Superflares and starspot activity on solar-type stars

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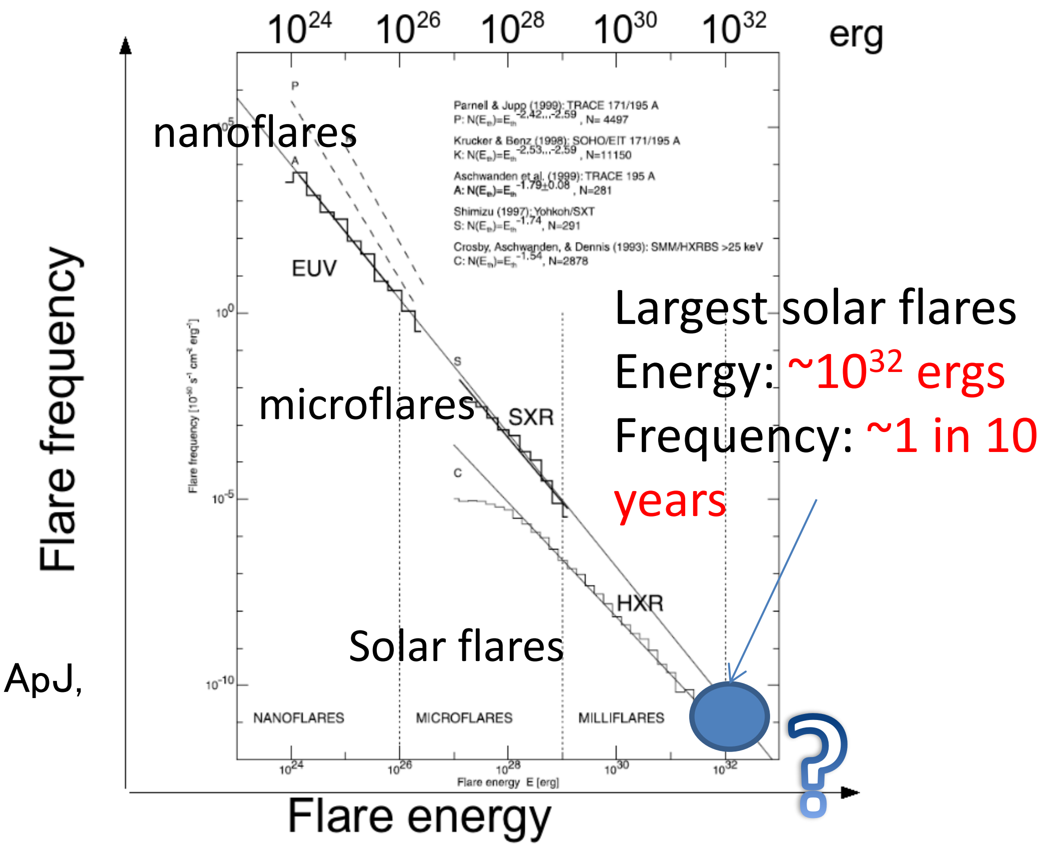
Energy-frequency distribution of solar flares

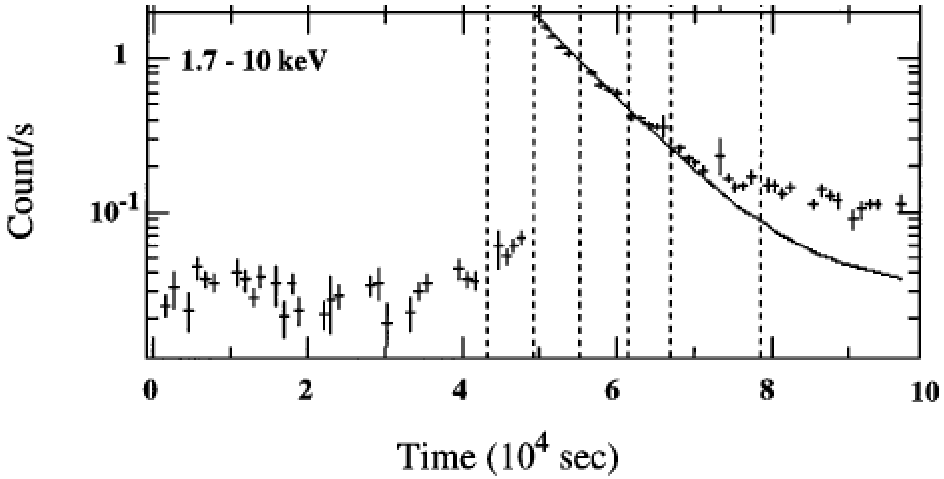
- Frequency of flares decreases as the flare energy increases.
  - Power-law distribution: $dN/dE \propto E^{-1.5 \sim -1.9}$
    - Flare energy: 10^{24} ~ 10^{32} ergs
  - Can flares with energy $>10^{32}$ erg occur on the Sun?
  - How frequently?



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

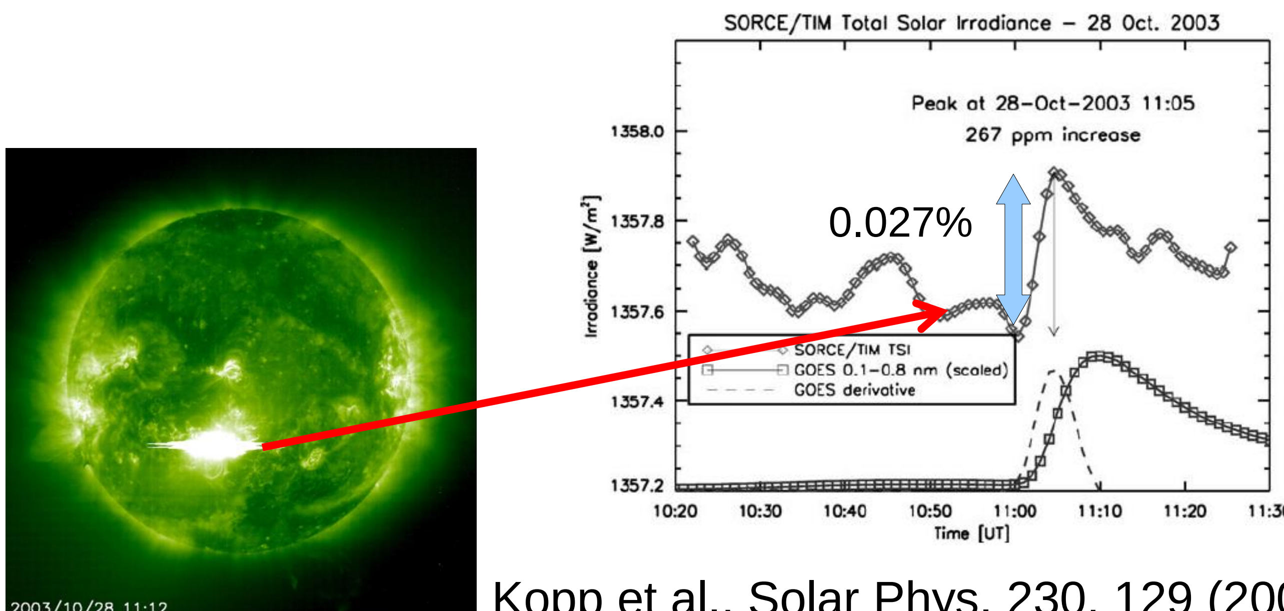


V773 Tau (T Tauri binary)
Tsuboi et al., ApJ, 503, 894 (1998)

- 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?

Kepler space telescope

- Kepler is the best space telescope to search for superflares.
  - High photometric precision (<~10^{-4} → X10 flares)
  - Continuous observations of large number of targets (~160,000 stars, 4 years)

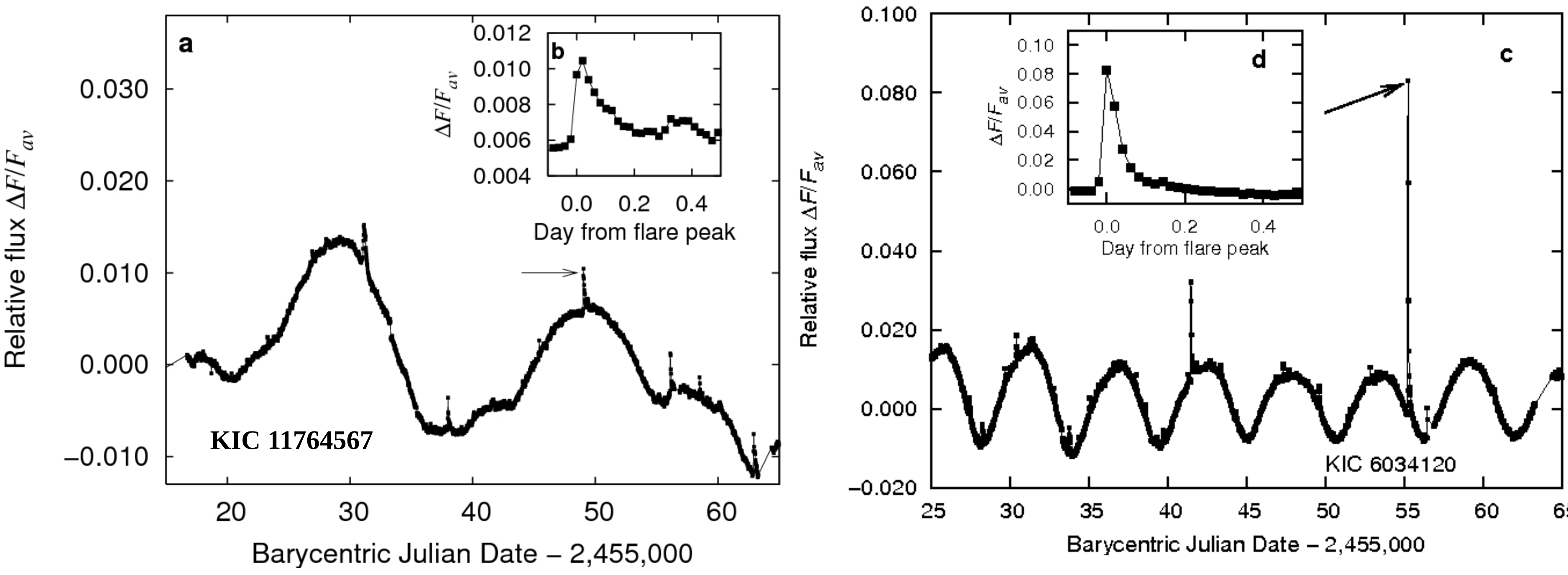


Kopp et al., Solar Phys. 230, 129 (2005)

Data

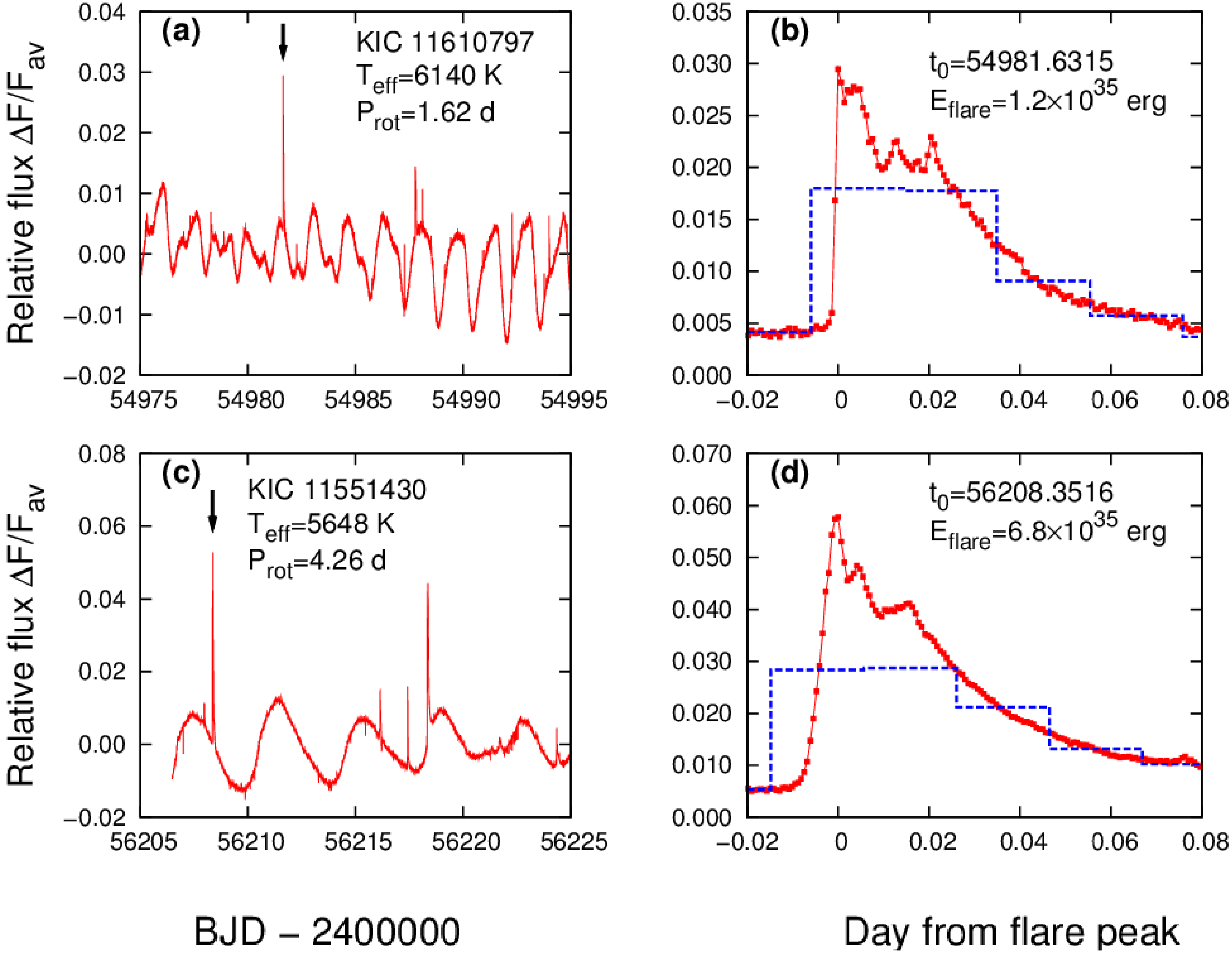
- We selected solar-type stars from the Kepler Input Catalog and analyzed both long and short cadence data.
  - Selection criteria: $5100 < T_{eff} < 6000K$, $\log g > 4.0$
  - Number of solar-type stars: ~90,000 (long) , ~1,400 (short)
  - Time-resolution: ~30min (long), ~1min (short)
  - Observation period
    - 2009/04-2010/09 (~500 days; long cadence data)
      - Shibayama et al. (2013) ApJS
    - 2009/04-2013/05 (~1400 days; short cadence data)
      - Maehara et al. (2015) EPS

Superflares (long cadence data)



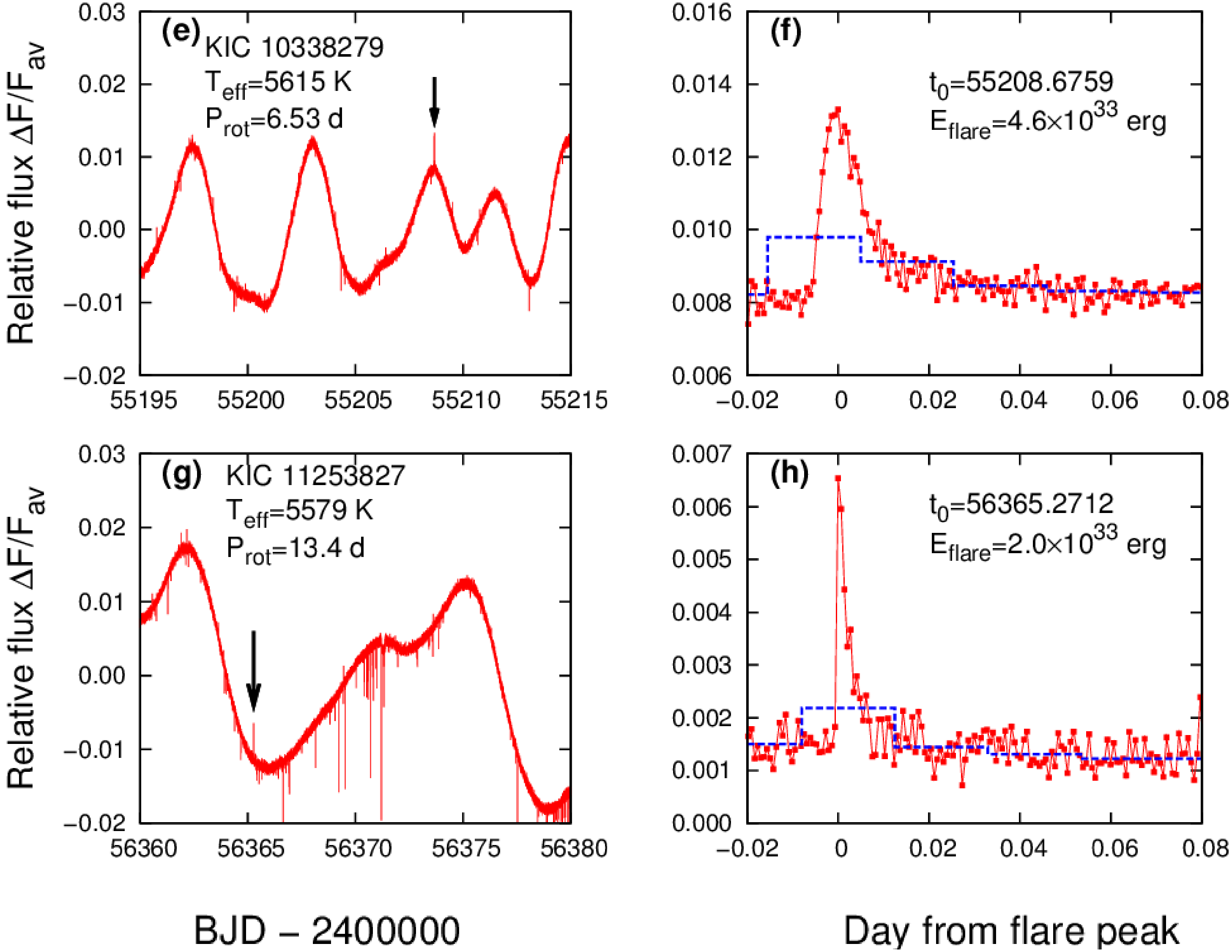
- Amplitude: 0.1-10%
- Duration: ~0.1 days
- Bolometric energy: 10^{33}-10^{36} ergs
  - 10-10,000 times larger than the largest solar flares (~10^{32} ergs)
- Number of flares: 1547 on 279 stars (Shibayama et al. 2013)

Superflares (short cadence data)

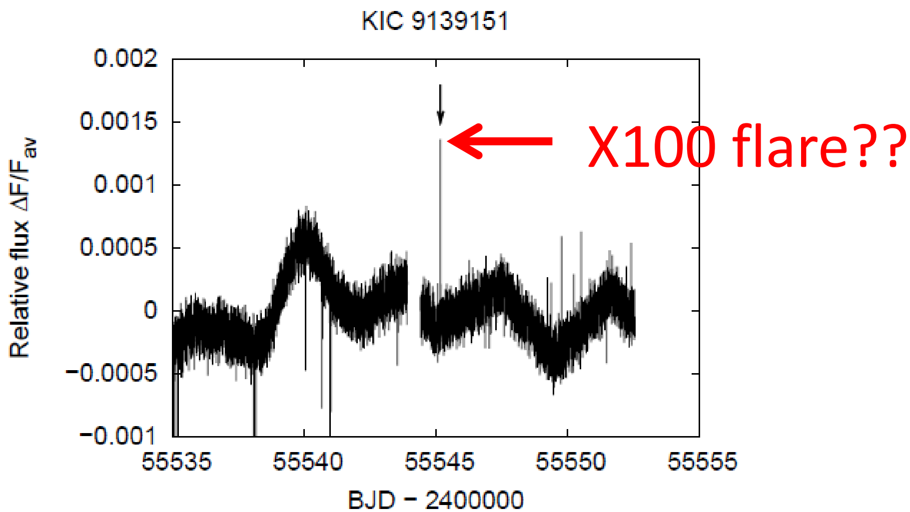


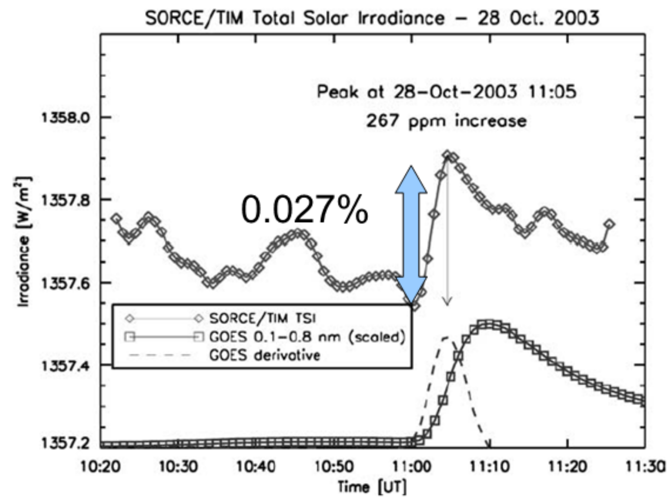
Maehara et al., EPS 67, 59 (2015)

Superflares (short cadence data)



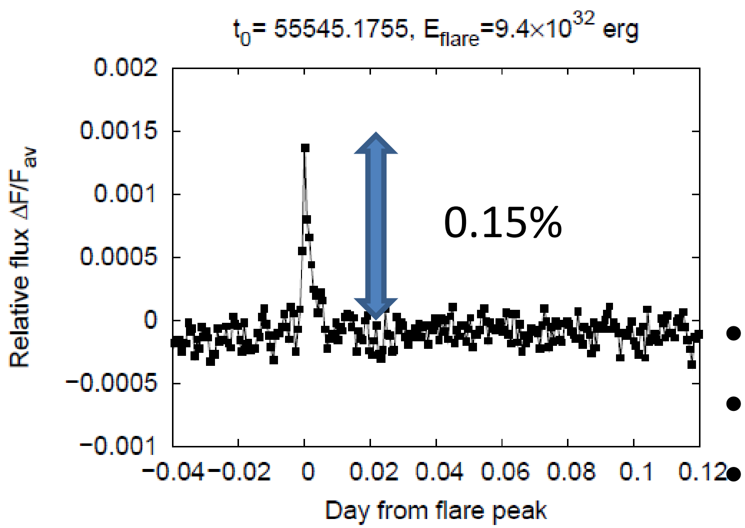
Superflares (short cadence data)





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

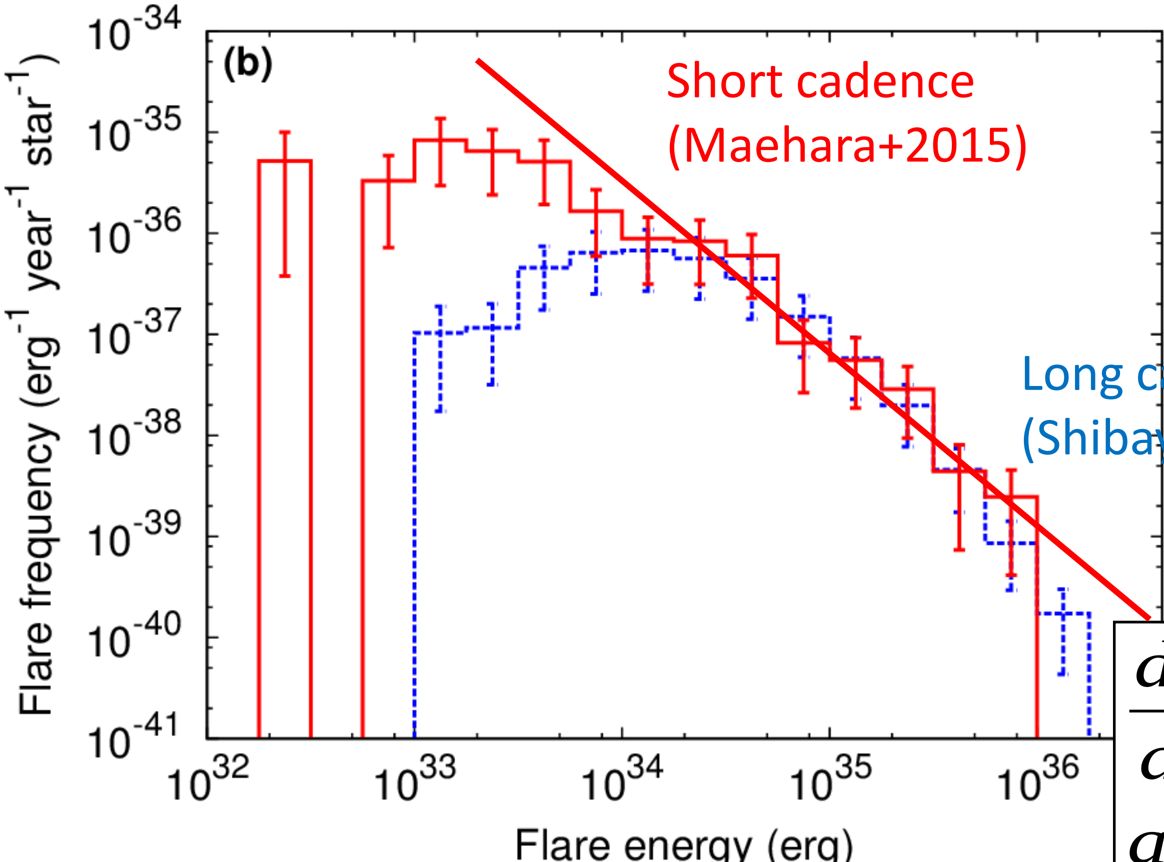
Solar flare (X17)



- Amplitude: 0.06 – 8%
- Duration: 5 – 120 min
- Bolometric energy: 2×10^{32} - 8×10^{35} erg
- Number of flares: 187 (on 23 stars)

Flare frequency distribution

- The frequency distribution can be represented by a power-law distribution (power-law index ~ -1.8 ー-1.5)
  - similar to that of solar flares

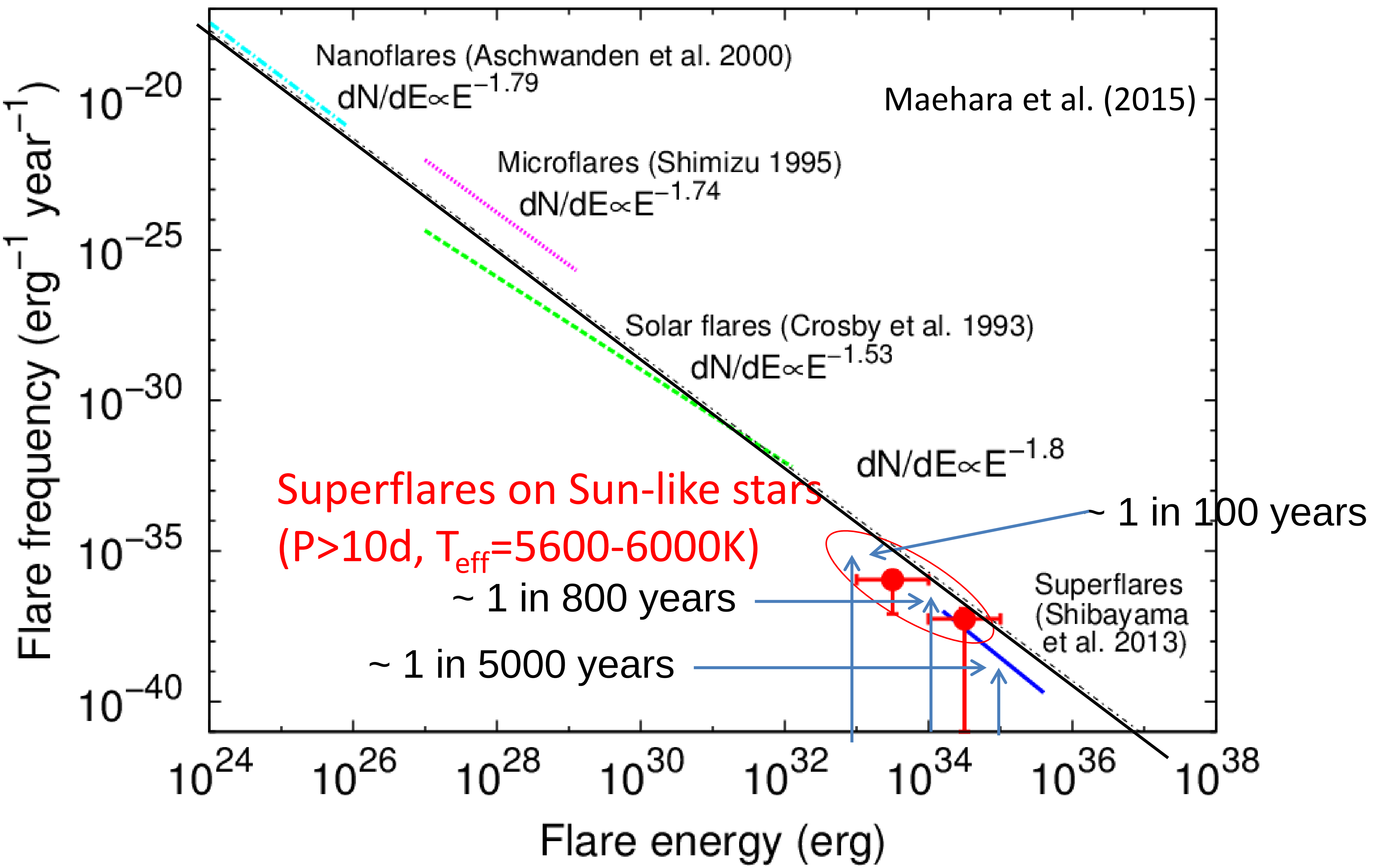


$$\frac{dN}{dE} \propto E^{-a}$$

$$a \approx 1.5 \pm 0.2$$

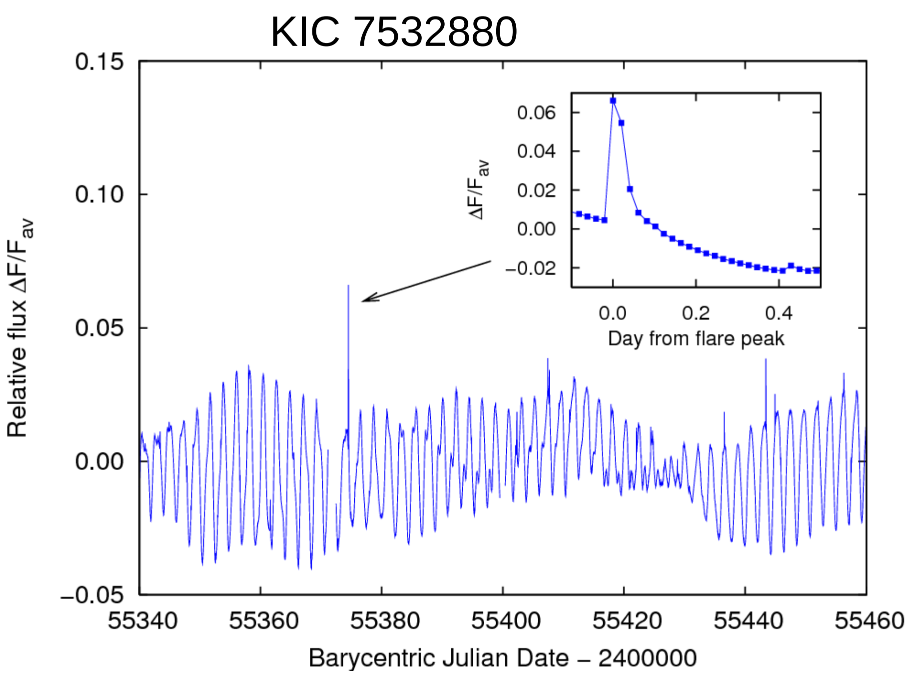
※Flare frequency = $\frac{Number\ of\ superflares}{(number\ of\ stars)\times(length\ of\ observation\ period)\times(bin\ width)}$

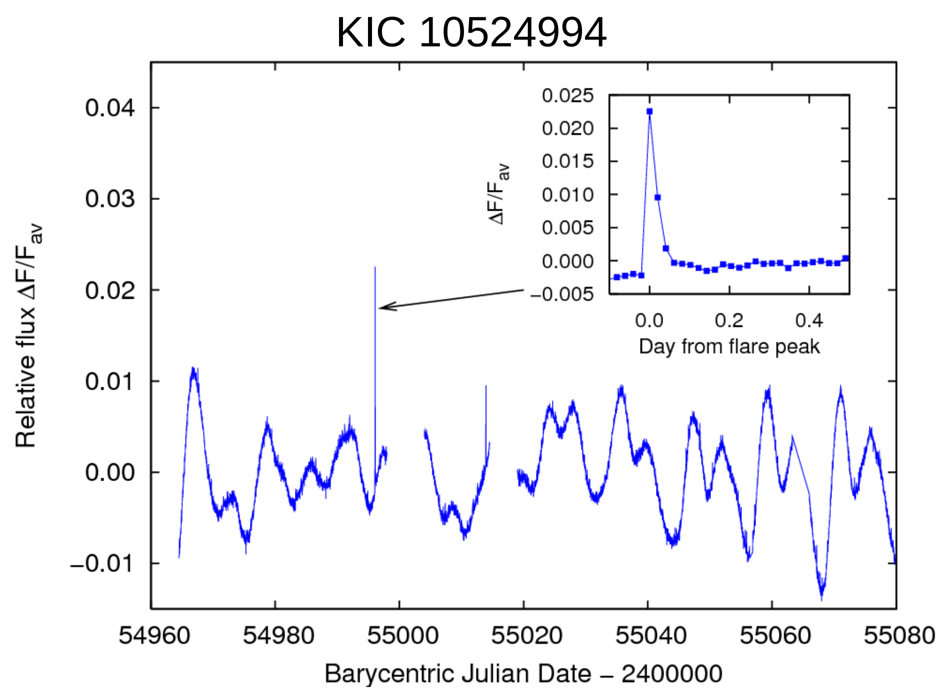
Flare frequency vs. flare energy



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.

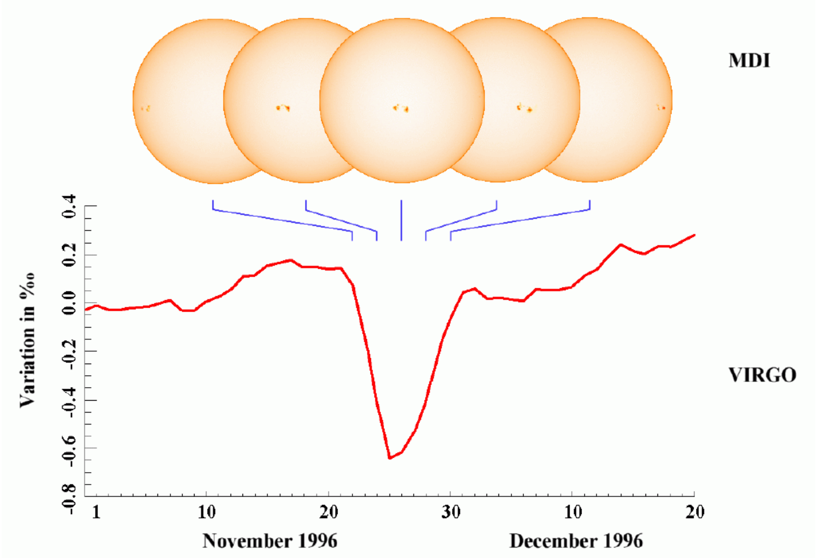




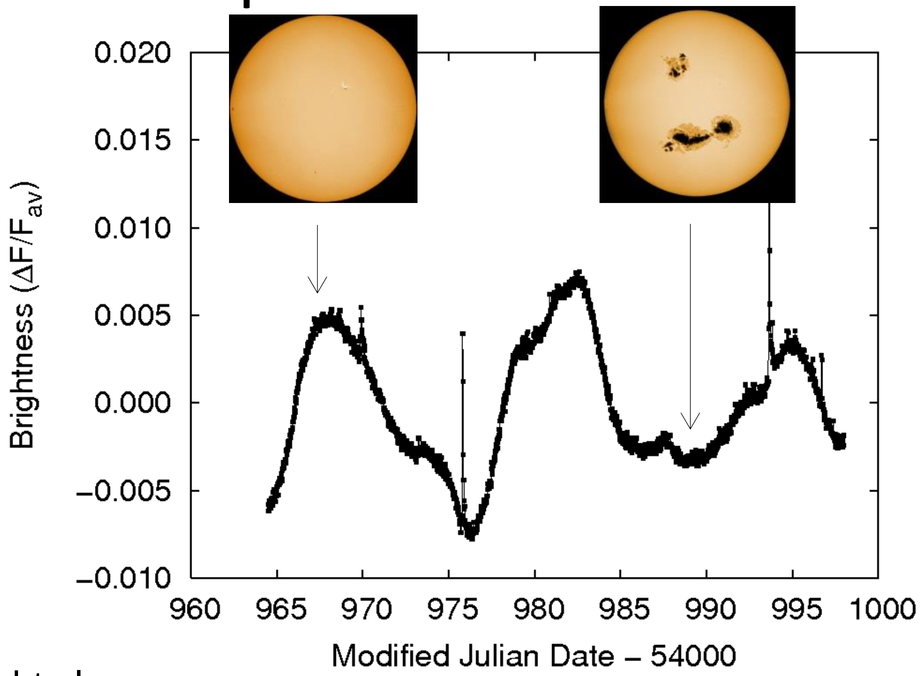
Long-term brightness variations

- 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

Sun



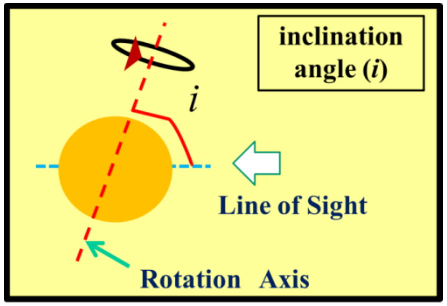
Superflare stars

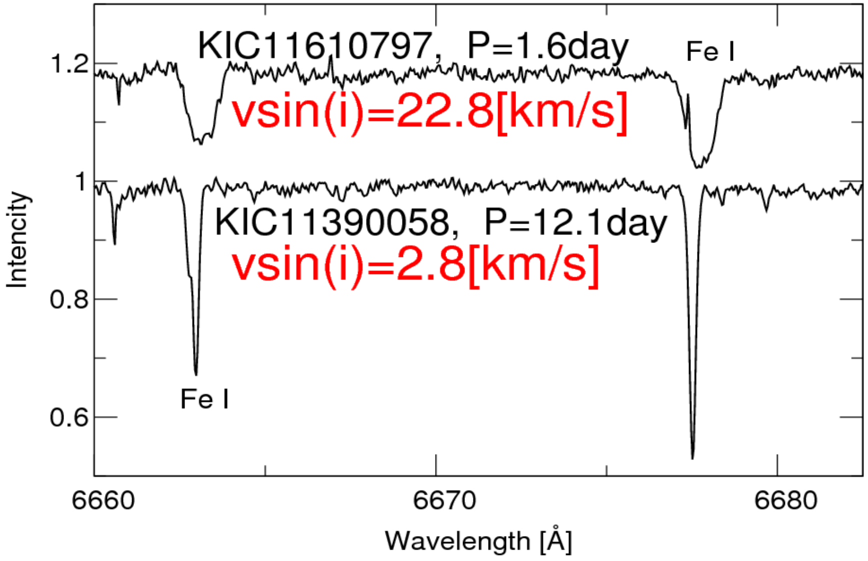


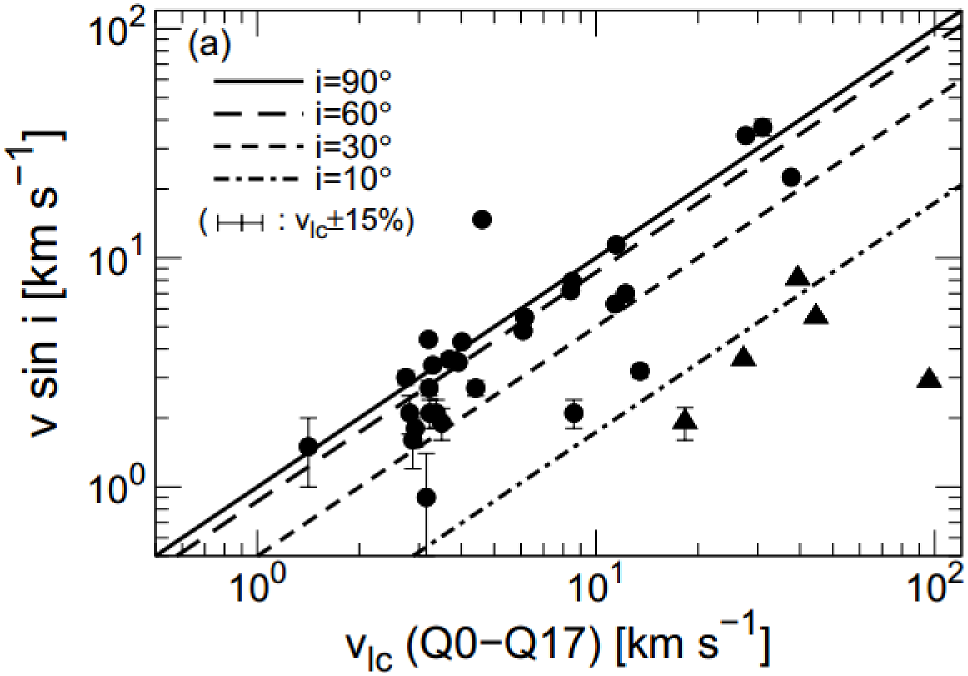
http://www.mps.mpg.de/projects/sun-climate/resu_body.html

Rotation velocity

- We performed high-dispersion spectroscopy of 50 superflare stars with Subaru telescope. (Notsu+ 2015a,b)
- Photometric periods of each star are consistent with rotation velocities .



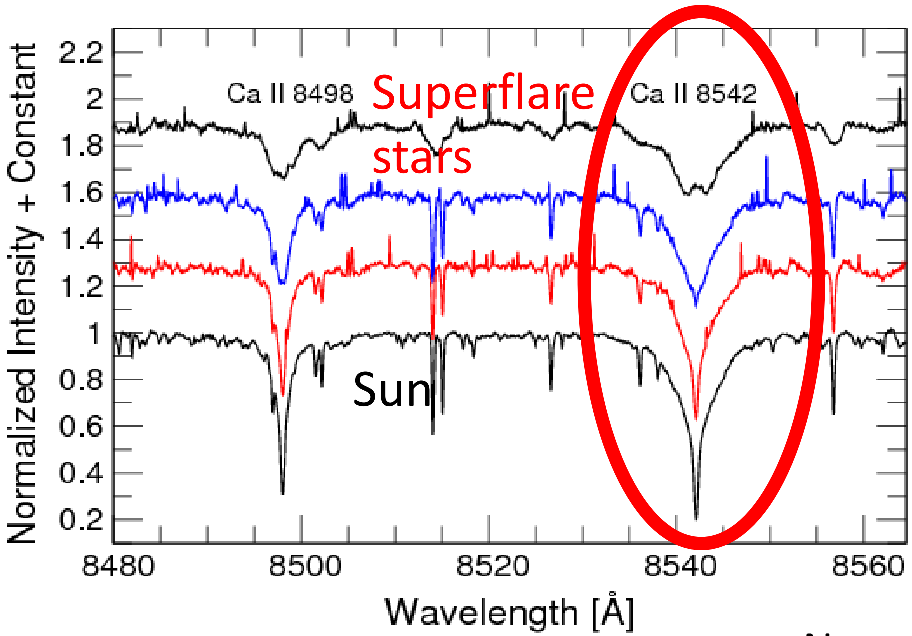


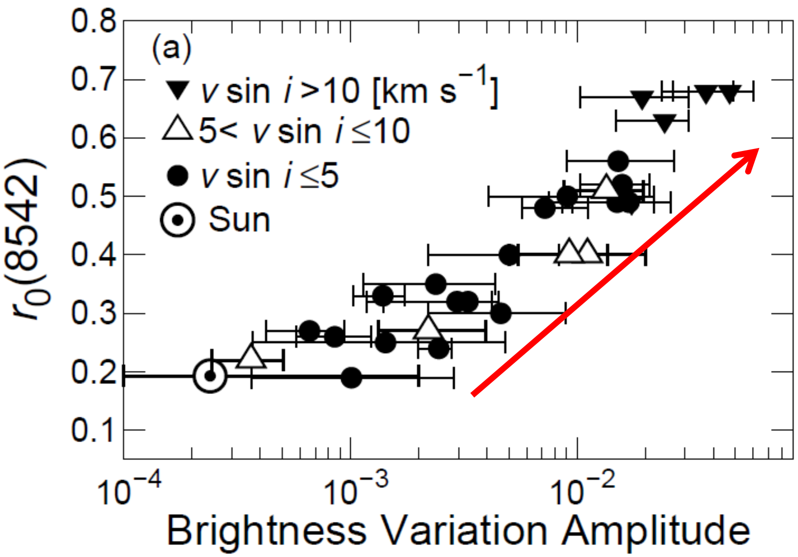


Notsu et al. 2015.

Spot size vs. intensity of CaII (8542)

- There is a clear correlation between the amplitude of photometric variation and CaII 8542 intensity.
  - CaII 8542 intensity → Chromospheric activity
- Amplitude of light variation → total area of starspots (active region)

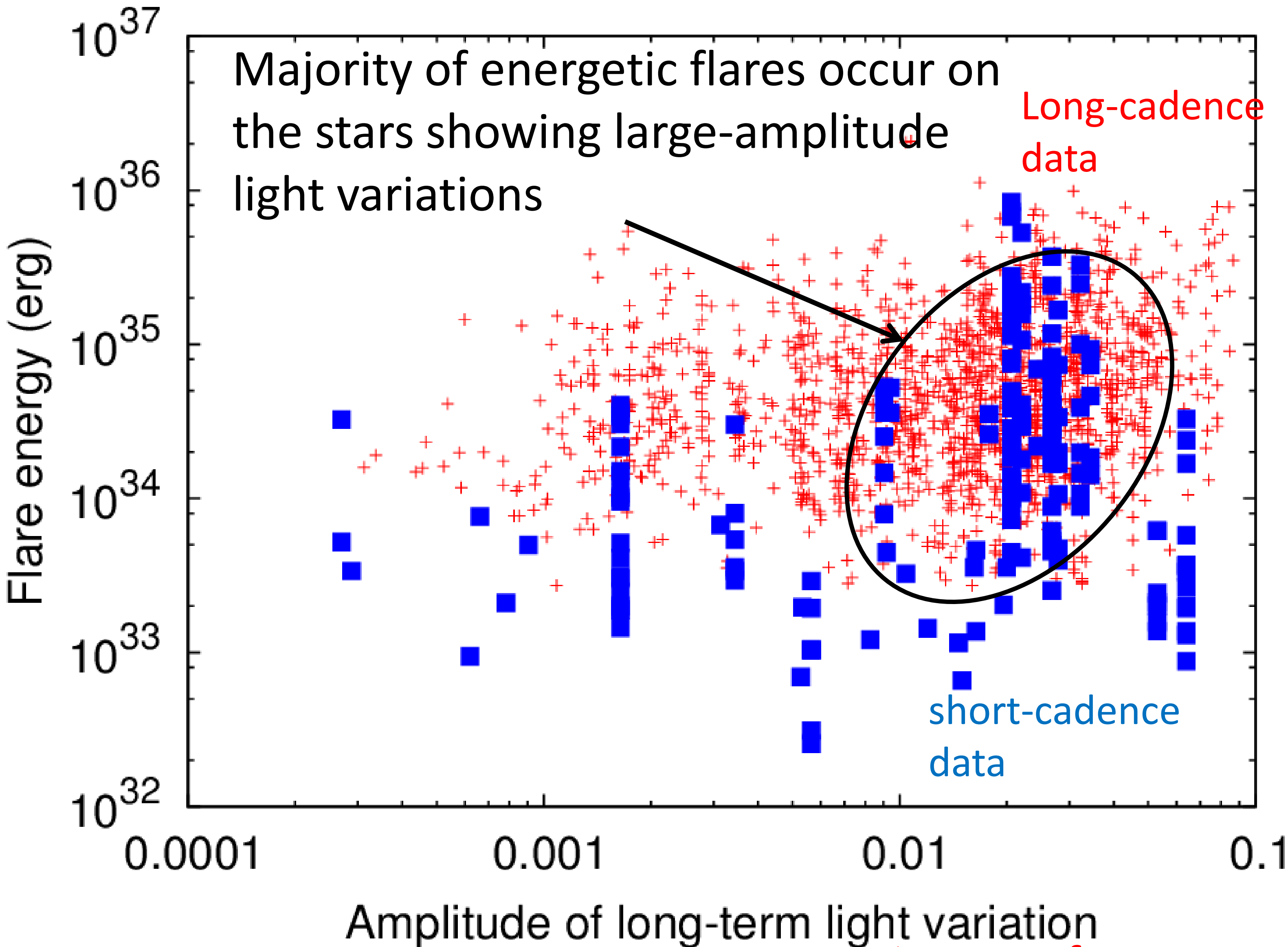




→ spot size

Notsu et al. (2015)

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.

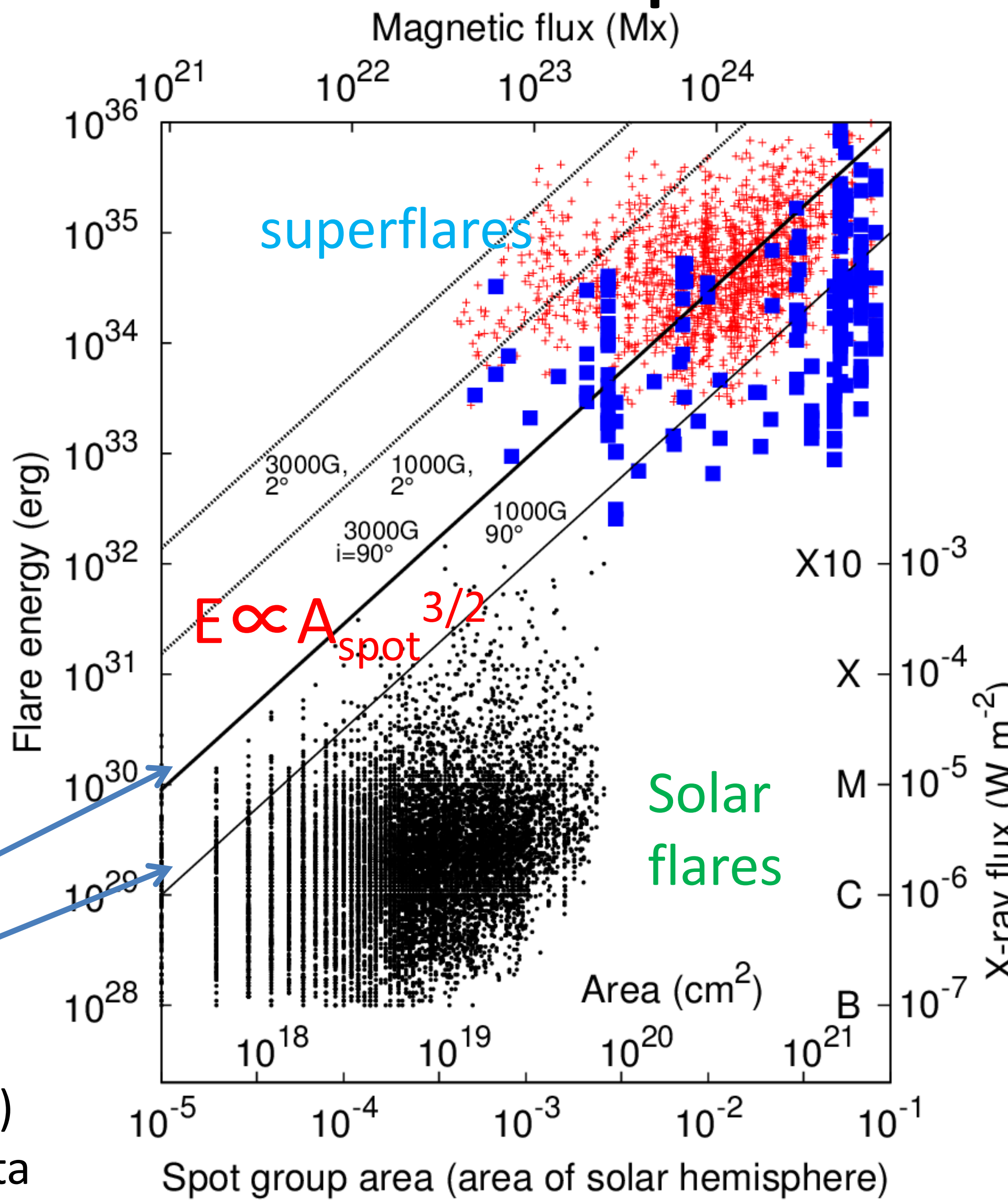
->Large starspots are necessary.

- Flares above the line may occur on the stars with low-inclination angle (or stars with polar spots?)

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

f=0.1, B=3000G

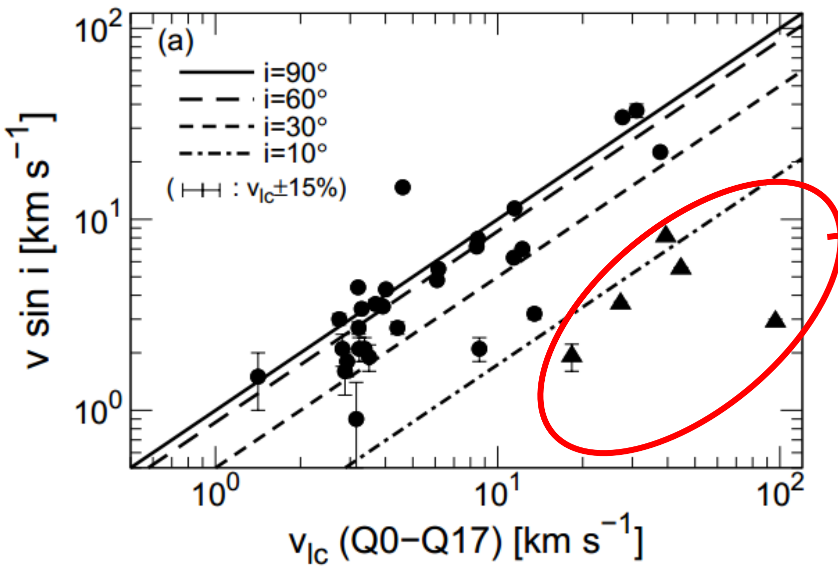
f=0.1, B=1000G

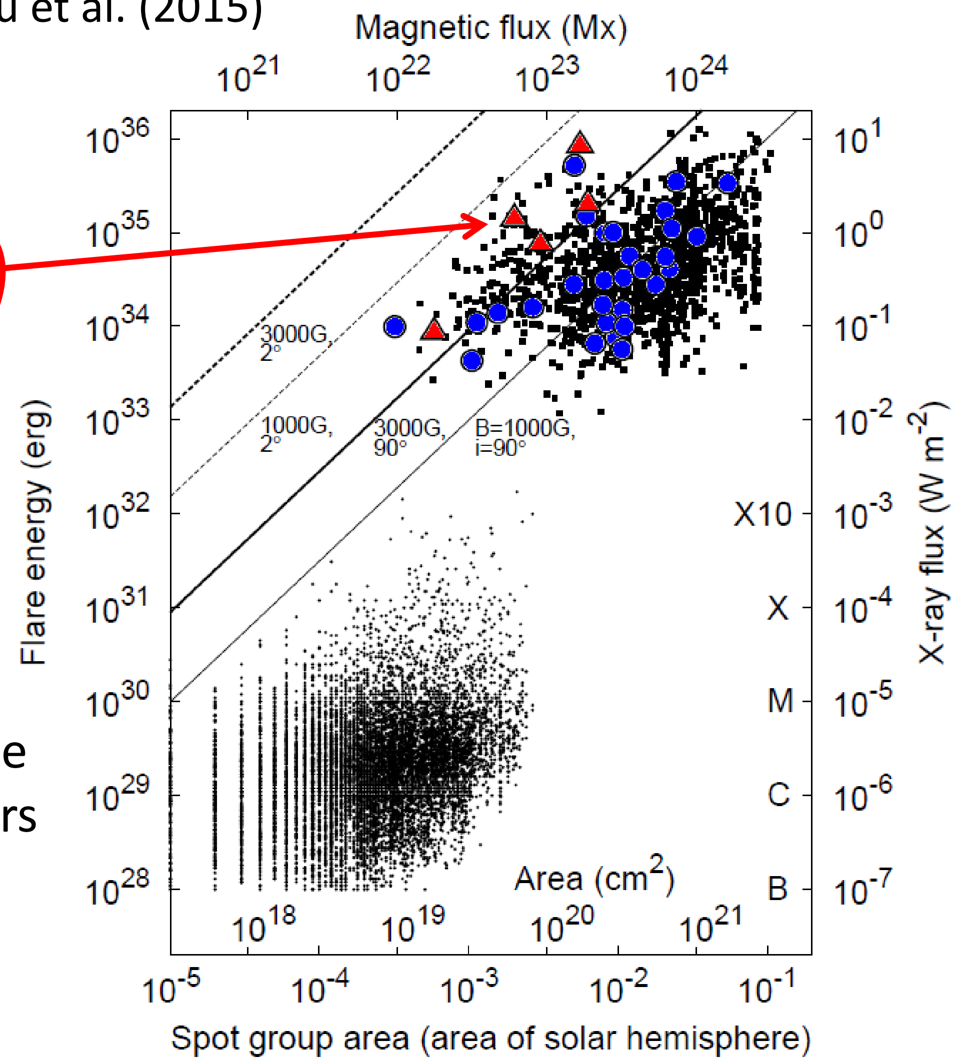


Shibata et al. (2013)
+ short cadence data

Flare energy vs. area of starspots

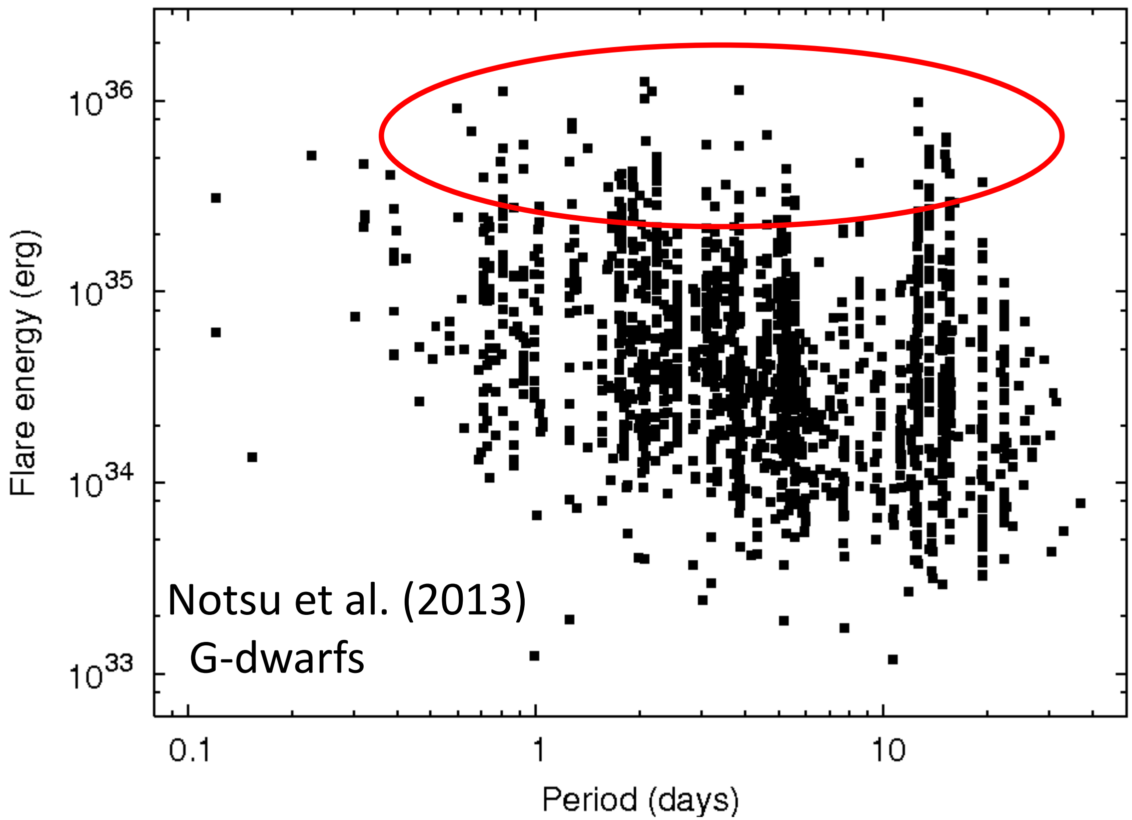
Notsu et al. (2015)





Flares above the line may occur on the stars with low-inclination angle or stars with “polar spots”.

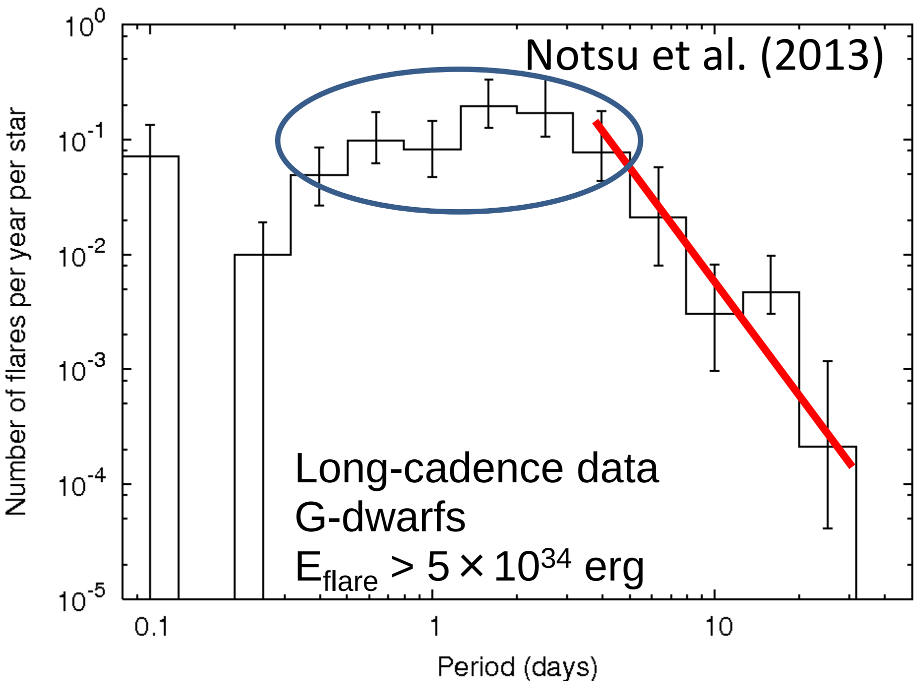
Flare energy vs. rotation period

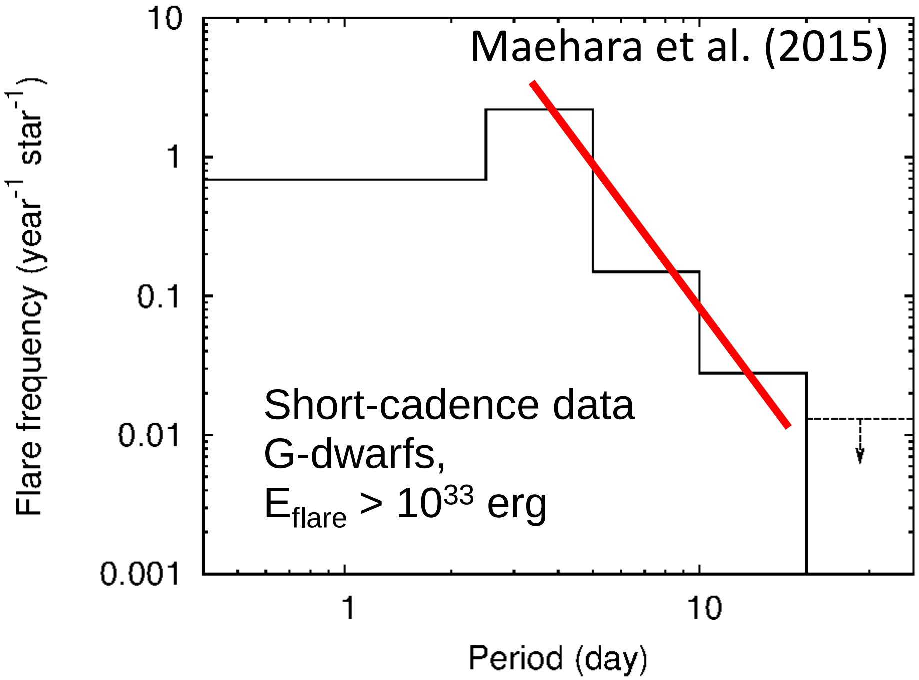


- The energy of the largest flares observed in a given period bin does not have a clear correlation with the rotation period.
  - Magnetic energy stored near the spots does not have a strong dependence on the rotation period.
  - Superflares may occur on the slowly rotating stars.

Flare frequency vs. rotation period

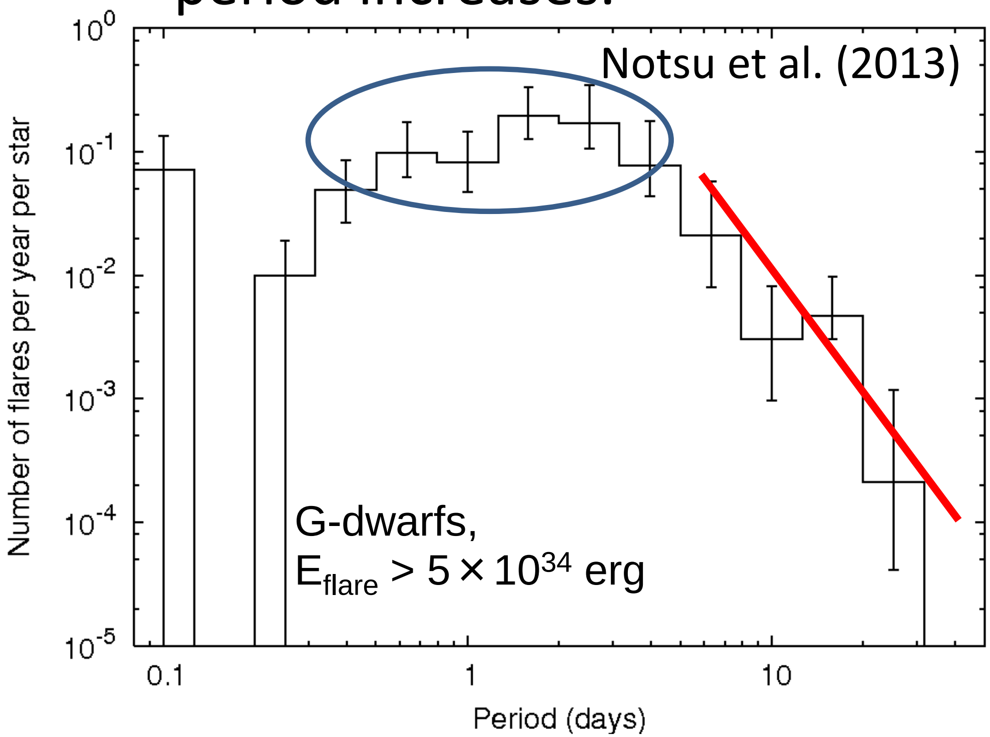
- The frequency of superflares decreases as the rotation period increases (P>3days).
  - The frequency of superflares shows the "saturation" for a period range < 3 days.

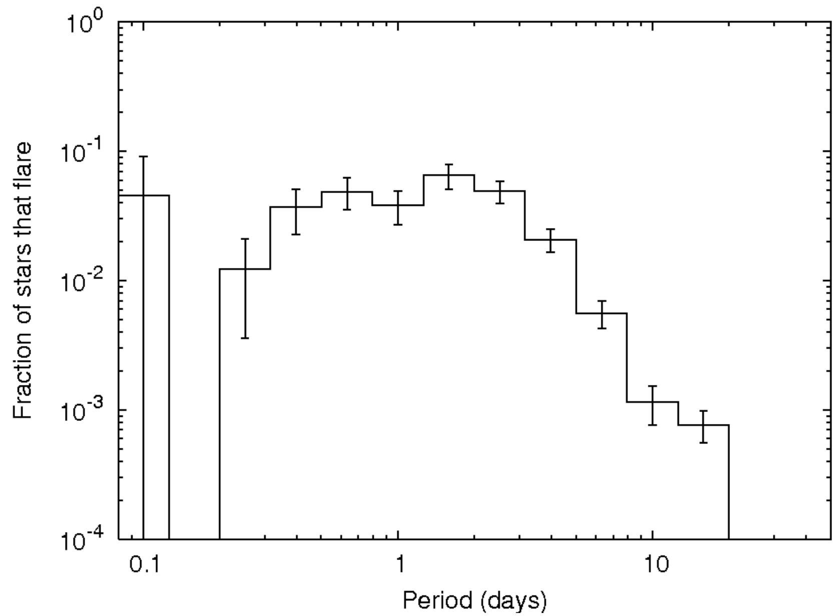




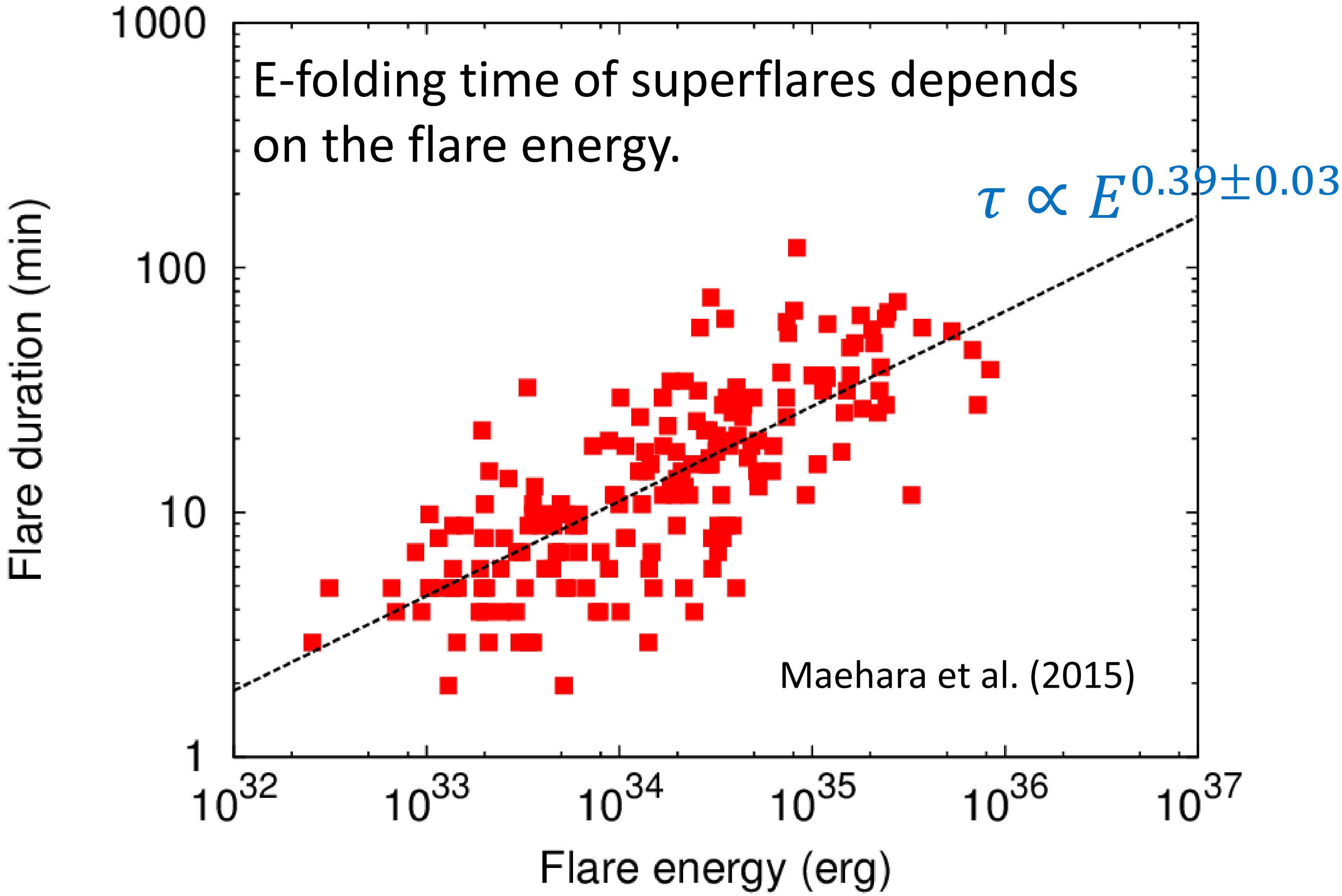
Flare frequency vs. rotation period

- The frequency of superflares decreases as the rotation period increases (P>3days).
  - The frequency of superflares shows the "saturation" for a period range < 3 days. → similar to the relation between Lx vs. Ro
  - The fraction of stars that flare also decreases as the rotation period increases.

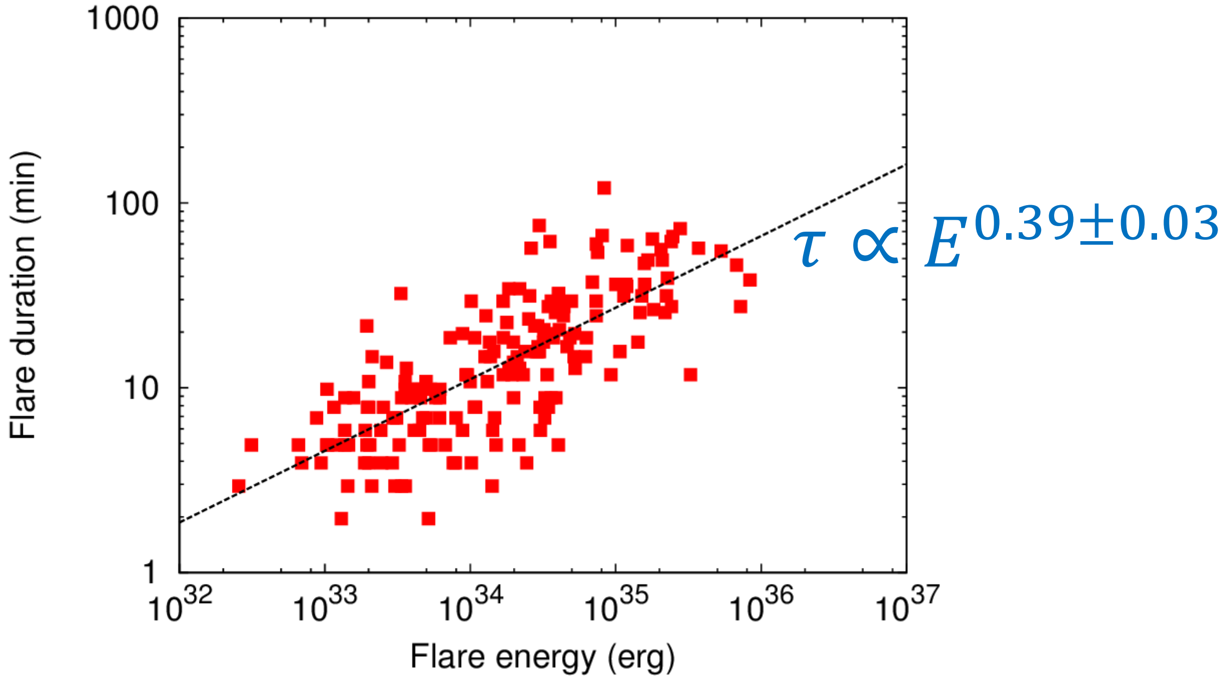




Flare duration vs. flare energy



Flare duration vs.flare energy

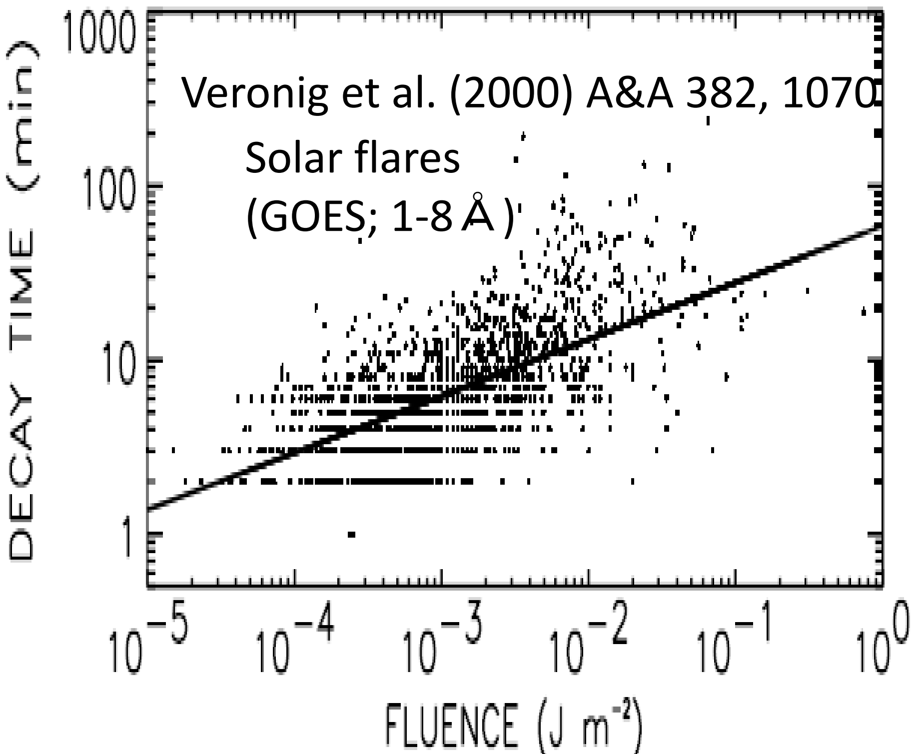


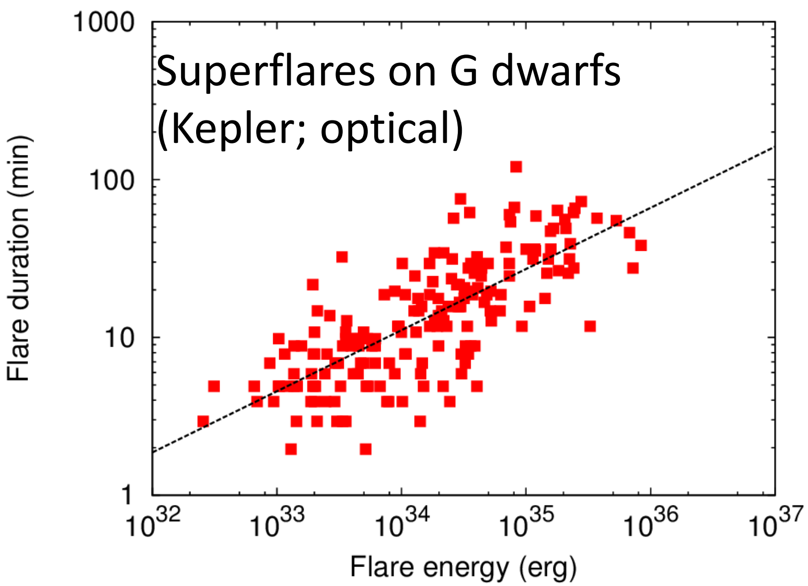
- Observation: e-folding time of flare ∝ (flare energy)$^{0.39}$
- Flare energy ∝ Magnetic energy ∝ volume × B^2
- Timescale of impulsive phase of flare ∝ Alfven time scale ∝ (scale length)/(Alfven velocity)

$$E \propto L^3 B^2, \quad \tau \propto L/v_A \rightarrow \quad \tau \propto E^{1/3}$$

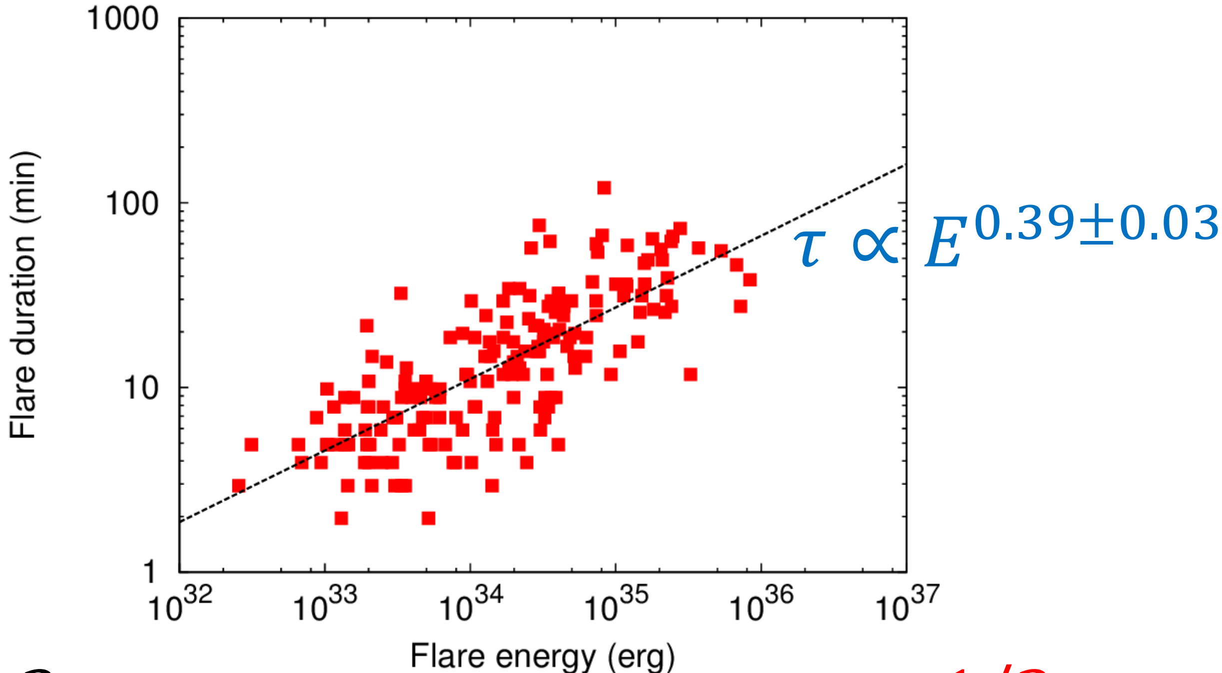
Flare duration vs. flare energy (solar flares)

- Decay time of solar flares also depends on the flare energy.
- decay time ∝ (flare energy)$^{0.2\text{-}0.3}$
- White light flares → Namekata-san's talk（16:30-16:45）





Flare duration vs.flare energy



$$E \;\propto\; L^3 B^2, \quad \tau \propto L/v_A \rightarrow \quad \tau \propto E^{1/3}$$

- The correlation between flare duration and energy comes from the difference in the scale length of each flare.
  - Flare oscillations would be used to check the difference in the scale length.

Results from Kepler

- Frequency distribution of superflares
  - Frequency distribution can be represented by the power-law function (index: ~-1.8)
    - The power-law distributions of superflares on Sun-like stars and that of solar flares are roughly on the same line ($E=10^{24}$-10^{36} erg)
    - Frequency: 10^{33} erg→ 1 in 100 yr, 10^{34} erg→ 1 in 800 yr, 10^{35} erg:→1 in 5000 yr

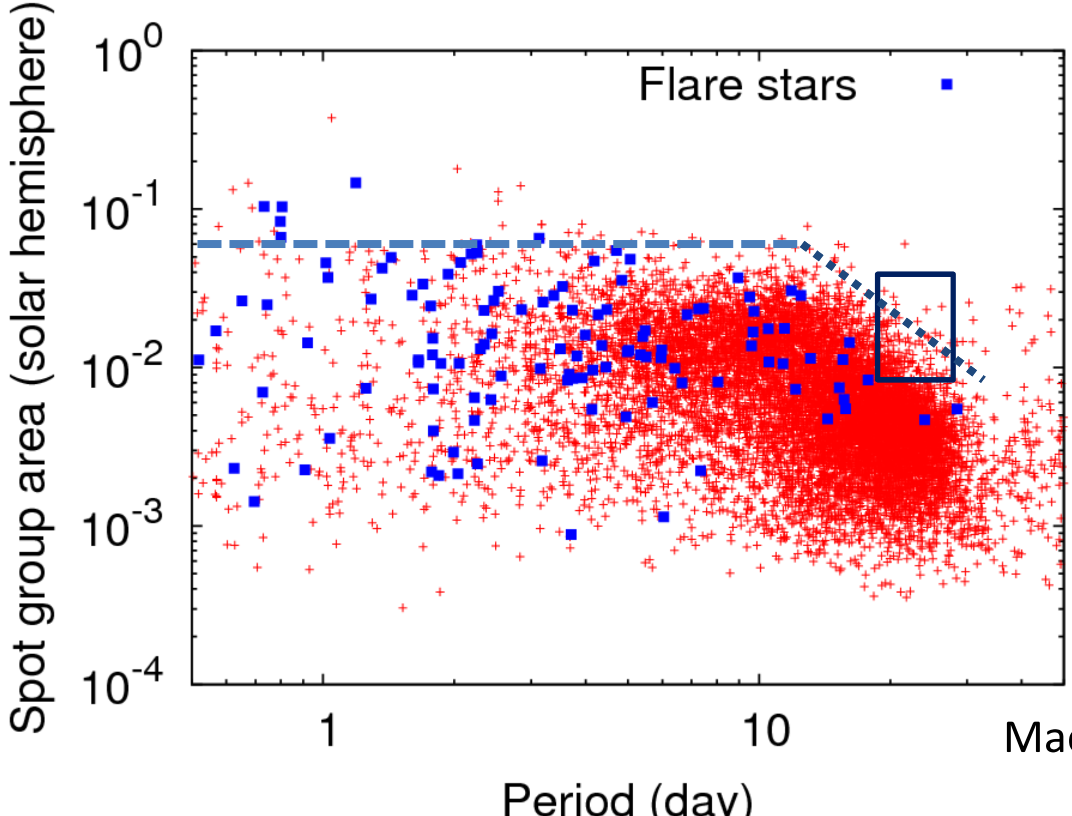
- Maximum energy of superflares vs. stellar properties
  - The maximum energy depends on the area of starspots
    - large starspots are necessary for superflares
    - no strong dependence on the rotation period
  - Flare frequency depends on the rotation period.

- Flare duration vs. flare energy
  - Duration of superflares is roughly proportional to $E^{0.39}_{flare}$
    - Solar flares: similar correlation between duration and energy

Starspots and superflares

Area of starspots vs. rotation period

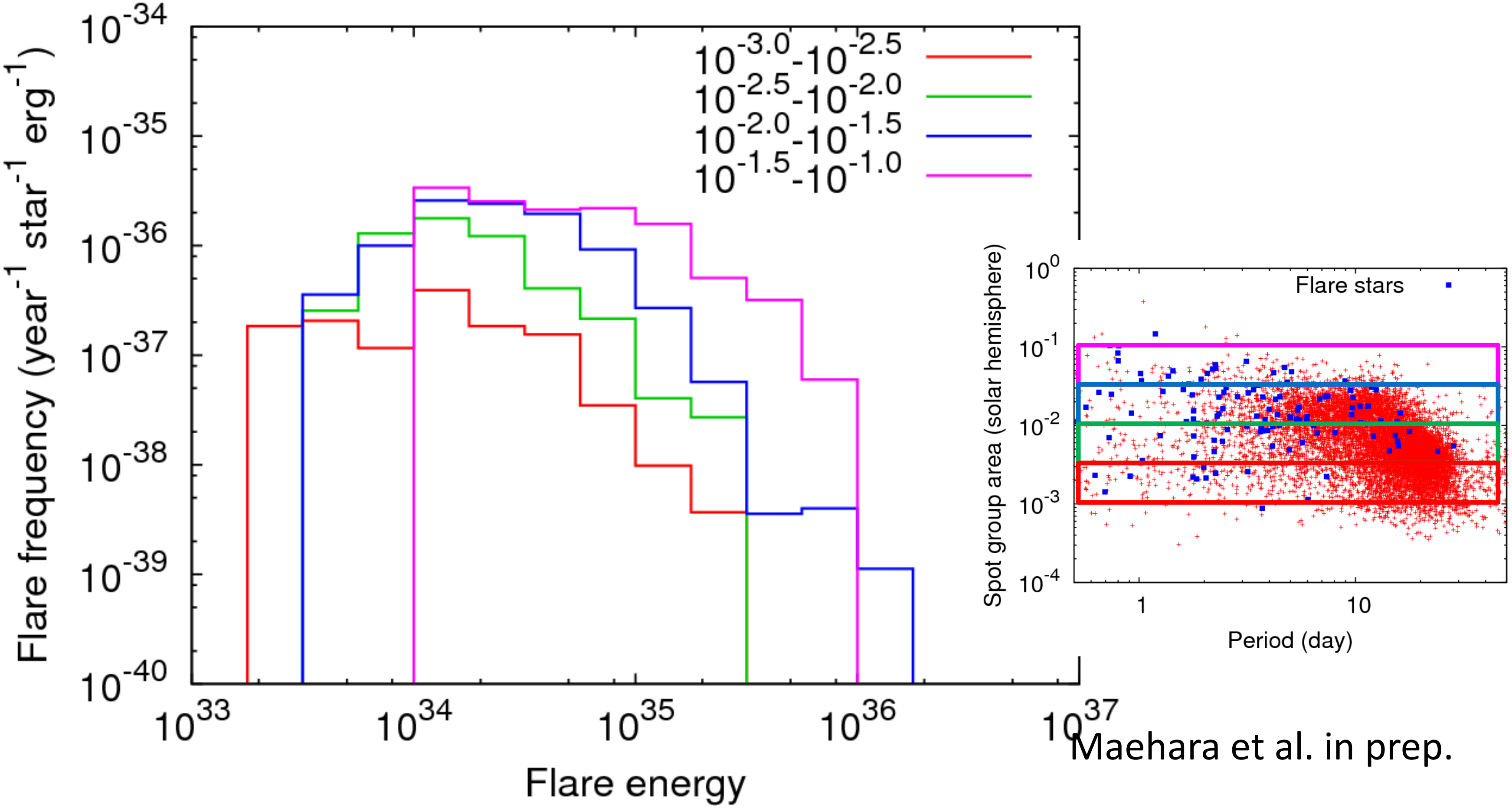
- Large starspots can be formed on slowly-rotating stars
  - P=20-30 days: ~1 × 10^{-2}
  - maximum size of starspots
    - P<13 days: starspots is constant (~5 × 10^{-2})
    - P>13 days: decreases as rotation period increases



Maehara et al. in prep.

Flare frequency and area of starspots

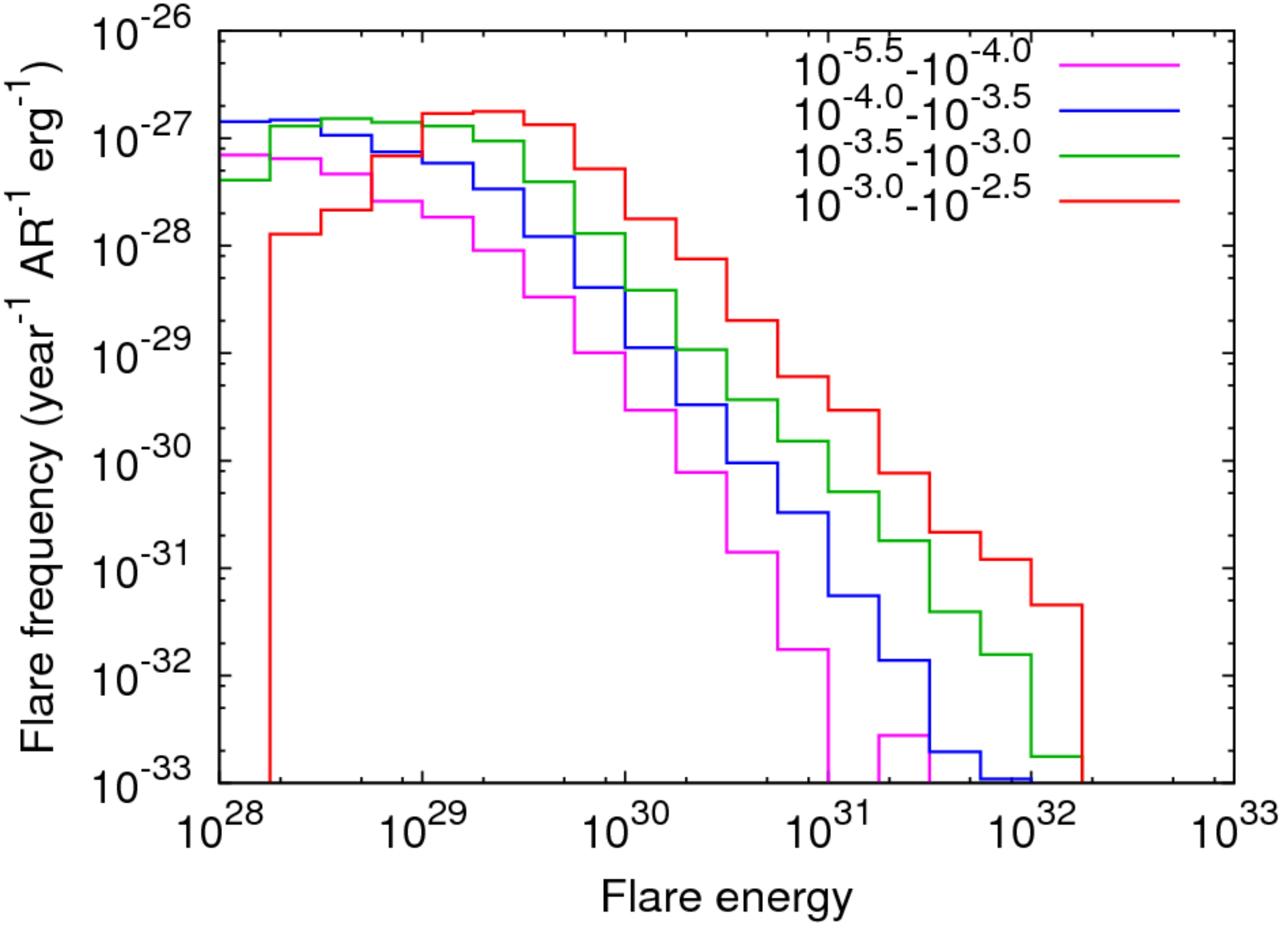
- Stars with larger starspots can produce more energetic and frequent superflares



Maehara et al. in prep.

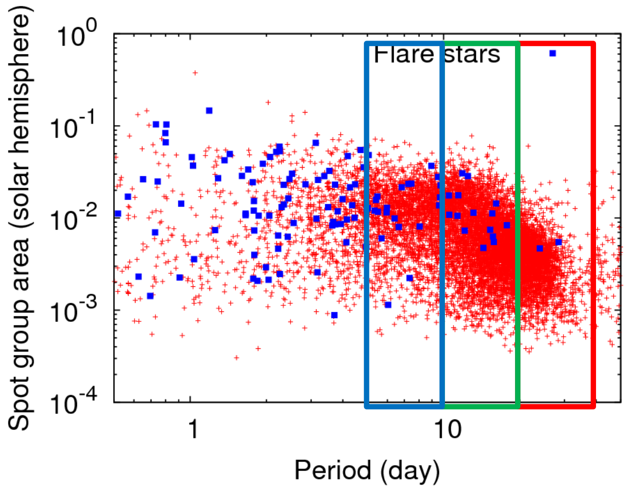
Flare frequency and area of sunspots

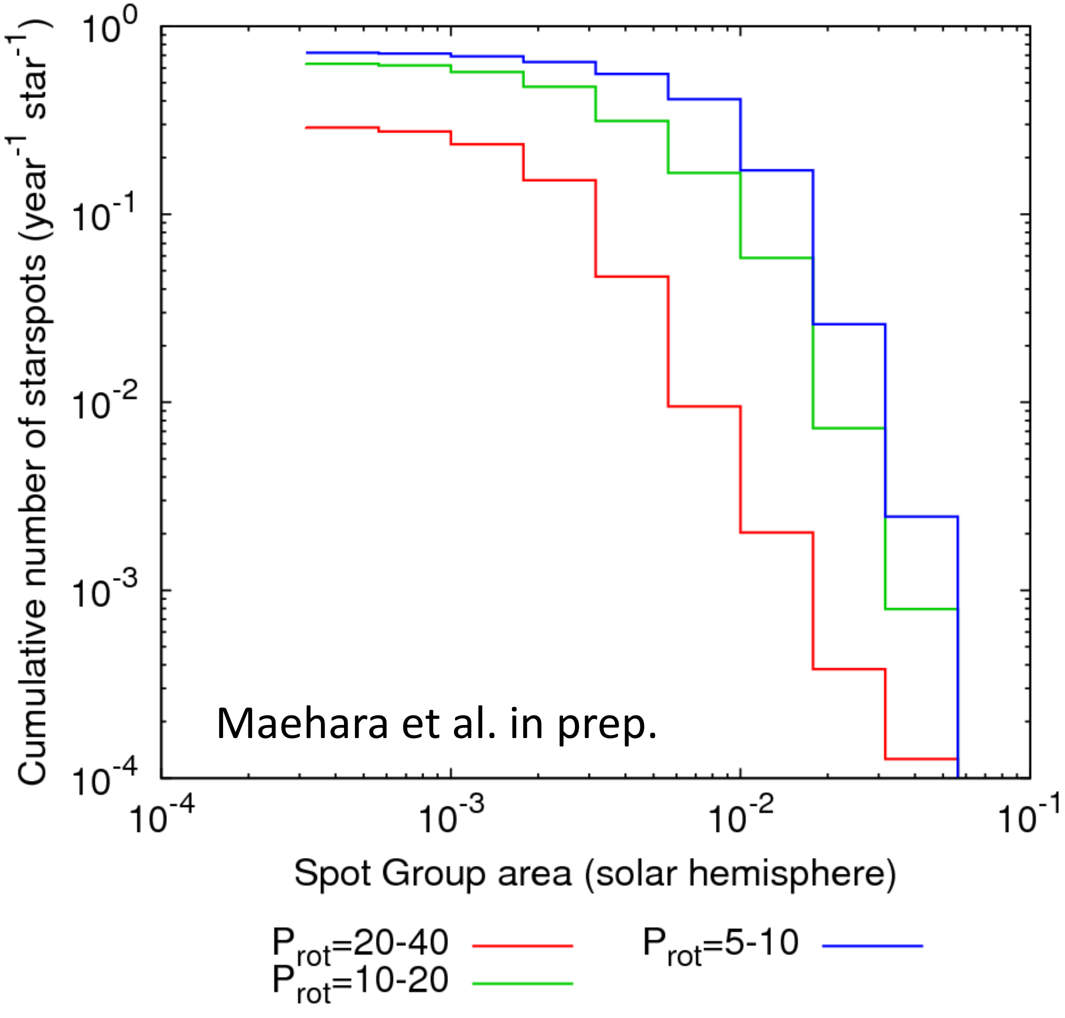
Larger sunspots can produce more energetic and frequent solar flares.



Occurrence frequency of large starspots

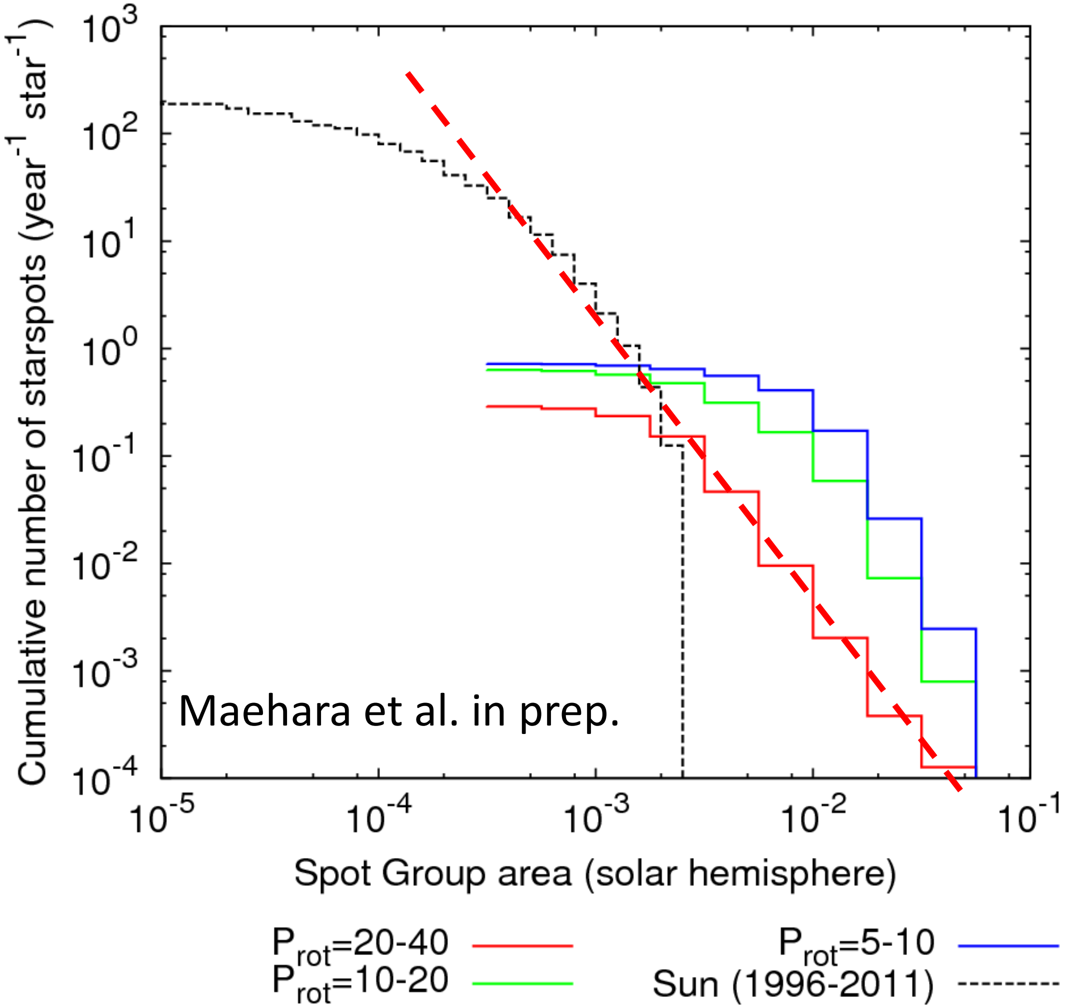
- Occurrence rate of large starspots depends on the rotation period.
  - ✓ Occurrence rate of starspots with a given area increases as the rotation period decreases.

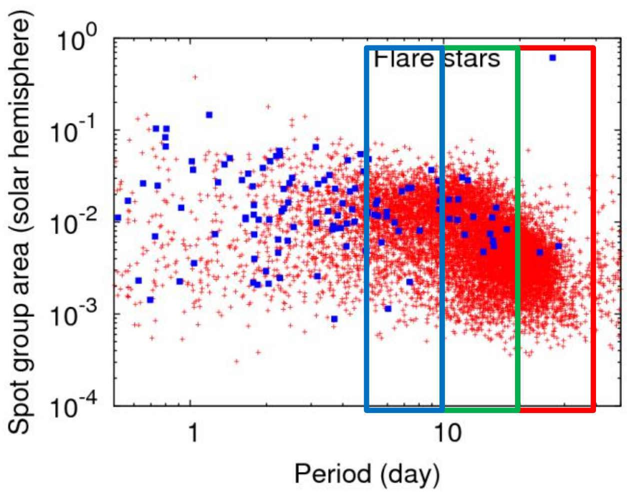




Occurrence frequency of large starspots

- Power-law slope of the cumulative occurrence rate of starspots is similar to the that of sunspots.





Summary and To Do

- Can superflares occur on our Sun?
  - Superflares (with Kepler)
    - Slowly-rotating stars also show superflares ($E=10^{34}$-10^{35} erg)
      - Average frequency: 1 in ~5000 years
    - Large starspots are key to produce superflares
      - E.g. flare energy vs. area of starspots
- Can our Sun produce large starspots?
  - How are large starspots formed on slowly-rotating stars?
    - Frequency, maximum size, life-time of spots, etc.
    - Activity cycle, solar/stellar dynamo