Flares and coronal mass ejections on cool stars

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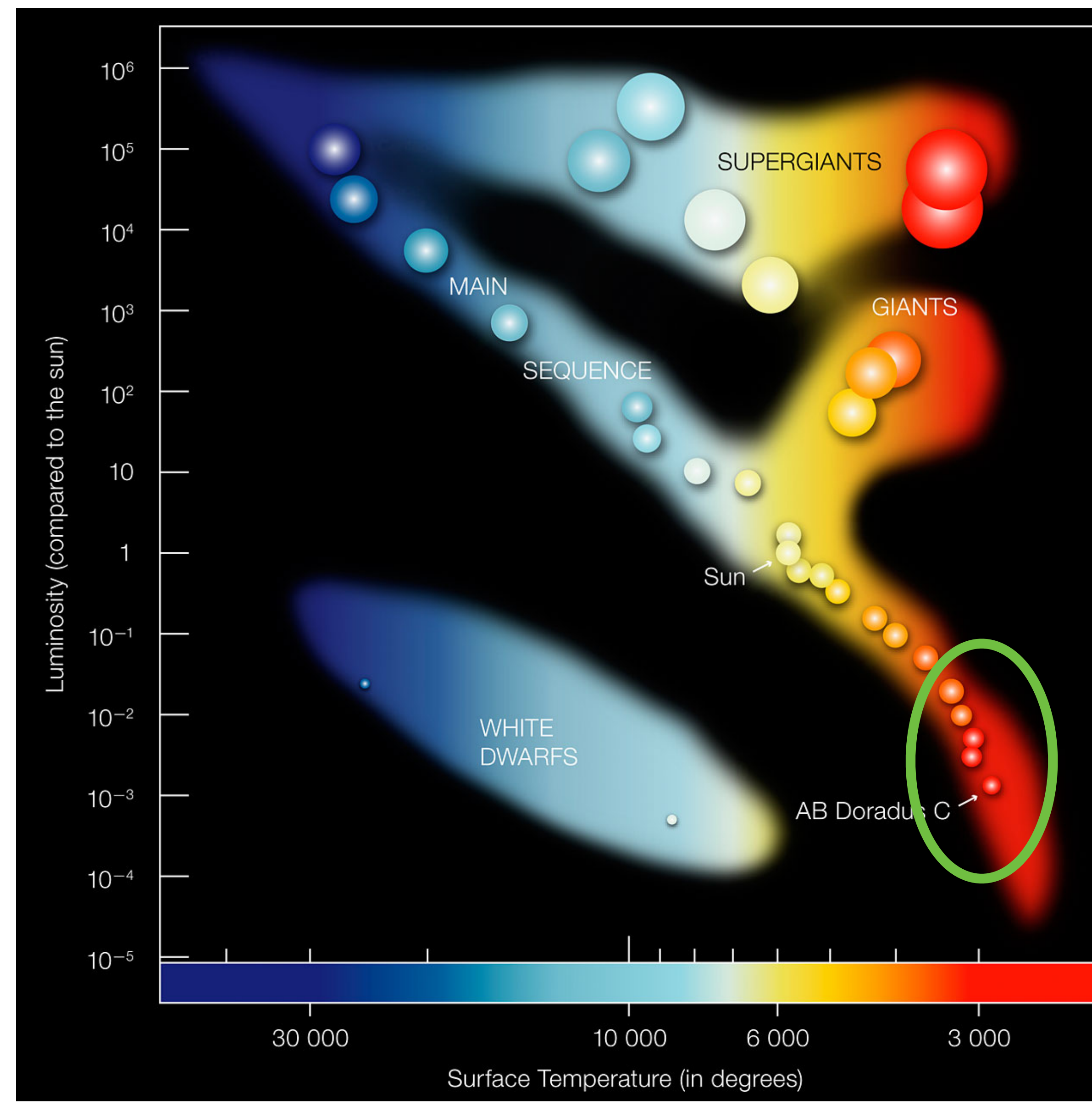
“Cool” stars?

- stars are categorized by their surface temperature into spectral classes (O-B-A-F-G-K-M/L-T-Y)

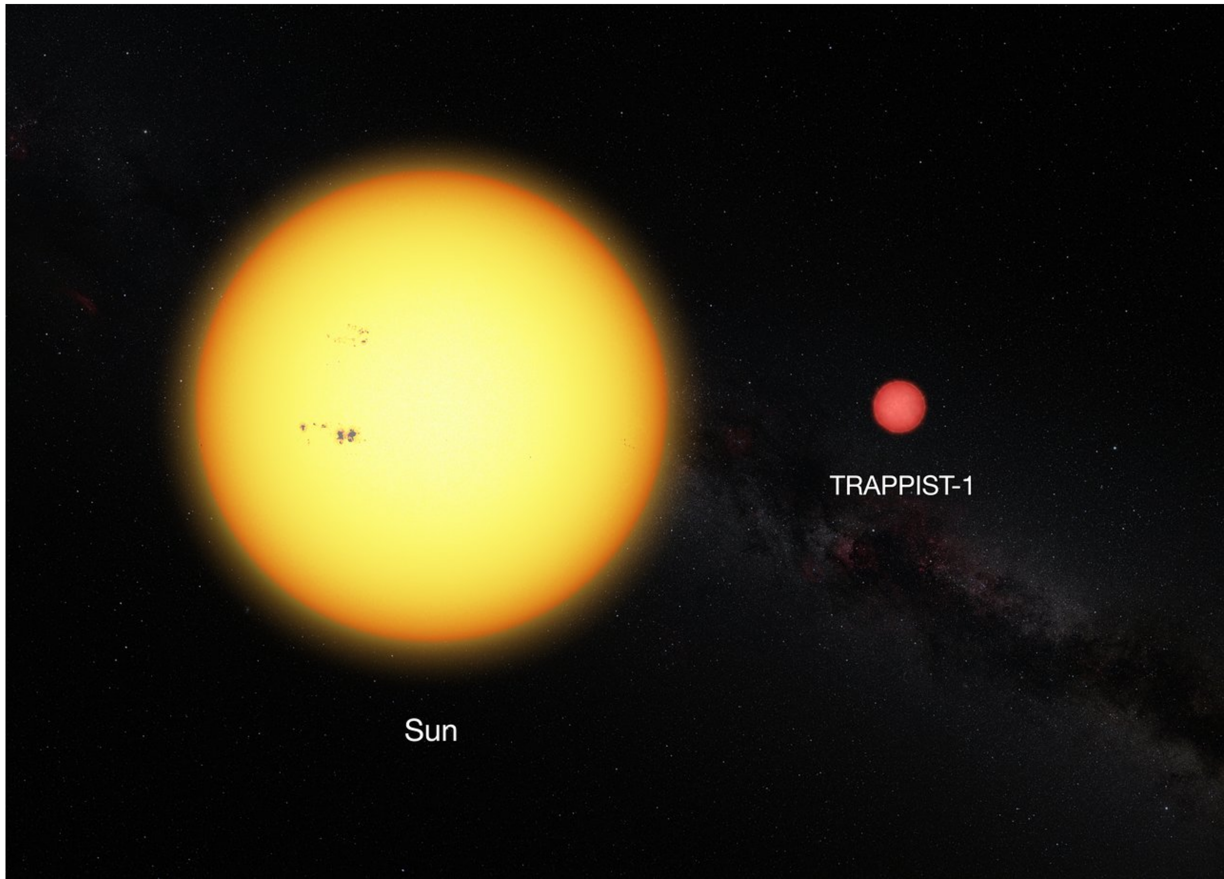
- “ultracool objects”:
    - M0-M9: 4000-2500 K
    - brown dwarfs (M7+): no stable ^{1}H fusion



Hertzsprung-Russell diagram

Why are they a hot topic?

- M-dwarfs are the most numerous stars in the Galaxy
- Planets are easier to detect around them (higher contrast, higher radial velocity change)
- Short orbital periods (no need to wait a year for a second eclipse to confirm)

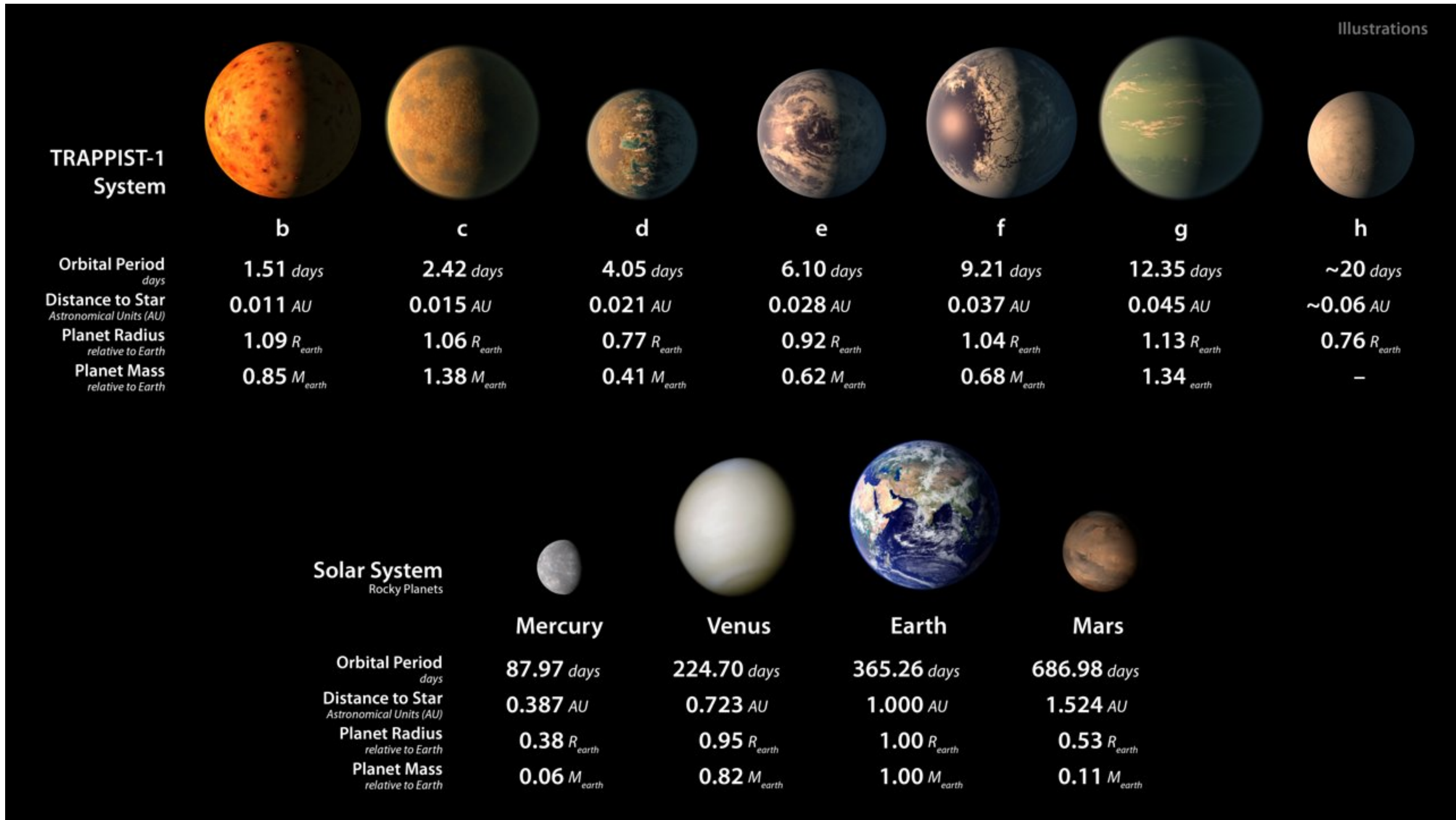


Case I
TRAPPIST-1

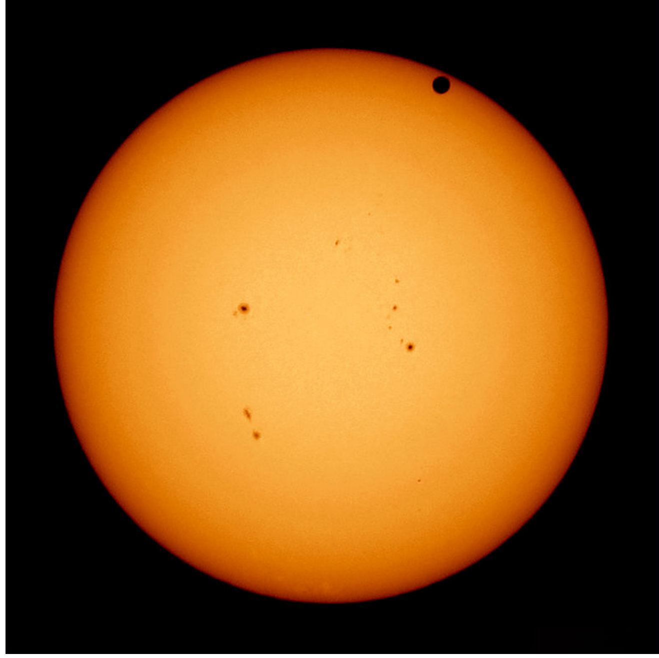
Flares from
space-borne
photometry

The TRAPPIST-1 system

- M8 star (~2500K), R~0.11R_{Sun}
- 7 terrestrial planets
- very short (1,2,4… day) orbit periods
- 3 within the habitable zone (might have liquid water)

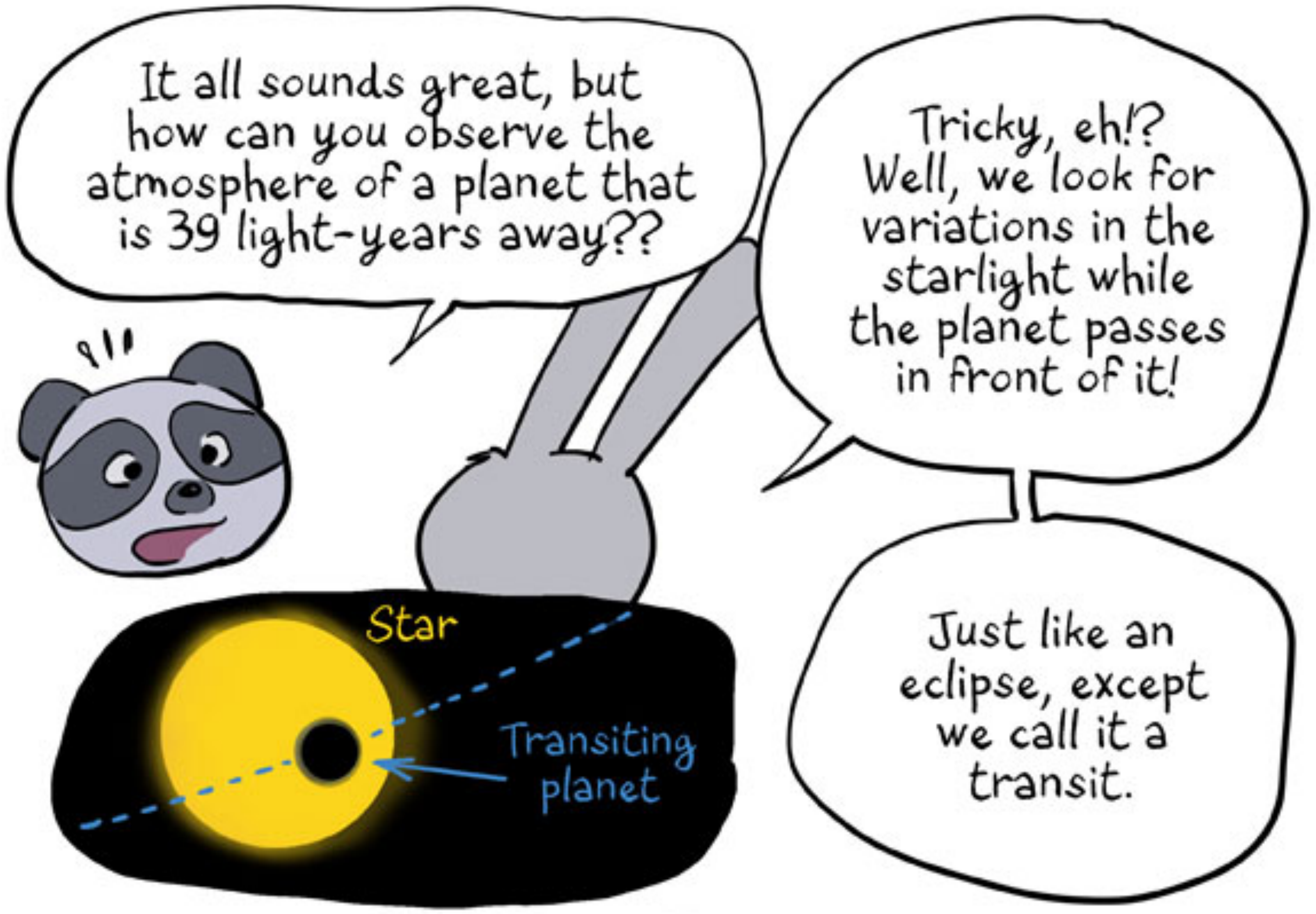


How did they find it?

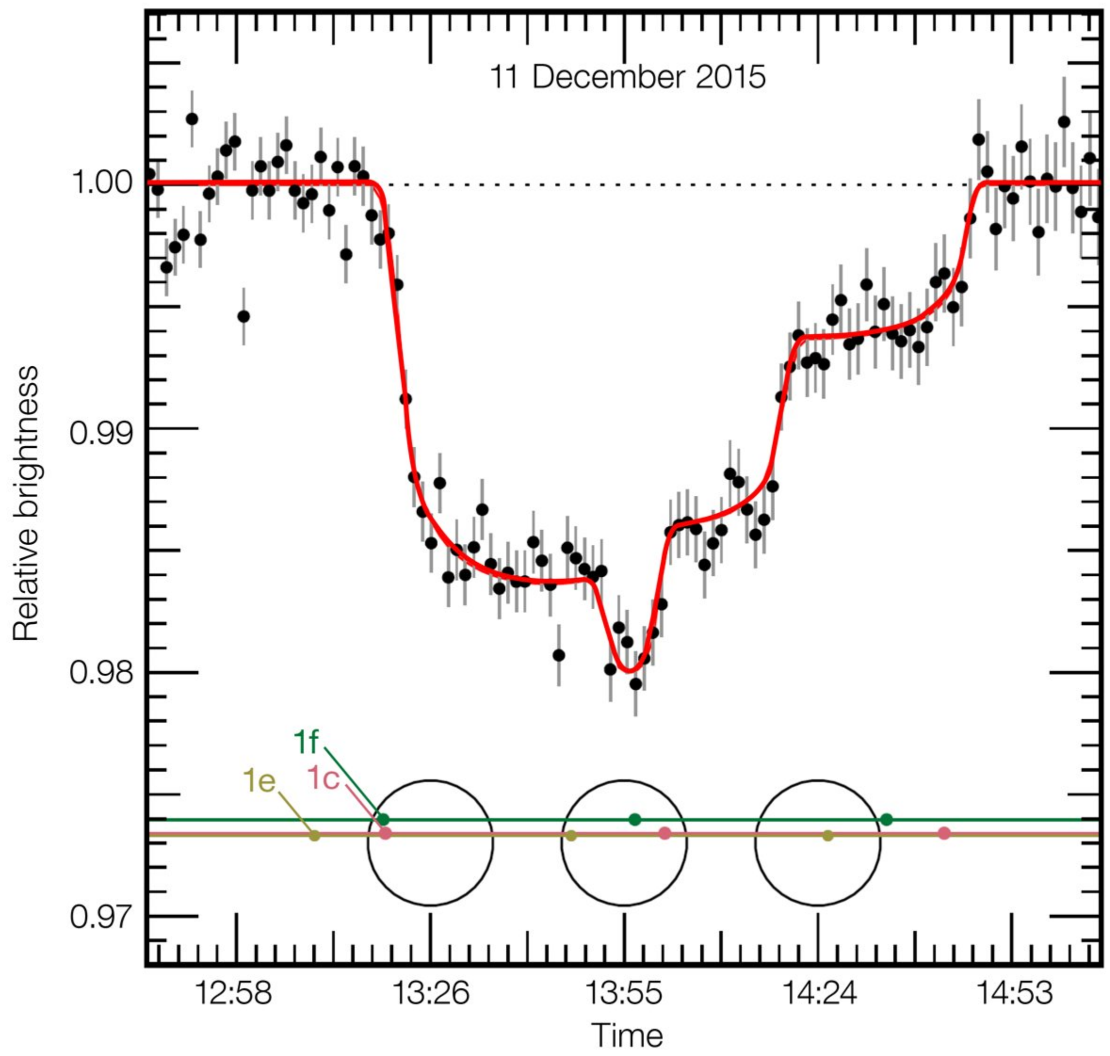


Venus transit
2012

Transit method
(we see the system in the orbital plane)



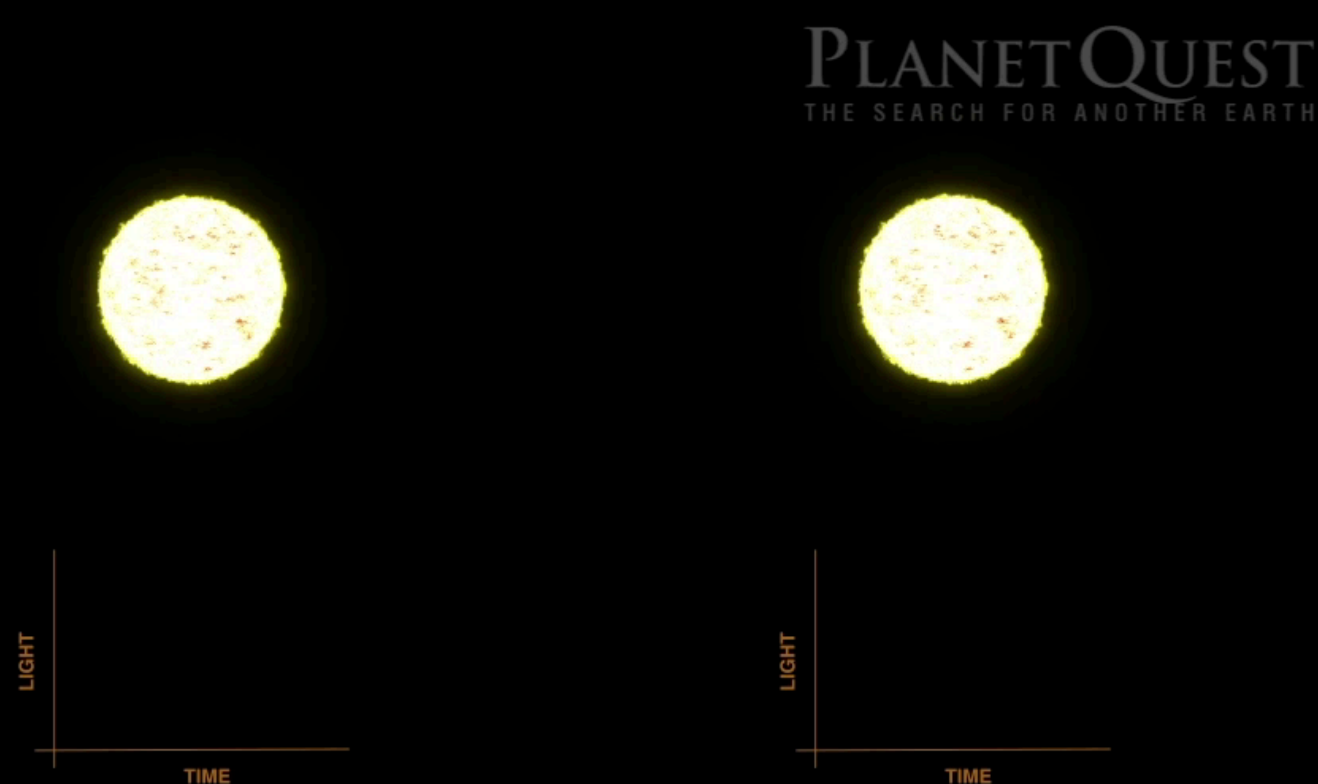
(also great for outreach :))



Exoplanet search methods

Radial velocity (630)

Eclipse (2717)



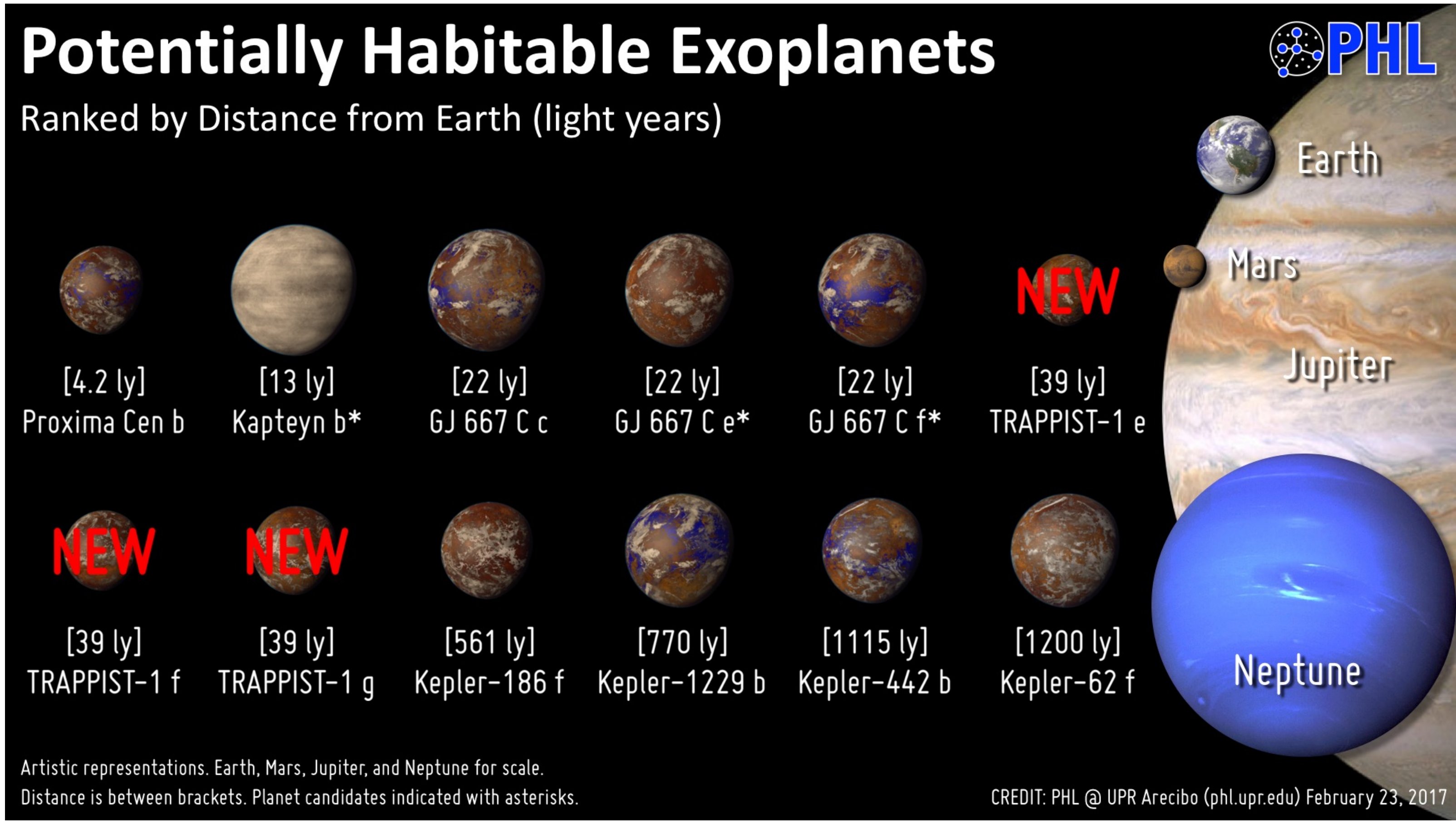
Astrometry (1)

Direct imaging (44)

Gravitational lensing (44)

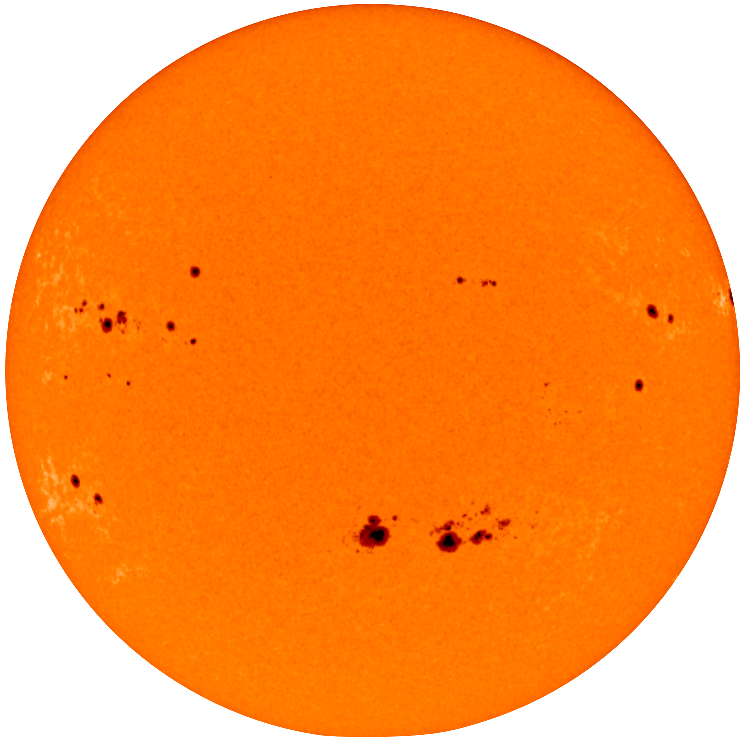
Why is it interesting?

- The first Earth-like planet (Kepler-186f) was announced in 2014
- There are only a handful of exoplanets in a habitable zone
- 3 of them in the TRAPPIST-1 system
- But M-dwarfs are not the nicest hosts for life…

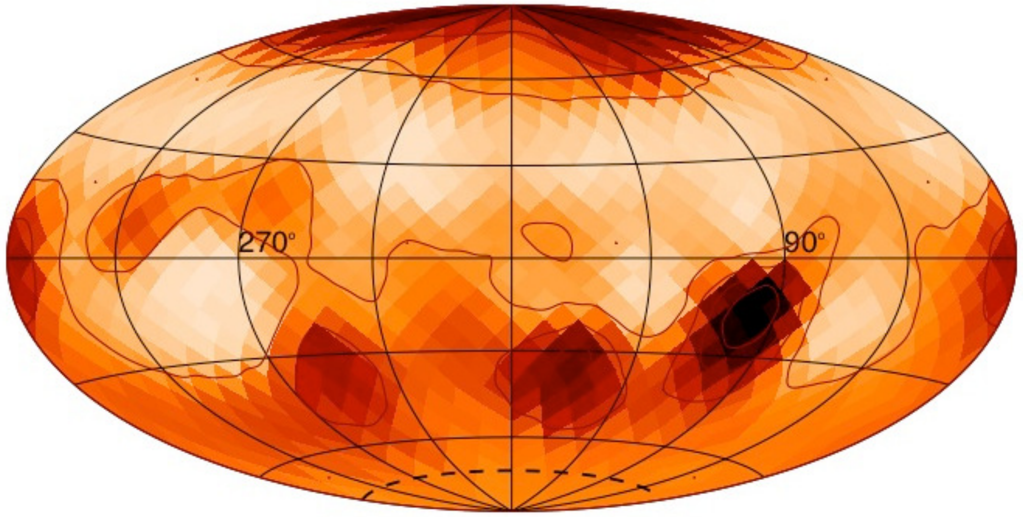


Stellar activity might be a problem

- Fast rotation → strong magnetic field
- Flux tubes crossing the surface → dark, cool spots (magnetic pressure helps the material inside the flux tubes to reach an equilibrium at lower temperature)
- field reconnection→ flares, coronal mass ejections (CMEs)

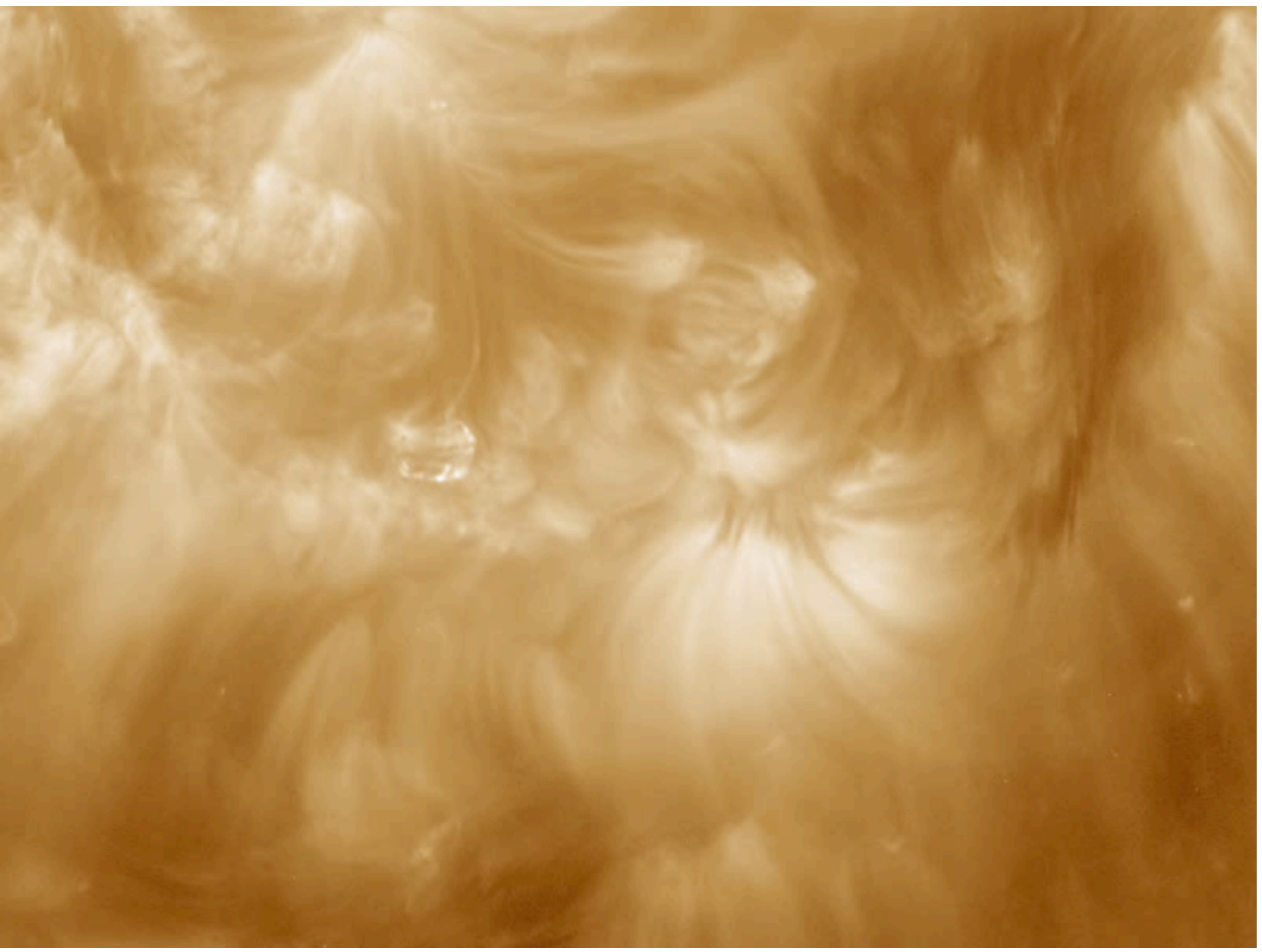


Sun at its maximum (2008)

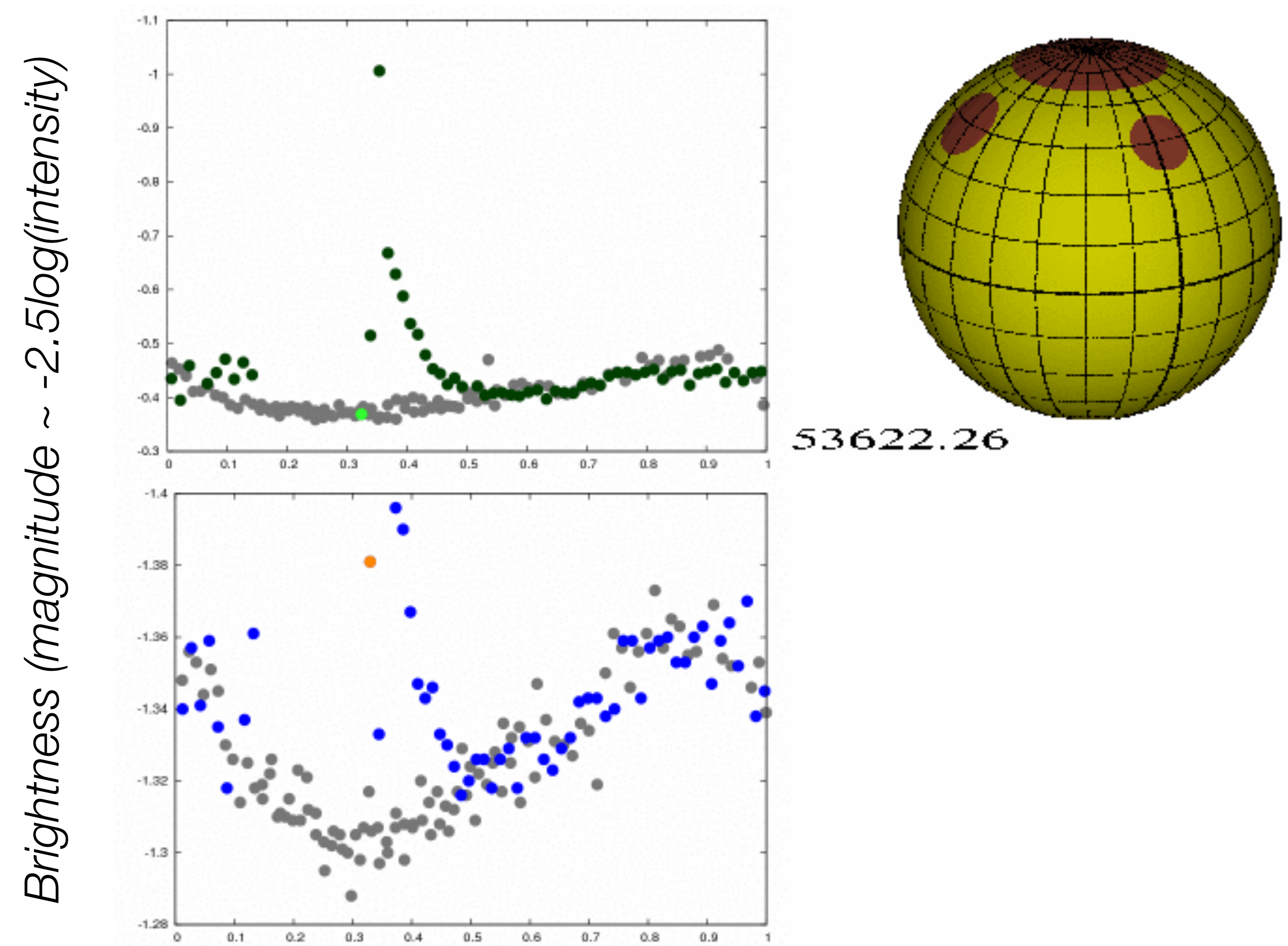


ζ Andromedae
Roettenbacher et al. 2016 Nature 533 217

Unfortunately on stars we have much less detail on the events: in most cases only the brightness changes (i.e., a light curve) is measured



Flare on the Sun
(2013, Solar Dynamic Observatory)



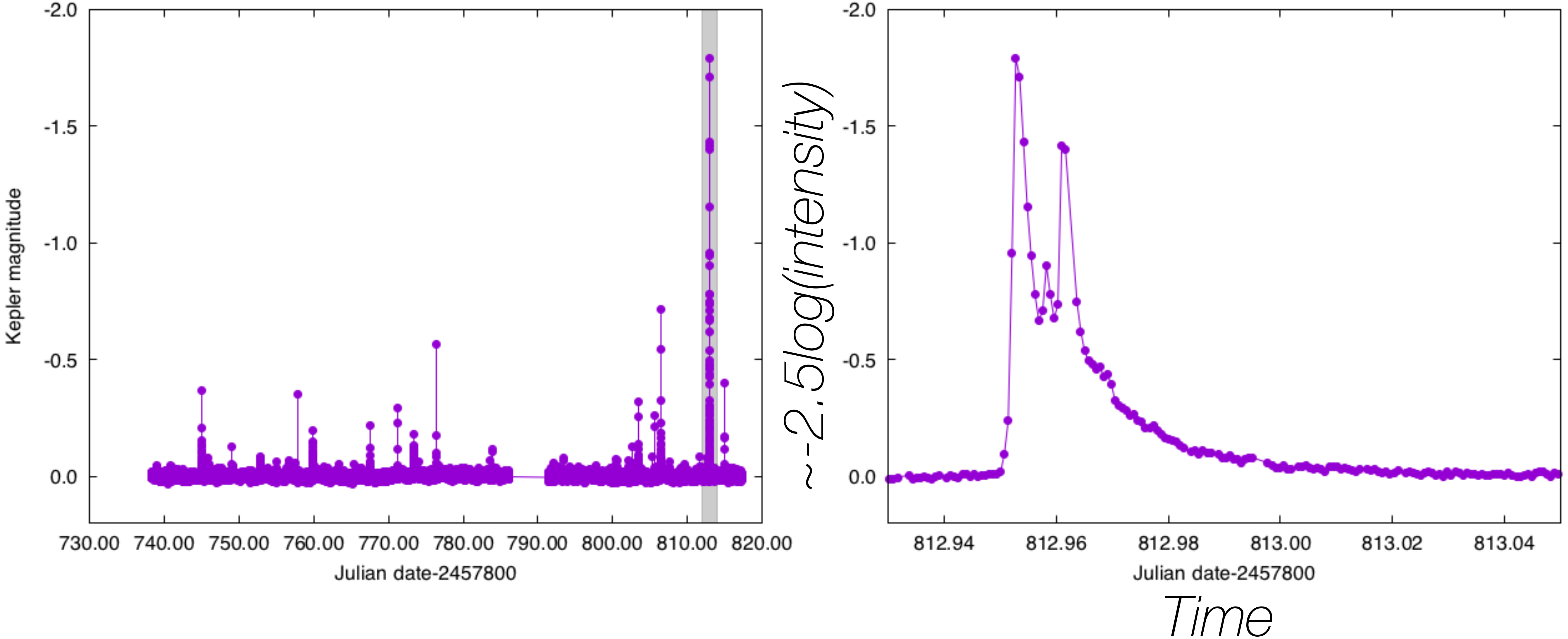
Rotational phase

Strong flare on an M-dwarf (EY Draconis)
the total intensity gets double
during the eruption

TRAPPIST-1 light curves from the Kepler/K2 mission

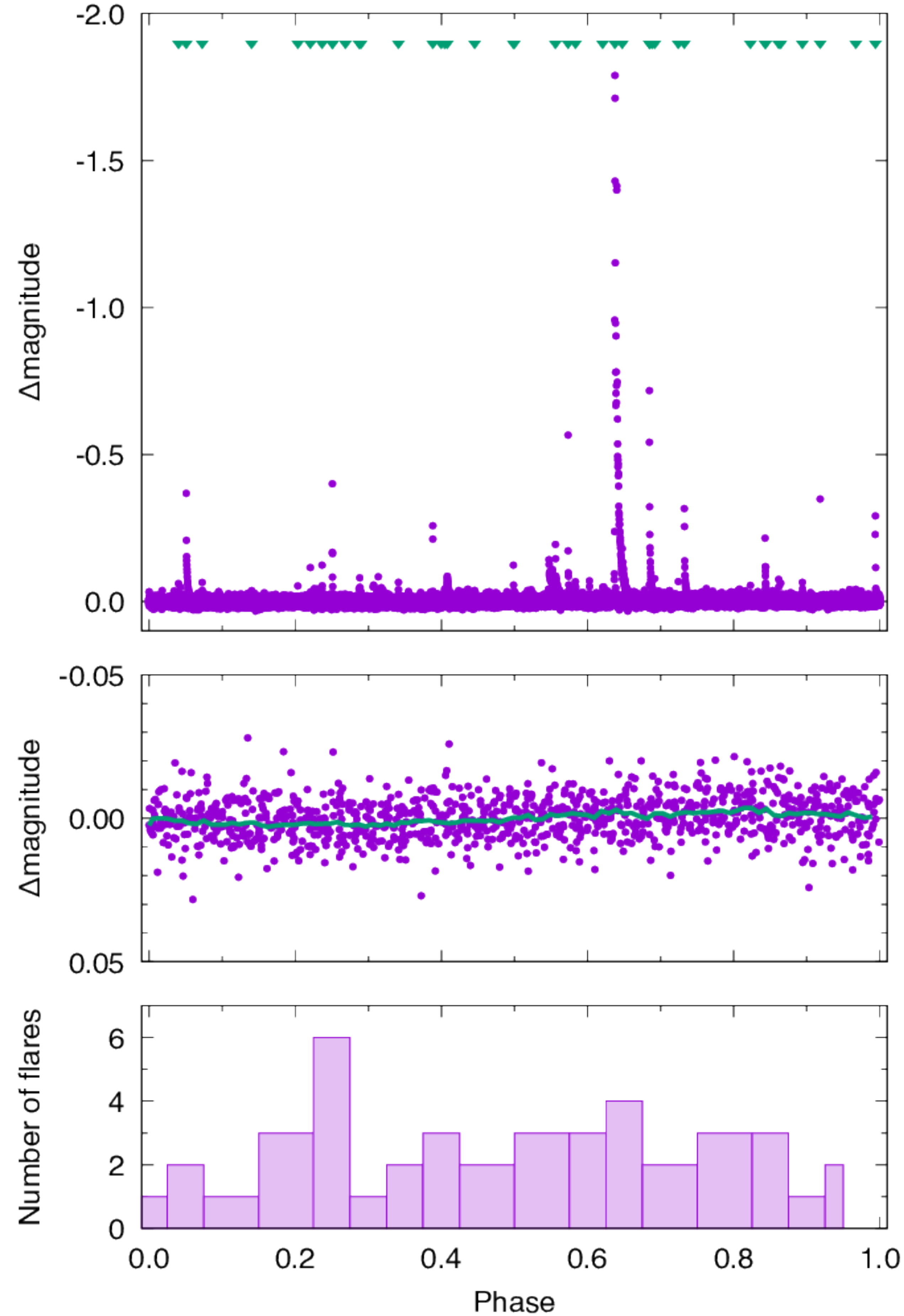
- The Kepler telescope obtained ~80 day-long precise light curve of TRAPPIST-1 in the K2 mission
- These uncalibrated raw pixel data are available to the community
- We found P_{rot}=3.295 days (cf. Gillon et al. 2016 had 1.4 days from ground photometry, that is consistent with $v\sin i$=6km/s, and Roettenbacher et al. 2017 found 0.82d in Spitzer data…)

Light curves from the Kepler/K2 mission

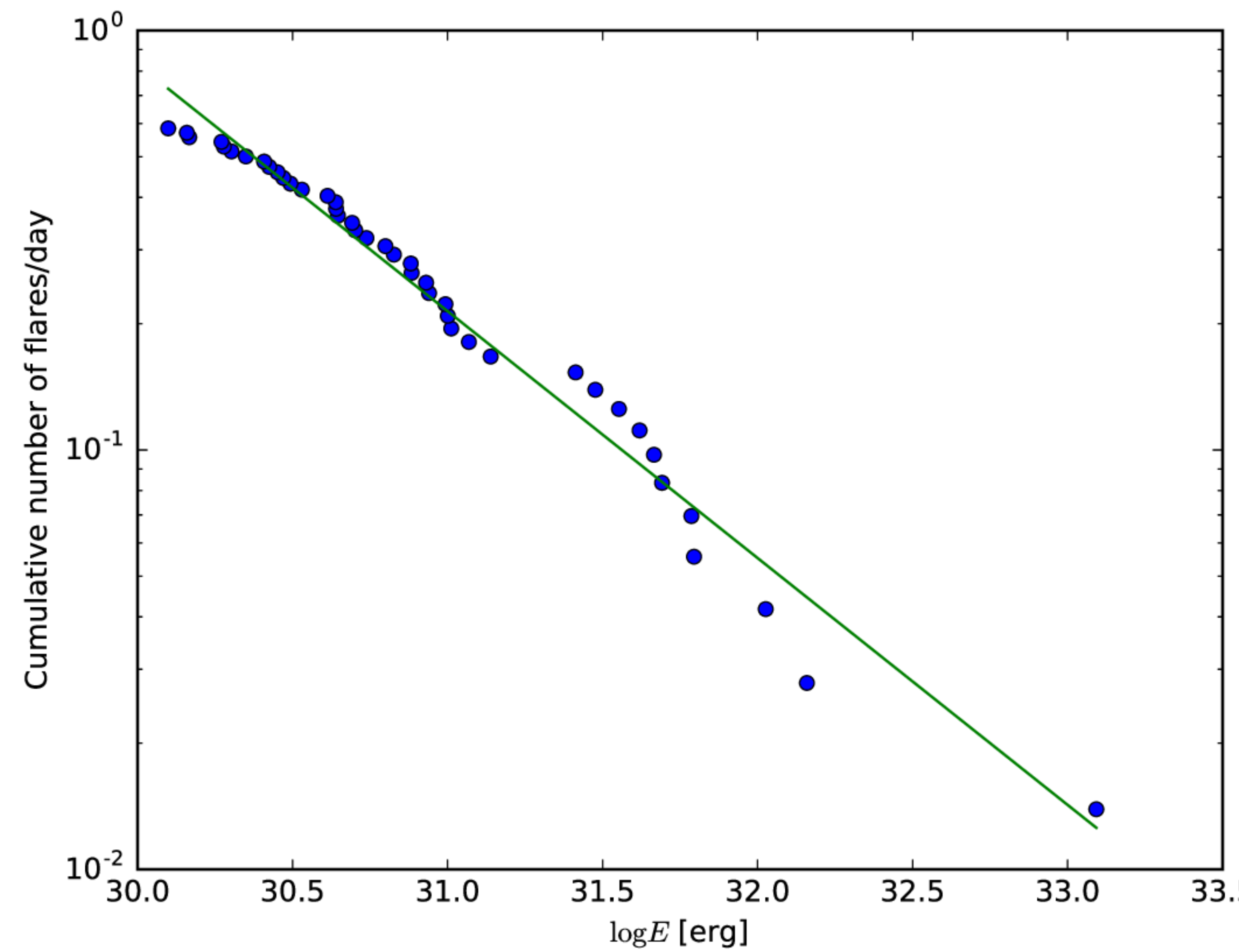


Suggesting that the TRAPPIST-1 might be not
the friendliest environment after all…

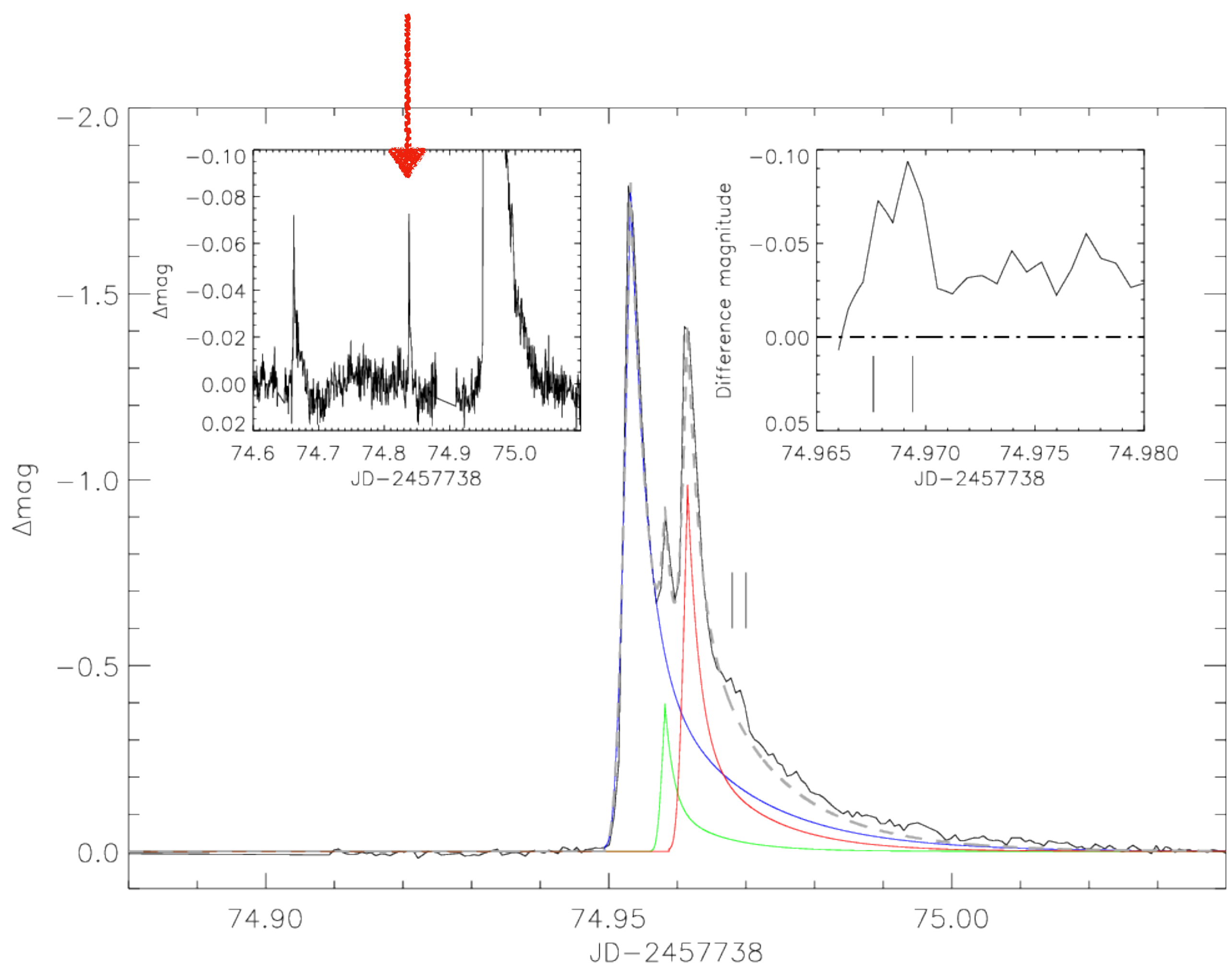
- Flares are found at every phase
- bit higher frequency at light curve minimum (~0.25 phase)
- strongest flares at maximum (0.55-0.75)

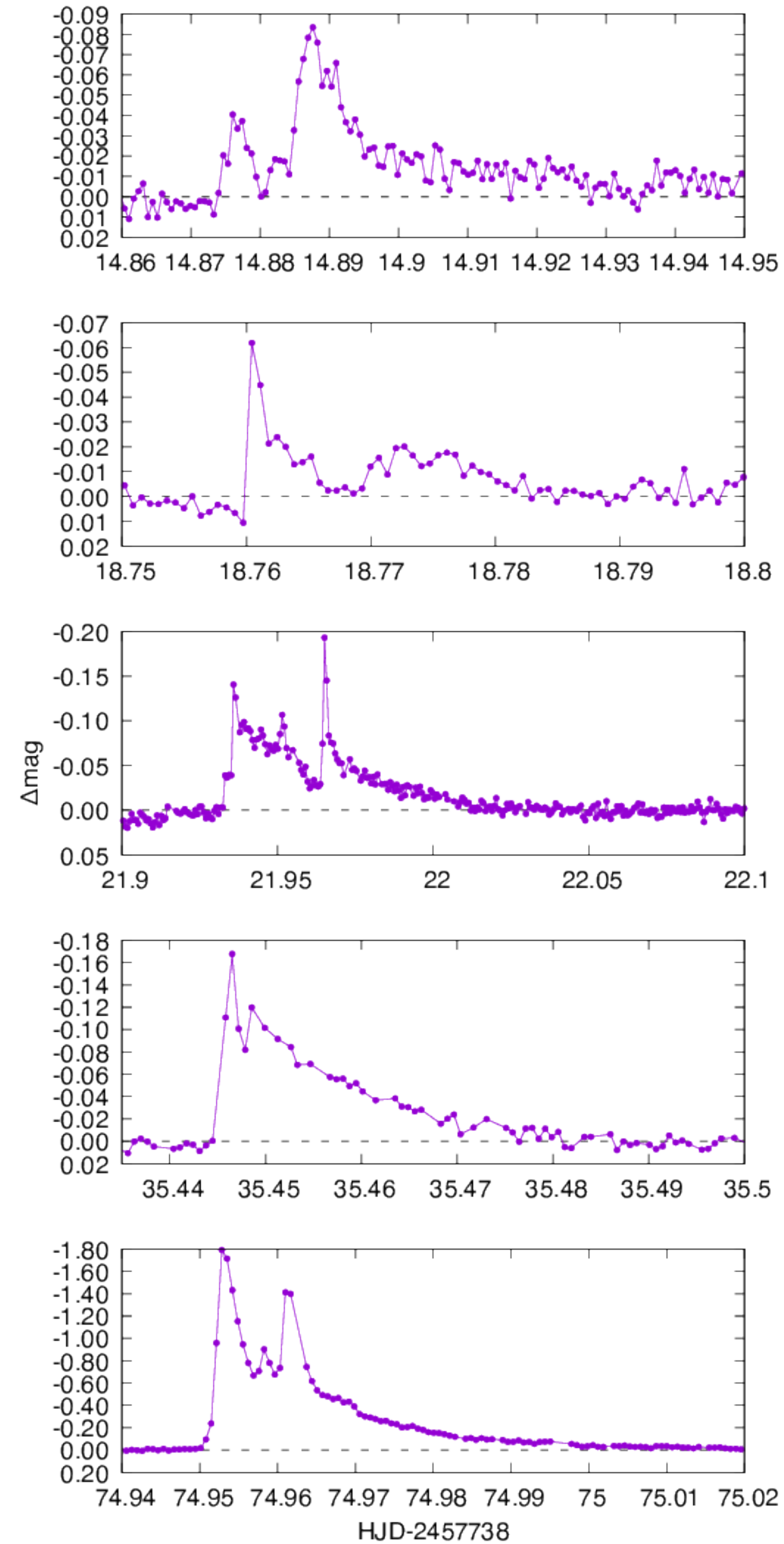


- Flares are found at every phase
- bit higher frequency at light curve minimum (~0.25 phase)
- strongest flares at maximum (0.55-0.75)
- Flares with ~1.26×10^{30}..1.24×10^{33} erg energies
- distribution suggests mostly non-thermal flares similarly to more active M-dwarfs



- There are several flares in the light curve (42)
- Some of them are complex eruptions
- One strong (Δmag=1.8) complex event
- ~with the energy of the Carrington-event
- Could be a sympathetic eruption triggered by an earlier one





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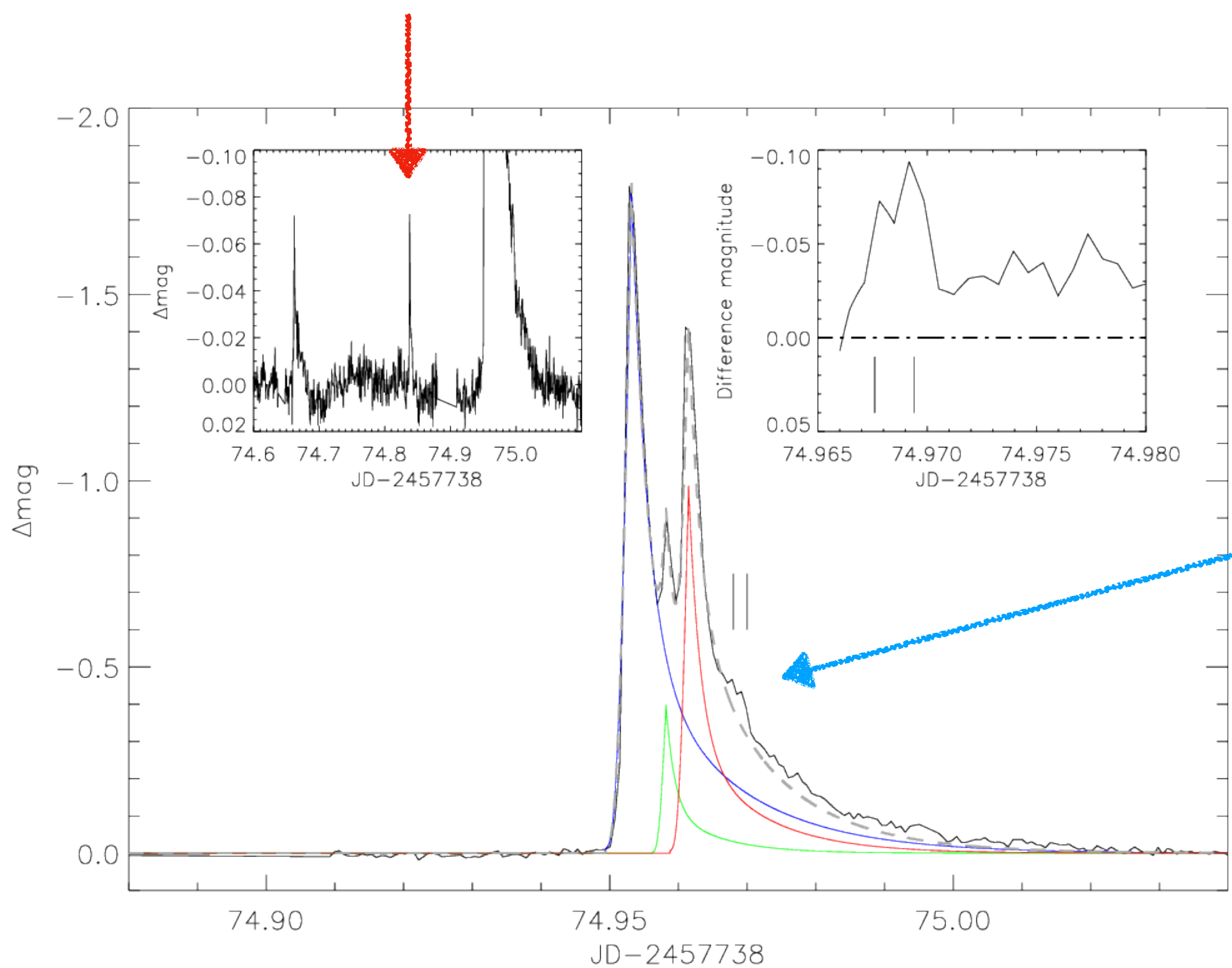
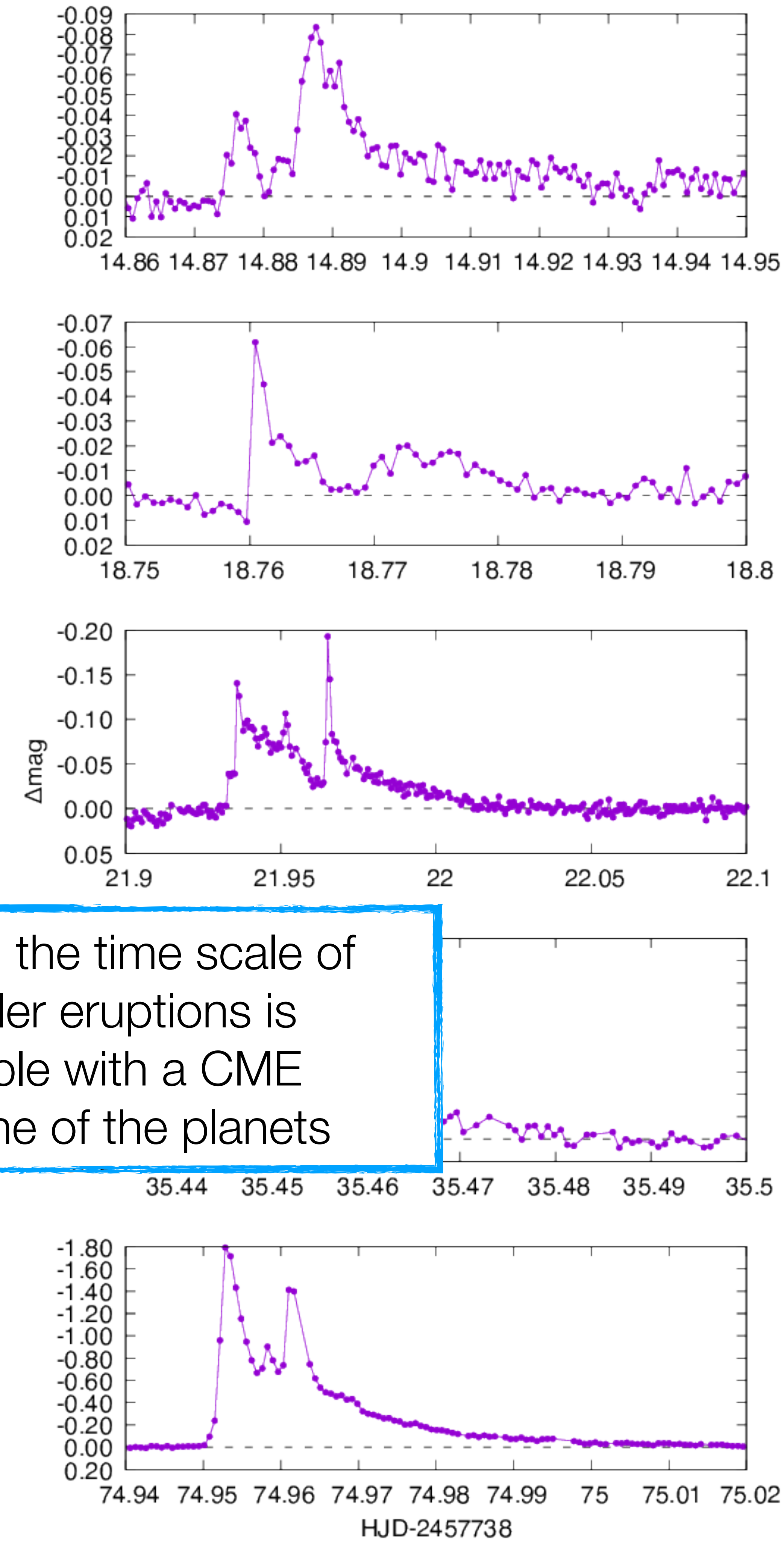
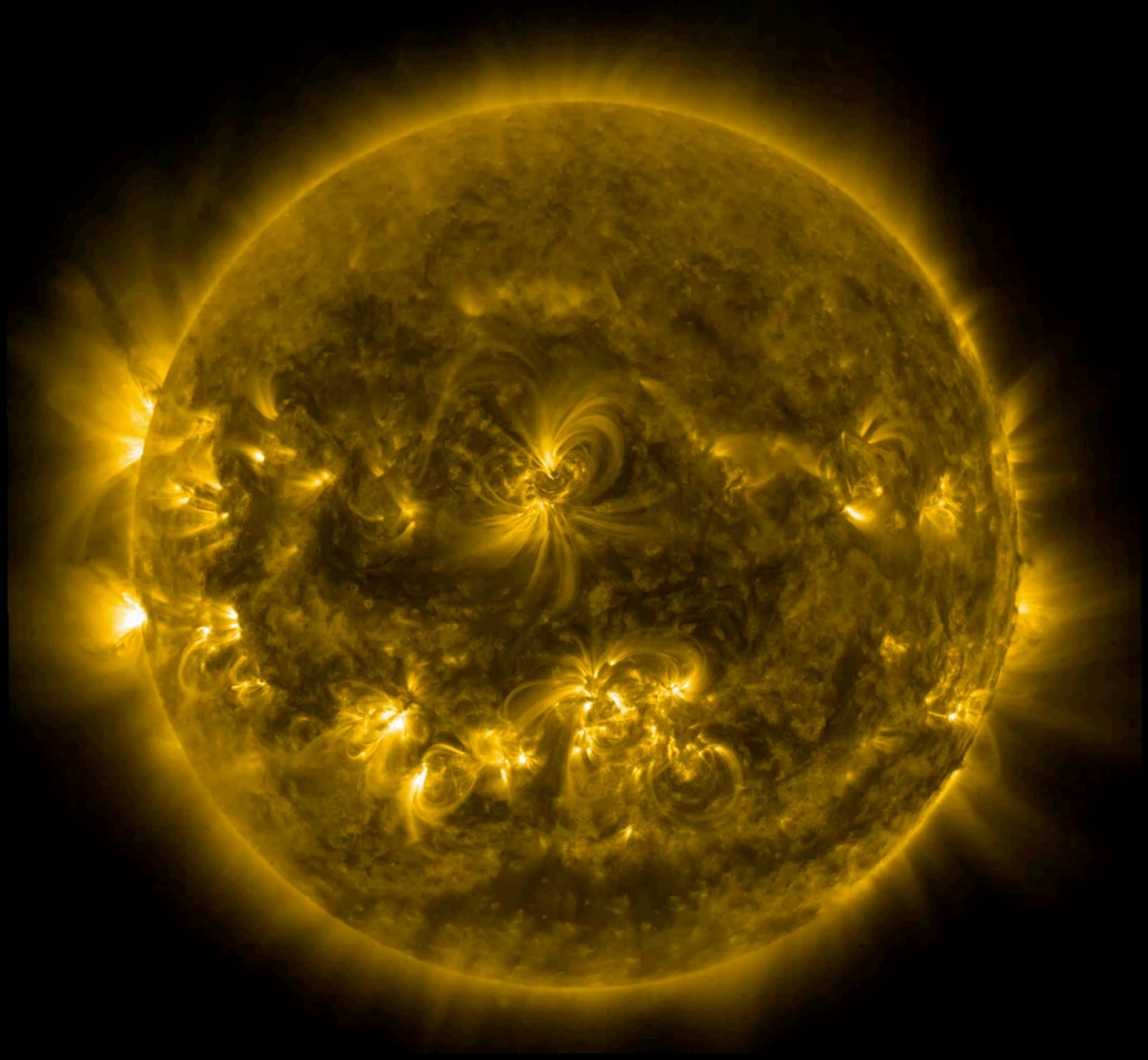
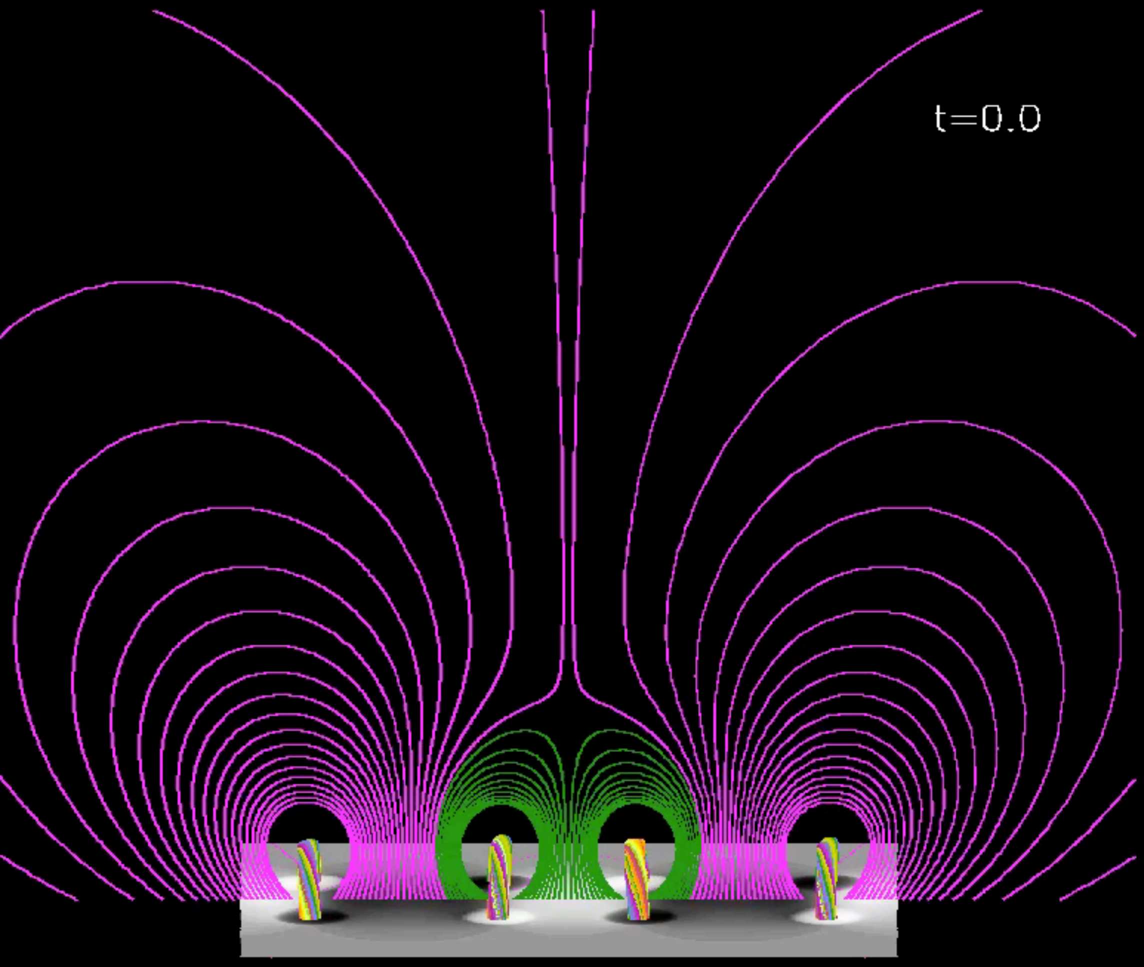


Fun fact: the time scale of the smaller eruptions is compatible with a CME hitting one of the planets



Solar flare event in 2014 where the surface perturbation of a flare can be well seen (Solar Dynamic Observatory data)





Numerical simulation of a global sympathetic flare event on the Sun from 2010 (Török et al. 2011)

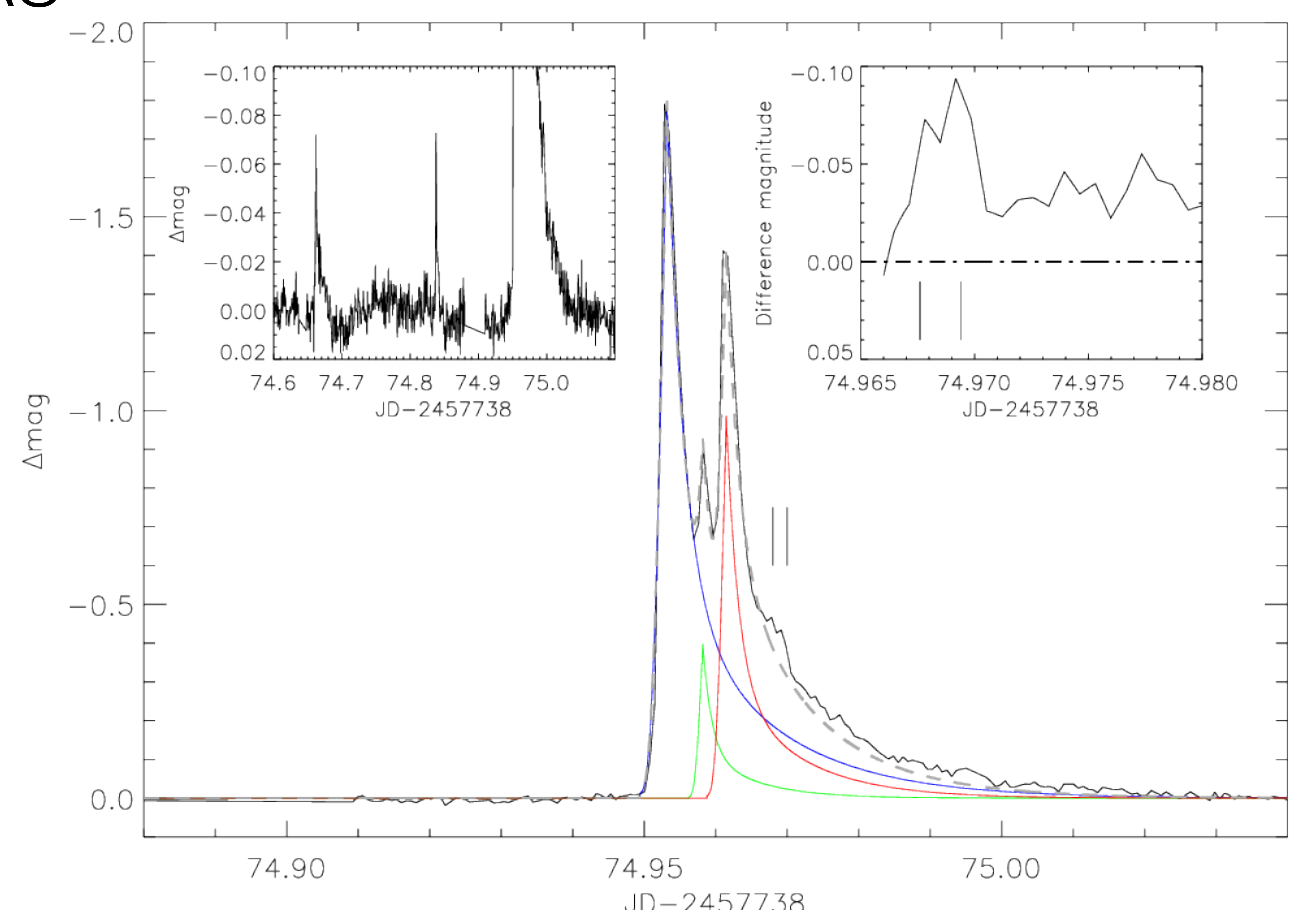
What could be the consequences of such an eruption?

- Venot et al. (2016): based on the 1985 flare of AD Leo (dV~0.5mag): the atmospheres of two hypothetical orbiting super-Earths would be significantly & irreversibily altered.

- Steady state would be reached in ~30 000 years, but large eruptions are more frequent → constantly changing atmosphere

- An eruption of this scale temporarily changes the habitable zone limits from 0.024-0.049AU to 0.048-0.097AU (very crude estimation)

max. Δmag~1.8



Bad news

- Flares can threat habitability:
    - can erode atmospheres
    - directly harm life on the surface

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Good news

- UV radiation could be absorbed by photochemical reactions in the high atmosphere and might not even reach surface
- a strong enough magnetic field could shield the planets

Bad news

- Flares can threat habitability:
    - can erode atmospheres
    - directly harm life on the surface
- Kay et al. (2016): Earth-like planets would need ~10..100G
- Vidotto et al (2013): even more, up to 1000G (Earth has ~0.5G)
- → quite unlikely

Good news

- UV radiation could be absorbed by photochemical reactions in the high atmosphere and might not even reach surface
- a strong enough magnetic field could shield the planets

- The flaring activity raises doubts on Earth-like life in the TRAPPIST-1 system
- BUT there might be still chance for life:
    - e.g. tardigrade on Earth survive basically everything
    - life could survive under surface of underwater (harder to detect)

- The flaring activity raises doubts on Earth-like life in the TRAPPIST-1 system
- BUT there might be still chance for life:
    - e.g. tardigrade on Earth survive basically everything
    - life could survive under surface of underwater (harder to detect)
    - O'Malley-James & Kaltenegger (2016) suggested protective bioluminescence: this could be detected by its correlation with eruptions!
    - the age of the system (3-8Gyr) could make life possible: earliest life on Earth dates back to 4Gyr (although complex life took longer time to form)

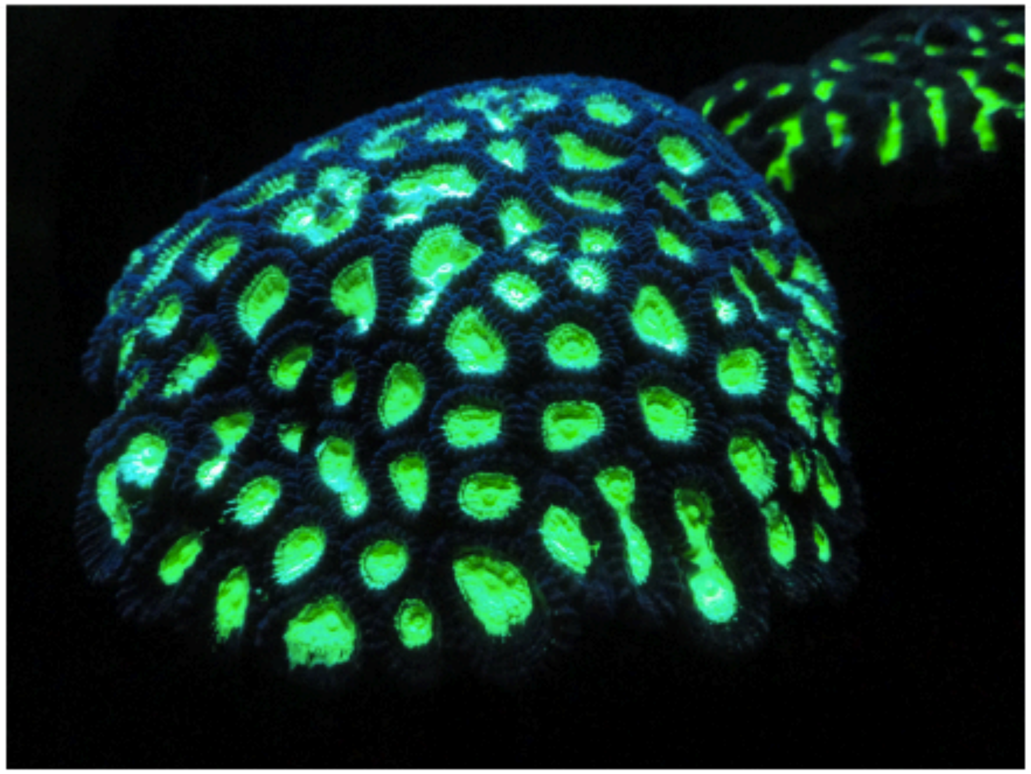
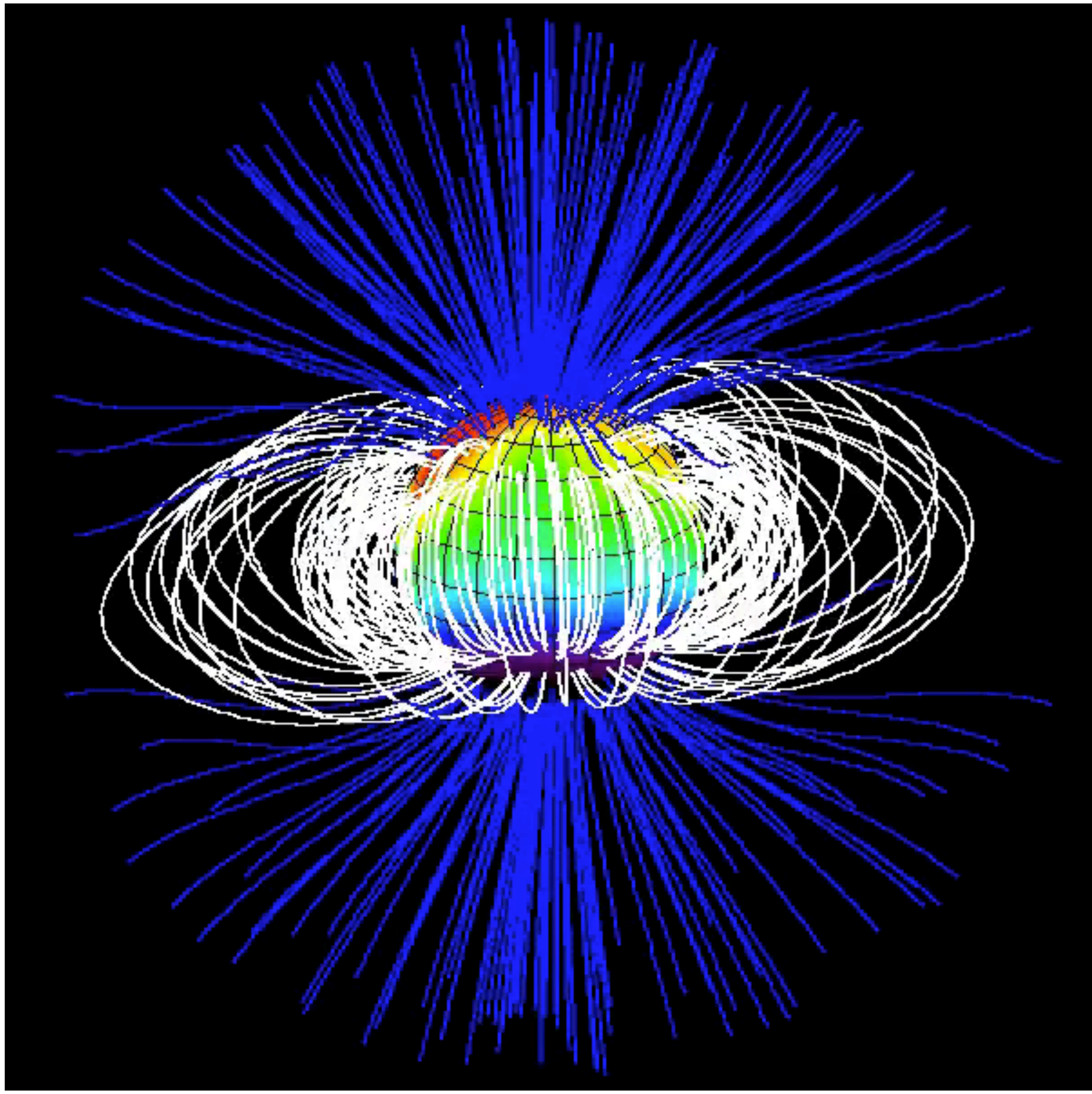


Figure 1. An example of coral fluorescence. Coral fluorescent proteins absorb near-UV and blue light and re-emit it at longer wavelengths (see e.g. Mazel & Fuchs

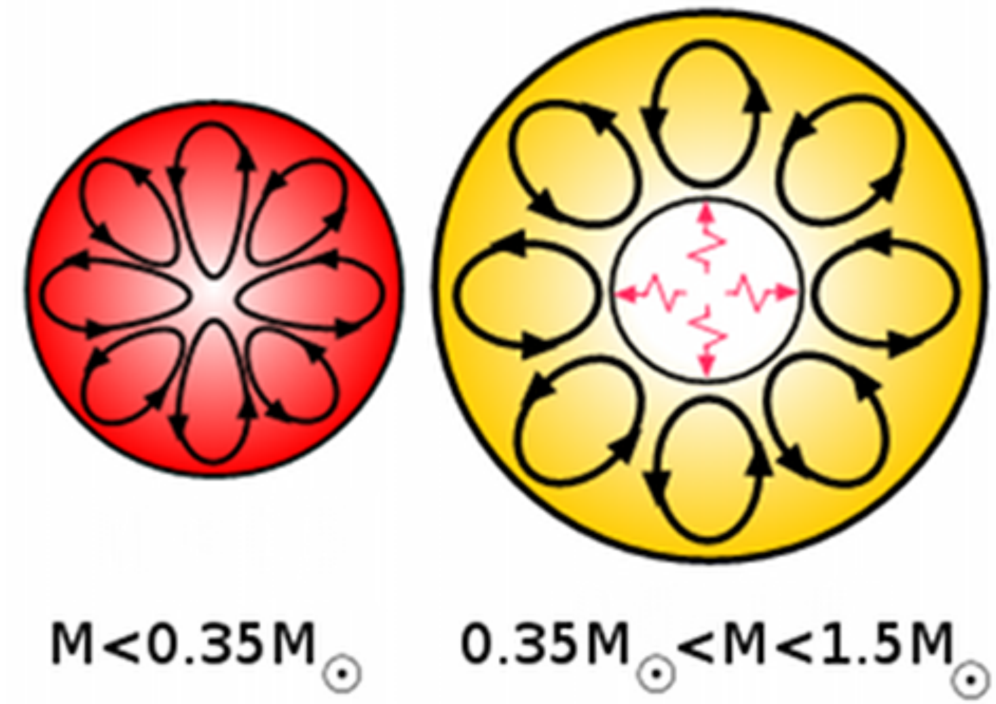
Case II
V374 Peg

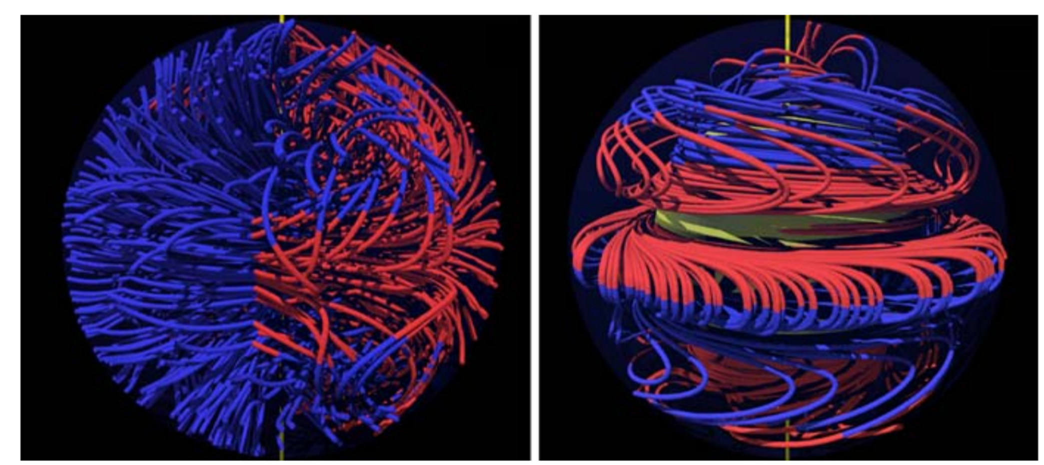
Ground-based photometry
&
high-resolution spectra



Reconstruction of the magnetic field by Zeeman-Doppler imaging (Donati et al. 2006)

- Fast rotation rate (P~0.5d)
- Low-mass ($0.28 M_{Sun}$) M-dwarf
- Magnetic fields are sustained in this mass-regime differently than in solar-like stars
- Stellar activity is possible but slightly different:
    - Slower surface evolution
    - No activity cycles expected
- Zeeman-Doppler Imaging shows stable dipole-like magnetic field

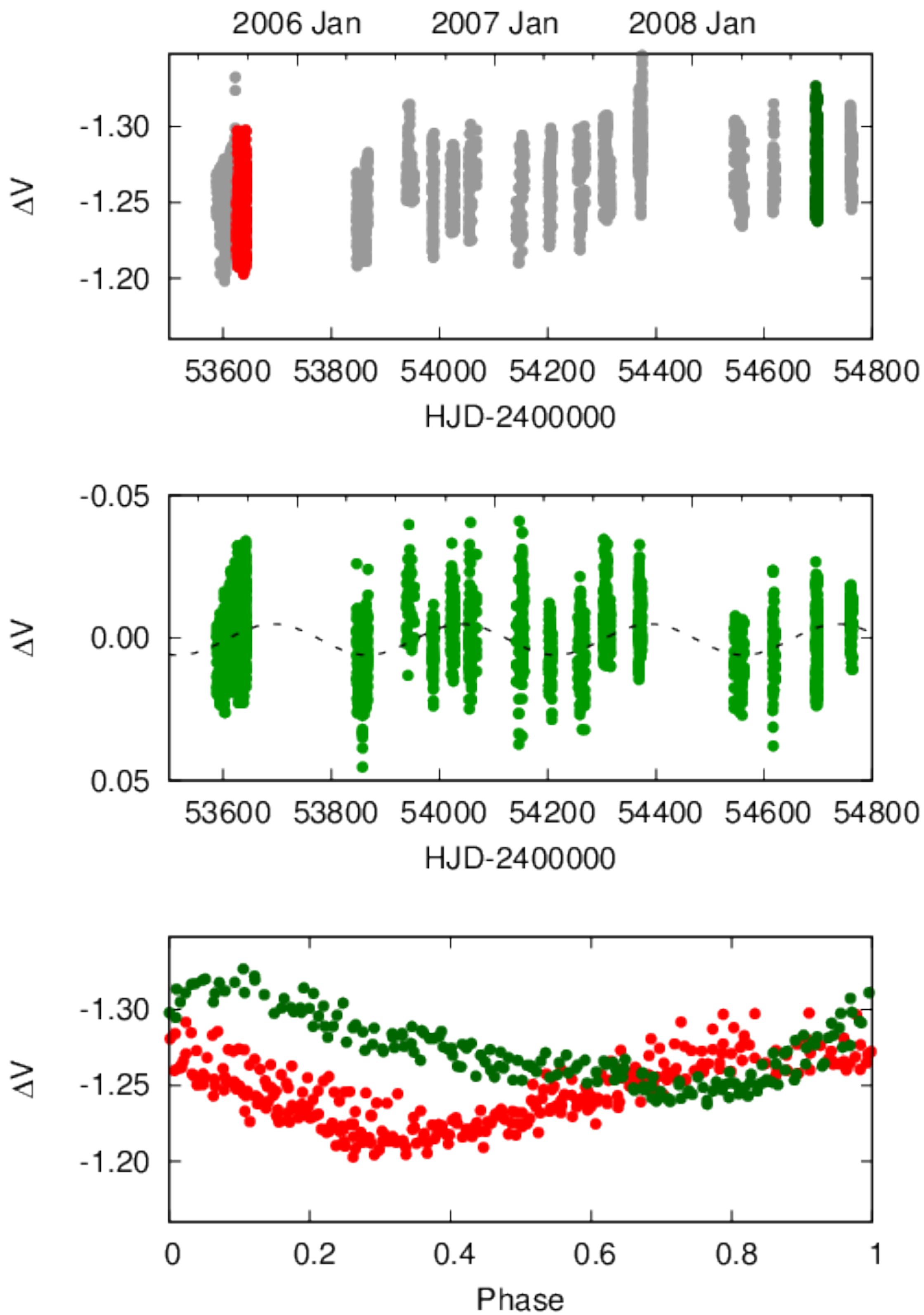




Possibly an α^2 dynamo

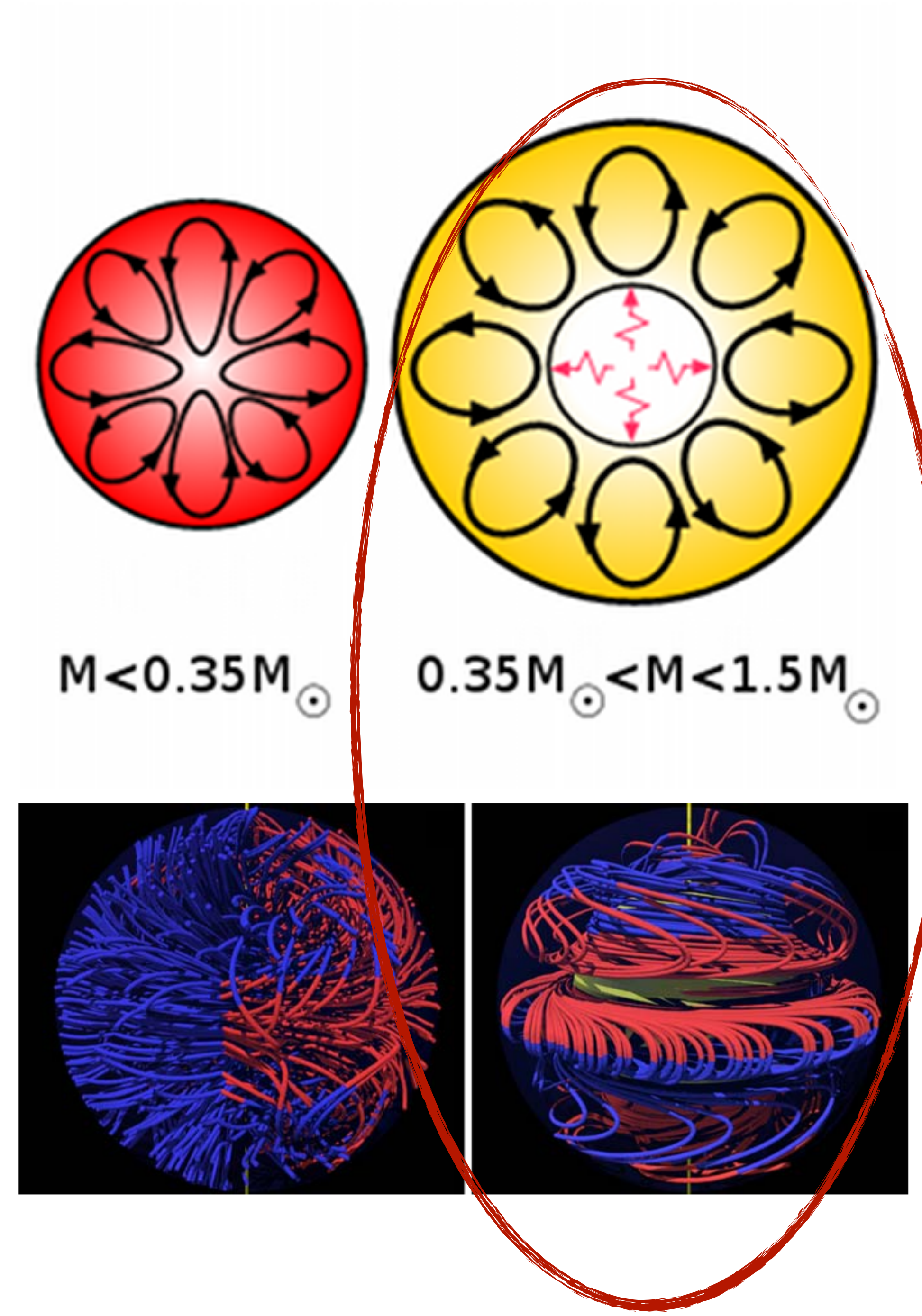
Solar-like $\alpha\Omega$ or distributed $\alpha^2\Omega$ dynamo

Different dynamos have different observable properties, e.g.:



activity cycles

flip-flop phenomenon



EY Draconis, hosting probably an αΩ dynamo

While on fully convective stars we expect:

stable magnetic field (at least a few 1000 rotations)

high-latitude spots

active nests at every longitude

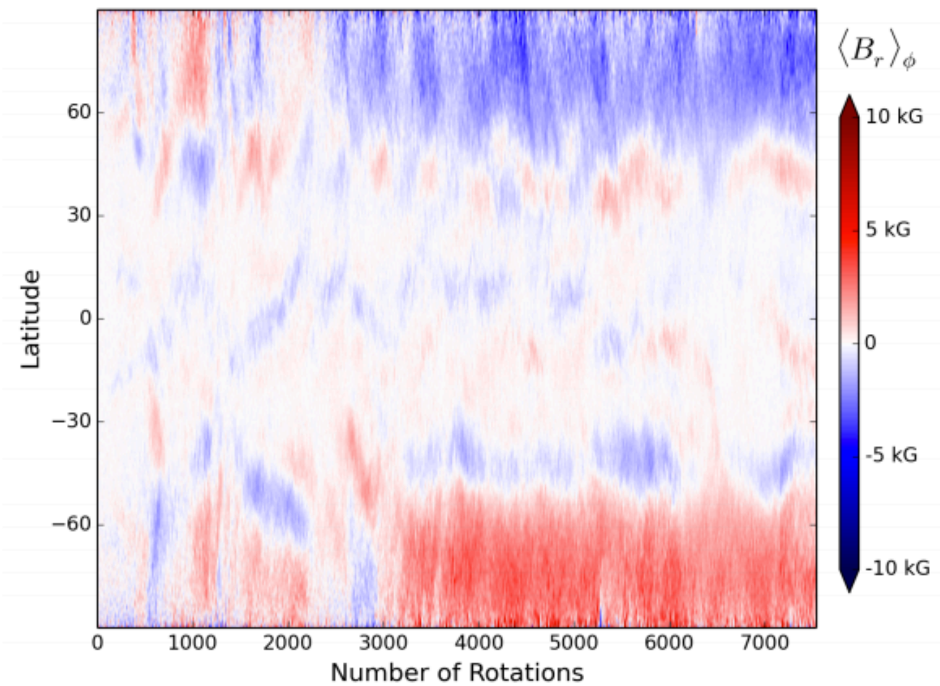
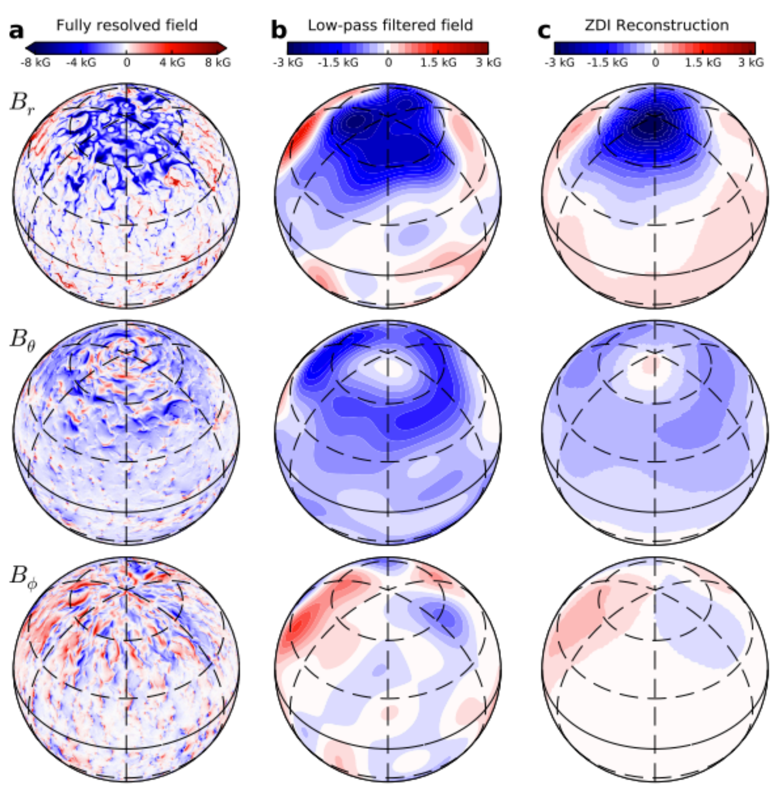
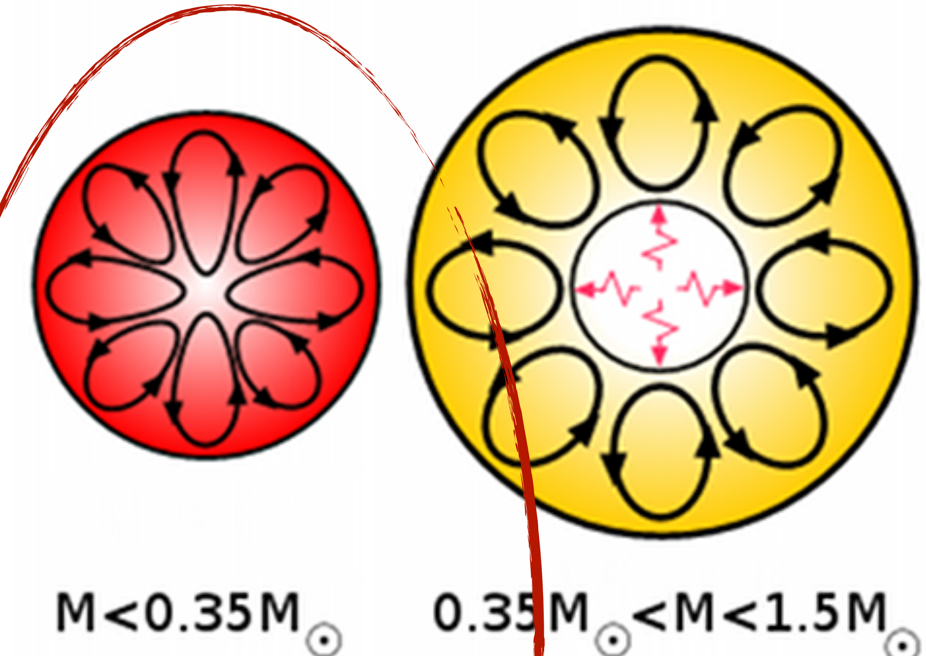
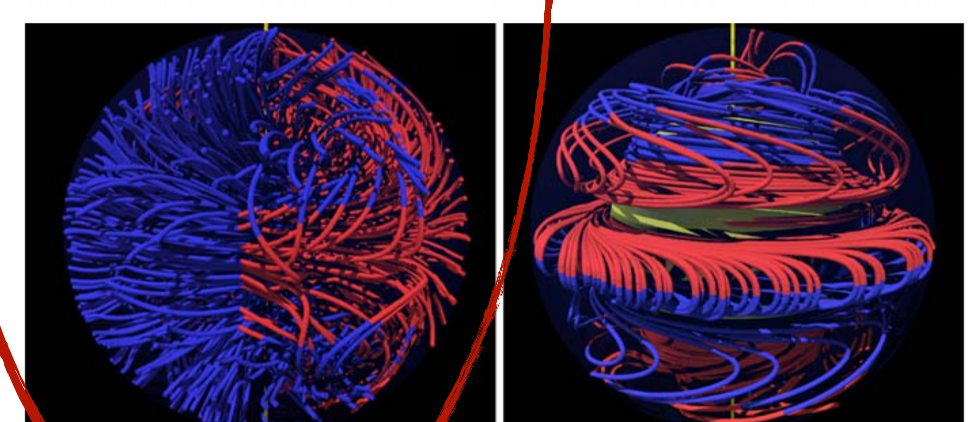


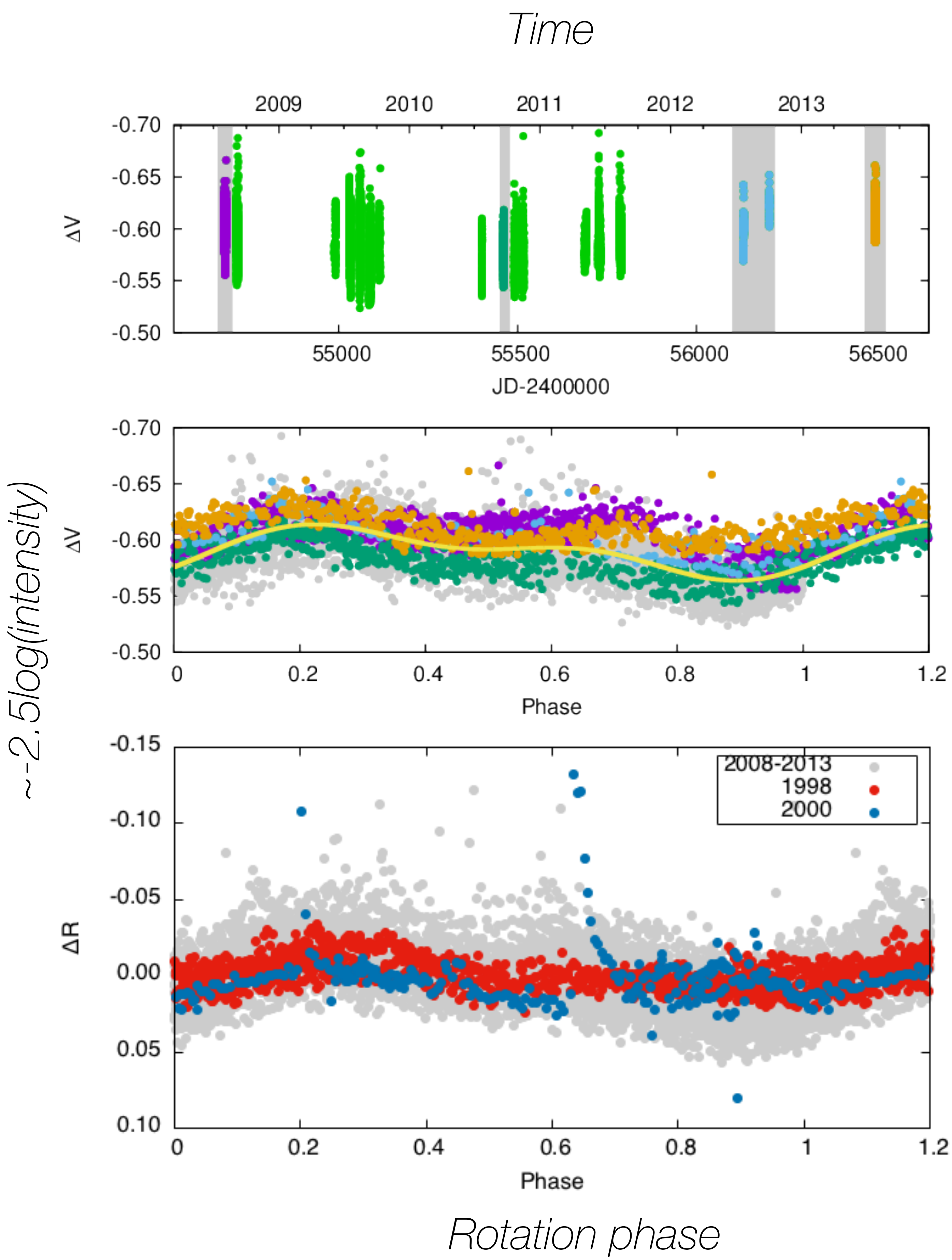
FIG. 2.— Temporal evolution of the azimuthally averaged radial component of the magnetic field at a radius of $0.99r_o$.



Numerical simulations of Yadav et al. (2015)



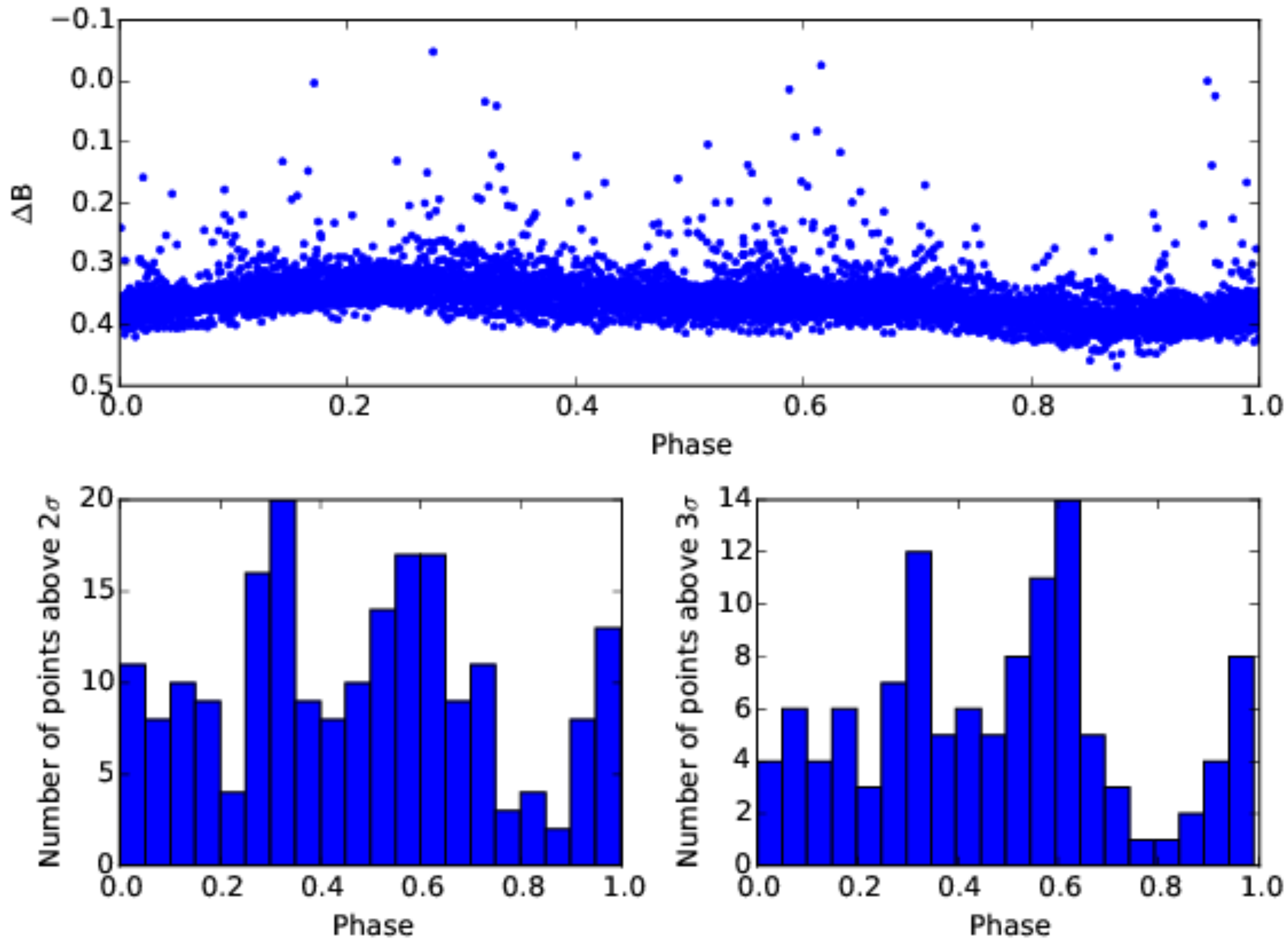




Indeed, the light curve is stable for 5 years!

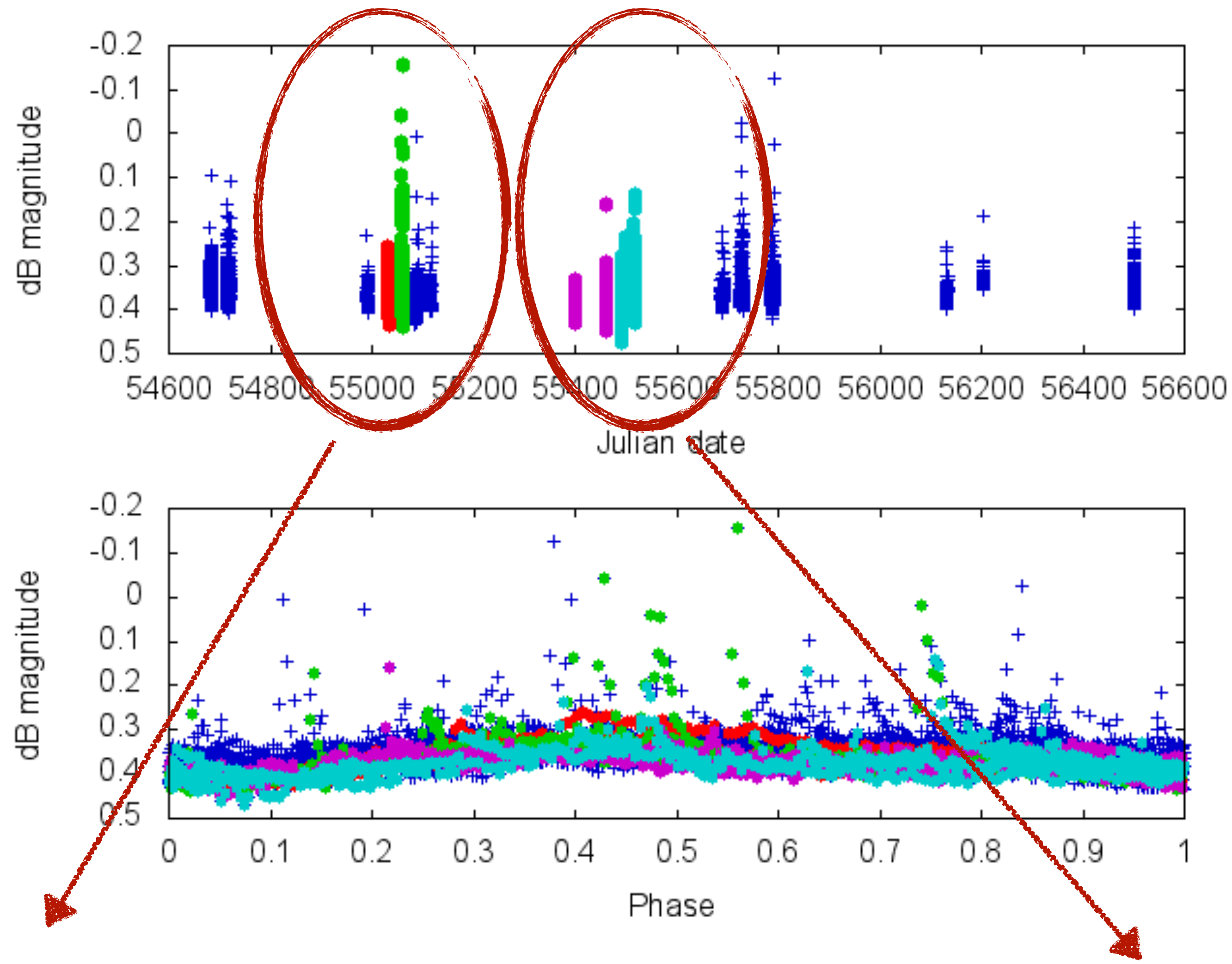
additional R_C photometry from 1998 and 2000 (Climenhaga Observatory) → only small changes in global structure in 15 years

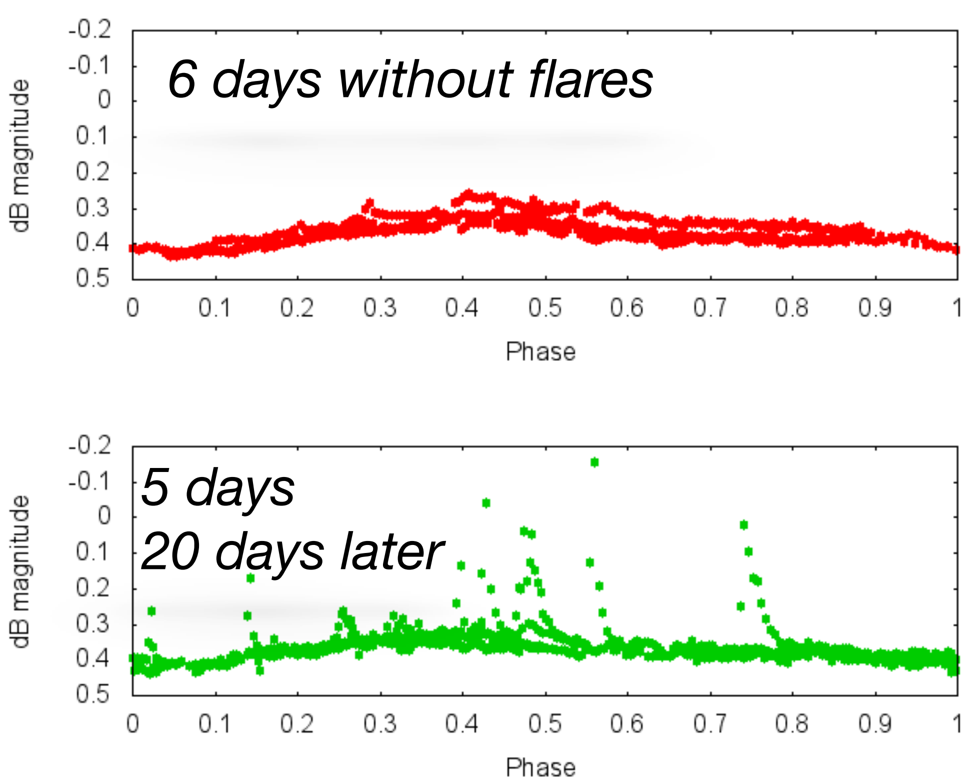
Flares & active nests

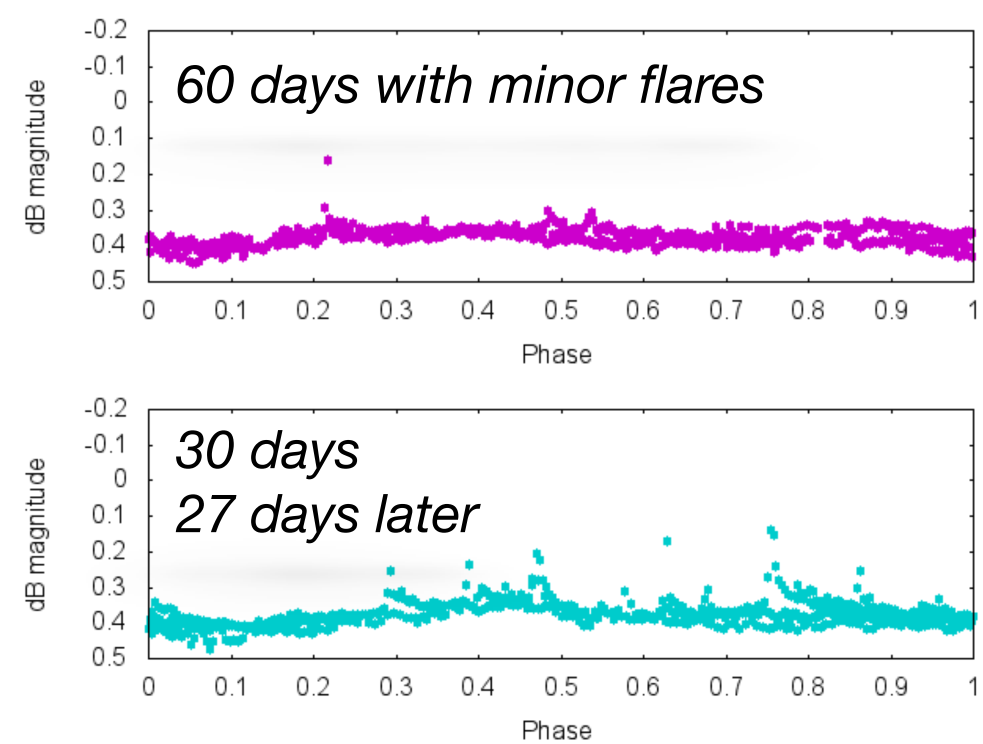


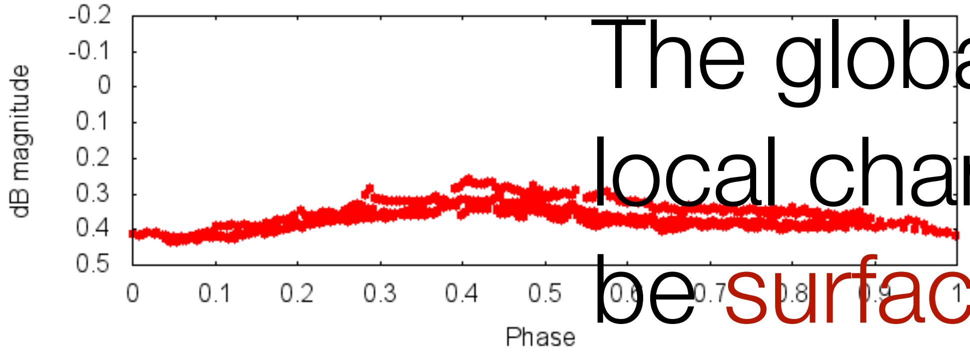
Flares appear at every longitude
(somewhat more frequent at
one of the spotted regions)

Energy buildup?



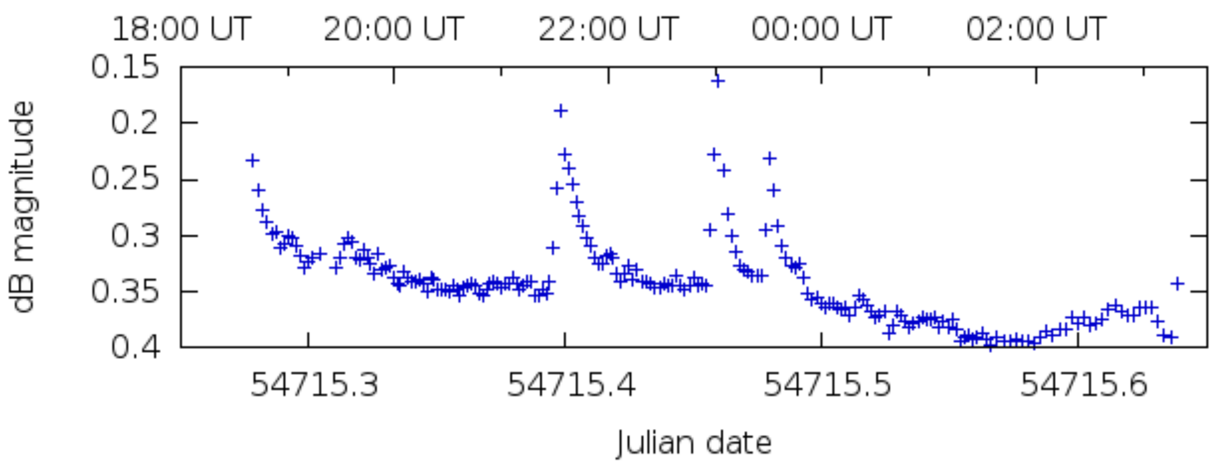


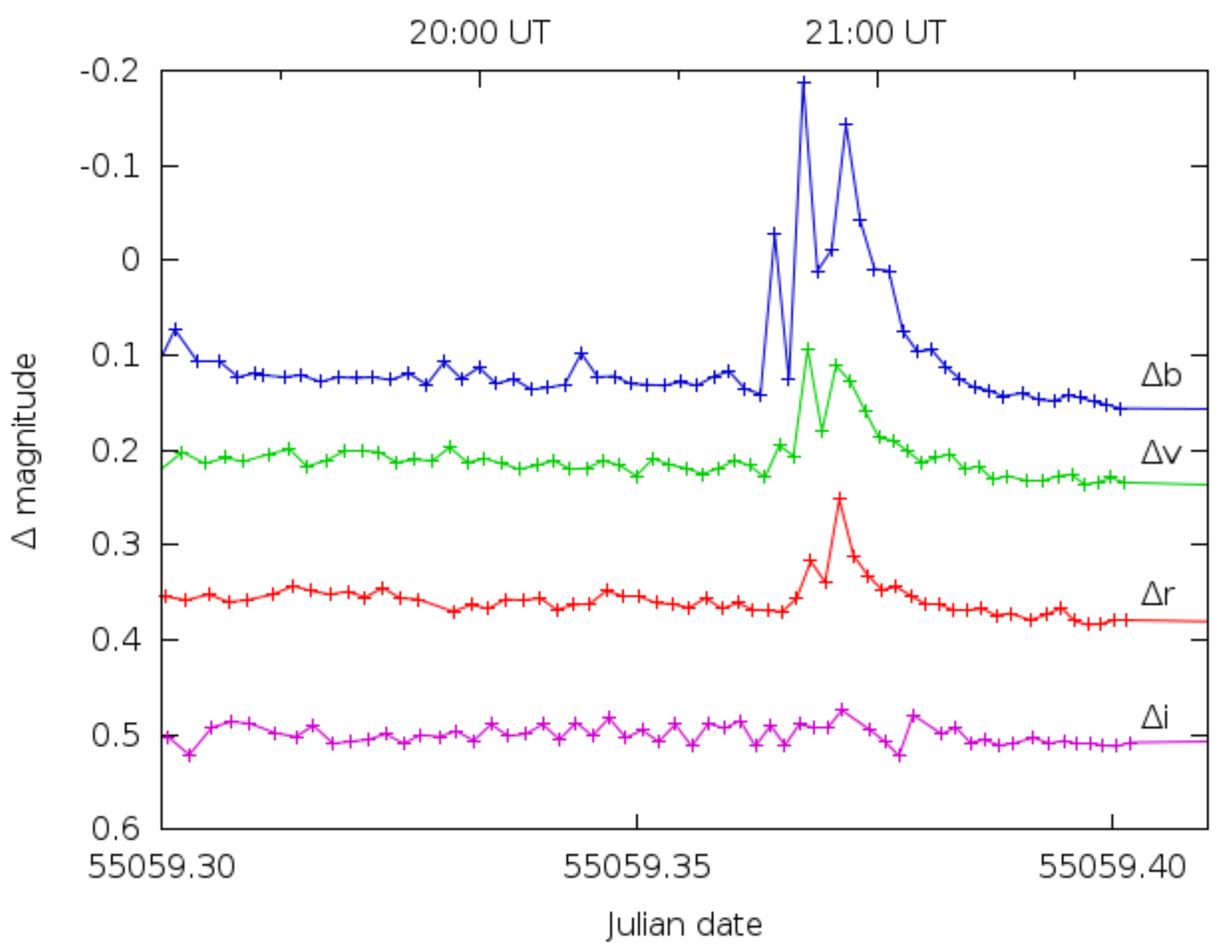


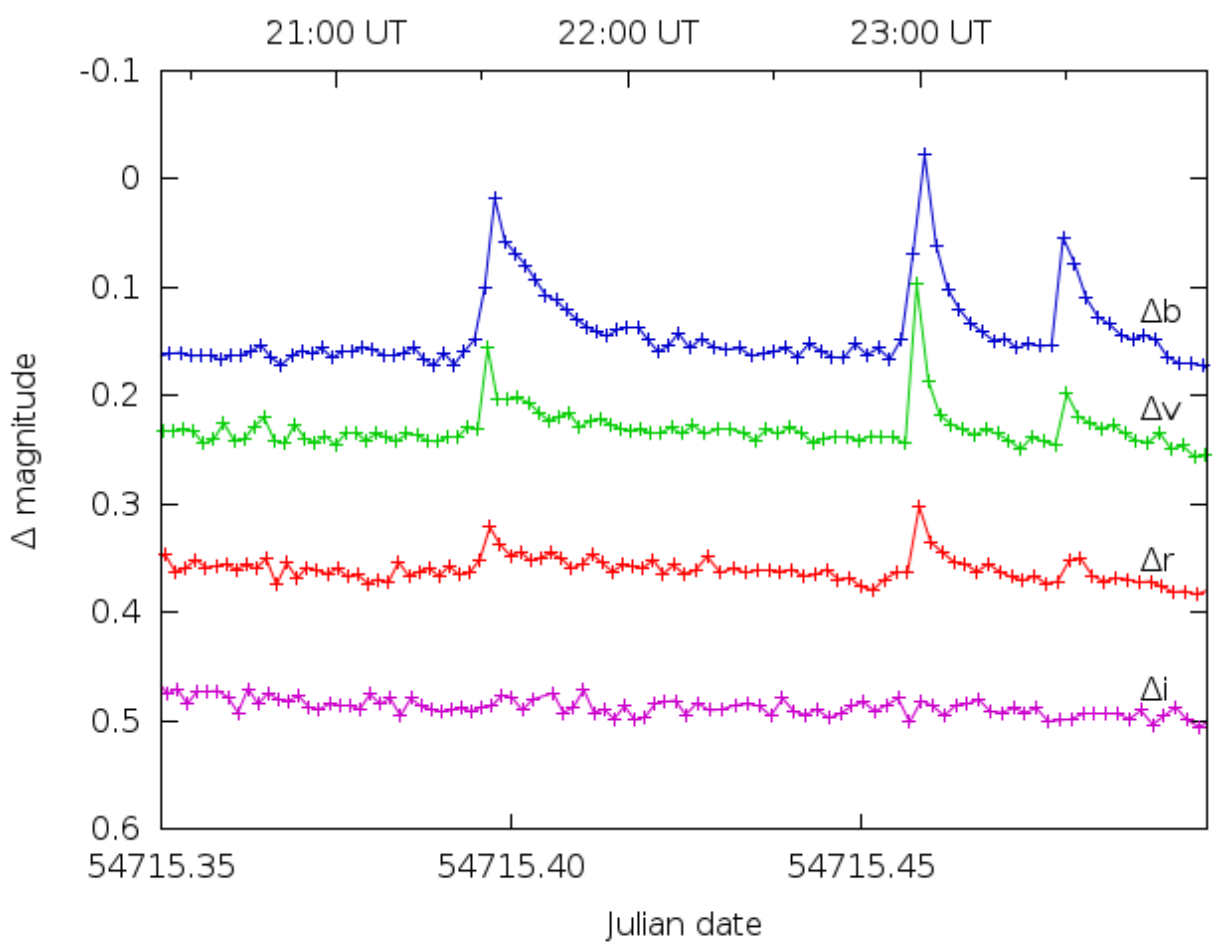


The global field is stable, but there is local change in the light curve: could be surfacing/decaying flux ropes (new, smaller spots appear/disappear)

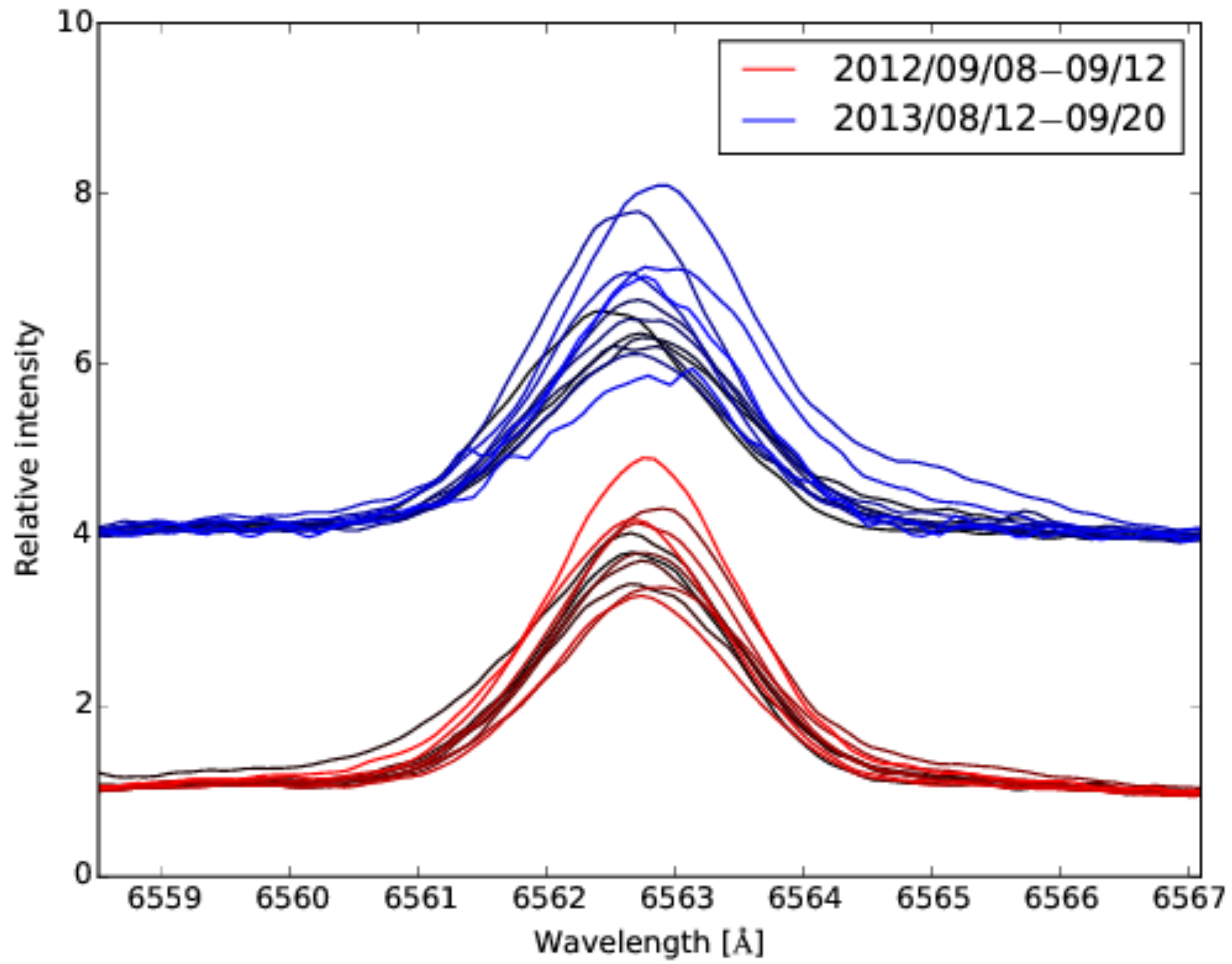
- Stronger flares can be seen in *BVR* passbands
- Can have complex structures & multiple eruptions
- Associated CMEs? (on the Sun always)
- Time scale ~10 mins
- No information on geometry
- Triggered events?





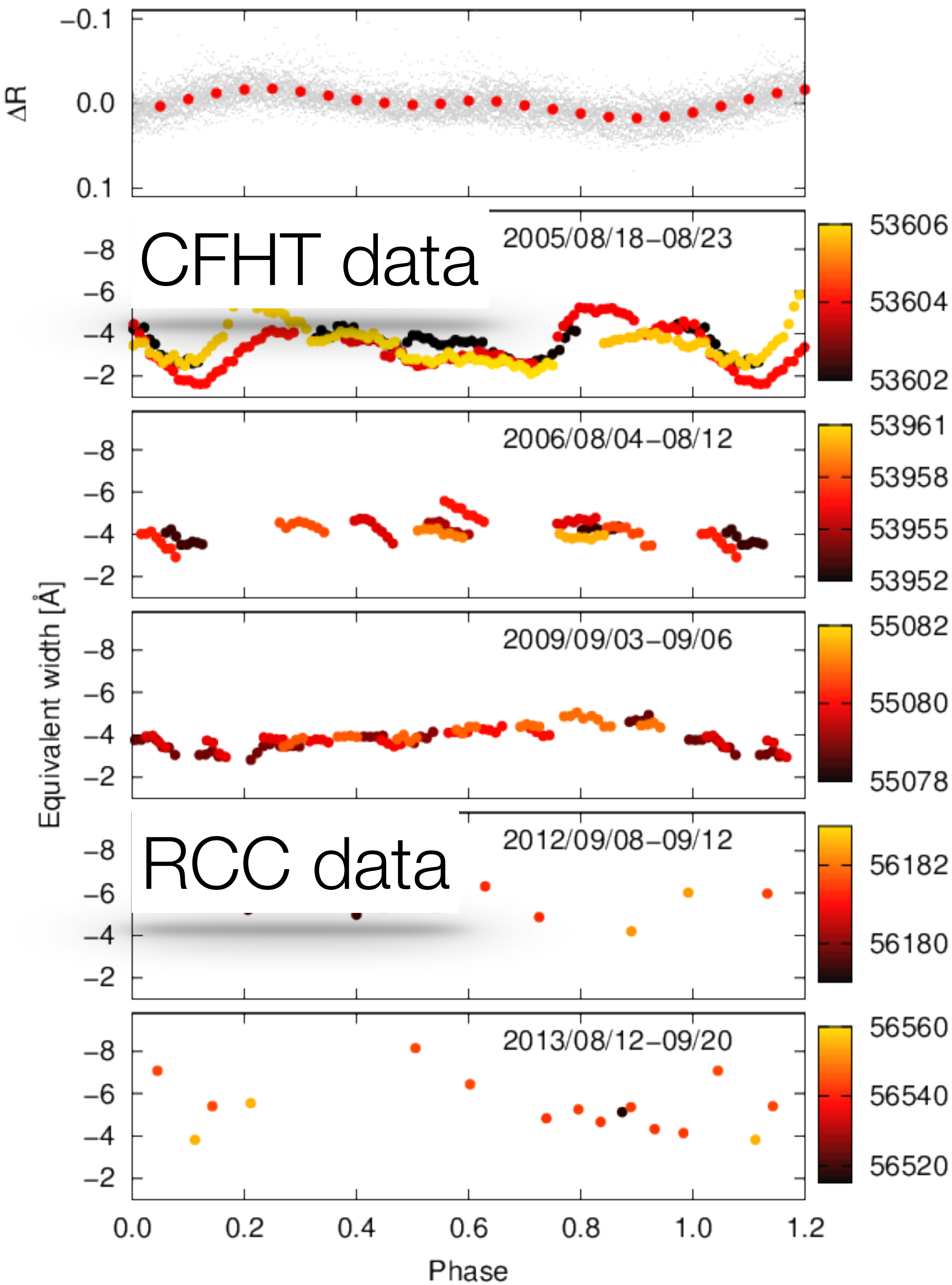


What about the chromosphere?

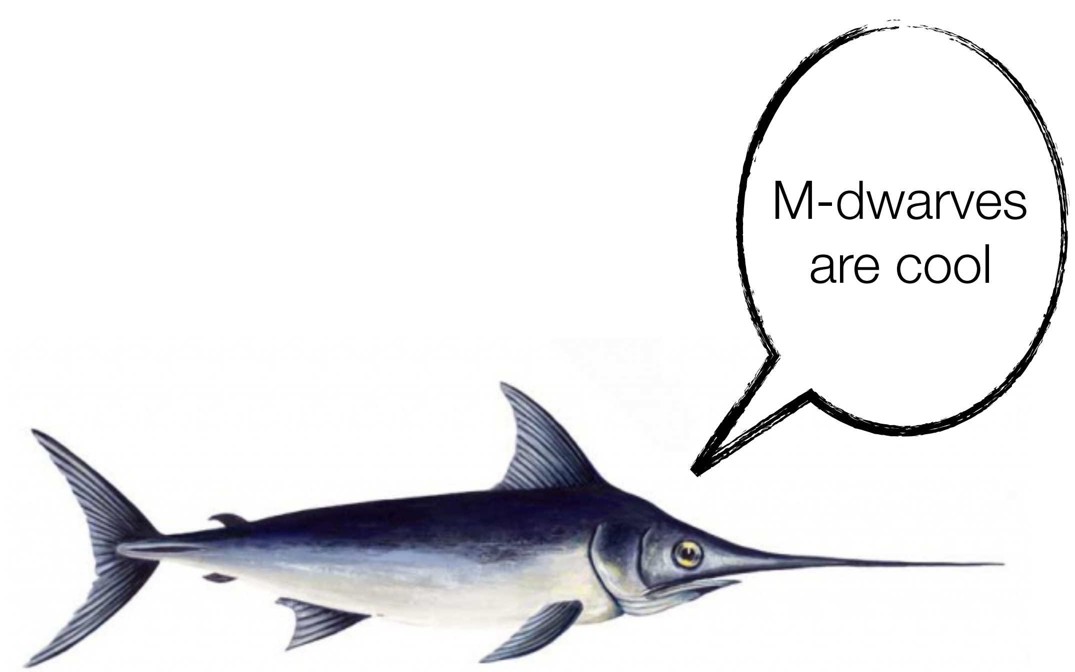


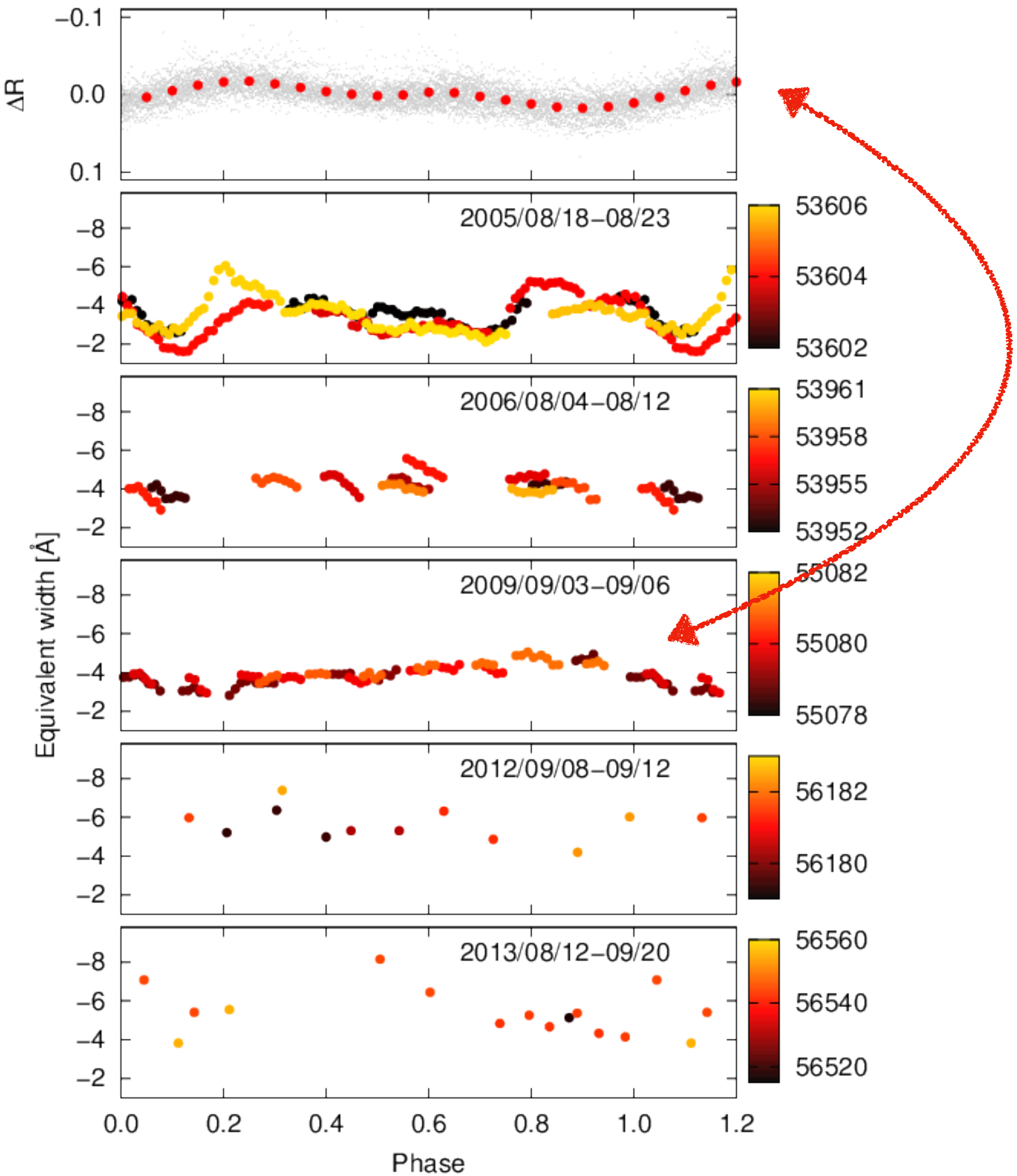
(Time is shown with increasing brightness)

Hα measurements from Piszkéstető: the chromosphere is highly variable

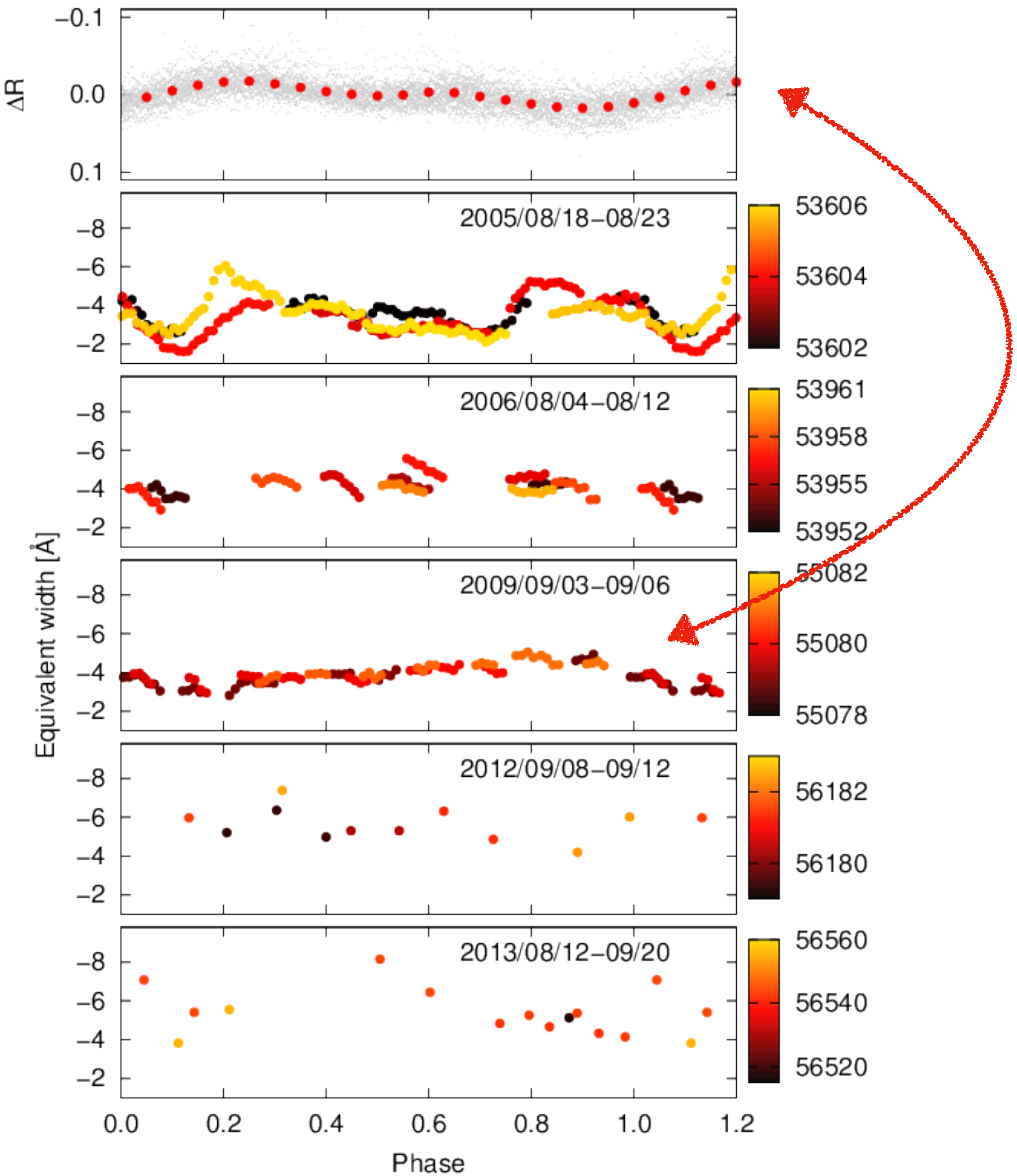


Later it turned out that there is a vast amount of unpublished data in the CFHT (Canada-France Hawaii Telescope)/ ESPaDOnS archive





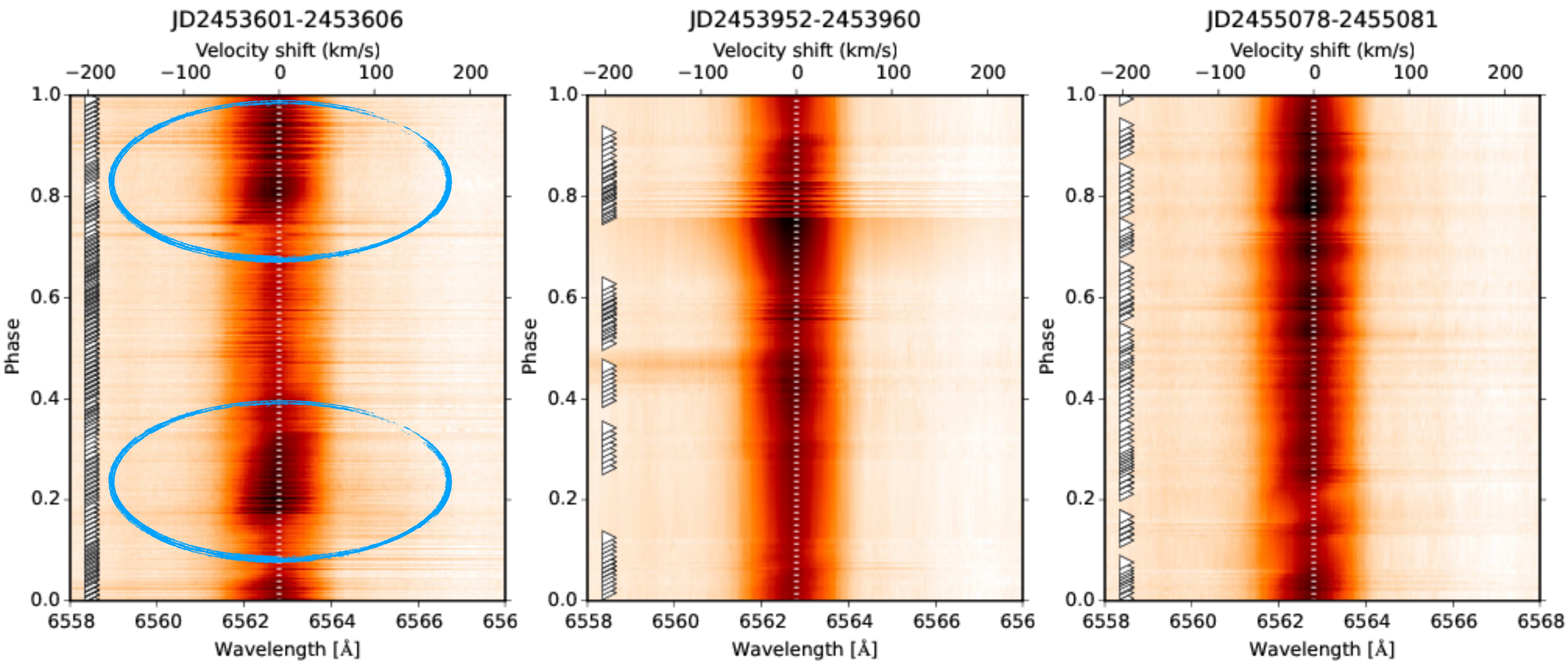
Anticorrelation between
the photosphere
& chromosphere
(Hα gets stronger
around cool, dark spots)



Anticorrelation between the photosphere & chromosphere (Hα gets stronger around cool, dark spots)

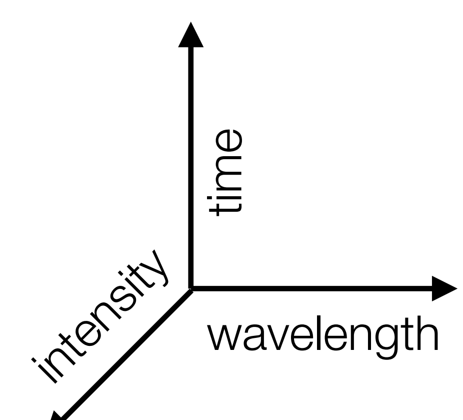
not much to see here…

The CFHT data gives a good phase coverage, high S/N, and good temporal resolution



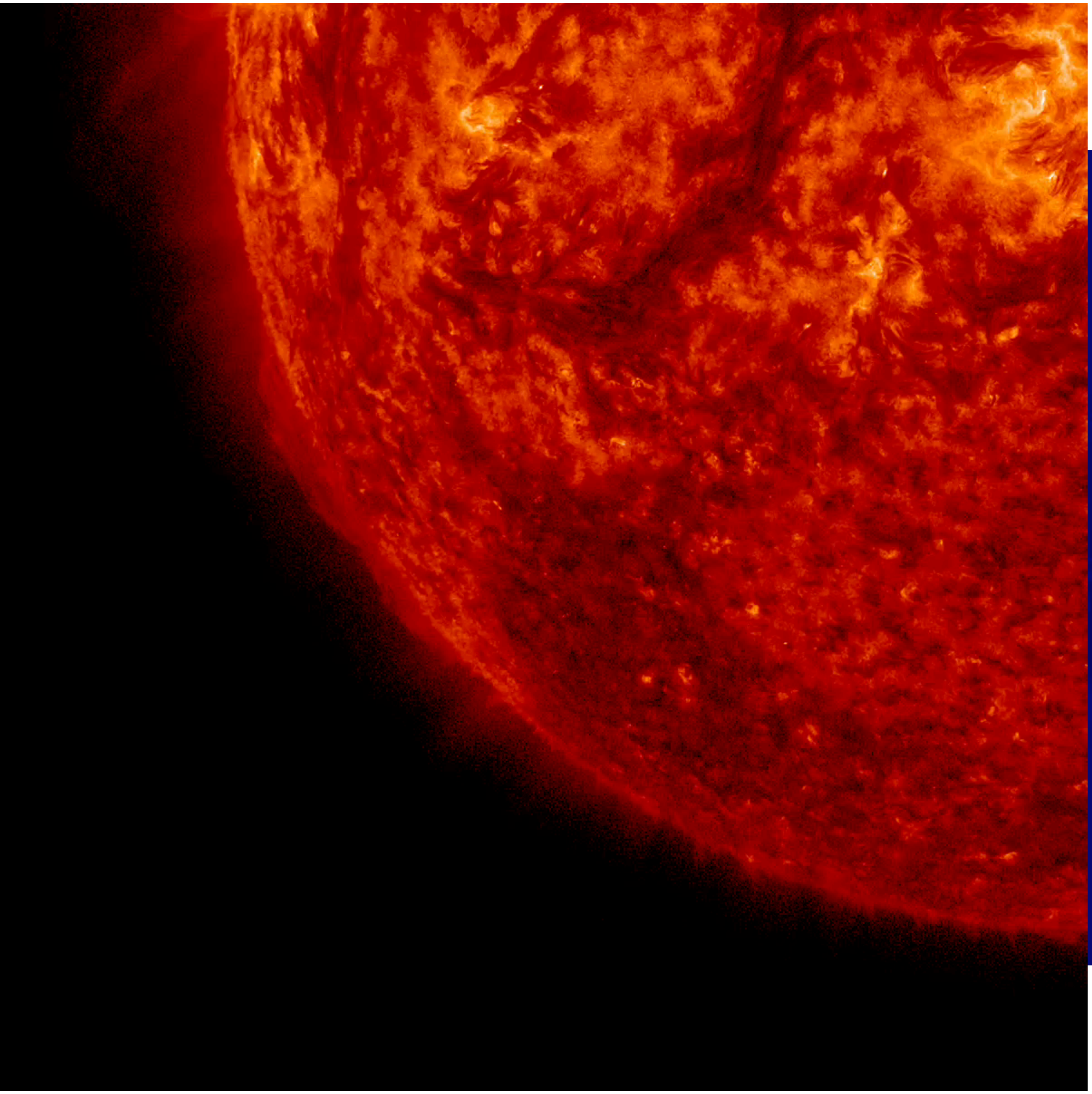
Flares in the Hα region

Two boring plots with no Hα variation

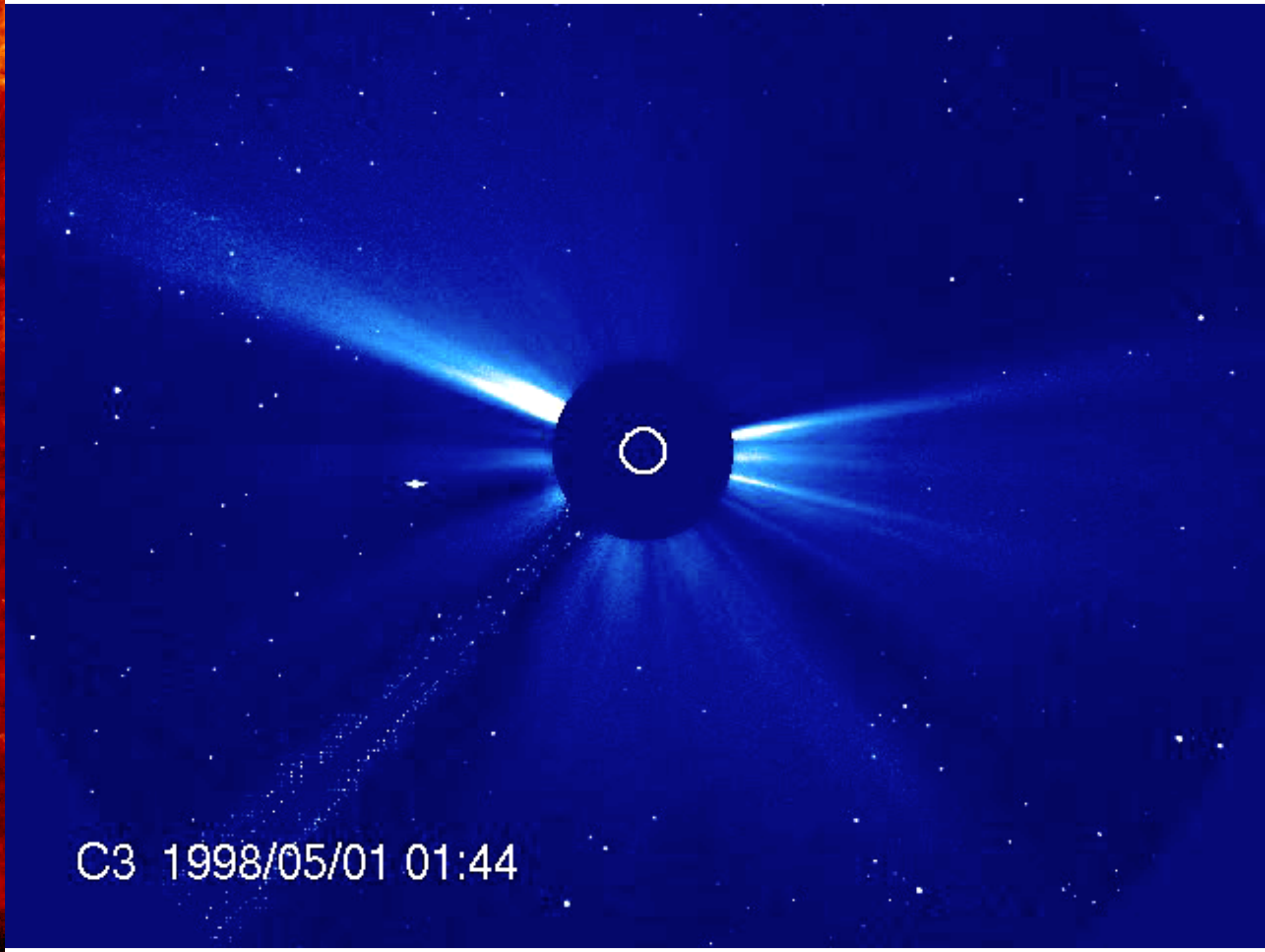


Decoding dynamic spectra

Can we detect coronal mass ejections (CMEs)?



CME on the Sun with
ejected/falling back plasma
(NASA SDO, 2015)



CME on the Sun
(NASA SOHO, 2000)

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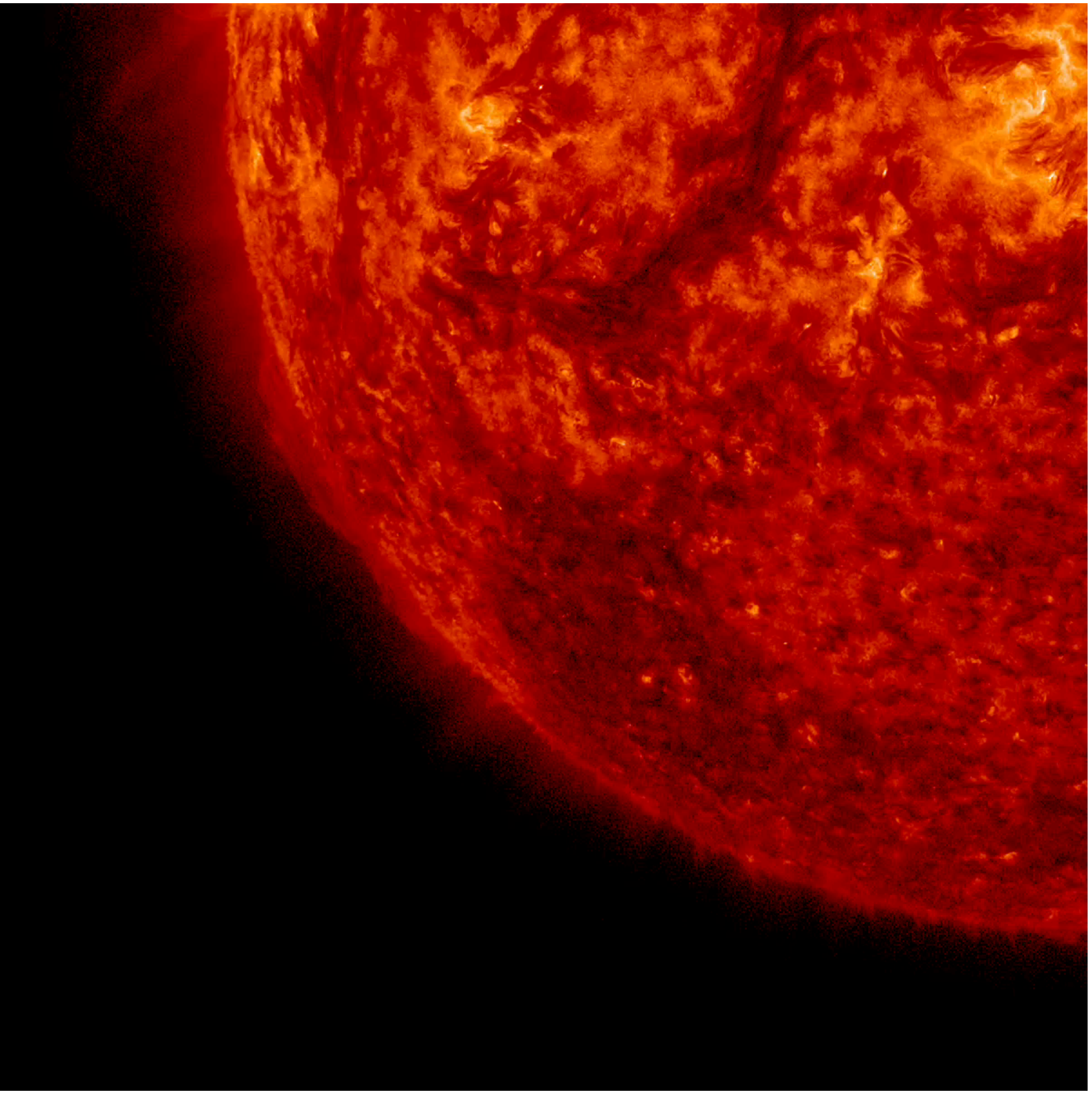
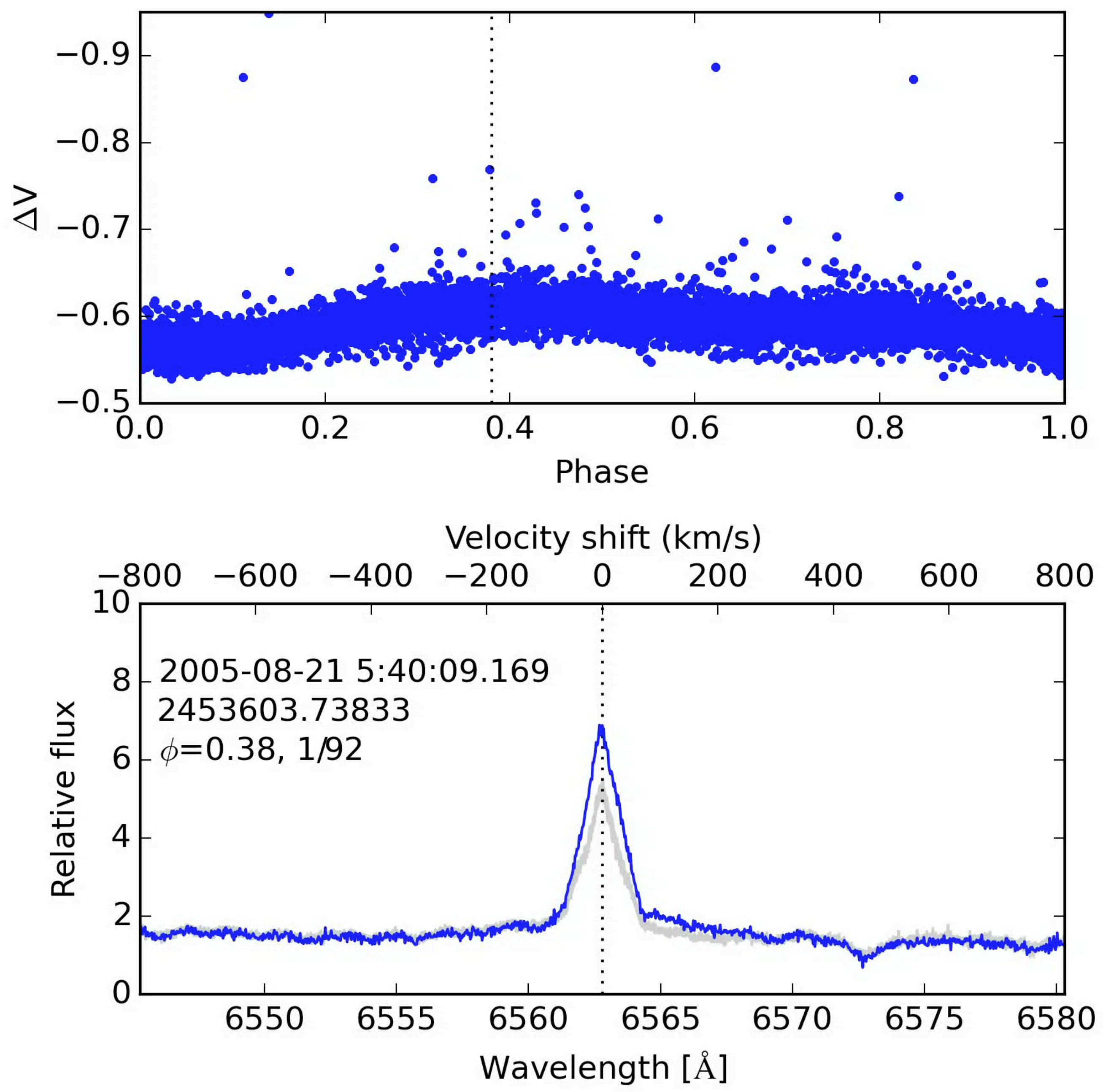
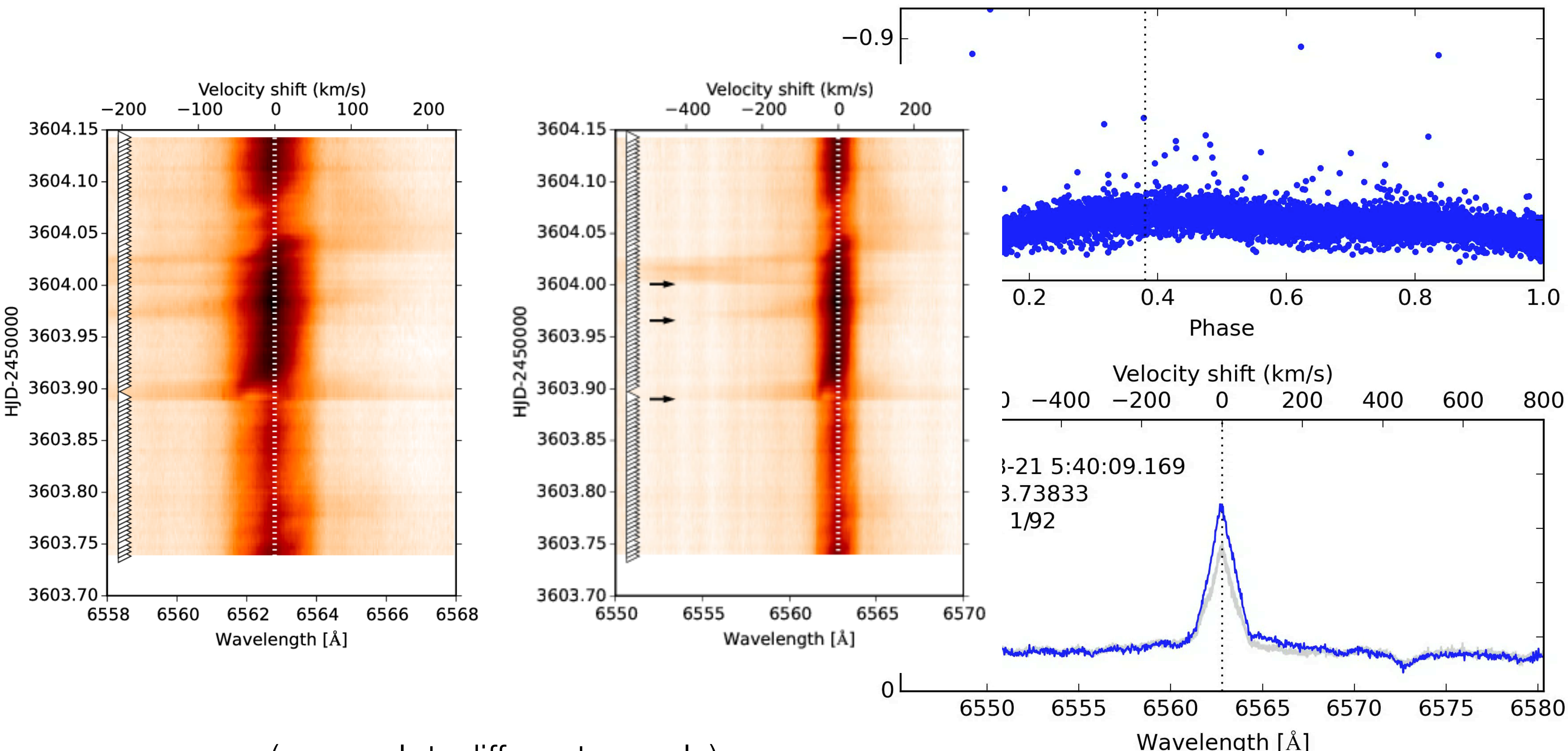


CME on the Sun



CME on V374 Pegasi

Can we detect coronal mass ejections (CMEs)?



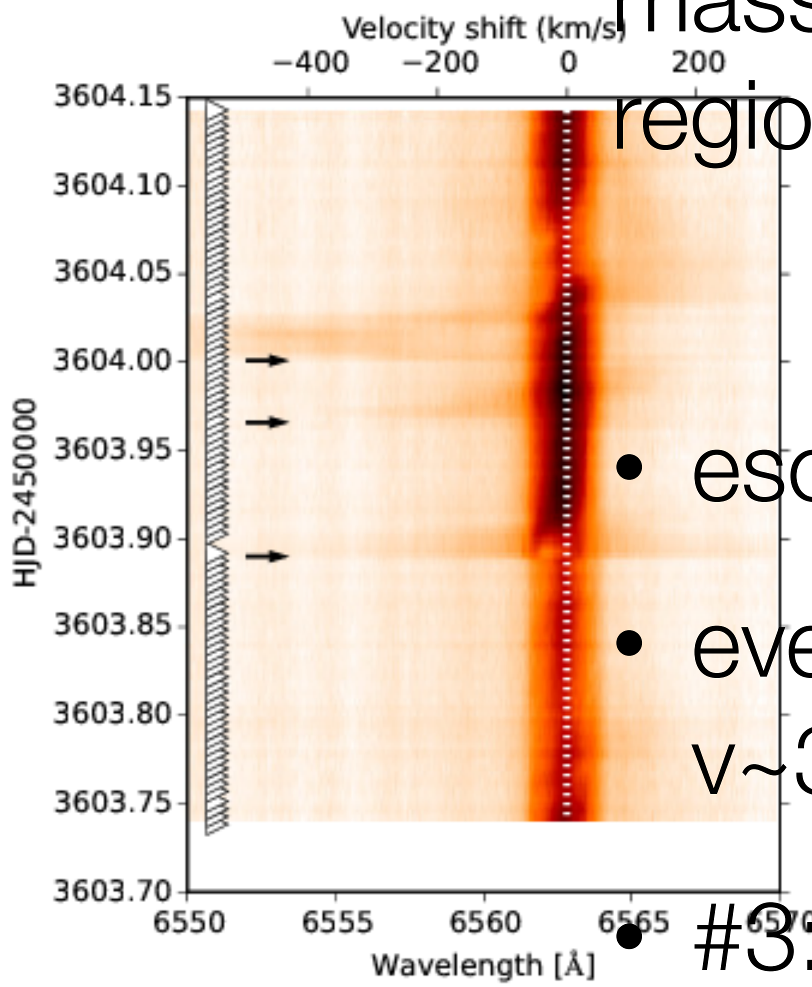
(same plot, different x scale)

Flares and multiple coronal mass ejections in the Hα region

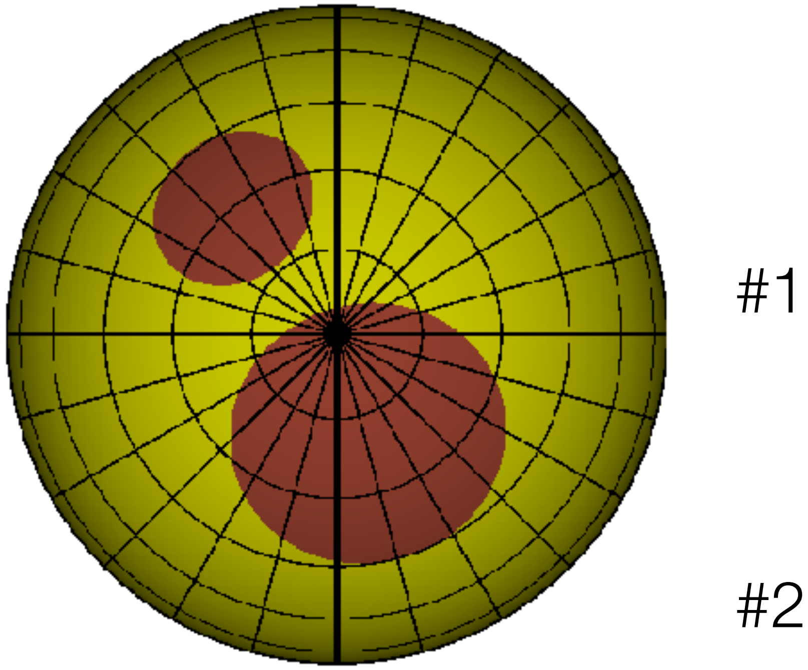
3

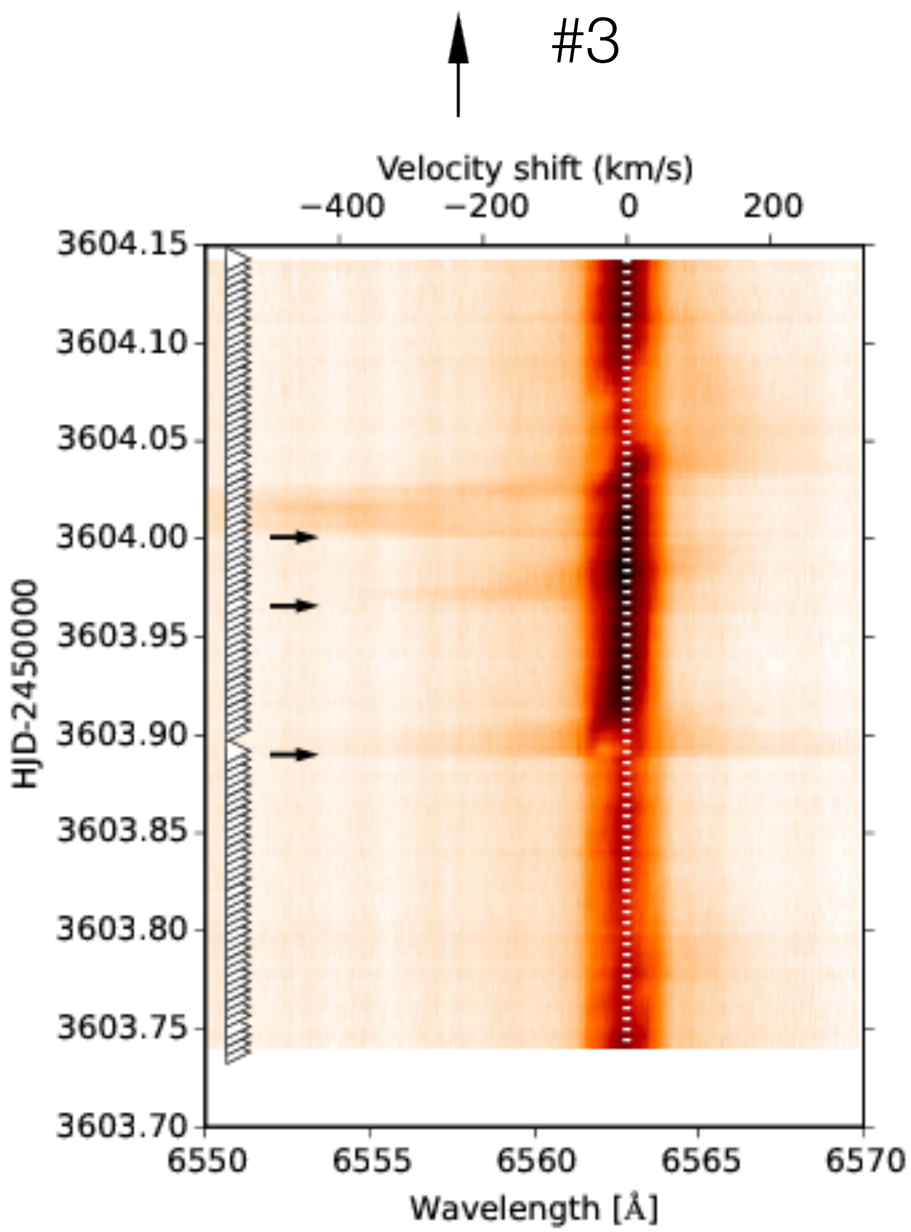
2

1



- escape velocity ~580km/s
- events 1&2: projected v~350km/s
- #3: v~675km/s → above v_e





We measure only projected velocity, but:

- IF the CMEs are connected to the large active region
- IF we trust the i=70° inclination
- IF we trust the photometric spot model
- IF we trust the estimated latitude (70°), too
- → ejection in the plane of sight
- → event #1: we observe ~16% of the ejection velocity (can be v_e~2200km/s)
- → event #2/3: observed velocity ~ v_e
- mass of ejecta: $M_{CME}>10^{16}$g (~massive solar CMEs)

"The three events span a time range of about three hours, which corresponds to about 30% of the stellar rotation period. If, as assumed above, the signatures are connected to the same active nest, then the rotation of the nest has a significant influence on the projected velocity of the events. BWE1 started at phase 0.72, while the centre of the large spotted region is at λ ≈ 340°,i.e. the 0.94 phase. If this eruption happened in the middle of this nest, we would thus only observe ~ 19% of the actual velocity (neglecting the effect of the latitude). For BWE2 and BWE3 this value is 95% and 98%, respectively. The large size of the active region (γ ≈ 42° radius), however, causes a rather large uncertainty in these estimated values."

Why spend so much time on one CME event?

- On the Sun we see 0.5-6 CMEs/day (depending on the activity cycle)
- On the Sun basically every strong flare is associated with a CME
- On other stars only a handful such event is known (<10)
- On V374 Peg we should see 15-60 CMEs/day based on the Sun, but there was only one in ~30hrs
- Preliminary result: a search in archive data for more than 40 stars yielded no further events

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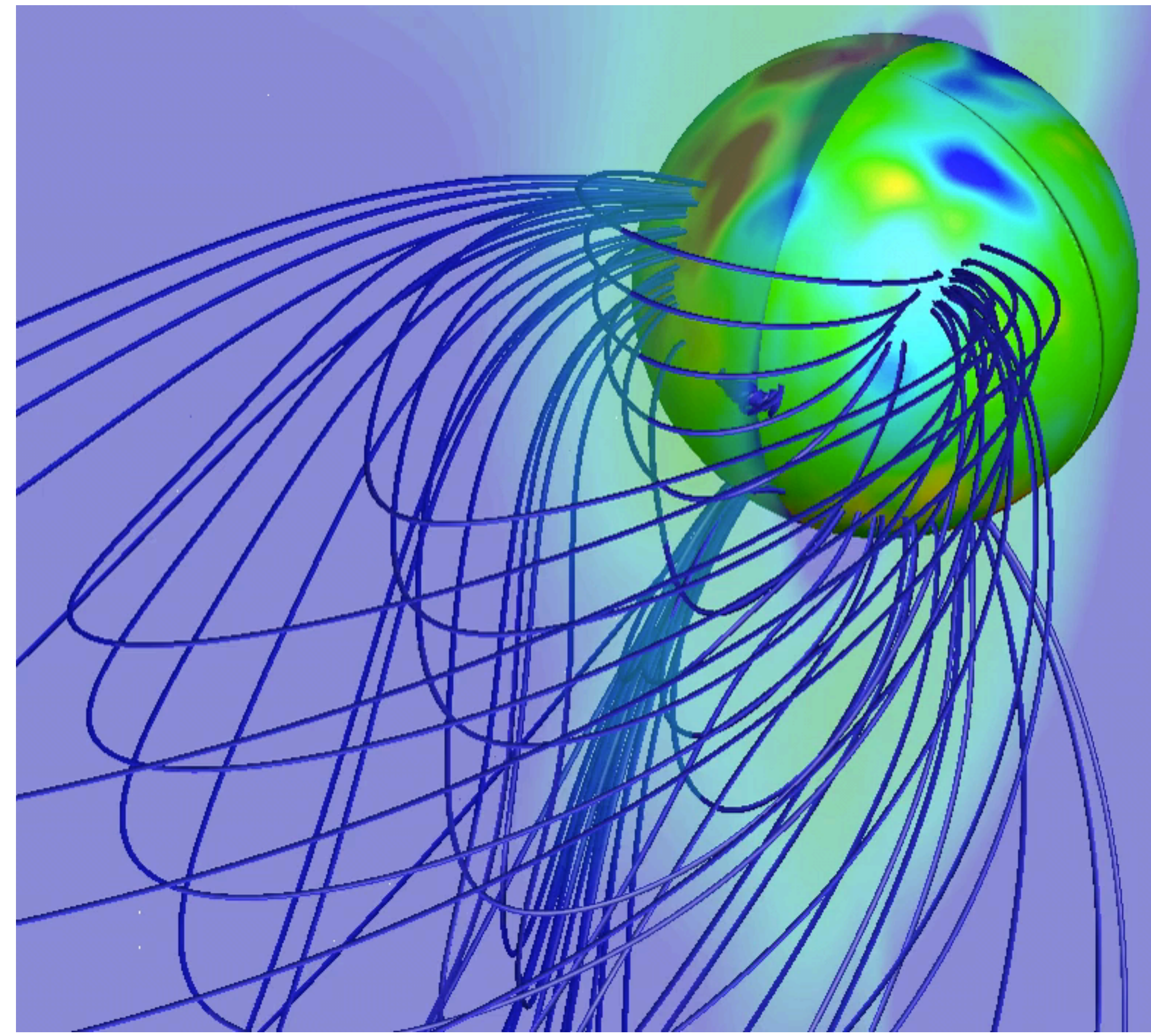

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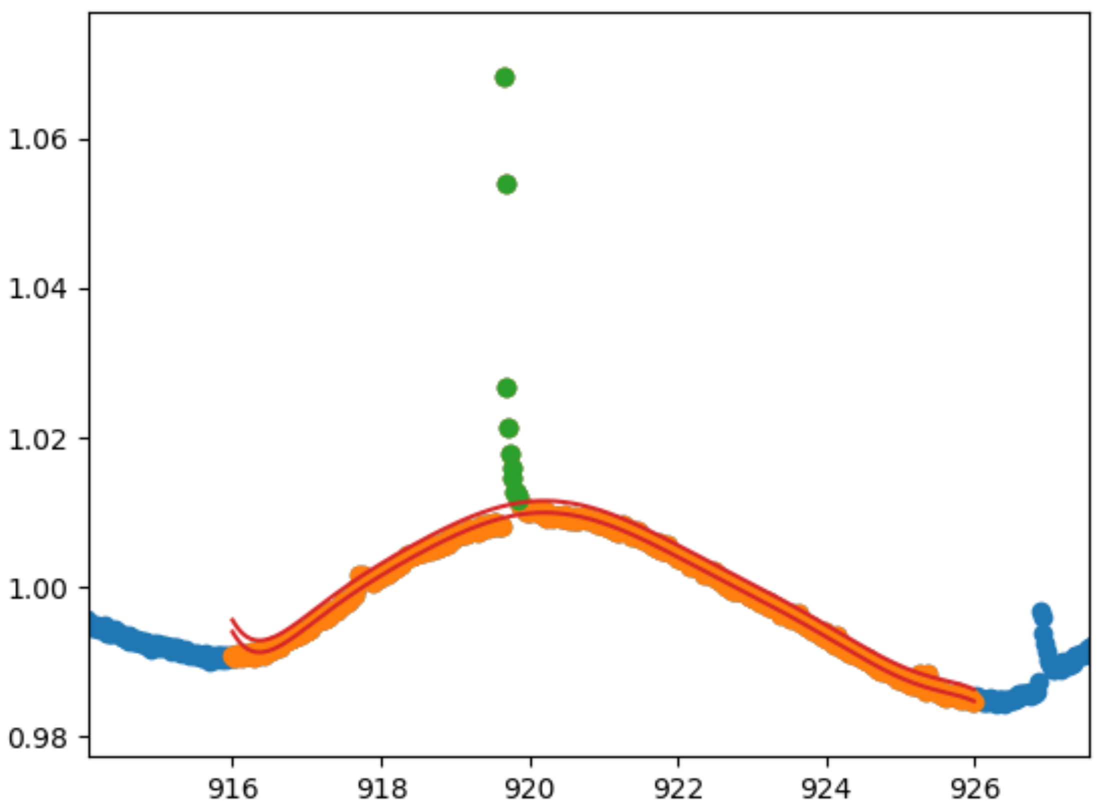
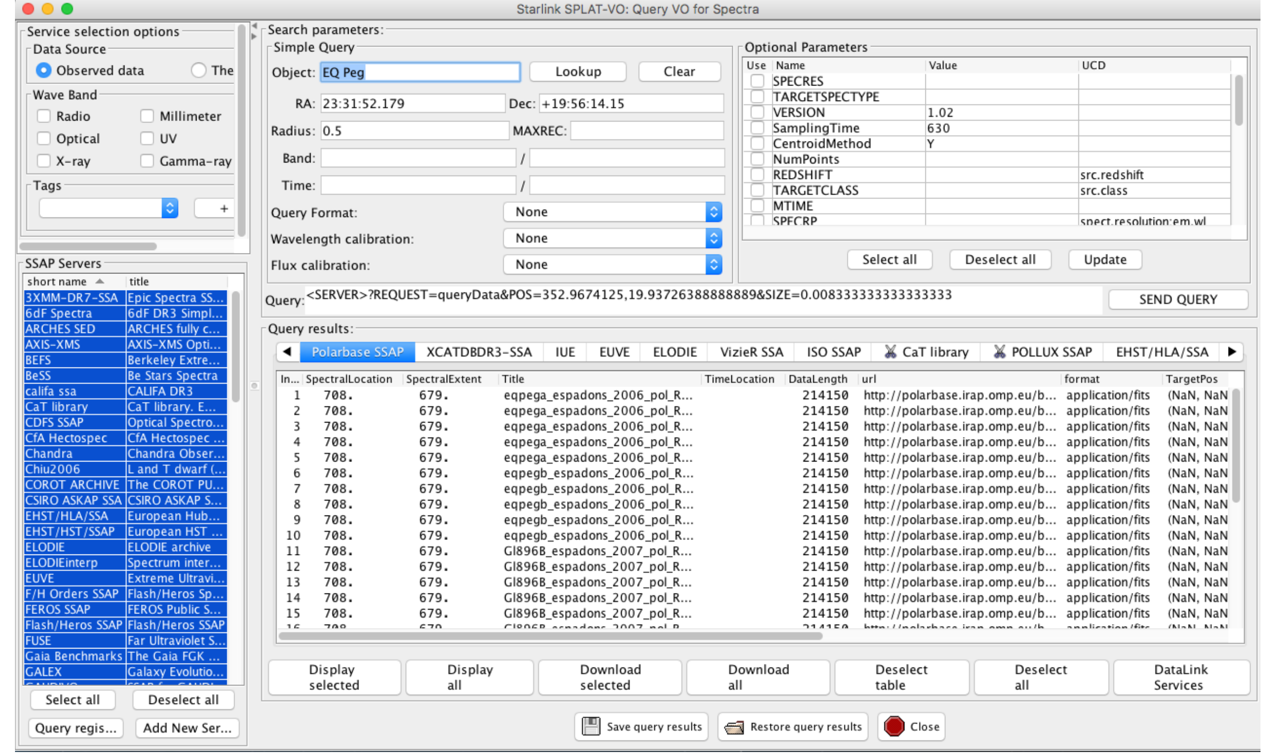
- Maybe we are not detecting many CMEs, because there actually are only few of them? It has been hypothesized that the strong magnetic fields on young stars could actually prevent a filament from erupting in analogy to solar failed eruptions (Drake et al. 2016).

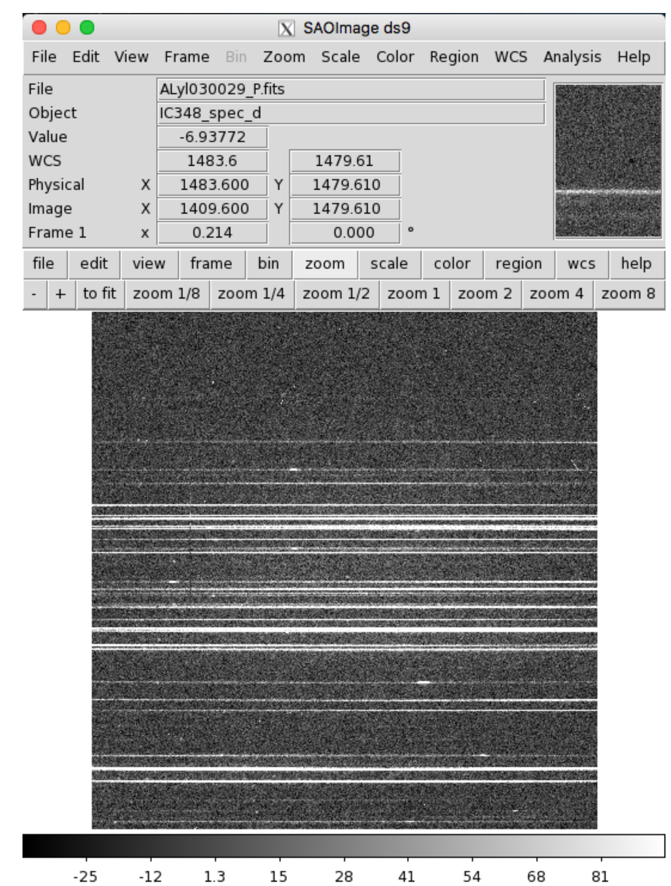
Outlook



New algorithm for flare detection using machine learning



CME hunt in an extended (~700 targets) list in archives using Virtual Observatory tools



CME hunt in open clusters with multi-object spectroscopy