Advances in flare mitigation and chemistry for JWST observations of TRAPPIST-1 and applications to the Early eVolution Explorer

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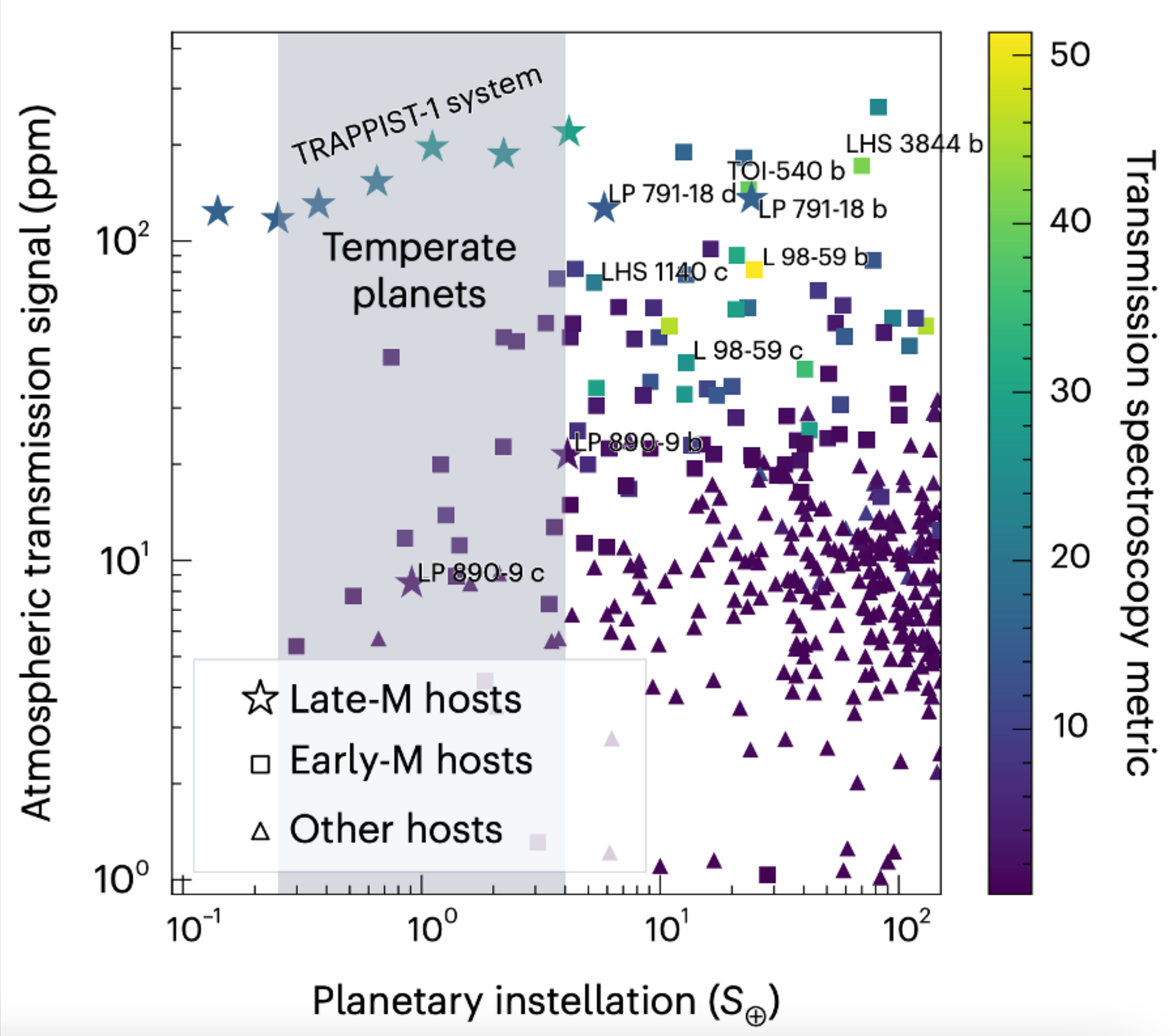
KnowThyStar2, Feb 6, 2025

TRAPPIST-1 as a benchmark for characterizing the habitability of M-dwarf systems

TRAPPIST-1 presents our best chance of detecting secondary atmospheres with JWST transmission spectroscopy

However, time-variable contamination from spots and flares exists at levels 2.5—10X greater than that of any atmospheric signals

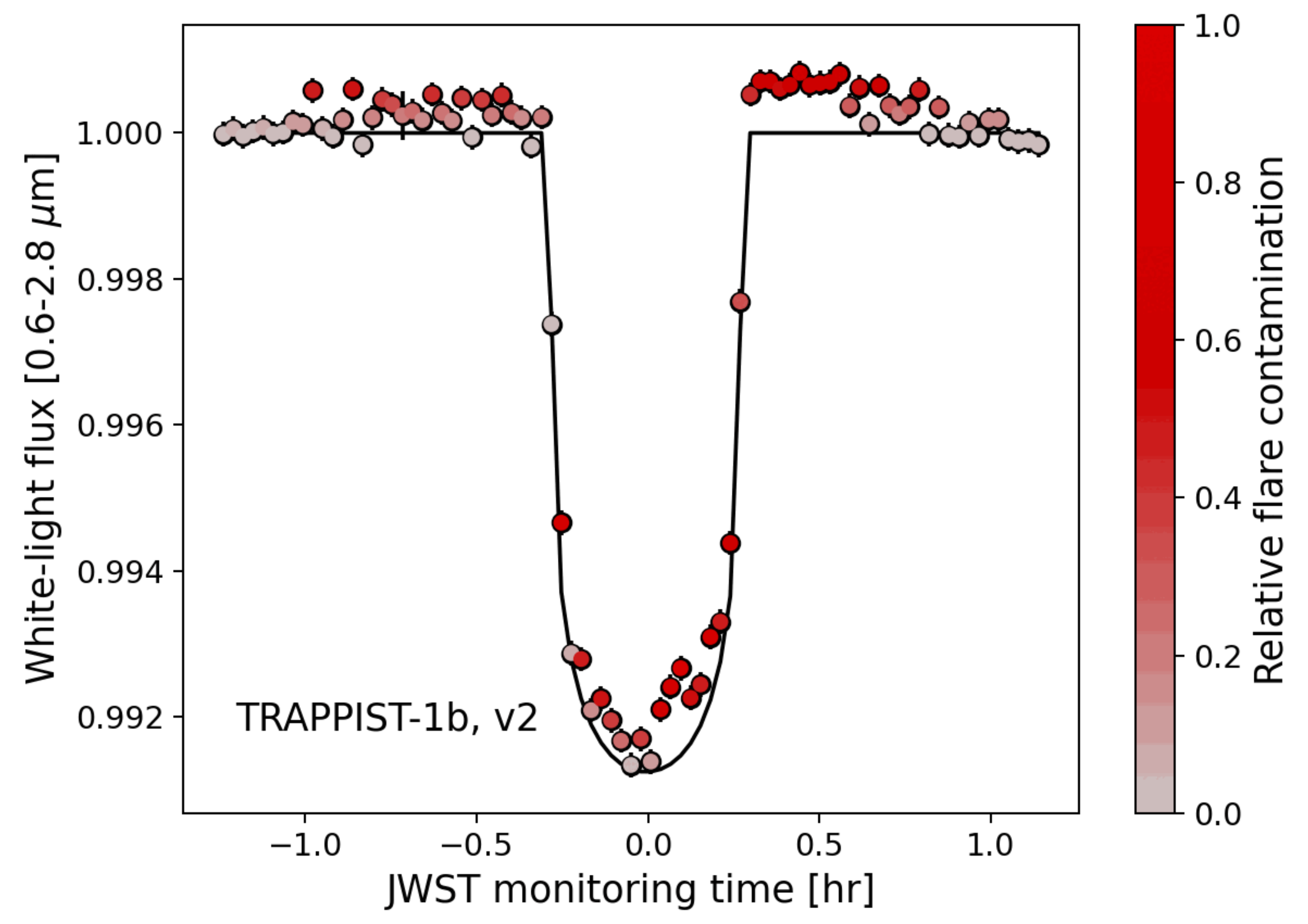
While spot mitigation may be achieved from transits of airless planets, the fast timescales of stellar flares require physical flare models



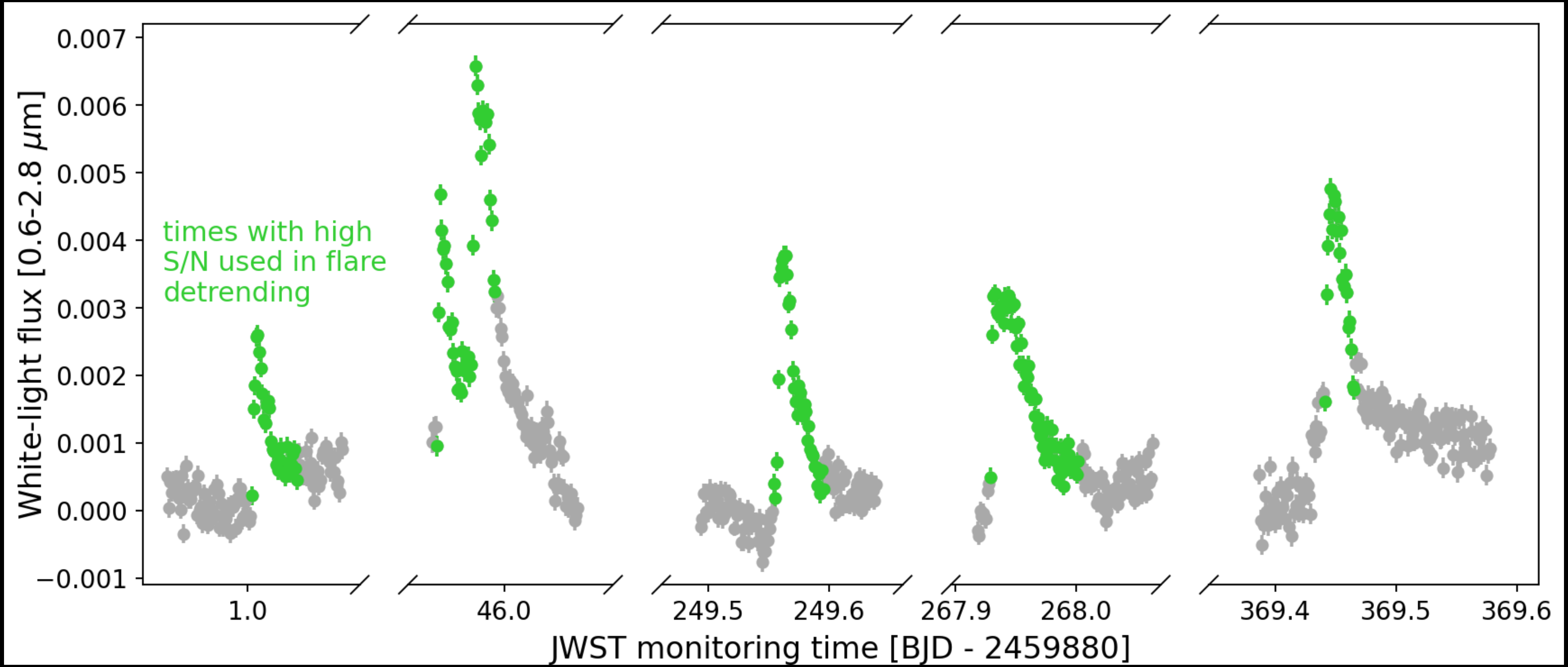
TRAPPIST-1 JWST Community Initiative, de Wit+ 2024, NatAst 8, 810

But is TRAPPIST-1 really our best chance to detect secondary atmospheres?

So far, flare contamination has been observed in about 60% of NIRISS and NIRSpec transit observations of TRAPPIST-1 b, c, d, f, and g



Spectral time series enable flare model tests to remove contamination



We test flare forward models on 189 separate integrations of 104 s obtained during the flare peak (5.5 hr in all), observed within the NEAT collaboration (PI: D. Lafrenière)

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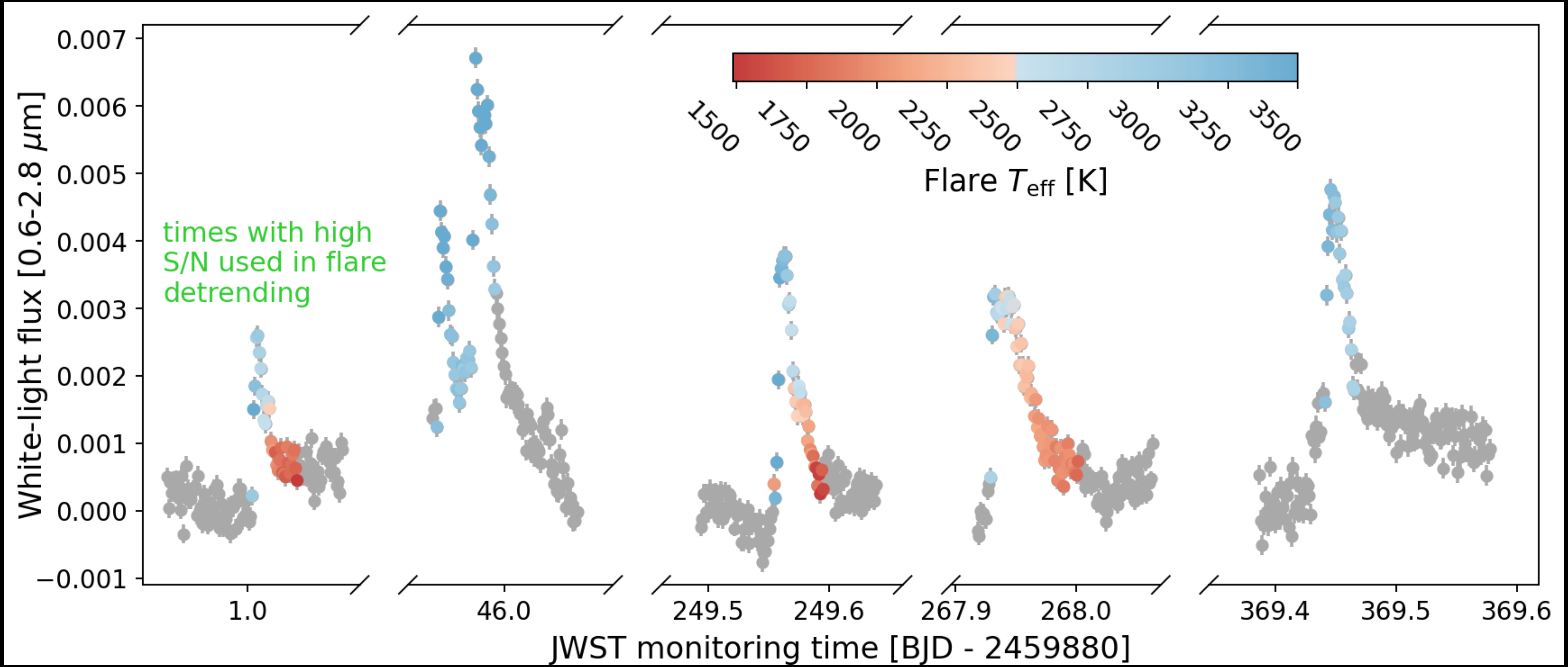

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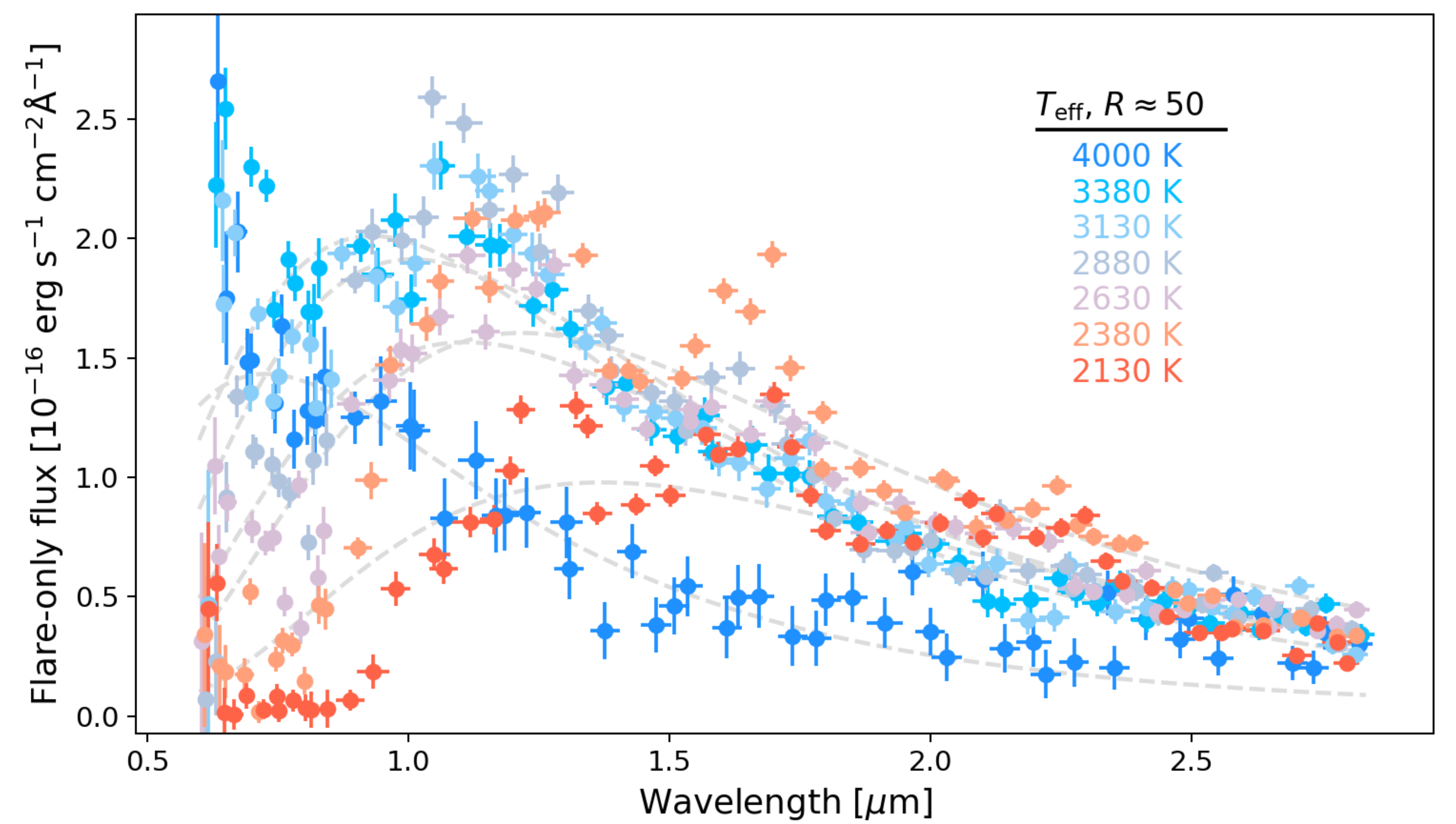
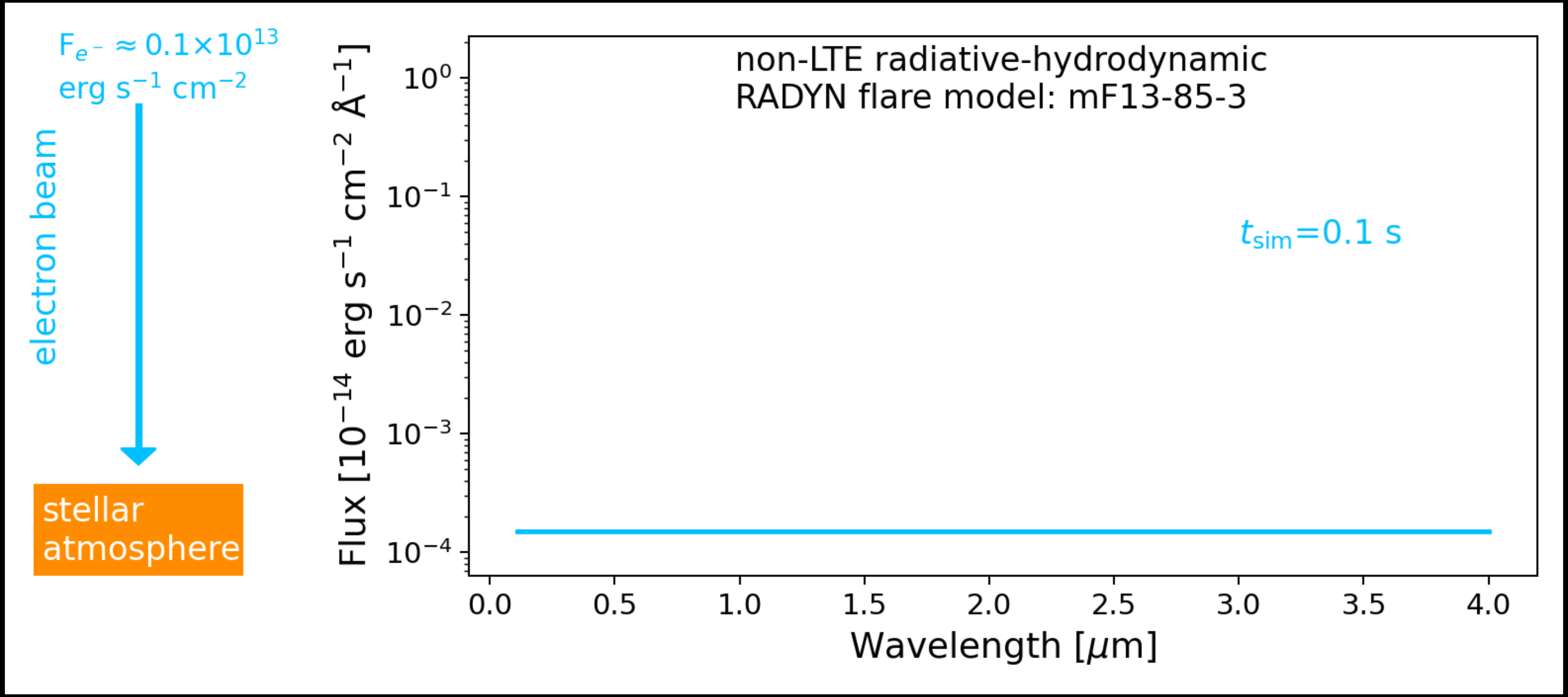
Fiducial flare spectra for a range of flare effective temperatures



RADYN: a fully self-consistent radiative-hydrodynamic tool for flare modeling



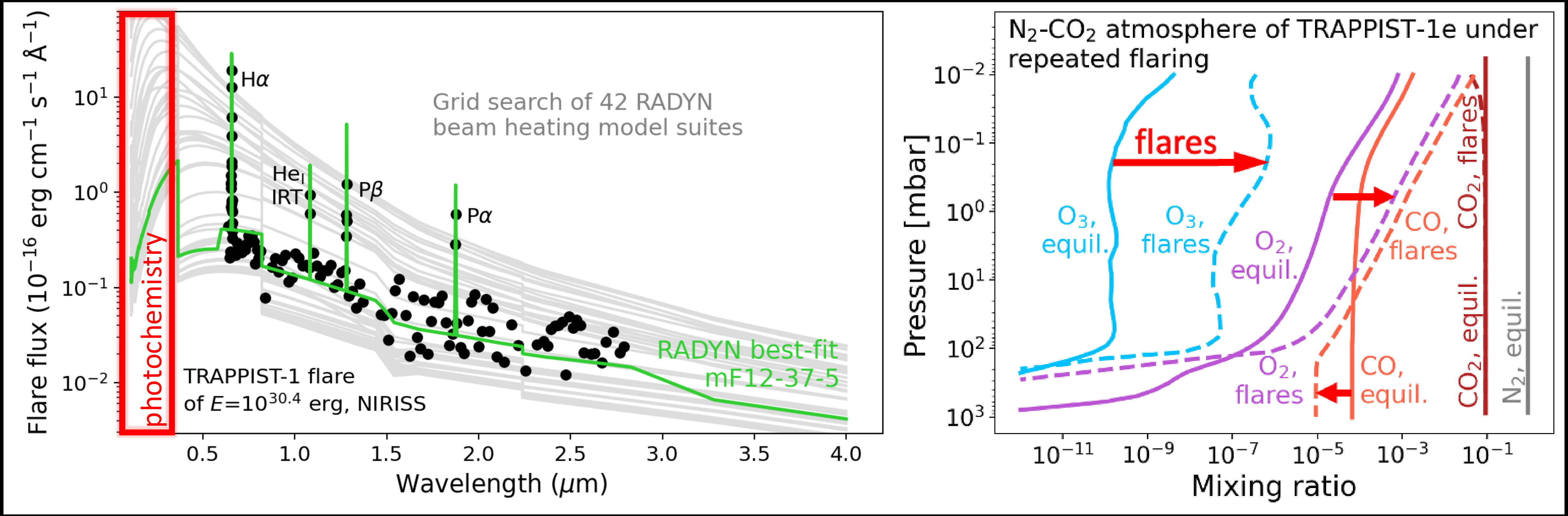
Non-LTE flare heating models (e.g. F13-85-3) are described by an electron beam with:

(1) a maximum electron flux (e.g. 10^{13} erg s^{-1} cm^{-2})

(2) a minimum electron cutoff energy (e.g. 85 keV)

(3) a power law index $\delta_{electron}$ of the relative distribution of energies (e.g. δ=3)

Grid search identification of best-fit RADYN models can help predict photochemistry

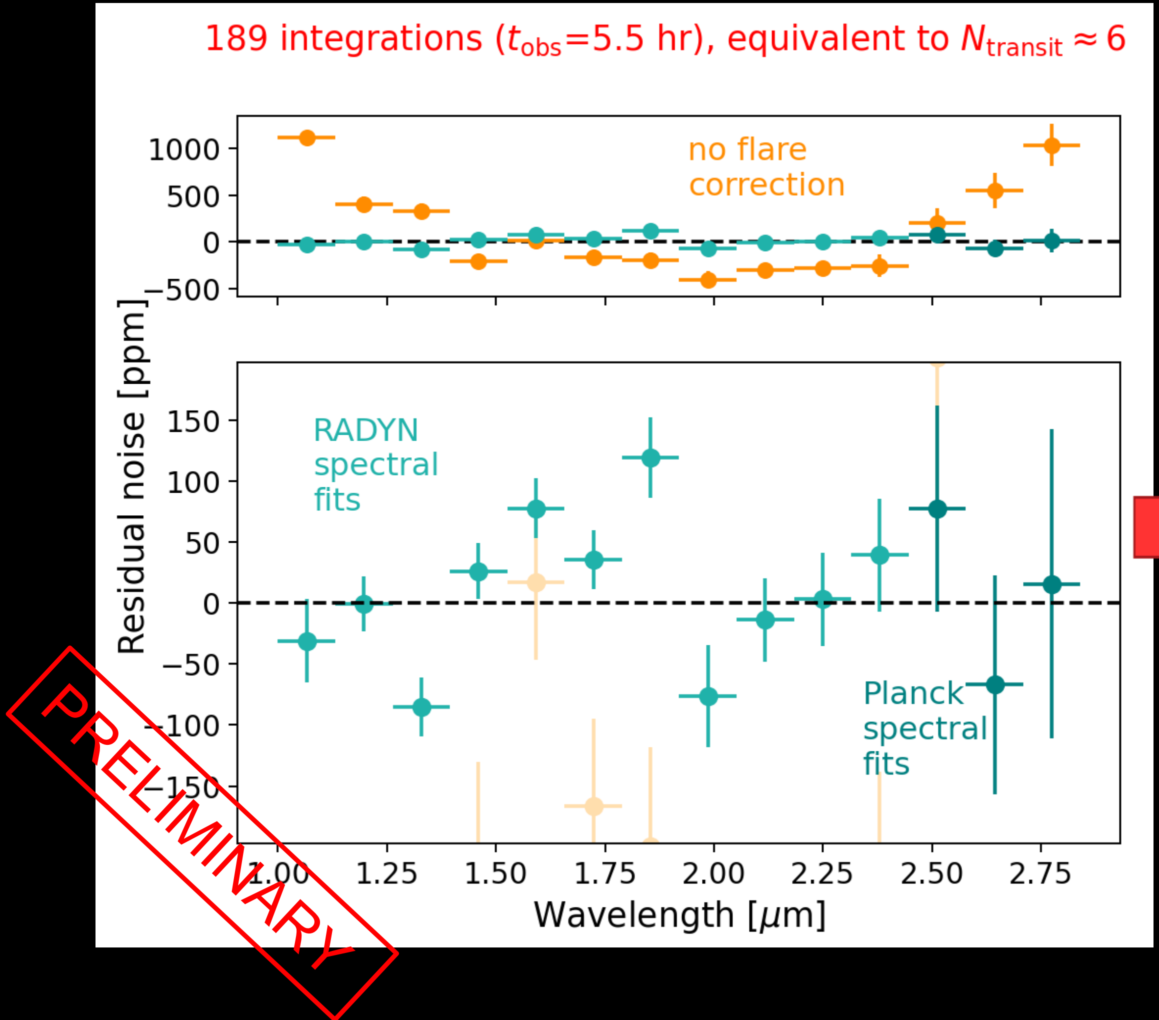


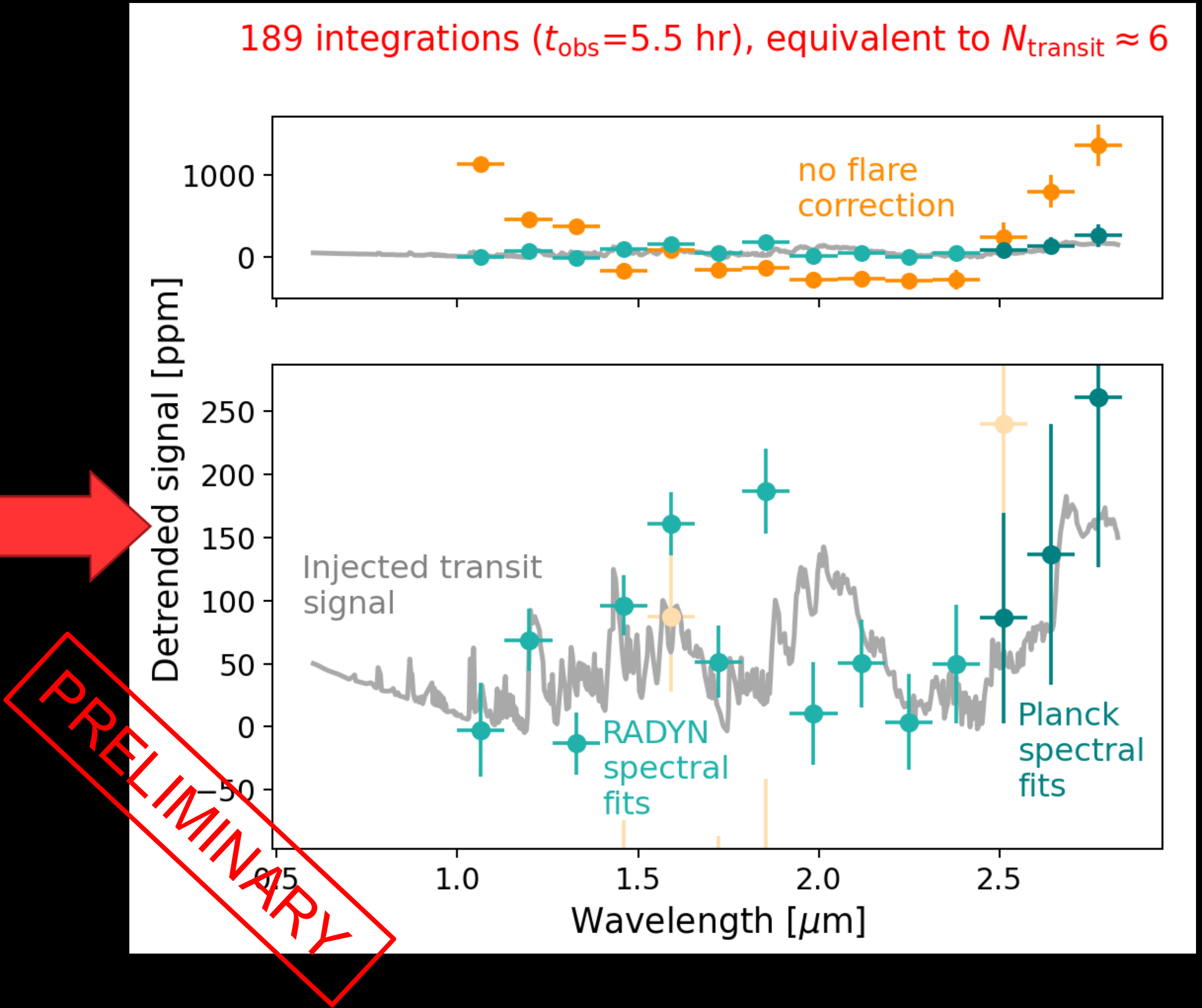
Howard+ 2023, ApJ 959, 64; Kowalski+ 2024, ApJ 969, 121

Hu, Yang, (incl. Howard)+ 2025, in prep

The new RADYN model grid of Kowalski+ 2024 spans four orders of magnitude in electron beam properties, enabling stringent tests against NIR flare spectra

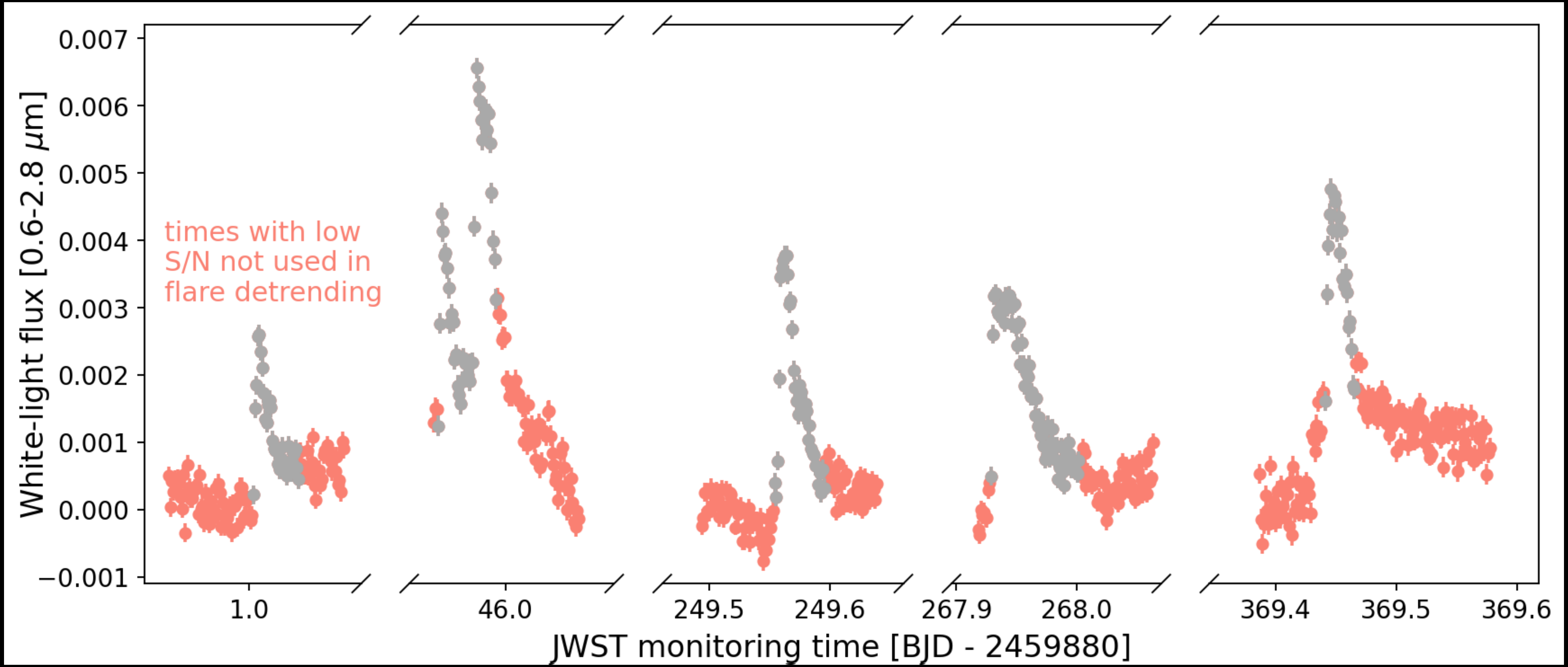
Preliminary results: sub-100 ppm residuals appear possible in “ideal” circumstances





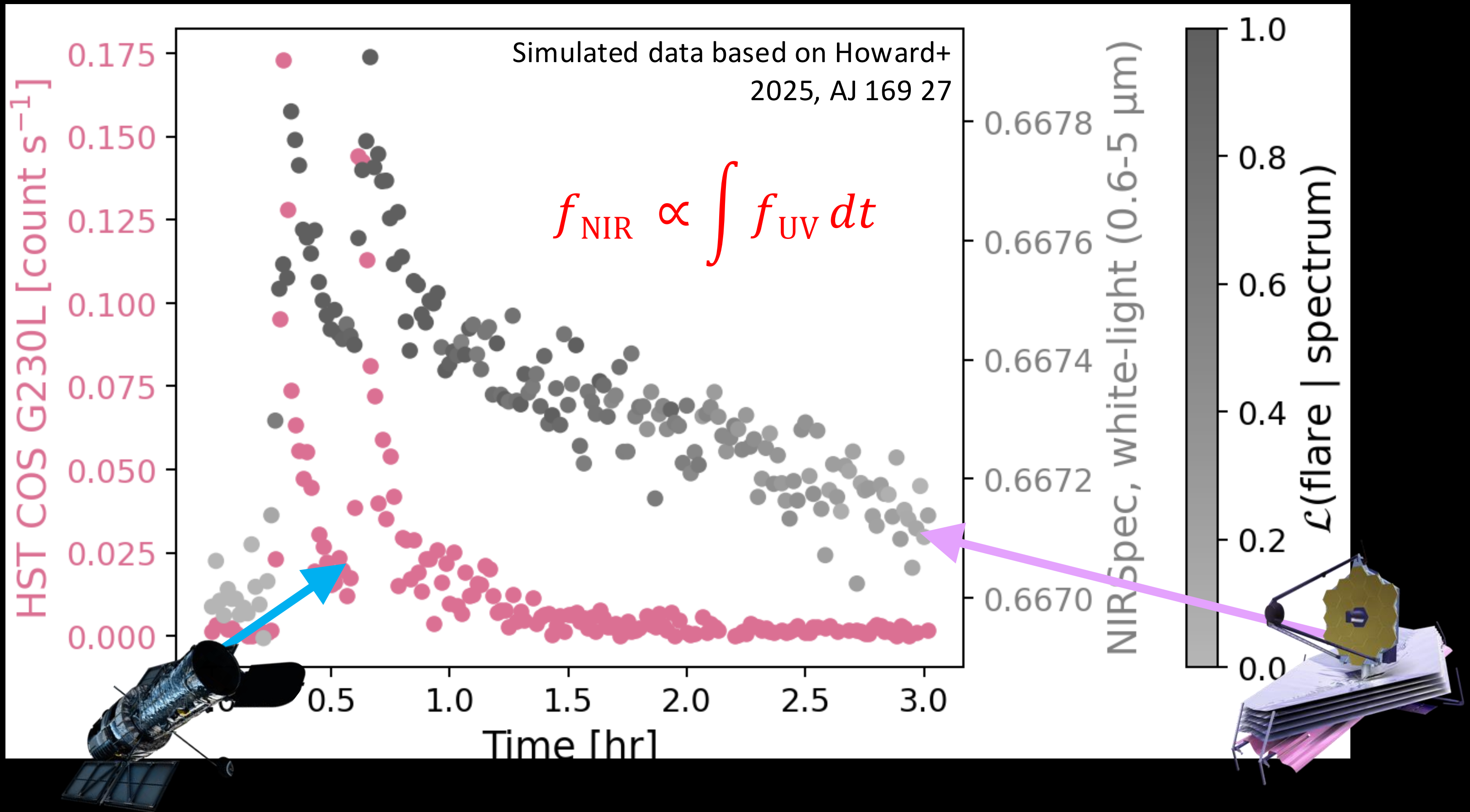
Only achieved for integrations with high signal/noise flares and fast-rise, exponential decay temperature evolution

What about flare correction in “non-ideal” (normal) circumstances?



~80% of integrations impacted by flares will occur during the low S/N flare decay

The opportunity of simultaneous NUV observations for stellar flare mitigation



Simulated data based on Howard+ 2025, AJ 169 27

Although decontamination in the absence of NUV data works well during the peak, the likelihood of correctly identifying decay phase emission without the UV is lower.

The Early eVolution Explorer (EVE), an astrophysics Small Explorer concept

EVE will investigate the earliest stages in the shared evolutionary pathways of stars and planets, with three goals*

(1) Detect dozens of planets younger than 30 Myr to assess their H_2O inventory

(2) Determine the effects of flares on atmospheric photochemistry

(3) Discover how accretion impacts angular momentum transport in young disks

EVE is a multi-wavelength successor to TESS:

- ✓ Simultaneous NUV, optical and IR photometry of 10^4 young stars
- ✓ Observes nearby clusters at 30 s cadence and with 20-30 d stares
- ✓ Three co-mounted telescopes of 10—20 cm and a 25 deg^2 field

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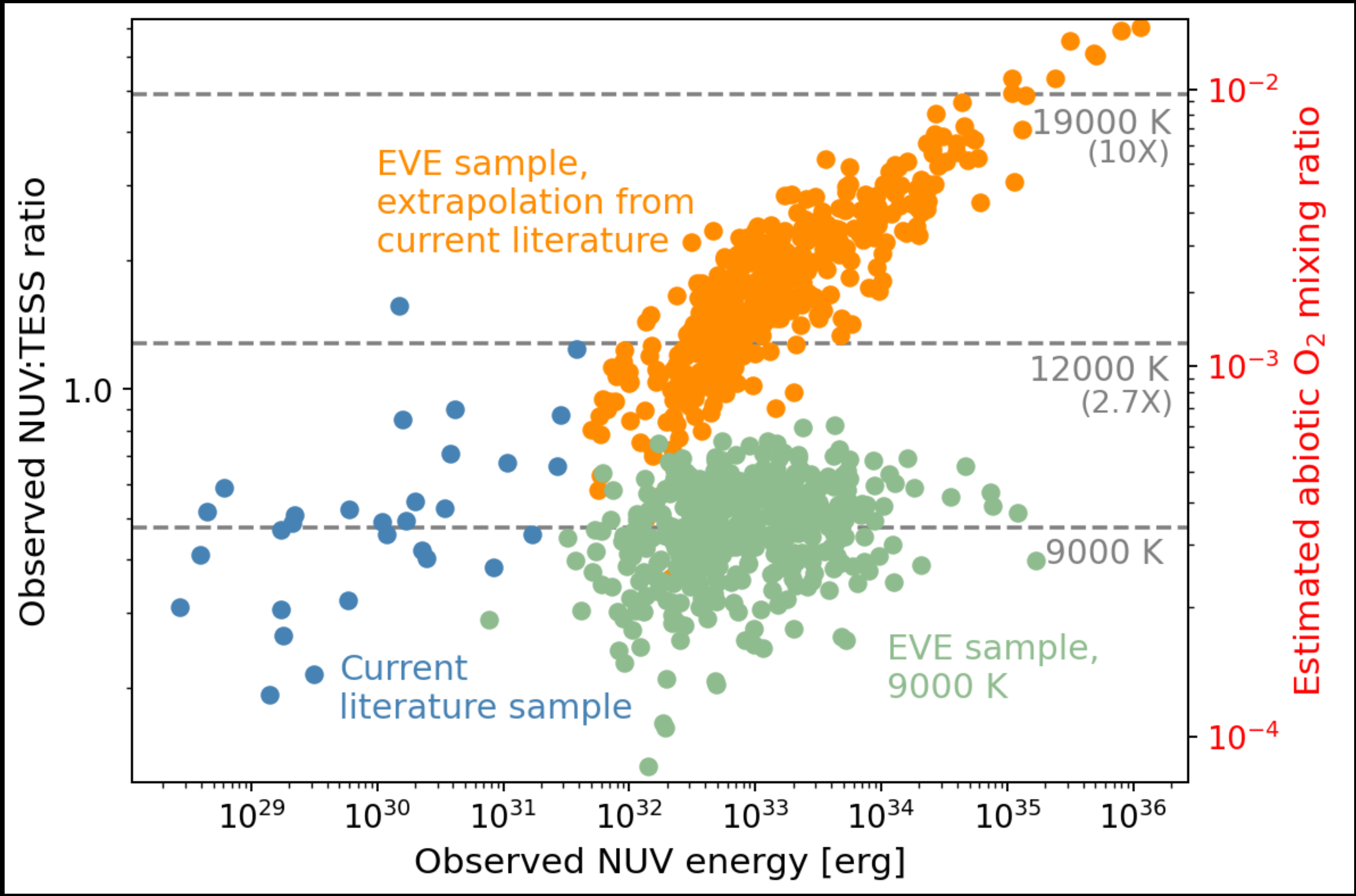
*and ancillary science goals, e.g. asteroseismology of low mass stars

The EVE flare objective: hypothesis and prediction

Few simultaneous observations of large flares exist, but they likely dominate the radiation environments of young planets

EVE will detect 650±100 events in Year 1, enabling the first tests of the UV:optical ratio across *O*(10^4) in flare size



Howard+ 2025, AJ 169, 27

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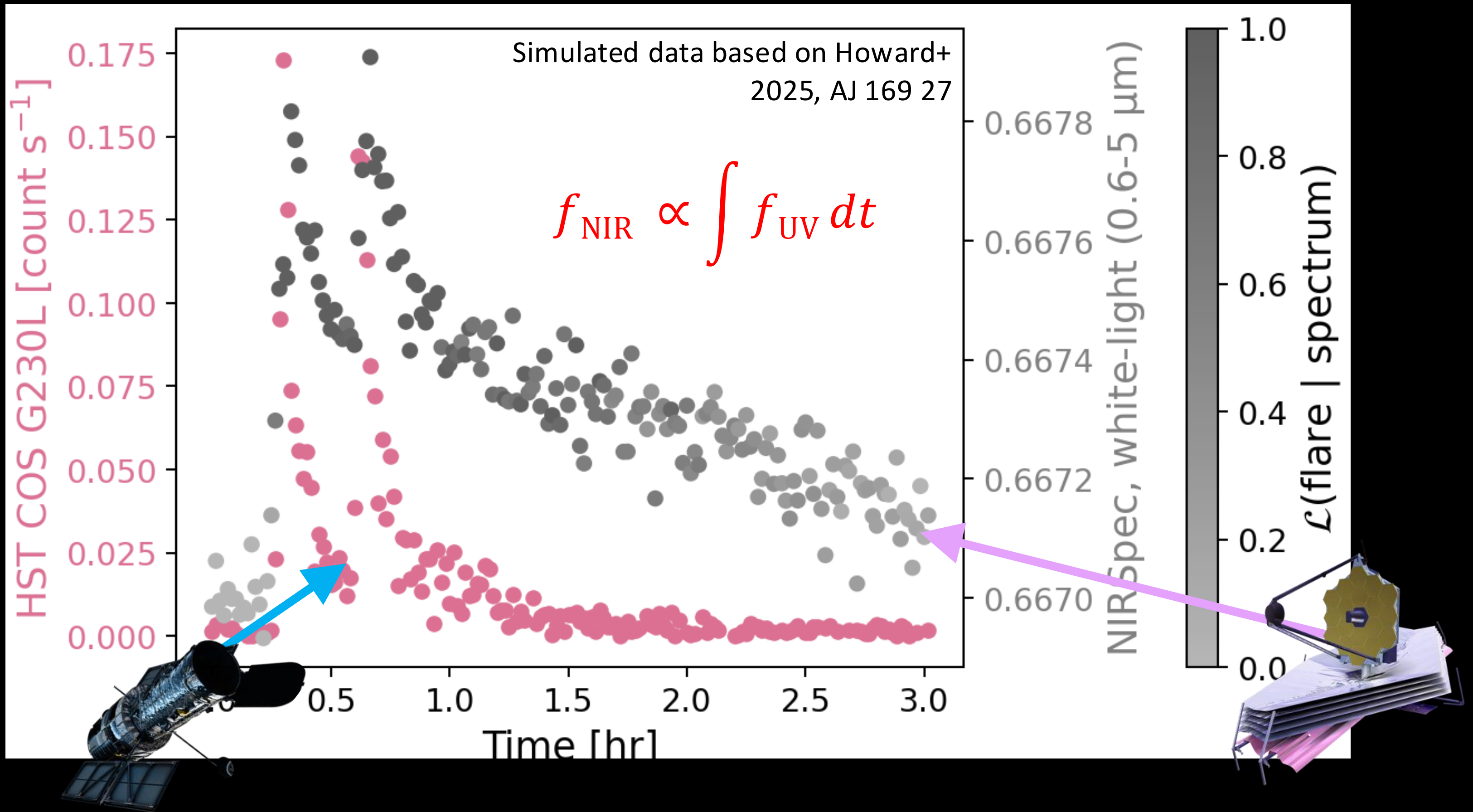
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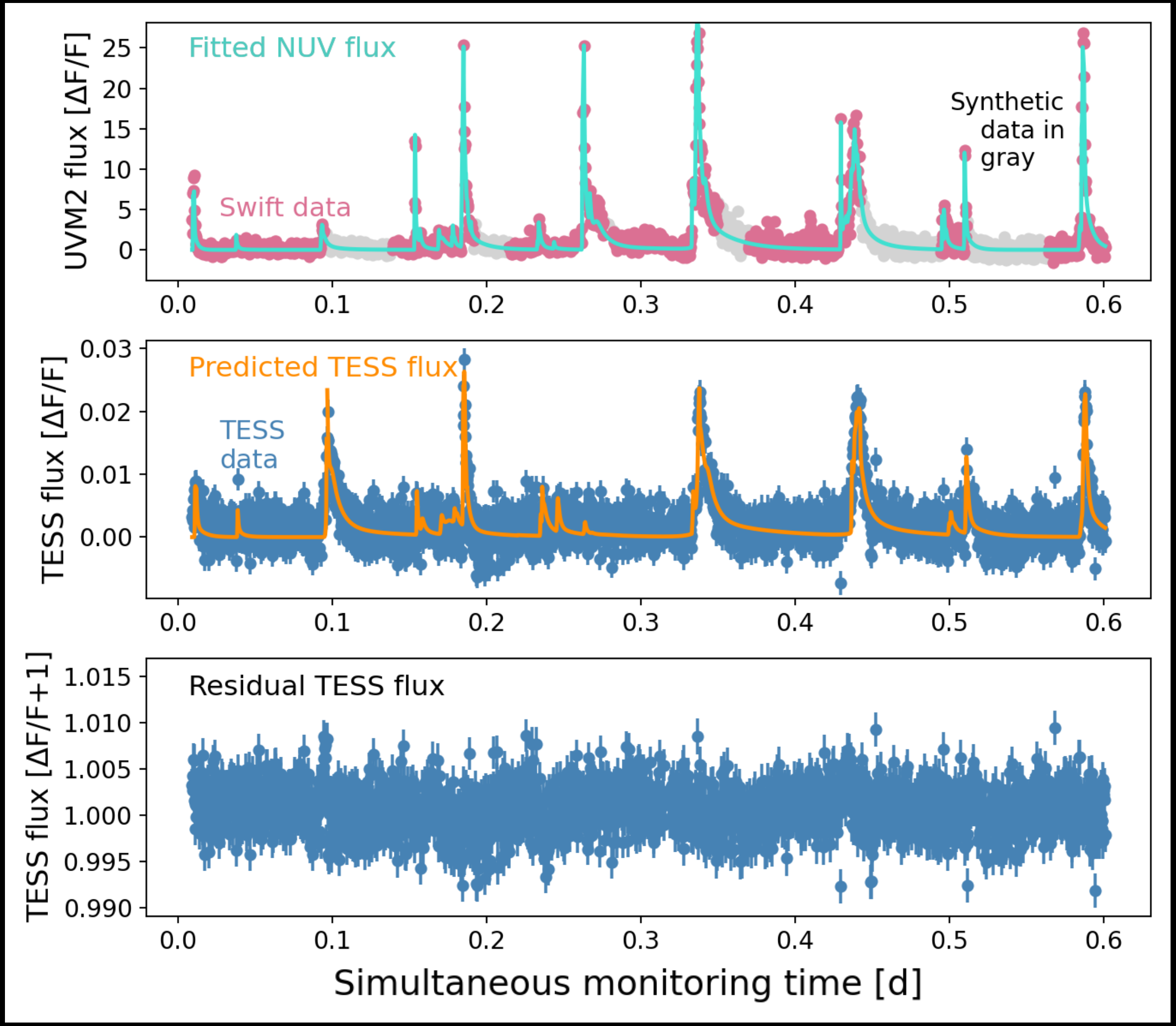
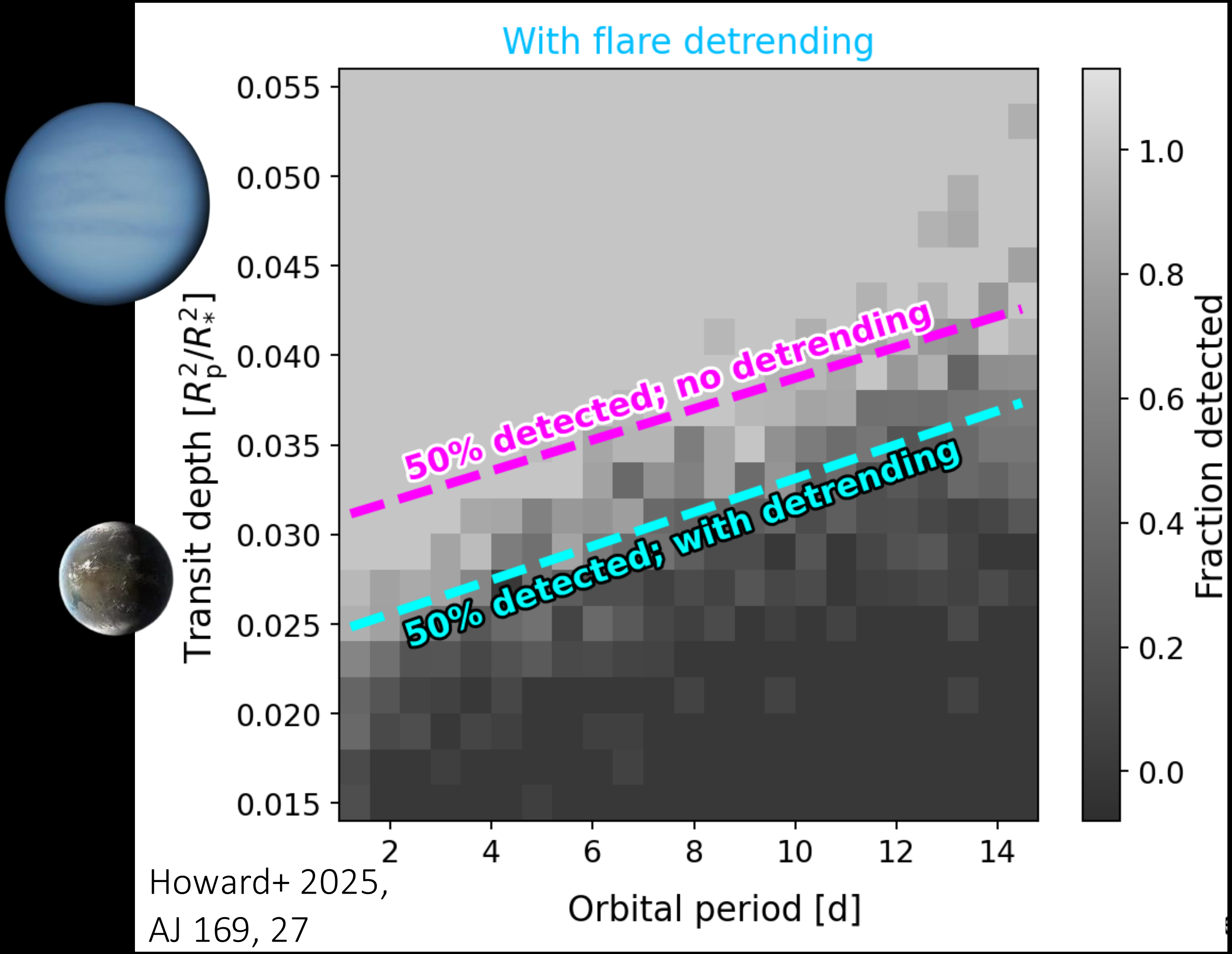
EVE will model and remove flares from optical data using simultaneous NUV data





Howard+ 2025, AJ 169, 27

Flare detrending increases sensitivity in transit depth by 20%, an increase of $0.44R_\oplus$ for a K7 dwarf that enables the detection of super-Earths

The Early eVolution Explorer (EVE), an astrophysics Small Explorer concept

EVE science team:

PI: Meredith MacGregor / JHU
Deputy PIs: Ann Marie Cody / SETI
Evgenya Shkolnik / ASU
Project Scientist: Mark Swain / JPL

Exoplanets Lead: Jenn Burt / JPL
Activity Lead: Ward Howard / CU Boulder
Accretion Lead: Laura Venuti / SETI

EVE
EARLY eVOLUTION EXPLORER

Neal Turner, Nick Wogan, Connor Robinson, Eric Gaidos, Adina Feinstein, George Zhou, Andrew Mann, James Rogers, Sydney Vach, Lukas Gehrig, Yasuhiro Hasegawa, Chris Johns-Krull, Rachel Osten

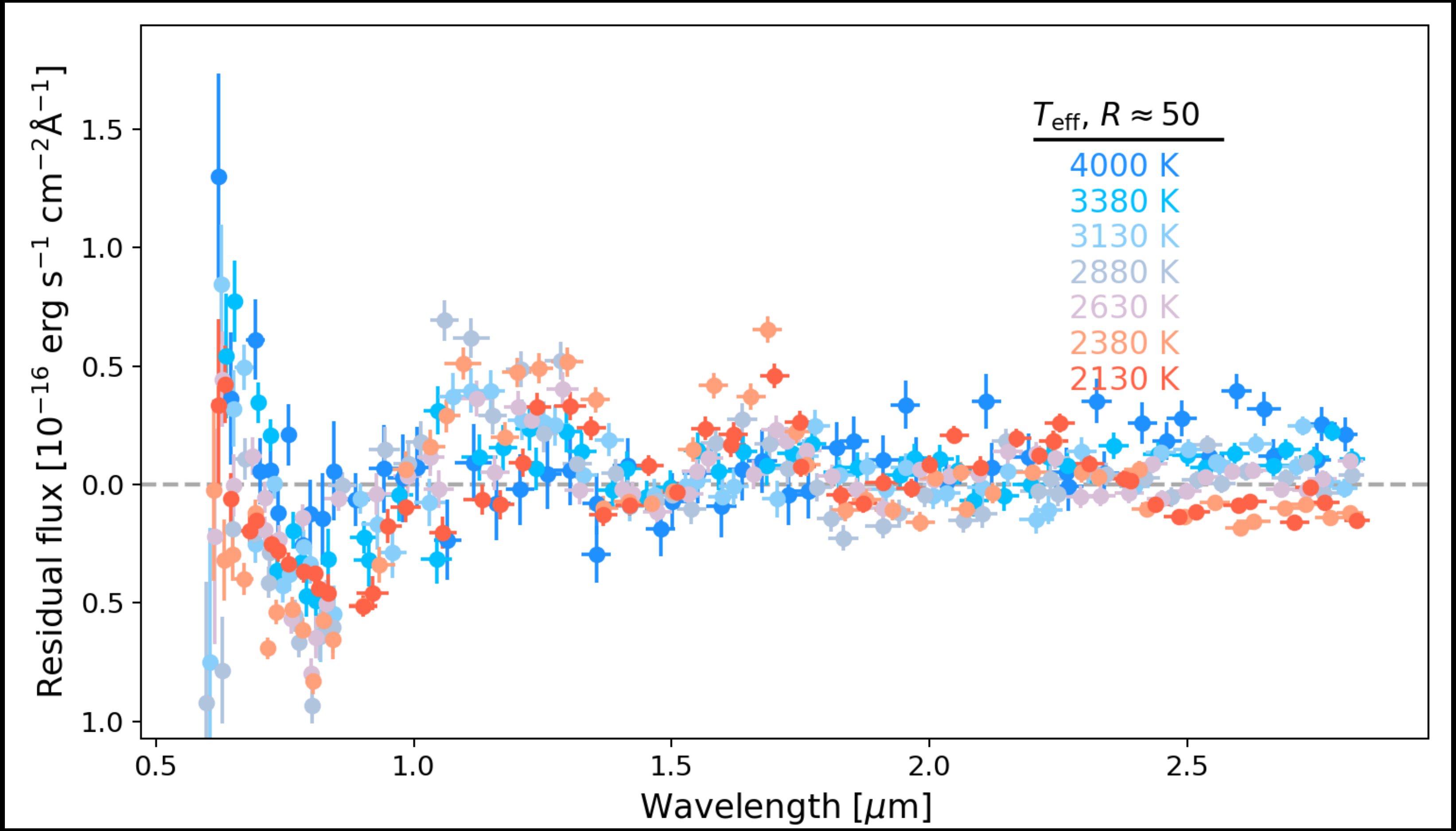
Key takeaways

- Flares occur during ~60% of transits, introducing contamination at levels up to an order of magnitude larger than the planetary signals
- Statistical characterization of infrared flaring is underway, made possible by increasing numbers of archival JWST observations
- A broad grid of new RADYN models is enabling progress toward sub-100 ppm flare correction and photochemistry, although much work remains!
- Simultaneous NUV observations substantially decrease uncertainty in both the photochemical radiation environment and flare decontamination efforts

Diversity is part of science, equity is part of science, inclusion is part of science

Backup Slides

Fiducial flare spectra for a range of flare effective temperatures



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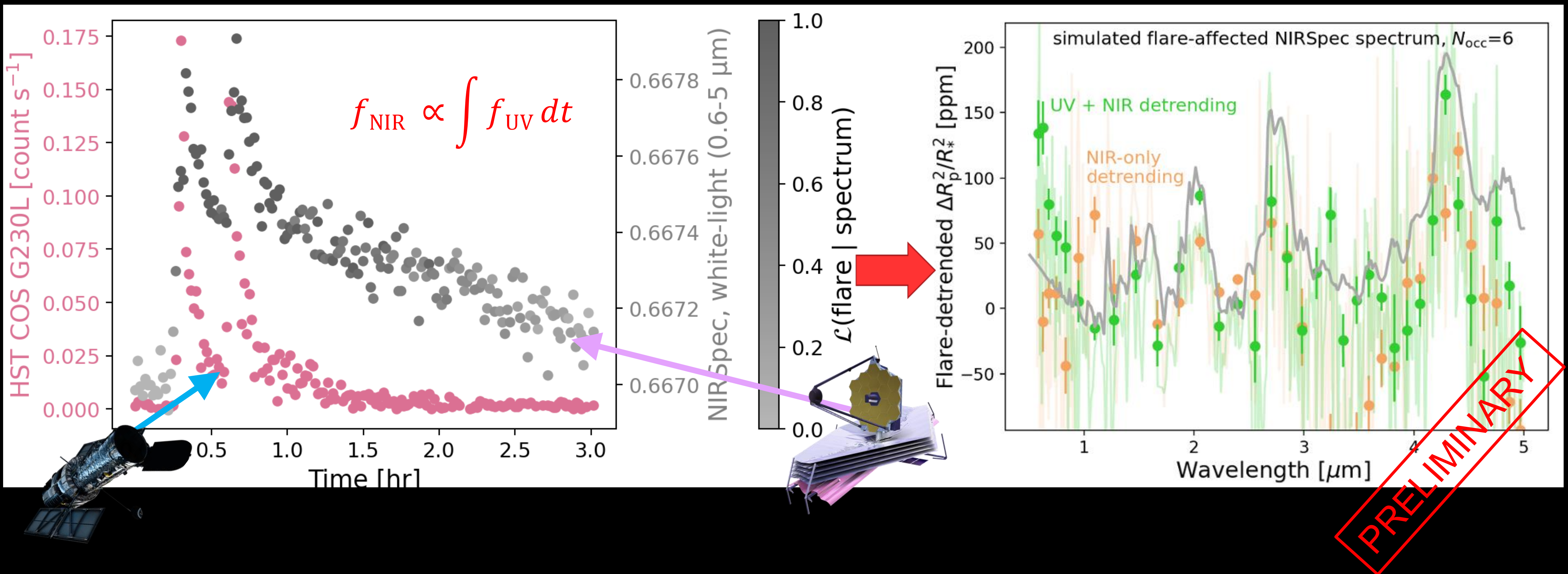

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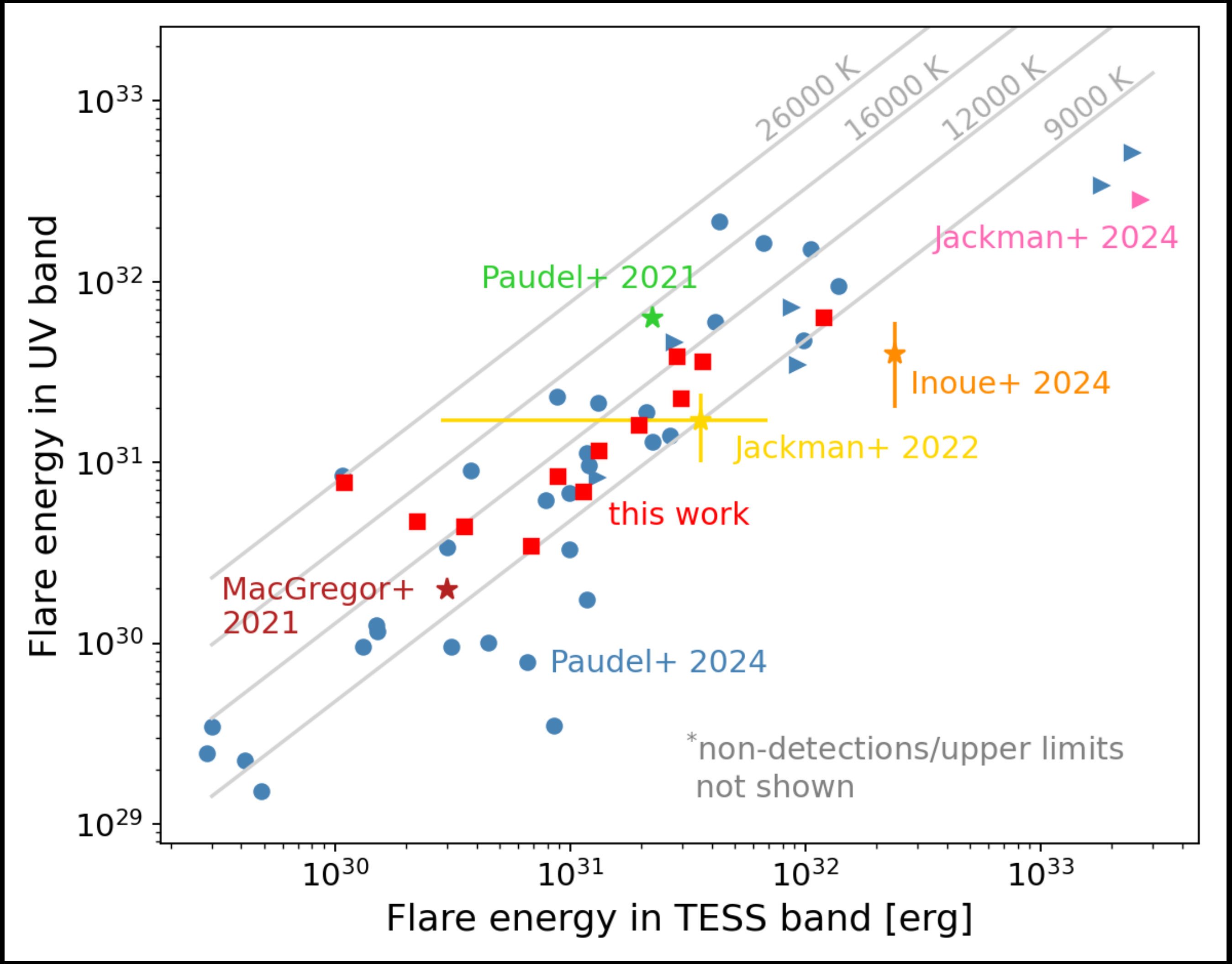
Only a few dozen flares have simultaneous UV and TESS observations ….



A ~9000 K blackbody is typical of many optical flare spectra, so is often assumed to hold into the UV as well

However, data from GALEX, *Kepler*, and TESS suggest the 9000 K scaling underestimates the true UV flux of some flares*

*Jackman+2023, Brasseur+ 2023, Paudel+ 2024

Paudel+ 2021, ApJ 922, 31. **MacGregor**+ 2021, ApJL 911, 25. **Jackman**+ 2022, MNRAS 517, 3832. **Inoue**+ 2024, PASJ 76, 175. **Jackman**+2024, MNRAS 529, 4354. **Paudel**+ 2024, arXiv:2404.12310, **Howard**+ 2024, under collaboration review.