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X-ray Spectroscopic Properties of M-dwarf Megaflares: Insights from the AU Mic and Fulcrum Multi-wavelength Campaigns

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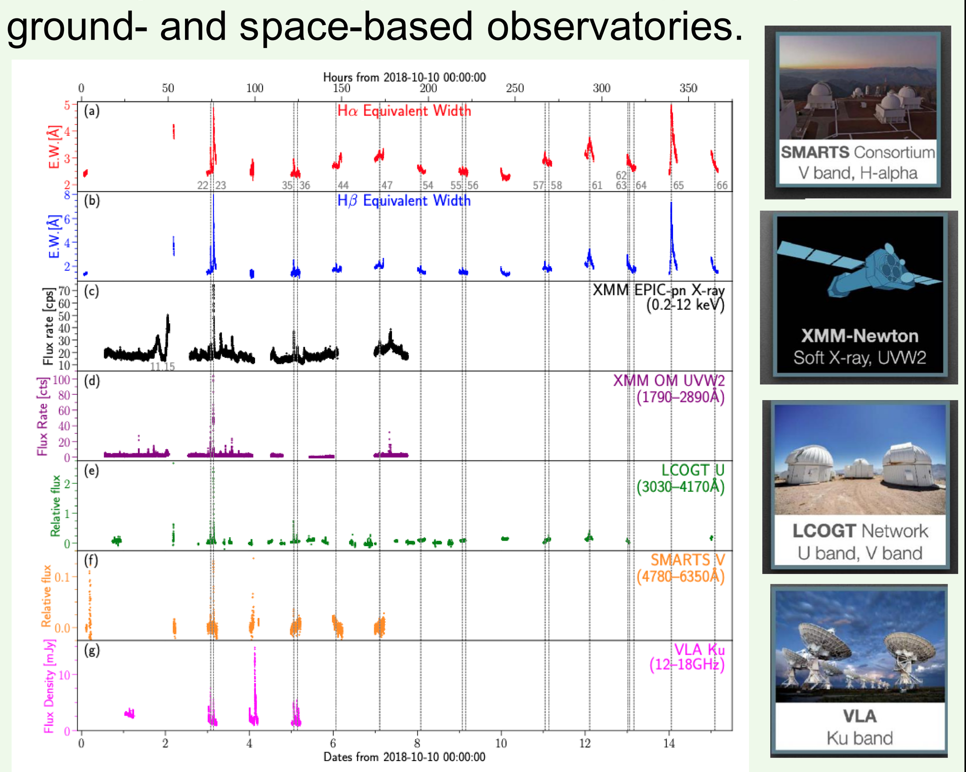
AU Mic, The Very Active M Dwarf

AU Mic is a nearby dM1e that is well known for being the most X-ray luminous star within 10 pc, having multiple planets, and having a debris disk with moving features. It is also known for its frequent and energetic flares, which makes it a popular target for M dwarf flare studies. In 2018, a 7-day campaign observed AU Mic with wavelength coverage from X-rays to radio, incorporating both ground- and space-based observatories.



[1] Tristan et al. (2023, ApJ, 951, 33)
Lightcurve analysis on Neupert effect

[2] Tristan et al. (2025, ApJ, 986, 53)
Radio flares

[3] This paper: Notsu et al. (2025 ApJ, 993, 212)
X-ray spectral properties and Hα&Hβ profiles
Other flares and quiescent emission also discussed.

[4] Tristan et al. (2026, ApJ, 997, 168)
Radio quiescent radiation

[Radio results: Poster P2060 by I. Tristan]

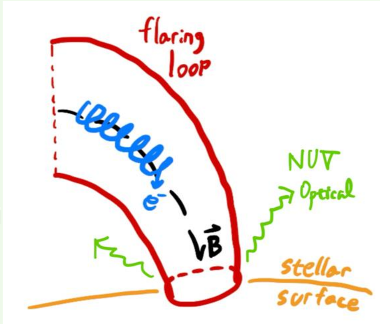
Flare time-evolution following the "standard model"

Magnetic Reconnection

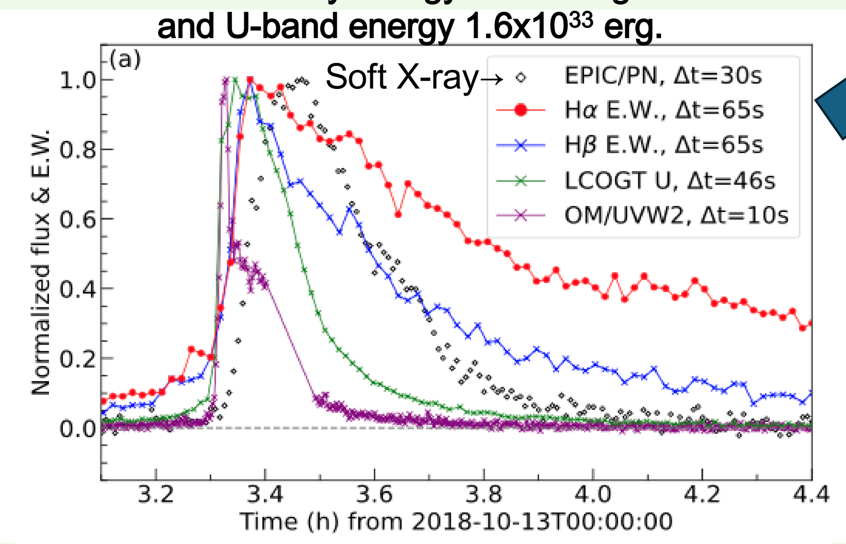
Non-thermal electrons (protons?) accelerated and propagated → radio (Gyrosynchrotron)

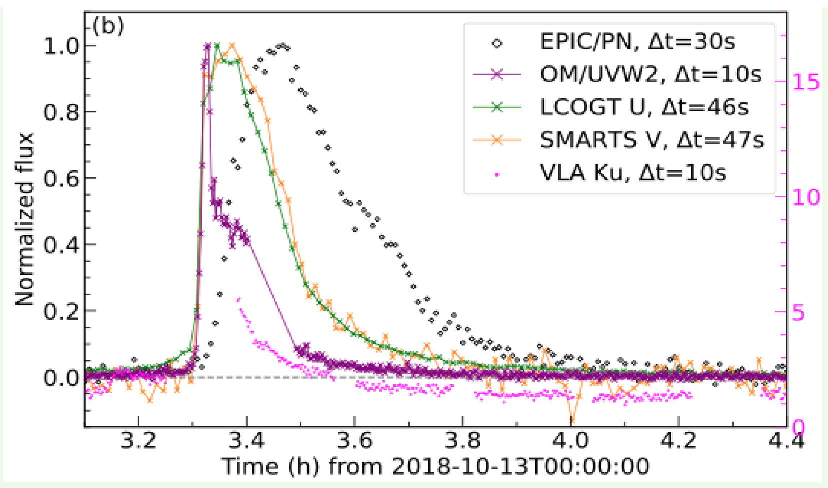
Lower atmosphere heated → Optical/NUV continuum

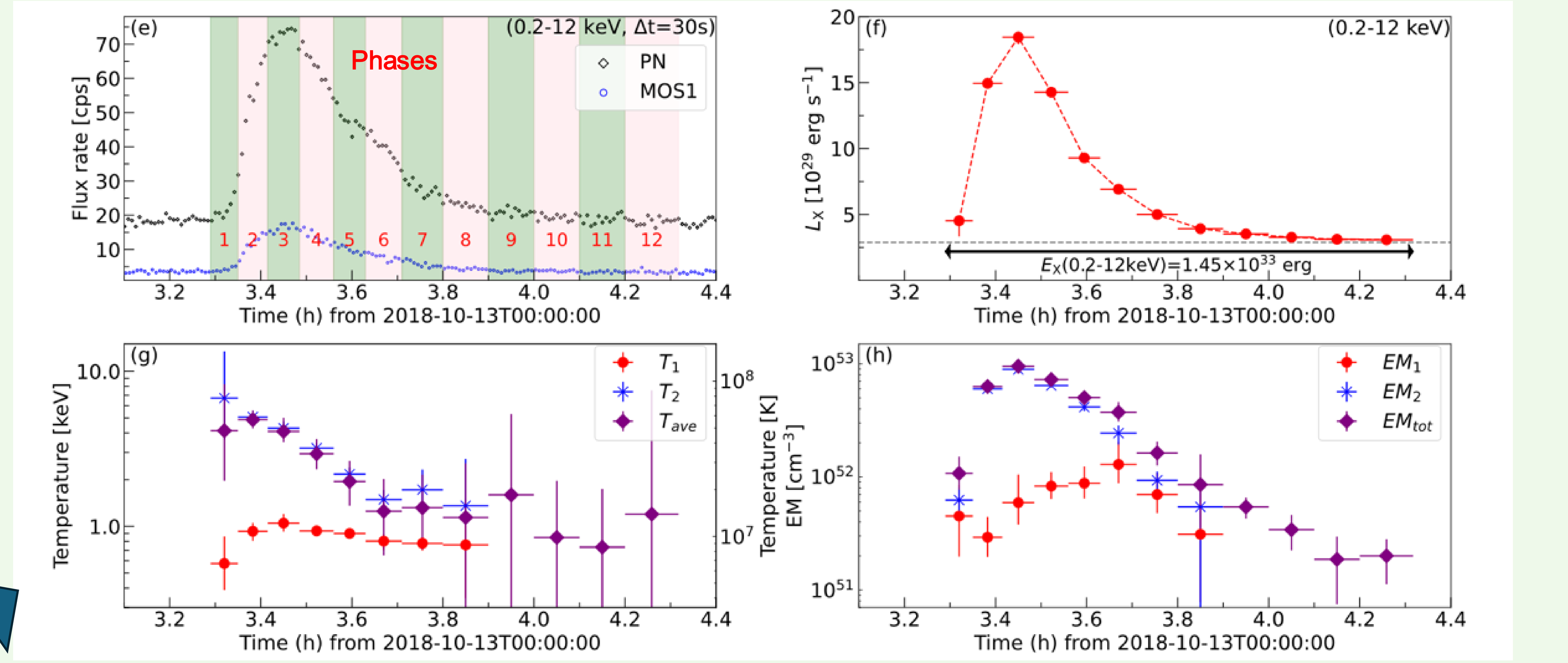
Chromospheric evaporation → Hα → Soft X-ray



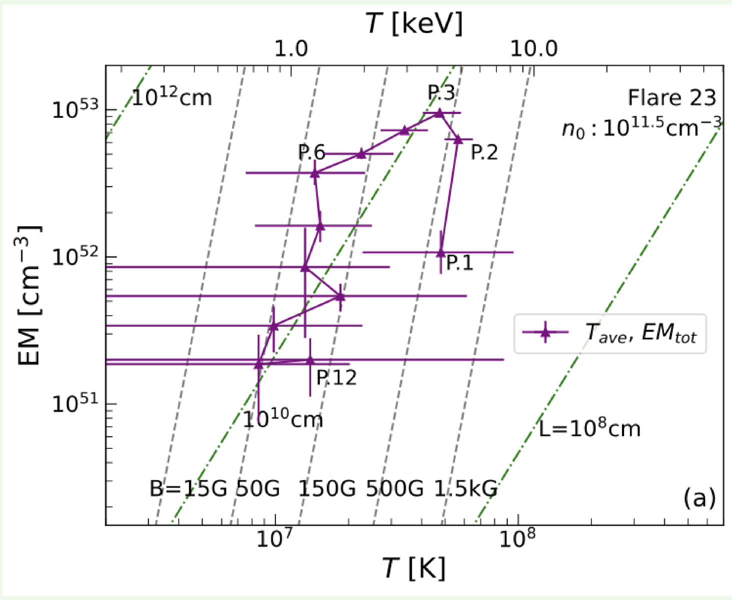
(a)&(b) The largest amplitude flare with X-ray energy 4x10^{33} erg and U-band energy 1.6x10^{33} erg.





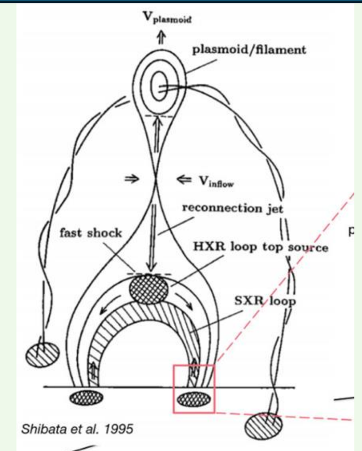


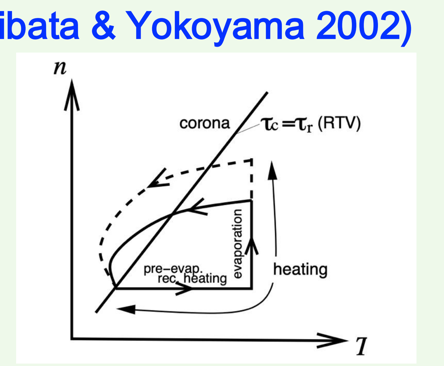
EM-T diagram time evolution for the largest flare in this study

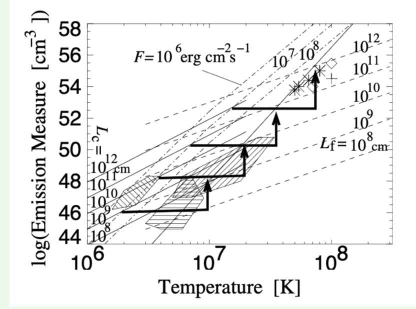


Dominant non-thermal energy injection (NUV) has already finished before X-ray emission evolves (Phase 2 & 3).

Flare H-R diagram of T-EM evolution track (Shibata & Yokoyama 2002)







↑ 7-day AU Mic campaign (e.g., Tristan et al. 2023, ApJ, 951, 33; Notsu et al. 2025, ApJ, 986, 53) ↑

[Executive Summary]

Extreme Flare Parameters: Two large-scale multi-wavelength campaigns (AU Mic & Fulcrum/CR Dra) captured M-dwarf megaflares exhibiting record-breaking NUV continuum luminosities, peak coronal temperatures of 30–50 MK, and enormous emission measures (10^{53}–10^{54} cm^{-3}).

The "Flare H-R Diagram" Holds: Synthesizing the time-resolved X-ray spectra, we found that the T-EM evolution tracks of impulsive megaflares follow counter-clockwise trajectories consistent with the standard solar flare model, while they have much larger loop structures.

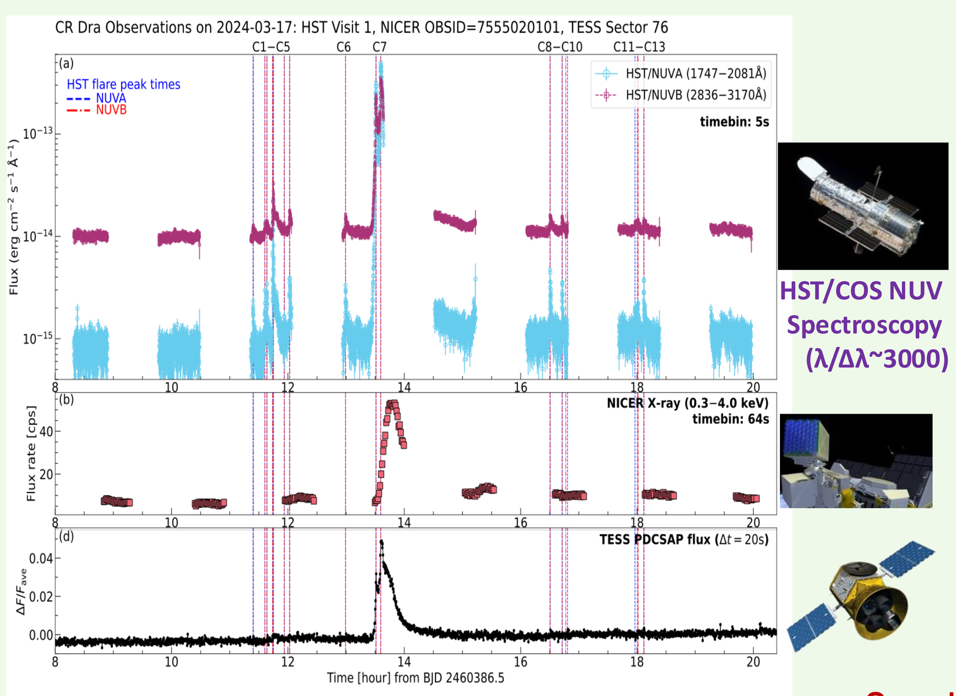
Bridging Stellar & Exoplanetary Physics: These megaflares are driven by solar-like mechanisms but scaled to stronger magnetic fields. These robust X-ray constraints are vital for RHD modeling and for evaluating how extreme EUV radiation drives atmospheric escape in exoplanets.

↓ Fulcrum multi-wavelength campaign (e.g., Kowalski et al. 2025, ApJ, 978, 81; Osten+/Notsu+ to be submitted) ↓

Hubble Space Telescope Treasury Program

Hubble/Cosmic Origins Spectrograph (COS, λ/Δλ~3000)
230ks (=63.8 hours), 1680-2080Å (NUVA) and 2770 - 3170Å (NUVB);

Target stars: CR Draconis (M1) and GJ 1243 (M4) -- very active flare stars
Simultaneous TESS data (optical/WL), often X-ray spectroscopy (NICER/Swift), and some ground-based optical spectroscopy/photometry(Seimei/APO/LCOGT)



230ks (=63.8 hours) HST observations in total
40 flares on CRDra (M1)
39 flares on GJ1243(M4)

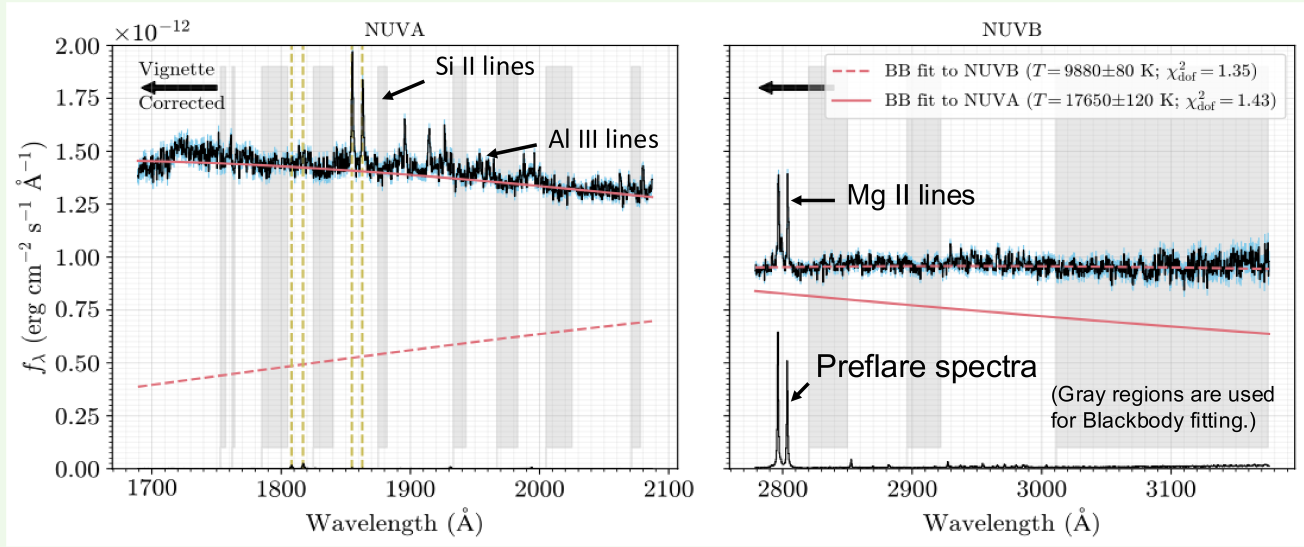
Including two large megaflares (E_{TESS}=7x10^{33} and 10^{35} erg)

HST/COS NUV Spectroscopy (λ/Δλ~3000)

Kowalski+2025 (published)
Two largest flares
Osten+ in prep
HST flare catalog
Notsu+ in prep
X-ray flares
Namekata+ in prep
Mg II line blueshifts

See also Poster P2021 by R. Osten !

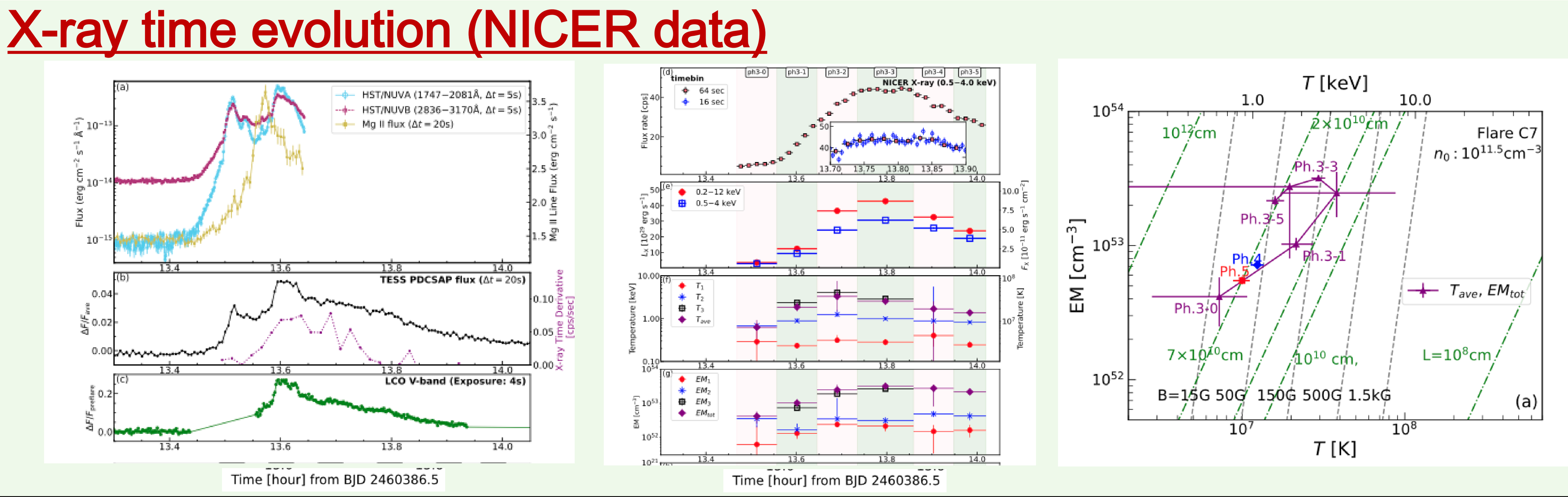
Flare peak HST spectra



← 1680-2080Å (NUVA) continuum brighter and "hotter" than 2770-3170Å (NUVB)

Much brighter FUV continuum than expected from conventional flare model results !!

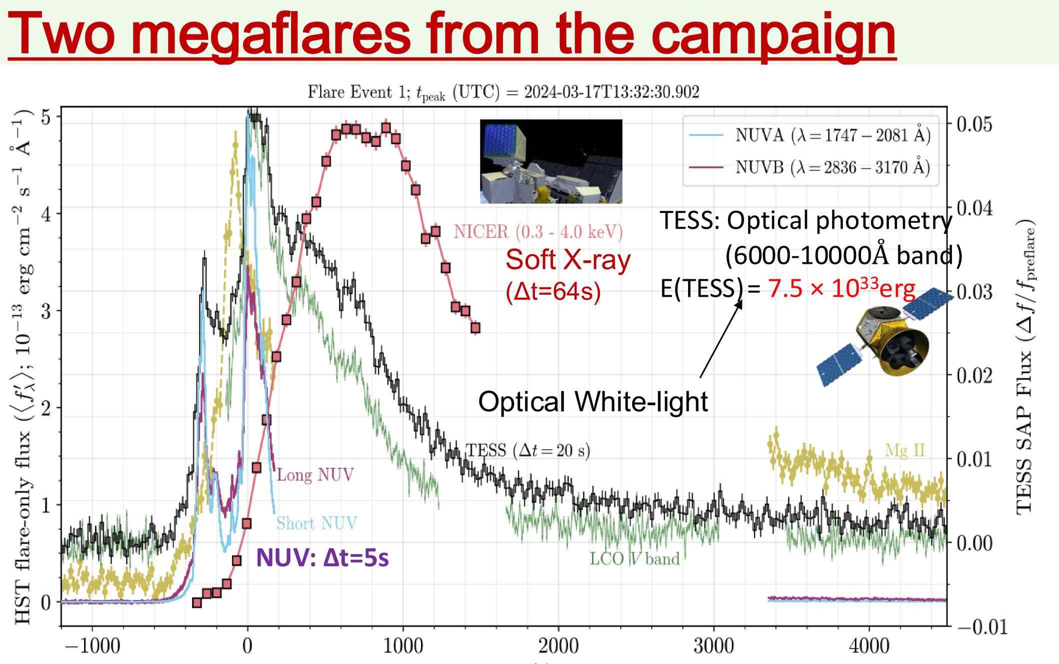
X-ray time evolution (NICER data)

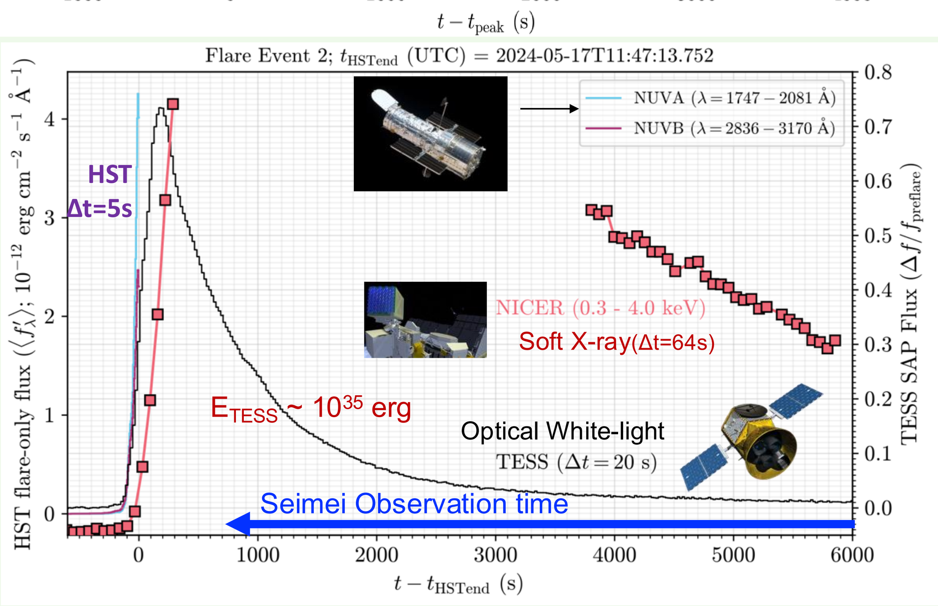


Peak coronal temperatures of megaflares: 30-50 MK

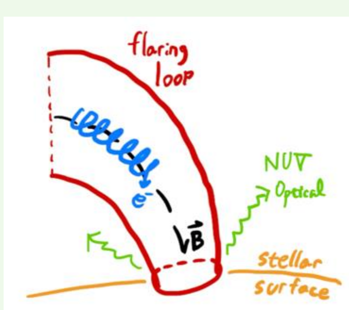
Similar flare H-R diagram evolutions are observed !
(cf. AU Mic results above)

Two megaflares from the campaign





X-ray (coronal) and Mg II (chromospheric) emissions are delayed to NUV/optical continuum emissions (cf. Neupert effect in solar flares).

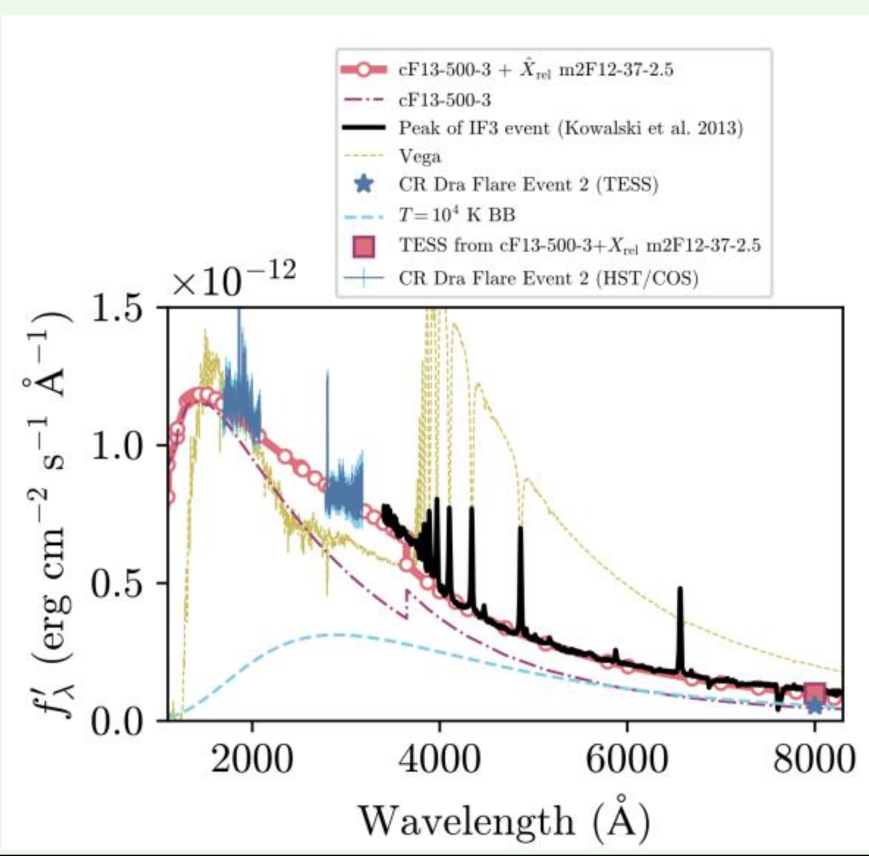


← The largest NUV flare luminosity observed to date from an M-dwarf.

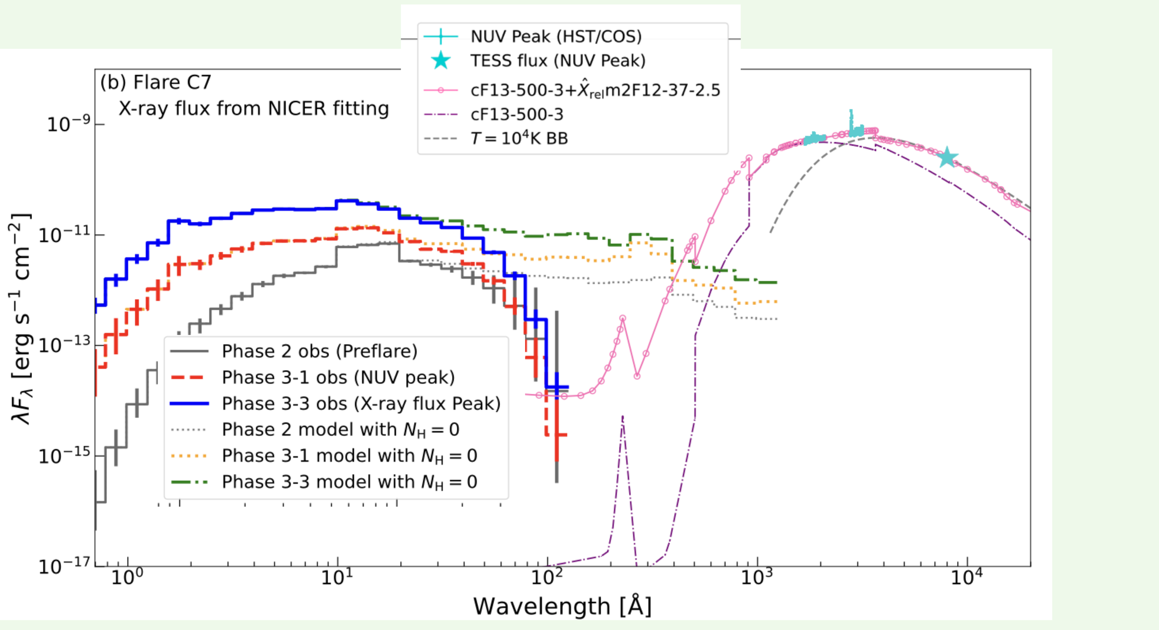
← Unfortunately, HST observation stopped due to an overlight condition.

Toward improved constraints of stellar high-energy radiation affecting exoplanet atmosphere

Rising NUV/FUV spectrum from the HST observation



NUV/FUV emissions are only a part of the whole process.
How are the relations with other wavelengths ?
(e.g., "thermal" soft X-ray emissions)



Rising NUV flare components
→ Large contributions to unobserved EUV fluxes of M-dwarf flare ?
- Insights for EUV flare observations with future missions (MANTIS, ESCAPE)