Superflares on solar-type stars

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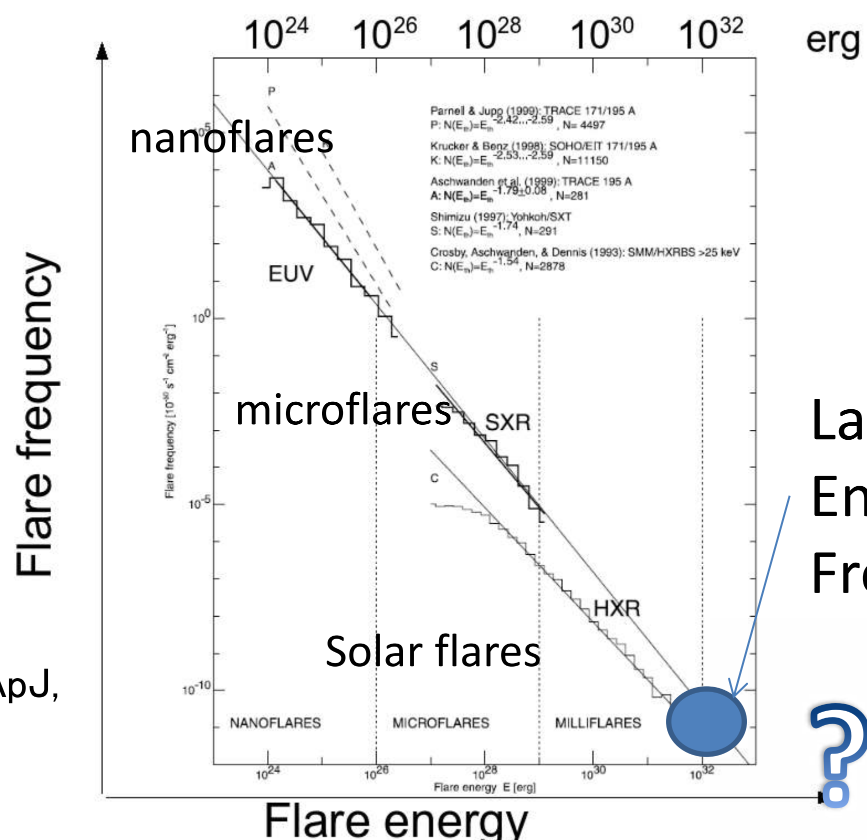
Maehara et al., Nature 485, 478 (2012)
Shibata et al., PASJ 65, 49 (2013)
Notsu et al., ApJ 771, 127 (2013)
Shibayama et al. ApJS 209, 5 (2013)
Notsu et al. PASJ 65, 112 (2013)

Energy-frequency distribution of solar flares

- Frequency of flares decreases as the flare energy increases.
- Power-law distribution: $dN/dE \propto E^{-1.5 \sim -1.9}$
  - Flare energy: $10^{24} \sim 10^{32}$ ergs
  - Frequency of solar flares with energy $>10^{32}$ erg **???**

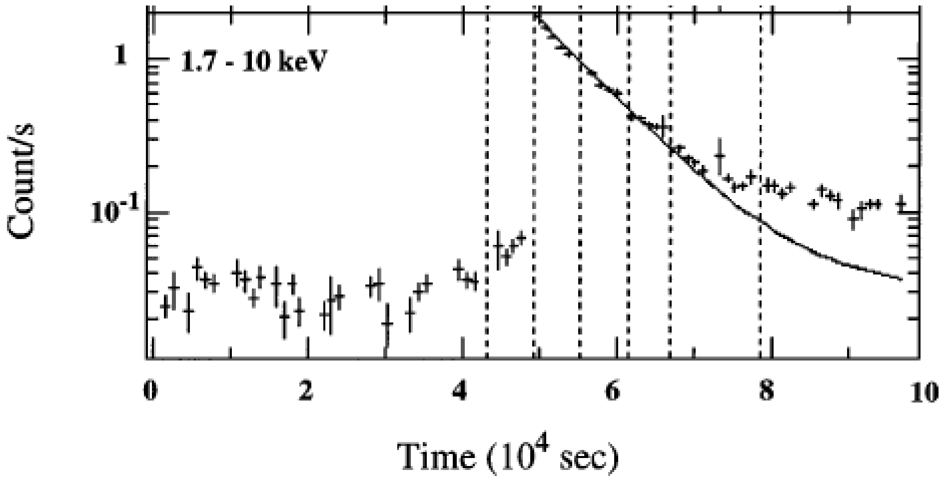


Largest solar flares
Energy: ~10^{32} ergs
Frequency: ~1 in 10 years

Aschwanden et al., ApJ, 535, 1047 (2000)

Superflares

- Larger flares (energy $10^{33} - 10^{38}$ ergs) are observed on a variety of stars.
  - close binary systems
  - YSOs (e.g. T Tauri stars)
  - →rapidly rotating stars

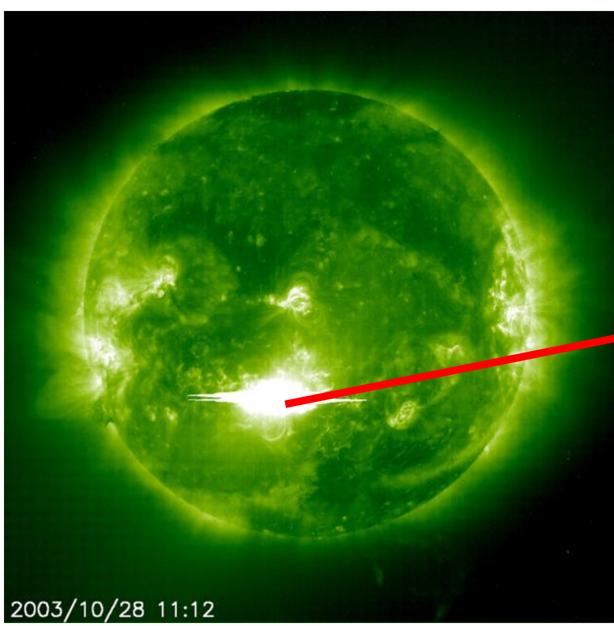


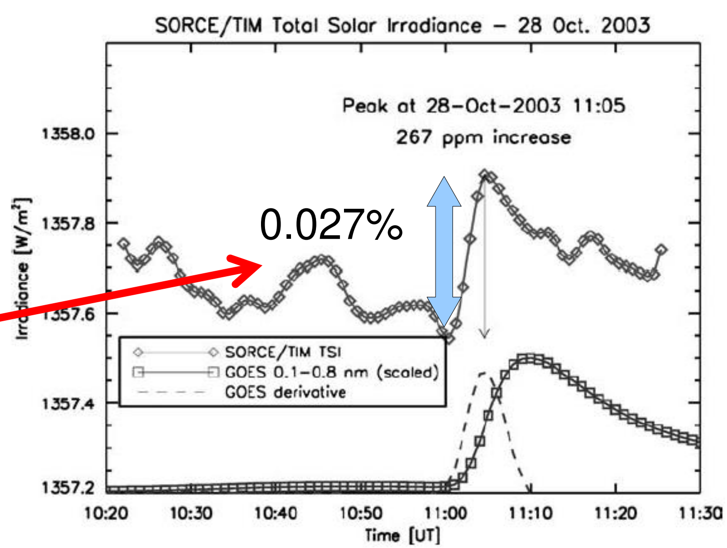
V773 Tau (T Tauri binary)
Tsuboi et al., ApJ, 503, 894 (1998)

- Schaefer et al. (2000) reported 9 superflares on ordinary solar-type stars (slowly rotating, not young G dwarfs).
  - Too few to discuss statistics.
    - frequency of superflares ?
    - relation between properties of the star and superflares ?
    - Can superflares occur on our Sun?

Difficulty of detection of flares on solar-type stars

- Detection of supreflares on solar-type stars is difficult
  - The change in the stellar brightness due to flares on solar-type stars is very small.
    - X17 solar flare: $\Delta F/F \sim 10^{-4}$ → X1000 flare: $\Delta F/F \sim 10^{-2}$
  - The frequency of superflares may be extremely low.
    - X1000 flares may be 100 times less frequent than X10 flares.



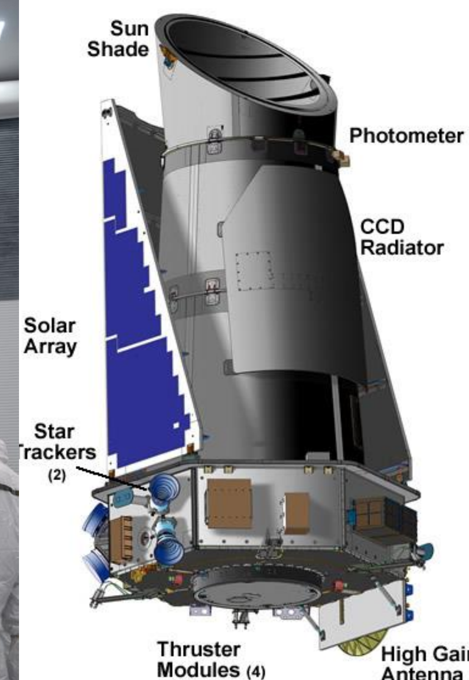


Kopp et al., Solar Phys. 230, 129 (2005)

Kepler Data

- Kepler is the best space telescope to search for superflares.
  - High photometric precision (~10^{-4})
  - Continuous observations of large number of targets (~160,000 stars)

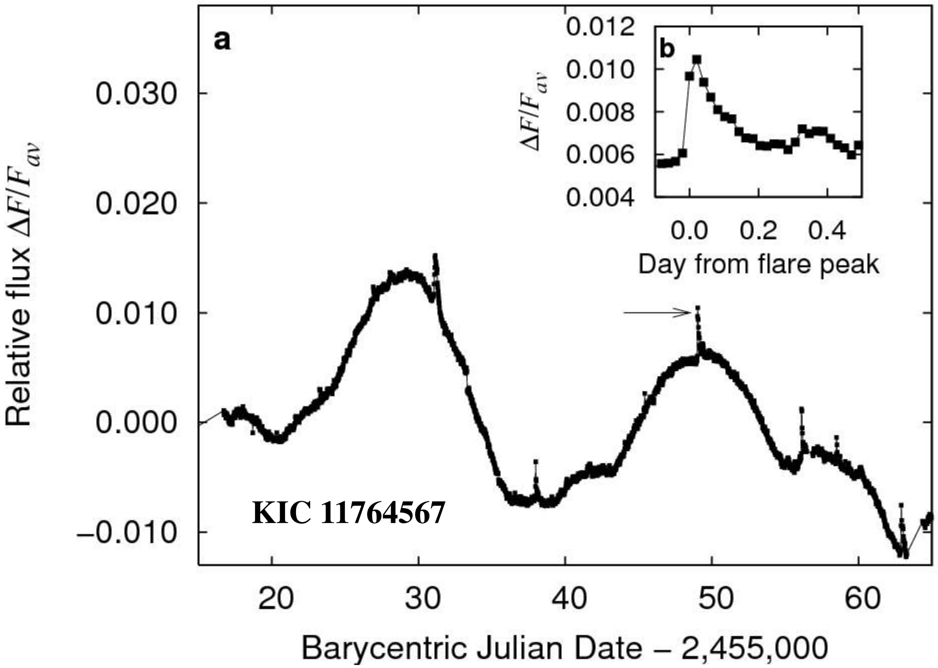
- We searched for flare-like events (sudden brightenings) from the Kepler public data.

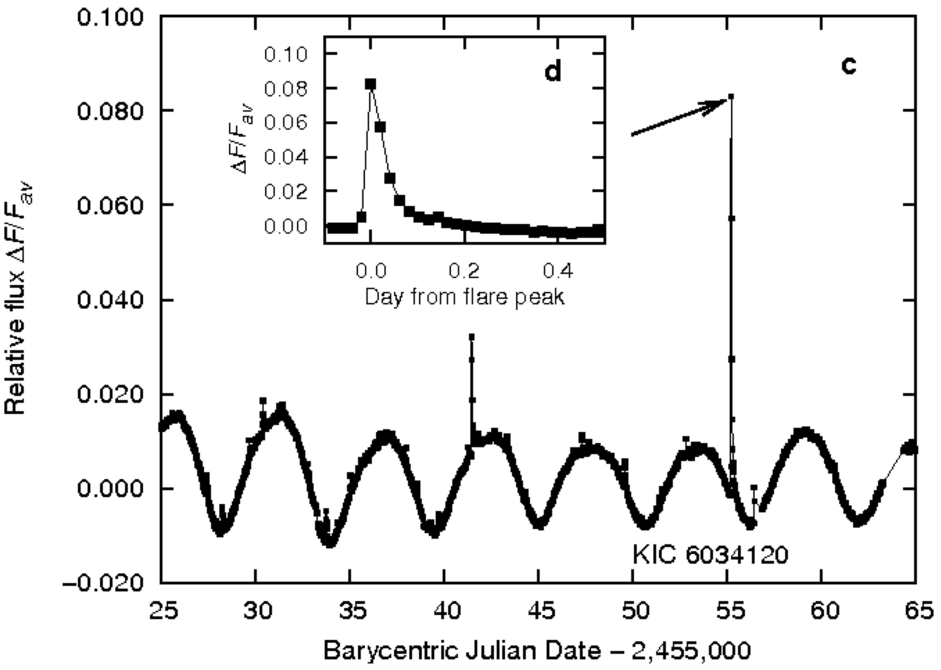


Data

- We selected G-dwarfs from the Kepler Input Catalog and analyzed both long cadence and short cadence data.
  - Selection criteria: $5100 < T_{eff} < 6000K$, $\log g > 4.0$
  - Number of G-dwarfs: ~90,000 (long) , ~1,300 (short)
  - Observation period
    - 2009/04-2010/09 (~500 days; long cadence data)
    - 2009/04-2012/10 (~1300 days; short cadence data)
  - Time-resolution: ~30min (long), ~1min (short)

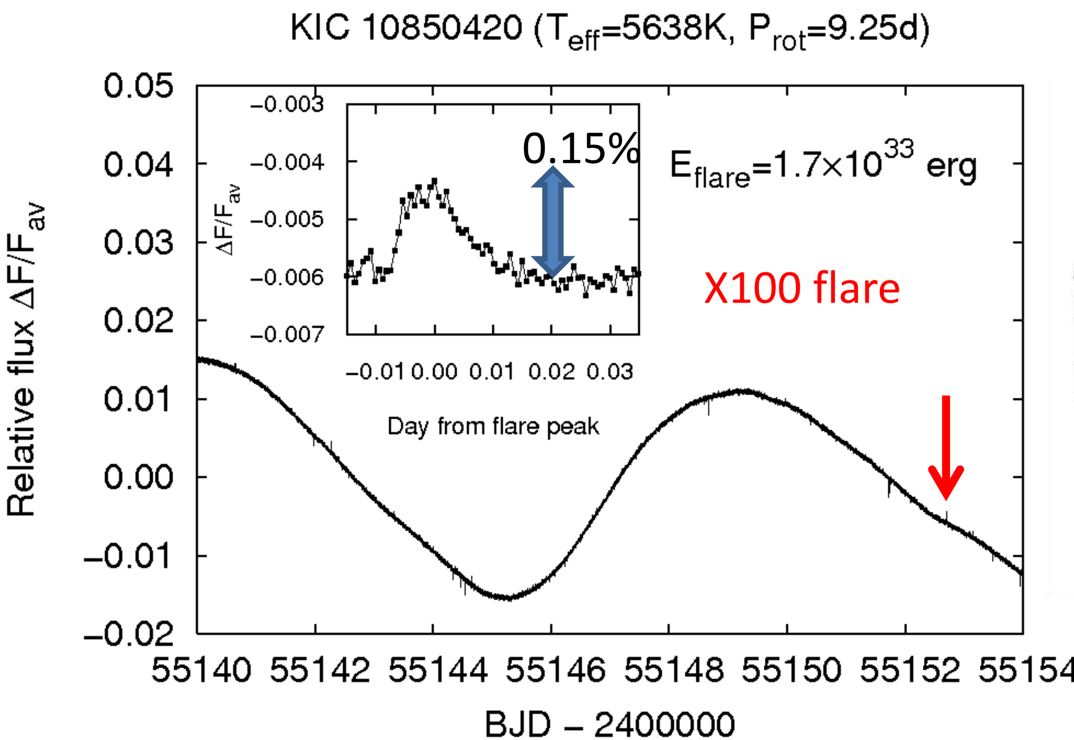
Superflares (long cadence data)

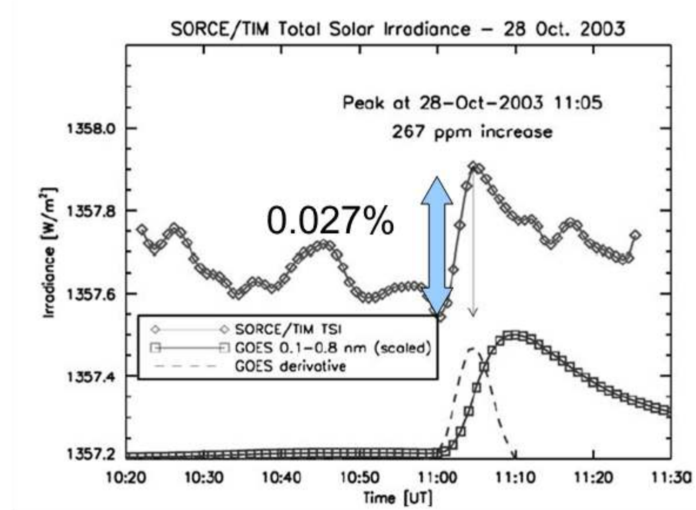




- Amplitude: 0.1-10%
- Duration: ~0.1 days
- Total energy: 10^{33}-10^{36} ergs
  - 10-10,000 times larger than the largest solar flares (~10^{32} ergs)
- Number of flares: 1547 (on 279 stars)

Flares detected from short cadence data



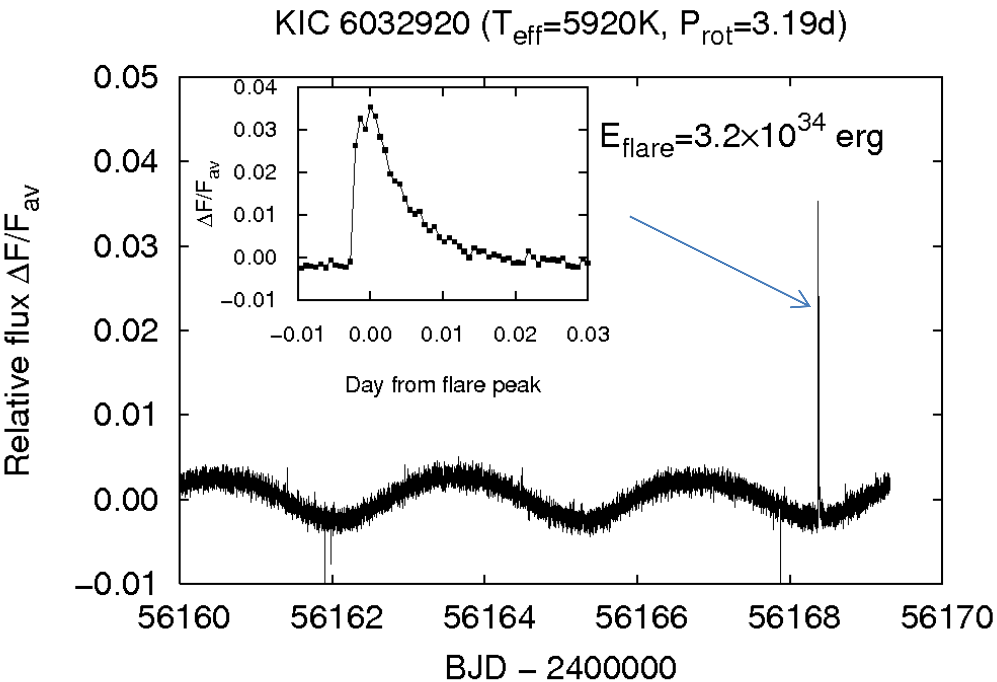


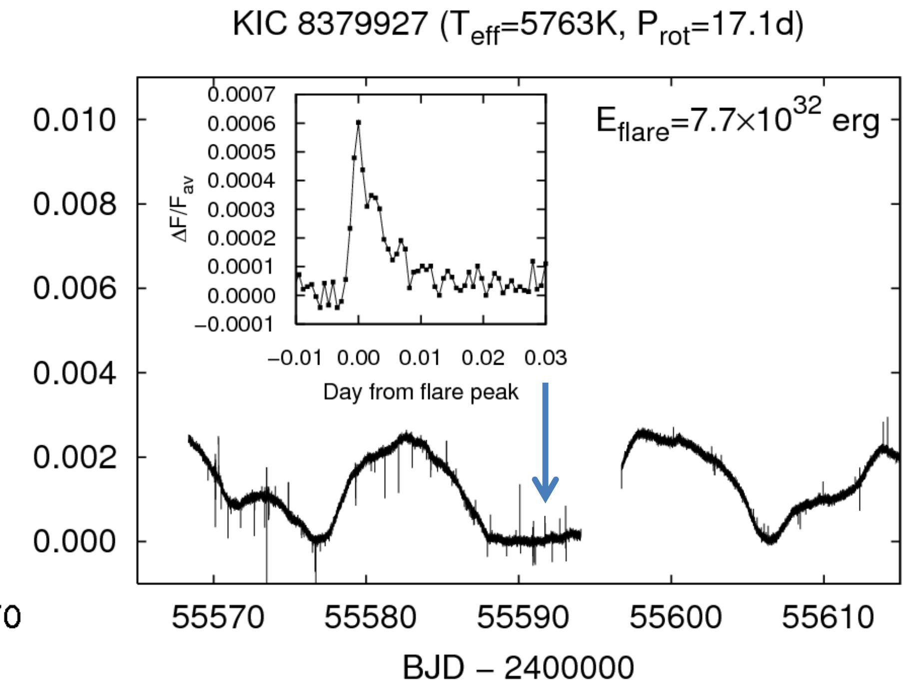
Kopp et al., Solar Phys. 230, 129 (2005)

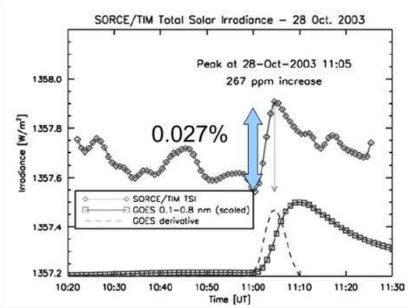
Solar flare (X17)

- Amplitude: 0.06 – 3%
- Duration: 6 – 30 min
- Energy: 8x10^{32} - 10^{35} erg (~X100-X10000)
- Number of flares: 153 (on 20 stars)

Flares detected from short cadence data





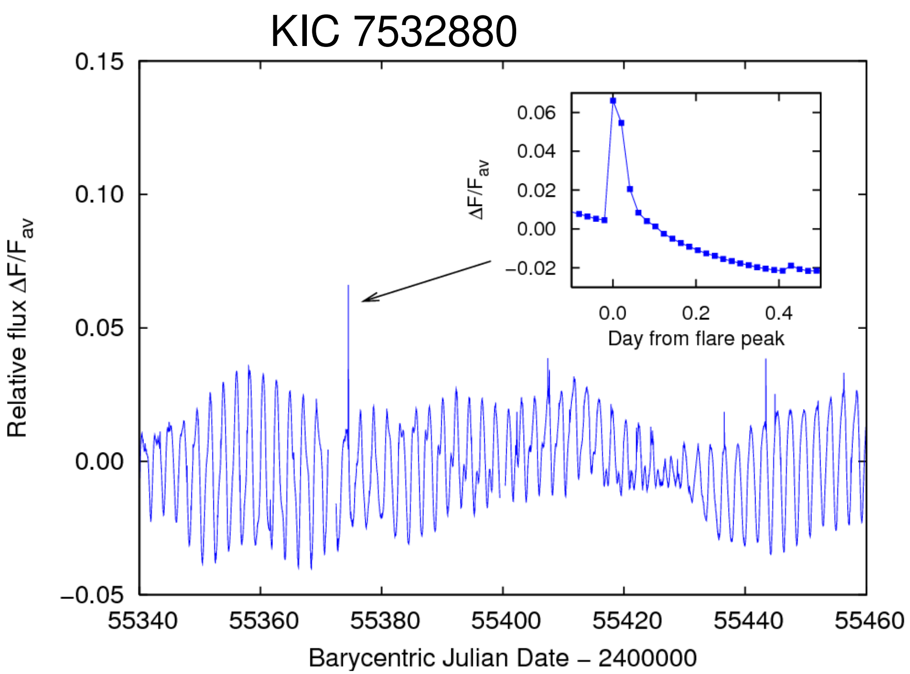


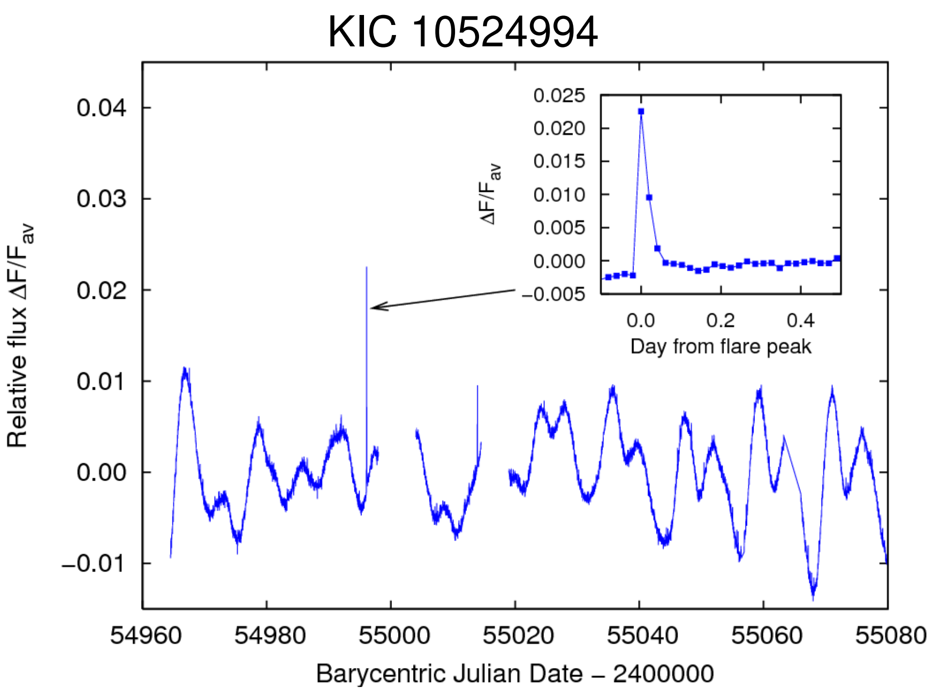
Kopp et al., Solar Phys. 230, 129 (2005)

Solar flare (X17)

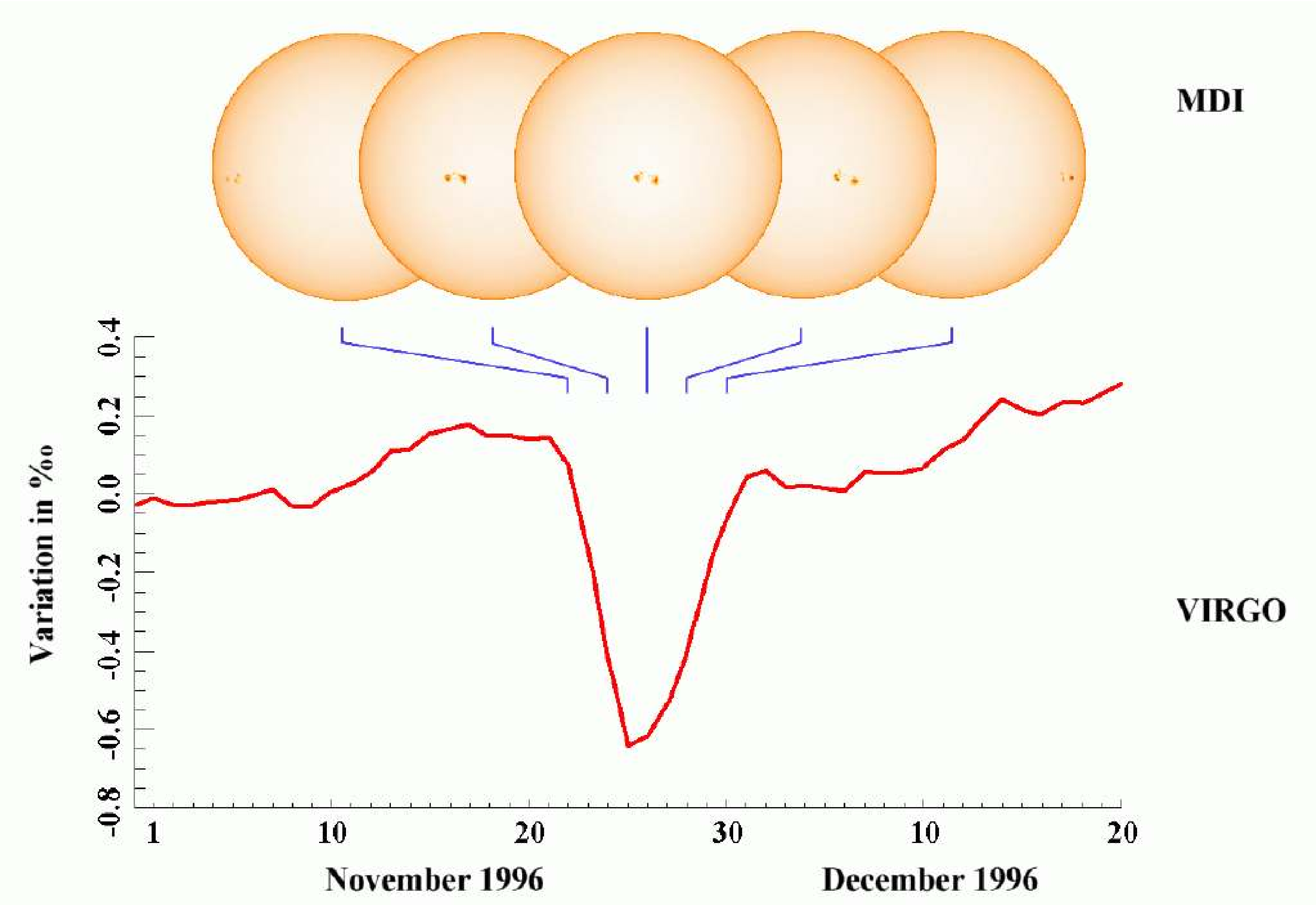
Long-term brightness variations

- Most of superflare stars show quasi-periodic brightness variations.
  - Period: ~0.5 – 30 days
  - Amplitude: 0.1 - 10%
    - Amplitude of light variations changes with time.





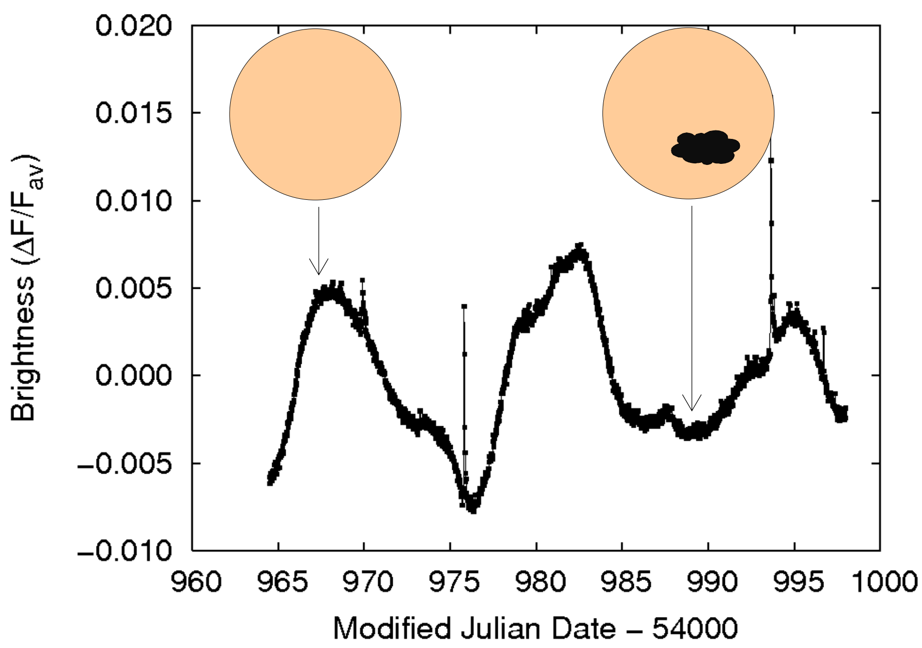
Light curve of the Sun



http://www.mps.mpg.de/projects/sun-climate/resu_body.html

Long-term brightness variations

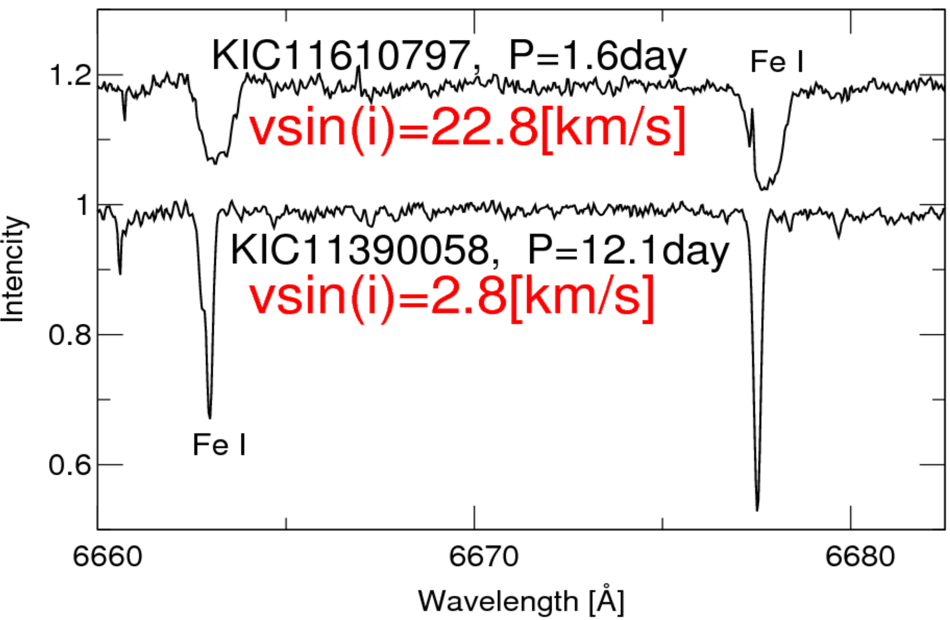
- If we assume that quasi-periodic light variations are caused by the rotation of the star with starspots,
  - Period of brightness variation → rotation period
  - Amplitude → total area of starspots

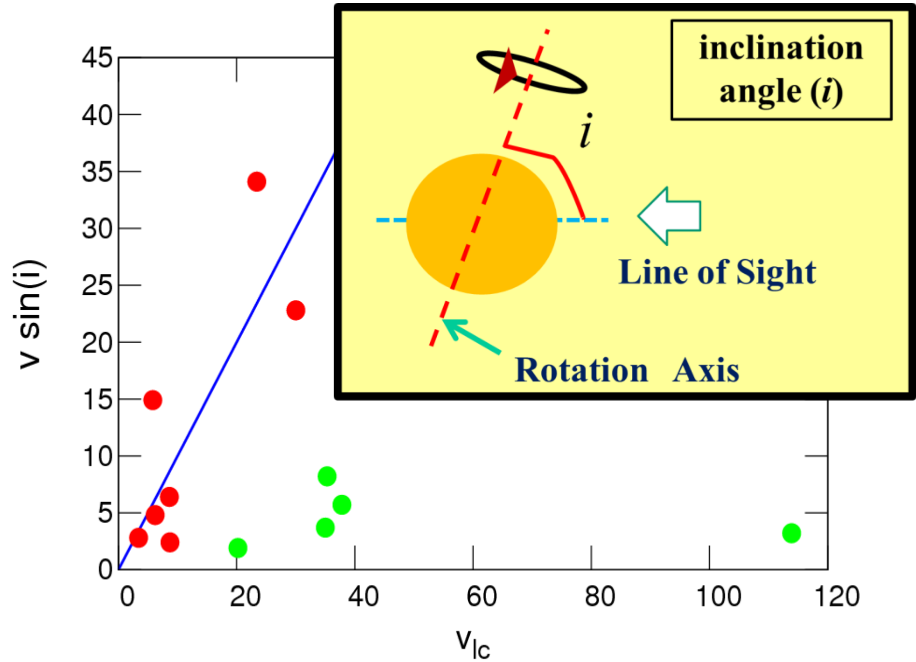


Rotation velocity

- We performed high-dispersion spectroscopy of superflare stars with Subaru telescope.
- Photometric periods of each star are consistent with rotation velocities.

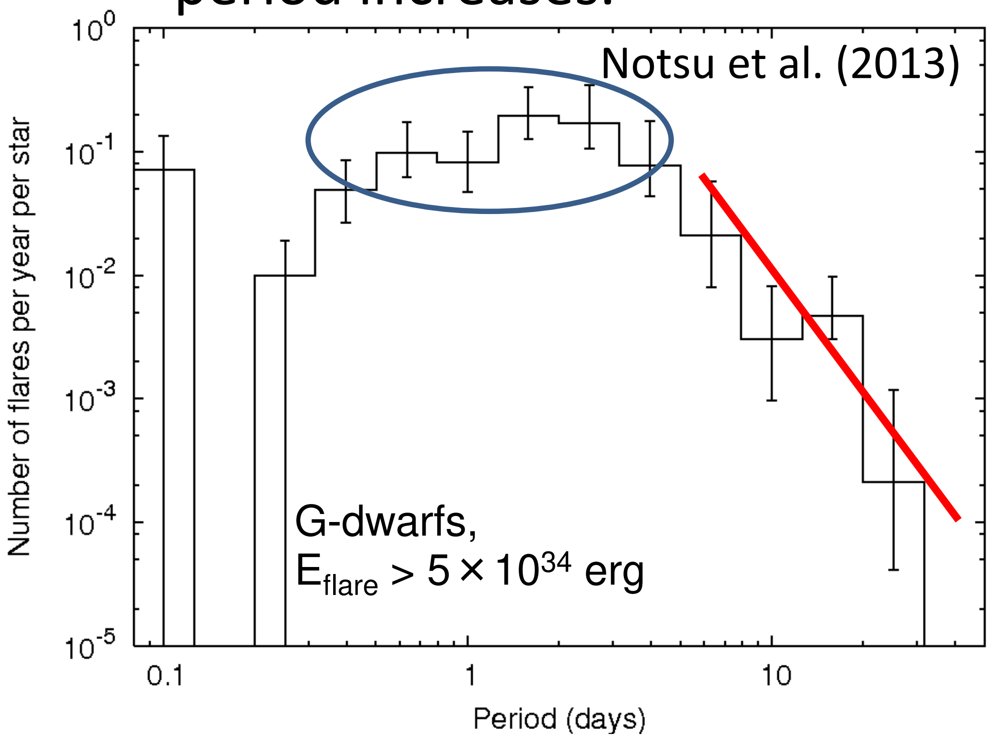
→ more details: Notsu et al. (S6-P-08, S6-P-09)

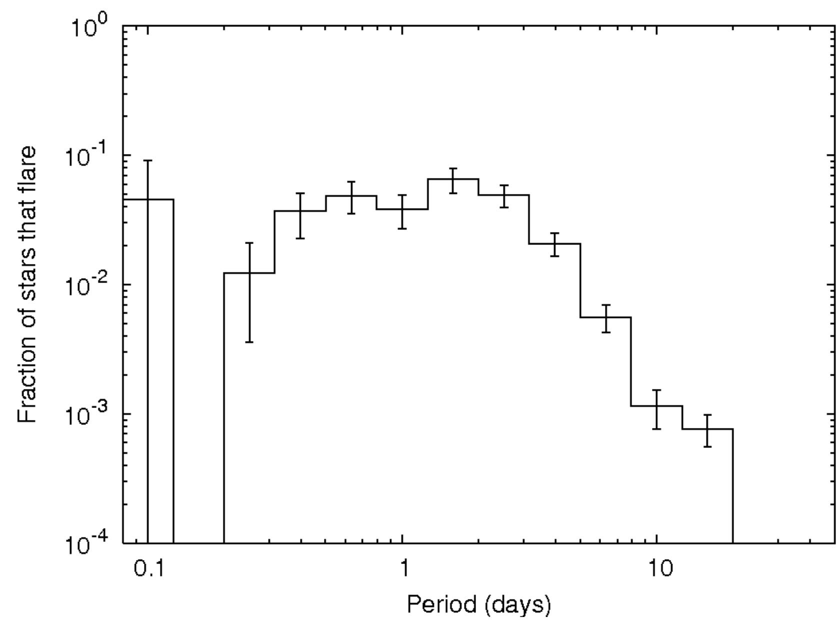




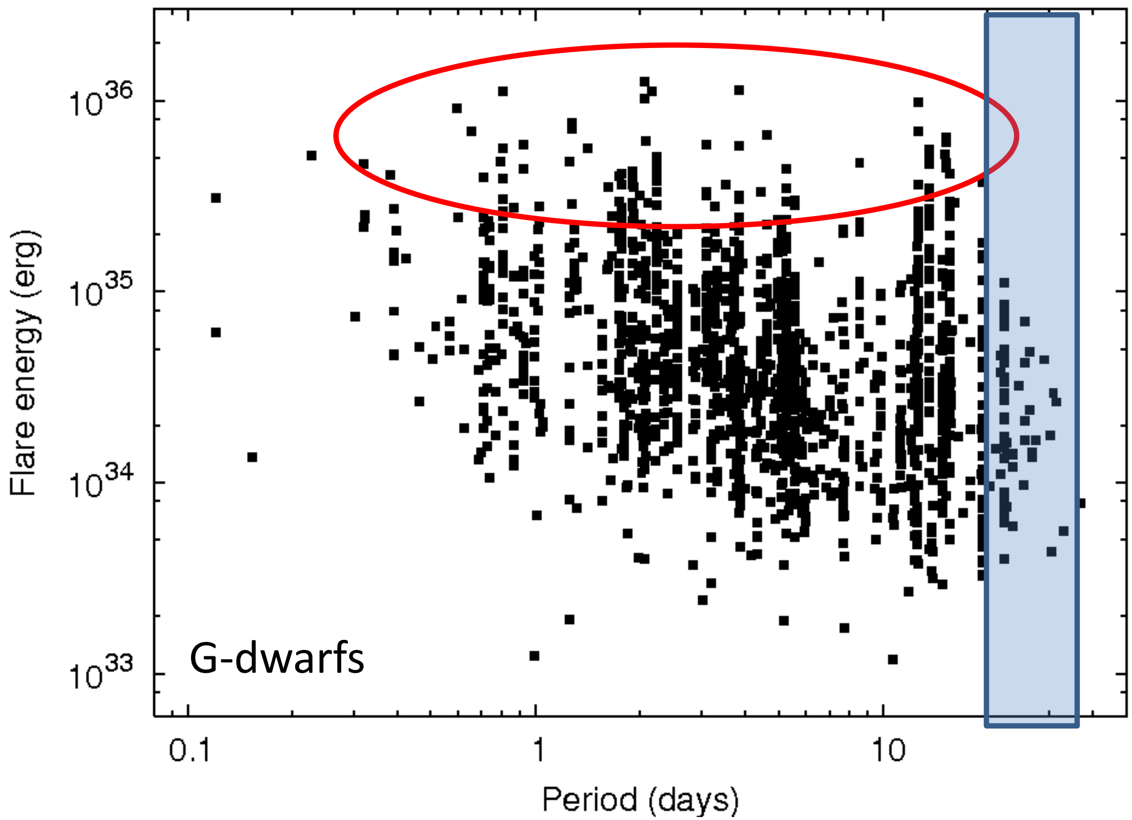
Flare frequency vs. rotation period

- The frequency of superflares decreases as the rotation period increases (P>2-3days).
  - The frequency of superflares shows the "saturation" for a period range < 2-3 days.
  - The fraction of stars that flare also decreases as the rotation period increases.





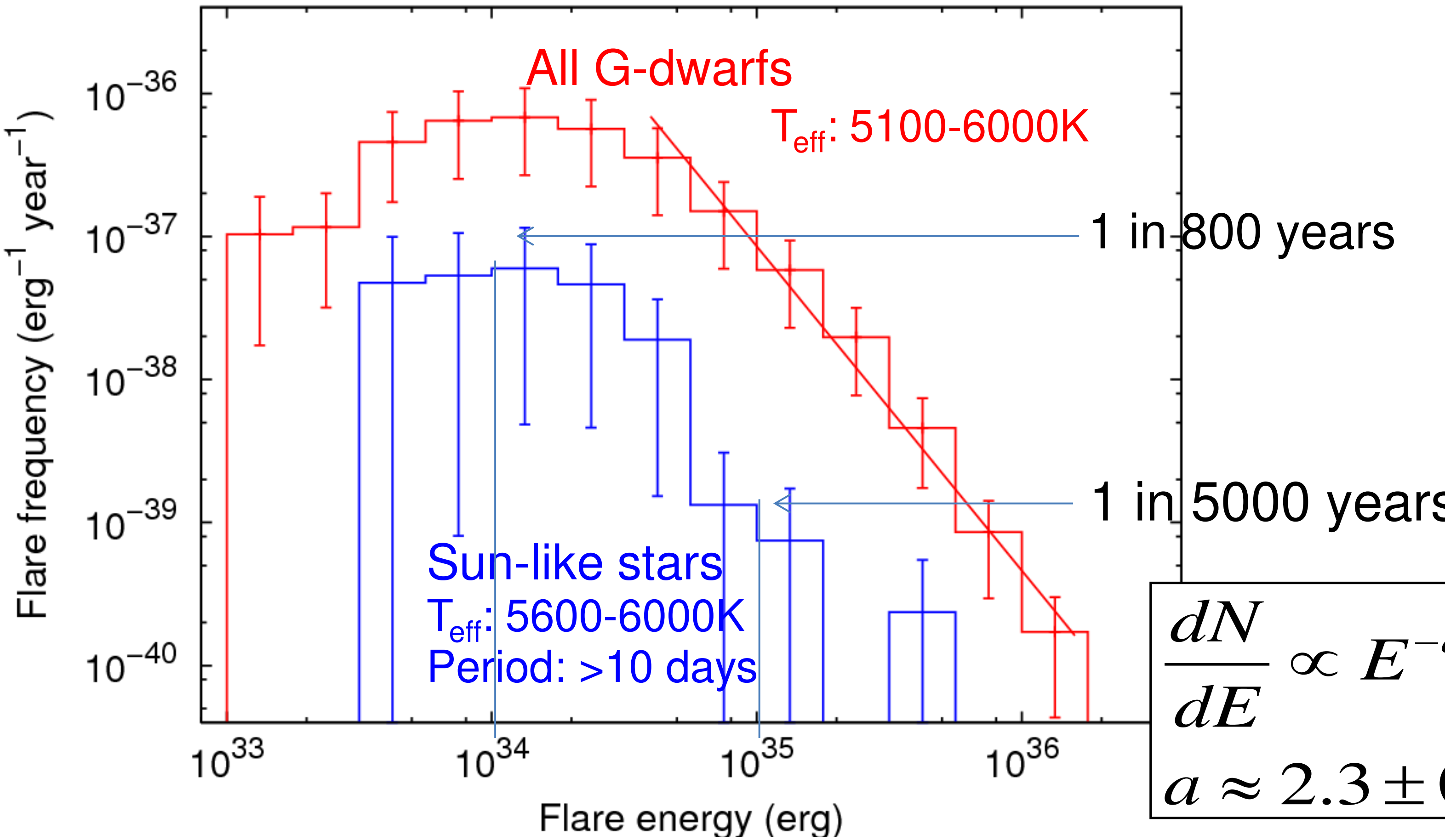
Flare energy vs. rotation period



- The energy of the largest flares observed in a given period bin does not have a clear correlation with the rotation period.
  - Magnetic energy stored near the spots does not have a strong dependence on the rotation period.
  - Superflares may occur on the slowly rotating stars

Flare frequency distribution

- Power-law distribution with the index of -2.3+/- 0.3
  - The frequency distribution is similar to that of solar flares.



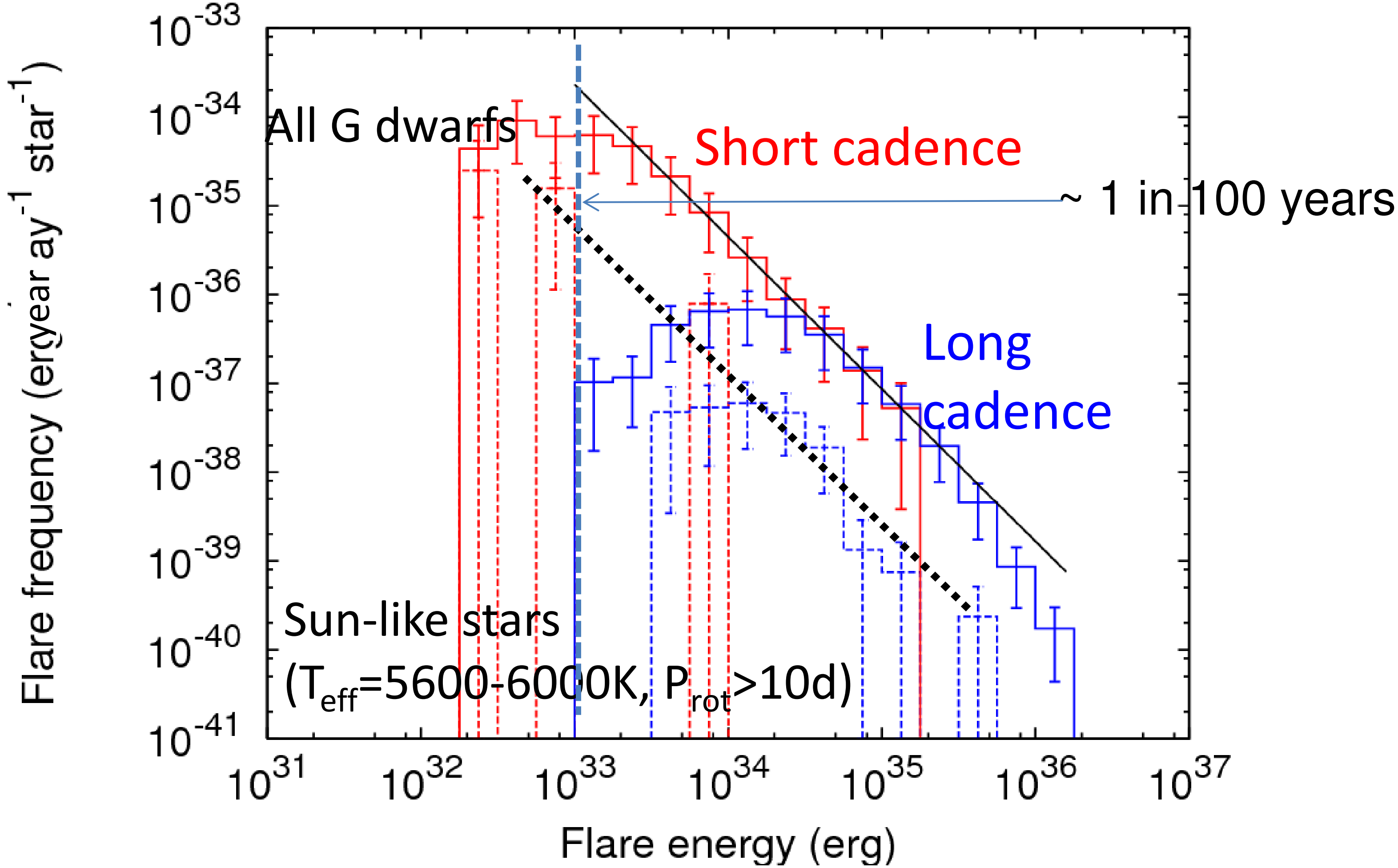
$$\frac{dN}{dE} \propto E^{-a}$$

$$a \approx 2.3 \pm 0.3$$

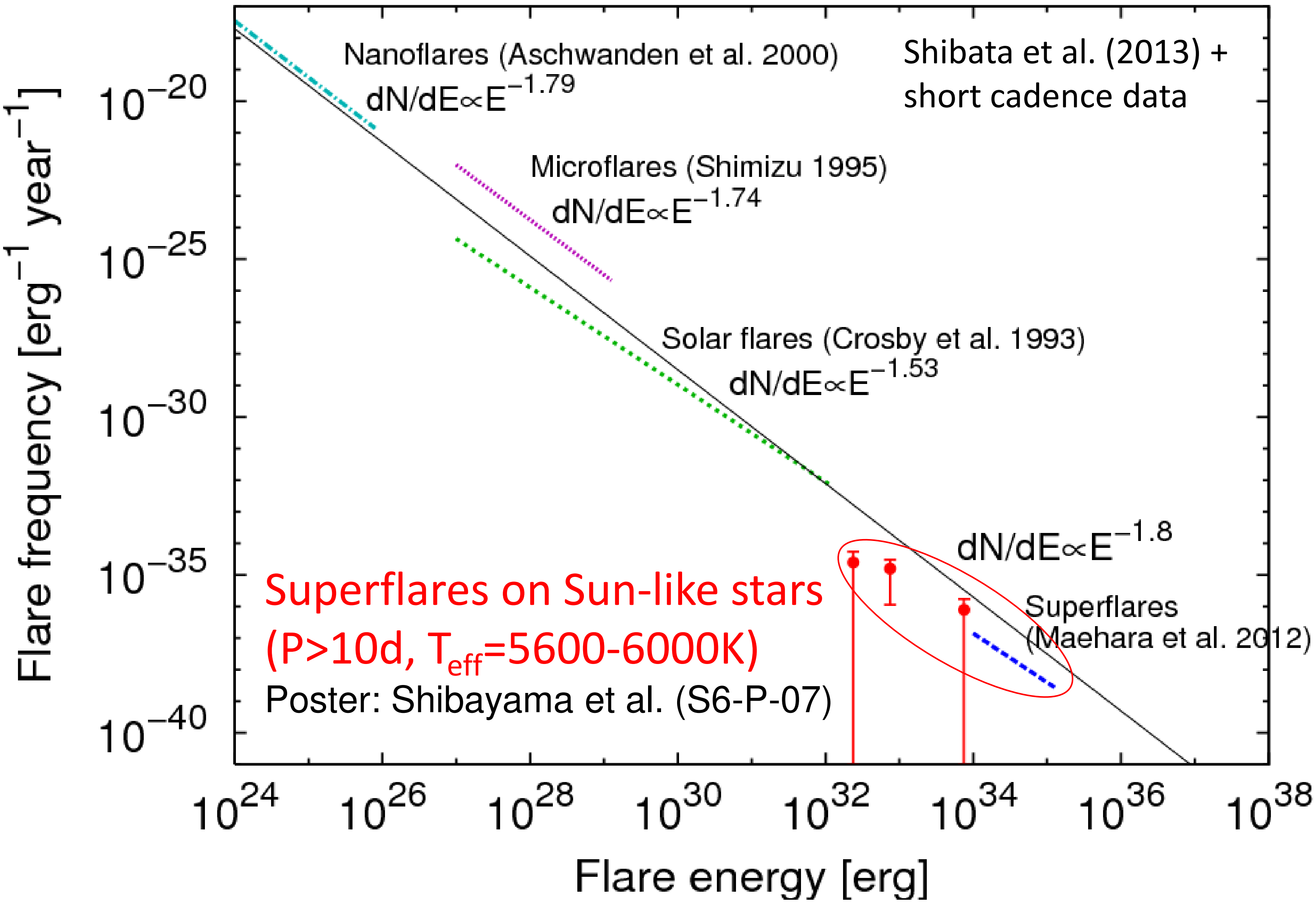
※Flare frequency = $\frac{\textit{Number of superflares}}{(\textit{number of stars}) \times (\textit{length of observation period}) \times (\textit{bin width})}$

Flare frequency distribution

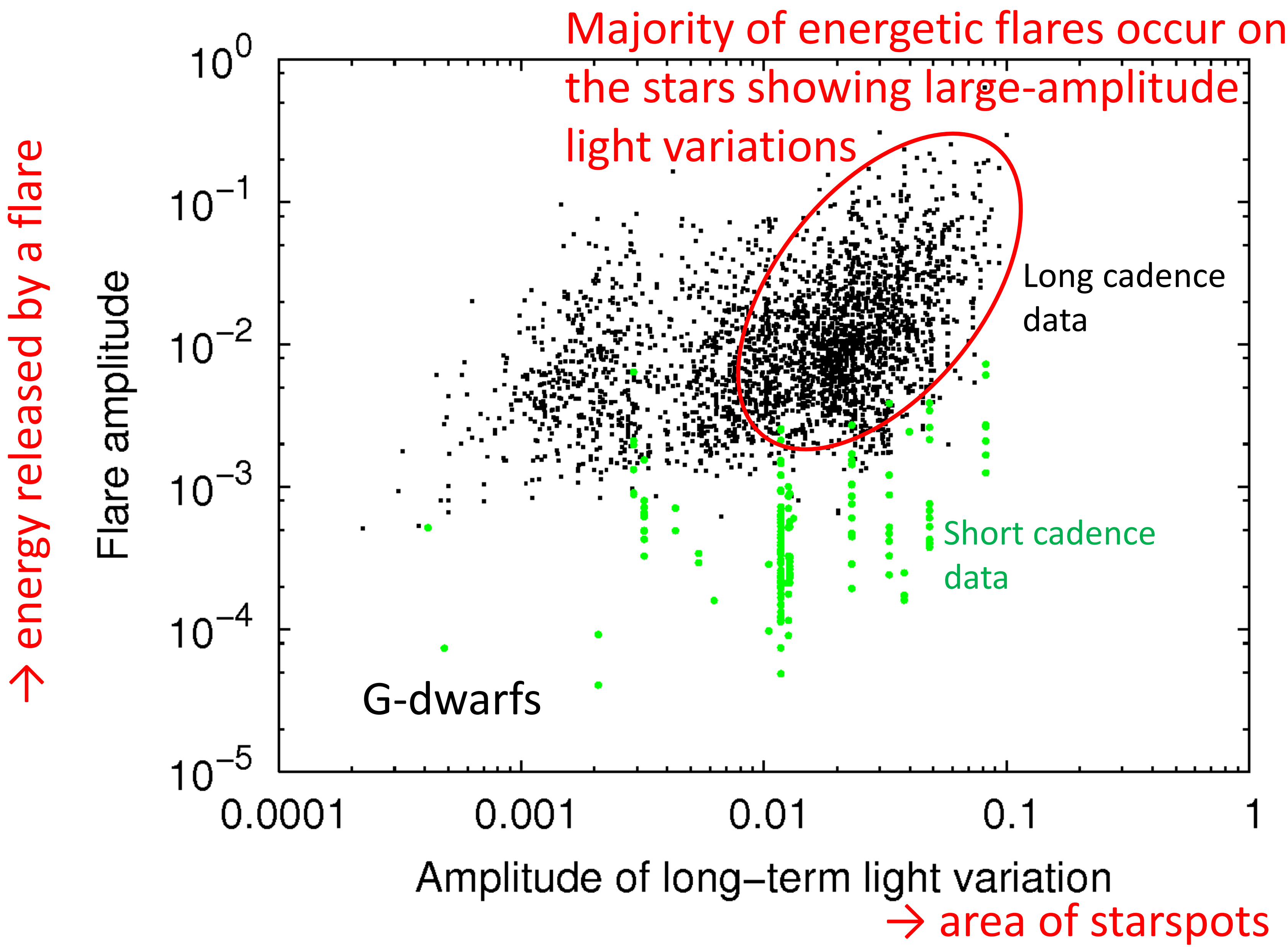
- Frequency distribution from short cadence data is consistent with that from long cadence data.



Flare frequency vs. flare energy



Flare energy vs. area of starspots



Flare energy vs. area of starspots

Basic mechanism of superflare is the same as that of solar flares (reconnection) .

Shibata et al. (2013)

$$E_{\rm flare} \approx f E_{\rm mag} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2}{8\pi} A_{\rm spot}^{3/2}$$

- Magnetic energy stored near the starspots is roughly proportional to $A_{spot}^{3/2}$

→ (largest energy of flares)∝(amplitude of light variations)$^{3/2}$

Flare energy vs. area of starspots

- Flare energy is consistent with the magnetic energy stored near the starspots.

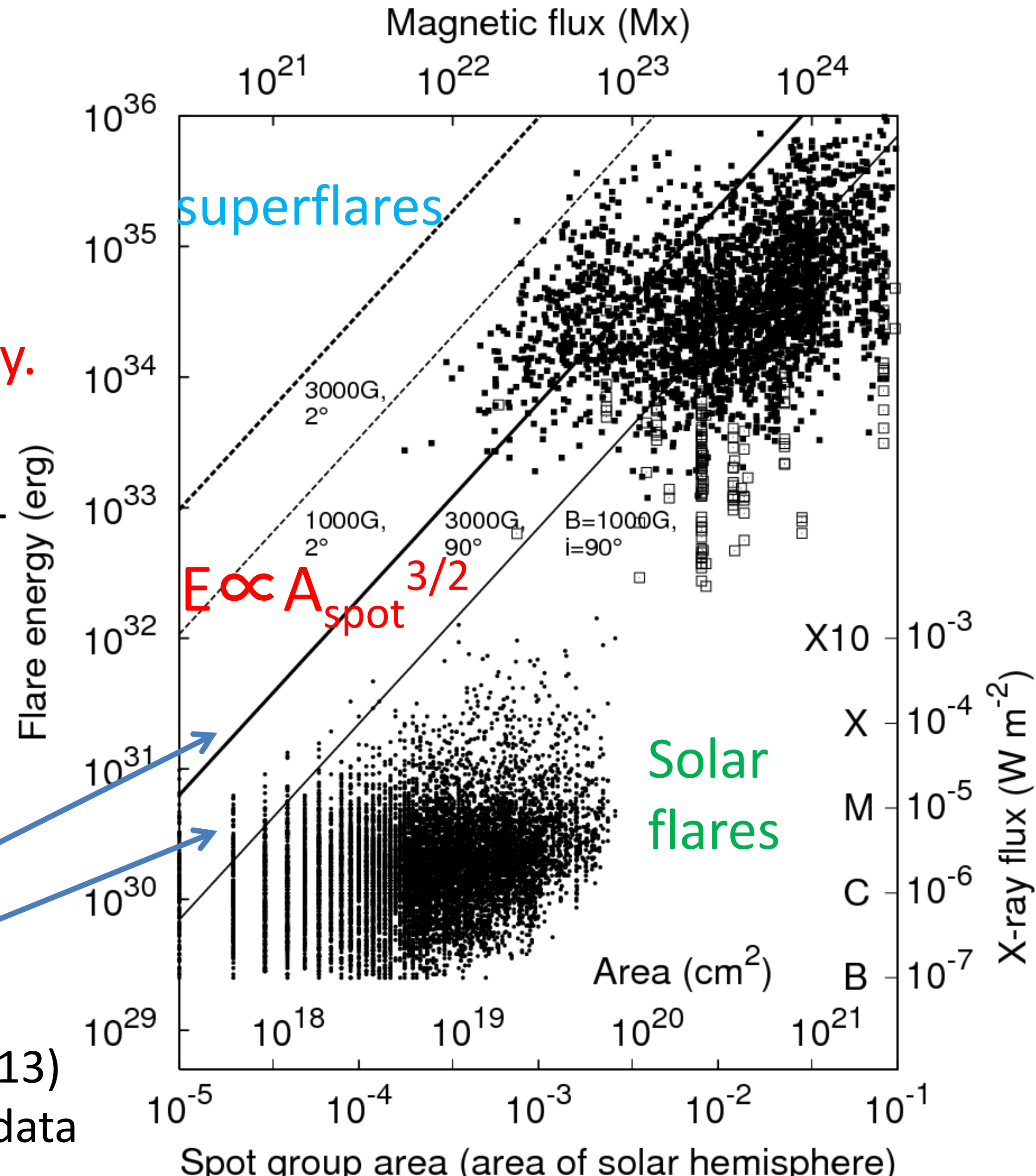
->Large starspots are necessary.

- Flares above the line may occur on the stars with low-inclination angle.

$$E_{\rm flare} \approx f E_{\rm mag} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2}{8\pi} A_{\rm spot}^{3/2}$$

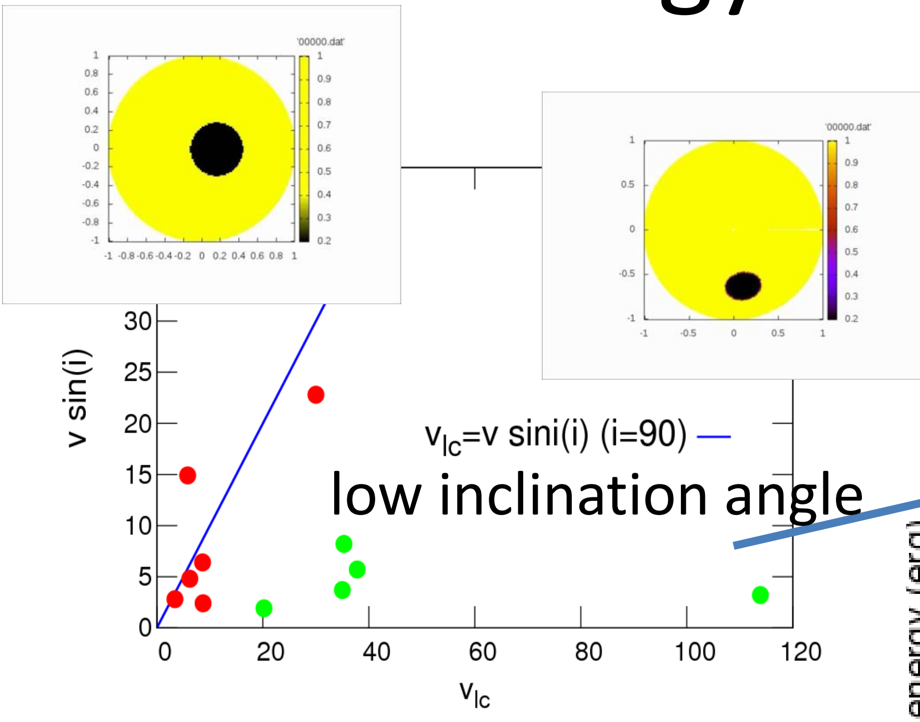
f=0.1, B=3000G

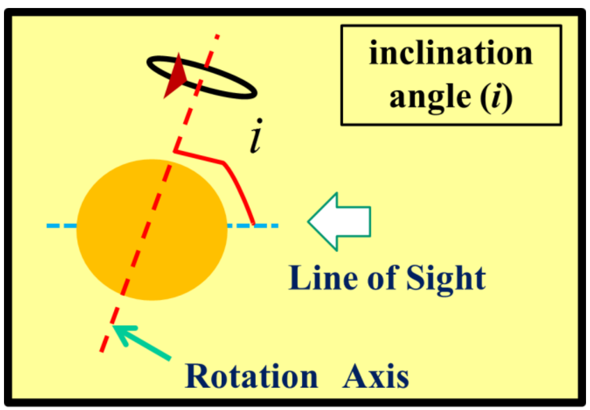
f=0.1, B=1000G

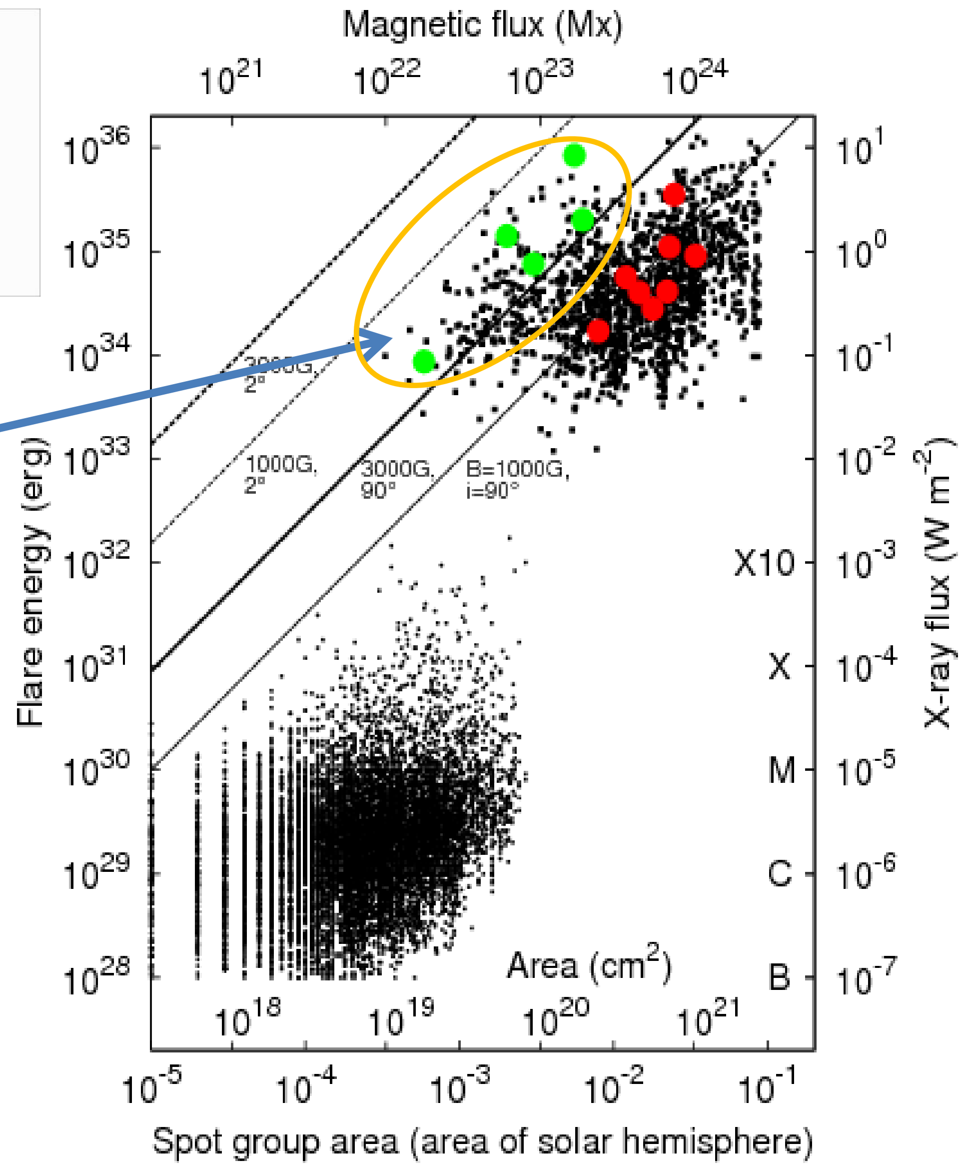


Shibata et al. (2013)
+ short cadence data

Flare energy vs. area of starspots



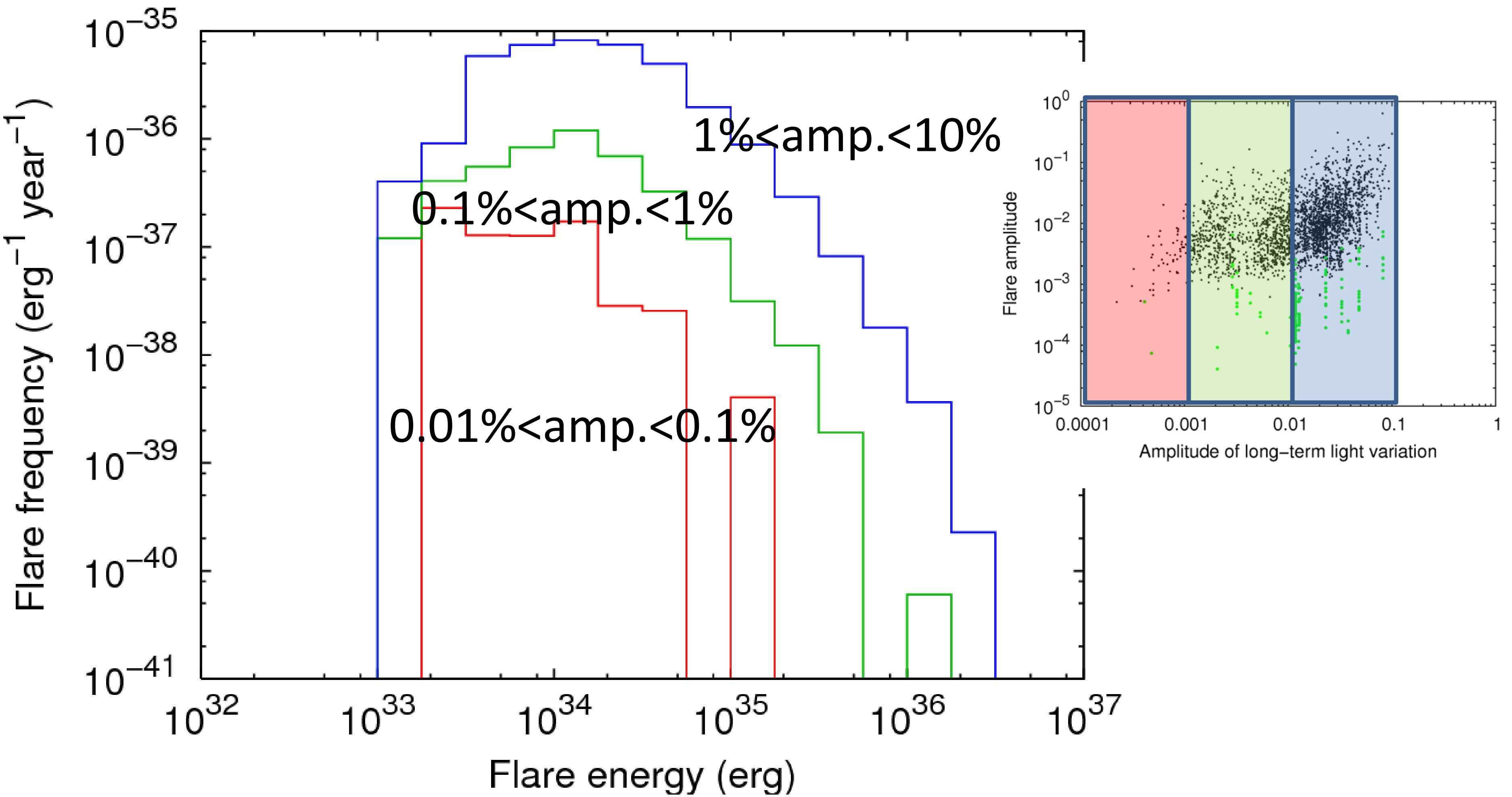




- Notsu et al. (S6-P-09)

Flare frequency and area of starspots

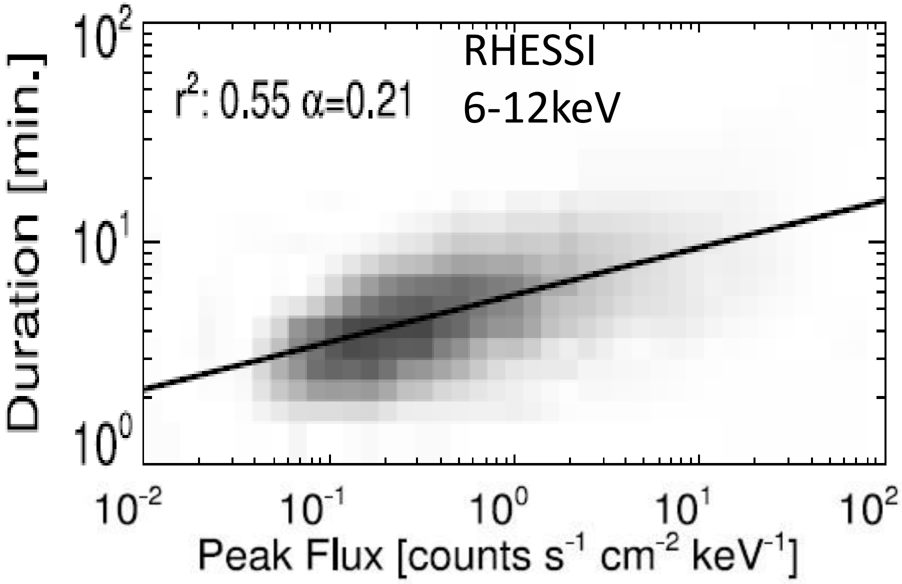
Stars with larger starspots show more frequent superflares

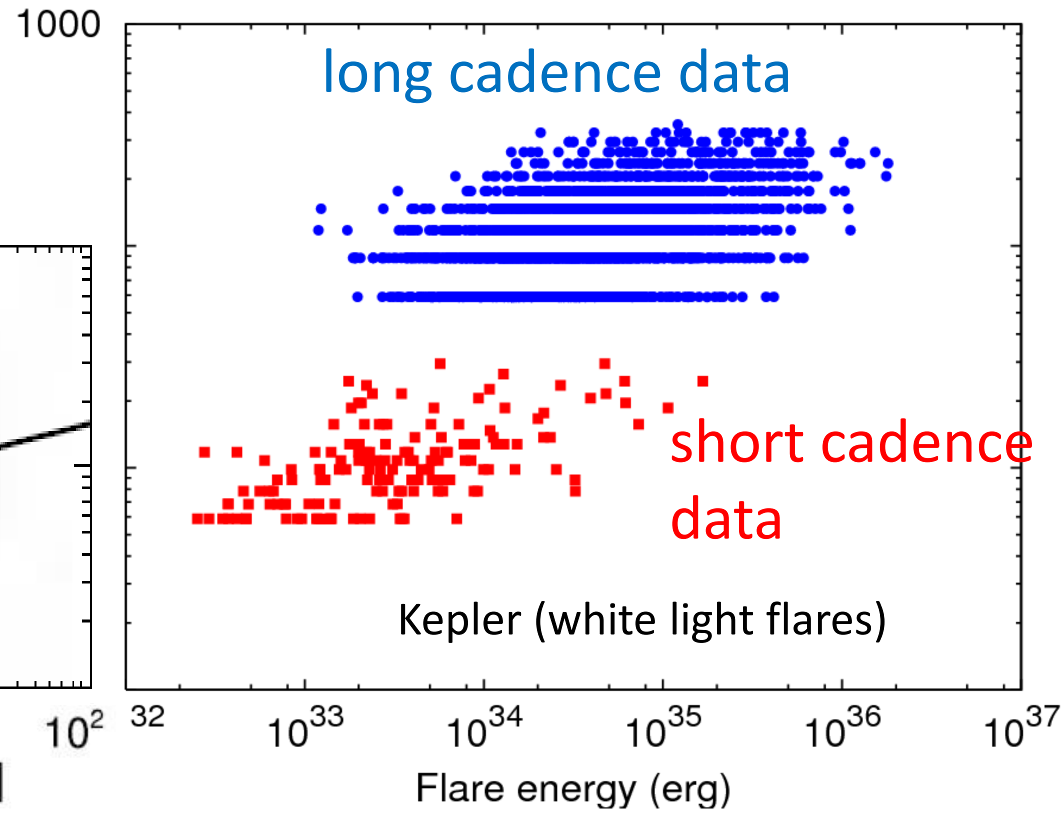


Flare duration vs. flare energy

- The duration of flares tends to increase as the flare energy increases.
  - similar to the relation between the duration and peak flux observed with RHESSI.

Christe et al. (2008) ApJ 677, 1385





Summary

- Frequency distribution of superflares on solar-type stars (G-dwarfs) is similar to that of solar-flares.
  - can be fitted by a power-law function (index: ~-2)
- Flare frequency depends the rotation period of the star.
  - Rapidly rotating stars show frequent superflares.
- The maximum energy of superflares depends on the total area of starspots.
  - large starspots are necessary for superflares.
  - does not show strong dependence on the rotation period
  - Superflares can occur on slowly rotations stars like our Sun.
- Follow-up spectroscopy is necessary.
  - Are superflare stars really similar to the Sun?
    - binarity, rotation velocity, inclination, existence of planets, etc.