AASTCS-5: Radio Exploration of Planetary Habitability
2017 May 11th (Thu) 9:20AM-9:40AM

Statistical studies of superflares on G-, K-, M- type stars from Kepler data

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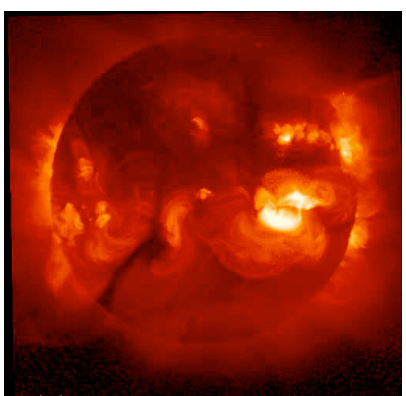
Reference:

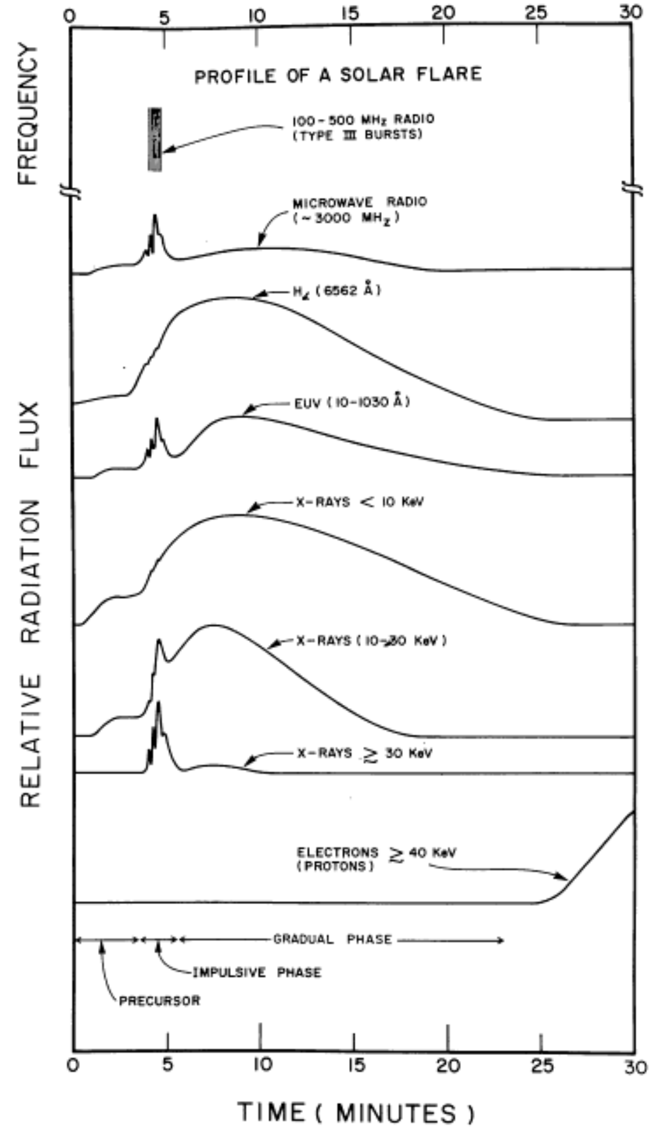
Maehara et al. 2012, Nature, 485, 478
Shibayama et al. 2013, ApJS, 209, 5
Notsu et al. 2013, ApJ, 771, 127
Shibata et al. 2013, PASJ, 65, 49
Candelaresi et al. 2014, ApJ, 792, 67
Maehara et al. 2015, EPS, 67, 59
Notsu et al. 2015a, PASJ, 67, 32
Notsu et al. 2015b, PASJ, 67, 33
Maehara et al. 2017, PASJ, doi: 10.1093/pasj/psx013
Maehara et al. in prep

Solar flares

- Large eruptive events in the solar atmosphere
  - Magnetic energy release by reconnection
- Observed in all wavelengths
  - Radio ~ X-ray
- Timescale: 1 min – 1 hour
- Total energy: $10^{29} - 10^{32}$ erg



← Yohkoh (JAXA/ISAS)
Soft X-ray



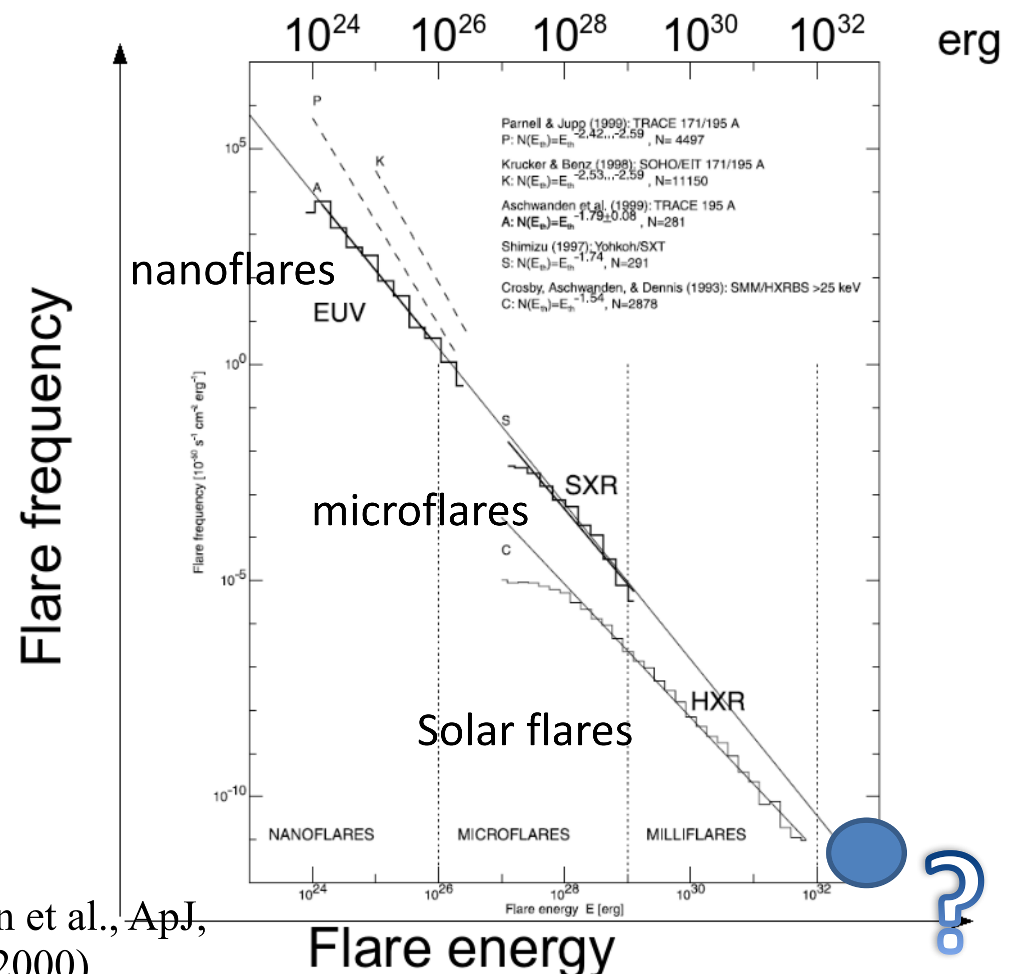
Kane (1974)

Frequency-energy 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

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

Can much larger flares (superflares) occur on our Sun?

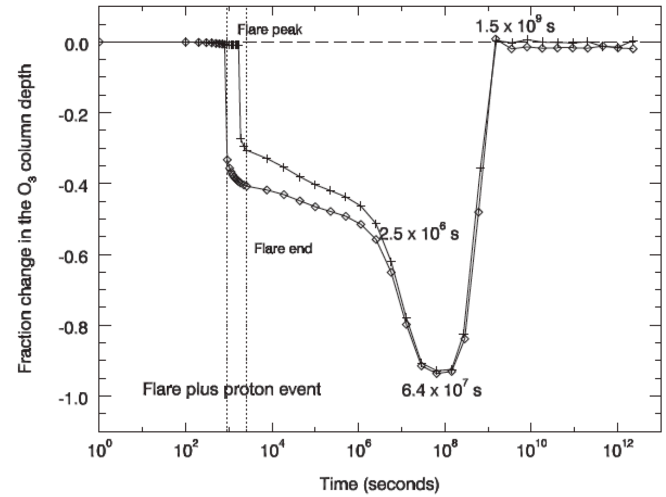


Aschwanden et al., ApJ, 535, 1047 (2000)

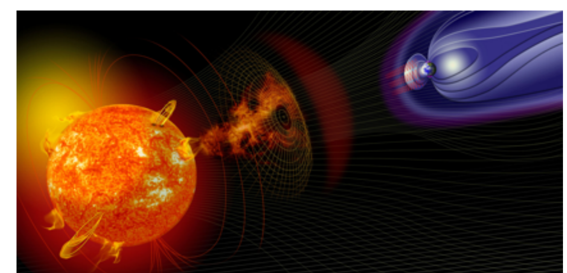
Potential impacts on habitability from large flares (superflares)

For example ….

[Segura et al. 2010 Astrobiology]
Ozone depletion of Earth-like planet orbiting a M-dwarf flaring star



[Airapetian et al. 2016 Nature Geoscience]
Active young Sun has large effects on atmospheric warming and prebiotic chemistry of early Earth.



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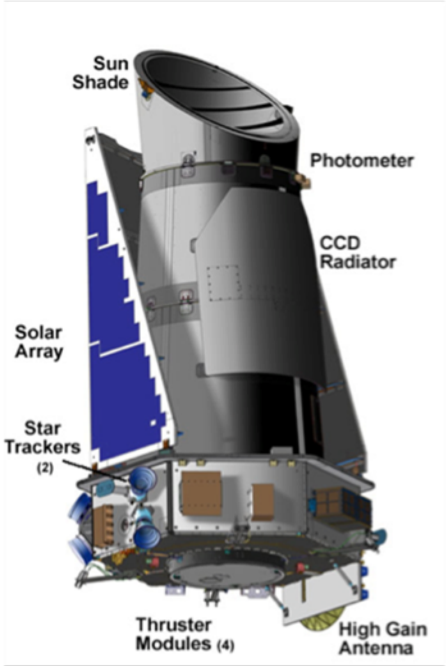
Statistical studies of flares on G,K,M-type stars are important for evaluating the potential impacts on (exo)planetary habitability

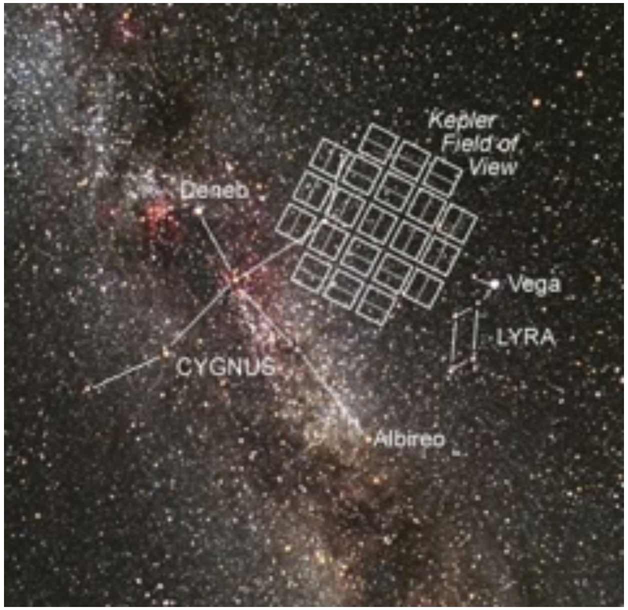
Kepler space telescope

- Kepler is the best space telescope to search for superflares.
  - High photometric precision (~10^{-4} → >10^{32} erg flares on G-dwarfs)
  - Continuous observations of large number of targets (~160,000 stars, 4 years)

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

- Long cadence: ~30min
- 109,092 G-, K-, M-dwarfs

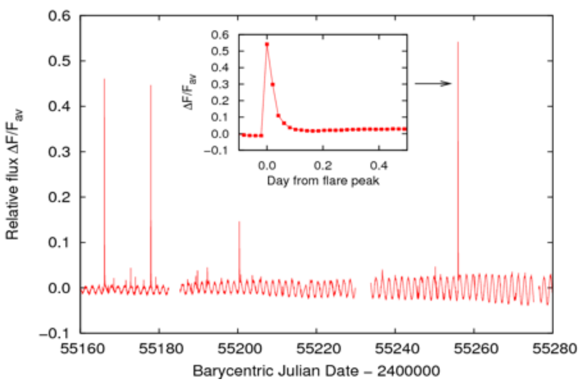




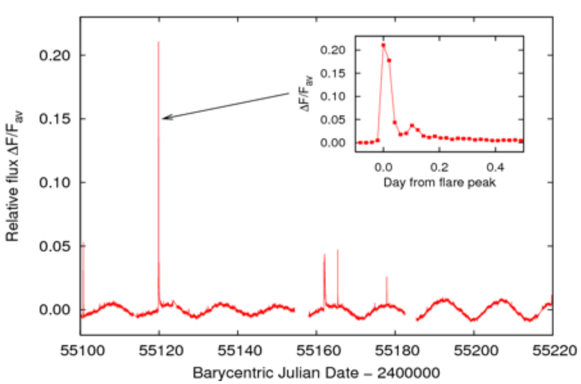
Flares detected by Kepler

1928 flares on 117 stars

KIC 6949412



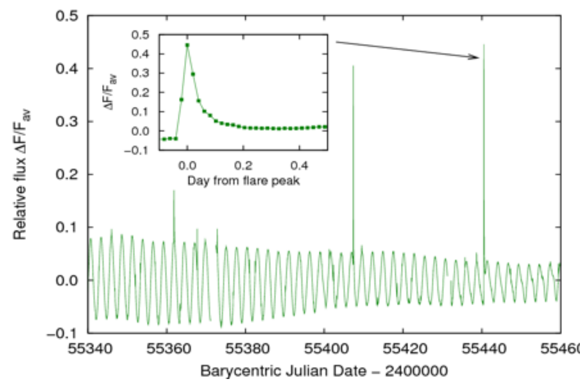
KIC 11349556



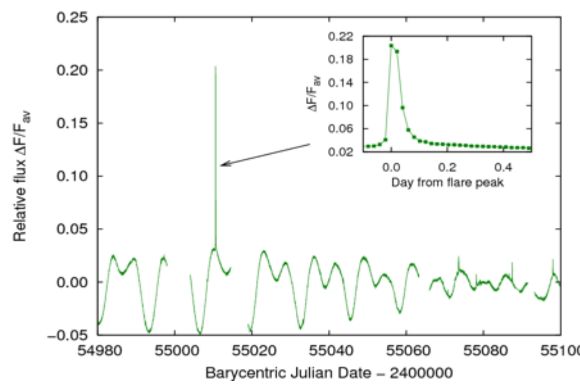
M-dwarfs

3355 flares on 399 stars

KIC 4349043



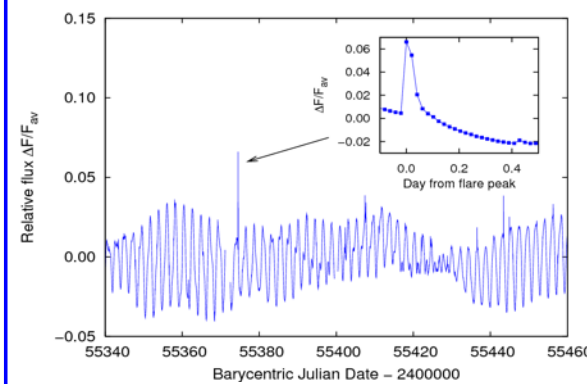
KIC 8142547



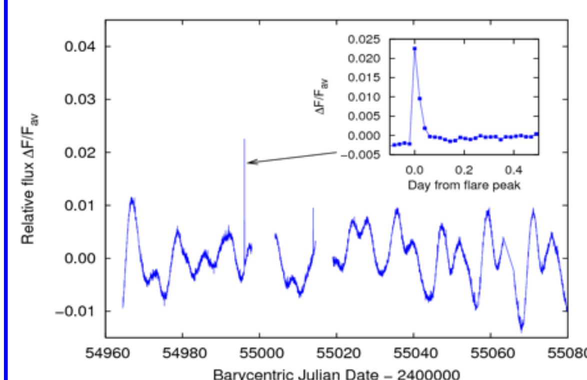
K-dwarfs

1547 flares on 279 stars

KIC 7532880



KIC 10524994

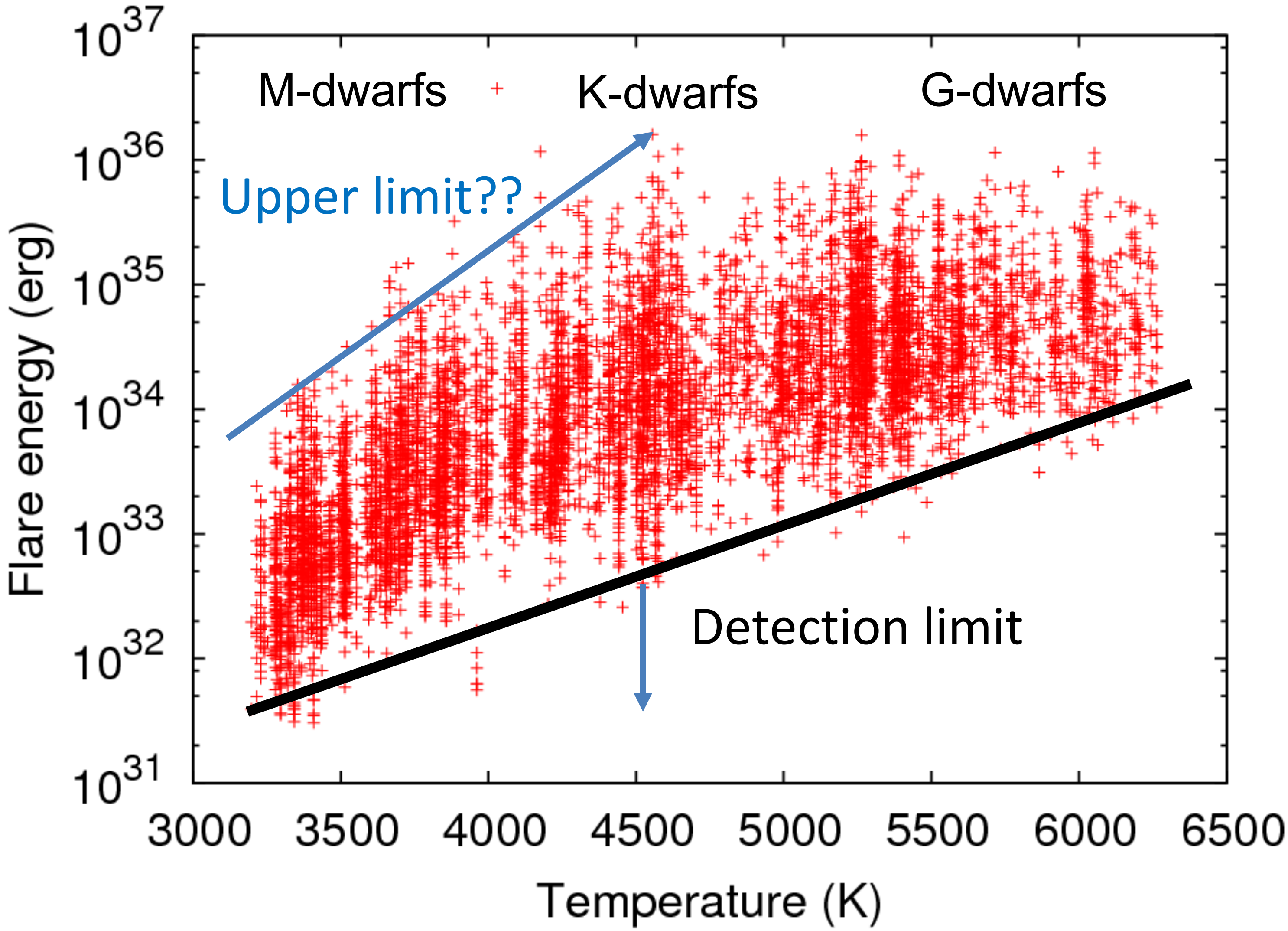


G-dwarfs

6830 superflares on 795 G,K,M-type stars.

(Maehara+2012 Nature, Shibayama+2013 ApJS, Canderalesi+2014 ApJ)

Flare energy vs. temperature



6830 superflares on 795 G,K,M-type stars.

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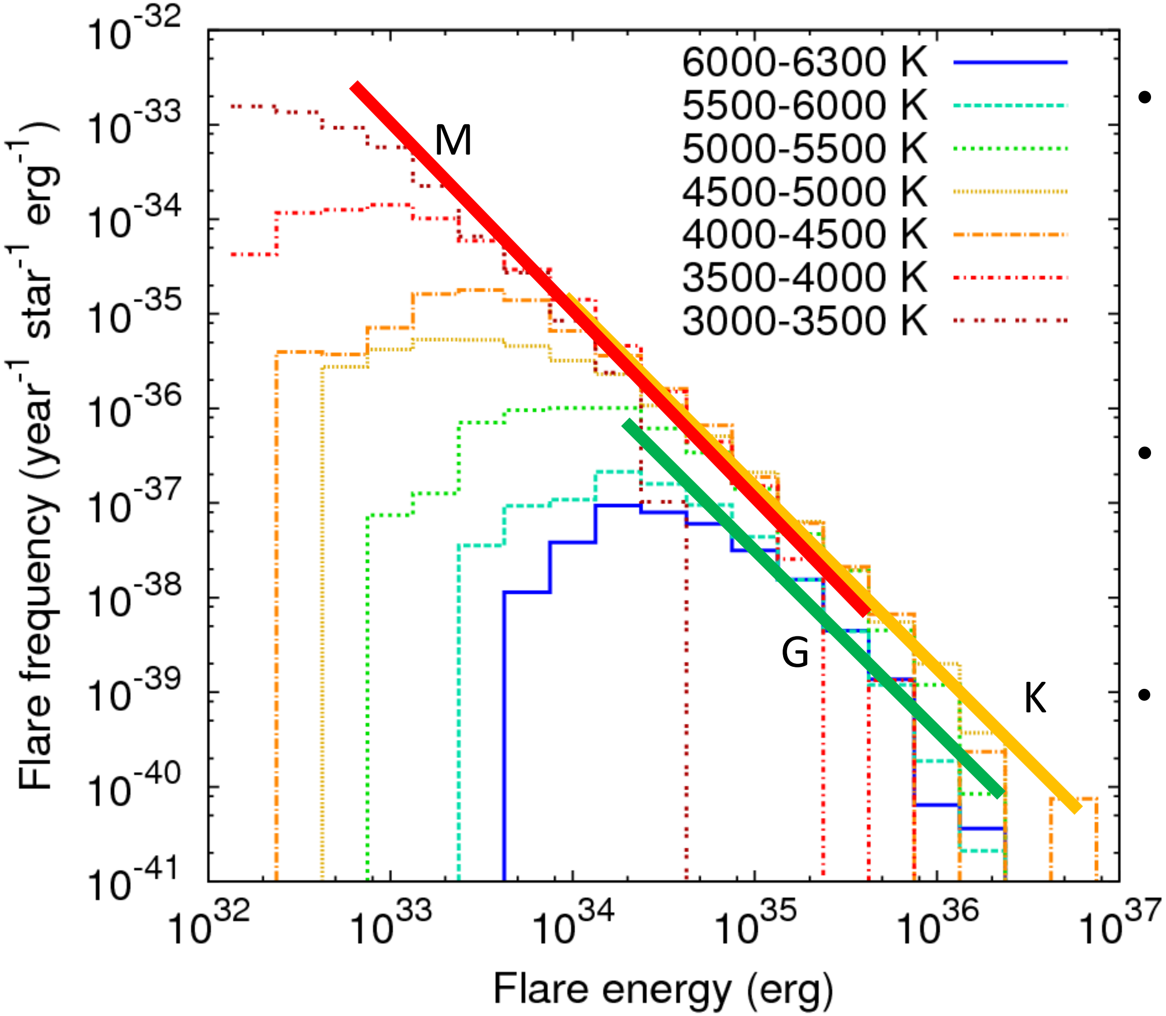
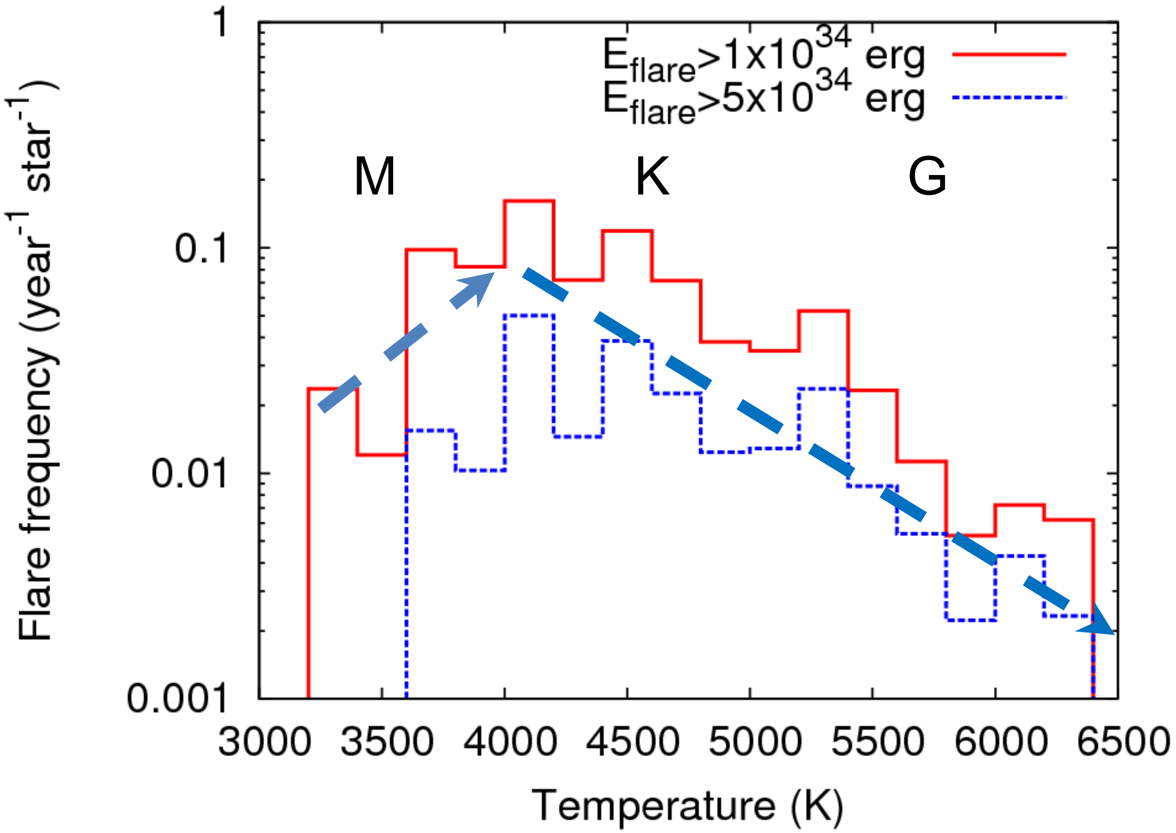
Occurrence frequency distribution



- The frequency distribution can be represented by the power-law function
  - power-law index ~ -1.9 - -1.8 (similar to solar flares.)
- K- and M-dwarfs show more frequent superflares than G-dwarfs.
- Flare energy of the largest superflares on M-dwarfs is smaller than those on K- and G-dwarfs.
  - K- & G-dwarfs: ~10^{36} erg
  - M-dwarfs: ~10^{35} erg

Flare frequency vs. temperature

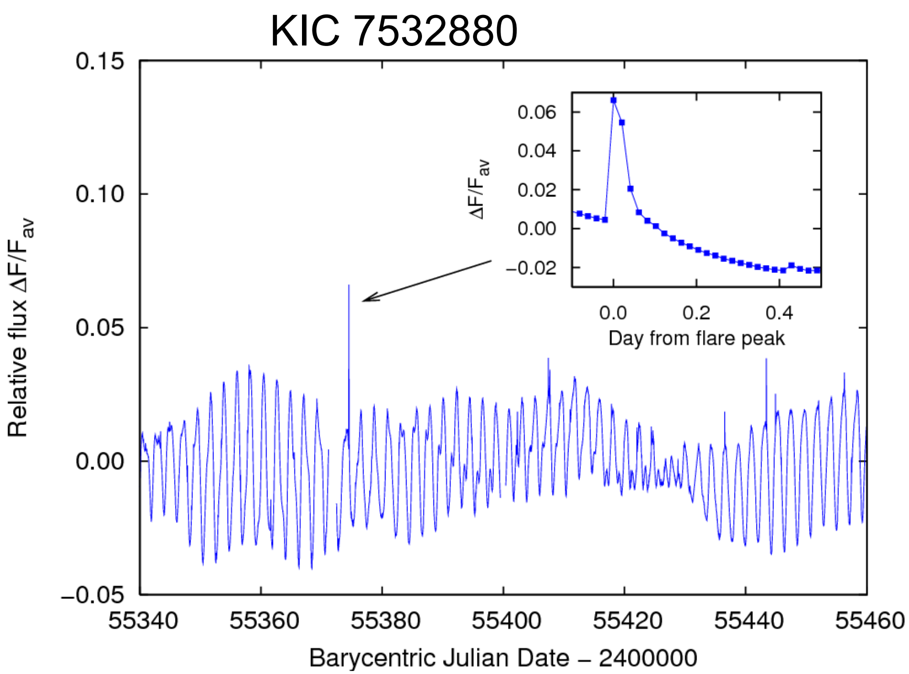


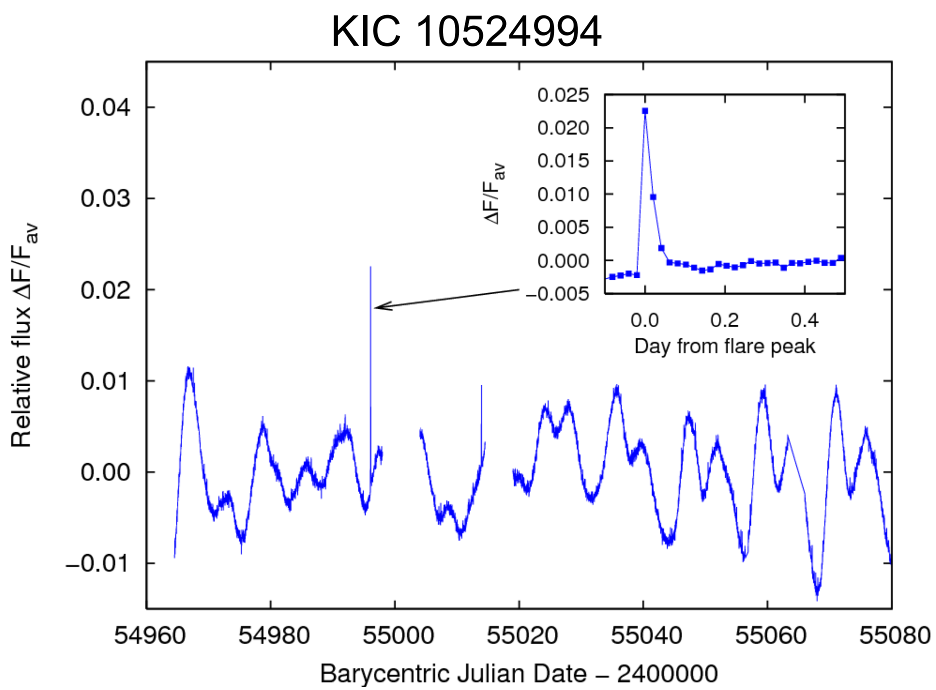
- Frequency of superflares with the energy of >5×10^{34} erg (>X5000)
  - Teff>4000 K: decreases as Teff increases.
  - Teff<4000 K: increases as Teff increases.
  - M dwarfs exhibit less frequent superflares

What is the reason for this difference??

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.

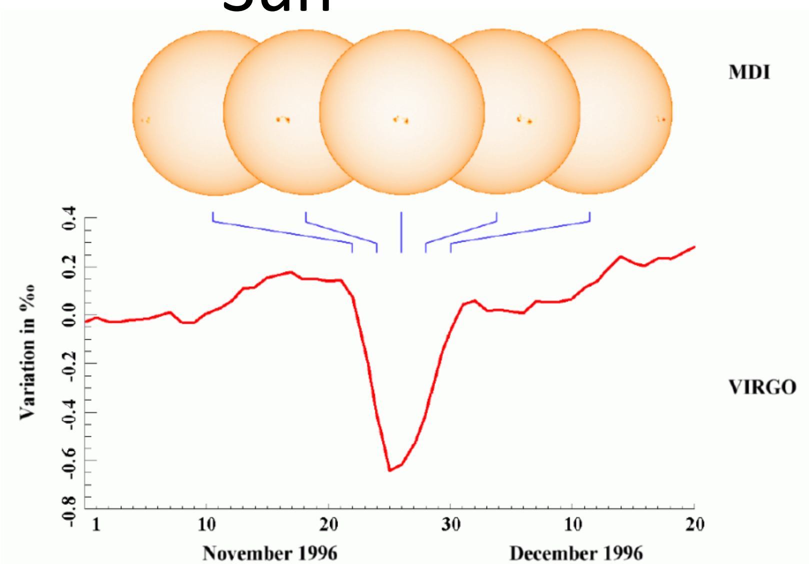




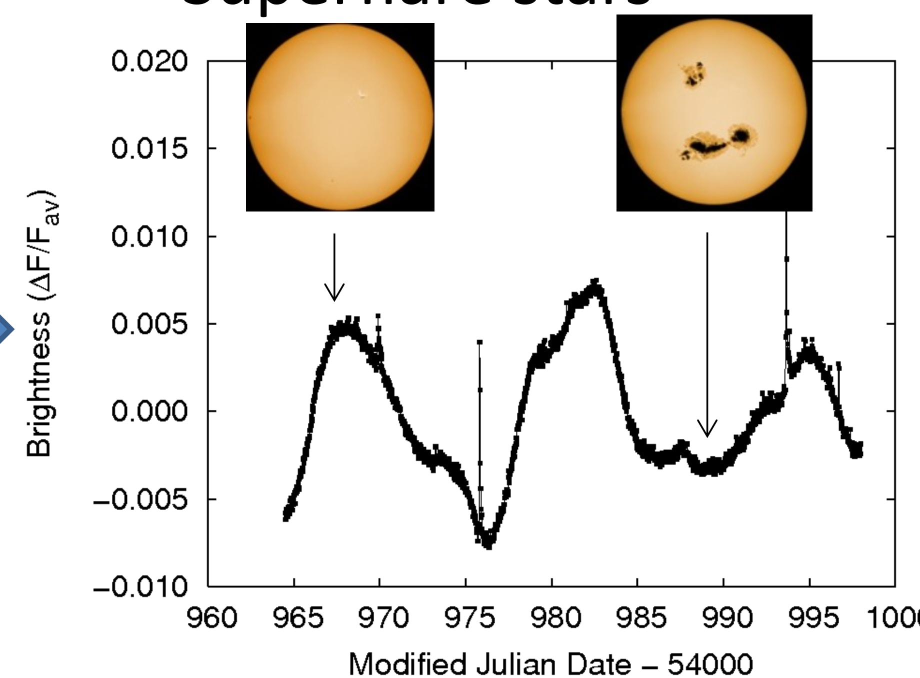
Long-term brightness variations

- 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

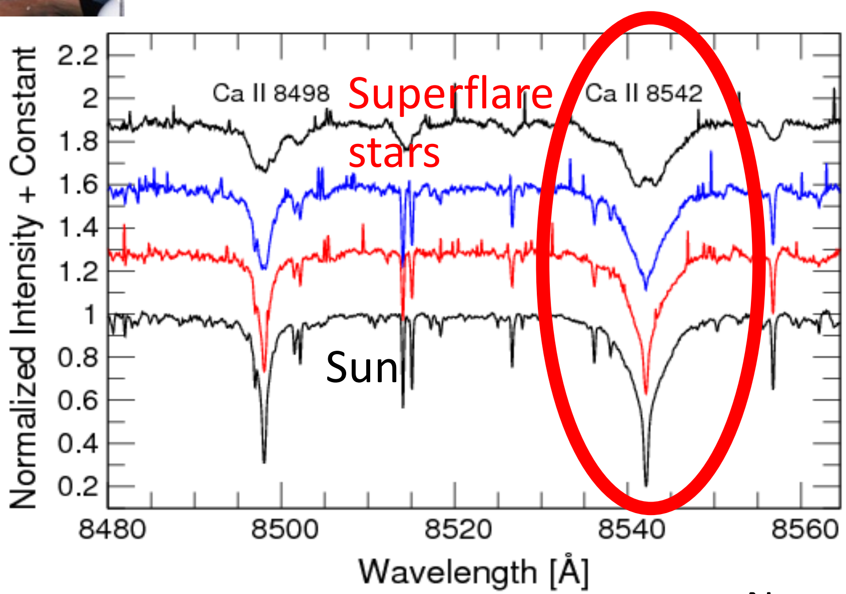


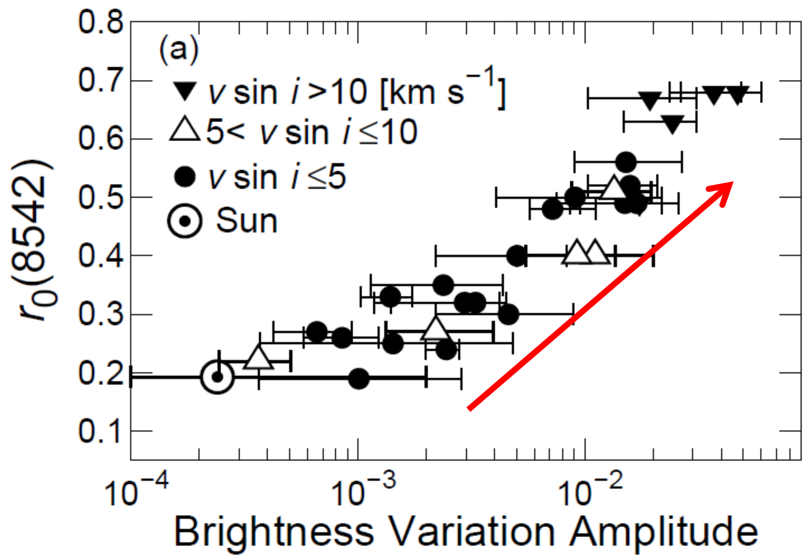
http://www.mps.mpg.de/projects/sun-climate/resu_body.html

Spot size vs. intensity of Ca II (8542)

- There is a clear correlation between the amplitude of photometric variation and CaII 8542 intensity.
  - CaII 8542 intensity (r_0(8542)) → Chromospheric activity
- Amplitude of light variation

→ total area of starspots (active region)





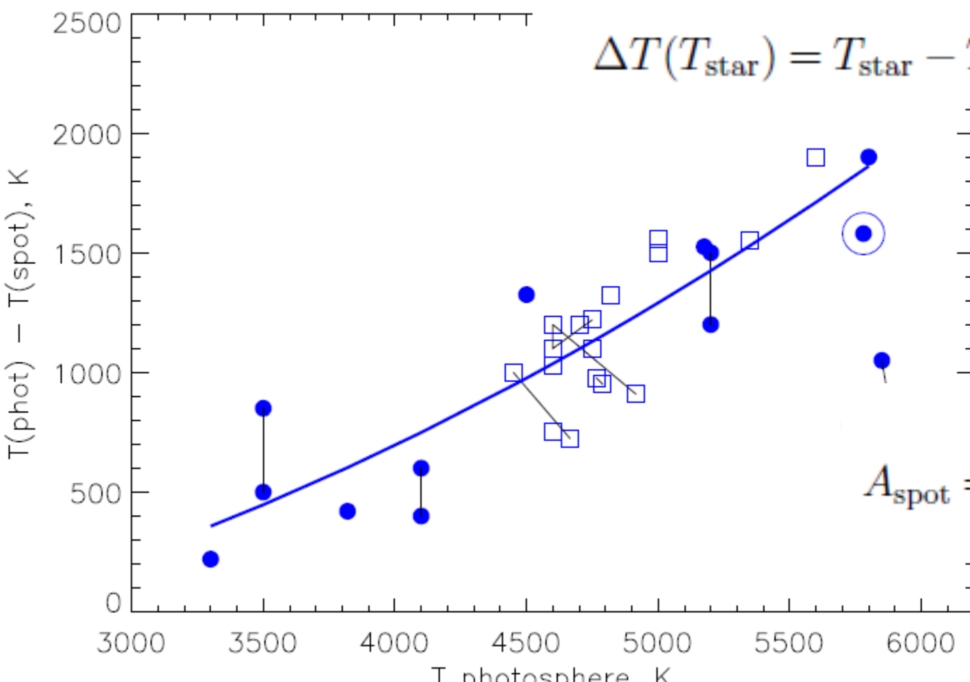
→ spot size

Notsu et al. (2015b)

As for spot coverage, Kepler results are consistent with spectroscopic results.

Estimation of starspot size

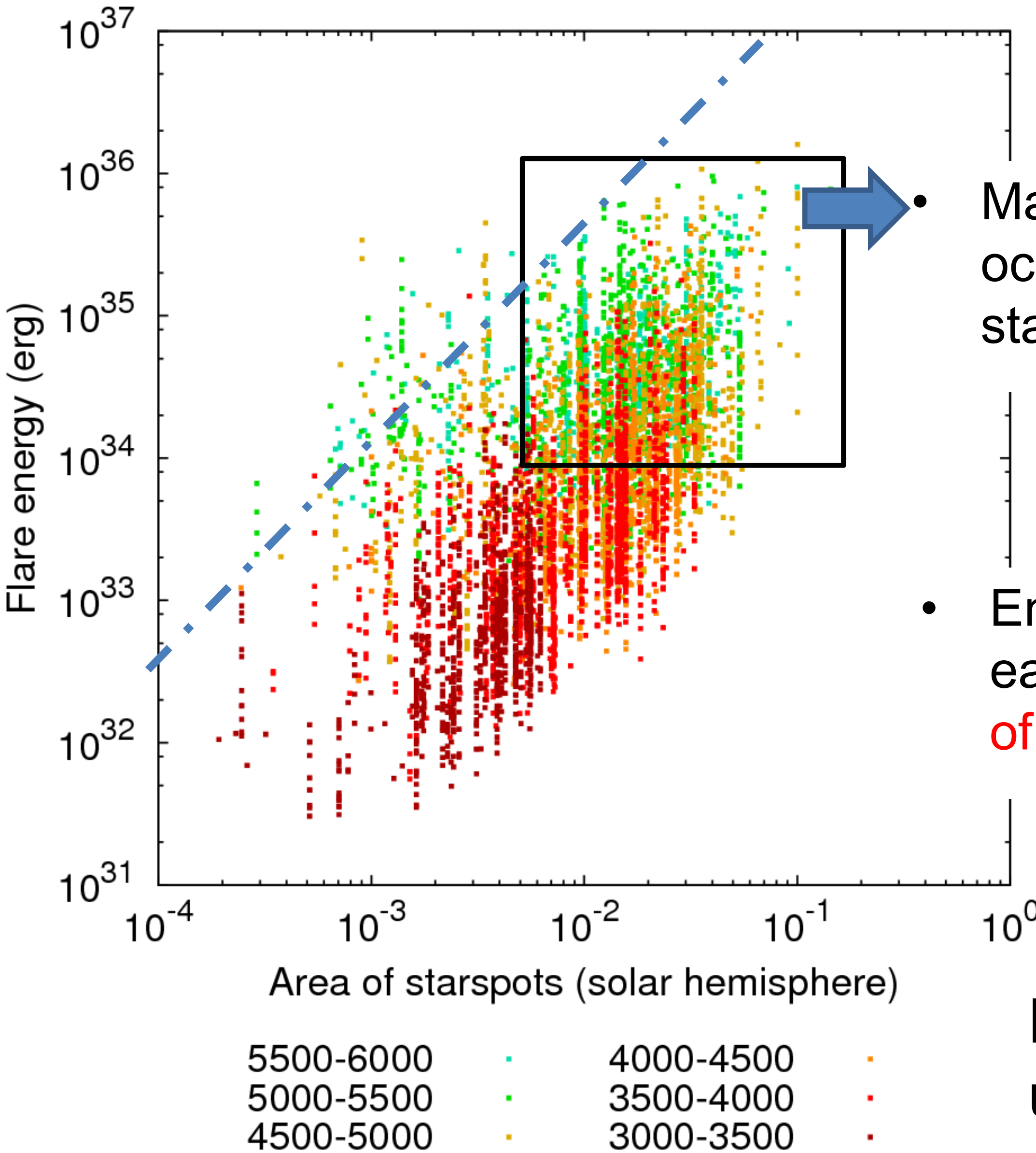
- We esitmate starspot coverage (A_{spot}) from brightness variation amplitude($\Delta F/F$) and the contrast between starspot and photosphere (temperature difference)
  - Brightness variation depends on Temperature and radius: Revised Keper Input Catalog (Huber et al. 2014)
  - Contrast of photosphere and spot: Berdyugina et al. (2005) from Doppler Imaging observations



$$\Delta T(T_{\rm star}) = T_{\rm star} - T_{\rm spot} = 3.58 \times 10^{-5} T_{\rm star}^2 + 0.249 T_{\rm star} - 808,$$

$$A_{\rm spot} = \left(\frac{R_{\rm star}}{R_\odot}\right)^2 \frac{T_{\rm star}^4}{T_{\rm star}^4 - \{T_{\rm star} - \Delta T(T_{\rm star})\}^4} \frac{\Delta F}{F},$$

Flare energy vs. spot area



- Majority of energetic superflares occurred on the stars with large starspots.

- Energy of the largest flares on each star depends on the area of starspots.

How can we explain this upper limit relation?

Flare energy vs. area of starspots

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

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

Shibata et al. (2013)

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

- Energy of the largest flare is also proportional to $A_{spot}^{3/2}$

Flare energy vs. spot area

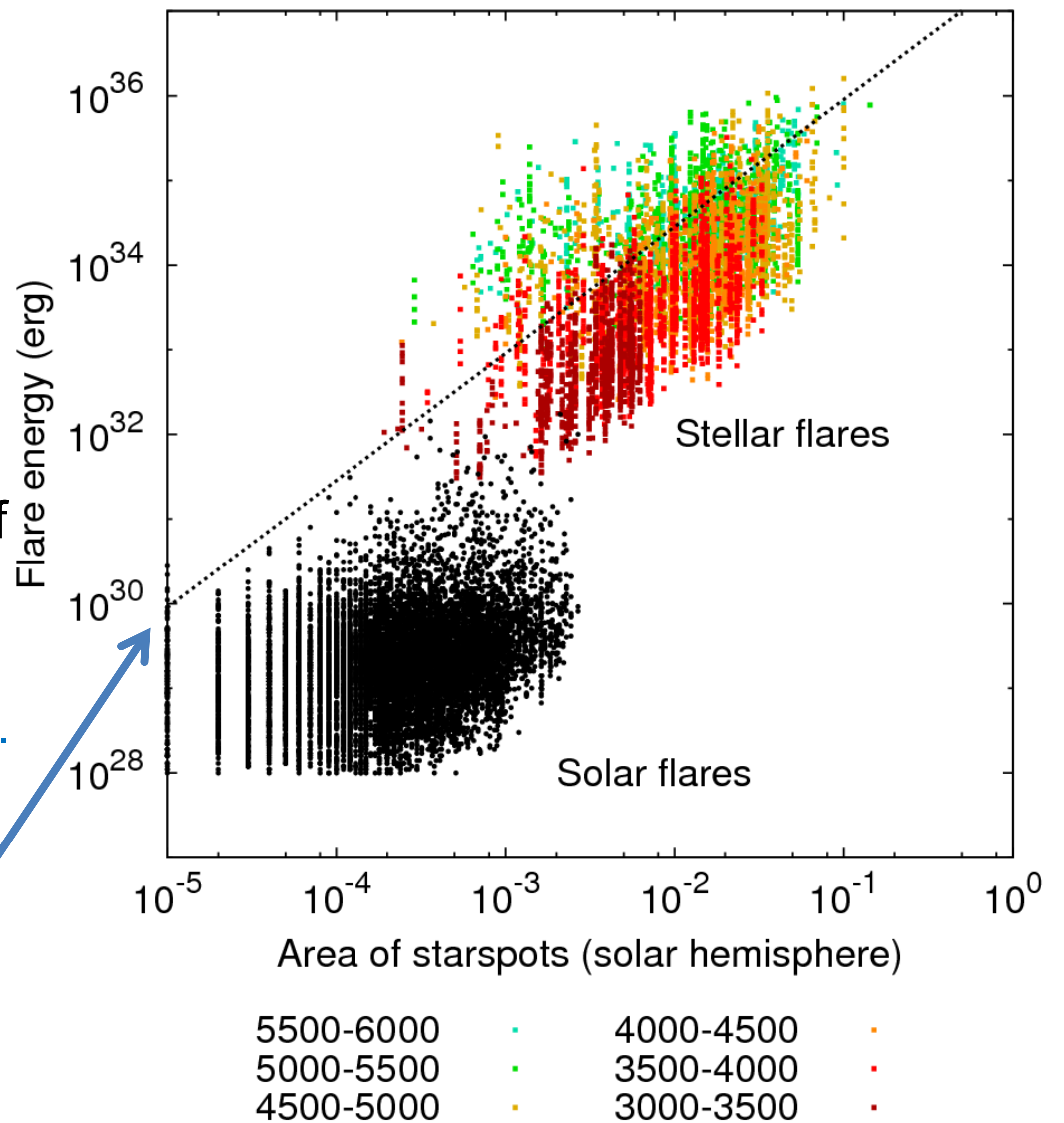
- Flare energy is consistent with the magnetic energy stored around the starspots.

->Large starspots are necessary.

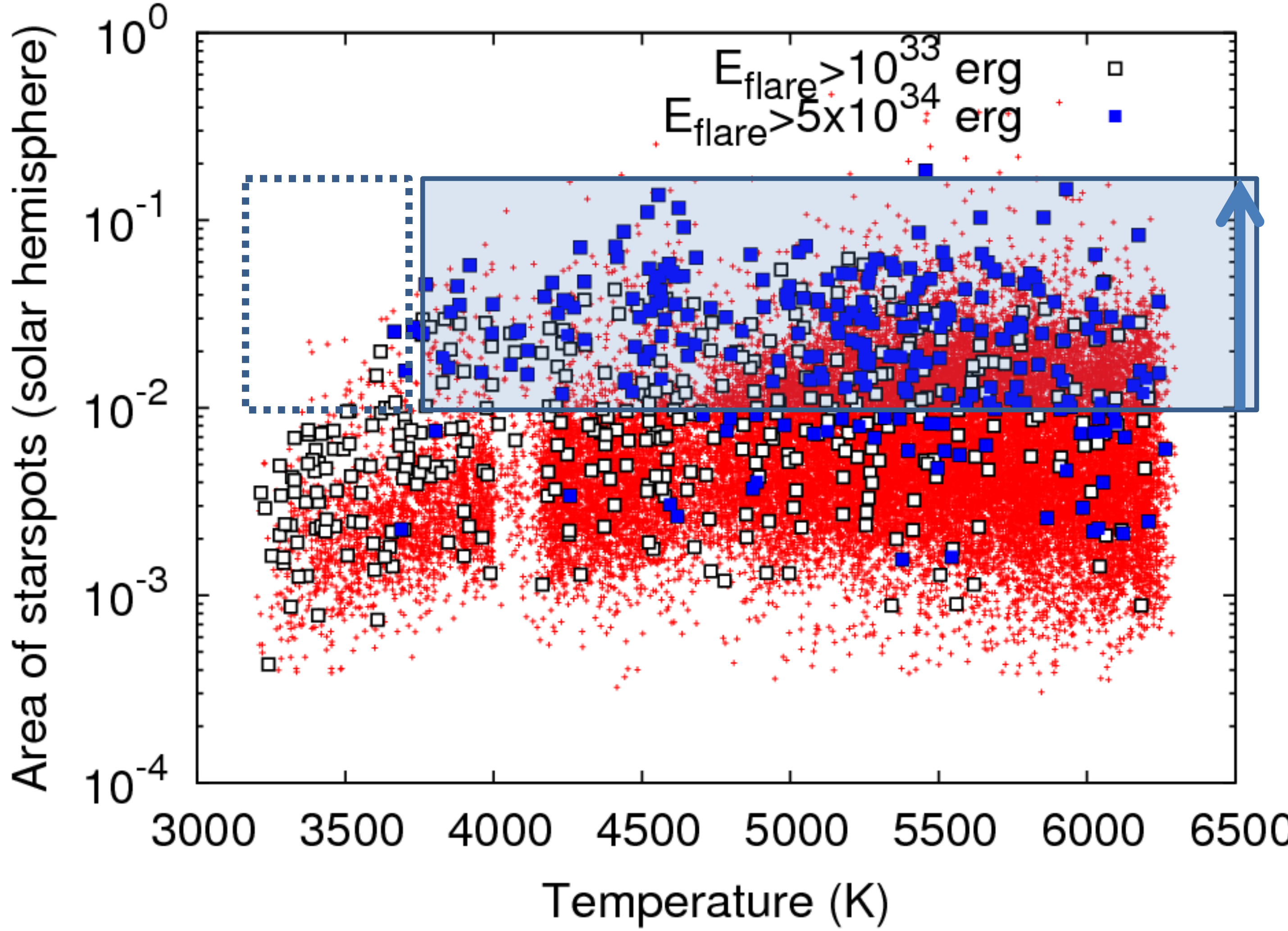
- Late M-dwarfs (T<3500K) have smaller starspots. ->Maximum of flare energy is small.
  - Stellar radius is small compared with G&K- dwarfs.

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

f=0.1, B=3000G



Spot area vs. temperature

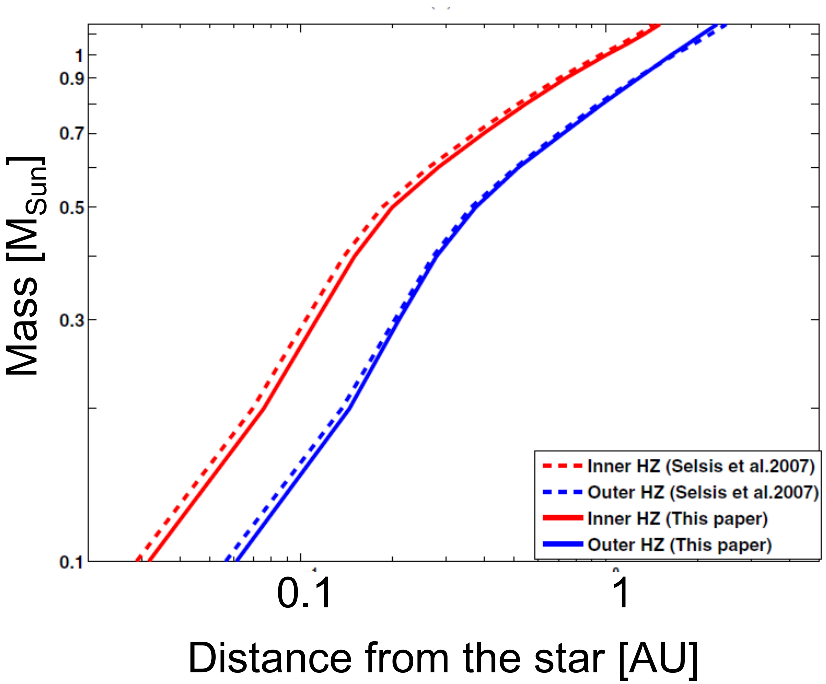


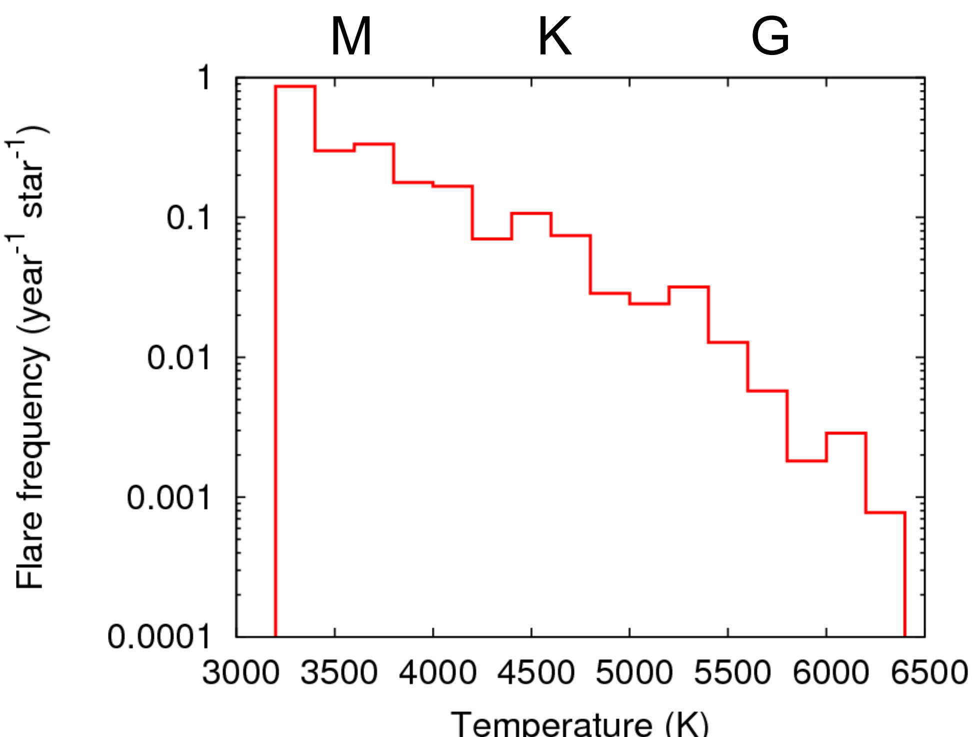
Most of the superflares occur on stars having starspots with >1% solar hemisphere.

Maximum sizes of starspots are small on M-dwarfs compared with G&K-dwarfs since stellar radius of M-dwarfs is smaller.

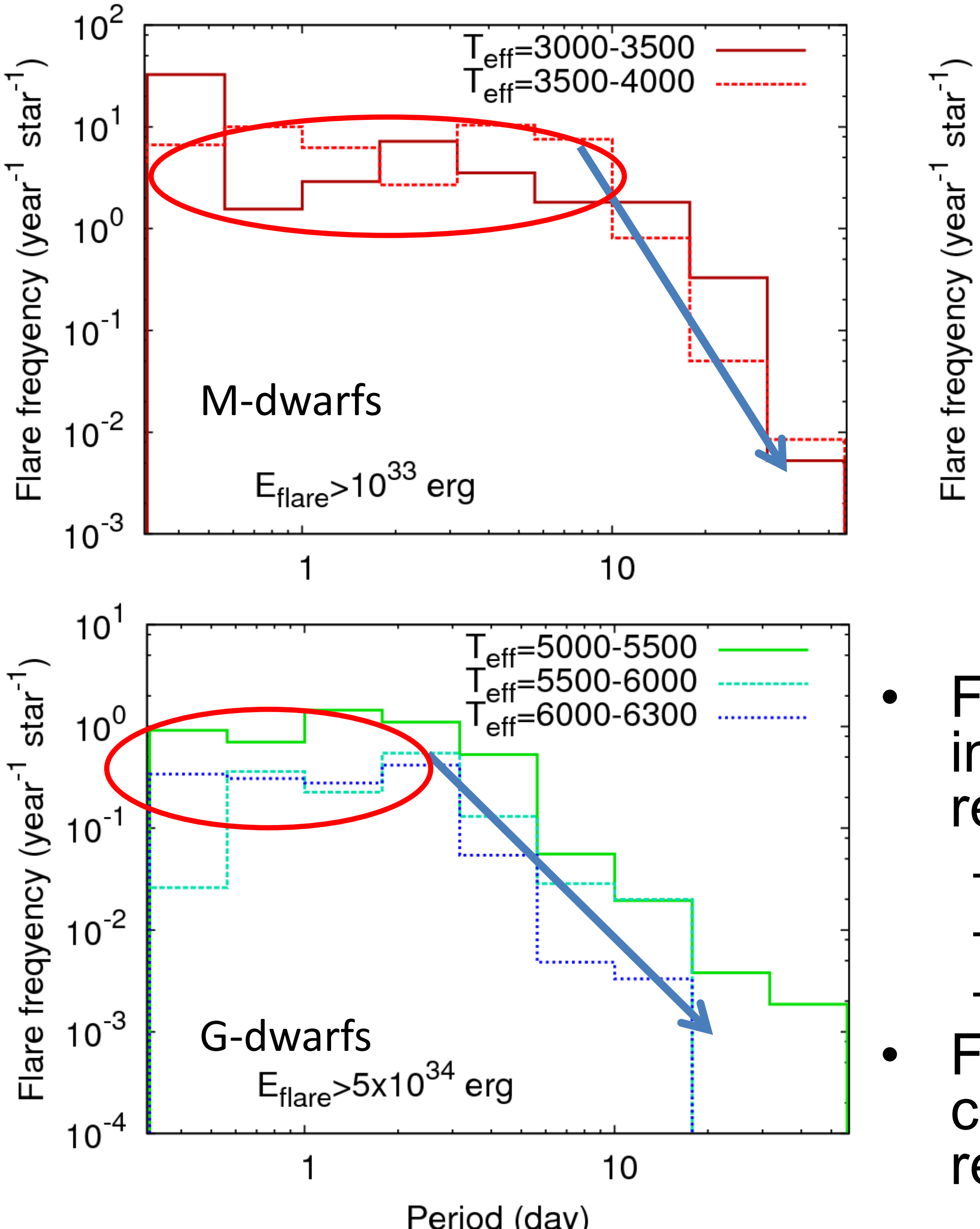
Flare frequency vs. temperature

- HZ distance depends on the T_{eff}
  - Flare flux at HZ depends on E_{flare} and T_{eff}
  - Smaller superflares can affect the planets in the HZ around M dwarfs.
- Frequency of flares comparable to the flare flux of >5×10[34] erg superflare at 1 A.U. (right figure)
  - M dwarfs exhibit more frequent "hazardous" flares for planets in HZ.





Flare frequency vs. rotation period



- Frequency decrease as P_{rot} increases in the long-period regime.
  - M: P>~10 days
  - K: P>~5 days
  - G: P>~3 days
- Flare frequency is roughly constant in the short-period regime.

Summary

- Frequency of superflares on G,K,M-dwarfs from Kepler data.
  - power-law distribution
  - Frequency vs. Temperature
    - Flare frequency decreases as T_{eff} increases (T>4000K)
  - Frequency vs. rotation
    - Flare frequency decreases as rotation period increases (P>3-10 days).

- Flare energy
  - Maximum flare energy depends on the area of starspots.
  - $E>10^{34}$ erg superflares require $A_{spot}>10^{-2}\ A_{1/2sun}$
- M-dwarfs
  - Maximum flare energy of M-dwarfs is smaller than those of G&K-dwarfs (<- stellar radius of M-dwarfs is smaller).
  - However, more frequent "hazardous" flares for the habitable planets.

Future: comparing with the observations of stellar CMEs ??

Long-term activity cycle ?? / Differential rotation ??