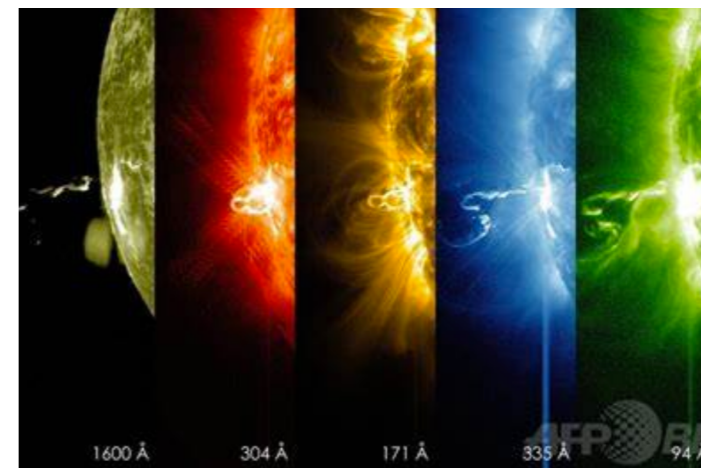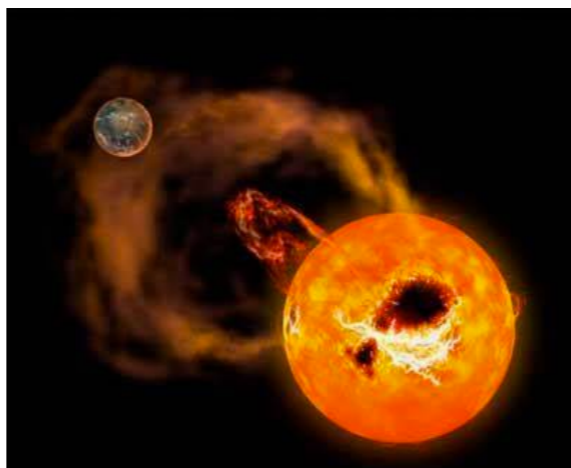# Multi-wavelength Real-time Study of Stellar Flares: Properties and Mechanisms

Yuan-Pei Yang (杨元培)

2025/05, EP Stellar Flare Meeting, Beijing

Mephisto Telescope

- The main features of Mephisto can be summarized as follows
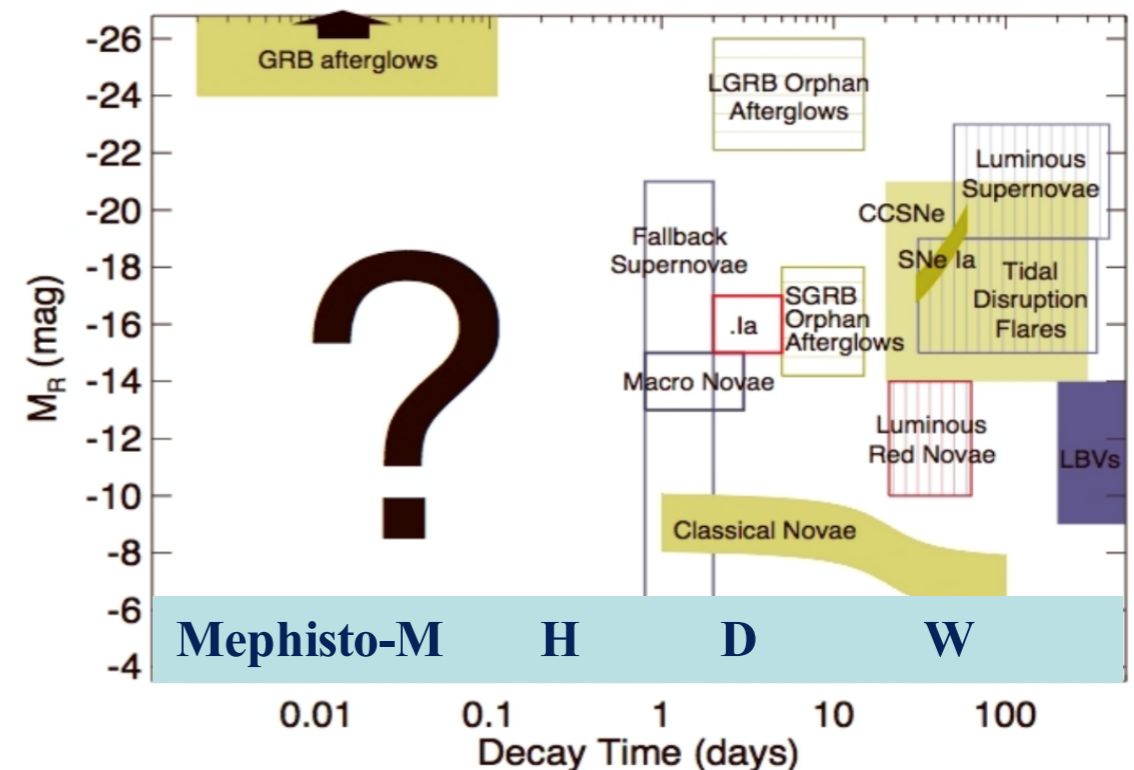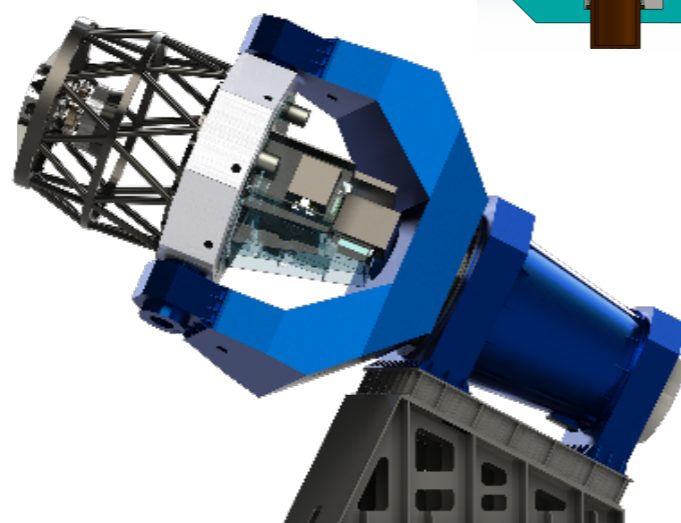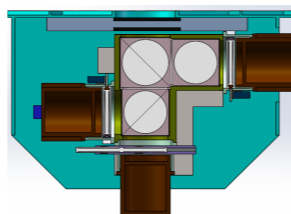
wide-field   **multi-channel**

$$\text{Mephisto} = \text{Survey} + \text{Real Color}$$

< sub-minute

- Such a characteristic of Mephisto will play an extremely important rule in searching and studying **fast transients with sub-minute durations**, because the time for the time of switching filter is about a few minutes for large optical telescopes.
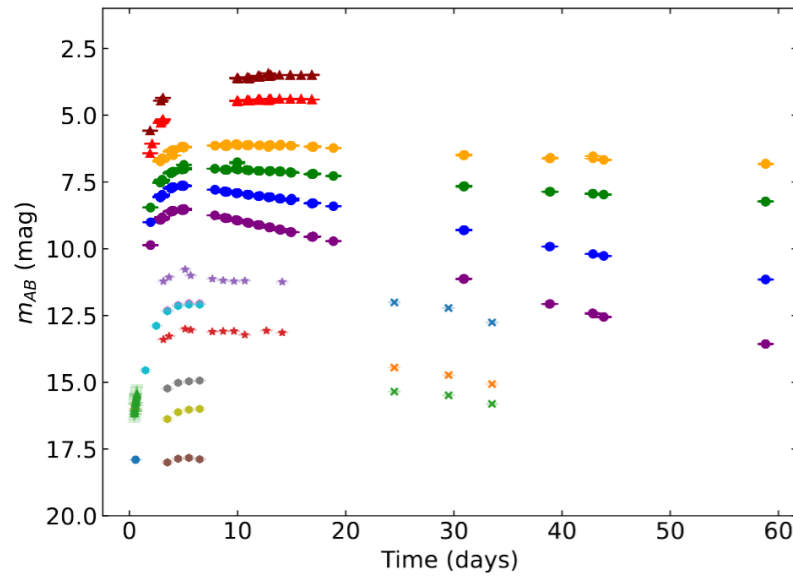

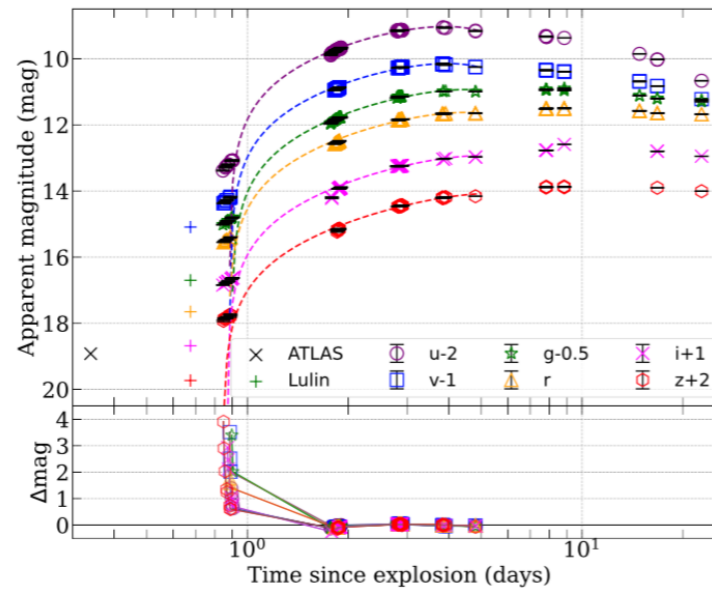**3 CCD mosaic cameras** (2×2 e2v CCD-290-99 mosaic) for the blue-, yellow- and red-channels

Mephisto Transients

SN 2023ixf

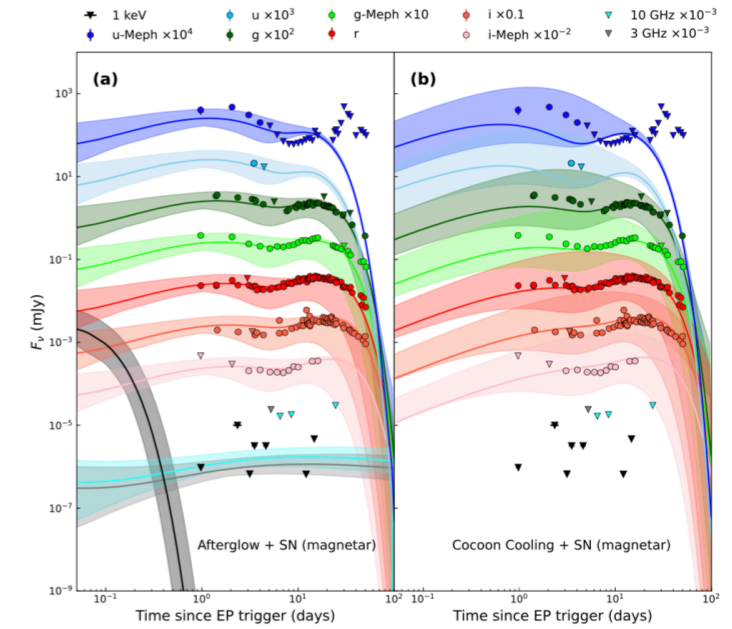
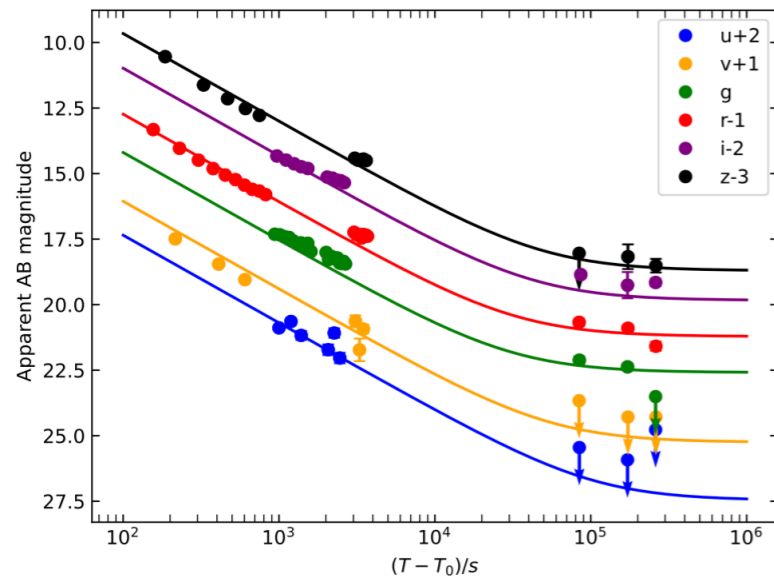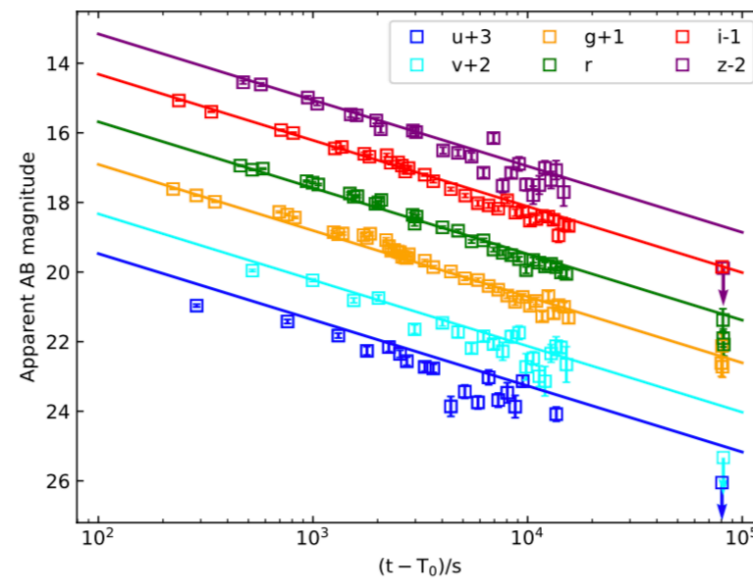### SN 2024ggi

EP 250108A

GRB 240825A

128s trigger

GRB 250101A

197s trigger

TDE: AT 2023clx

Yang +, 2024, ApJ; Chen +, 2024, ApJL, Li +, 2025, arXiv; Cheng +, 2025, ApJ; Du +, 2025, arXiv, Zhong +, 2024, RAA
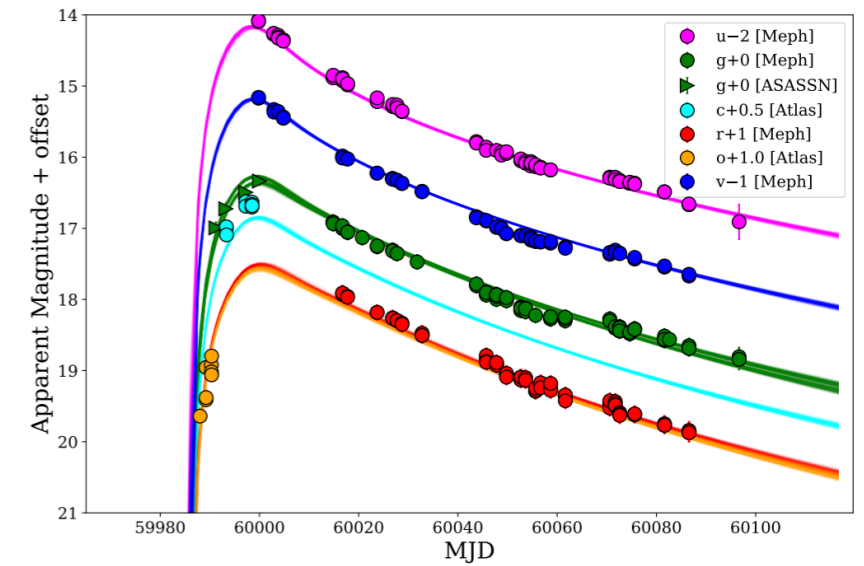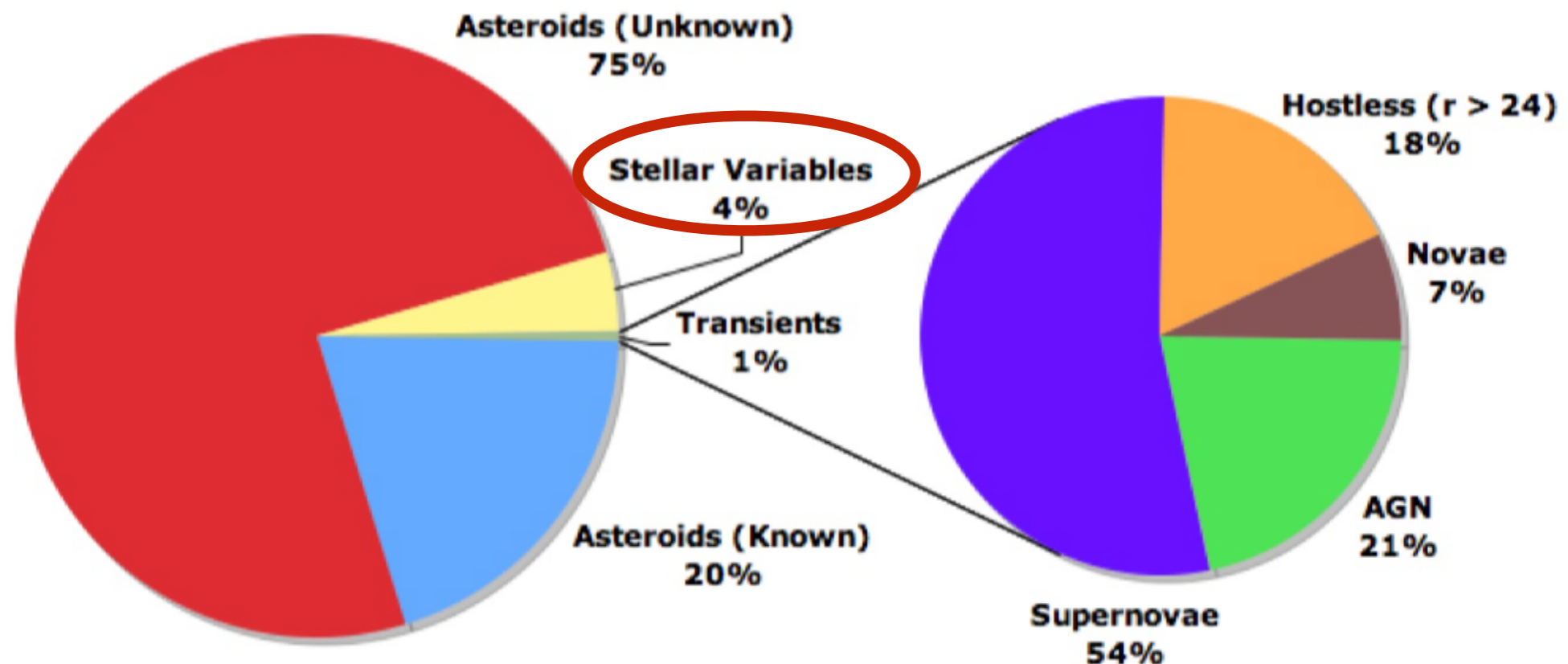
Transient Survey

- A nightly targeted search of nearby rich clusters (**Virgo, Coma, and Fornax**) using the 3.6-m CFHT-COVET and the 100-inch (2.5-m) du Pont telescopes has revealed **the extensive foreground fog (asteroids, M dwarf flares, dwarf novae)** and **the background haze (distant, unrelated SN)**

- For example. 28 COVET transients were discovered during a pilot run in 2008A (7 hours). Of the 2,800 candidates, the COVET pipeline automatically rejected 99% as asteroids or Galactic objects.

- Stellar variables account for ~ **4% of all events**, and their detection rate is about four times of other astrophysical transients.

Stellar Flares

- Low mass stars comprise **nearly 70% of stars** in the Galaxy, their flares represent a major source of transient variability in time domain surveys.

- Stellar flares are usually defined as **catastrophic releases of magnetic energy** leading to particle acceleration and electromagnetic radiation accompanied by coronal mass ejections.

- Frequent flaring occurs on stars with **an outer convection zone**, and the timescale of energetic fares is longer than that of less energetic flares. Meanwhile, the larger the flare luminosity, the smaller the flaring frequency.

Kowalski+, 2024
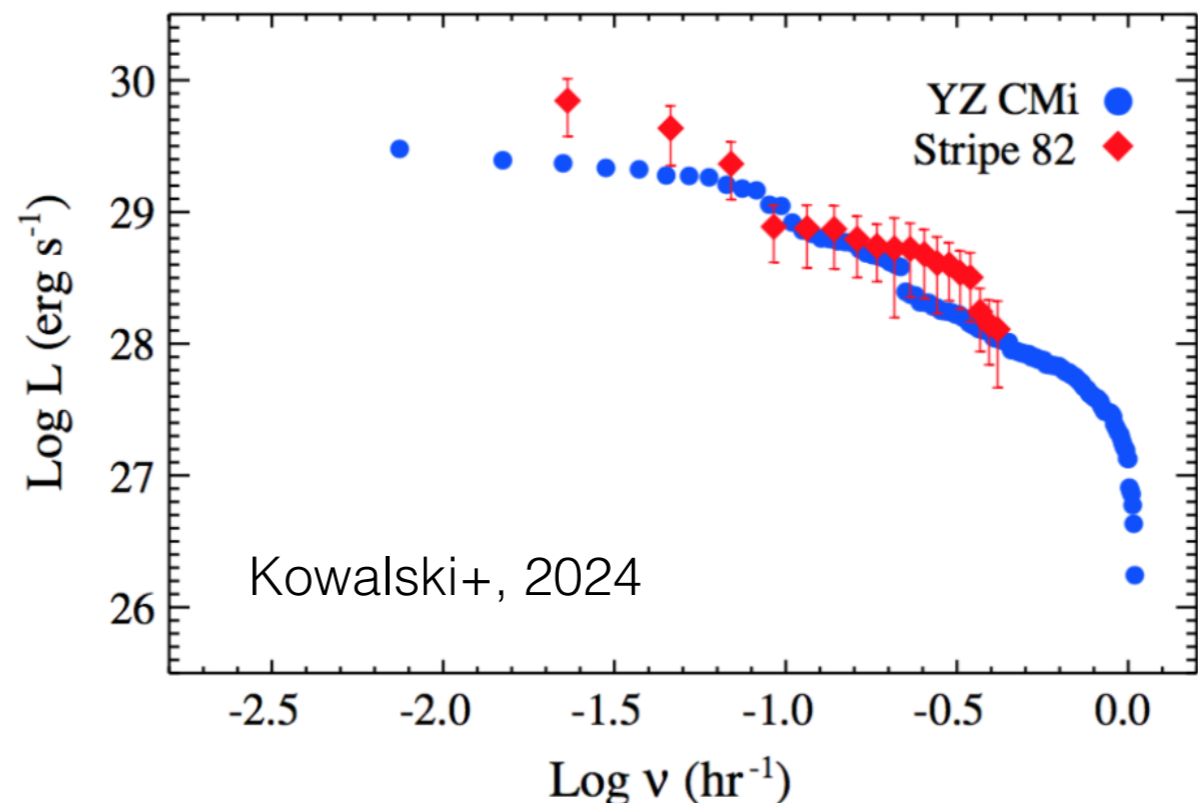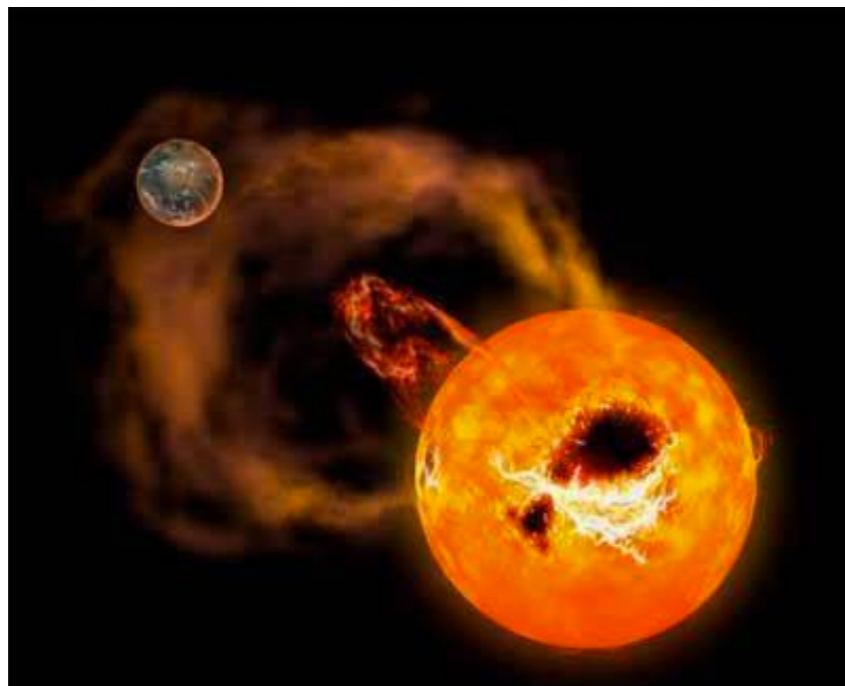
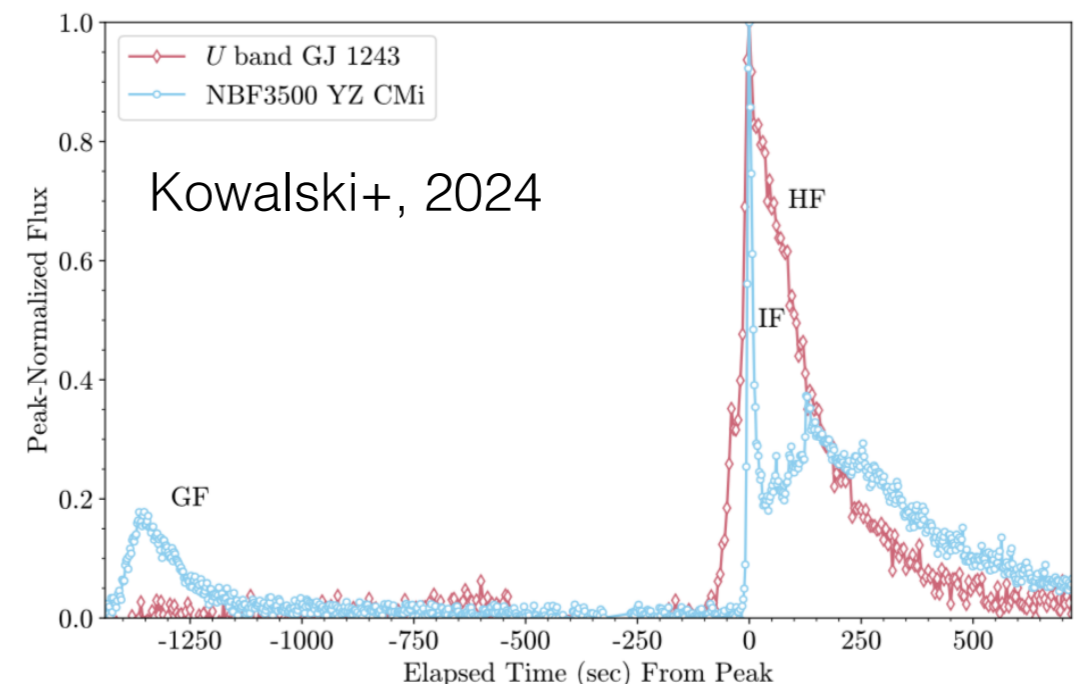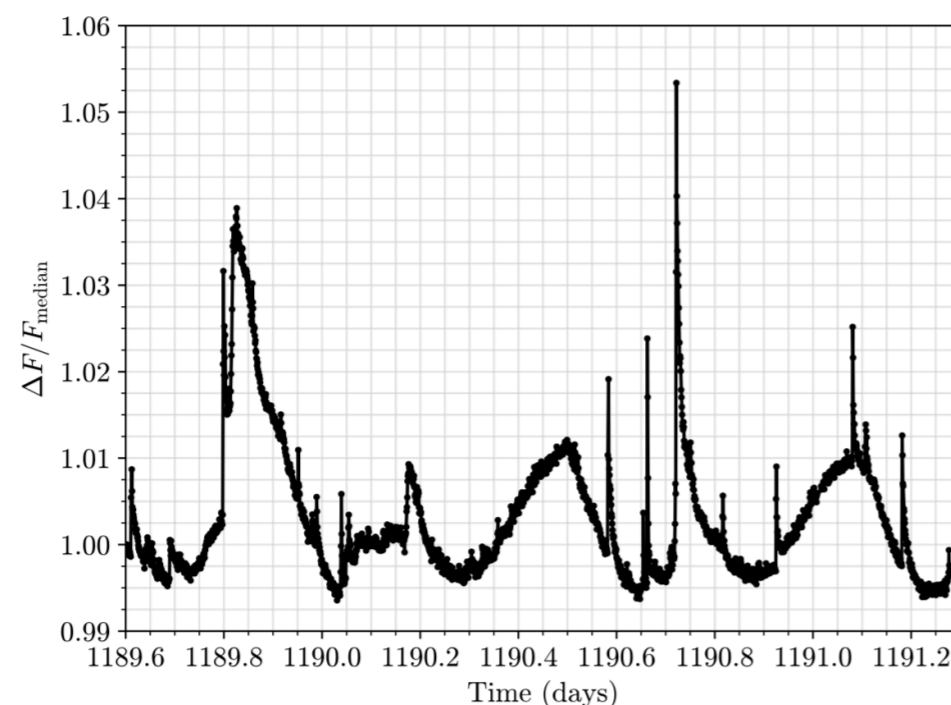# Solar Flares vs Stellar Flare

Shibata & Yokoyama, 1999, ApJL
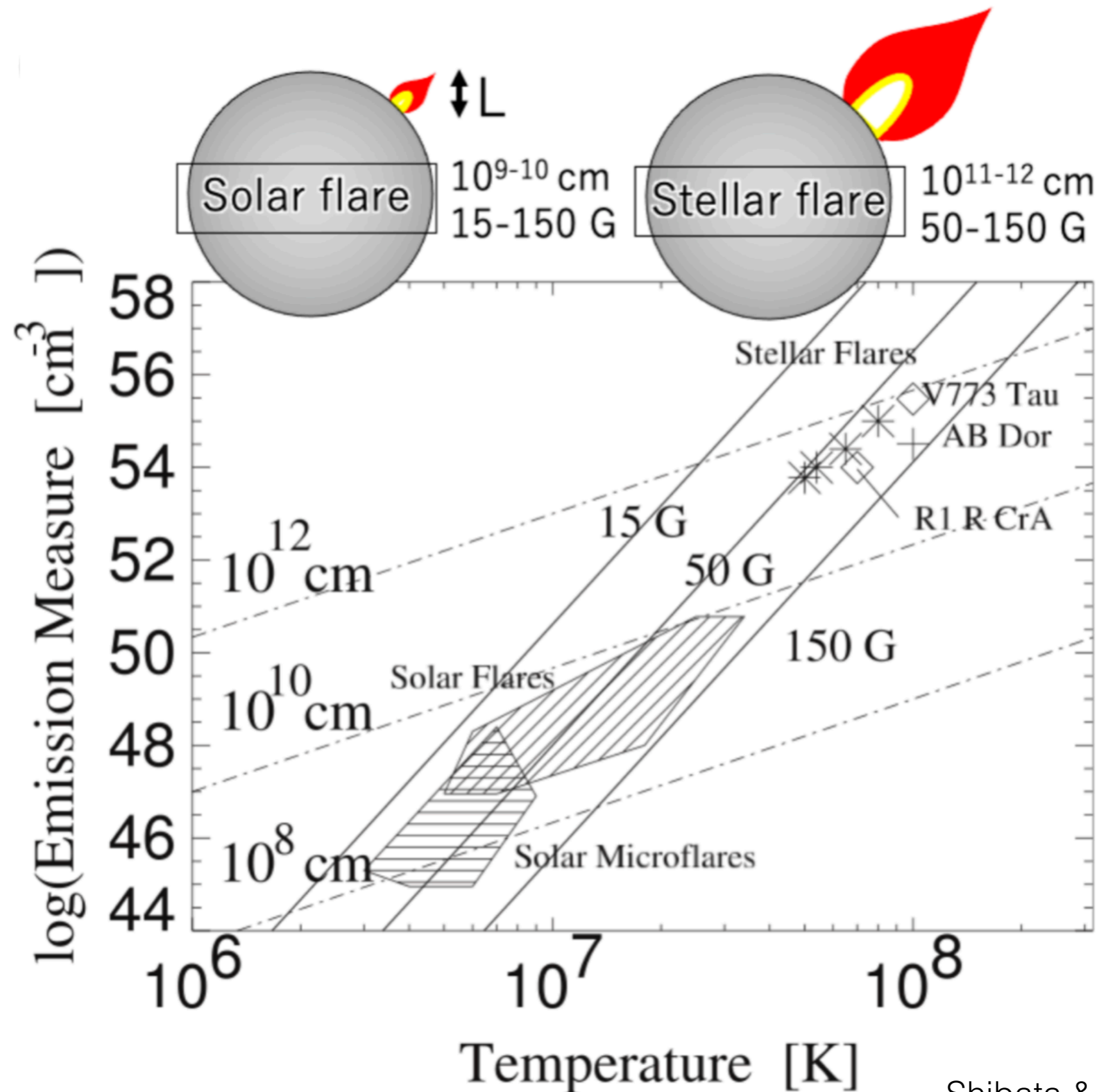
Light Curve Feature

- Over short timescales of **minutes to a few hours**, stellar flares emit energy ranging from 10^23 erg (**nanoflares**) to 10^31 − 10^38 erg (**superflare**). There is relation between the duration and the energy of the stellar flares.

$$\Delta t \sim t_{1/2} \simeq 63 \text{ s} \left(\frac{E}{10^{32} \text{ erg}} \right)^{0.3}$$

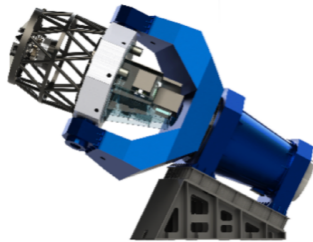- Observations of over 38,000 M dwarfs in the SDSS revealed that the fraction of "active" stars increases dramatically from types M0 to M6, **peaking near spectral type M7-M8**.

- Flare light curves generally consist of **a sudden increase** in brightness that is most extreme in the near UV and blue optical, followed by **a long tail** as the star gradually returns to its quiescent state.

Kowalski+, 2024

Spectral Feature

$T_{BB} = 12,100$ K ———
$T_{BB} = 13,700$ K + $T_{BB} = 4700$ K – – –
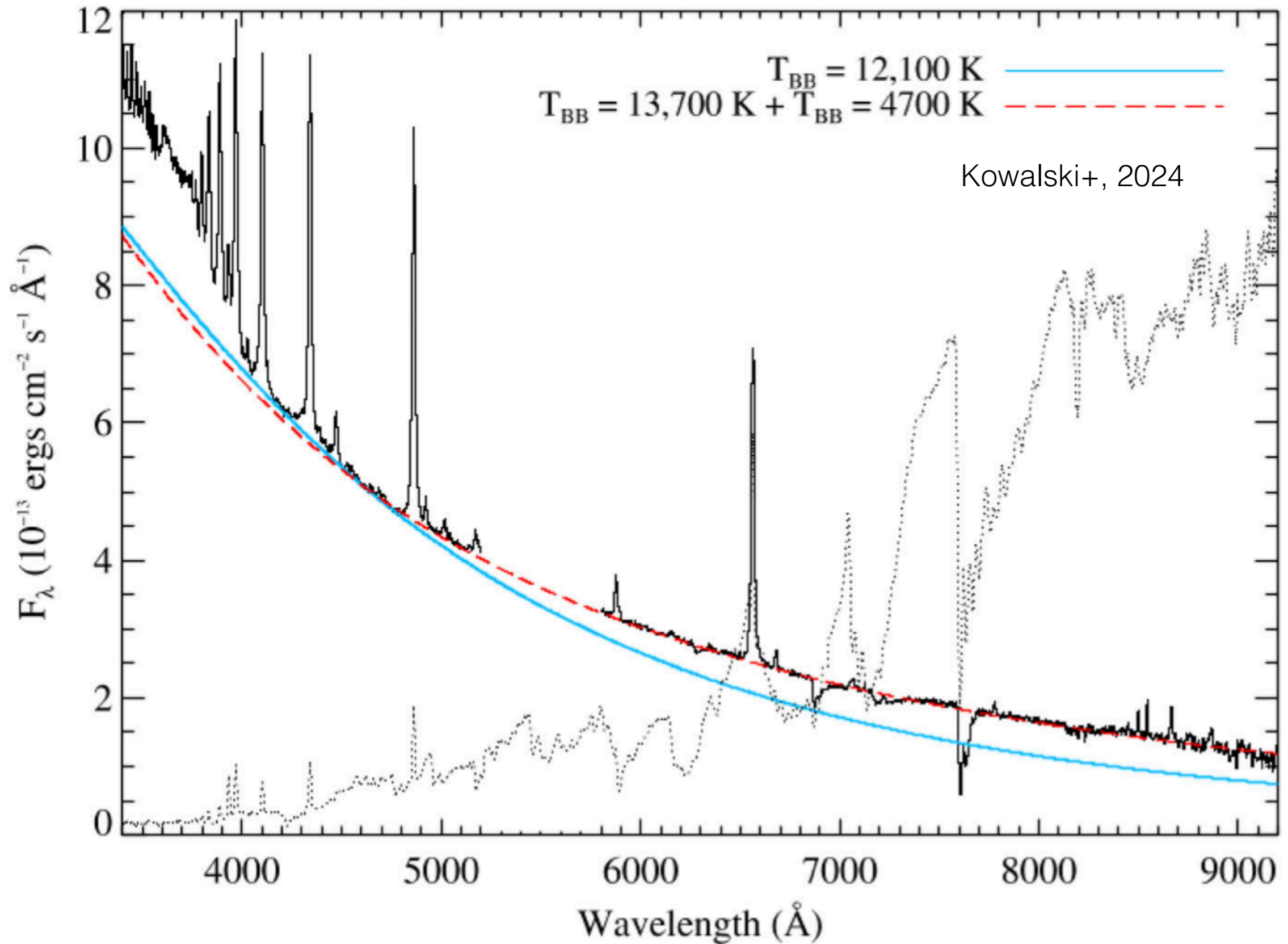
Kowalski+, 2024
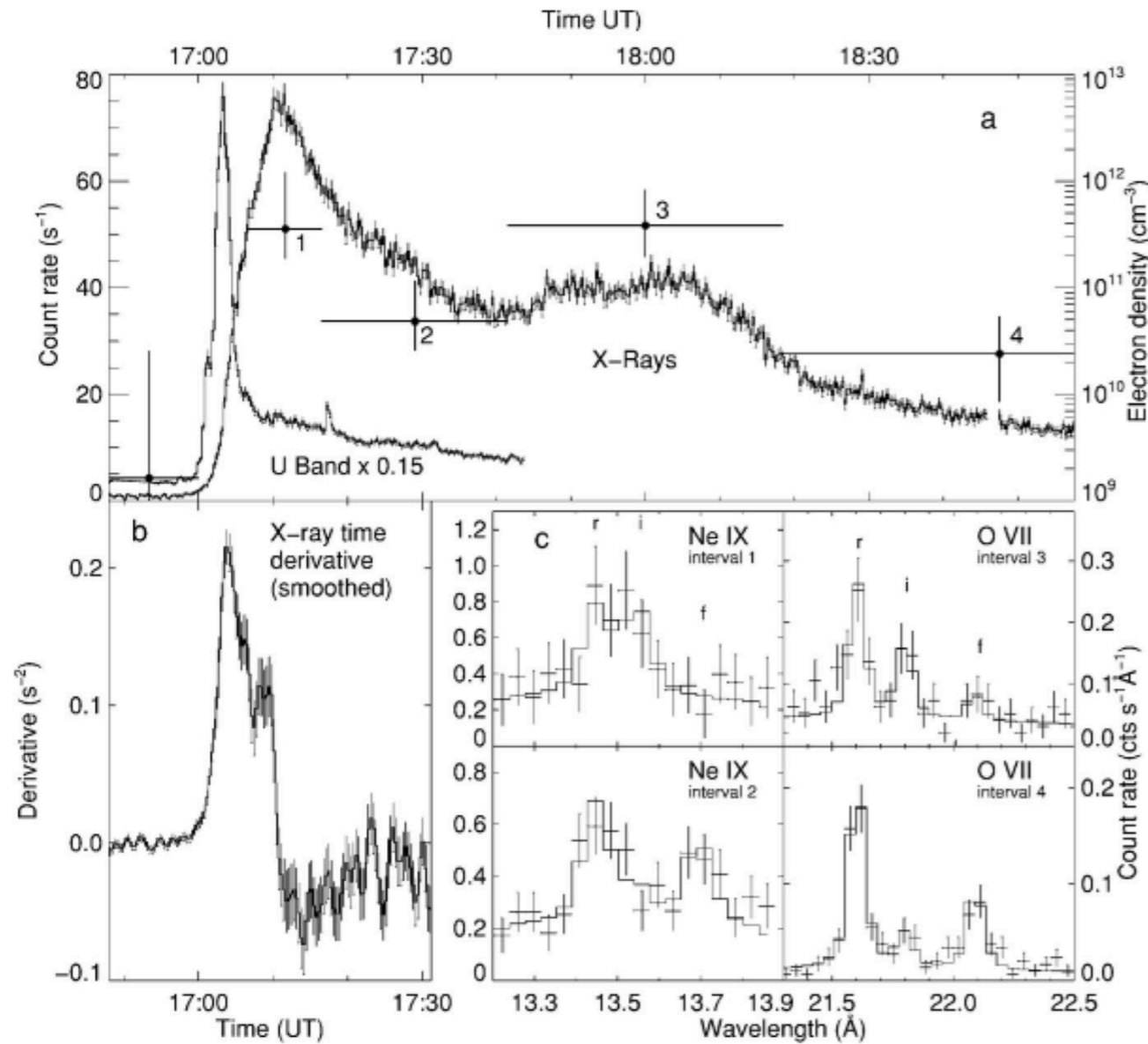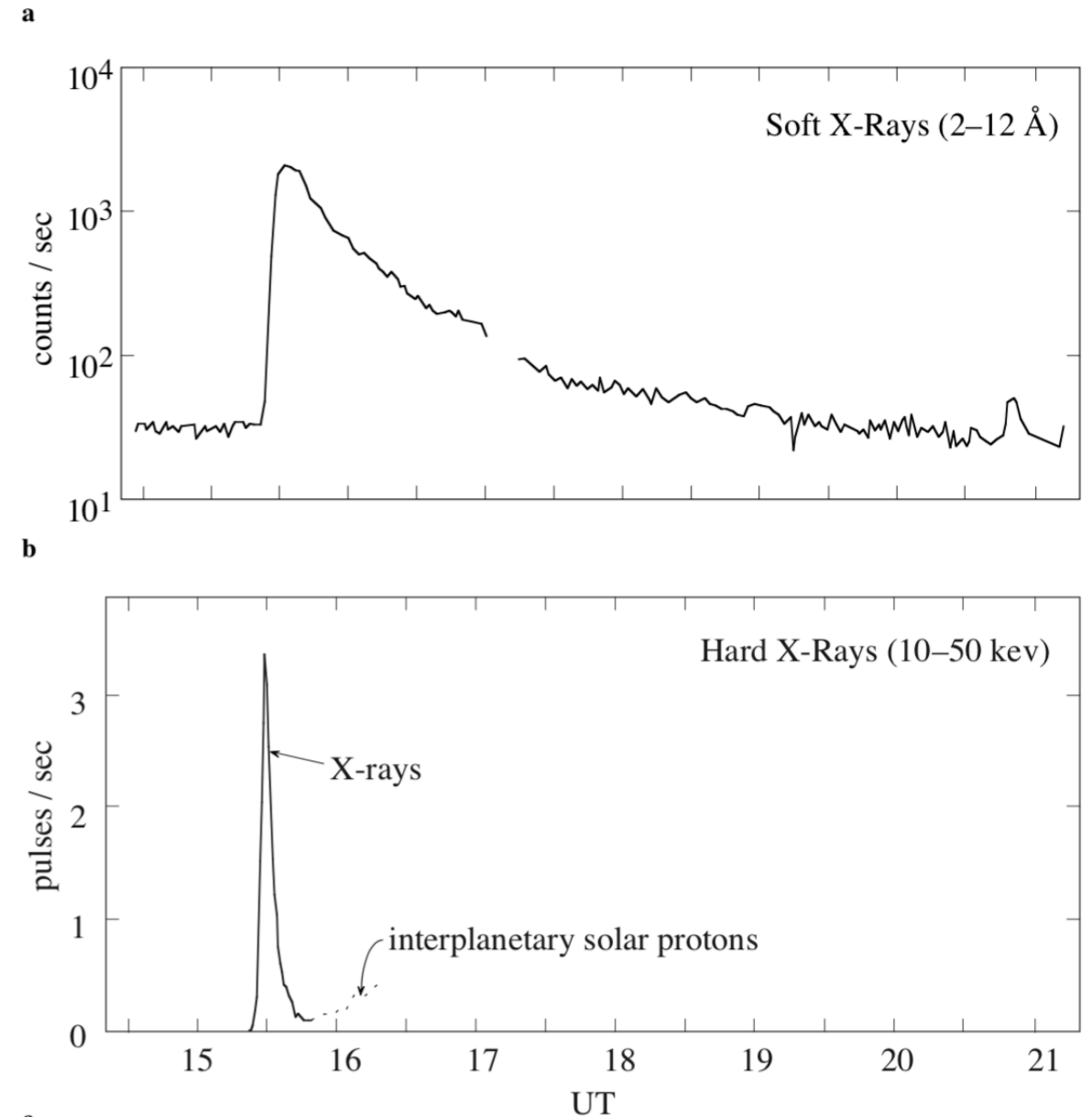
Neupert Effect as A Bridge
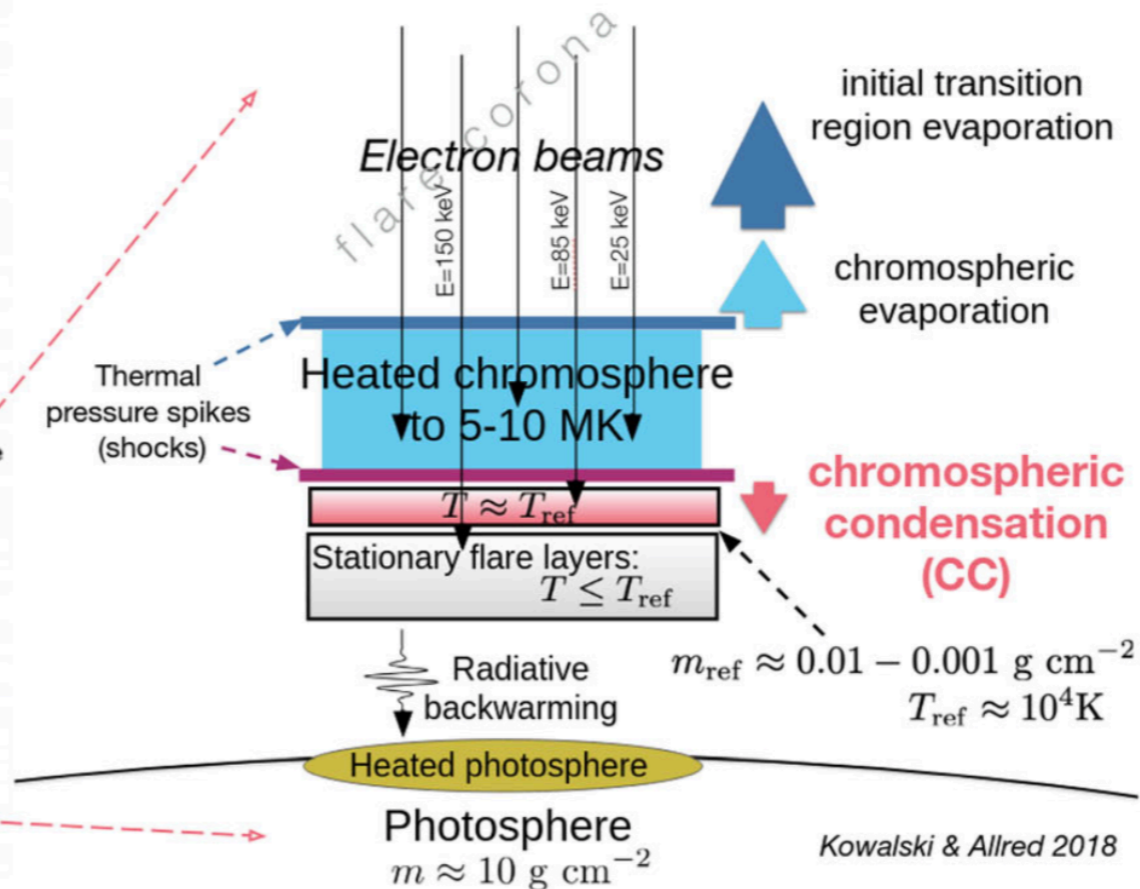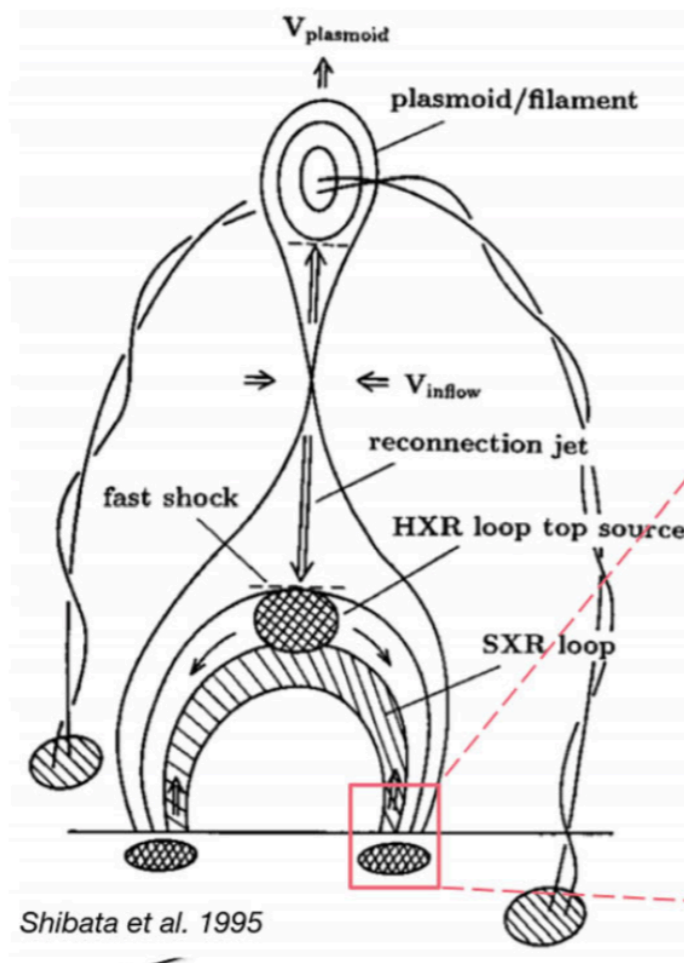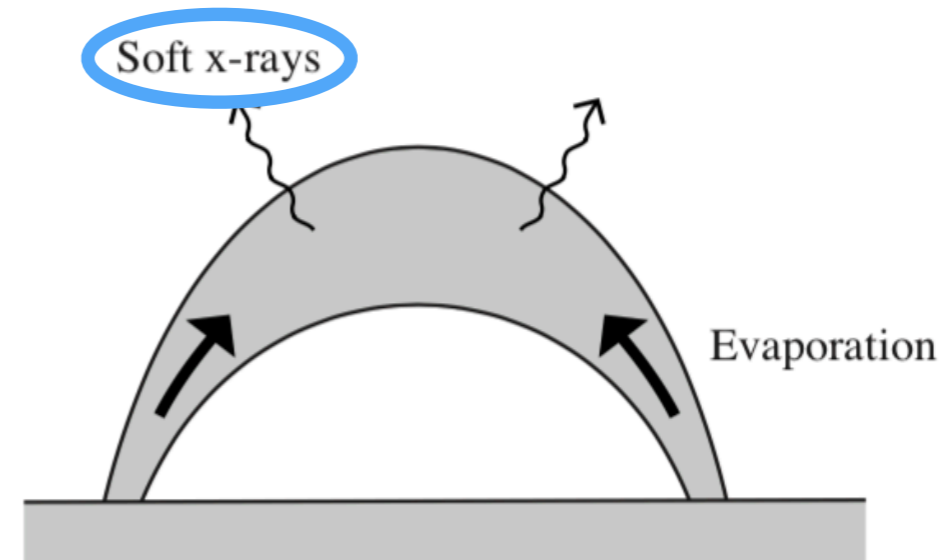
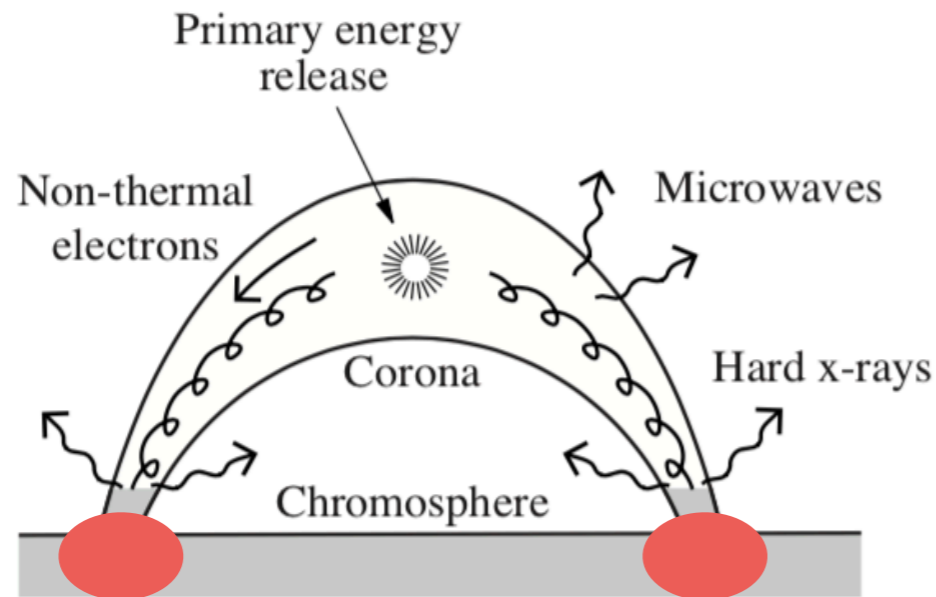$$F_{\text{opt}} \propto F_{\text{HXR}} \propto dF_{\text{SXR}}/dt$$

Stellar Flare in Proxima Centauri
Kowalski+, 2024

Solar Flare
Priest & Forbes, 2002

CSHKP Model for Stellar Flares

Primary energy release

Non-thermal electrons

Microwaves

Corona

Hard x-rays

Chromosphere

Optical emission

Soft x-rays

Evaporation

$V_{plasmoid}$

plasmoid/filament

V_{inflow}

reconnection jet

fast shock

HXR loop top source

SXR loop

Shibata et al. 1995

flare corona

Electron beams

E=150 keV

E=85 keV

E=25 keV

Thermal pressure spikes (shocks)

initial transition region evaporation

chromospheric evaporation

Heated chromosphere to 5-10 MK

$T \approx T_{ref}$

Stationary flare layers: $T \leq T_{ref}$

chromospheric condensation (CC)

$m_{ref} \approx 0.01 - 0.001$ g cm^{-2}

$T_{ref} \approx 10^4$K

Radiative backwarming

Heated photosphere

Photosphere $m \approx 10$ g cm^{-2}

Kowalski & Allred 2018

Survey of Stellar Flares

- Kowalski et al. (2009) presented a flare rate analysis of 50,130 M dwarf light curves in SDSS Stripe 82.

- For stars of spectral types M0-M6 with u<22 mag on Stripe 82, SDSS detected **270 flares with a u-band magnitude change of at least 0.7**

- Flares as large as $\Delta u \sim$ **5 mag** were observed in both early and late type M stars, but flares of Δu < **2 mag** dominate the sample.

- While **the flare contrast is greatest in u**, most flares will be visible (although with a smaller increase in brightness) in g, r, and to a lesser extent in i.
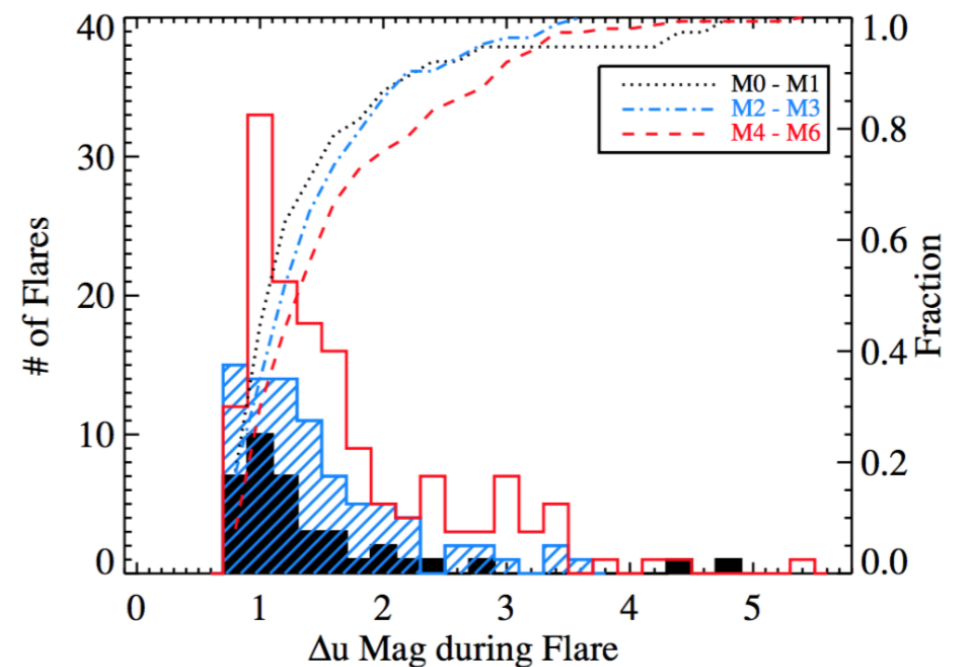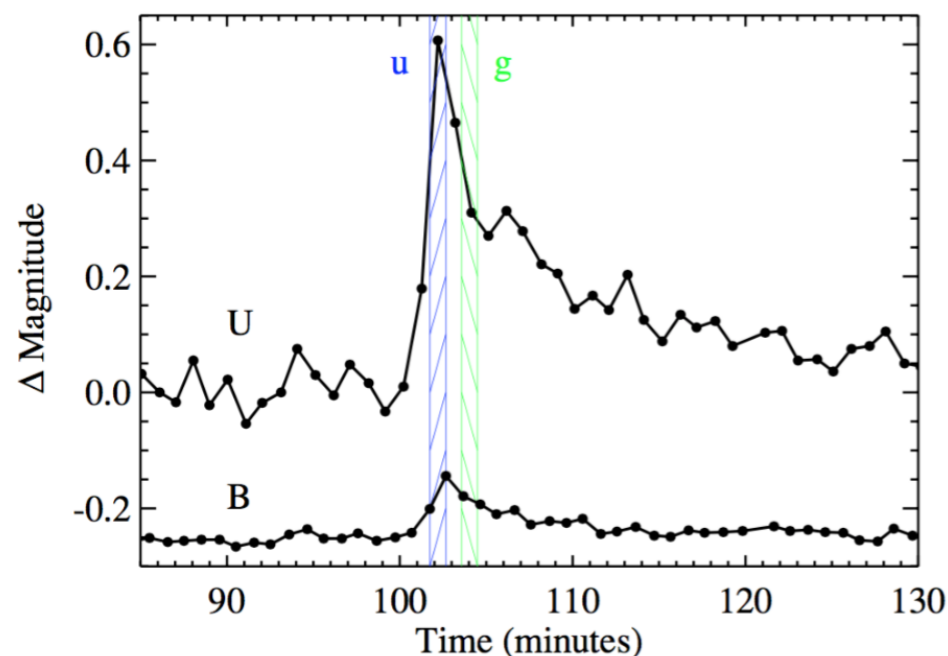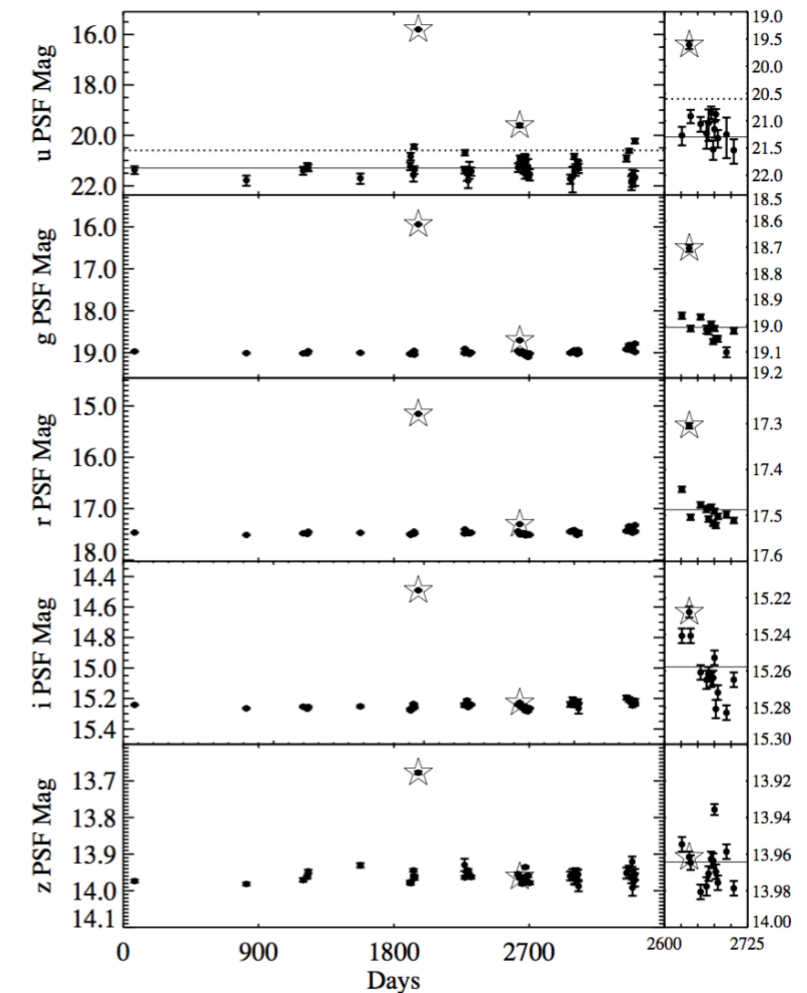
Kowalski+, 2009

Detection Rate of Stellar Flare

- The observed flare rate is very strongly dependent on the line of sight through the Galaxy **95% of the flaring observations occur on stars that are within 300 pc of the plane**, and the flare rate ranges from 0 to 8 flares/hr/deg2 depending on Galactic latitude.

- For the Stripe 82 data, the mean flare rate density is $\Sigma_{S82} \sim 1.3 \text{ flares hr}^{-1} \text{ deg}^{-2}$.

- with a u mag increase of Δu>0.7 as the common flare detection threshold and u<22. The flare rate density for Mephisto could be estimated by

$$\Sigma = 10^{\frac{3(m_u - m_{S82})}{5}} \Sigma_{S82} \sim 0.5 \text{ flares hr}^{-1} \text{ deg}^{-2}$$ **for Mephisto**

- for **m_u=21.3 mag with one minute exposures**

Spatial Division	Mean # Flares hr^{-1} deg^{-2}
$23° < |b| < 45°$	2.0
$45° < |b| < 55°$	0.9
$55° < |b| < 64°$	0.7
$45° < l < 90°$	1.5
$90° < l < 135°$	0.7
$135° < l < 191°$	0.9

Kowalski+, 2009

Toy Model for Stellar Flare

- Assuming that both the star and the flare emit blackbody radiation, the total flux during the flare phase could be calculated by

Emission from a star and its flare

$$F_\nu = \pi \left(\frac{R_s}{D}\right)^2 \left[B_\nu(T_f)x^2 + B_\nu(T_s)\right]$$
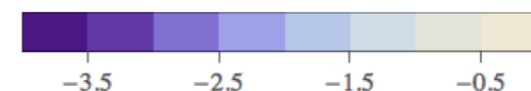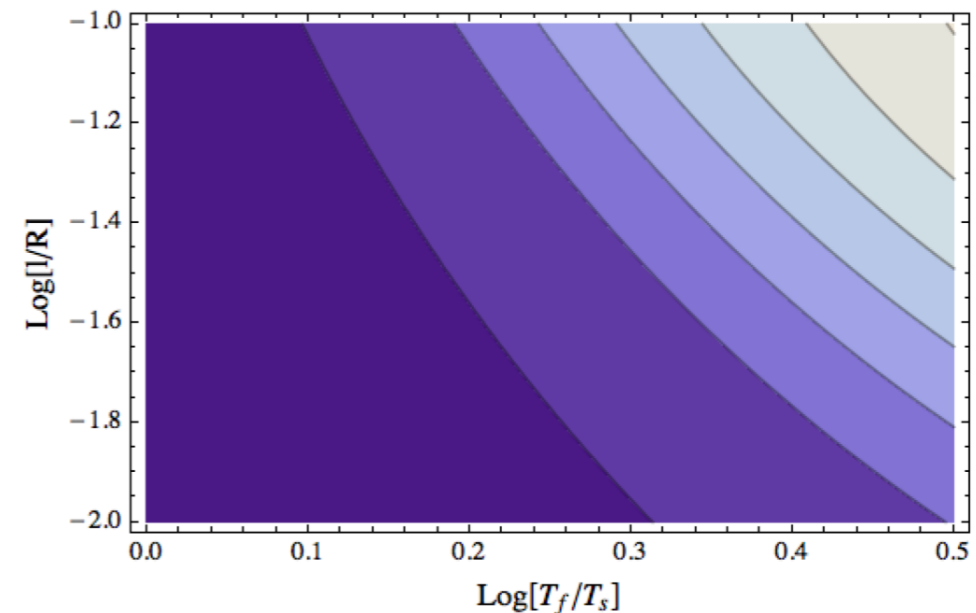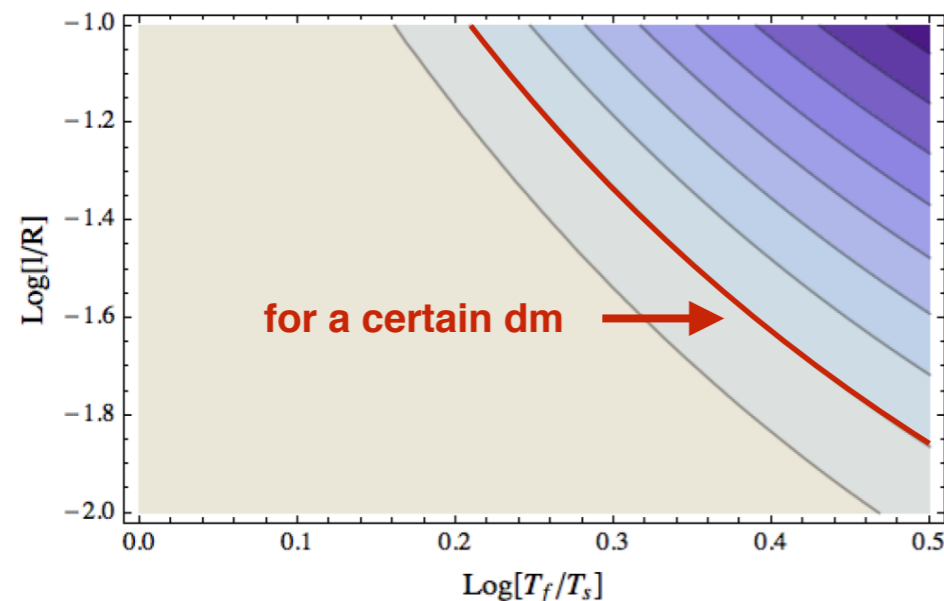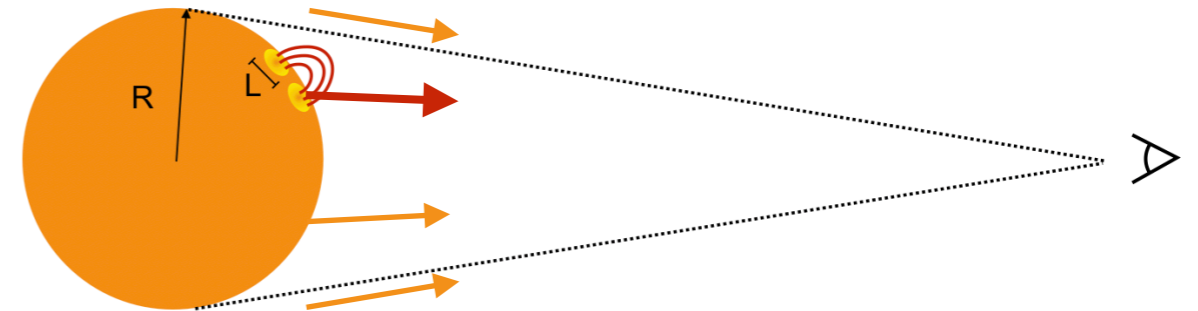
flare　　　**star**

with

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT) - 1} \quad \text{and} \quad x \equiv \frac{R_f}{R_s}$$

- For a certain frequency, the magnitude difference between the flare phase and the quiescent phase as

$$\Delta m \equiv -2.5\log\left(\frac{F_\nu}{F_{\nu,0}}\right) = -2.5\log\left[\frac{\exp(h\nu/kT_s) - 1}{\exp(h\nu/kT_f) - 1}x^2 + 1\right]$$

for a certain dm

Mock Simulation Test

- We consider that a M dwarf and a stellar flare has

$$R_s = 0.4 R_\odot, \quad T_s = 3500 \text{ K}, \quad d = 10 \text{ pc}$$
$$R_{f,0} = 0.1 R_s, \quad T_{f,0} = 10 T_s$$

- The evolutions of the scale and effective temperature of the stellar flare may be assumed to be

$$R_f = R_{f,0} \left(\frac{t}{t_0} \right)^{0.5}, \quad T_f = T_{f,0} \left(\frac{t}{t_0} \right)^{-1}$$

- We simulate the magnitudes at different bands based on the flare dynamics and blackbody radiation and add a fluctuation of $\Delta m < 0.05$ mag


consistent with the input evolution
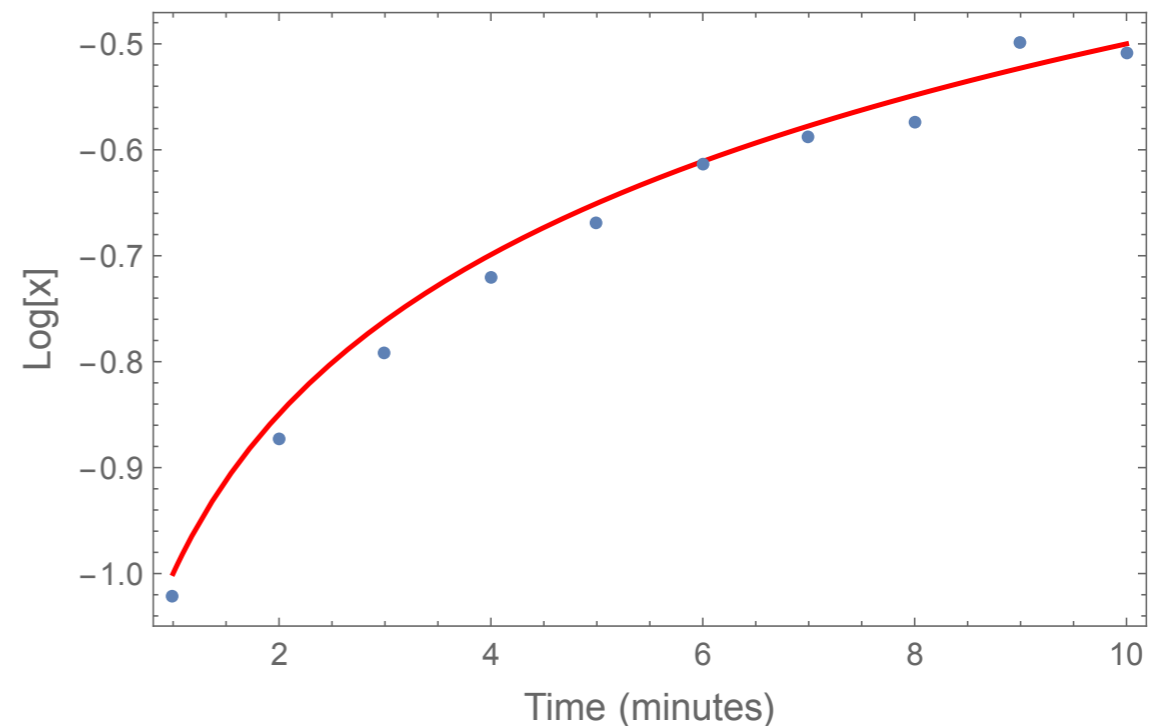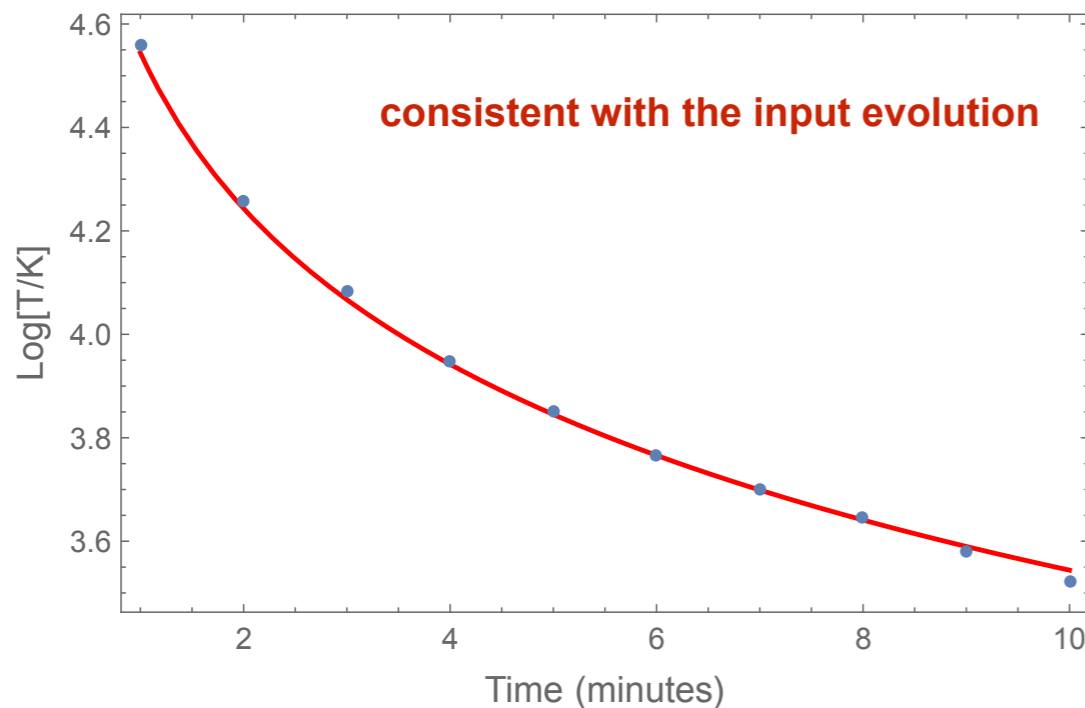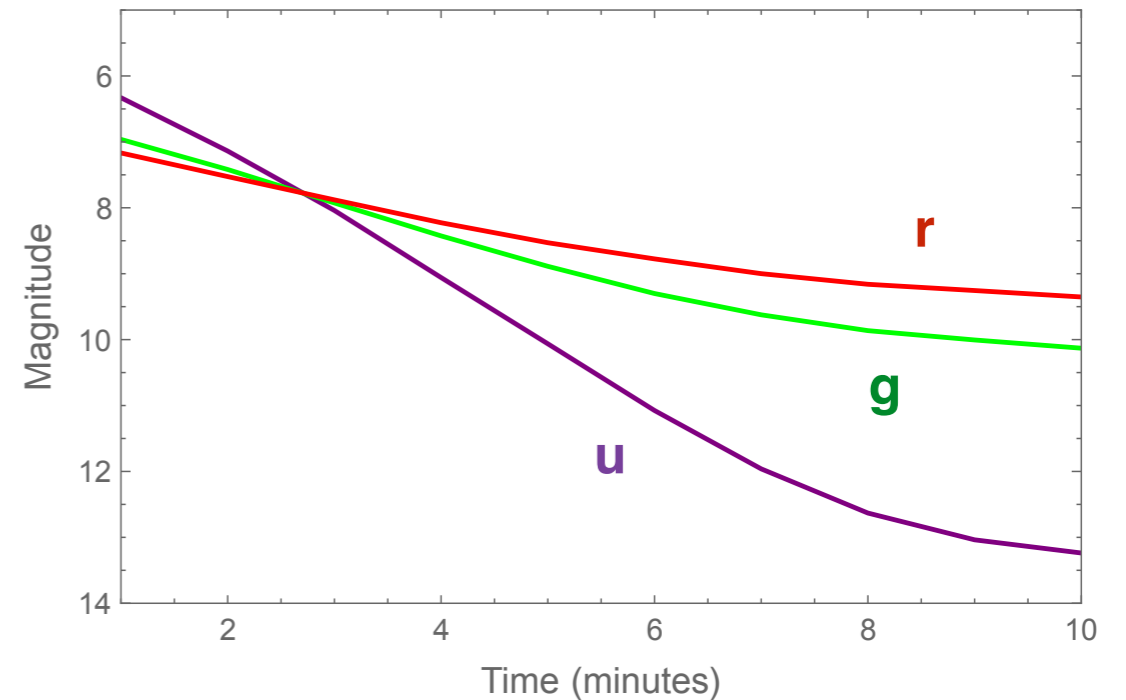
AD Leo Flaring Star

- **AD Leo (M3.5 Ve)** is one of the most active single M dwarfs in the northern hemisphere. In many aspects, flares on AD Leo resemble those on the Sun.

- Photoelectric photometry in the Johnson UBVR filters was obtained with the McDonald Observatory **2.1 m Struve telescope equipped with a two-channel photometer**.

- AD Leo was observed with the primary channel, while the second channel monitored the sky conditions

- **Integrations of 0.8 s in each filter, combined with 0.2 s for filter rotation, resulted in a 4 s cycle time.**
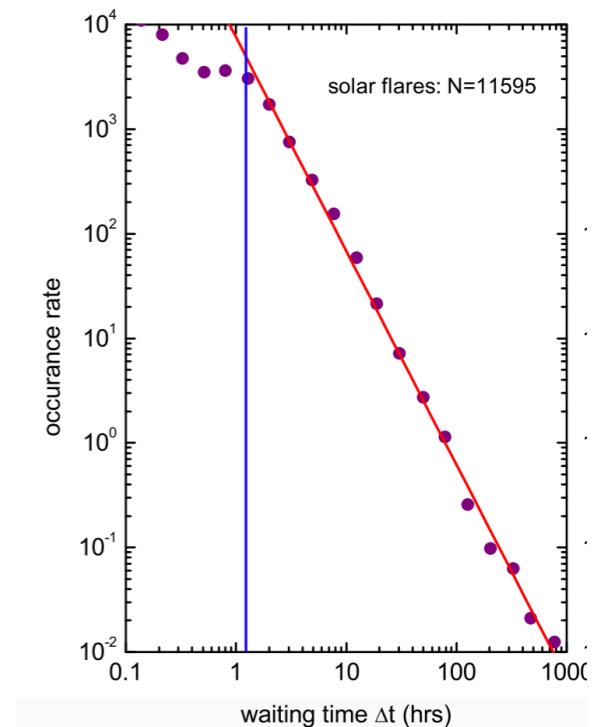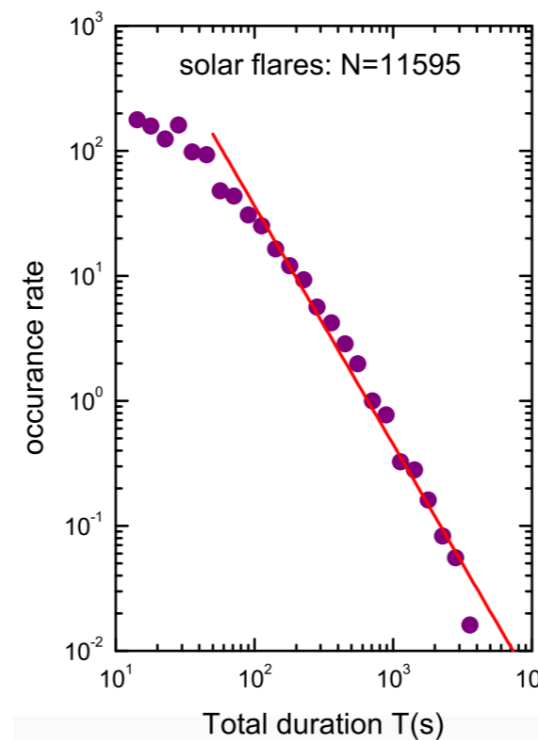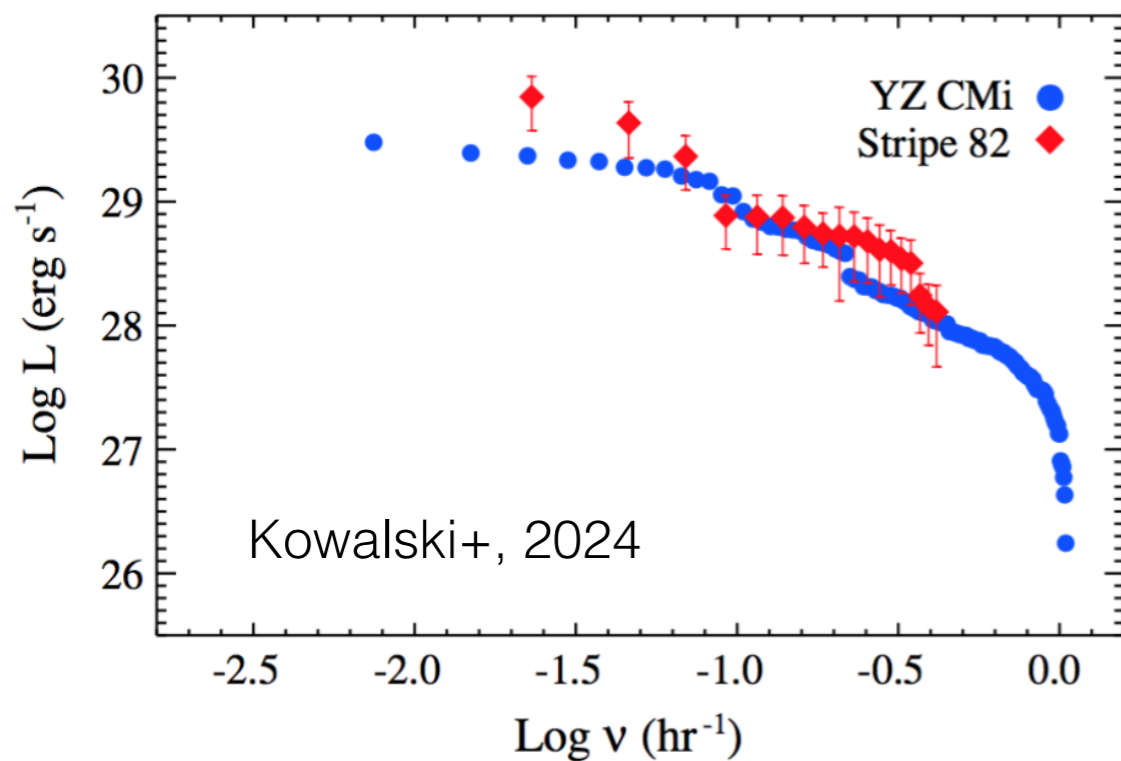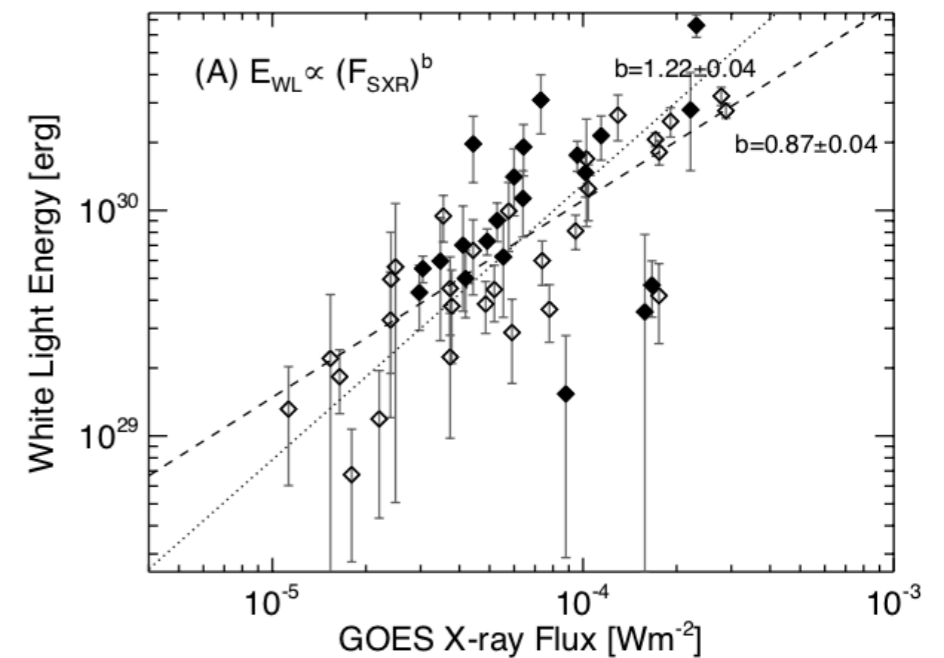
Flare #8

Hawley +, 2003, ApJ
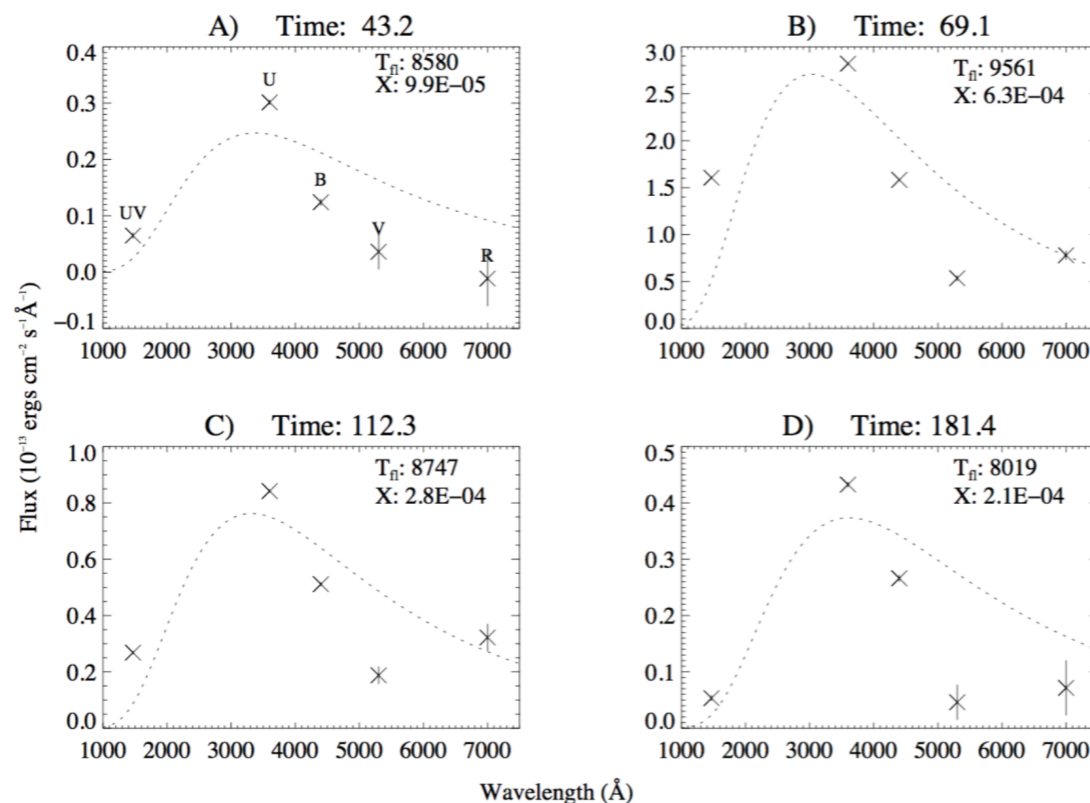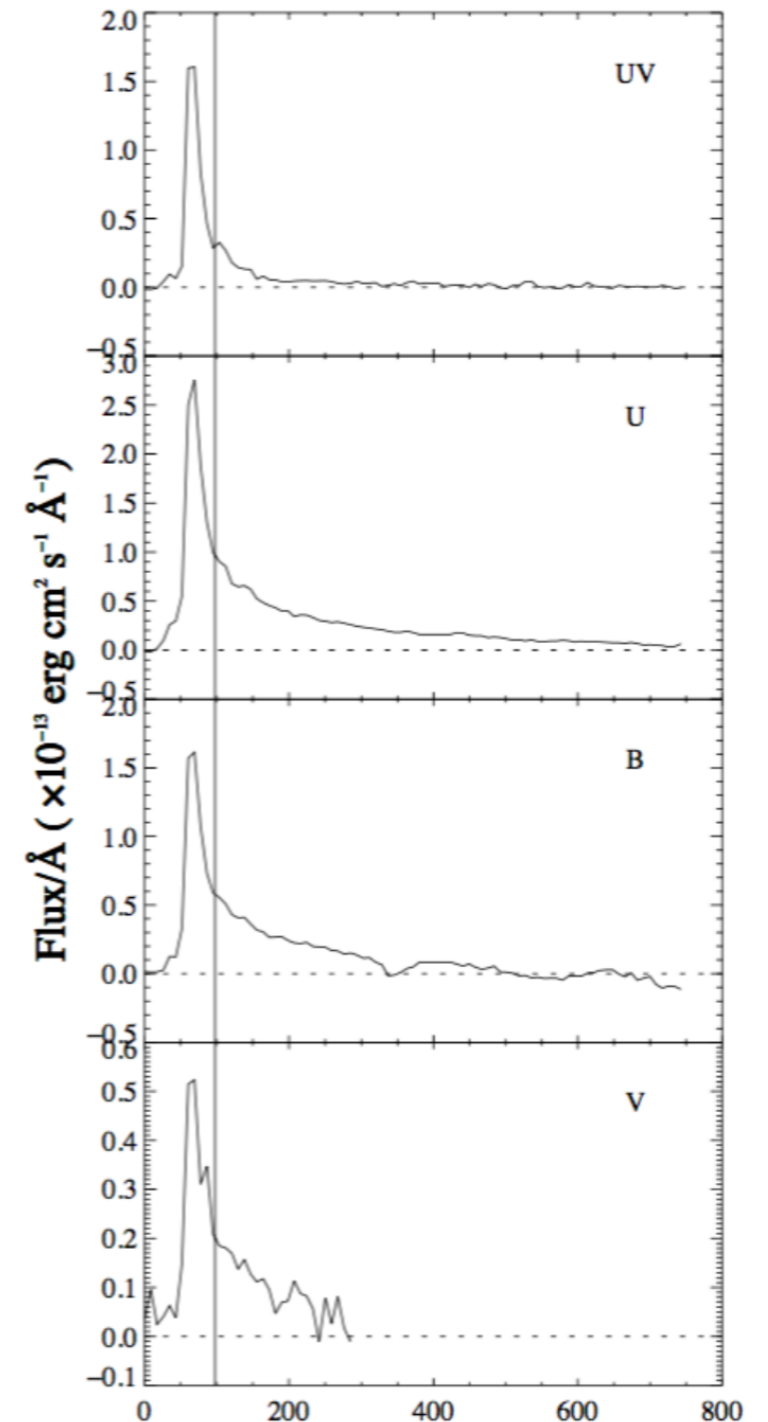
Temperature and Area of AD Leo
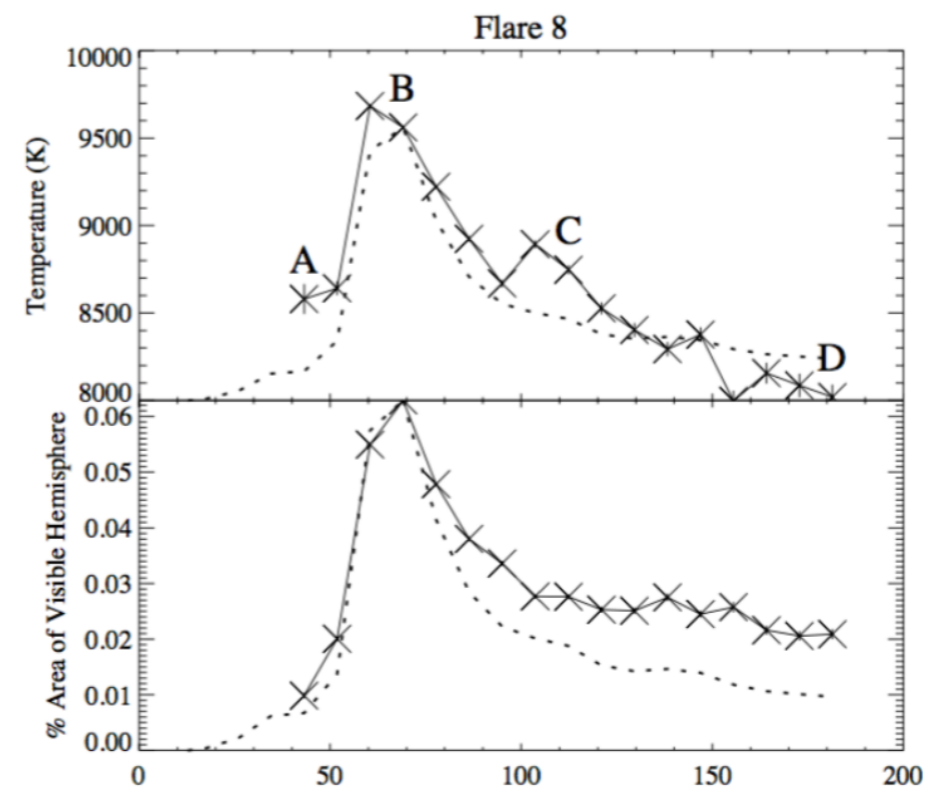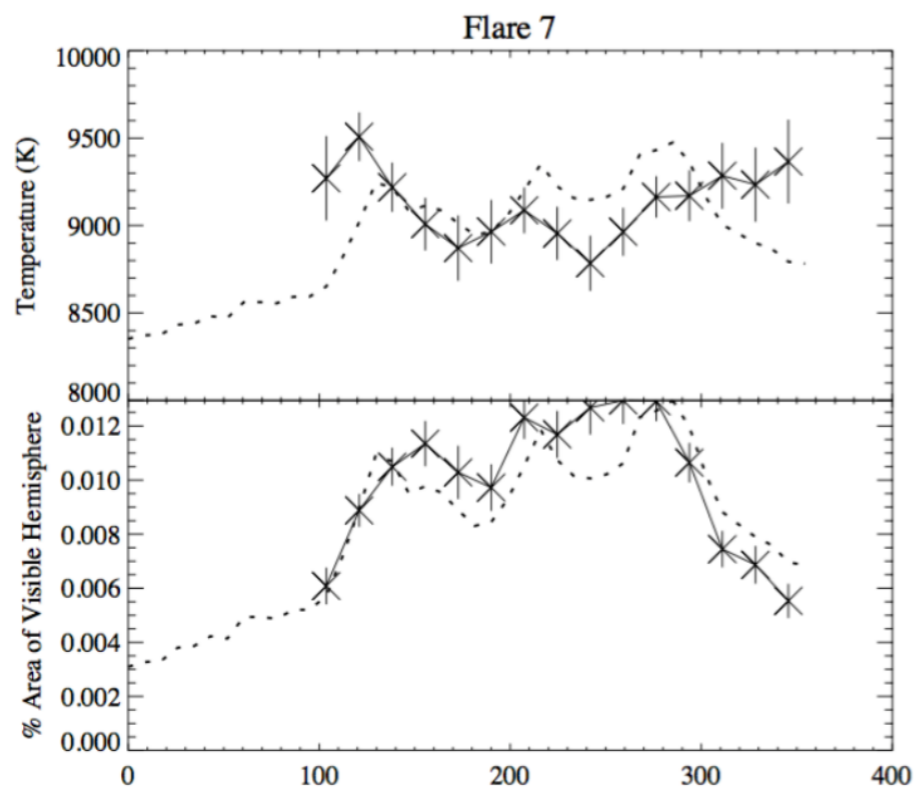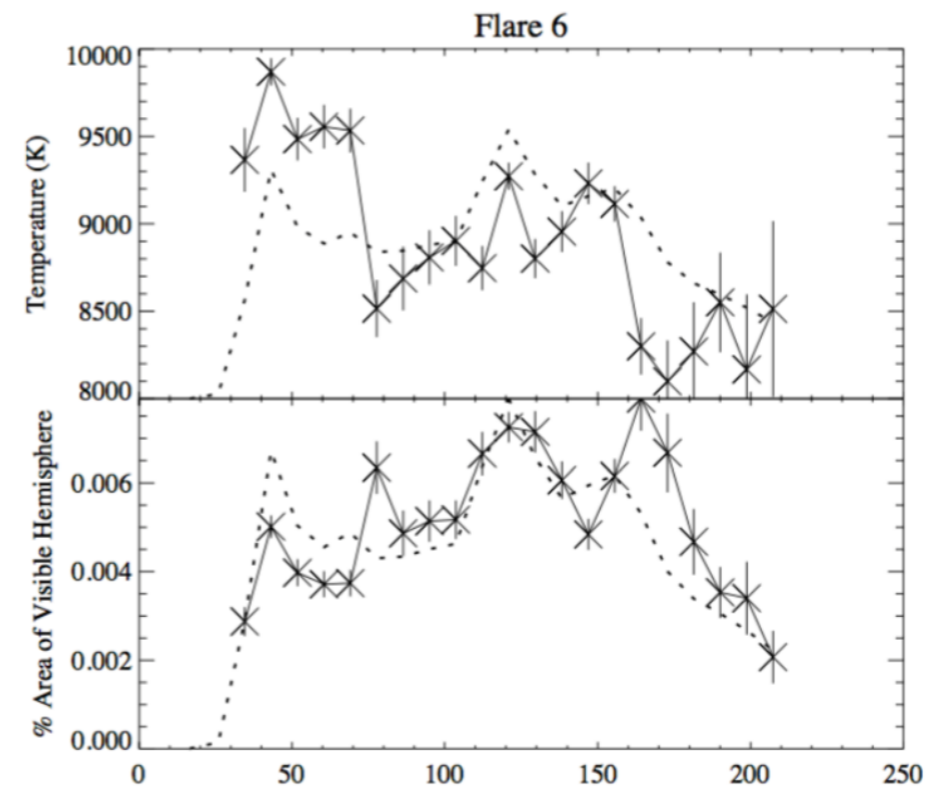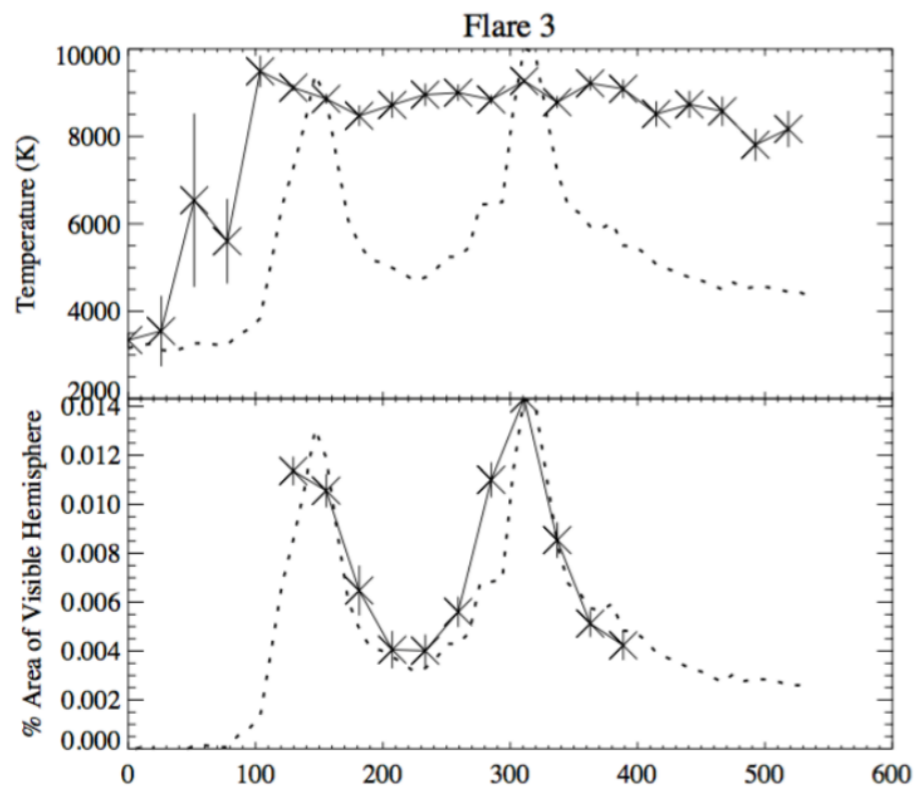
Implication of Flare Rate: Burst Group

Kowalski+, 2016

Kowalski+, 2024

Wang & Dai, 2013, NaPh
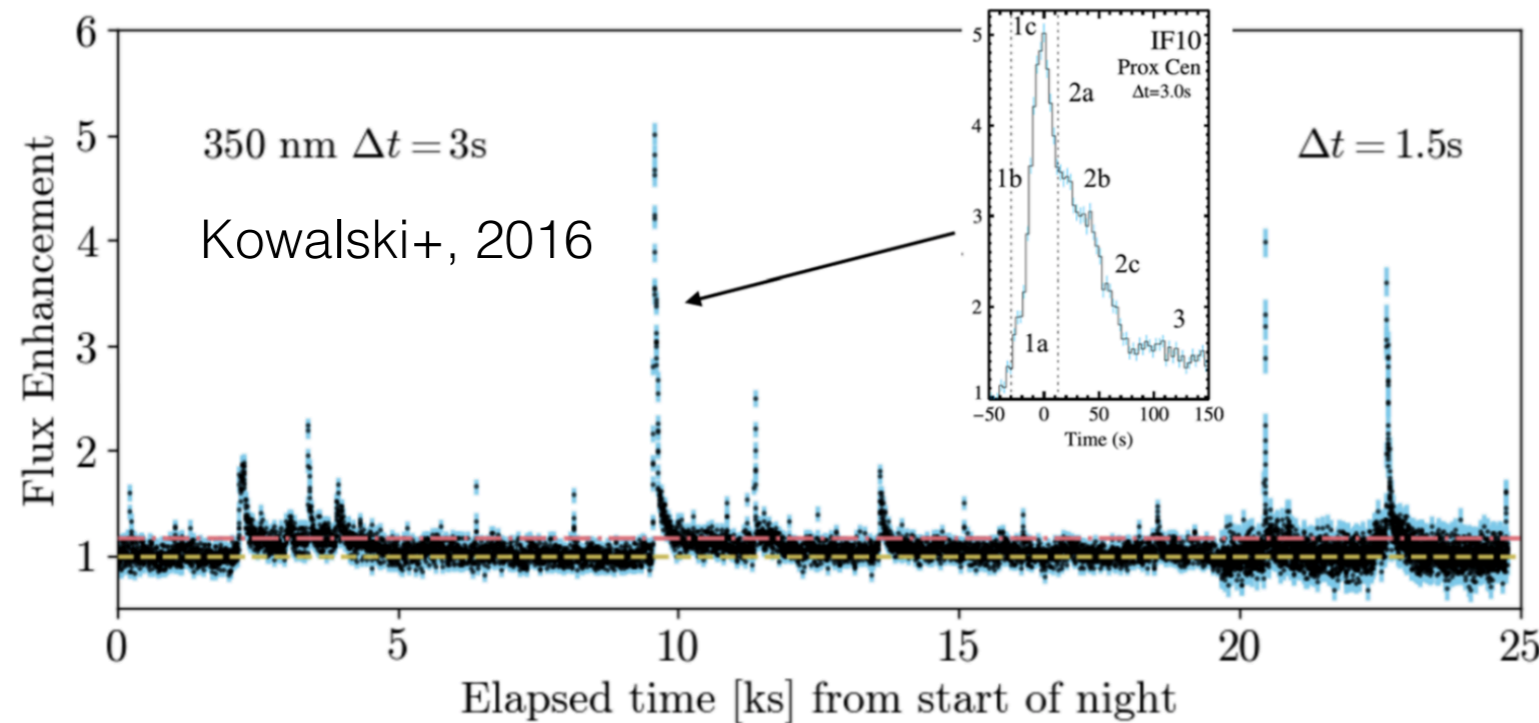
Summary

- The main features of Mephisto can be summarized as follows

$$\text{Mephisto} = \text{Survey} + \text{Real Color}$$

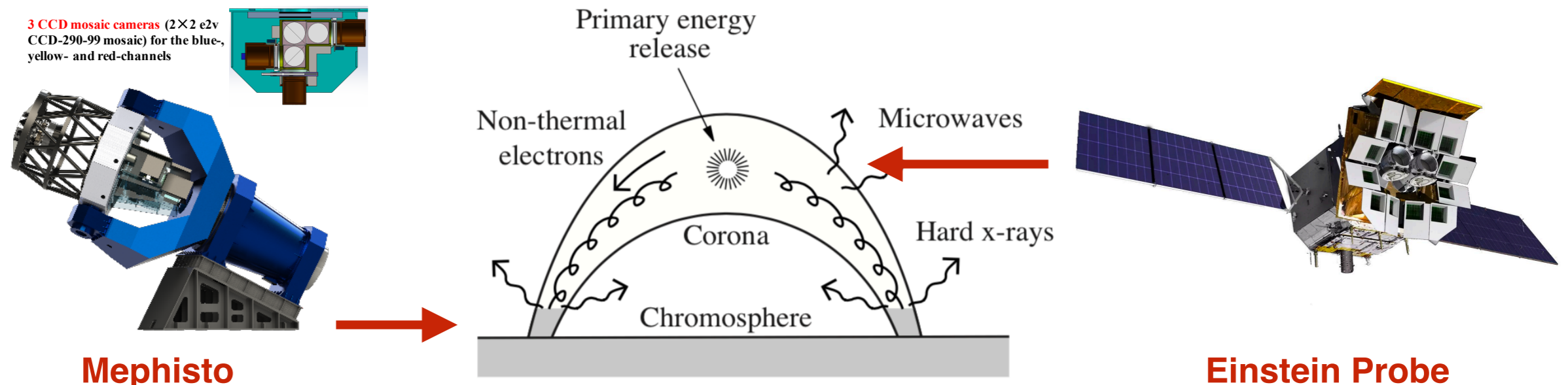- Stellar flares represent a major source of transient variability in time domain surveys and have a short duration and a significant color evolution

- Mephisto can provide a sample of the flaring stellar (with effective temperature, flare scale, etc.) during its survey program.

3 CCD mosaic cameras (2×2 e2v CCD-290-99 mosaic) for the blue-, yellow- and red-channels

Primary energy release

Non-thermal electrons

Microwaves

Corona

Hard x-rays

Chromosphere

Mephisto

Einstein Probe

Thank You!