The Charge-to-Mass Dependence of Solar Energetic Particle Spectral Breaks

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LWS Meeting
Caltech
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Sources of Data

ACE:

SIS:	**$2 \leq Z \leq 28$;**	**~10 to 200 MeV/nuc**
ULEIS:	**$1 \leq Z \leq 26$;**	**~0.1 to 8 MeV/nuc**
EPAM:	**$1 \leq Z \leq 26$;**	**~0.1 to ~5 MeV/nuc**

STEREO

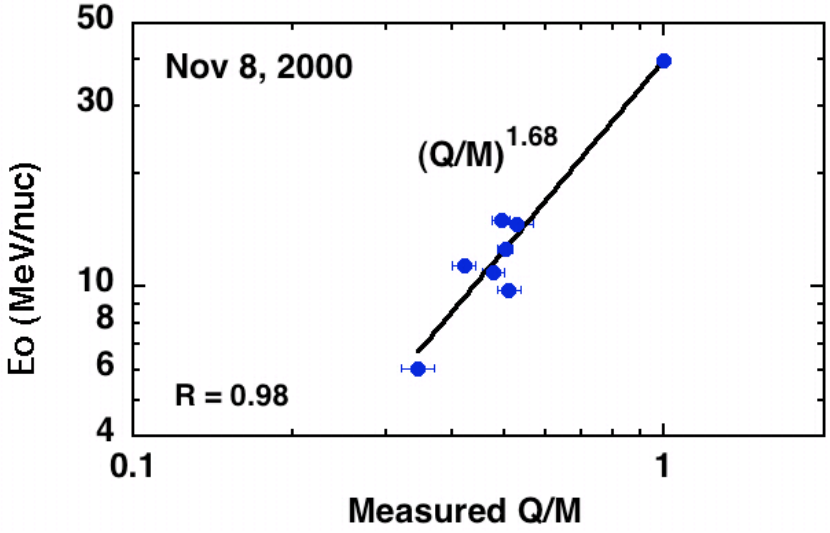
LET	**$1 \leq Z \leq 26$;**	**~2 to ~30 MeV/nuc**

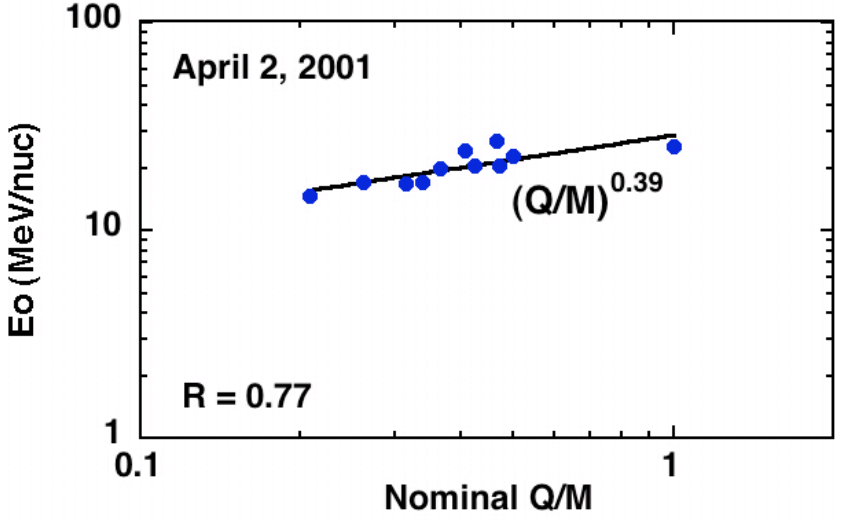
SAMPEX:

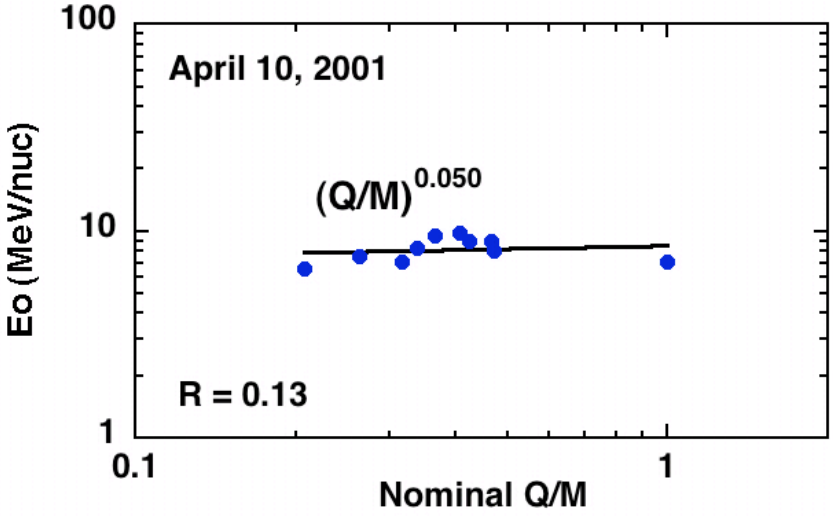
PET:	**H, He**	**~20 to 400 MeV/nuc**
MAST:	**Q-States**	**~20 to 60 MeV/nuc**

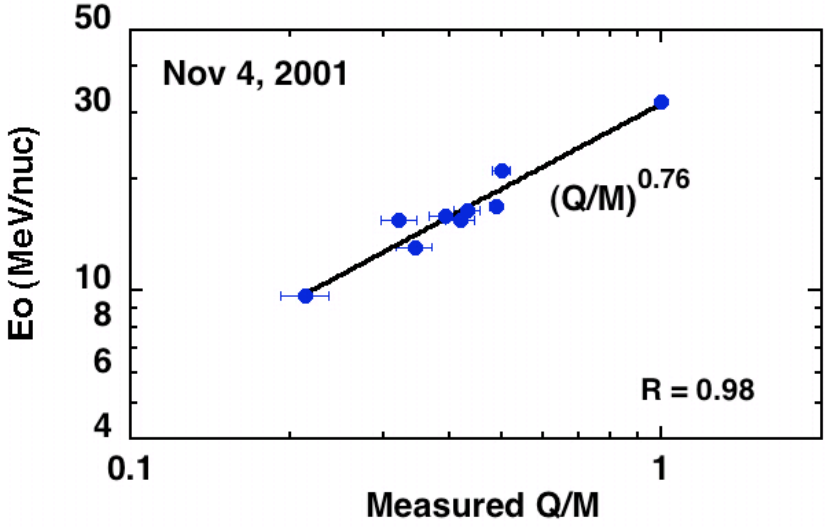
GOES-11	**H, He**	**~5 to ~100 MeV/nuc**

Plots of the Ellison Ramaty E-folding Energies vs Q/M

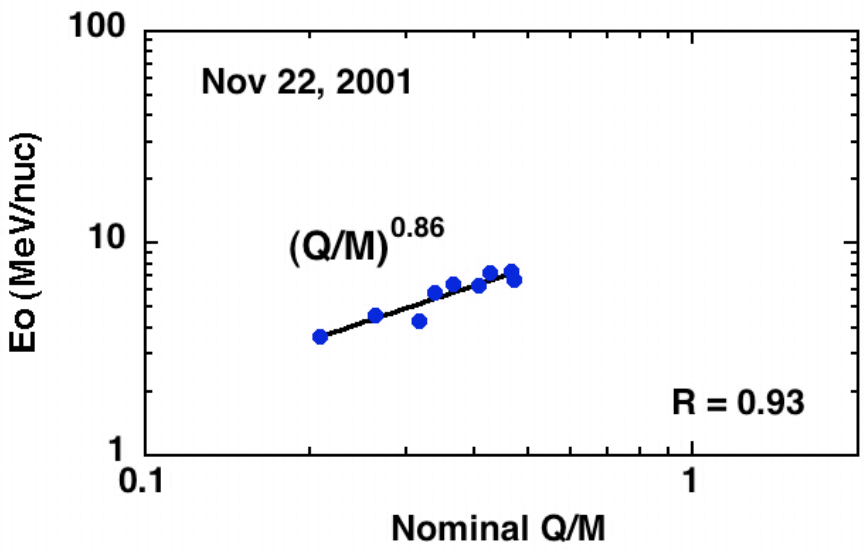


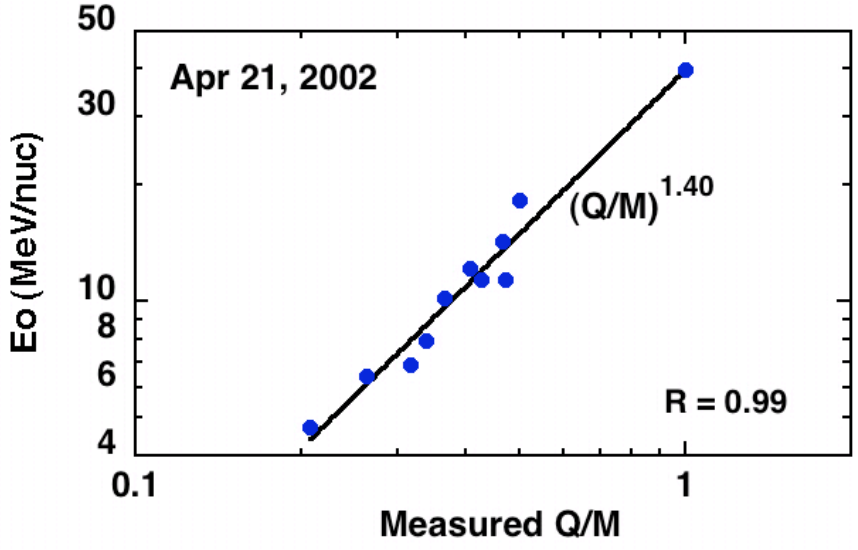


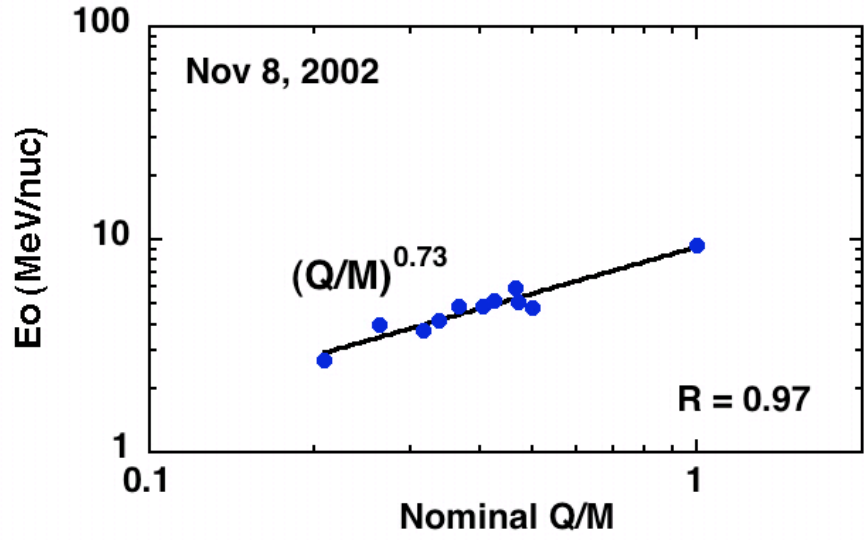


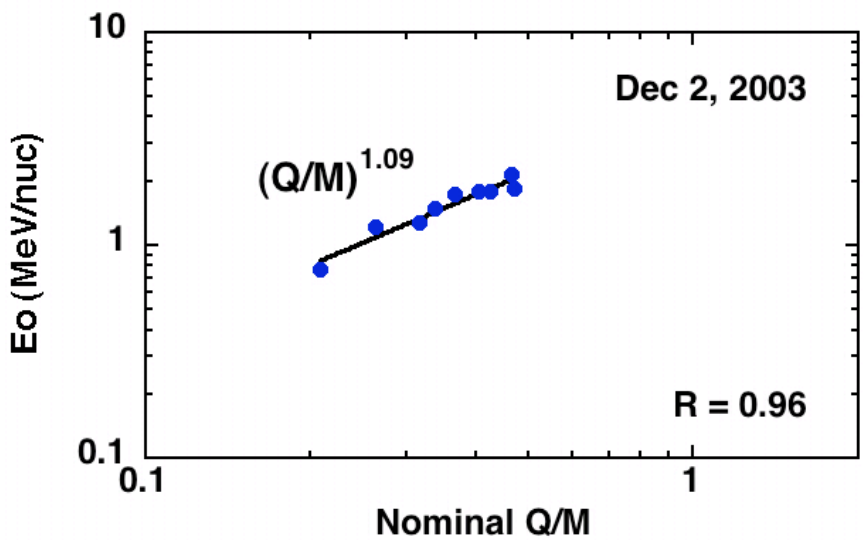


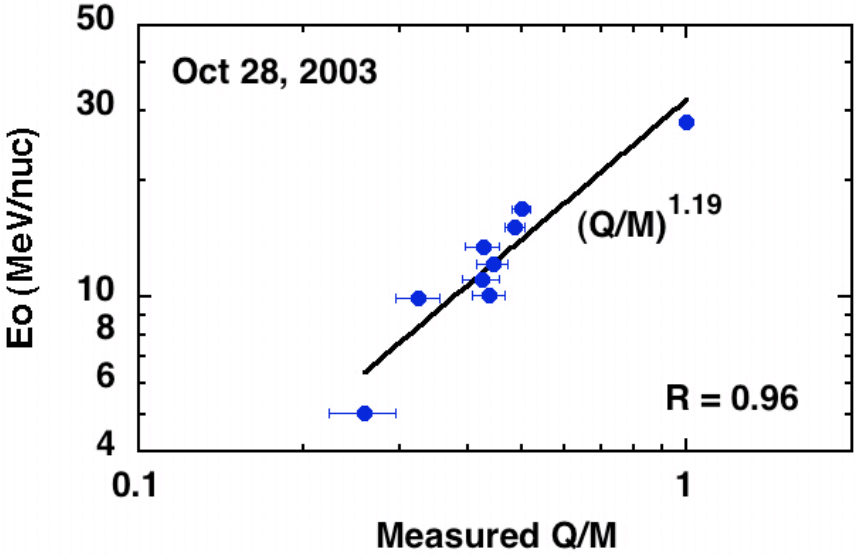
Mewaldt et al.
ICRC, 2007

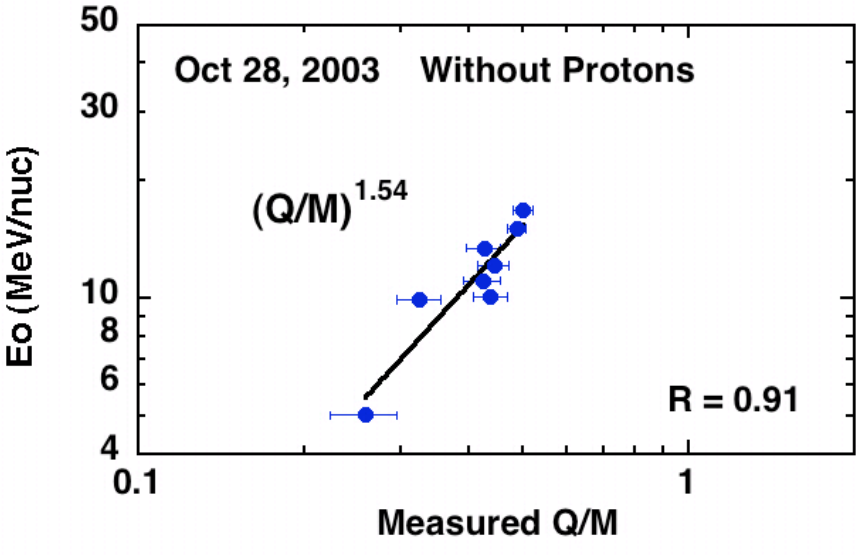

Nov 22, 2001
(Q/M)^0.86
R = 0.93
Eo (MeV/nuc)
Nominal Q/M
100
10
1
0.1
1

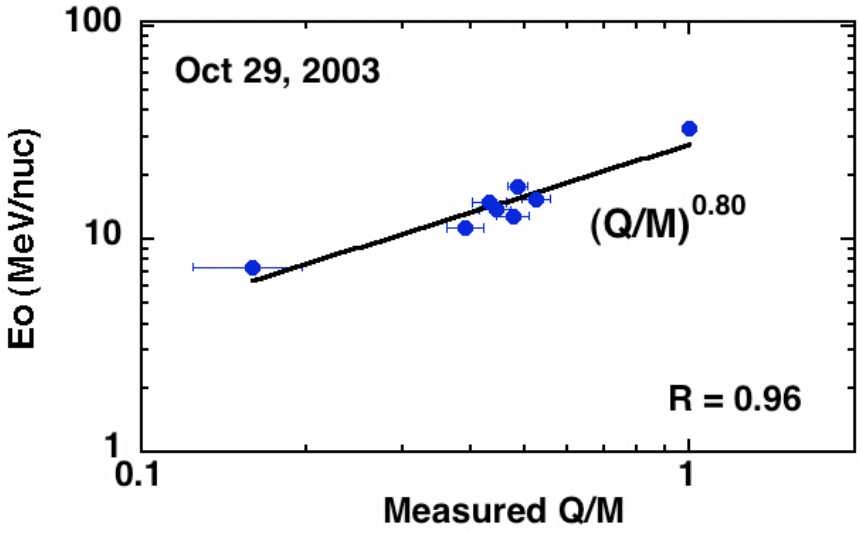

Apr 21, 2002
(Q/M)^1.40
R = 0.99
Eo (MeV/nuc)
Measured Q/M
50
30
10
8
6
4
0.1
1

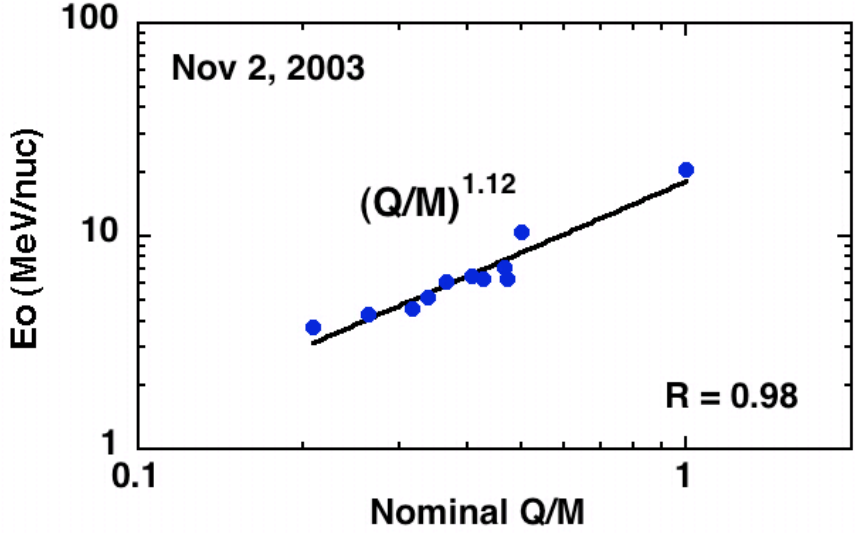

Nov 8, 2002
(Q/M)^0.73
R = 0.97
Eo (MeV/nuc)
Nominal Q/M
100
10
1
0.1
1

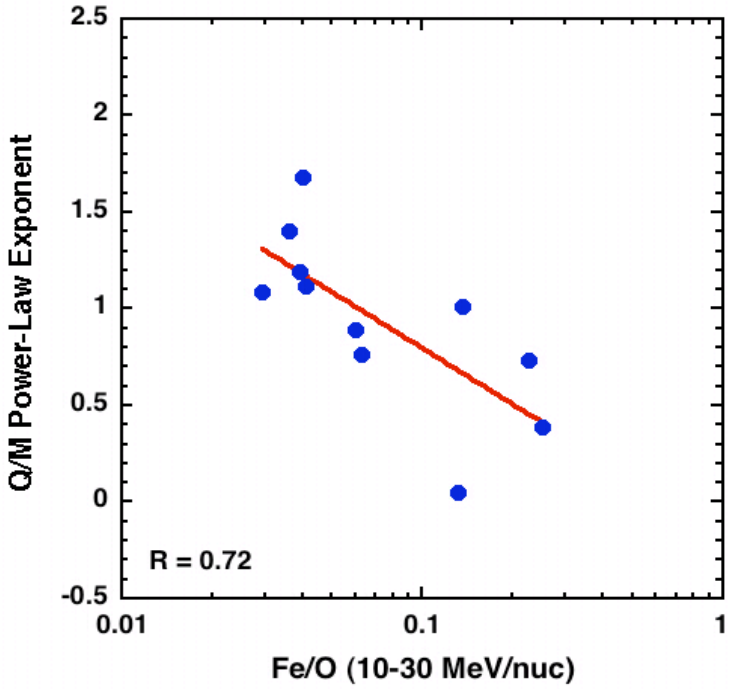

Dec 2, 2003
(Q/M)^1.09
R = 0.96
Eo (MeV/nuc)
Nominal Q/M
10
1
0.1
0.1
1

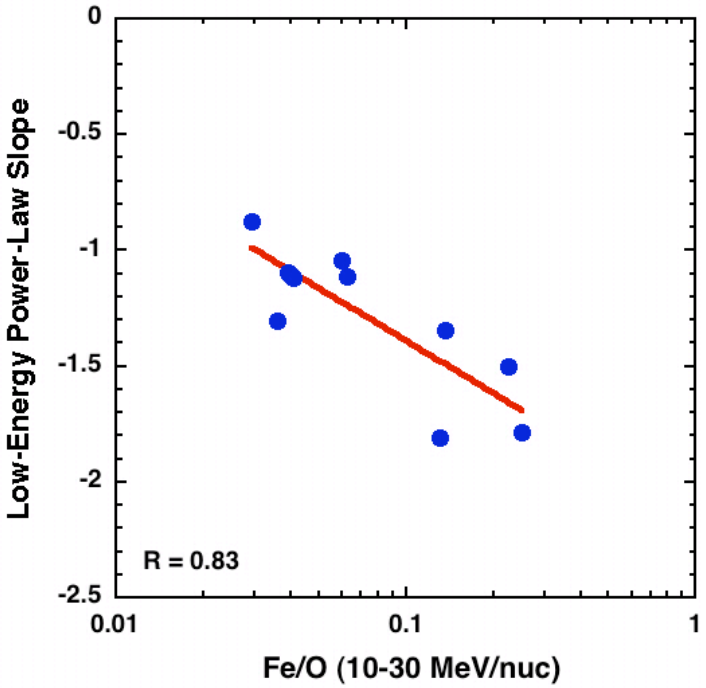

Oct 28, 2003
(Q/M)^1.19
R = 0.96
Eo (MeV/nuc)
Measured Q/M
50
30
10
8
6
4
0.1
1

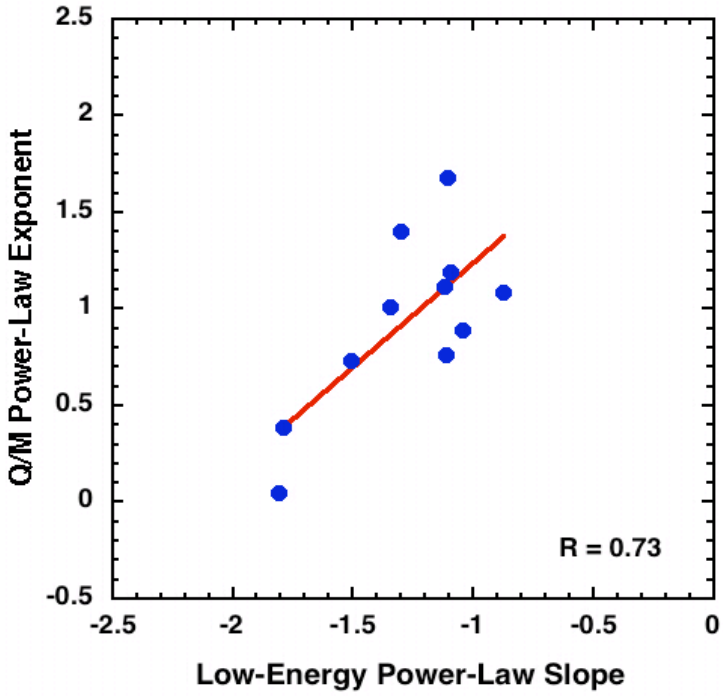

Oct 28, 2003 Without Protons
(Q/M)^1.54
R = 0.91
Eo (MeV/nuc)
Measured Q/M
50
30
10
8
6
4
0.1
1

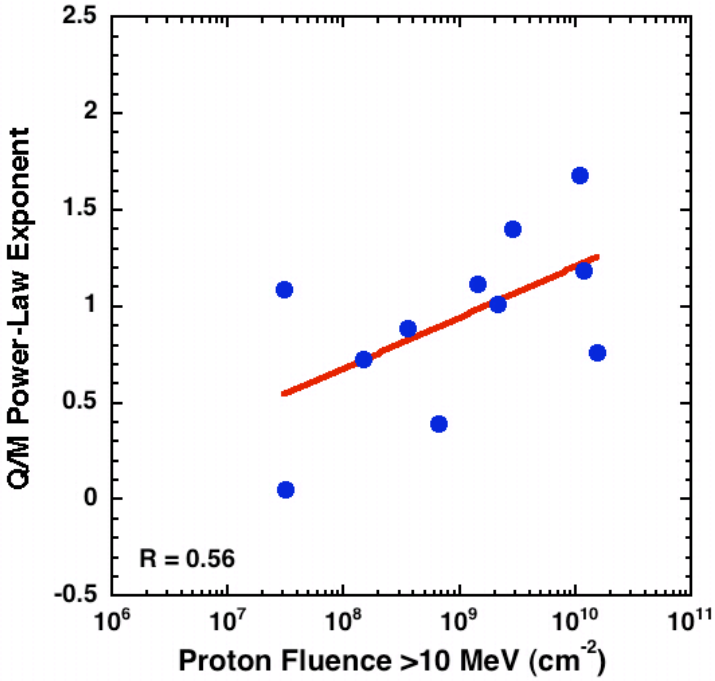

Oct 29, 2003
(Q/M)^0.80
R = 0.96
Eo (MeV/nuc)
Measured Q/M
100
10
1
0.1
1


Nov 2, 2003
(Q/M)^1.12
R = 0.98
Eo (MeV/nuc)
Nominal Q/M
100
10
1
0.1
1

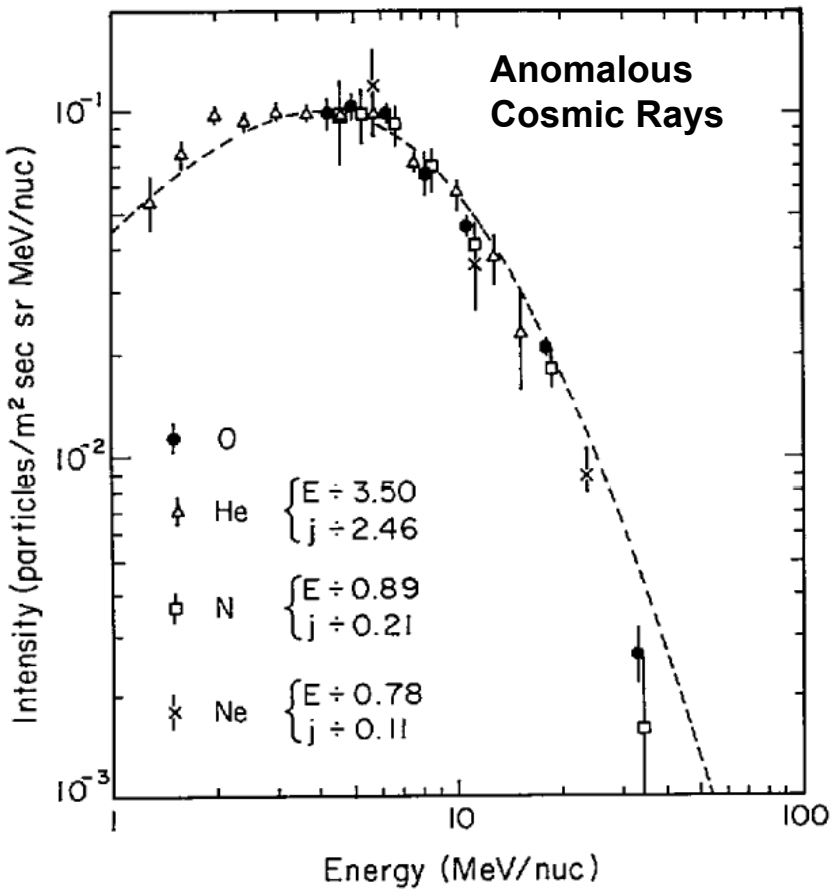








Mewaldt et al.
ICRC, 2007



Cummings, Stone & Webber

Cohen et al. (2005) suggest that the spectral breaks in fluence spectra are most likely related to diffusion effects such as escape from the shock region (see Li et al. 2005).

In this case, the position of the breaks should scale according to their diffusion coefficients,

$\kappa = 1/3\ v\ \lambda$

Assuming λ is a power law in rigidity,

$\kappa \sim (M/Q)^{\alpha}(E)^{(\alpha+1)/2}$

The spectral breaks should occur at the same value of κ, in which case

$E_1/E_2 = [(Q/M)_1 / (Q/M)_2]^{2\alpha/(\alpha+1)}$

$E_1/E_2 = [(Q/M)_1 / (Q/M)_2]^{2\alpha/(\alpha+1)}$

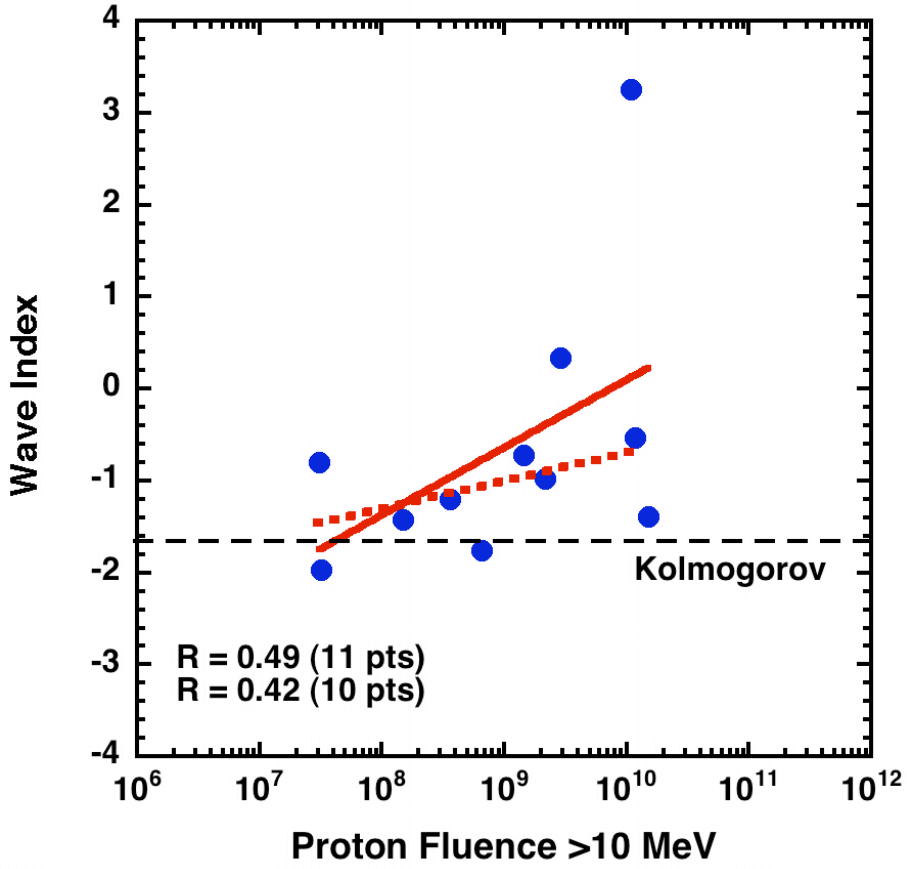
Which implies $\alpha = b/(2-b)$ where b is our Q/M index

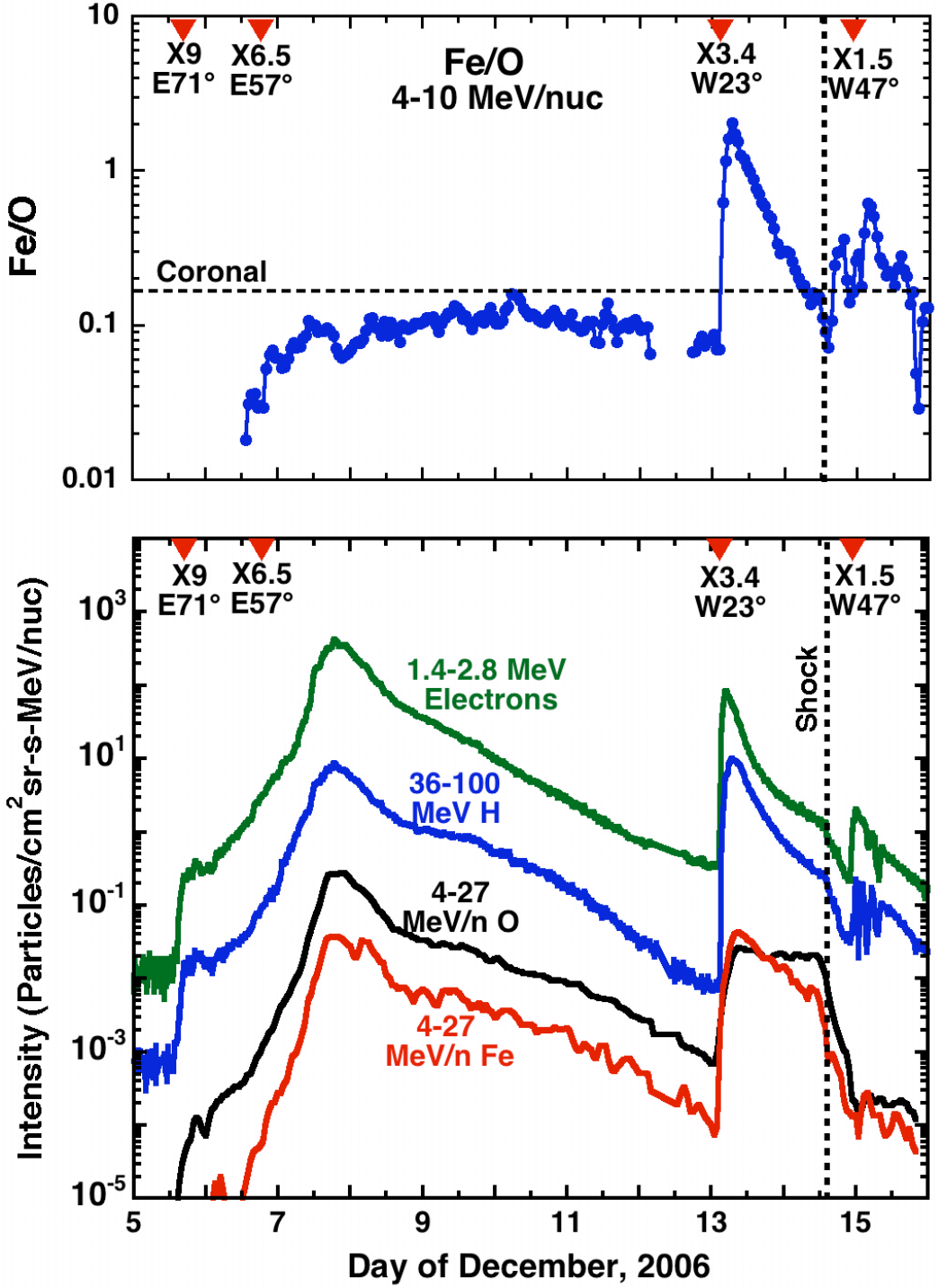
Values are typically $\alpha \approx 1$, but vary considerably, suggesting considerable variation in the rigidity dependence of the diffusion coefficient

The values of α can be related to the turbulence spectrum, assumed to be a power-law in wave number, or k^q, by

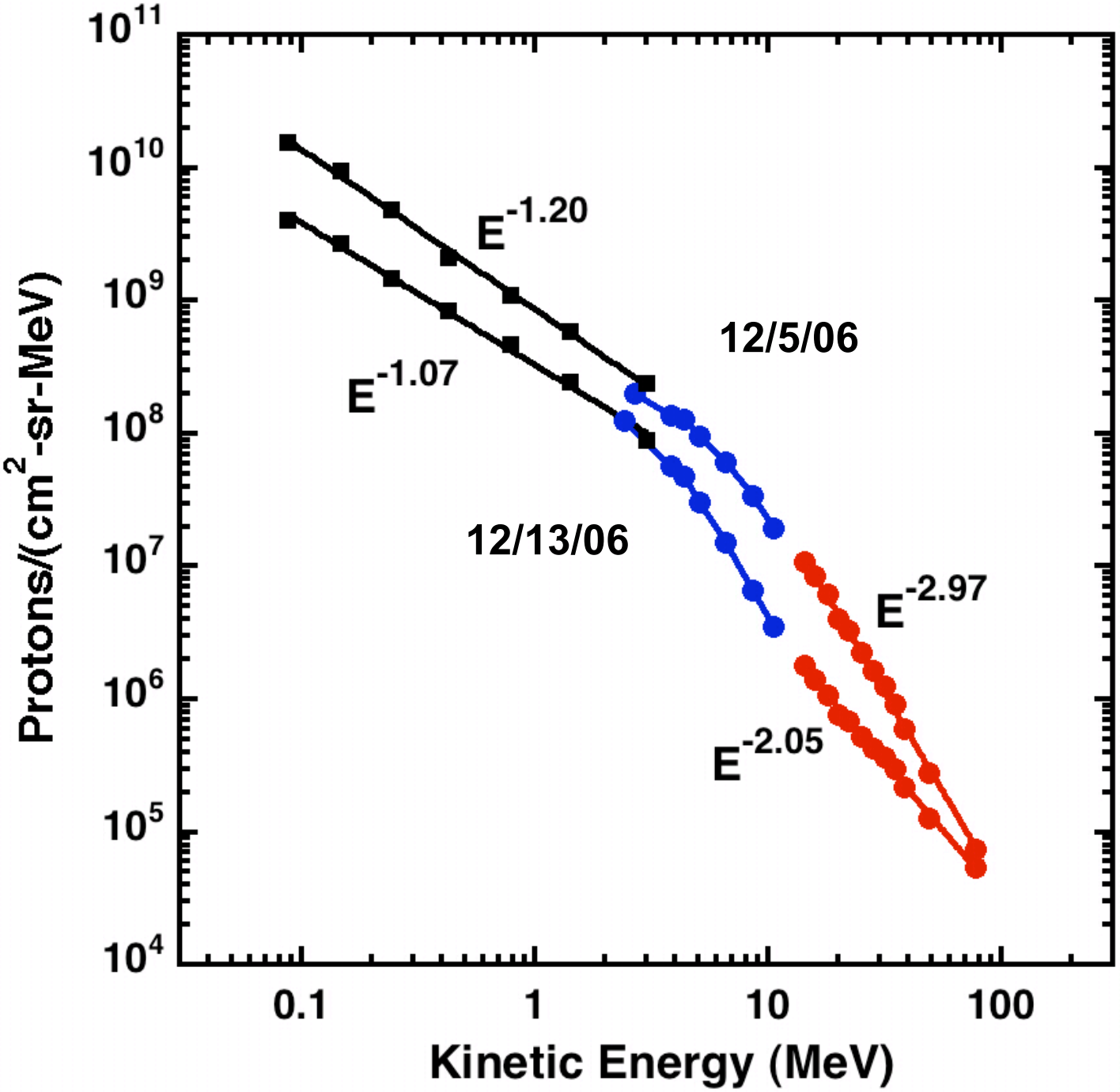
$\alpha = 2+q$ (Droege, 1994)

Wave indices ≥ 0 suggest that an additional source of turbulence is present.



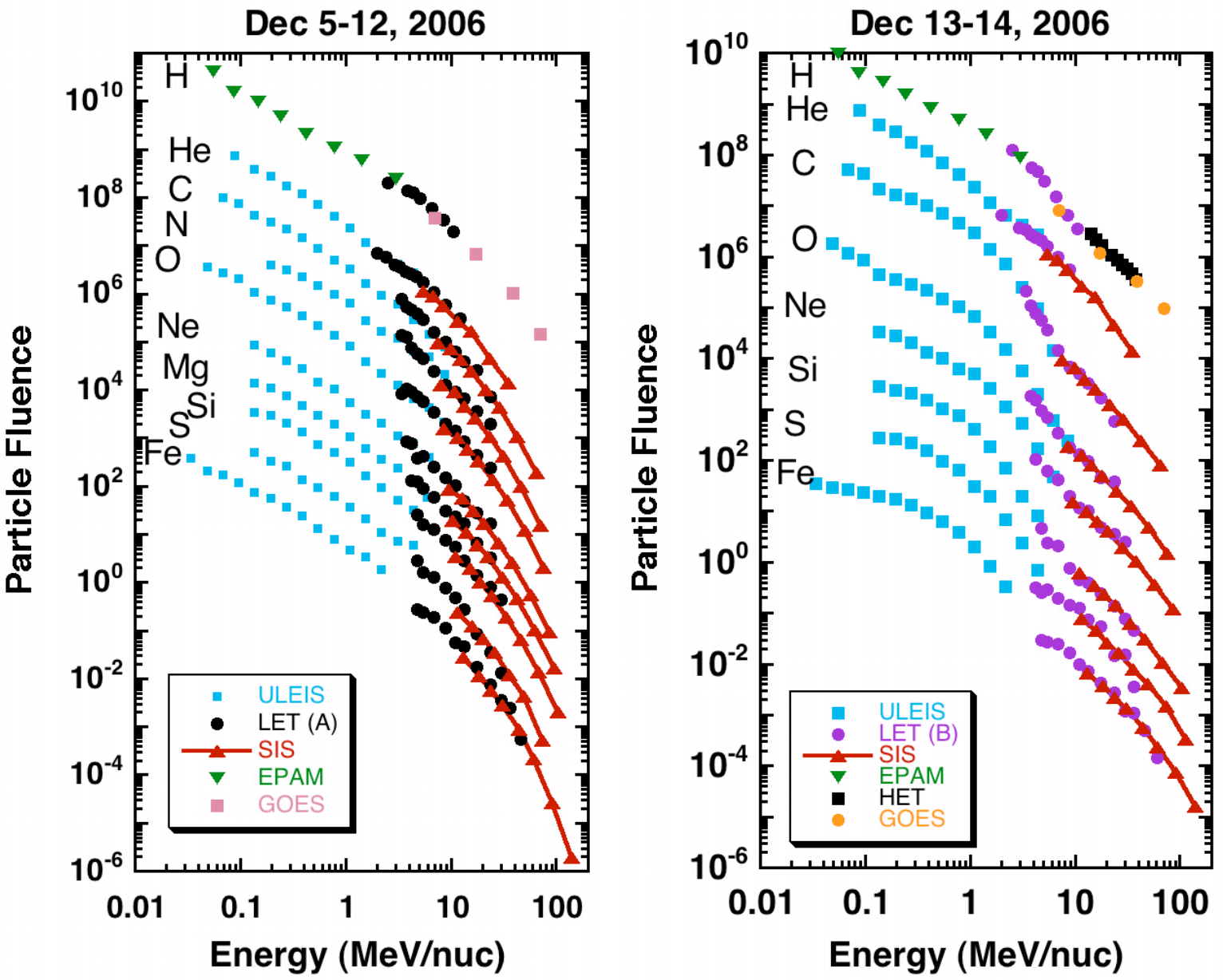


The December, 2006 SEP Events

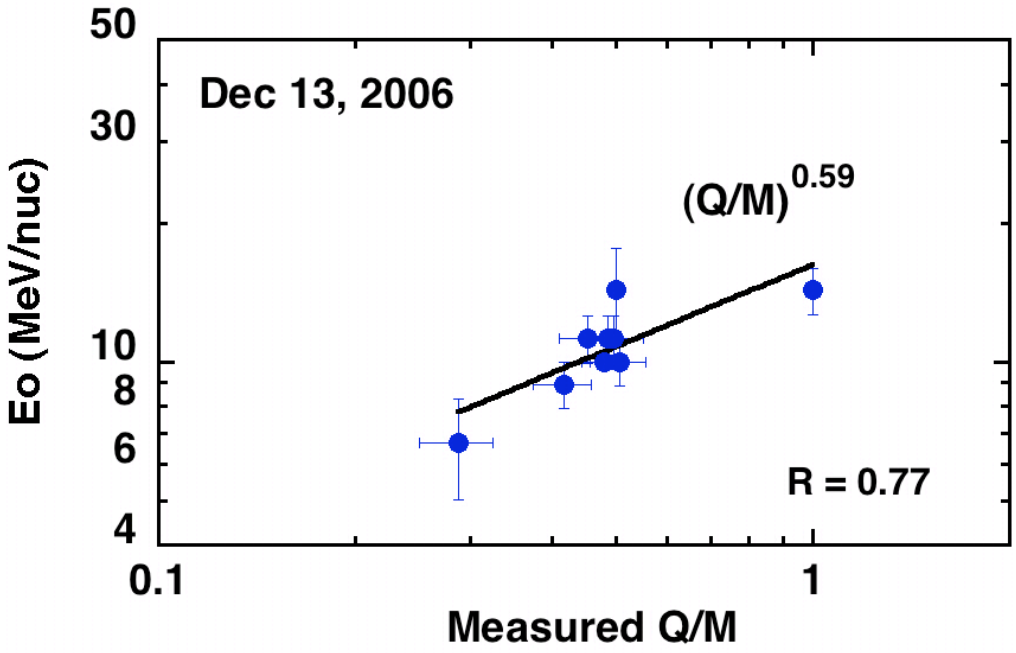

Protons/(cm^2-sr-MeV)
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
0.1
1
10
100
Kinetic Energy (MeV)
$E^{-1.20}$
$E^{-1.07}$
12/5/06
12/13/06
$E^{-2.97}$
$E^{-2.05}$

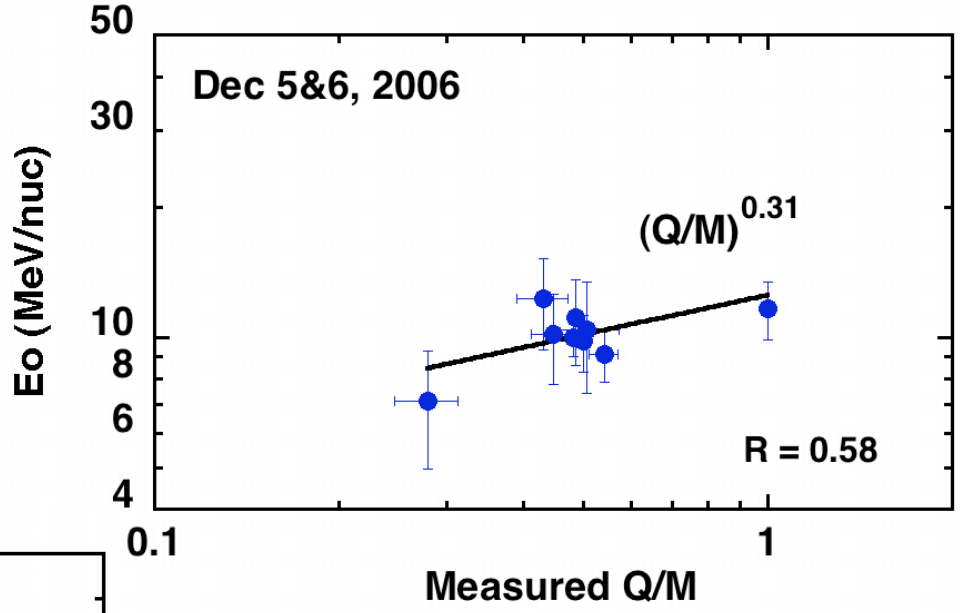
All species have the same spectral shape

Shifted spectra to minimize energy dependence (Cohen et al. 2005, 2007)

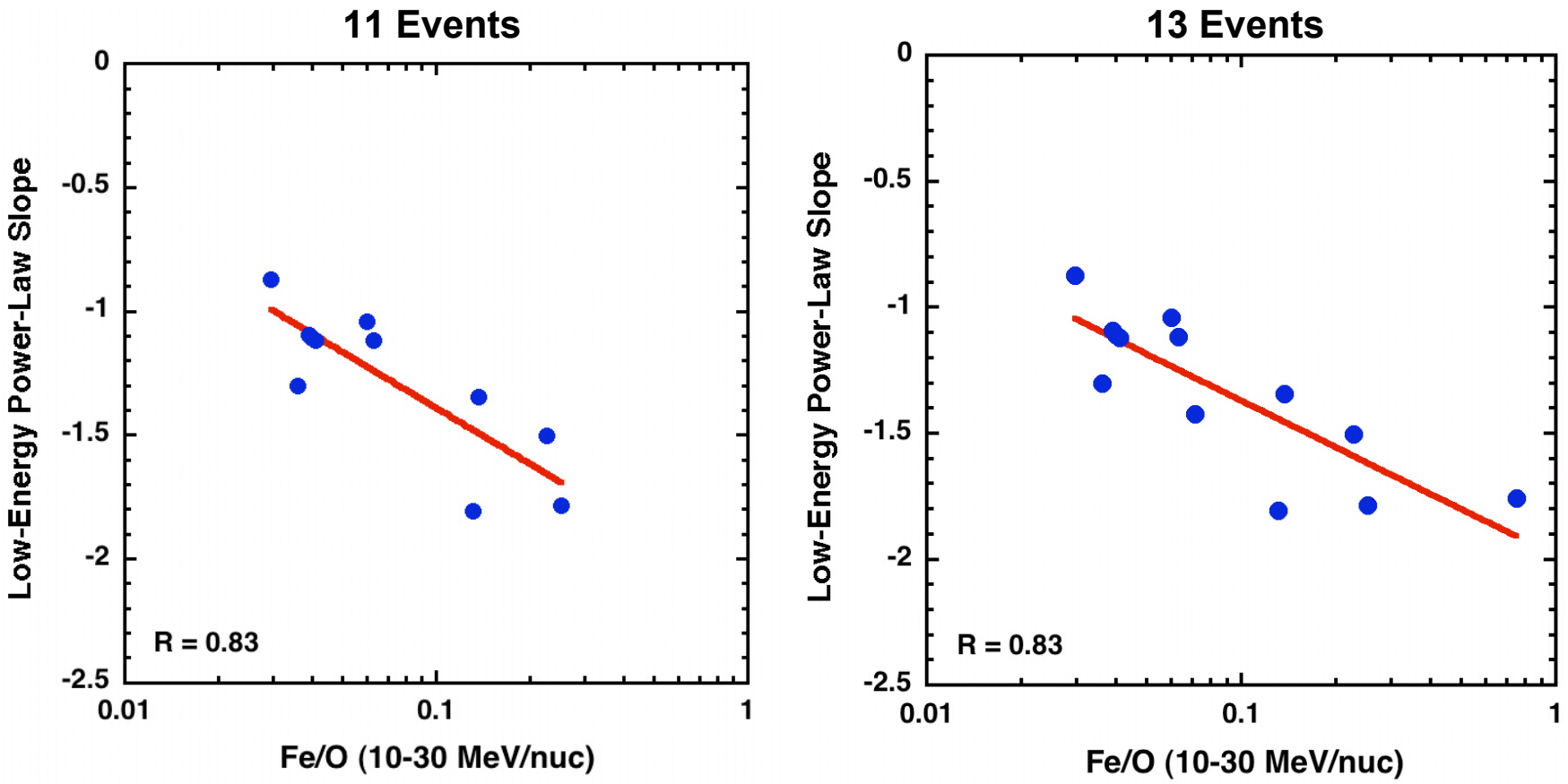


Fit Oxygen with Ellison-Ramaty spectrum - Determine other E_o values by using energy-shift values.

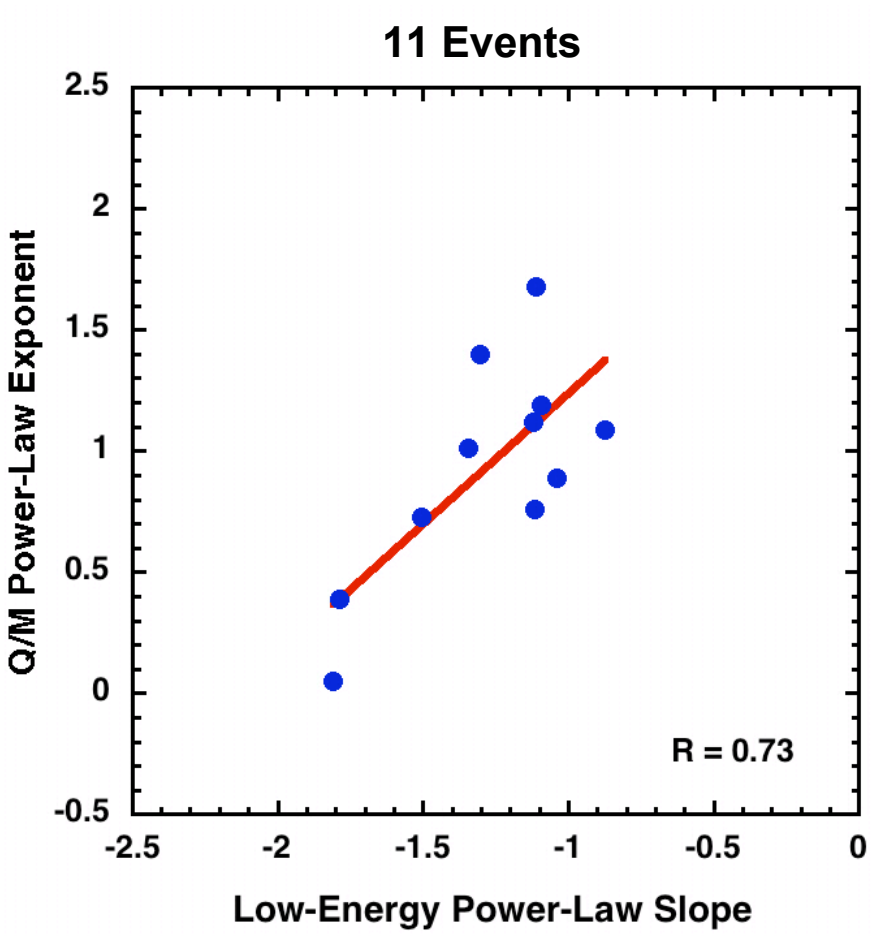


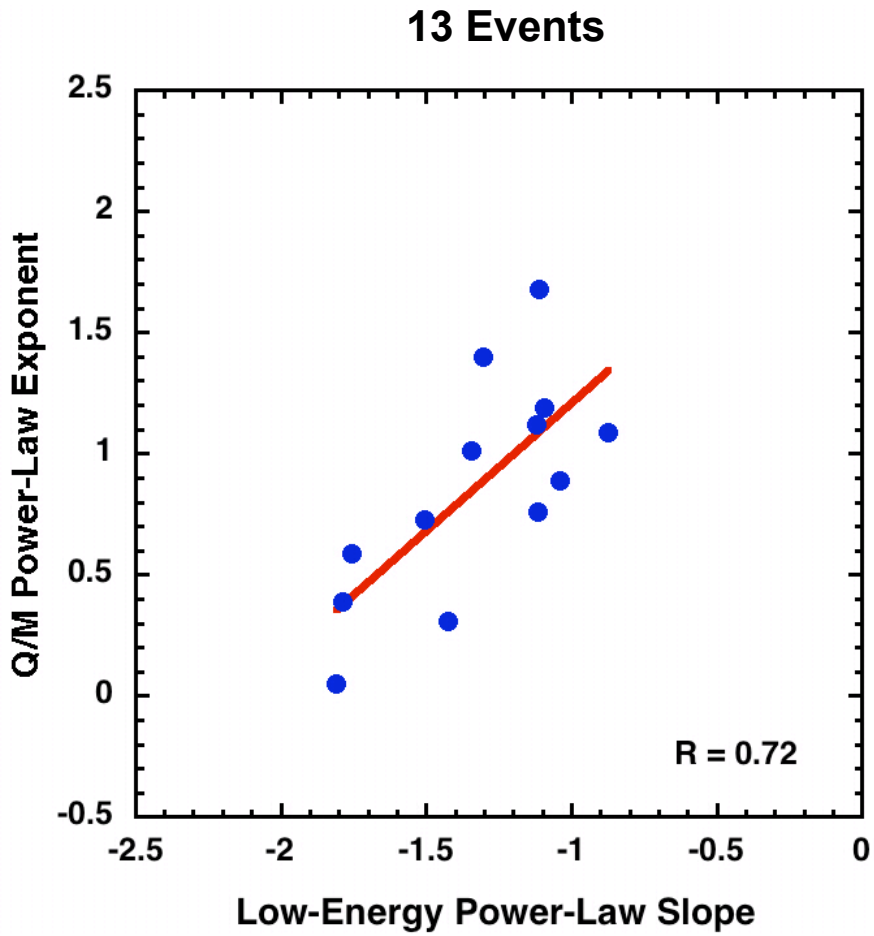


Effect of adding two Fe-rich events

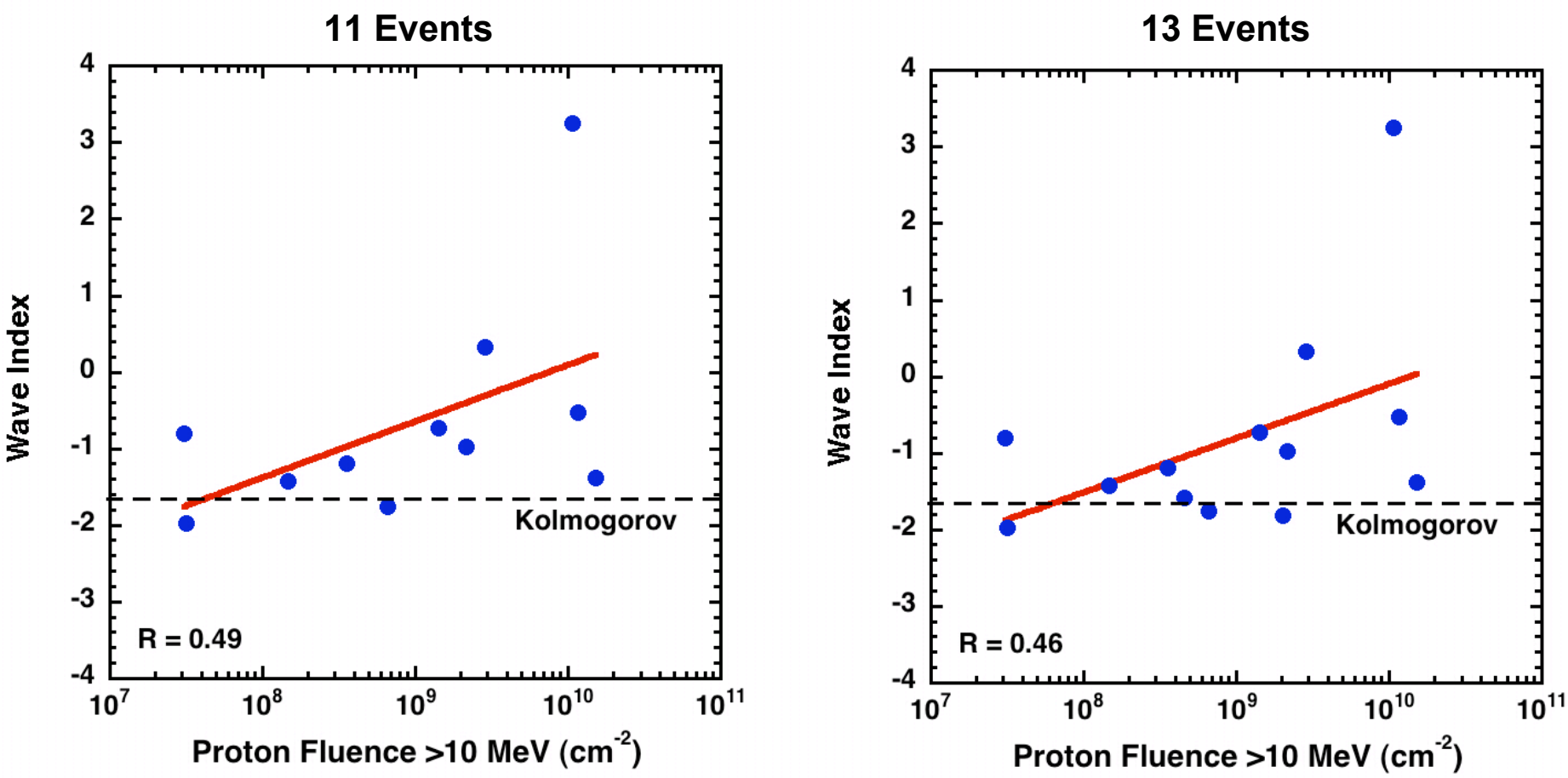


Still see strong correlation of Q/M index with the low-energy spectral slope

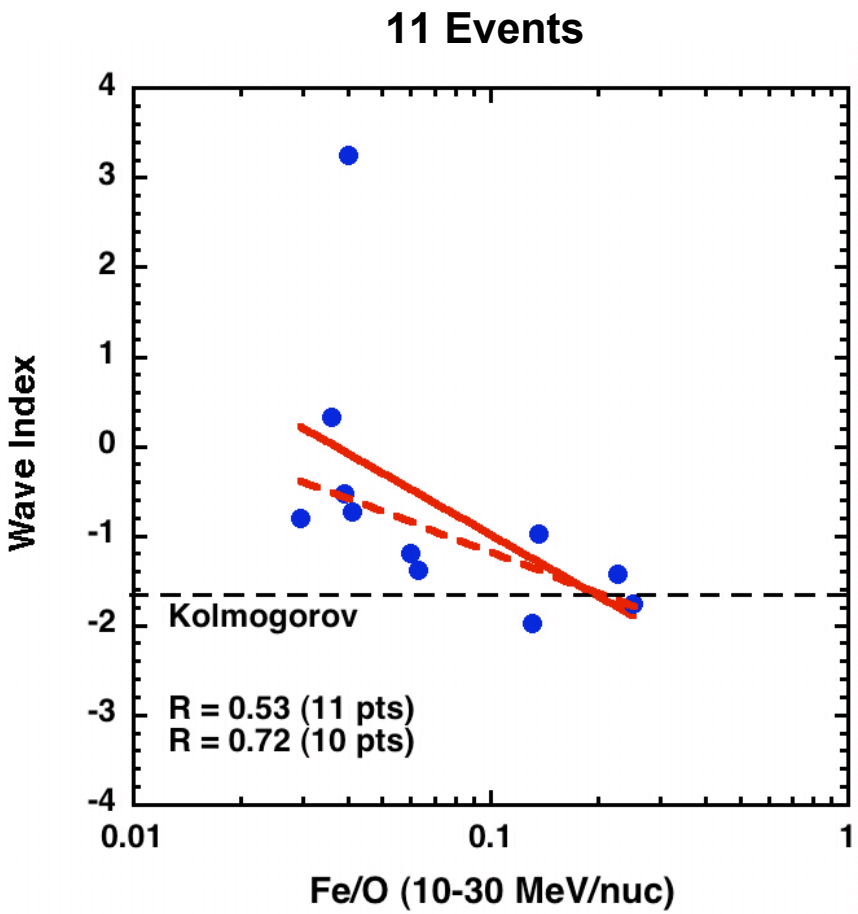


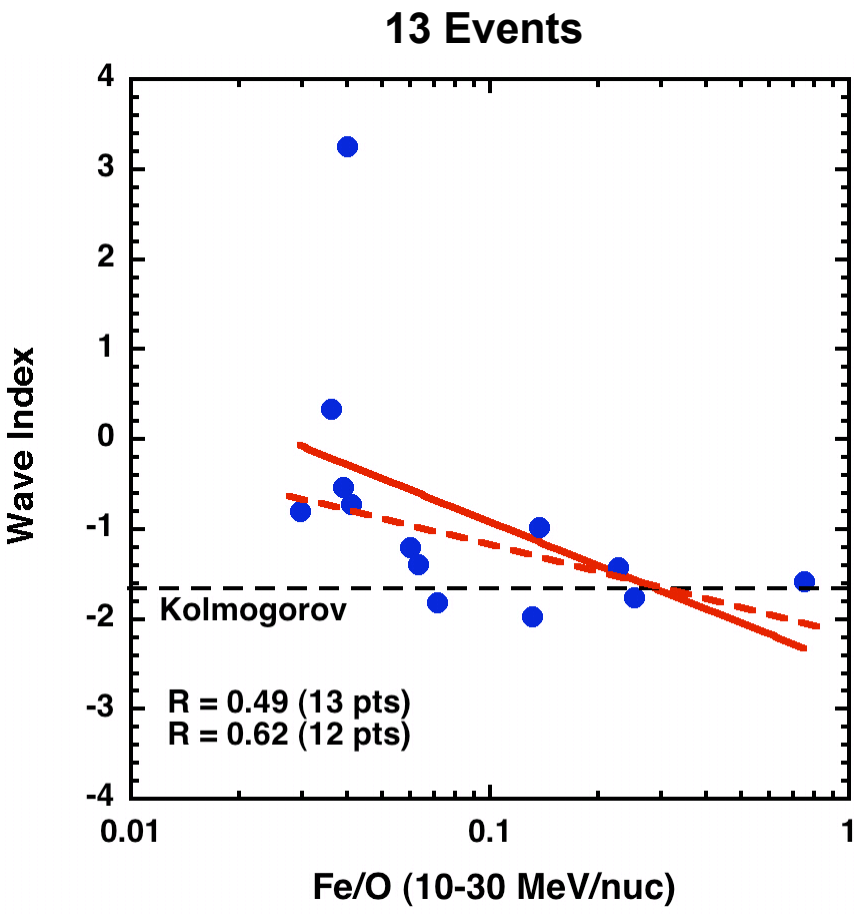


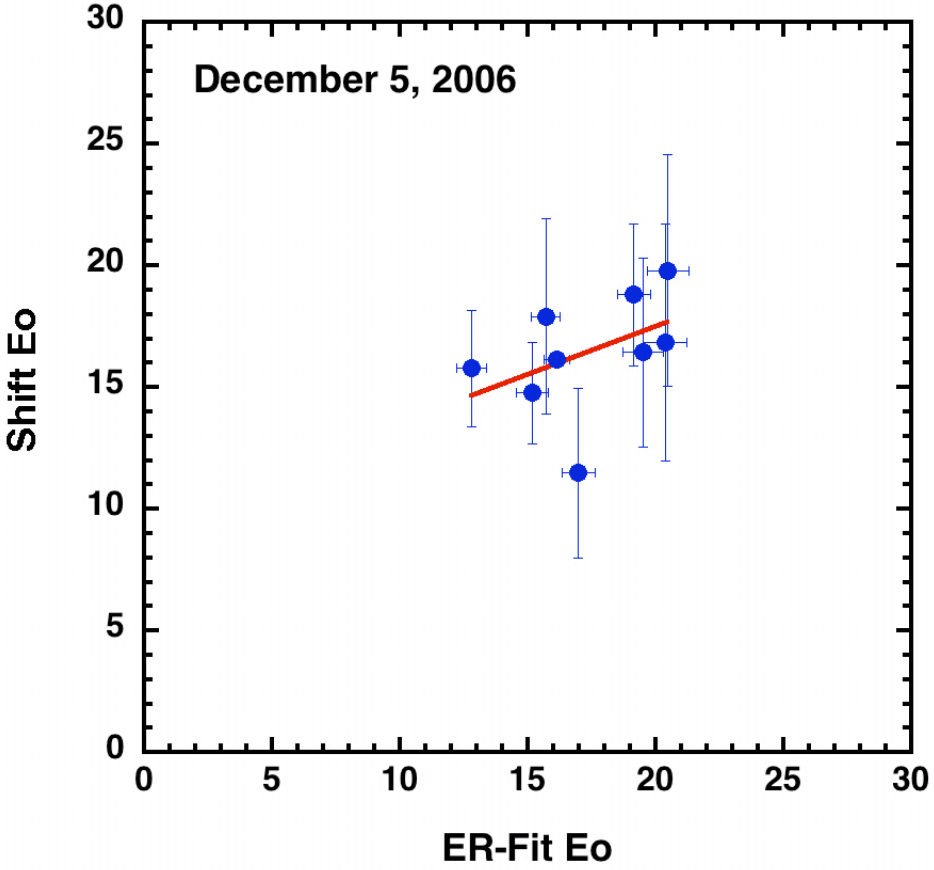
Wave Index versus Proton Fluence



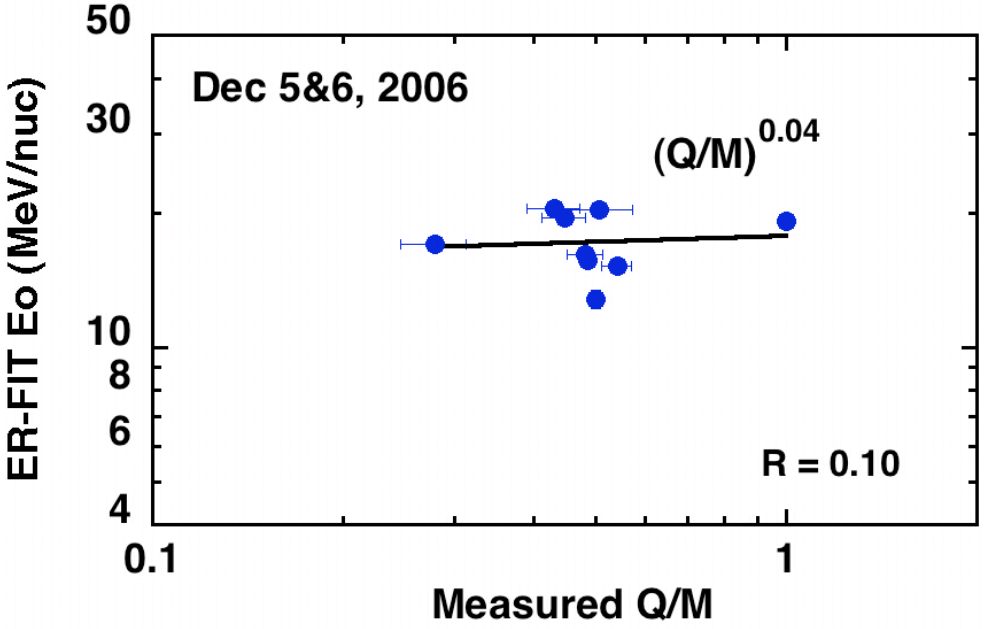
Wave index vs Fe/O



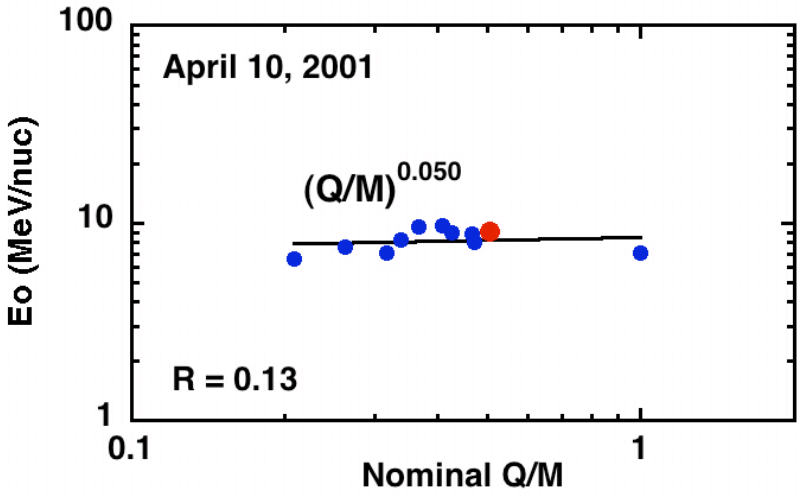


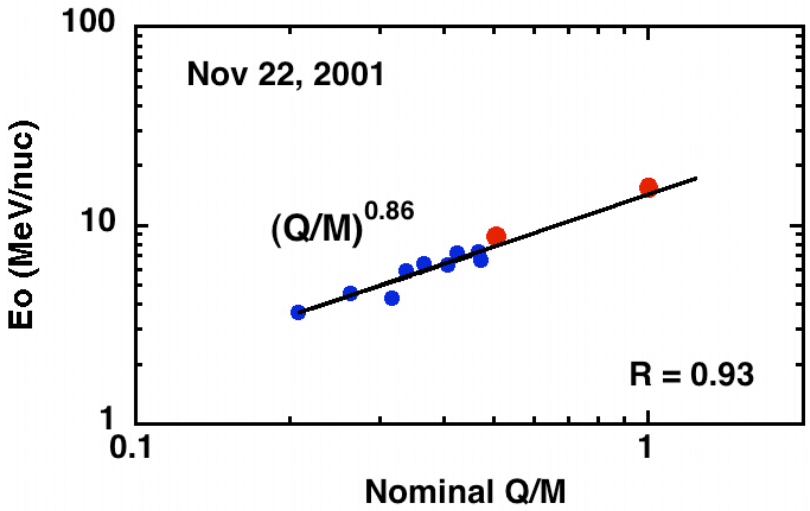


Compare “Shift” and Fitting approaches



Filling in missing H and He points





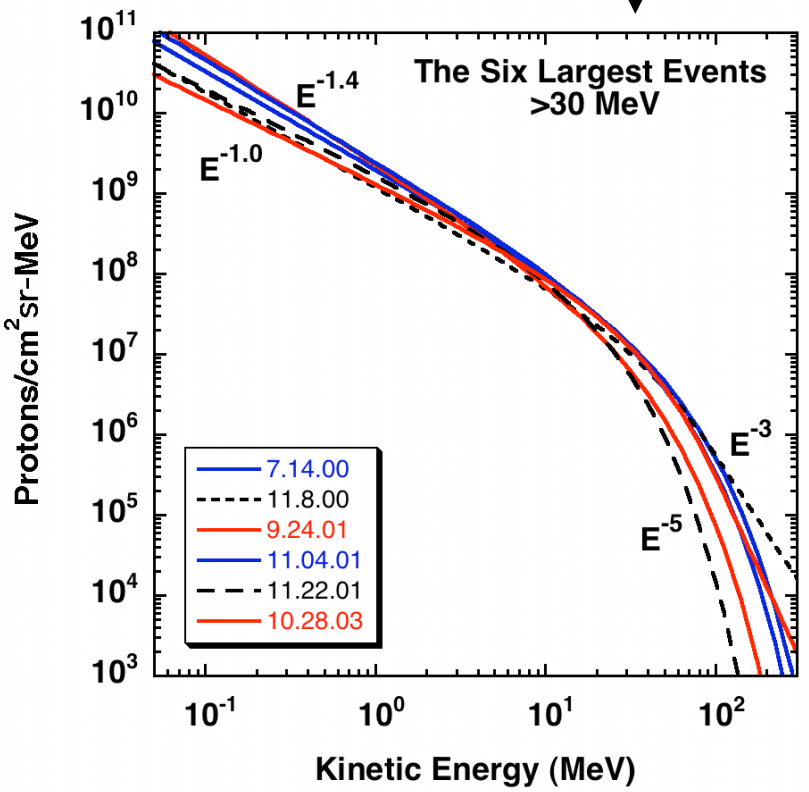
Fits to the Top 20 Events from Solar Cycle 23

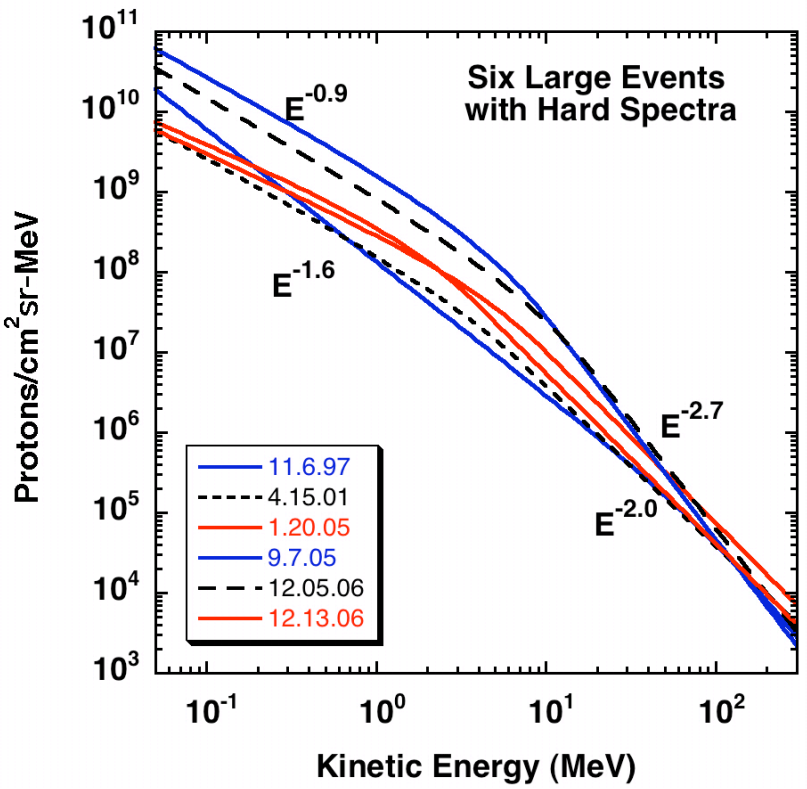
(based on >30 MeV proton fluence)

Plan to correlate spectral parameters with other solar/interplanetary parameters - work in progress

Quasi-Perpendicular?

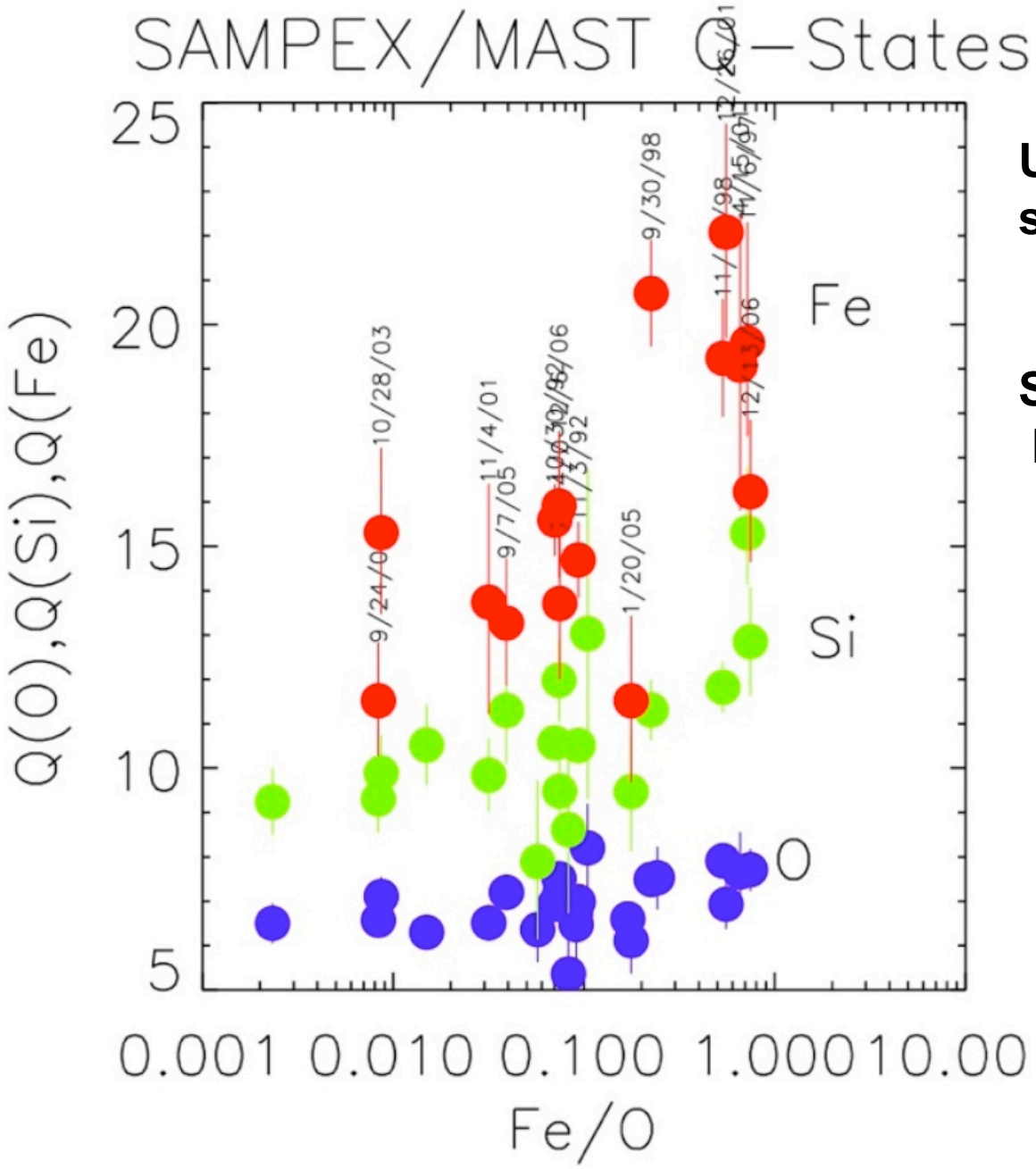
Quasi-Parallel?





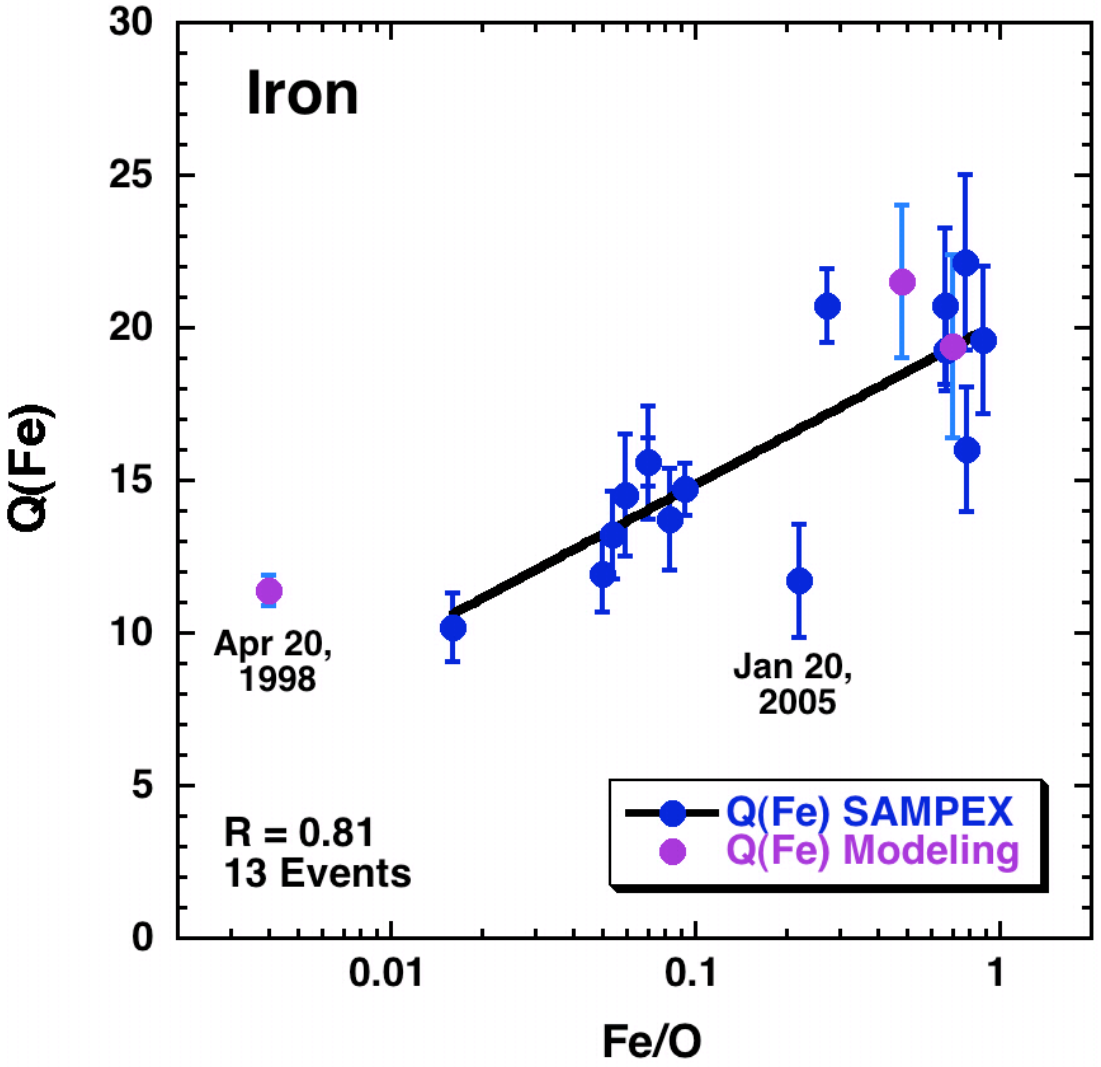
Updated Charge State Data and Correlations

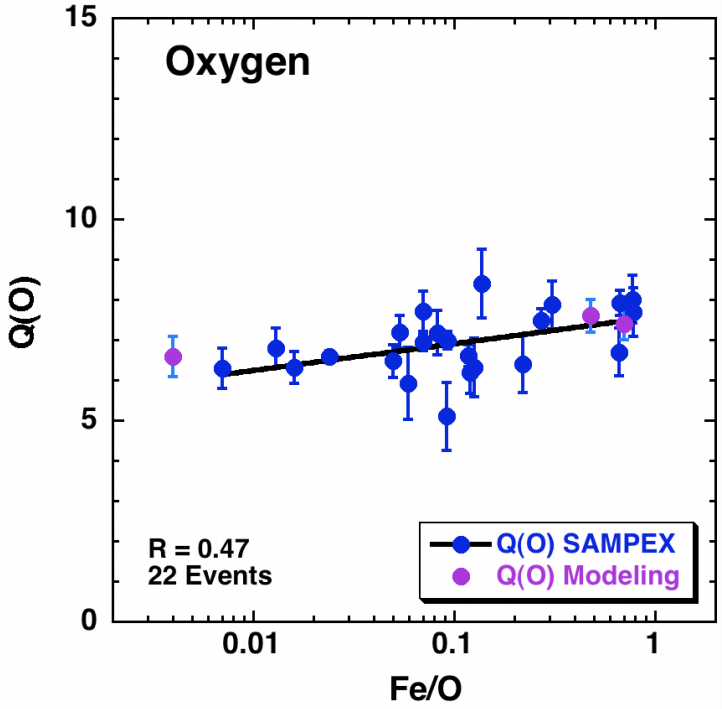
- Labrador et al. - AGU Poster
- Mewaldt and Labrador - AGU Invited talk

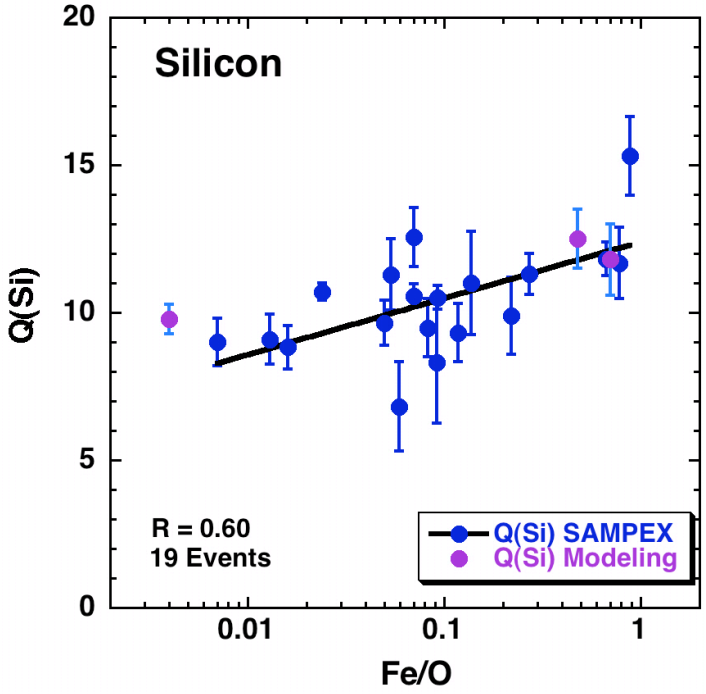


Updated charge-state summary from SAMPEX

See Poster SH52A-0906 by Labrador et al.



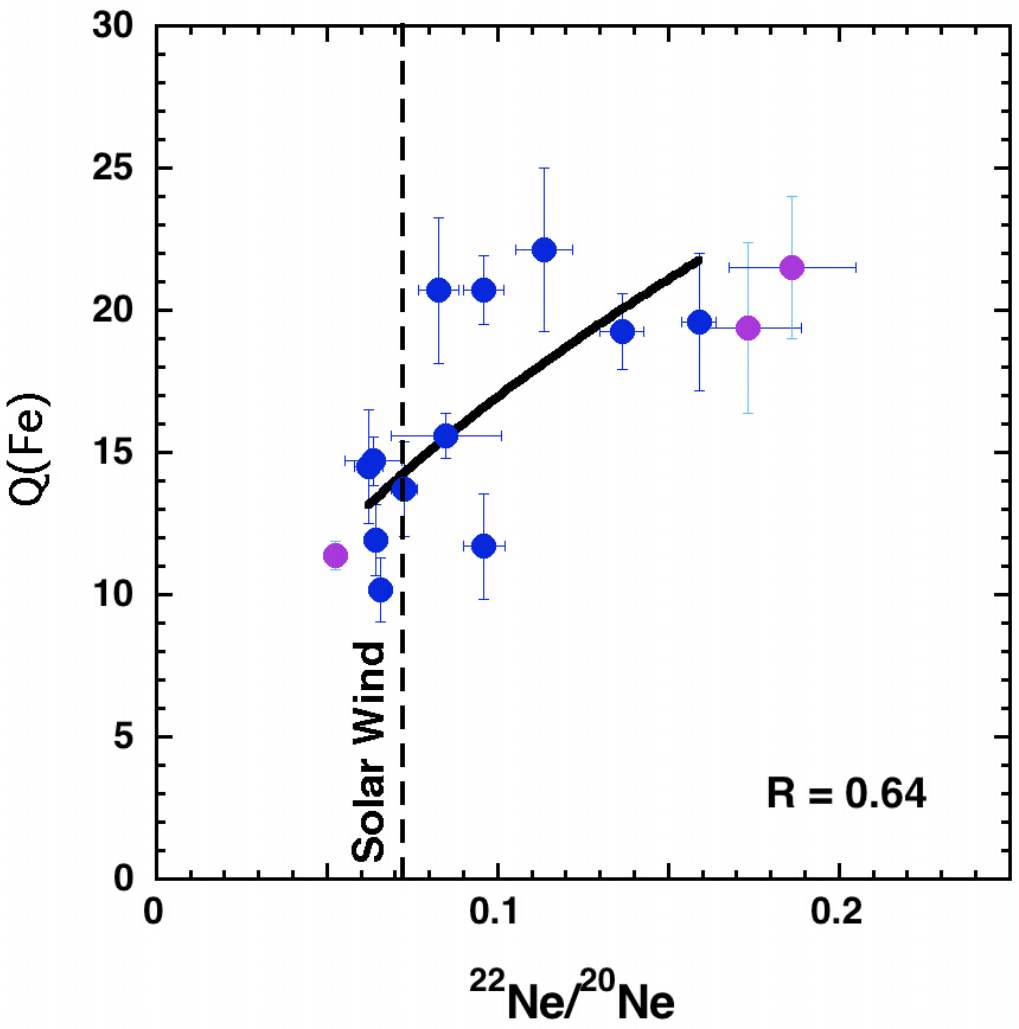




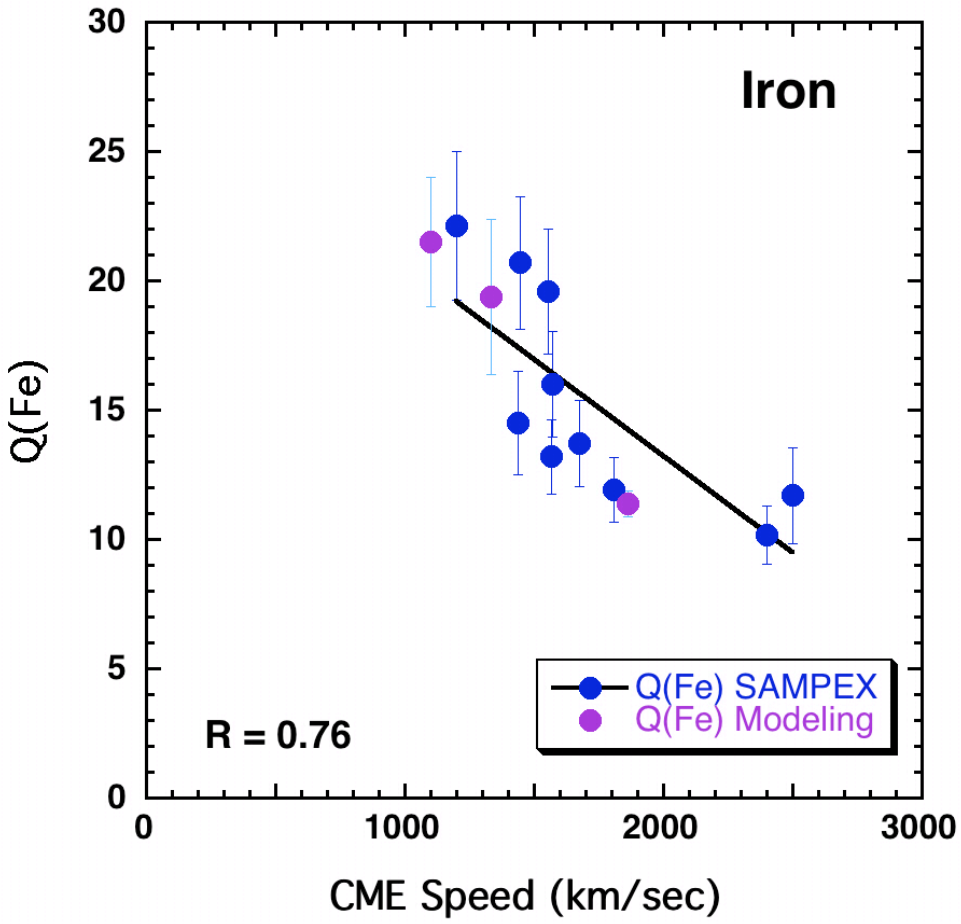
Mewaldt et al., Fall AGU 2007, SH-54B-01
See also Poster SH52A-0906 by Labrador et al.

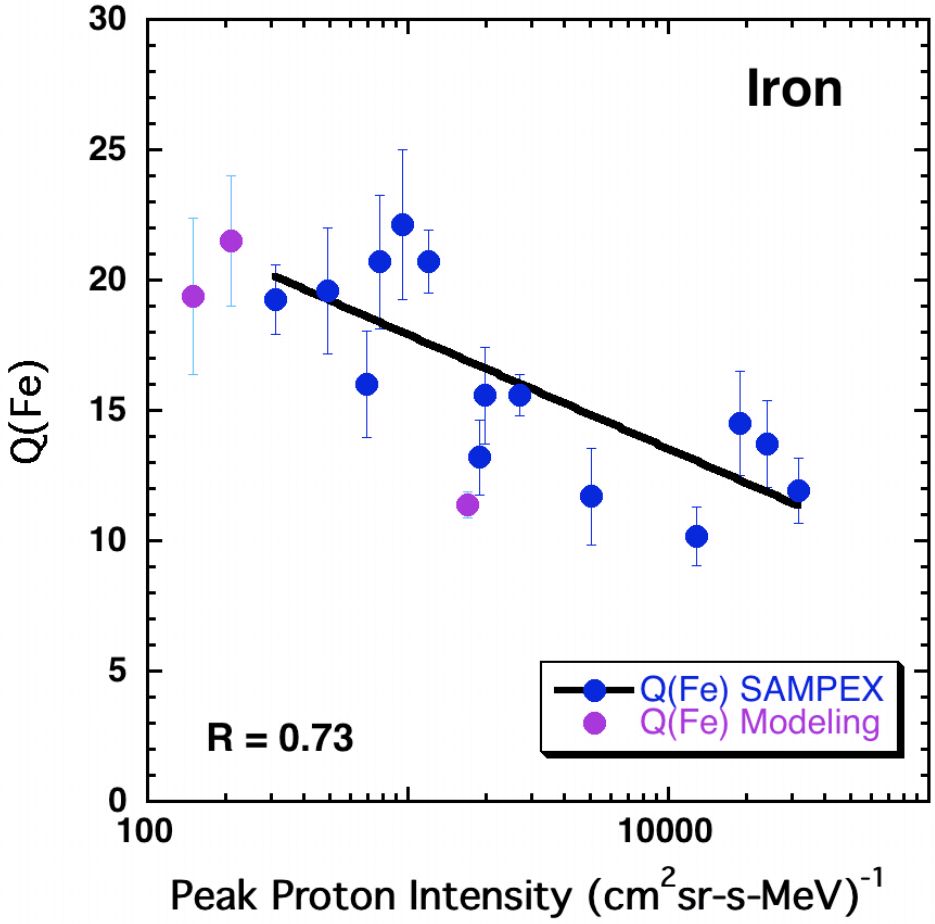
There is also a correlation of Q(Fe) with ^{22}Ne enrichments

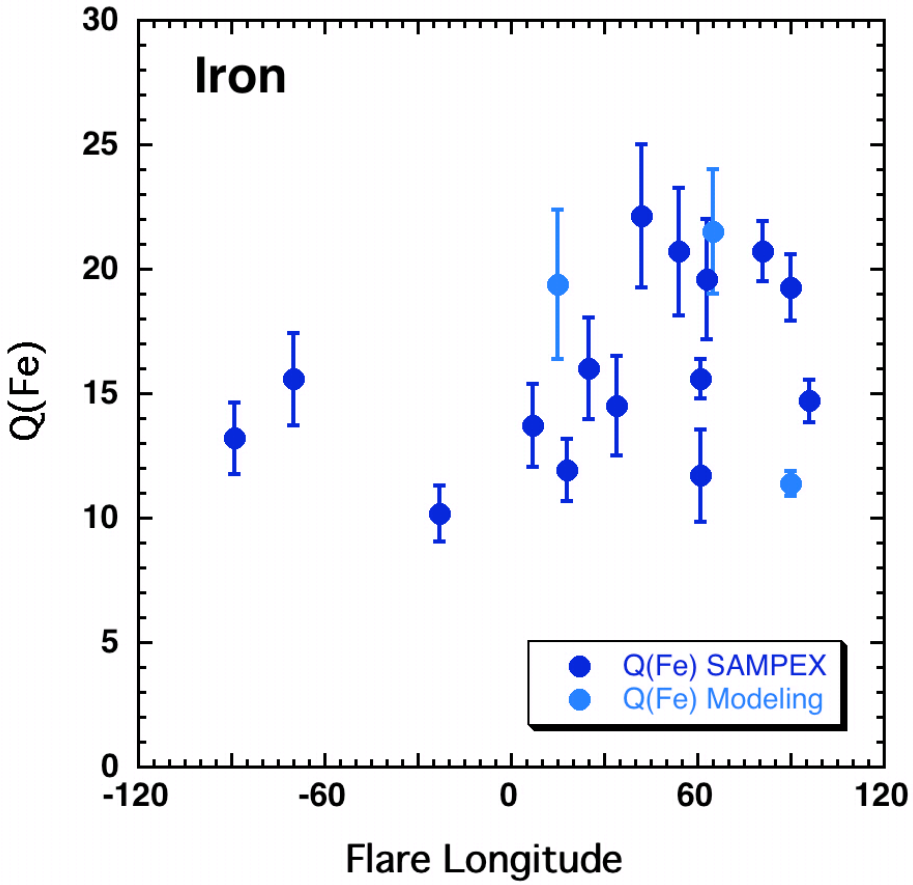
- **Consistent with mixing in flare material**
- **Not expected from stripping models unless acceleration favors high-rigidity species**

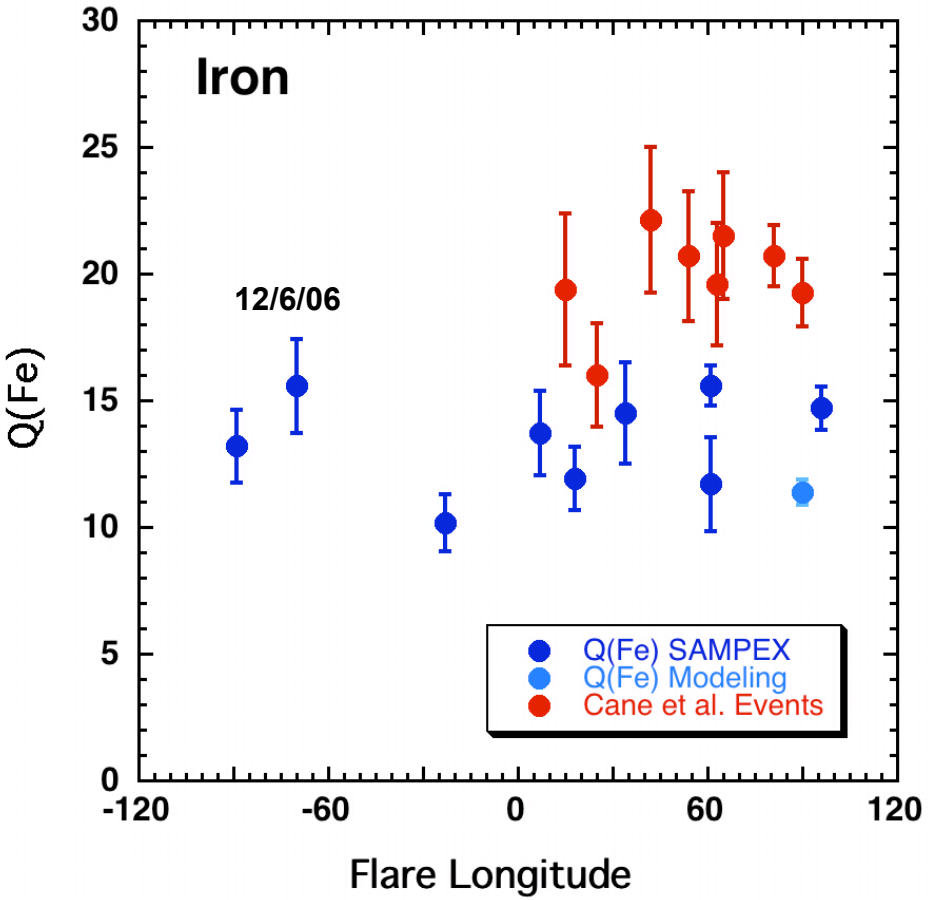


SEP events with Q_{Fe} >16 result from intermediate-speed CMEs (1000 - 1600 km/sec) rather than high-speed CMEs. The resulting solar proton events are more than an order of magnitude smaller than the largest events of the solar cycle. This favors models that mix flare and shock-accelerated material.









Most events with Q(Fe) >16 occur in the western hemisphere

Cane et al. suggest that prompt events with Fe enhanced by >x2 include flare-accelerated ions

Observed longitude distribution is consistent with this

Labrador et al. - Poster SH52A-0906

Progress:

- Three additional events with charge state data (other is 9/7/05)
- Two added to correlation plots
- Added additional H and He points
- Fit spectra to the 20 biggest SEP events of cycle 23

Issues:

- Need a robust method of determining break energies (other functional forms?)
- Don't learn much from events with minimal Q/M fractionation
- Dec 13, 2006 event is somewhat of an anomaly (Fe/O ~0.75)
- Can we use indirect measures of charge states?

Plans:

- Assess how many more events we can easily add
- Consider other spectral forms
- Write paper discussing correlations and theoretical interpretation