MAXI symposium Dec 6, 2016 Riken, Wako, Saitama 13:55-14:25 invited

Superflares on Sun-like Stars

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Kwasan and Hida Observatories,

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Collaborators : Hiroyuki Maehara, Takuya Shibayama, Yuta Notsu, Shota Notsu, Satoshi Honda, Daisaku Nogami, Takuya Takahashi, Hiroaki Isobe

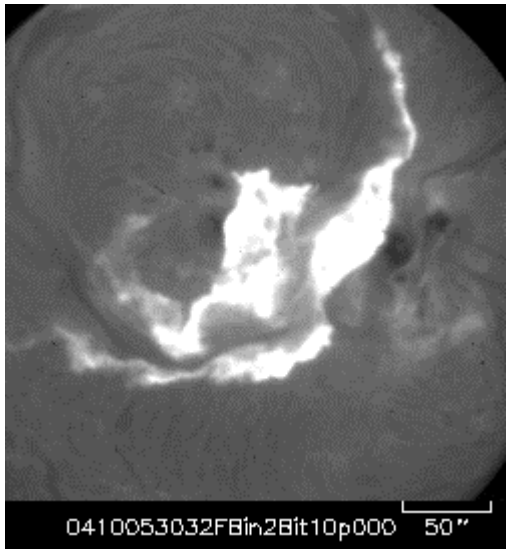
Introduction to Solar Flares

Special entertainment

Kojiki and the Universe
(古事記と宇宙)

Kitaro and Shibata

Let's enjoy
Various movies of
Solar flares and
Eruptions with
Kitaro-san's Music
Kojiki : Orochi
(7 min)

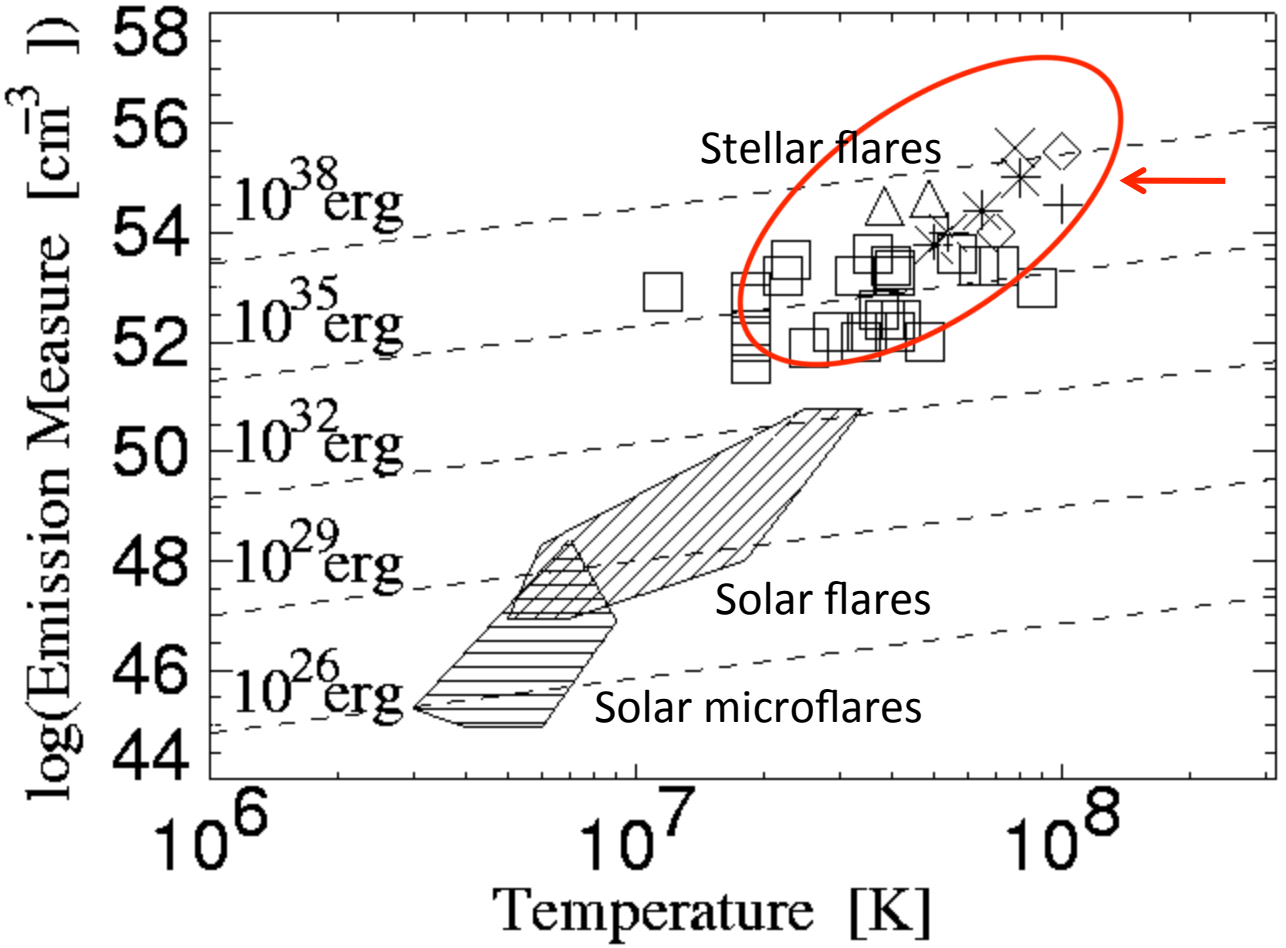


Orochi is 8 headed
dragon monster

Stellar Flares

Total energy of stellar flares

(Feldman+ 1995, Koyama+ 1996, Tsuboi+ 1998, Ozawa+ 1999, Hamaguchi+ 2000, Imanishi+ 2001)



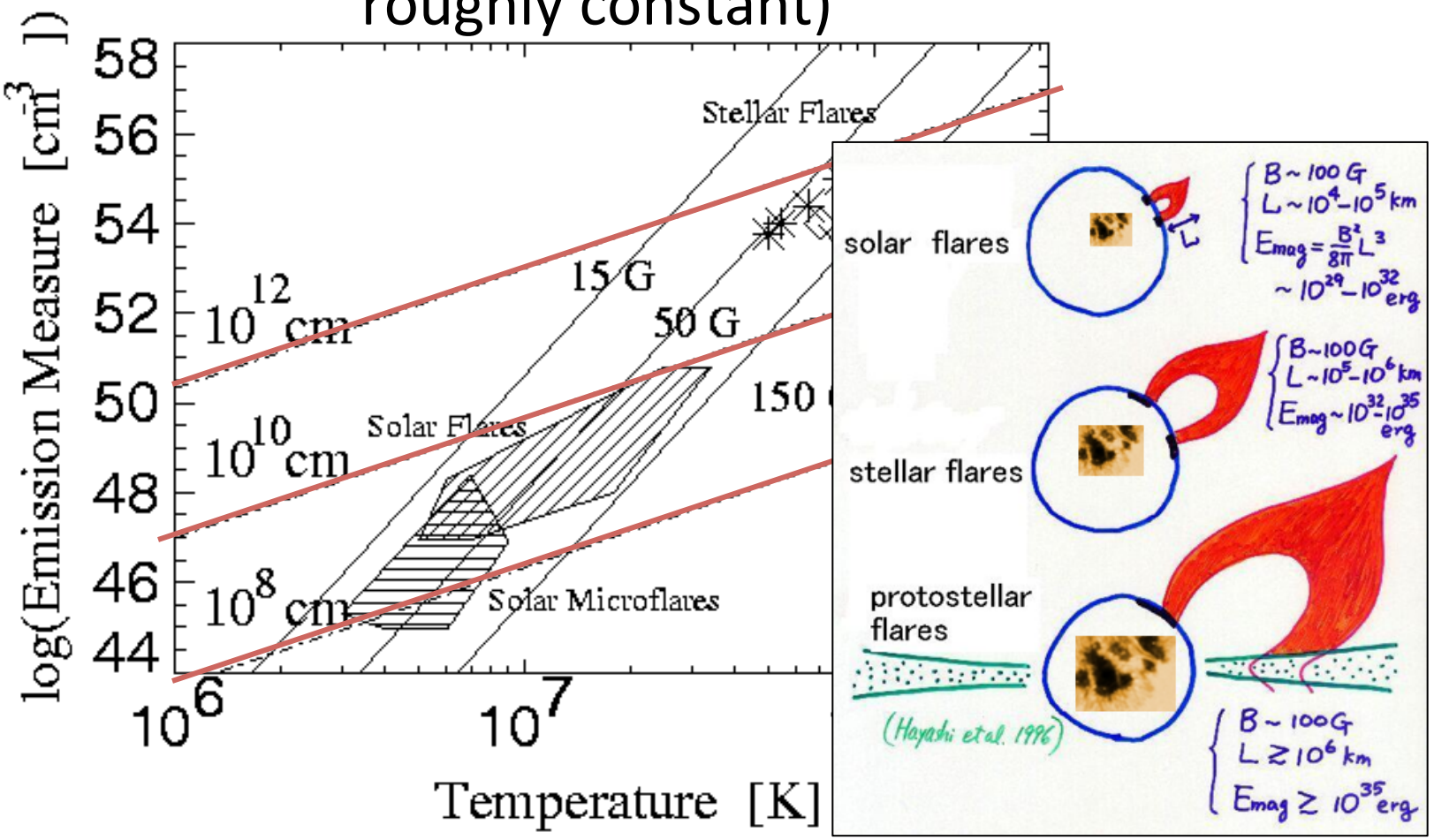
Superflares

Their energy = 10-10^6 times that of the largest solar flares

Their host stars are young stars and binary stars with fast rotation

Shibata and Yokoyama (2002)

Q: What determines flare total energy ?
A: loop length (because magnetic field strength is roughly constant)



The reason why stellar flares are hot
=> loop lengths of stellar flares are large

Shibata and Yokoyama (2002)

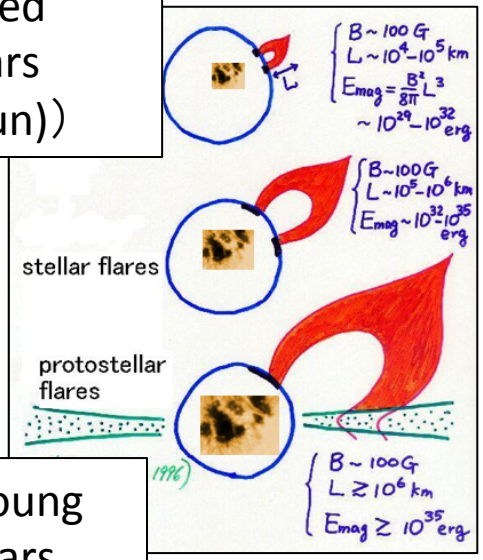
Cf Isobe et al. 2003,
Aulanier et al. 2013

Why young stars produce superflares ?

- Answer：young star's rotation is fast

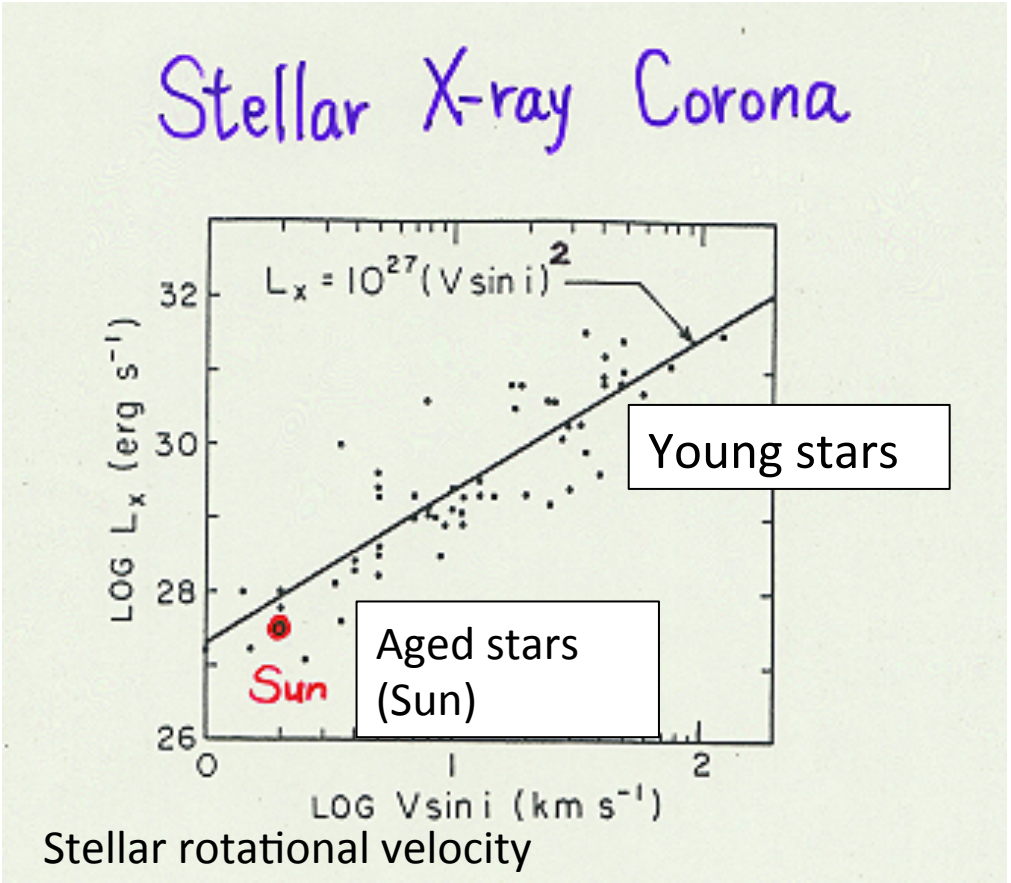
（so dynamo is active and total magnetic flux is large => loop is large）

Aged stars (Sun))



Young stars

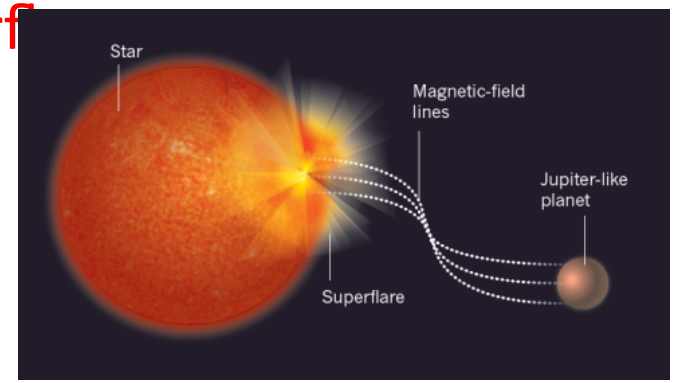
Stellar X-ray Luminosity



Stellar rotational velocity

Questions

- Previously, it has been believed that the Sun does not produce superflares (> 10^33 erg), because the Sun is old and is slowly rotating.
- However, Schaefer et al. (2000) discovered 9 superflares on ordinary solar type stars with slow rotation.
- Schaefer et al. argued that the Sun would never produce superflares, because they believed that hot Jupiter is a necessary condition to produce superf

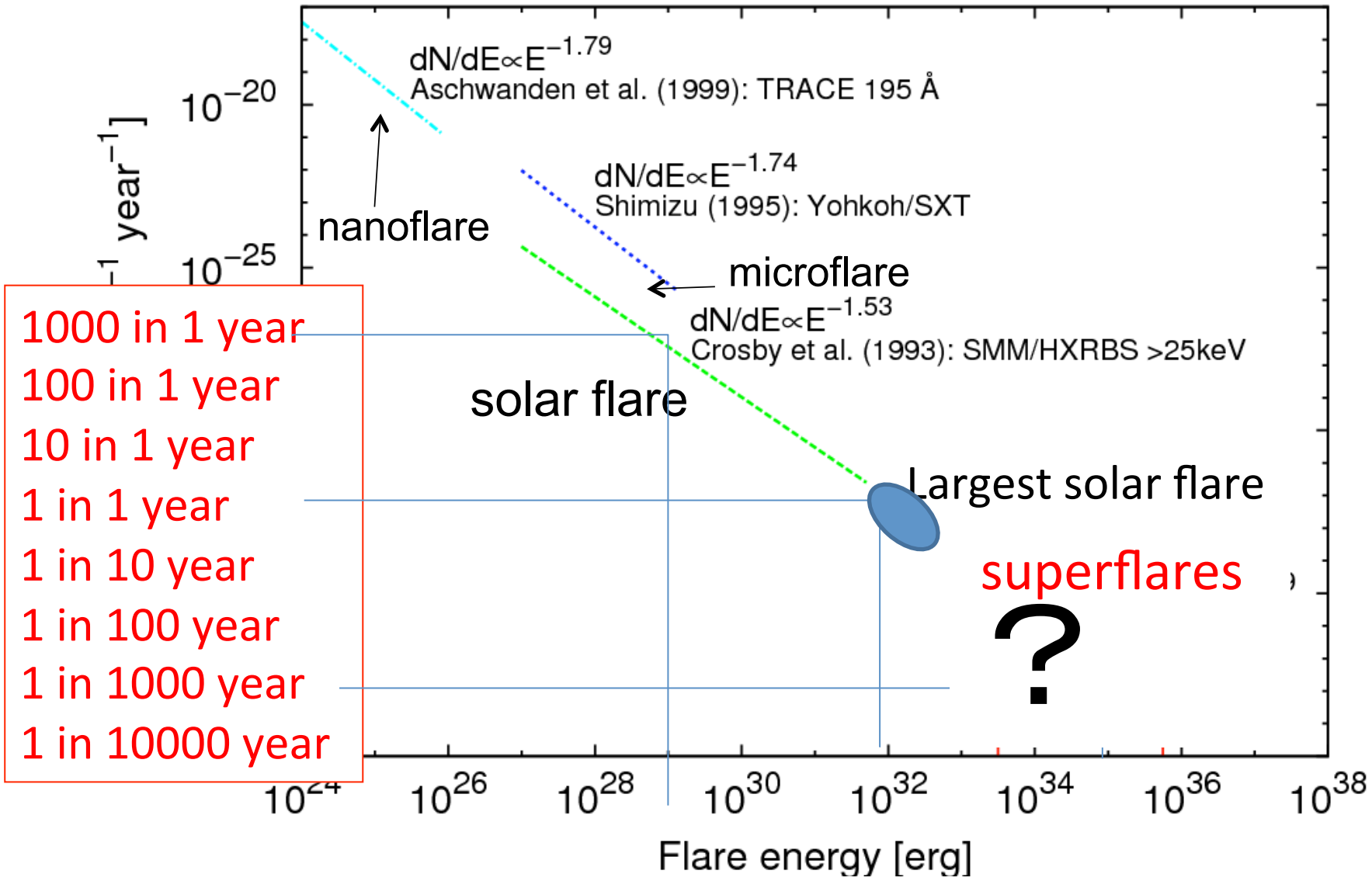


- Are superflares really occurring on ordinary solar type stars ?
- Are hot Jupiters necessary condition for superflares ?

Superflares on Solar Type Stars

Maehara et al. (2012) Nature, 483, 478

statistics of occurrence frequency of solar flares, microflares, nanoflares



How can we observe superflares on the Sun ?

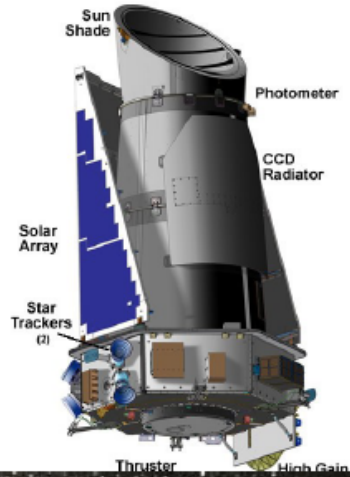
- If empirical statistics rule of solar flares is applied to much larger flares (superflares), then the frequency of superflares with energy 1000 times larger than the largest solar flares might occur once in 10000 years.
- However, the period of modern observations of the Sun with telescope is only 400 years.
- How can we observe the Sun for 10000 years ?

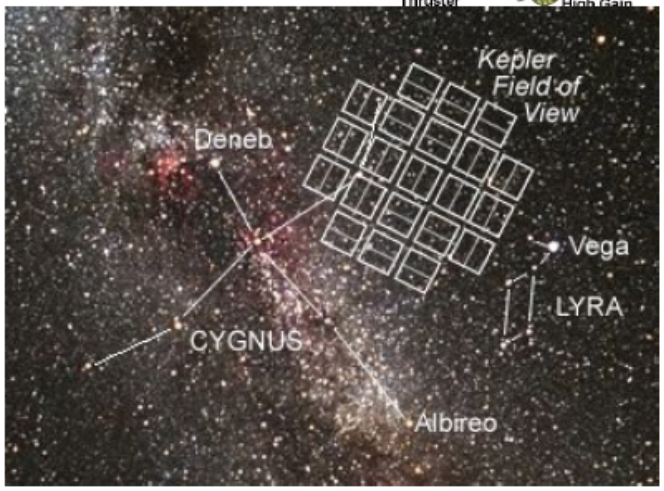
- If we observe 10000 solar type stars (similar to our Sun) for 1 year, we can get the data similar to the data obtained from 10000 years observations of the Sun !

Prof Sekiguchi kindly told me that
the Kepler satellite is taking such data !

Kepler satellite (NASA)

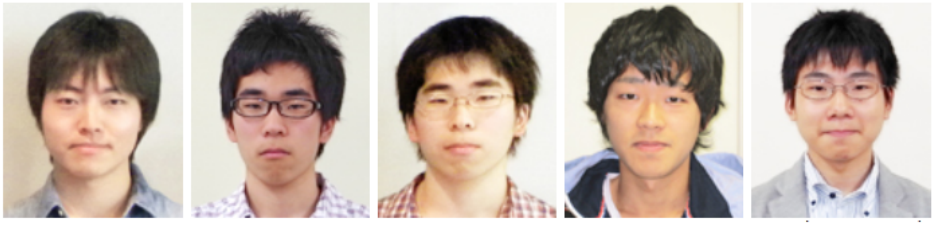
- Space mission to detect exoplanets by observing transit of exoplanets
- 0.95 m telescope
- Observing 160,000 stars continuously (from 2009 to 2013). Among them, 80000 are solar type stars.
- ~30 min time cadence (public data)





Superflares on Solar Type Stars : Our study (Maehara et al. 2012)

- Hence we searched for superflares on solar type stars using Kepler satellite data, which include data of 83000 solar type stars
- Since the data are so large, we asked 1st year undergraduate students to help analyzing these stars, because students have a lot of free time (2010 fall)



- Surprisingly, we (they) found 365 superflares on 148 solar type stars (G-type main sequence stars)

LETTER

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Superflares on solar-type stars

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Daisaku Nogami[1] & Kazunari Shibata[1]

Undergraduate students

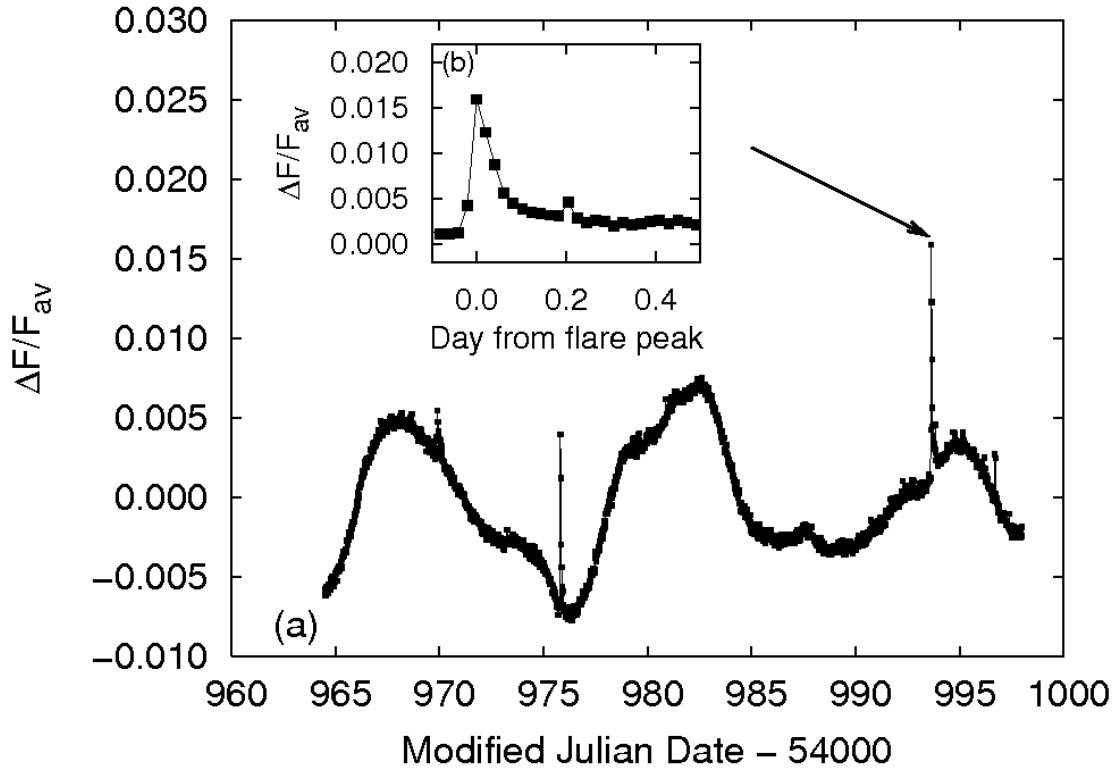
Solar flares are caused by the sudden release of magnetic energy stored near sunspots. They release 10^{29} to 10^{32} ergs of energy on a timescale of hours[1]. Similar flares have been observed on many stars, with larger 'superflares' seen on a variety of stars[2,3], some of which are rapidly rotating[4,5] and some of which are of ordinary solar type[3,6]. The small number of superflares observed on solar-type stars has hitherto precluded a detailed study of them. Here we report observations of 365 superflares, including some from slowly rotating solar-type stars, from about 83,000 stars observed over 120 days. Quasi-periodic brightness modulations observed in the solar-type stars suggest that they have much larger starspots than does the Sun. The maximum energy of the flare is not correlated with the stellar rotation period, but the data suggest that superflares occur more frequently on rapidly rotating stars. It has been proposed that hot Jupiters may be important in the generation of superflares on solar-type stars[7], but none have been discovered around the stars that we have studied, indicating that hot Jupiters associated with superflares are rare.

We searched for stellar flares on solar-type stars
sequence stars) using data collected by NASA's Kepler[8]
the period from April 2009 to December 2009 (a brief s
flare search method is described in the legend of Fig. 1 a
is provided in Supplementary Information). We use
temperature ($T_{\rm eff}$) and the surface gravity ($\log(g)$) ava
Kepler Input Catalog[9] to select solar-type stars. The se
are as follows: $5{,}100\,{\rm K} \leq T_{\rm eff} < 6{,}000\,{\rm K}, \log(g) \geq 4.0$. Th
of solar-type stars are 9,751 for quarter 0 of the Kepl
length of observation period is about 10 d), 75,728 for q
83,094 for quarter 2 (90 d) and 3,691 for quarter 3 (90

We found 365 superflares (flares with energy >10
solar-type stars (light curves of each flare are s
Supplementary Fig. 8 and properties of each flare st
Supplementary Table 1). The durations of the detec
are typically a few hours, and their amplitudes are ge
0.1–1% of the stellar luminosity. The bolometric lumi
bolometric energy of each flare were estimated from th

typical superflare observed by Kepler

Brightness of a star and a flare



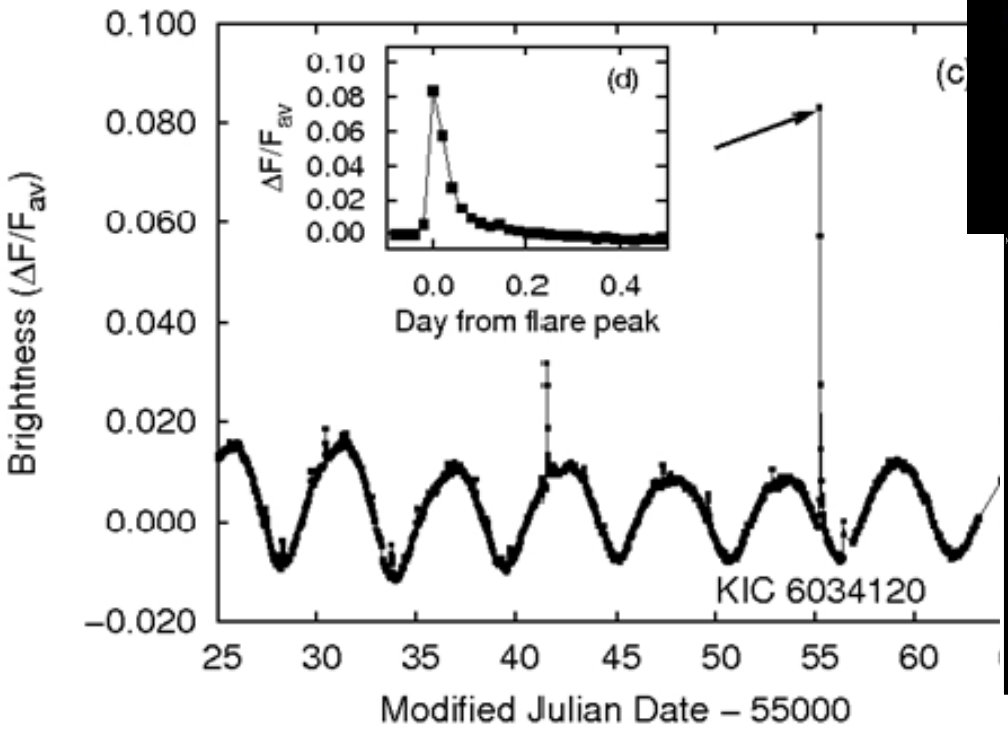
Total energy ~ 10^35 erg

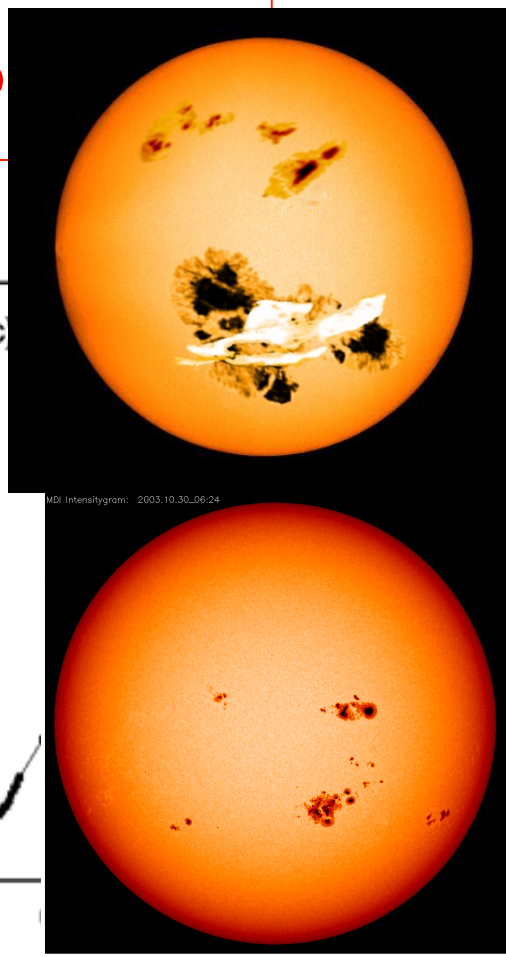
Time (day)

Maehara et al. (2012)

What is the cause of stellar brightness variation ?

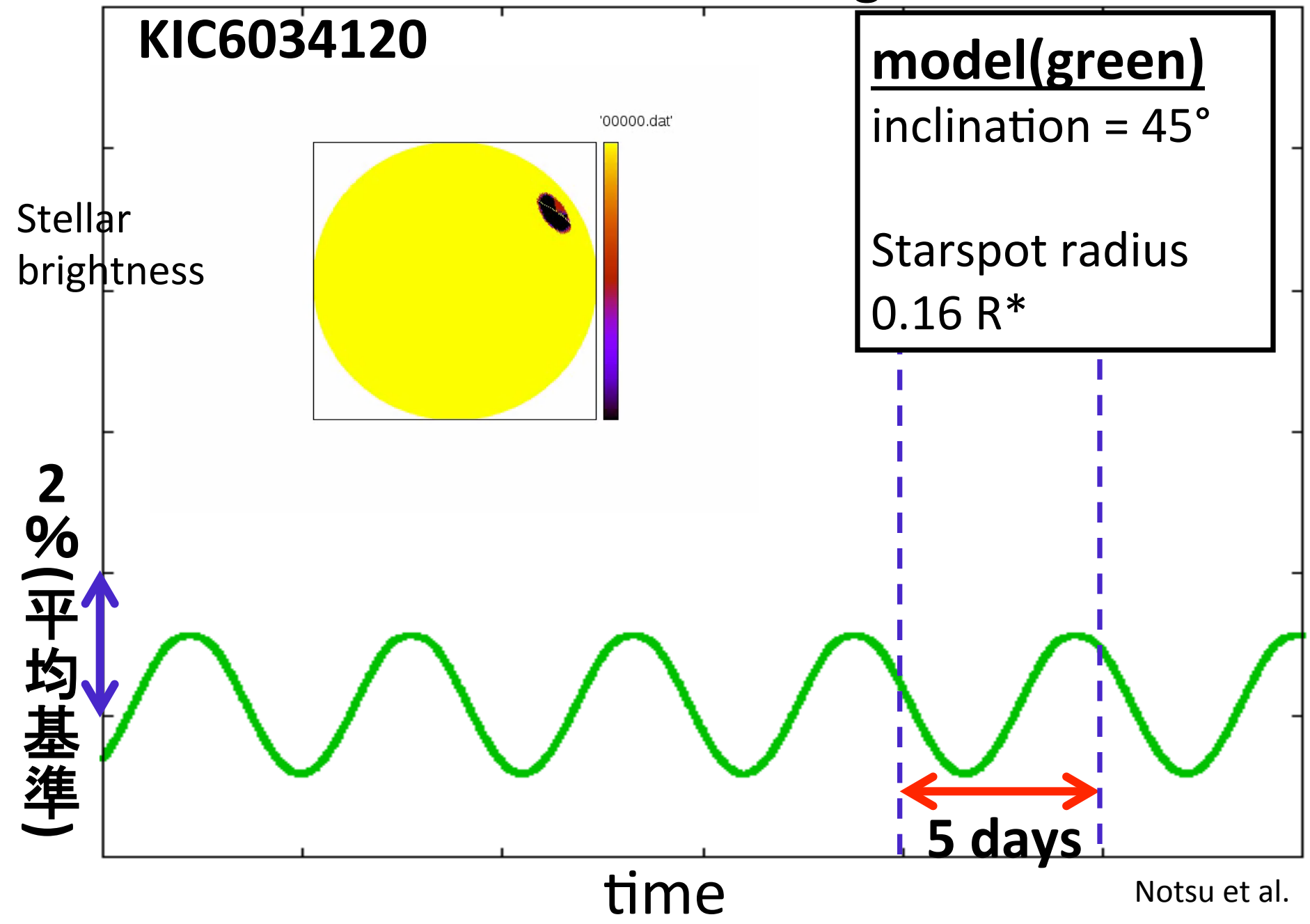
Brightness of a star and a flare



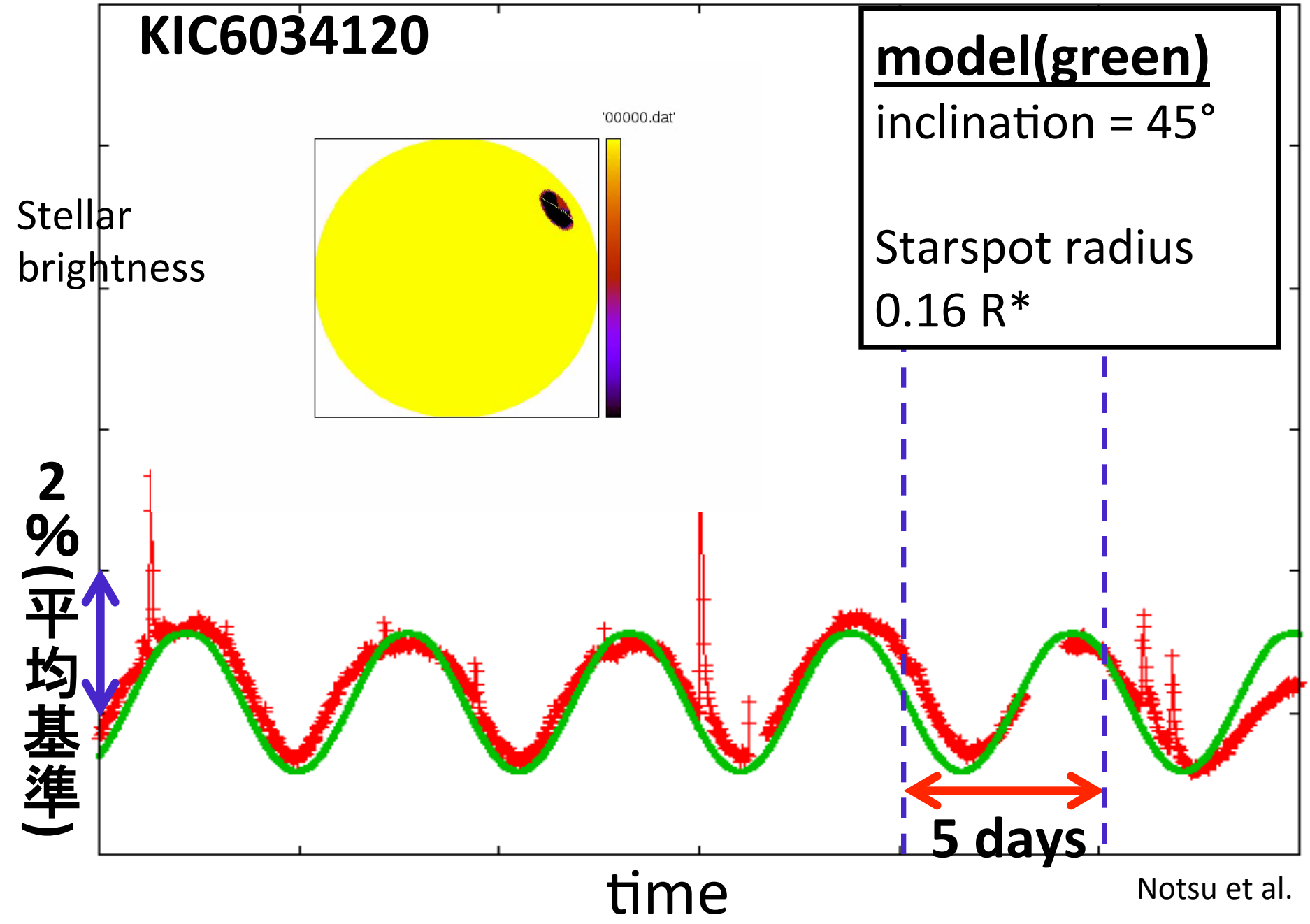


It is likely due to rotation of a star with a big star spot

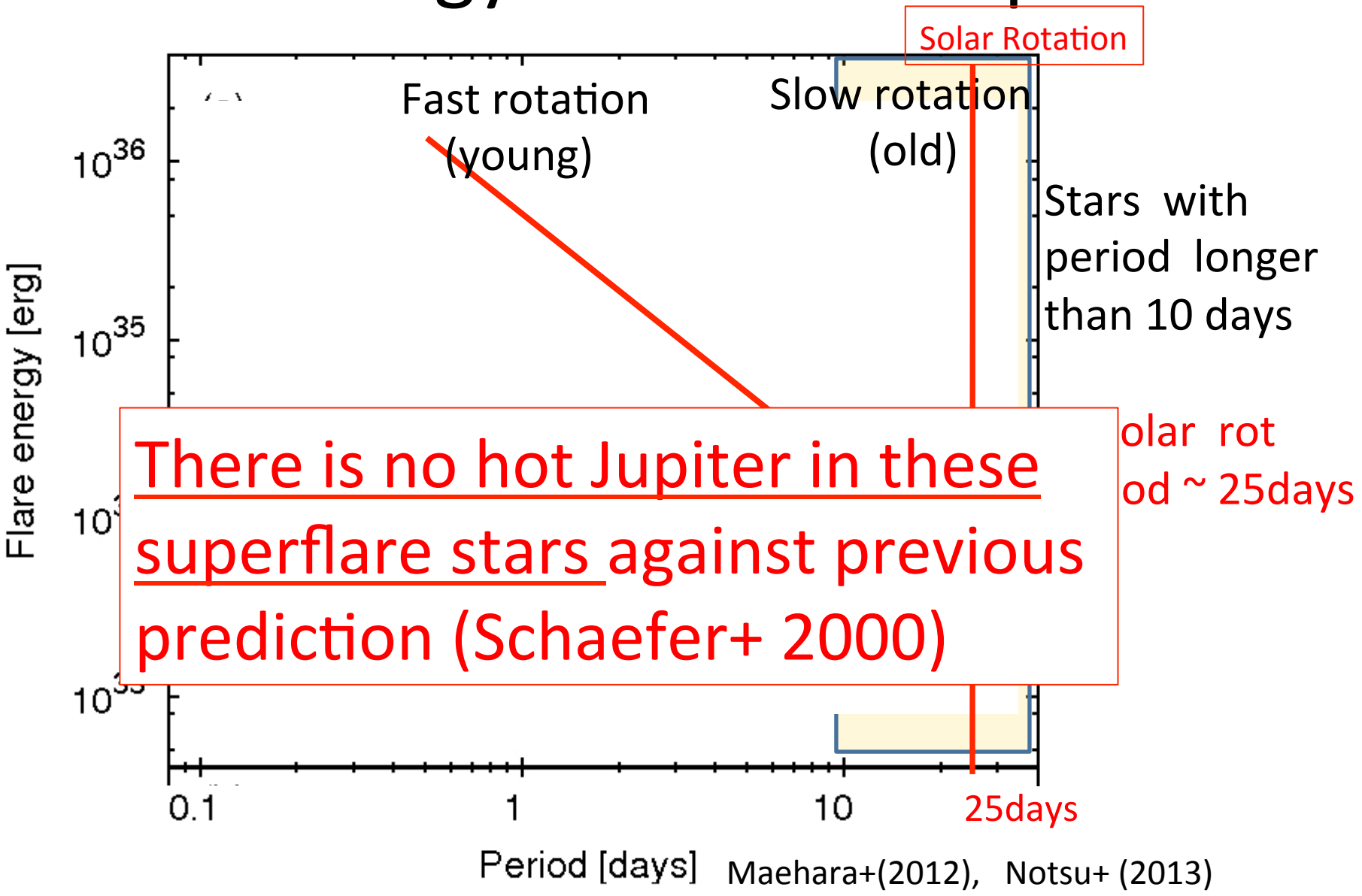
Model calculation of stellar brightness variation



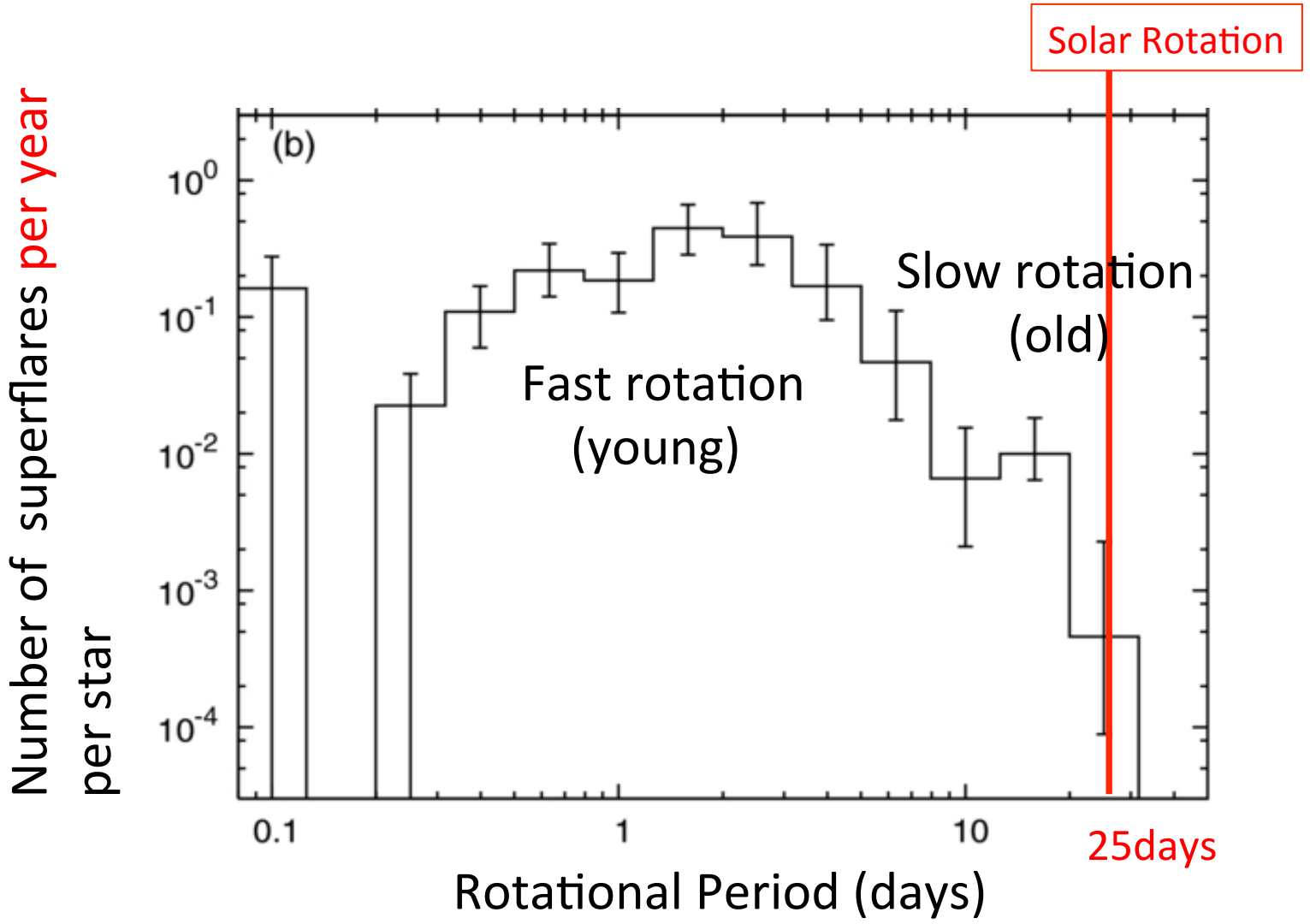
Model calculation of stellar brightness variation



Flare energy vs rotational period

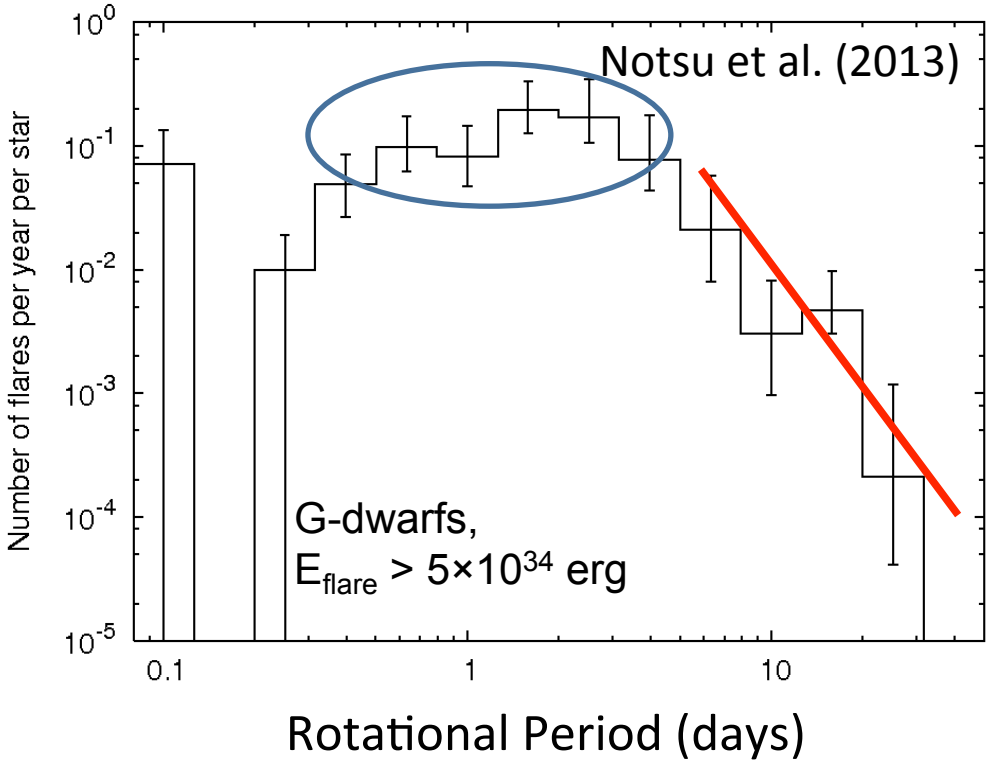


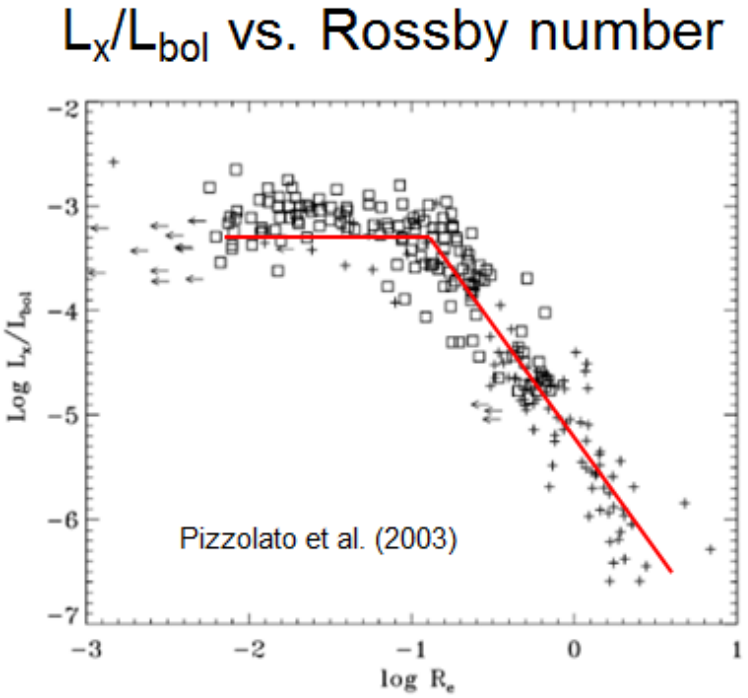
What is the frequency of superflares ? (NotsuY+ 2013)



Flare frequency vs. rotation period

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

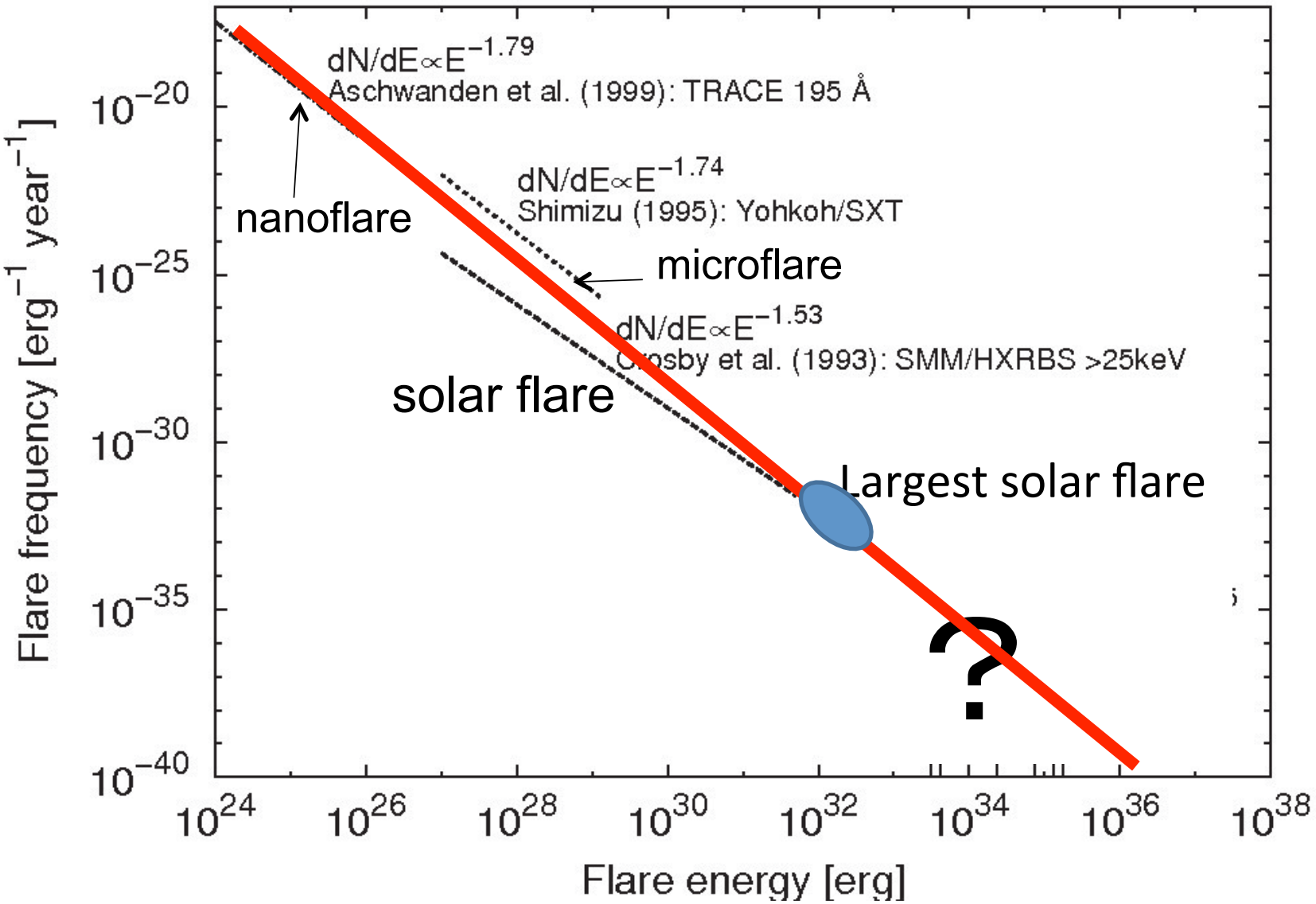




(Ro = P_rot/t_conv)

Comparison of statistics between solar flares/microflares and superflares

Shibata et al. 2013



Comparison of statistics between solar flares/microflares and superflares

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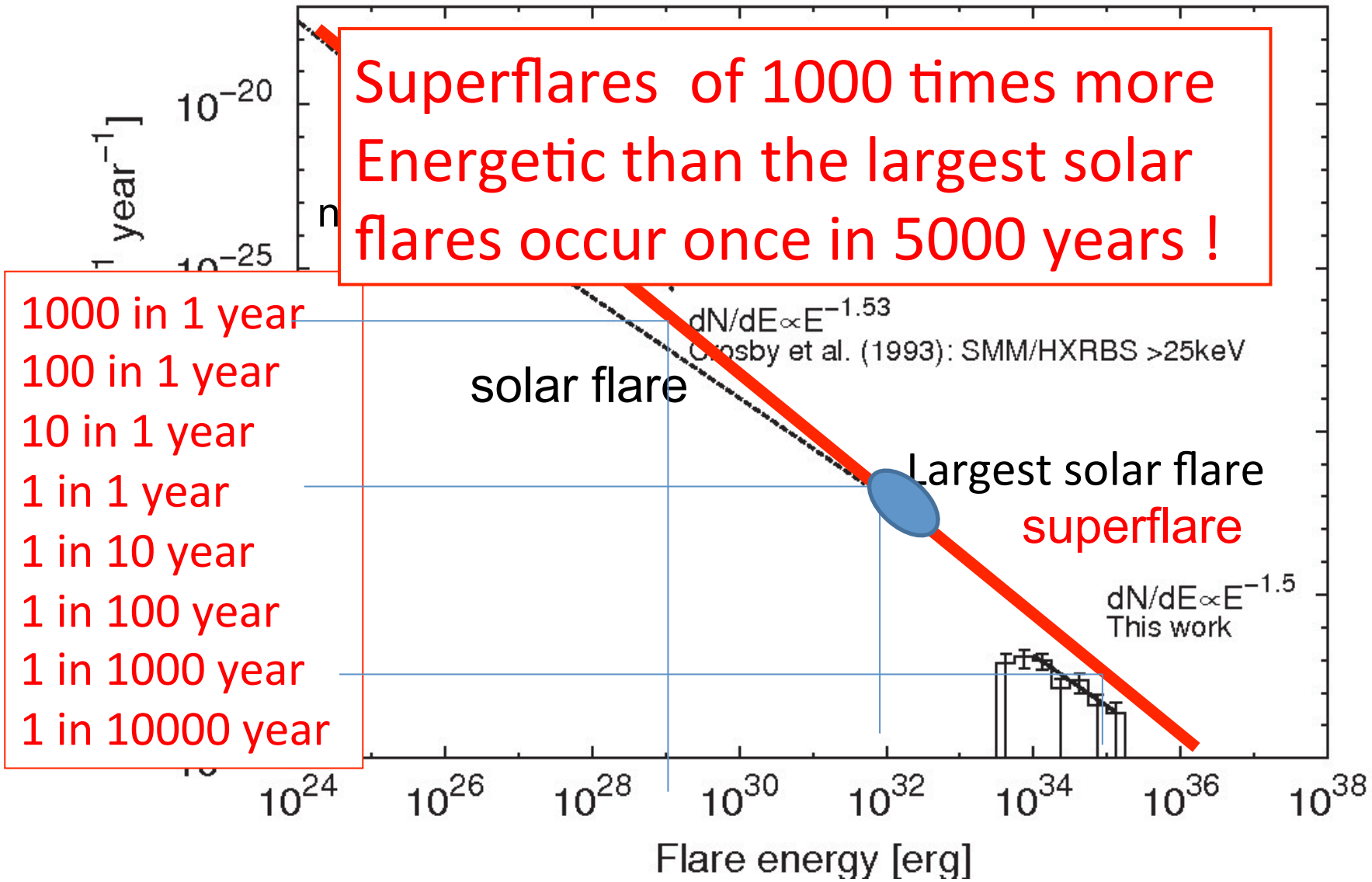


Flare energy vs sunspot area

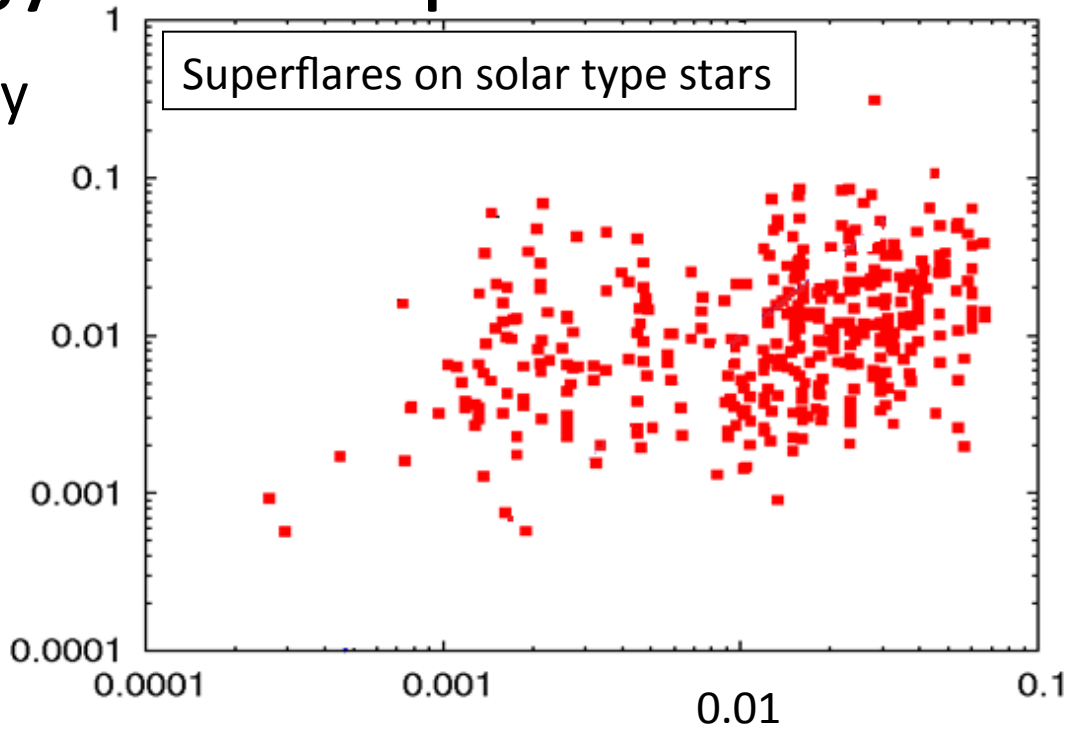
Flare Energy

10^35 erg X10000

10^34 erg X1000

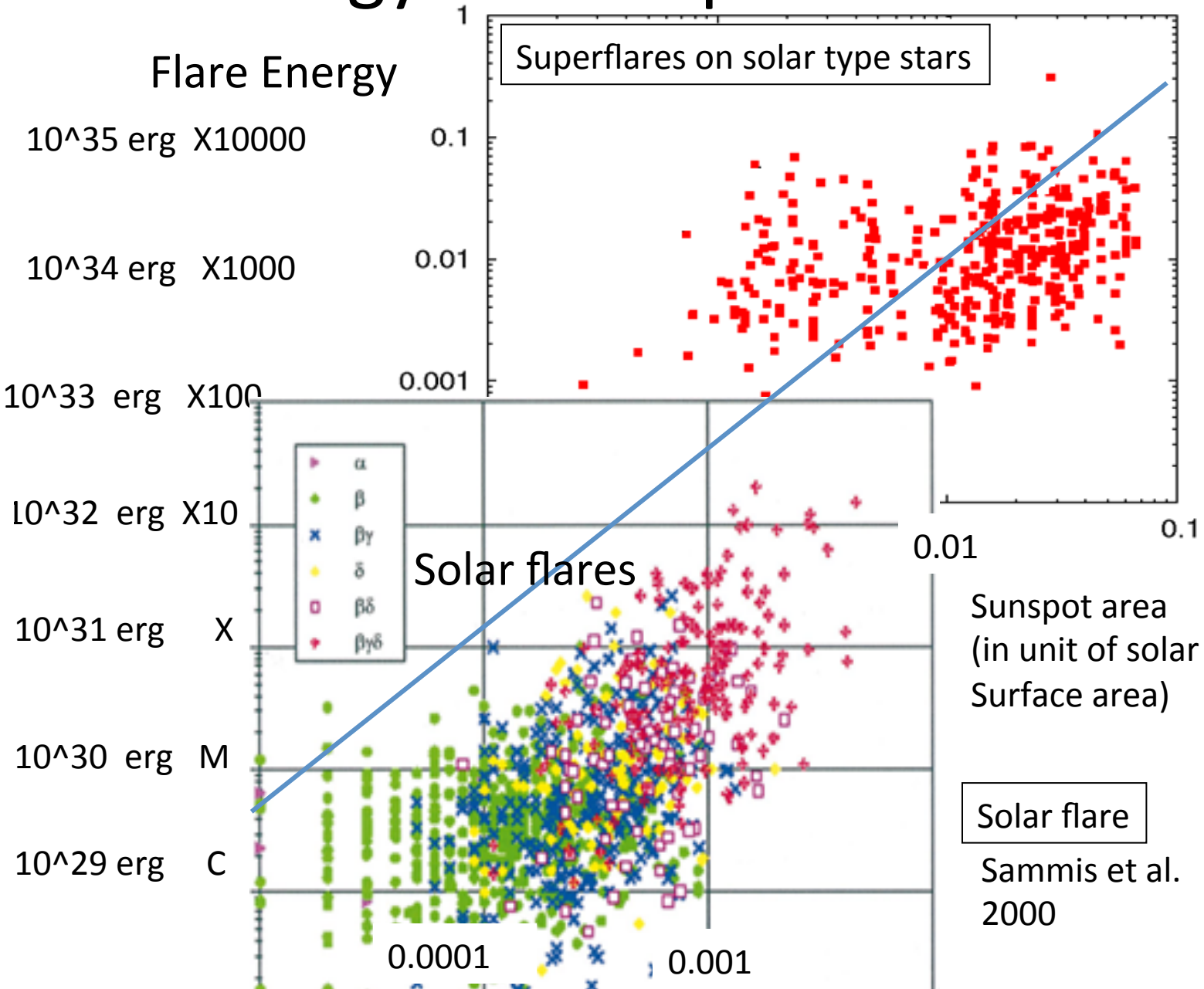
10^33 erg X100

l0^32 erg X10



Sunspot area
(in unit of solar surface area)

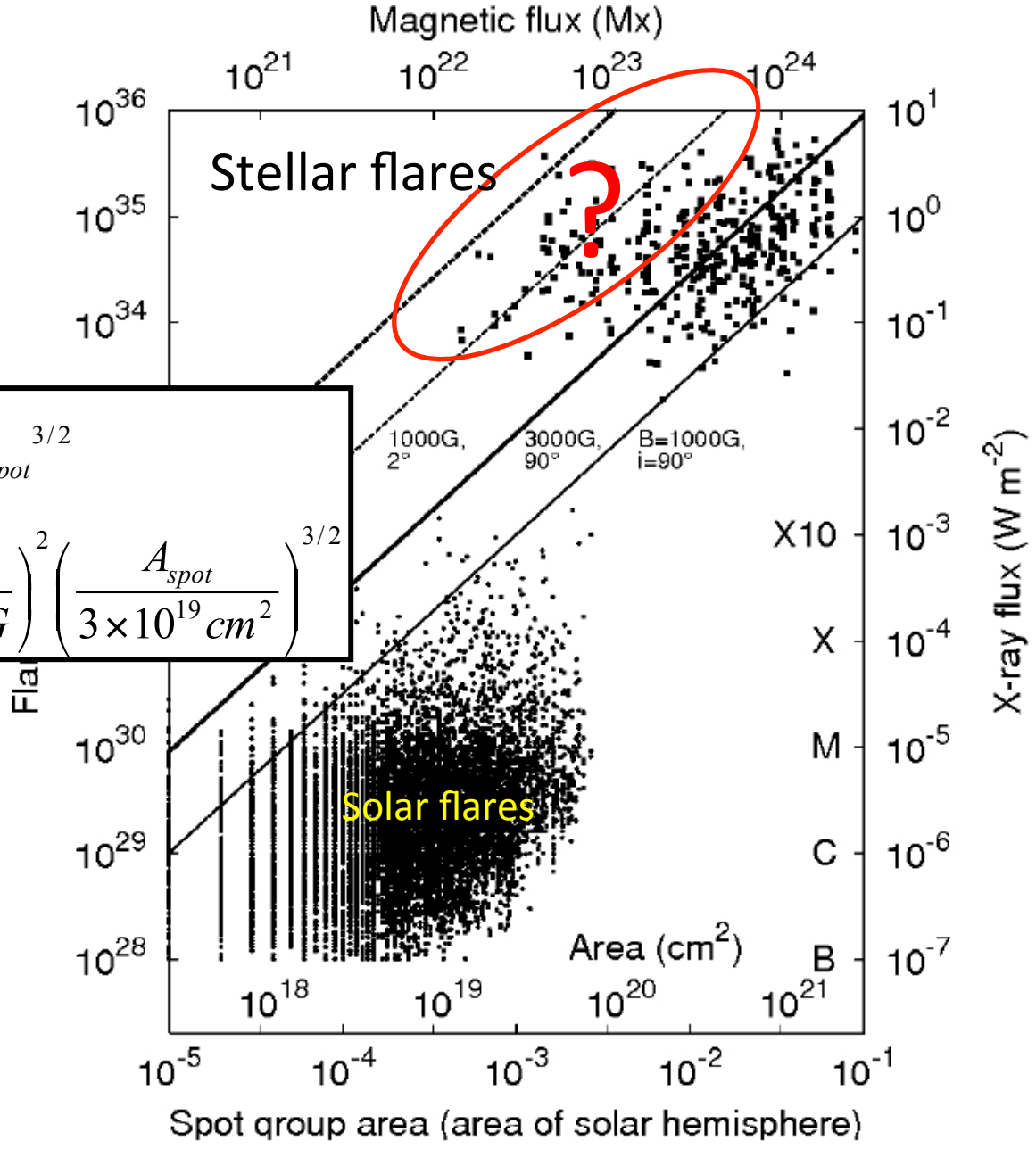
Flare energy vs sunspot area



Flare energy vs sunspot area (magnetic flux)

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

$$\approx 7\times10^{32}\ [erg]\left(\frac{f}{0.1}\right)\left(\frac{B}{10^3 G}\right)^2\left(\frac{A_{spot}}{3\times10^{19}cm^2}\right)^{3/2}$$



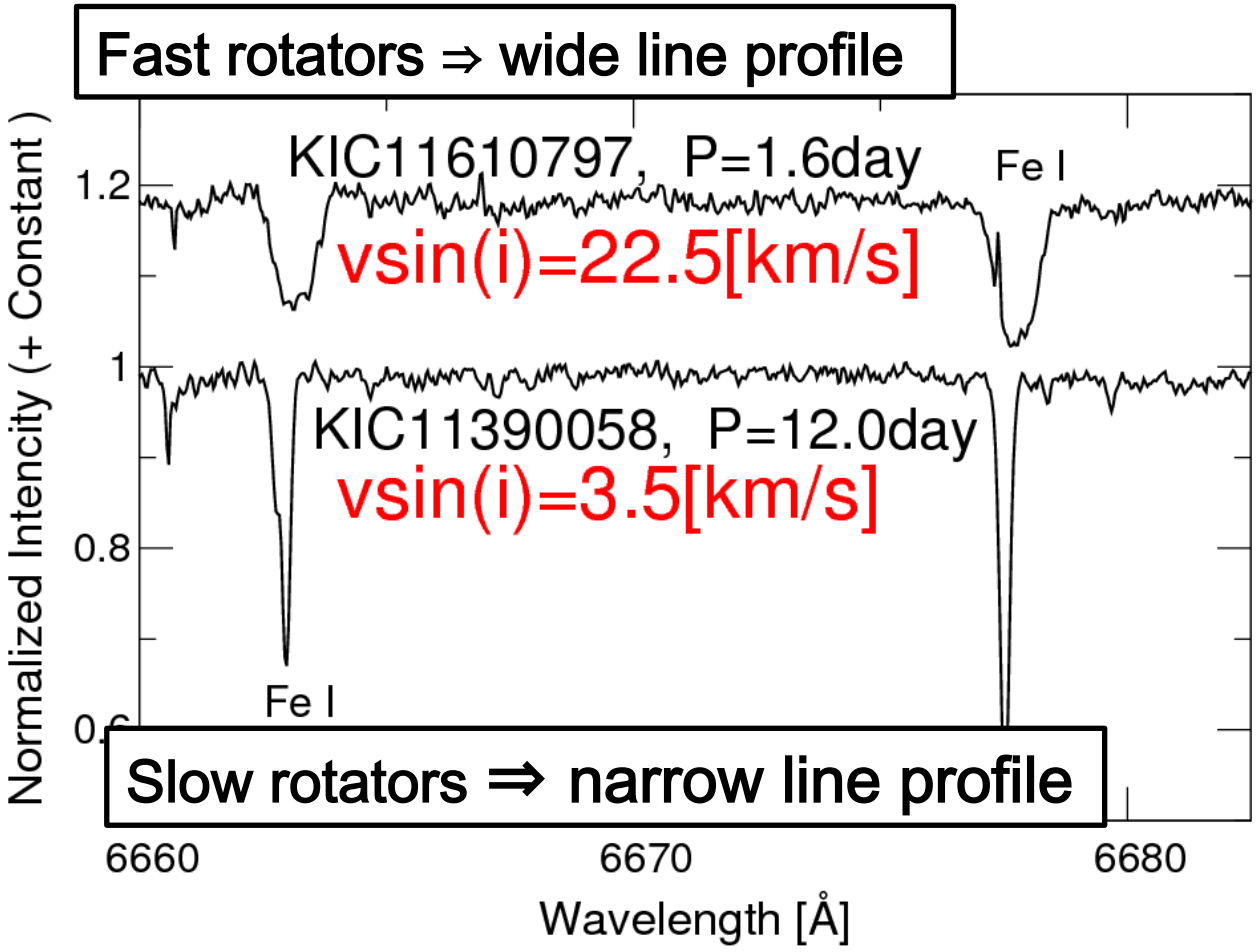
Shibata et al. (2013)

Spectroscopic Observations of Superflare Stars

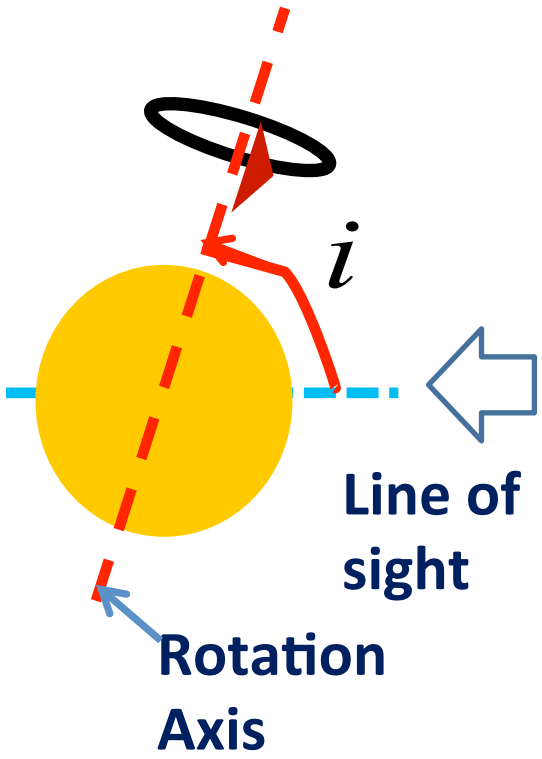
Notsu et al. (2015) PASJ

Projected rotation velocity ($v \sin i$)

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



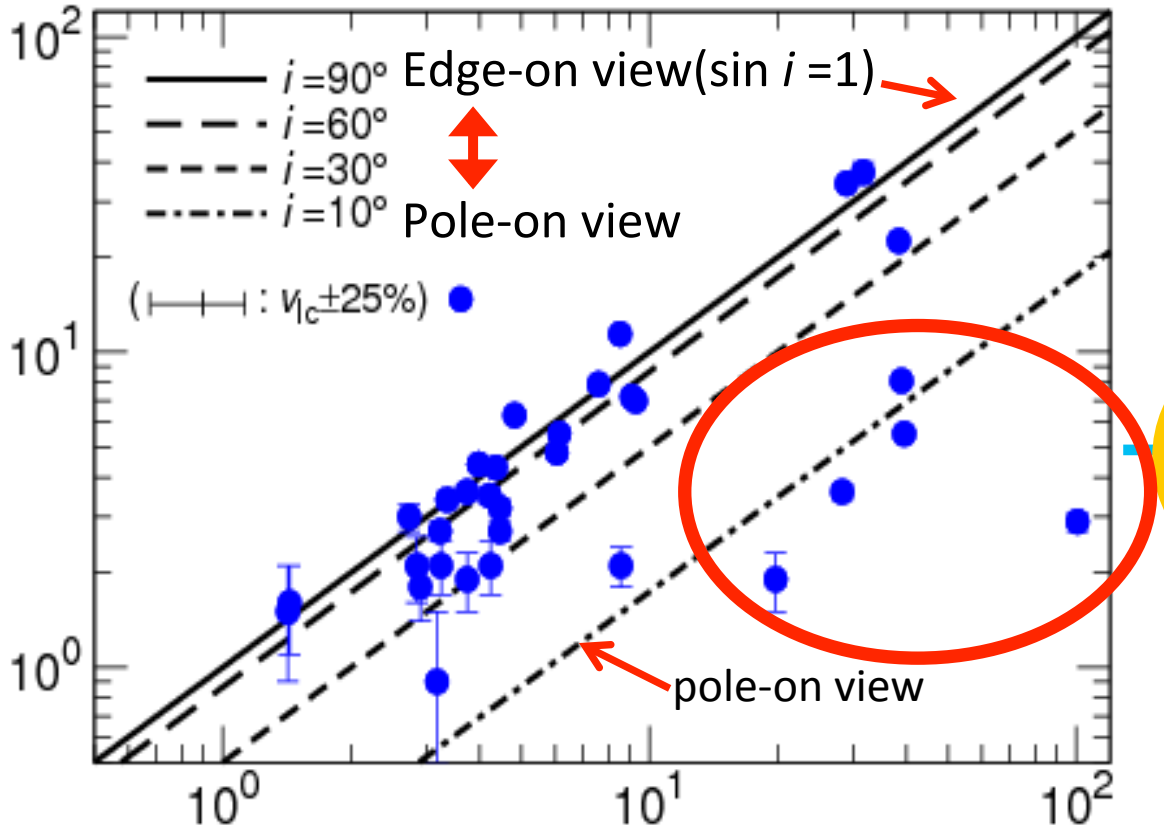
Notsu, Y. et al. (2015)



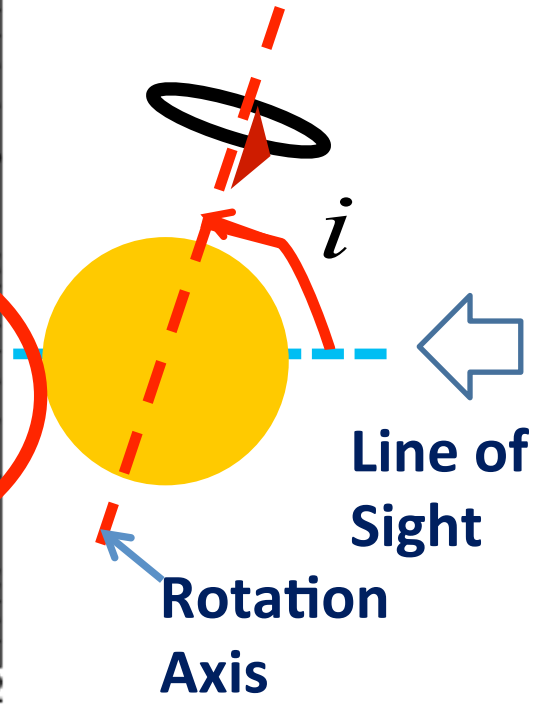
※Measurement methods
Takeda et al.(2008etc)

Rotation Period ⇔Brightness variation period ?

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



v sin i [km s^{-1}]



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

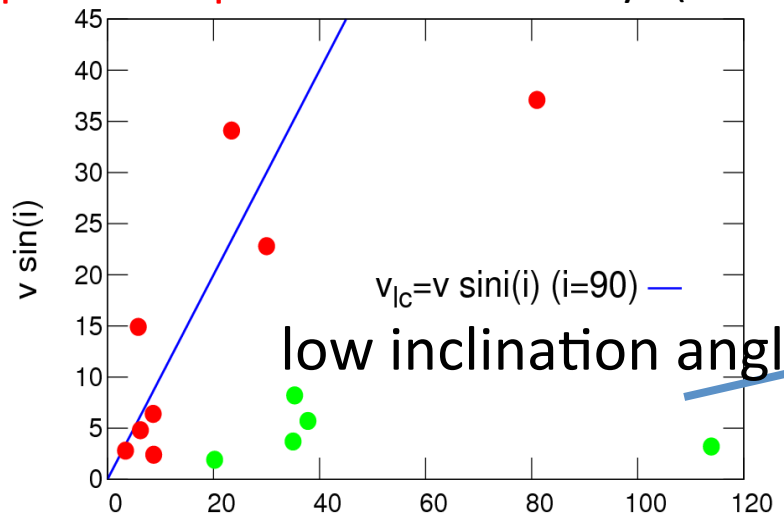
$$v_{lc} \approx \frac{2\pi R_{star}}{P}$$

Notsu, Y. et al. (2015)

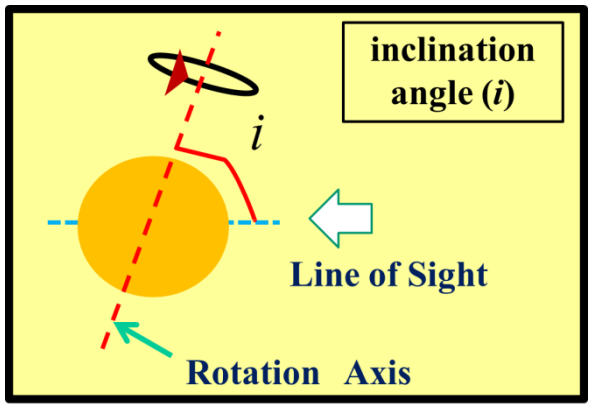
※Sun: V_{rot} ~ 2 [km s^{-1}]

Flare energy vs. area of starspots

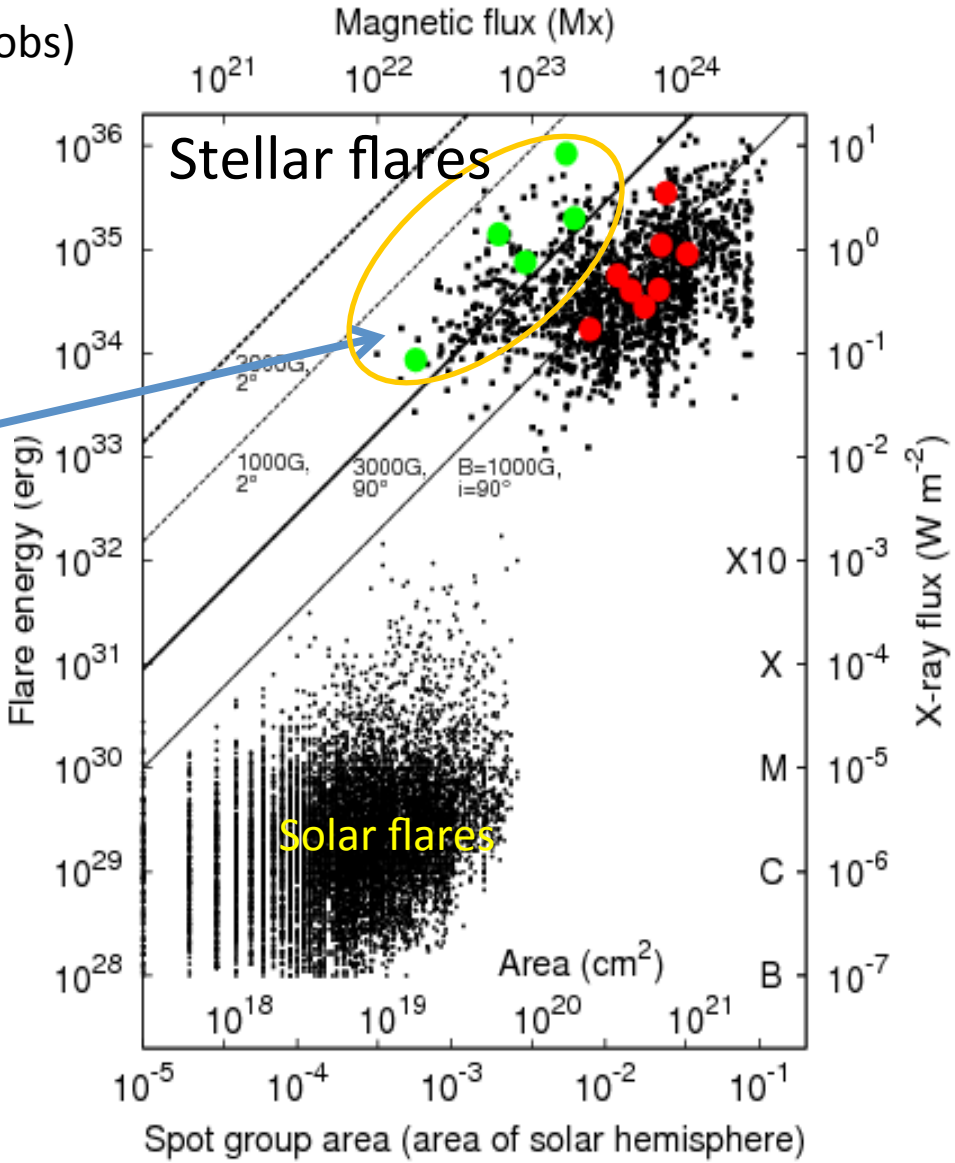
Spectroscopic rotational velocity (Subaru obs)



Photometric rotational velocity



Notsu, Y. et al. (2015)



Spectroscopic Observations of Solar type stars causing superflares will be extremely important

Okayama 3.8m New Technology Telescope of Kyoto Univ (under construction)

New Technology
1. Making Mirrors with Grinding
2. Segmented mirror
3. Ultra Light mounting

High speed photometric and spectroscopic observation of

Transient objects

Gamma ray bursts

Exoplanets

Stellar flares (superflares)

Budget for operation
Is still lacking.
Please support us !

mpleted ~ 2017

courtesy of Prof. Nagata (Department of Astronomy , Kyoto University)

Summary

- Using Kepler data, we found 365 superflares (10^33-10^36 erg) on 148 solar type stars (among 80000 stars) during 120 days (Maehara+ 2012). => 1547 superflares from 279 solar type stars during 500 days (Shibayama + 2013).
- Superflares occur on Sun-like stars (5600-6000K and slow rotation) with frequency such that superflares with energy 10^33-10^35 erg (X100-X10000 solar flare) occur once in 500-5000 years
- These stars have large star spot (Notsu+ 2013).
- Rotational velocity and large star spot of 34 superflare stars has been confirmed by spectroscopic observations (Notsu+ 2015)
- Simultaneous X-ray and optical observations of these superflares would be extremely important !

Thank you for your attention