Stellar flares
in photometric time-series data

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& PLATO STESCI WGflares

Aims of WG "Stellar flares"

(a sub-group in WP123 100)

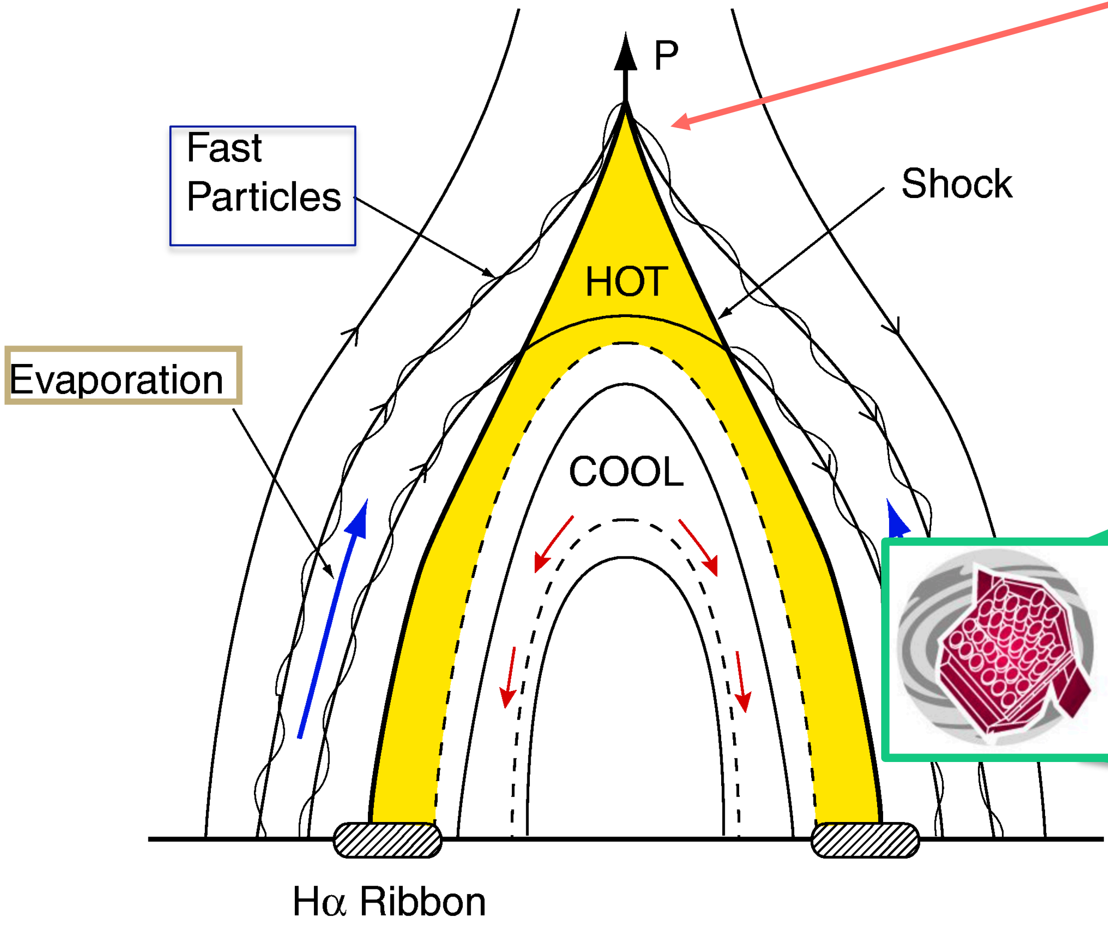
(A) Removal of flare events to "clean" lightcurve for other purposes,
e.g. search for periodic signals (planets, rotation, oscillations, …)

(B) Study the physics of stellar flares
-- Flares are crucial for habitability … and stellar physics --

Status of WG "Stellar flares"

- starting NOW
- no results from coordinated efforts yet

Standard solar flare scenario



Cargill & Priest (1983)

Magn. Reconnection
releases energy

↓

Electron acceleration
(radio gyro-synchrotron emission)

↓

Non-thermal hard X-rays
+ optical white-light emission

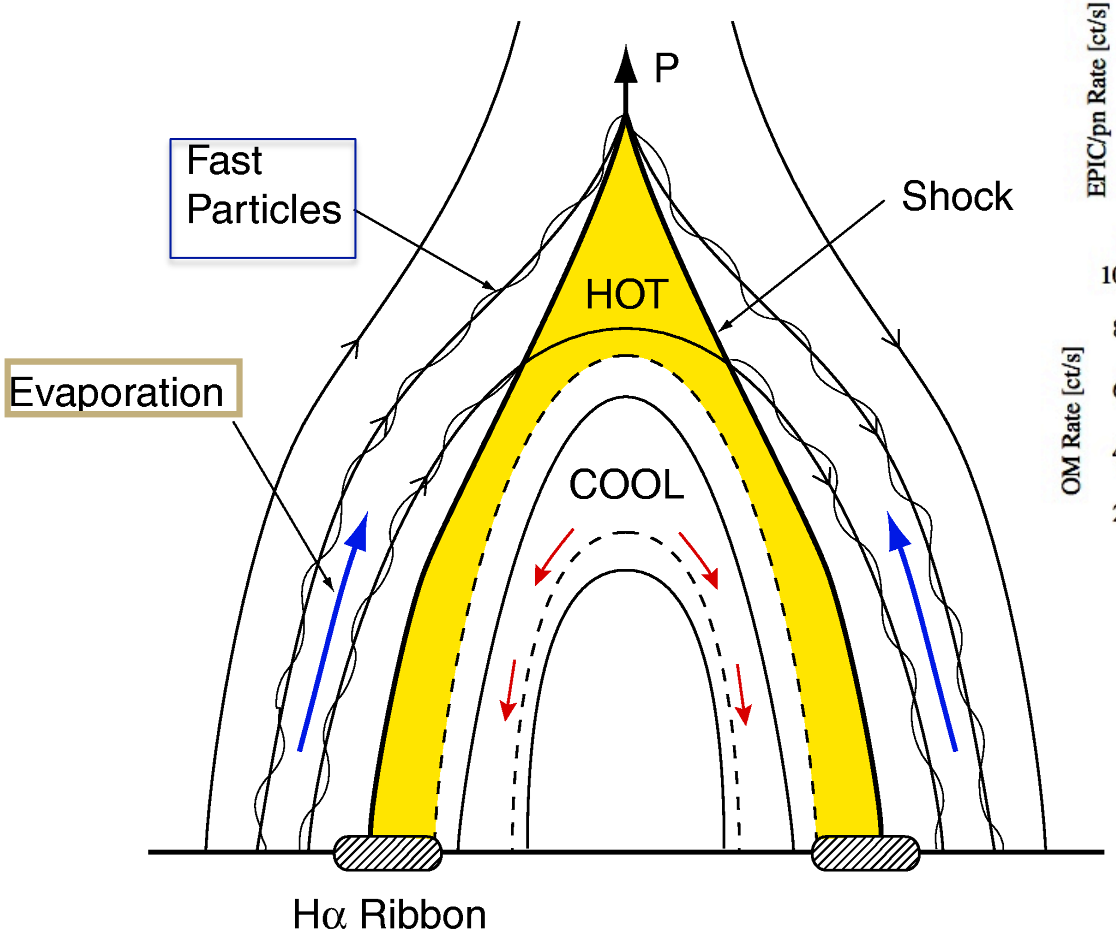
plato

Chromospheric
evaporation

↓

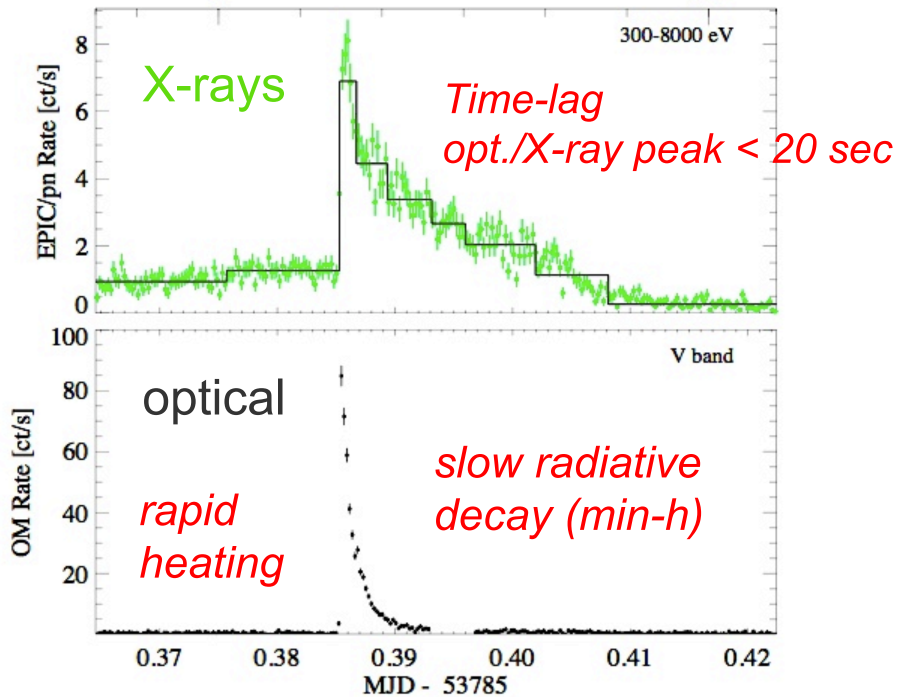
Hα emission
soft X-rays emission

Standard solar flare scenario confirmed for stars



Cargill & Priest (1983)

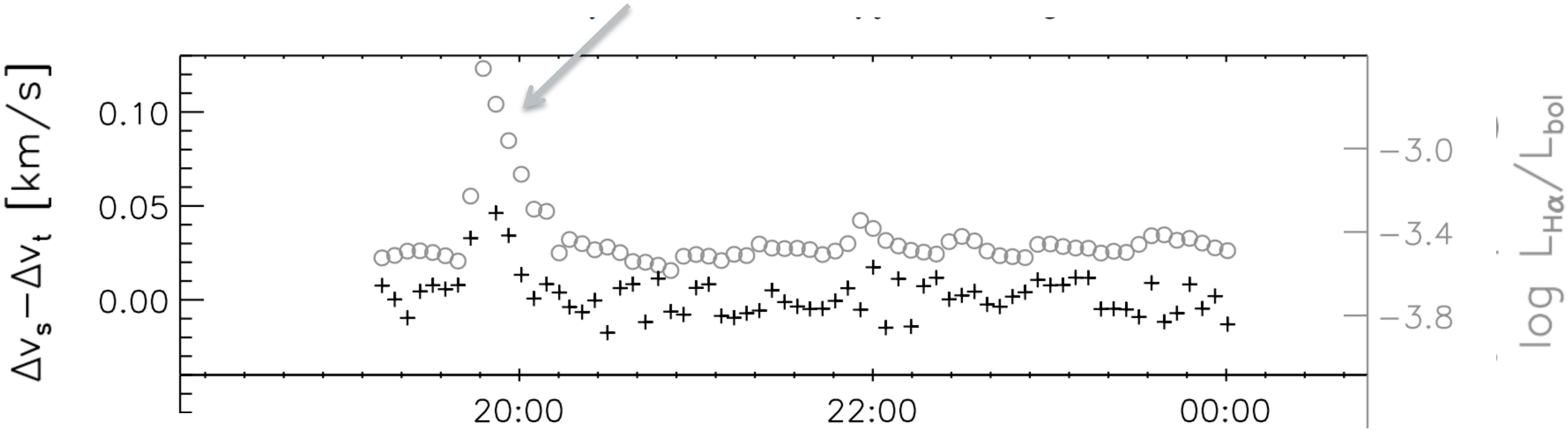
Multi-wavelength lightcurve of a flare on an M dwarf



Standard flare scenario predicts optical flare preceeding X-ray flare because chromosphere is heated directly by accelerated electrons, and corona lights up in X-rays after evaporation of chromosphere.

Effect of flares on RV measurements

Hα flare on CN Leo (M dwarf)

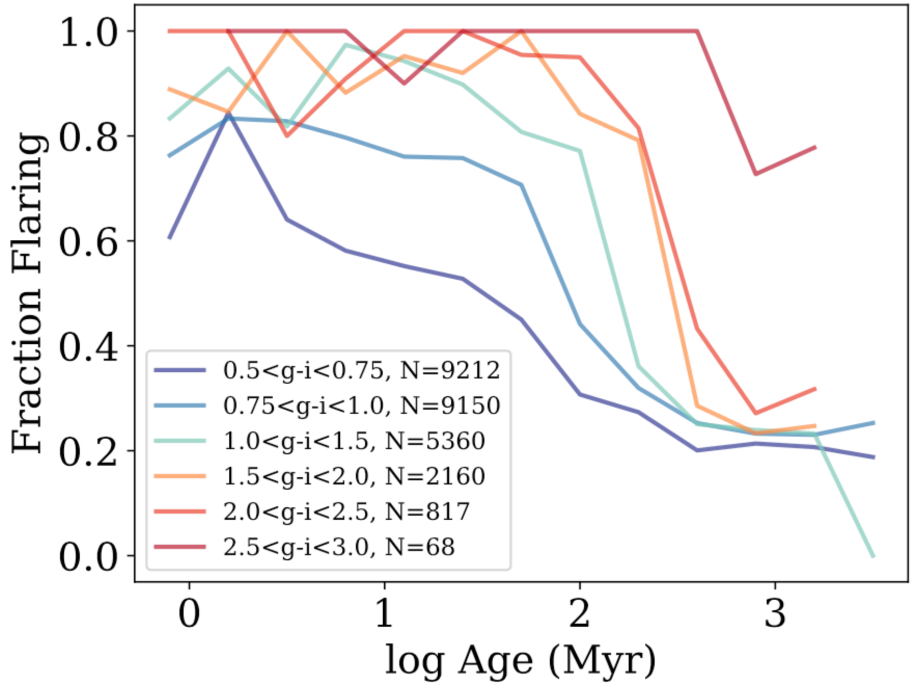


Reiners et al. (2009)

- *Flares produce large RV jitter*
- *small flares not easily detected in spectra still induce RV variation (verified by correlation analysis)*

Relevance of flares for G dwarfs

Kepler sample of ~ 27000 stars
with measurement of P_{rot} (as age proxy):



Davenport et al. (2019)

RESULTS:

** flare rate higher for lower-mass stars*

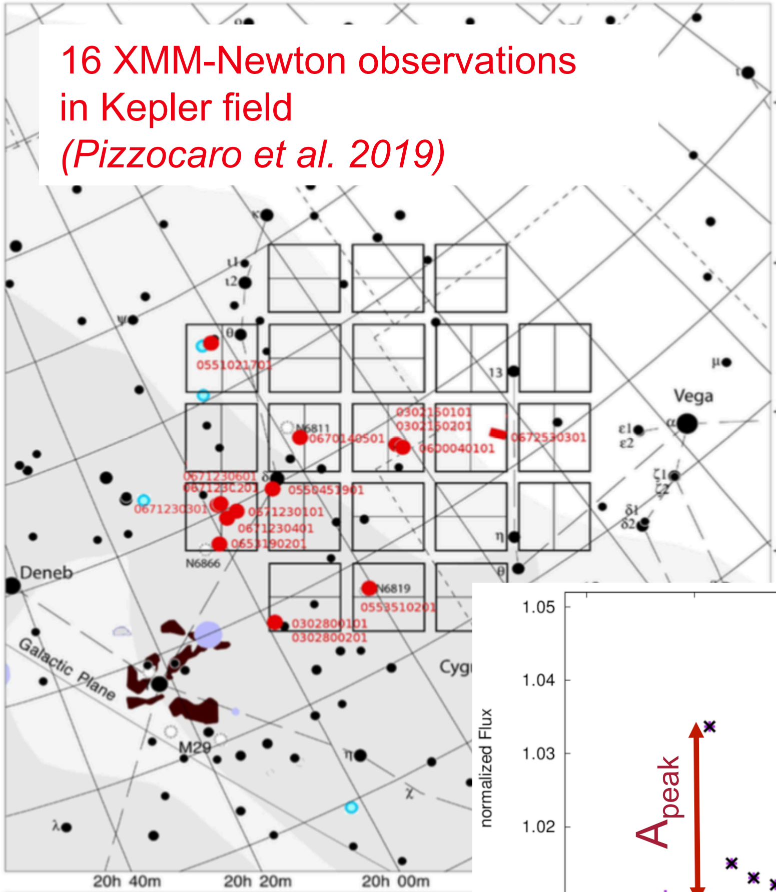
** drop of flare rate with age stronger for higher-mass stars*

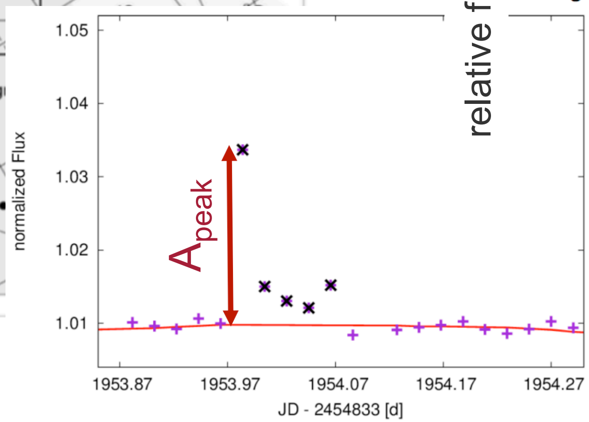
But:

**** even at Gyr age ~ 20% of G stars show flares***

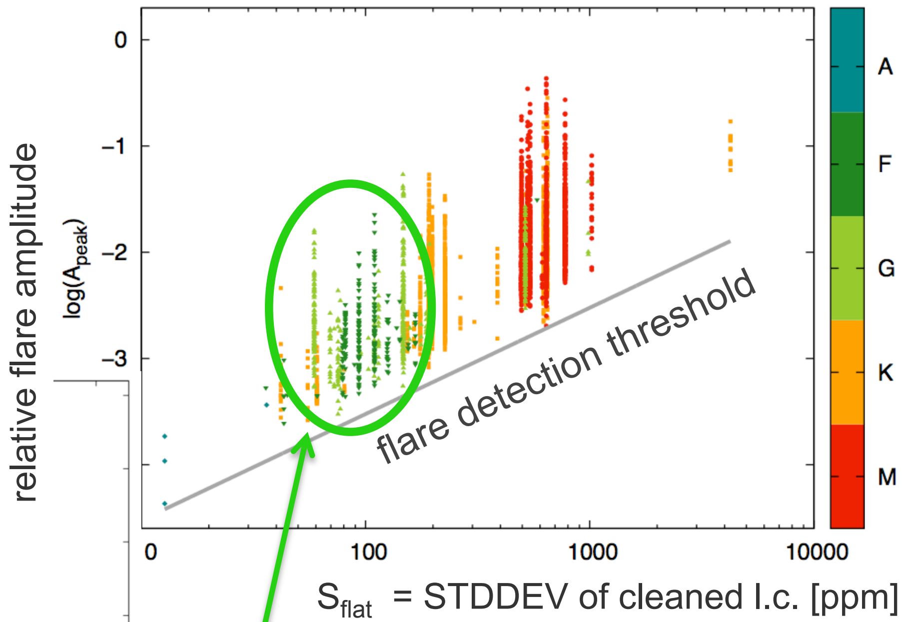
Note:
Contamination by sub-giants
→ true flare rate of G dwarfs may be higher

Relevance of flares for G dwarfs





→ X-ray selected sample of 125 main-sequence stars with Kepler lightcurves



Many strong + weak flares on G dwarfs

Flare identification + validation

in photometric high-cadence lightcurves

Steps:

(1) flare detection
[identification of data points possibly belonging to flares ("outliers")]

(2) flare validation
[identification of flares among "outliers"]

(3) extraction of physical information from flare signature,
e.g. peak luminosity, energy, duration

(1) Identification of candidate flares

This step depends crucially on a proper treatment of other (smooth) variability, i.e. the rotational modulation.

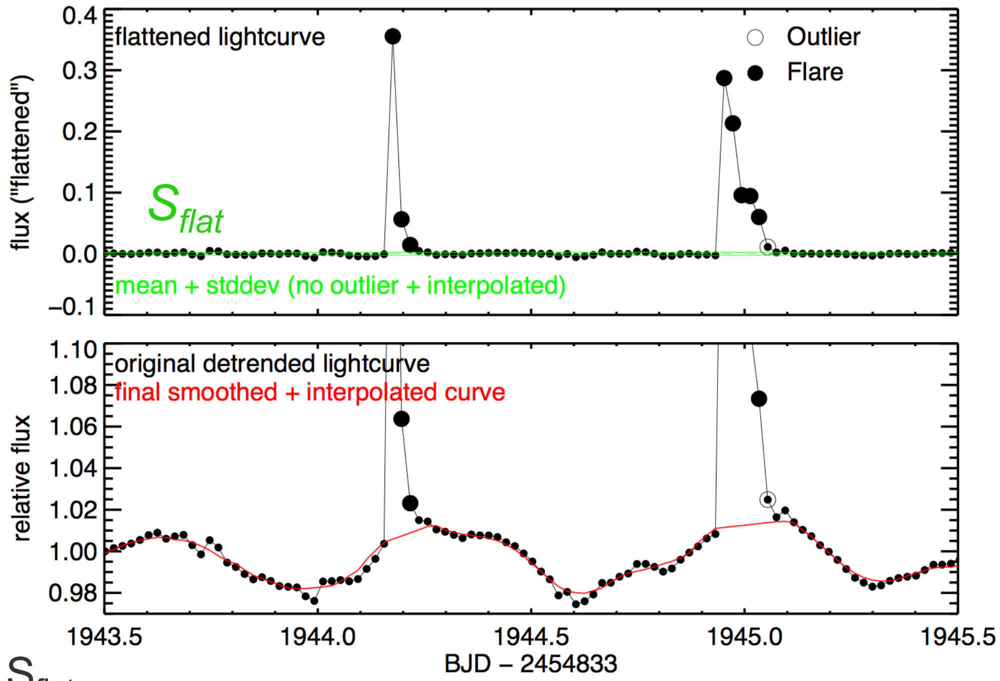
Method 1:

smoothing + σ-clipping

Iteration

1. Boxcar smoothing of lightcurve (red curve)
2. Subtraction of smoothed curve (top panel)
3. Determination of STDDEV, S_{flat} (green)
4. Flagging and removal of "outliers" i.e. data points Xσ above STDDEV, S_{flat}
5. Flare candidate: minimum of X consecutive outliers

K2 lightcurve of an M dwarf



Stelzer et al. (2016)

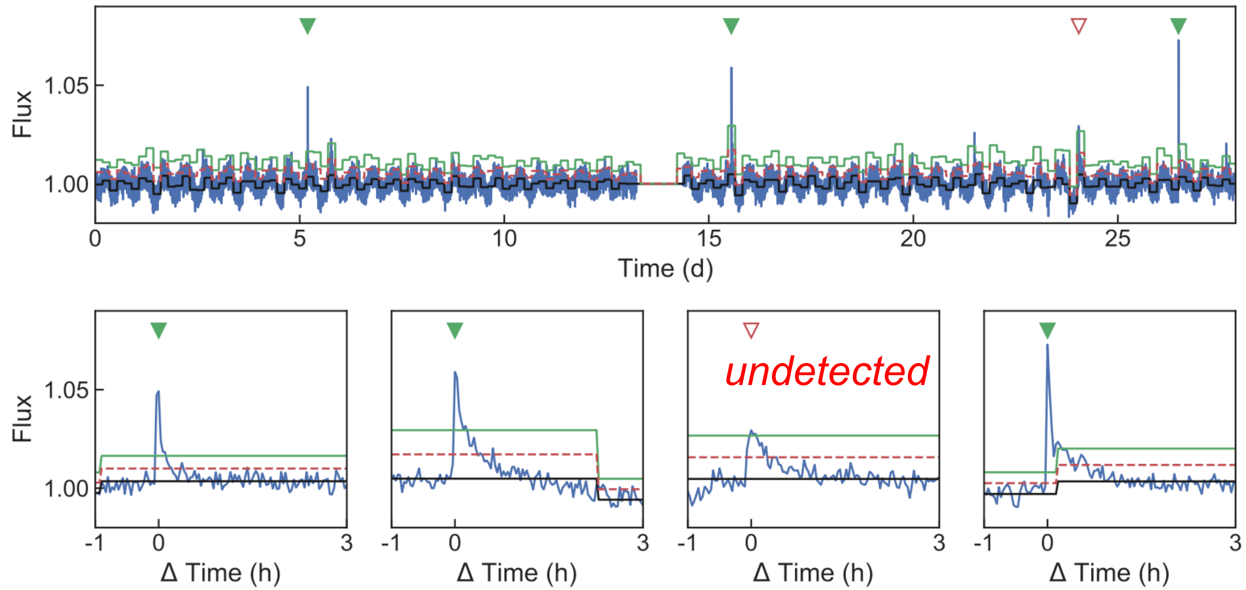
(1) Identification of candidate flares

This step depends crucially on a proper treatment of other (smooth) variability, i.e. the rotational modulation.

Method 2:

running median + σ-clipping

1. Local median, e.g. 4.3h
   (black curve)
2. Identification of outliers with respect to the local median
   (points above green lines)
3. Flare candidate:
   consecutive outliers that form a decreasing flux sequence



Günther et al. (2019)

The rotational signal is not subtracted and small flares are missed because the STDDEV is large.

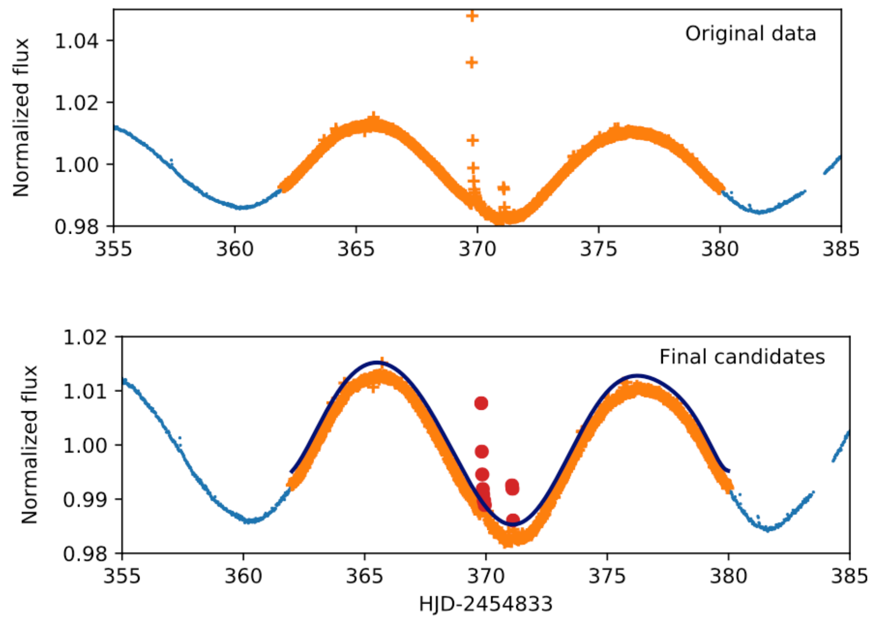
(1) Identification of candidate flares

This step depends crucially on a proper treatment of other (smooth) variability, i.e. the rotational modulation.

Method 3:

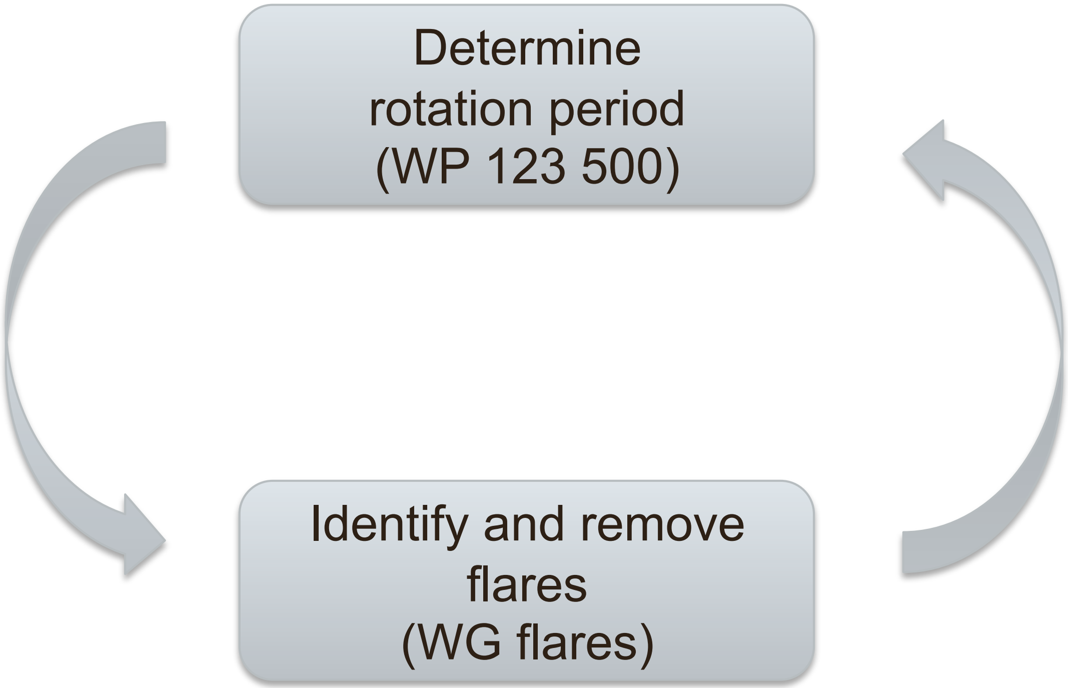
polynomial fit + σ-clipping

1. Polynomial fit to windows of 1.5 P_{rot} (black curve)
2. Identification of outliers with RANSAC (red in bottom panel)
3. Flare candidate: minimum of X consecutive outliers



Vida et al. (2018)

Possible approach in WP123



Other WPs 120 :

Please provide sets of lightcurves
for tests of flare detection algorithms.

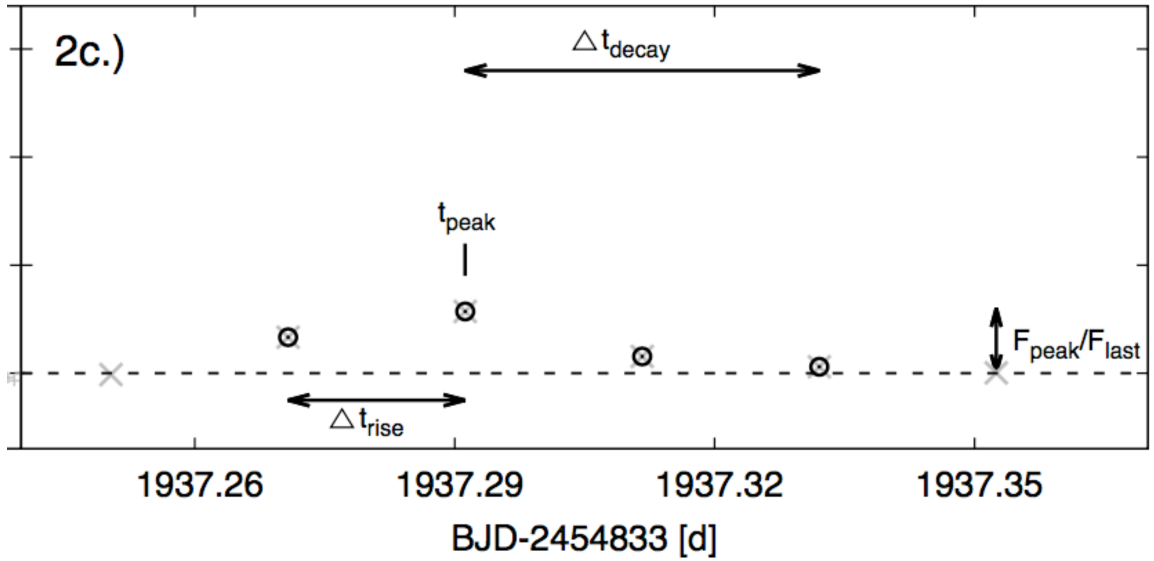
(2) Flare validation

This implementation requires some knowledge on what a stellar flare looks like.

Method:

automated verification of "typical" flare morphology:
- -- e.g. decay time > rise time
- -- condition on relative intensity of outliers, e.g. $F_{peak}/F_{last} > X$

Raetz et al., in prep.



There are different variants of these criteria.

(3) Extraction of flare physical information

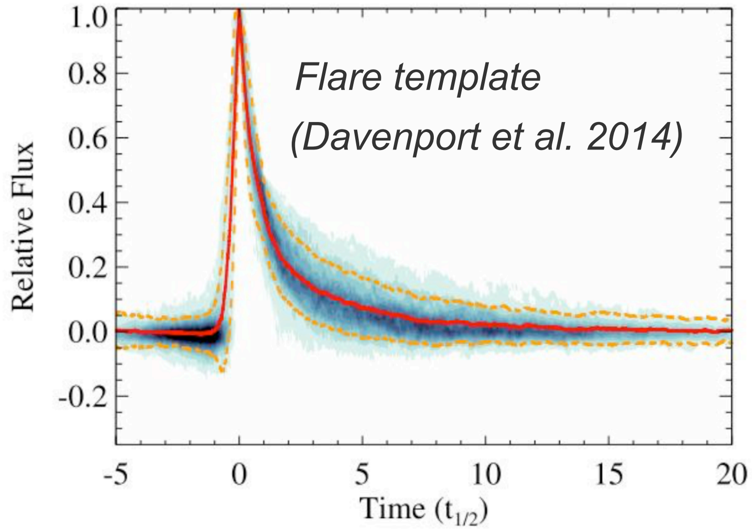
This implementation requires some knowledge on what a stellar flare looks like.

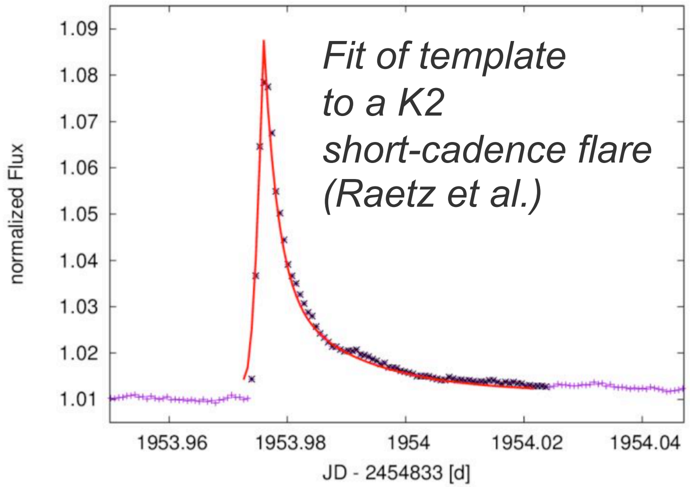
Method 1a:

Definition of a flare template and fitting it to lightcurve

Output:
* detailed time evolution: τ_{rise}, τ_{decay}
* equivalent duration (ED)
* flare energy = ED * L_{qui}

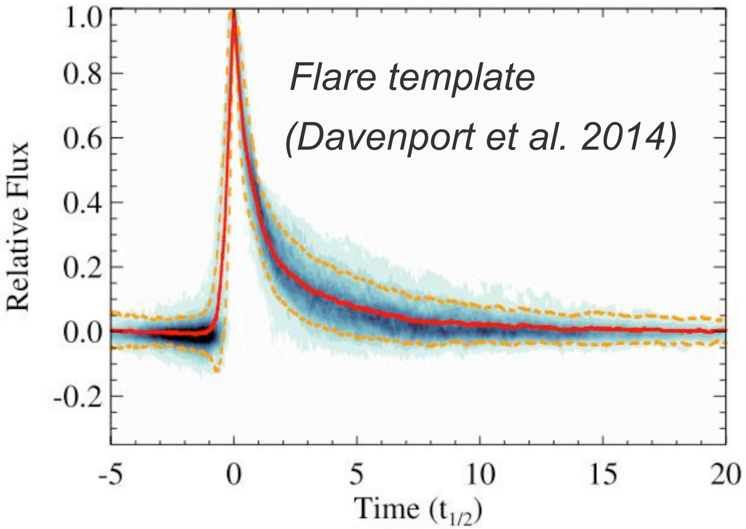
L_{qui}… from magnitude in instrument band





(3) Extraction of flare physical information

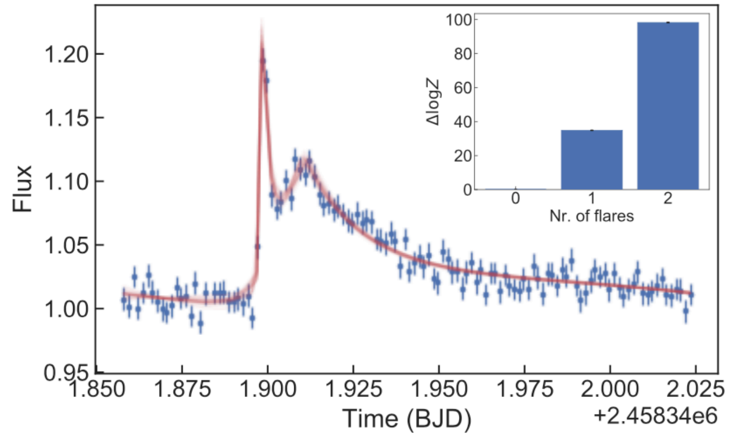
This implementation requires some knowledge on what a stellar flare looks like.



Method 1b:

Fitting multiple flare templates
to lightcurves with close succession of peaks

Output:
* same parameters as before
* number of templates that best describes the lightcurve determined through a Bayesian model



Günther et al. (2019)

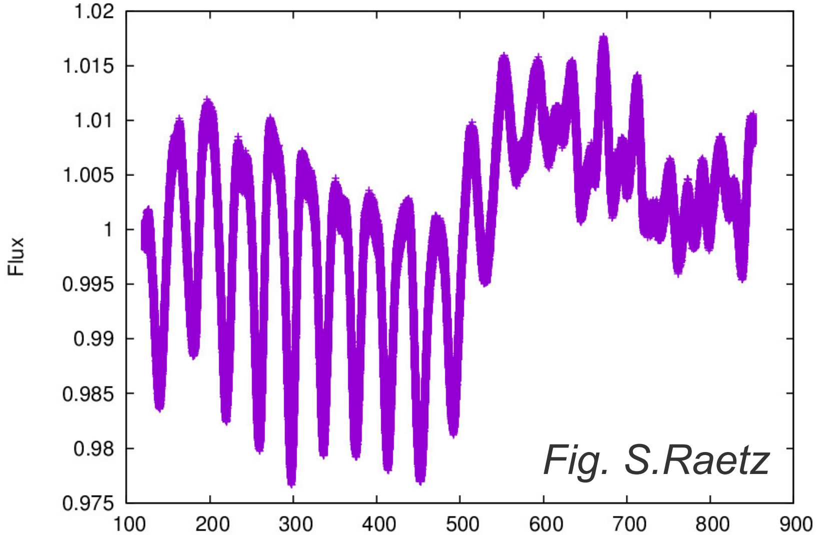
Simulations - PLATO lightcurves with flares

Simulated PLATO lightcurve

-- based on a real Kepler lightcurve
where outliers removed, smoothed,
gaps interpolated

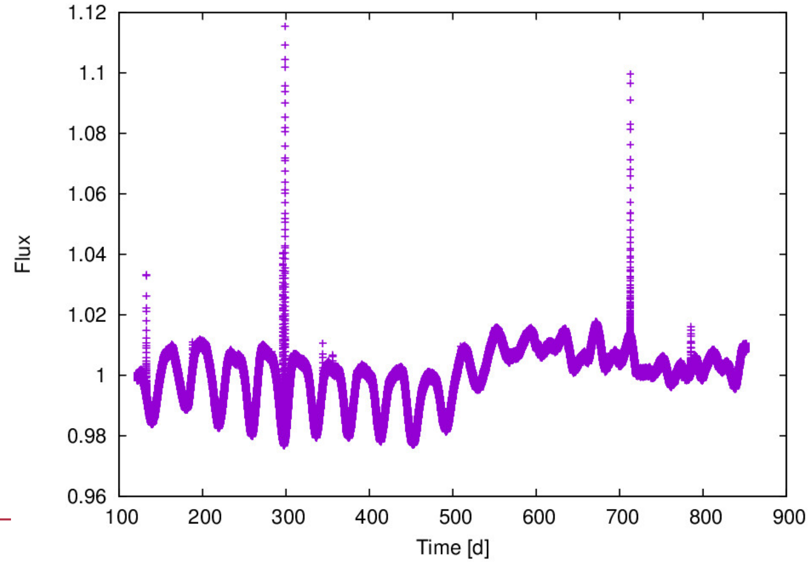
-- noise added based on the PSLS
('PLATO solar-like light curve simulator',Samadi et al. 2019)

-- interpolated to 25s cadence



Simulated PLATO lightcurve after flare injection

(see next slide)



Simulations – Flare injection

Properties of injected flares

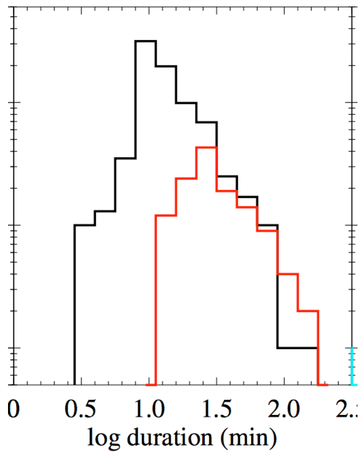
(based on observed Kepler/K2 flares for M stars):

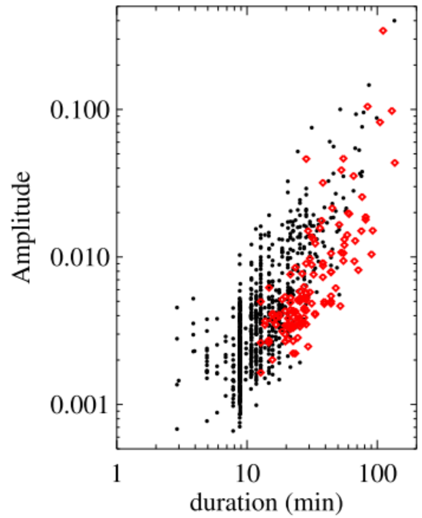
* assumption of a power-law distribution for the flare duration, τ

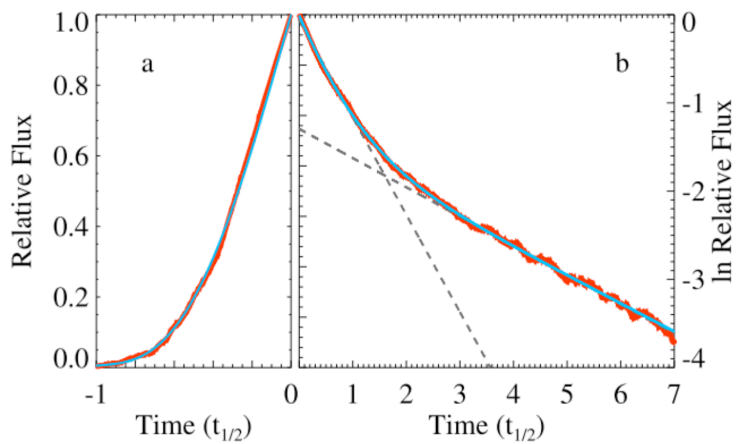
* drawing flare amplitude A_{peak} randomly from a relation with τ

* inject the flares at random time τ_{peak}; assuming a flare rate, $v[N_{flares}/d]$

* apply flare template shape → τ_{rise}, τ_{decay}

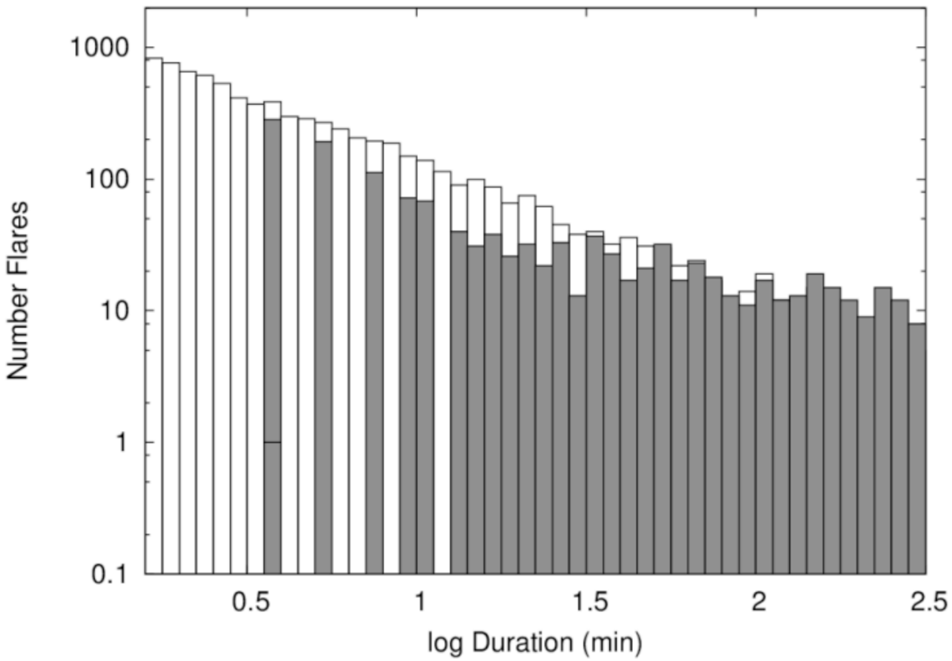






S.Raetz

Simulations – Flare recovery



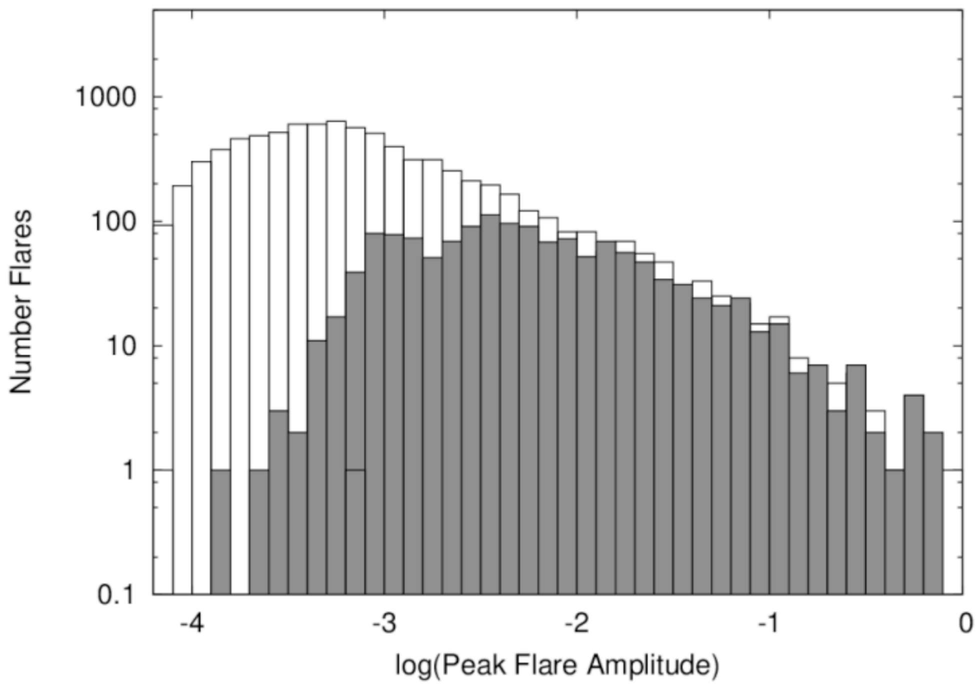
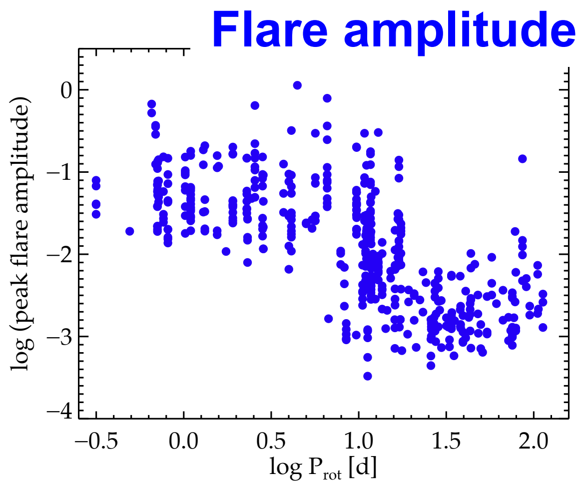


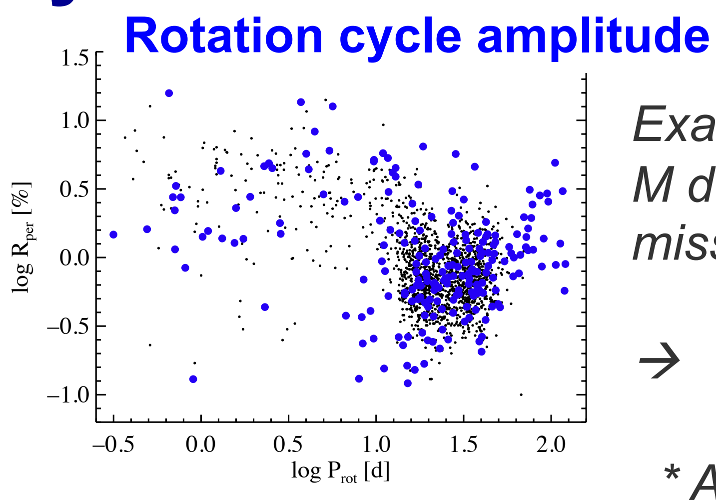
Fig. S.Raetz

FIRST RESULTS:

** 17 % of injected flares recovered with detection algorithm No.2*
** short flares recovered (down to τ ~ 3 min)*
** low-amplitude flares missed (for A_{peak} < 2%)*
**** recovery complete to 90% for τ > 20 min and A_{peak} > 1%***

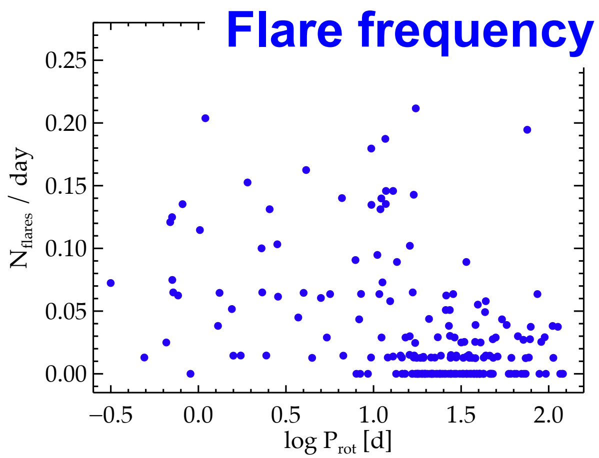
Science with stellar flares:
Rotation-activity relation

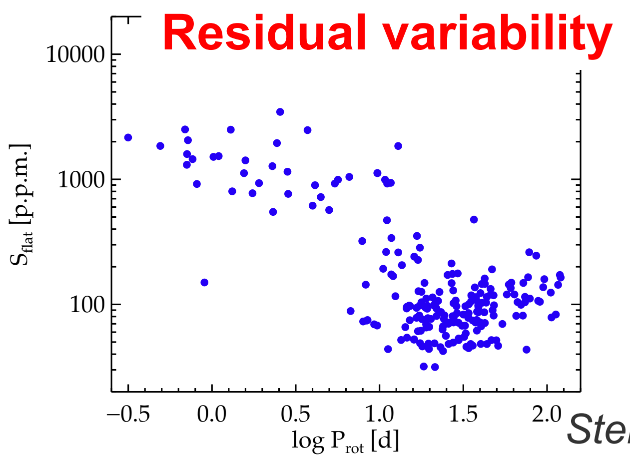




Example:
M dwarfs observed in K2 mission

→





* *A clear bimodality with high activity for P<10 d and low activity for P>10d in all activity diagnostics:*
- *-- flares,*
- *-- rotational modulation,*
- *-- residual “noise”, S_{flat}*

Stelzer et al. (2016); Raetz et al. (2019)

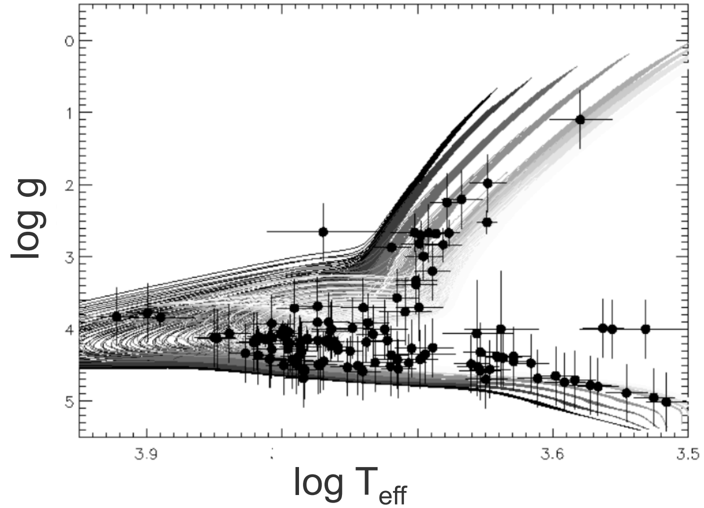
Activity related photometric variability across spectral type

Table 5: Mean values and standard deviations measured for photometric activity diagnostics in the *Kepler* / *XMM-Newton* sample.

increasing variability ↓

SpT	N_f/day	$\log R_{per}$ [%]	S_{ph} [ppm]
A	0.001	−1.02	$3.47 \cdot 10^2$
F	0.01	−0.74	$1.10 \cdot 10^3$
G	0.02	0.01	$5.39 \cdot 10^3$
K	0.04	0.25	$8.69 \cdot 10^3$
M	0.12	0.46	$1.10 \cdot 10^4$
	flare rate	*amplitude of rot.mod.*	*STDDEV (dominated by rot.mod.)*

Pizzocaro et al. (2019)



Variability due to rotational modulation as well as flares are present in G stars.

Thank you !

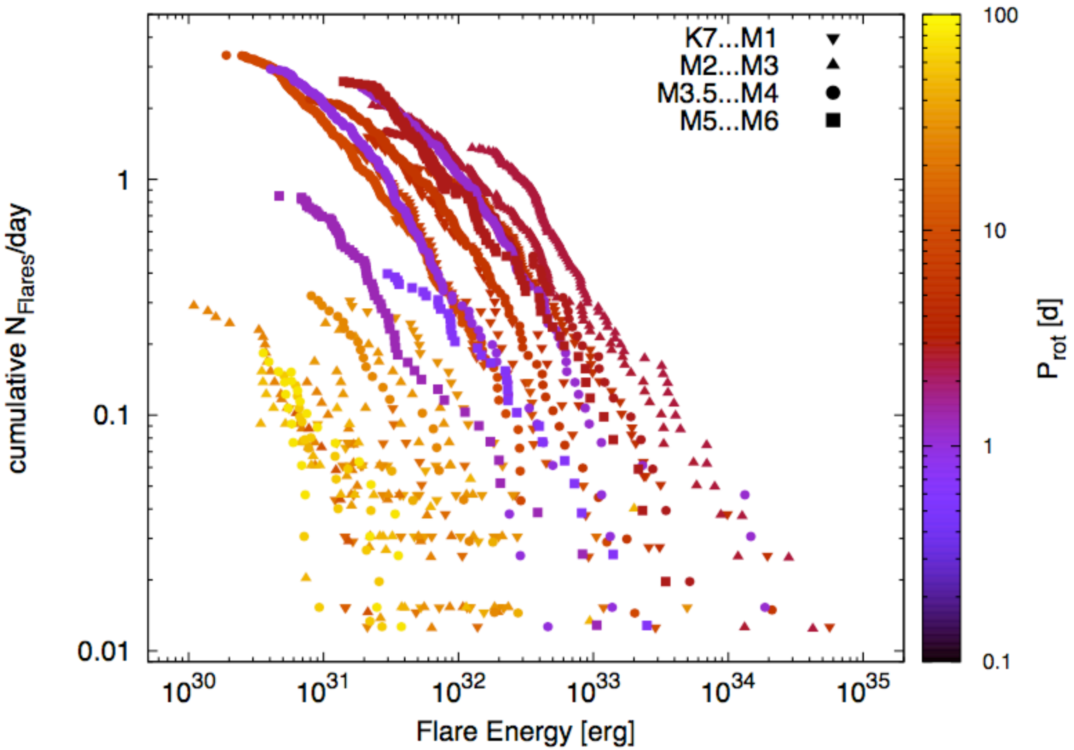
Science with stellar flares:
Flare energy number distributions

Example:
M dwarfs observed in K2 mission (short cadence)

→

** Slow rotators have flares of lower energy than fast rotators*

** Slow rotators have less flares than fast rotators*



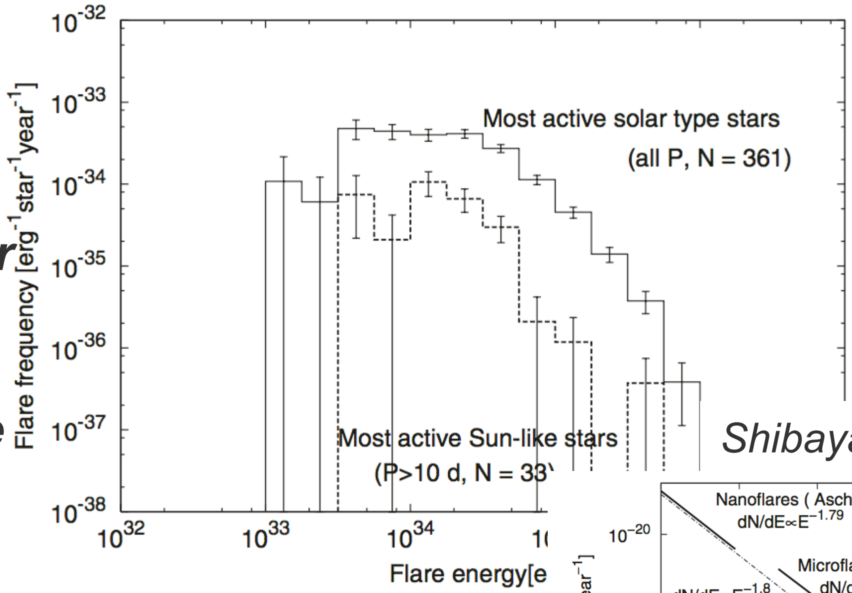
Raetz et al., in prep.

Science with stellar flares:
Flare energy number distributions

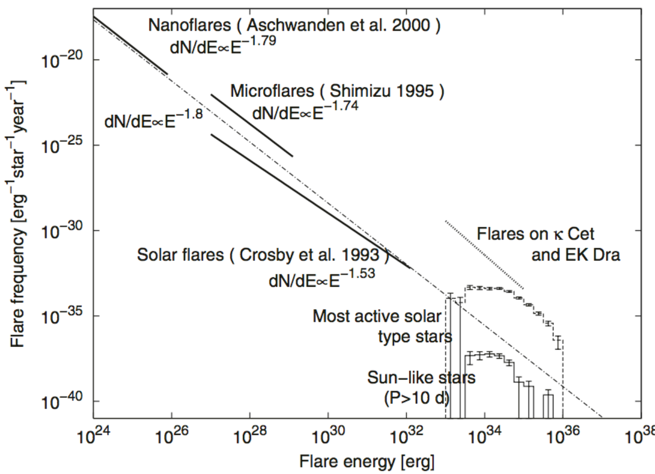
Example:
G dwarfs observed with Kepler
→

** The most active G stars have superflare rate > 1/10 N_{SF}/d*

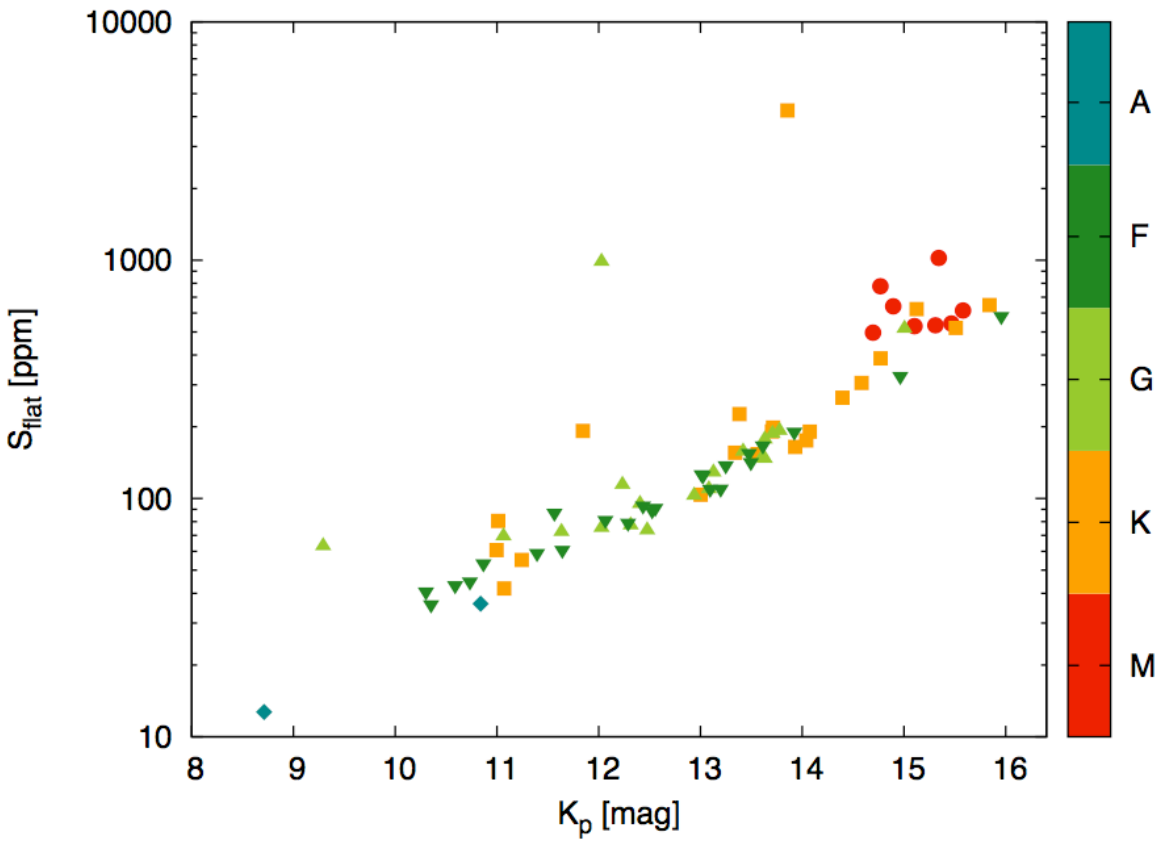
** Kepler superflare G dwarfs follow similar flare energy number distribution as the Sun*
→ smaller flares likely present



Shibayama et al. (2013)

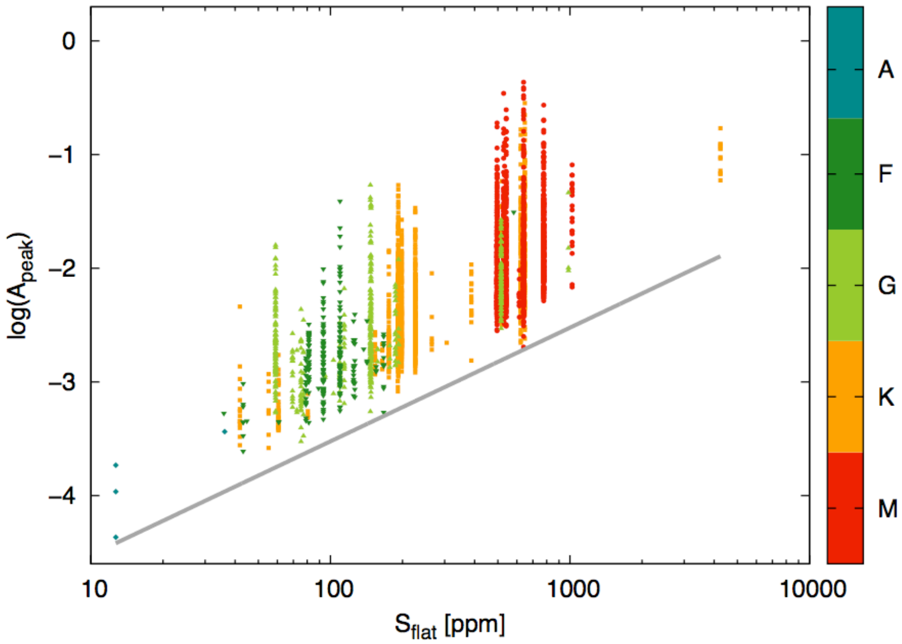


Kepler / XMM-Newton sample (Pizzocaro et al. 2019):

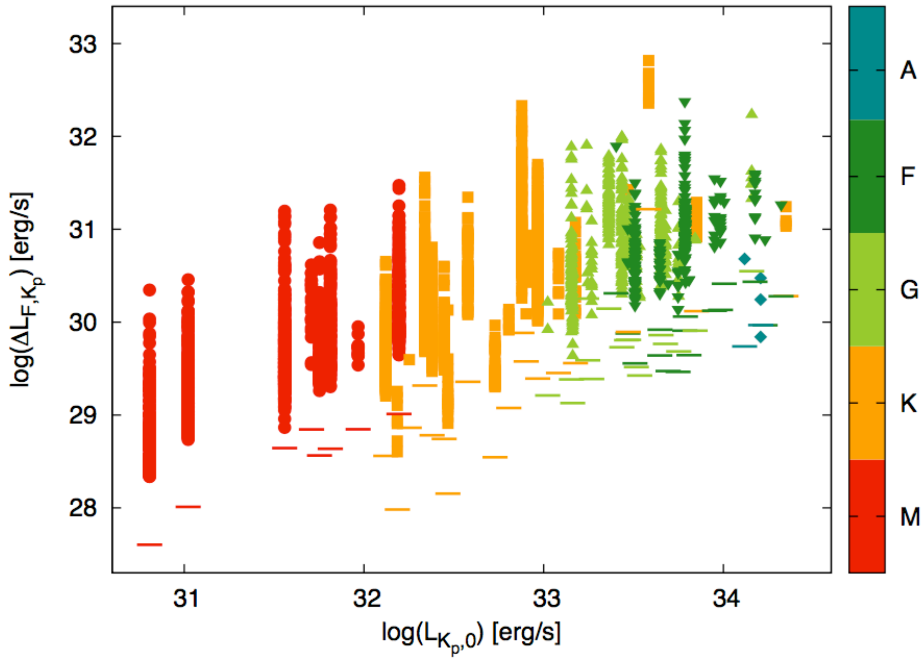


*The detection threshold for flares (X * S_{flat}) depends on brightness.*

Kepler / XMM-Newton sample (Pizzocaro et al. 2019):



relative flare amplitude



absolute flare amplitude