

# Superflares on solar-type stars

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Maehara et al., Nature 485, 478 (2012)    Shibata et al., PASJ 65, 49 (2013)

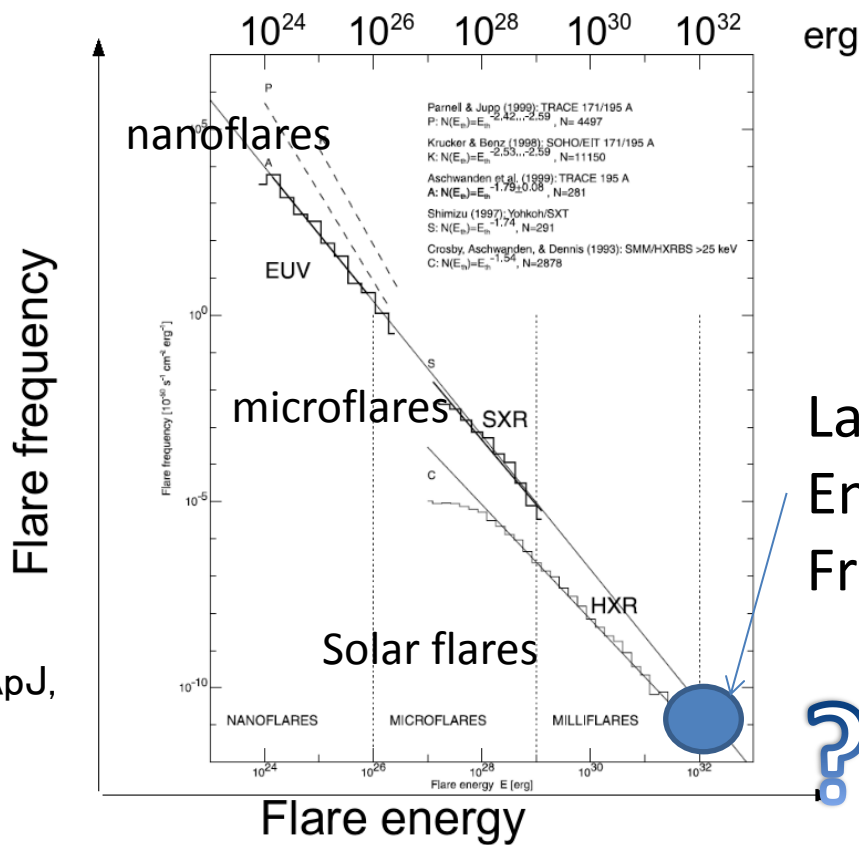
Notsu et al., ApJ 771, 127 (2013)

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 ???



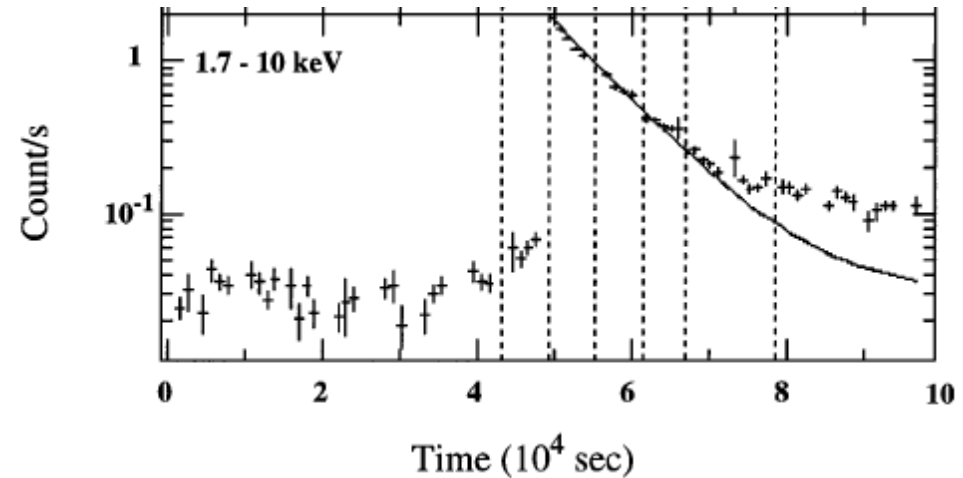
Largest solar flares  
Energy:  $\sim 10^{32}$  ergs  
Frequency:  $\sim 1$  in 10 years

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

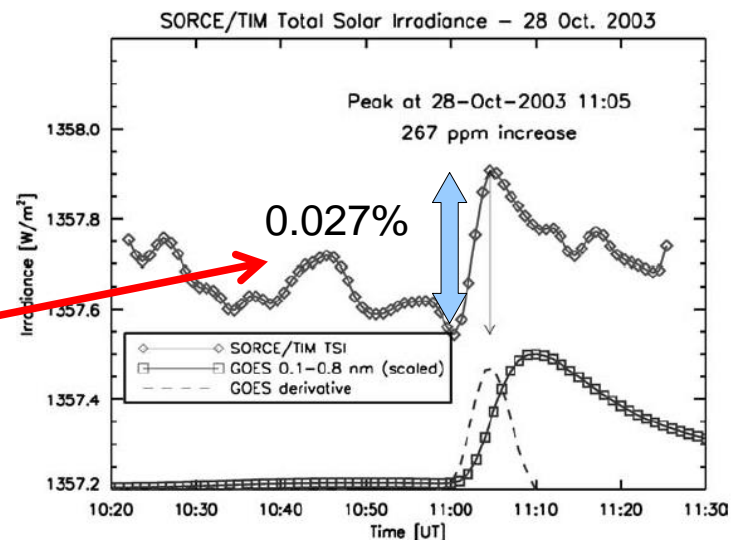
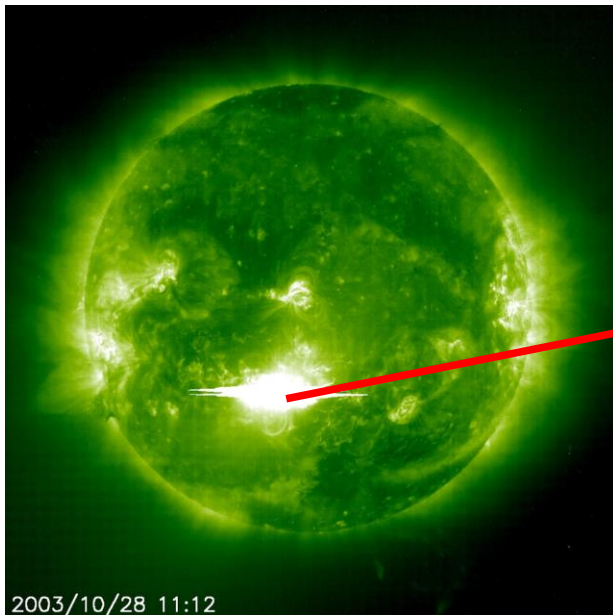


V773 Tau (T Tauri binary)  
Tsuboi et al., ApJ, 503, 894 (1998)

- 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.

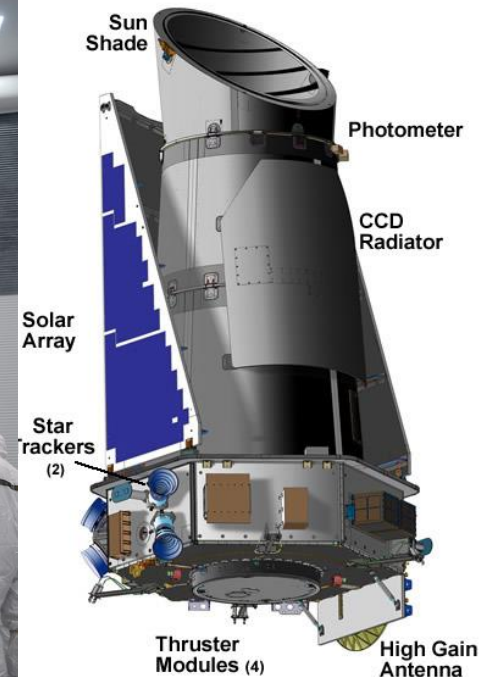


Kopp et al., Solar Phys. 230, 129 (2005)

# Kepler Data

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

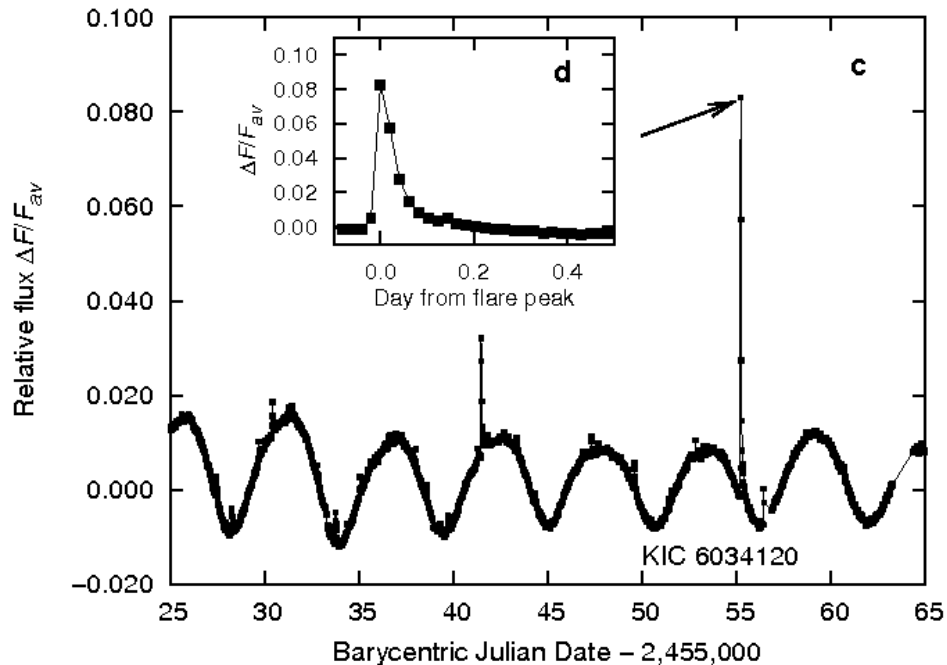
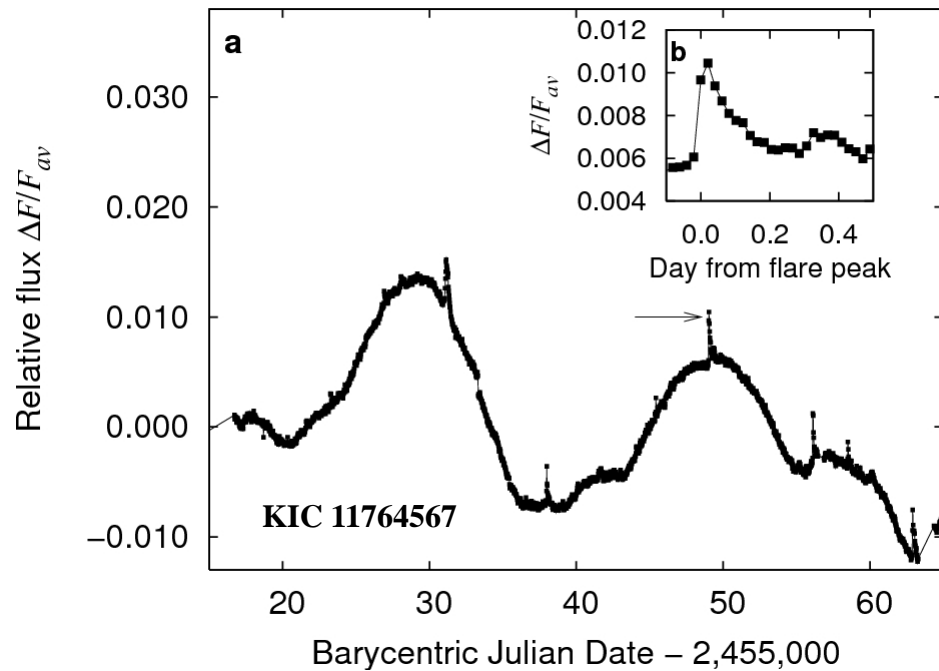
- We searched for flare-like events (sudden brightenings) from the Kepler public data.



# Data

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

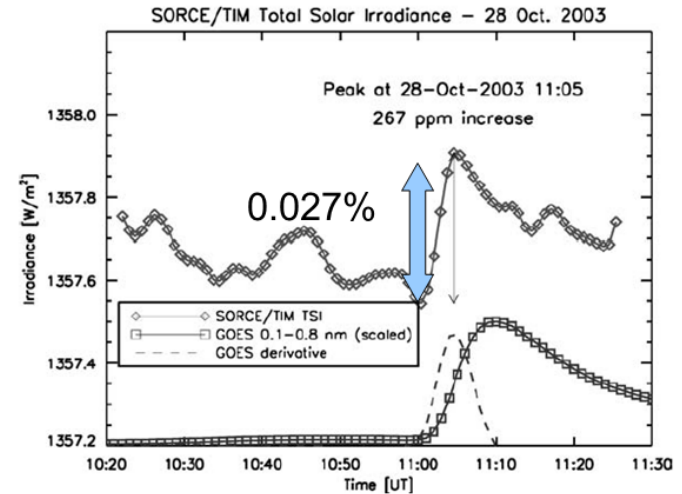
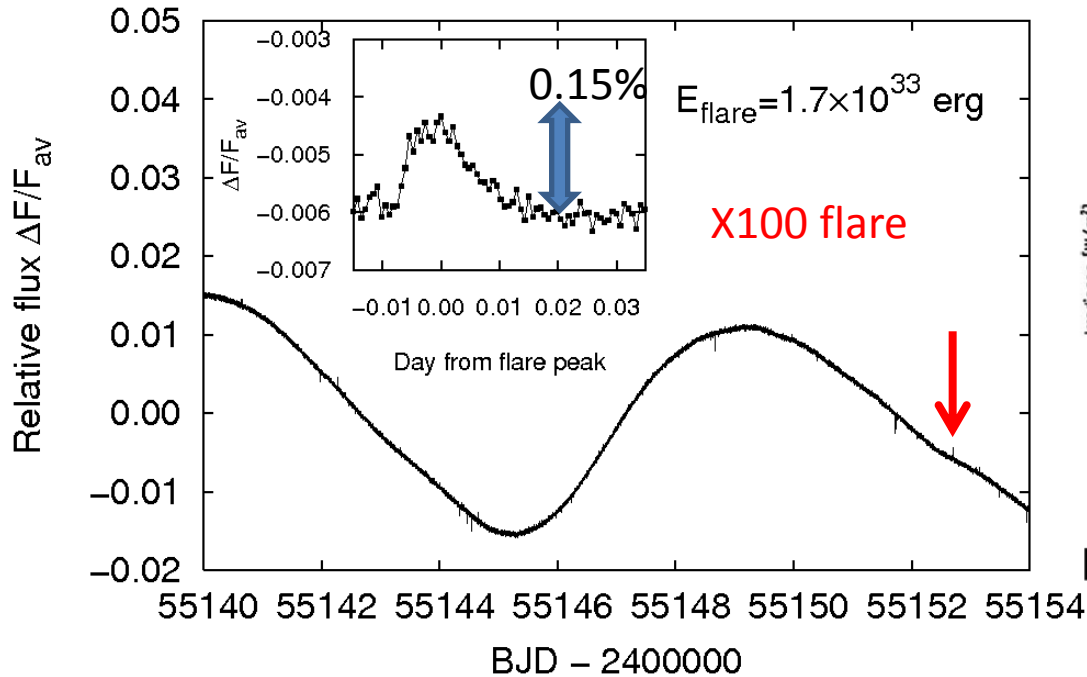
# Superflares (long cadence data)



- 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 ( $\sim 10^{32}$  ergs)
- Number of flares: 1547 (on 279 stars)

# Flares detected from short cadence data

KIC 10850420 ( $T_{\text{eff}}=5638\text{K}$ ,  $P_{\text{rot}}=9.25\text{d}$ )



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

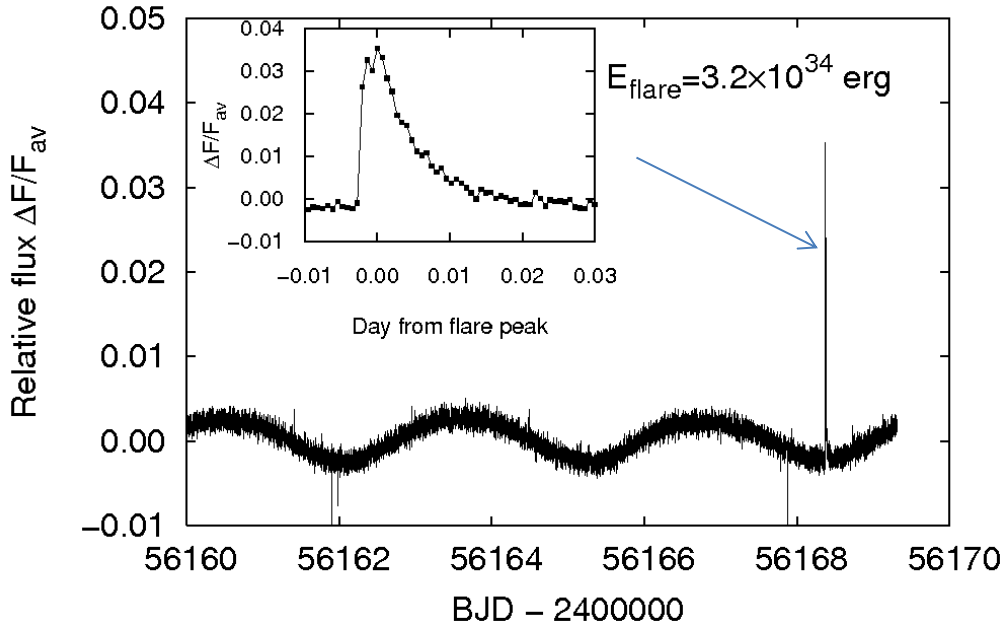
Solar flare (X17)

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

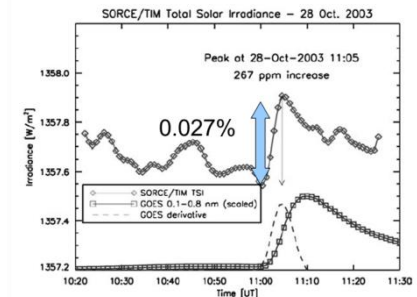
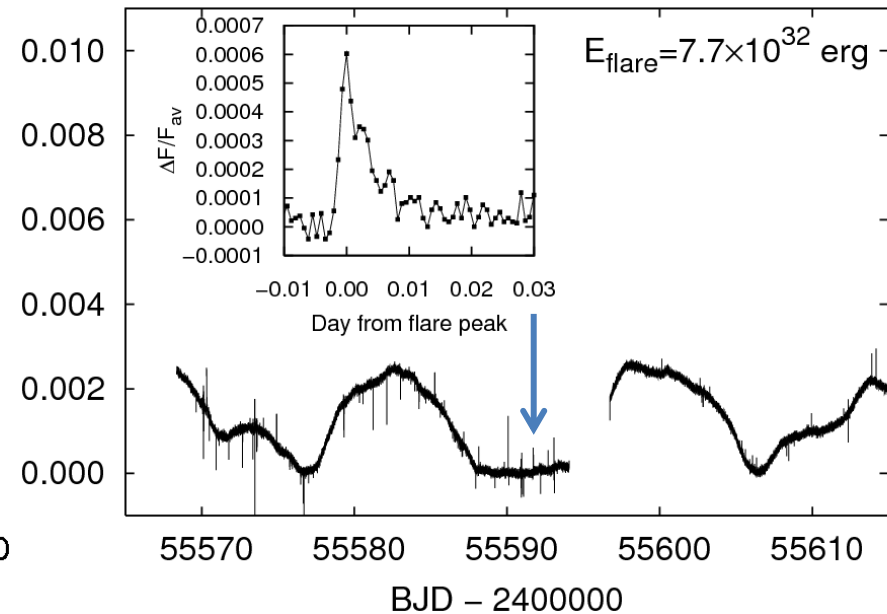


# Flares detected from short cadence data

KIC 6032920 ( $T_{\text{eff}}=5920\text{K}$ ,  $P_{\text{rot}}=3.19\text{d}$ )



KIC 8379927 ( $T_{\text{eff}}=5763\text{K}$ ,  $P_{\text{rot}}=17.1\text{d}$ )

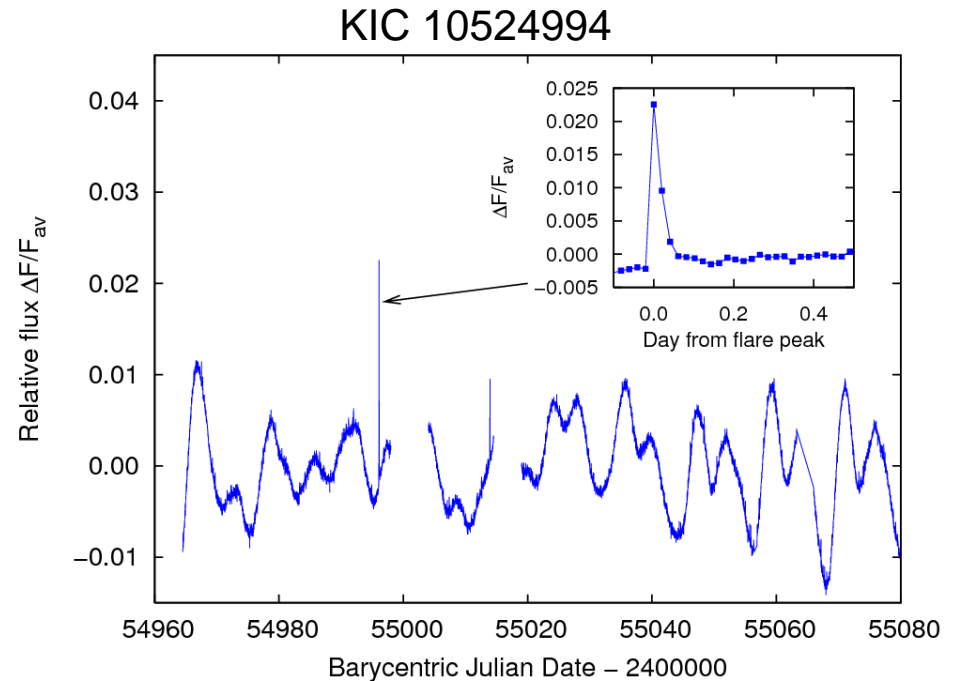
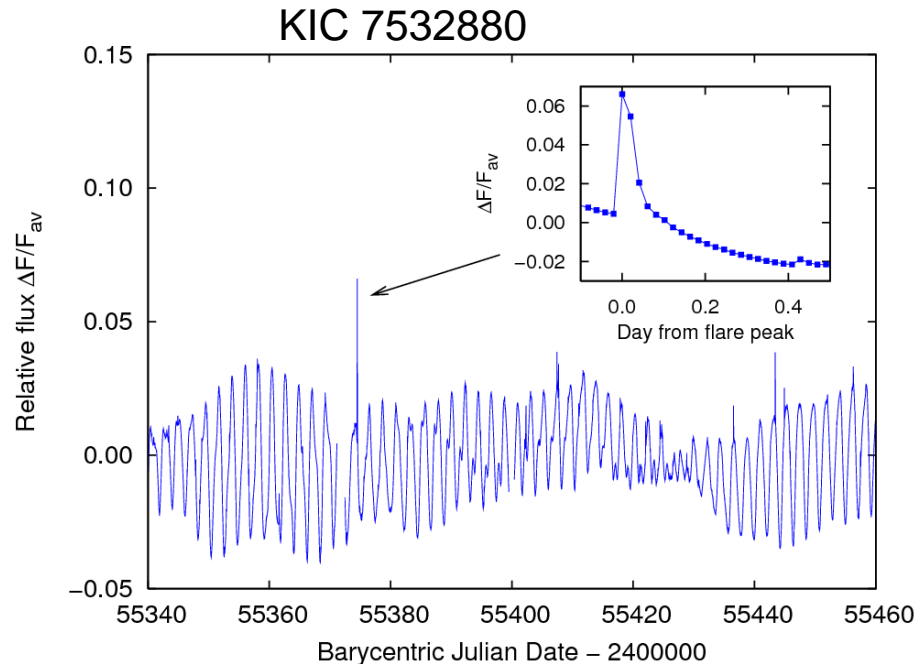


Solar flare (X17)

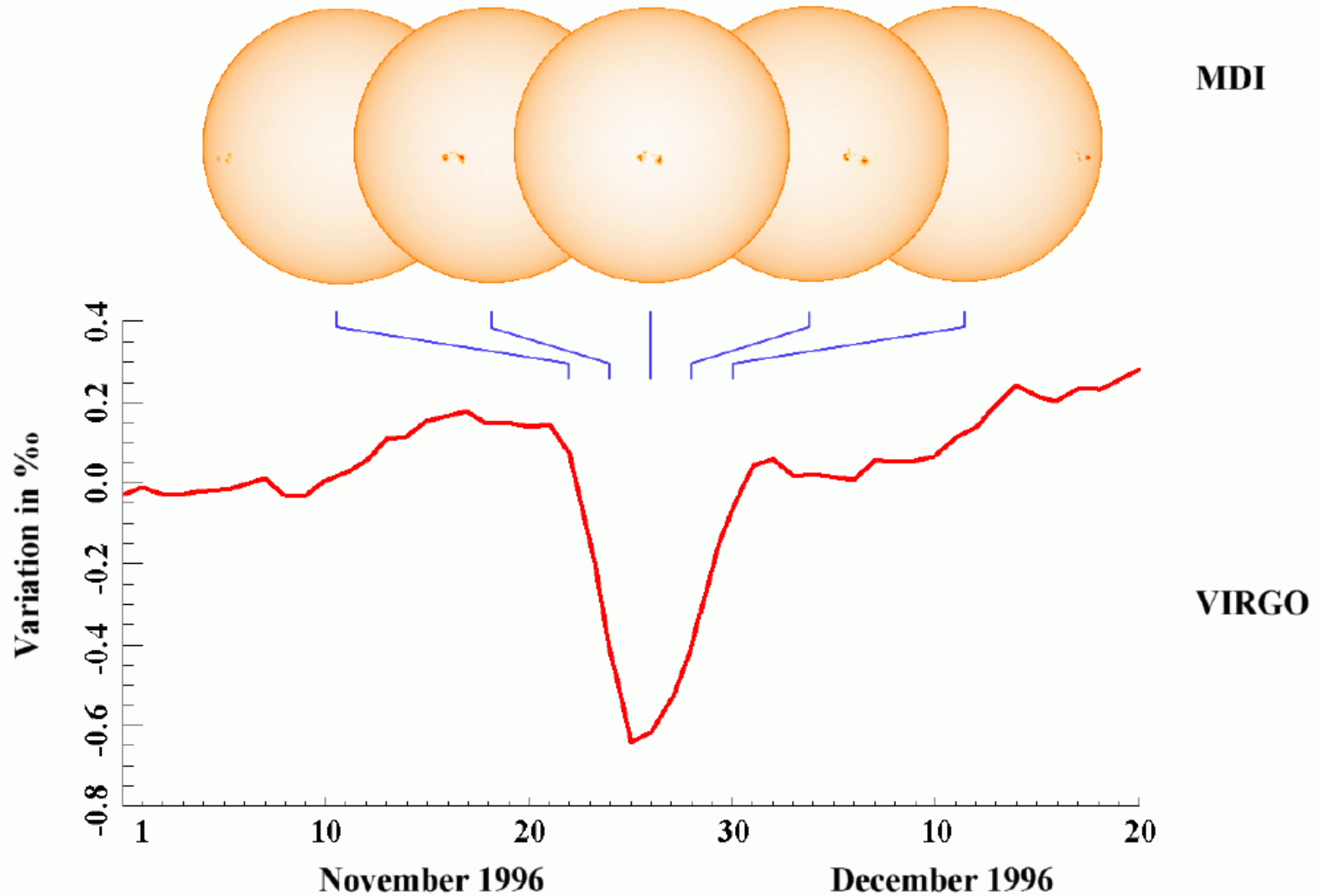
Kopp et al., Solar Phys. 230, 129 (2005)

# Long-term brightness variations

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

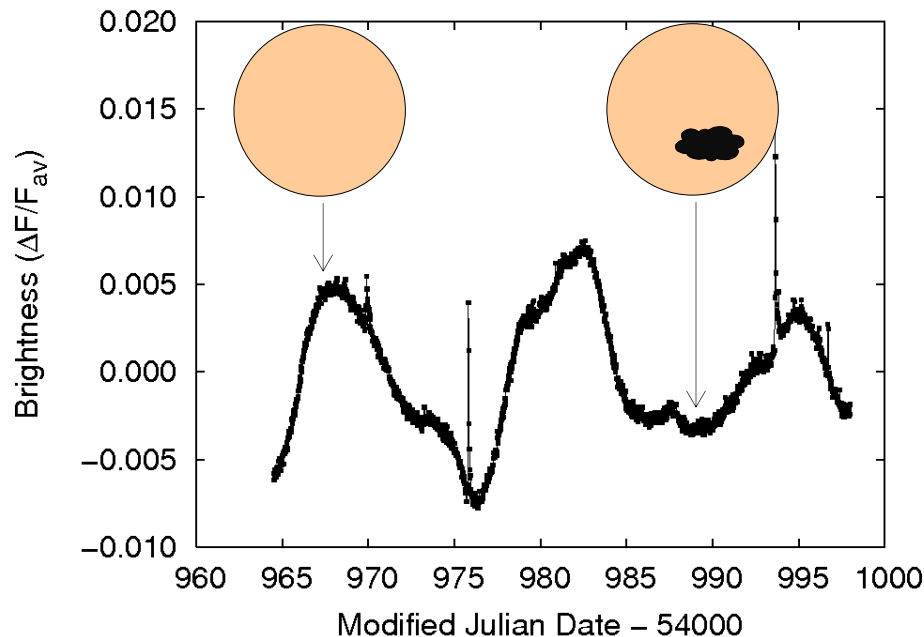


# Light curve of the Sun



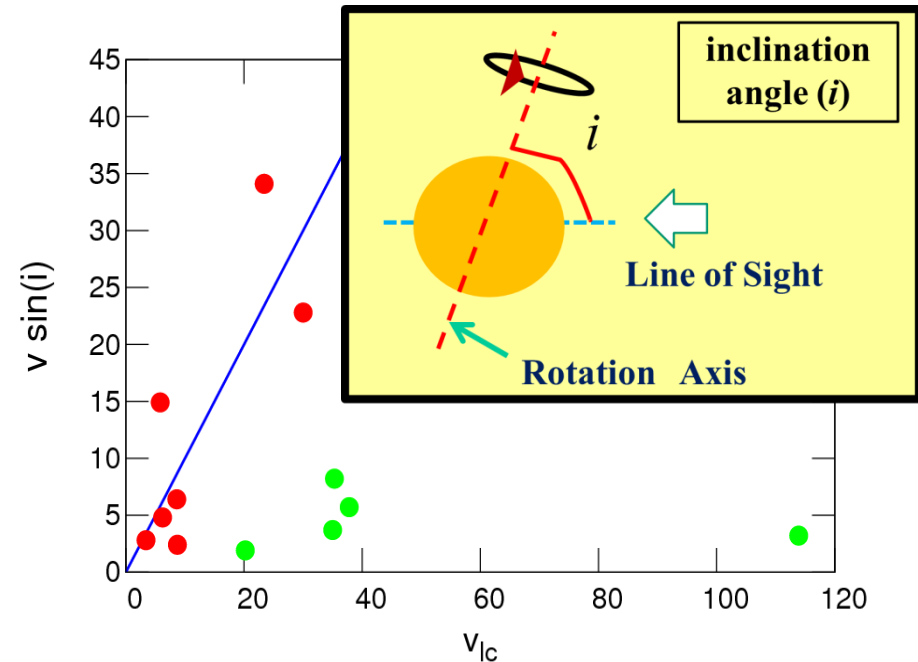
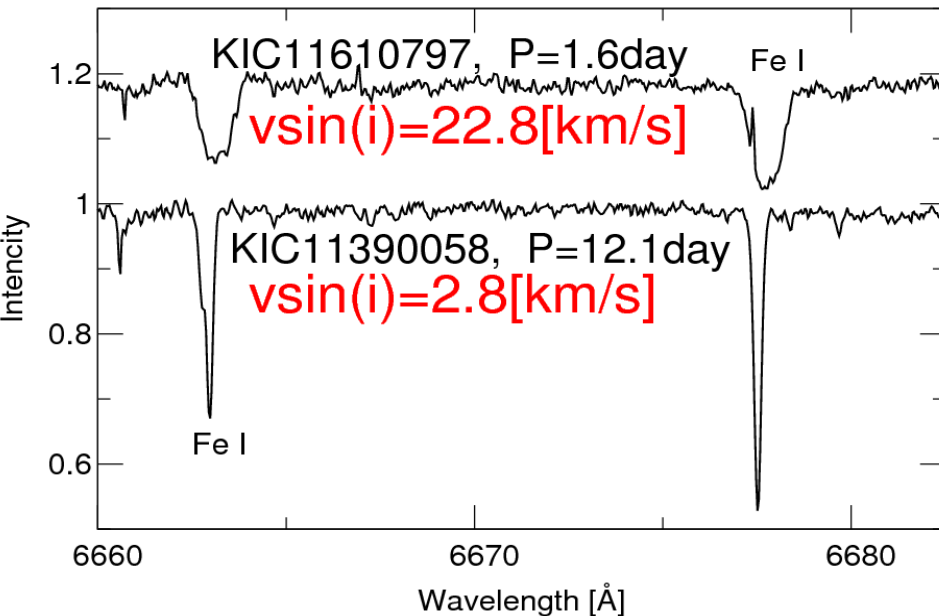
# Long-term brightness variations

- 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



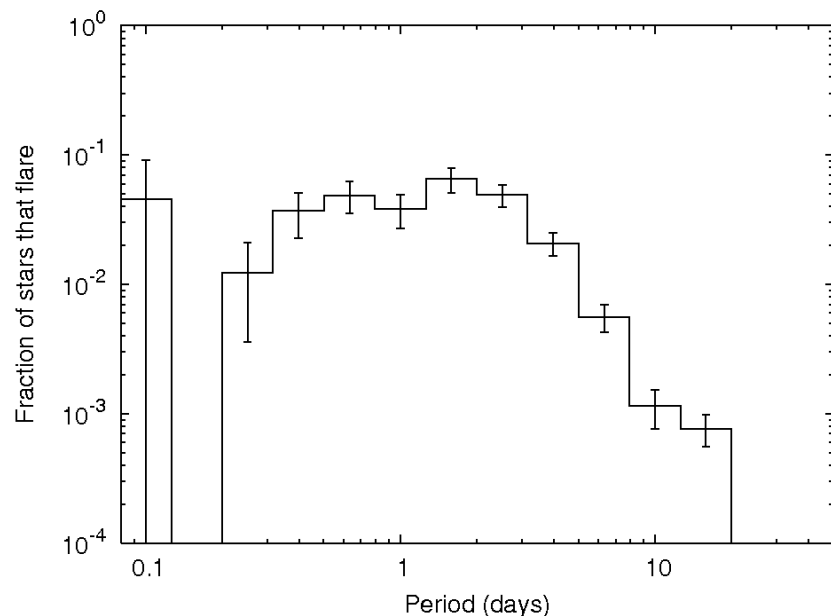
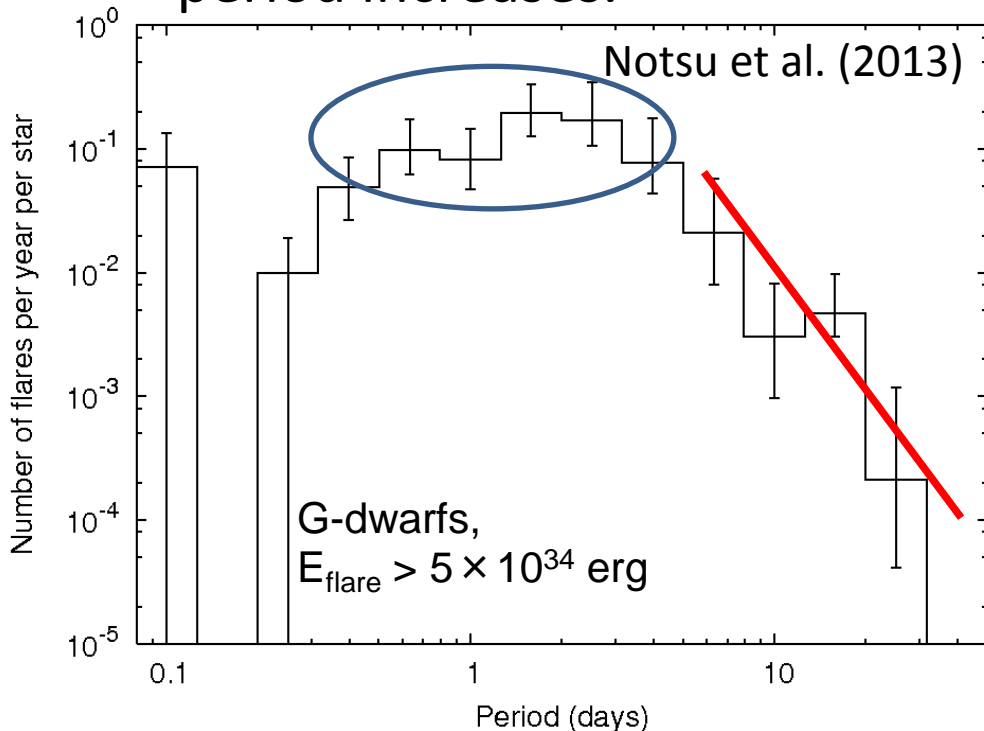
# Rotation velocity

- 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)

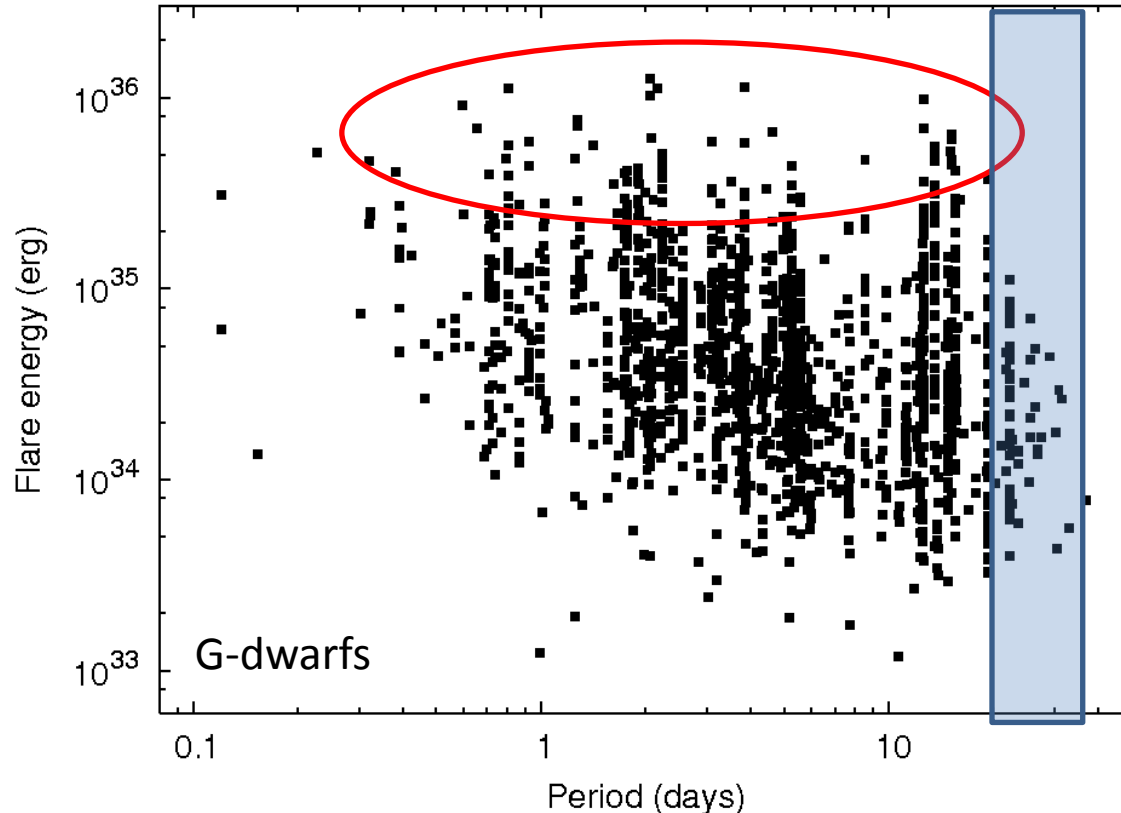


# Flare frequency vs. rotation period

- The frequency of superflares decreases as the rotation period increases ( $P > 2-3$  days).
  - 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.



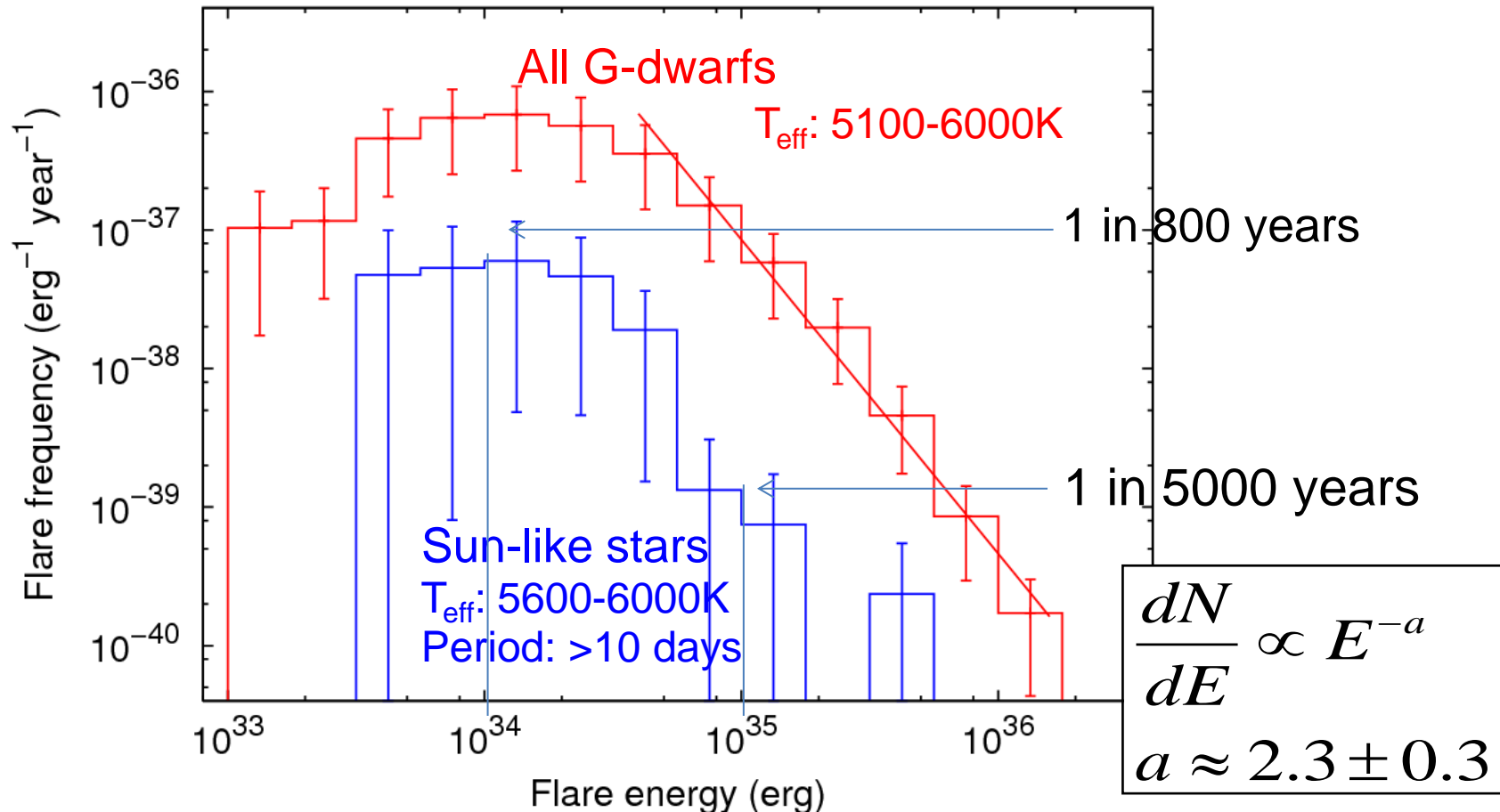
# Flare energy vs. rotation period



- 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  $-2.3 \pm 0.3$ 
  - The frequency distribution is similar to that of solar flares.

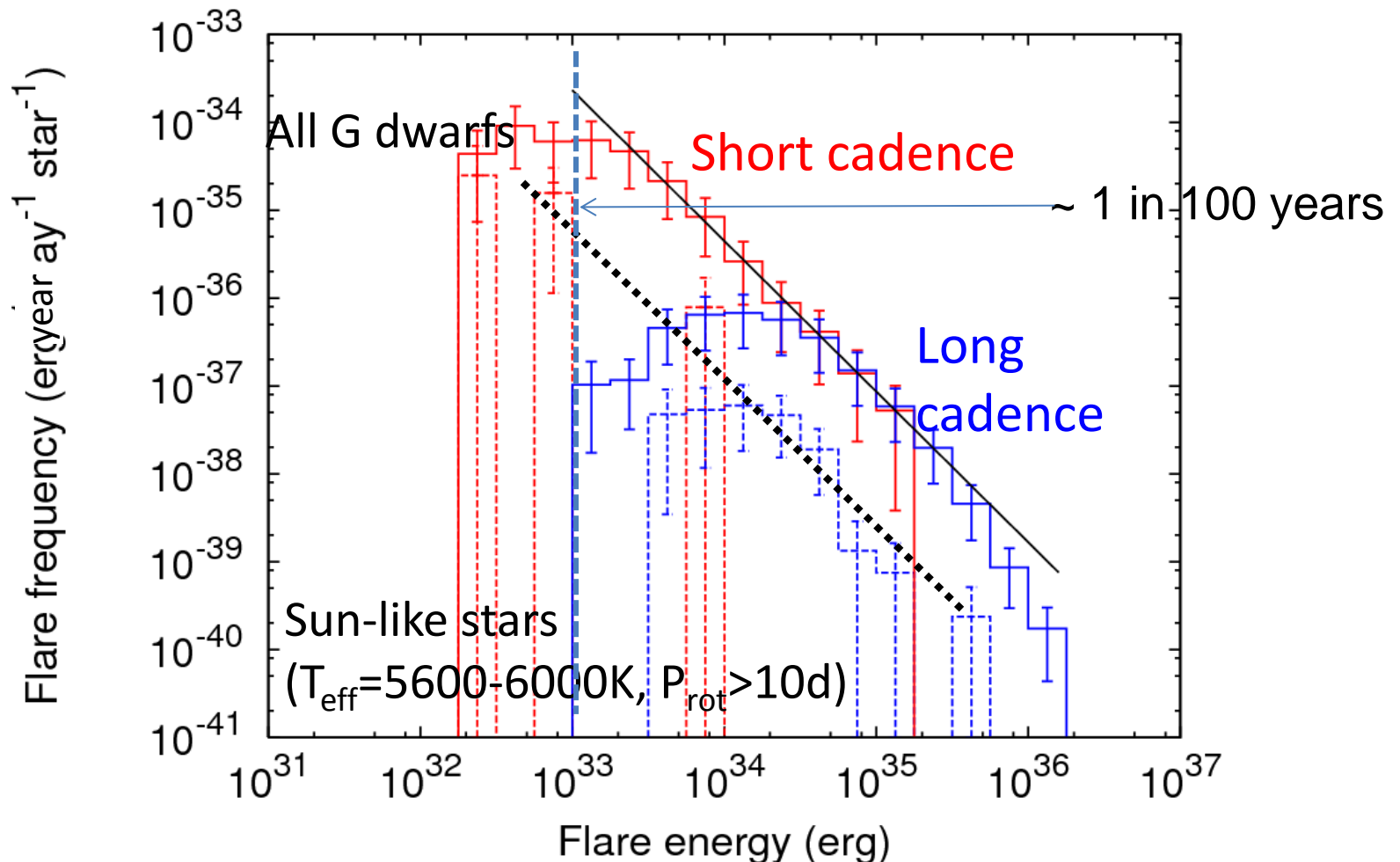


$$\text{Flare frequency} = \frac{\text{Number of superflares}}{(\text{number of stars}) \times (\text{length of observation period}) \times (\text{bin width})}$$

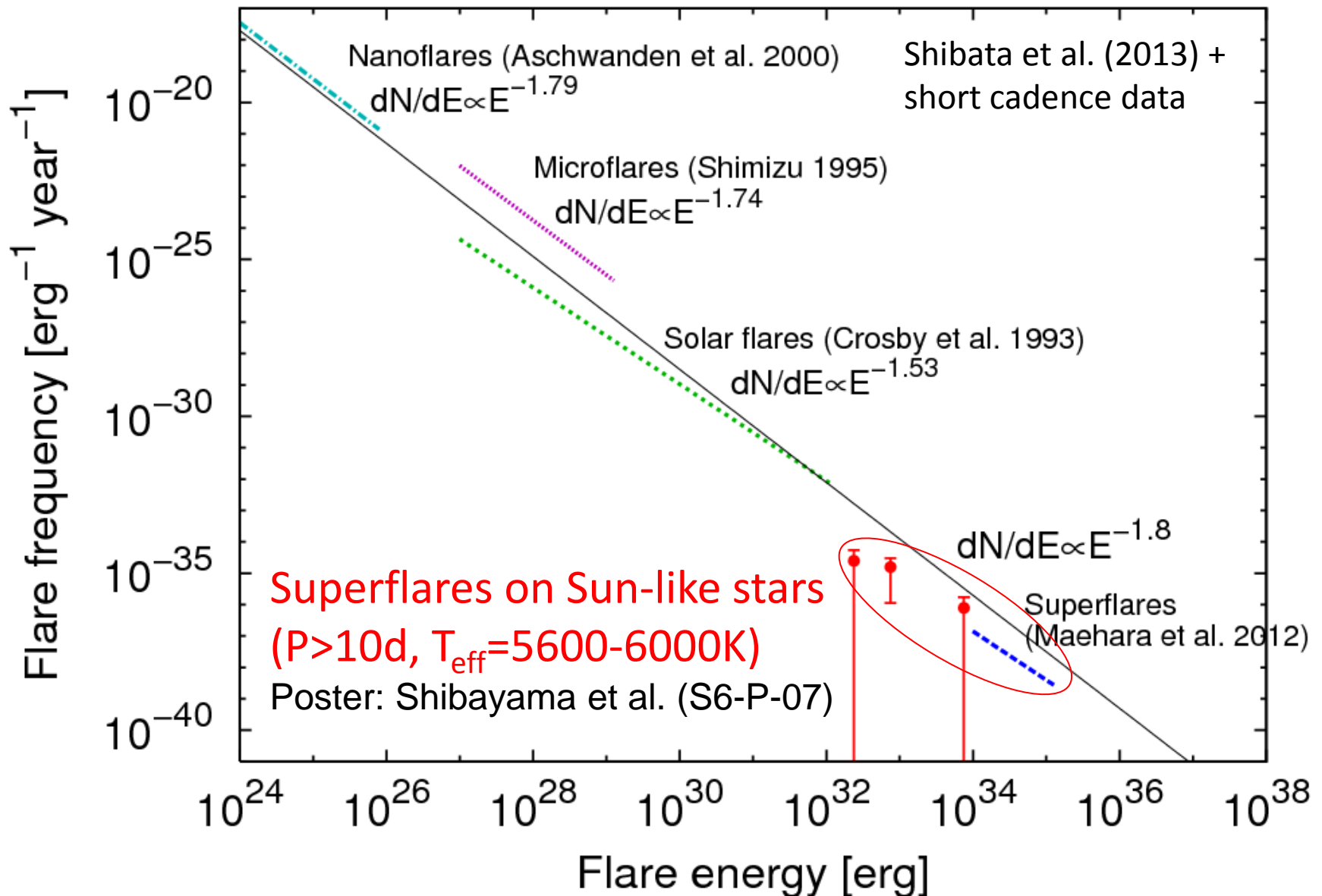


# Flare frequency distribution

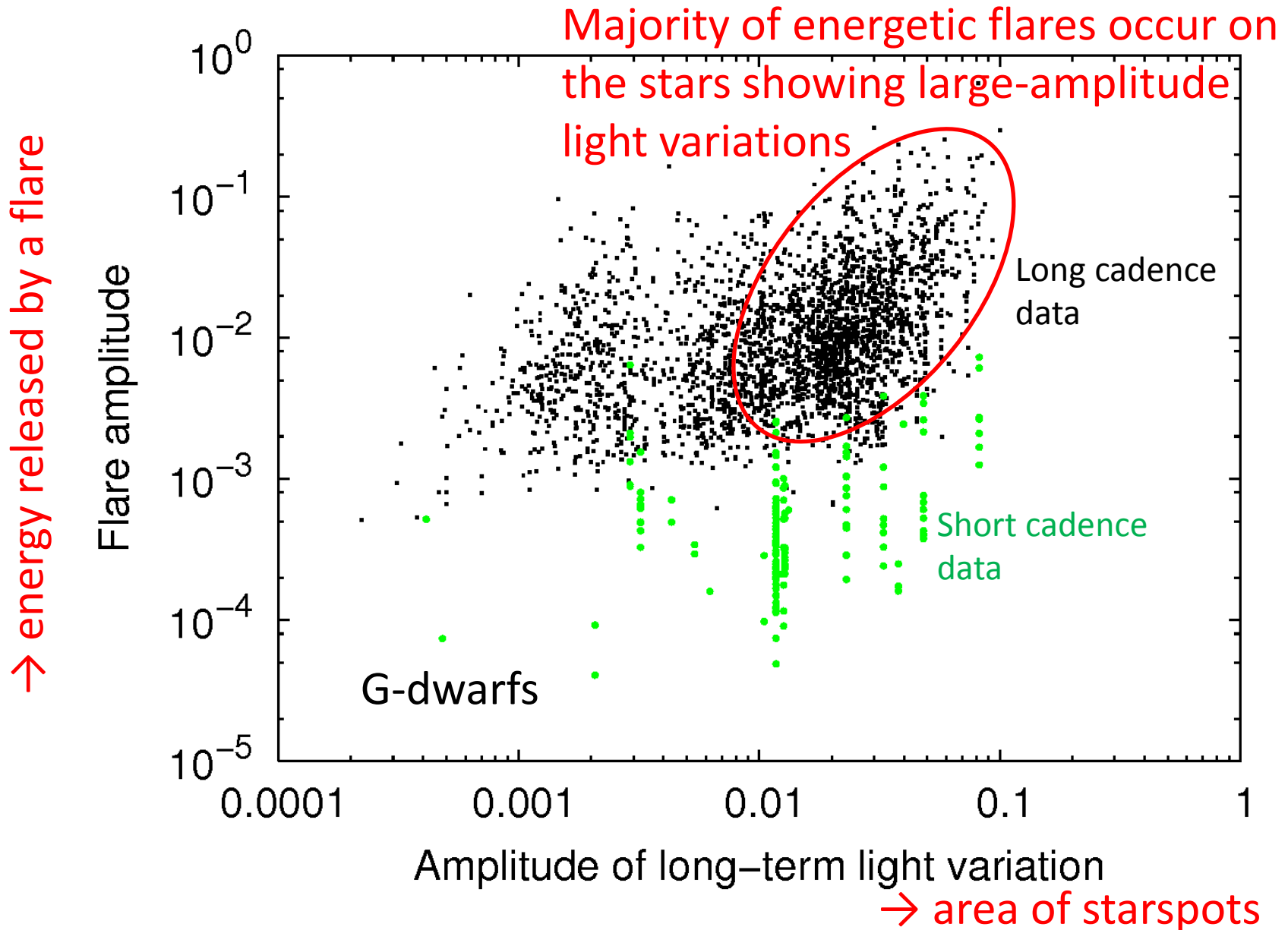
- Frequency distribution from short cadence data is consistent with that from long cadence data.



# 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)

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

- Magnetic energy stored near the starspots is roughly proportional to  $A_{\text{spot}}^{3/2}$
- (largest energy of flares)  $\propto$  (amplitude of light variations) $^{3/2}$

# Flare energy vs. area of starspots

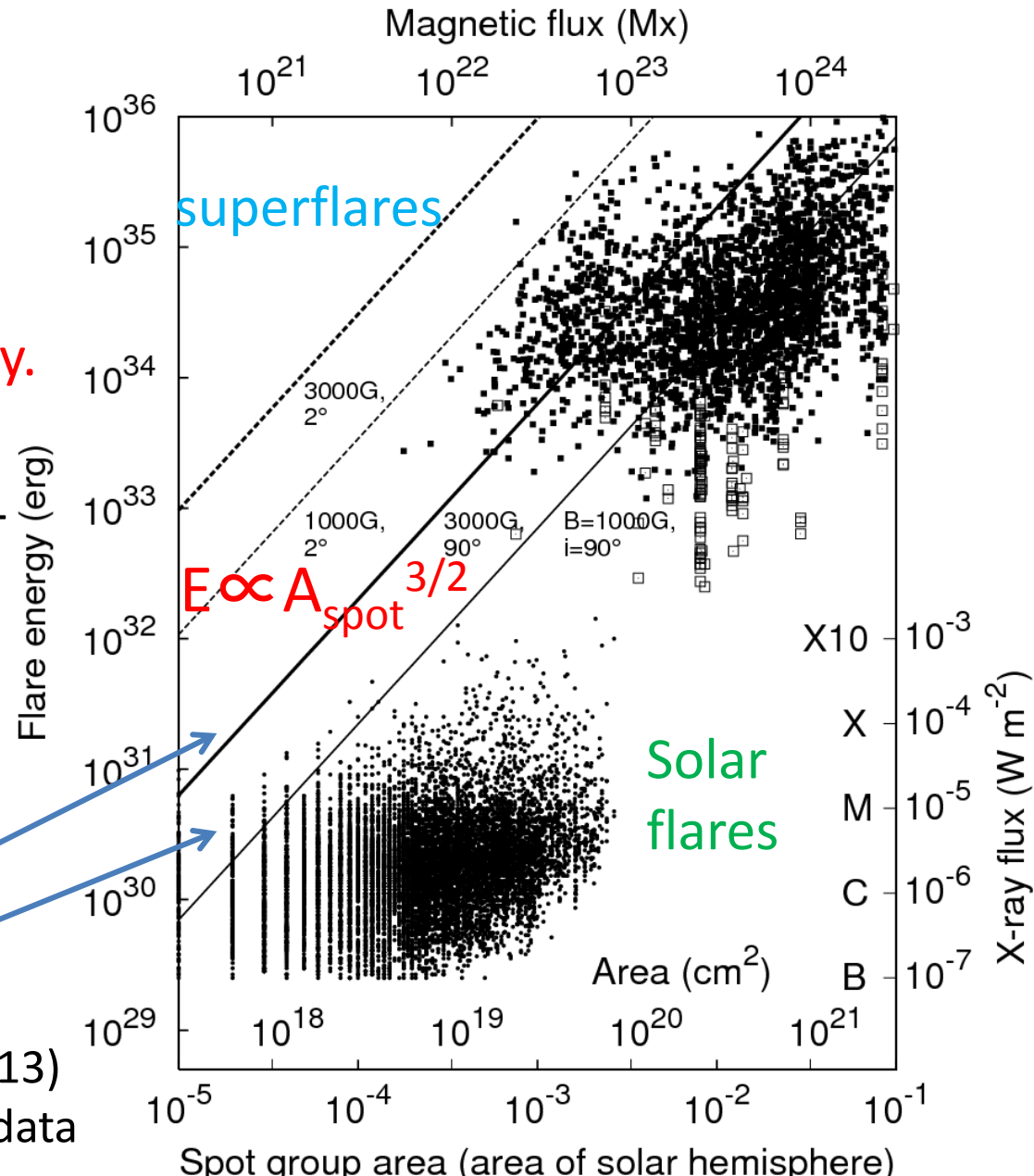
- Flare energy is consistent with the magnetic energy stored near the starspots.
- > Large starspots are necessary.
- Flares above the line may occur on the stars with low-inclination angle.

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

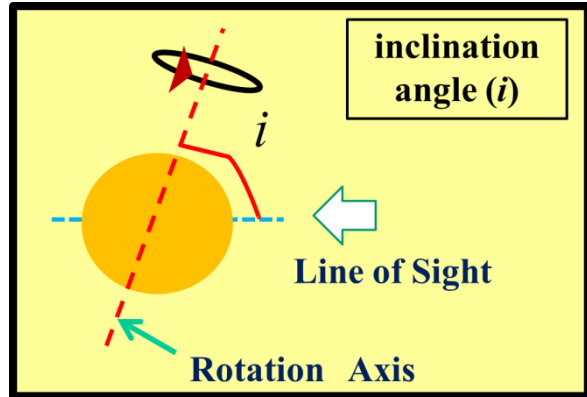
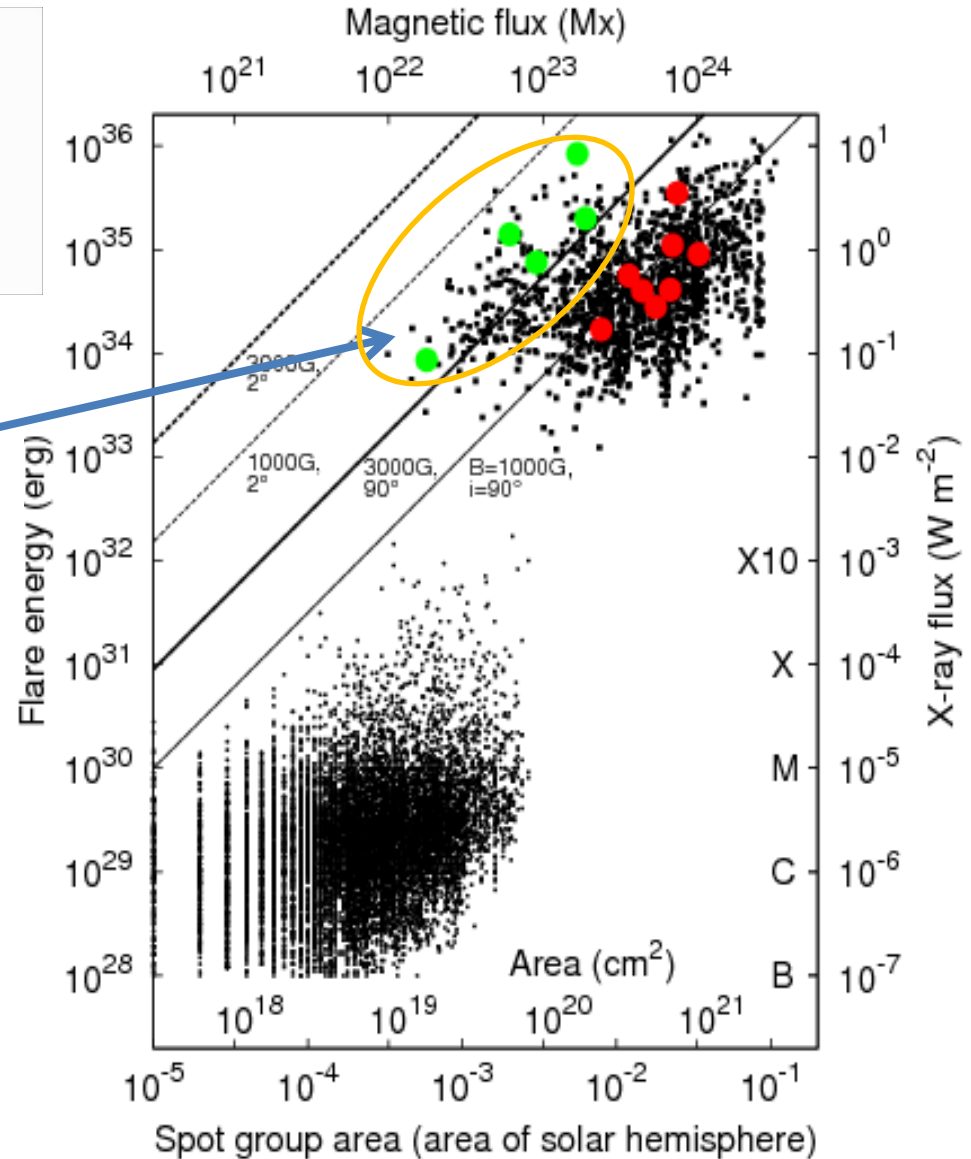
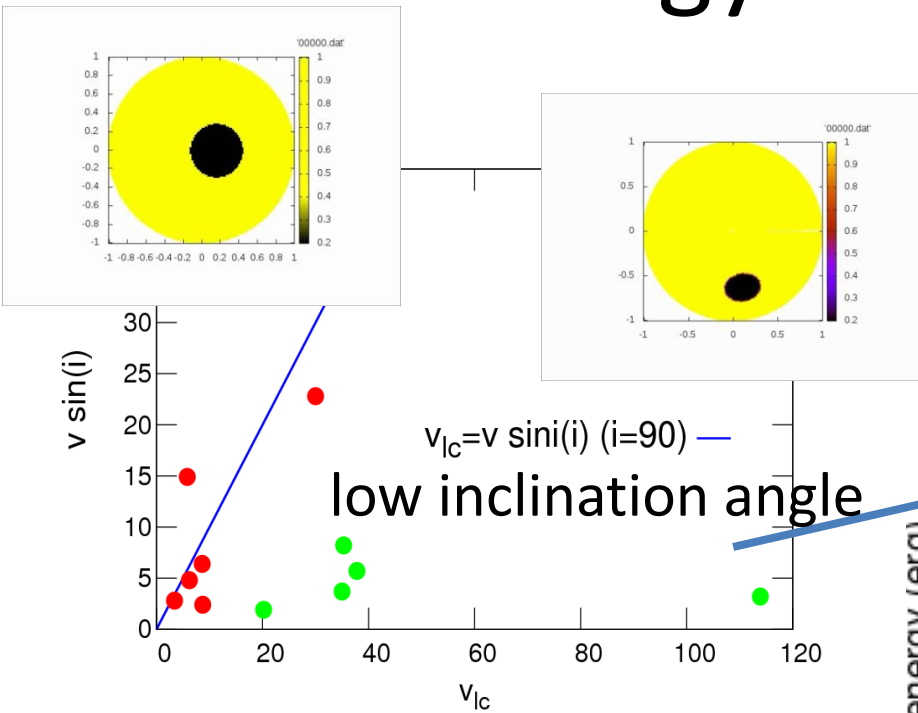
$$f=0.1, B=3000\text{G}$$

$$f=0.1, B=1000\text{G}$$

Shibata et al. (2013)  
+ short cadence data



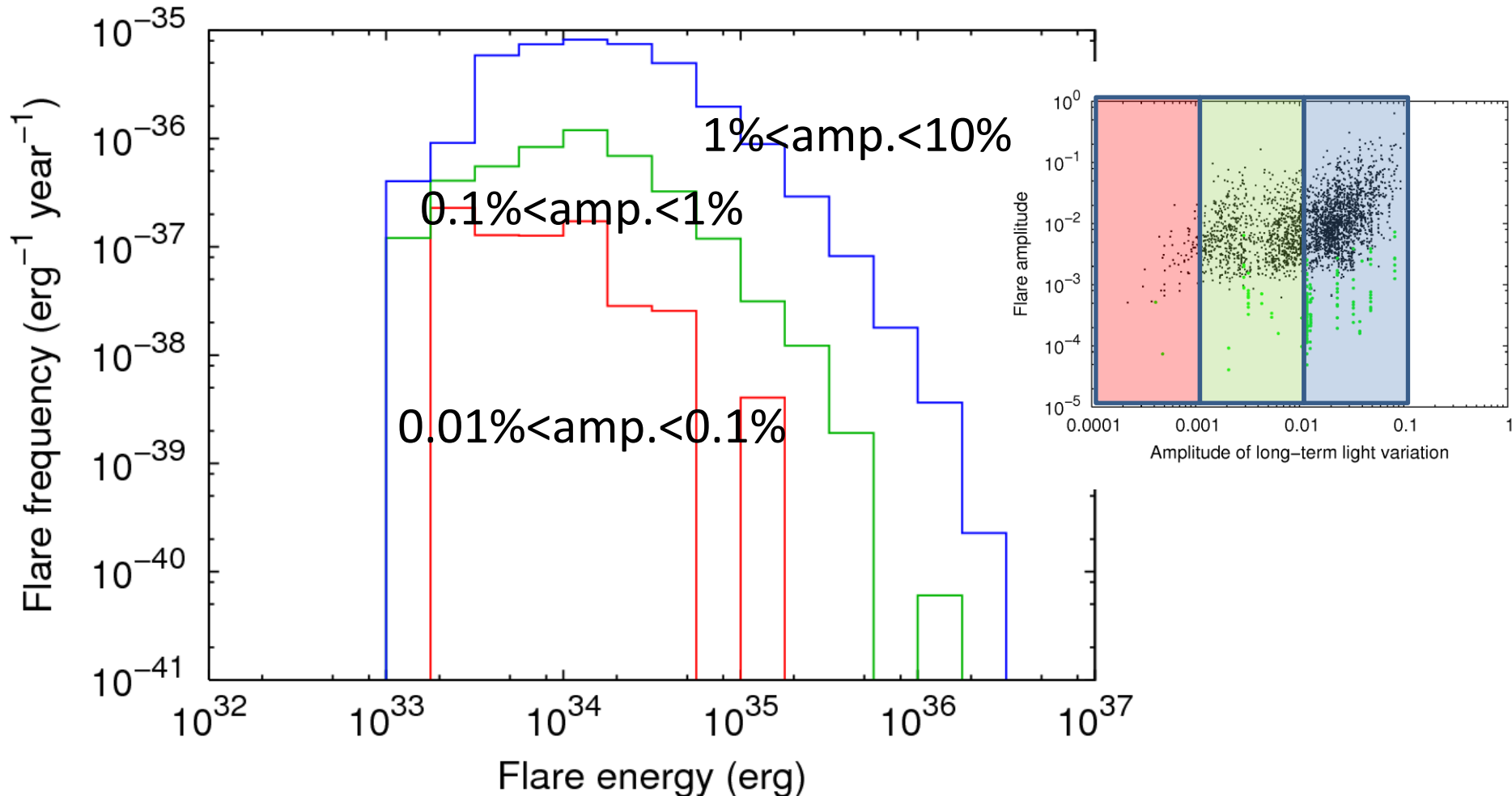
# Flare energy vs. area of starspots



• Notsu et al. (S6-P-09)

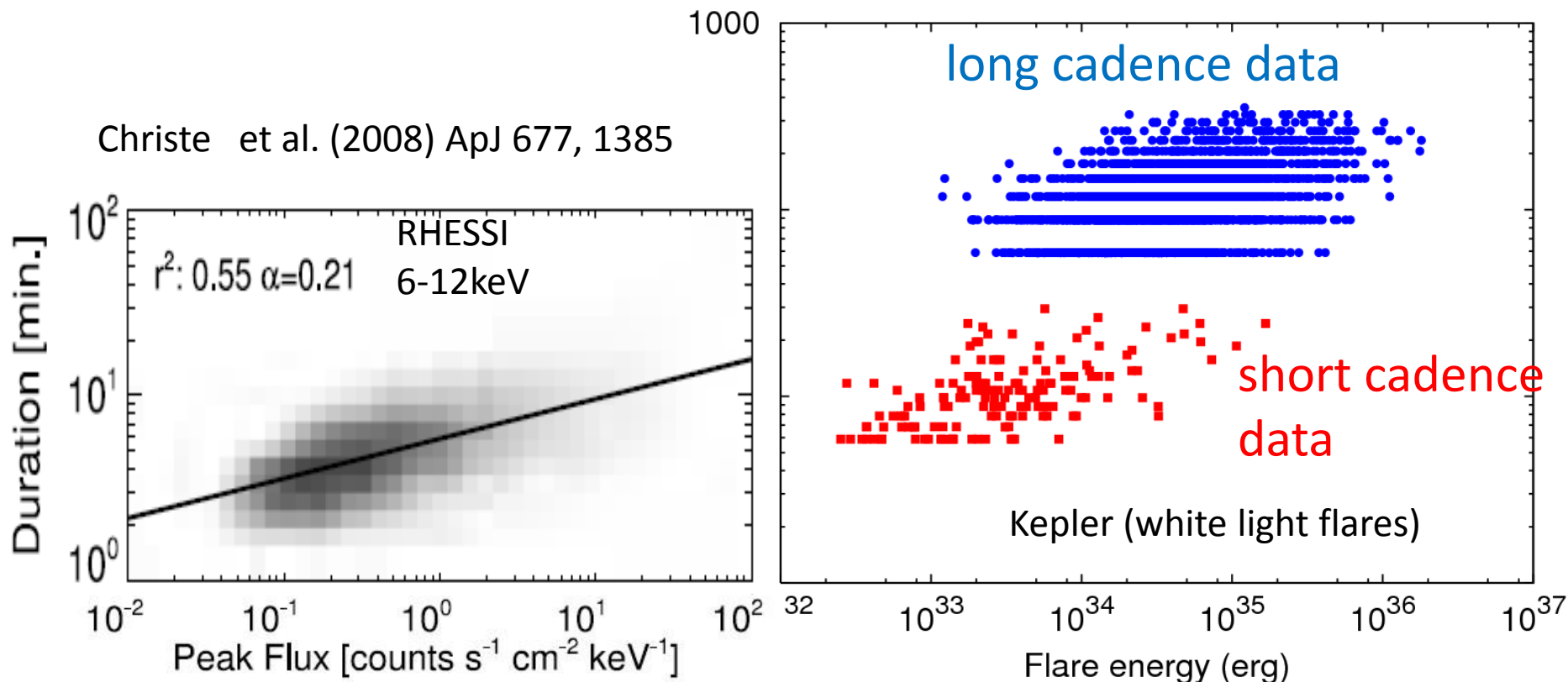
# Flare frequency and area of starspots

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.





# 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:  $\sim -2$ )
- 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.