Observations of Stellar Flares
(mostly on M dwarfs)

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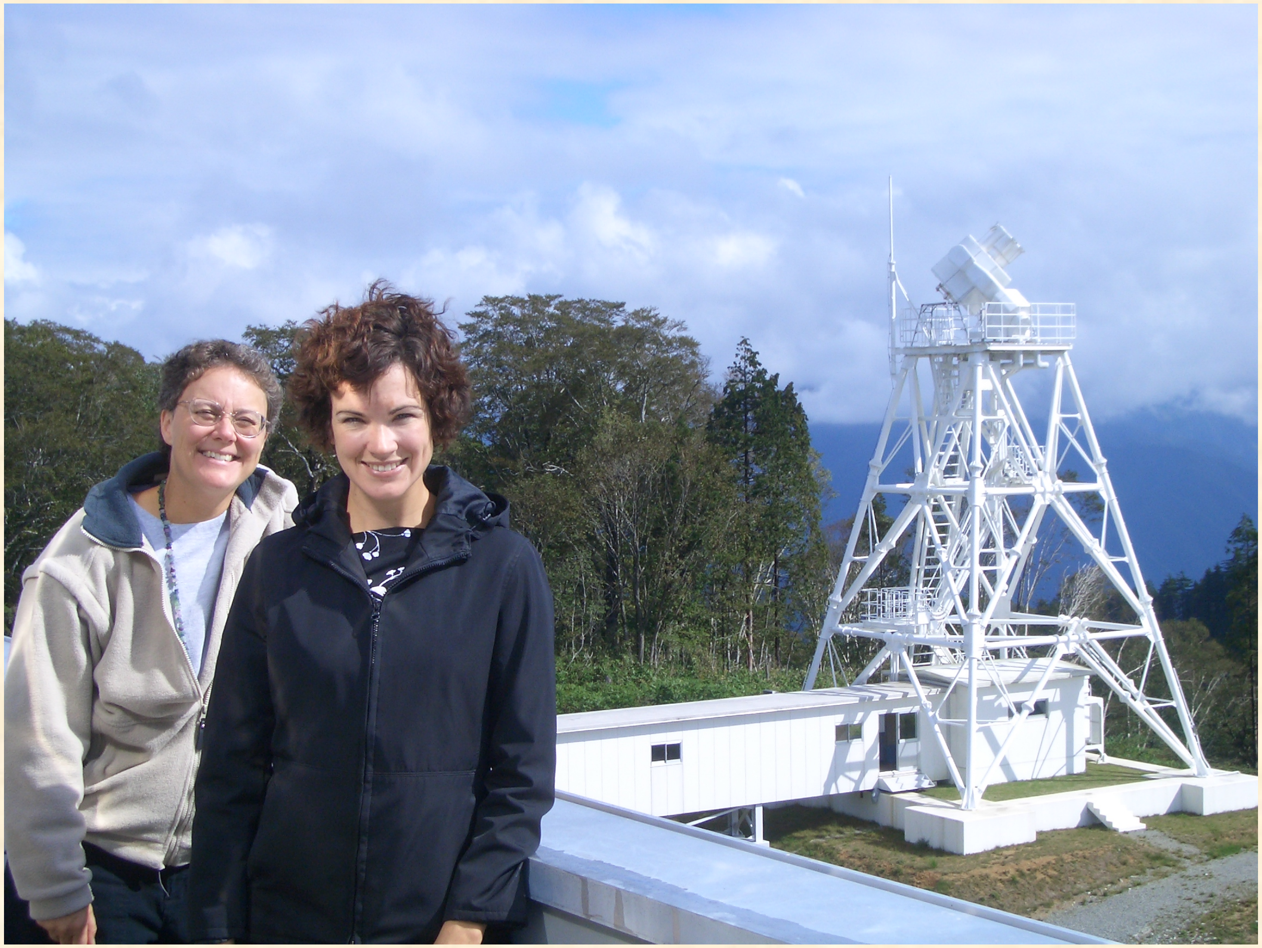
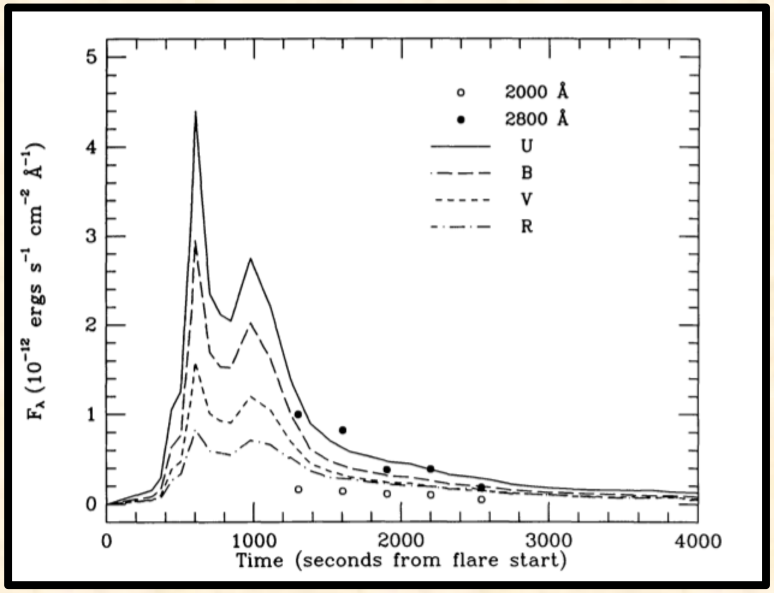
2005 visit to Kyoto and Hida observatory
rebirth of interest in flares!

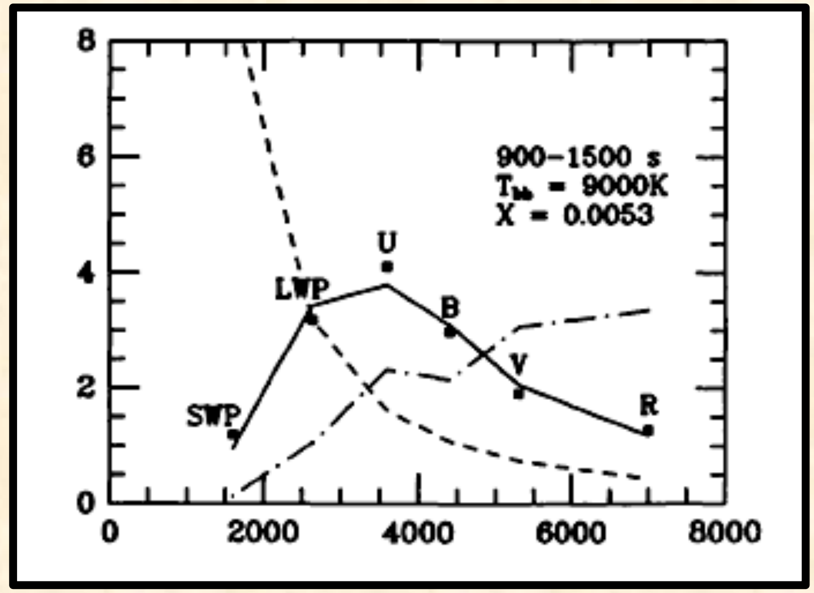


The Great Flare of 12 April 1985 on AD Leo (dM3e)

Hawley & Pettersen (1991)



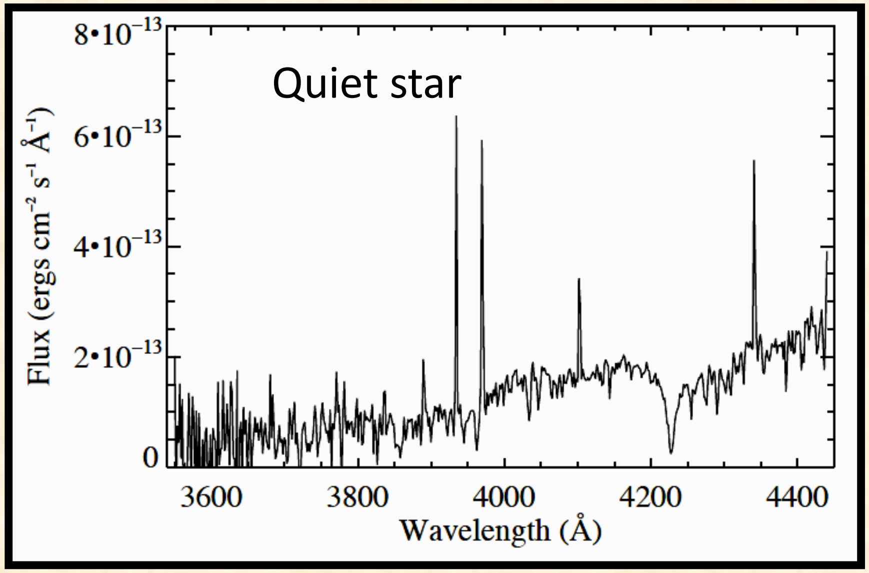
Giant flare (>10^{34} ergs – superflare!) makes star 100 times brighter in blue and near-UV. Data in several colors from McDonald Observatory (also spectra) and UV from IUE satellite.

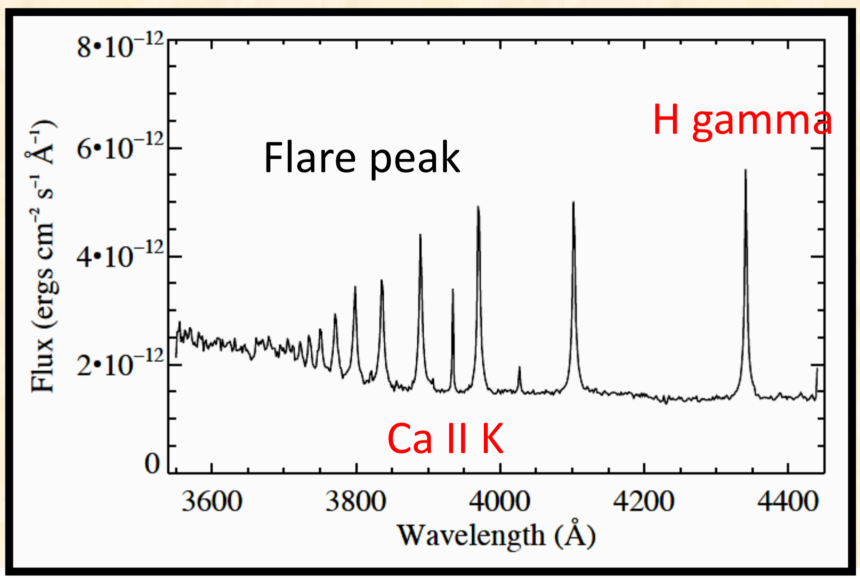


White light flare continuum in broad band colors exhibits the shape of ~ 10,000K blackbody, covering 0.5% of the stellar surface.

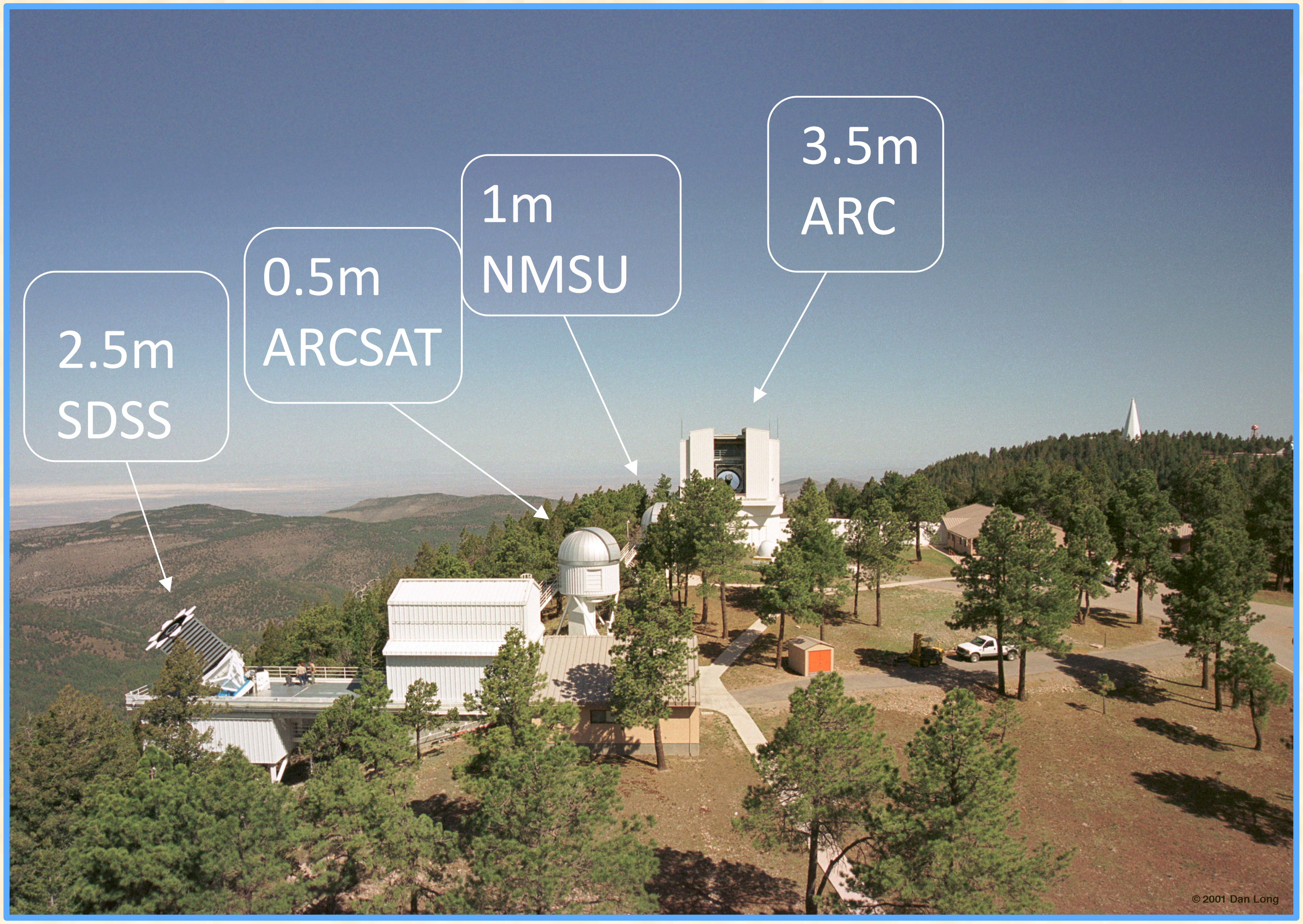
The Great Flare of 1985 on AD Leo (dM3e)

Spectrum of blue continuum in the flare appears to be due to a hot blackbody with T ~ 10,000K, and no obvious Balmer jump at 3656A

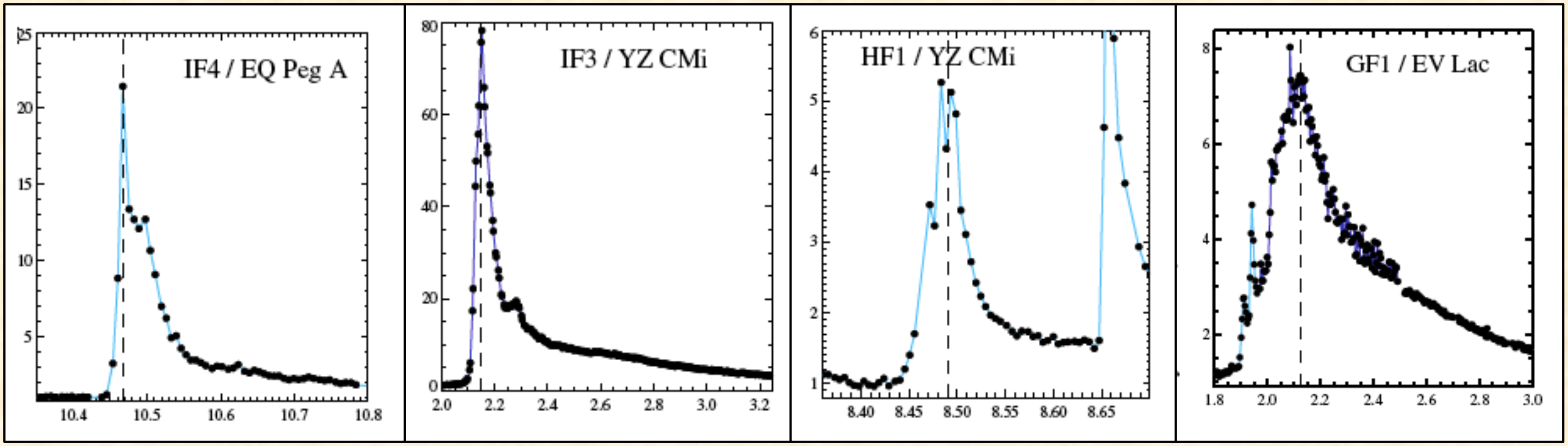




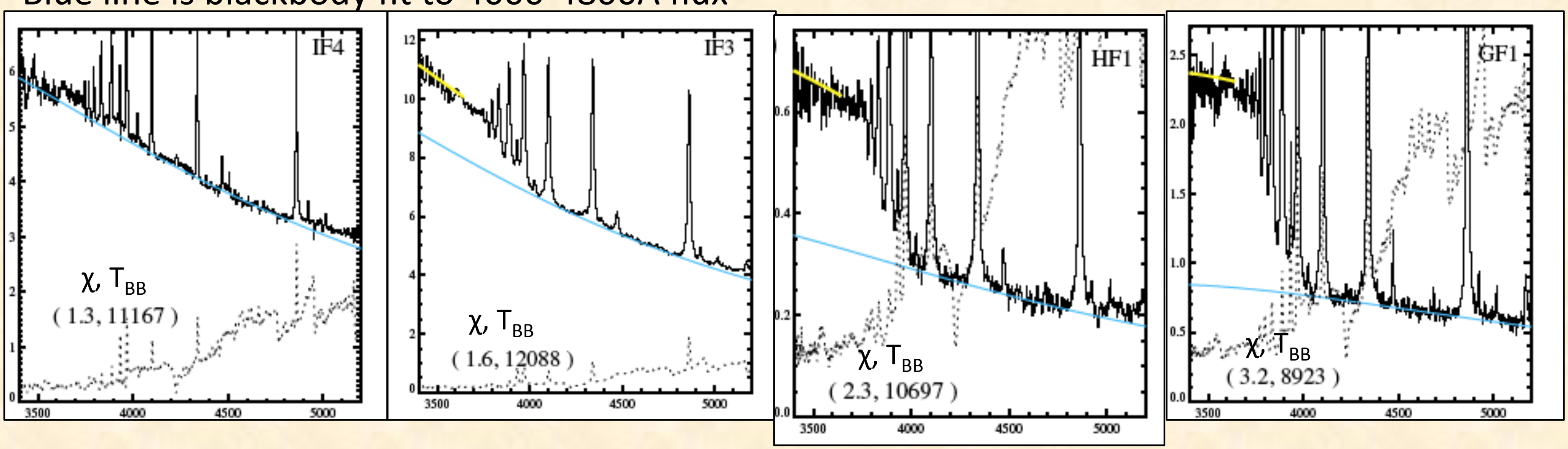
Apache Point Observatory
Sunspot, New Mexico, USA



Kowalski, Hawley et al 2013 (K13) flare atlas – 20 flares with U band photometry and simultaneous spectra. Flare light curves – impulsive (IF), hybrid (HF), gradual (GF)



Flare spectra show small Balmer continuum component (BaC) in IF, larger in HF, most in GF
Blue line is blackbody fit to 4000-4800A flux

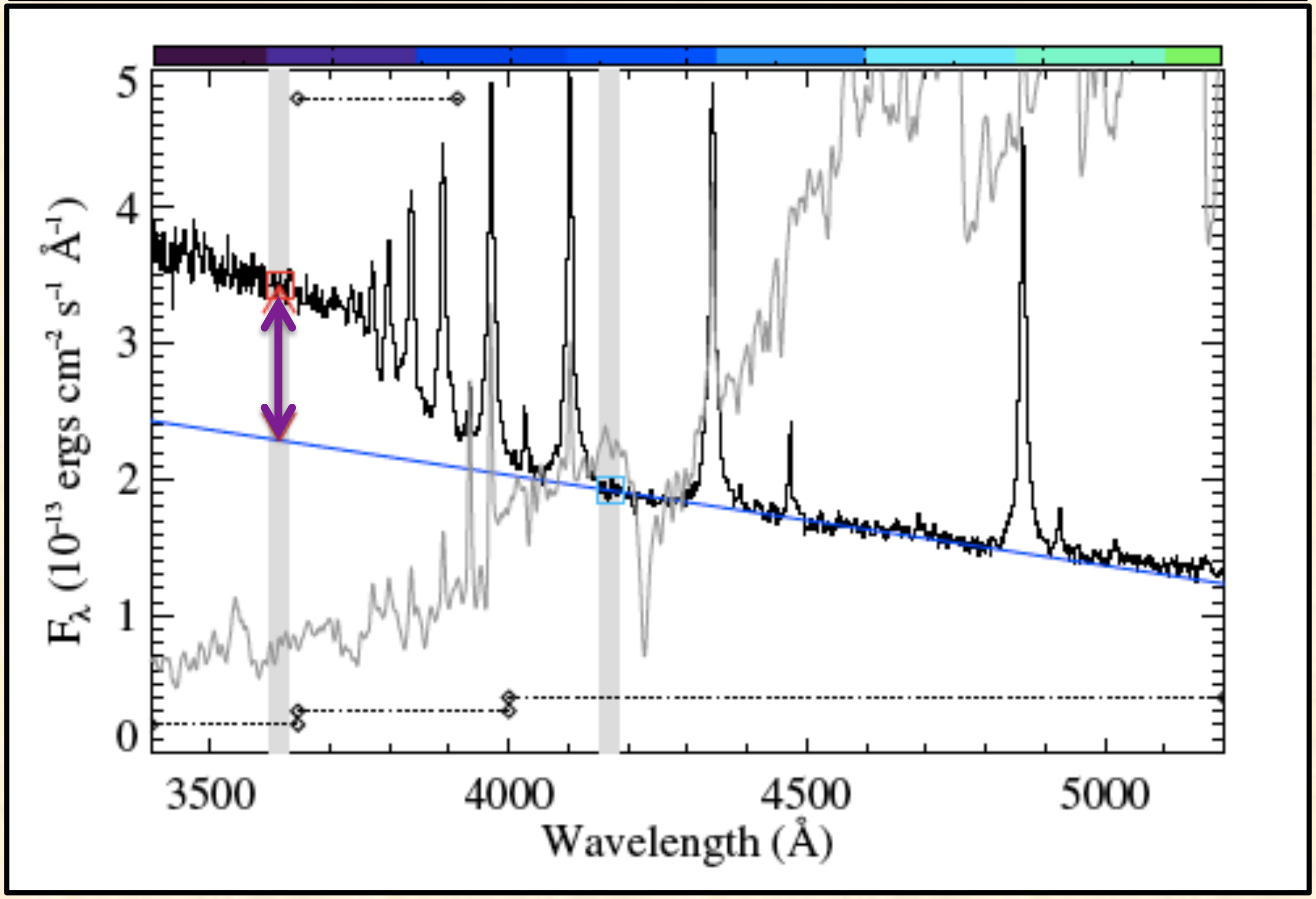


Measure importance of Balmer continuum relative to hot blue (blackbody-like) continuum using χ = flux(3615)/flux(4170)

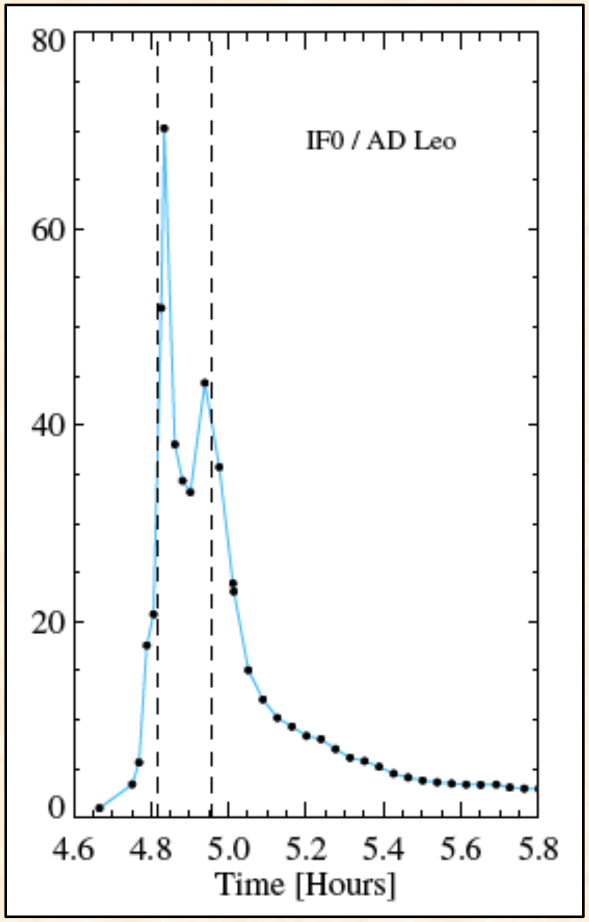
Impulsive flares have $\chi \sim$ 1-2, hotter T_{BB}

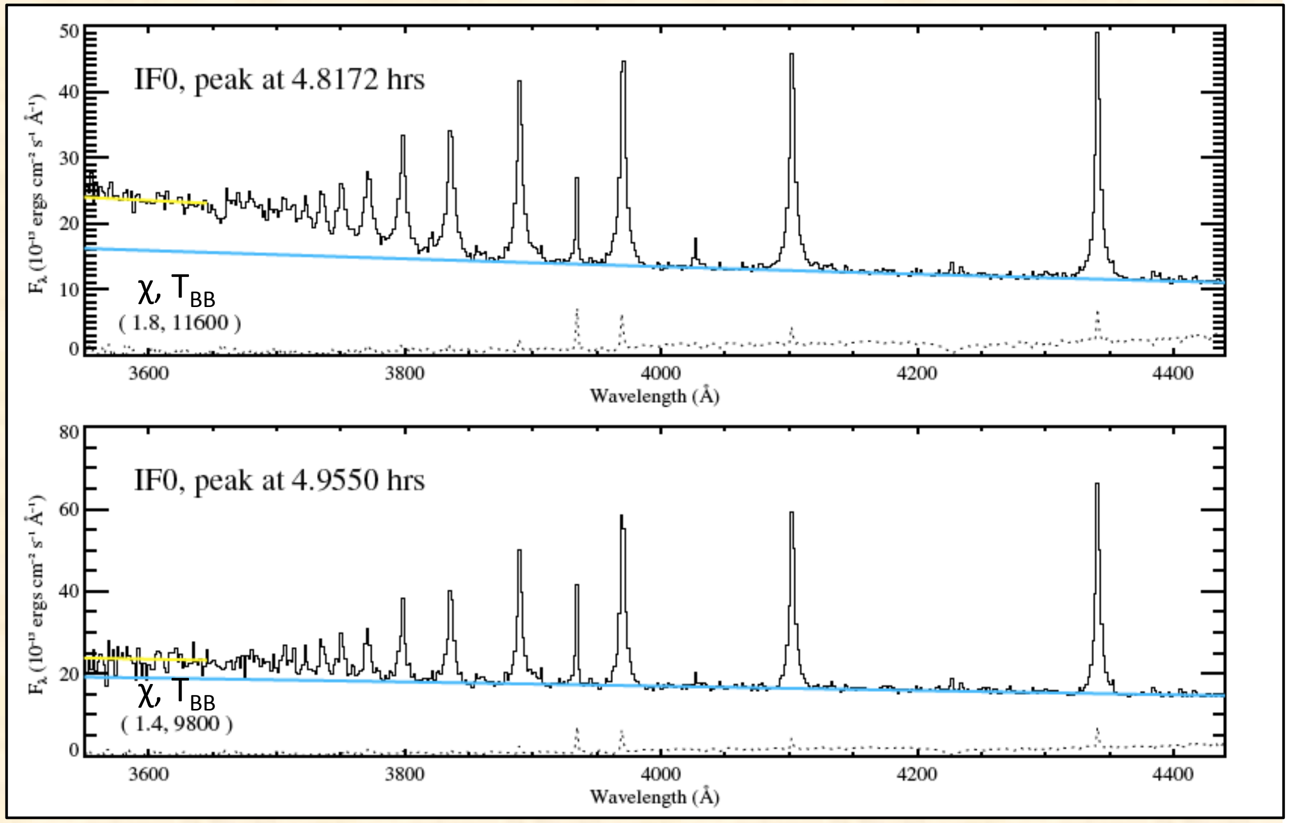
Hybrid flares have $\chi \sim$ 2-3, intermediate T_{BB}

Gradual flares have χ > 3, cooler T_{BB}



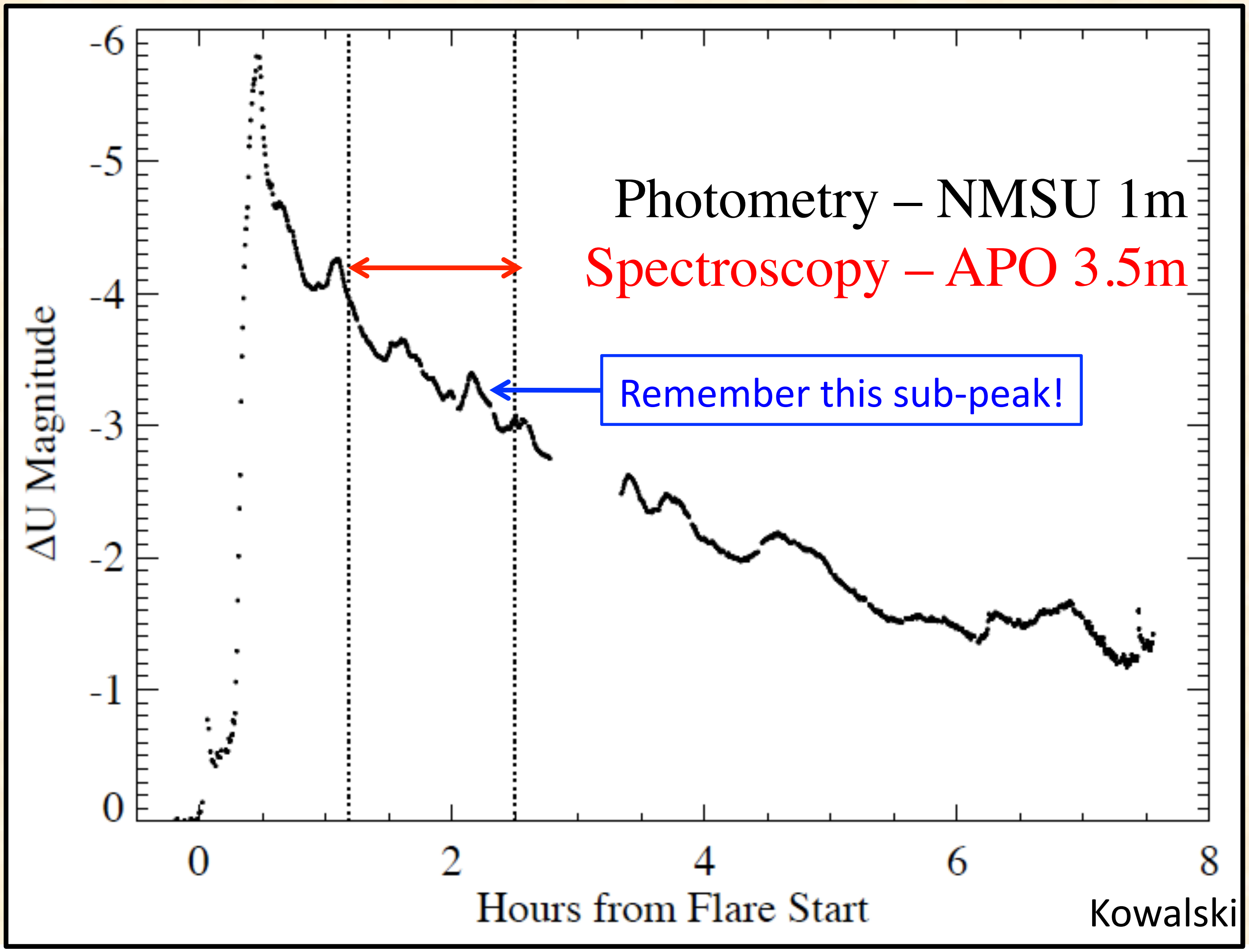
The Great Flare on AD Leo, revisited





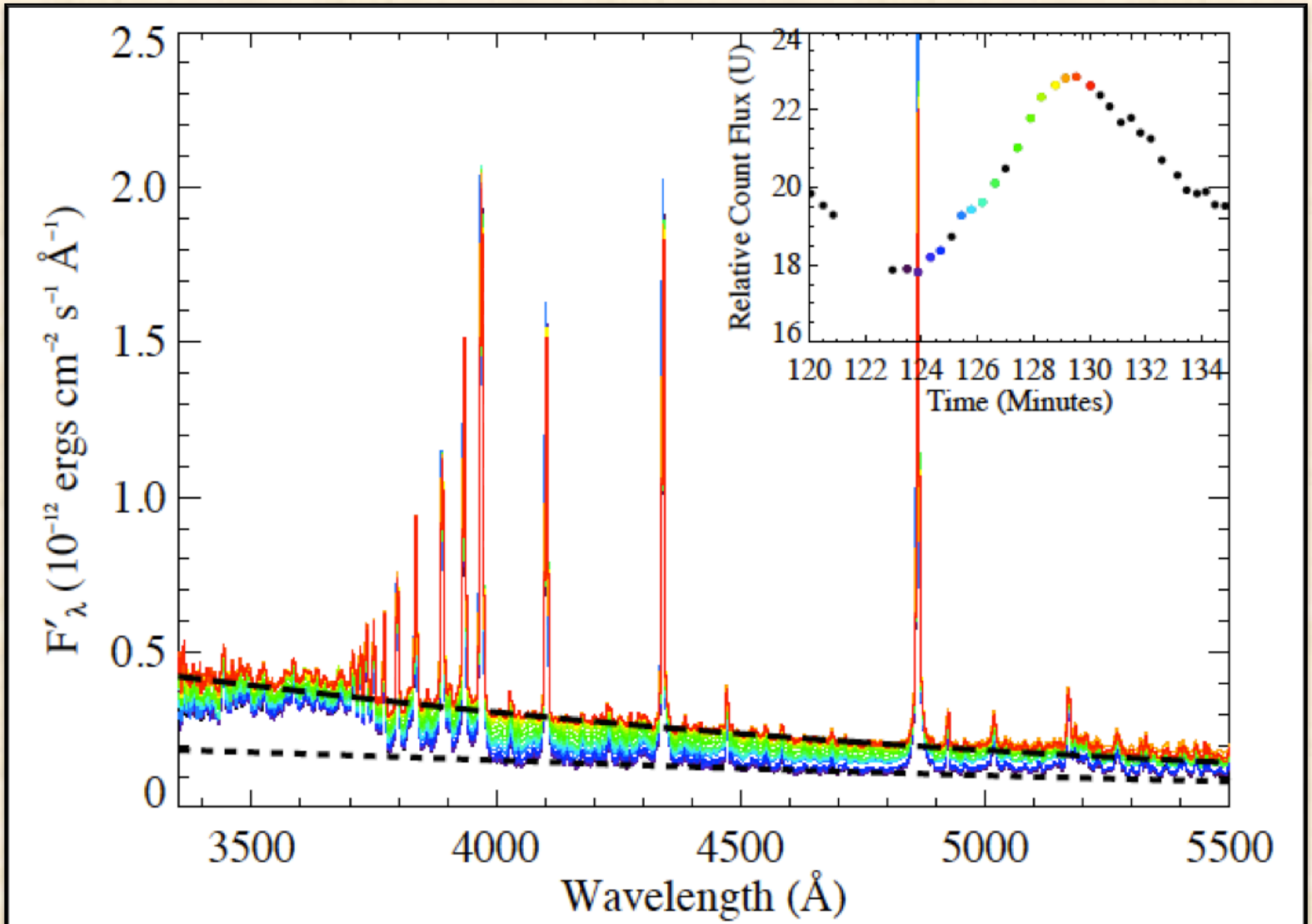
The Mega Flare of 16 Jan 2009 on YZ CMi (dM4.5e)

Notice: many sub-peaks during decay from main flare

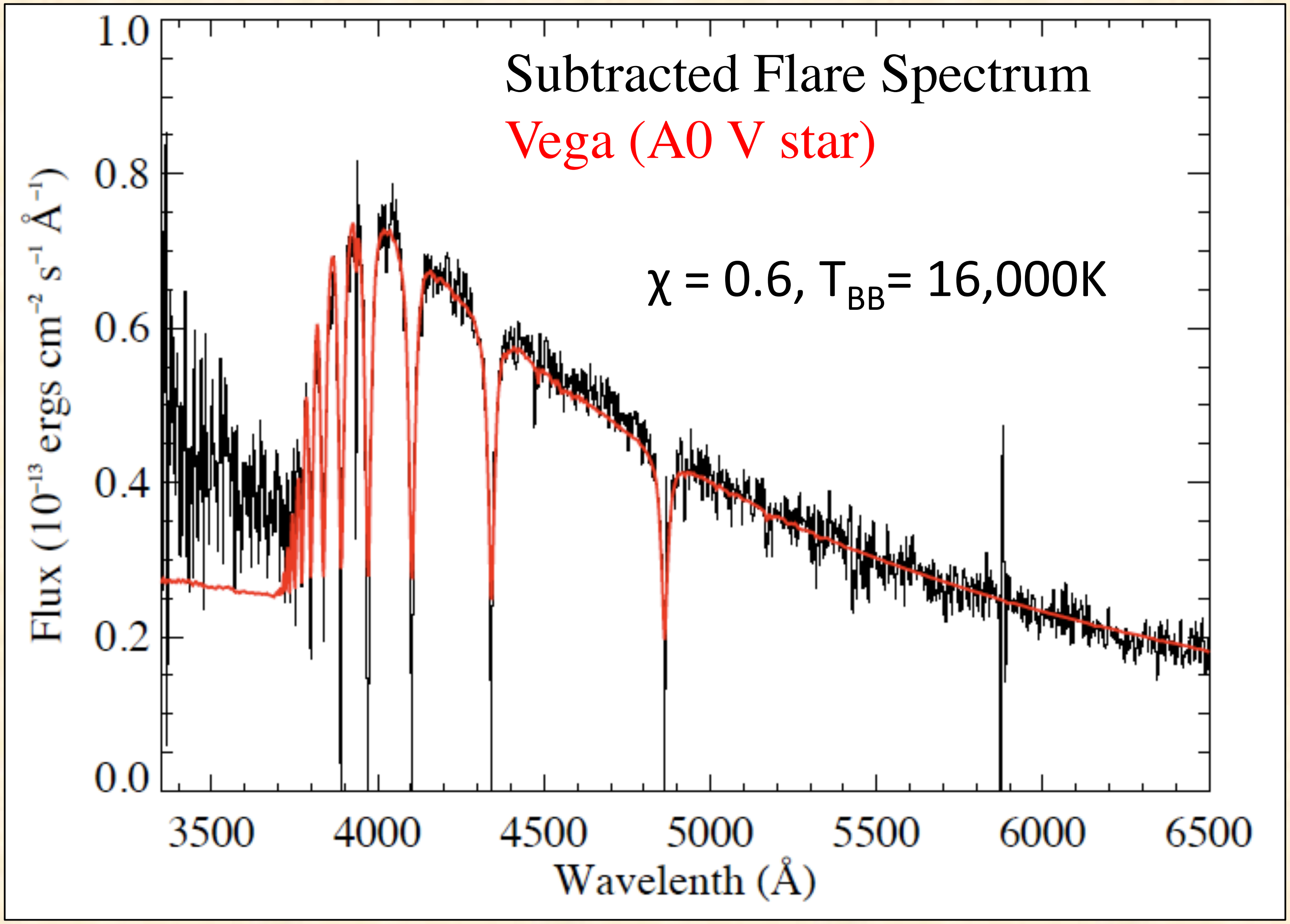


Kowalski et al (2010)

Shape of blue continuum changes during sub-peak

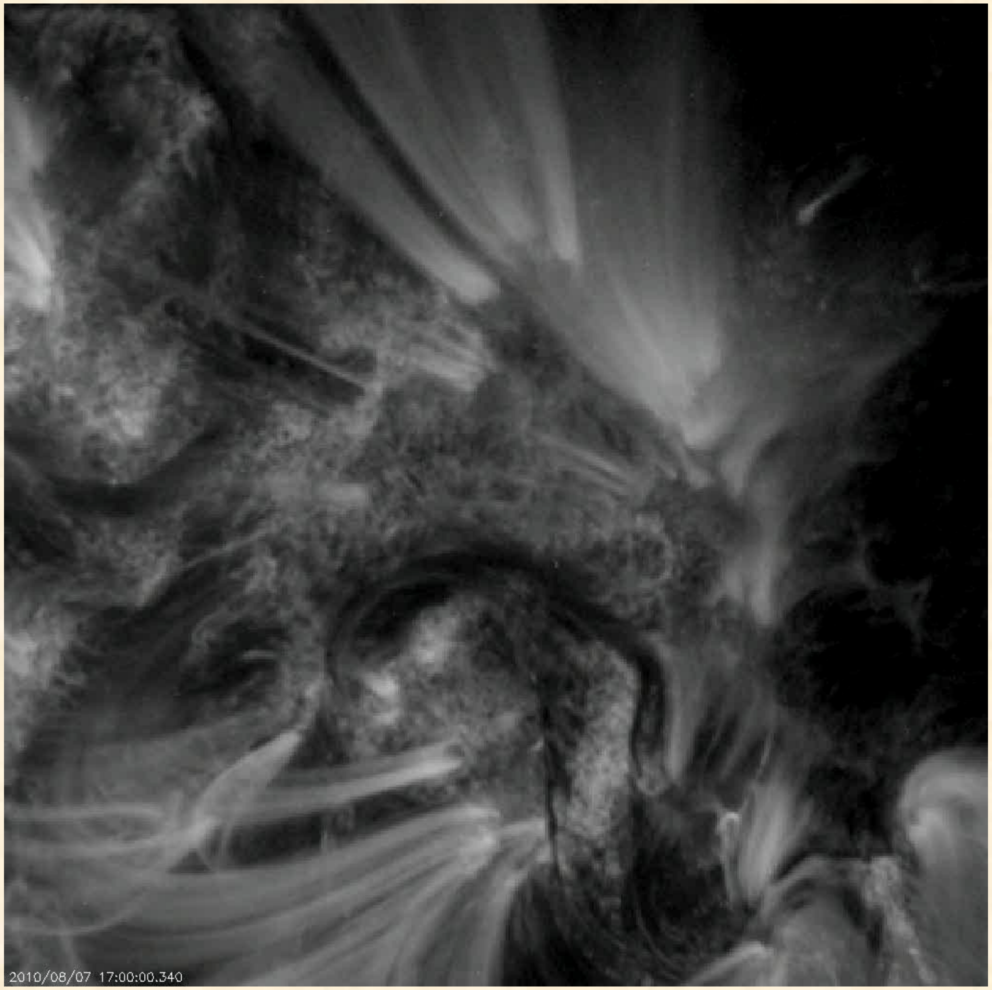


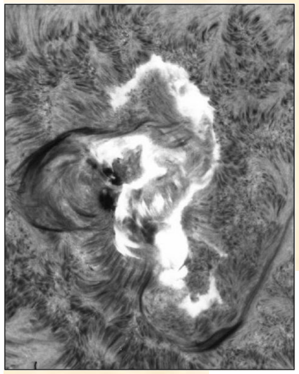
Newly formed flare emission looks like an A star!



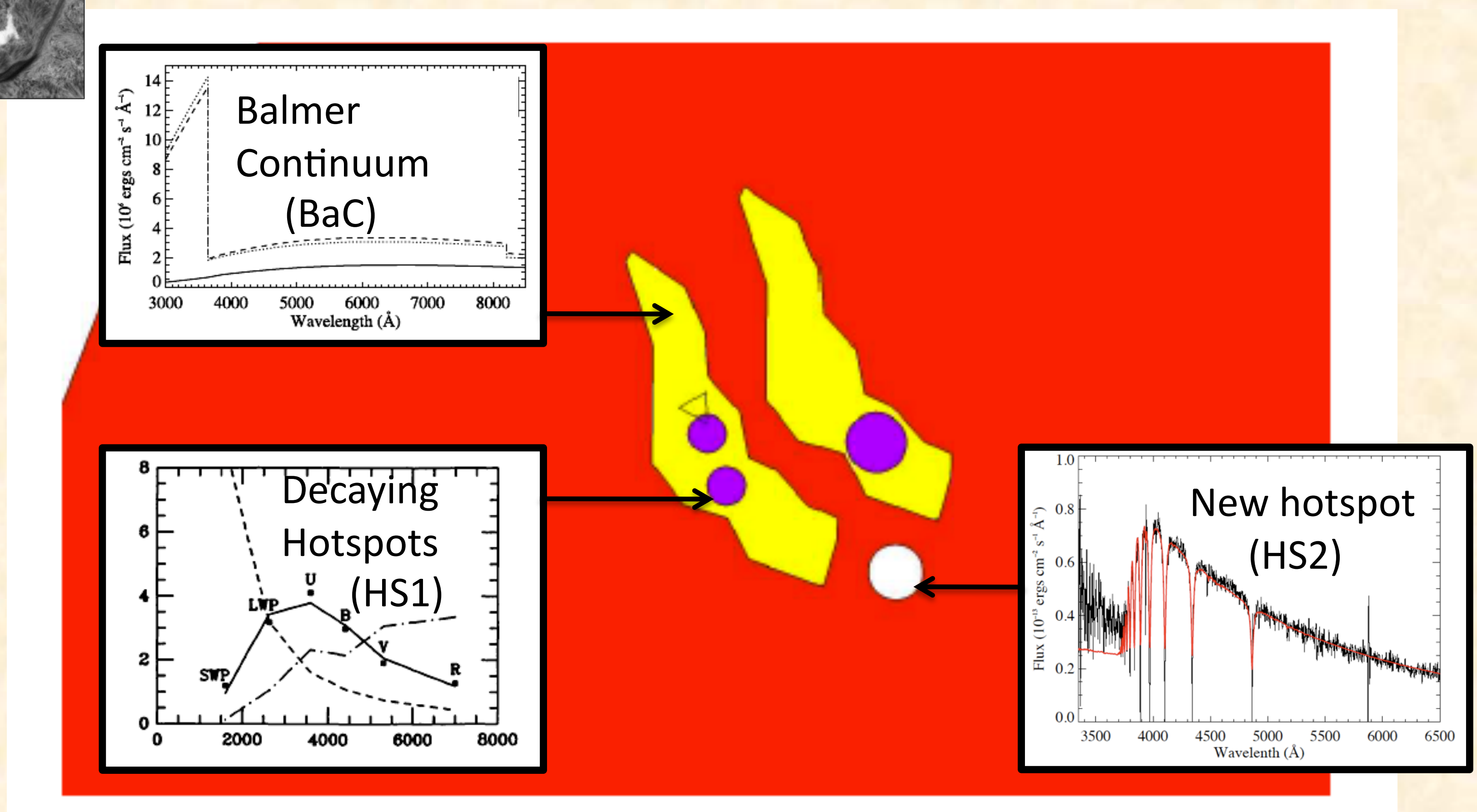
Kowalski et al 2010

Small solar flare (SDO 8/7/2010) shows 2-ribbon structure, loop footpoints





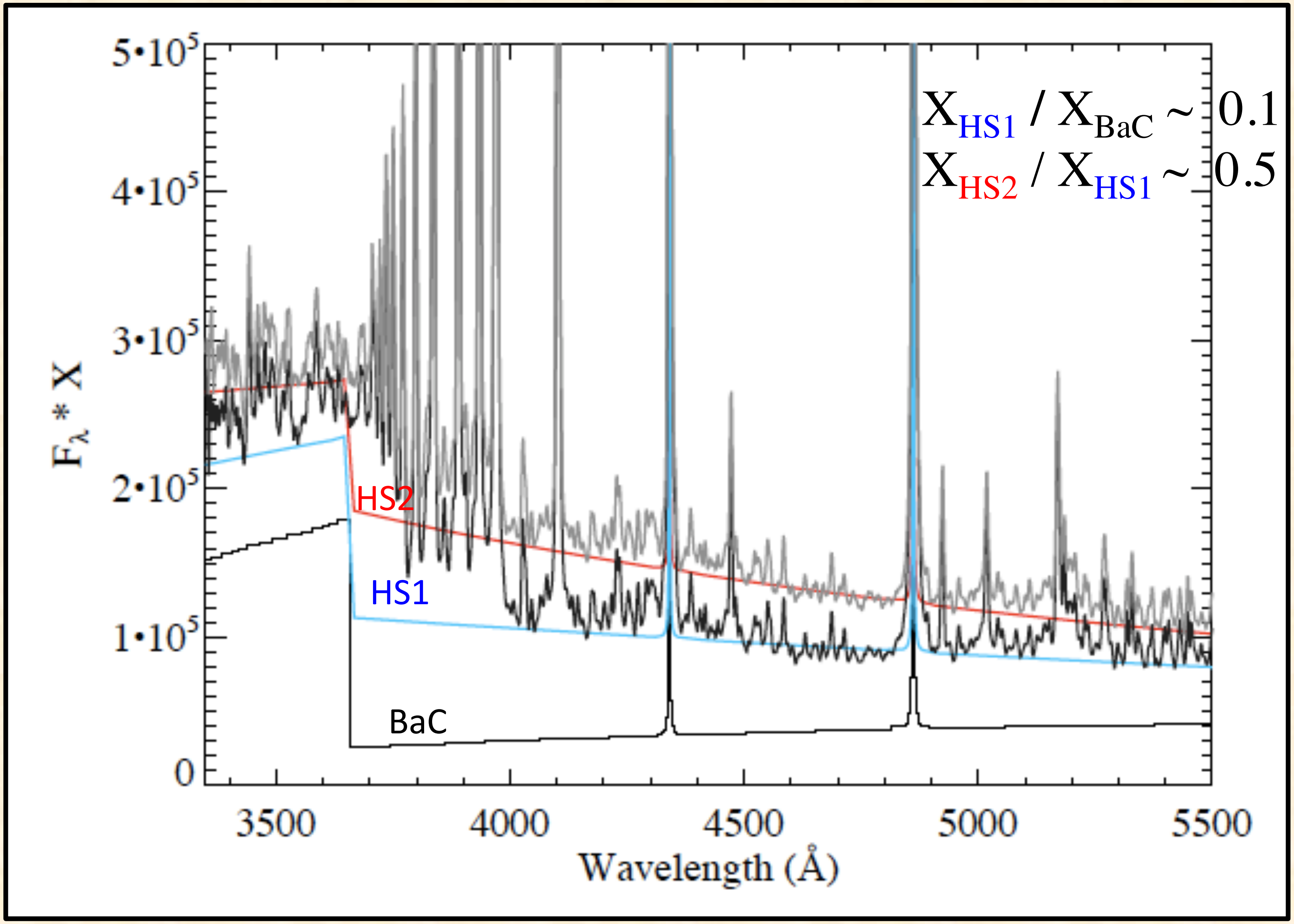
We adopt a similar model for a stellar flare



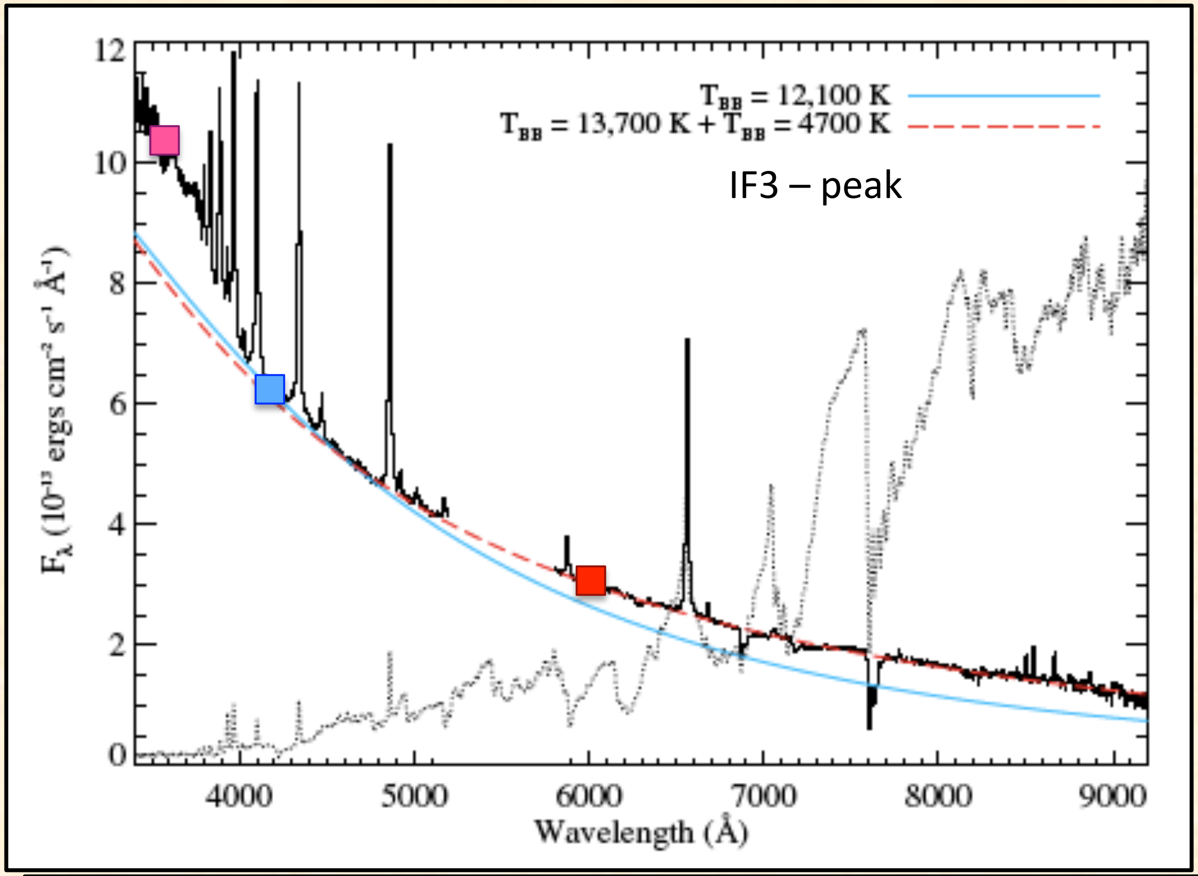
Kowalski et al 2012

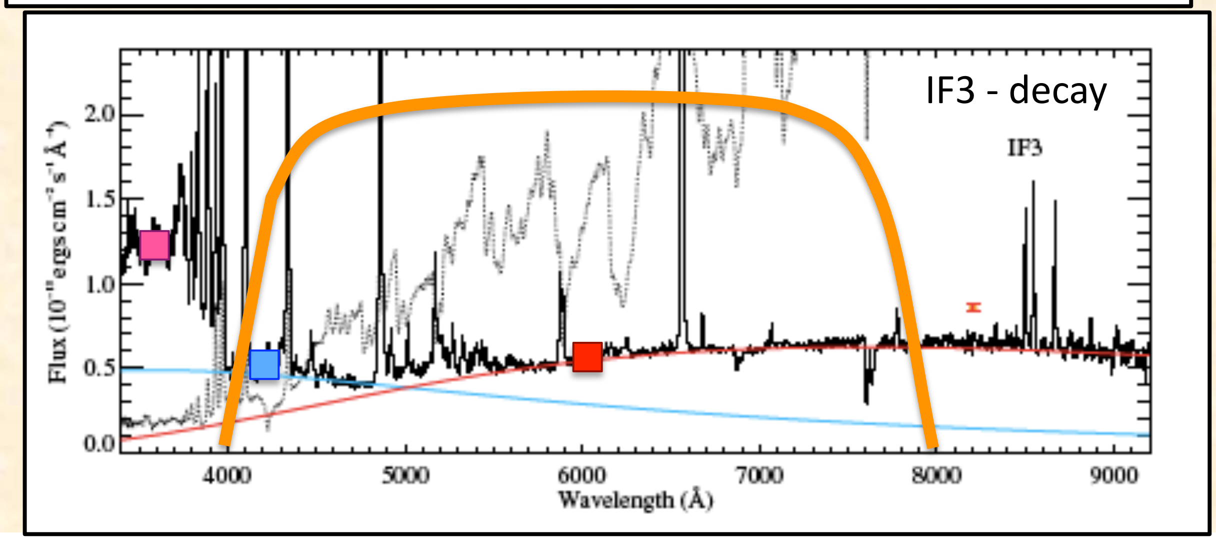
Reasonable area coverage of components matches flare spectra:

BC = Balmer continuum, HS1 = decaying hotspots, HS2 = new hotspot



Kowalski et al (2012)





But wait! There is also a red continuum component that gets stronger in the gradual decay phase.

Does this come from continued heating at late times? Or backwarming from hot overlying loops?

We can diagnose the strength of this component with an additional measurement of flux at 6000A (red box). Purple box is 3615A and blue box is 4170A as used before to measure χ.

Important for Kepler data!!

Information from spectroscopy of M dwarf flares

- White light continuum dominates flare energy
- Observe Balmer continuum, hot blue (blackbody-like) continuum and red continuum components – BaC and red continuum typically more important during later stages of evolution of a single flare.
- Different kinds of flares have different continuum contributions at peak: Impulsive flares (IF) have more and hotter blue (BB-like) emission, Hybrid and Gradual flares have relatively more Balmer continuum
- Following solar 2-ribbon flare analogy, can fit blue spectra (BaC, BB) with reasonable area coverage of older decaying components and new hotspots

Flare photometry with ULTRACAM*

(Kowalski, Mathioudakis, Hawley et al 2016 – K16)

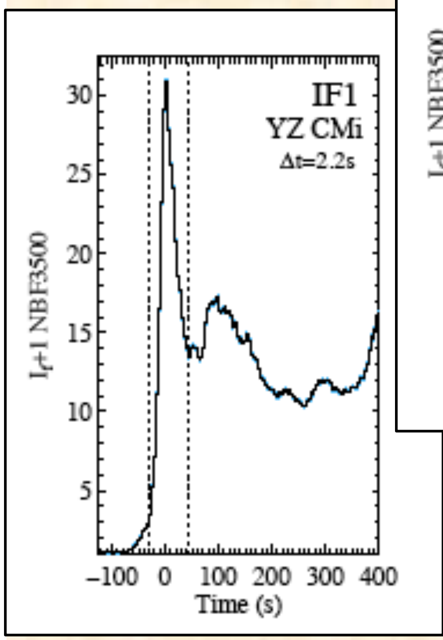
- 3-channel simultaneous photometry (2 dichroics)
- custom narrowband filters for flare observations:
  - 3500A (Balmer continuum)
  - 4170A (blue continuum)
  - 6010A (red continuum)
- very high cadence (1-2 sec), frame transfer (no gaps)
- Observing runs at WHT (La Palma, Spain) and NTT (La Silla, Chile)
- some simultaneous spectroscopic observations at APO and SALT
- note ROSA camera at Dunn Solar telescope has same filters and can take similar data on the Sun

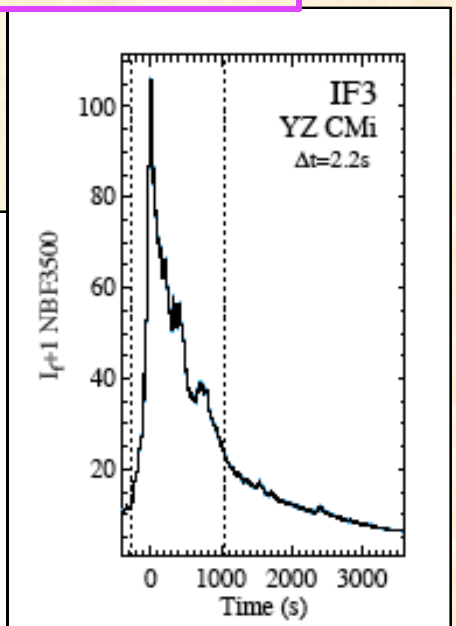
*ULTRACAM reference: Dhillon et al 2007

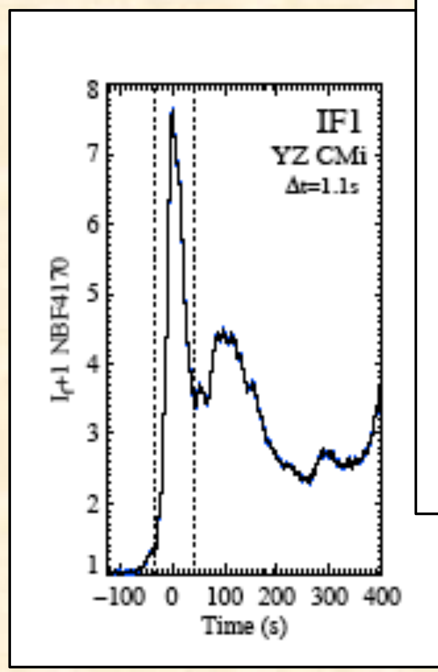
ULTRACAM light curves of flares on YZ CMi

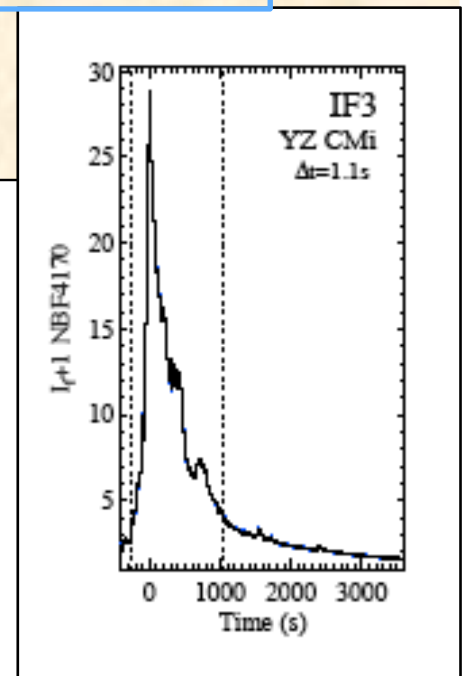
Balmer continuum filter 3500A,
Slower evolution, more flux
in decay phase

Blue continuum filter 4170A
Measures hot blackbody-like
emission, faster evolution,
less flux in decay phase





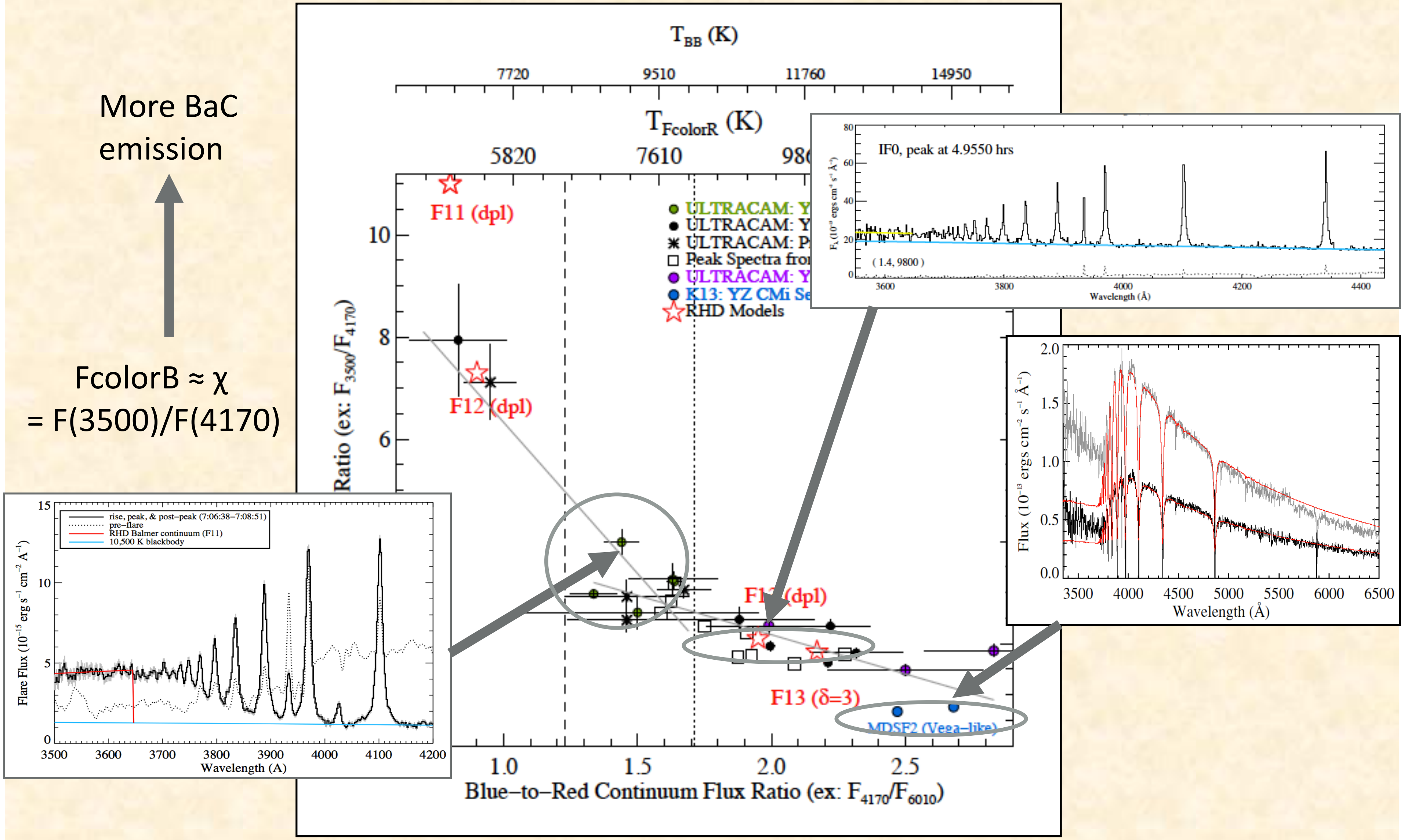




Flare Color-Color Diagram connects photometry to spectra

More BaC emission

FcolorB ≈ χ
= F(3500)/F(4170)

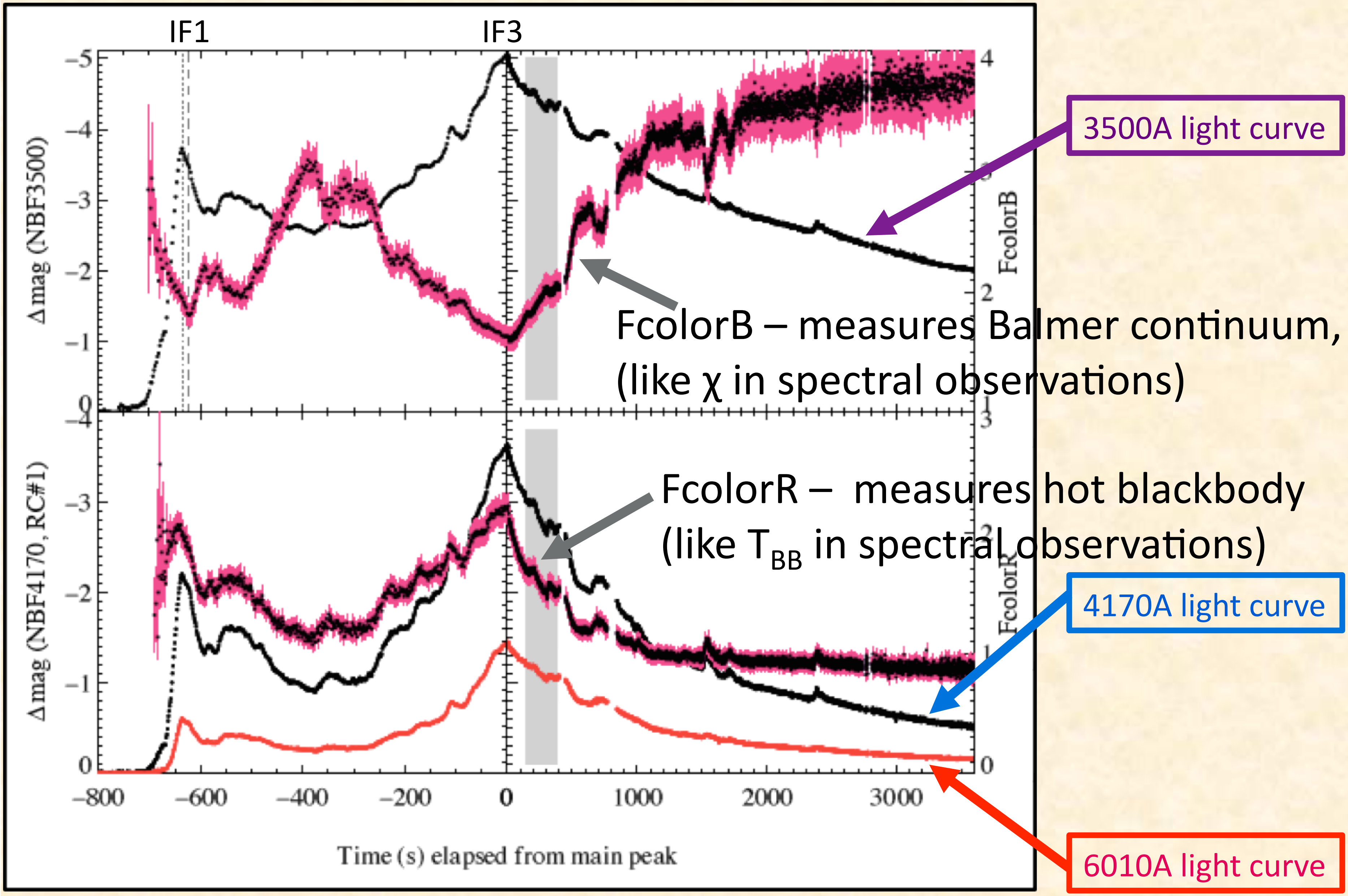


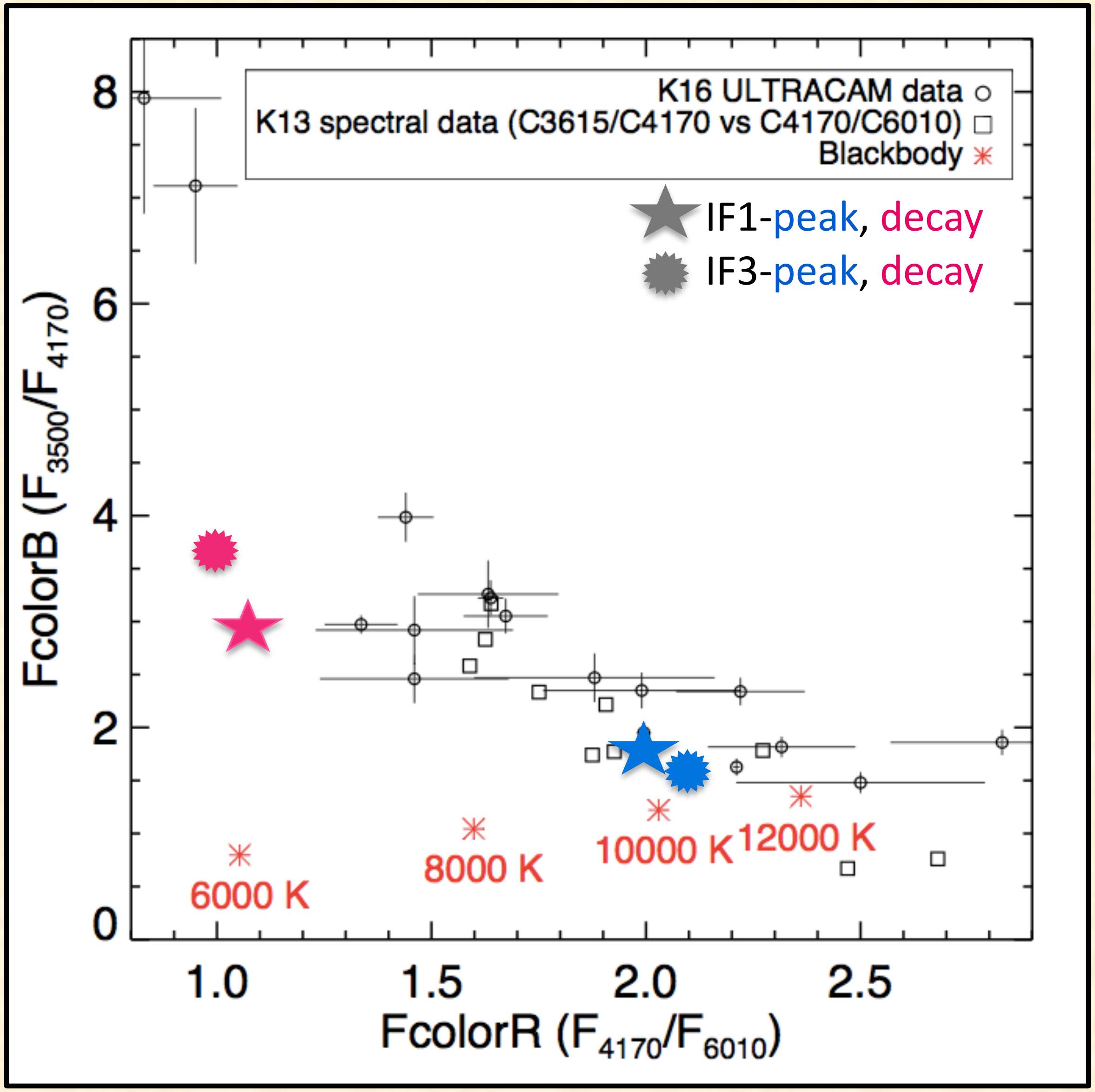
FcolorR = F(4170)/F(6010)

More blue continuum (BB-like) emission

Kowalski, Mathioudakis, Hawley et al.
2016 ApJ

Evolution of flare colors during IF1 and IF3 flares on YZ CMi





More BaC emission

More blue continuum (BB-like) emission

Outstanding Problems from M-dwarf Stellar Flare Observations

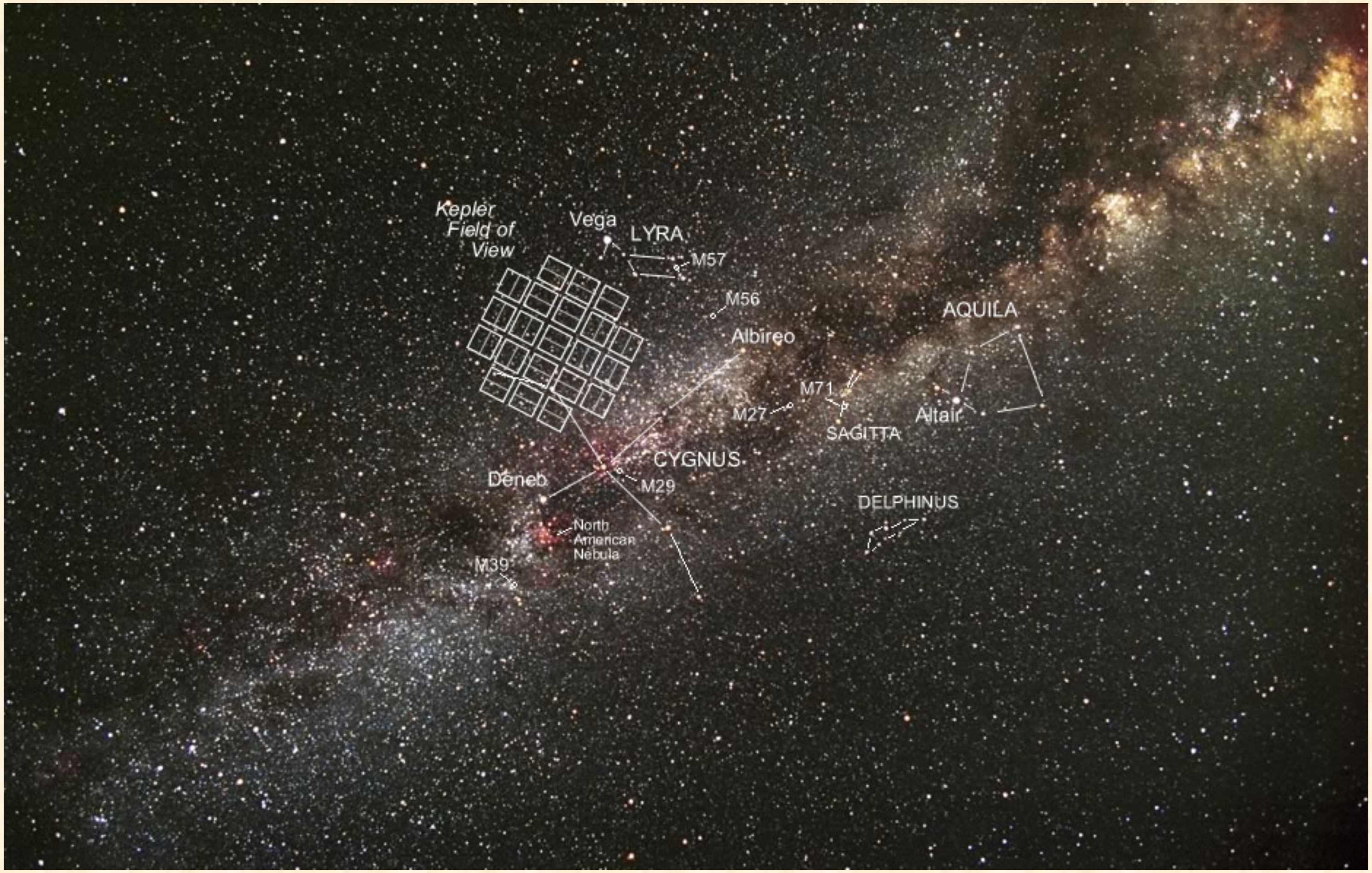
1. How do flare heating mechanisms generate Balmer continuum, hot blue (BB-like) continuum, and (for large flares with strong decay phase) cooler red continuum radiation during different stages of flare evolution? (next talk addresses new flare models!)
2. Is all the continuum radiation coming from the same spatial region?
3. How does the area coverage of the different flare continuum components evolve?
4. Does the Sun show these same continuum properties?
5. Do superflares on solar-type stars show these same continuum properties?

More to learn from stars: Kepler satellite!

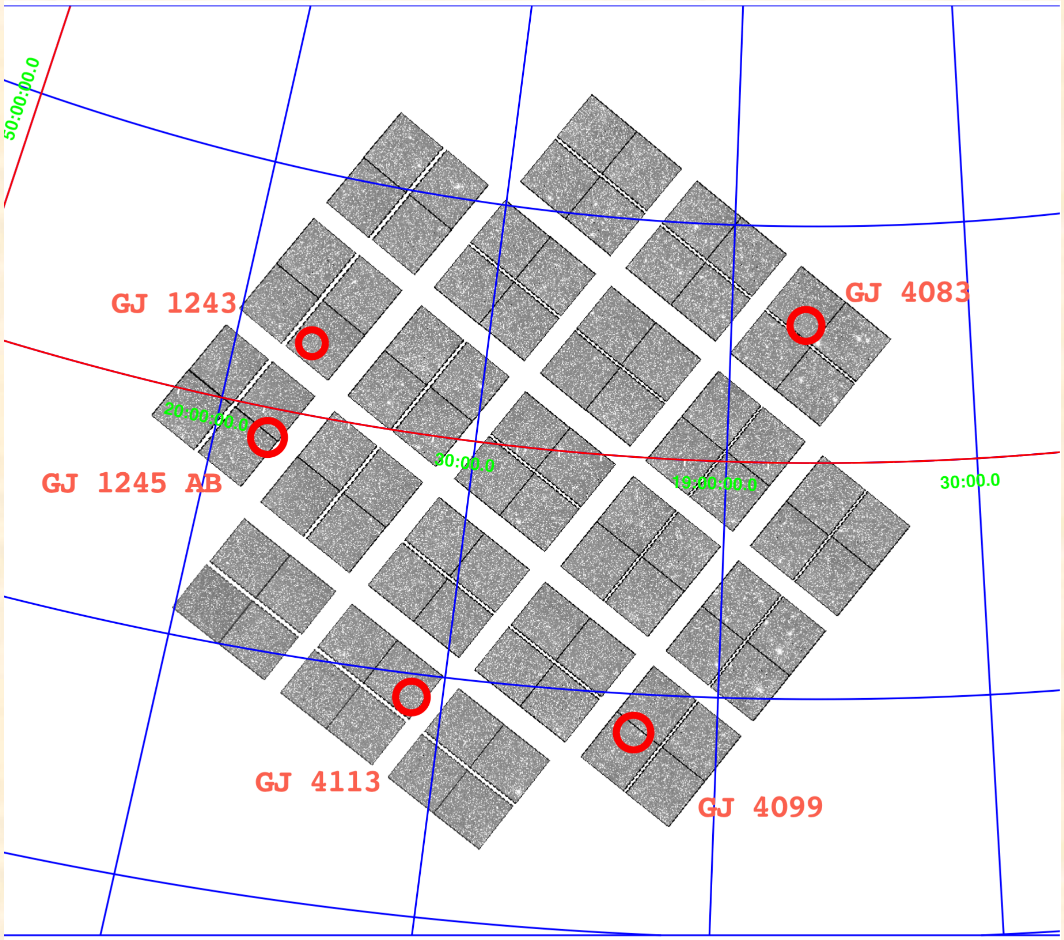
- Observed 150,000 stars in 100 sq degree field in Cygnus/Lyra
- Photometry with 1 or 30 minute cadence for months/years, superb precision (few x 10^{-6})
- Great for observing flares! Also starspots, pulsations, binary stars, (planets)
- 30 min cadence data has been examined by Walkowicz et al (2011) – GKM dwarfs; Maehara, Shibayama, Notsu, Nogami, Shibata (and many others from Japanese superflare group) – G dwarfs, superflares (also now short cadence data)
- GO programs for 1 minute cadence data on active and inactive M dwarfs, goals to determine flare frequency distributions, energies, timing of flares, correlation with starspots, etc.

→ properties of flares as an ensemble

Kepler field of view (between Cygnus and Lyra)



M dwarfs in our flare program



Active

GJ 1243 – dM4e

GJ 1245AB – 2 x dM5.5e

Inactive

GJ 4083 – dM3.5

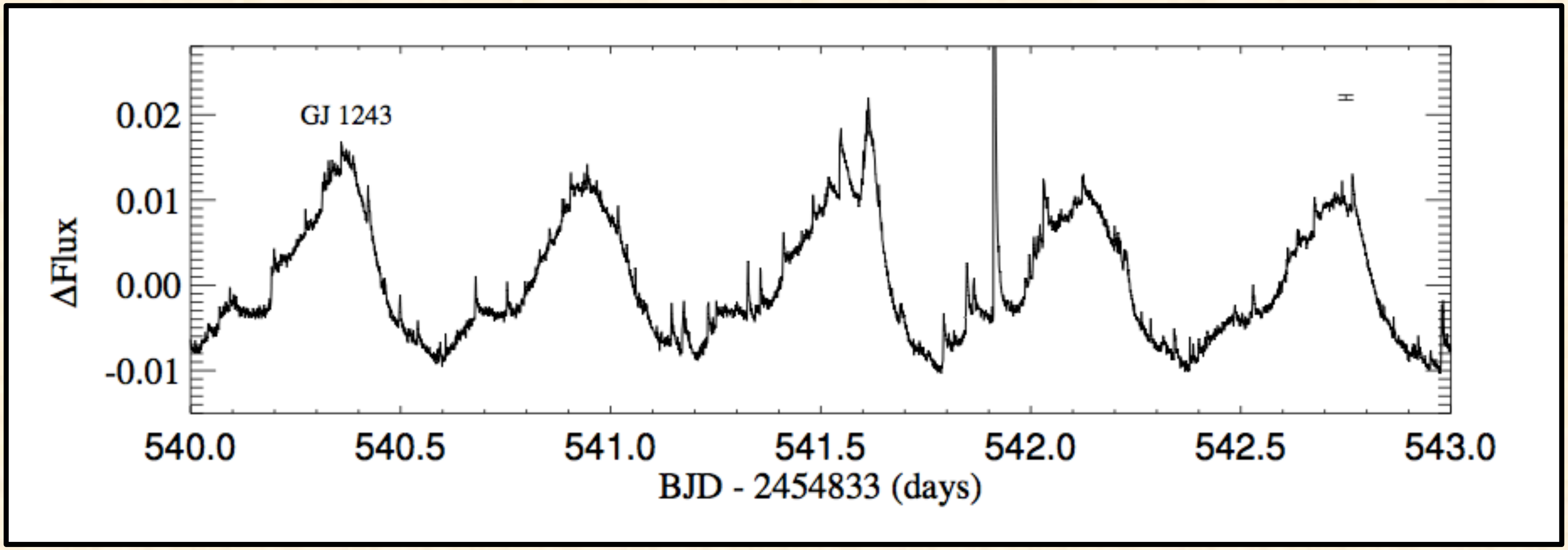
GJ 4099 – dM1

GJ 4113 – dM1.5

GJ 1243 – dM4e, similar to AD Leo, YZ CMi

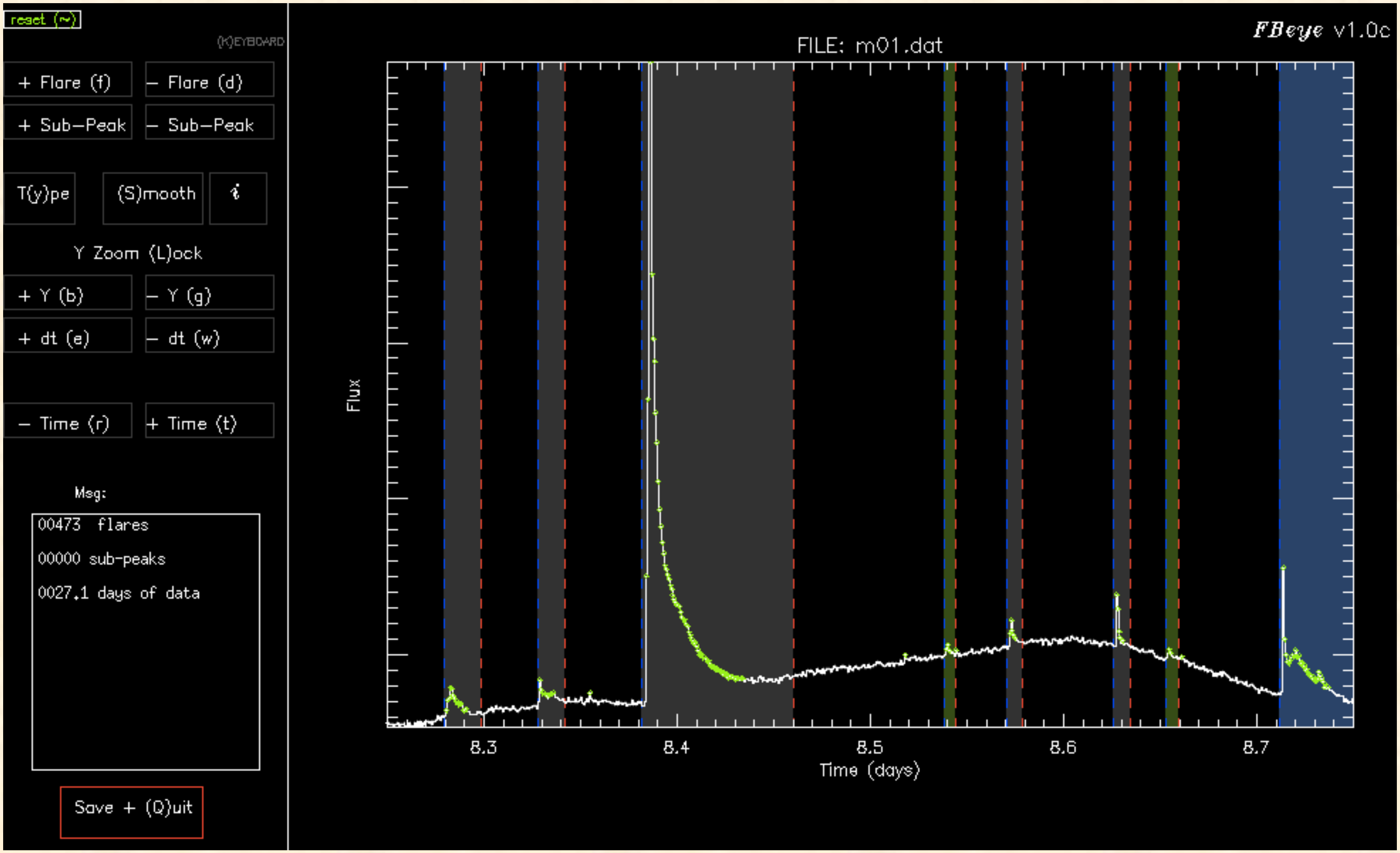
-- Many, many, many flares (>1000 in 2 months!)

-- Periodic (0.59 day, 3%) stable variation due to starspots



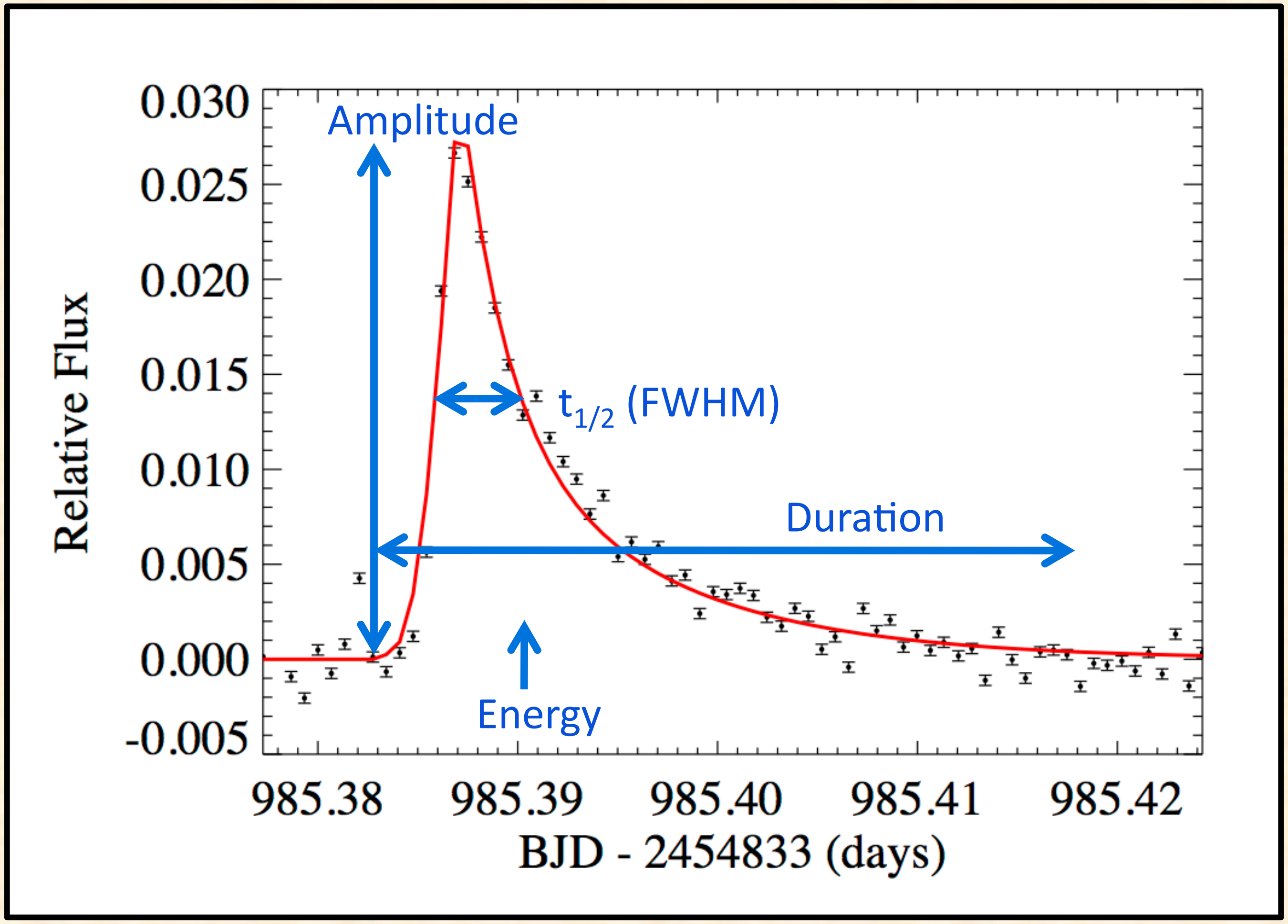
Finding Flares – FBEye

automatic flare identification (IDL, on github)



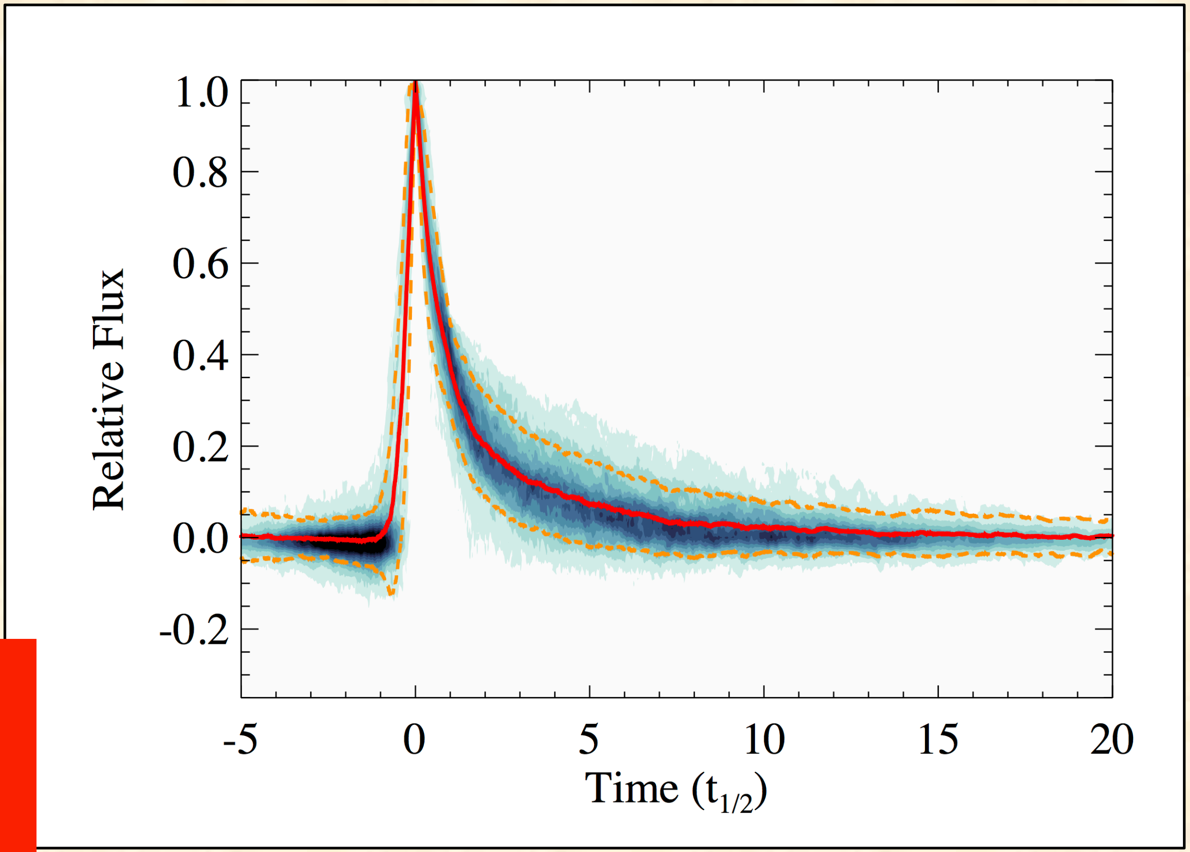
Davenport et al (2014a)

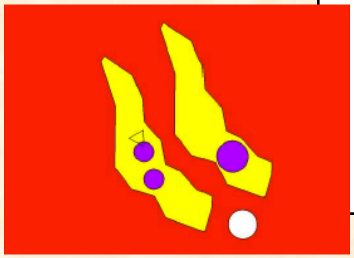
Classical light curve



Flare Light Curve Morphology

light curve model based on superposition of ~900 good S/N classical flares, 11 months of GJ 1243 SC data, scaled by amplitude and $t_{1/2}$



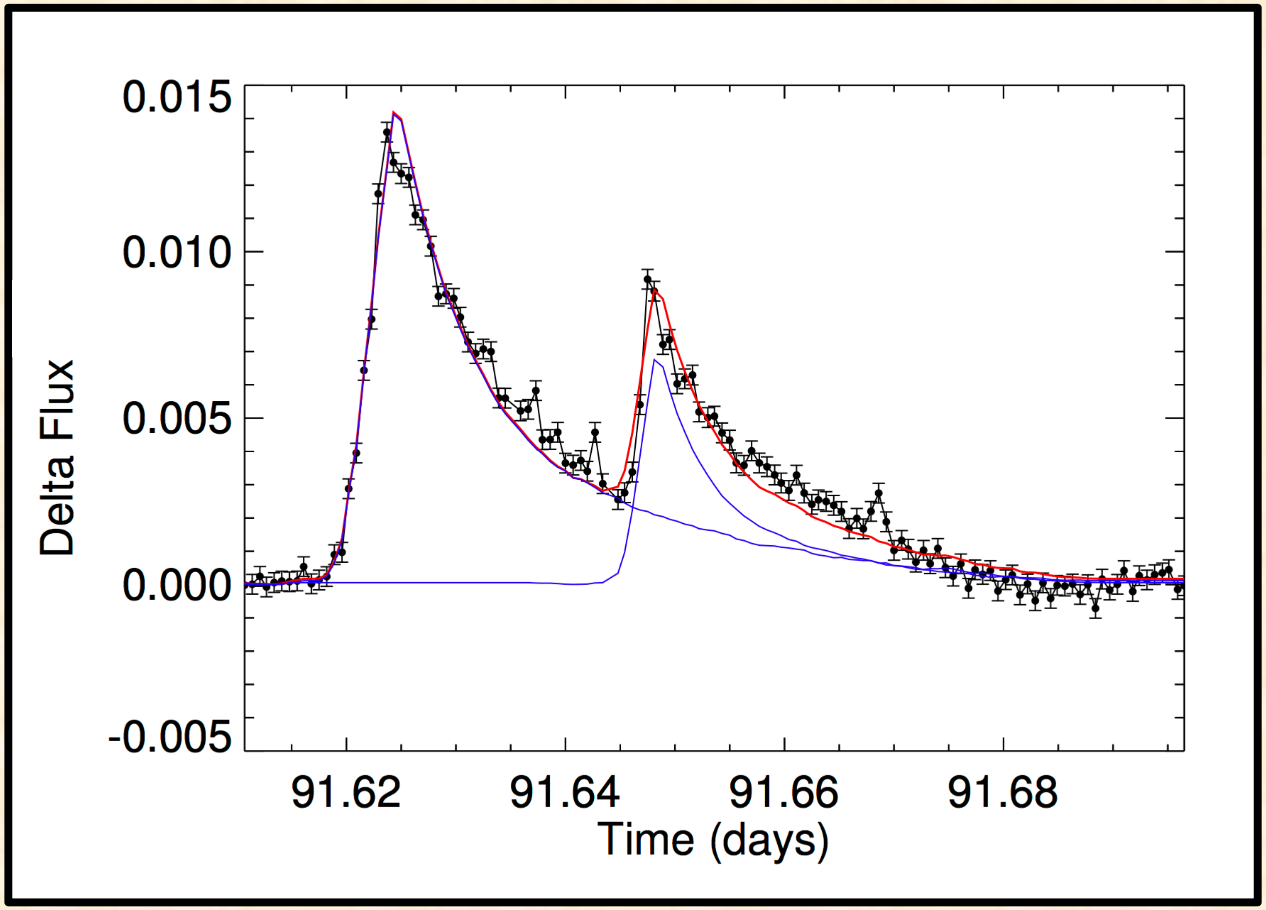


Possible connection to spectroscopic hot spot model: rise = adding new hotspots, beam heating; fast decay = decaying hotspots; slow decay = BaC/red continuum from flare ribbons
Need models to confirm!

Davenport et al (2014a)

Complex Flares

(more than one peak before returning to quiet flux)

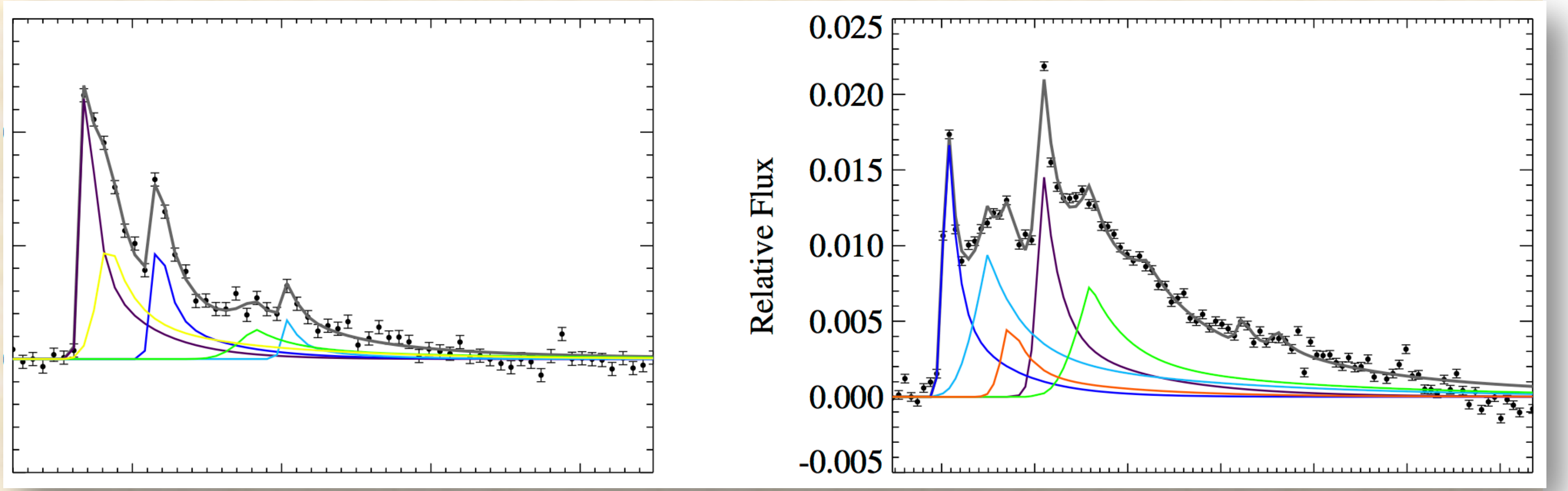


Often well fit by combining classical light curves

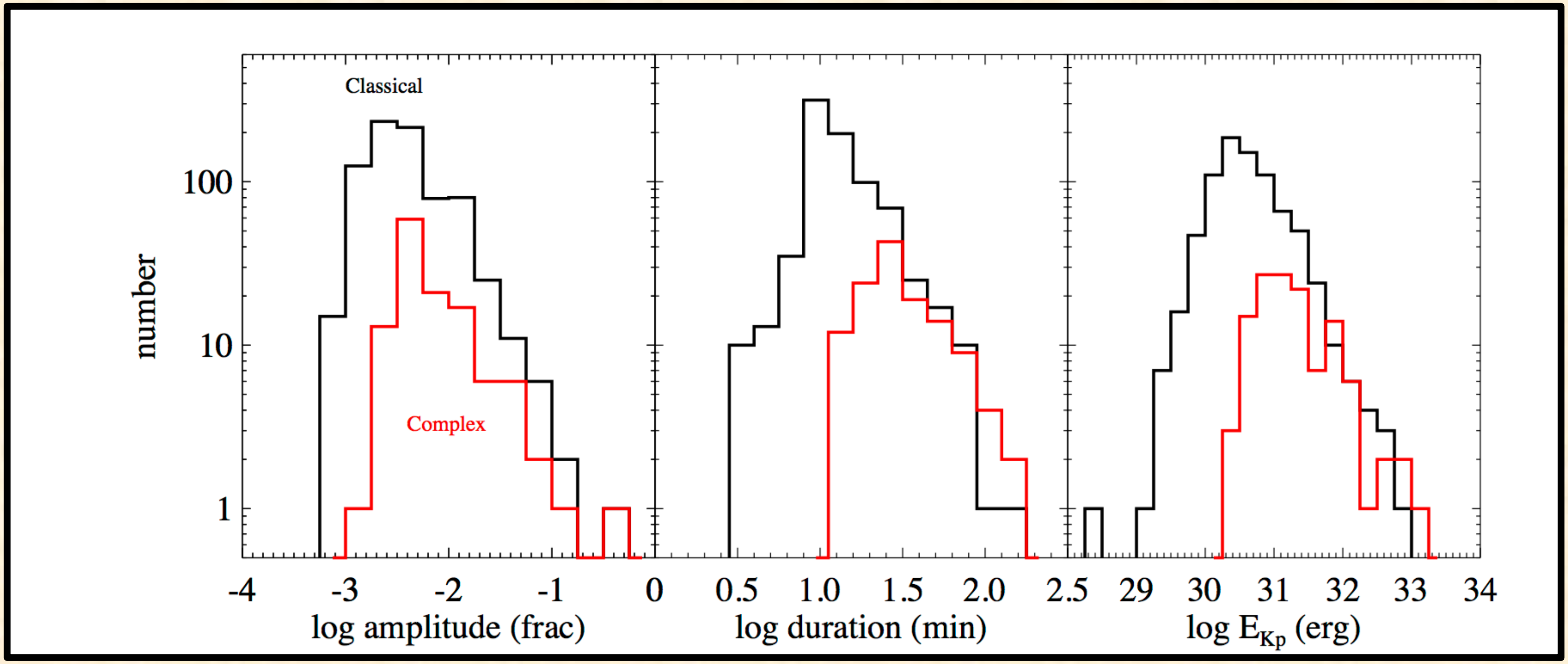
Complex Flares

Well fit even for quite complicated light curves!

Does this indicate triggering of secondary flares in same active region? (QPP? Nakariakov et al)

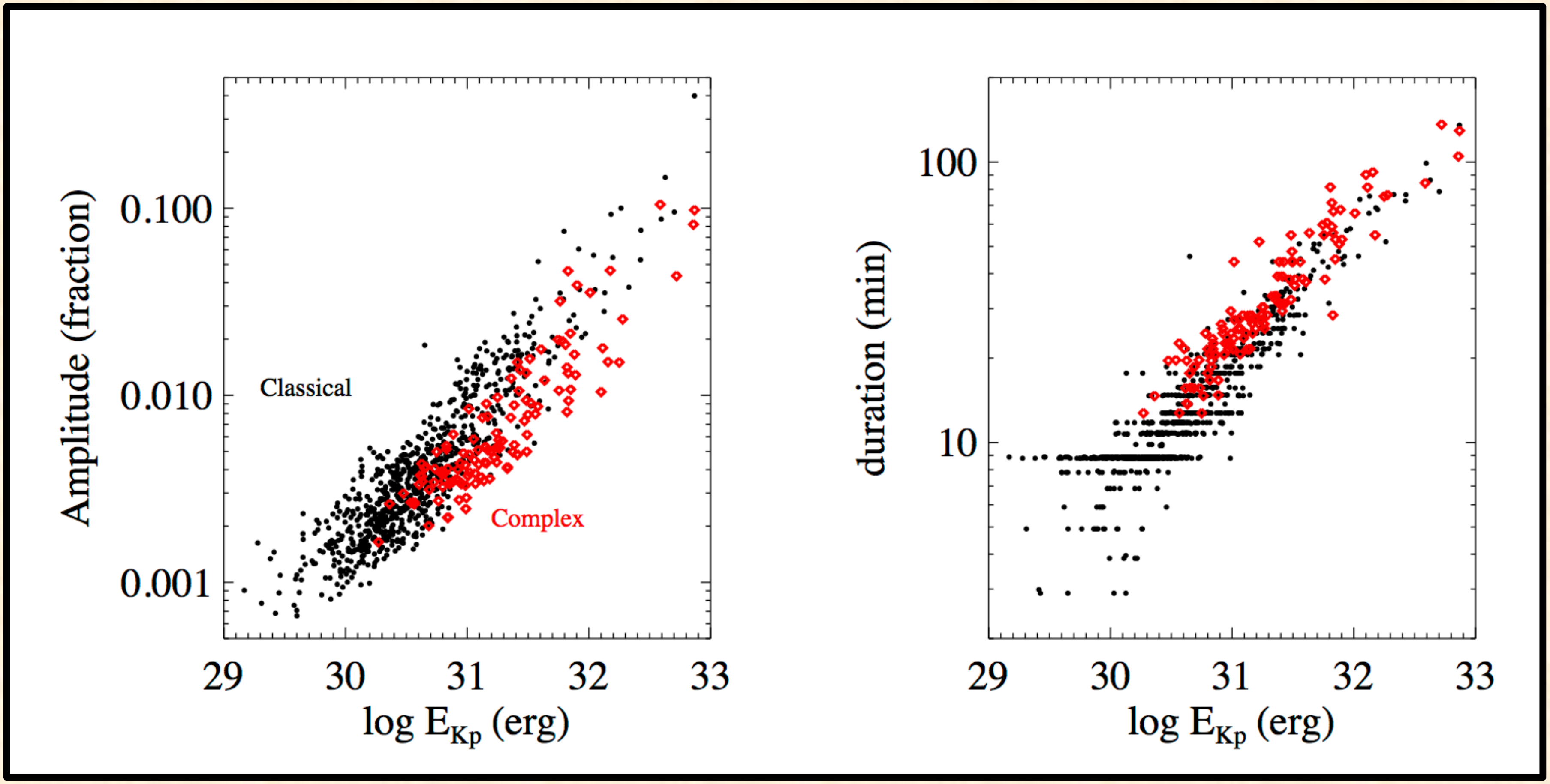


Properties of GJ 1243 flares



Hawley et al 2014

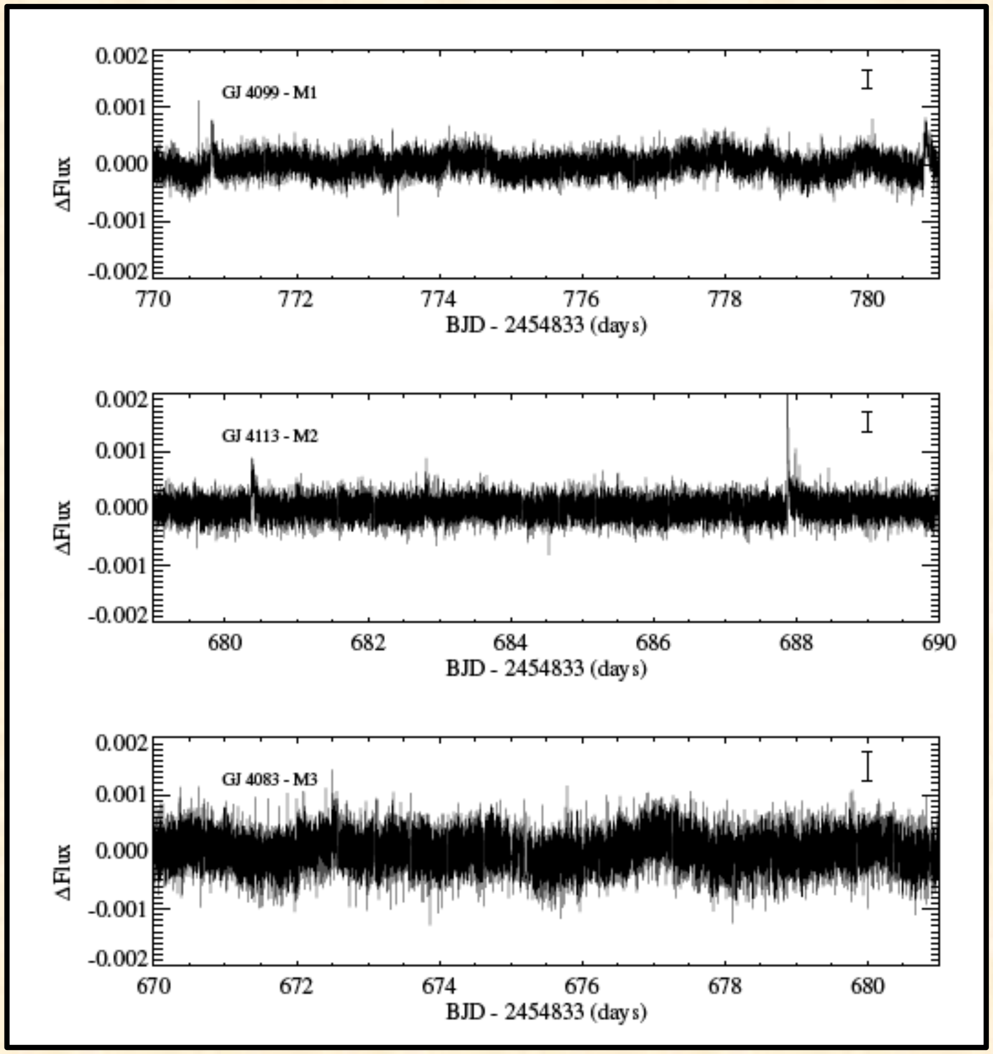
Aggregate flare properties



Higher energy flares have larger amplitudes and longer duration.
Complex flares have longer durations and higher energies at same amplitude

Light curves of inactive M dwarfs
no or tiny spots at few x 0.01% level
still some flares!

No spots!



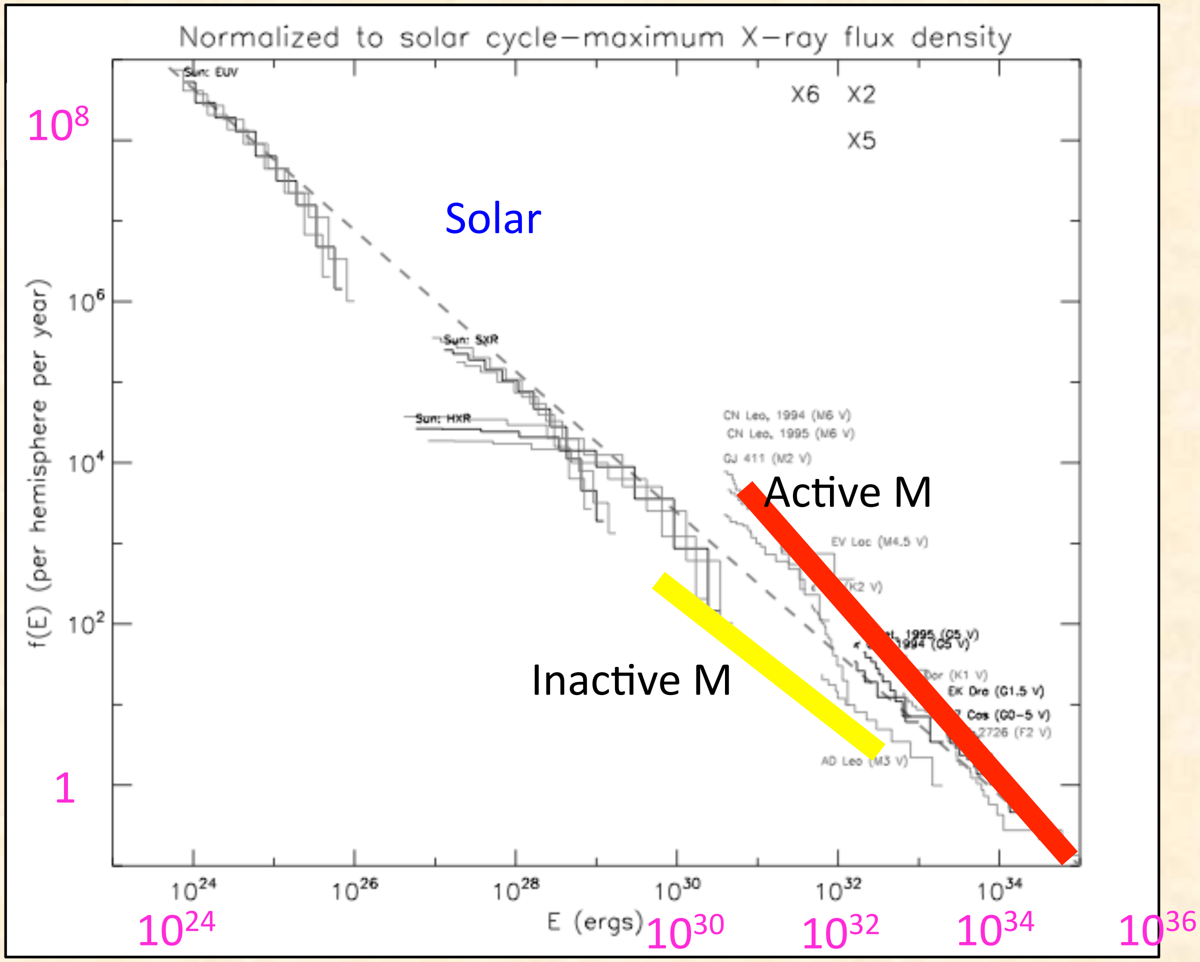
Flares can be >10^{32} ergs, similar to medium-large flares on GJ 1243 and stronger than solar flares!

Solar/stellar flare frequencies (Schrijver 2012)

more

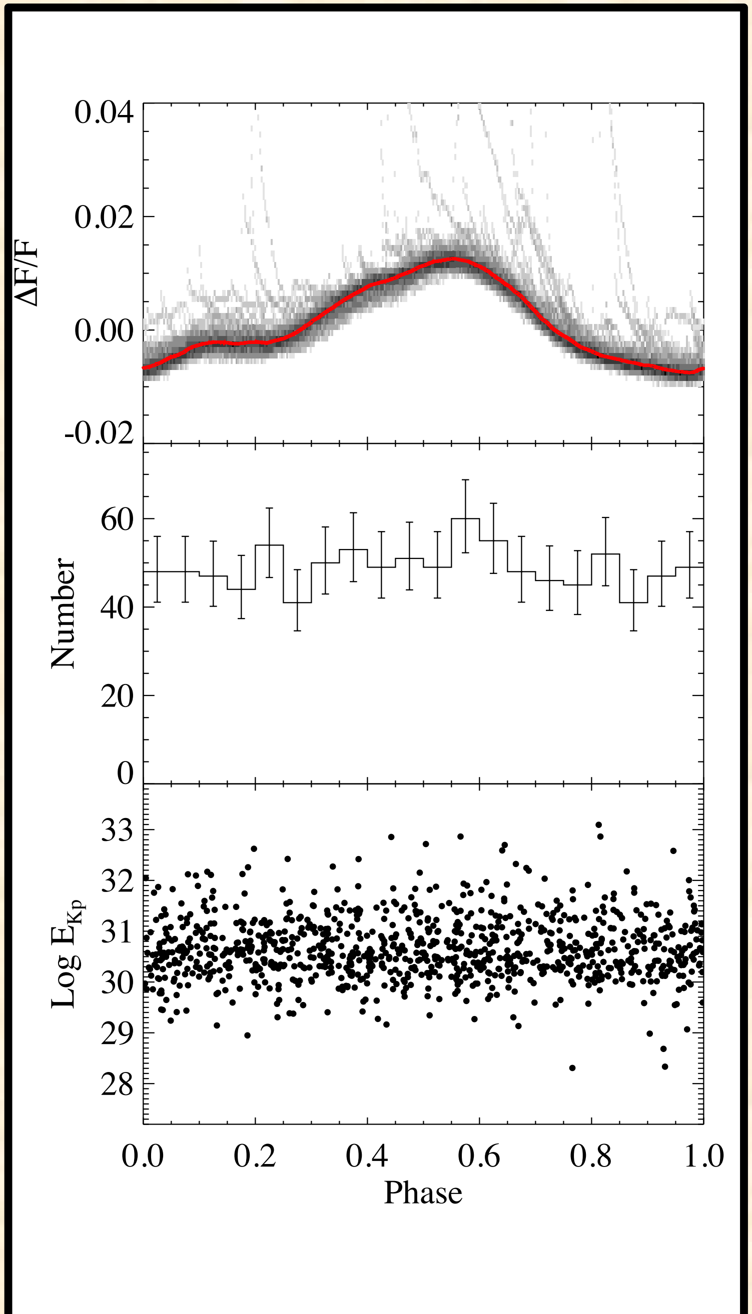
Flare
Frequency
(#/yr)

less



Flare energy (ergs)

Examining correlation between flares and starspots



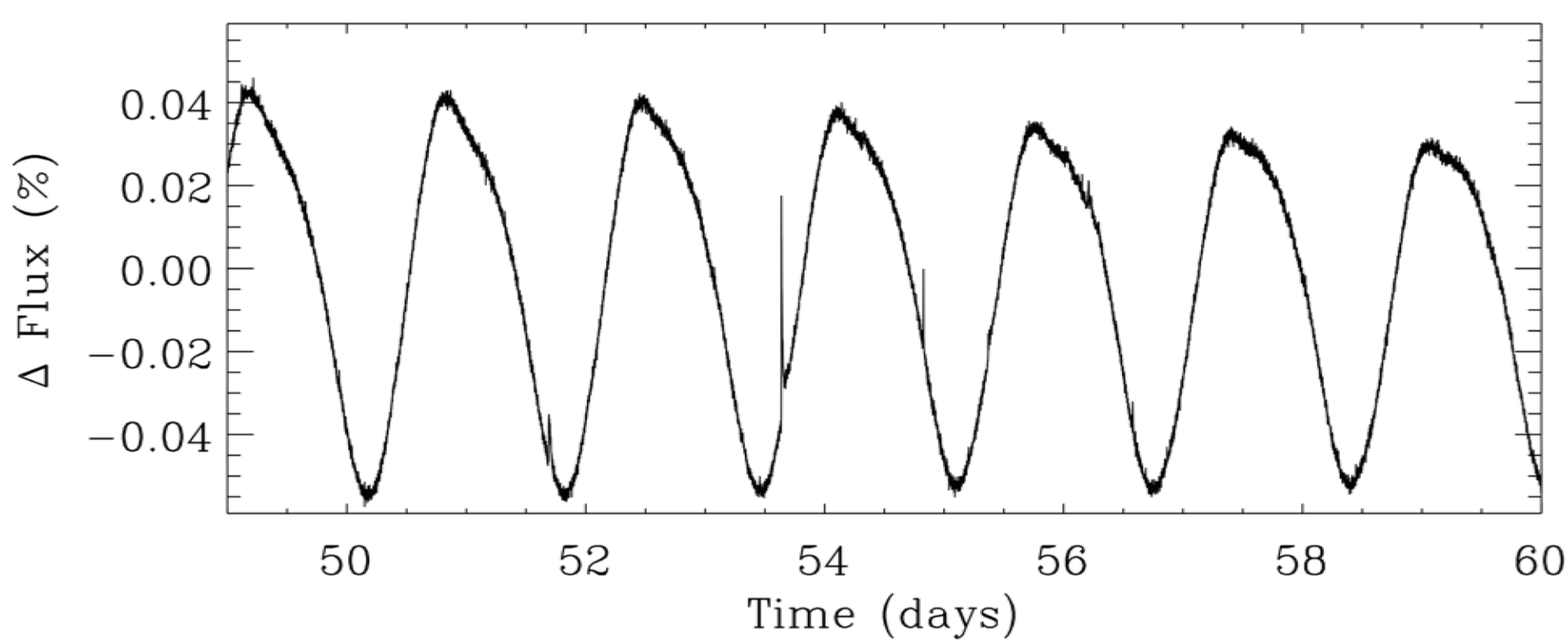
- GJ 1243 light curve folded on 0.59 day period

- Flare frequency and energy do not correlate with phase of starspot

- Flares not spatially associated with starspot?!

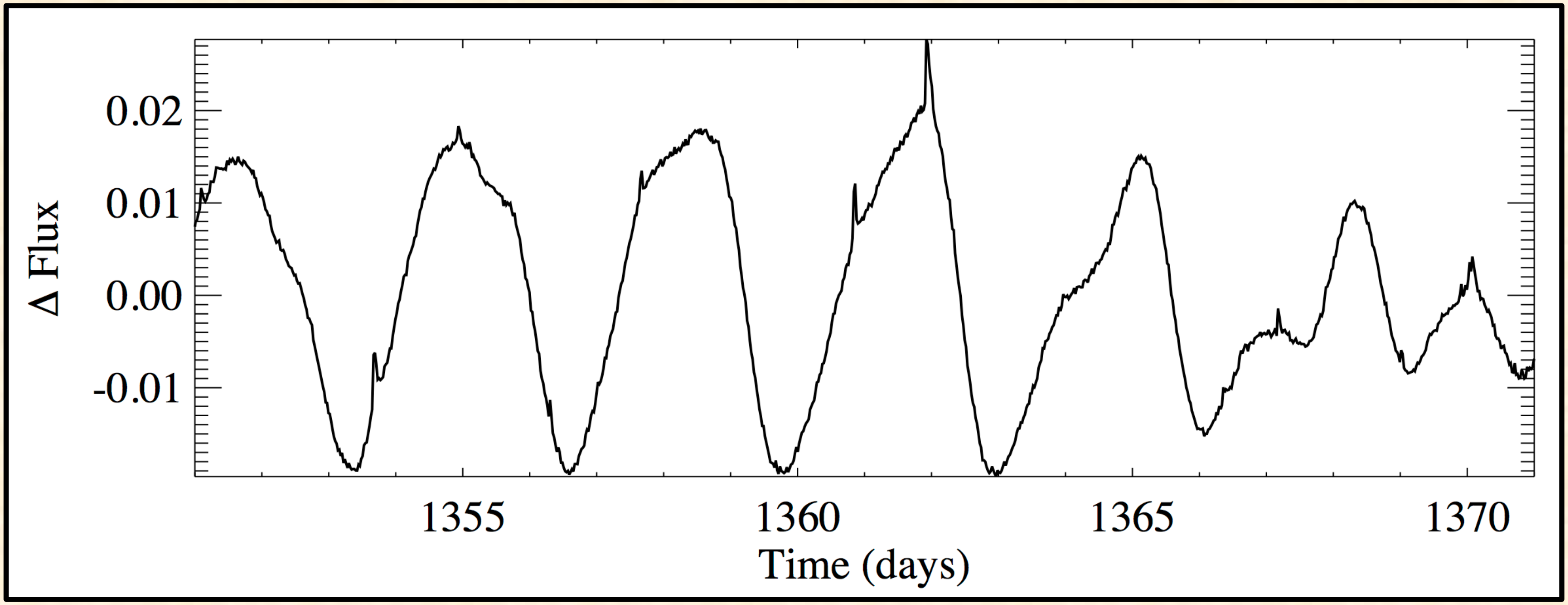
K dwarf light curve

longer (~2 day) period, 9% variation, bigger spots, some spot evolution, fewer but higher energy flares

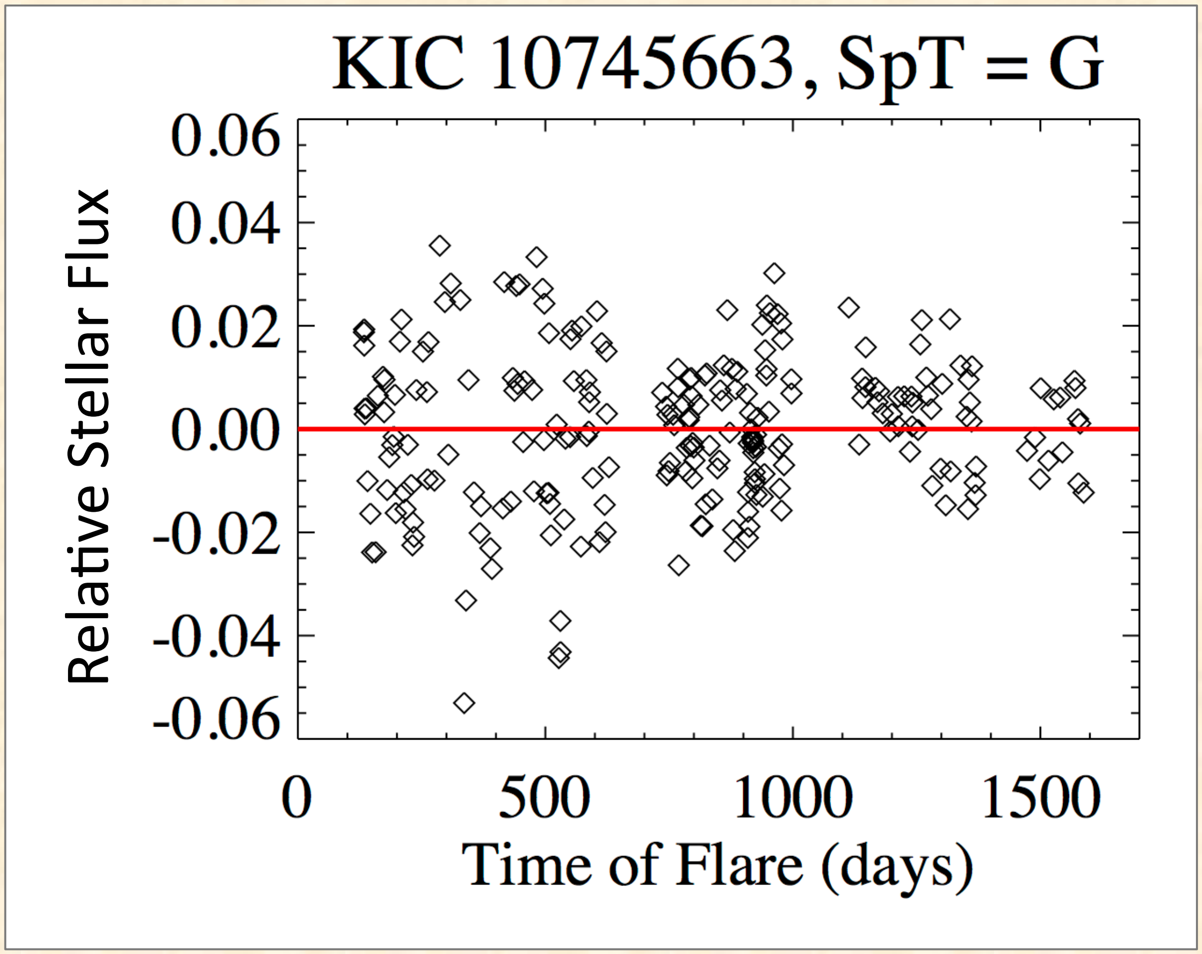


G dwarf light curve

longer (~3 day) period, 4% variation, very fast spot evolution, fewer but higher energy flares



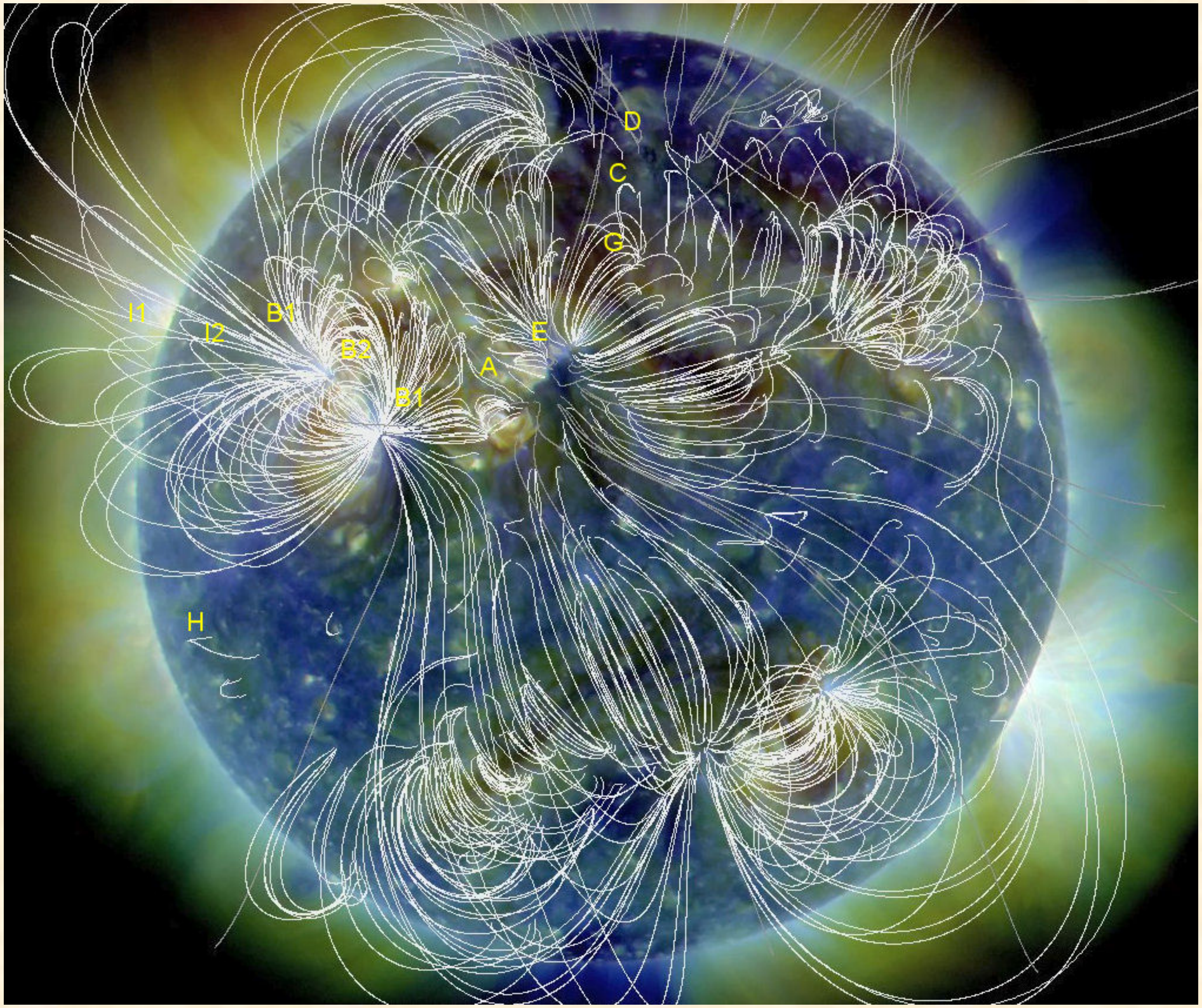
Flares do not correlate with starspot phase (when star is brighter or darker)



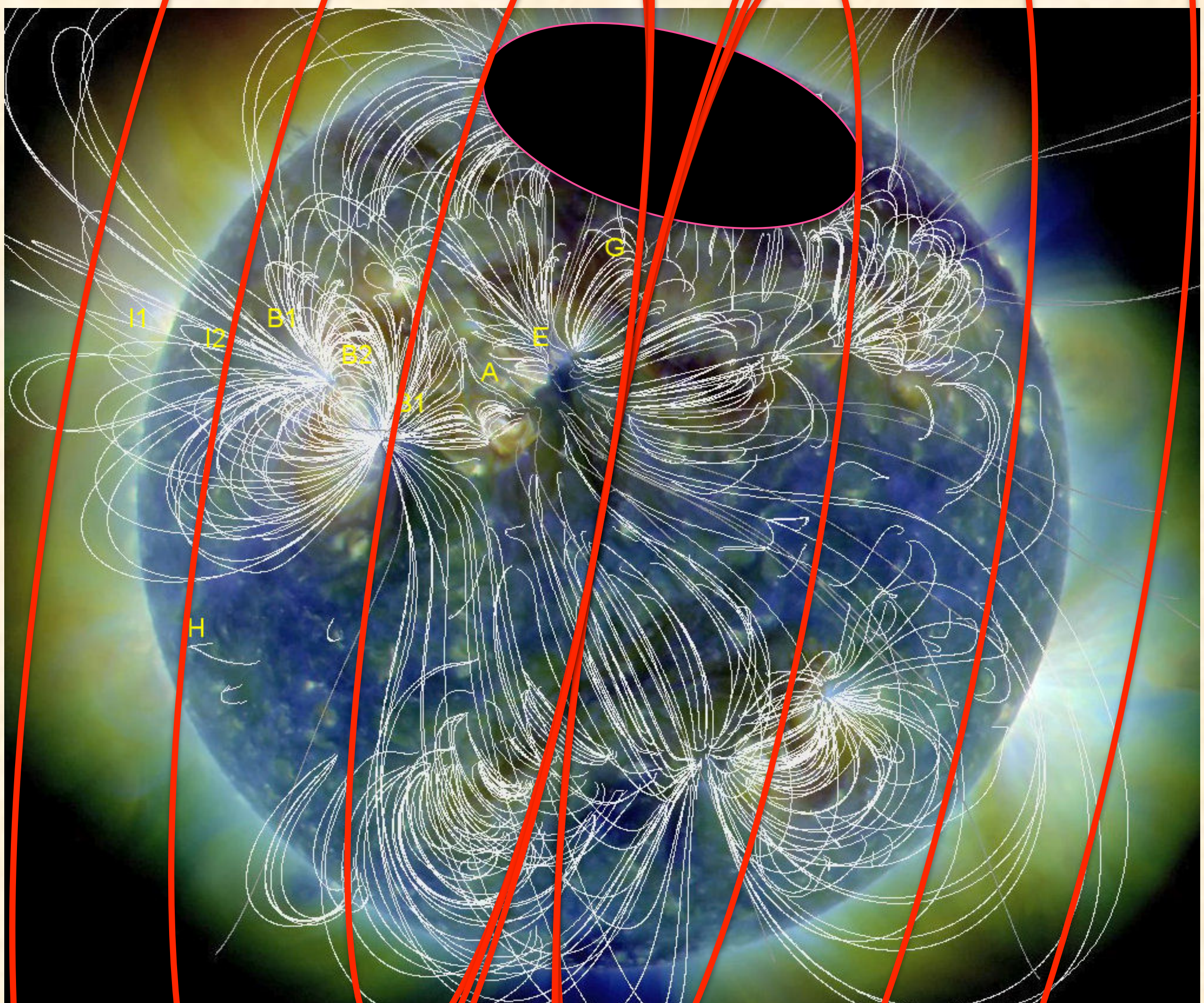
Possible interpretation

- Large-scale (dipole) magnetic field component produces large dark regions ("starspots") but not flares
- Small-scale, complex magnetic field component produces more sunspot-like active regions and flares
- Recent observations show large filling factor of small scale (mixed-polarity) magnetic field (Berdyugina et al 2015)
- Recent observations and models show both large and small scale magnetic field components are needed to explain rotational evolution (Garroffo et al 2015)

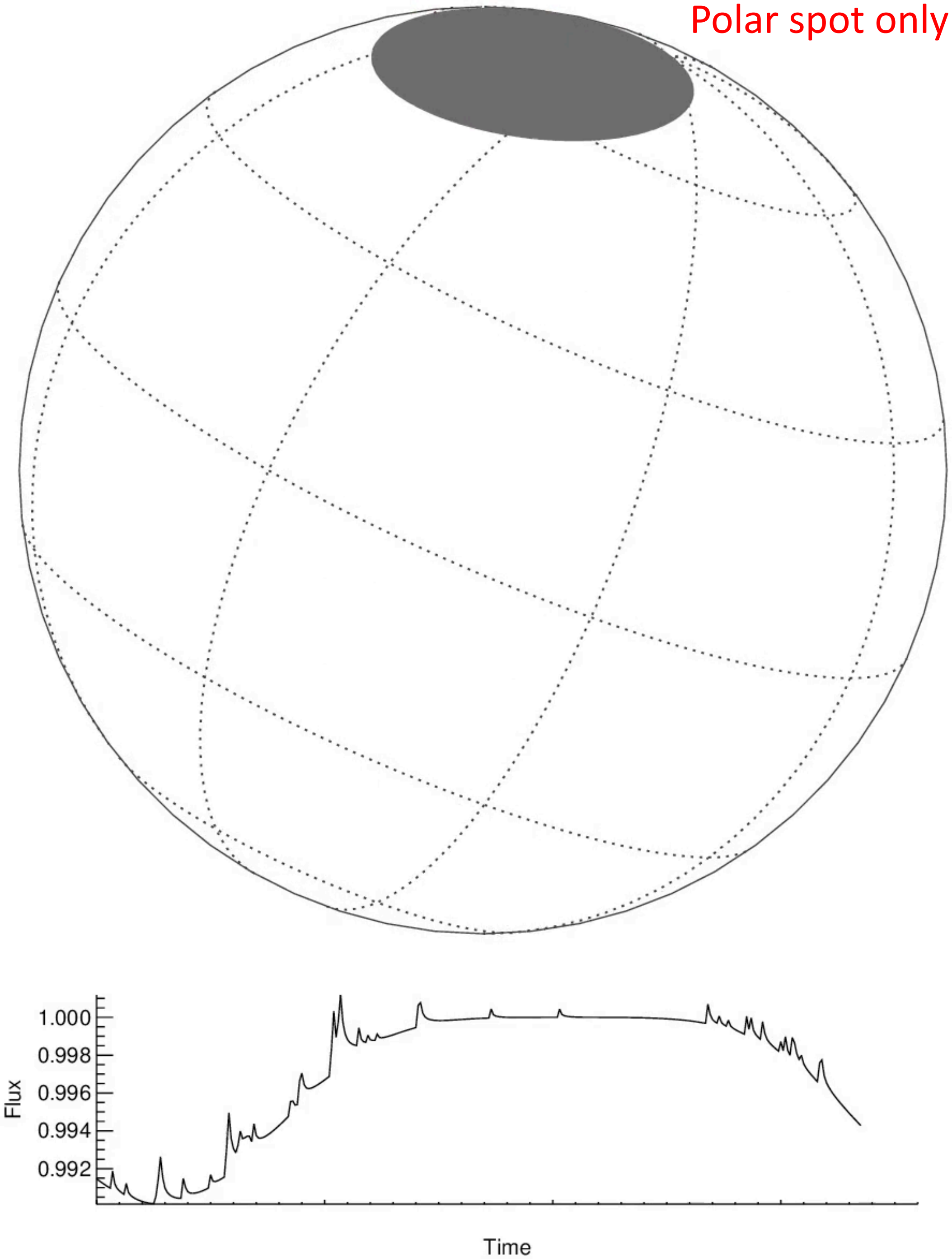
Magnetic field map of the Sun on 8/1/2010



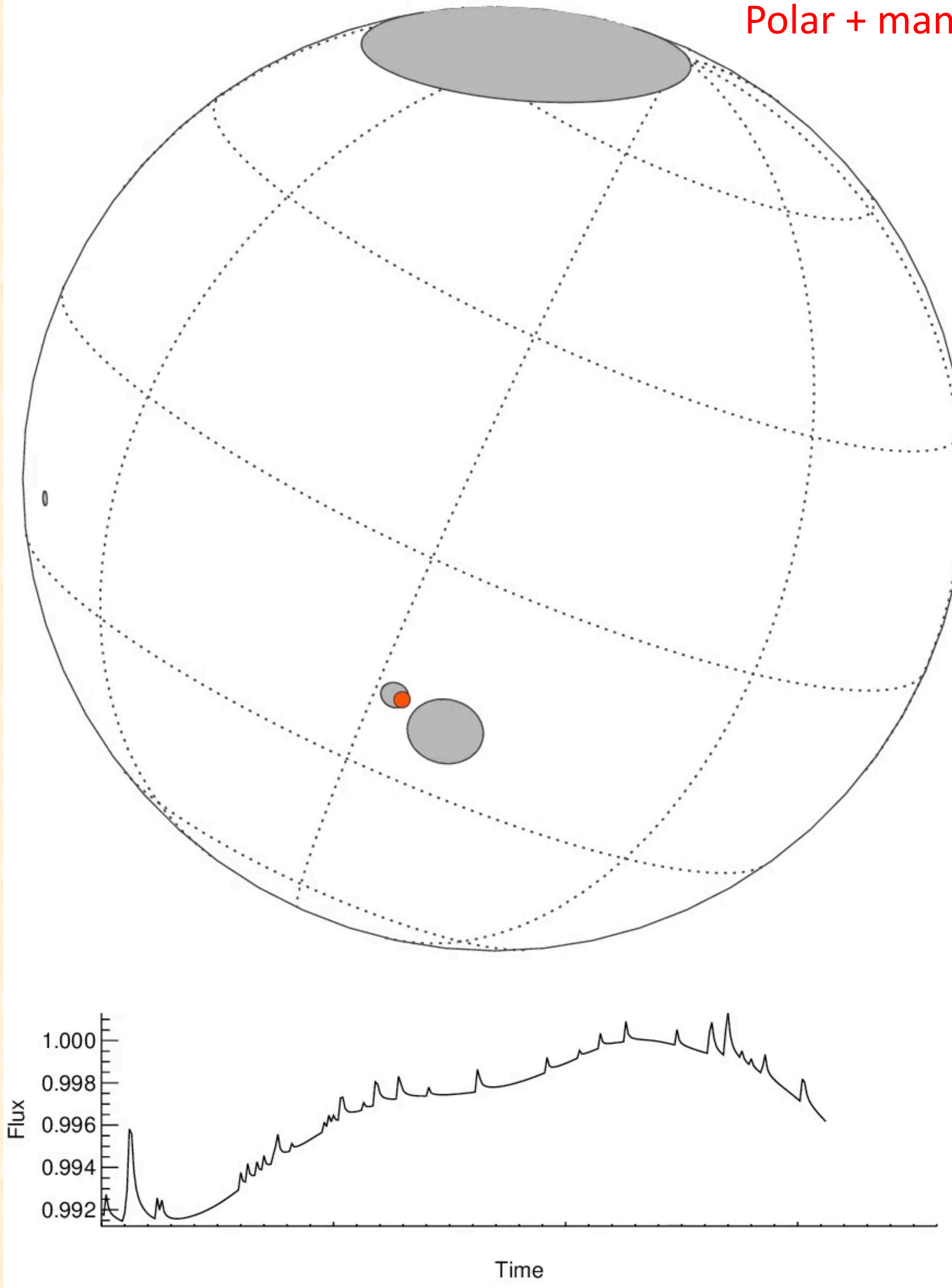
Possible magnetic field configuration on flare star? But probably with more and stronger active regions!

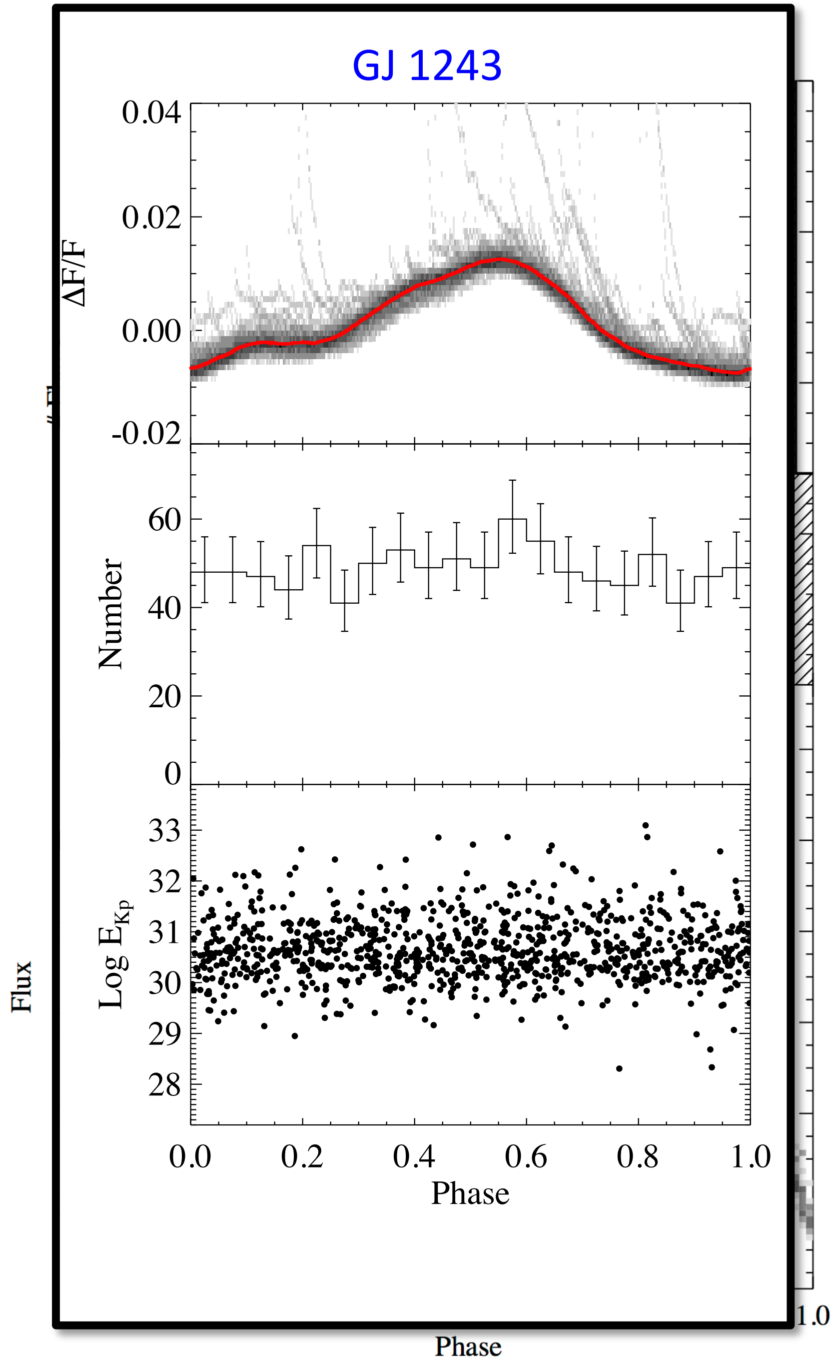


Polar spot only

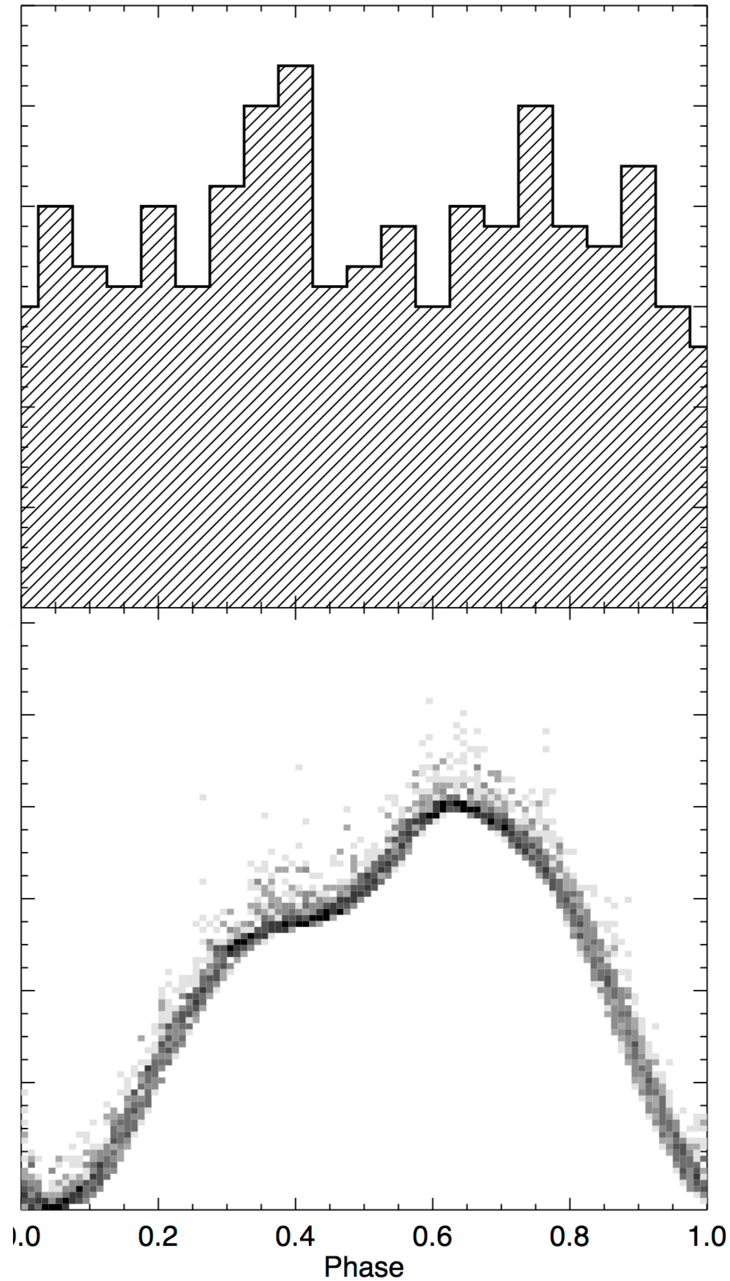


Polar + many small spots





Polar + many small spots



(Some of) what we have learned from Kepler stellar flare studies (so far)

– Great way to observe large samples of white light flares
− Light curve morphology very similar in nearly all classical flares on M dwarfs
− Complex flares may be superposition of classical flares triggered in same active region
− Flare occurrence and energy (for active M dwarfs) not correlated with starspot location – many spots always on surface? Complicated magnetic field geometry?
− Active M dwarfs flare ~ 50x more frequently than inactive ones at same energy

TO DO:

Must get spectra during evolution of G-dwarf superflare to understand the physics of the continuum formation and see if it is similar to the M dwarfs!

It is hard because G-dwarf superflares don't occur very often, maybe once in few days

Hope that new Japanese 3.8 meter telescope will be able to do this!


ARC 3.5m Telescope
Apache Point Observatory
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