GLAST Measurements of Pion-decay and Neutron Emission in Solar Flares

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Neutral- and charged-pion production resulting from p-p and p-α interactions become significant in solar flares when the accelerated-ion energy spectrum is sufficiently hard. The threshold energies for these interactions are ~300 MeV and ~200 MeV nucleon^{-1}, respectively.

The decay of pions produces gamma-ray emission most easily observed at energies >10 MeV. Neutral pions decay into two ~70 MeV gamma rays in the pion rest frame which are Doppler shifted resulting in a broad feature centered at ~70 MeV. Charged pions decay into positrons and electrons which produce gamma-ray continuum emission resulting from bremsstrahlung and annihilation of the positrons in flight.

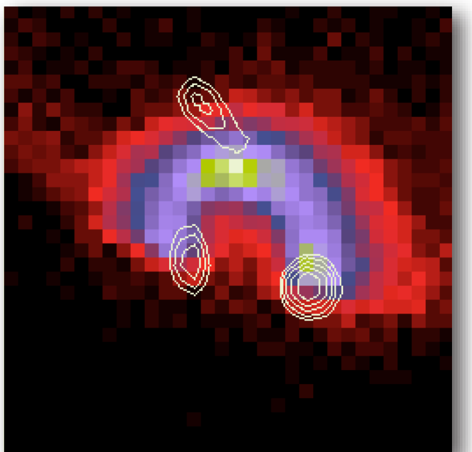
GLAST will be able to measure the highest-energy portion of this pion-decay emission with excellent sensitivity. Comparison of such measurements with determinations of the accelerated-ion spectrum derived from deexcitation-line measurements at lower energies (as with the GBM) will probe the accelerated-ion spectrum at energies up to several GeV.

We discuss pion production in solar flares and how the decay emission depends on the accelerated-ion spectrum and on the magnetic field and density where the pions decay.

We also discuss neutron production in solar flares since GLAST will also be sensitive to neutrons.

Nuclear Interactions in Solar Flares

Yohkoh



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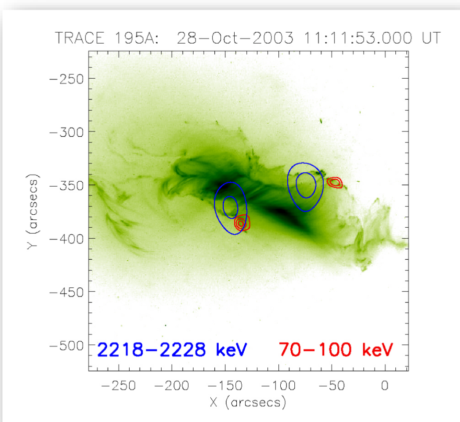
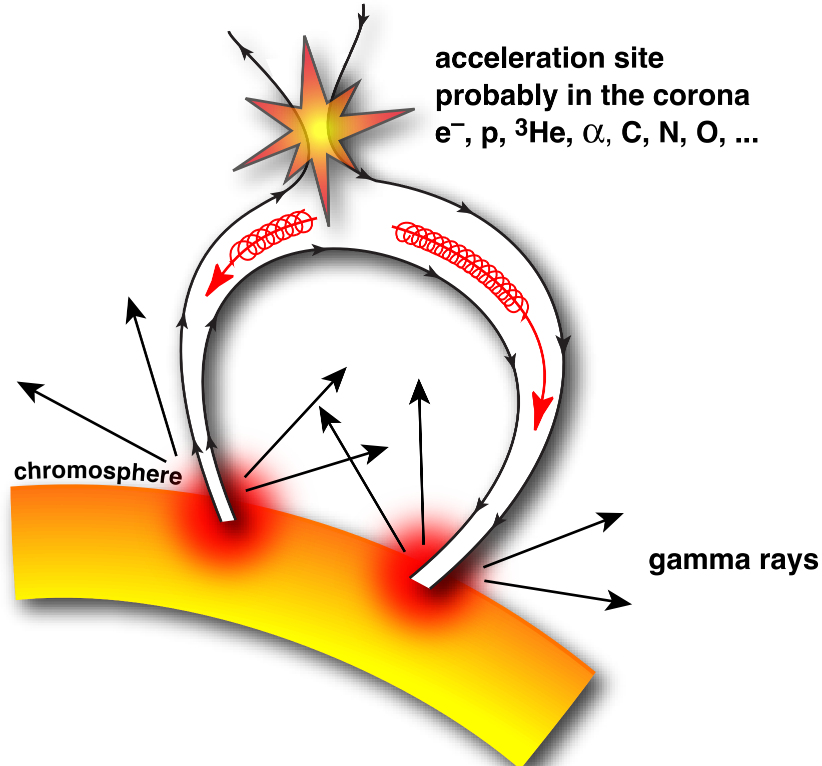




Nuclear interactions of flare-accelerated ions mostly occur at the footpoints of magnetic loops

Nuclear Emission Processes

γ-ray lines

$$\left.\begin{matrix}p\\ \alpha\end{matrix}\right\} + {}^{12}C \longrightarrow {}^{12}C^{*4.439}$$

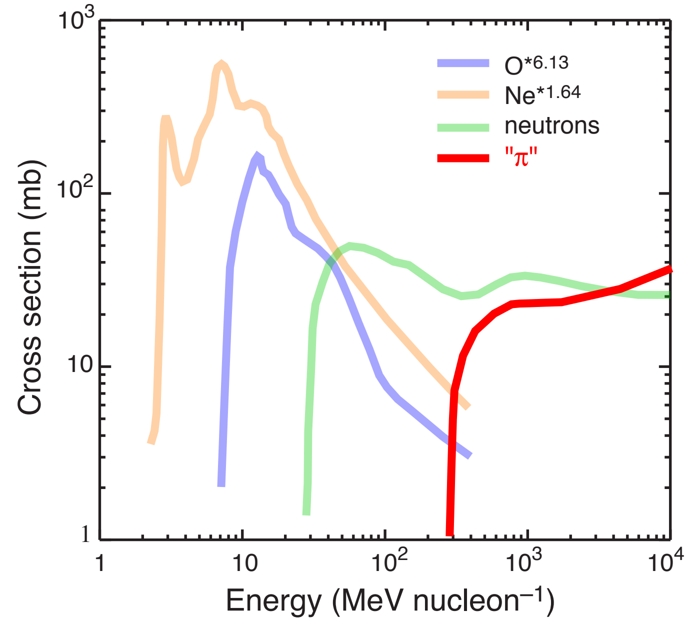
$$\left.\begin{matrix}p\\ \alpha\end{matrix}\right\} + {}^{16}O \longrightarrow {}^{12}C^{*4.439} + \ldots$$

$$\alpha + {}^{4}He \longrightarrow {}^{7}Li^{*0.478}$$

$$\alpha + {}^{4}He \longrightarrow {}^{7}Be^{*0.429}$$

neutrons

$$\left.\begin{matrix} p + {}^{4}He \longrightarrow n + \ldots \\ \alpha + \alpha \longrightarrow n + \ldots \\ \left.\begin{matrix}p\\ \alpha\end{matrix}\right\} + {}^{12}C \longrightarrow n + \ldots \end{matrix}\right\} \begin{matrix}\text{escape to Earth} \\ \text{capture on photospheric H} \longrightarrow D + \gamma_{2.223}\end{matrix}$$



positrons

$$\left.\begin{matrix} \left.\begin{matrix}p\\ \alpha\end{matrix}\right\} + {}^{12}C \longrightarrow {}^{11}C \longrightarrow e^{+} \\ \left.\begin{matrix}p + p\\ p + \alpha\end{matrix}\right\} \longrightarrow \pi^{+} \longrightarrow e^{+} \end{matrix}\right\} \gamma_{511,\ \text{cont.}}$$

pions

$$\left.\begin{matrix}p + p\\ p + \alpha\end{matrix}\right\} \longrightarrow \left.\begin{matrix}\pi^{0}\\ \pi^{+,-}\end{matrix}\right\} \longrightarrow \begin{matrix}\gamma \\ e^{+,-} \longrightarrow \gamma_{511,\ \text{cont.}}\end{matrix}$$

pions are produced in interactions of the highest-energy accelerated ions and are observable via their decay radiation

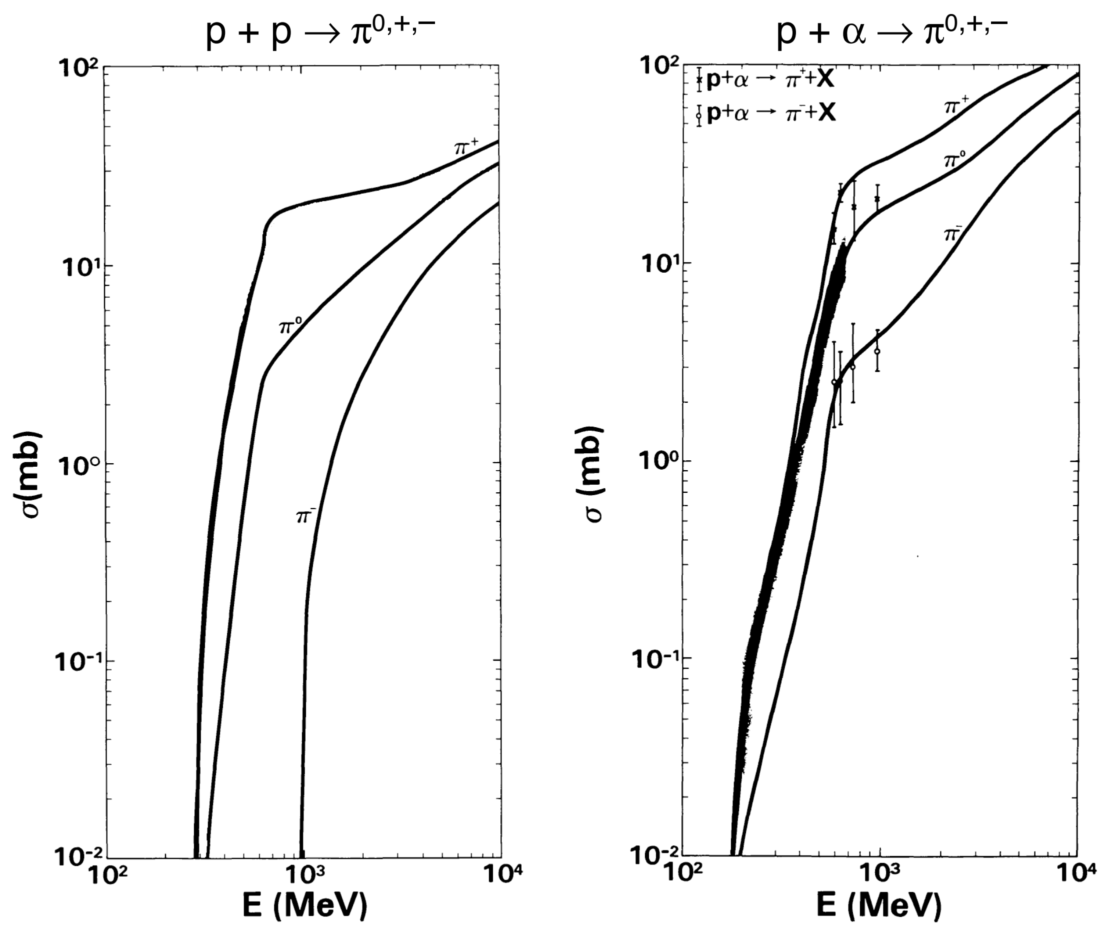
Pion Production Cross Sections

p–p reactions

$$p + p \rightarrow \pi^0 + X$$
$$p + p \rightarrow \pi^+ + X$$
$$p + p \rightarrow \pi^- + X$$
$$p + p \rightarrow n + X$$
$$p + p \rightarrow p + X \text{ (inelastic)}$$

p–α reactions

$$p + \alpha \rightarrow \pi^0 + X$$
$$p + \alpha \rightarrow \pi^+ + X$$
$$p + \alpha \rightarrow \pi^- + X$$
$$p + \alpha \rightarrow n + X$$
$$p + \alpha \rightarrow p + X \text{ (inelastic)}$$



Secondary Energy Distributions

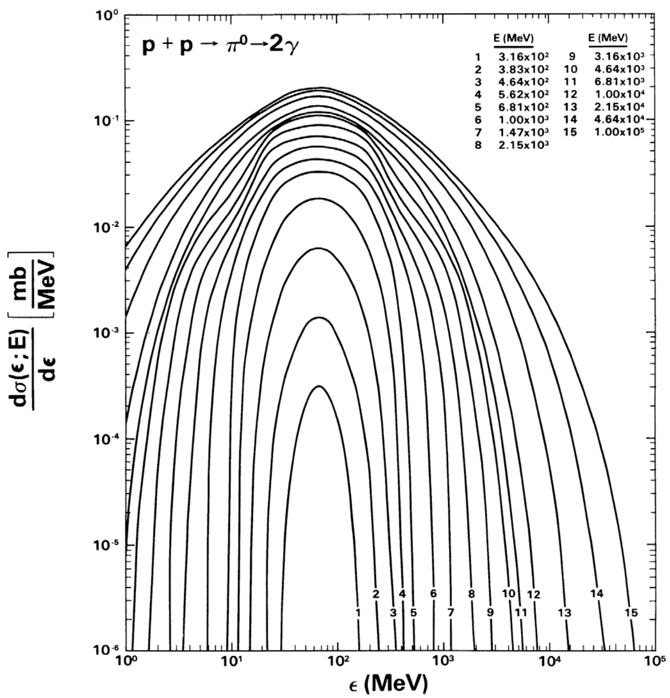
$$\left.\begin{matrix} p+p \\ p+\alpha \end{matrix}\right\} \longrightarrow \pi^0 \longrightarrow \gamma_{68\ \mathrm{MeV}}$$

$$\left.\begin{matrix} p+p \\ p+\alpha \end{matrix}\right\} \longrightarrow \pi^+ \longrightarrow \mu^+ + \nu$$
$$\mu^+ \longrightarrow e^+ + \nu + \bar{\nu}$$

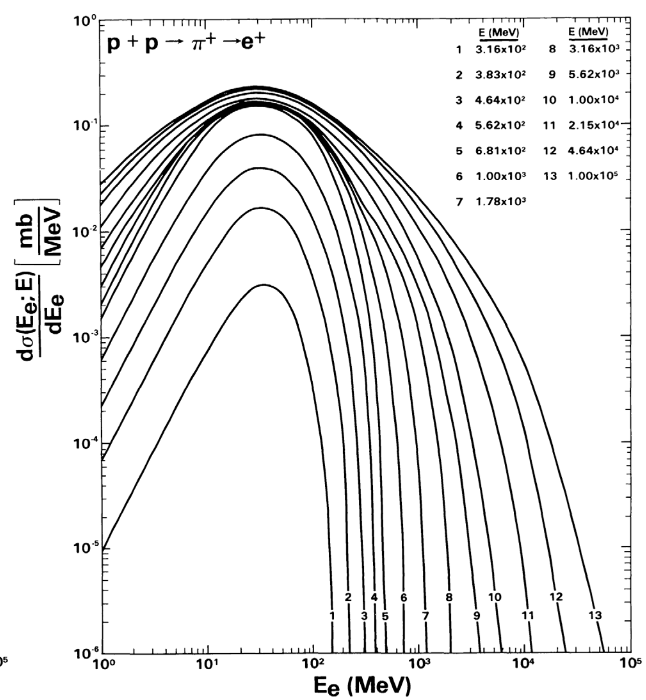
$$\left.\begin{matrix} p+p \\ p+\alpha \end{matrix}\right\} \longrightarrow \pi^- \longrightarrow \mu^- + \nu$$
$$\mu^- \longrightarrow e^- + \nu + \bar{\nu}$$

Spectra of secondary products have been calculated using isobaric and scaling models along with pion production data (Murphy, Dermer & Ramaty 1987)

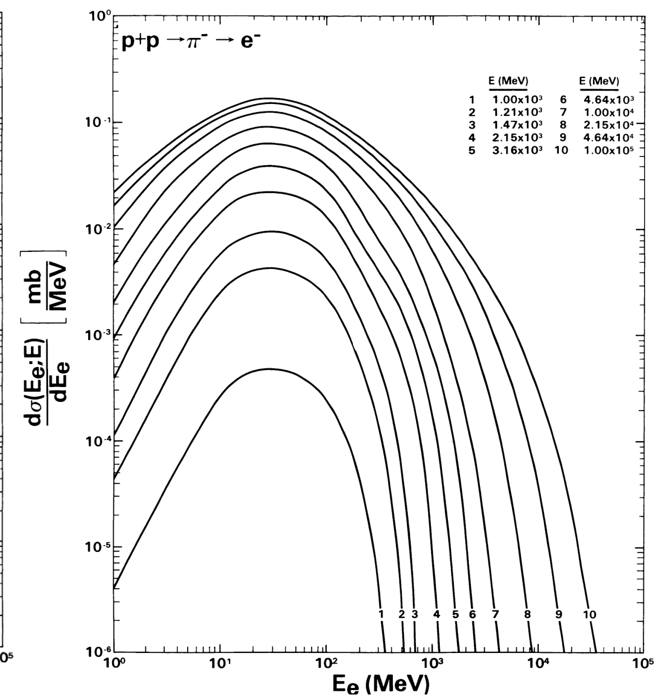
π^0



e^+



e^-



Radiation from Secondary Positrons and Electrons

electrons: bremsstrahlung continuum

positrons:
- bremsstrahlung continuum
- $e^+ - e^-$ annihilation radiation:
  - after thermalization $\longrightarrow$ 511 keV line*
  - in-flight $\longrightarrow$ continuum from Doppler-broadened 511 KeV line

These processes compete with *Coulomb* and *synchrotron* energy losses

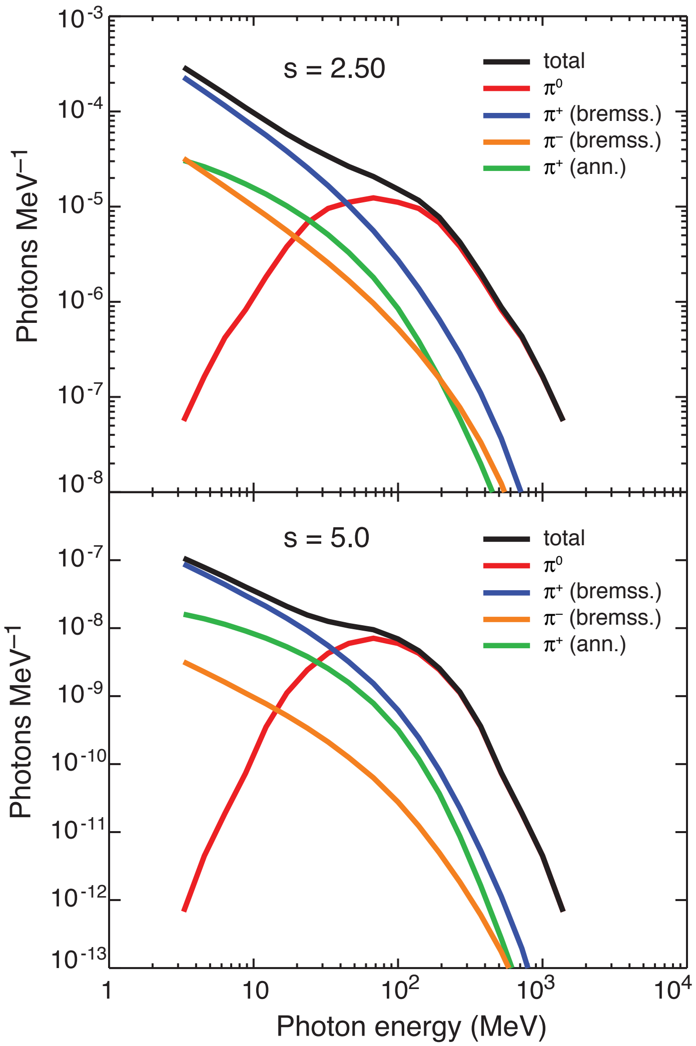
➠ **The radiation from these charged seconday electrons and positrons depends on the ambient *magnetic field* and *density***

*most of these photons are Compton-scattered out of the line as they escape the Sun because the pions are produced very deep in the solar atmosphere

Calculated Pion-decay Photon Spectra

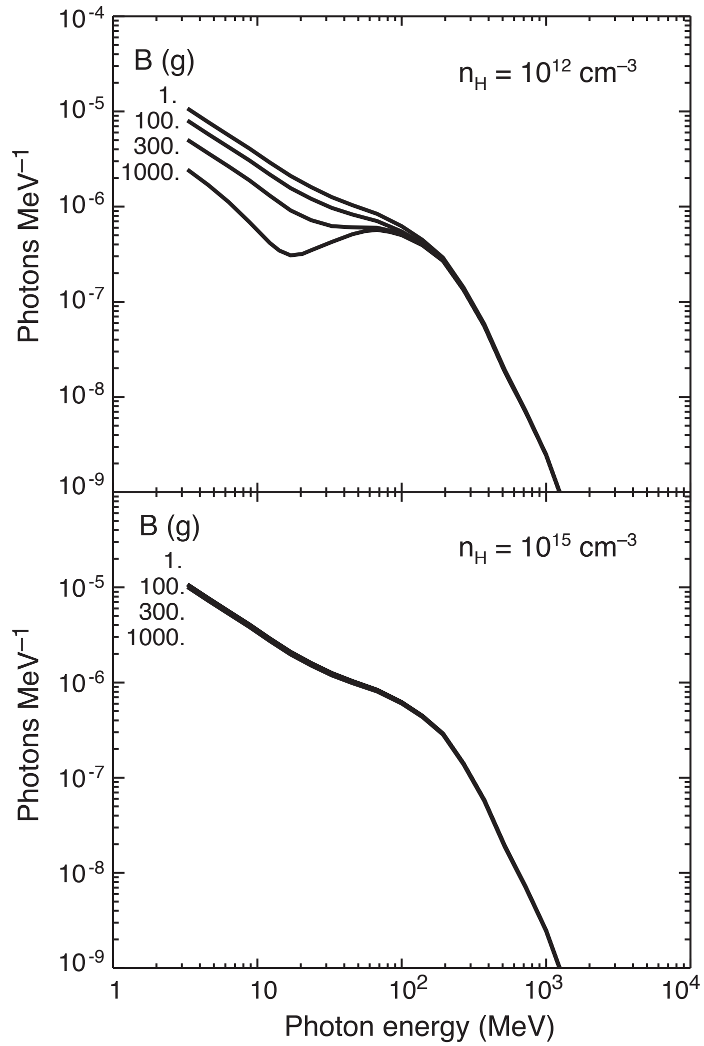
The accelerated-ion spectral index affects the shape of the pion-decay photon spectrum:

1. harder spectrum → broader π^0 component
2. different mix of charged-π components

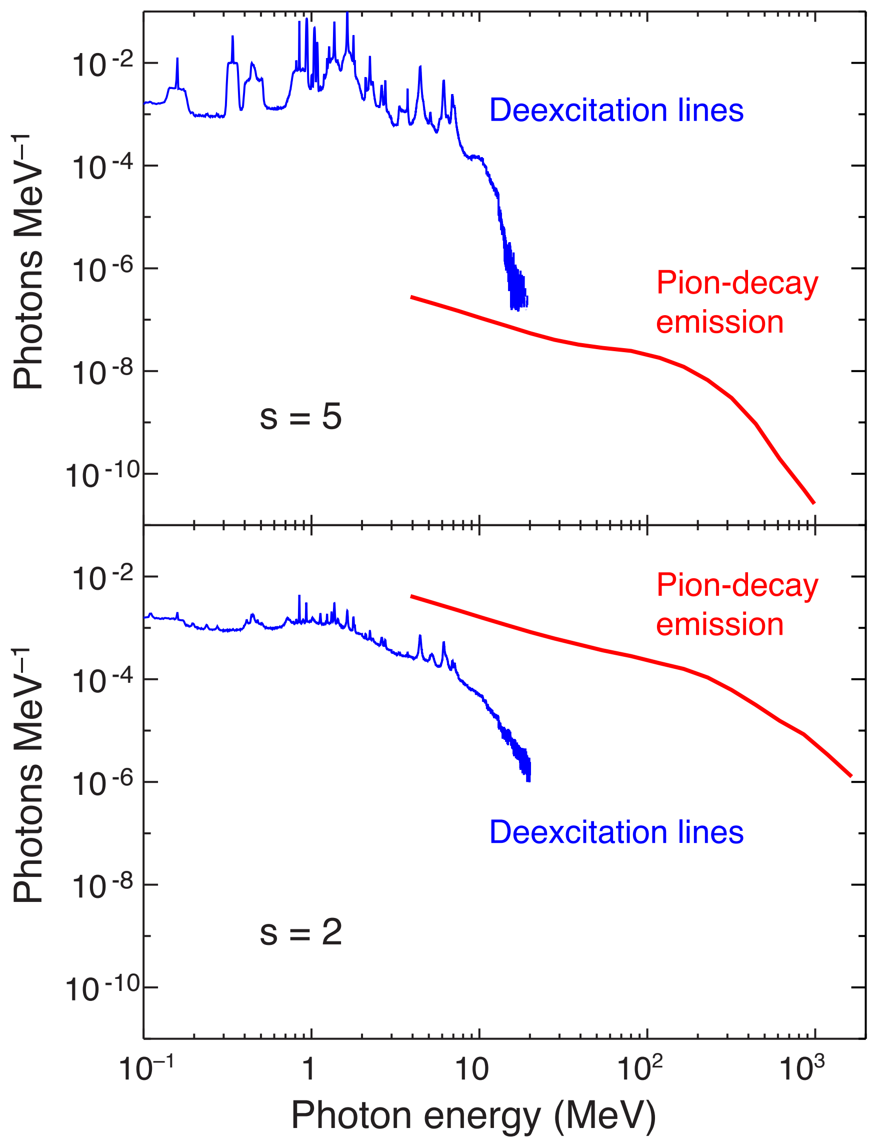


The magnetic field and ambient density affect the shape of the pion-decay photon spectrum:

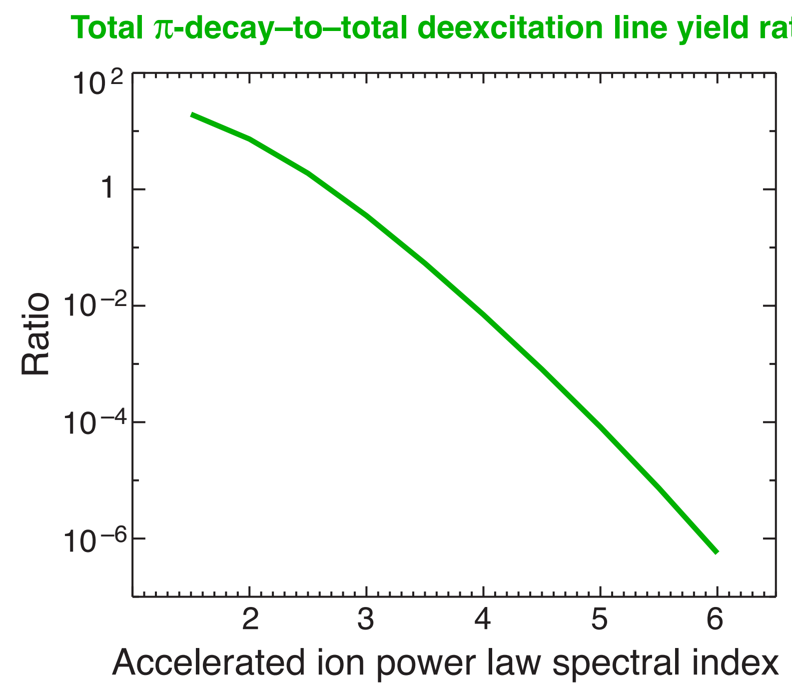
1. low density → strong magnetic-field dependence
2. high density → weak magnetic-field dependence



Calculated Pion-decay Photon Spectra (cont.)



The ratio of pion-decay emission to nuclear deexcitation-line emission depends very strongly on the steepness of the accelerated-ion kinetic-energy spectrum



This ratio can be used to determine the accelerated-ion spectral index

Neutrons

Neutron production reactions

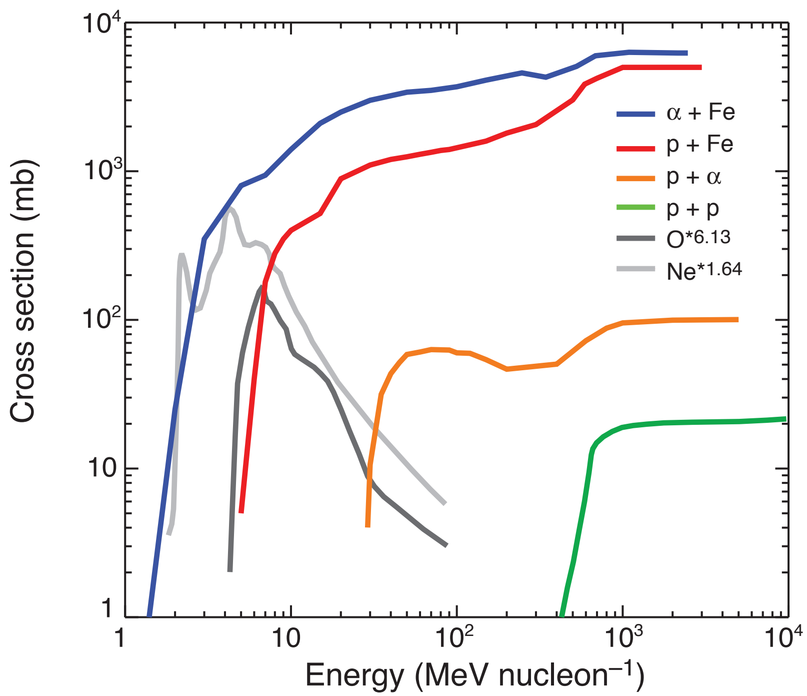
$p + p \longrightarrow n + \ldots$

$p + {}^{4}He \longrightarrow n + \ldots$

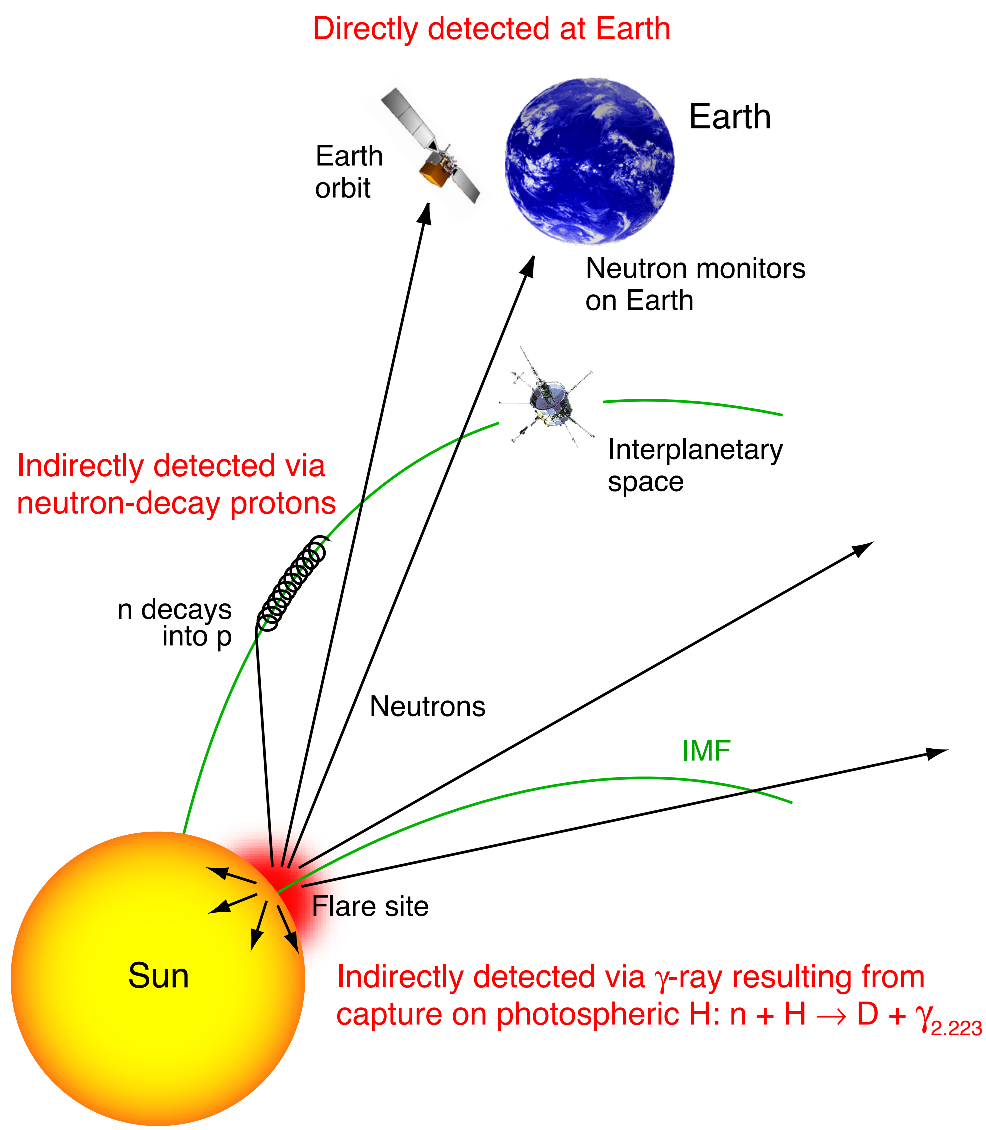
$\alpha + \alpha \longrightarrow n + \ldots$

$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{12}C \longrightarrow n + \ldots$

and inverse reactions

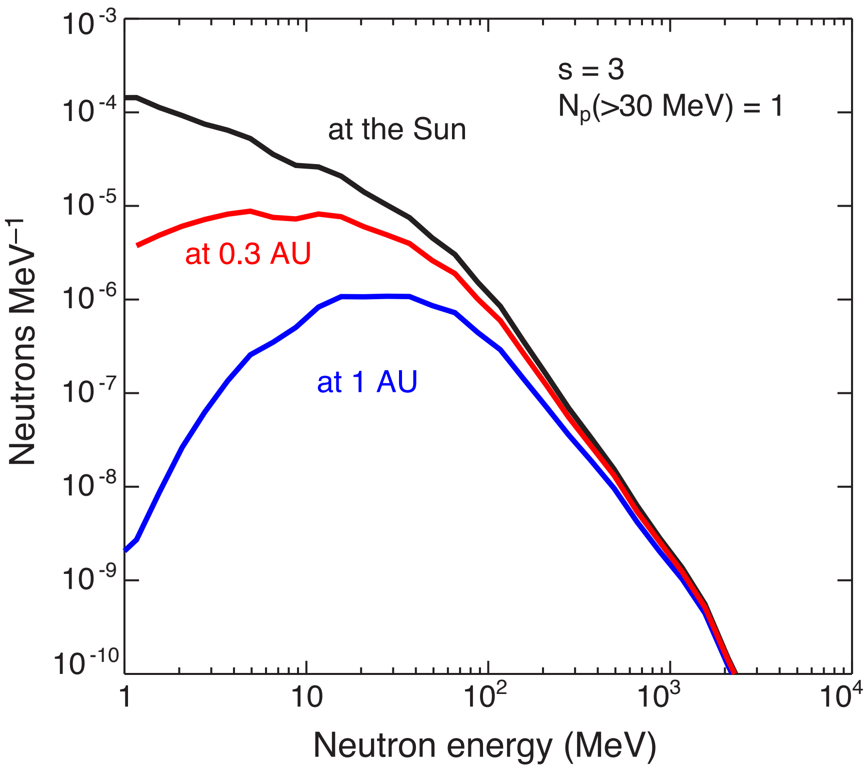


Neutrons are “detectable” either directly or indirectly

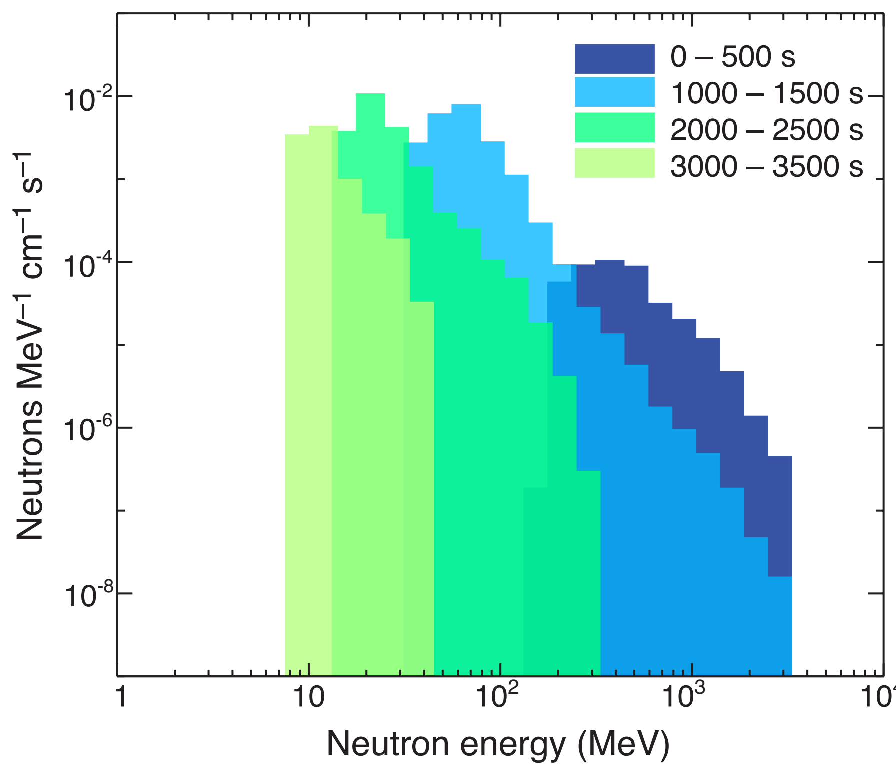


Neutron Production (cont.)
Energy Spectra

Neutron lifetime (τ_{mean} = 886 s) alters the kinetic-energy spectrum with distance from Sun



Differing neutron velocities result in time-dependent arriving-neutron spectra due to velocity dispersion



Future Plans

To take advantage of GLAST's sensitivity to high-energy gamma-ray emission, we will improve several areas of our pion-production computer model:

1. Improved cross sections
    a. treat the production channels near threshold separately rather than the current inclusive treatment
    b. improve treatment at highest energies by including the diffractive portion of the cross section (e.g., Kamae et al. 2004)

2. Extend the treatment to anisotropic accelerated-ion angular distributions

3. Extend the calculations to the higher gamma-ray energies (>3 GeV) to directly explore the shape of the accelerated-ion spectrum at such energies