High Dispersion Spectroscopy of Solar-Type Stars showing Superflares

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Solar flares

- Solar Flares

▪Most energetic explosions on the surface of the Sun

▪Magnetic energy release

▪Hα, X-ray emission etc

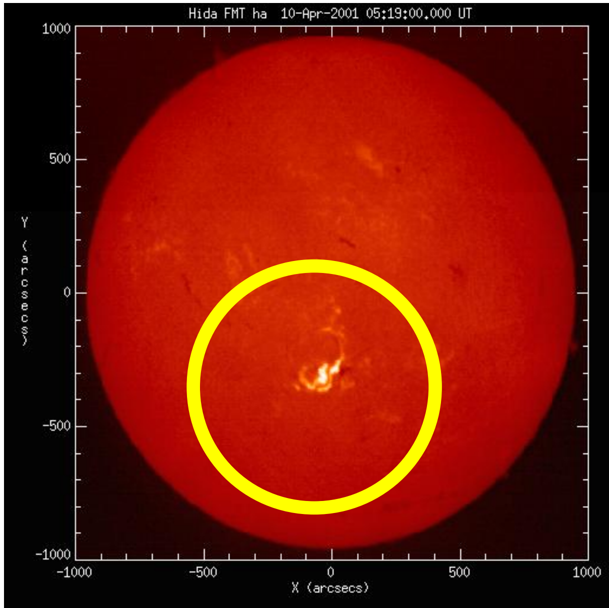
▪Time scale ~ 1min – 1hour

▪Total energy ~ **10^{29} - 10^{32}erg**

Understanding solar flares is the first step of investigating stellar flares.

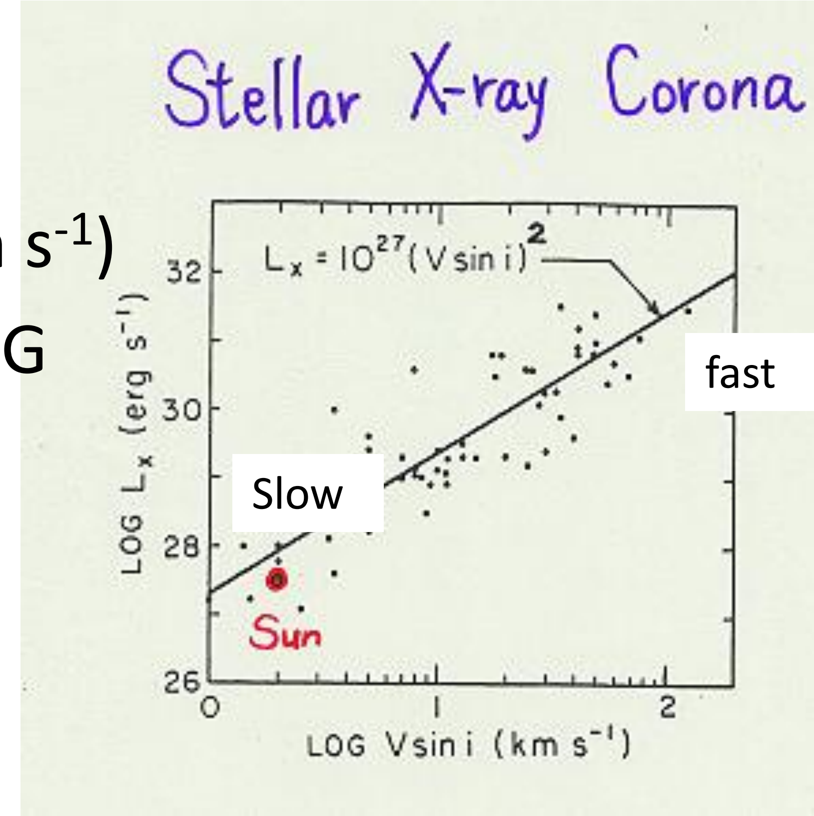
Yohkoh / ISAS
Soft X-ray (1keV)

Hα 10,000K
Hida/Kyoto Univ.



Stellar flares

- **Young** stars or **close binary** stars often produce **superflares**.
  10- 10^6 times more energetic (**10^{33} - 10^{38}erg**) than the largest solar flares (~10^{32}erg).



(Pallavicini et al. 1981)

- Such stars **rotate fast** (10 -100 km s^{-1}) and the magnetic fields of a few kG are distributed in large regions on the stellar surface.

In contrast, the sun slowly rotates (~2 km s^{-1}) and the magnetic fields are weak.

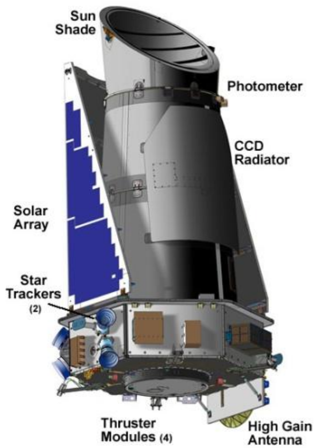
⇒ Superflares cannot occur on Sun-like stars ･･･??

Superflares on solar-type stars??

But amazingly, Schaefer et al. (2000) discovered 9 superflares on ordinary solar-type (G-type main sequence) stars with slow rotation!!

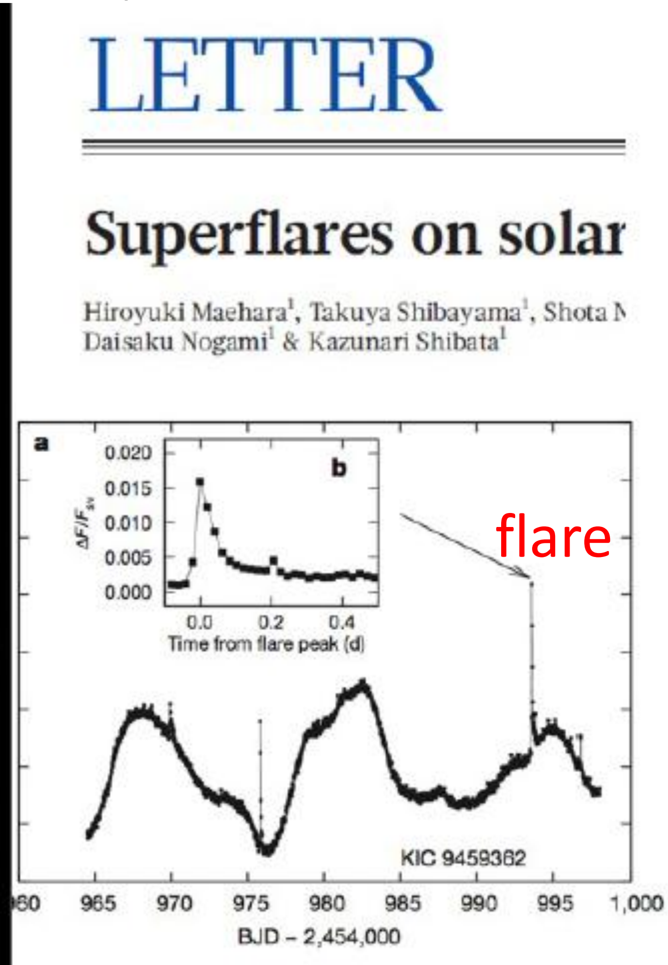
- Flare frequency, and the detailed properties of superflare stars are still not clear because of few observations.
- **Are superflares really occurring on solar-type stars with slow rotations?**

⇒ Our motivation of this research using Kepler spacecraft data.



Superflares discovered by Kepler spacecraft

Maehara et al.
(May 24th 2012, Nature)



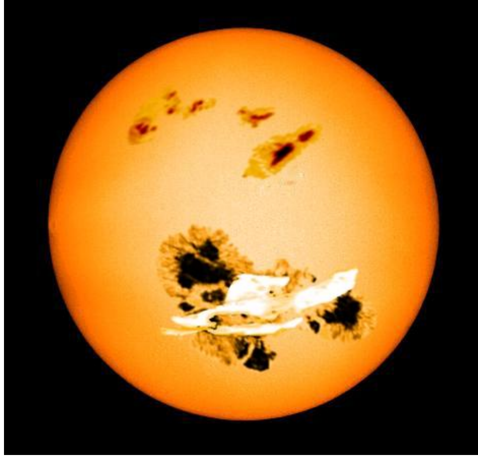
- We searched for superflares on solar-type (G-type main sequence; 5100<Teff<6100, log g >4.0) stars by using Kepler high precision ($<10^{-4}$) photometric data.
- Surprisingly, we found 365 superflares on 148 solar-type stars.

※Kepler observes ~80,000 G-type stars.

- <u>Statistical analyses</u>

⇒Superflares of 1000 times more energetic than the largest solar flares occur once in 5000 years !

What is the cause of stellar brightness variation ?

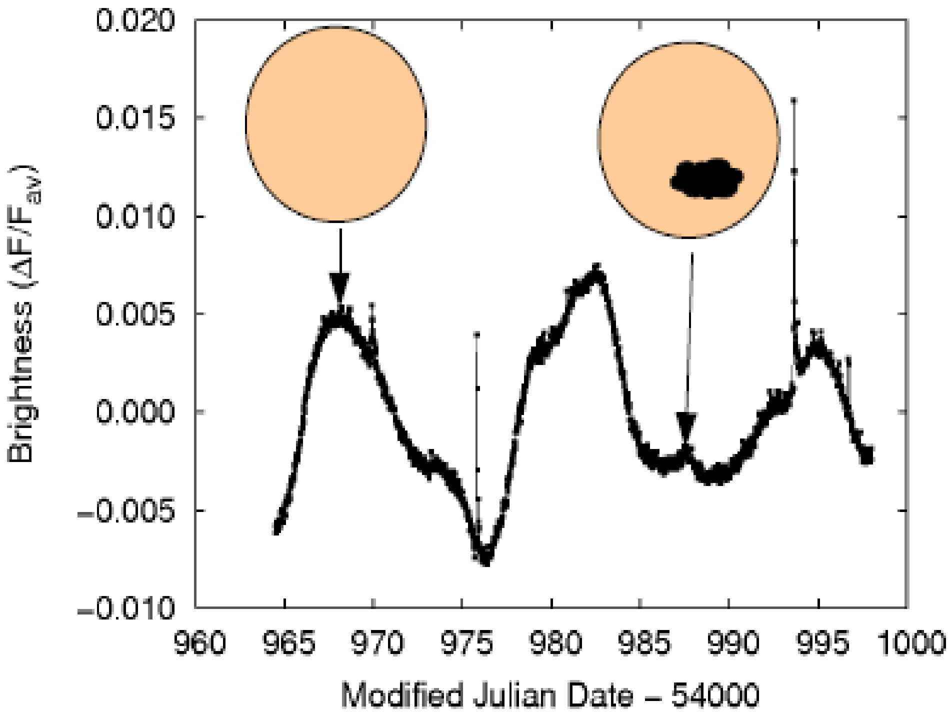


?? Rotation of a star with large starspots ??

- Brightness variation

  Period ⇒ Stellar rotational period

  Amplitude ⇒ Sizes of statspots on the stellar surface



Maehara et al. (2012)

Spot magnetic energy can explain the energy of superflares!?

cf. Shibata et al. 2013 PASJ in press

Is this true??

⇒ High Dispersion Spectroscopic Observations

Purposes of Subaru/HDS Observations

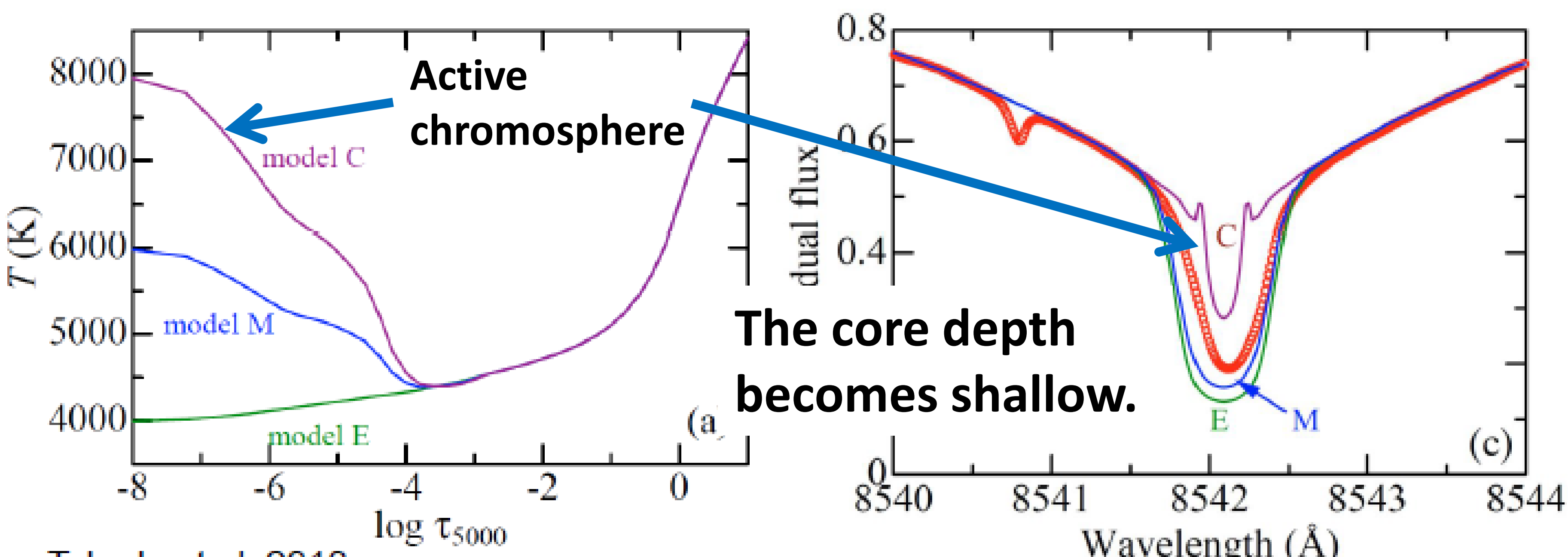
①Do superflare stars really have large starspots??

We confirm this by investigating the chromospheric activity,

using the line profile of Ca II IR triplet lines (8498/8542/8668) and Hα(6563).

↓Core profiles of CaII 8542 with different temperature structures↓

The core depth of Ca II lines are used as an indicator of Chromospheric activity.



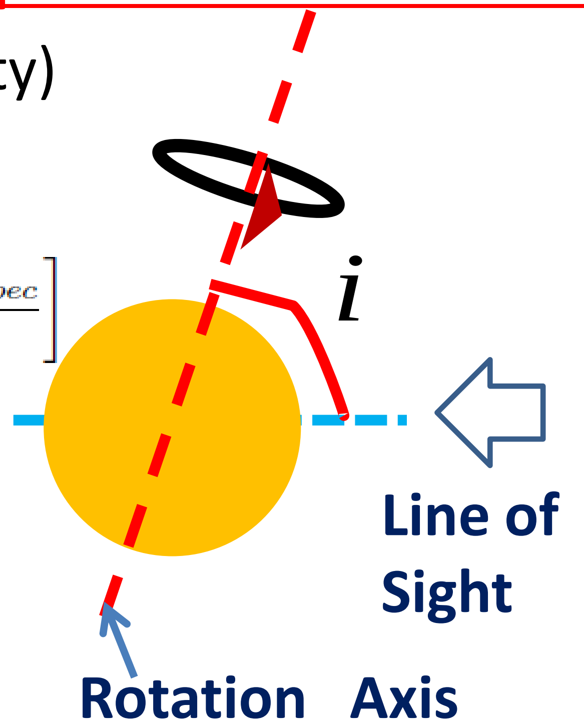
Takeda et al. 2010

Purposes of Subaru/HDS Observations

②Does the brightness variation really correspond to the rotation?

We compare *v* sin *i* (projected rotational velocity) with the velocity estimated from period of the brightness variation.

$$i = \arcsin\left[\frac{(v\sin i)_{spec}}{v}\right]$$



We can estimate stellar inclination angle (i).

Inclination angle is important for estimating the **spot sizes** from the brightness variation.

③ Investigating binary fractions of superflares

Measuring Radial velocity (RV) changes

The possibility of orbital motion of close binary systems??

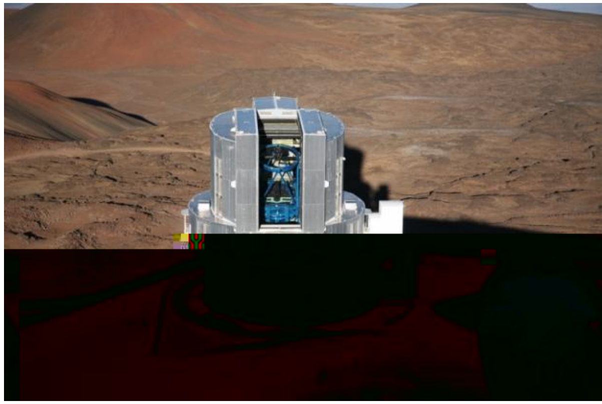
(Generally, close binary systems have large flares.)

Do single stars like the Sun really have superflares??

Subaru/HDS observations of Solar-Type Superflare stars

- S11B-137S (P.I.: Y. Notsu) 2011 Aug. 3 , Service Program

  Pilot study for one superflare star KIC6934317



- S12B-111B (P.I.: Y. Notsu)
  - Obs. Date: 2012 Aug. 6-8 (half night)

    Sep. 22-25(half night)
  - R~50,000, λ: 6100~8820 Å (Ca II IRT , Hα)
  - S/N ~ 100 @ 8500 Å
  - Exp time: 1-2h x (2~3)
  - **24 superflare stars**

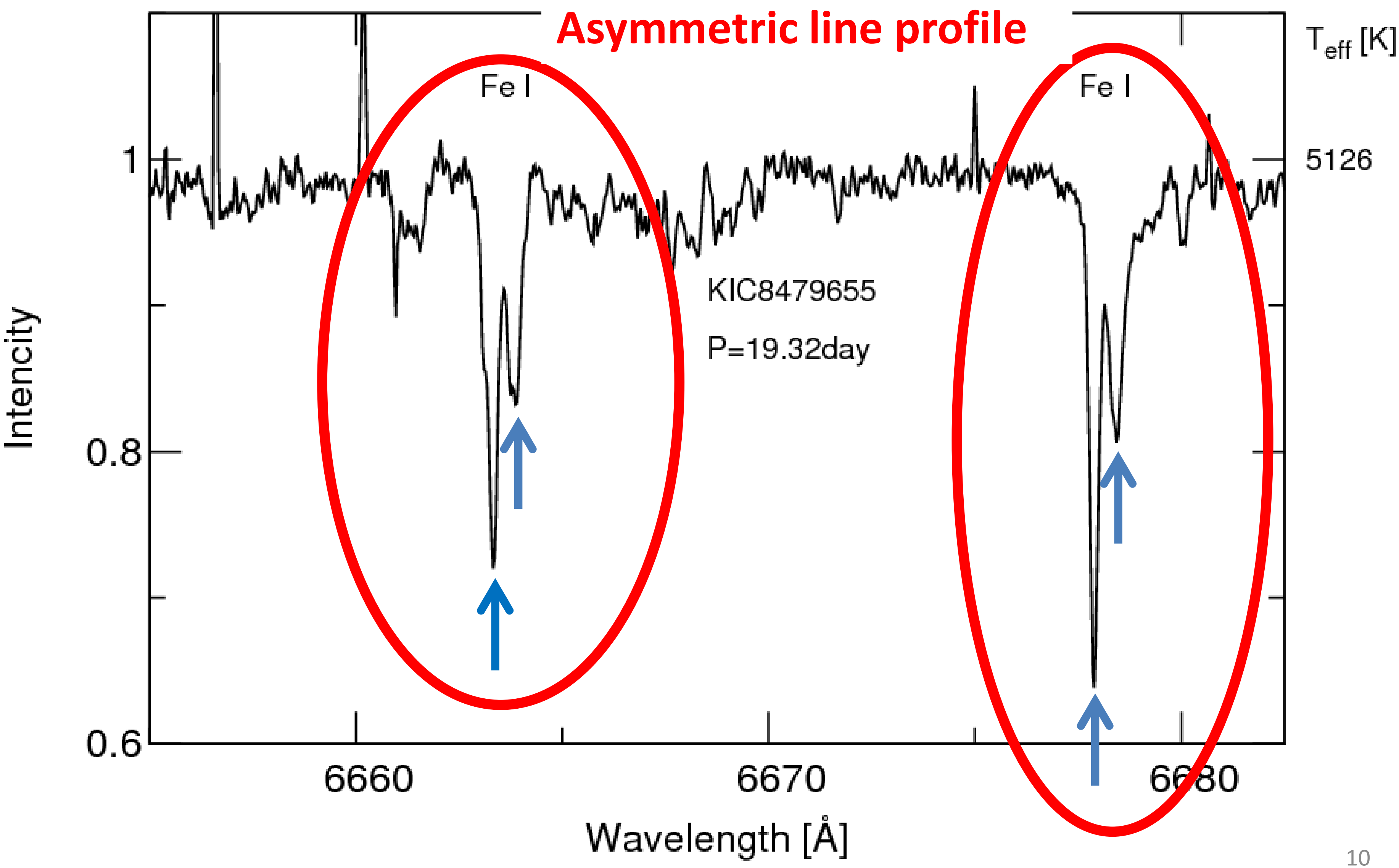
    22 G-dwarf (5100K<Teff<6000K, log g> 4.0) + 2 K-dwarf

    10 ≦ I mag ≦ 14

    0.7 < P ≲ 20 (day) Brightness varitaion period

Spectroscopic binary

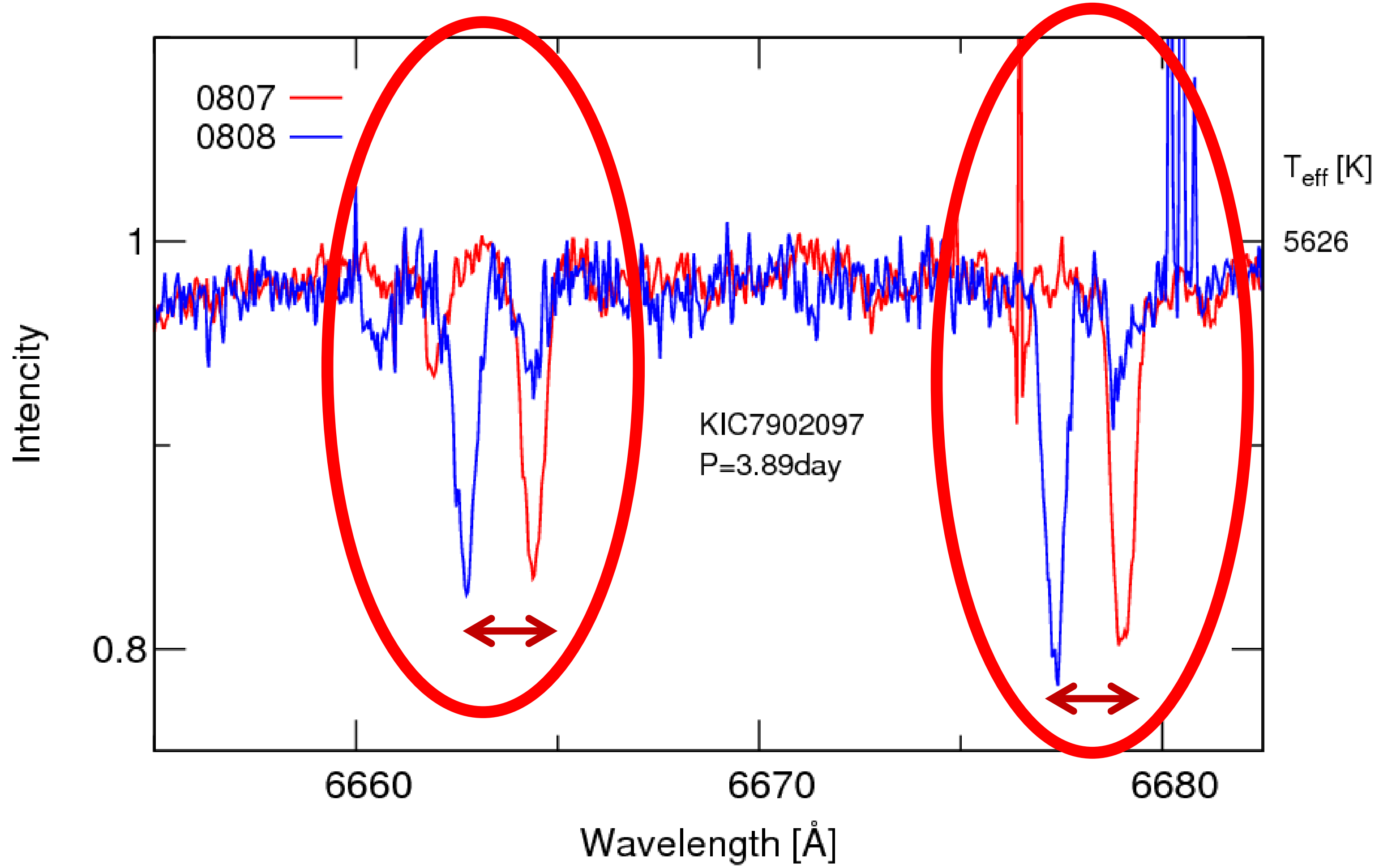
- **Double line Profile** Sample



Spectroscopic binary

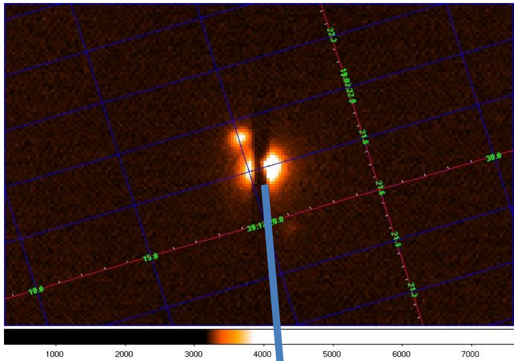
- **Radial Velocity change**

(Sample) KIC7902097 Radial Velocity change ≈76.7 km/s



About half of the target stars are binary.

- **We will talk about the single stars in the following.**



Slit Viewer Image of HDS

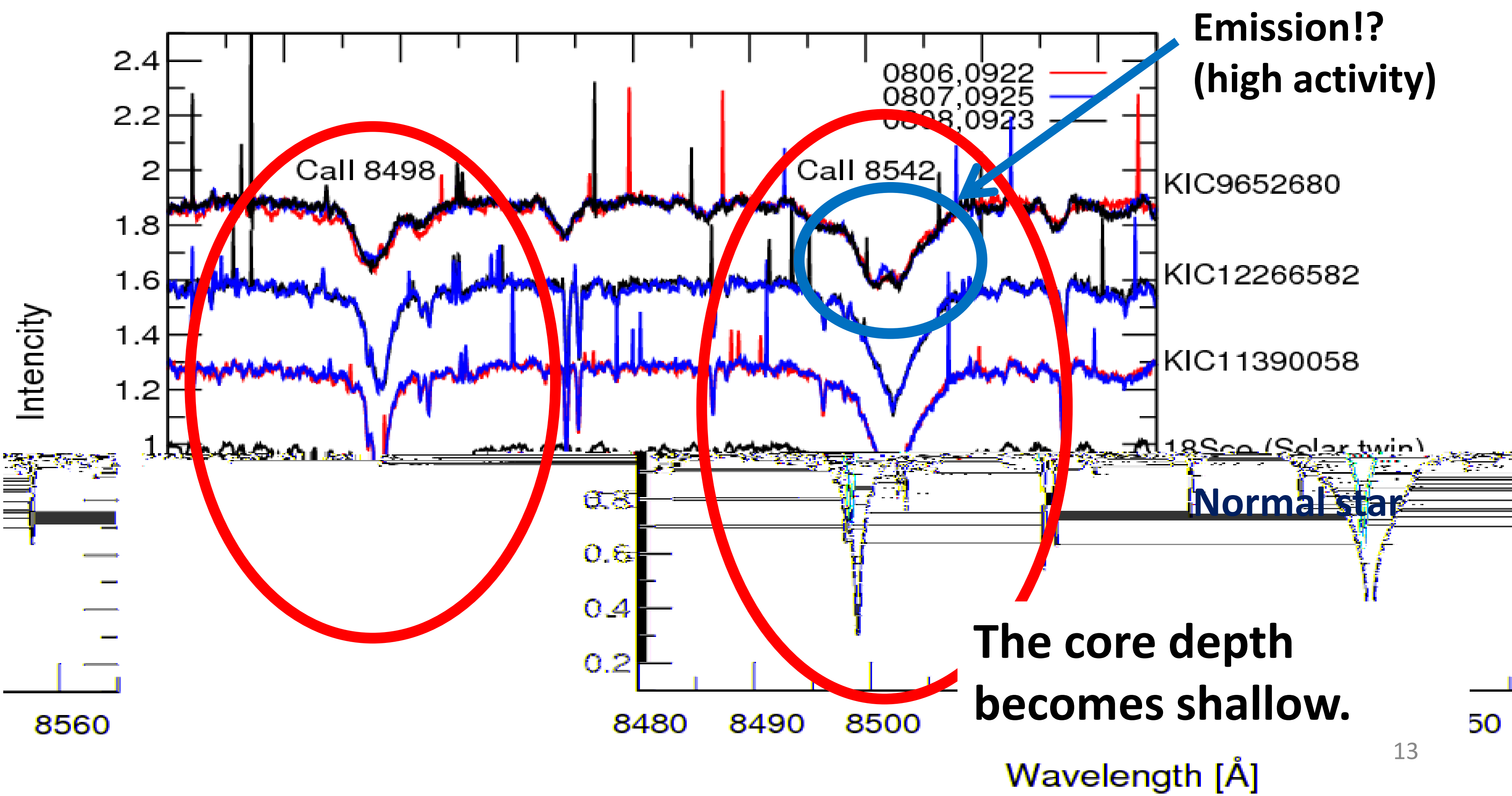
Number of Stars

The number in parentheses is that of the star P>10day.

Teff	Total	Single	Spectroscopic Binary	Visual Binary
5600～6000K	11	7(1)	2	2 (**No spectroscopy**)
5100～5600K	11	4	6(2)	1
<5100K	2	1	1	0
Total	**24**	**12**	9	3

Chromospheric activity (CaII 8498/8542)

- As the 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 !?

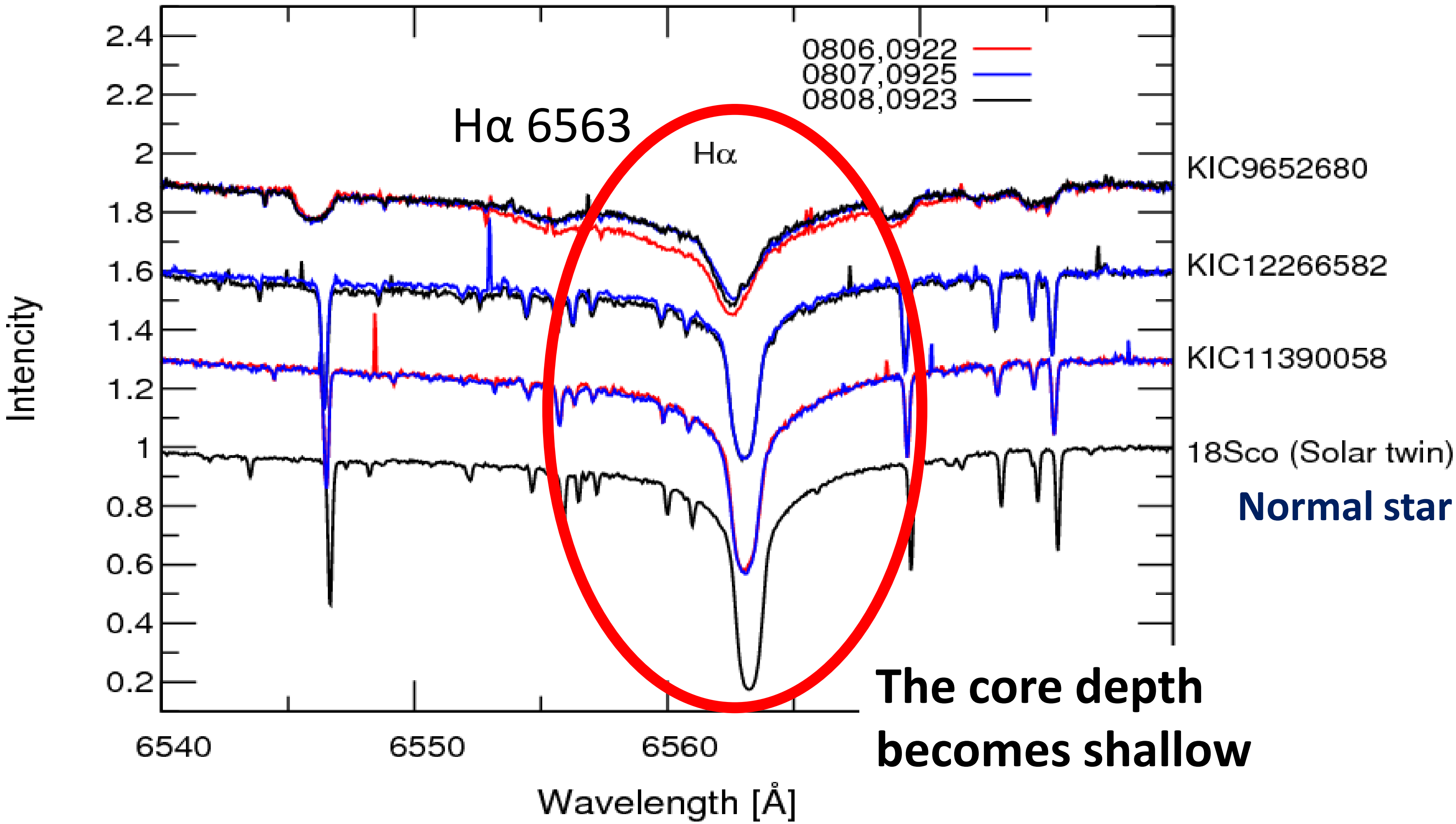


Chromospheric activity (Hα)

The core flux of Hα also shows the activity.

(Hα line is widely used for the Sun)

The good correlation with the result using Ca II triplet.

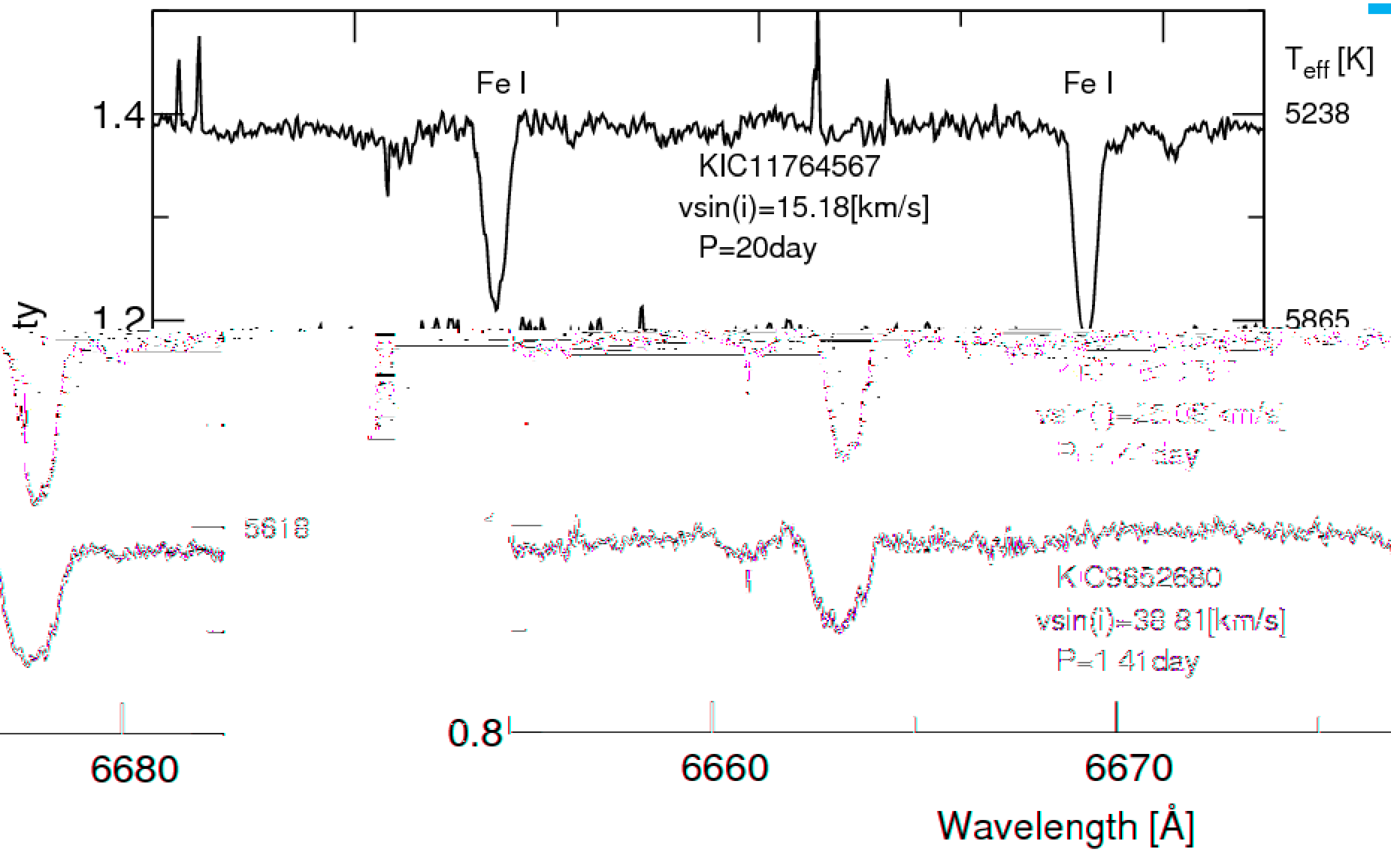


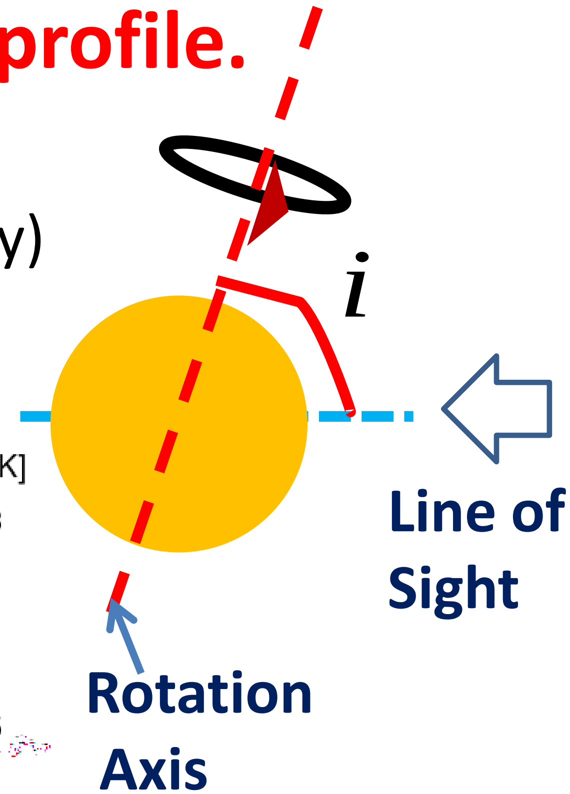
The core depth becomes shallow

Rapidly rotating stars

Rapidly rotating stars show wide line profile.

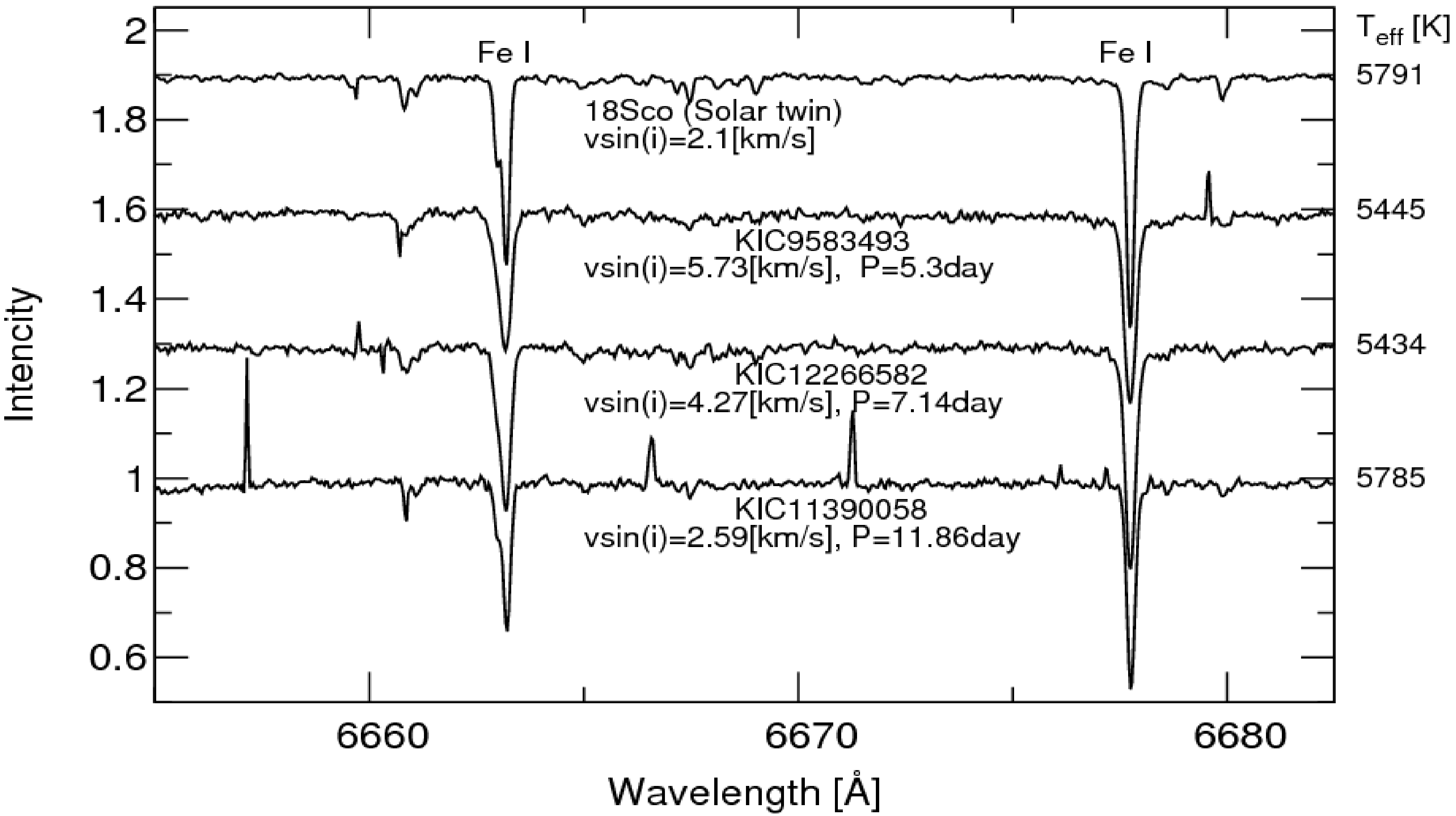
We measured "*v* sin *i* " (projected rotational velocity) by applying the method by Takeda et al. (2008)





Slowly rotating stars

Slowly rotating stars (like our Sun) show narrow line profile.



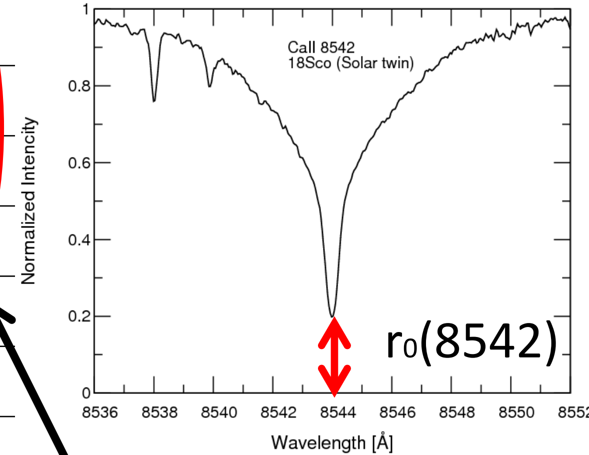
Vsin i error
~ 10%

Single stars

Ca II 8542

$$r_0(8542) = F_{8542} / F_{cont}$$

KIC	Teff[K]	log g	P[day]	*v* sin *i* [km/s]	$r_0(8542)$
8429280	4616	4.39	1.17	**20**	**0.67**
11764567	5238	4.38	20	**15.18**	**0.49**
4831454	5298	4.59	5.19	~0	**0.5**
12266582	5434	4.35	7.14	4.27	**0.52**
9583493	5445	4.50	5.3	5.73	**0.51**
9652680	5618	4.80	1.41	**38.81**	**0.68**
4742436	5628	4.15	2.34	2.71	0.3
6503434	5714	4.29	3.89	5.27	0.27
11390058	5785	4.30	11.86	2.59	0.32
11610797	5865	4.50	1.69	**25.08**	**0.63**
9412514	5958	4.22	1.85	7.69	0.22
3626094	5835	4.26	0.72	2.37	0.24
Comparison	---	---	---	---	---
18Sco	5791	4.40	---	2.1	0.2
61Vir	5571	4.67	---	0.46	0.19
59Vir	6234	4.25	---	6.68	**0.4**



r0: core depth

High activity !?

← Solar analog (18Sco)
← Non-active (61Vir)
← Active (59Vir)

r0 error : mainly depend on determination of continuum (<0.1)

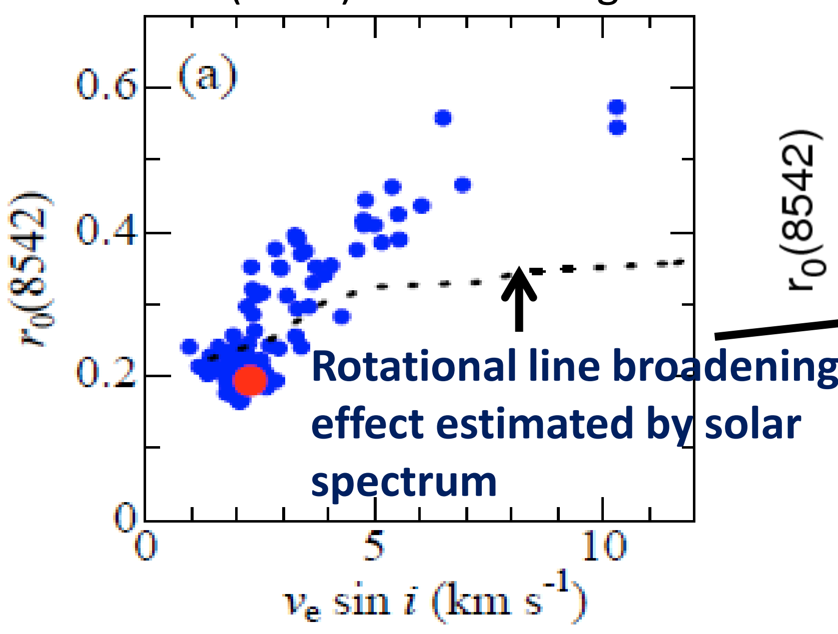
Vsin(i) vs Chromospheric Acticvity

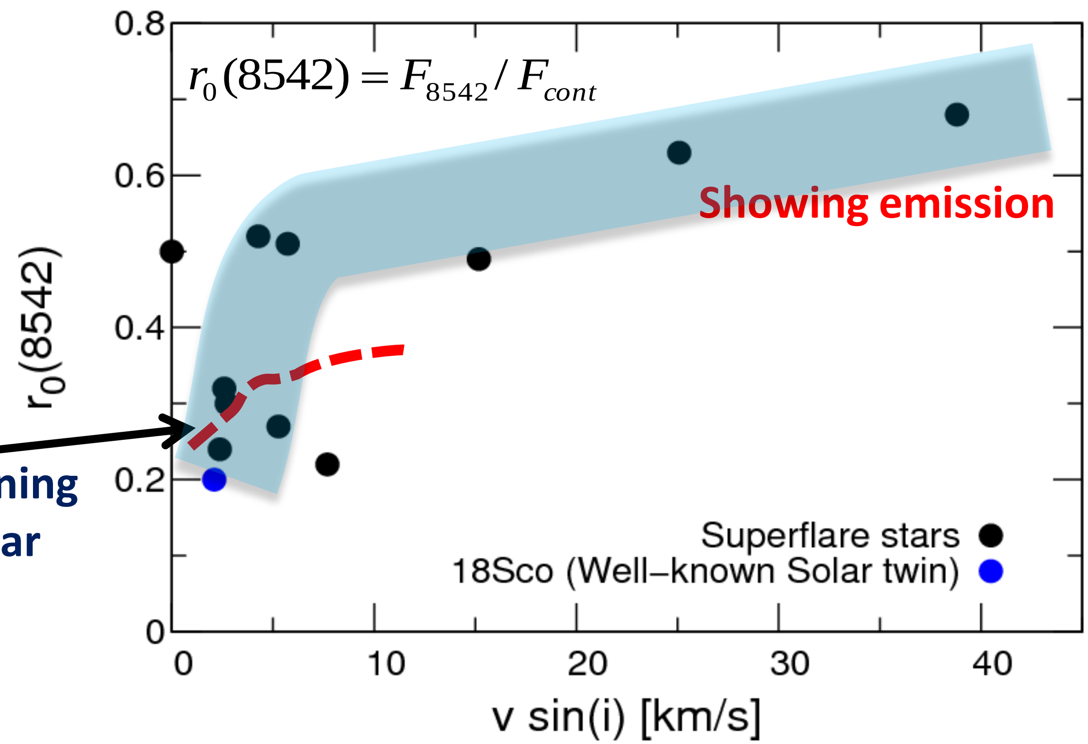
- There are correlations between *v* sin *i* and chromospheric activity. Many stars show high activity compared to the Sun.
- Our result is consistent with the previous research about general solar-analog stars by Takeda et al. (2010).

  ※Chromospheric activity is related to **rotational**-induced stellar dynamo (mechanism of generating stellar magnetic field.)

High r_0(8542)⇒Superflare stars have large starspots.

Takeda et al.(2010) Solar-analog stars





Flare energy vs sunspot area

Notsu et al. 2013 in prep.

Flare energy

10^35 erg

10^34 erg

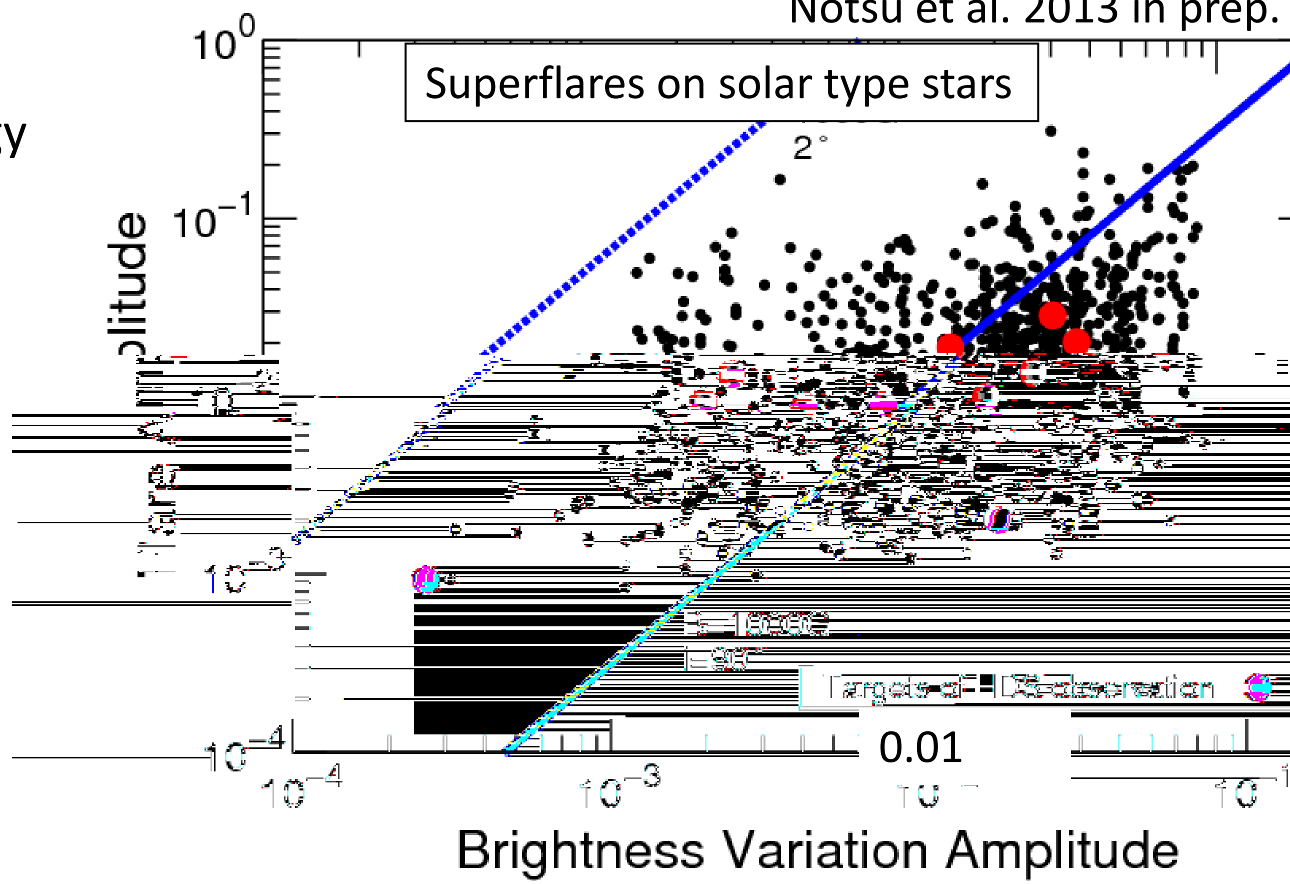
10^33 erg

10^32 erg

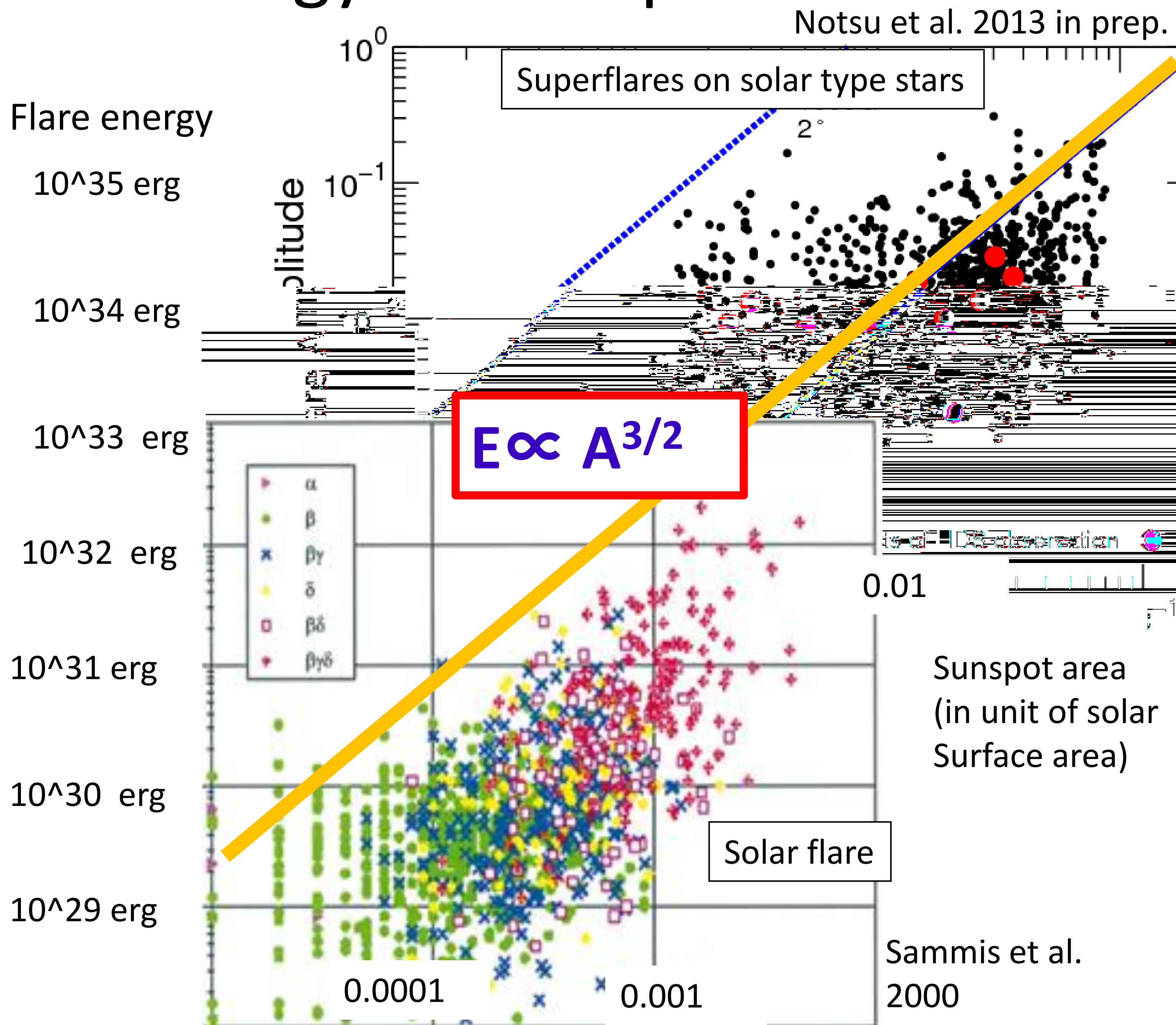
10^31 erg

10^30 erg

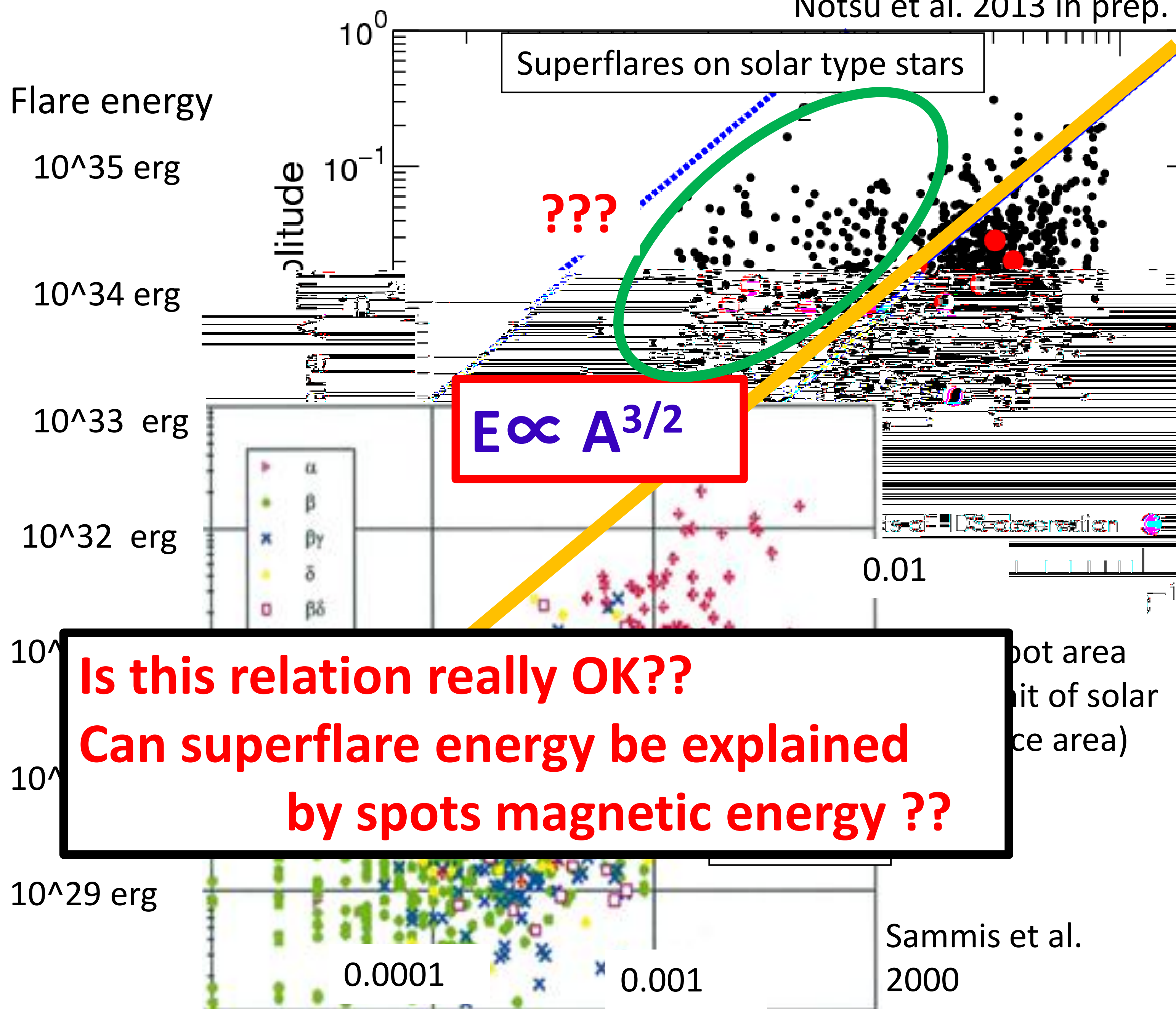
10^29 erg



Flare energy vs sunspot area



Flare energy vs sunspot area



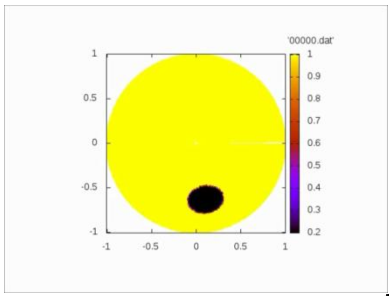
Is this relation really OK??

Can superflare energy be explained by spots magnetic energy ??

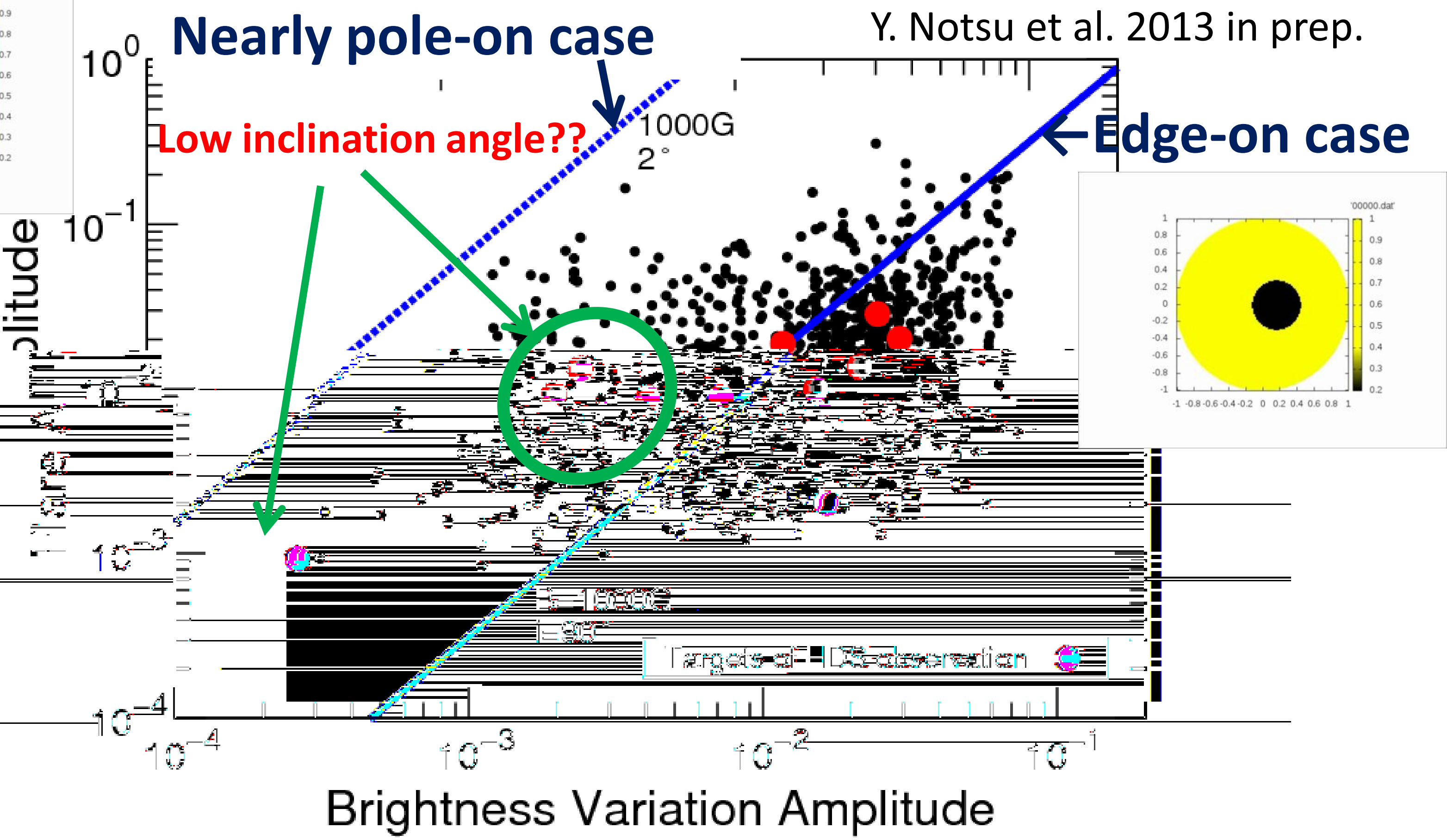
Effects of Inclination angle on the relations between Brightness variations and Flare Amplitude

$E \propto A^{3/2}$

$$\Delta F_{flare} \propto 10\left(\frac{B}{1000\mathrm{G}}\right)^2\left(\Delta F_{rot}\frac{1}{\sin i}\right)^{3/2}$$



Corresponding to Flare Energys

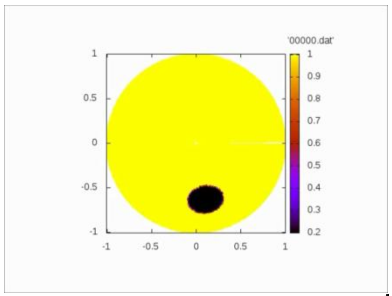


Corresponding to Spot sizes

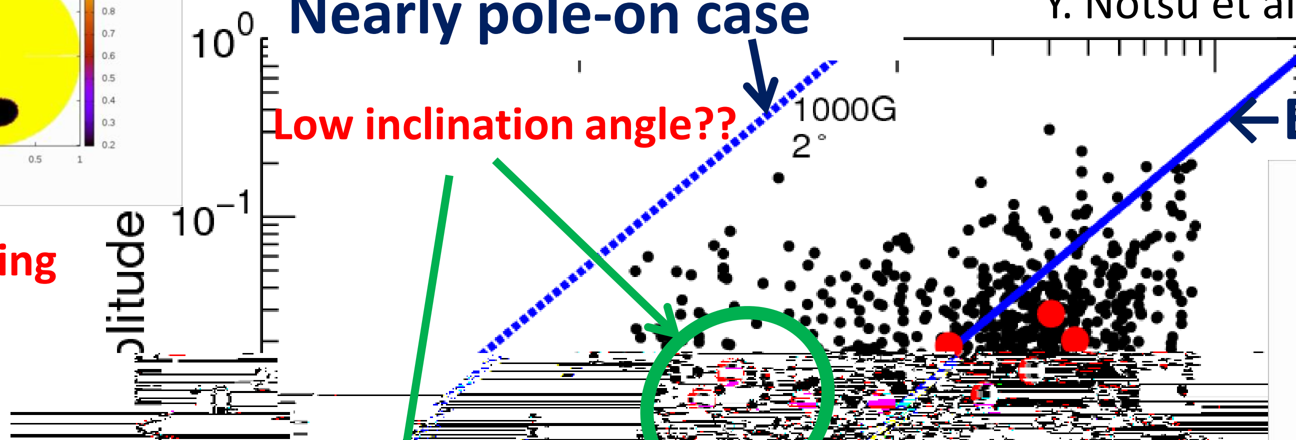
Effects of Inclination angle on the relations between Brightness variations and Flare Amplitude

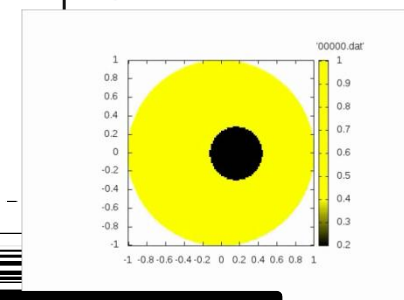
$E \propto A^{3/2}$

$$\Delta F_{flare} \propto 10\left(\frac{B}{1000\mathrm{G}}\right)^{2}\left(\Delta F_{rot}\frac{1}{\sin i}\right)^{3/2}$$



Corresponding to Flare Energys





Superflare energies can be explained by the magnetic energy stored around the starspots.

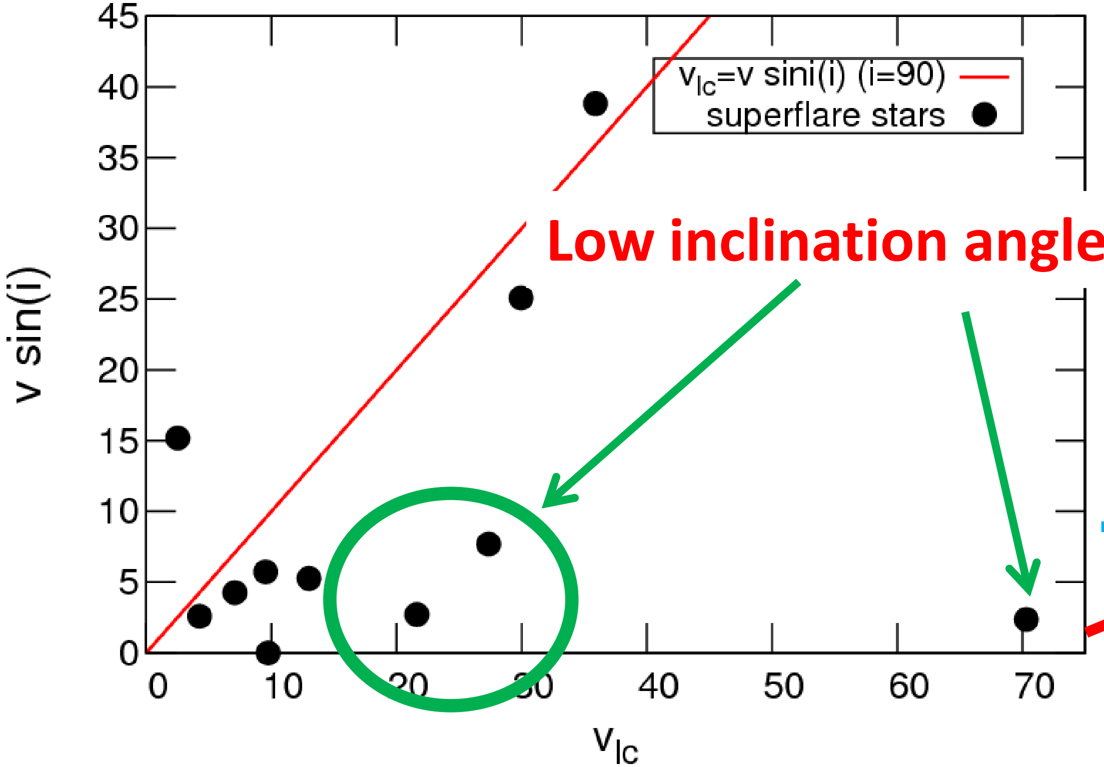
If the object has low inclination angle, the data point move to the left. Is it OK??

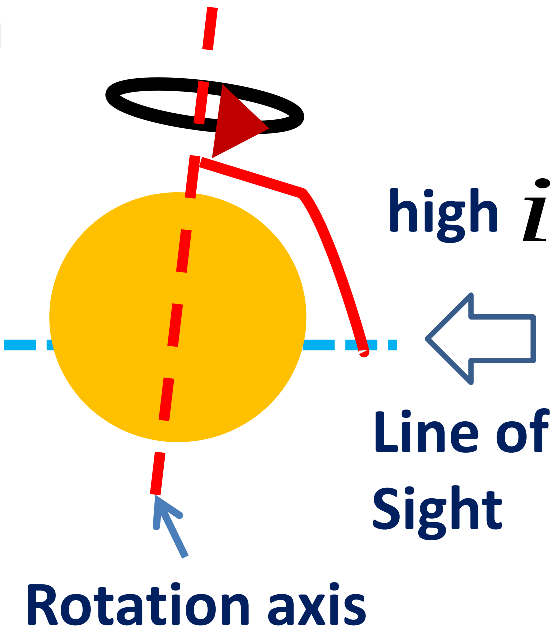
Corresponding to Spot sizes

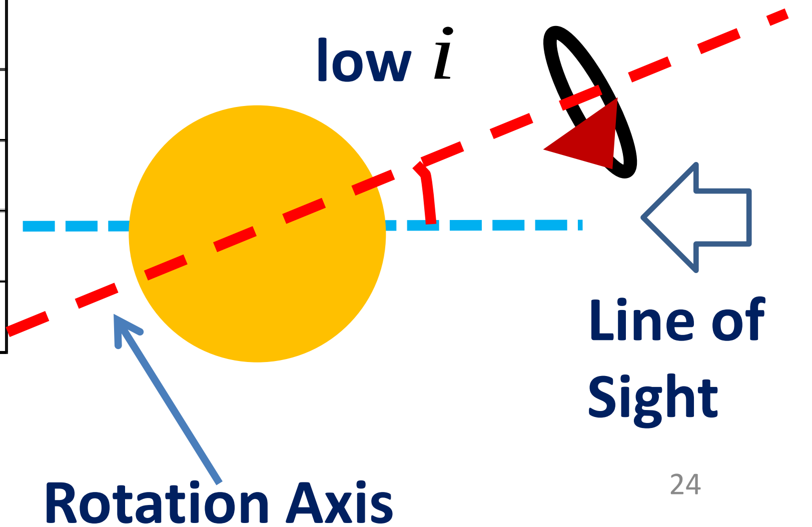
vsin(i) vs velocity estimated from the brightness variation

$$v_{lc} \approx \frac{2\pi R_{sun}}{P} \qquad i \approx \arcsin\left[\frac{(v \sin i)_{spec}}{v_{lc}}\right]$$

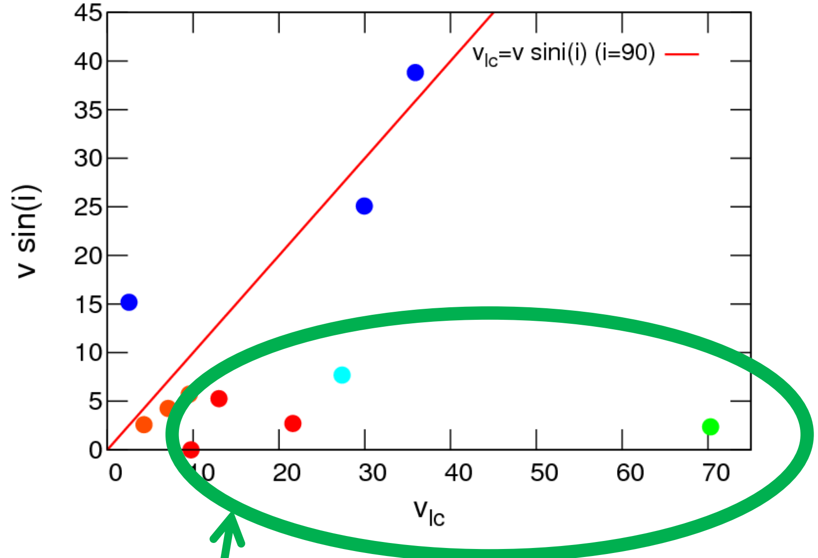
P[day]: Brightness variation period







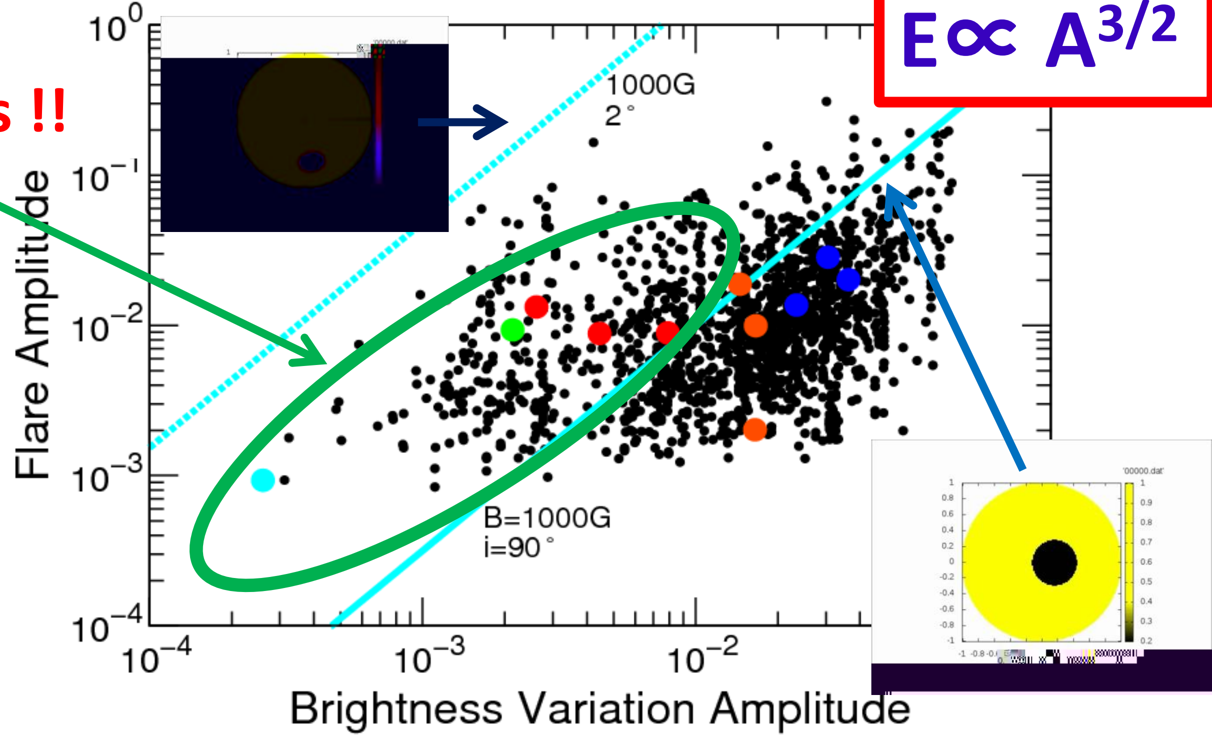
These two figures are consistent!!



Low inclination angle stars !!

The same color data points in each figure correspond to the same star groups

$E \propto A^{3/2}$



Summary

High dispersion spectroscopy of solar-type **supreflare** stars.

– About **half** of solar-type superflare stars are **binary**.

– Superflare stars show **choromospheric activity** and this suggests the existence of **large starspots**

– Assuming that the brightness **variation period** correspond to the rotational period is **consistent with the value of *v* sin *i*** (projected rotational velosity) measured from spectroscopic results.

・Li abundances of superflare stars → Honda-san's poster