Puzzles and potential for gamma-ray line observations of solar flare ion acceleration

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Outline:

Diagnostics of ion acceleration in flares

Some illustrative results from RHESSI

Science with MAX & beyond

Motivation

Particle acceleration in solar flares is of interest:

In its own right

As an analog for studying processes in astrophysical and other contexts

The solar accelerators are:

Highly efficient (order of half of the magnetic energy converted directly to high-energy particles)

Highly powerful (ions accelerated up to cosmic ray energie of a few GeV)

Very fast (ions acclerated to tens of MeV in times ~ 1 s and to GeV in ~ 1 min, but lasting up to hours)

Ion Acceleration

Is more difficult to study than electron acceleration:

Photons are scarce and harder to stop (gammas vs. x-rays from electrons)

Neutrons decay before reaching Earth except at high energies

Is particularly revealing of physics because there are multiple species

Narrow nuclear de-excitation lines from excitation by protons, alpha

Broad de-excitation lines from excitation by heavy ions

Positron-annihilation line from nuclear decays and pion decays

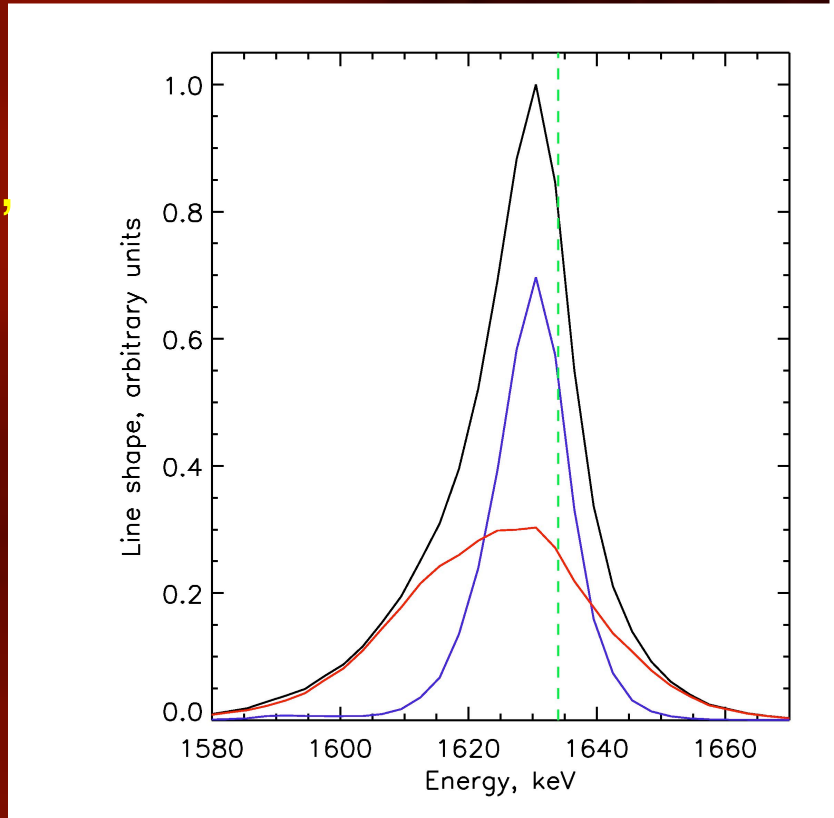
Neutron capture line at 2.2 MeV

Is interesting in terms of connections to ions measured in interplanetary s

and to spectra and composition of cosmic rays

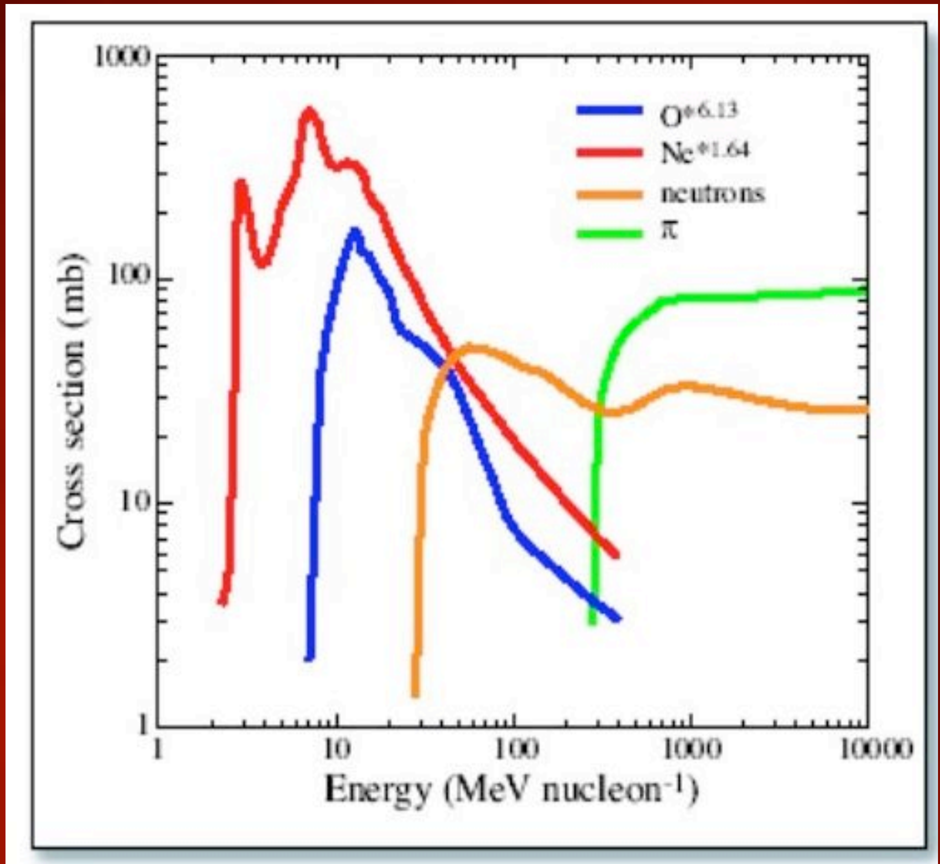
NUCLEAR DE-EXCITATION LINES

(R. Murphy, G. Share, A. Y. Shih, D. Smith, W. Gan)



Line ratios give:

- Accelerated particle spectrum
- Abundances in local medium



Line shapes give:

- Alpha/proton ratio
- Angle of magnetic loop
- Pitch-angle distribution of ions

Positron annihilation line:

Created by spallation, etc. by higher energy ions than de-excitation l
Also created by pion decay (highest-energy ions of all)

Flux therefore related to ion spectrum

Doppler profile of the line gives temperature of annihilation medium
(a broad component from charge exchange in flight also possible

Amount of 3-gamma continuum (from orthopositronium) constrains
density and ionization state of annihilation medium

There are very few ways to study the state of the flaring atmosphere

Neutron-capture line at 2.2 MeV:

- Like positrons, created from spallation products (tens of MeV ior
- Brightest line, most sensitive tracer of ion acceleration
- Line decay profile can constrain 3He abundance in solar atmosphere

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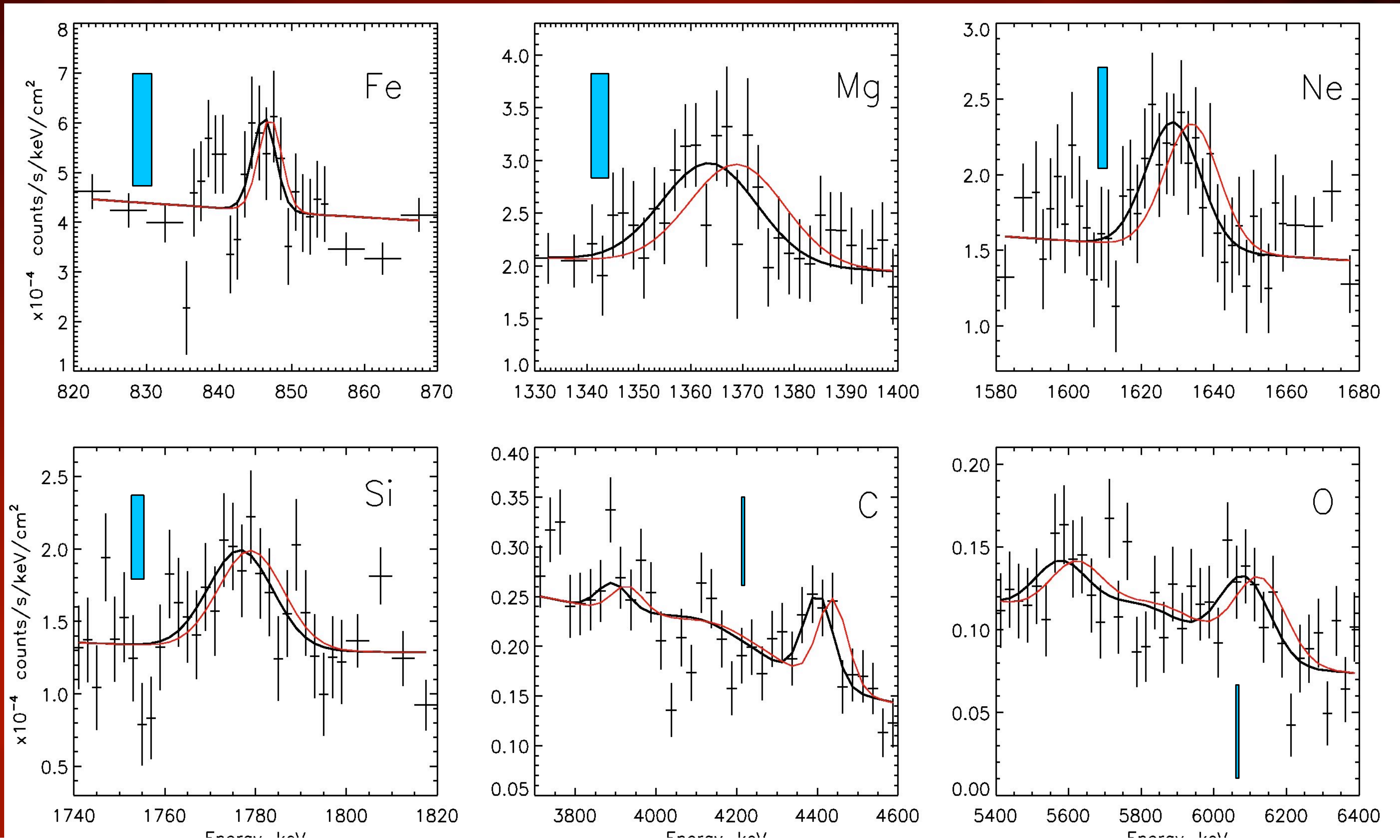
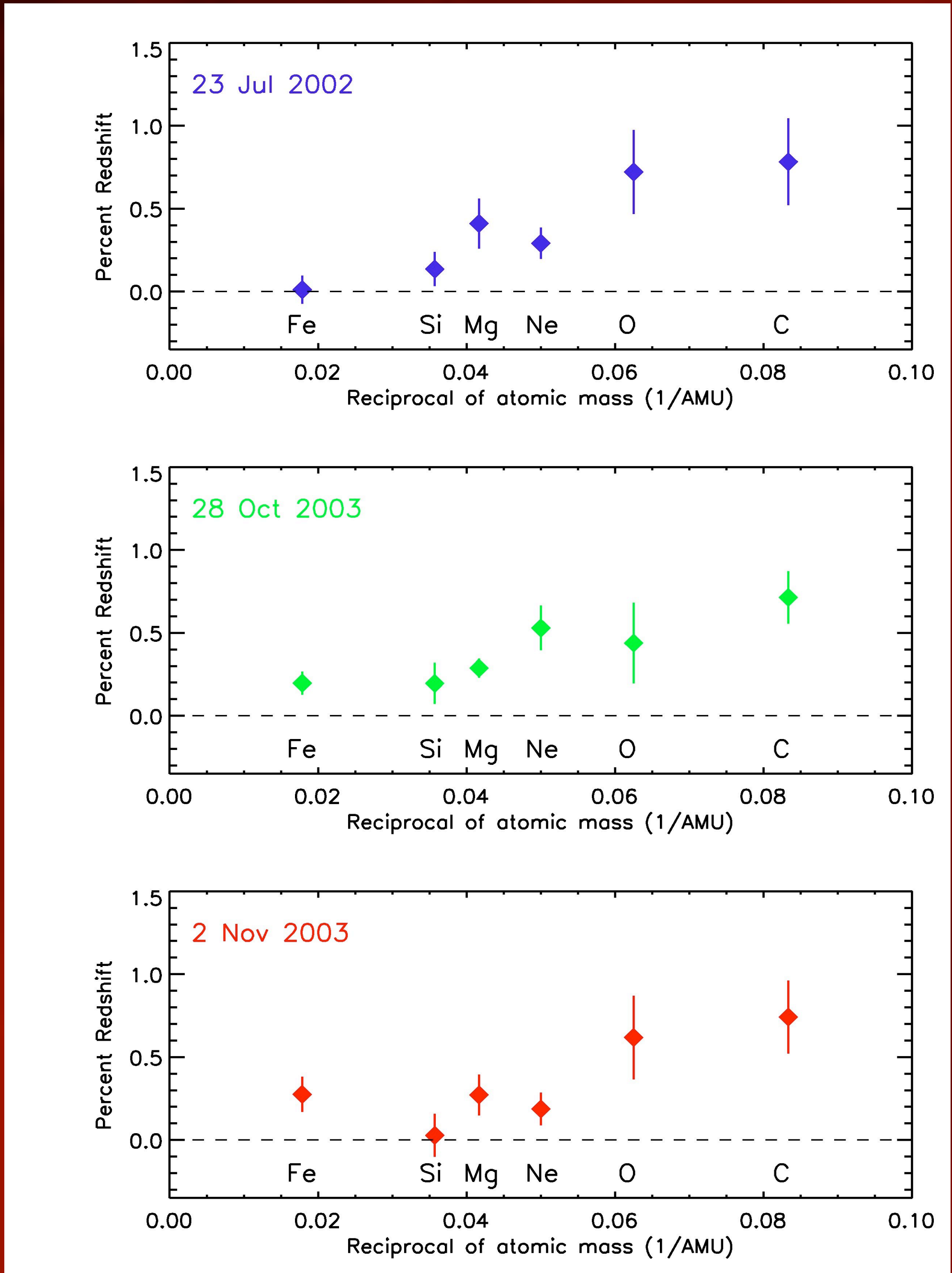
All narrow nuclear deexcitation lines are resolved, and show Doppler redshifts and broadening

Blue bars show instrumental FWHM

7/23/03 X4.8 flare



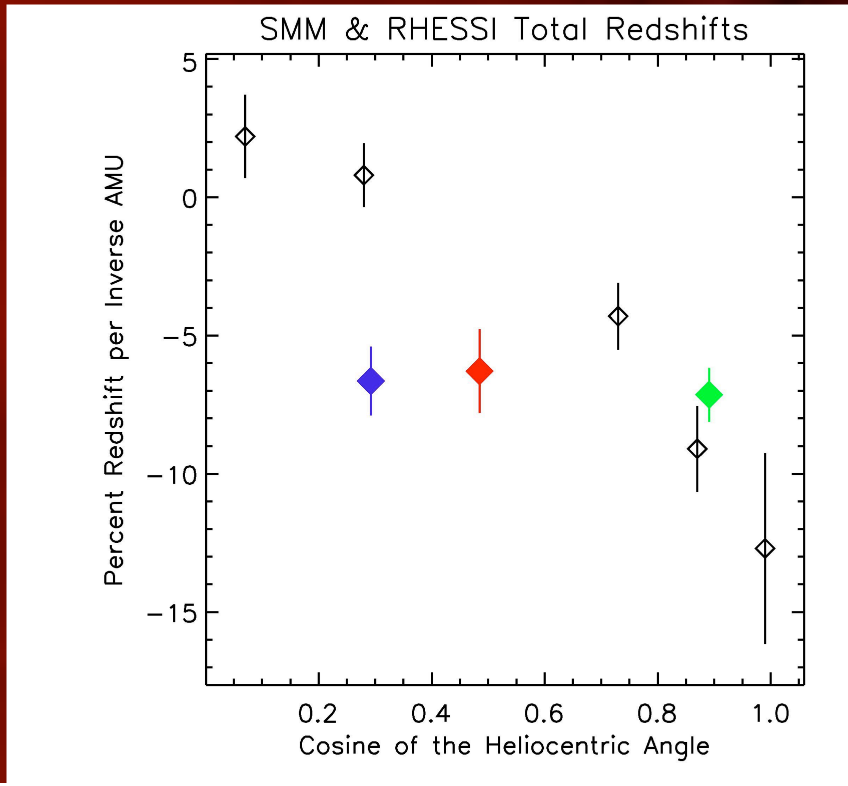
Redshift versus mass

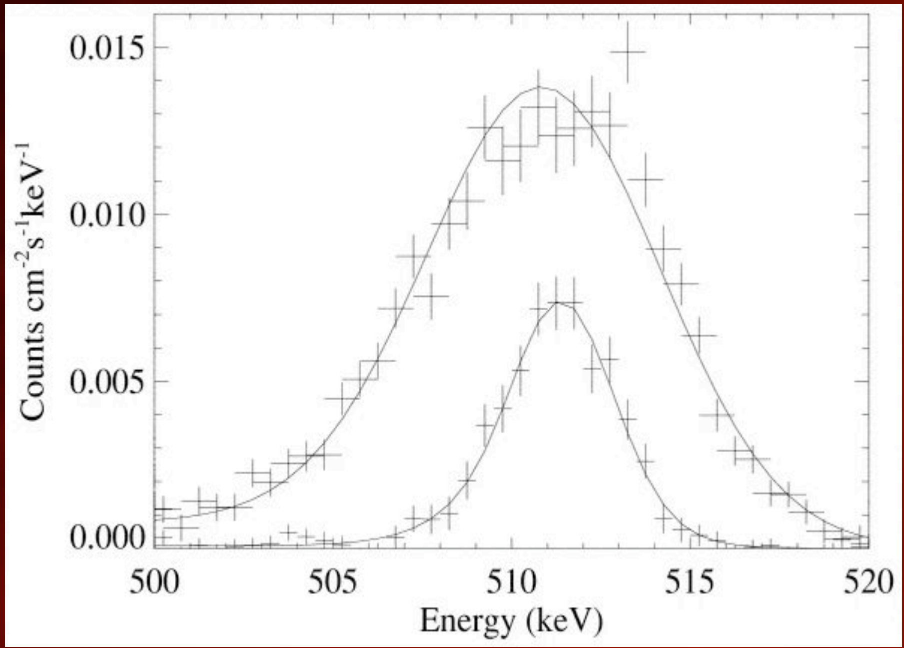


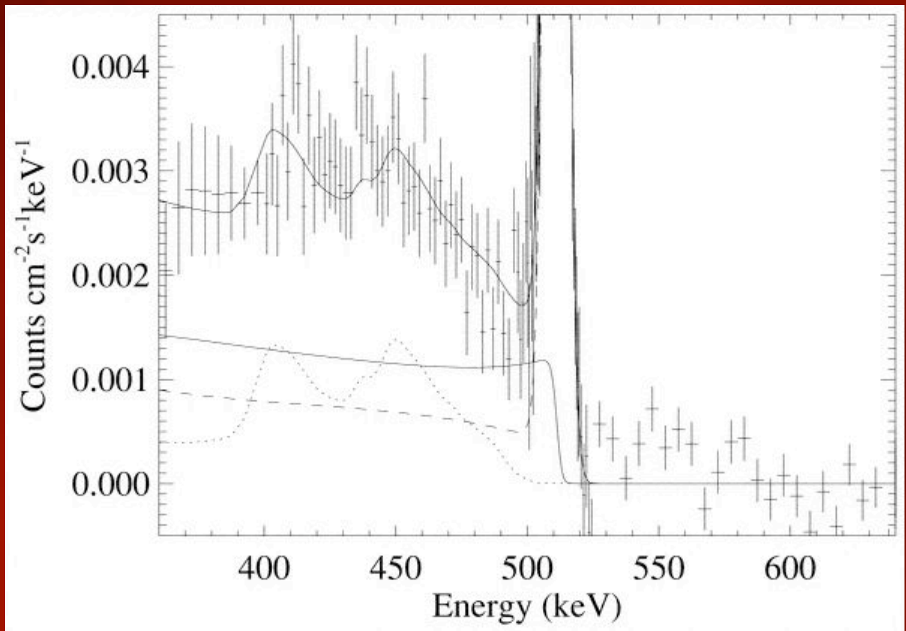
Redshift vs. heliocentric angle:

Summed flares from SMM
(Share et al. 2002 ApJ 573, 464)

Three individual RHESSI flares







Positron annihilation line from early in the 28 October 2003 flare is extremely broad; gets narrow later on.

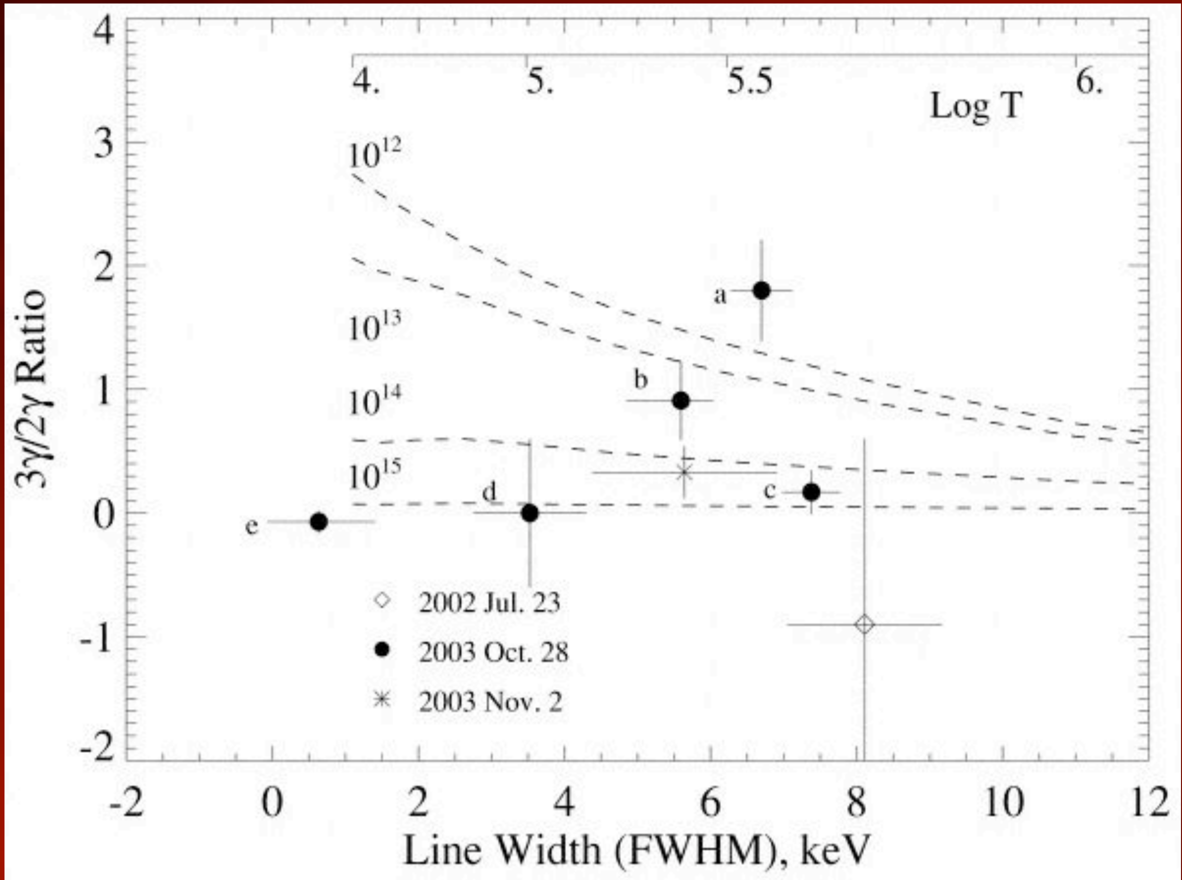
Suggests a dense, hot flaring atmosphere around 300,000 K; Cooling is very efficient here, so this is extremely far from equilibrium.

Region below the line shows positronium continuum, alpha/alpha line complex, and instrumental Compton plateau.

Alpha/alpha lineshapes are the most sensitive probe of ion angular distribution, but better statistics neede

From G. Share et al. 2004, ApJ 615, 196

Constraints on density and temperature of the annihilation medium from three RHESSI flares



From G. Share et al., ibid.

28 October shows evolution to deeper parts of solar atmosphere -- pion component taking over?

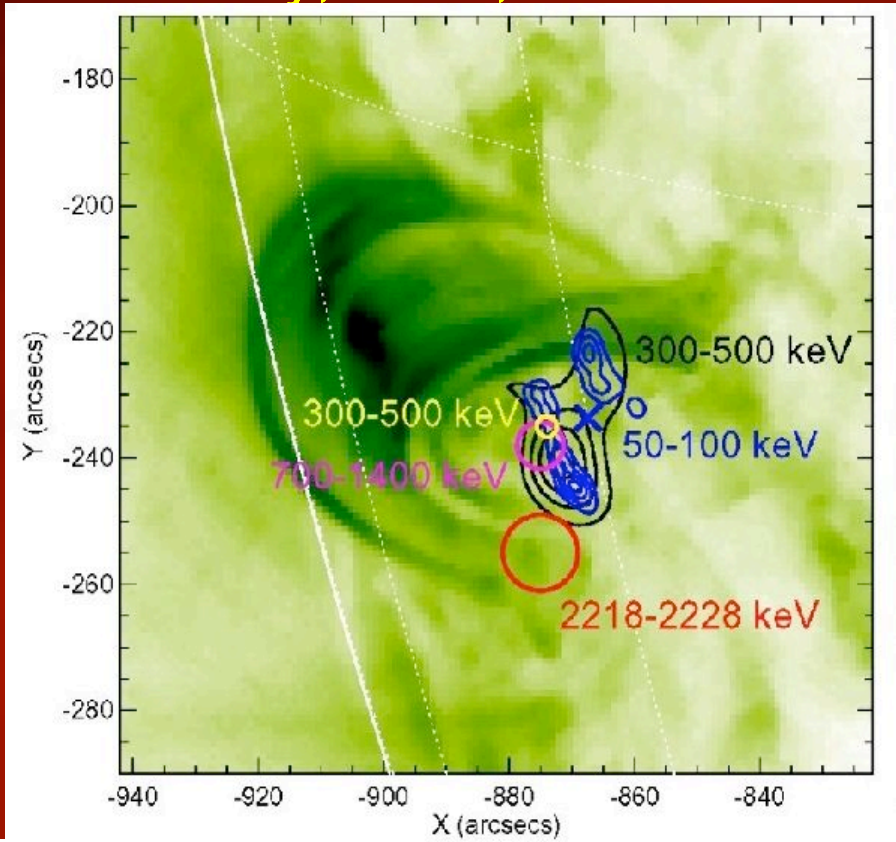
This technique, like all shown here, is strongly limited by available counting statistics

FIRST ARCSECOND IMAGING OF MeV GAMMA-RAYS: Neutron capture line at 2.2 MeV (G. Hurford, UCB)

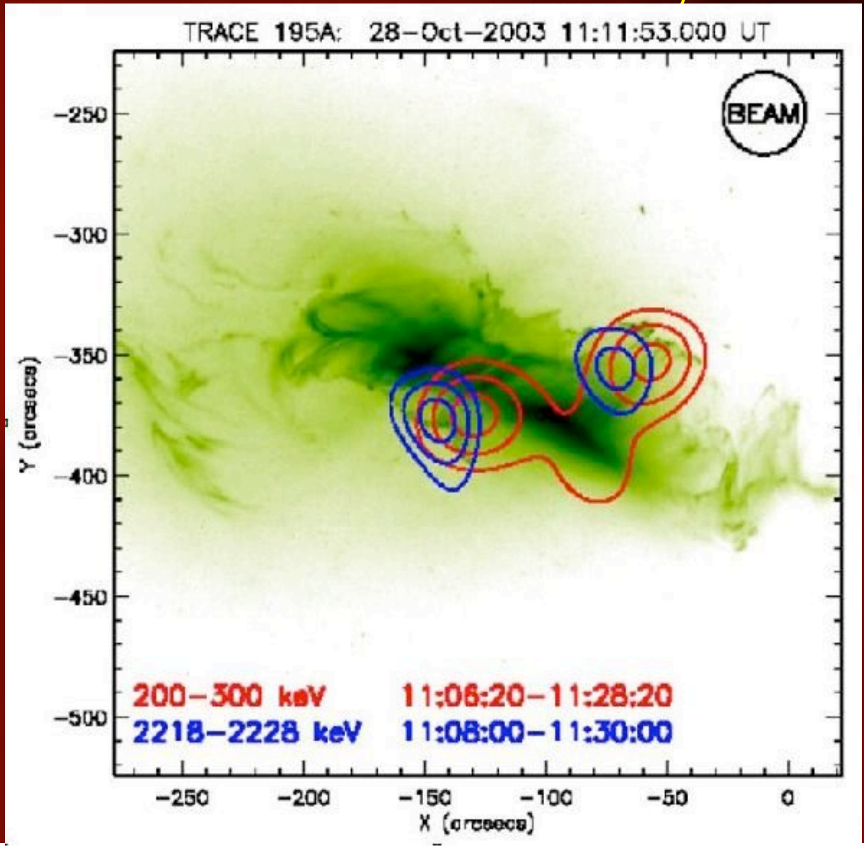
Ion acceleration and electron acceleration are not co-located!

-> Strong constraints on acceleration models

23 July, 2002, GOES X4.8



28 October 2003, GOES X1



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Science with focusing instruments

Requirements for significant improvements in observations at 511 keV and 847 keV:

FOV: 1.5' (minimum) to 3' (preferred) radius

Bandwidth: minimum +/-15 keV around 511 keV
minimum +/-15 keV around 847 keV

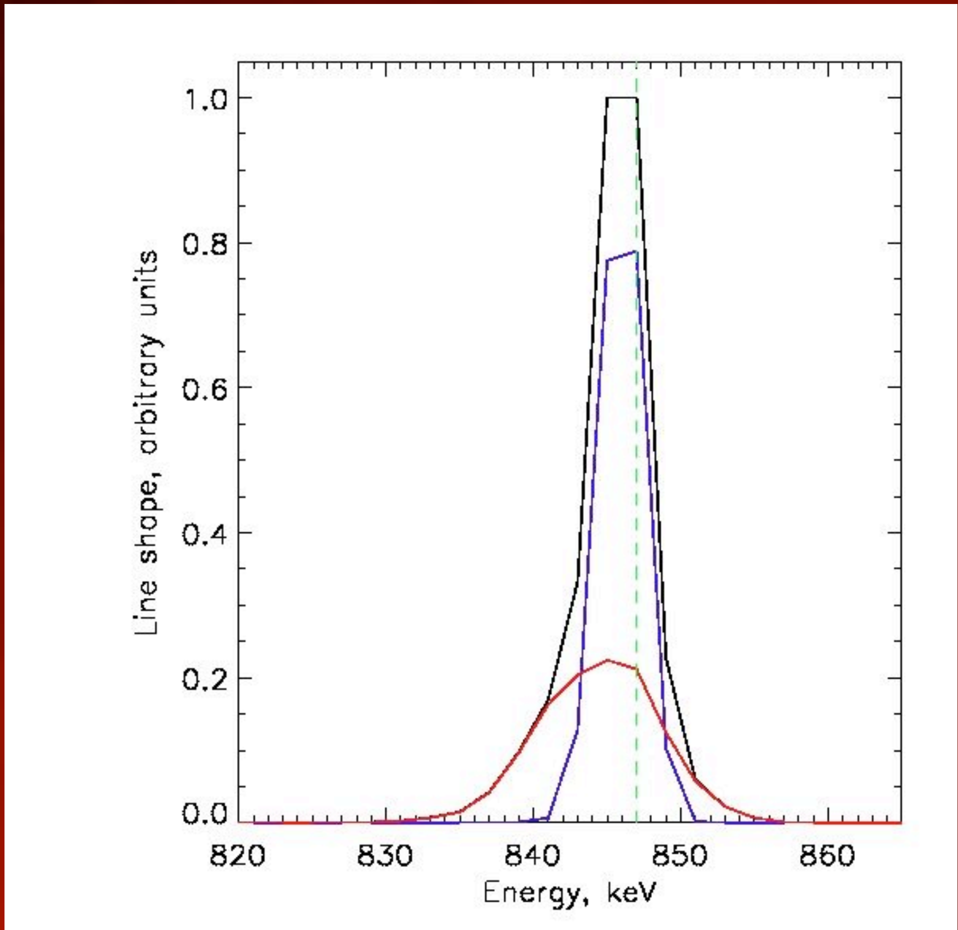
Resolution: minimum 3 keV FWHM, 1.5 keV desired (Ge)

Effective area: > 500 cm2 (10x RHESSI)
(note: flare background is dominated by flare continuum!)

Exposure time: 3 months observing over a 3 year mission
should get 3-10 major flares if good active regions are given a high priority as TOO

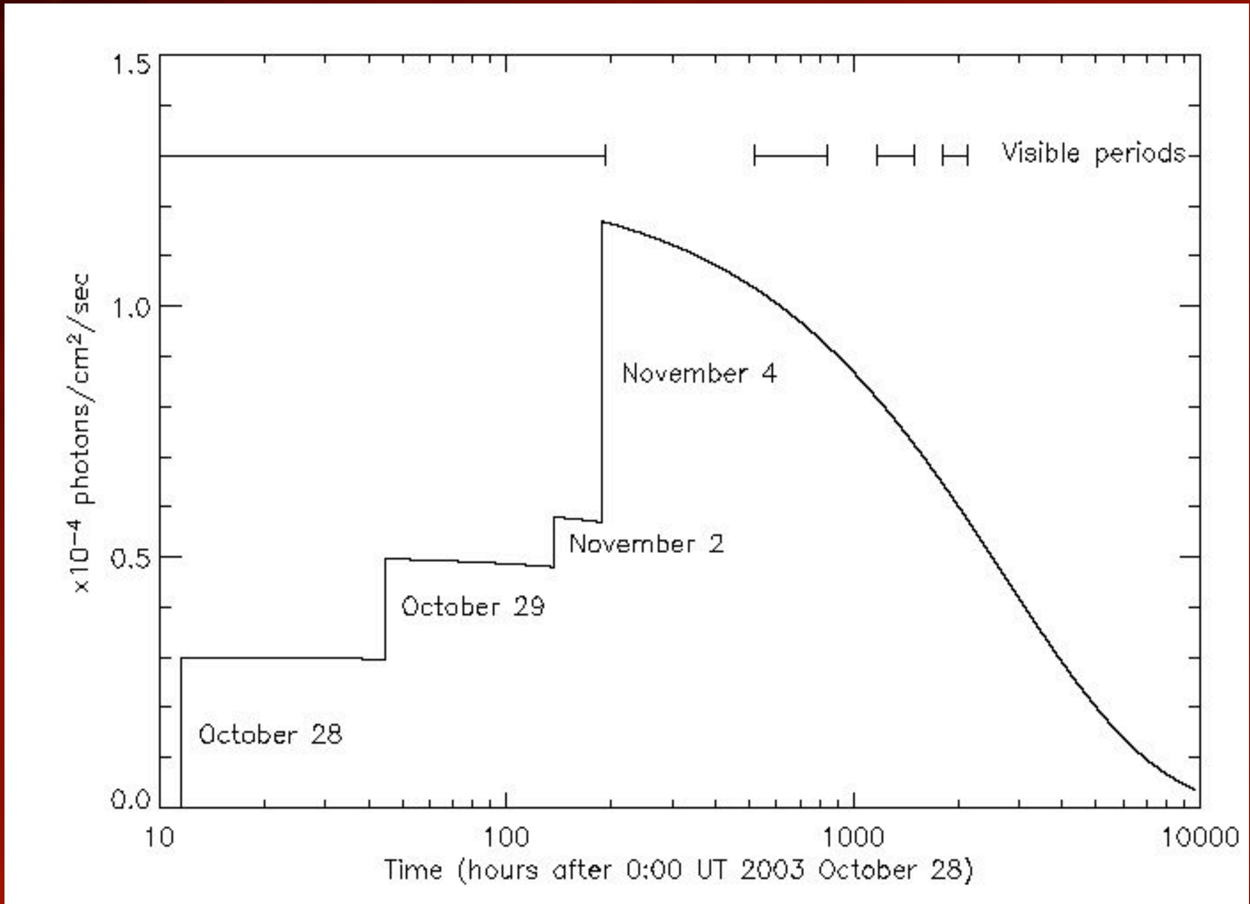
Although the Fe de-excitation line at 847 keV is relatively narrow,

good resolution can separate t
alpha and proton components
constrain the angular distributi
and field tilt.



Model calculated by R. Murphy, NRL;
alpha/p = 0.5, spectral index -4.75,
downward isotropic ion distribution

The delayed 847 keV line from the radioactivity of 56Co should appear after very large flares; it has not yet been observed.



Estimated flux at 847 keV from solar radioactivity after the Halloween 2003 flares. Calculated by A. Shih from theoretical estimate by Ramaty & Mandzhavidze 2000 (IAU symposium # 195, p. 123)

The initial flux will cons the spectrum and fluen energetic ions

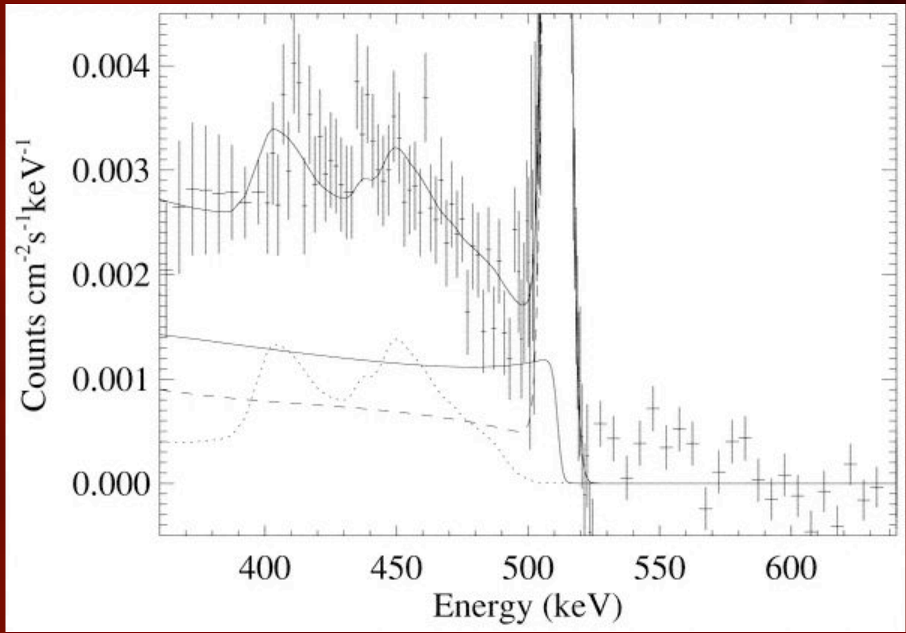
The decay will serve a tracer to study solar atmospheric mixing

Knowing where to poin in later stages will be a issue

At 511 keV, the lineshape will easily be obtained

The positronium continuum may be accessible from the step across the line

Separation of the alpha/alpha line (and alpha/alpha science!) can be achieved by an extension down to 400 keV plus a simple hard x-ray detector to pin down the underlying continuum from 100-400 keV



Hard x-ray observations of electron bremsstrahlung:

1) Coronal heating question: do microflares and nanoflares increase in number at low luminosities sufficiently to keep the solar corona at MK temperatures?
Critical observations: extremely high sensitivity, coverage from abou 3-30 keV (thermal/nonthermal spectral transition) with ~ 1 keV energy resolution (Ge/Si/CZT), modest spatial resolution (1 arcmin) (this is for identification and energetics, not true imaging)

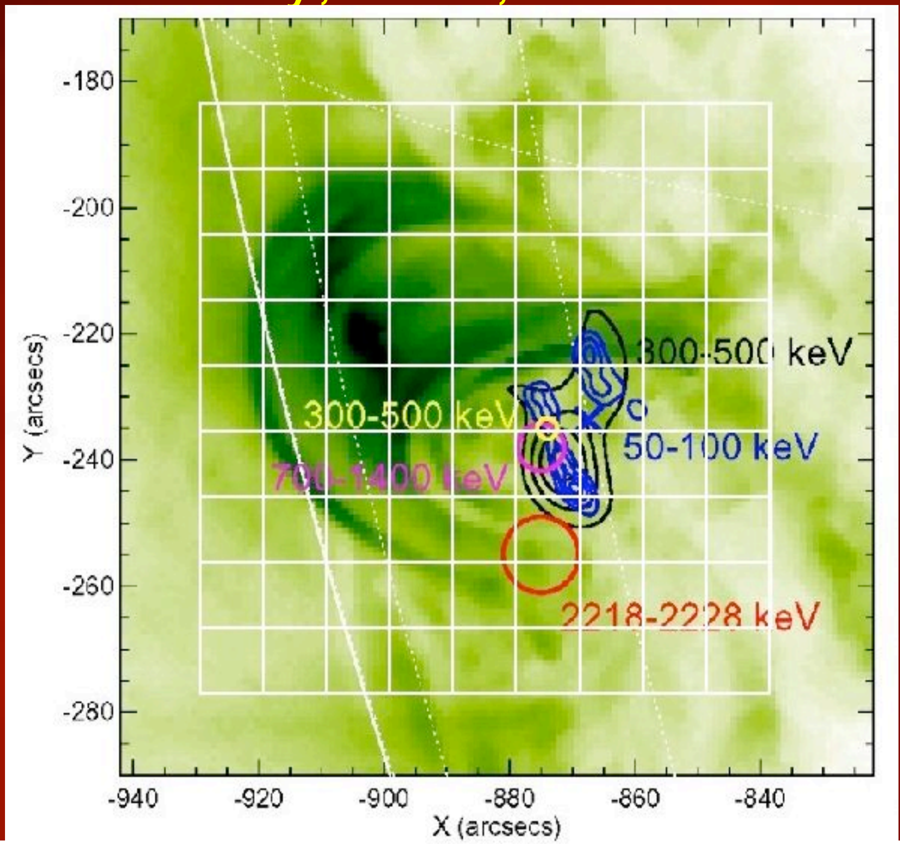
2) Hope for first observations of high-coronal x-ray sources without flares (upward electron beams associated with type III radio bursts) Expected to show nonthermal spectrum all the way down to bottom of the range. Combine with radio data to derive electron energetics coronal density, magnetic field. Compare with heliospheric e-.

Data to beat: RHESSI at 50 cm2 background-dominated across this ra

Imaging science at 2.2 MeV: real imaging at 10" or better will be a leap beyond RHESSI's new results.

1) True imaging?
2) Inversion of ring response off-axis for simple concentrators?
3) Multiple sub-lenses with an array of focal plane detectors and different fields of view? Energy/angle muliplexing? (9x9 10" pixels

23 July, 2002, GOES X4.8



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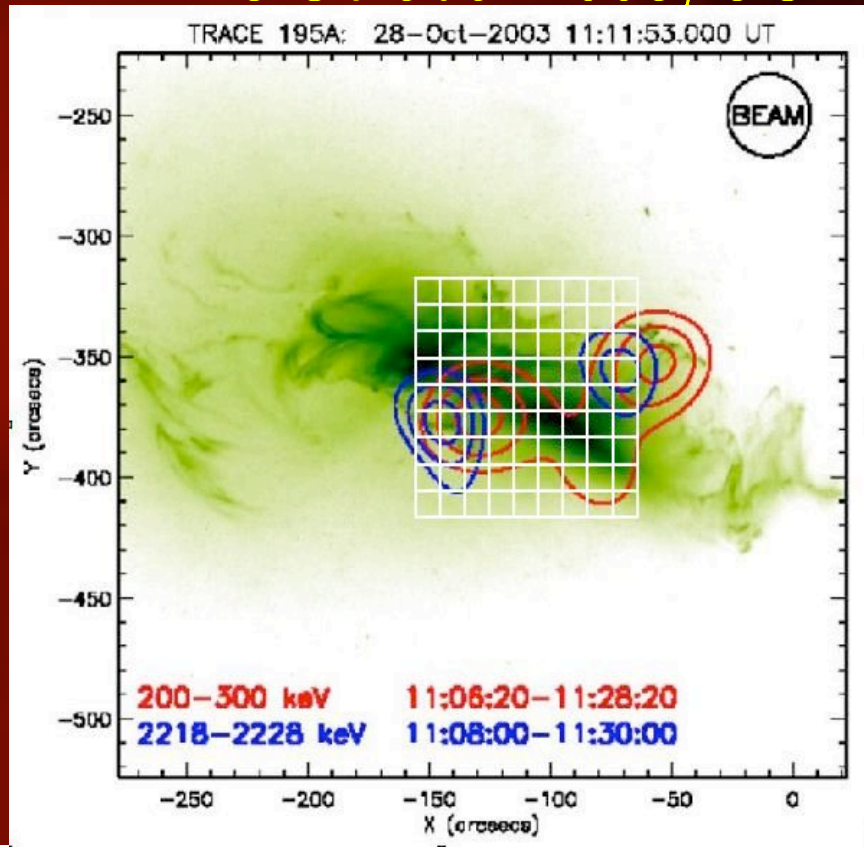

Conclusions:

RHESSI & SPI have tantalized us with the possibilities of high resolution spectroscopy for unique solar studies, but

WE NEED MORE PHOTONS!

MAX, for example, as designed for cosmic astrophysics, is also ne ideal for many of the solar science goals. Ge resolution is critical.

The ability to point at the Sun should be built into MAX design and other astrophysics missions

Significant time (order of 1 month/year, TOO mode) should be reserved for solar observations in such missions

(Note: good gamma-ray flares also occur outside solar maximum!)