

Solar Energetic Particles: recent observational progress for shock-related and impulsive events

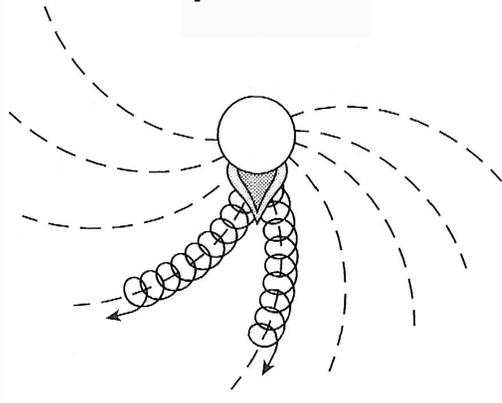
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and Joe Dwyer³*

¹University of Maryland, ²Aerospace Corporation, ³Florida Institute of Technology

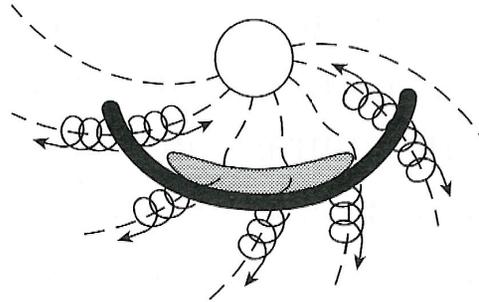
*Shine 2004 Workshop, Big Sky, Montana
June 27 - July 2, 2004*



Impulsive



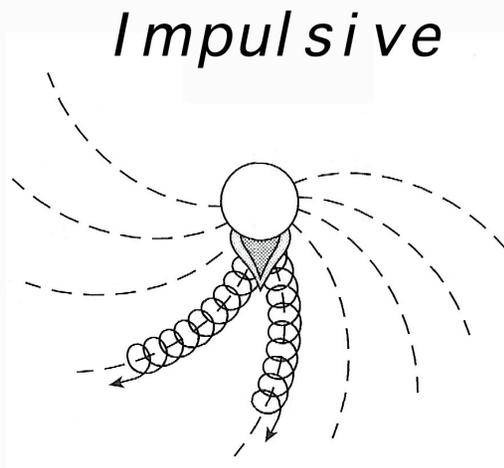
Gradual



Issues:

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

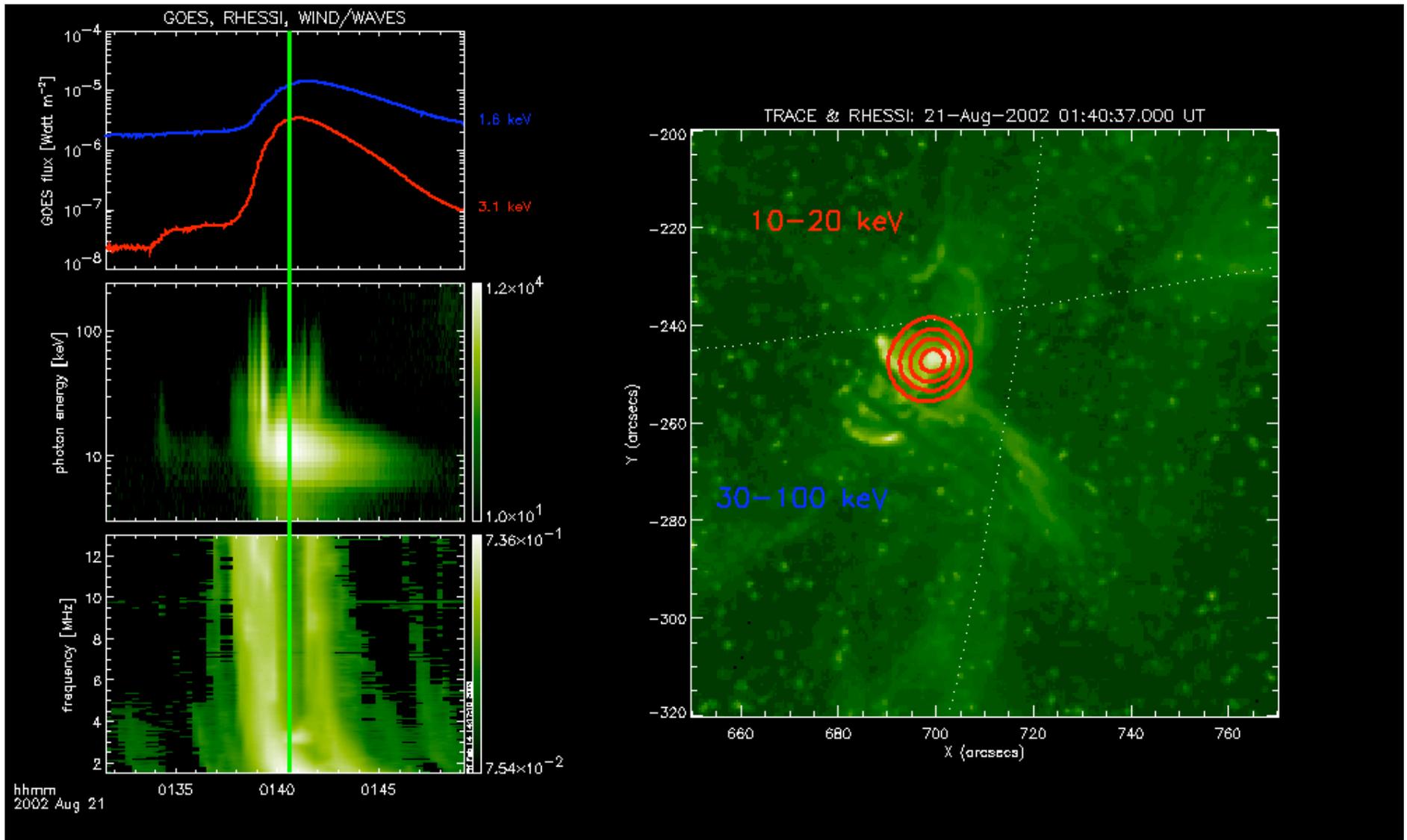
After Reames, SSR, 1999



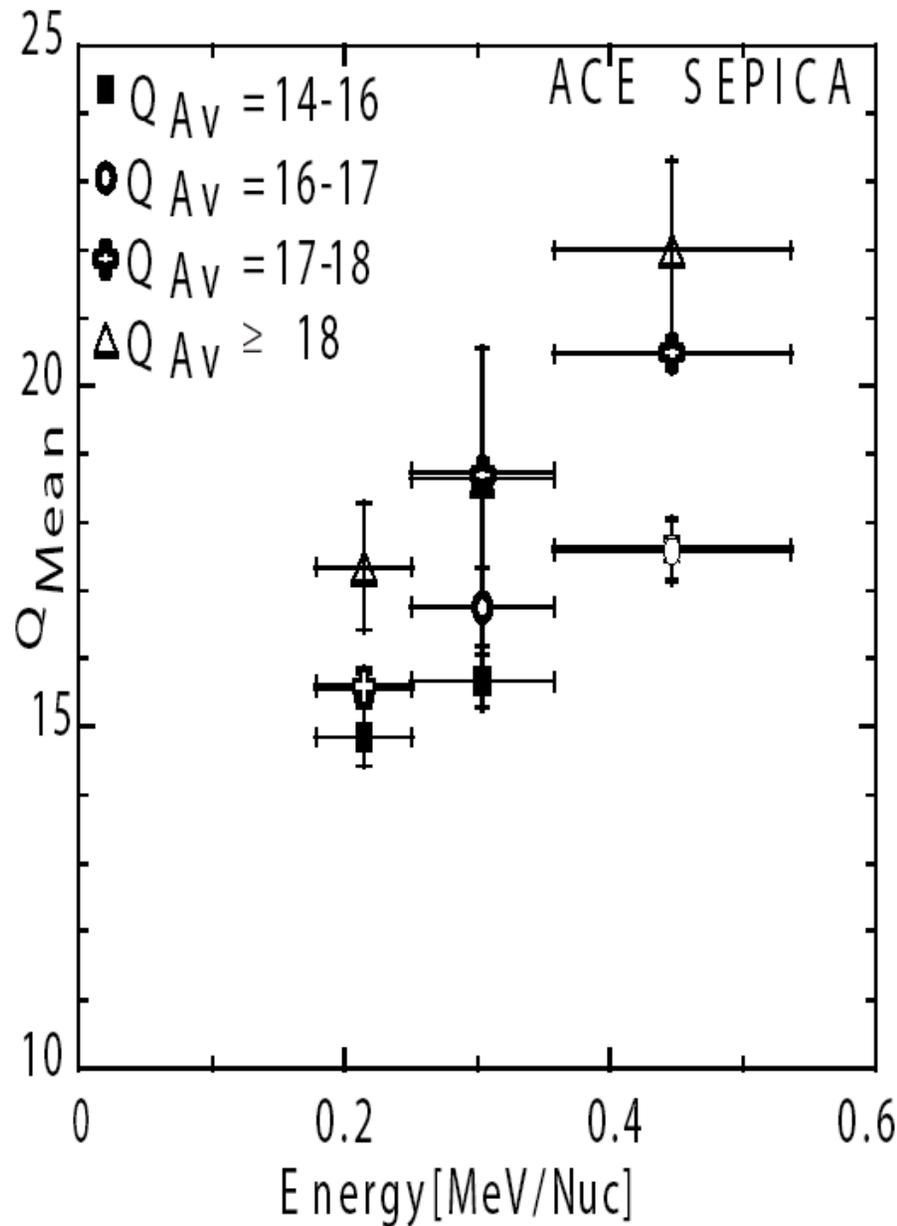
*Recent progress enabled
by particle instrument
improvements in
sensitivity & resolution;
RHESSI / TRACE*

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

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



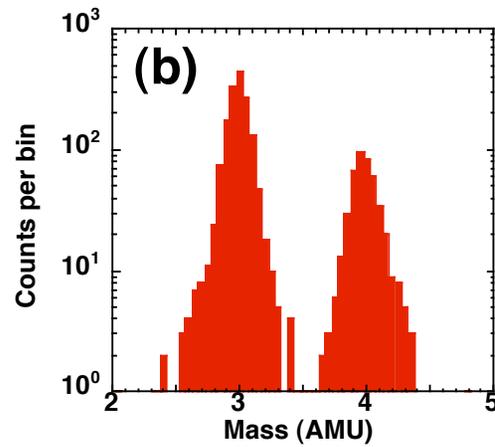
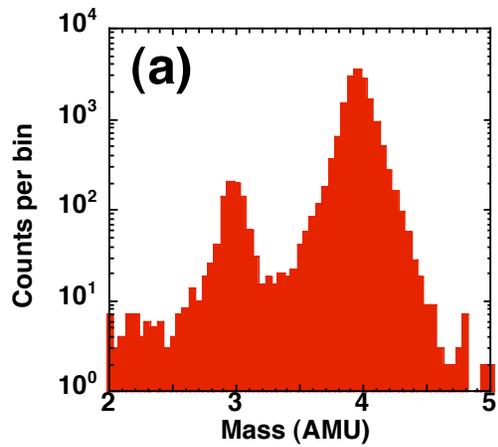
Krücker et al., Fall AGU, SH11D-030, 2003



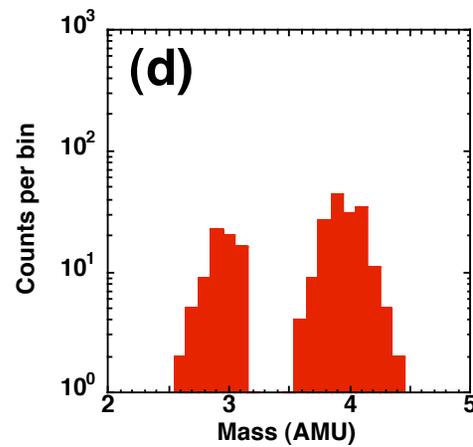
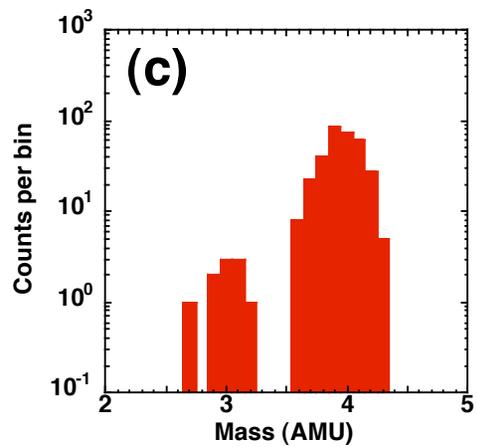
Strong energy dependence of the Fe Q state attributed to stripping during and after acceleration

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

ACE He mass resolution

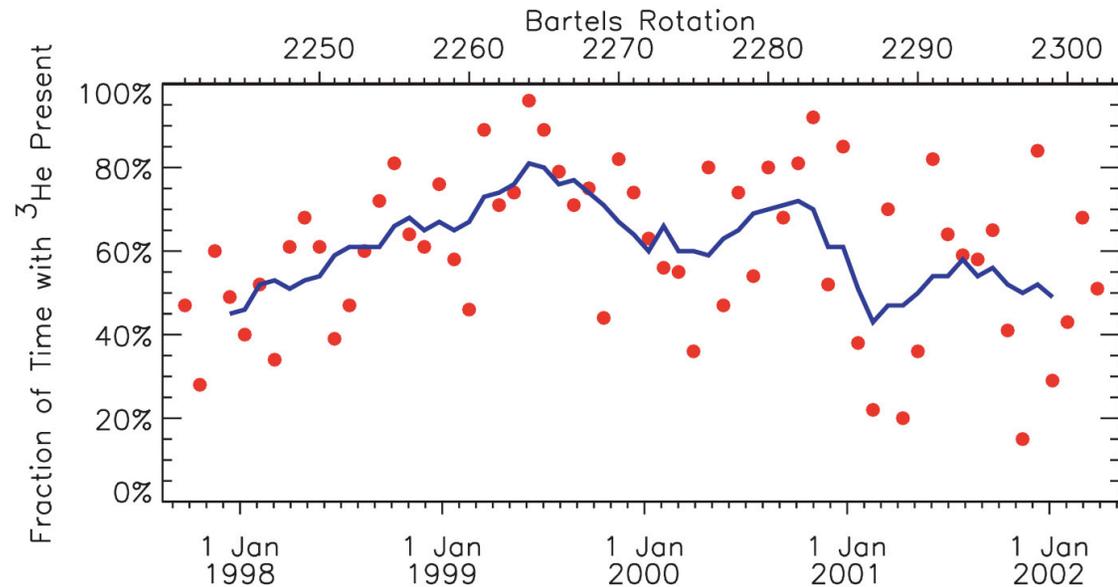
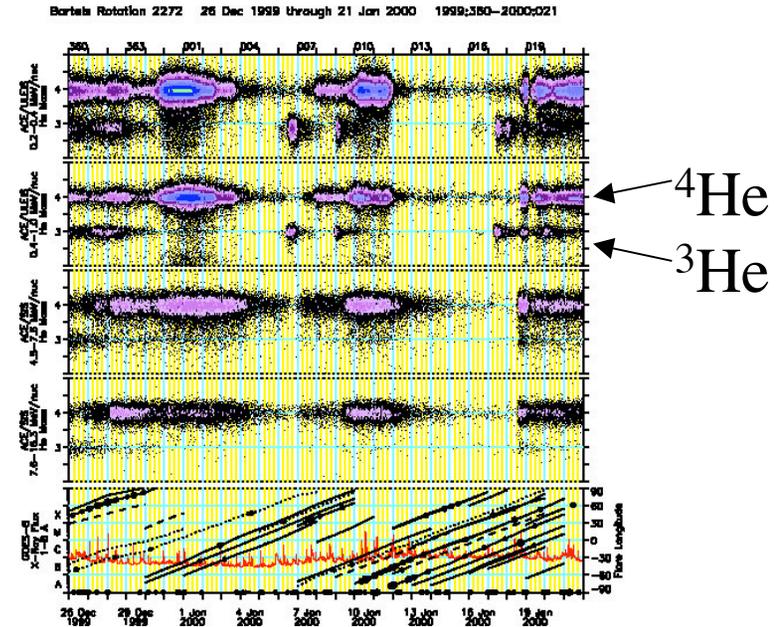


□ 750 keV/n



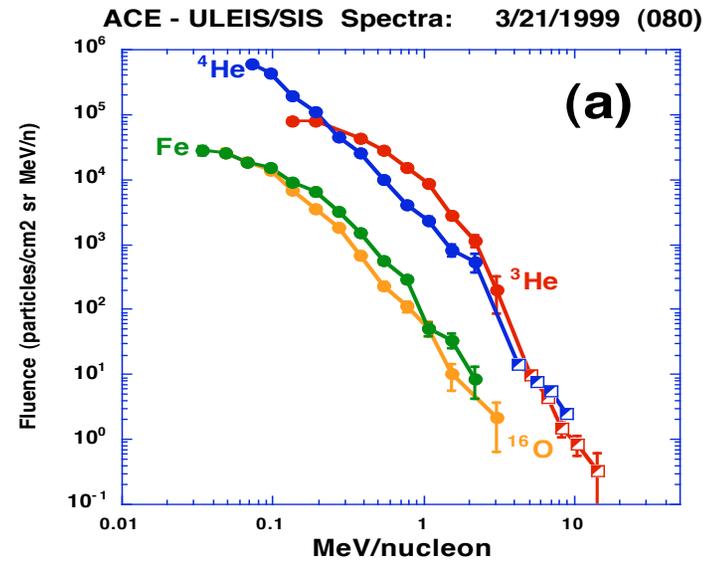
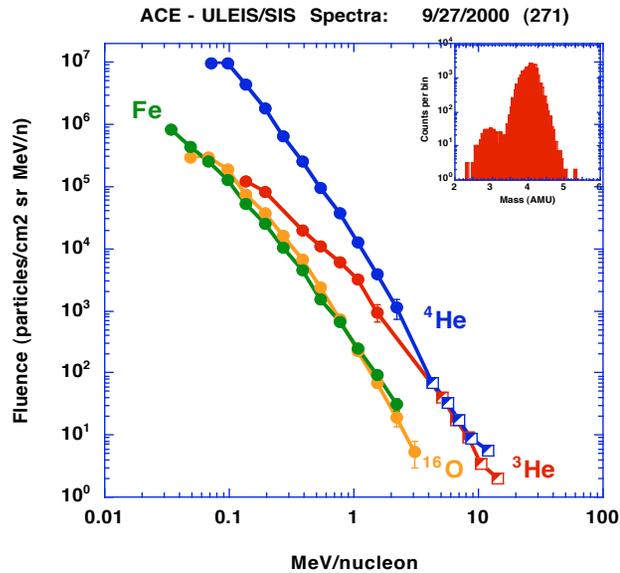
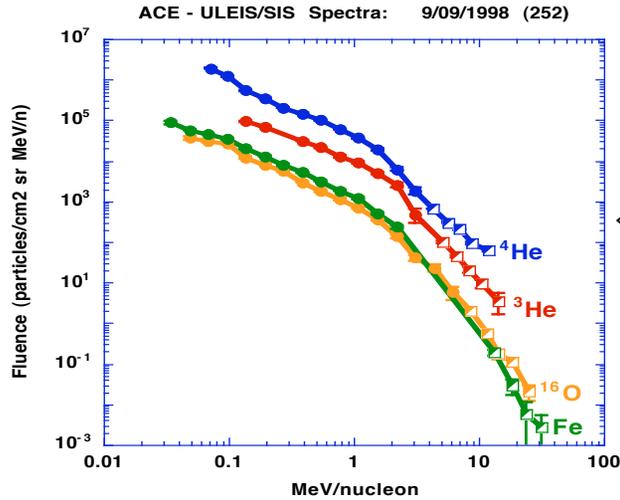
□ 7.5 MeV/n

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

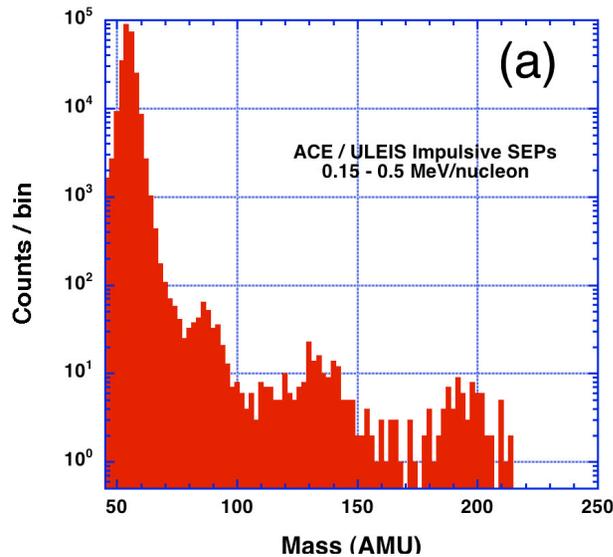


Variety of spectral shapes:

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



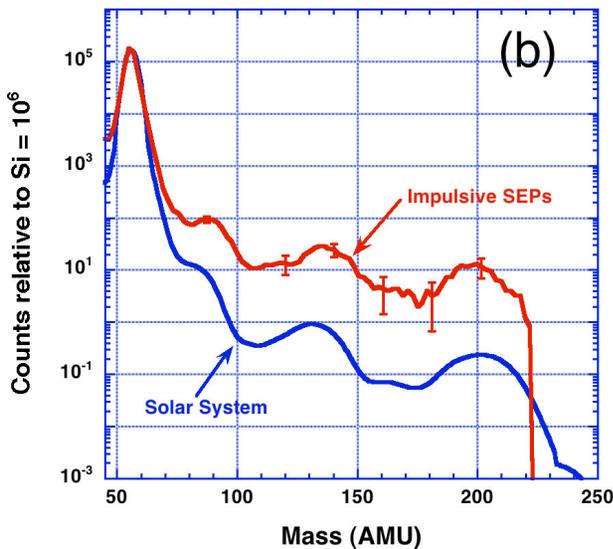
UH nuclei in ^3He rich flares --



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.

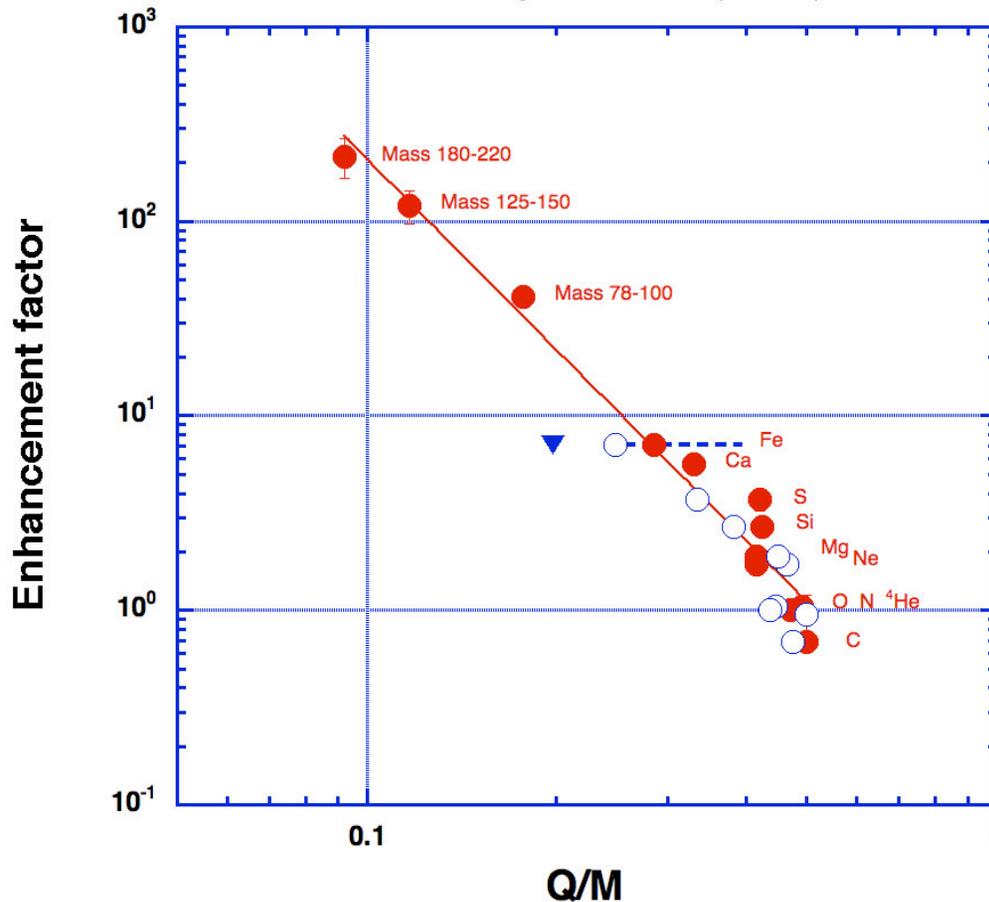
Mass histogram of events showing Fe peak and range out to ~220 AMU; note structure



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

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

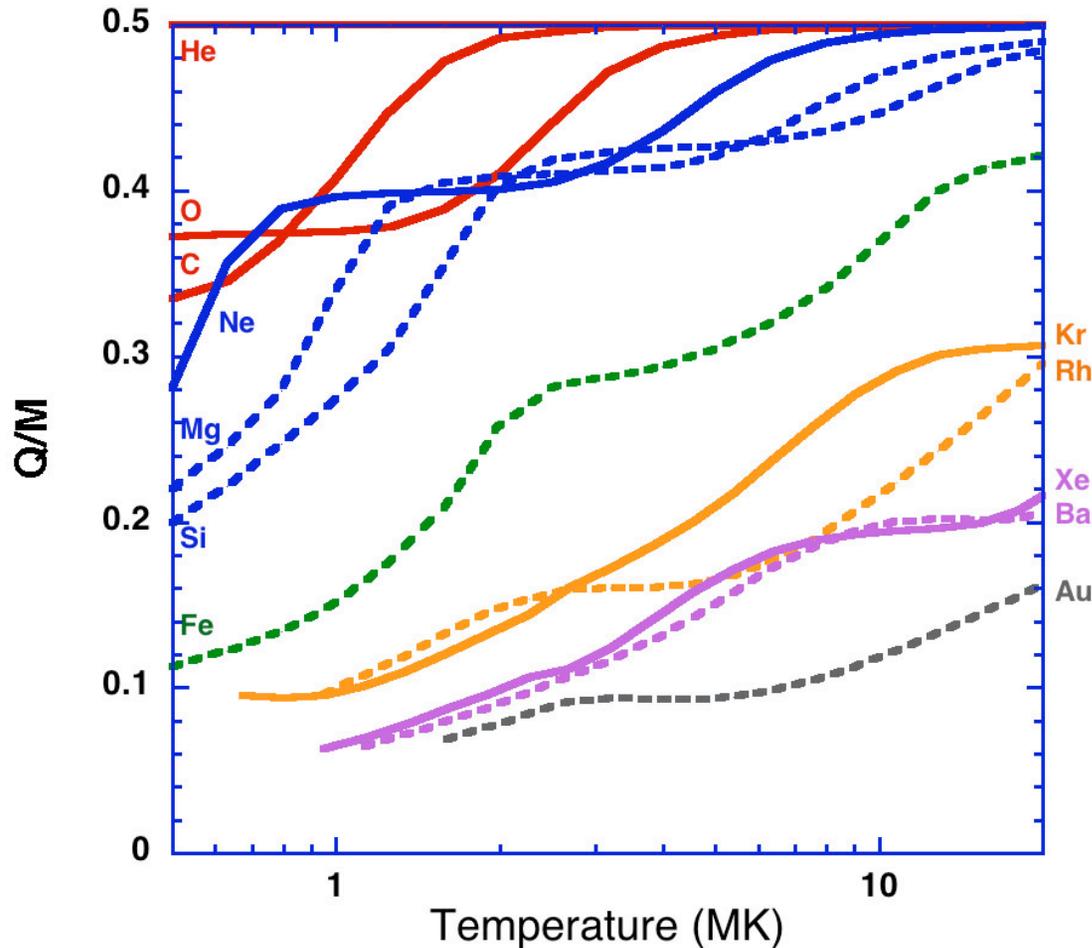
UH nuclei in ^3He rich flares --



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 Q s are ambiguous

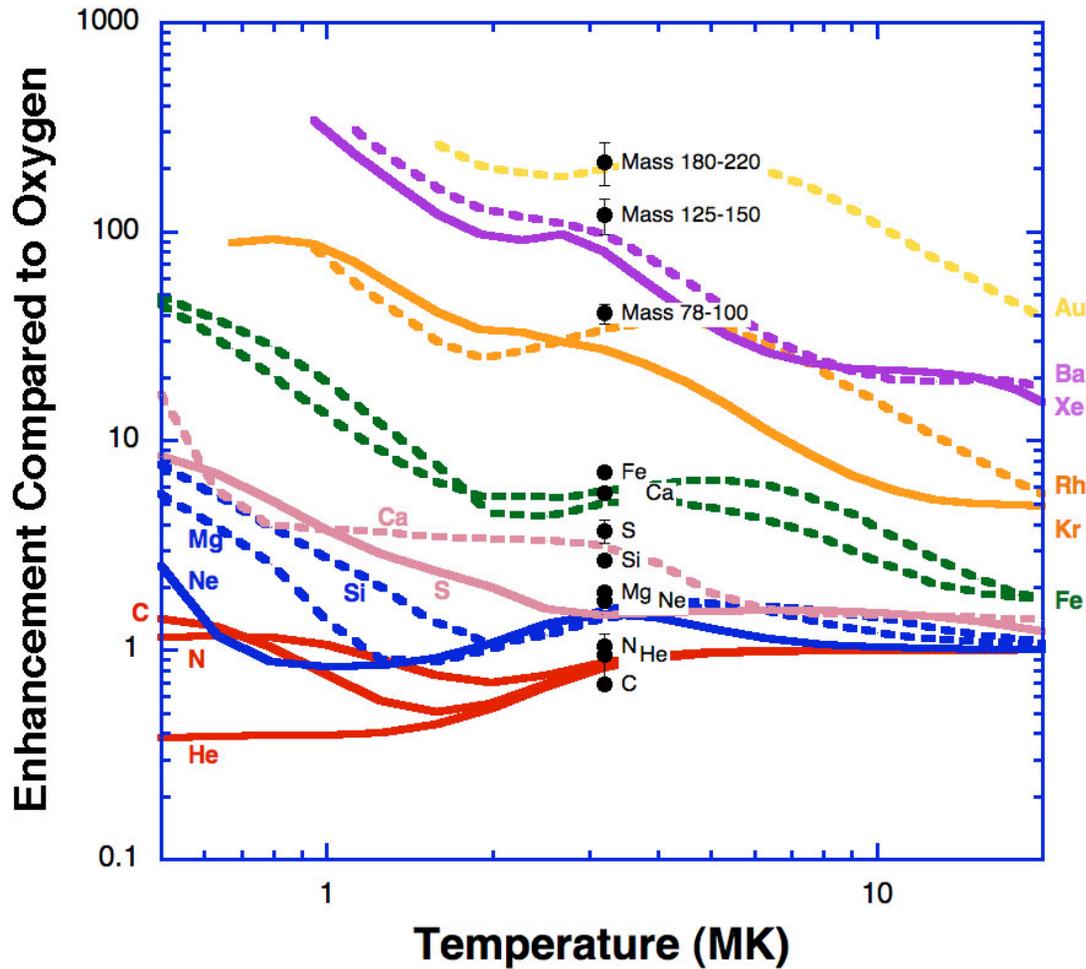
UH nuclei in ^3He rich flares --



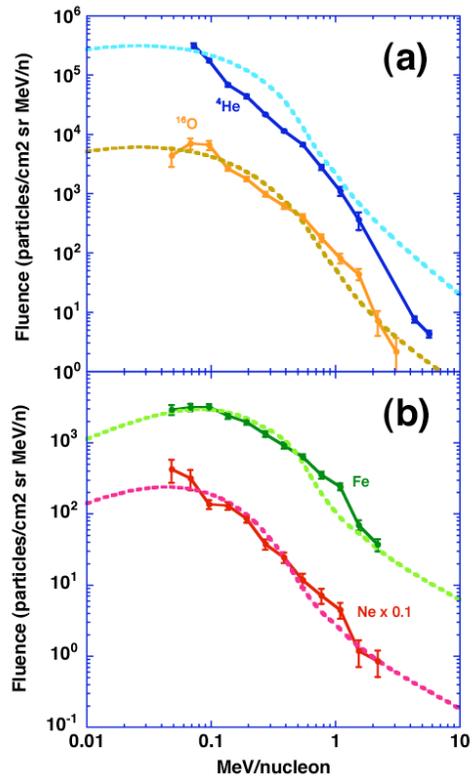
Calculated UH ionization states at temperatures typical of coronal regions result in Q/M ratios much lower than for lighter nuclei.

In addition, there is almost a continuous distribution of Q/M states, so a resonance mechanism seems unlikely

UH nuclei in ^3He rich flares --

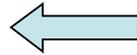


If the enhancements are proportional to $(Q/M)^{\alpha}$ as in gradual SEP events, then there is a range of temperatures that might work

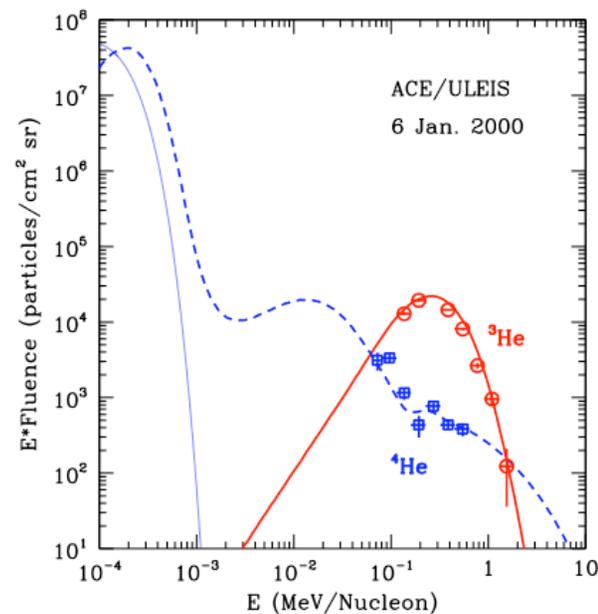


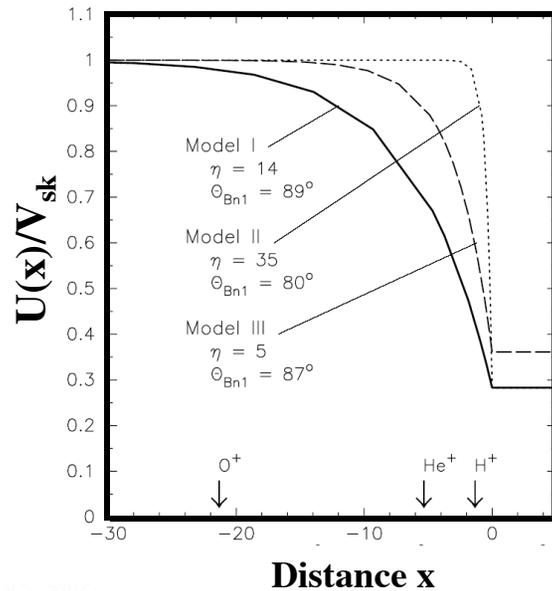
Recent progress in models --

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

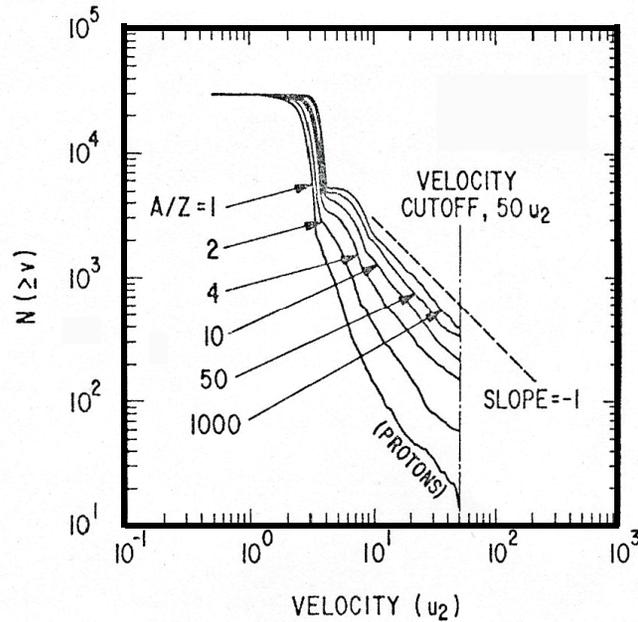


Stochastic acceleration model of Li and Petrosian can reproduce complex ^3He vs ^4He spectra



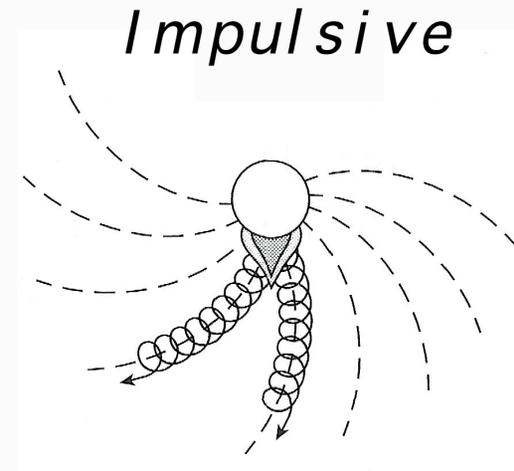


So far, none of the existing models can simultaneously fit the 3He enhancement along with the heavy and UH ion abundances (and electrons)



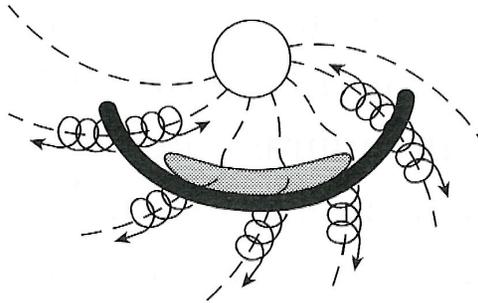
The abundance enhancement ordering by a power law in Q/M ratio may suggest preferential enhancement by a “smoothed shock” acceleration model -- but this has not been examined in any detail, and would likely not fit the 3He .

SUMMARY - IMPULSIVE SEPs:



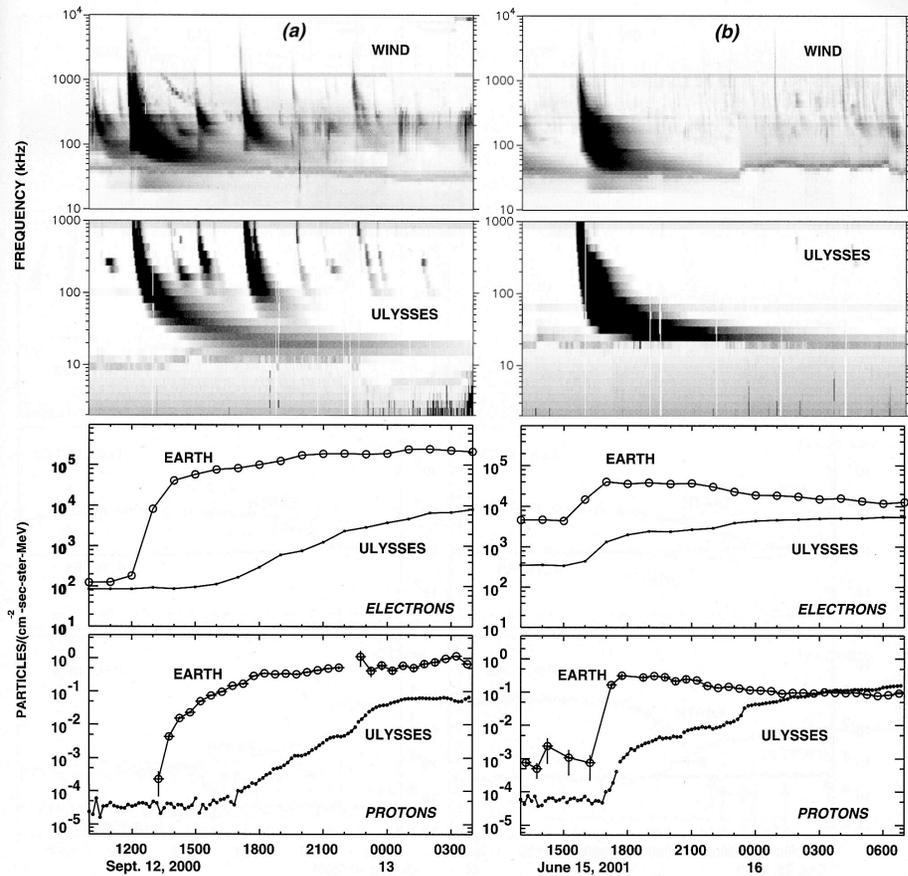
- *new properties of ^3He -rich events observed with advanced instruments have revealed qualitatively new features of the particle spectra, abundances, and abundance patterns*
- *RHESSI, TRACE, and ACE may allow definitive identification of a some individual events at the sun*
- *theoreticians are actively 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*

Gradual



*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*



Cane & Erickson examined Type III bursts in the low corona and interplanetary particles, suggesting significant escape of flare particles to IP medium

Poorly connected events may still be a source of particles, with particles undergoing longitudinal transport in the IP medium

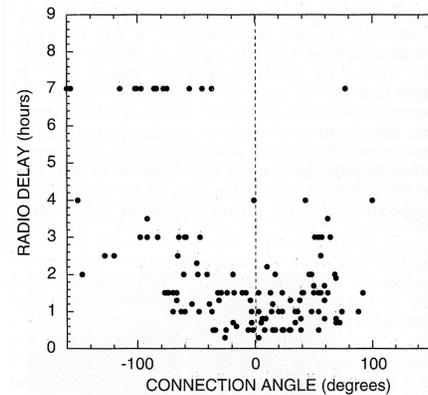
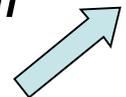
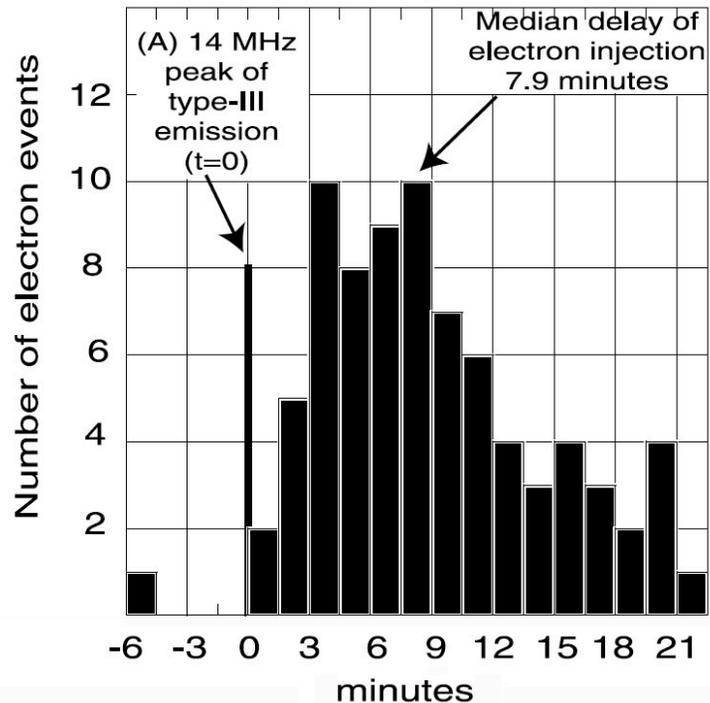
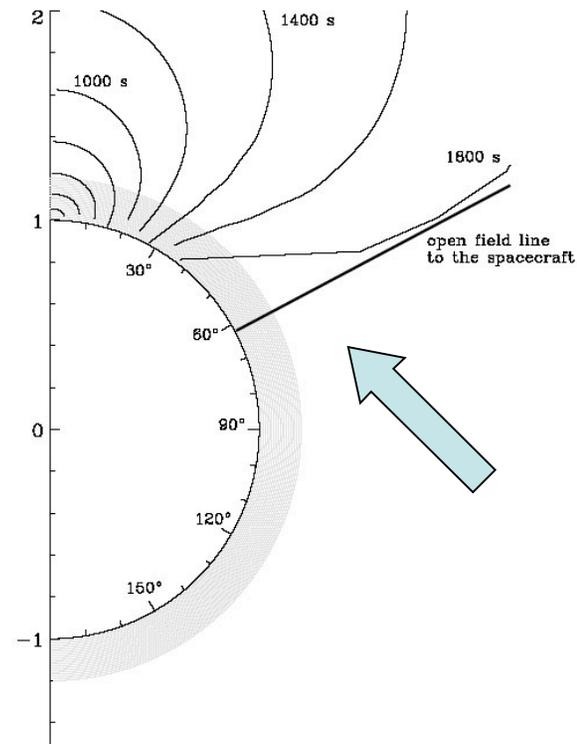


Figure 2. Radio burst delays, as illustrated in the previous figure, are shown as a function of the magnetic connection of IMP 8 to the associated flare for >20 MeV proton events. Delays of 7 hours correspond to events in which the burst did not intersect the plasma line. In some cases this may be caused by an intrinsic cutoff in the emission rather than a very low drift rate.



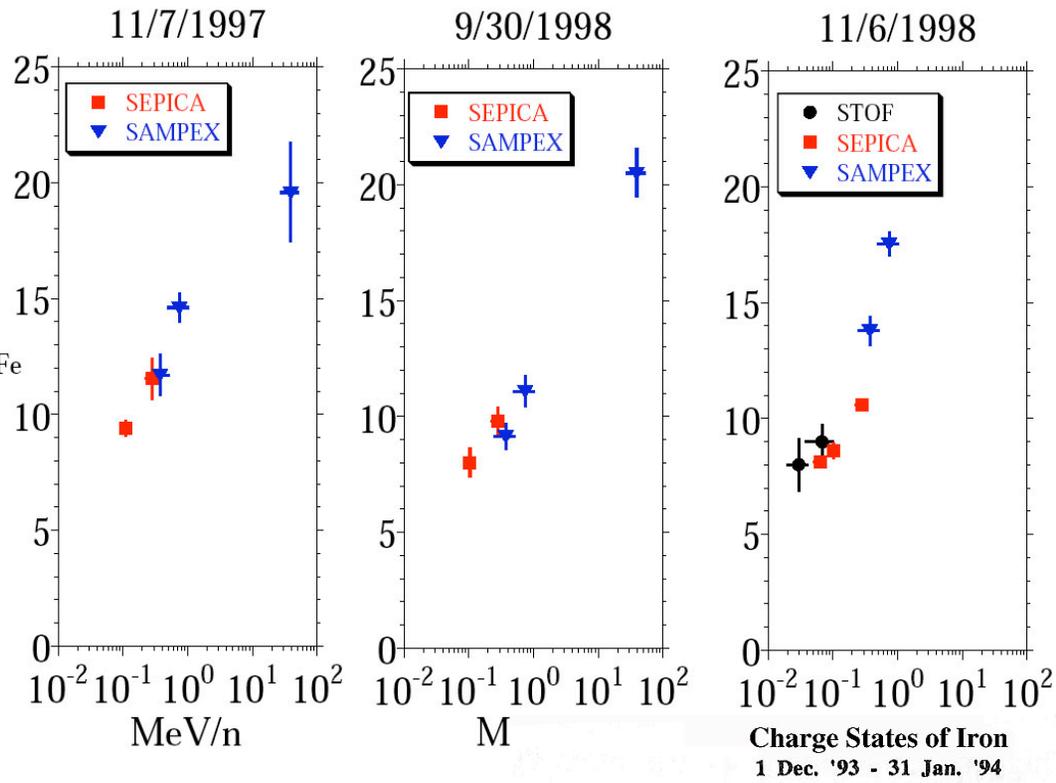
Delays of electron injection of ~10 minutes after start of electromagnetic emissions

May be due to geometry of connection to event & transient waves rather than flare itself

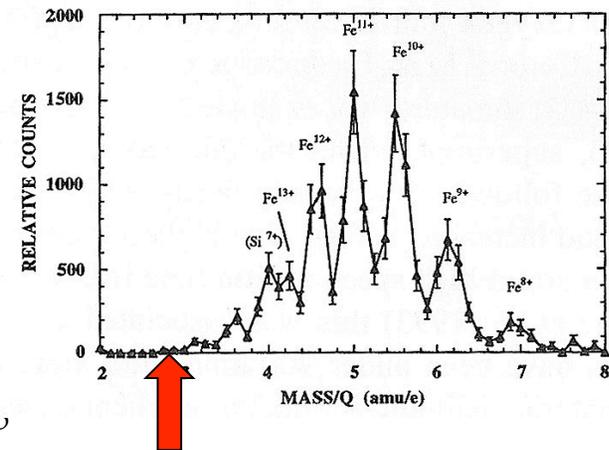


Haggerty and Roelof, ApJ., 2002; Krucker et al, ApJ, 1999.

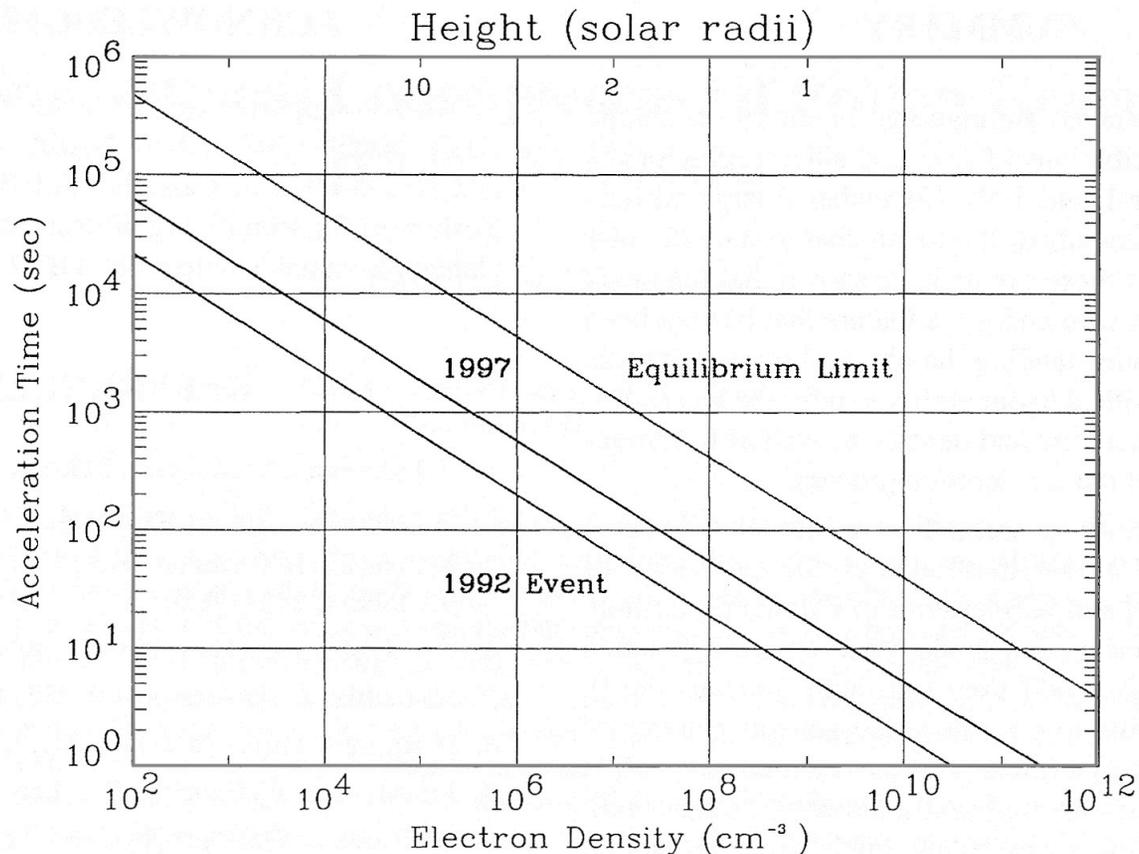
*Energy dependent
Iron Q states
in large SEP
events --*



*Note that the $\langle Q \rangle = 20$ is
virtually absent in the solar
wind*



Model of SEP stripping during acceleration --

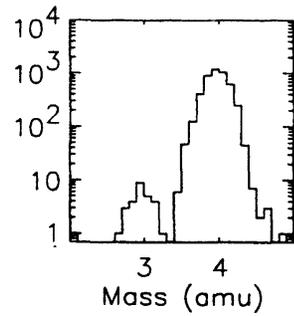
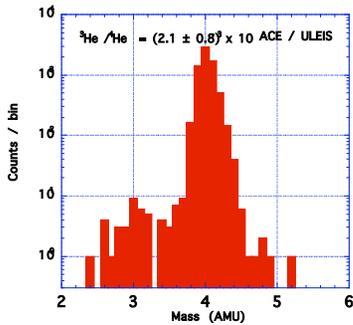


Barghouty & Mewaldt, *AIP Conf Proc.* 528, 71, 2000

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

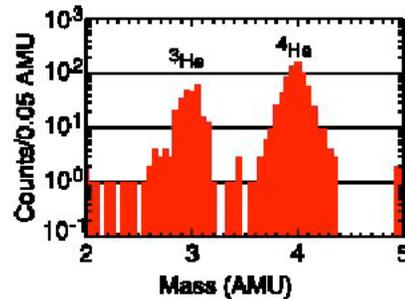
- Shock acceleration model gives stripping proportional to density and acceleration time
- reproduces observed energy dependence of Q
- estimate ~ 1 Rs for Nov 1997 event if accel. time is comparable to x-ray time scale of ~ 10 s
- equilibrium model gives greater grammage & therefore lower height (~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

^3He observed in some shock related events with abundance \gg solar wind value

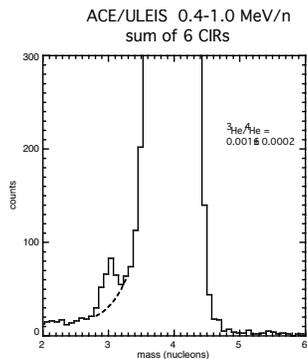


• *Gradual SEPs*

^3He in Nov 97 SEP event; ^ April 2000 IP shock event -->



• *Traveling IP shocks*

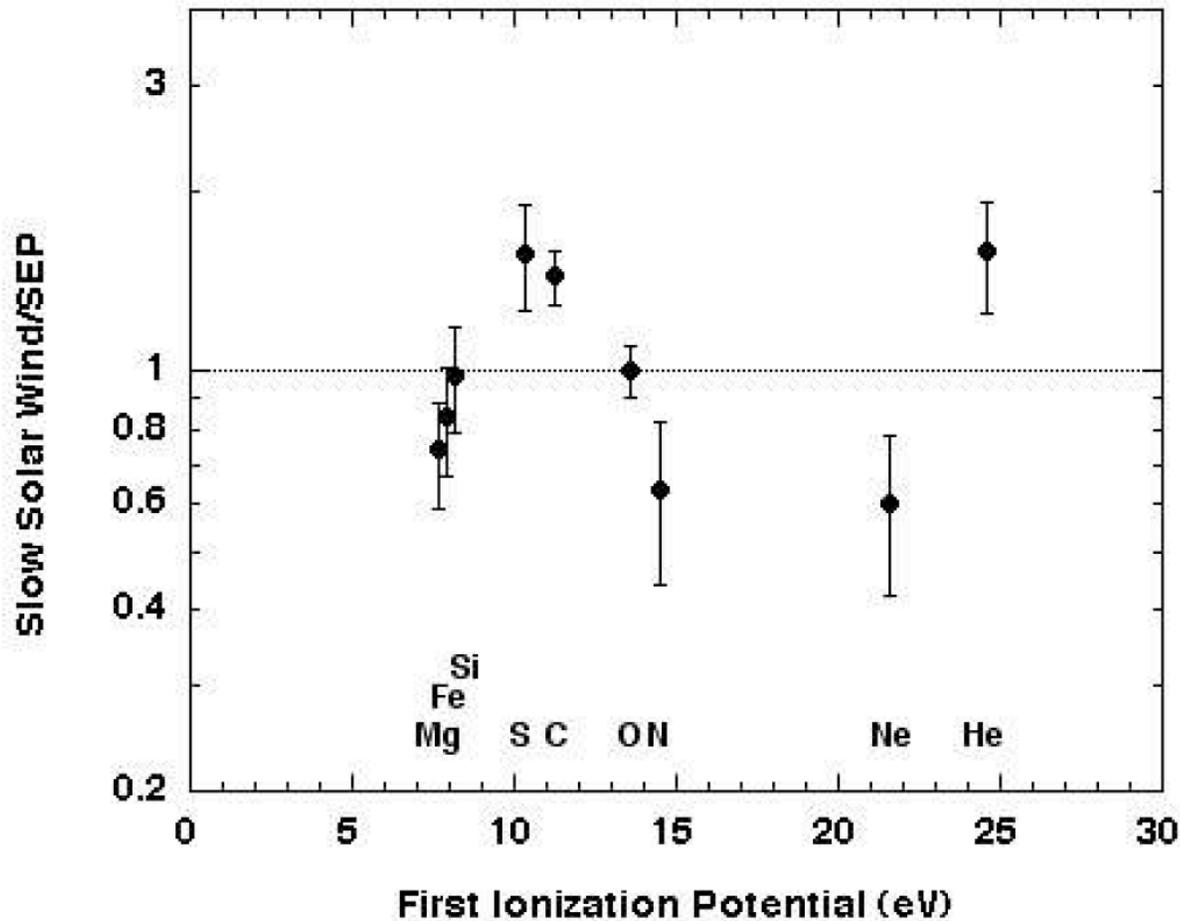


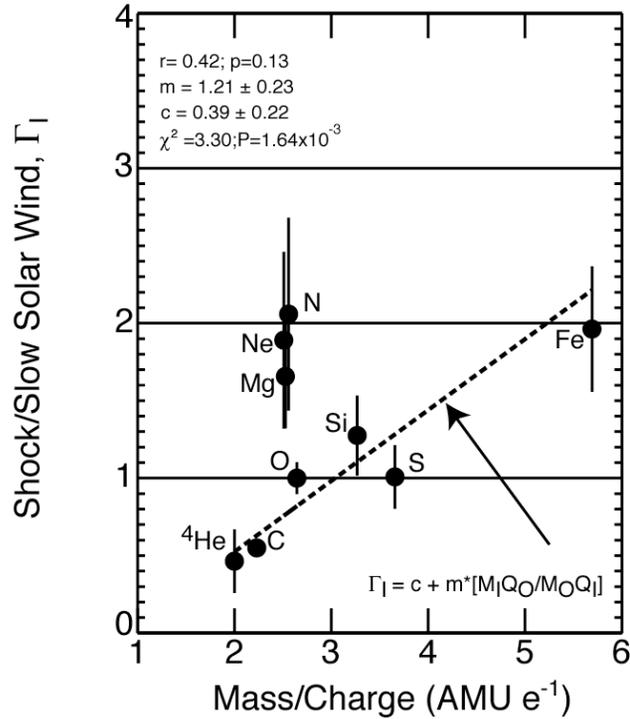
<-- ^3He in 6 CIRs -- ACE/ULEIS

• *CIRs*

Mason et al 1999; Wiedenbeck et al. 2000; Desai et al. 2001; Dwyer et al. 2002

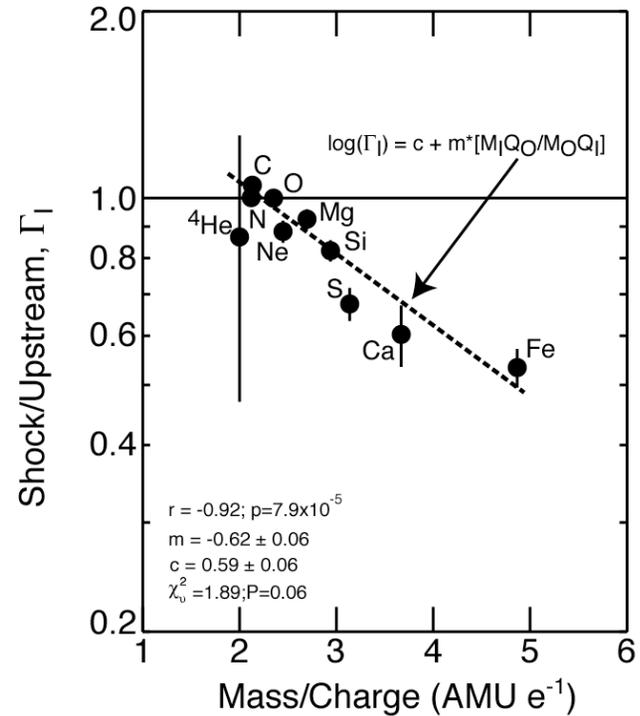
SEP composition is different from slow solar wind --





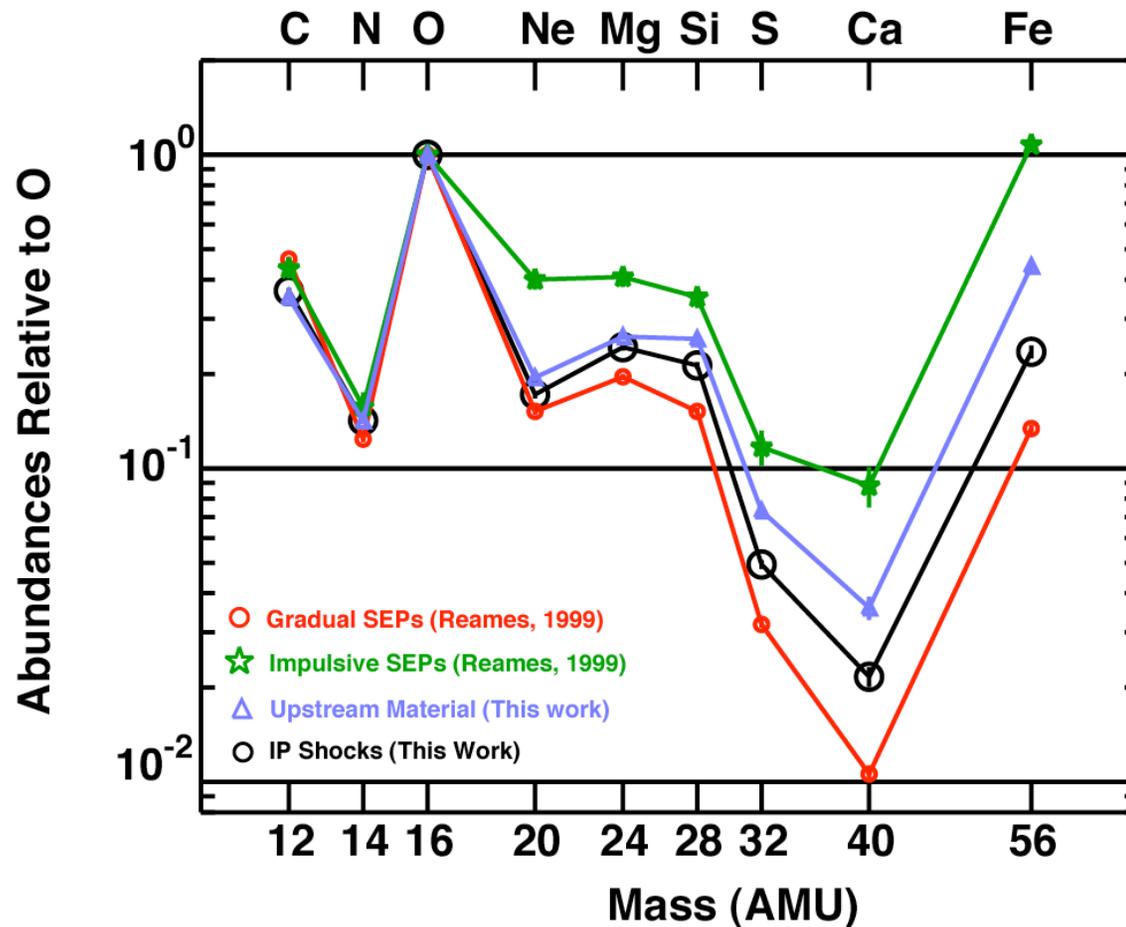
Survey of composition in 72 IP shocks, 1997-2002

- average abundances do not correlate well with solar wind

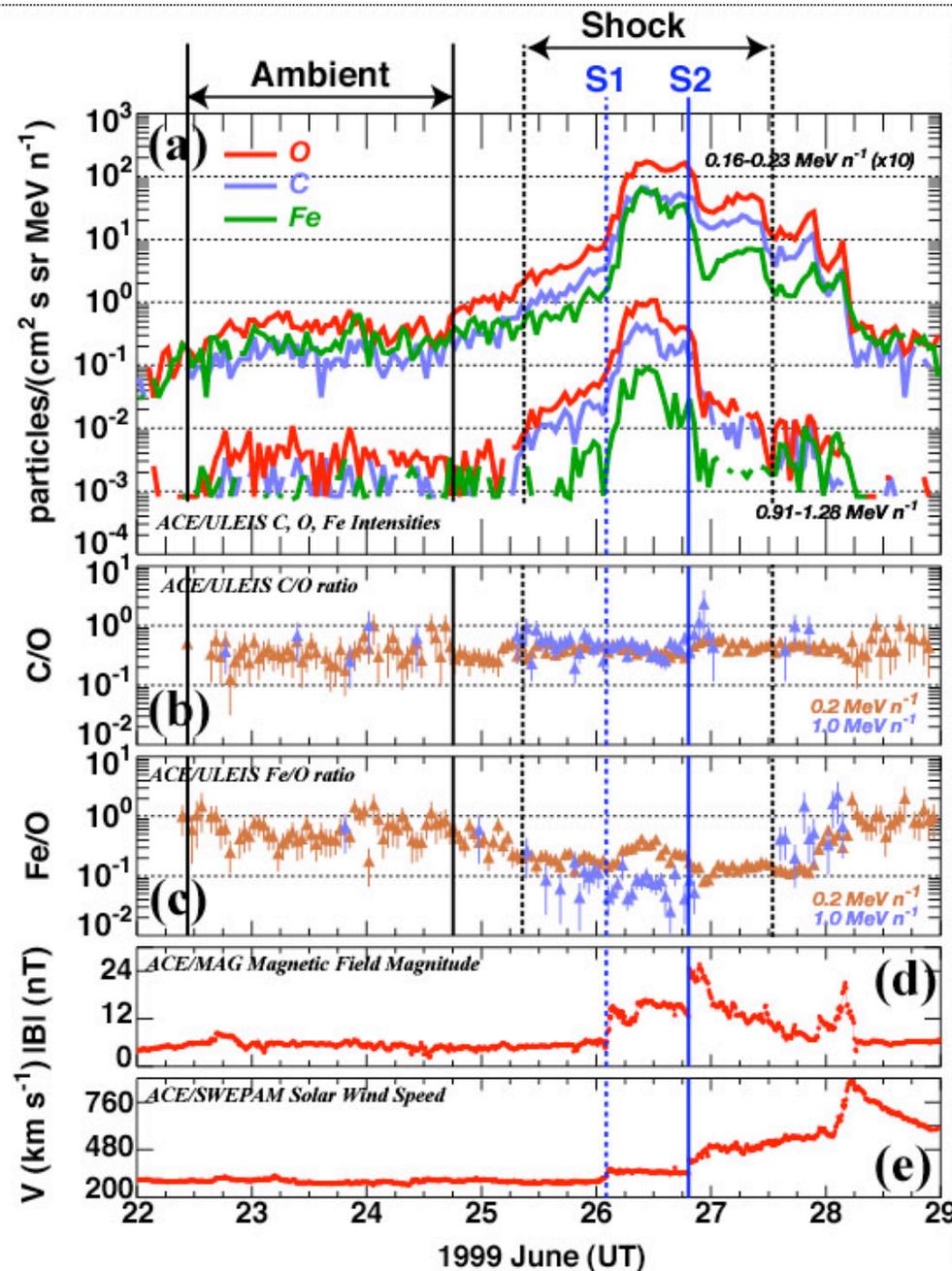


- abundances correlate well with abundances measured upstream of each shock



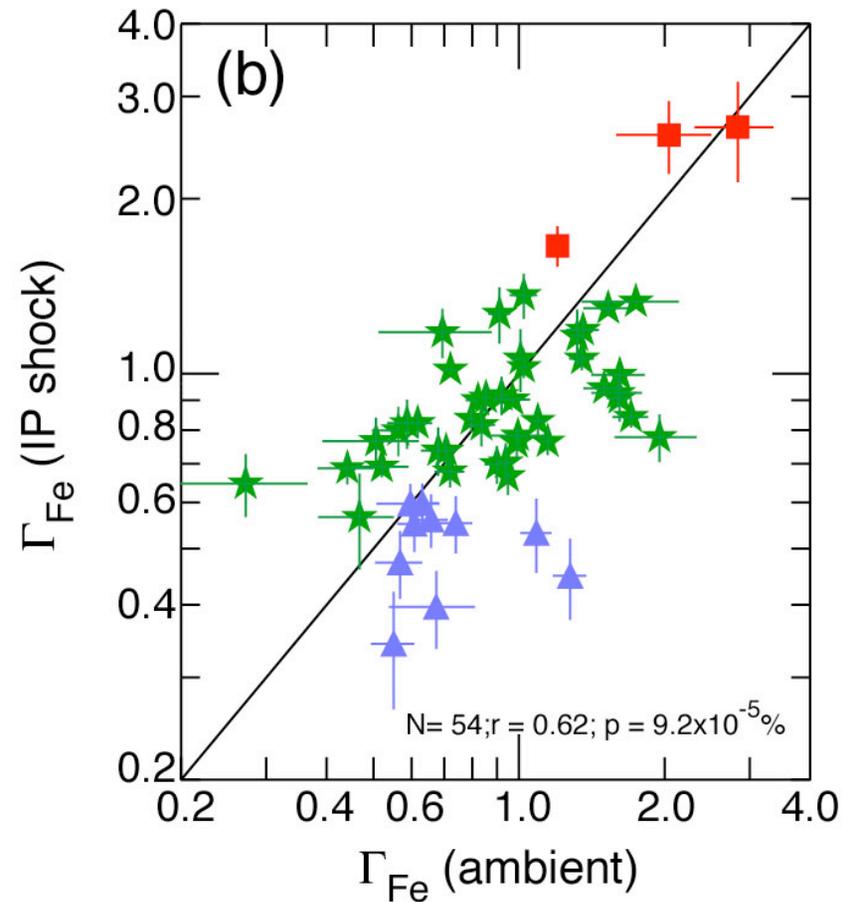
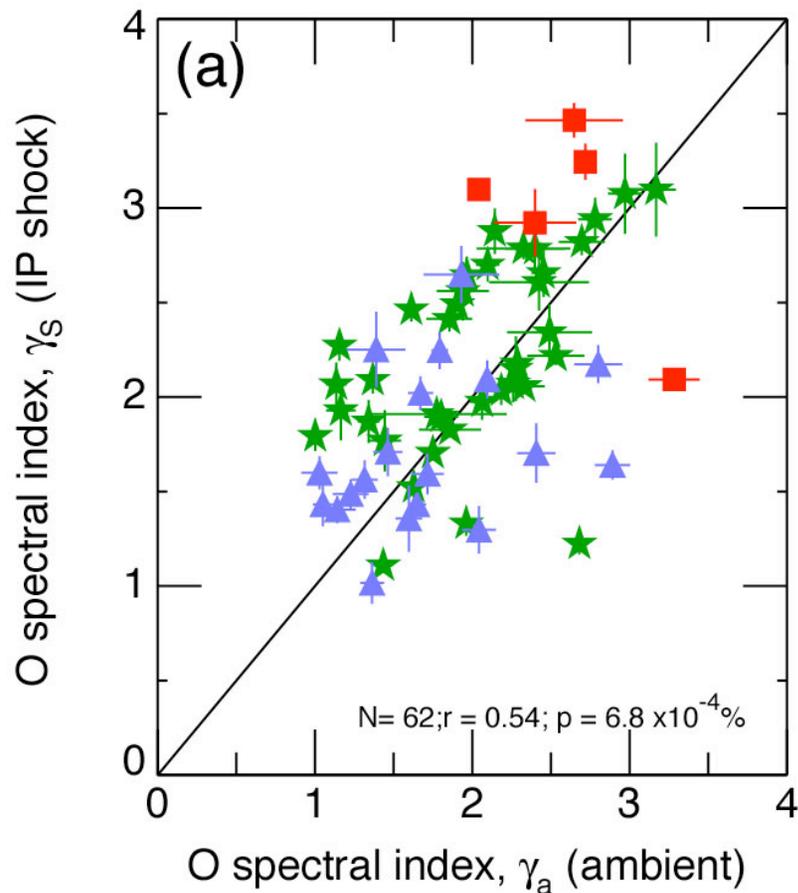


Average abundances of shock accelerated particles lie in between those of impulsive and gradual solar energetic particle events



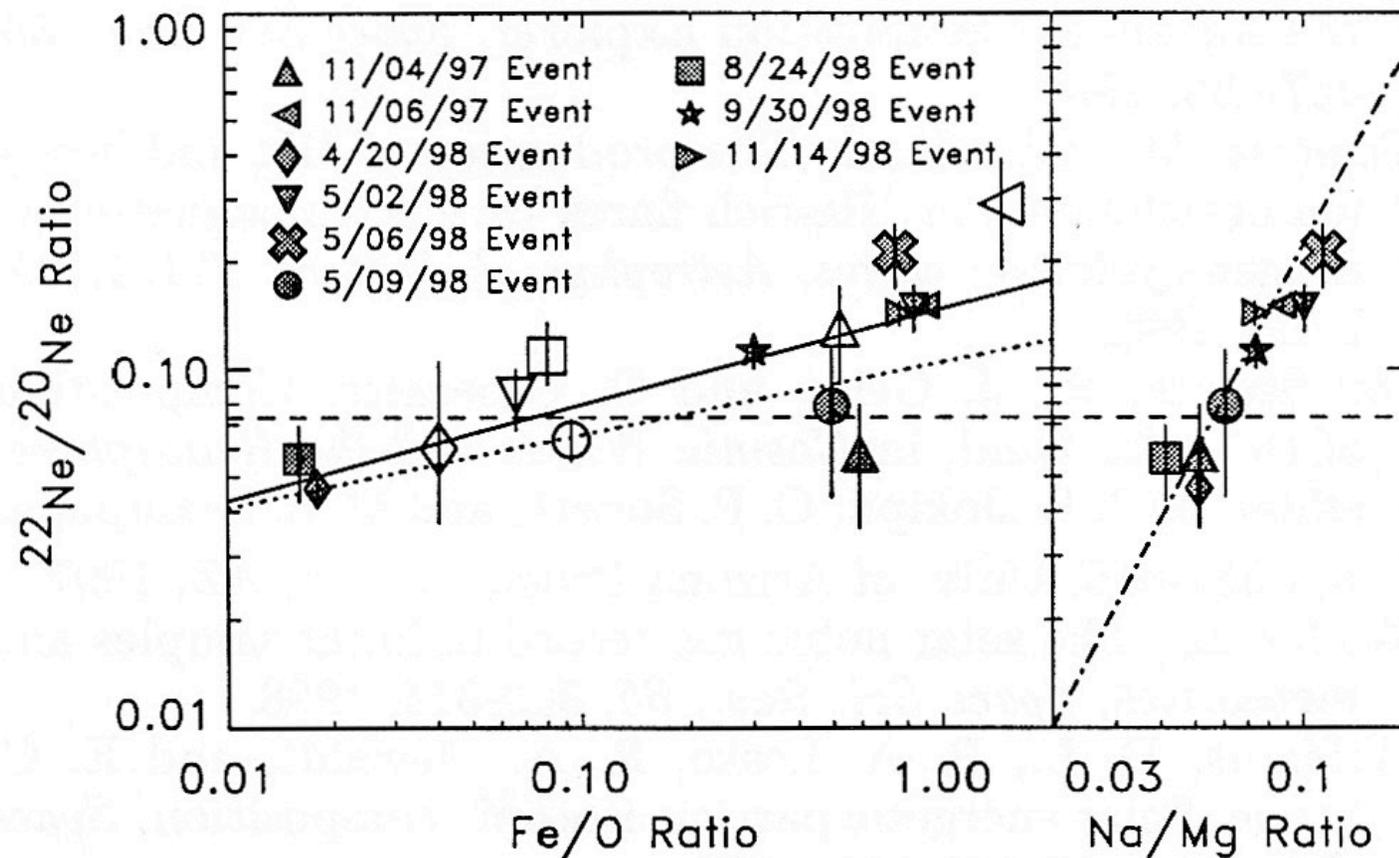
Case by case approach --

- *for each event ...*
- *measure “event averaged” composition*
- *compare with candidate source populations: SEPs, solar wind, ambient upstream particles*

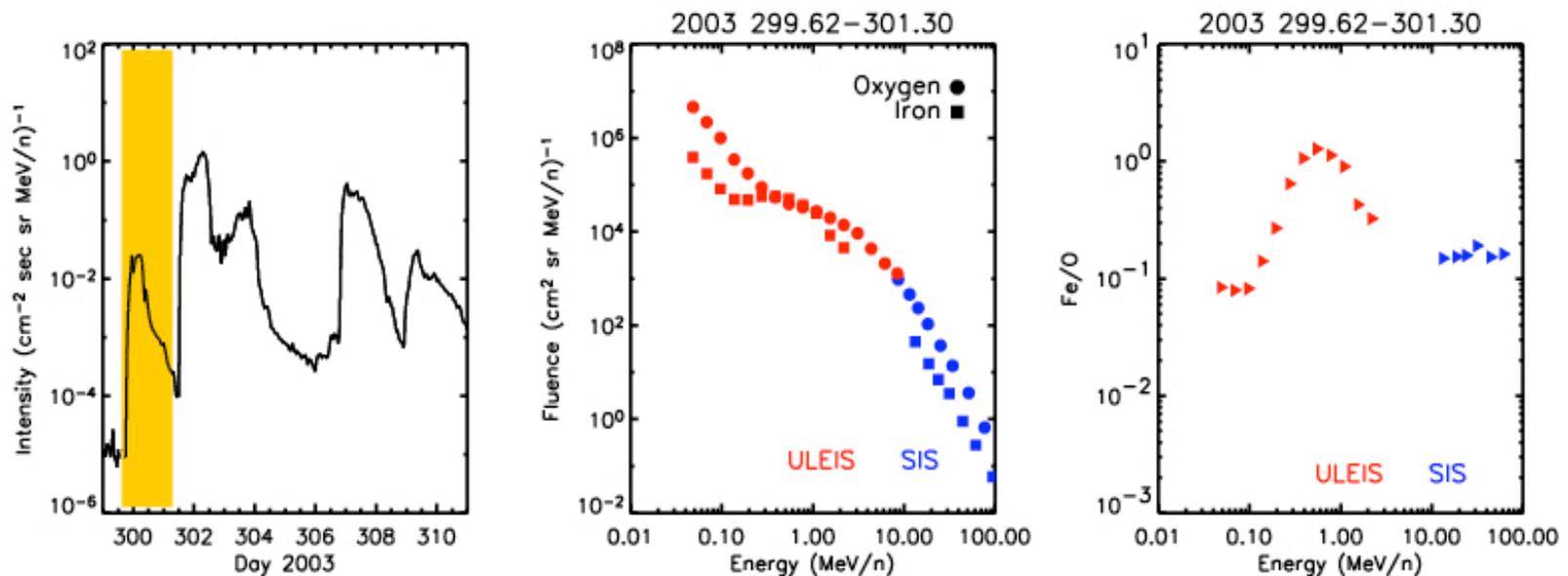


The spectral index and \square of the ambient population show significant correlation with the spectral index at the shock -- simple diffusive theory would say they are totally unrelated

SEP isotopic composition of heavy ions shows large variations --

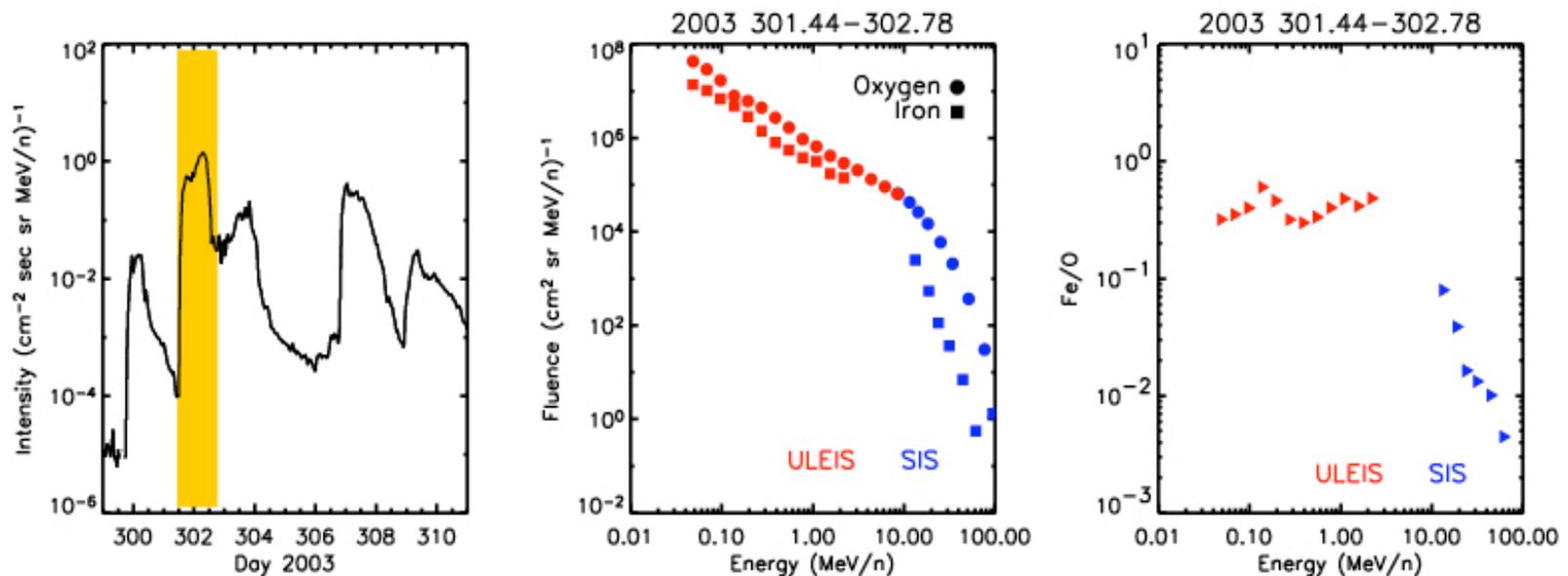


O, Fe Fluences for Event 1



- Roll-off in spectra \sim few MeV/n to softer power law
- Fe/O independent of energy above 10 MeV/n

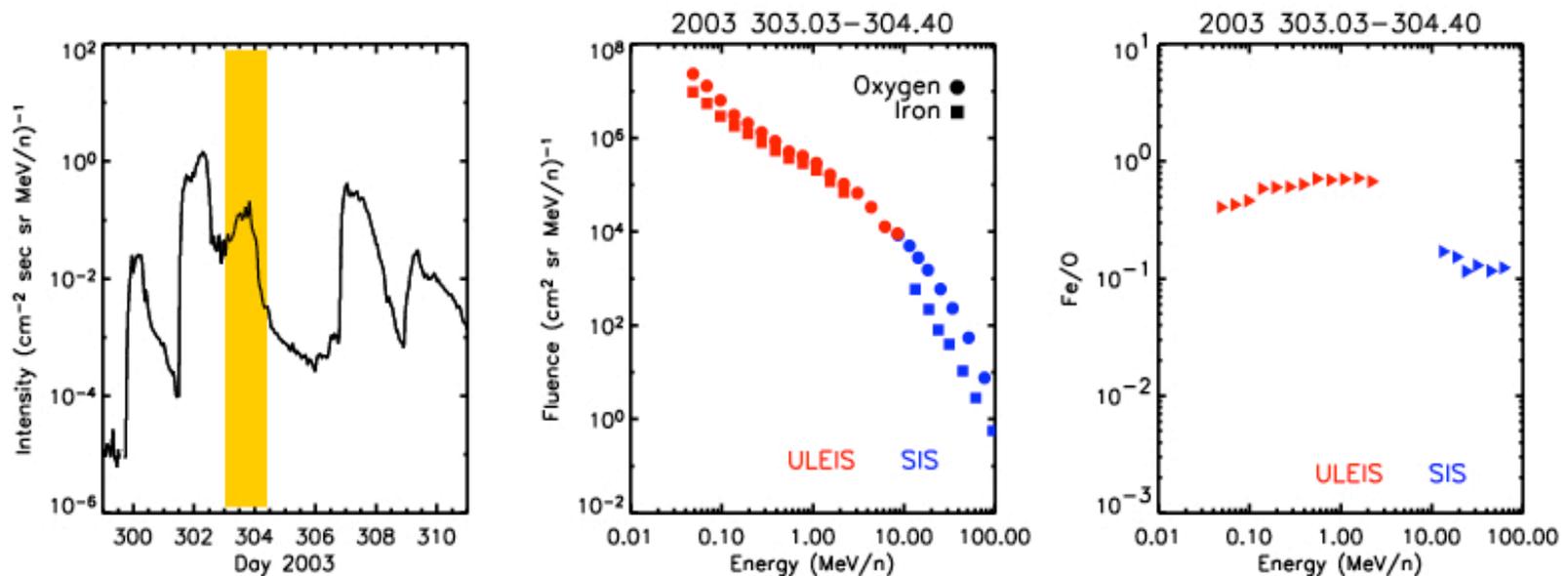
O, Fe Fluences for Event 2



- Roll-off in spectra \sim few MeV/n , maybe exponential
- Power law below roll-off
- Fe/O decreases with energy above 10 MeV/n

Cohen et al., 2003 Fall AGU meeting

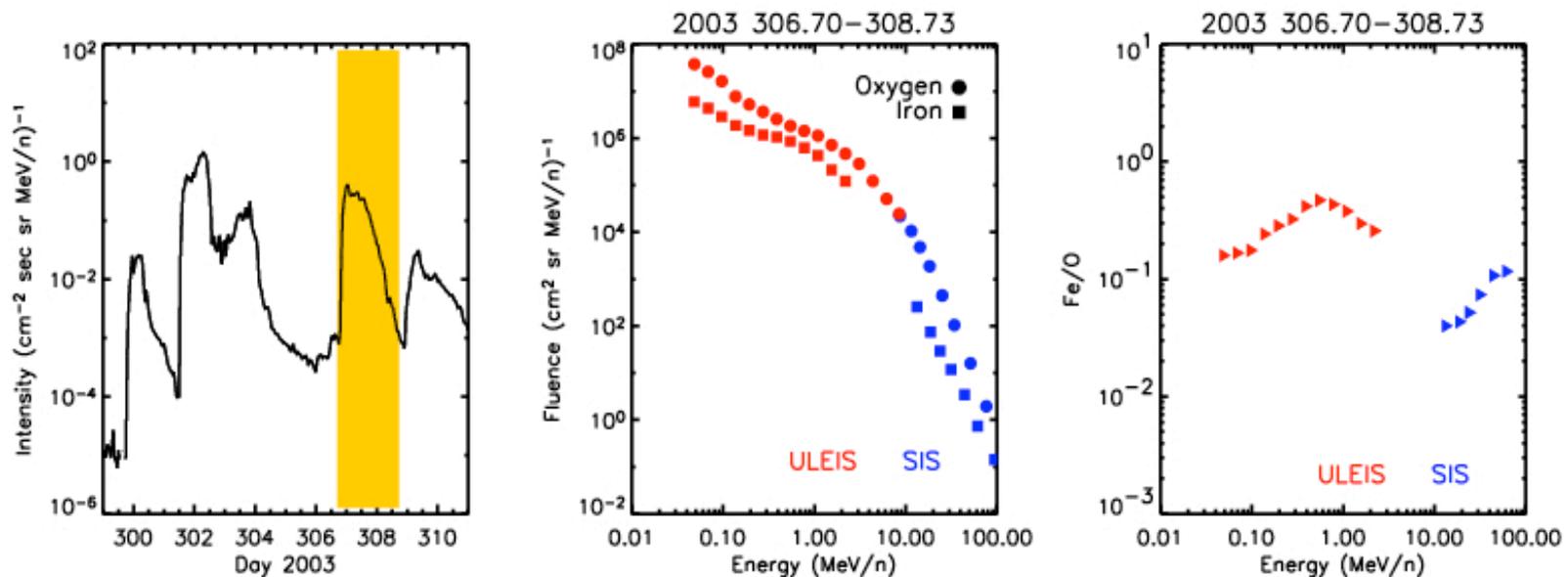
O, Fe Fluences for Event 3



- Roll-off in spectra \sim few MeV/n to softer power law
- Power law below roll-off
- Fe/O independent of energy above 10 MeV/n

Cohen et al., 2003 Fall AGU meeting

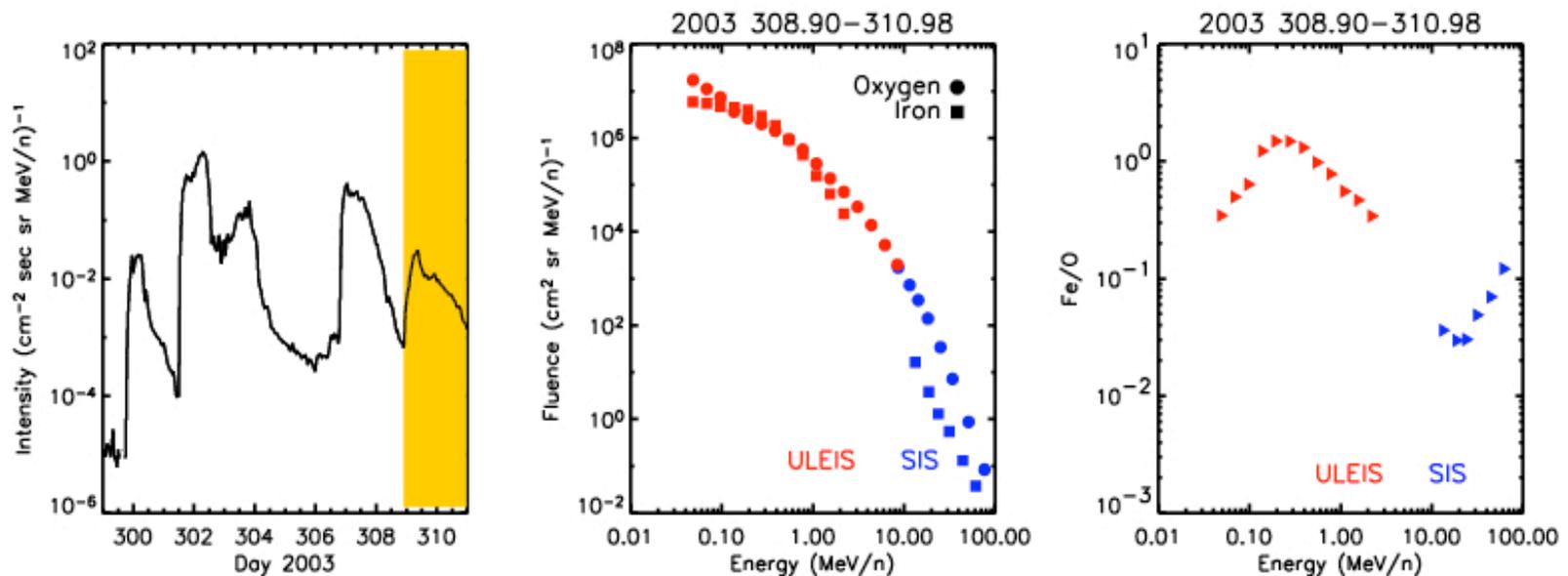
O, Fe Fluences for Event 4



- Roll-off in spectra ~ 1 MeV/n to softer power law
- Power law below roll-off
- Fe/O increasing with energy above 10 MeV/n

Cohen et al., 2003 Fall AGU meeting

O, Fe Fluences for Event 5



- Roll-off in spectra below ~ 1 MeV/n to softer power law
- Fe/O increasing with energy above 10 MeV/n

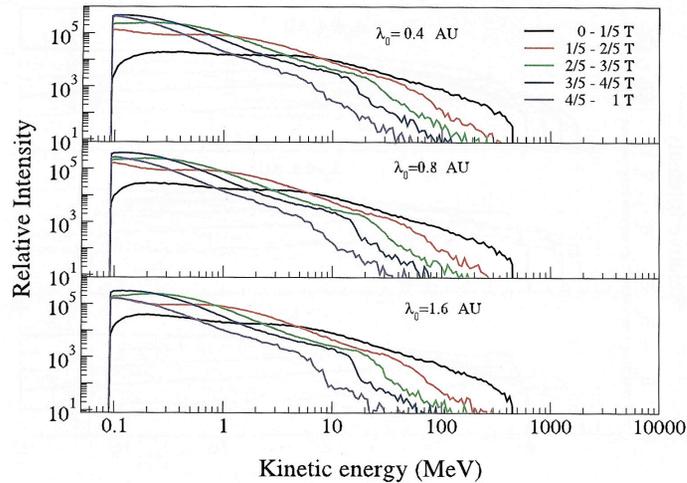
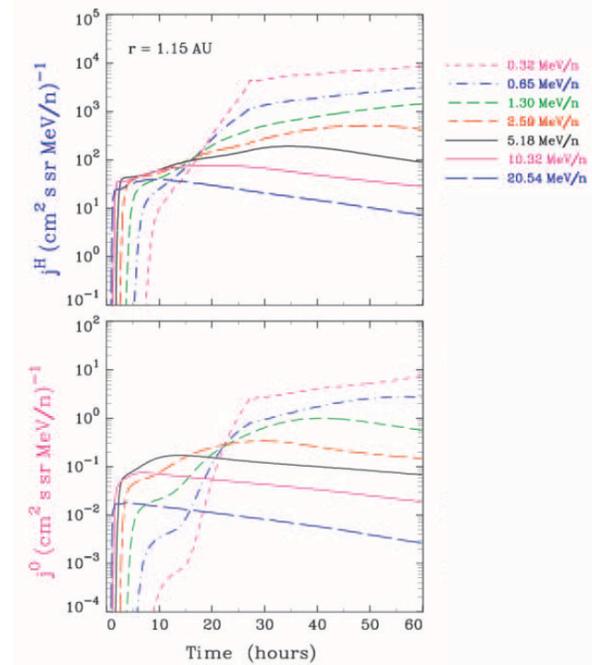


Figure 8. The particle spectrum at 1 AU generated by a weak shock and observed at different times for three different mean free paths. In the figure, $T = 2.25$ days and the spectra are obtained for a time interval of 10.8 hours.

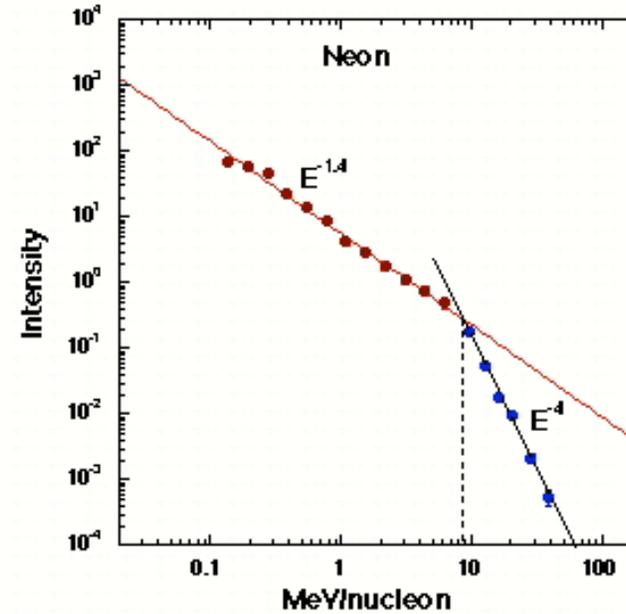
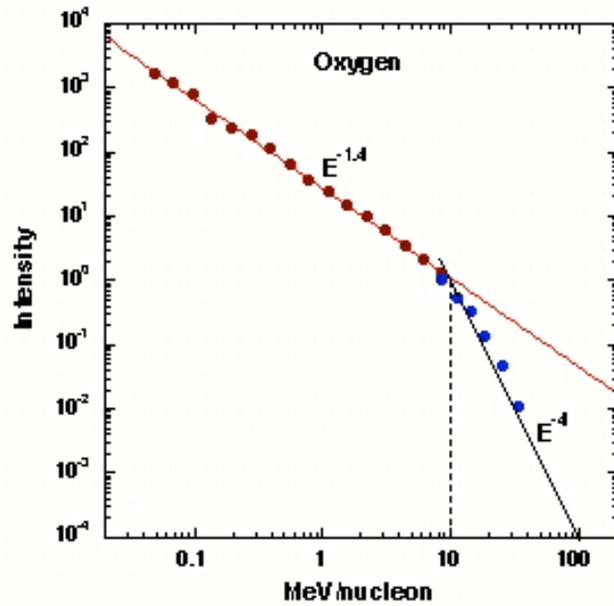
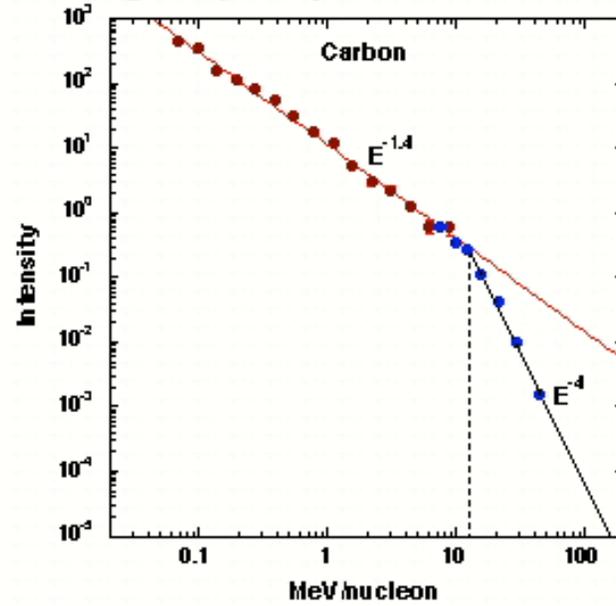
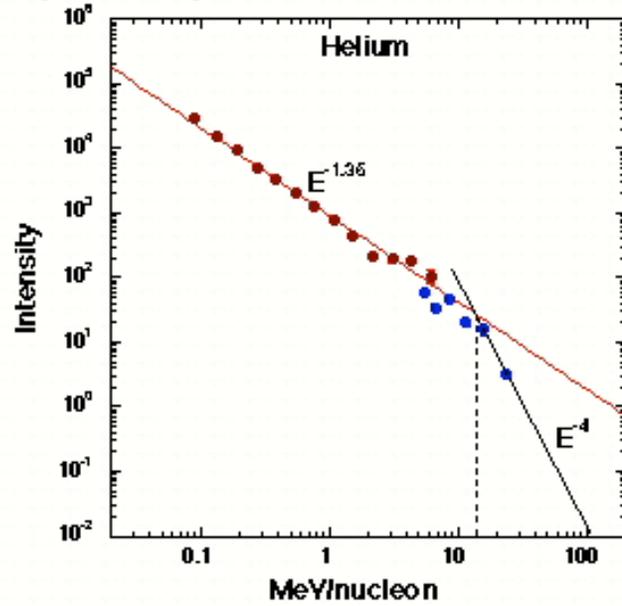
- *Ng et al. 2003, includes particle induced wave amplification*
- *both models sum spectra to produce predictions for observers at different radii*

New, more realistic models, e.g.

- *Li et al. 2003 model includes expanding shock followed by escape and IP transport*

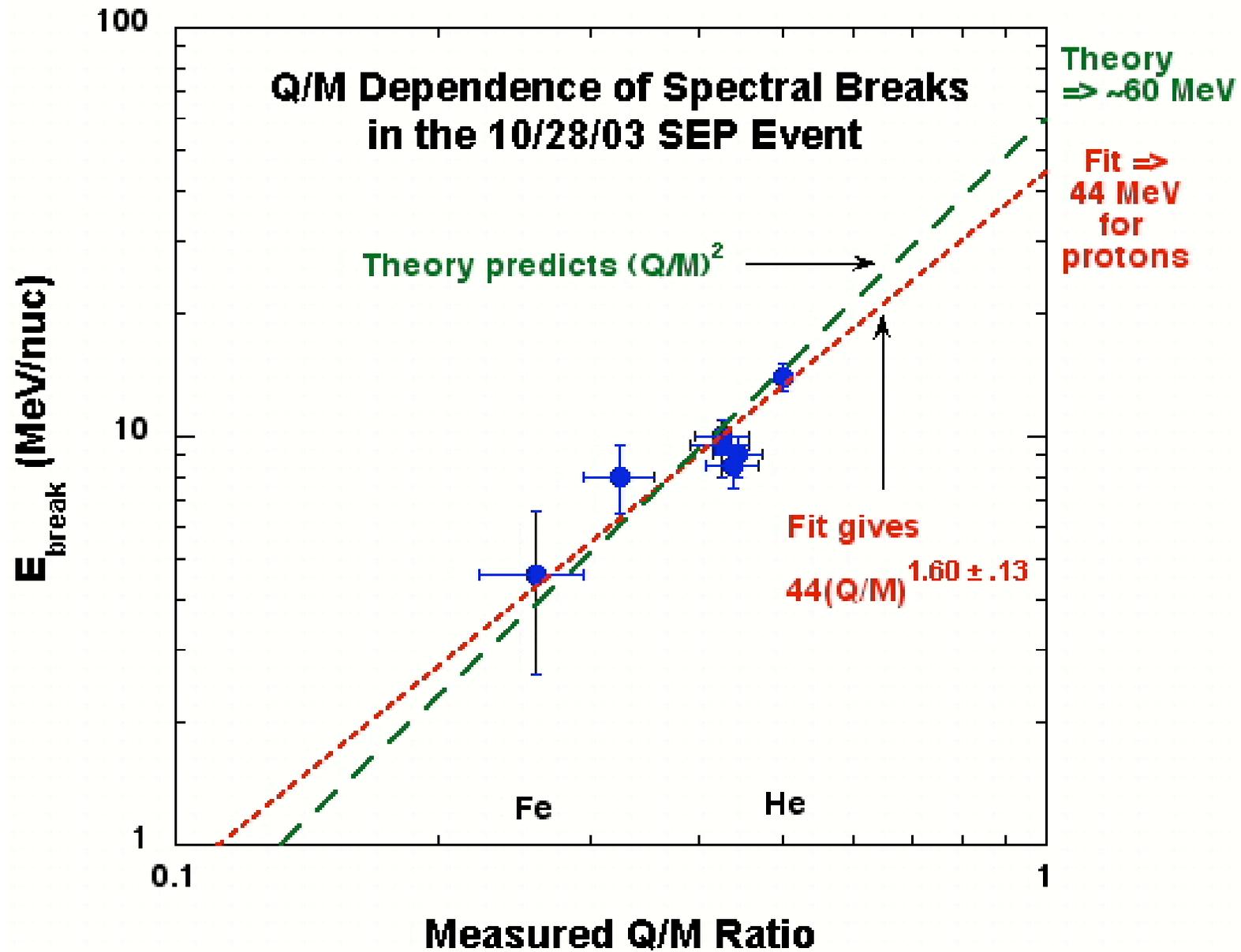


Spectra just after shock arrival show rigidity-dependent breaks



See Zank et al. 2000 for prediction of spectral break

Mewaldt et al., 2003 Fall AGU



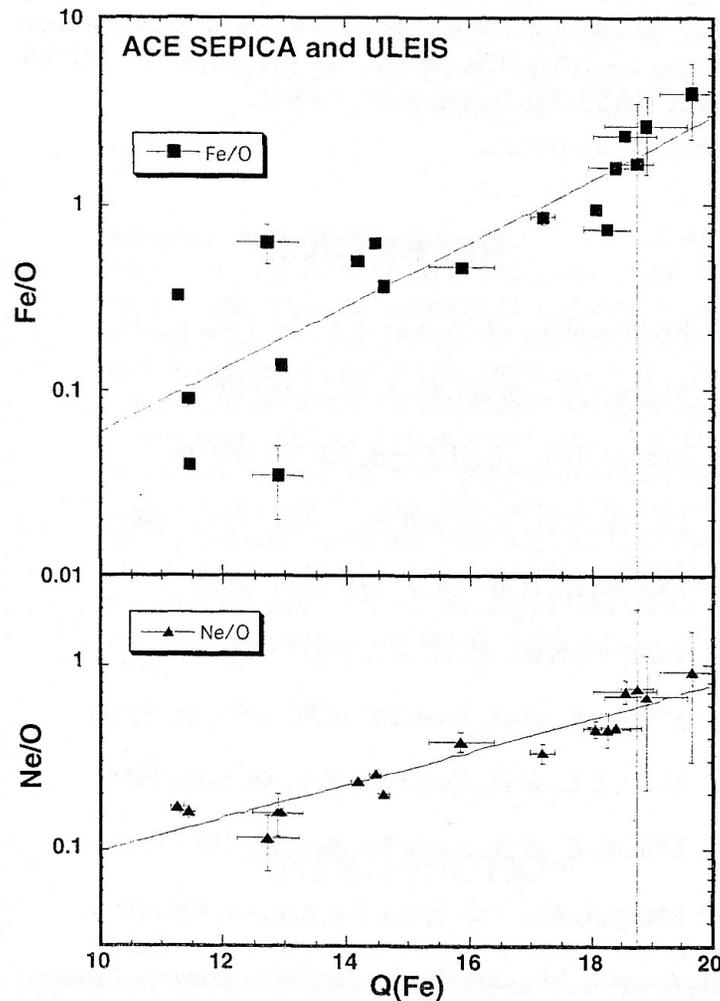
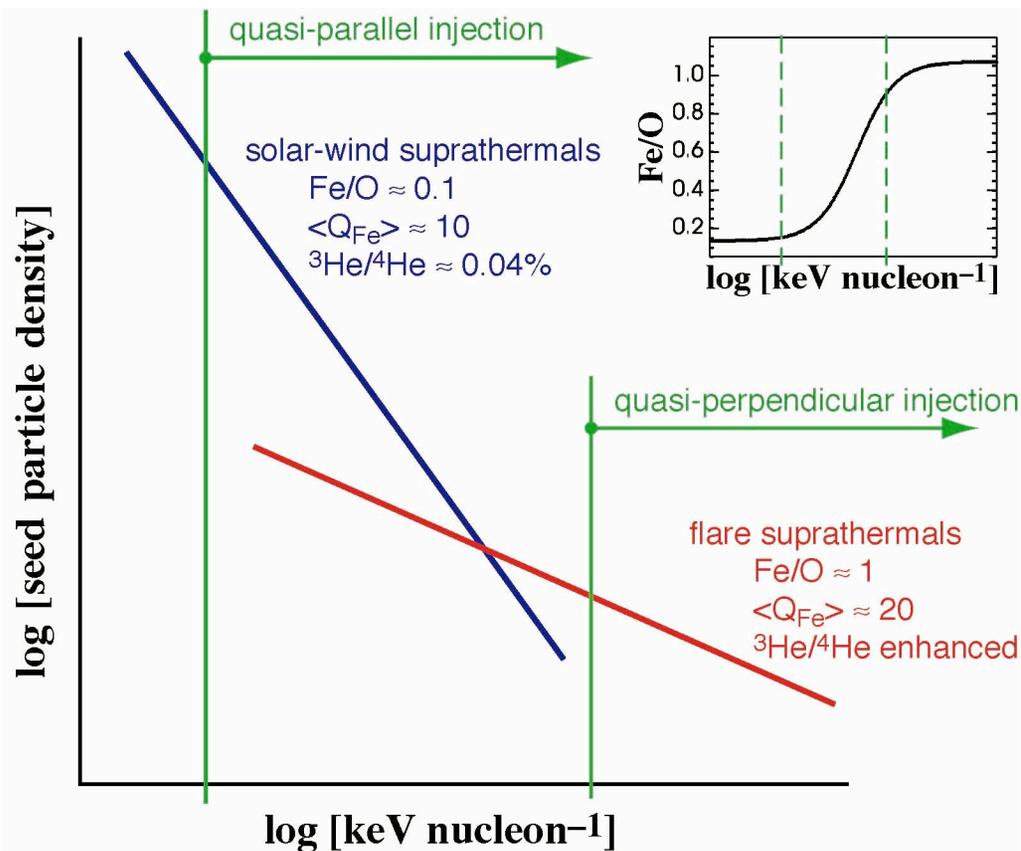


FIGURE 2: Fe/O and Ne/O ratio as a function of Q_{Fe} .

Möbius et al., AIP Conf. Proc. 528, 2000

Additional feature of ionization states (0.18-0.44 MeV/n):

- *events with high Fe/O also tend to have higher Fe ionization states*
- *if an acceleration effect, this is unexpected, since the Fe enhancement increases as the Fe Q/M ratio becomes closer to that of O!*
- *if a stripping effect after acceleration, hard to see how the high Fe/O is correlated*

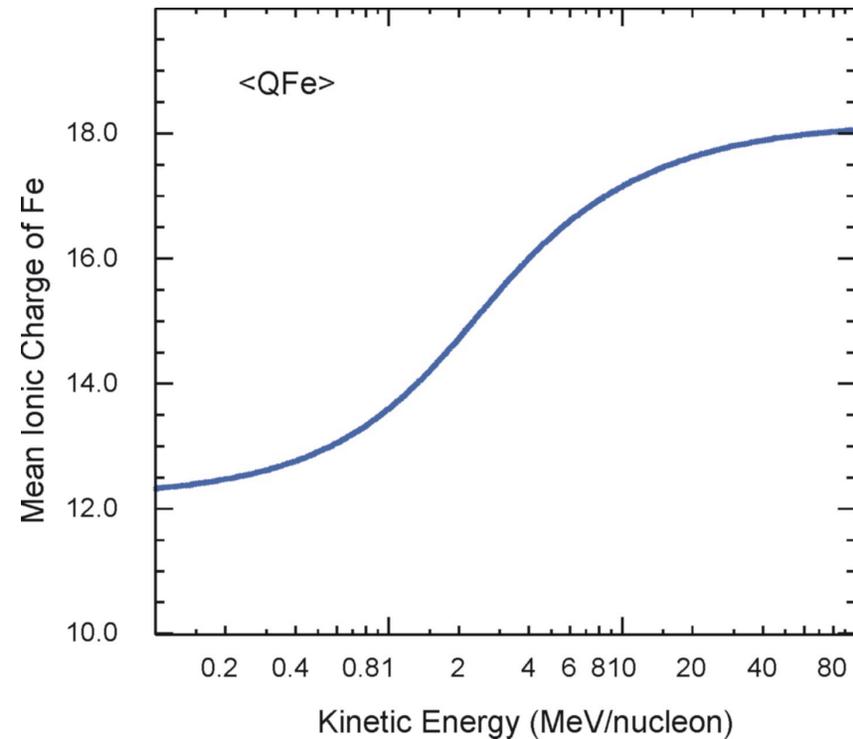
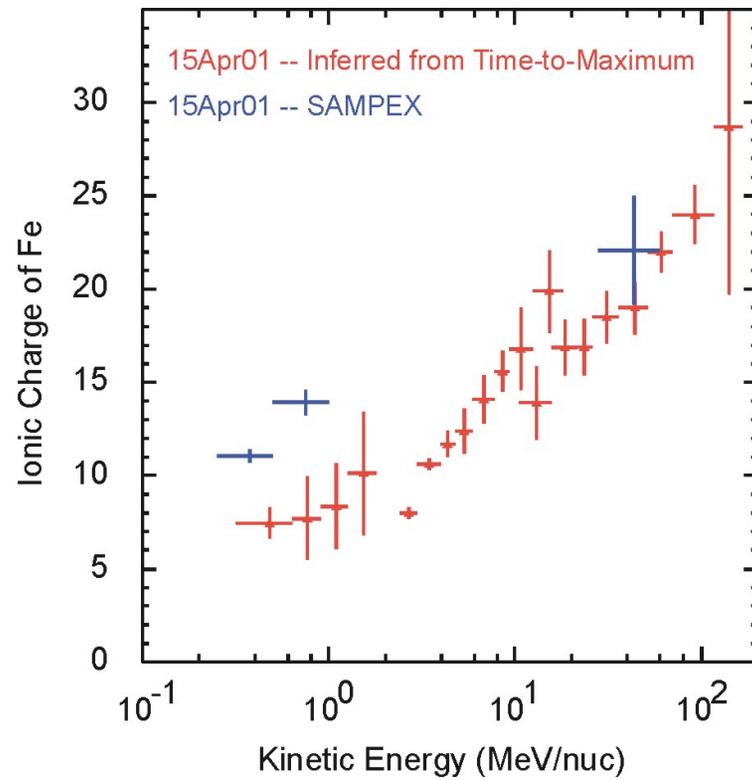


Model of Tylka & Lee (2004):

- emphasizes spectral and compositional features*
- uses mixture of seed populations*
- gives energy dependent composition and correlation of Q state and abundance observed by Möbius*

Energy-Dependent Fe Charge States

From these calculations



SAMPEX: Labrador et al. 2003

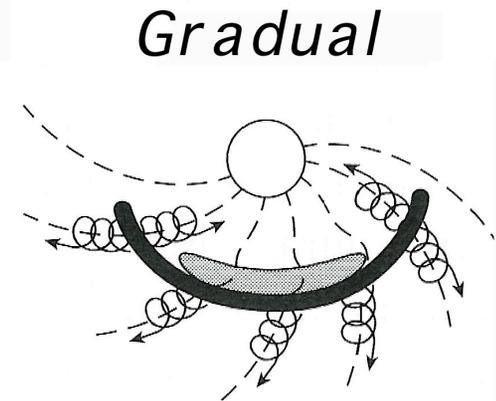
Mazur, private communication.

TTM: Dietrich & Tylka 2003

Tylka et al., SHINE 2004

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 R_s or more) ?*
- *shock acceleration is mechanism of choice for most models -- role of acceleration vs. release vs. IP propagation (w waves) not yet separated*
- *field is moving towards a much more quantitative phase, critical for LWS and supporting Exploration Vision*