TIME-RESOLVED MULTI-BAND IMAGING OF STELLAR FLARES IN YOUNG OPEN CLUSTERS AND NEARBY M-DWARF STARS

CASE OF PLEIADES, PRAESEPE, EVLAC AND GJ1243

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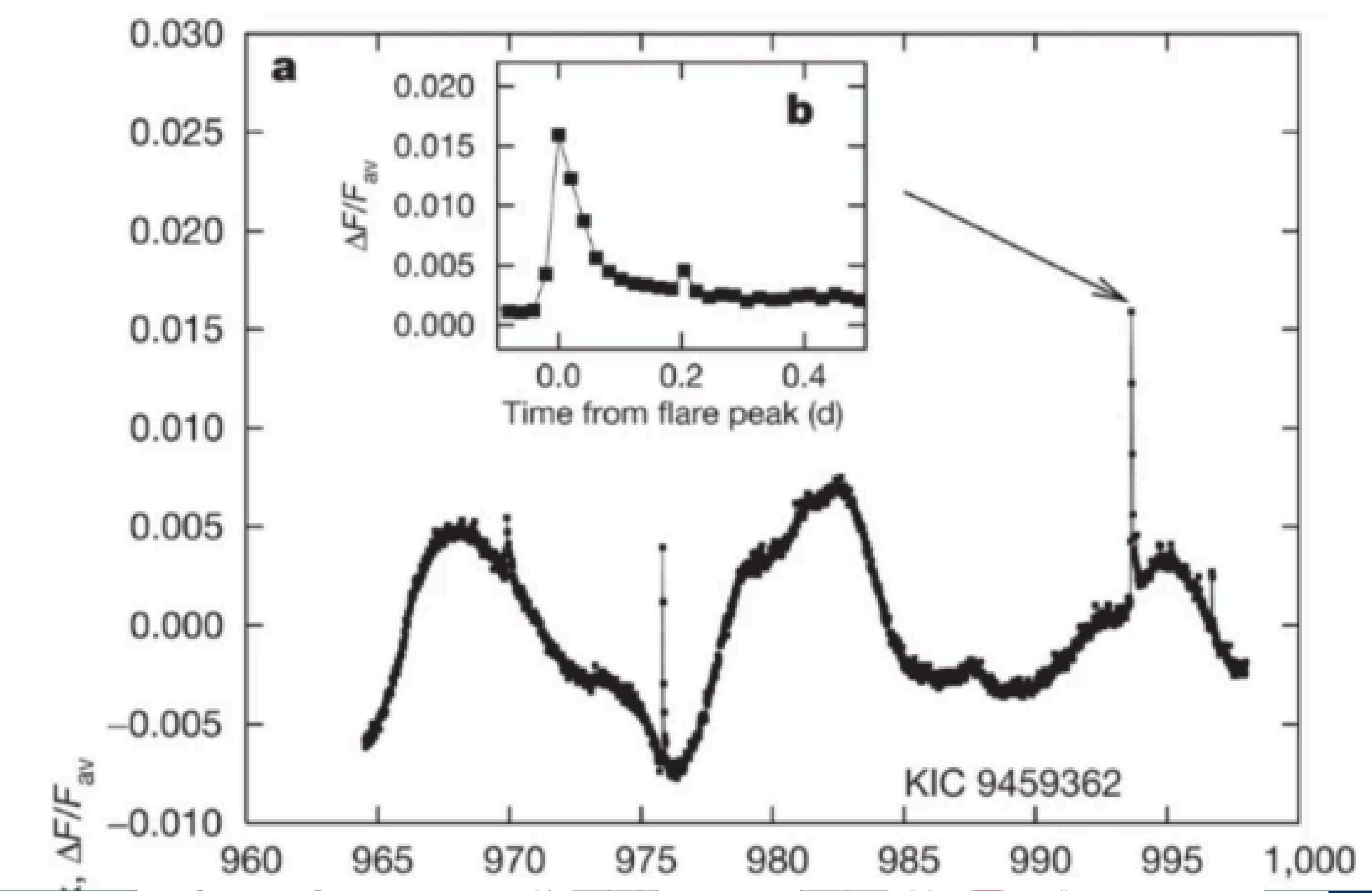
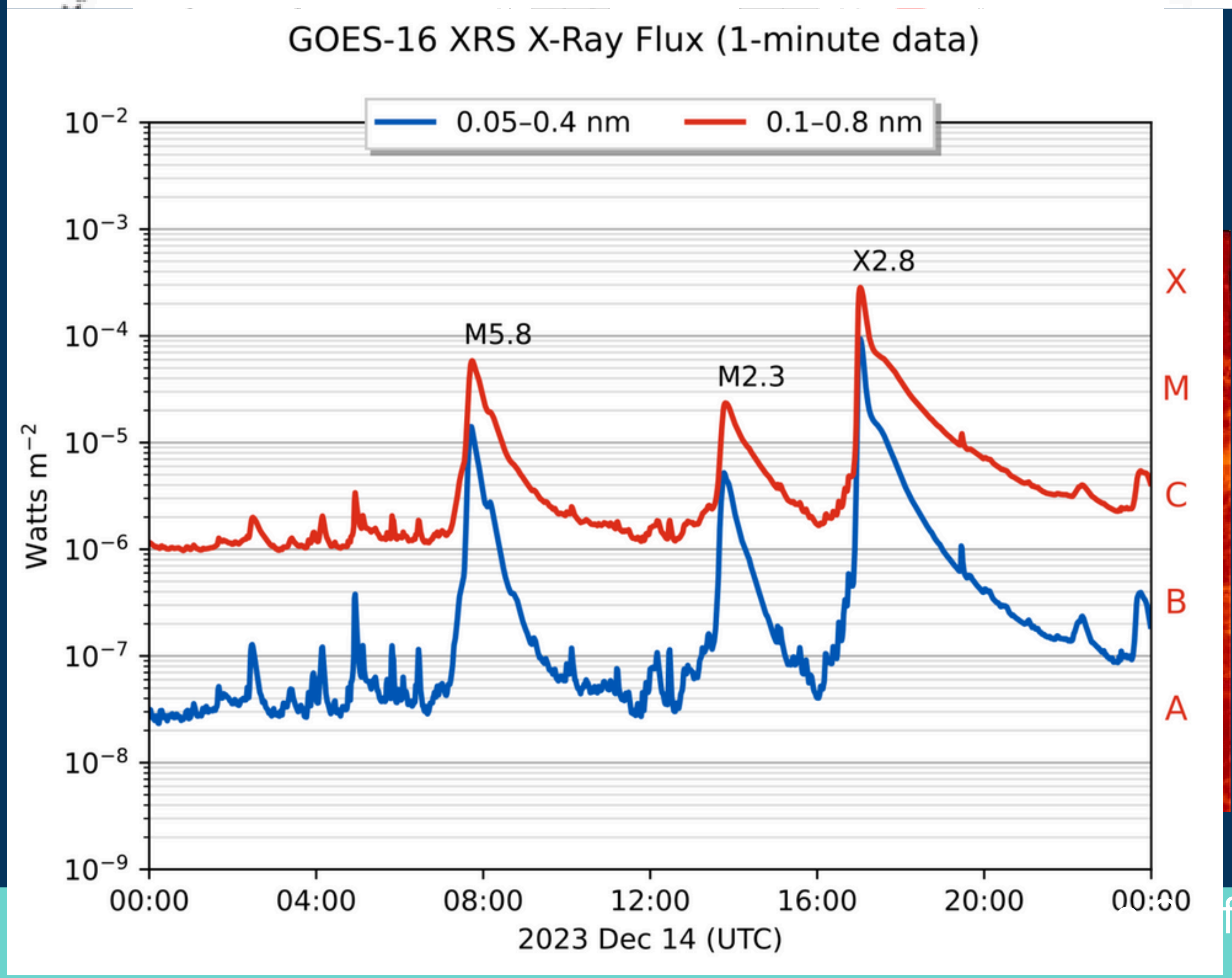
Seimei Users Meeting
Tokyo University of Science,
Ookayama Campus
September 2-4, 2025

Solar and stellar flares

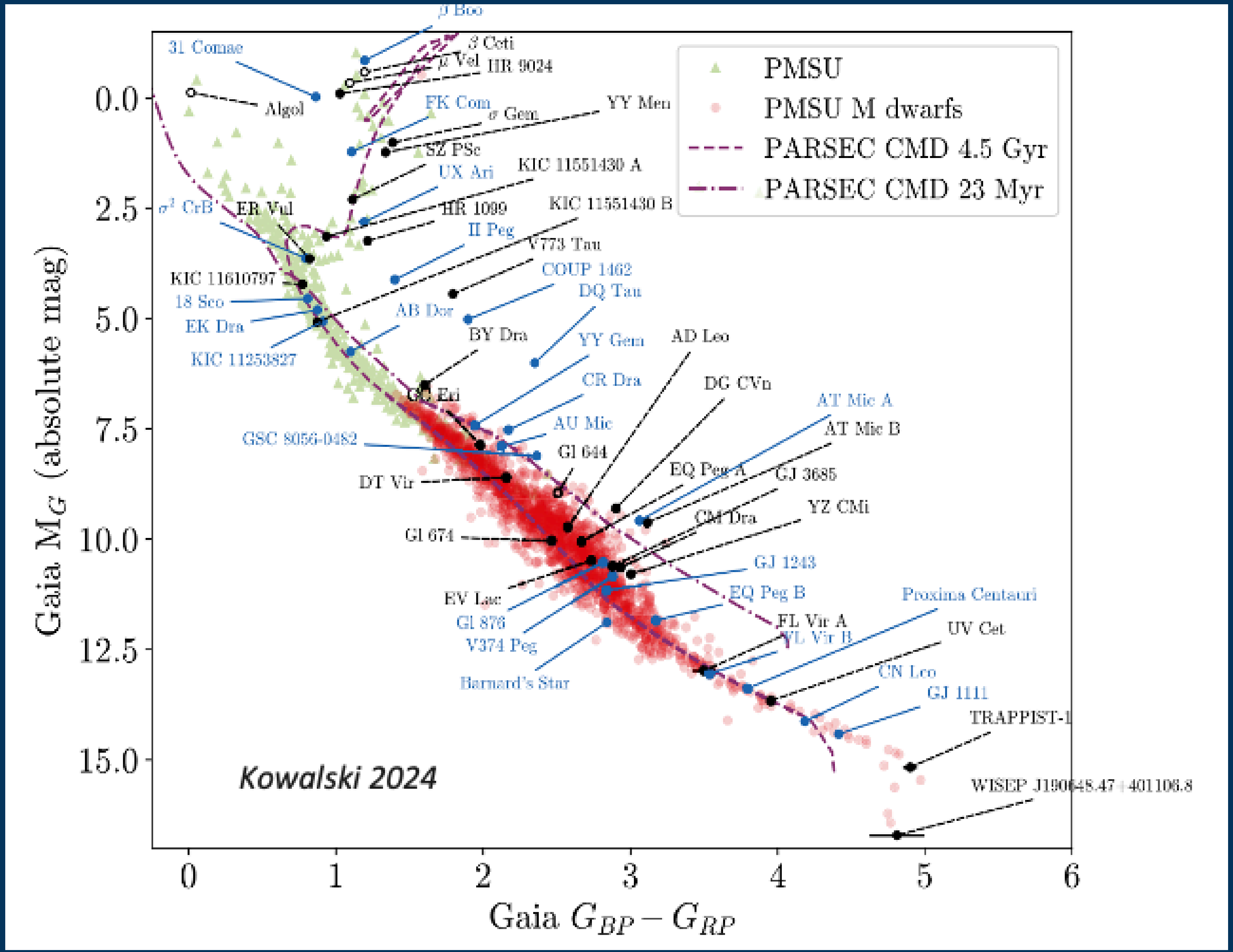
- Source of Solar and stellar flares → magnetic energy stored around spots, and released through magnetic reconnection. (Shibata & Magara, 2011; Davenport+2012)
- Solar flares release energy in range of 10^{24} - 10^{32} erg (Aschwanden+2000). Flare energy in other stars could reach 10^{33} - 10^{36} erg → superflares. (Aschwanden+2008; Benz & Gudel,2010)
- Flares and superflares are often observed through sudden brightenings in sun/stellar light curves.

Figure 1: Light curve of typical superflares.



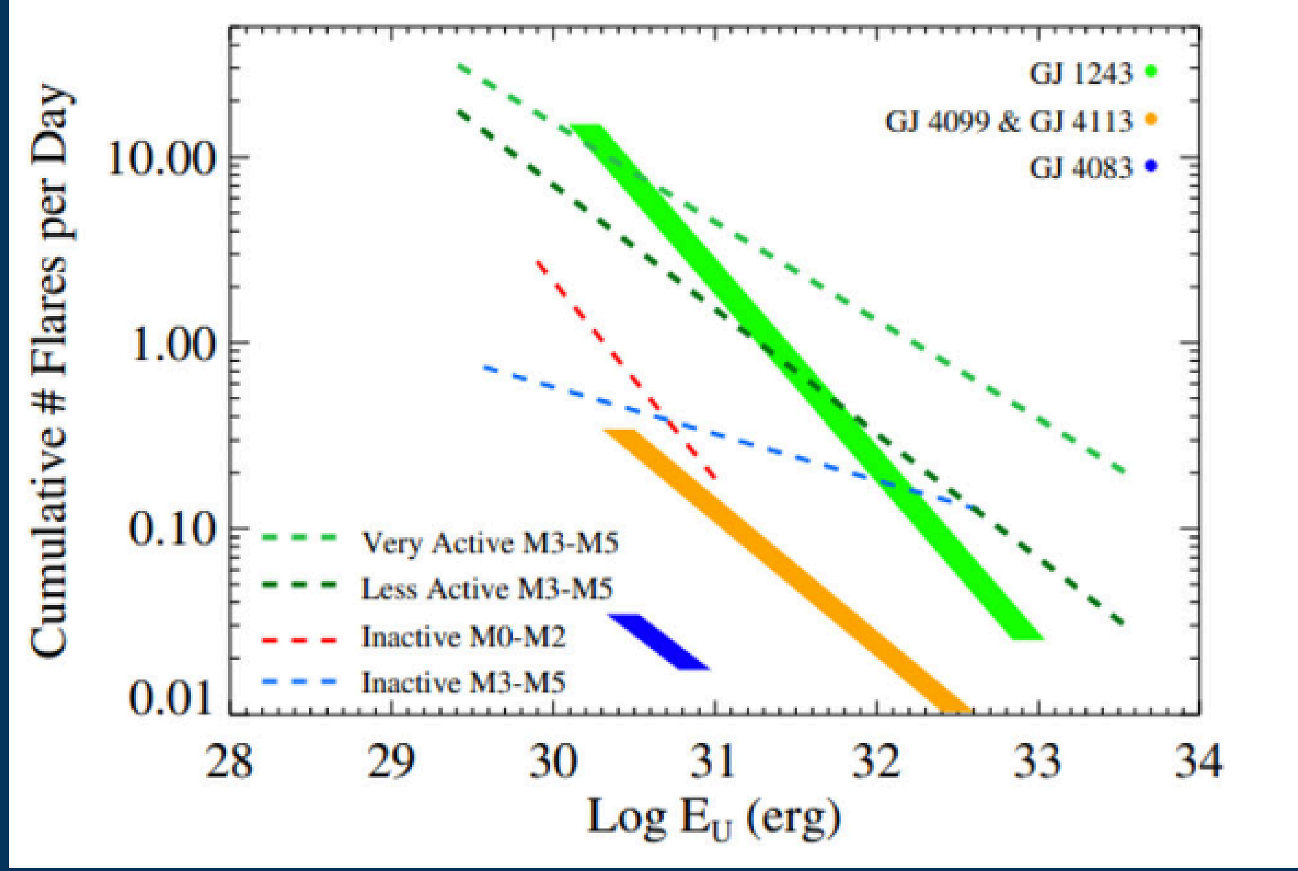


Superflares on various type of stars



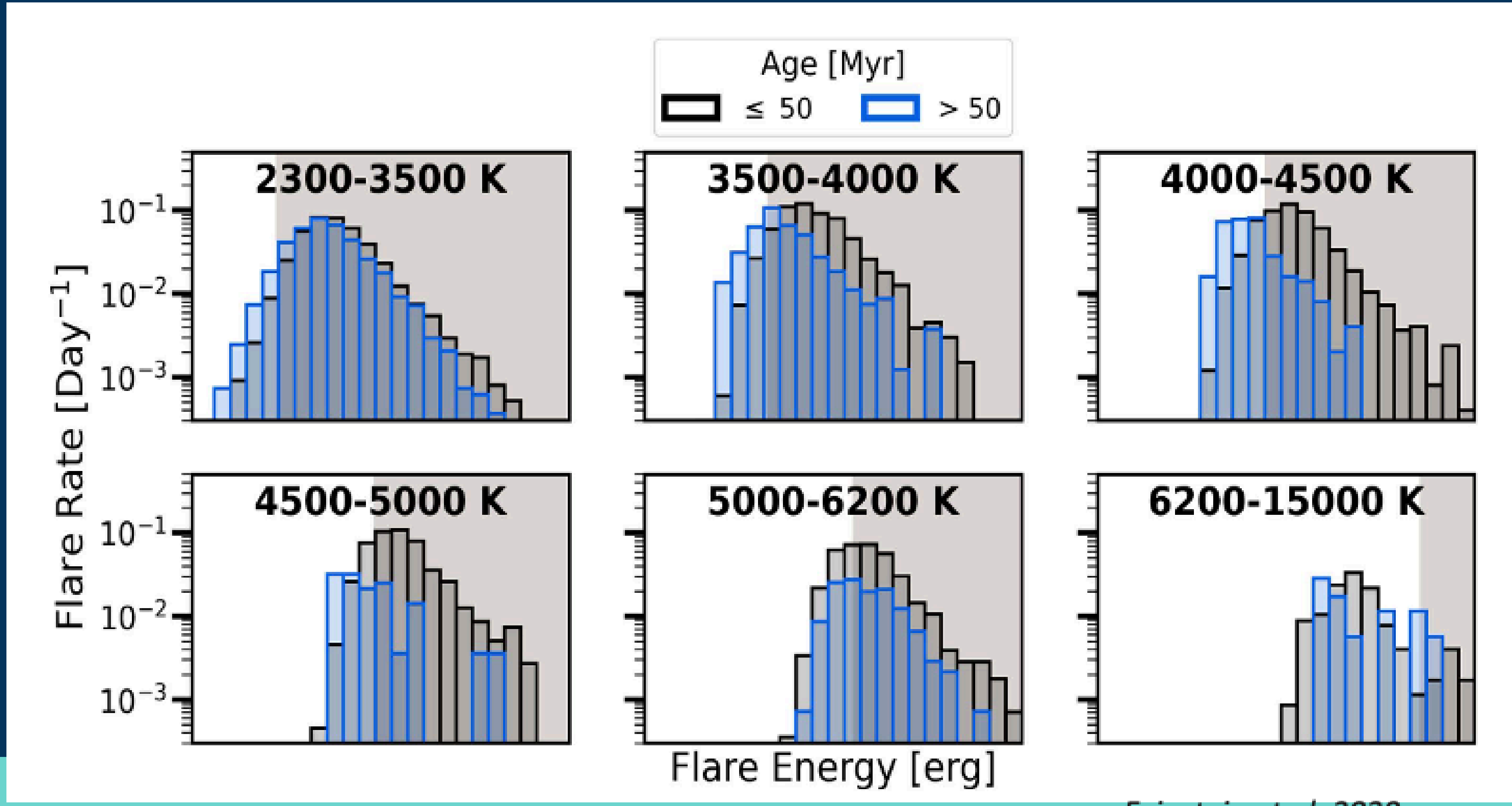
- Flares are observed on a wide range of stars, including M, K, and G-type dwarfs, and even some giant stars.
- Young stars, close binary stars, and late-type (dMe) stars are known to produce frequent flares.

Kowalski 2024

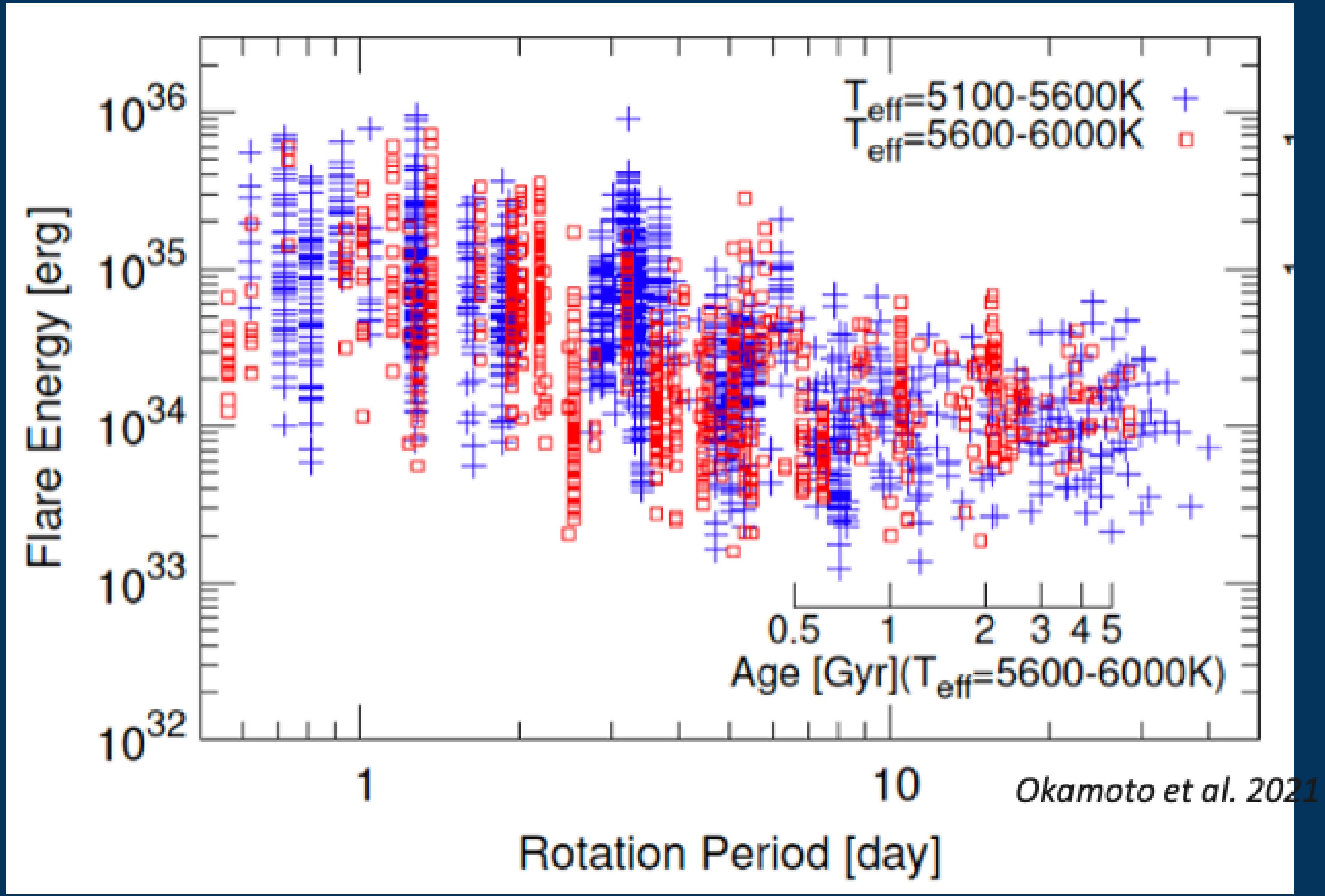


Role of age in flare activity

- Previous studies have confirmed that flaring rates generally decline with age.
- Young stars exhibit particularly vigorous magnetic activity.



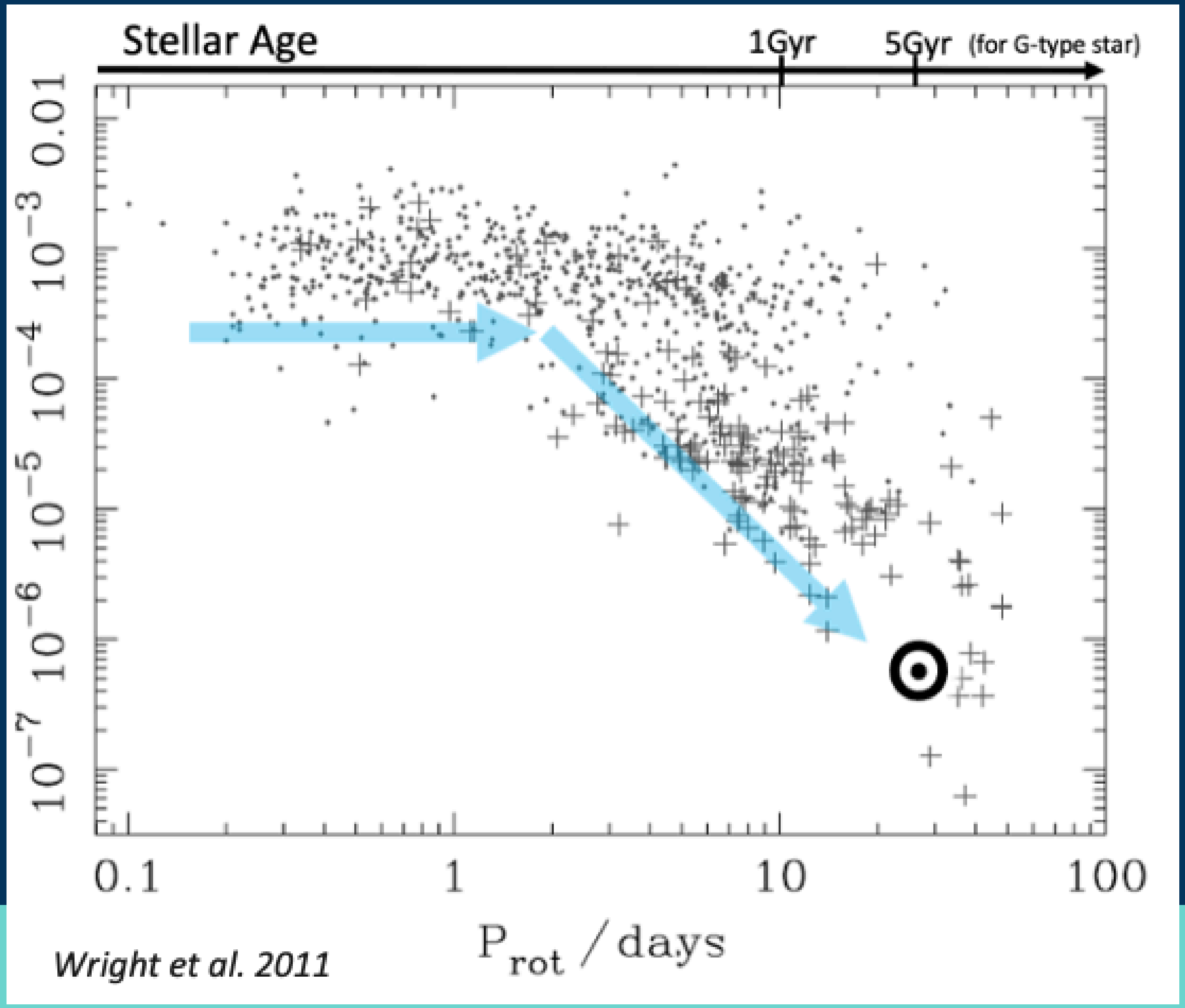
Feinstein et al. 2020



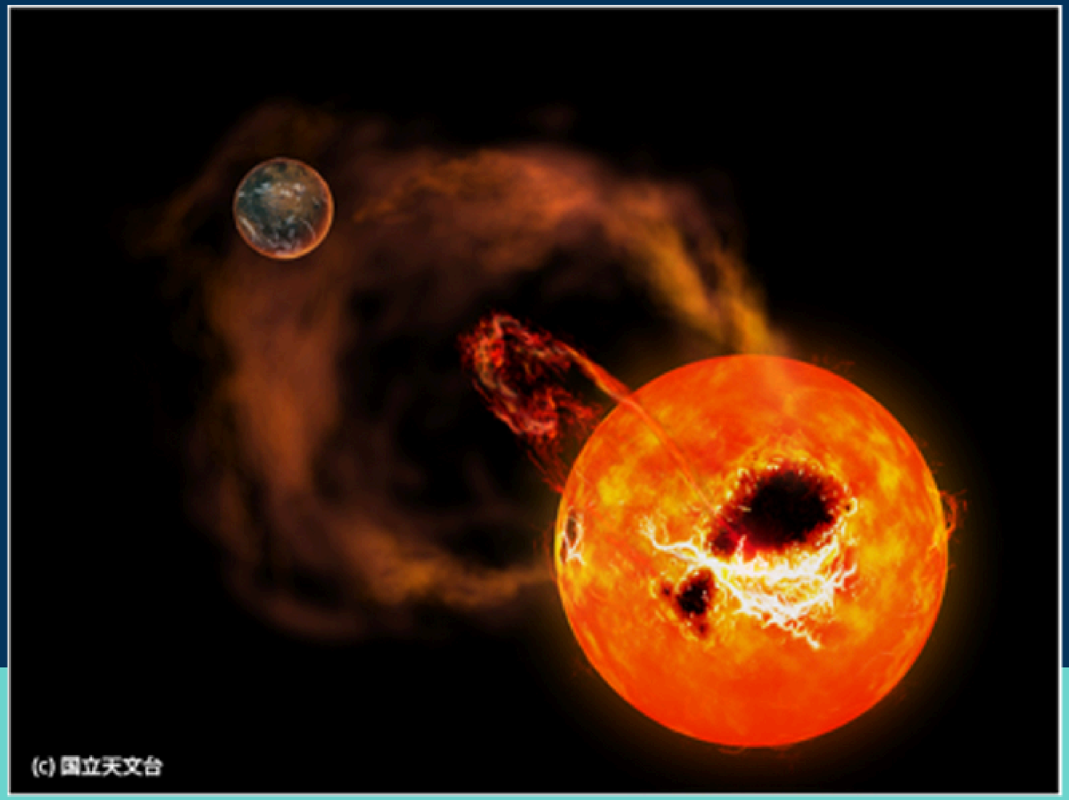
Okamoto et al. 2021

Aim: Stellar activity evolution

Deriving a relation between flare energy and flare frequency, star's rotation, spectral type, and star's age → stellar activity evolution



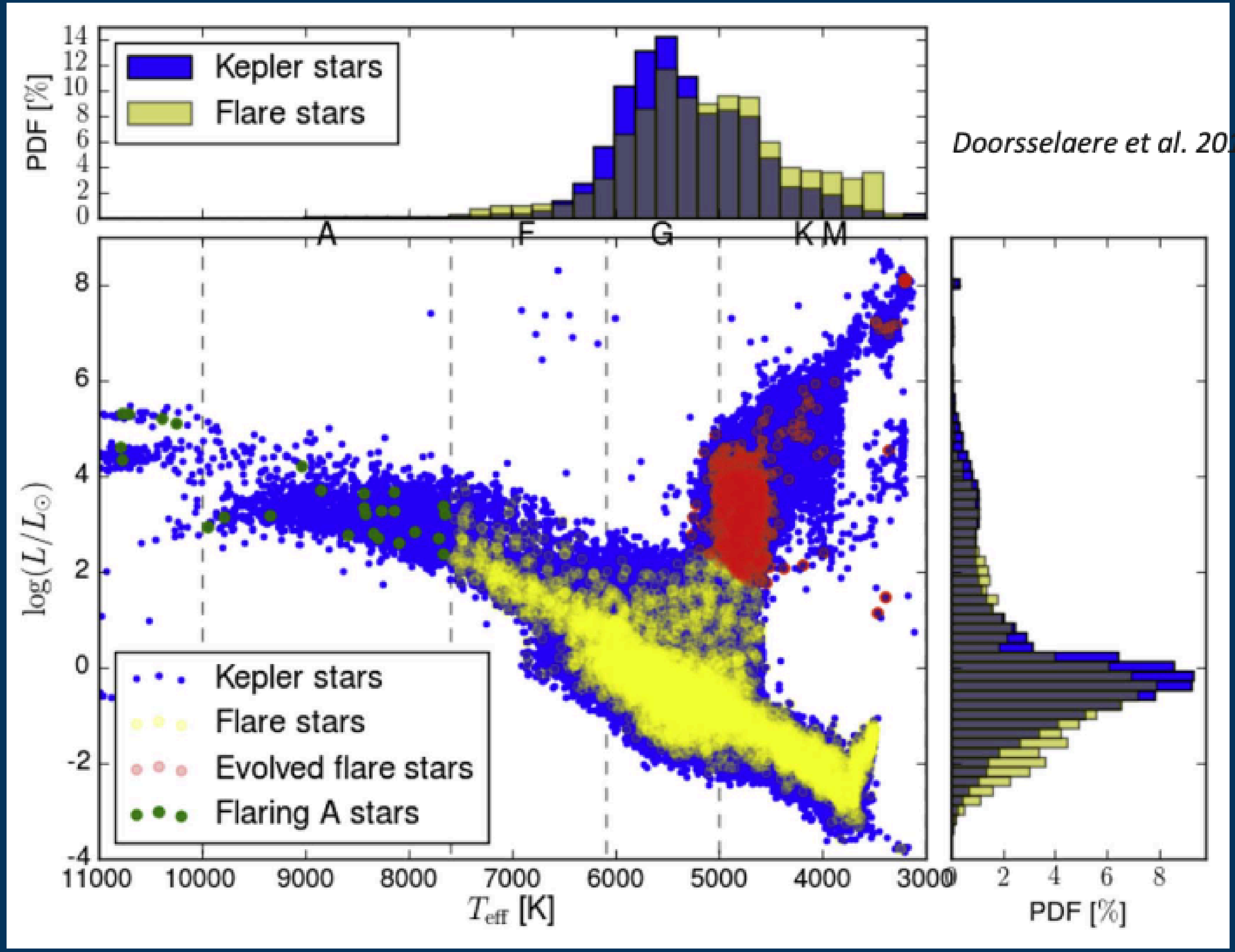
This stellar activity evolution impacts various stellar phenomena, including rotation, and the properties of surrounding environments.



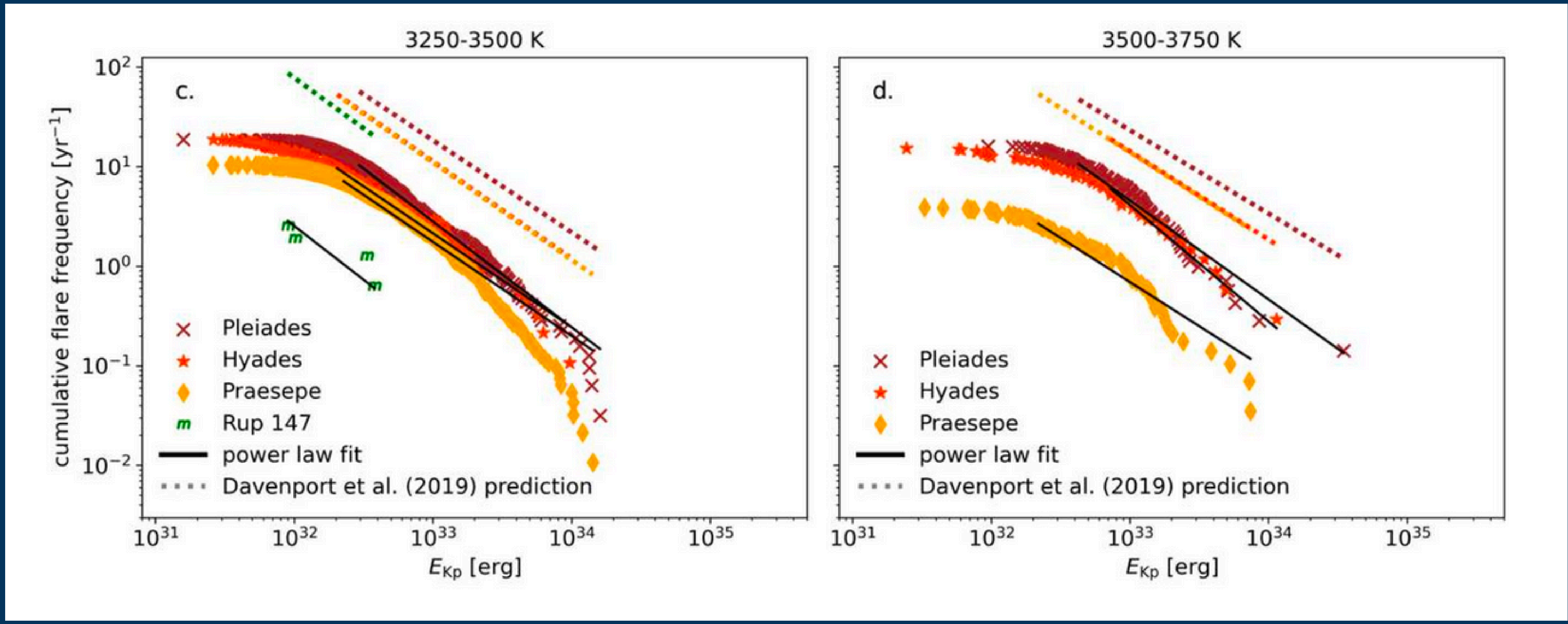
Young open cluster is a good target for this purpose.

Previous studies (Kepler/K2)

Kepler provided 1-minute cadence data and 30-minute long cadence data. K2 also provided observations of flares in open clusters.

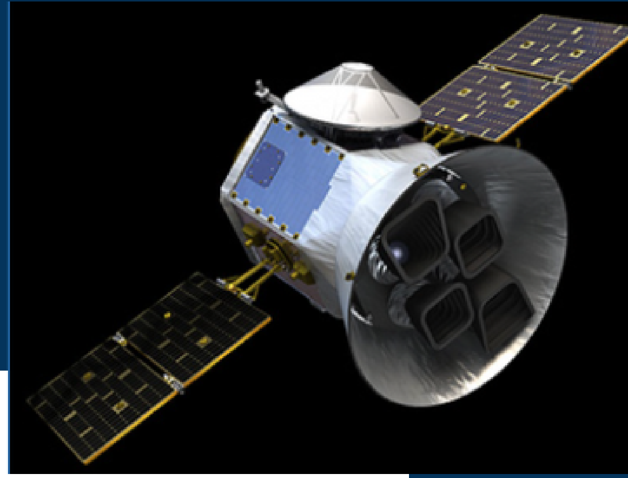


Doorsselaere et al. 2017

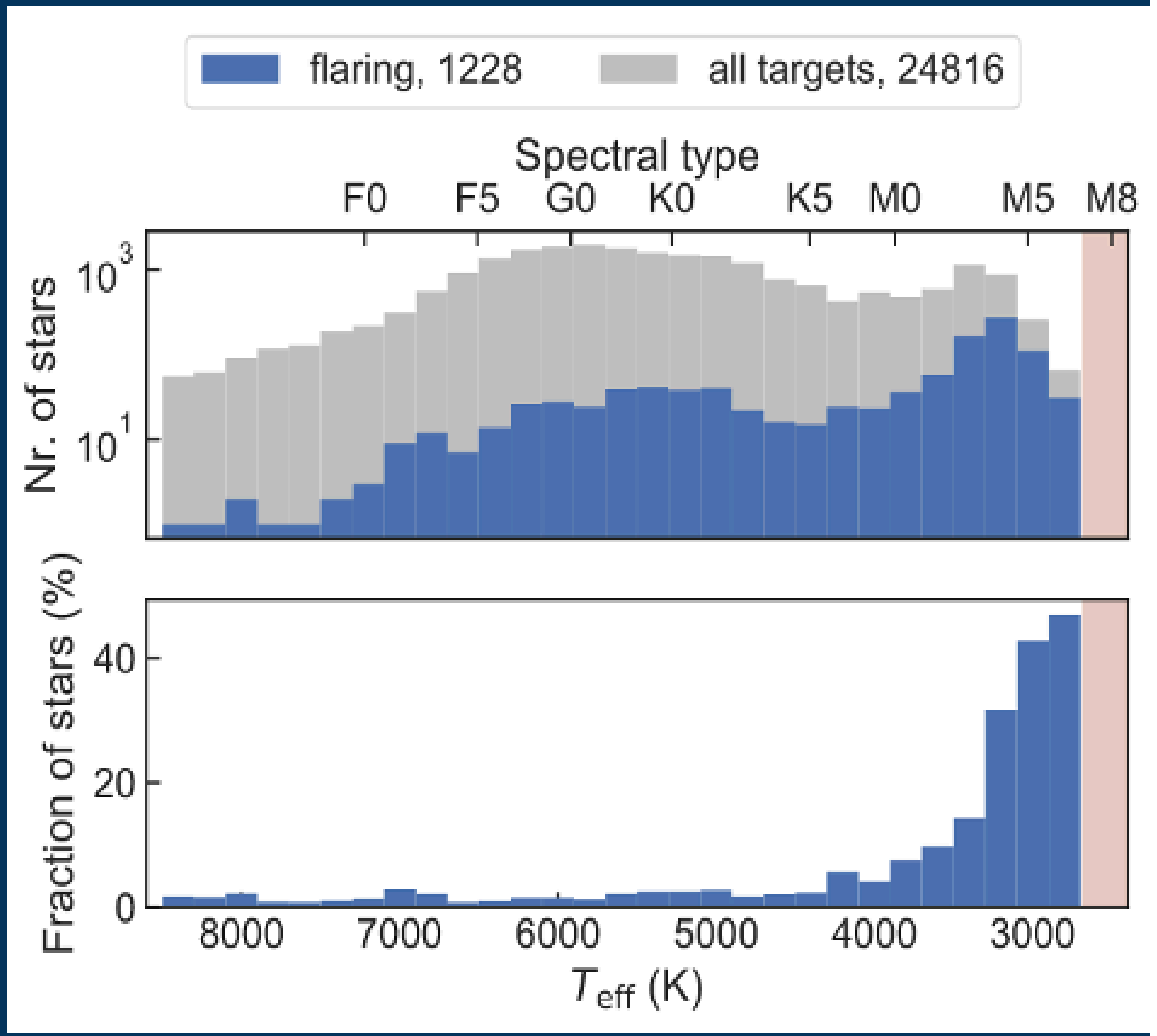


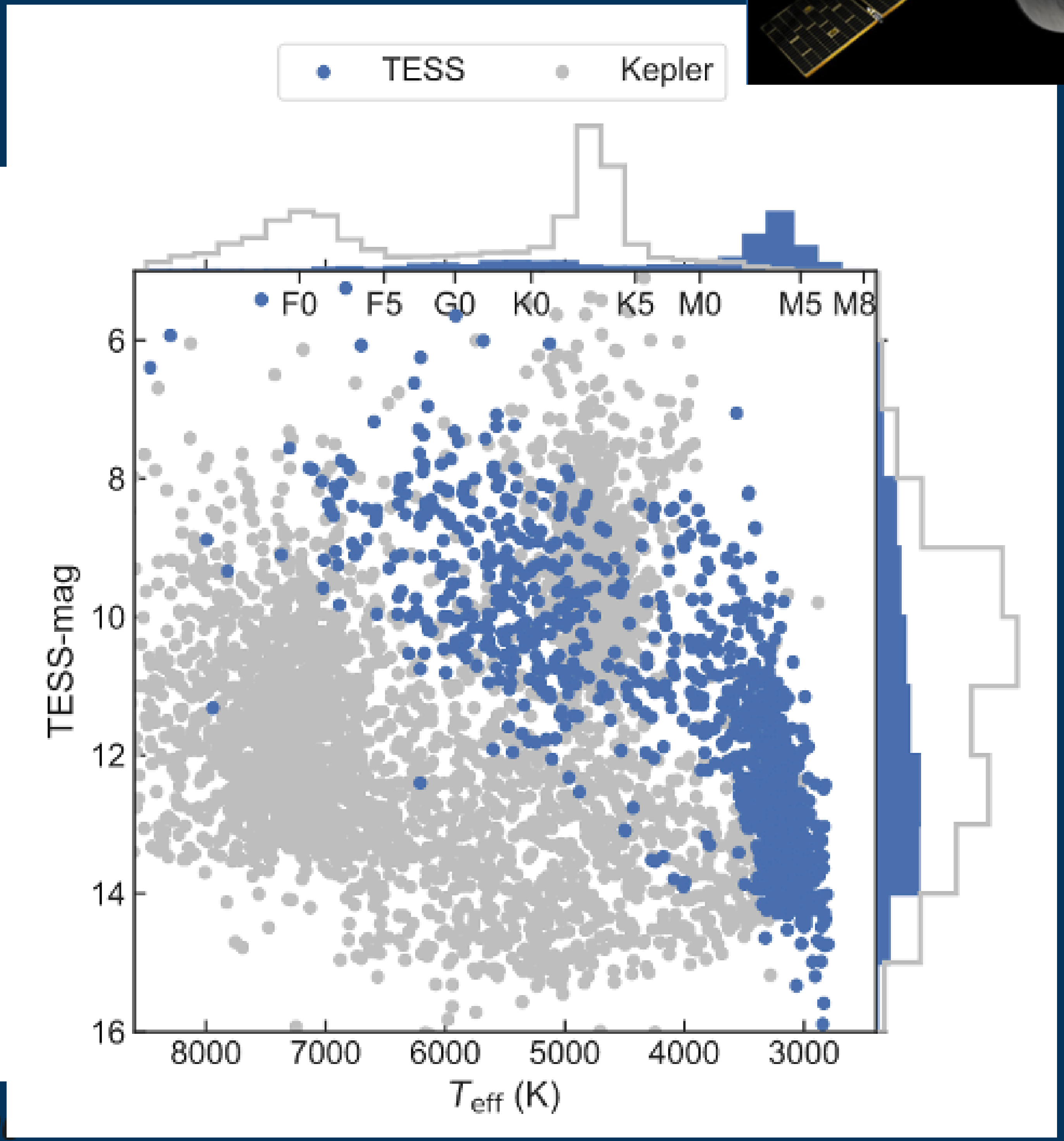
They reported that younger and later-type stars cause large flares, but the power law index of flare frequency distributions is almost same among different age and different types stars. (Ilin et. al. 2021)

Previous studies (TESS)



- TESS has short-cadence (20 seconds, and 2 minute) data for many stars and 30-minute cadence for millions.

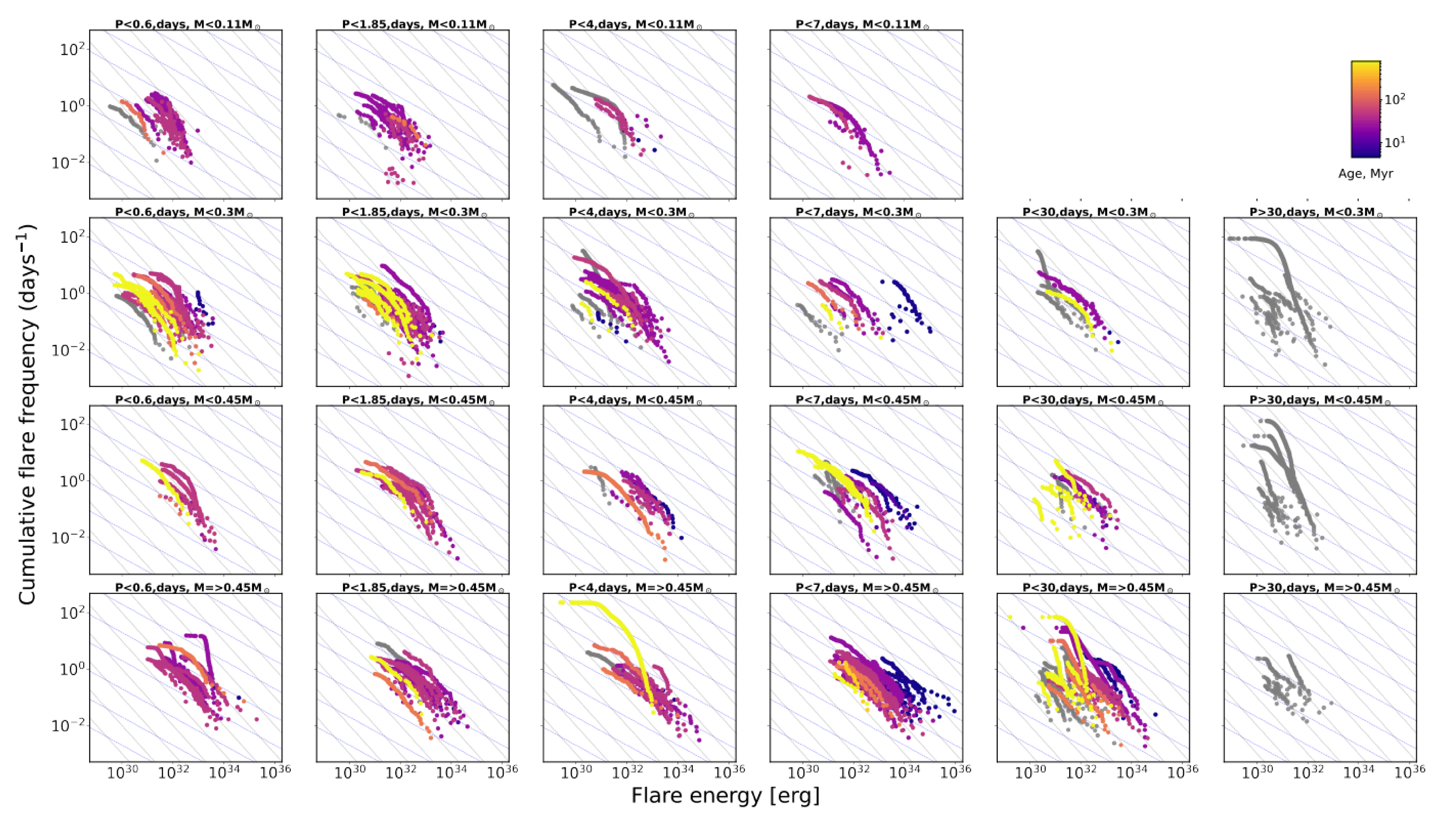




Gunther et al. 202

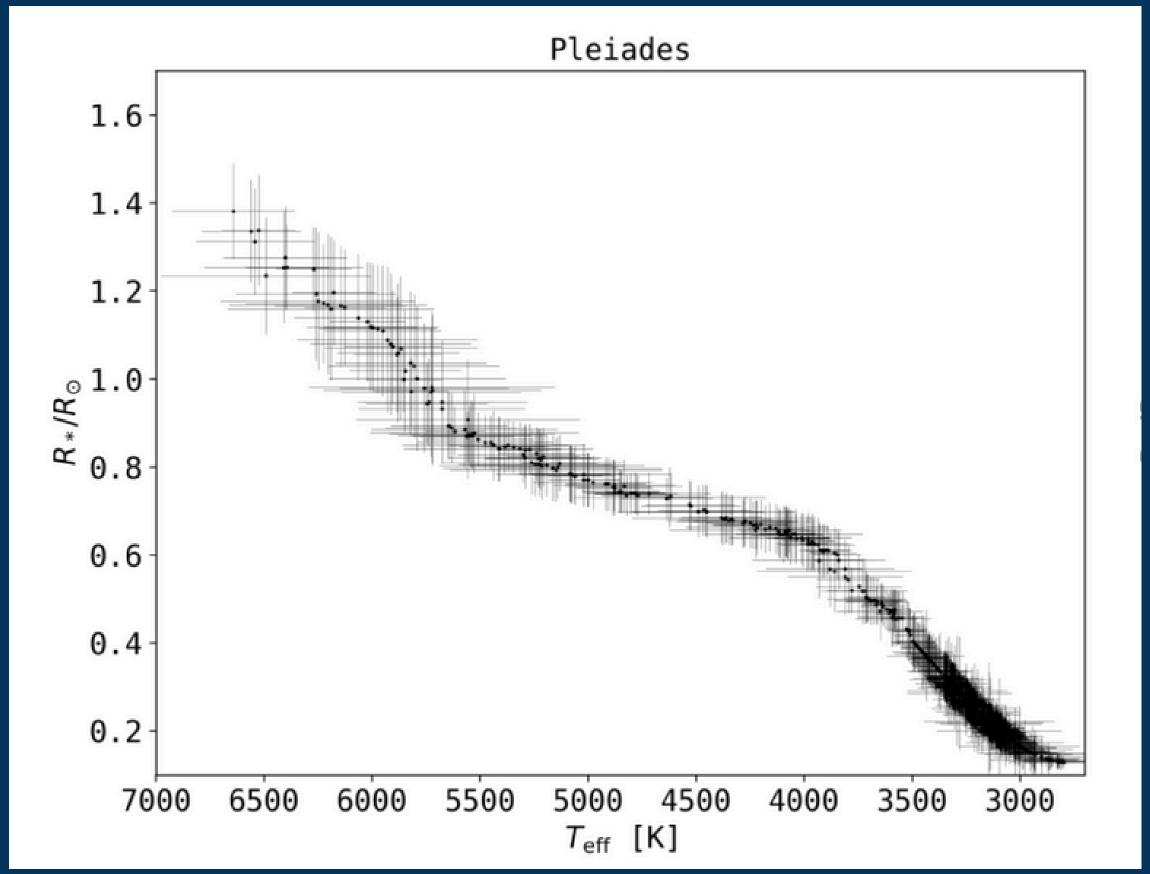
Previous studies (TESS)

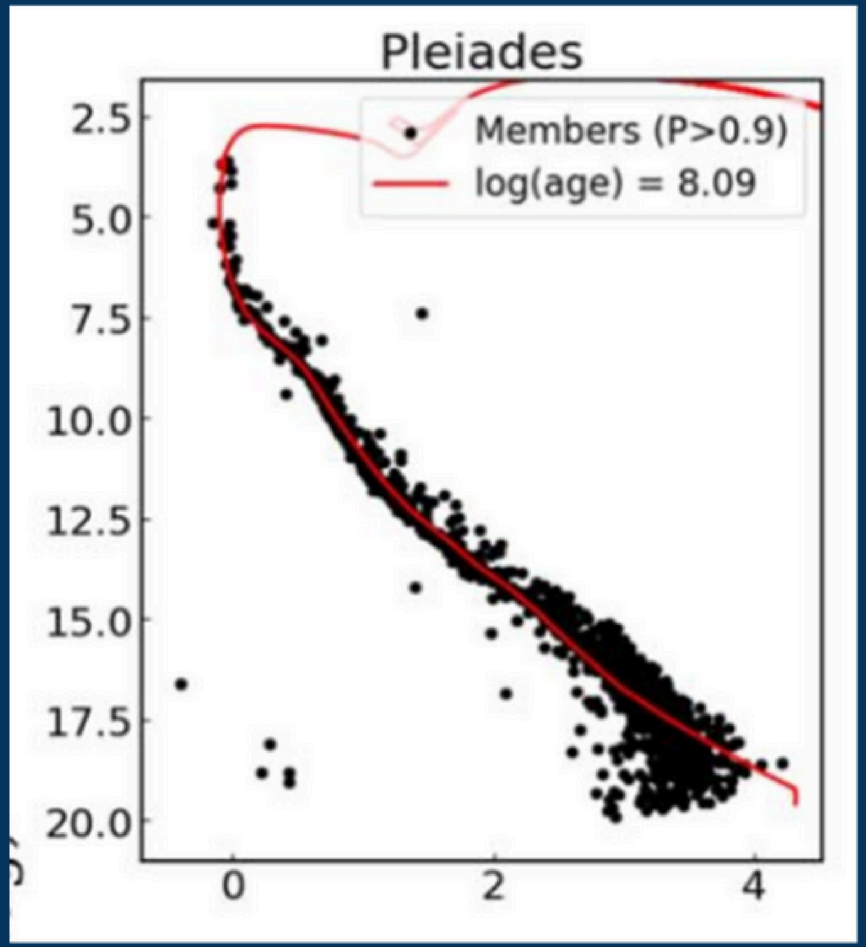
- Stellar age is not the sole parameter governing flare behaviour based on young moving group members. (Mamonova et. al. 2025)
- Although Feinstein et al. (2024) found that flare rates are higher when stars are young (less than 50 Myr) and decrease with age, this does not apply to all M dwarfs.

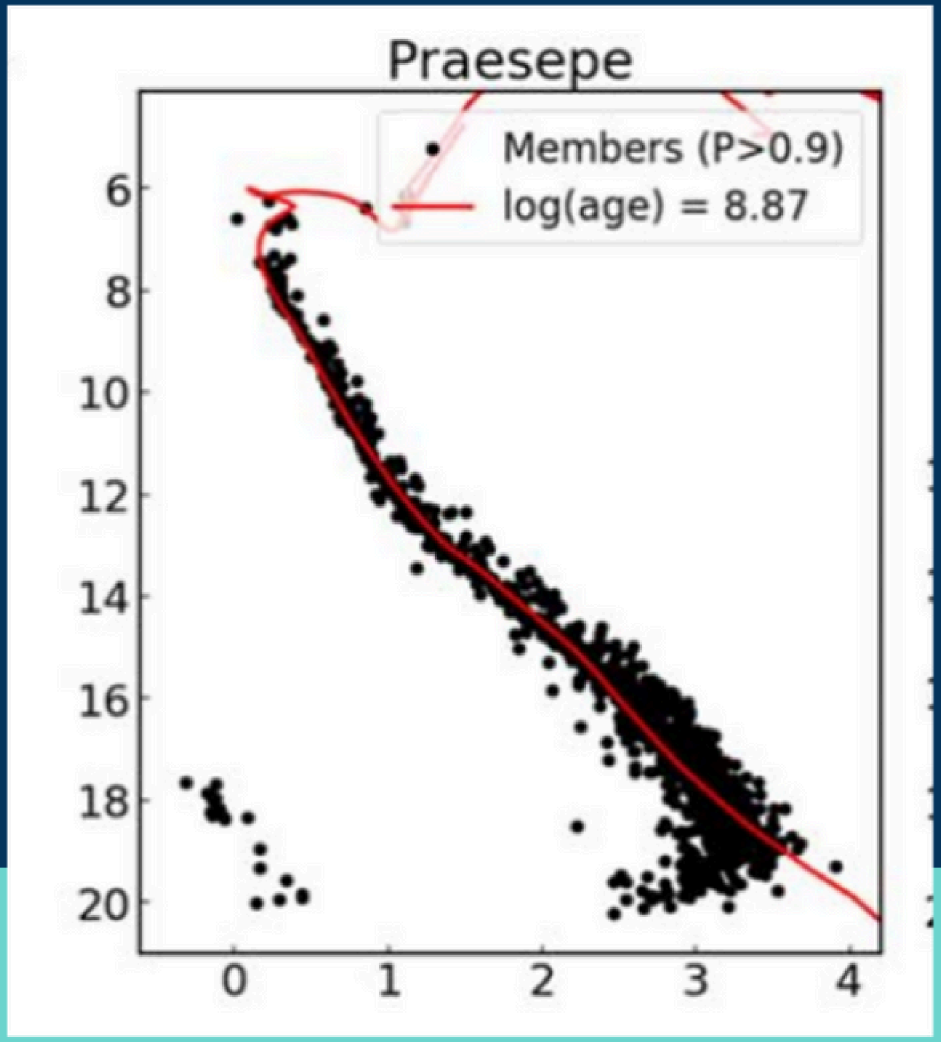


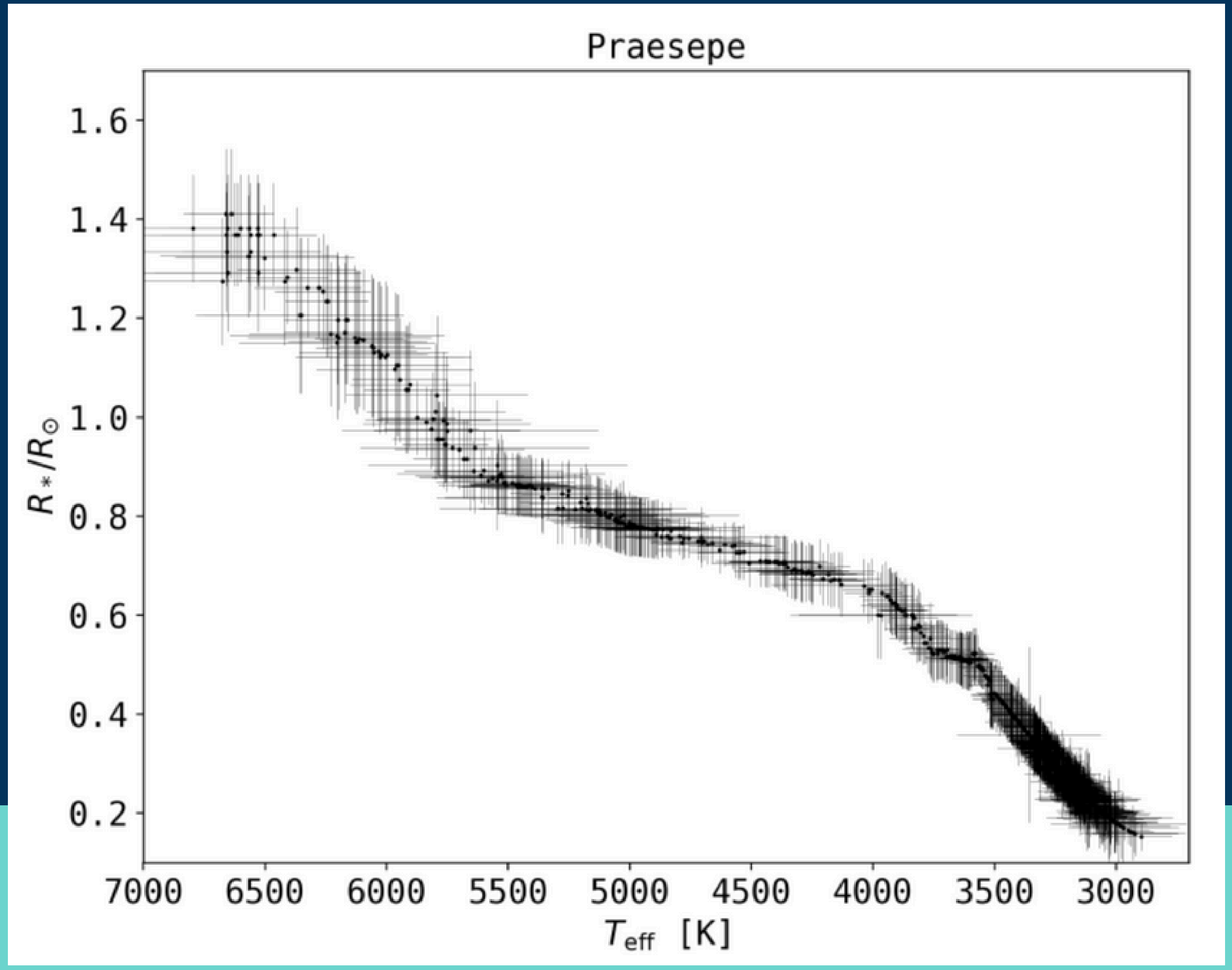
Our target: Pleiades and Praesepe

- Angular width ~110 arcminutes
- RA, Dec: 3° 47m 24", +24° 7' 0"
- Distance: ~135 pc
- Age: ~123 Myr





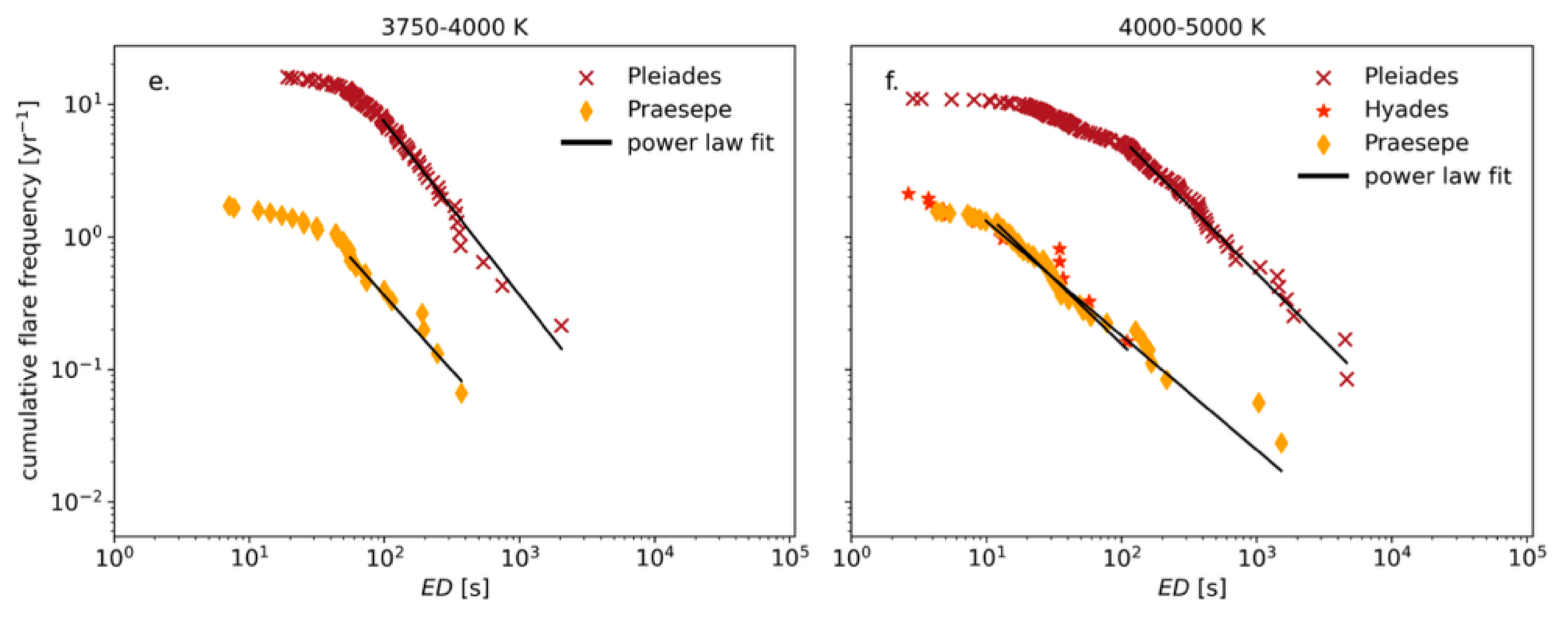


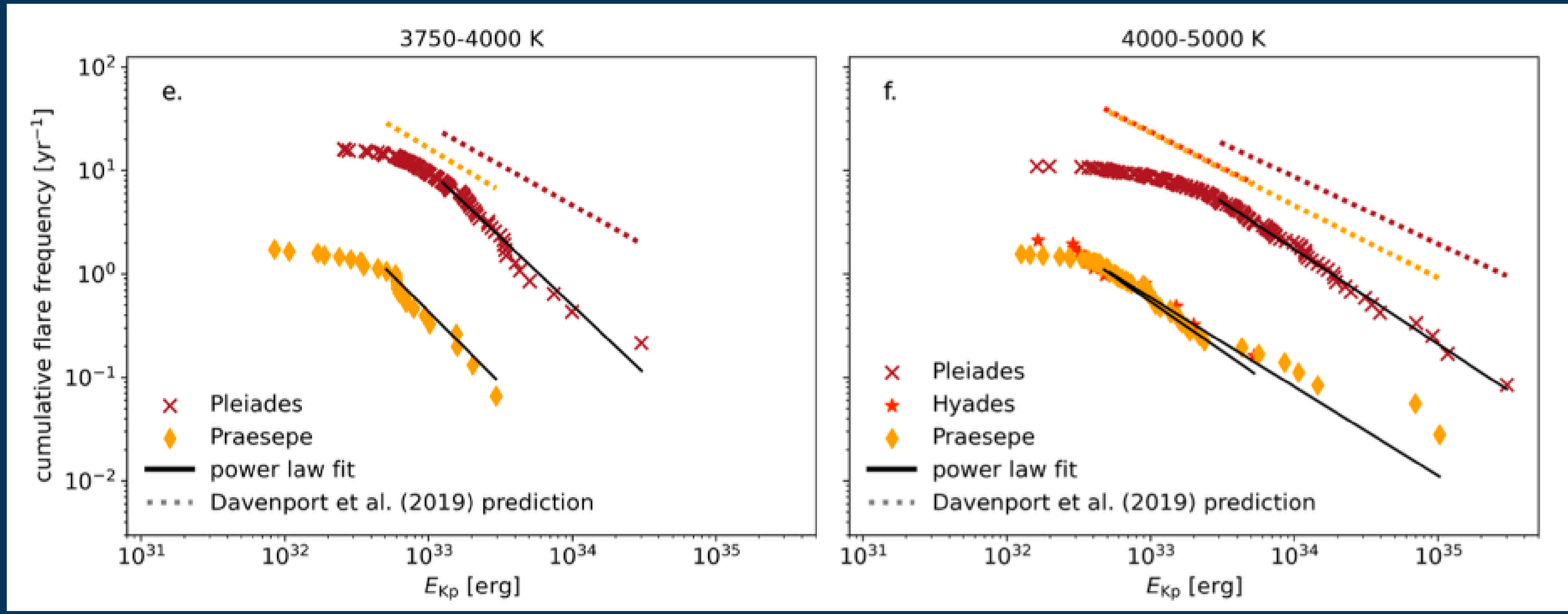


- Angular width ~95 arcminutes
- RA, Dec: 8° 40m 24", +19° 59' 0"
- Distance: ~187 pc
- Age: ~741 Myr

Flare Activity in Pleiades

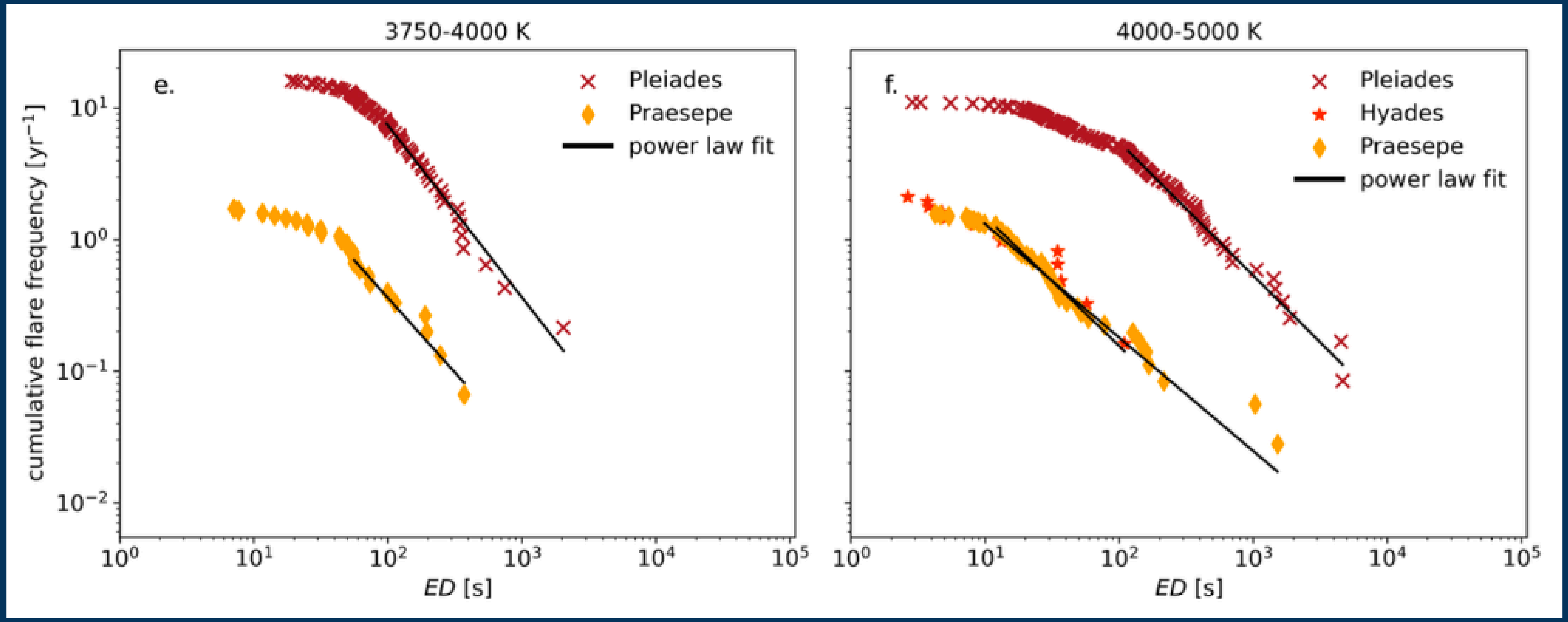
- Pleiades places it in the young regime where stellar magnetic activity is particularly vigorous and undergoes significant evolution.
- The Pleiades contains a significant number of late-type (K and M) stars suitable for this study.
- This is result study of Ilin et al. (2021)

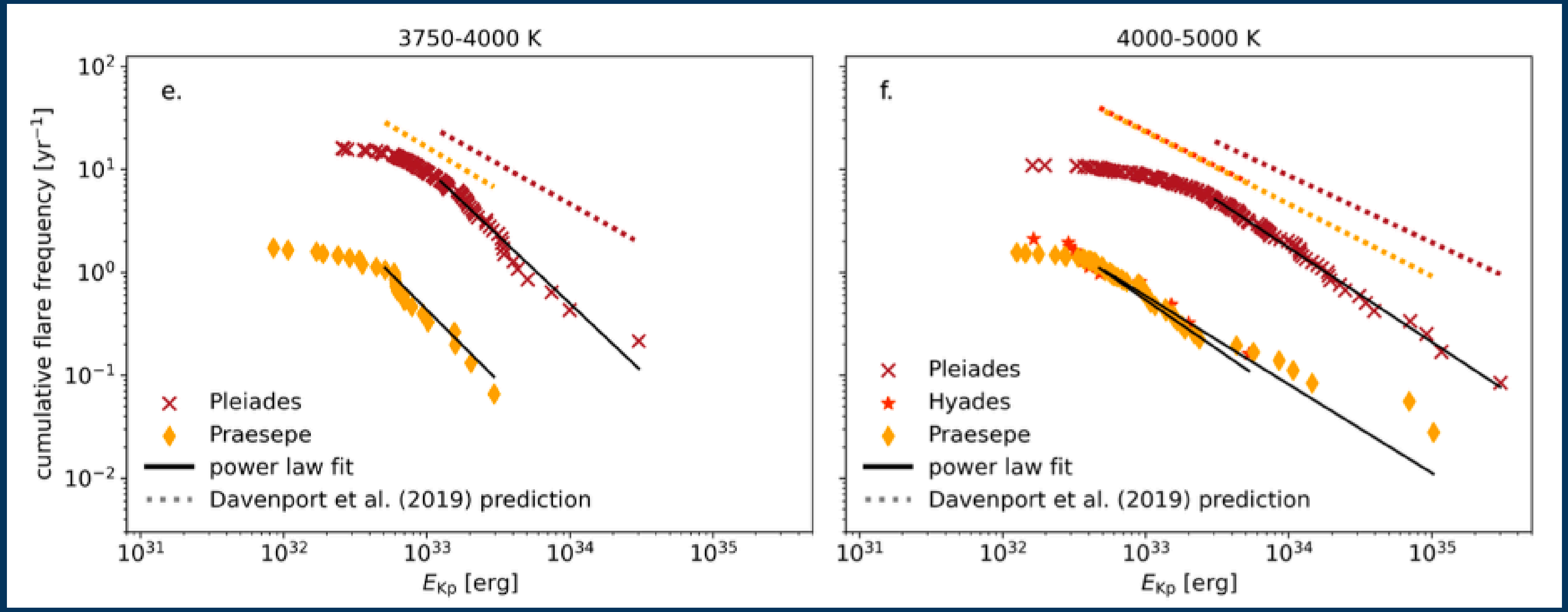




Flare Activity in Praesepe

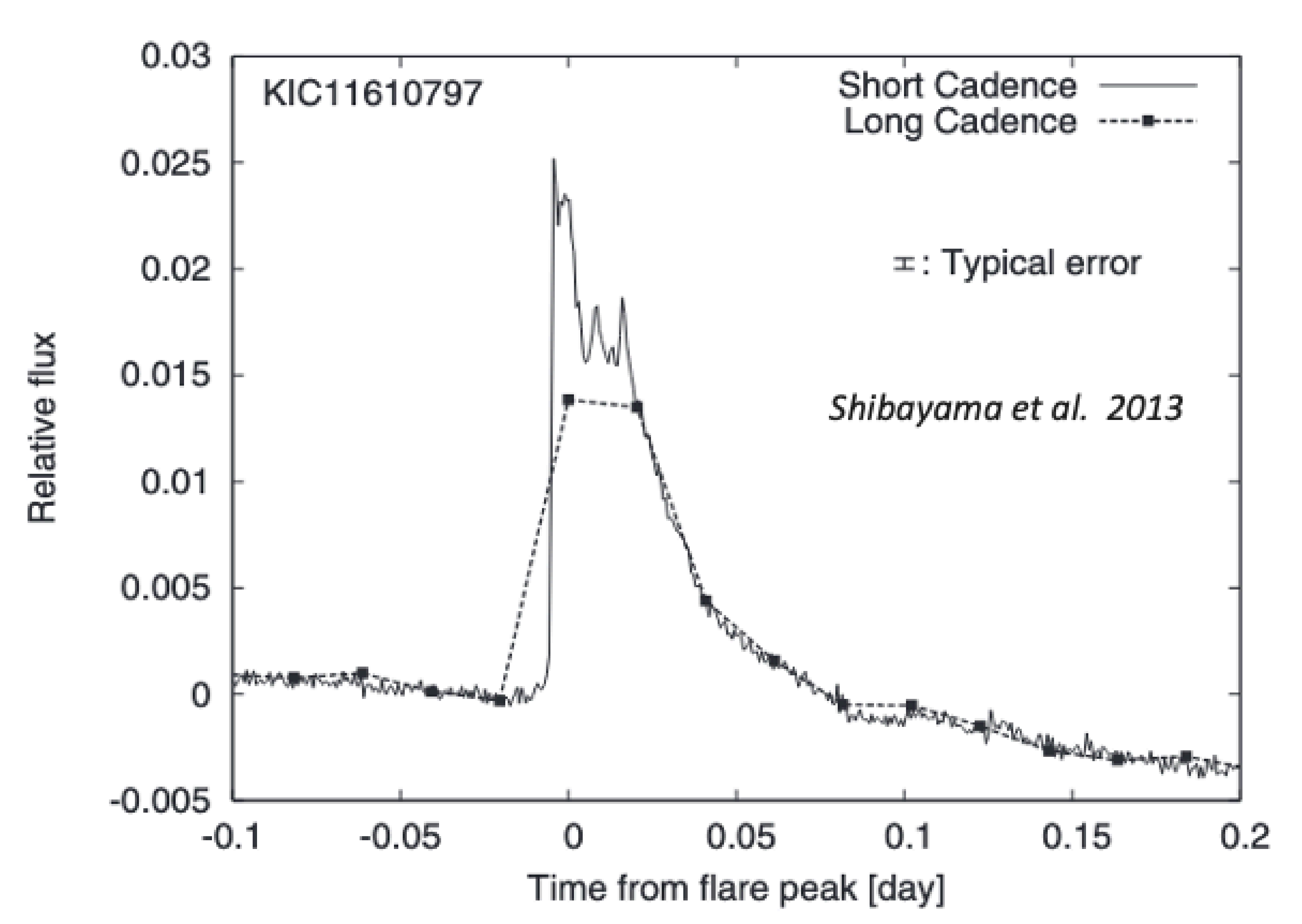
- The Praesepe age (~0.75 Gyr) provides a critical age contrast compared to the younger Pleiades (~0.125 Gyr).
- a significant number of late-type (K and M) stars suitable for this study.
- This is result study of Ilin et al. (2021)





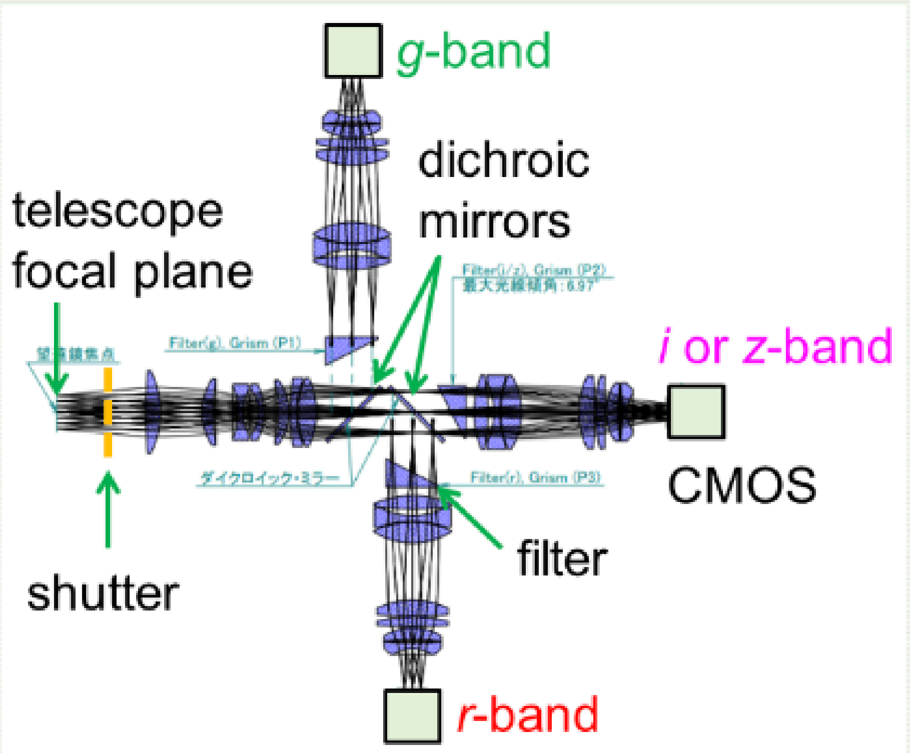
Limitation: Low Time Resolution (Kepler/K2 Long Cadence)

- Energies of flares found in Kepler 30 min cadence light curves are underestimated by about 25% compared to 1 min cadence (Yang et al. 2018).
- It is also insufficient to resolve the rapid, impulsive phase of flares.

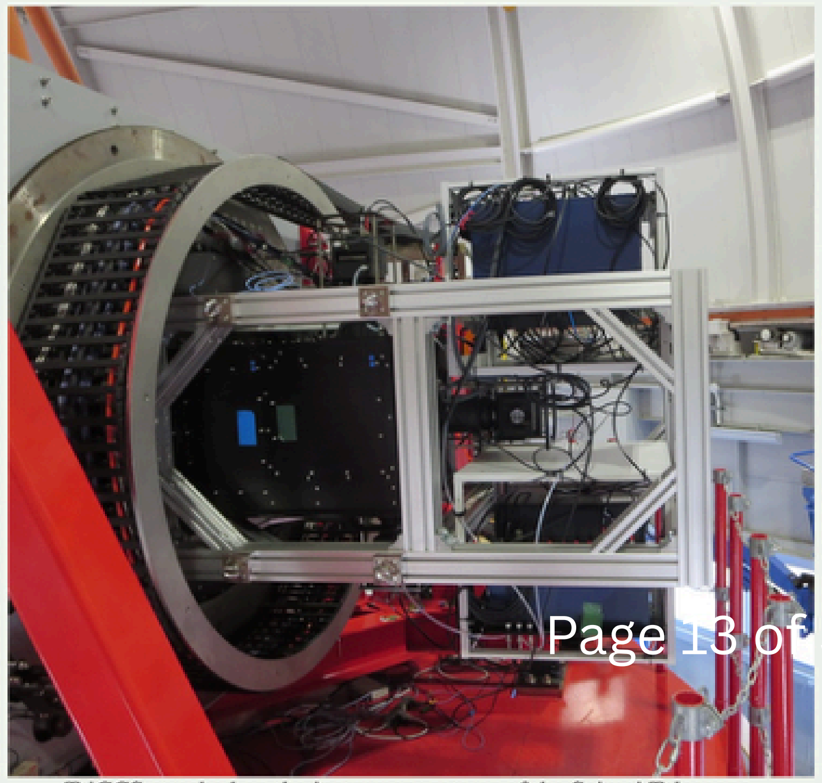


TriCCS camera

- CMOS Camera and Spectrograph, hereafter TriCCS, is a tricolor imager mounted on Kyoto University 3.8 m telescope (the Seimei telescope).
- TriCCS uses CMOS sensors as the detectors so that it can take high-speed images.
- Seimei+TriCCS have 12.5x7.5 arcminutes of FoV.



TriCCS optics in the imaging mode.


TriCCS attached on the instrument rotator of the Seimei Telescope.

The observation

- Awarded three observation runs on Seimei telescope (25A-K-0031).
    a. January 6-10, 2025
    b. March 17-20, 2025
    c. June 4-8, 2025
    d. 27 June, and July 3,4, 6 (DDT KyotoU)
- Determining the FoV
    - Look for flare variable stars like BYDra, UV, eruptive*.
    - Typical magnitude of M-type stars is about 15 or brighter.
    - FoV aladin: 11.73′ x 7.385′
    - Check the X-ray catalogue to see if the stars has already observed by the X-ray satellite because stellar flare emit strong x-ray emission.
    - Check the TESS data for approximate flaring rate.

TriCCS FoV for Pleiades in Aladin.

The observation

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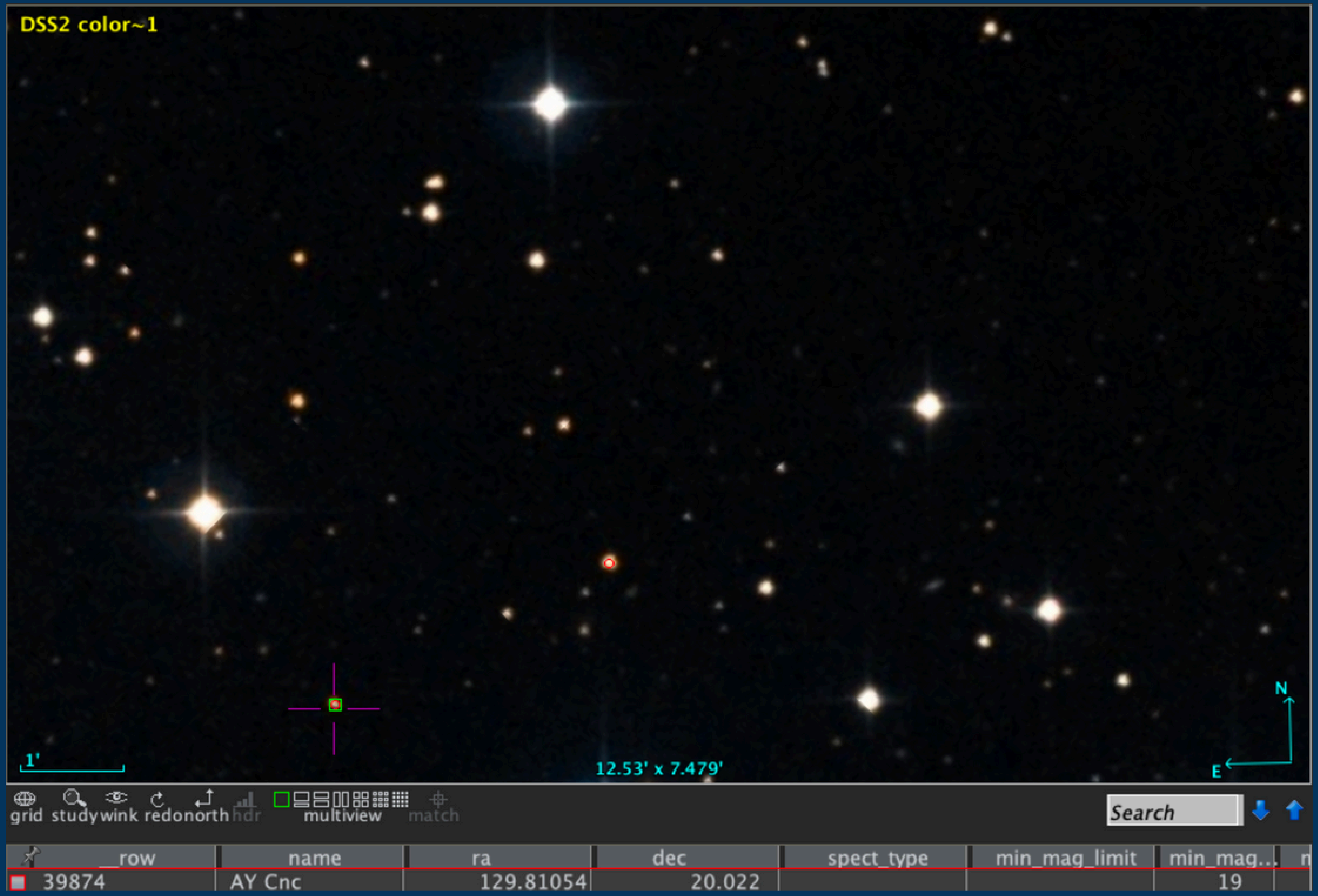


TriCCS FoV for Praesep in Aladin.

Observation summary

a. First Observation January 6-10 2025

- Date: from January 6-10 2025
  - All dates are first half night
  - January 7-8 good condition → target M45
  - January 6,9 cloudy → no data
  - January 10 good condition → target M35 and NGC2632
- First target: M45 (Pleiades) (Total observation ~**8.57 hours, NO flares detected**)
- Third target: NG2632 (Praesepe) (Total observation ~**1.95 hours, NO flares detected**)

b. Second Observation March 17-20 2025

- Date: from March 17-20 2025
  - All dates are first half night
  - March 17 cloudy → no data
  - March 18 good condition → target NGC2632
  - March 19 good condition → target M67 and NGC2632
  - March 20 good condition → target M67
- First target: NGC2632 (Praesepe) (Total observation ~**6.39 hours, NO flares detected**)

Observation summary

c. **Third Observation June 4-8 2025**

- Date: June 4-8 2025
  - All dates are second half night
  - June 4 good condition → target GJ1243 GJ 1243
  - June 5 good condition → target GJ1243
  - June 6,7,8 cloudy → no data
- Observed object: GJ1243 (Total observation ~ **4.1 hours, NO flares detected**)

d. **Fourth observation run June27 and 3,4,6 July 2025 DDT**

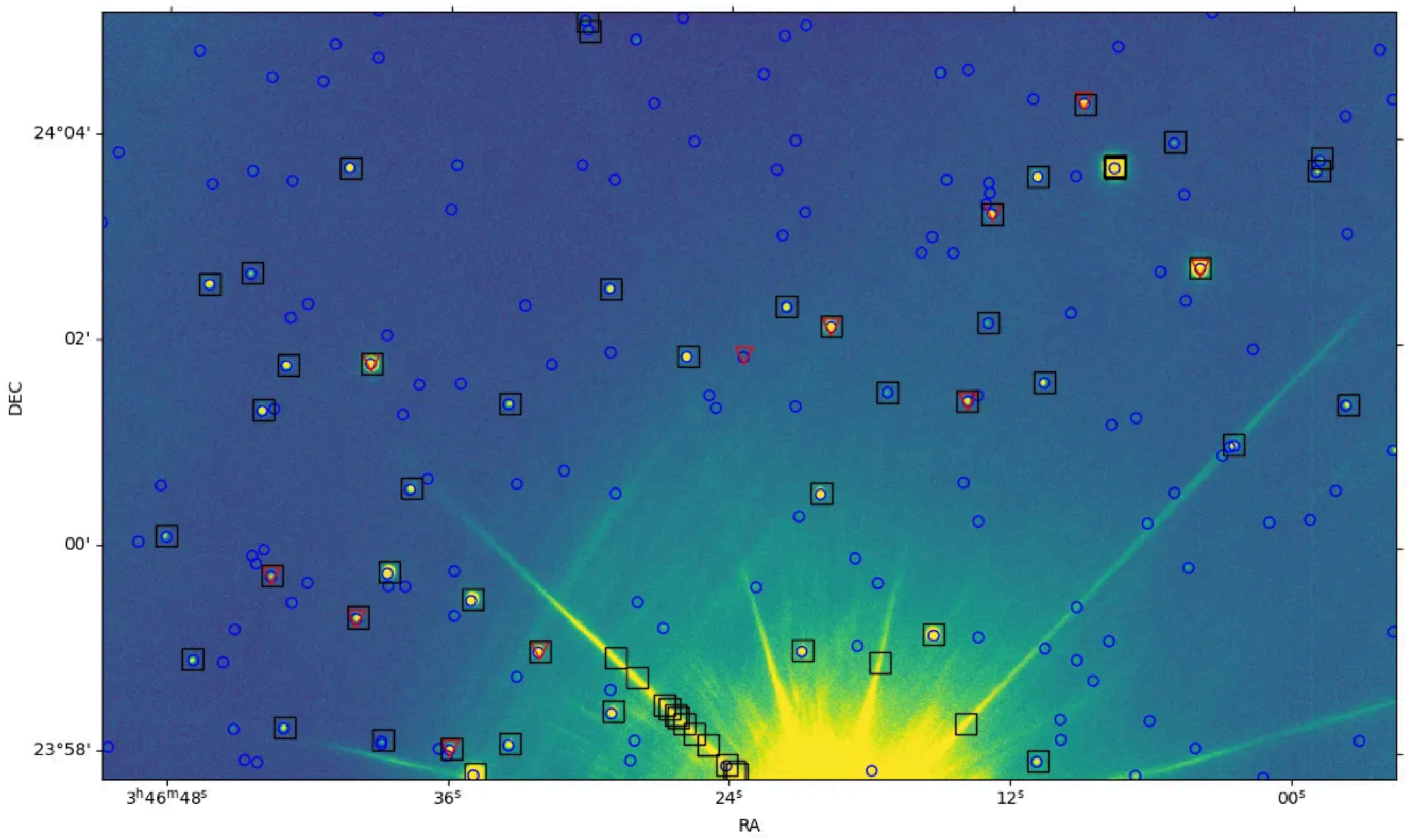
- Date: June 27, and July 3, 4, and 6 (remote observation)
  - June 27 failed → don't know how to do remote observation
  - July 3, 6 (second half) good condition → target GJ1243
  - July 4 (first half) good condition → target GJ1243
- Target: GJ1243 (Total g-band observation **~7 hours** and **r-band ~4.7 hours, 2 flares detected**)

Observation summary (analysis only)

e. Namizaki-san EV-Lac data

- Date: Sept 7, 11, 12, 13, 14, and 15 2022
  - Sept 7 (second half night) good condition → Ev Lac
  - Sept 11 (full night) bad condition → Ev Lac
  - Sept 12, 13 (full night) good condition → Ev Lac
  - Sept 14, 15 (second half night) good condition → Ev Lac
- Target: Ev Lac (Total all bands observation **~22.42 hours, 12 flares detected**)

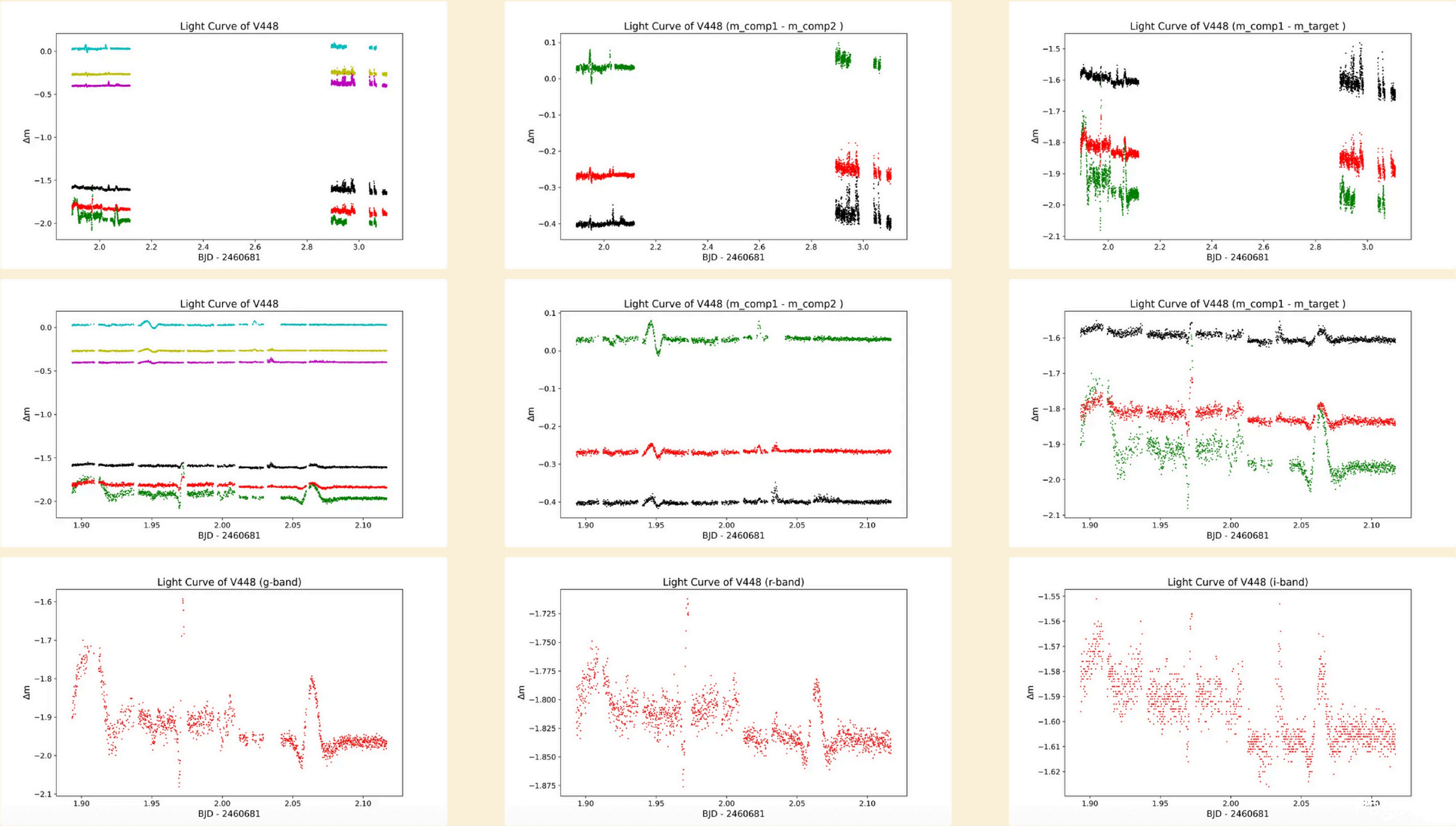
The result (Pleiades)



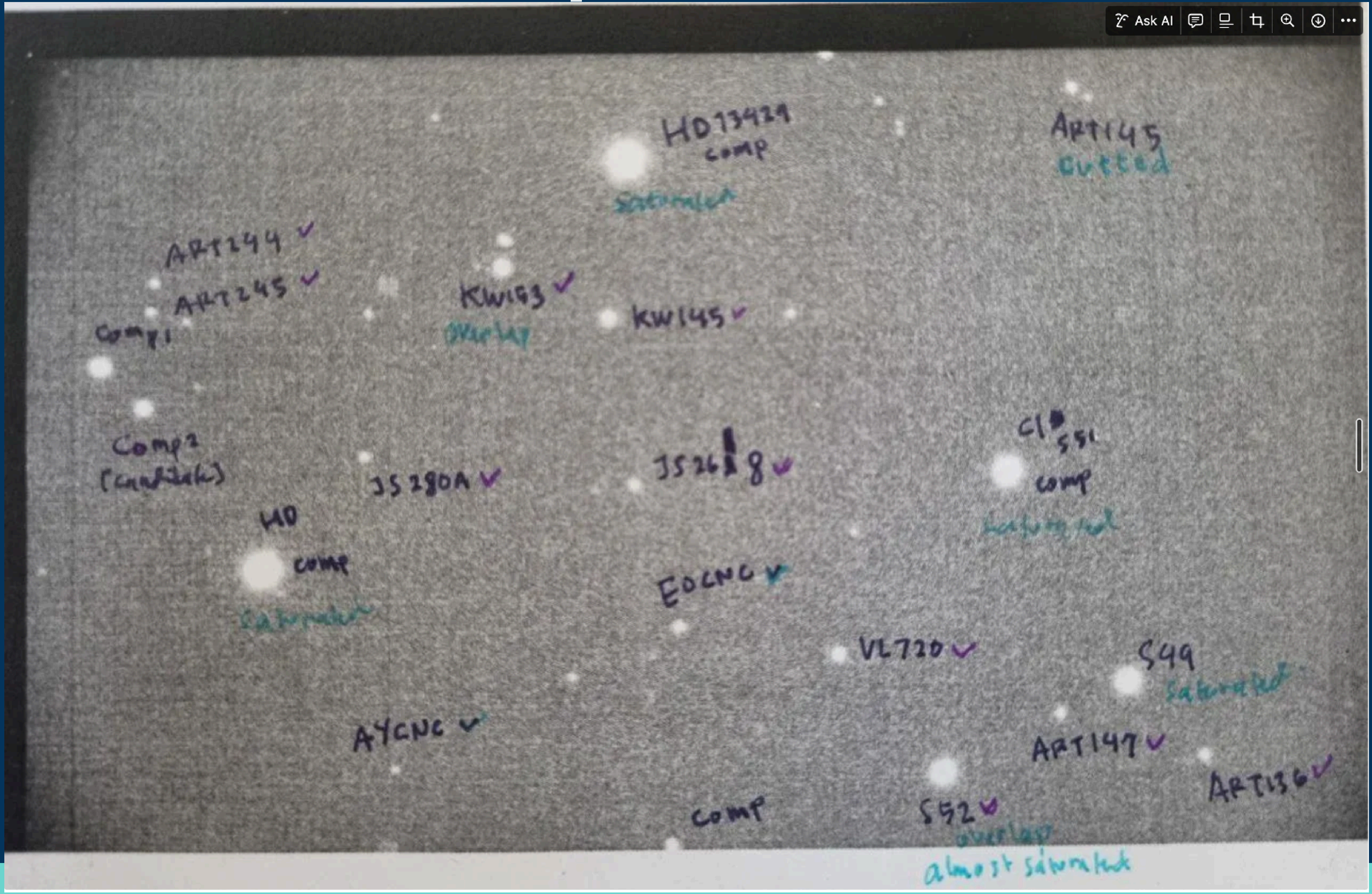
The M45 field of view. Blue circles represent the catalog's stars. Black squares represent the result of the daofind task in PYRAF. Red triangles represent the stars from variable star catalog.

- First target: M45 (Pleiades) (Total observation **~8.57 hours, NO flares detected**)
  - Properties
    - Center FoV: 03:46:23.46 +24:01:10.8 (TriCCS FoV 12.5 x 7.5 arc minutes)
    - Distance: ~138pc or 440 light years
    - Age: 123 Myr.
    - angular size: 110 arc minutes
  - On Jan 7, one data cube contain 1000 and 300 frames. Each frames has 10s exposure time. Total observation **5.27 hours**.
  - On Jan 8, one data cube contain 300 and 150 frames. Each frames has 10s exposure time. Total observation **3.3 hours.**
  - Total observation **~8.57 hours.**
  - Three comparison stars:
    - two comparison stars (G8III and K2III) good count.
    - one comparison star saturated (F1III).
  - M-dwarf stars (based on General Catalog of Variable Stars (June 2022 version)):
    - 6 variable stars. Id based on objects detected by daofind pyraf.
    - V1189Tau(id:63), V1044Tau(no LC), **V448**(id:24), *V530*(id:43), V1042(id:69; LC error), PQTau(id:40).
    - From these stars, V530 dan V448 looks like having flare candidates.
    - But, from its distance, V530(~2.5kpc) is likely not the member of M45. Only, V448 that belong to M45 and showing flare-like light-curve.
  - Objects listed in Simbad database outside above variable stars:
    - 3 objects. Id based on objects detected by daofind pyraf.
    - CL22814(id:62), CL22989(id:449), CL22983(id:58), CXOP(id:46)
    - None show flare-like light-curve.
  - Unknown objects not listed above mentioned:
    - 18 objects. Id based on objects detected by daofind pyraf.
    - UNK#11 show flare-like light-curve.

▼ light curve of V448Tau



The result (Praesepe)

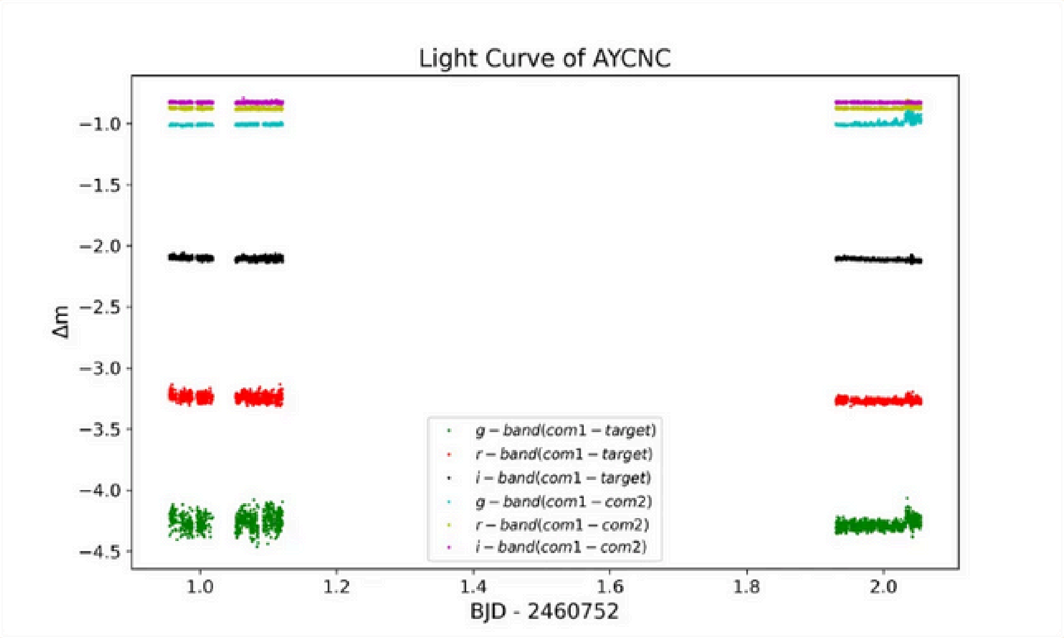


▼ Third target: NG2632 (Praesepe) (Total observation ~**1.95 hours, NO flares detected**)

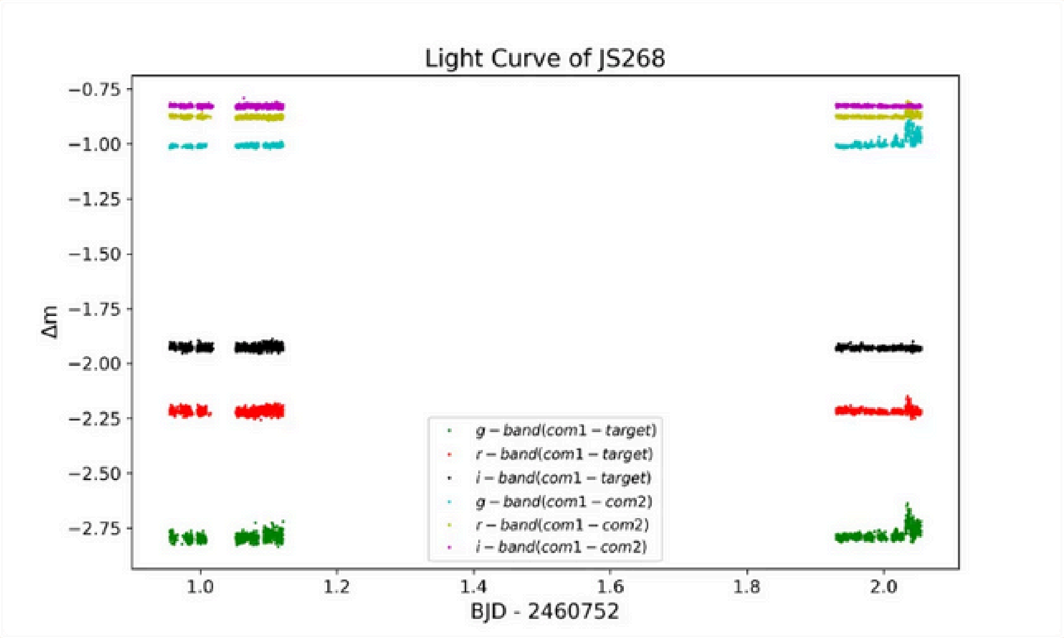
- Properties:
  - Center FoV: 08:39:02.15 +20:04:14.0 with TriCCS FoV 12.5 x 7.5 arc minutes.
  - Distance: ~187 pc
  - Age:~741 Myr
  - Angular size
- On Jan 10, one data cube contain 100 and 300 frames. Each frames has 10s exposure time. Total observation **1.95 hours**.
- Two eruptive stars based on General Catalog of Variable Stars (June 2022 version).
  - EoCNC. No sign of flares in light curve
  - AYCNC. No sign of flares in light curve.
- Two comparison stars

▼ First target: NGC2632 (Praesepe) (Total observation **~6.39 hours, NO flares detected**)

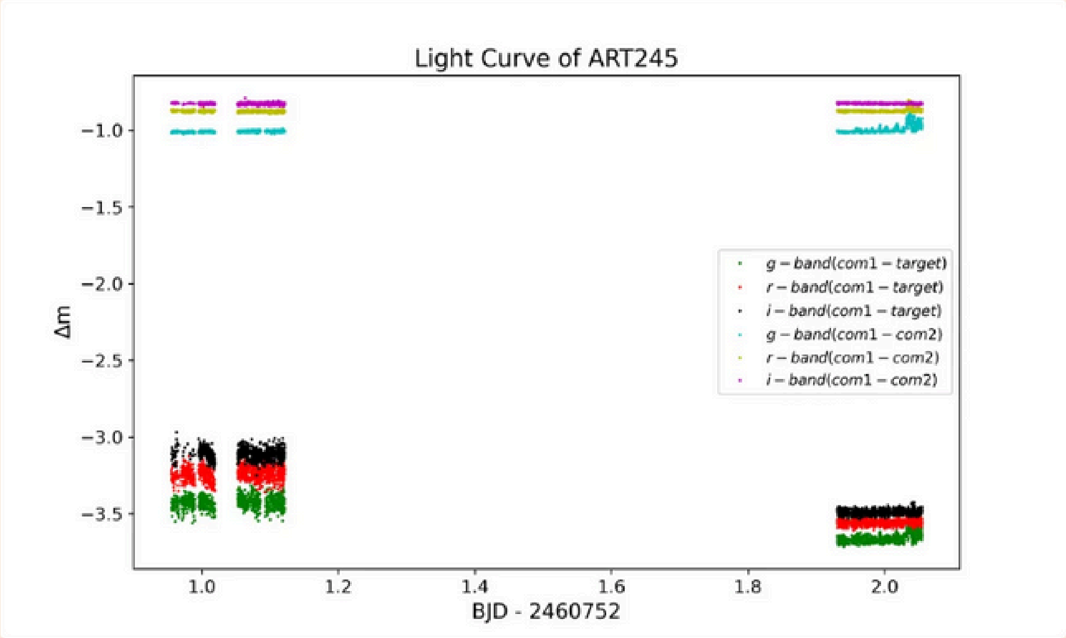
- Properties
  - Center FoV: 08:39:02.15 +20:04:14.0 with TriCCS FoV 12.5 x 7.5 arc minutes.
  - Distance: ~187 pc
  - Age:~741 Myr
  - Angular size
- On March 18, one data cube contain 300, 200, 150 and 100 frames. Each frames has 10s exposure time. Total observation **3.75 hours.**
- On March 19, one data cube contain 200 and 150 frames. Each frames has 10s exposure time. Total observation **2.64 hours.**
- Total observation **~6.39 hours.**
- Two eruptive stars: (based on General Catalog of Variable Stars June 2022 version.
  - EoCNC. No sign of flares in light curve
  - AYCNC. No sign of flares in light curve.
- Two comparison stars



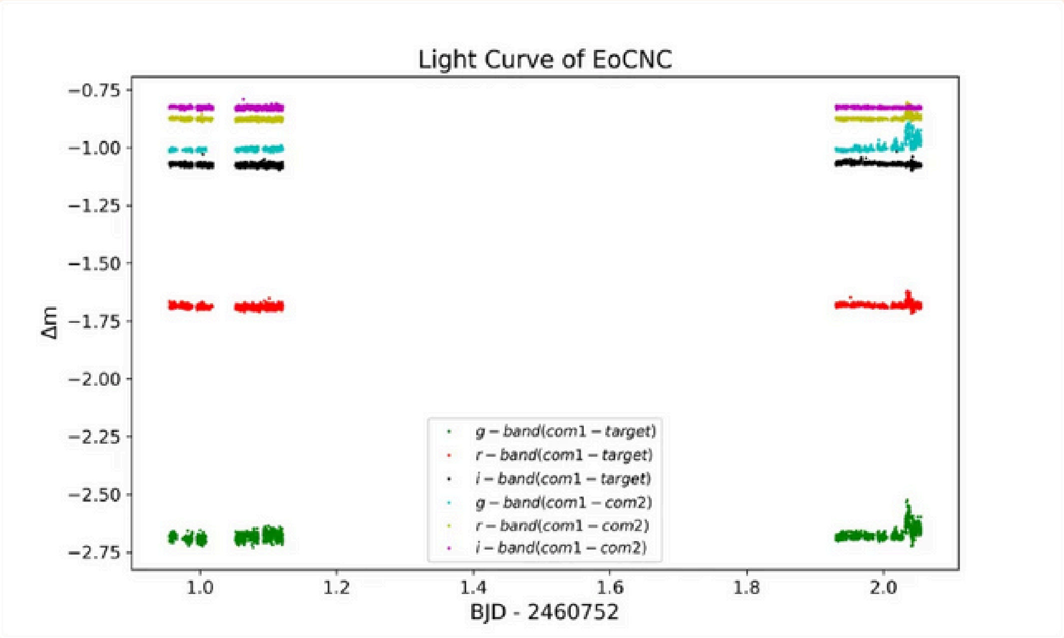
Light Curve of AYCNC
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



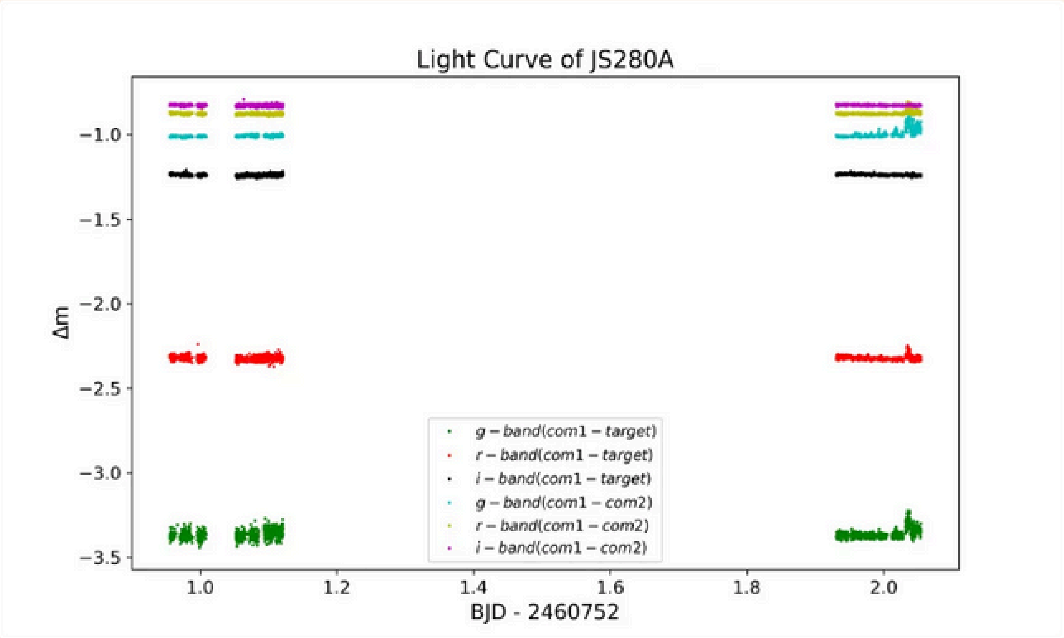
Light Curve of JS268
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



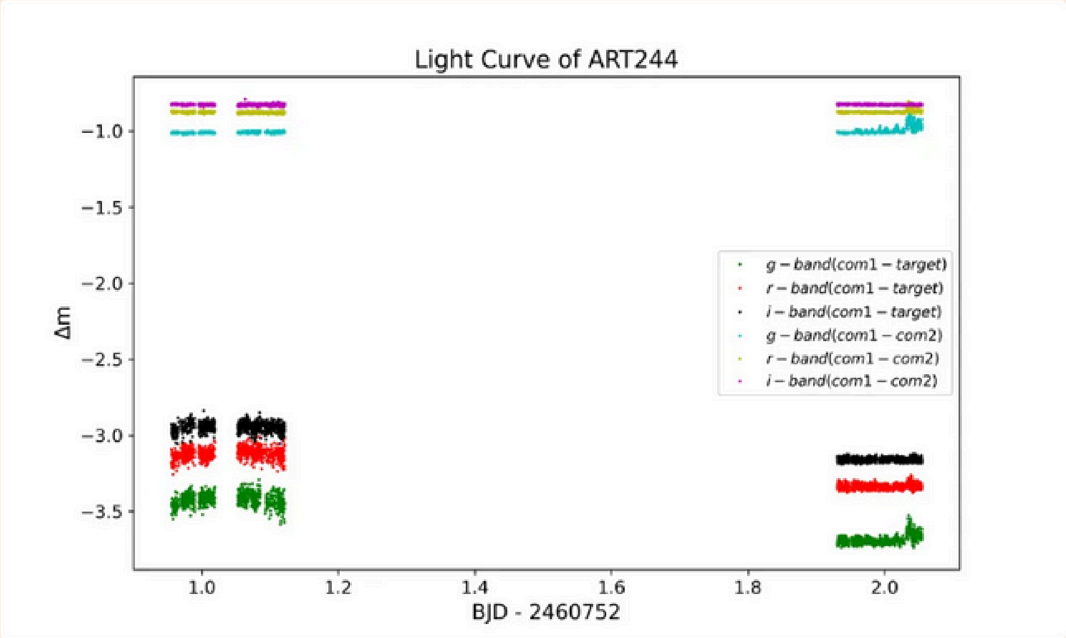
Light Curve of ART245
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



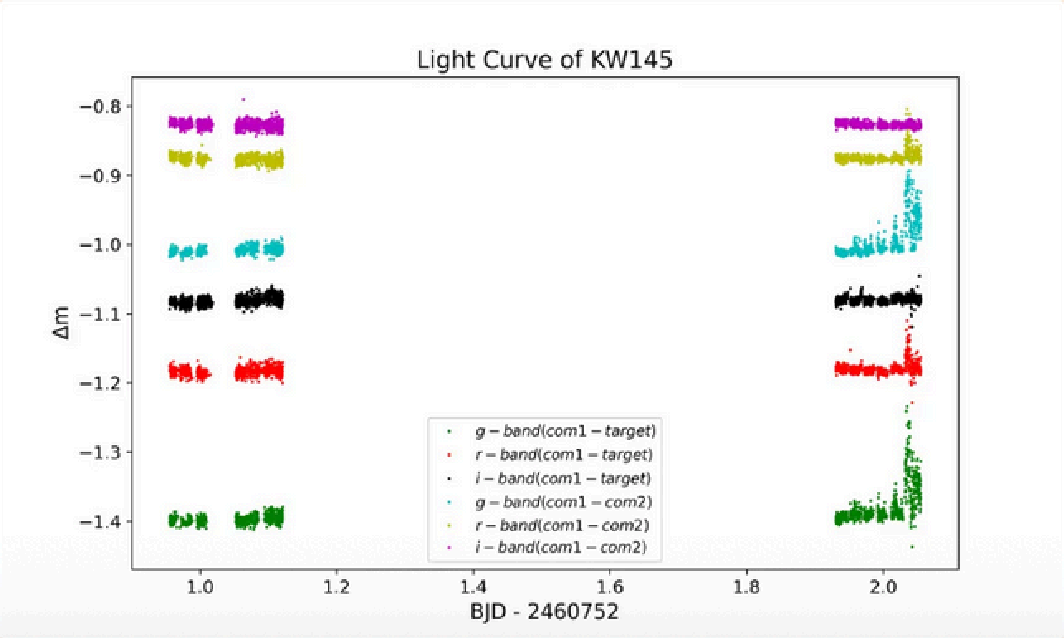
Light Curve of EoCNC
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



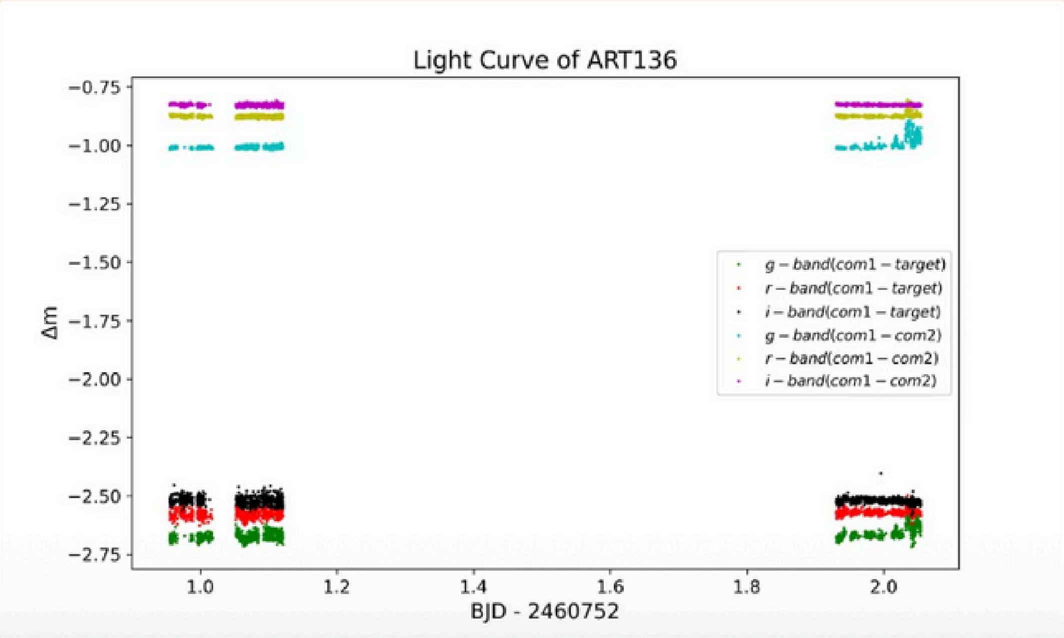
Light Curve of JS280A
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



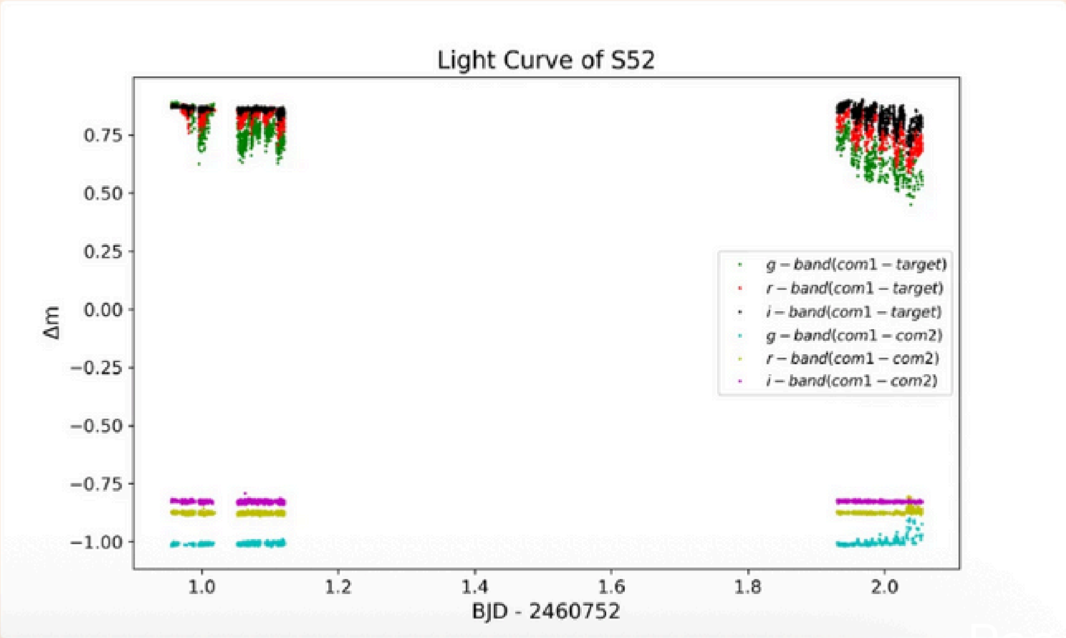
Light Curve of ART244
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



Light Curve of KW145
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



Light Curve of ART136
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)



Light Curve of S52
Δm
BJD - 2460752
g − band(com1 − target)
r − band(com1 − target)
i − band(com1 − target)
g − band(com1 − com2)
r − band(com1 − com2)
i − band(com1 − com2)

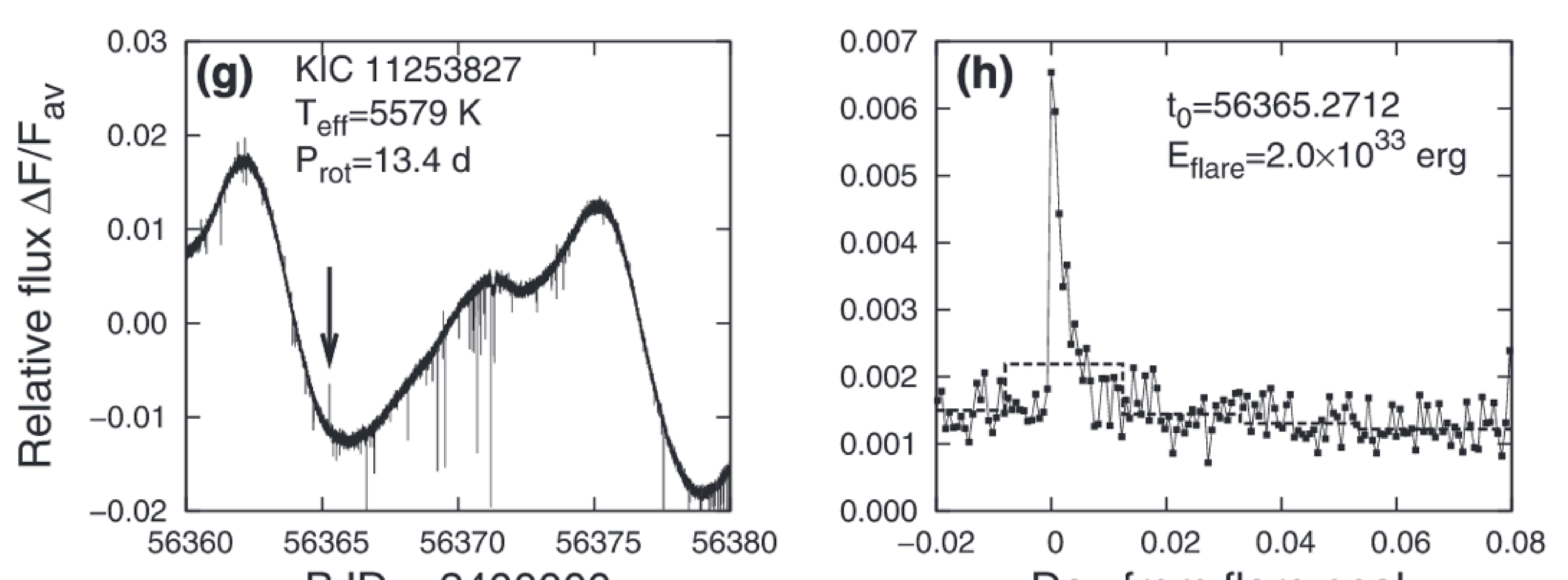
New objective

- Due to unsatisfactory results of the 1st and 2nd observation runs and considering the amount of data and time that we need to obtain, we changed the objective and object for the 3rd observation run.

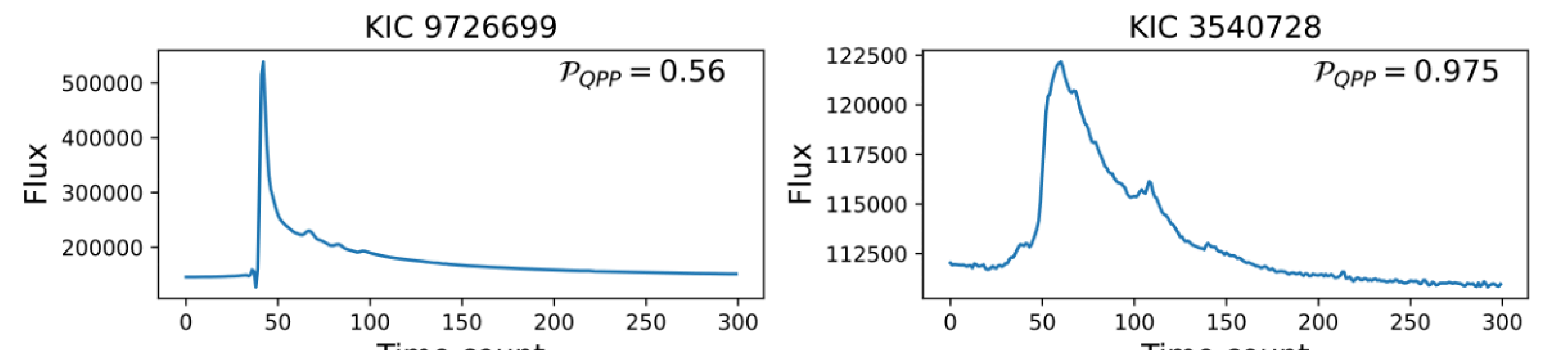
- The primary focus of the third observation run will be on detecting and analyzing superflares originating from nearby M-dwarf stars.

Low Time Resolution: Missing Short-Duration Phenomena

- Crucially, low time resolution data cannot resolve short-duration phenomena within flares.
- One key example is Quasi-Periodic Pulsations (QPPs).
- QPPs are thought to provide insights into flare energy release mechanisms. Detecting and analyzing QPPs requires high-cadence observations.



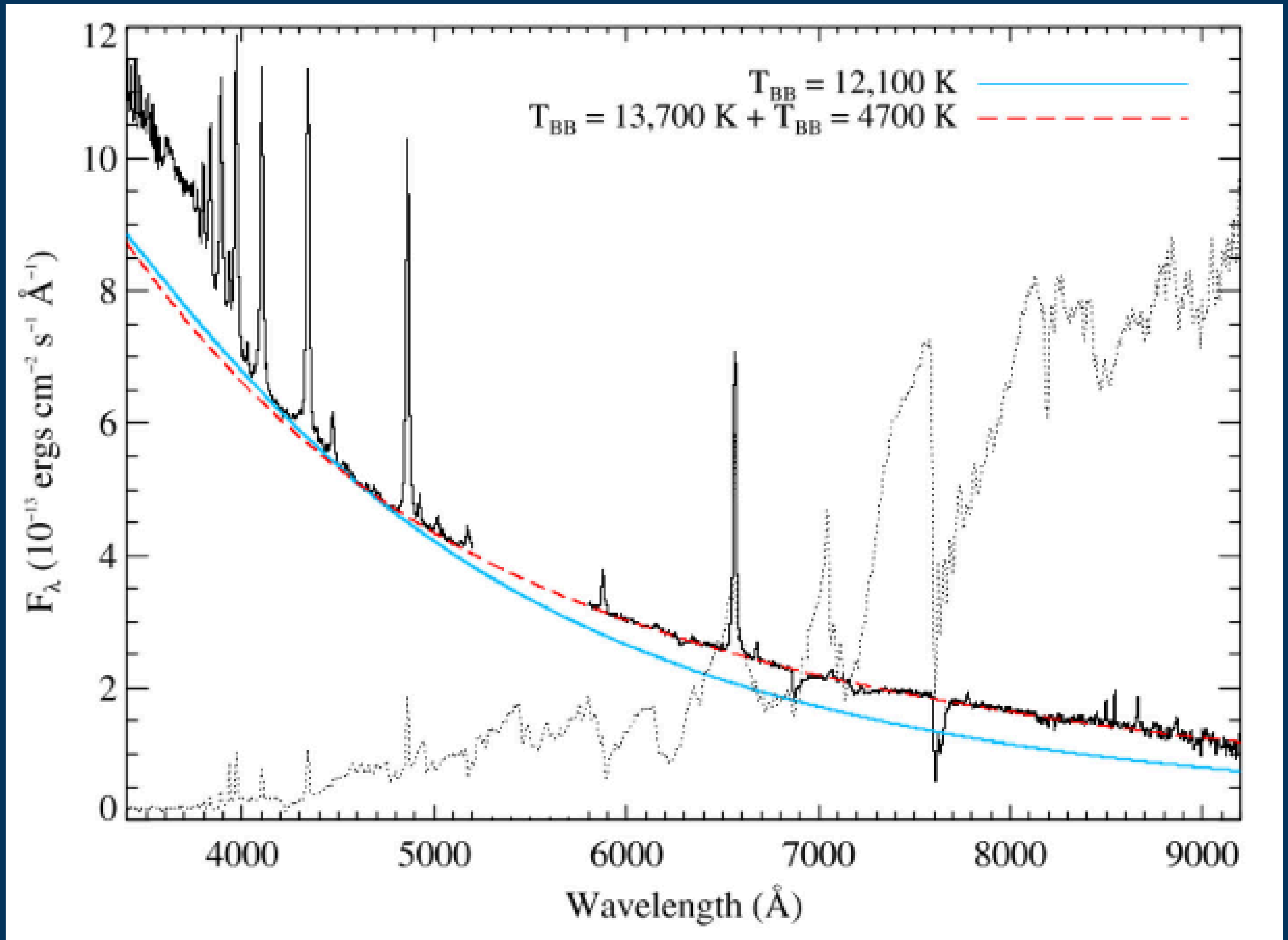
Maehara et al. 2015



Belov et al. 2024

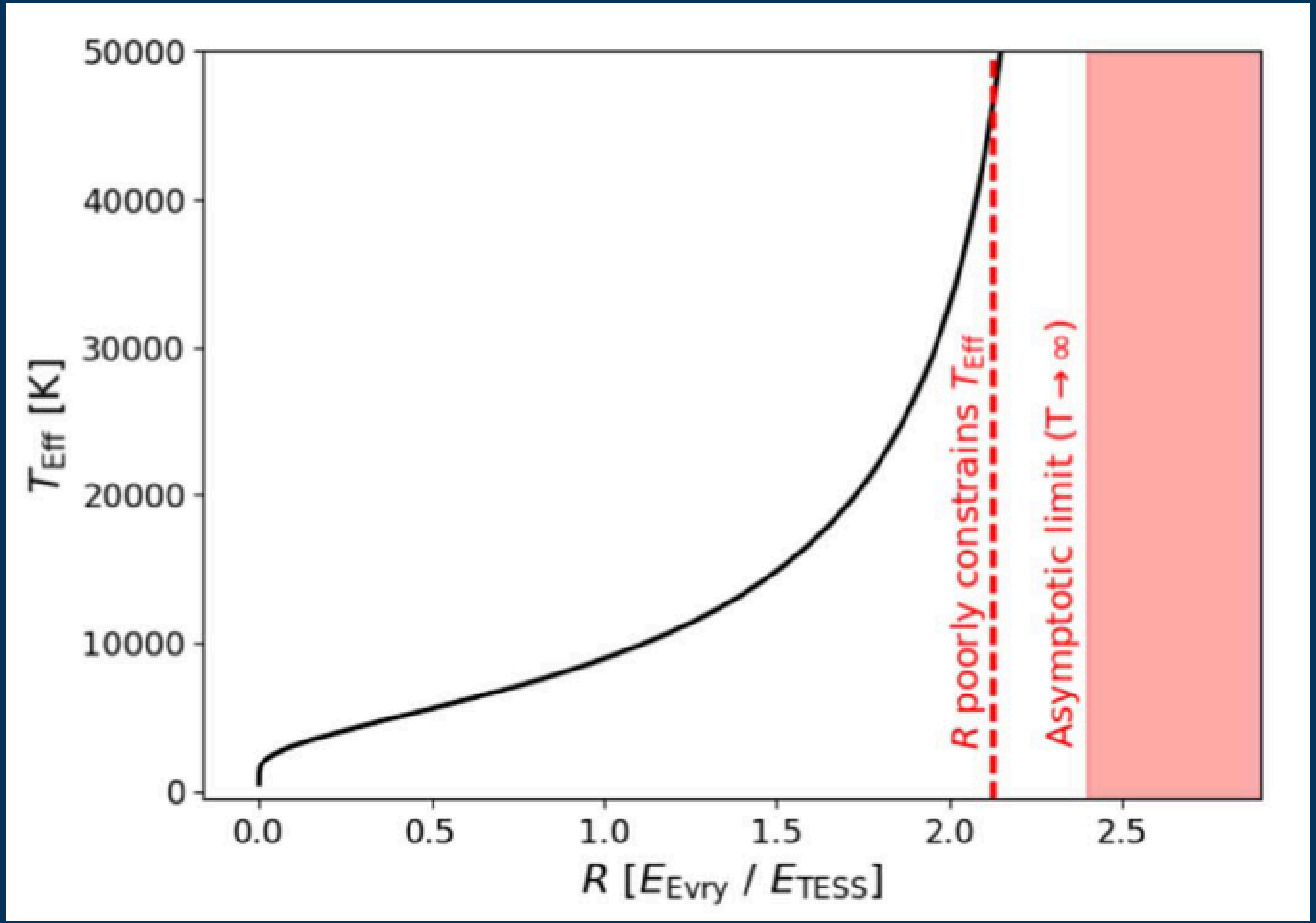
Limitation: Single-Band Photometry

- Most large flare surveys are single-band.
- Single-band data limits the ability to diagnose flare plasma properties, such as temperature.
- This is because different wavelengths probe different physical conditions and temperatures within the flare plasma.



The Need for Multi-Band Analysis

- Multi-band photometry allows for the construction of flare spectra at different times.
- These spectra can be compared to theoretical models (e.g., radiative-hydrodynamic models) to infer physical conditions like temperature, density, and energy transport.
- Studies of M dwarf flares have shown the importance of optical depths and radiative transfer effects in interpreting broadband photometry.



simultaneous observations in two different broadband filters can be used to estimate the temperature of a flare, assuming it emits like a blackbody (Howard et al. 2020)

New target: Ev Lac & GJ1243

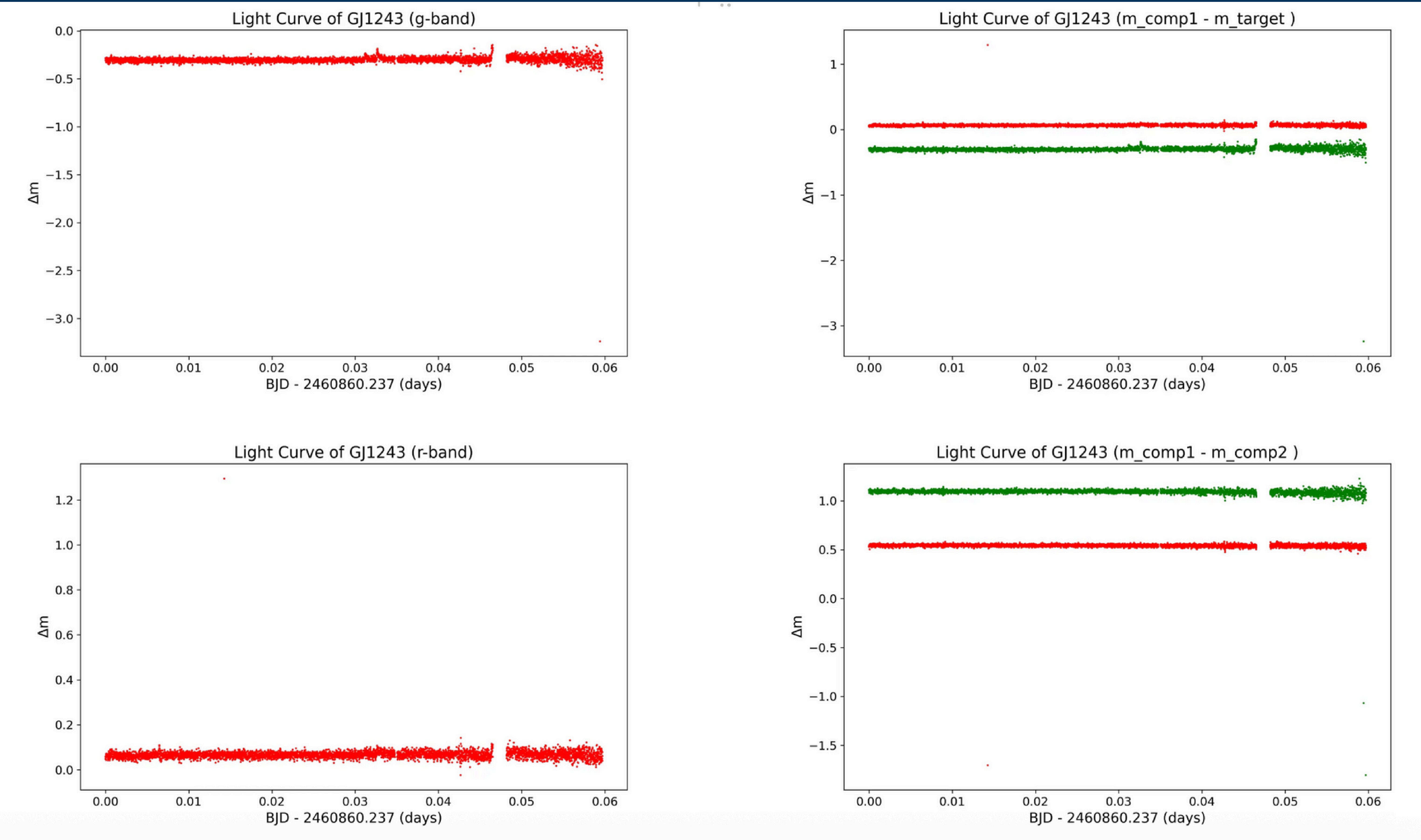
▼ Target: Ev Lac (Total all bands observation **~22.42 hours, 12 flares detected**)

- Properties
  - Distance: 5.1 pc or 16.476 light years
  - Right ascension: 22h 46m 48.686s; dec: 44° 19' 55.032''
  - Mass: 0.35 Msun
  - Spectral type: M3.5
  - Luminosity: 0.171 Lsun
  - Temperature: 3291 K
  - apparent mag: 10.3
  - absolute mag: 11.7
  - period: 4 days

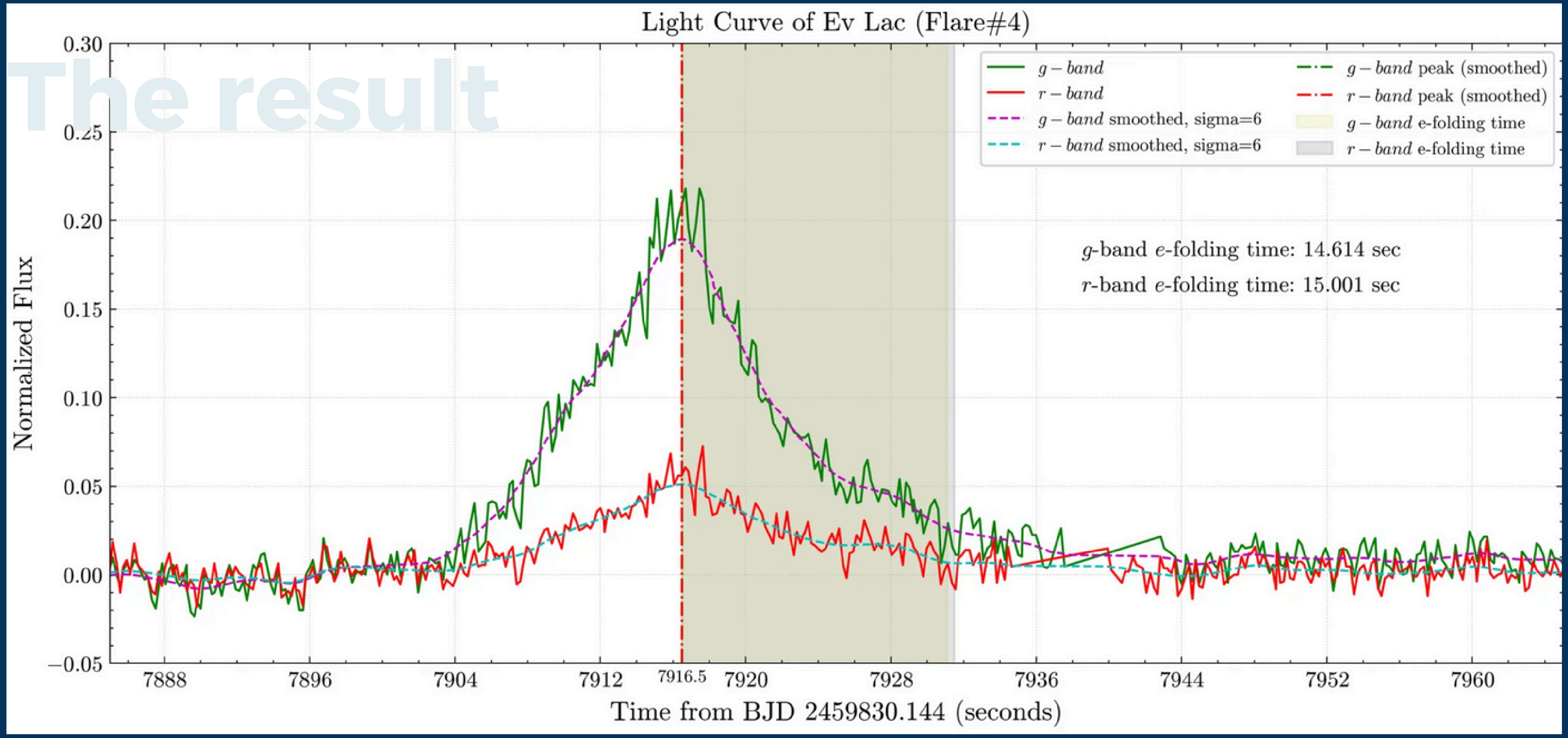
▼ Target: GJ1243 (Total g-band observation **~7 hours** and **r-band ~4.7 hours, 2 flares detected**)

- Properties:
  - GJ 1243 → one of the most studied-M-dwarf. Stellar Catalog ★ G 208-42 | Stellar Catalog
  - Right ascension: 19h 51m 9.606s; dec: 46° 29' 4.465''
  - Distance: 12 pc or 39 light years
  - Period: 0.5 days
  - Mass: 0.3 Msun
  - Temperature: 3.278K
  - Apparent mag:

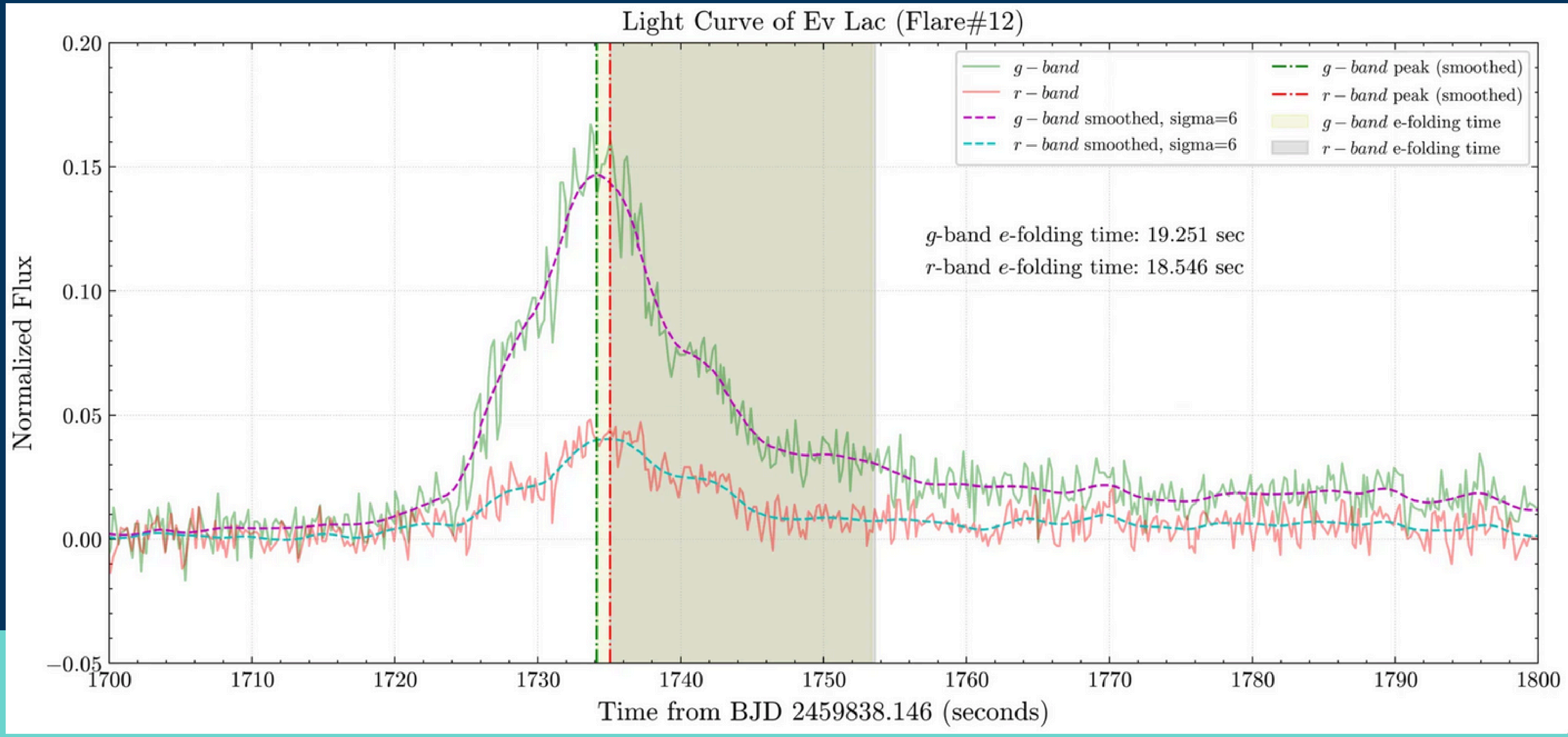
The result


Light Curve of GJ1243 (g-band)
Δm
BJD - 2460860.237 (days)
Light Curve of GJ1243 (m_comp1 - m_target)
Δm
BJD - 2460860.237 (days)
Light Curve of GJ1243 (r-band)
Δm
BJD - 2460860.237 (days)
Light Curve of GJ1243 (m_comp1 - m_comp2)
Δm
BJD - 2460860.237 (days)

The result

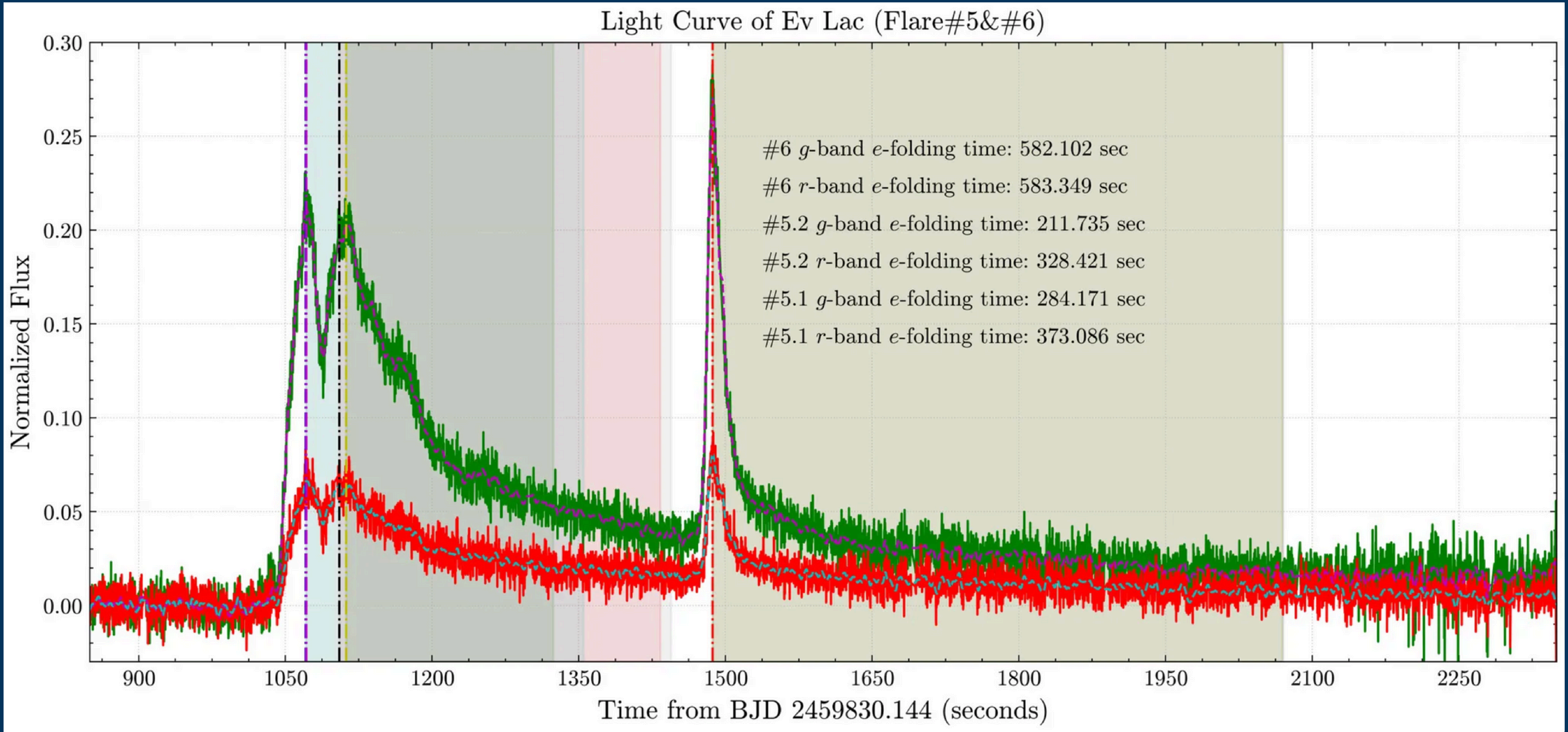


Light Curve of Ev Lac (Flare#4)
$g-band$
$r-band$
$g-band$ smoothed, sigma=6
$r-band$ smoothed, sigma=6
$g-band$ peak (smoothed)
$r-band$ peak (smoothed)
$g-band$ e-folding time
$r-band$ e-folding time
g-band e-folding time: 14.614 sec
r-band e-folding time: 15.001 sec
Normalized Flux
Time from BJD 2459830.144 (seconds)
7916.5



Light Curve of Ev Lac (Flare#12)
$g-band$
$r-band$
$g-band$ smoothed, sigma=6
$r-band$ smoothed, sigma=6
$g-band$ peak (smoothed)
$r-band$ peak (smoothed)
$g-band$ e-folding time
$r-band$ e-folding time
g-band e-folding time: 19.251 sec
r-band e-folding time: 18.546 sec
Normalized Flux
Time from BJD 2459838.146 (seconds)

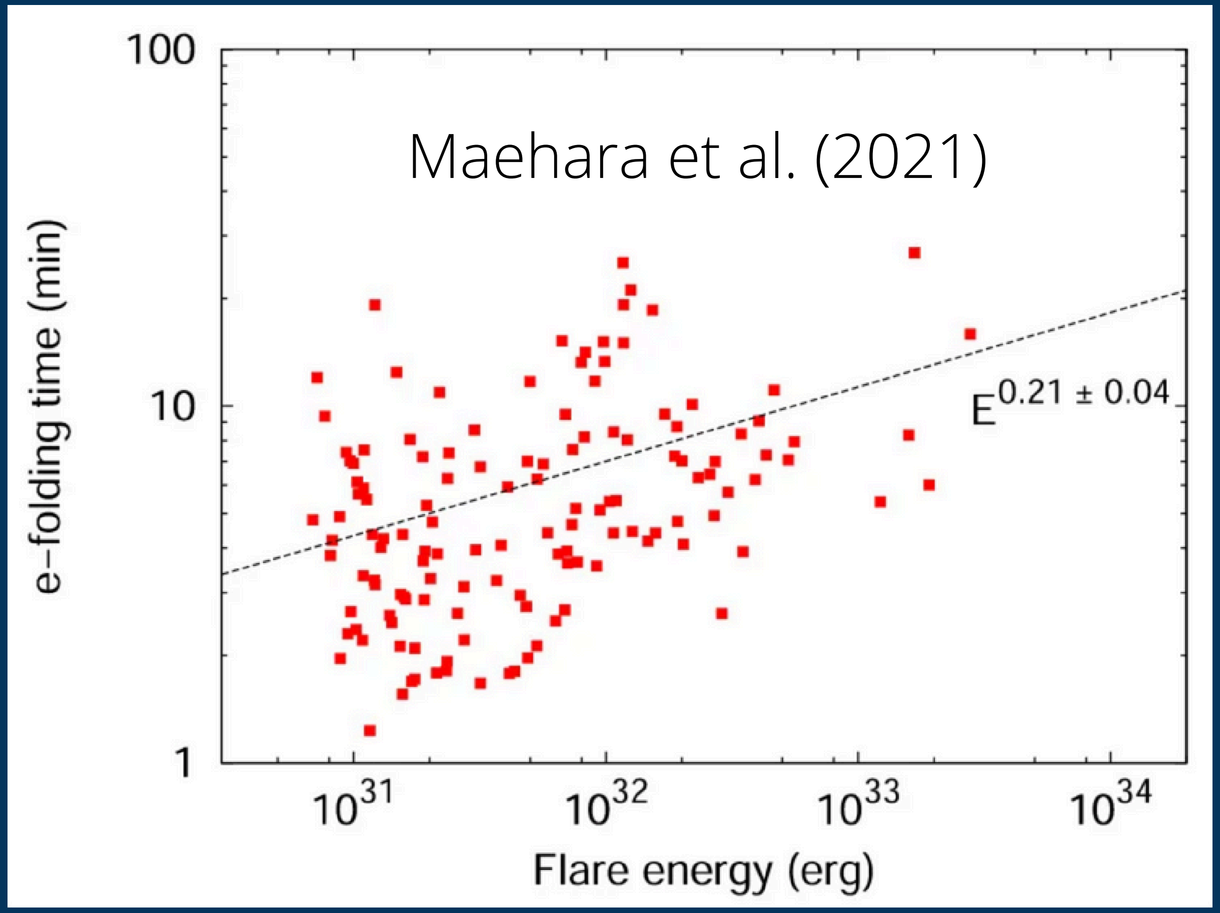
The result



Light Curve of Ev Lac (Flare#5&#6)
Normalized Flux
0.30
0.25
0.20
0.15
0.10
0.05
0.00
#6 g-band e-folding time: 582.102 sec
#6 r-band e-folding time: 583.349 sec
#5.2 g-band e-folding time: 211.735 sec
#5.2 r-band e-folding time: 328.421 sec
#5.1 g-band e-folding time: 284.171 sec
#5.1 r-band e-folding time: 373.086 sec
900
1050
1200
1350
1500
1650
1800
1950
2100
2250
Time from BJD 2459830.144 (seconds)

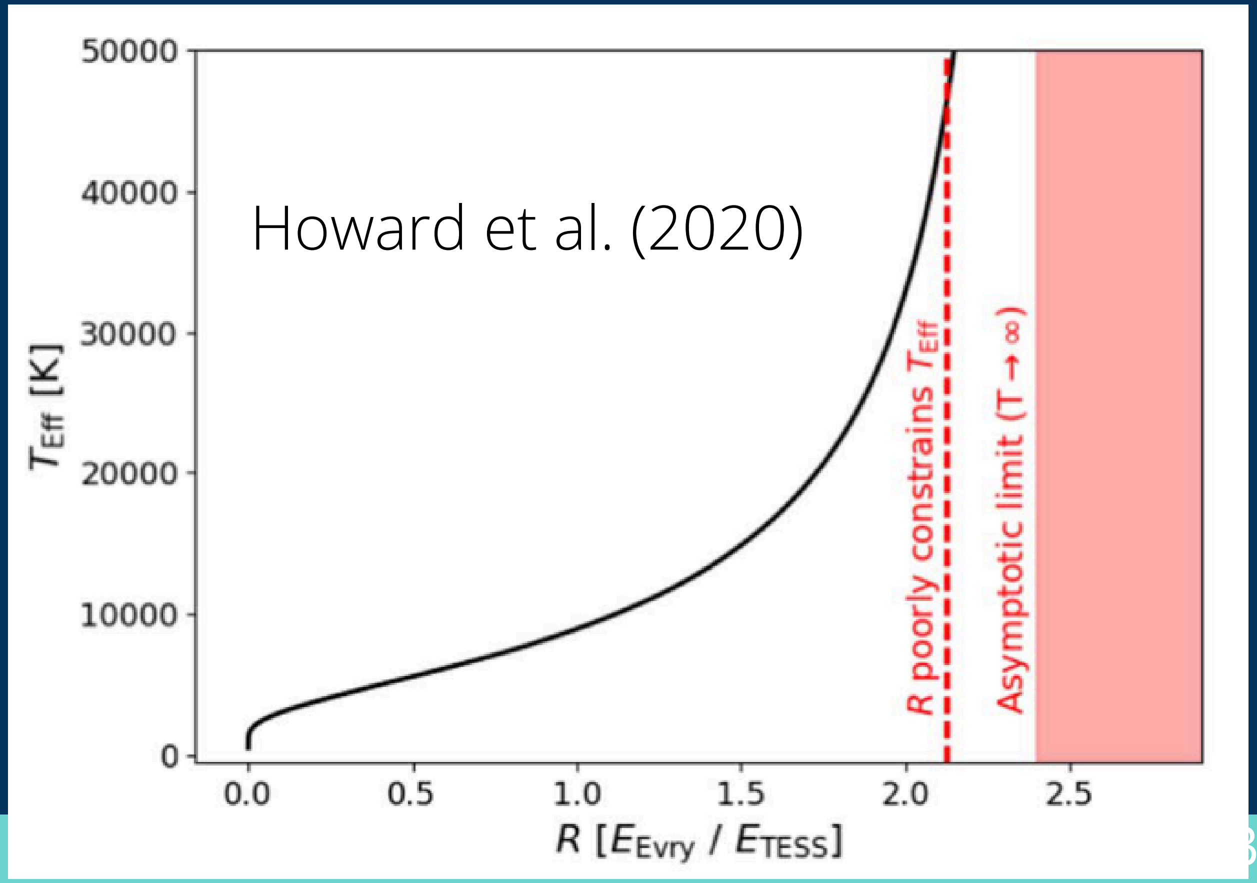
Summary

- Awarded total 7 nights observation time on Seimei telescope divided into three observation runs from Kyoto University time.
- We couldn't detect any flares for our initial target (Pleiades and Praesepe). This led to the object changing to a nearby active M-dwarf.
- We have detected 14 flare candidates (12 flares from EV Lac and 2 flares from GJ1243).
- The longest flare e-folding time is ~580 seconds.
- We also detected the symmetry shape of flares from two short-period events.



Future works

- Relation between e-folding time and flare energy.
- Estimate the temperature of a flare.
- Analysis of short-duration flares.



ありがとうございます

Terima Kasih