Annihilation Radiation in Solar Flares and Supernova Remnants

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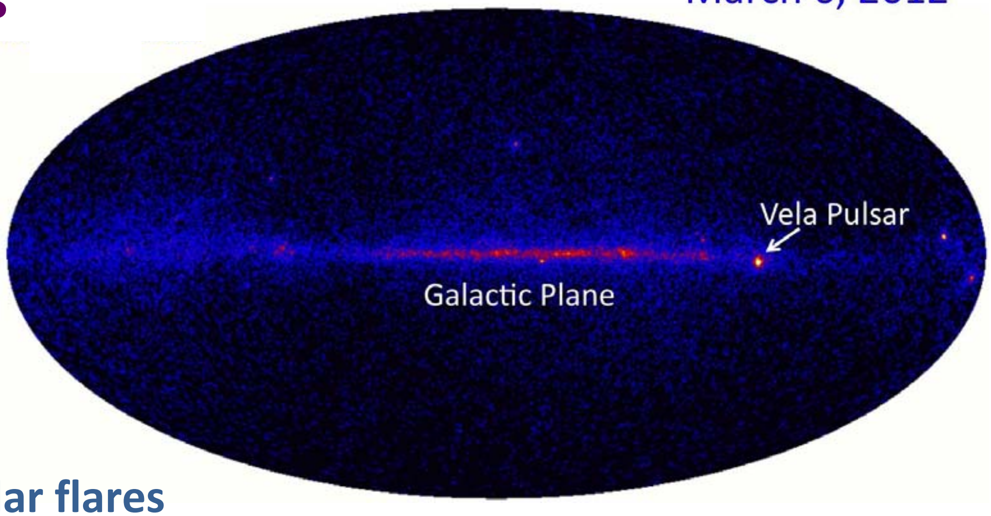
Positrons in Astrophysics

Mürren, Switzerland 19-23 March 2012

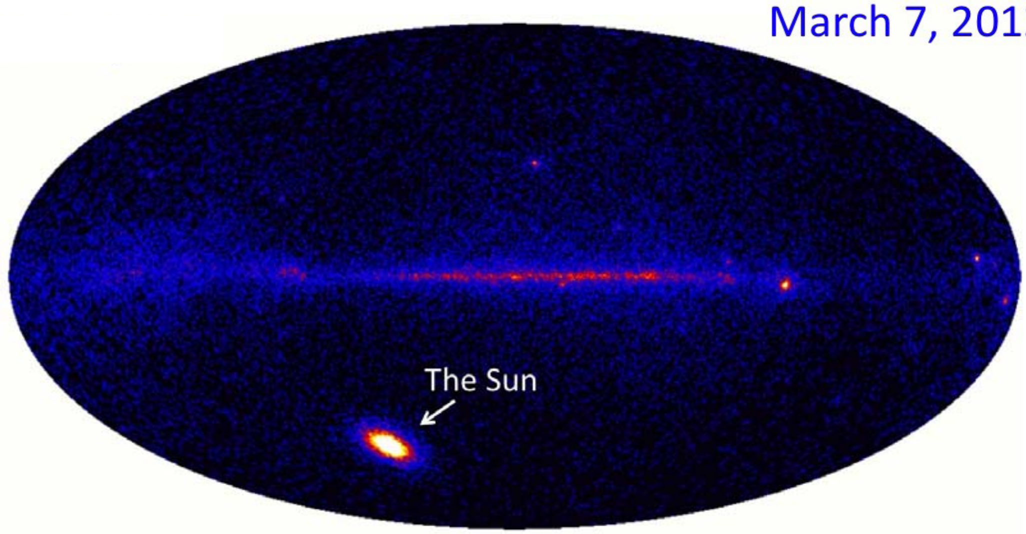
March 6, 2012



1. γ rays, neutrons, and positrons from Solar flares
2. Fate of positrons: spectral calculations
3. Observations and comparison with data
4. e^+ and γ rays in SNRs

Fermi >100 MeV γ-ray sky

March 7, 2012



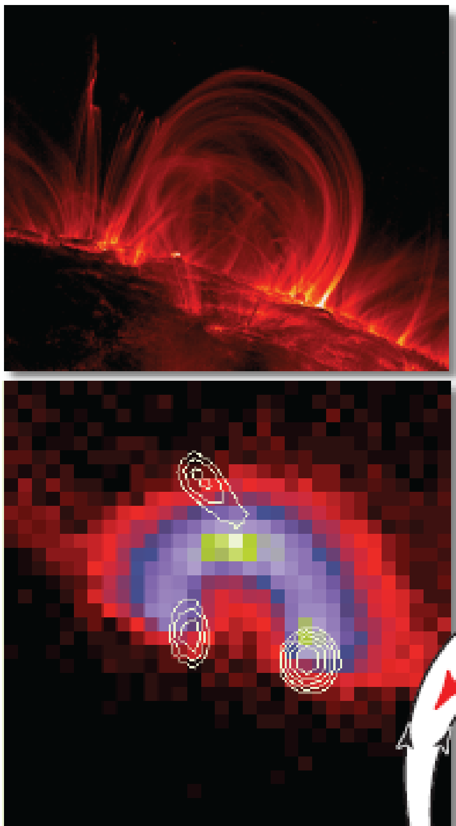
Solar flare γ-ray astronomy:

- Composition
- Particle Acceleration
- Properties of medium

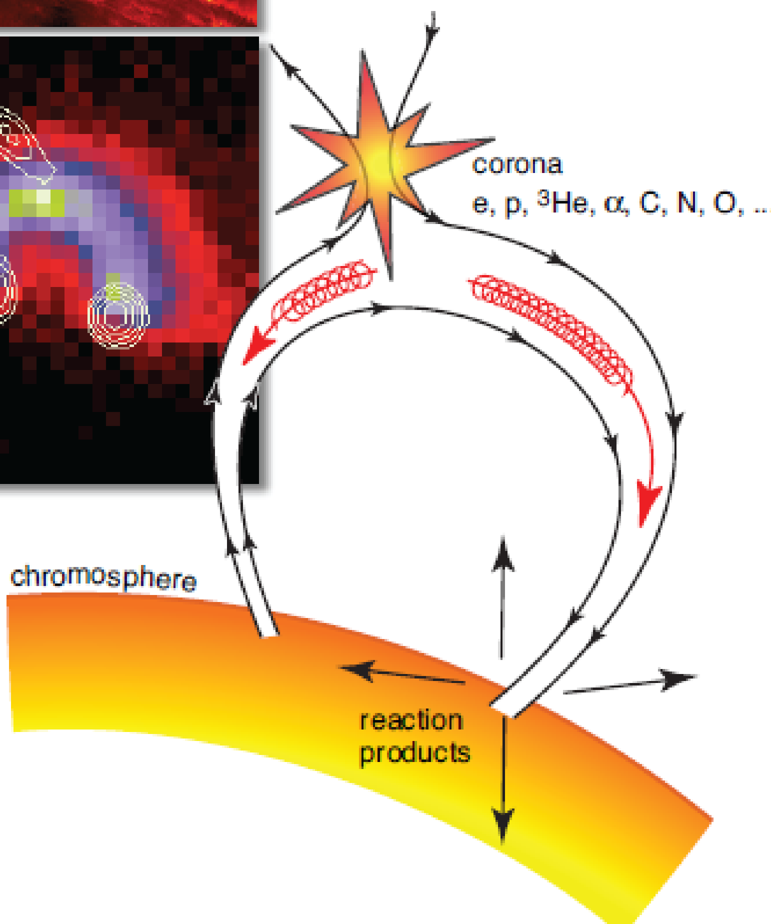
Annihilation line shape depends on the temperature, density and ionization state of the medium

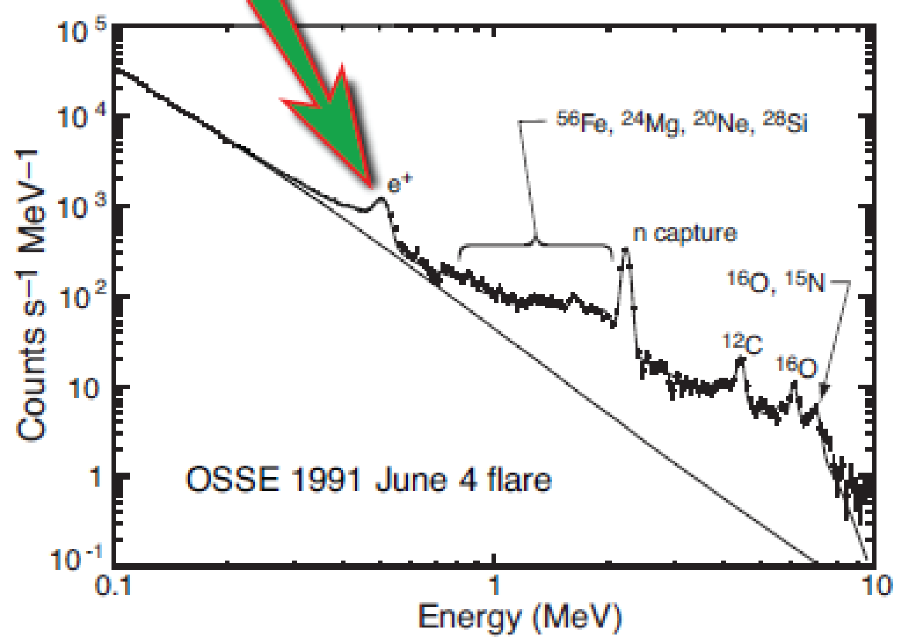
$$\Delta E, Q_{3\gamma}/ Q_{2\gamma}$$

1. γ ray, neutron, and positron production in Solar flares



particle	emission
electrons:	X- and γ-ray bremsstrahlung, gyrosynchrotron
ions:	excited nuclei $\rightarrow$ γ-ray line radiation (~1–8 MeV)
	neutrons $\rightarrow$ { escape to space; capture on H $\rightarrow$ 2.223 MeV line }
	radioactive nuclei $\rightarrow e^+ \rightarrow \gamma_{511}$
	$\pi \rightarrow \gamma$ (decay, $e^\pm$ bremsstrahlung, γ_{511})





γ rays from Solar Flares

γ-ray lines

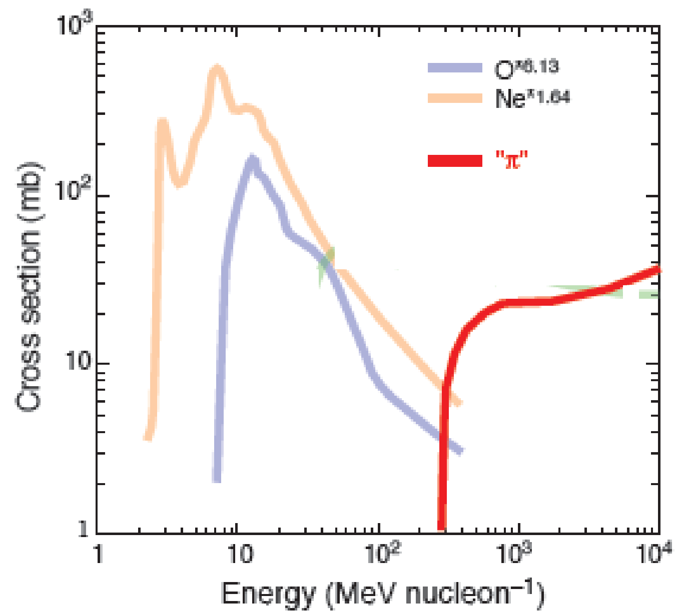
$$\left.\begin{array}{l} p \\ \alpha \end{array}\right\} + {}^{12}C \rightarrow {}^{12}C^{*4.439}$$

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

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

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

Broad and narrow lines



neutrons

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

$$\alpha + \alpha \rightarrow n + \ldots$$

$$\left.\begin{array}{l} p \\ \alpha \end{array}\right\} + {}^{12}C \rightarrow n + \ldots$$

escape to Earth

capture on photospheric H $\rightarrow$ D + $\gamma_{2.223}$

positrons

$$\left.\begin{array}{l} p \\ \alpha \end{array}\right\} + {}^{12}C \rightarrow {}^{11}C \rightarrow e^{+}$$

$$\left.\begin{array}{l} p + p \\ p + \alpha \end{array}\right\} \rightarrow \pi^{+} \rightarrow e^{+}$$

$\gamma_{511,\ cont.}$

pions

$$\left.\begin{array}{l} p + p \\ p + \alpha \end{array}\right\} \rightarrow \left.\begin{array}{l} \pi^{0} \\ \pi^{+,-} \end{array}\right\} \rightarrow \begin{array}{l} \gamma \\ e^{+,-} \rightarrow \gamma_{511,\ cont.} \end{array}$$

Diagnostics of continuum and line γ rays, and particles in space requires comprehensive time-dependent model to understand flares

γ rays from Solar Flares

γ-ray lines

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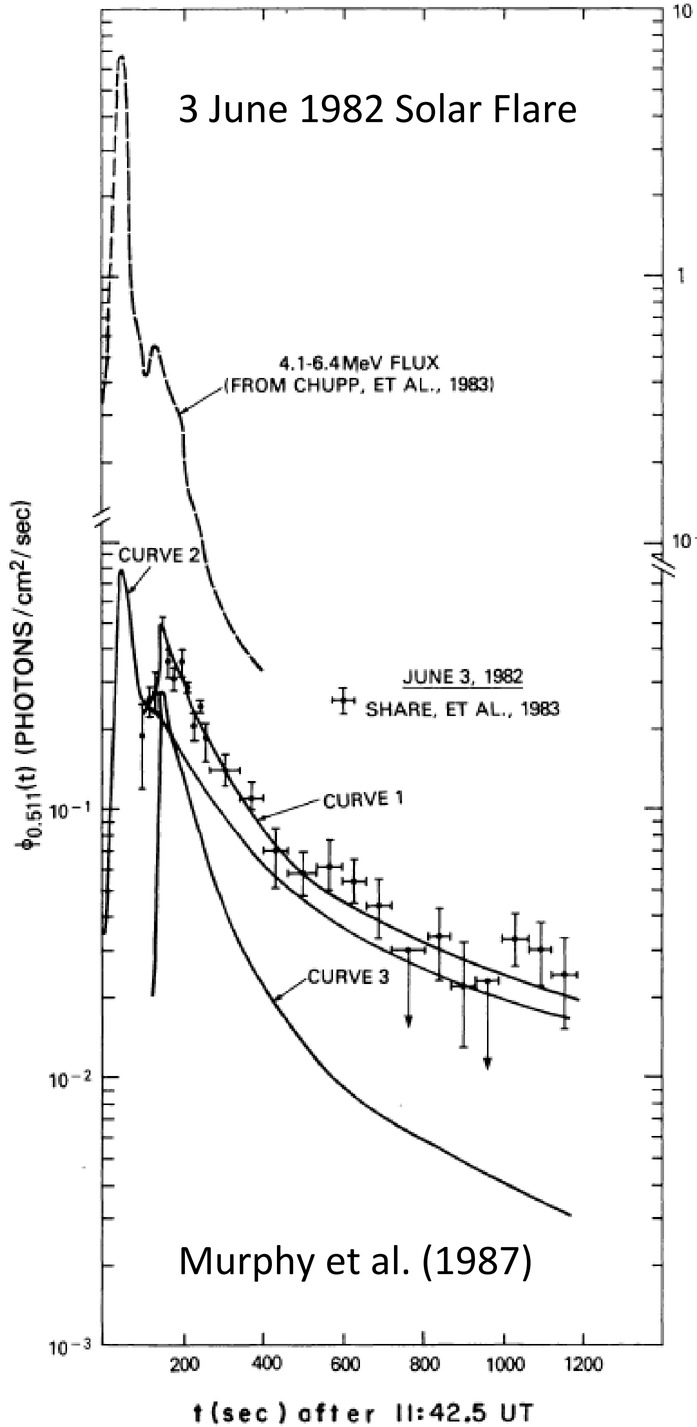


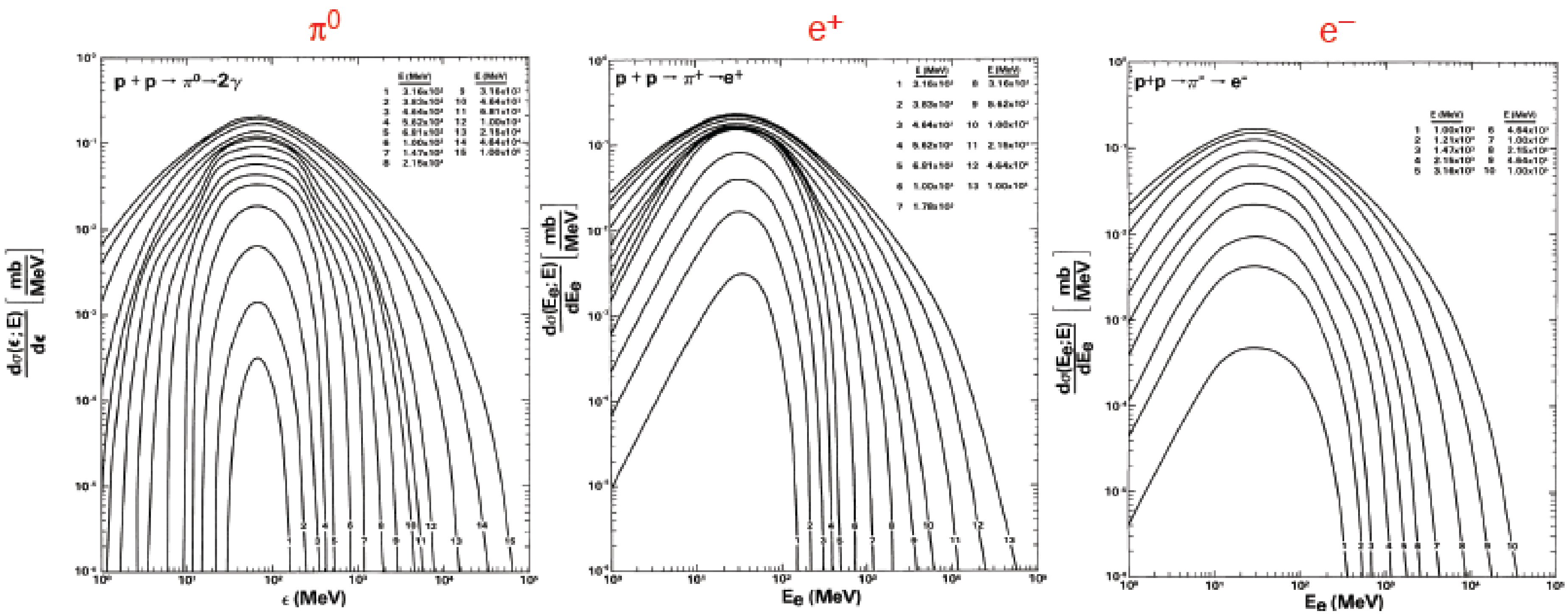
Pion Production from Solar Flares

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

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

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

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



Neutrons from Solar Flares

Neutron production reactions

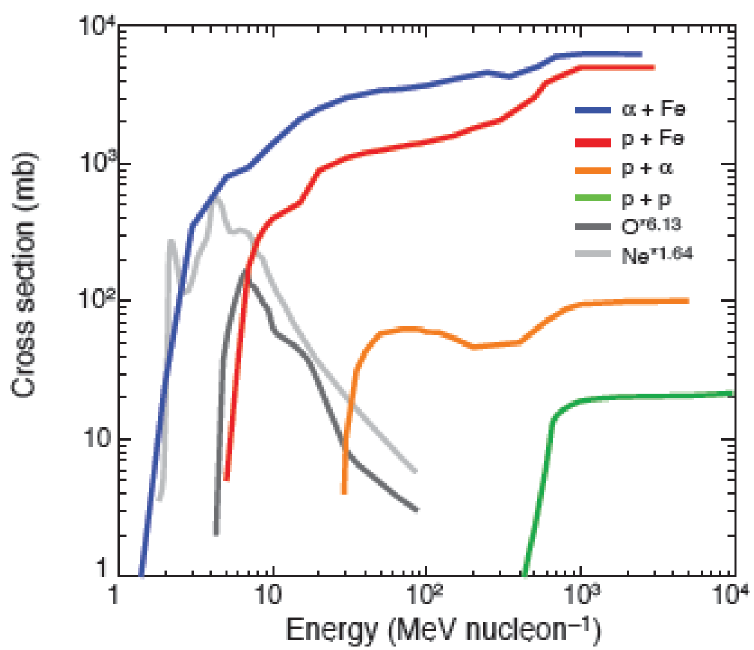
$p + p \longrightarrow n + \ldots$

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

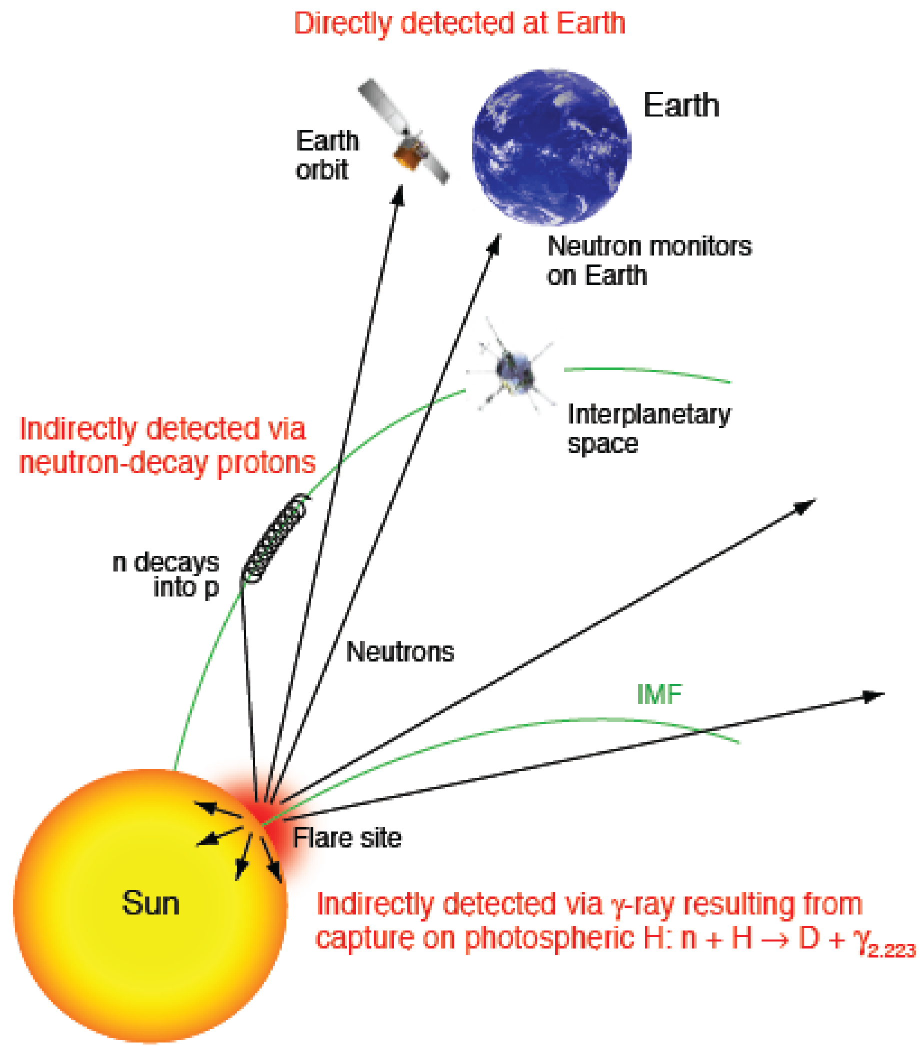
$\alpha + \alpha \longrightarrow n + \ldots$

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

and inverse reactions

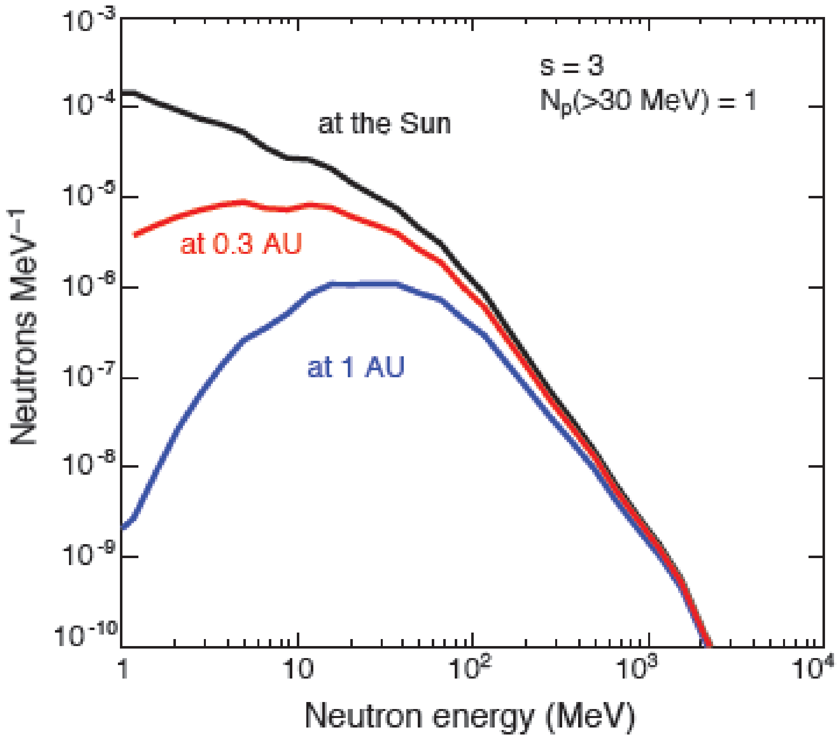


Neutrons are "detectable" either directly or indirectly

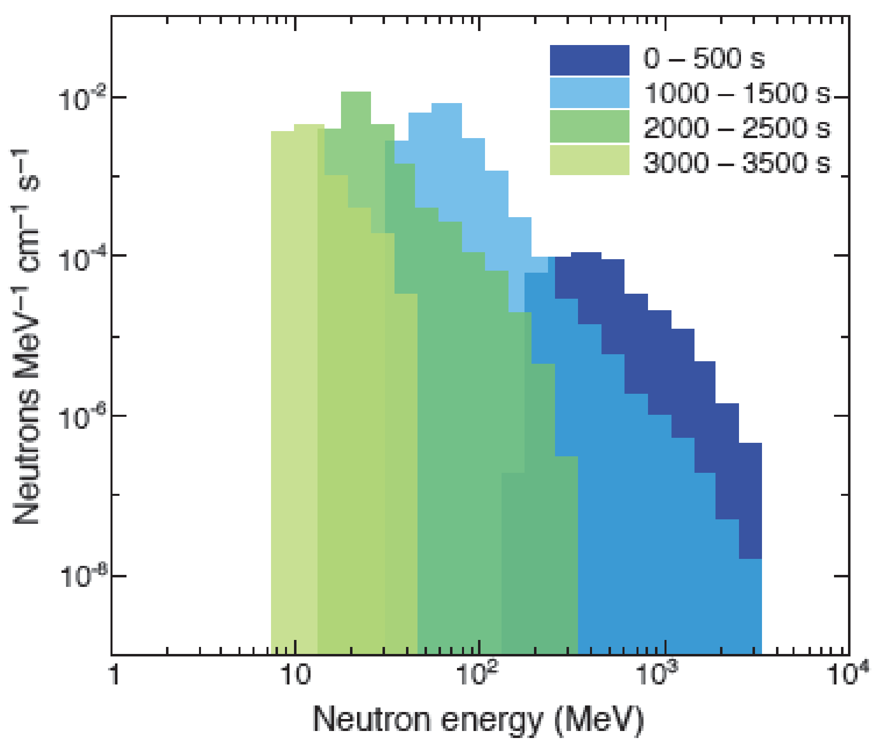


Neutrons in Space and at Earth

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



Positrons from Solar Flares

Radioactive positron emitters

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{12}C \longrightarrow {}^{11}C \longrightarrow e^{+}$$

	τ (sec)
${}^{16}O$	9.6×10^{-11}
${}^{11}C$	1800

Pions

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

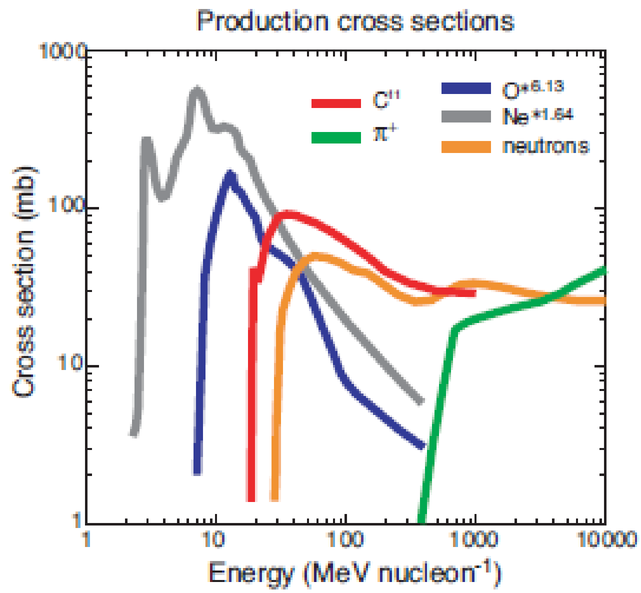
$$\hookrightarrow e^{+} + \nu + \overline{\nu}$$

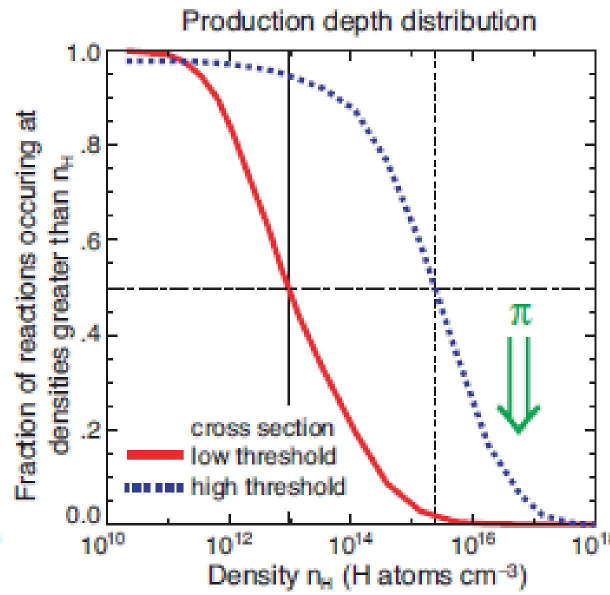
	τ (sec)
π^{+}	3.8×10^{-8}
μ^{+}	2.1×10^{-6}

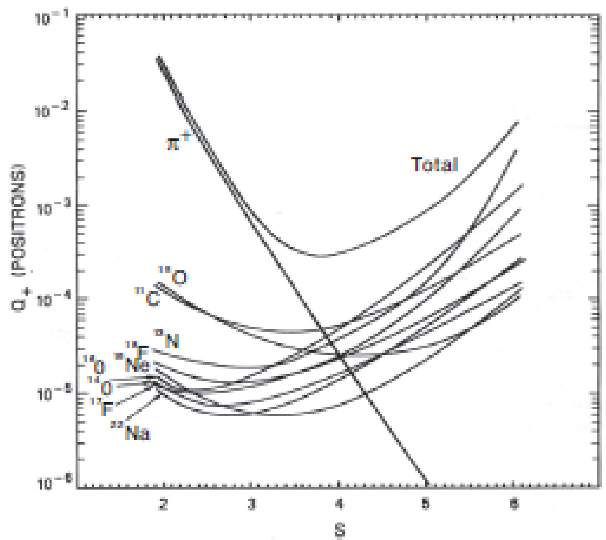
Other sources

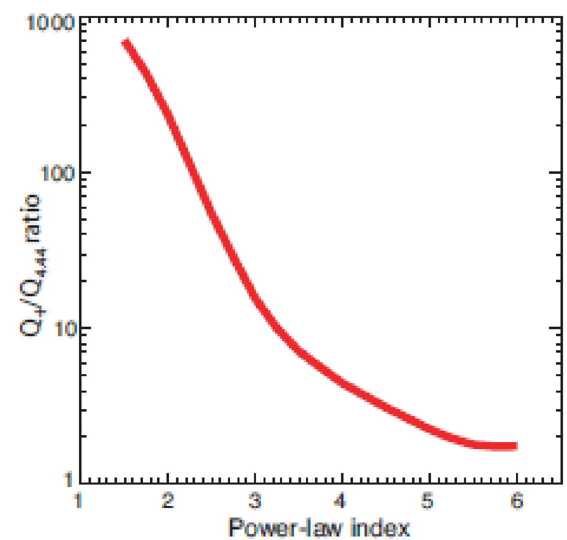
$$\gamma + \gamma \longrightarrow e^{+} + e^{-}$$

$$\gamma + B \longrightarrow e^{+} + e^{-}$$









Radiation from Electrons and Positrons

electrons: bremsstrahlung continuum

positrons:
- bremsstrahlung continuum
- $e^+ - e^-$ annihilation radiation:
  - after thermalization → 511 keV line*
  - in-flight → 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

2. Fate of Positrons: Spectral Calculations

Direct annihilation with electrons

1. with free electrons (df)
2. with bound electrons of H and He (dab)

Positronium formation ($e^+ + e^- \longrightarrow Ps$, $E_b = 6.8$ eV)

3. radiative combination with free electrons (rc)
4. charge exchange with H and He (ce)

$$E_{th} = 13.6 - 6.8 = 6.8 \text{ eV (H)}$$
$$24.6 - 6.8 = 17.8 \text{ eV (He)}$$

Two possible Ps spin configurations

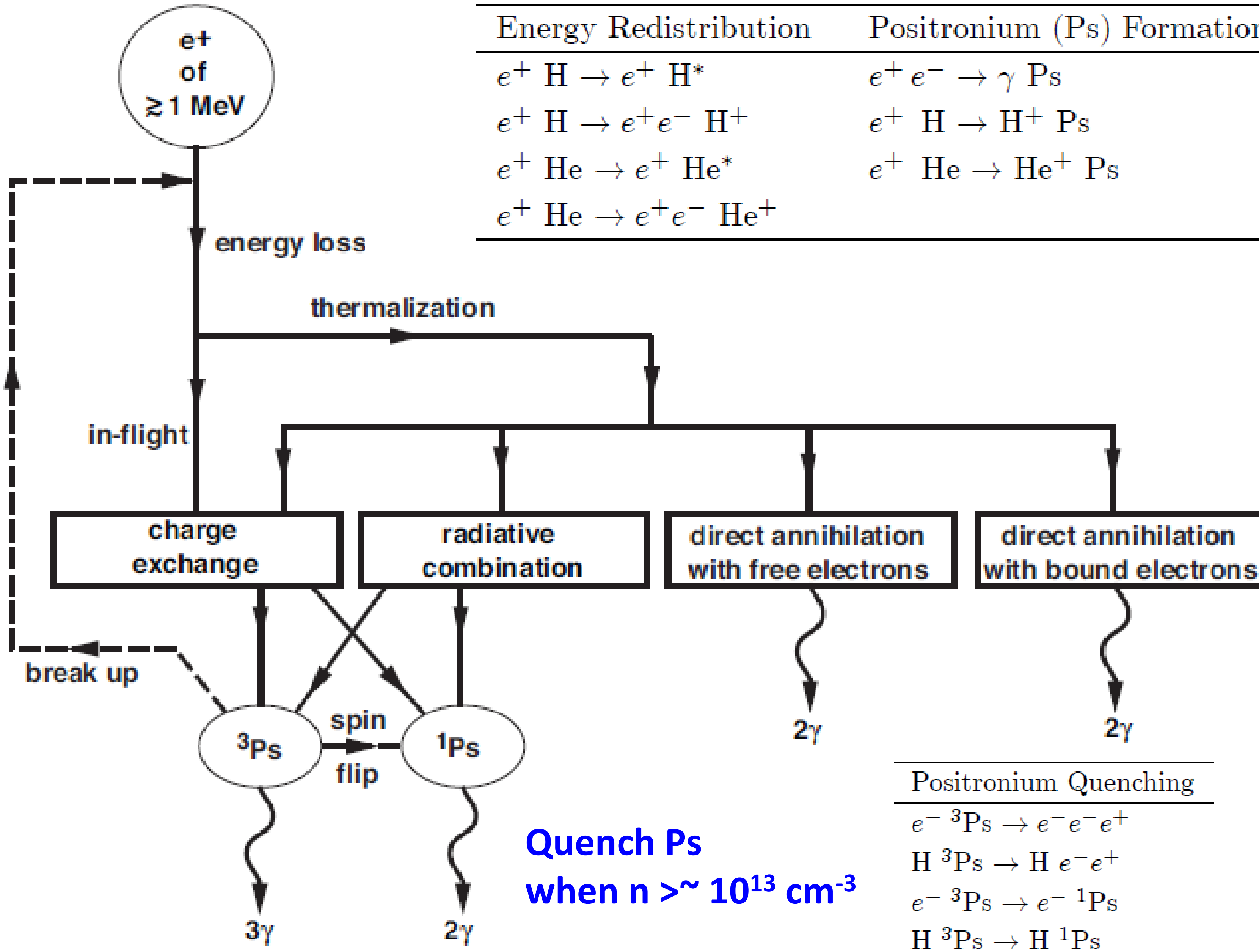
$e^+\uparrow$ $e^-\uparrow$ S = 1 "triplet" or "ortho" ^{3}Ps (3 states: $S_z = -1, 0, 1$)

$e^+\uparrow$ $e^-\downarrow$ S = 0 "singlet" or "para" ^{1}Ps (1 state: $S_z = 0$)

$\longrightarrow$ always formed in 3:1 ratio

ground state, $n_{Ps} = 1$ | $\tau_1 = 1.25 \times 10^{-10}$ s, $\tau_3 = 1.4 \times 10^{-7}$ s

excited states, $n_{Ps} > 1$ | $\tau_{ann} > \tau_{deexcite}$ $\longrightarrow$ always annihilates from ground state

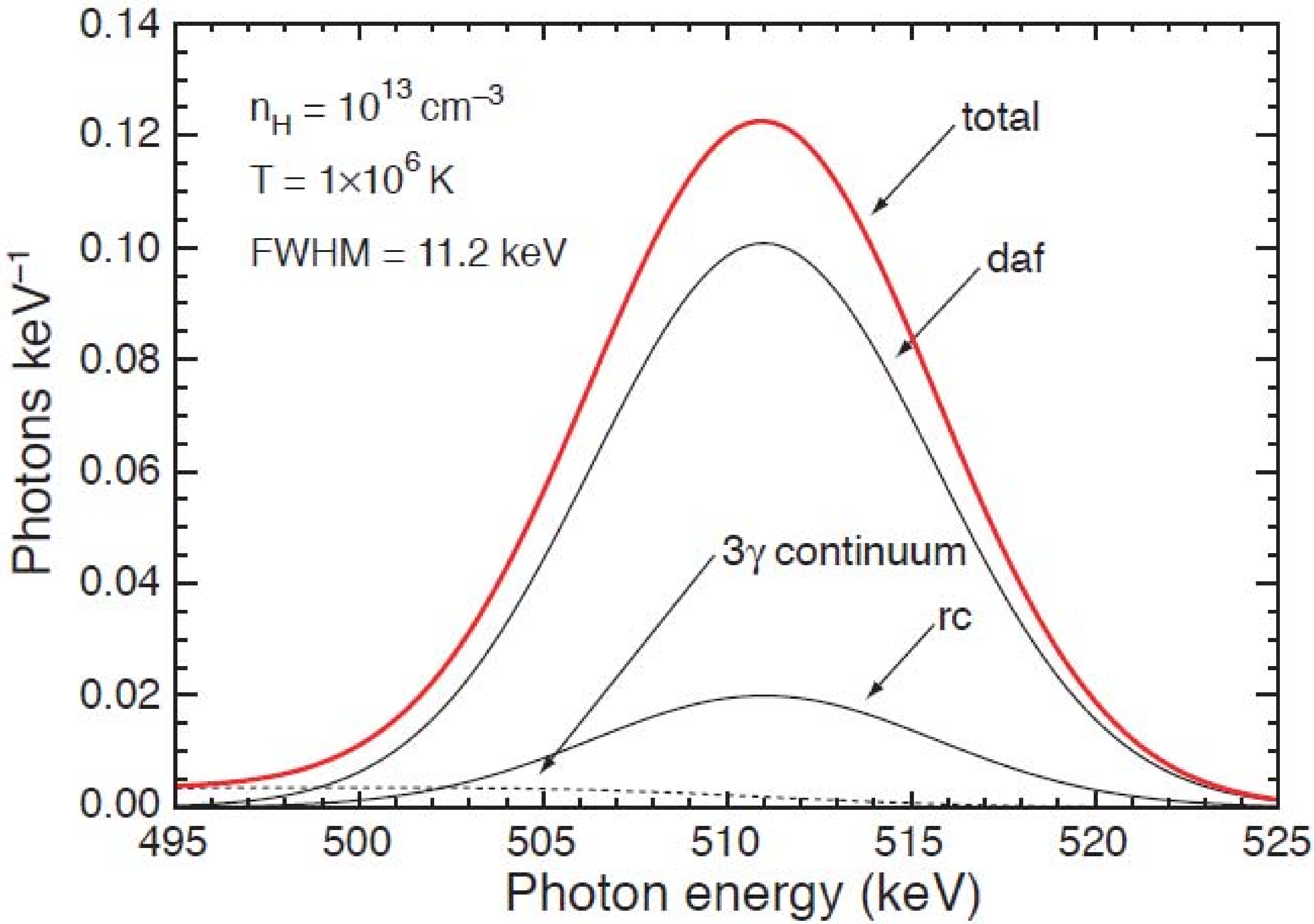


Energy Redistribution	Positronium (Ps) Formation
$e^+ \mathrm{H} \rightarrow e^+ \mathrm{H}^*$	$e^+ e^- \rightarrow \gamma\ \mathrm{Ps}$
$e^+ \mathrm{H} \rightarrow e^+ e^- \mathrm{H}^+$	$e^+ \mathrm{H} \rightarrow \mathrm{H}^+ \mathrm{Ps}$
$e^+ \mathrm{He} \rightarrow e^+ \mathrm{He}^*$	$e^+ \mathrm{He} \rightarrow \mathrm{He}^+ \mathrm{Ps}$
$e^+ \mathrm{He} \rightarrow e^+ e^- \mathrm{He}^+$	

Quench Ps when $n \gtrsim 10^{13}\ \mathrm{cm}^{-3}$

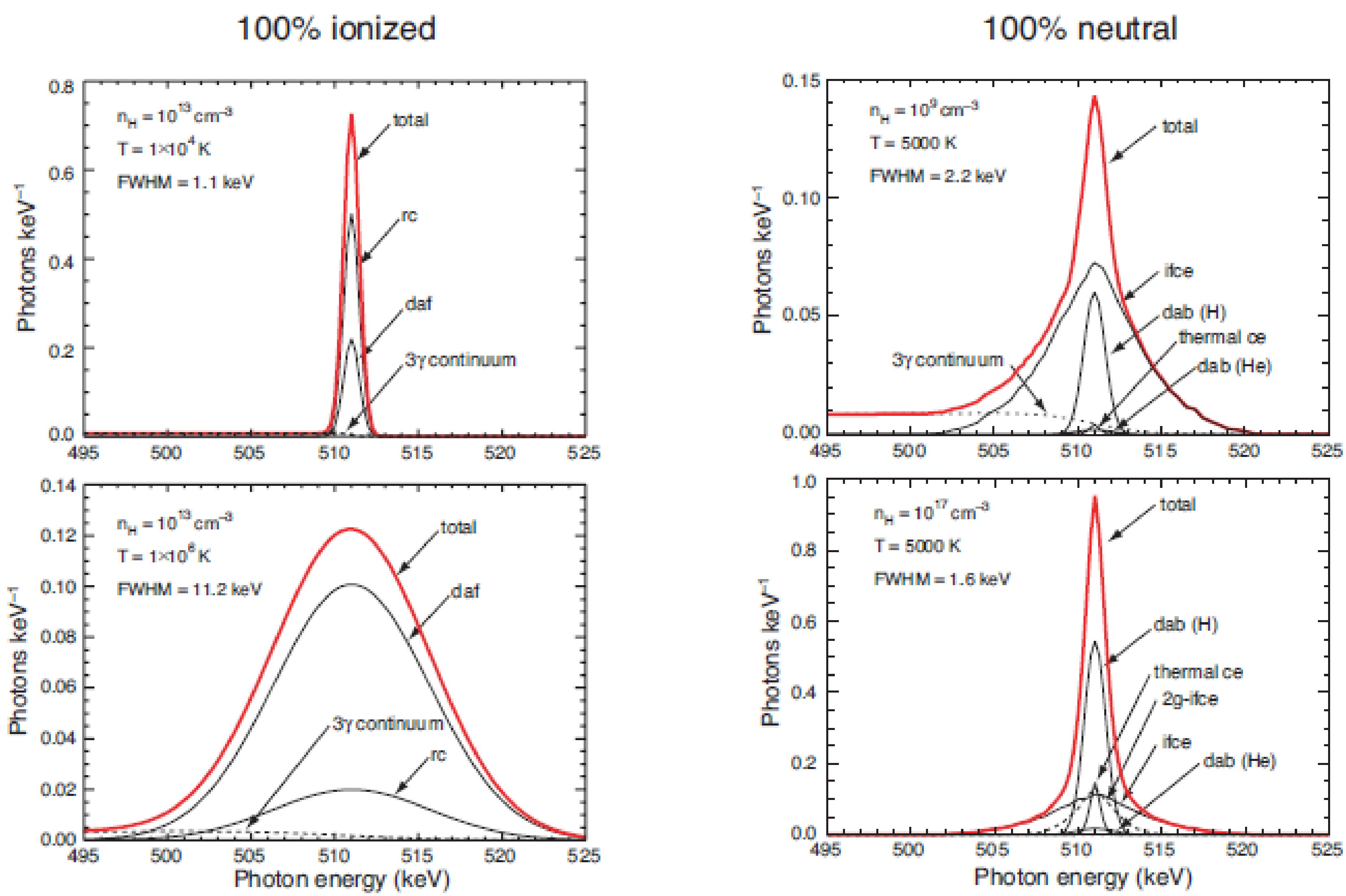
Positronium Quenching
$e^- \, {}^3\mathrm{Ps} \rightarrow e^- e^- e^+$
$\mathrm{H}\, {}^3\mathrm{Ps} \rightarrow \mathrm{H}\, e^- e^+$
$e^- \, {}^3\mathrm{Ps} \rightarrow e^- \, {}^1\mathrm{Ps}$
$\mathrm{H}\, {}^3\mathrm{Ps} \rightarrow \mathrm{H}\, {}^1\mathrm{Ps}$
$\mathrm{H}^+ \mathrm{Ps} \rightarrow \mathrm{H}\, e^+$
$\mathrm{He}^+ \mathrm{Ps} \rightarrow \mathrm{He}\, e^+$

Annihilation Line Shapes

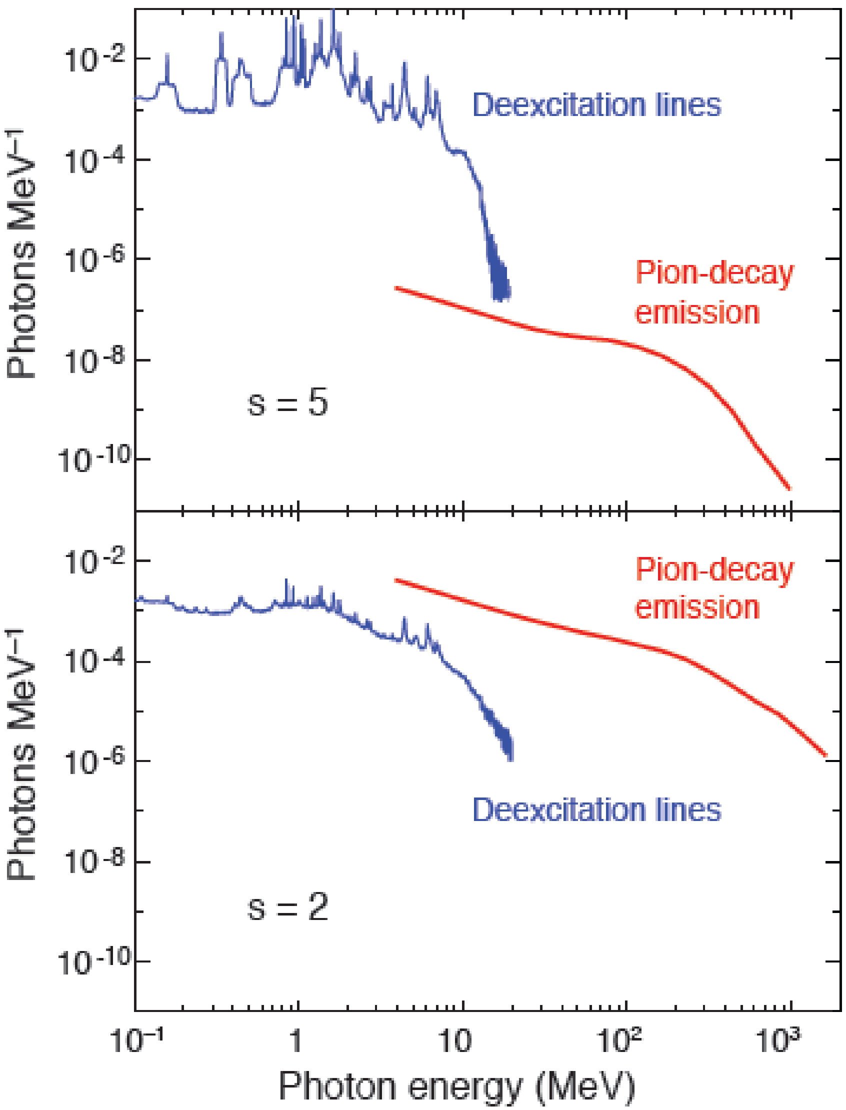


$$\mathrm{FWHM} = mc^2\sqrt{\ln 2\left(\frac{kT}{mc^2}\right)} = 1.1\ \mathrm{keV}\sqrt{\frac{T}{10^4\ \mathrm{K}}},$$

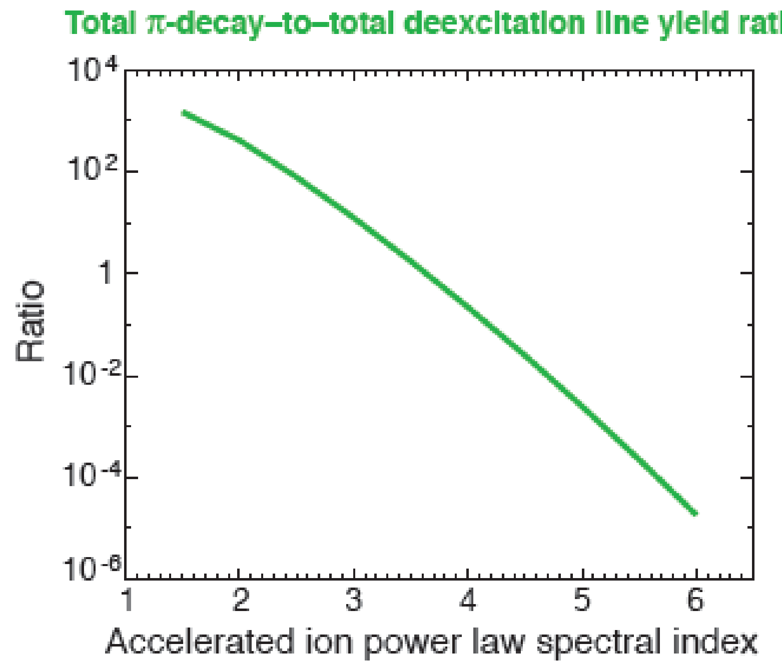
Annihilation Line Shapes



MeV-GeV Spectra



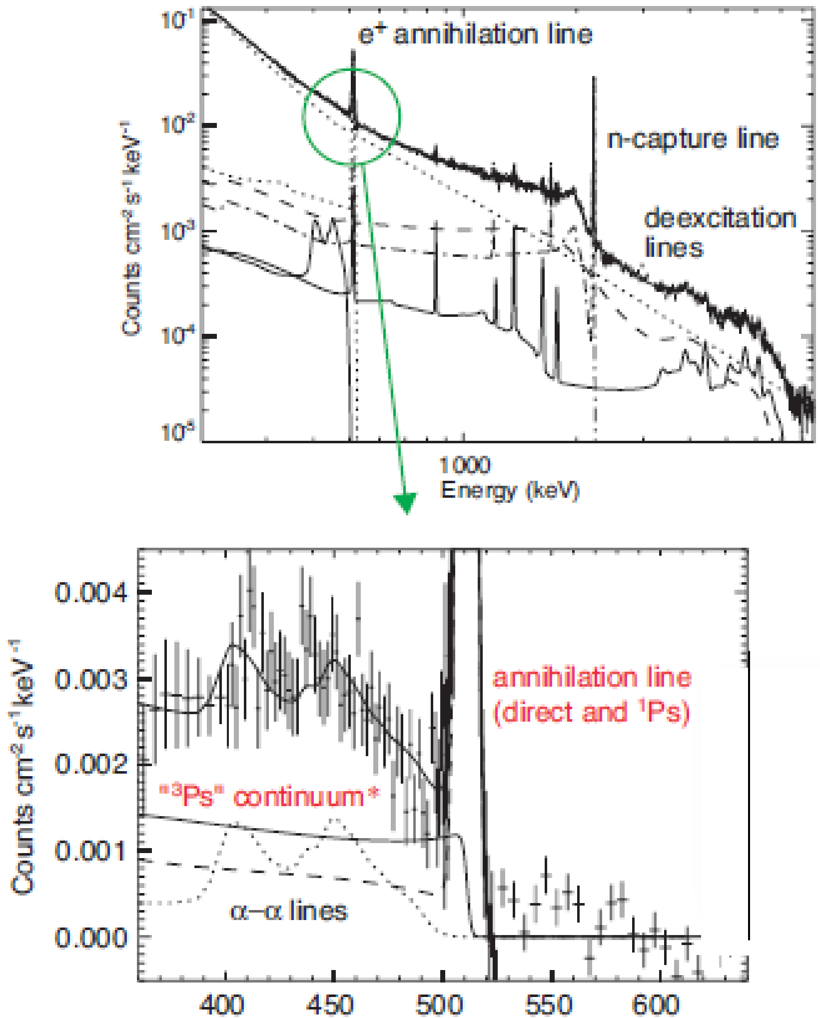
The ratio of pion-decay emission to nuclear deexcitation-line emission depends very strongly on the steepness of the accelerated-ion kinetic-energy spectrum



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

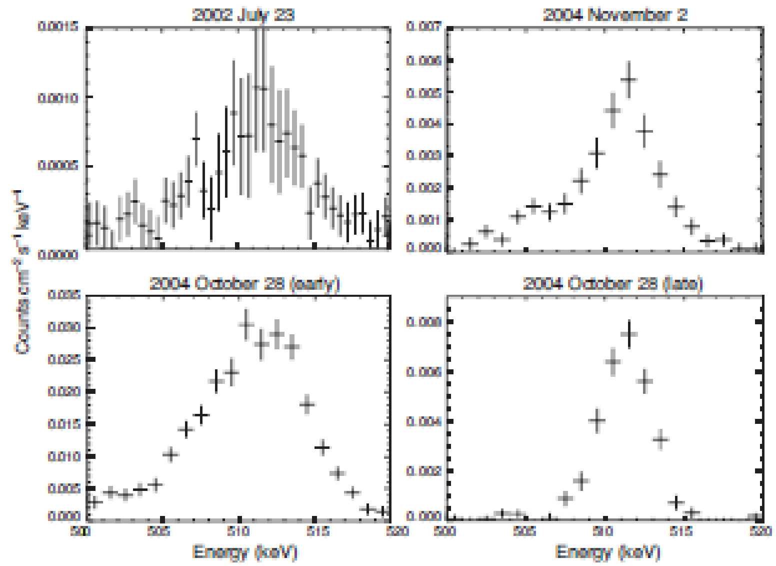
3. Observations and Comparison with Data

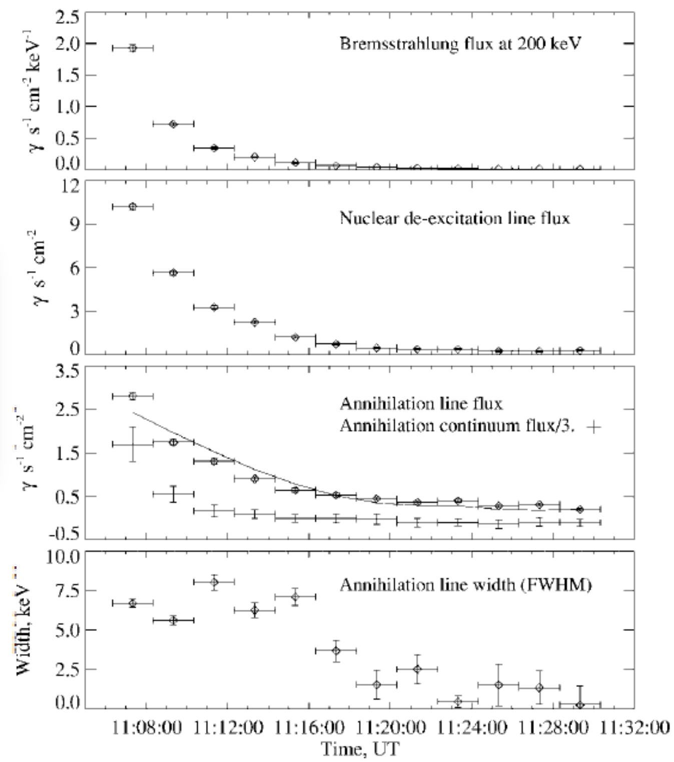
RHESSI observations of Solar Flares
28 October 2003



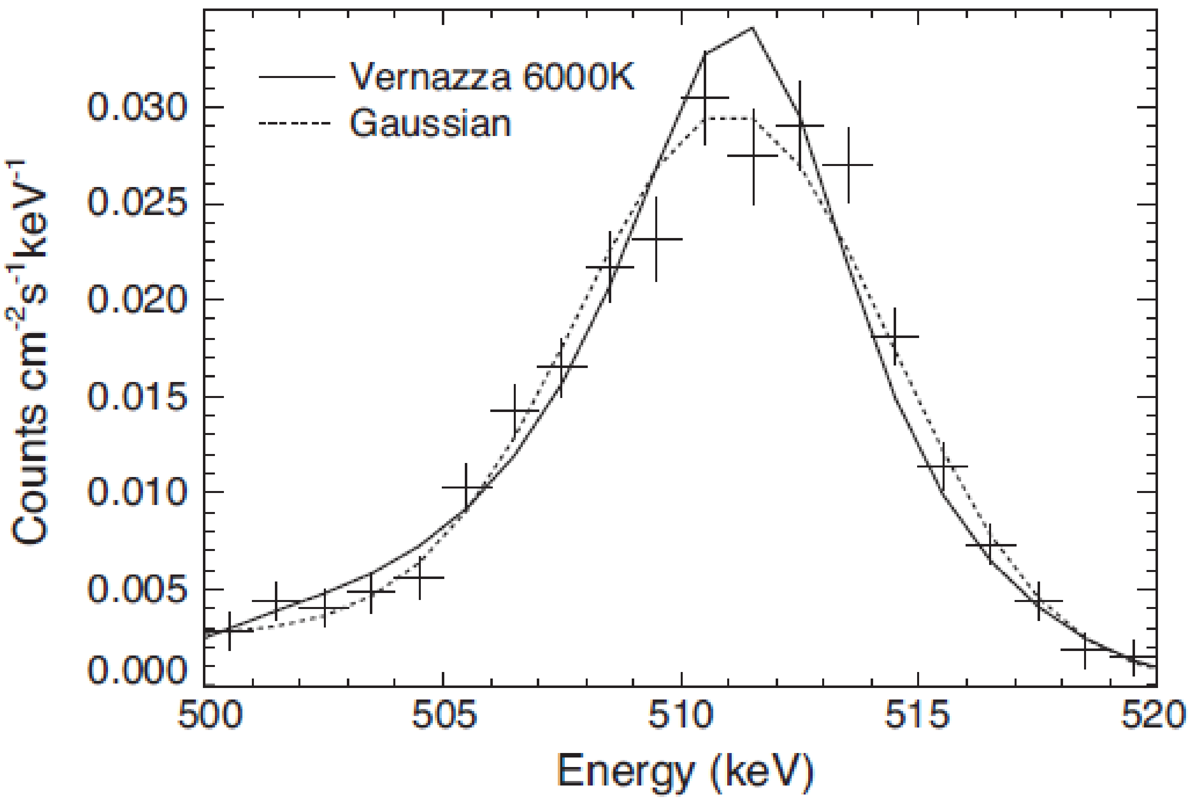
*probably dominated by Compton-scattered continuum from line

Share et al. (2004)





2003 October 28 Broad Line



Measured:
FWHM = 6.7 ± 1.5 keV
$Q_{3\gamma}/Q_{2\gamma} = 1.8 \pm 0.4$

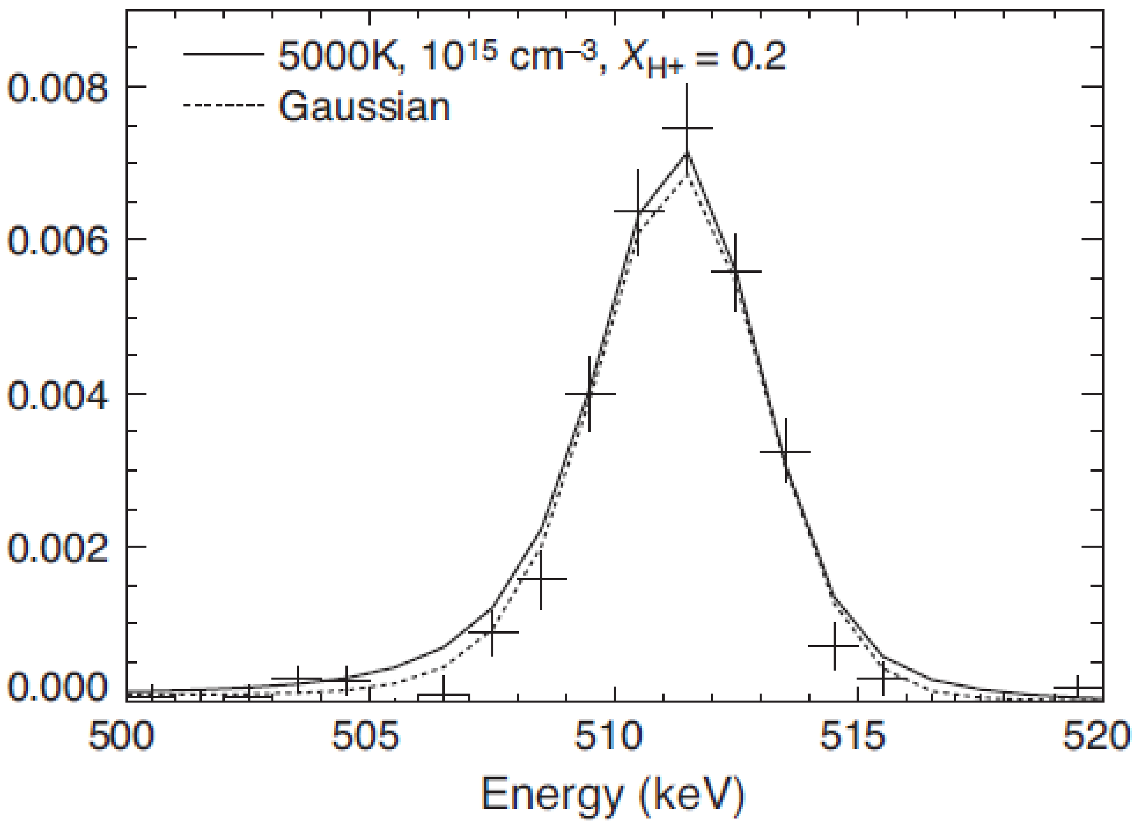
Vernazza at 6000 K provides an adequate fit to the shape
BUT
the $Q_{3\gamma}/Q_{2\gamma} = 3.5$ is too large
and $n_H = 10^{13}$ cm^{-3}

(Nuclear reactions require $n_H = 10^{14} - 10^{15}$ cm^{-3})

The Gaussian width implies
$T = 3 - 4 \times 10^5$ K
BUT
$Q_{3\gamma}/Q_{2\gamma} < 0.2$

π^+ production due to the very hard spectrum could allow this

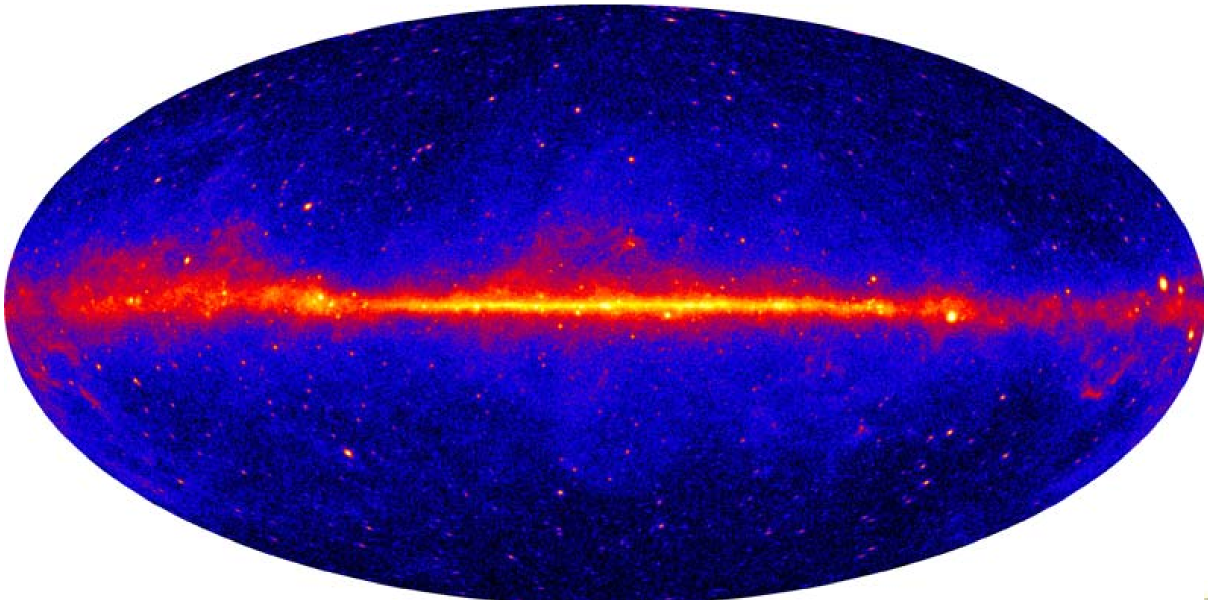
2003 October 28 Narrow Line



Measured:
FWHM = ~1 keV
$Q_{3\gamma}/Q_{2\gamma} < 0.3$ (99% UL)

Good fit requires:
- low temperature
- high density
- ionization

4. Positrons and γ rays in SNRs



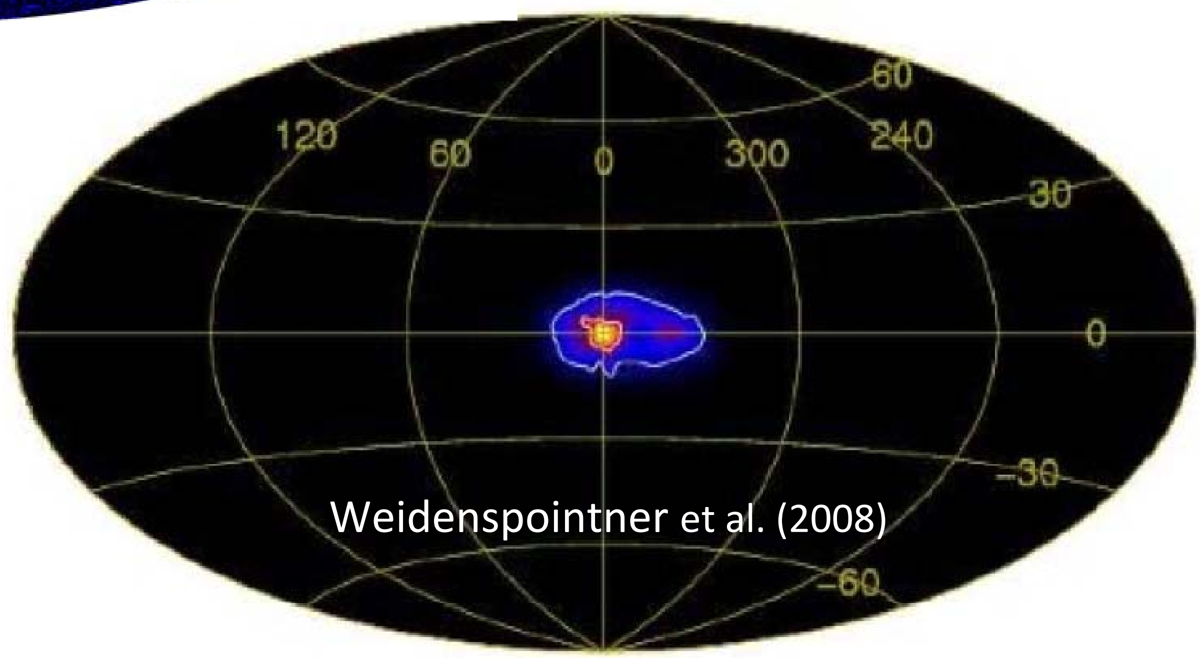
Fermi 3 year (> 1 GeV) sky

2nd Fermi Gamma-ray Source Catalog (Nolan et al. 2012)

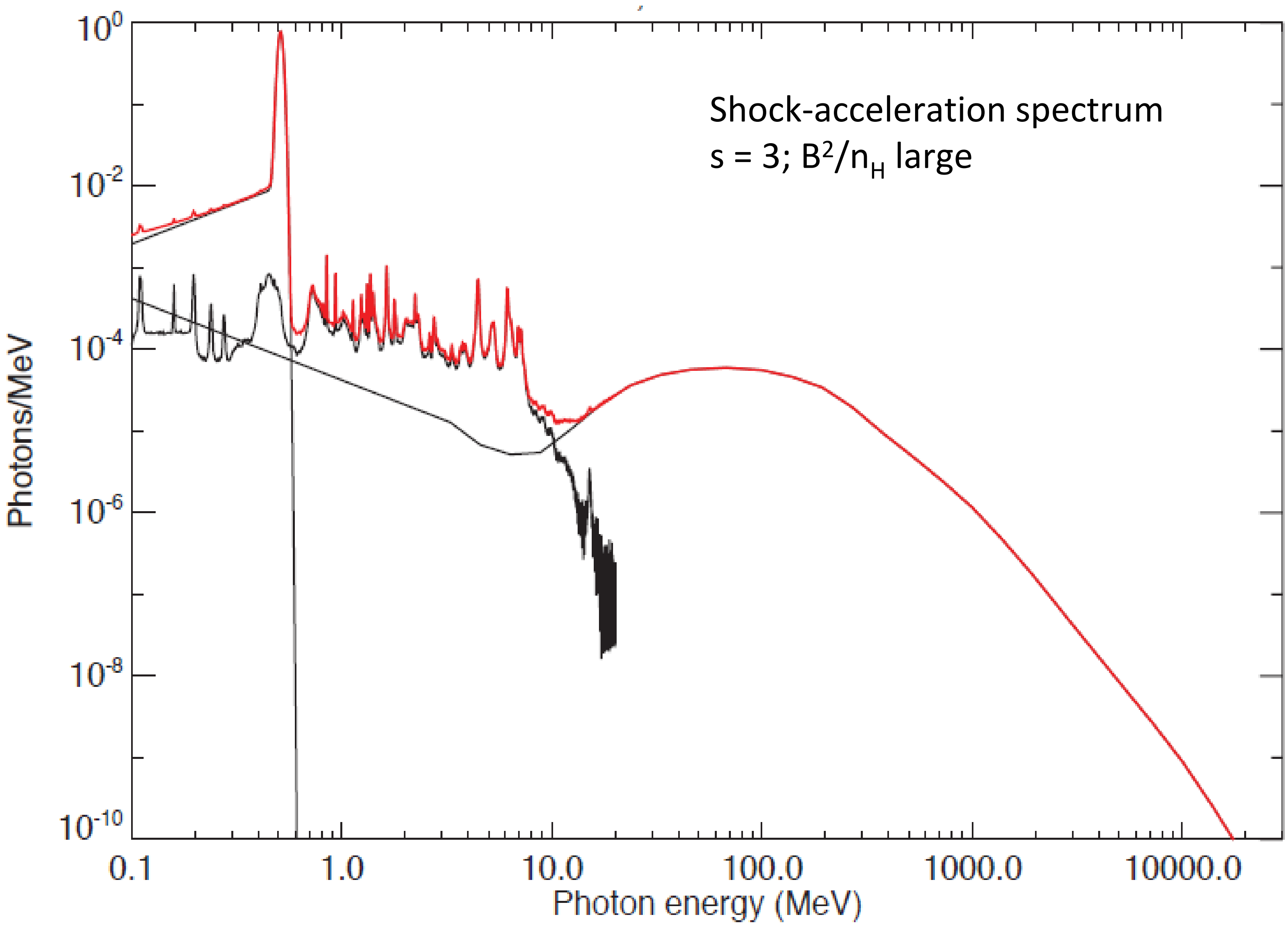
62 SNR associations
6 identifications
W44, W51C, IC 443
W28, W30, Cygnus Loop

Put in >100 MeV flux $\Rightarrow$ 0.511 MeV flux

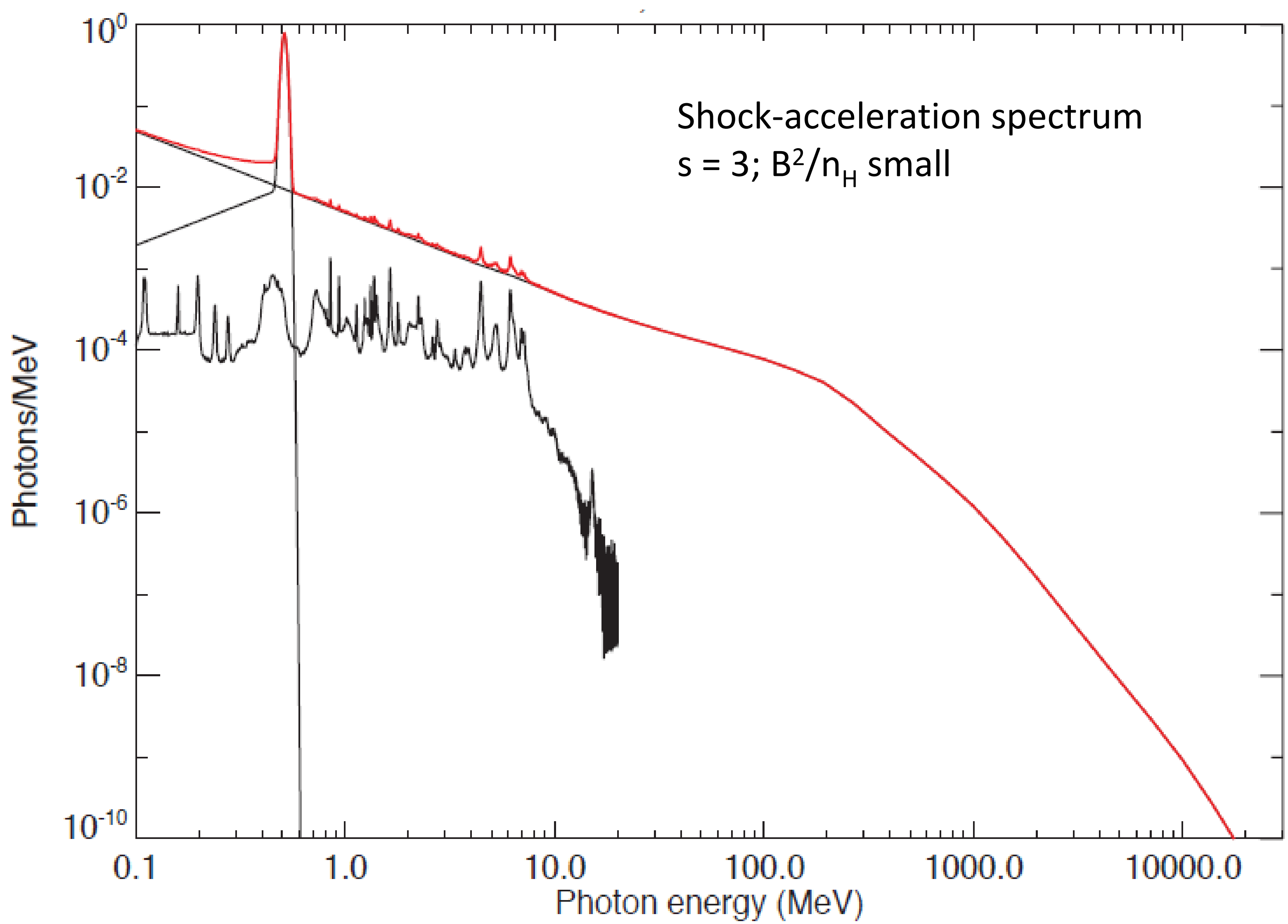
Thick target ($\therefore$ maximum annihiliation flux)



Weidenspointner et al. (2008)

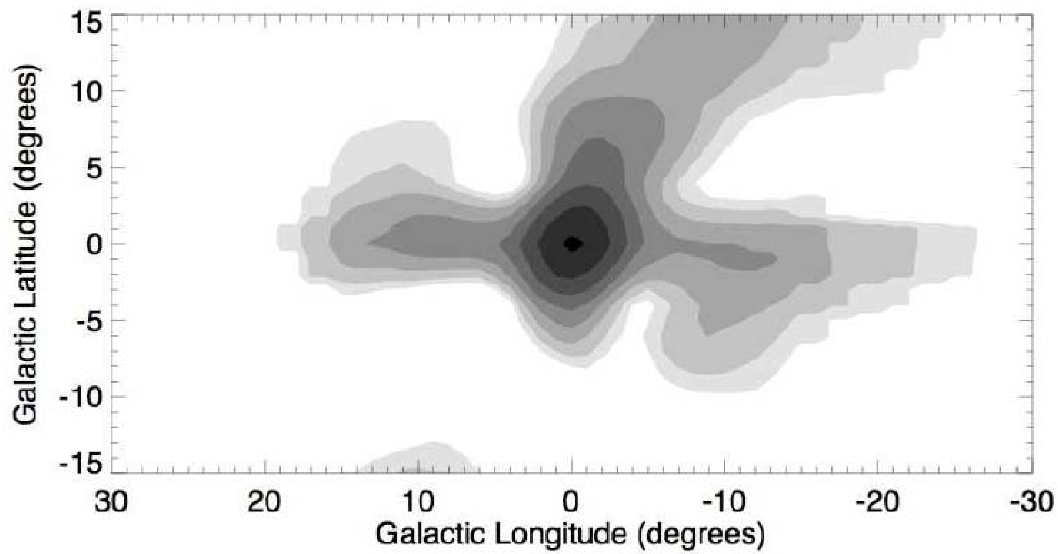


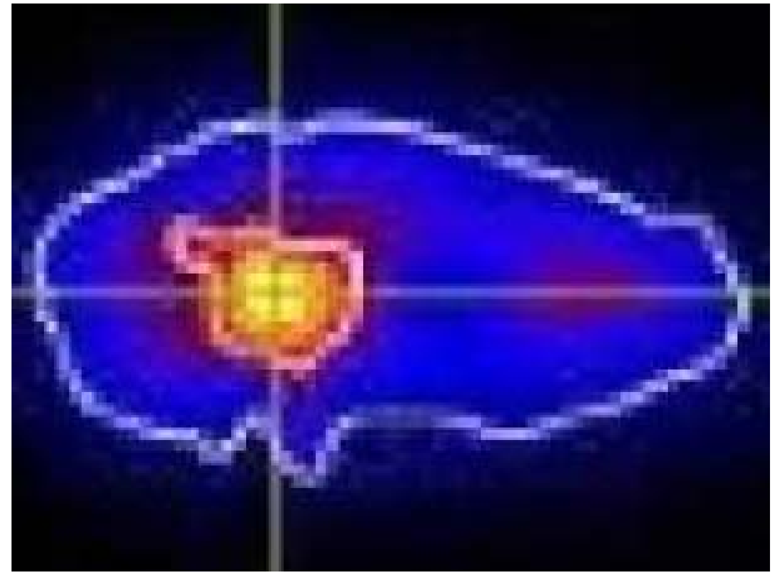
Shock-acceleration spectrum
s = 3; B²/n_H large
Photons/MeV
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
0.1
1.0
10.0
100.0
1000.0
10000.0
Photon energy (MeV)



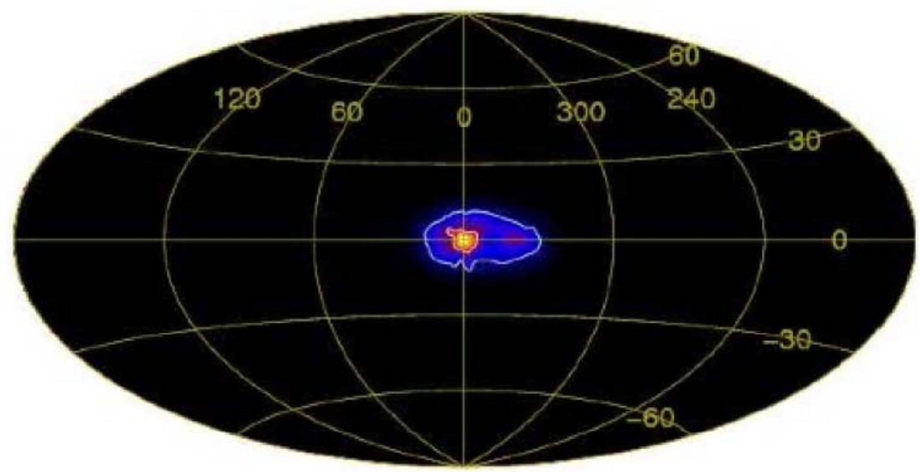
→Weak annihilation flux

Origin of bulge annihilation radiation





- Positive galactic plane: 2.9 ± 0.2,
- Negative galactic plane: 3.1 ± 0.3,
- Central bulge: 6.0 ± 0.4,
- Positive latitude enhancement: 2.2 ± 0.2,
- Mirror region: 0.8 ± 0.1 ,



Weidenspointner et al. (2008)

Purcell et al. (1997)

Models for Galactic Annihilation Radiation

Source	Process	Comments
Massive stars: ^{26}Al	β^+-decay	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{24}Ti	β^+-decay	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	Assuming $f_{e^+,esc}$=0.04
Novae	β^+-decay	Insufficent e^+ production
Hypernovae/GRB: ^{56}Ni	β^+-decay	Improbable in inner MW
Cosmic rays	p-p	Too high e^+ energy
LMXRBs	$\gamma - \gamma$	Assuming $L_{e^+} \sim 0.01\ L_{obs,X}$
Microquasars (μQs)	$\gamma - \gamma$	e^+ load of jets uncertain
Pulsars	$\gamma - \gamma$ / $\gamma - \gamma_B$	Too high e^+ energy
ms pulsars	$\gamma - \gamma$ / $\gamma - \gamma_B$	Too high e^+ energy
Magnetars	$\gamma - \gamma$ / $\gamma - \gamma_B$	Too high e^+ energy
Central black hole	p-p	Too high e^+ energy, unless B >0.4 mG
	$\gamma - \gamma$	Requires e^+ diffusion to ~1 kpc
Dark matter	Annihilation	Requires light scalar particle, cuspy DM profile
	Deexcitation	Only cuspy DM profiles allowed
	Decay	Ruled out for all DM profiles
Observational constraints		

Prantzos et al. (2011)

Annihilation Fountain
Dermer & Skibo (1997)

Past episode of starburst activity

Ginga 6.7 keV

Quenching of Sgr A*

Radio/X-ray structures

Fermi bubbles

Conclusions

Positron annihilation in solar flares occurs in a wide range of conditions

2003 October 28 : 3 – 4 × 10^5K, >10^{15} cm^{-3} , ionized
(broad) high $Q_{3\gamma}/Q_{2\gamma}$ may be due to deep production by π

2003 October 28 : 5000 K, ~10^{15} cm^{-3}, X_{H+} > 20%
(narrow)

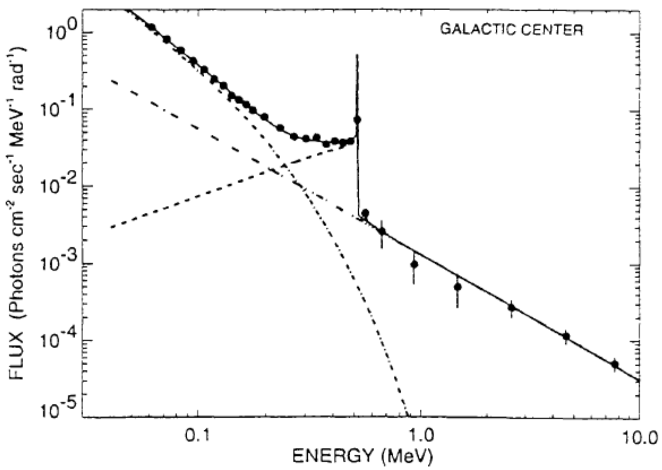
Predict annihilation line intensity given >100 MeV flux from SNRs

Not likely to be tested soon

Prediction for annihiliation fountain

Width of the 2γ 0.511 MeV line from annihilation in hot gas broader than Galactic disk 0.511 MeV line emission, and the 3γ Ps continuum fraction *f* will be spatially varying

Annihilation in the ISM



OSSE data (Kinzer et al. 1999)

Measured: ΔE, $Q_{3\gamma}$/ $Q_{2\gamma}$

Medium: T, n_H, X_{H+}, X_{He+}, X_{He++}

Annihilation on Dust

Guessoum et al. (2005)