Starspots on late-type stars and their correlation with flare activity

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1.Stellar flares detected by Kepler

Kepler space telescope found thousands of “superflares” on G-, K-, and M-type stars.

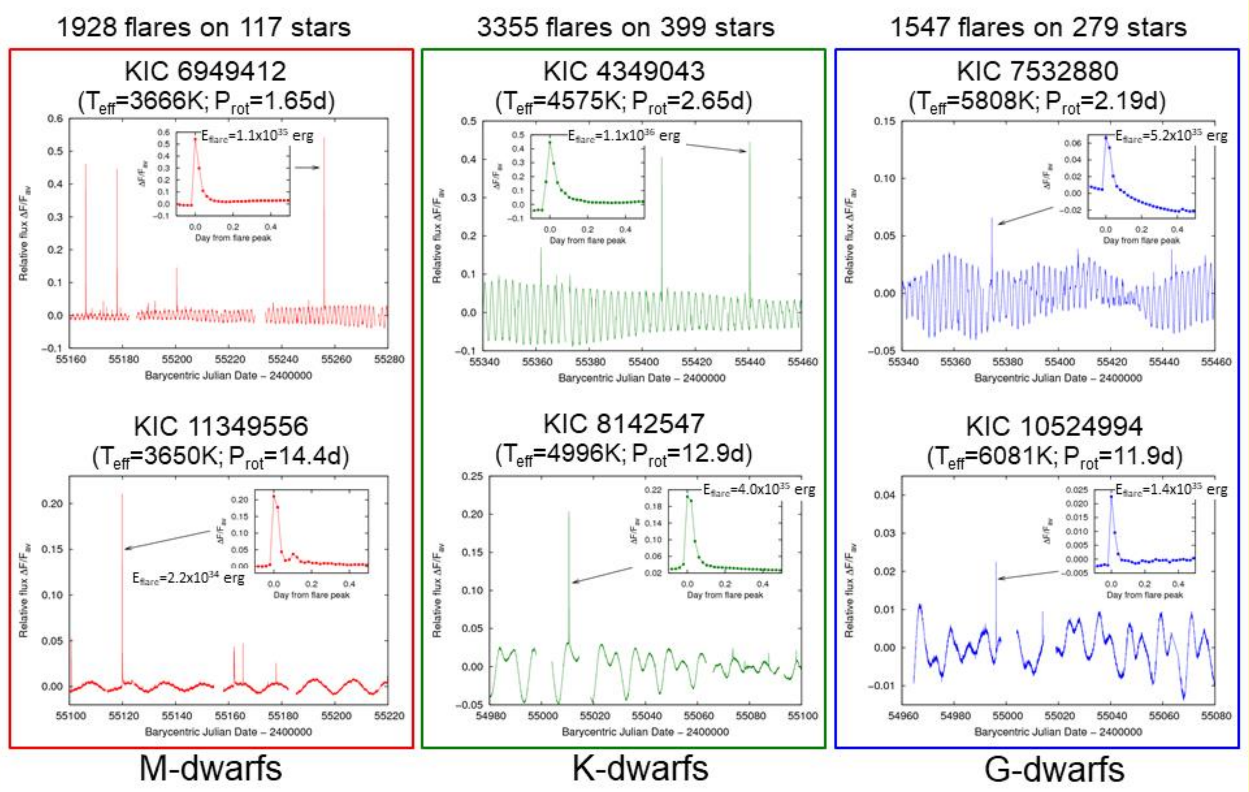

Fig. 1: Light curves of superflares on G-, K-, and M-type stars.

- The typical duration of detected flares is ~0.1 days.
- The amplitude of the largest flares depends on the effective temperature of stars.
  - M dwarfs: >100%
  - K dwarfs: ~50%
  - G dwarfs: <10 %
- The bolometric energy released by flares ranges from 10^{32} to 10^{36} erg.

2. Starspots on superflare stars

Most of stars exhibiting superflares show quasi-periodic light variations (fig. 1).

- Period: 0.5—30 days
- Amplitude: 0.1—20%

※Amplitude and light curve shape of quasi-periodic light variations change with time.

These brightness variations are thought to be caused by the rotation of stars with large starspots.

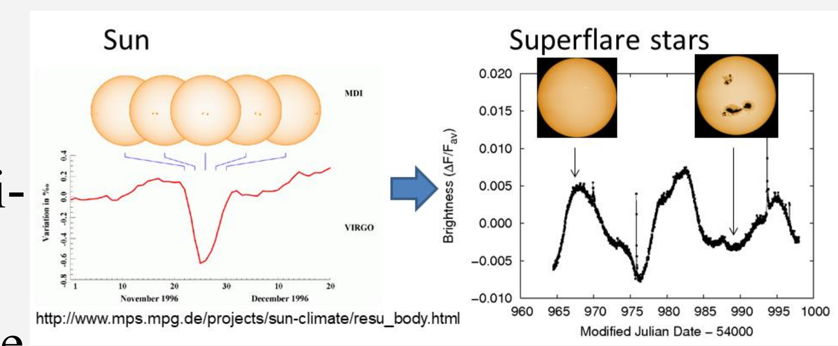

Fig. 2: Light curves of the Sun and superflare star

We estimated the area of starspots (S_{spot}) from the amplitude of the periodic brightness modulations ($\Delta F/F$) by using the following equation.

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

*ΔT : temperature difference between photosphere and spots

$$\Delta T(T_{\rm star}) = T_{\rm star} - T_{\rm spot} = 3.58\times10^{-5} T^2_{\rm star} + 0.249 T_{\rm star} - 808,$$

(from Berdyugina 2005)

3. Superflares and temperature of stars

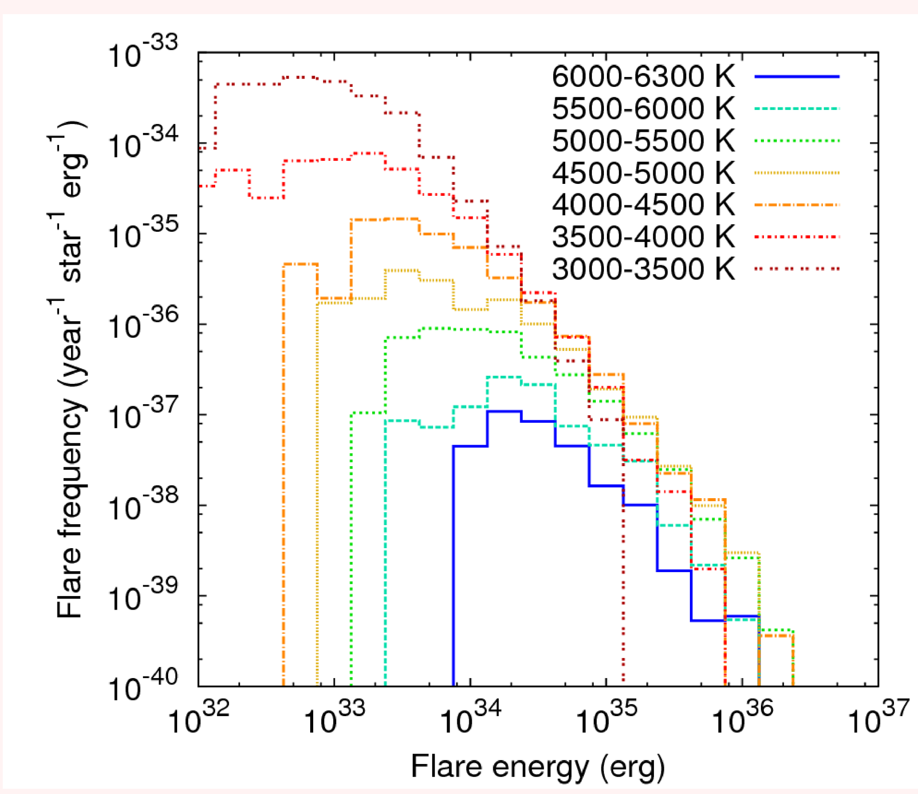

Fig. 3: Frequency distributions of superflares as a function of flare energy

- Flare frequency distributions on the stars with different temperatures can be represented by the power-law functions with the similar power-law index (-2.0—-1.8).
- K– and M-dwarfs exhibit more frequent superflares than G-dwarfs.
- Bolometric energy of the largest superflares on M-dwarfs is smaller than K- and G-dwarfs.
- Frequency of “hazardous” superflares for exoplanets in H.Z. increases as T_{eff} decreases.

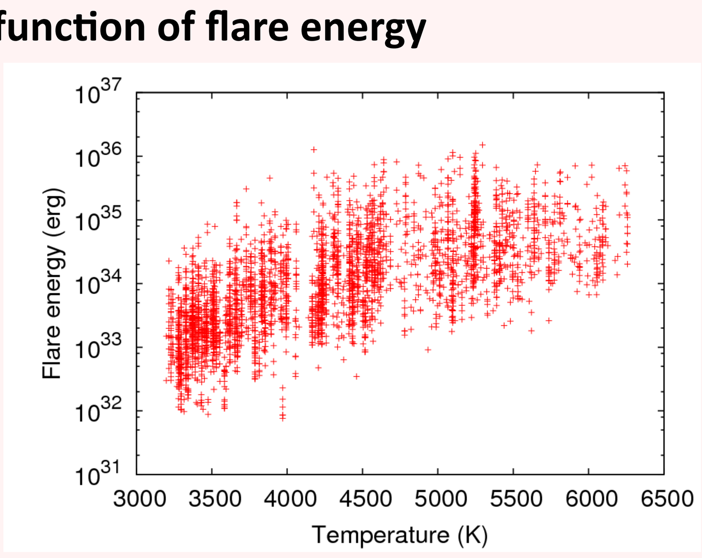

Fig. 4: Scatter plot of the bolometric energy of flares as a function of the effective temperature

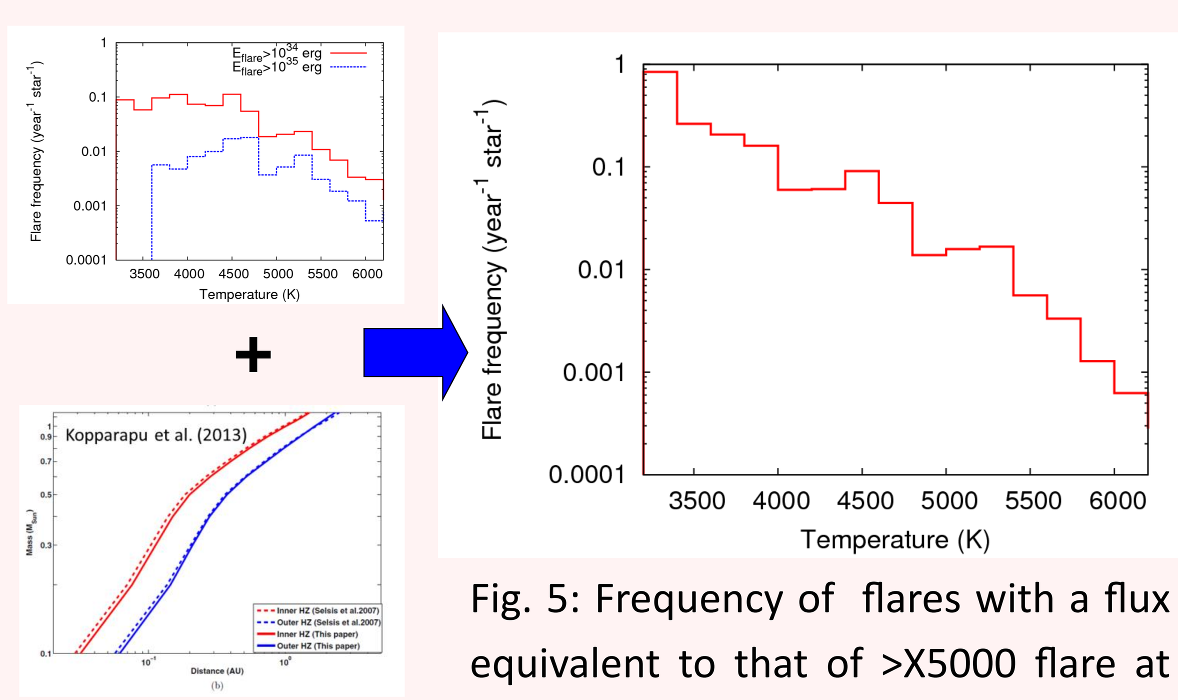

Fig. 5: Frequency of flares with a flux equivalent to that of >X5000 flare at habitable zone

4. Superflares and area of starspots

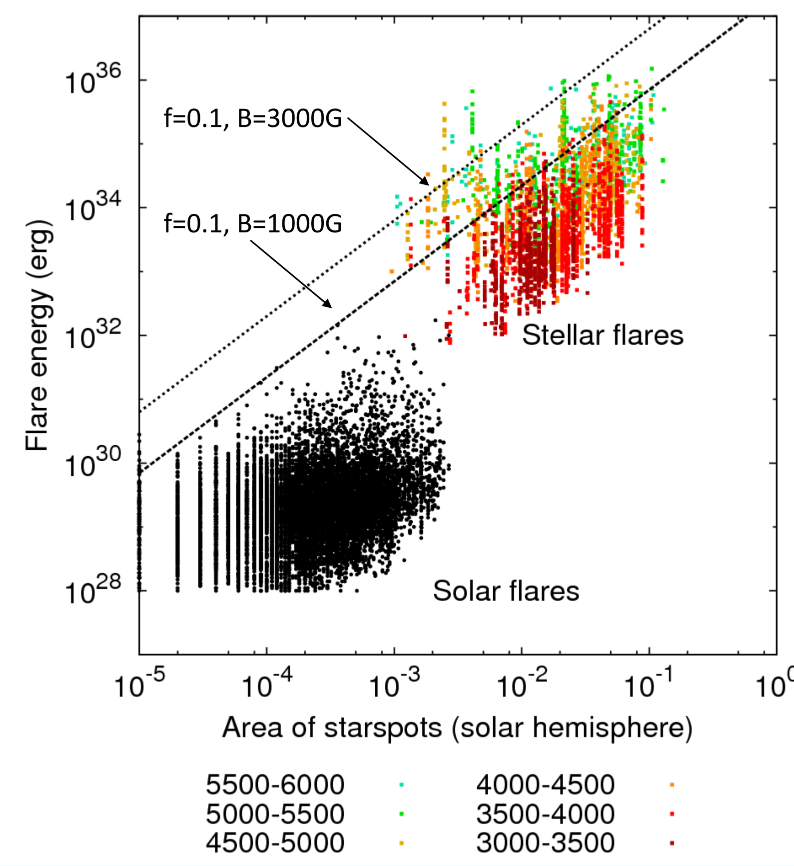

Fig. 6: Scatter plot of flare energy as a function of the area of starspots/sunspots

- Bolometric energy of the largest flares depends on the area of starspots (Fig. 6).
  - Flare energy is consistent with the magnetic energy stored around starspots. $E_{\rm flare} \approx f E_{\rm mag} \approx f\frac{B^2 L^3}{8\pi} \approx f\frac{B^2}{8\pi} A^{3/2}_{\rm spot}$
- Frequency distributions of superflares originating from stars with different spot sizes shows power-law distribution with the similar power-law index (Fig. 7).
- Frequency distributions of superflares originating from stars with the same spot size but different temperature are roughly the same power-law distribution (Fig. 8).

→ Flare activity level depends on spot size

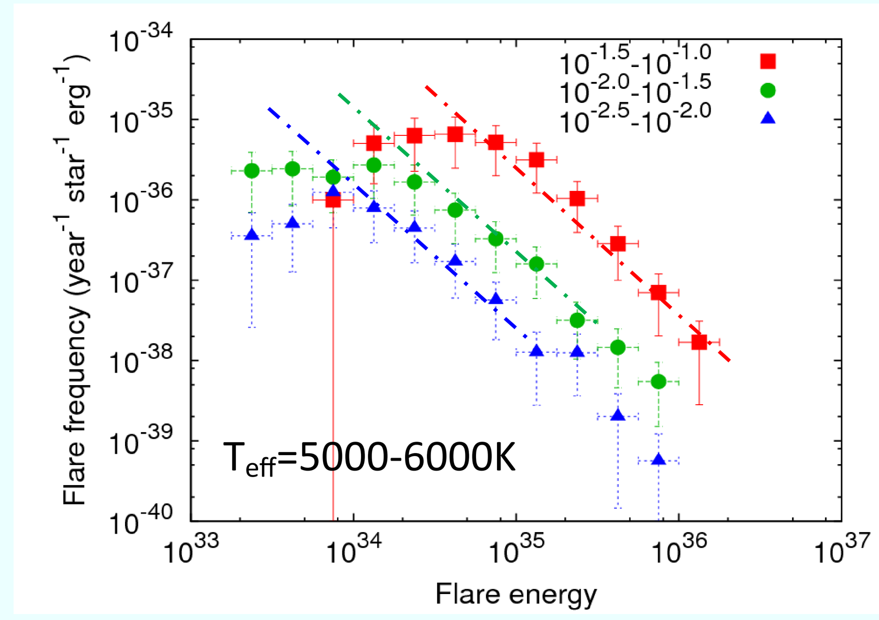

Fig. 7: Frequency distribution of superflares originating from stars with different spot sizes.

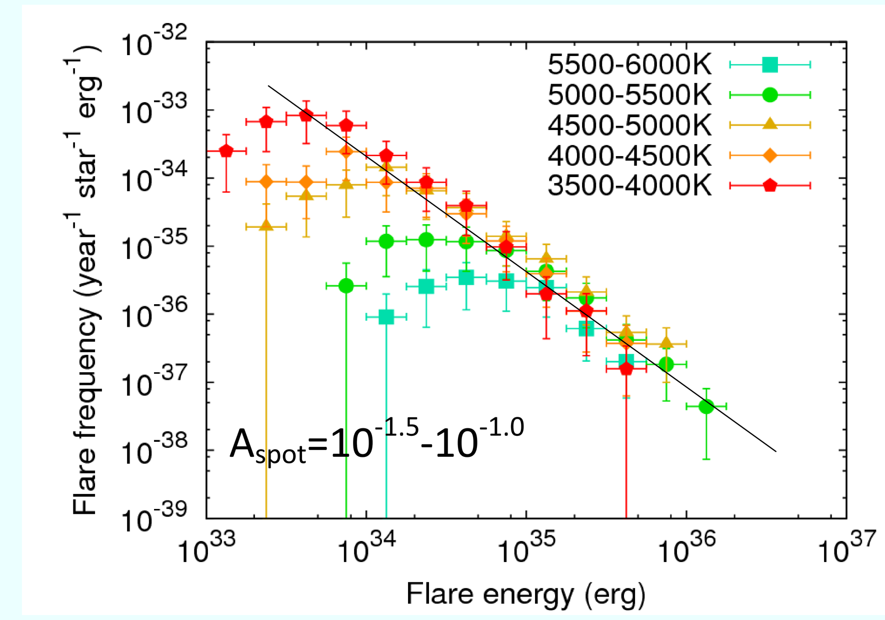

Fig. 8: Frequency distribution of superflares originating from stars with the same spot size but different temperature.

5. Superflares and Rossby number

- **Flare frequency**
  - Ro<~0.3: constant
  - Ro>~0.3: decreases as Ro increases

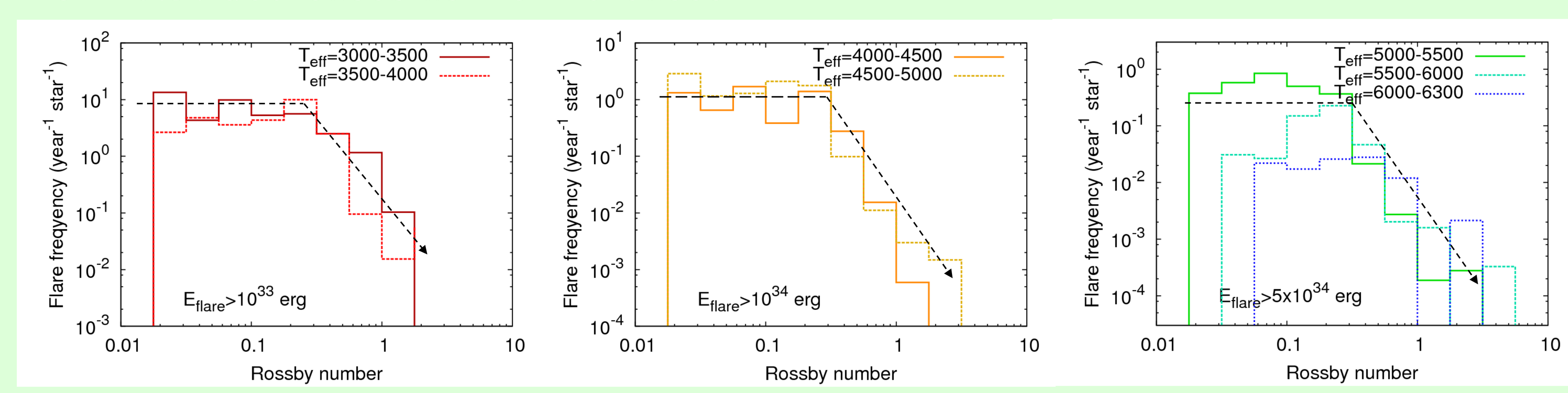

Fig. 9: Flare frequency as a function of Rossby number

- **Bolometric energy of the largest flares**
  - Ro<~0.2-0.3 No clear dependence on Rossby number
  - Ro>0.5: $E_{flare;\,max}$ decreases as Ro increases

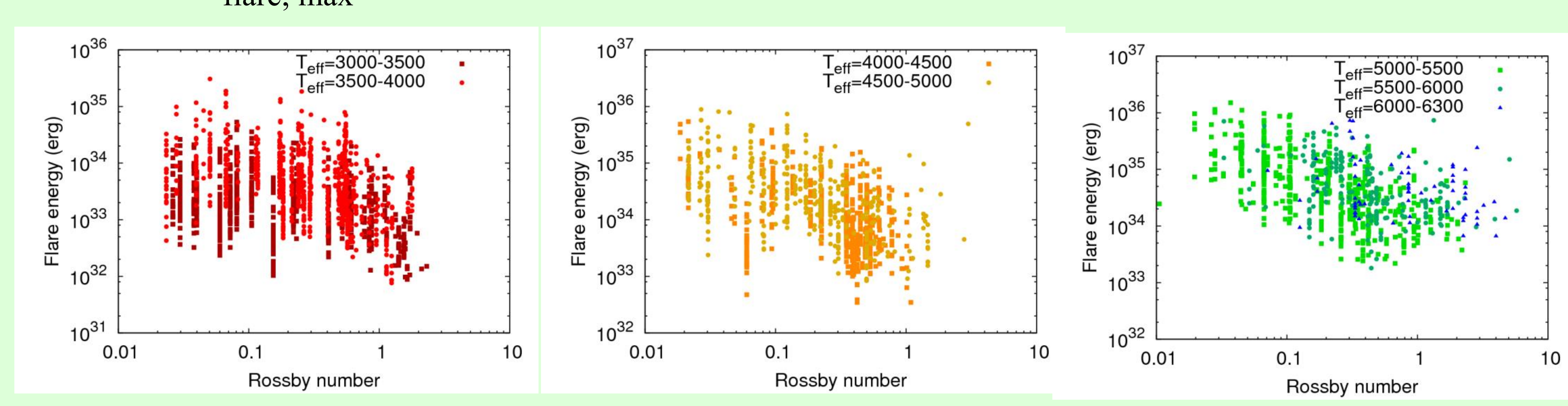

Fig. 10: Scatter plot of flare energy as a function of Rossby number

- Area of the largest starspots depend on Rossby number

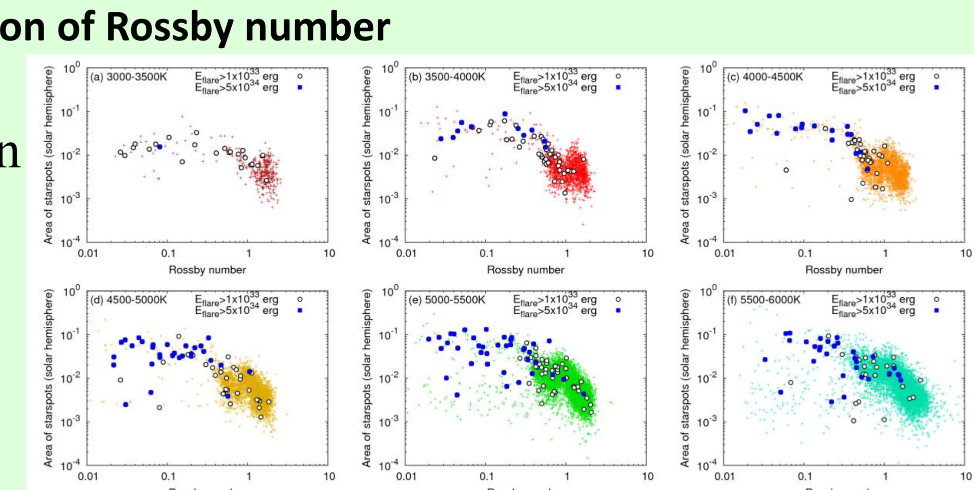

Fig. 11: Scatter plot of the area of starspots as a function of Rossby number