

# Particle Acceleration near the Sun

**R. P. Lin**

Physics Dept & Space Sciences Laboratory  
University of California, Berkeley

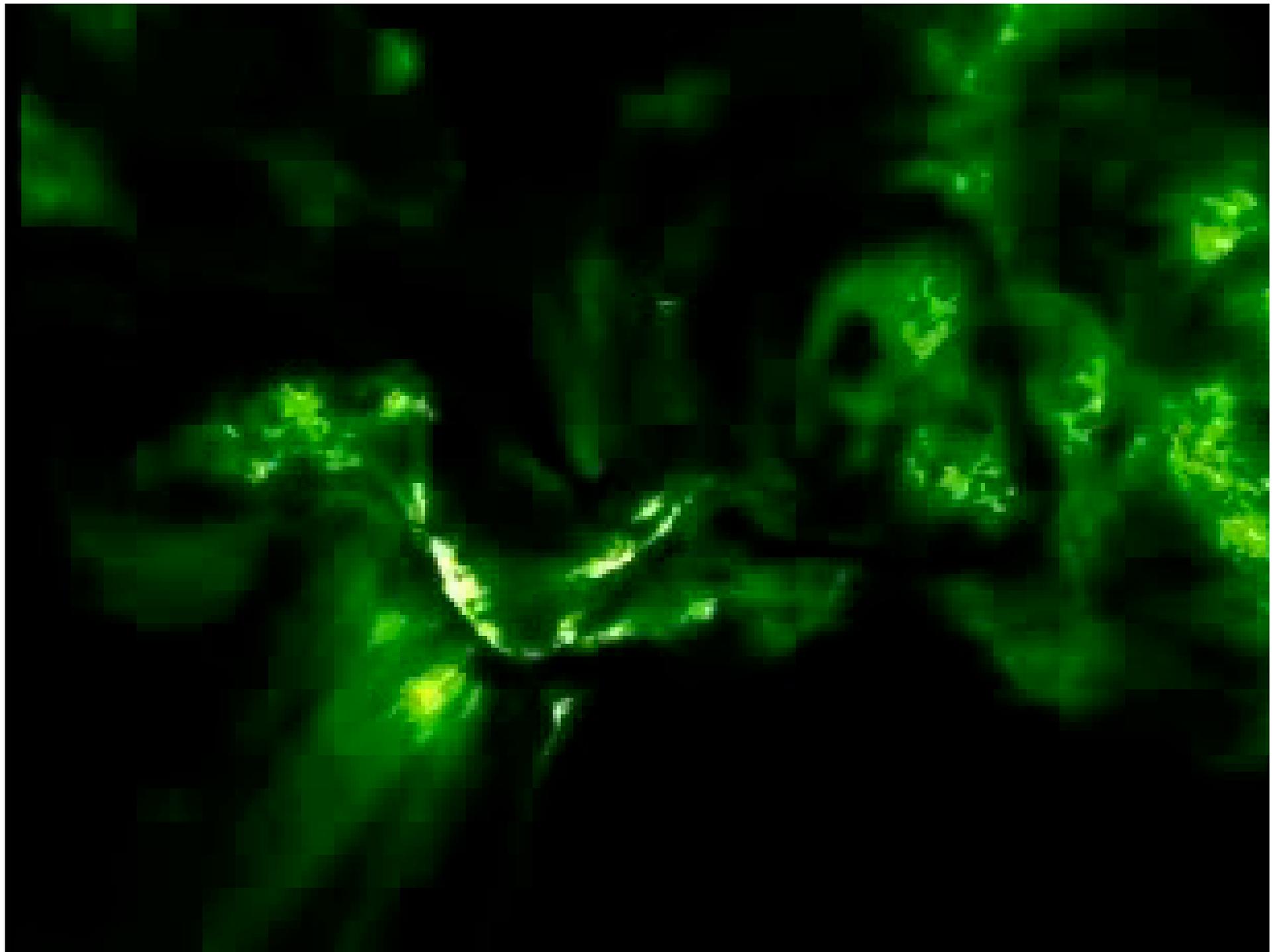
with help from R.Mewaldt, L. Wang, and the RHESSI  
team

The Sun is the most energetic particle accelerator in the solar system:

- *Ions up to  $\sim 10$ s of GeV*
- *Electrons up to  $\sim 100$ s of MeV*

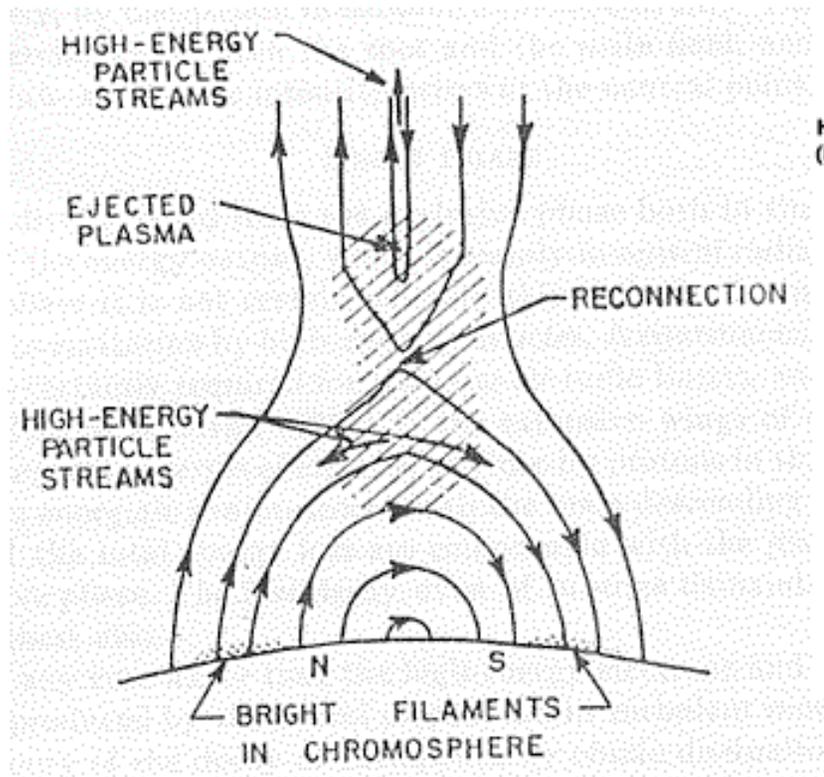
Acceleration to these energies occurs in transient energy releases, in two (!) processes:

- *Large Solar Flares, in the lower corona*
- *Fast Coronal Mass Ejections (CMEs), in the inner heliosphere,  $\sim 2-40$  solar radii*

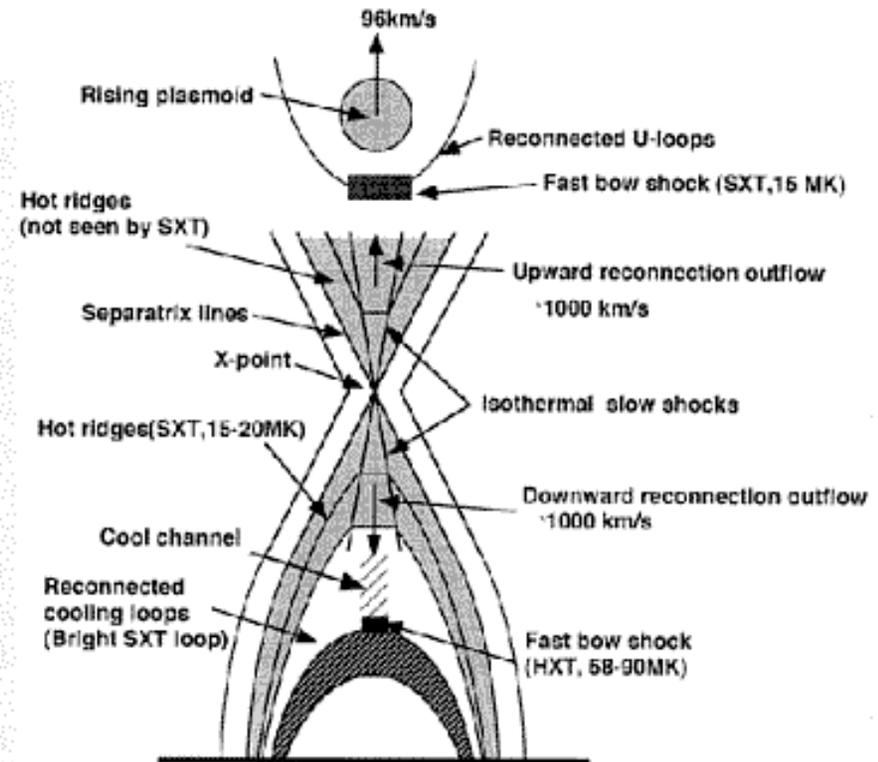


# 'Standard' model

This has evolved to keep pace with observations

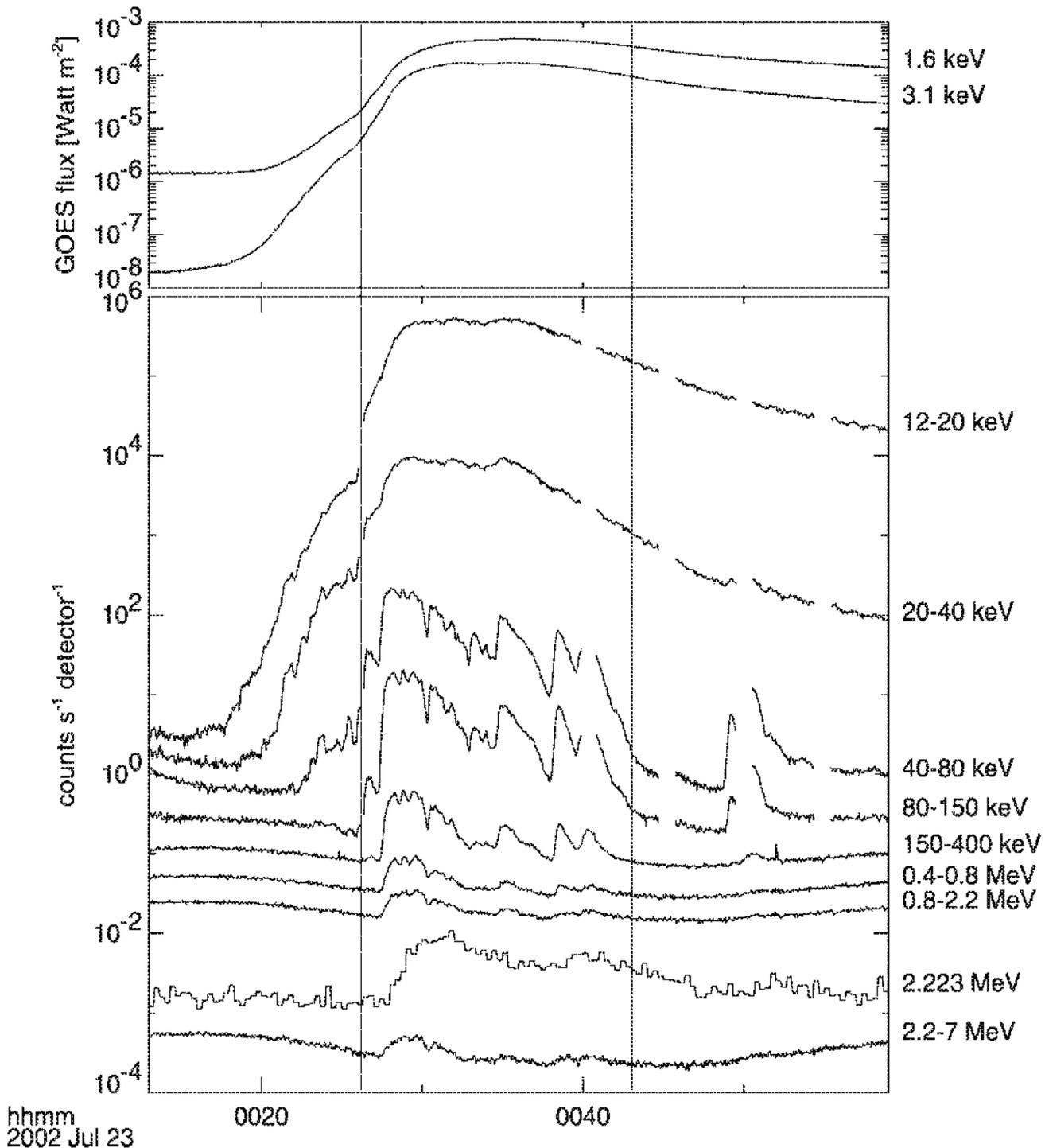


Sturrock 1966



Tsuneta 1997





Thermal Plasma

$\sim 3 \times 10^7 \text{ K}$

23 July 2002

X4.8 Flare

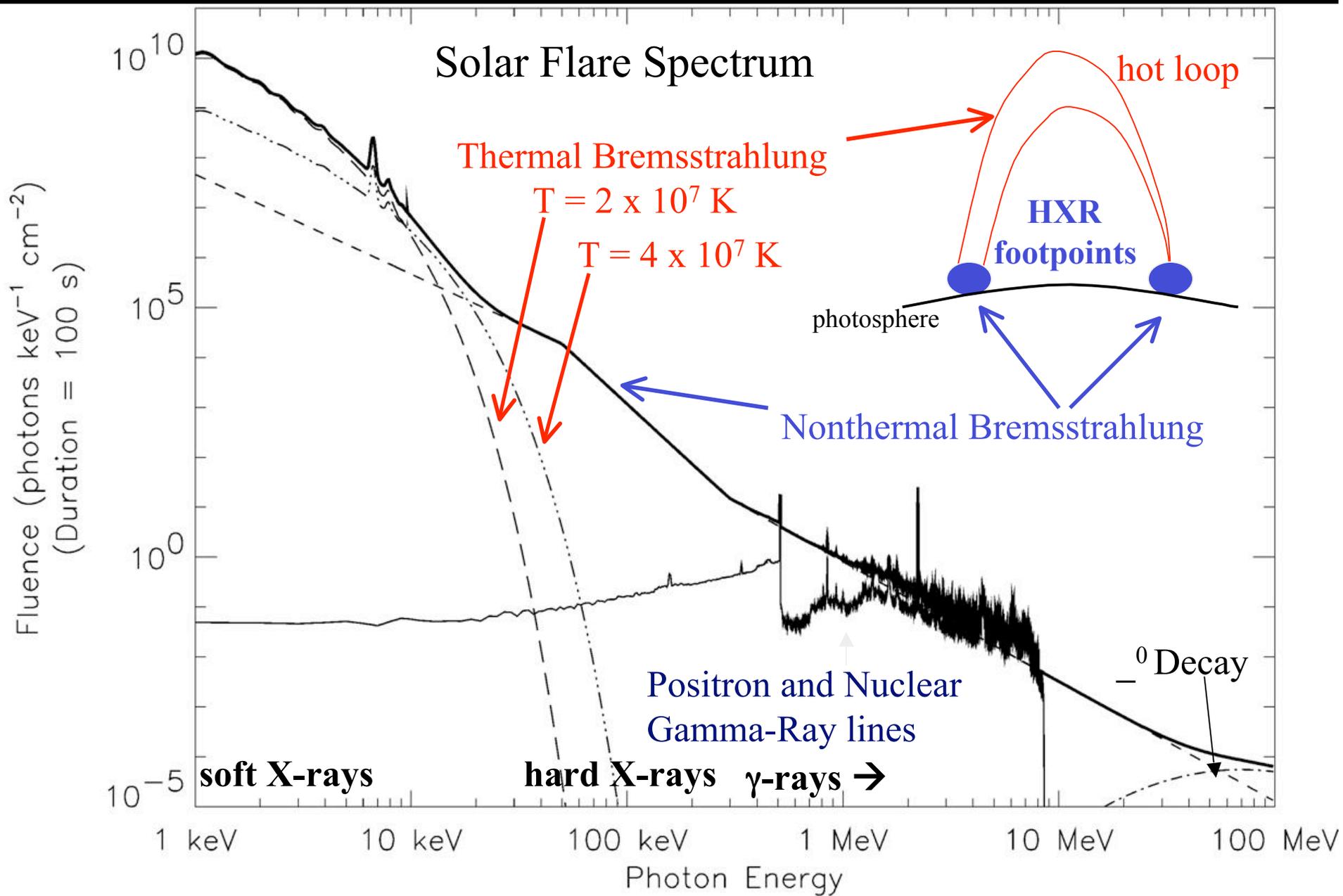
(Lin et al 2003)

Accelerated Electrons

$\sim 10 \text{ keV}$  to  $> 10 \text{ s MeV}$

Accelerated Ions

$\sim 1$  to  $> 100 \text{ s of MeV}$



# **Large solar flares are the most powerful explosions in the solar system**

*Up to  $\sim 10^{32} - 10^{33}$  ergs released in  $\sim 10 - 10^3$  s*

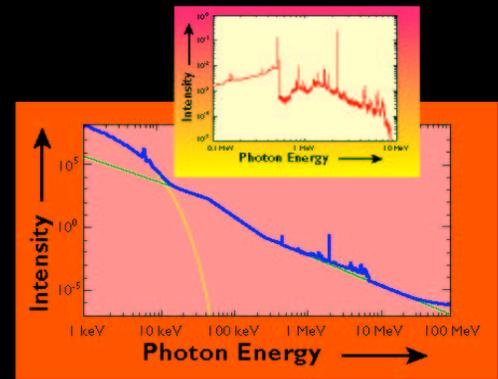
*Flare-accelerated  $\sim 20-100$  keV electrons contain  $\sim 10-50\%$  of total energy released*

*In large flares,  $>\sim 1$  MeV ions contain comparable energy*

**$\Rightarrow$  Particle acceleration is intimately related to flare energy release**

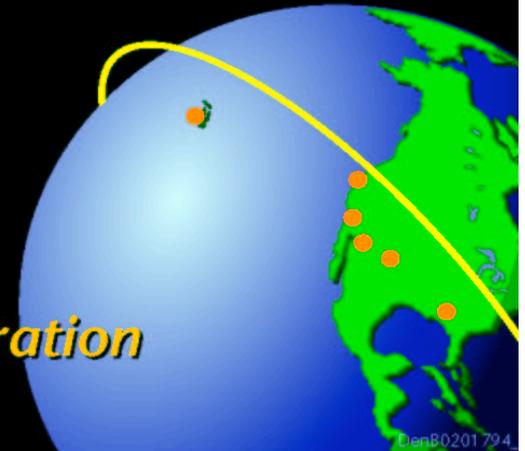
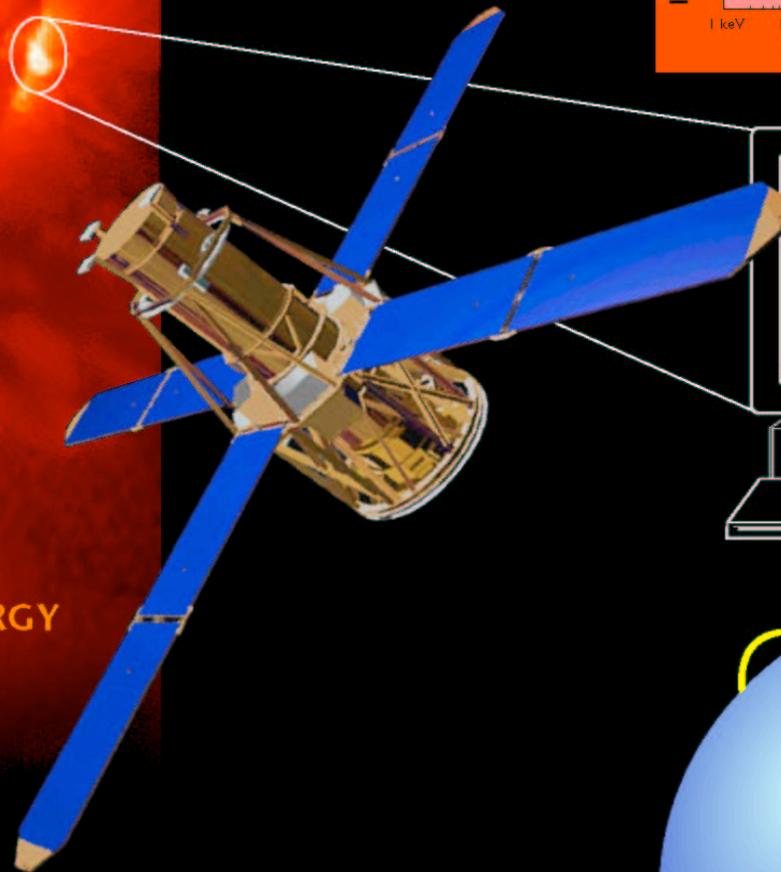
*The total energy released by all flares, down to microflares/nano-flares may be significant for the heating of the solar corona*

# High-Resolution Spectroscopic Imaging of Solar Flares in X Rays and Gamma Rays



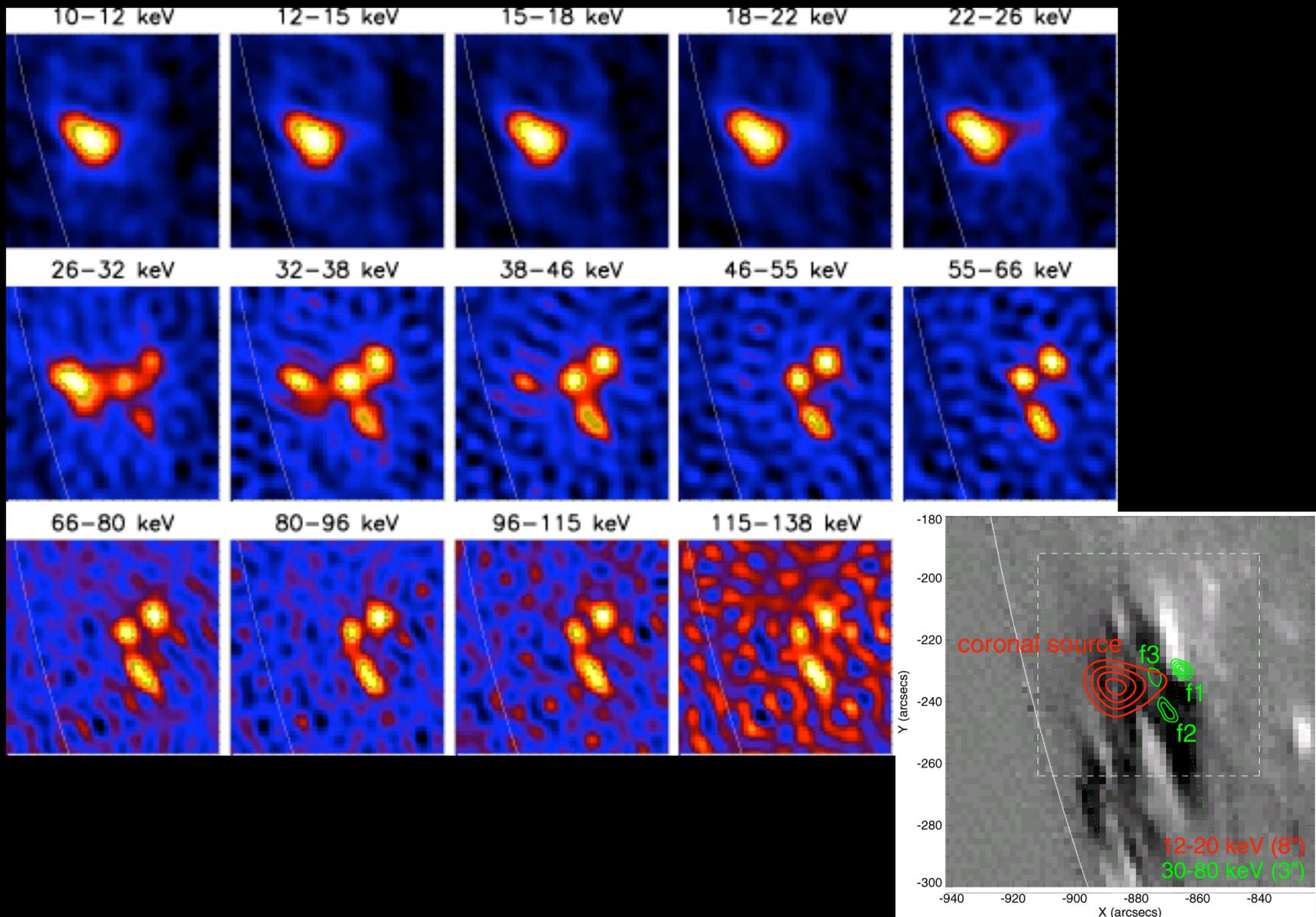
# RHESSI

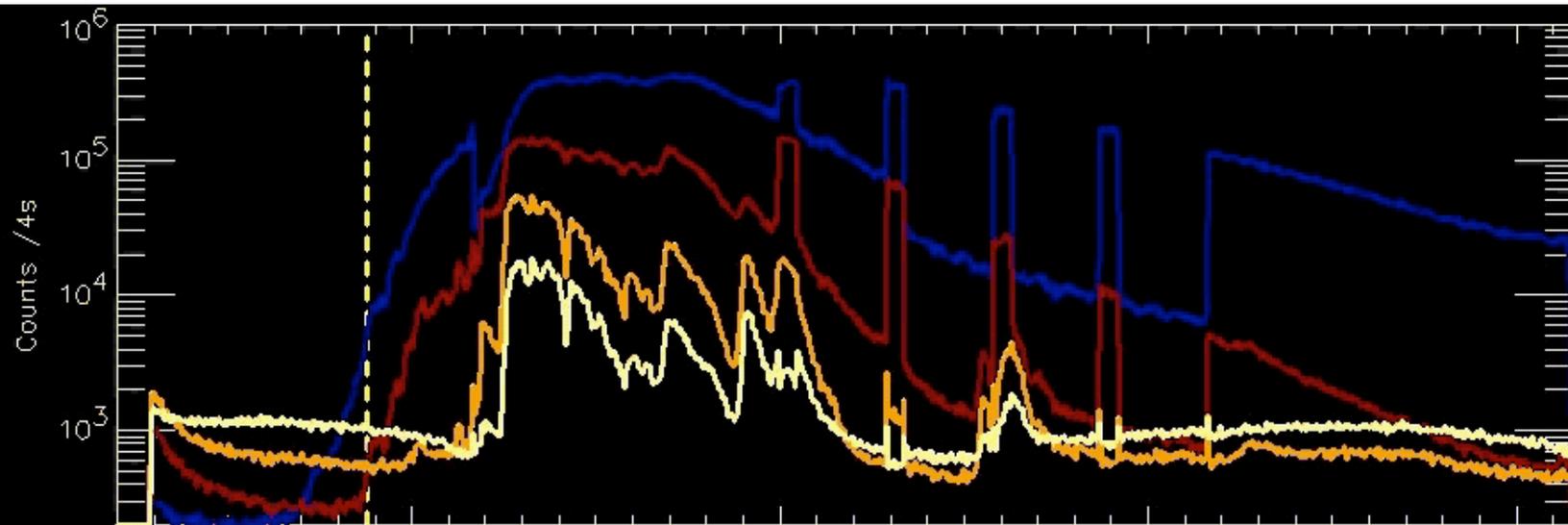
THE REUVEN RAMATY HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER



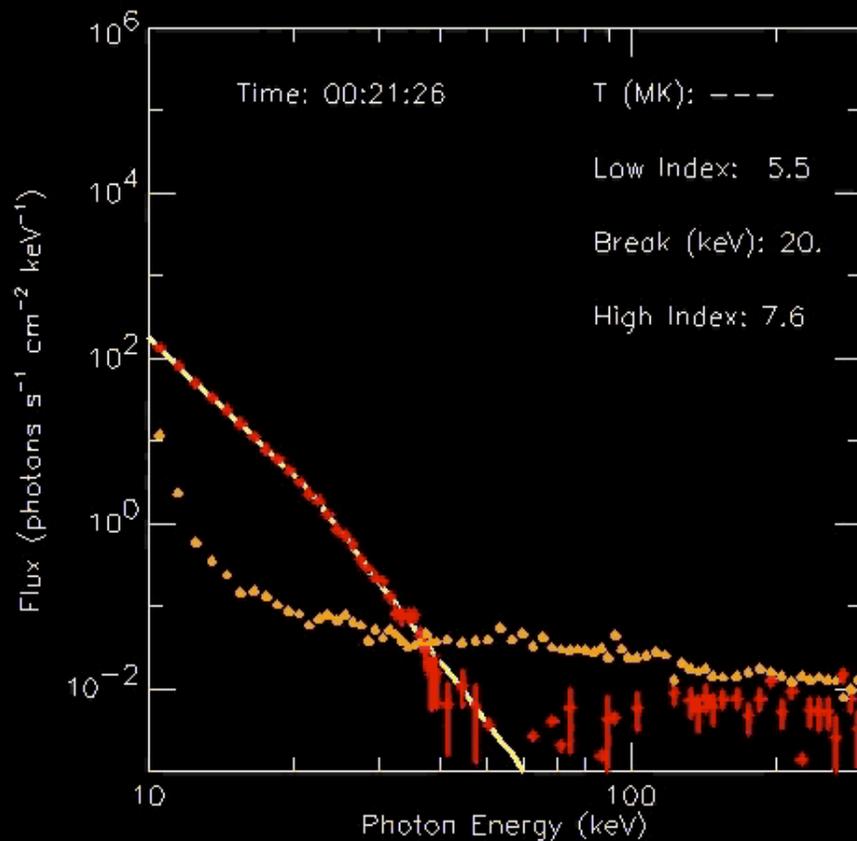
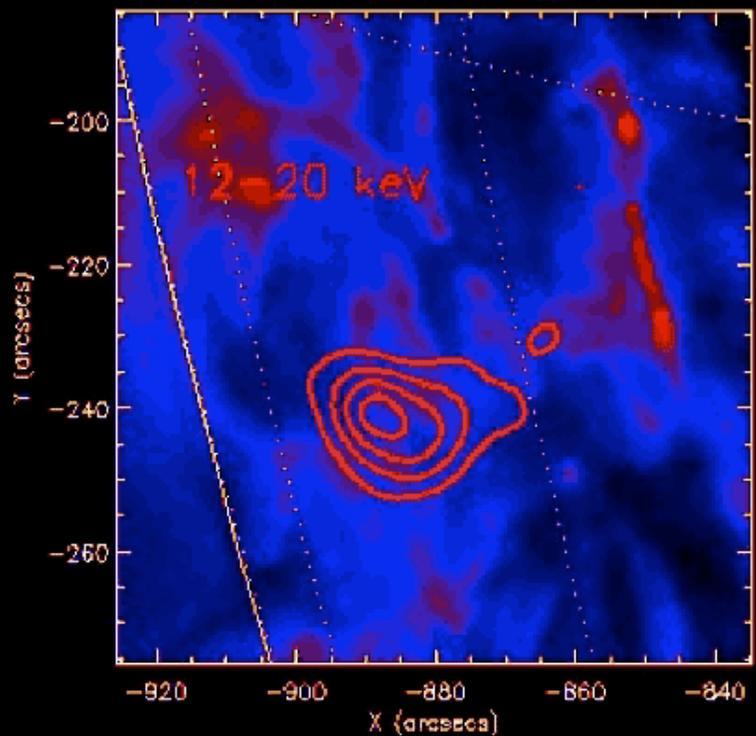
*To explore the basic physics of particle acceleration and explosive energy release in solar flares*

# Imaging spectroscopy



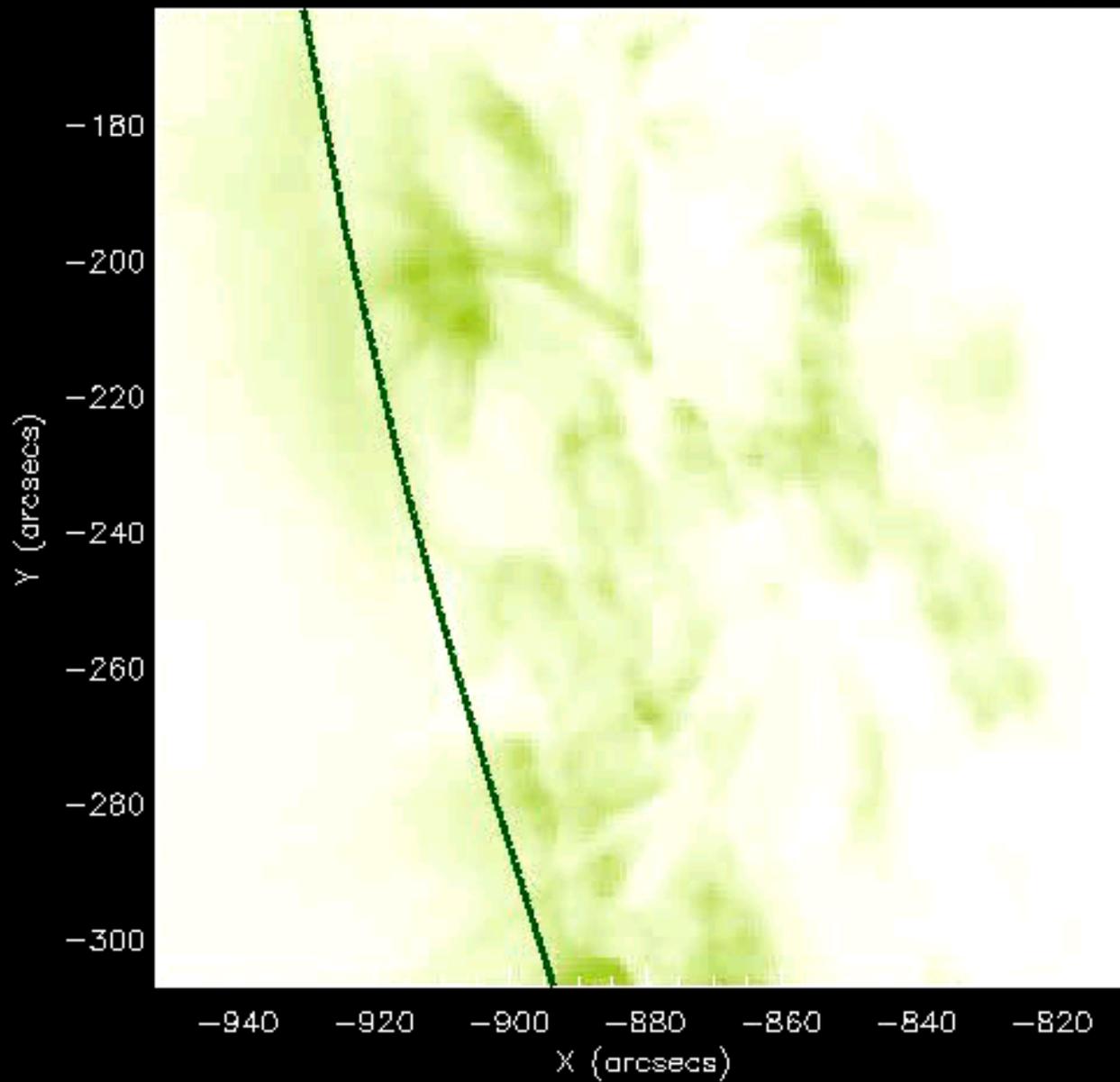


TRACE 195A: 23-Jul-2002 00:21:29.000 UT



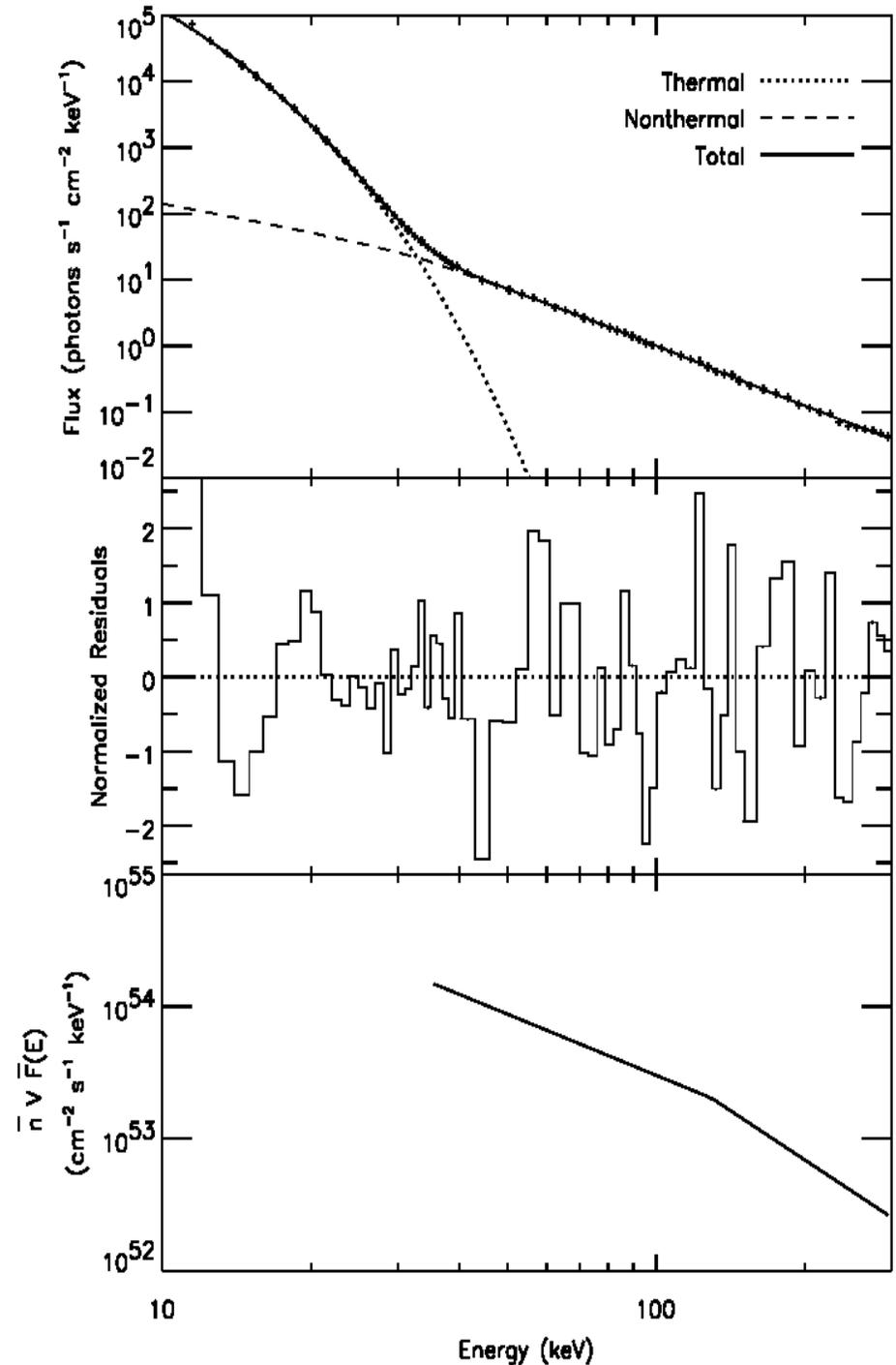
RHESSI & TRACE 195A: 23-Jul-2002 00:20:02.000 UT

**Pre-impulsive  
phase:  
RHESSI-  
TRACE movie**



# Mean Electron Flux Fit 2002 July 23 Flare

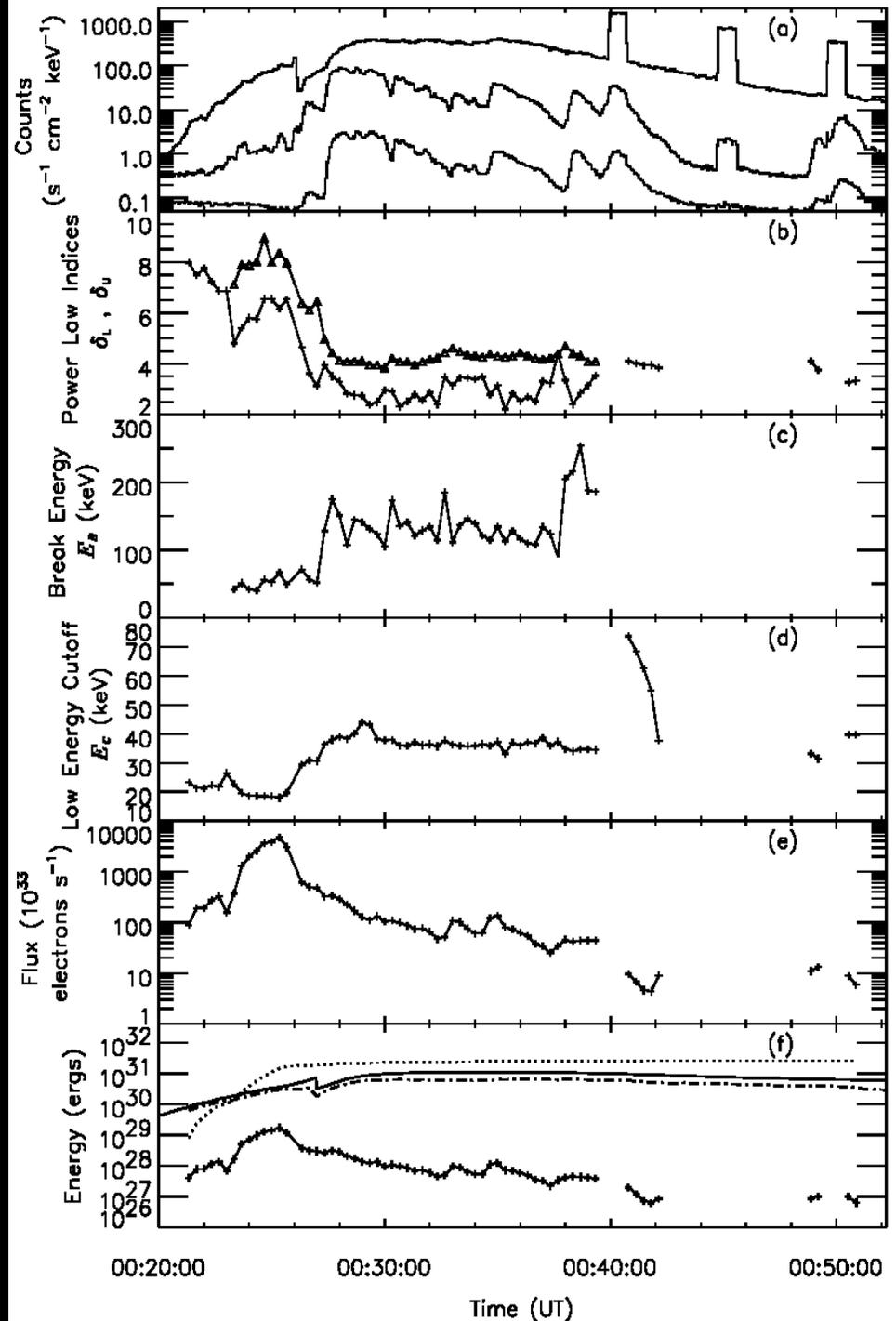
- 00:30:00 – 00:30:20 UT,
- Isothermal component +  
double power-law
- $T = 37$  MK
- $EM = 4.1 \times 10^{49} \text{ cm}^{-3}$
- $nVF = 6.9 \times 10^{55} \text{ cm}^{-2} \text{ s}^{-1}$
- $E_c = 34 \text{ keV}$
- $\alpha_L = 1.5$
- $E_B = 129 \text{ keV}$
- $\alpha_U = 2.5$



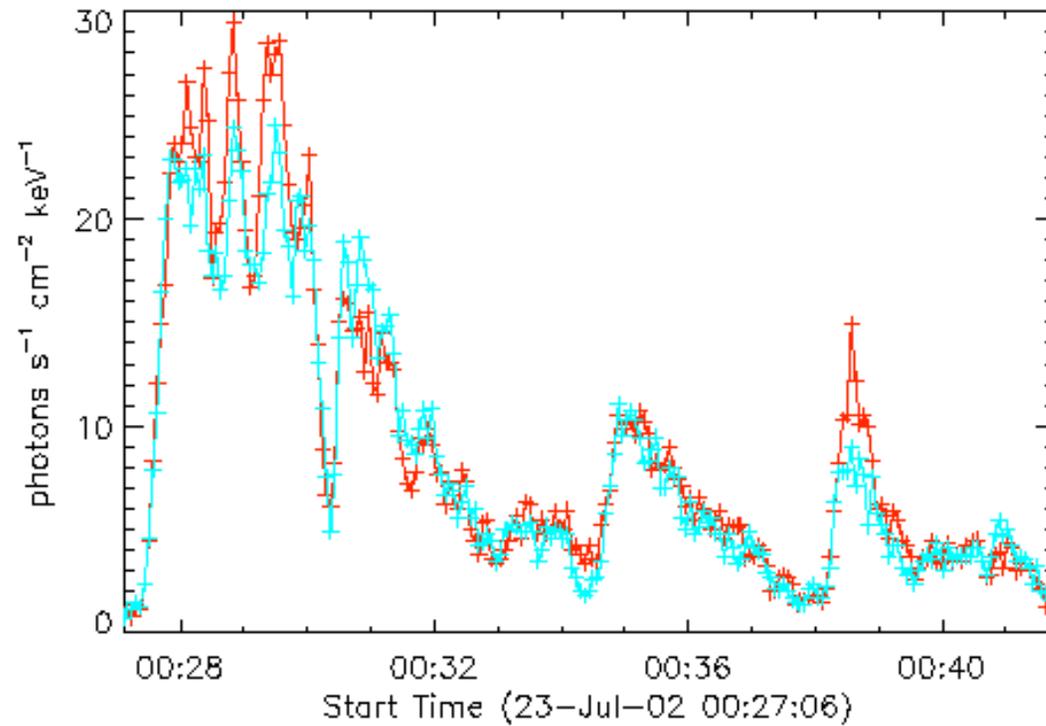
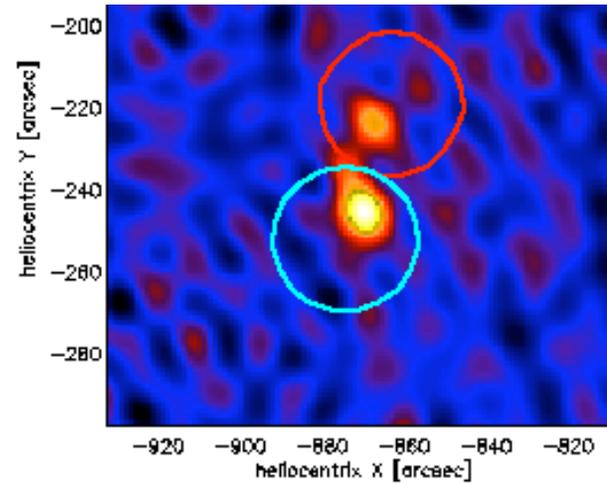
# Thick-Target Bremsstrahlung Fits

- Isothermal Component + bremsstrahlung from double power-law electron flux distribution
- Energetics (Panel f):
  - Solid Line: GOES isothermal
  - Dot-Dash Line: RHESSI isothermal
  - Dotted Line: RHESSI nonthermal
  - Lower Curve (plus signs): energy injection rate ( $\text{erg s}^{-1}$ )

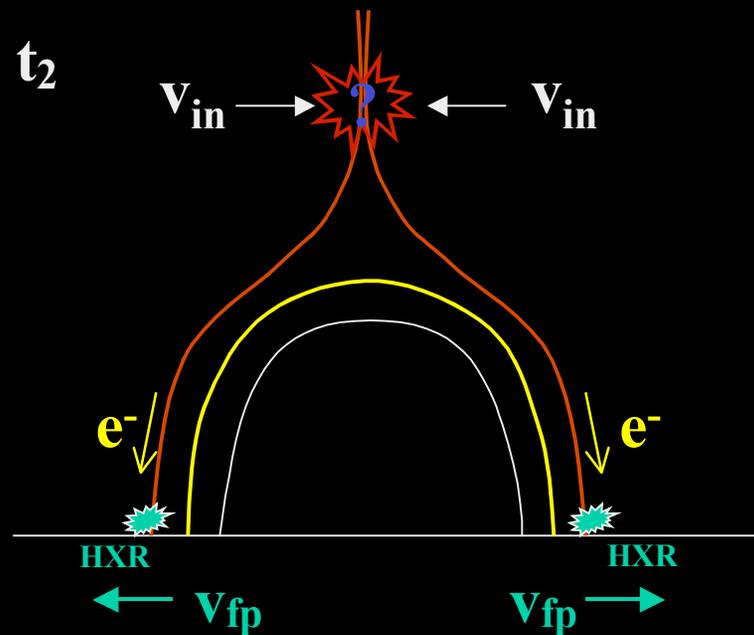
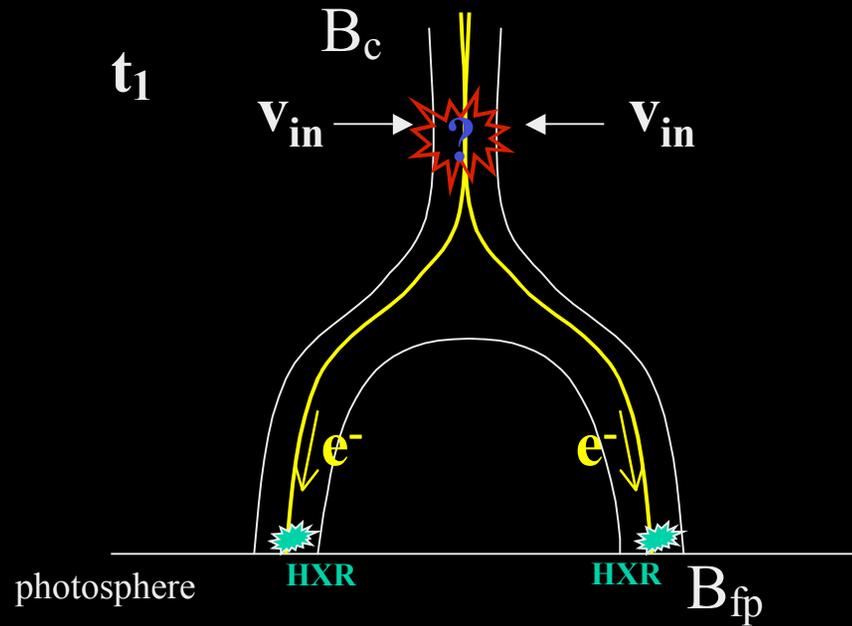
Holman, G. D., Sui, L.,  
Schwartz, R. A., & Emslie, A. G. 2003,  
Ap. J. Letters, 595, L97



# Krucker & Lin 2004



# HXR source motions in magnetic reconnection models

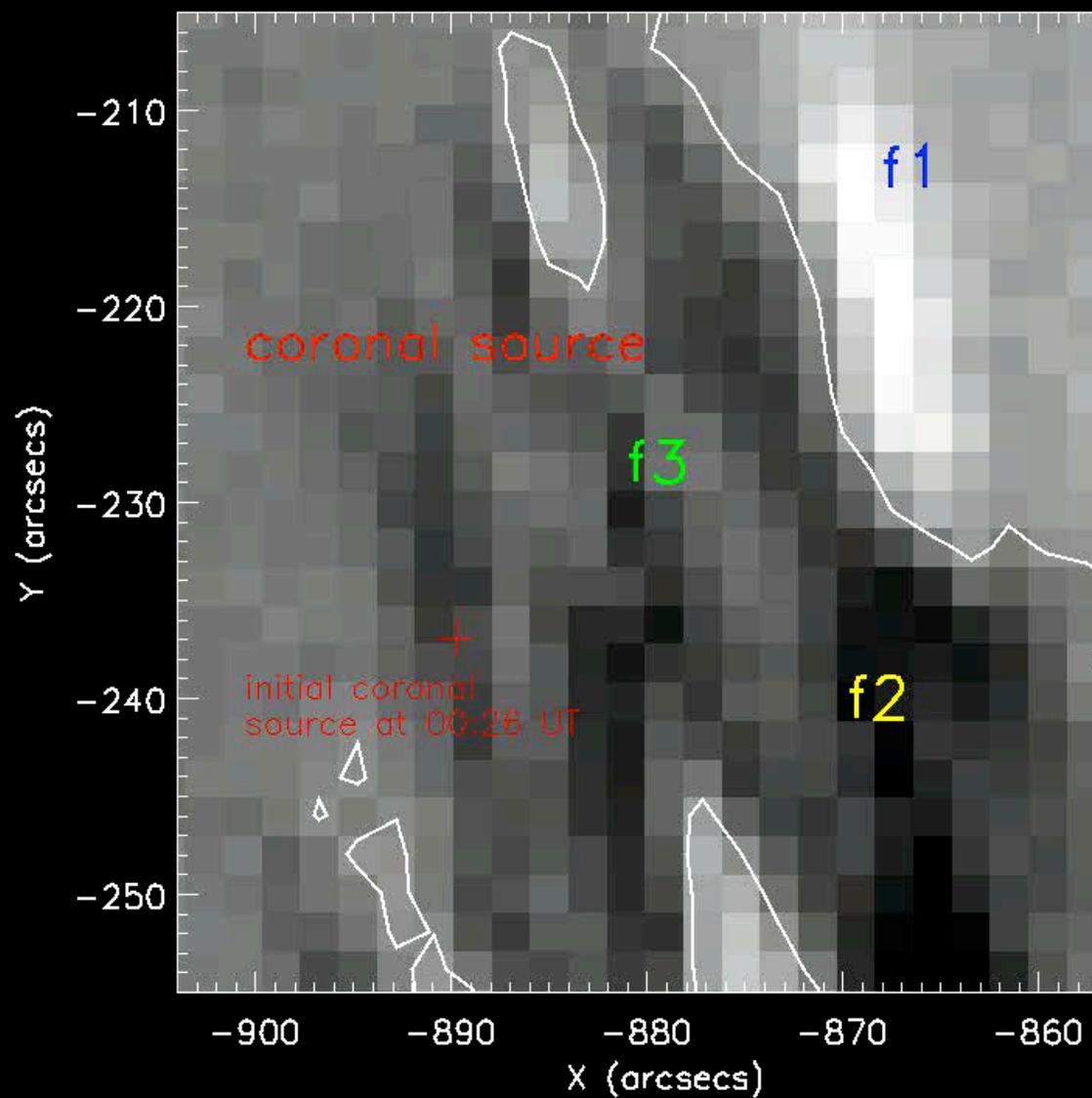
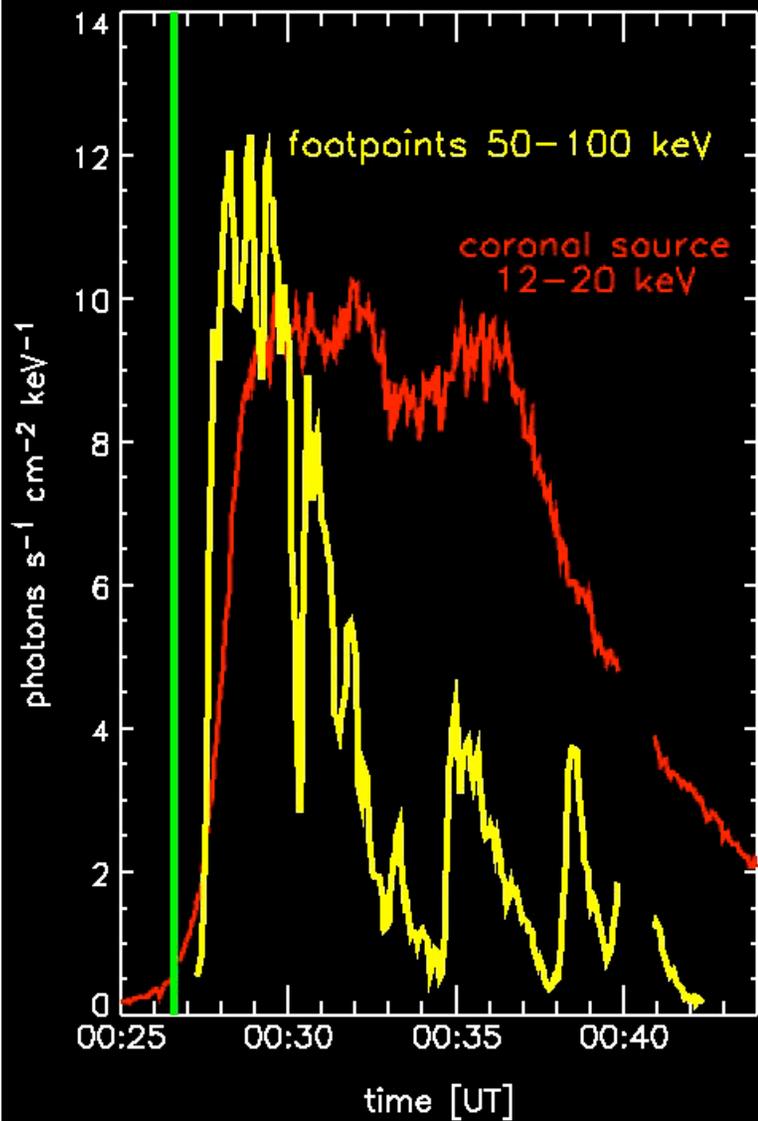


$v_{in}$  = coronal inflow velocity  
 $B_c$  = coronal magnetic field strength

$v_{fp}$  = HXR footpoint velocity  
 $B_{fp}$  = magnetic field strength in HXR footpoint  
 $\sim$  photospheric value

$$v_{in} B_c = v_{fp} B_{fp}$$

2002 JULY 23



# Velocity-HXR flux correlation

Rough correlation  
between  $v$  and HXR flux

$$d\Phi = B v a dt$$

Reconnection rate

$$d\Phi/dt = B v a$$

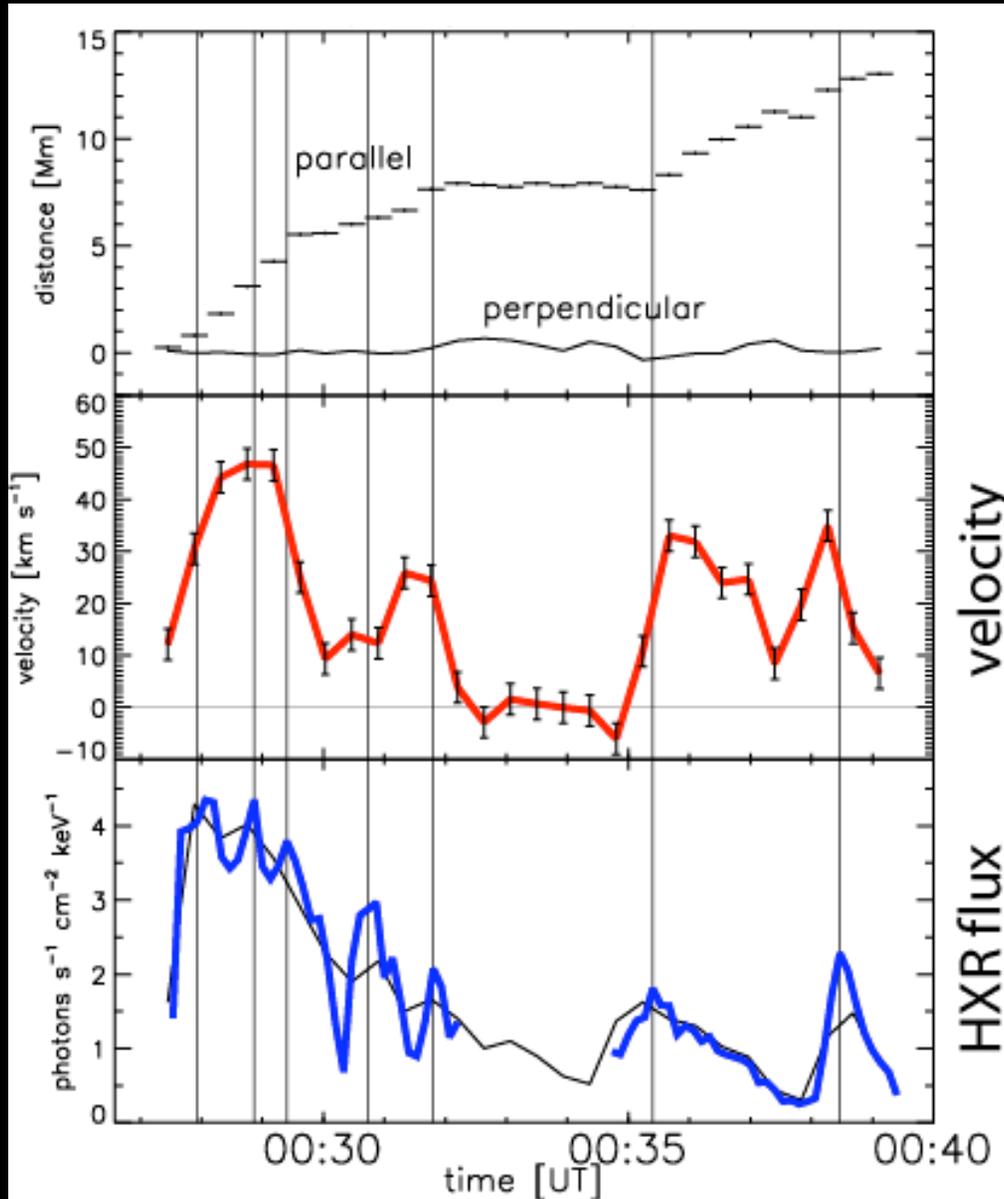
$$\sim 2 \times 10^{18} \text{ Mx/s}$$

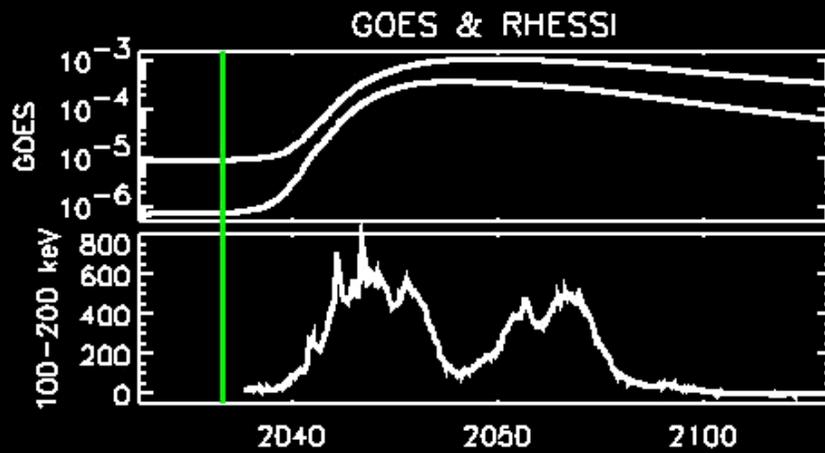
$$E = vB \sim 5 \text{ kV/m}$$

$v$  = velocity

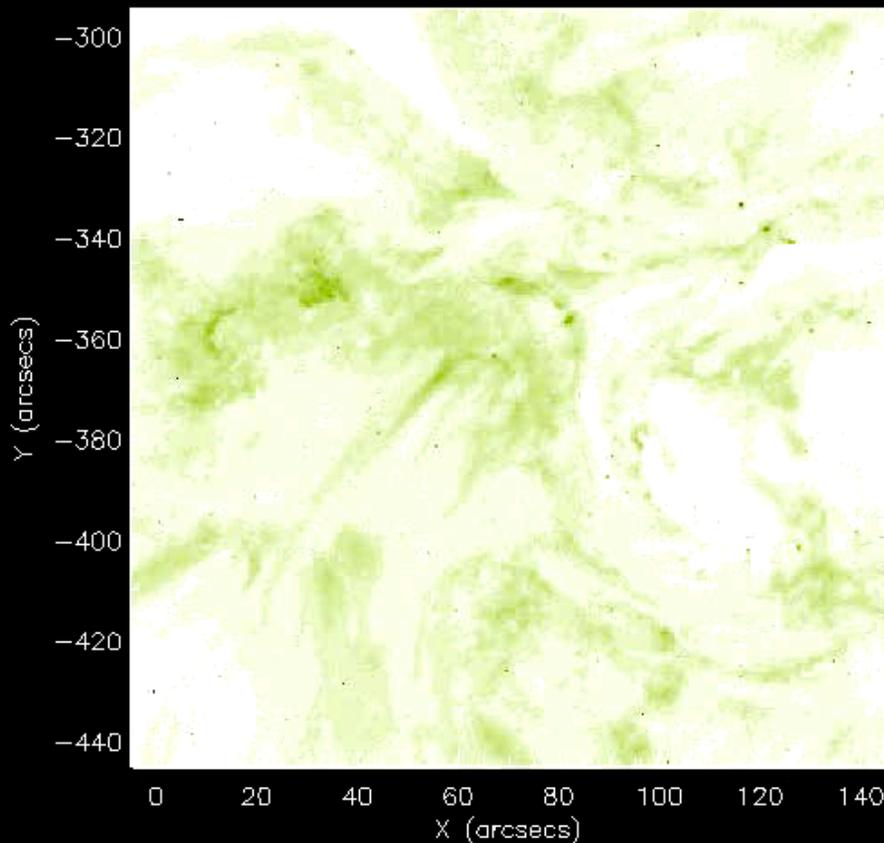
$B$  = magnetic field strength

$a$  = footpoint diameter





TRACE & RHESSI: 29-Oct-2003 20:38:39.000 UT

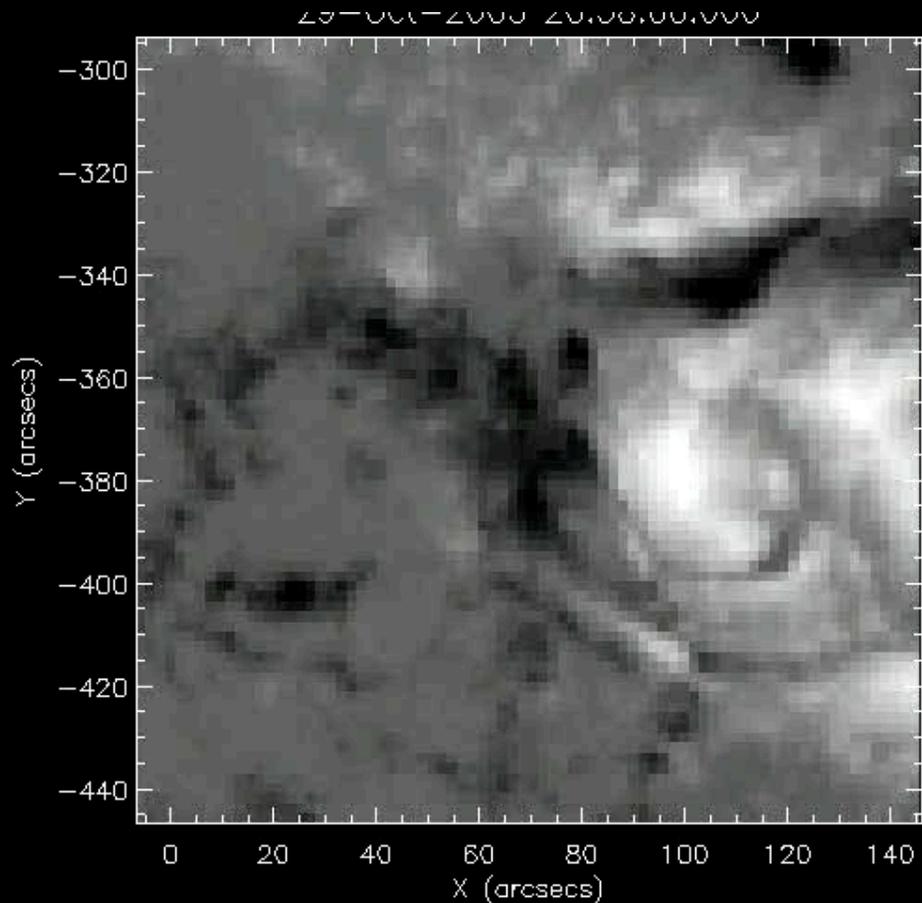


# TRACE-RHESSI movie Oct 29, 2003 Krucker 2004

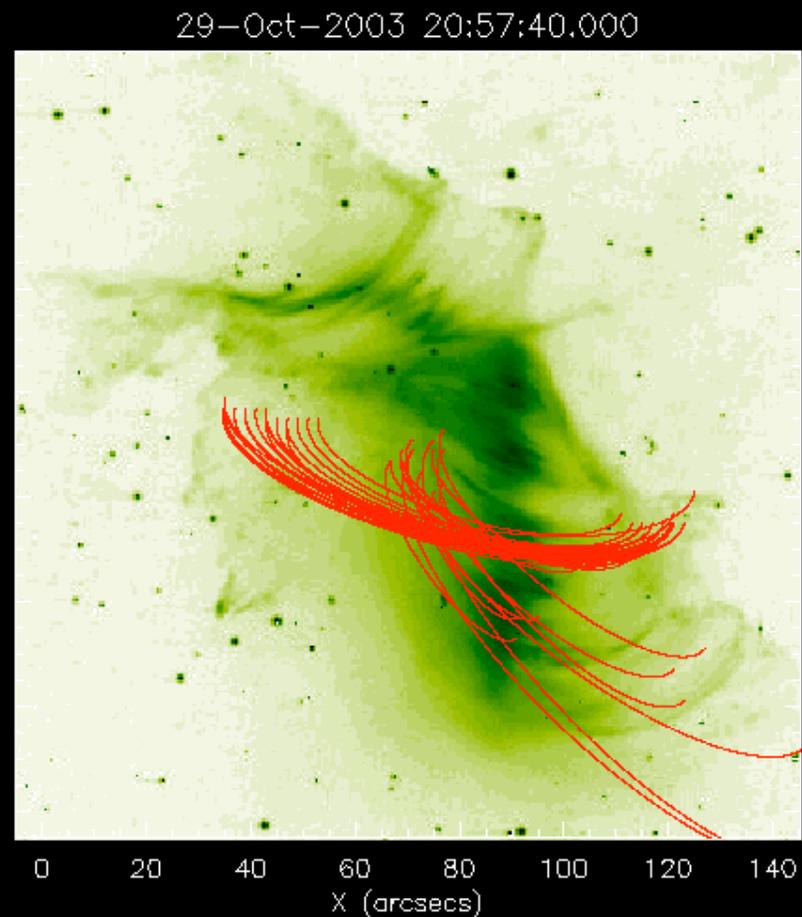
green TRACE images: 195A  
b/w TRACE images: 1600A  
Red RHESSI 10-20 keV  
Blue RHESSI 50-100 keV

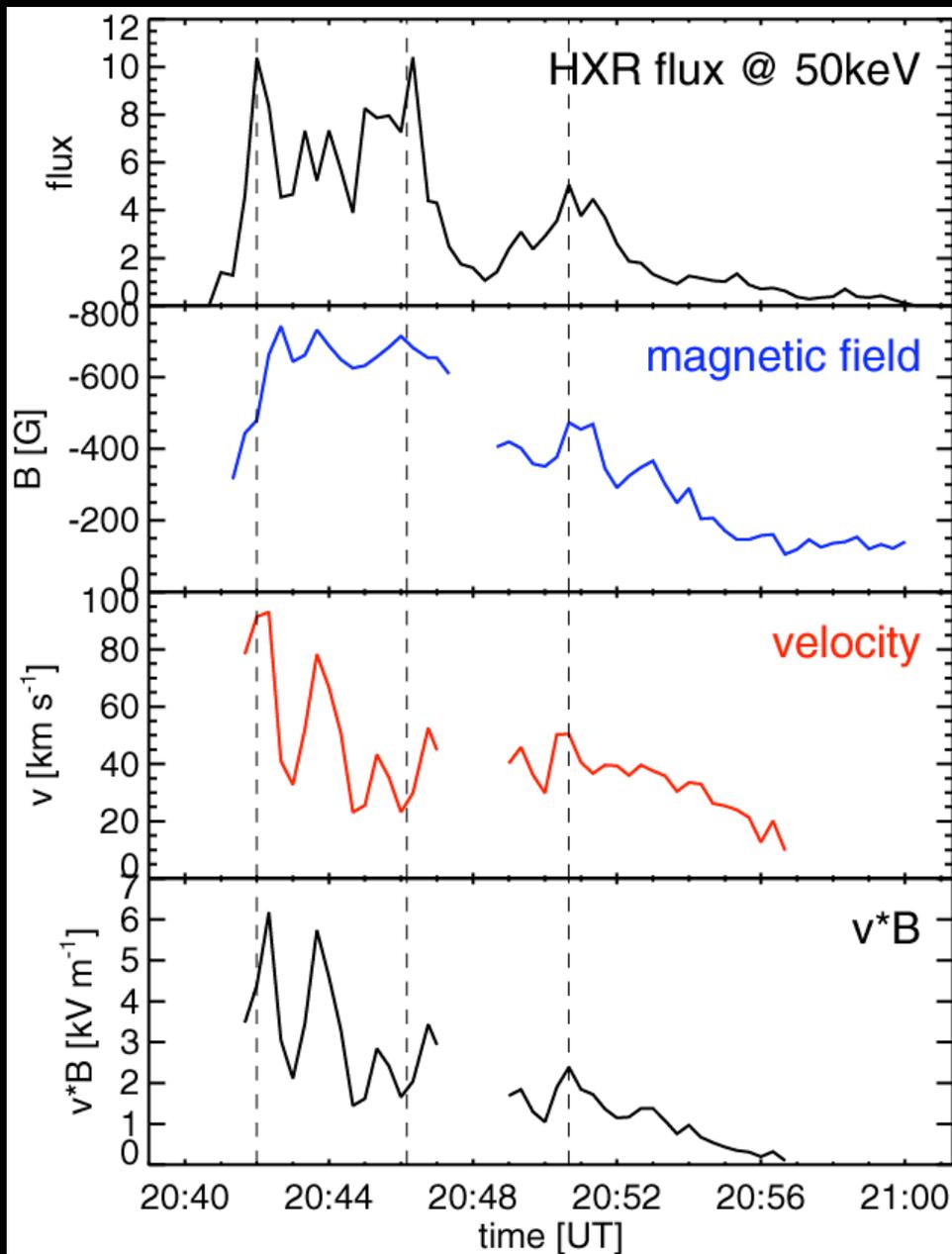
# Movie with connected footpoints (Krucker & Lin 2004)

## MDI Magnetograph



## TRACE w/semicircles connecting RHESSI footpoints

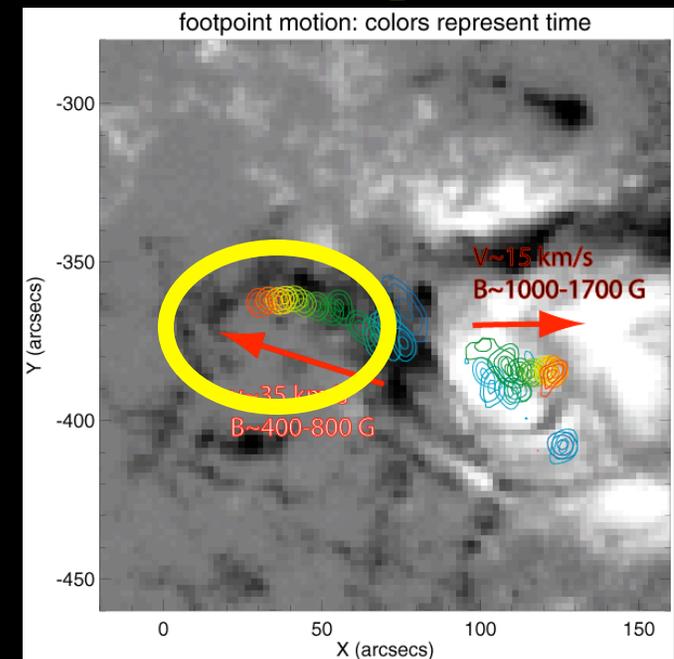




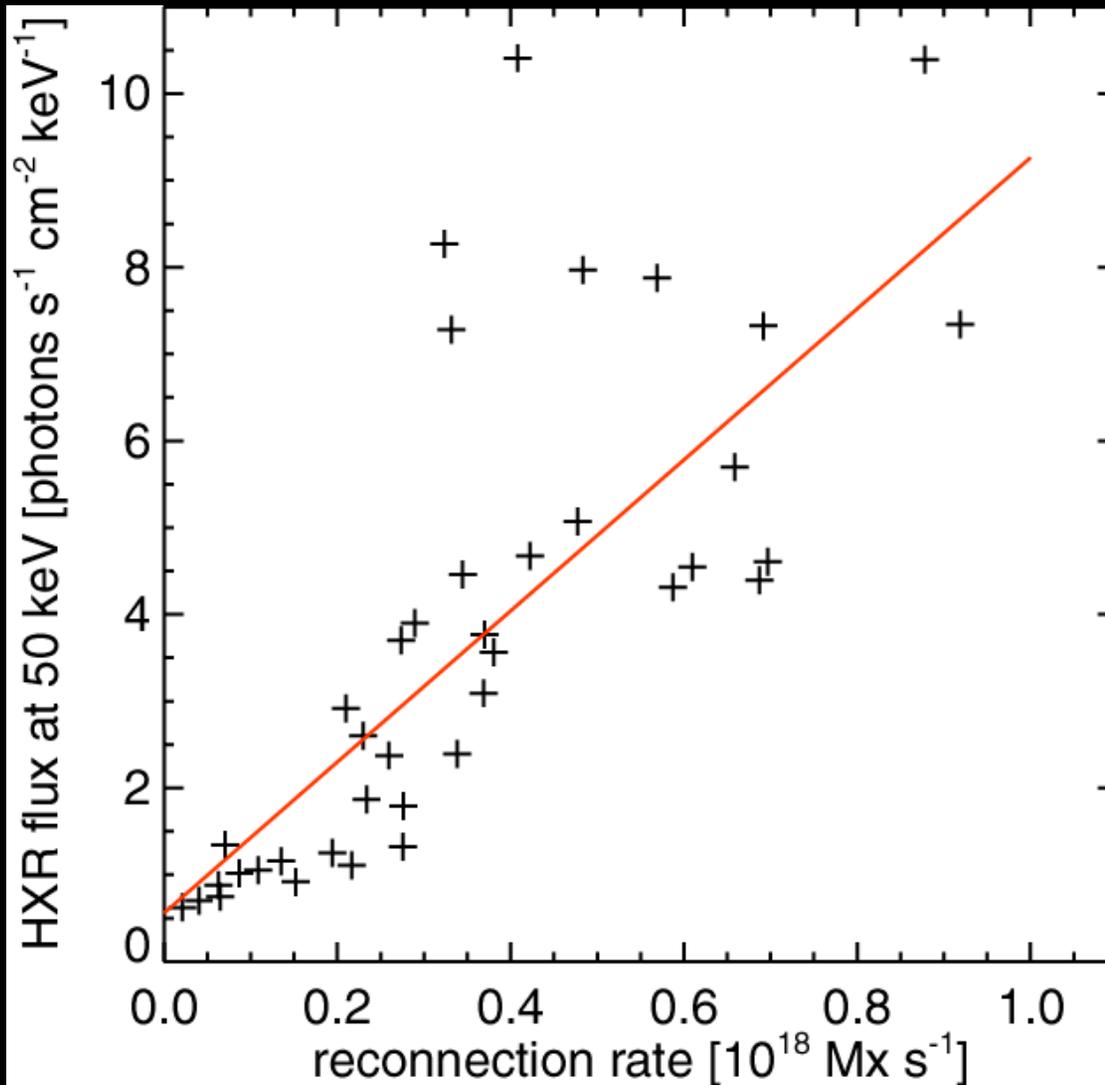
HXR flux and footpoint motion.

Initial peaks show complex HXR source structure => velocity is hard to determine

Second phase has simpler structure (2 footpoints)



# Reconnection rate and HXR flux



Reconnection rate

$$d\Phi/dt = B v a$$

$$\sim 10^{18} \text{ Mx/s}$$

$$\Rightarrow E = v B \sim 2 \text{ kV/m}$$

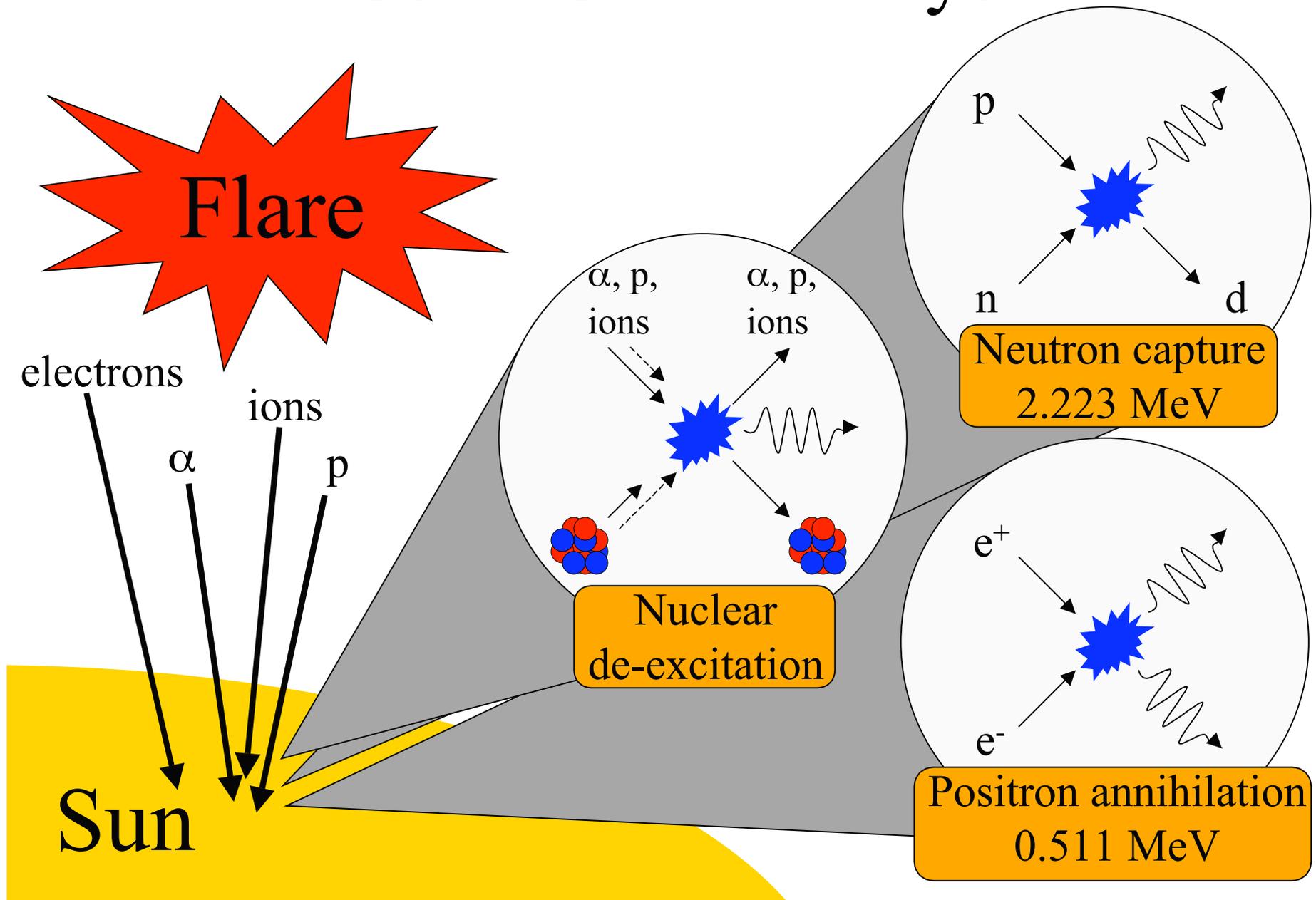
$v$  = velocity

$B$  = magnetic field strength

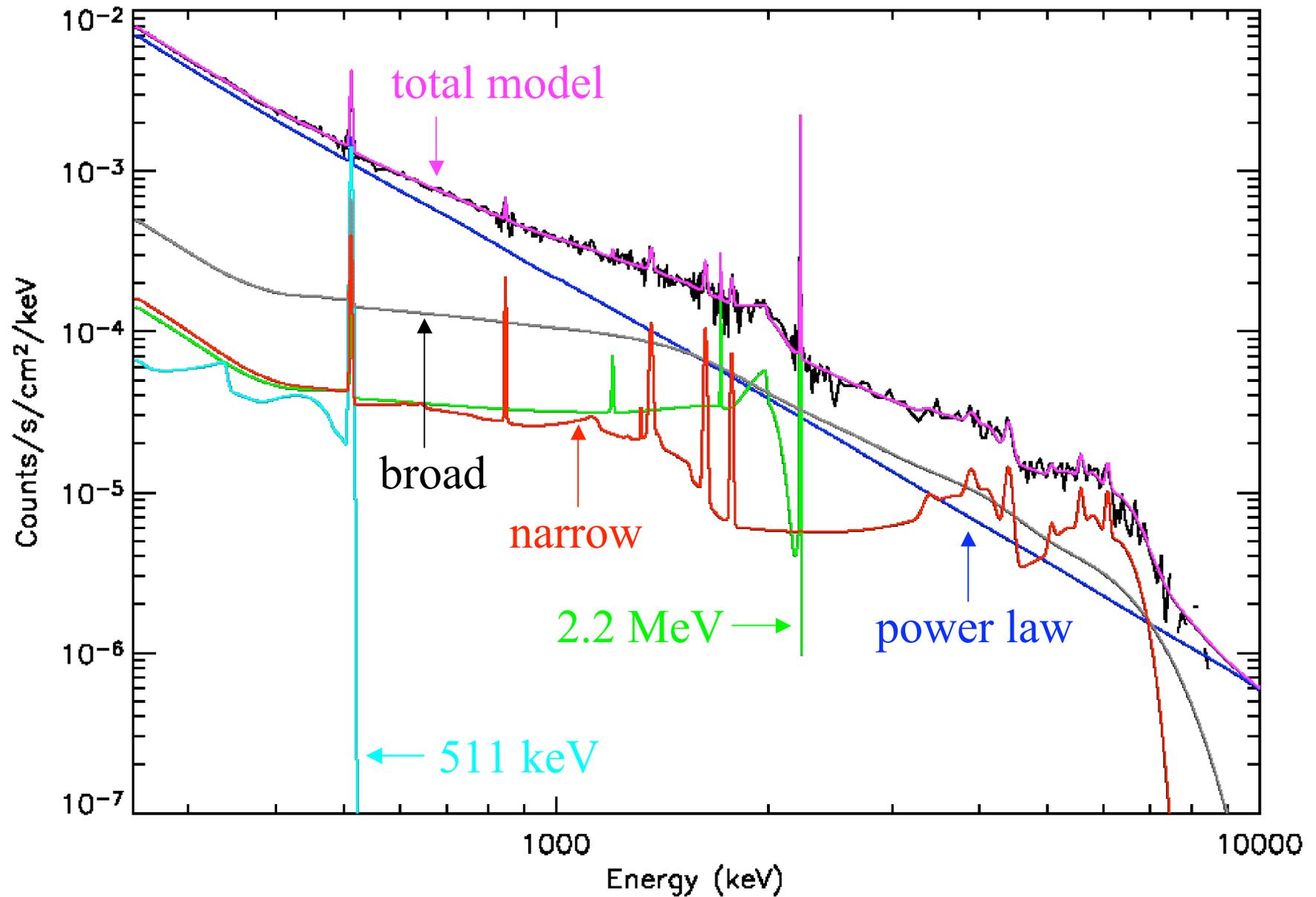
$a$  = footpoint diameter  
 $\sim 2000 \text{ km}$

(Krucker & Lin 2004)

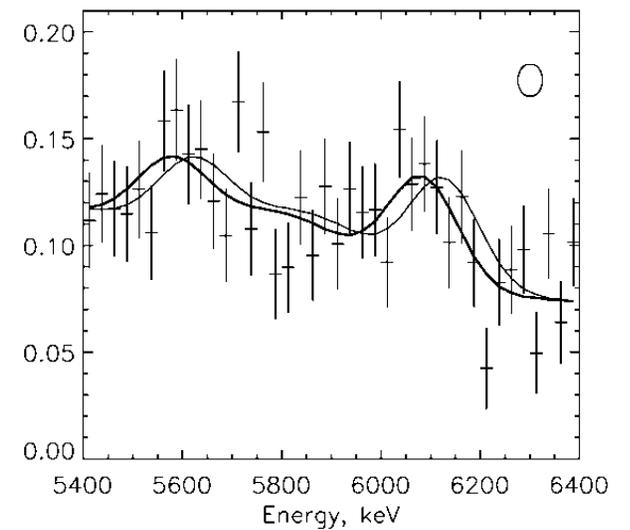
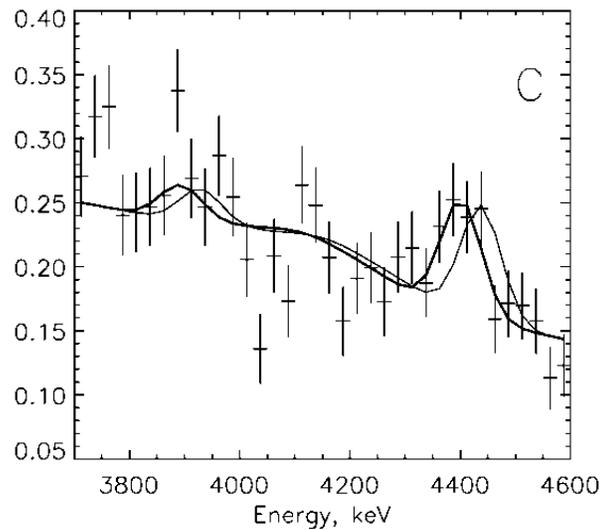
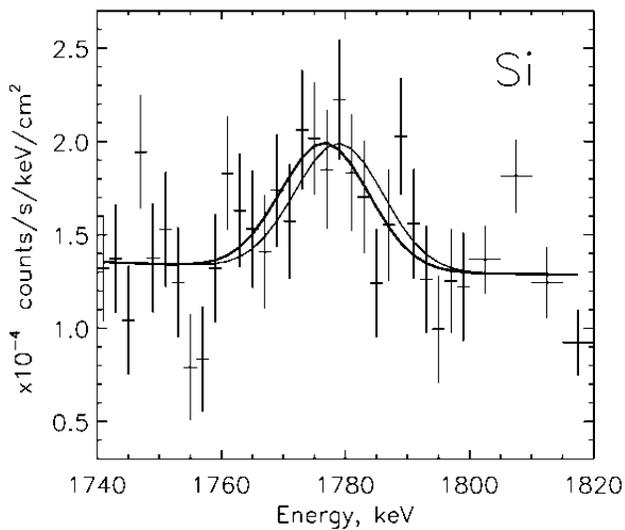
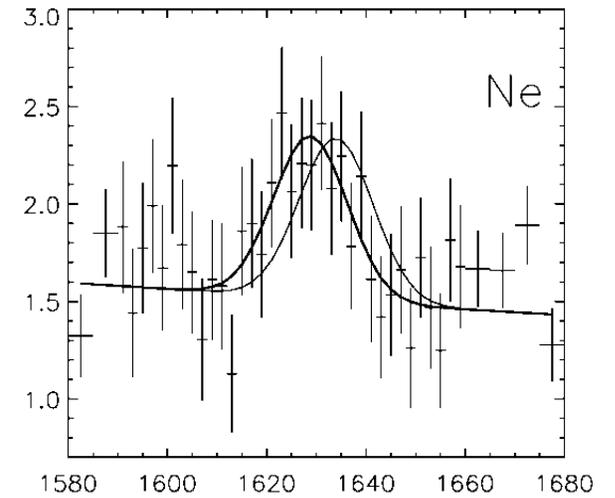
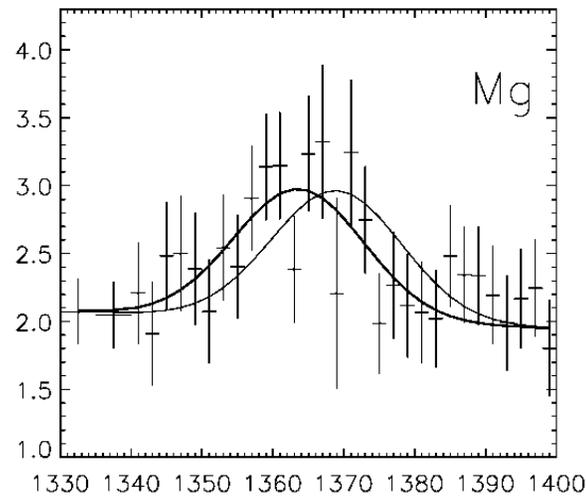
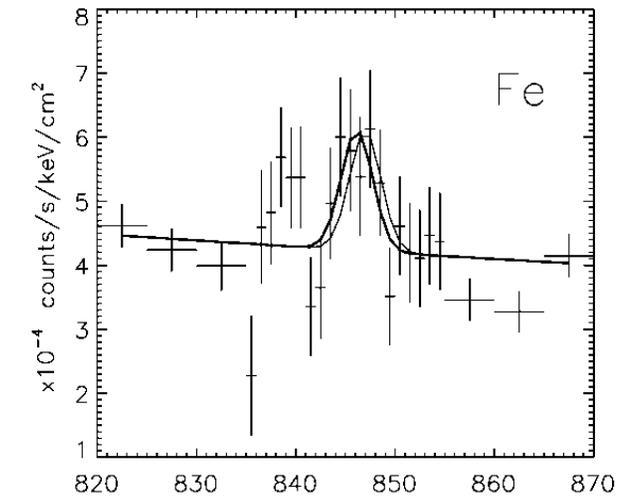
# Solar Gamma Rays



# Spectral Components

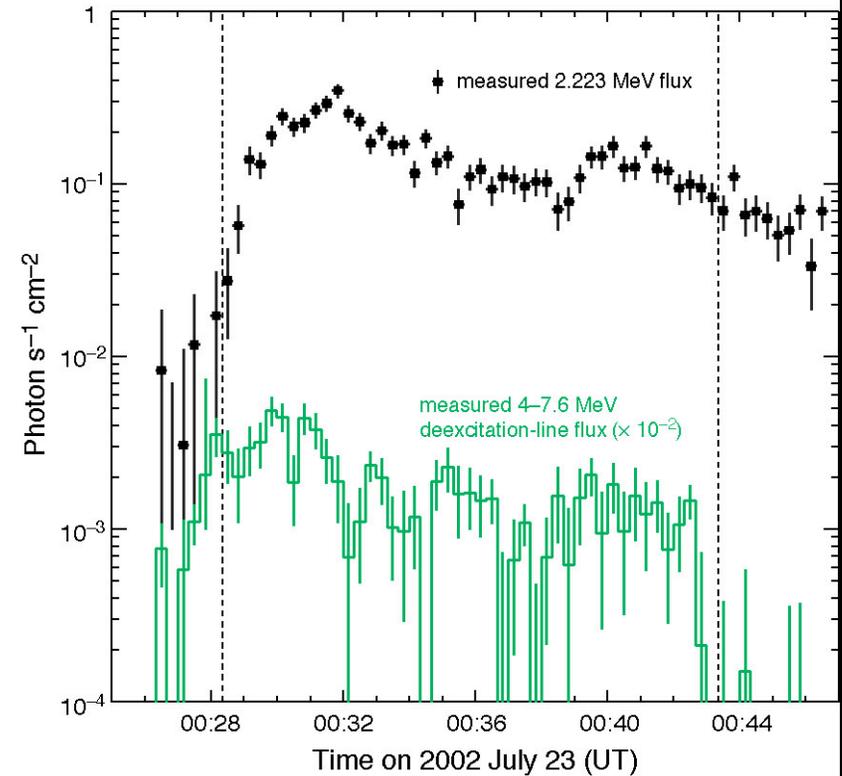
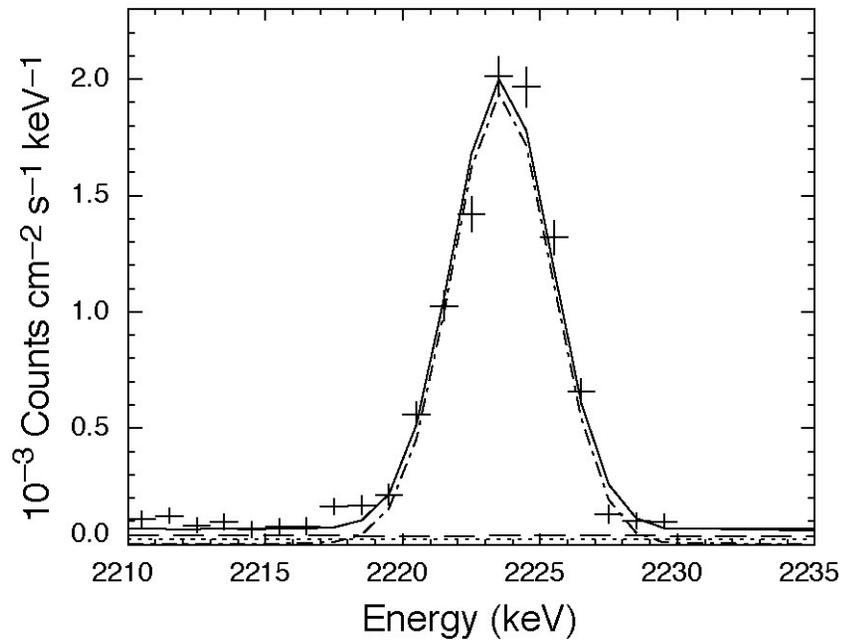


# 23 July 2002 flare nuclear de-excitation lines (Smith et al. 2003)



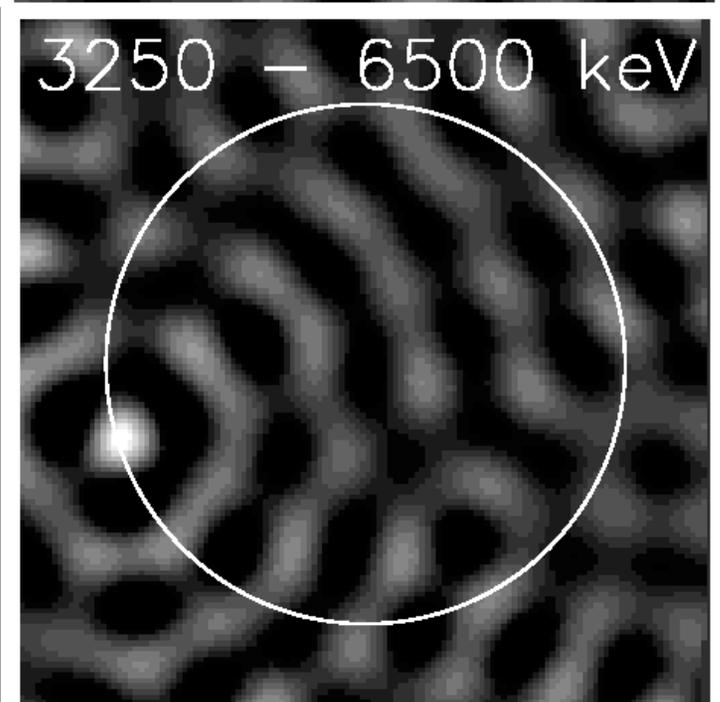
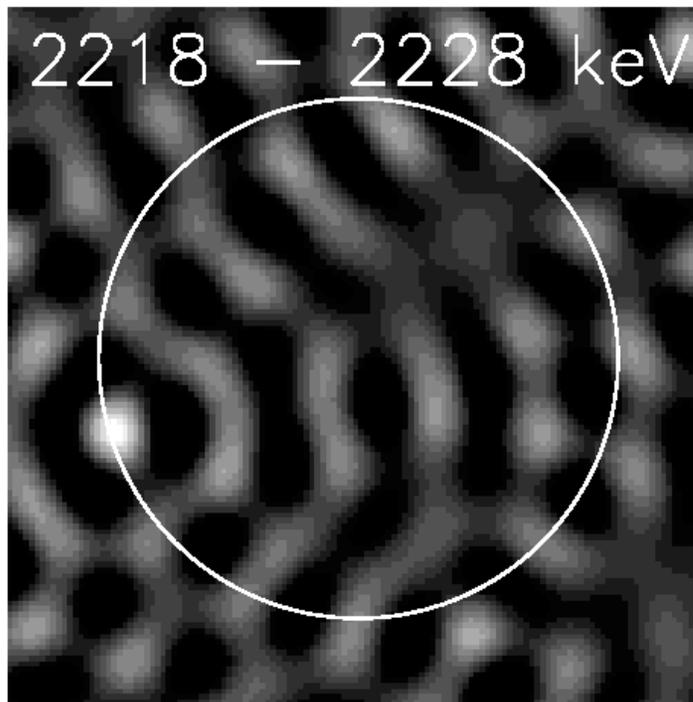
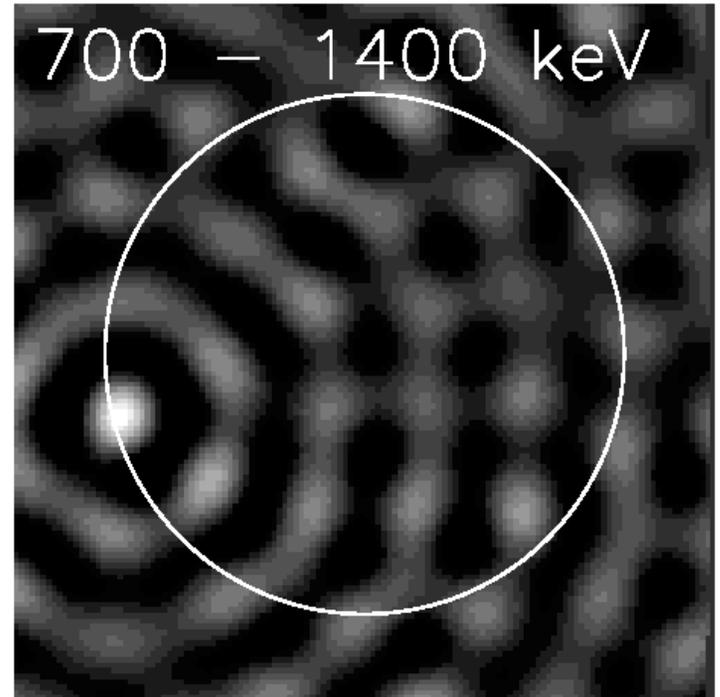
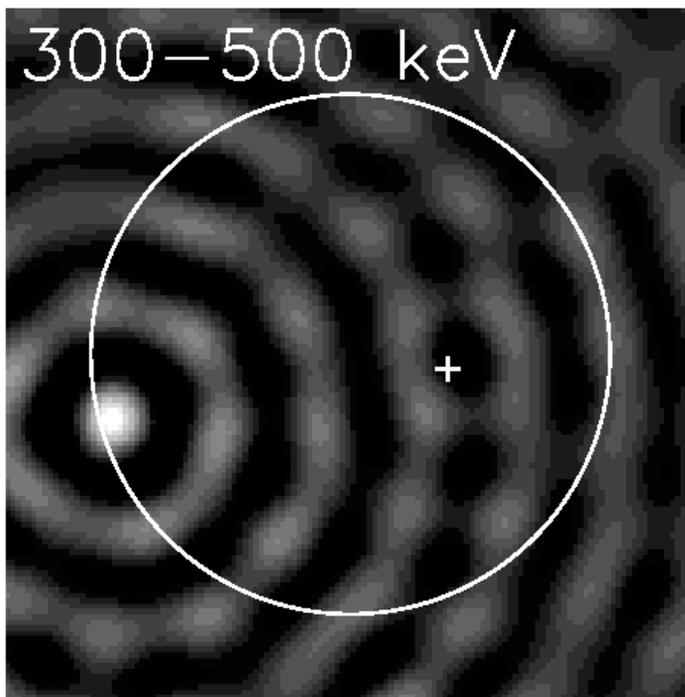
# Murphy et al. 2003

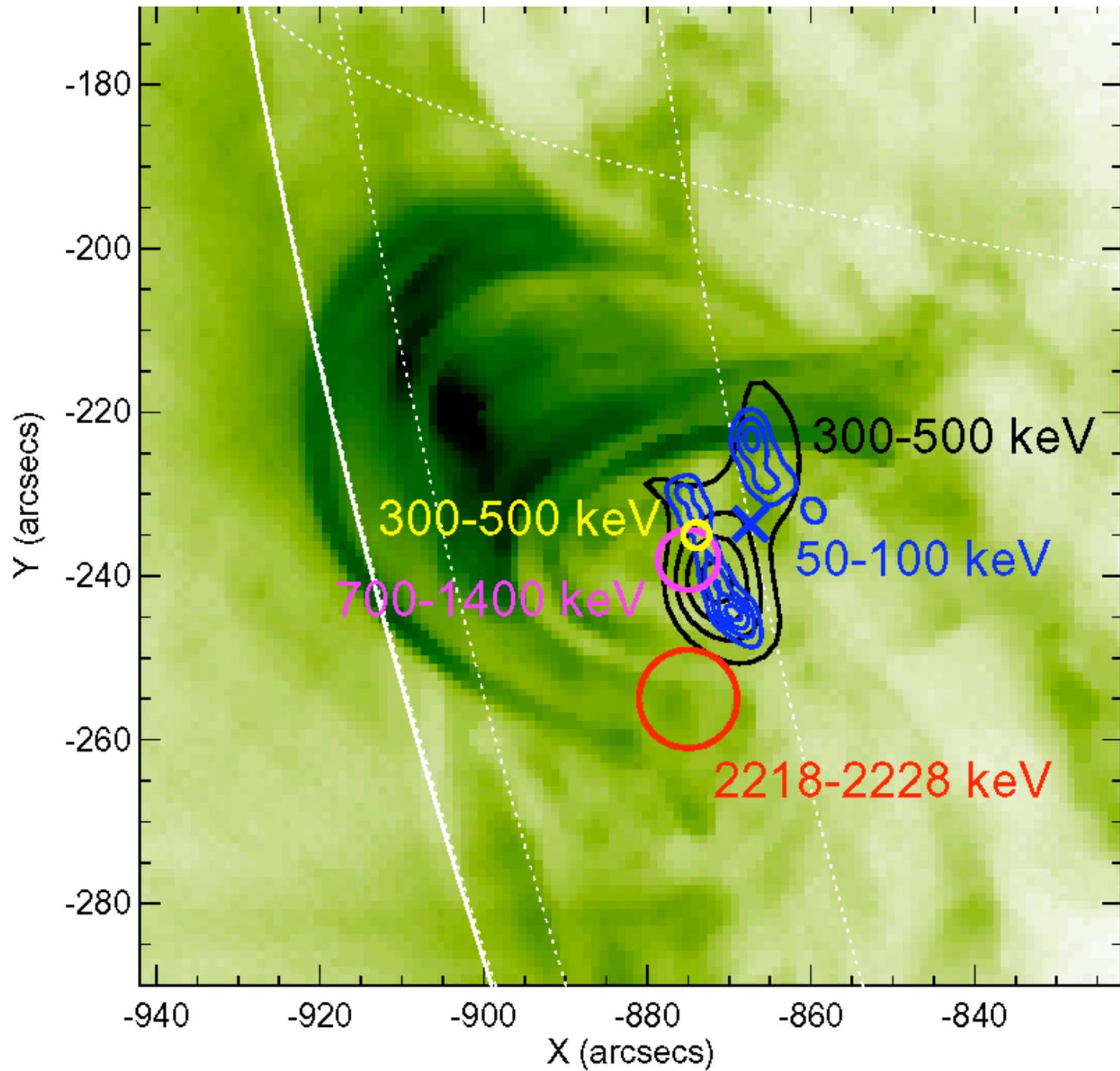
## 2002 July 23 Solar Flare RHESSI Neutron Capture-Line Observations



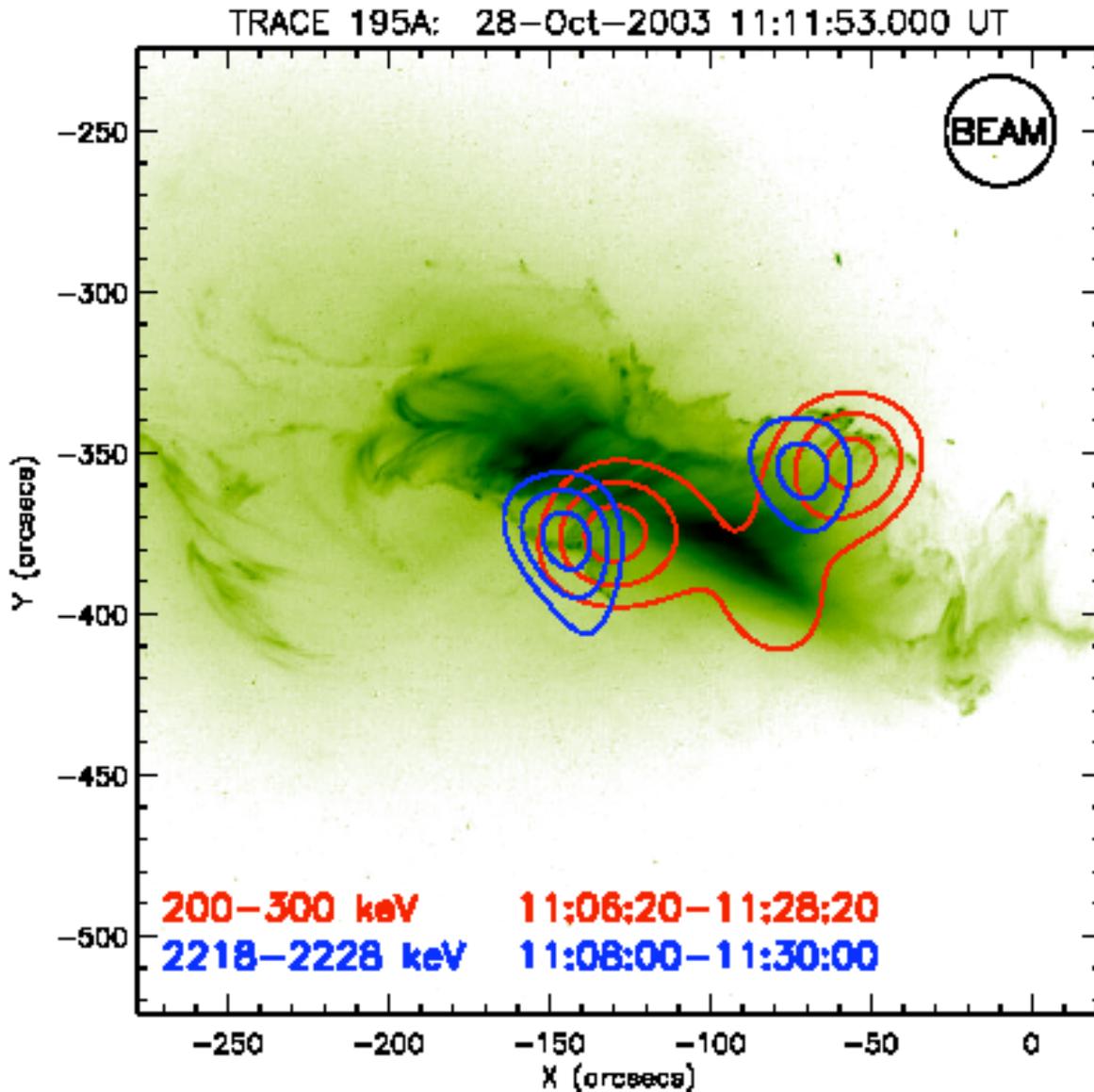
**The time history of the neutron-capture line  
depends on the photospheric  $^3\text{He}/\text{H}$  ratio**

Hurford et  
al., 2003





# Electrons vs protons



200-300 keV HXR  
(electrons) footpoints are  
moving along ribbons

2.2 MeV image (protons)  
is averaged over 22 min,  
delayed by  $\sim 100$  s from  
electrons

## CONCLUSIONS:

Electrons and protons  
both close to ribbon, but  
separated by  $\sim 10^4$  km

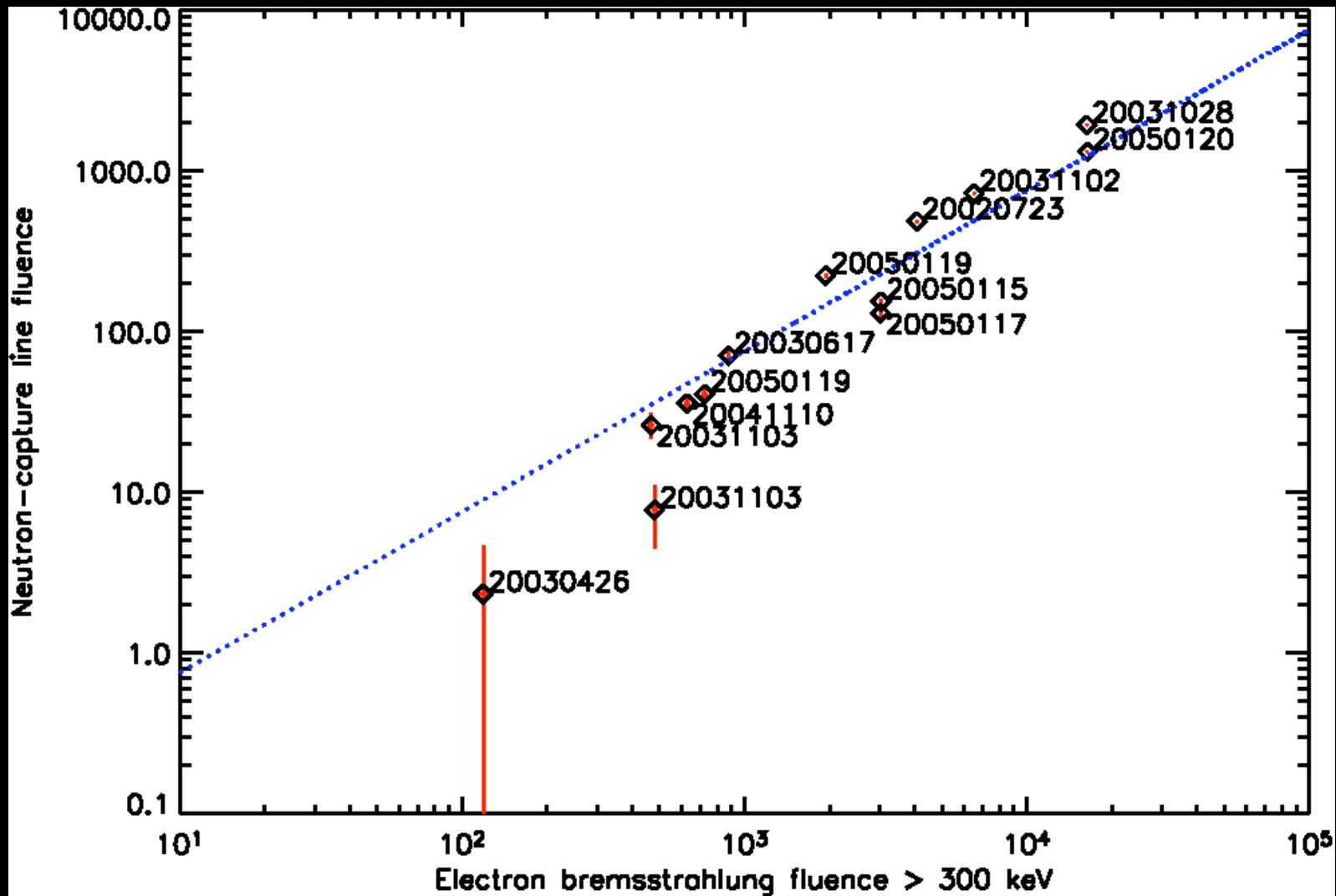
# RHESSI Gamma-Ray Flares



Ramaty High Energy  
Solar Spectroscopic  
Imager (RHESSI)

2002 July 23	X4.8
2003 June 17	M6.9
2003 October 28	X17
2003 October 29	X10
2003 November 2	X8.3
2003 November 3	X3.9
2004 November 10	X2.5
2005 January 15	X2.6
2005 January 17	X3.8
2005 January 19	X1.3
2005 January 20	X7.1

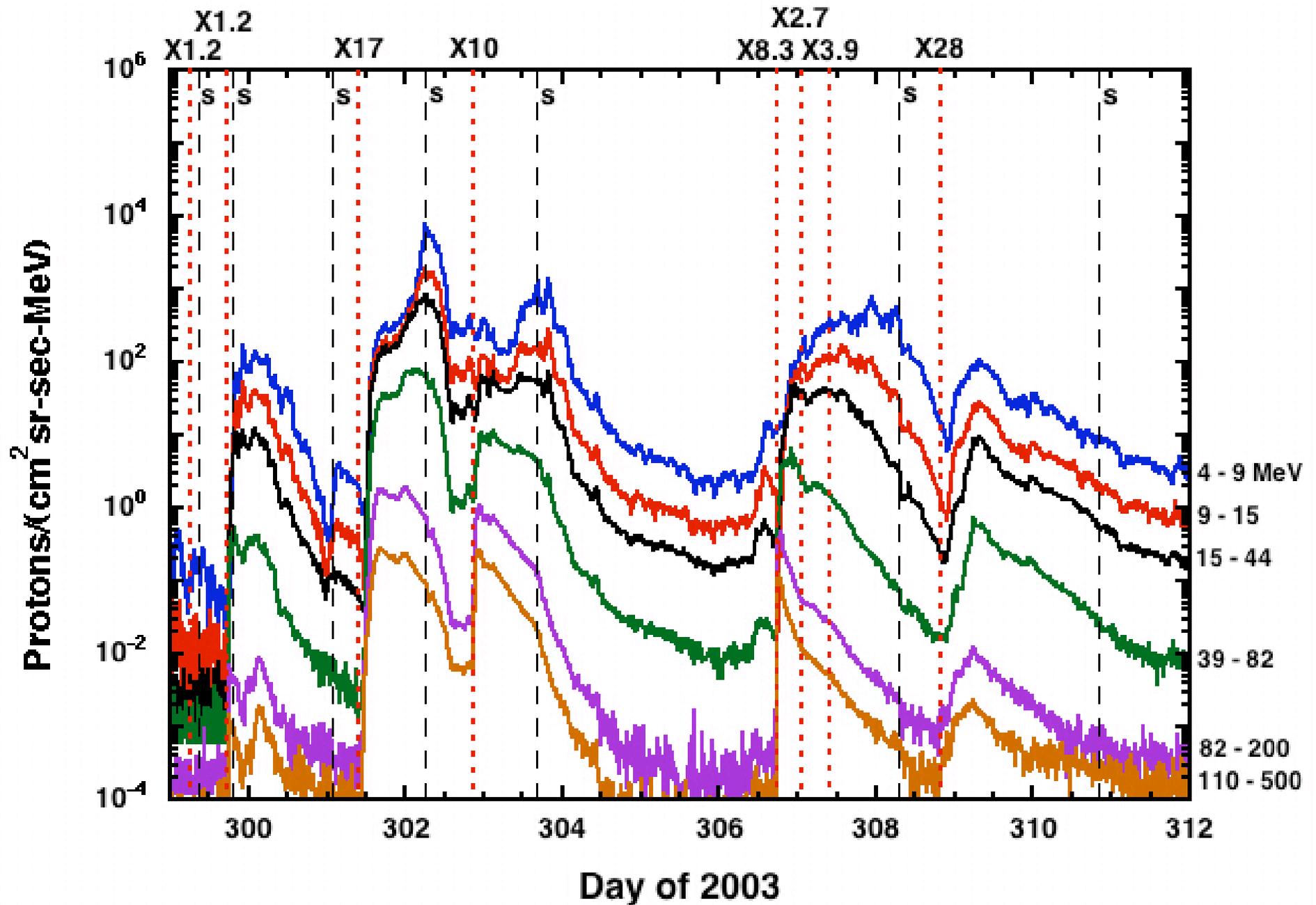
# After correction for limb darkening



## Large (L)SEP events

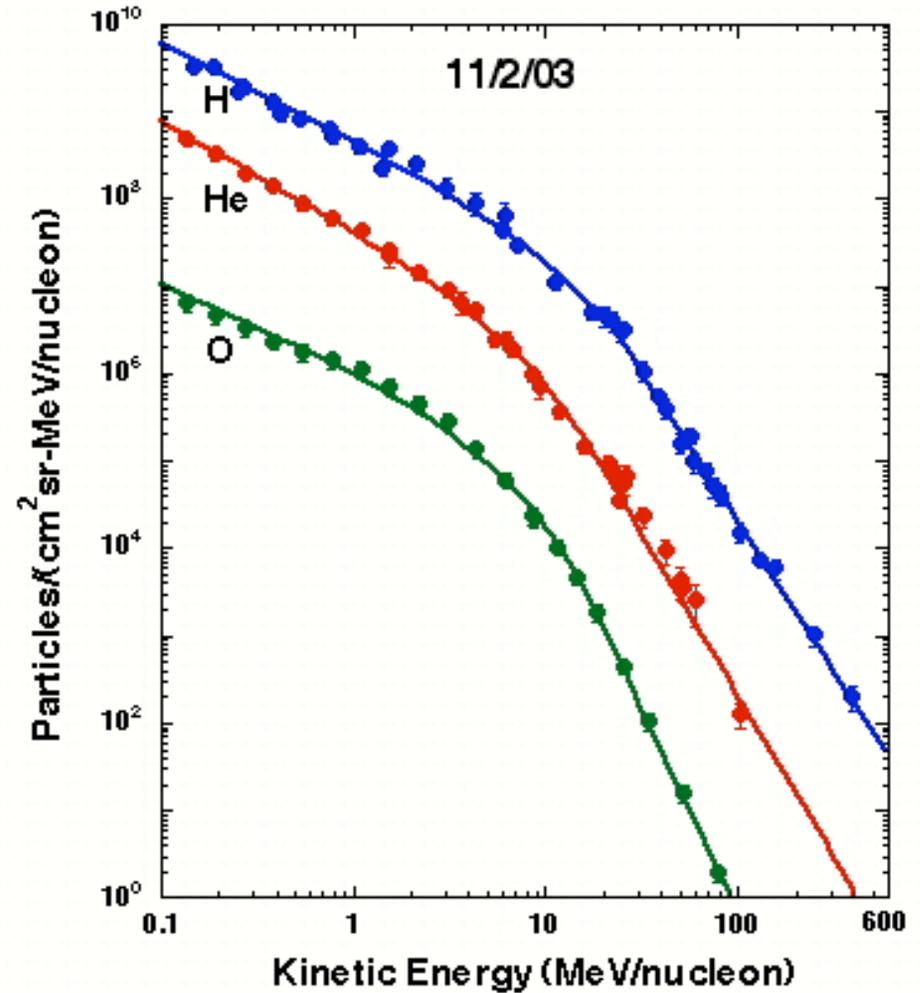
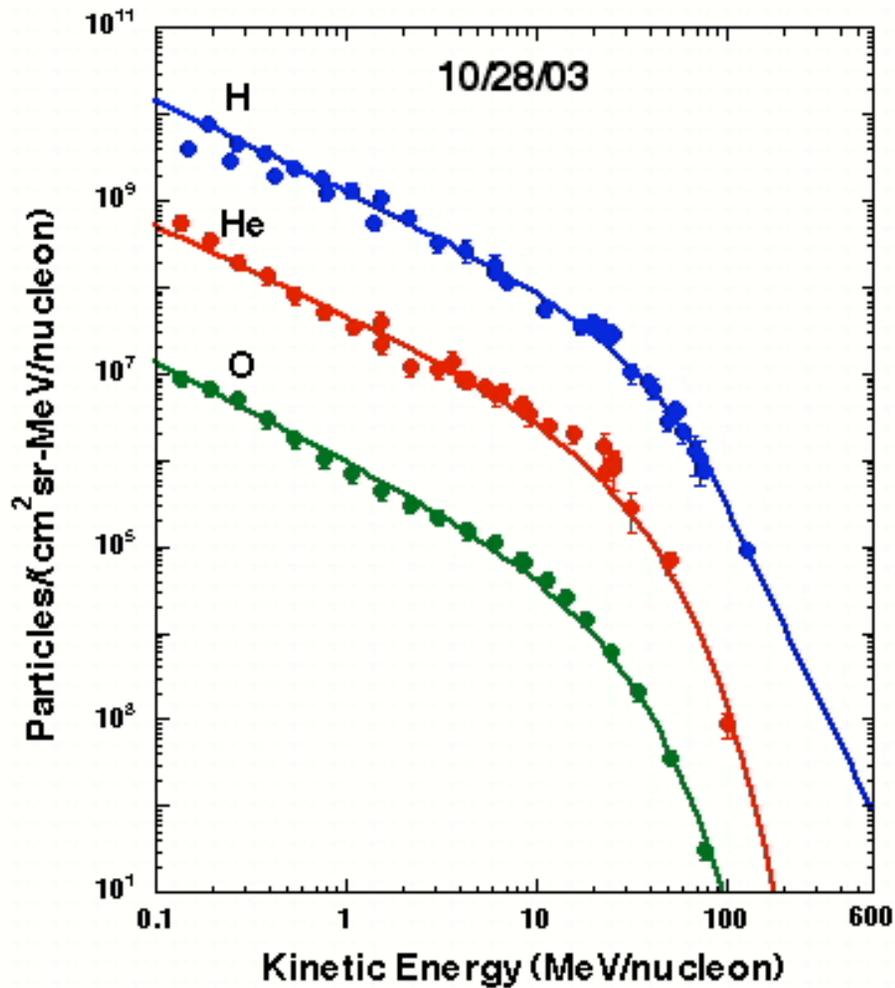
- *tens/year at solar maximum*
- *dominated by:*
  - *>10 MeV **protons** (small e/p ratio)*
  - *Normal coronal composition (?)*
  - *Normal coronal charge states (?)*
- *SEPs seen over  $>\sim 100^\circ$  of solar longitude*
- *associated with:*
  - *Fast Coronal Mass Ejections (CMEs)*
  - *Large flares (but sometimes missing)*
  - *Gradual ( $\sim$ hours) soft X-ray bursts*  
*(also called Gradual SEP events)*

\* Acceleration by fast CME driven shock wave  
in inner heliosphere,  $\sim 2-40$  solar radii

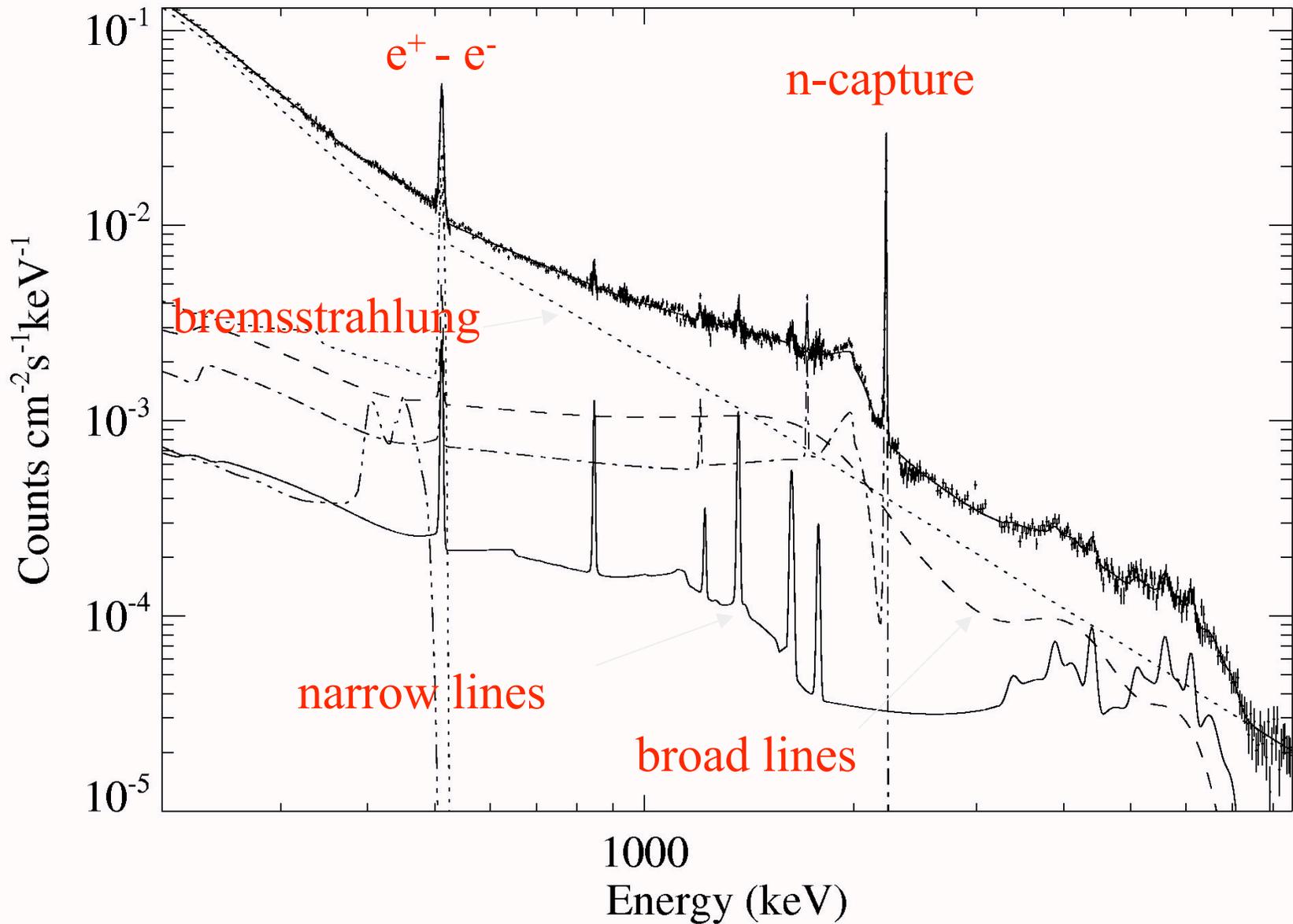


Mewaldt et al 2004

## H, He, and O Spectra at 1 AU from ACE/GOES/SAMPEX



(Mewaldt et al. 2004)

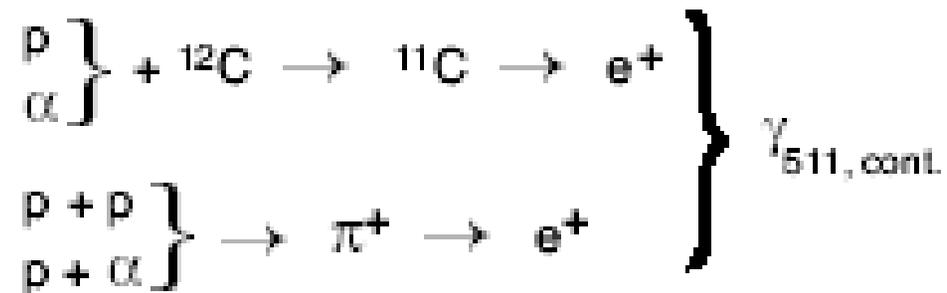


Oct. 28, 2003, RHESSI solar count spectrum from 11:06:20 - 11:10:04  
(Smith et al. 2004, Share et al. 2004)

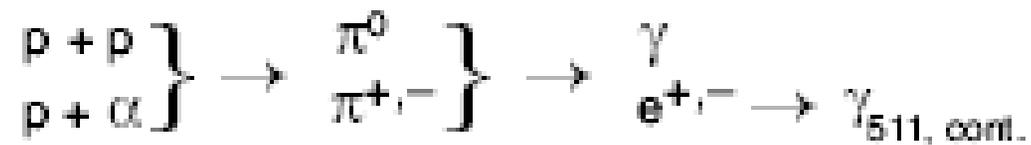
### neutrons



### positrons

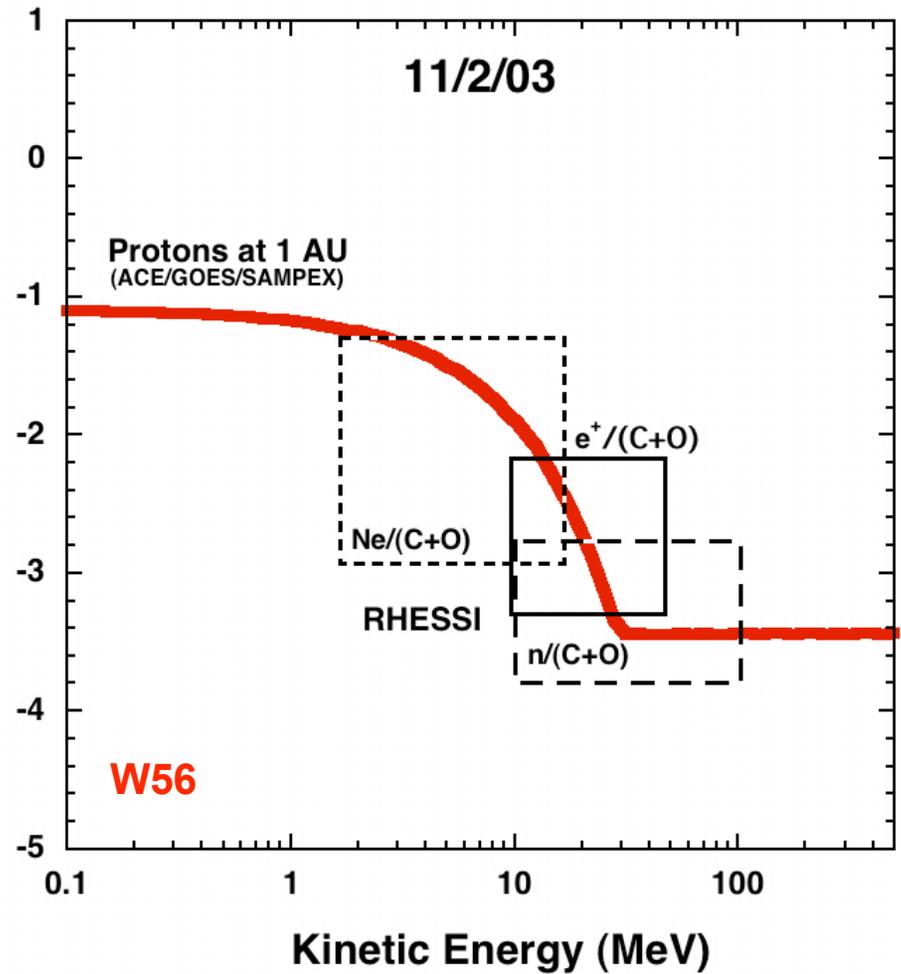
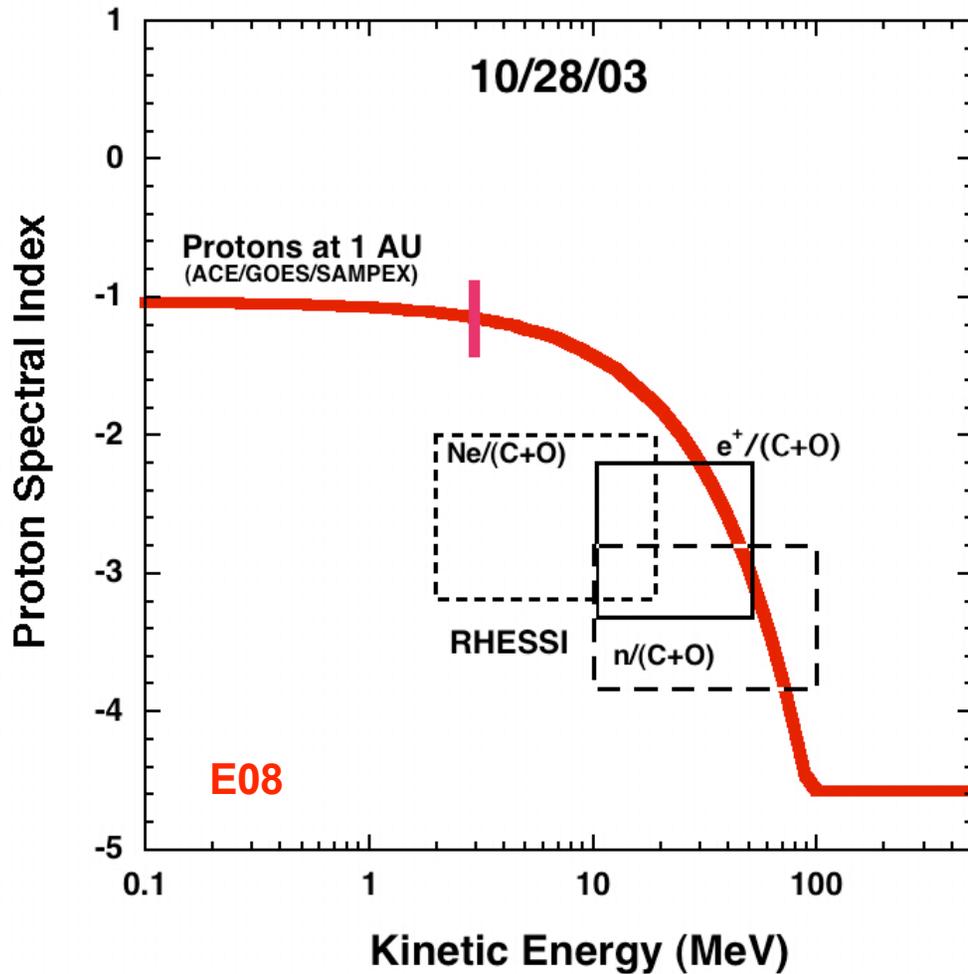


### pions



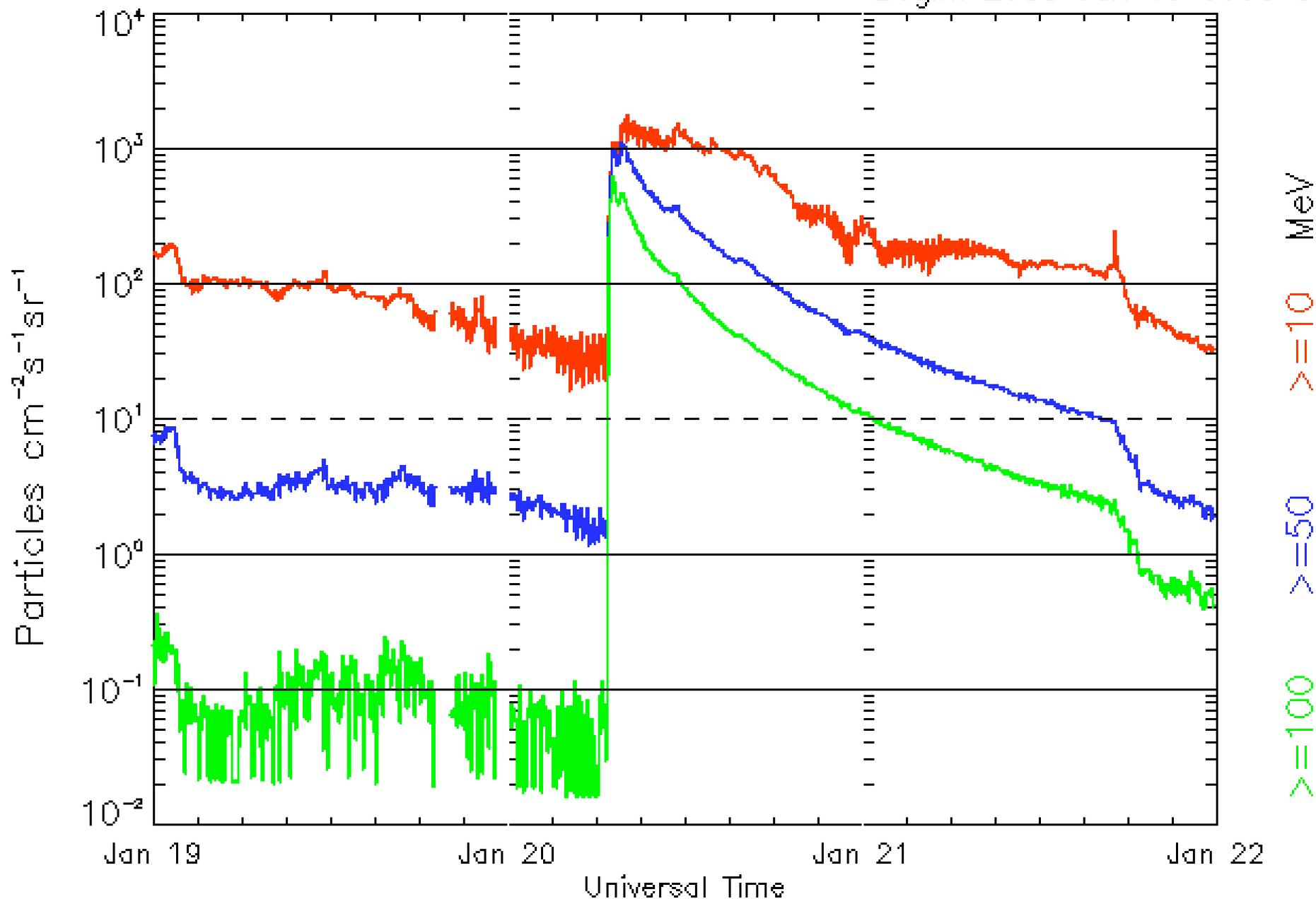
Murphy  
2004

# Comparison of SEP spectral indices from in-situ and $\gamma$ -ray data



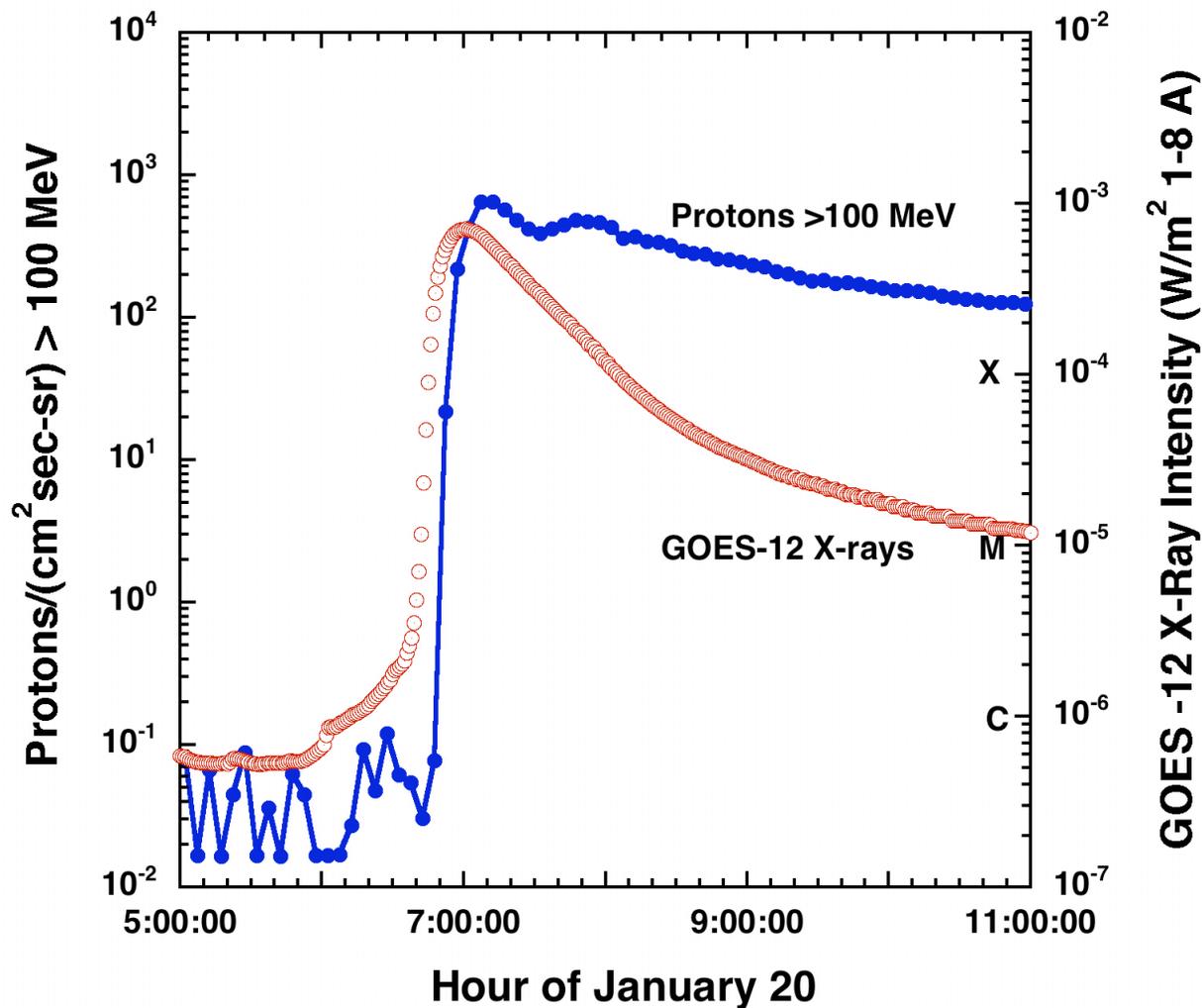
GOES11 Proton Flux (5 minute data)

Begin: 2005 Jan 19 0000 UTC



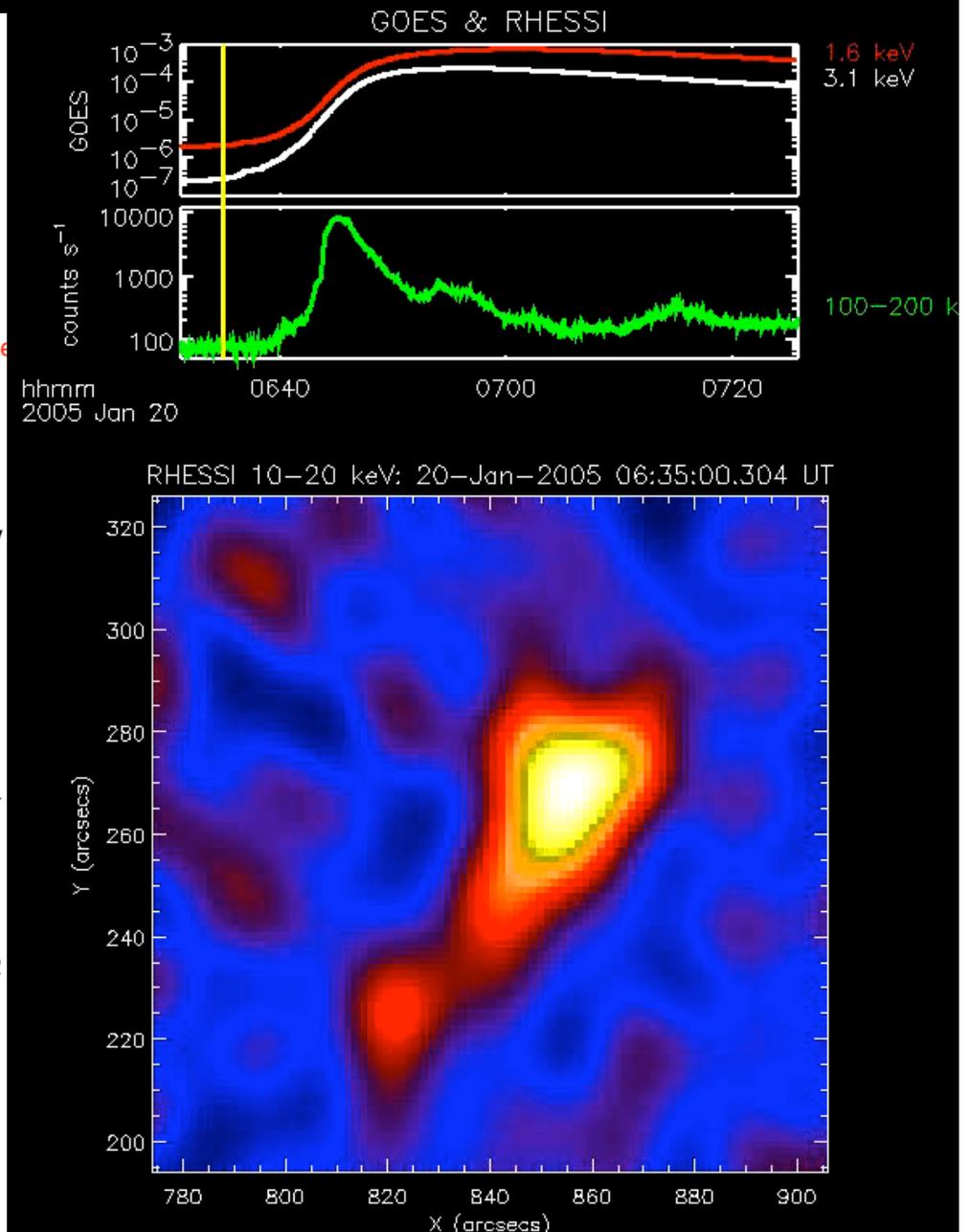
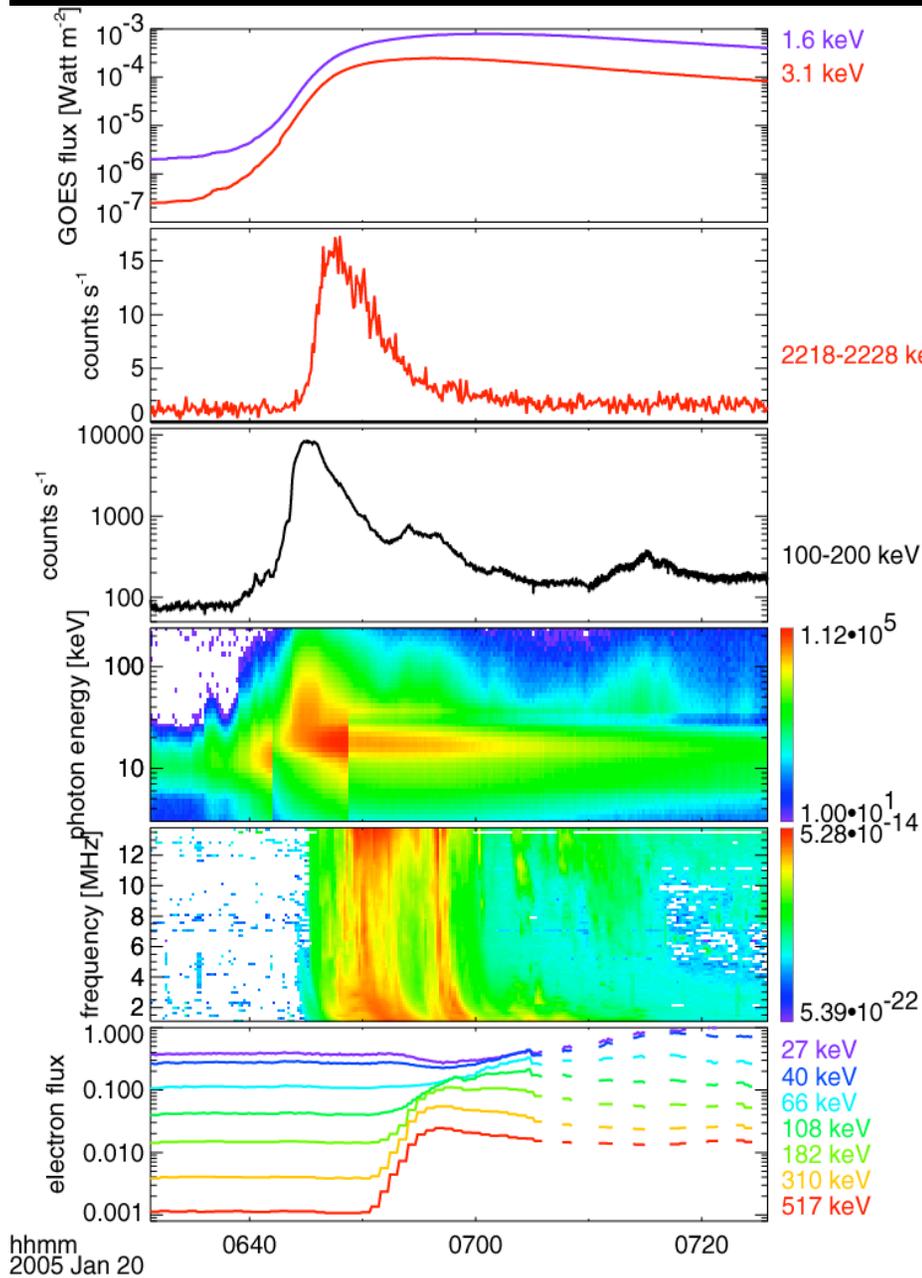
Updated 2005 Jan 21 23:56:05 UTC

NOAA/SEC Boulder, CO USA



In the Jan 20 Event the high energy particle-intensities reach Earth just minutes after the x-rays from the flare (Mewaldt et al 2005)

# Krucker et al 2005

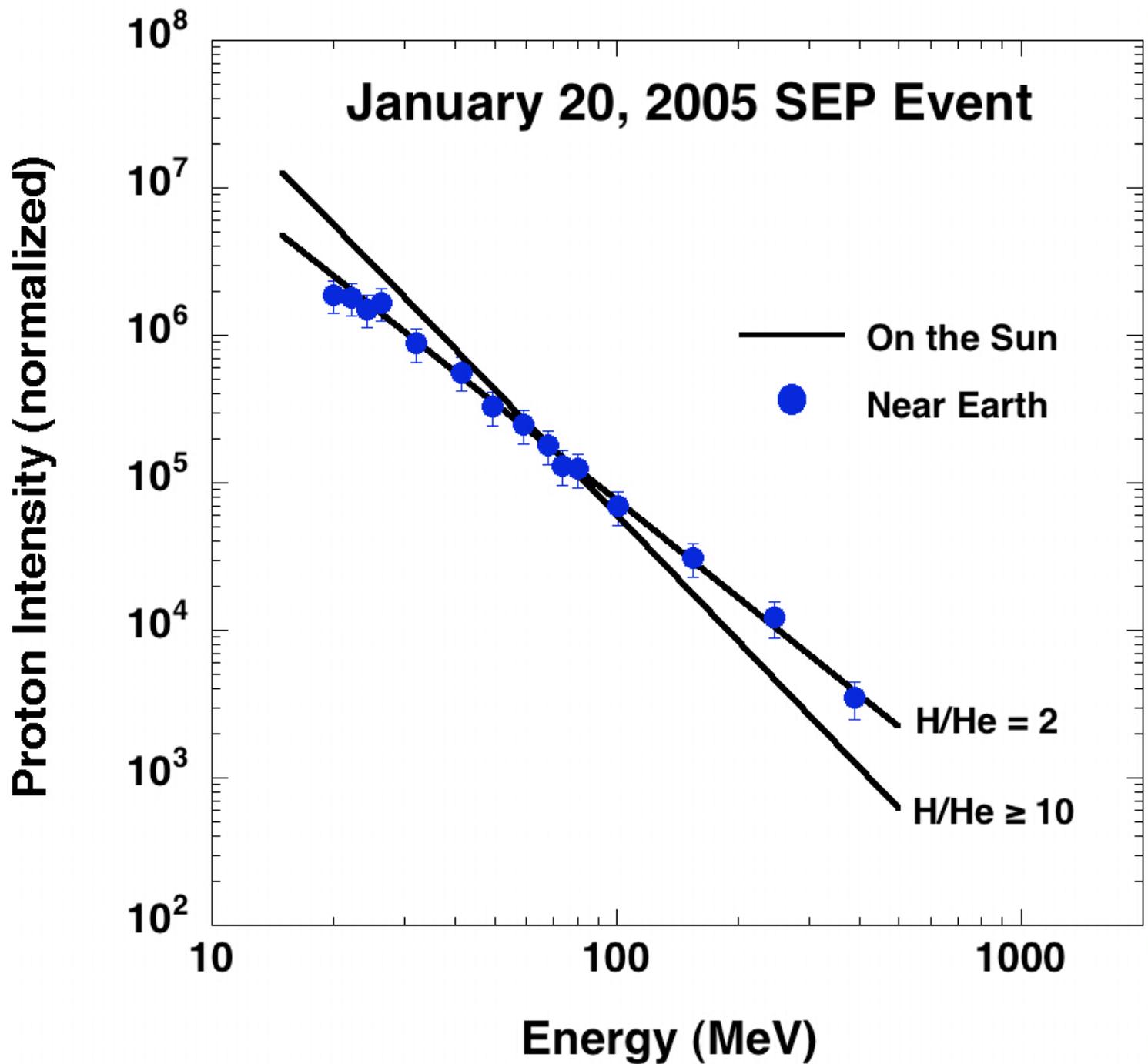


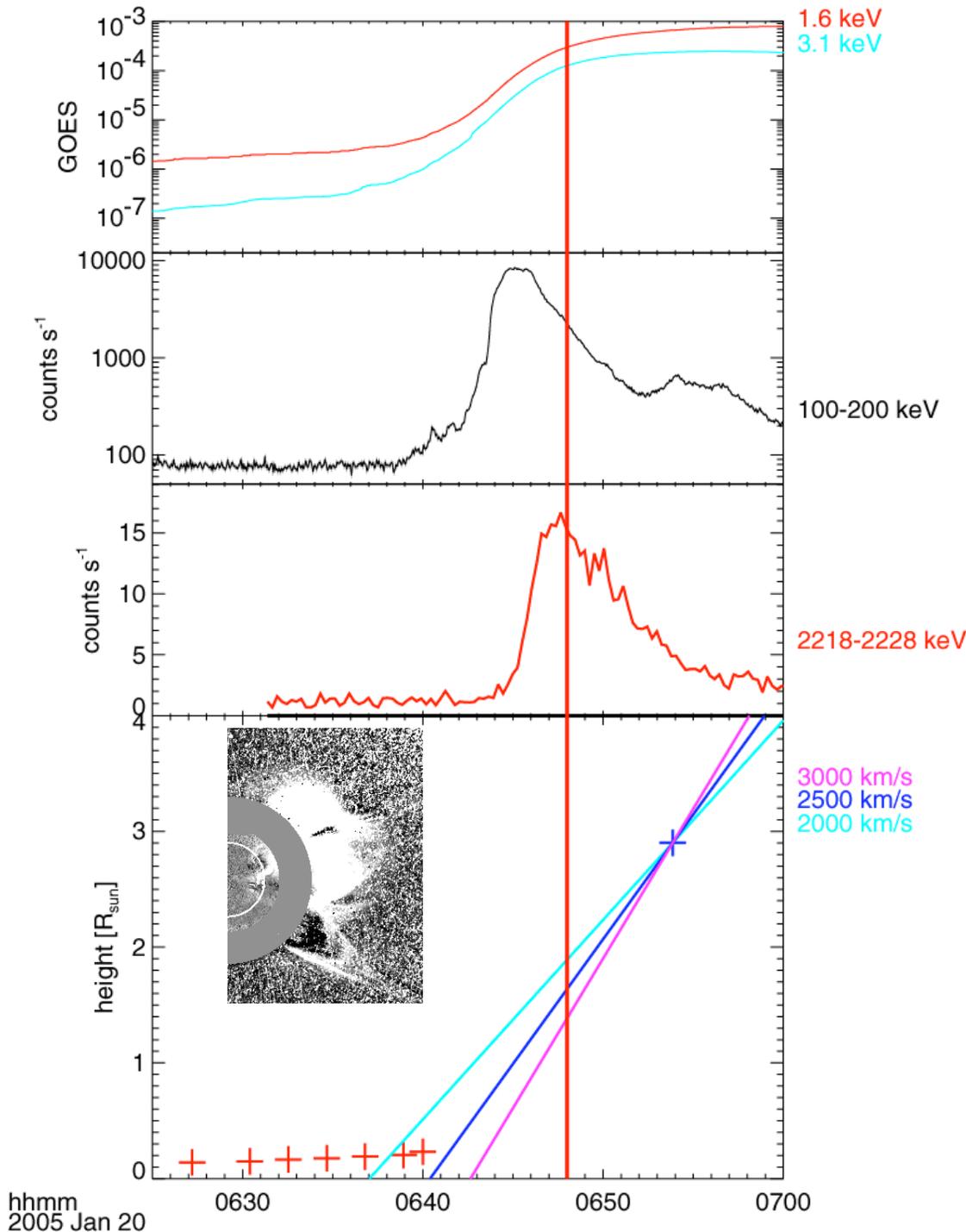
# RHESSI Gamma-ray Spectrum - 20 Jan 05 Flare

1000  
Energy (keV)

Proton  
spectrum:

RHESSI  
Gamma-rays  
(lines)  
vs  
SEPs at 1AU  
(blue points)





## Timing

**Red vertical line (06:48UT):**  
Solar release time assuming first  
arriving particles travel at  $v=c$   
along  $L=1.2$  AU

HXR peak at 06:45:00UT

**2.2 MeV peak at 06:47:30UT**

06:54UT: CME at  $\sim 3$  R<sub>sun</sub>

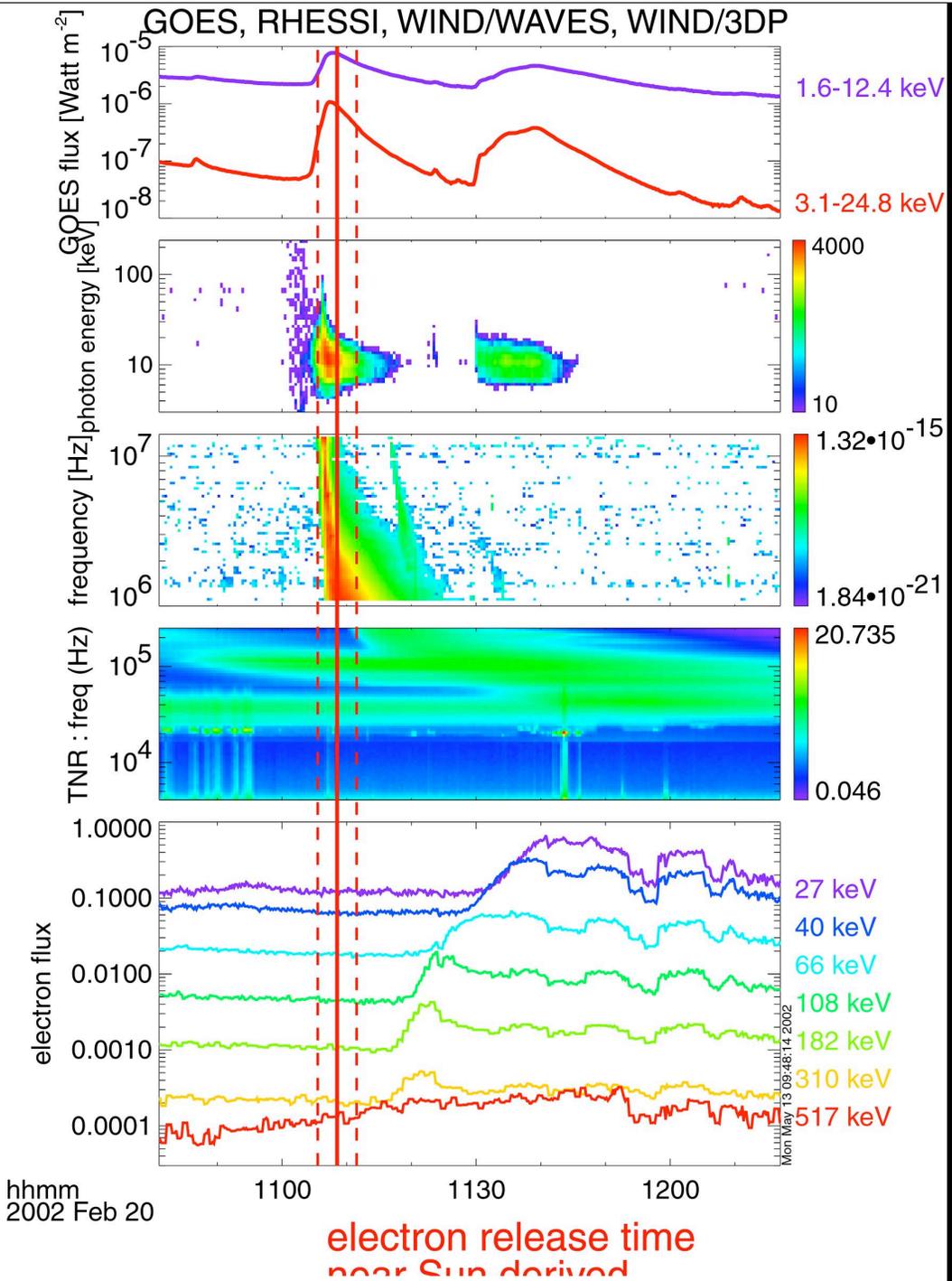
Line: 2500 km/s CME speed

**Red crosses: Rising SXR loops**

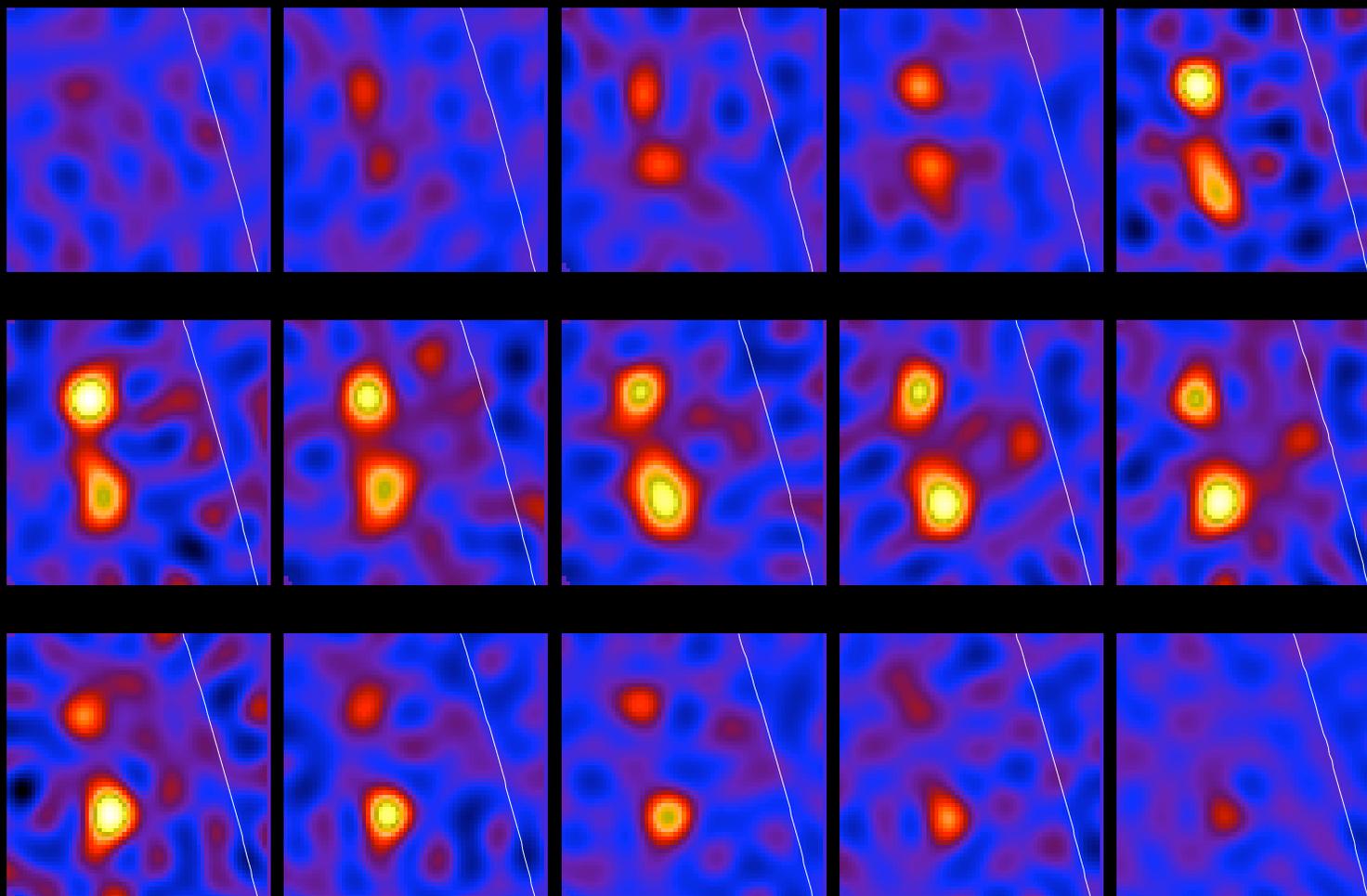
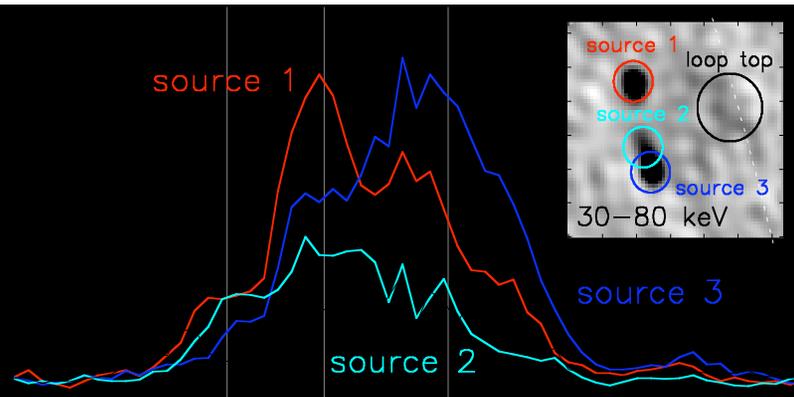
# Electron -<sup>3</sup>He-rich SEP events

- *~1000s/year at solar maximum*
- *dominated by:*
  - **electrons** of *~0.1 (!) to ~100 keV energy*
  - **<sup>3</sup>He** *~10s keV/nuc to ~MeV/nuc*  
*x10-x10<sup>4</sup> (!) enhancements*
  - **heavy nuclei: Fe, Mg, Si, S** *enhancements*
  - *high charge states*
- *associated with:*
  - *small flares/coronal microflares*
  - *Type III radio bursts*
  - *Impulsive soft X-ray bursts (so also called*  
*Impulsive SEP events*)

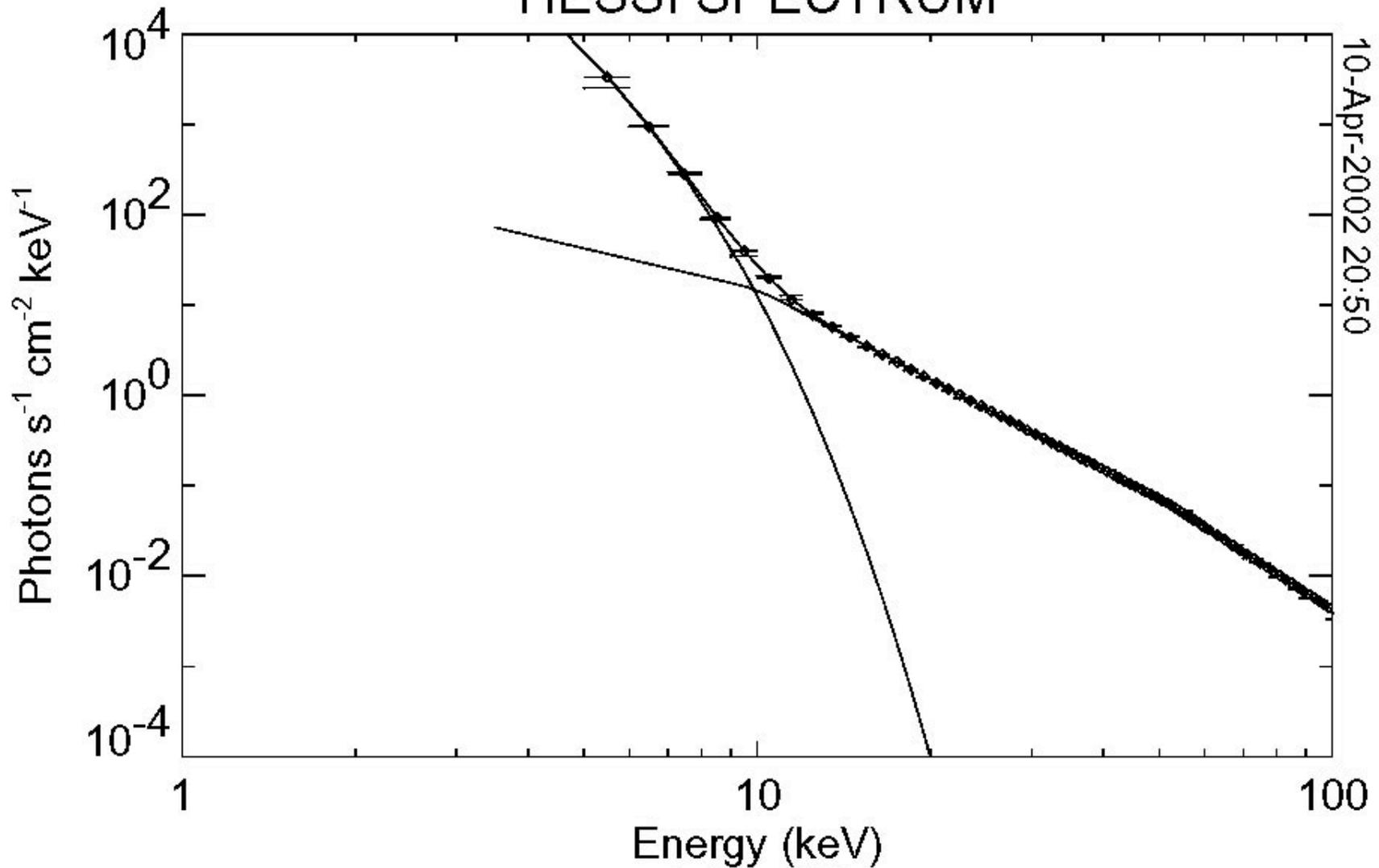
# Krucker and Lin 2002



**30-80 keV**  
**64''x64''**  
**(Krucker and Lin 2002)**



# HESSI SPECTRUM

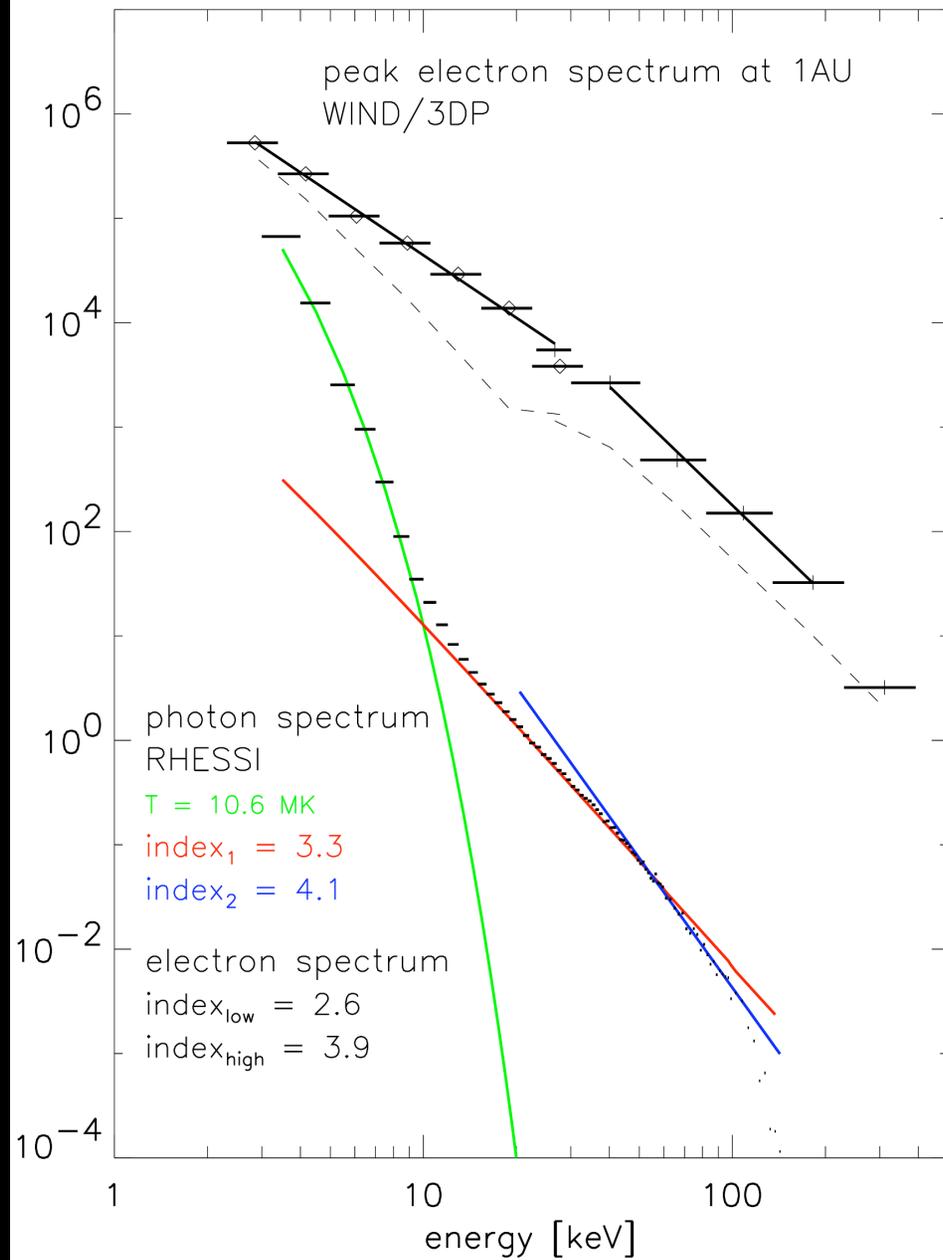


Interval 0

11:06:11.99 - 11:06:24.00

f\_vth\_bpow parameters: 0.4495, 0.9123, 0.07185, 3.319, 52.00, 4.121

FEBRUARY 20, 2002: 11:06:00 – 11:06:40



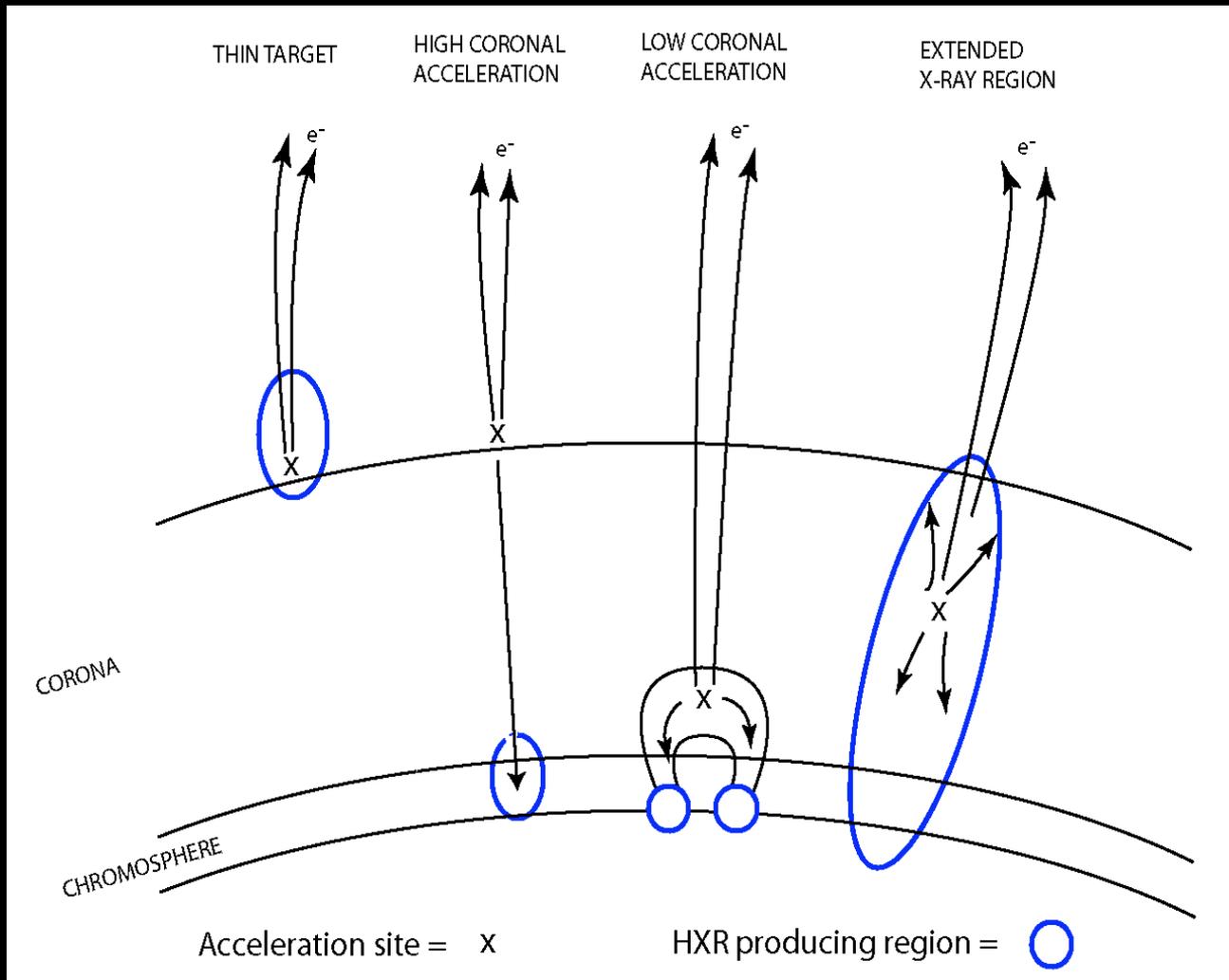
# Different models

1) THIN target

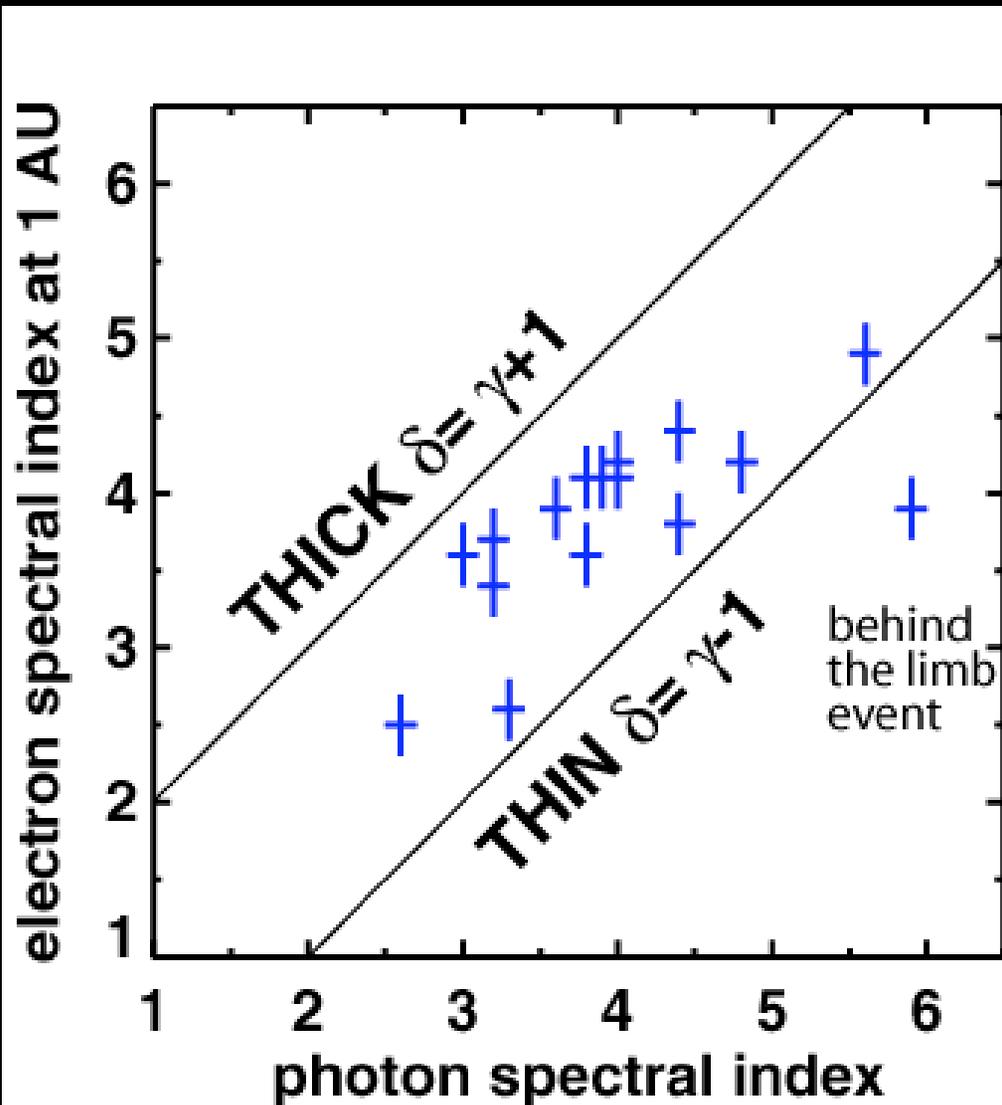
2+3) THICK target

4) mixed case

3) +escape



# Comparing spectra



PHOTON SPECTRA:

Power law fit to HXR spectra averaged over peak

ELECTRON SPECTRA:

Power law fit to peak flux

Assuming power spectra:

THIN:  $\delta = \gamma - 1$

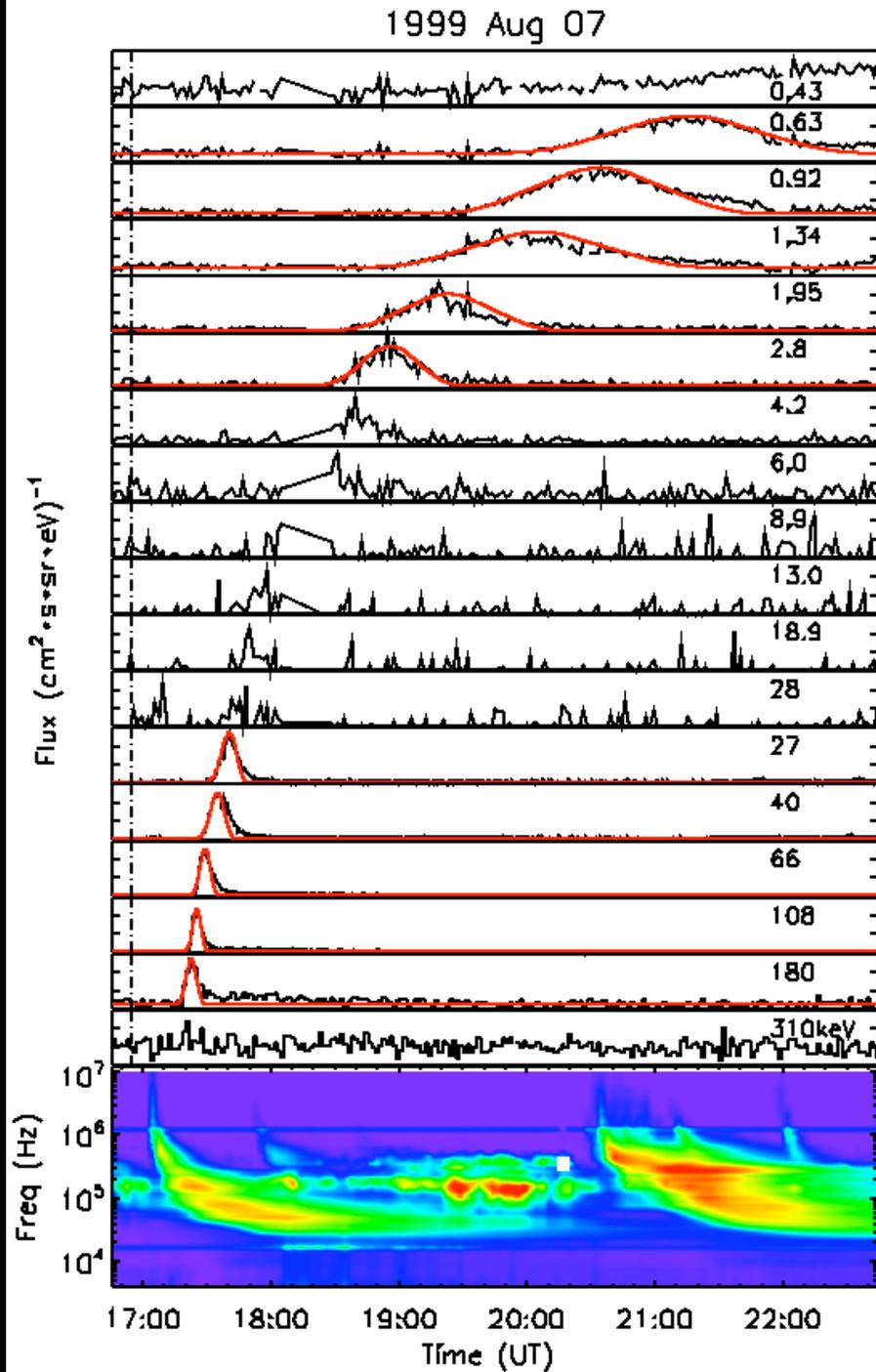
THICK:  $\delta = \gamma + 1$

RESULTS:

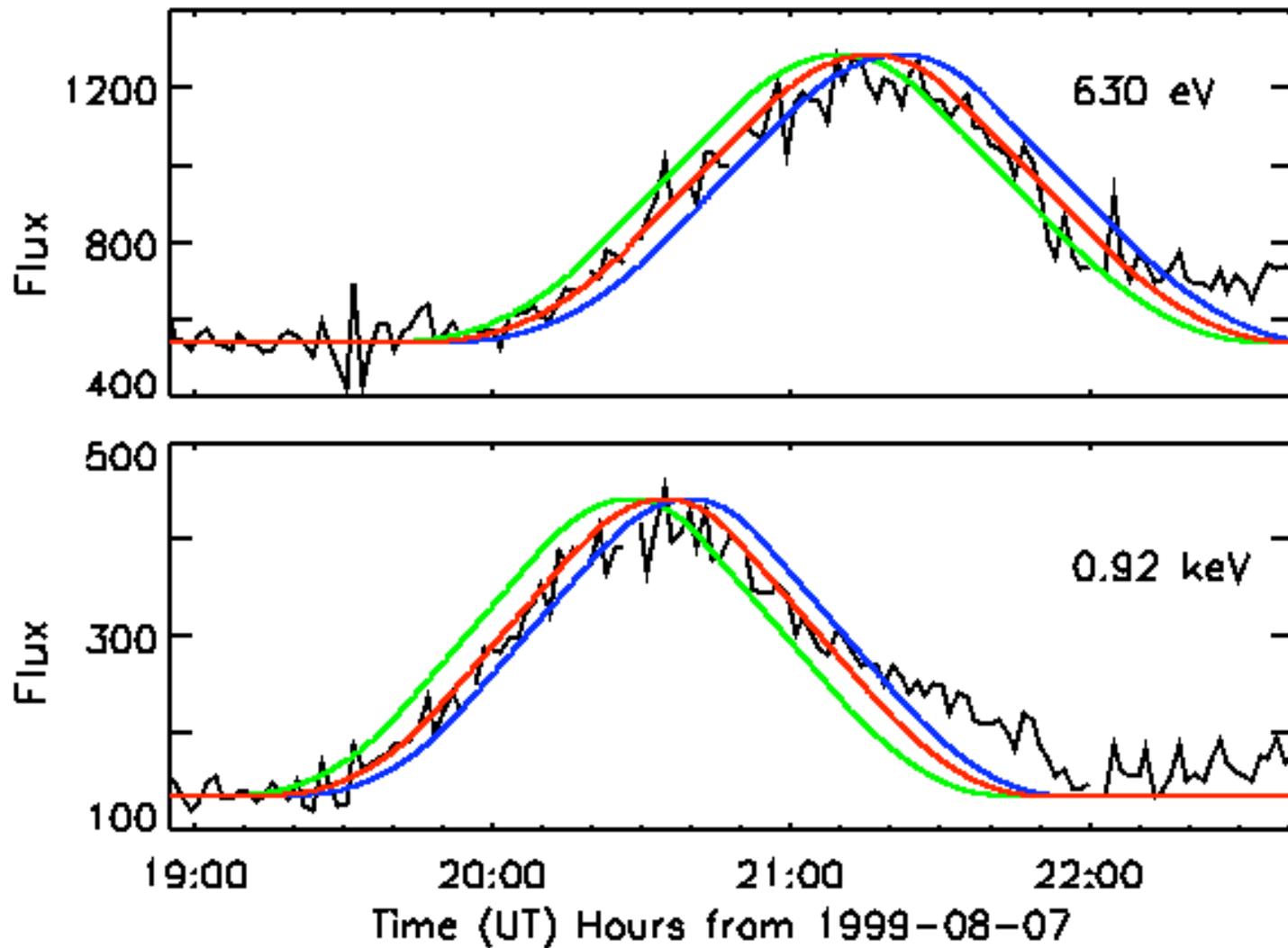
- 1) correlation seen
- 2) values are between

Assume triangular  
injection (equal rise  
and fall) at Sun

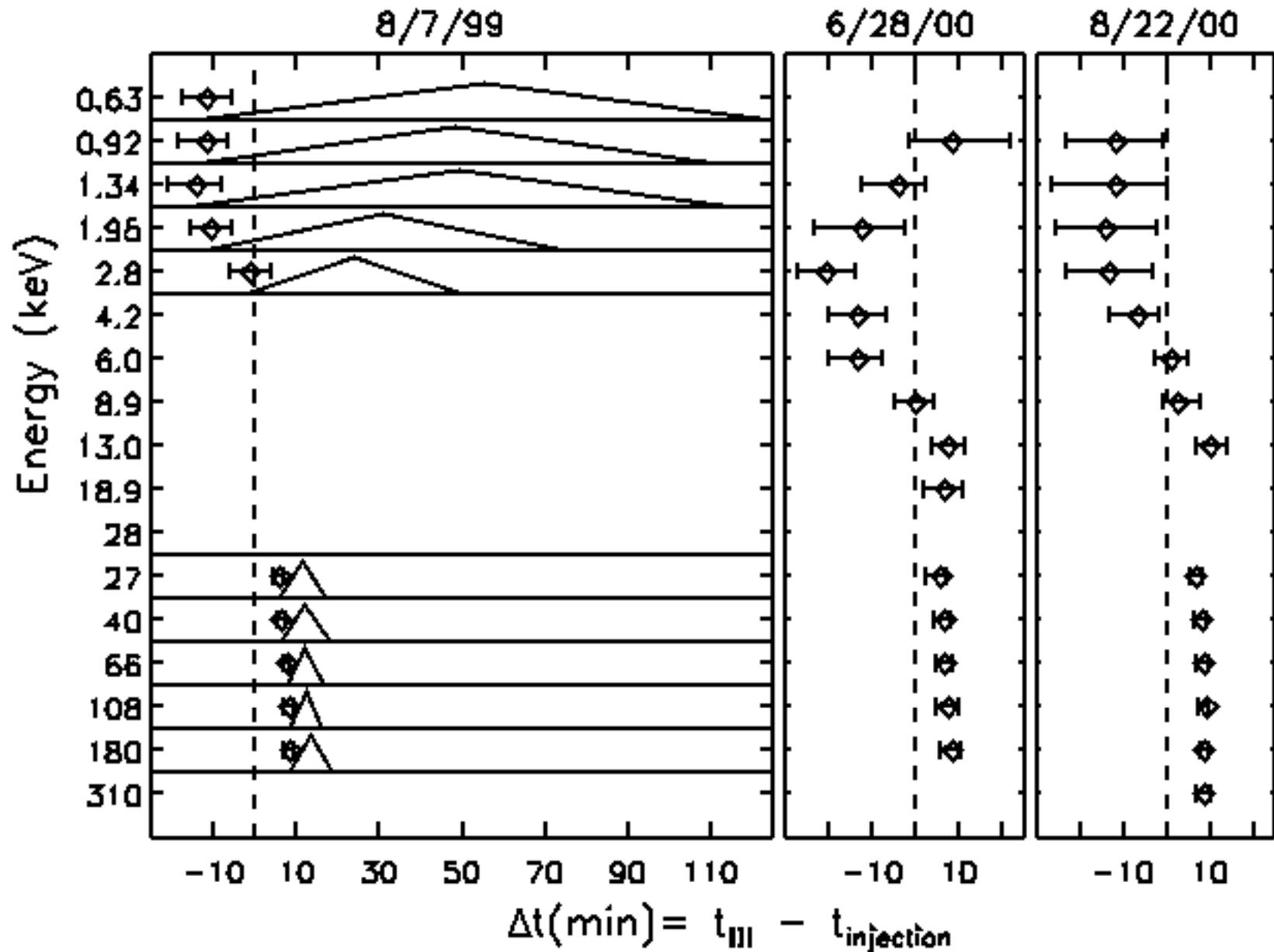
Wang, Lin, Krucker,  
& Gosling, 2005



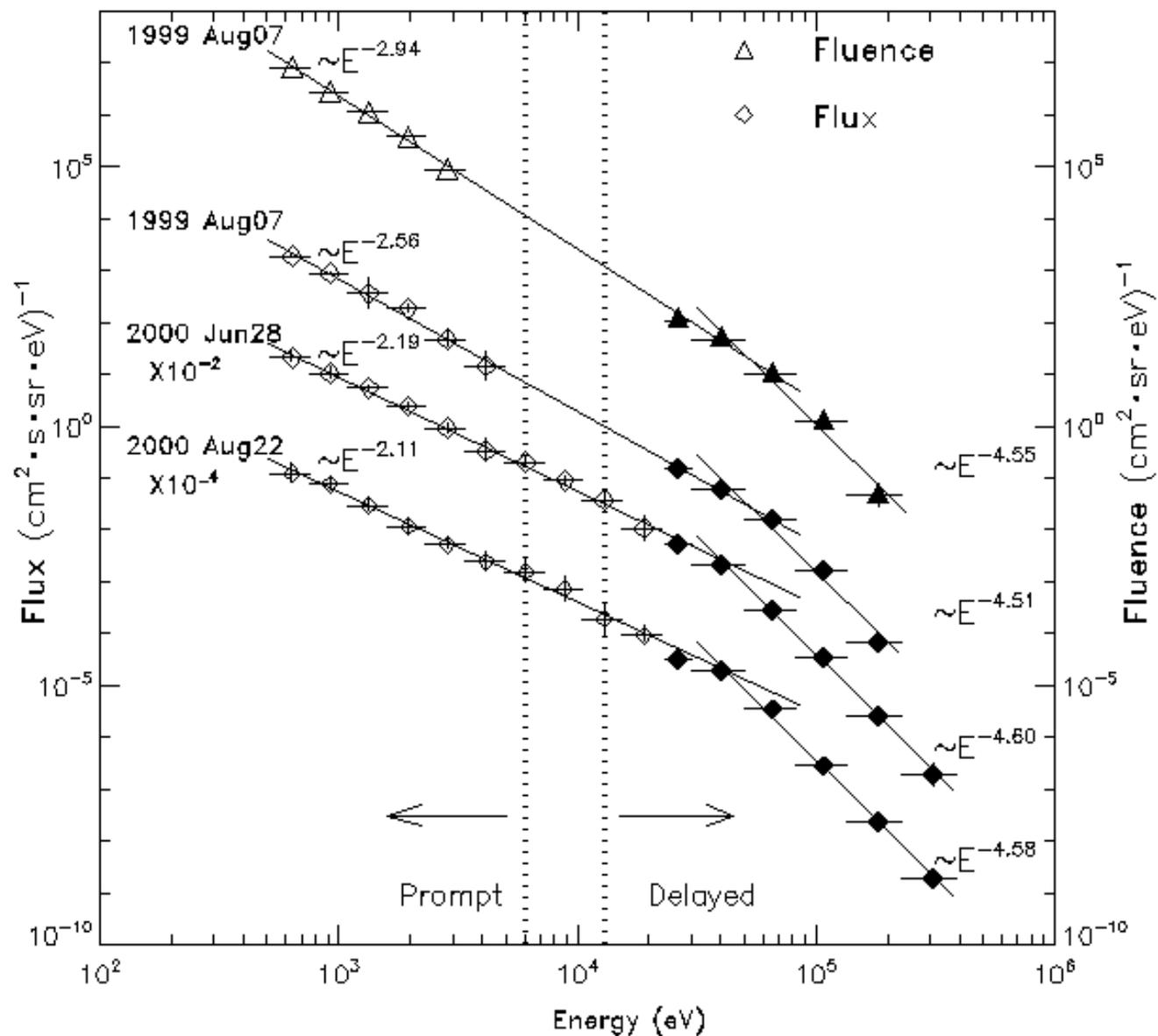
# Wang, Lin, Krucker, & Gosling 2005



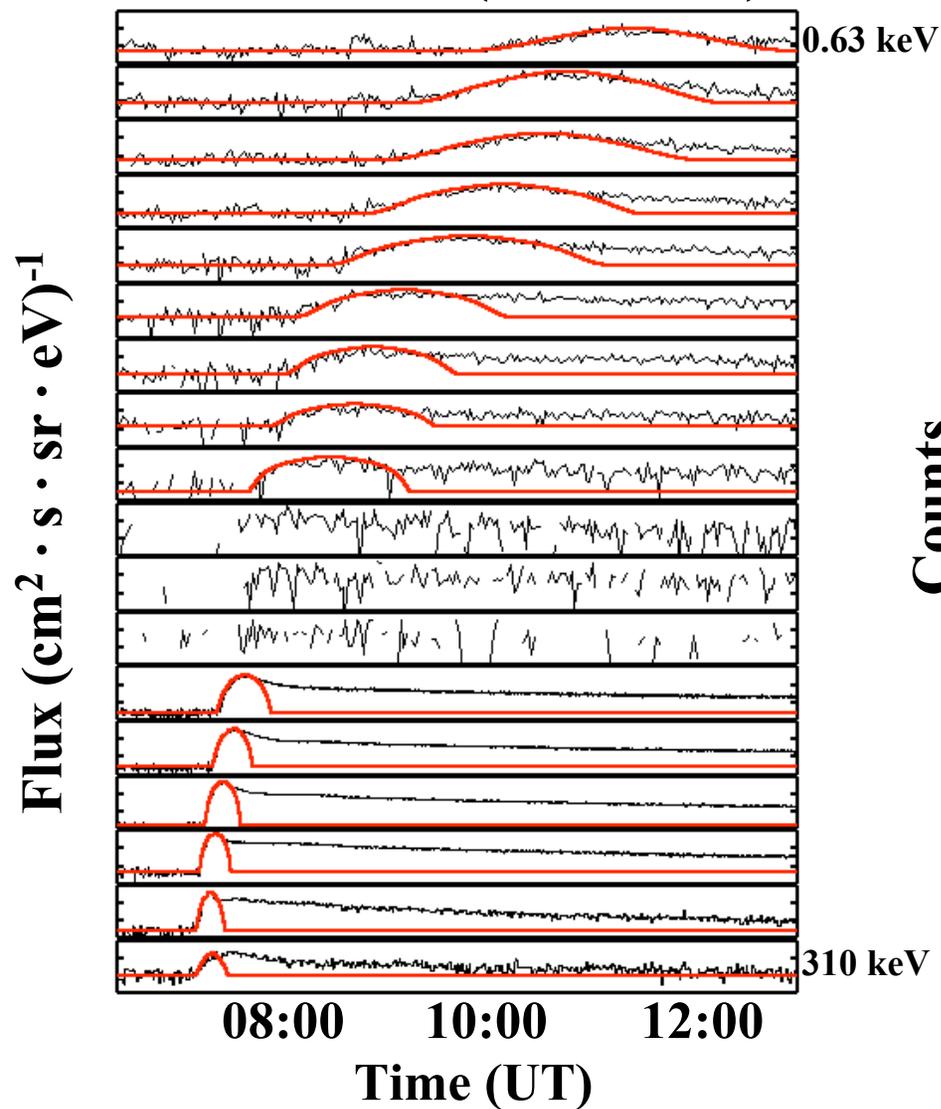
# Wang, Lin, Krucker, & Gosling 2005



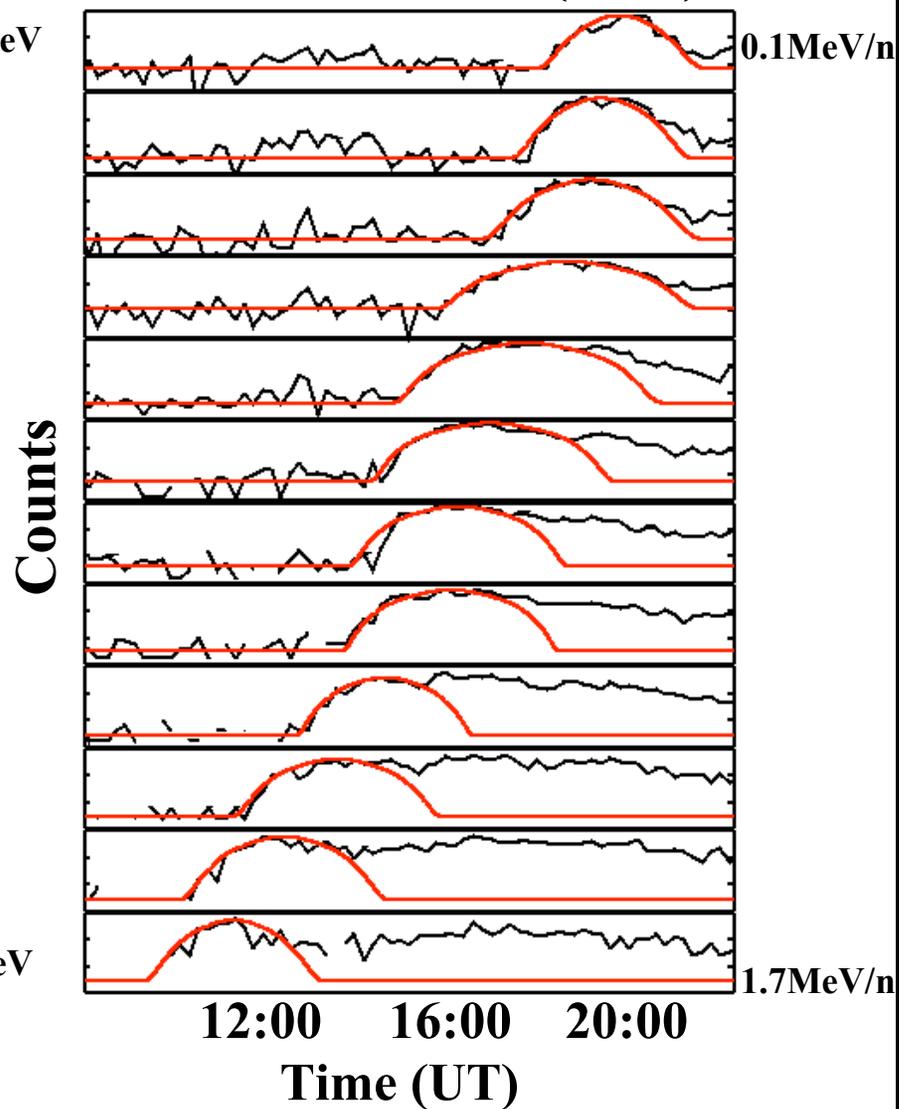
# Wang, Lin, Krucker, & Gosling 2005



## 2000 Jun 4 (Electrons)



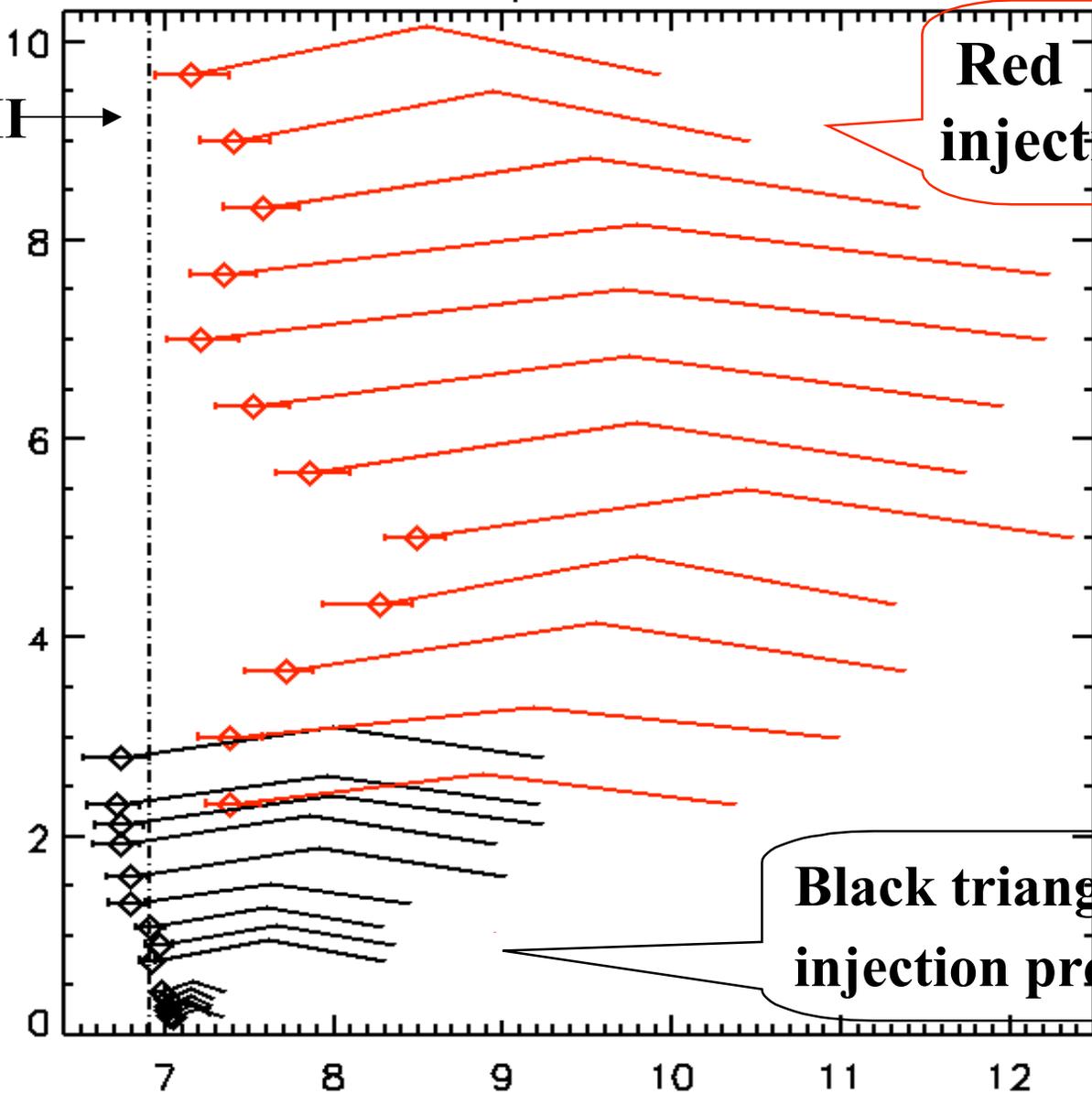
## 2000 Jun 4 (Ions)



2000-06-04/00:00:00 at t=0

Type III →

$1/V$  (hour/AU)



Red triangles: Ion injection profiles

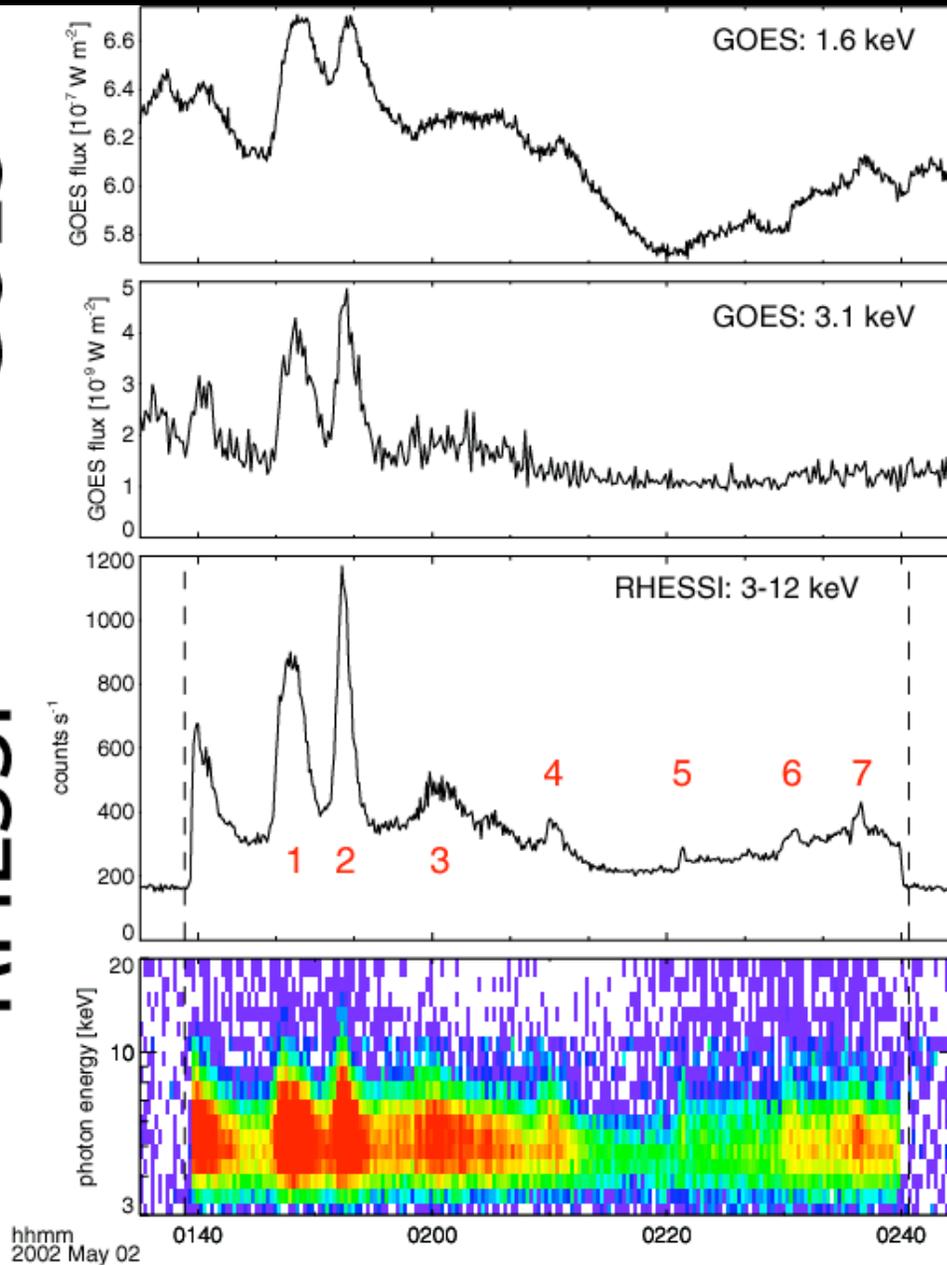
*Wang, et al., 2005*

Black triangles: Electron injection profiles

T [hours]

GOES

RHESSI



1 orbit = 1 hour

# RHESSI and GOES

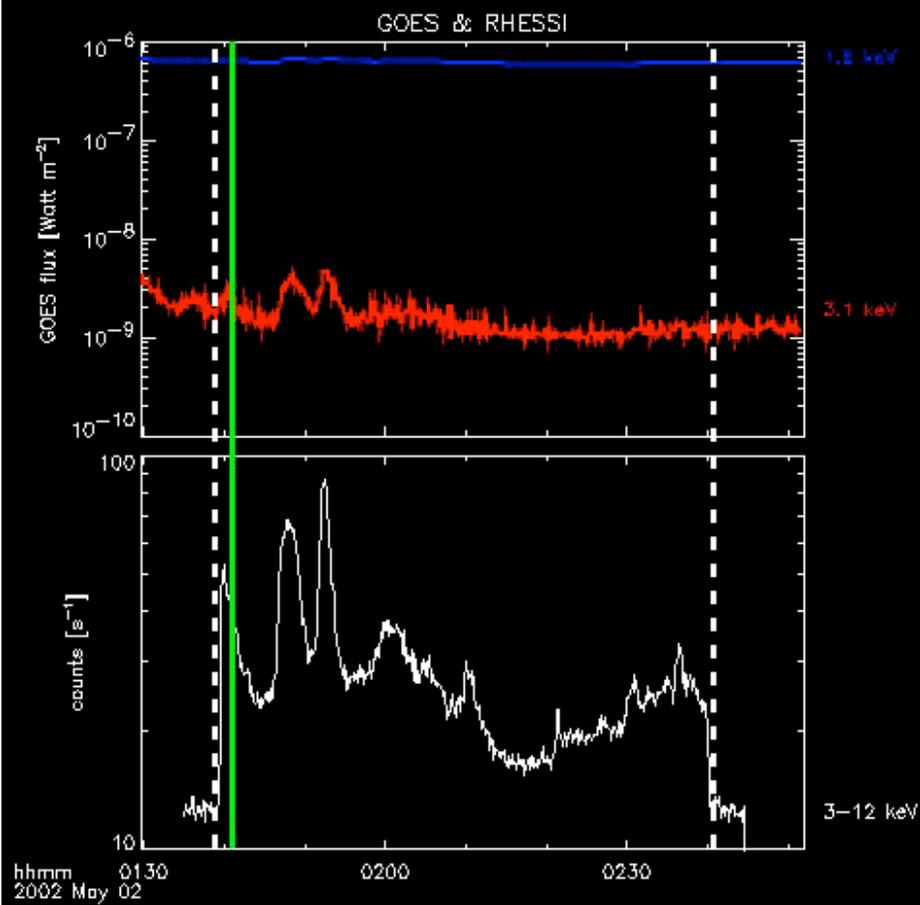
GOES in LINEAR scale!

GOES background B6  
microflares: A6 or smaller

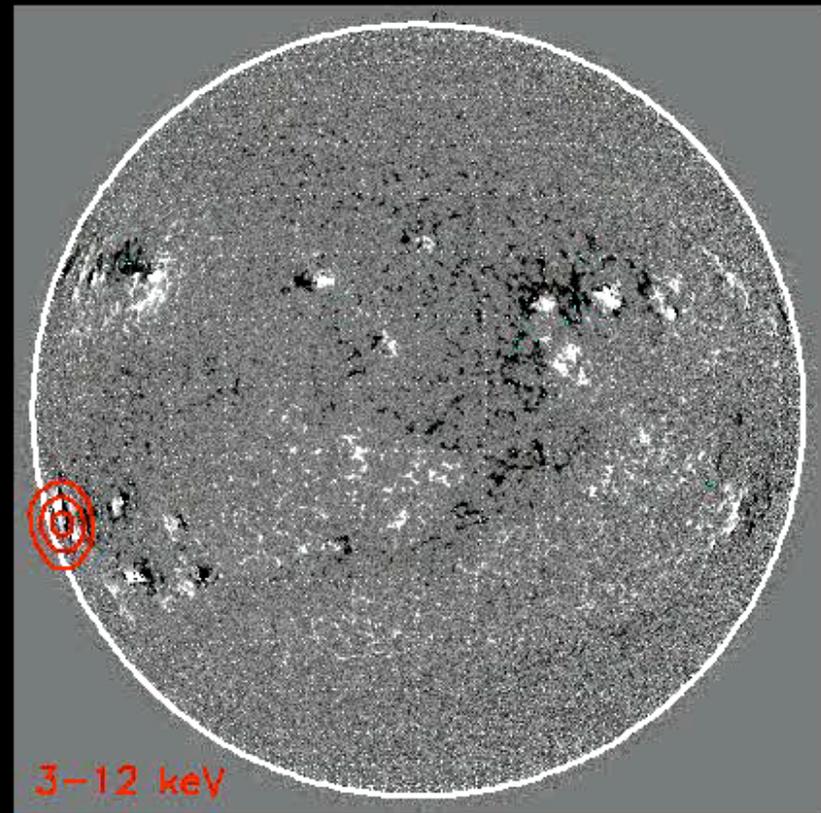
At least 7 microflares

Spectrogram plot:  
energy vs time  
colors represent counts

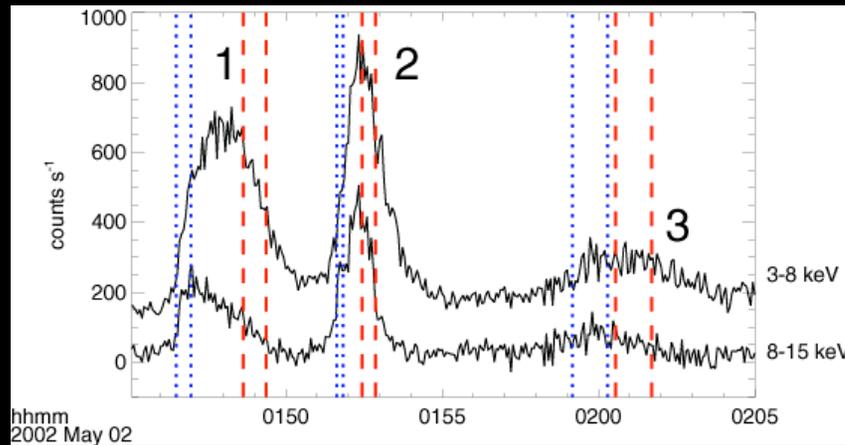
# Microflares are from ARs



2-May-2002 01:41:00.000



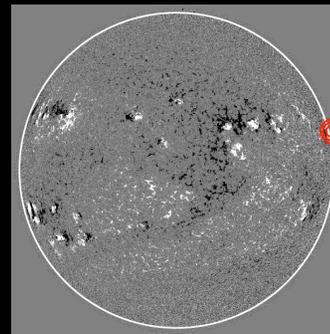
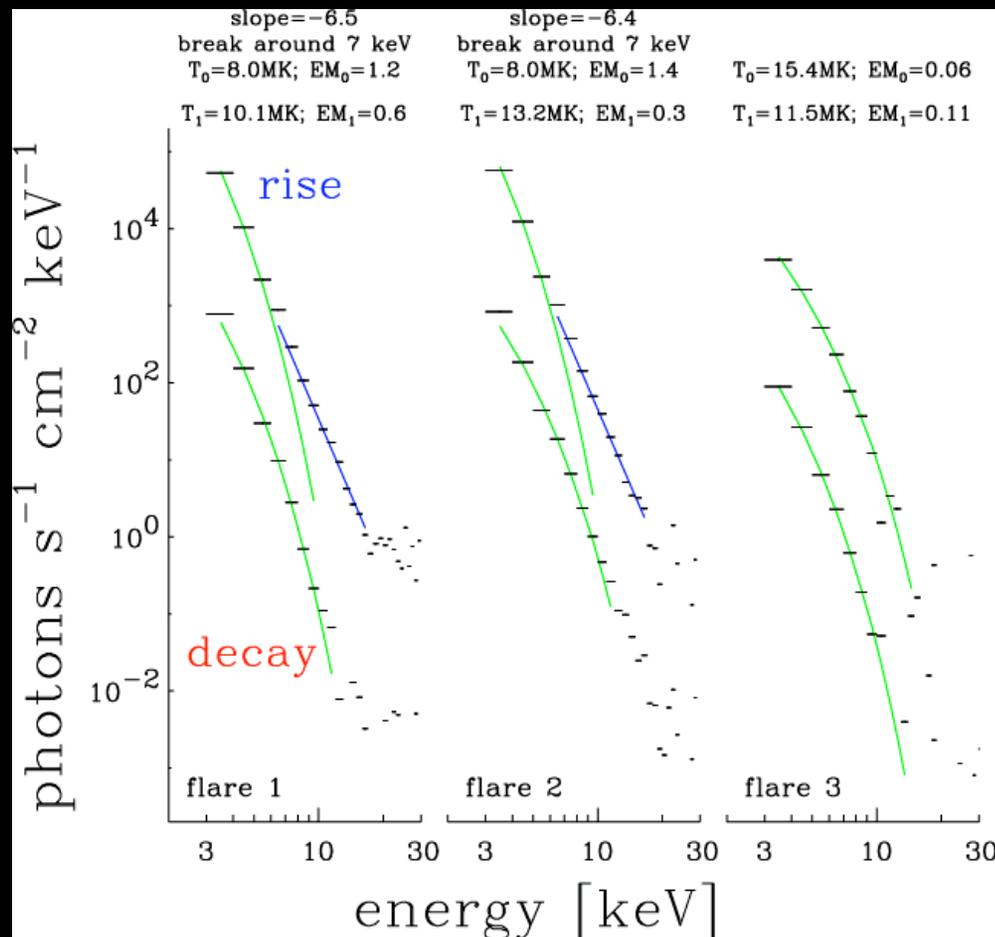
# Micro-flare Spectra



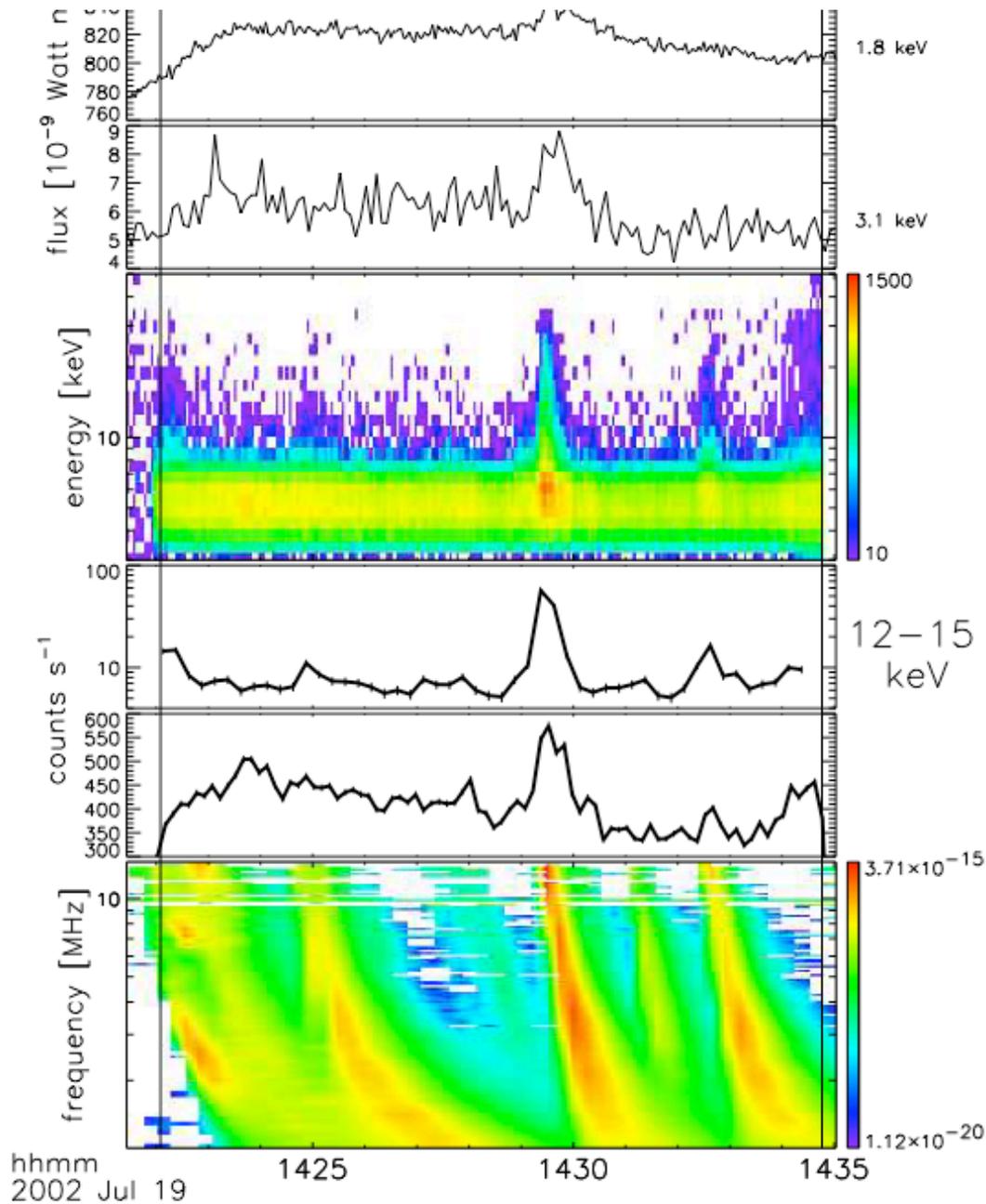
Thermal  $\sim 10\text{-}15 \times 10^6\text{K}$

+

Non-thermal tail w/steep  
power law ( $\delta \sim 4\text{-}7$ )



Flare 3 is  
behind the limb,  
non-thermal  
emission occulted



Panel 1,2: GOES (A3  
above B8 bkgd)  
VERY small!

Panel 3: RHESSI  
Spectrogram

Panel 4: RHESSI non-  
thermal (12-15 keV)

Panel 5: thermal (3-12  
keV) channel

Panel 6: Radio  
Spectrogram from  
WIND/WAVES

# Solar Wind Electrons

**Core** ==>

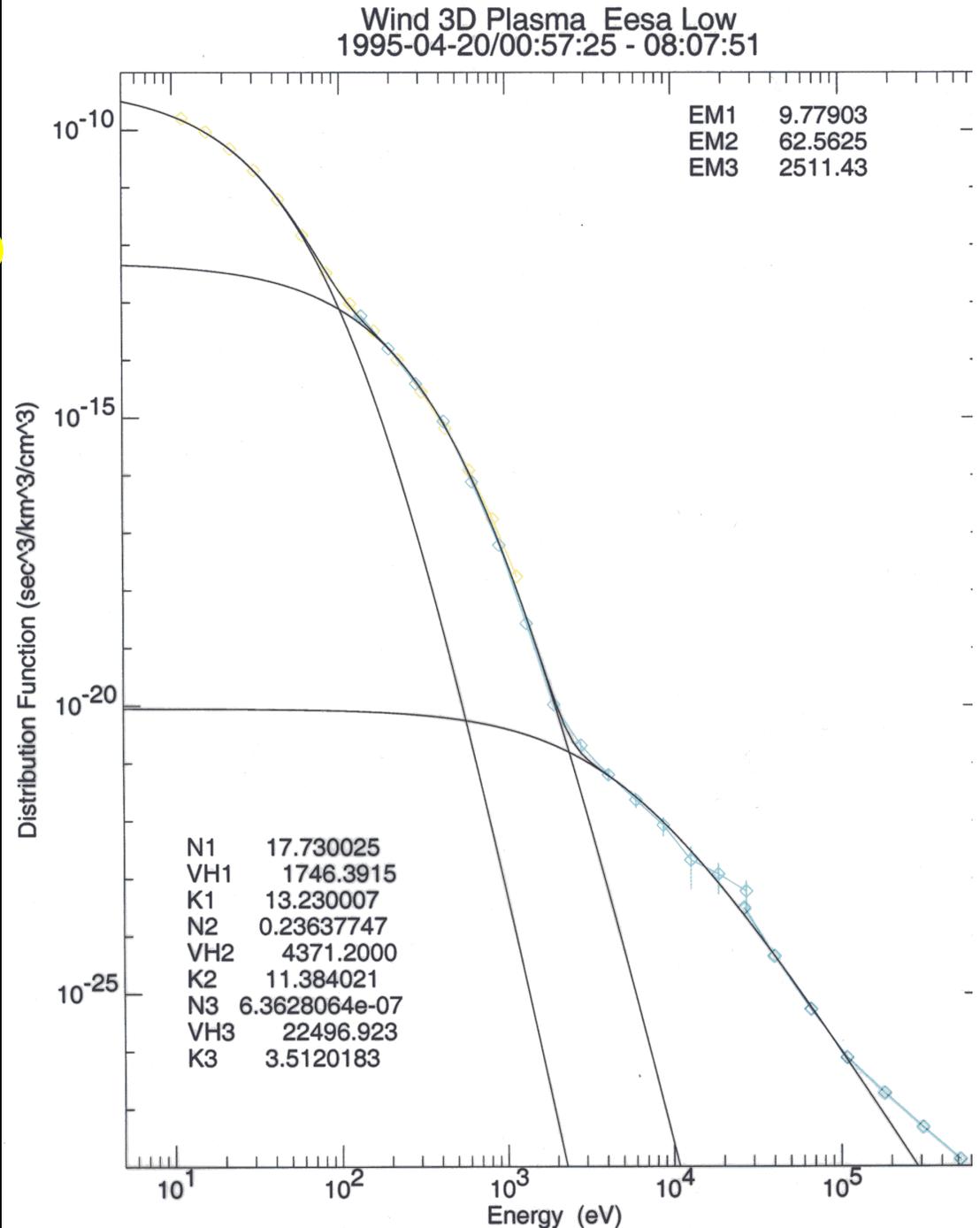
(solar wind plasma electrons)

**Halo/Strahl** ==>

(heat flux from  $\sim 10^6$  K corona)

**Superhalo** ==>

(remnant from microflares, coronal heating and/or solar wind acceleration?)



# HESSI PI and Co-Is

Robert Lin  
Gordon Hurford  
Norman Madden

University of California, Berkeley  
University of California, Berkeley  
LBNL, Berkeley

PI  
Imaging Scientist  
Germanium Detectors

Brian Dennis  
Carol Crannell  
Gordon Holman  
Reuven Ramaty  
Tycho von Roseninge

GSFC/682  
GSFC/682  
GSFC/682  
GSFC/661  
GSFC/661

Mission Scientist  
Education & Outreach  
Flare Theory  
Flare Theory  
ACE Collaboration

Alex Zehnder

Paul Scherrer Inst. Switzerland

Telescope design and fabrication

Frank van Beek

Driebergen, The Netherlands

Grids and Imaging

Patricia Bornmann  
Richard Canfield  
Gordon Emslie  
Hugh Hudson

NOAA  
Montana State University  
Univ. of Alabama, Huntsville  
Solar Physics Research Corp.

GOES Collaboration  
Ground-based Observations  
Flare Theory  
Imaging

Arnold Benz  
John Brown  
Shinzo Enome  
Takeo Kosugi  
Nicole Vilmer

Inst. of Astronomy, Zurich, Switzerland  
Univ. of Glasgow, Scotland  
NAO, Japan  
NAO, Japan  
Observatoire de Paris, Meudon, France

Radio Observations.  
Flare Theory  
Radio Observations  
Imaging  
Data Analysis



# RHESSI Co-Investigators

- *UC Berkeley*: David Smith, Sam Krucker, Jim McTiernan
- *Lockheed Palo Alto Research Laboratory*: Tom Metcalf, Markus Aschwanden
- *Naval Research Laboratory*: Gerry Share, Ron Murphy
- *GSFC*: Richard Schwartz
- *U. Maryland*: Ed Schmahl

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Steven Christe, UCB

Amir Caspi, UCB

Albert Shih UCB

Linhui Sui, Catholic U

Martin Fivian, ETHZ

## *RHESSI project team at:*

UCB

Goddard Space Flight Center

Paul Scherrer Institute (Switzerland)

