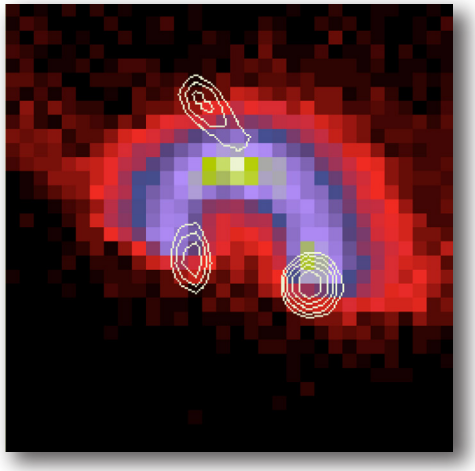
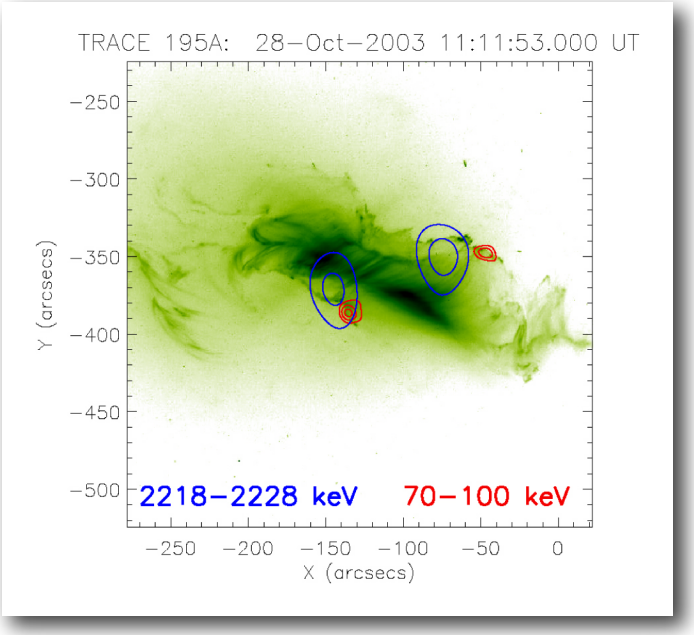
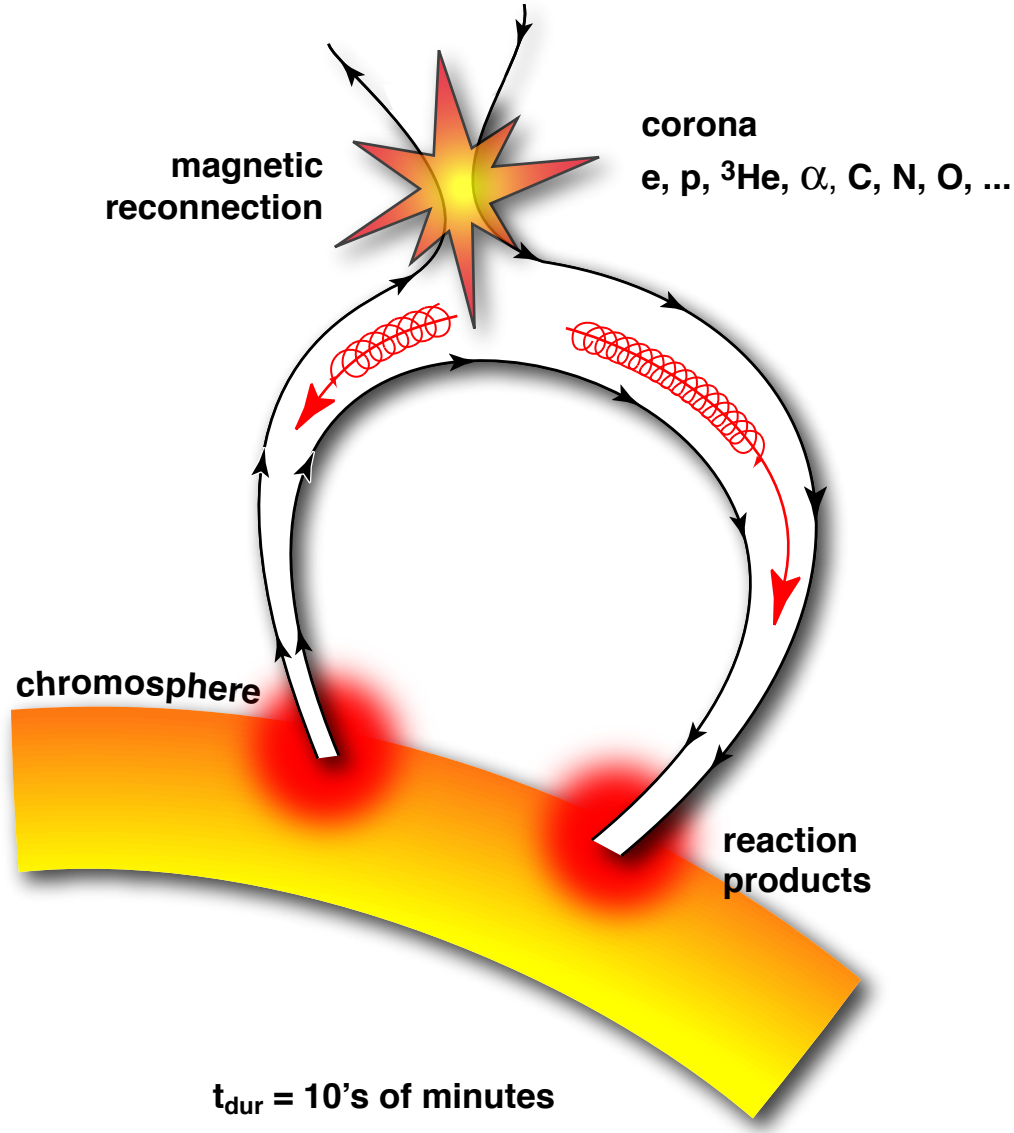
γ-ray and Neutron Production in Solar Flares

Yohkoh



RHESSI





Products of Accelerated-Particle Interactions

Products of ion nuclear interactions

excited nuclei

radioactive nuclei

neutrons

π^+, π^-, π^0

Observable emission

e^-: X- and γ-ray bremsstrahlung

ions:

excited nuclei $\rightarrow$ prompt γ-ray line radiation

radioactive nuclei $\rightarrow \begin{cases} \text{delayed } \gamma\text{-ray line radiation} \\ e^+ \rightarrow \gamma_{511} \text{ \& continuum} \end{cases}$

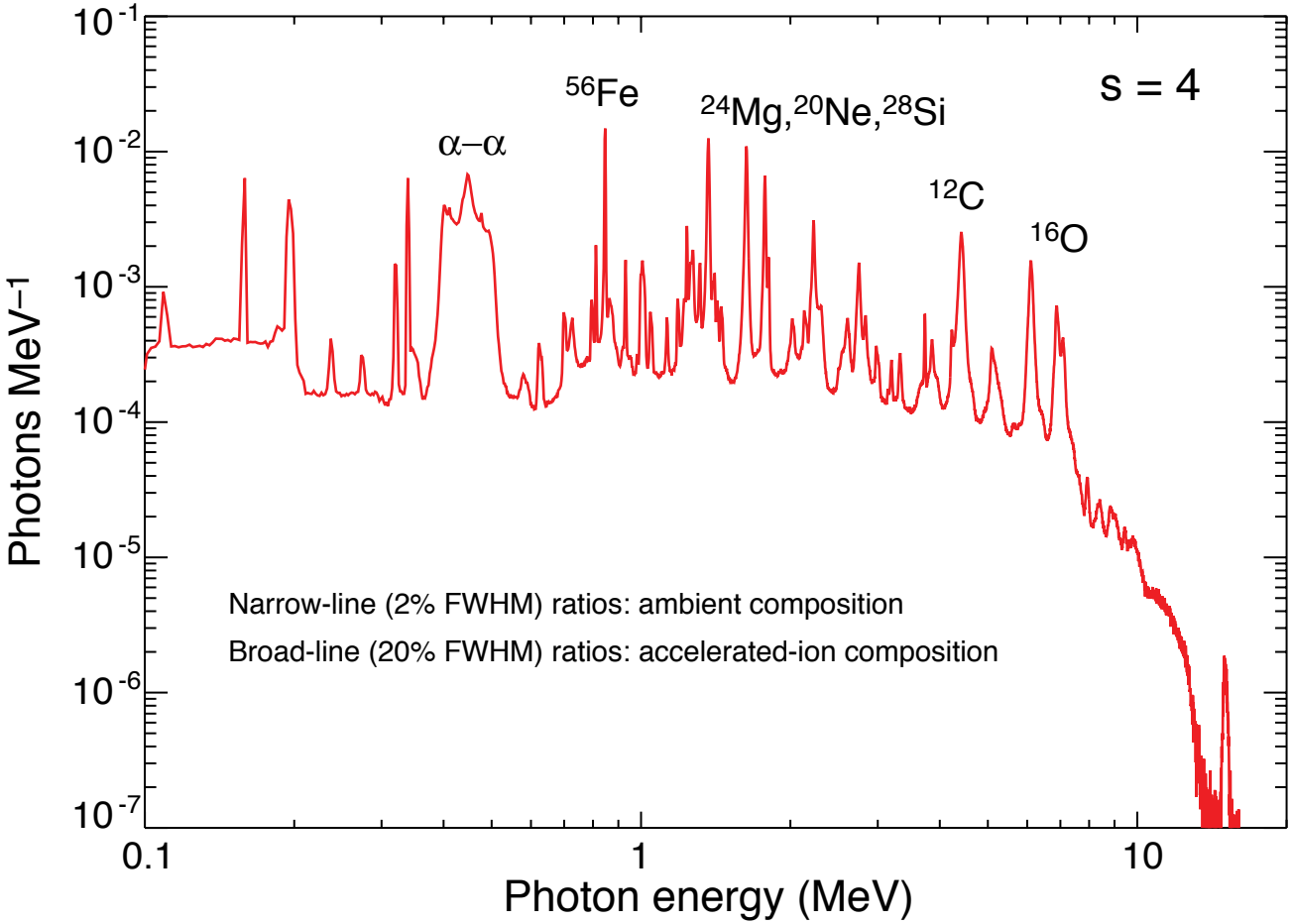
neutrons $\rightarrow \begin{cases} \text{escape into space (and n-decay protons \& electrons)} \\ \text{capture on H} \rightarrow d + \gamma_{2.223} \end{cases}$

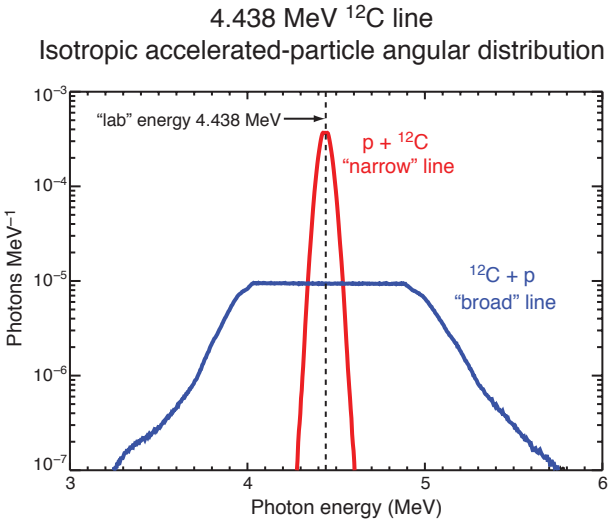
$\pi \rightarrow$

$\pi^0 \rightarrow 2\gamma \qquad m_{\pi^0} = 135 \text{ MeV} \rightarrow \varepsilon_\gamma = 67.5 \text{ MeV}$

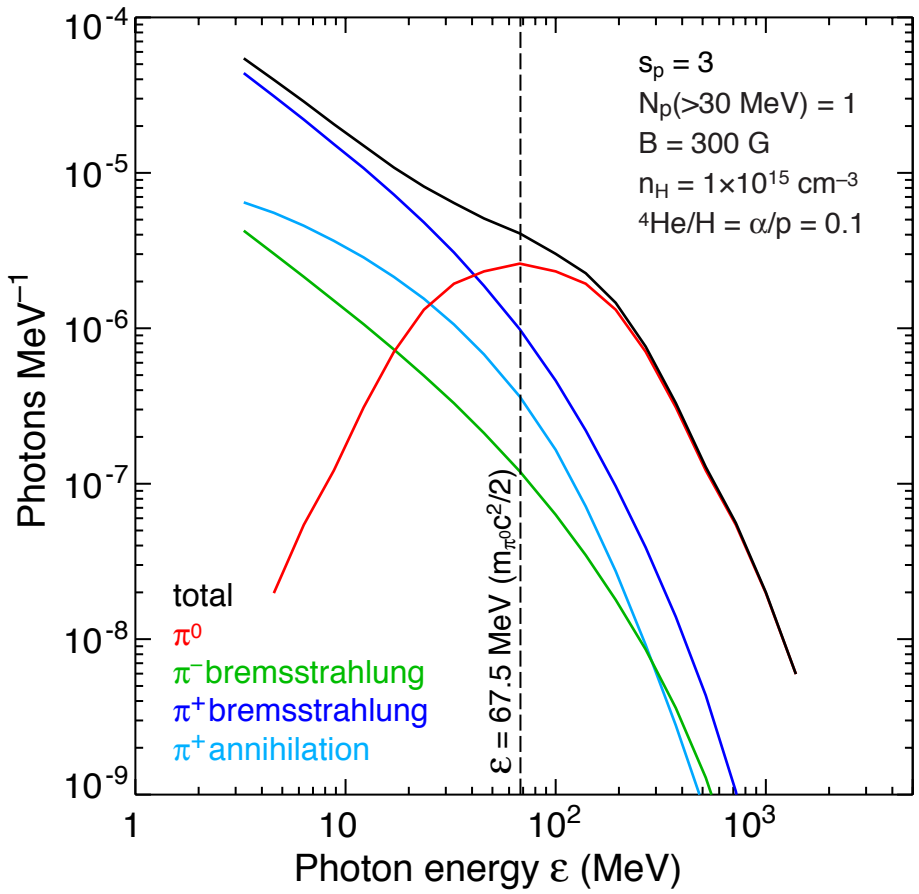
$\pi^{+,-} \rightarrow e^{+,-} \rightarrow$ γ_{511} (annihilation, line & in-flight continuum)
continuum emission via bremsstralung

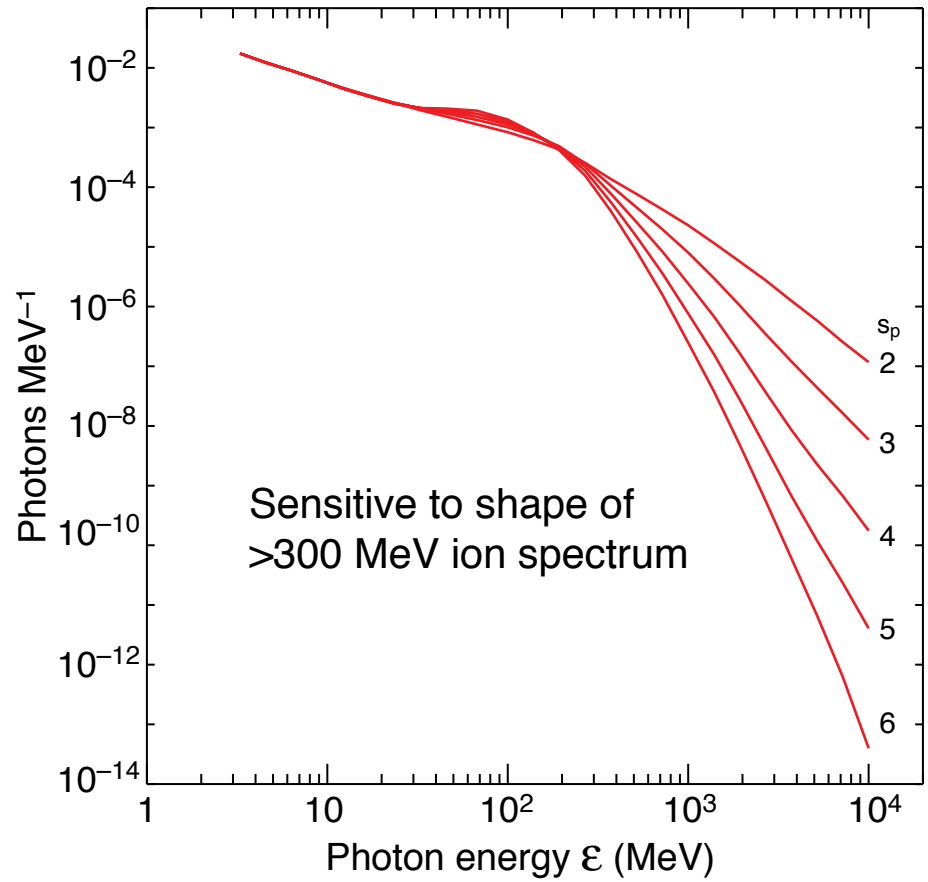
Deexcitation-line Spectrum



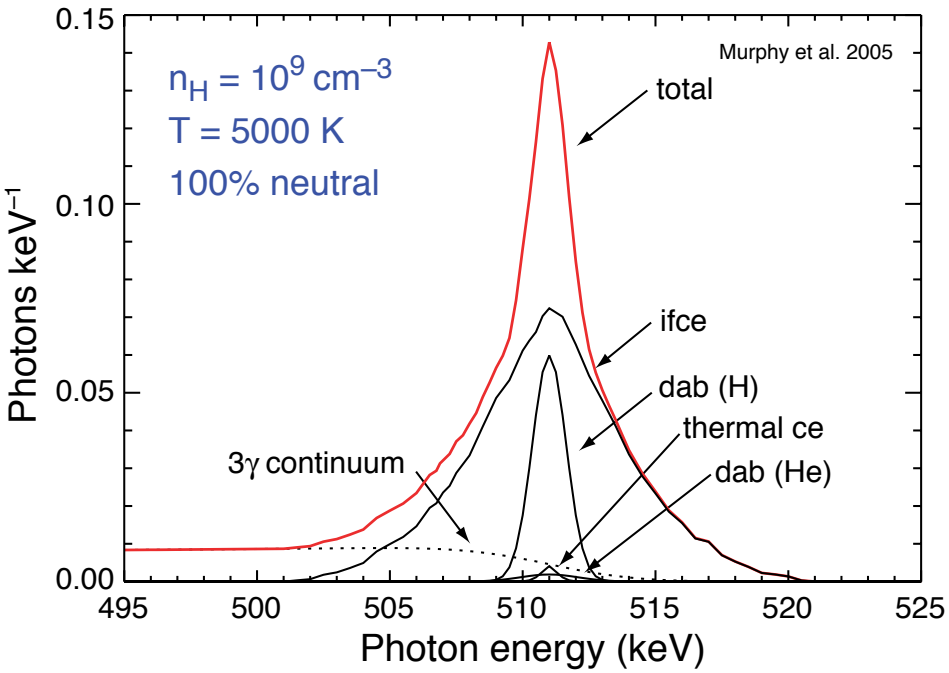


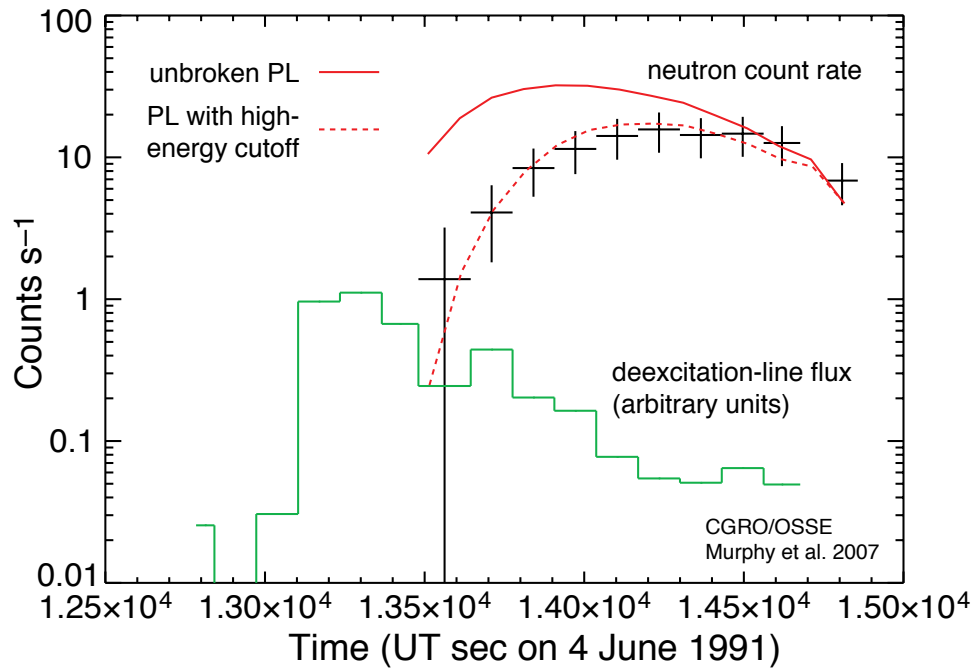
Pion-decay Spectra



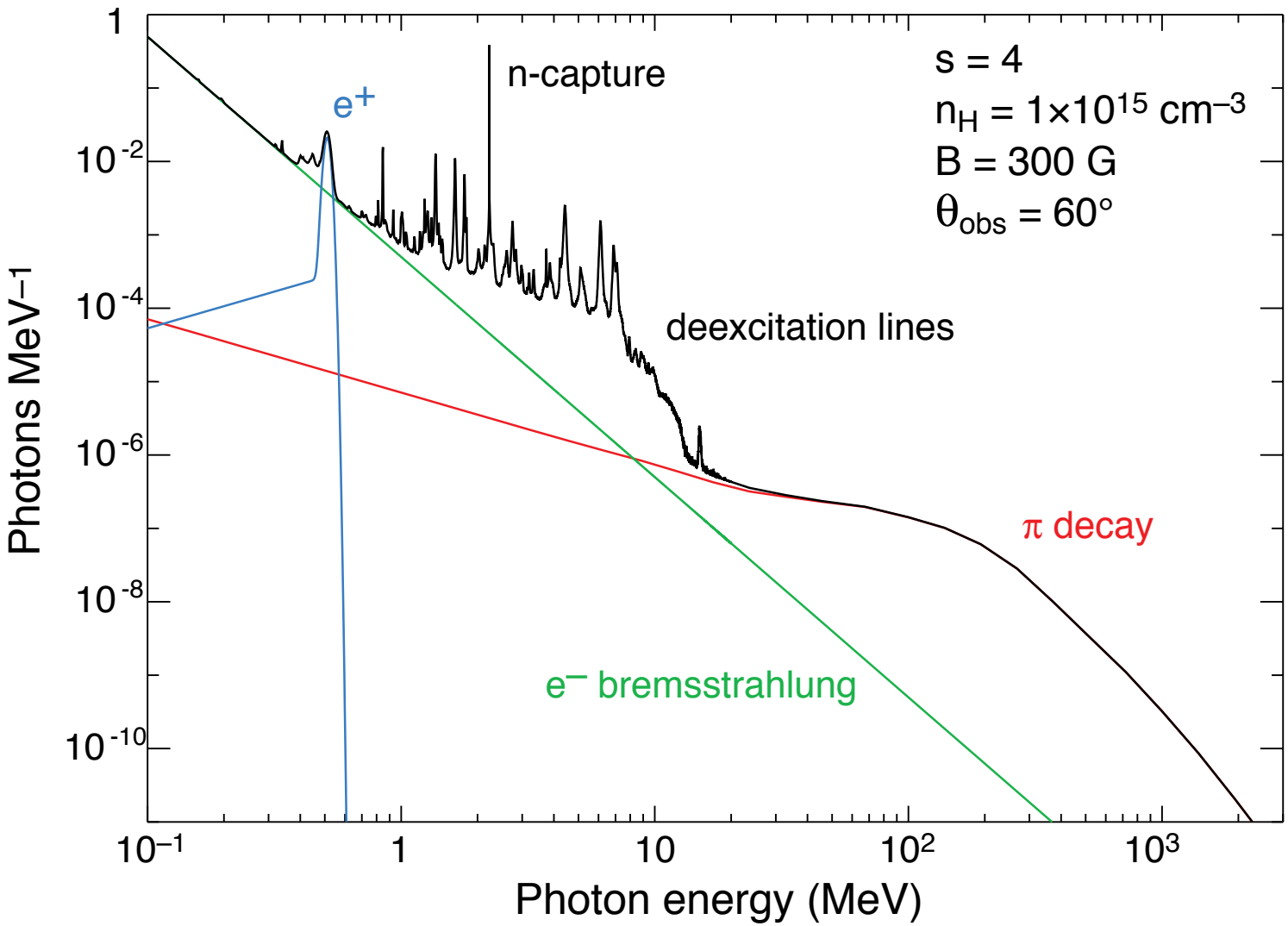


Annihilation Line and Neutrons

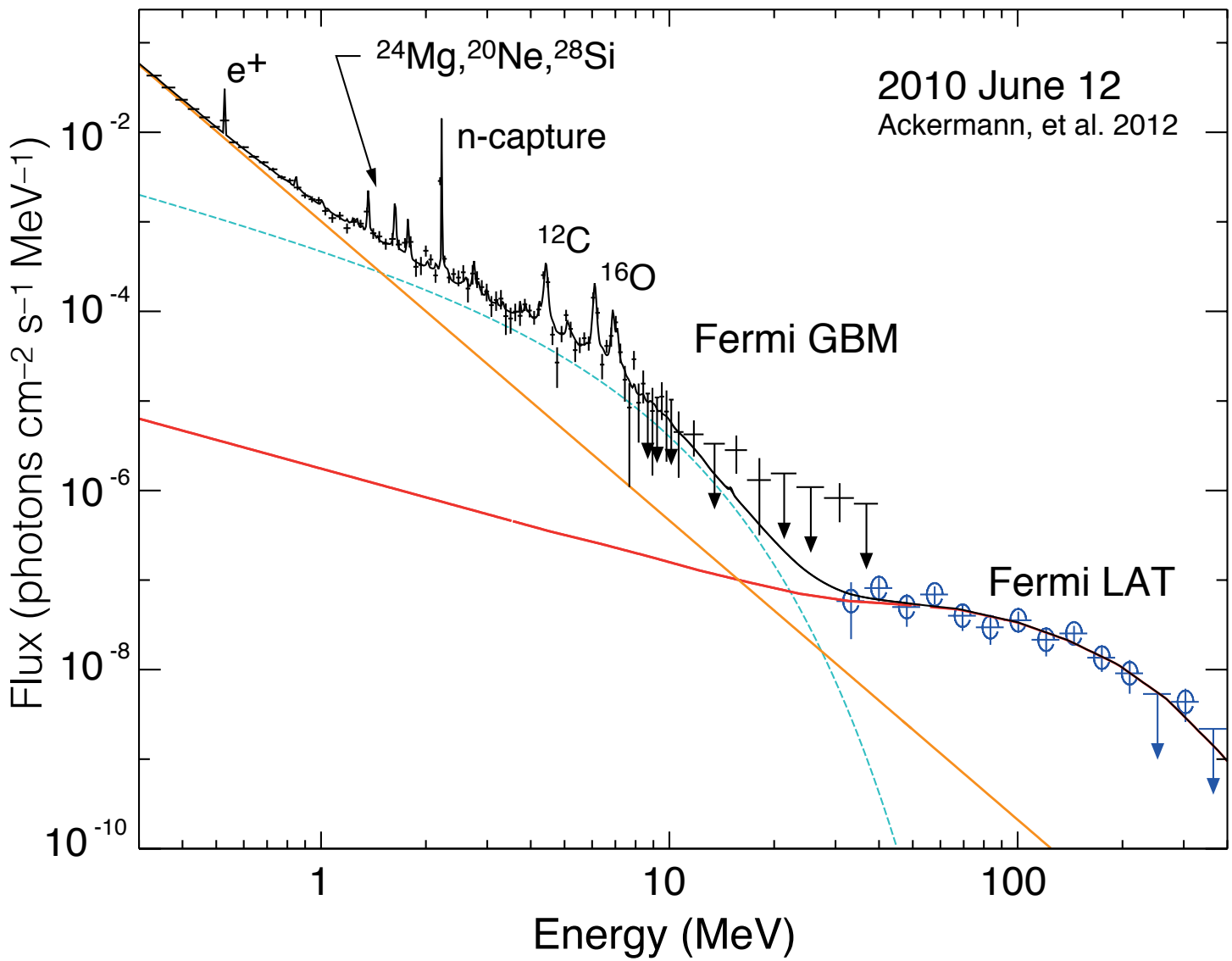




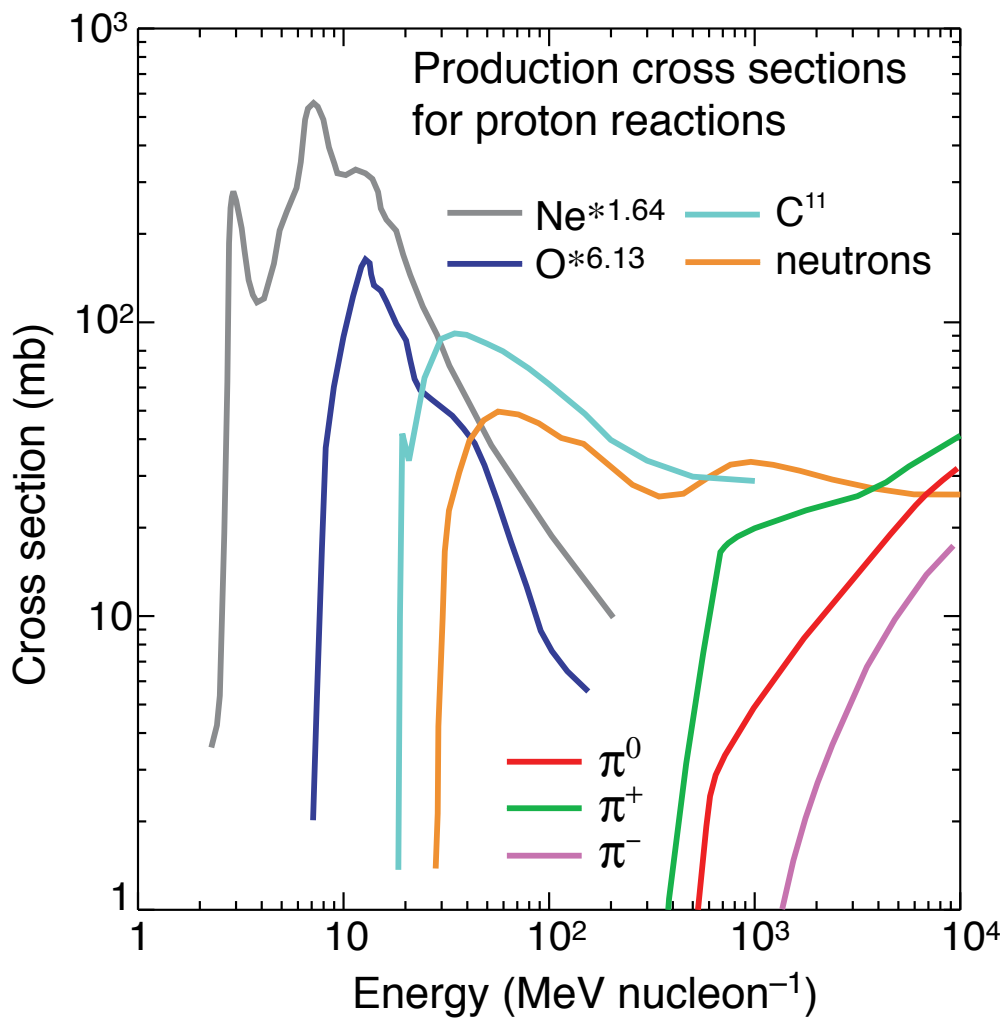
Total Gamma-ray Spectrum



Solar-flare Gamma-ray Observations

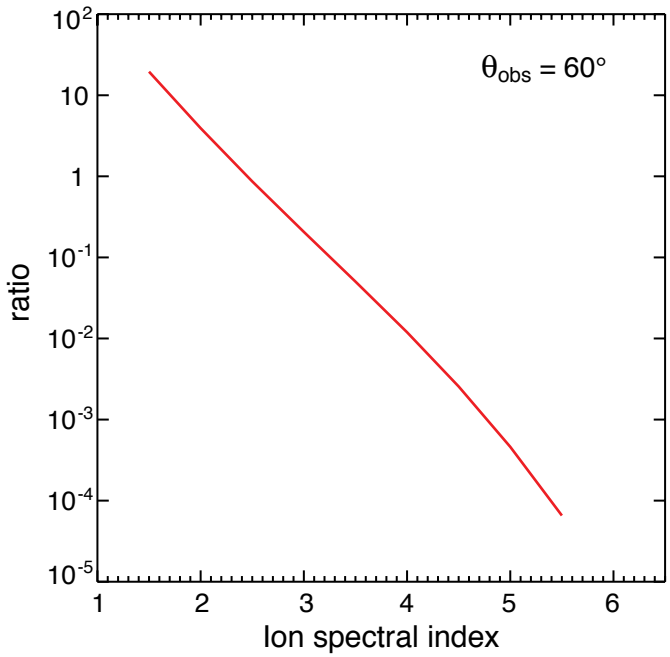


Cross Sections and Ion-energy Dependences



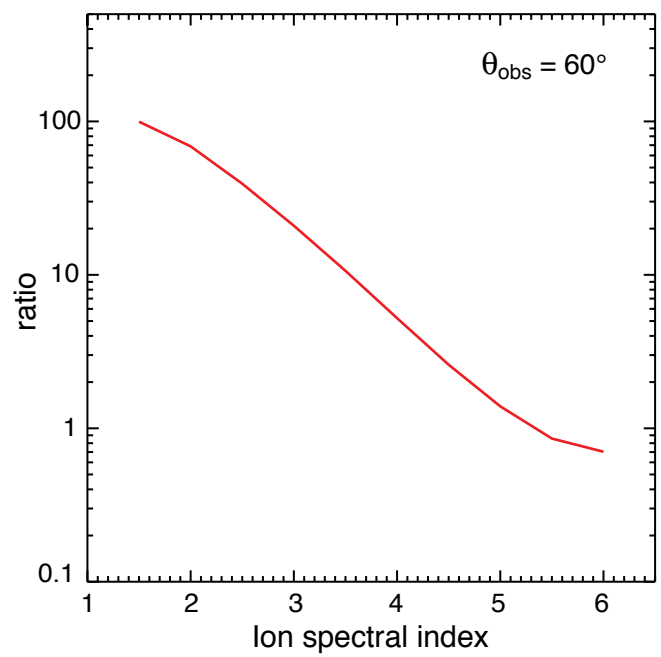
Radiation	Ion energy
deexcitation lines	2–20 MeV nucleon^{-1}
n-capture	10–30 MeV nucleon^{-1}
neutrons @ Earth	>30 MeV nucleon^{-1}
π-decay	$\gtrsim$300 MeV nucleon^{-1}

Ion Spectral Shape from Emission Ratios



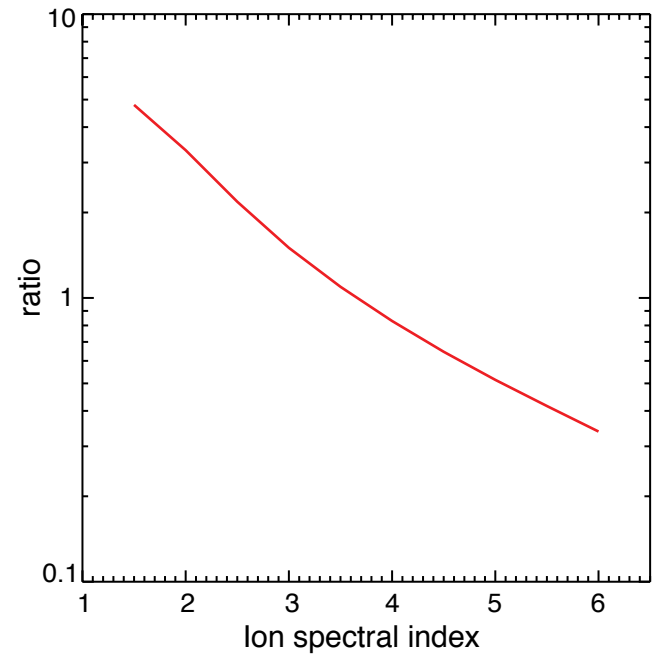
Q_{π}(>100 MeV)/$Q_{2.2}$

[>300 MeV] — [10–30 MeV]



$Q_{2.2}/Q_{4.4}$

[10–30 MeV] — [5–15 MeV]

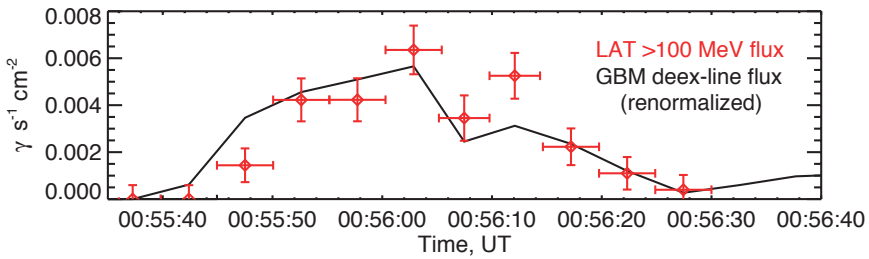


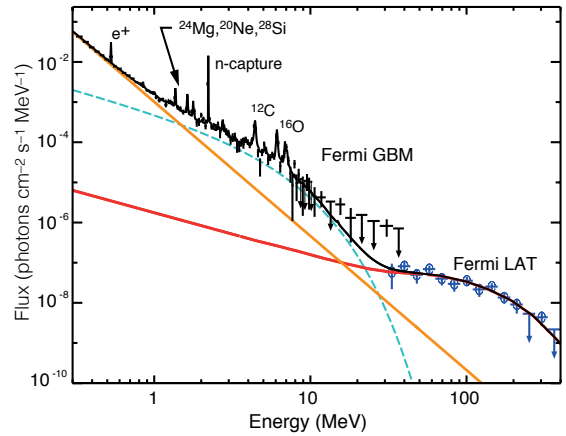
$Q_{6.1}/Q_{1.6}$

[10–20 MeV] — [2–10MeV]

Deriving Ion Spectral Index from Fermi LAT and GBM Data

2010 June 12 flare
Ackermann, et al. 2012

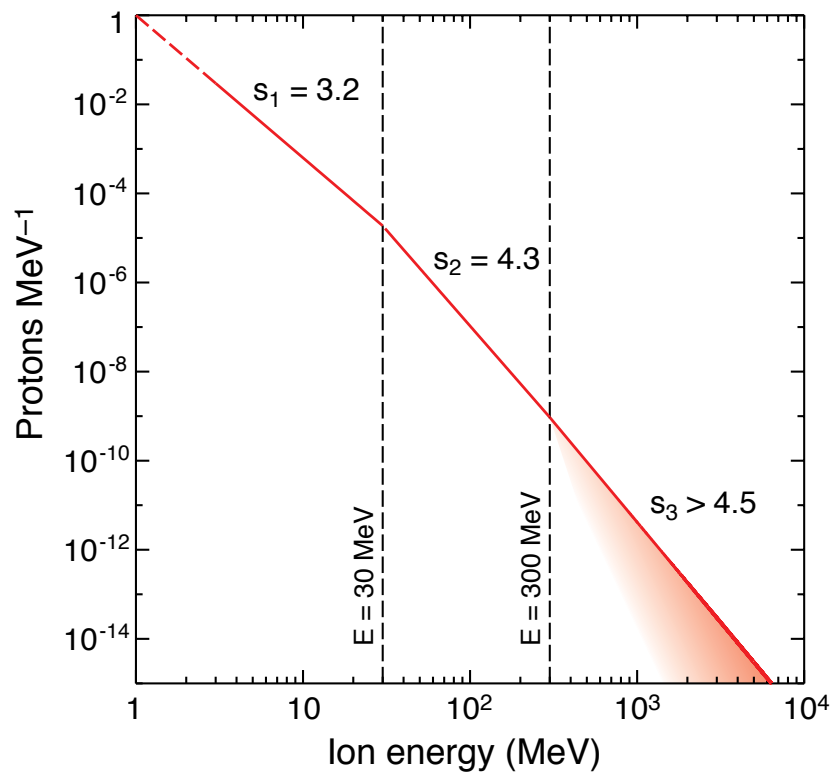




$\frac{\text{n-capture}}{\text{deex lines}}$ $s_1 = 3.2$

$\frac{\pi\text{-decay}}{\text{n-capture}}$ $s_2 = 4.3$

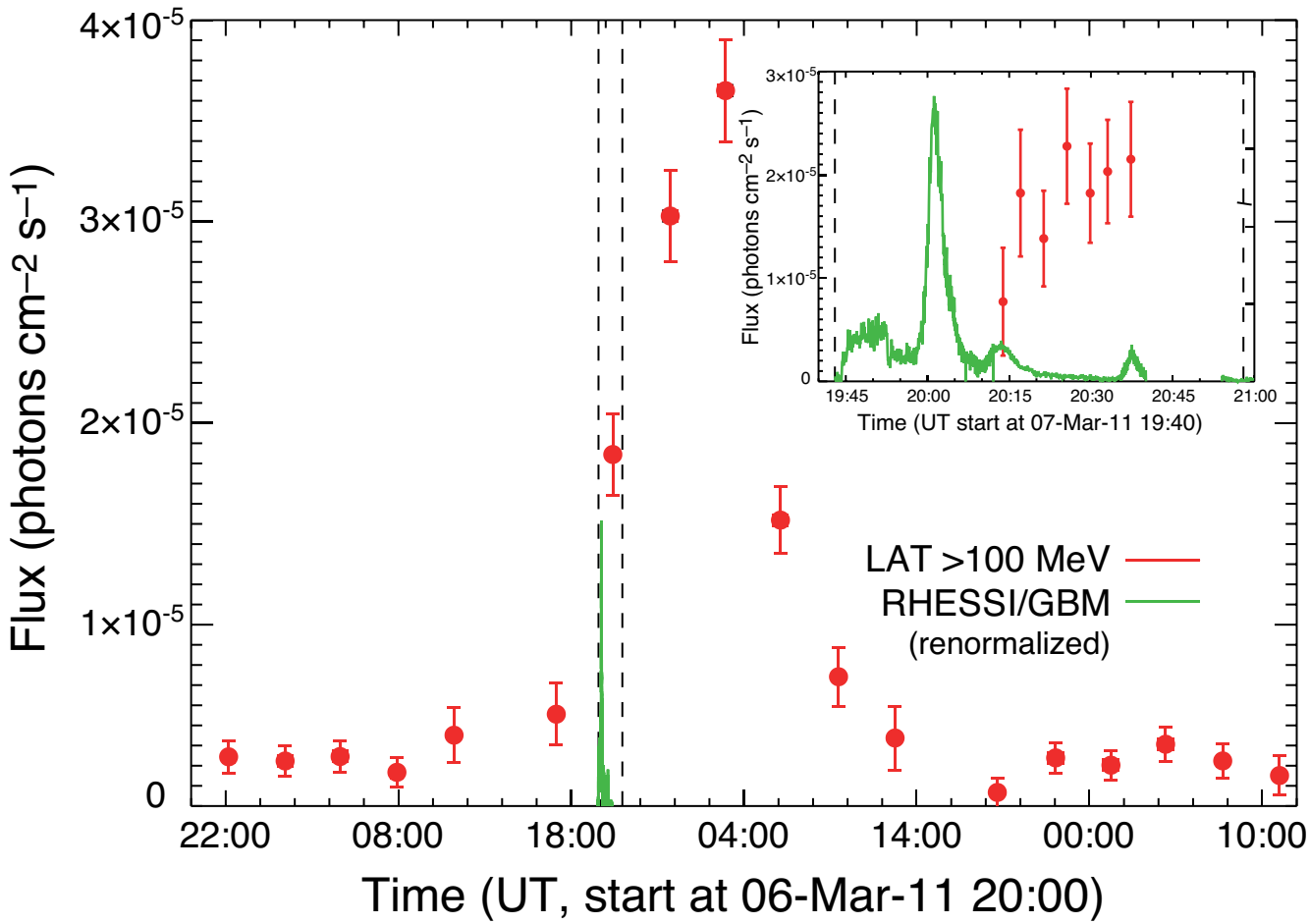
π-decay spectral shape $s_3 > 4.5$



Long-duration Events

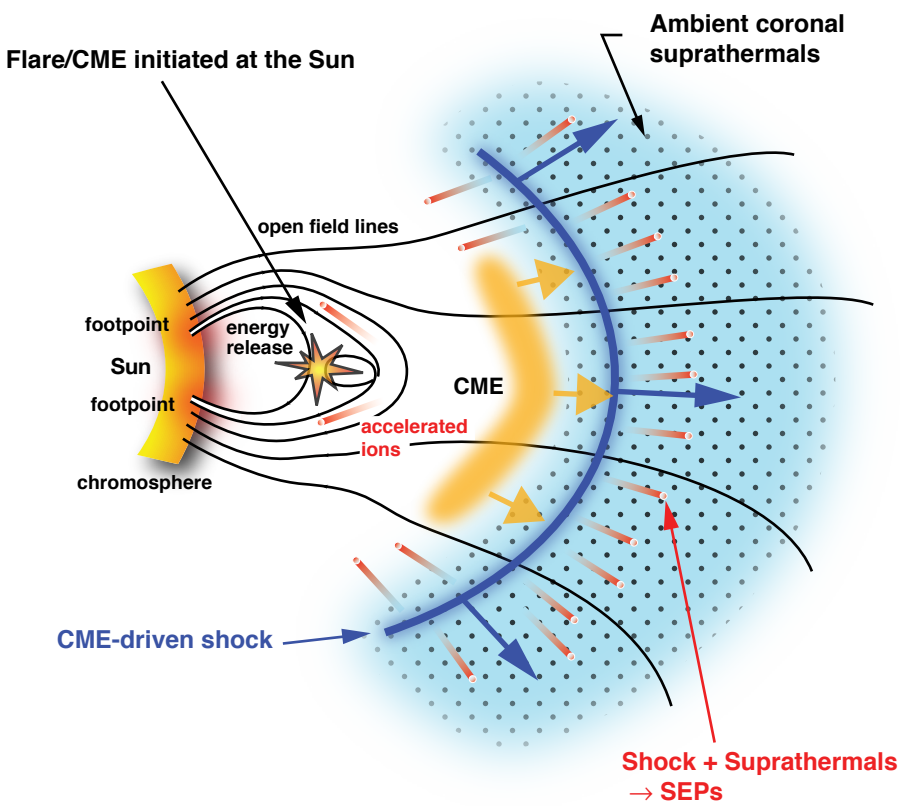
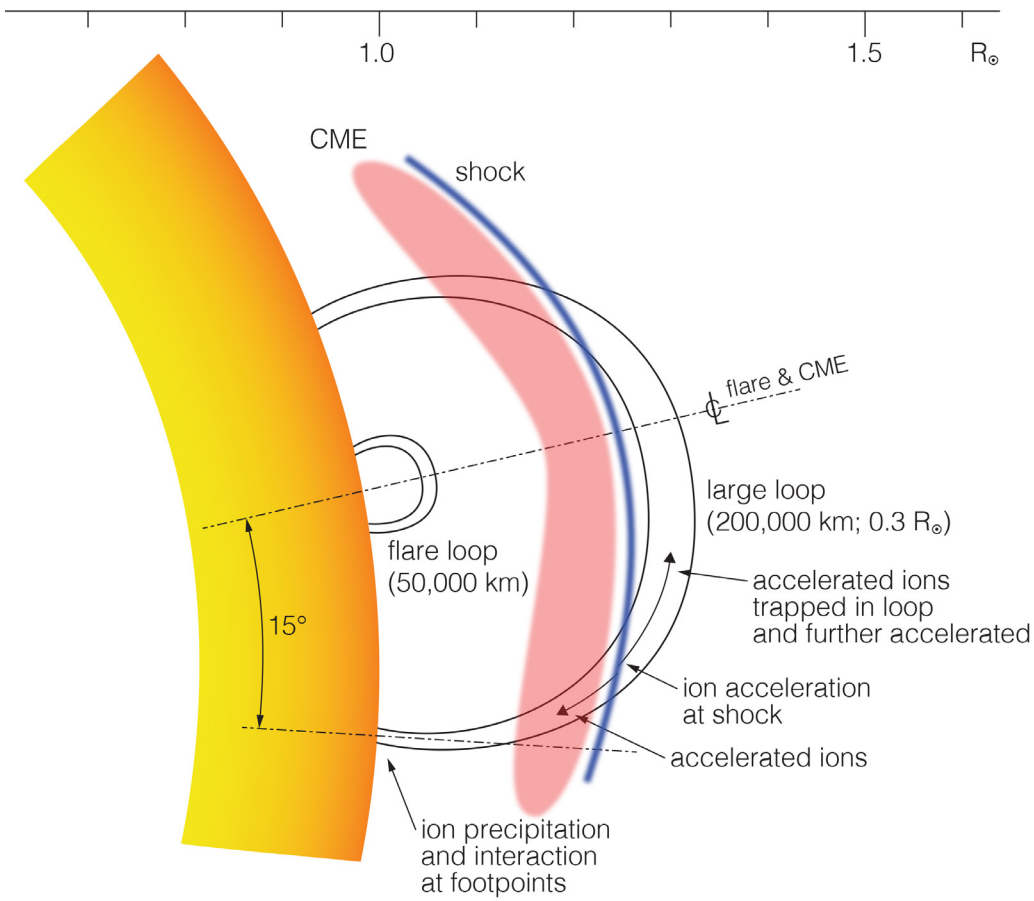
High-energy emission continues long after the impulsive phase

2011 March 7 flare
Ackermann, et al. 2014
G. Share (priv. comm.)



Source of Long-duration Emission

- continuous acceleration in a flare loop
- impulsive acceleration – trapping
- CME/shock acceleration – precipitation

2012 Mar 7 emission for 20 hr.
Ajello, et al. 2014

2013 Oct 11 over-the-limb flare
Pesce-Rollins, et al. 2015 (in prep.)