Statistical approach for the origin of white-light emission of white-light flares

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White-light flare

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

→ Non-thermal electrons

Structures of the HXR and WL are very similar (length ~30″)

→ Physically linked mechanisms

Original accelerated e^- energy of WL:

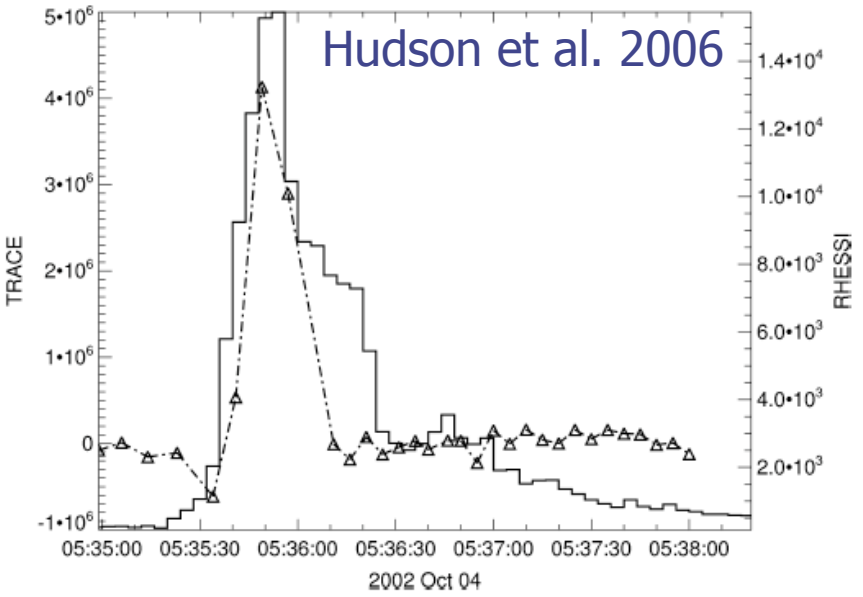
>50keV: Neidig (1989) etc.

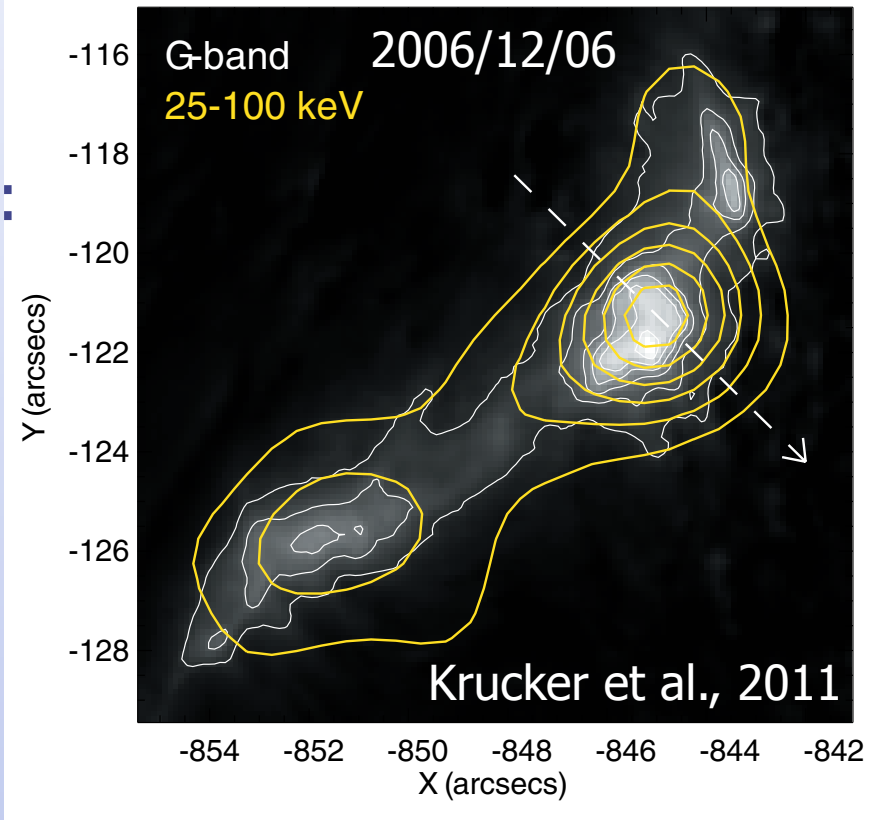
>25keV: Fletcher et al. (2007)

>40keV: Watanabe et al. (2010)

→ Can be explain by HXR energy

Any other origins for white-light emission?





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@RHESSI (Kontar et al., 2008)

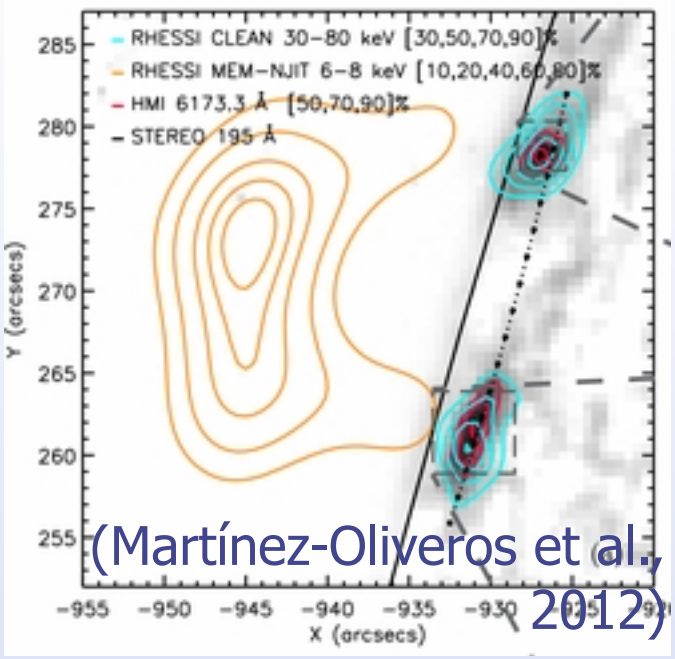
30-80 keV HXR@RHESSI (Martínez-Oliveros et al., 2012)

SDO/HMI WL

100

G-band (Carlsson et al., 2007)

0 Continuum



(Martínez-Oliveros et al., 2012)

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

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

High Energy Proton Beams for WLFs

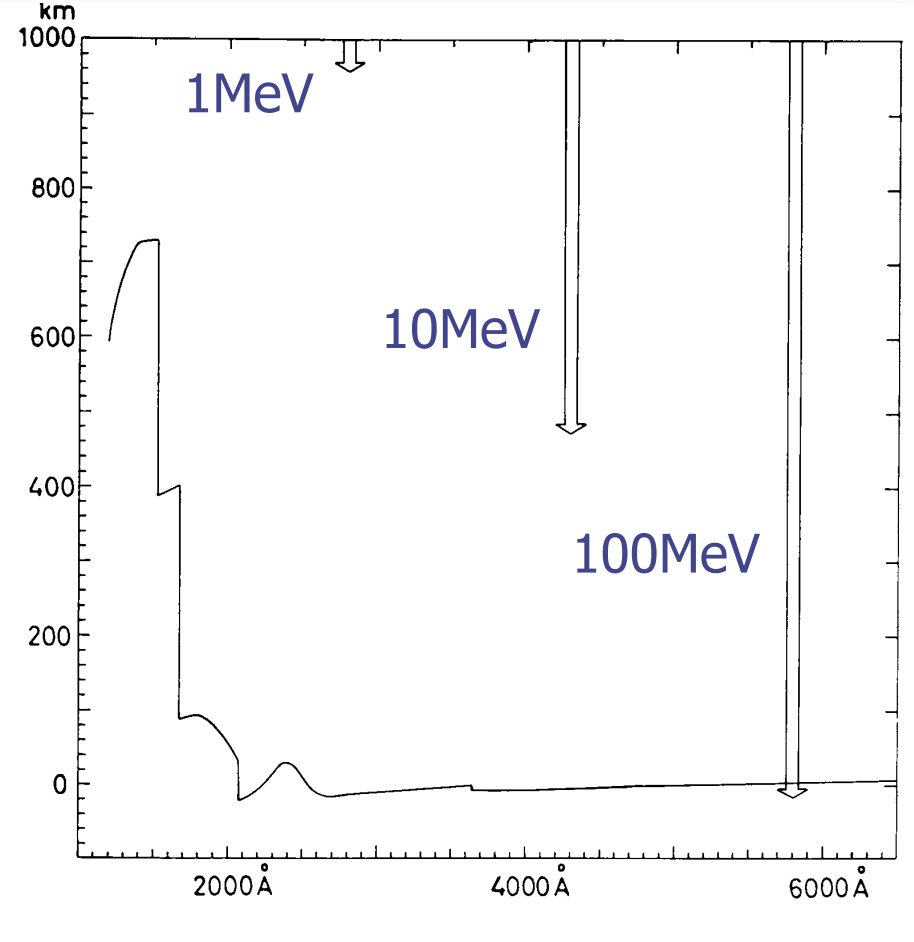
Energy Transport Mechanisms for WLFs (Neidig, 1989)

- Heat conduction
- Electron beams
- High-energy proton beams
- Low-energy protons
- Irradiation by 1-8A X-rays
- Irradiation by 10-1030Å (EUV) emission
- Alfven waves

>20MeV protons can penetrate to the photosphere. (Švestka 1970)

Evidence of ion acceleration:

- Solar neutrons
- Line γ-rays (2.2MeV neutron capture, ^{12}C, ^{16}O, ^{20}N lines, etc.)



The heights of formation of the continuum (τ =1@5000Å) and proton penetration depth (Švestka 1970)

Statistical study of white-light flares

>M-class events from Jan 2011 to Feb 2016

719 events

Hinode Flare Catalogue (Watanabe et al., 2012)

SOT/RGB data exists

101 events

Flare mode observation (SOT/RGB data exists) + HMI continuum

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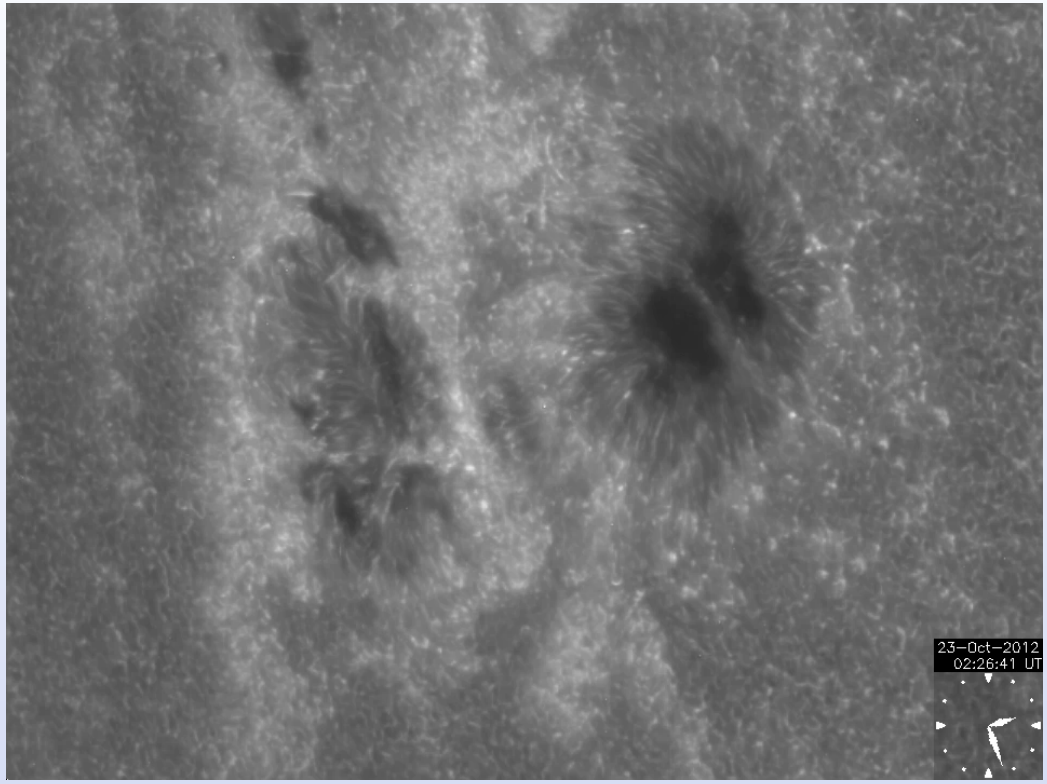
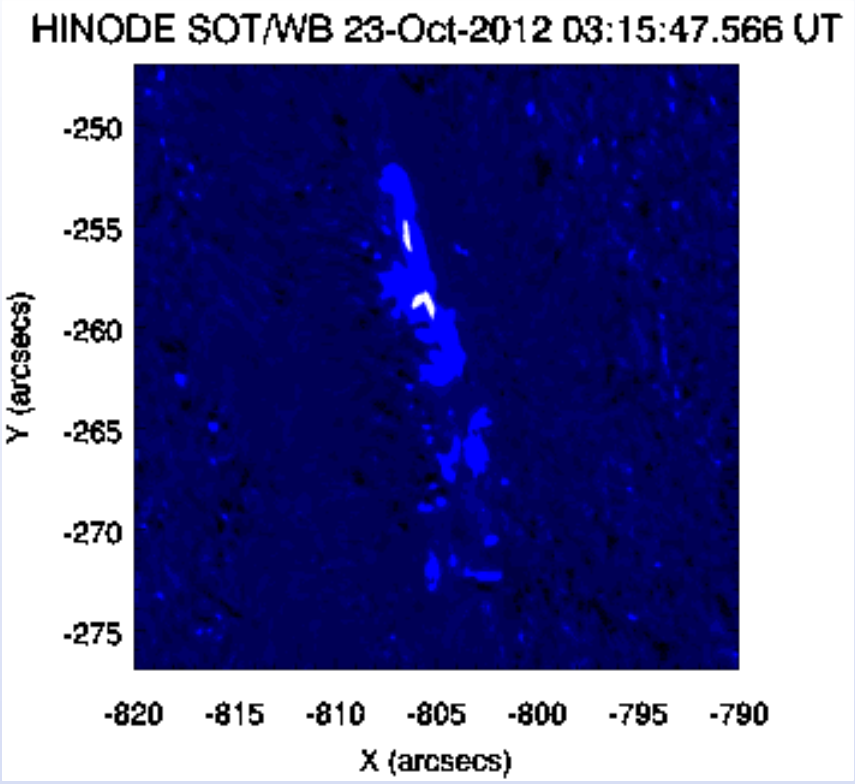
>1MeV emission @*RHESSI* and/or *Fermi*/GBM

- 2012 Oct 23 X1.8 flare
- 2015 Jun 25 M7.9 flare

2012 Oct 23 White-light flare

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

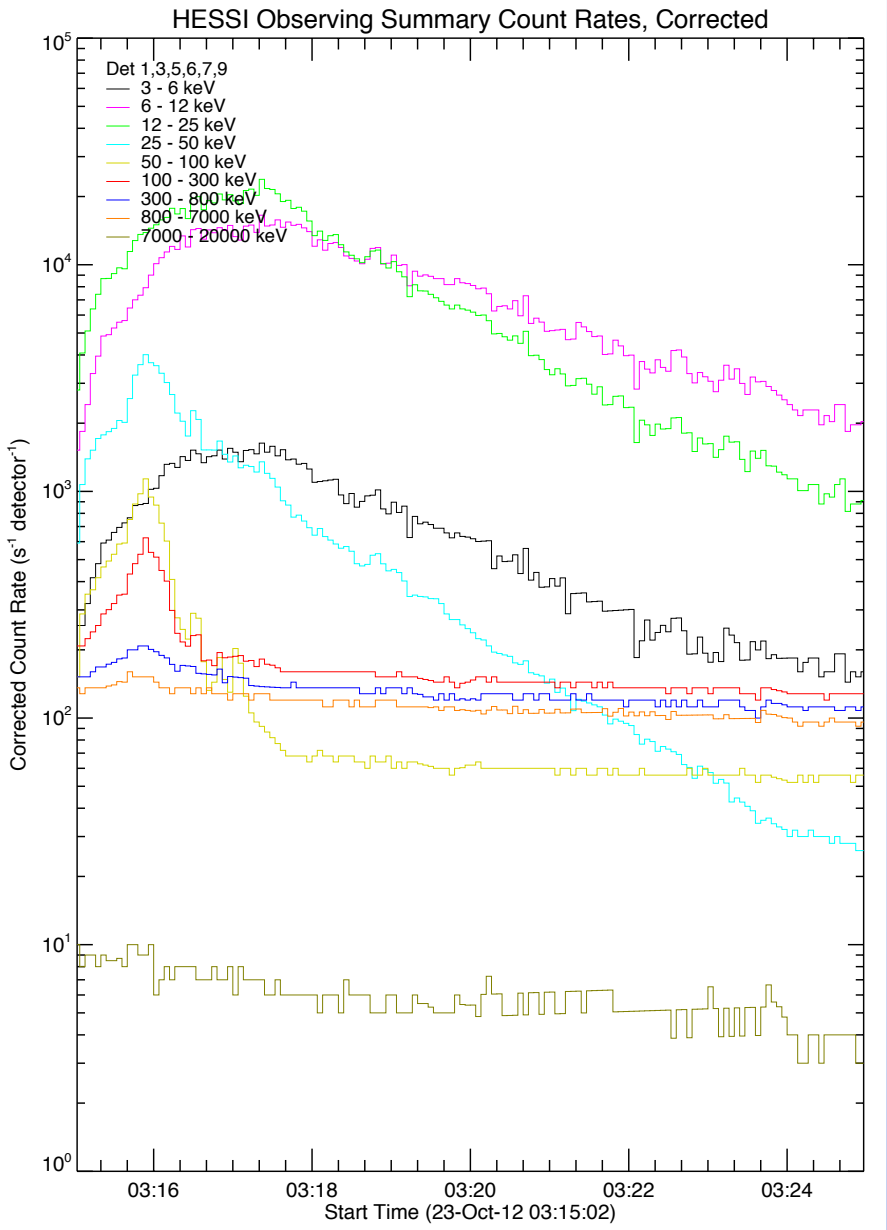


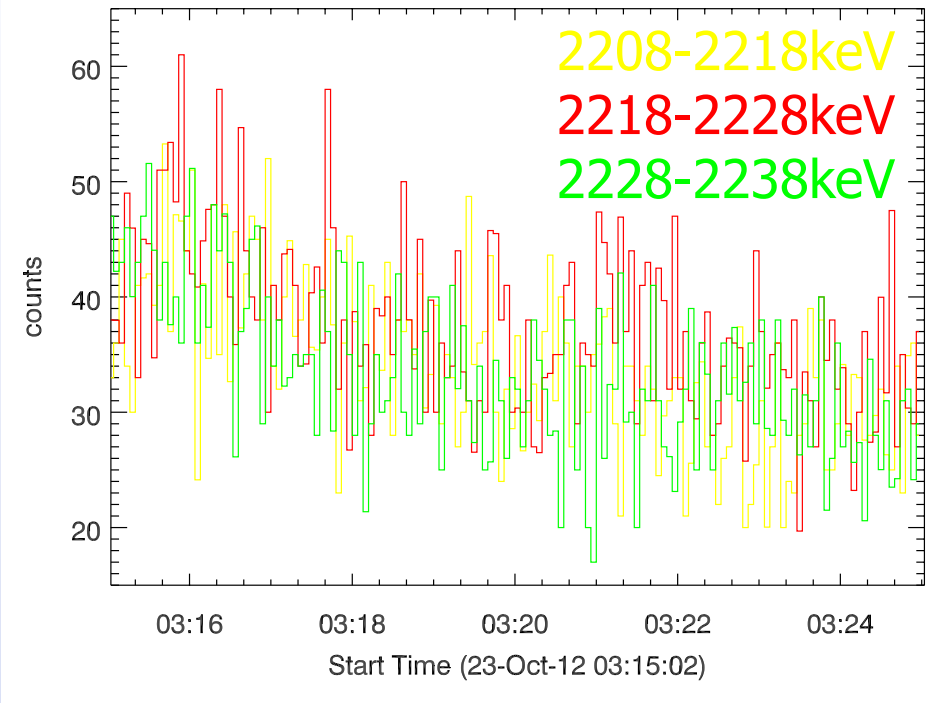


- White-light enhancements can be seen almost at the same location as the Ca II H ribbons.
- *RHESSI* and *Fermi*/GBM observe >1MeV γ-ray emissions

2012 Oct 23 White-light flare

RHESSI HXR & γ-ray

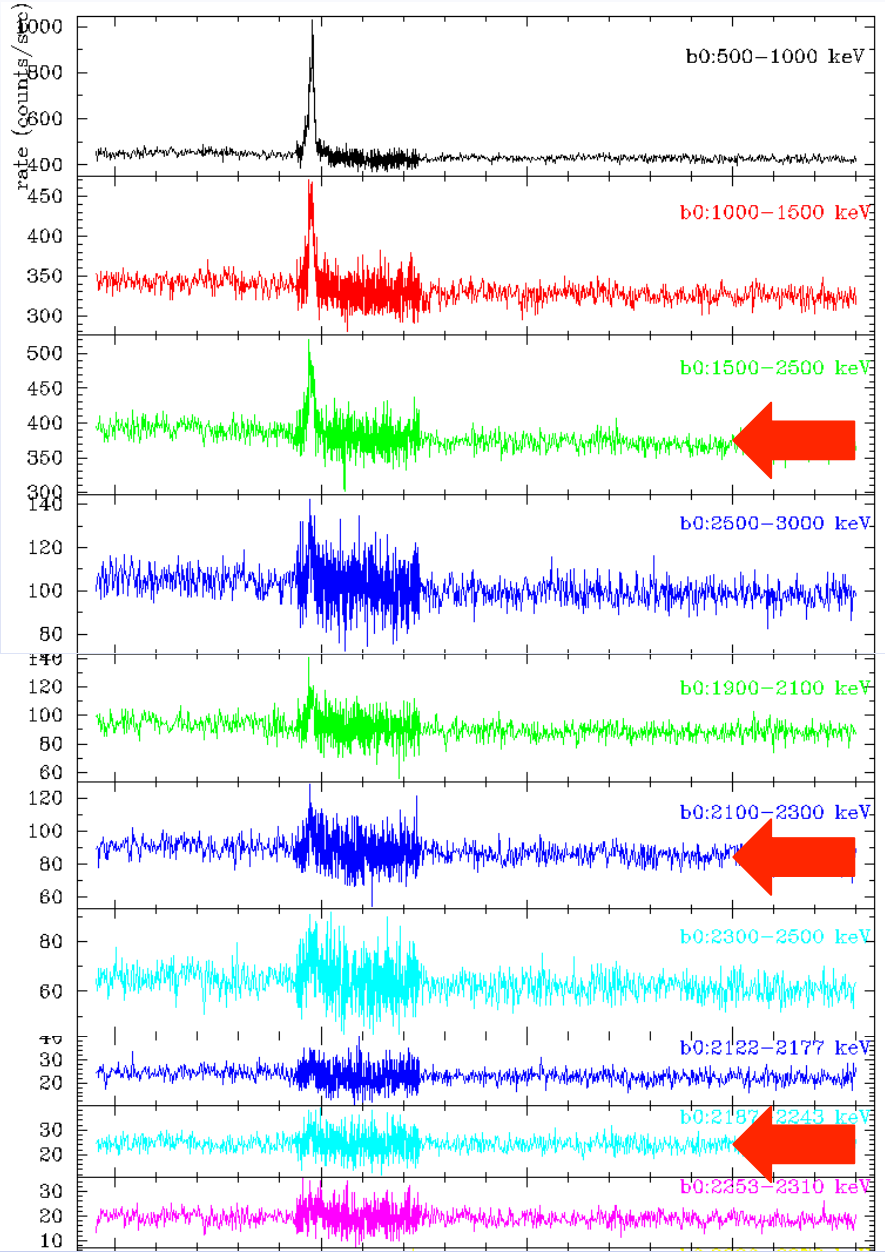


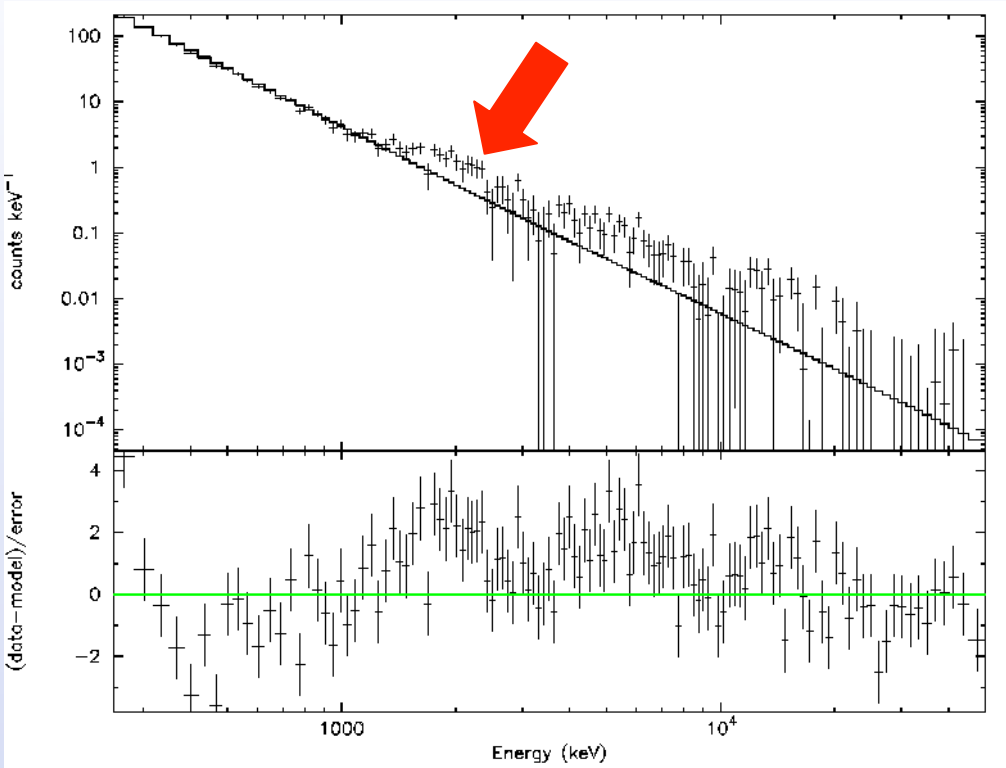


- *RHESSI* showed high energy emission (800-7000keV range).
- No clear evidence of 2.2MeV.

2012 Oct 23 White-light flare

Fermi/GBM HXR & γ-ray

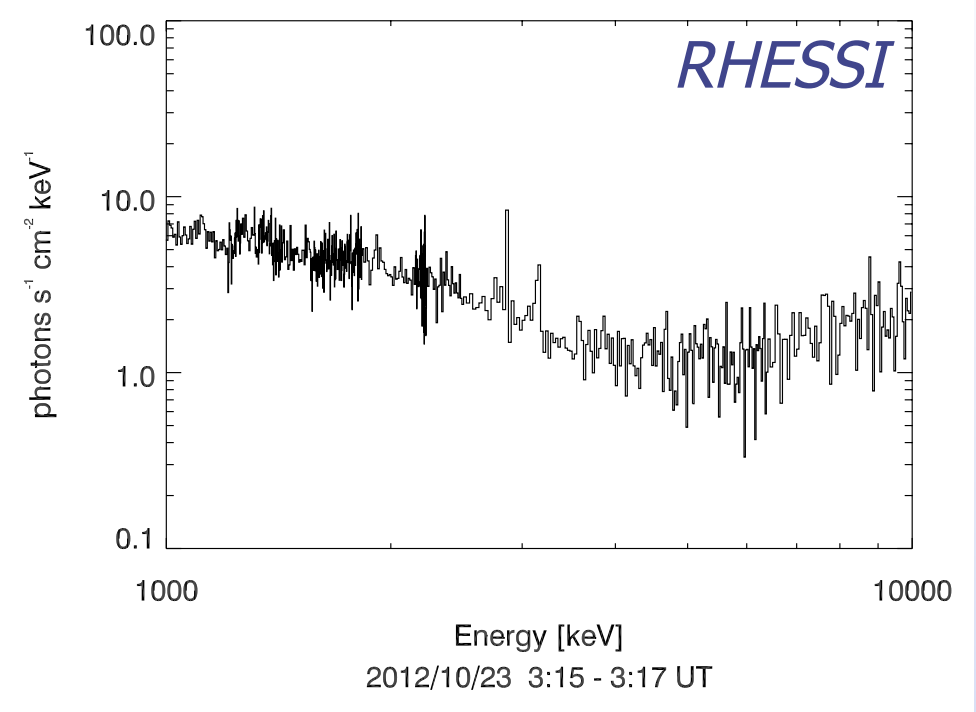


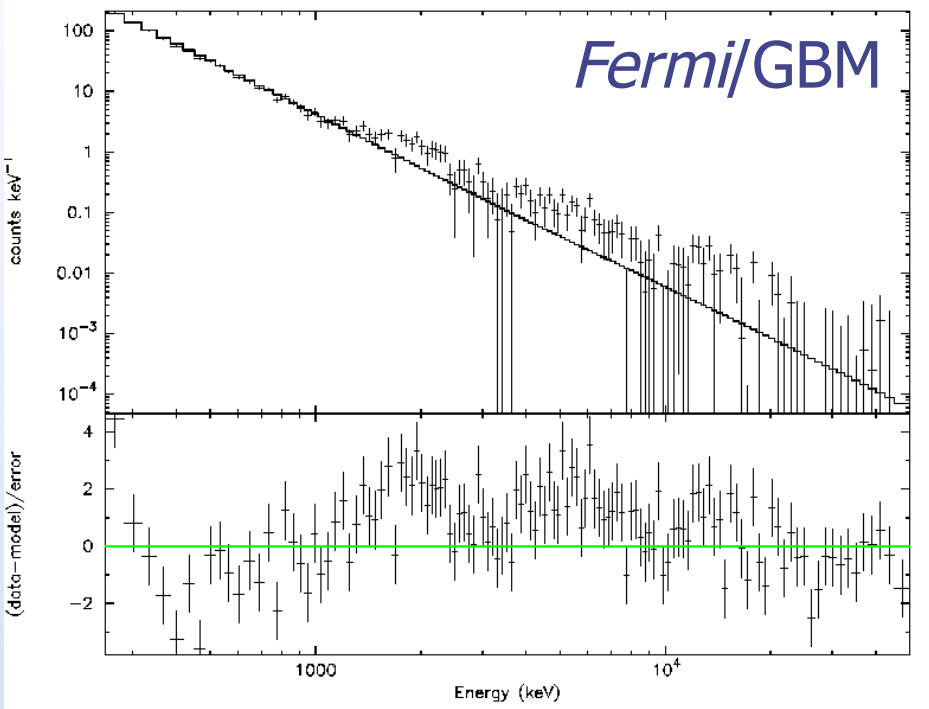


- *Fermi*/GBM showed high energy emission (>1MeV).
- No clear evidence of 2.2MeV.

2012 Oct 23 White-light flare

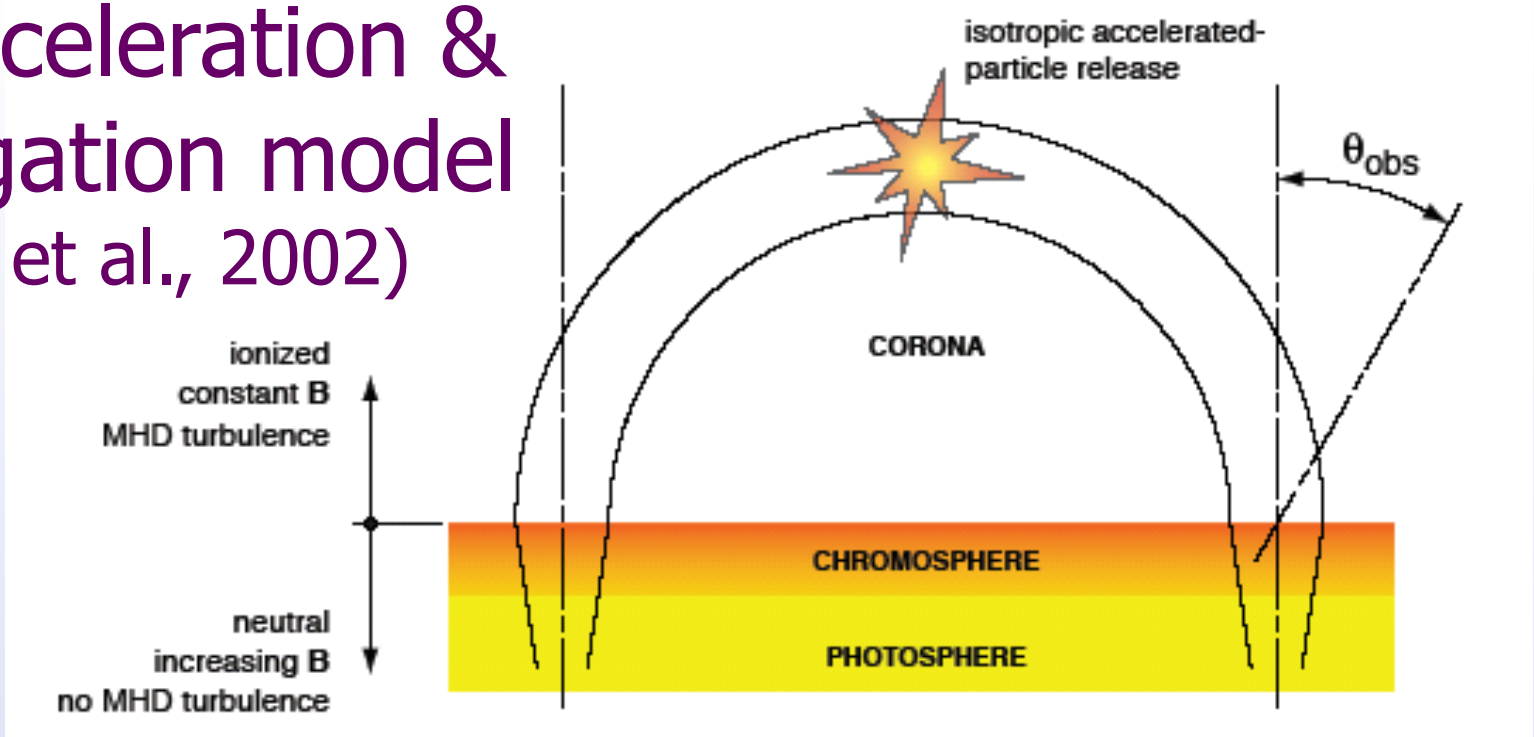
HXR & gamma-ray spectra





- No clear 2.2MeV line → buried in electron bremsstrahlung?
- Flux = 4.4 photons/s/cm^2/keV around 2.2MeV @RHESSI
- Try to calculate proton flux @ 2012 Oct 23 flare
- 2.2MeV line strength adopt to accelerated ion composition, atmospheric model, flare location, and so on…

Ion acceleration & propagation model (Hua et al., 2002)



– Acceleration parameters –

- acceleration release time history
- spectrum (power-law spectral index)
- accelerated ion composition

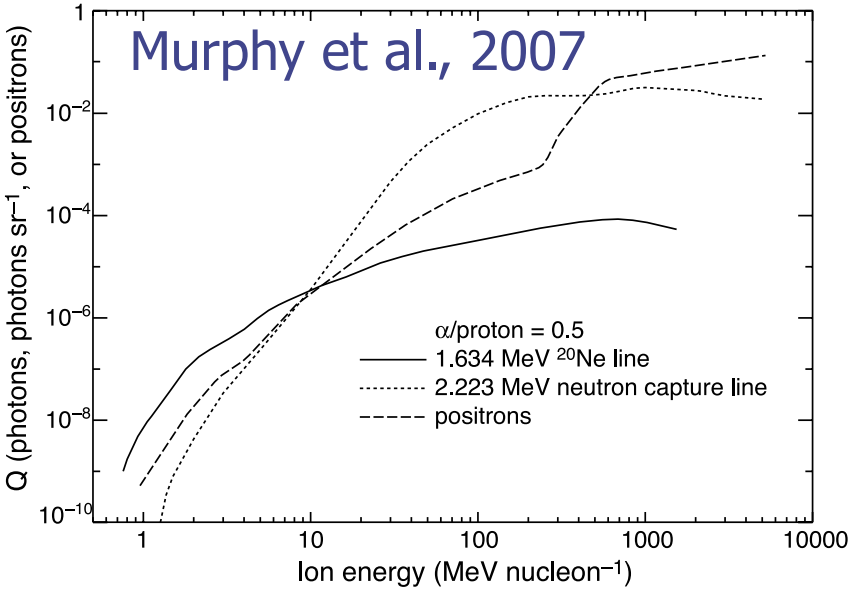
– Physical parameters –

- loop length
- pitch-angle scattering
- magnetic convergence
- ambient composition
- atmospheric model
- flare heliocentric angle

2012 Oct 23 White-light flare

Accelerated ion flux and energy

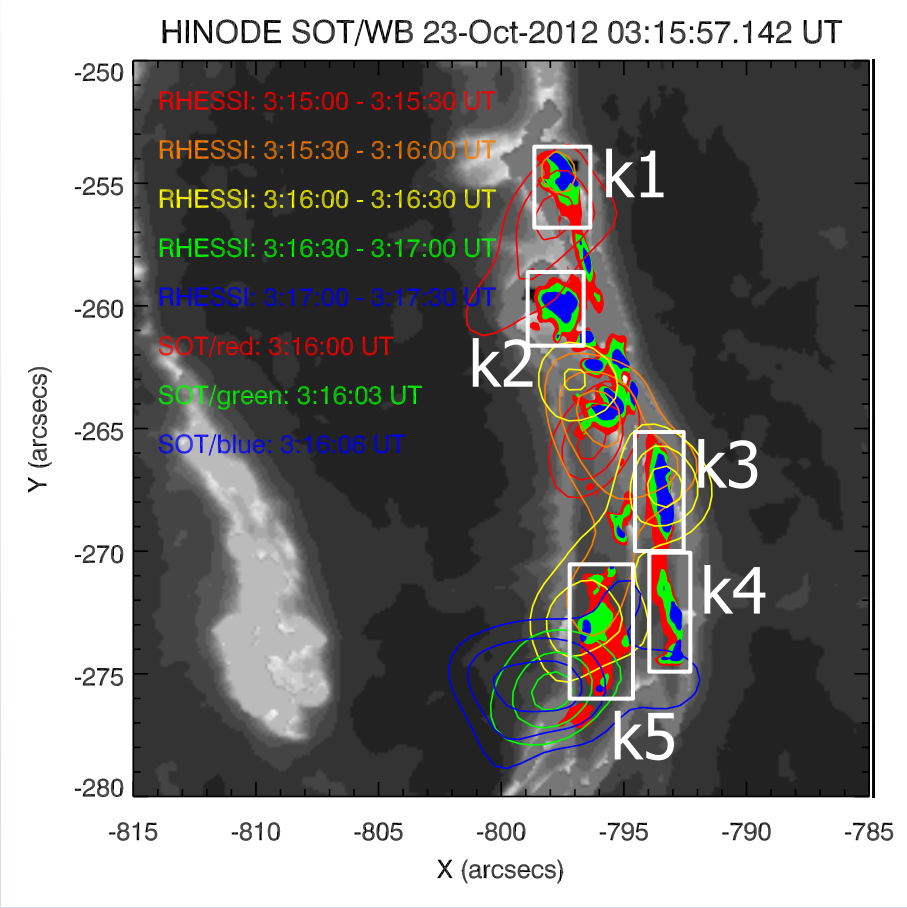
- Acceleration parameters –
  - release time history : –
  - accelerated ion composition : α/p=0.5, ^{3}He/^{4}He=1
  - power-law spectral index : –
- Physical parameters –
  - flare loop length : –
  - pitch-angle scattering : λ= 300
  - magnetic convergence : δ= 0.2
  - ambient composition : coronal (He/H=0.1, Ne/O=0.25)
  - atmospheric model : Avrett, 1981
  - flare heliocentric angle : θ_{obs} = 75° (S18 E58)
  - photospheric ^{3}He/H : 3.7×10^{-5}



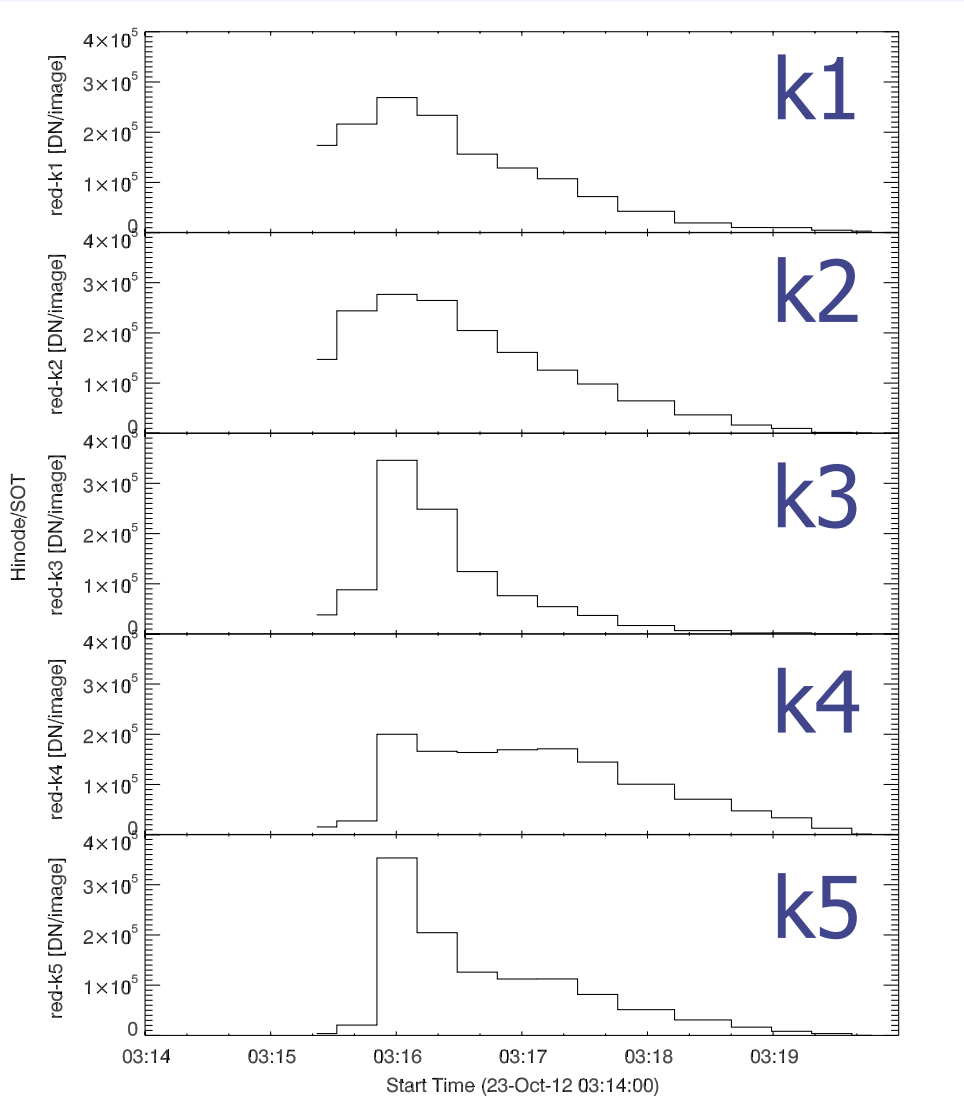
2.2MeV yield ratio:
10^{-2} photons/sr @ 100MeV
↓
Total ion energy:
1.6×10^{28} erg/s
↑
Same order of WL & HXR emissions

2012 Oct 23 White-light flare

Hinode/SOT red & *RHESSI* HXR



Hinode: Red

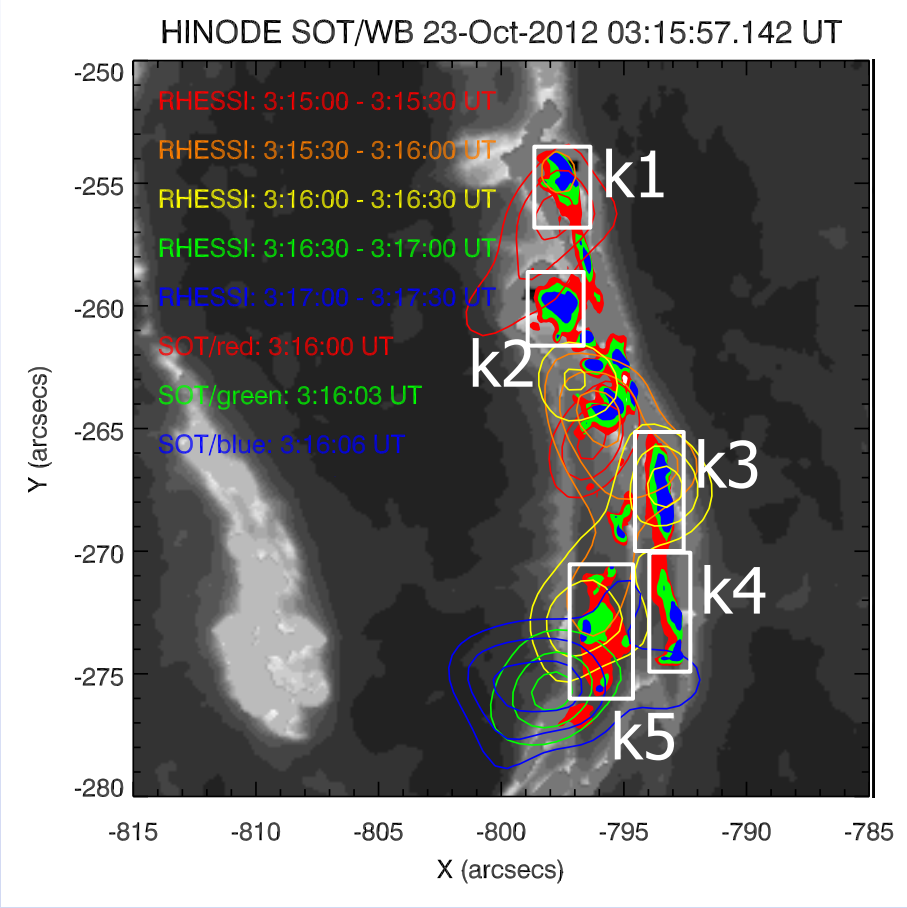


RHESSI: 35-100keV

To compare the WL ribbons with the *RHESSI* HXR, we only use detectors #1-4.

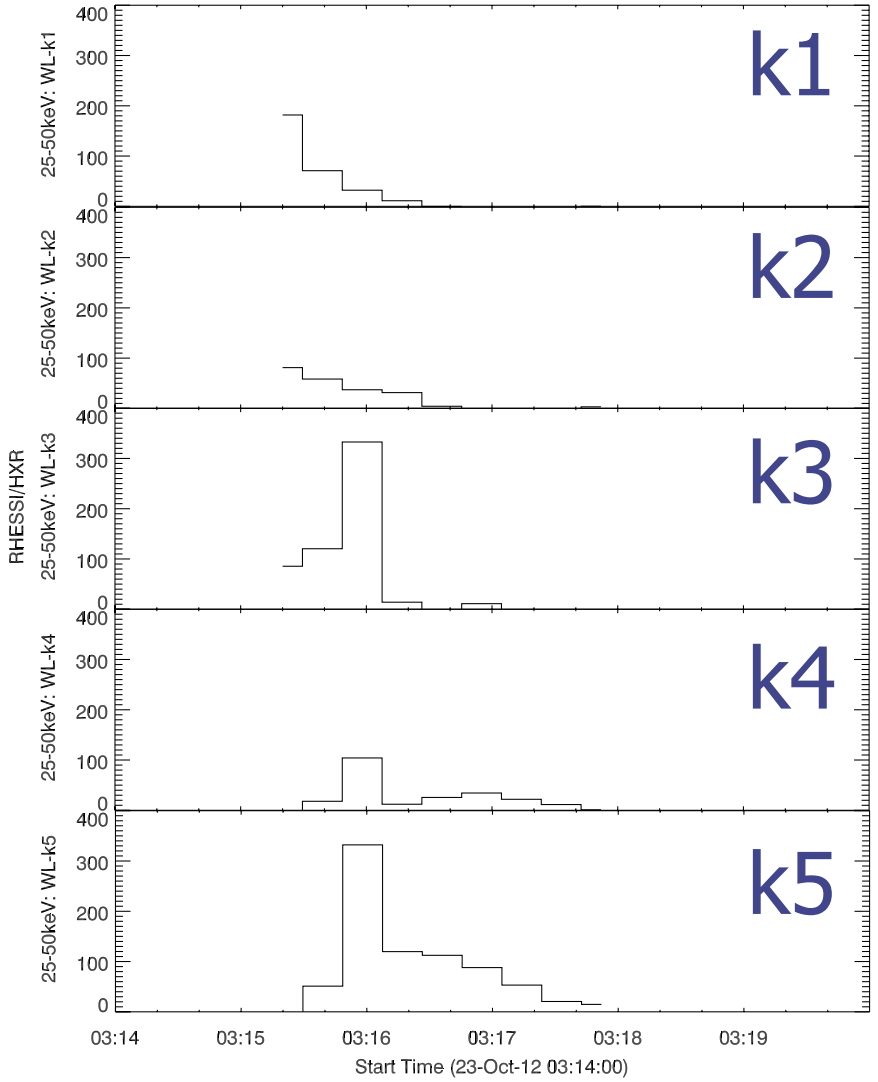
2012 Oct 23 White-light flare

Hinode/SOT red & *RHESSI* HXR



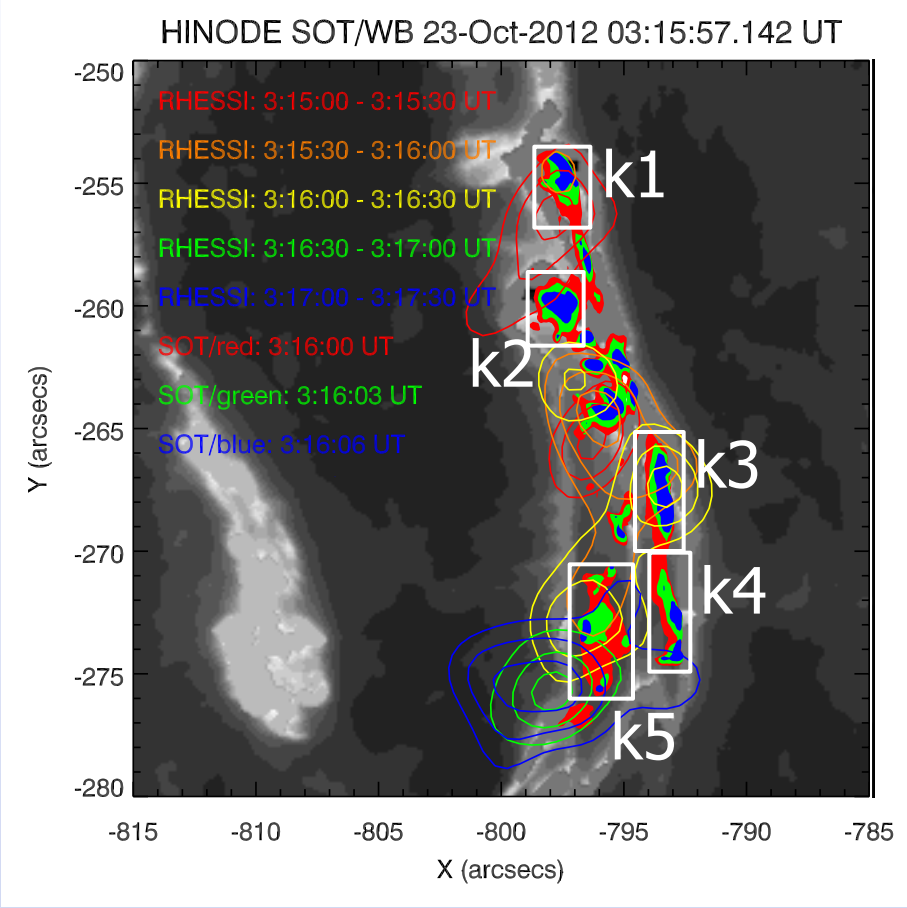
RHESSI: 35-100keV

RHESSI: 25-50keV



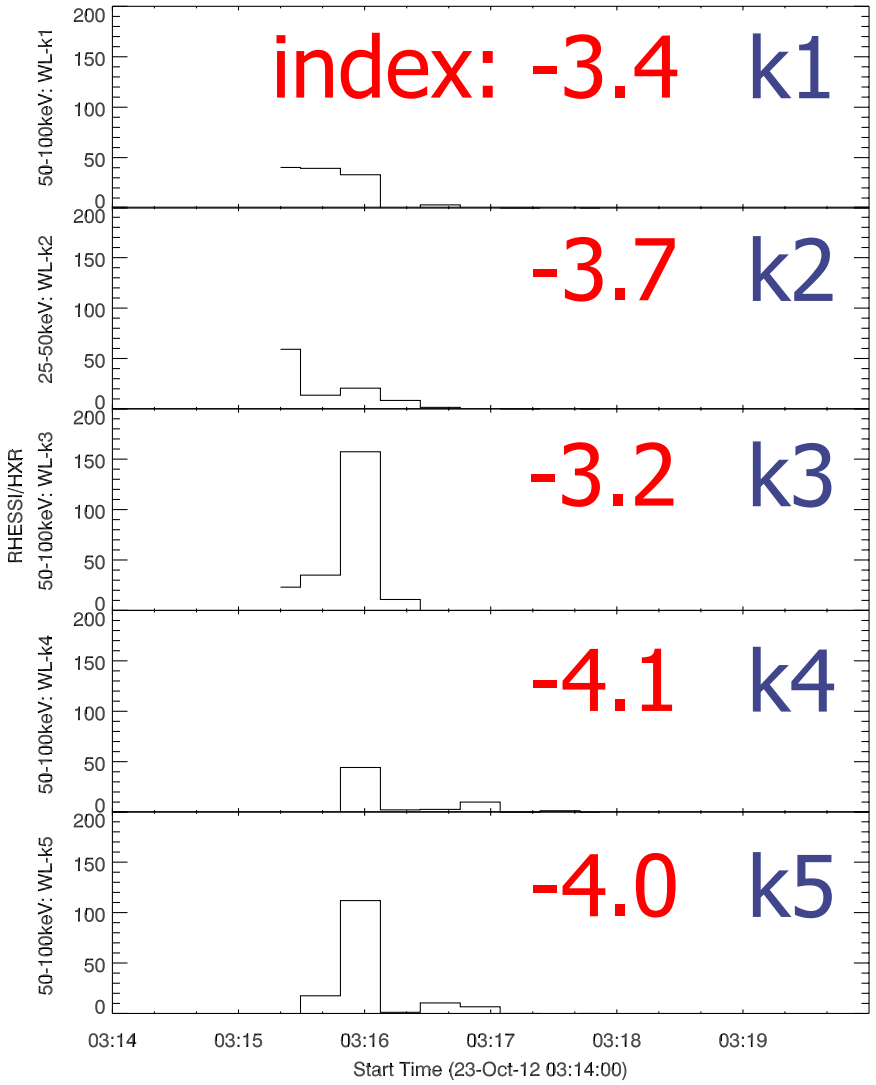
2012 Oct 23 White-light flare

Hinode/SOT red & *RHESSI* HXR



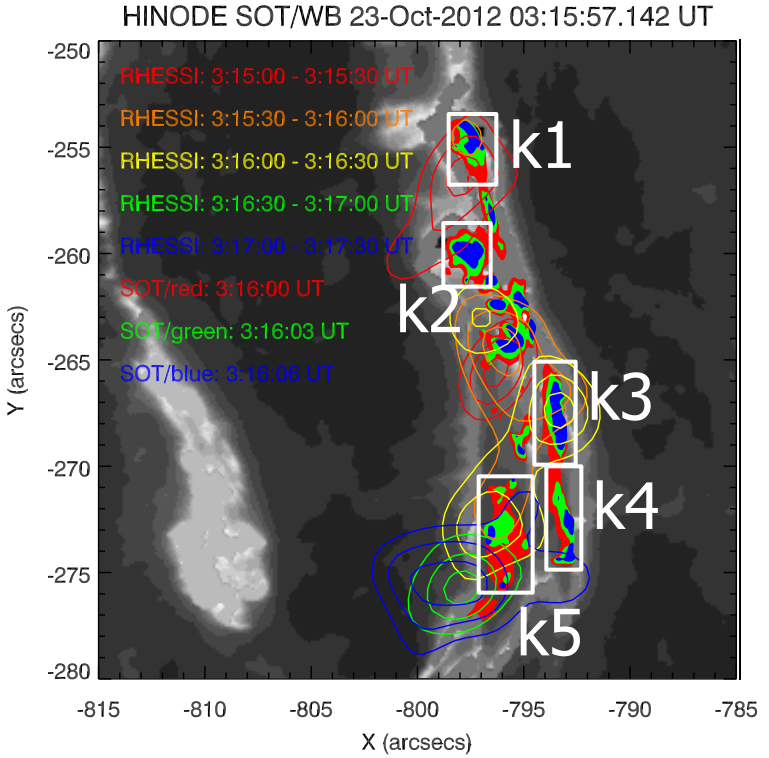
RHESSI: 35-100keV

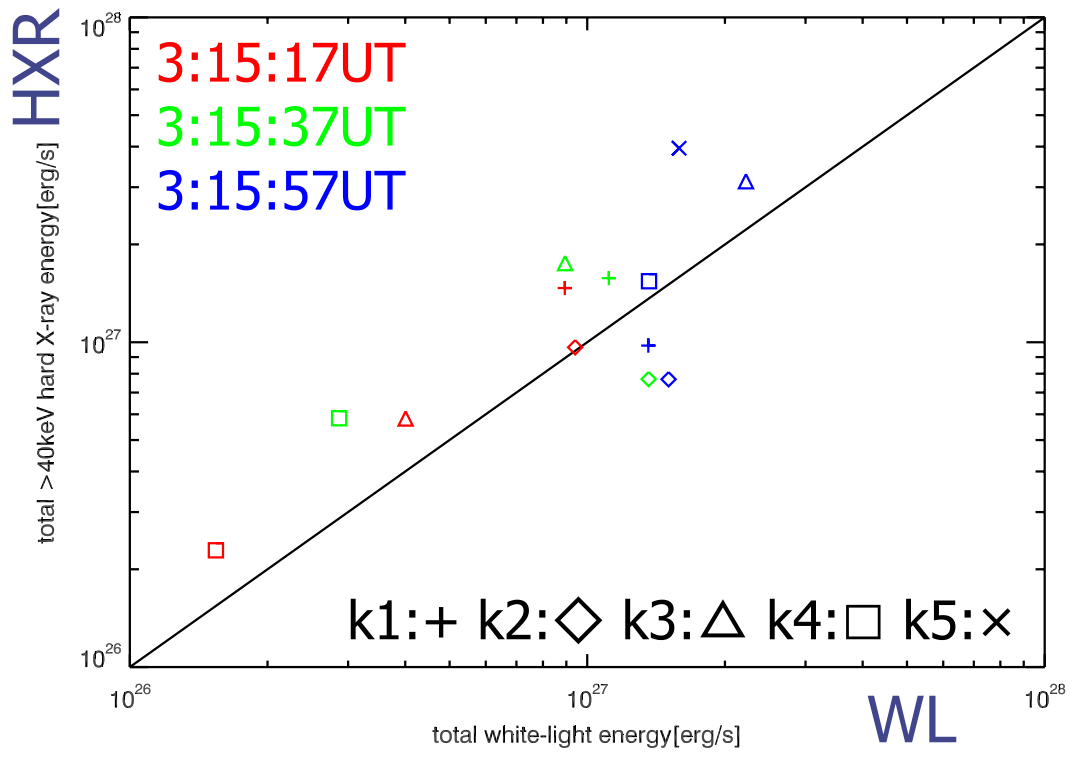
RHESSI: 50-100keV



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.

Statistical study of white-light flares

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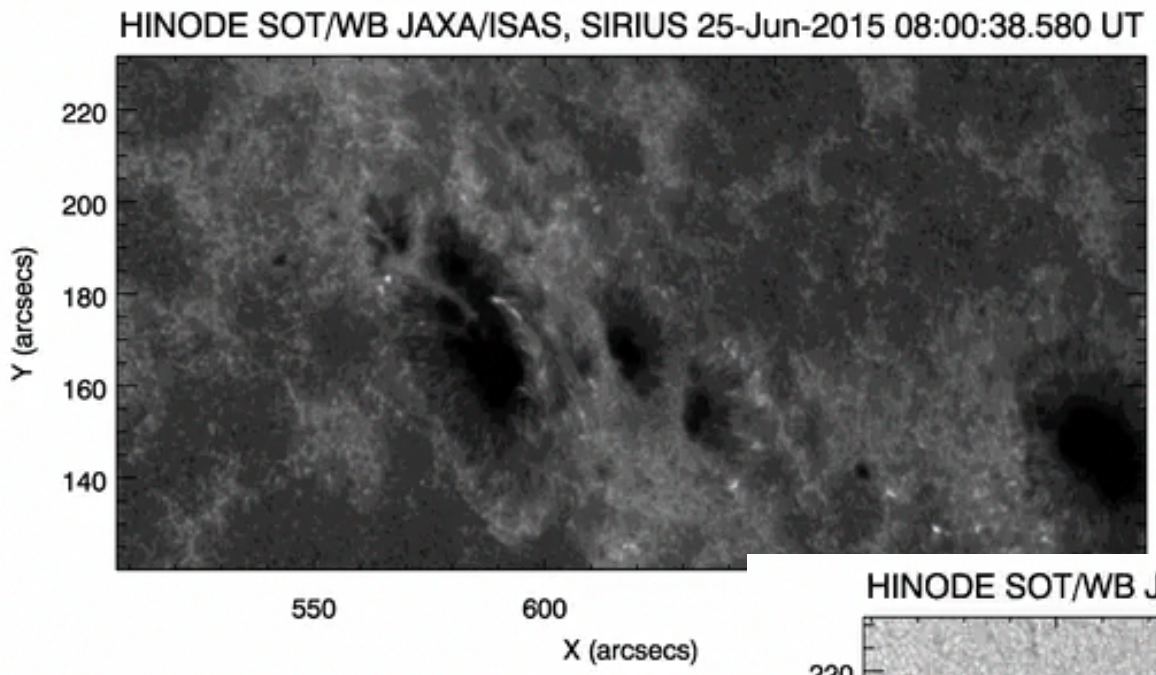
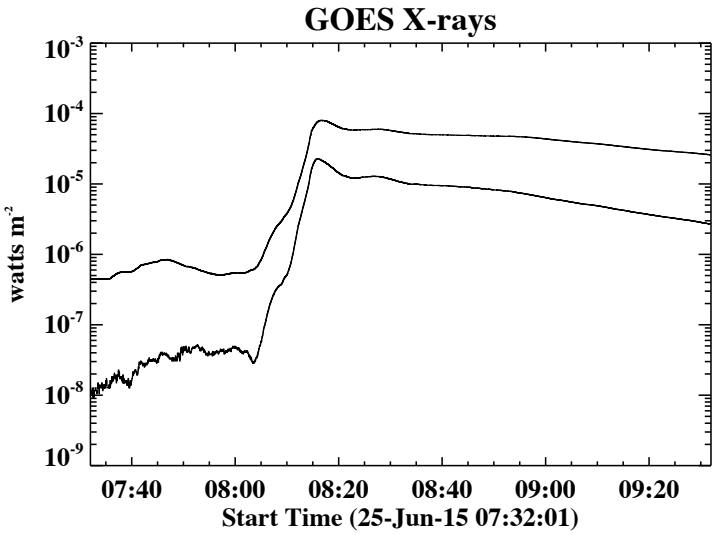
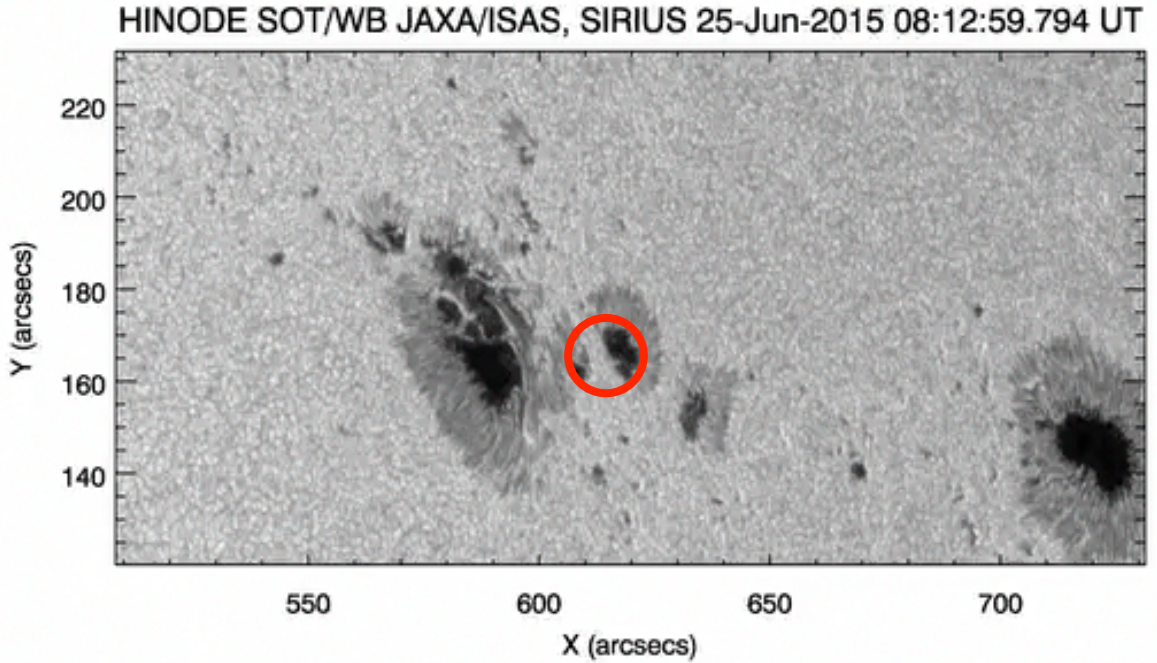
SOT-blue high cadence observation of WLF
2015/06/25 08:02UT M7.9





The first Blue-cont. rich observation by *Hinode*



SOT-blue high cadence observation of WLF
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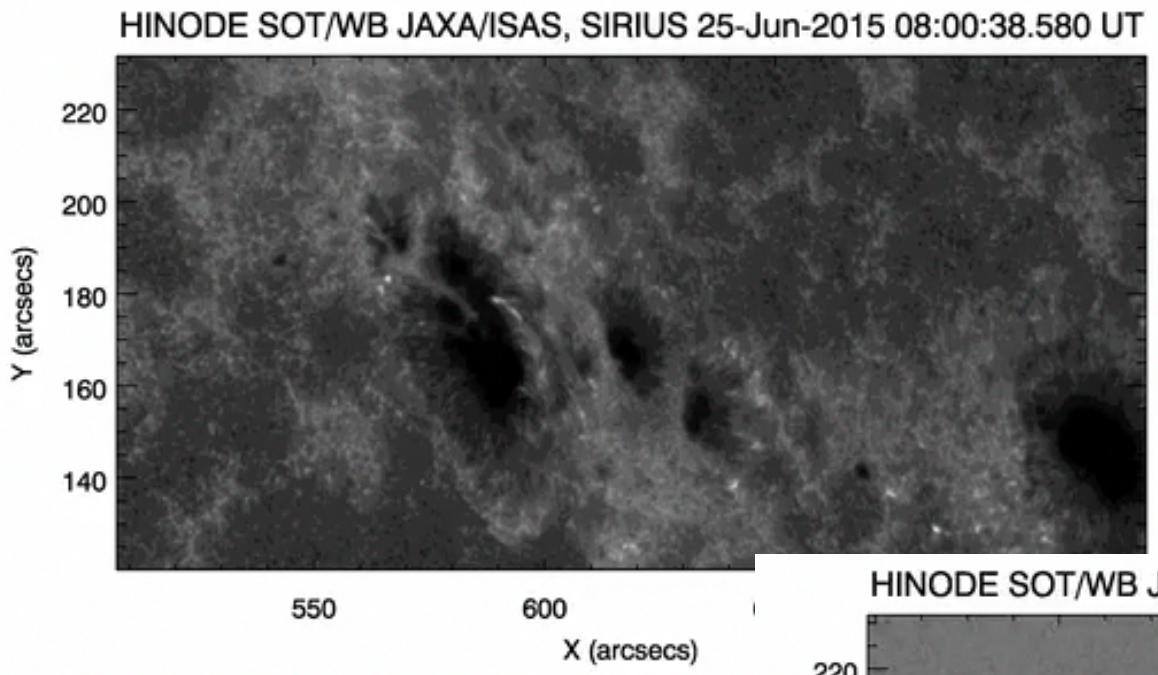
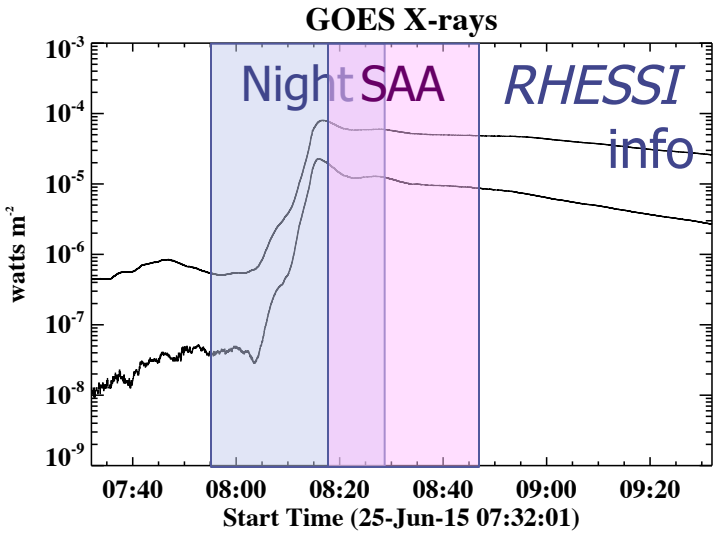
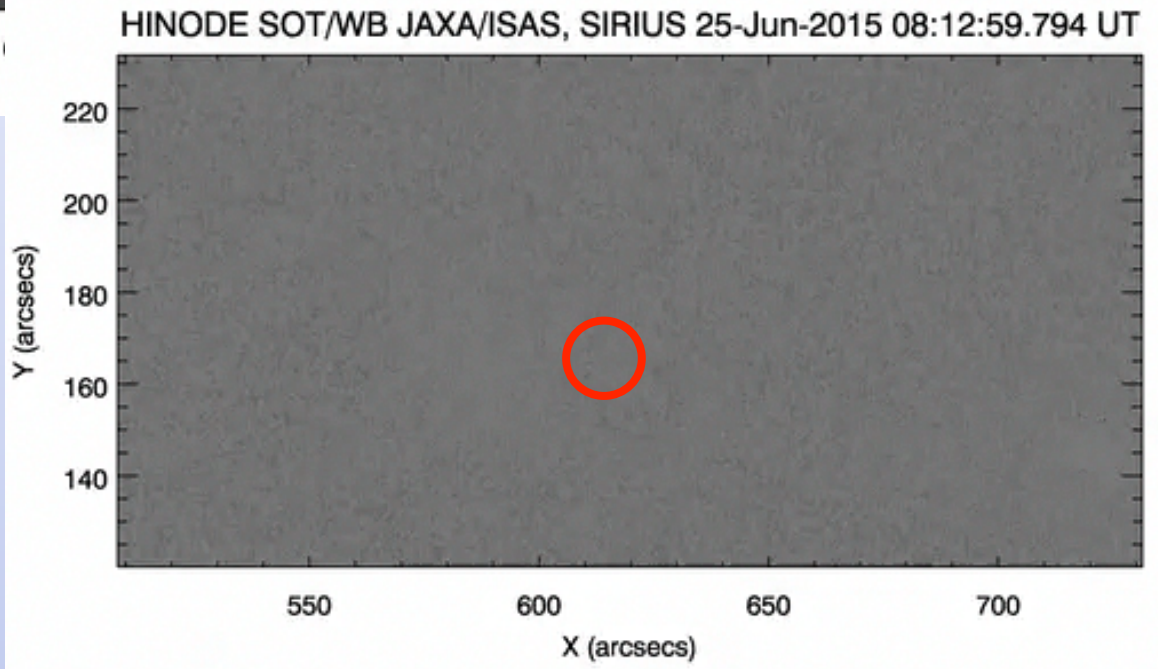




The first Blue-cont. rich observation by *Hinode*

- No *RHESSI* data
  (No *SUZAKU* data)

Fermi/GBM observed hard X-ray from the Sun



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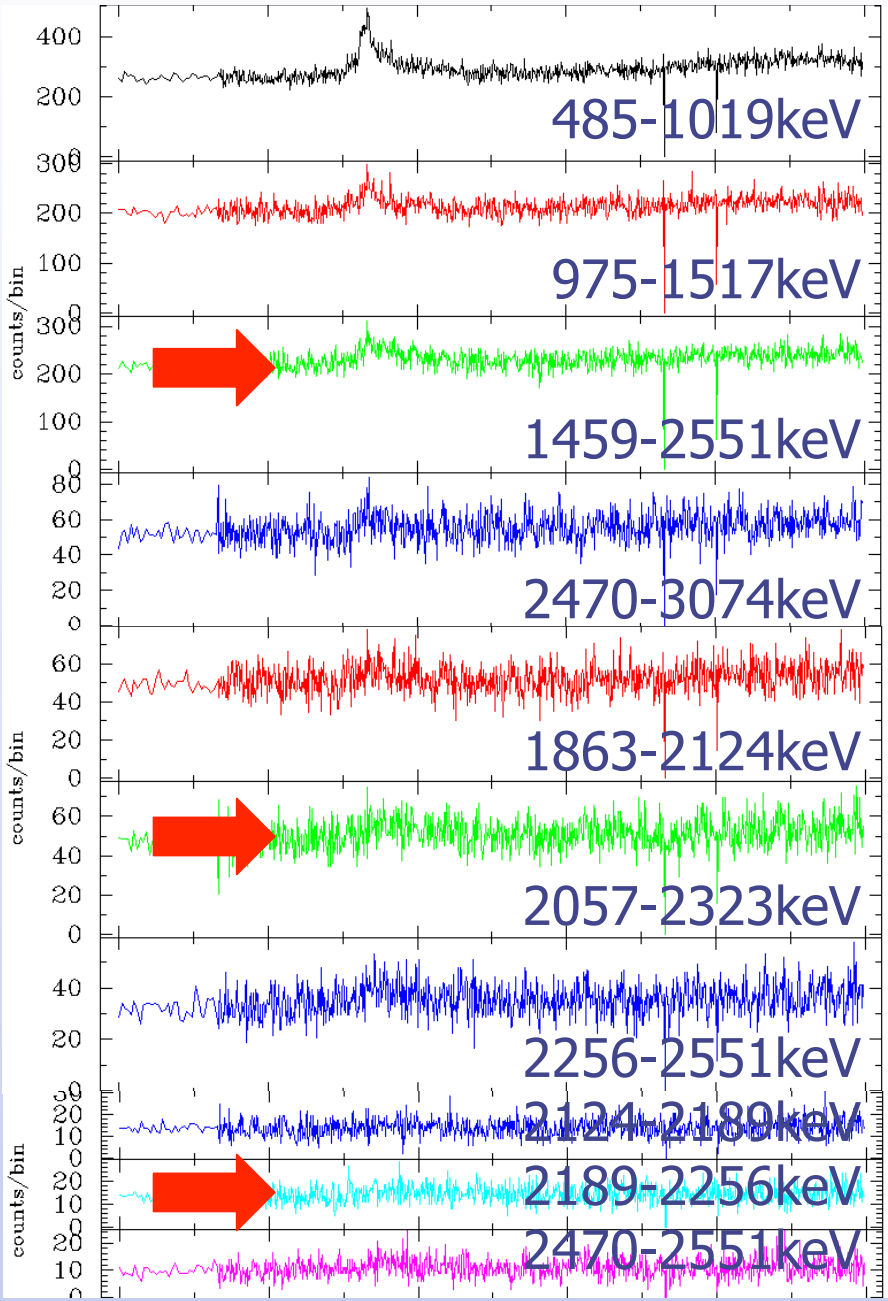
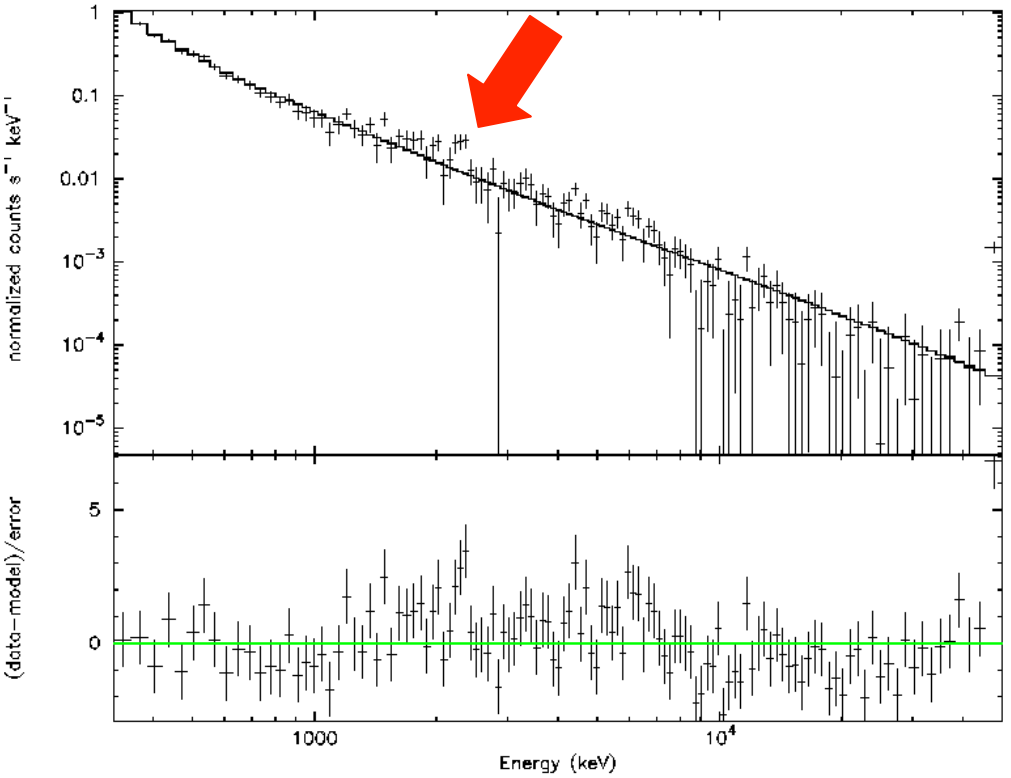


2015/06/25 08:02UT M7.9
Fermi/GBM HXR & γ-ray



- *Fermi*/GBM showed high energy emission (>1MeV).
- Small evidence of 2.2MeV...
- Intensity is very small.

SOT-blue high cadence observation of WLF
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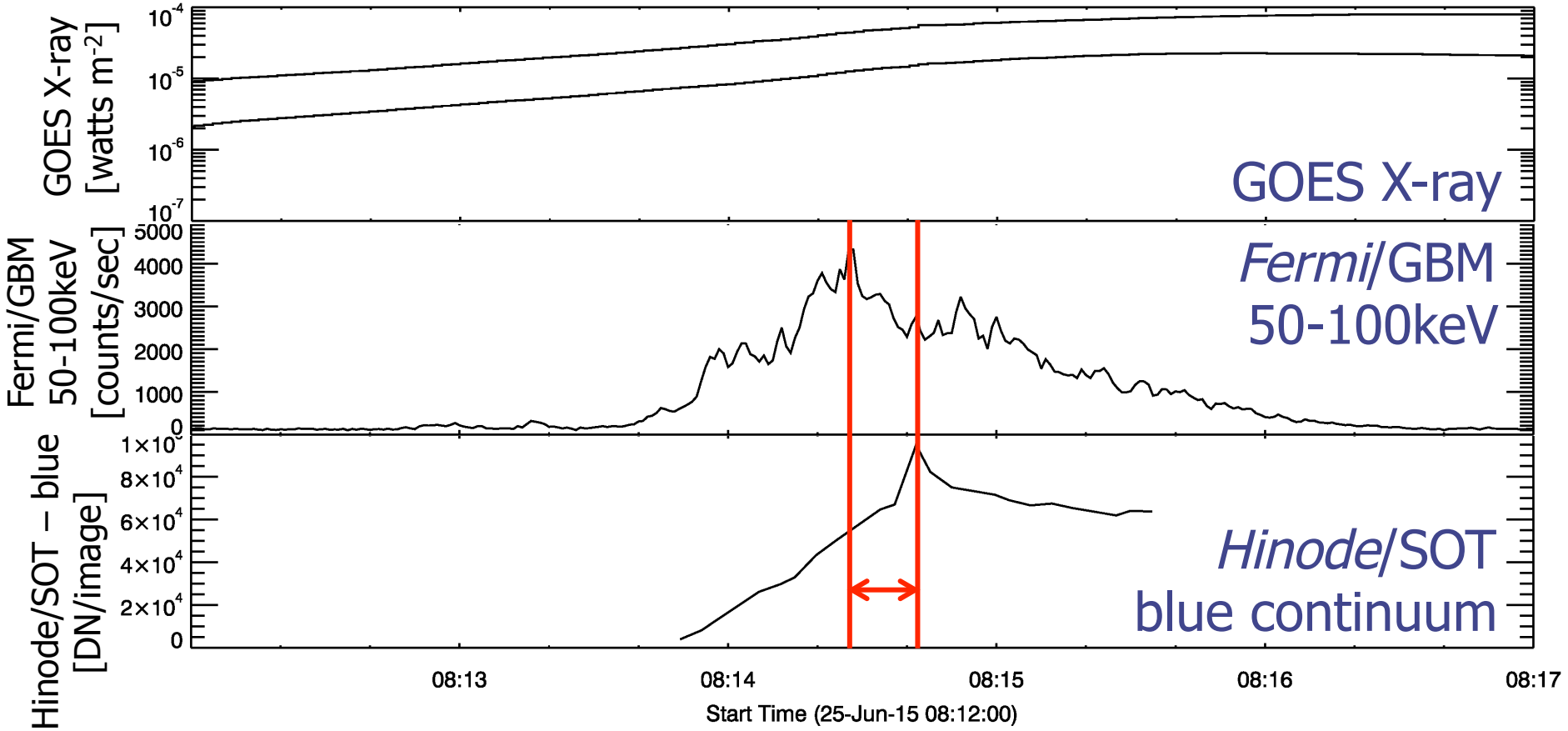

White-Light emissions are well correlated with hard X-ray and radio emissions (Location & Profile) → Non-thermal electrons

There is a time lag of emission peak ~20 sec

Discussion & Summary

WLF with γ-ray emissions on 2012 Oct 23

- No clear evidence of 2.2MeV emission.
- Accelerated ion energy: ~ 10^{28} erg
  → We couldn't reject ions as the origin of WL
- WL and HXR emissions occurred at almost the same location.
- Peak of HXR is a little bit earlier than the peak of WL. (← ~20sec @ 2015 Jun 25 event)
- Relationship between WL and HXR emission is proportional.
  → WL can be explain by >40keV acc. e-
- If we observe the position difference of HXR and 2.2MeV γ-ray emissions with WL enhancements, we can determine the origin of WL emissions.