The RHESSI (Ramaty High Energy Solar Spectroscopic Imager) Mission

R. P. Lin

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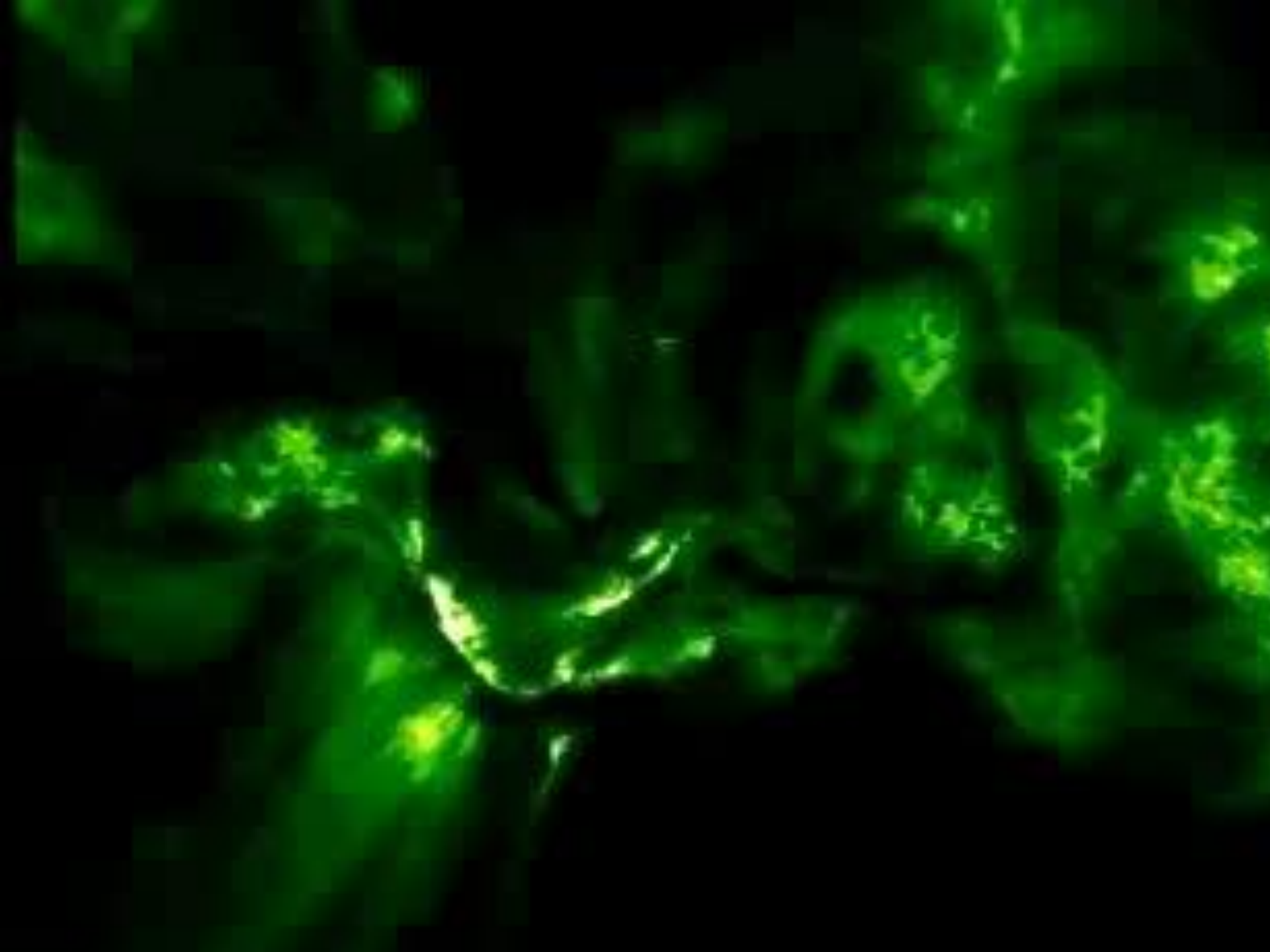
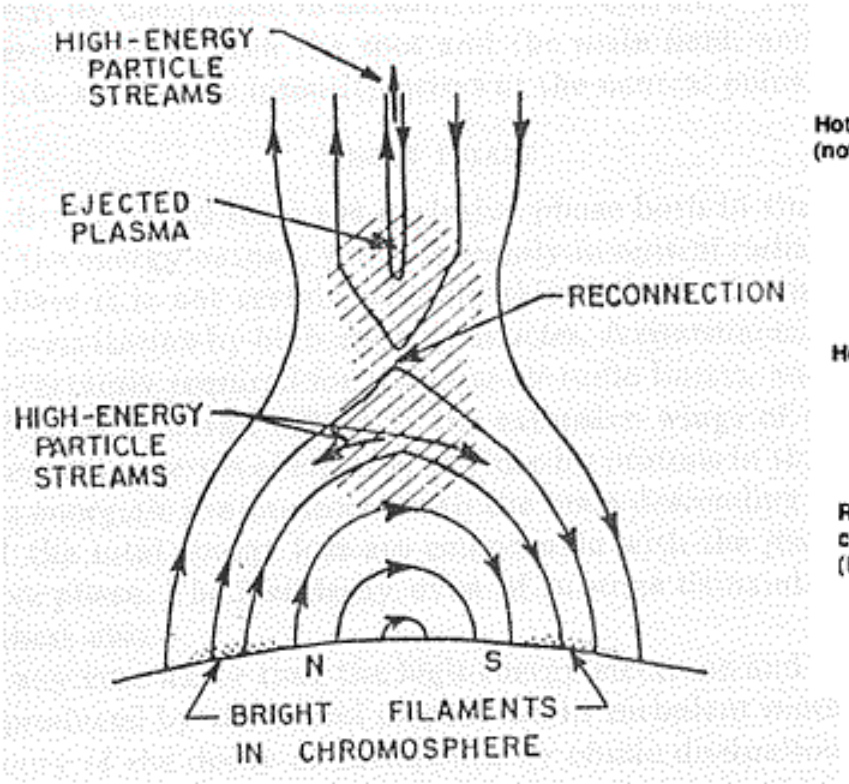
& the RHESSI team

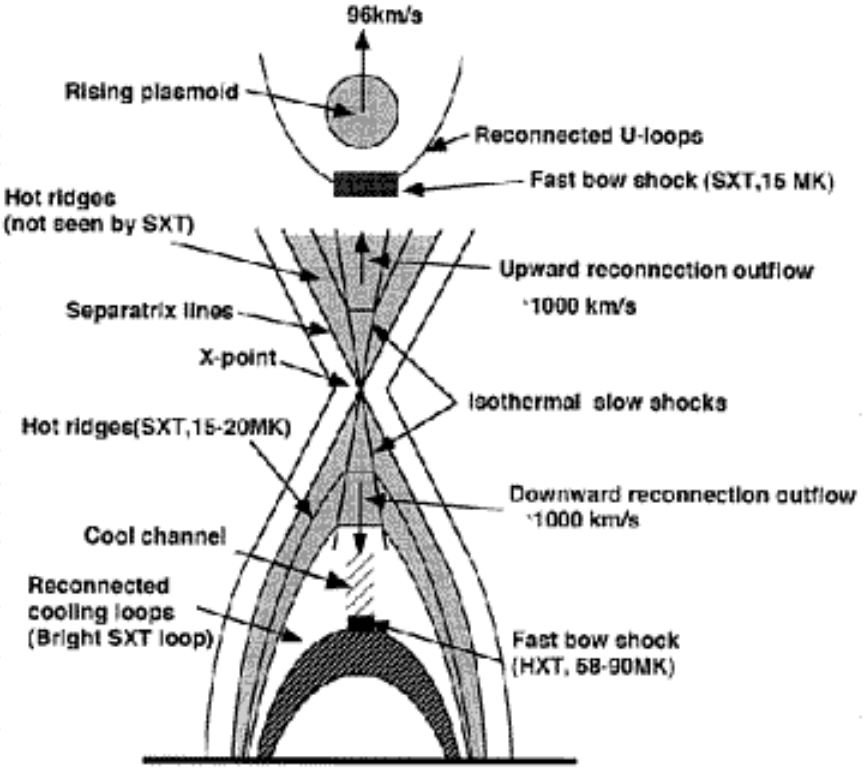


'Standard' model

This has evolved to keep pace with observations



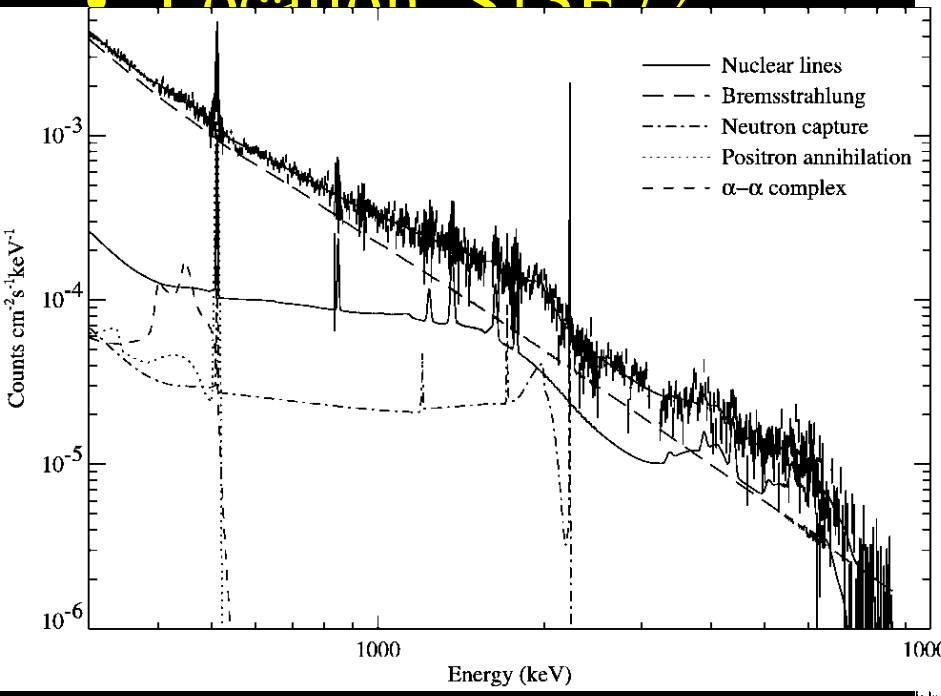
Sturrock 1966

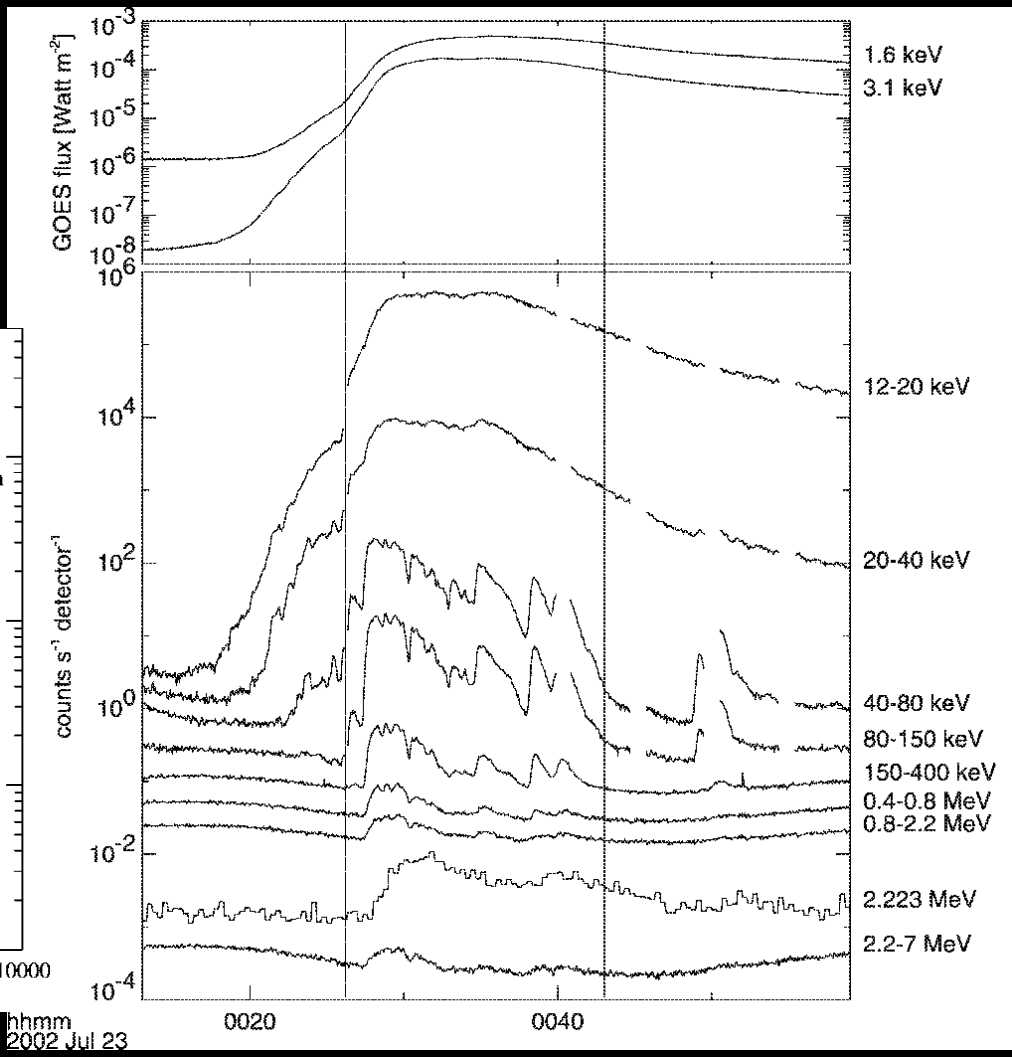


Tsuneta 1997

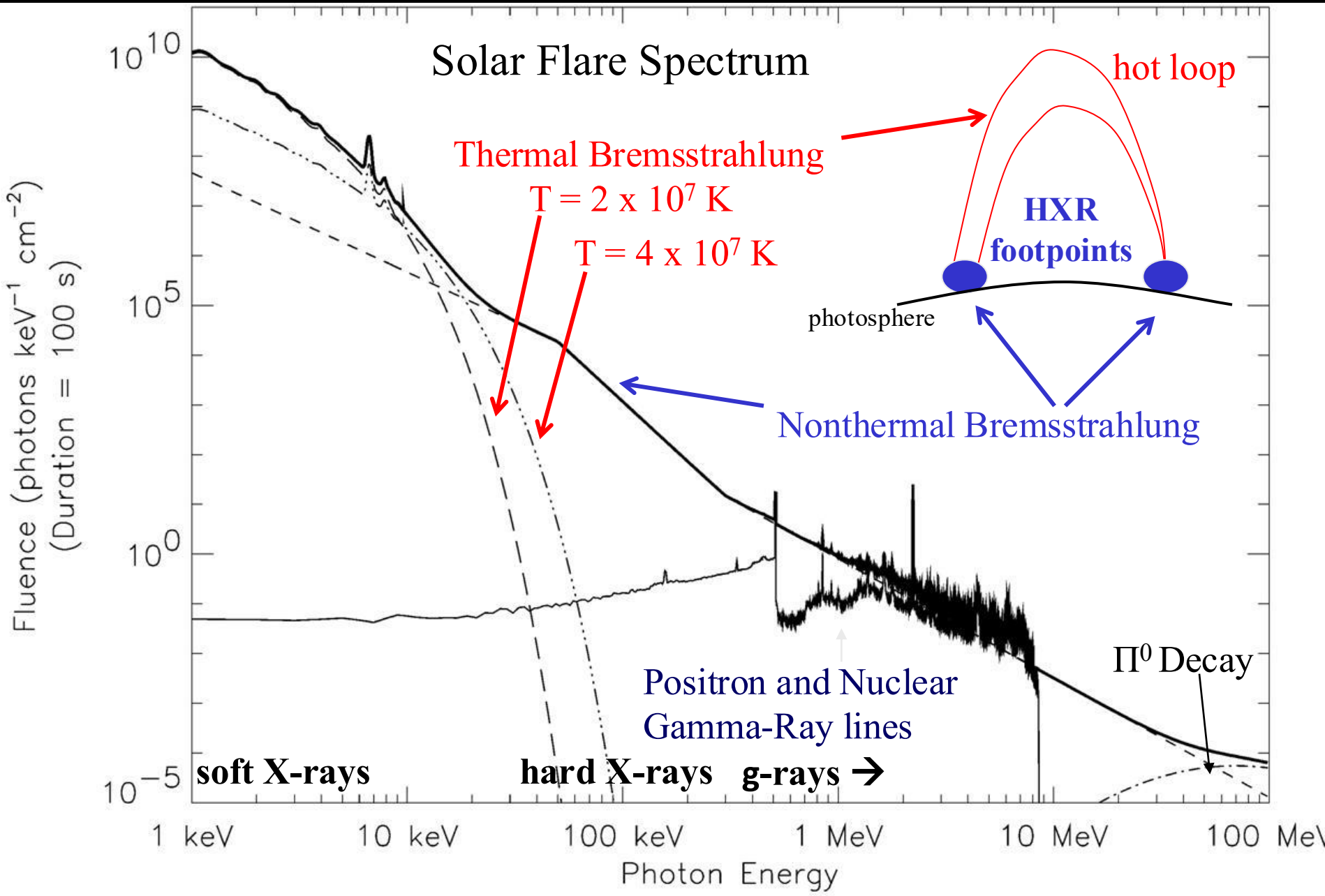
X-Class Flare of 2002 July 23

- 00:27:20-00:43:20 UT
- GOES X4.8
- Location: S13E72





(Lin et al. 2003)


Solar Flare Spectrum
hot loop
Thermal Bremsstrahlung
T = 2 x 10^7 K
T = 4 x 10^7 K
HXR
footpoints
photosphere
Nonthermal Bremsstrahlung
Positron and Nuclear
Gamma-Ray lines
Π0 Decay
soft X-rays
hard X-rays
g-rays →
Fluence (photons keV^-1 cm^-2)
(Duration = 100 s)
10^10
10^5
10^0
10^-5
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
Photon Energy

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

- Ions up to ~ 10s of GeV
- Electrons up to ~100s 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, ~2-40 solar radii

Non-thermal X-rays ($E_e >> kT$) => ~ 10^{32} ergs in ~20-100 keV electrons in ~ 10^3 seconds

= ~10^{29} ergs/s

=> ~10^{36} electrons/s!

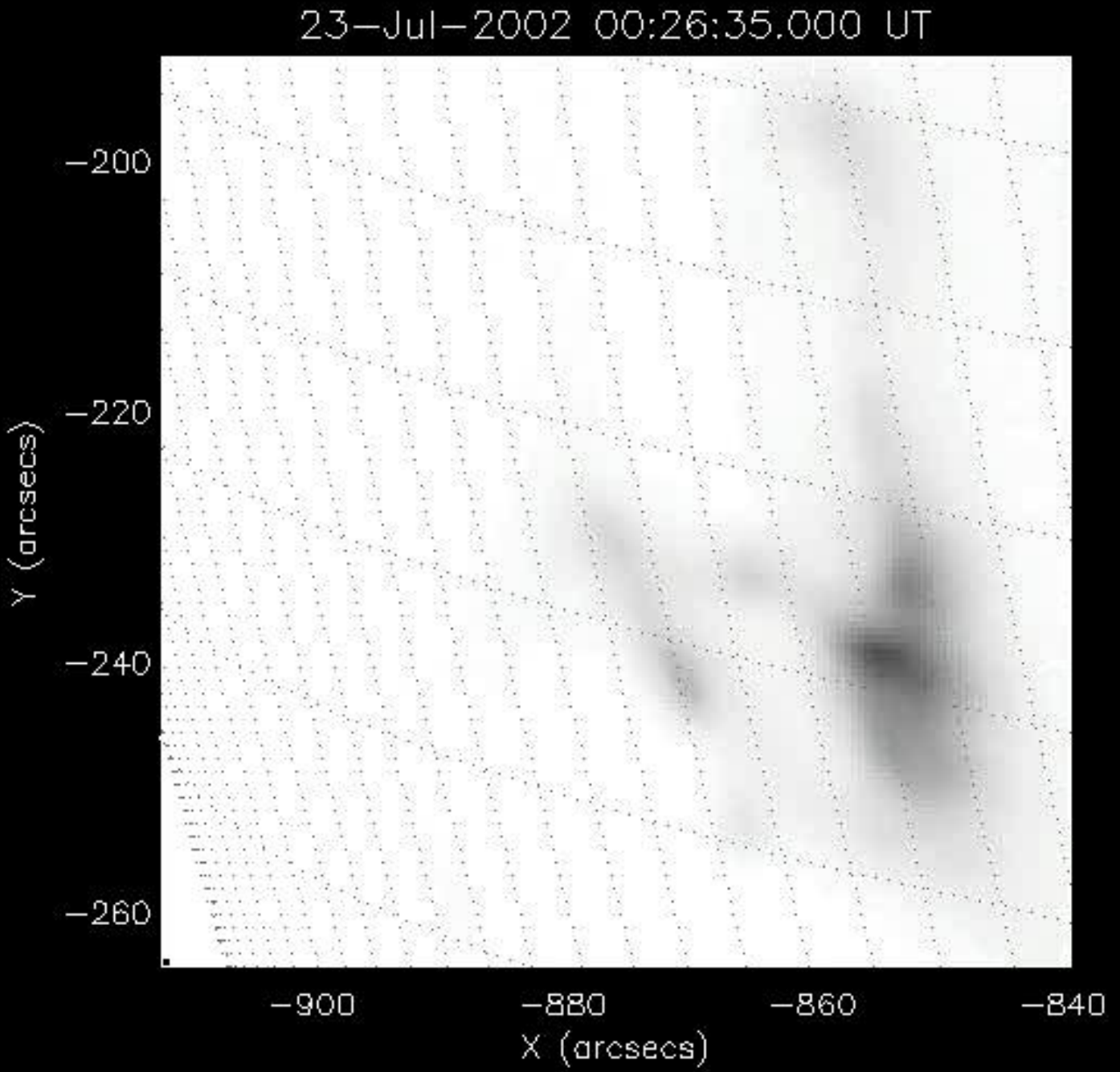
=> empty entire flare loop!!

=> ~10^{17} amps!!

What about thermal emission from confined

~10^8 K plasma ($kT \sim E_e$) ?

Main phase:
RHESSI-Hα
movie
23 July 2002



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

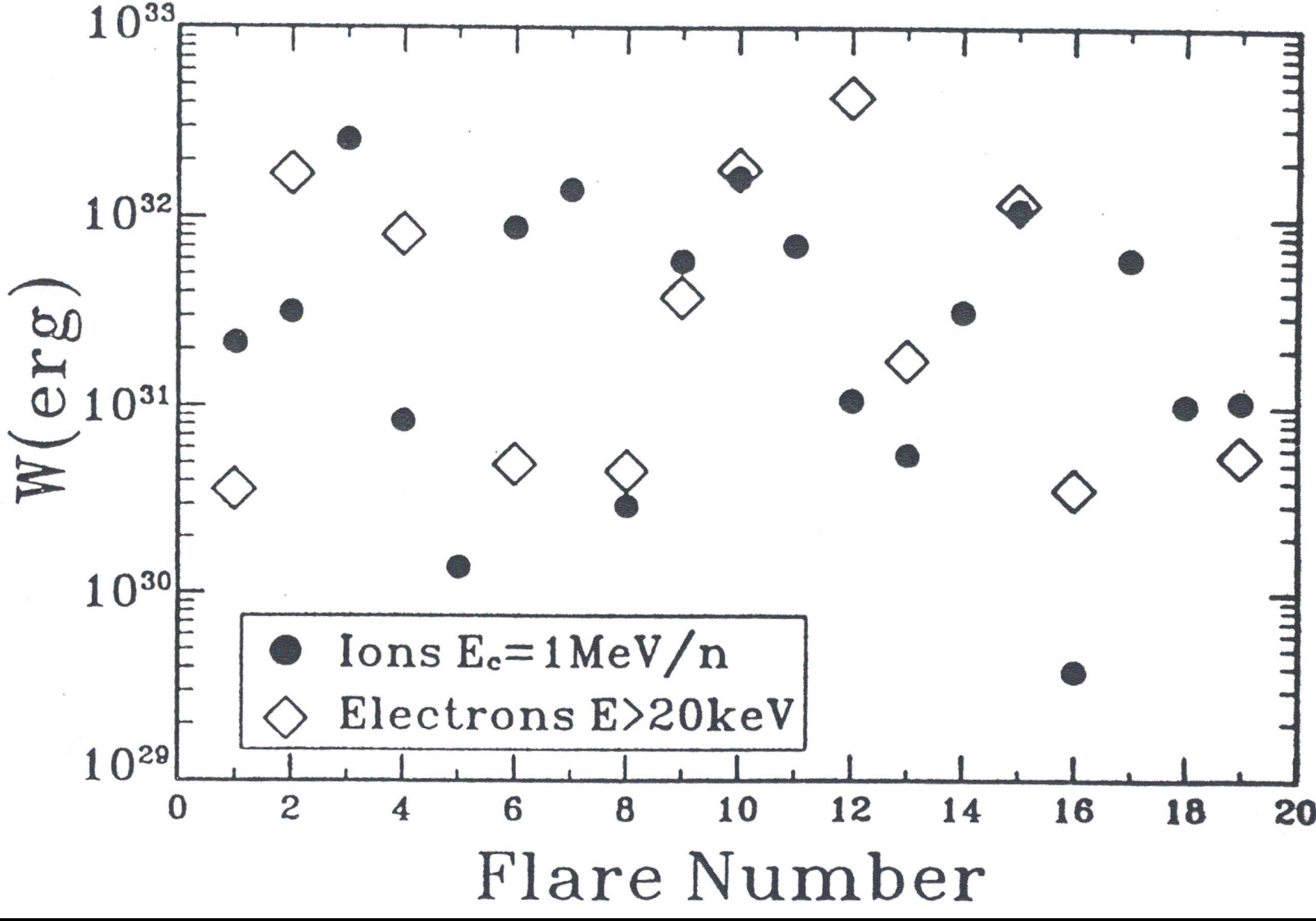
Up to ~ 10^{32} - 10^{33} ergs released in ~ 10 – 10^{3} s

Flare-accelerated ~20-100 keV electrons contain ~10-50% of total energy released

In large flares, >~1 MeV ions contain comparable energy

⇒Particle acceleration is intimately related to flare energy release

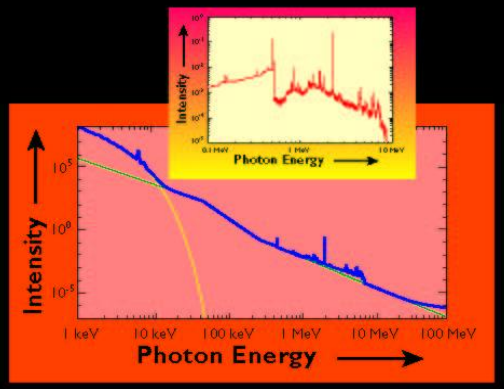
The total energy released by all flares, down to microflares/nano-flares may be significant for the heating of the solar corona

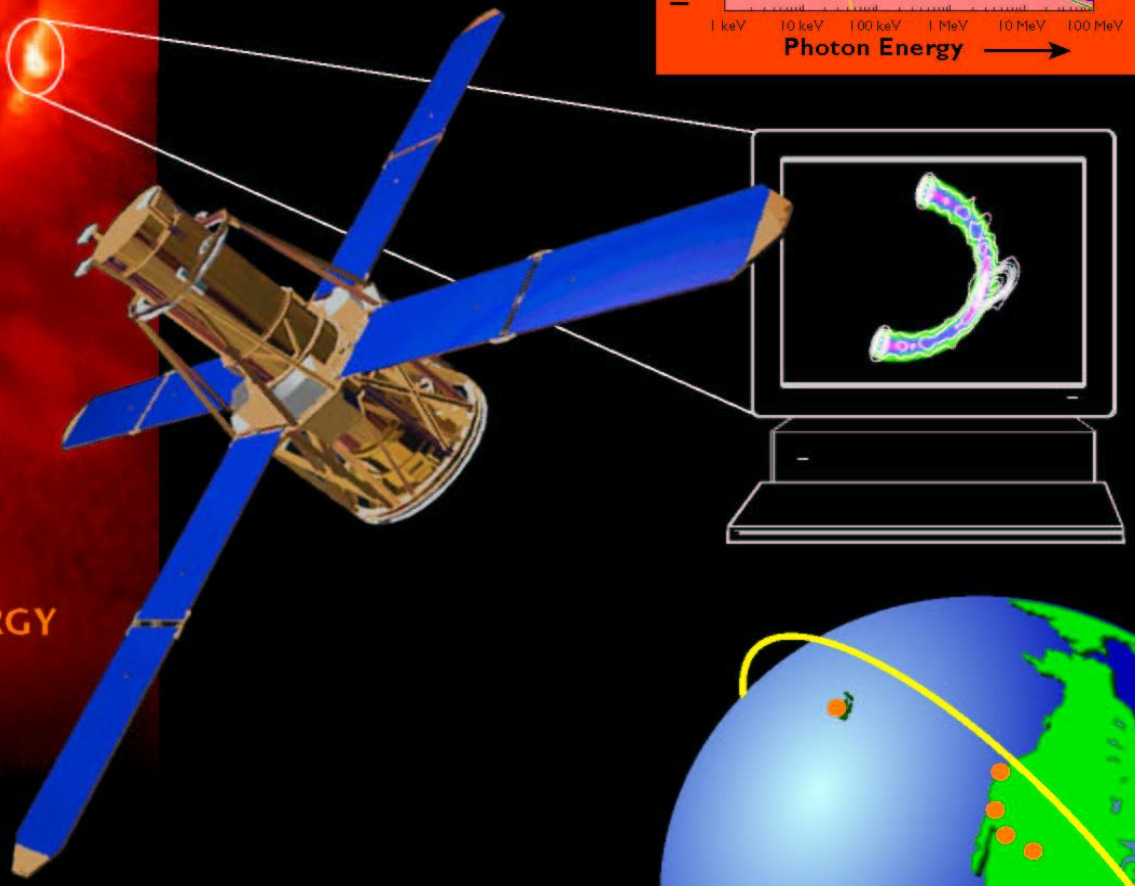

10^{33}
10^{32}
10^{31}
10^{30}
10^{29}
W(erg)
Ions E_c=1MeV/n
Electrons E>20keV
0
2
4
6
8
10
12
14
16
18
20
Flare Number

RHESSI

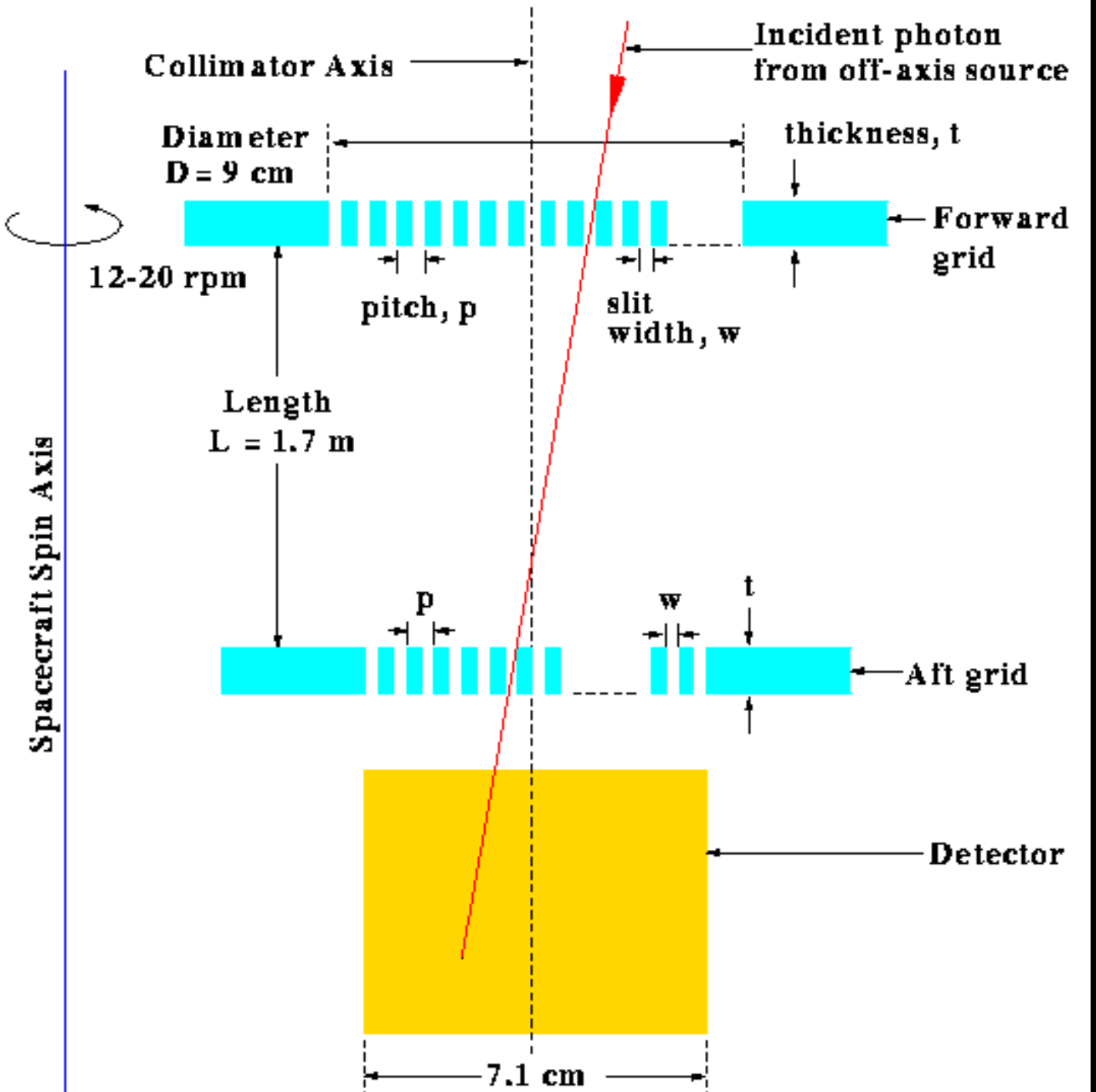
THE REUVEN RAMATY HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER

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

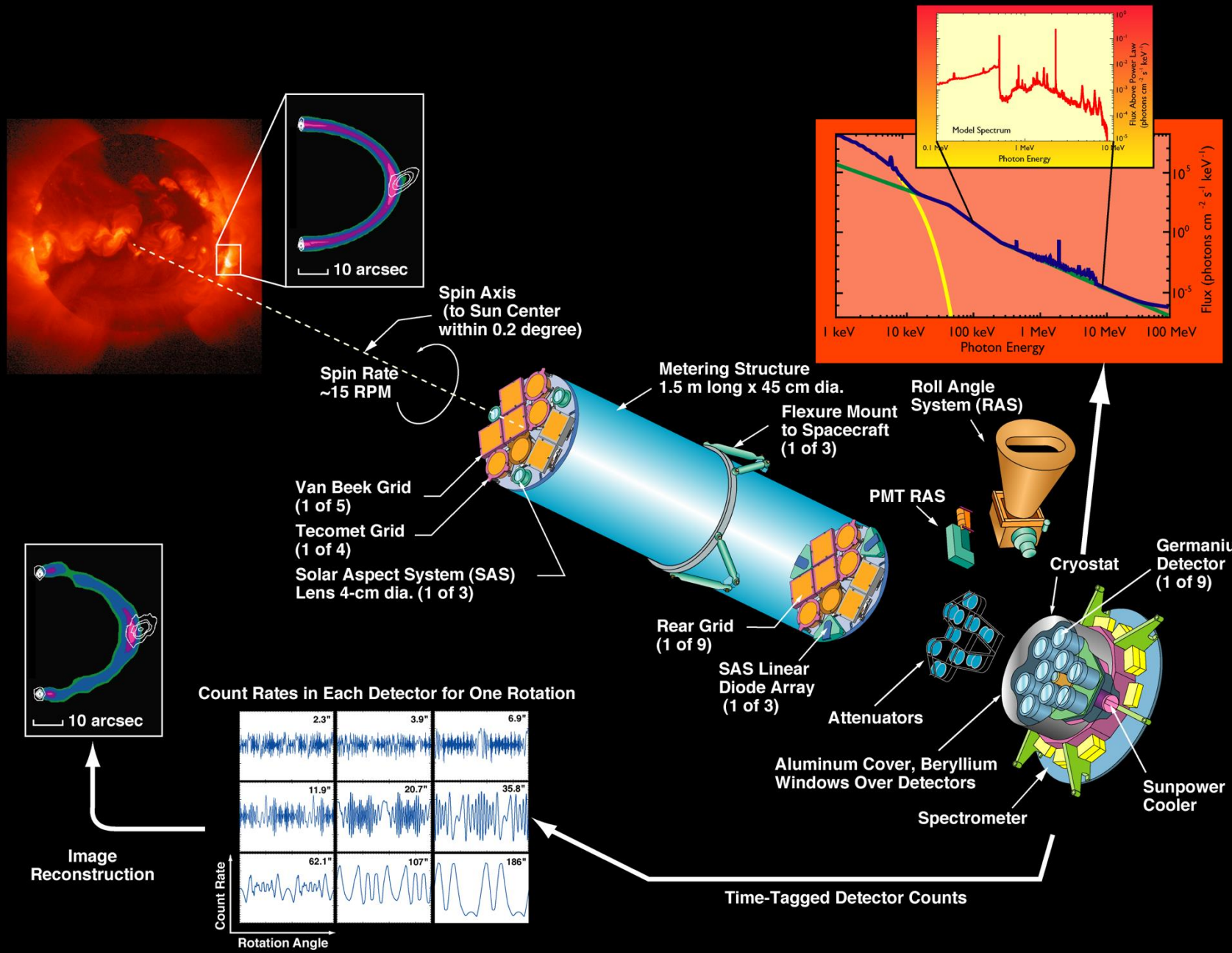


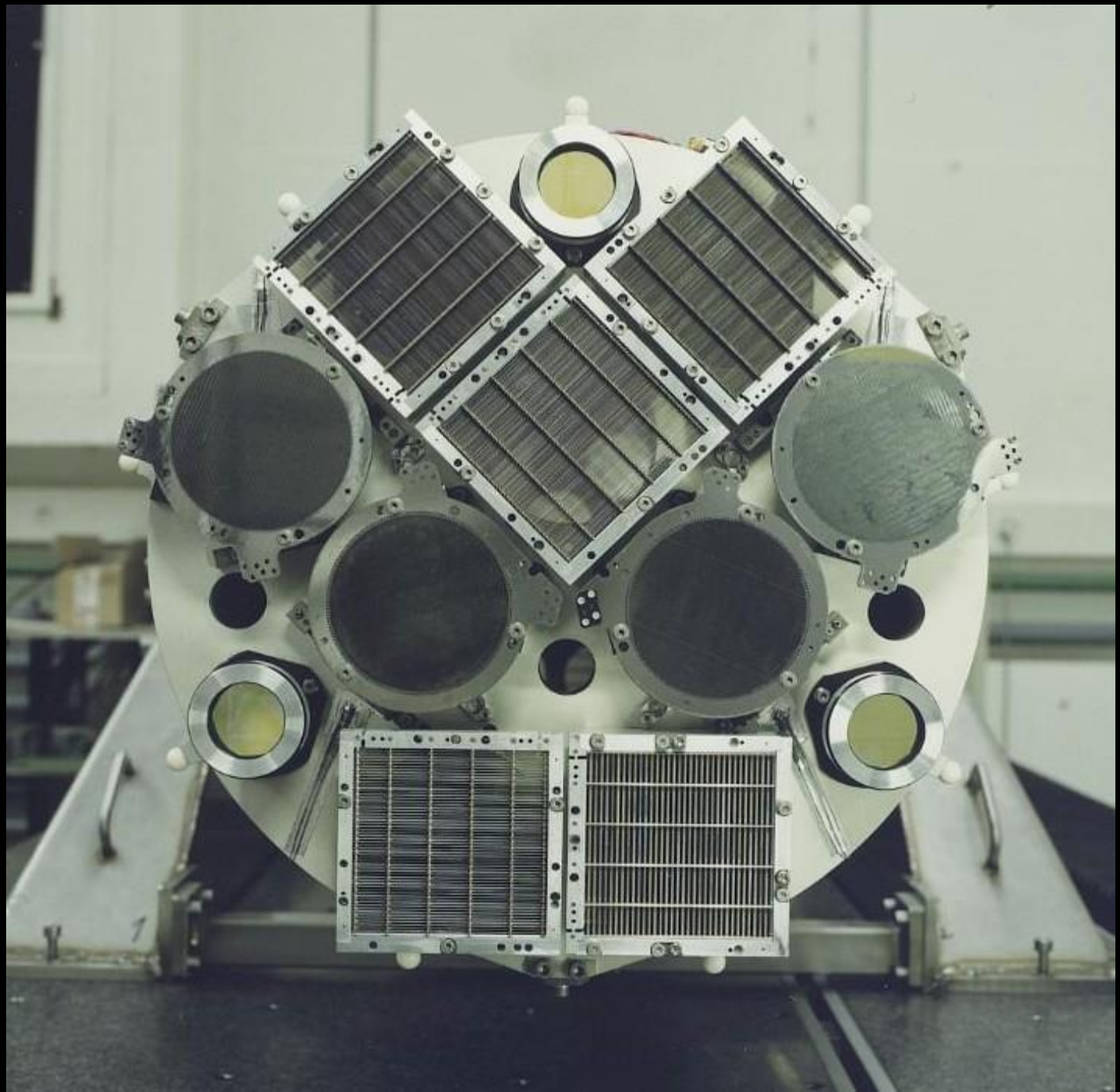


To explore the basic physics of particle acceleration and explosive energy release in solar flares

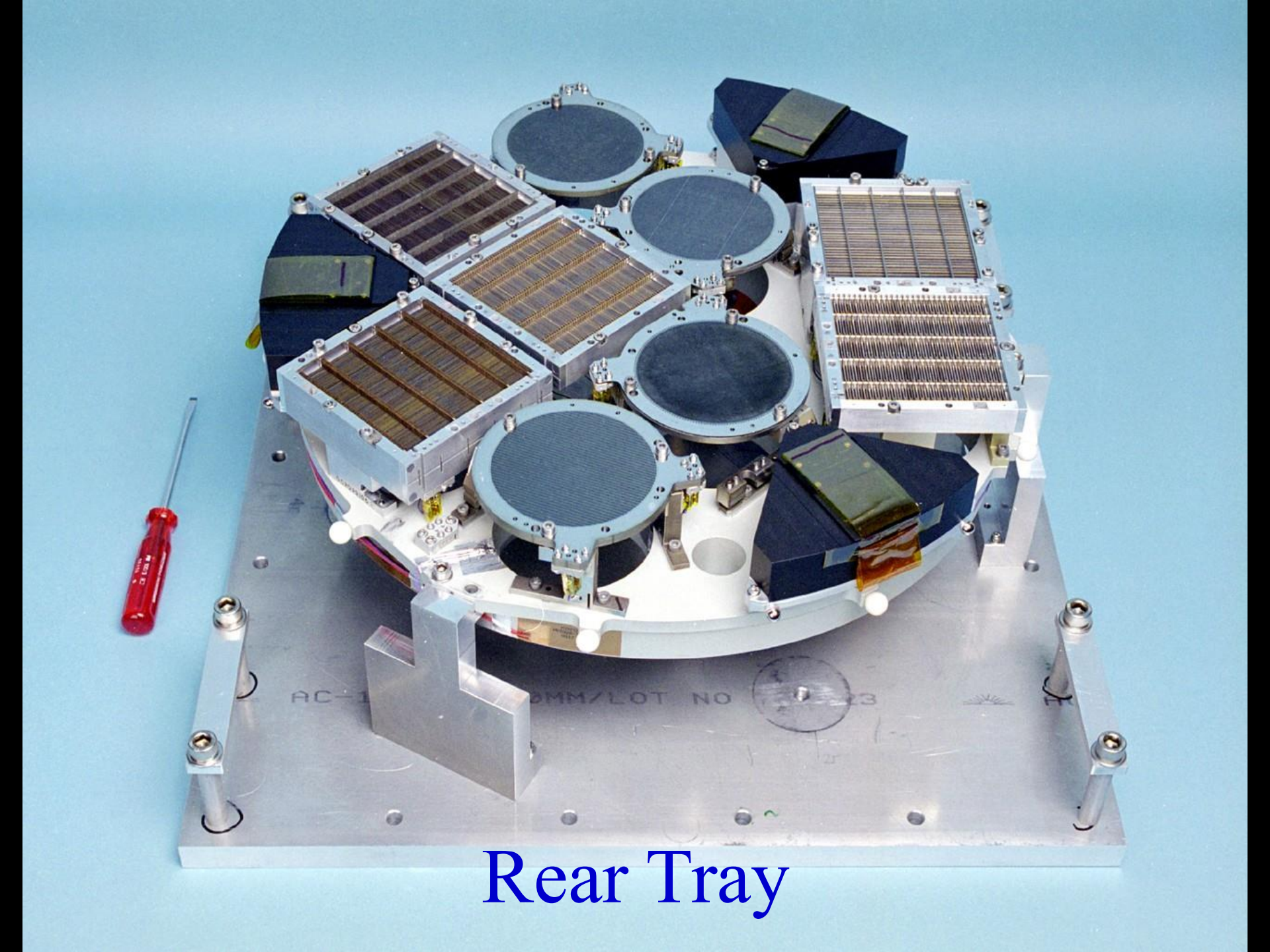

Collimator Axis
Incident photon
from off-axis source
Diameter
D = 9 cm
thickness, t
Forward
grid
12-20 rpm
pitch, p
slit
width, w
Length
L = 1.7 m
Spacecraft Spin Axis
p
w
t
Aft grid
Detector
7.1 cm

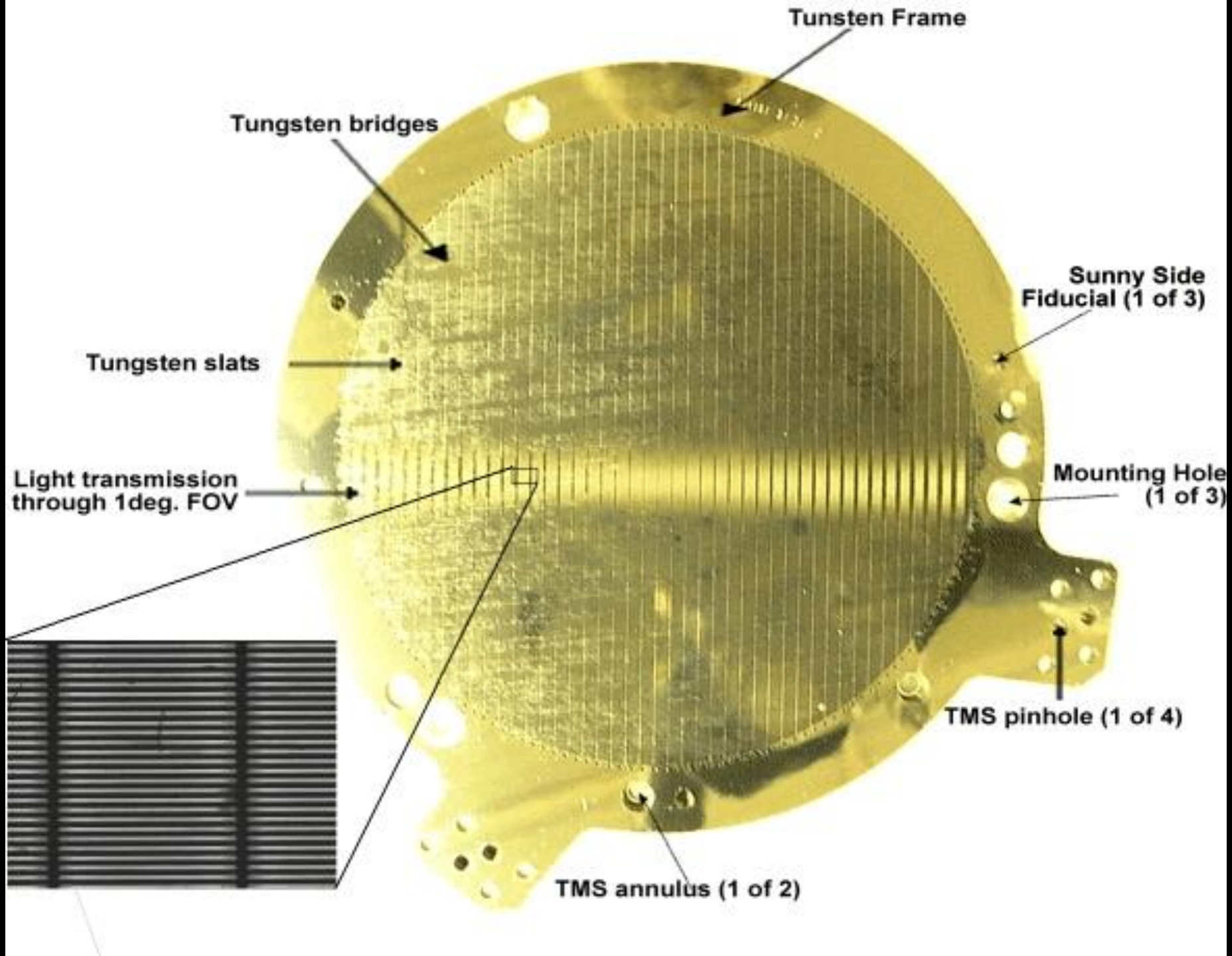
RHESSI Imaging Spectroscopy



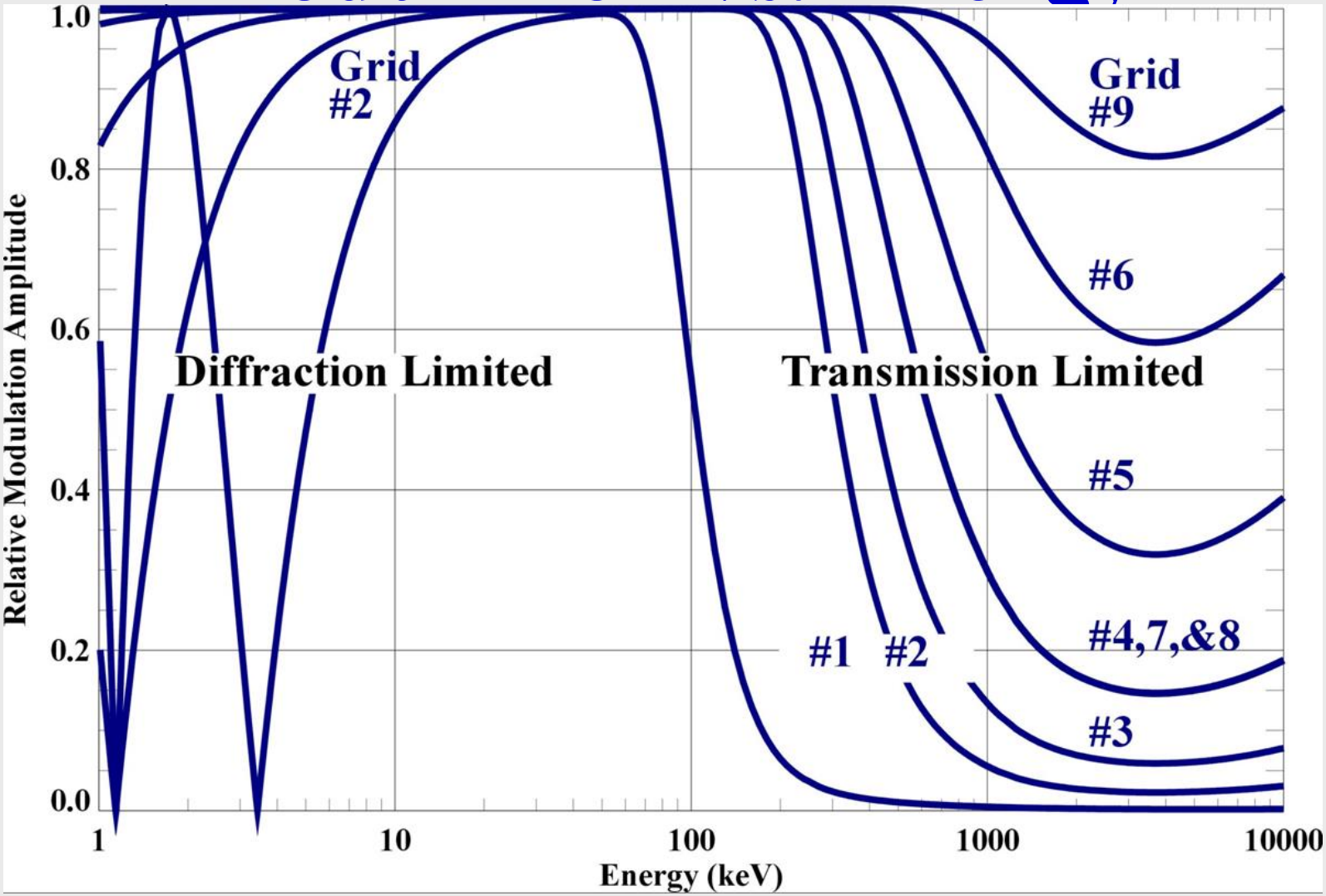


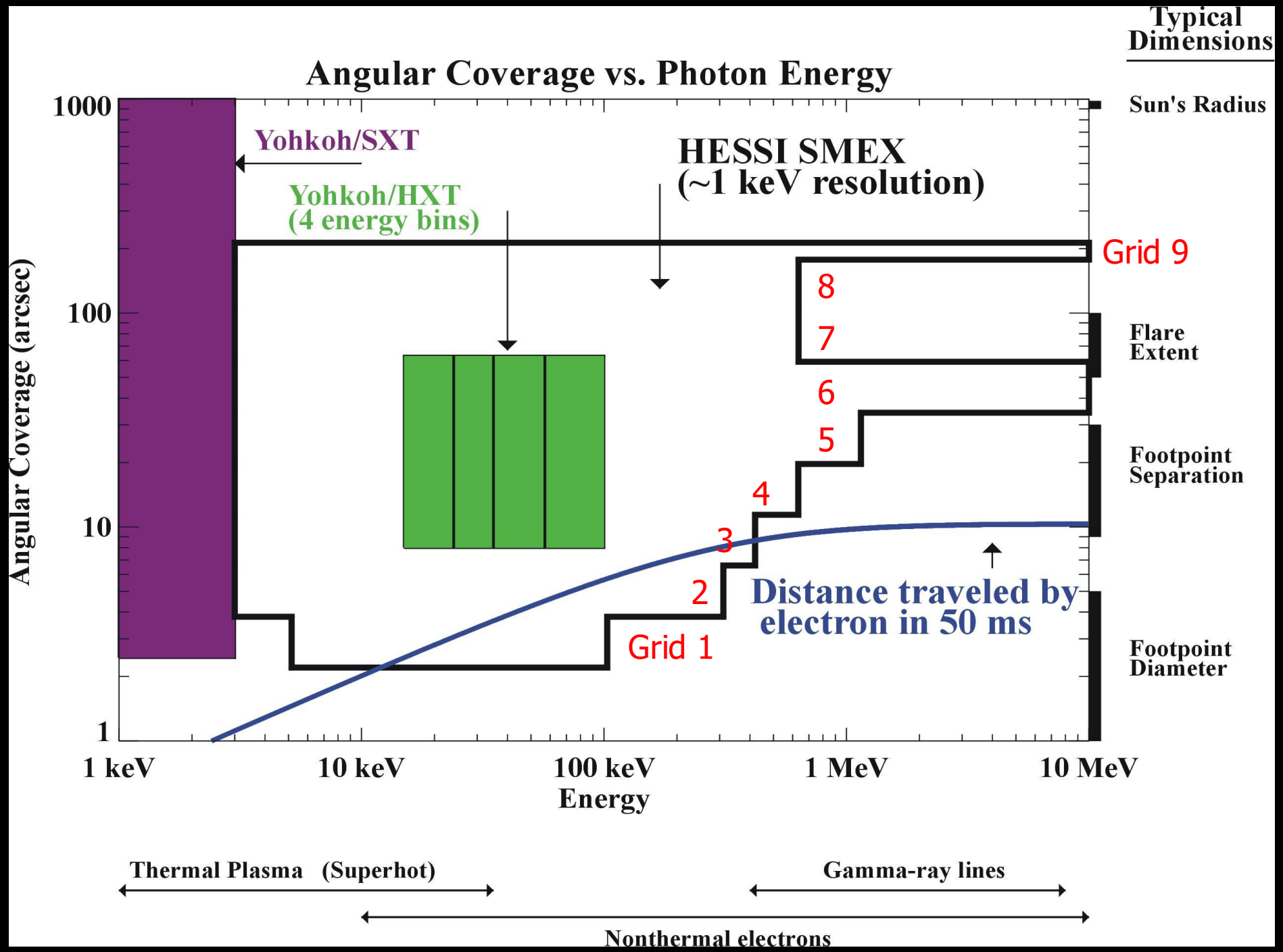
Imager – side view


Rear Tray


Tunsten Frame
Tungsten bridges
Sunny Side
Fiducial (1 of 3)
Tungsten slats
Light transmission
through 1deg. FOV
Mounting Hole
(1 of 3)
TMS pinhole (1 of 4)
TMS annulus (1 of 2)

Modulation vs. Energy




Typical Dimensions
Angular Coverage vs. Photon Energy
1000
100
10
1
Angular Coverage (arcsec)
Yohkoh/SXT
Yohkoh/HXT
(4 energy bins)
HESSI SMEX
(~1 keV resolution)
Grid 9
8
7
6
5
4
3
2
Grid 1
Distance traveled by electron in 50 ms
Sun's Radius
Flare Extent
Footpoint Separation
Footpoint Diameter
1 keV
10 keV
100 keV
1 MeV
10 MeV
Energy
Thermal Plasma (Superhot)
Gamma-ray lines
Nonthermal electrons

Germanium Detector Design

COLLABORATIVE EFFORT OF
UCB, LBNL, ORTEC

MANUFACTURED AT ORTEC

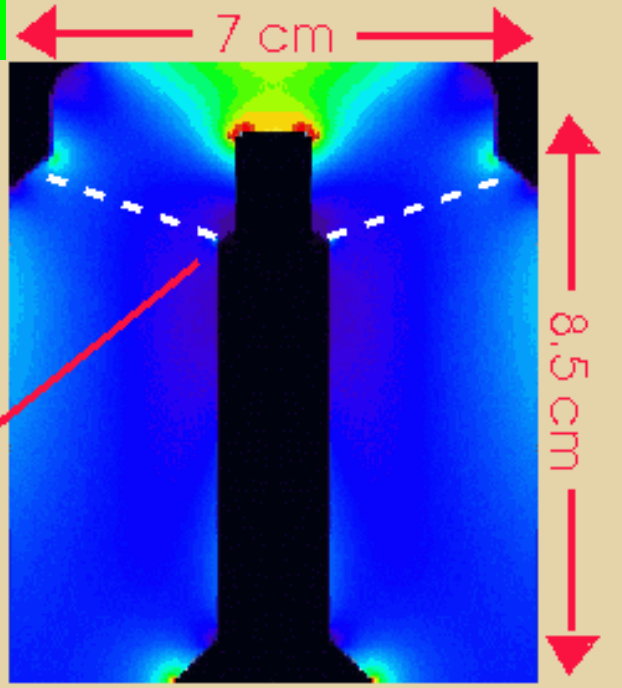
HYPERPURE Ge; SLIGHTLY N–TYPE

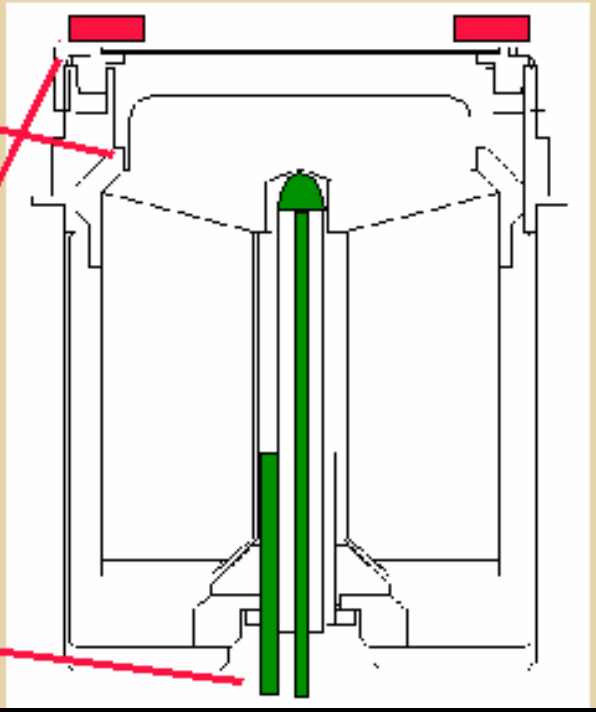
STEP AT INNER Li ELECTRODE
PROVIDES TWO SEGMENTS

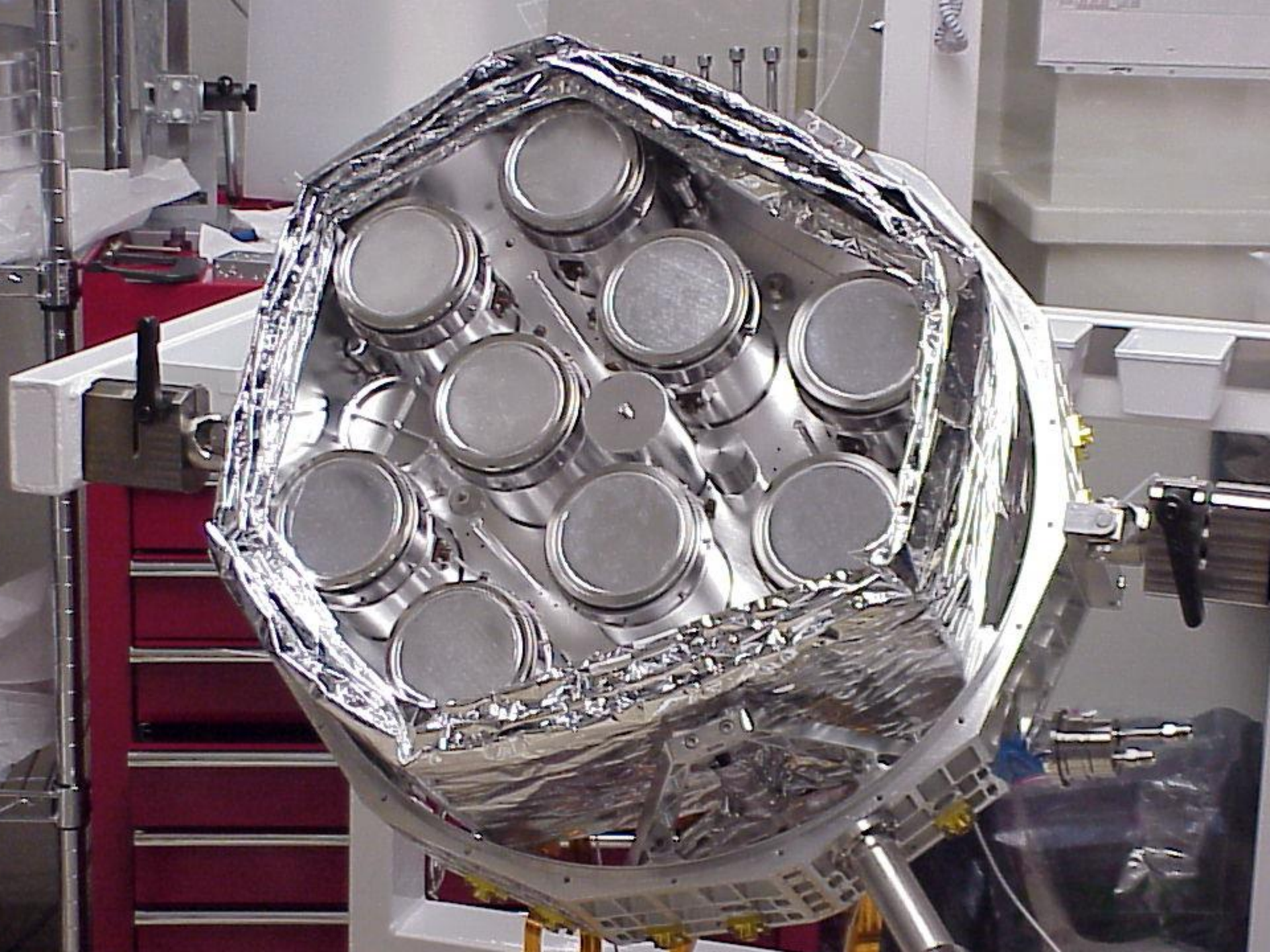
CORNER NOTCH PULLS THE
"CRITICAL" FIELD LINE TO A
PREDICTABLE POSITION

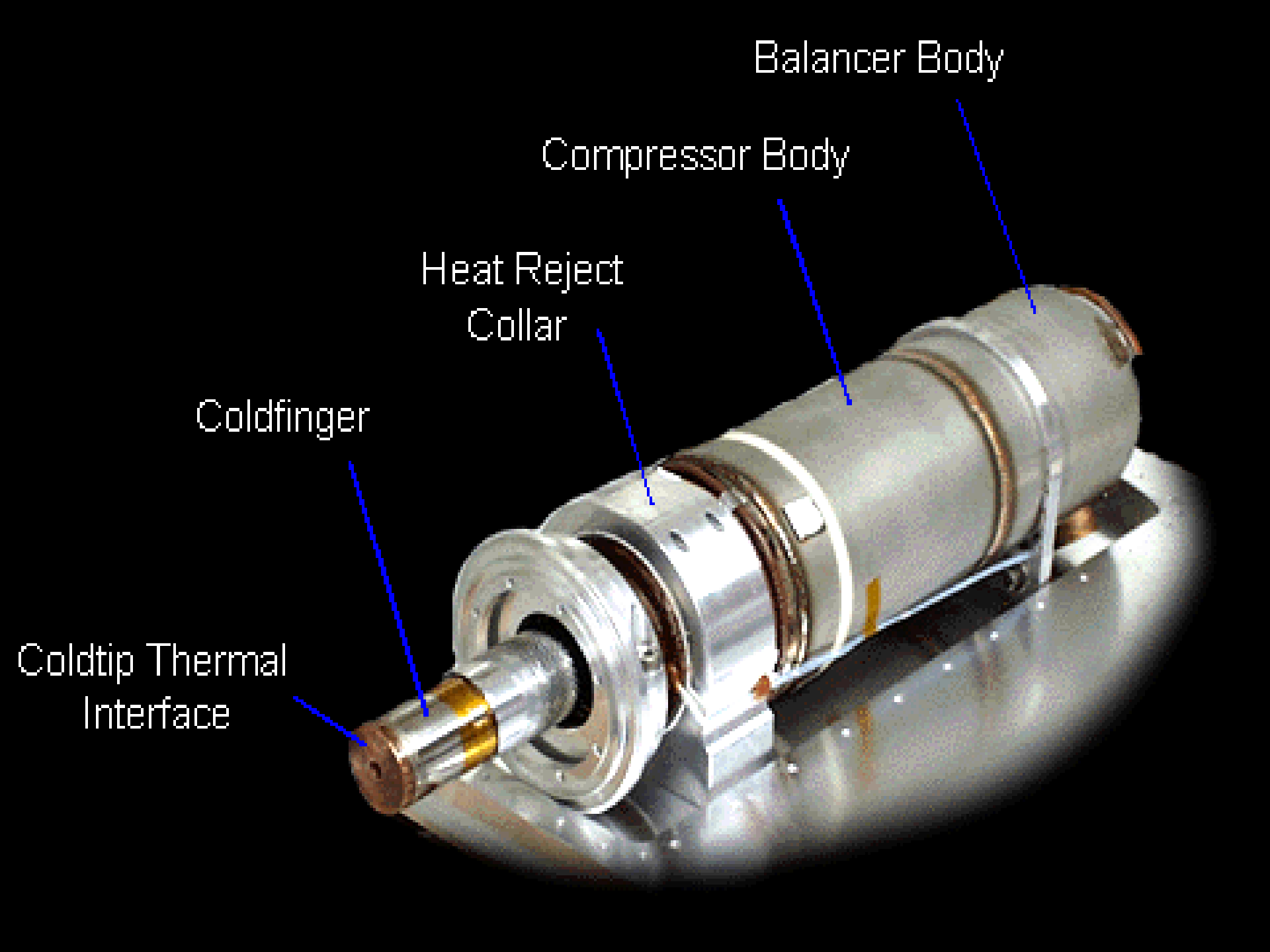
GRADED–Z SHIELDING PROTECTS
THE REAR SEGMENT FROM
SOLAR X–RAYS NOT STOPPED
BY THE FRONT

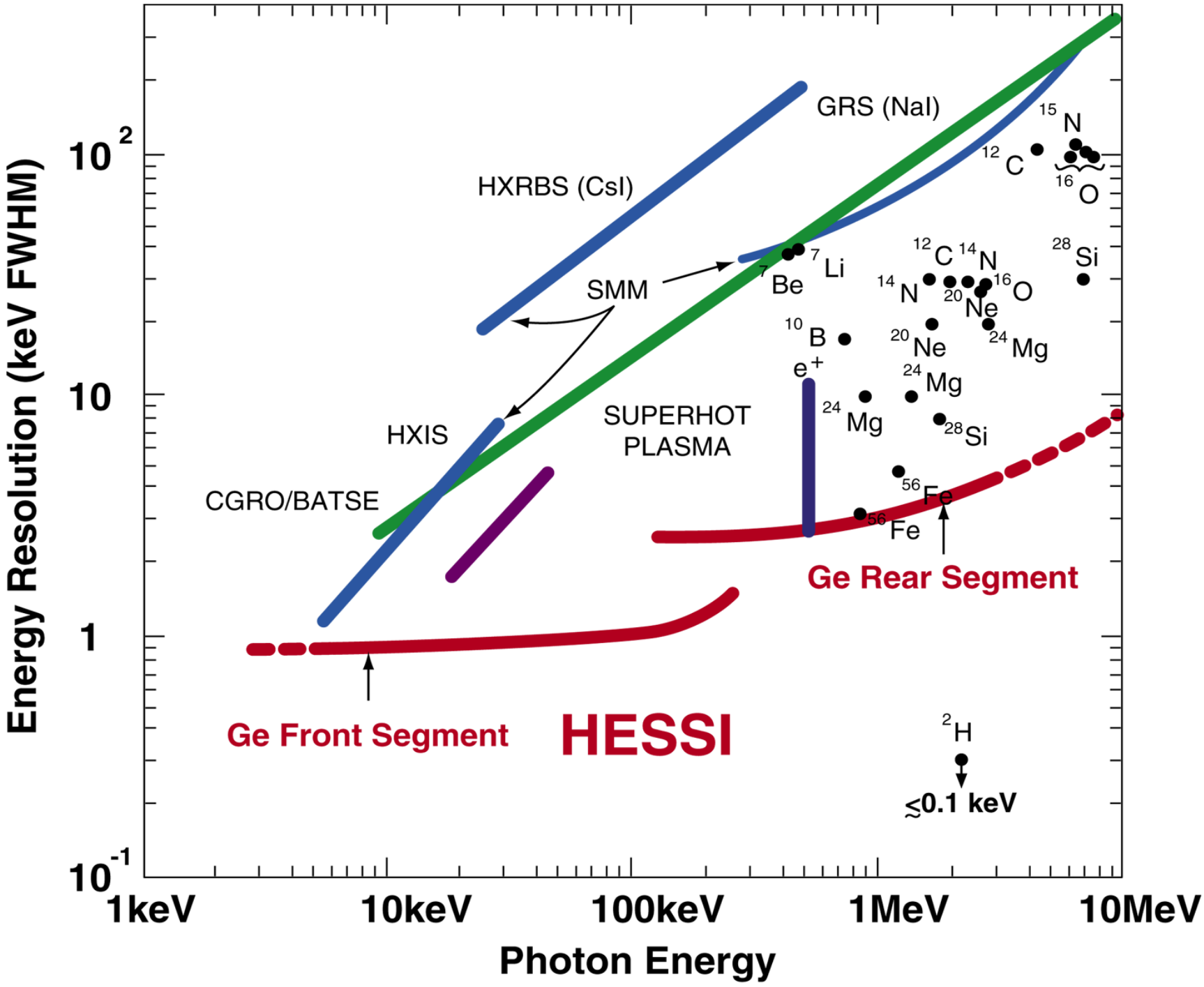
FRONT AND REAR SEGMENTS
READ OUT FROM THE TWO
HALVES OF THE INNER CONTACT

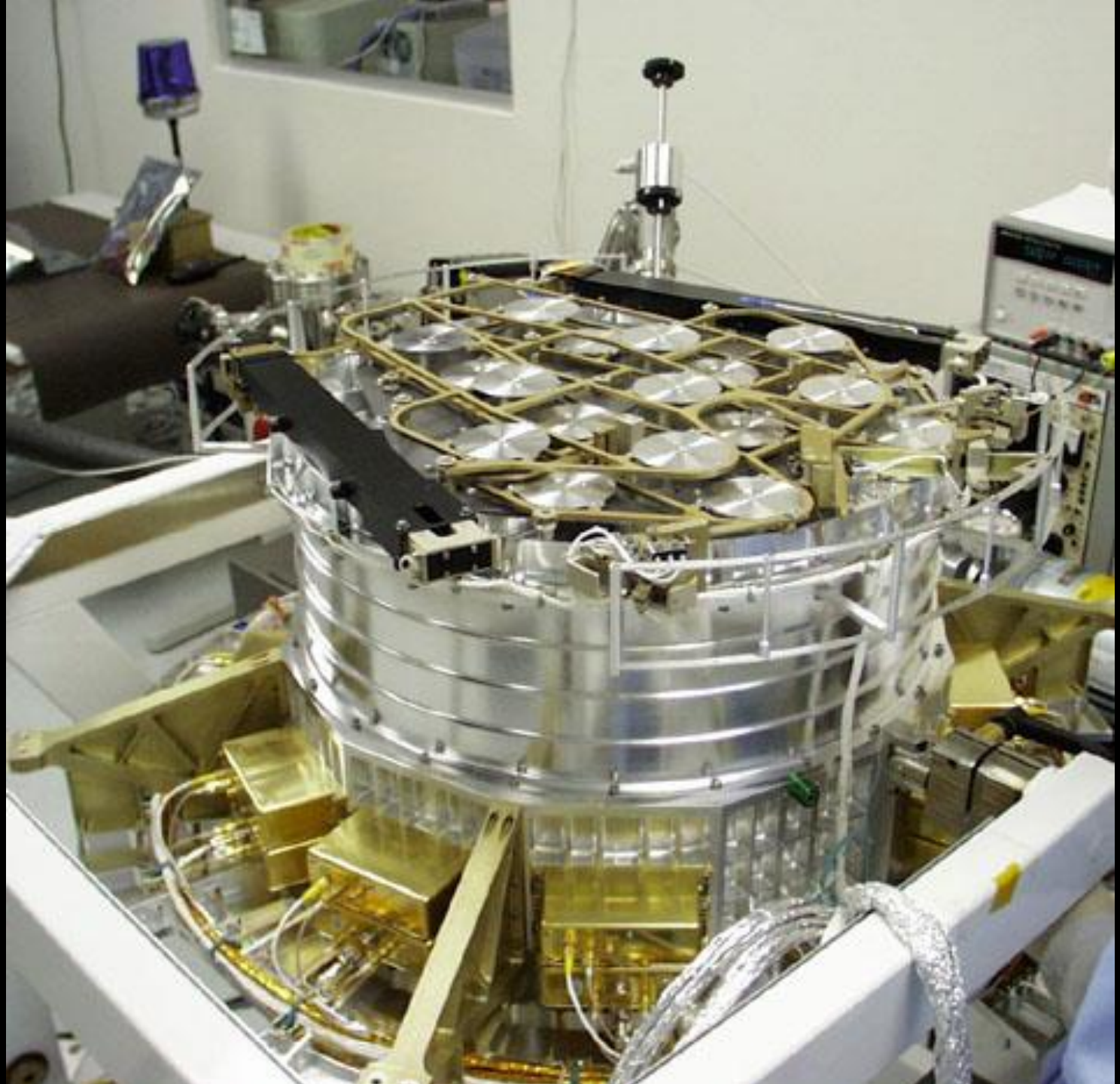




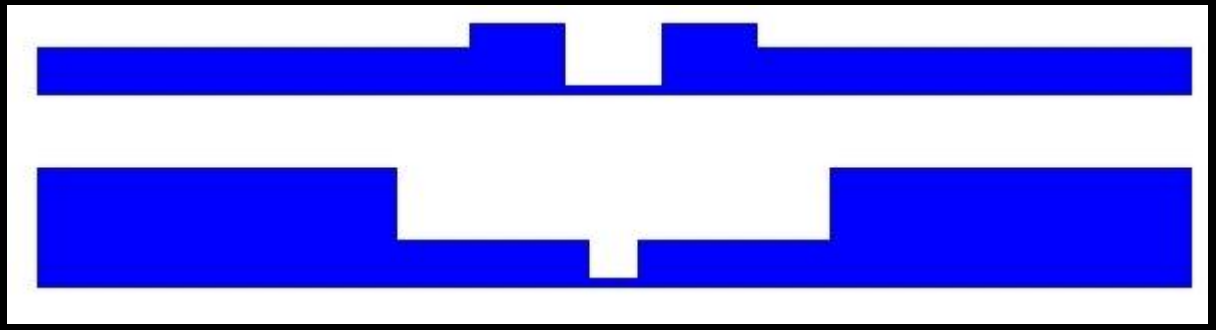



Balancer Body
Compressor Body
Heat Reject
Collar
Coldfinger
Coldtip Thermal
Interface

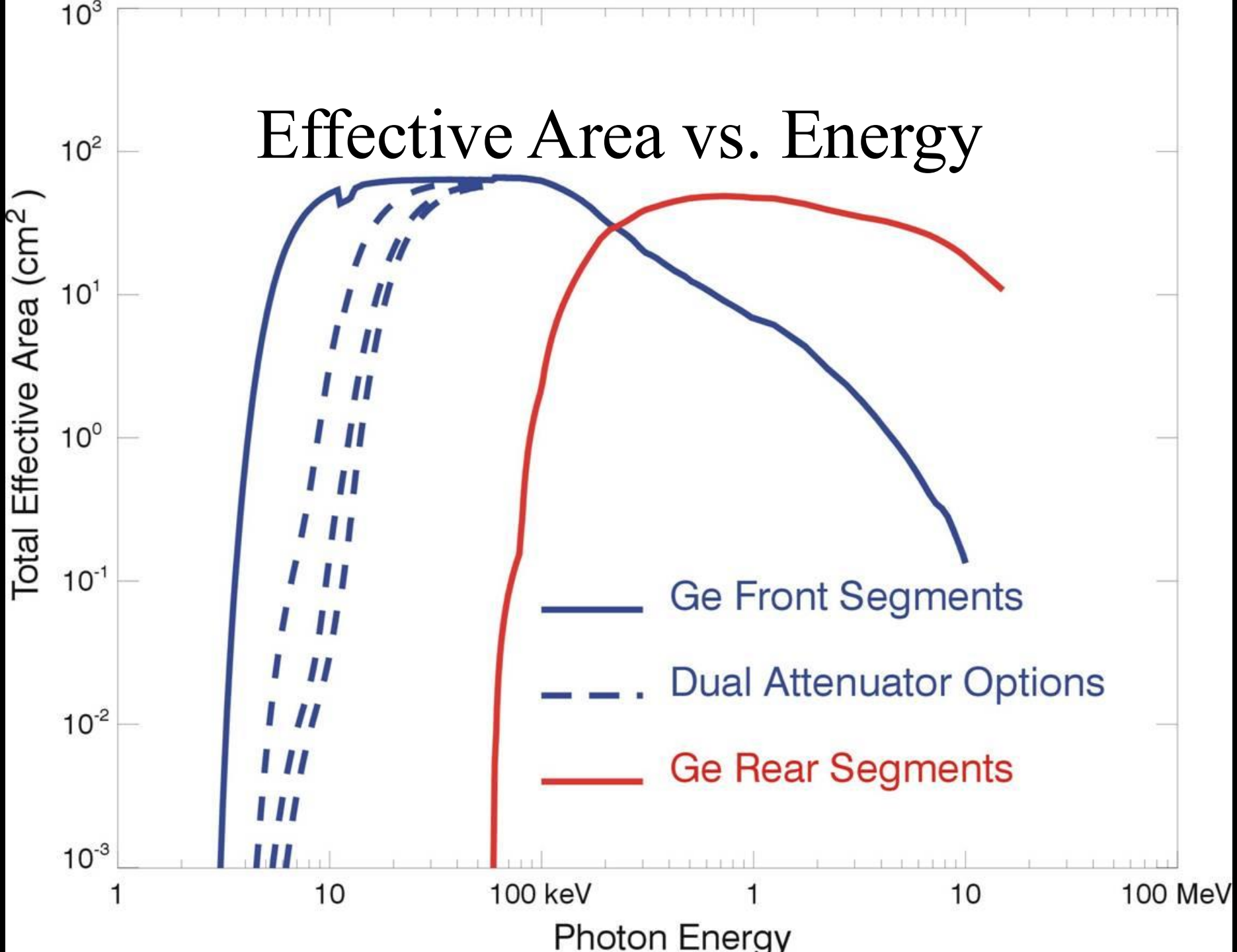

Energy Resolution (keV FWHM)
10 2
10
1
10 -1
1keV
10keV
100keV
1MeV
10MeV
Photon Energy
GRS (NaI)
HXRBS (CsI)
SMM
HXIS
CGRO/BATSE
SUPERHOT
PLASMA
Ge Rear Segment
Ge Front Segment
HESSI
15 N
12 C
16 O
7 Be
7 Li
12 C
14 N
28 Si
14 N
20 Ne
16 O
10 B
20 Ne
24 Mg
e +
24 Mg
24 Mg
28 Si
56 Fe
56 Fe
2 H
≲0.1 keV



#1 Attenuators



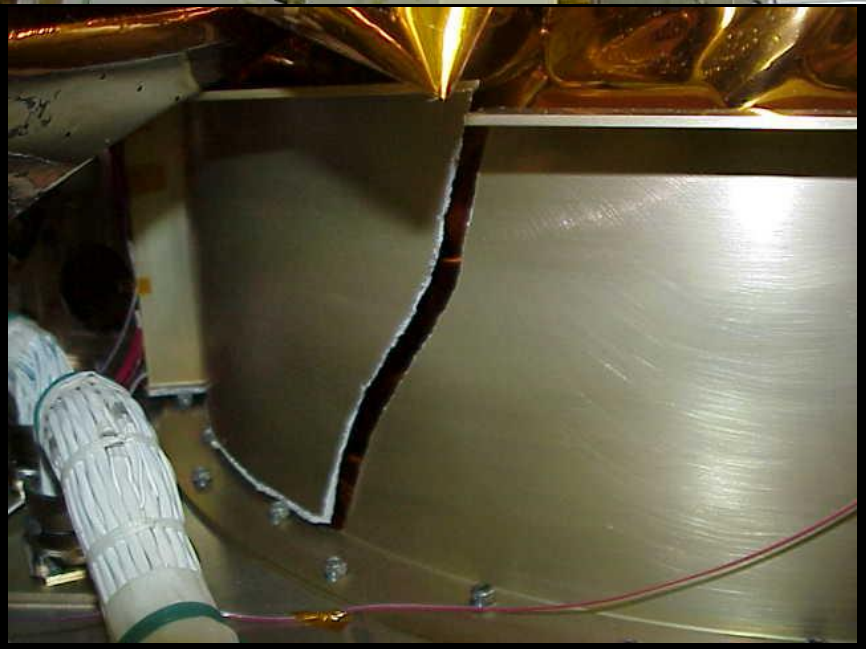
Effective Area vs. Energy



Paul Turin

Dave Pankow

RHESSI vibration test anomaly



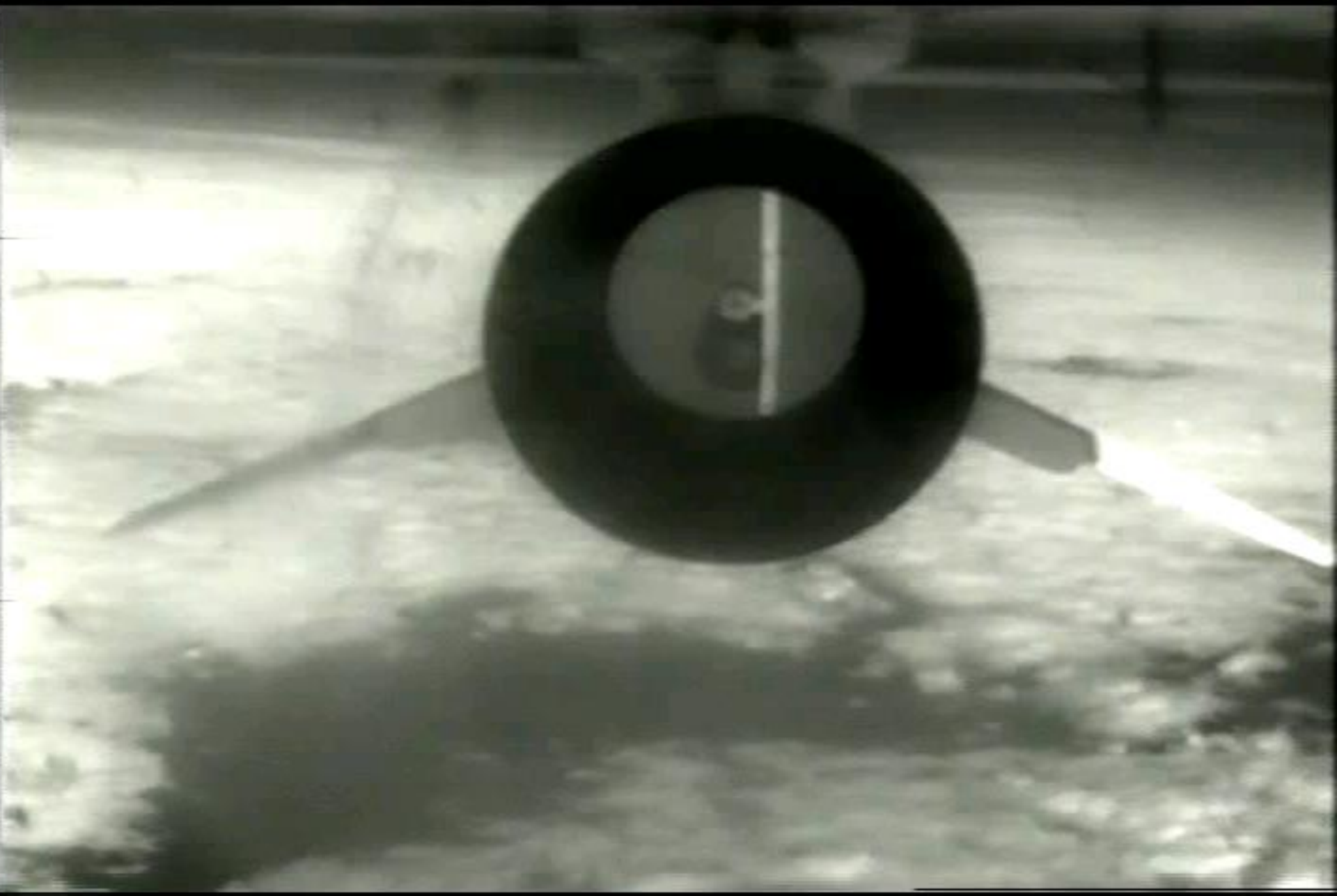
SPACEFLIGHT NOW

Posted: June 4, 2001

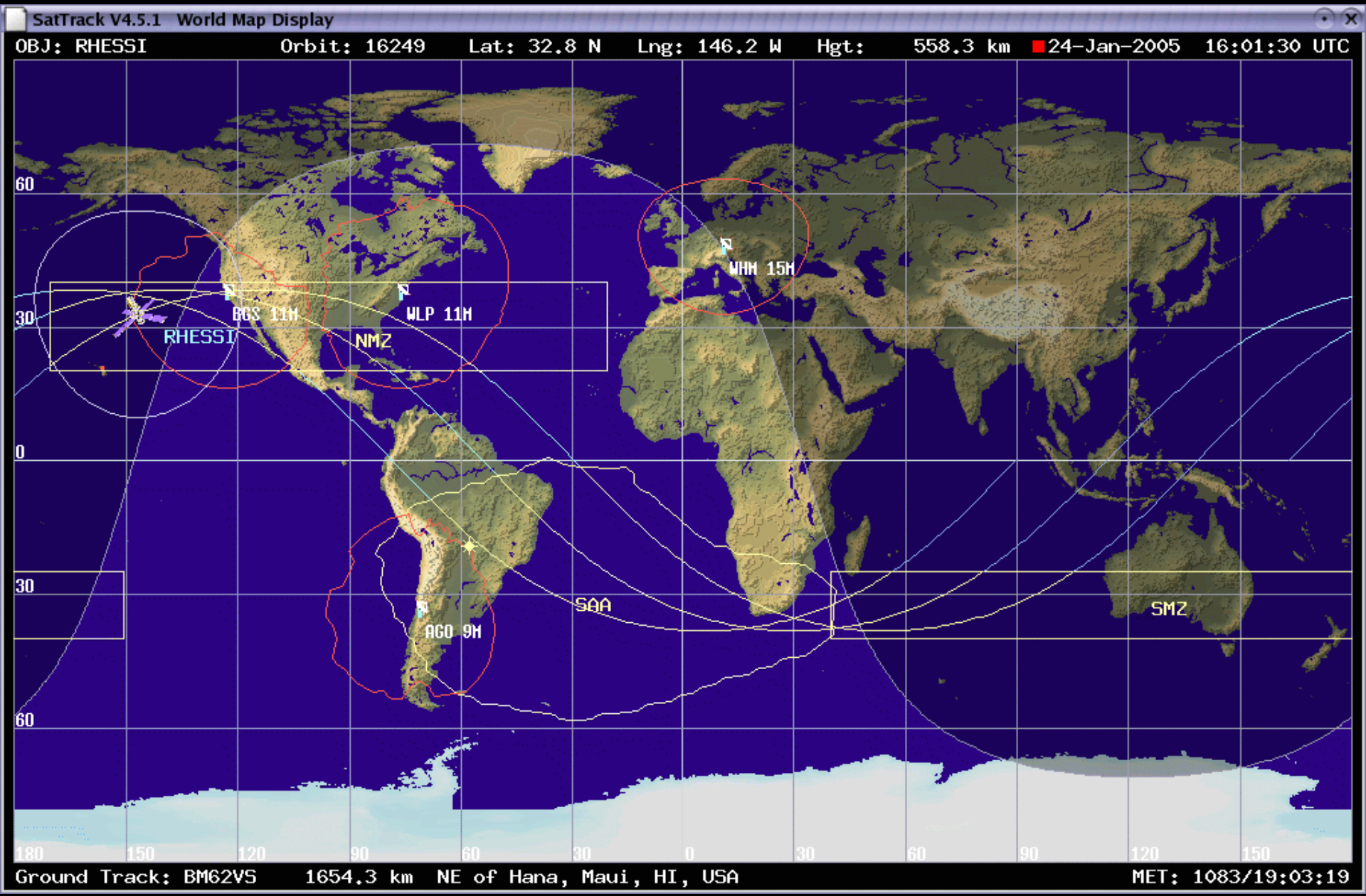
X-43A launch failure

Next Pegasus rocket launch delayed in X-43A aftermath

The High Energy Solar Spectroscopic Imager, or HESSI satellite, was scheduled to rocket into space on Thursday aboard an air-launched Orbital Sciences Pegasus XL booster.

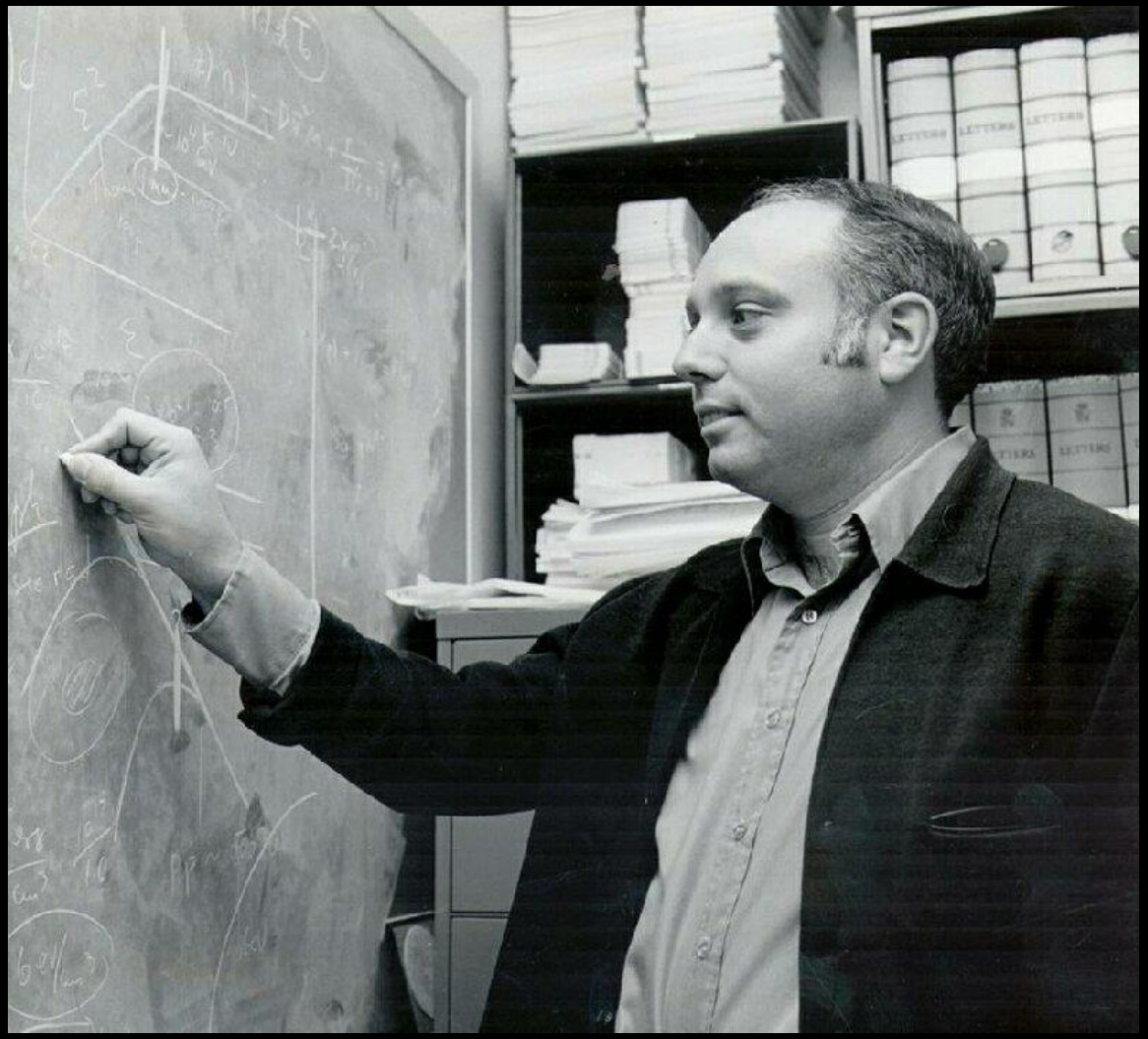


RHESSI launch February 5, 2002

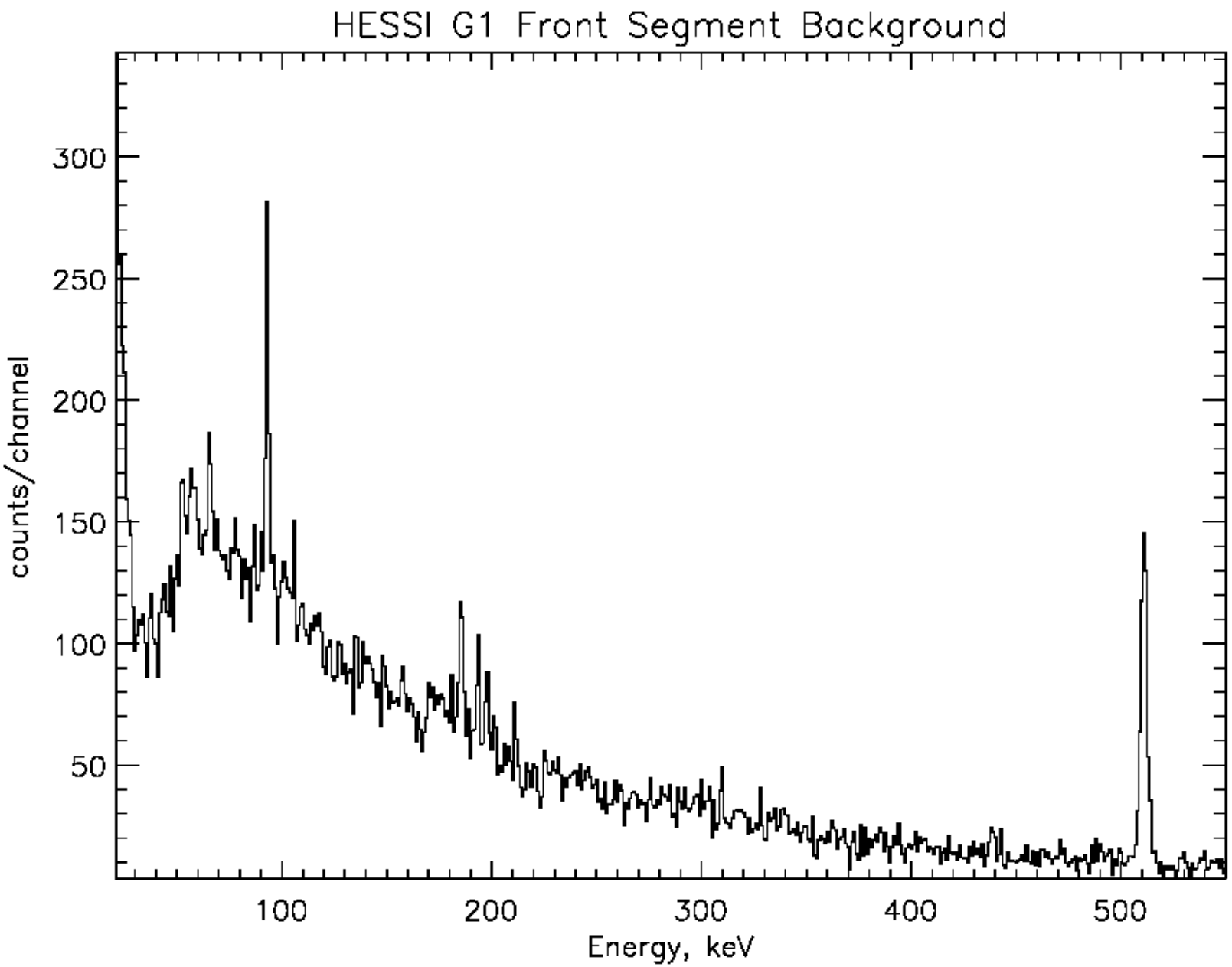

SatTrack V4.5.1 World Map Display
OBJ: RHESSI Orbit: 16249 Lat: 32.8 N Lng: 146.2 W Hgt: 558.3 km 24-Jan-2005 16:01:30 UTC
60
30
0
30
60
BGS 11M
WLP 11M
WHM 15M
RHESSI
NMZ
SAA
AGO 9M
SMZ
180
150
120
90
60
30
0
30
60
90
120
150
Ground Track: BM62VS 1654.3 km NE of Hana, Maui, HI, USA
MET: 1083/19:03:19

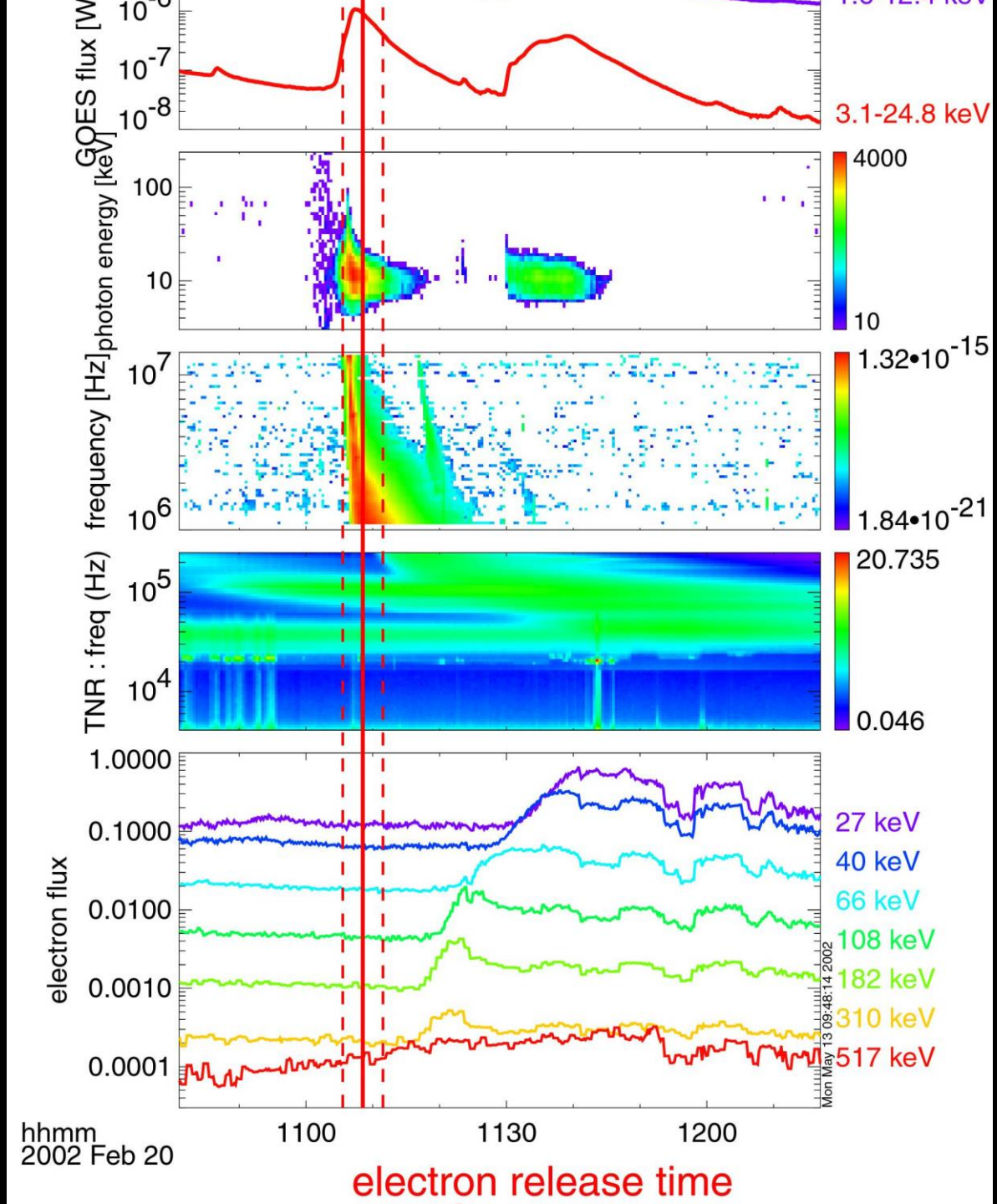
U.C. Berkeley Mission Operations Center

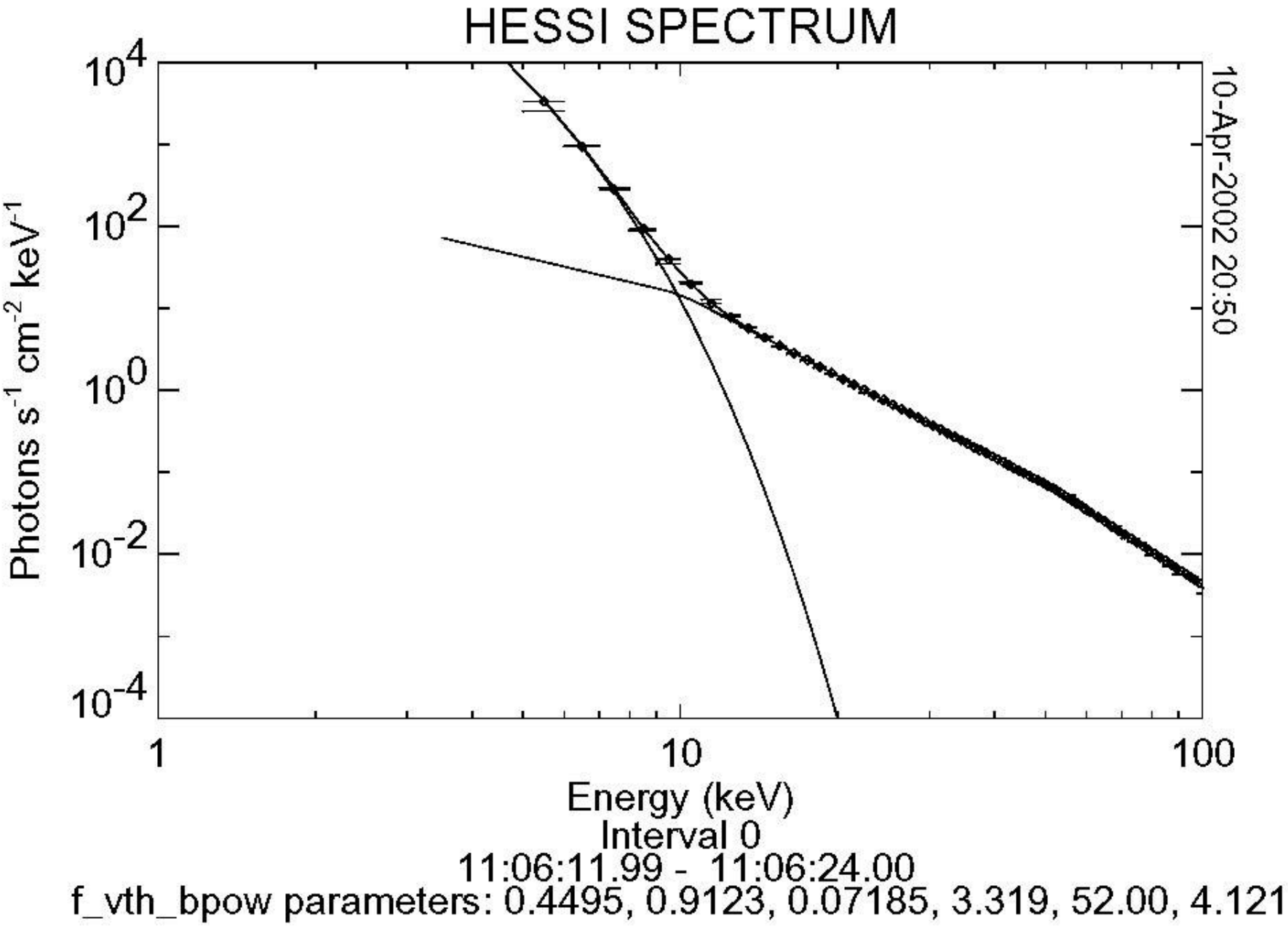
BGS Antenna, Equipment Racks and FOT Workstations at the UCB Mission Operations Center



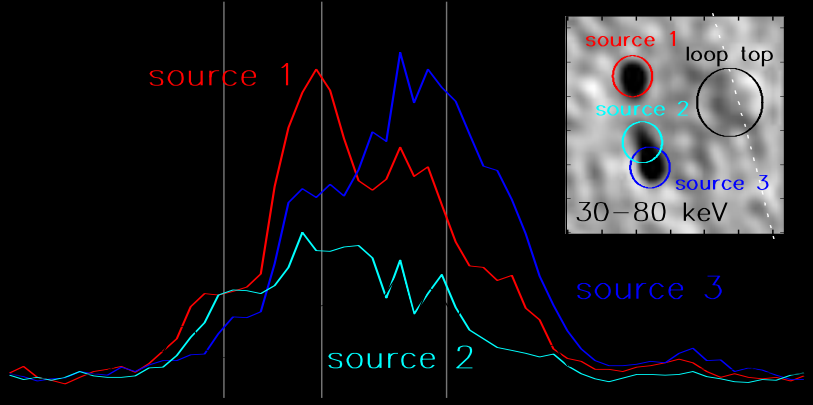
Reuven Ramaty (1972)
1937 – 2001

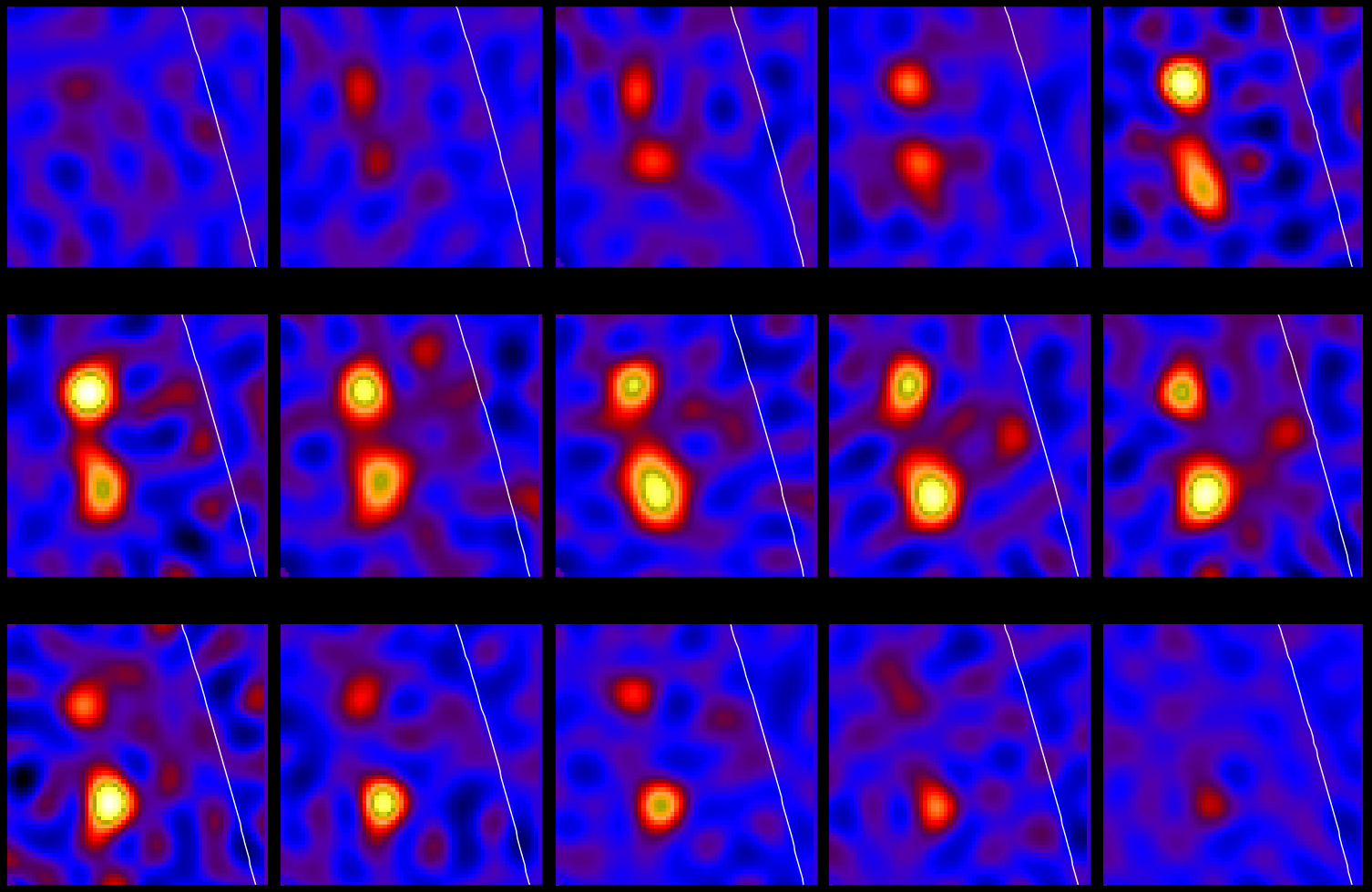

HESSI G1 Front Segment Background
counts/channel
300
250
200
150
100
50
100
200
300
400
500
Energy, keV

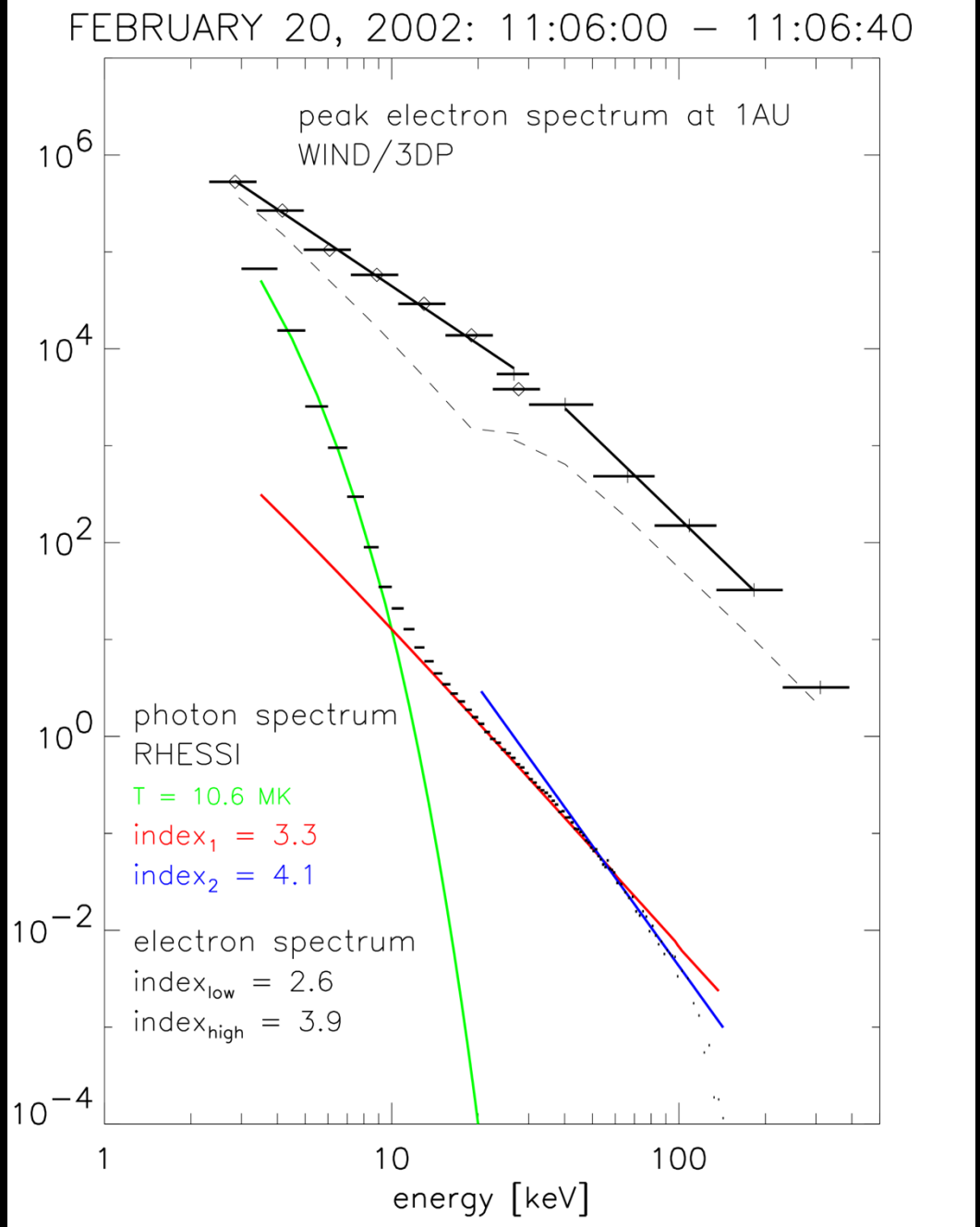

GOES flux [W
10^-6
10^-7
10^-8
3.1-24.8 keV
photon energy [keV]
100
10
4000
10
frequency [Hz]
10^7
10^6
1.32•10^-15
1.84•10^-21
TNR : freq (Hz)
10^5
10^4
20.735
0.046
electron flux
1.0000
0.1000
0.0100
0.0010
0.0001
27 keV
40 keV
66 keV
108 keV
182 keV
310 keV
517 keV
Mon May 13 09:48:14 2002
hhmm
2002 Feb 20
1100
1130
1200
electron release time


HESSI SPECTRUM
10-Apr-2002 20:50
Photons s-1 cm-2 keV-1
10^4
10^2
10^0
10^-2
10^-4
1
10
100
Energy (keV)
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

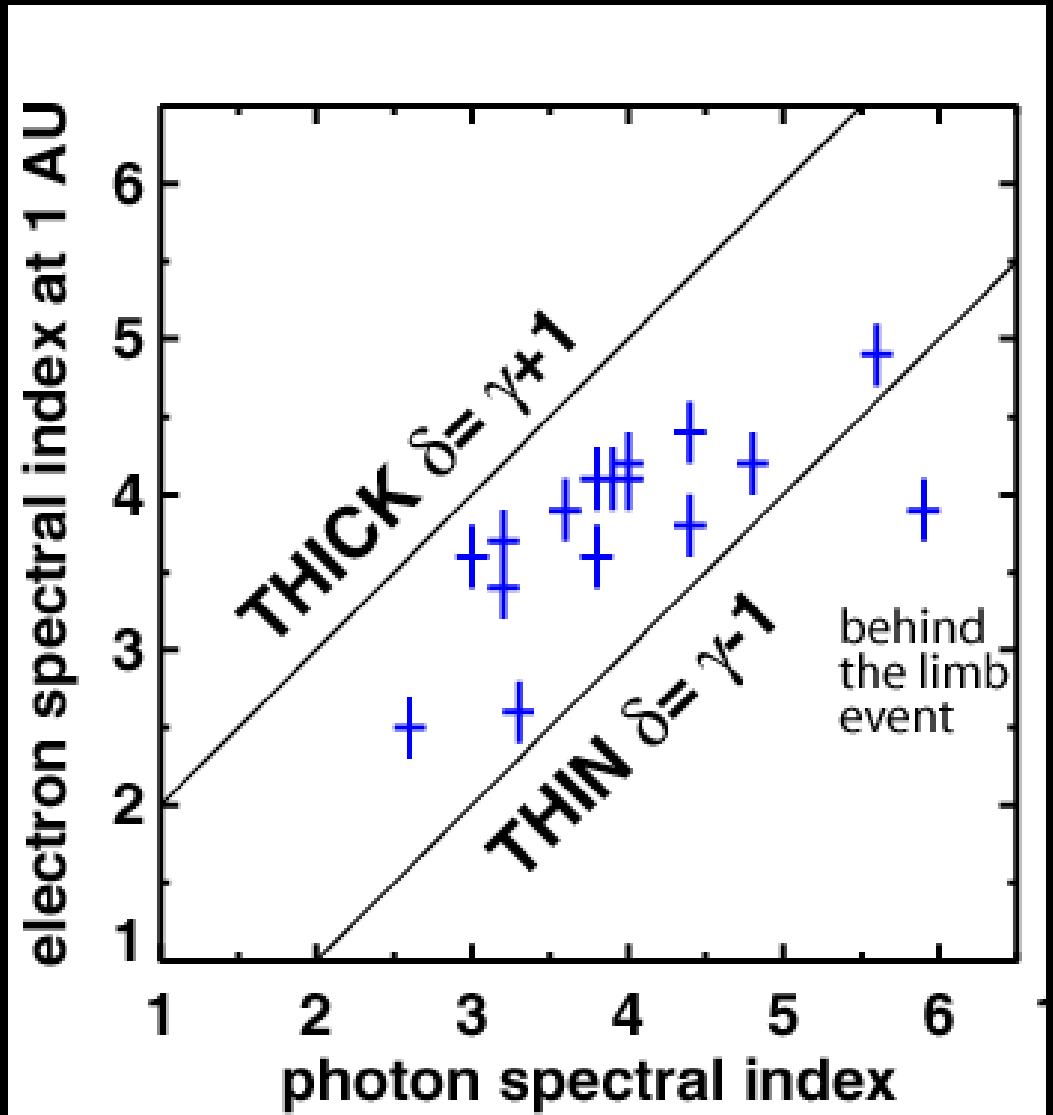
30-80 keV
64”x64”
(Krucker and Lin 2002)






FEBRUARY 20, 2002: 11:06:00 – 11:06:40
peak electron spectrum at 1AU
WIND/3DP
photon spectrum
RHESSI
T = 10.6 MK
index1 = 3.3
index2 = 4.1
electron spectrum
indexlow = 2.6
indexhigh = 3.9
10^6
10^4
10^2
10^0
10^-2
10^-4
1
10
100
energy [keV]

Comparing spectra



PHOTON SPECTRA:
Power law fit to HXR spectra averaged over peak

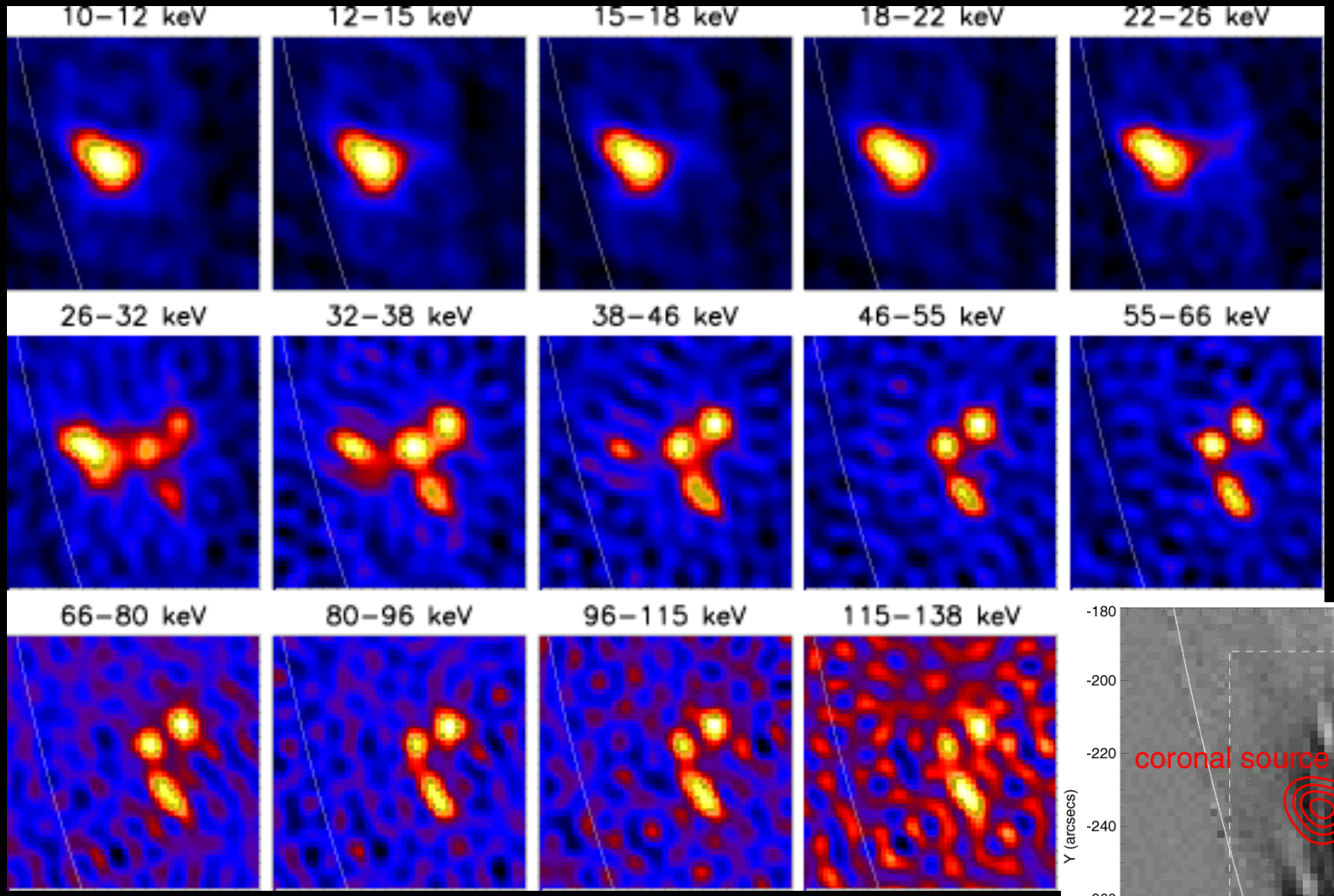
ELECTRON SPECTRA:
Power law fit to peak flux

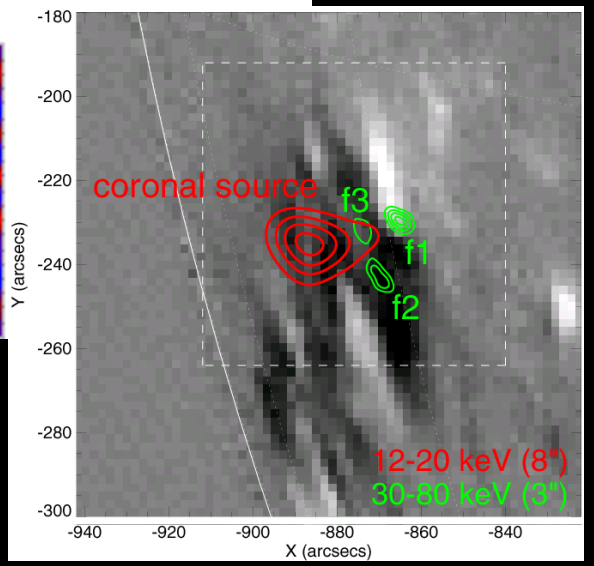
Assuming power spectra:

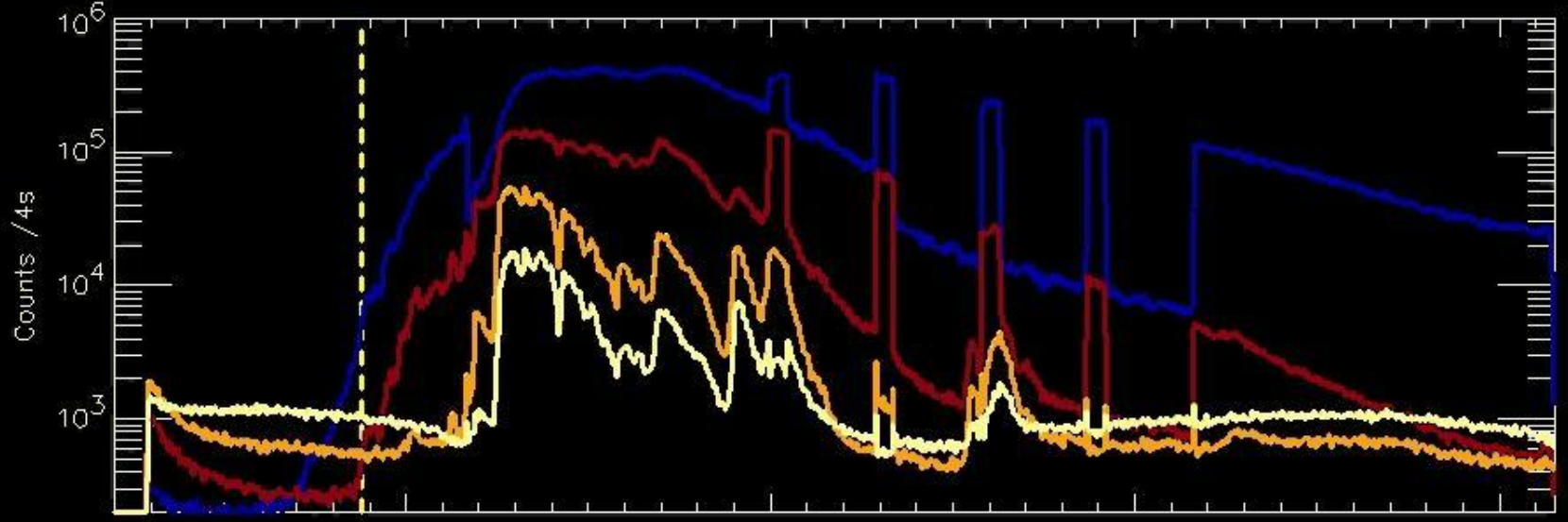
THIN: $d = g - 1$
THICK: $d = g + 1$

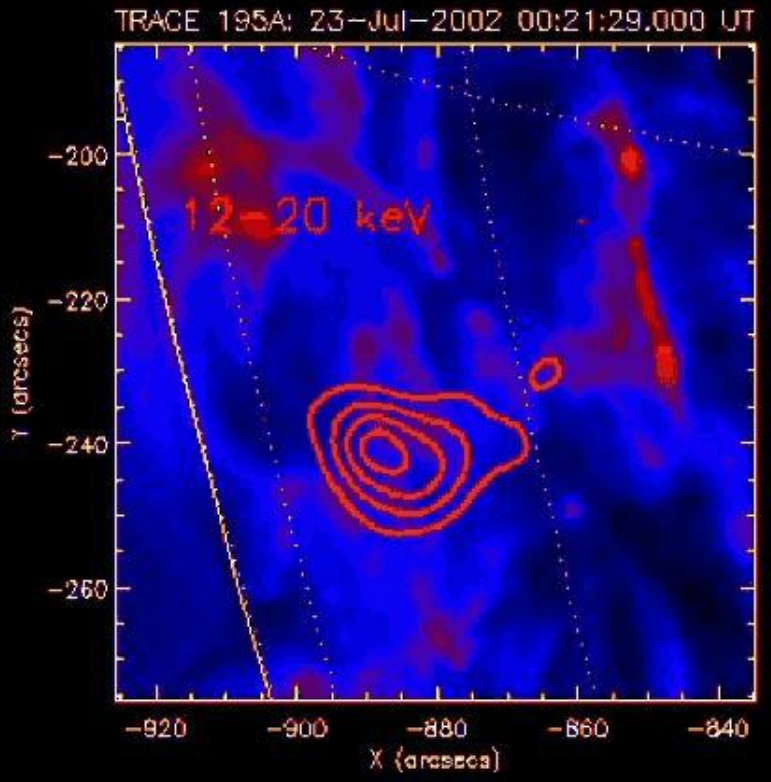
RESULTS:
1) correlation seen
2) values are between

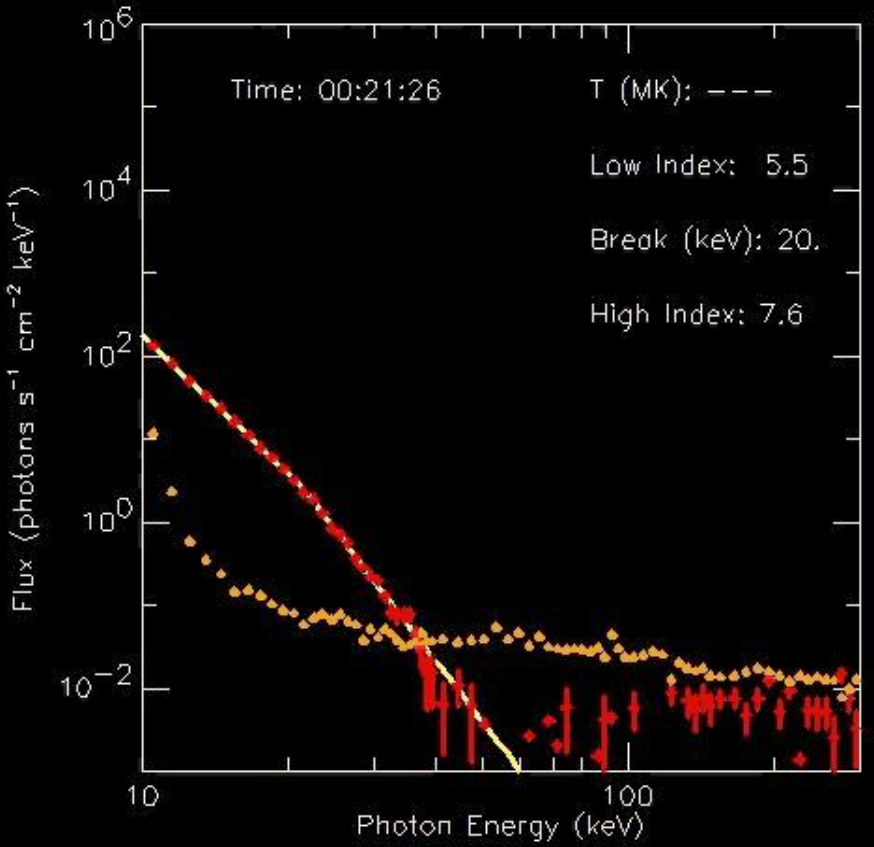
Imaging spectroscopy



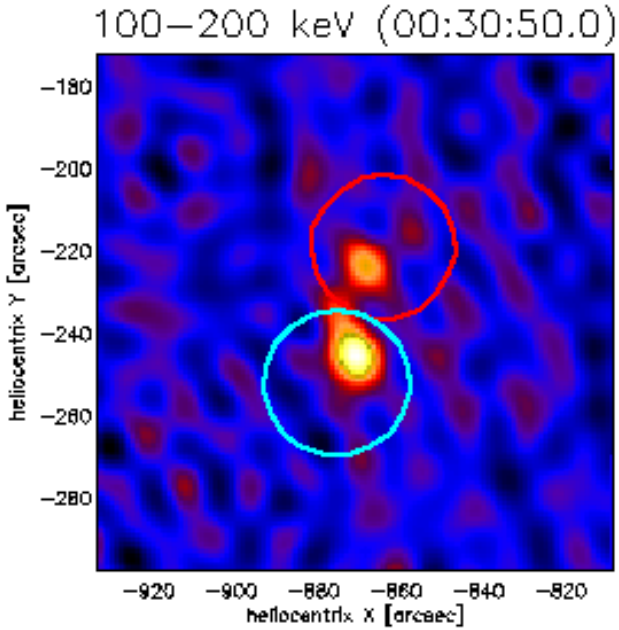


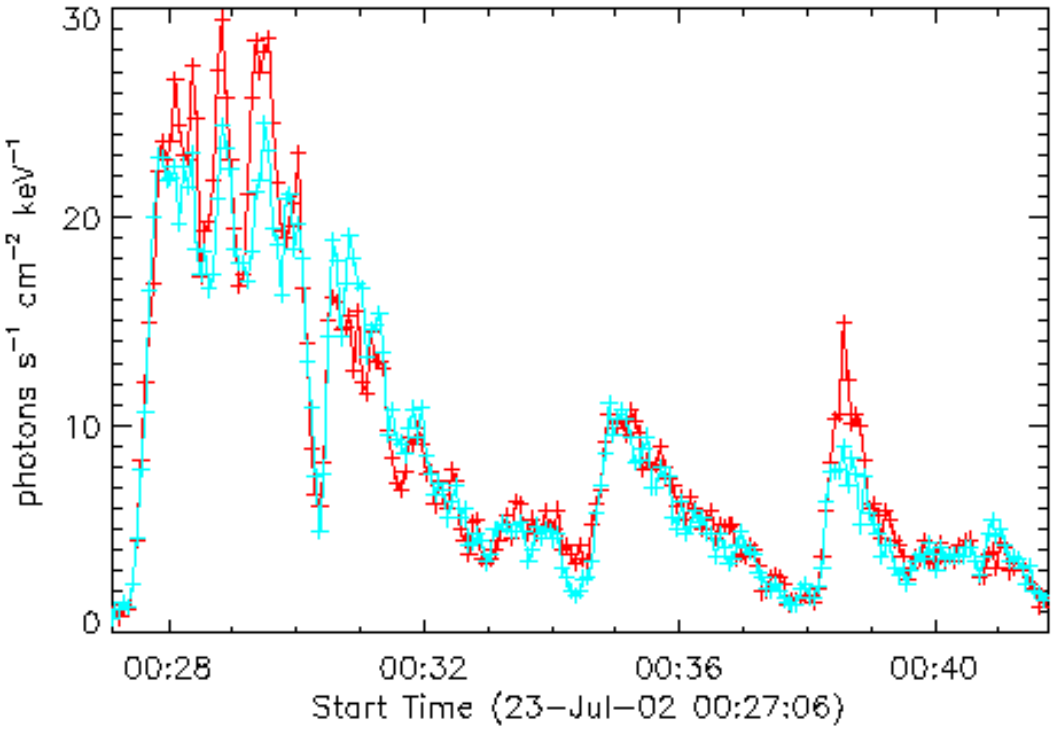

Counts /4s
10^6
10^5
10^4
10^3

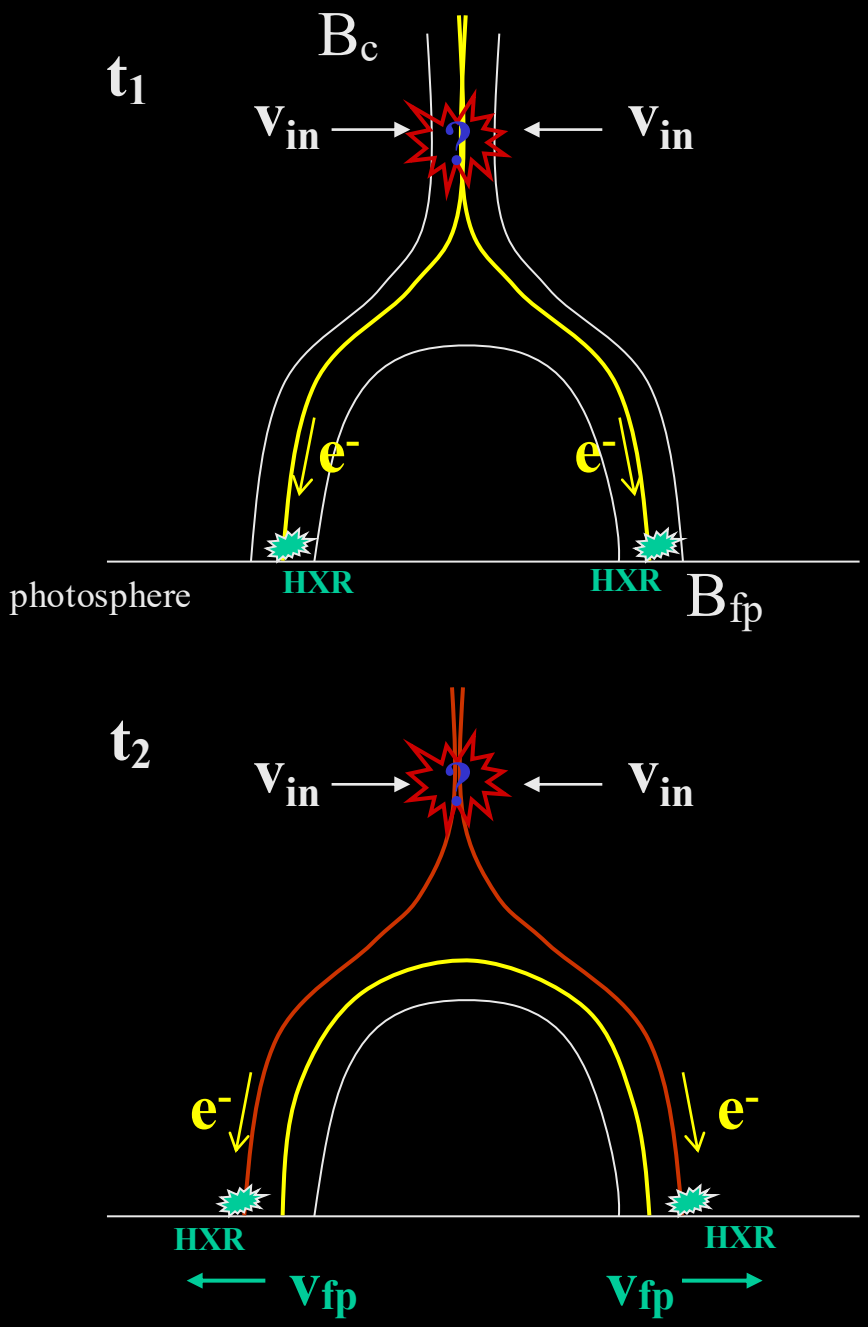

TRACE 195A: 23-Jul-2002 00:21:29.000 UT
12-20 keV
Y (arcsecs)
-200
-220
-240
-260
-920
-900
-880
-860
-840
X (arcsecs)


Time: 00:21:26
T (MK): ---
Low Index: 5.5
Break (keV): 20.
High Index: 7.6
Flux (photons s^{-1} cm^{-2} keV^{-1})
10^6
10^4
10^2
10^0
10^{-2}
10
100
Photon Energy (keV)

Krucker & Lin 2004







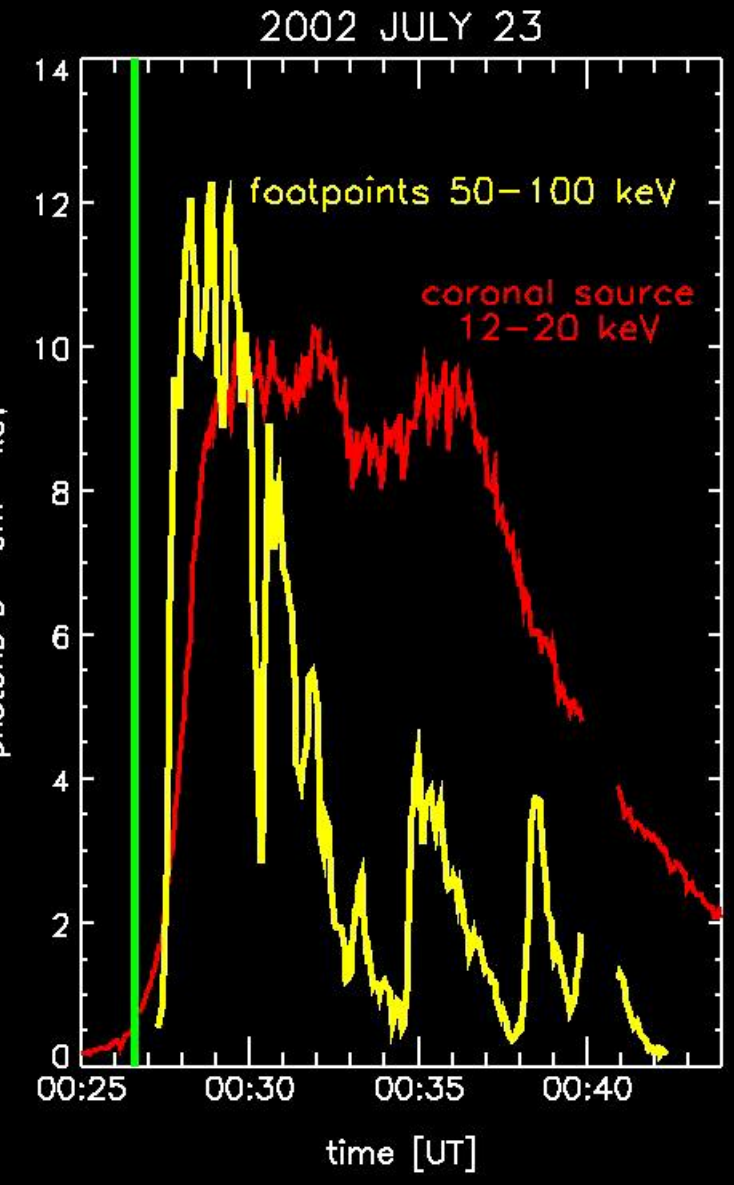
HXR source motions in magnetic reconnection models

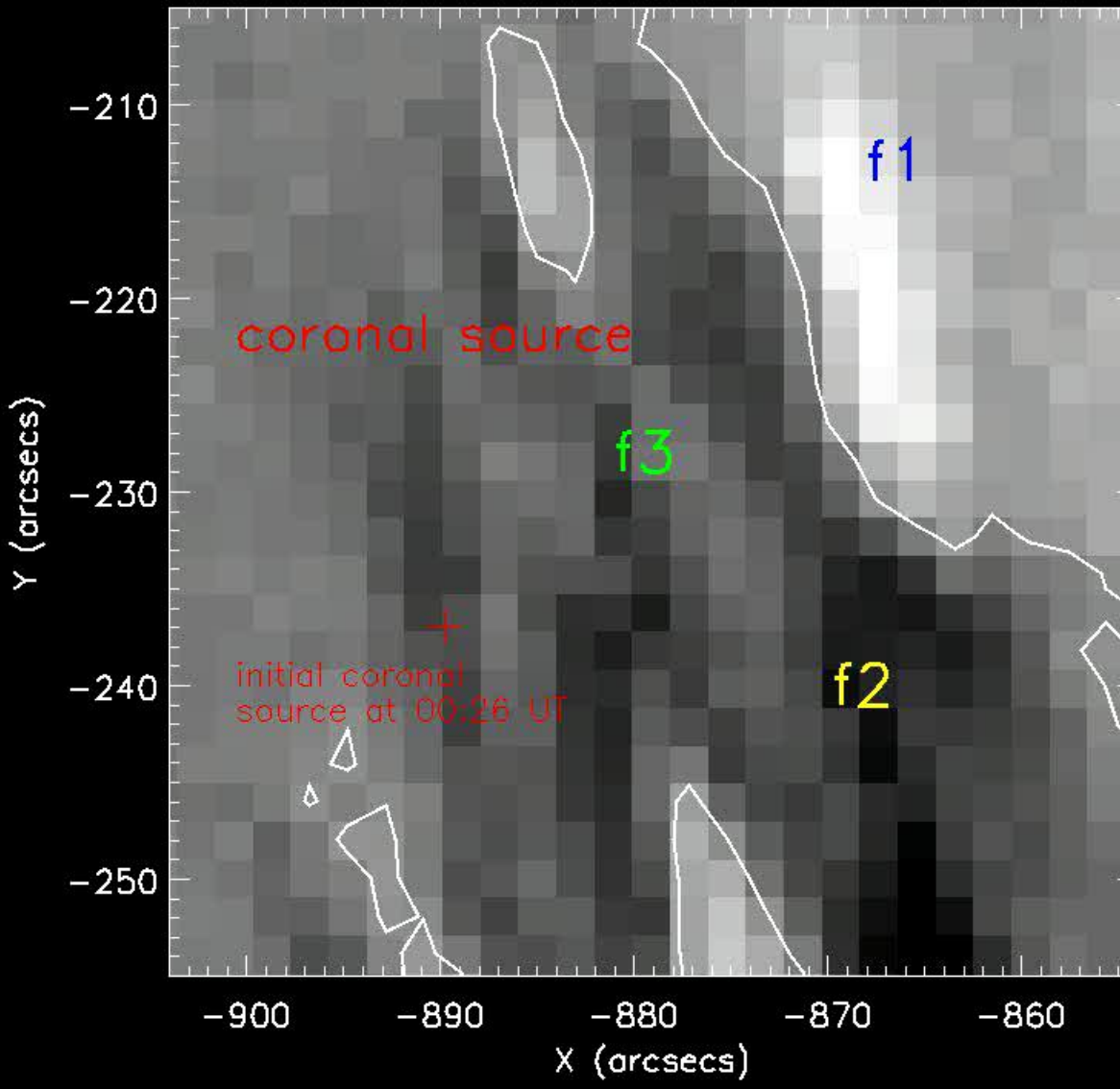
Yohkoh observations:
Sakao et al. 1994, 1995

Simple motion in 2 dimensions; in 3 dimensions motion is likely more complex.

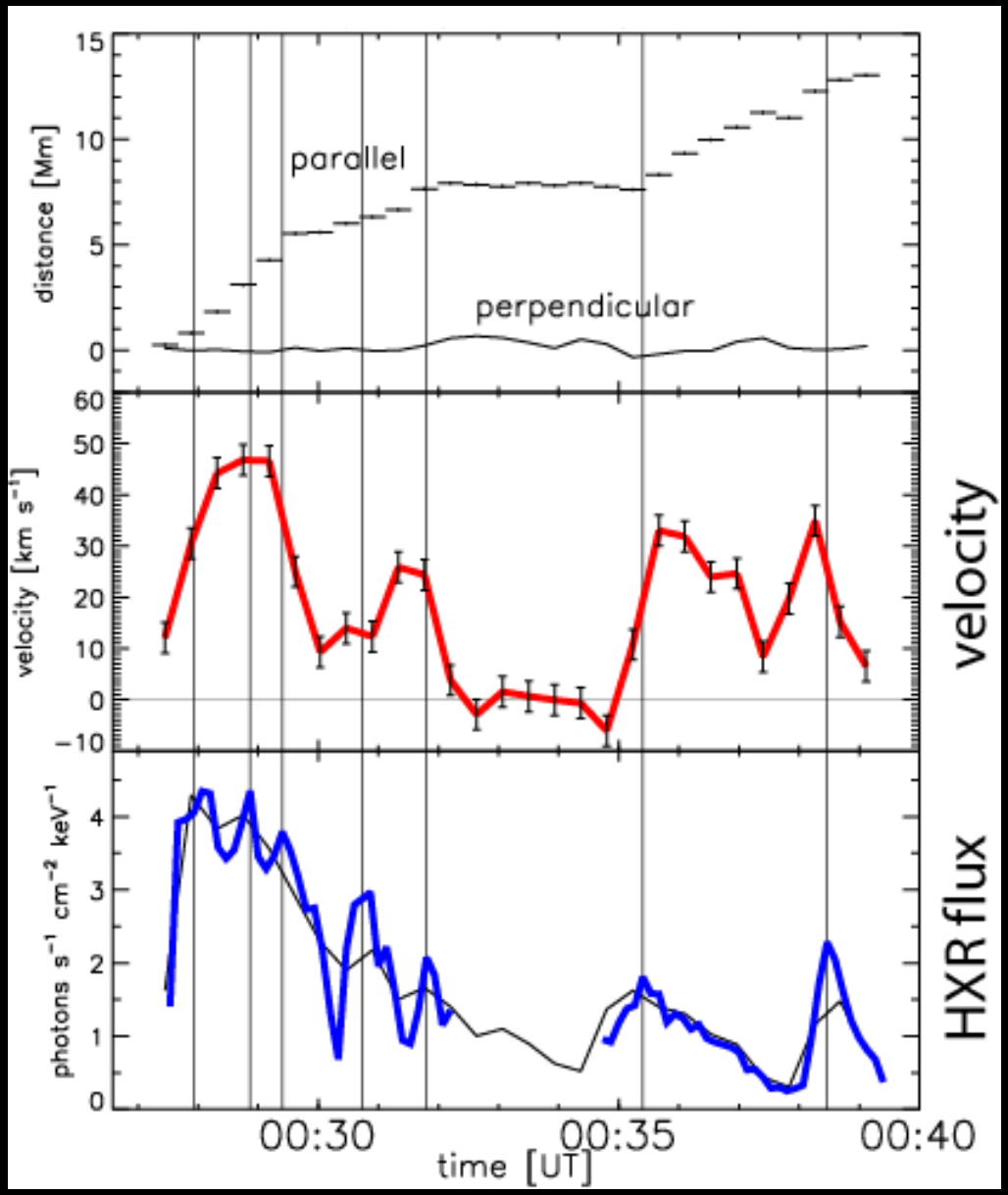
v_{in} and B_c are difficult to observe; Easier to observed are v_{fp} and B_{fp}

v_{in} = coronal inflow velocity
v_{fp} = footpoint velocity
B_c = coronal magnetic field strength
B_{fp} = magnetic field strength in HXR source
~ photospheric value


2002 JULY 23
footpoints 50–100 keV
coronal source
12–20 keV
14
12
10
8
6
4
2
0
00:25
00:30
00:35
00:40
time [UT]


f1
coronal source
f3
initial coronal
source at 00:26 UT
f2
−210
−220
−230
−240
−250
Y (arcsecs)
−900
−890
−880
−870
−860
X (arcsecs)

Velocity-HXR flux correlation



Rough correlation between v and HXR flux

$dF = B\ v\ a\ dt$

Reconnection rate

$dF/dt = B\ v\ a$

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

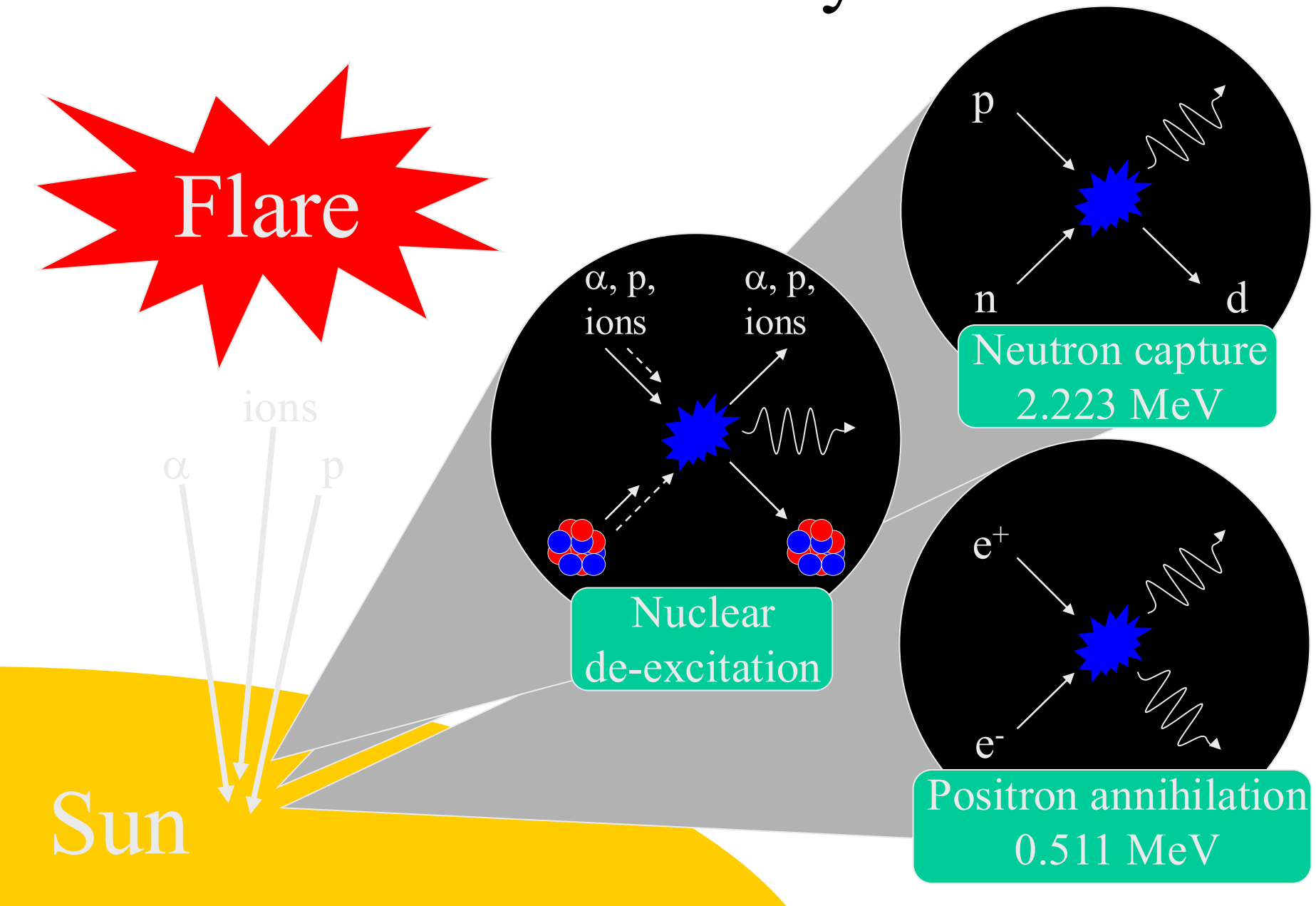
$E = vB \sim 5$ kV/m

v= velocity

B= magnetic field strength

a=footpoint diameter

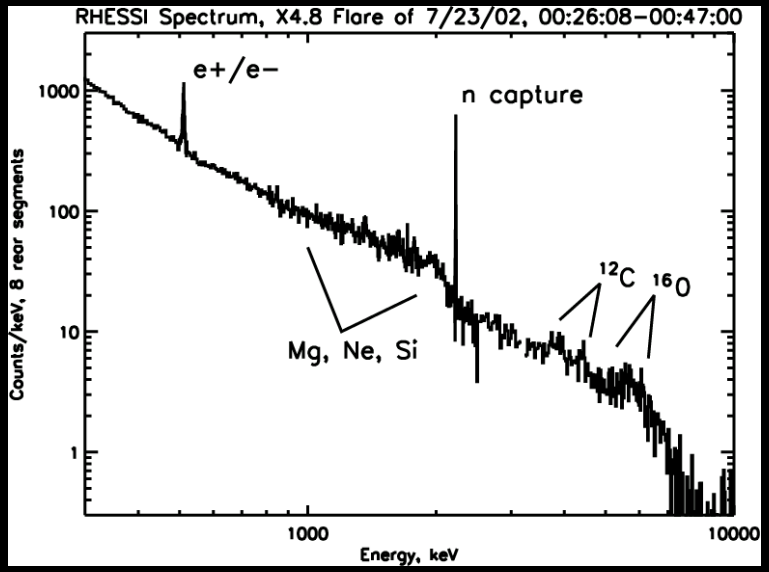
Solar Gamma Rays Lines

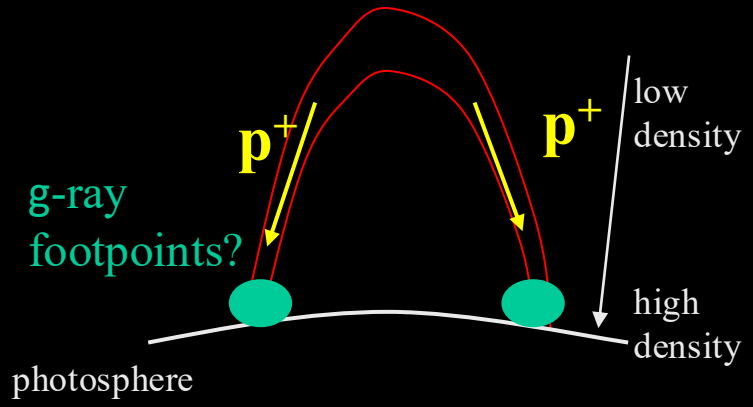


g-ray imaging with RHESSI

Gordon Hurford et al. 2003, 2004

- Before RHESSI, no imaging in the g-ray range available
- RHESSI g-ray imaging at 35” and 180” resolution (compared to 2” for HXRs, i.e. electrons)
- Low photon statistics: integration over total flare duration needed
- 2.2MeV line is best candidate

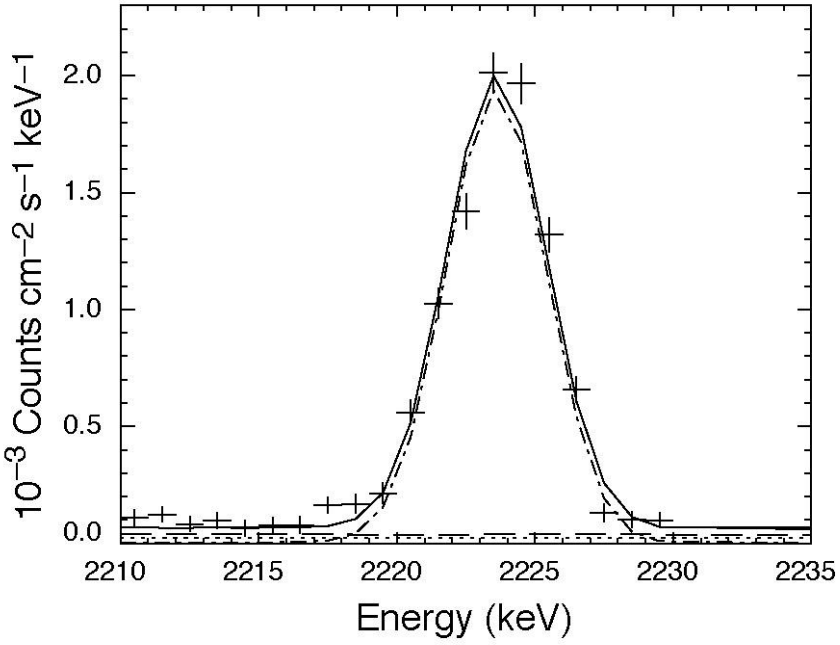


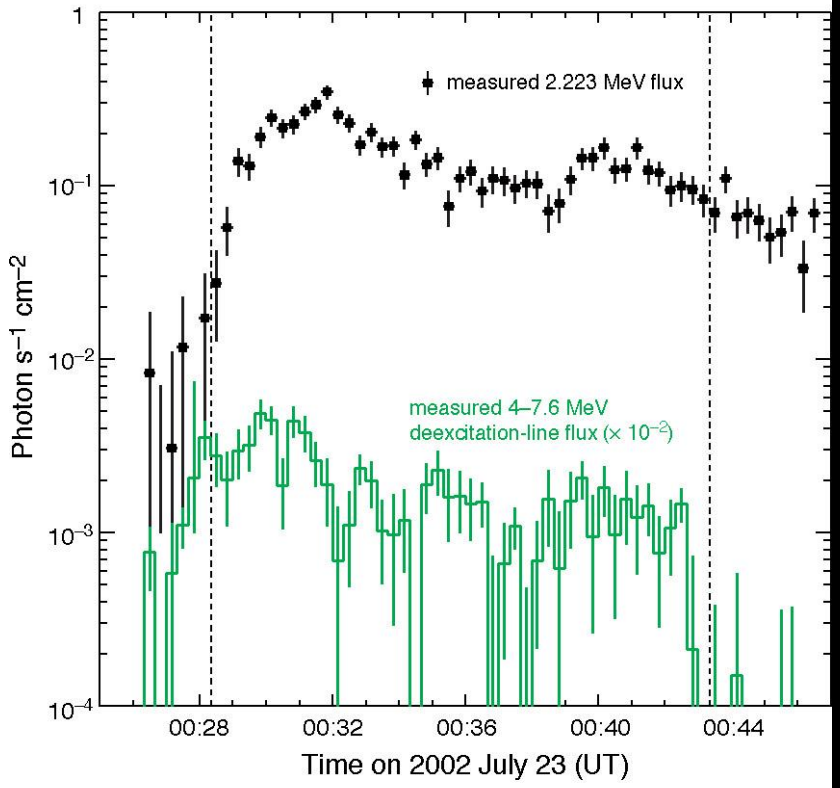


Where are the g-ray footpoints relative to the HXR footpoints?

Murphy et al. 2003

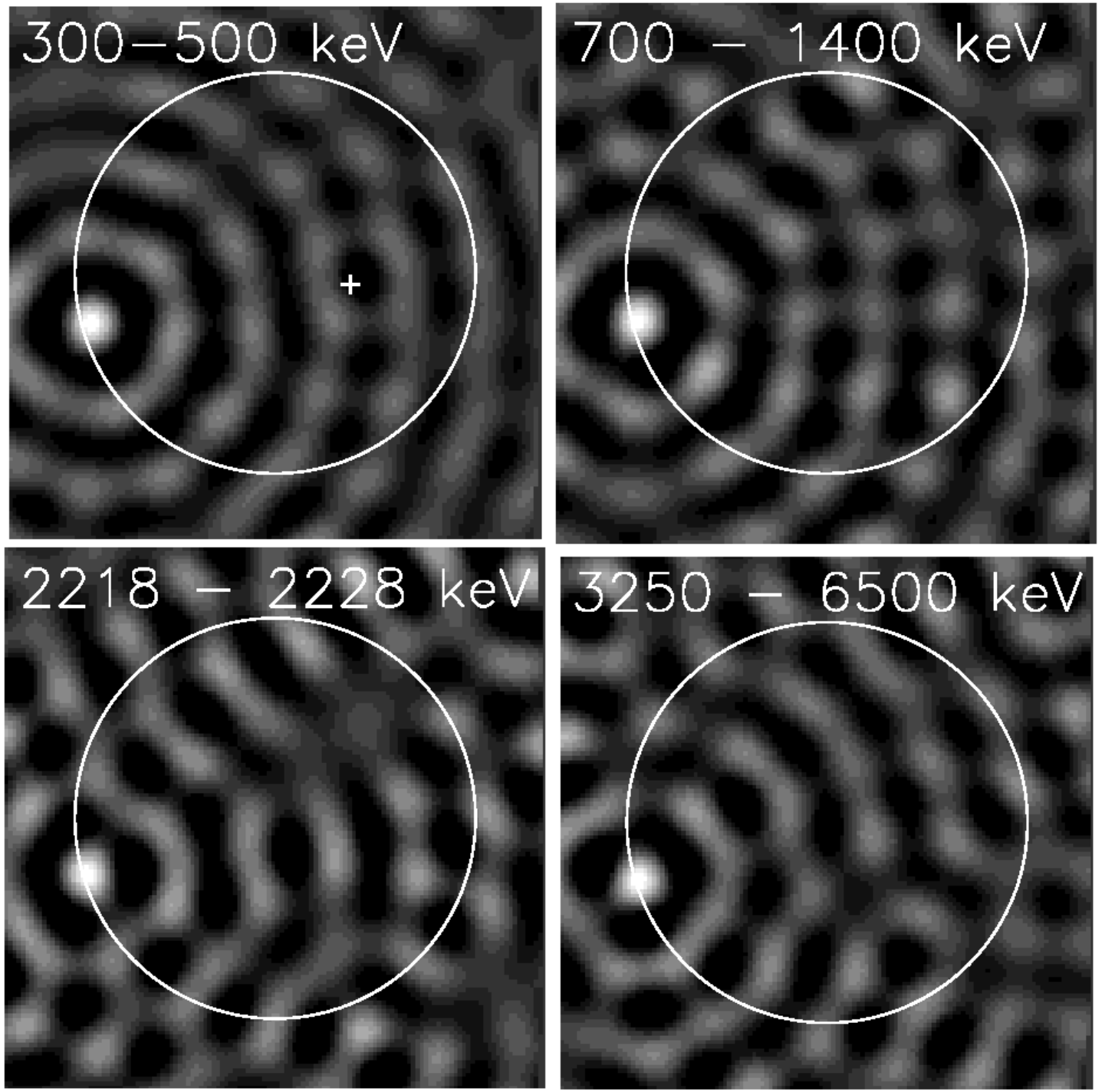
2002 July 23 Solar Flare
RHESSI Neutron Capture-Line Observations

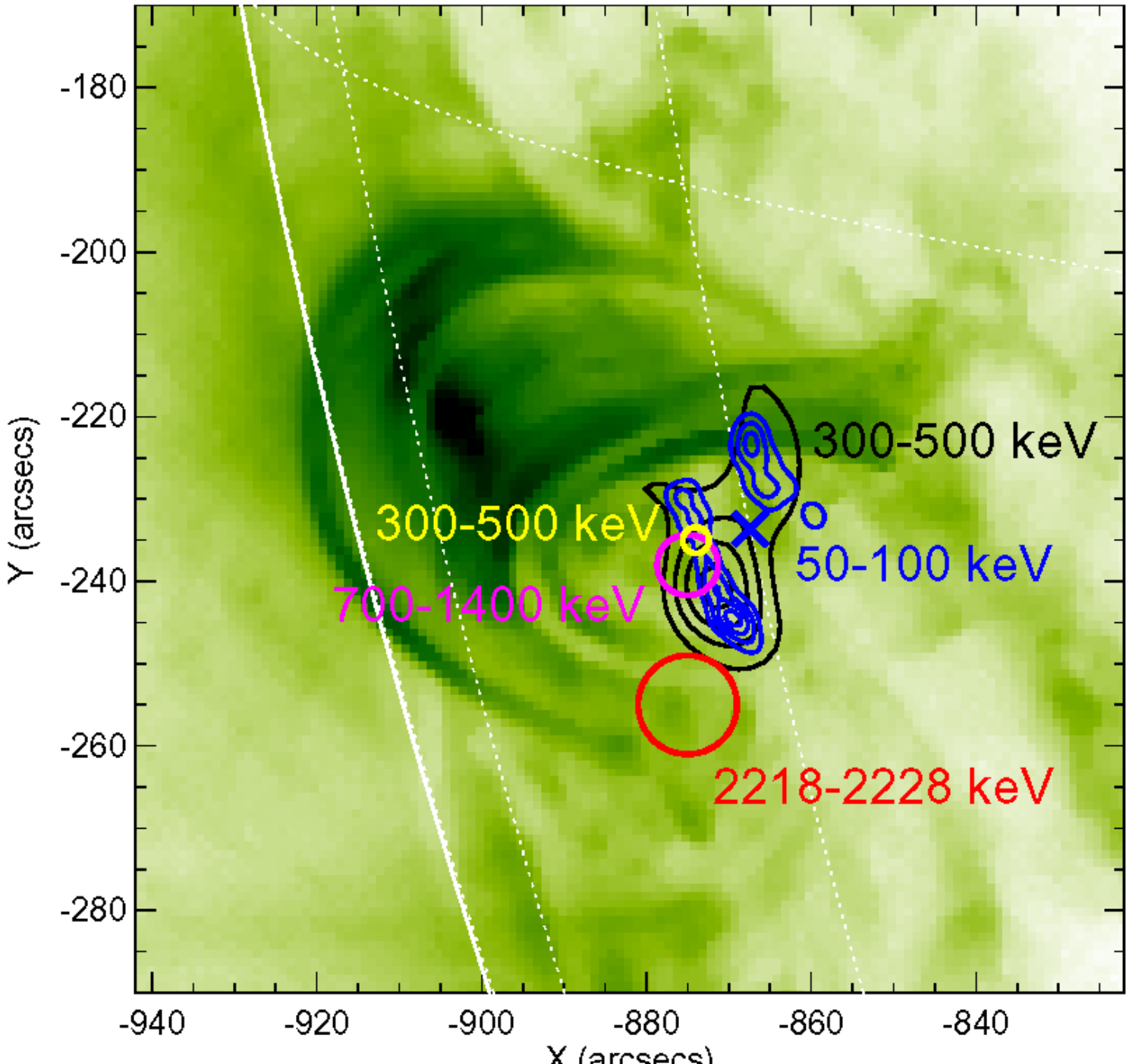




The time history of the neutron-capture line depends on the photospheric ^{3}He/H ratio

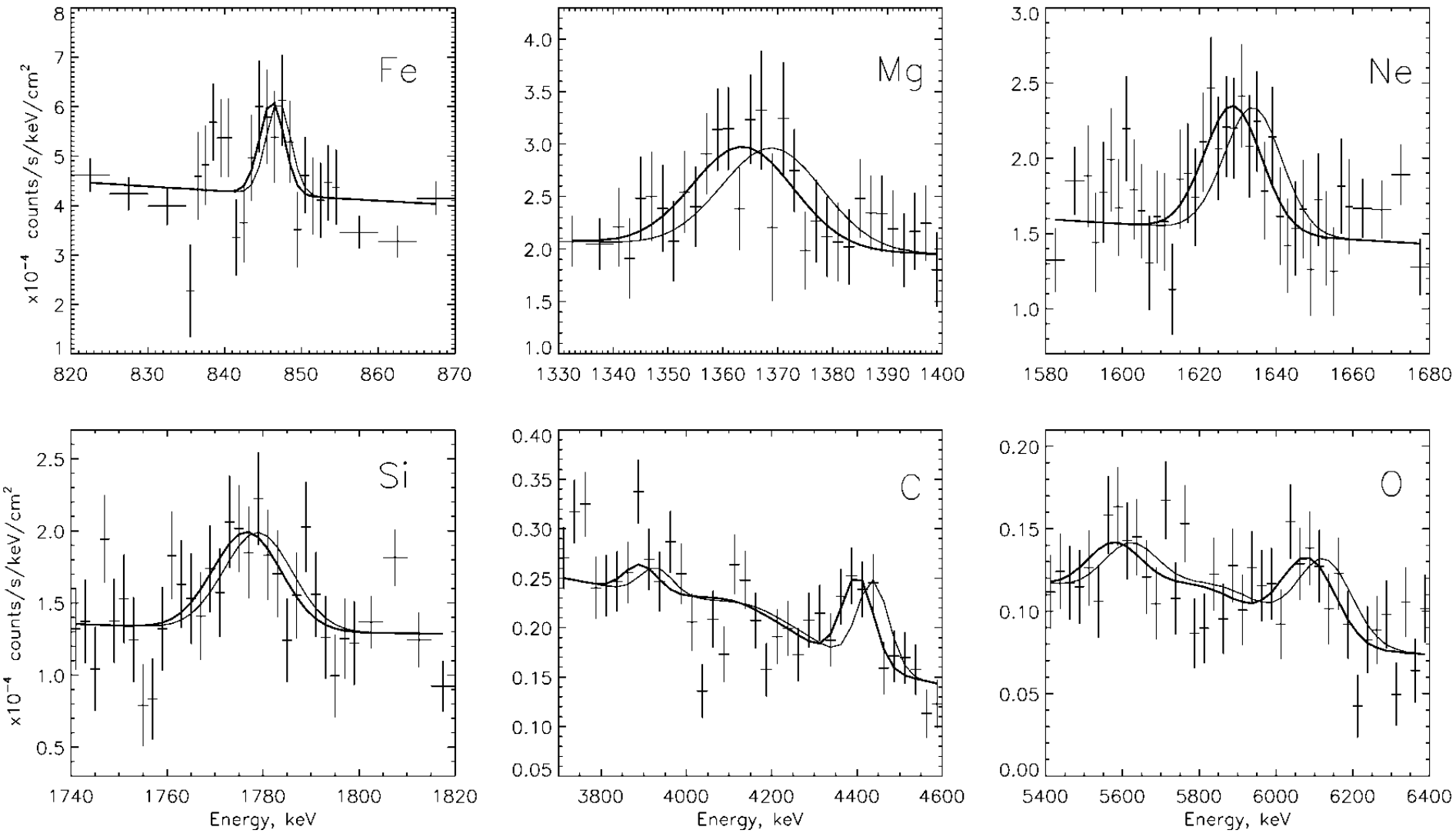
Hurford et al., 2003



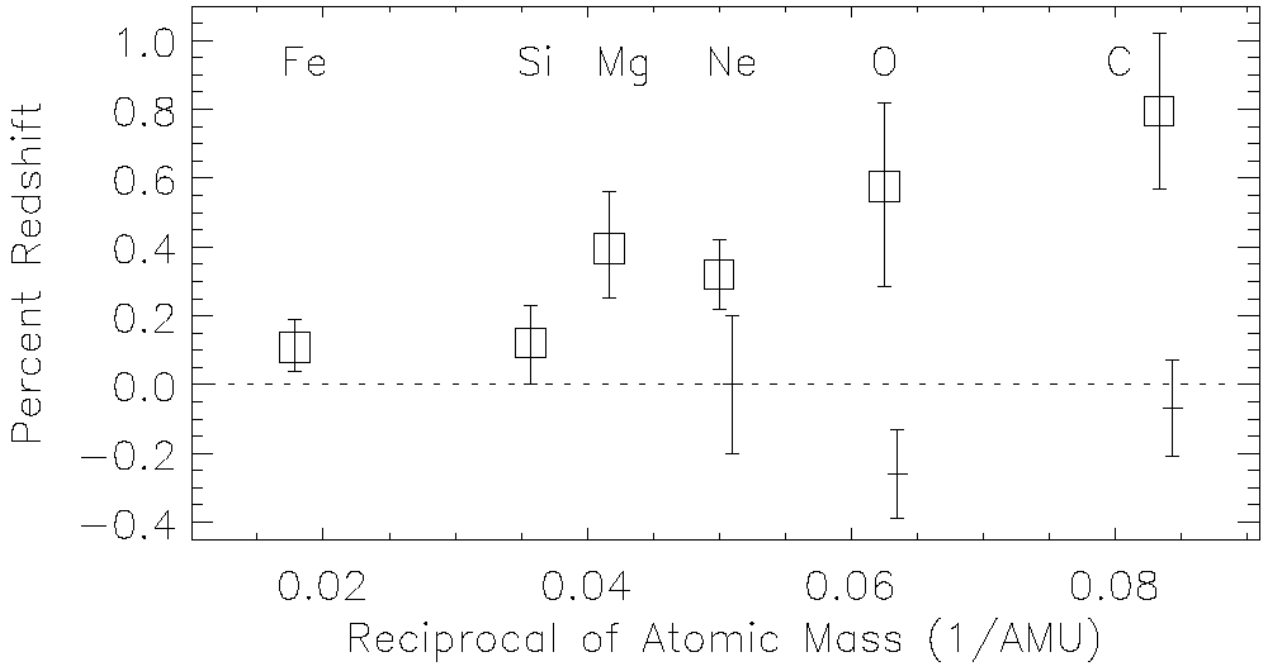

-180
-200
-220
-240
-260
-280
Y (arcsecs)
-940
-920
-900
-880
-860
-840
X (arcsecs)
300-500 keV
300-500 keV
50-100 keV
700-1400 keV
2218-2228 keV

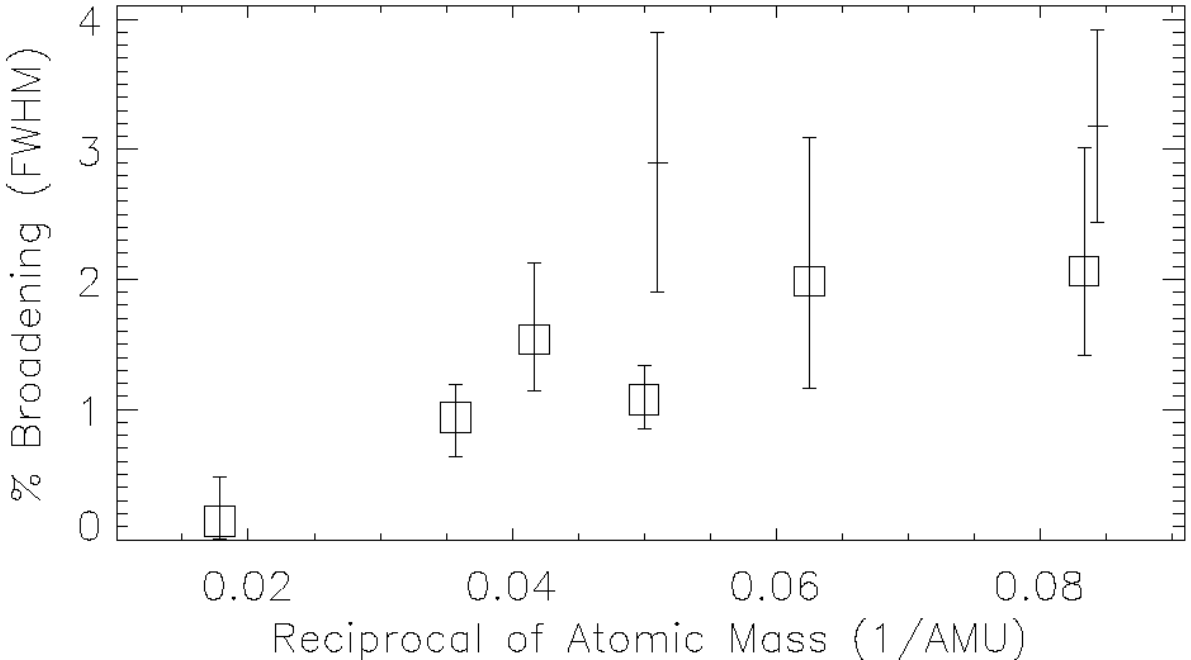

Jul 22 2002 20:47:30

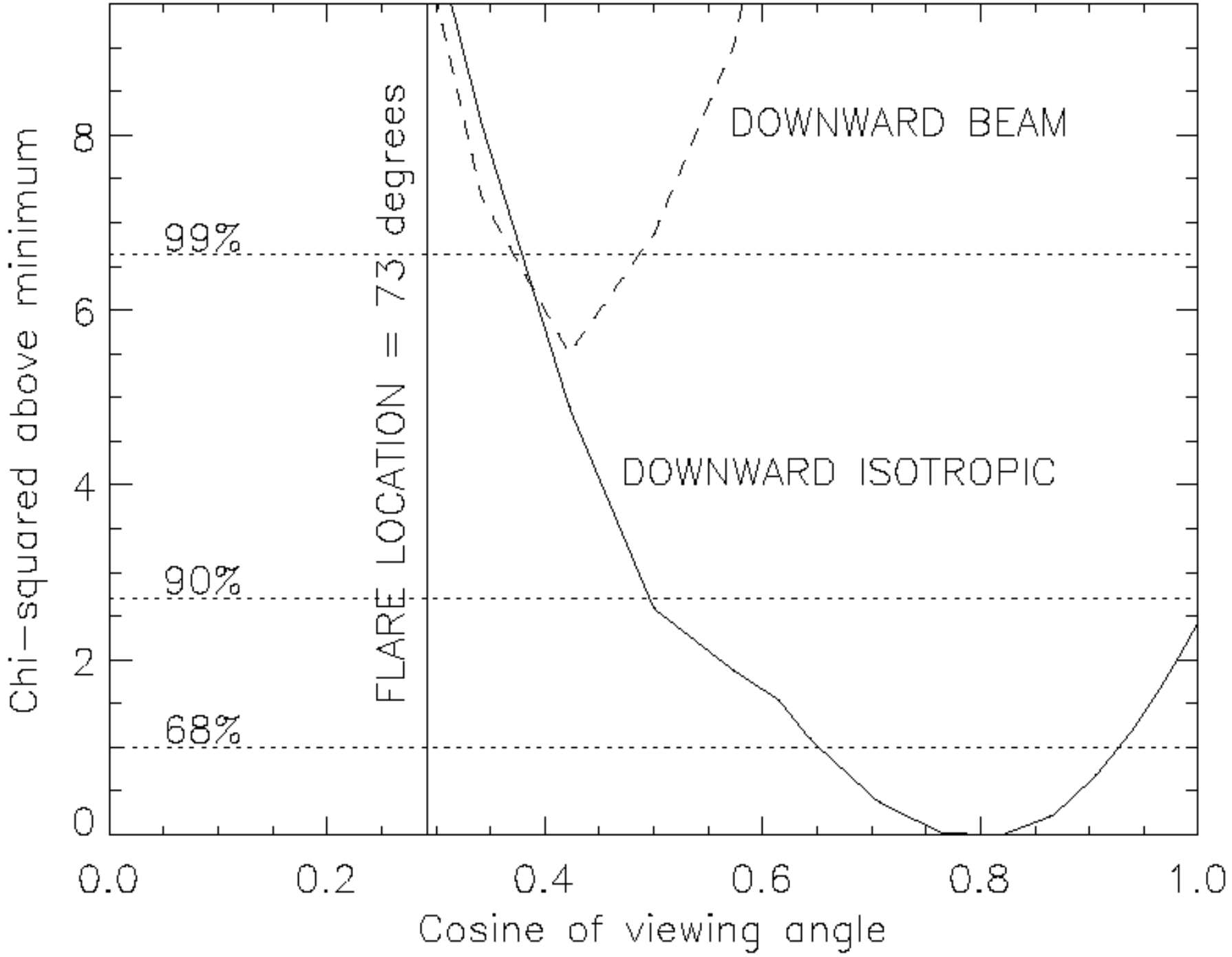
23 July 2002 flare nuclear de-excitation lines
(Smith et al. 2003)



Smith et al., 2003






Chi-squared above minimum
0
2
4
6
8
99%
90%
68%
FLARE LOCATION = 73 degrees
DOWNWARD BEAM
DOWNWARD ISOTROPIC
0.0
0.2
0.4
0.6
0.8
1.0
Cosine of viewing angle

Derivation of Mean Electron Flux & Injected Electron Flux Distributions

- Mean Electron Flux:

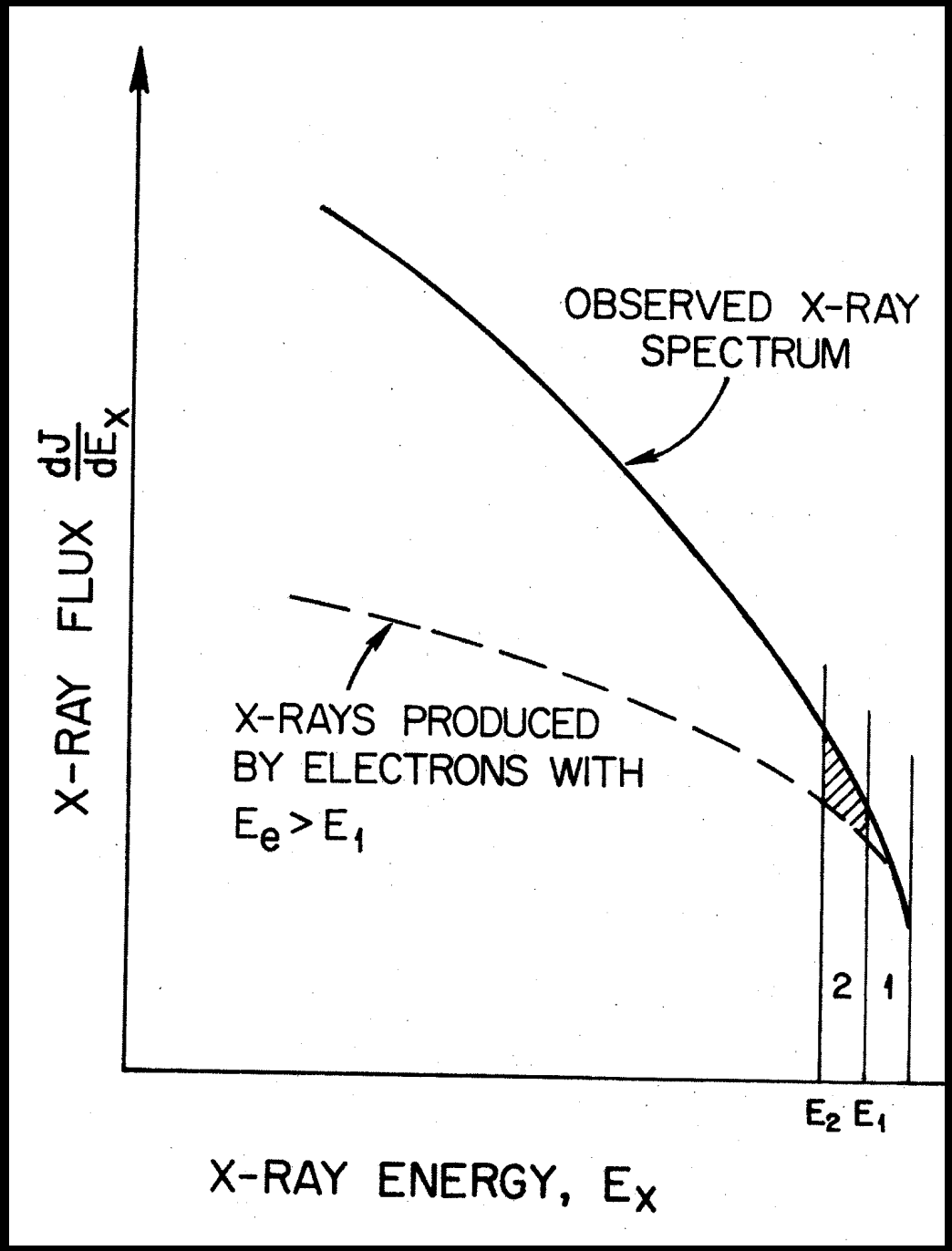
$$I(\varepsilon) = \frac{\bar{n}V}{4\pi R^2} \int_{\varepsilon}^{\infty} \bar{F}(E)\,\sigma(\varepsilon, E)\,dE$$

- Injected Electron Flux:

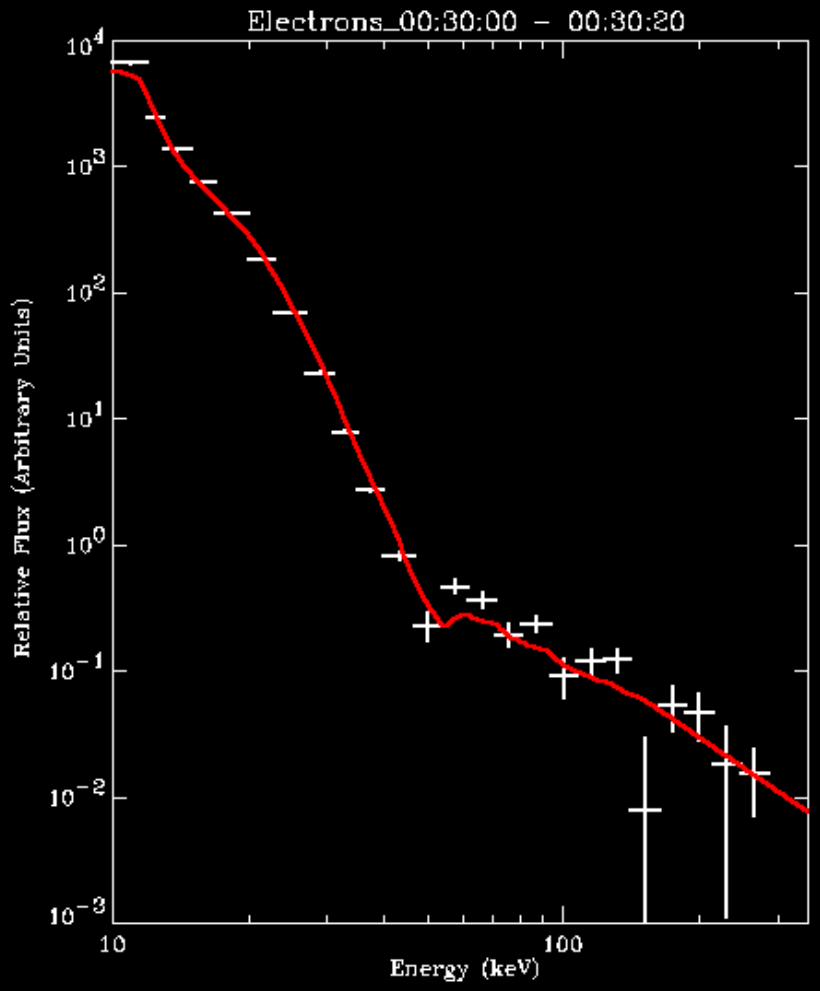
$$I(\varepsilon) = \frac{n}{4\pi R^2} \int_{\varepsilon}^{\infty} F(E') \int_{\varepsilon}^{E'} \frac{\sigma(\varepsilon, E)\mathrm{v}}{dE/dt}\,dE\,dE'$$

$$dE/dt \propto n/\mathrm{v} \qquad \text{(collisional losses)}$$

ε : photon energy
E : electron energy
σ : bremsstrahlung cross section
V : source volume
n : plasma density
R : 1 AU
I : photon flux
v : electron speed


OBSERVED X-RAY SPECTRUM
X-RAYS PRODUCED BY ELECTRONS WITH $E_e > E_1$
X-RAY FLUX $\frac{dJ}{dE_X}$
2
1
E_2 E_1
X-RAY ENERGY, E_X

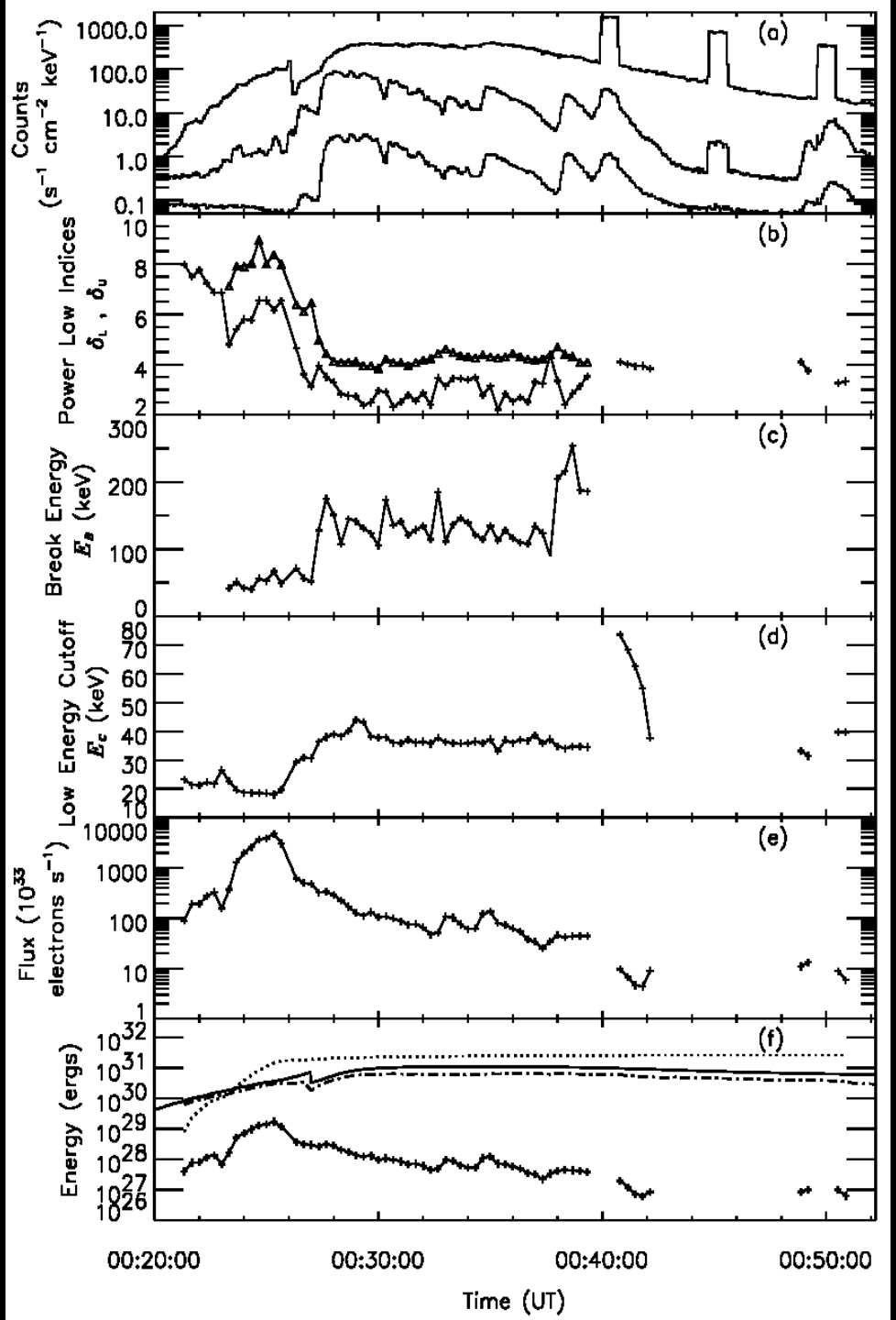
Results Comparison: 23 July 2003, 00:30:00 - 00:30:20



- White: Johns & Lin (1992)
- Red: Piana et al. 0th order regularization

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 (erg s^{-1})



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

Energetics – 23 July 2002 Flare

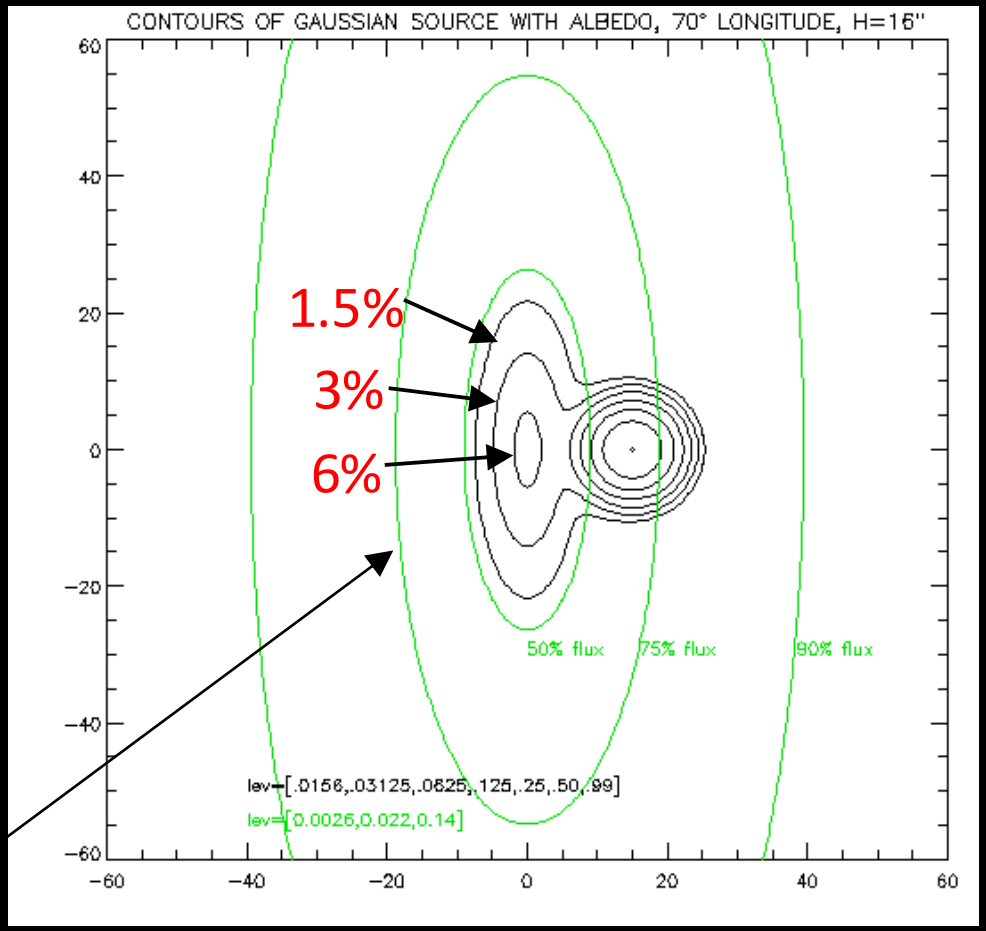
- Accelerated Electrons: > ~2 x 10^{31} ergs
  ~1/2 in coronal pre-impulsive phase!

- Accelerated Ions (>2.5 MeV) : ~ 10^{31} ergs

- Thermal Plasma: ~ 10^{31} ergs

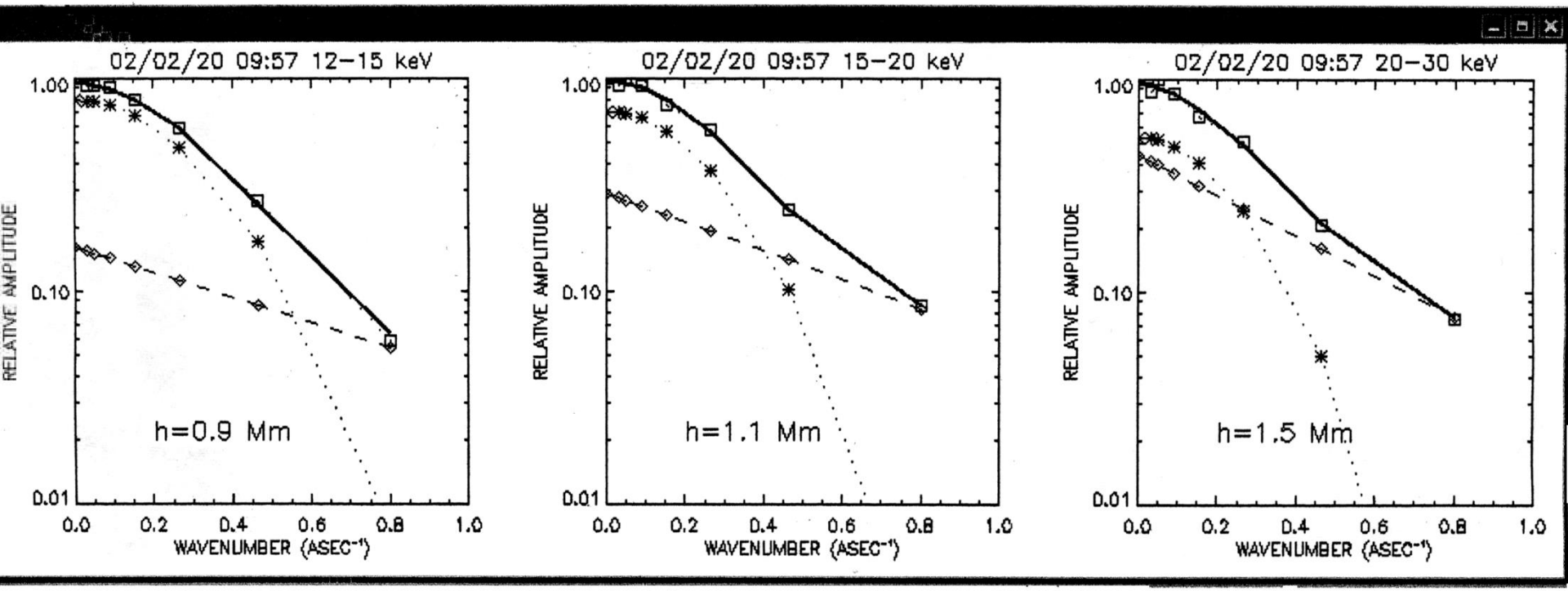
WITH IMAGING DOWN TO THE 1% LEVEL AND ZERO NOISE

Contours of an 8″ FWHM Gaussian source with its associated albedo patch. (factor of 2 contours)



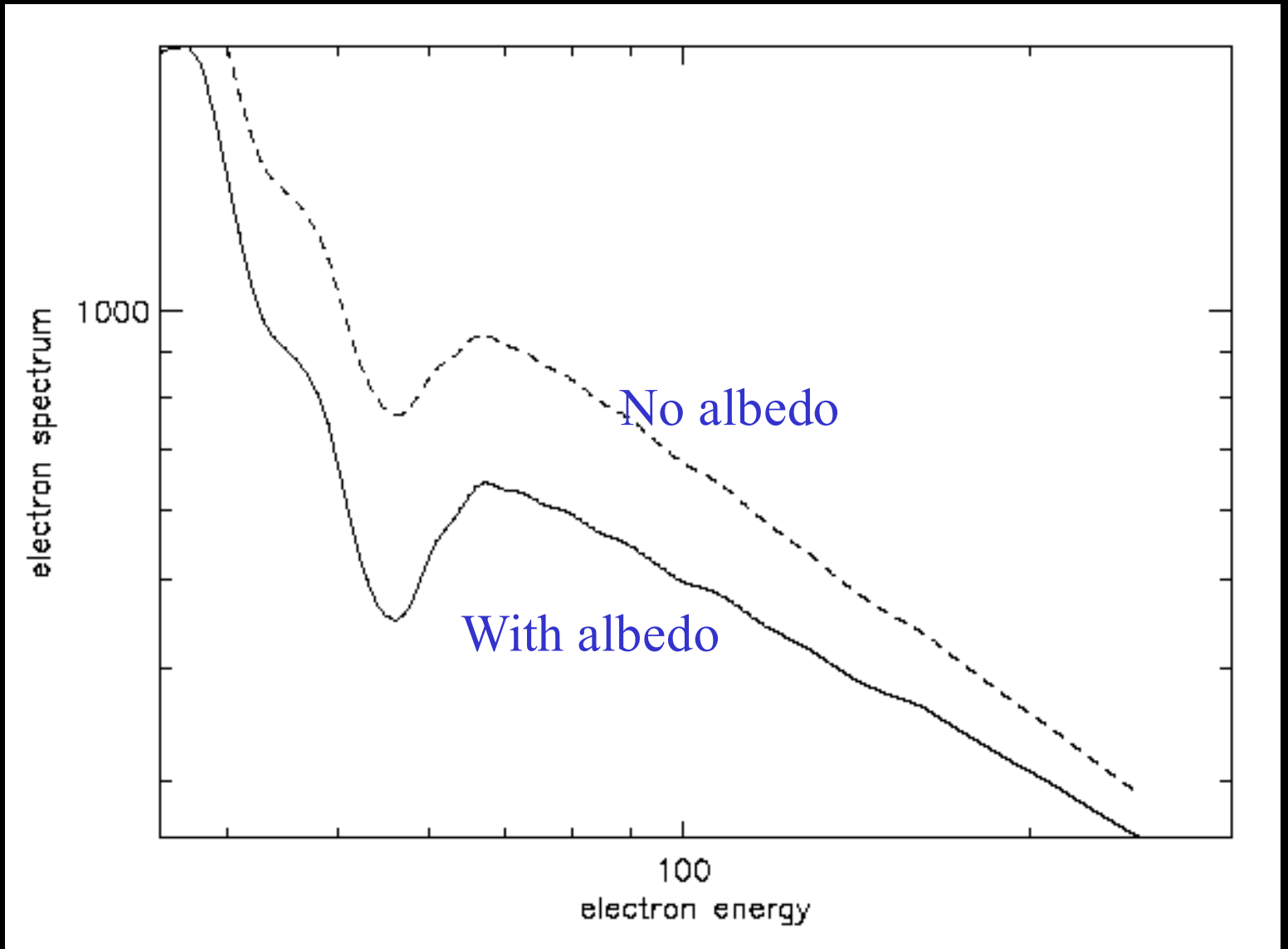
The green contours show the levels of integrated albedo flux. The 2nd green (~35''x100'') contour contains 75% of the albedo flux, assumed here to be 50% of the primary source flux.

E J Schmahl (2004)

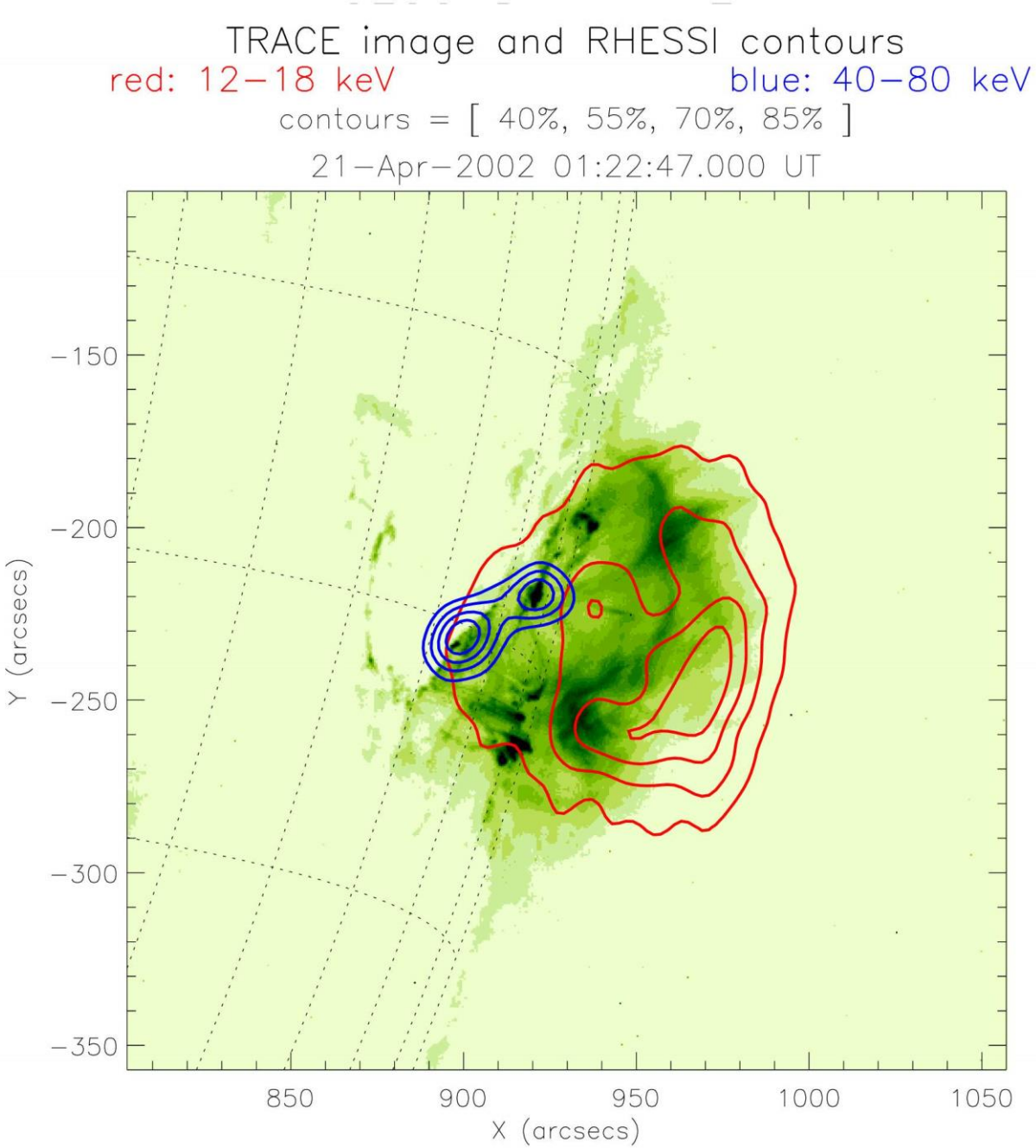

02/02/20 09:57 12–15 keV
02/02/20 09:57 15–20 keV
02/02/20 09:57 20–30 keV
RELATIVE AMPLITUDE
1.00
0.10
0.01
h=0.9 Mm
h=1.1 Mm
h=1.5 Mm
0.0
0.2
0.4
0.6
0.8
1.0
WAVENUMBER (ASEC⁻¹)

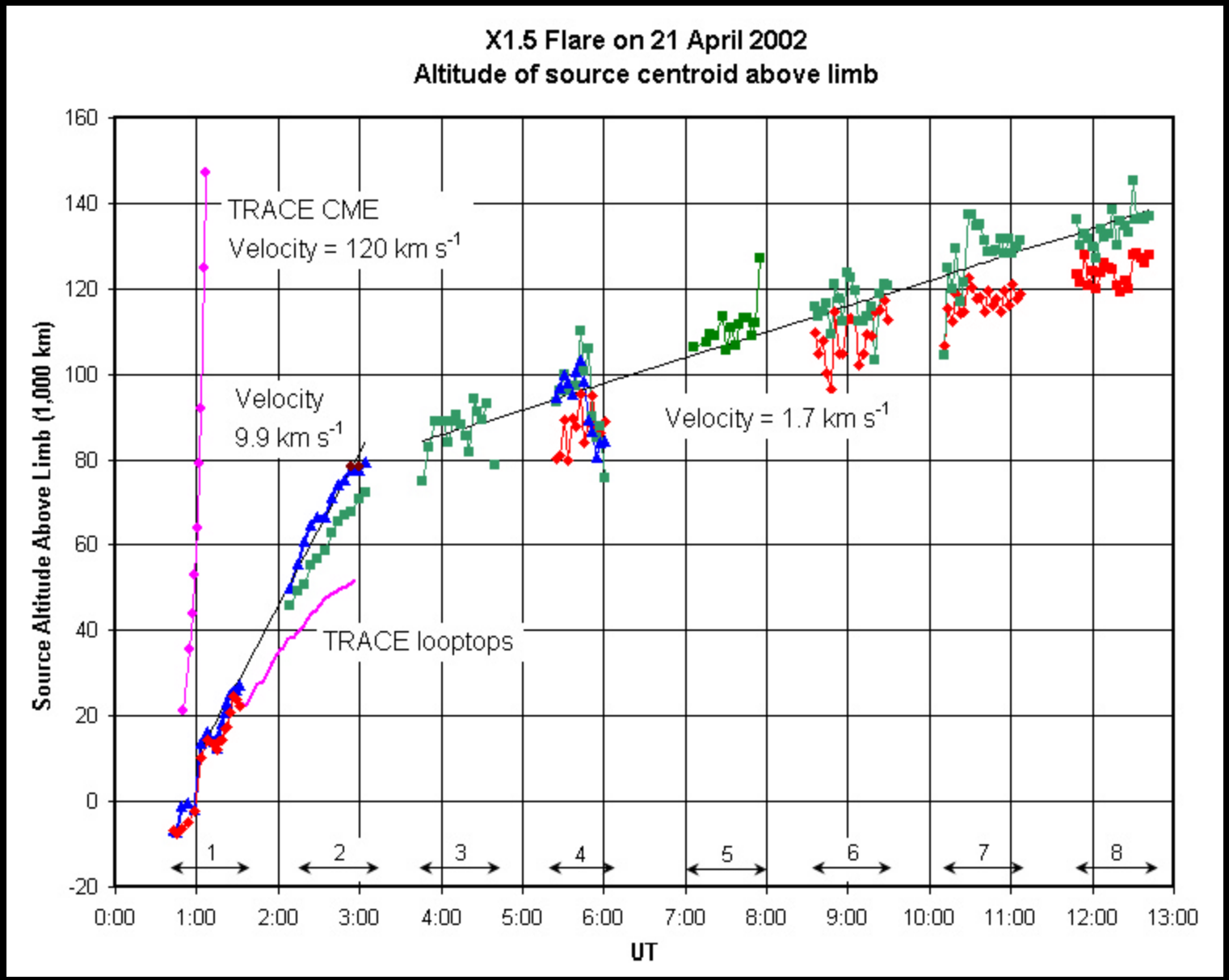
Pileup Corrections:

Use only those photons for which the live-time > 80%

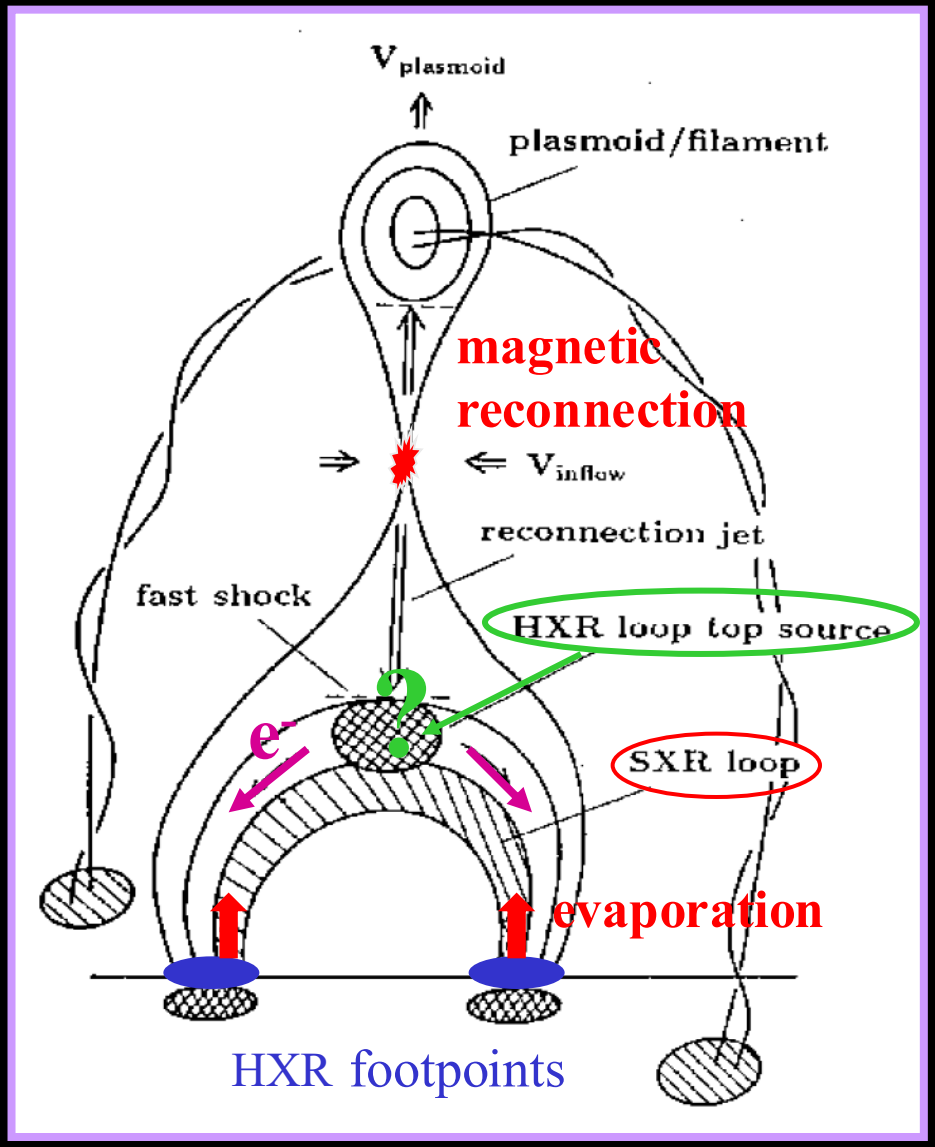



Apr 17 2002 23:59:32


TRACE image and RHESSI contours
red: 12–18 keV
blue: 40–80 keV
contours = [40%, 55%, 70%, 85%]
21–Apr–2002 01:22:47.000 UT
–150
–200
–250
–300
–350
Y (arcsecs)
850
900
950
1000
1050
X (arcsecs)


X1.5 Flare on 21 April 2002
Altitude of source centroid above limb
Source Altitude Above Limb (1,000 km)
160
140
120
100
80
60
40
20
0
-20
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
UT
TRACE CME
Velocity = 120 km s-1
Velocity
9.9 km s-1
Velocity = 1.7 km s-1
TRACE looptops
1
2
3
4
5
6
7
8

Magnetic reconnection model

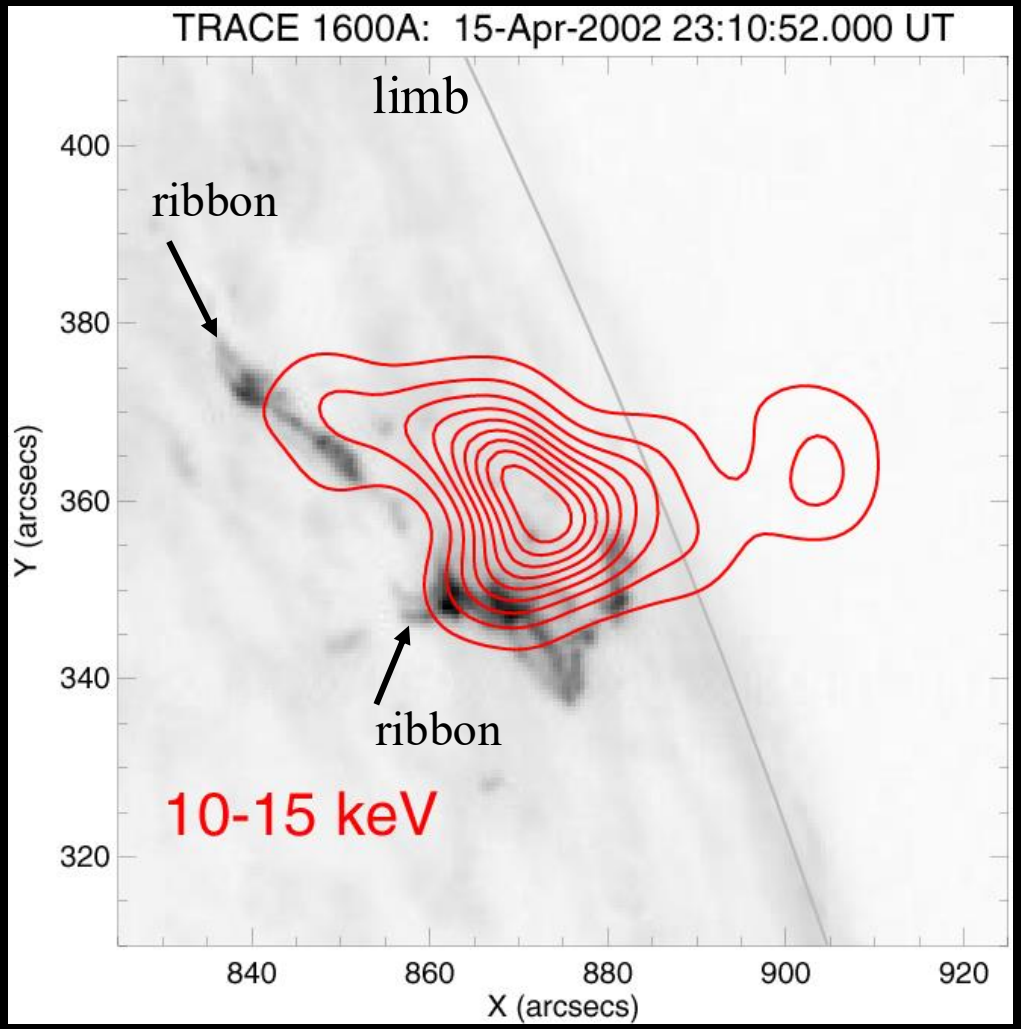


1) Release of magnetic energy
2) Accelerated electrons produce HXRs and heat loop
3) Above loop top source not understood
4) Ion acceleration even less understood. RHESSI provides first imaging.

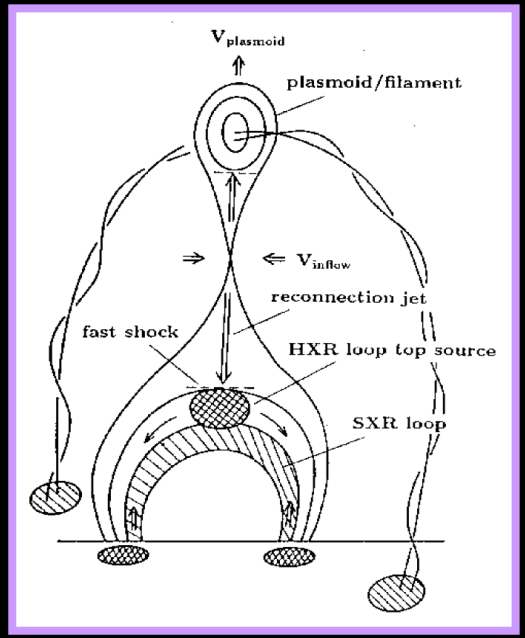
from Shibata

Evidence for the Formation of Large-Scale, Reconnecting Current Sheet

Linhui Sui, Gordon D. Holman



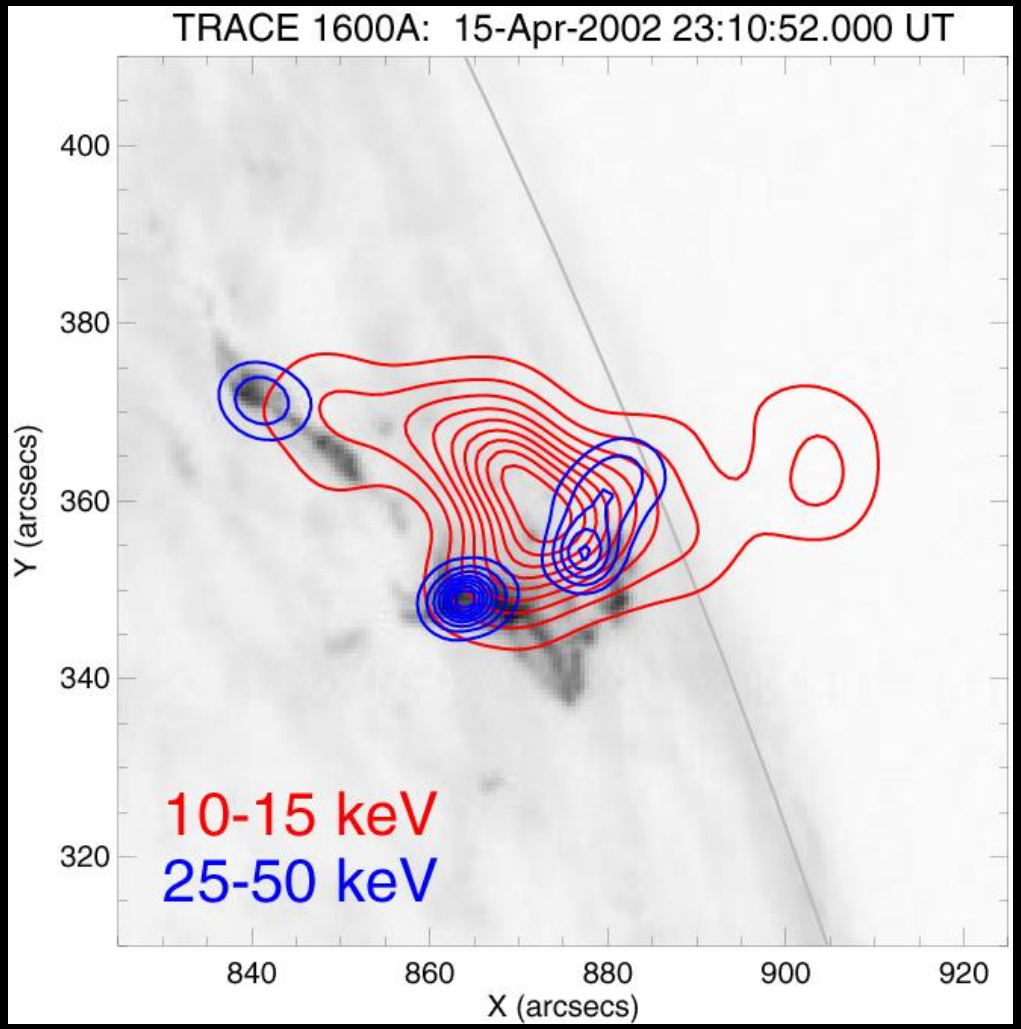
Cusp-shaped loop; Possible formation of current sheet?



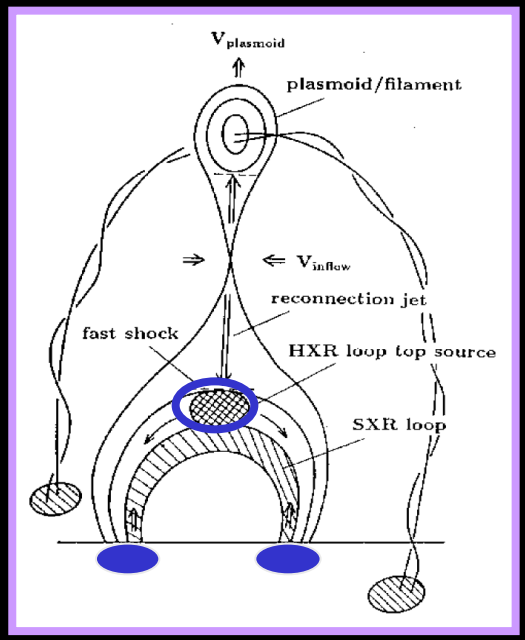
From Shibata

Evidence for the Formation of Large-Scale, Reconnecting Current Sheets

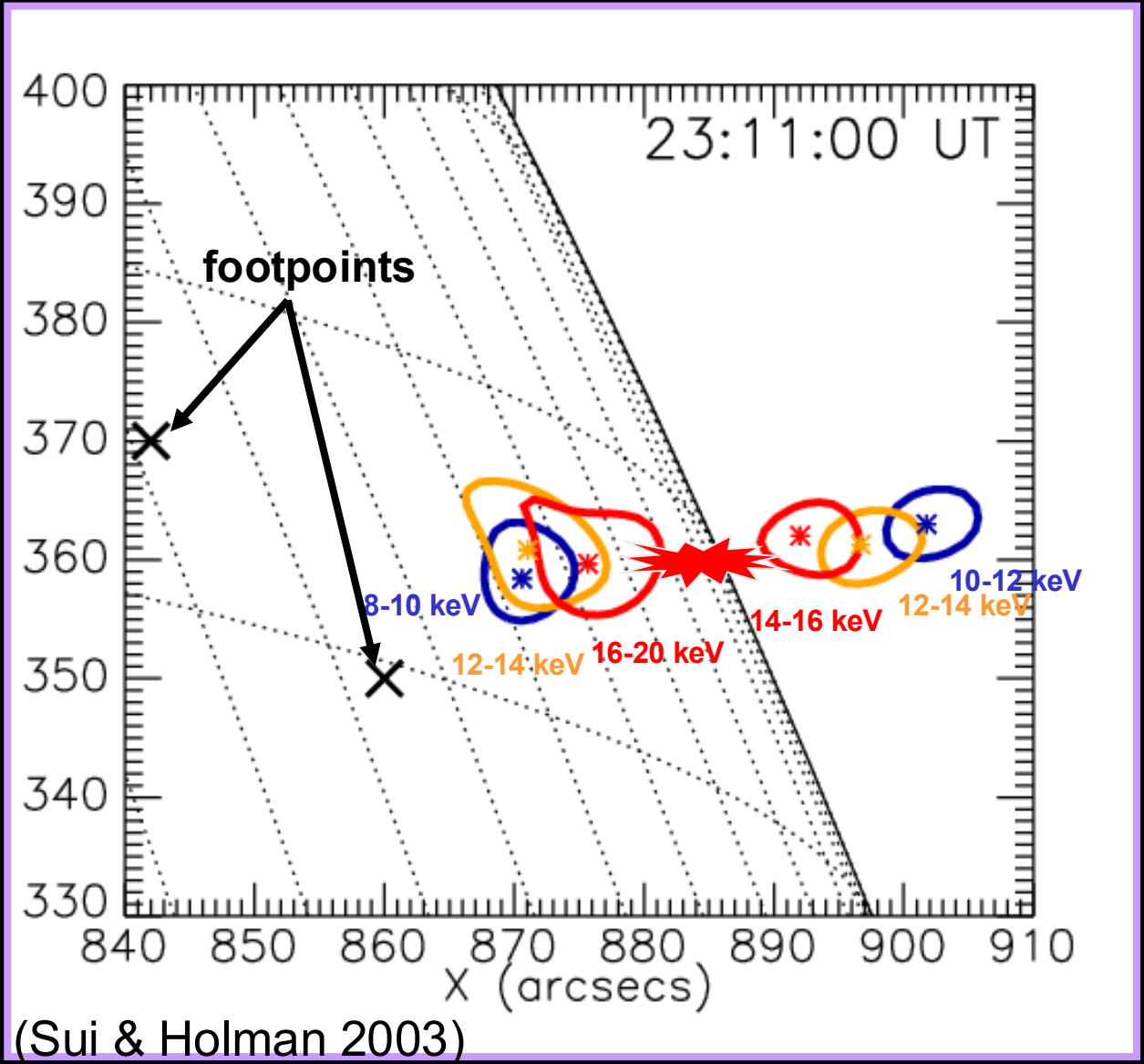
Linhui Sui, Gordon D. Holman



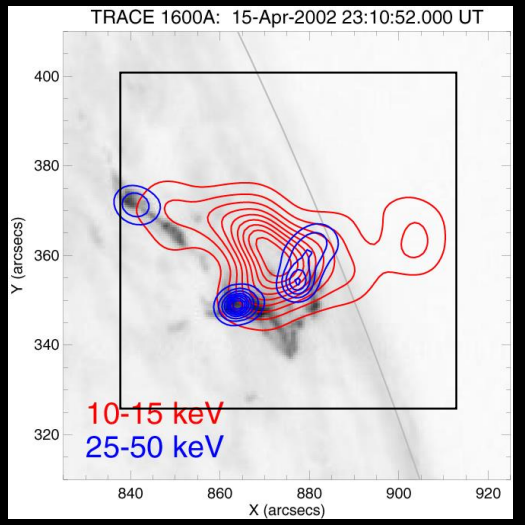
HXR emissions from
1) footpoints
2) source in corona?
   or projection effect?

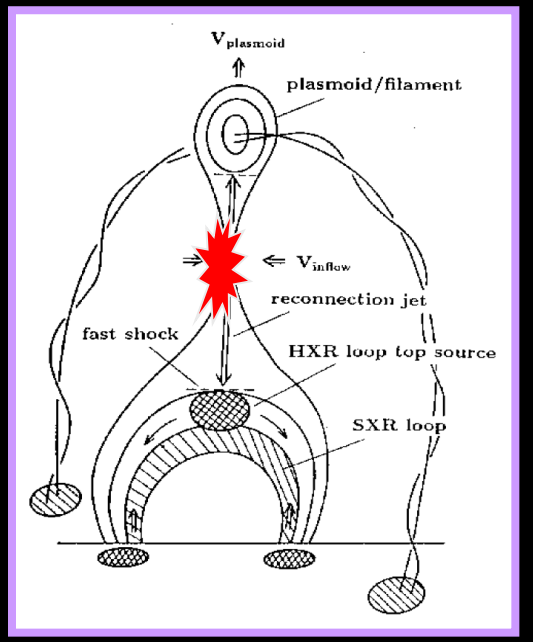


Temperature gradient is observed

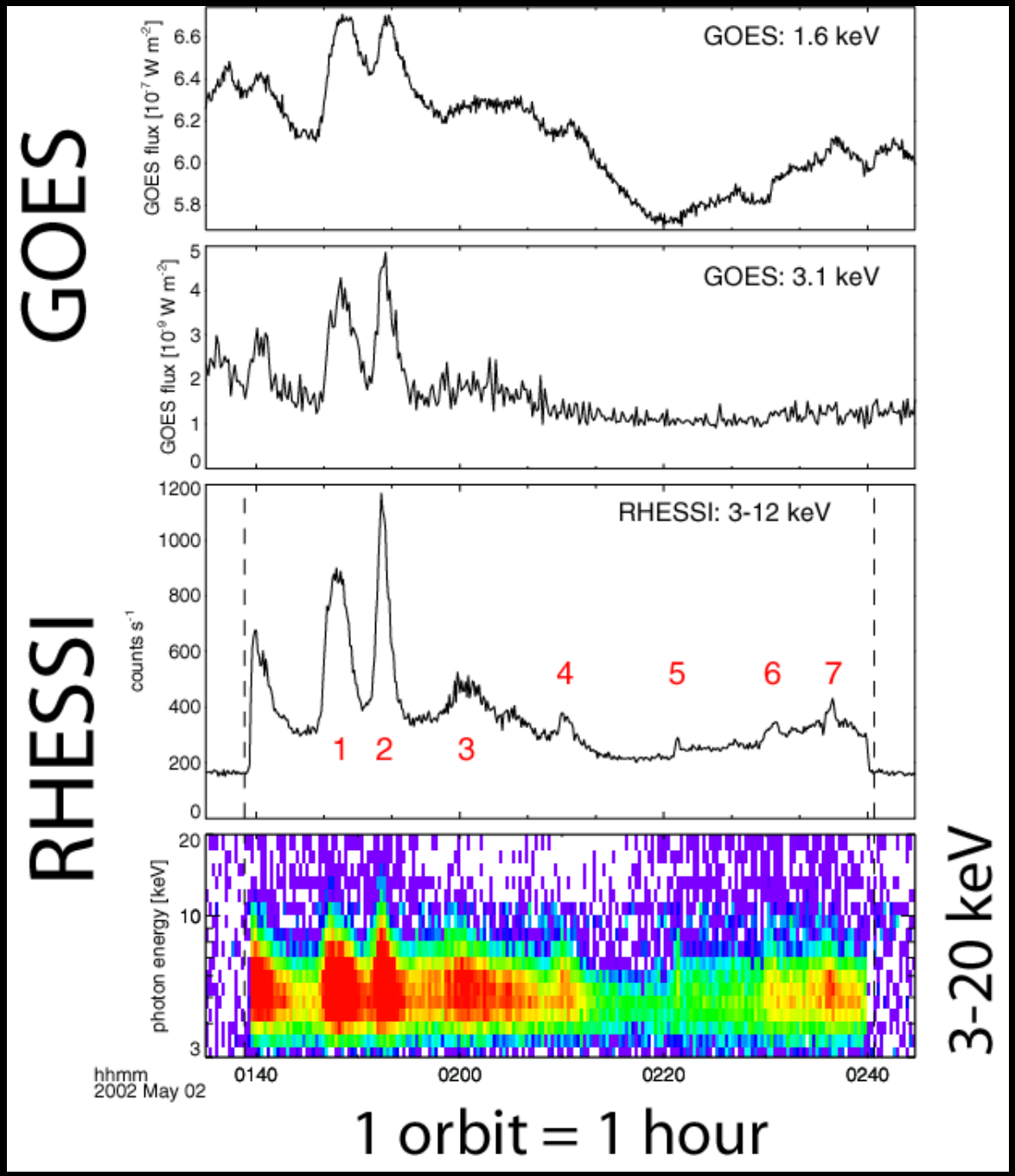


(Sui & Holman 2003)





RHESSI and GOES



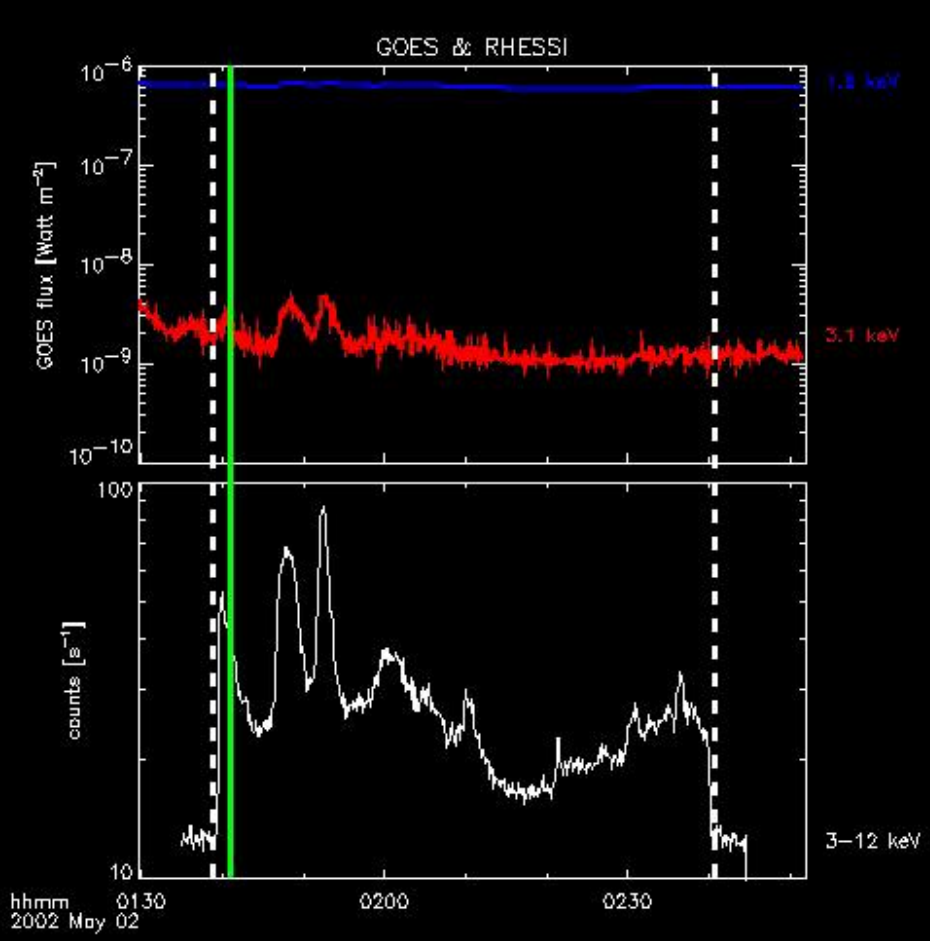
GOES in LINEAR scale!

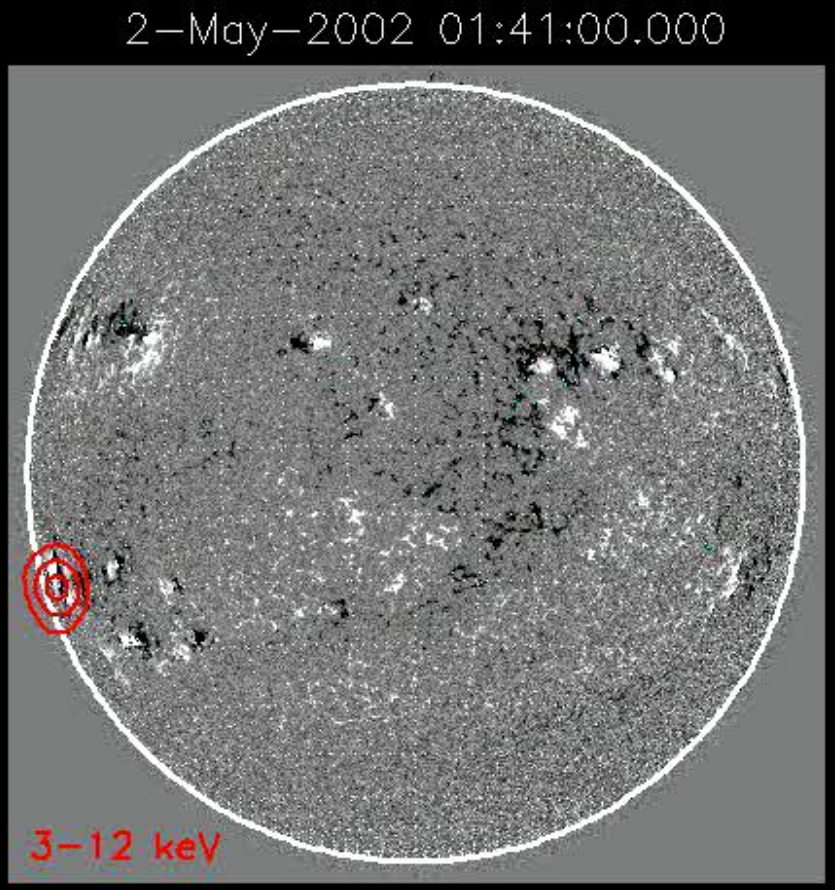
GOES background B6 microflares: A6 or smaller

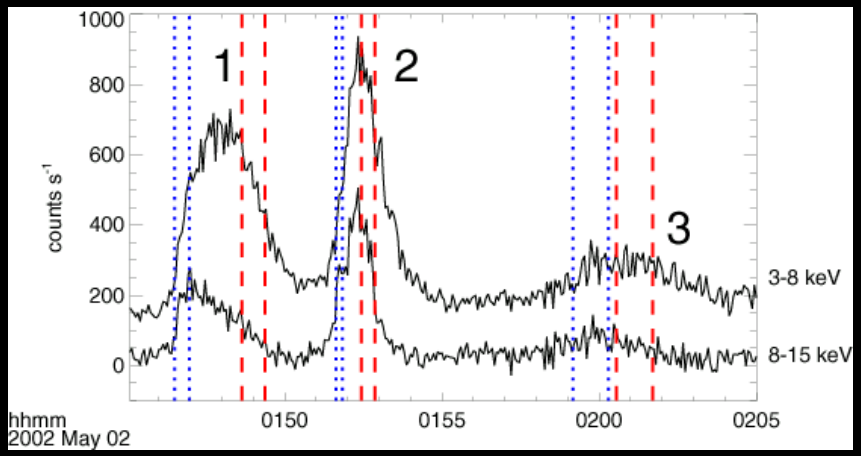
At least 7 microflares

Spectrogram plot: time-energy, colors represent counts

Microflares are from ARs

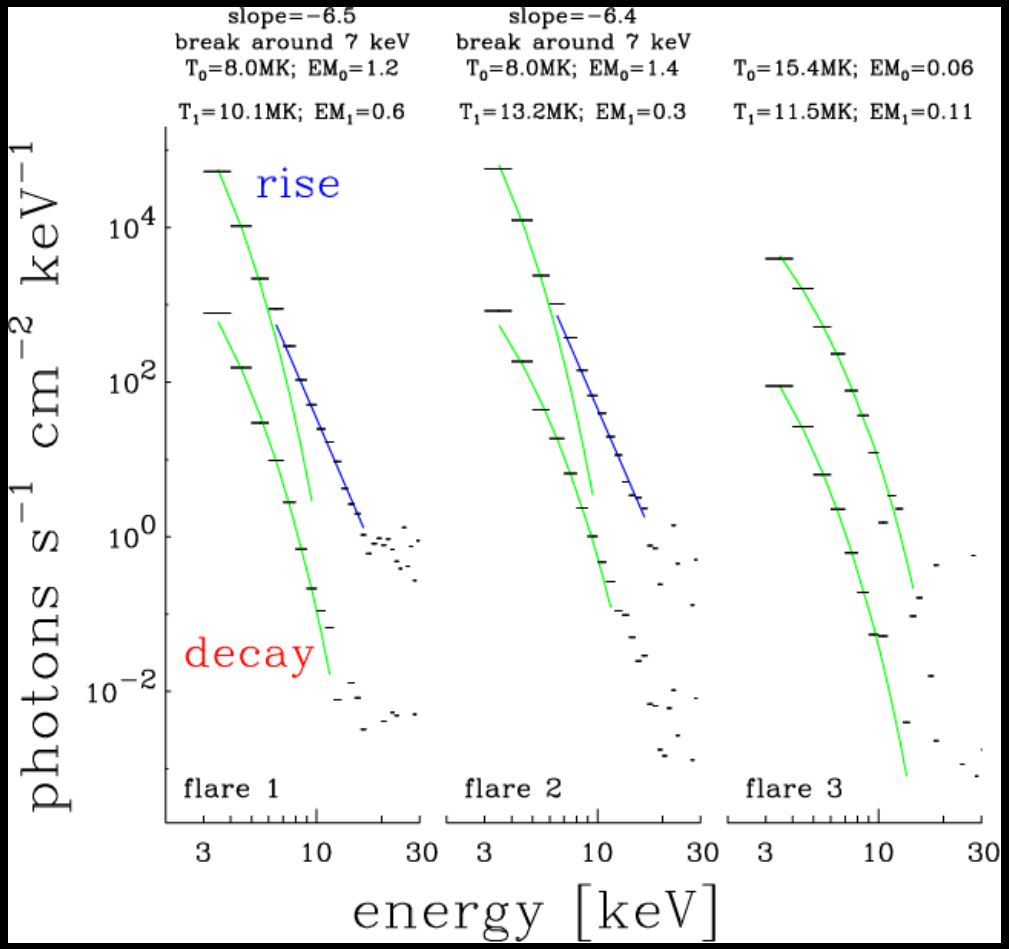


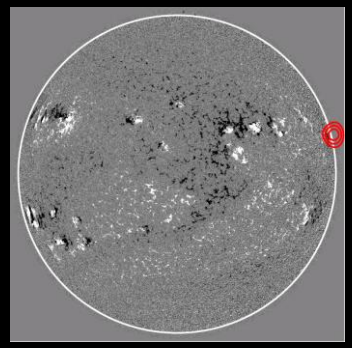




Spectra

- Fitting is difficult
- Steep spectra (d~4-7)
- Low turnover energy: down to 7 keV
- Non-thermal energy around 1e27-1e28 erg





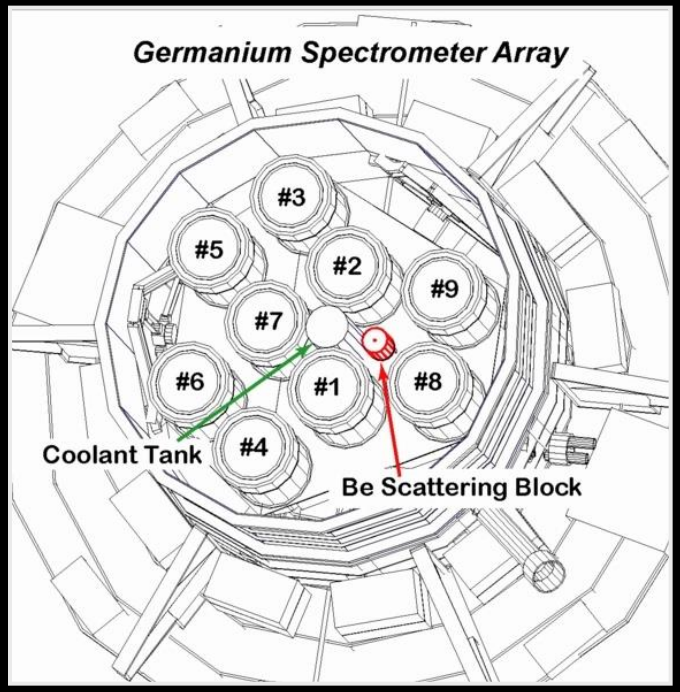
Flare 3 is behind the limb, non-thermal emission occulted

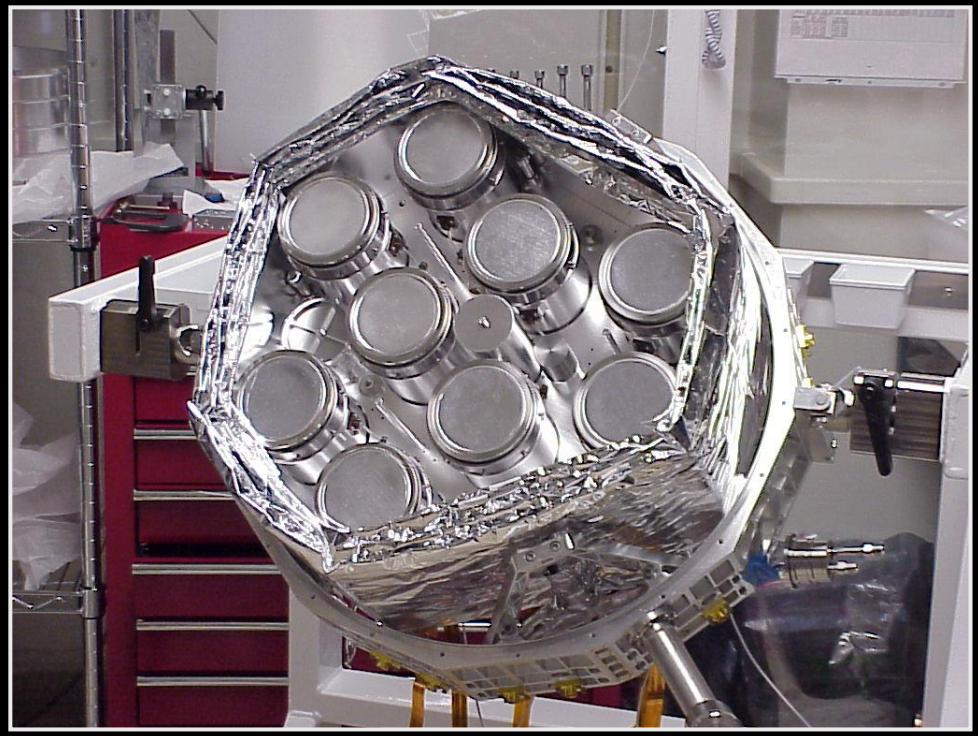
RHESSI as a Polarimeter (20 – 100 keV)

A small (3 cm diam by 3.5 cm high) cylinder of Be serves as a Compton scattering element.

The Ge detectors measure the distribution of the scattered radiation.

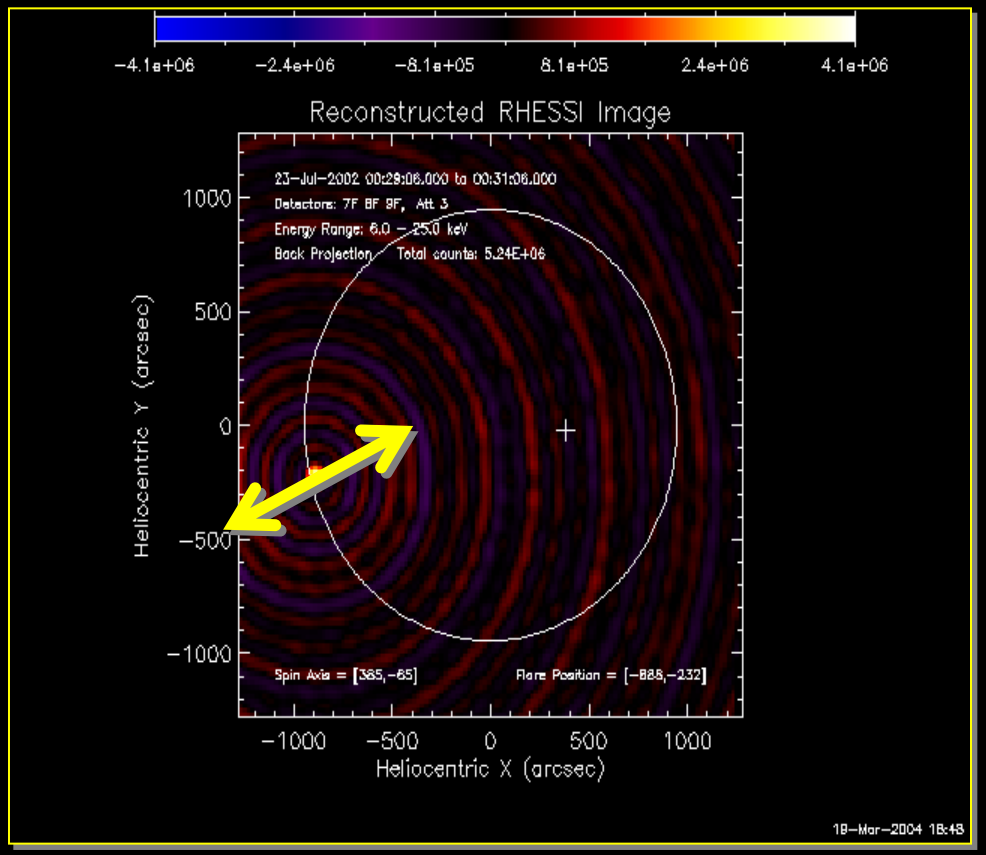
The rotation of the spacecraft rotation provides an effective method for fine sampling of the scatter distribution.

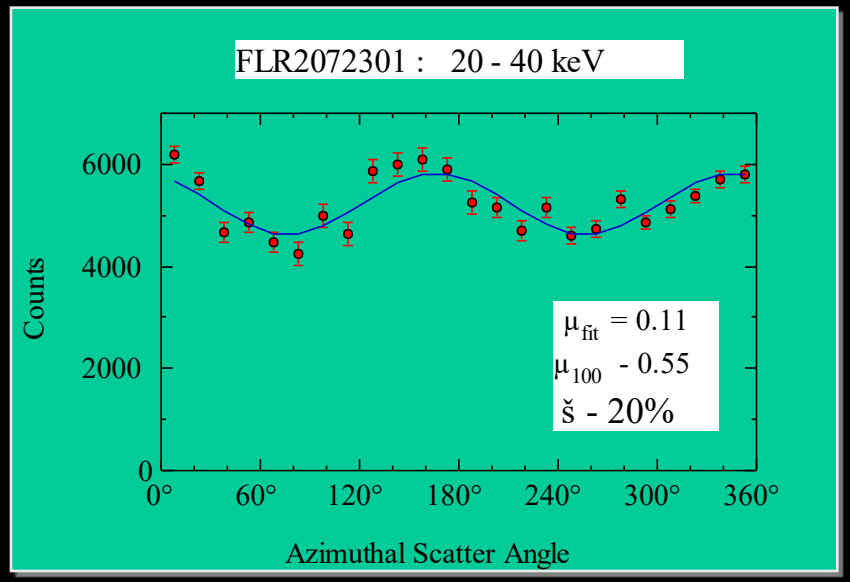




X4.8 Flare of 23-July-2002

20 - 40 keV Polarization

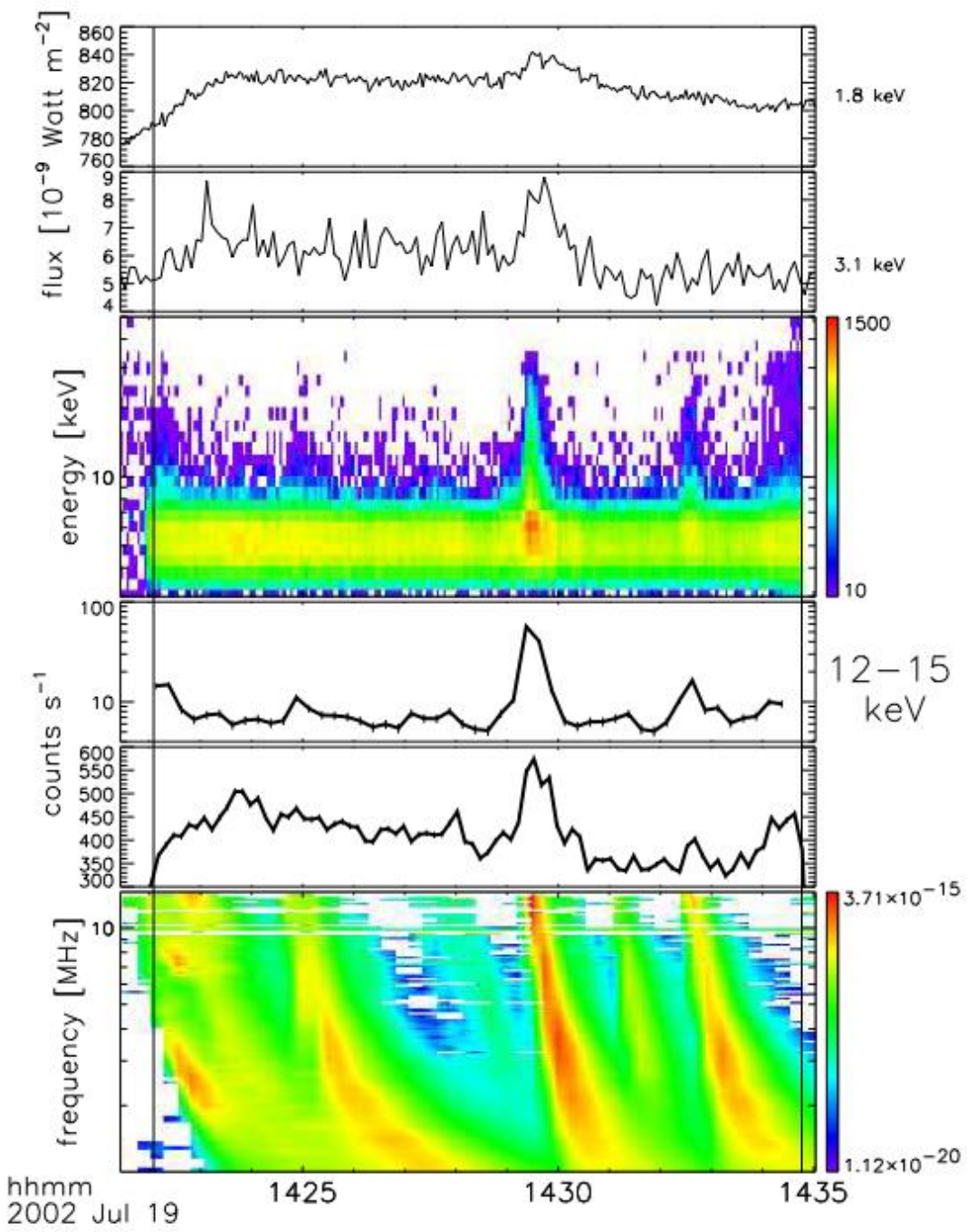




Flare location : S13E72

Π≈ 20%

Φ ≈72° ± 5°



Panel 1,2: GOES (Class 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

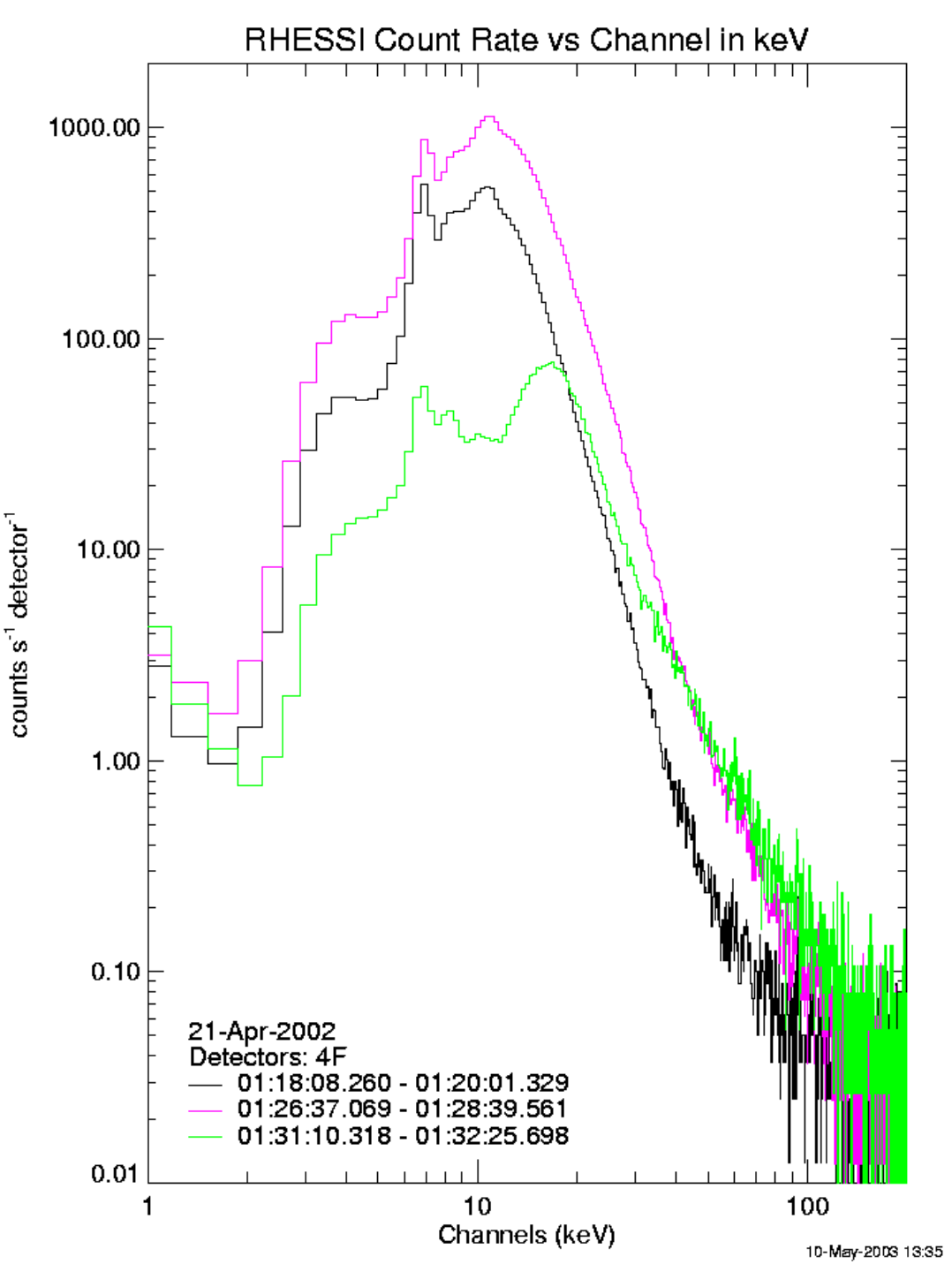
RHESSI Spectra

Thin Shutters (A1)

Thin + Thick (A3)

Detector #4

1-minute accumulations



Complementary Observations

TRACE	UV & EUV high resolution images
SOHO	EIT - EUV images
	CDS/SUMER/UVCS – UV/EUV spectra
	LASCO - Coronagraph images
	Particle spectra and abundances
GOES - SXI	Soft X-ray images
Wind & ACE	Energetic particle spectra and abundances
	Low-frequency radio and energetic electrons
Coronas/RESIK	Soft X-ray spectra
Ground-based Observatories	
	Radio and optical images and spectra
	Magnetograms
	Hα polarization

PHOTON-BASED IMAGING

DATA CONSISTS OF ENERGY AND TIME-TAGGED PHOTONS => WIDE RANGE OF TRADE-OFFS POSSIBLE:

- TIME RESOLUTION
- SPATIAL RESOLUTION
- ENERGY RESOLUTION
- IMAGE FIELD OF VIEW
- IMAGE QUALITY
- IMAGING SPEED

RHESSI DATA ACCESS

1. DATA AVAILABLE ON-LINE WITHIN 48 HOURS TO COMMUNITY

2. PI TEAM AND COMMUNITY HAVE EQUAL ACCESS TO DATA ANALYSIS SOFTWARE ONLINE

http://hesperia.gsfc.nasa.gov/rhessidatacenter/

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