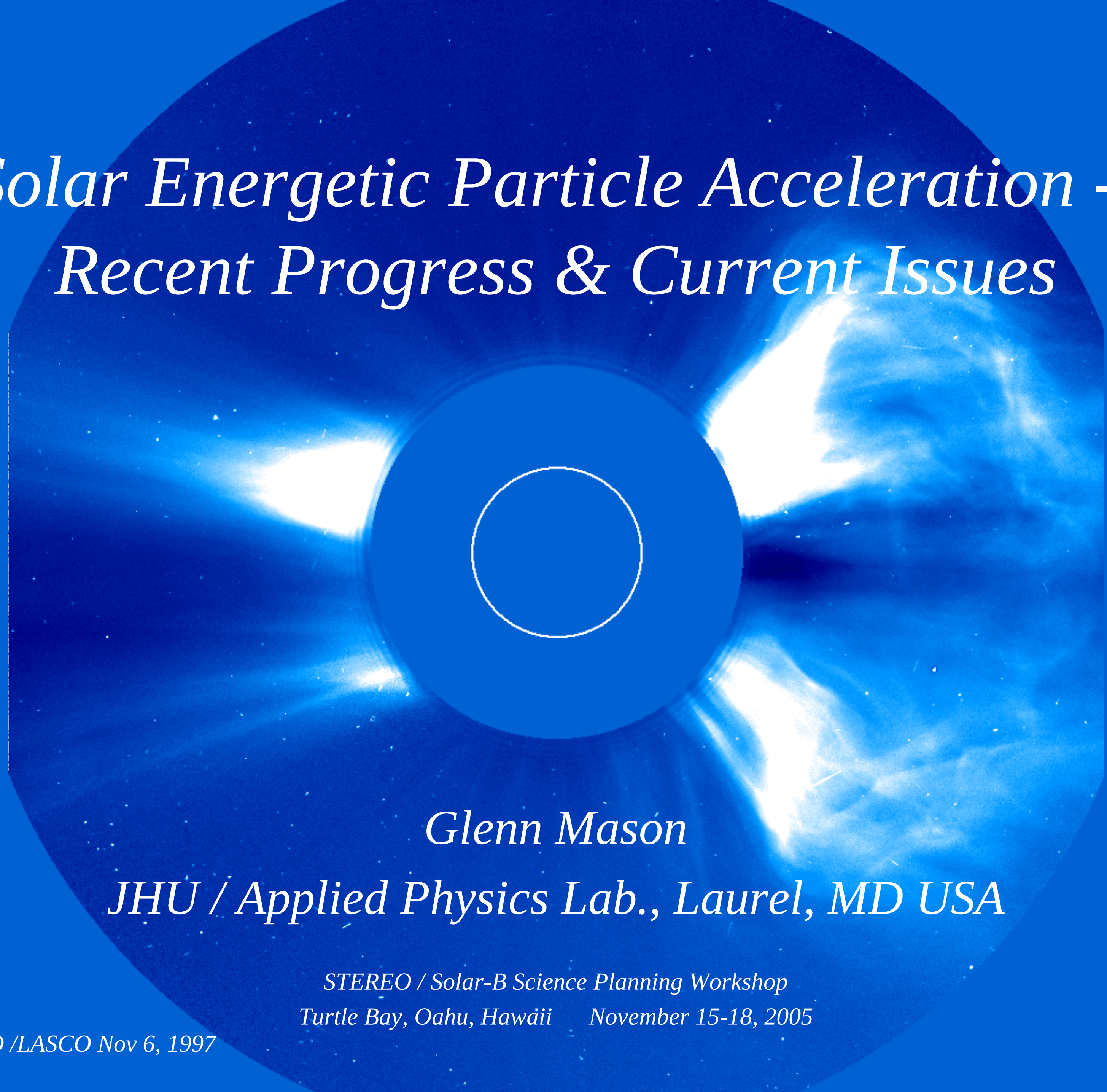
Solar Energetic Particle Acceleration -- Recent Progress & Current Issues



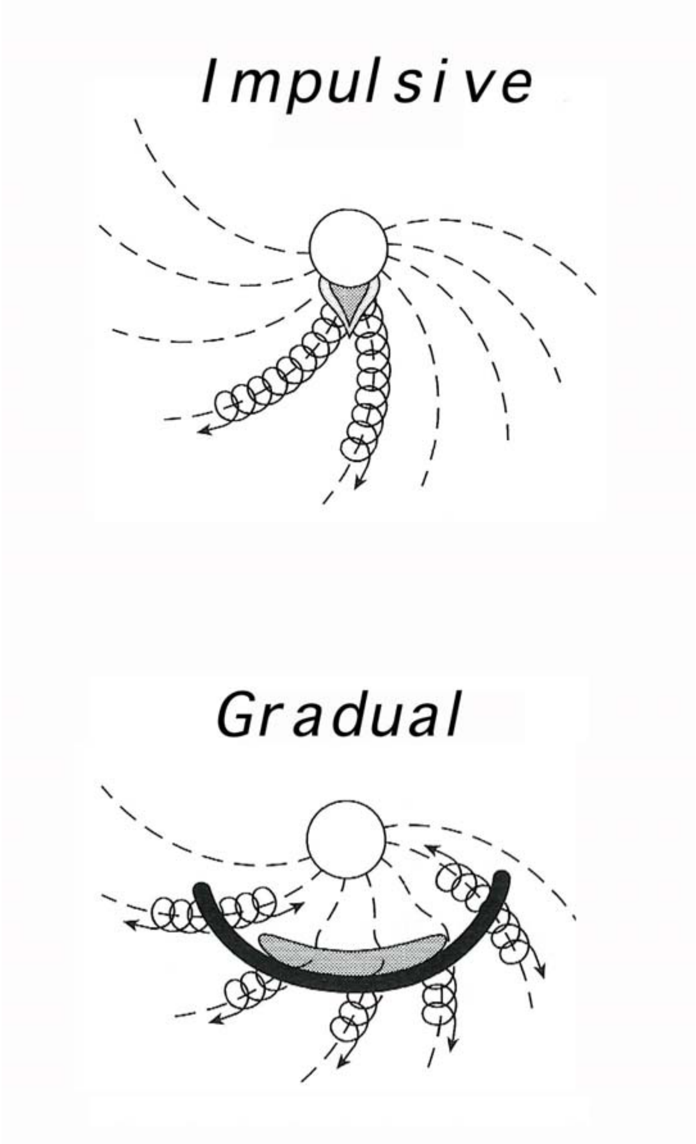
Glenn Mason

JHU / Applied Physics Lab., Laurel, MD USA

STEREO / Solar-B Science Planning Workshop

Turtle Bay, Oahu, Hawaii   November 15-18, 2005

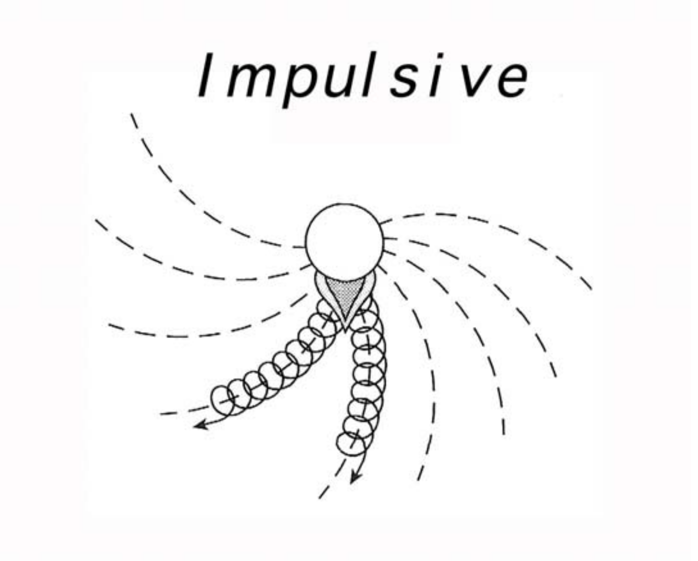
Image: SOHO /LASCO Nov 6, 1997



After Reames, SSR, 1999

Issues:

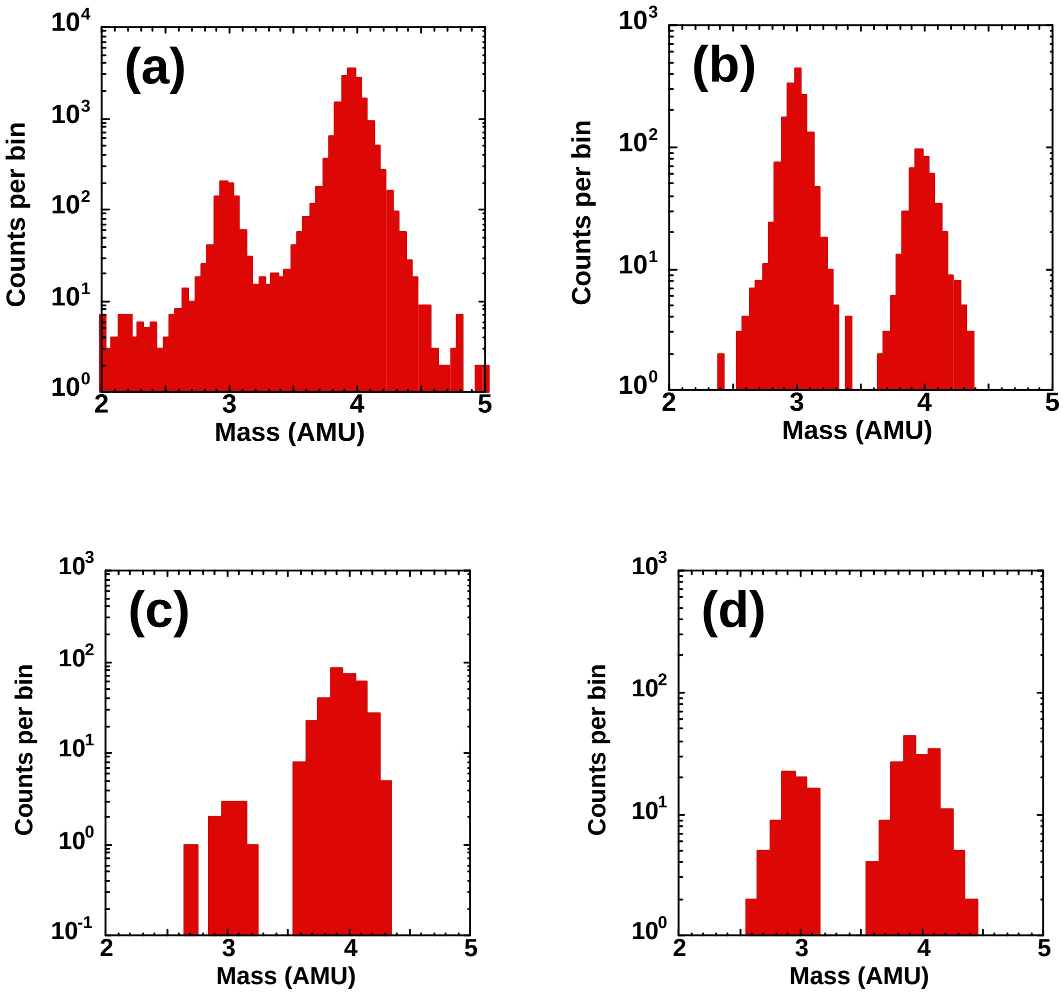
- *what material accelerated?*
- *where?*
- *how?*
- *transport (gradual events)*



Recent progress enabled by particle instrument improvements in sensitivity & resolution; RHESSI / TRACE

- *Where? New progress with RHESSI / TRACE*
- *What material? New progress with ionization states*
- *How: New features of: spectra, composition, event to event variation; models*

ACE He mass resolution

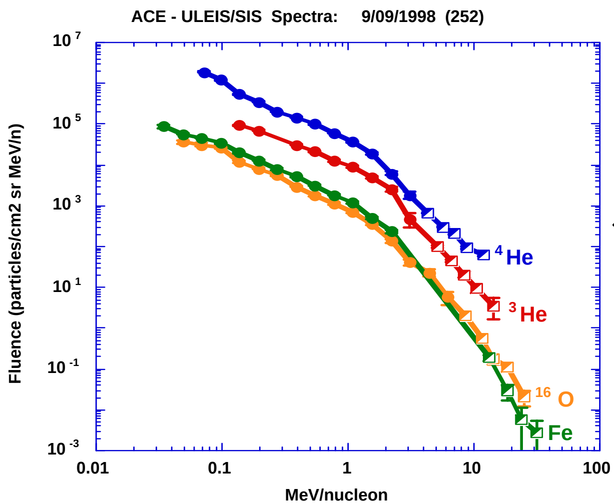


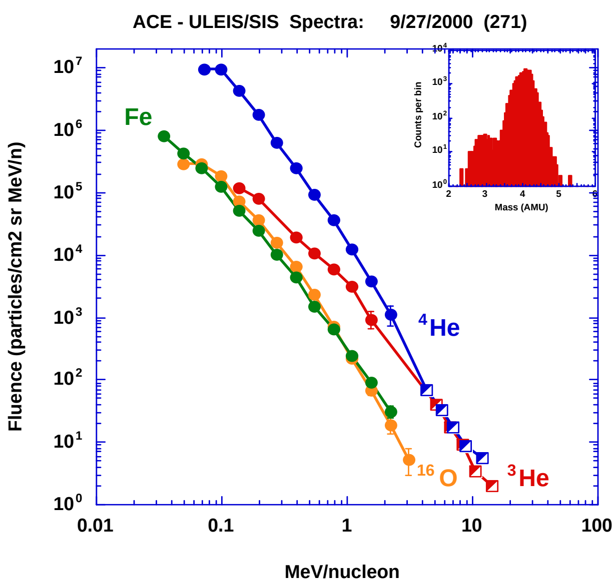
← 750 keV/n

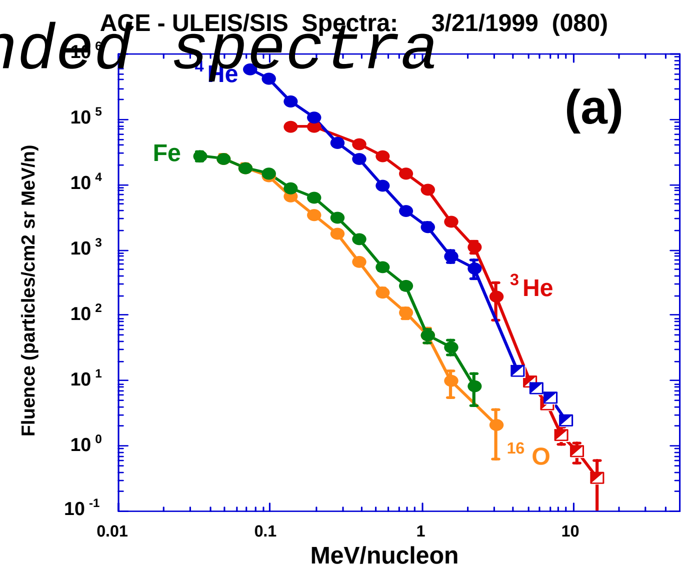
← 7.5 MeV/n

Variety of spectral shapes:

- *^{3}He often has unique shape*
- *power laws, or*
- *broken power laws*
- *rounded spectra*

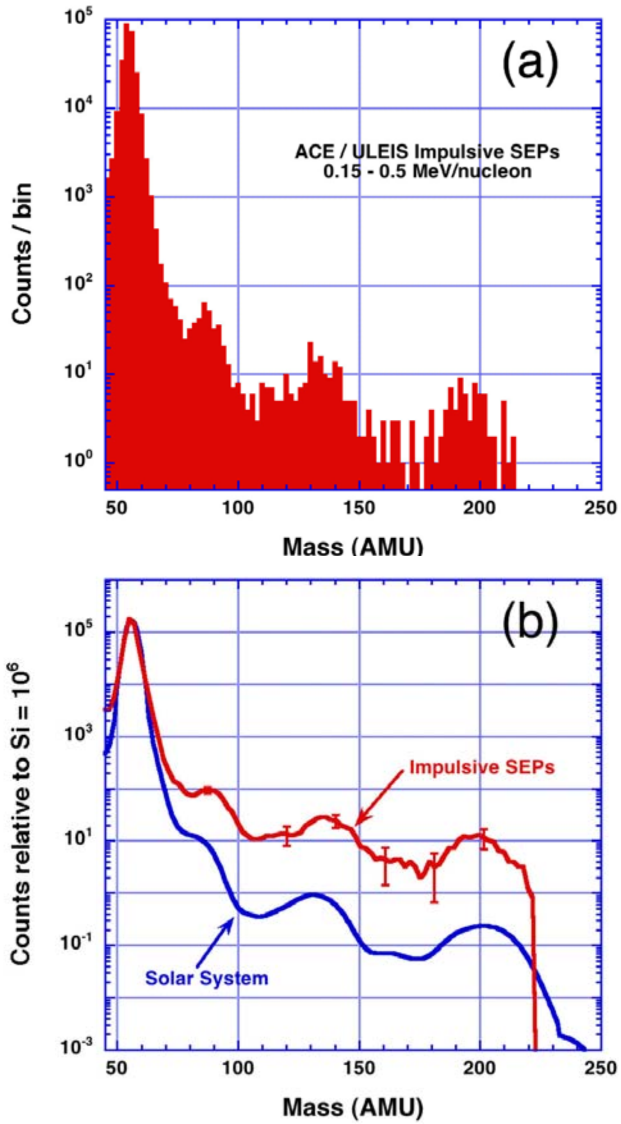






Mason et al., ApJ, 574, 1039, *2002*

UH nuclei in ^{3}He rich flares --



Enhanced UH in 3.3-10 MeV/n impulsive SEPs discovered by Reames (2000)

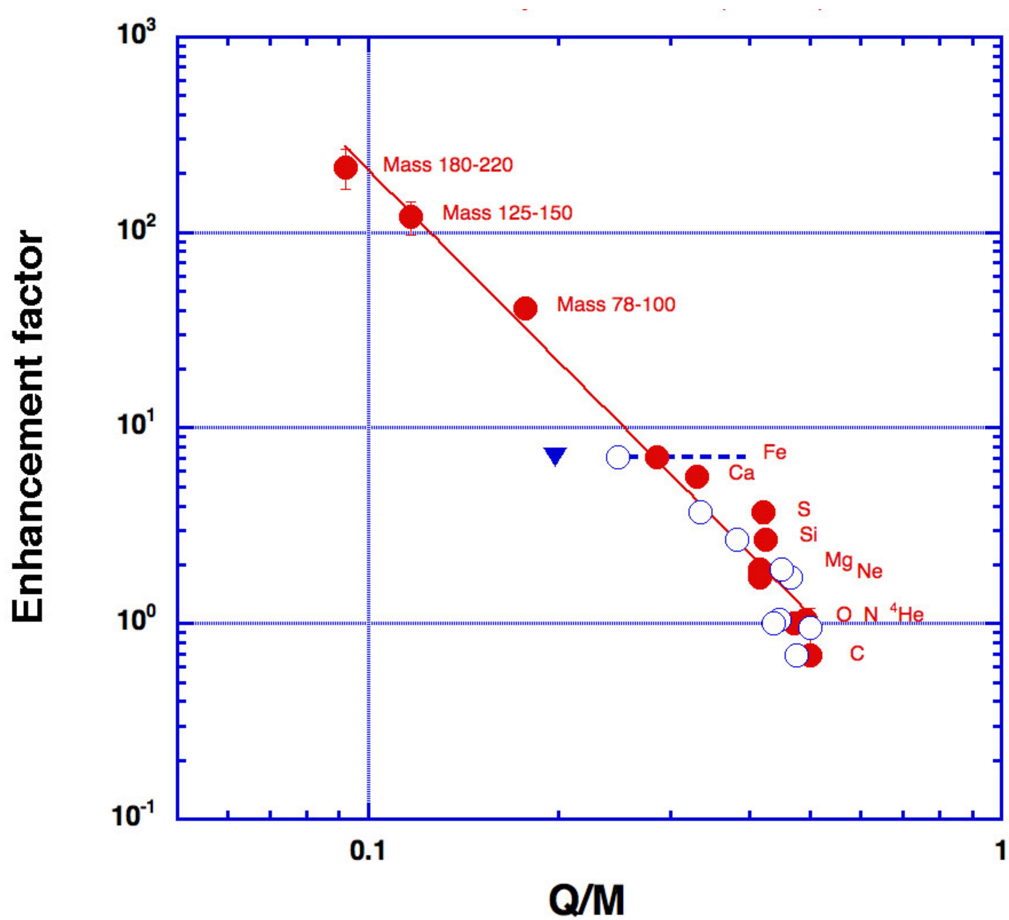
In range 150-500 keV/n, ACE/ULEIS observes many more events.

Mass histogram of events showing Fe peak and range out to ~220 AMU; note structure

Smoothed ULEIS distribution (red) compared with smeared solar system abundances: enhancement increases with mass

Mason et al., ApJ, 606, 555, *2004*

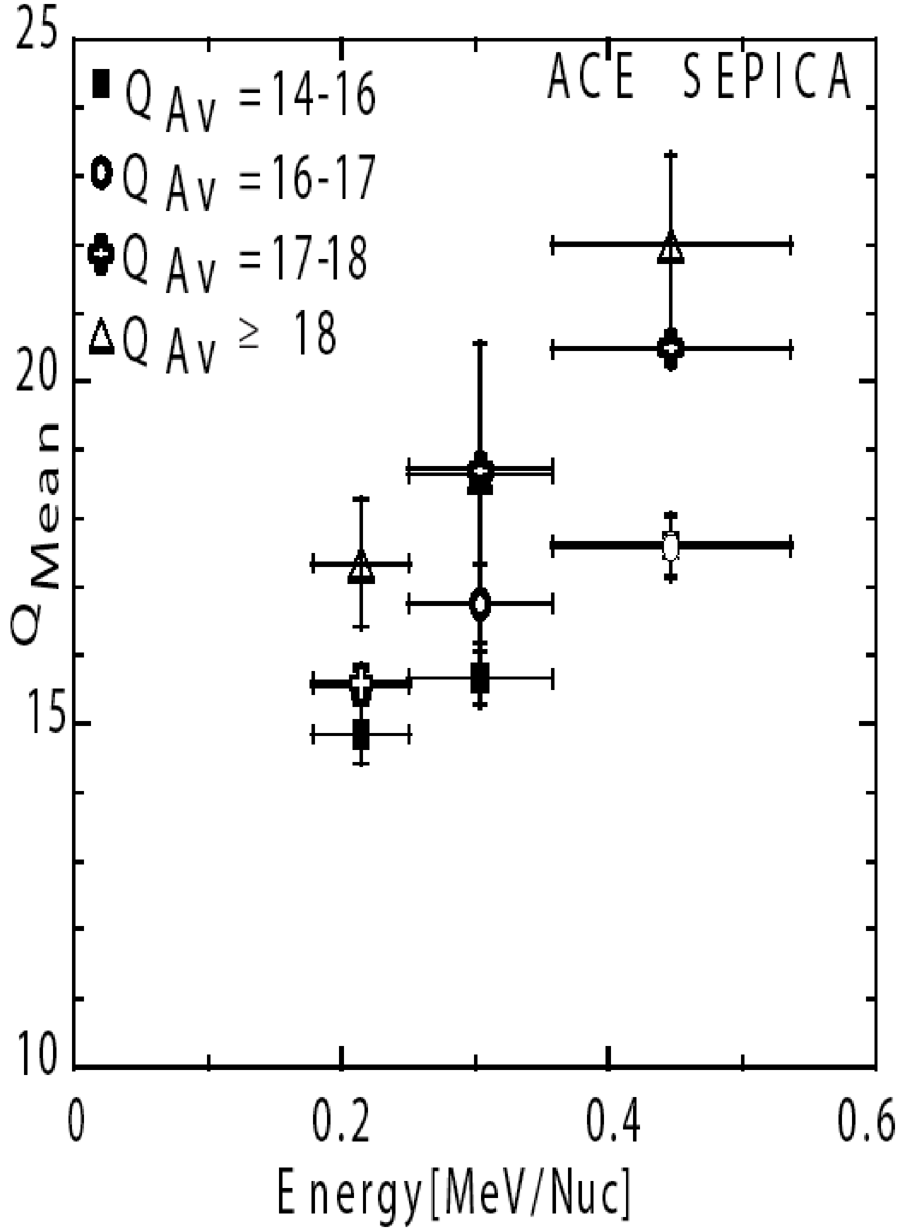
UH nuclei in ^{3}He rich flares --



Mason et al., ApJ, 606, 555, *2004*

Enhancement also shows a general ordering by Q/M ratio, as seen by Breneman & Stone in large, gradual SEP events.

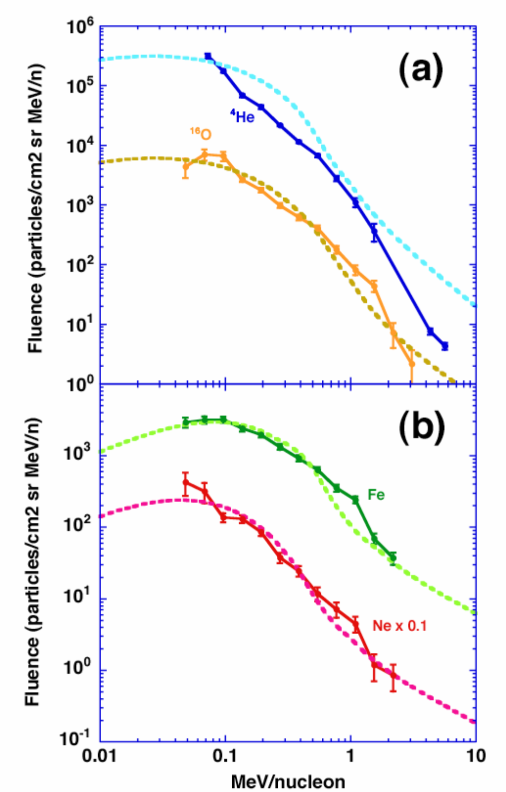
However, it is not clear what Q states we should use & if stripping occurs during acceleration, the Qs are ambiguous



Strong energy dependence of the Fe Q state attributed to stripping during and after acceleration

Energy Dependence of Fe Q states in 7 impulsive events from 1997 - 2000

Möbius et al., 28th ICRC, 6, 3273, 2003



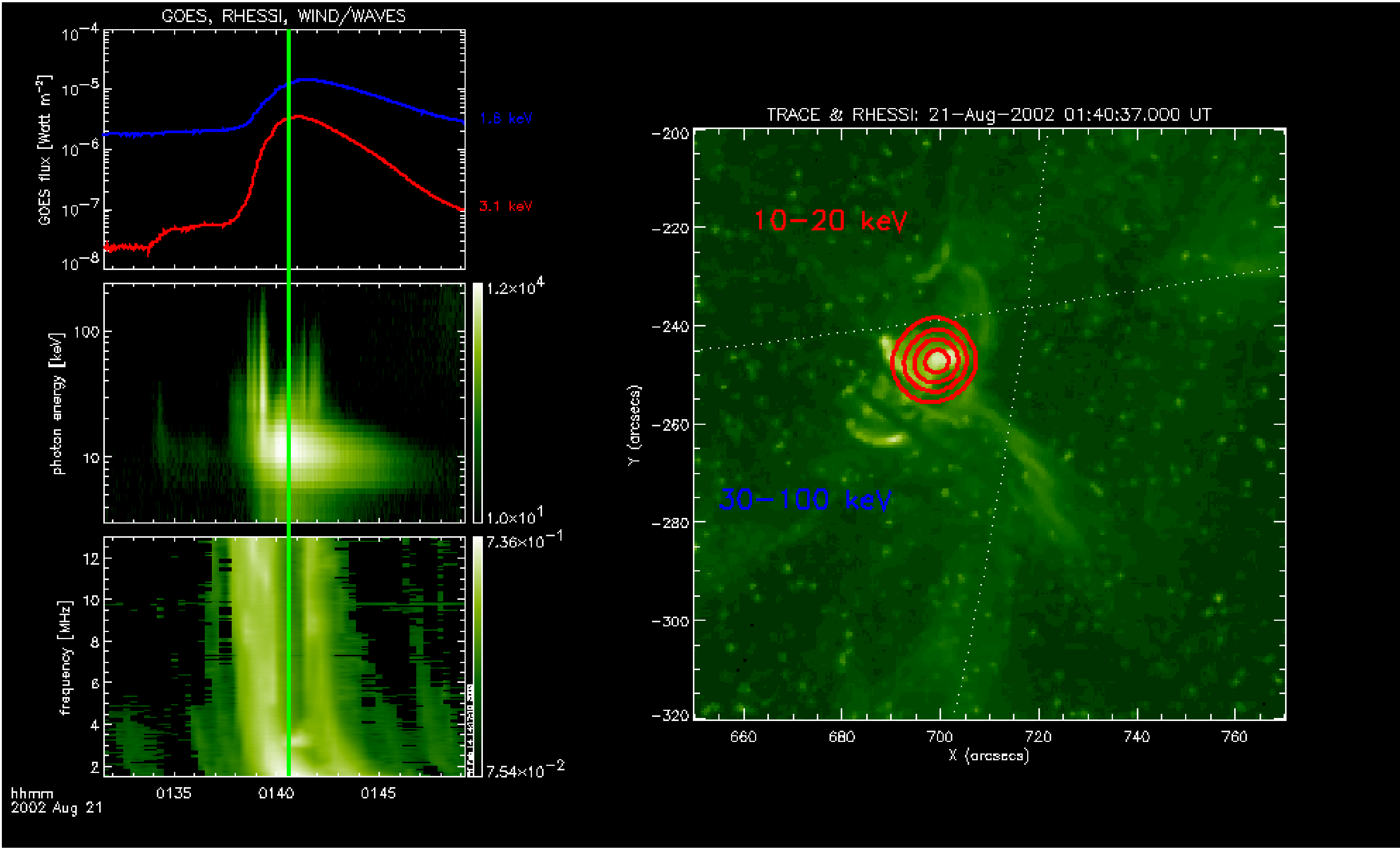
Recent progress in models --

- *cascading MHD resonance model of Miller can reproduce curved spectral forms, and composition of heavy ions up to Fe*

Stochastic acceleration model of Liu and Petrosian can reproduce complex ^{3}He vs ^{4}He spectra

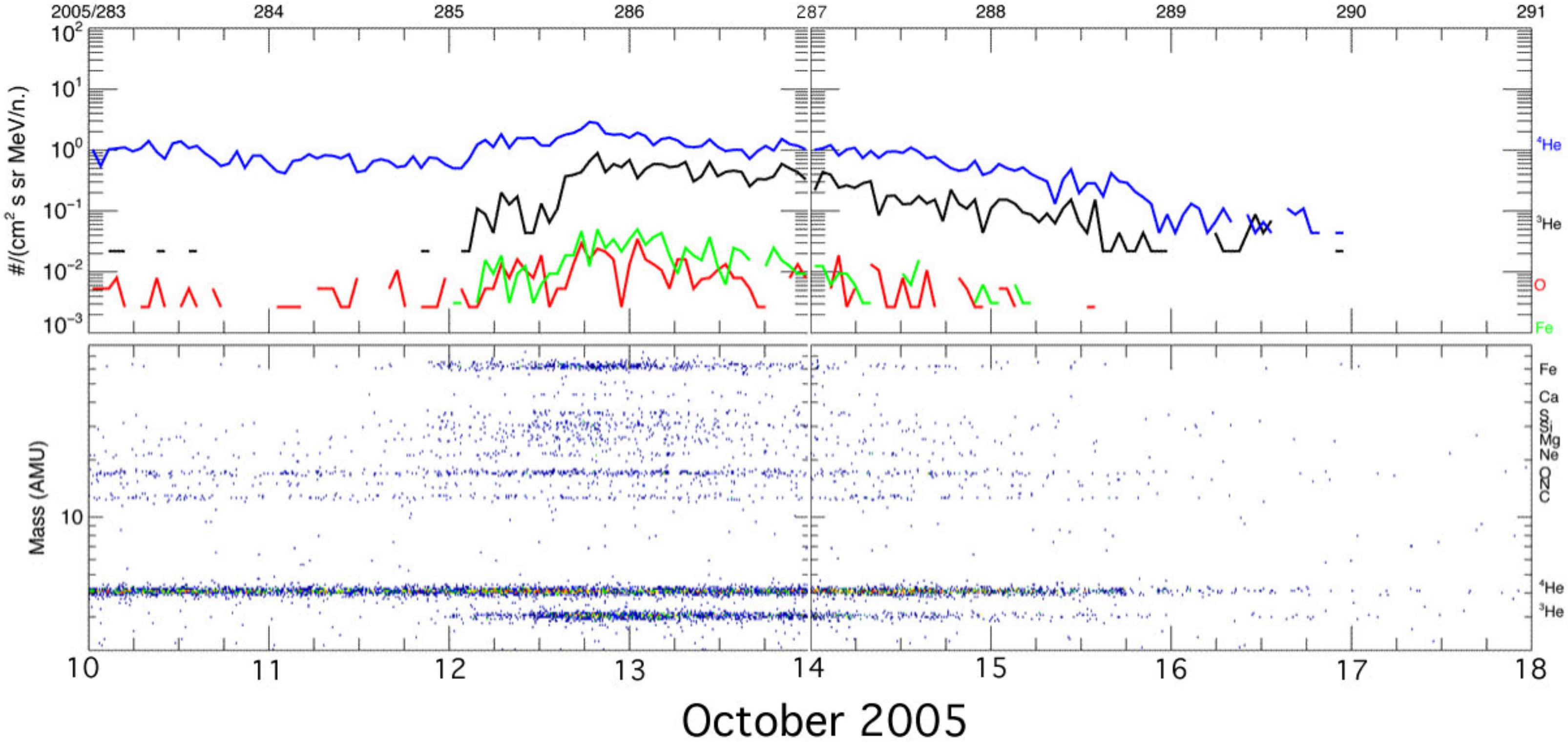
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

RHESSI / ACE survey of source regions for ^{3}He rich flares



Krucker et al., Fall AGU, SH11D-030, 2003

Example of nearly steady emission of 3He over a multi-day period in Oct 2005 -- were connected to region for ~50° of solar rotation

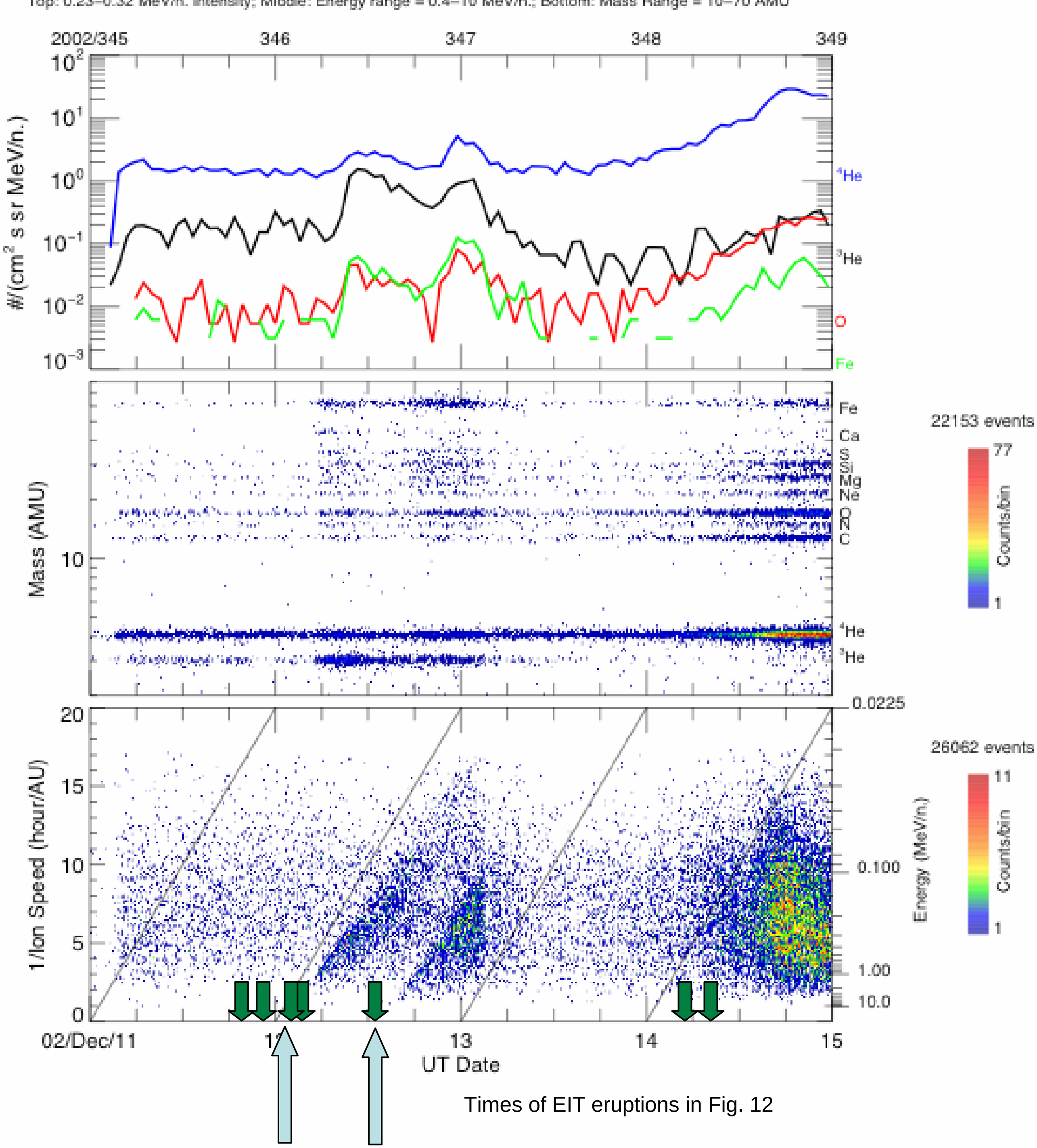


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

SOHO

EIT

195



Relation between recurrent jets and particle activity --

Active region-coronal hole systems show a strong tendency to produce recurrent jets. If these systems are the source of impulsive SEPs then the recurrent behavior should also be reflected in in situ particle measurements.

= time of impulsive electron event on Wind (Linghua Wang, private communication)

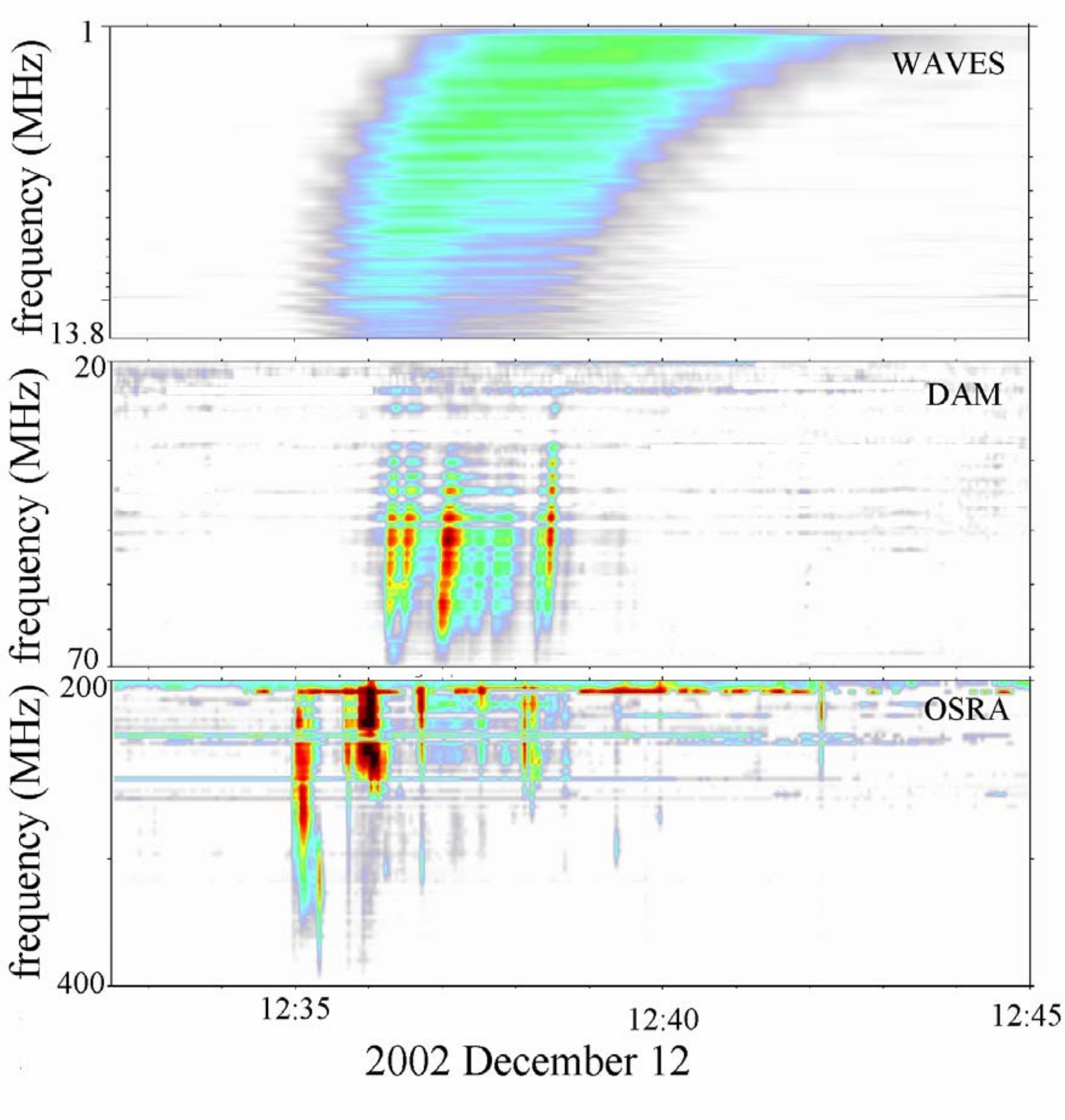
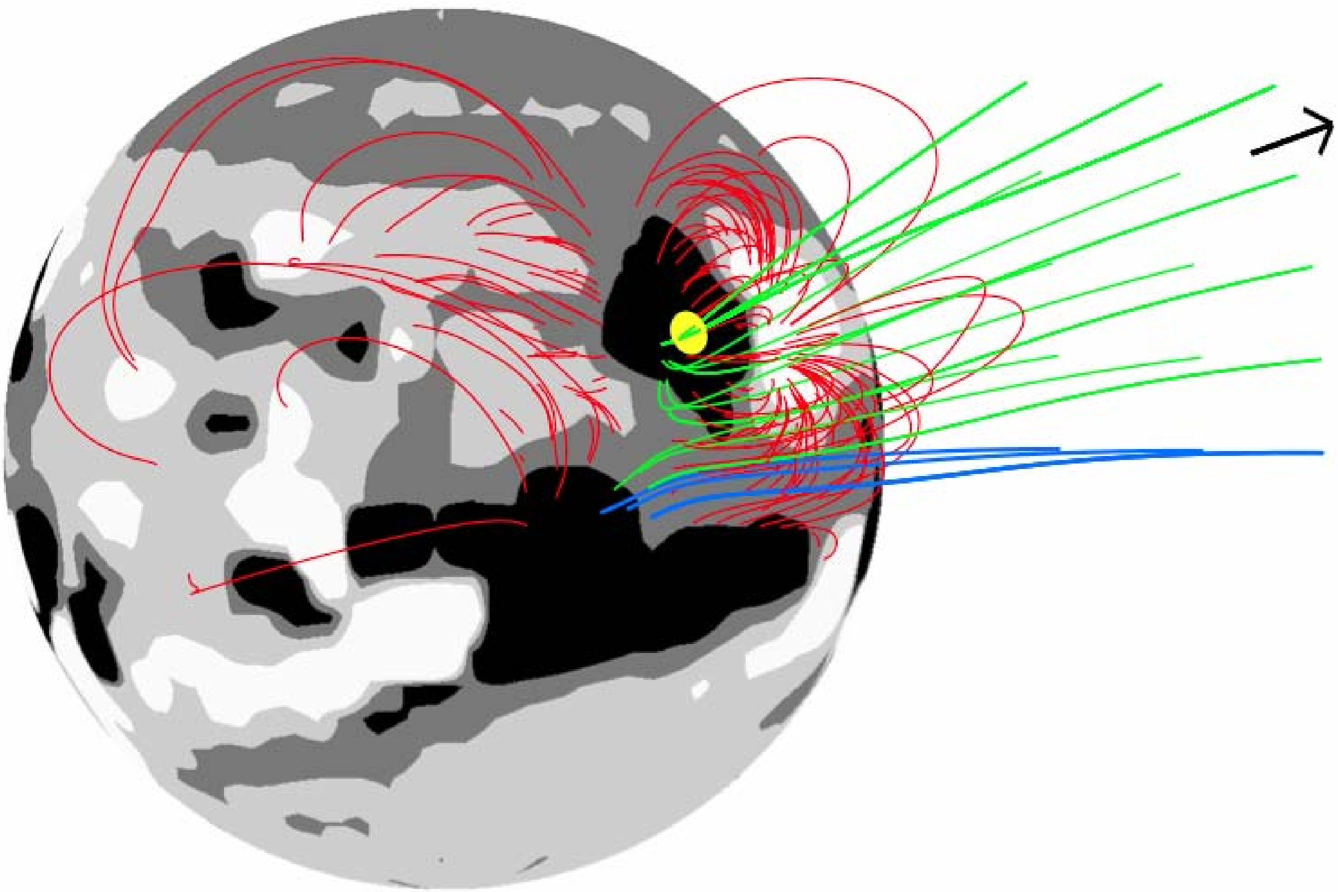


Fig. 5 2002 December event. Radio spectra measured in three frequency ranges; the emission is characterized by a series of type III bursts drifting from decimetric to kilometric wavelengths.

Pick et al. 2006 (in preparation)



(d) 2002 DECEMBER 12

Wang, Pick, & Mason, ApJ, 2006 (in press)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

SOHO

EIT

195

SOHO

EIT-dit

195

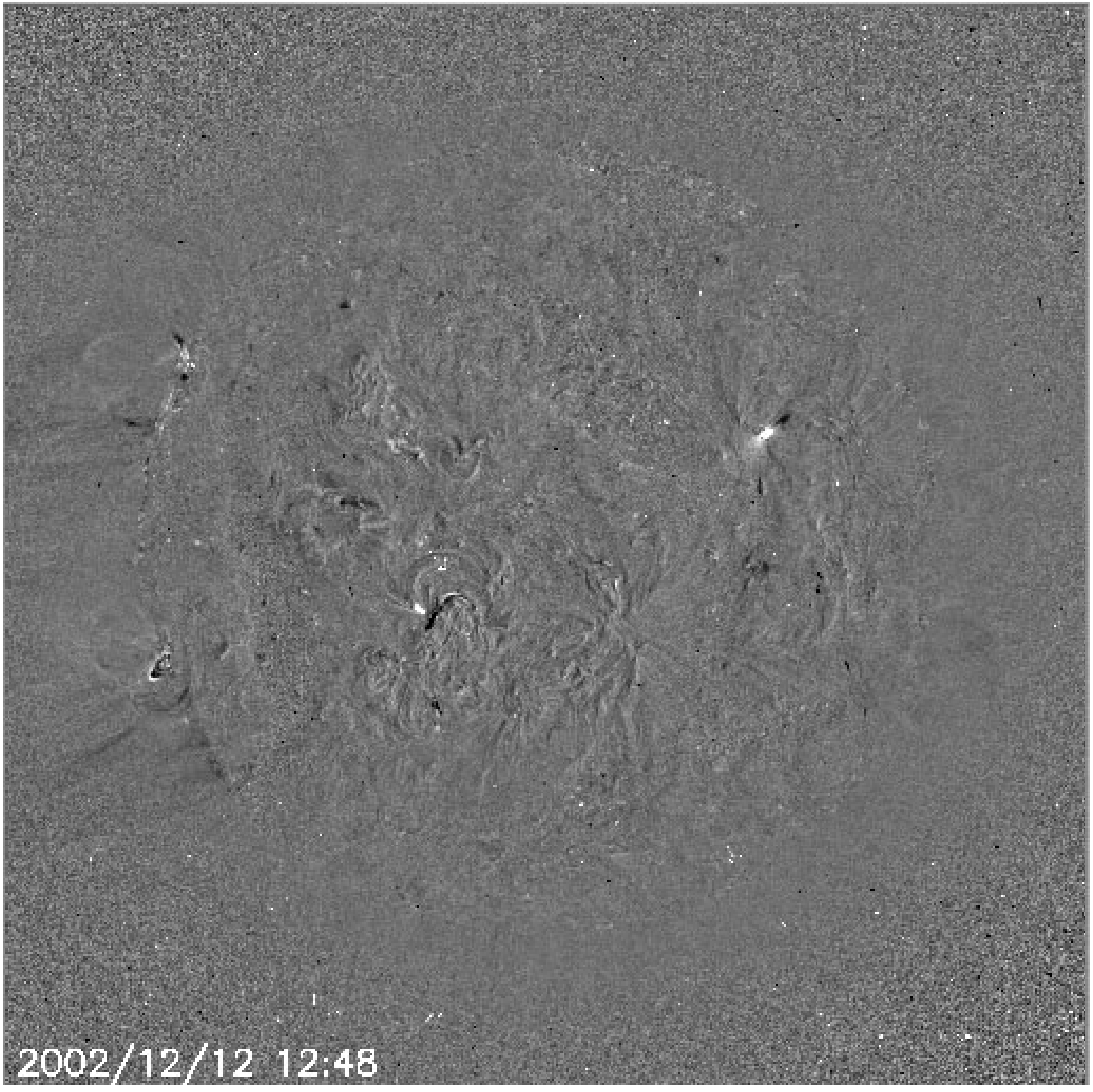
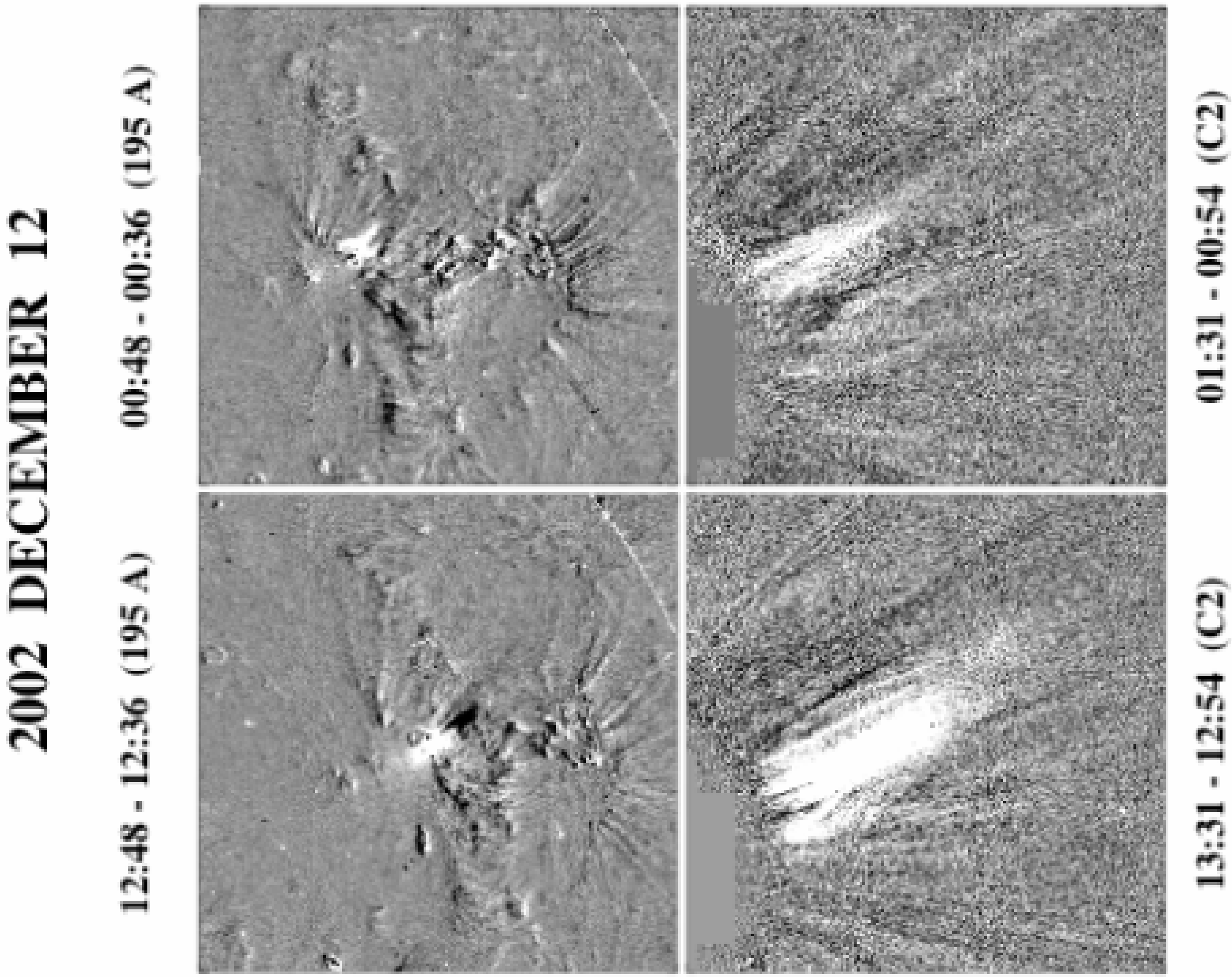


Fig. 12

EIT jet | White light



Two EUV jets emitted by same active region; 2nd, brighter, one is 12 hr after the first, and is associated with one of the SEP events in table 1; Note the “wishbone” shape in the event at 00:48 UT

Wang, Pick, & Mason, ApJ, 2006 (in press)

Fe XII L195 jets are commonly observed when magnetic bipoles emerge inside or near coronal holes, which in turn are embedded inside large unipolar regions (Wang et al. 1993; Wang & Sheeley 2002)

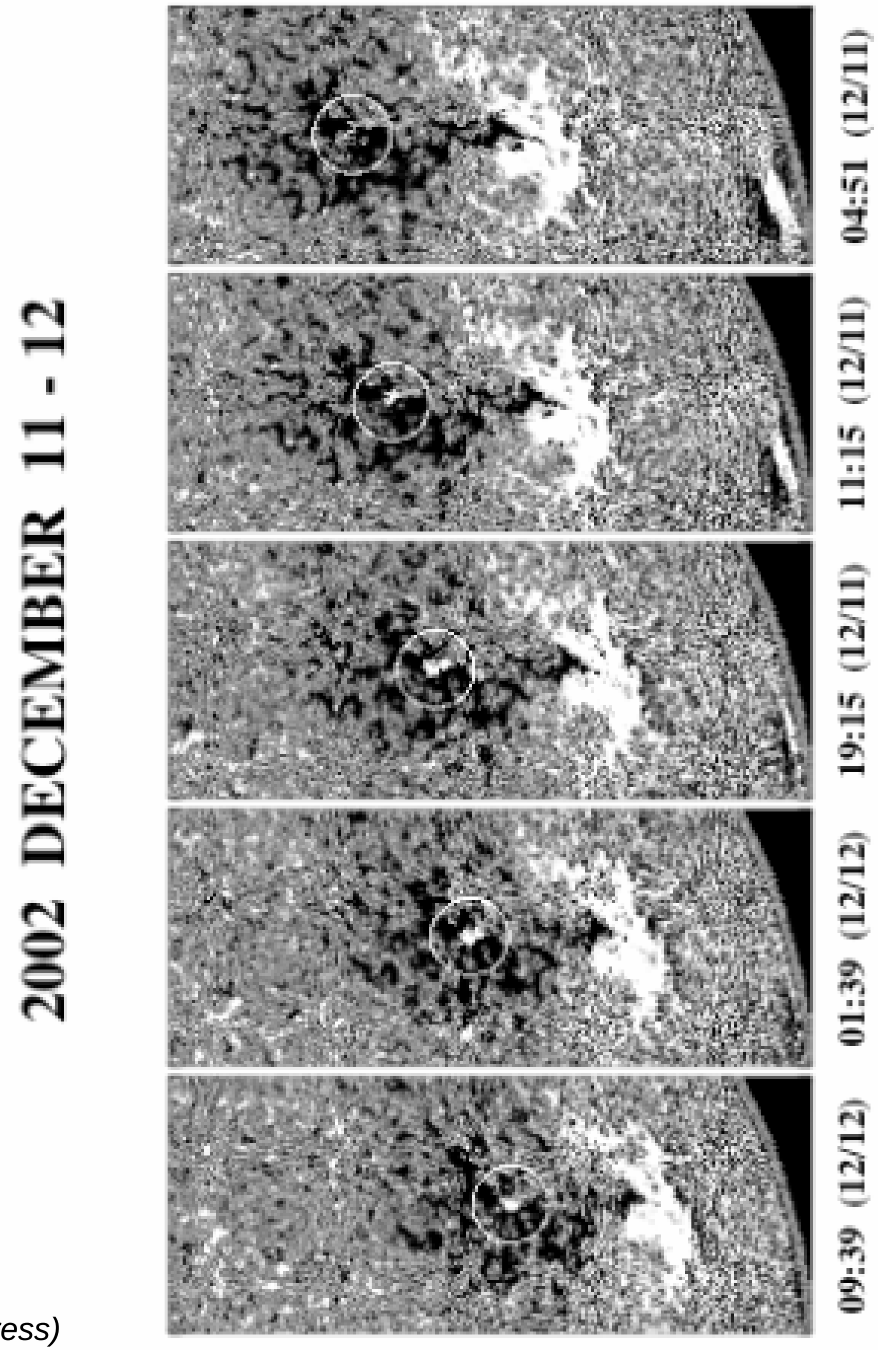


Fig. 13 Sequence of MDI Ni I λ6768 magnetograms showing emergence of positive polarity flux within a large negative-polarity area during the day preceding the LASCO/EIT ejections of 12/2/02. The eruptions were centered

about the newly emergent bipole.

Grey scale: B_{los} <-20 G (black) to B_{los} > 20G (white)

Wang, Pick, & Mason, ApJ, 2006 (in press)

Yohkoh images of an x-ray jet

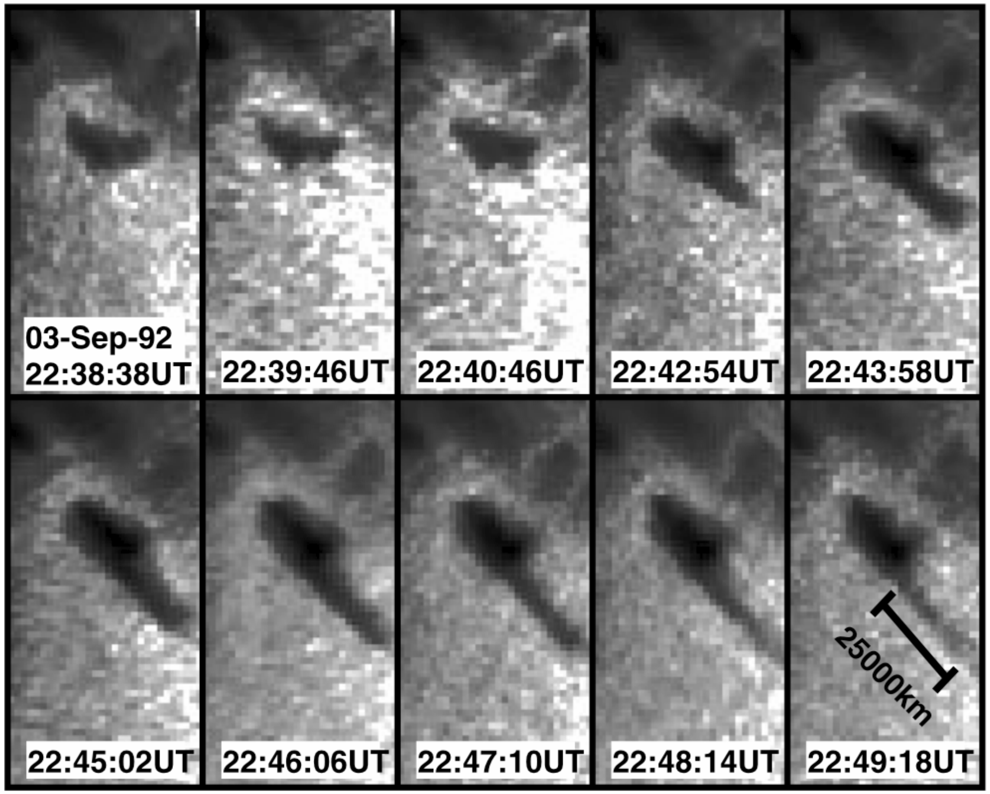


FIG. 1.—Example of an X-ray jet (1992 September 3 event)

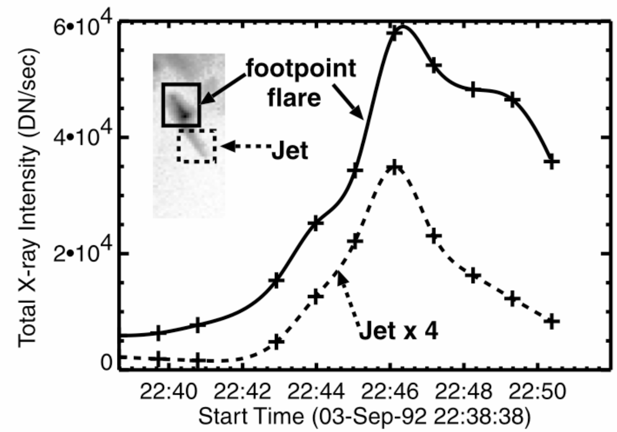


FIG. 2.—Time profile of X-ray intensity of the jet and the footpoint flare.

Wavelength 3-40 Å

~1.5x10^6 - few x 10^7K

Shimojo & Shibata ApJ, 542, 1100, 2000

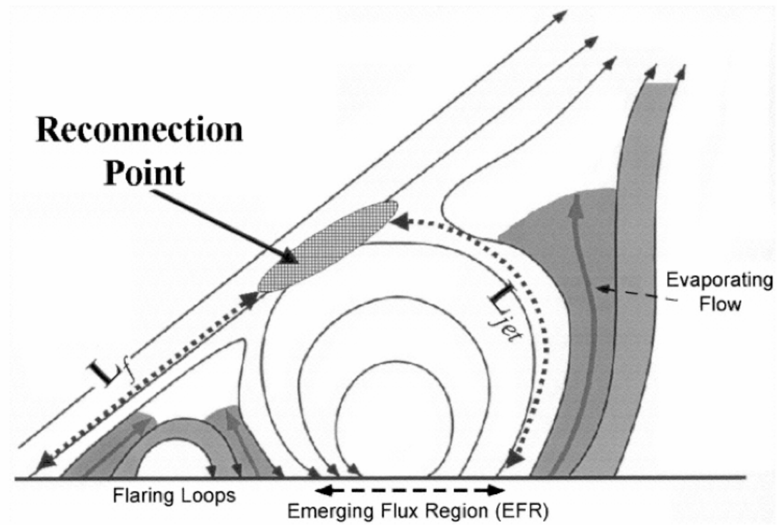


FIG. 7.—Reconnection jet model from Shimojo & Shibata (2000), based on magnetic reconnection and a jet. L_{jet} and L_f are the distances from the reconnection region to the flare and associated jet.

Shimojo and Shibata 2000 model for Solar X-ray jets (ApJ, *542,* 1100)

Also used by Kahler et al. 2001 (ApJ *562*, 558)

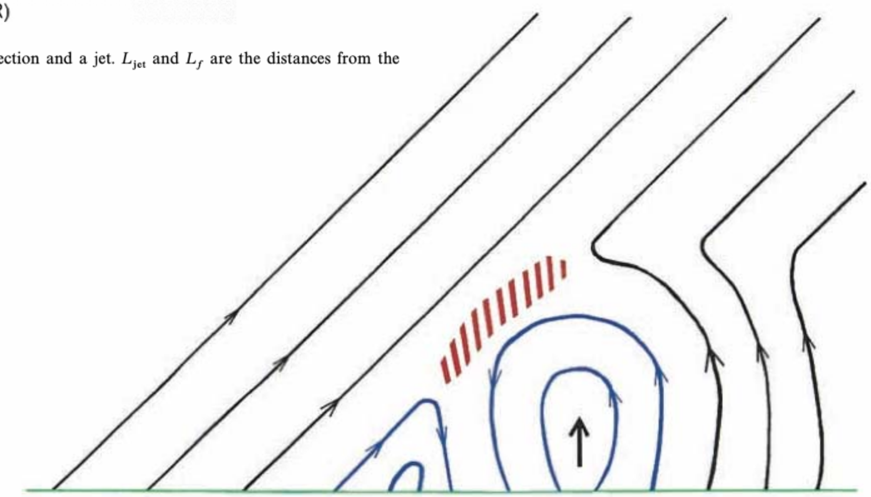
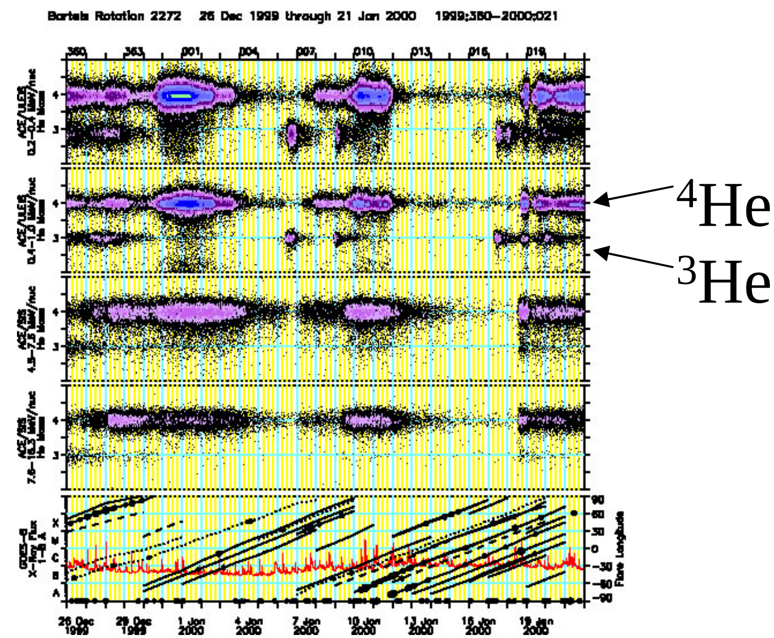
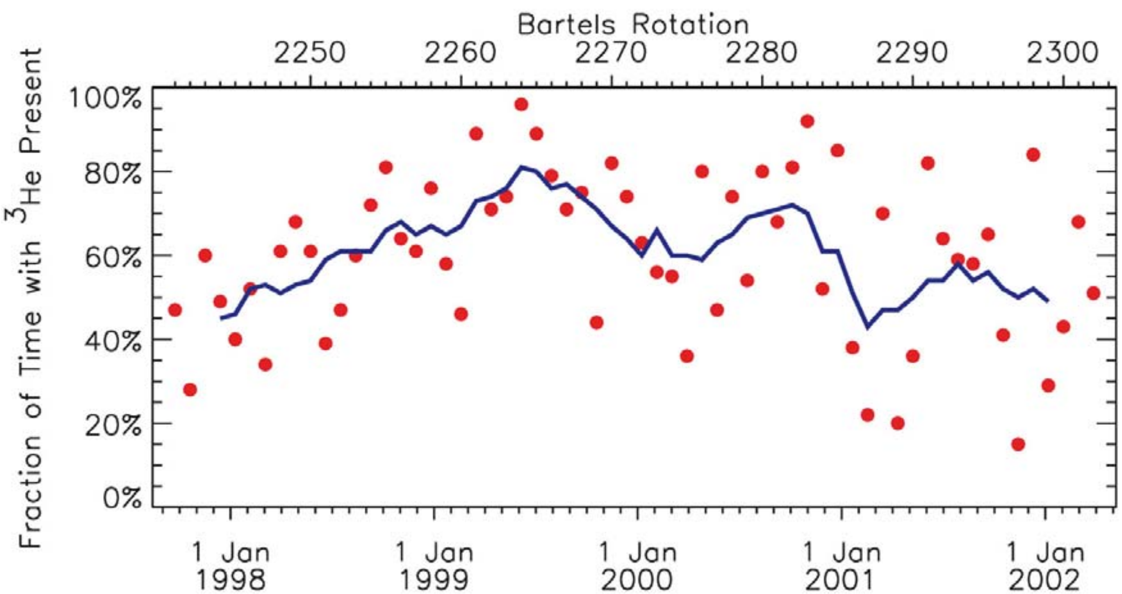


FIG. 1.—Example of the magnetic topology that produces X-ray jets, type III radio bursts, and impulsive SEP events. Closed (*blue*) field lines emerging from the photosphere reconnect (*red hatched region*) with overlying open (*black*) field lines of opposite polarity. Energetic particles are accelerated by resonant wave-particle interactions in this turbulent region, producing SEPs with unusual abundances that can easily escape. Plasma can also escape to form a narrow CME.

Reames 2002 Impulsive flare model (ApJ *571,* L63)

^{3}He is present in the interplanetary medium most of the time during solar active periods

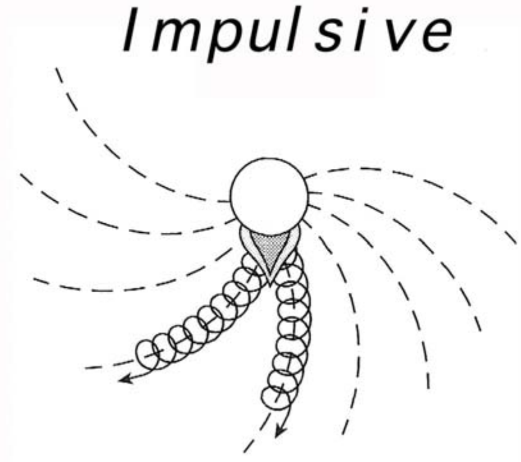




Wiedenbeck et al. Solar Wind 10, AIP Conf Proc in press 2003

SUMMARY -

IMPULSIVE SEPs:

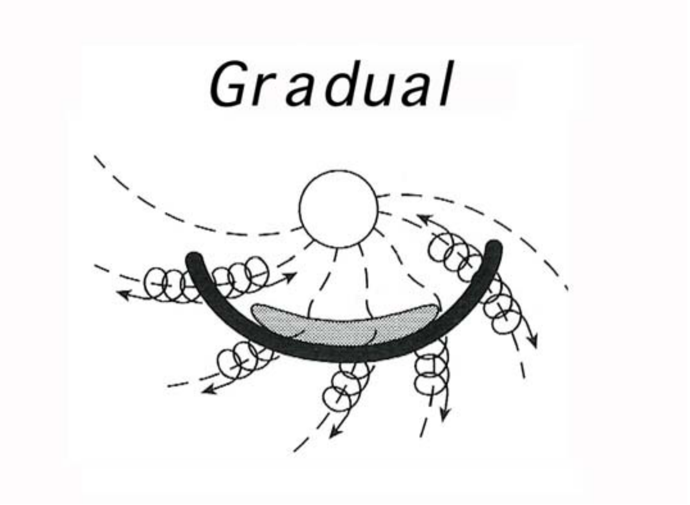


• *new properties of ^{3}He-rich events observed with advanced instruments have revealed qualitatively new features of the particle spectra, abundances, and abundance patterns*

• *RHESSI, TRACE, and ACE may allow definitive identification of a some individual events at the sun*

• *theoreticians are actively examining new models: models need to address all the data, including ionization states that may indicate stripping*

• *the combination of observational and theoretical activities promise new insights in the next year or so*



Recent progress enabled by particle instrument improvements in sensitivity & resolution; SOHO CME observations

- *Where? New progress with Wind, SOHO*
- *What material? New progress with ionization states, composition -- tracer elements*
- *How: New features of: spectra, composition, event to event variation; models*

Thanks to participants in “Group C” of Wintergreen, VA workshop, Oct 16-20, 2005

Jim Adams, Tim Bastian, C. M. S. Cohen, Len Fisk, Bernard Flick, Ghee Fry, Toni Galvin, Joe Giacalone, Dennis Haggerty, George Ho, Steve Johnson, Randy Jokipii, Jon Krall, David Lario, Bob Lin, Glenn Mason (co-chair), Dick Mewaldt, Ralph McNutt, John Raymond, Ed Roelof, Don Smart, Leonard Strachan, Larry Townsend, Tycho von Rosenvinge, Gary Zank (co-chair), Thomas Zurbuchen, Ron Zwickl

Acceleration at or close to the sun

- Are some or most particles accelerated at or close to the flare site?
- Why are some events rich in heavy nuclei such as Fe?
- What are the causes of high-energy (>30 MeV/nucleon) variability in SEPs?
- Particle acceleration at perpendicular shocks vs. parallel shocks
- What determines when there will be a rapid time to maximum (e.g., Jan 20, 2005) and when there will be a gradual time to maximum (e.g., October 28, 2003)? (also a transport issue?)

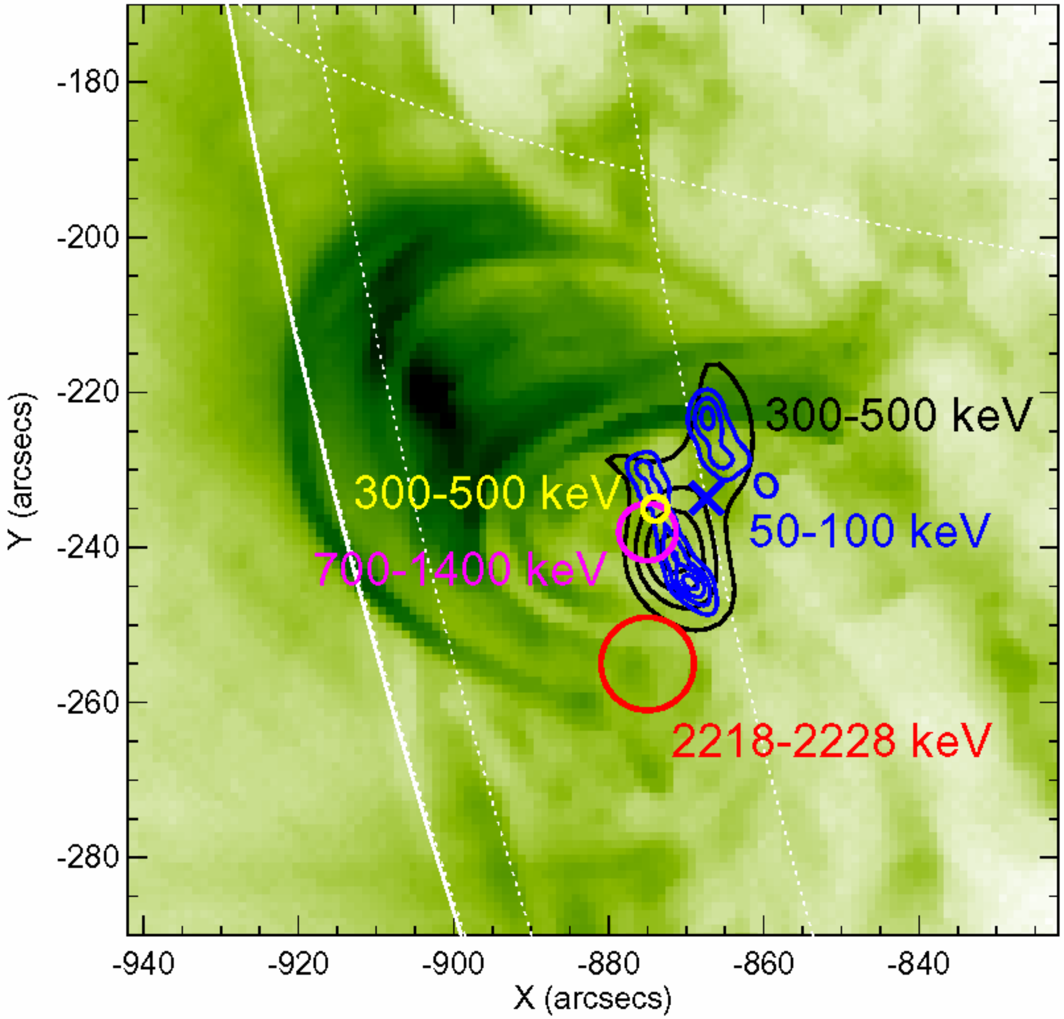
Wintergreen workshop, Group C report

Acceleration site --

- *in the low corona (~< 1Rs)*

- *or further out? (several to several 10s of Rs)*
- *do both types of events occur?*

New Physics Insights from Current Work -



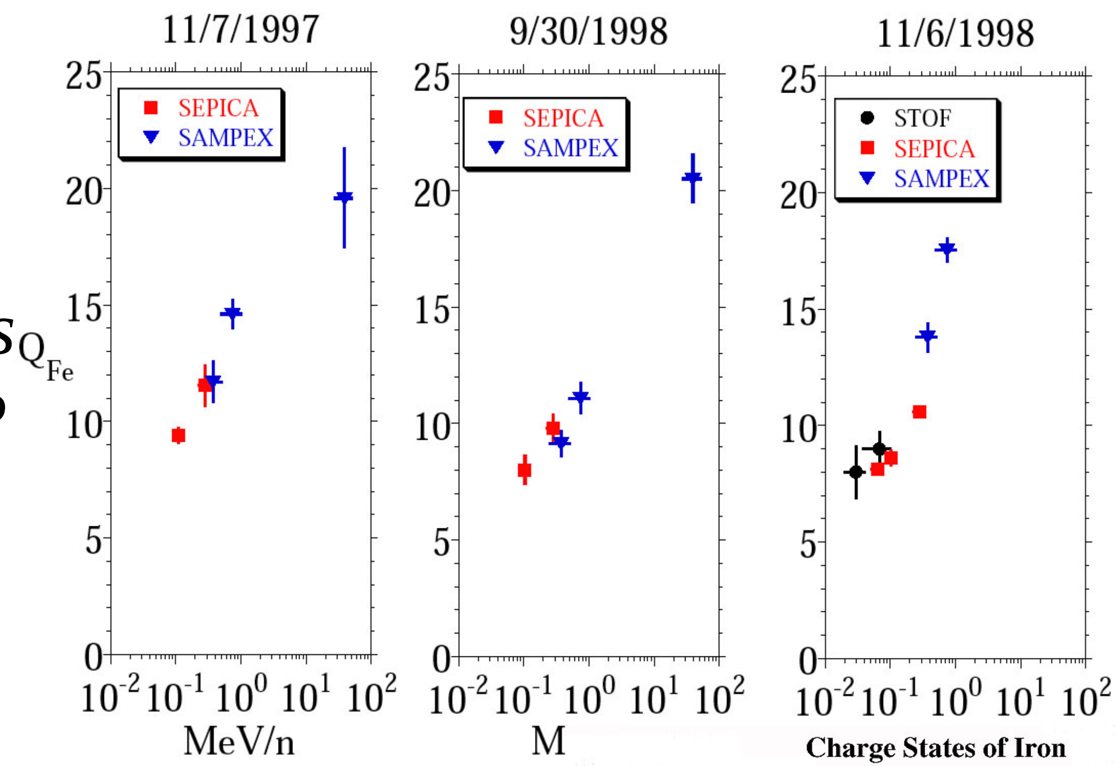
RHESSI and TRACE allow imaging of energetic electrons (blue) and ions (red) in a solar flare --

surprisingly, they are in different locations

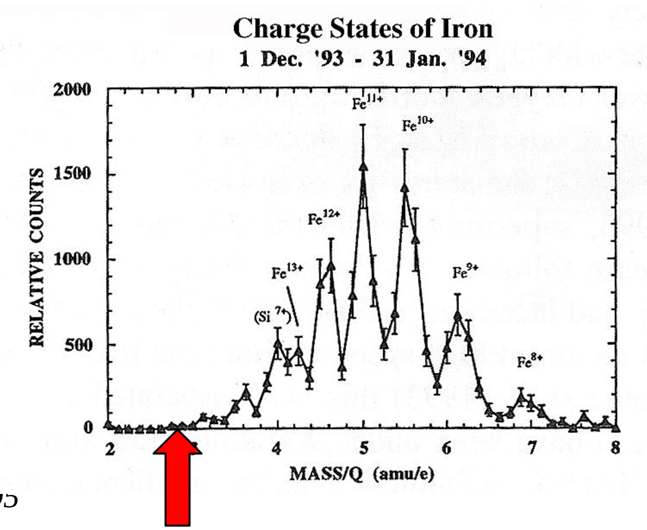
July 23, 2002 event
courtesy Bob Lin

Wintergreen workshop, Group C report

Energy dependent Iron Q states in large SEP events --

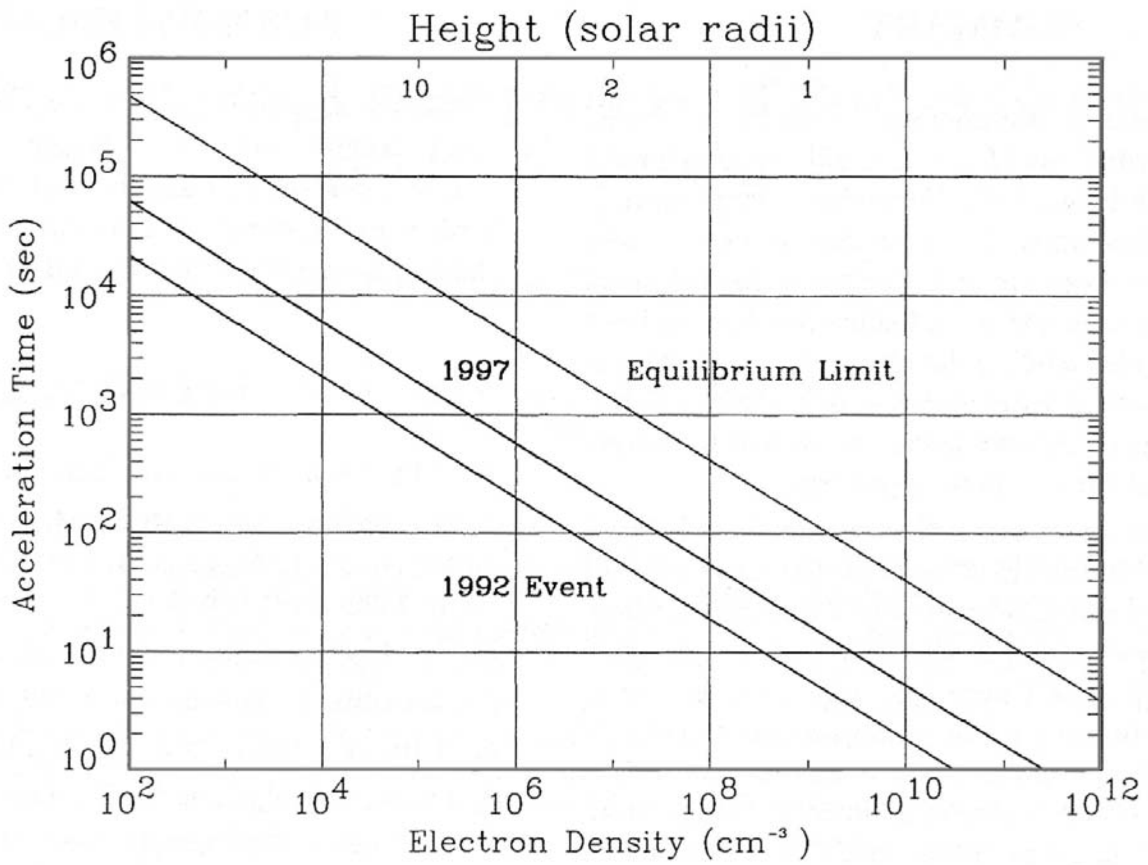


Note that the <Q> = 20 is virtually absent in the solar wind



Popecki et al., Proc. 28th ICRC, 6, 3283, 2003; Galvin et al. SSR, 72, 65, 1995

Model of SEP stripping during acceleration --

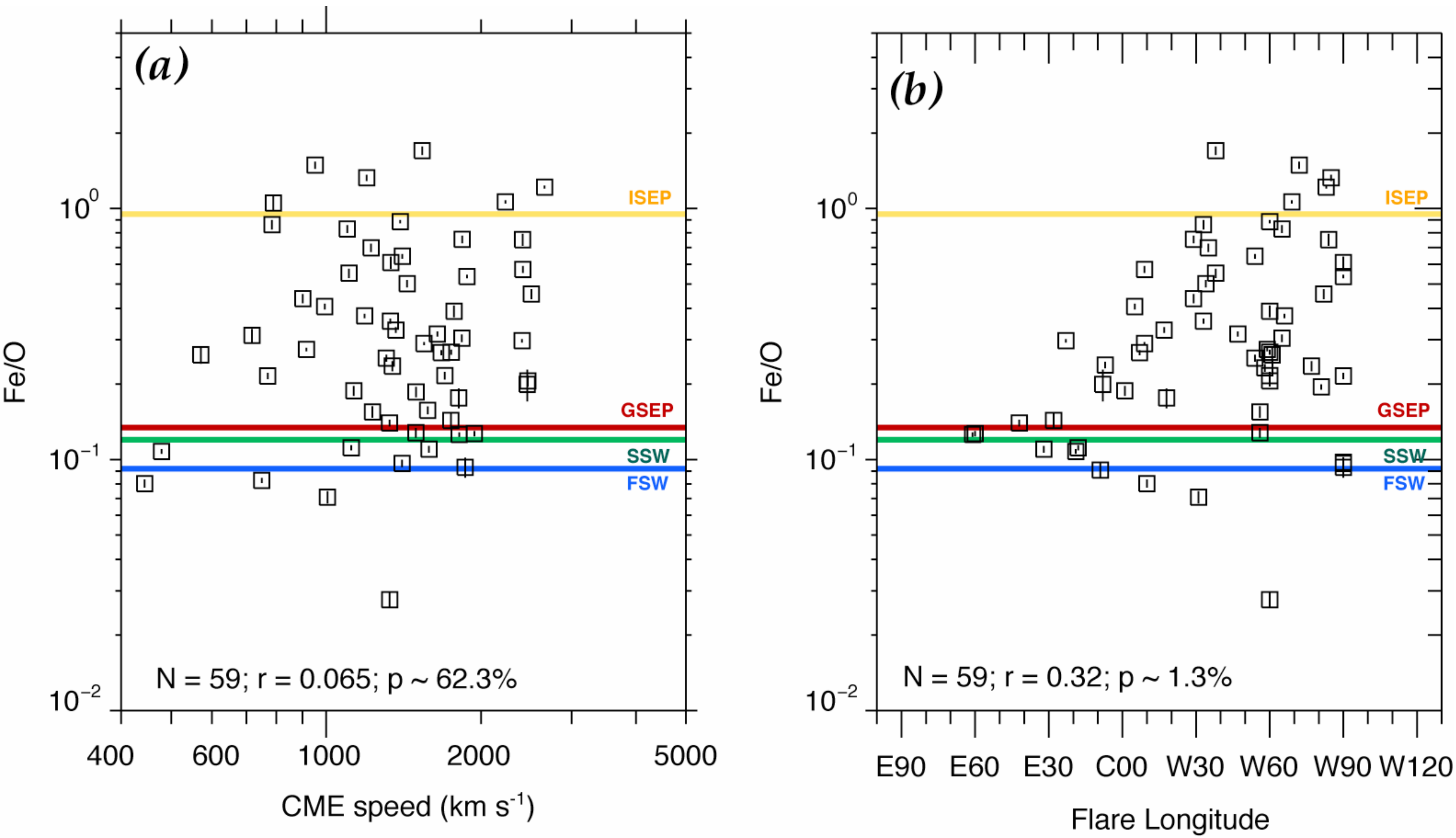


Barghouty & Mewaldt, AIP Conf Proc. 528, 71, 2000

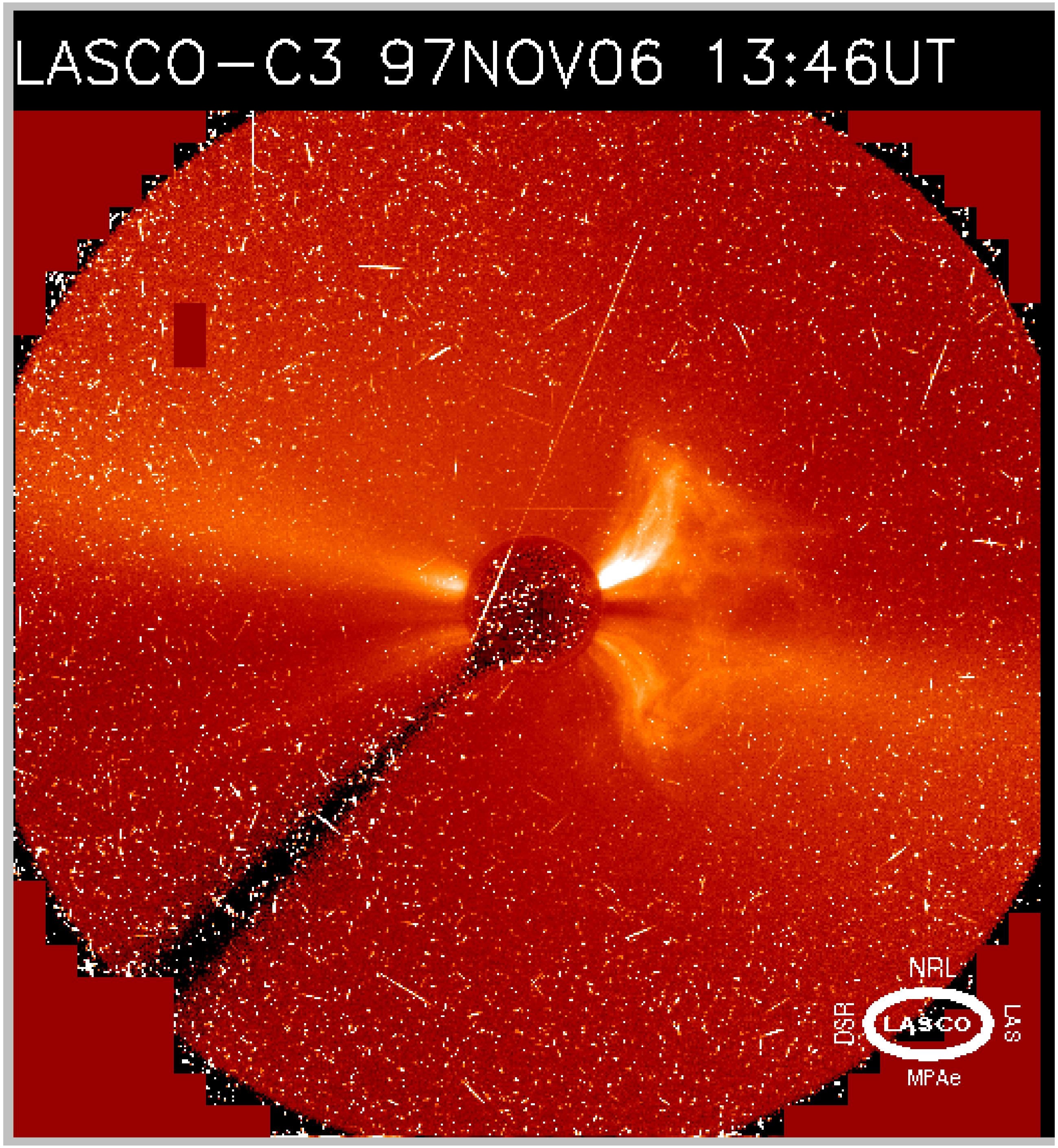
see also *Reames, Ng, and Tylka, GRL, 26*, 3585, 1999

- Shock acceleration model gives stripping proportional to density and acceleration time
- reproduces observed energy dependence of Q
- estimate ~1 Rs for Nov 1997 event if accel. time is comparable to x-ray time scale of ~10 s
- equilibrium model gives greater grammage & therefore lower height (~0.1 Rs)

Fe/O ratio is poorly correlated with CME speed & flare longitude



Desai et al., 2006, in preparation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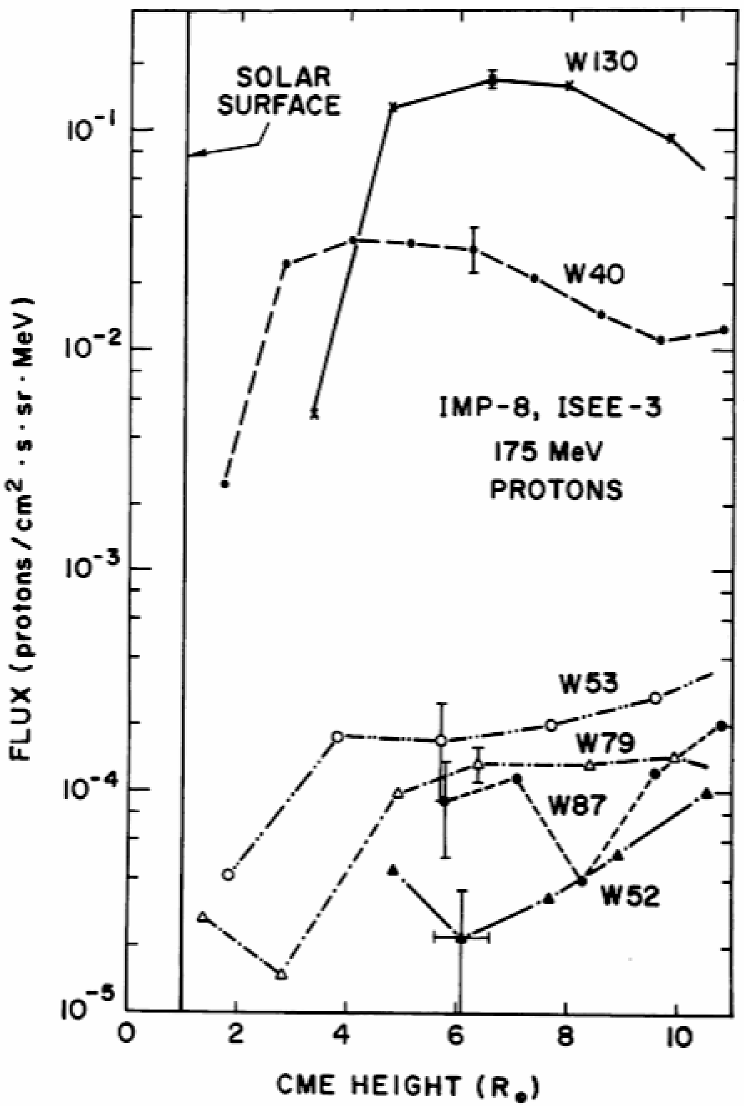


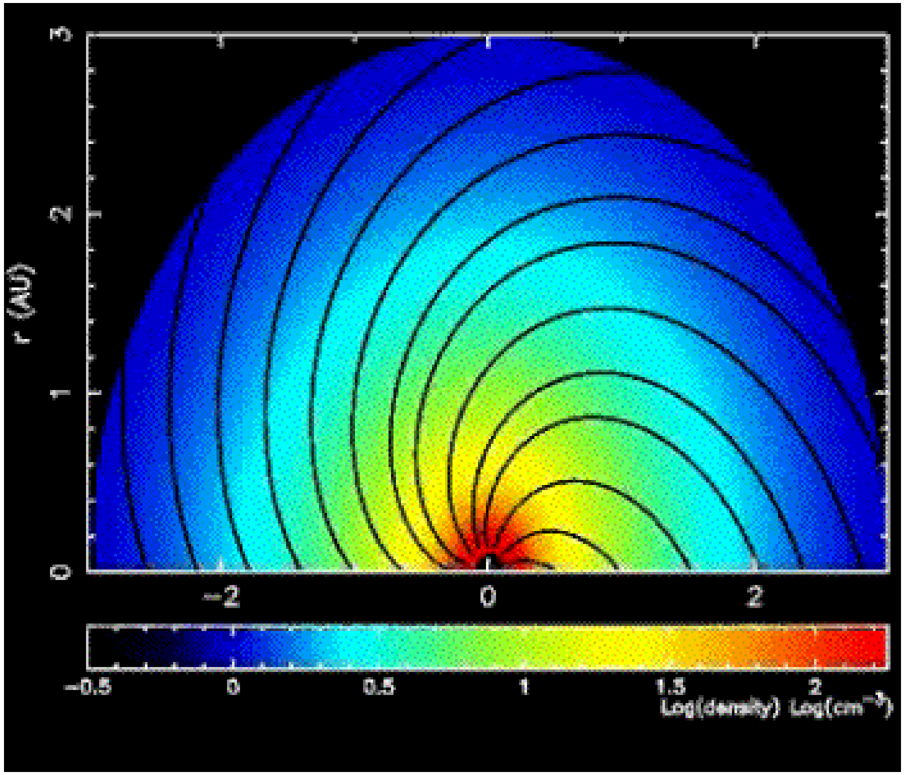
FIG. 1.—Profiles of injected 175 MeV proton fluxes corrected by eq. (1) vs. the heights of the leading edges of the associated CMEs observed by the Solwind coronagraph. Longitudes of associated Hα flares are given for each SEP event. From Kahler et al. (1990).

Kahler, ApJ 428, 837, 1994

Kahler 1994:

- *estimated SEP injection profiles as function of CME heights*
- *find that peaks of high energy protons (470 MeV - 4 GeV) occur when CME heights reach 5-15Rs or greater*
- *onsets occur no earlier than maxima of flare impulsive phases*
- *conclude that for these events the SEP injection is from a single CME-driven shock*

New Physics Insights from Current Work -



2D models of CME propagation in the heliosphere

increased realism of interplanetary magnetic field and IP medium

courtesy Gary Zank

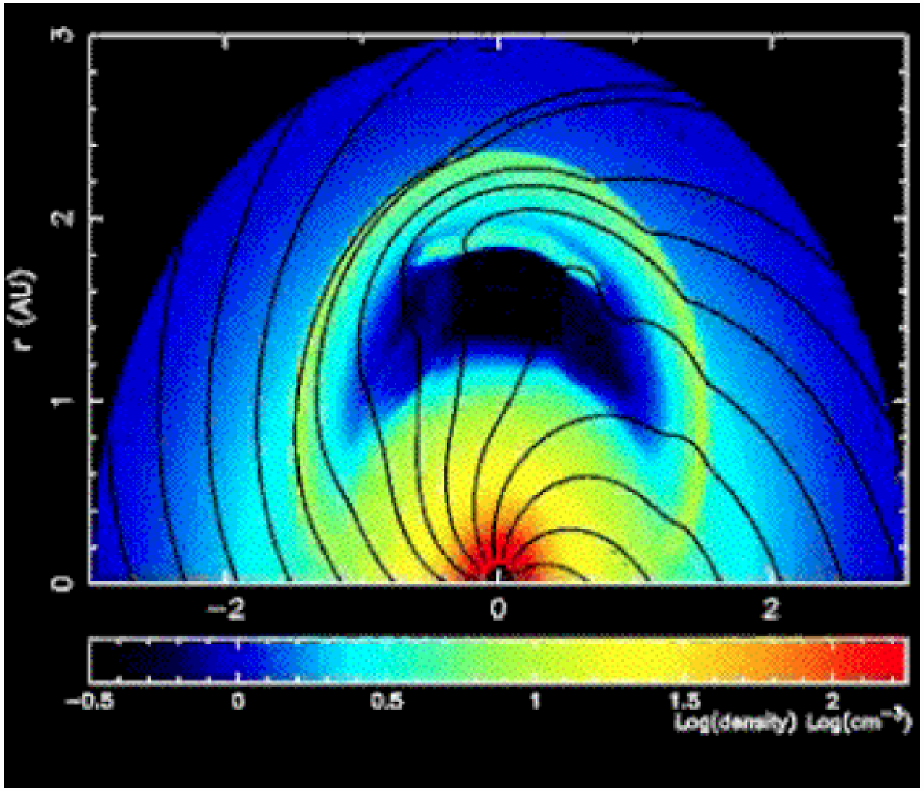
Wintergreen workshop, Group C report

What is the longitudinal extent of SEP acceleration along the shock?

How does the acceleration site connect magnetically to Earth?

How can one predict when there will be a large shock spike such as in the one in October 1989?

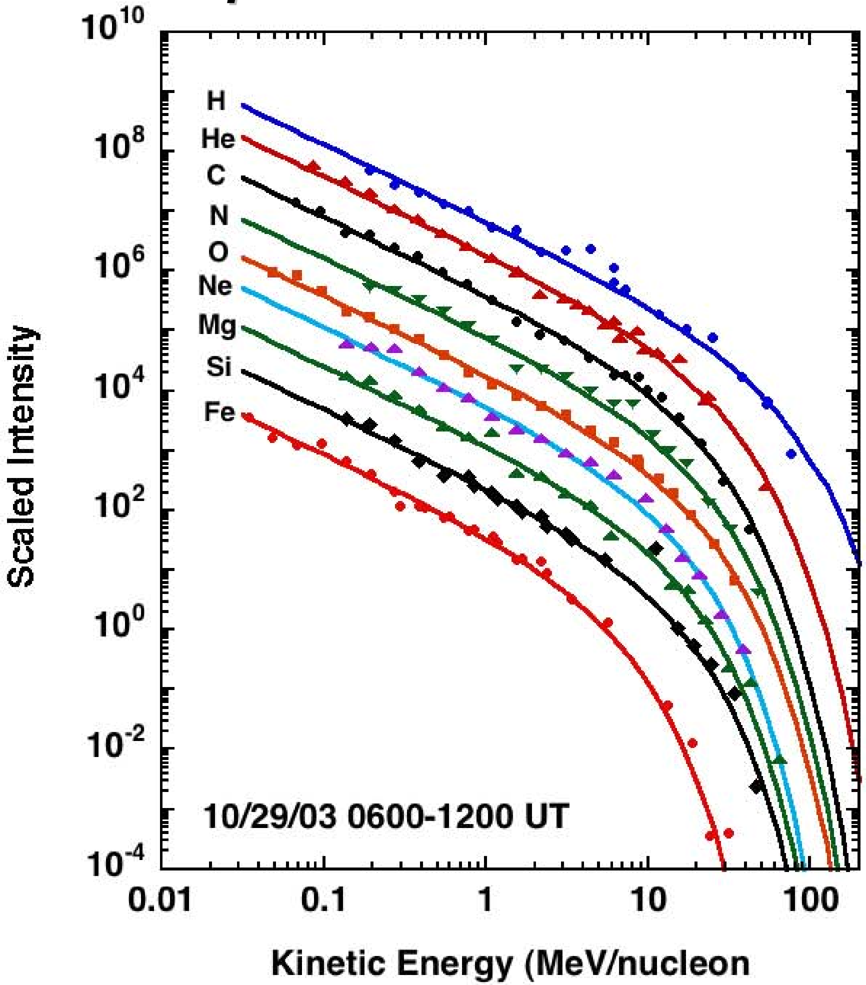
How do the maximum flux and fluence vary with distance from the Sun?

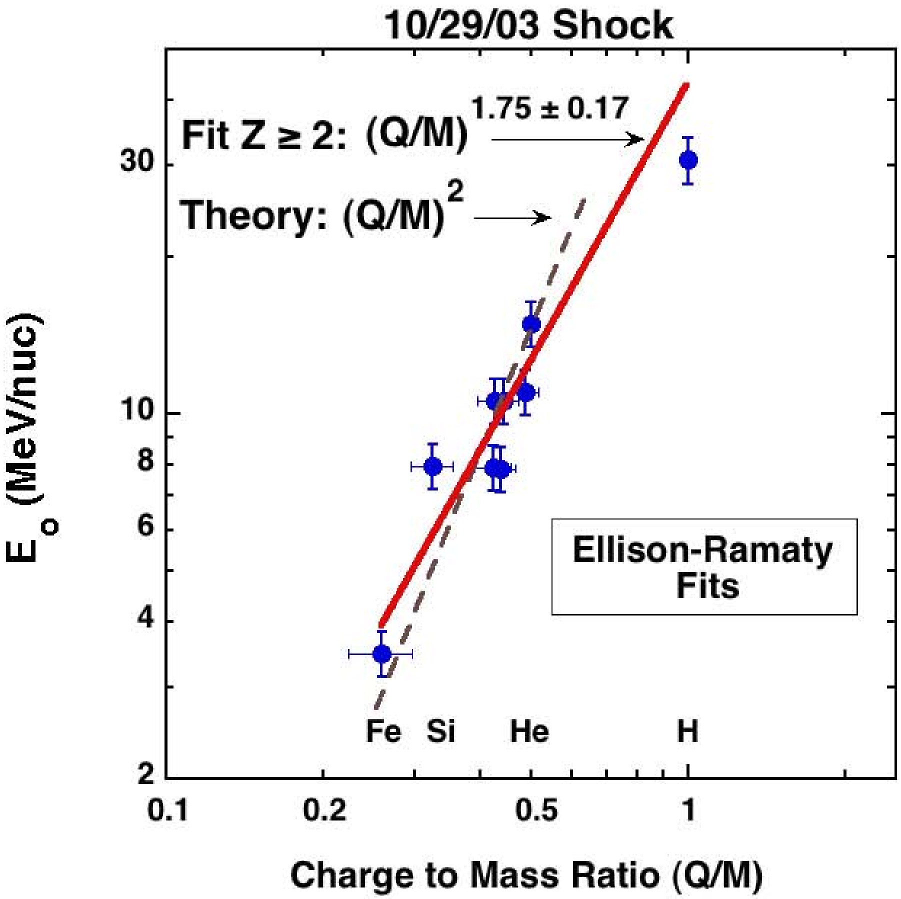


Do the flanks and nose of the shock accelerate particles with the same spectrum?

New Physics Insights from Current Work -

Spectral "breaks" as tracers of escape from shock--





Wintergreen workshop, Group C report

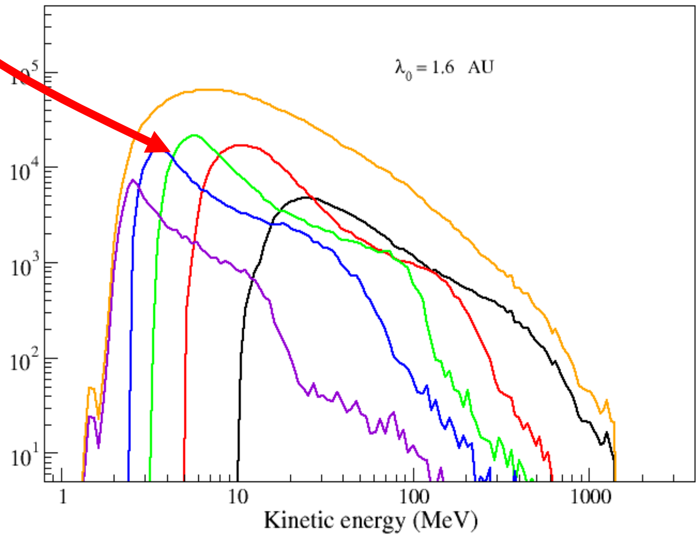
courtesy Dick Mewaldt

New Physics Insights from Current Work -

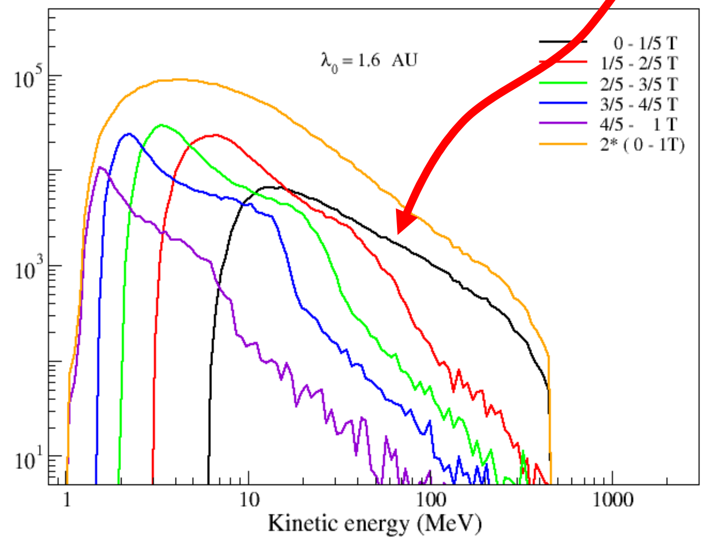
New models produce spectral breaks

Total or cumulative spectrum at 1AU, integrated over the time from shock initiation to the arrival of the shock at 1AU.

Strong shock case

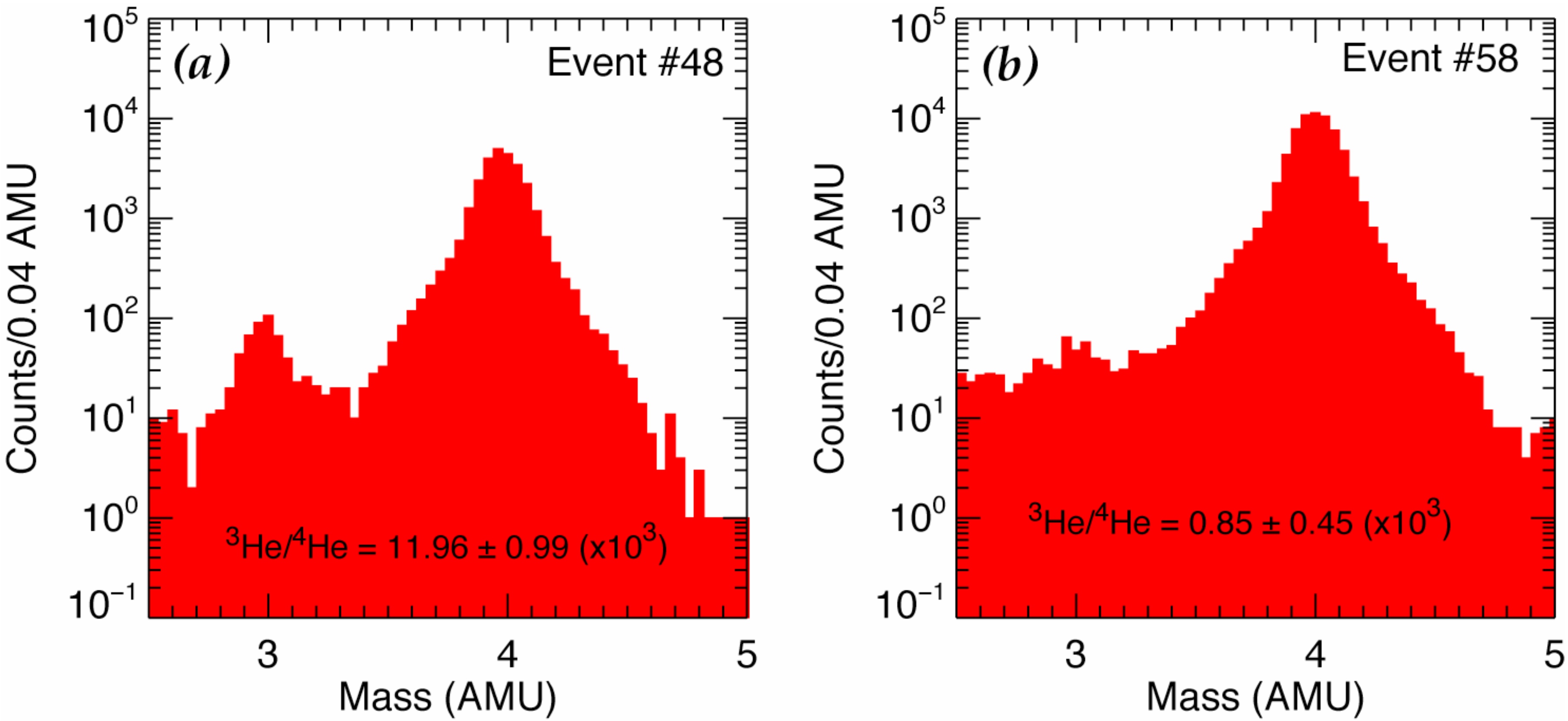


Weak shock case



courtesy Gary Zank
Wintergreen workshop, Group C report

He histograms for 2 LSEP events
29 of 64 events have finite ^{3}He



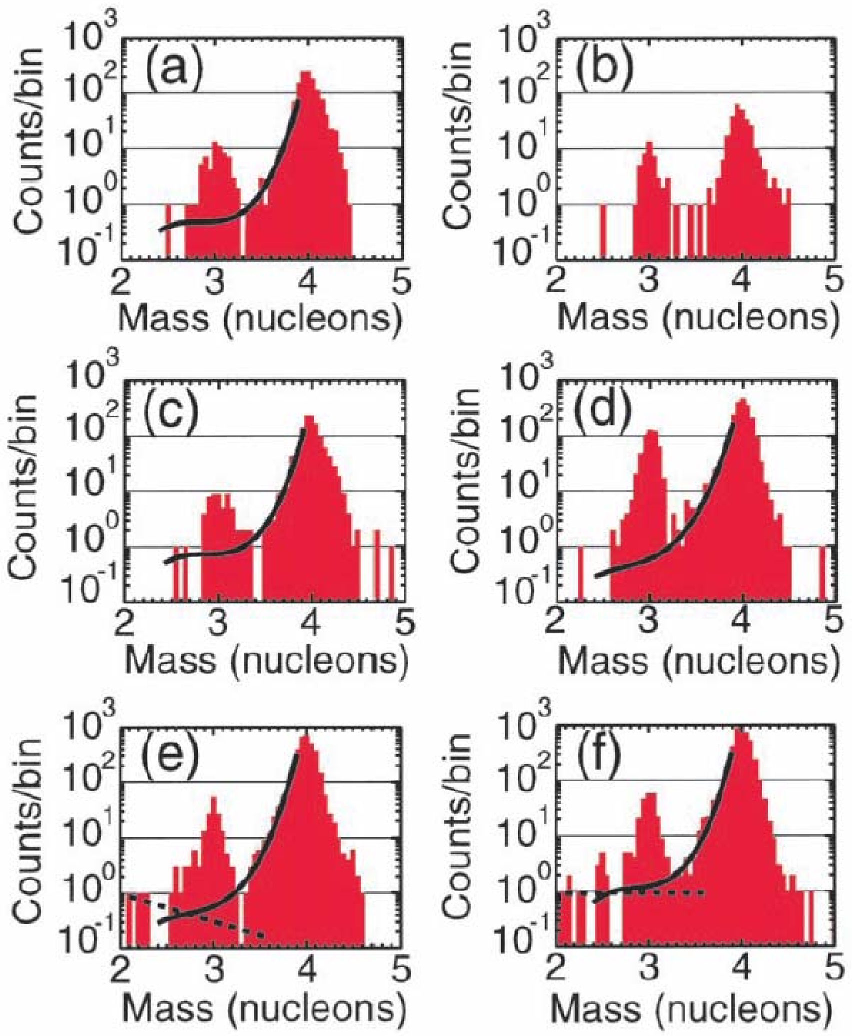
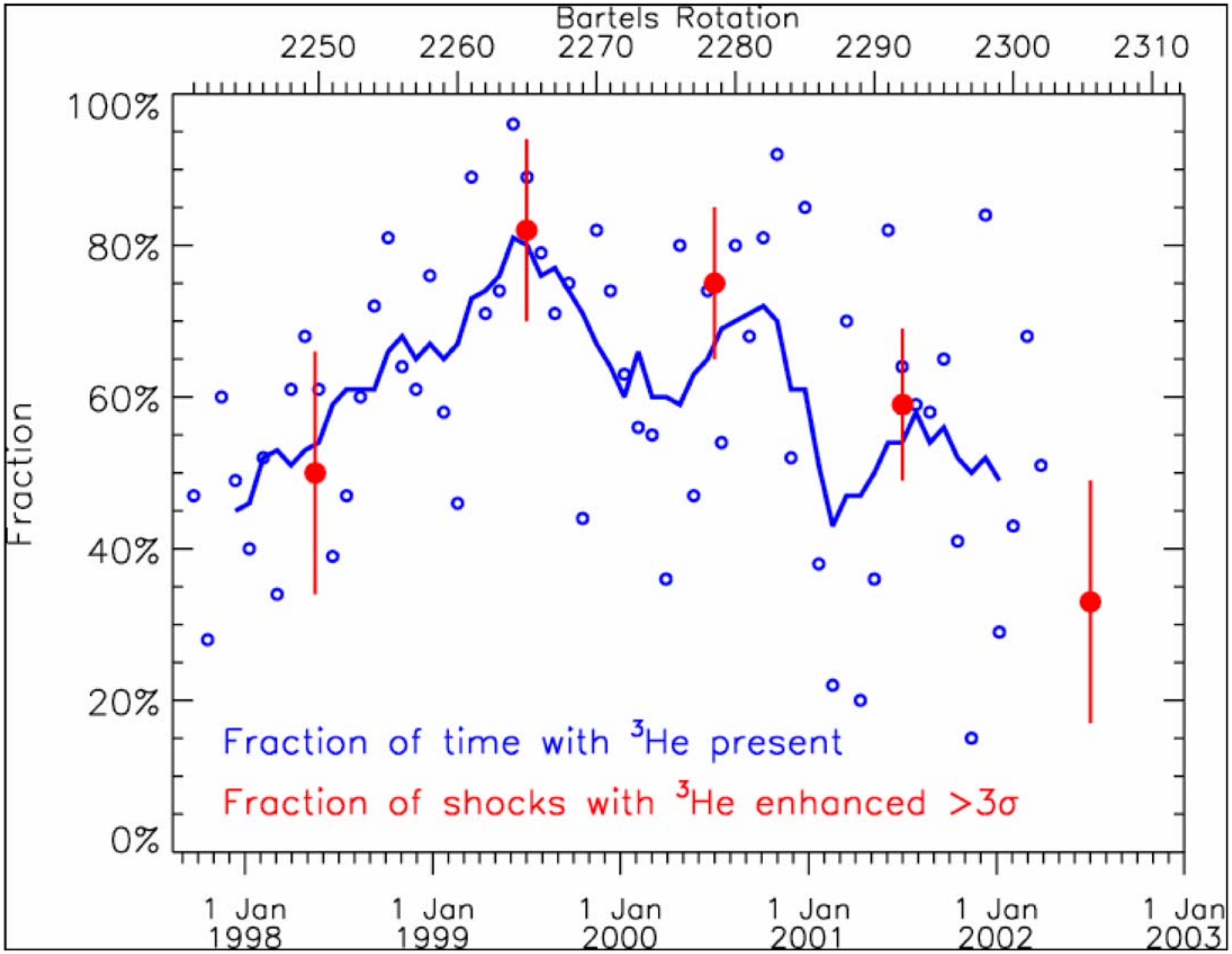


FIG. 2.—The 0.5–2.0 MeV nucleon^{-1} mass histograms for the six ^{3}He-enriched IP shock events listed in Table 1. The solid curves and dashed lines are used to estimate contributions of spillover from ^{4}He and the background, respectively, to the ^{3}He mass peak.

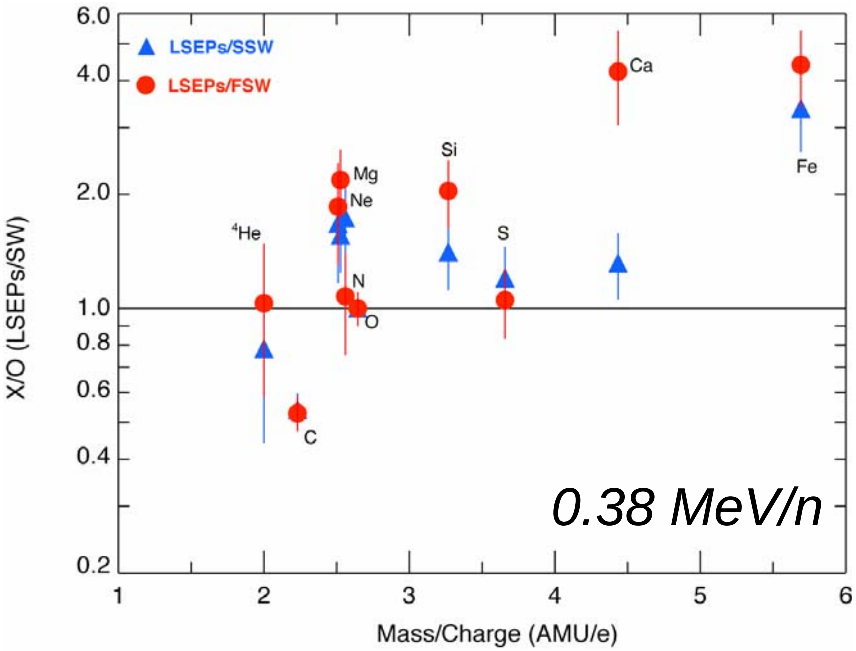
Mass spectra of energetic ^{3}He and ^{4}He ions in interplanetary shocks showing examples of large ^{3}He enrichments

Desai et al., *ApJ Letters*, 2001

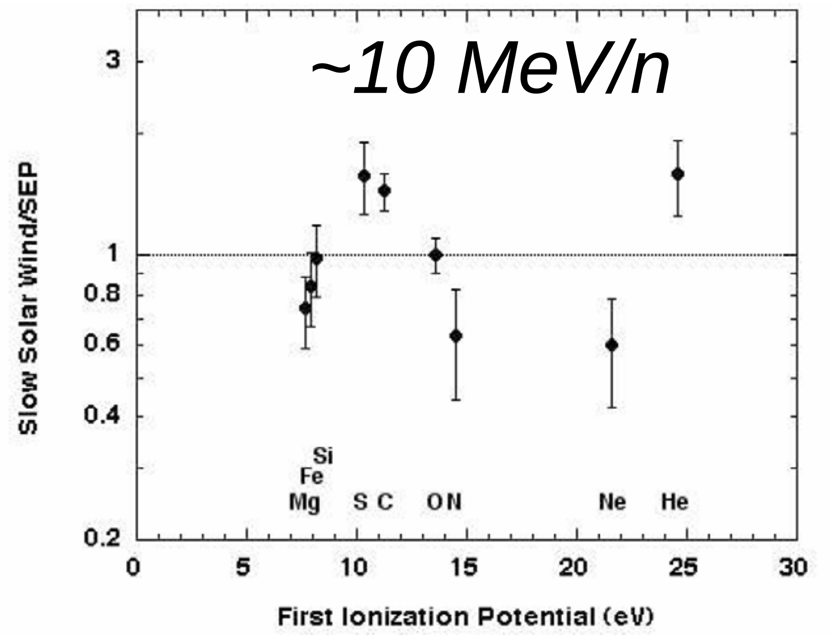


Stone, Desai, & Wiedenbeck, 2003

LSEP abundances are not organized by M/Q when normalized to solar wind values

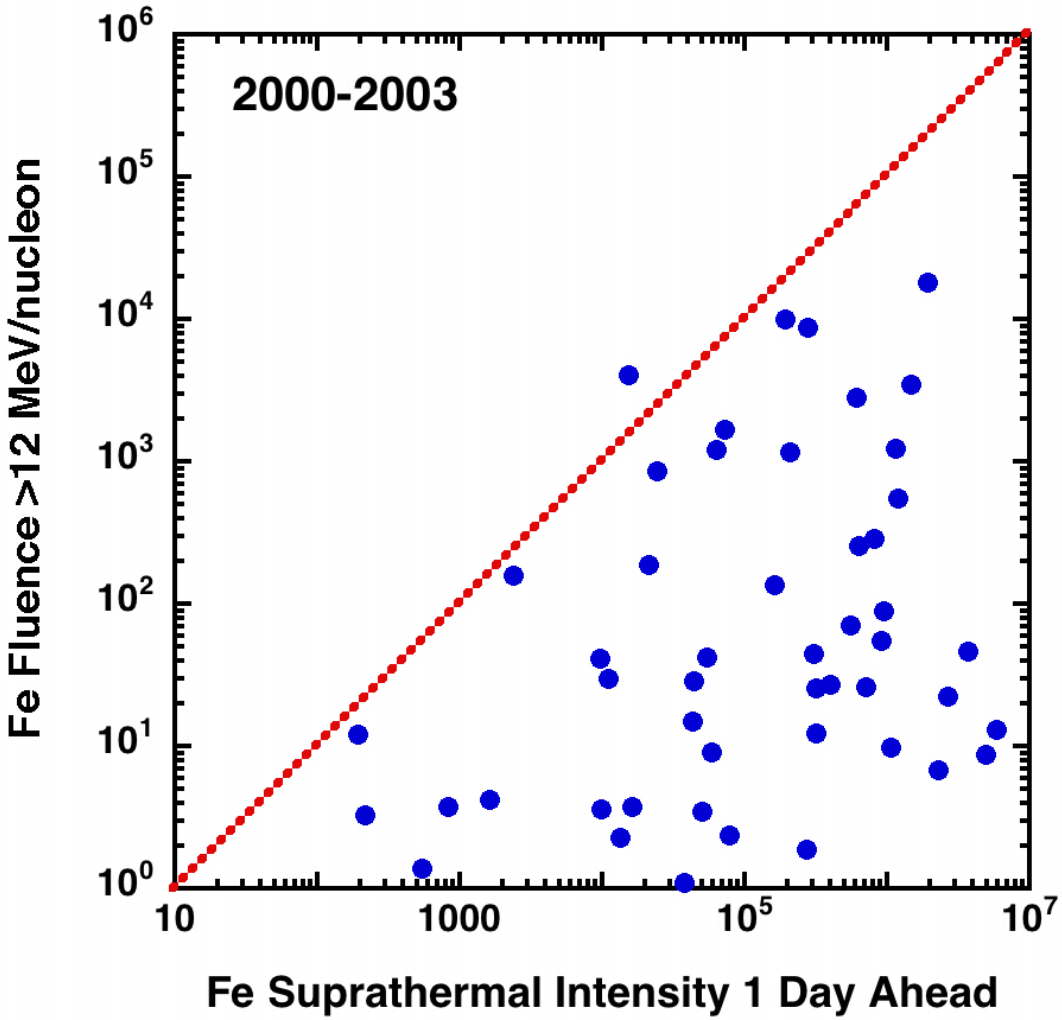


Desai et al., 2006, in preparation



Mewaldt et al., Adv. Space Res., 30, 79, 2002

New Physics Insights from Current Work -



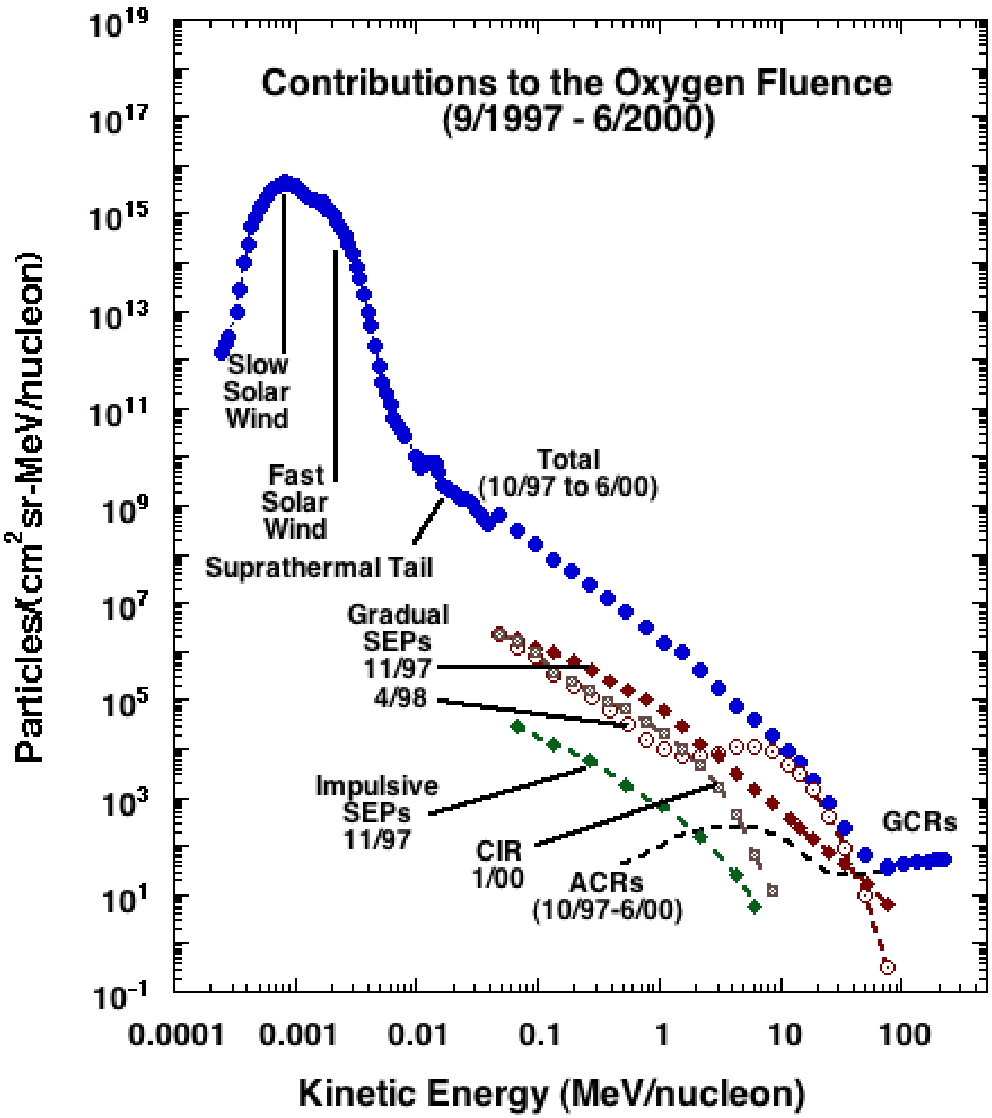
Large SEP event maximum intensities depend on prior suprathermal seed population -- may be critical for predictions

SEP Events 2000-2003

courtesy Dick Mewaldt

Wintergreen workshop, Group C report

New Physics Insights from Current Work -



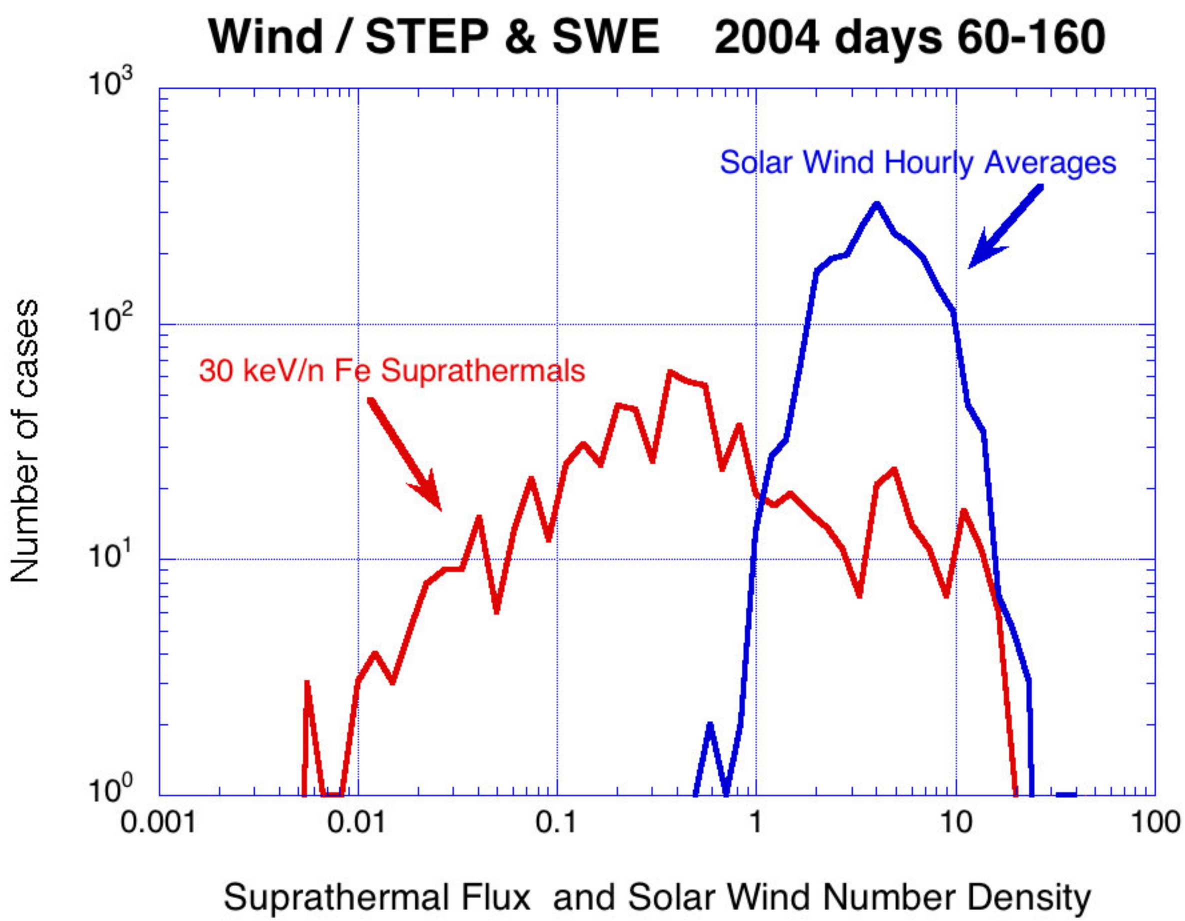
New evidence that suprathermal ions are the seed population for CME driven shock accelerated particles

If so, then <u>intensity</u> of SEP events will depend on ST ions

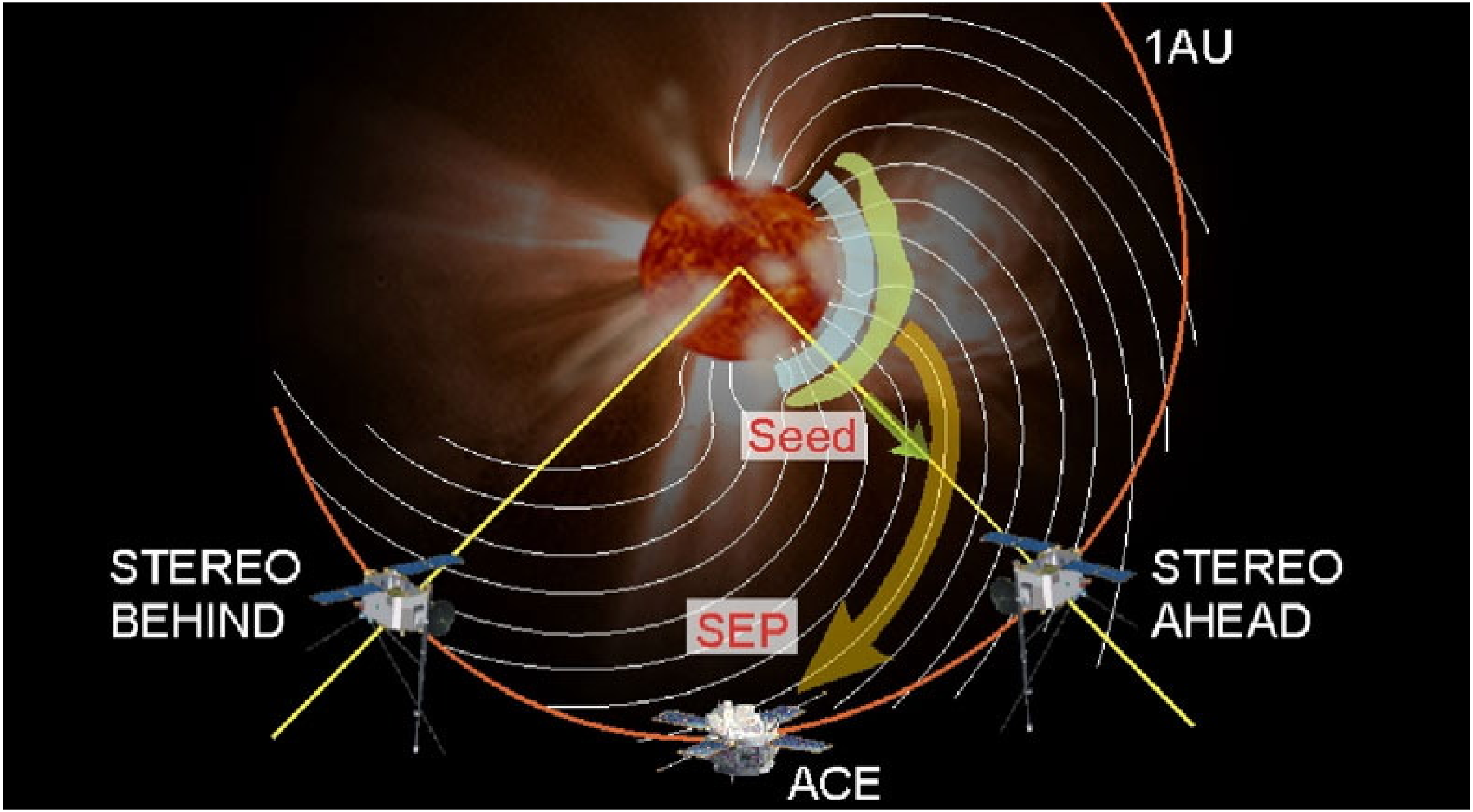
courtesy Dick Mewaldt

Wintergreen workshop, Group C report

Suprathermals show ~100 times more variation in intensity than solar wind density -- possibly a critical issue in energetic particle intensities



STEREO + 1 AU measurements will give unique new perspective



Wintergreen workshop, Group C report

courtesy Mihir Desai

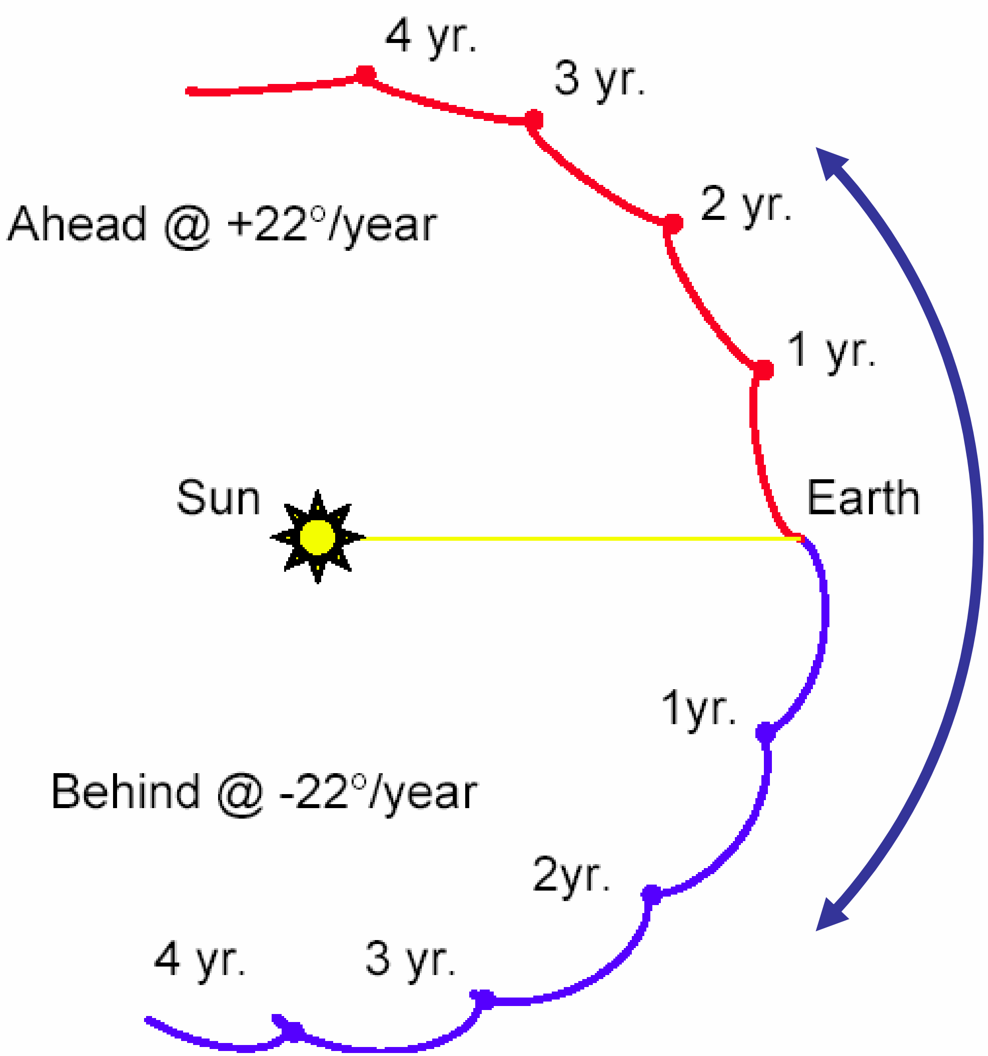
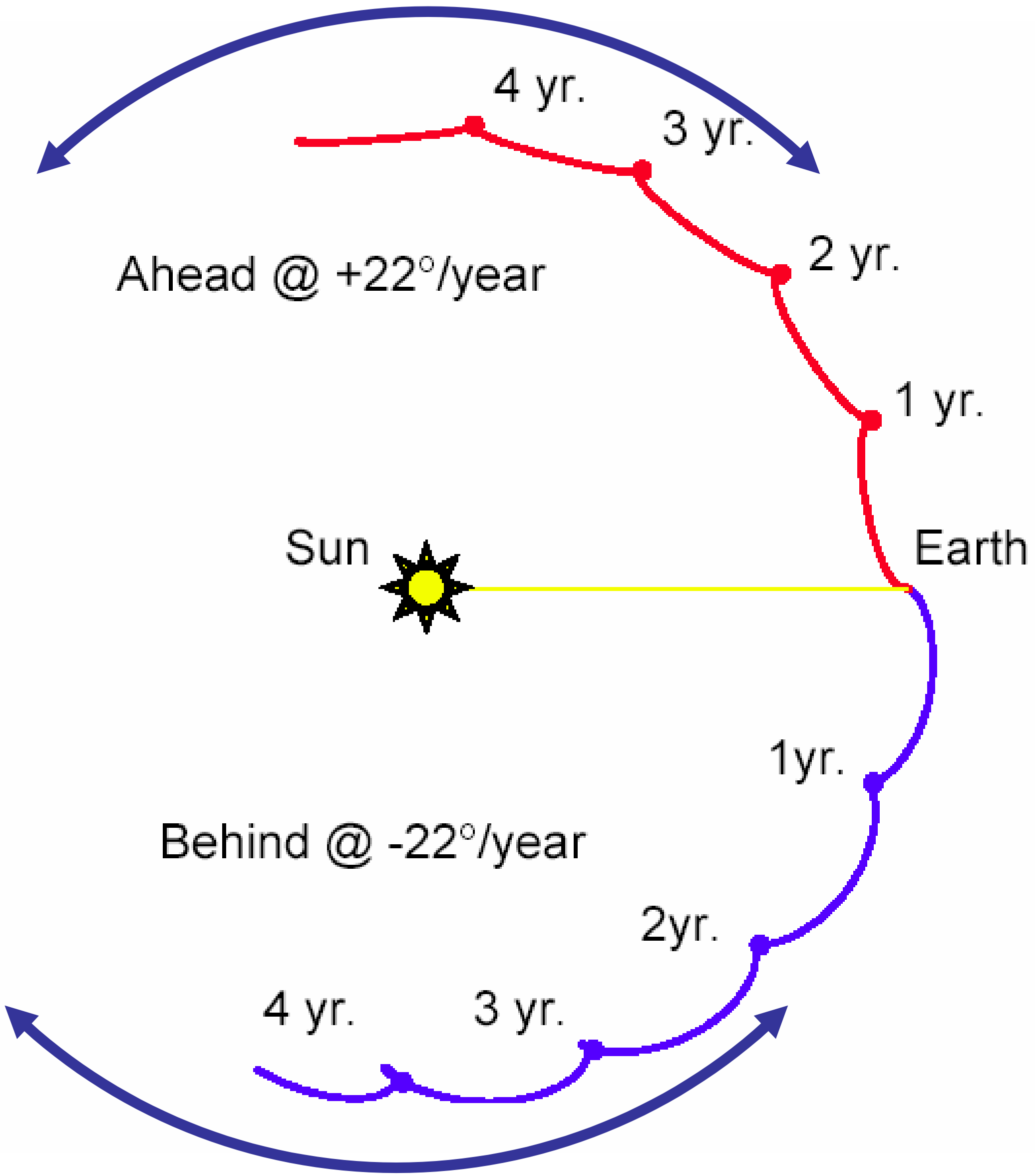


Figure: P. Sharer, STEREO PDR

Initial Studies:

- ***CME geometry***
- ***Shock surface roughness***
- ***Particle acceleration***
- ***Sites of Acceleration***



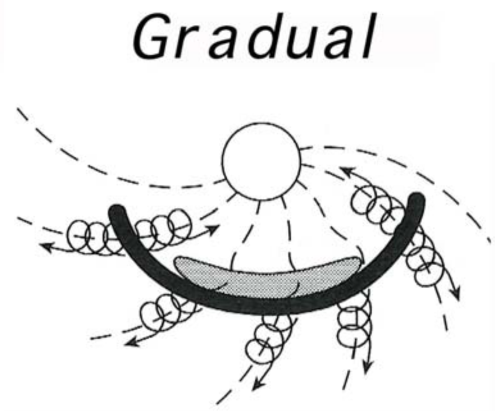
Later Studies:

- *CME images & in-situ properties*
- *Particle acceleration sites (maybe)*

Figure: P. Sharer, STEREO PDR

SUMMARY --

GRADUAL SEPs:



- *new properties observed with advanced instruments and addressed with much more sophisticated models -- compared to impulsive events, these are much better understood.*

- *seed population: solar wind composition does not fit range of either elemental abundances or ionization states. Suprathermal seed population identified as playing a key role, but this region not well understood. Mixtures of seed populations? Role of stripping?*

- *acceleration site: low in the corona (Type III bursts, stripping) or further out -- how much further out (several Rs or more) ?*

- *shock acceleration is mechanism of choice for most models -- role of acceleration vs. release vs. IP propagation (w waves) not yet separated*

SUMMARY --

Impulsive SEPs:

• *may be fundamental to understanding processes such as reconnection and associated particle acceleration*

• *play a significant role in providing at least part of the seed population for large SEP events*

• *CHALLENGE for STEREO / SOLAR-B: how to select & observe the parent regions?*

Gradual SEPs:

• *critical for large scale events & space weather*

• *STEREO / SOLAR-B / ACE will provide multi point "ground truth" measurements allowing tests of models & scenarios that are now largely only partly tested or untested (shock / flux rope topology; seed particles; SEP release; SEP acceleration)*