The Source Material
for Solar Energetic Particle Events

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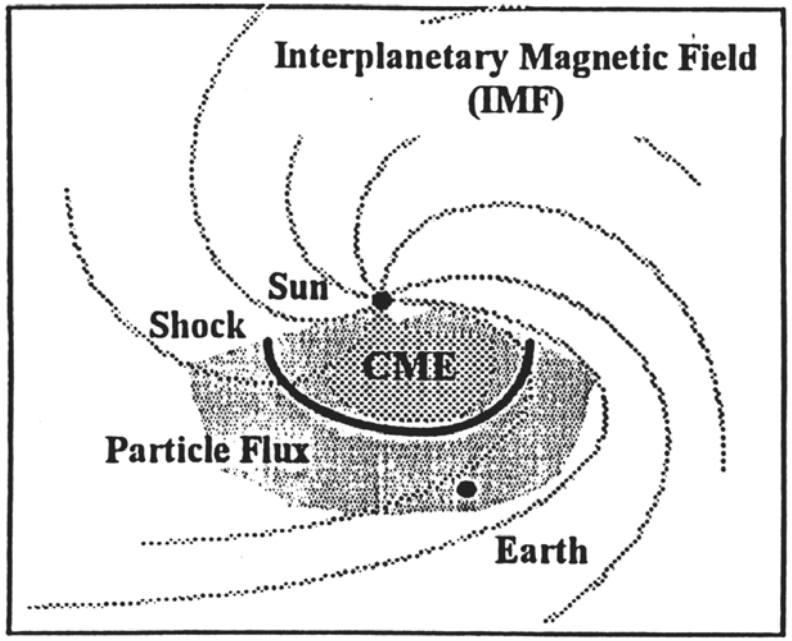
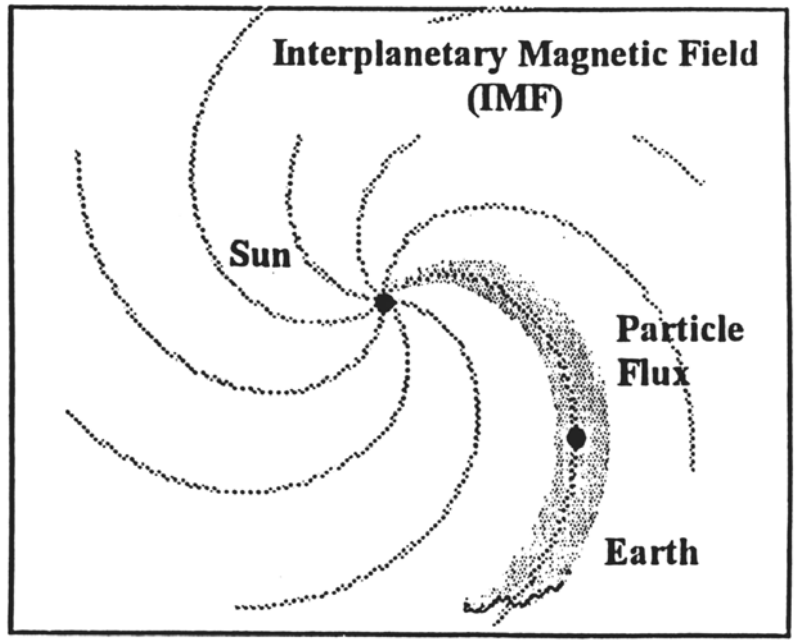
Two Classes of Solar Energetic Particle Events

CME-Associated (Gradual Event)



Proton-Rich
Long-Lived (Days)
60-180 Degrees Solar Longitude

Impulsive Flare-Associated (Impulsive Event)



Electron-Rich
Short-Lived (Hours)
30-45 Degrees Solar Longitude

Coronal composition
Fe/O ≈ 0.1 - 0.2
^{3}He/^{4}He ≈ .0004
Q(Fe) ≈ 14
Shocks accelerate solar wind

He/H, heavy ion enrichments
Fe/O ≈ 1
^{3}He/^{4}He ≈ 0.1 - 10
Q(Fe) ≈ 20
Heated flare material accelerated

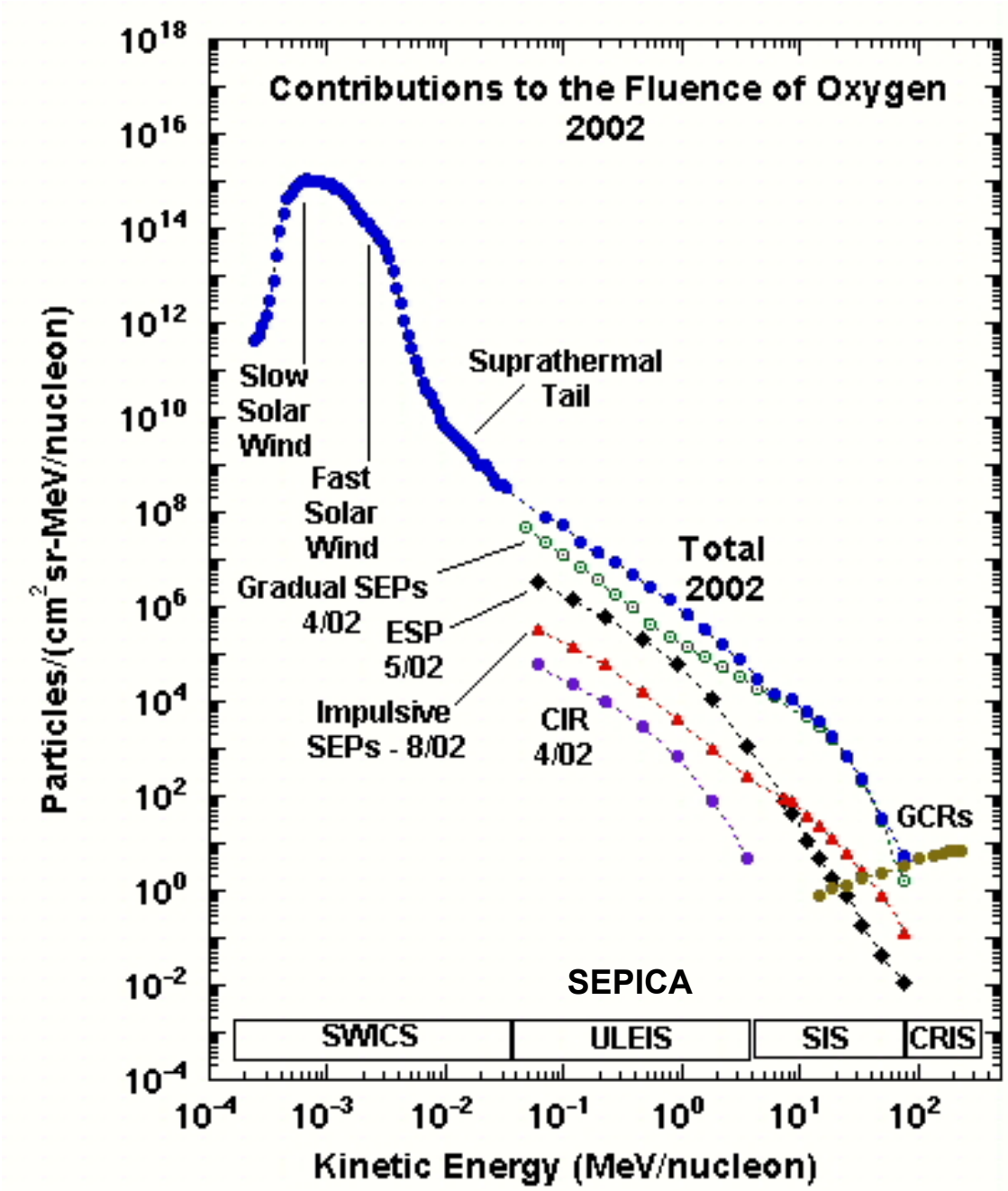
Criteria summarized by Reames (1995, 1998)

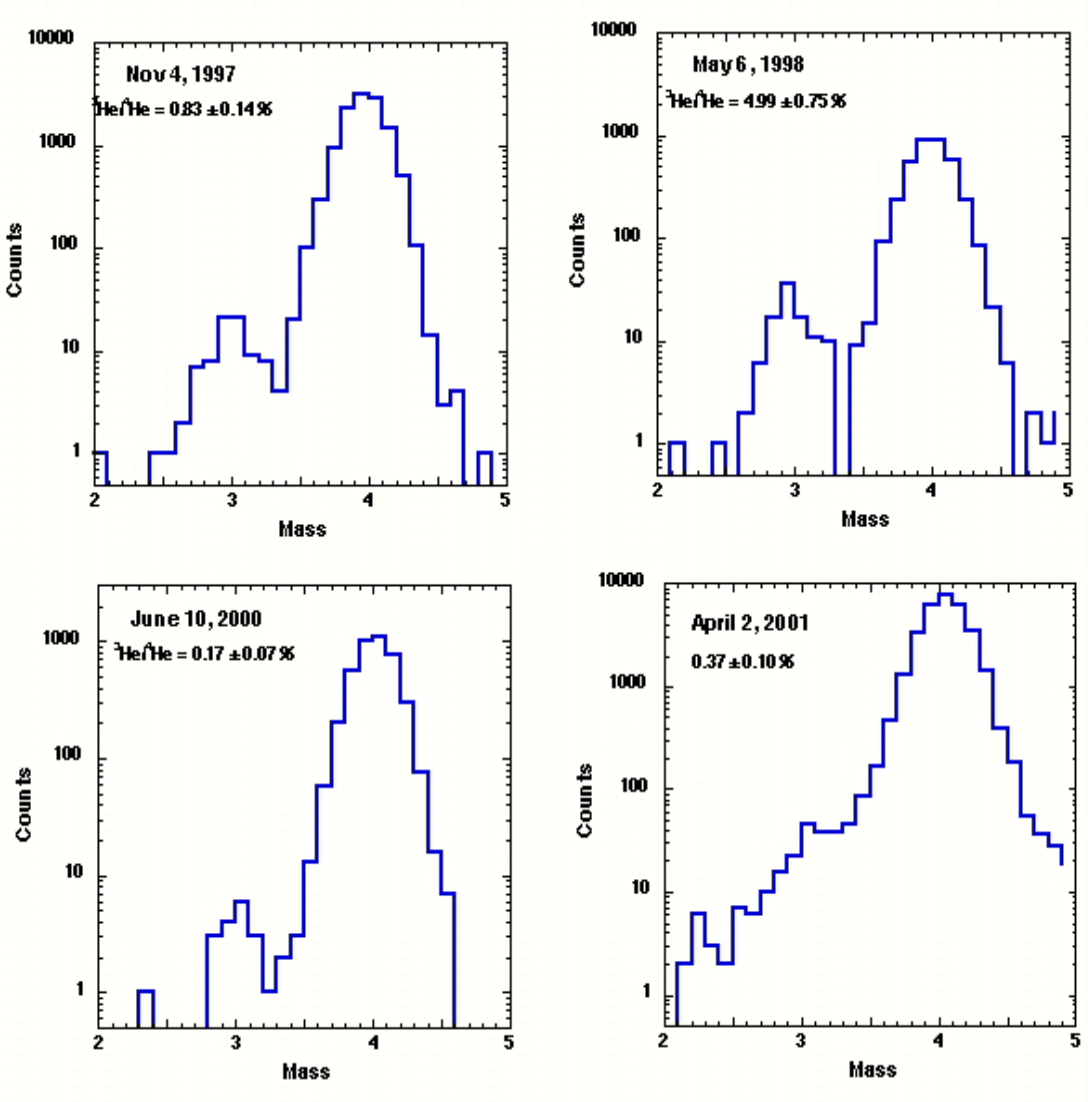
Outline:

What's wrong with the simple two-class picture?

Evidence for other seed populations

- **Impulsive flare contributions for gradual events**
- **Another look at FIP fractionation - compare SEPs/SW**
- **If not solar wind, then what else is accelerated?**

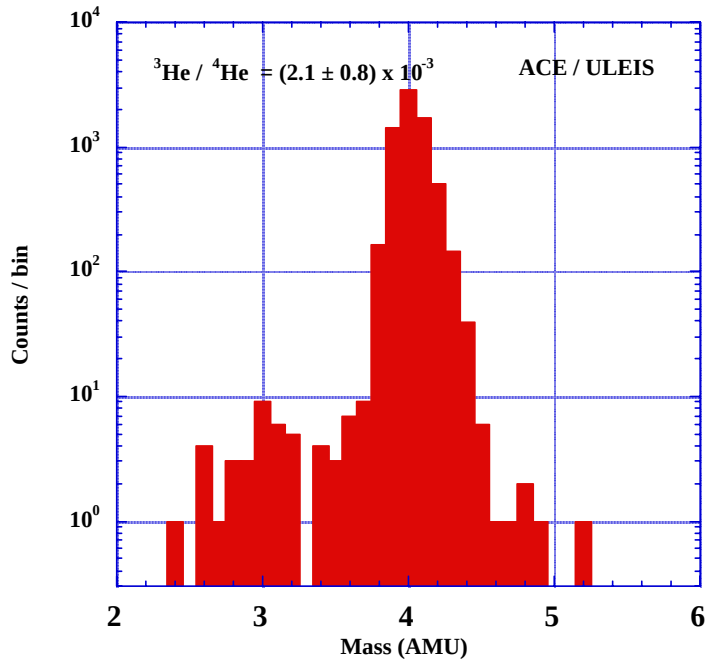

Contributions to the Fluence of Oxygen
2002
Particles/(cm^{2}sr-MeV/nucleon)
Kinetic Energy (MeV/nucleon)
Slow Solar Wind
Fast Solar Wind
Suprathermal Tail
Gradual SEPs 4/02
ESP 5/02
Impulsive SEPs - 8/02
CIR 4/02
Total 2002
GCRs
SEPICA
SWICS
ULEIS
SIS
CRIS



8 to 15 MeV/nuc ACE/SIS data
(Cohen et al. 1999, Wiedenbeck et al. 2000)
(See also SOHO/ERNE -Kocharov et al. 2001)

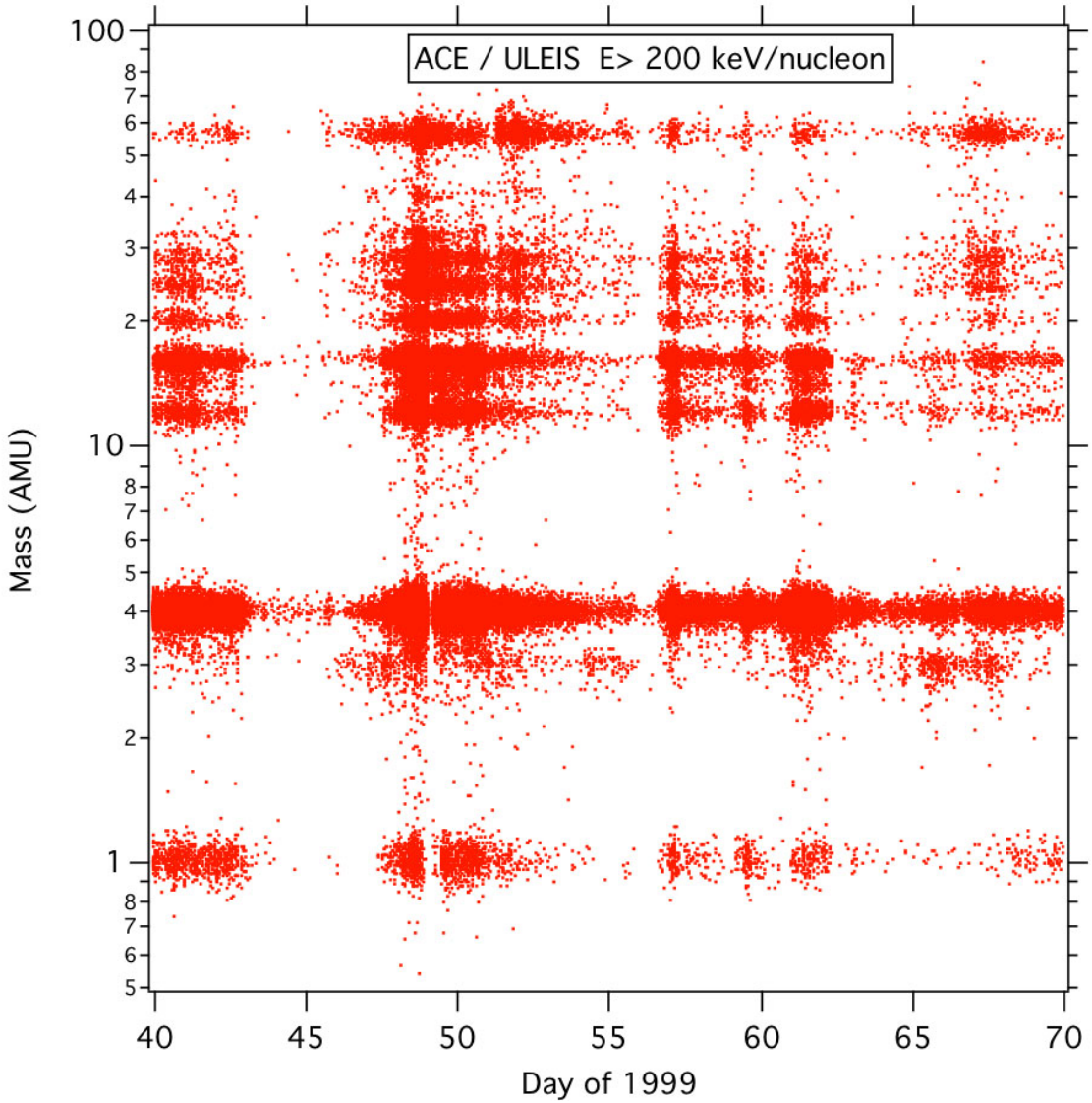
Most large gradual events contain ^{3}He at ~5 to ~50 times its abundance in the solar wind

=> "Hybrid events"



Mason et al. (1999)

Mason et al: Hybrid events result from shock-accelerated remnants of earlier impulsive flare particles

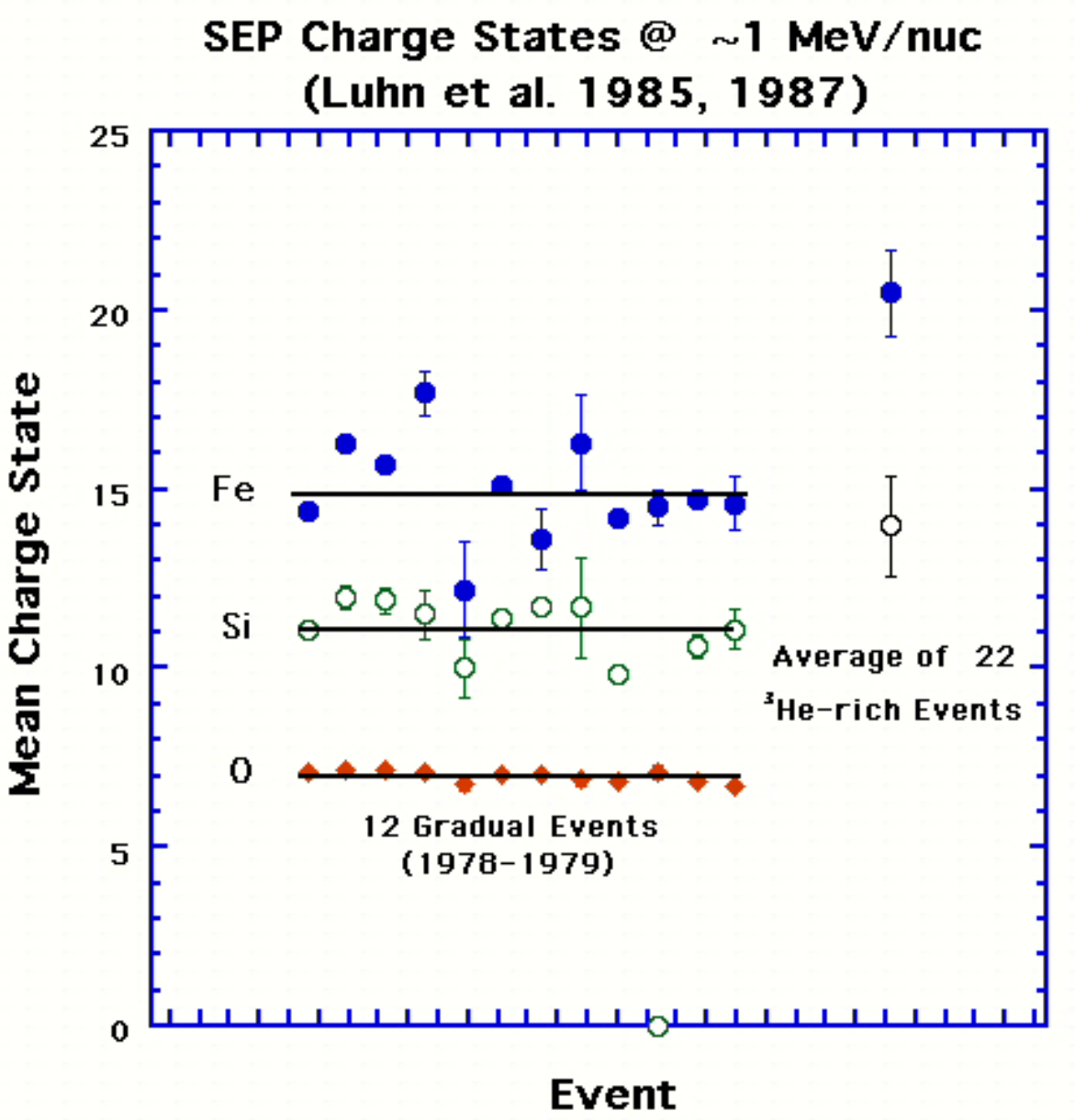


Fe

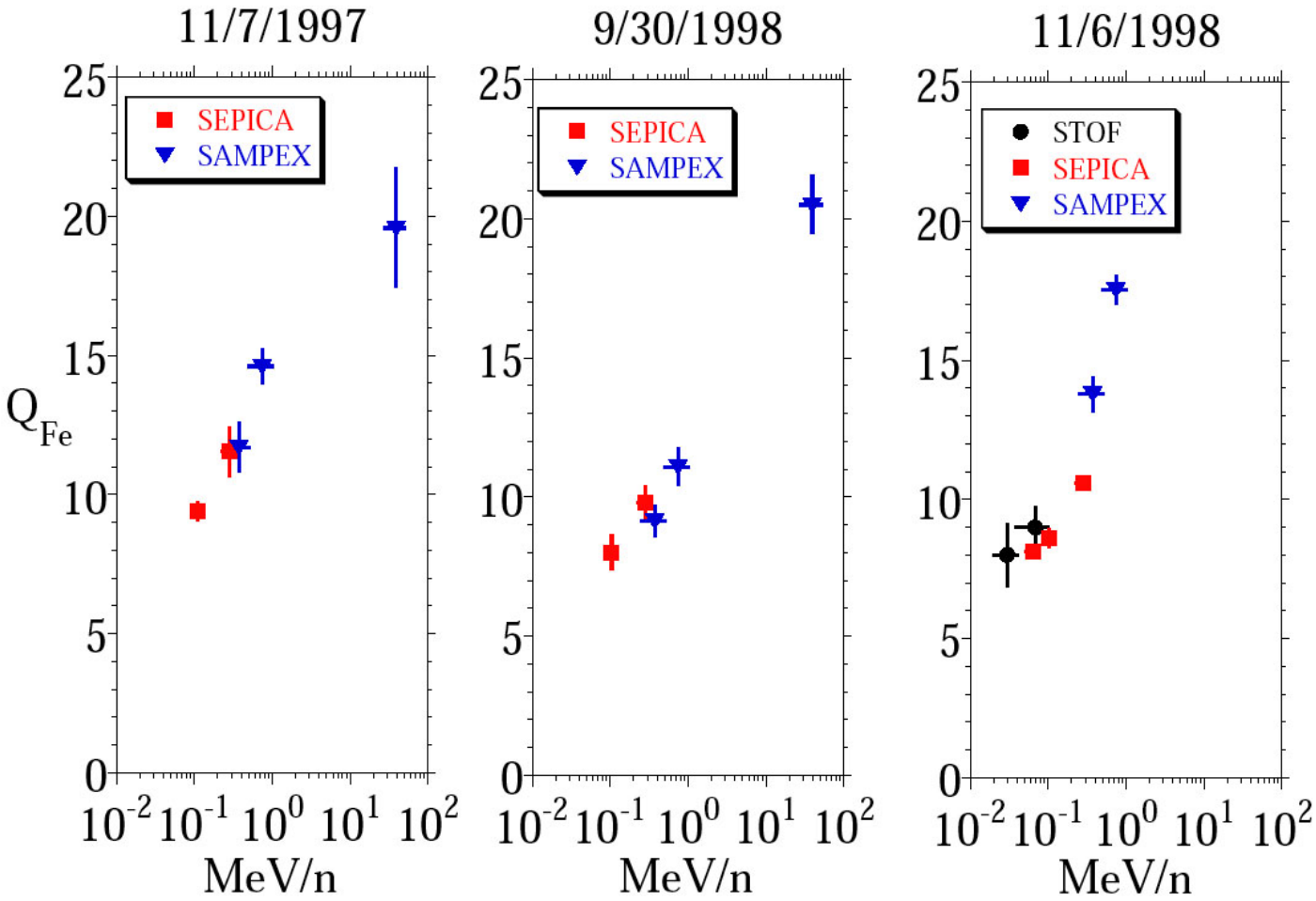
^{3}He

^{3}He and Fe are usually present in the interplanetary medium as a result of small impulsive events

(Mason et al. 1999)


SEP Charge States @ ~1 MeV/nuc
(Luhn et al. 1985, 1987)
Mean Charge State
25
20
15
10
5
0
Fe
Si
O
12 Gradual Events
(1978-1979)
Average of 22
3He-rich Events
Event

Measurements from SAMPEX/ACE/SOHO show that Charge States in many Gradual Events are Energy Dependent



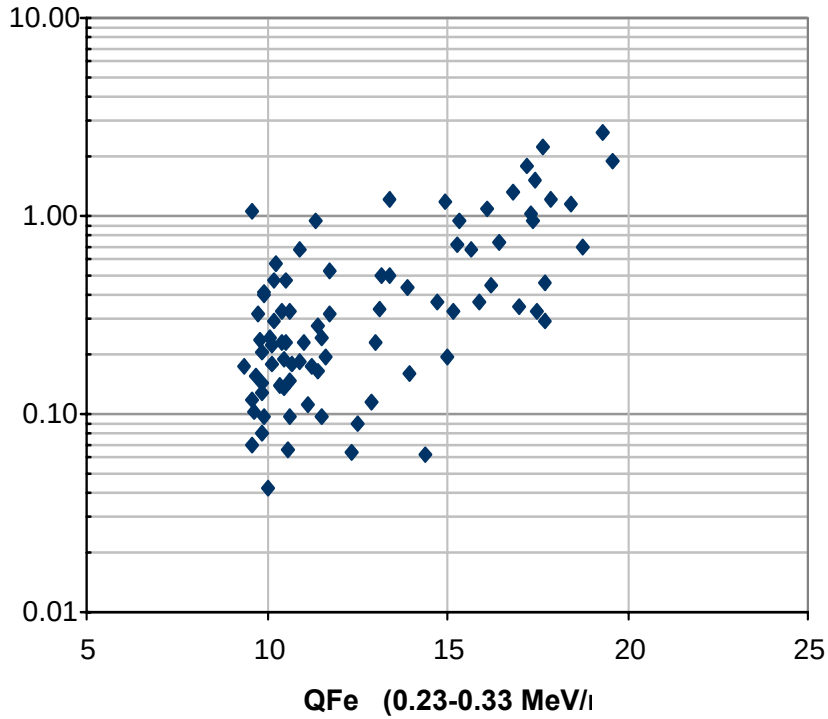
Mix of flare & shock?

Stripping during acceleration?

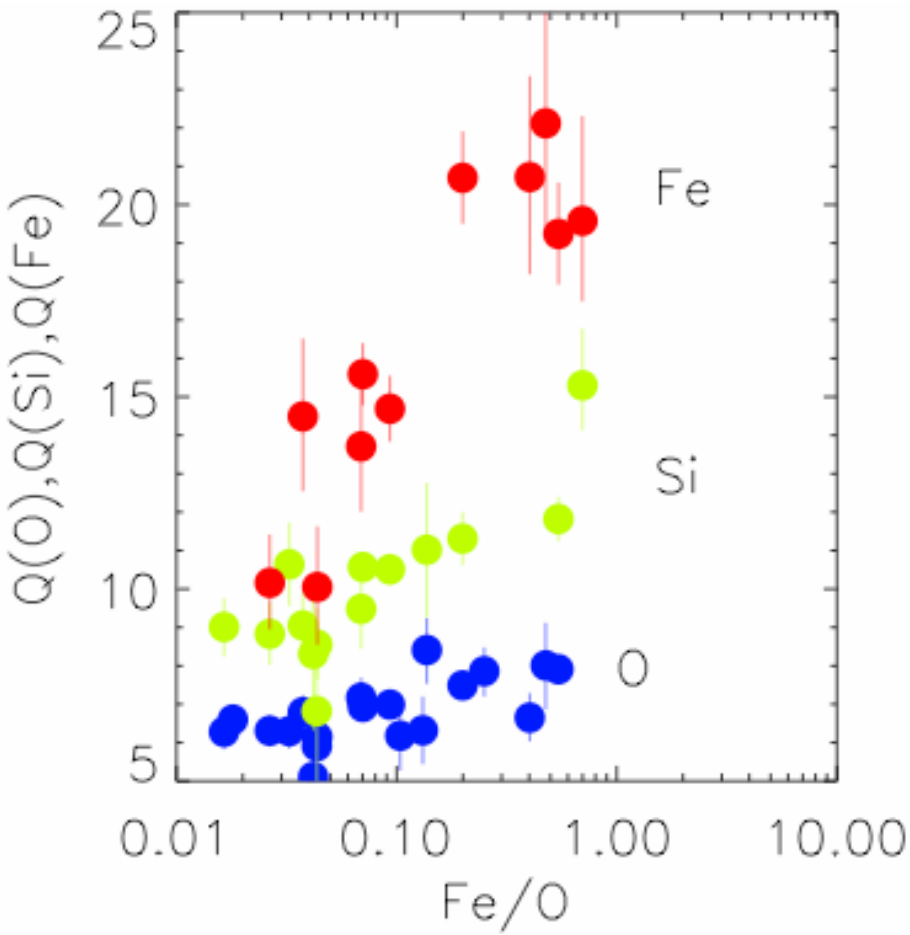
(**Moebius et al., Mazur et al., Labrador et al., Klecker et al.**)

Composition and Charge-State Correlations

~0.3 MeV/nuc - ACE/SEPICA

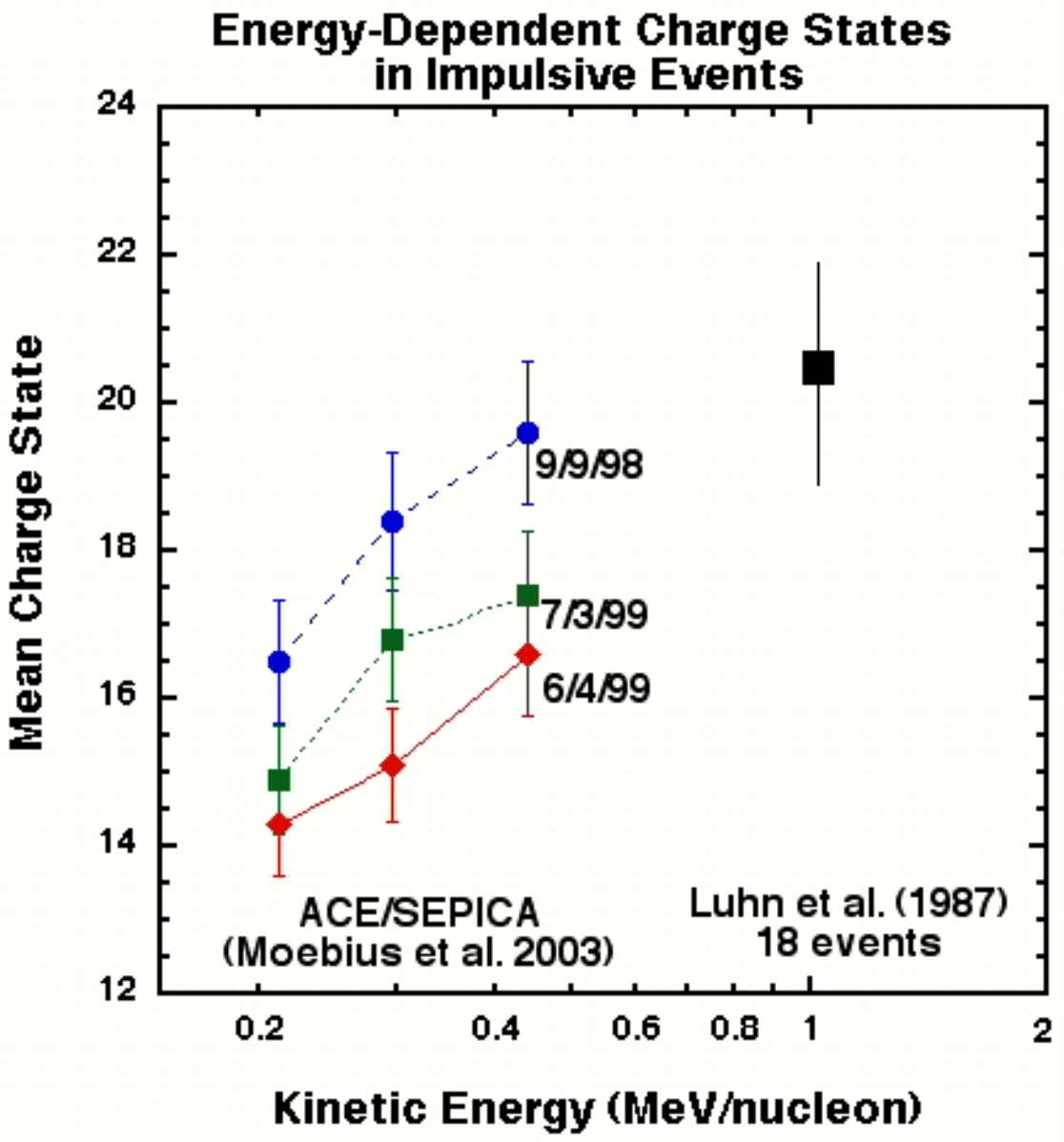


~30 MeV/nuc - SAMPEX



Popecki et al., Moebius et al.

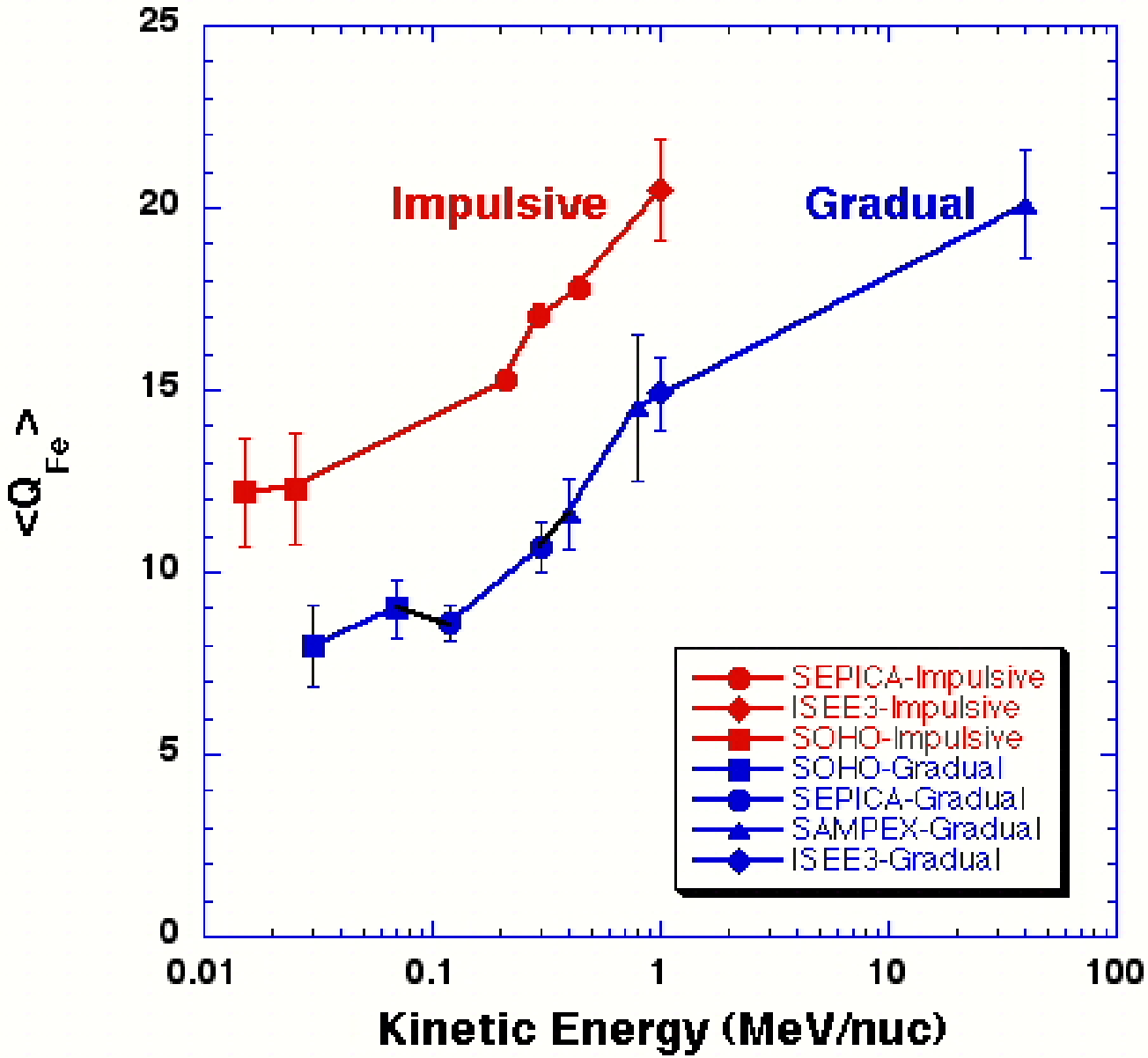
Leske et al., Labrador et al.



Moebius et al. interpret this as evidence of stripping in the low corona, starting from Q ≈ 10.

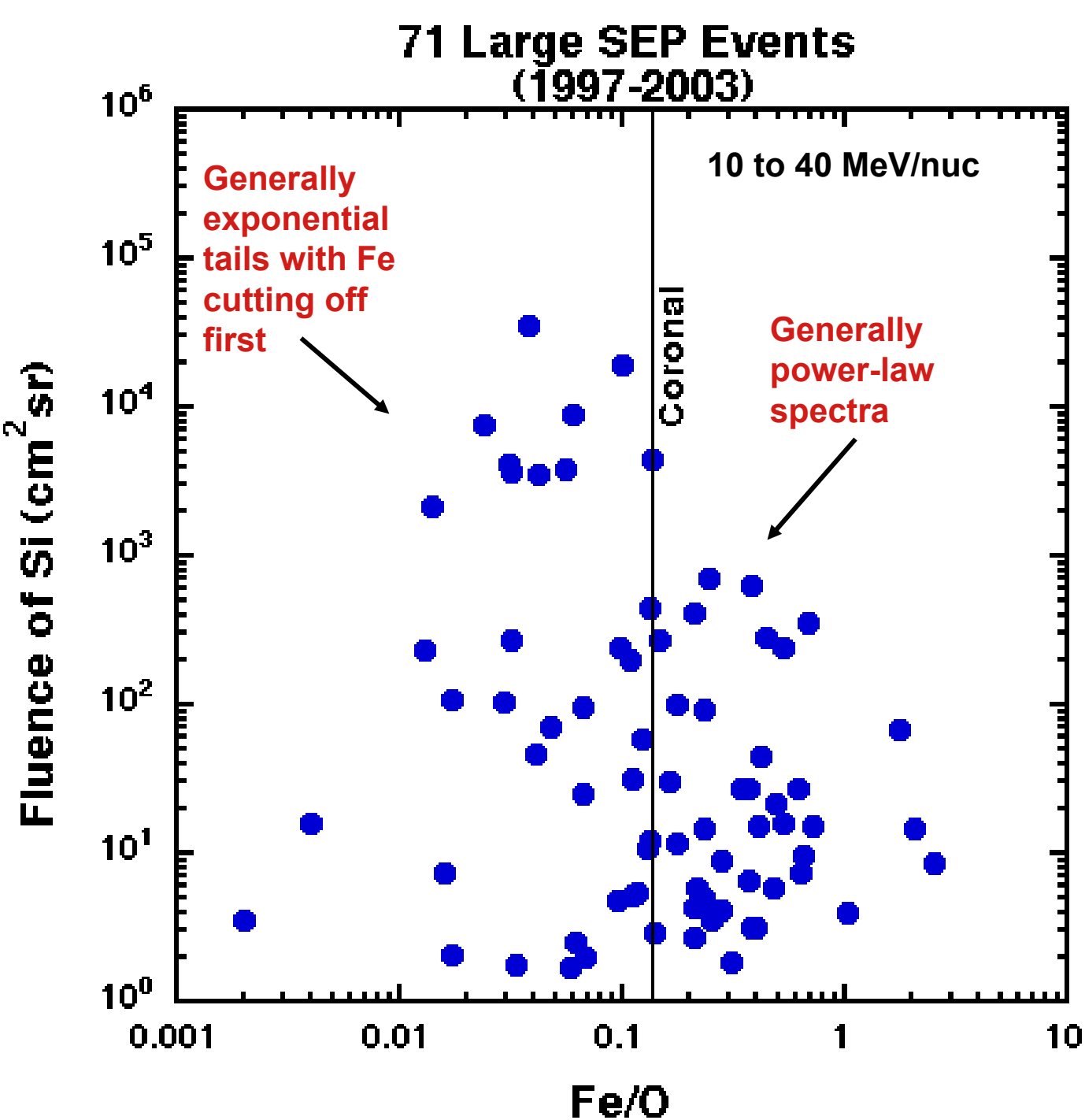
This requires $nT \sim 10^{10}\ cm^{-3}s$

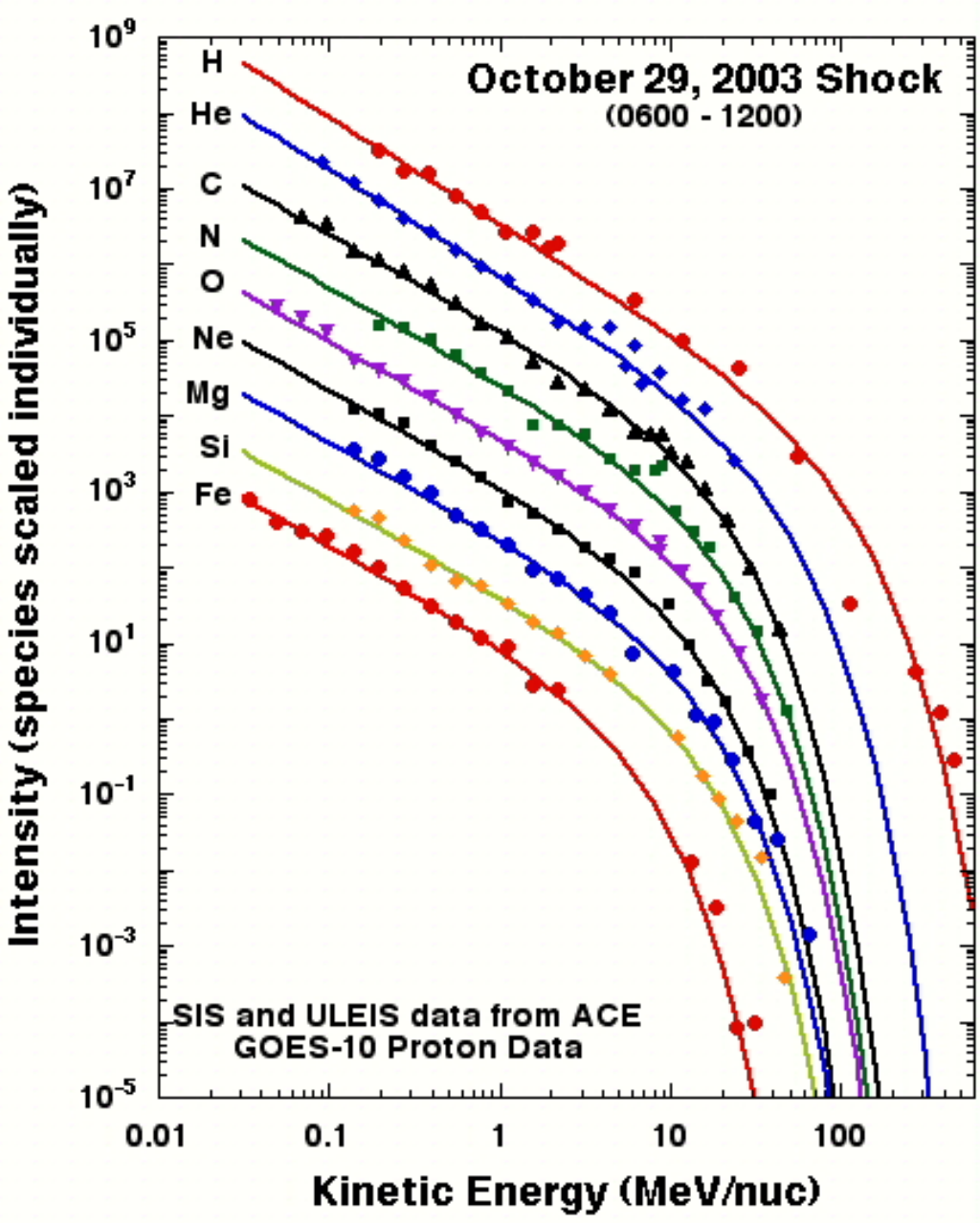
(see Kovaltsov et al. 2003; Kocharov et al.)

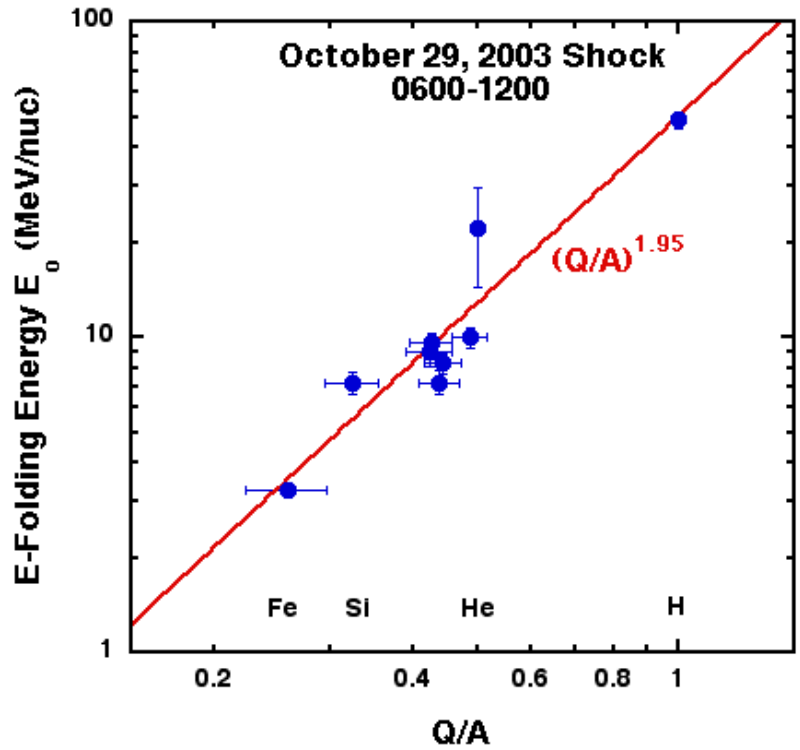


Challenge for the simulators:

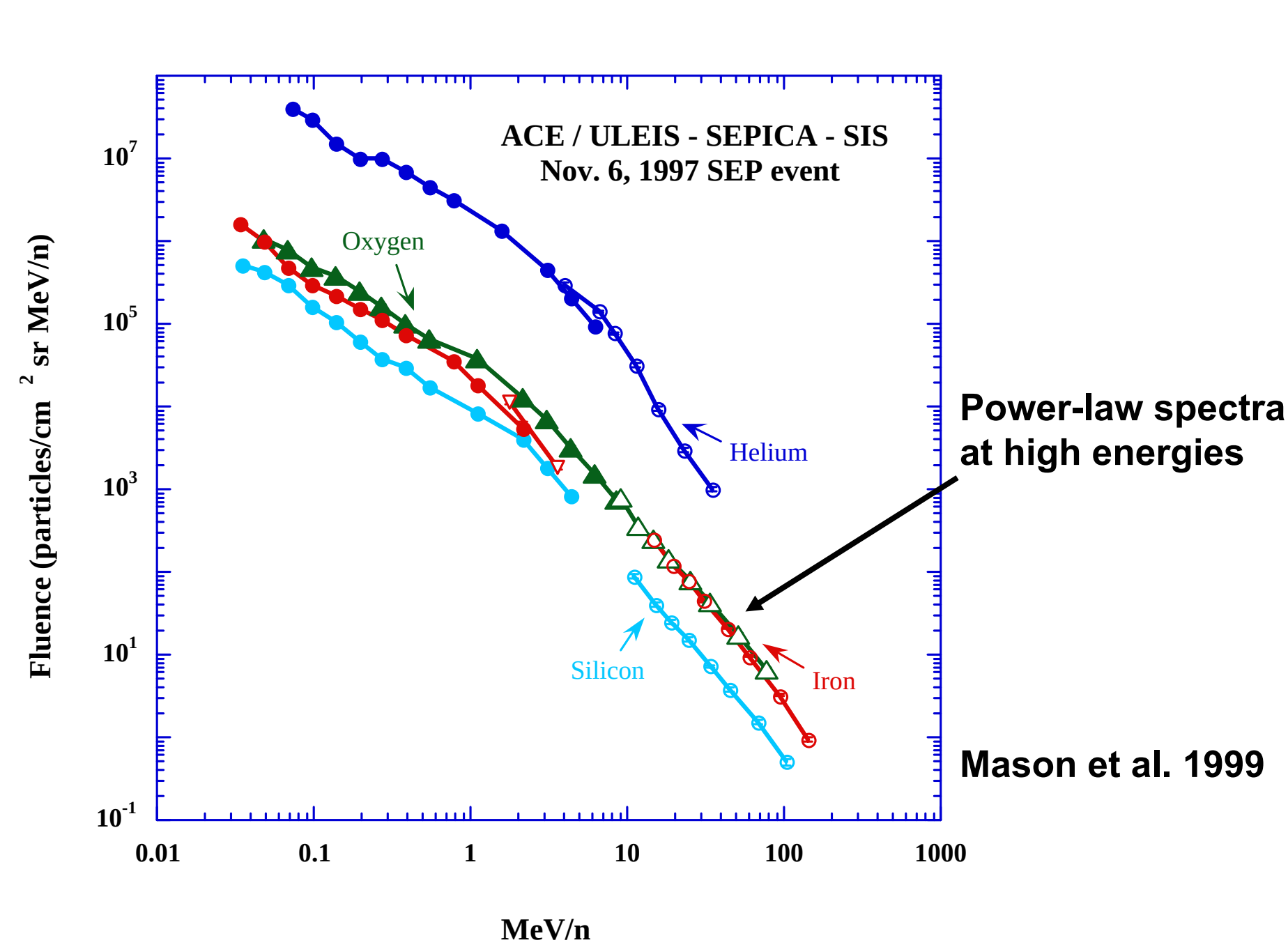
Can a CME shock turn the red curve into the blue curve?

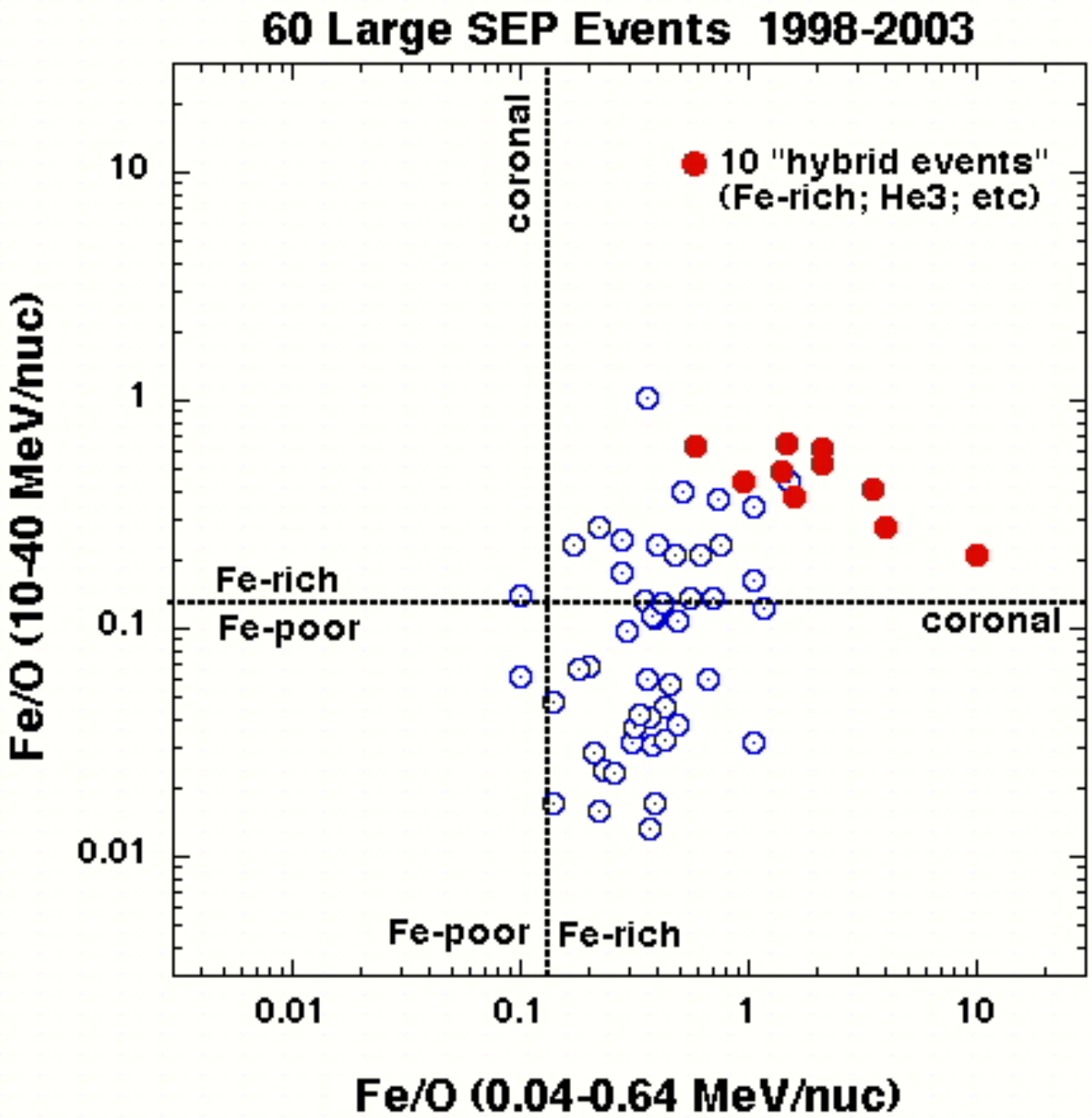

71 Large SEP Events
(1997-2003)
10 to 40 MeV/nuc
Generally exponential tails with Fe cutting off first
Generally power-law spectra
Coronal
Fluence of Si (cm^{-2}sr)
Fe/O
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.001
0.01
0.1
1
10





See also Tylka et al. (2000, 2002)


ACE / ULEIS - SEPICA - SIS
Nov. 6, 1997 SEP event
Oxygen
Helium
Silicon
Iron
Fluence (particles/cm 2 sr MeV/n)
MeV/n
10^7
10^5
10^3
10^1
10^-1
0.01
0.1
1
10
100
1000
Power-law spectra at high energies
Mason et al. 1999

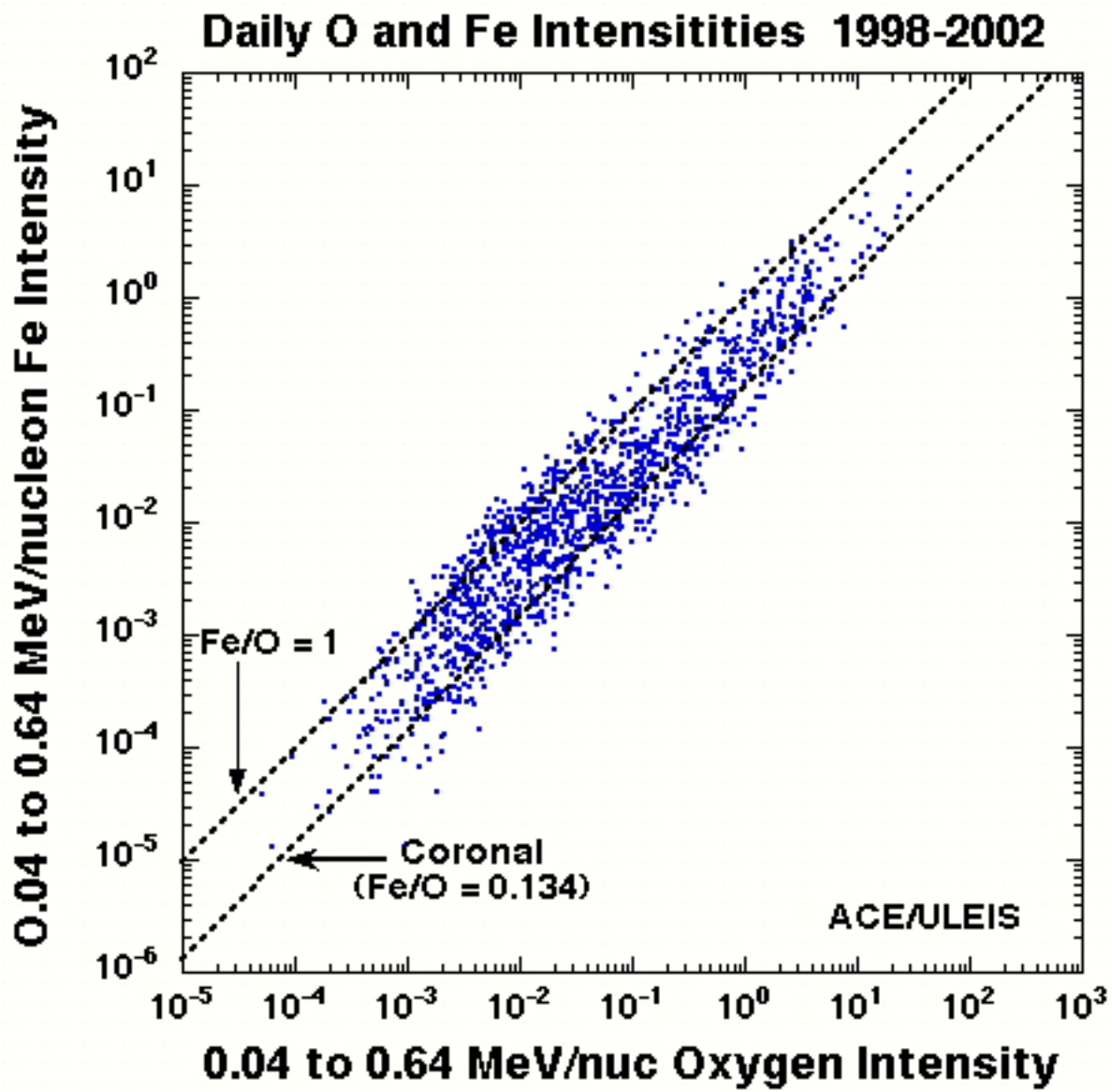


Note: Most (>90%) of large SEP events are Fe-rich!

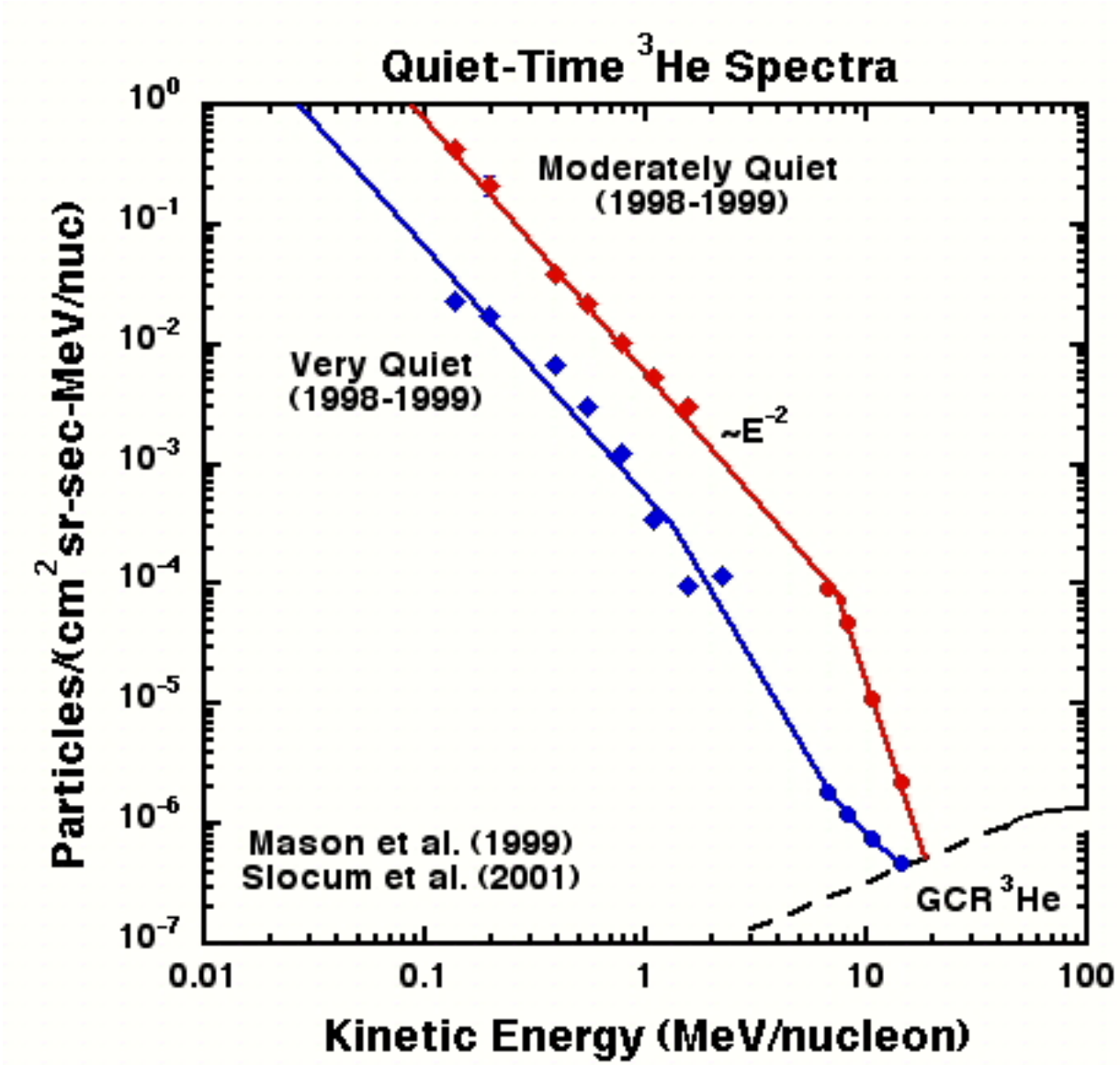
Surprising, since shocks at 1 AU accelerate Fe less efficiently than lighter ions (Desai et al. 2003)

Are Q/M-dependent acceleration effects different near the Sun?

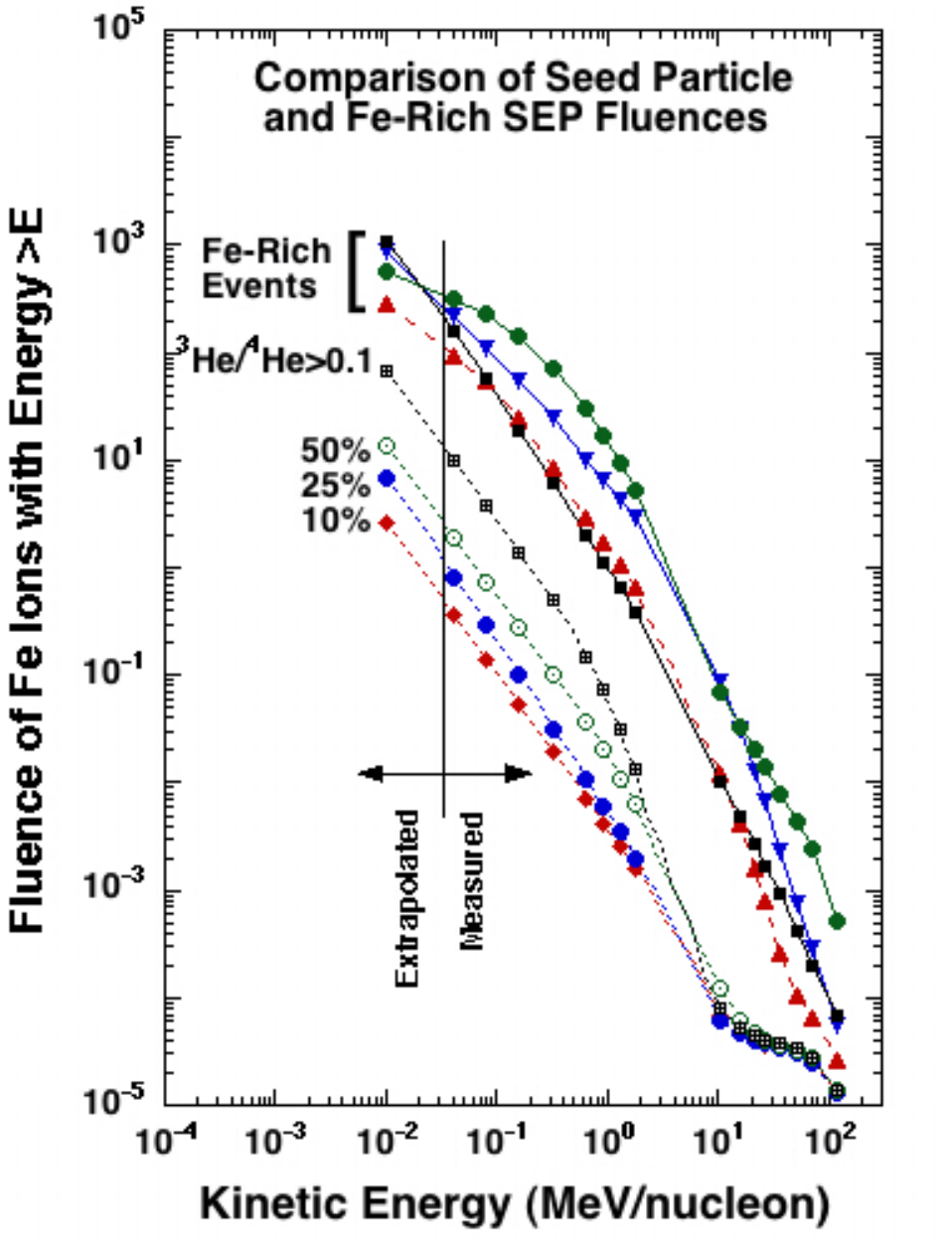
Is there Q/M-dependent injection? (Tylka et al., next talk)



Suprathermals >40 keV/nuc provide an Fe-rich seed population for interplanetary shocks

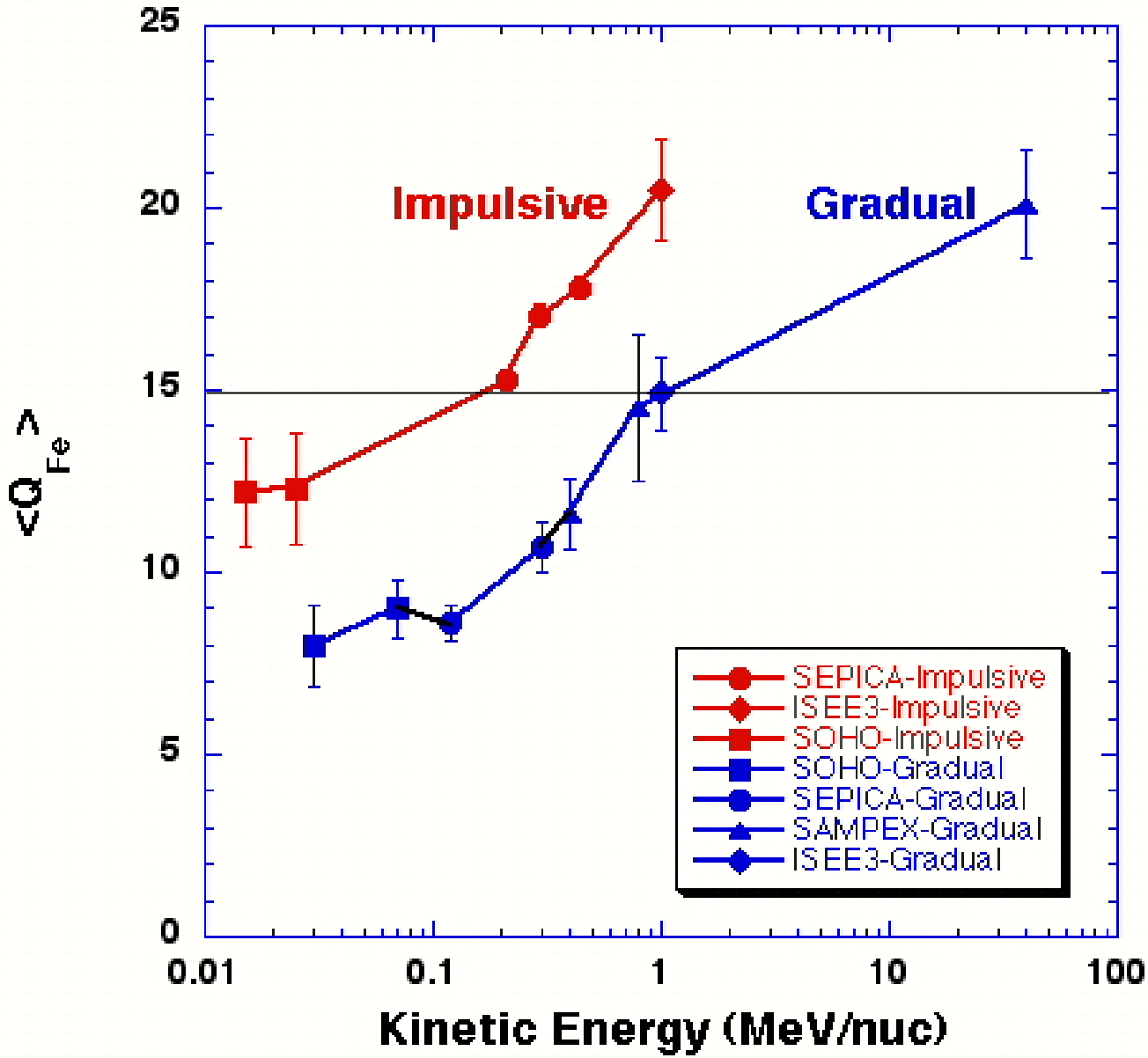

Quiet-Time 3He Spectra
Moderately Quiet
(1998-1999)
Very Quiet
(1998-1999)
~E-2
Mason et al. (1999)
Slocum et al. (2001)
GCR 3He
Particles/(cm2 sr-sec-MeV/nuc)
Kinetic Energy (MeV/nucleon)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0.01
0.1
1
10
100

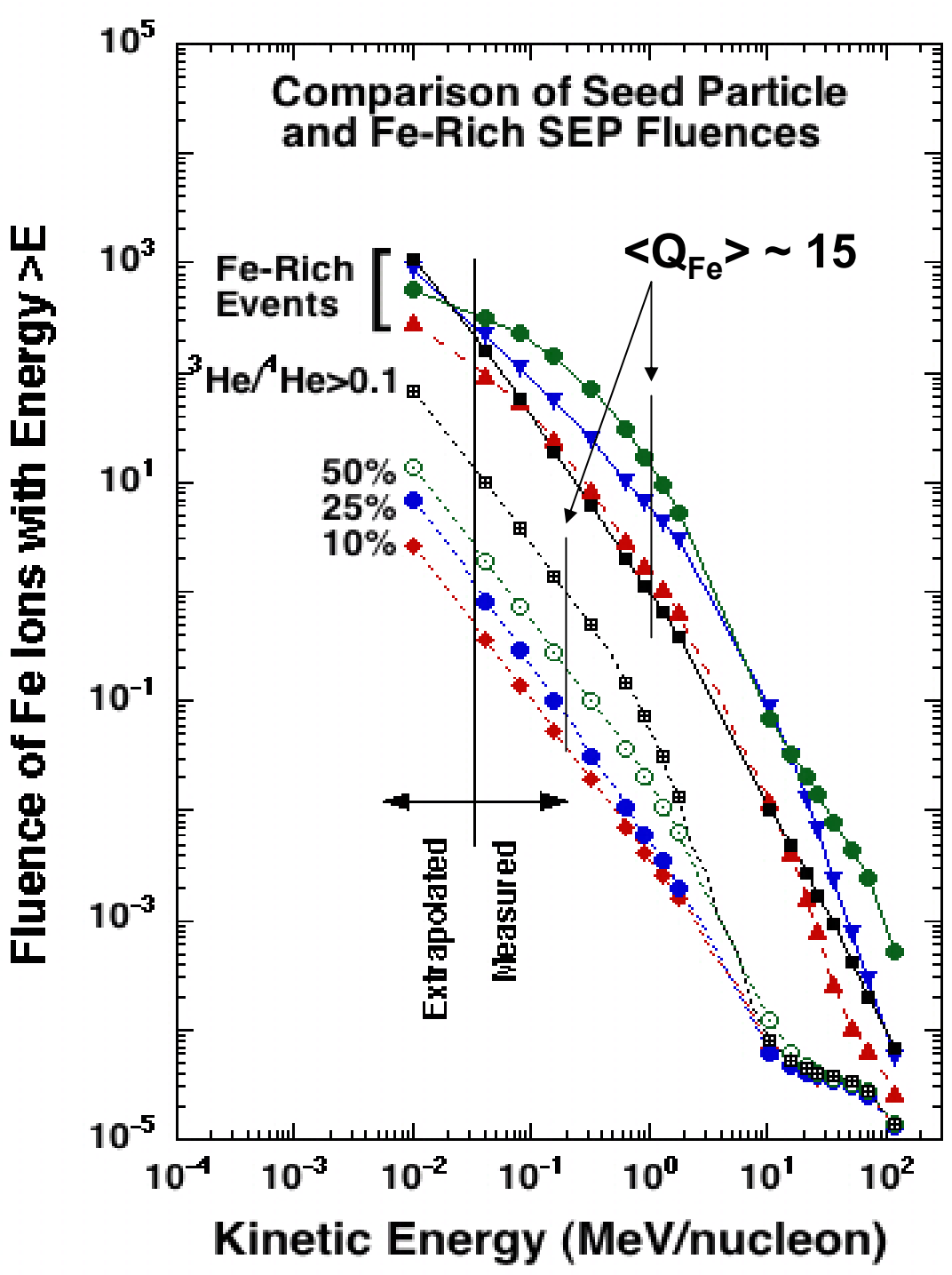
However, it is not clear that there is enough remnant Fe to account for all of the Fe in Fe-rich "hybrid" events (Mewaldt et al. 2003)



There is enough remnant Fe to account for high-energy (e.g., >3 MeV/nuc) Fe in hybrid events.

But it will not all be highly ionized


25
20
15
10
5
0
0.01
0.1
1
10
100
Kinetic Energy (MeV/nuc)
<Q Fe>
Impulsive
Gradual
SEPICA-Impulsive
ISEE3-Impulsive
SOHO-Impulsive
SOHO-Gradual
SEPICA-Gradual
SAMPEX-Gradual
ISEE3-Gradual



The integral density of Fe with Q ≥ 15 is greater in "hybrid events" than in suggested remnant seed populations

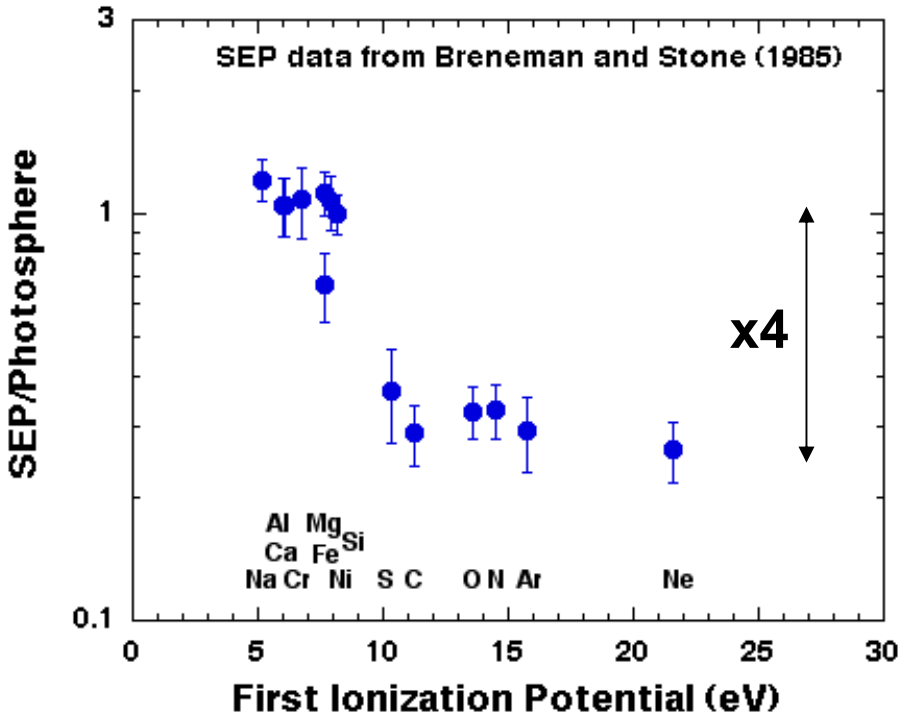
=> need another source of highly- ionized Fe

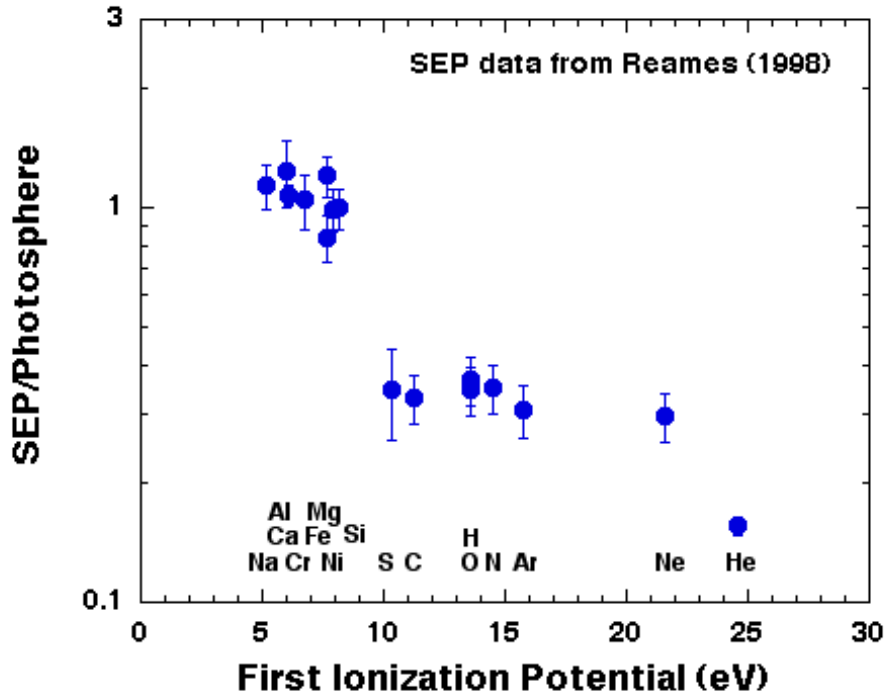
Other possibilities:

- **Direct flare contributions (Cane et al. 2003)**
- **Shock accelerates particles from the associated flare (Mewaldt et al.. 2003, Li and Zank, 2004)**
- **Acceleration of CME/flare ejecta from a preceeding event (Mewaldt et al. 2004)**

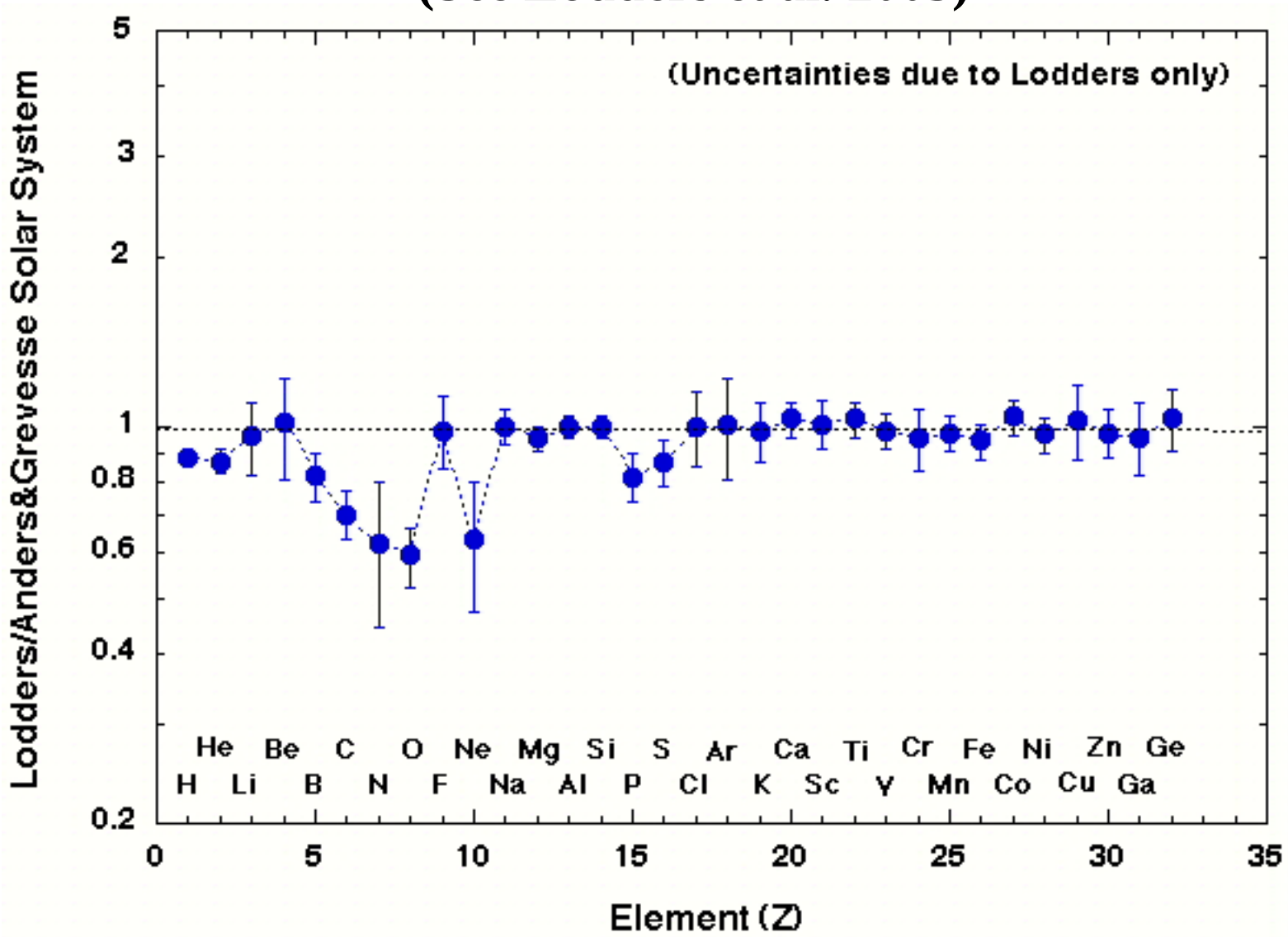
SEPs with FIP > 10 eV are depleted relative to photospheric abundances

Coronal composition is fractionated with respect to the photosphere by ion-neutral fractionation processes

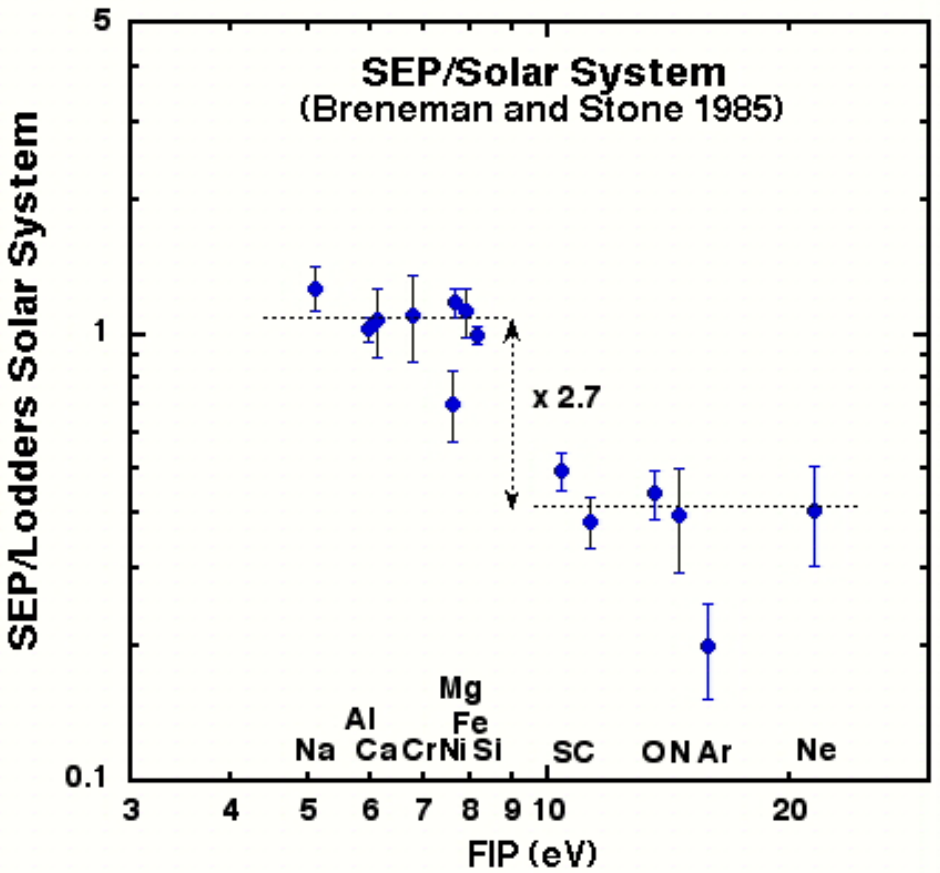


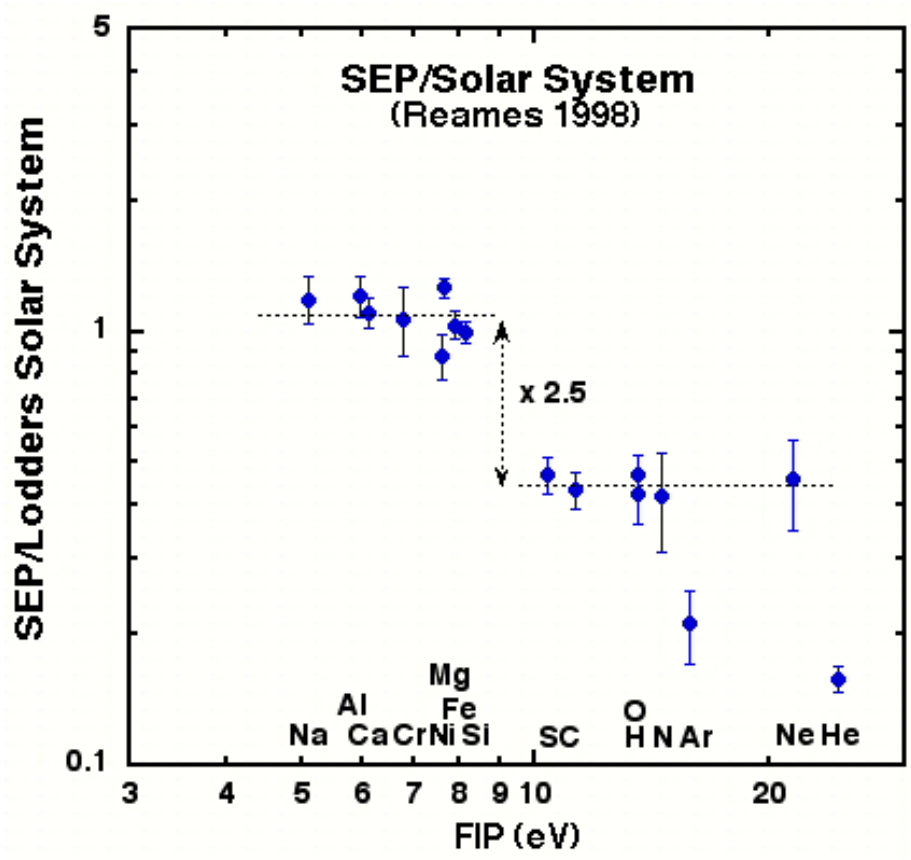


Updated Solar Photospheric Abundances
(See Lodders et al. 2003)

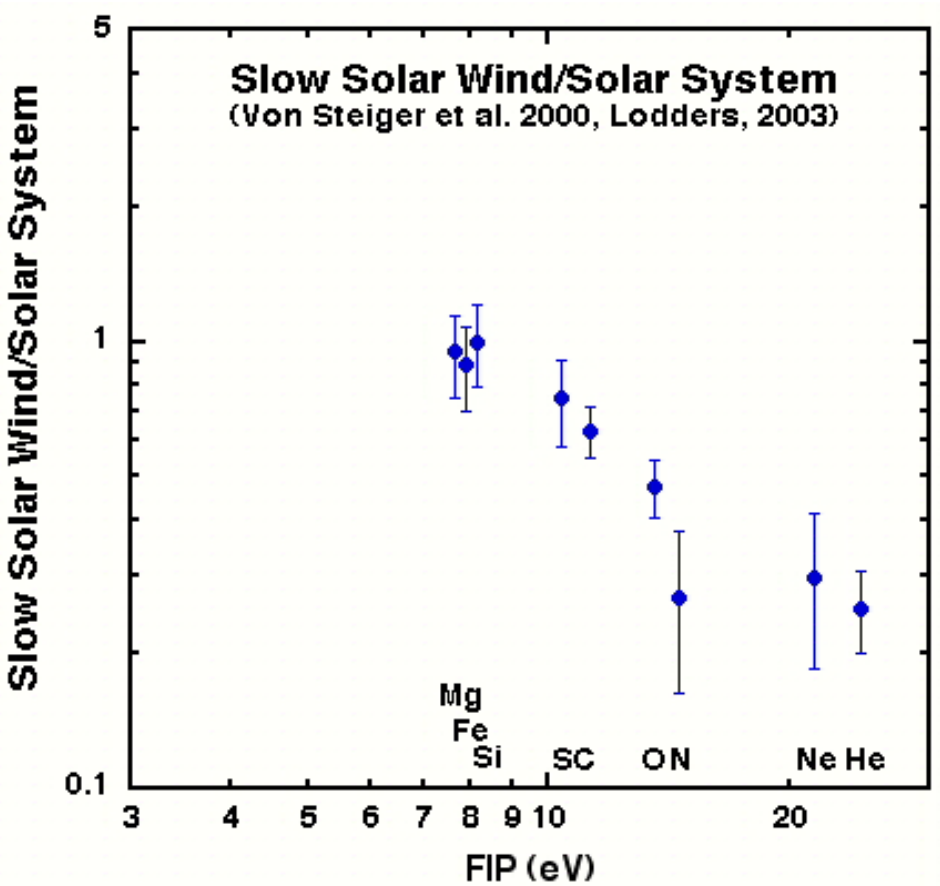


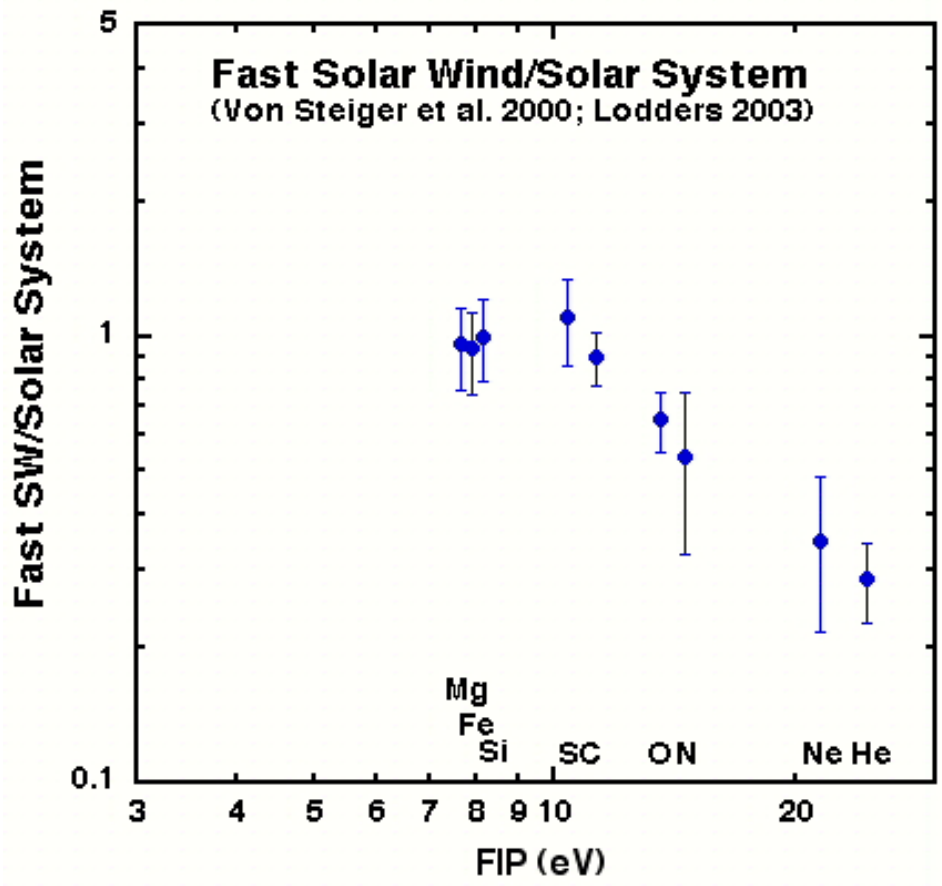
Updated SEP FIP-fractionation Patterns



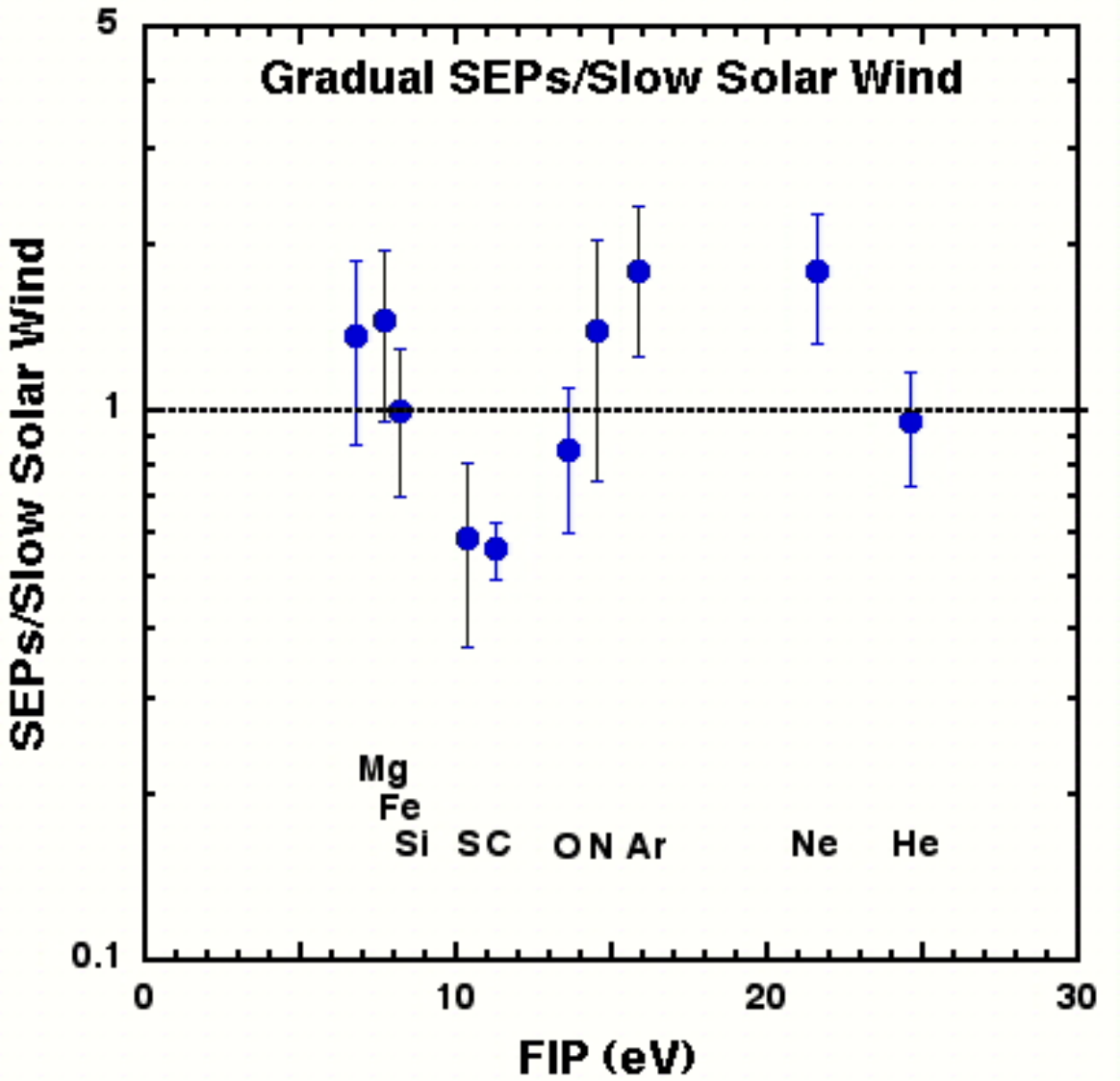


Solar Wind FIP-Fractionation Patterns





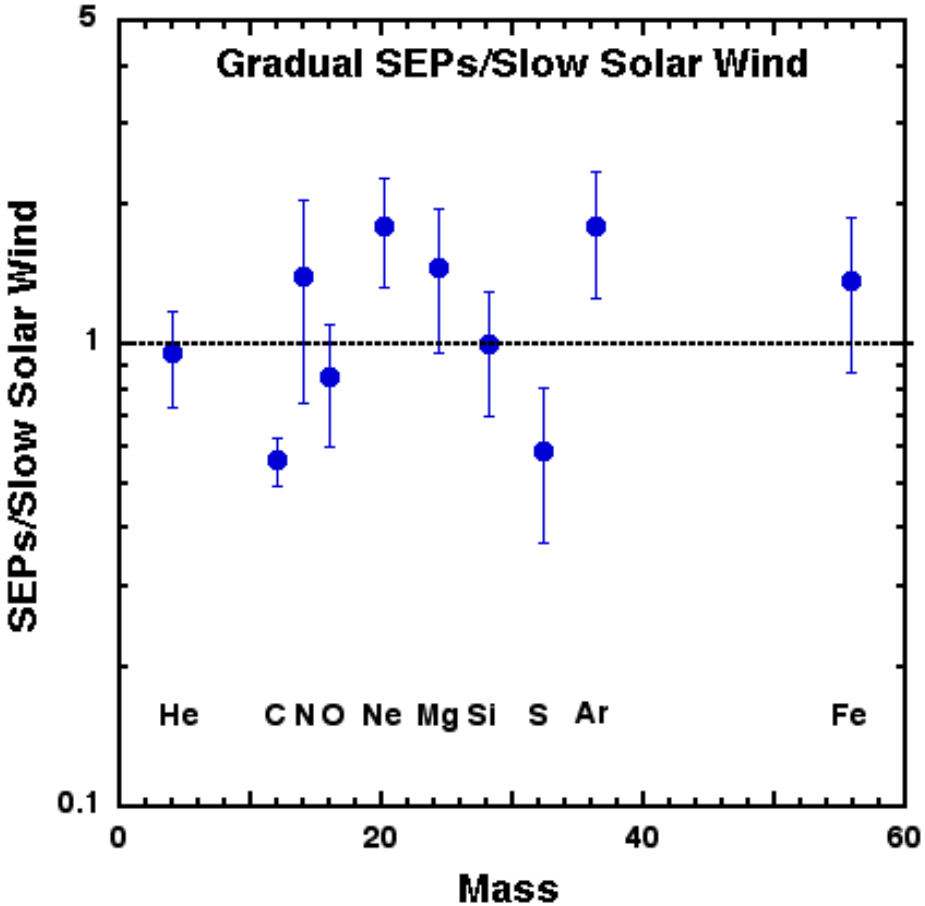
The composition of SEPs and Solar Wind differ in several important ways

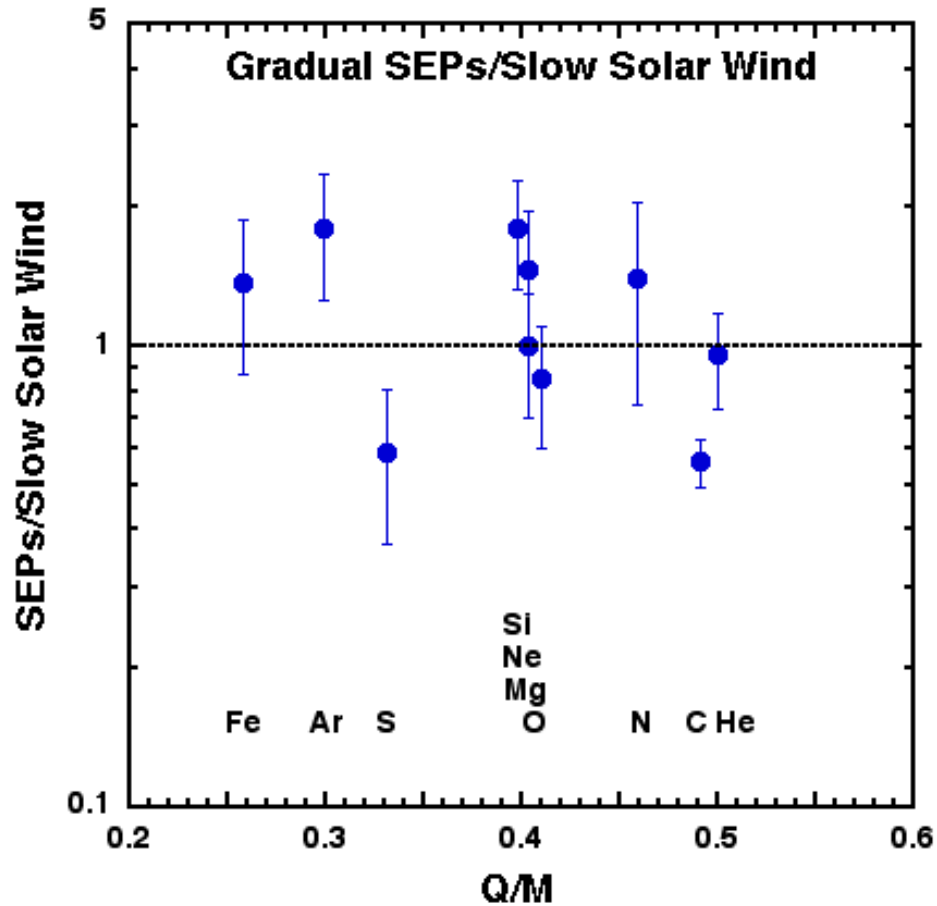


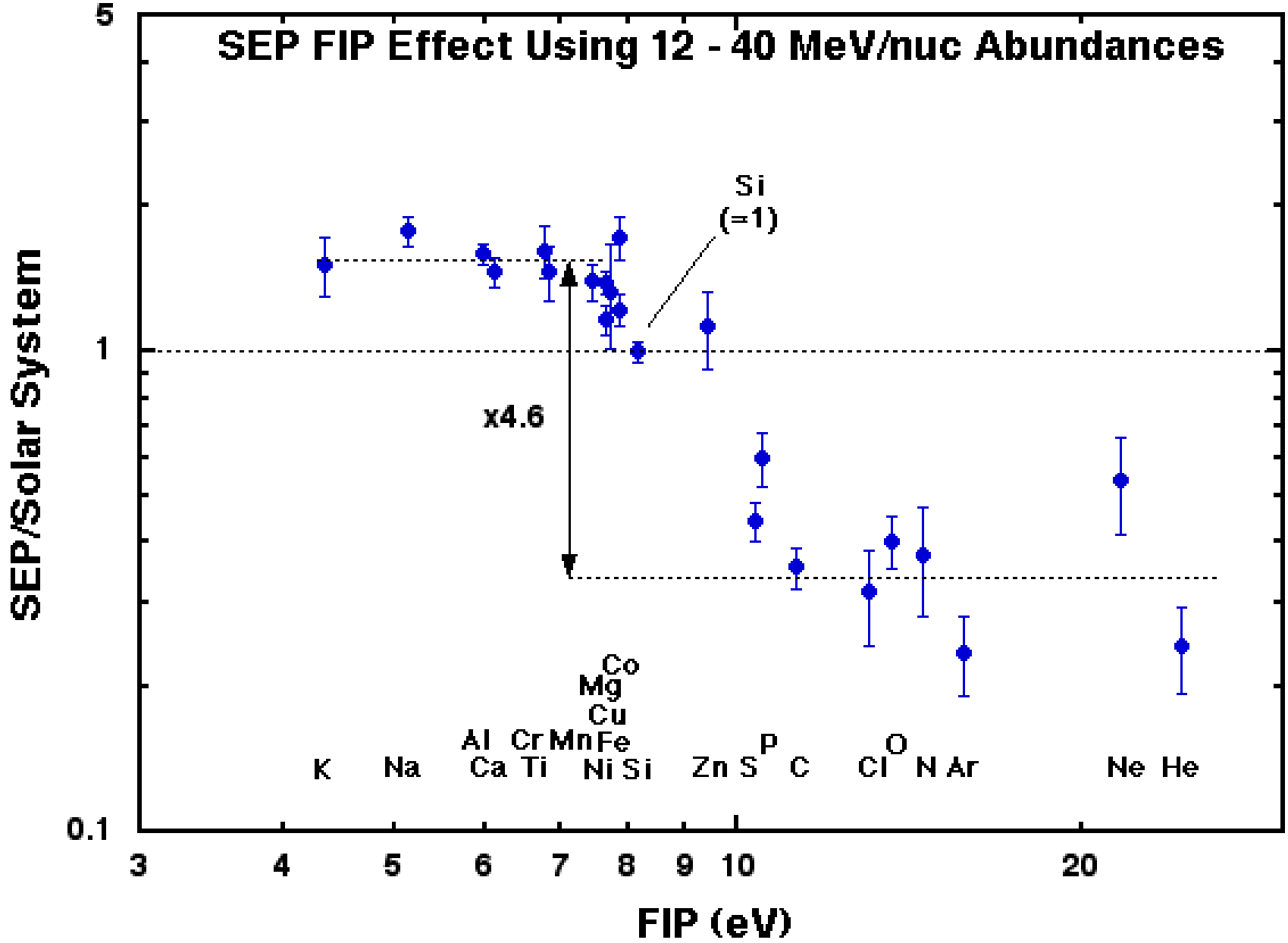
	SOLAR WIND	SEPS
C/O	0.7	0.4
Ne/O	0.10	0.15
S/Si	0.33	0.22

Models that accelerate SEPs from the solar wind need to explain these differences

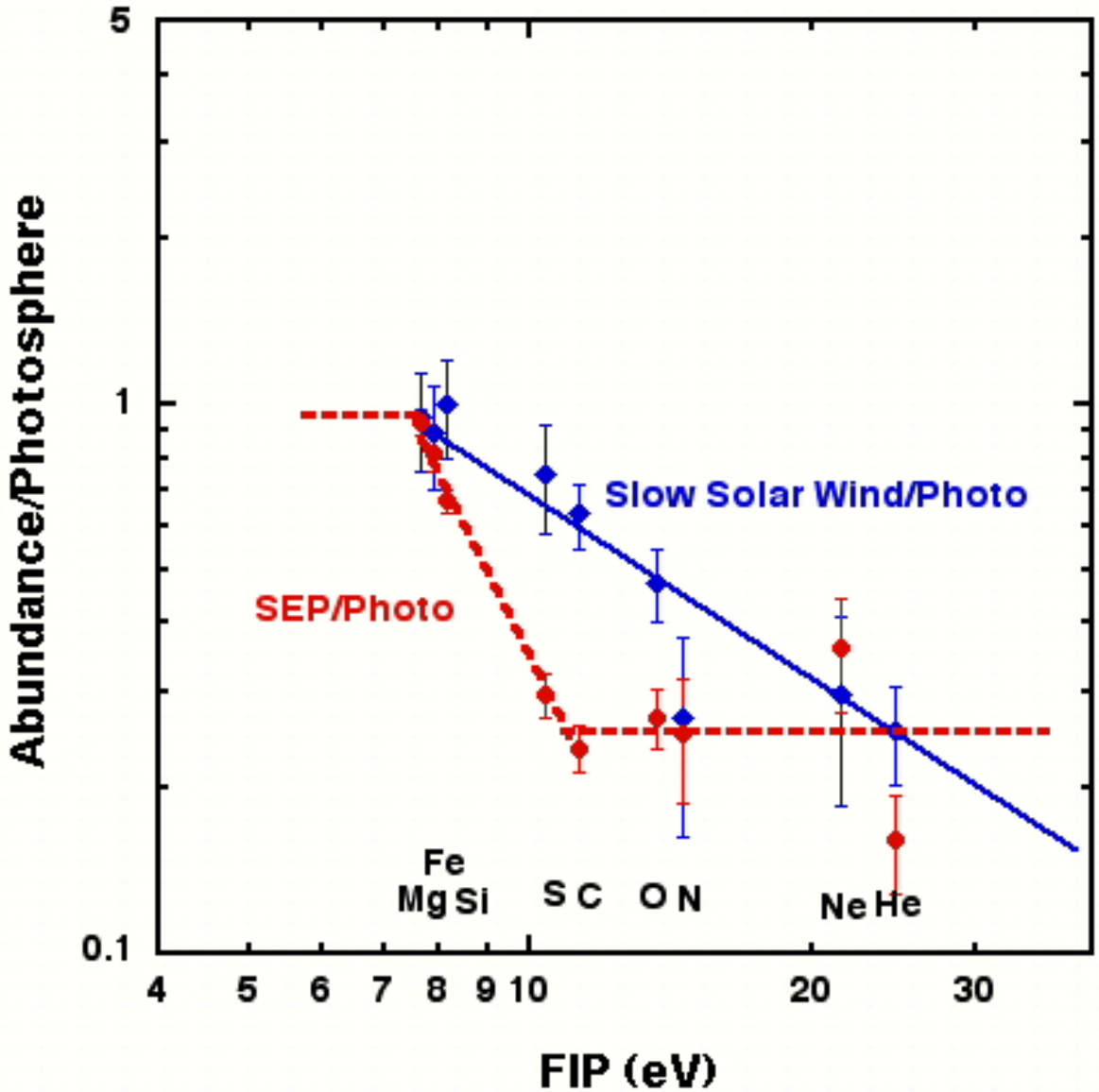
It is not possible to obtain the SEP composition by mass, Q/M, Z, or FIP-dependent fractionation. We conclude that most SEPs do not originate from the bulk solar wind






SEP FIP Effect Using 12 - 40 MeV/nuc Abundances
SEP/Solar System
5
1
0.1
Si
(=1)
x4.6
Co
Mg
Cu
Al Cr Mn Fe
P
O
K Na Ca Ti Ni Si Zn S C Cl N Ar Ne He
3 4 5 6 7 8 9 10 20
FIP (eV)

SEPs show a larger FIP effect than Solar Wind



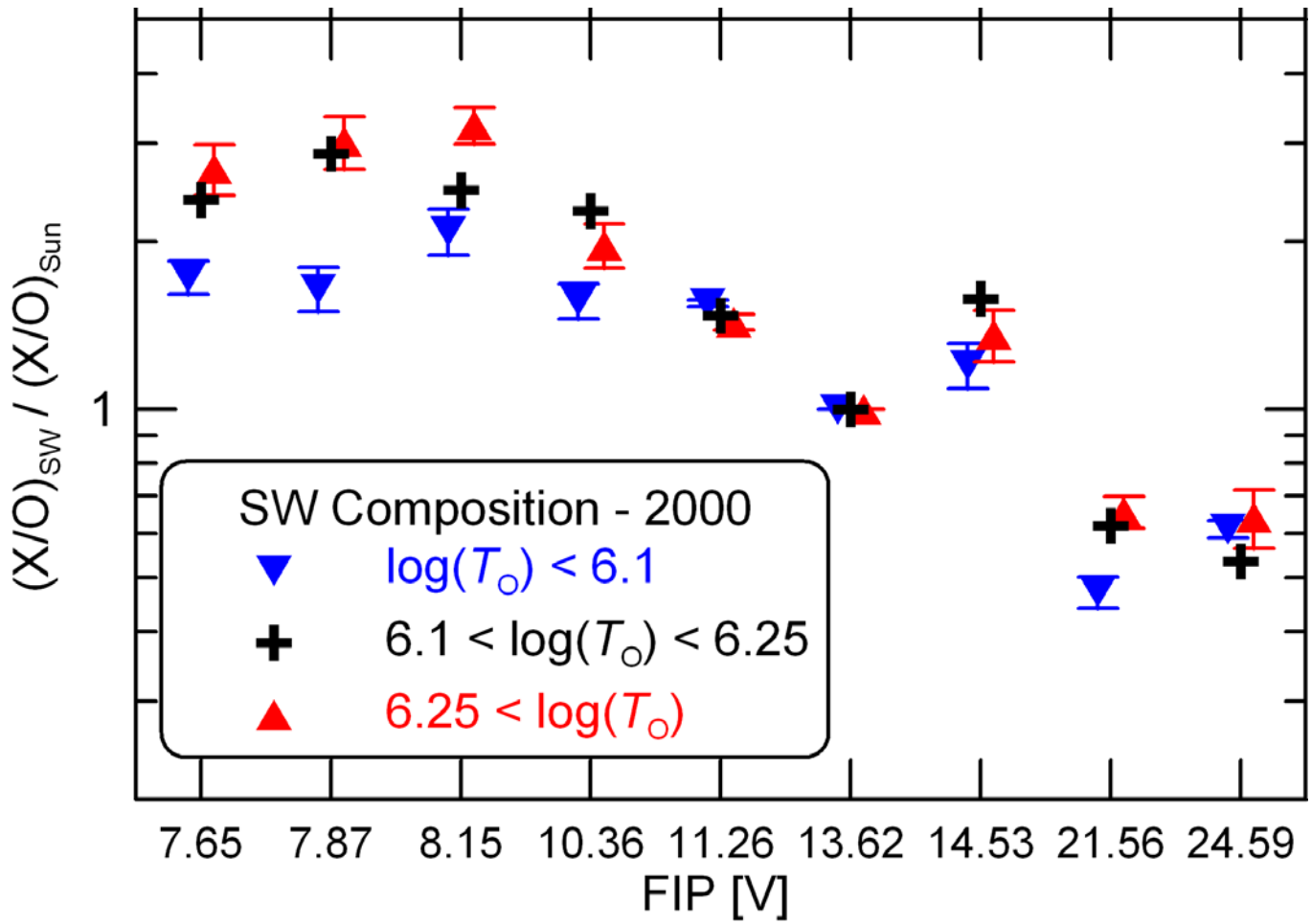
FIP-effect in coronal loops grows with time (Feldman 1998)

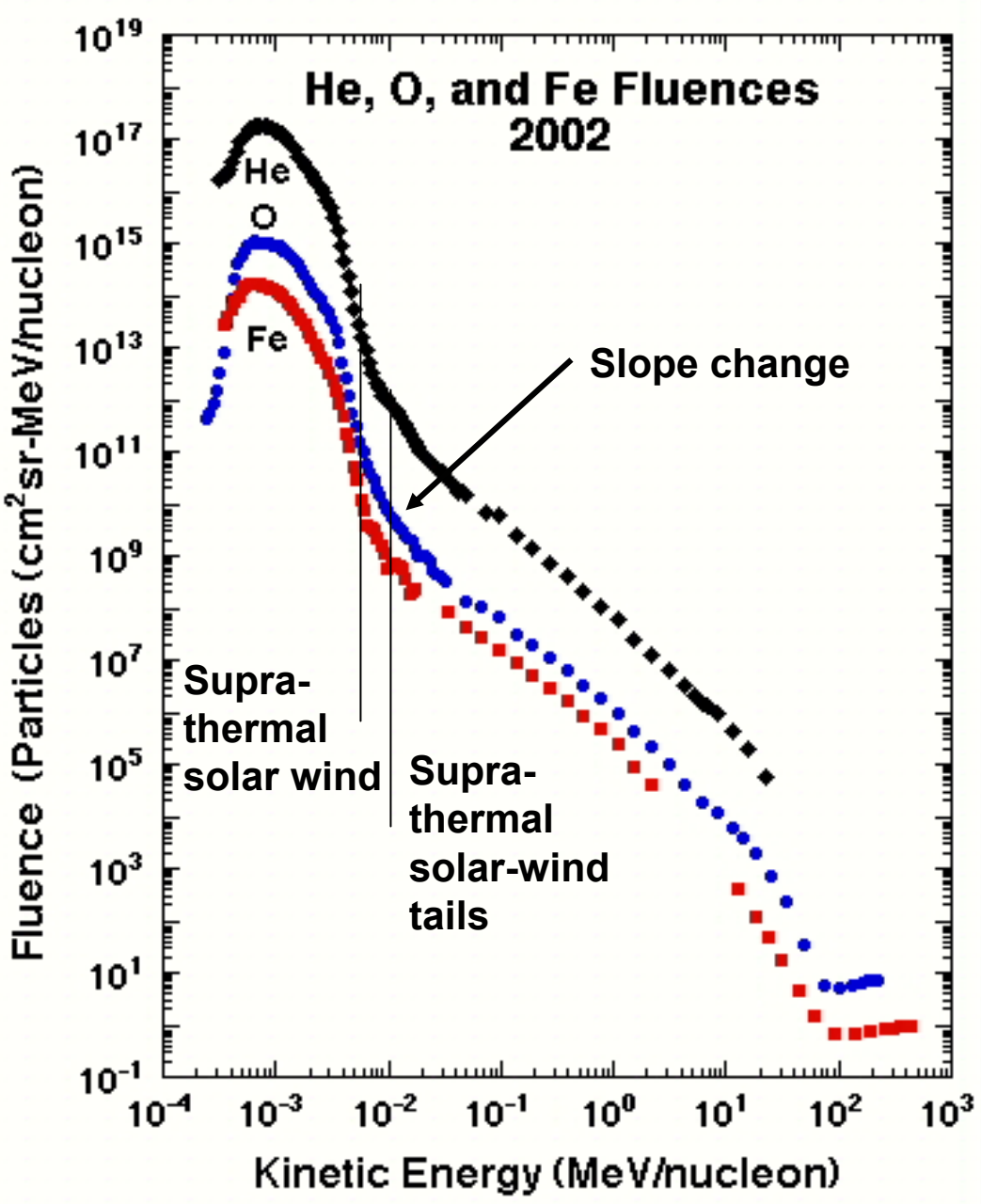
Larger loops have a bigger FIP effect

Maybe:
SW from small loops
SEPs from large loops

(see also Zurbuchen & von Steiger, 2003)

Zurbuchen and von Steiger (2003) suggested that high-temperature solar wind has a composition that agrees more with SEPs





What other seed population, when mixed with flare material, accounts for gradual SEPs?

Inner-source pickup ions? No! - no singly-charged SEPs

Suprathermal solar wind?

Suprathermal solar-wind tails?

CME ejecta?

Summary

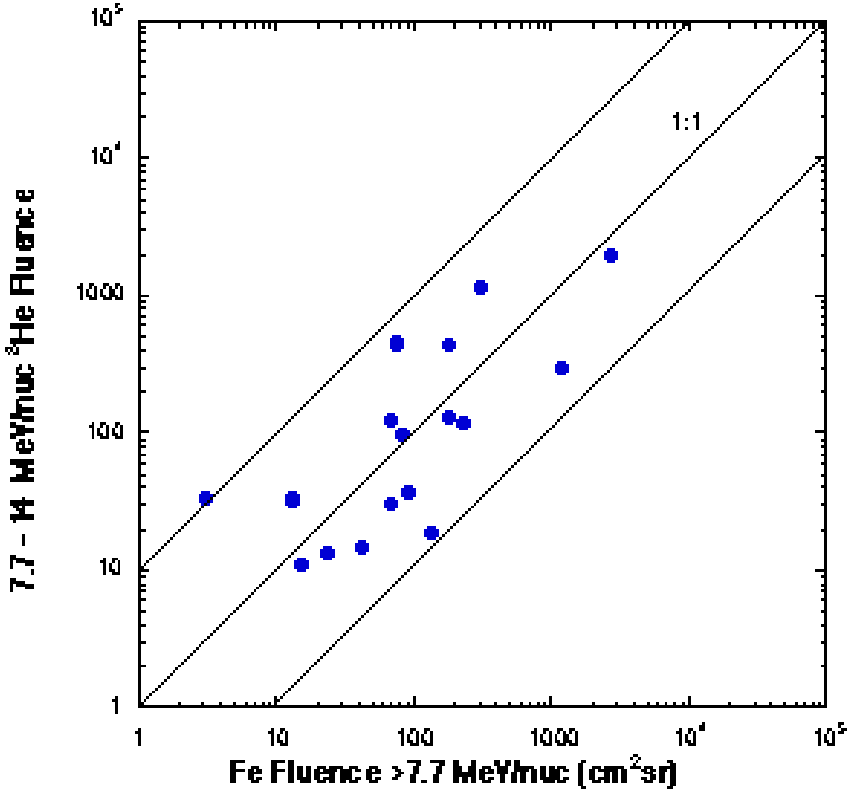
- More than 90% of all SEP events are Fe-rich
- Flare material (either remnant or contemporaneous) is observed in most gradual SEP events
- There are significant differences between the SEP and solar wind compositions - organized best by FIP, suggesting different samples of coronal material
- Bulk solar wind is not a major source of gradual SEPs
- The source of "normal" SEPs is still unidentified - Possibilities include:
  - High-temperature solar wind
  - High energy tails on solar wind (5 to 10 keV/nuc)
  - Suprathermal tails (>10 keV/nuc)
  - Coronal ejecta released during the event?

What About ^{3}He?

- In hydrid events ^{3}He/Fe ~ 1

- But in ^{3}He-rich events and quiet periods ^{3}He/Fe ~ 10!

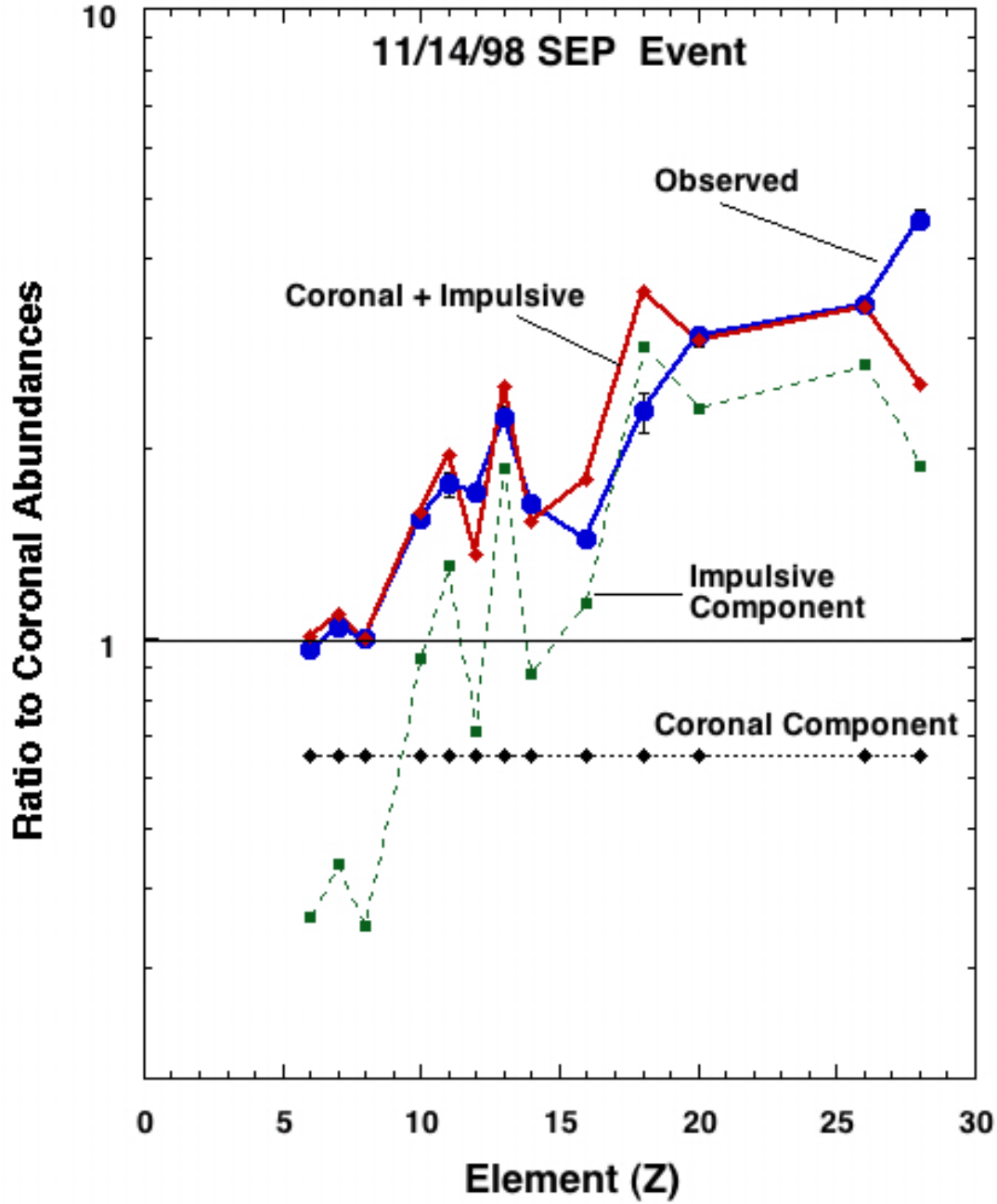
This suggests that there will not be enough Fe if remnant flare material supplies the ^{3}He in gradual events.



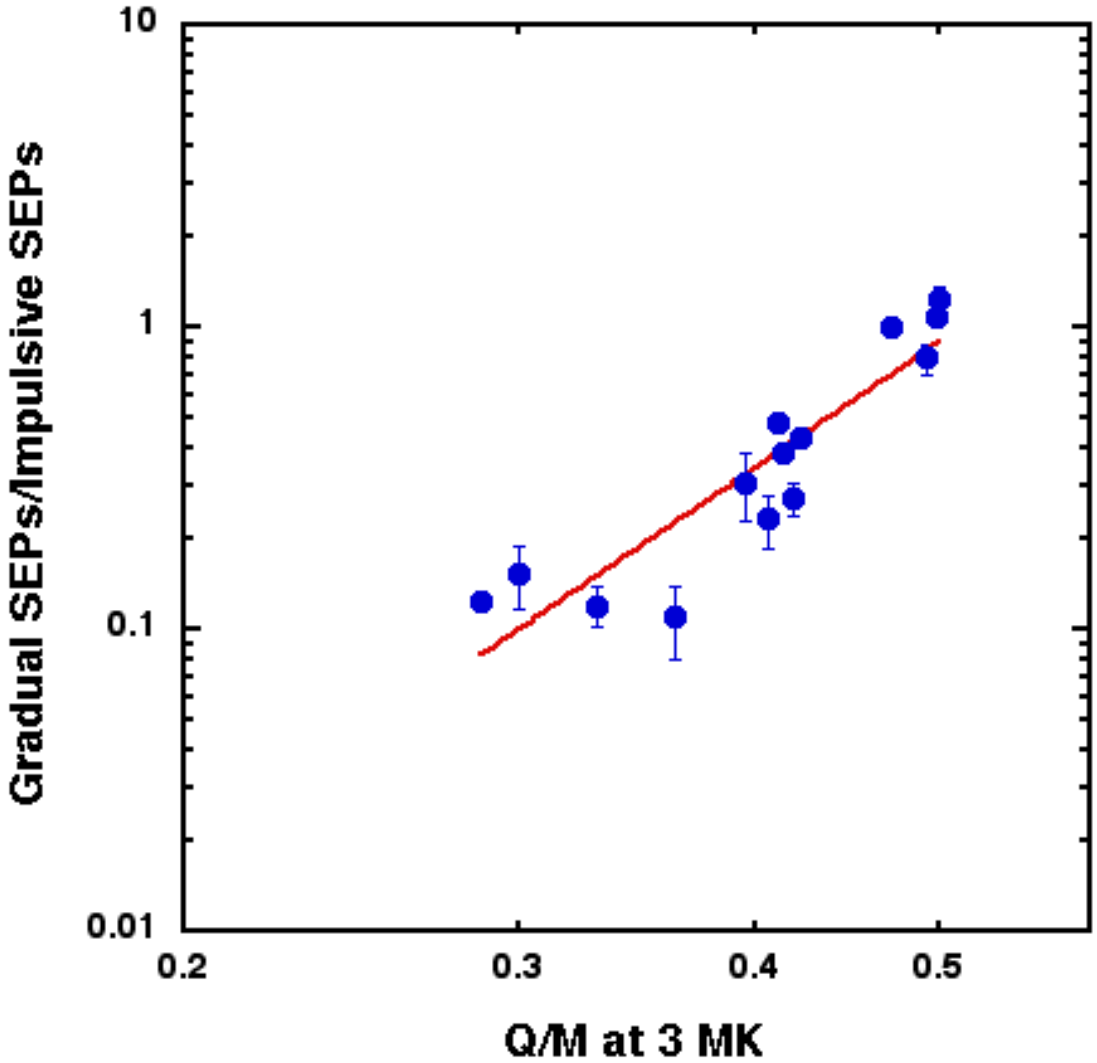
We need another source of Fe.

Possibilities include:

- Flare accelerated Fe (Cane et al. 2003)
- Shock-acceleration of Fe from the associated flare

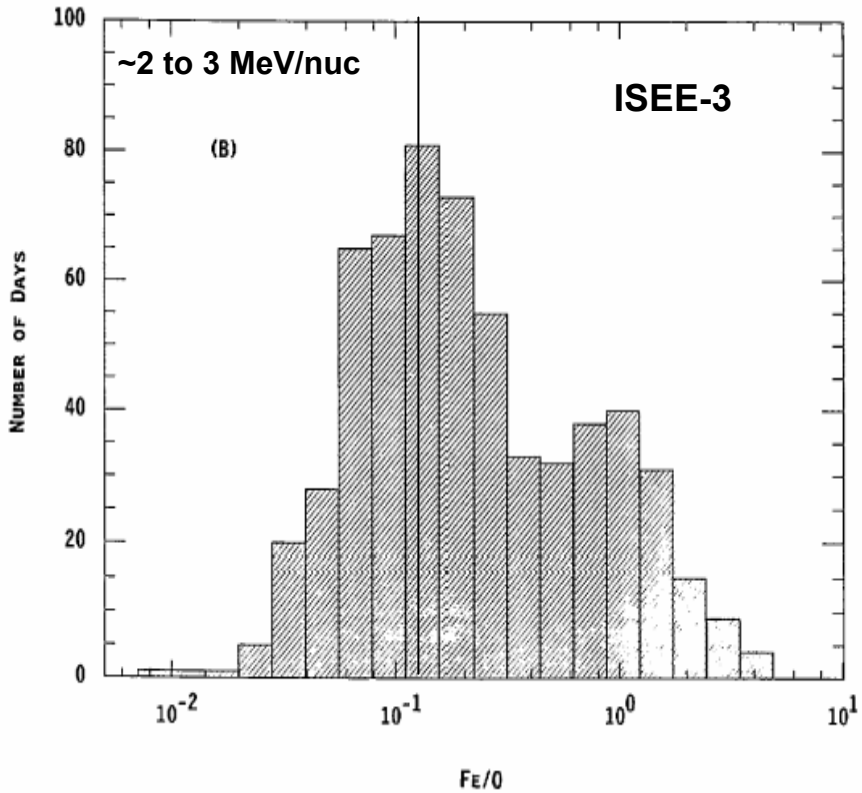

11/14/98 SEP Event
Observed
Coronal + Impulsive
Impulsive Component
Coronal Component
Ratio to Coronal Abundances
Element (Z)
10
1
0
5
10
15
20
25
30

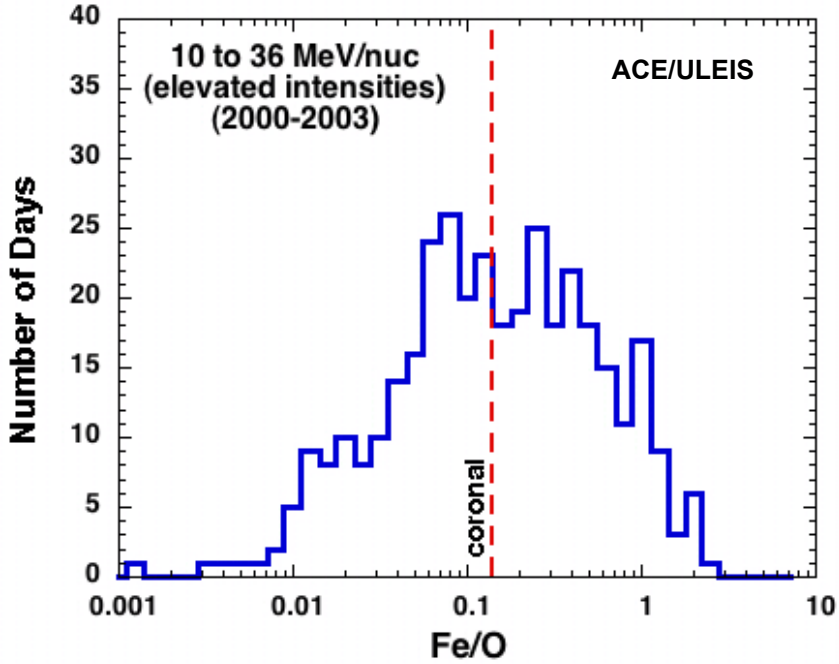
Can Q/M-dependent acceleration of impulsive flare material alone account for the composition of gradual SEPs? No!

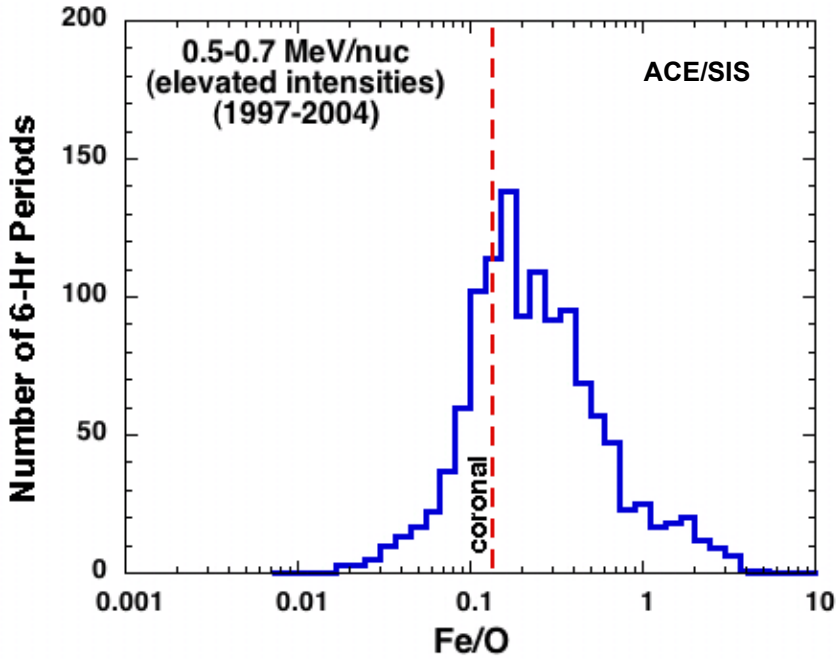


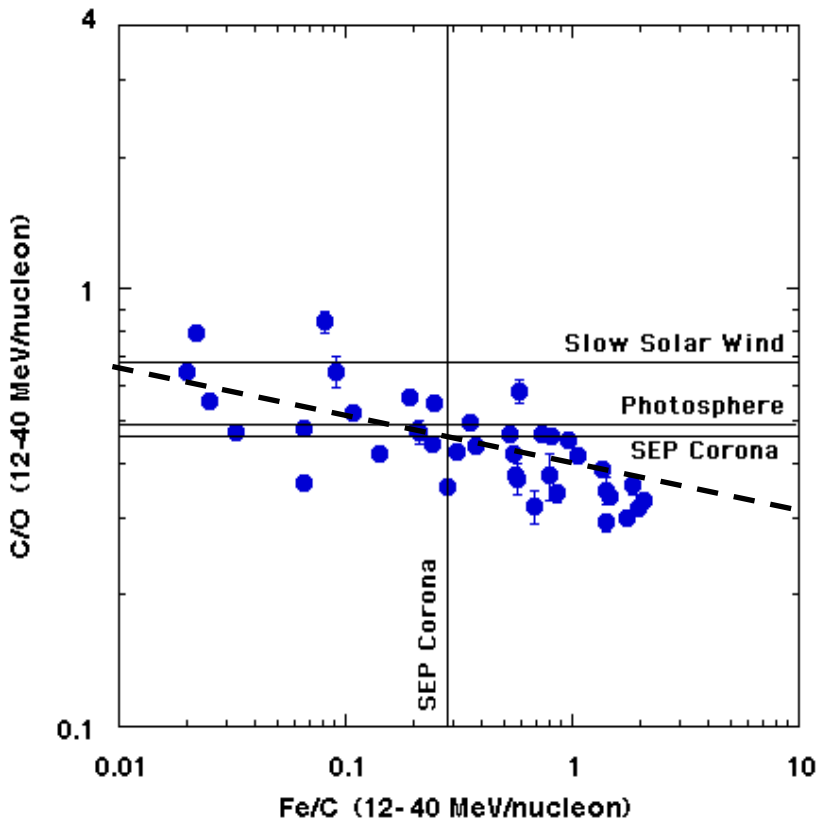
Bi-modal Fe/O Behavior ????

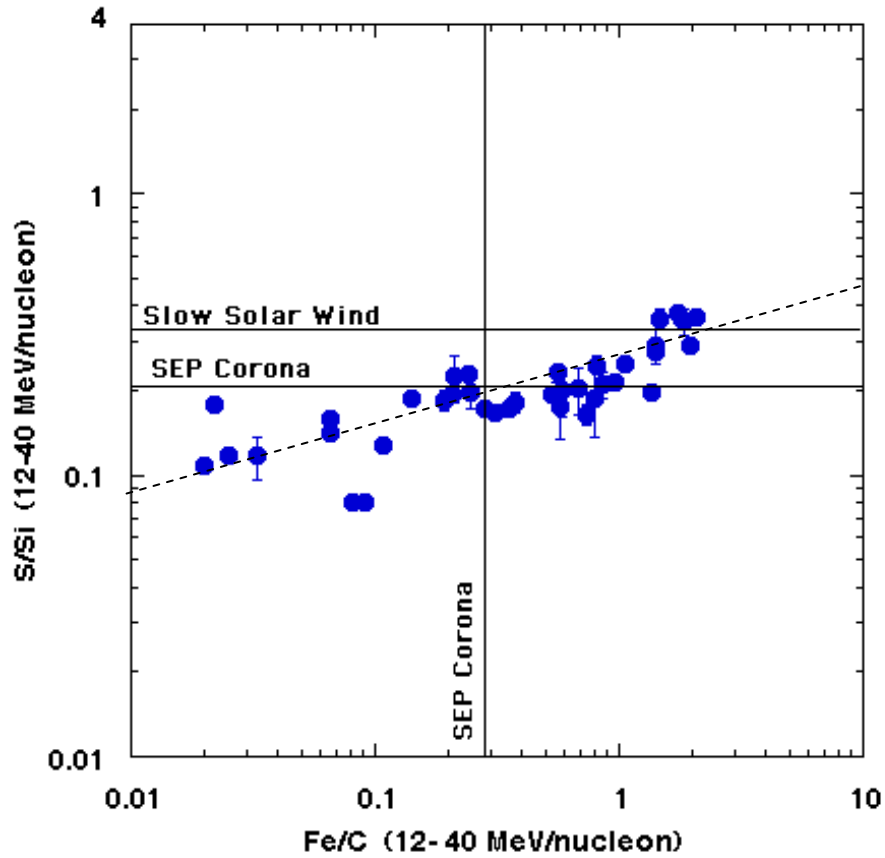
ISEE-3: 598 most active days
1978-1987 Reames, 1988

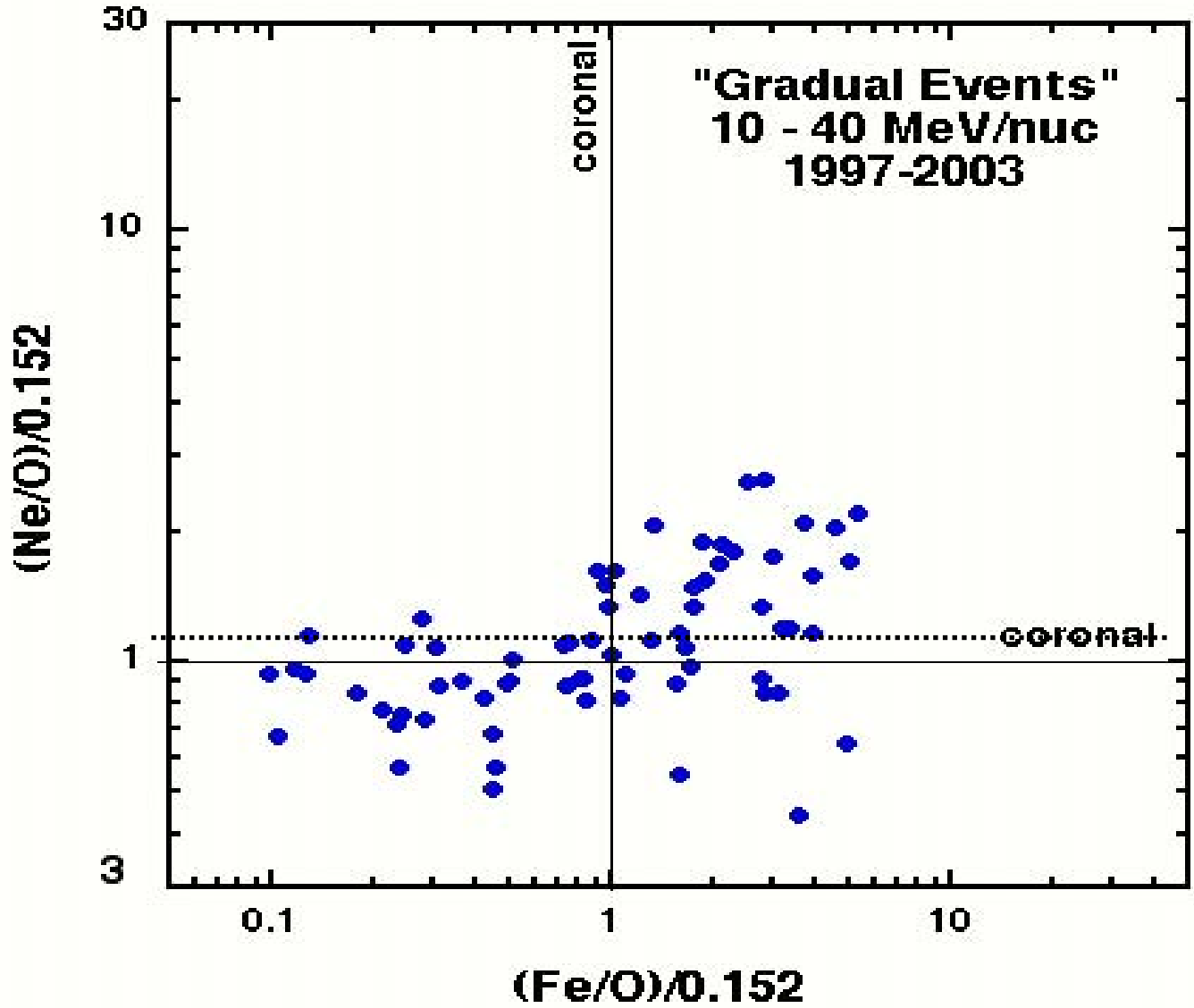


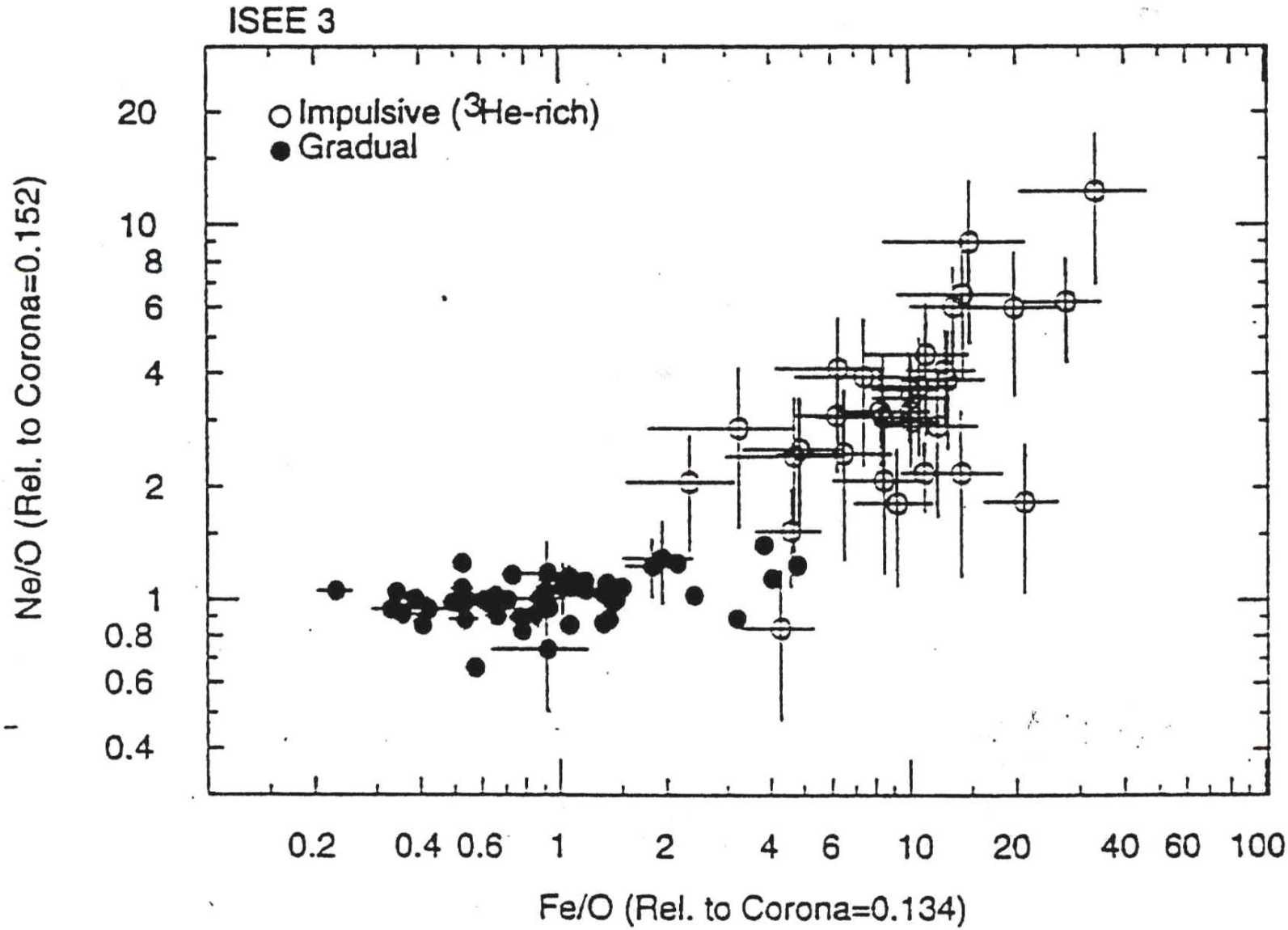




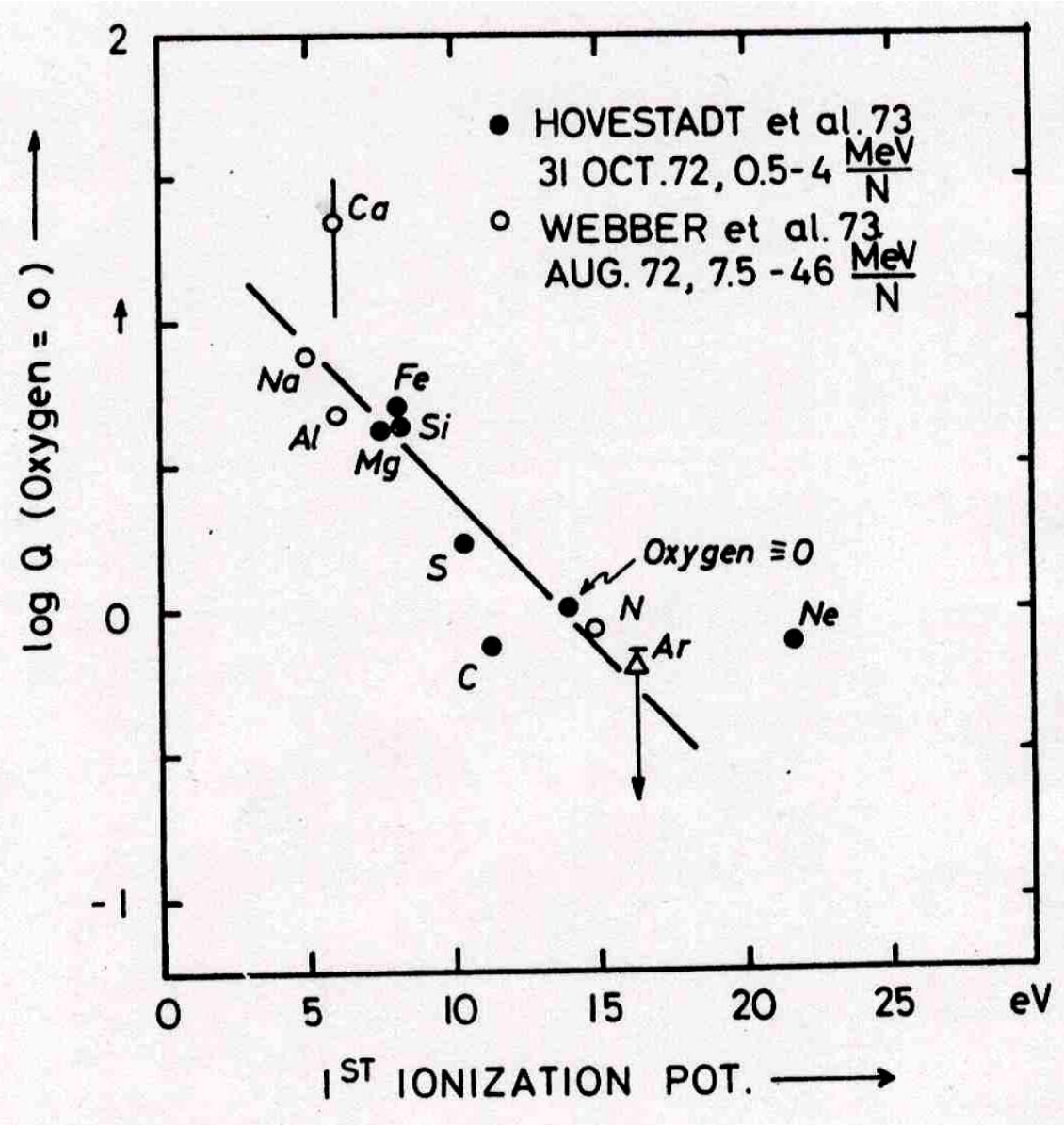

4
1
0.1
C/O (12-40 MeV/nucleon)
Slow Solar Wind
Photosphere
SEP Corona
SEP Corona
0.01
0.1
1
10
Fe/C (12-40 MeV/nucleon)


4
1
0.1
0.01
S/Si (12-40 MeV/nucleon)
Slow Solar Wind
SEP Corona
SEP Corona
0.01
0.1
1
10
Fe/C (12-40 MeV/nucleon)


"Gradual Events"
10 - 40 MeV/nuc
1997-2003
coronal
coronal
30
10
1
3
0.1
1
10
(Ne/O)/0.152
(Fe/O)/0.152



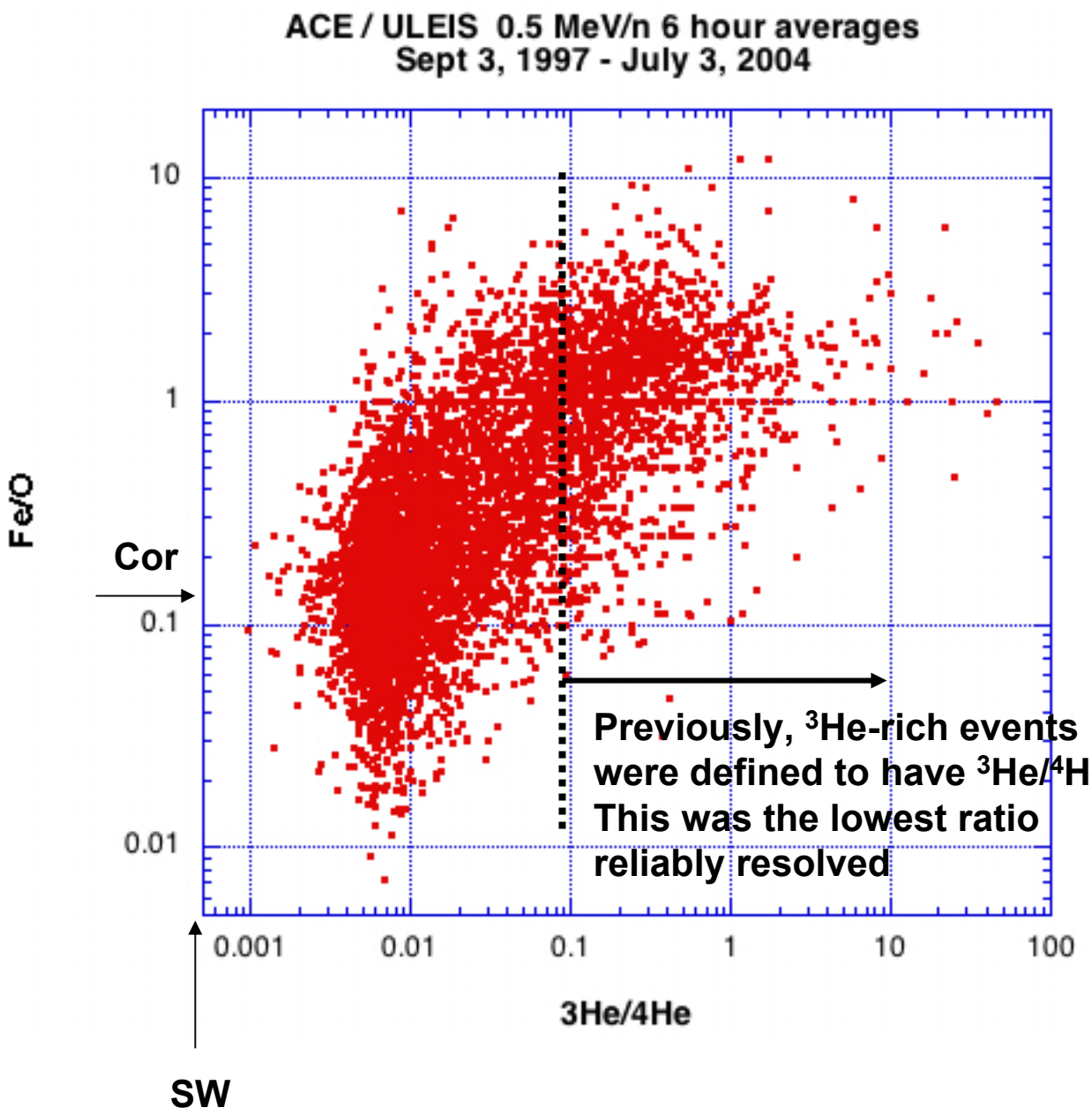
Reames, Meyer, and von Rosenvinge (1994)



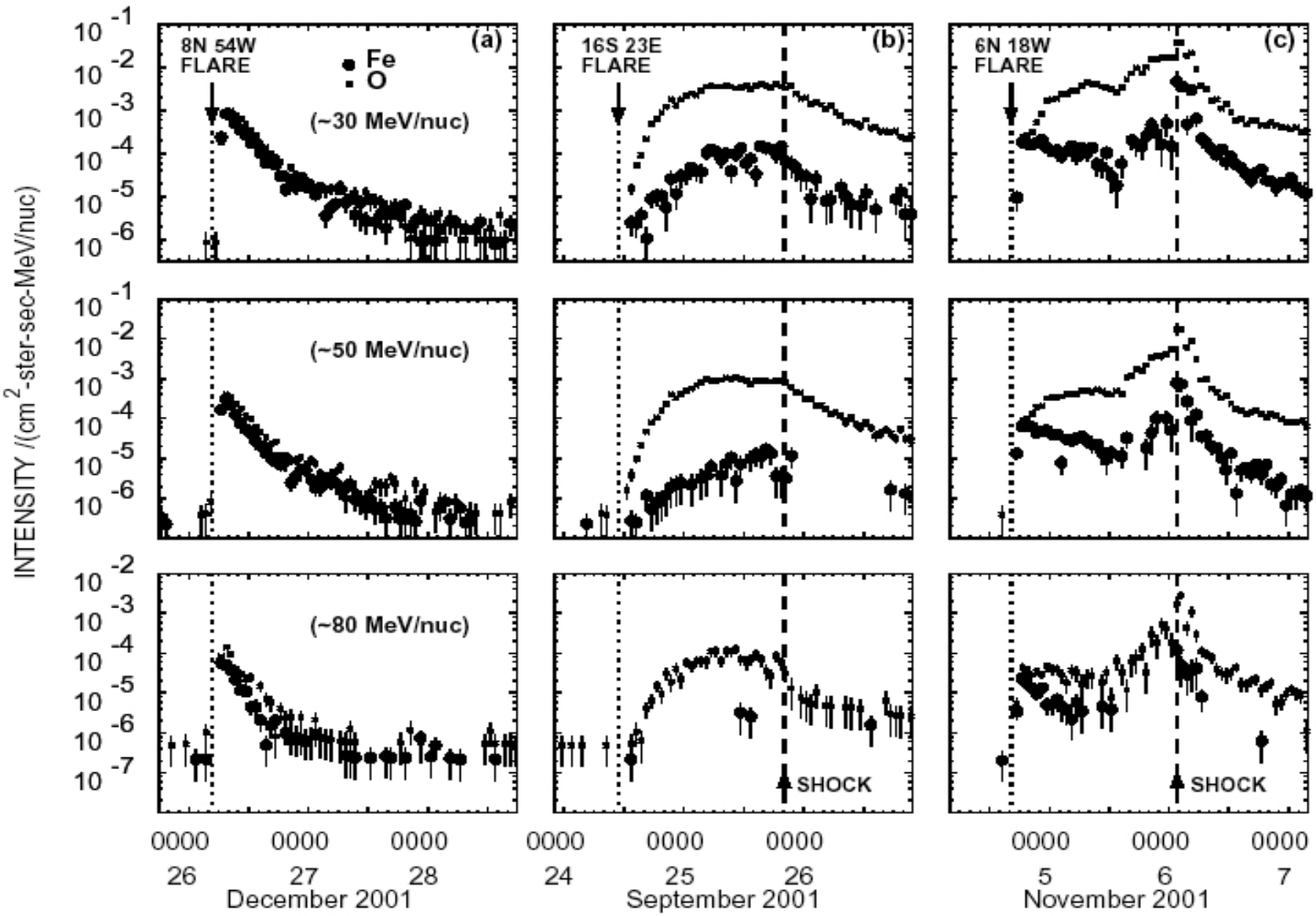
D. Hovestadt, Solar Wind 3, 1974

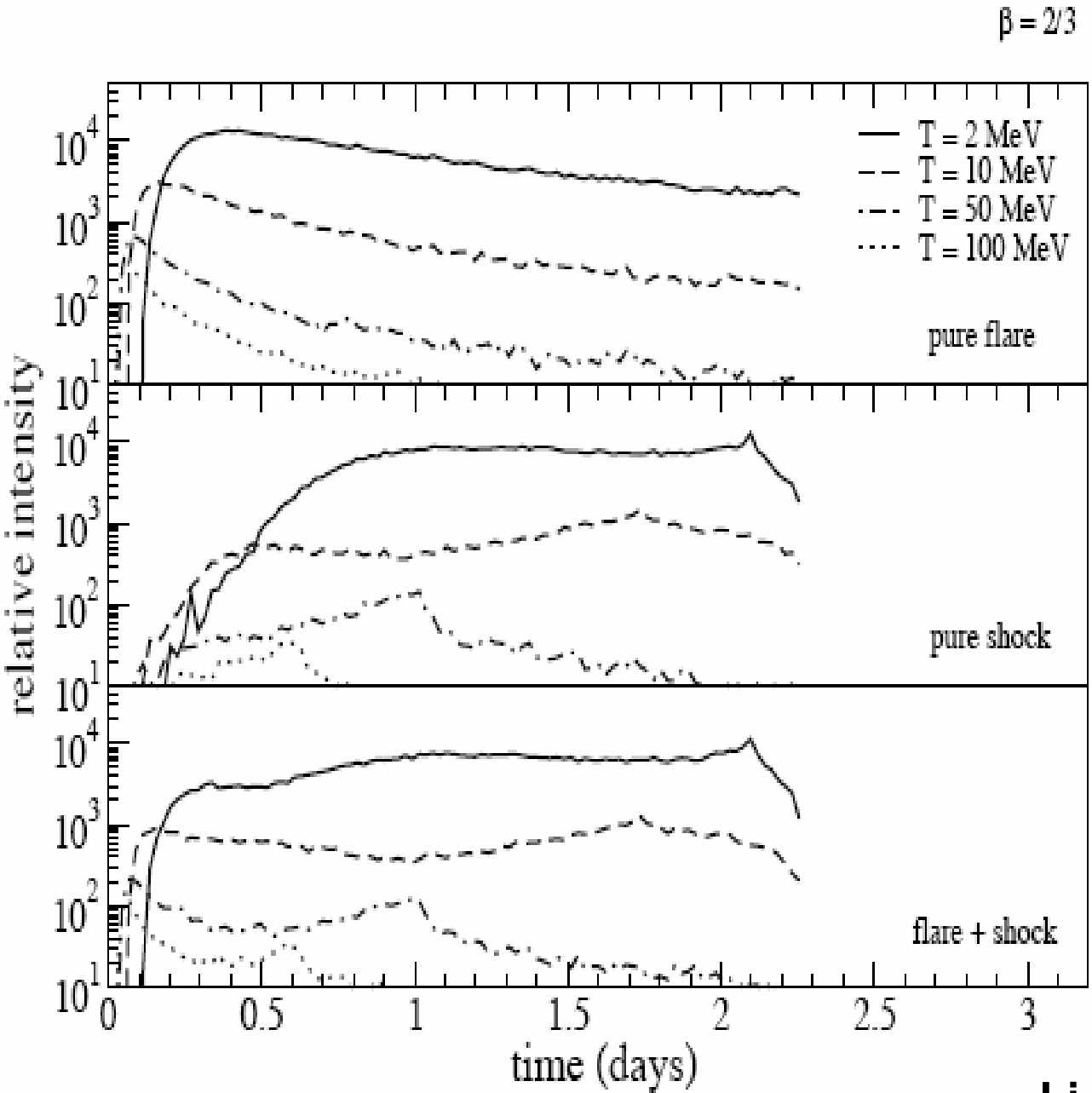
First suggestion that SEPs are fractionated according to their first ionization potential (FIP)

Earlier, Havnes had recognized this for galactic cosmic rays



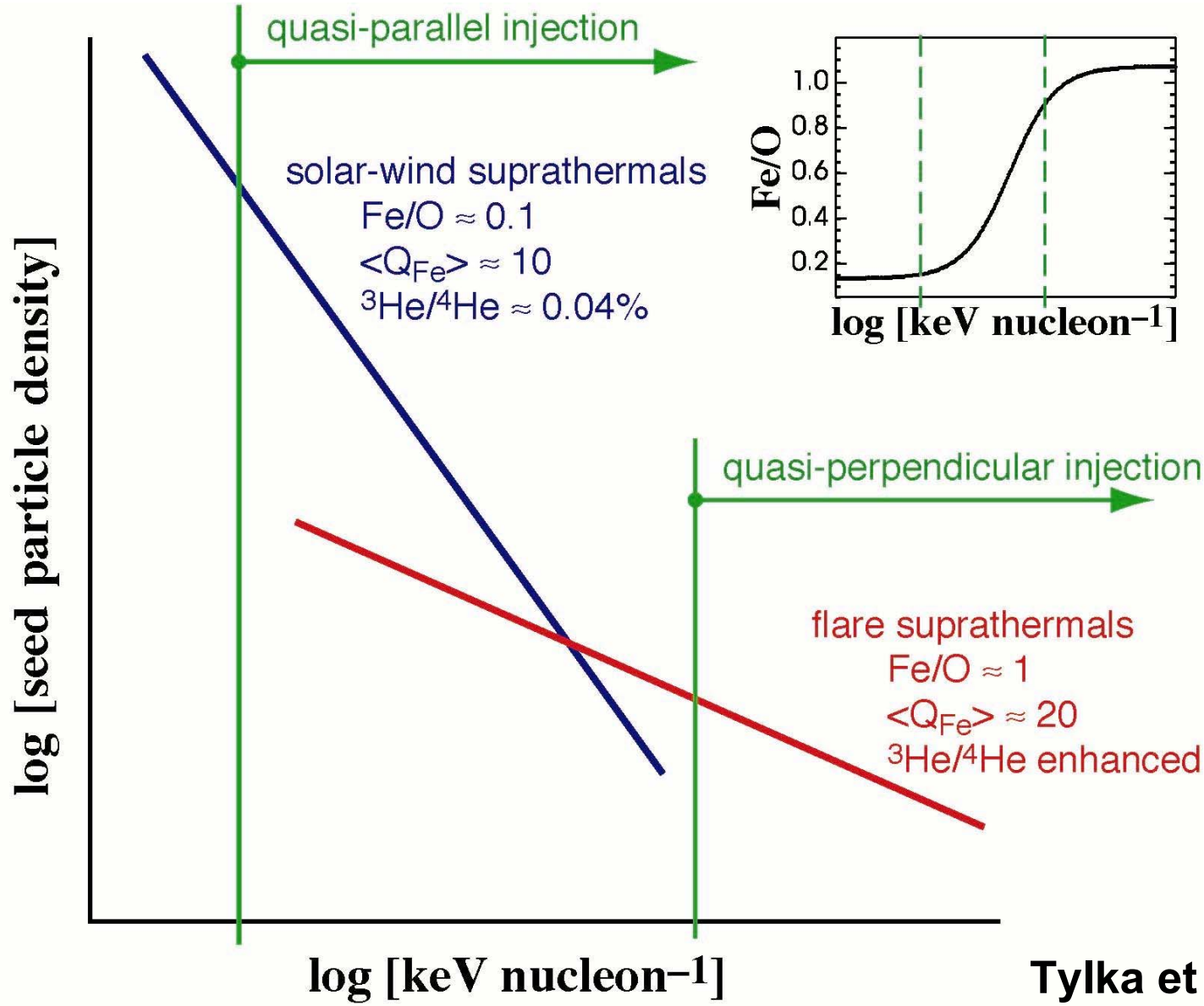
^{3}He-rich and Fe-rich events are not a clearly defined separate class - they are part of a continuous distribution


8N 54W
FLARE
(a)
Fe
O
(~30 MeV/nuc)
16S 23E
FLARE
(b)
6N 18W
FLARE
(c)
(~50 MeV/nuc)
(~80 MeV/nuc)
SHOCK
SHOCK
INTENSITY /(cm -ster-sec-MeV/nuc)
0000
26
27
28
December 2001
24
25
26
September 2001
5
6
7
November 2001



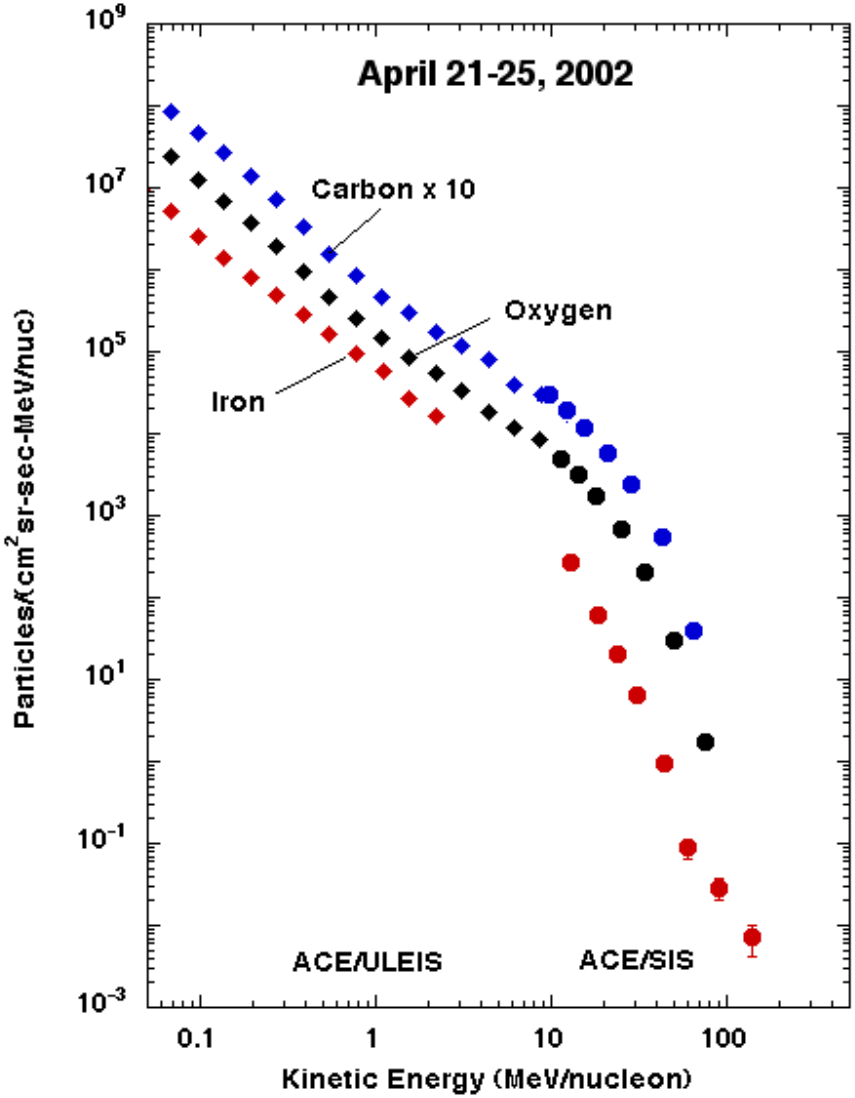
Li and Zank (2004)

Tylka et al: Composition variations are a result of shock geometry



But, are these assumptions satisfied close to Sun?

Tylka et al. 2004


April 21-25, 2002
Carbon x 10
Oxygen
Iron
ACE/ULEIS
ACE/SIS
Particles/cm2sr-sec-MeV/nuc)
Kinetic Energy (MeV/nucleon)
10^9
10^7
10^5
10^3
10^1
10^-1
10^-3
0.1
1
10
100