Energetic Neutral Atoms (ENAs) from solar flare(s)

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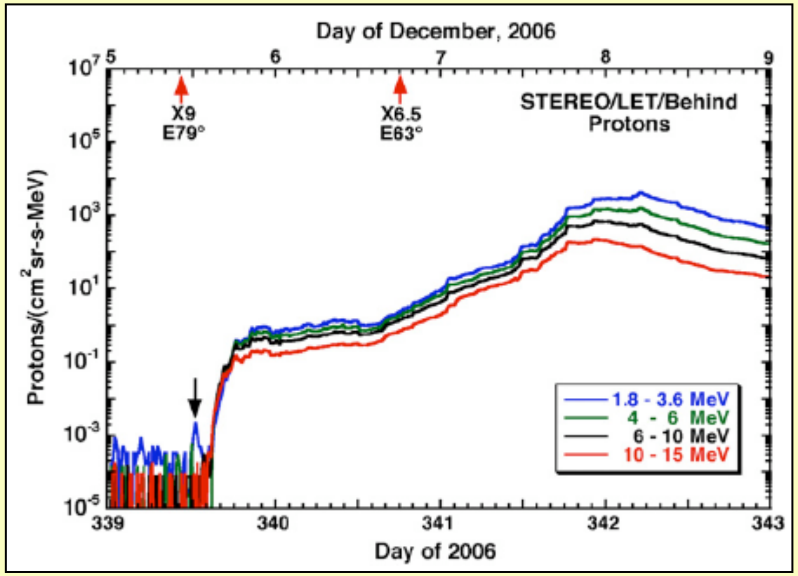
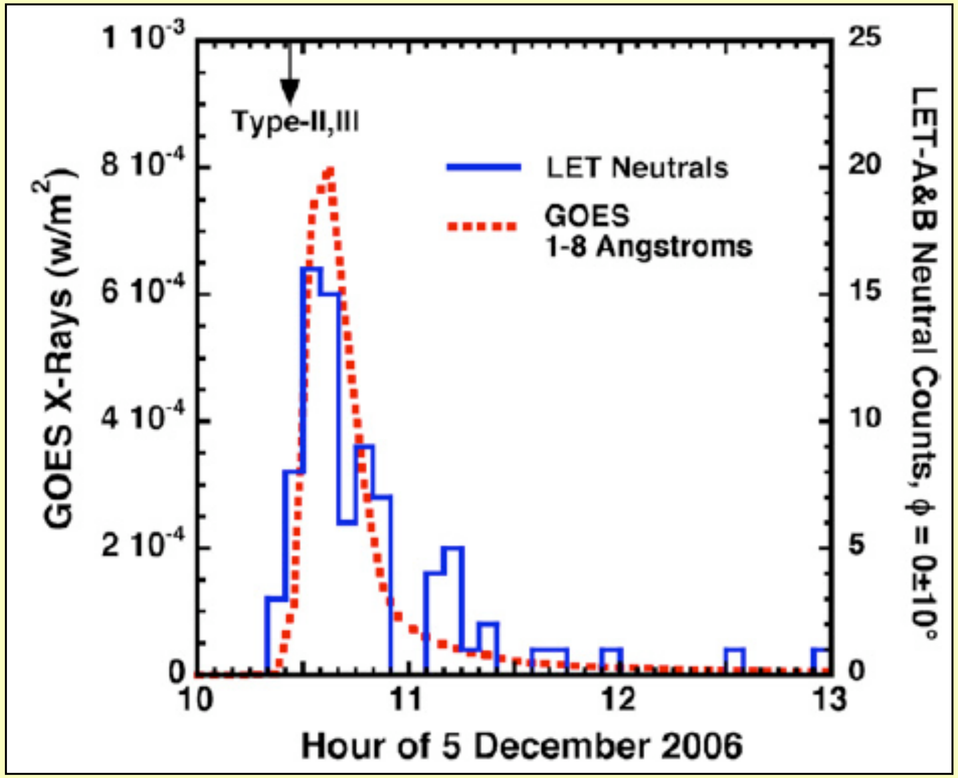
Energetic Neutral Atoms*

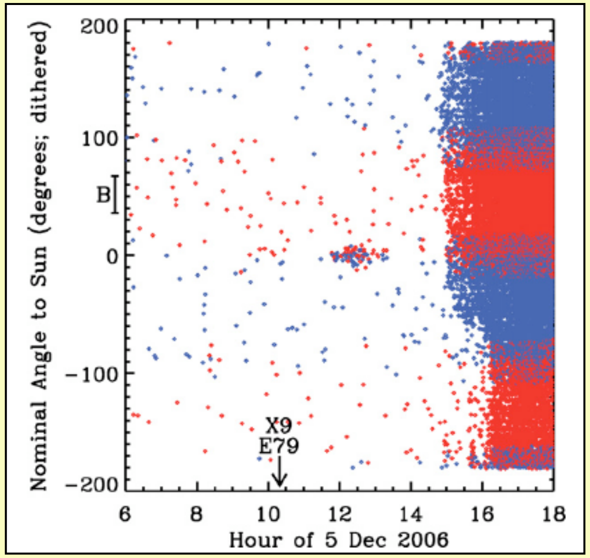
- An entirely new flare-associated “neutral particle” has appeared
- The ENAs are the first guide to the “subcosmic rays” - particles neither thermal nor detectable
- If, that is, they can be associated with the flare γ-ray sources.

* See Mewaldt et al. (ApJ 693, L11, 2009)

Mewaldt et al. Figures

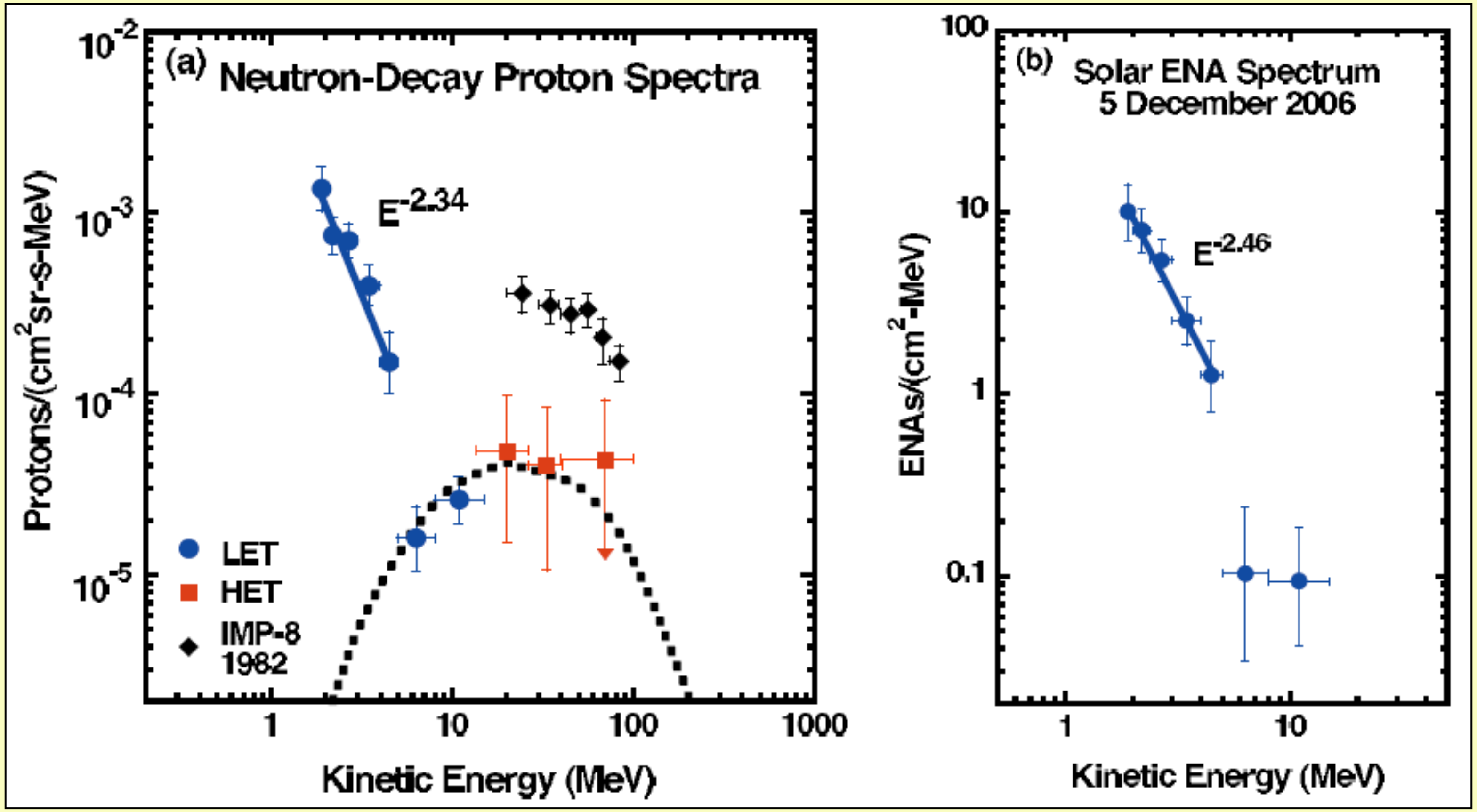






- The STEREO observations provide both spatial and temporal signatures that clearly identify the particles as hydrogen
- The injection times closely match the GOES light curve of the flare

Mewaldt et al. Figures (II)



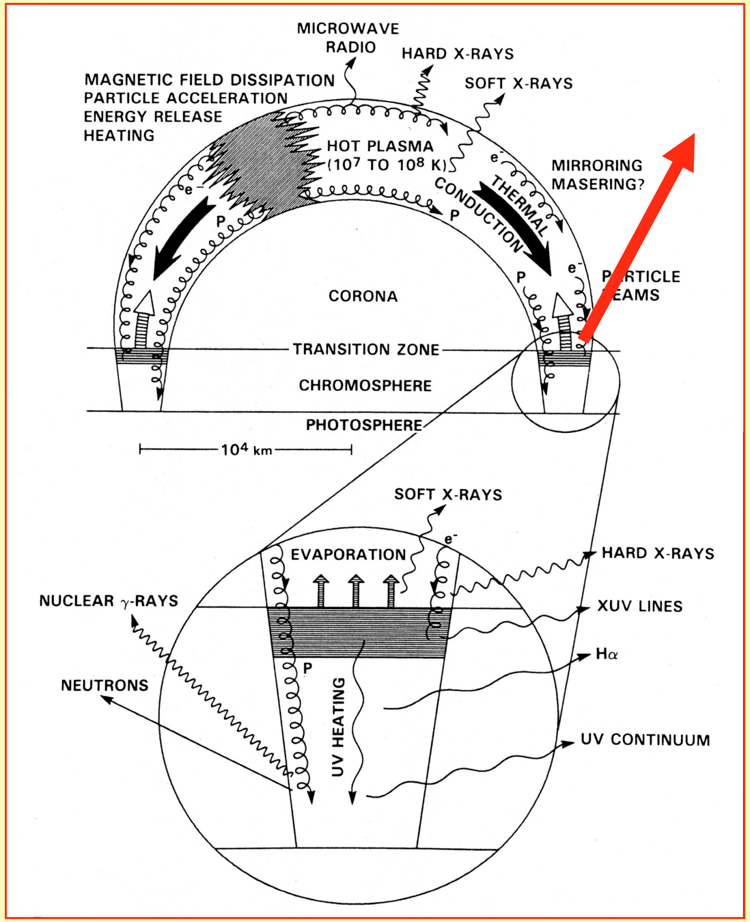
- The HET counts resemble those expected from neutron decay
- The LET spectrum appears to steepen > 5 MeV

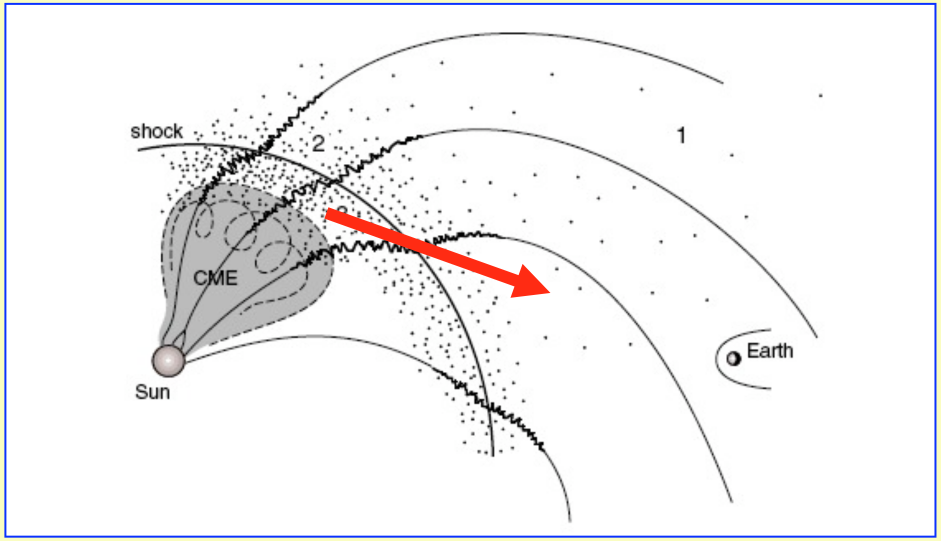
How many particles?

- Mewaldt et al. estimate a total of 1.8×10^{28} ENA particles (hydrogen atoms) assuming isotropic emission in a hemisphere
- RHESSI γ-ray observations imply a total of 1.3×10^{31} protons above 30 MeV
- Assuming a spectral index of 3.5, this implies a total of 2×10^{34} protons above 1.6 MeV

The escape efficiency of 2 MeV ENAs may be of order 10^{-6}

Whence flare ENAs?





Neutralization and re-ionization on open field lines: Mikic & Lee, 2006

Neutralization and re-ionization on closed field lines: Dennis & Schwartz, 1989

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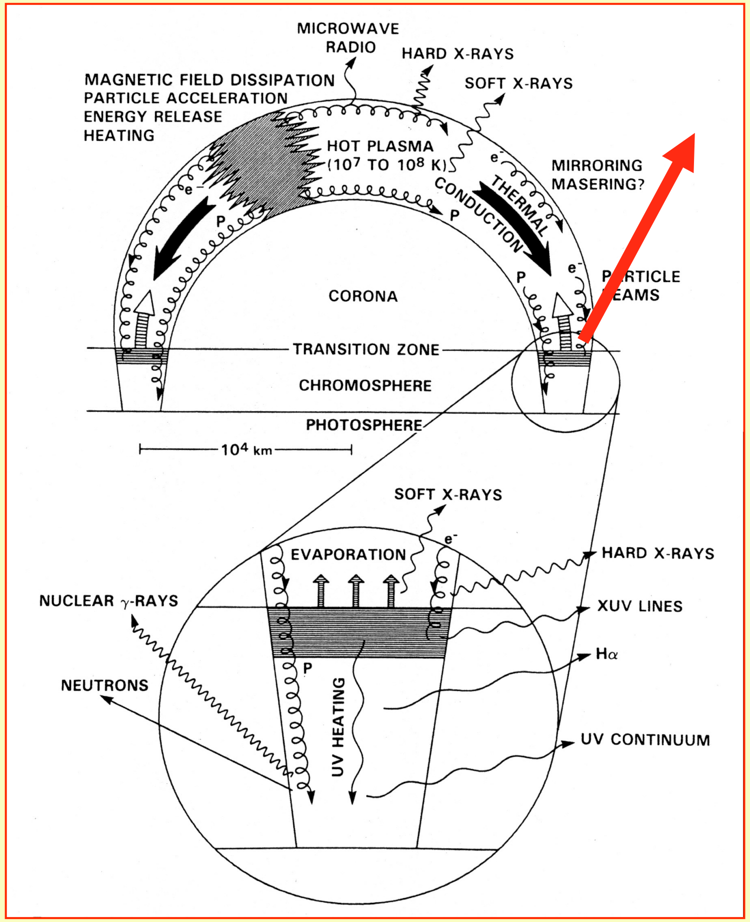

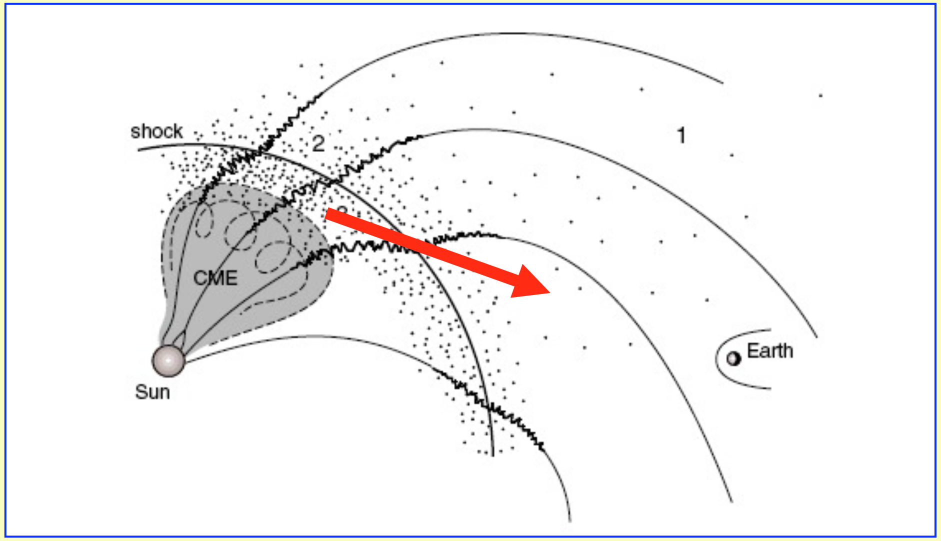

Neutralization and re-ionization on open field lines: Mikic & Lee, 2006

timing wrong

Neutralization and re-ionization on closed field lines: Dennis & Schwartz, 1989

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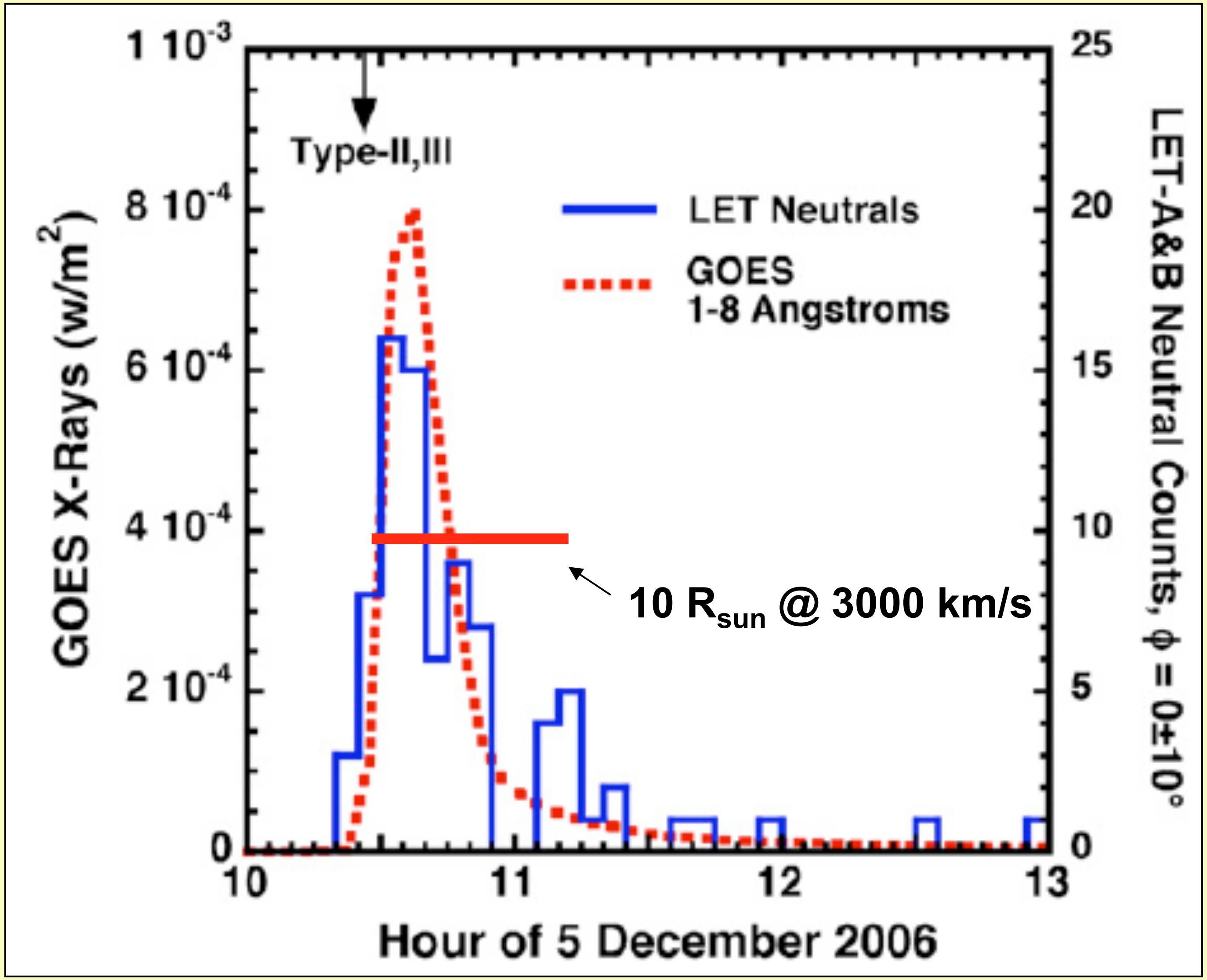
$\tau_{strip} \sim 120$

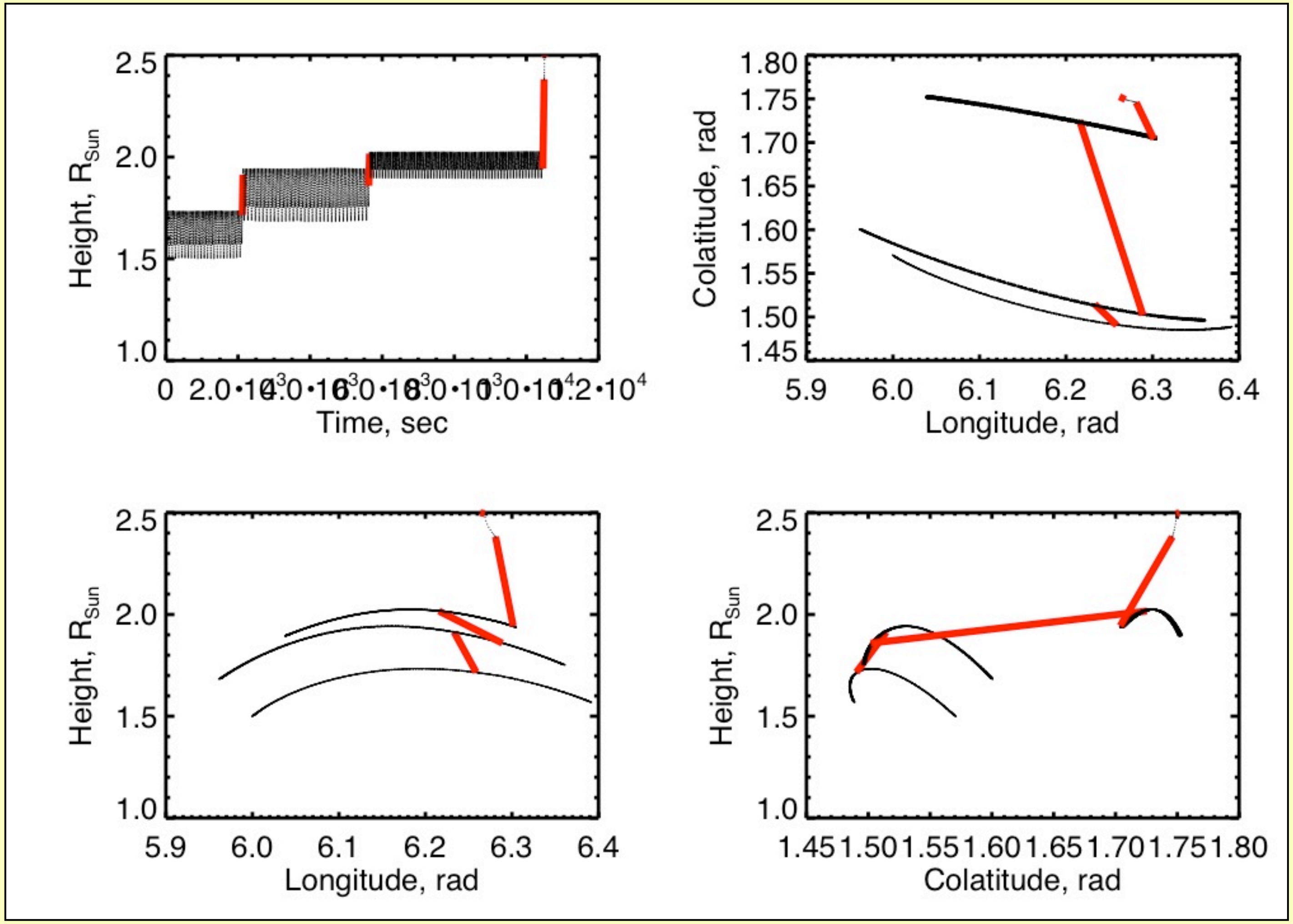
Timing wrong for CME shock?



Monte Carlo simulations

- Neutral hydrogen and protons are alternative states of the same particle. Can multiple ionizations and neutralizations allow a few flare ENAs to originate from the flare γ-ray sources in the deep corona?
- If so, do the emergent ENAs retain any information about the spectrum, source structure, or time profile?
- Everything is very complicated, so we are trying to extract answers via Monte Carlo simulations embodying enough of the physics

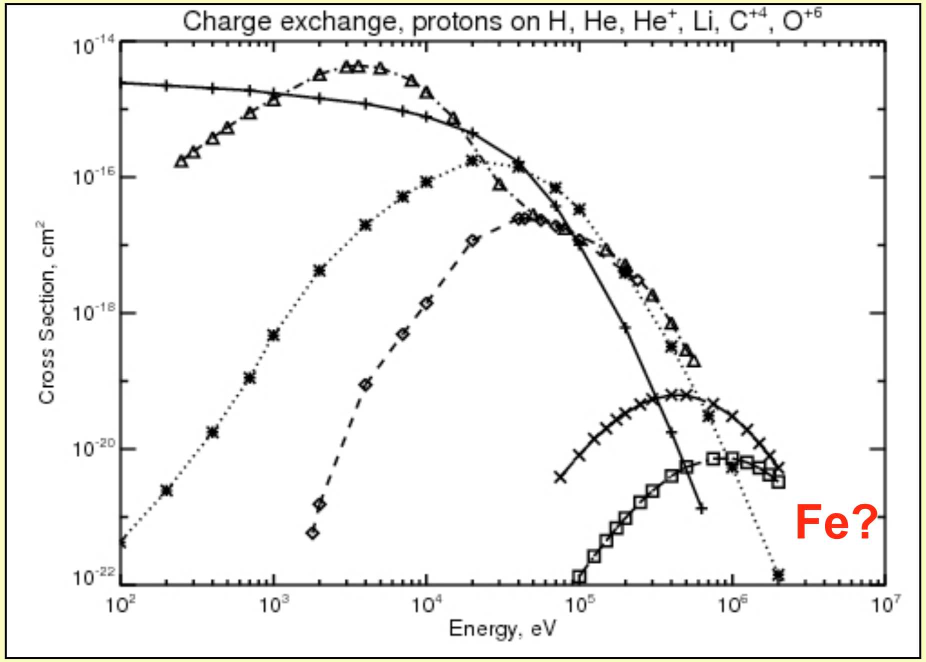
Proton injected at 1.6 R_{sun} @ 2 MeV (example)

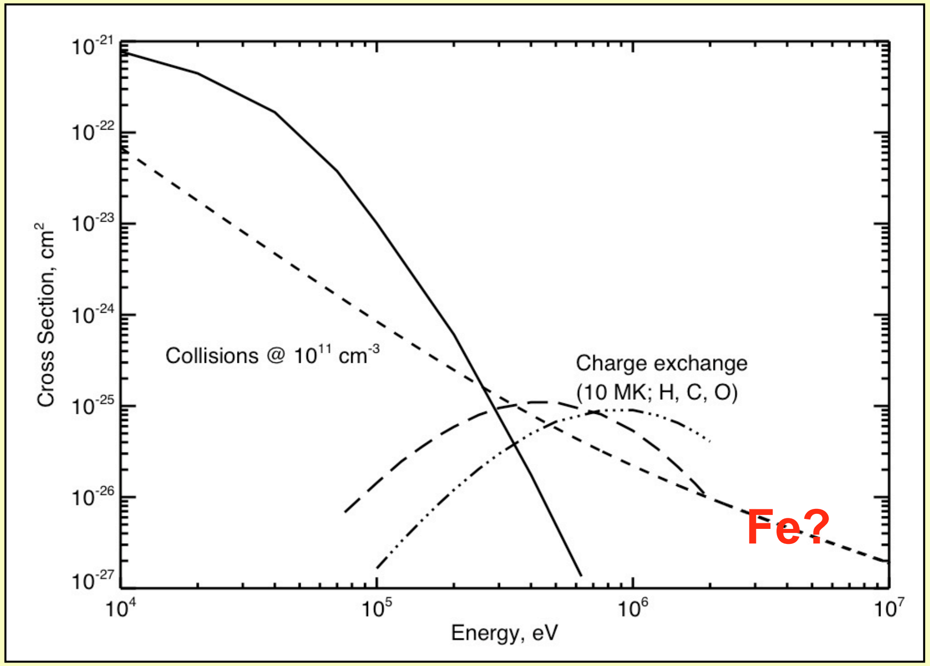


What do we want to learn from the Monte Carlo model?

- The escape efficiency as a function of injection height and other parameters
- The spectrum of the escaping ENAs, ditto
- The angular distribution of the emerging ENAs
- The spatial structure of the apparent ENA source

Some necessary physics





- Charge exchange cross-sections (H-like and He-like only)
- Charge exchange vs collisions

- Impact ionization $\sigma_i = 2.3 \times 10^{-17} E_p^{-0.897}$ cm^2 (Barghouty, 2000)

Notes on Monte Carlo model

- The calculation includes ion flight with RK4 tracing of the guiding center in a Schrijver-DeRosa PFSS model of the coronal field (Hudson et al., 2009)
- Ion dE/dx from Weaver & Westphal (2003); ion stripping from Barghouty (2000); charge-exchange on K-shell minor ions from Kuang (1992); ionization equilibrium from Mazzotta
- The plots show successive ion and neutral flights (red) for a few particles with different fates

Status of work

- We have been trying to do this simulation for about one year
- Senior research Hudson got to a certain point but could go no further
- Brilliant student Chronopoulos may succeed in getting a proper code working before he goes off to graduate school
- …

Conclusions

- The Mewaldt et al. (2009) result is one of the most important for flare high-energy physics in this century, since it opens a vast new parameter space
- Interpretation is wide open at present. Our Monte Carlo model suggests that ENA escape from the flare γ-ray sources may be feasible, but it is preliminary work
- If the ENAs come from CME shock acceleration, we will need to revise our views of where this is happening