Superflare Workshop 2016
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Spectroscopic observations of solar-type superflare stars

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Reference:
Notsu, Y. et al. 2015a, PASJ, 67, 32
Notsu, Y. et al. 2015b, PASJ, 67, 33
Honda et al. 2015, PASJ, 67, 85
Nogami et al., 2014, PASJ, 66, L4
Notsu, S. et al., 2013, PASJ 65 112

Topics

High Dispersion Spectroscopy of Solar-type Superflare Stars (Subaru/HDS)

I. Temperature, surface gravity, metallicity, and vsin i

(Notsu, Honda, Maehara, et al. 2015, PASJ, 67,32)

II. Stellar rotation, starspots, and chromospheric activities

(Notsu, Honda, Maehara, et al. 2015, PASJ, 67,33)

III. Li abundances of superflare stars

(Honda, Notsu, Maehara et al. 2015, PASJ, 67, 85)

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III. Li abundances of superflare stars

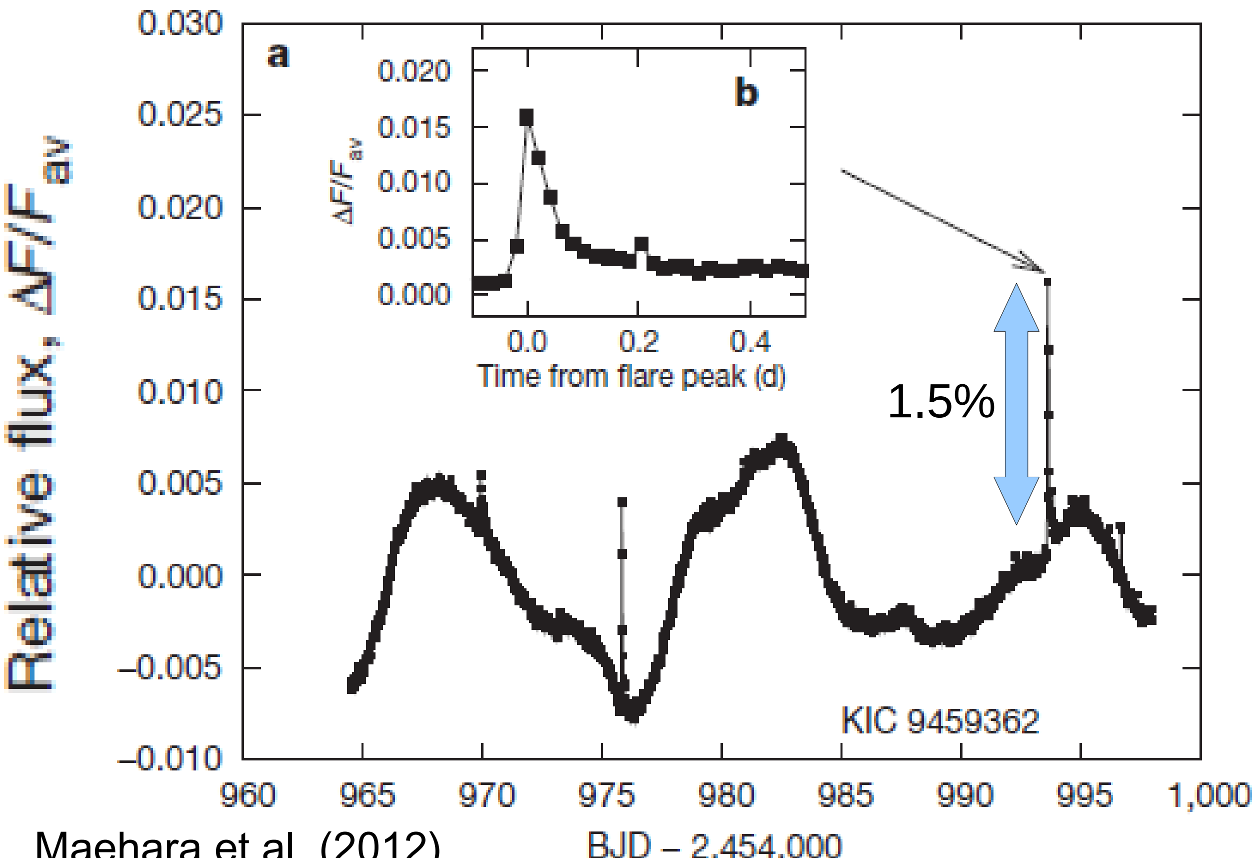
(Honda, Notsu, Maehara et al. 2015, PASJ, 67, 85)

Discoveries of superflares with *Kepler* data

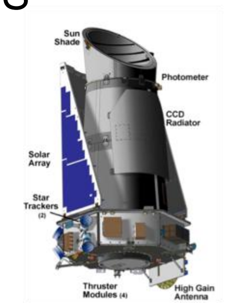
We discovered many (>1000) superflares (10^{33} ~ 10^{36} erg : 10 ~ 10^4 times more energetic than the largest solar flares) on many (~300) solar-type (G-type main sequence) stars.

(Maehara et al. 2012 Nature,
Shibayama et al. 2013 ApJS
Maehara et al. 2015 EPS)

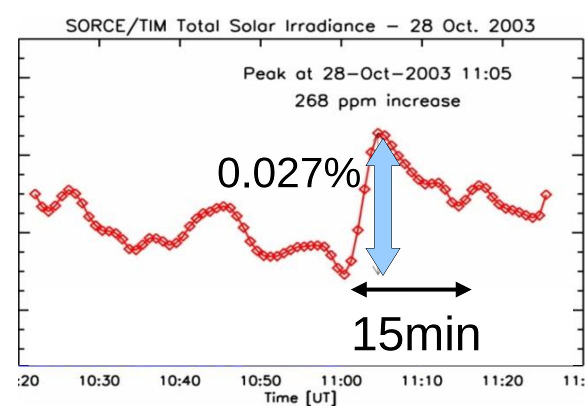
Lightcurve of superflare ↓



Maehara et al. (2012)



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



Kopp et al. (2005)

Can large starspots explain the brightness variation?

Many superflare stars show quasi-periodic brightness variations.

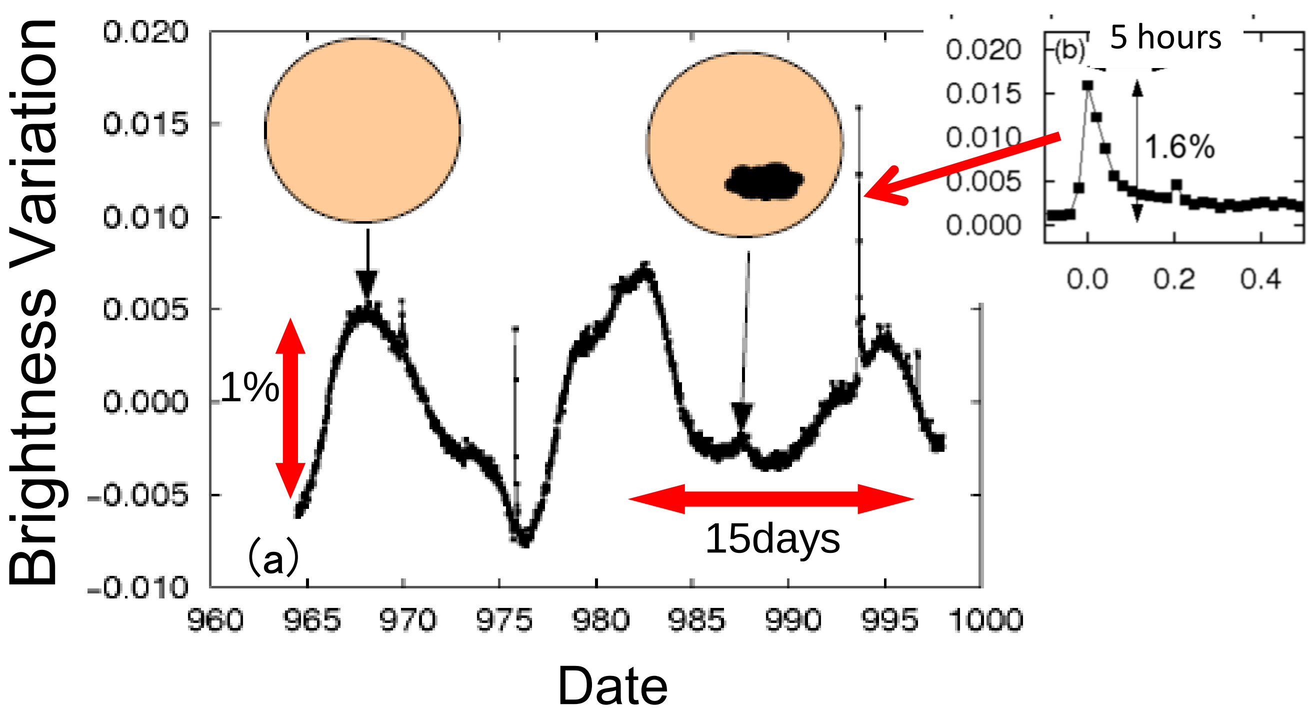
Rotation of a star with large starspots!?

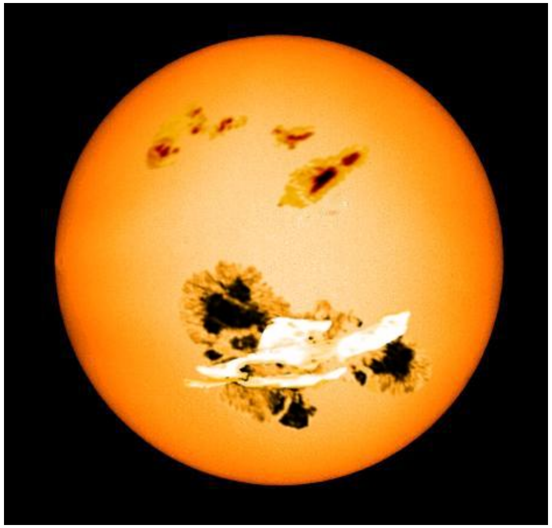
Amplitude ≒ starspot coverage

Notsu Y. et al. (2013)

Amplitude: Much larger than the effect of the rotation of the Sun with sunspots

Sun:0.01～0.1%, Superflare stars：0.1～10%





Artificial Image of a superflare star

<Remaining Questions>

Are large starspots really exist?

Can the brightness variations be explained by the rotation of stars with large starspots ?

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

Detailed spectroscopic observations !!

High Dispersion spectroscopy with Subaru/HDS

We observed 50 superflare stars.

6 nights in total (2011-2013)

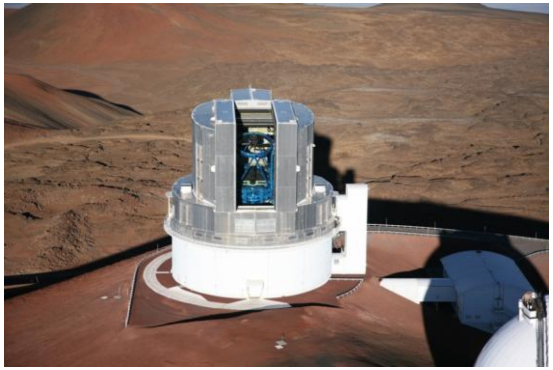
- Wavelength(λ) : 6100 - 8800Å
- R(=λ/Δλ)=50,000-100,000
- Exposure Time : 5min-2h each (V=10~14 mag)

More than half (34 stars) of 50 targets have no evidence of binary system.

-They are ordinary solar-type stars.

⇒We conduct detailed analyses for these 34 "single"stars.

Subaru Telescope (at Maunakea, Hawaii)



Reference:

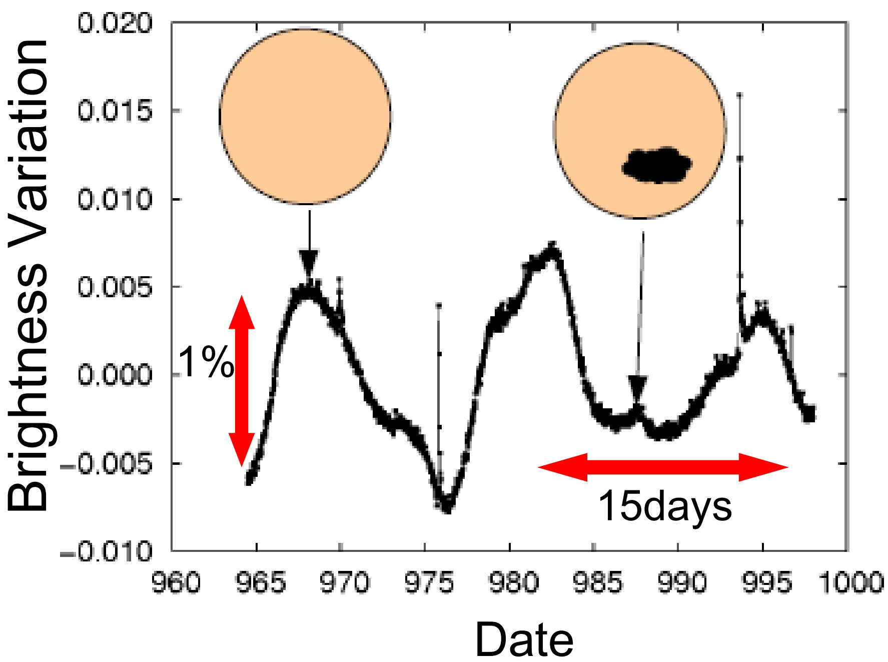
Notsu, Y. et al. (2015a, PASJ 67, 32) & (2015b, PASJ, 67, 33)

Can the brightness variations be explained by the rotation of stars with large starspots ?

- Rotation Period ⇔Brightness variation Period ?

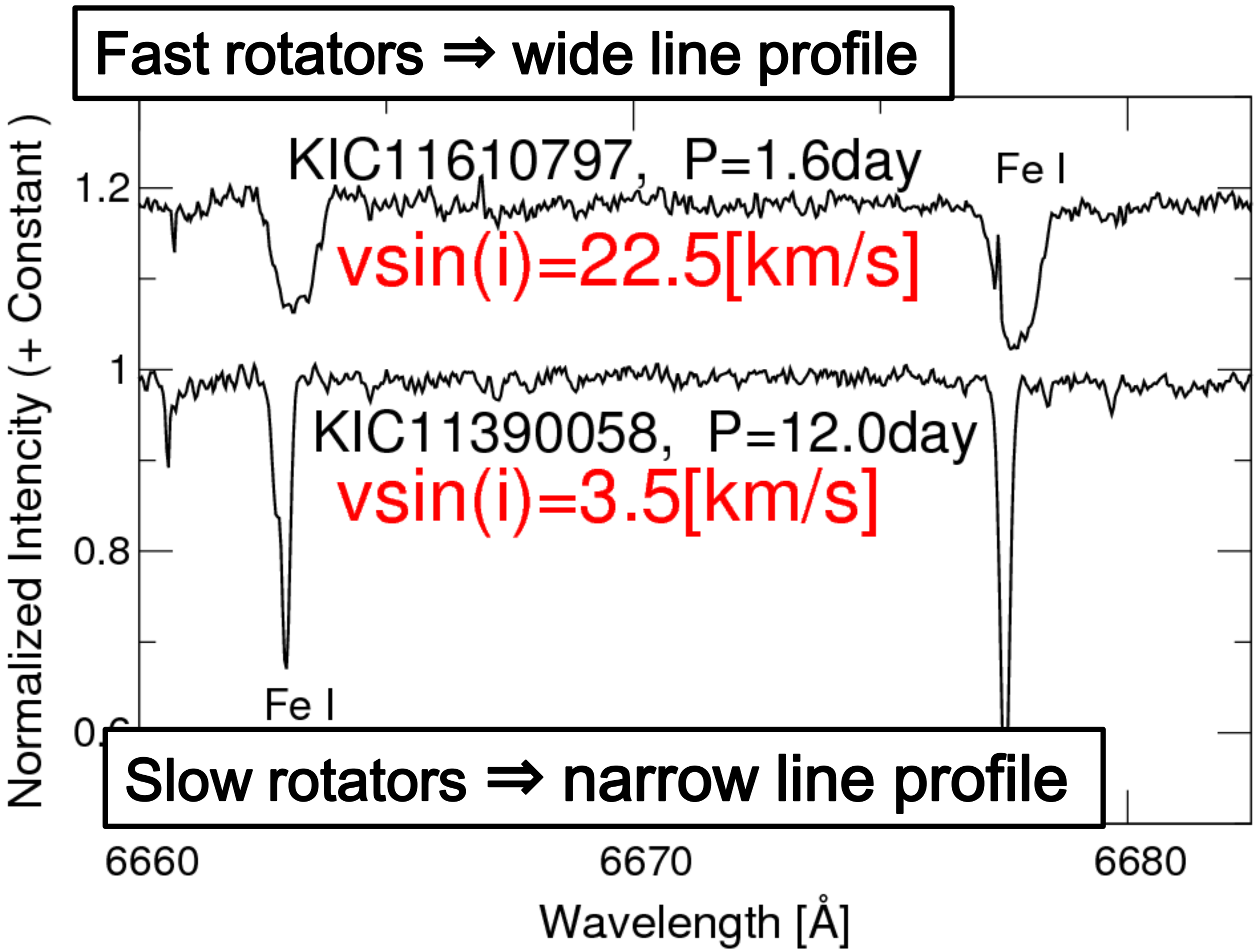
  ⇒We compared the brightness variation with the rotation velocity estimated from spectroscopic data.

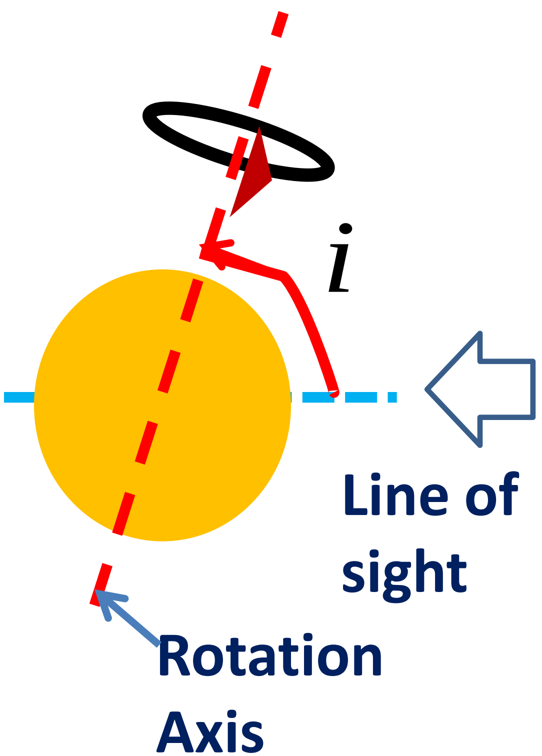
- Do superflare stars really have large starspots?



Projected rotation velocity ($v \sin i$)

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

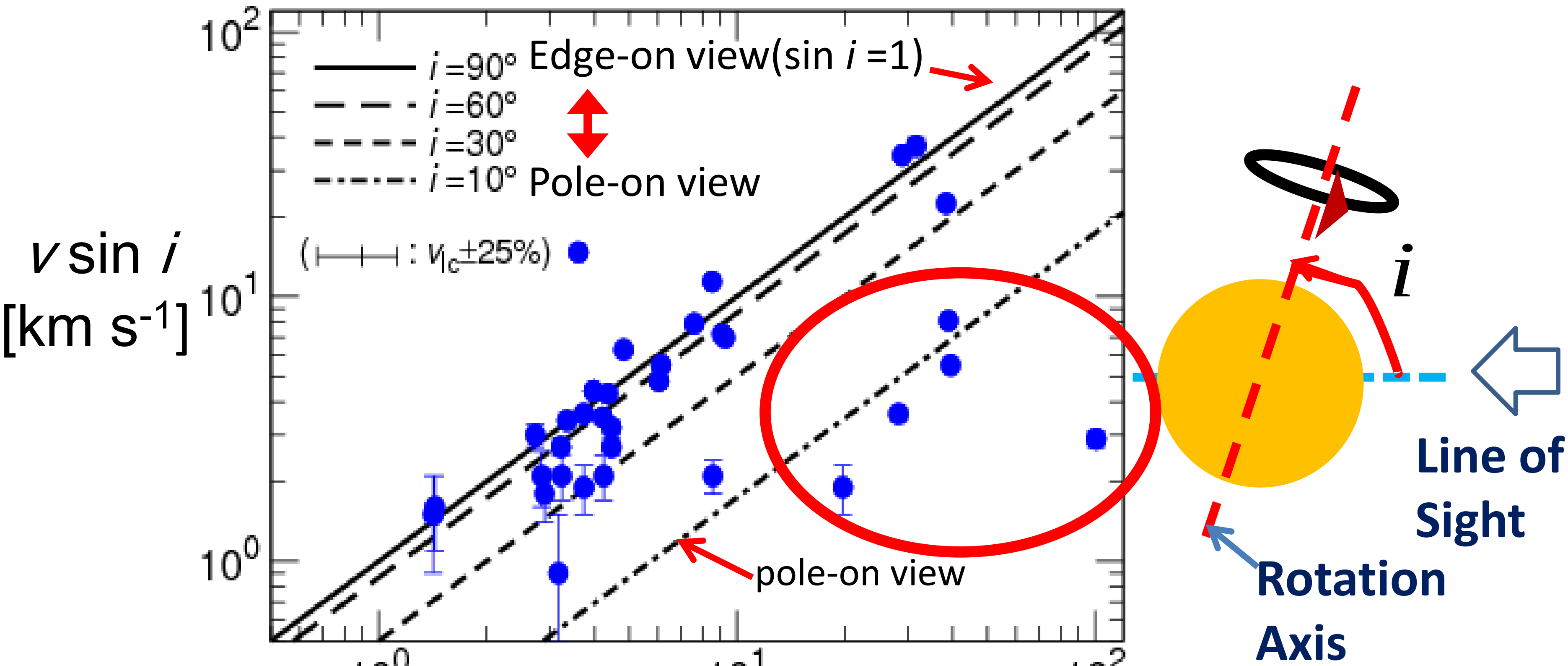




※Measurement methods
Takeda et al.(2008etc)

Rotation Period ⇔Brightness variation period ?

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



Velocity estimated from brightness variation period (V_{lc}[km s^{-1}])

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

※Sun: Vrot ~ 2 [km s^{-1}]

Flare energy vs. area of starspots

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

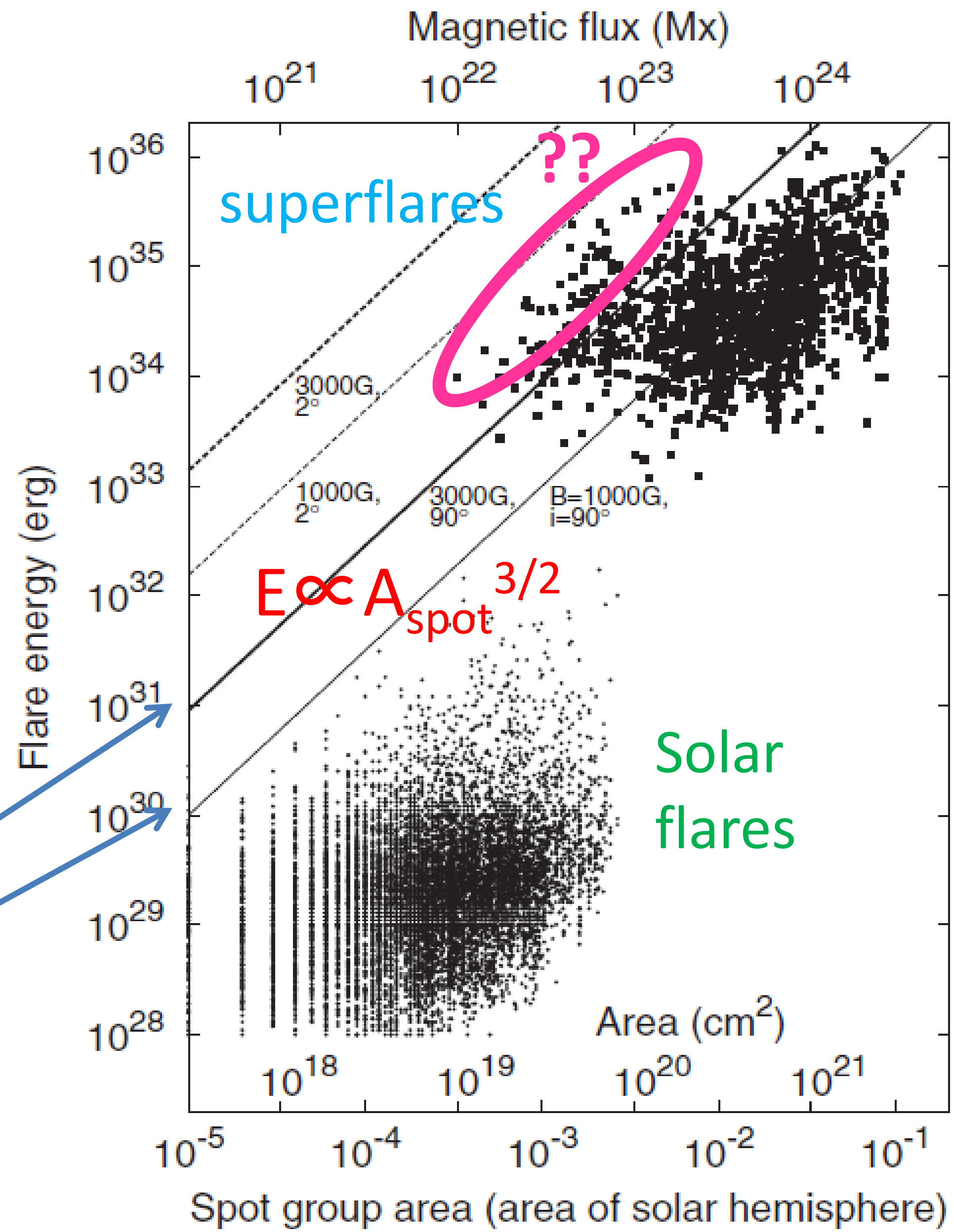
->Large starspots are necessary.

- Flares above the line may occur on the stars with low-inclination angle.

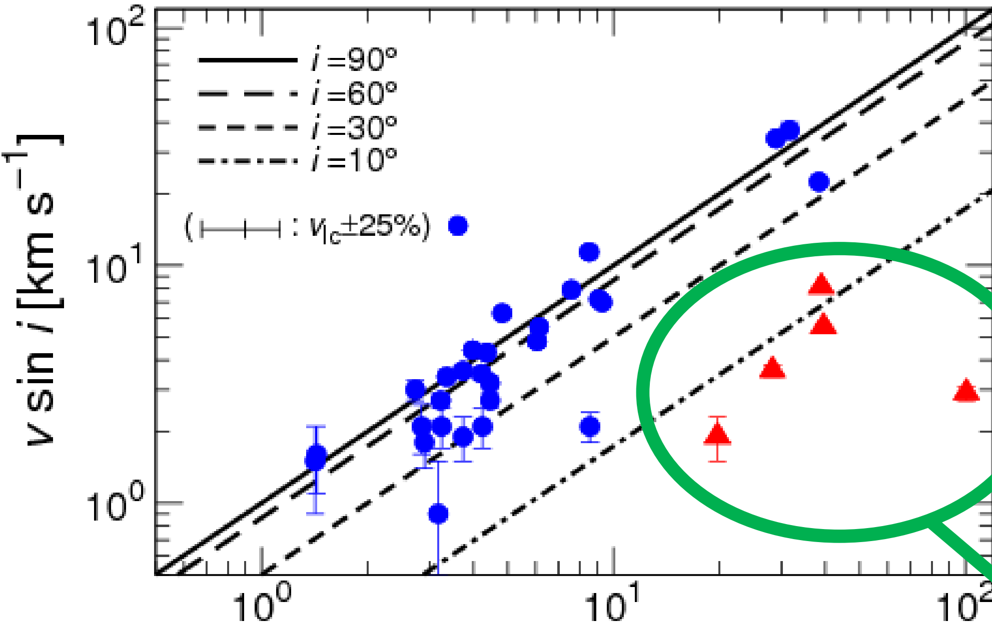
$$E_{\rm flare} \approx f E_{\rm mag} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2}{8\pi} A_{\rm spot}^{3/2}$$

f=0.1, B=3000G

f=0.1, B=1000G



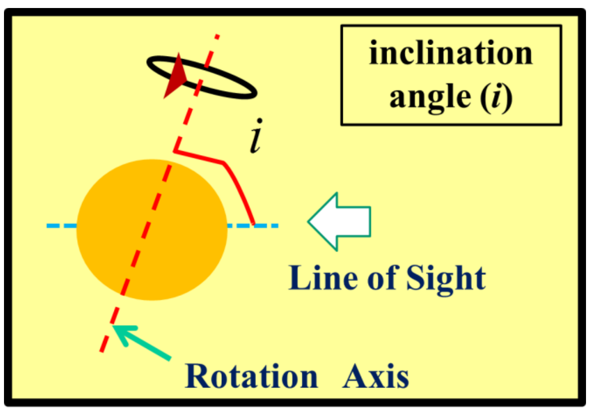
Notsu et al. (2013)

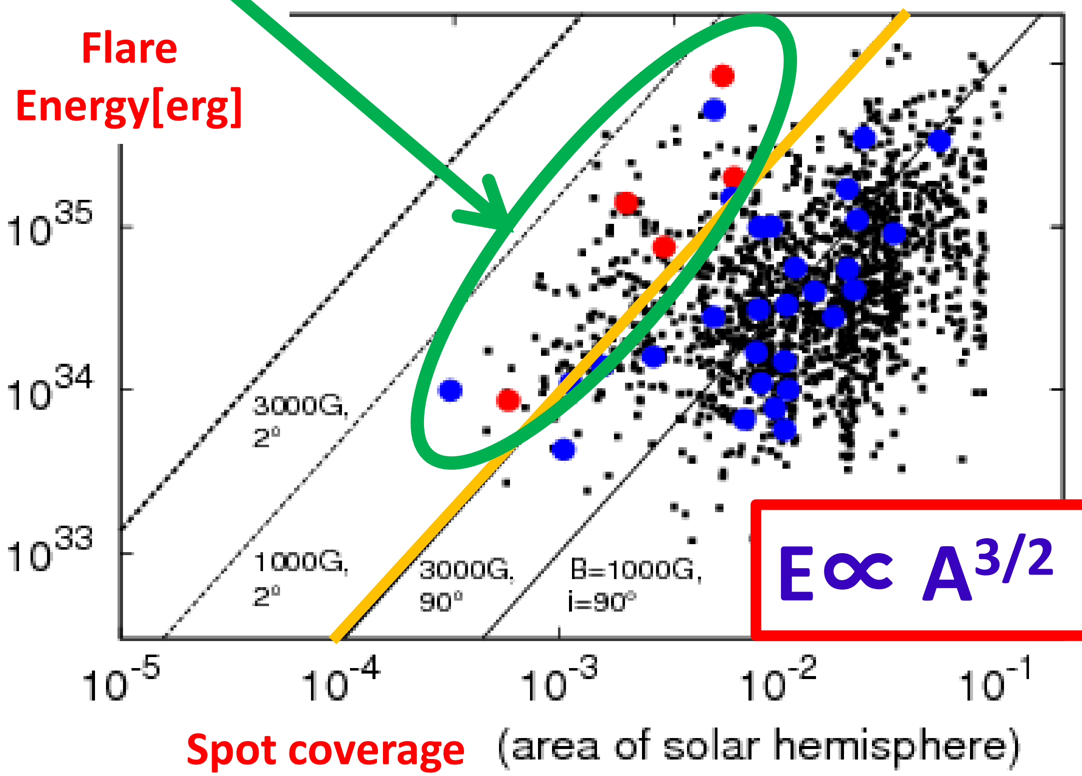


Velocity estimated from brightness variation period(V_{lc}[km s^{-1}])

These two figures are consistent !!

Low inclination angle !!





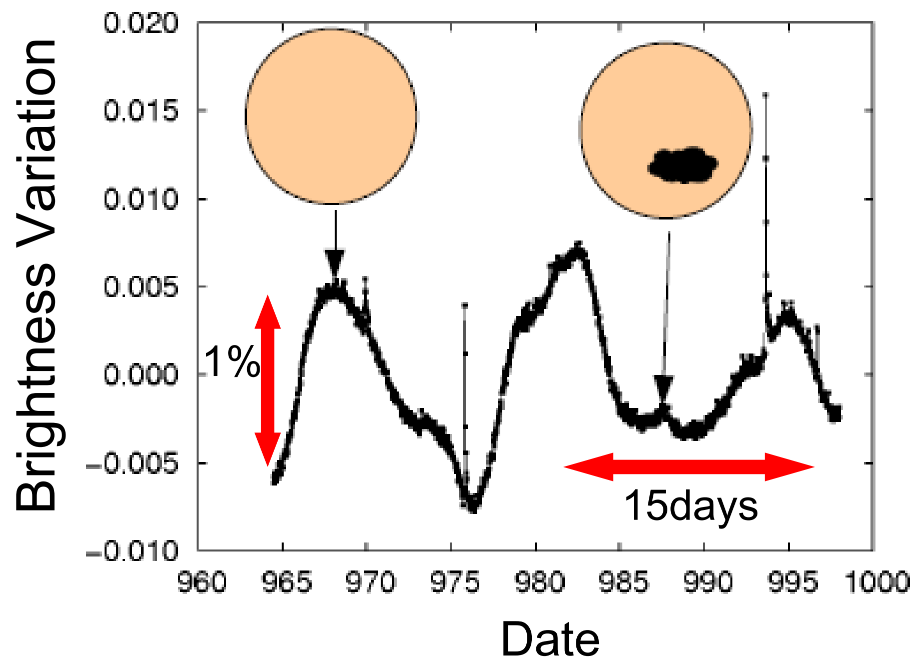
Can the brightness variations be explained by the rotation of stars with large starspots ?

- Rotation Period ⇔Brightness variation Period ?

  ⇒We compared the brightness variation with the rotation velocity estimated from spectroscopic data.

  ⇒They are consistent!!

- Do superflare stars really have large starspots?



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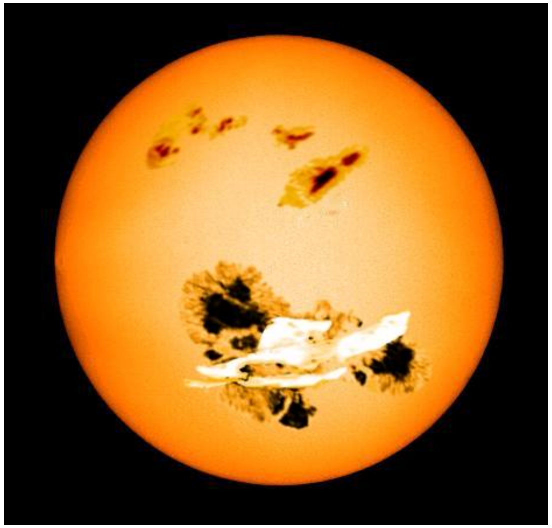
- Rotation Period ⇔Brightness variation Period ?

  ⇒We compared the brightness variation with the rotation velocity estimated from spectroscopic data.

  ⇒They are consistent!!

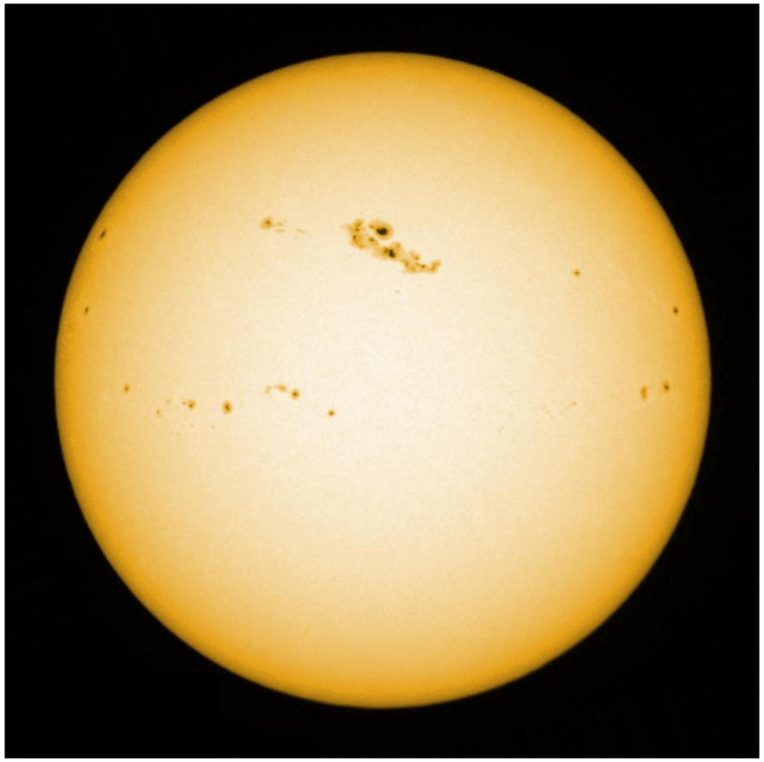
- Do superflare stars really have large starspots?

  We investigate the existence of starspots by using the intensity of Ca II lines!

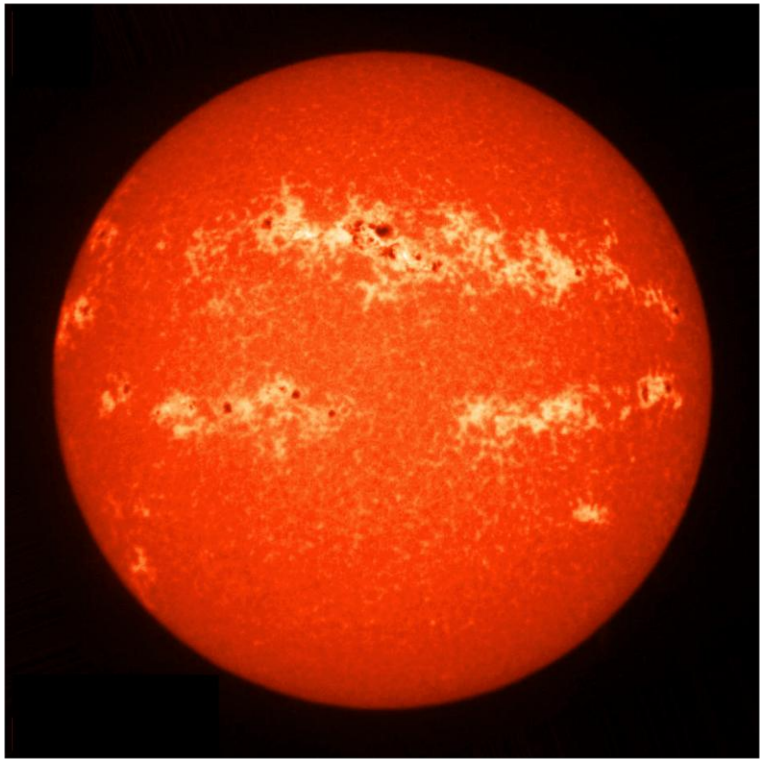


Artificial Image of a superflare star

Strong magnetic field area around starspots show strong Ca II emission!!



The Sun with visible light

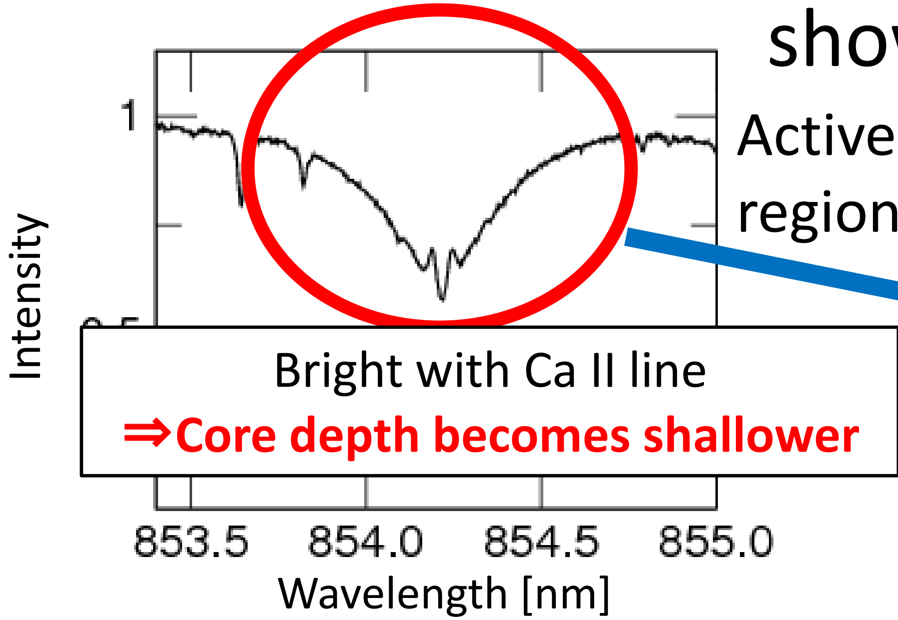


The Sun with Ca II K line

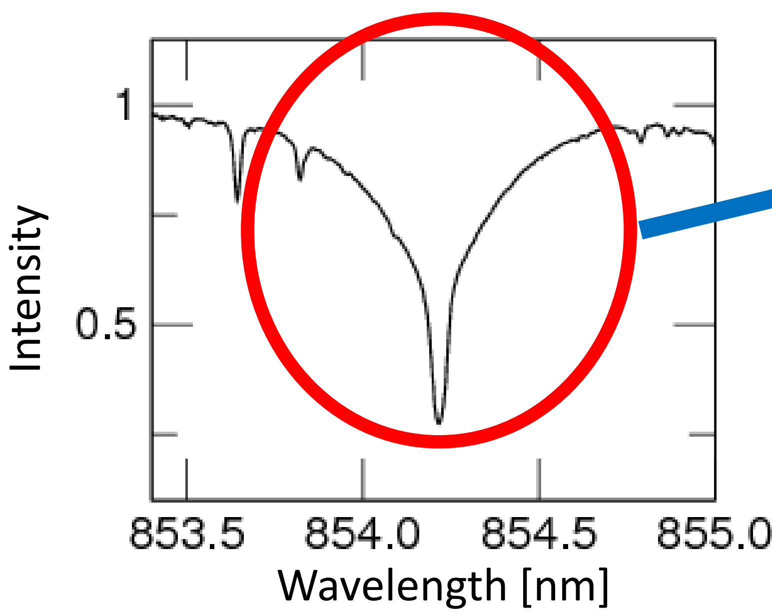
(BigBear Solar Observatory data)

We can indirectly investigate the existence of large starspots by using the intensity of Ca II lines.

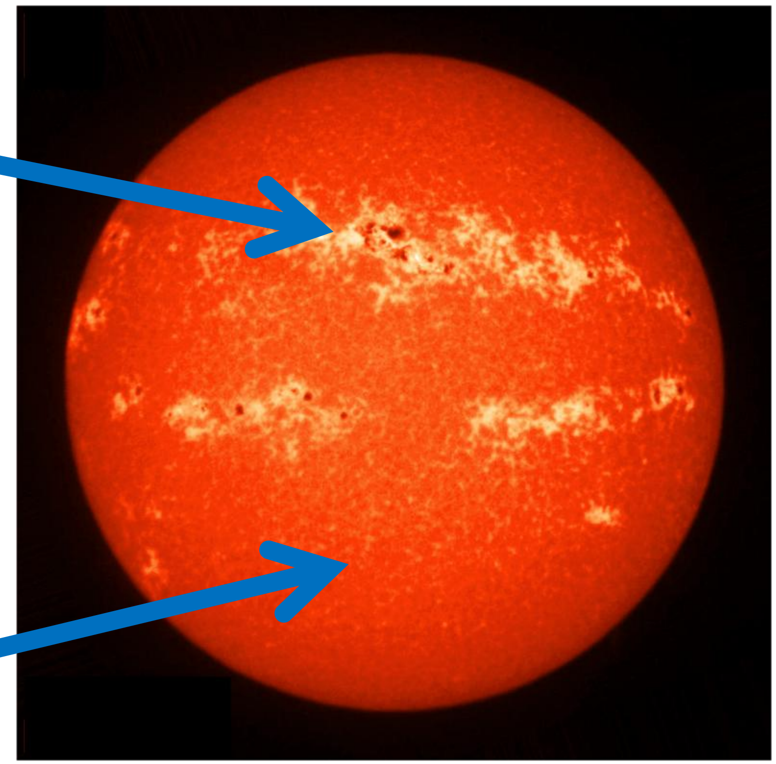
Strong magnetic field area around starspots show strong Ca II emission!!



Active region



Quiet Region

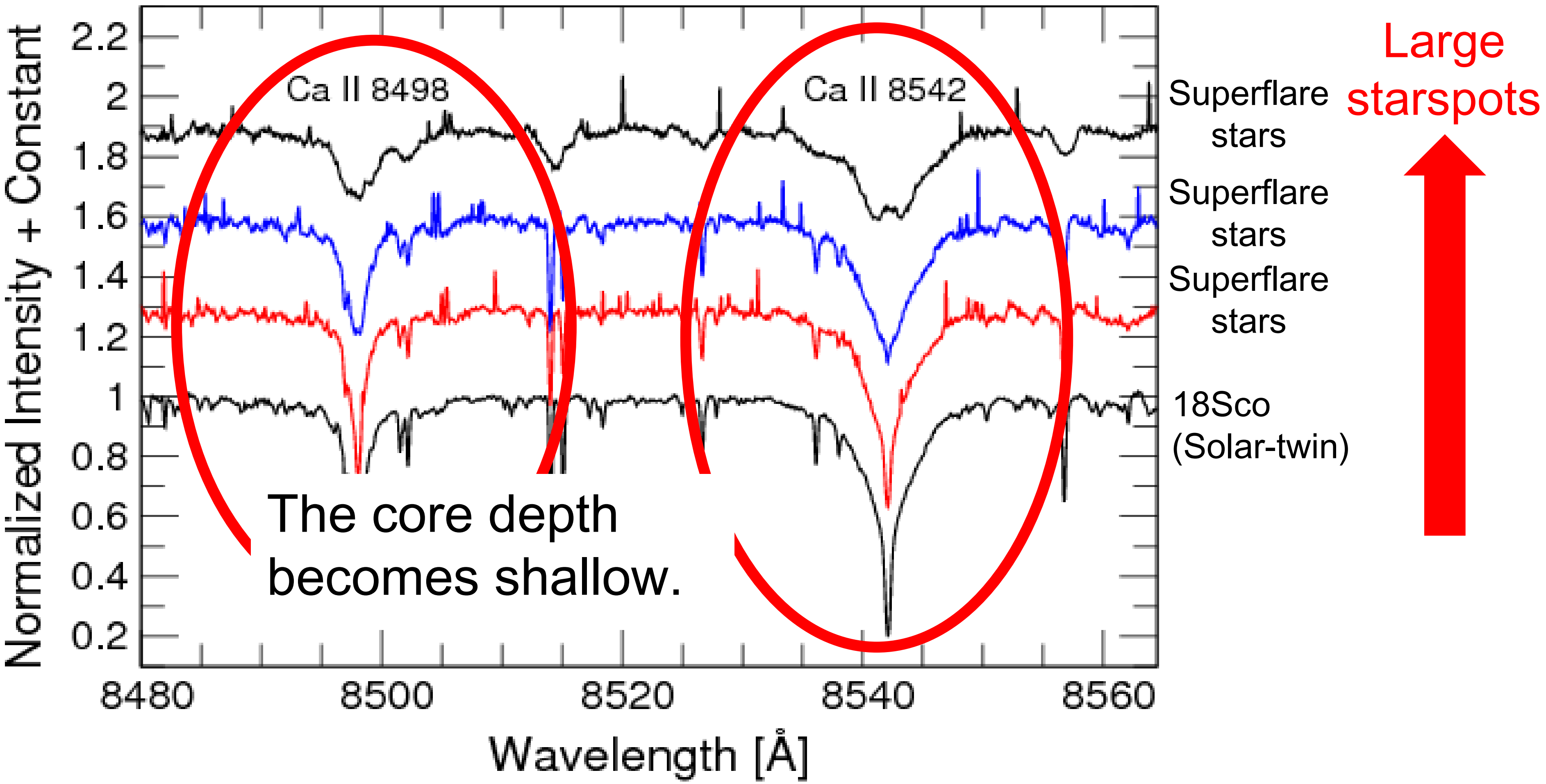


The Sun with Ca II line

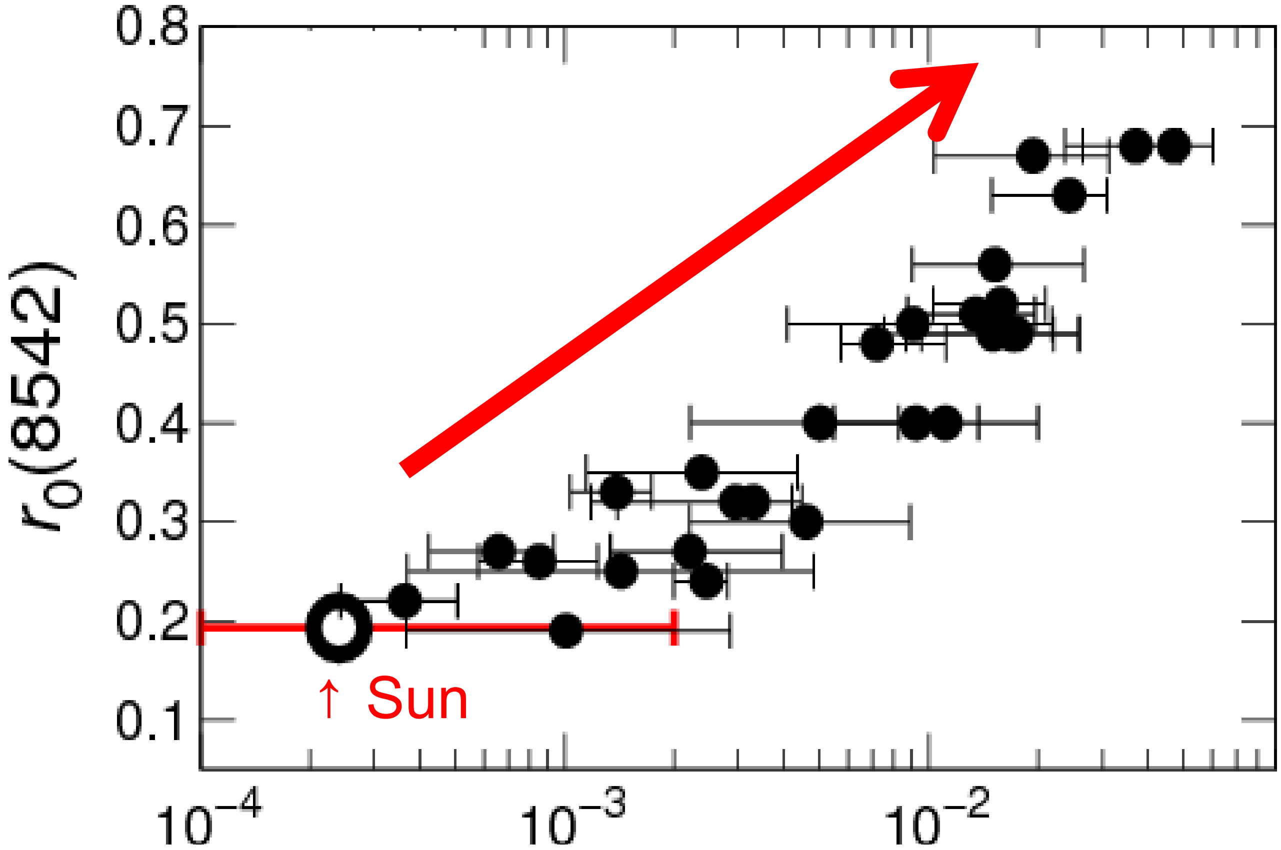
(BigBear Solar Observatory data)

Indirect estimation of starspot coverage with Ca II lines

- As the magnetic activity enhanced, the core depth become shallow because of the greater amount of the emission from the chromosphere.
- Chromospheric activity ⇒These stars have large starspots !

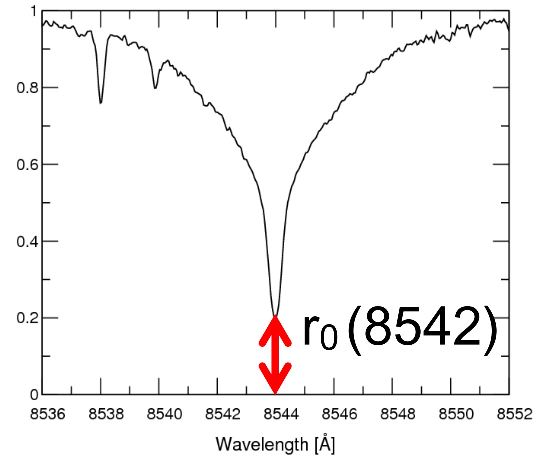


Starspot coverage vs Ca II 8542 intensity



Brightness Variation Amplitude ≒ starspot coverage

r0: Normalized intensity of Ca II 8542



All the targets that are expected to have large starspots because of their large brightness variation amplitude in Kepler data show high (Ca II) magnetic activities.

Summary of the first part

- We conducted spectroscopic observations of 50 solar-type superflare stars with Subaru/HDS.

(Notsu et al. 2015a&2015b PASJ)

- Brightness variation of superflare stars can be explained by the rotation with large starspots !!

  - Rotation Period ⇔Brightness variation Period

    ⇒They are Consistent !

  - Correlation between the brightness variation amplitude and the intensity of Ca II lines

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(Honda, Notsu, Maehara et al. 2015, PASJ, 67, 85)

Are superflare stars young or old stars ?

- Our spectroscopic data (Notsu+2015a&b PASJ)
  - We confirmed that the many of the target superflare stars are ordinary solar-type stars.
  - Some target stars rotate slowly. (v_{rot} < 5 km/s & P_{rot}> 10days)

  ⇒ Can slowly-rotating old stars like our Sun be superflare stars !?

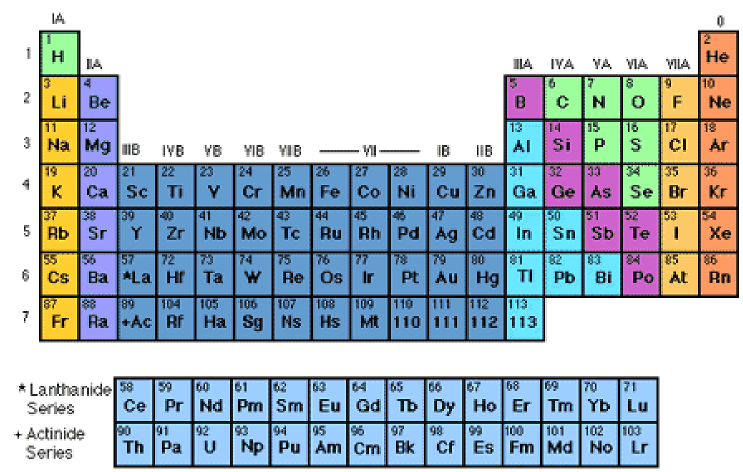
- However, estimation of stellar age is difficult…

  ⇒ Li abundance analysis can be useful!?

  (Our spectroscopic data include Li I 6708Å line)

Lithium

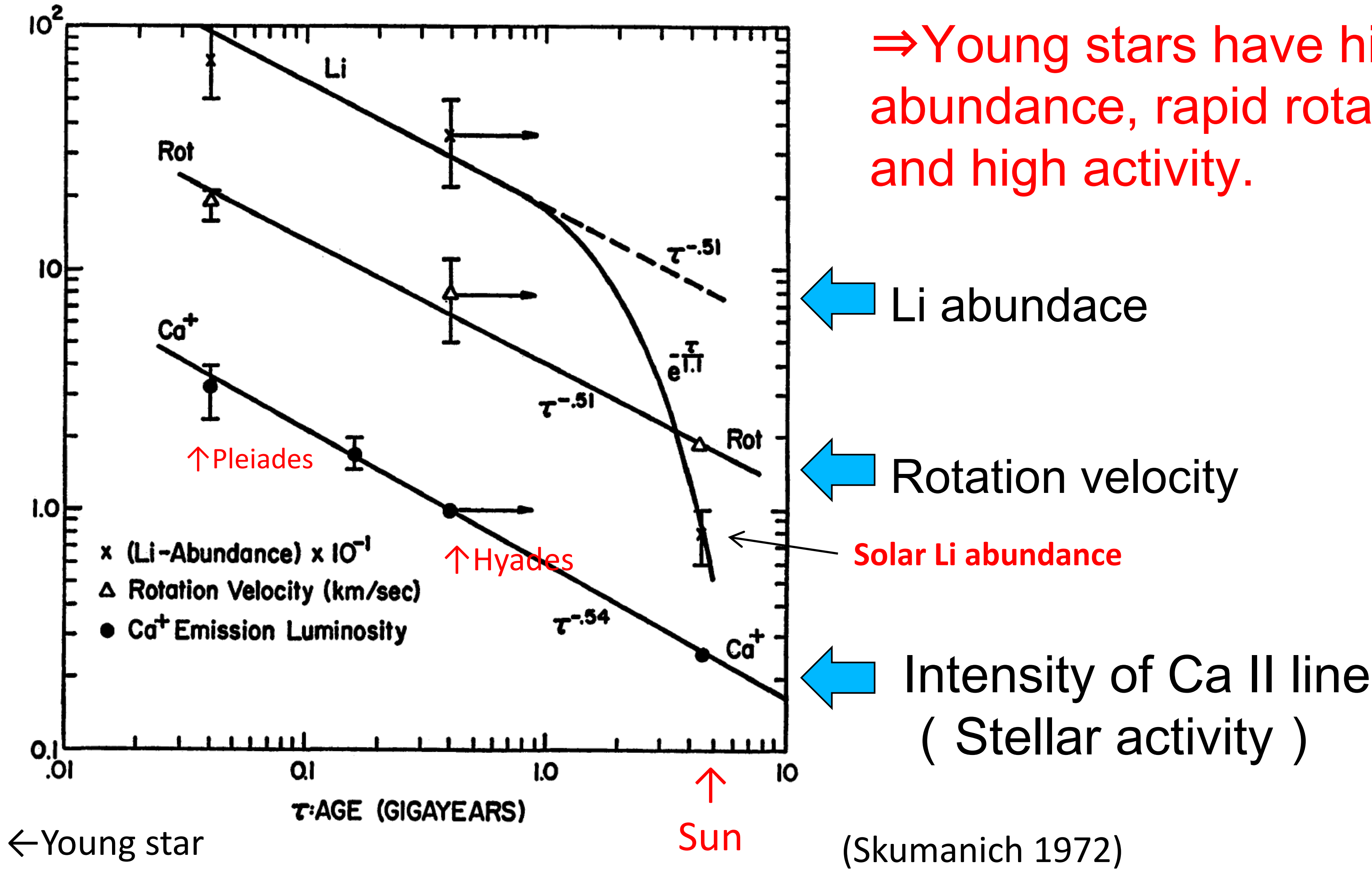
- Light element, atomic number 3
- Easily destroyed in the stellar interiors
  - higher than ∼2.5×10^6K (^{7}Li), 2.0×10^6K (^{6}Li)
  - diagnostic of age in late-type stars (effects of convection zone)
- 2 stable isotopes (^{6}Li, ^{7}Li)
  - ^{7}Li > 90%
- One useful line 6708 Å



Li abundance can reflect the age of solar-type stars.

- Lithium is easily destroyed in the hotter region of stellar atmospheres.

⇒Young stars have high Li abundance, rapid rotation, and high activity.



(Skumanich 1972)

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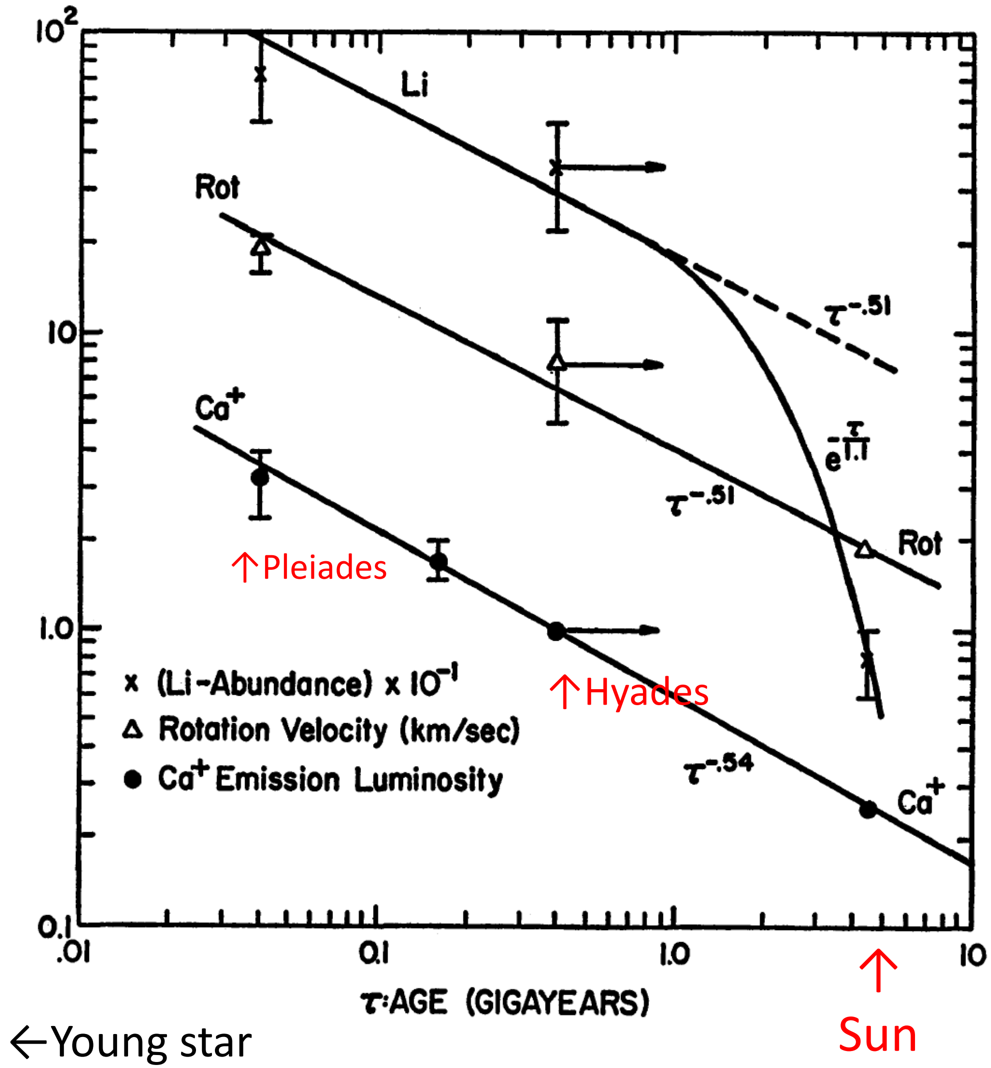


(Skumanich 1972)

⇒Young stars have high Li abundance, rapid rotation, and high activity.

⬇

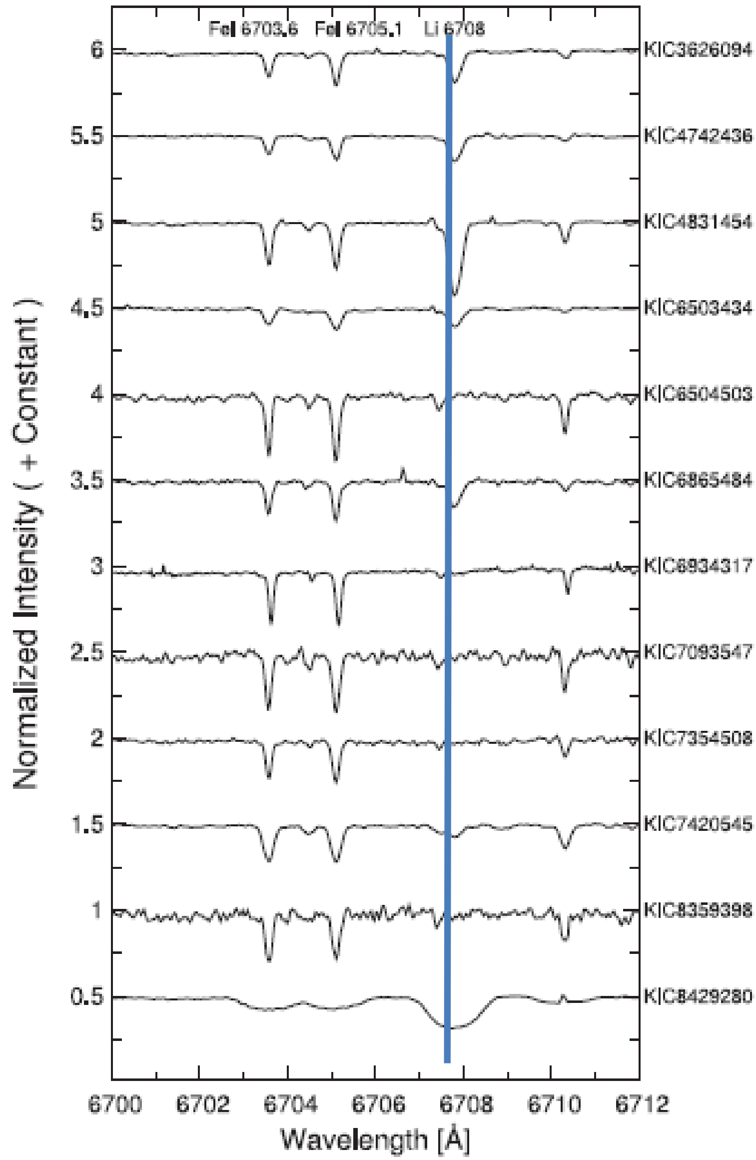
We can roughly estimate the age of superflare stars using Li abundance.

Sample spectra of Li I 6708Å regions

- We derive the Li abundances for the 34 single superflare stars.

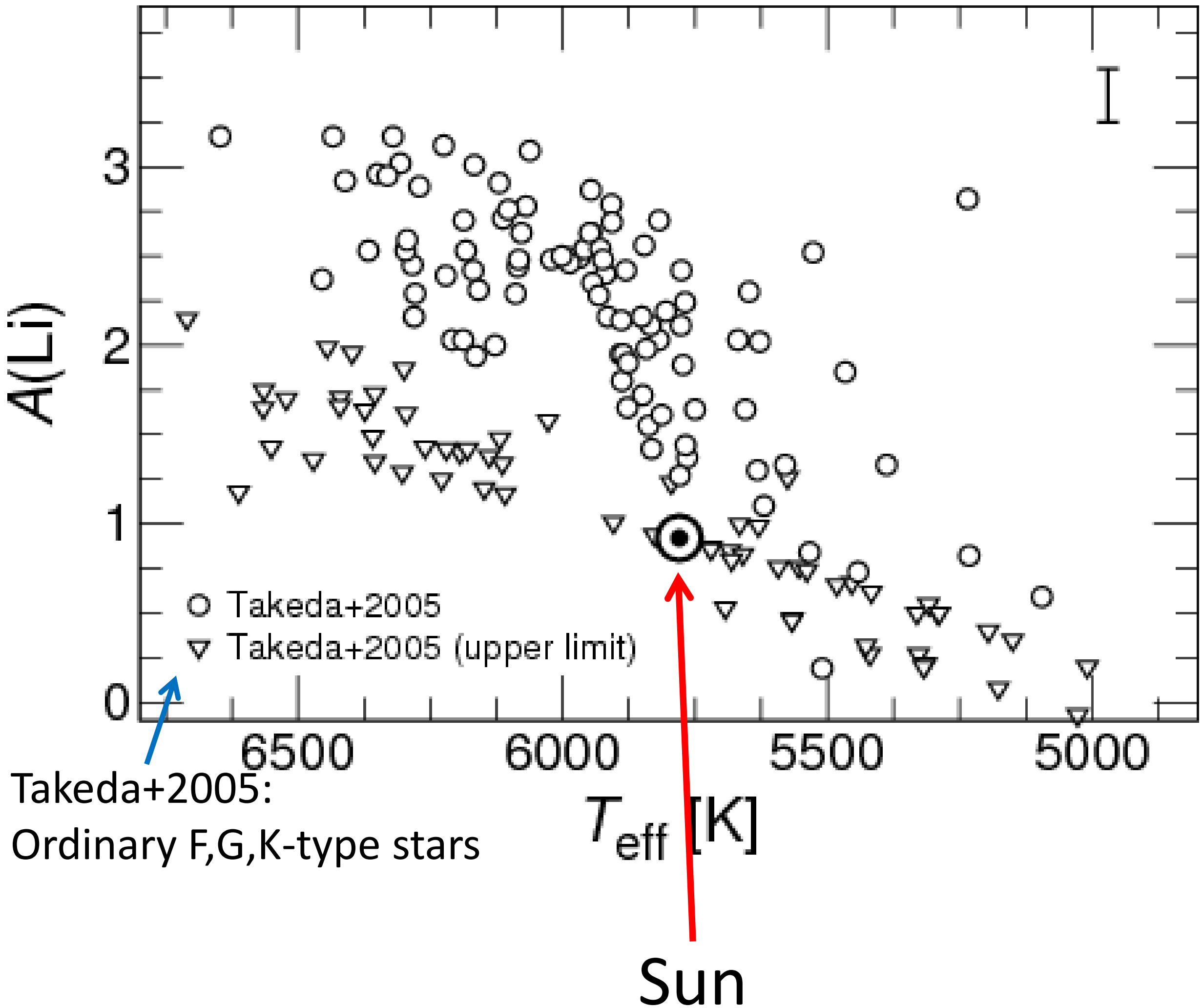
- Using the stellar parameters (e.g., T_{eff}, log g, [Fe/H]) determined by Notsu+2015a

- We used the spectral fitting using the analysis program SPTOOL (Takeda 1995)



Honda et al. 2015

Lithium abundances vs. T_{eff} of ordinary solar-type stars



Takeda+2005:
Ordinary F,G,K-type stars

$A(Li) = \log_{10}(N_{Li}/N_H) + 12.0$

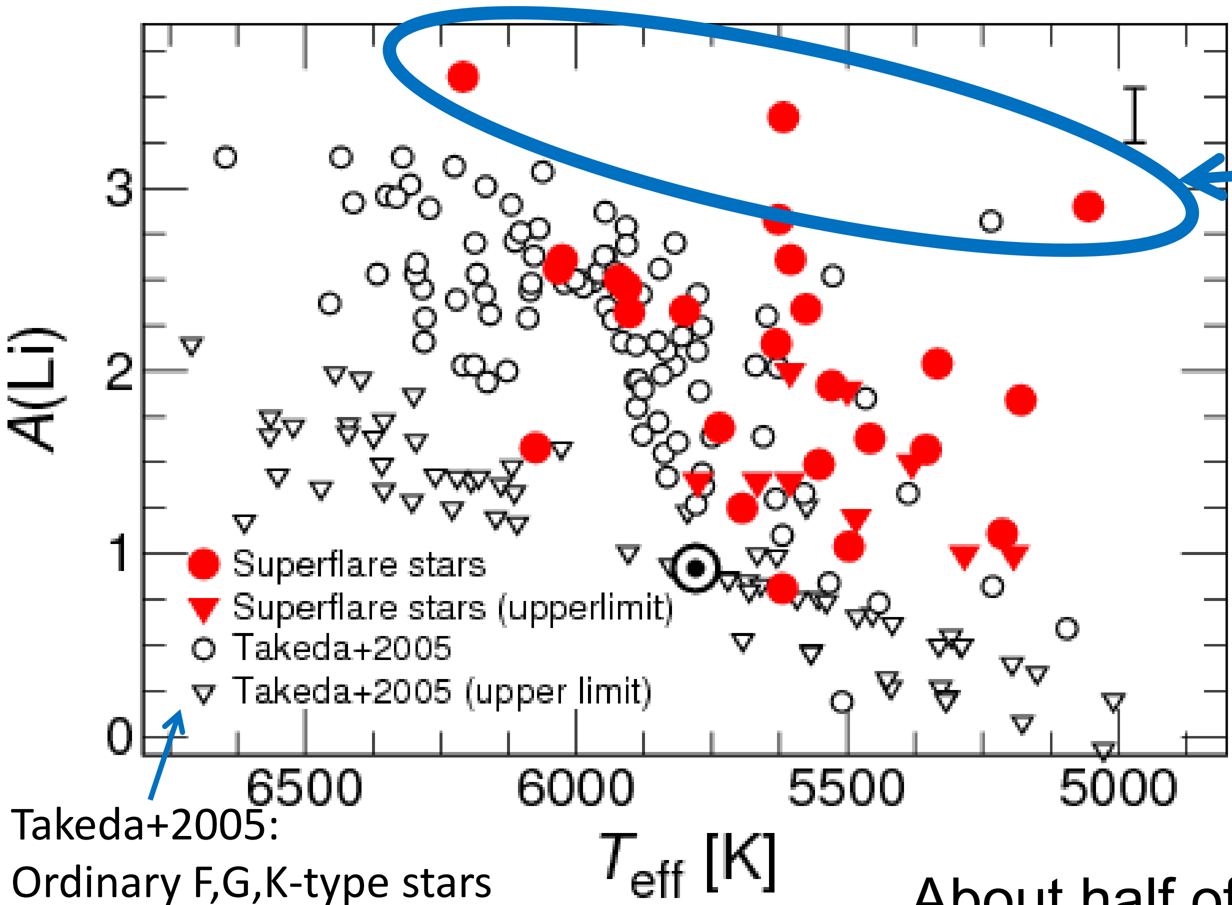
<u>T_{eff} < 5500K</u>

Development of the convection zone
⇒ Li abundance decreases

<u>T_{eff} ~ 5780 K (around the Sun)</u>

- Large difference
- The Sun has low Li abundance

Lithium abundances vs. T_{eff} of superflare stars



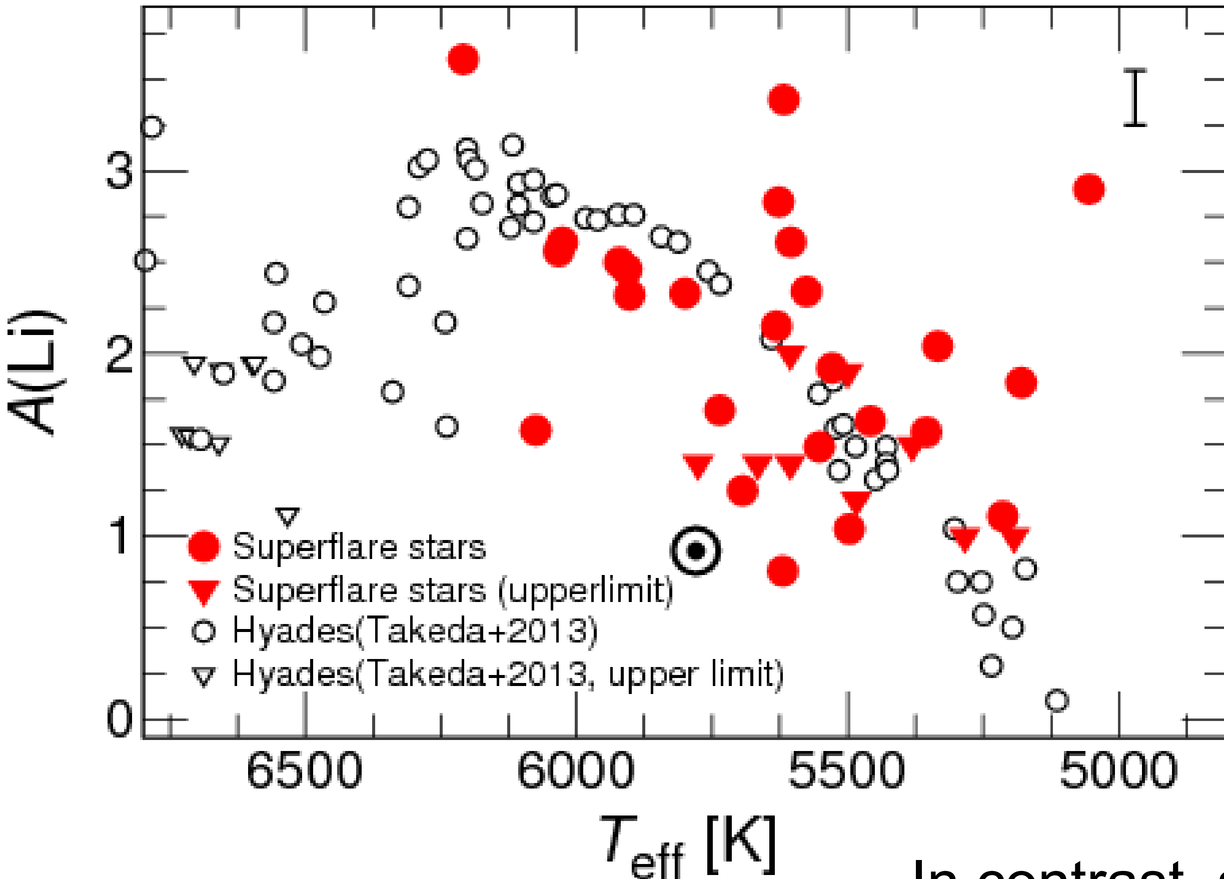
These stars show an especially high value of Li, to be very young stars.

Takeda+2005: Ordinary F,G,K-type stars

About half of the target superflare stars do not show high values of Li abundance compared with solar-type stars.

$A(Li) = \log_{10}(N_{Li}/N_H) + 12.0$

Lithium abundances vs. T_{eff} with Hyades Cluster (Age = 6.25×10^8 year)

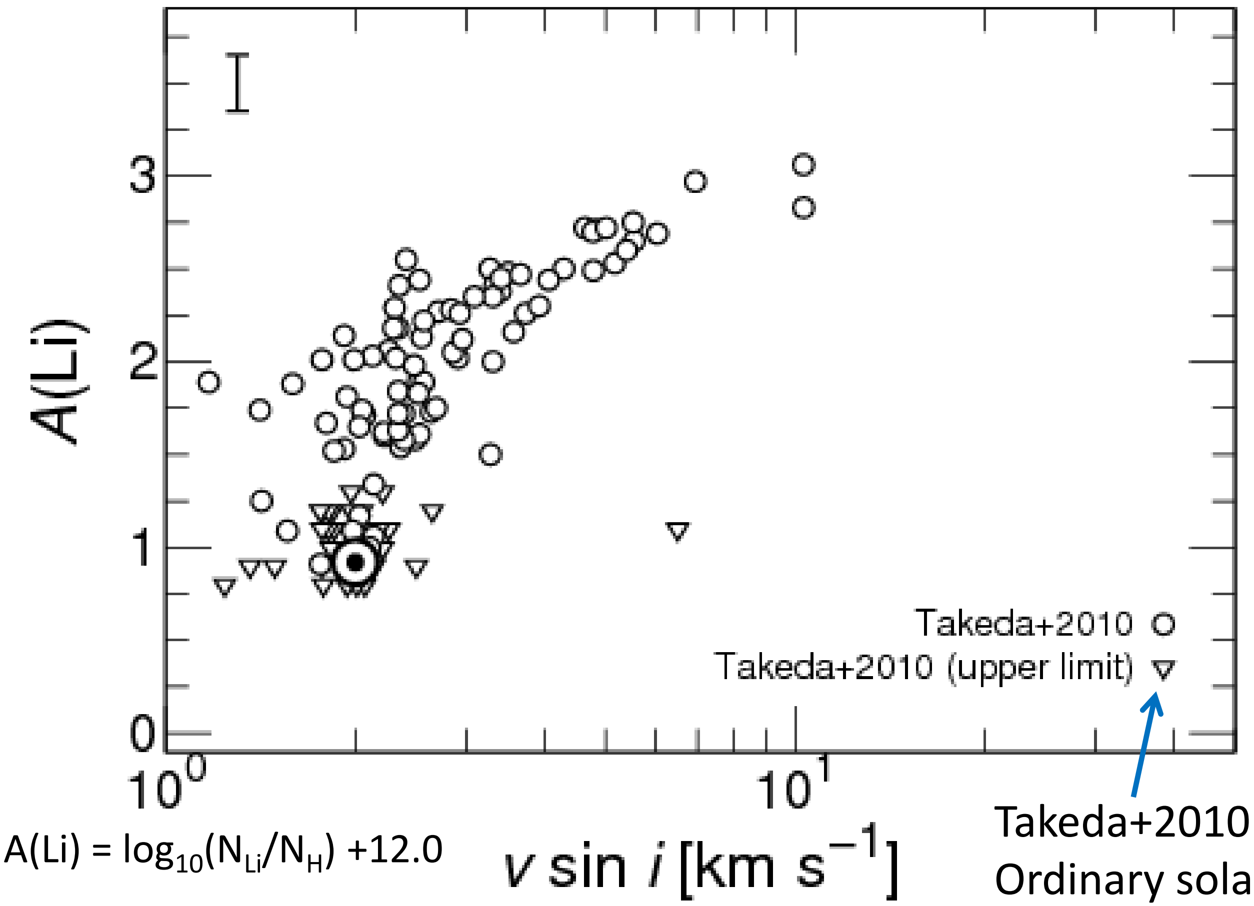


About half of stars show high Li (=younger) compared with Hyades cluster (Age = 6.25×10^8 year)

In contrast, some of the target superflare stars show lower Li abundance (=older) compared with Hyades cluster.

$A(Li) = \log_{10}(N_{Li}/N_H) + 12.0$

Projected rotation velocity (v sin i) vs. Lithium of ordinary solar-type stars



$A(Li) = \log_{10}(N_{Li}/N_H) + 12.0$

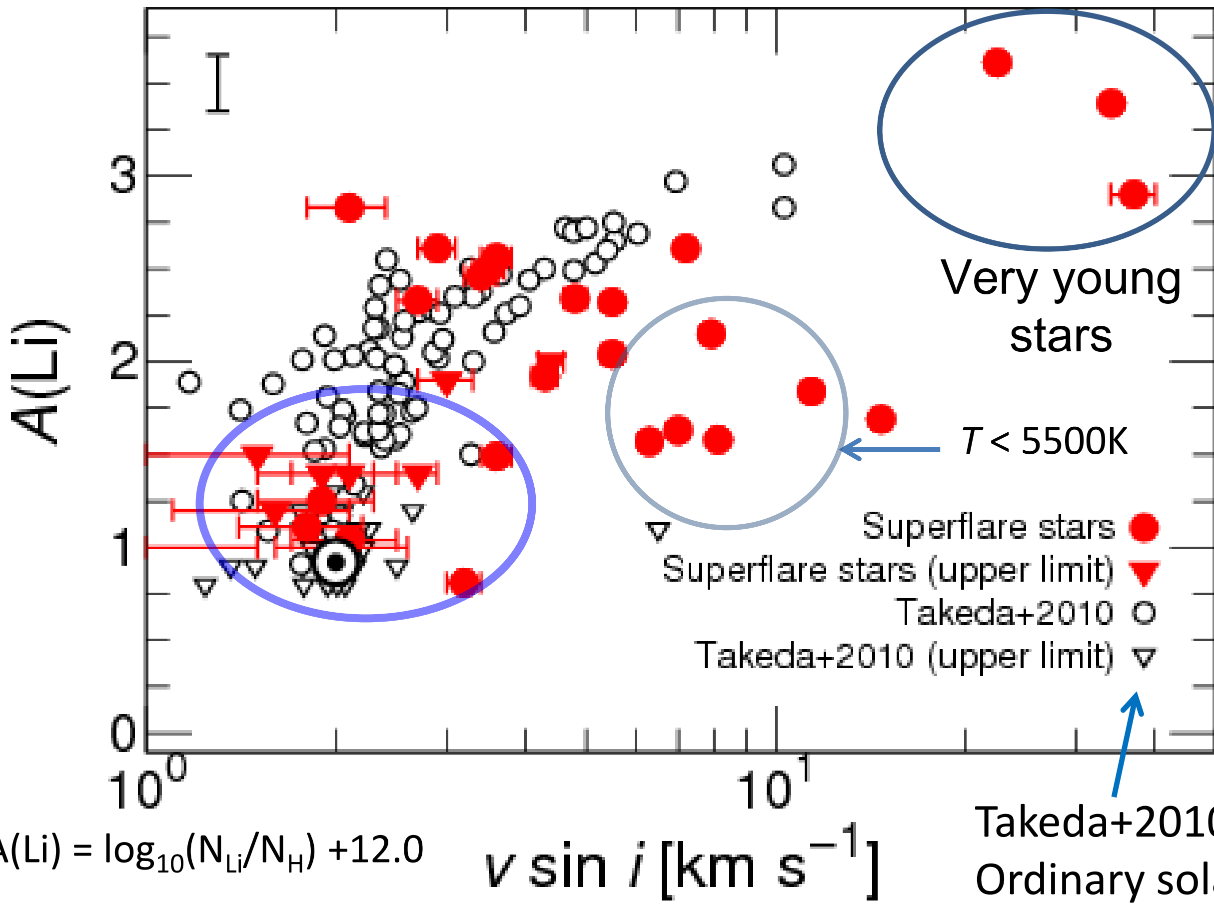
Takeda+2010:
Ordinary solar-type stars

In general, the stellar rotation has a correlation with the age and activity.
(cf. Skumanich 1972)

Young stars rapidly rotate and Li abundance is high

Old stars slowly rotate and Li abundance is low

Rotation velocity (v sin i) vs. Lithium of superflare stars



$A(Li) = \log_{10}(N_{Li}/N_H) + 12.0$

Takeda+2010:
Ordinary solar-type stars

Some superflare stars show small vsini and low Li abundance.

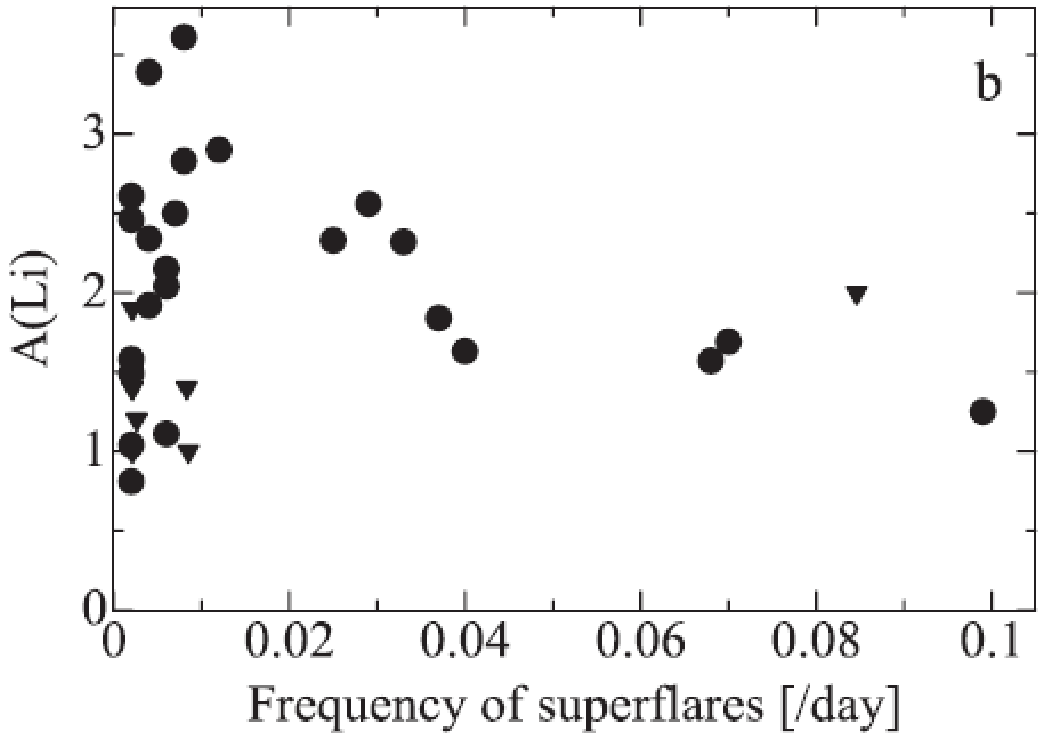
This results may indicate that those stars are not young.

Superflare stars are not necessarily young.

Li abundances and Frequency of superflares

^{6}Li could possibily be produced by the reaction ^{4}He (^{3}He, *p*) ^{6}Li in situ by solar like flares. (e.g., Tatischeff & Thibaud 2007)

Superflare stars could be good objects to investigate whether flare can make Li or not.



No positive correlation between flare frequency and Li abundance
→ No evidence of Li production by superflare.

In this context, it is also important to investigate the ratio of ^{6}Li to ^{7}Li in superflare stars in the future.

Li abundance analyses of superflare stars

Honda+2015, PASJ

- We have estimated the Li abundance of superflare stars and investigated the correlations of Li abundance with stellar parameters.

- Our spectroscopic observations show that slightly young (rapid rotation) solar-type stars tend to produce superflares, but that old superflare stars exist.
- There is a possibility that superflares could be generated on our present Sun.

- We could not find any evidence of nucleosynthesis of Li in stellar flares from our observations.
  - Li isotope abundances of superflare stars would clarify the issue of Li production in stellar flare.

Summary

- We conducted spectroscopic observations of 50 solar-type superflare stars with Subaru/HDS.

  (Notsu et al. 2015a&2015b PASJ, Honda et al. 2015 PASJ)

  - Brightness variation of superflare stars can be explained by the rotation with large starspots.

    (v sin i, choromospheric lines(Ca II))

  - Old slowly-rotating stars like the Sun can have superflares

    (rotation, Li abundances)

.

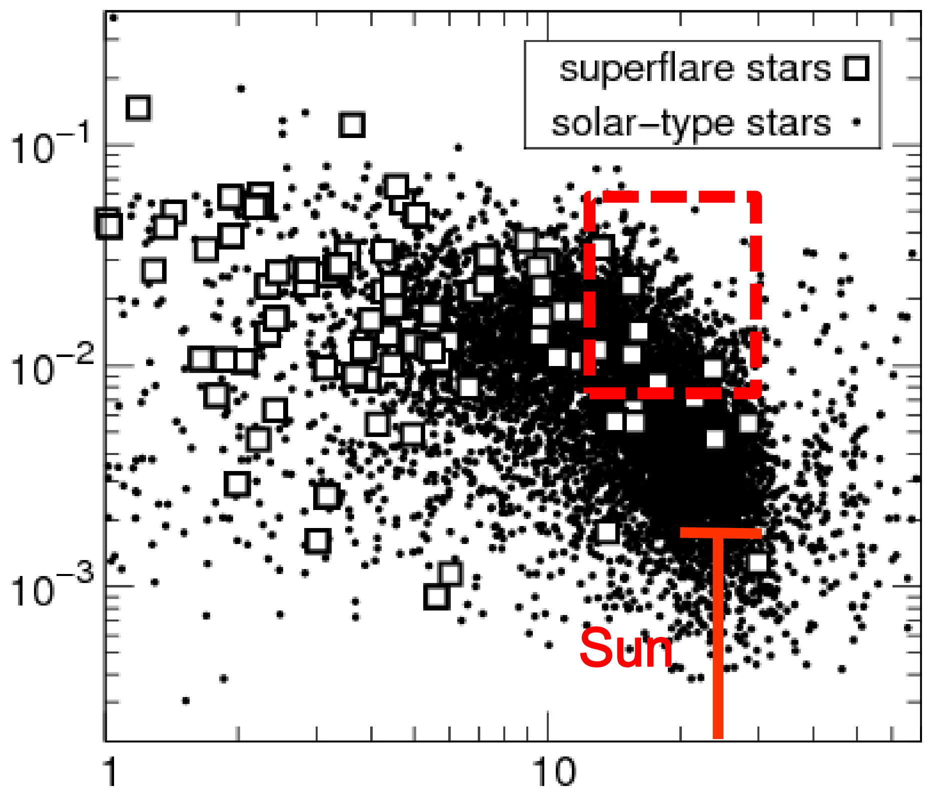
(Future research)
Can the superflare occur on the Sun ?

→<u>Why slowly-rotating Sun-like stars have large starspots ?</u>

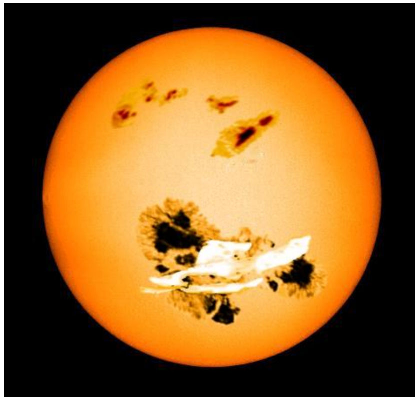
- Long-term activity change ?
- Lifetime of starspots ??

→ Monitoring observations !!

Starspot coverage



Rotation period (day)



Maehara et al. 2016 in prep

Our Future Plans

Monitoring observations with

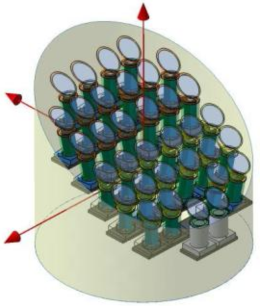
Kyoto-Okayama 3.8m new telecope

2018 or 2019? ~

- Continuous Monitoring of many superflare stars and stars with large starspots.
  (e.g., Investigating long-term changes of large starspots, differential rotation, etc)

Collaborations with other telescopes and satellites

- TESS (2017-) and PLATO (2024-) after Kepler:
  Discovering more bright superflare stars
  ~Synergy with 3.8m telescope



The details are in the final day discussions !!

Summary

・We conducted spectroscopic observations of 50 solar-type superflare stars with Subaru/HDS.

(Notsu et al. 2015a&2015b PASJ, Honda et al. 2015 PASJ)

- Brightness variation of superflare stars can be explained by the rotation with large starspots.

(v sin i, choromospheric lines(Ca II))

- Old slowly-rotating stars like the Sun can have superflares

(rotation, Li abundances)

Future: Continuous Monitoring of large starspots are important

The details are in the final day discussions !!