ION ACCELERATION IN FLARES

OR

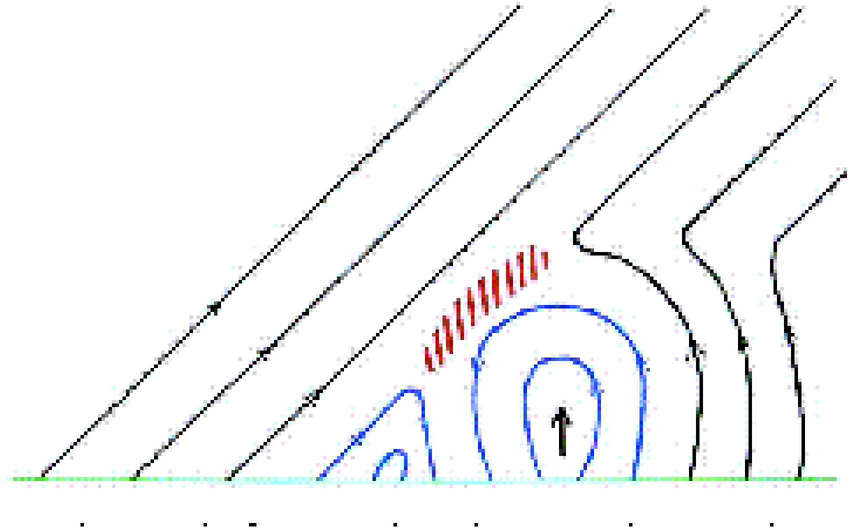
WHAT WE CAN LEARN FROM

GAMMA-RAY LINES

What do these emissions reveal about the site and nature of energetic particle production in flares?

What information do they provide on the magnetic field geometry, including possible extensions to open field lines?

Impulsive SEP's/X-ray events: to date no coincident γ-ray line and particle events. Limits on ions at Sun for these events? (Alexander, today)



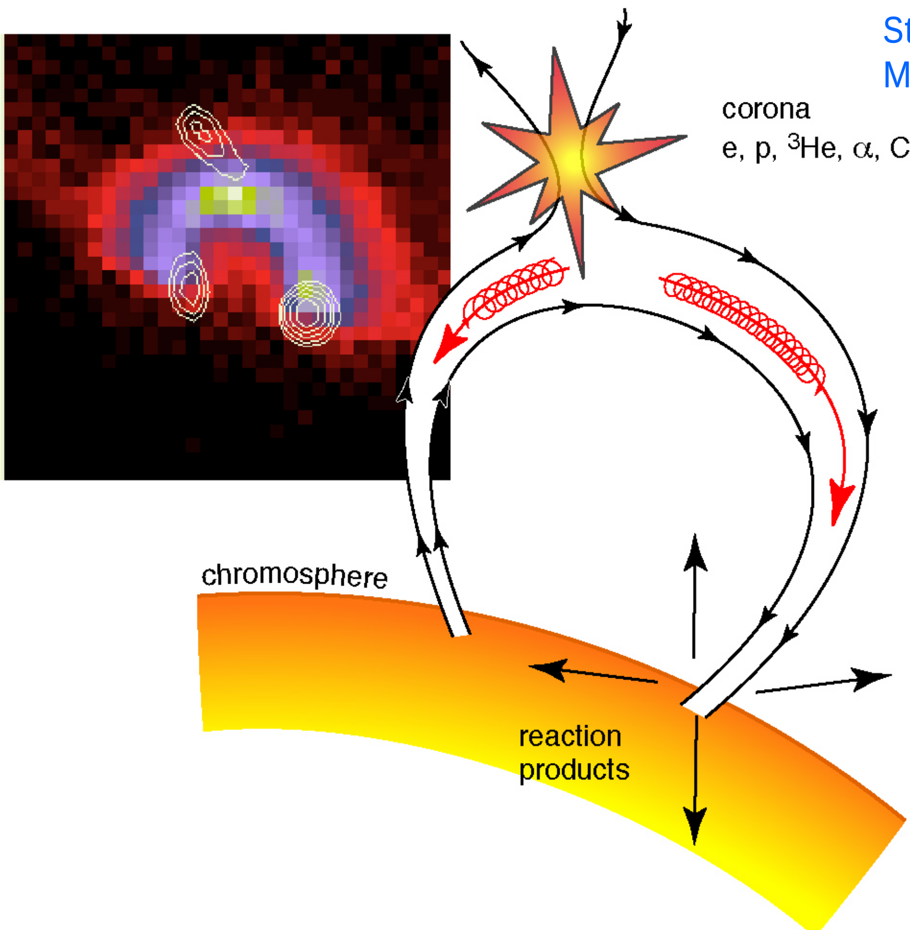
Large CME's/ gradual SEP events – several coincident γ-ray line and particle events.

Magnetic topology cartoon, Reames 2002

γ-RAY AND NEUTRON PRODUCTION IN SOLAR FLARES

Loop-top source

Stochastic Acceleration throughout the loop - Miller/Petrosian



electrons: X- and γ-ray bremsstrahlung

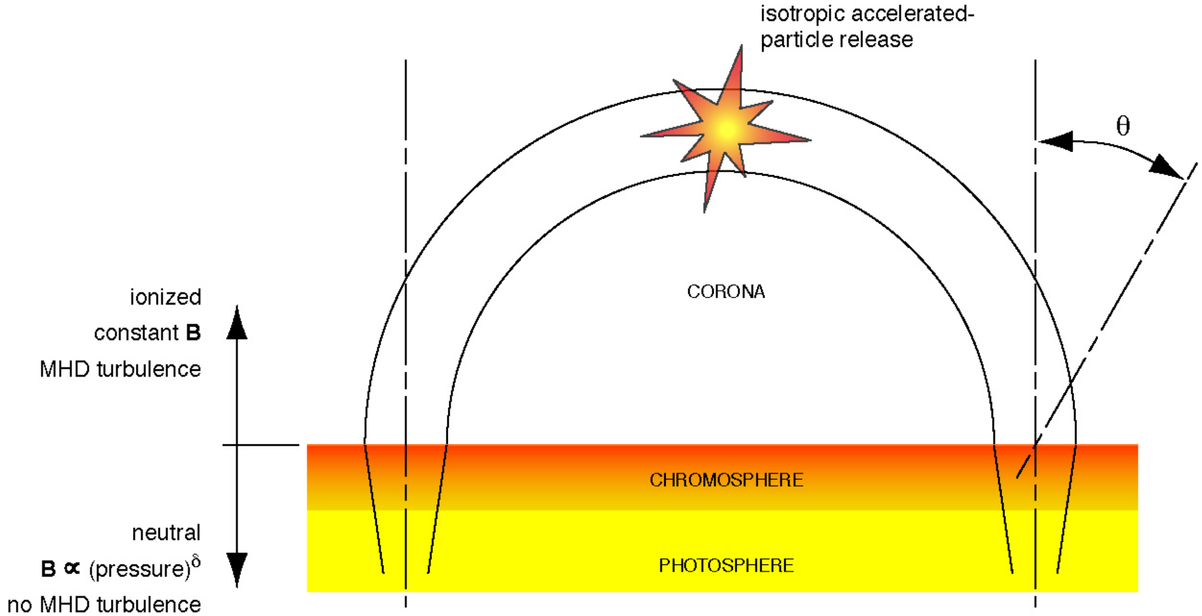
ions: excited nuclei $\rightarrow$ γ-ray line radiation (1–8 MeV)

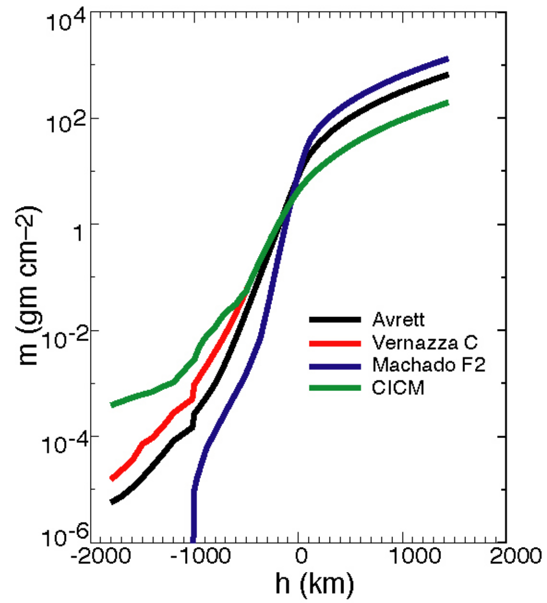
neutrons $\rightarrow$ { escape to space / capture on H – 2.223 MeV line

radioactive nuclei $\rightarrow e^+ \rightarrow \gamma_{511}$

$\pi \rightarrow \gamma$ (decay, $e^\pm$ bremsstrahlung, γ_{511})

Magnetic Loop Model

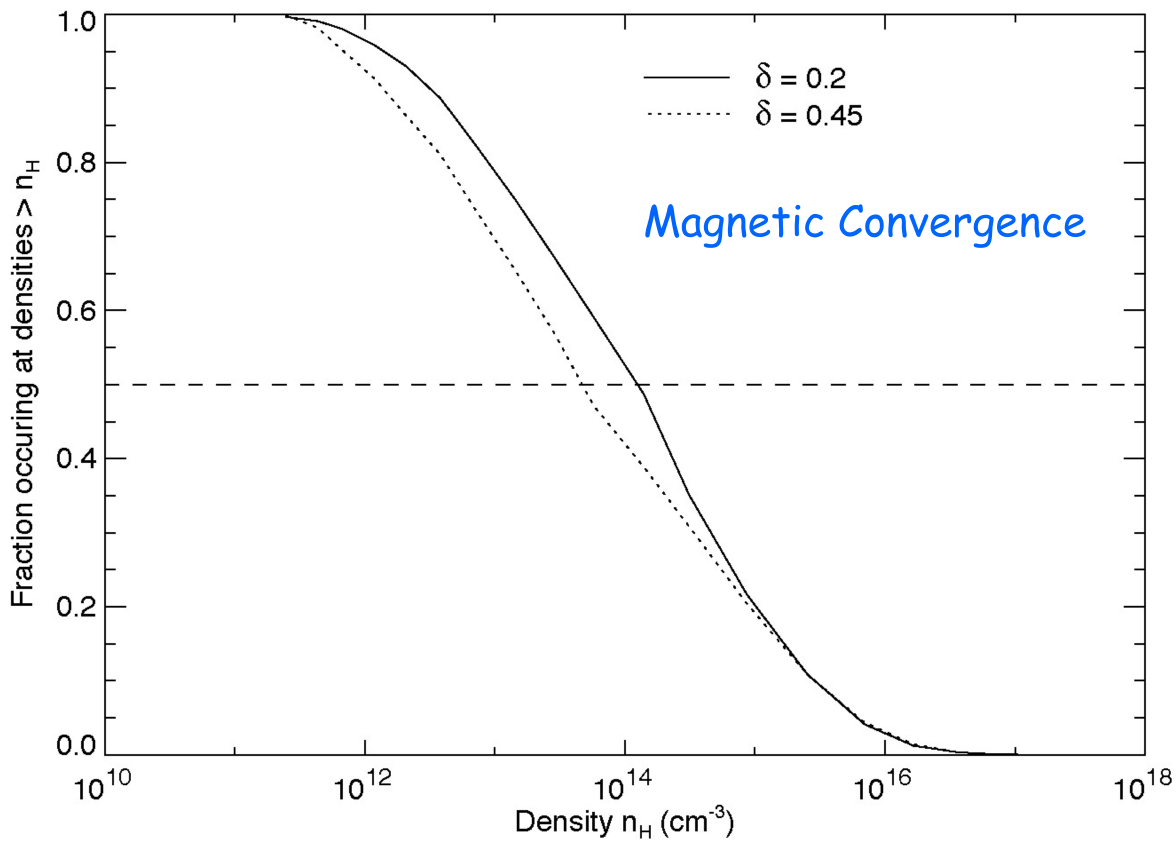




- Scattering due to MHD turbulence replenishes the loss cone: $\lambda = \frac{\Lambda}{L_C}$ $\frac{\text{(mean free path)}}{\text{(loop half length)}}$
- Mirroring due to magnetic field convergence: $B(h) \propto P(h)^{\delta}$
- Atmospheric model
- Accelerated-particle spectral index
- **B** perpendicular to solar surface at footpoints

Depth Distribution of Nuclear Interactions Affected by Spectrum, Atmospheric model, Angular Distribution, and Magnetic Convergence

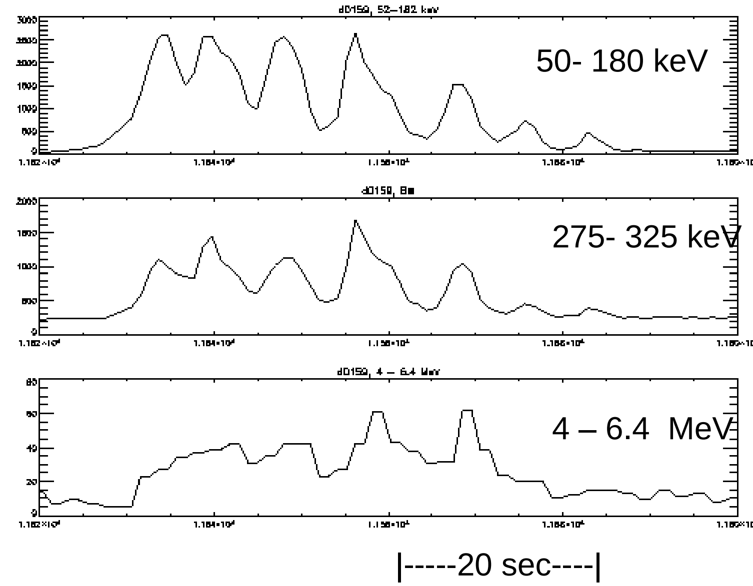
Power-law with index = 4.2. Downward distribution; Λ =300 (Hua et al.)

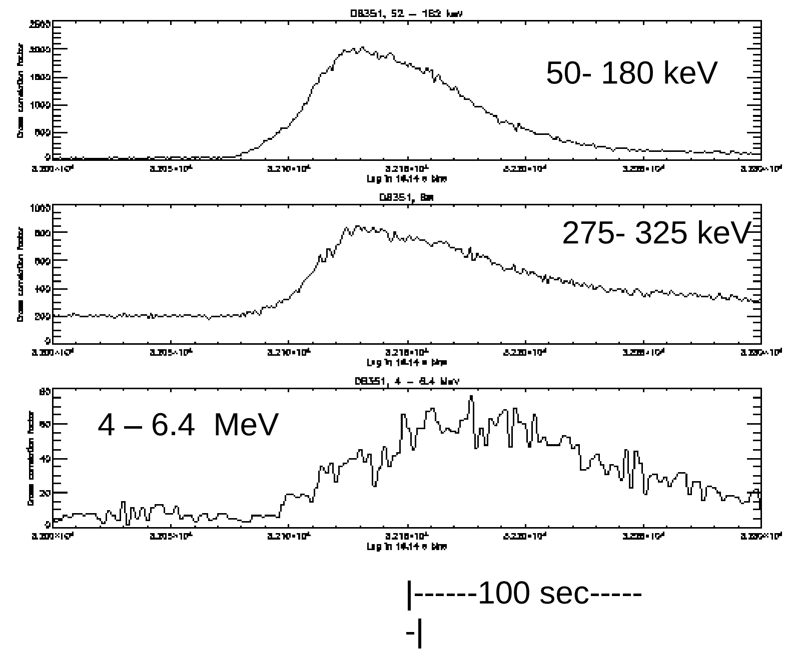


Time delays in γ-ray line emission can be as small as <2 sec to as large as 10's of sec.

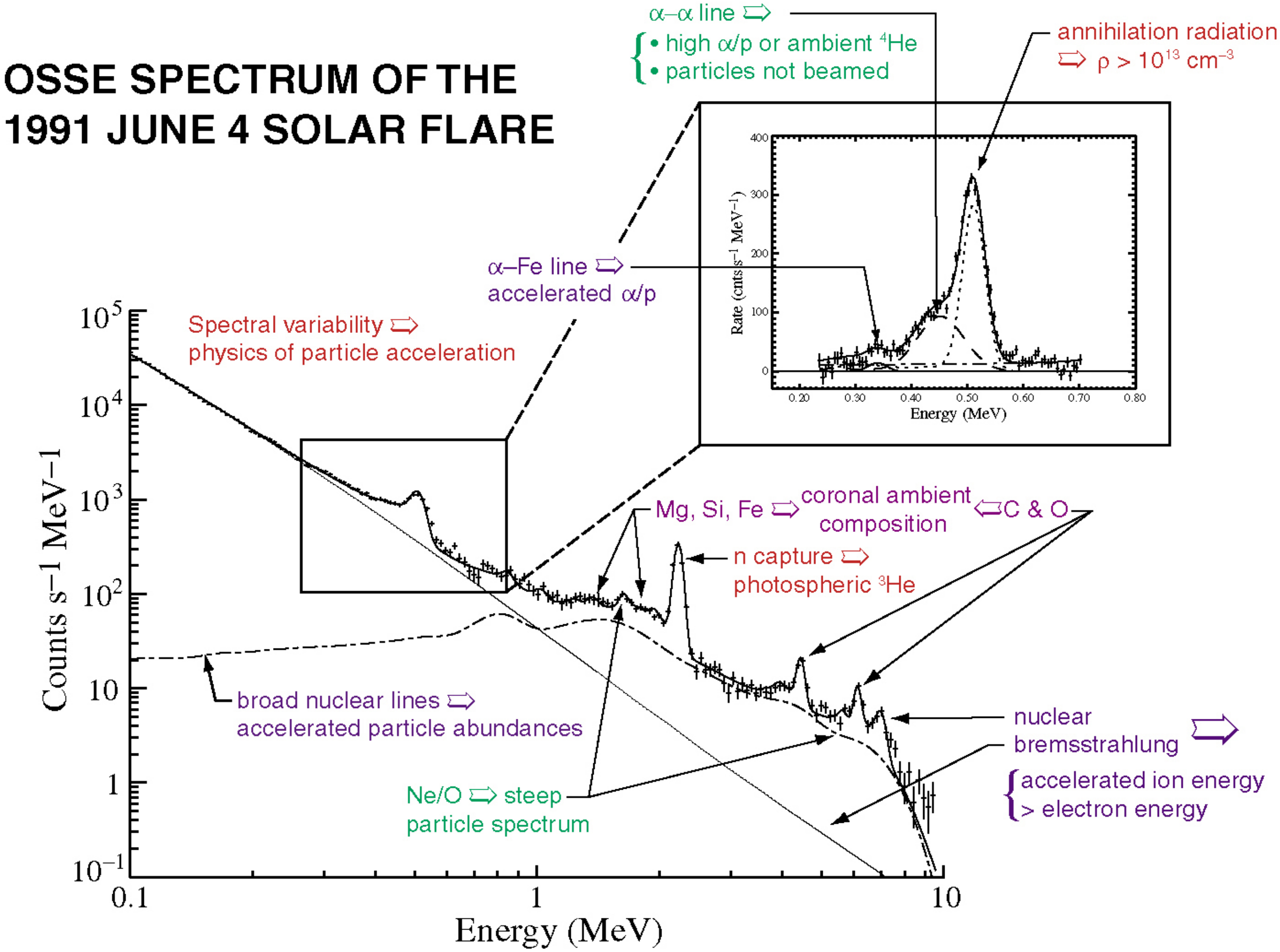
γ-ray line emission in 2002 July 23 flare may be delayed by ~10 sec from hard X-rays.

What does this say about acceleration-transport? Is delay from trapping or is it intrinsic to the acceleration process?

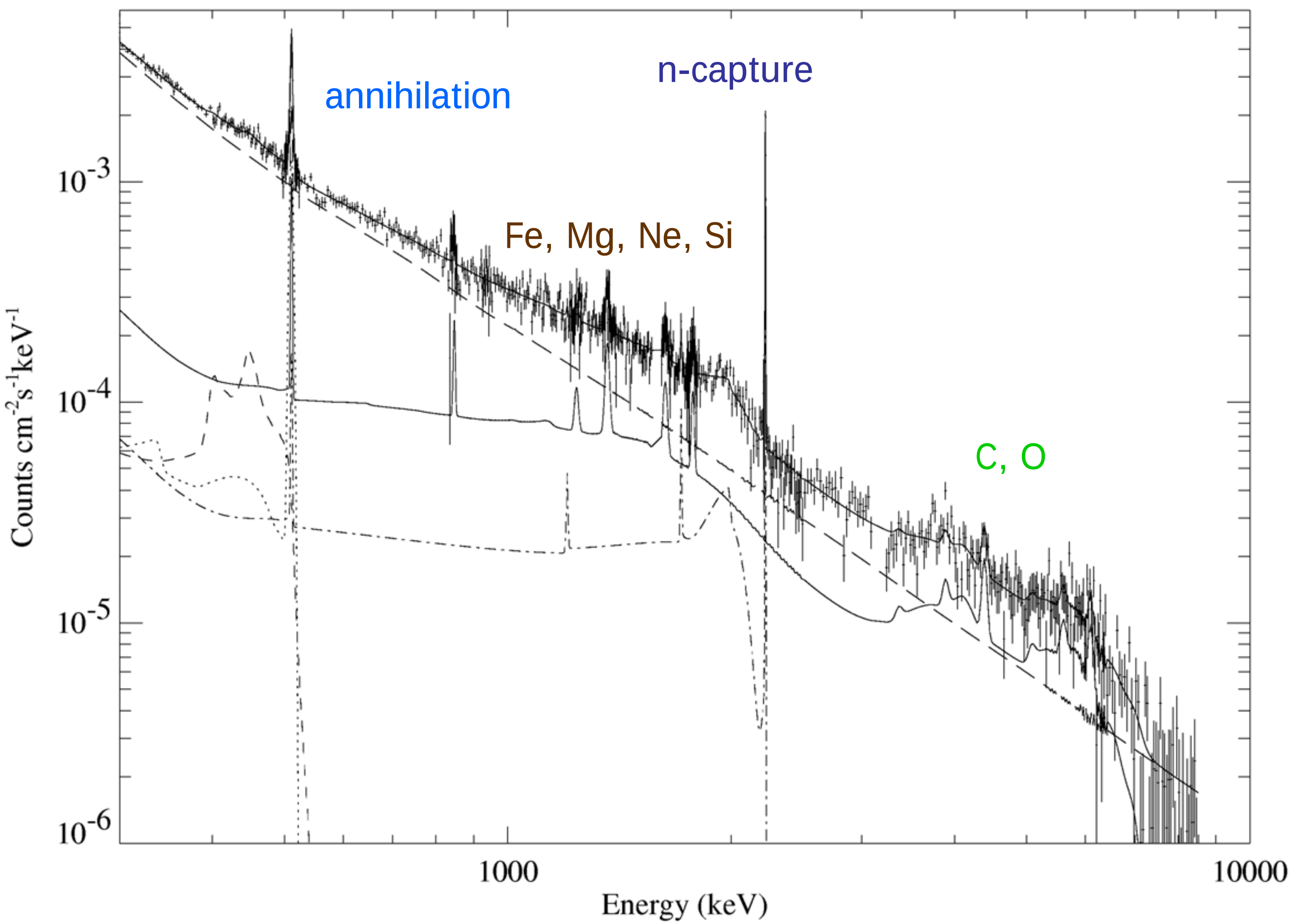




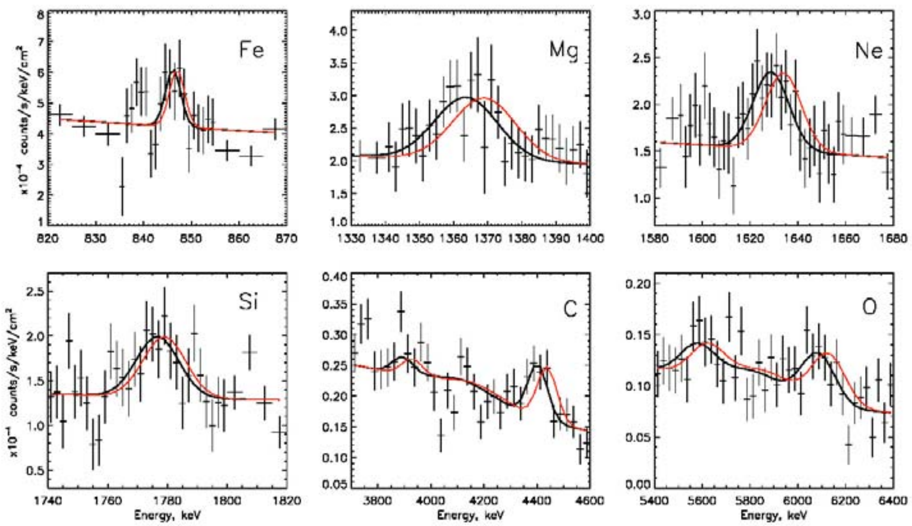
The Physics of Flares Revealed by γ-Ray Spectroscopy



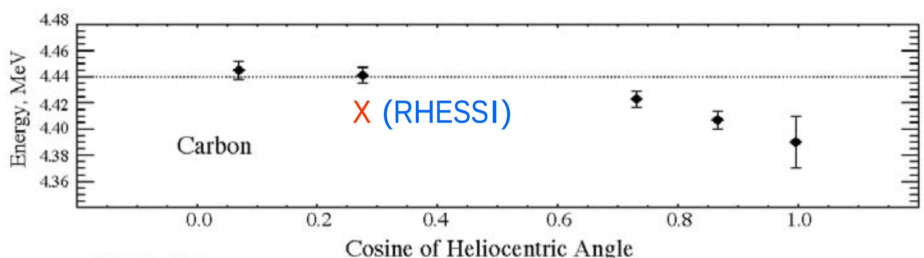
Fit to the RHESSI 2002 July 23 Spectrum



Smith et al. (2003) Line Shift Measurements



Line shifts imply strong downward-directed angular distribution ($\lambda < 300$)

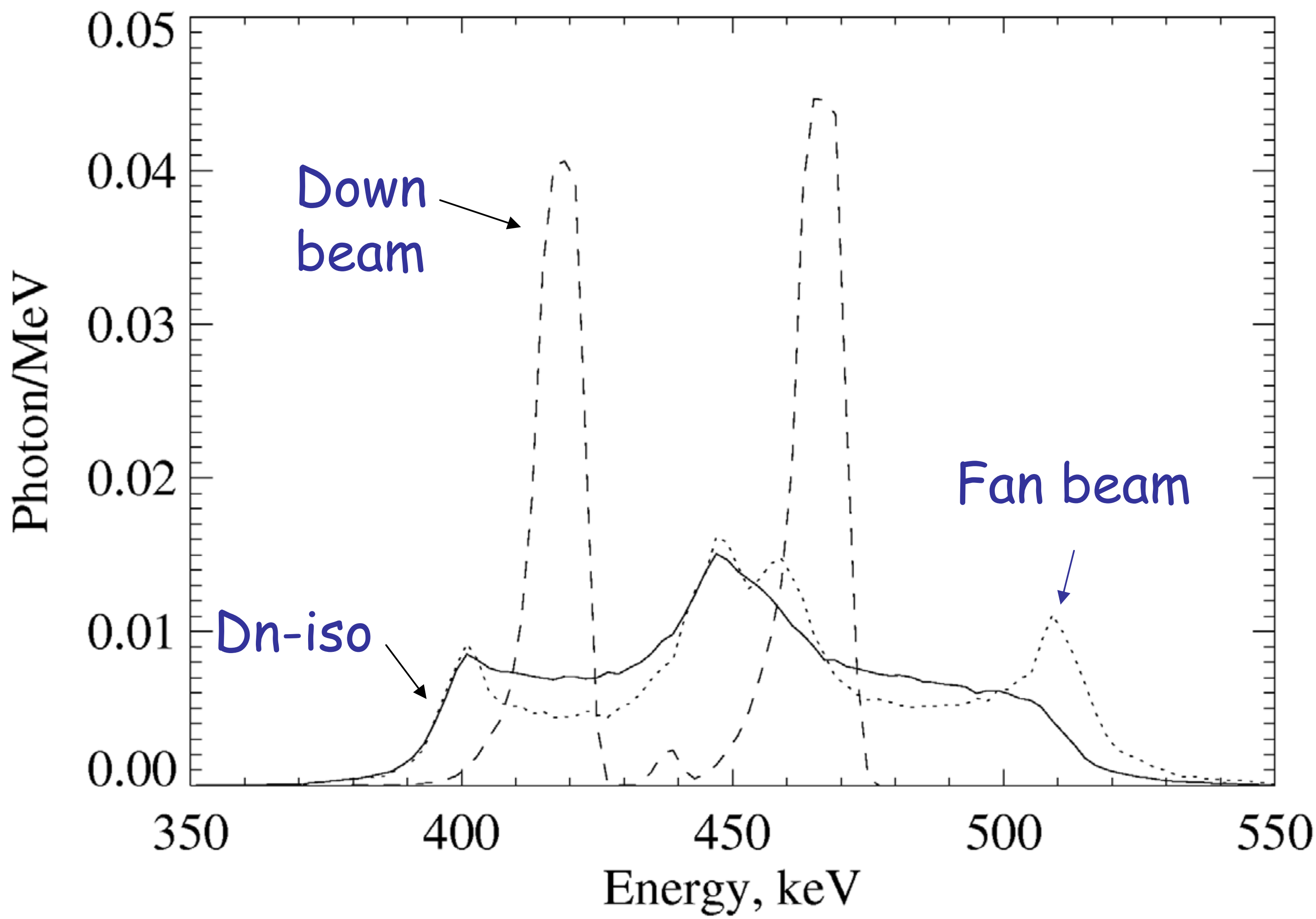


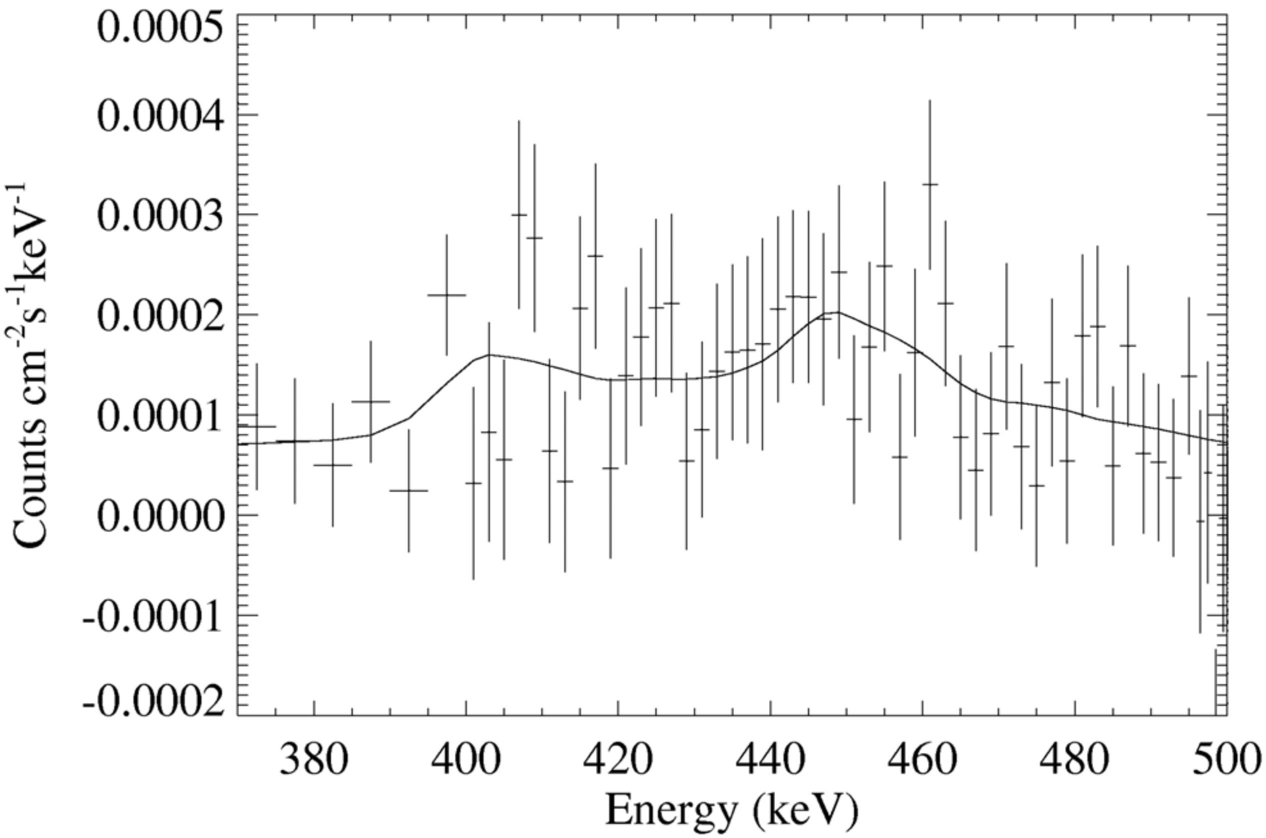
SMM

Share et al.

Such large redshifts in the 23 July 2002 flare not expected at 73° heliocentric angle. This suggests that the loop may be tilted toward earth or highly beamed hard spectrum.

Calculated Shapes of α-He Lines at 73° for Different Particles Distributions





Fit to RHESSI Spectrum

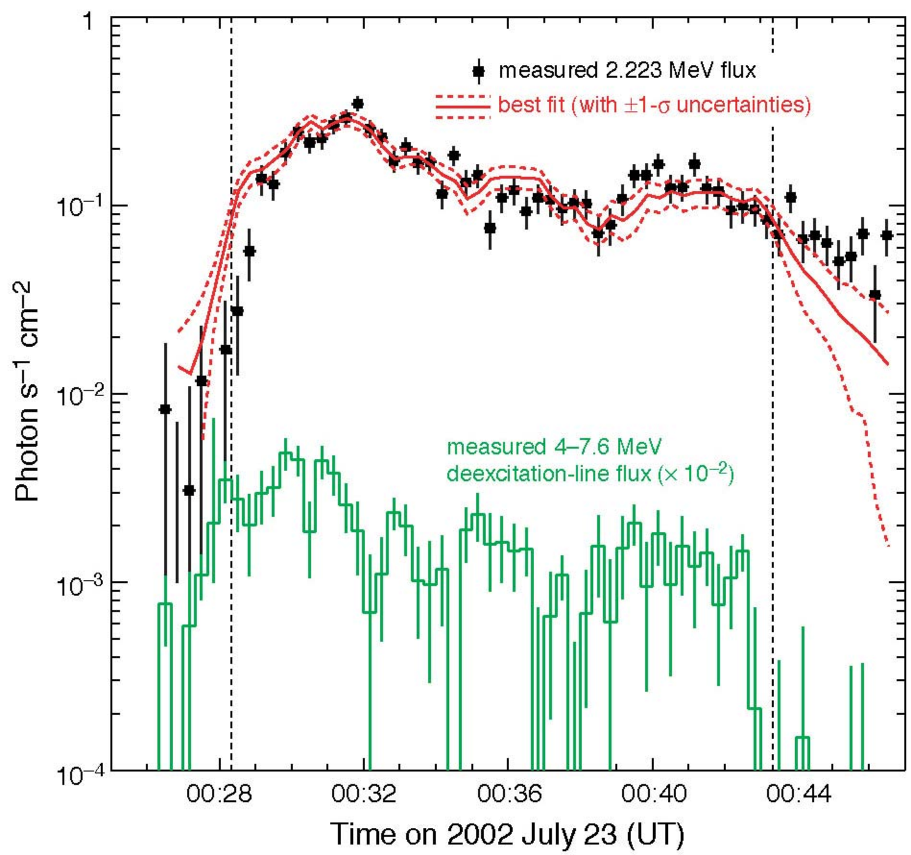
α-He line shape fit by downward isotropic or fan beam interacting particle distributions, but not by downward beam. Also consistent with forward isotropic with loop tilted by 40°.

n-Capture Line Time Profile also Dependent on Angular Distribution

2.223 MeV line emitted when neutrons slow down and are captured on H.

Time profile dependent on: accelerated particle angular distribution and spectra; concentration of ^3He; magnetic field convergence; loop tilt; and atmospheric model.

RHESSI 2.223 MeV data from 2002 July 23 flare are consistent with downward isotropic distribution at 73° for highly convergent magnetic field. **Tilted loop may also give consistent time profile.**



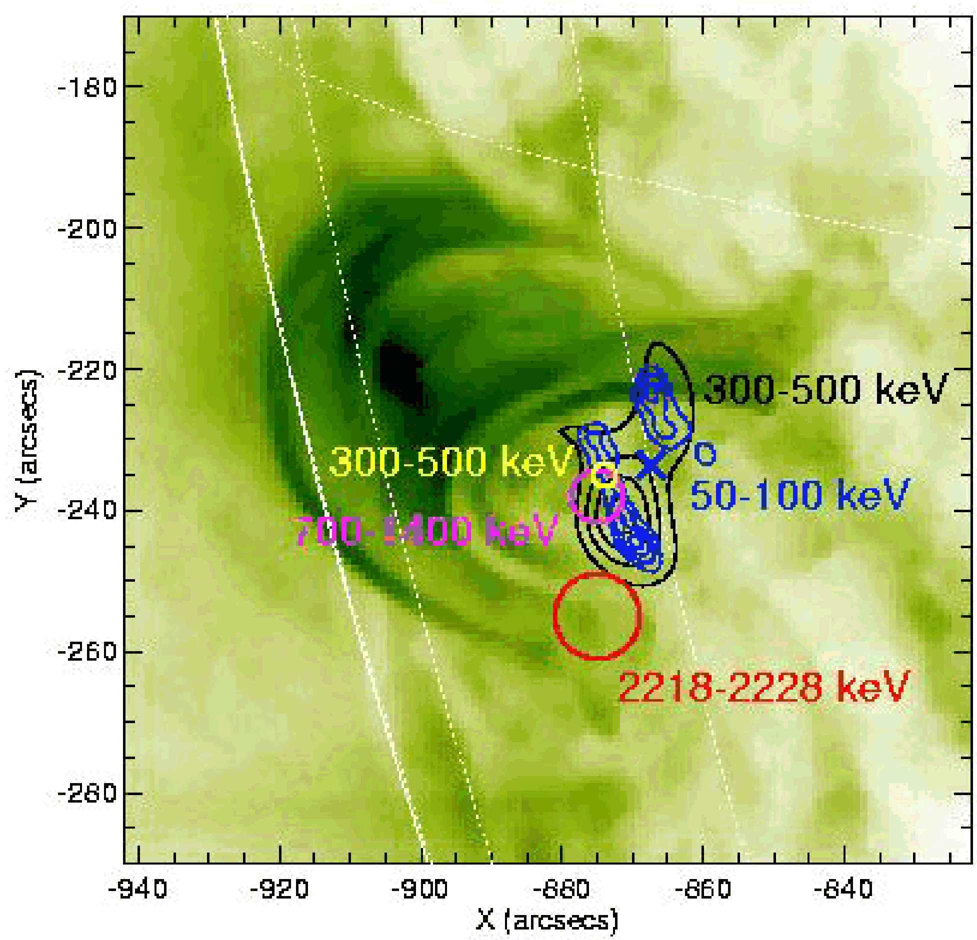
Murphy et al. 2003

Different Ion and Electron Interaction Locations?

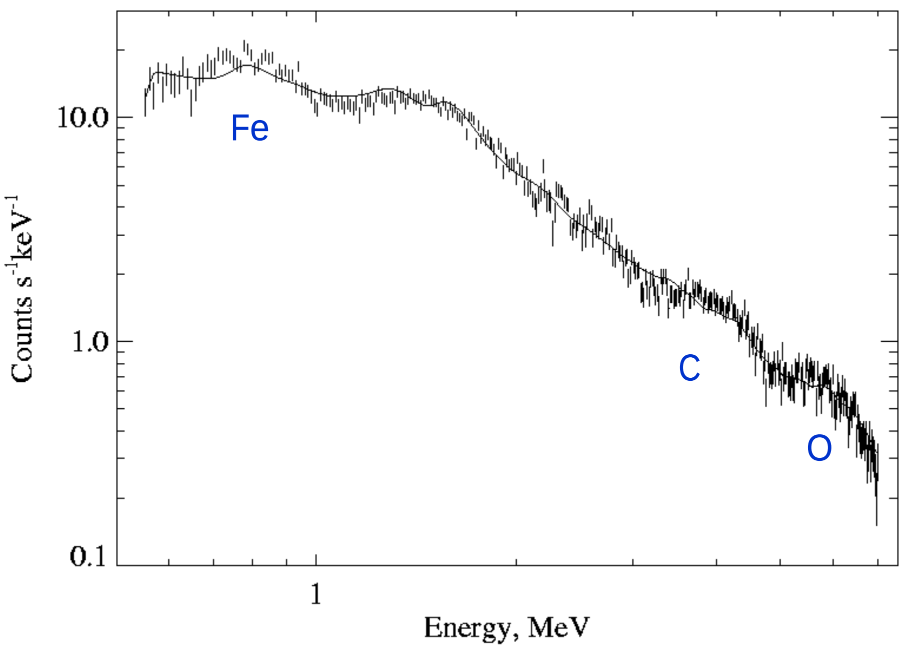
RHESSI image of 2002 July 23 flare. Location of ion (2.223 MeV line) source displaced by 20 ± 6 arc sec from hard X-ray source (Hurford, et al. 2003). No significant hard X-ray emission found at ion source.

Post-flare loops observed 90 min after the flare by TRACE are shown in the background.

Miller suggests that ions require longer loops to be accelerated. Is this the case here or is an electric field required to separate the ions and electrons?



Gamma-Ray Spectrum from Accelerated Heavy Ions

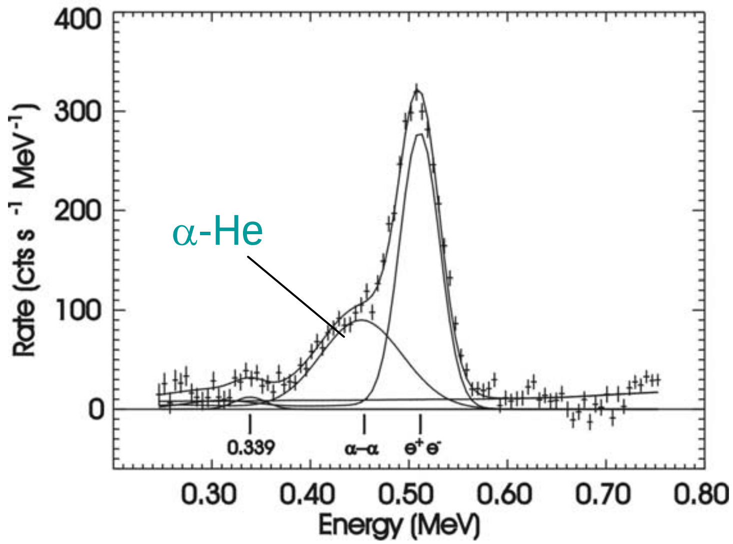


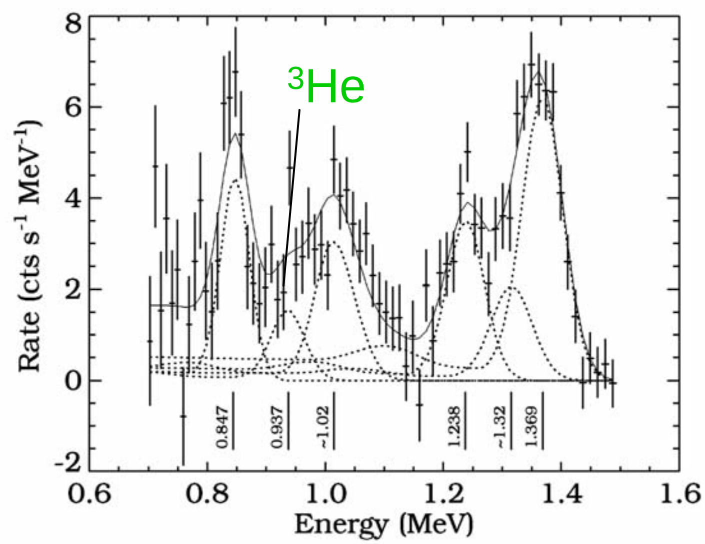
Fit using RKL (1979) unresolved component and interacting accelerated particles with impulsive composition, a/p = 0.5, PL index 4.5, and downward isotropic distribution.

- Accelerated heavy ions excited by interaction with ambient H and He.
- De-excitation lines are Doppler broadened by ~25%.
- Broad-line spectrum from sum of 19 SMM flares is revealed by subtracting best fitting narrow-line and bremsstrahlung components.
- Fe and C are resolved. The Fe, Mg, Ne, and Si lines between 1 - 2 MeV cannot be resolved.
- Major uncertainty is the shape of the 'unresolved line' component that is expected to peak in the 1 - 3 MeV region.

Helium Abundance from γ-Ray Line Spectra

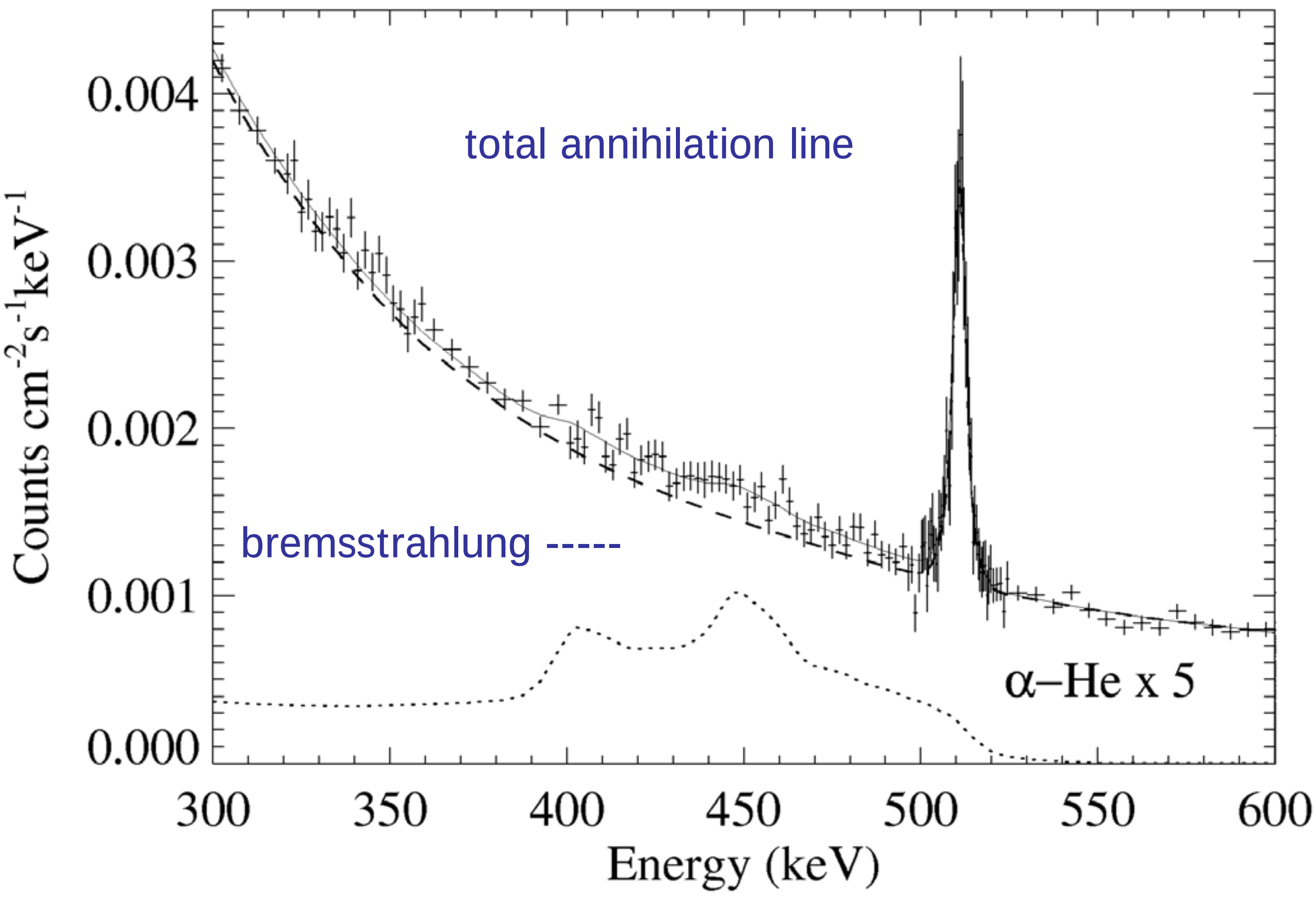
- Relative intensity of the α-He line feature suggests either enhanced accelerated α/p ratio or enhanced ambient He/H ratio at the flare site.
- Intensity of line at 0.339 α-^{56}Fe can discriminate between the two.
- Line at 0.937 MeV also expected from the ^{3}He interactions.
- **Studies suggest enhanced α/p ratio (~0.5) and evidence for ^{3}He/ ^{4}He ~ 0.1**





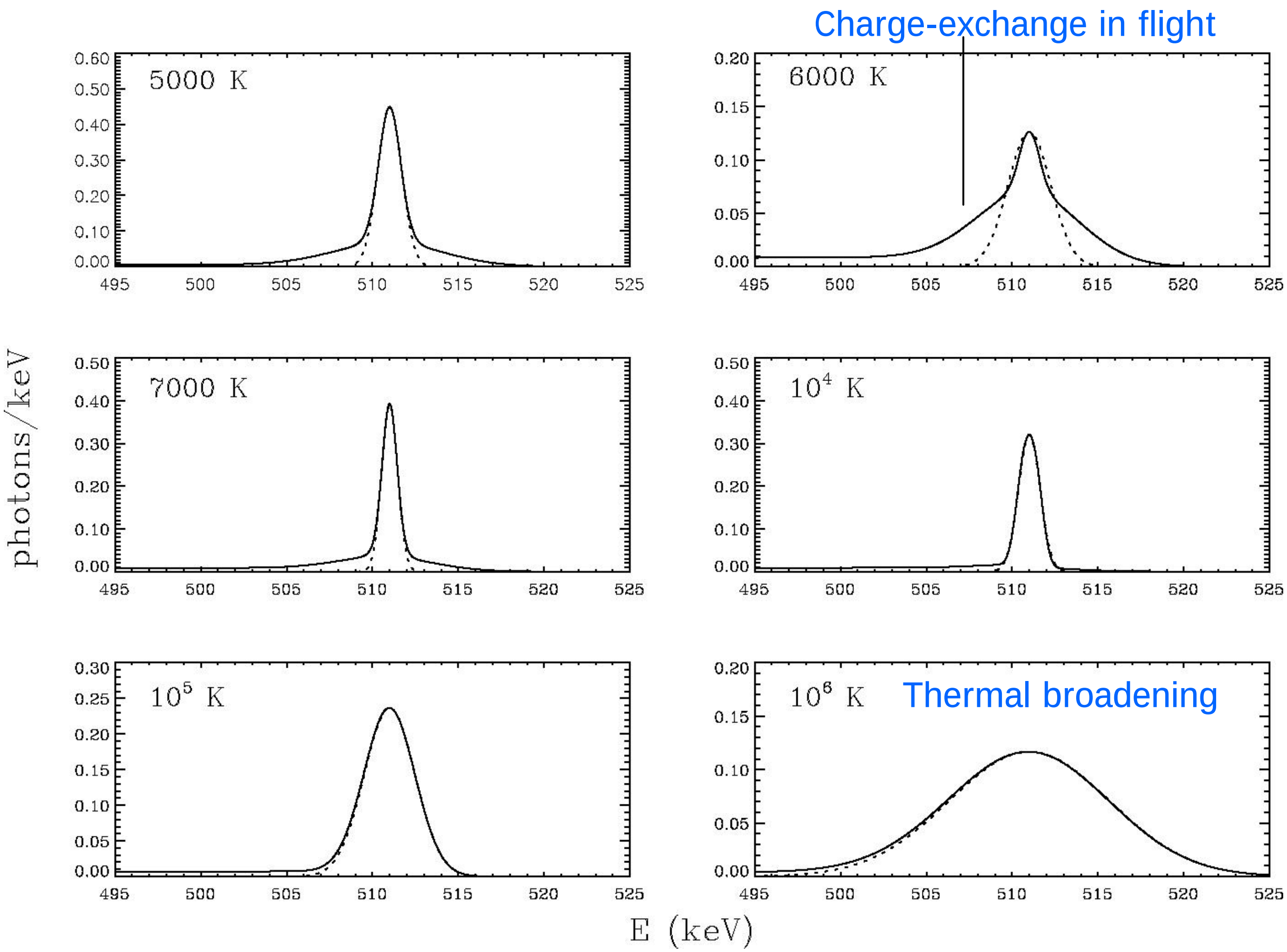
Fit to the RHESSI Annihilation Line Spectrum

Upper Limit on Positronium Continuum



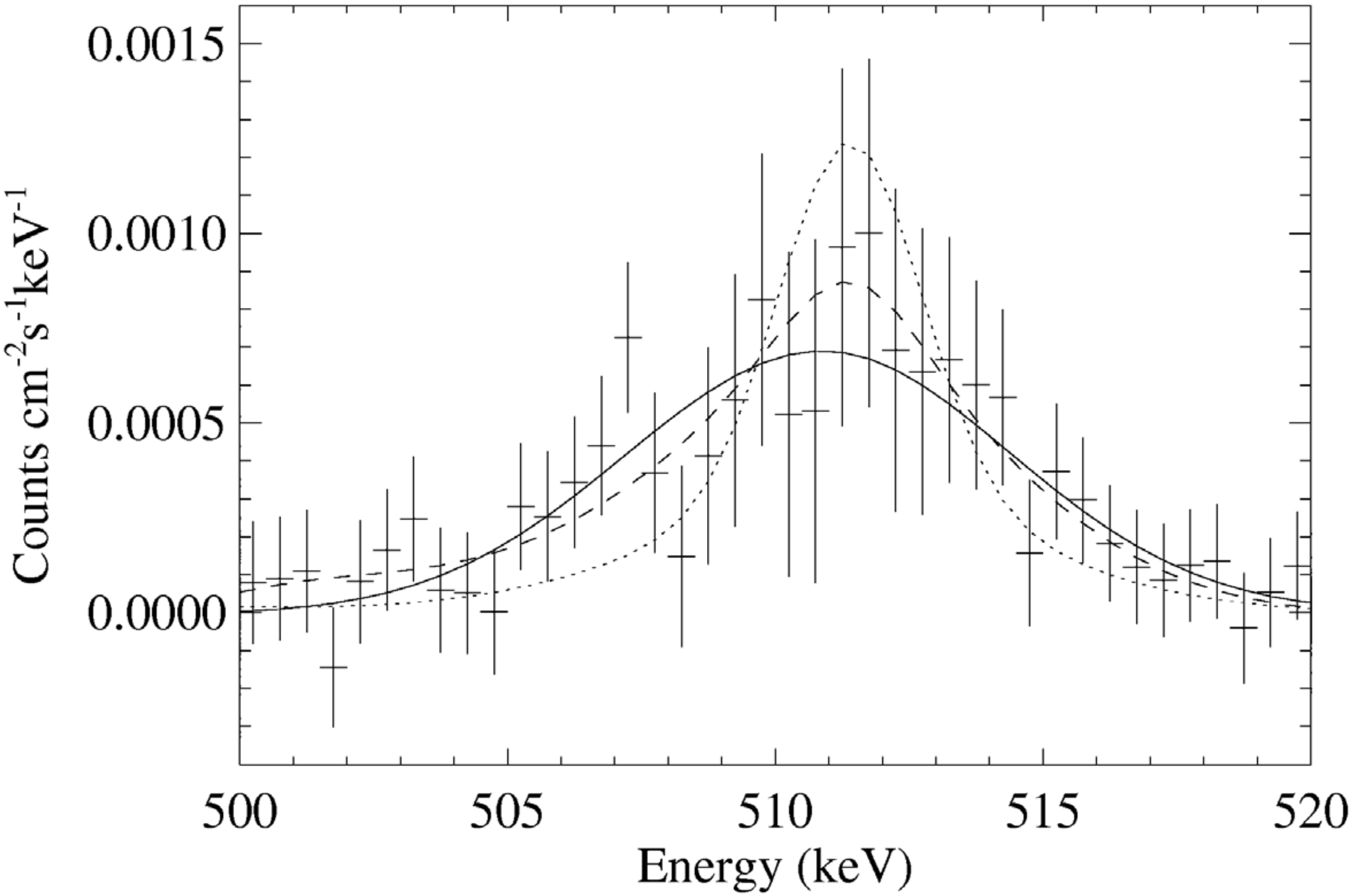
Line shapes in a quiet solar atmosphere

Skibo, Guessoum, & Ramaty

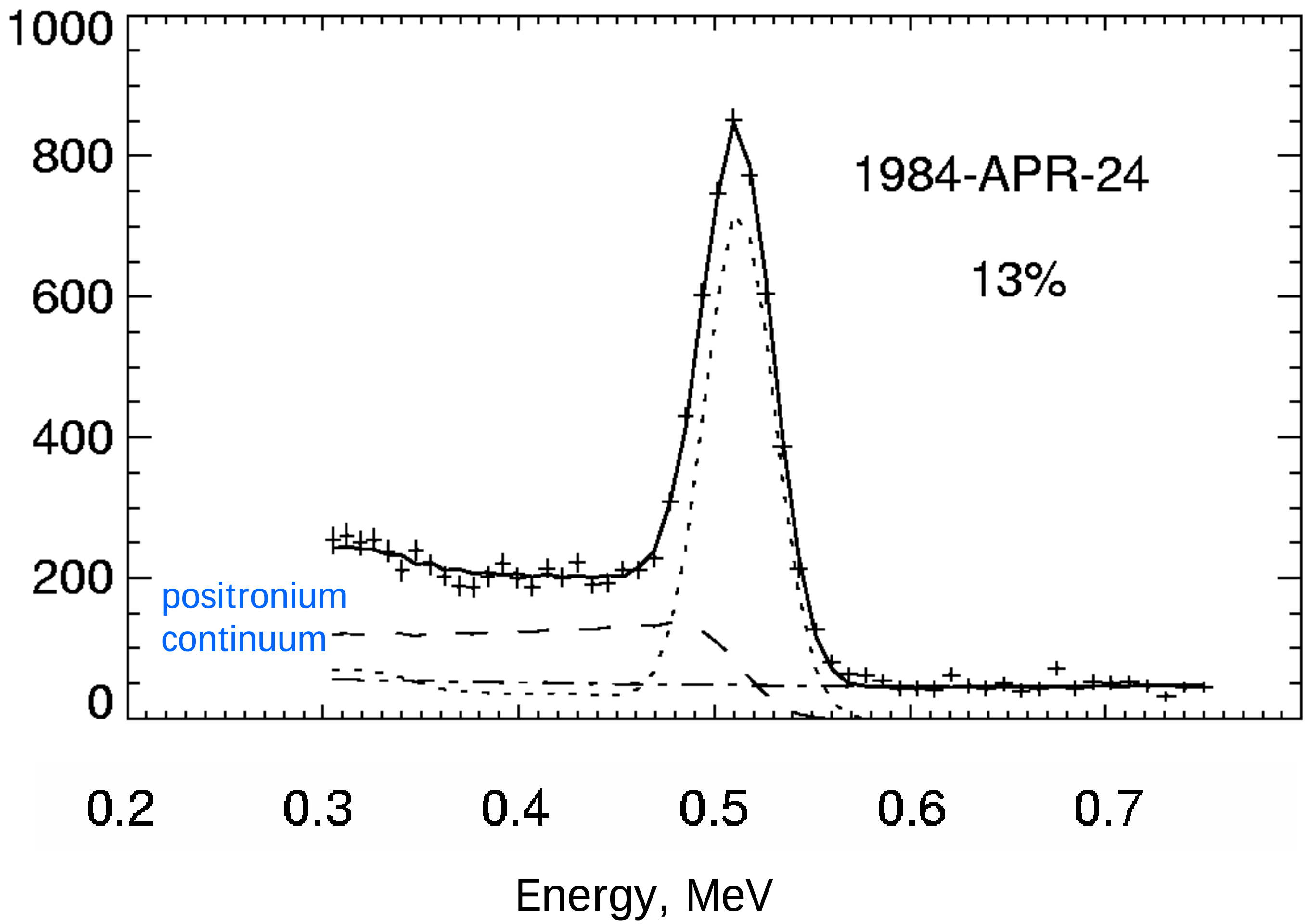


Fits to the solar annihilation line

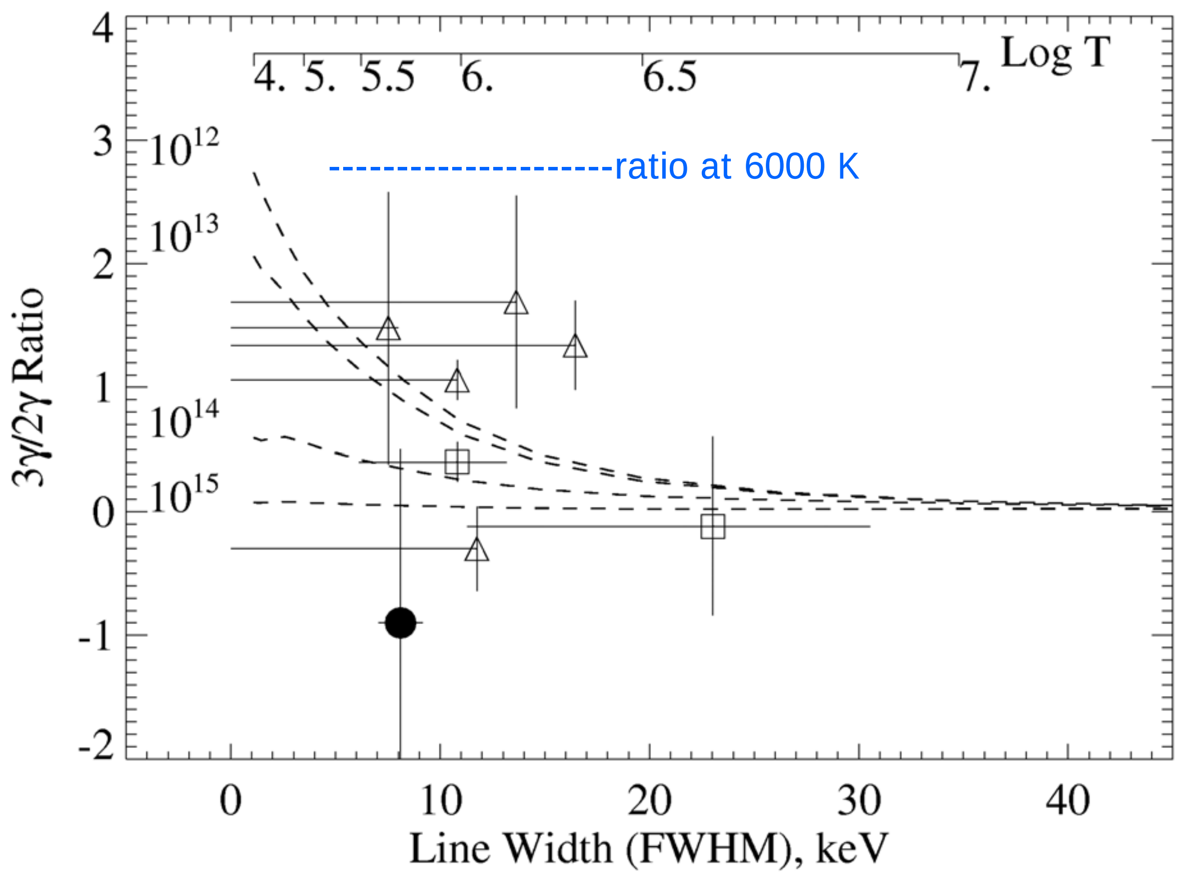
Gaussian - solid
6000 K - dashed
5000 K -dotted (1% probability)



Flare spectrum with positronium continuum



Annihilation in an ionized medium



SMM $3\gamma/2\gamma$ measurements are inconsistent with annihilation at 6000K.

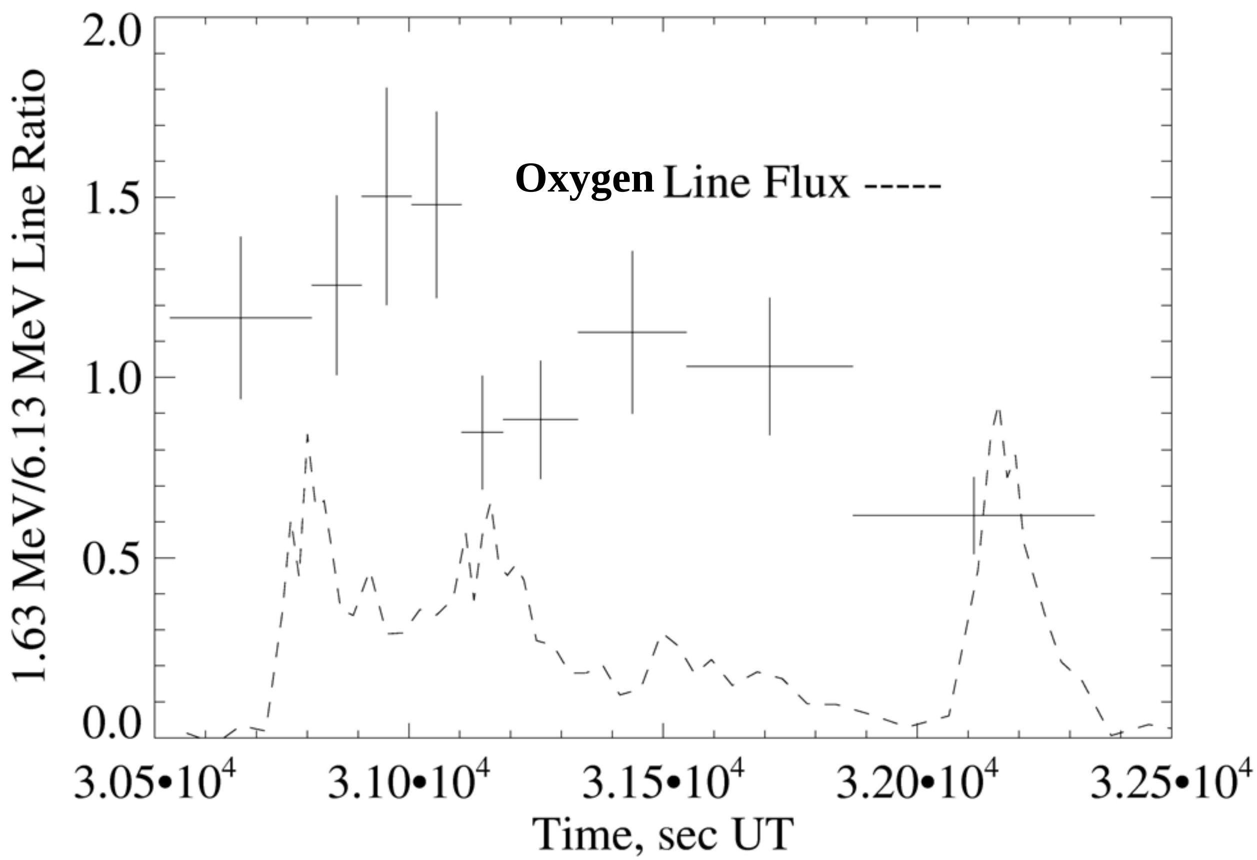
RHESSI width and SMM ratios consistent with production in warm/hot ionized medium (5×10^5 K). High density and high temperature! [Upsets Hugh et al.]

Parameter Constraints

- **Convergence** (δ): delay of line emission relative to electron bremsstrahlung
- **Scattering** (λ): narrow line Doppler shifts
- **Atmospheric model**: positron annihilation $3\gamma/2\gamma$ ratio
- **Spectral index** (s): narrow line fluence ratios ($^{16}O/^{20}Ne$, 2.22/4.44, neutrons)

Spectral Variability Within A Flare

Measured by Ne / O line ratio.



Electron/Ion Energetics Study

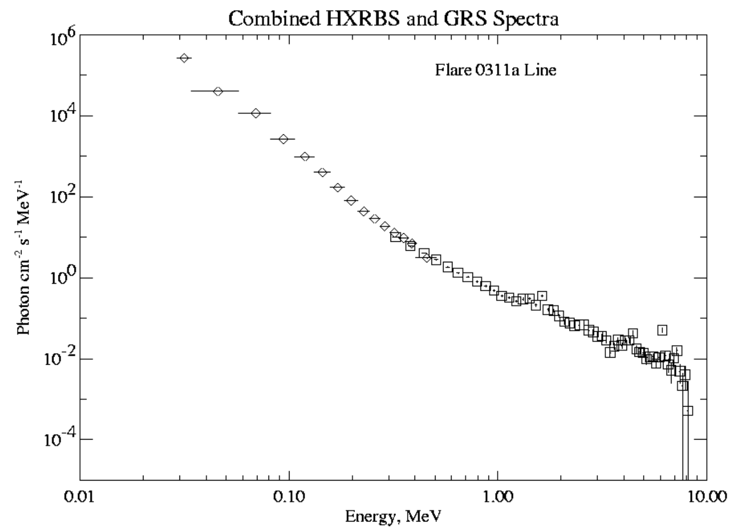
176 flares jointly analyzed with *SMM* GRS & HXRBS

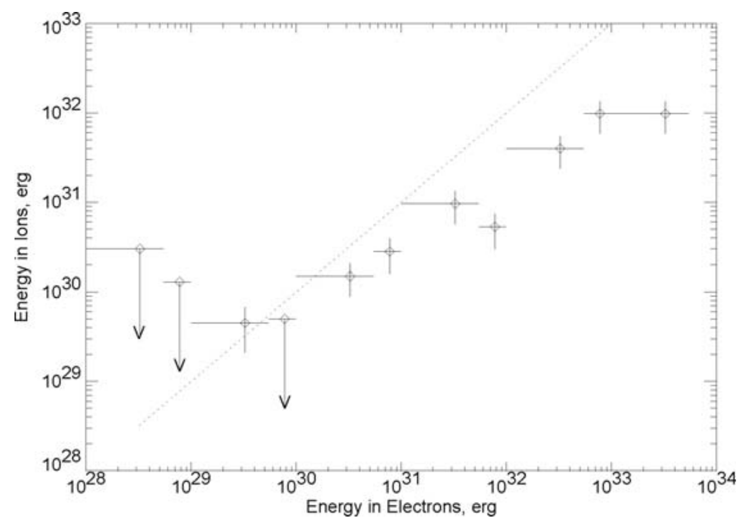
HXRBS data fit from ~40 keV -500 keV with power law: energy in >20 keV electrons obtained. Difficult to measure index at low energy. May overestimate electron energy

Sum GRS spectra based on electron energy; fit for nuclear lines and assume ion power law with index 4.2 to obtain energy in ions.

<u>Ions are energetically important in large flares with emission >300 keV.</u> Ions contain 10% to 100% of the energy in electrons >20 keV.

Rate of energy depositions of electrons and ions are comparable in the 23 July 2002 flare.



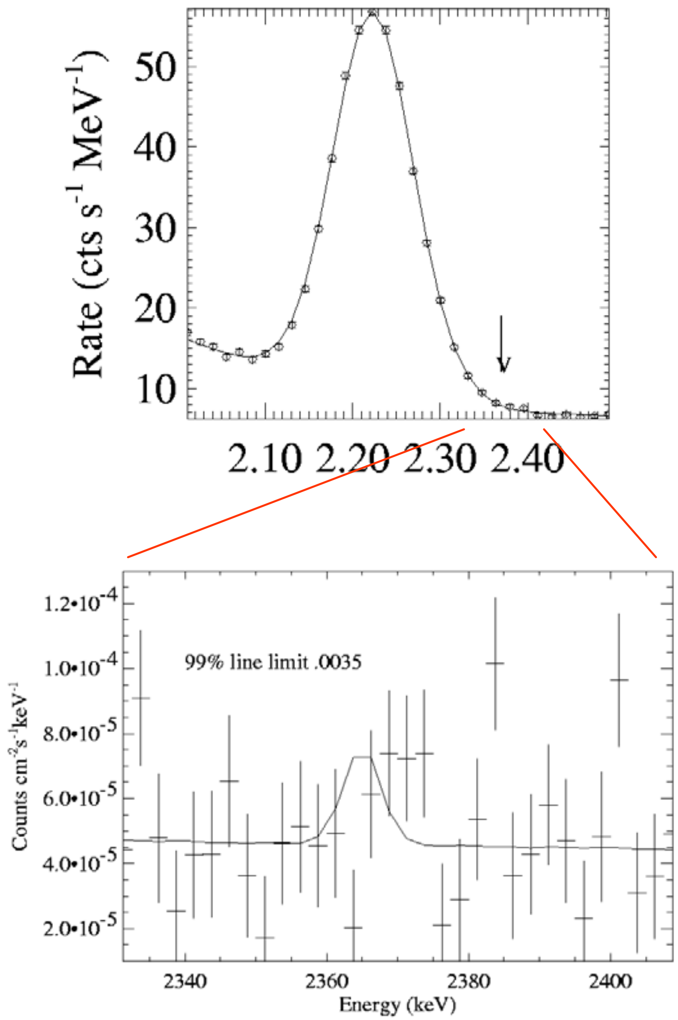


Energy in 0.5 MeV Protons from Capture Lines

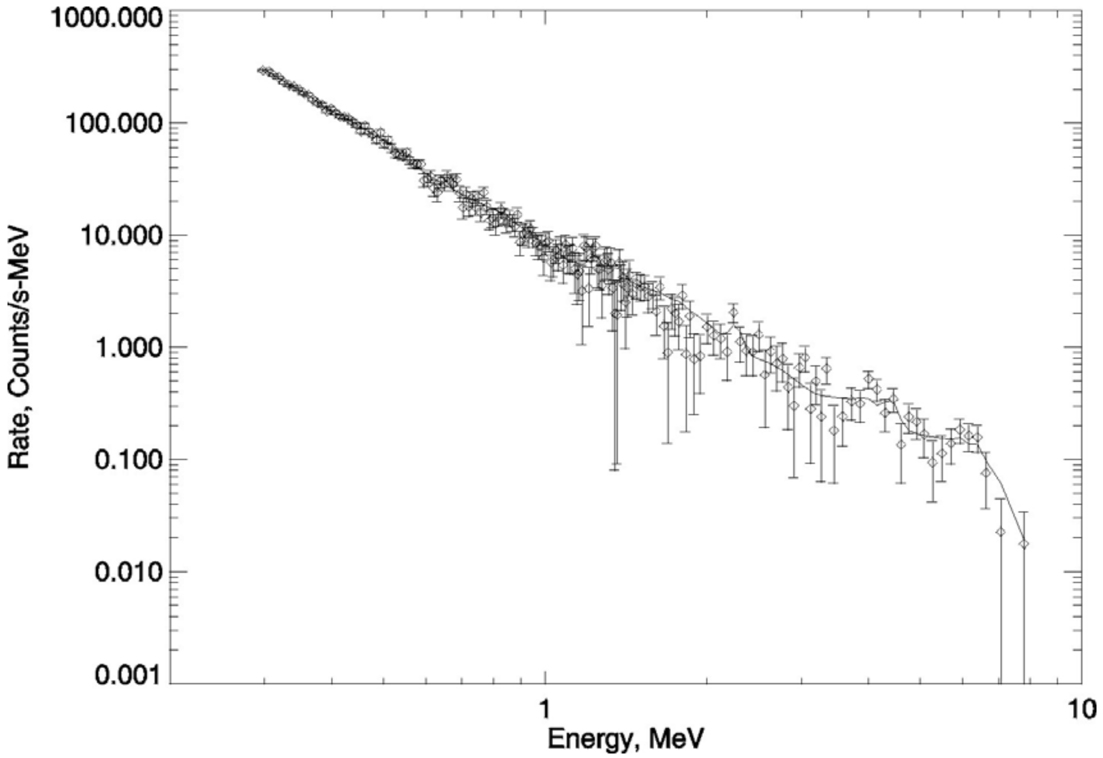
Most important capture line: $^{12}C(p,\gamma)^{13}N$ (2.365 MeV).

SMM obtained upper limits. Most sensitive line is at 2.365 MeV but it is adjacent to strong 2.223 MeV n-capture line.

RHESSI obtained about the same upper limit in the 2002 July 23 flare.



What about flares >300 keV with no clear line emission?



Summed spectrum from 40 flares individually only detected up to 1 MeV extends up to 8 MeV!

Is there a nuclear contribution? Evidence in fall-off > 7 MeV. Where is the 2.2 MeV line?

What we have learned from solar γ-ray observations

Accelerated ions at the Sun:

Spectrum: power-law index ~3.5 - 5; variable

Composition: α/p ~0.5, heavy ion composition similar to impulsive SEPs; ^{3}He.

Directionality: downward-isotropic interacting- particle distribution (pitch-angle scattering in the corona). Loops tilted from normal.

Energetics: comparable energies in accelerated ions and electrons in flares with emission >300 keV.

Delays: acceleration or trapping.

Interaction region: different from electrons.

Ambient Medium:

Composition where particles interact (chromosphere) similar to that found in the corona (FIP effect; varies from flare-to-flare)

Positrons annihilate at either 6000 K or

~5 x 10^{5} K (from width). Density can be measured from continuum/line ratio. Puzzling.