High-time-cadence spectroscopy of stellar flares

using the 3.8-m Seimei telescope

Hiroyuki Maehara

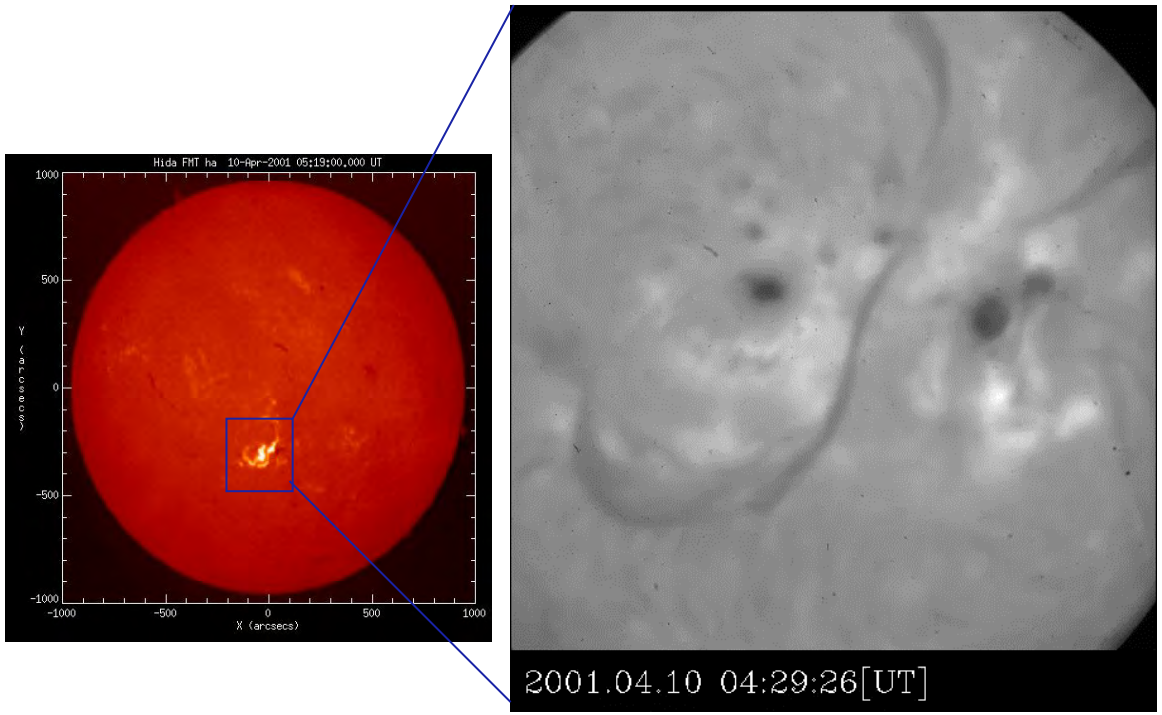
(National Astronomical Observatory of Japan)

国立天文台 NAOJ National Astronomical Observatory of Japan

Okayama Observatory, Kyoto University SEIMEI TELESCOPE

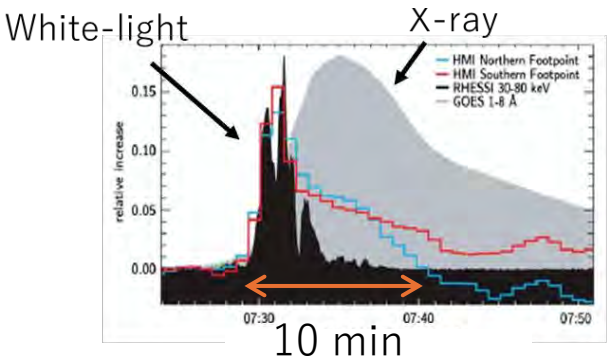
Solar/stellar flares

- Sudden and rapid brightening events on the Sun & stars
  - Observed in various wavelengths (from radio to X-ray)
- Flares are caused by sudden and rapid release of magnetic energy via magnetic reconnection.

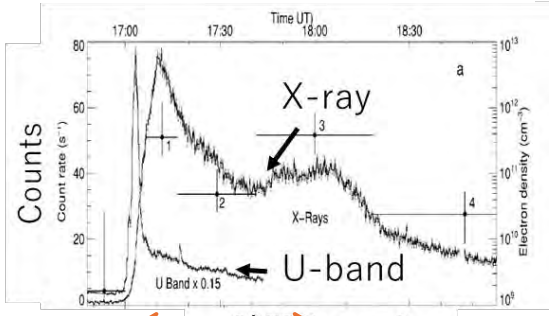


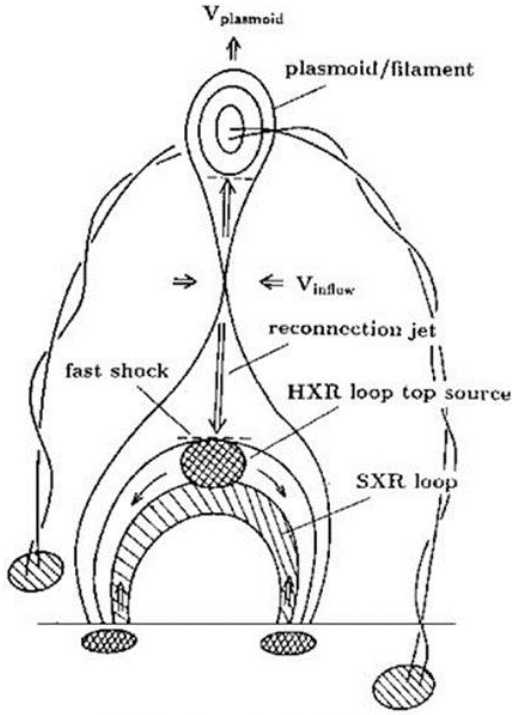
Hα Image of solar flare (Hida Observatory, Kyoto University)

Solar flare (Martinez+2012)



Stellar flare (Gudel+2002)



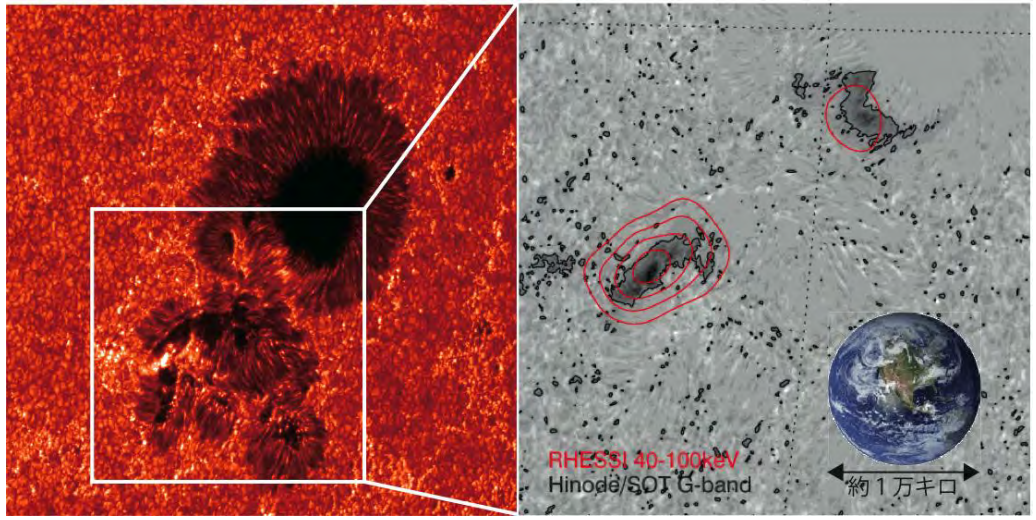


Shibata et al. 1995

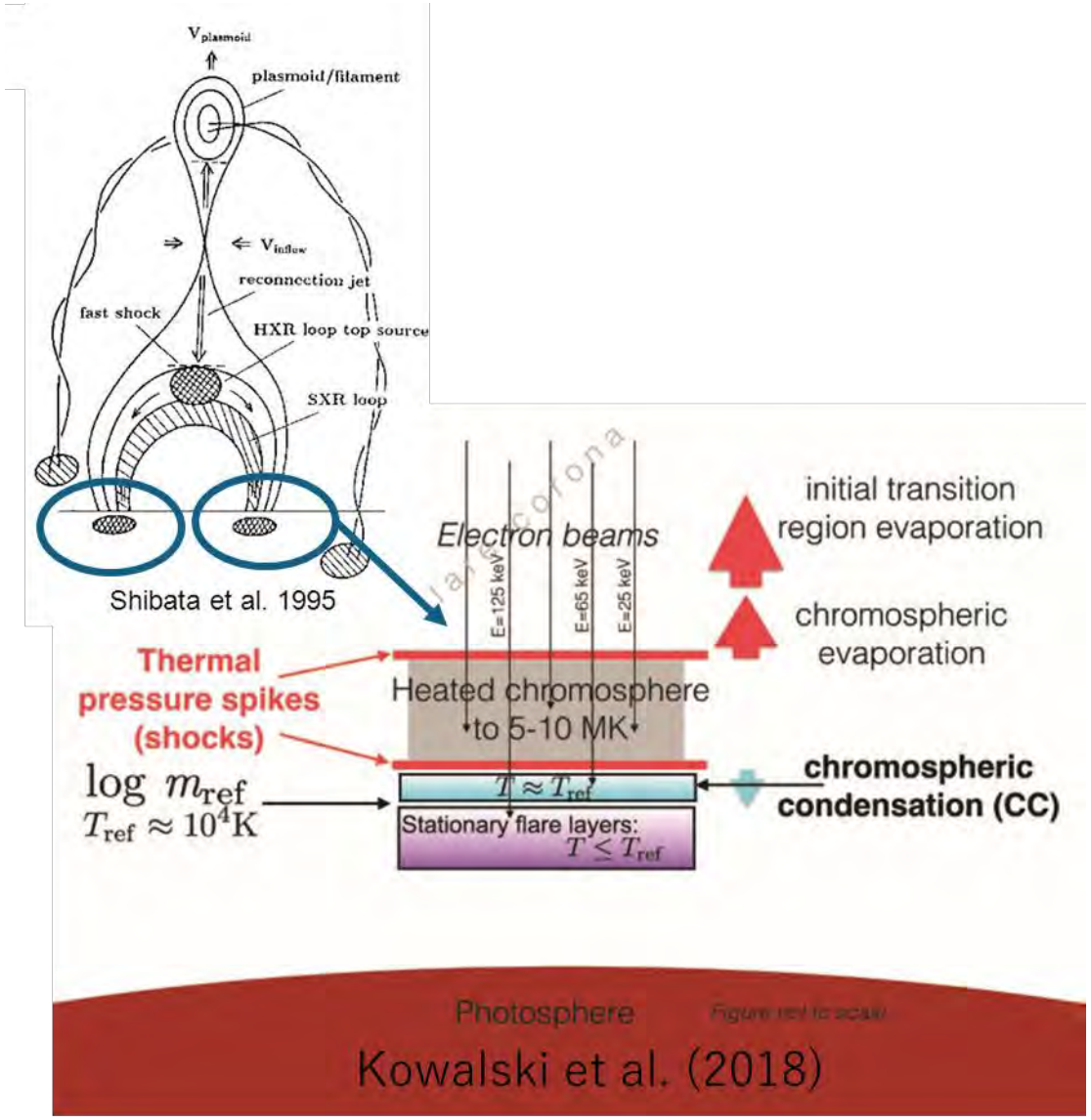
White-light emission of solar flares

- White-light emission of flares comes from the lower chromosphere / upper photosphere.
- The spatial location and temporal change of white light emissions are well-correlated with those of hard X-ray emissions.

- Non-thermal electrons highly accelerated by flares are responsible for producing white-light emission.



Watanabe et al. (2010)



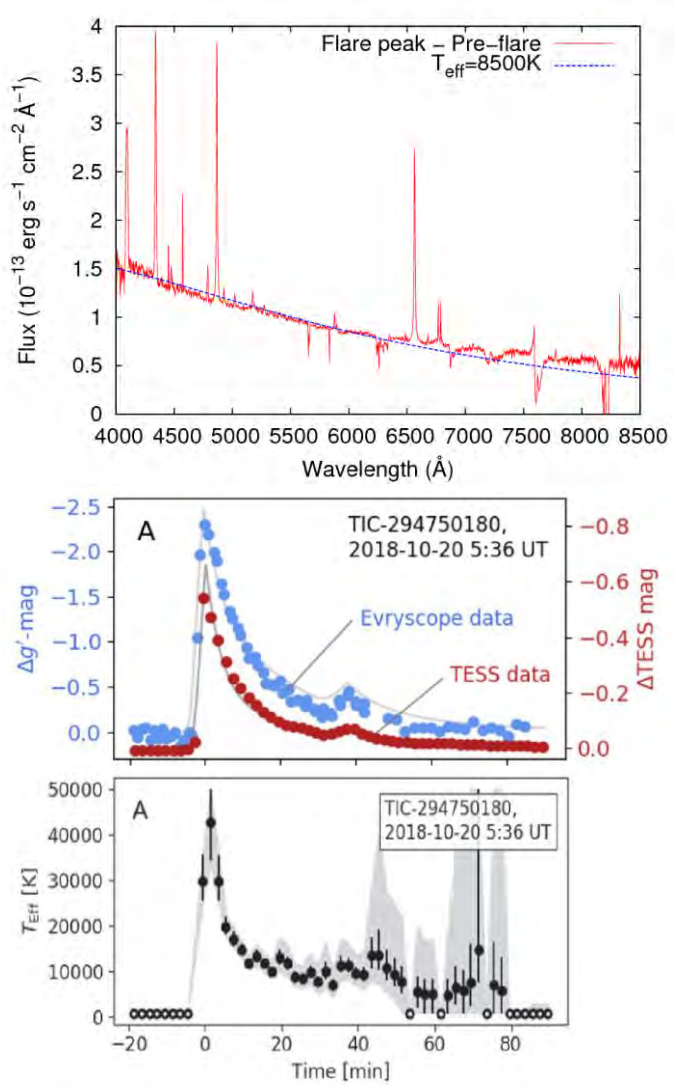
White-light emission of stellar flares

- Stellar flares show Blackbody-like spectral energy distribution with the effective temperature of ~10000 K.
  - "~10000 K blackbody" assumption is often used to estimate bolometric energy of flares.

- Recent studies found that T_{eff} of flare continuum changes with time.
  - Some flares show much higher T_{eff} (>30000 K) at flare peak.
  - Howard et al. (2020): Based on 2-band photometry (only g'- and TESS-band) with 20-120-sec cadence
  - Ichihara et al. (2025): Based on spectroscopy with ~80-sec cadence

Rise time of flare: < ~1 min

- We need to perform time-resolved spectroscopy covering NUV-visible wavelength with a shorter time cadence (<~10 sec) for understanding the nature of flare continuum emission around the flare peak.



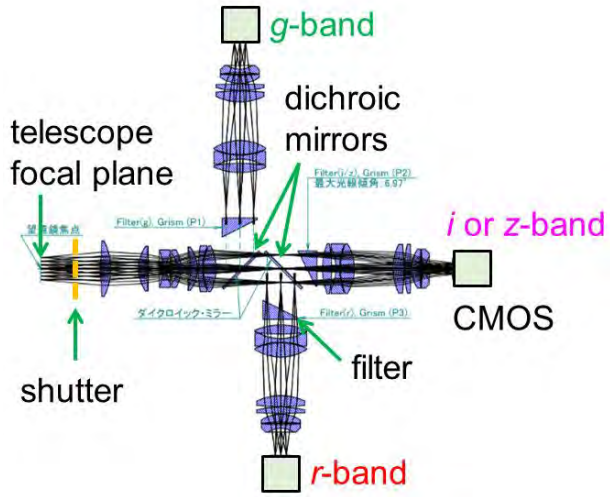
Howard et al. (2020)

Observations with 3.8-m Seimei telescope & TriCCS

- We performed high-time-cadence spectroscopy of active M-dwarfs using the 3.8-m Seimei telescope and TriCCS simultaneously with TESS photometry.
  - TriCCS (long slit mode)
    - 3 CMOS detectors (g-, r-, and iz-bands)
    - Maximum frame rate: 96 fps
    - Wavelength coverage: 385-1050 nm ($\lambda / \Delta\lambda$ ~700@Hα)
    - Slit width × length : 1” × 10’
    - https://www.o.kwasan.kyoto-u.ac.jp/inst/triccs/

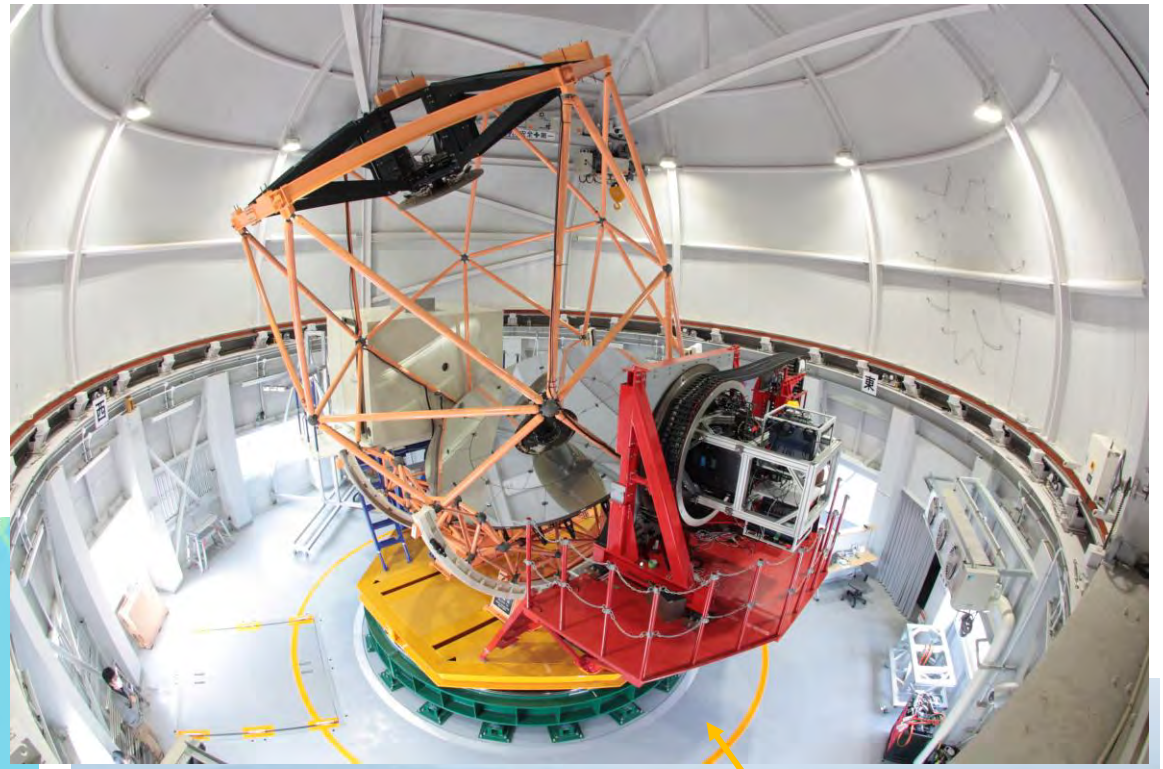


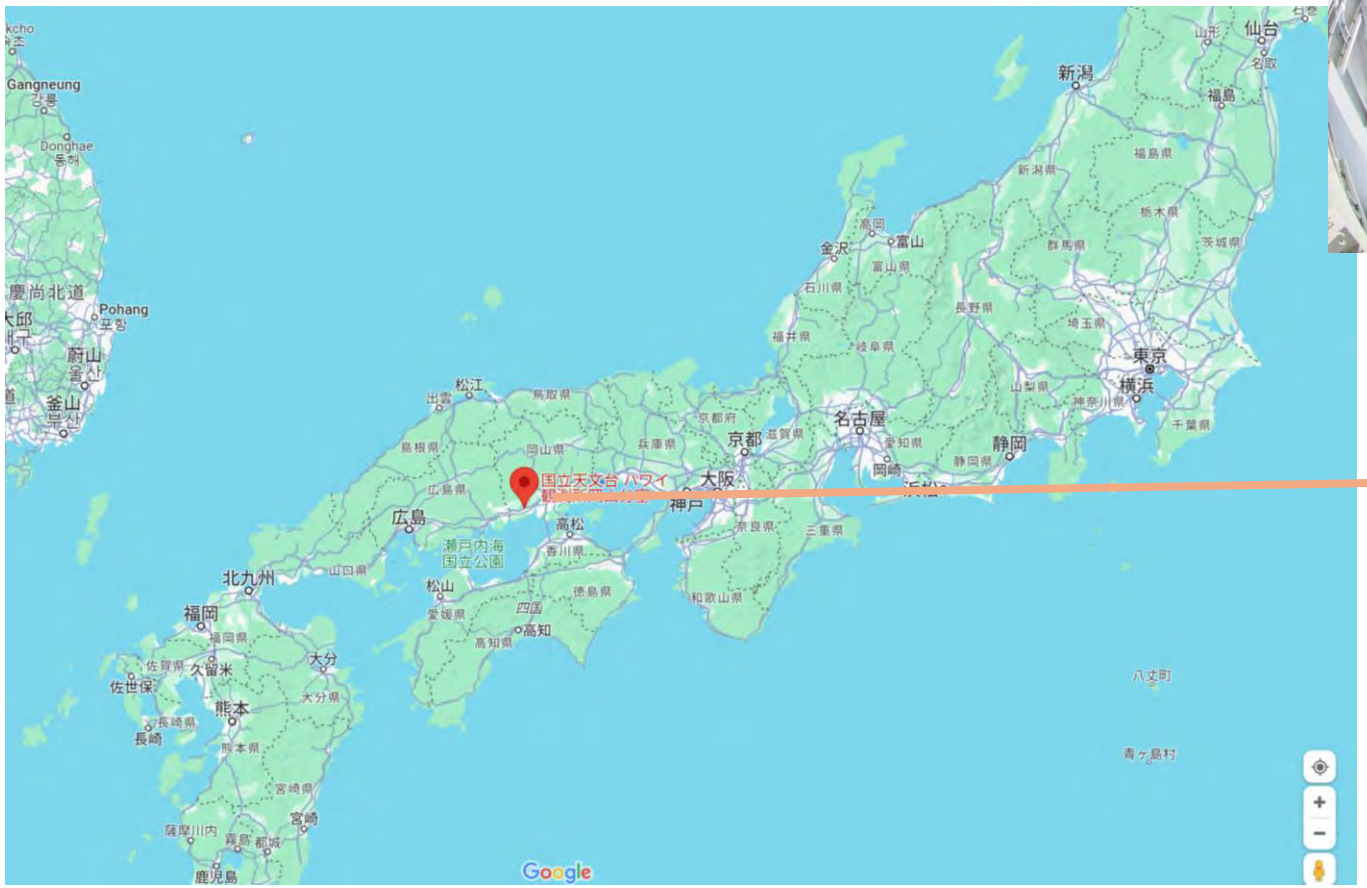
- Target objects
  - GJ 1243 (2024/07/26 – 07/31)
    - Prot=0.592 days (Savanov & Dmitrienko 2011)
    - flare rate ~ 0.2 day^{-1} for $E_{flare}>10^{32}$ erg (Hawley+2014)
    - Exp. time: 10-20 sec.
  - YZ CMi (2025/01/15 – 02/09)
    - Prot=2.779 days (Morin＋2008)
    - flare rate ~ 2 day^{-1} for $E_{flare}>10^{32}$ erg (Maehara＋2021)
    - Exp. time: 2-3 sec.



3.8-m “Seimei” Telescope

- Largest Opt.-NIR telescope in Japan
  - located at Okayama, Japan
  - segmented mirror telescope
- Science observations started in 2019.

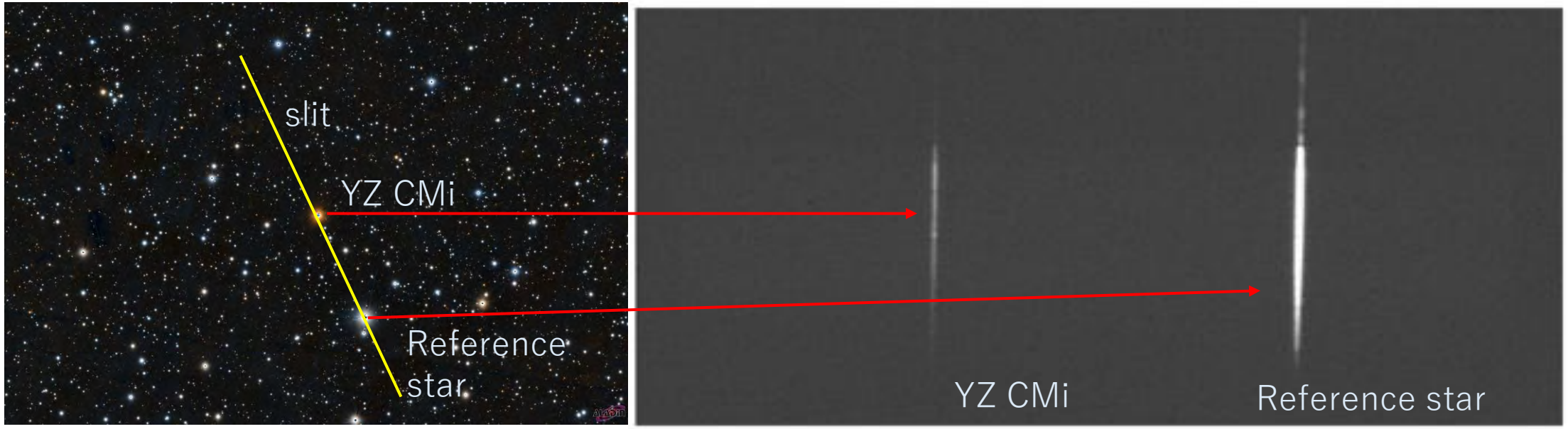






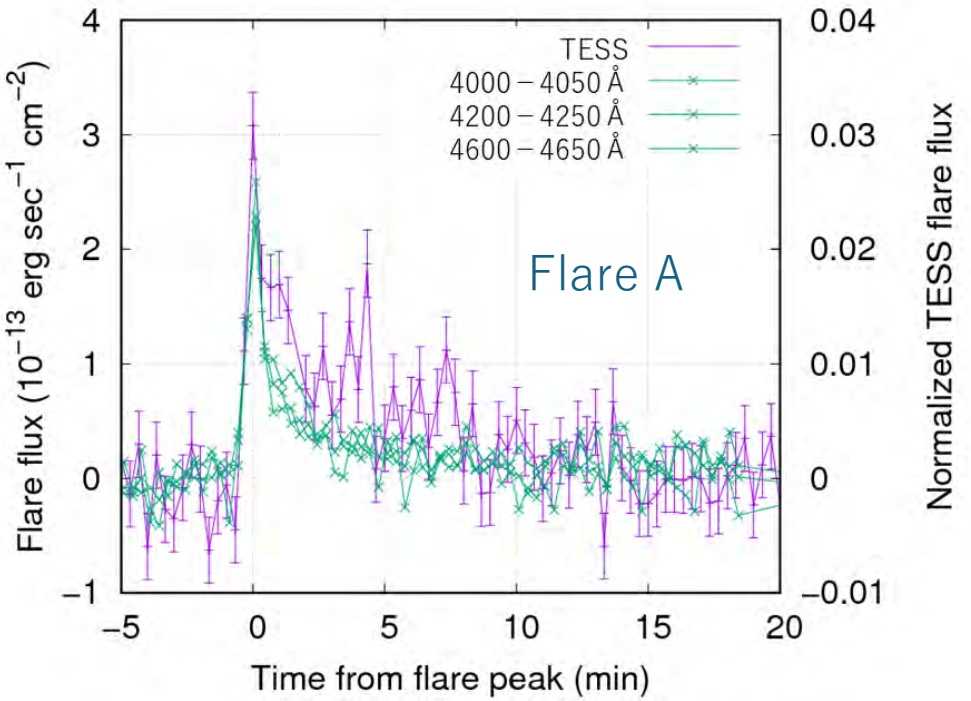
Observations with 3.8-m Seimei telescope & TriCCS

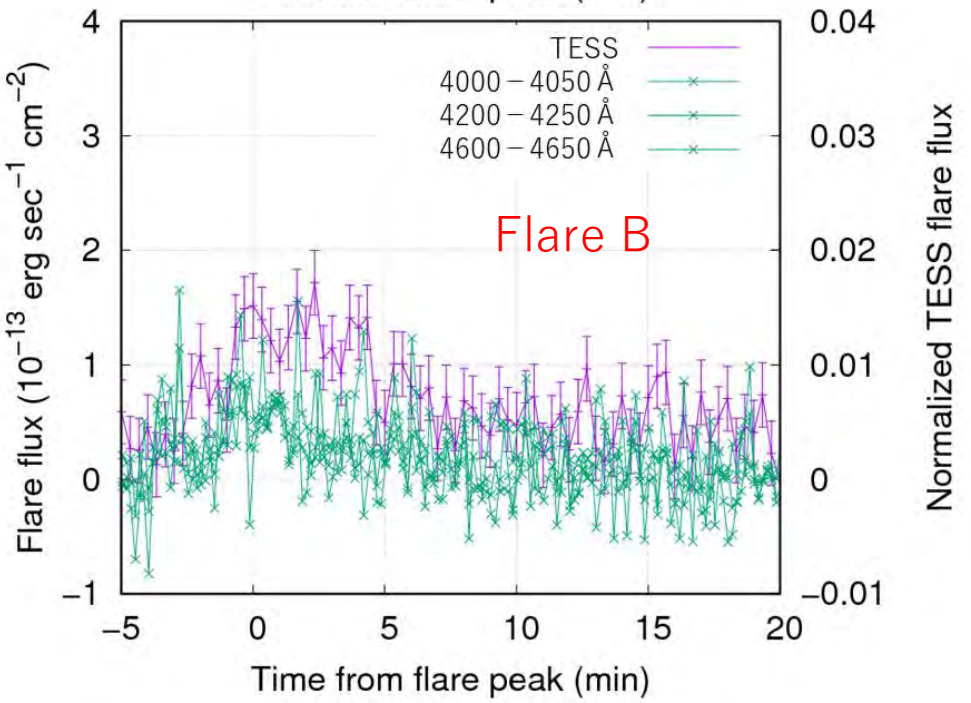
- Wide field of view and long slit length of TriCCS enable us to obtain spectra of the target object and the nearby reference star simultaneously.
- We performed flux calibration of the target object for each exposure by using reference star spectra.
  - We can correct changes in observed flux due to non-astrophysical origins (e.g., atmospheric extinction).



GJ 1243

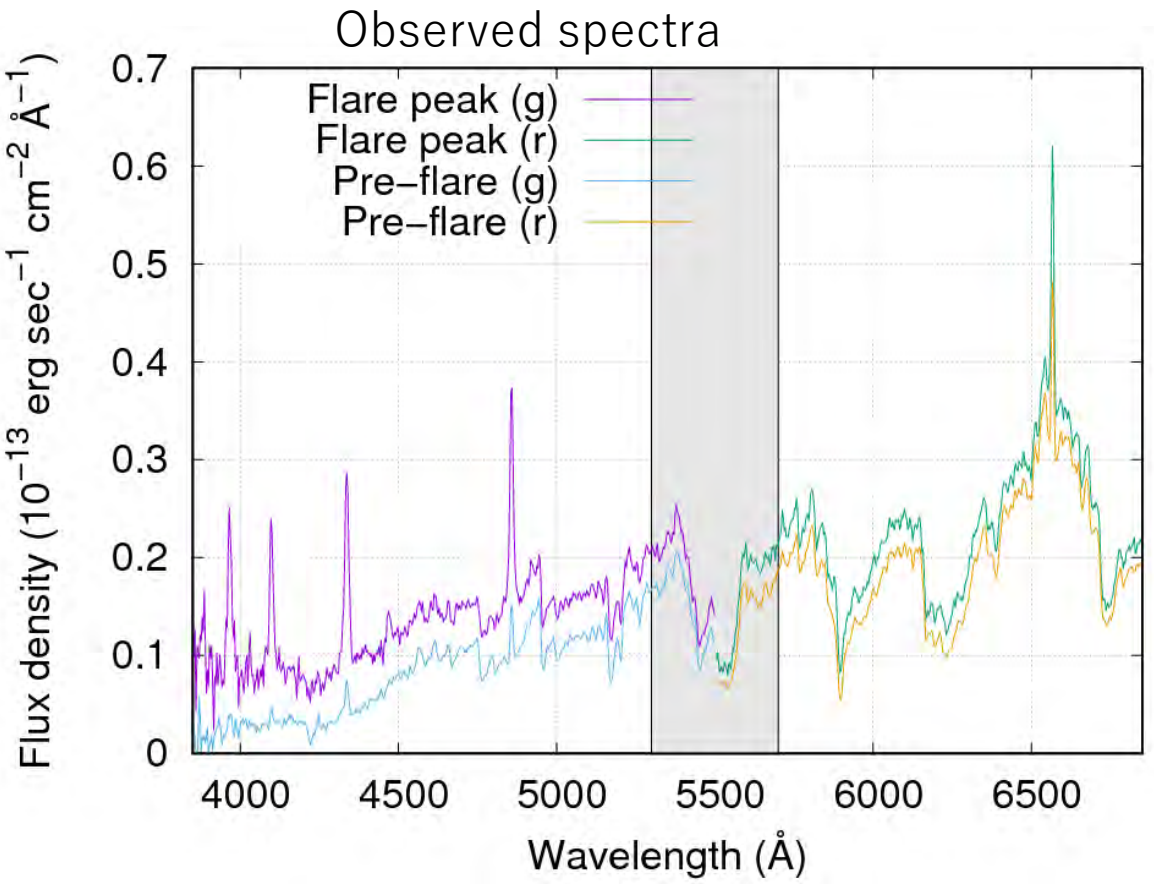
- We observed two flares showing different temporal properties with Seimei and TESS.
  - Flare A: Impulsive flare
    - $\Delta F/F \sim 3.1\%$ @TESS-band
    - $\tau_{flare} \sim 180$ sec @TESS-band
    - $E_{flare} \sim 2 \times 10^{31}$ erg @TESS-band
  - Flare B: gradual flare
    - $\Delta F/F \sim 1.4\%$ @TESS-band
    - $\tau_{flare} \sim 900$ sec @TESS-band
    - $E_{flare} \sim 3 \times 10^{31}$ erg @TESS-band
  - Flare energies of these flares in the TESS-band are roughly the same.

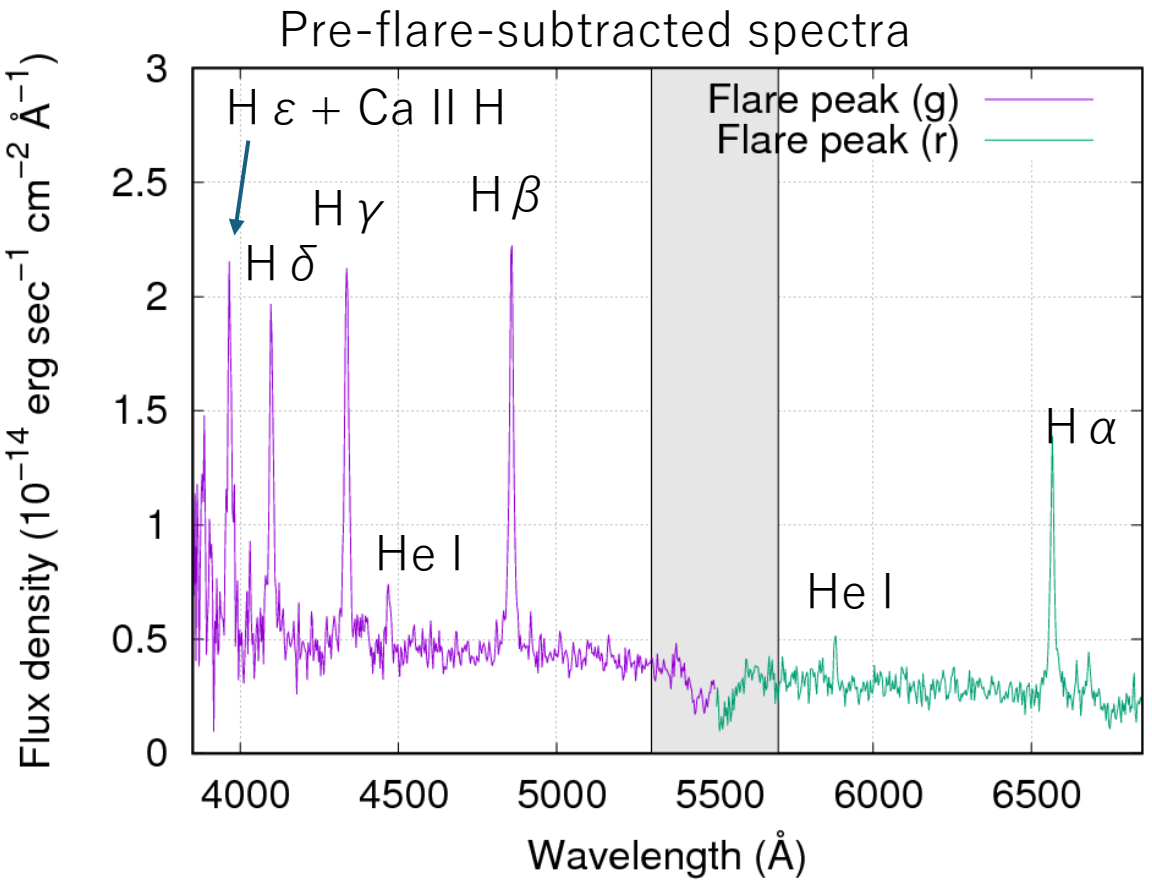




GJ 1243: flare spectrum at flare A peak

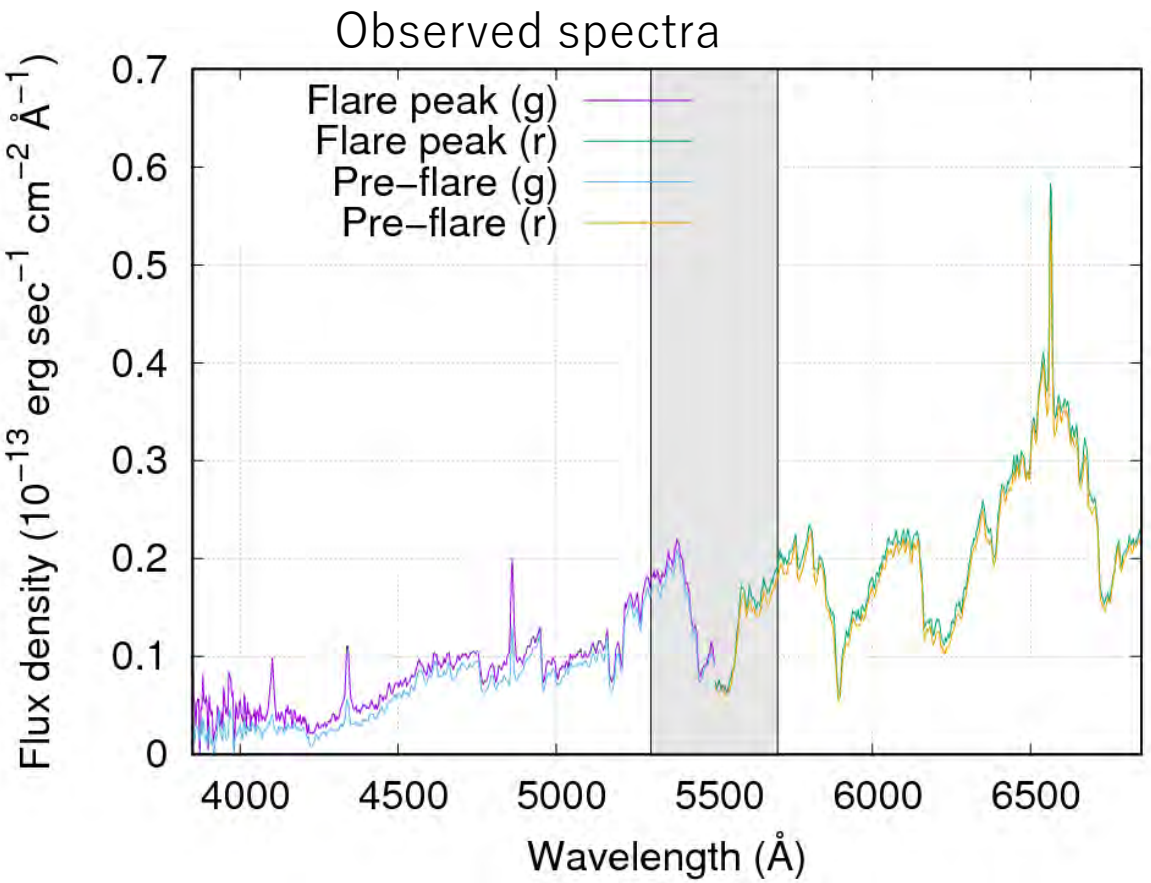
- $\Delta F/F_{\text{pre-flare}} \sim 50\%$@4600 Å

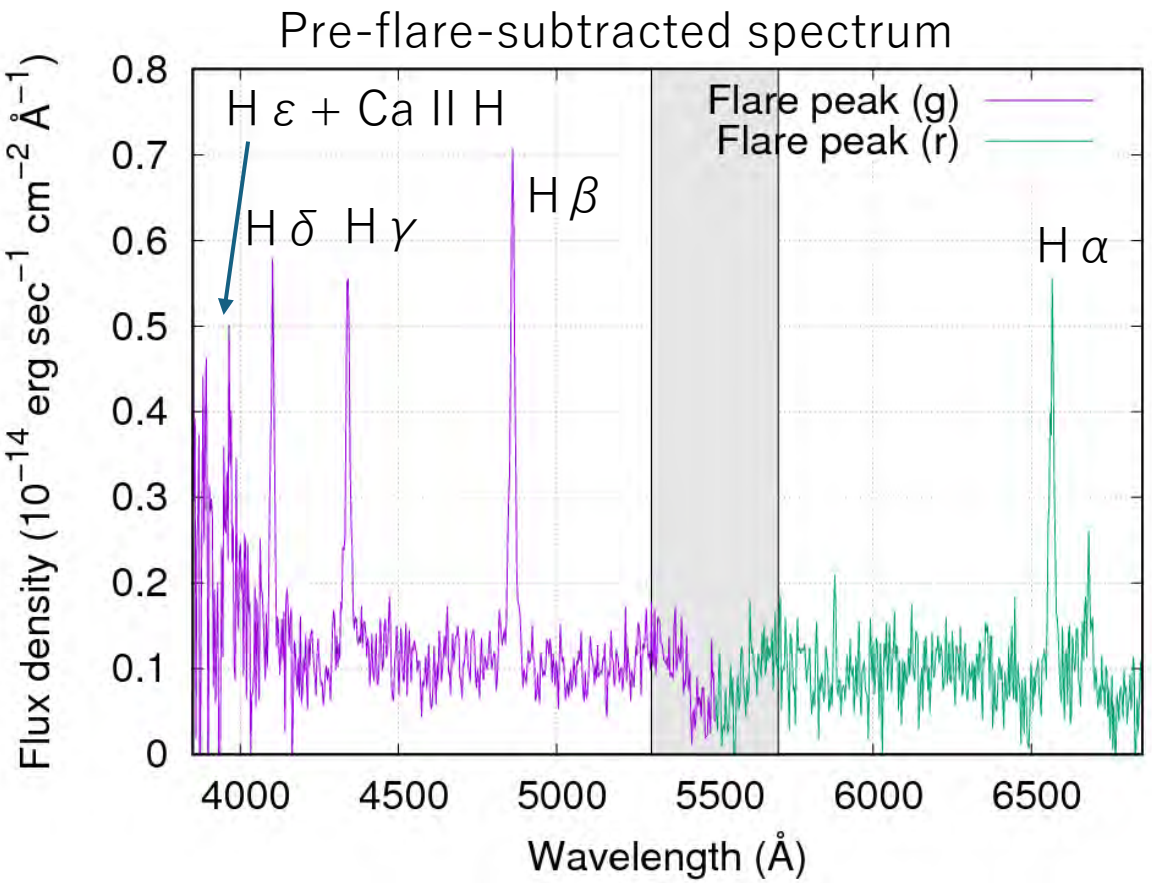




GJ 1243: flare spectrum at flare B peak

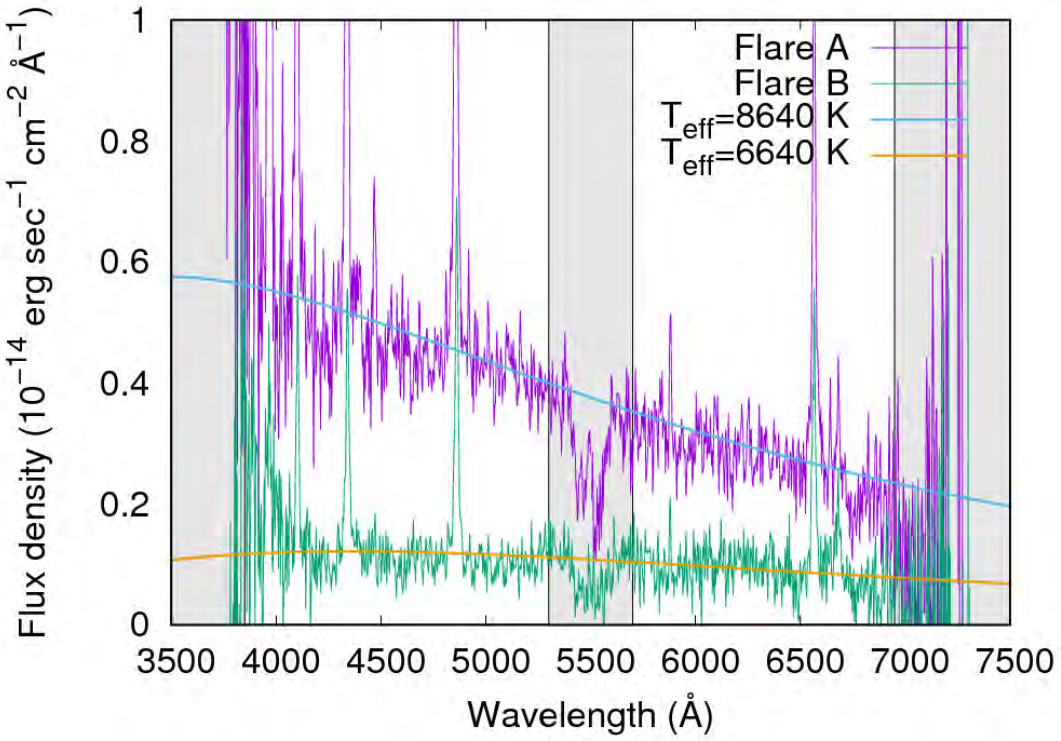
- $\Delta F/F_{\text{pre-flare}} \sim 10\%$@4600 Å

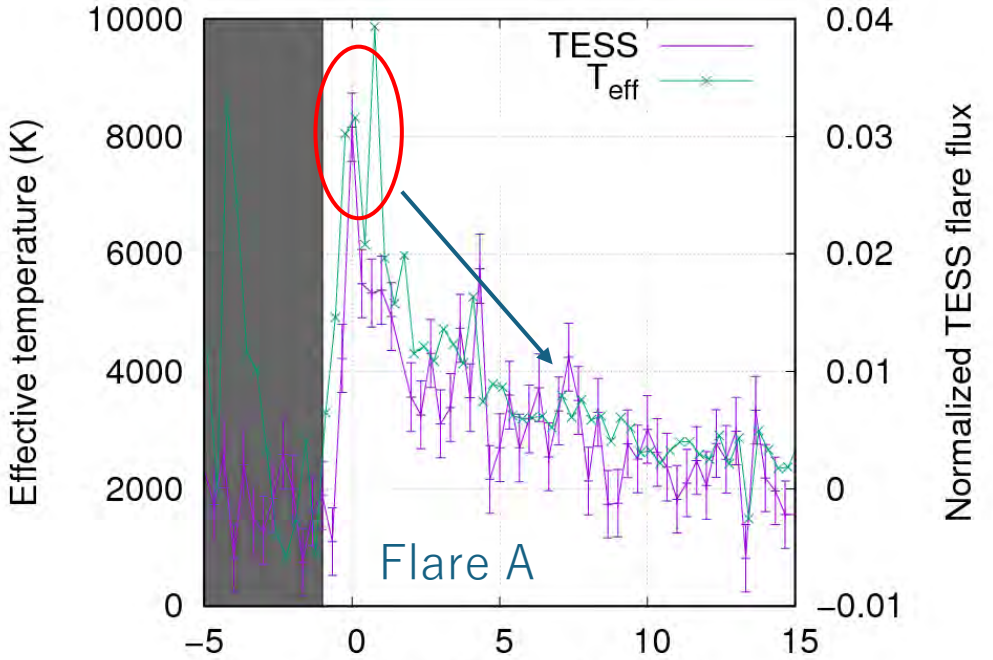


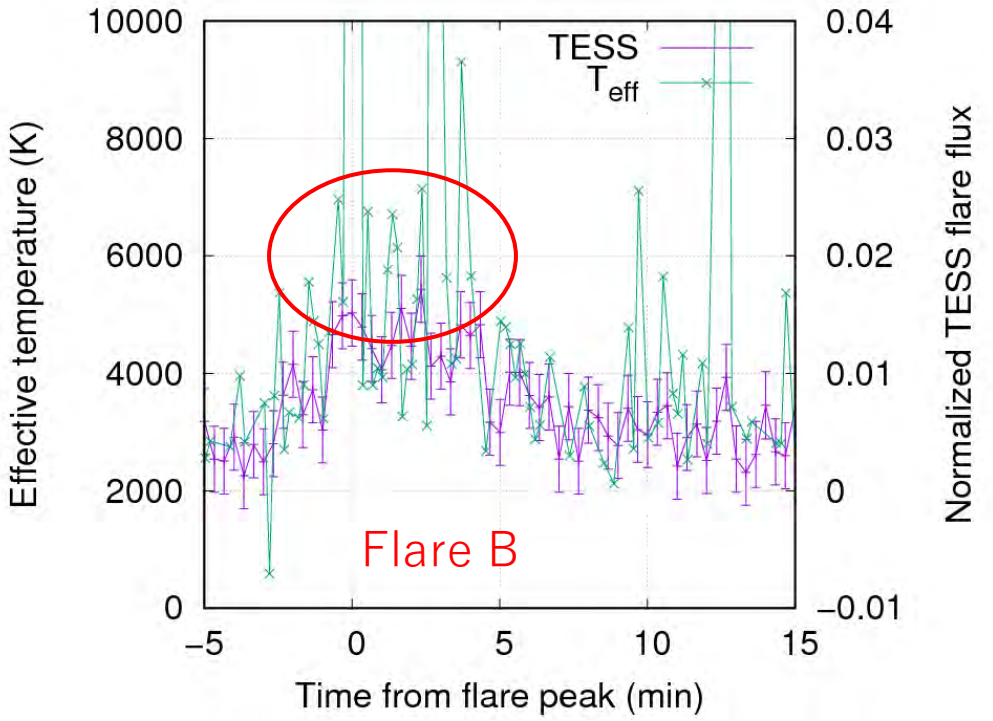


GJ1243: T_{eff} variations

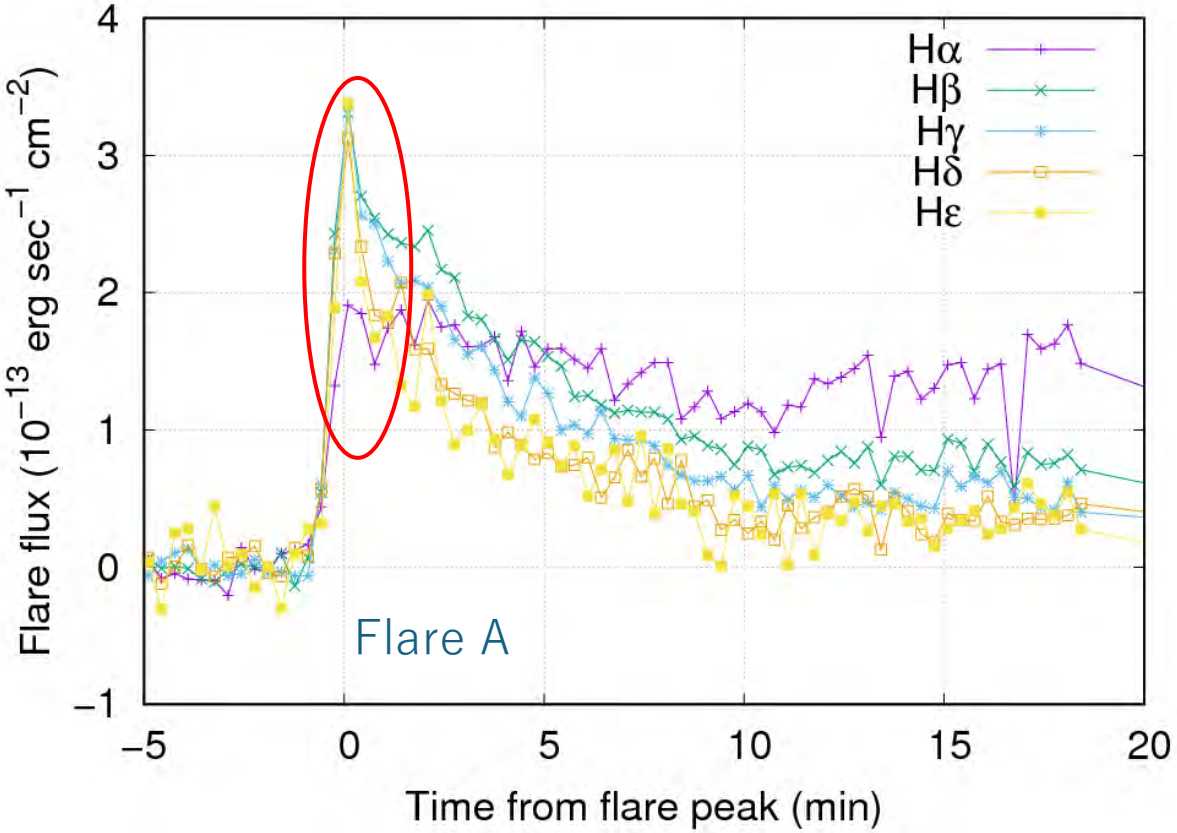
- We estimate T_{eff} by fitting the Blackbody function to pre-flare-subtracted spectra (except for emission lines).
- Flare A: T_{eff}~8000 K at flare peak
- Flare B: T_{eff}~6000 K at flare peak
- T_{eff} decreases as the flare decays.

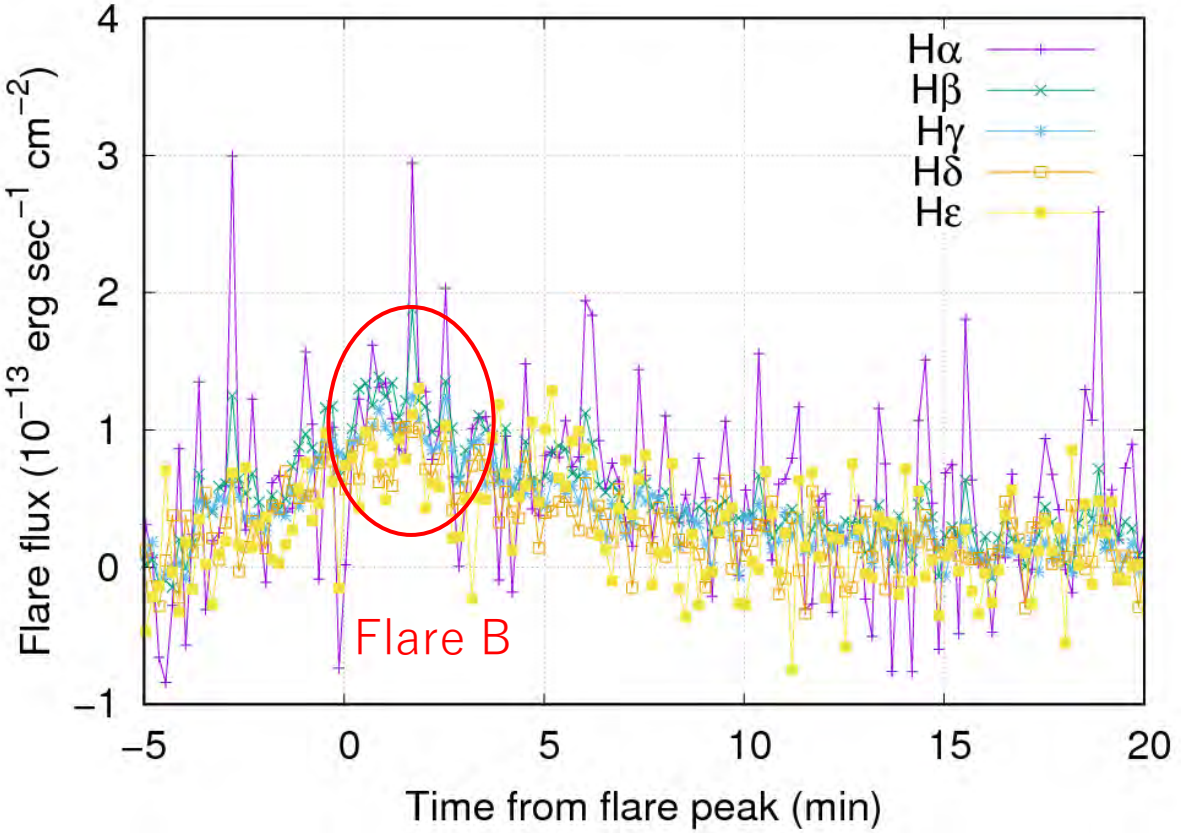






GJ1243: Flare light curve (Balmer lines)

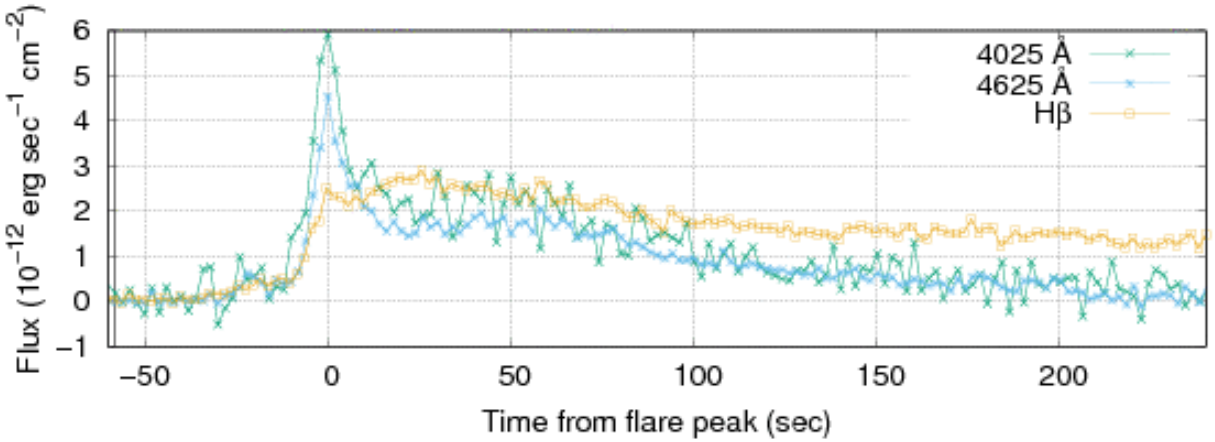




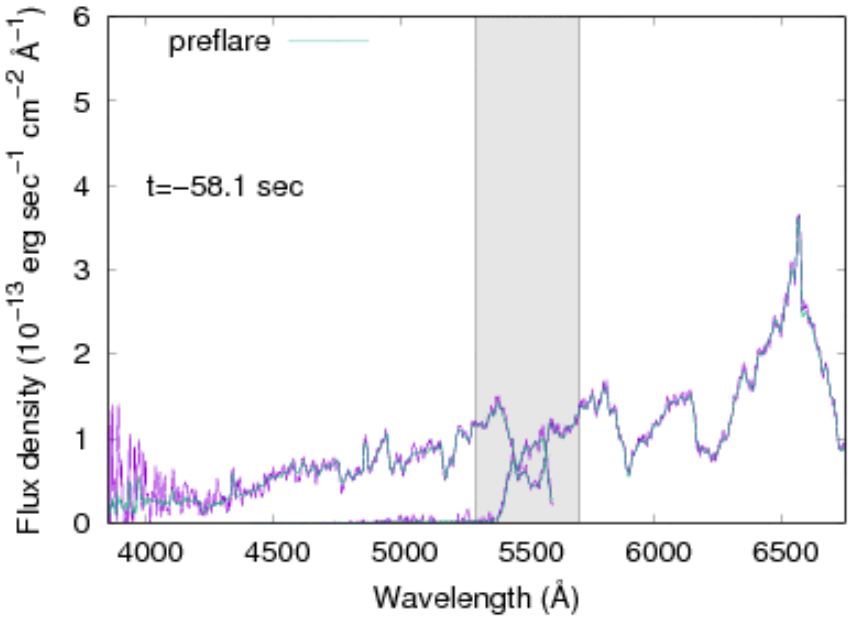
- Line flux at flare peak
  - Hε ~Hδ ~Hγ ~Hβ >Hα
  - Hα/Hγ ~0.6
- Decay time
  - Hα >Hβ >Hγ >Hδ >Hε

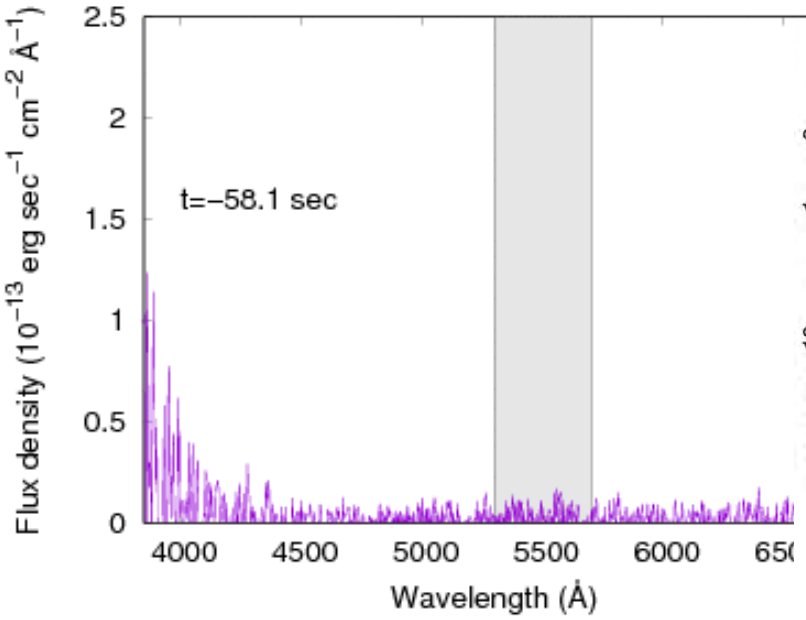
- Line flux at flare peak
  - Hα ~ Hβ >Hγ >Hδ >Hε
  - Hα/Hγ ~1.1
- Decay time
  - Hα ~Hβ ~Hγ ~Hδ ~Hε

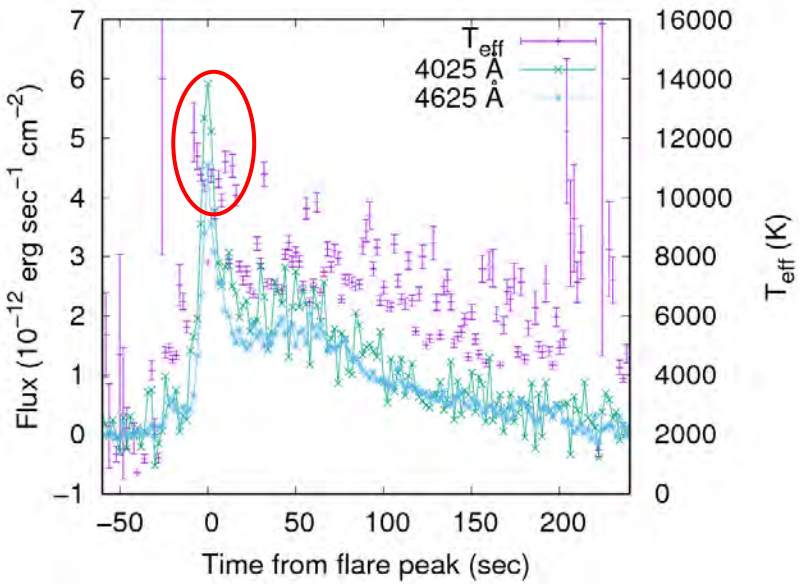
YZ CMi (1)



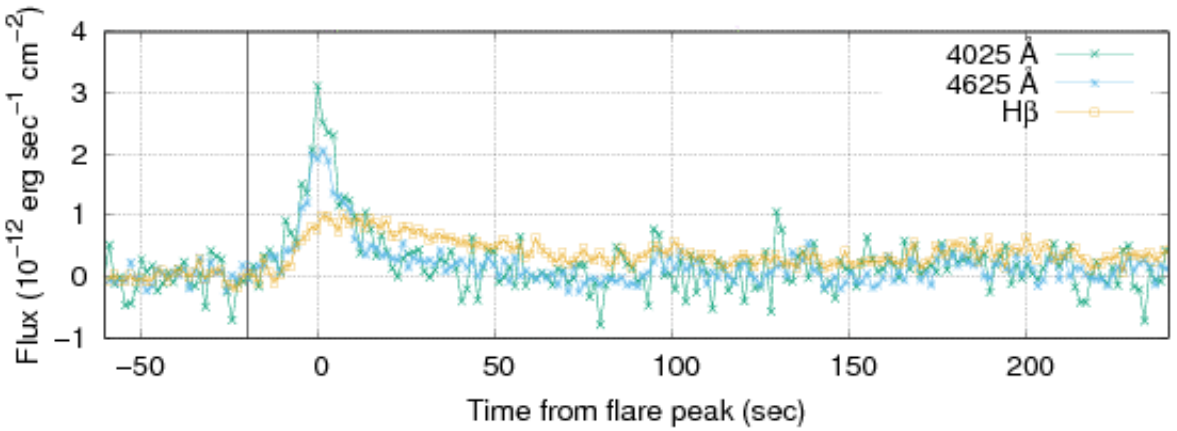
- We detected several impulsive flares on YZ CMi.
  - Time cadence ~2.0 sec
- τ_{rise} ~10 sec
- T_{eff} ~ 10000 K at flare peak



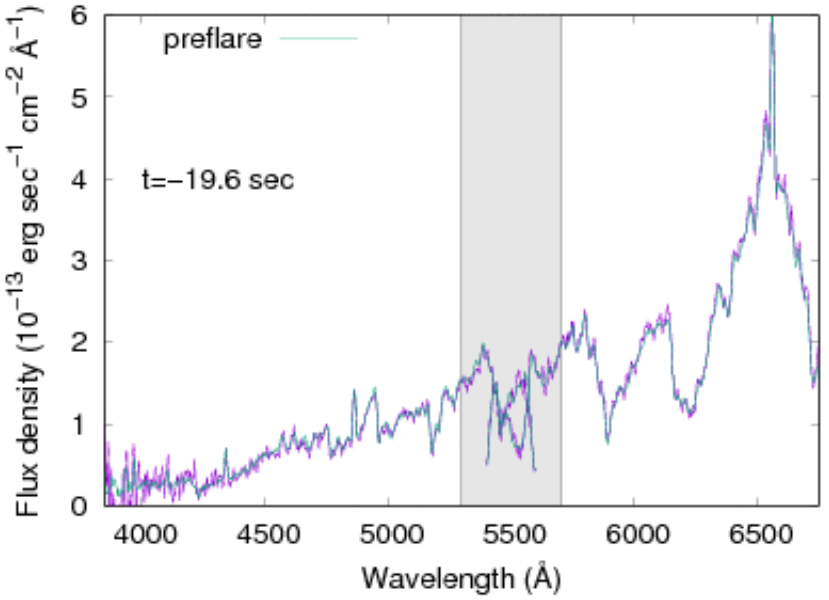


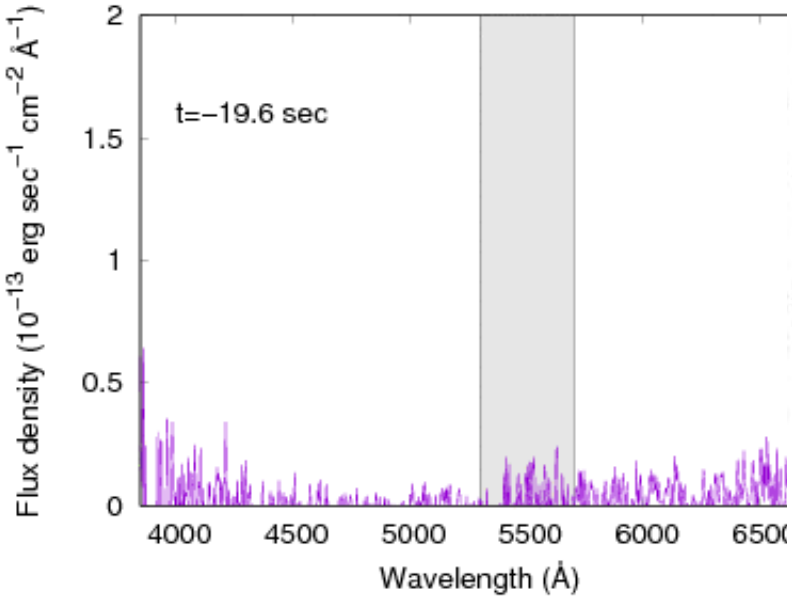


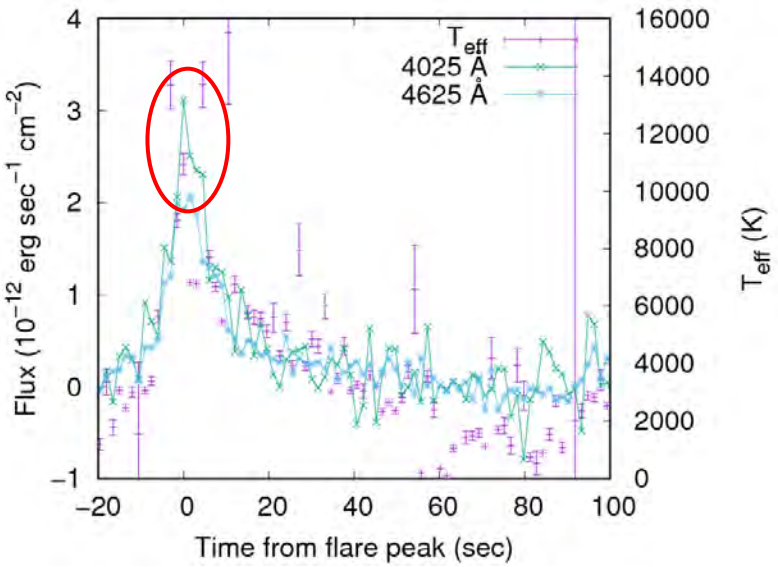
YZ CMi (2)



- We detected several impulsive flares on YZ CMi.
  - Time cadence ~1.5 sec
- τ_{rise} ~8 sec
- T_{eff} ~ 10000 K at flare peak







Summary

- We performed high-time-cadence spectroscopy of stellar flares on M-dwarfs using the 3.8-m Seimei telescope.
  - GJ 1243: 10-20 sec cadence
    - 1 impulsive flare and 1 gradual flare
  - YZ CMi: 1.5-3 sec cadence
    - 2 impulsive flares
  - We investigated temporal variations of the effective temperature of flare continuum and the Balmer line flux during flares.

- T_{eff} depends on the temporal profile of flares.
  - Impulsive flare: ~8000 – ~10000 K @ flare peak
  - Gradual flare: ~6000 K @ flare peak

- Balmer lines: The Hα line was weaker than other Balmer lines at the peak timing of impulsive flares.
  - Impulsive flare: Hα/Hγ ~ 0.6 @ flare peak
  - Gradual flare: Hα/Hγ ~ 1.1 @ flare peak