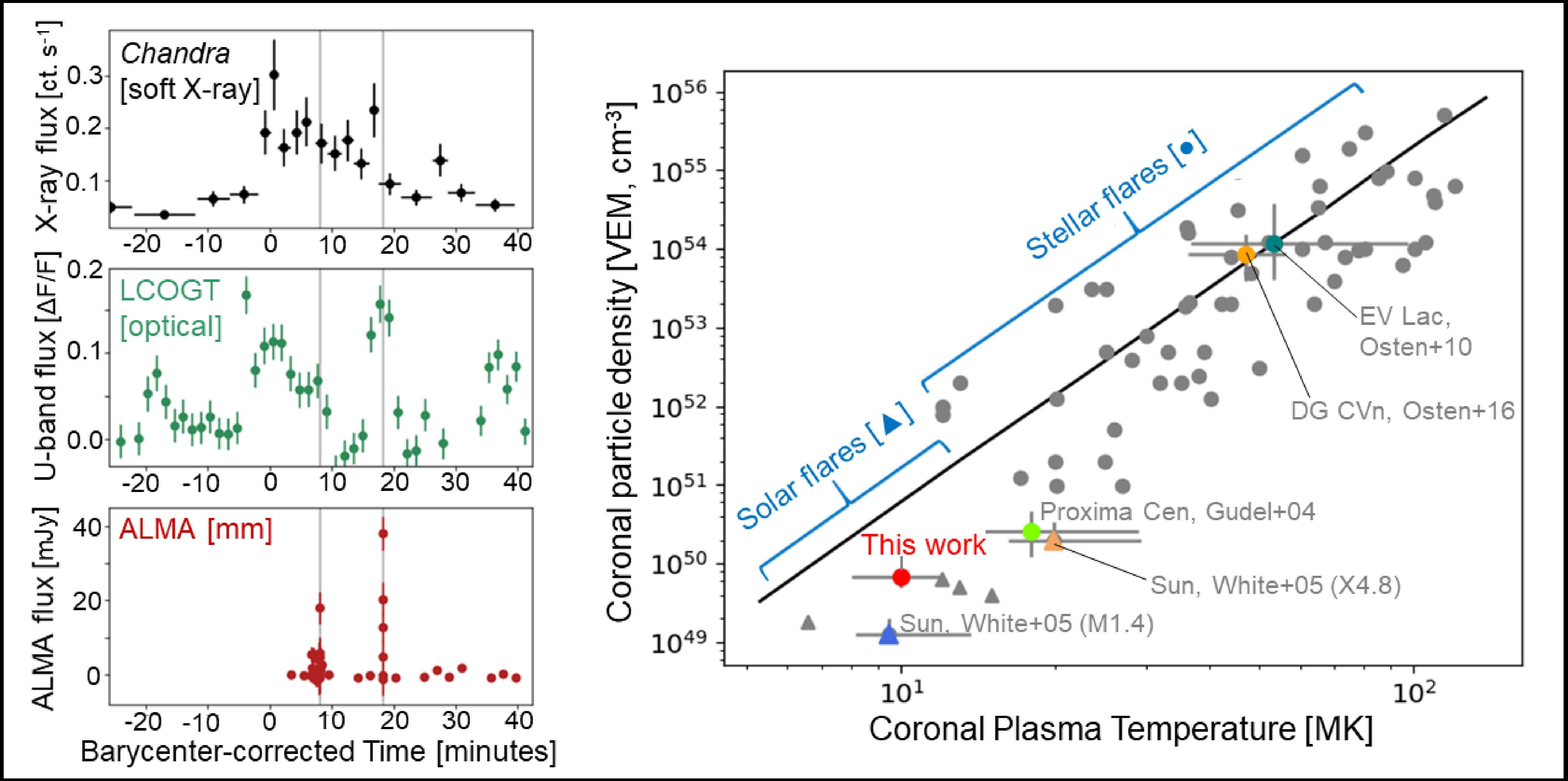
LCOGT 1-m
optical photometry

HST
UV (space)

Chandra
X-ray (space)

Key results from the initial pan-chromatic ALMA flare campaign of Proxima Cen

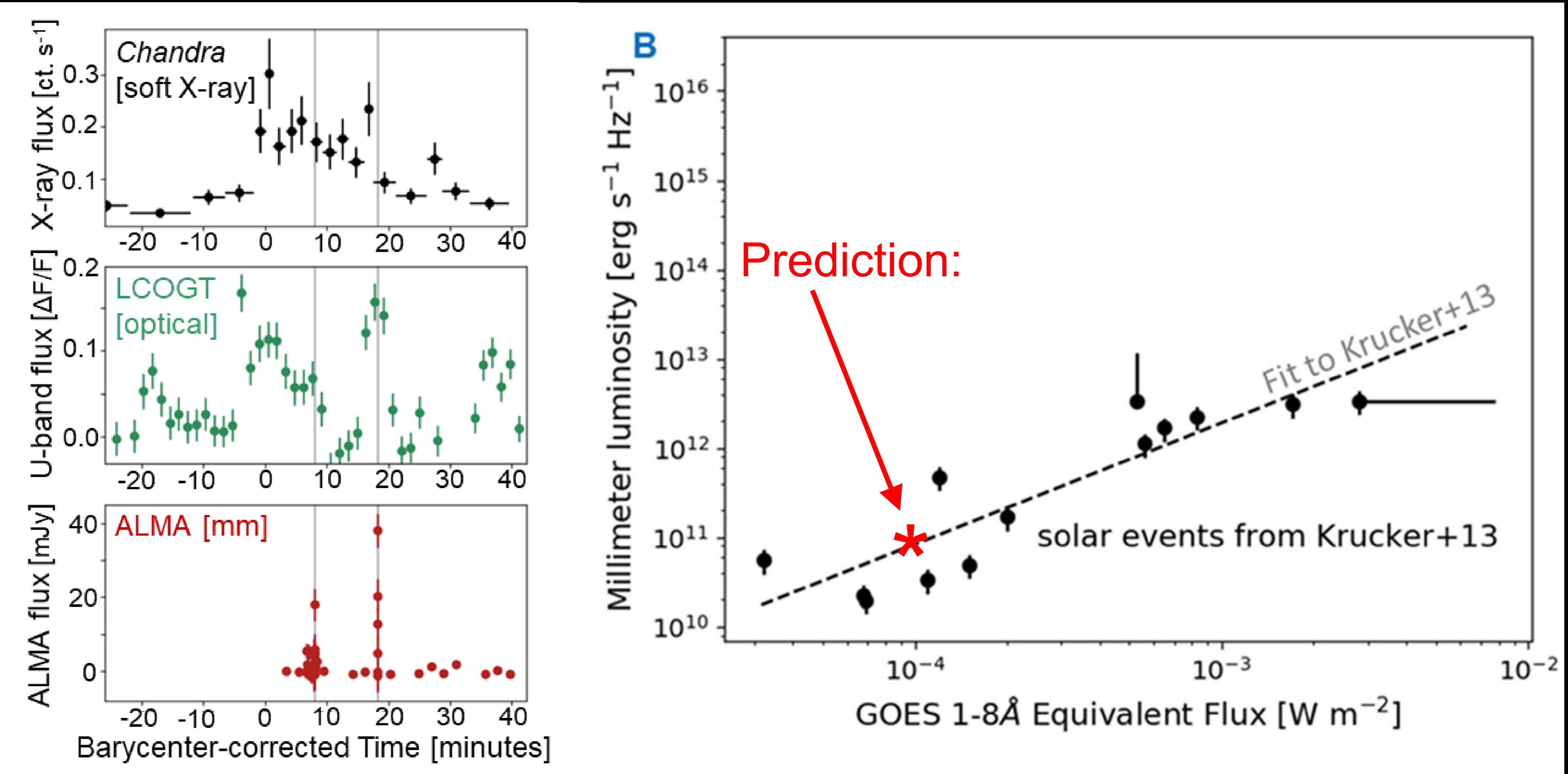
The first flare observed with *Chandra* and ALMA compared with solar flares



Howard+ (2022), ApJ, 938, 103

Key results from the initial pan-chromatic ALMA flare campaign of Proxima Cen

The soft X-ray is typical of solar flares— what about the millimeter?



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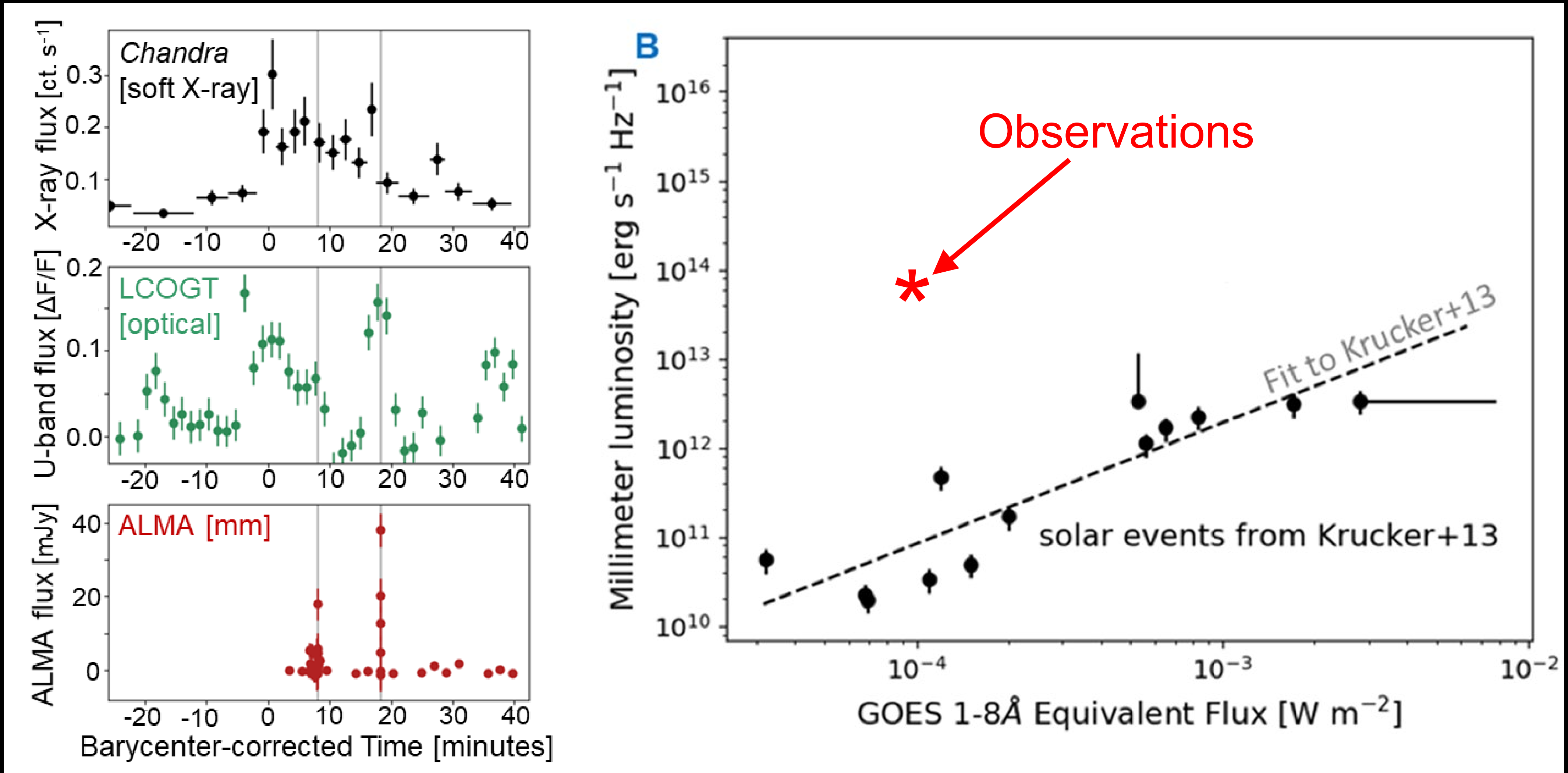


Howard+ (2022), ApJ, 938, 103

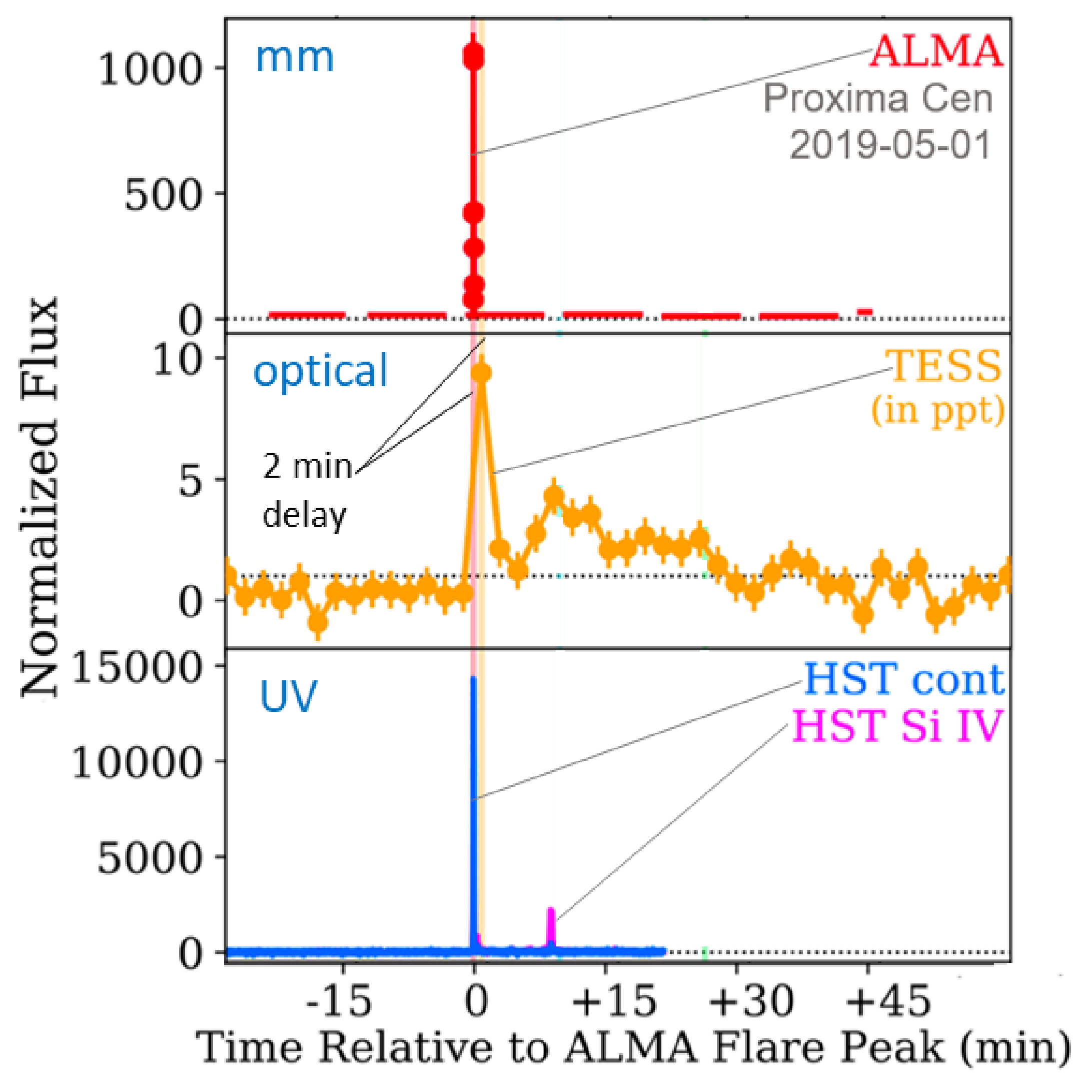
Key results from the initial pan-chromatic ALMA flare campaign of Proxima Cen

Millimeter and UV emission trace each other closely in a large flare, while optical emission is delayed

Could millimeter observations trace the high energy radiation environment of exoplanets?

We need more than one star to find out!

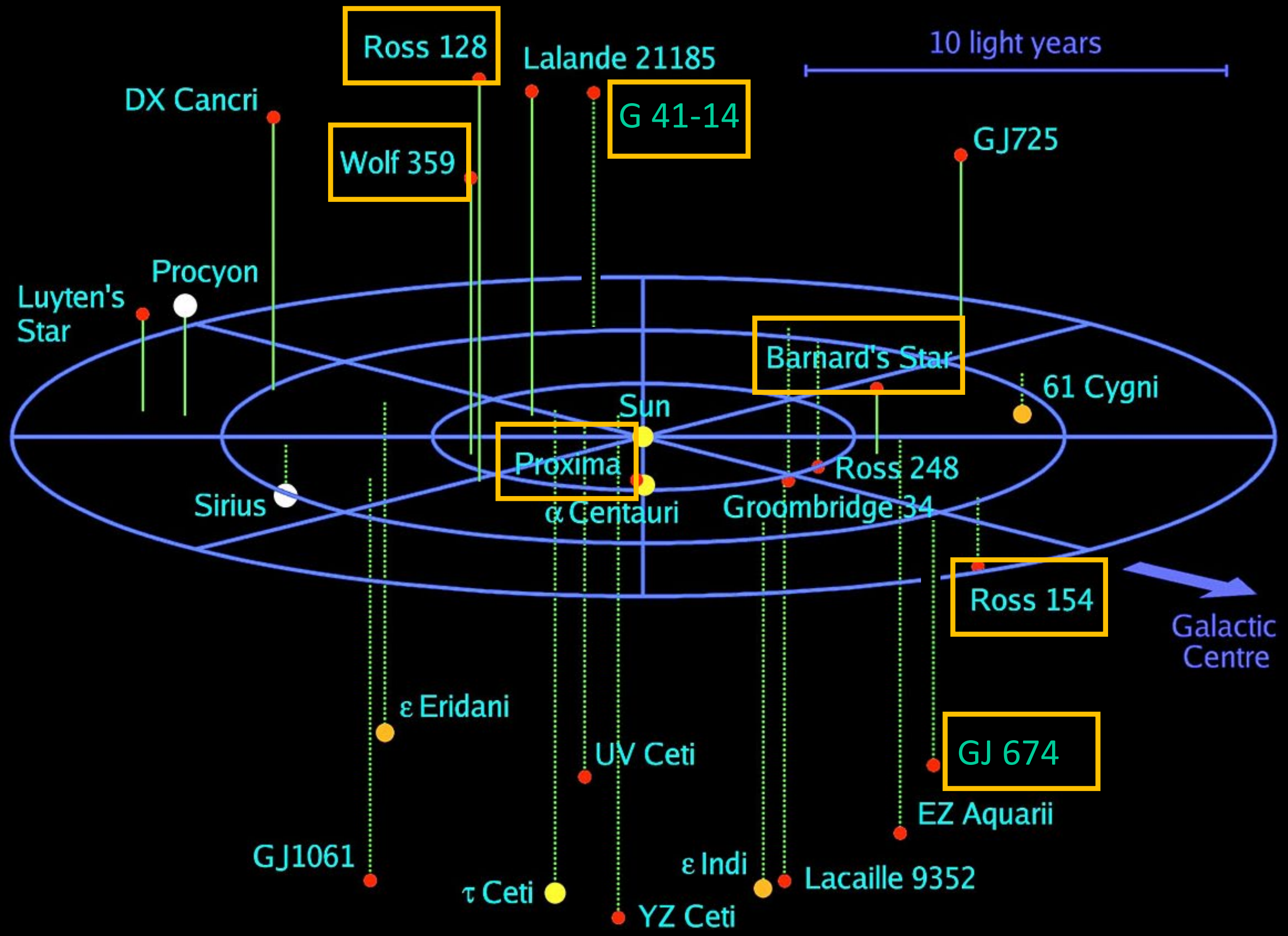
Large flare from Proxima on May 1, 2019



MacGregor, …., **Howard**+ 2021, ApJ Letters 911, 25

X-ray to millimeter flares throughout the solar neighborhood

I am leading a simultaneous campaign at X-ray, NUV, and optical wavelengths for the first population of ALMA flares from 6-7 M-dwarfs of various ages and activity levels*



* ALMA Cycle 9 PI: **Howard**, ALMA Cycle 8 PI: MacGregor, *Chandra* & *Swift* Science-PI: **Howard**, HST PI: MacGregor, NICER PI: Paudel, Evryscope PI: Law, TESS Cycle 5 PI: MacGregor

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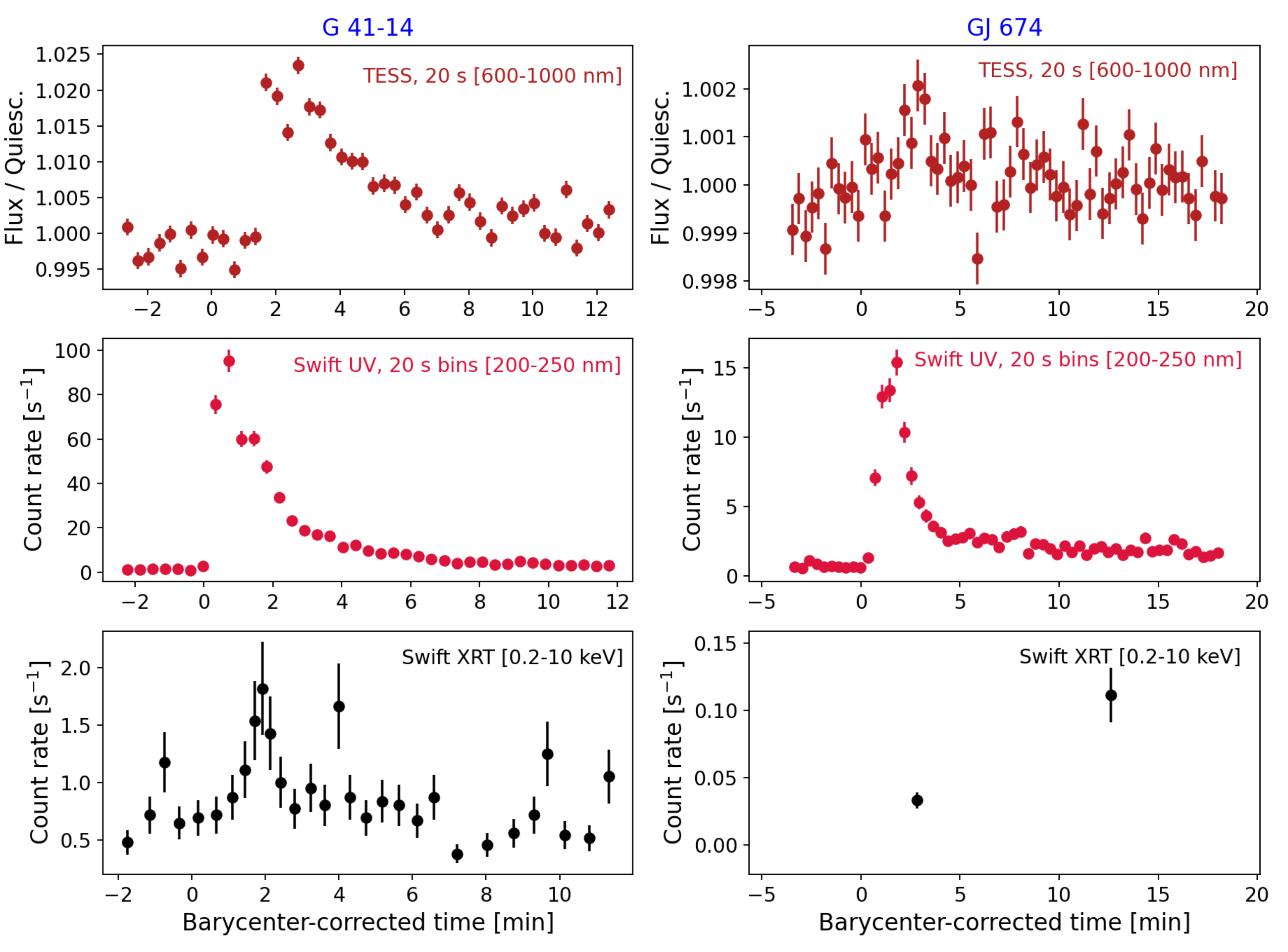
Target	SpT	D (pc)	Age (Gyr)	Radio/mm	Optical	UV/X-ray
Proxima Centauri	M5.5V	1.3	4.85	ALMA	TESS Evryscope Du Pont LCOGT	HST Swift Chandra
Barnard's Star	M4V	1.8	10	ALMA	Evryscope	Swift NICER
Wolf 359	M6V	2.0	0.1 – 0.35	ALMA	Evryscope	HST Swift Chandra NICER
Ross 154	M3.5V	2.9	<1	ALMA	Evryscope	Swift NICER
Ross 128	M4V	3.4	9.5	ALMA	Evryscope	Swift NICER
GJ 674	M2.5V	4.5	0.1 – 1	ALMA	TESS	Swift
G 41-14	M3.5V	6.8	~0.2	ALMA	TESS	Swift

* ALMA Cycle 9 PI: **Howard**, ALMA Cycle 8 PI: MacGregor, *Chandra* & *Swift* Science-PI: **Howard**, HST PI: MacGregor, NICER PI: Paudel, Evryscope PI: Law, TESS Cycle 5 PI: MacGregor

X-ray to millimeter flares throughout the solar neighborhood

We explore the timing and energy budget of flares with 20 sec TESS, NUV, and soft X-ray data

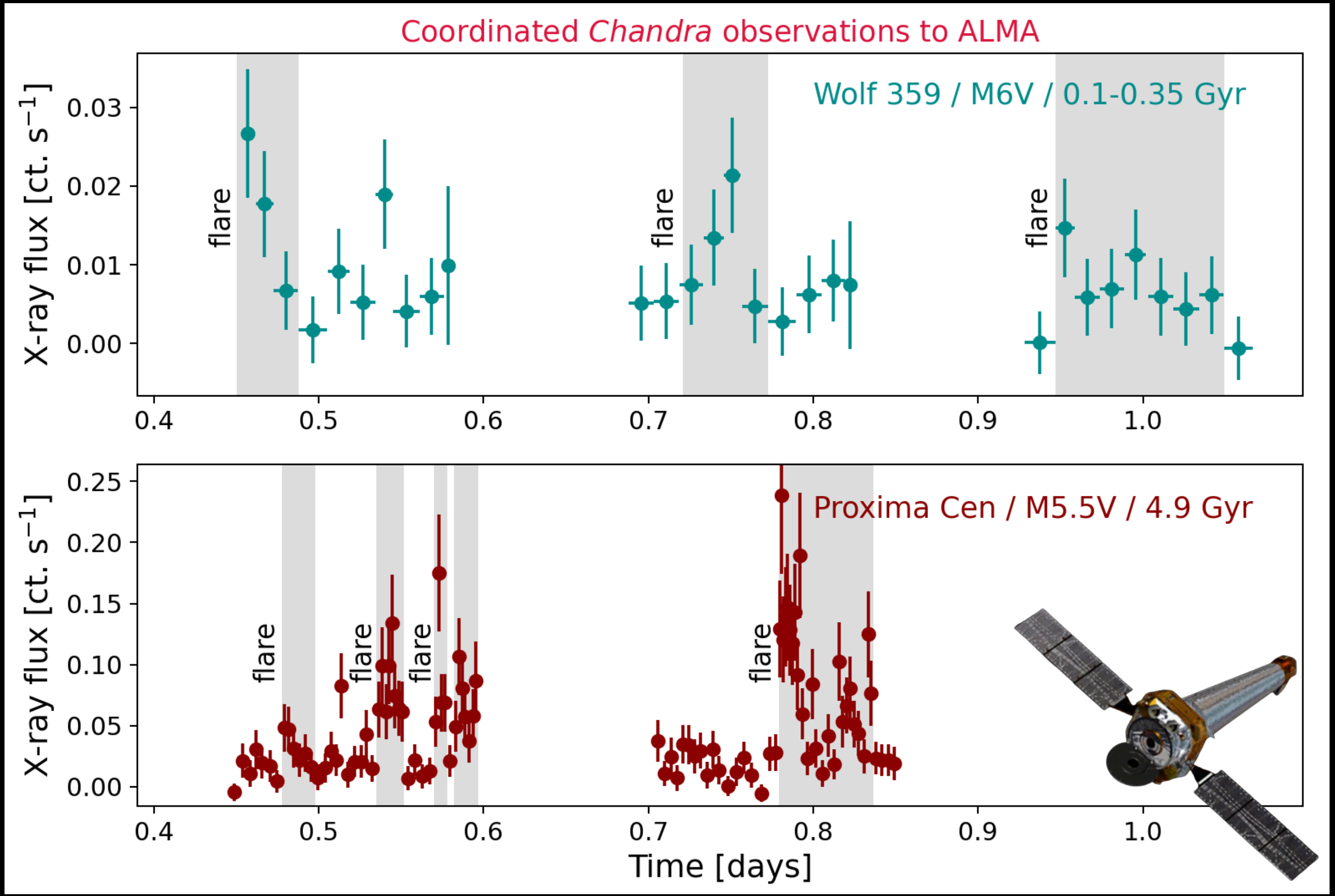
Different NUV flares have different amounts of red optical and X-ray emission



Howard+ 2024, in preparation

X-ray to millimeter flares throughout the solar neighborhood

High energy observations obtained with *Chandra* at the same time as ALMA



Wolf 359 / *Chandra* DDT 23208839 (**Howard**); Proxima / DDT 20208674 (MacGregor)

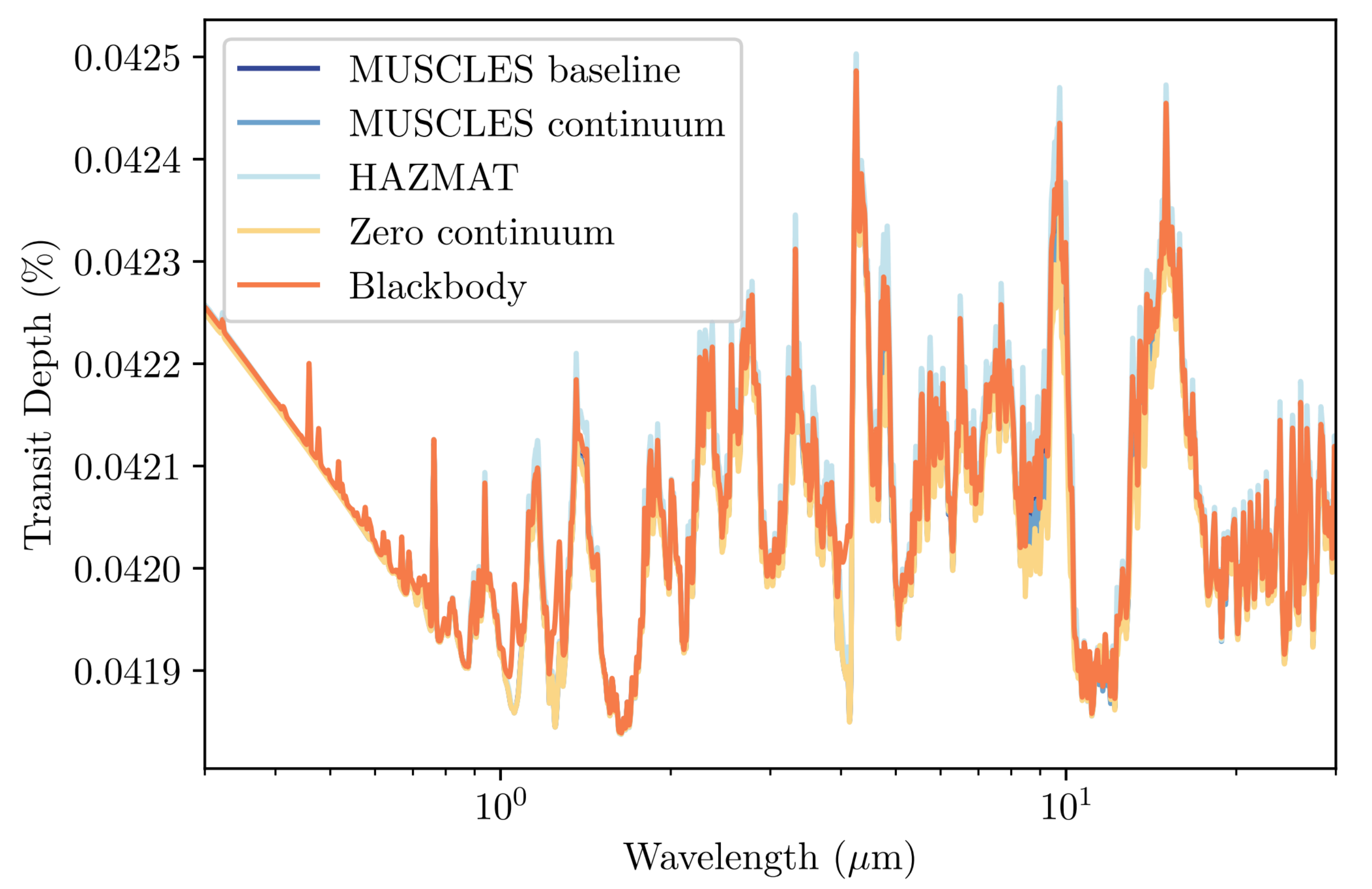
Wolf 359 is a young analog of Proxima Cen, allowing us to explore the evolution of the flare properties with age

Why do multi-wavelength flares matter for planetary atmospheres?

The high-energy stellar emission is a key source of uncertainty in interpreting transit spectra

Accurate scaling relations from optical to XUV wavelengths lead to better photochemical models

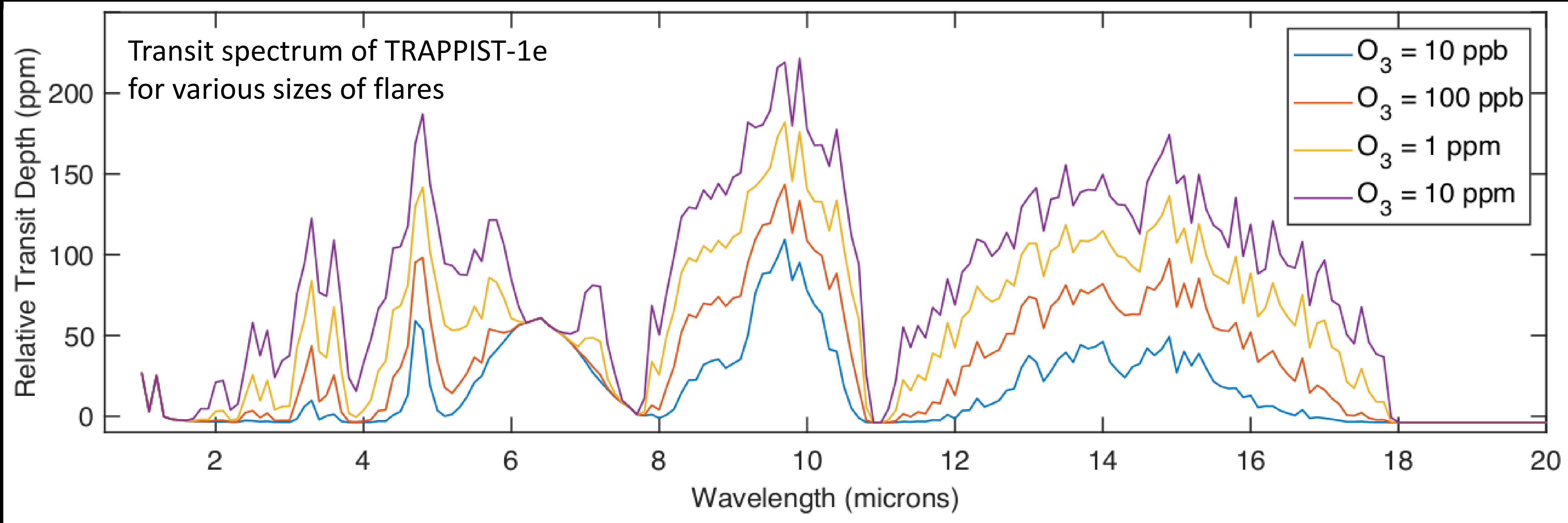
Model transmission spectrum of super-Earth GJ 176b



Teal+ 2022, ApJ 927, 90, "Effects of UV Stellar Spectral Uncertainty on the Chemistry of Terrestrial Atmospheres"

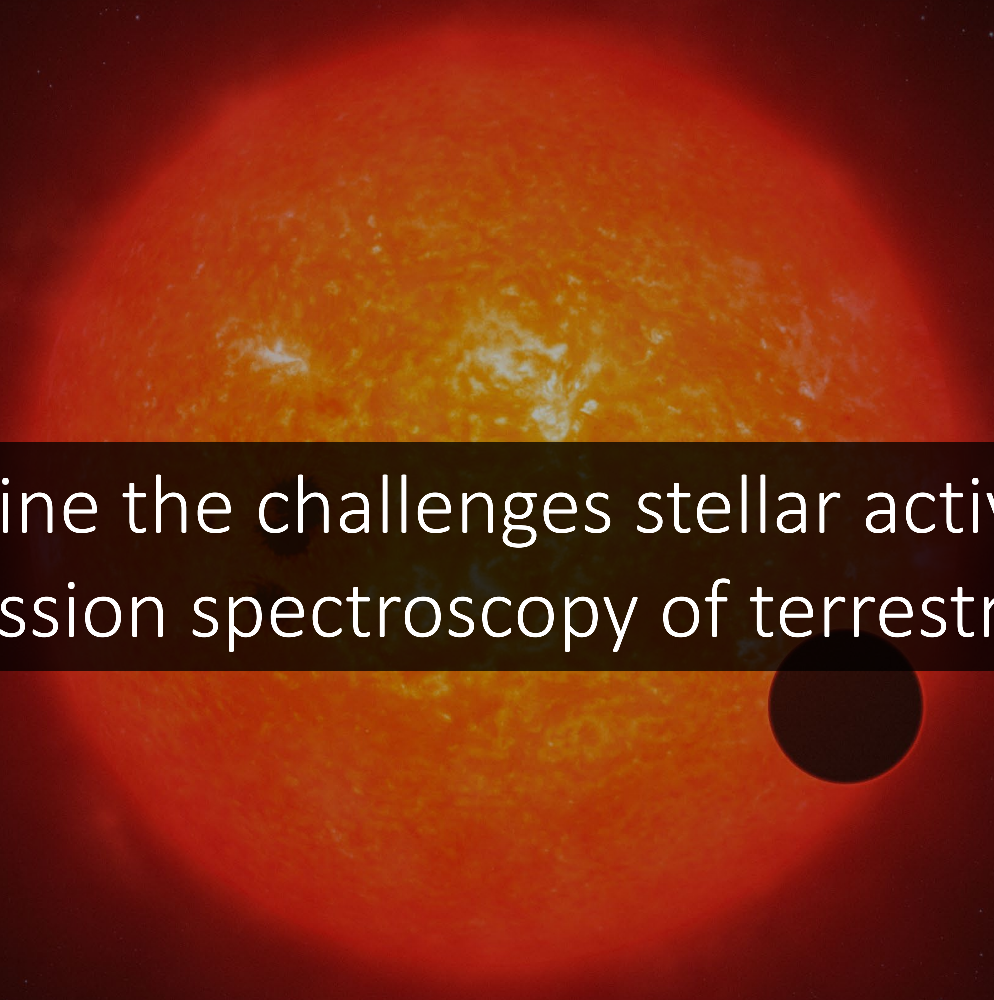
Why do multi-wavelength flares matter for planetary atmospheres?

Atmospheres of rocky exoplanets targeted with JWST transmission spectroscopy are particularly sensitive to flares



Schaefer, MacGregor, **Howard**+ in preparation

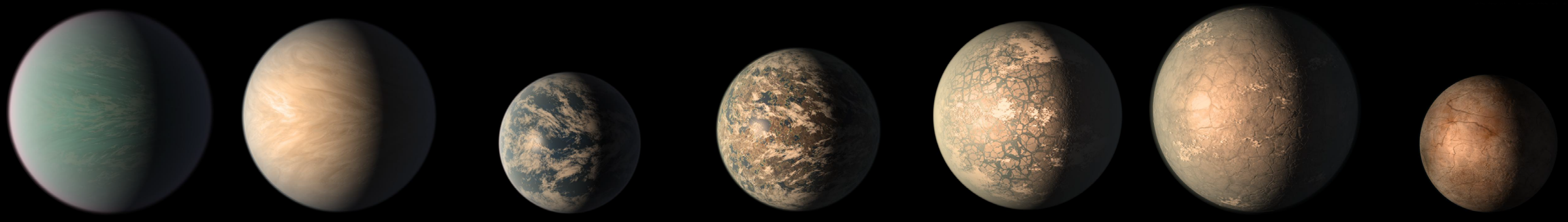
Research question (2)



Determine the challenges stellar activity creates for transmission spectroscopy of terrestrial planets

A NEAT opportunity for JWST transit spectroscopy of the TRAPPIST-1 system

TRAPPIST-1 System
Feb. 2018

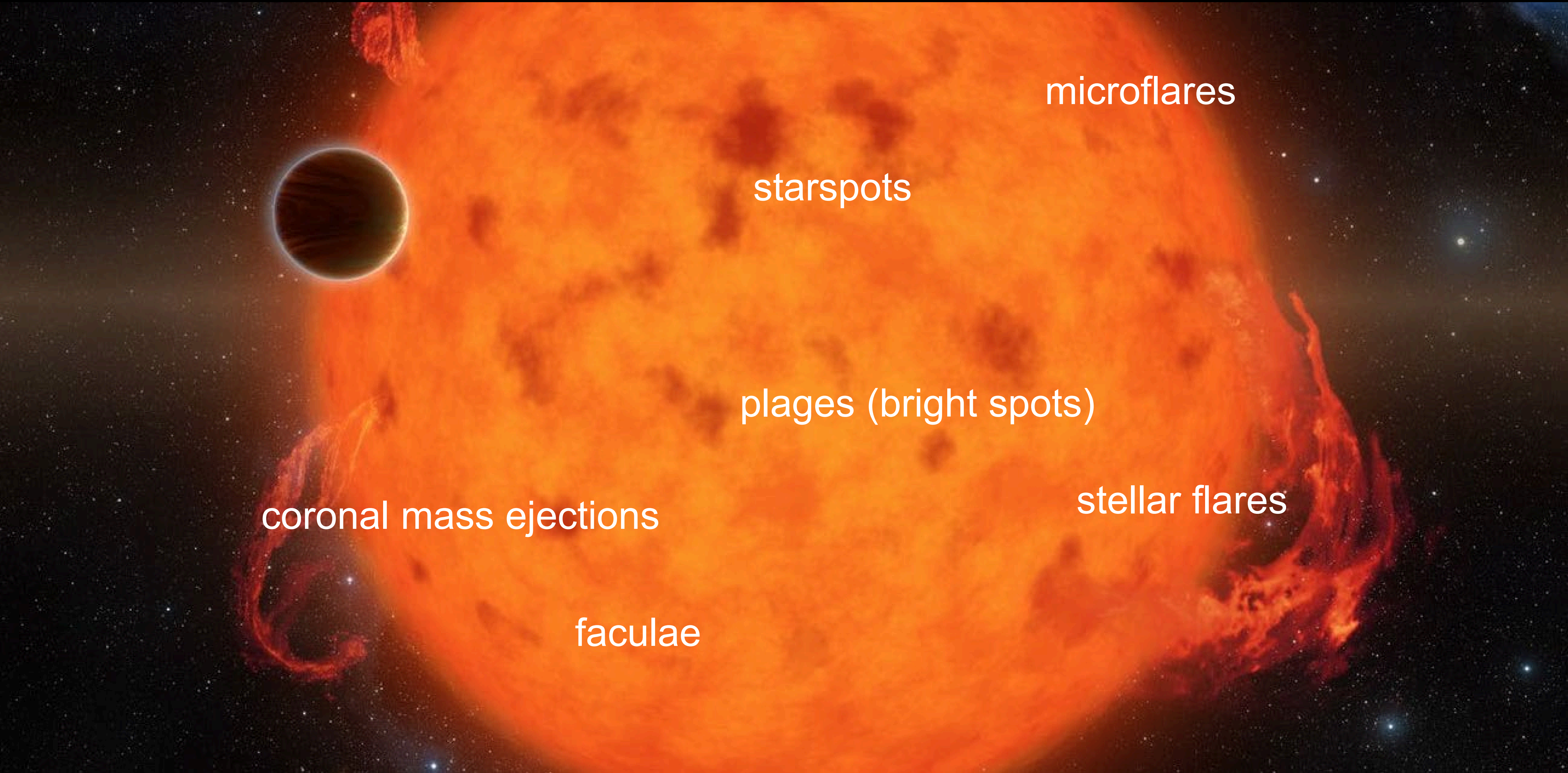


	b	c	d	e	f	g	h
Orbital Period	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.36 *days*	18.76 *days*
Distance to Star	0.0115 *AU*	0.0158 *AU*	0.0223 *AU*	0.0293 *AU*	0.0385 *AU*	0.0469 *AU*	0.0619 *AU*
Planet Radius	1.12 R_{earth}	1.10 R_{earth}	0.78 R_{earth}	0.91 R_{earth}	1.05 R_{earth}	1.15 R_{earth}	0.77 R_{earth}
Planet Mass	1.02 M_{earth}	1.16 M_{earth}	0.30 M_{earth}	0.77 M_{earth}	0.93 M_{earth}	1.15 M_{earth}	0.33 M_{earth}

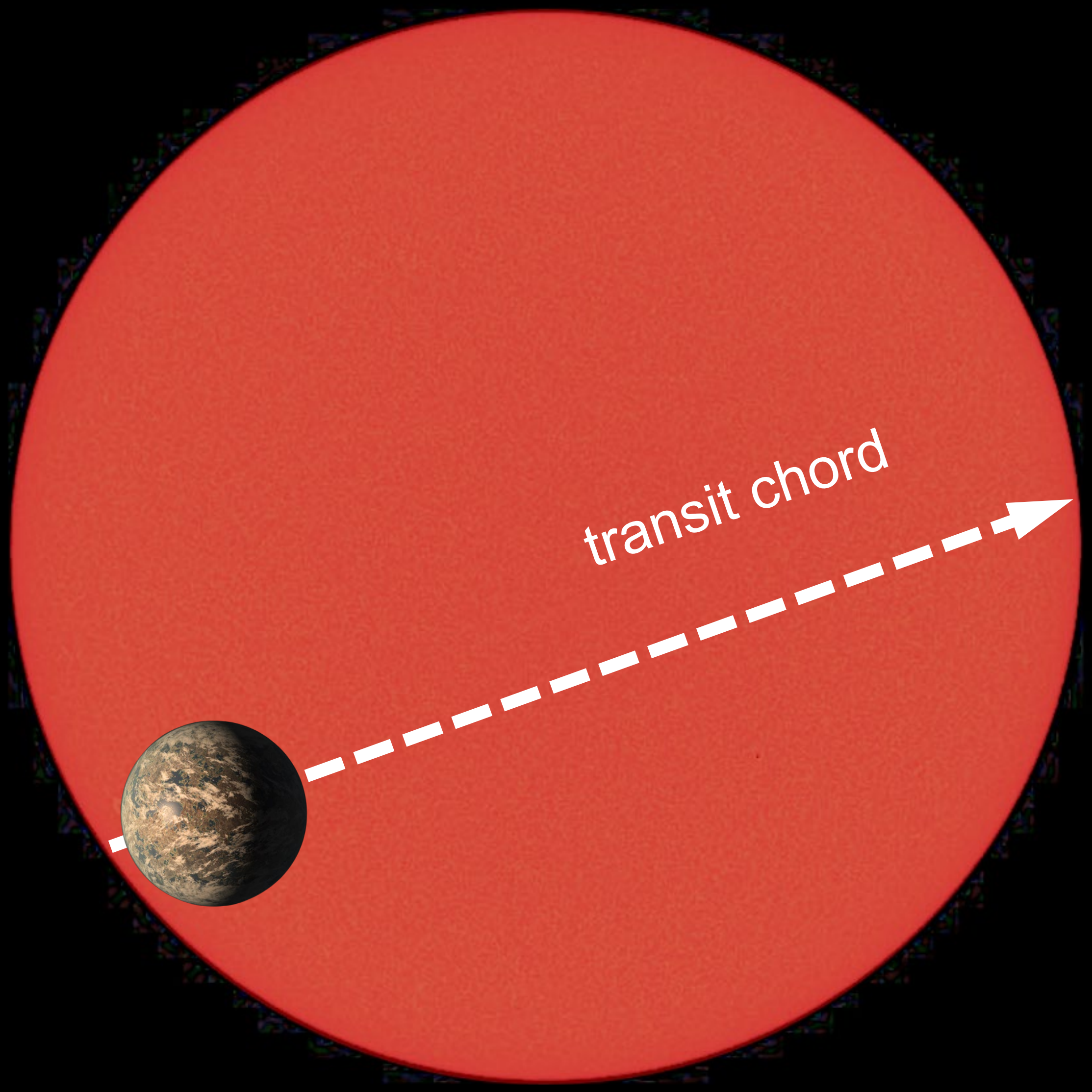
TRAPPIST-1 is a nearby M8 dwarf that hosts 7 terrestrial planets, 3 of which are in the habitable zone.

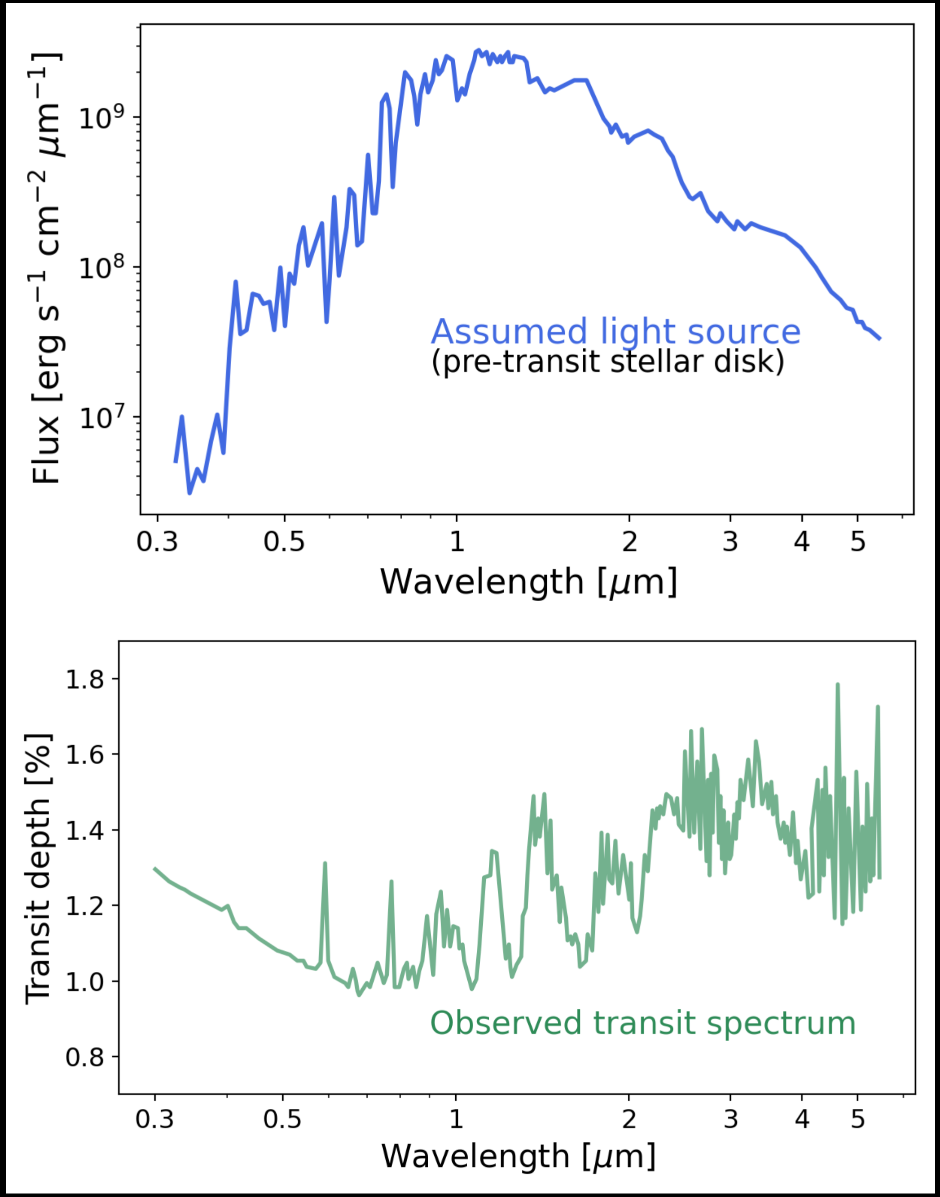
Numerous JWST programs are targeting the TRAPPIST-1 planets for transmission spectroscopy, including the NIRISS Exploration of the Atmospheric diversity of Transiting exoplanets (NEAT) collaboration (PIs: David Lafrenière, Olivia Lim)

TRAPPIST-1's stellar activity does not make transit spectroscopy easy!



Why does any of this matter for transit spectroscopy? The transit light source effect





Rackham+ 2018, ApJ 853, 122

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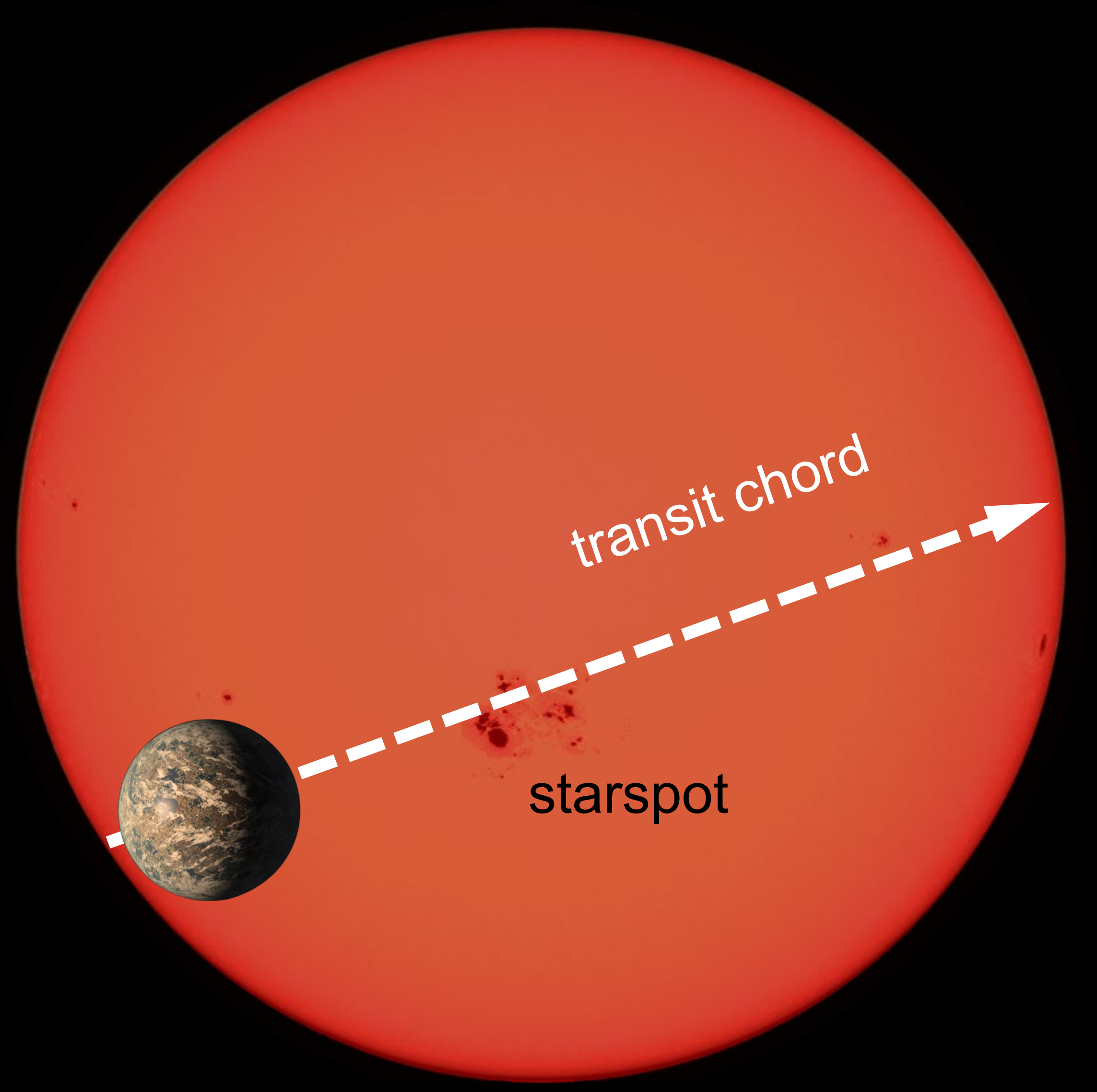
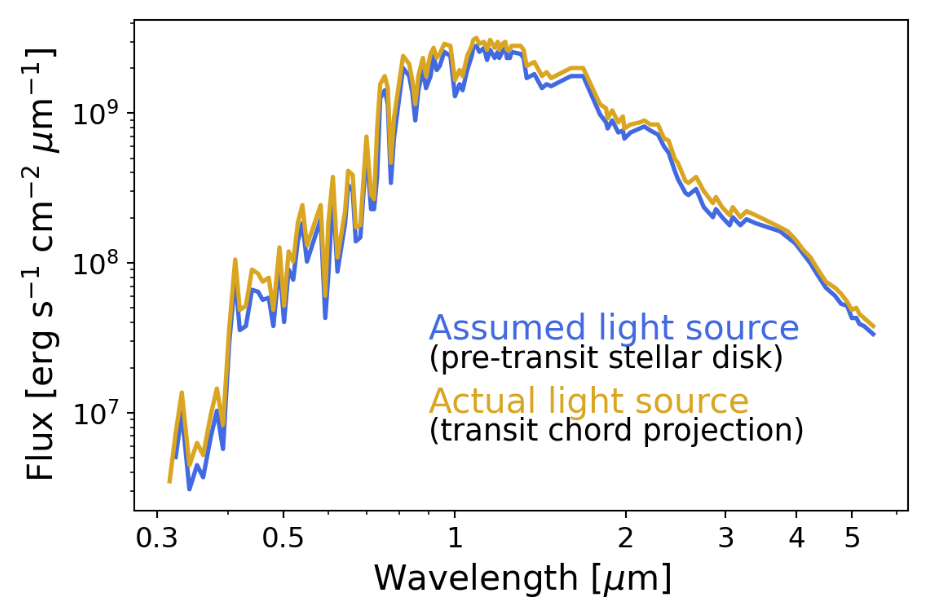
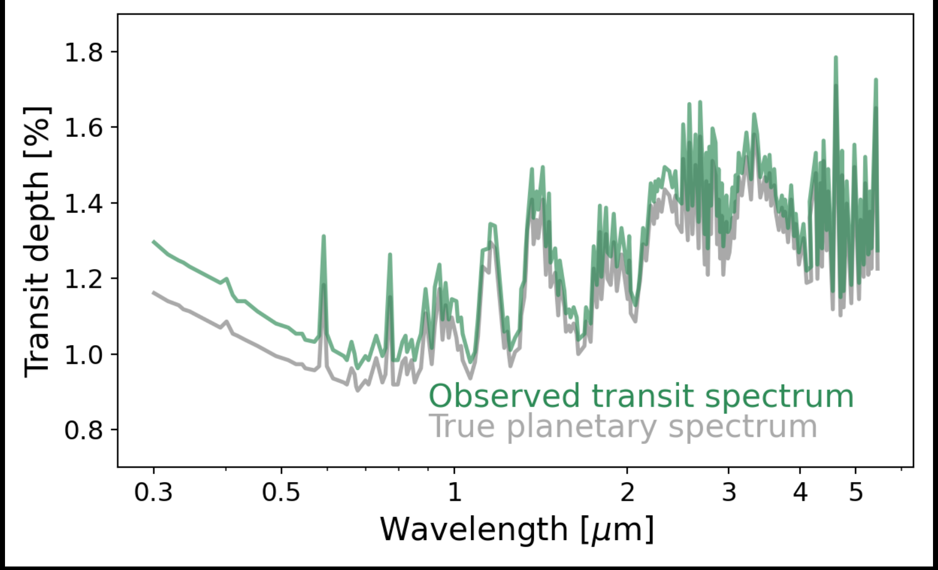
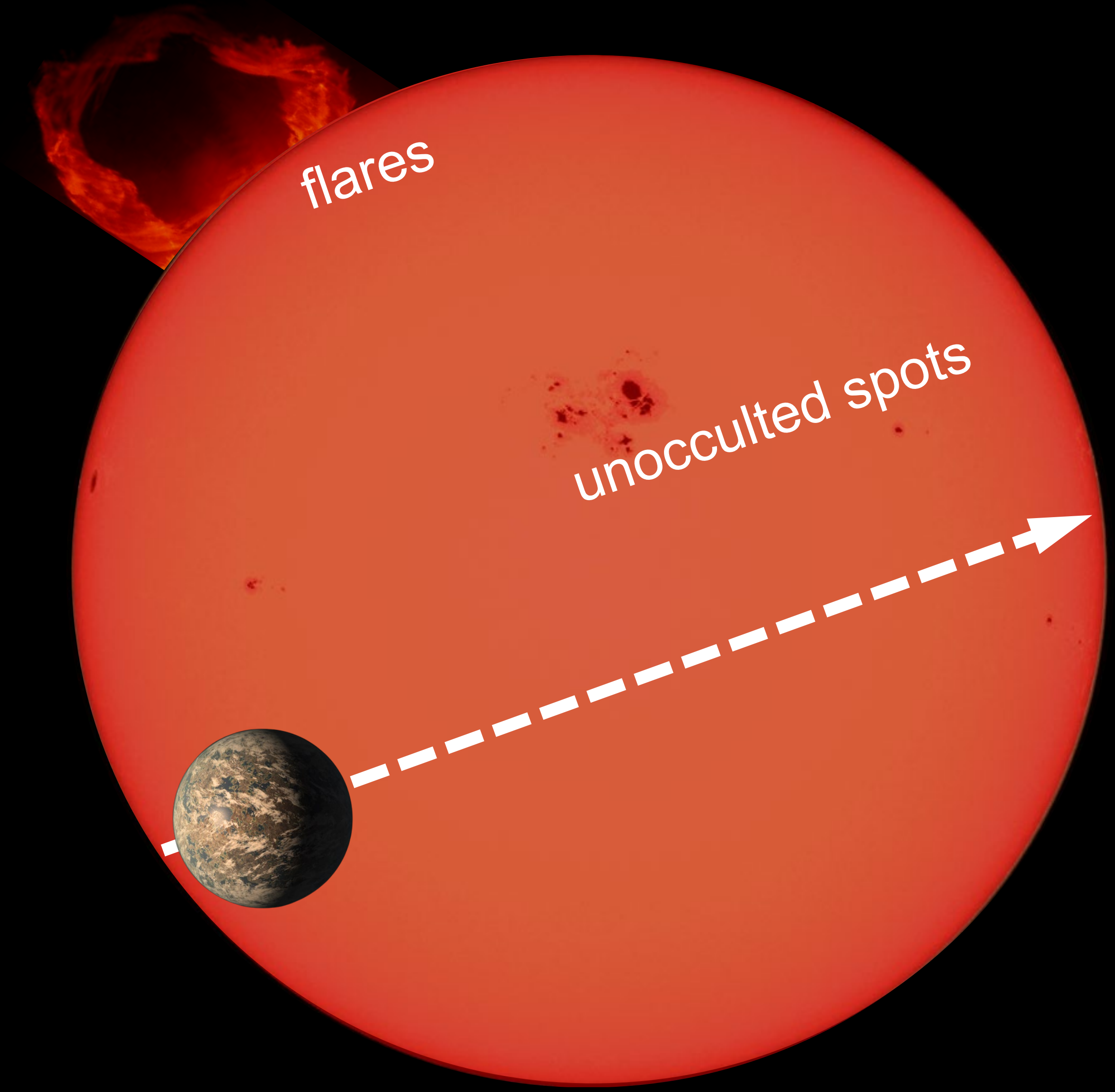






Rackham+ 2018, ApJ 853, 122

Why does any of this matter for transit spectroscopy? The transit light source effect



Any difference between the spectrum of the transit chord and the rest of the star leads to contamination, including:

(1) occulted starspots

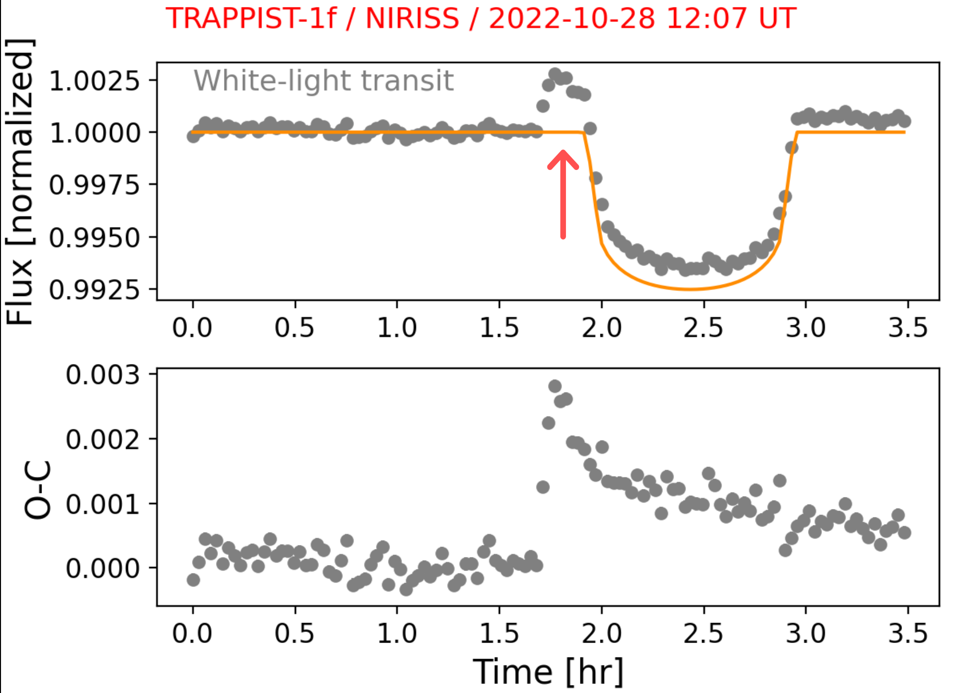
(2) unocculted starspots

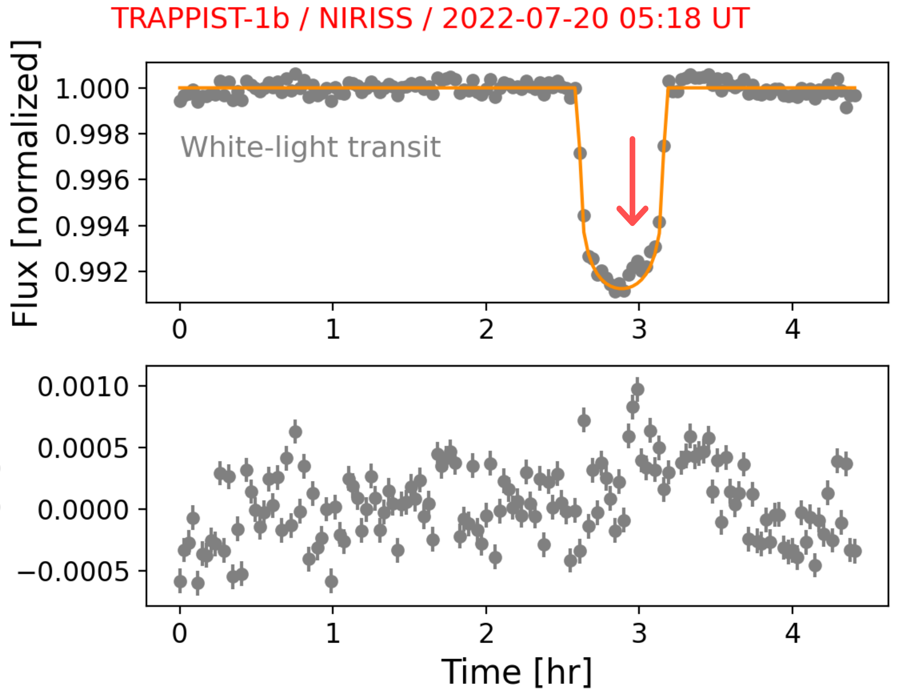
(3) time variability such as flares

TRAPPIST-1 is an extremely active flare star

So far, flare contamination has been observed in NIRISS and NIRSpec transit spectroscopy of TRAPPIST-1 b, d, f, and g

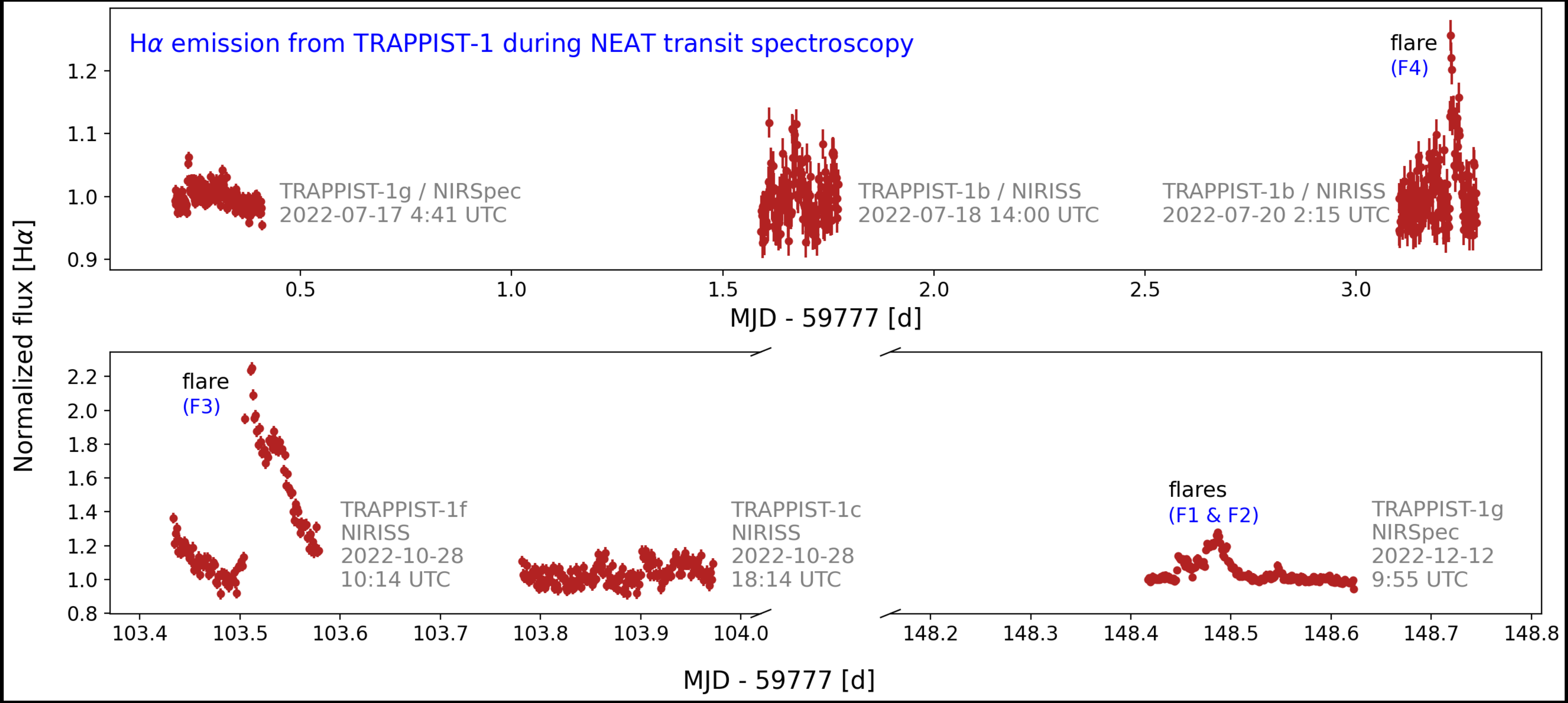
Howard+ (2023), ApJ, arXiv:2310.03792





Monitoring stellar activity in the Hα line during transit spectroscopy observations

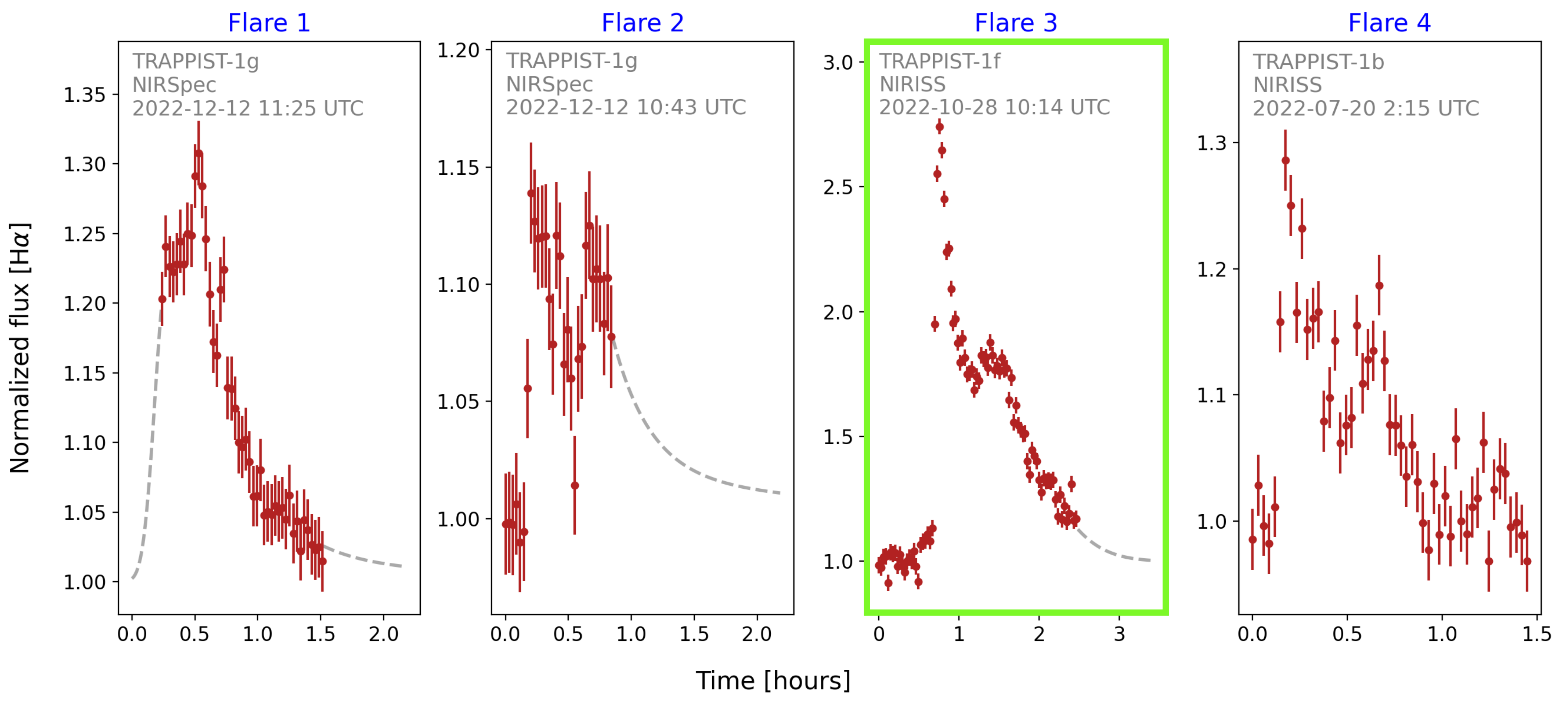
NIRISS and NIRSpec cover the Hα line where stellar activity is most prominent



Howard+ 2023, ApJ, arXiv:2310.03792

Monitoring stellar activity in the Hα line during transit spectroscopy observations

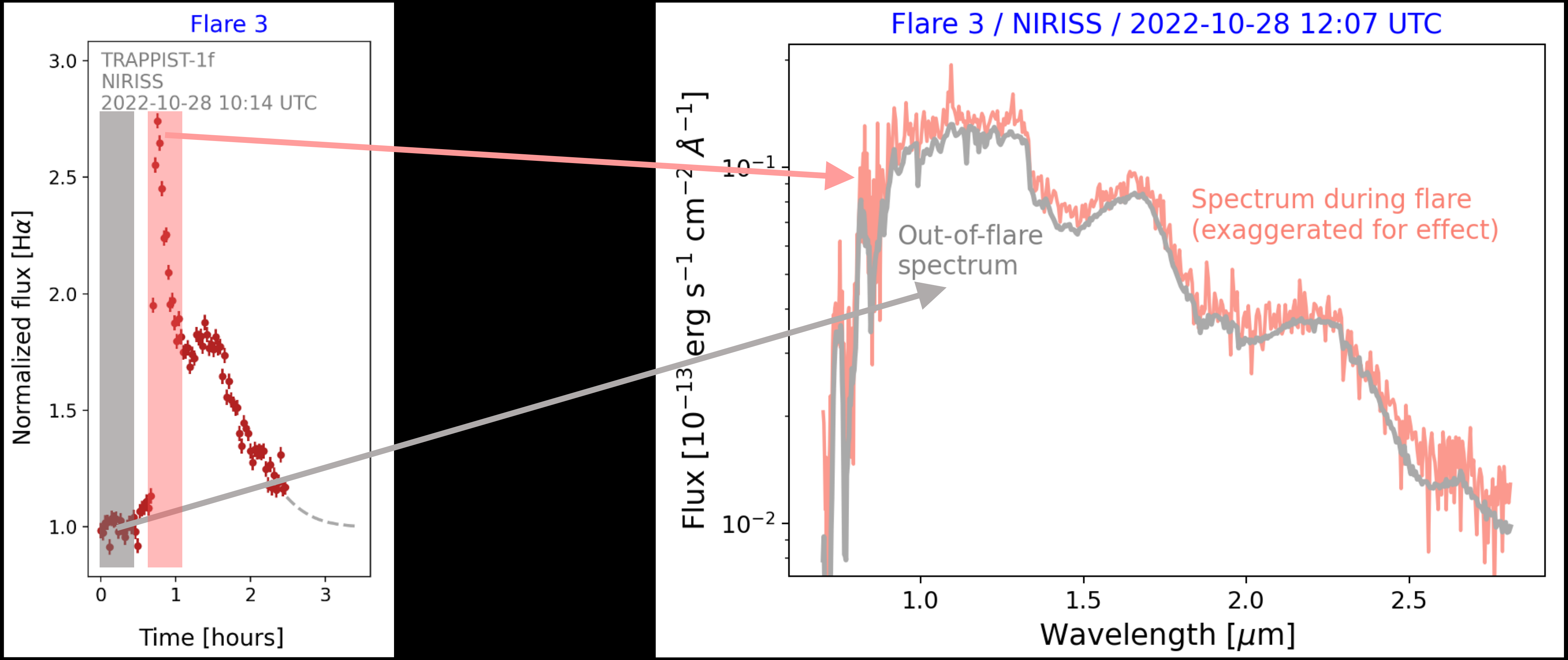
We observe four large flares in the Hα light curves, shown in detail below:



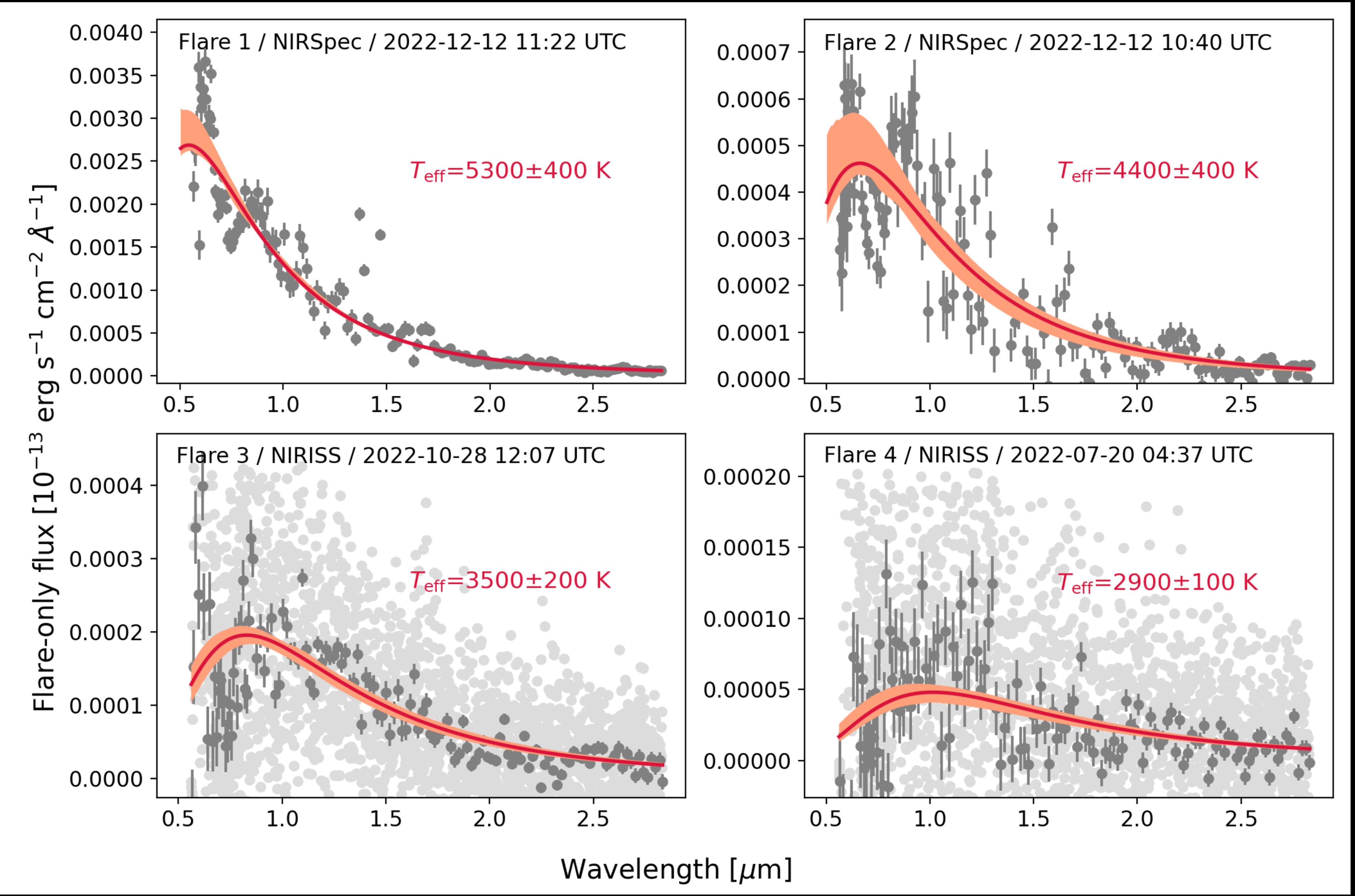
Howard+ 2023, ApJ, arXiv:2310.03792

Exploring the NIR spectra of flares with JWST

Subtract spectra of integrations during the flare from integrations during quiescence to create flare-only spectra



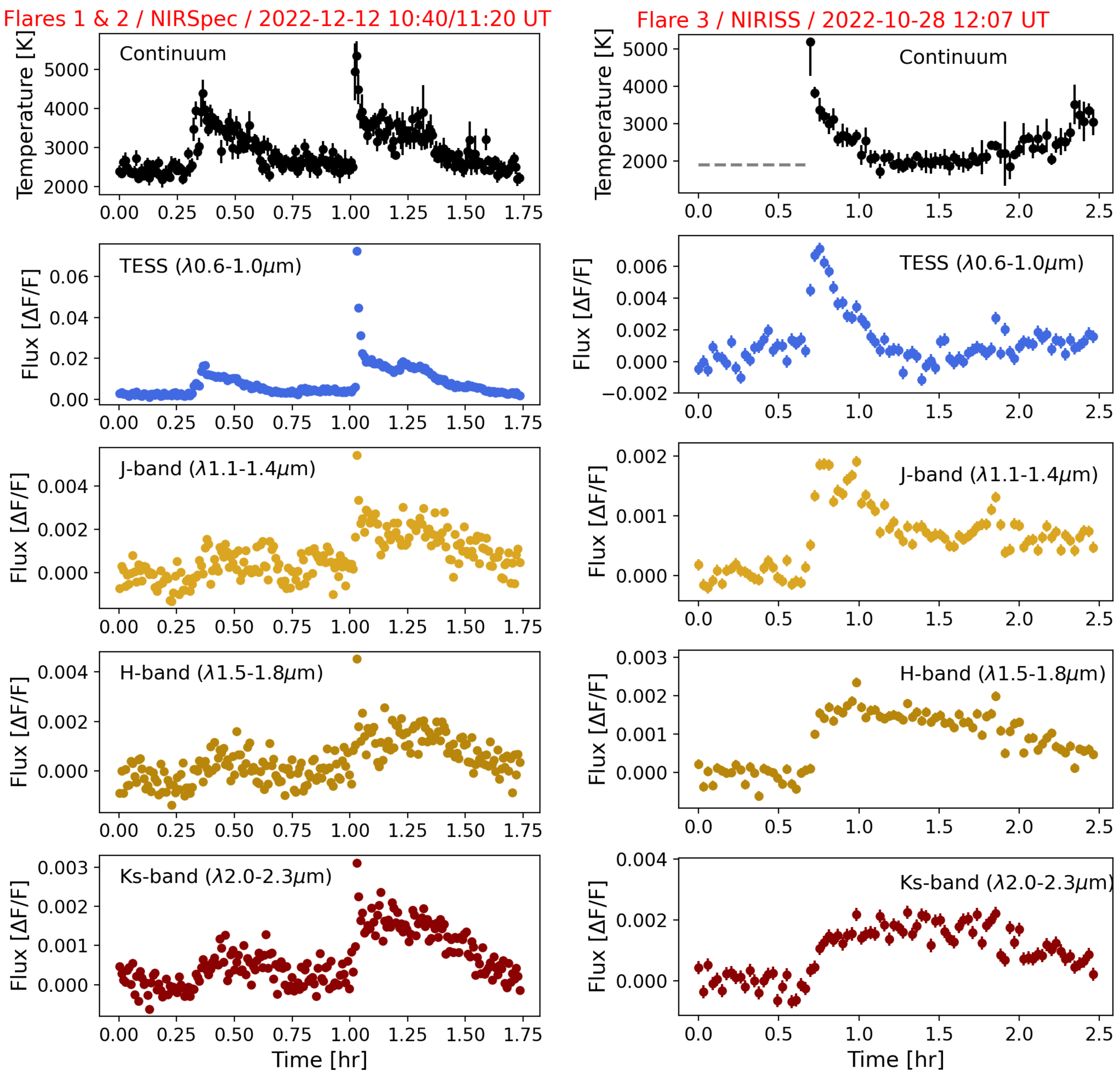
First characterization of flare continuum beyond 1 μm in any stellar flare



Howard+ 2023, ApJ, arXiv:2310.03792

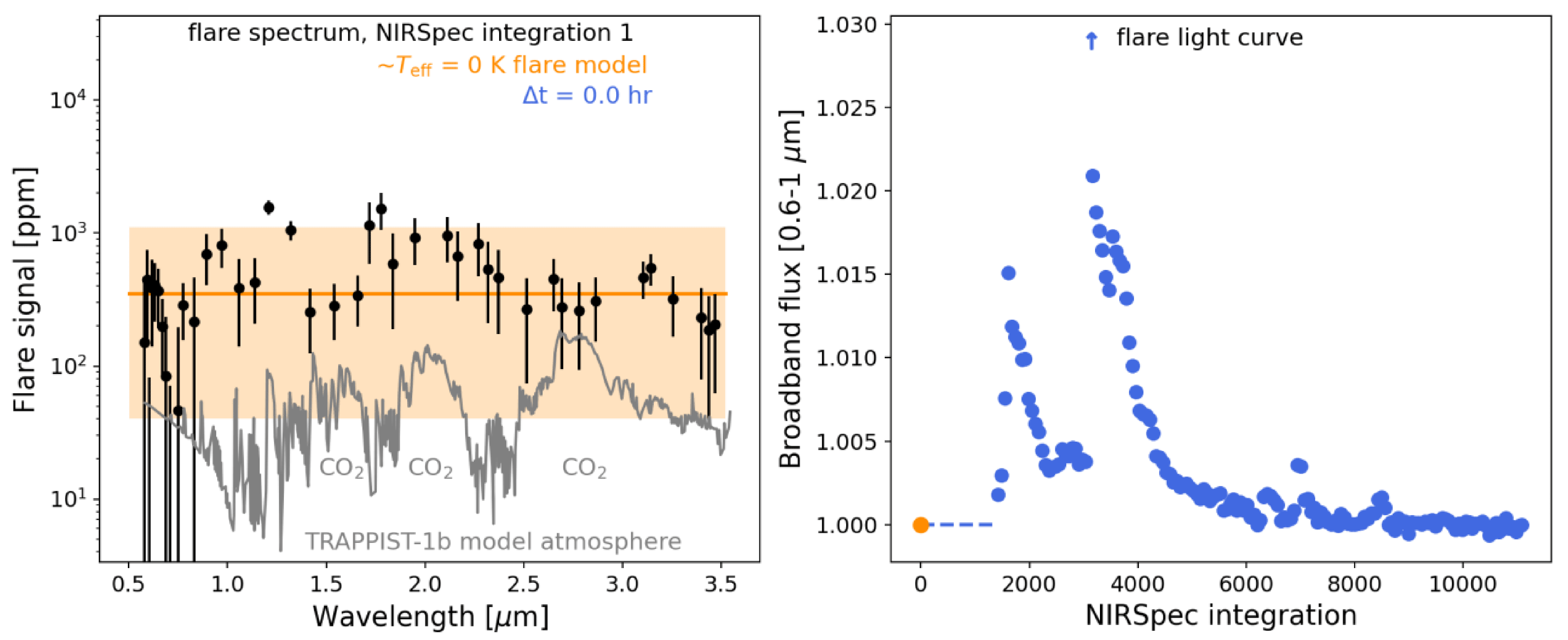
Broadband NIR light curves

Longer wavelength bands release less energy and show a longer decay



Howard+ 2023, ApJ, arXiv:2310.03792

Evolution of the flare continuum in time



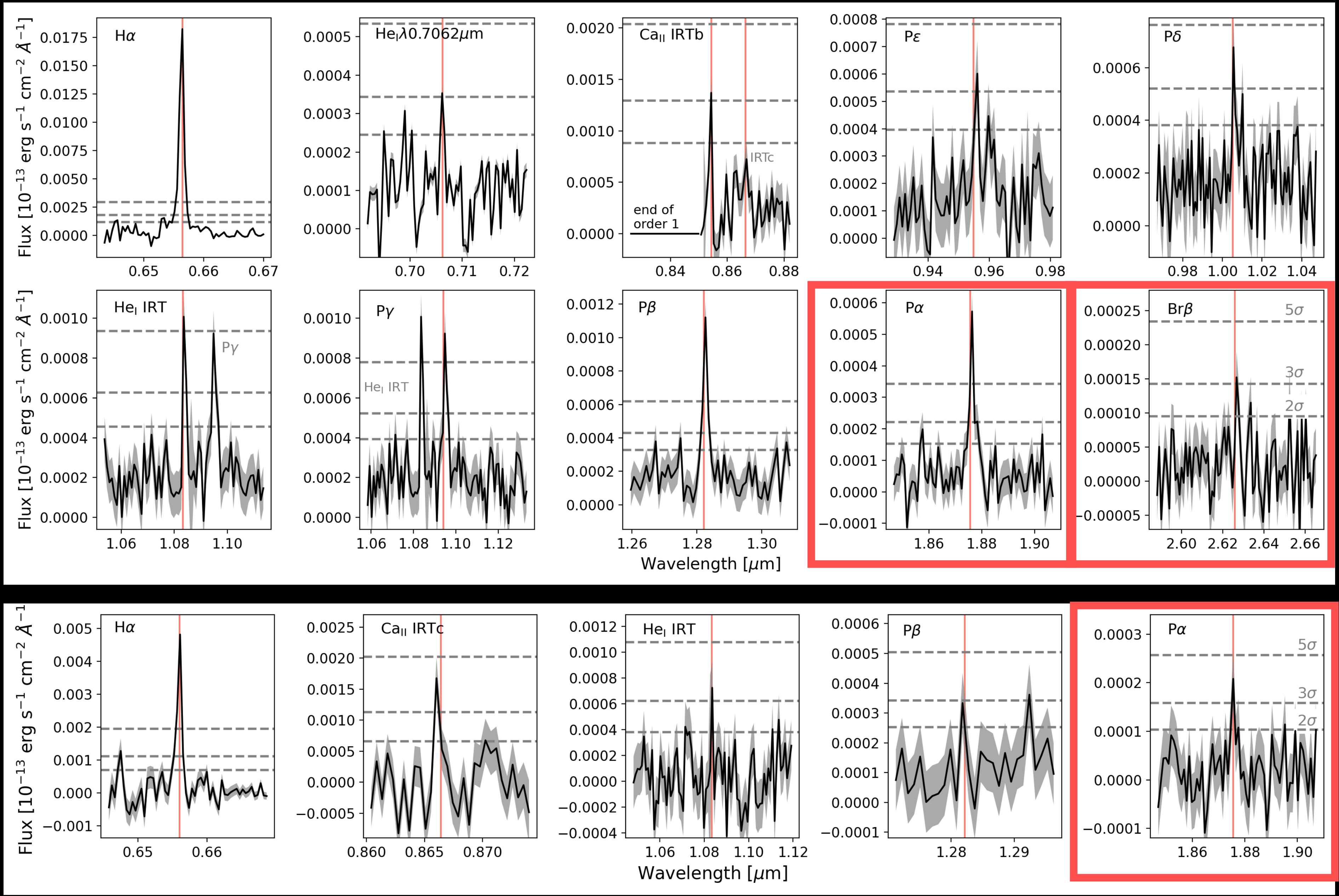
Howard+ 2023, ApJ, arXiv:2310.03792

10-bar CO2 atmosphere model for TRAPPIST-1b reproduced from Lustig-Yaeger+ 2019, AJ 158, 27

NIRISS detects NIR emission lines in the flare-only spectra, including some firsts

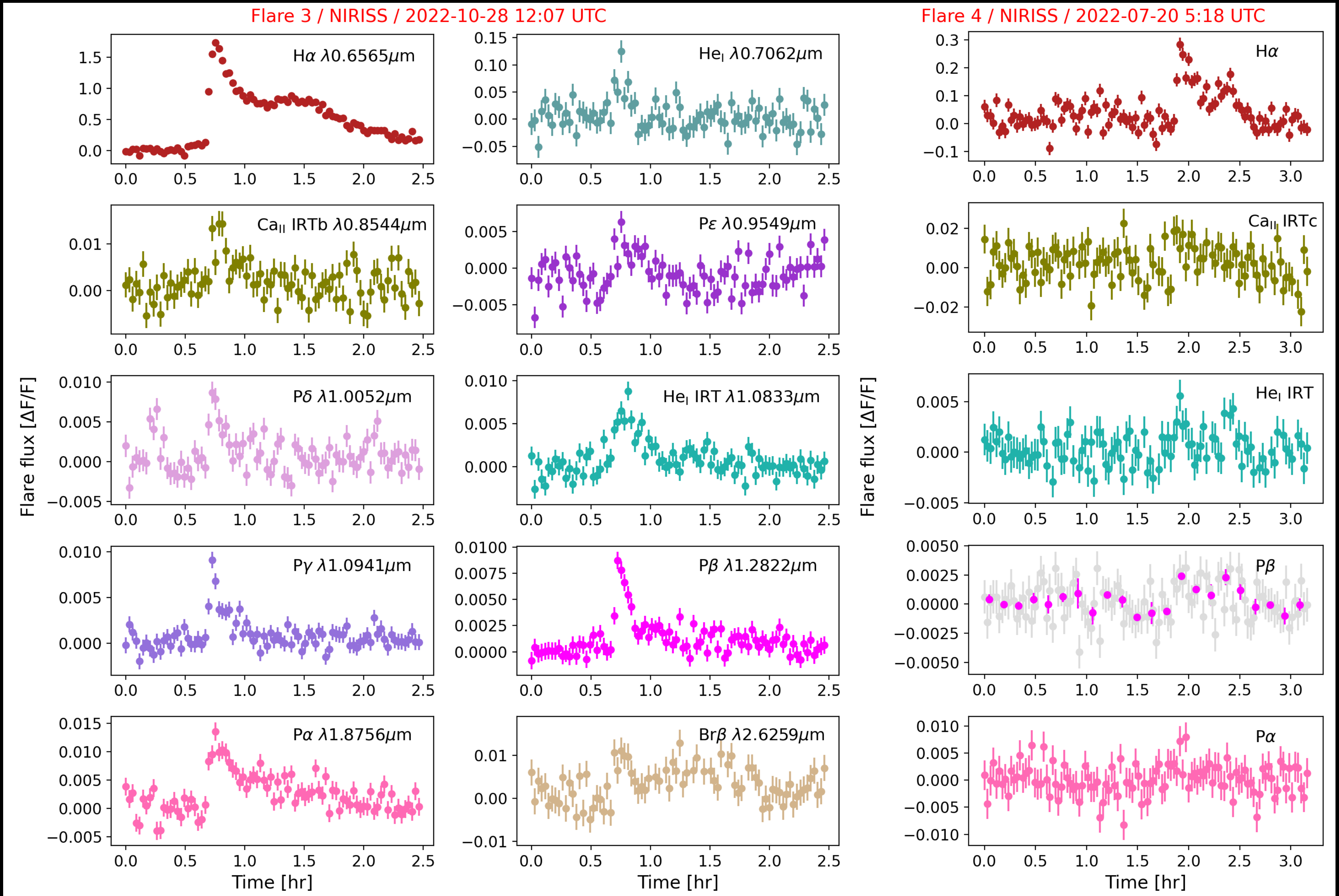
Flare 3 / NIRISS

Flare 4 / NIRISS



Howard+ 2023, ApJ, arXiv:2310.03792

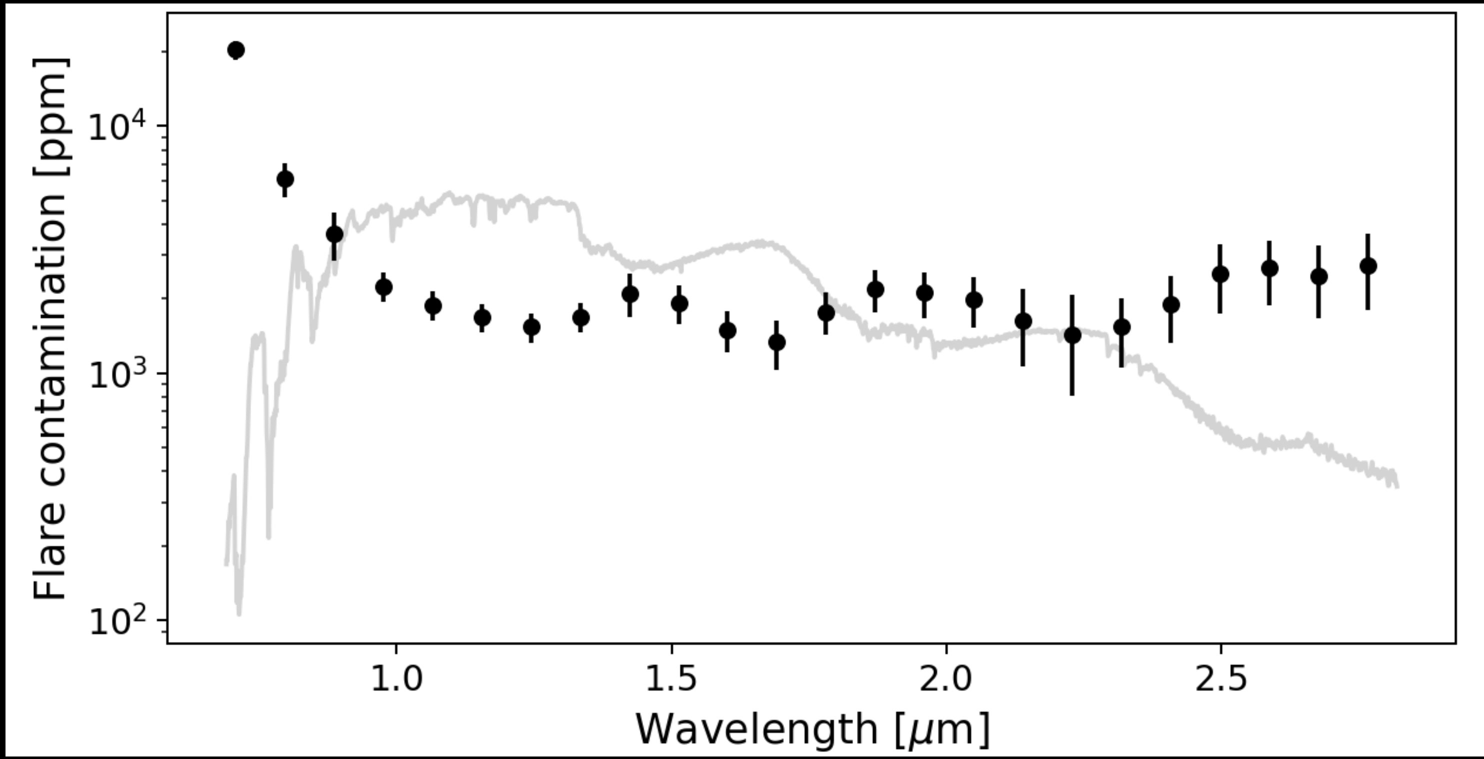
NIRISS detects many flare lines, including some firsts



Howard+ 2023, ApJ, arXiv:2310.03792

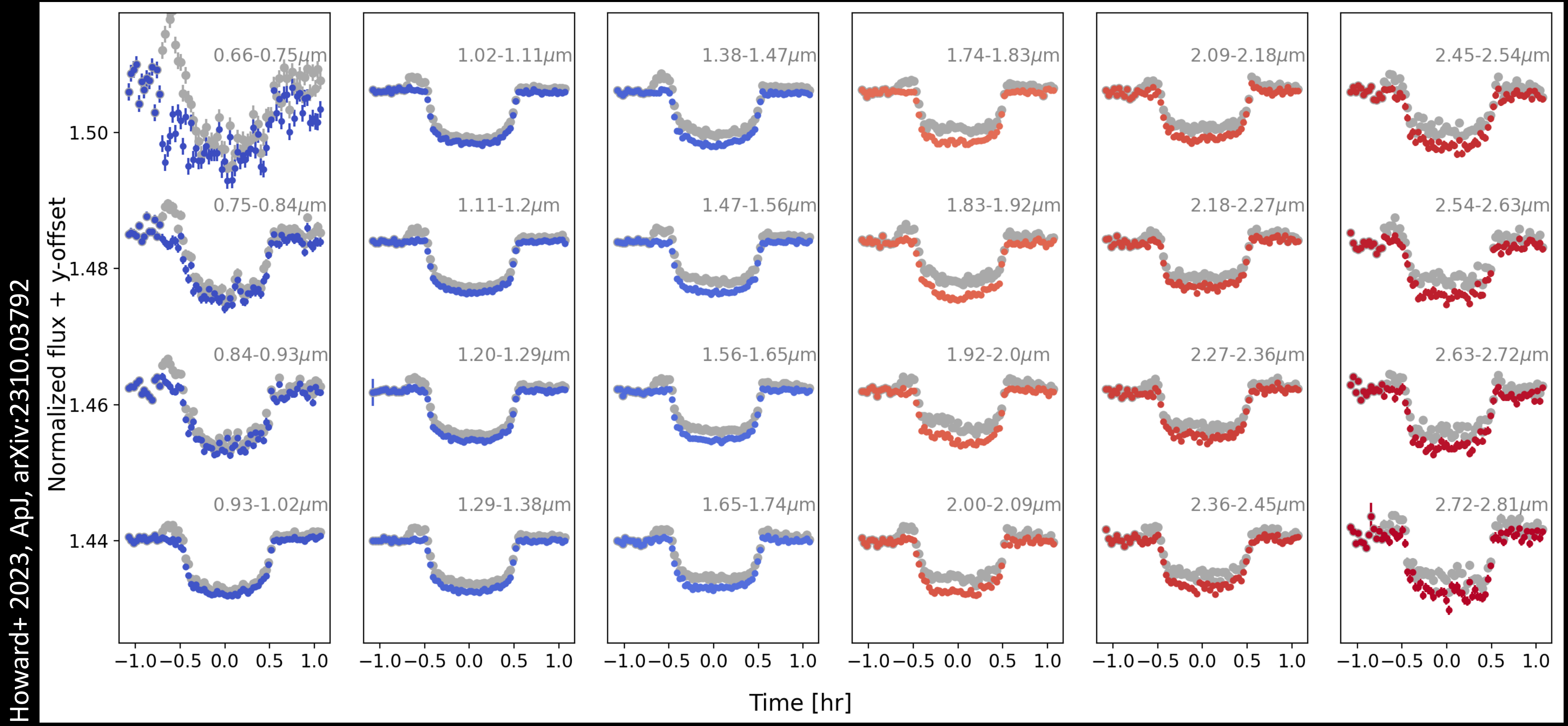
Removing the flare line and continuum from the transit spectrum

Flare contamination ranges from 20000±1700 ppm at 0.7 μm, 2100±400 ppm at 2 μm and 2700±900 ppm at 2.8 μm



Goal: Use our NIRISS flare spectra to mask out lines and subtract the best-fit blackbody from the transit spectrum

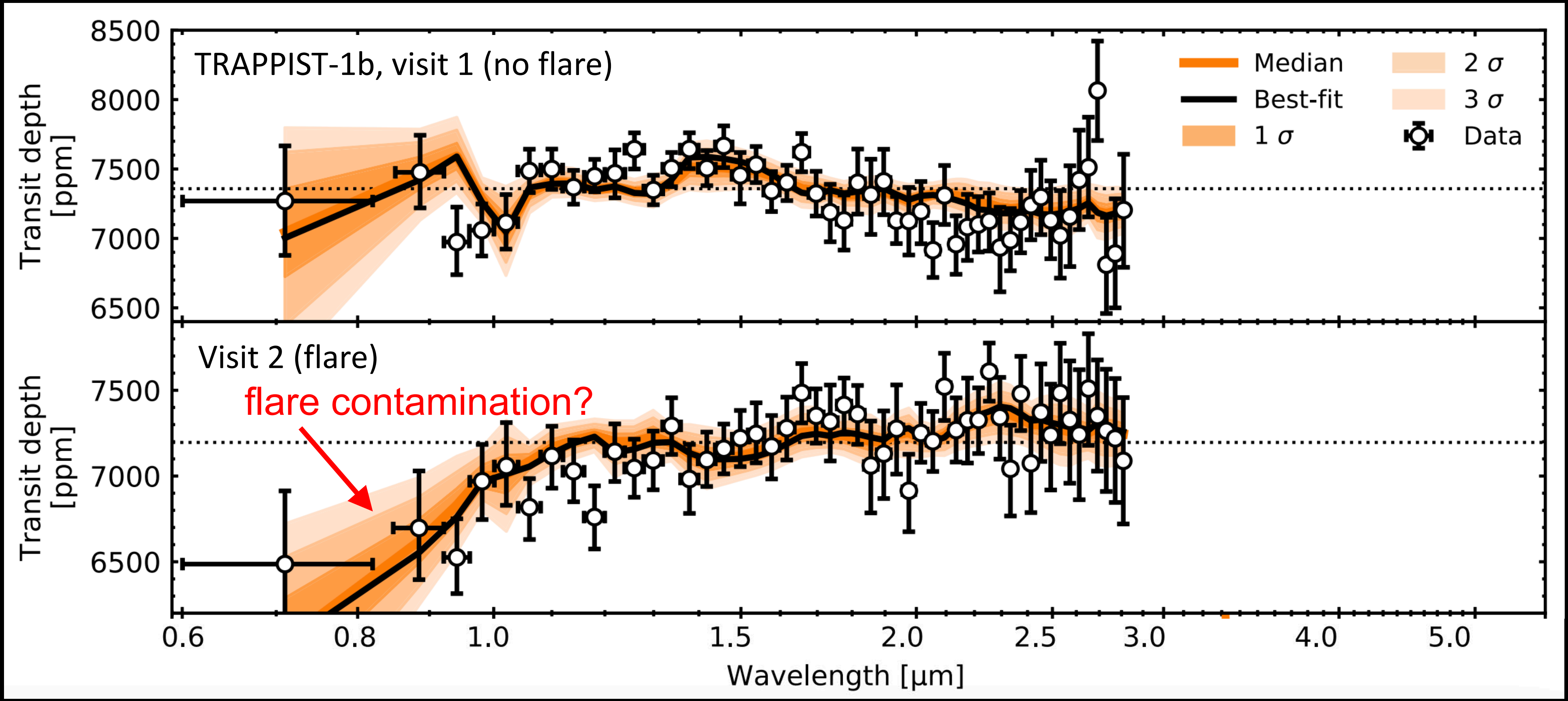
Removing the flare spectrum from the transit of TRAPPIST-1f



Up to 80% of flare contamination can be removed, especially from 1.0—2.4 μm

Next steps: Removal of flare contamination from TRAPPIST-1b transmission spectrum?

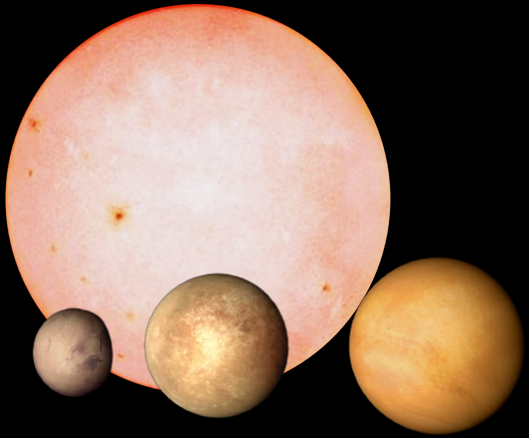
Lim+ 2023, ApJ Letters, arXiv:2309.07047



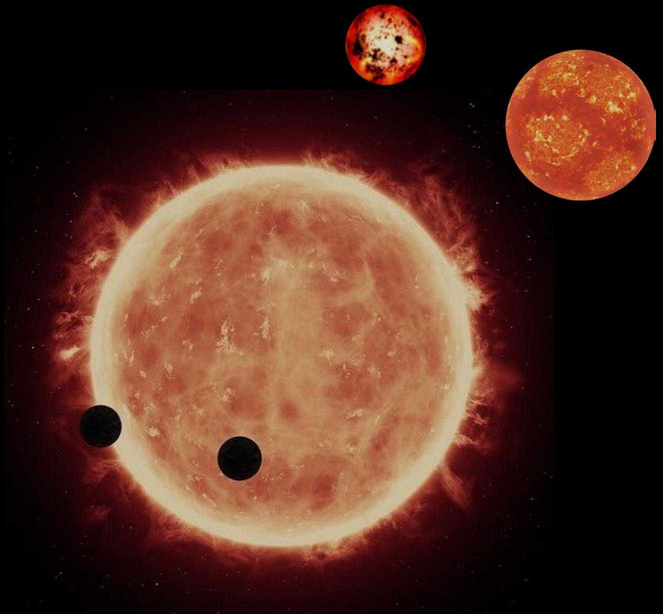
Does flare mitigation have broader applicability?

YES!

AU Mic b
Orbits M1 dwarf flare star
(JWST GTO 1184, likely
Cycle 3 or 4 GO target)



L 98-59 b, c, and d
Orbit M3 flare star
(JWST GO 1201, 1224,
2512, 3730, 3942, 4098)



LTT 1445A b and c
Orbit M3 flare star
(JWST GO 2512, 2708,
likely Cycle 3 or 4 target)

A NEAT opportunity for JWST transit spectroscopy of the TRAPPIST-1 system

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COLLEGE OF ARTS AND SCIENCES


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(Flares Lead)


Adam Kowalski


Alexander Brown

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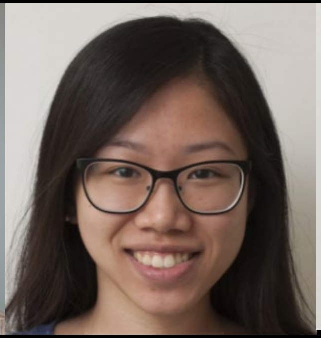
Meredith MacGregor

Université de Montréal

TROTTIER INSTITUTE
FOR RESEARCH ON
EXOPLANETS

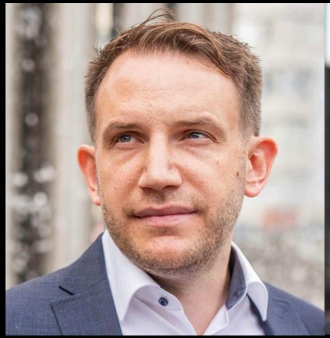

David Lafrenière / PI


Olivia Lim/ PI


Michael Radica

CORNELL UNIVERSITY FOUNDED A.D. 1865


Laura Flagg


Björn Benneke


René Doyon


Pierre-Alexis Roy


Caroline Piaulet

STScI | SPACE TELESCOPE
SCIENCE INSTITUTE


Néstor Espinoza

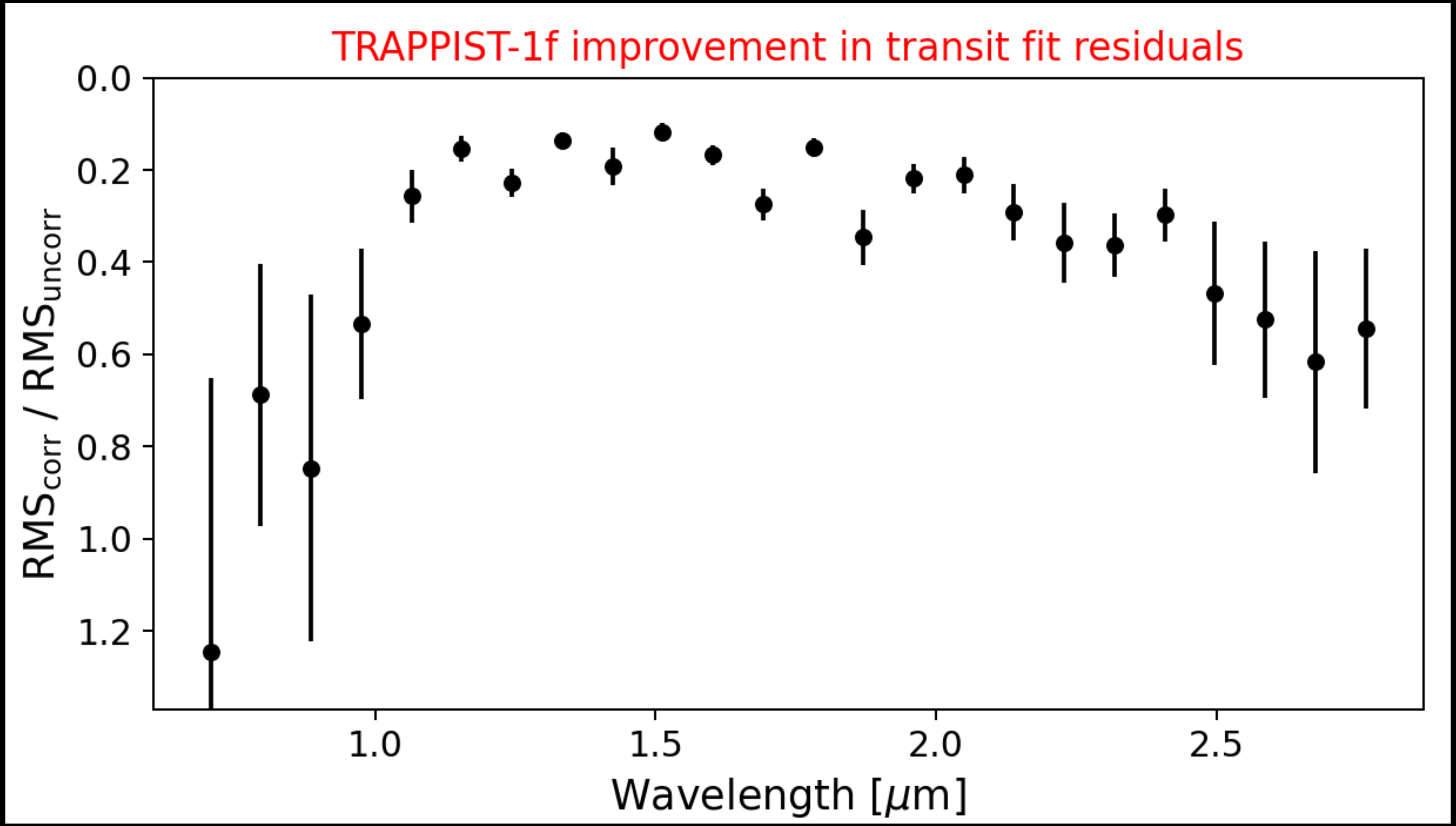
Key takeaways

- Flares drive photochemistry in exoplanet atmospheres and are a key source of unpredictable contamination for transit spectroscopy
- No one wavelength describes a flare, so multi-wavelength observations are needed to understand the energy budgets of flares
- We characterize the continuum spectra of flares in the NIR and find up to 80% of contamination can be removed from transit spectroscopy
- Flare mitigation may be a viable pathway to increase the impact of transit observations of small planets around active stars

Backup Slides

Assessing the improvement to the transit light curves after flare removal

Howard+ 2023, ApJ, in press

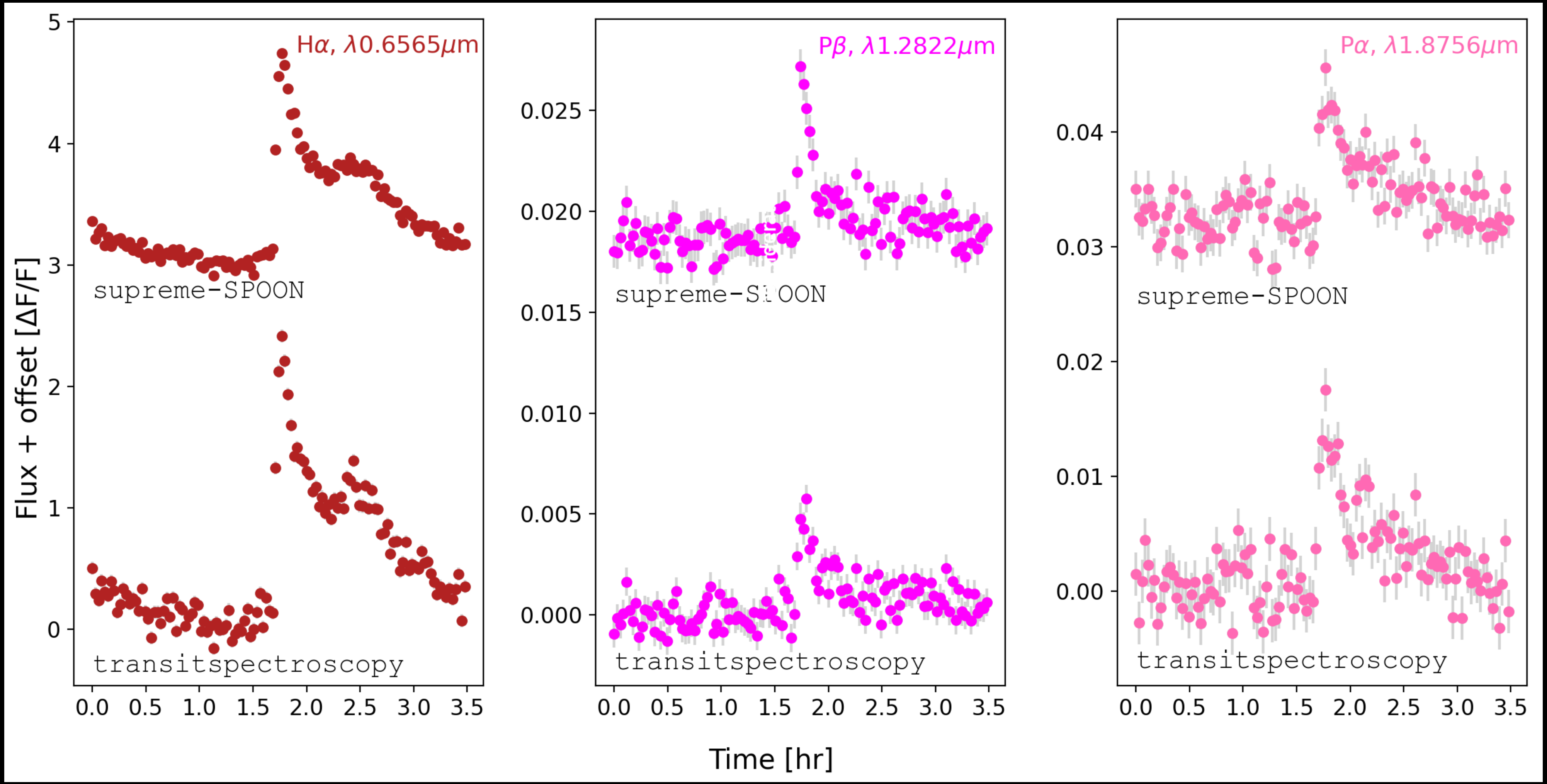


We find up to 80% of flare contamination can be removed, with mitigation most effective from 1.0—2.4 μm

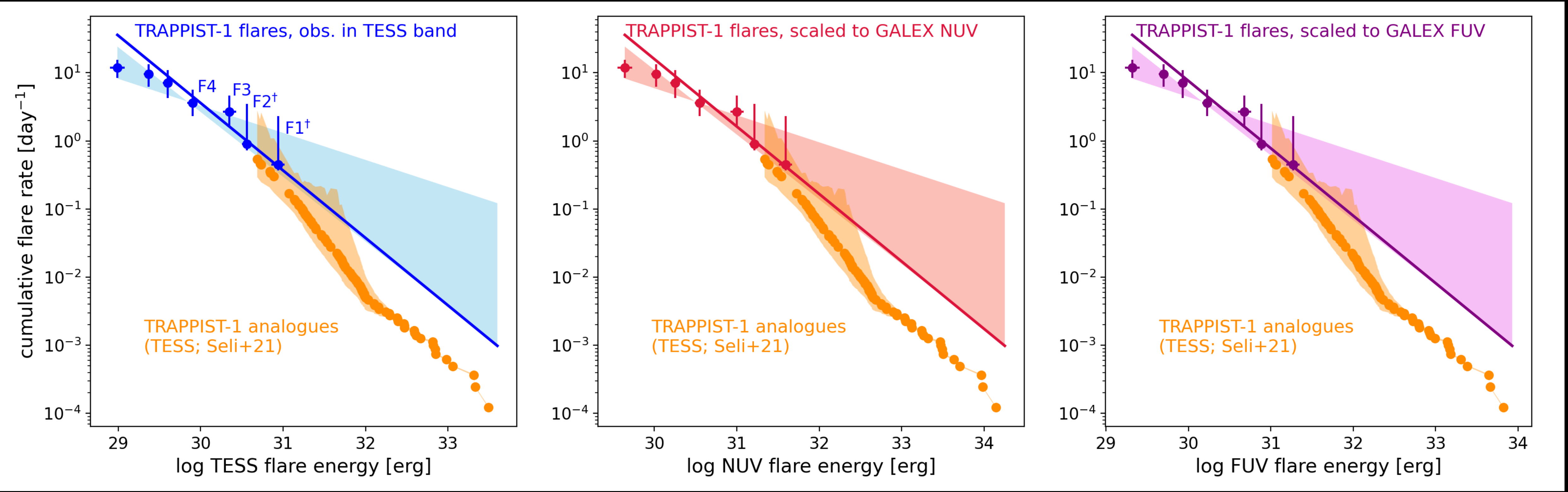
Validating flare light curves with multiple pipelines

NIRISS flares are reduced with both `supreme-SPOON` (Radica+ 2023) and `transitspectroscopy` (Espinoza 2022), NIRSpec flares with `Eureka!` (Bell+ 2022)

Howard+ 2023, ApJ, under consideration



Flare frequency distribution of TRAPPIST-1 in the TESS bandpass



Reversed Paschen decrement of M-dwarf flares