Solar White-Light Flares

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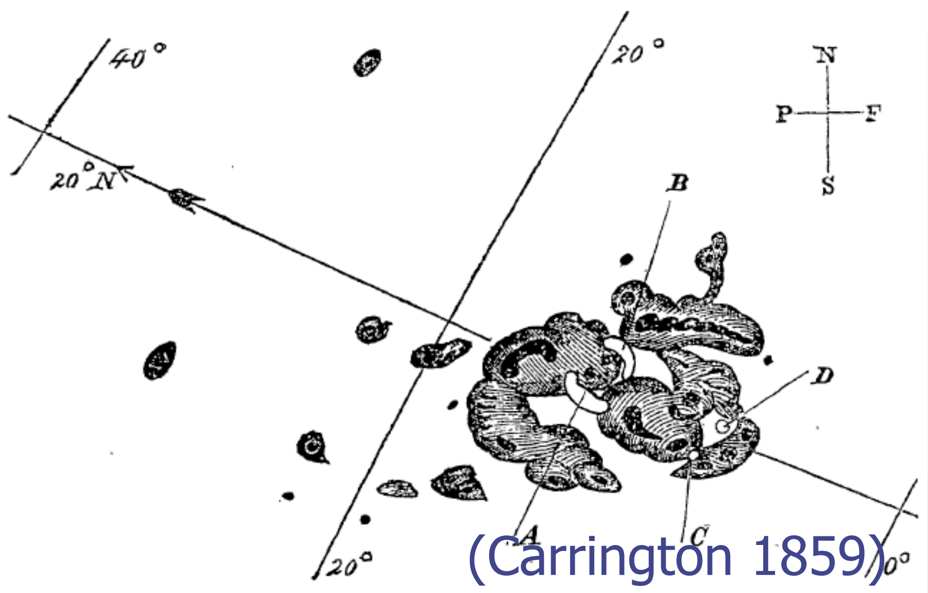
Superflares on Solar-type Stars and Solar Flares, and Their Impacts on Exoplanets and the Earth @ Kyoto Univ. *2016 March 1*

White-light flare

The most famous and the first WLF was the Carrington flare.

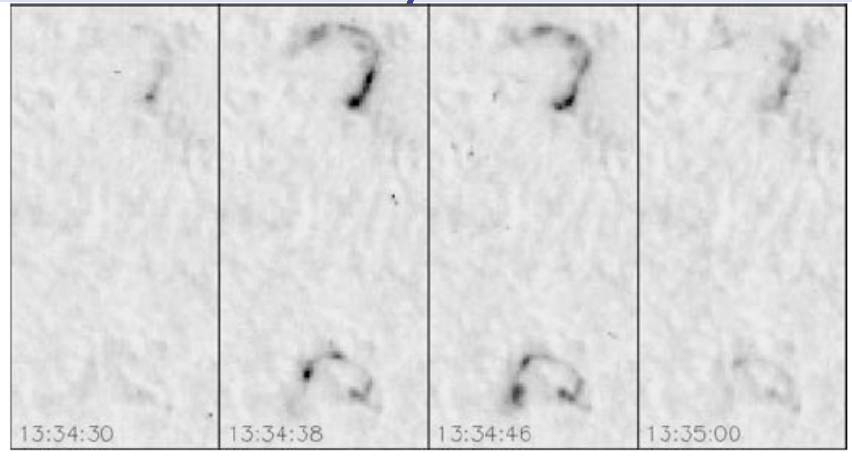


(Carrington 1859)

The frequency of occurrence of white-light flares in solar max.
~15 events/year
↓
Rare event

Very rare event observed only from large solar flares (X-class etc.)
(Hiei 1982, Neidig 1989)
↓
White-light emissions from C-class flares also observed thanks to accurate photometry by Satellites
(Matthews et al. 2003, Hudson et al. 2006)

2004 July 24 C4.8



(Hudson et al. 2006)

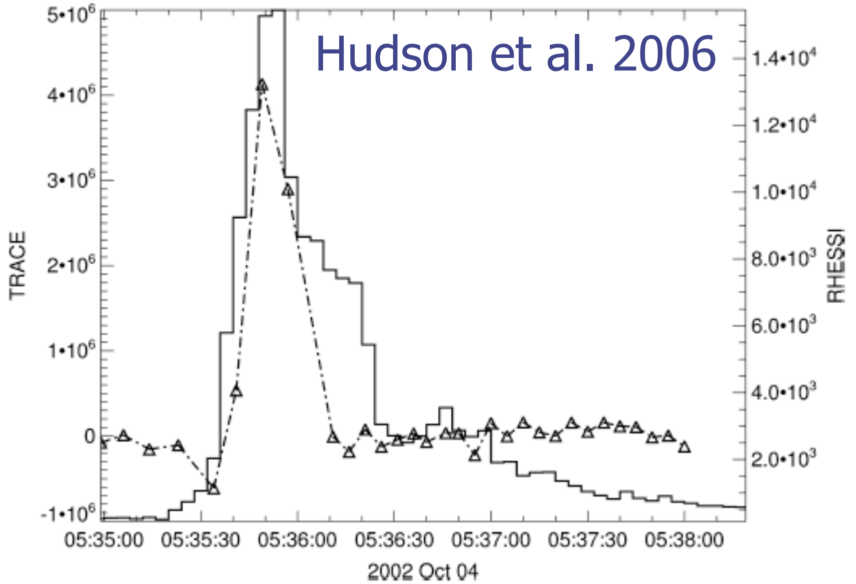
White-light flare

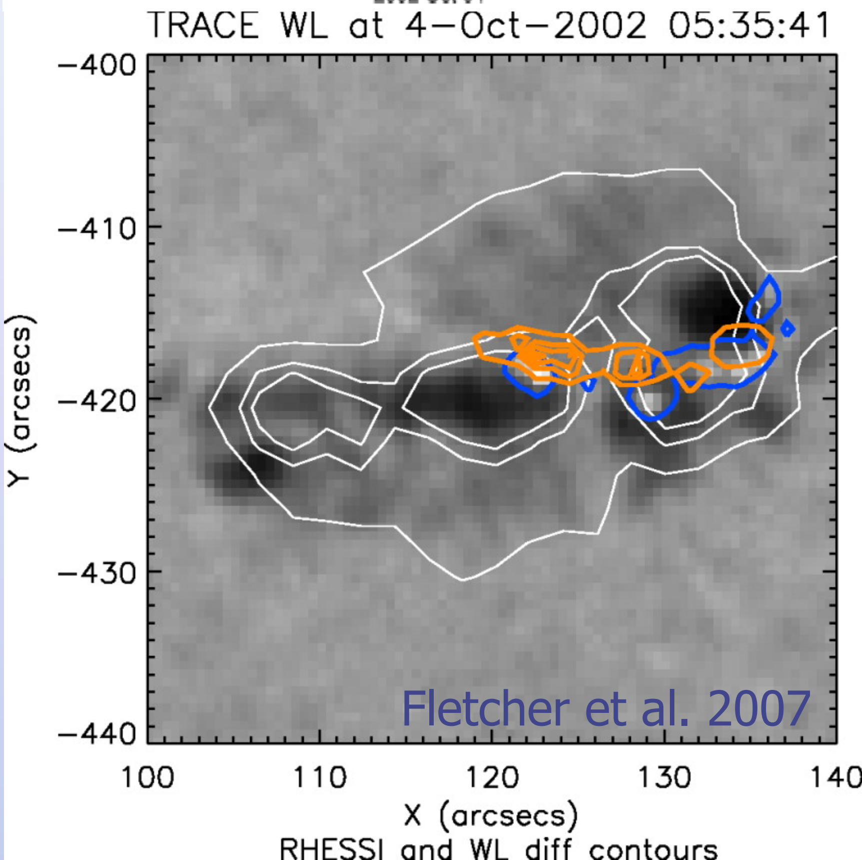
White-Light emissions are well correlated with hard X-ray and radio emissions (Location & Profile)
→ Non-thermal electrons

Original accelerated electron energy of WL emission:
- >50keV: Neidig (1989) etc.
- >25keV: Fletcher et al. (2007)
- >40keV: Watanabe et al. (2010)

etc…

White-light flare observations:
- TRACE(WL+UV)
- Hinode/SOT (G-band, R, G, B)
- SDO/HMI (Continuum)
- IRIS
- Ground telescopes





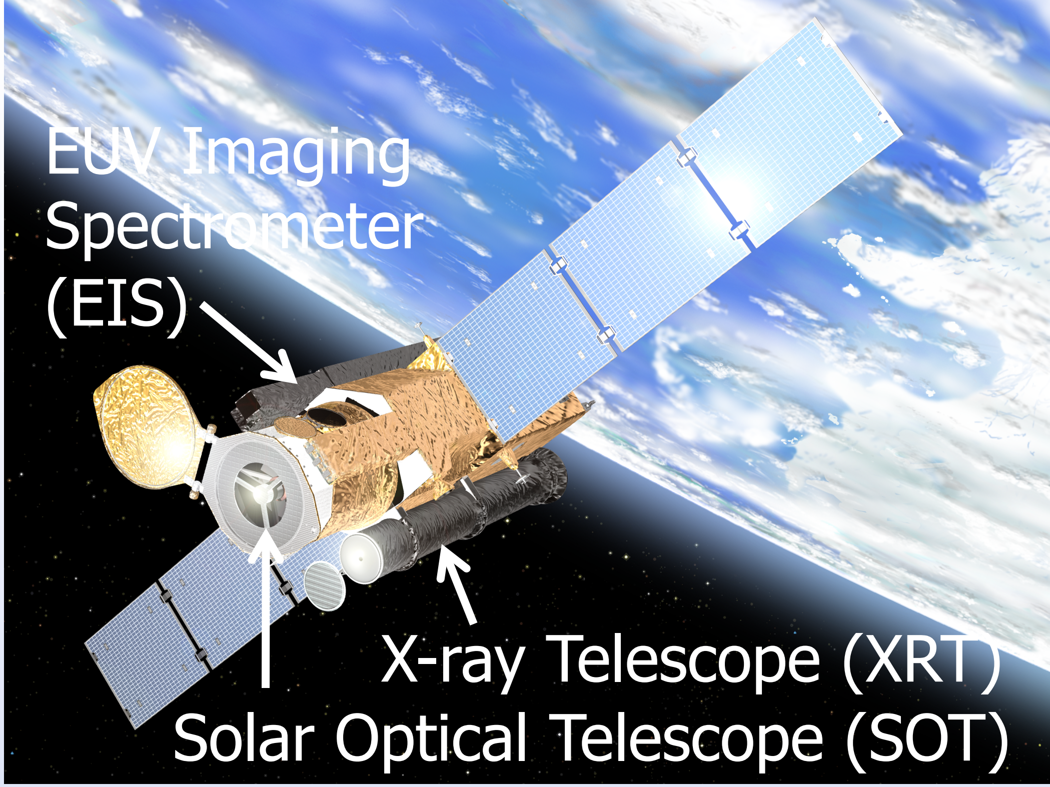
Hinode

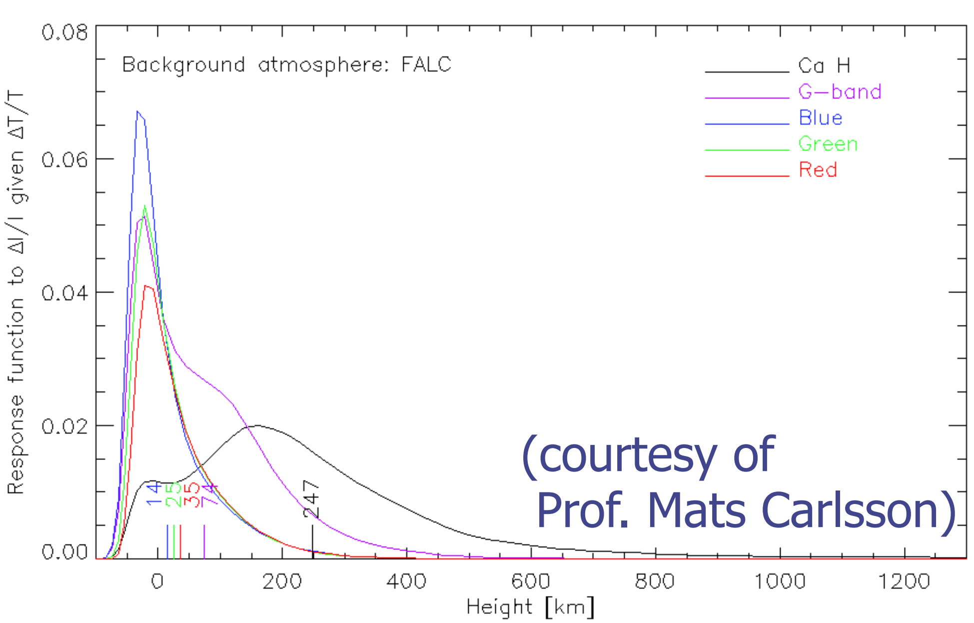
- Solar Optical Telescope (SOT)
- X-ray Telescope (XRT)
- EUV Imaging Spectrometer (EIS)

SOT/BFI:

- CN (3883 Å)
- Ca II H (3969 Å)
- CH (4305 Å)
- Continuum
  - Blue:4505 Å,
  - Green:5550 Å,
  - Red:6684 Å

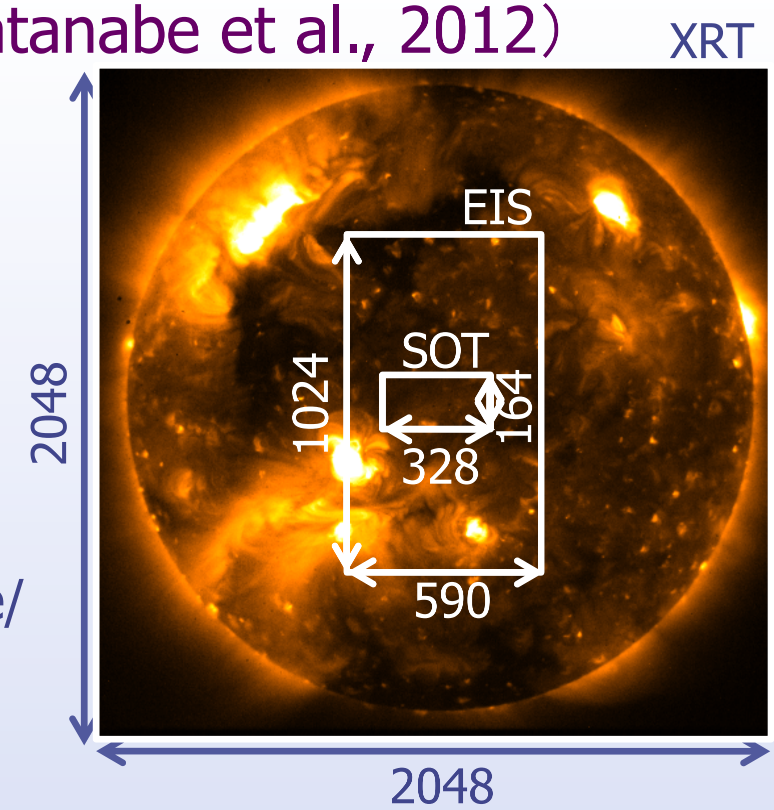
These bands can be used for white-light flare observation





(courtesy of Prof. Mats Carlsson)

Hinode Flare Catalogue (Watanabe et al., 2012)



Not all flares are seen by Hinode

Flare occurs when Hinode is observing
+ Inside Hinode FOV

⇩

Hinode Flare Catalogue

http://st4a.stelab.nagoya-u.ac.jp/hinode_flare/

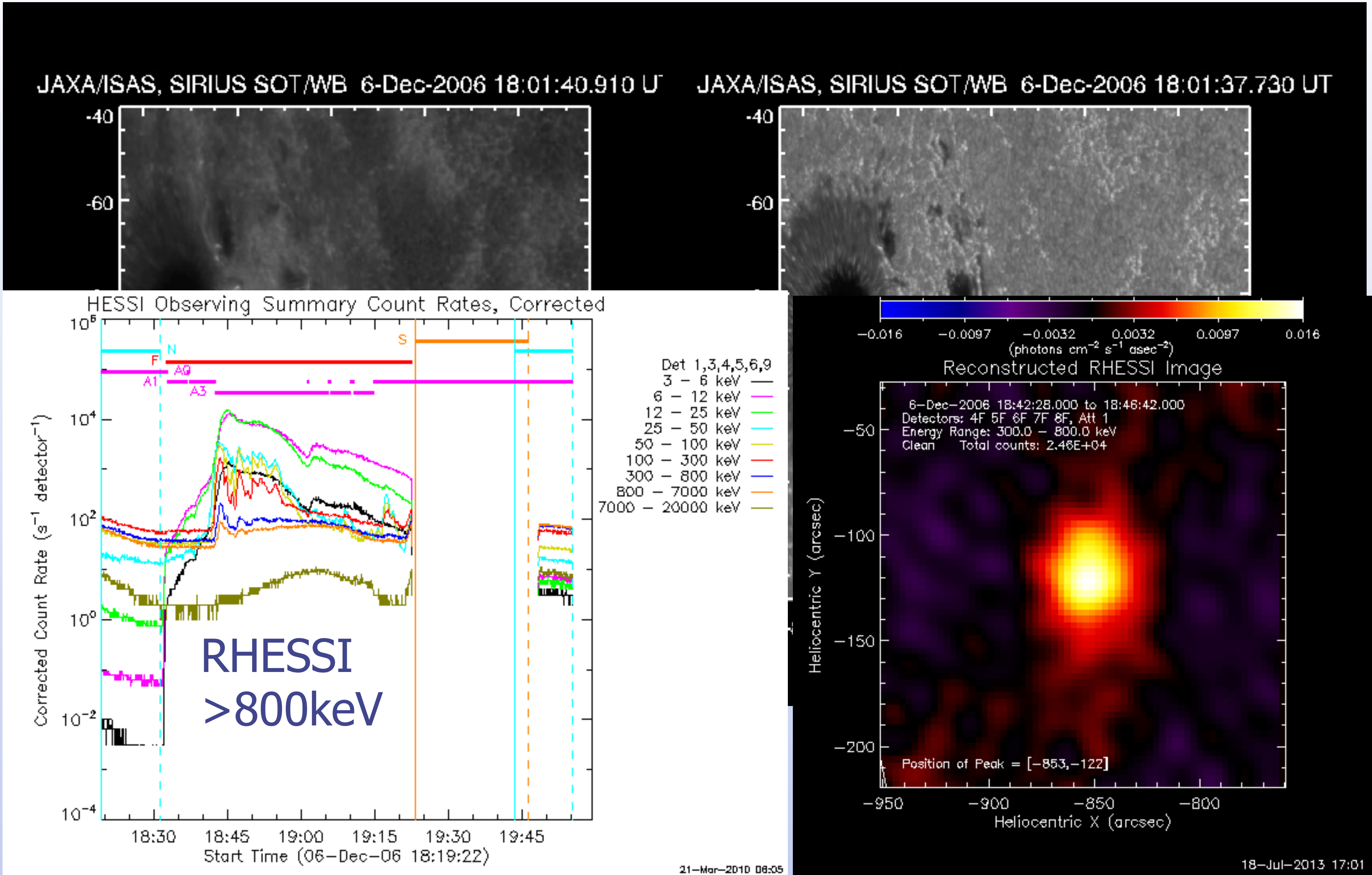
- Hinode (images of SOT, XRT and EIS)
- RHESSI (observed largest energy range)
- NoRH (link to the event page)

Hinode Flare Catalogue | Hinode flare Databook

GOES class	XRT	SOT (FG)	SOT(SP)	EIS	Total #
X	33 (67.3%)	22 (44.9%)	16 (32.7%)	17 (34.7%)	49
M	394 (55.9%)	208 (29.5%)	213 (30.2%)	132 (18.7%)	705

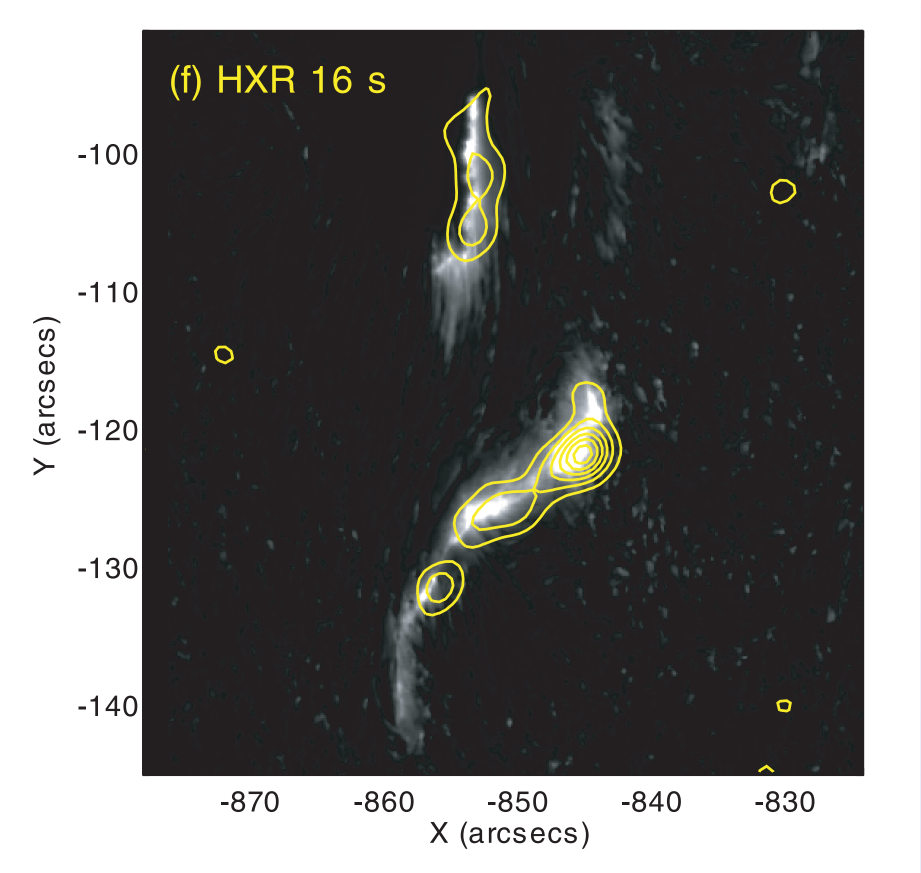
2006 Dec 6 White-light flare

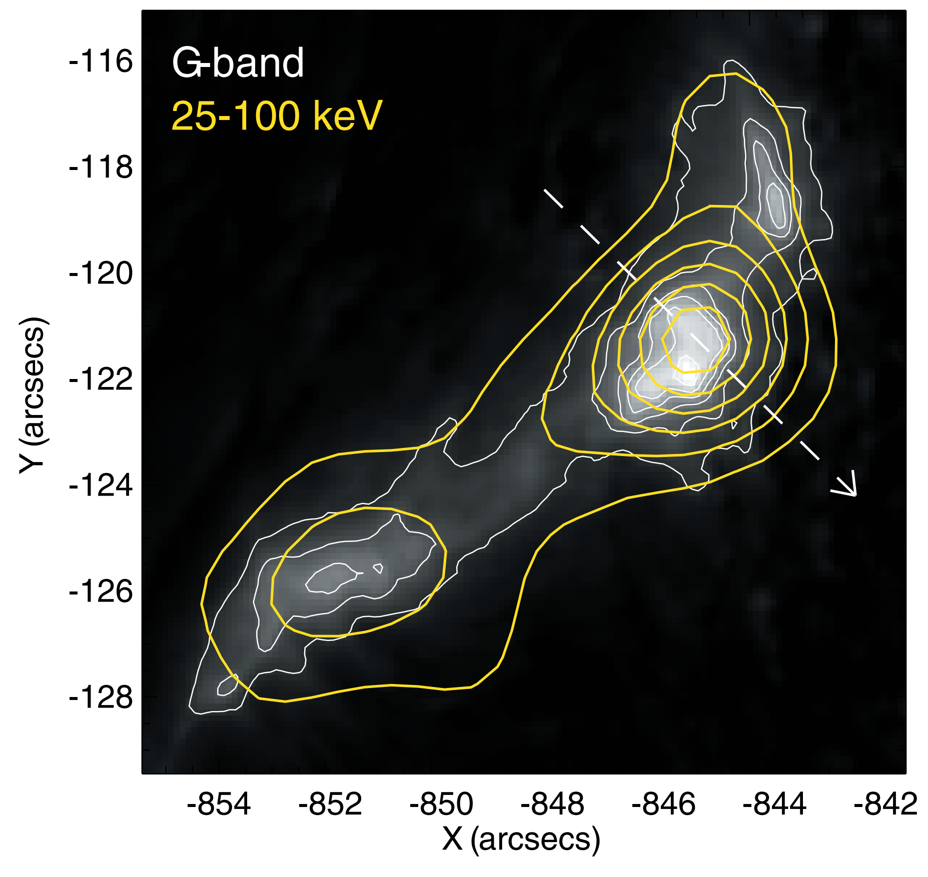
SOT/G-band + RHESSI



2006 Dec 6 White-light flare

SOT/G-band + RHESSI (Krucker et al., 2011)





The hard X-ray and white-light (G-band) data show very similar ribbon structures (length ~30”), and this result strongly suggests that the flare emission in white light and in hard X-rays have physically linked emission mechanisms.

2006 Dec 14 White-light flare

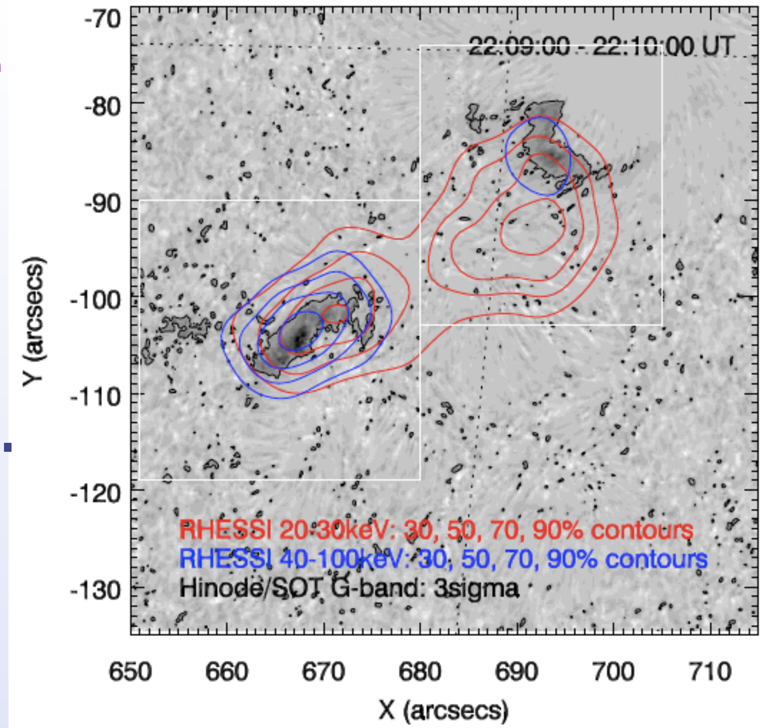
SOT/G-band + RHESSI
(Watanabe et al., 2010)

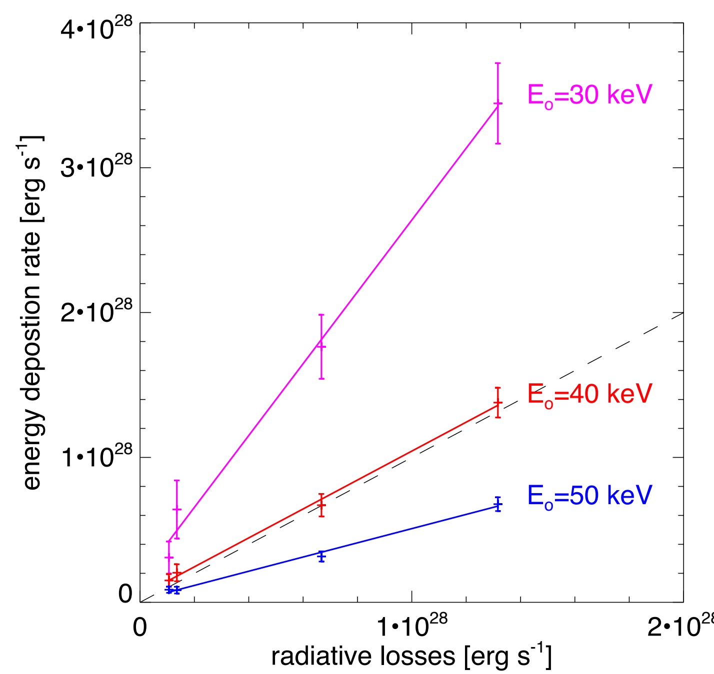
White-light & hard X-ray emissions were seen at almost the same location.

- Power of accelerated electrons
  → Thick Target Model
- Power of White-Light emission
  → Blackbody

The power of white-light (G-band) emission can be explained by >40keV non-thermal electrons.

WL and HXR emission is seen almost at the same horizontal position
→ There is a problem related to the emission height





WL & HXR emission height

Corona / Chromosphere / Photosphere

km

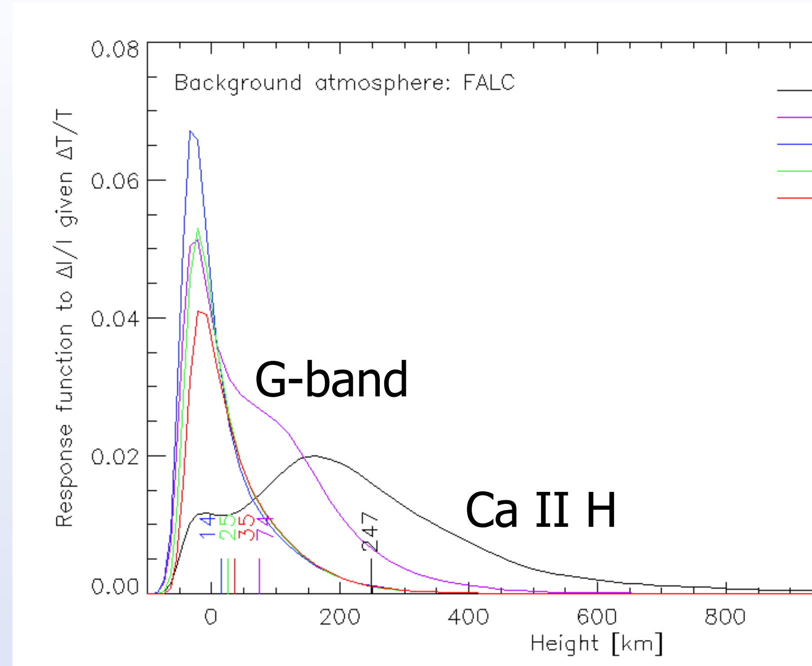
6500 ← 50-100keV HXR (From Yohkoh events, Matsushita et al., 1992)

1000 ← Thermalize 50-100keV electrons (density = $10^{13.5}/cm^3$, Neidig 1989)

600 ← 50-100keV HXR (from a RHESSI event, Kontar et al., 2008)

100

0 ↕ G-band (Carlsson et al., 2007) Continuum

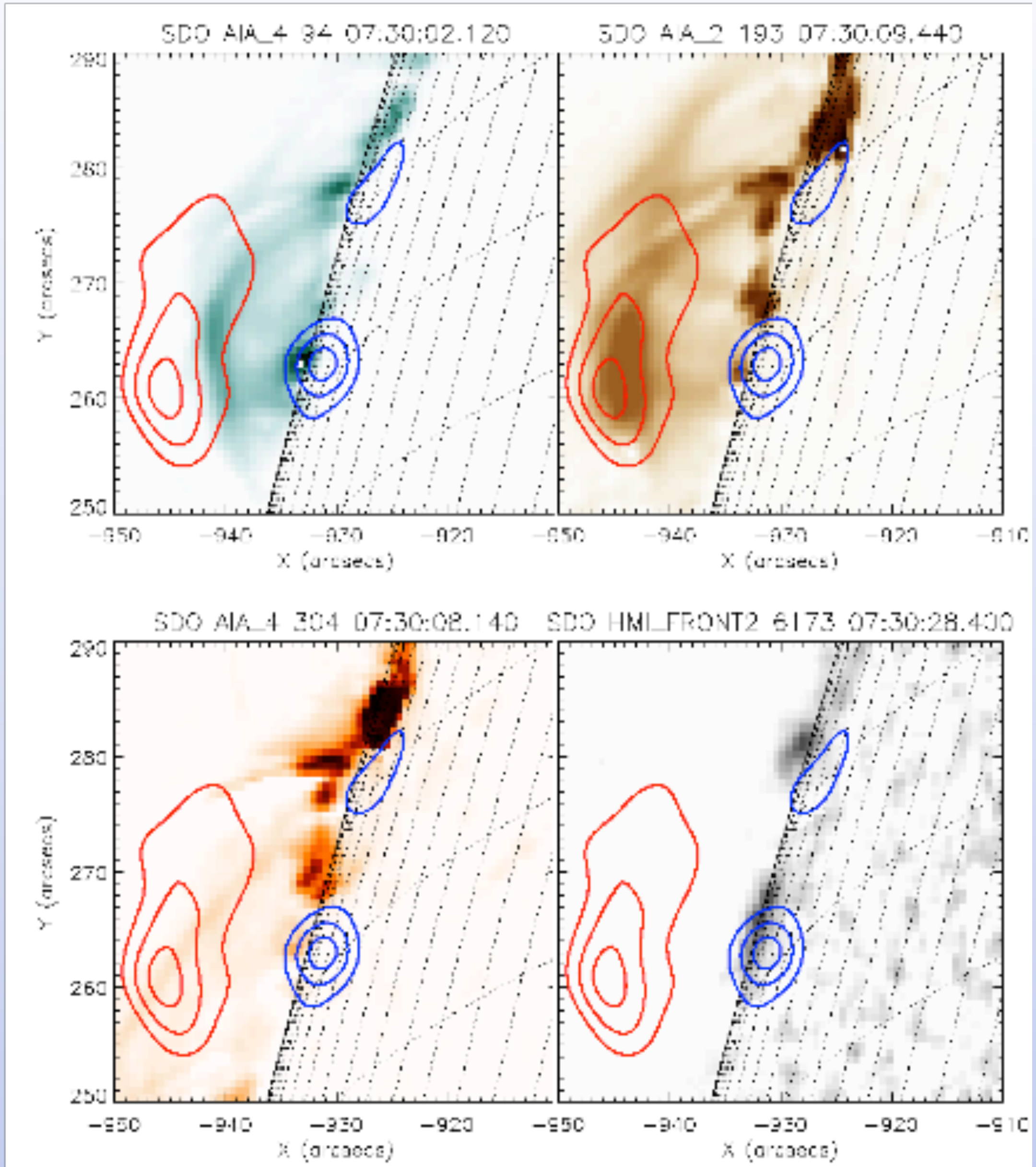


The data suggest a difference of more than 500km between the emission sites.

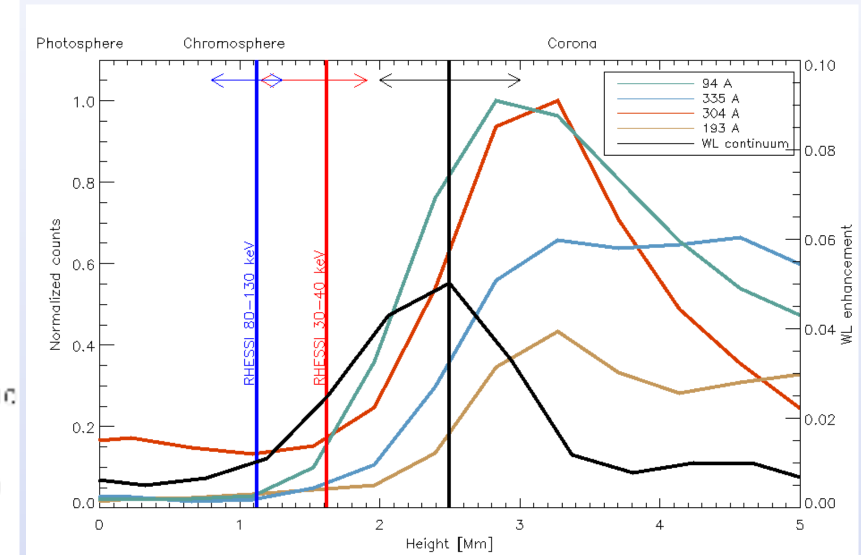
>900keV are needed to reach the photosphere (Neidig, 1989)

2011 Feb 24 White-light flare

SDO/AIA, HMI + RHESSI (Battaglia & Kontar, 2011)



WL emission is located in the upper chromosphere



WL (black) emission located higher than HXR (blue, 25-50keV) emission

↓

Origin of WL emission is low energy electrons (<12keV)

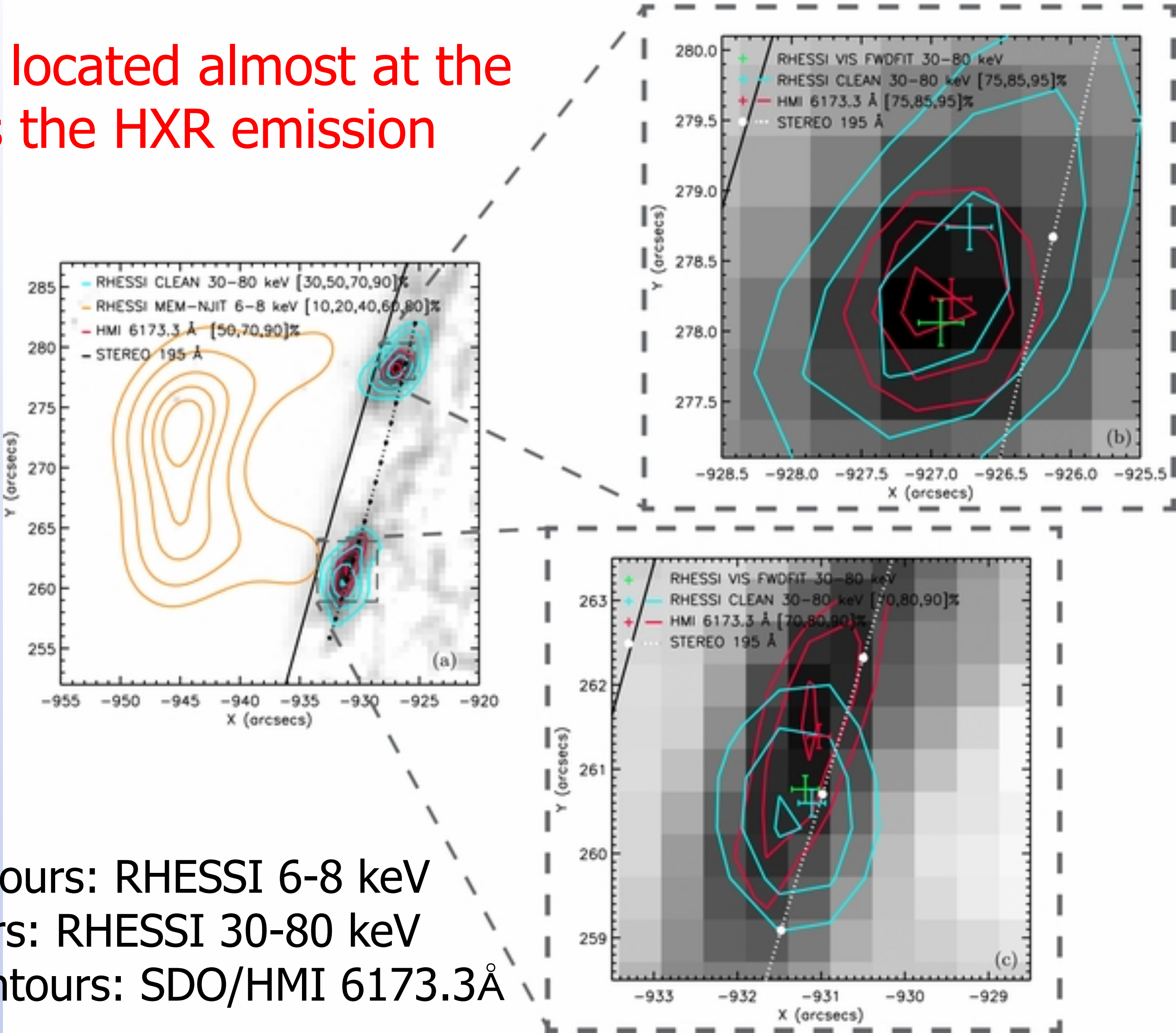
2011 Feb 24 White-light flare

SDO/HMI + RHESSI (Oliveros et al., 2012)

WL emission is located almost at the same height as the HXR emission

Emission height
- White-light: 195±70 km
- Hard X-ray: 305±170 km

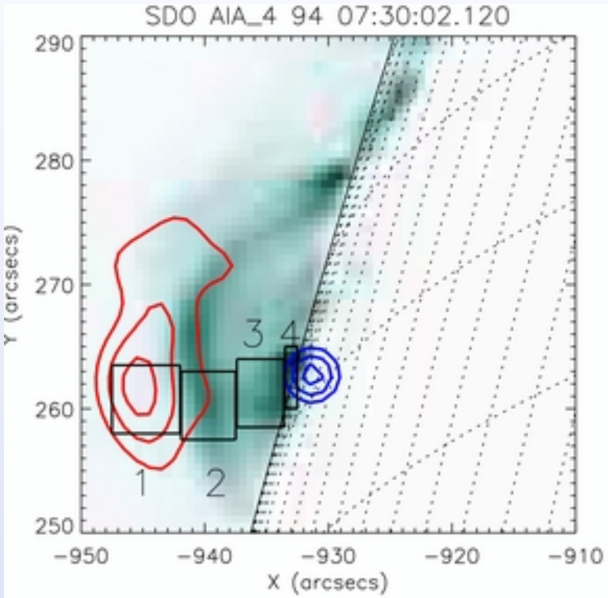
Accelerated e^- (30-80keV) reach very near the photosphere.

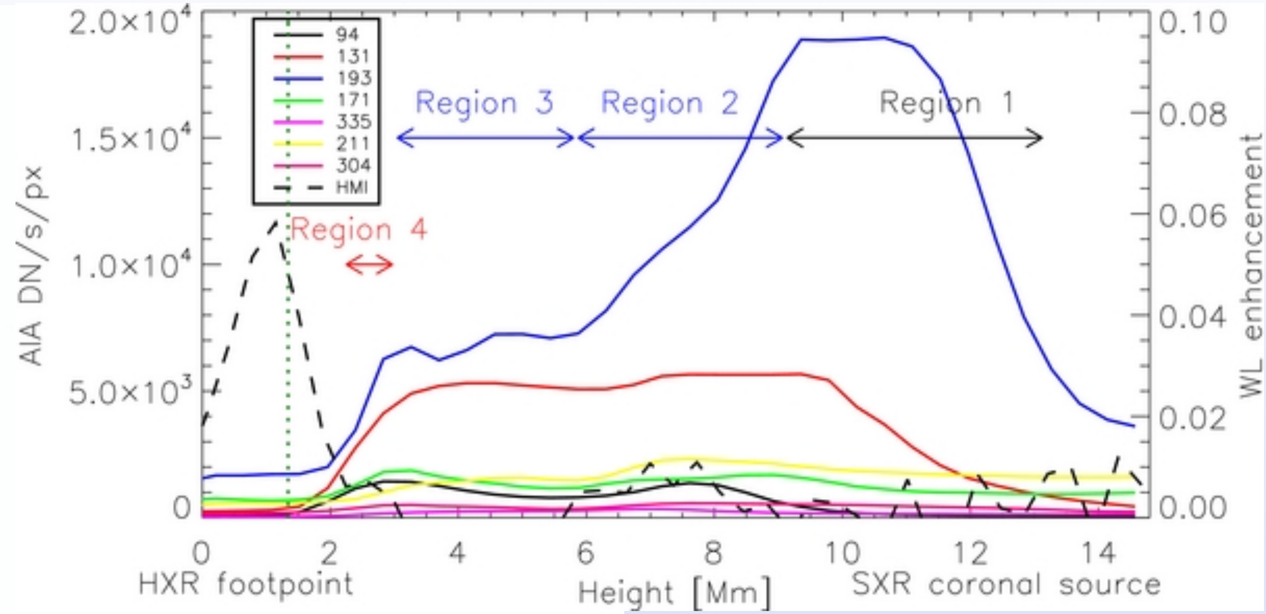


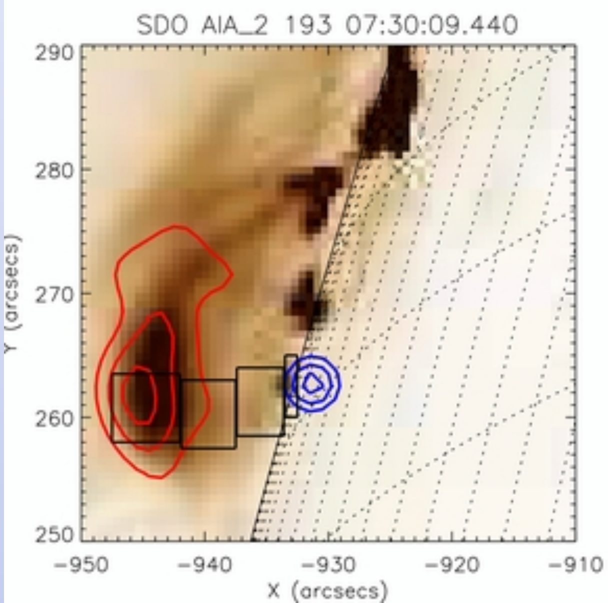
Orange contours: RHESSI 6-8 keV
Blue contours: RHESSI 30-80 keV
Magenta contours: SDO/HMI 6173.3Å

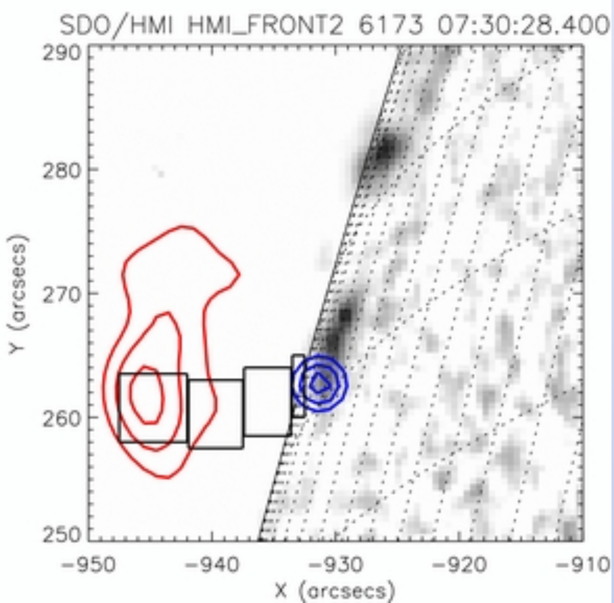
2011 Feb 24 White-light flare

SDO/AIA, HMI + RHESSI (Battaglia & Kontar, 2011)









WL emission located 1000km above the photosphere, and HXR source located 400km above the WL emission

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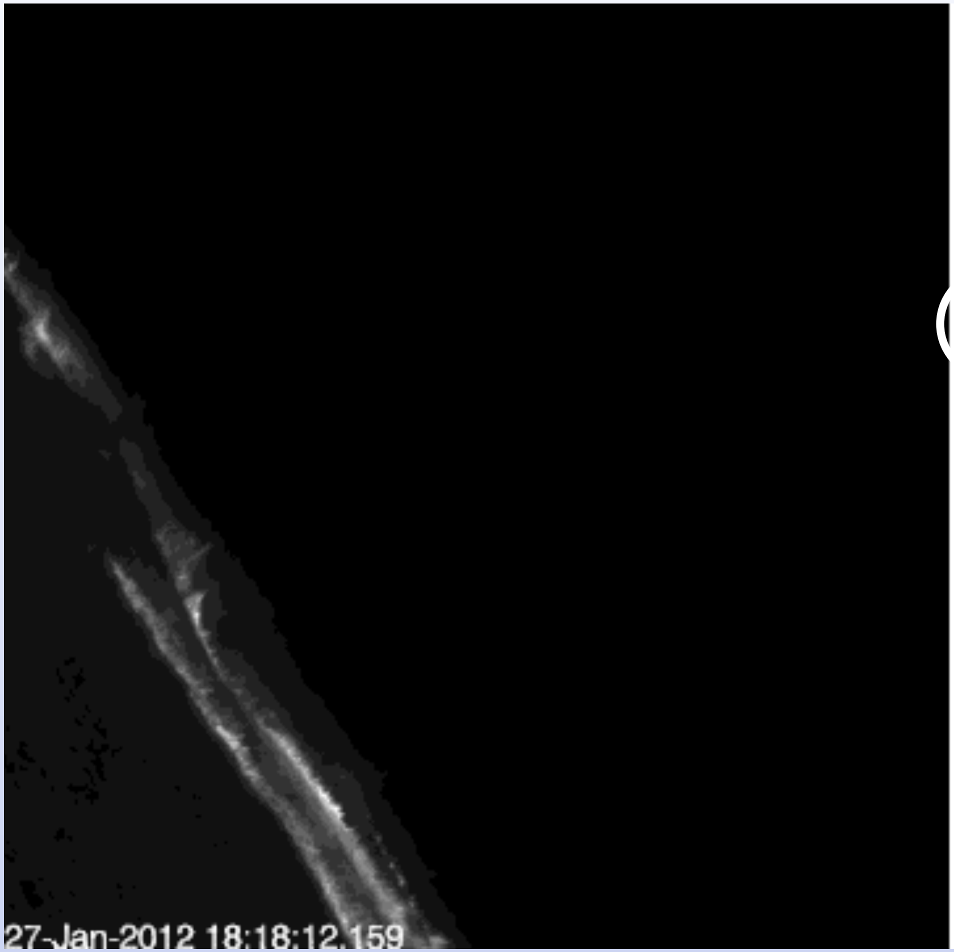
Height difference

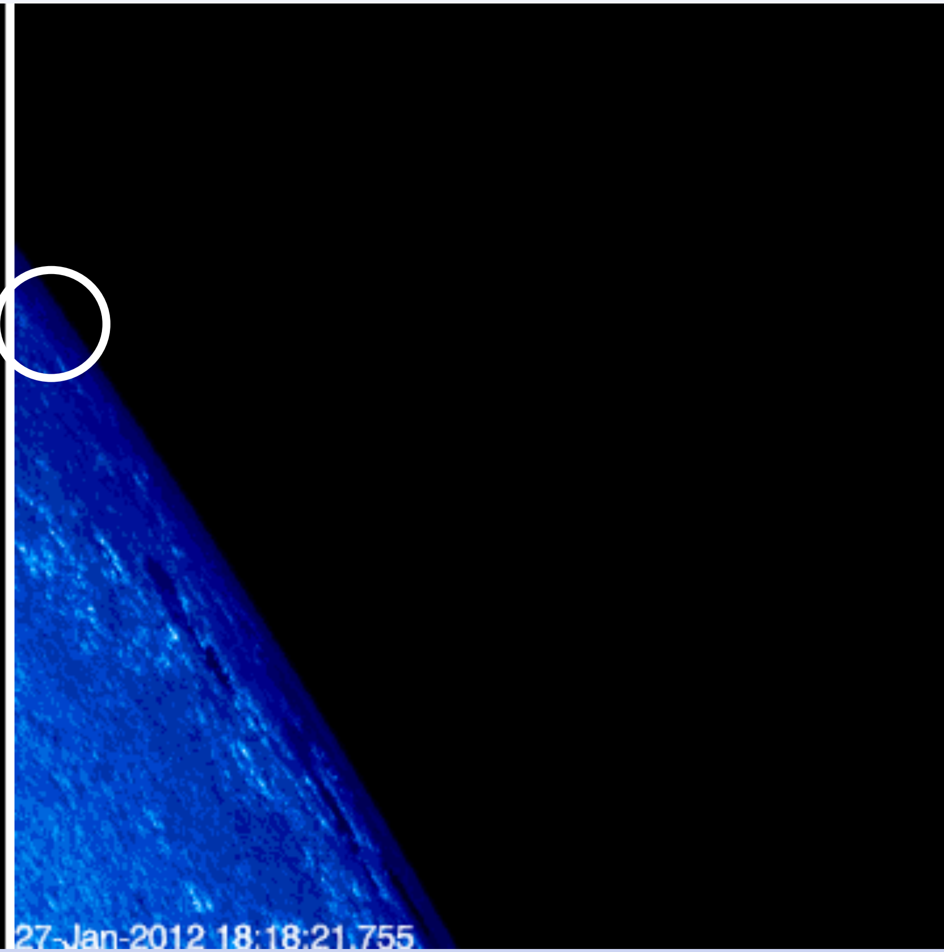
2012 Jan 27 White-light flare

Hinode/RGB (Watanabe et al., 2013)

Ca II H



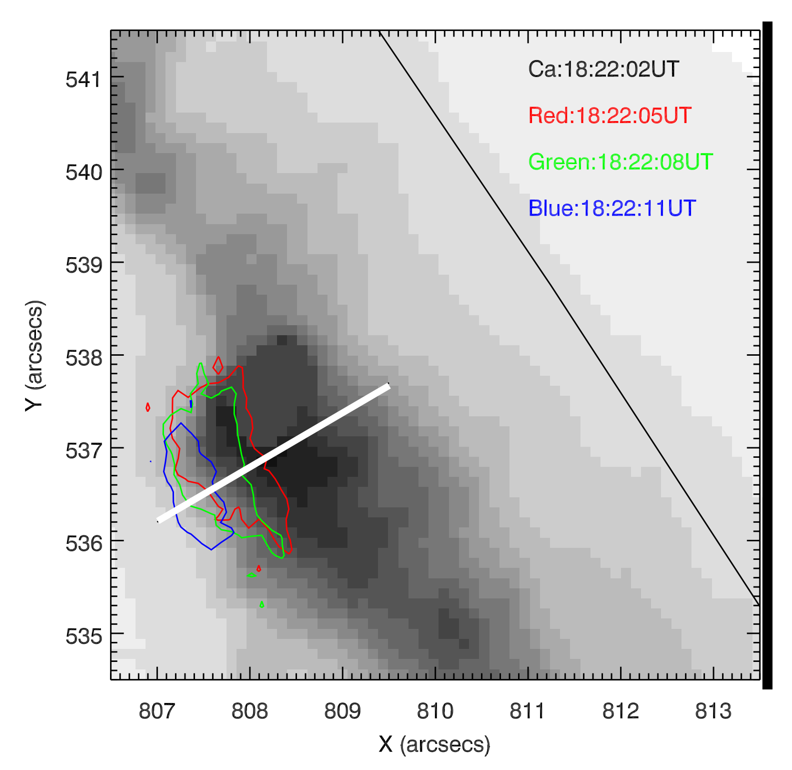
Red Green Blue

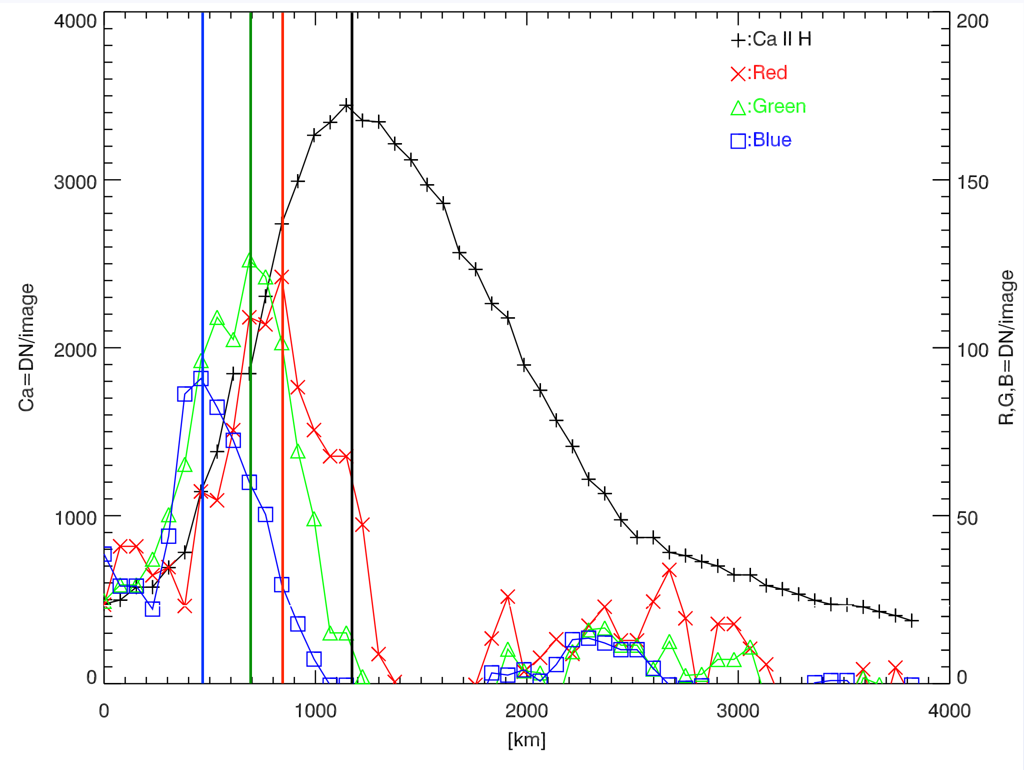


Continuum emission from the white-light flare is seen at almost the same location as where strong Ca emission was observed

2012 Jan 27 White-light flare

Hinode/RGB (Watanabe et al., 2013)





Emission location of Ca, red, green and blue are slightly different

→ Location difference is due to the emission height difference

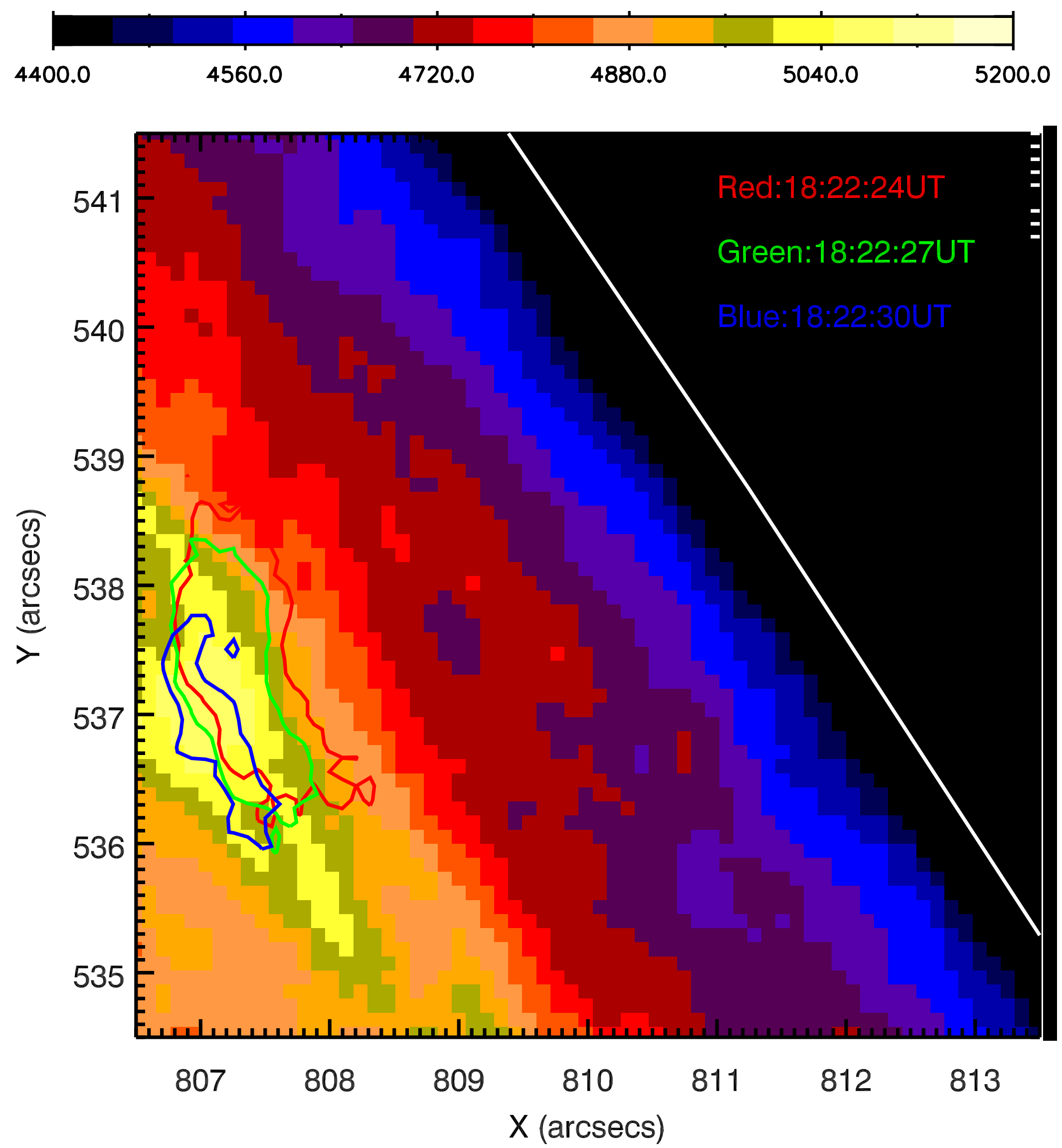
The Ca emission exists from chromosphere to photosphere

→ The edge of the Ca emission might be in the solar photosphere

→ white-light emission was emitted from the photosphere

2012 Jan 27 White-light flare

Hinode/RGB (Watanabe et al., 2013)



Temp of WL：~5000K

	18:22:05	18:22:24
Red	4952 K	4965 K
Green	4997 K	5020 K
Blue	4976 K	5033 K

→ high temp in lower layer

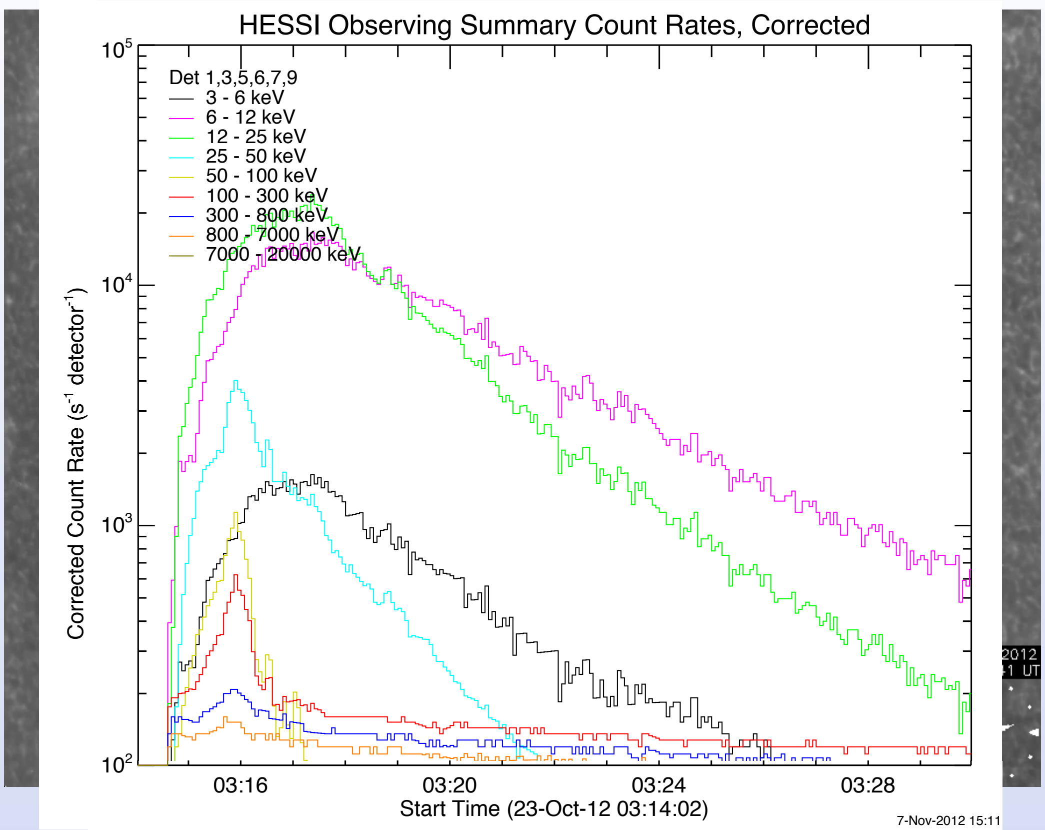
Something penetrates the lower atmosphere near the photosphere and heats the lower layer more than the higher atmosphere

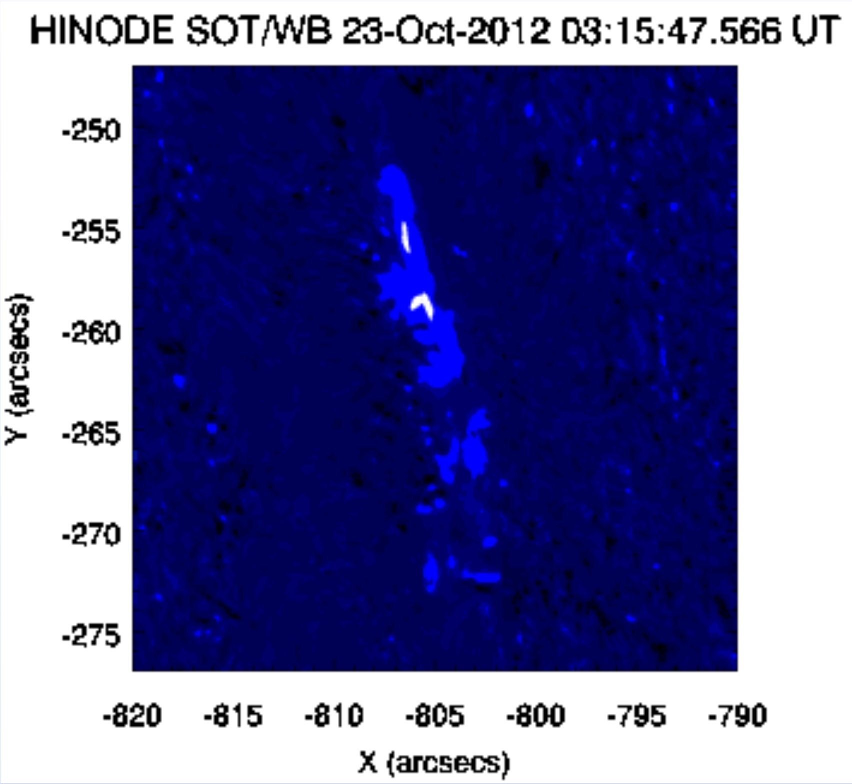
↓

Accelerated e^- directly reach the photosphere?

2012 Oct 23 White-light flare

GOES: 03:13 – 03:21 – 03:17UT S13E58 X1.8

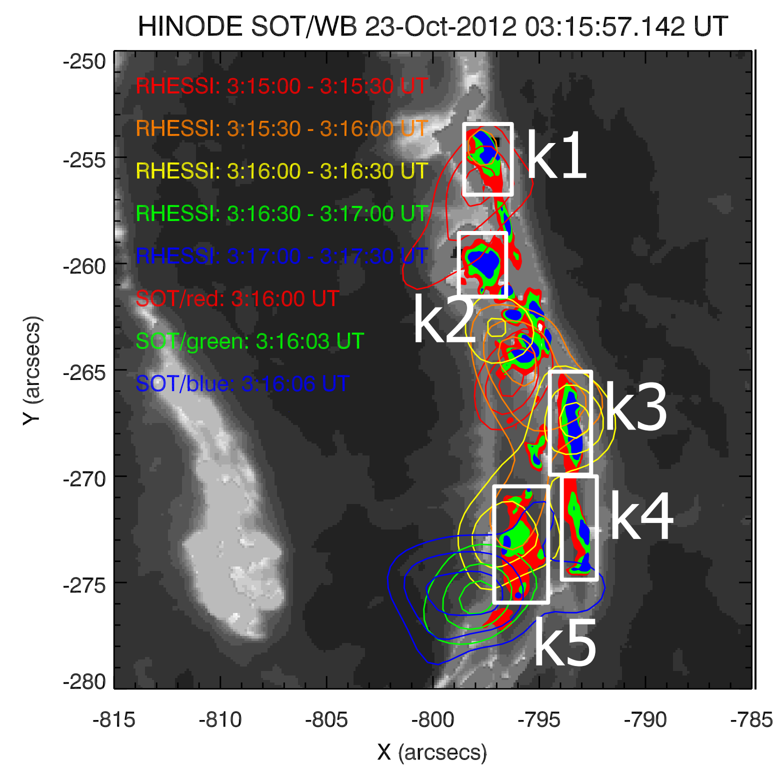


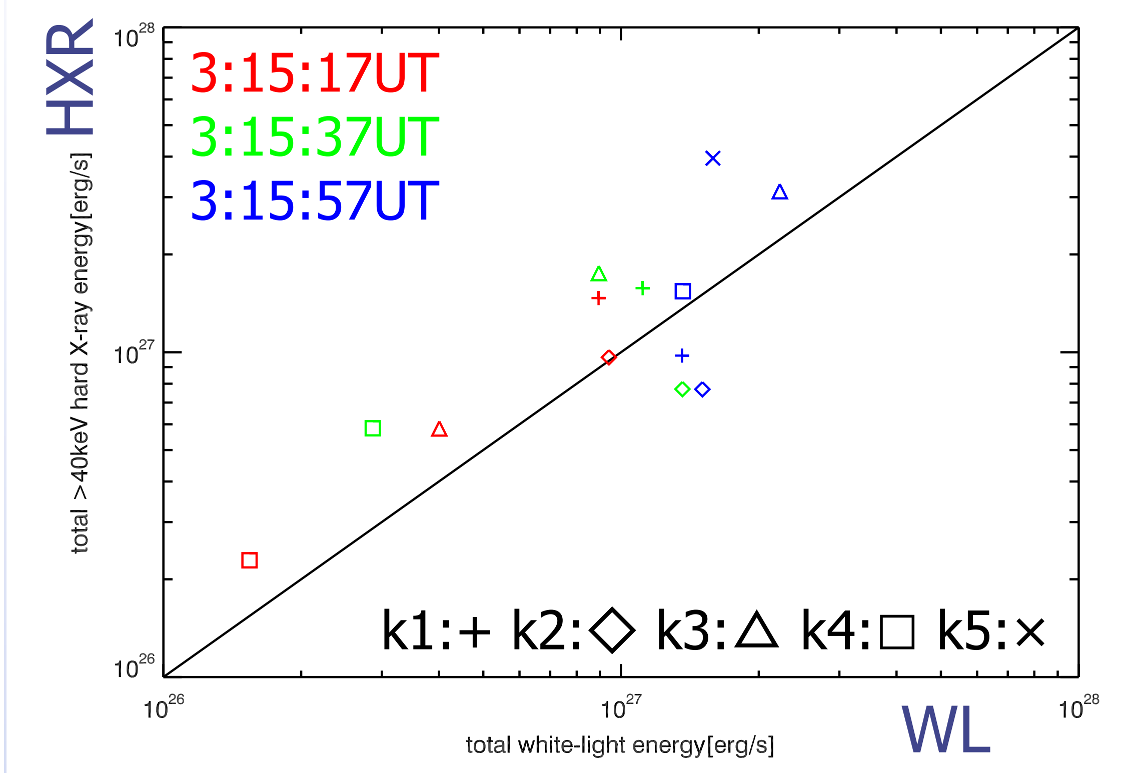


- White-light enhancements can be seen almost at the same location as the Ca II H ribbons.
- RHESSI showed high energy emission (800-7000 keV range).
- To compare the WL ribbons with the RHESSI HXR, we only use detectors #1-4 (which have good resolution).

2012 Oct 23 White-light flare

Hinode/SOT red & RHESSI HXR

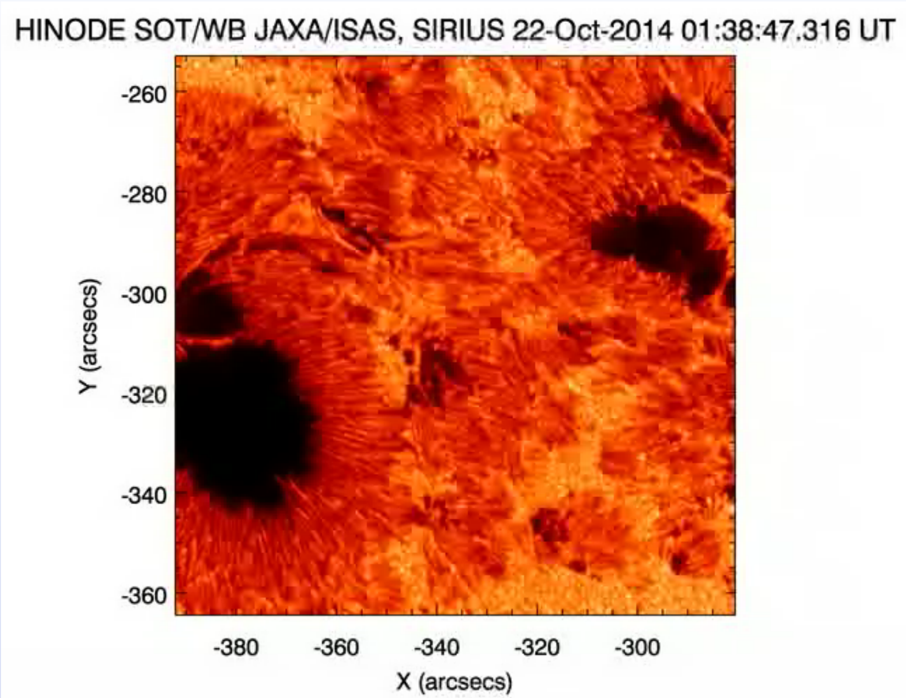


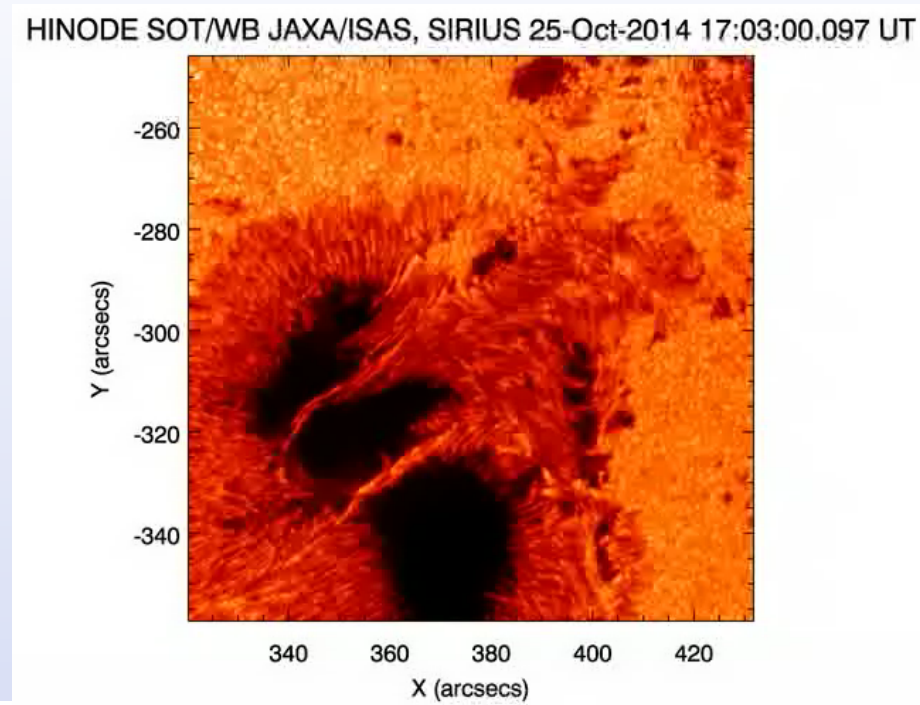


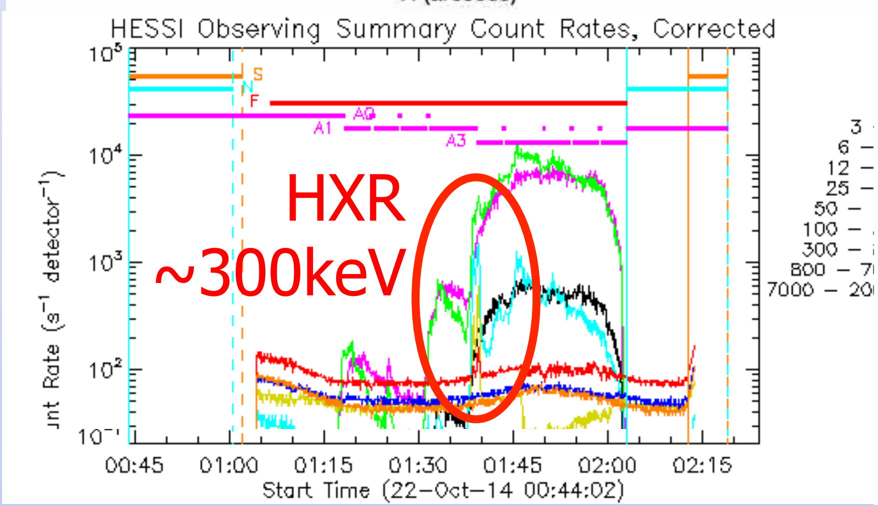
- Relationship between total energy of WL & accelerated e-
- Proportional relationship can be seen.
- When we use 40keV for the lower energy cutoff, the total energy of accelerated electrons becomes the same as the total energy of white-light emission.

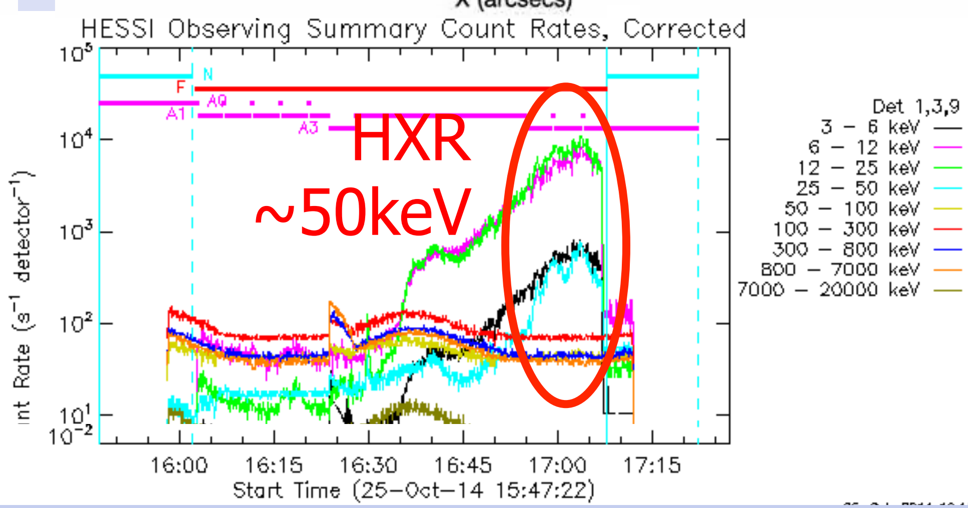
WLF & Non-WLF @ NOAA 12192

2014/10/22 01:16UT M8.7   2014/10/25 16:55UT X1.0









Event Selection

>M-class events from Jan 2011 to Dec 2014 — 454 events

↓

SOT/RGB data exists — 81 events

- 29 events → WL (8X, 21M)
- 52 events → NWL (7X, 45M)

↓

SDO/HMI data exists — 79 events

- 31 events → WL (10X, 21M)
- 48 events → NWL (5X, 43M)

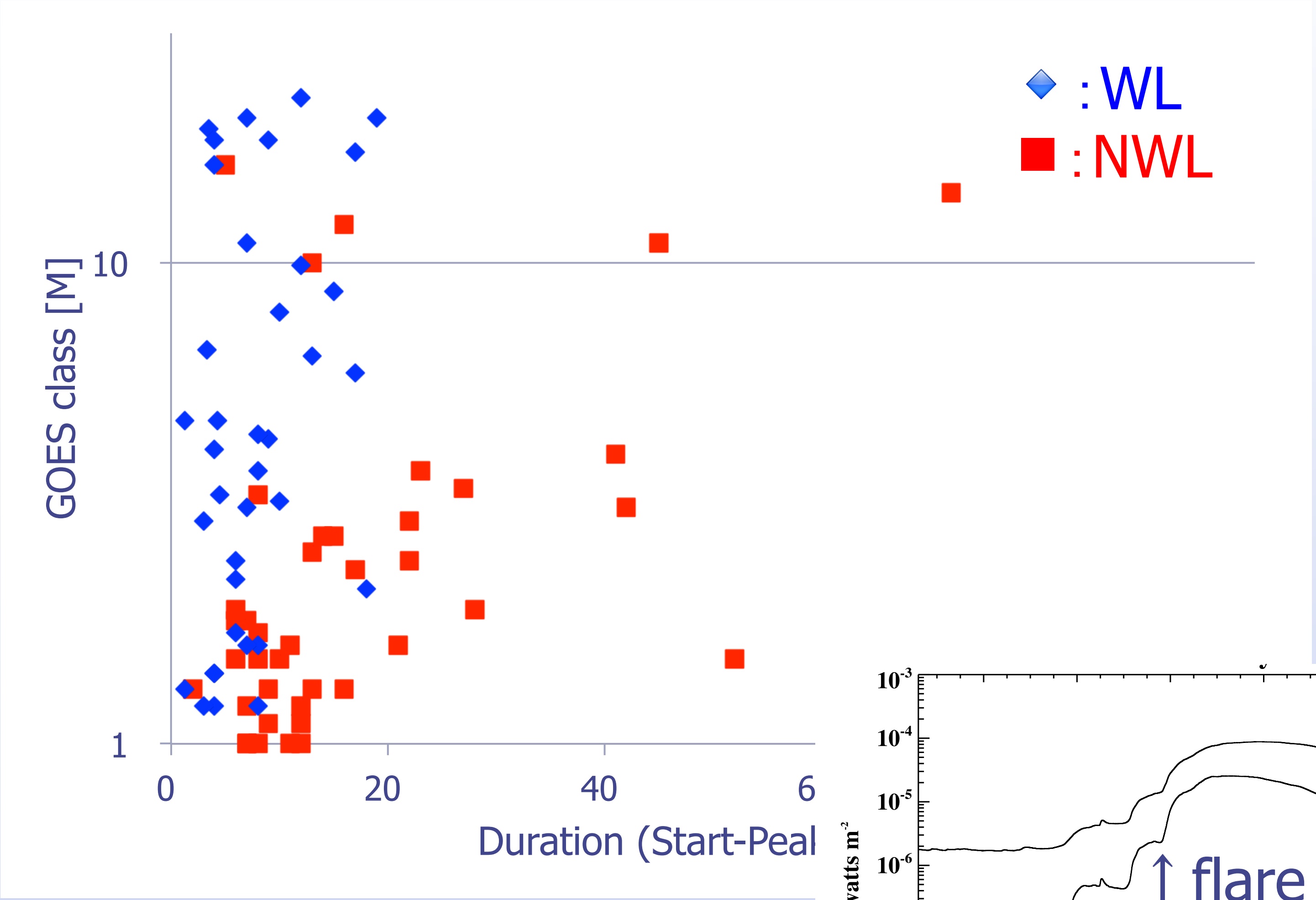
Hinode Flare Catalogue (Watanabe et al., 2012)

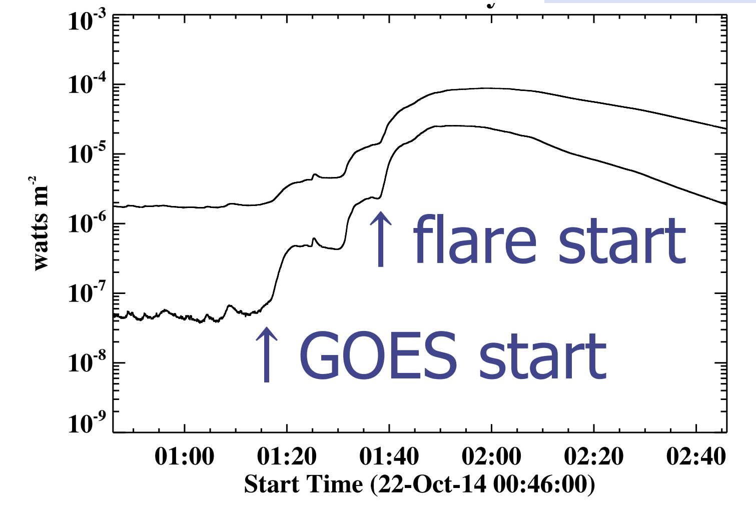
Flare mode observation (SOT/RGB data exists)

	HMI WL	HMI NWL
SOT WL	22 (8X, 14M)	7 (0X, 7M)
SOT NWL	9 (2X, 7M)	41 (5X, 36M)
	WL	NWL

Statistical analysis with GOES & Hinode/SOT, SDO/HMI

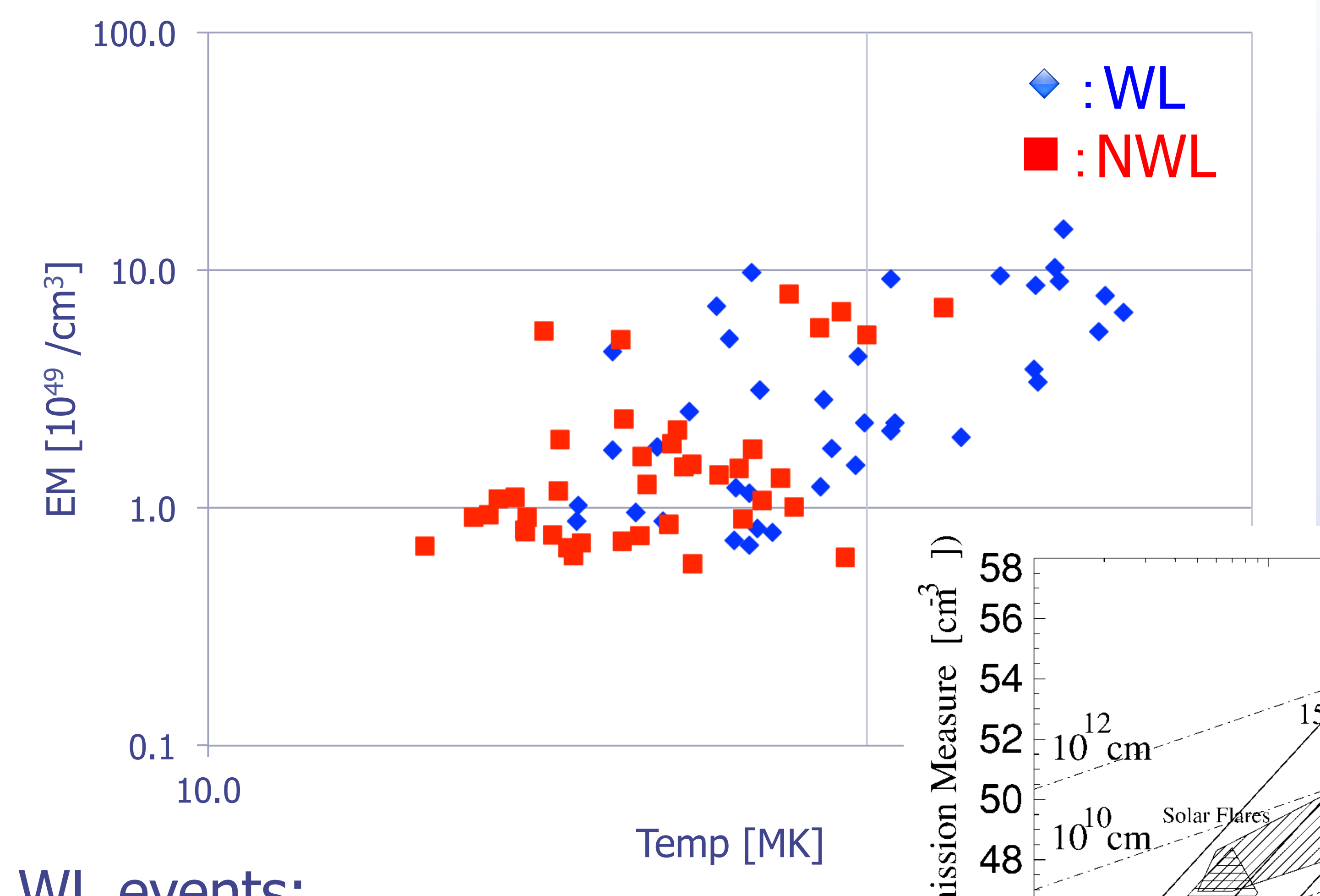
GOES X-ray Duration

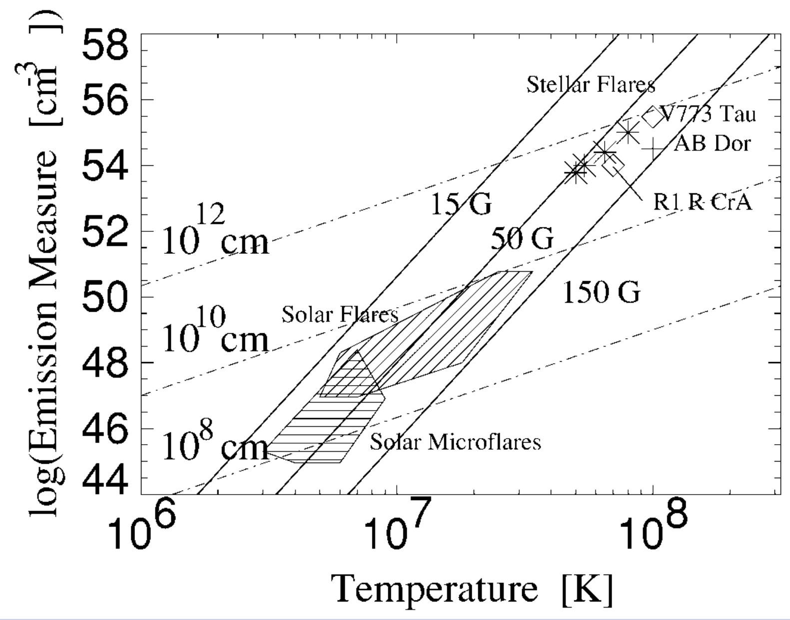




Durations of WL events are shorter than NWL events (most WL events <20 min.) ⇒ Impulsivity

Temperature & Emission Measure





Shibata & Yokoyama 1999

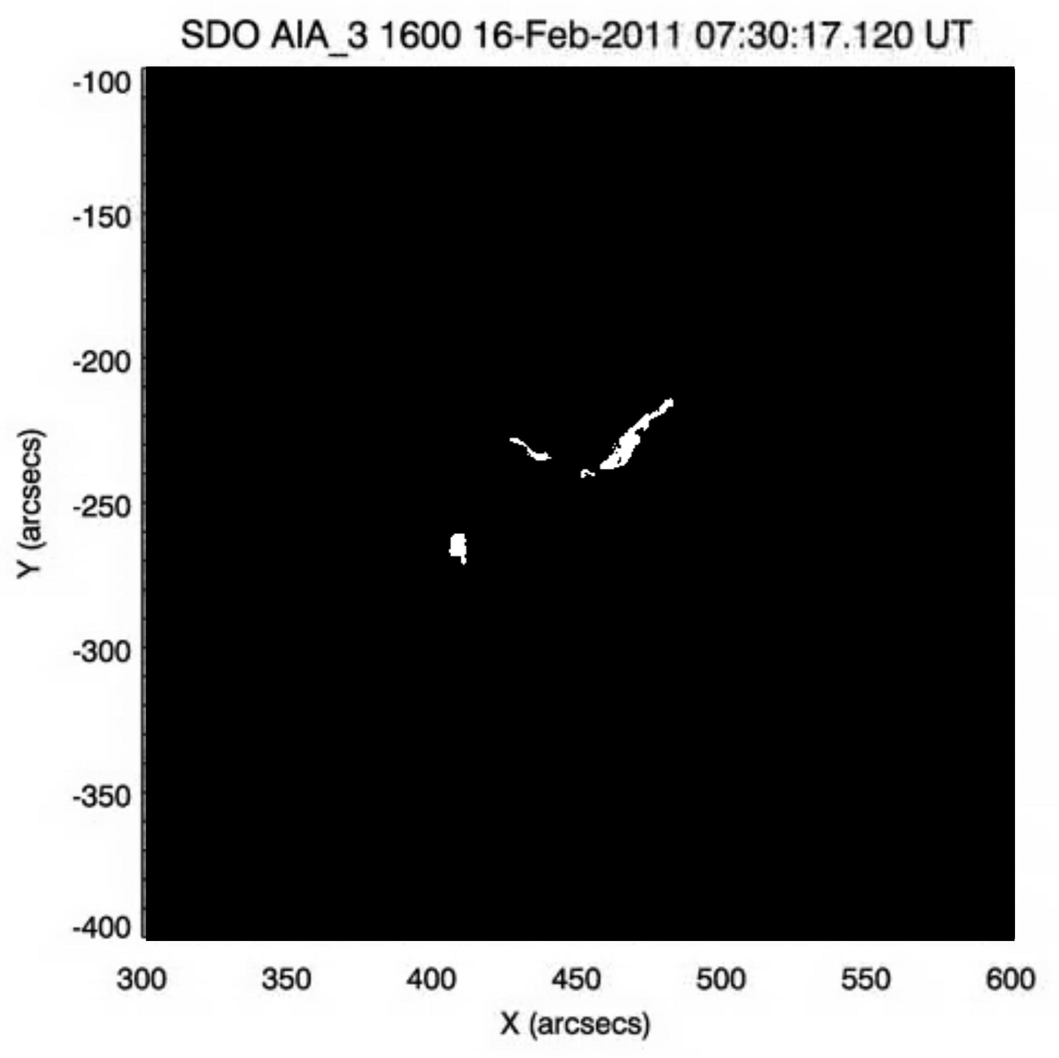
WL events:

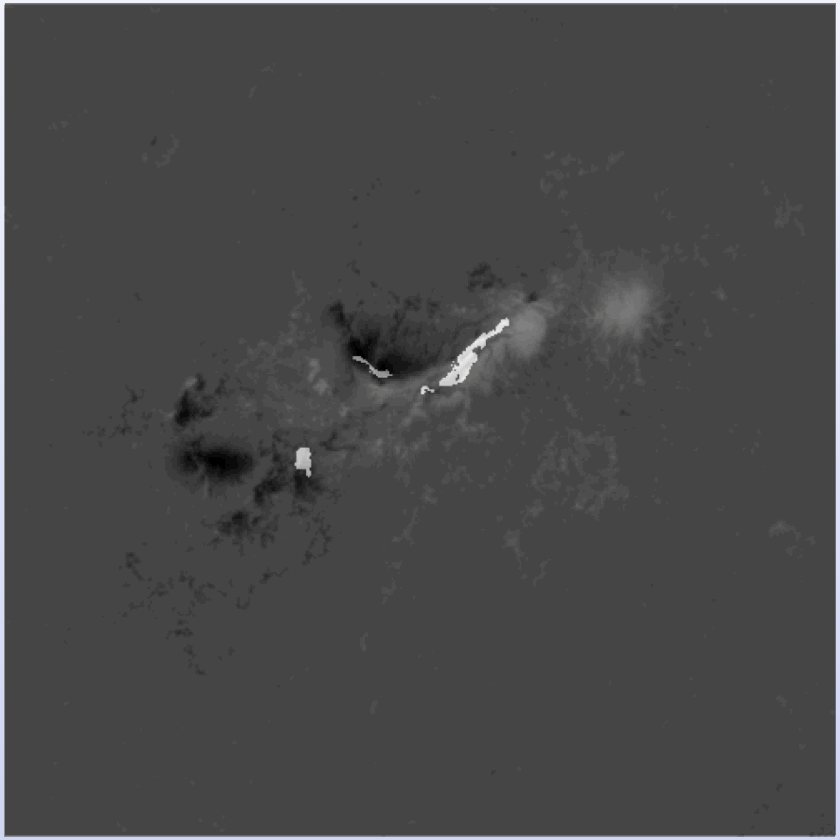
- slightly higher temperature
- lower EM for a given T

⇒ Strong magnetic field?

Flare Ribbon Area & Field Strength

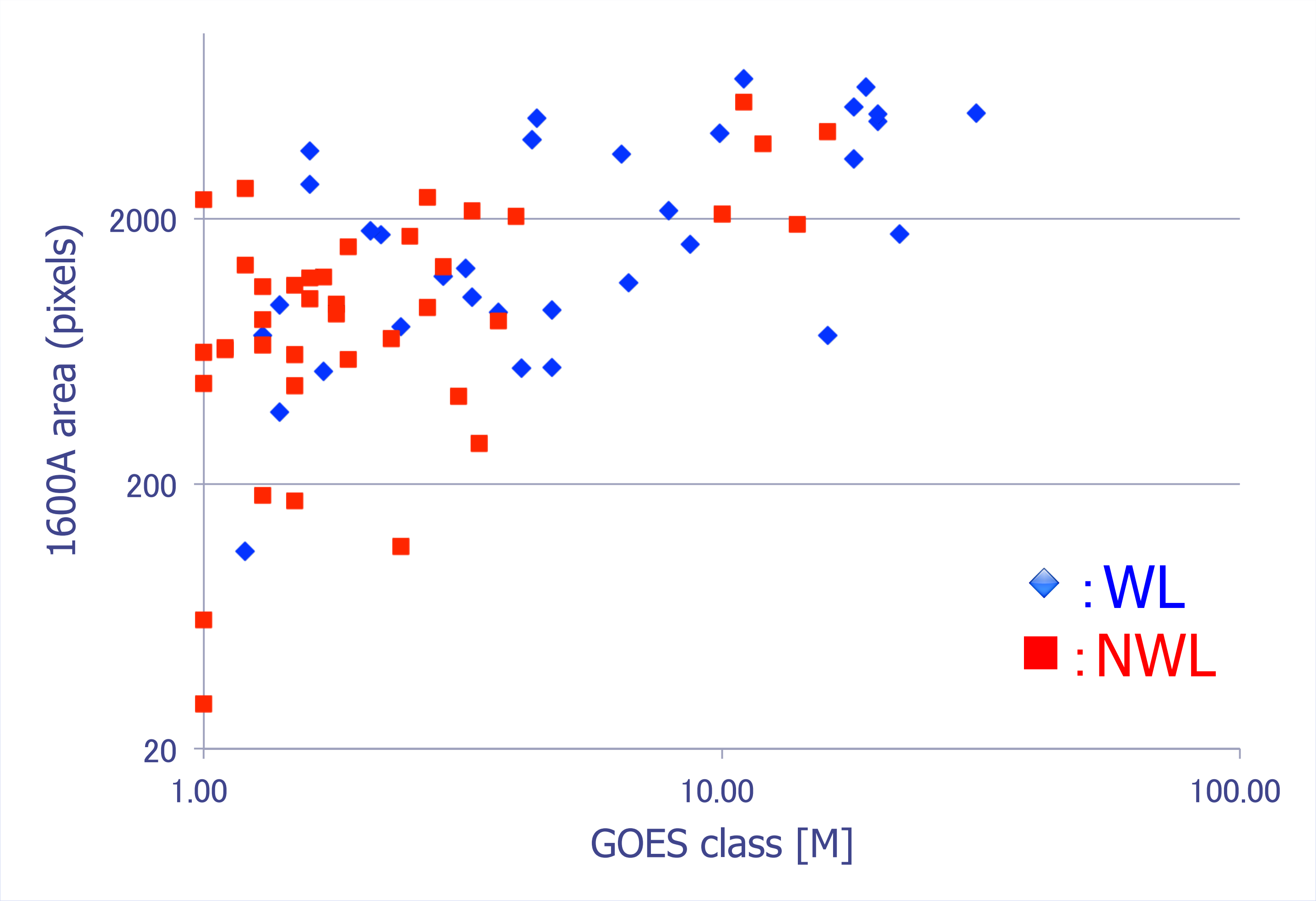
SDO/AIA 1600Å ribbon & SDO/HMI field strength





⇒ Estimate 1600Å ribbon area and field strength

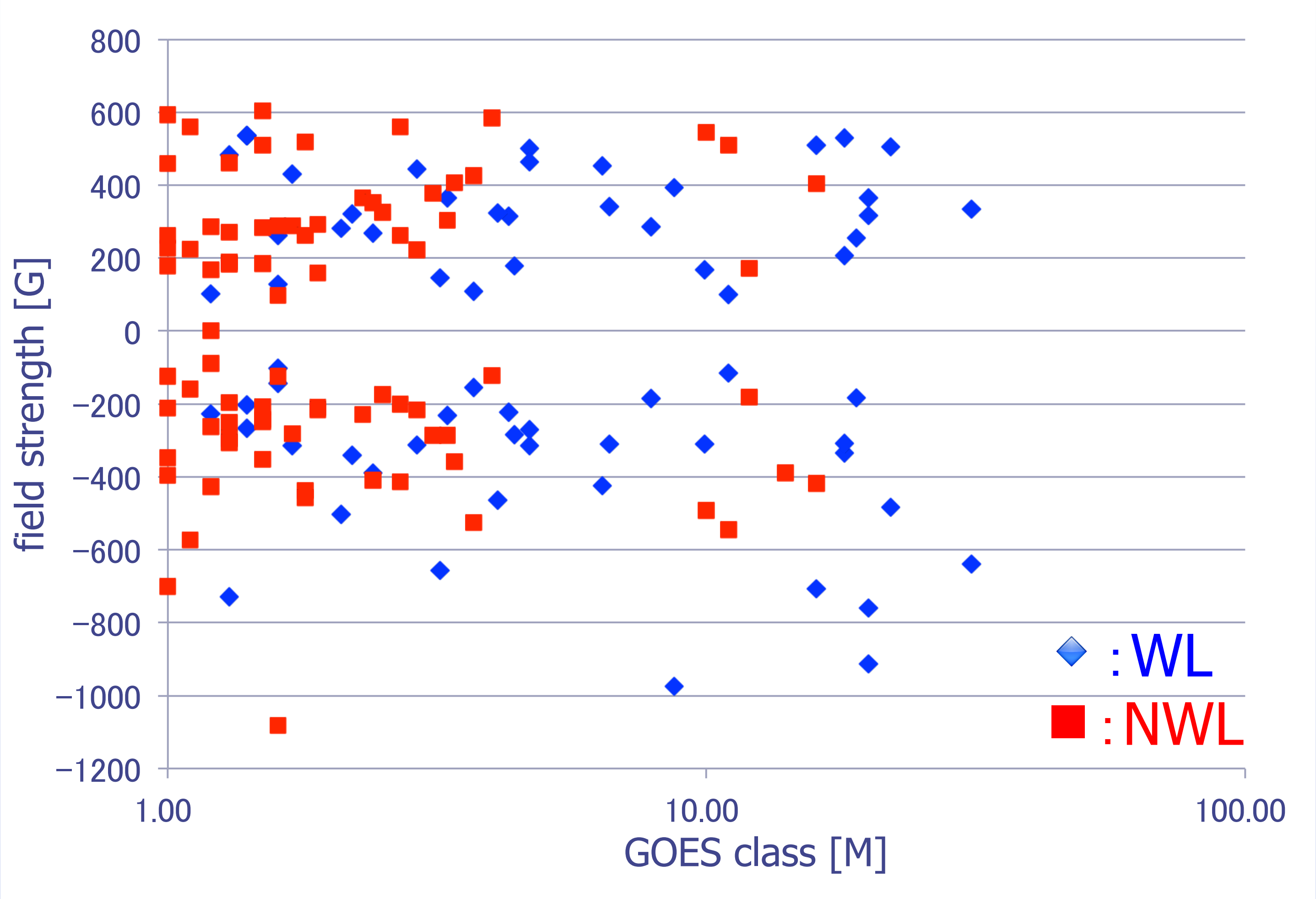
Flare ribbon area (AIA 1600Å)



- 1600Å ribbon area is roughly correlated with GOES class
- Area of WL events are larger than those of NWL events?

⇒ WL events have large area?

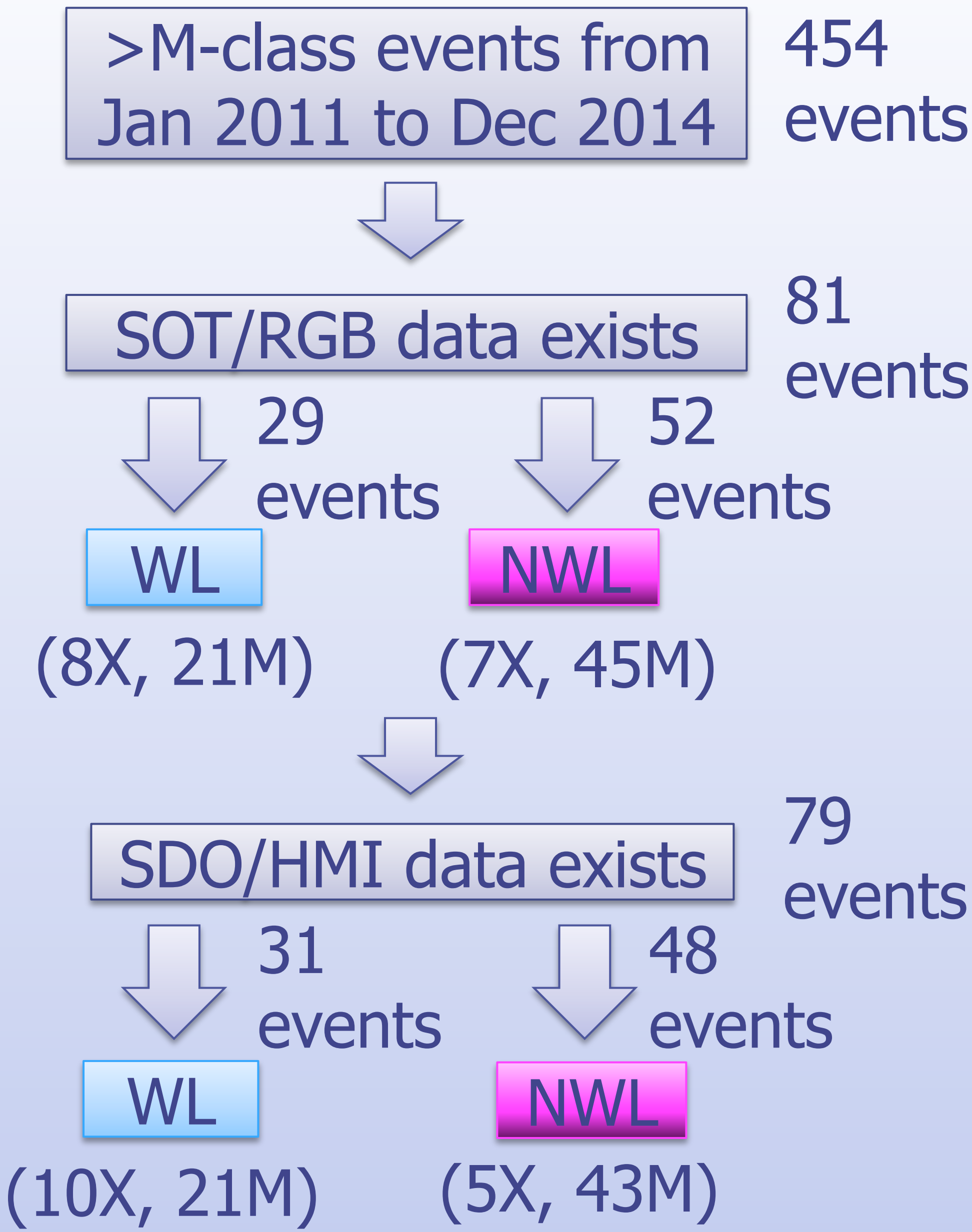
Field Strength (HMI @1600Å ribbon)



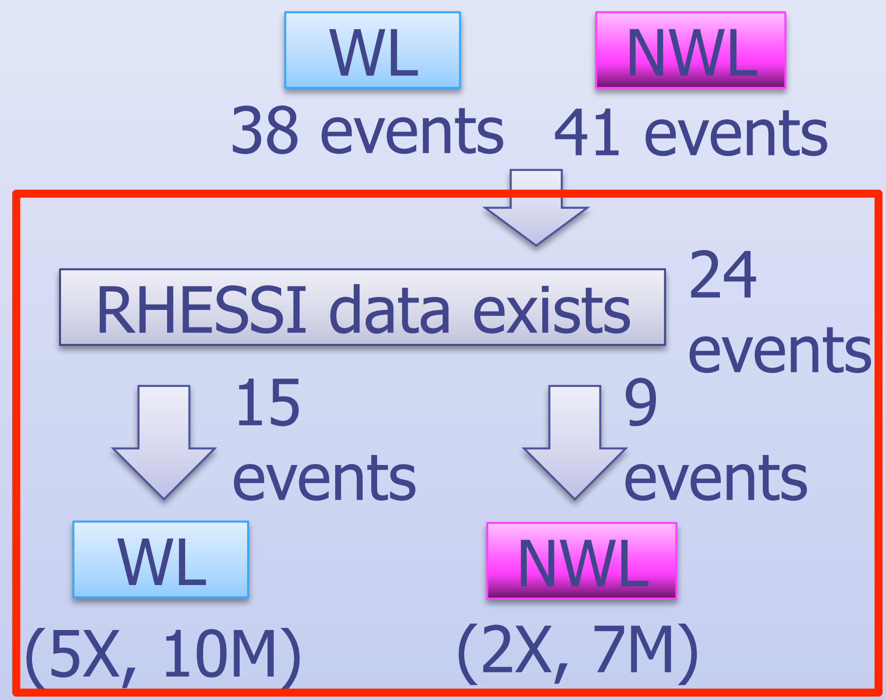
No clear difference in photospheric field strength between WL and NWL events.

⇒ Should check coronal field strength

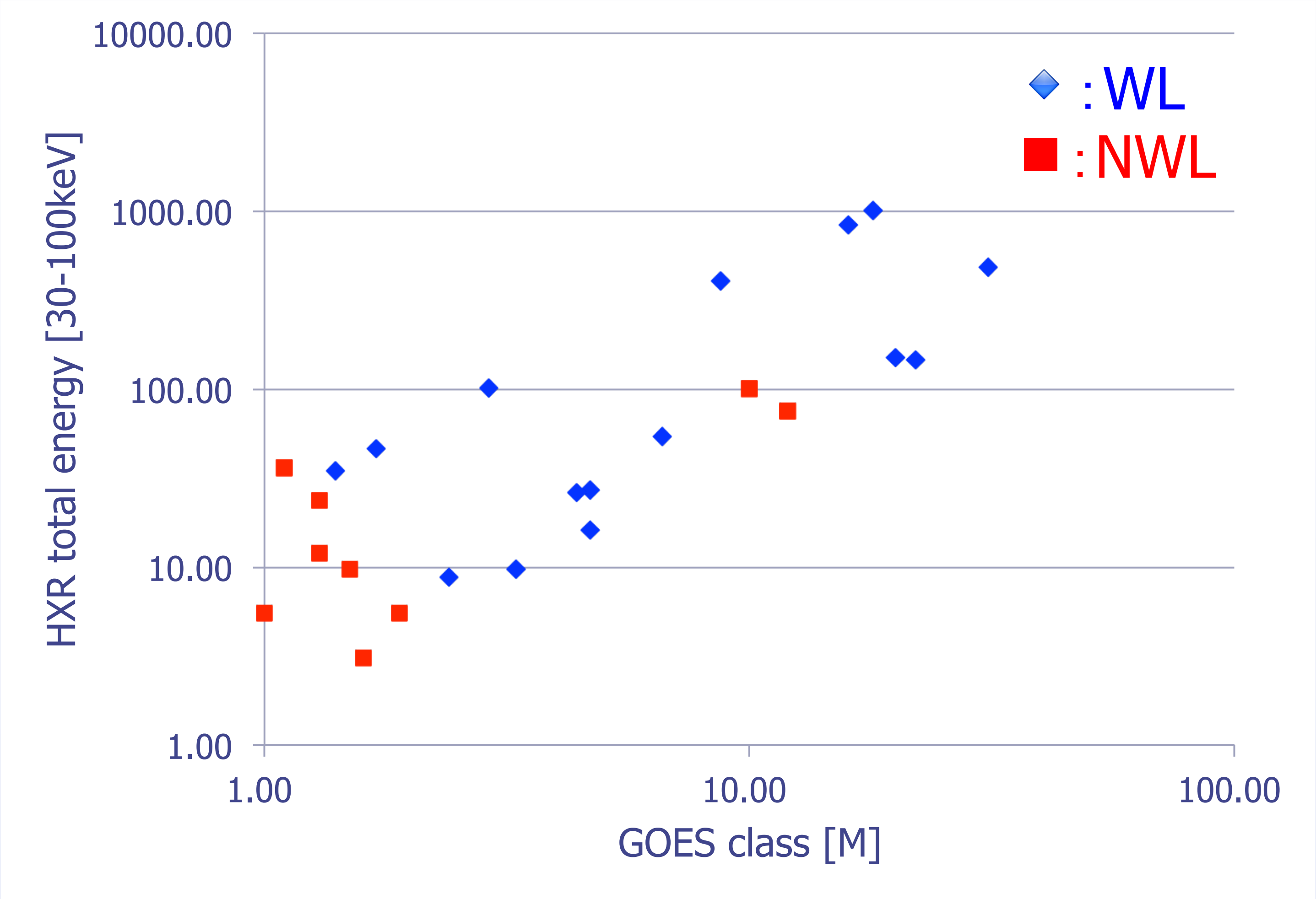
Event Selection



	HMI WL	HMI NWL
SOT WL	22 (8X, 14M)	7 (0X, 7M)
SOT NWL	9 (2X, 7M)	41 (5X, 36M)

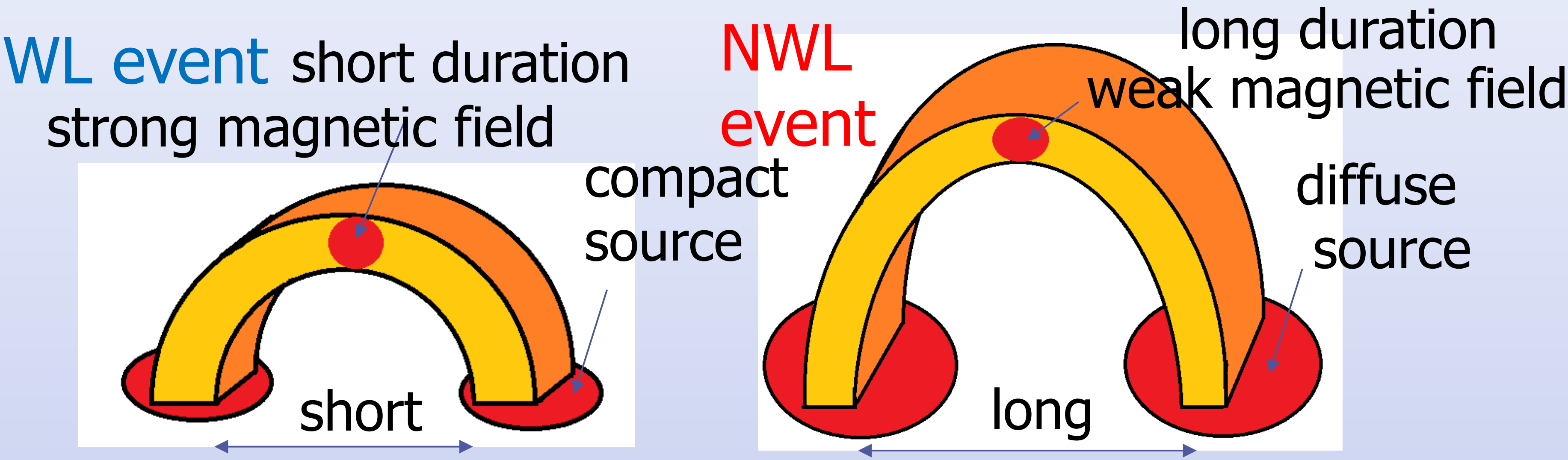


Non-thermal energy (HXR energy)



- The non-thermal photon counts for the WL events are larger than for the NWL events.

Summary	WL	NWL
① Flare duration	<20 min	>20 min
② EM vs Temperature	Slightly low	Slightly high
③ Flare ribbon area	Large	Small
④ Field strength (NoRP)	Strong	Weak
⑤ HXR energy	Large	Small



Generating Factor of Solar WL emissions

A large amount of accelerated non-thermal electrons precipitate (into a compact region) within a short duration.