Superflares on solar-type stars

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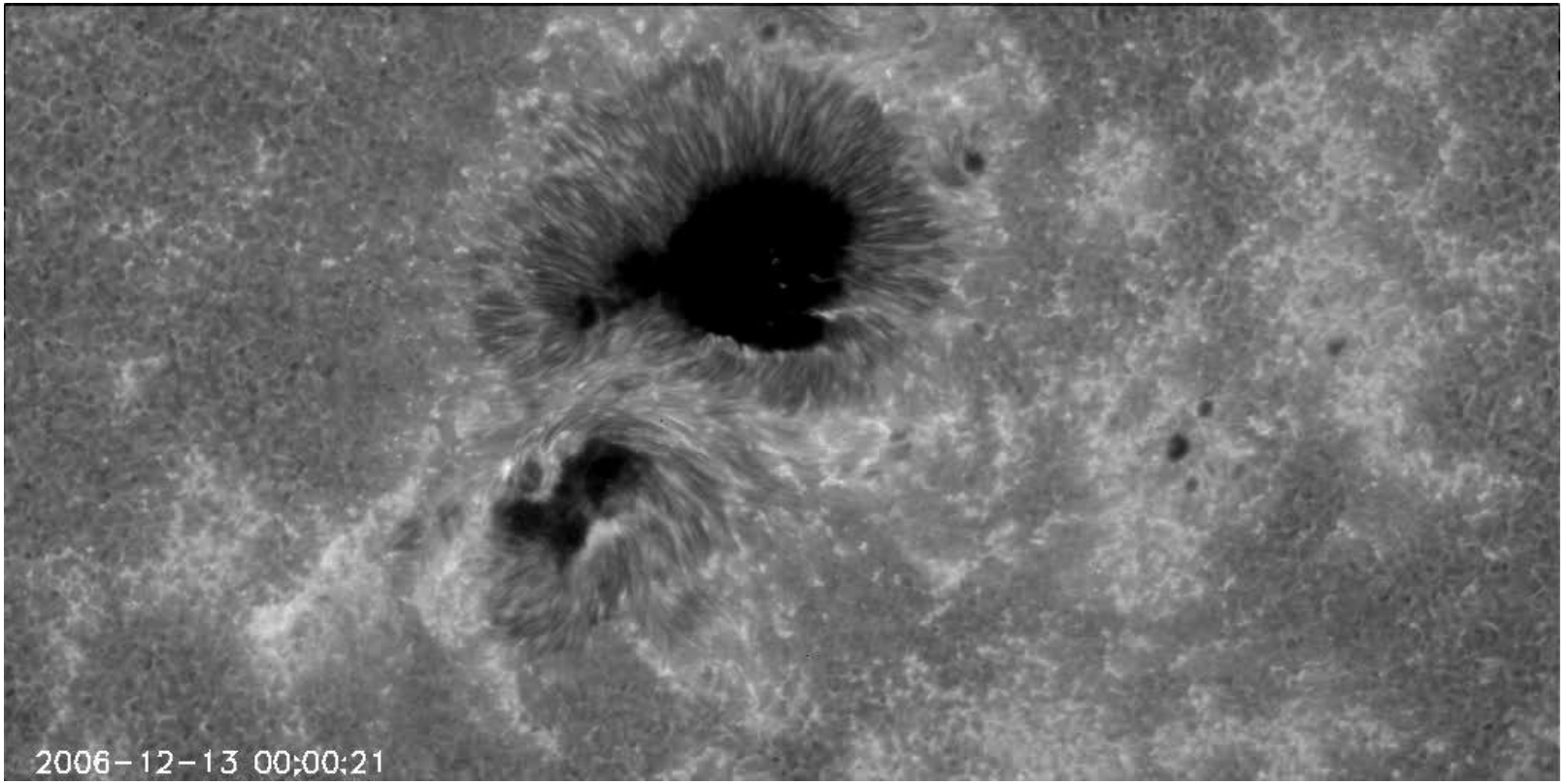
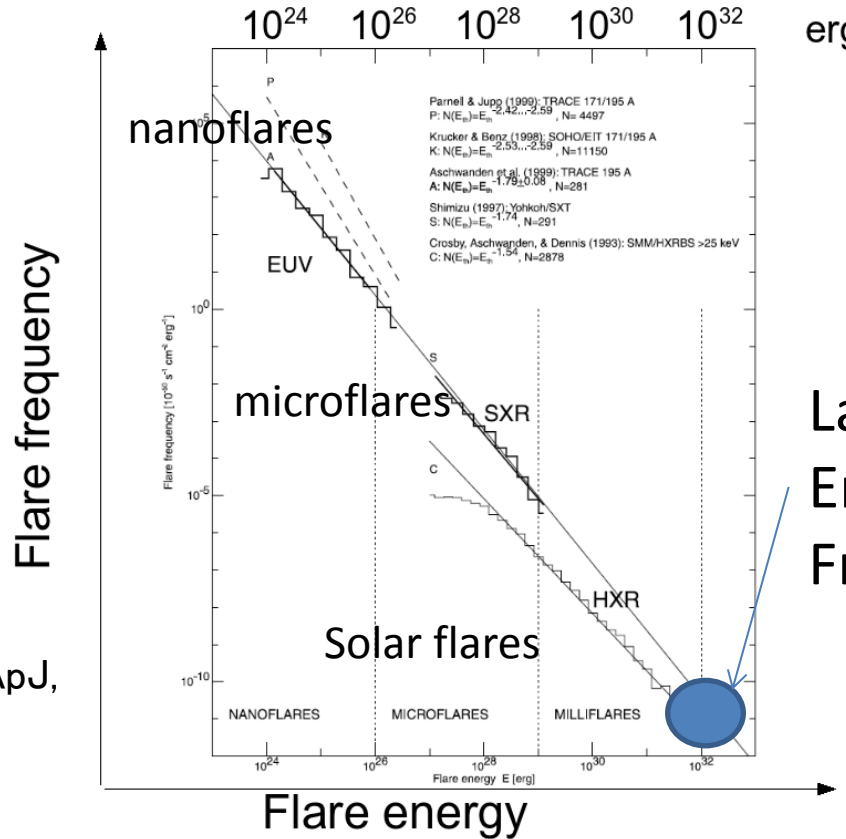
Solar flares

- Large eruptive events in the solar atmosphere
  - typical energy: 10^{29} – 10^{32} ergs
  - caused by magnetic reconnection



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 **???**

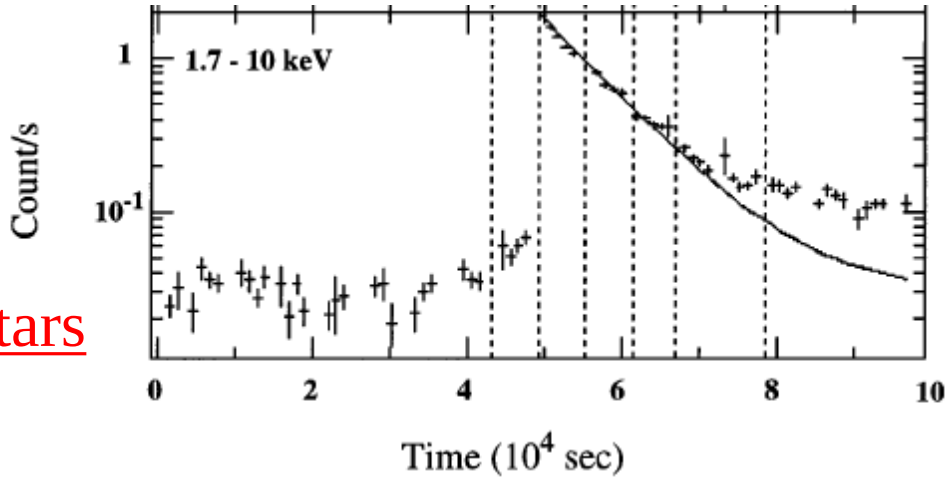


Largest solar flares
Energy: ~10^{32} ergs
Frequency: ~1 in 10 years

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)
  - →young, rapidly rotating stars

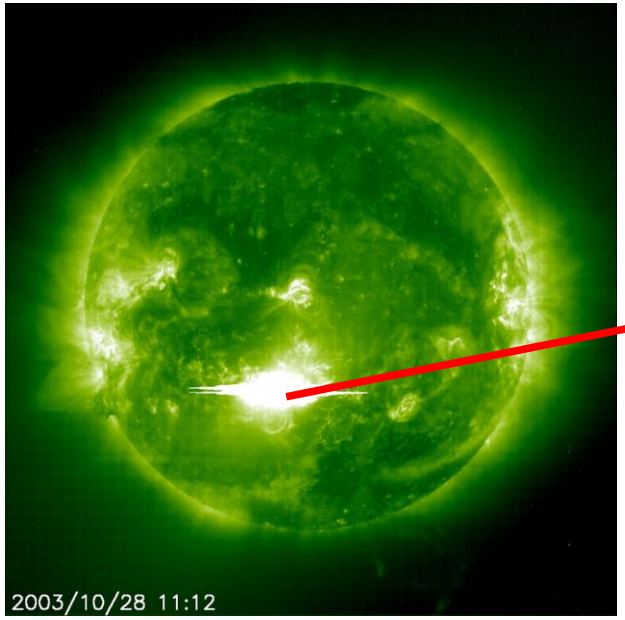


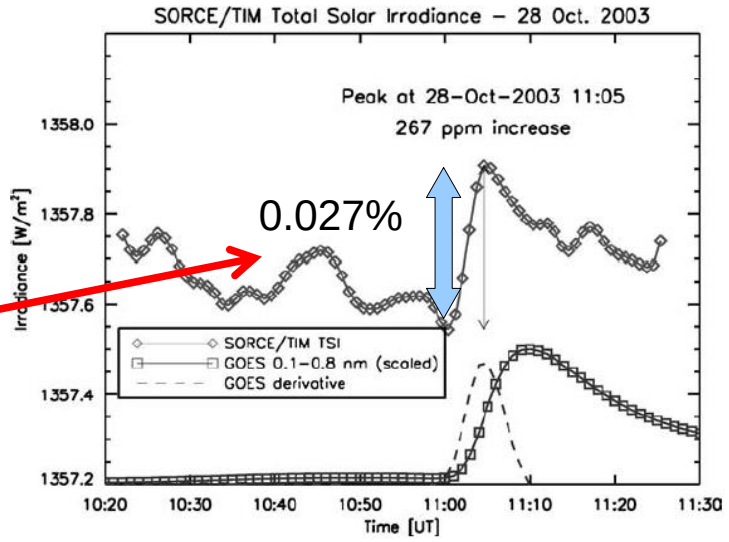
V773 Tau (T Tauri binary)
Tsuboi et al., ApJ, 503, 894 (1998)

- 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 ?

Photometry of flares on solar-type stars

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



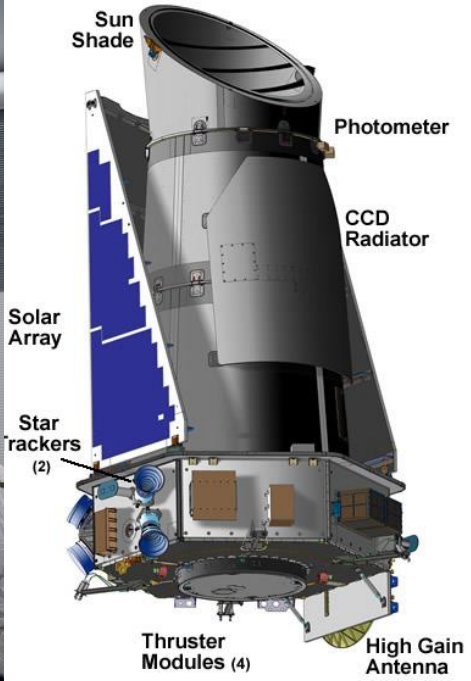


Kopp et al., Solar Phys. 230, 129 (2005)

Kepler Data

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

- We searched for flare-like events (sudden brightenings) from the Kepler public data (Q0-Q6).

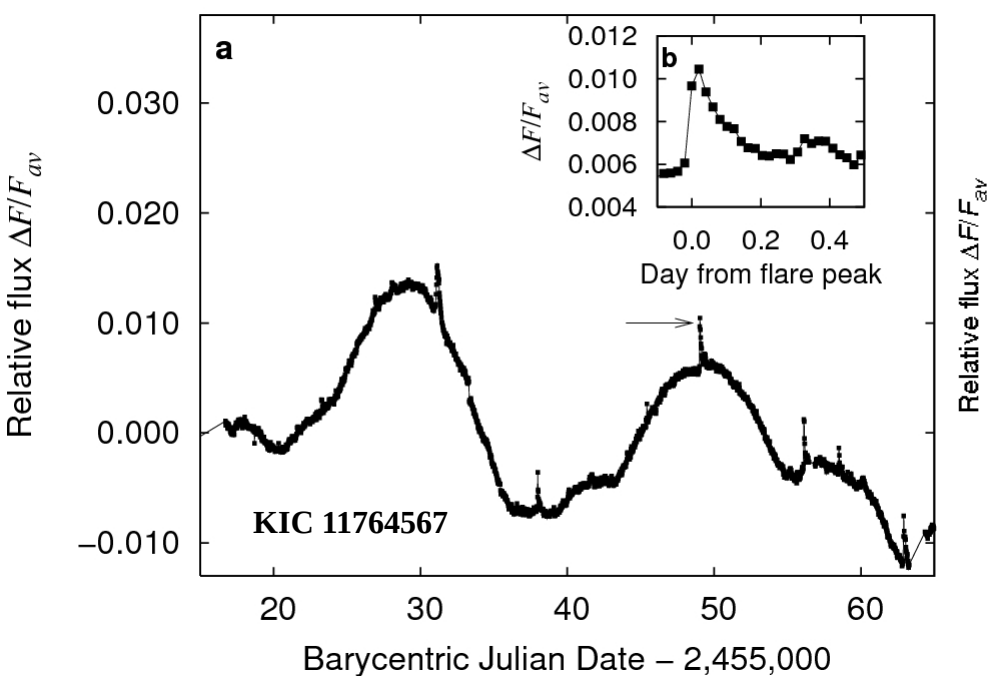


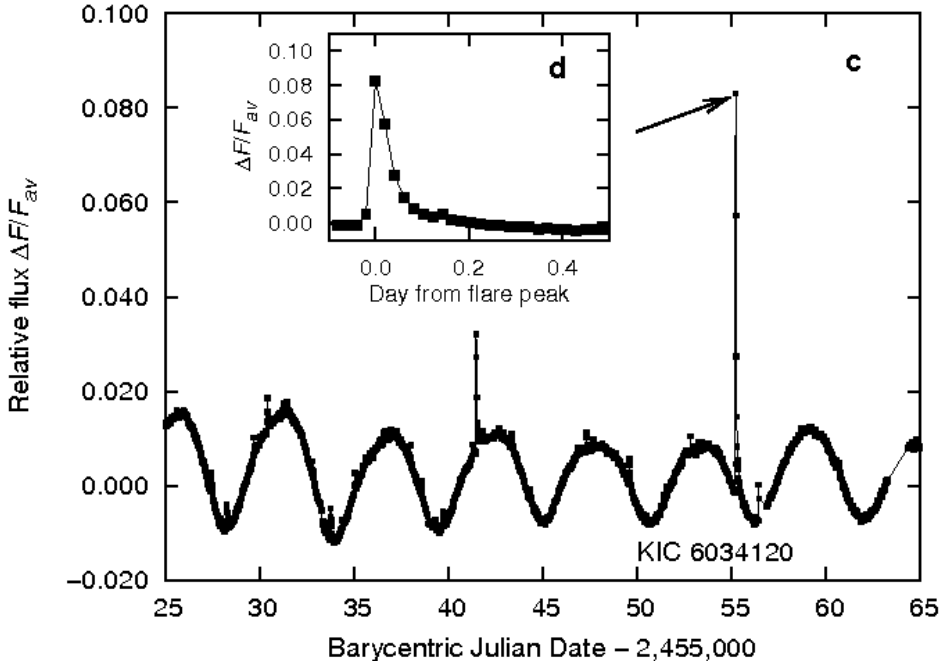
data

- We selected G-, K-, and M-dwarfs from the Kepler Input Catalog.
  - G-dwarfs: 5100 < T_{eff} < 6000K, log g > 4.0: ~90,000
  - K-dwarfs: 3900 < T_{eff} < 5100K, log g > 4.0: ~25,000
  - M-dwafs: ~3500< T_{eff} < 3900K, log g > 4.0: ~2,000

- We analyzed the long time cadence data.
  - Time-resolution: ~30min
  - Observation period: 2009/04-2010/08 (Q0-Q6)

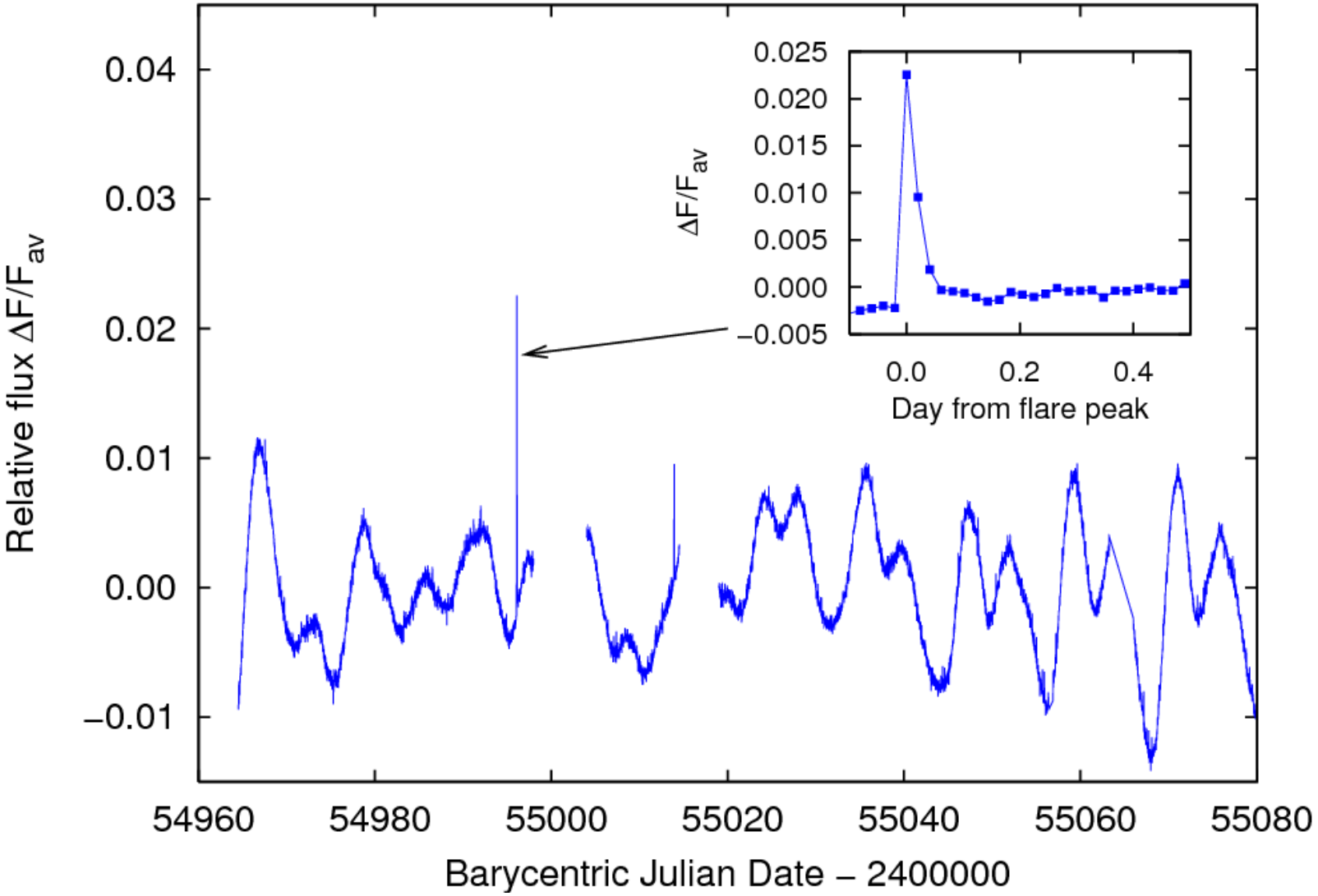
Light curves of superflares on G-dwarfs





- 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)

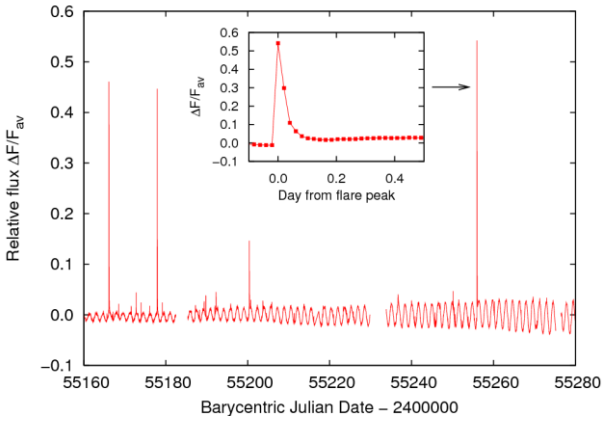
Superflares on a G-dwarf KIC 10524994



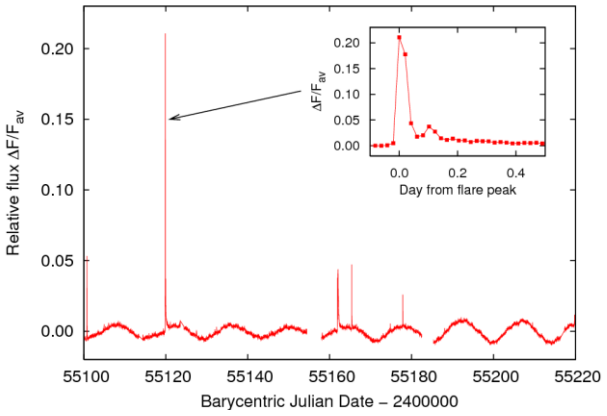
Light curves of superflares

1928 flares/117 stars

KIC 6949412



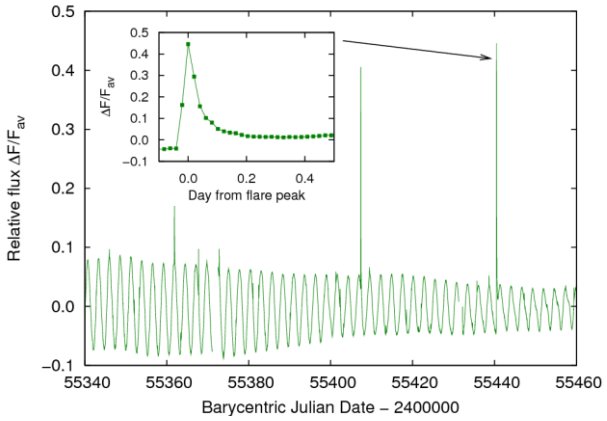
KIC 11349556



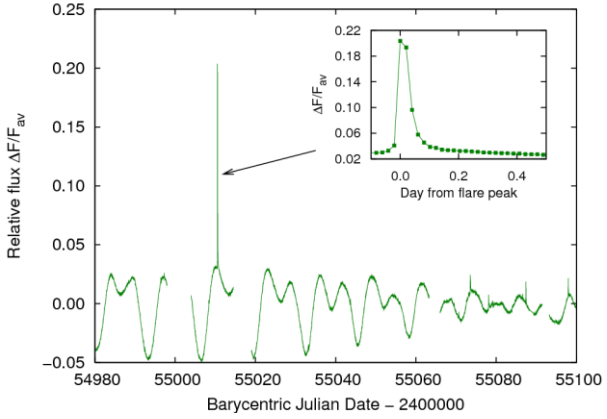
M-dwarfs

3355 flares / 399 stars

KIC 4349043



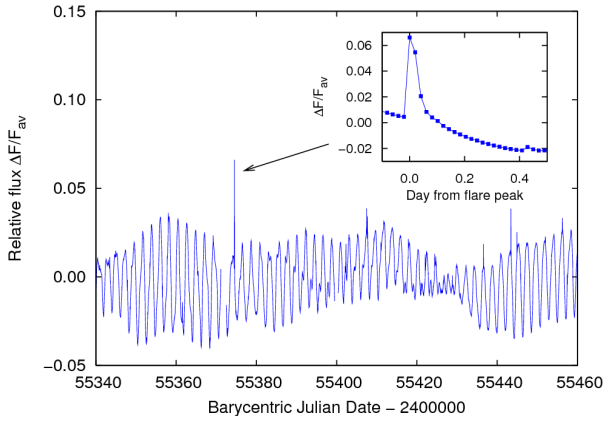
KIC 8142547



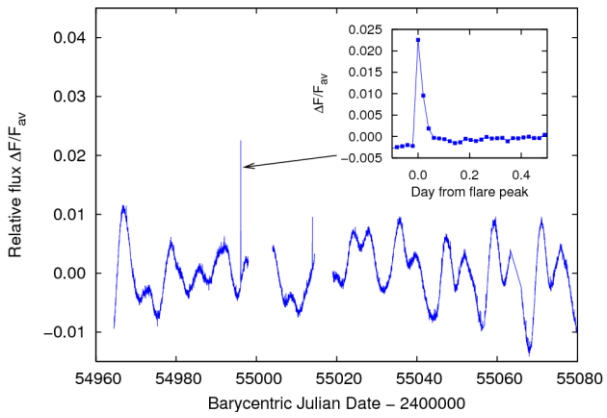
K-dwarfs

1547 flares / 279 stars

KIC 7532880



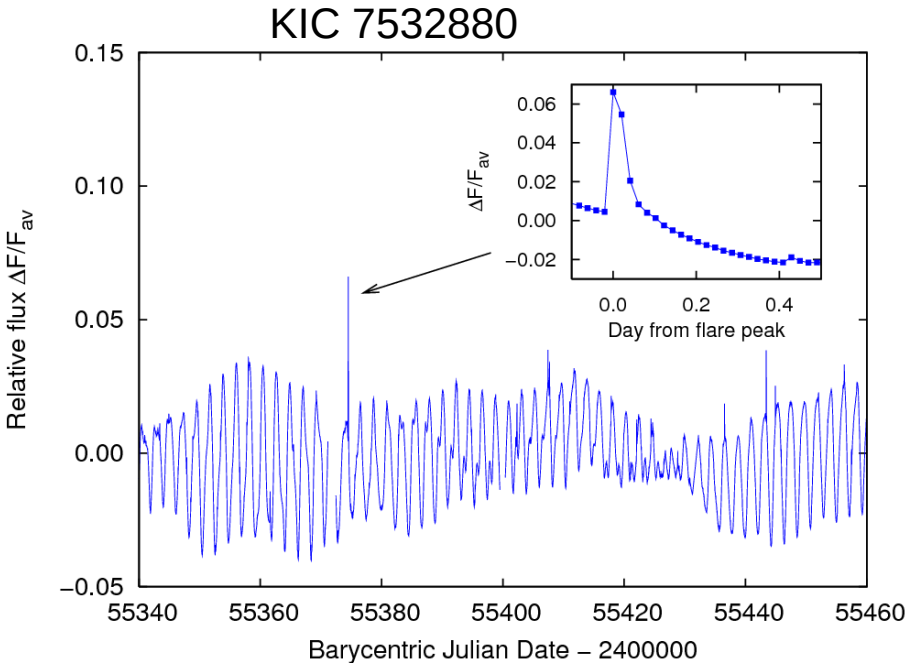
KIC 10524994

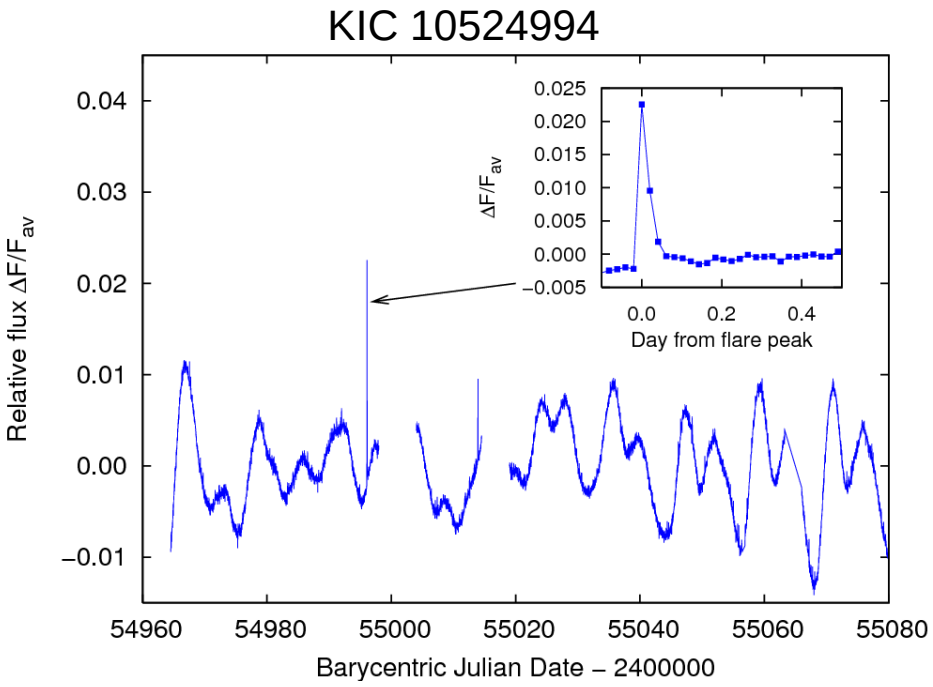


G-dwarfs

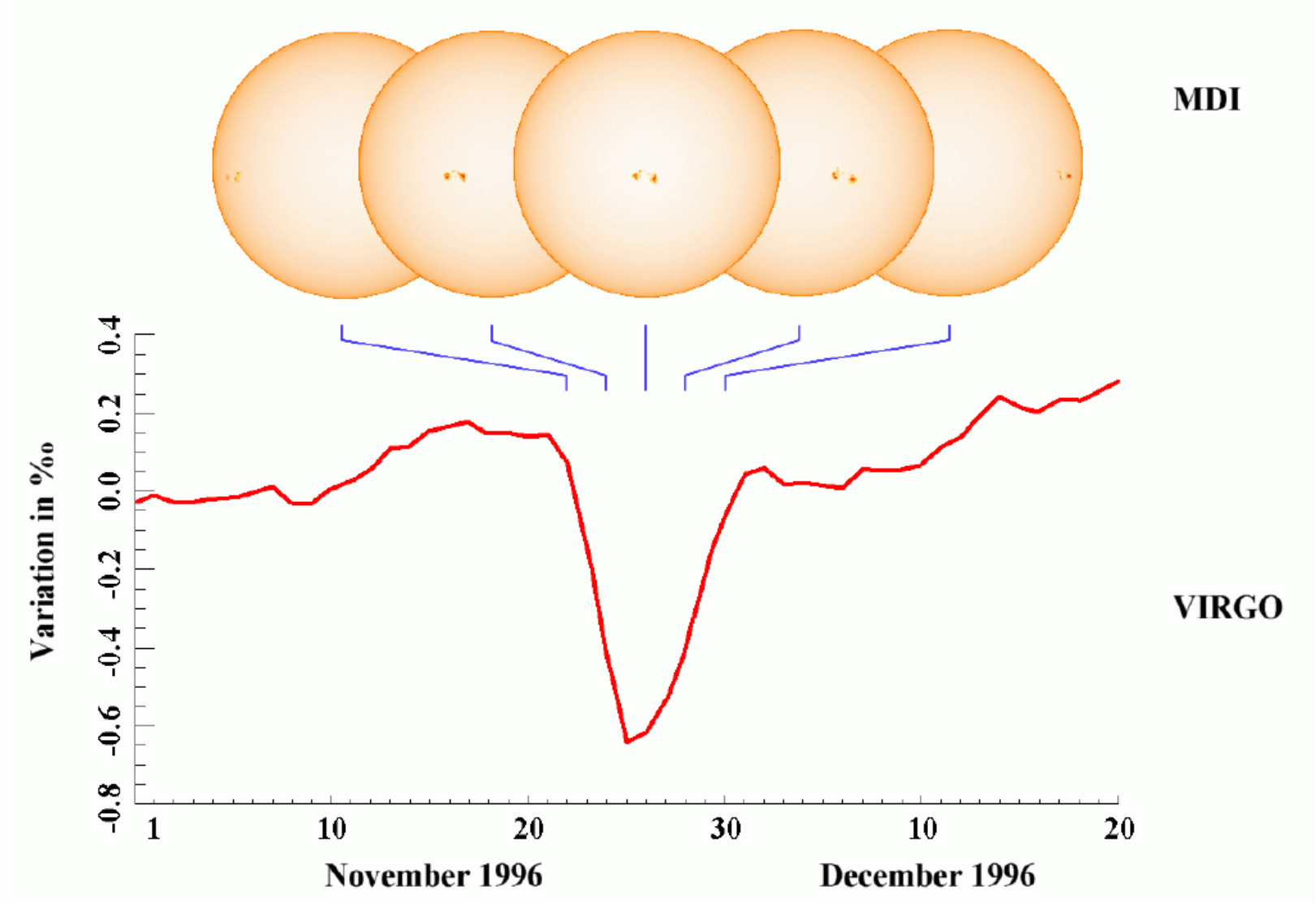
Long-term brightness variations

- Most of superflare stars show quasi-periodic brightness variations.
  - Period: 1 – ~30 days
  - Amplitude: 0.1 - 10%
    - Amplitude of light variations changes with time.





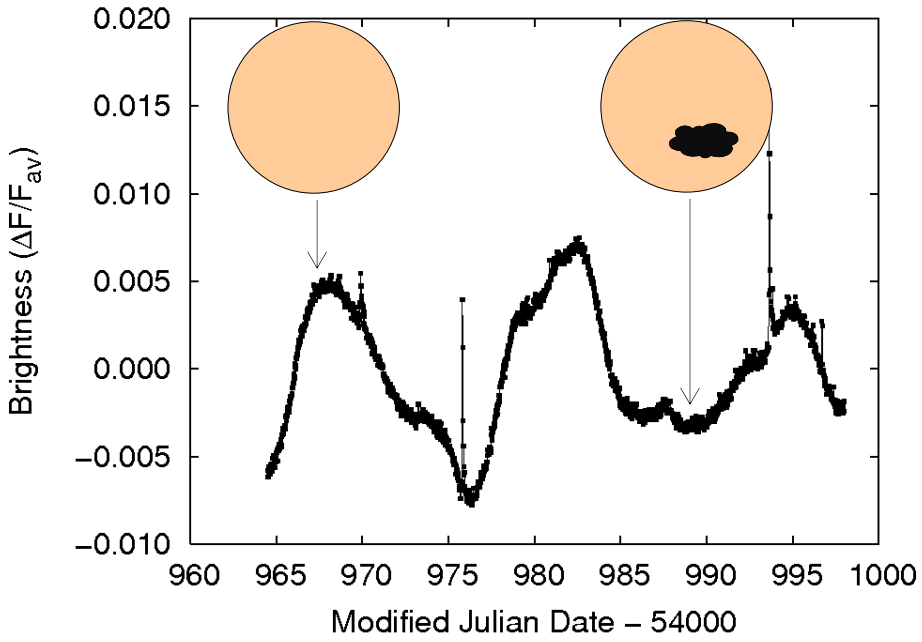
Light curve of the Sun



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

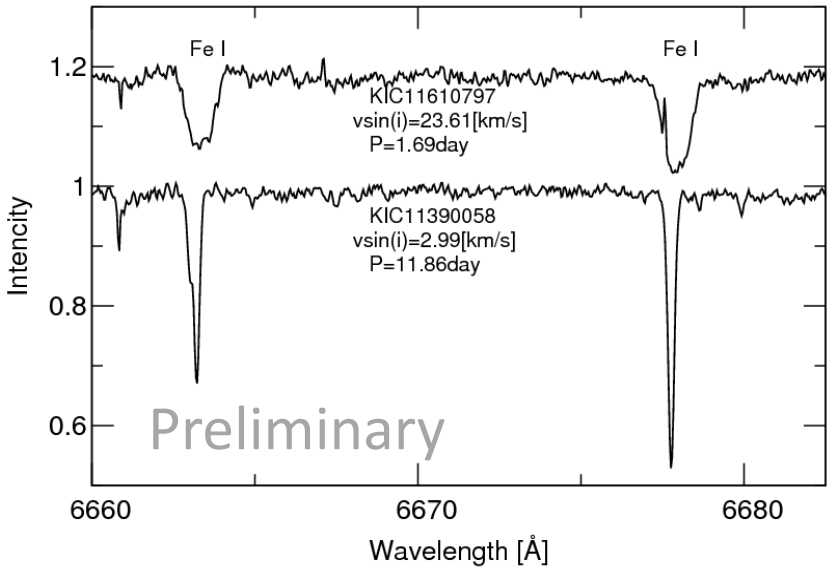
Long-term brightness variations

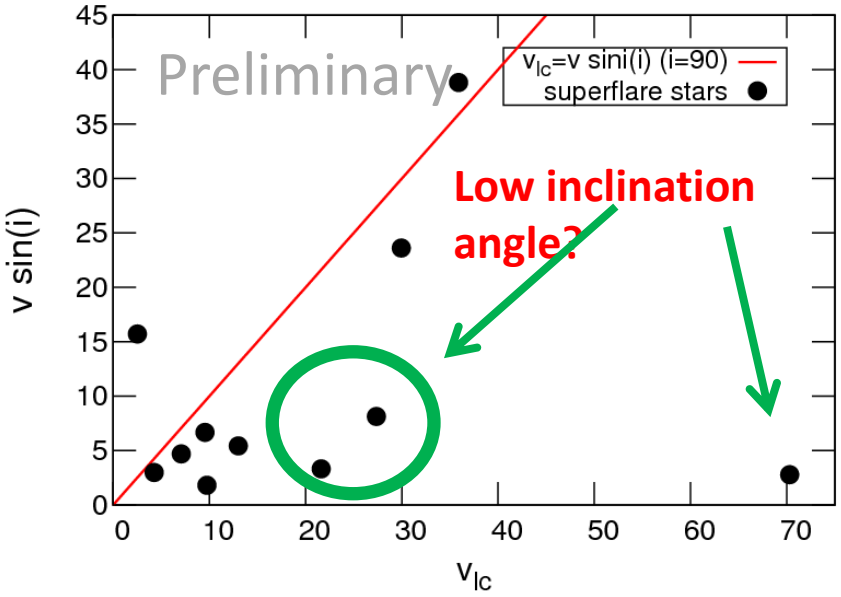
- If we assume that quasi-periodic light variations are caused by the rotation of the star with starspots,
  - Period of brightness variation → rotation period
  - Amplitude → total area of starspots



Spectroscopy with Subaru/HDS

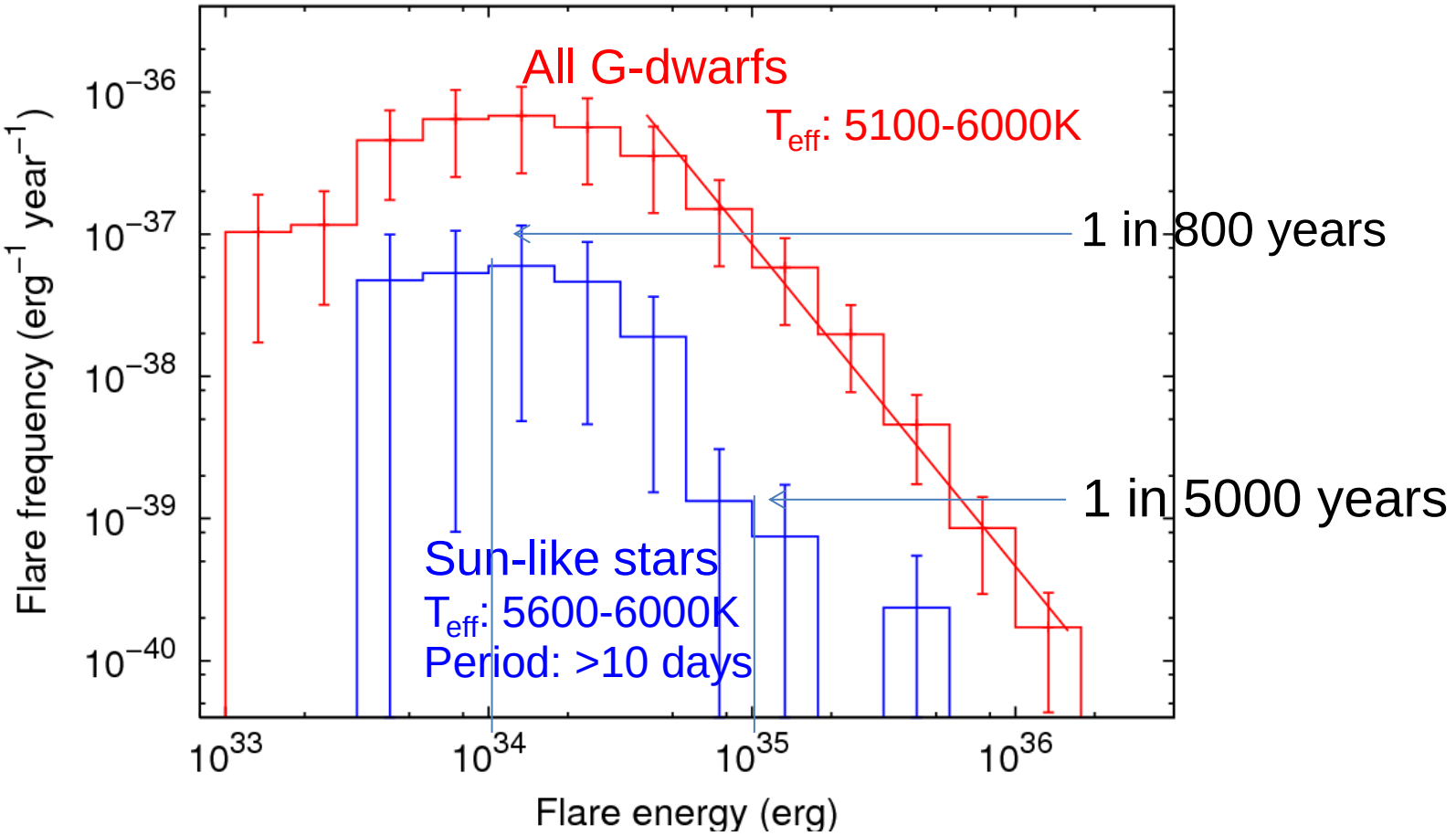
- We performed high-dispersion spectroscopy of superflare stars with Subaru telescope.
- Photometric periods of each stars are consistent with rotation velocities.





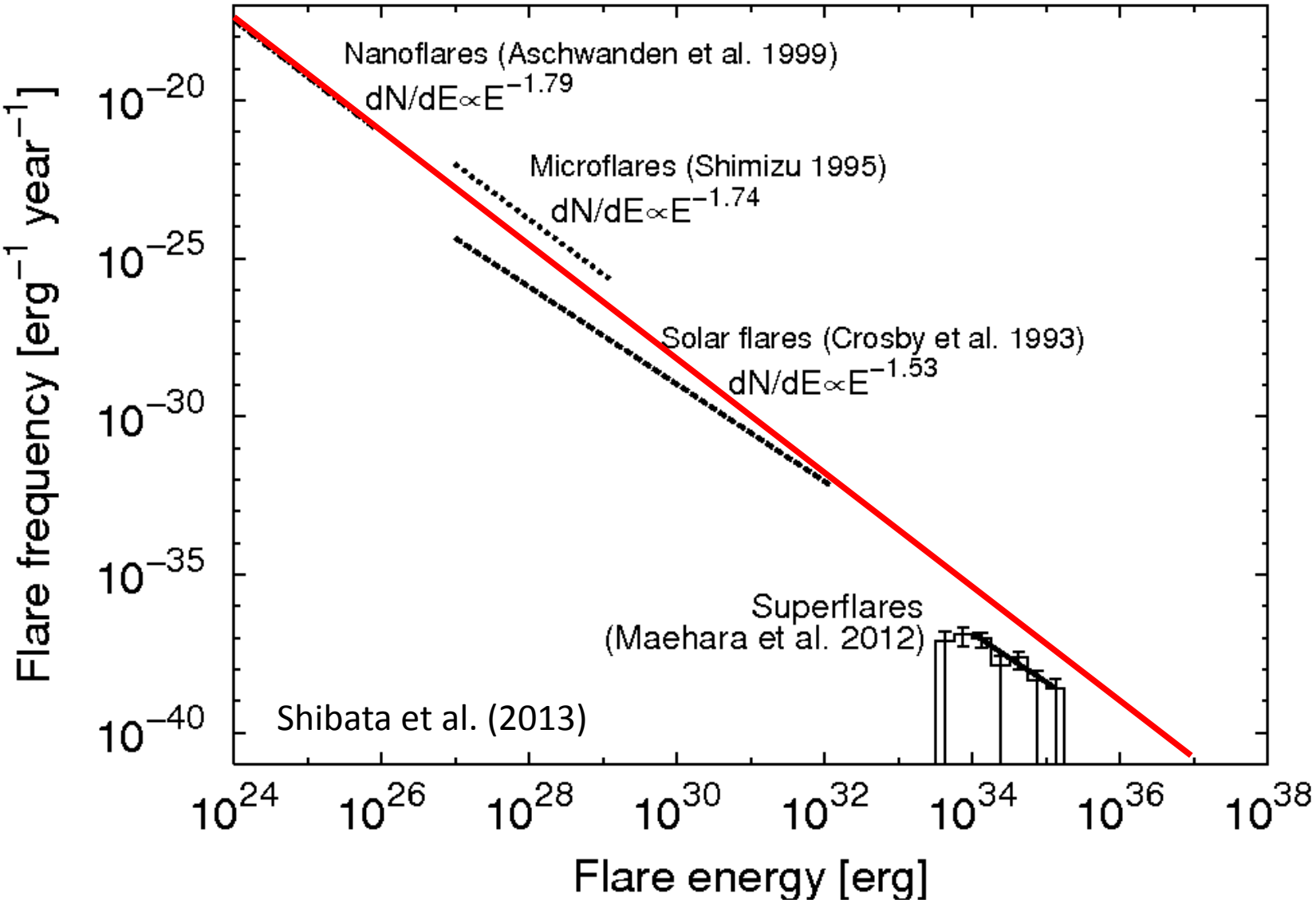
Frequency distribution

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



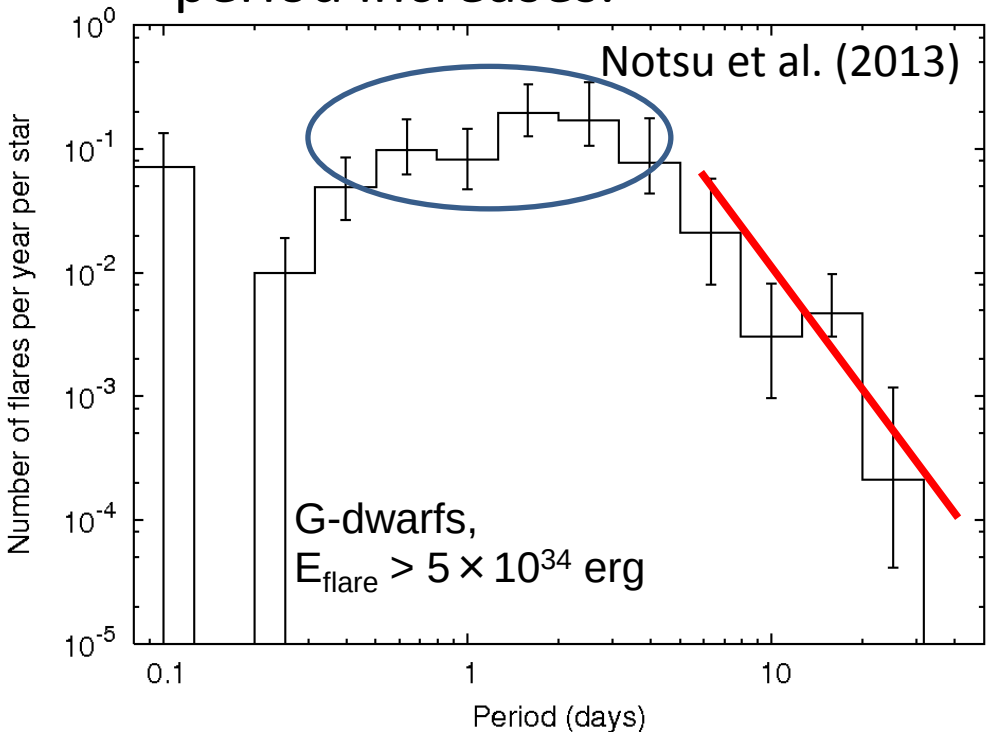
※*Flare frequency* = $\frac{Number\ of\ superflares}{(number\ of\ stars)\times(length\ of\ observation\ period)\times(bin\ width)}$

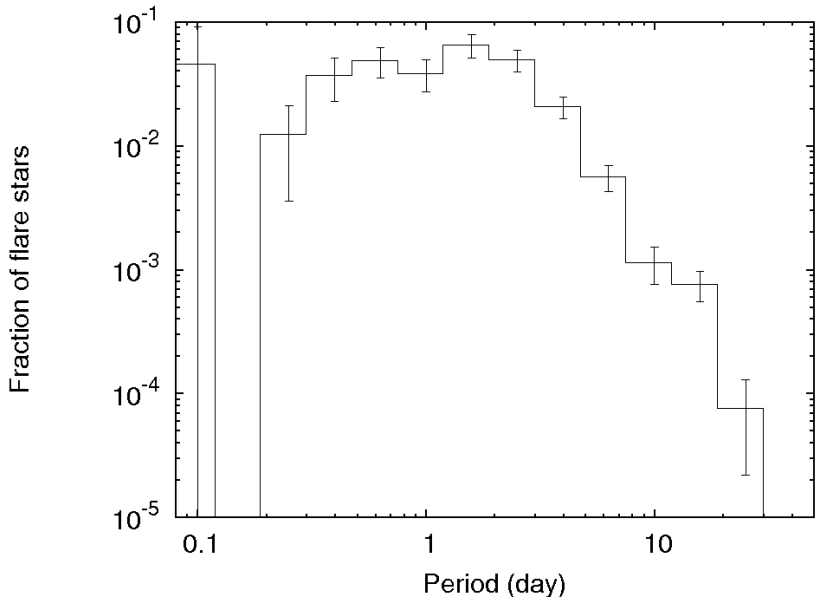
Frequency distribution



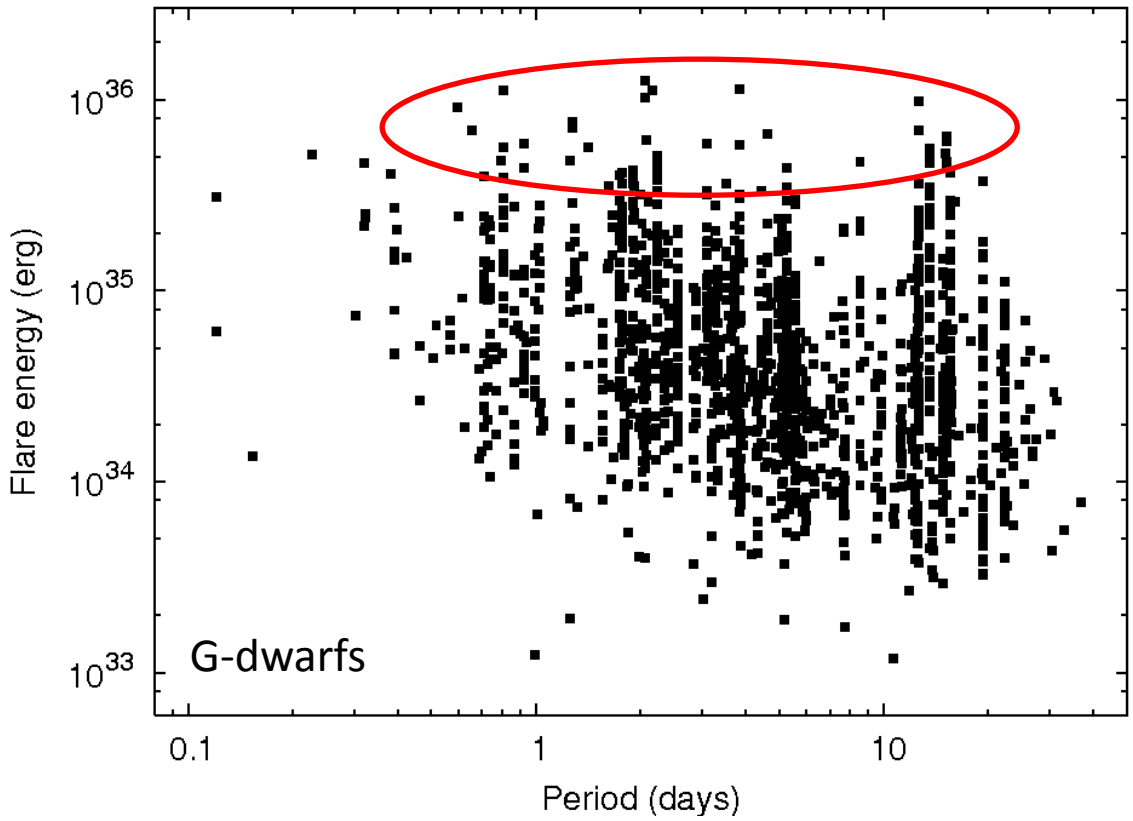
Flare frequency vs. rotation period

- 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.



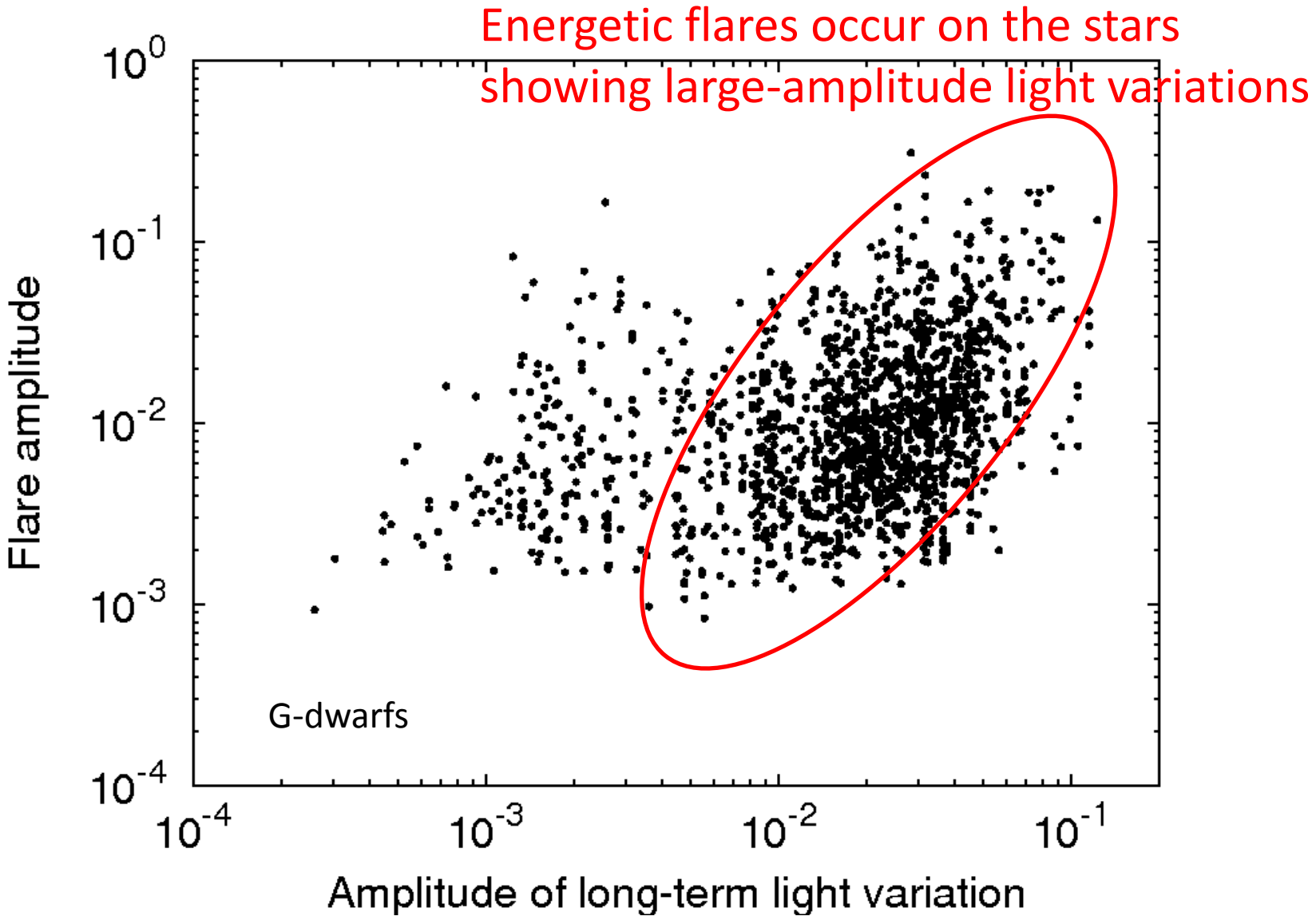


Flare energy vs. rotation period



- 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 energy vs. spot size



Flare energy vs. spot size

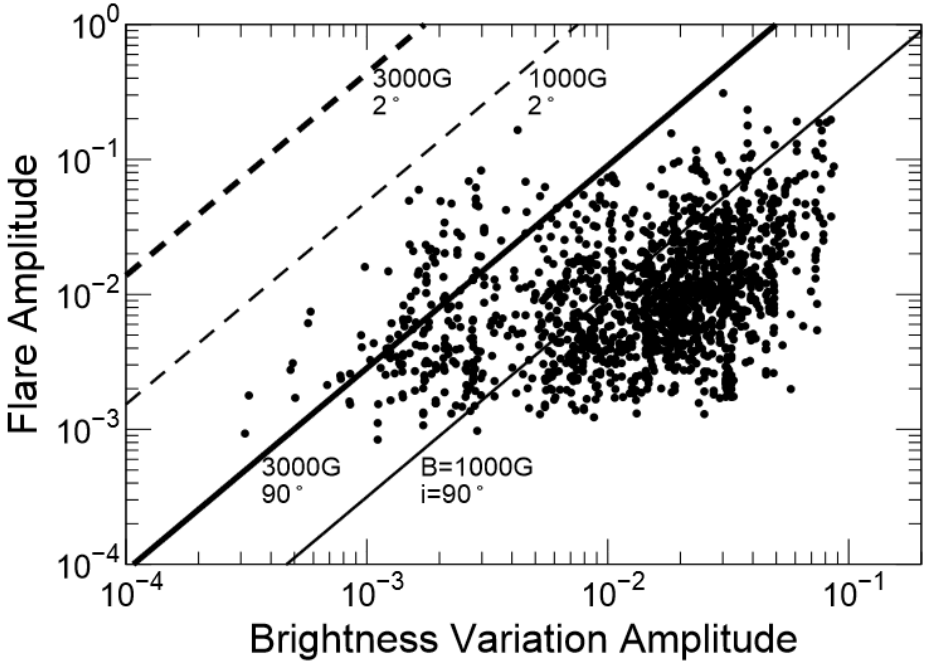
$$E_{\rm flare} \approx f E_{\rm mag} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2}{8\pi} A_{\rm spot}^{3/2}$$

Maehara et al (2012)
Shibata et al. (2013)
Notsu et al. (2013)

- Magnetic energy stored near the starspots is roughly proportional to $A_{spot}^{1.5}$
- If we assume that the amplitude of long-term light variations corresponds to the total area of starspots,

(upper limit of flare amplitude) ∝ (the amplitude of light variations)$^{1.5}$

- Flare energy is consistent with the magnetic energy stored near the starspots.
  - Flares above the line may occur on the stars with low-inclination angle



Summary

- Frequency distribution of superflares on solar-type stars (G-dwarfs) can be fitted by a power-law function.
  - Similar to those of solar-flares and stellar flares on red-dwarfs
- Flare frequency depends the rotation period of the star.
  - Rapidly rotating stars show frequent superflares.
- Energy of superflares depends on the total area of starspots.
  - does not depend on the rotation period
  - Large starspots are necessary for superflares.