2nd LAMOST-Kepler workshop
2017 August 1st (Tue)
16:30 - 17:00 (23+7min)

Active stars in the Kepler field of view

Yuta Notsu

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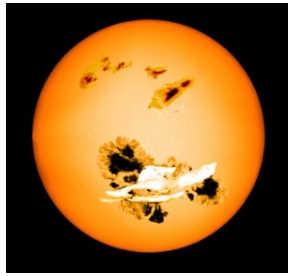
S. Notsu, K. Namekata, K. Ikuta, D. Nogami, K. Shibata (Kyoto Univ., Japan)
(+ S. Hawley (Univ. of Washington, USA))

Reference:

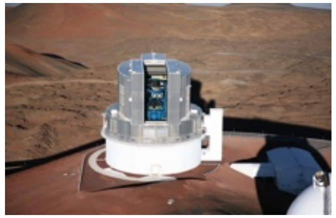
Maehara et al. 2012, Nature, 485, 478
Shibayama et al. 2013, ApJS, 209, 5
Notsu et al. 2013, ApJ, 771, 127
Shibata et al. 2013, PASJ, 65, 49
Maehara et al. 2015, EPS, 67, 59
Notsu et al. 2015a&b, PASJ, 67, 32&33
Karoff et al. 2016, Nature Communications, 7, 11058
Maehara et al. 2017, PASJ, 69, 41
Notsu et al. in prep

Topics

[1.1] Superflares found from Kepler data



[1.2] Superflare studies with our high dispersion spectroscopic observations (Subaru 8.2m & APO 3.5m)



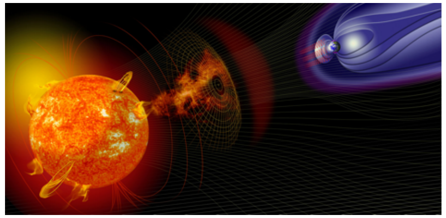
[2] Superflare studies with LAMOST-Kepler Survey data

(Summary of Karoff et al. 2016

and introduction of collaborative studies

we are NOW working on)

Solar flares



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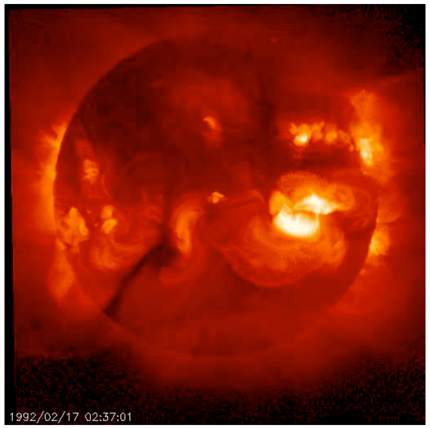
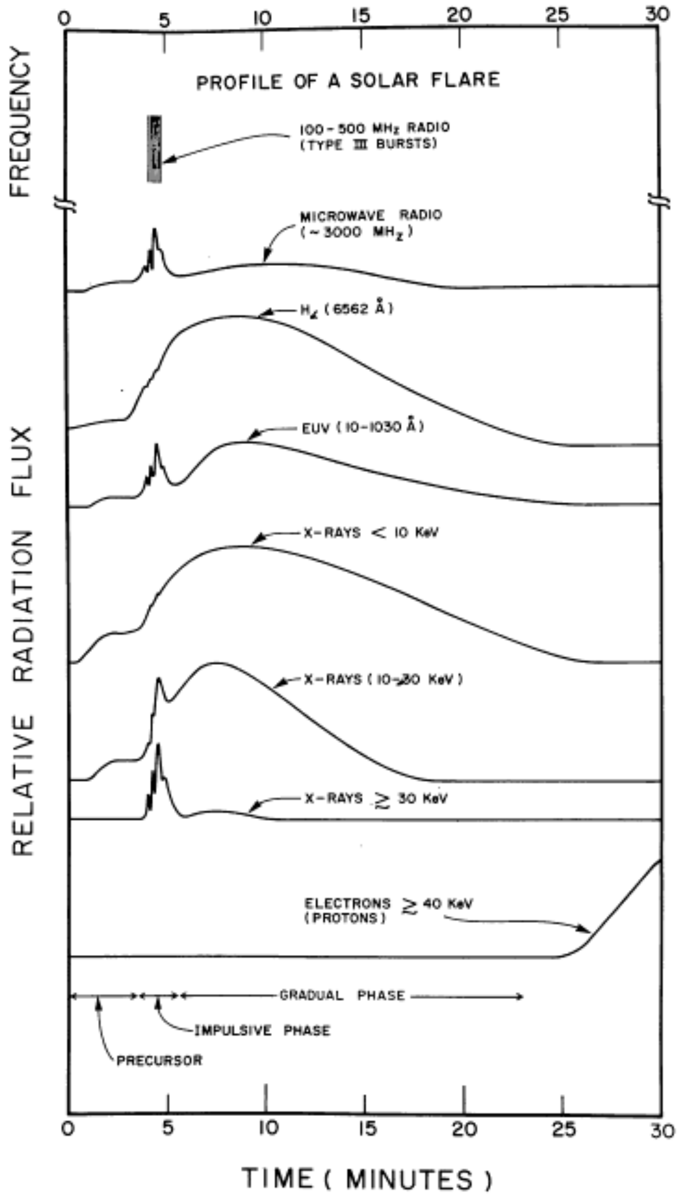
- Large eruptive events in the solar atmosphere
  - Magnetic energy release by reconnection
- Observed in all wavelengths
  - Radio ~ X-ray
- Timescale: 1 min – 1 hour
- Total energy: 10^{29} – 10^{32} erg



← Yohkoh (JAXA/ISAS)
Soft X-ray



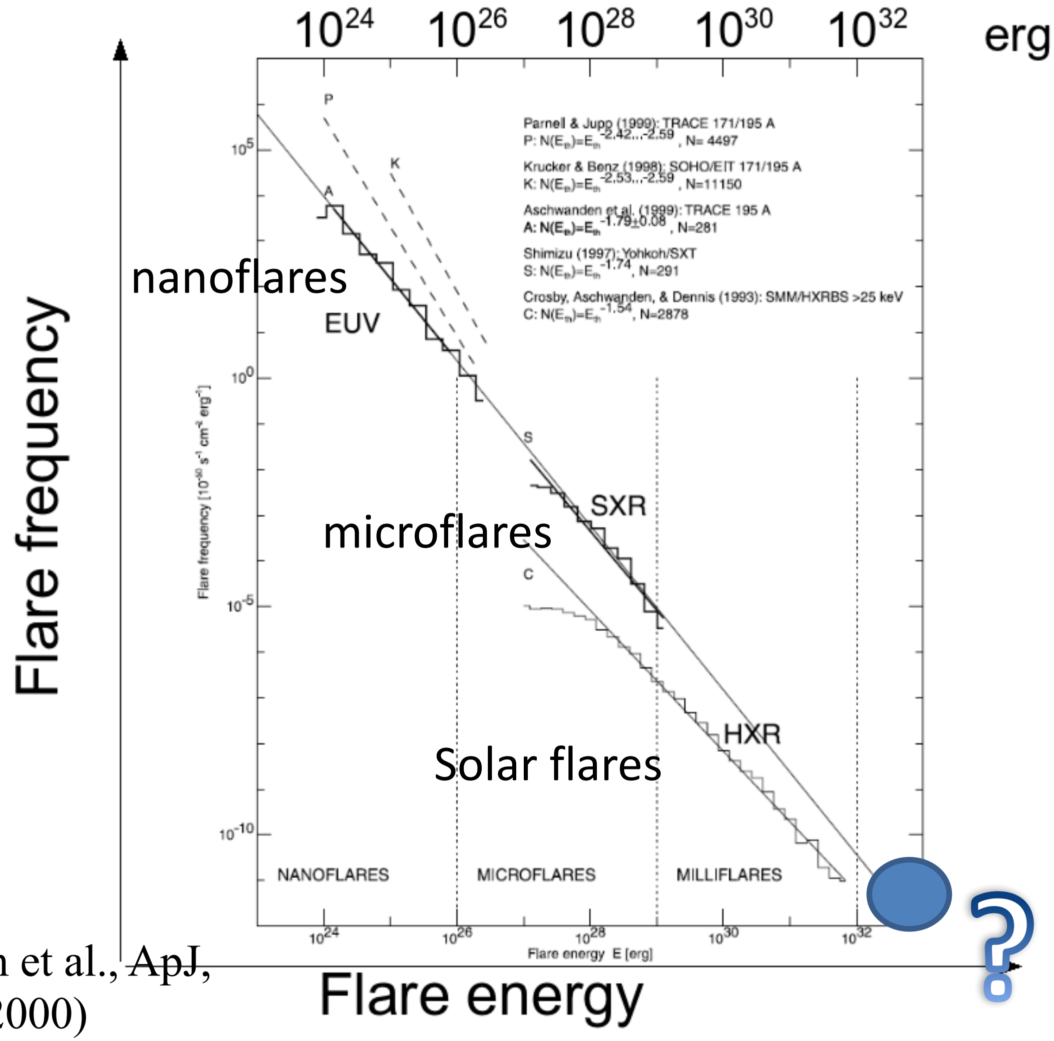
Kane (1974)

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?



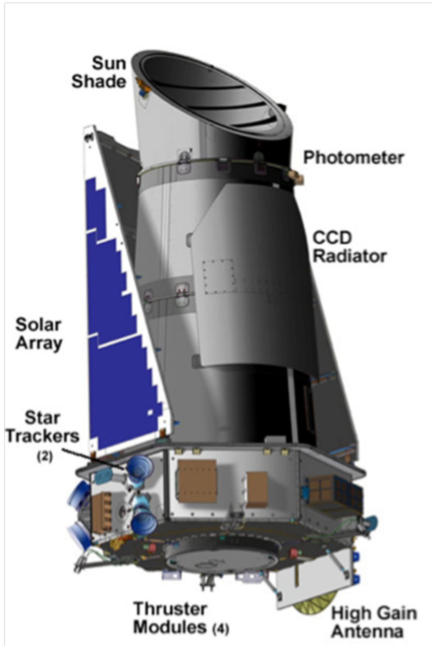
Aschwanden et al., ApJ, 535, 1047 (2000)

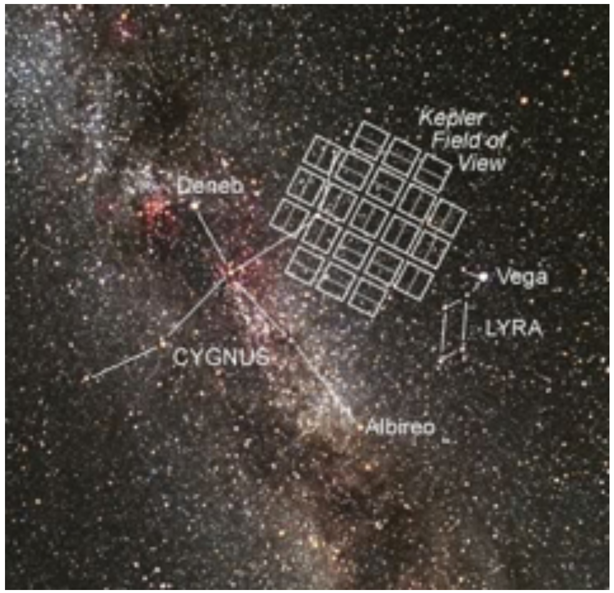
Kepler space telescope

- 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.

[solar-type (G-type main sequence) stars]
Long (30-min) cadence data
~90,000 stars
Short (1-min) cadence data
~1,400 stars





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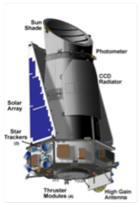
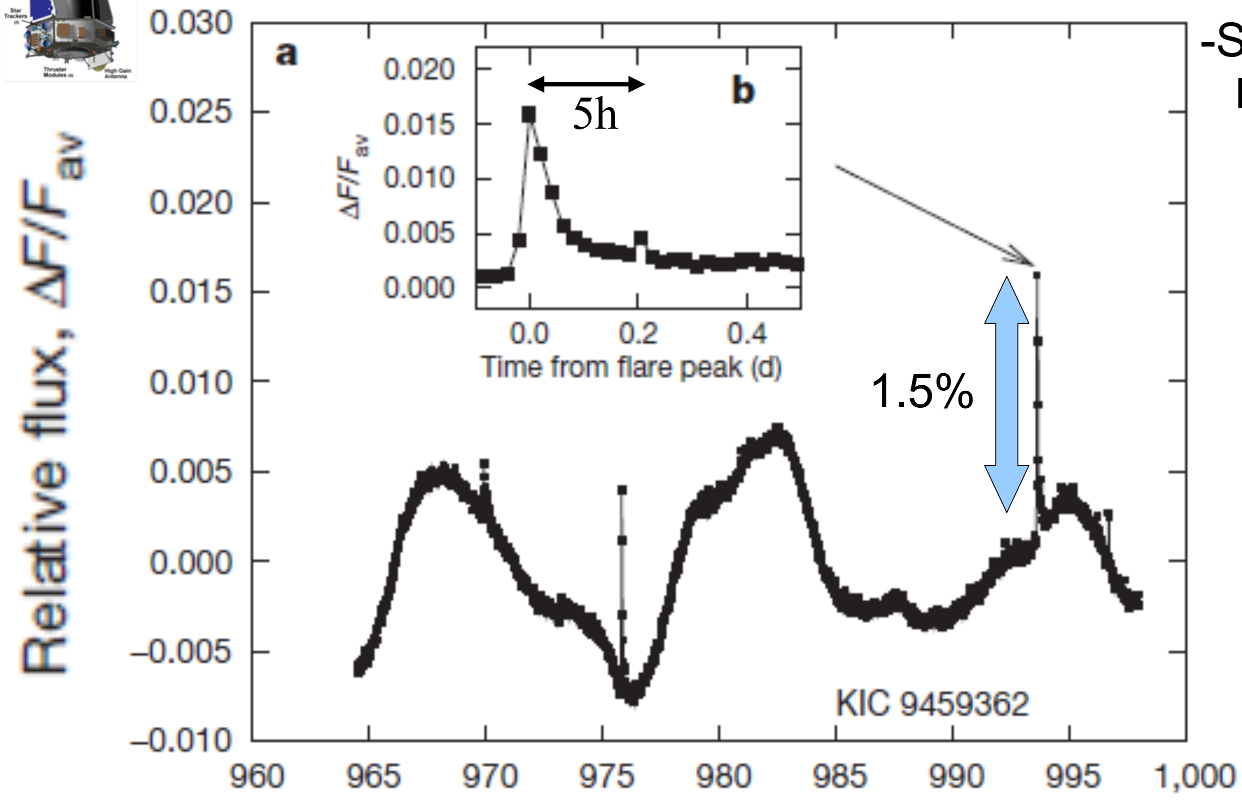
<u>Discoveries of superflares with *Kepler* data</u>

We discovered many (>1000) superflares ($10^{33} \sim 10^{36}$erg: $10 \sim 10^4$ times more energetic than the largest solar flares) on many (~300) solar-type (G-type main sequence) stars.



Lightcurve of superflare ↓



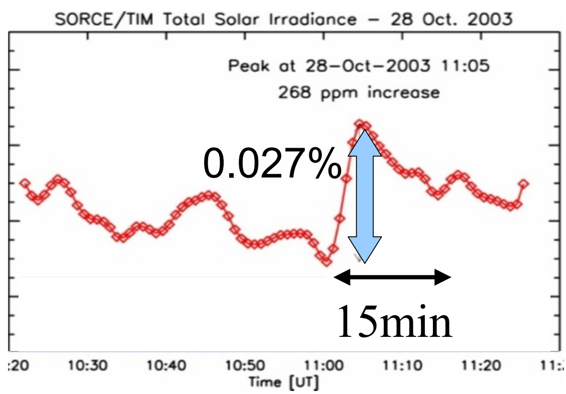
Maehara et al. (2012) BJD – 2,454,000

[Data]

-Long (30-min) cadence data
  Shibayama+2013 (~90,000 stars)
  ~500 days

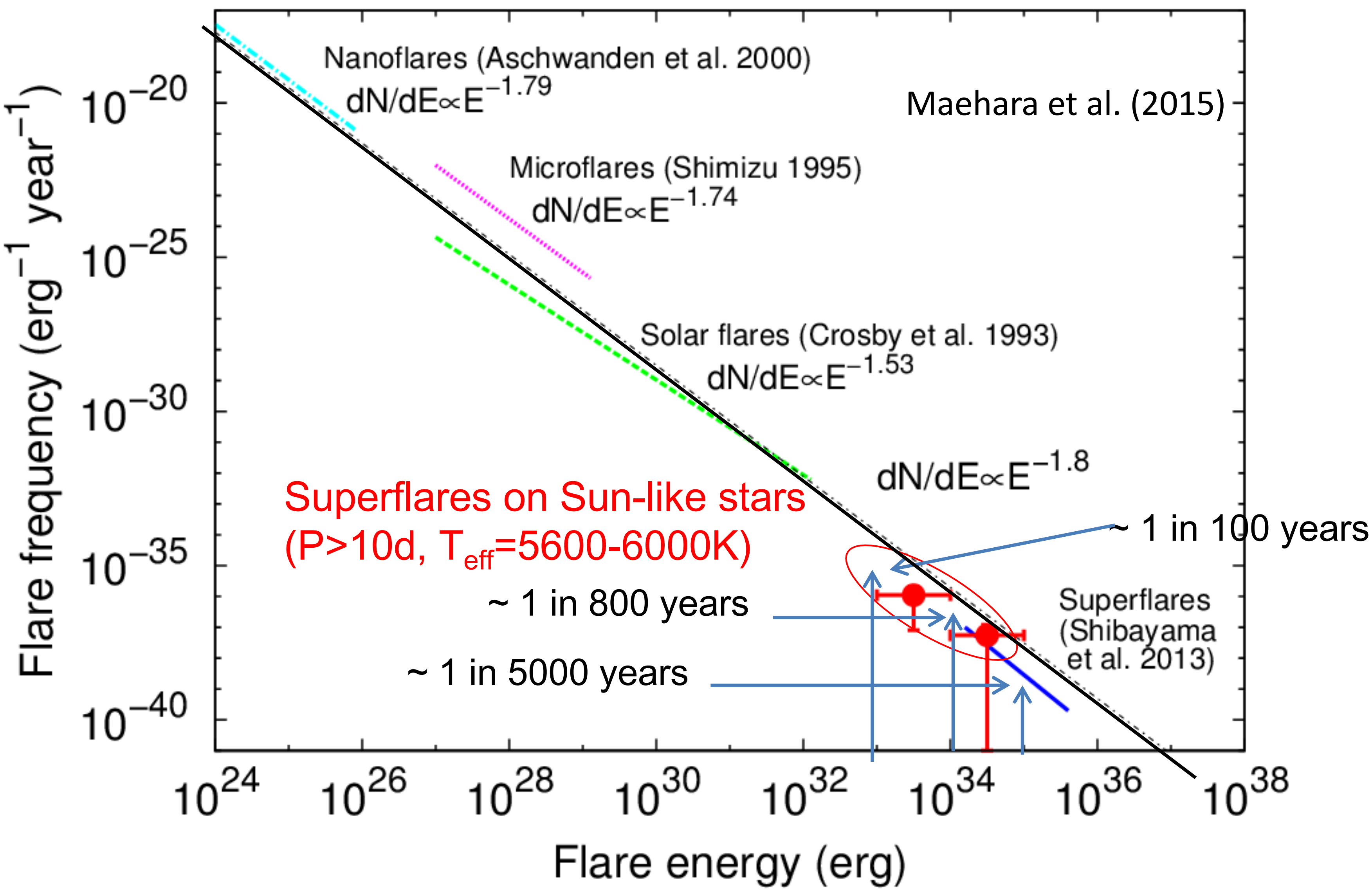
-Short (1-min) cadence data
  Maehara+2015 (~1,400 stars)
  ~all data

Cf. Example of large solar flares (Solar brightness variation)



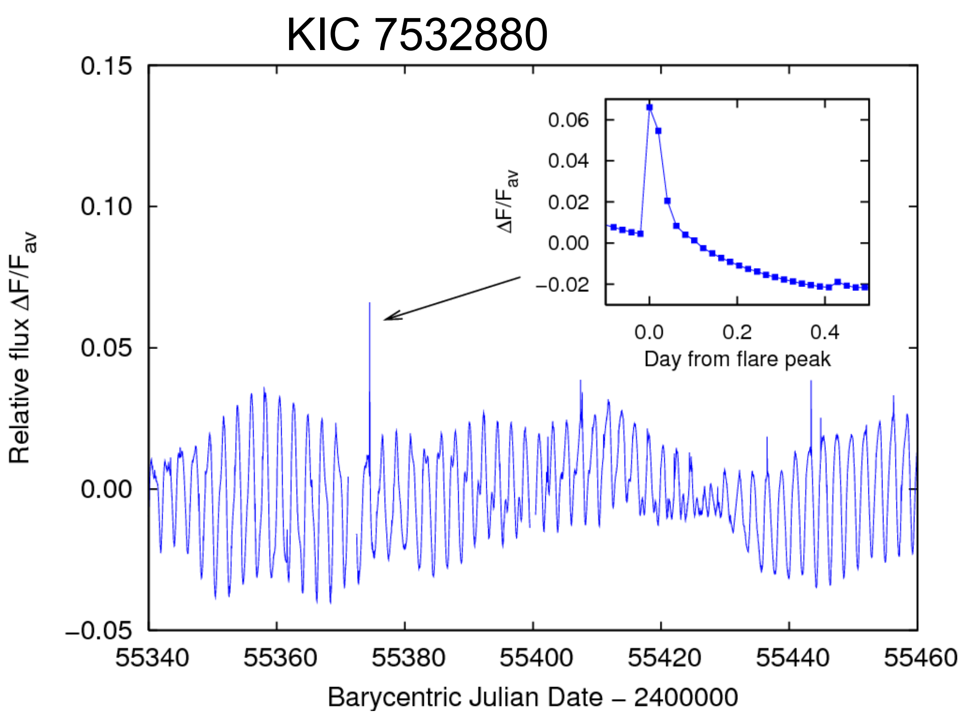
Kopp et al. (2005)

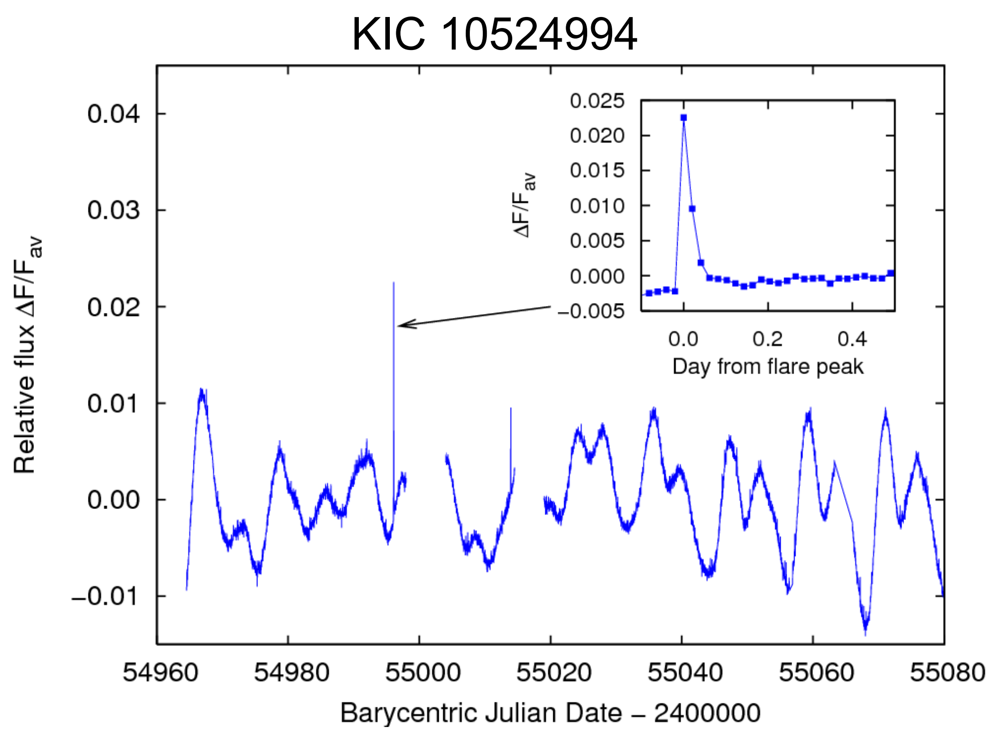
Flare frequency vs. flare energy



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.





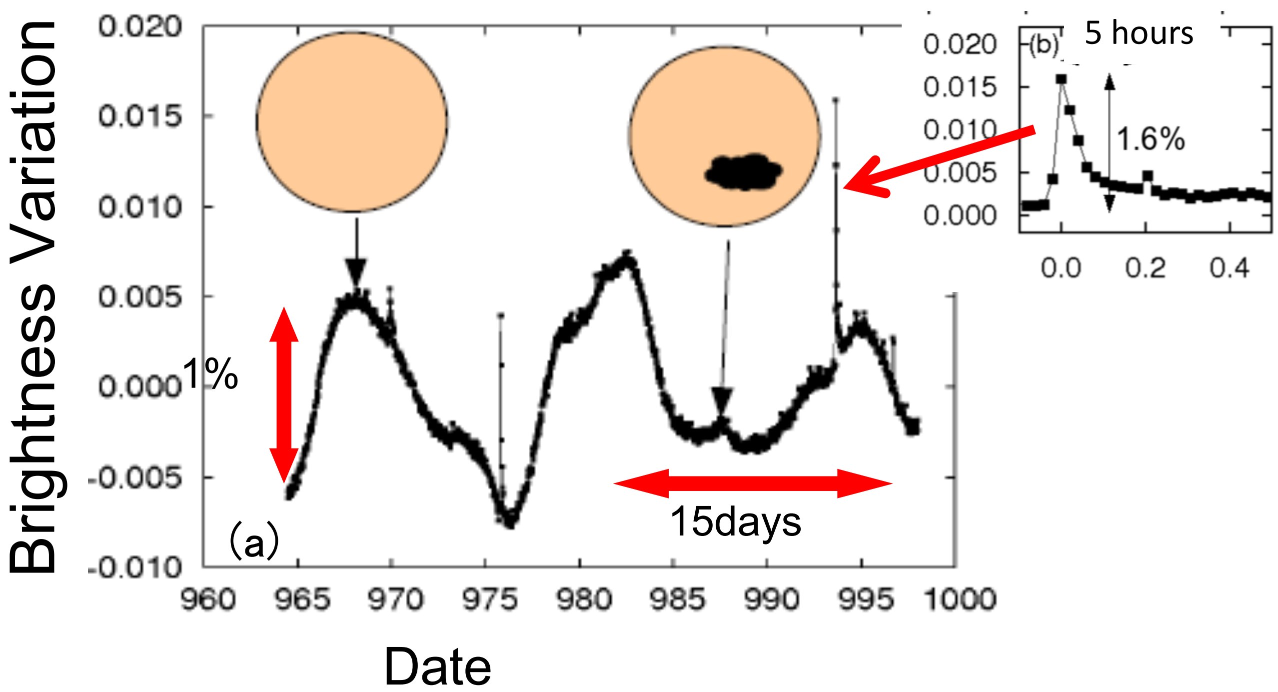
Can large starspots explain the brightness variation?

Many superflare stars show quasi-periodic brightness variations.

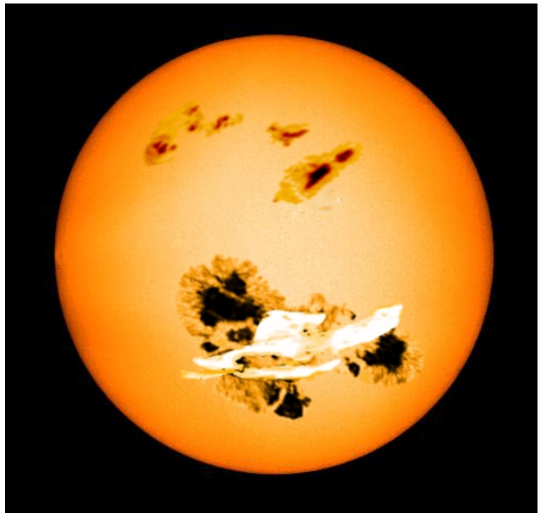
Rotation of a star with **large starspots**!?

Period of brightness variation → rotation period

Brightness Variation Amplitude → total area of starspots

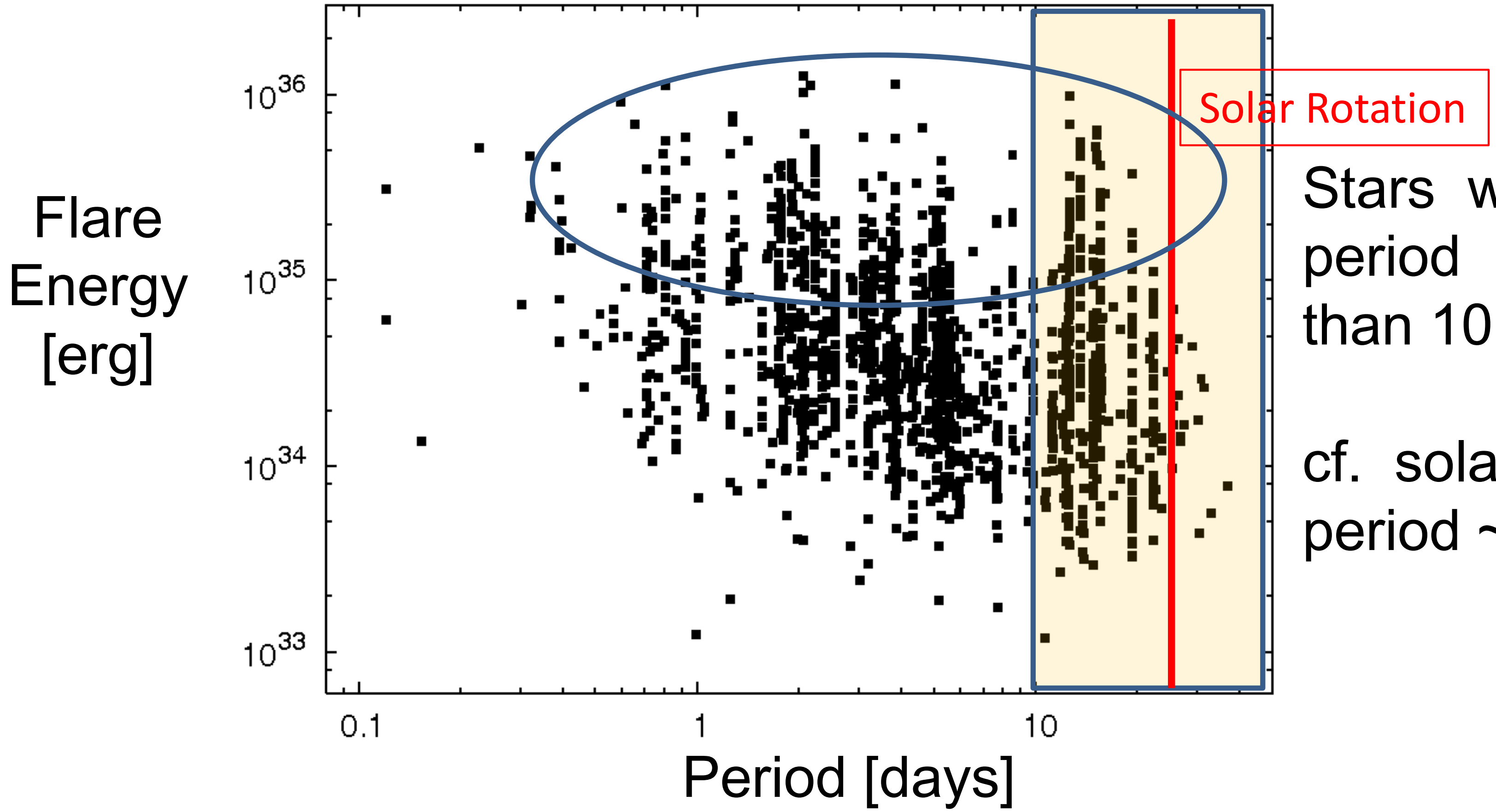


Notsu Y. et al. (2013)



Artificial Image of a superflare star

Flare energy vs. rotation period



Stars with period longer than 10 days

cf. solar rot period ~ 25days

- The energy of the largest flares observed in a given period bin does **not** have a clear correlation with the rotation period.
  - Superflares may occur on the slowly-rotating stars.
  - (In addition, flare frequency decrease as rotation period increases.)

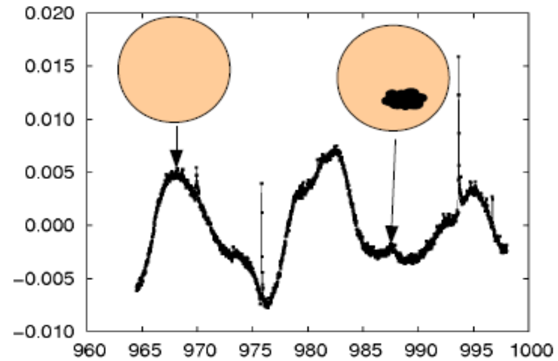
<Assumptions>

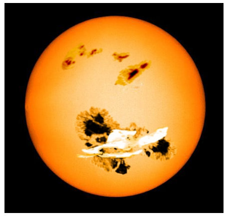
Period of brightness variation

→ rotation period

Brightness Variation Amplitude

→ total area of starspots





Are these assumptions right?

((We cannot reject the other effects (binary etc.)
only with Kepler photometric data.))

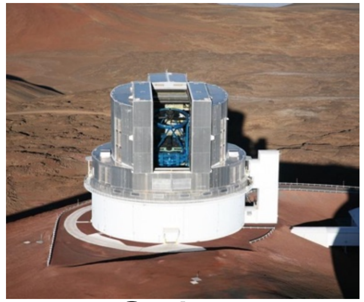
Spectroscopic observations !!

Spectroscopic observations with Subaru and APO 3.5m

○**Subaru/HDS** (during 2011-2013, Notsu+2015a&b PASJ):

50 superflare stars (from 30min cadence data)

R=λ/Δλ=50,000 ~ 100,000 & λ=6100~8800A (Ca II IRT, Ha)



Subaru
(at Hawaii)

○**Apache Point Observatory (APO)**

3.5m telescope (2016~, Notsu+ in prep)

15(+3 also in Subaru) superflare stars (from 1min cadence data)

R=λ/Δλ=32000 & λ=3,200~10,000A (Ca II HK, Ca II IRT, Ha)

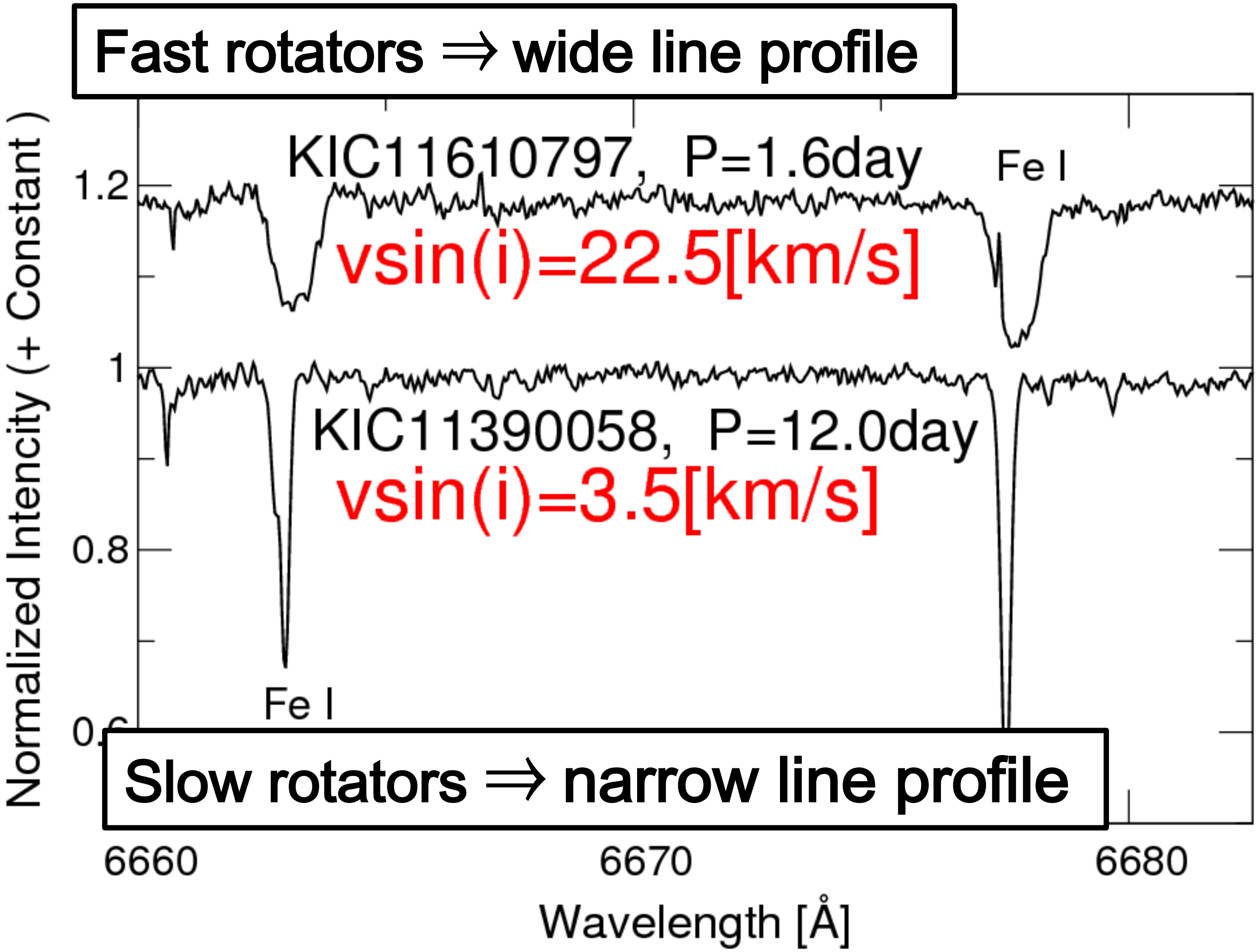
Apache Point
Observatory
(at New Mexico)

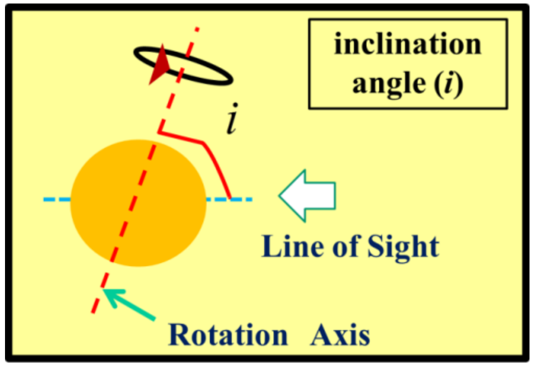
More than half (~47 stars) of the 65 target stars are found to be single solar-type stars !!

We conduct detailed analyses for these 47 “single” stars.

Projected rotation velocity (*v* sin *i*)

We can estimate projected rotation velocity (v sin i) from the Doppler broadening of absorption lines.

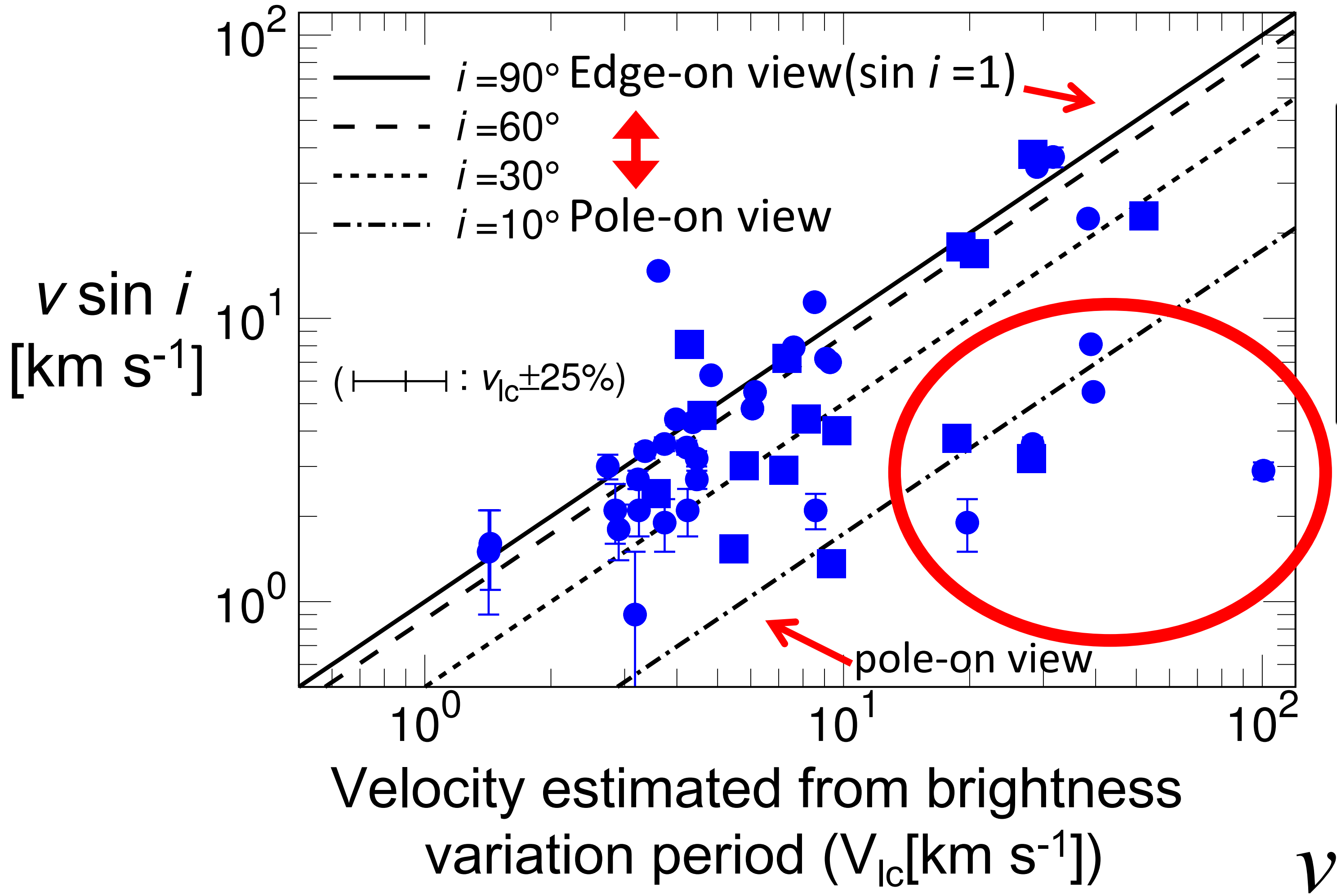


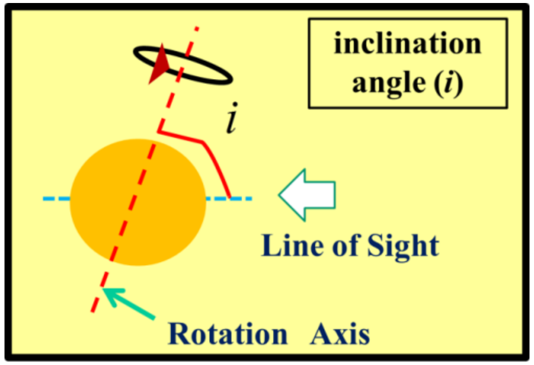


※Measurement methods
Takeda et al.(2008etc)

Rotation Period ⇔Brightness variation period ?

Most of the data points locate below the line of i=90°
⇒"Brightness variation≒Rotation" is OK!!



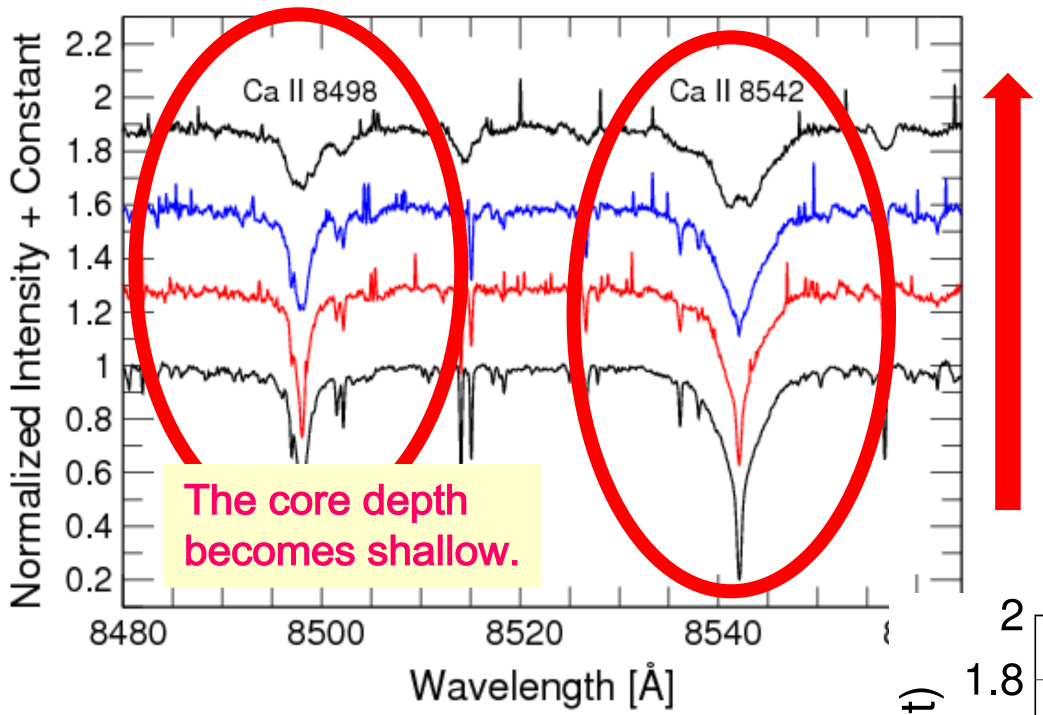


$$v_{lc} \approx \frac{2\pi R_{star}}{P}$$

※Sun: Vrot ~ 2 [km s^{-1}]

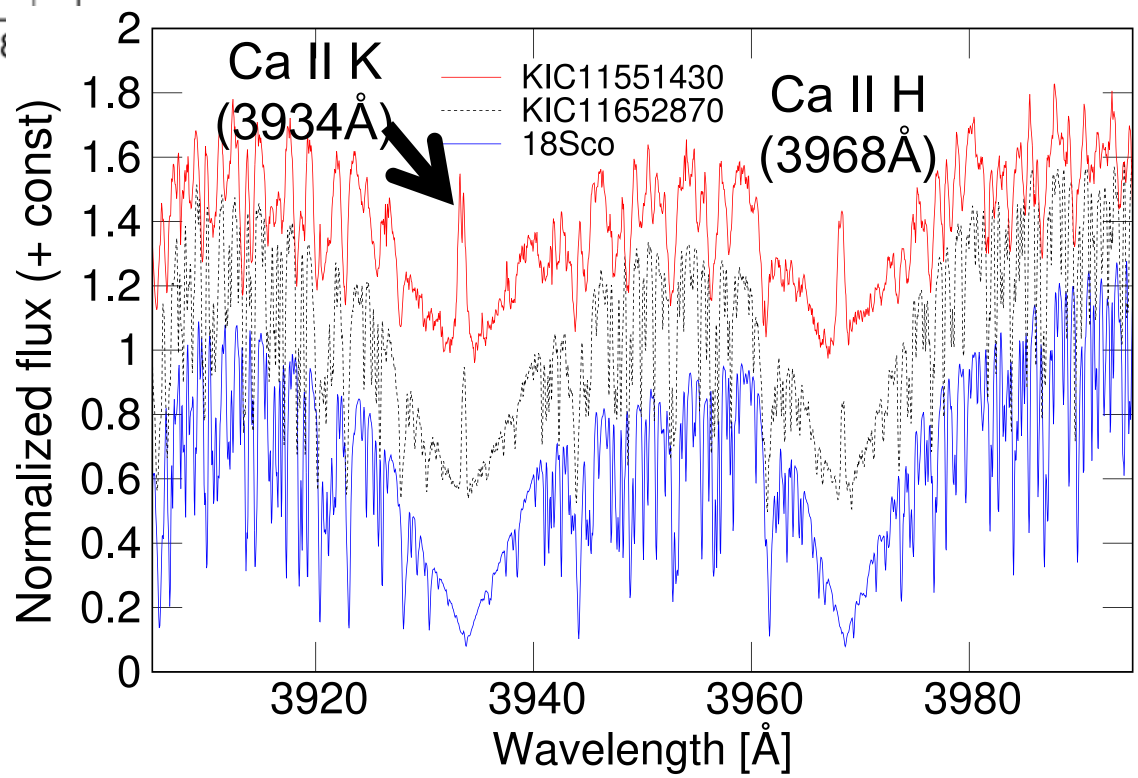
Notsu+2015b & 2017 in prep

Indirect estimation of starspot coverage with Ca II lines



As the magnetic activity enhanced, the core depth becomes shallow because of the greater amount of the emission from the chromosphere.

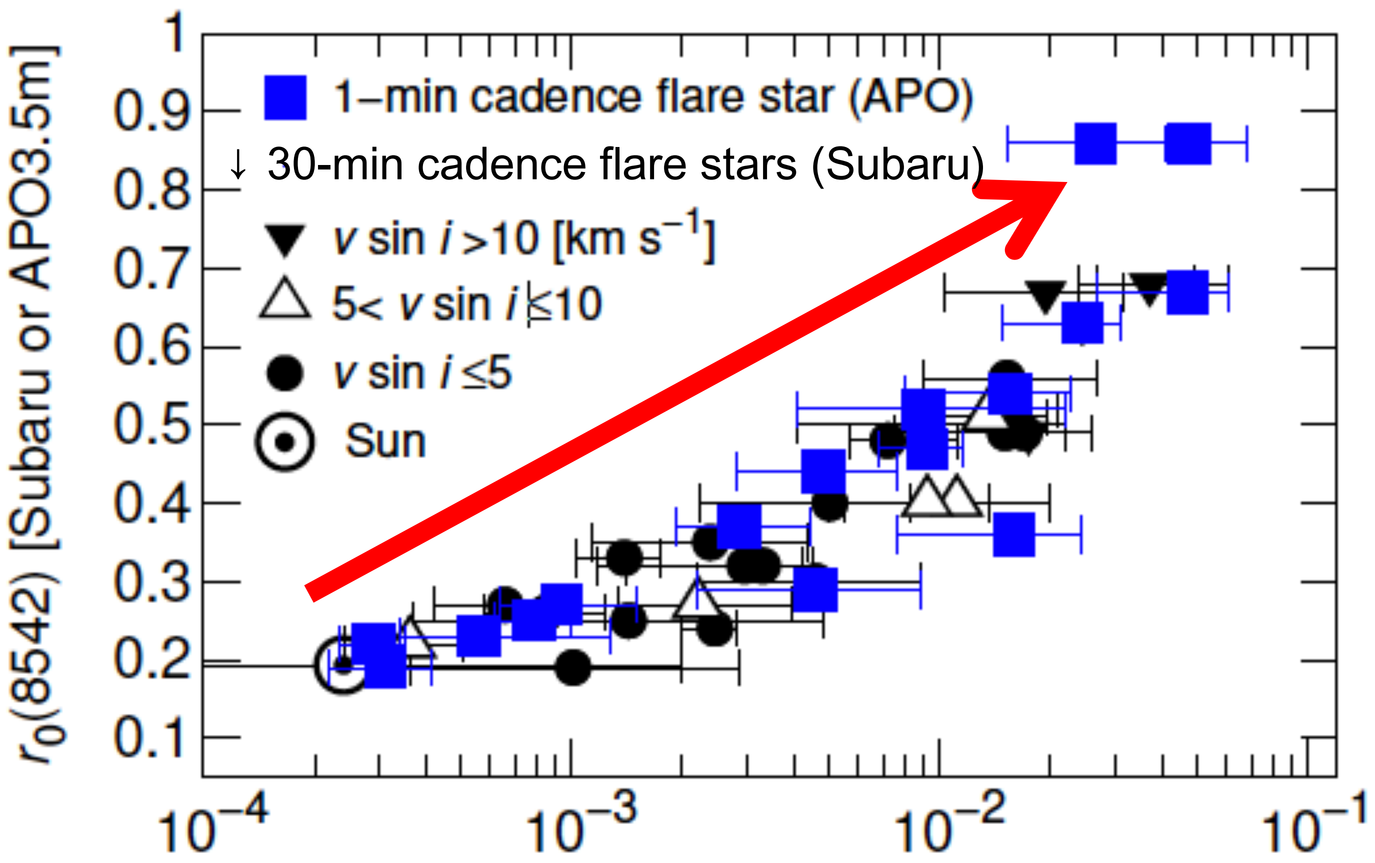
⇒ We can indirectly confirm existence of large starspots !!



In both figures, the bottom spectrum is solar-twin star (18Sco), and the others are superflare stars.

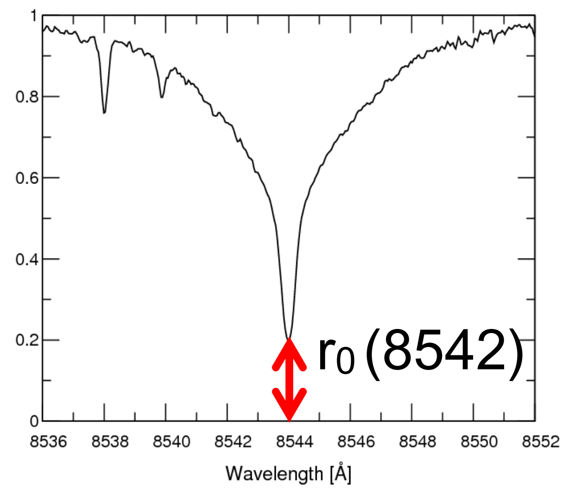
Notsu+2015b & 2017 in prep

Starspot coverage vs Ca II 8542 intensity



Brightness Variation Amplitude (Kepler) ≒ starspot coverage

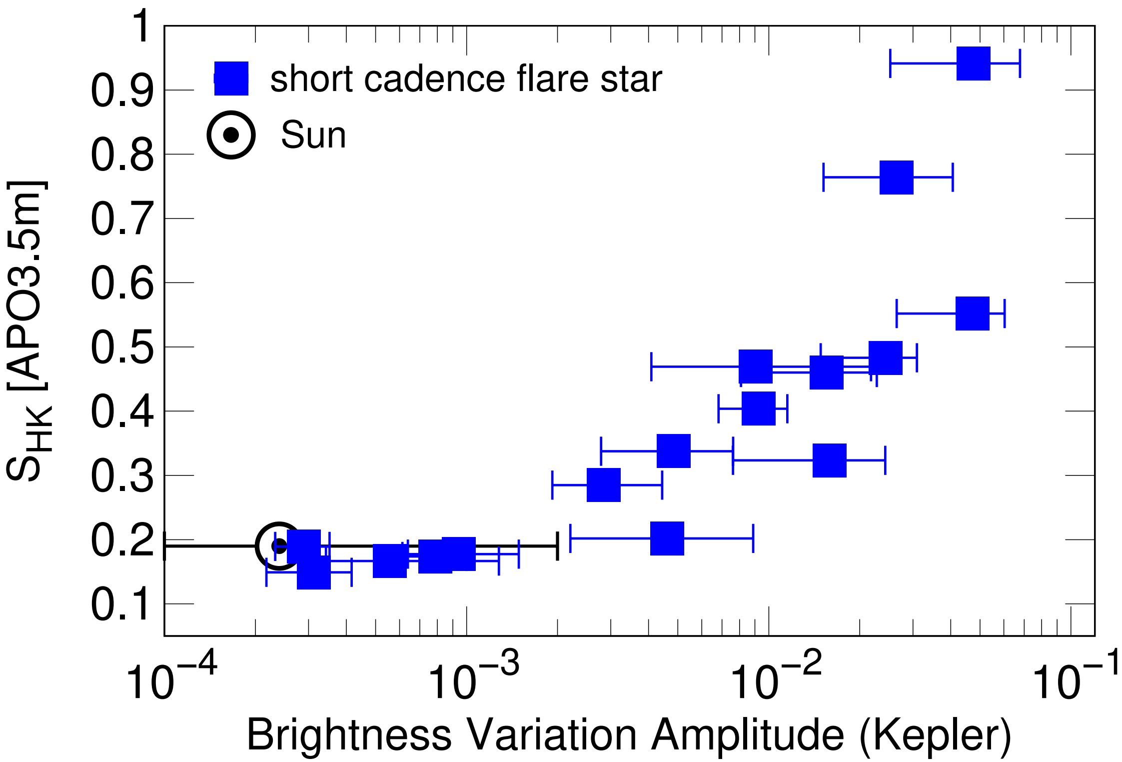
r_0: Normalized intensity of Ca II 8542

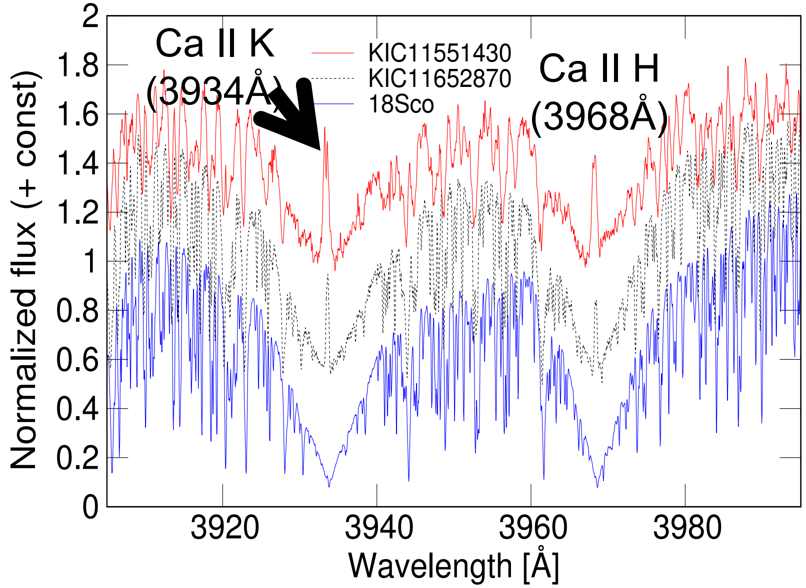


- There is a clear correlation between the amplitude of photometric variation and Ca II intensity.
- **As for spot coverage, Kepler results are consistent with spectroscopic results.**

Notsu+2015b & 2017 in prep

Starspot coverage vs. Ca II HK





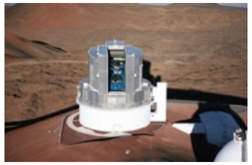
Brightness Variation Amplitude (Kepler) ≒ starspot coverage

- Ca II H&K lines, which are observed only at APO observations (not with Subaru) show basically the same results as those from Ca II 8542.

Summary of Part I : Superflare studies with Kepler and high-dispersion spectra (Subaru & APO3.5m)

○ Kepler discovered many (>1000) superflares on many (~300) solar-type (G-type main sequence) stars.

○ Brightness Variations of Kepler data

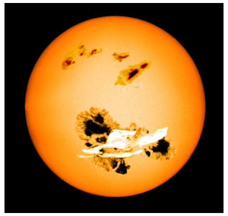


Period of brightness variation → rotation period (0.5 – 30 days)

Brightness Variation Amplitude → total area of starspots (0.1-10%)

– supported from spectroscopic observations

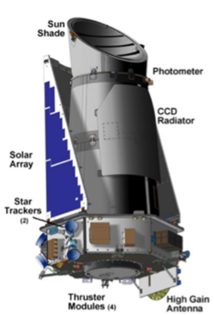
- vsin i
- intensity of chromospheric lines (Ca II IRT & Ca II HK)

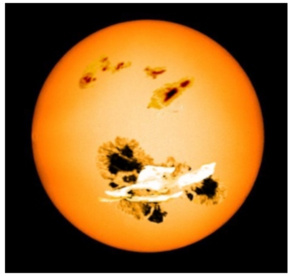


○ Superflare stars (including slowly-rotatings stars) are characterized by the existence of large starspots (active regions).

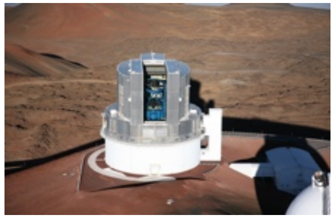
Topics

[1.1] Superflares found from Kepler data





[1.2] Superflare studies with our high dispersion spectroscopic observations (Subaru 8.2m & APO 3.5m)



[2] Superflare studies with LAMOST-Kepler Survey data

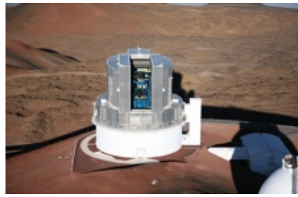
(Summary of Karoff et al. 2016

and introduction of collaborative studies

we are NOW working on)

Superflare studies with LAMOST

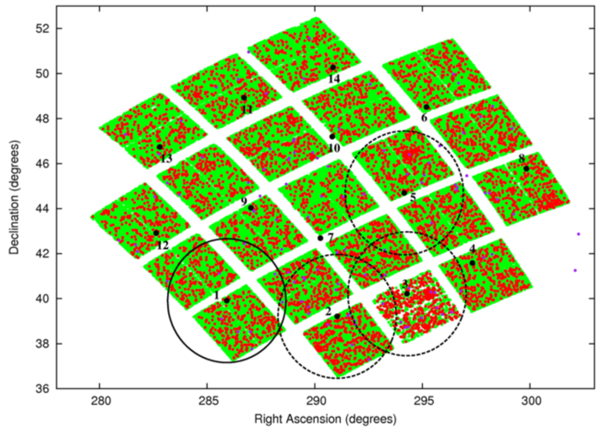
- **Our previous high-dispersion spectroscopic observations (Subaru & APO 3.5m)**
  - detailed analyses (R>λ/Δλ=32000)
    (atmospheric parameters, vsini, Ca II, etc)
  - limited number of observed stars (~65 stars) & Only superflare stars



- **LAMOST-Kepler survey**
  - Mainly strong lines (=1,800)
  - Much larger sample size of observed stars

Karoff et al. 2016

5648 solar-type stars including 48 superflare stars



How superflare stars are generally characterized compared with other stars, including the Sun.

C. Karoff (Aarhus Univ)

Karoff et al.
(2016 Nature Communications)

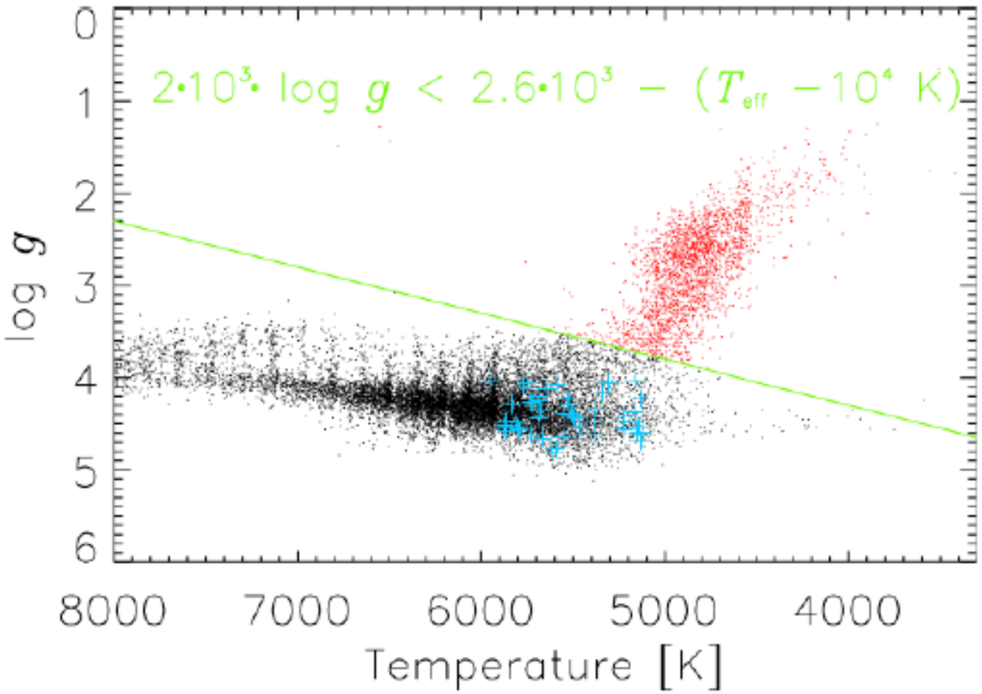
C. Karoff
(Aarhus Univ,
Denmark)

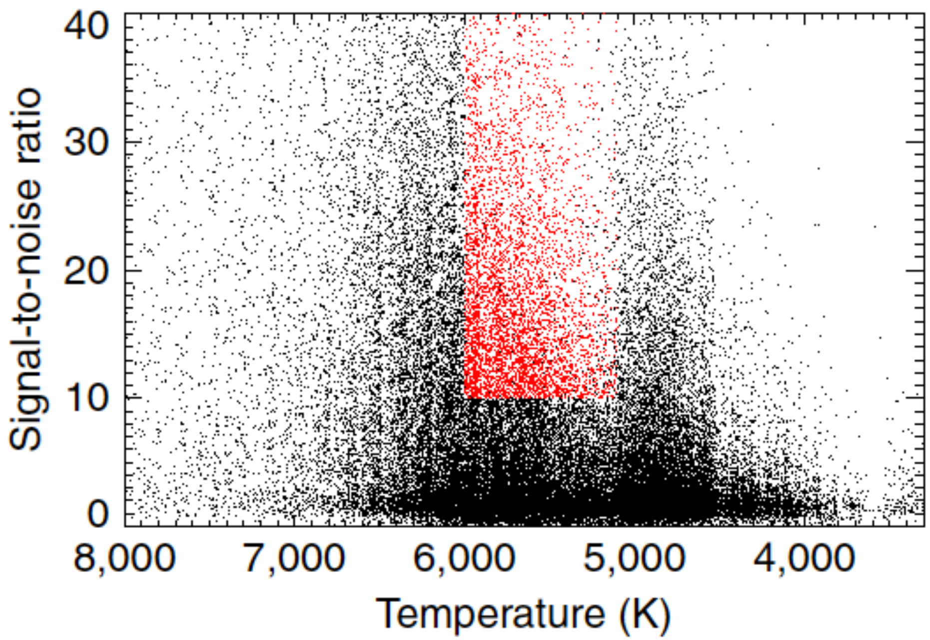
ARTICLE
Received 29 Jun 2015 | Accepted 17 Feb 2016 | Published 24 Mar 2016
DOI: 10.1038/ncomms11058 OPEN

Observational evidence for enhanced magnetic activity of superflare stars

Christoffer Karoff[1,2], Mads Faurschou Knudsen[1], Peter De Cat[3], Alfio Bonanno[4], Alexandra Fogtmann-Schulz[1], Jianning Fu[5], Antonio Frasca[4], Fadil Inceoglu[1], Jesper Olsen[6], Yong Zhang[7], Yonghui Hou[7], Yuefei Wang[7], Jianrong Shi[8] & Wei Zhang[8]

5648 main-sequence stars with effective temperature between 5000 and 6000 K and S/N > 10 (including 48 superflare stars)

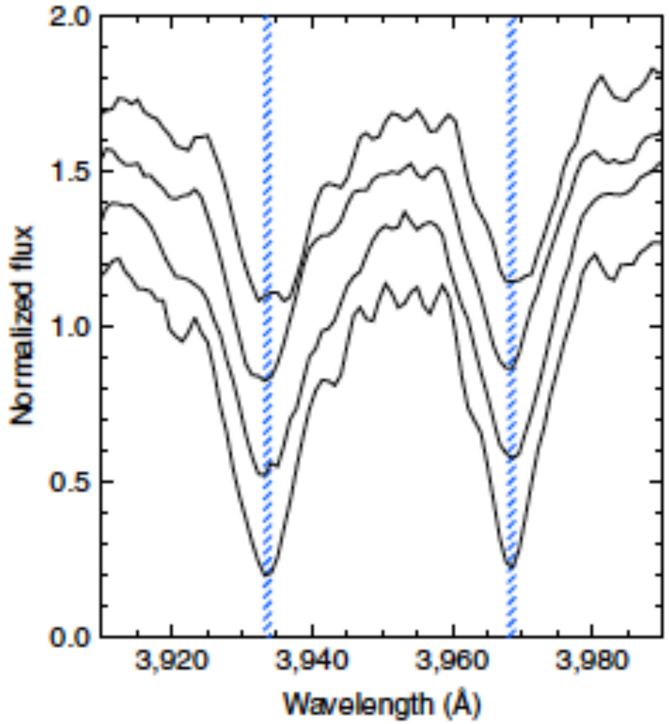




71733 spectra in total

Ca II H&K S index of LAMOST spectra

LAMOST spectra: 5648 solar-type stars including 48 superflare stars



$$S = \alpha \cdot \frac{H + K}{R + V}$$

H & K

Recorded counts in a 1.09Å full-width at half-maximum triangular bandpasses centred on the H and K lines at 396.8 and 393.4 nm.

V & R

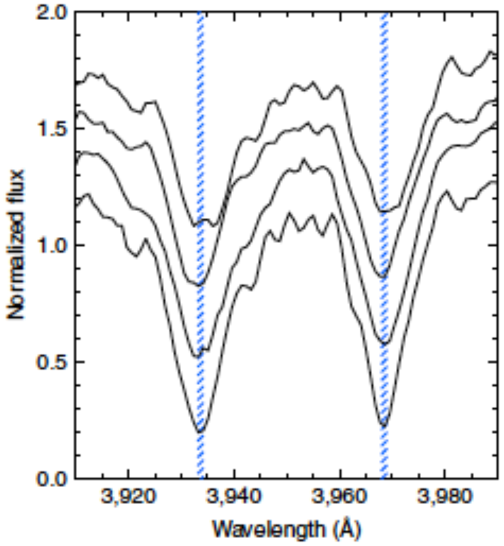
20 Å wide reference bandpasses centered on 390.1 and 400.1 nm.

α: Normalization constant

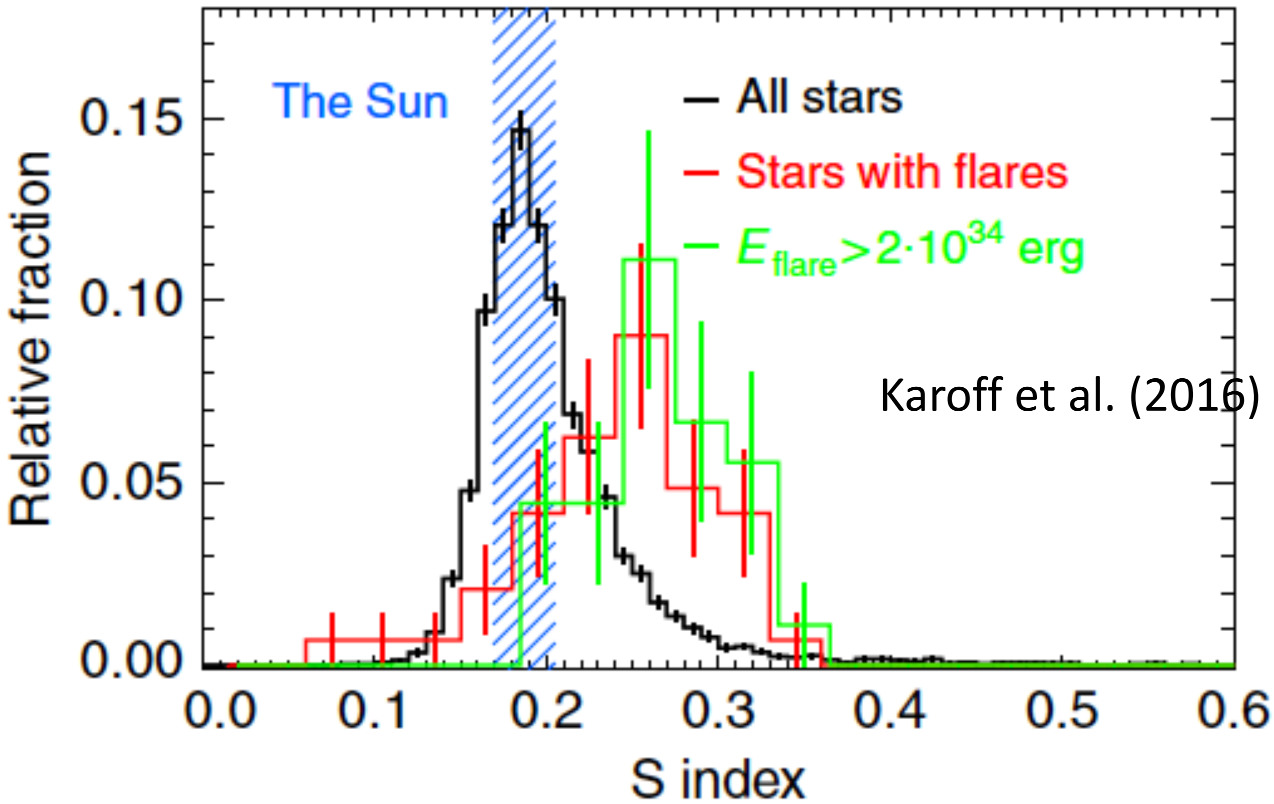
Karoff et al.
(2016 Nature Communications)

Ca II H&K S index of LAMOST spectra

LAMOST spectra: 5648 solar-type stars including 48 superflare stars



$$S = \alpha \cdot \frac{H + K}{R + V}$$

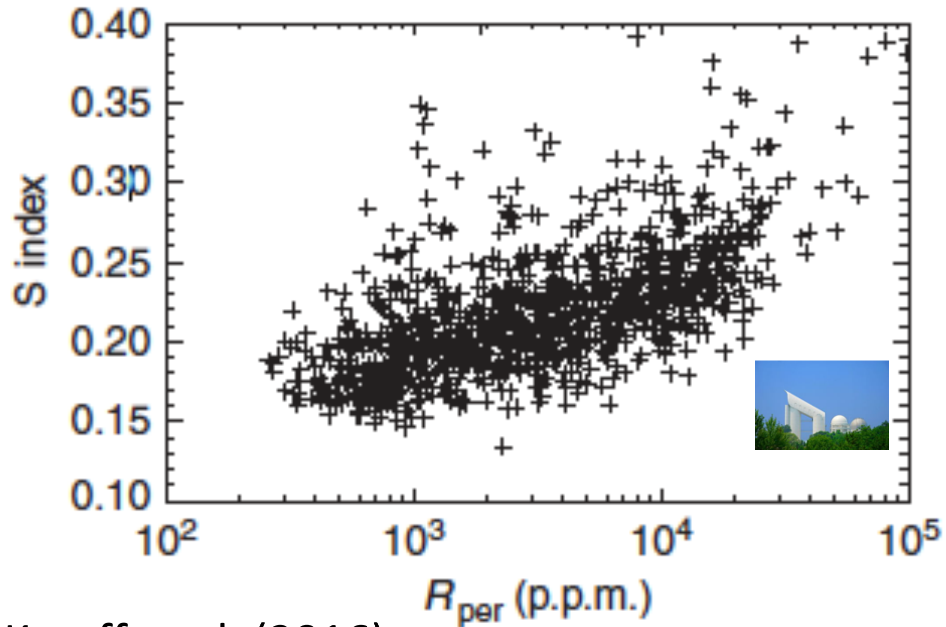


Superflare stars are generally characterized by larger chromospheric emissions than other stars.

→ Superflare stars have large active regions and starspots, as also suggested from Kepler data.

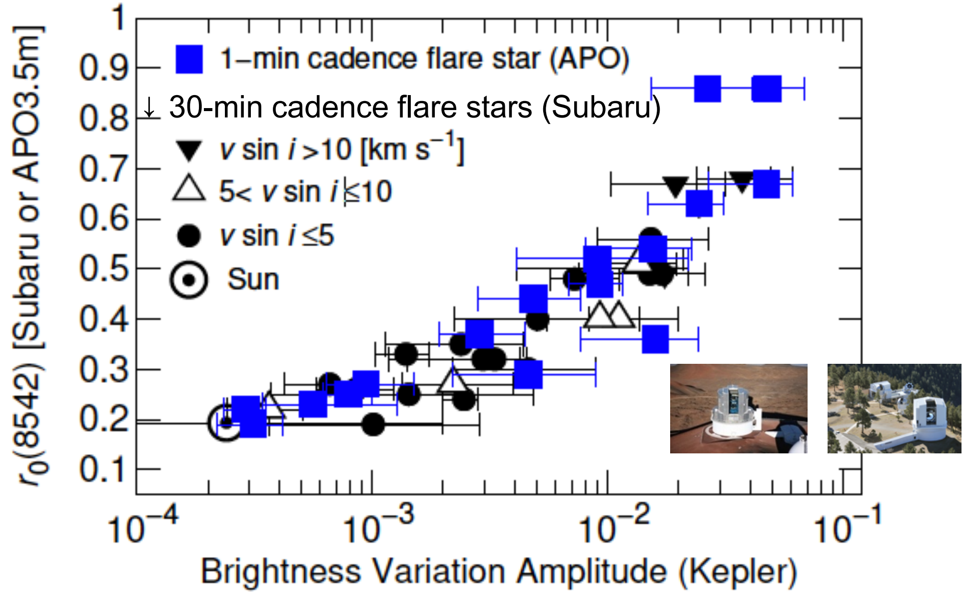
Comparison of LAMOST data with Kepler & high-dispersion spectroscopic data

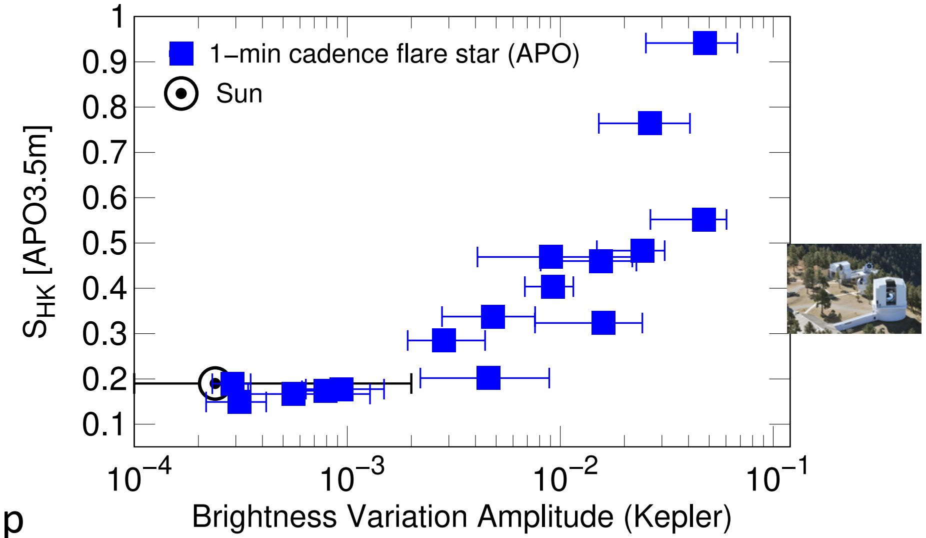
LAMOST S index (Ca II HK) vs. Kepler Brightness Variation Amplitude



Karoff et al. (2016)

Ca II intensity (Subaru & APO3.5m) vs. Kepler Brightness Variation Amplitude





Notsu+2015b & 2017 in prep

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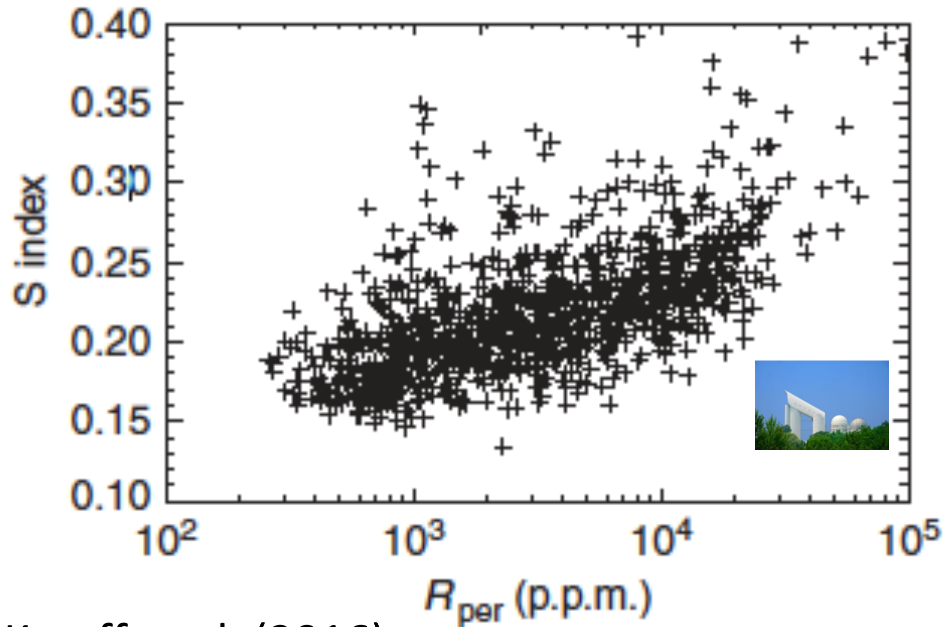

Karoff et al. (2016)

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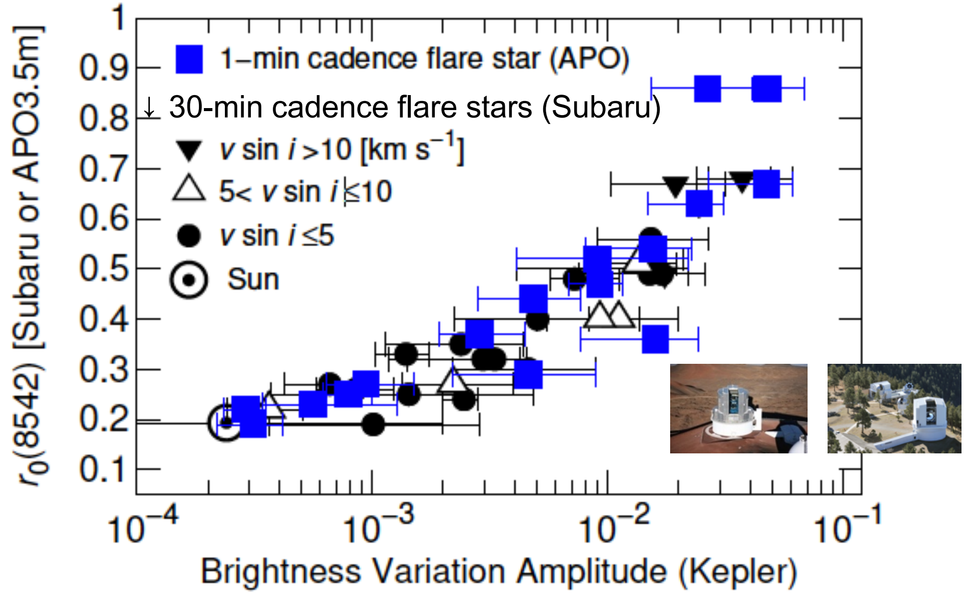


Notsu+2015b & 2017 in prep

As for spot coverage, results from ①, ②, and ③ are roughly consistent.

- ① Kepler : Brightness Variation Amplitude
- ② High dispersion spectroscopy (Subaru & APO): Ca II lines
- ③ LAMOST Ca II H&K S index (low resolution but large number of samples useful for many purposes)

Comparison of Ca II H&K lines with other chromospheric lines (Ca II 8542)

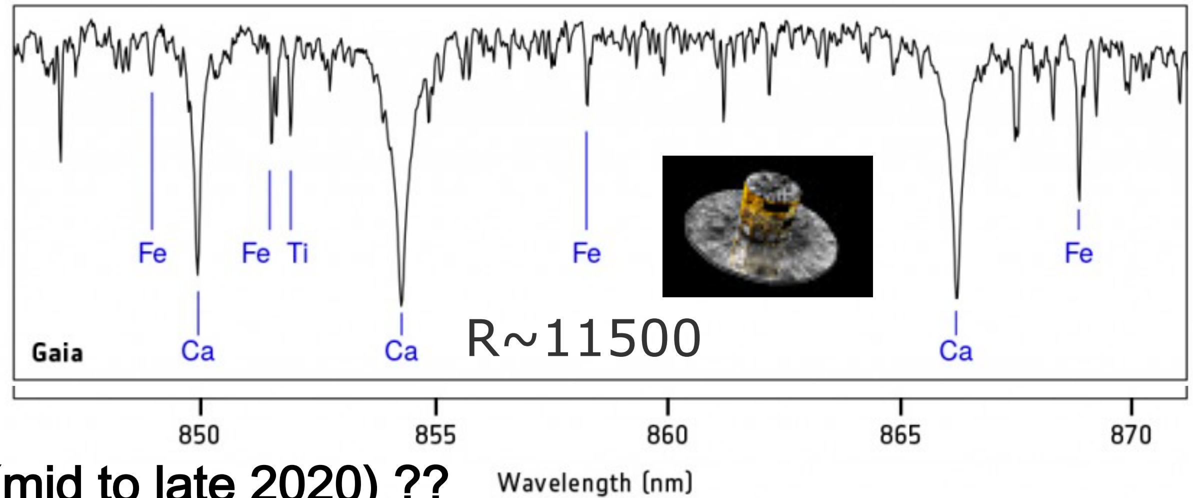
- One collaborative study we have just tried (Notsu & Karoff)

Many chromospheric lines used for stellar activity studies:
Ca II H&K (3933/3968Å), Ca II IRT (8498/8542/8662Å)
Hα 6563Å, He I 5876Å, etc

Historically, Ca II H&K lines have been widely used.
It is interesting to compare how well correlate with other lines.

Gaia spectroscopy (including Ca II IRT)

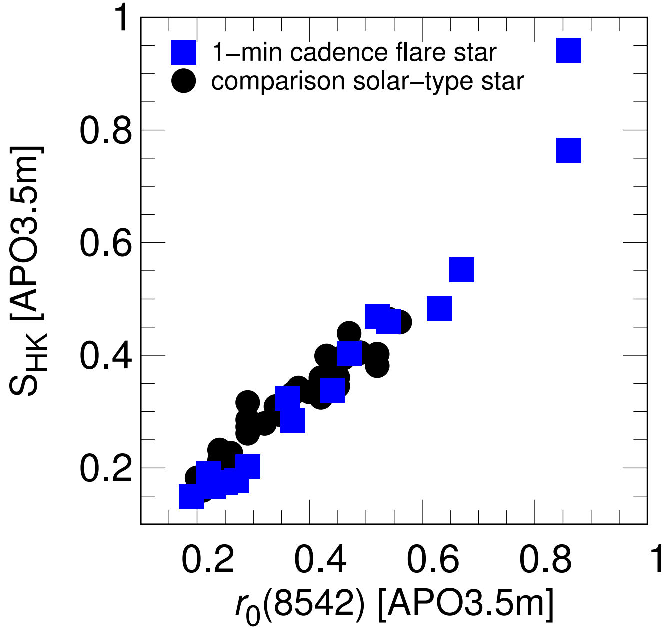
In future, Ca II IRT lines are possibly important with Gaia data??

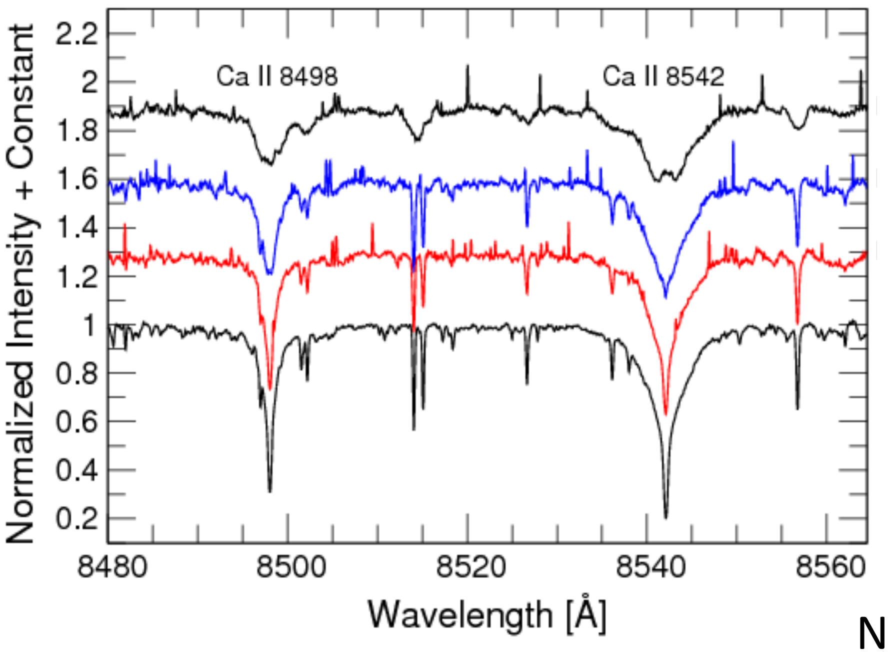


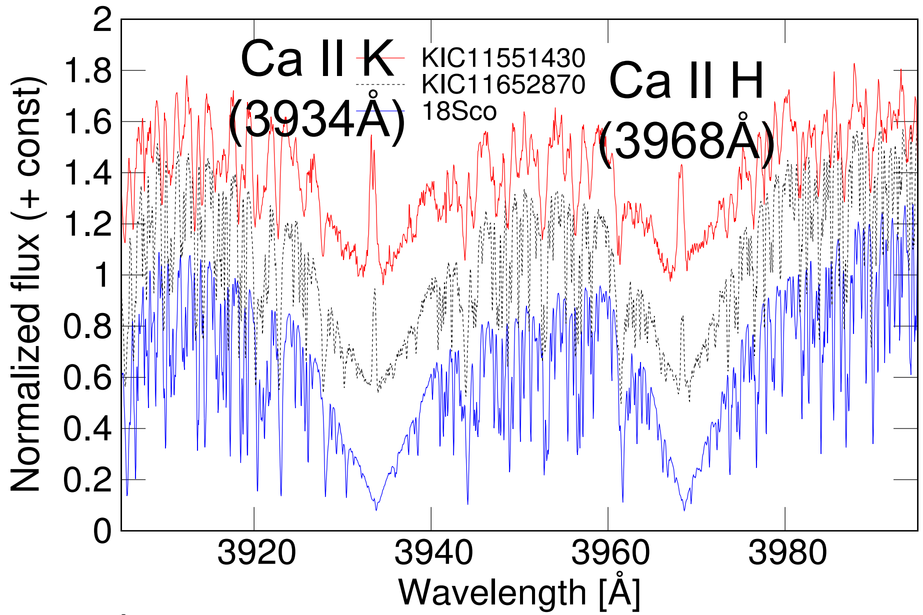
Gaia Third release (mid to late 2020) ??

Comparison of Ca II H&K lines with other chromospheric lines (Ca II 8542)

In high dispersion spectra:

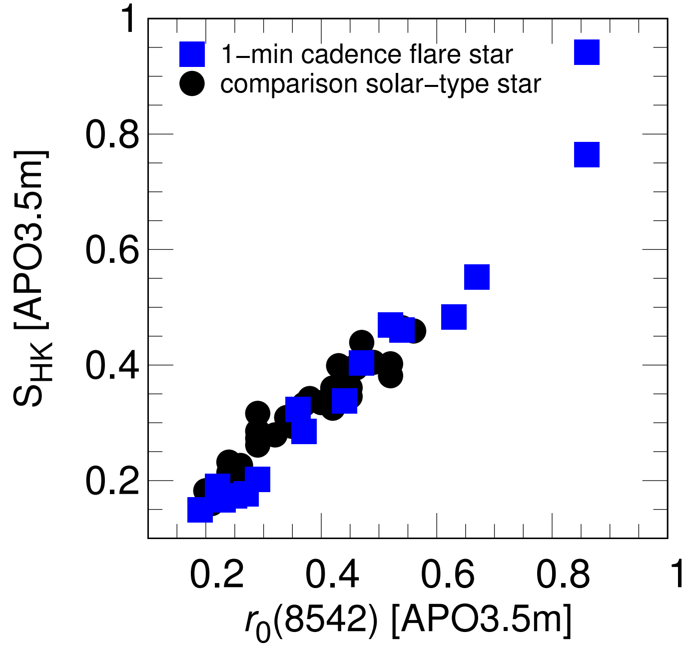






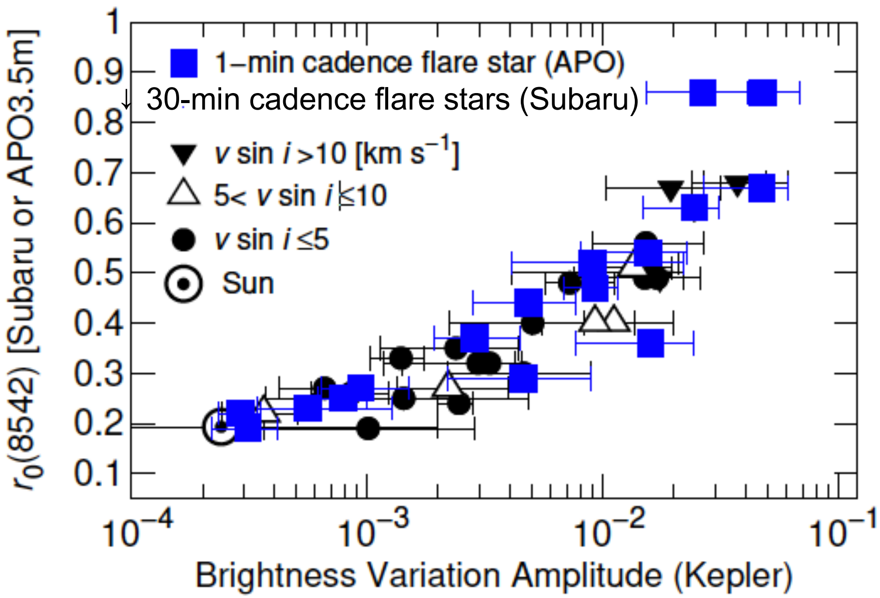
Notsu et al. in prep

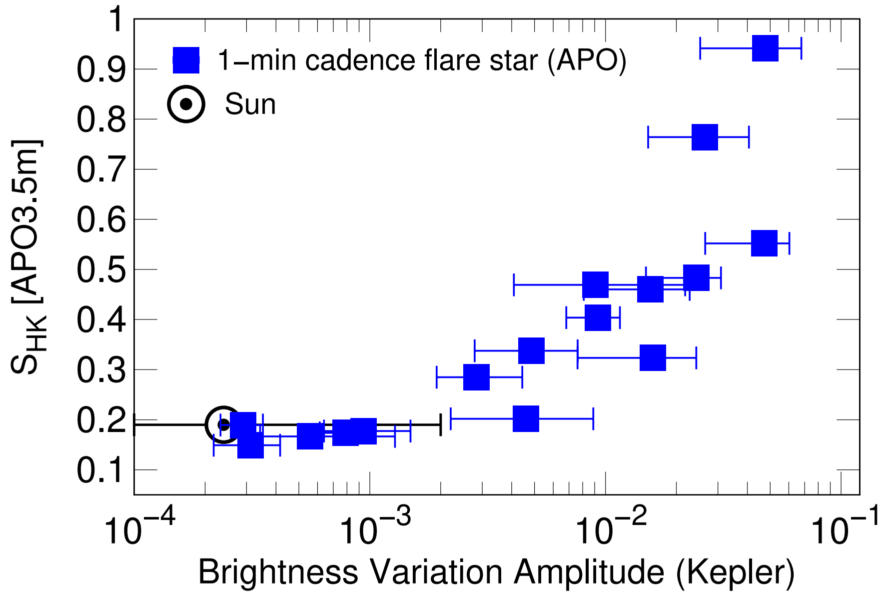
Comparison of Ca II H&K lines with other chromospheric lines (Ca II 8542)



In high dispersion spectra:

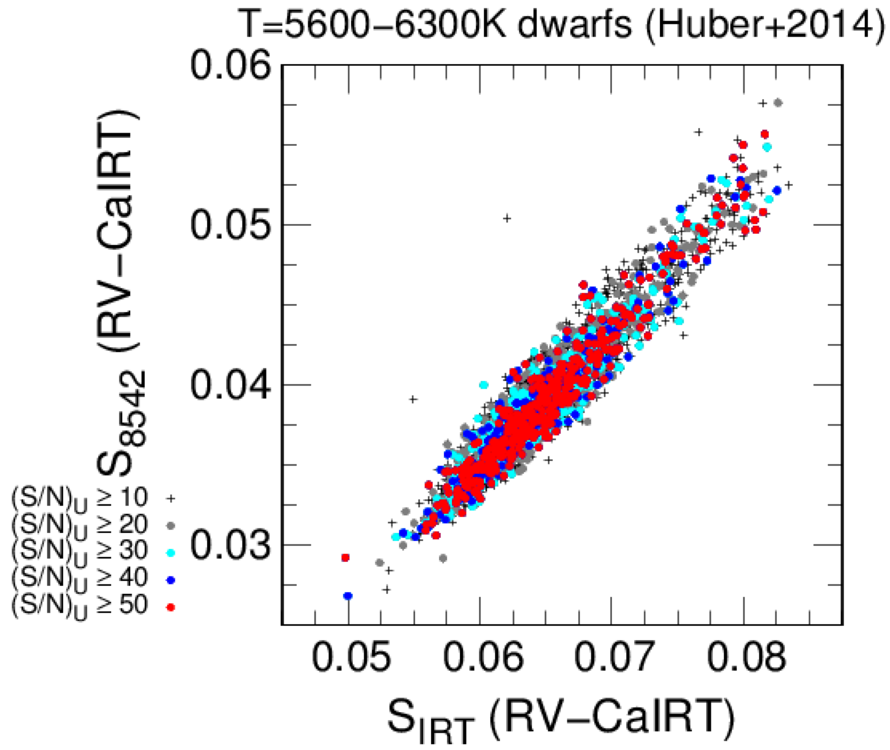
Notsu et al. in prep

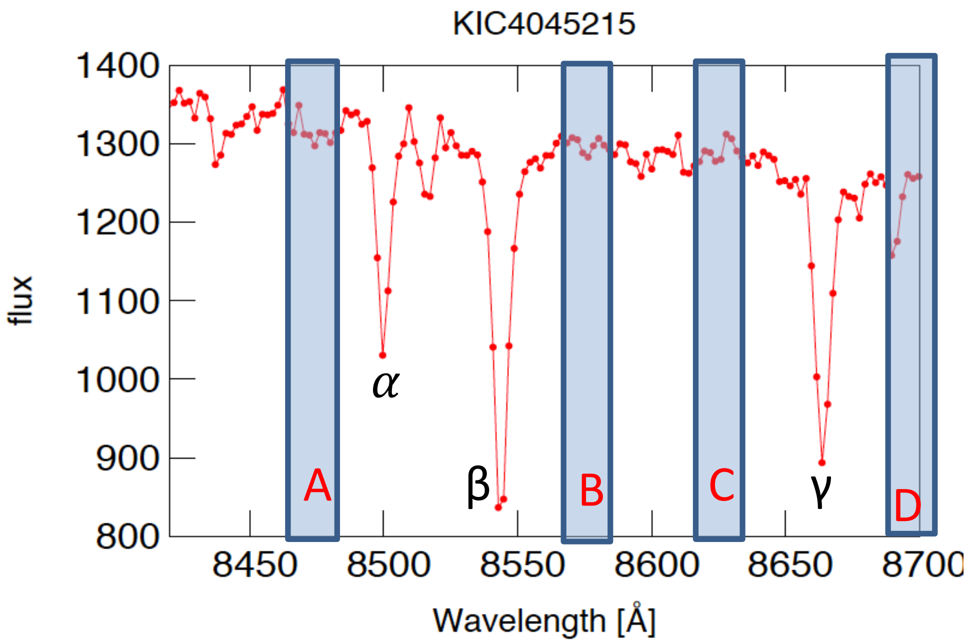




Comparison of Ca II H&K lines with other chromospheric lines (Ca II 8542)

In LAMOST spectra (R=1800) :





Triangles around (FWHM=2.18Å)

α: Ca II 8498.023Å

β: Ca II 8542.091Å

γ: Ca II 8662.141Å

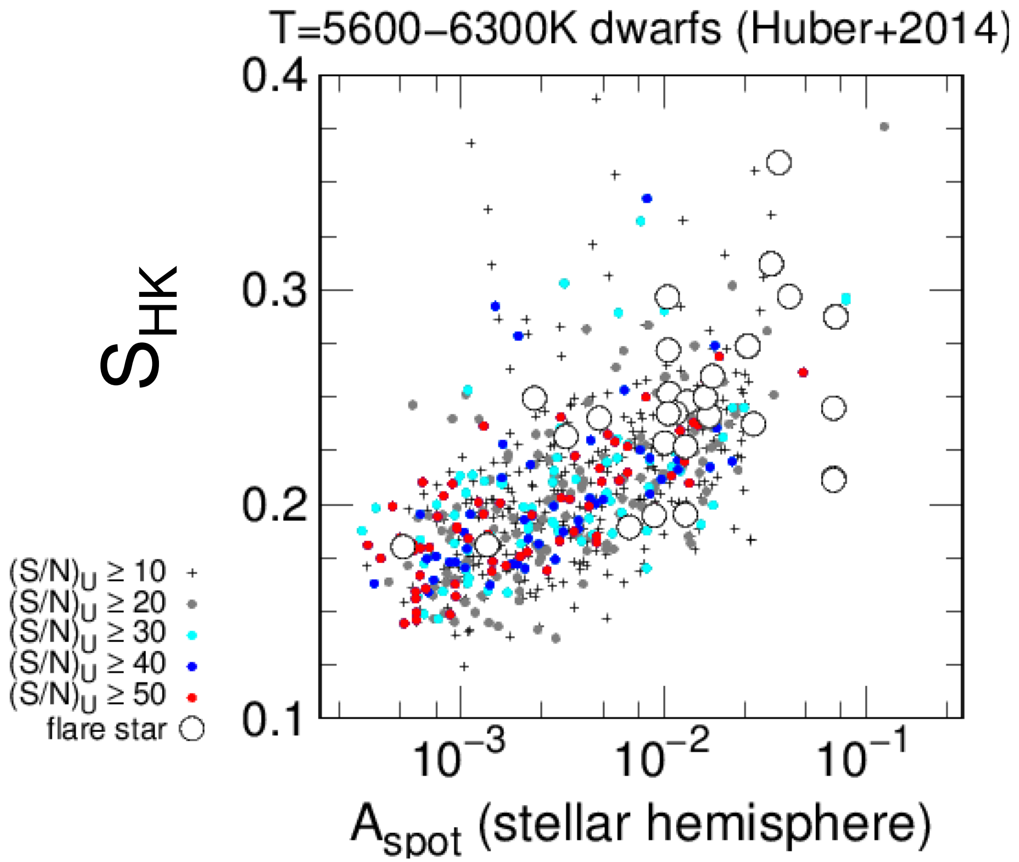
$$S_{8542} = \frac{\beta}{A+B}$$

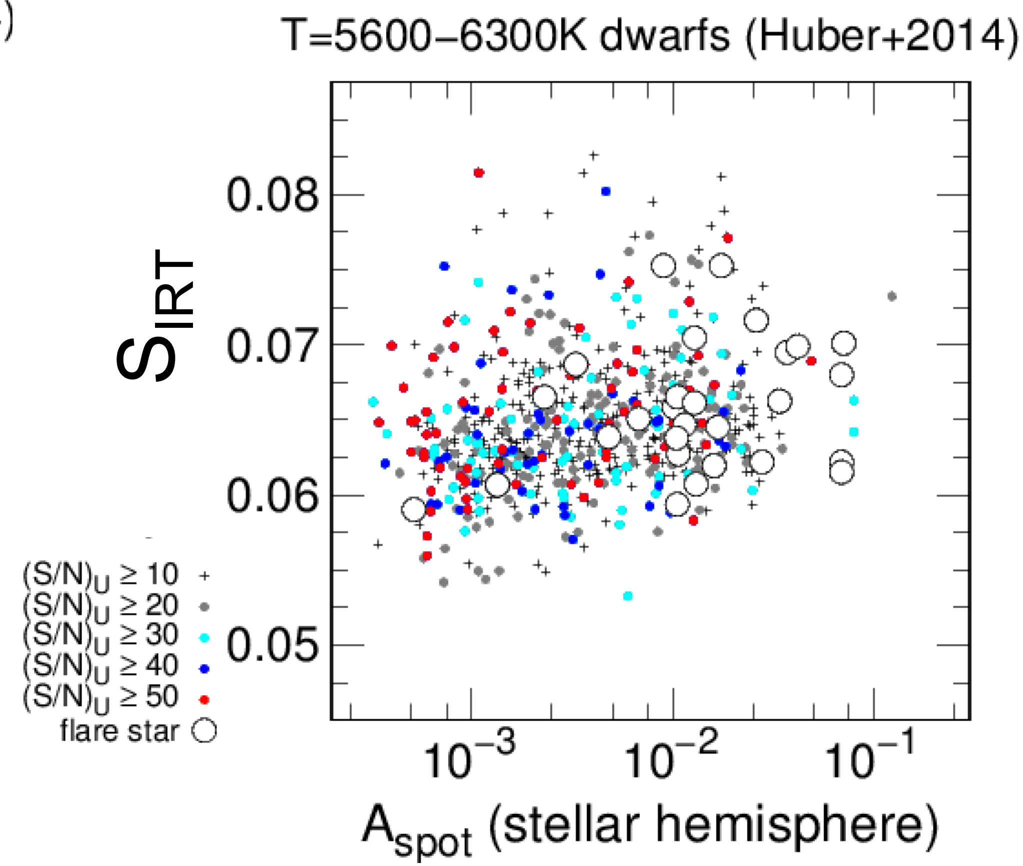
$$S_{IRT} = \frac{\alpha+\beta+\gamma}{A+B+C+D}$$

Comparison of Ca II H&K lines with other chromospheric lines (Ca II 8542)

!! Very Prelimnary results !!

In LAMOST spectra (R~1800), Ca II HK spectra are better indicator if we compare with Kepler data ??
How about Gaia (R~11500)??





Sumary of Part 2:
Superflare studies with LAMOST-Kepler Survey data

○ Ca II H&K data (Karoff+2016: 5648 stars with 48 flare stars)
Superflare stars are generally characterized by larger chromospheric emissions than other stars.

○ As for spot coverage, results from ①, ②, and ③ are roughly consistent.

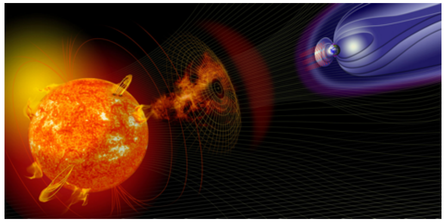
- ① **Kepler** : Brightness Variation Amplitude
- ② **High dispersion spectroscopy** (Subaru & APO): Ca II lines
- ③ **LAMOST** Ca II H&K S index (low resolution but large number of samples useful for many purposes)

○ Comparison of Ca II H&K lines with Ca II IRT (8542)

- High dispersion spectroscopy (R~32000): good correlation
- LAMOST (R=1800): a bit hard ?? (Ca II 8542: not so good)
- Gaia (R~11500): ??

○ Future comparison?: M-dwarfs (e.g, Frasca's talk, Chang et al. 2017), TESS data, other survey(4-most etc), …. etc

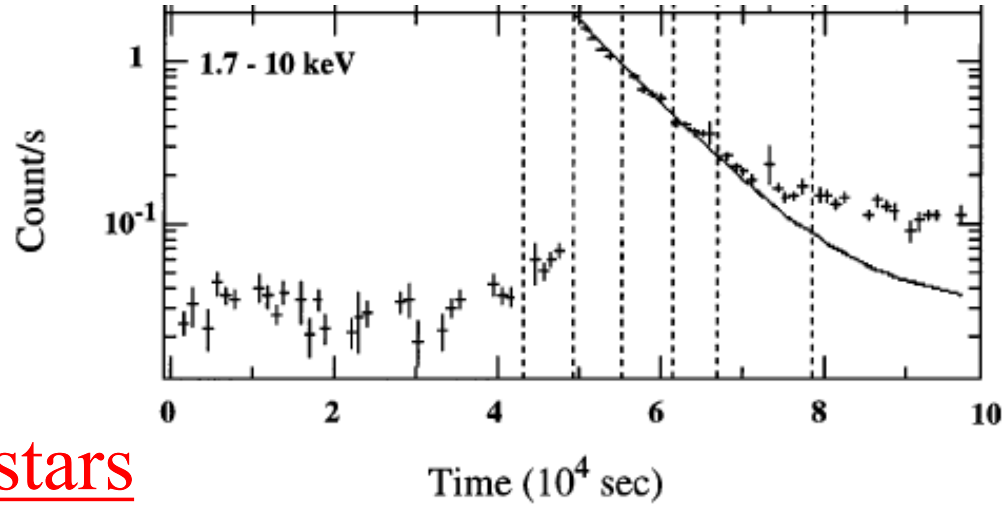
Backup slides



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)
  - Active M-dwarfs

  → Mainly <u>rapidly rotating stars</u>



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

In contrast, the Sun is not young and rotates slowly

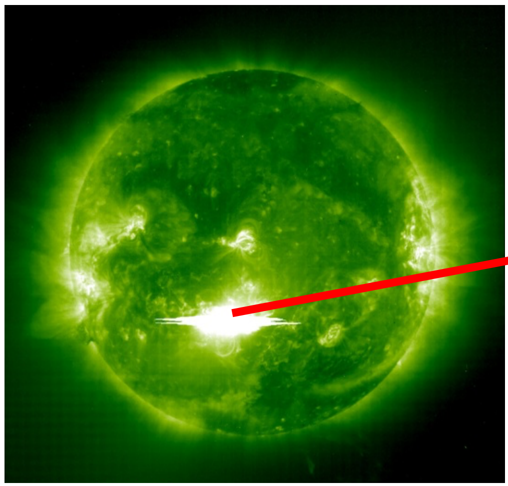
→ It has been believed our Sun does not have superflares.

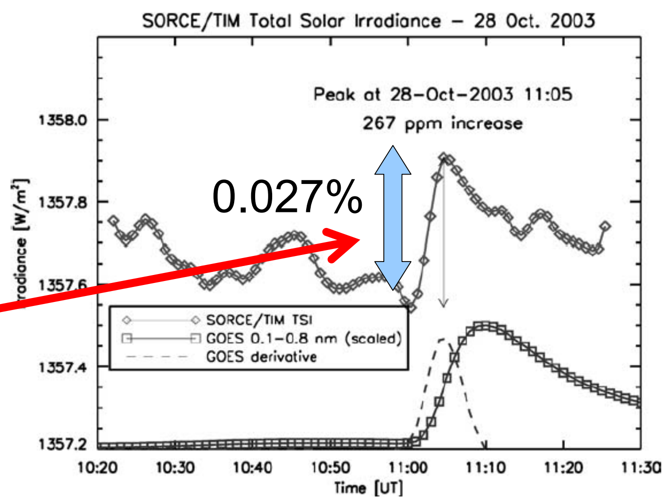
Really ??

Difficulties of detection of flares on solar-type stars

- 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.
- Flares are suddent and impulsive events !

→ Continus monitoring observation with high time resolution is importanet.



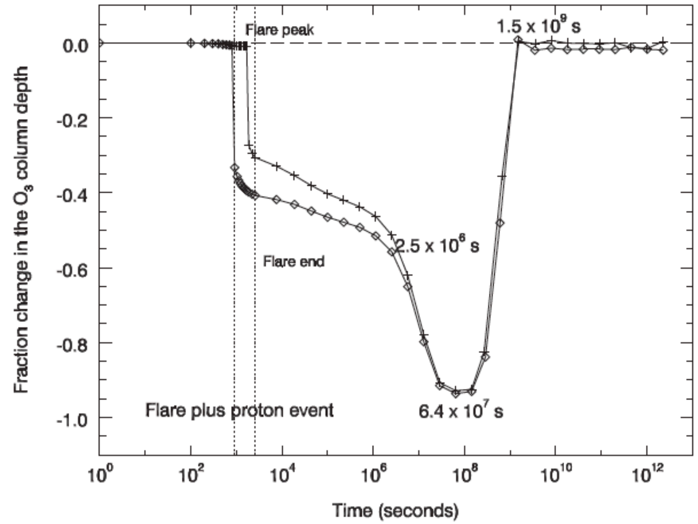


Kopp et al., Solar Phys. 230, 129 (2005)

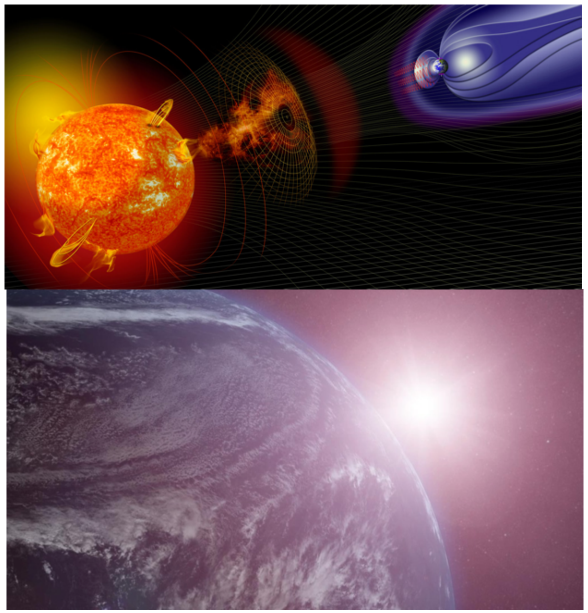
Potential impacts on habitability from large flares (superflares)

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.



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

Flare energy vs. area of starspots

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

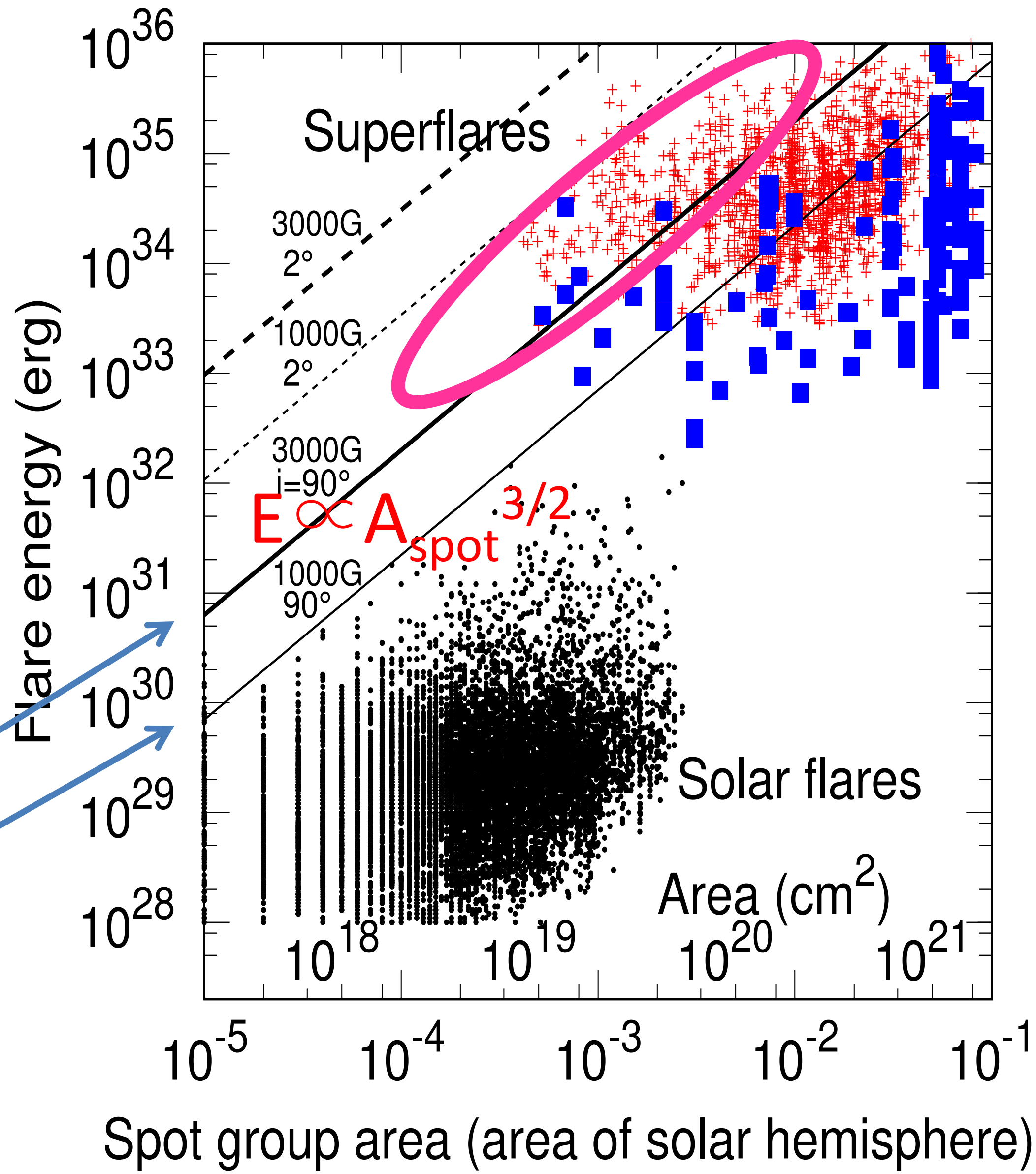
⇒Large starspots are necessary.

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

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

f=0.1, B=3000G

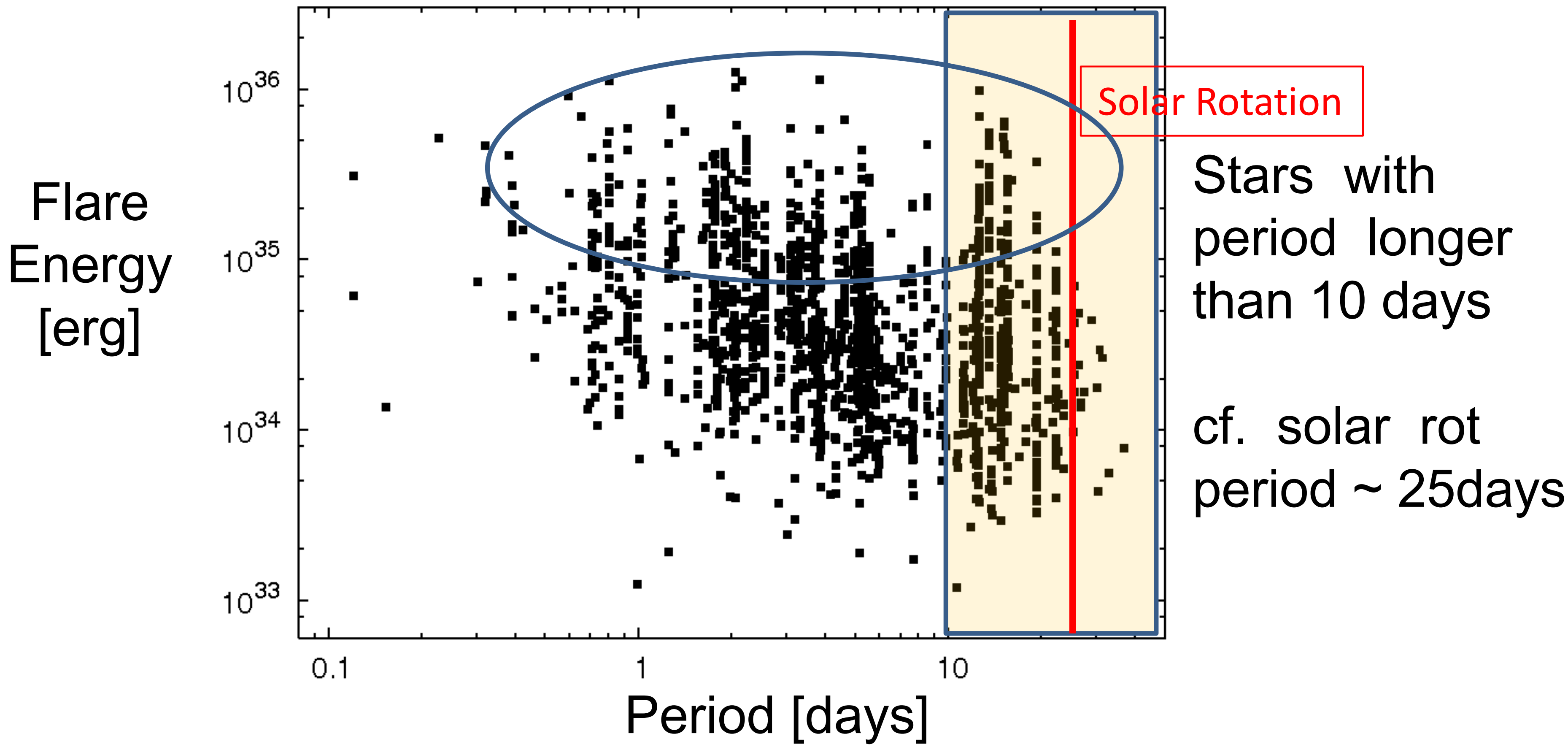
f=0.1, B=1000G



Notsu+2013

Maehara+2015 EPS

Flare energy vs. rotation period

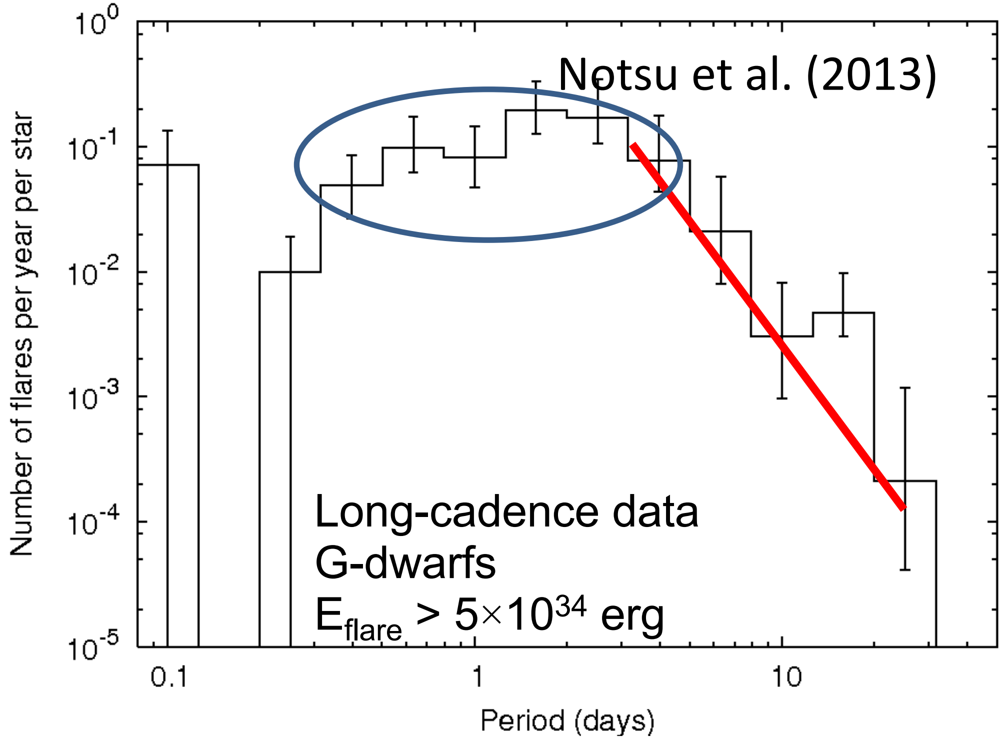


- The energy of the largest flares observed in a given period bin does **not** have a clear correlation with the rotation period.
  - Superflares may occur on the slowly-rotating stars.
  - (Of course, flare frequency decrease as rotation period increases.)

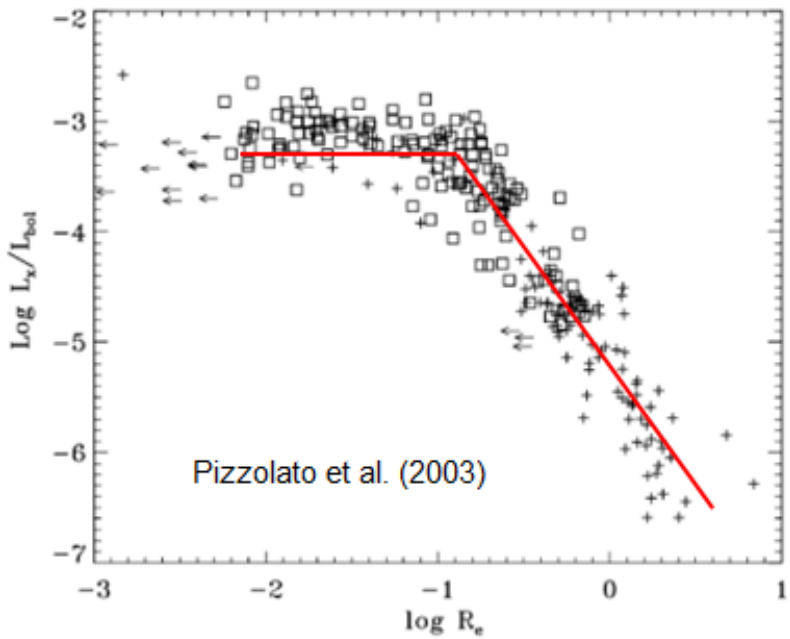
Flare frequency vs. rotation period

- The frequency of superflares decreases as the rotation period increases (P>2-3days).
  - The frequency of superflares shows the "saturation" for a period range < 3 days.

    → similar to the relation between Lx vs. Rotation period

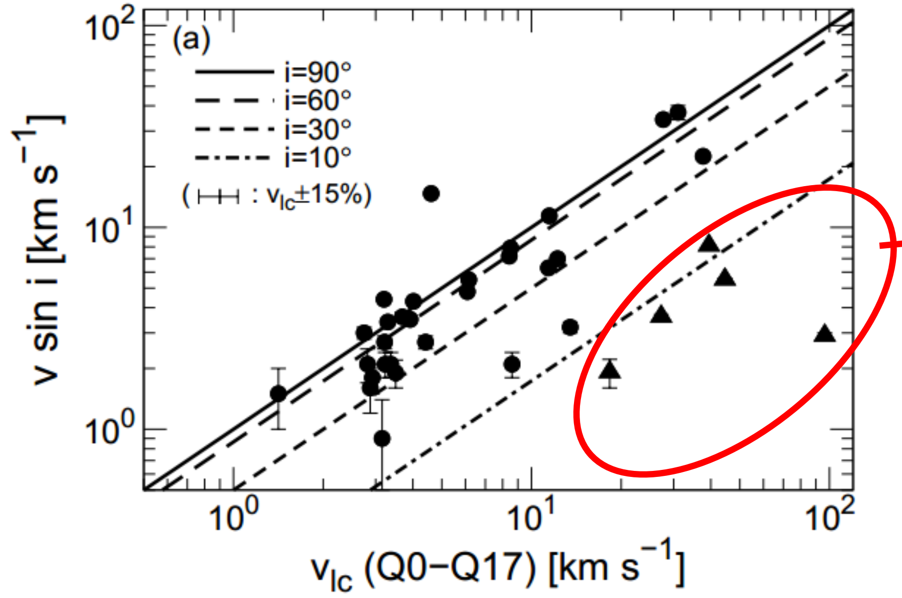


L_X/L_{bol} vs. Rossby number

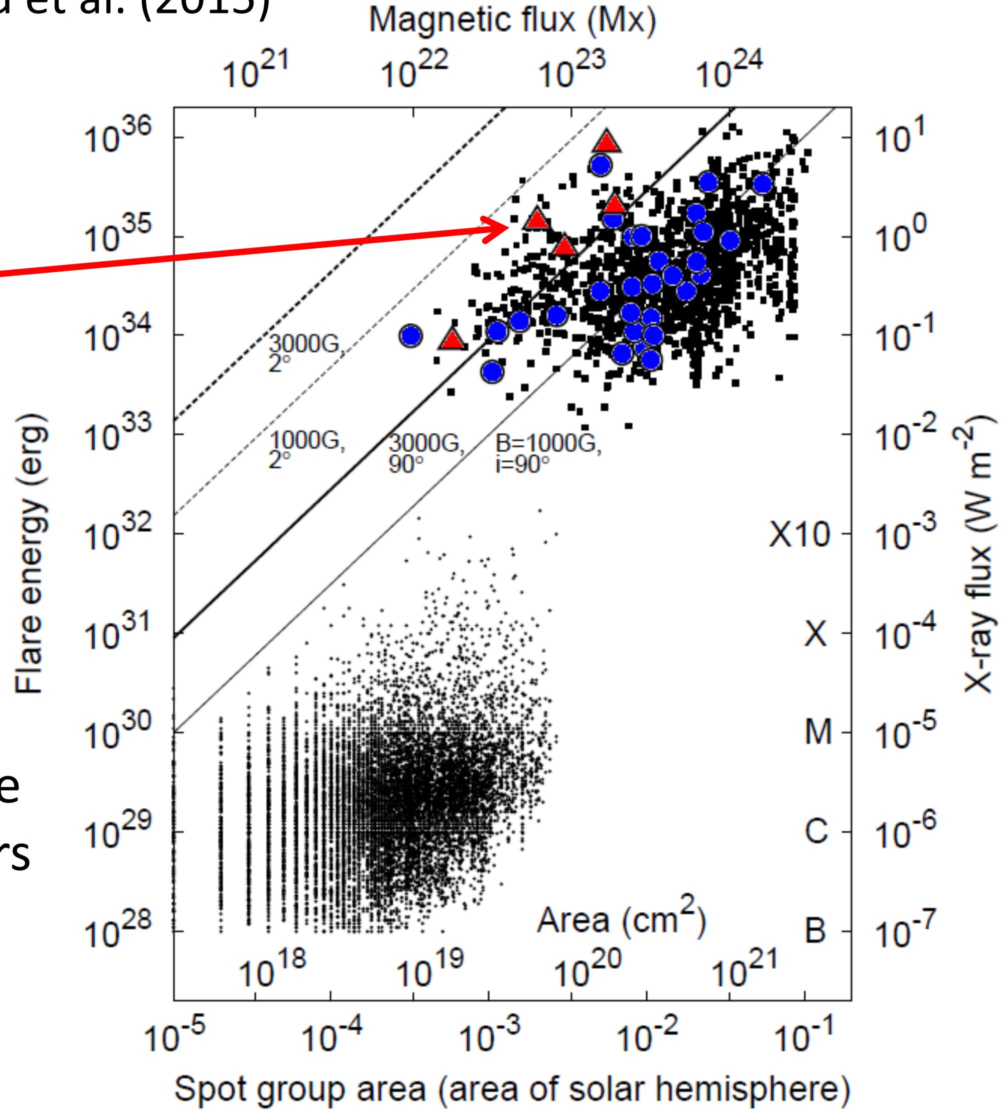


(Ro = P_rot / t_conv)

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”.

Evidence of superflare ?

LETTER

doi:10.1038/nature11123

A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan

Fusa Miyake[1], Kentaro Nagaya[1], Kimiaki Masuda[1] & Toshio Naka

Increases in ^{14}C concentrations in tree rings could be attributed to cosmic-ray events[1–7], as have increases in ^{10}Be and nitrate in ice cores[8,9]. The record of the past 3,000 years in the IntCal09 data set[10], which is a time series at 5-year intervals describing the ^{14}C content of trees over a period of approximately 10,000 years, shows three periods during which ^{14}C increased at a rate greater than 3‰ over 10 years. Two of these periods have been measured at high time resolution, but neither showed increases on a timescale of about 1 year (refs 11 and 12). Here we report ^{14}C measurements in annual rings of Japanese cedar trees from AD 750 to AD 820 (the

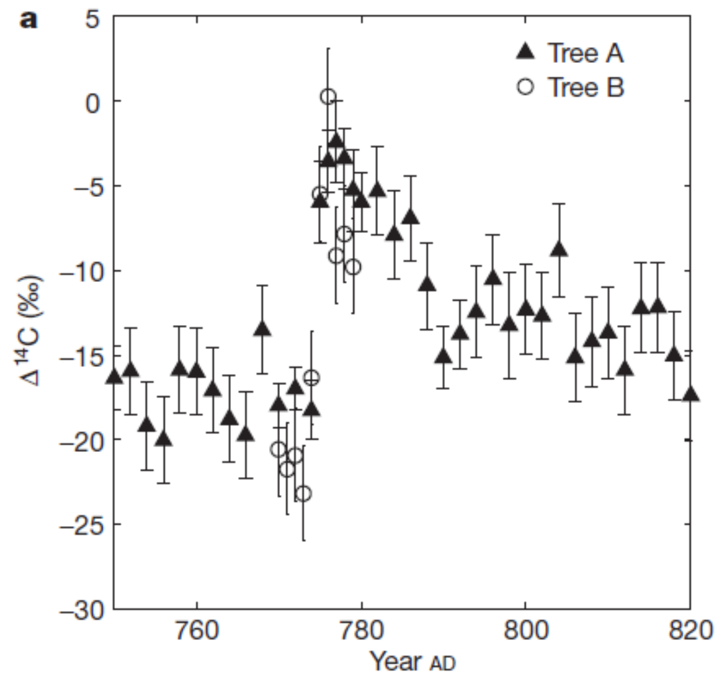


Figure 1 | Measured radiocarbon content and comparison with IntCal98. The concentration of ^{14}C is expressed as $\Delta^{14}C$, which is the deviation (in ‰) of the $^{14}C/^{12}C$ ratio of a sample with respect to modern carbon (standard sample), after correcting for the age and isotopic fractionation[30]. **a**, $\Delta^{14}C$ data for tree A (filled triangles with error bars) and tree B (open circles with error bars) for the period AD 750–820 with 1- or 2-year resolution. The typical precision of a single

Corresponding to 10^34-10^35 erg superflare
If this is due to a solar flare

(Miyake et al. Nature , 2012, June, 486, 240)

Another evidence ?

From Miyake et al. (2013)
Nature Communications 2783