Coronal hard X-rays, CMEless X-class flares, and fast atoms

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Overview

- Coronal hard X-ray sources[**]
- Global waves (CME shocks[§], EIT waves, Moreton waves, type II bursts)
- CMEless flares[*]
- Energetic neutral atoms (ENAs[†]) and their implications

[**]Krucker et al (A&A Rev. 16, 155, 2008)

[§]Ontiveros & Vourlidas (ApJ 693, 237, 2009)

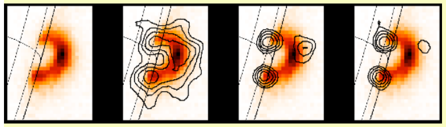
[*]Gopalswamy et al. (Proc. IAU 257, 283, 2009)

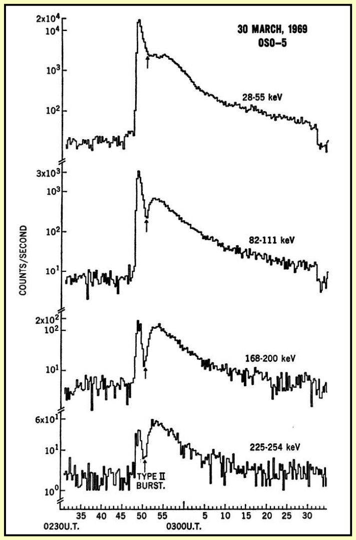
[†]Mewaldt et al. (ApJ 693, L11, 2009)

Coronal Hard X-ray Sources

- There are lots of meter-wave radio source types (I, II, III, IV, V, …), so why not hard X-rays?
- They're there: Frost & Dennis (1971); Hudson (1978); Krucker et al. (2008)
- The remarkable Masuda source (Masuda et al. 1994, 2000; Krucker et al. 2008) needs special discussion
- An identification with the CME process seems to be developing

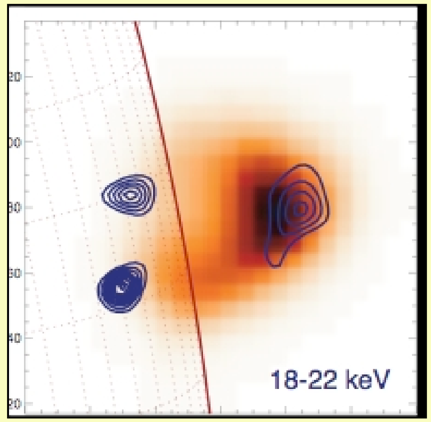
Coronal Hard X-rays: Krucker et al. 2008

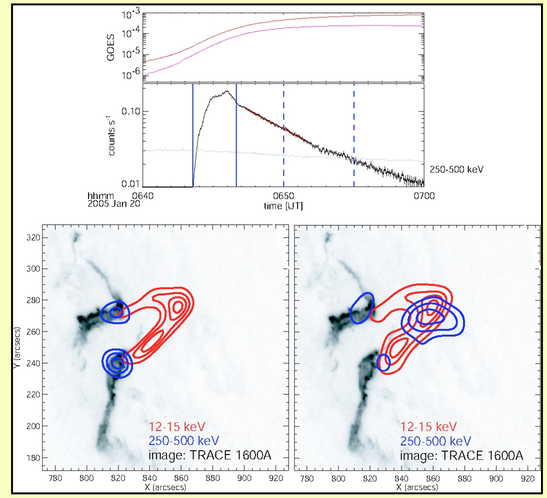


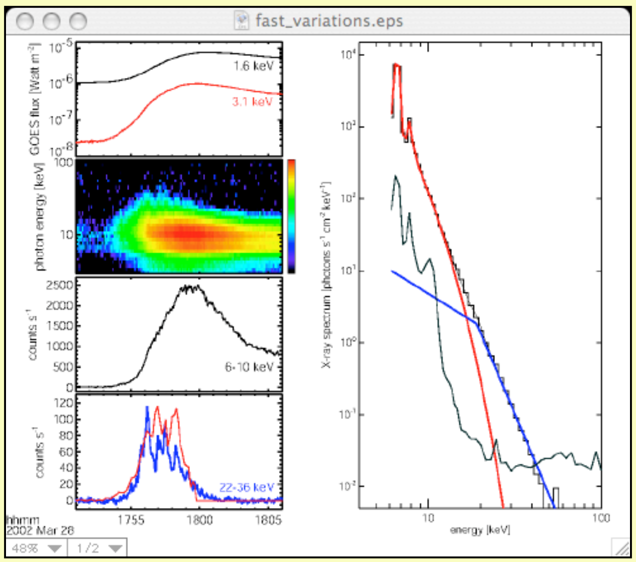


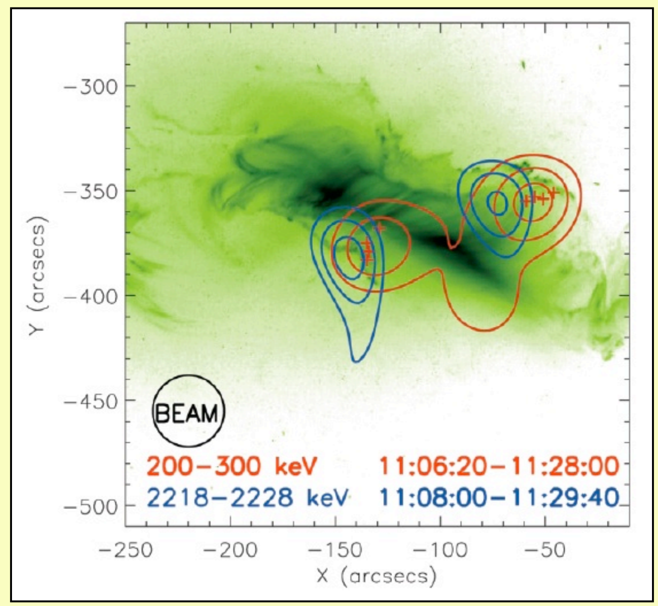
Old

New



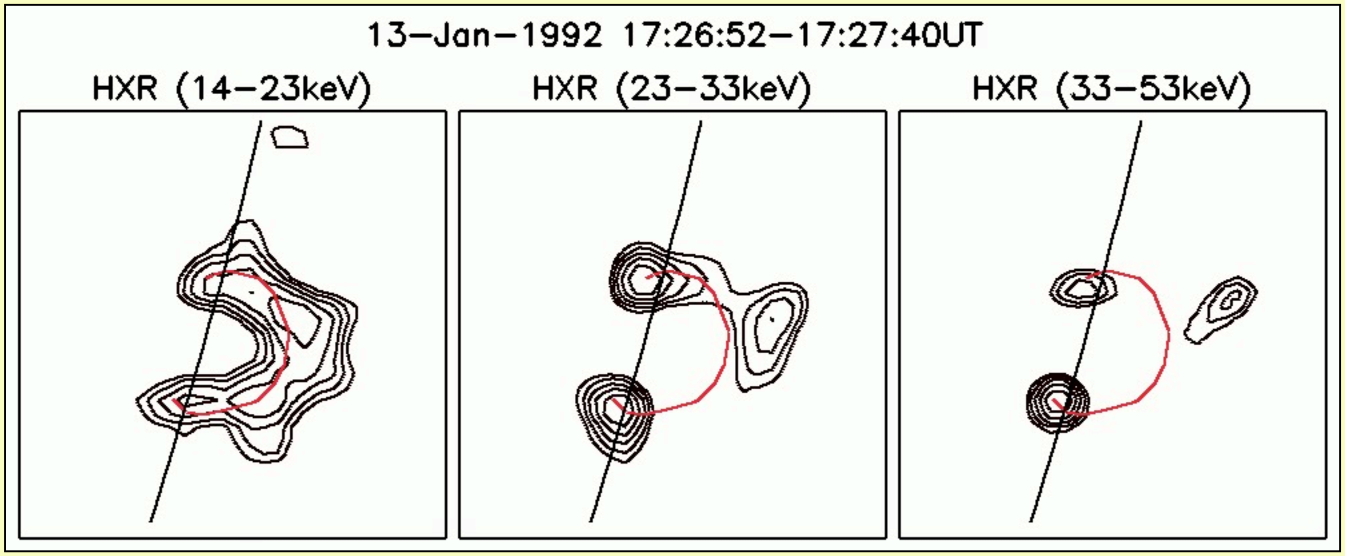




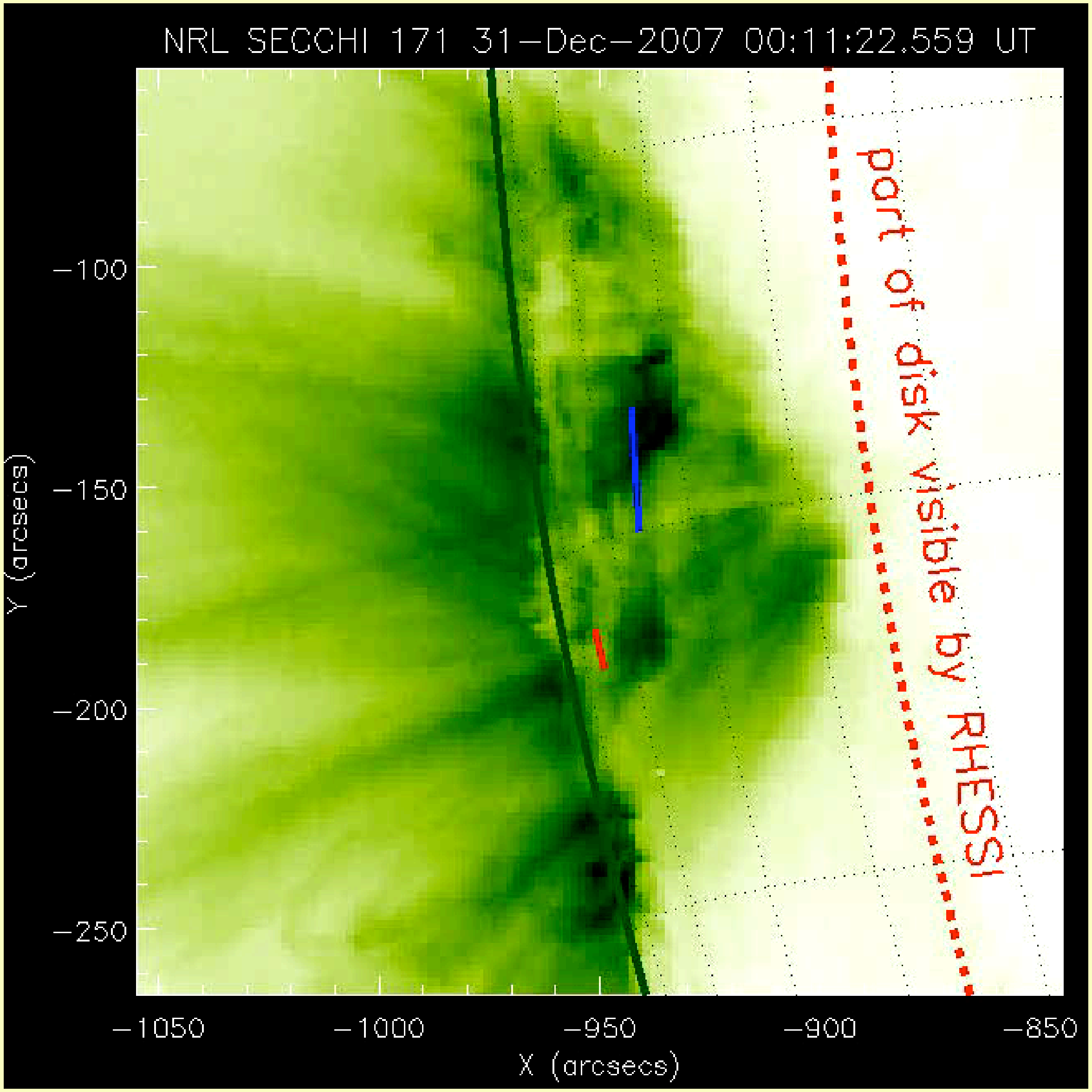


Impulsive-phase Coronal HXR

- Masuda source - unusual but well-known example
- Dec. 31 2005 - maybe RHESSI's best counterpart; Krucker slides follow
- No time to discuss Sui-Holman or implosions



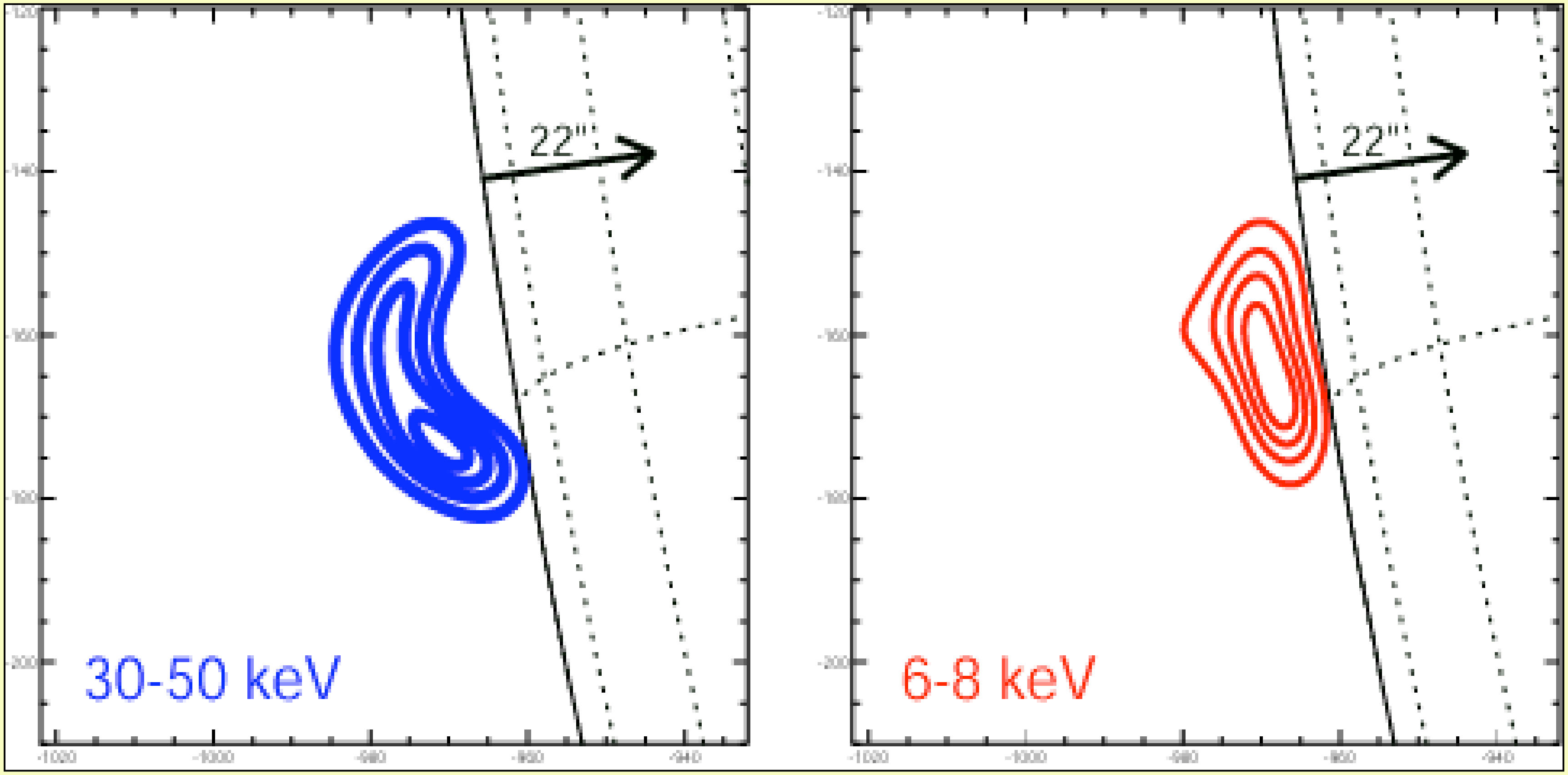
STEREO/RHESSI 31 Dec. 2007



- Complex flare ribbons
- Ribbons (red and blue lines) on disk for Behind.
- The flare ribbons are NOT visible in RHESSI images**!**

RHESSI hard X-ray imaging

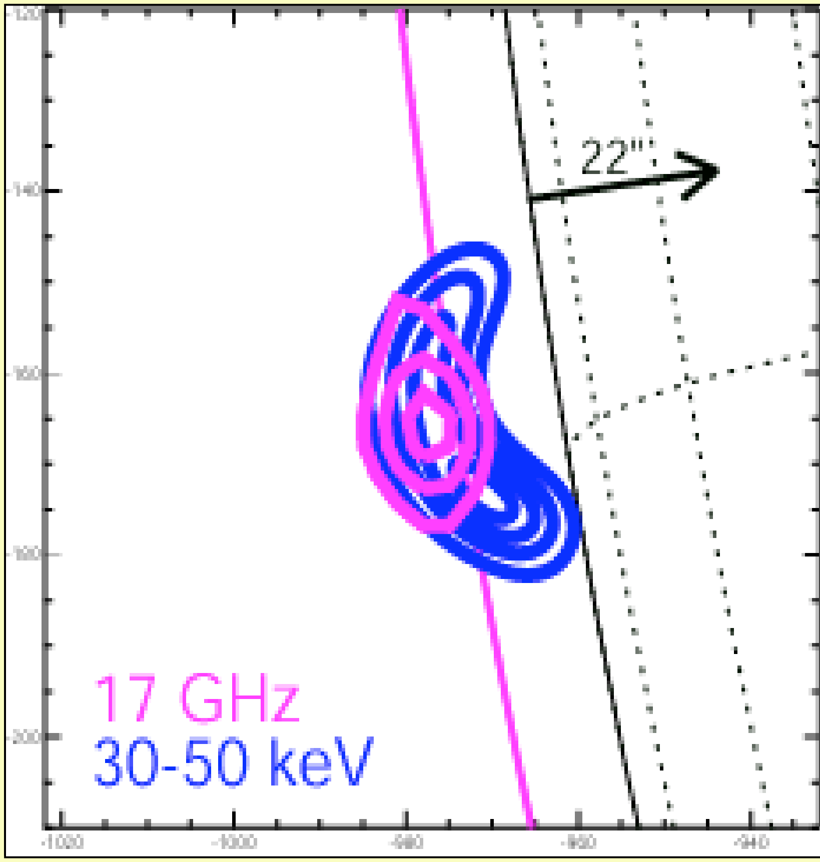
HXR peak (impulsive phase) SXR peak

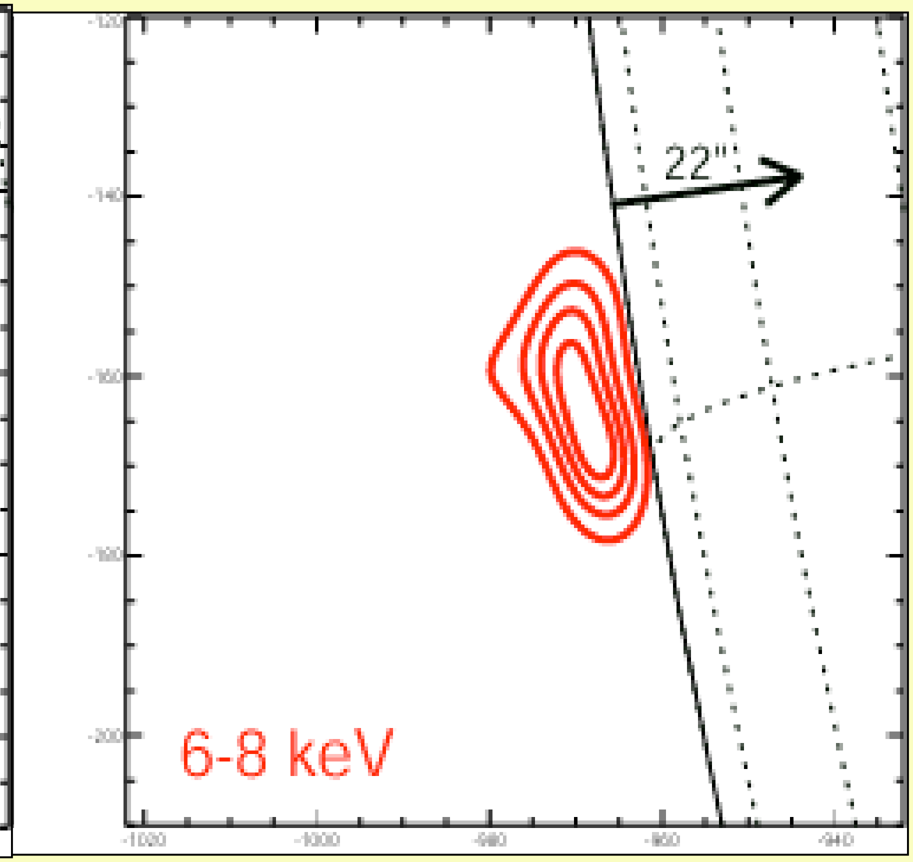


The HXR source is above the SXR loops! Masuda-like!

Nobeyama microwave imaging

HXR peak (impulsive phase) SXR peak





The microwave limb is higher; 17 GHz co-spatial with HXR

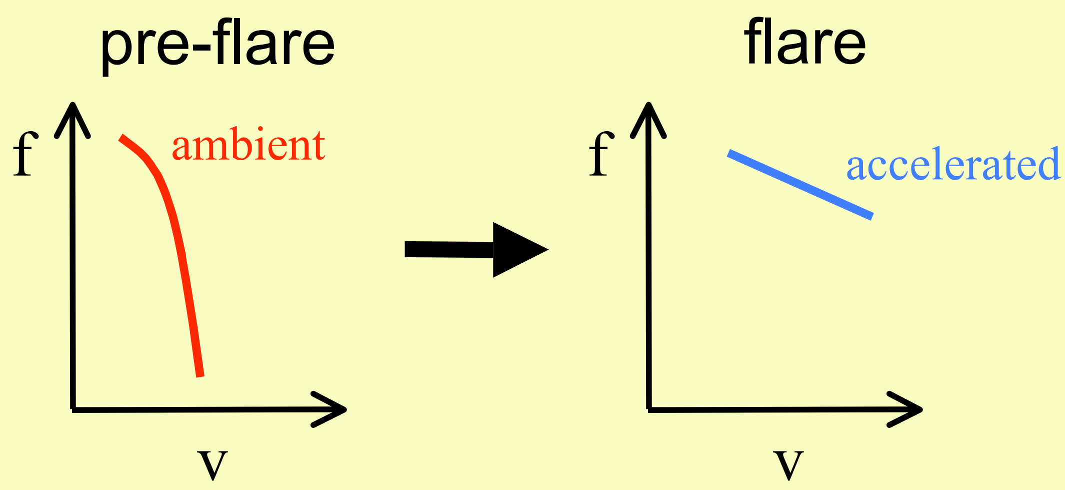
$N_{HXR} \gtrsim N_{thermal}$ means

- Almost all the energy is in accelerated electrons
- Collisional heating is very fast (~ 5 keV/s at 10^9 cm^{-3}; see McKenzie et al. 1973)

→ ALL electrons must be accelerated

→ The above-the-loop-top source is the acceleration region

→ Plasma beta in above-the-loop-top source ~ 1

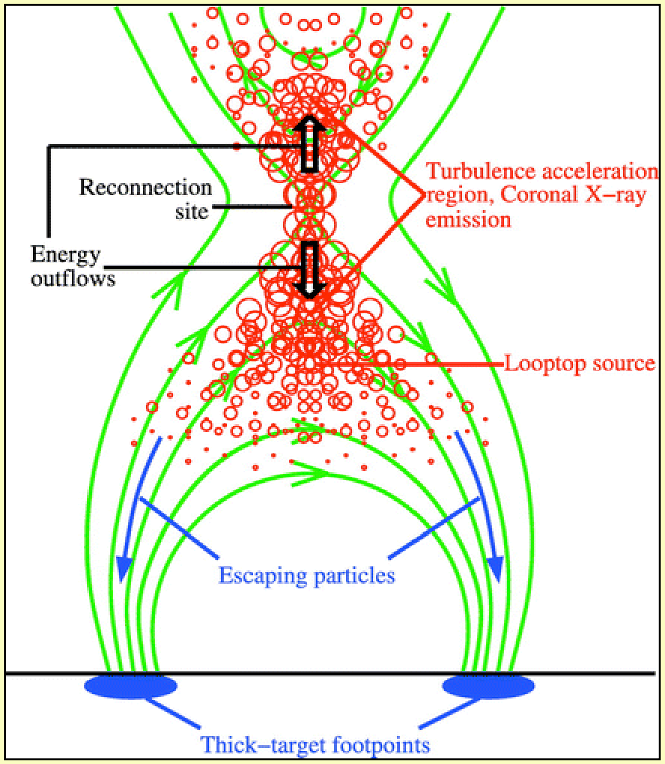


McKenzie's rule* for thin-target bremsstrahlung:

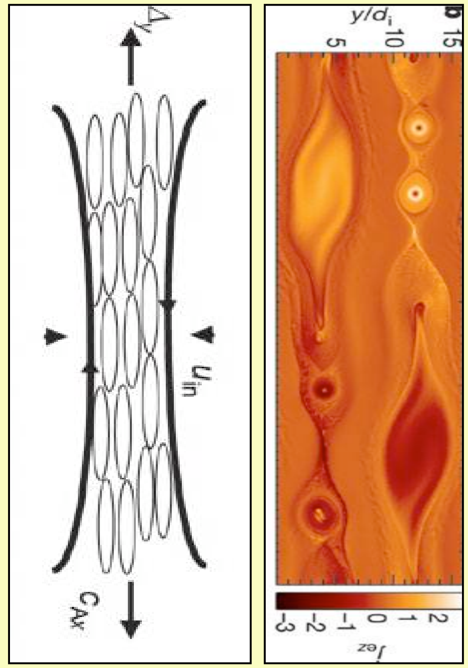
$$dT_e/dt = 5/n_9 \text{ keV/s}$$

*need to check: Solar Phys. 28, 175, 1973

Reconnection?



Turbulence (e.g.
Liu et al. 2007)



Contracting islands
(Drake et al. 2006)

Drake et al. :

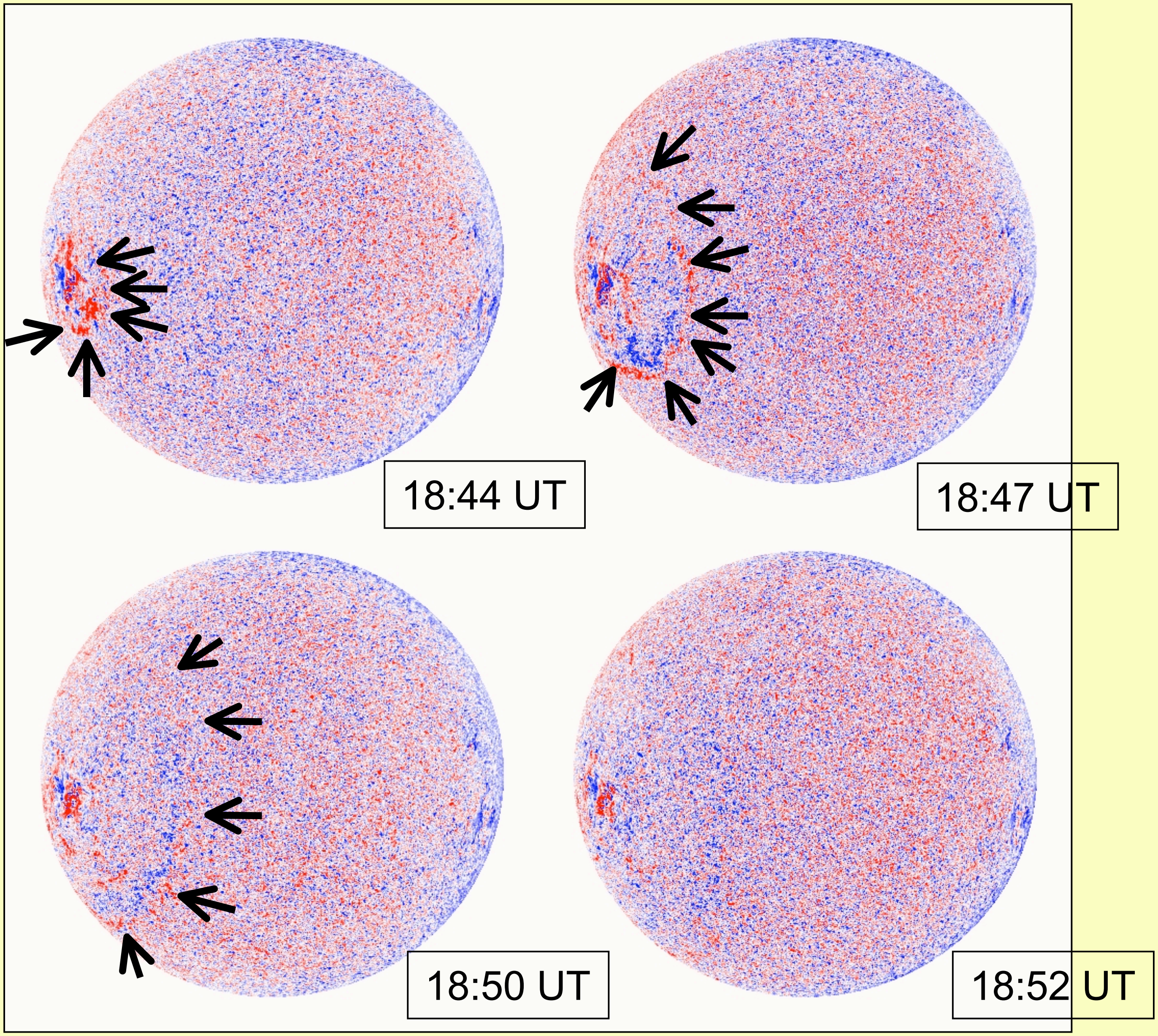
- **extended acc. region**
- **all electrons are acc.**
- **power law distribution**
- **β~1 stops contraction**
- **β~1 stops acceleration**

The time evolution is given by acceleration and escape

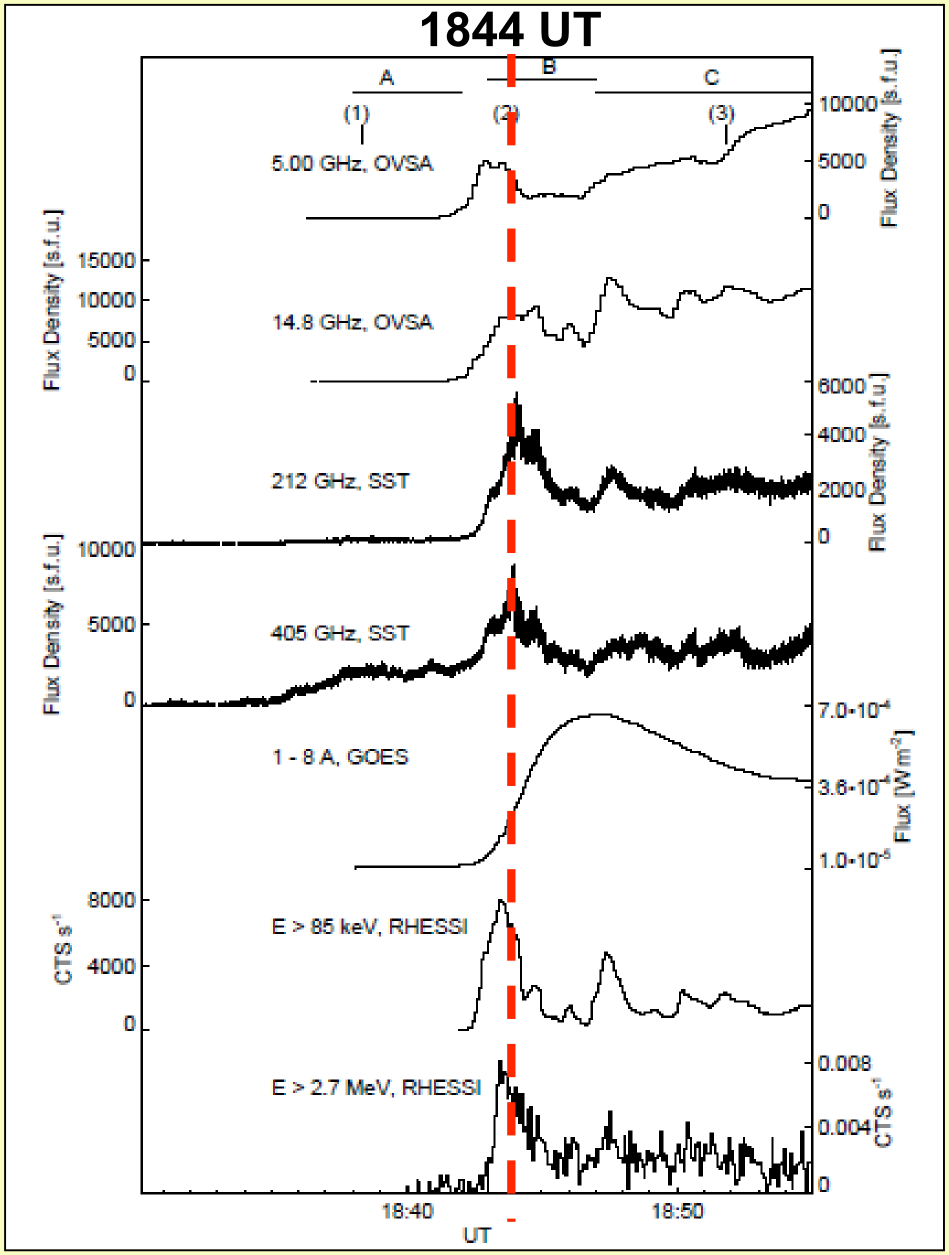
Global Waves

- SSC* shock; Type II burst; Moreton wave; EIT wave
- Major controversy on the interpretation of the metric type II and Moreton wave: is it a blast wave, distinct from the CME?
- Gopalswamy et al (2009) list of CMEless X-class flares (cf. de La Beaujardière et al. 1994).

*Storm Sudden Commencement, a term from geomagnetism



Subtracted Doppler Images (R-B Wing) Showing Down-Up Pattern



Kaufmann et al. (2008)

The wave appears near the peak of the impulsive phase of the high-energy flare …

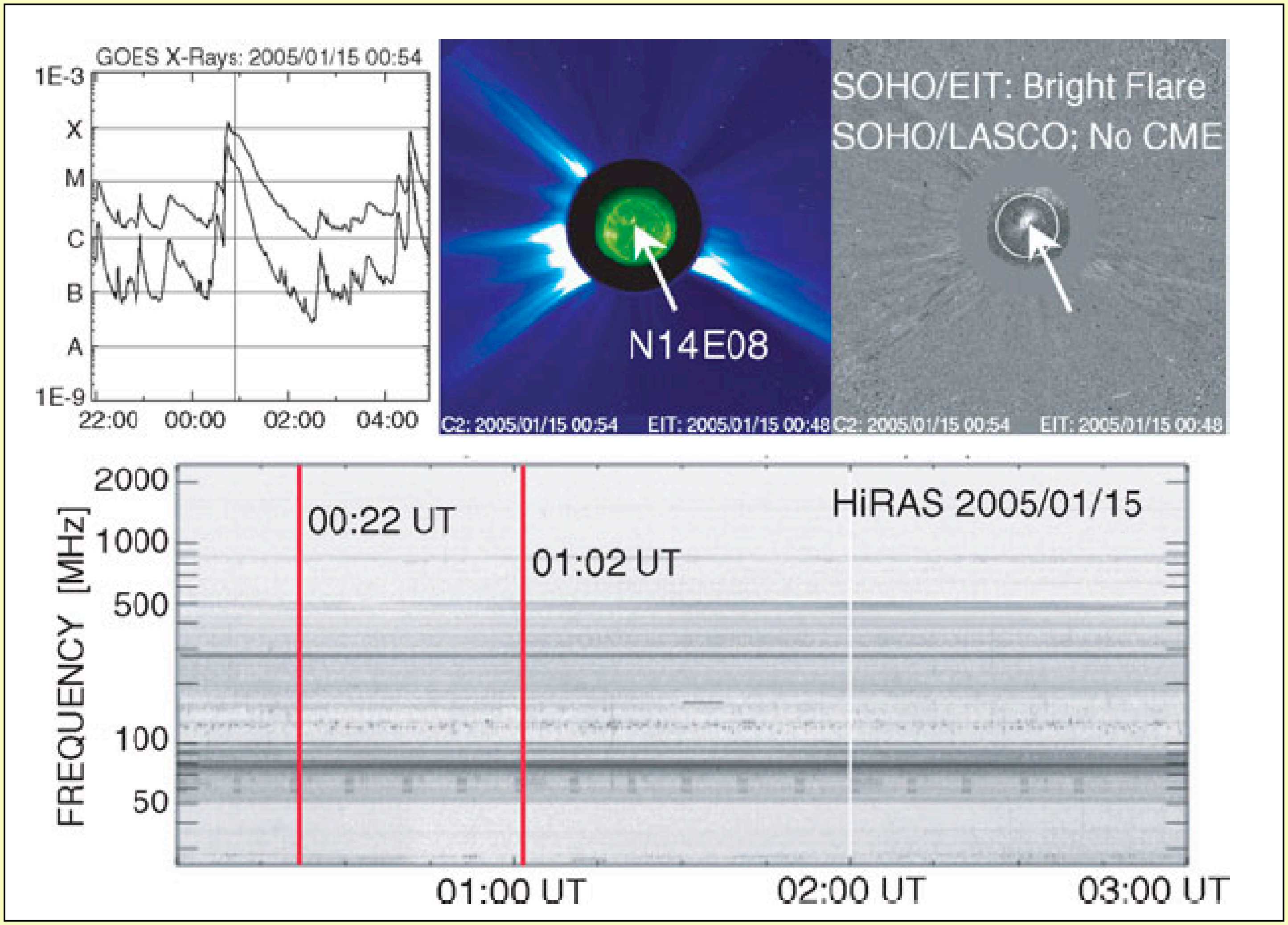
CMEless X-class flare list (13/93)

Table 1. X-class flares without CMEs during solar cycle 23 and their properties

#	Flare Start	Peak	Dur	Imp	Location	AR #	Hα	III	μfpk/flux
1	2000/06/06 13:30	13:39	16	X1.1	N18E12	9026[d]	N	N	2.7/560
2	2000/09/30 23:13	23:21	8	X1.2[c]	N07W90	9169	N	N	15.4/2800
3	2001/04/02 10:04	10:14	16	X1.4	N17W60	9393	1B[e]	Y	15.4/1200
4	2001/06/23 04:02	04:08	9	X1.2[c]	N10E23	9511	1B	N	5/100
5[a]	2001/11/25 09:45	09:51	9	X1.1[c]	S16W69	9704[d]	N	N	15.4/130
6	2002/10/31 16:47	16:52	8	X1.2[c]	N29W90	0162	N	N	8.8/3300
7[b]	2004/02/26 01:50	02:03	20	X1.1[c]	N14W15	0564	2N[e]	N	15.4/830
8	2004/07/15 18:15	18:24	13	X1.6	S11E45	0649	N	N	8.8/530
9	2004/07/16 01:43	02:06	29	X1.3	S11E41	0649	N	N	15.4/1900
10	2004/07/16 10:32	10:41	14	X1.1	S10E36	0649	1F[e]	Y	15.4/1200
11	2004/07/17 07:51	07:57	8	X1.0	S11E24	0649	3B[e]	N	5/820
12	2005/01/15 00:22	00:43	40	X1.2	N14E08	0720	1F	N	15.4/3000
13[a]	2005/09/15 08:30	08:38	16	X1.1	S12W14	0808	2N	N	15.4/4100

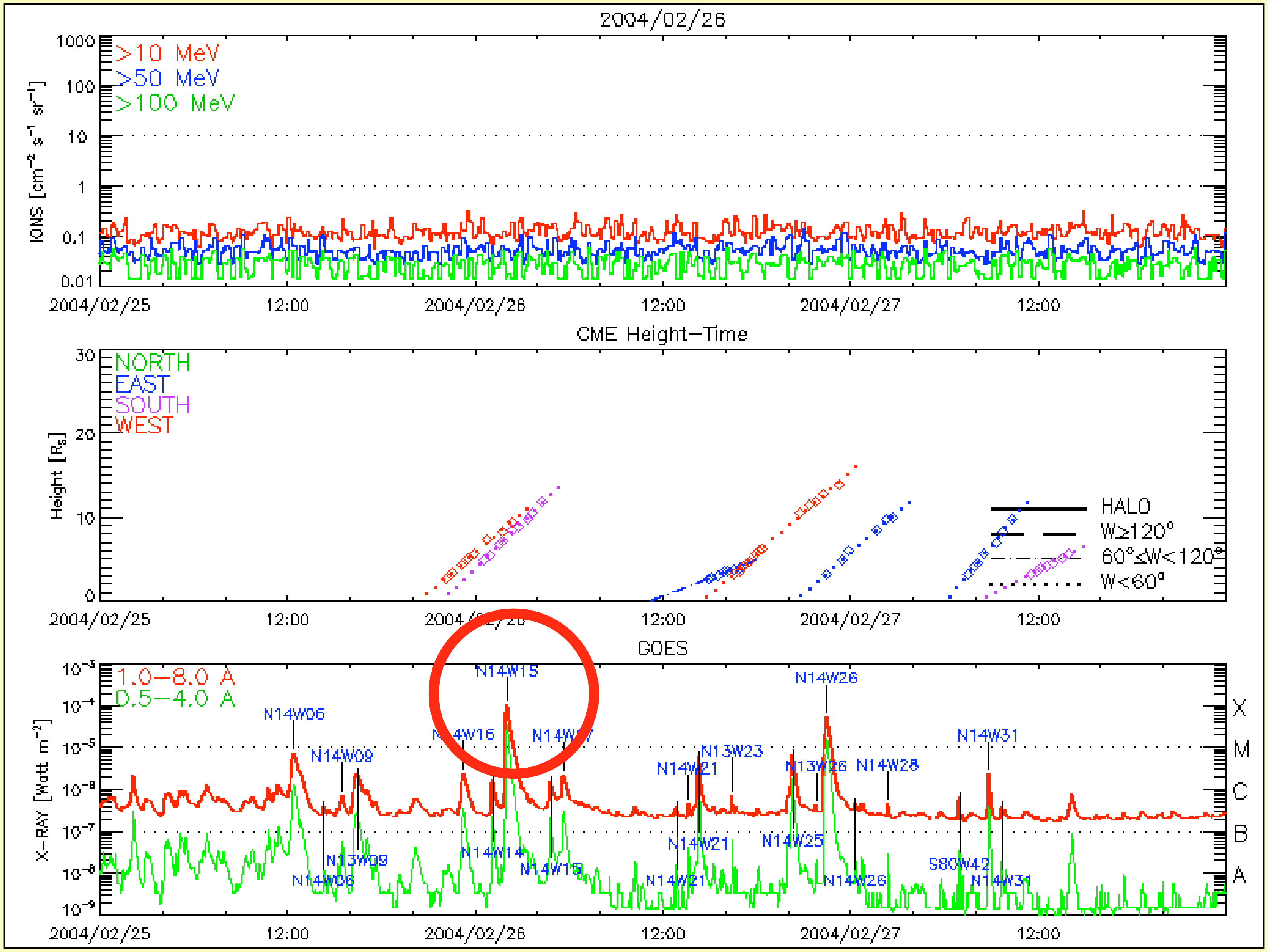
Gopalswamy et al. 2009

A CMEless X-class flare



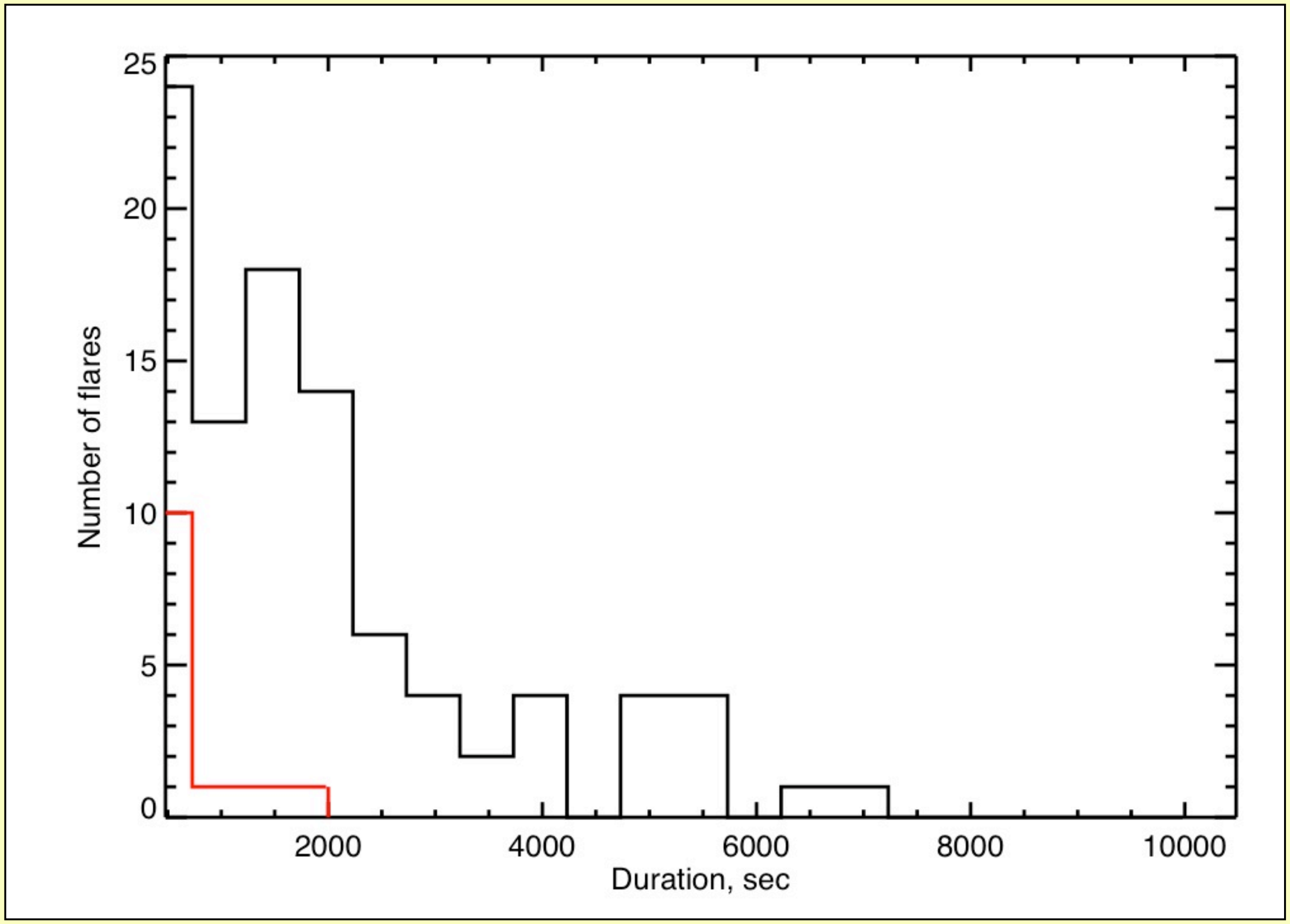
Gopalswamy et al. 2009

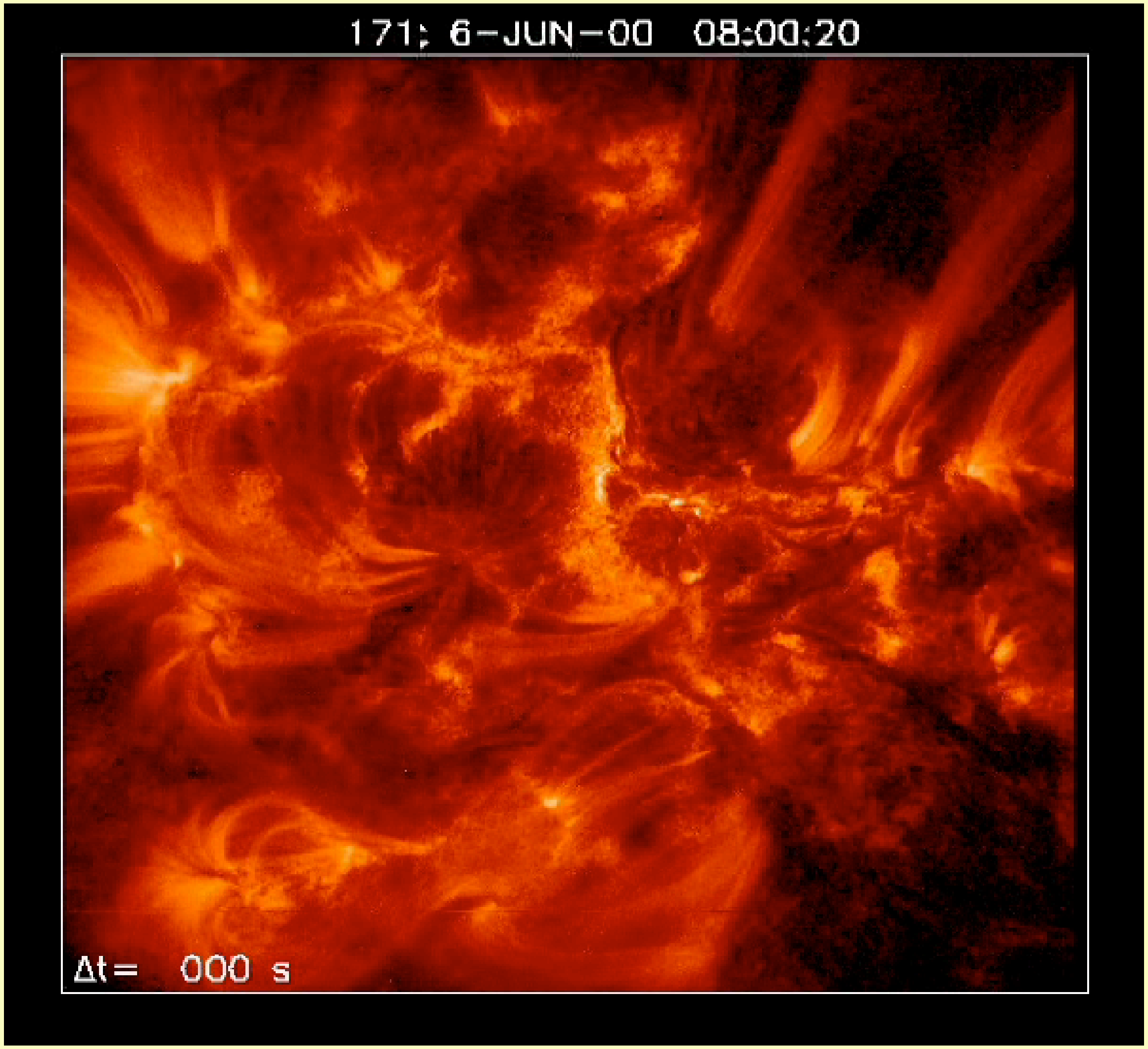
Another CMEless X-class flare



CUA LASCO CME catalog

CMEless GOES durations





Movie courtesy of Ignacio Ugarte-Urra
CMEless flare at 13:30-13:39 (peak)

CMEless flares seen in X-radiation

- The hard X-ray spectral evolution is entirely “soft-hard-soft” rather than “soft-hard-harder”
- The soft X-ray events are not “long decay” LDE events
- There are minimal ramp-up precursor soft X-ray patterns

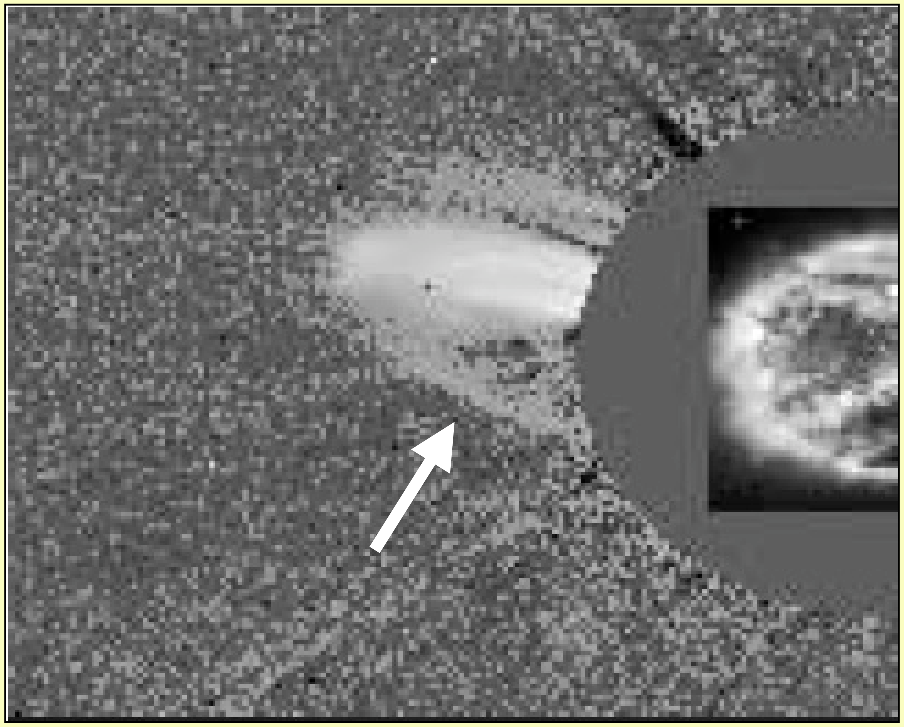
LASCO shock signatures

Table 1
All High-Speed CMEs ($V > 1500$ km s^{-1}) Between 1997 and 1999

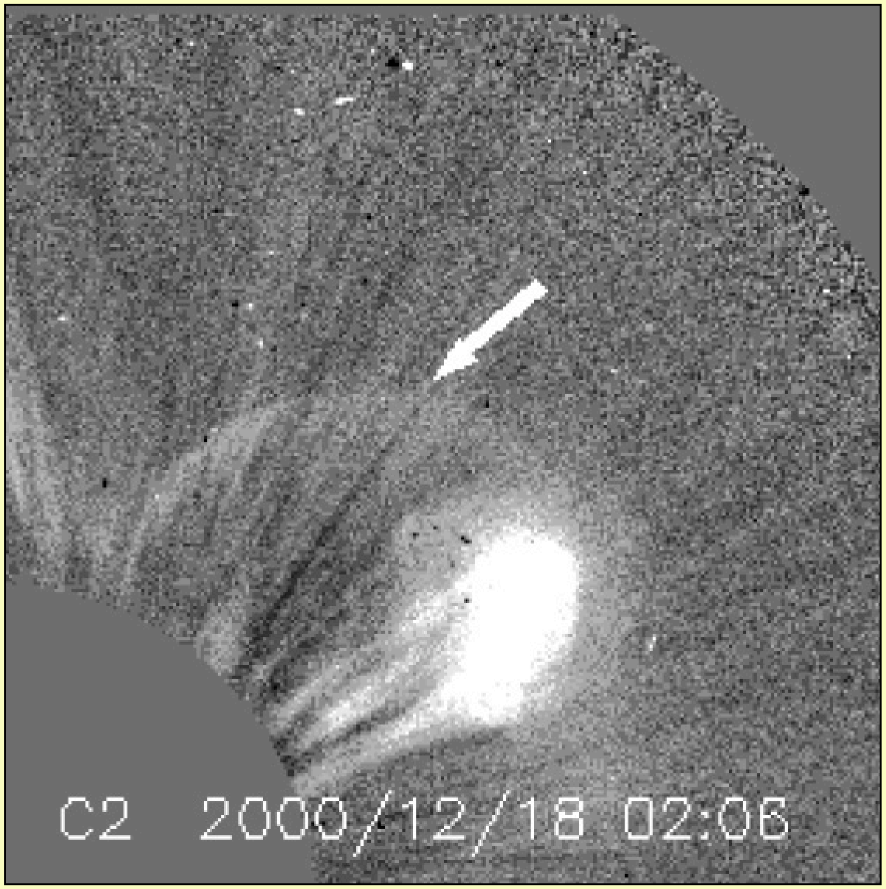
Event	CME Date	First Appearance (C2 UT)	Linear Speed (km s^{-1})	AW (deg)	P.A. (deg)	Type II (Dm)
1	1997 Nov 6	12:10:00	1556	360	262	Yes
2	1998 Mar 31	6:12:00	1992	360	177	No
3	1998 Apr 20	10:07:00	1863	165	278	Yes
4	1998 Apr 23	5:27:00	1618	360	116	Yes
5	1998 May 9	3:35:58	2331	178	262	Yes
6	1998 Jun 4	2:04:00	1802	360	314	No
7	1998 Nov 24	2:30:00	1798	360	226	No
8	1998 Nov 26	6:18:05	1505	360	198	No
9	1998 Dec 18	18:21:00	1749	360	36	Yes
10	1999 May 3	6:06:00	1584	360	88	Yes
11	1999 May 27	11:06:00	1691	360	341	Yes
12	1999 Jun 1	19:37:00	1772	360	359	Yes
13	1999 Jun 4	7:26:54	2230	150	289	Yes
14	1999 Jun 11	11:26:00	1569	181	38	Yes
15	1999 Sep 11	21:54:00	1680	120	13	No

Ontiveros & Vourlidas. 2009

Examples from Vourlidas et al. 2003



1999 April 2



2000 Dec. 18

Conclusions

- The wave signatures are especially prominent in the flanks of the CME
- The wave signatures don't look like the cartoons
- The CME phenomenon is probably central to the large-scale coronal nonthermal effects
- CMEless flares have clearly distinguishable hard X-ray properties
- CMEless flares have an upper cutoff in energy

Something new has been learned

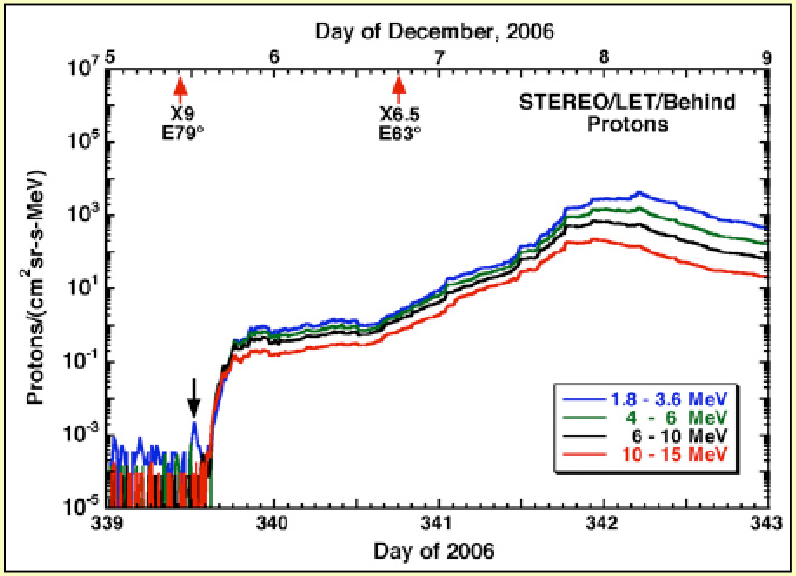
- The classical Uchida theory for type II / Moreton wave excitation is a flare-excited blast wave in the MHD fast mode
- Powerful flares without waves contradict this picture; the Gopalswamy et al. sample is convincing
- The blast waves - which must occur - must be weak
- The flanks of driven waves have properties resembling those of blast waves

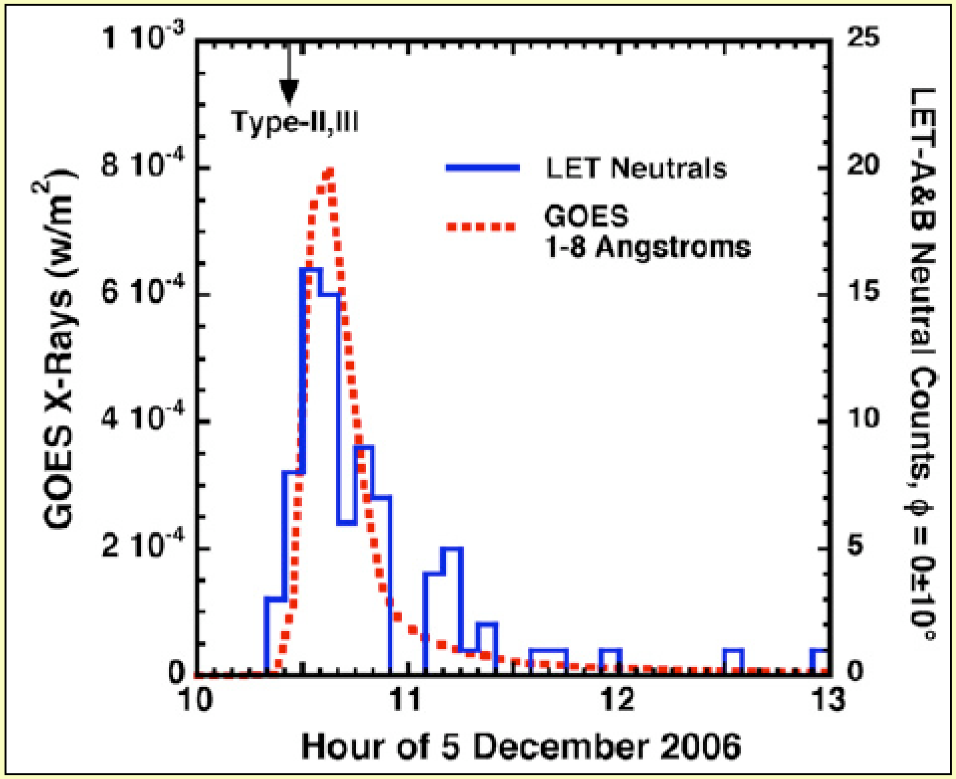
Energetic Neutral Atoms*

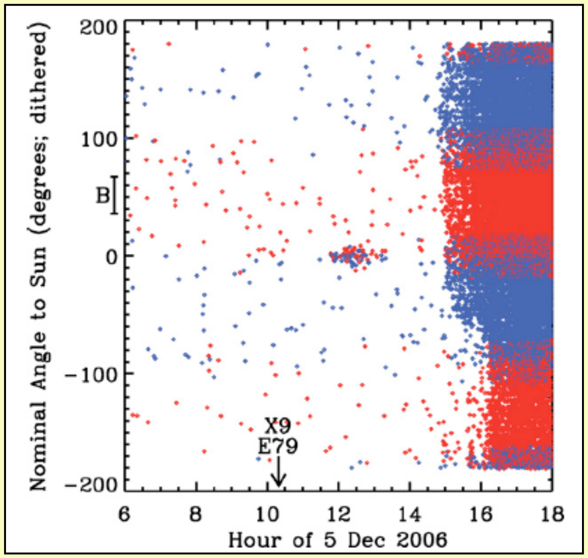
- An entirely new flare-associated "neutral particle" has appeared on the scene
- The ENAs are the first guide to the "subcosmic rays" - particles neither thermal nor detectable
- Are they associated with the flare γ-ray sources, or with the CME shock?

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

Mewaldt et al. Figures

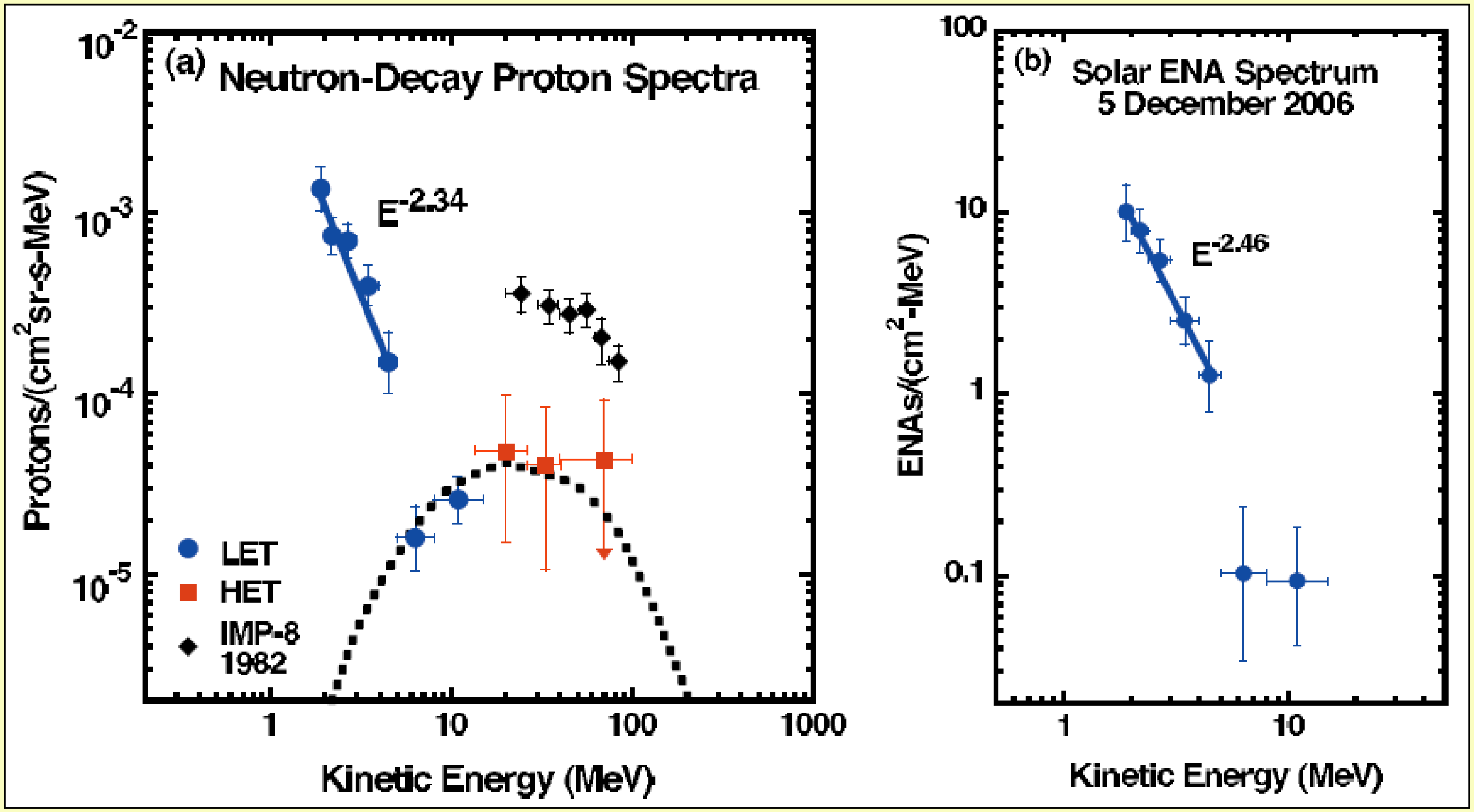






- The STEREO observations provide both spatial and temporal signatures that clearly identify the particles as hydrogen
- The injection times closely match the GOES light curve of the flare

Mewaldt et al. Figures (II)



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

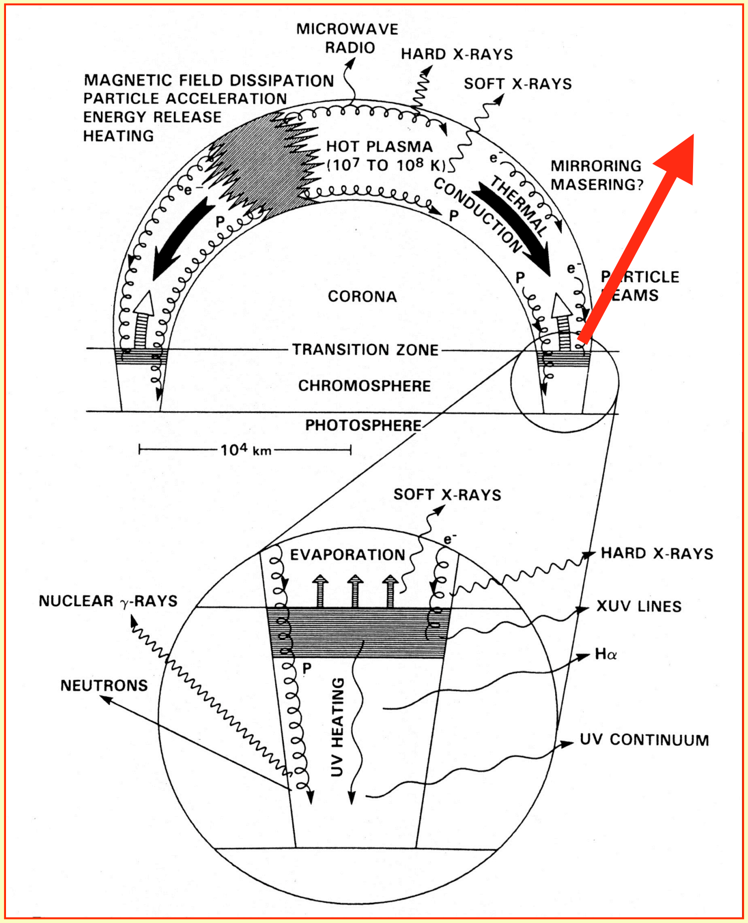
How many particles?

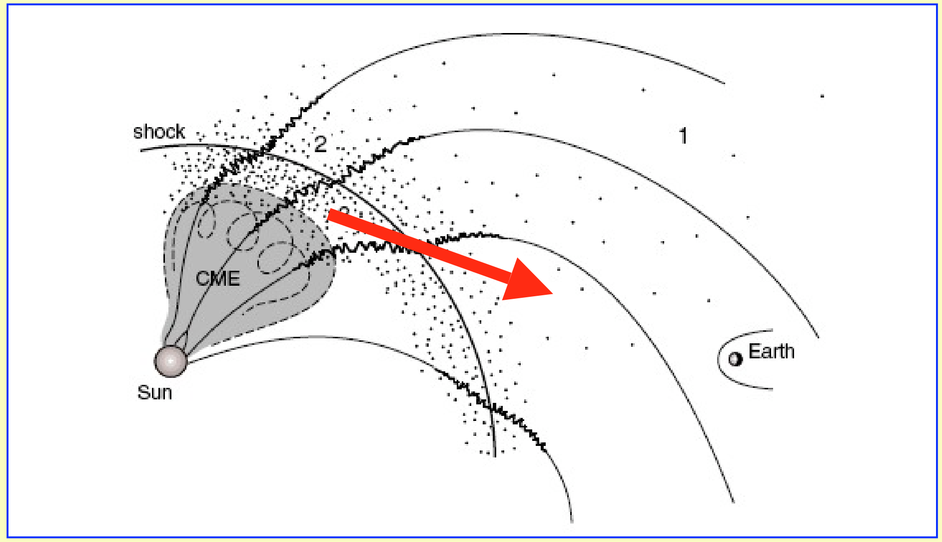
- Mewaldt et al. estimate a total of 1.8×10^{28} ENA particles (hydrogen atoms) assuming isotropic emission in a hemisphere
- RHESSI γ-ray observations imply a total of 1.3×10^{31} protons above 30 MeV*
- Assuming a spectral index of 3.5, this implies a total of 2×10^{34} protons above 1.6 MeV

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

*estimate courtesy of Albert Shih (GSFC)

Whence flare ENAs?



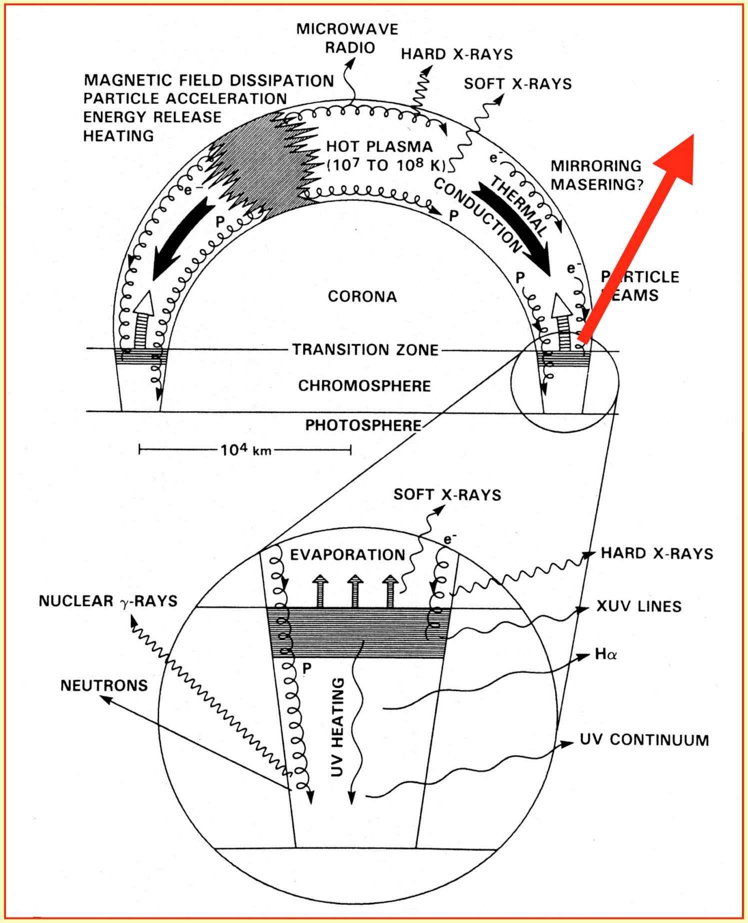


Neutralization and re-ionization on open field lines: Mikic & Lee, 2006

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

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

Whence flare ENAs?



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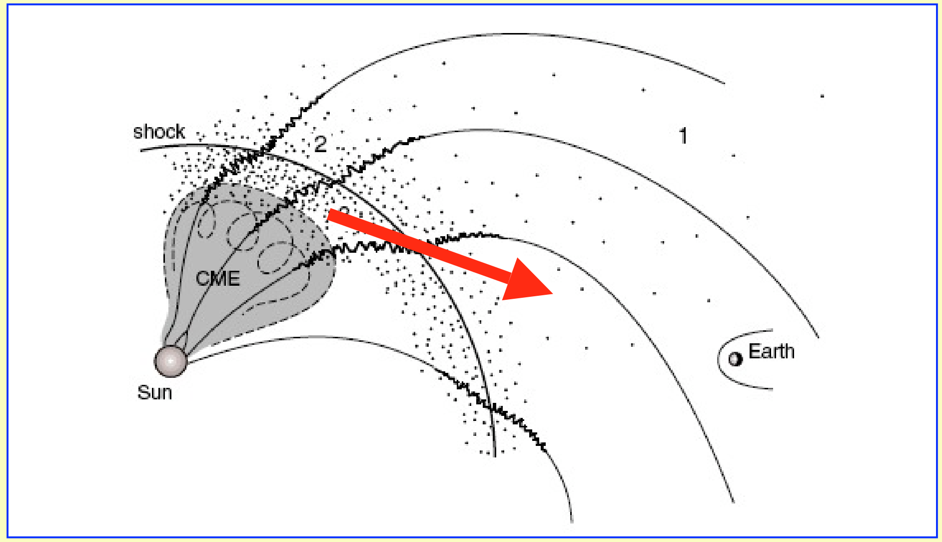


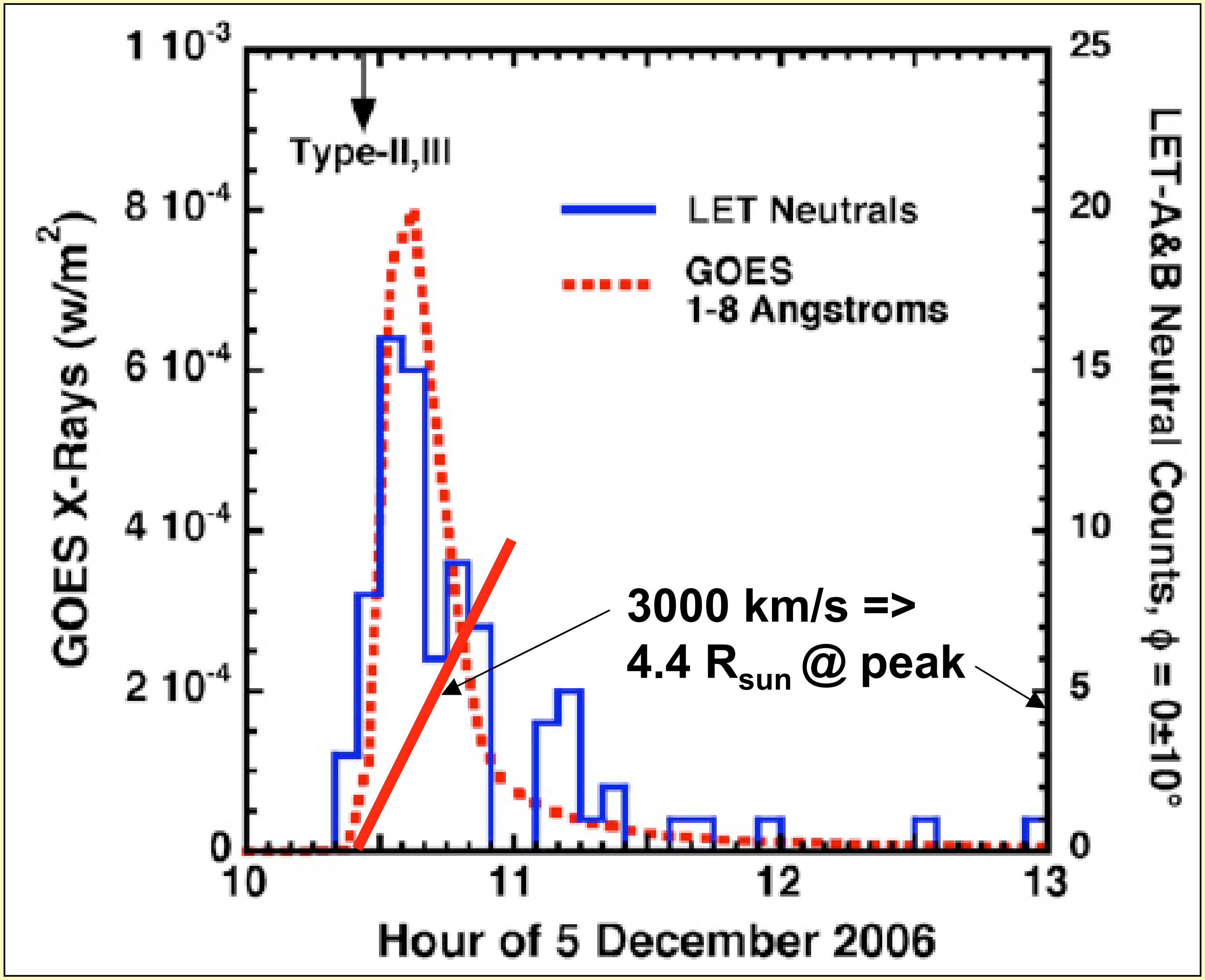
Neutralization and re-ionization on open field lines: Mikic & Lee, 2006

timing wrong?

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

τ_{strip} ~ 120!

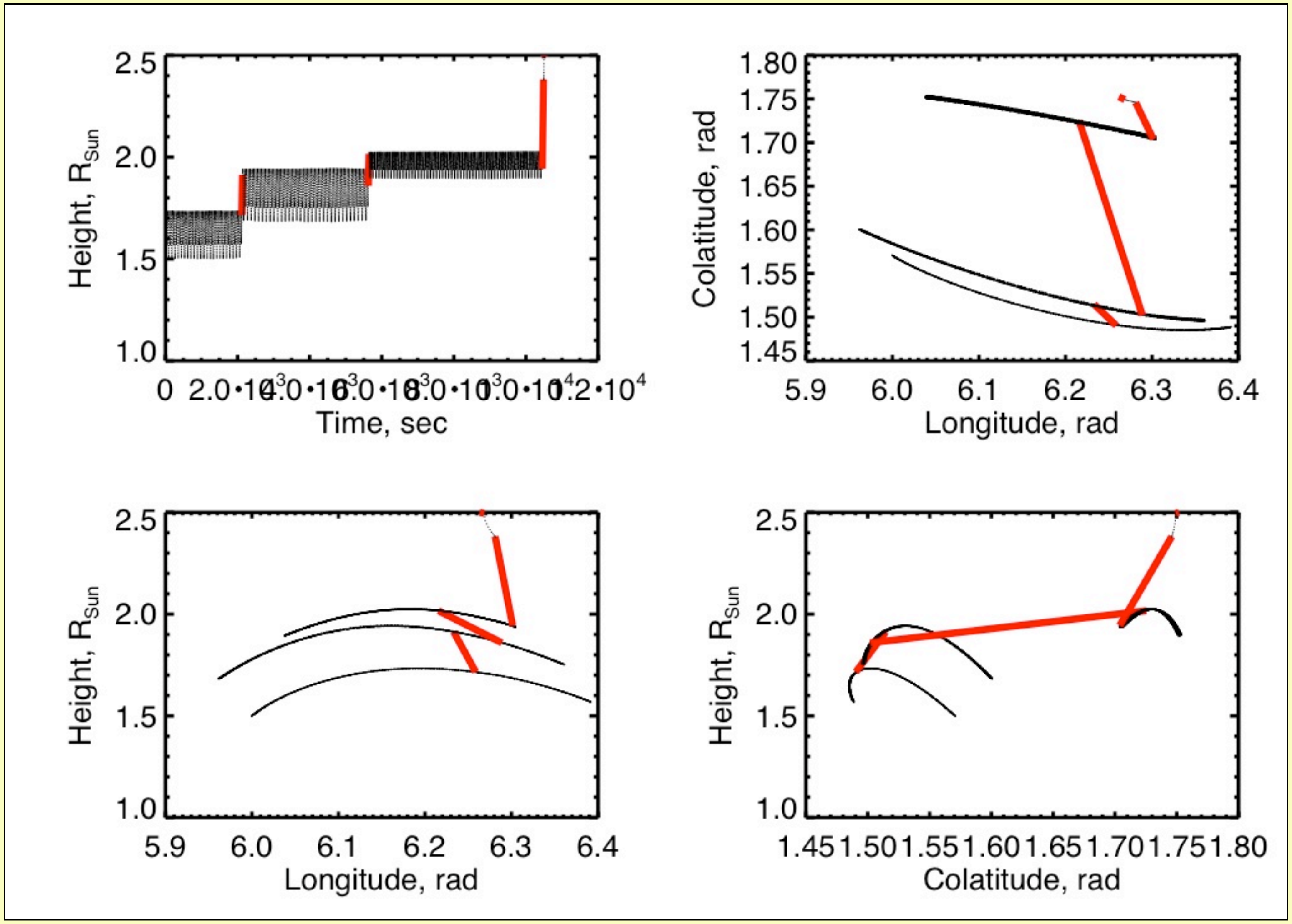
Timing wrong for CME shock?



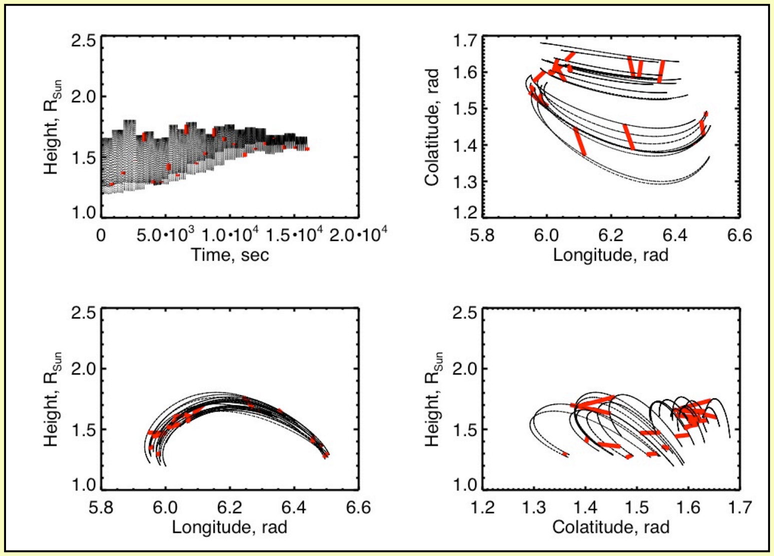
Monte Carlo simulations

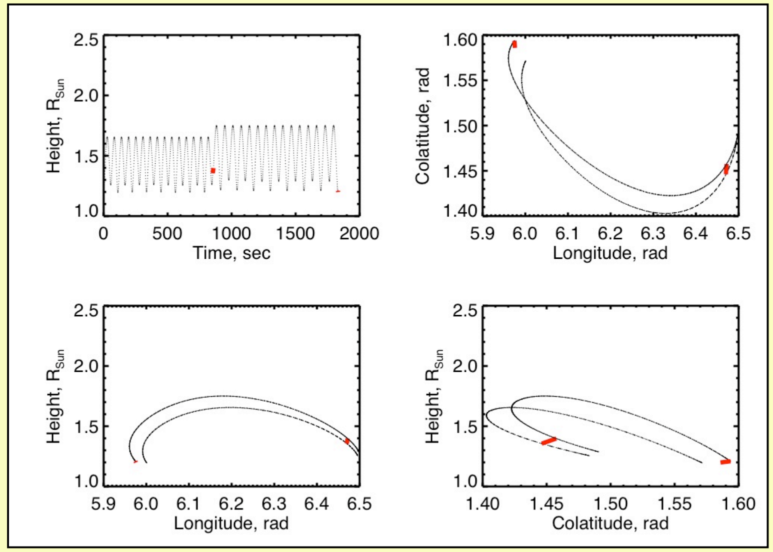
- Neutral hydrogen and protons are alternative states of the same particle. Can successive ionizations and neutralizations allow flare ENAs to originate from the flare γ-ray sources in the deep corona?
- If so, do the emergent ENAs retain any information about the spectrum, source structure, or time 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)



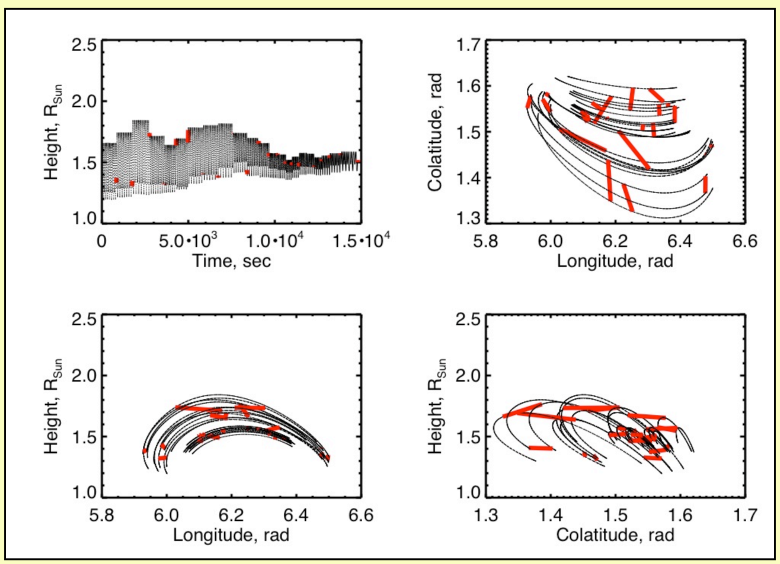
Protons injected at 1.2 Rsun @ 2MeV (examples)

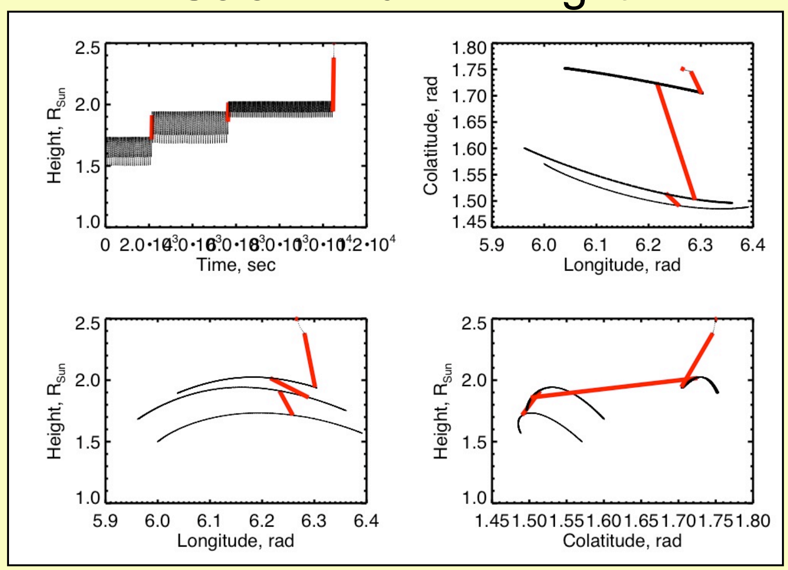




1. Energy decay
3. Time out

2. Footpoint ENA flight
4. Solar wind ENA flight

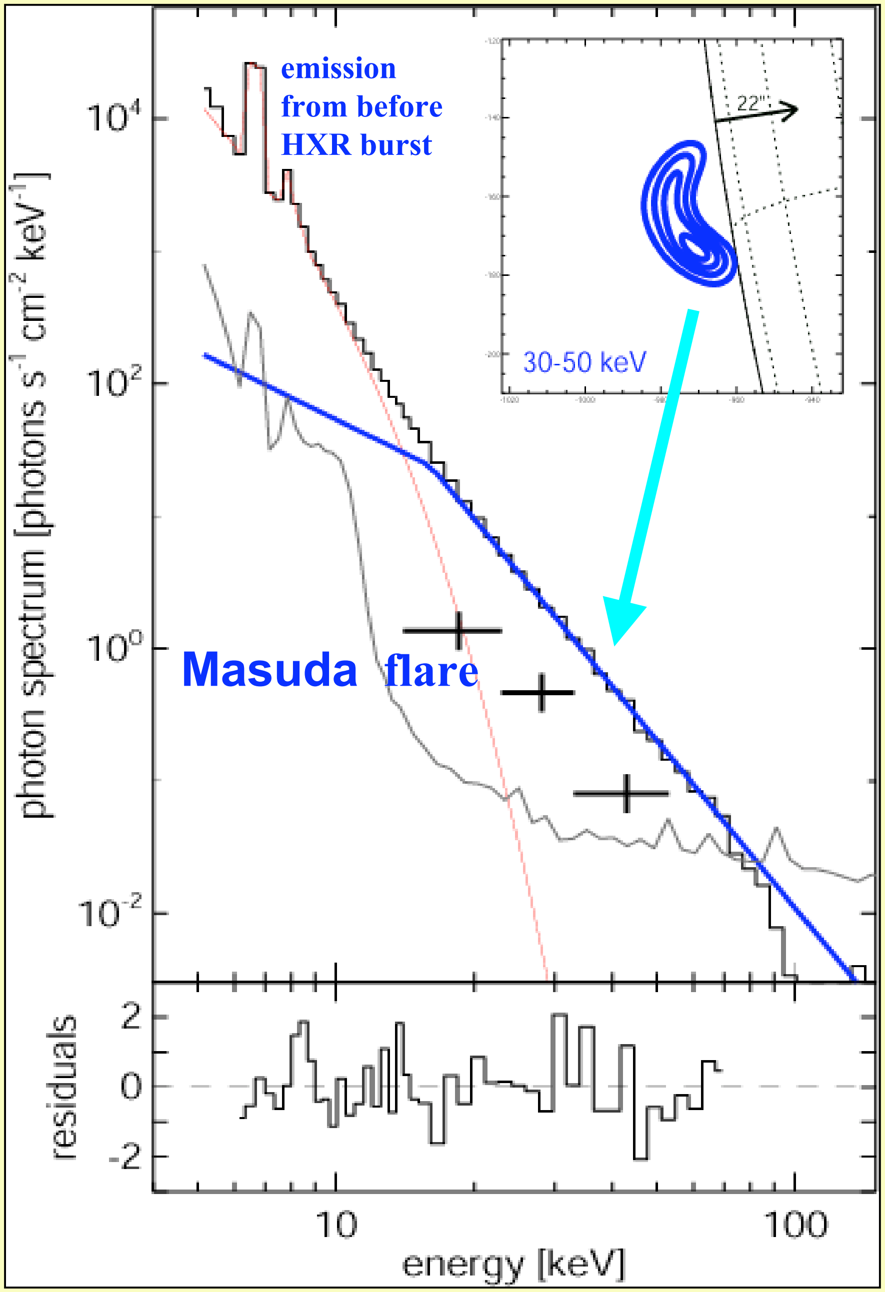




Conclusions

- 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 may need to revise our views of where this can happen

Extra items



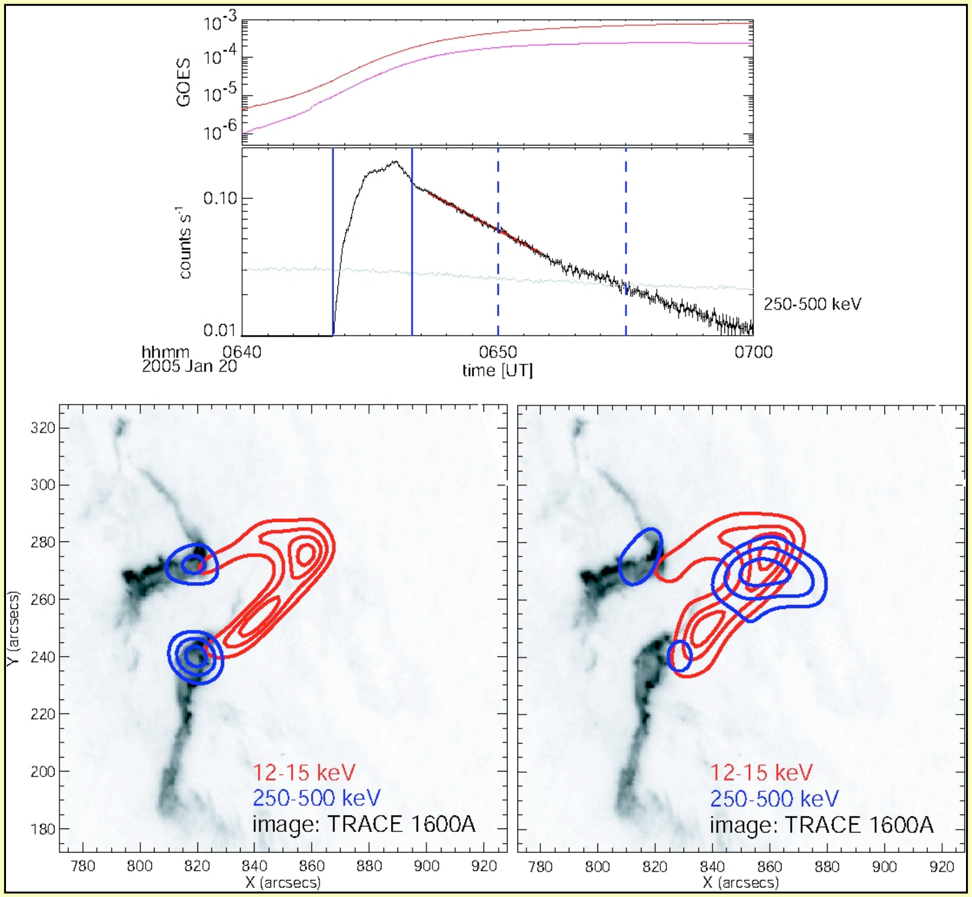
Hard X-ray spectra

Power-law spectrum with index γ ~ 4.2

- Non-thermal spectrum
- Microwave spectrum is consistent with gyrosynchroton emission
- The above-the-loop-top source is non-thermal!

Extended Coronal HXR

- Coronal hard X-ray sources are prevalent, but faint
- We are coming to believe that they are strongly associated with CMEs, rather than the flare process itself



Conclusions

- Extended hard X-ray sources probably occur in every CME event
- At least one example is unresolvably large for RHESSI
- Large numbers of relativistic electrons are required

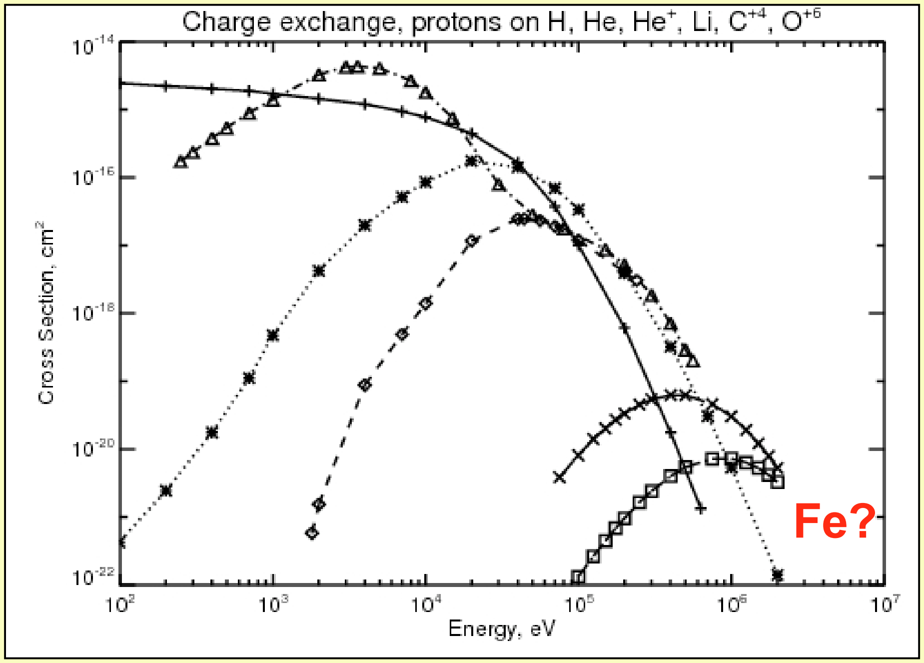
Comments

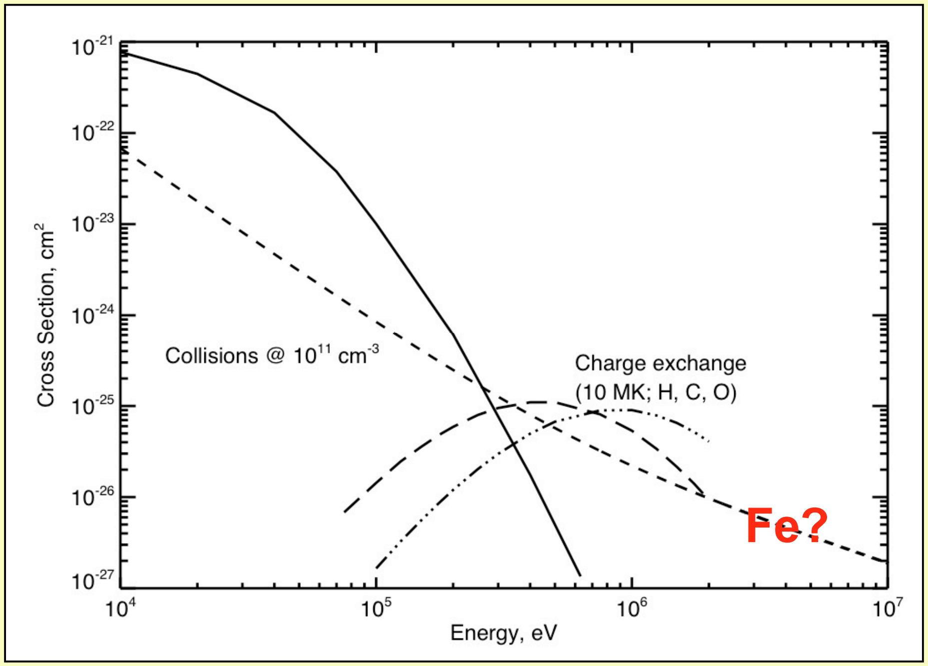
- The relationships between these sources and the meter-wave phenomena are complex (see Pick & Vilmer 2008)
- “Svestka’s giant arches” may have been an early view of some of the phenomenology
- The CSHKP cartoons don’t adequately capture this aspect of flares

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

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)

Challenge

- How can we make new progress in high-energy solar physics?
  - RHESSI follow-ons (γ-rays; HXR focusing optics)
  - A Nobeyama microwave follow-on (FASR)
  - Other radio facilities (ALMA, LOFAR etc…)
  - A dedicated flare ENA observation