Update on Spectra and Properties of Ground-Level Events during Solar Cycle 23

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Second GLE Workshop
University of Alabama at Huntsville
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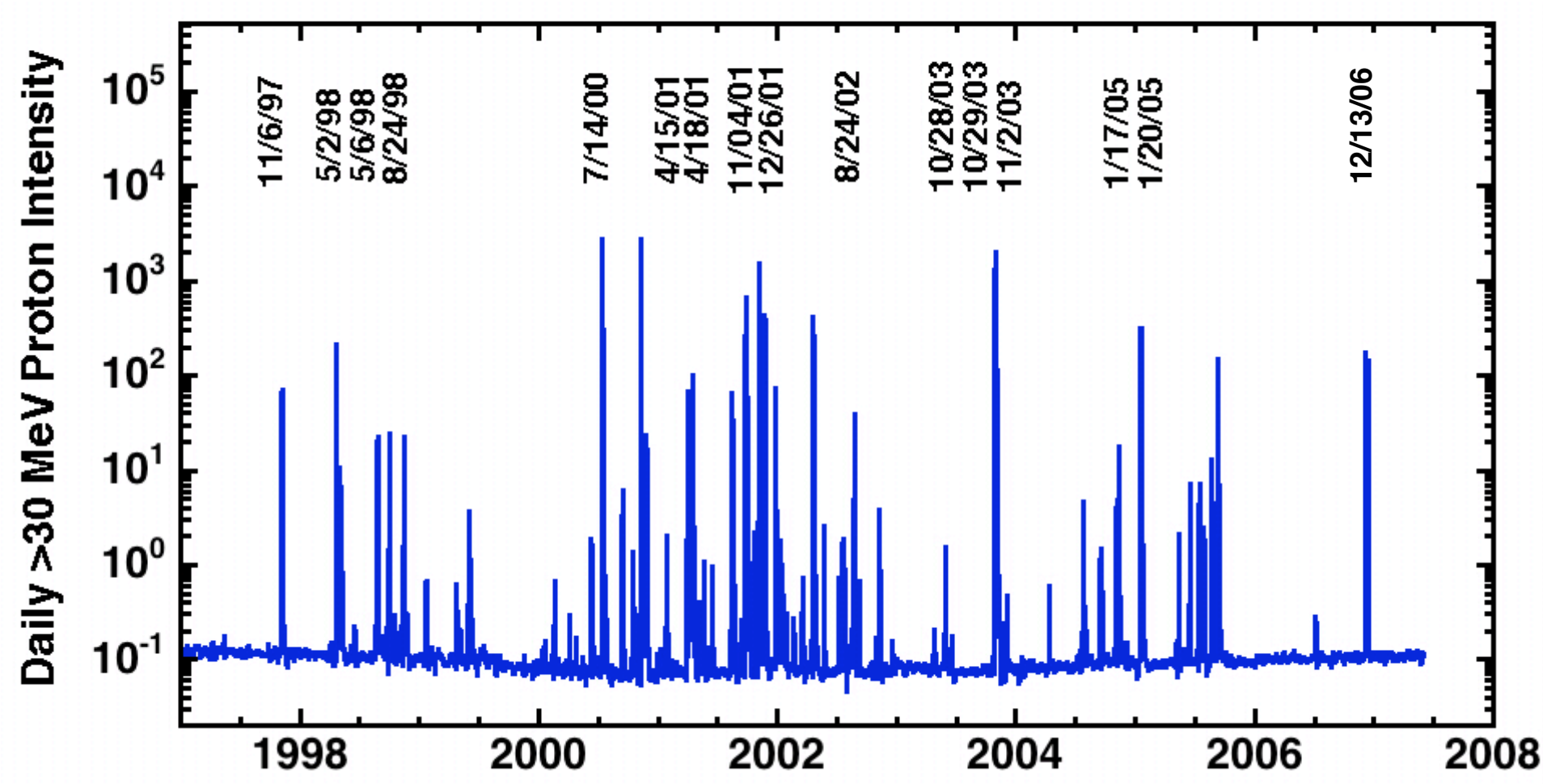
Daily average >30 MeV proton intensity for solar cycle 23
[Ground level events (GLEs) are indicated]



Data from GOES 8, 10, 11, and 12

Sources of SEP 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:	Protons	~0.03 to ~5 MeV

STEREO

LET:	H, He:	2 to 12 MeV
	$3 \leq Z \leq 28$:	4 to 30 MeV/nuc
HET:	H, He:	14 to 100 MeV

SAMPEX:

PET:	H, He	~20 to ~400 MeV/nuc
MAST:	O-Fe Q-states	~20 to ~90 MeV/nuc

GOES-8, 11	H, He	~5 to ~100 MeV/nuc

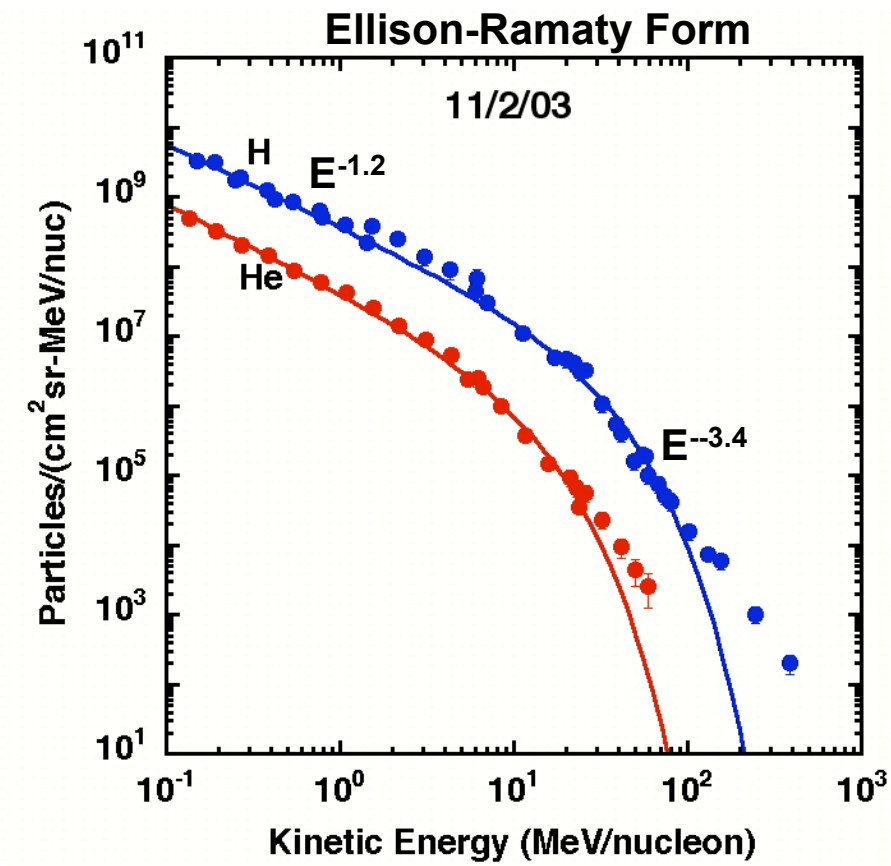
Approachs to Fitting Spectra (see Mewaldt et al. 2005):

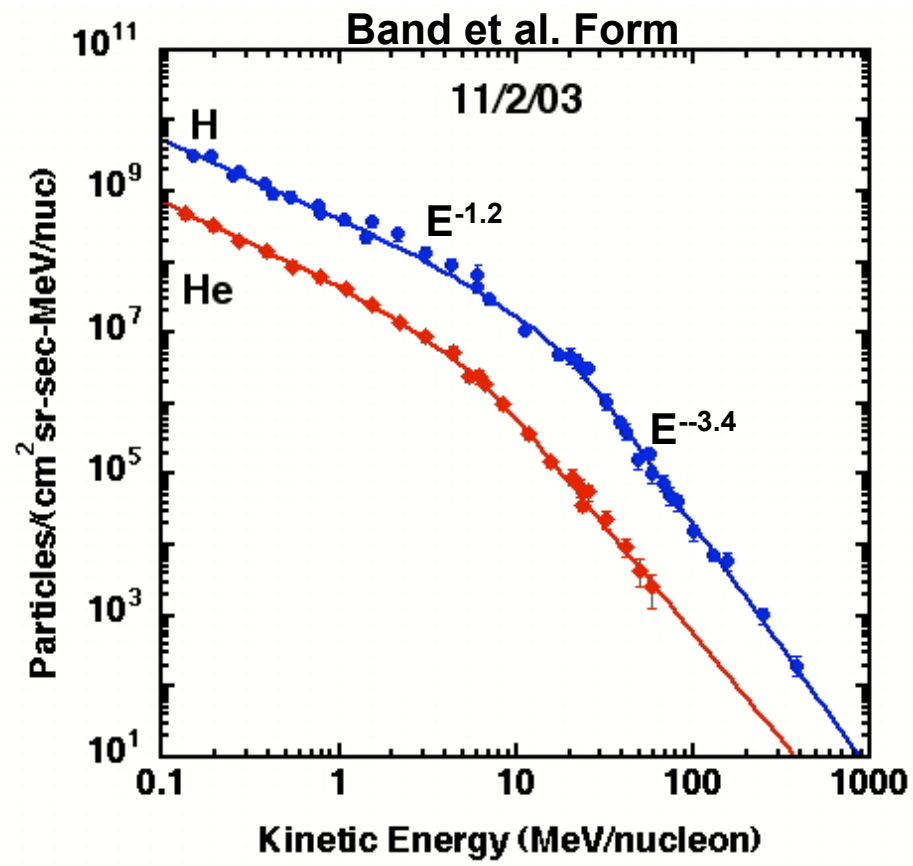
All 16 GLE spectra were better fit by the double-power-law form due to Band et al. (1993), than by the Ellison-Ramaty form (power-law with exponential cutoff)

Band et al. spectrum:

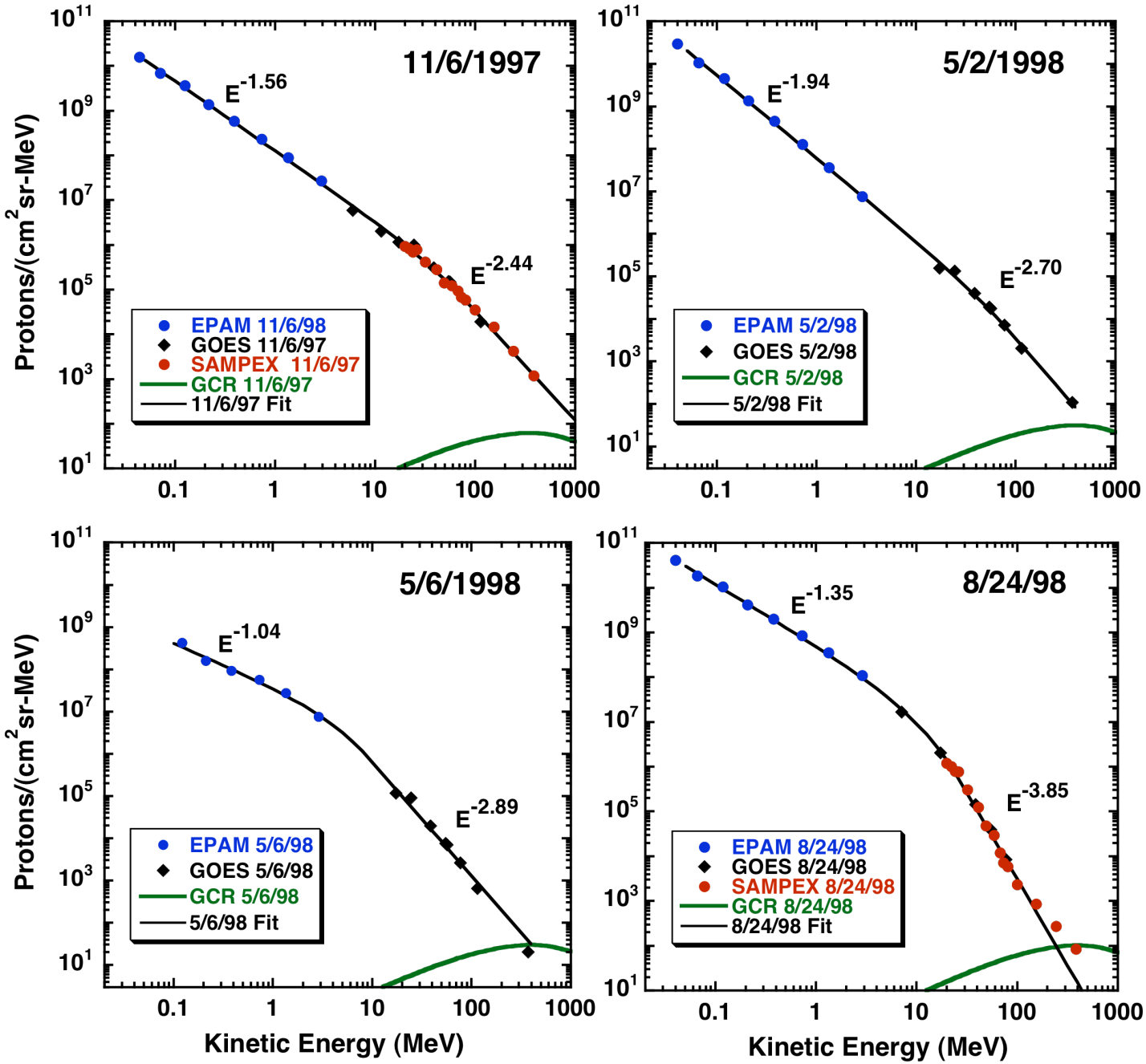
$$dJ/dE = CE^{-\gamma_a} \exp(-E/E_o) \quad \text{for } E \le (\gamma_b - \gamma_a)E_o;$$

$$dJ/dE = CE^{-\gamma_b} \{[(\gamma_b - \gamma_a)E_o]^{(\gamma_b - \gamma_a)} \exp(\gamma_b - \gamma_a)\} \quad \text{for } E \ge (\gamma_b - \gamma_a)E_o$$





Measured and fit fluence spectra for the first four GLE events

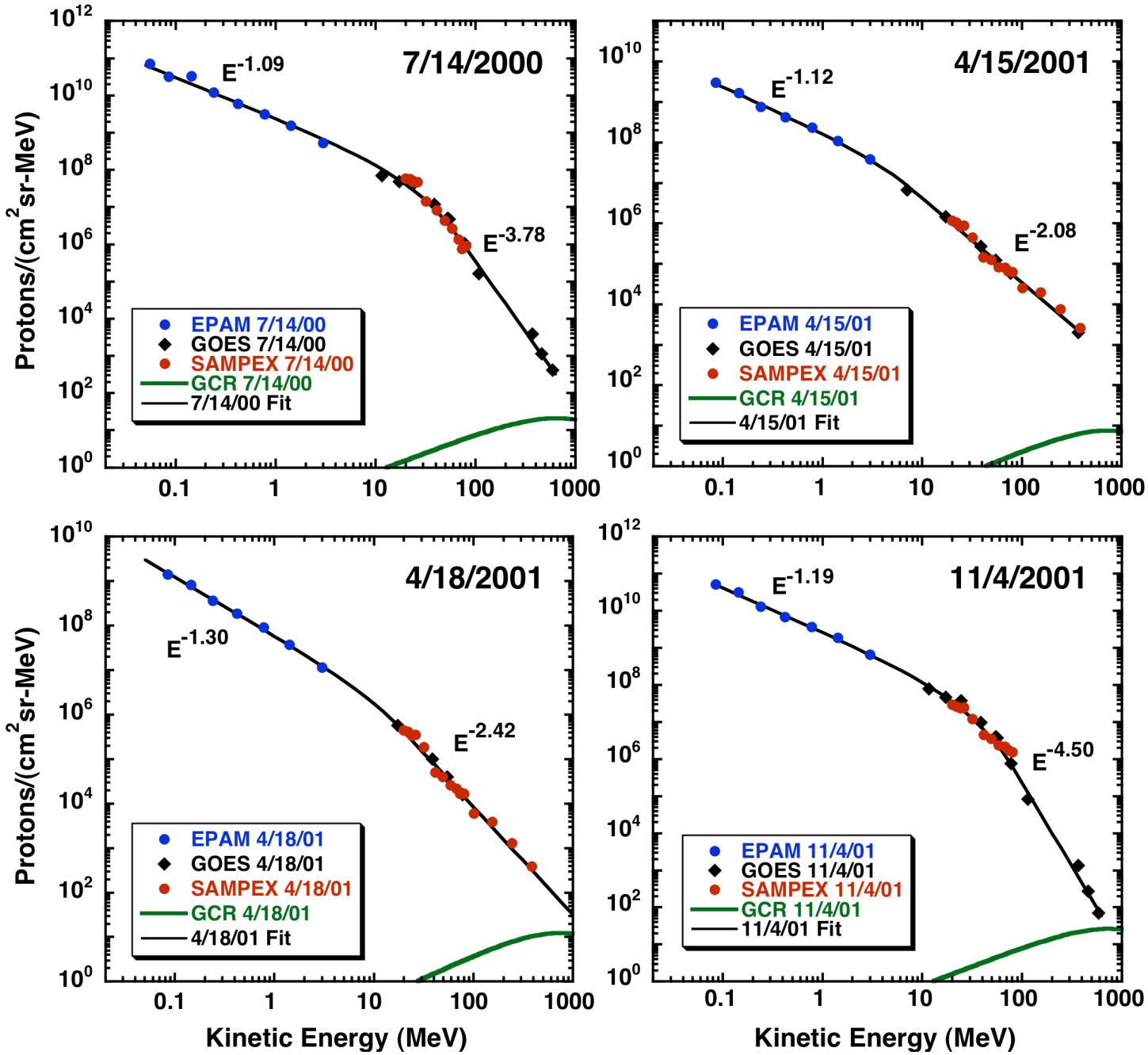


Spectral slopes above and below the break energy are indicated

Nominal GCR fluences are also shown. The expected GCR fluences have been subtracted from the plotted points

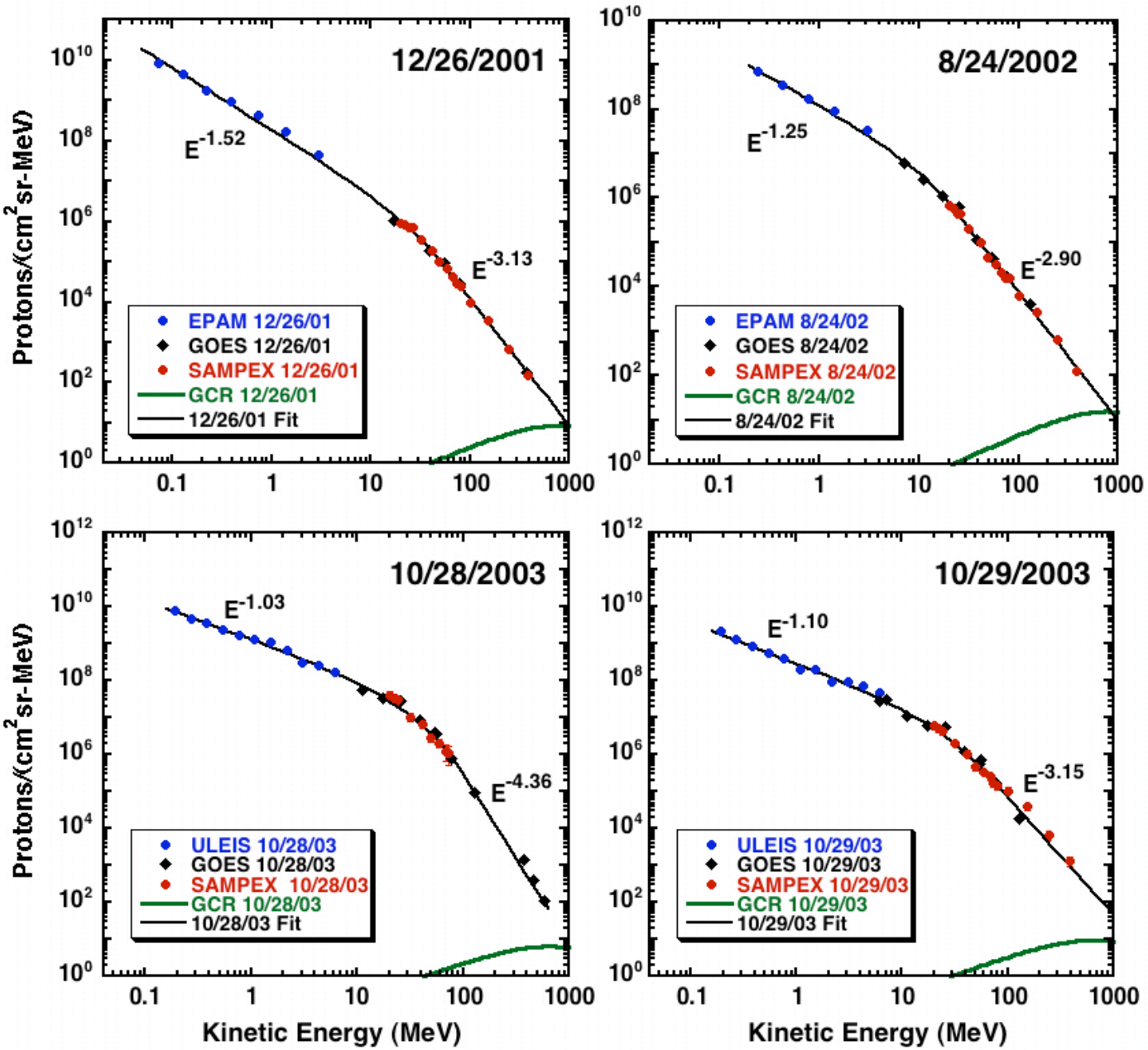
Mewaldt et al. 2009

Measured and fit spectra for GLE events #5 - #8



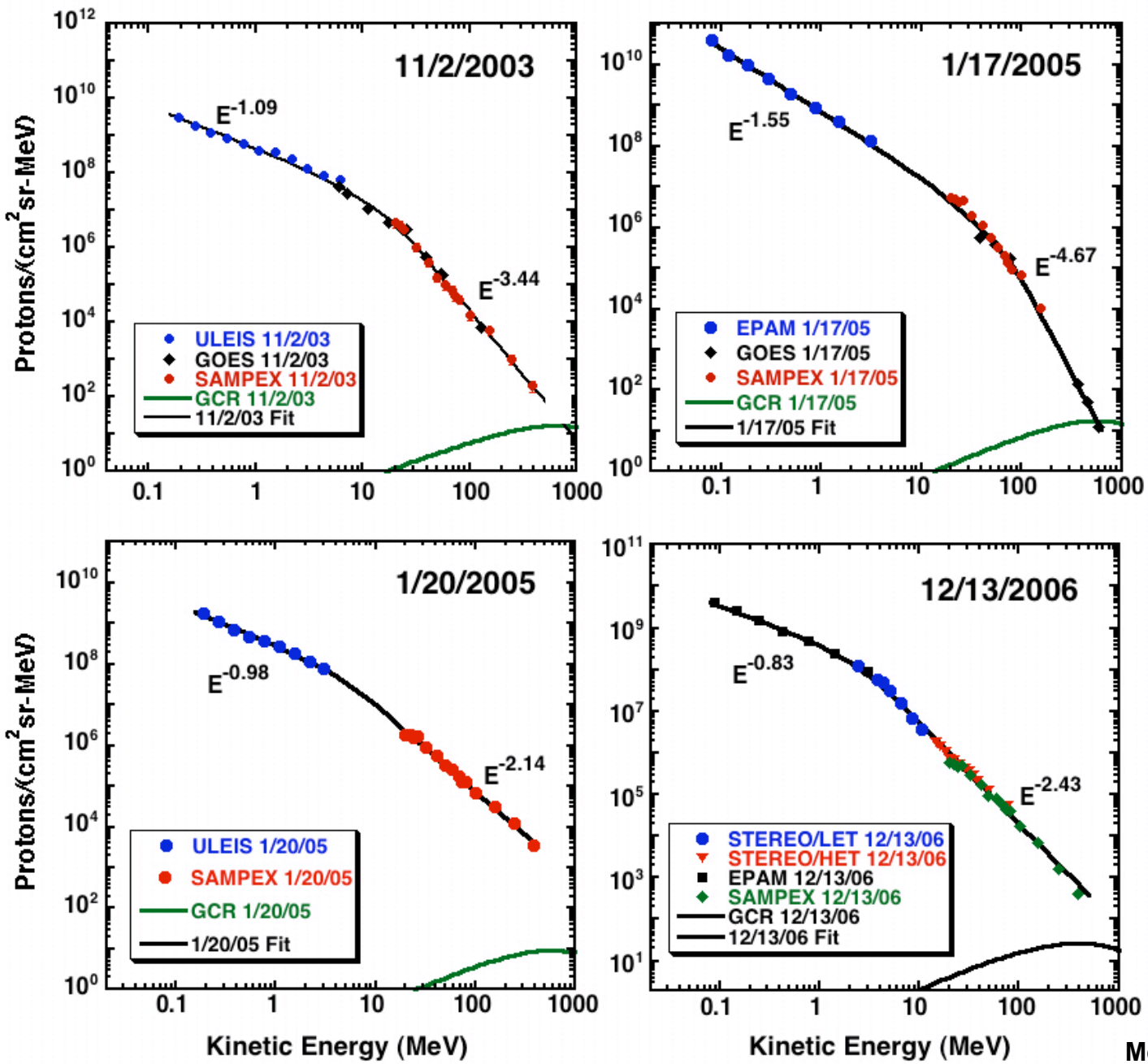
Mewaldt et al. 2009

Measured and fit spectra for GLE events #9 - #12

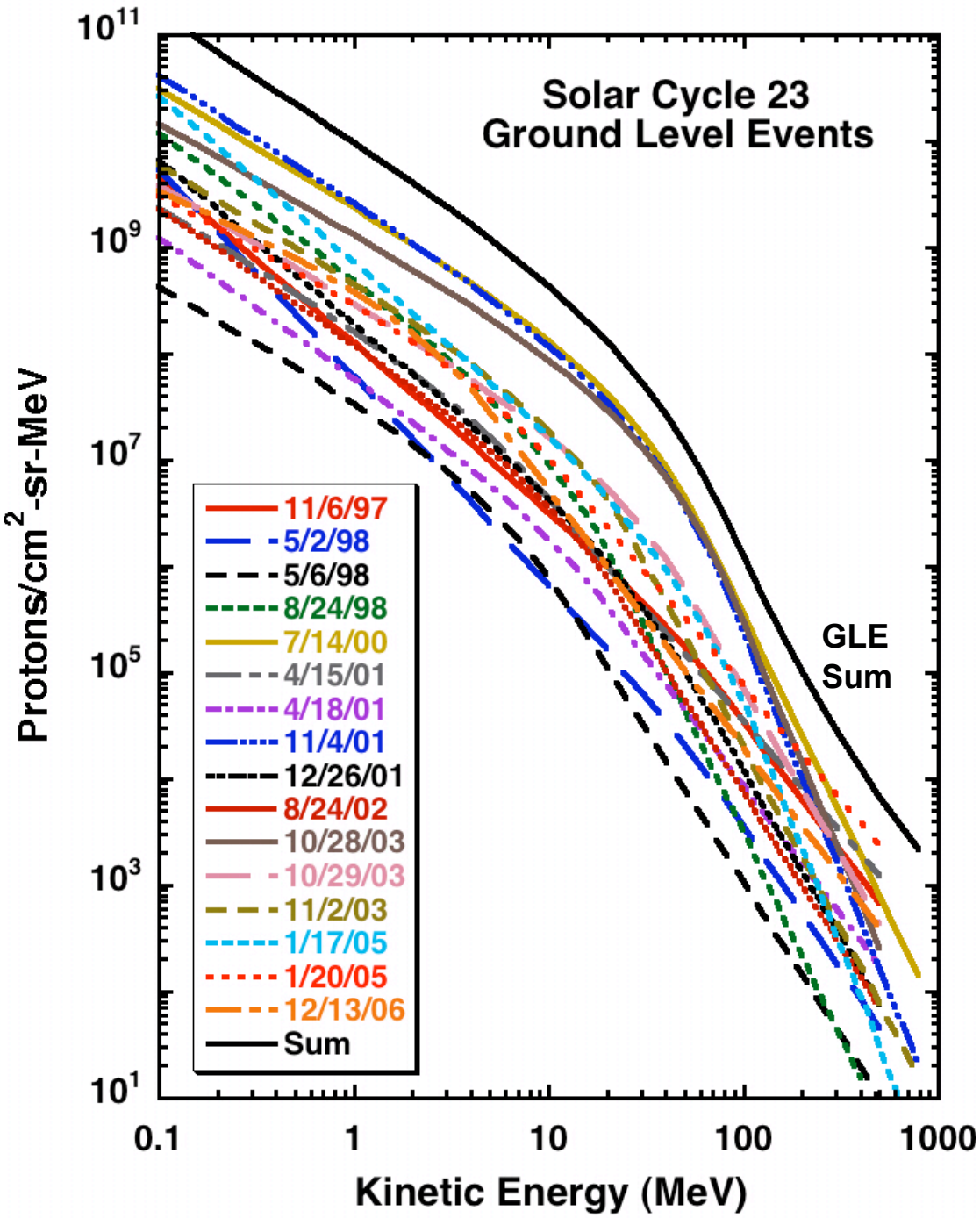


Mewaldt et al. 2009

Measured and fit spectra for GLE events #13 - #16



Mewaldt et al. 2009



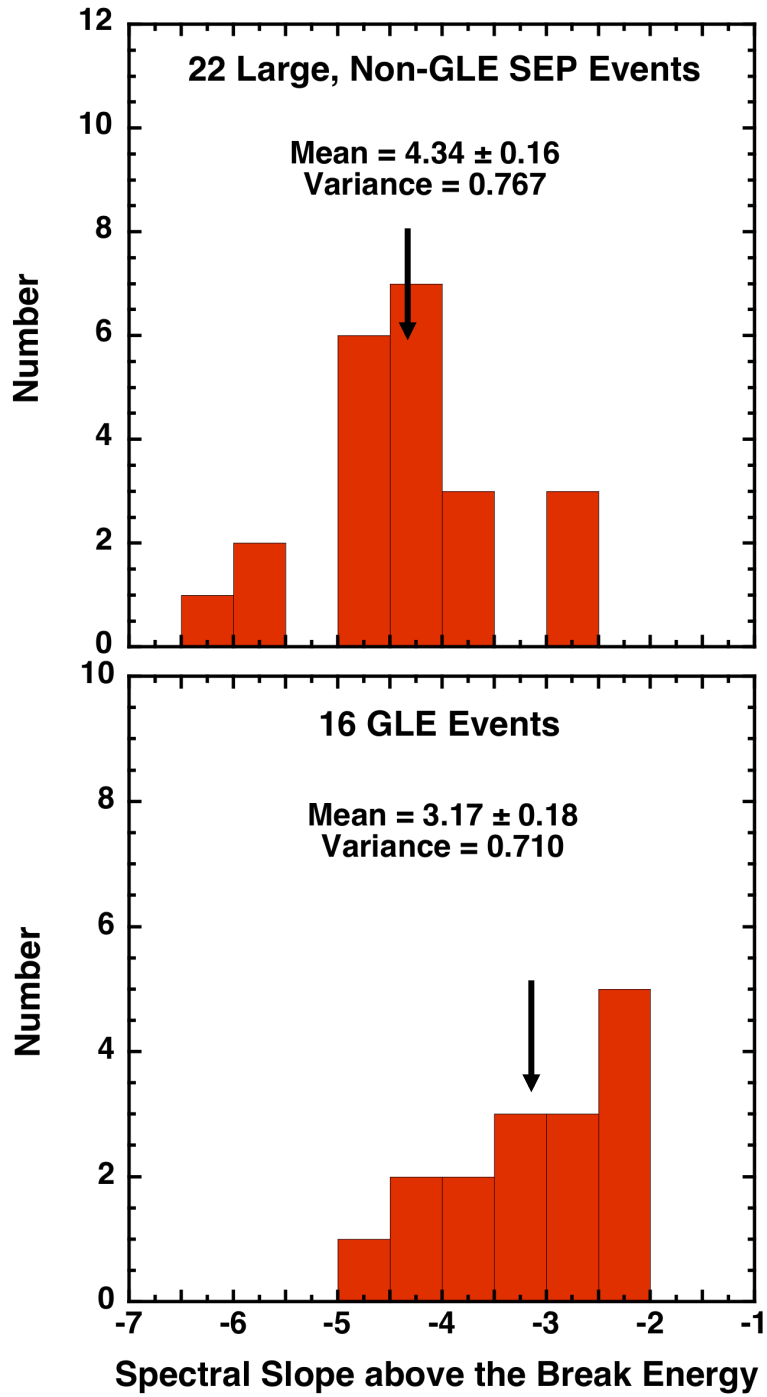
Comparison of GLE spectral fits

Note: Fits shown only over interval with data

7/14/00, 11/4/01, 10/28/03 have steeper spectra >40 MeV

The GLE "sum" curve makes up ~50% of the solar cycle fluence of 10-100 MeV protons (see Mewaldt et al. 2007a)

Mewaldt et al. 2009



As might be expected, the high-energy (>~30 MeV) spectra of GLEs are significantly harder, on average, than for a sample of large, non-GLE events

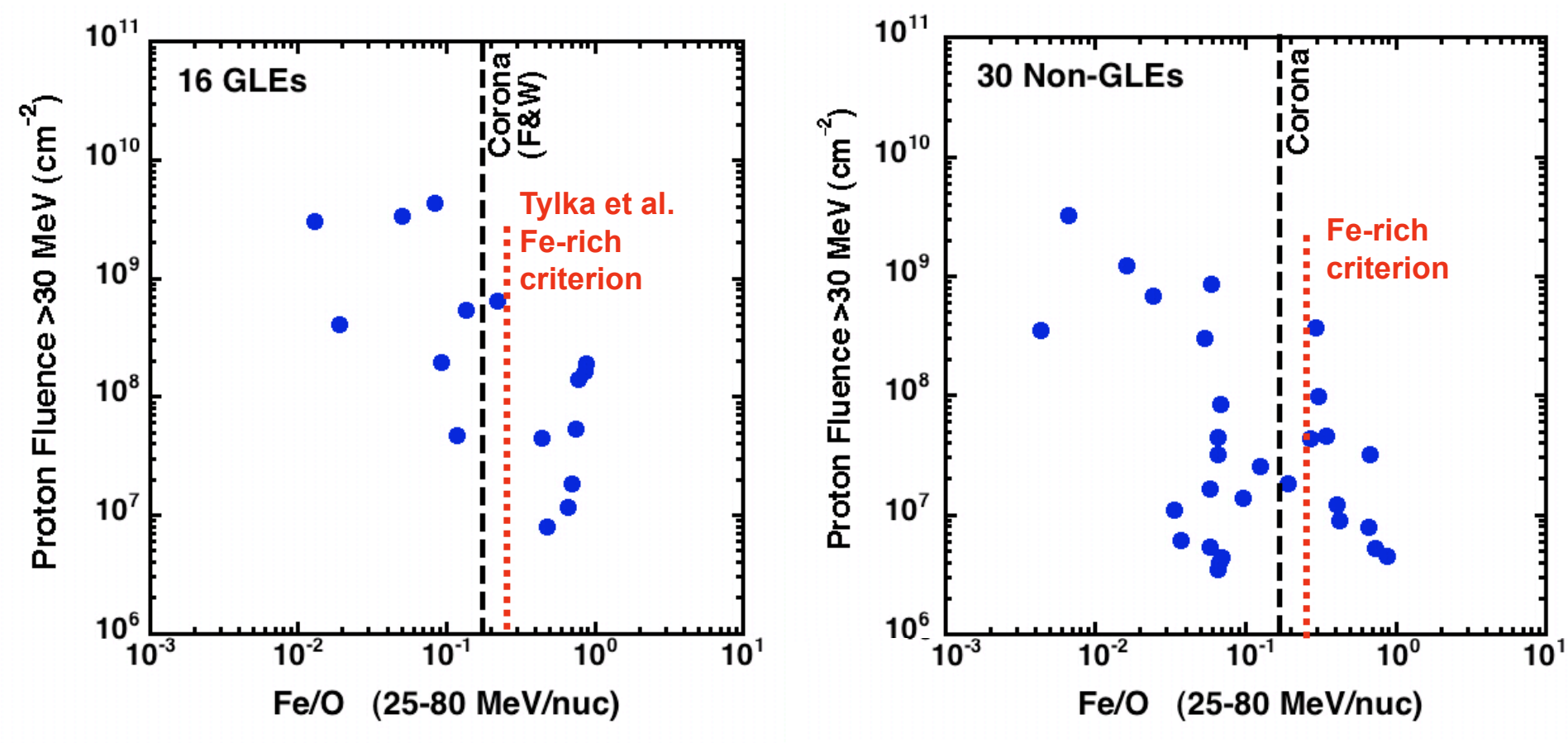
Note: several of the non-GLEs events have comparable >100 MeV fluences but apparently do not meet the peak >500 MeV intensity requirement to be a GLE

The spectral slopes below the break energy are similar in these two samples with mean slopes of ~ -1.25

Mewaldt et al. 2009

Tylka et al. (2005) reported that 33 of 38 GLEs from 1976 - 2003 were were Fe-rich (Fe/O ≥0.27) in the ≥40 MeVnuc interval. By this criterion only 50% of SC-23 events are Fe-rich at 25 - 80 MeV/nuc

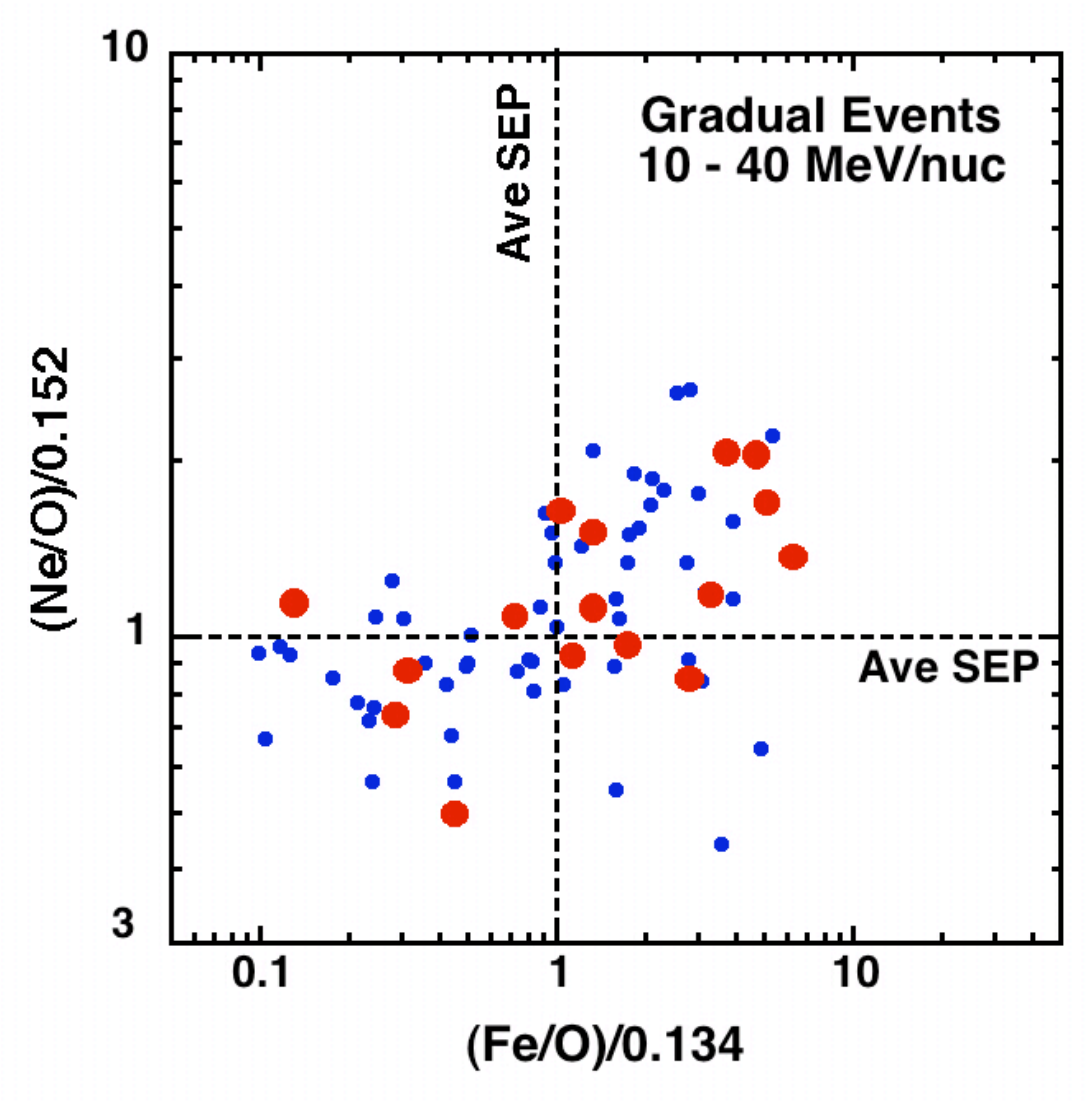
For non-GLE events 33% are Fe-rich, so GLEs are somewhat Fe-rich



ACE/SIS data; see also Cane et al. (2006) and Mewaldt et al. (2006)

Both Fe/O and Ne/O are somewhat enriched in GLEs

These enrichments may be signatures of flare material (remnant suprathermal material accelerated by the shock or directly accelerated flare particles)



Both Ne and Fe are enriched in a majority of GLE events

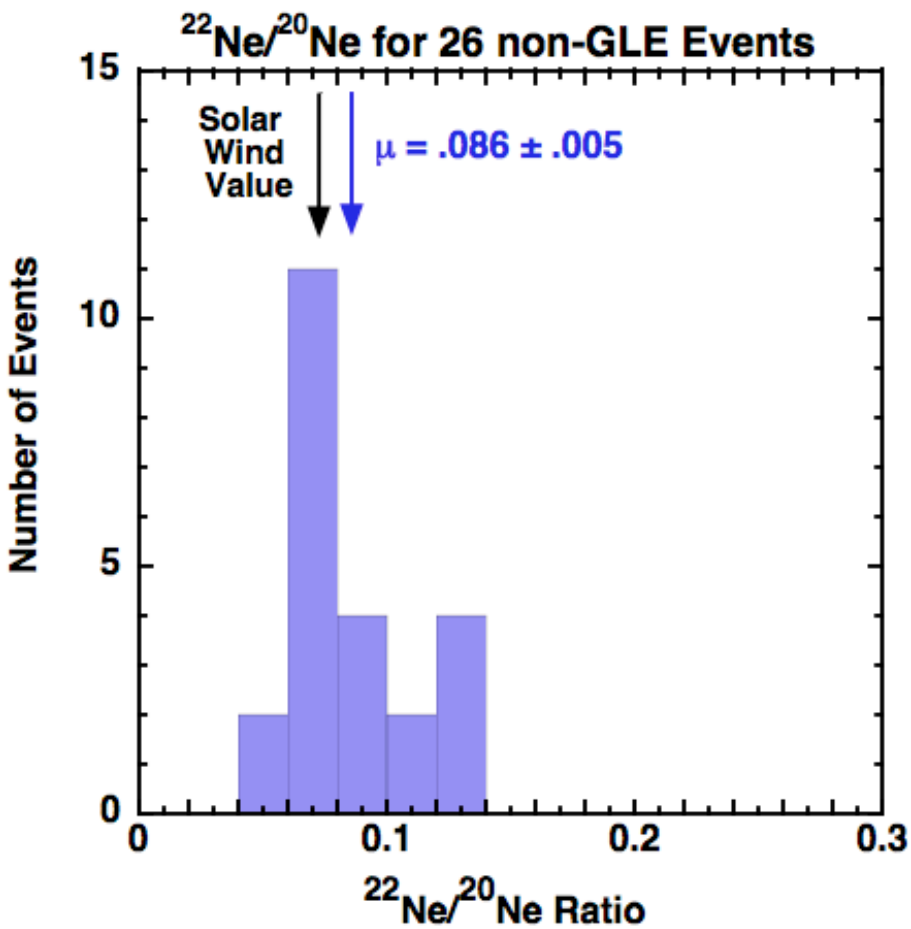
2	8
3	3

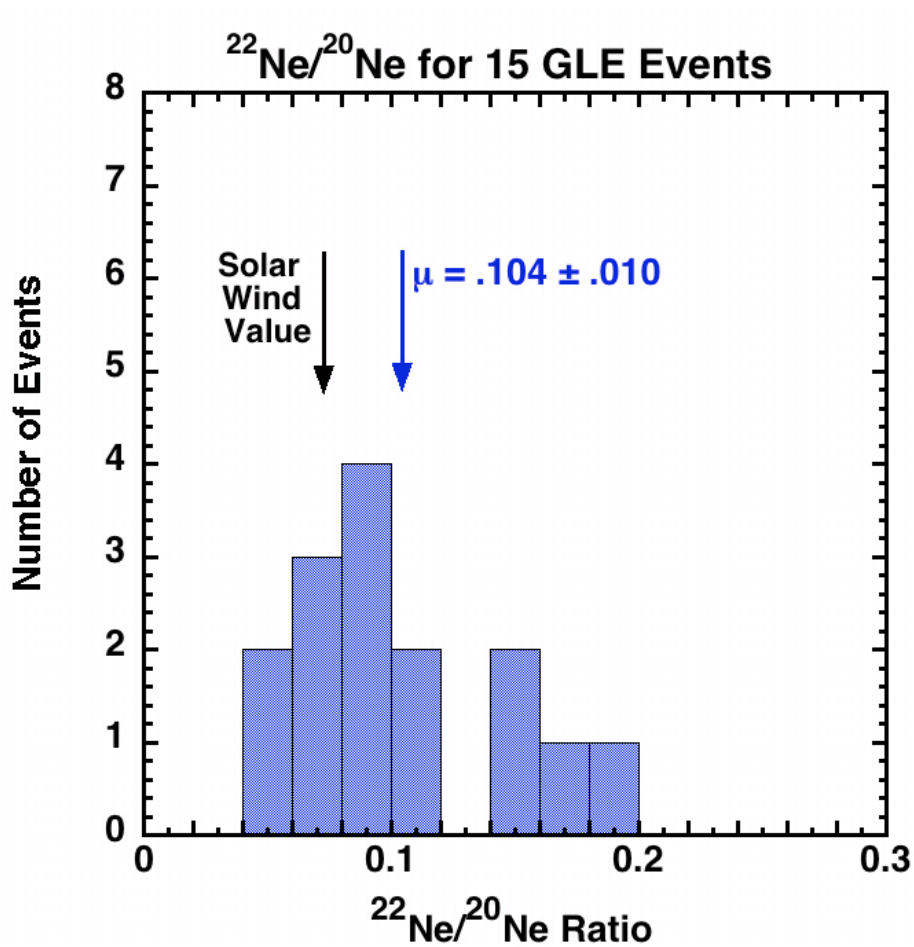
The 16 GLEs (red) are compared with non-GLE events from 1997-2003 (blue)

Adapted from Mewaldt et al. 2006, 2007
Average SEP values from Reames (1995)

The $^{22}Ne/^{20}Ne$ ratio in GLEs is somewhat greater than in non-GLE events, indicating more M/Q fractionation

Enriched ^{22}Ne is also characteristic of impulsive flare material



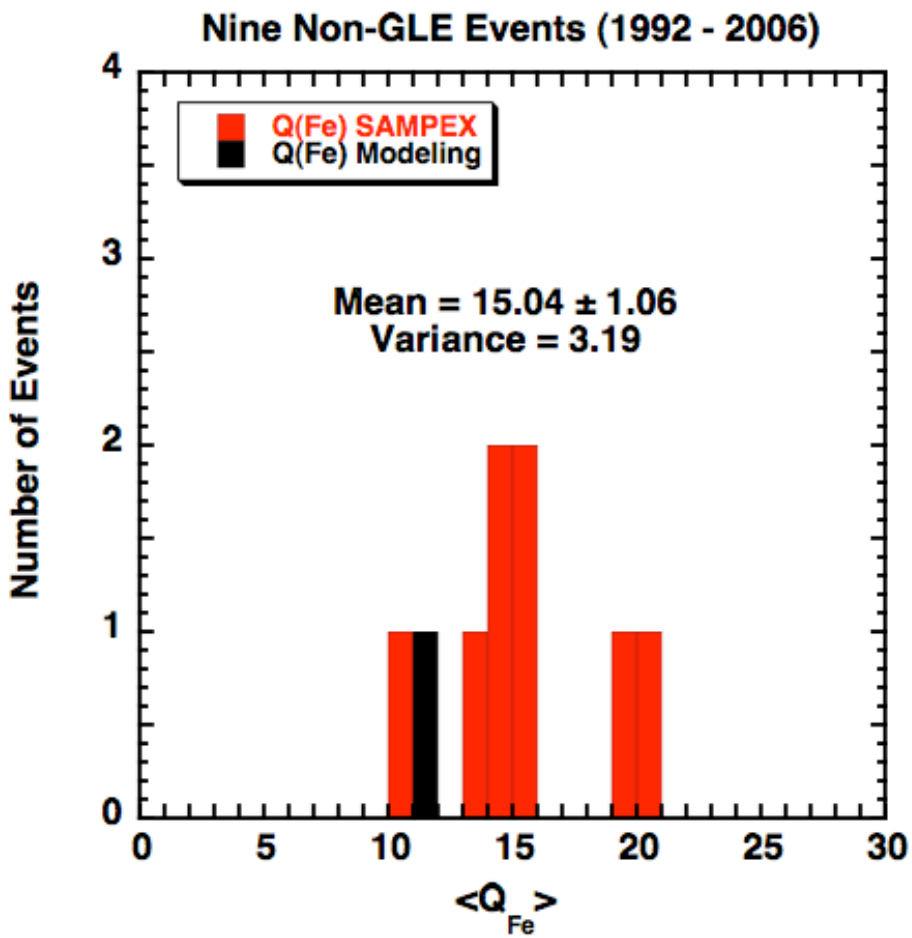


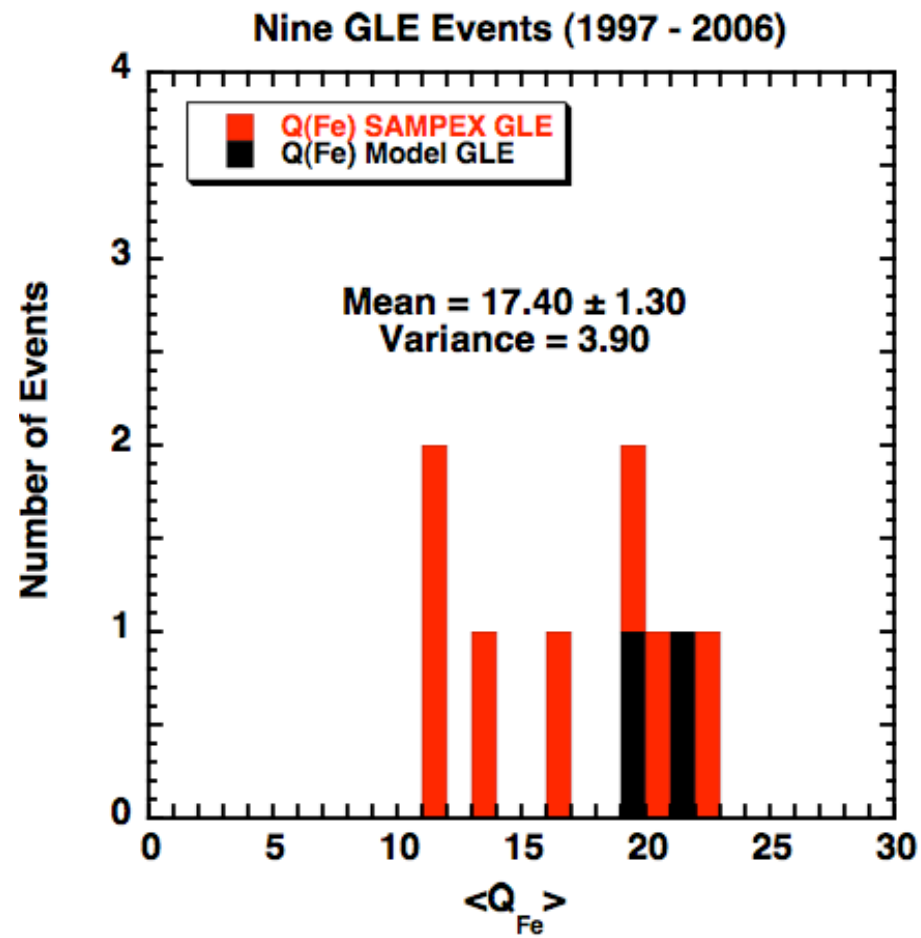
Updated data from Leske et al. (2007)

Mewaldt et al. 2009

The mean charge-state of Fe in GLEs is somewhat greater than in a sample of other large SEP events

Measurements from SAMPEX/PET (25 - 80 MeV/nuc)
Model results from Cohen et al. (1999) and Tylka et al. (2000)



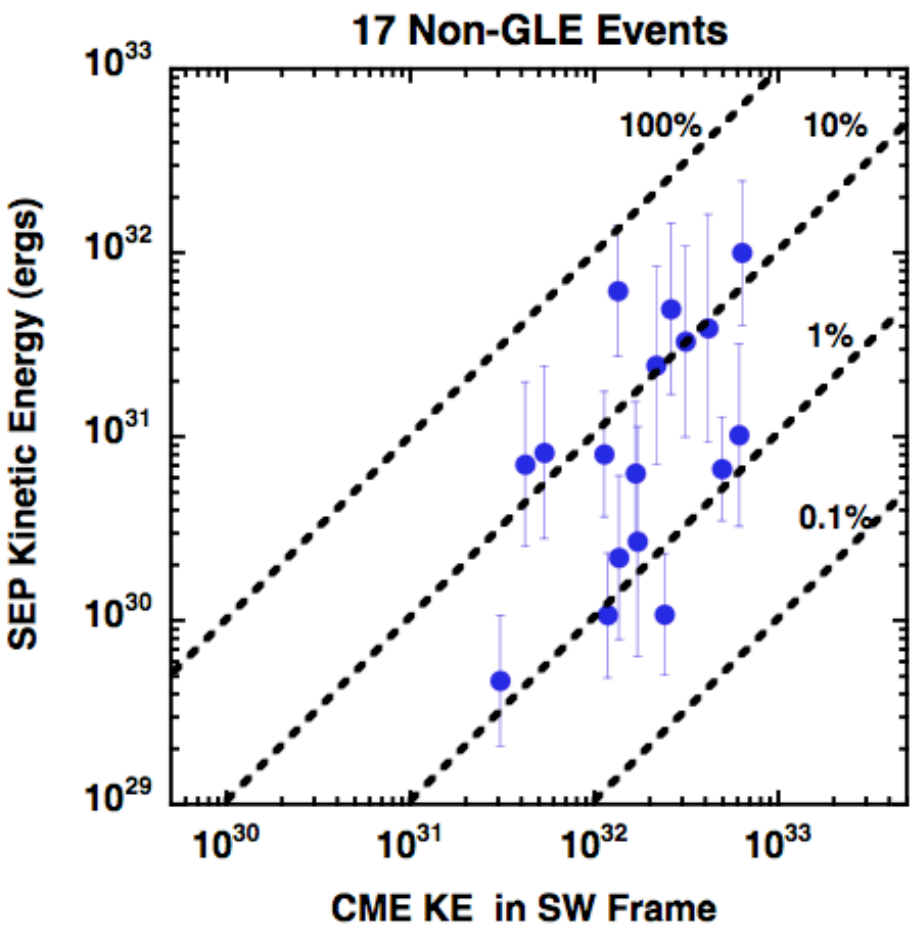


Mewaldt et al. 2009

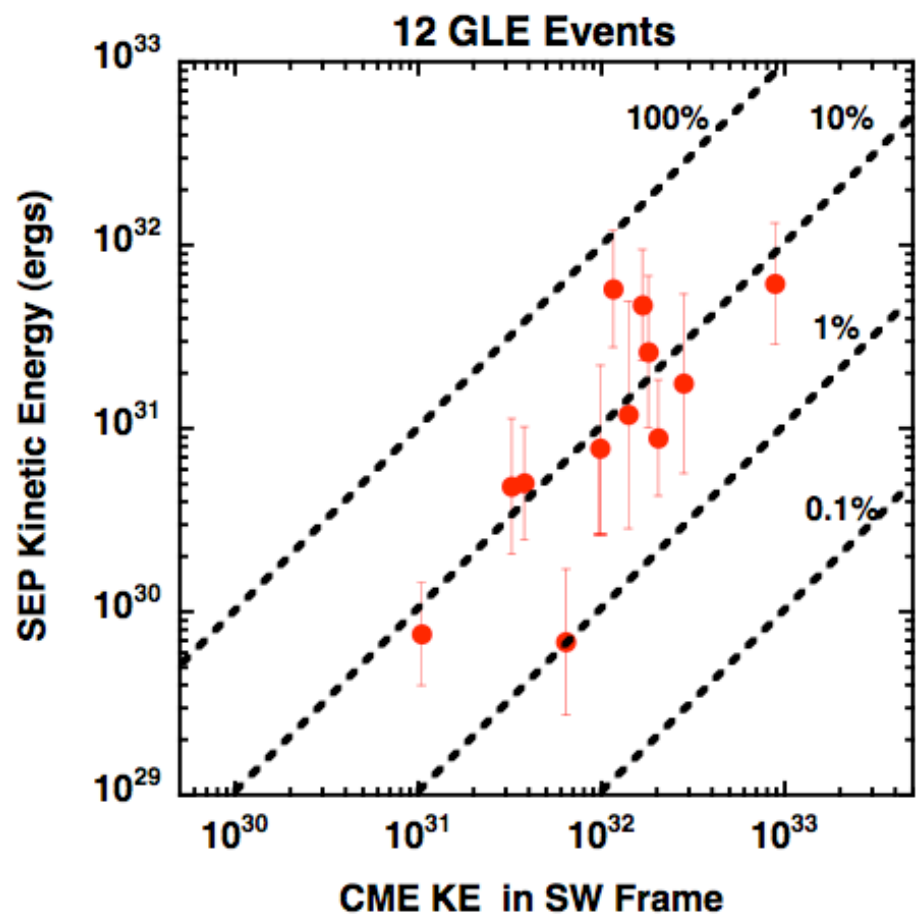
Updated data from Labrador et al. (2005)

The average acceleration efficiency appears to be somewhat higher in GLE events

Mean = 9.6%

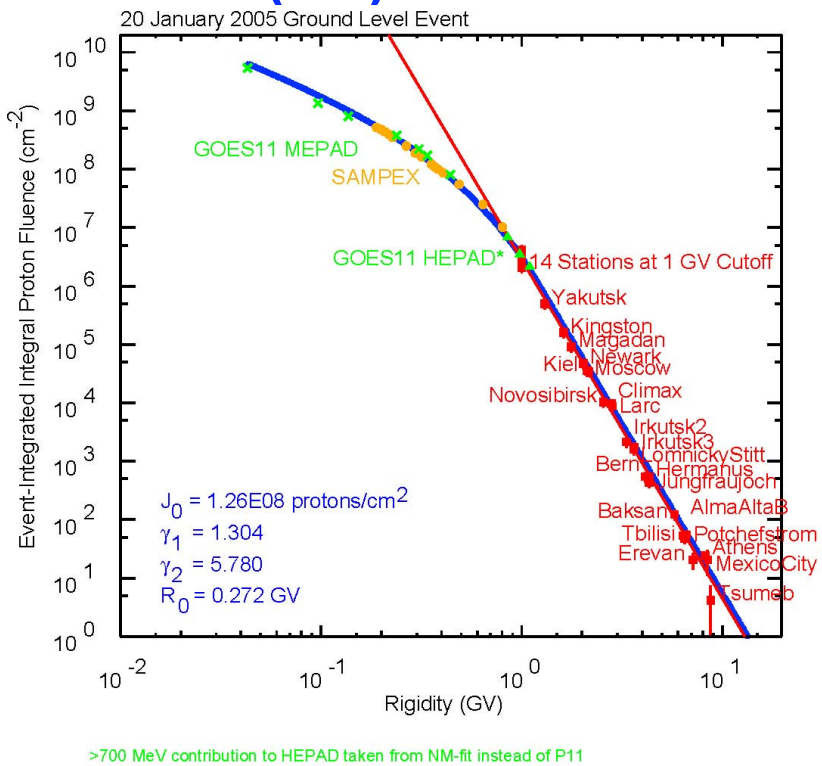


Mean = 13.6%



Event-Integrated GLE Proton Spectra
Tylka & Dietrich (GLE Workshop 2009)

J(>R) ~ Band



$$J(>\mathrm{R}) = J_0\ R^{-\gamma_1} exp(-R/R_0)$$

$$\text{for } \mathrm{R} \leq (\gamma_2 - \gamma_1) R_0$$

$$J(>\mathrm{R}) = J_0\ R^{-\gamma_2}\ \{[(\gamma_2 - \gamma_1) R_0]^{(\gamma_2 - \gamma_1)} exp(\gamma_1 - \gamma_2)\}$$

$$\text{for } \mathrm{R} \geq (\gamma_2 - \gamma_1) R_0$$

$$(4 \text{ Parameters: } J_0,\ \gamma_1,\ \gamma_2,\ R_0)$$

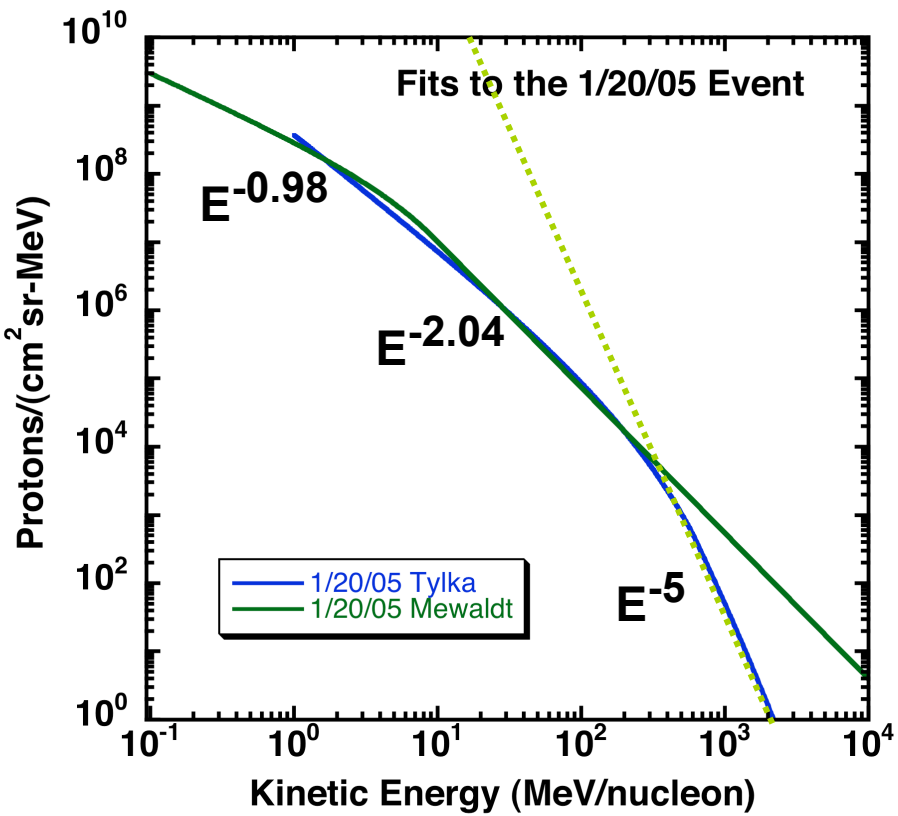
The Band function:

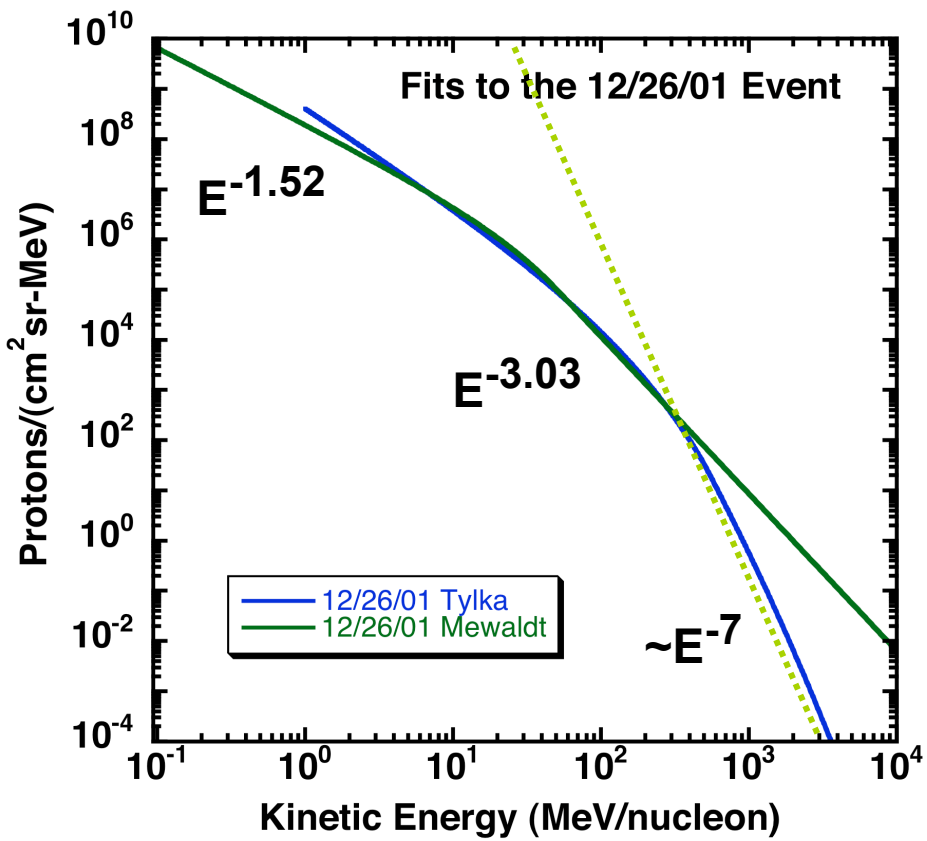
- smoothly rolls one power-law into another power-law,
- both the function and its first derivative are continuous.

* Band et al., ApJ 413, 281 (1993)

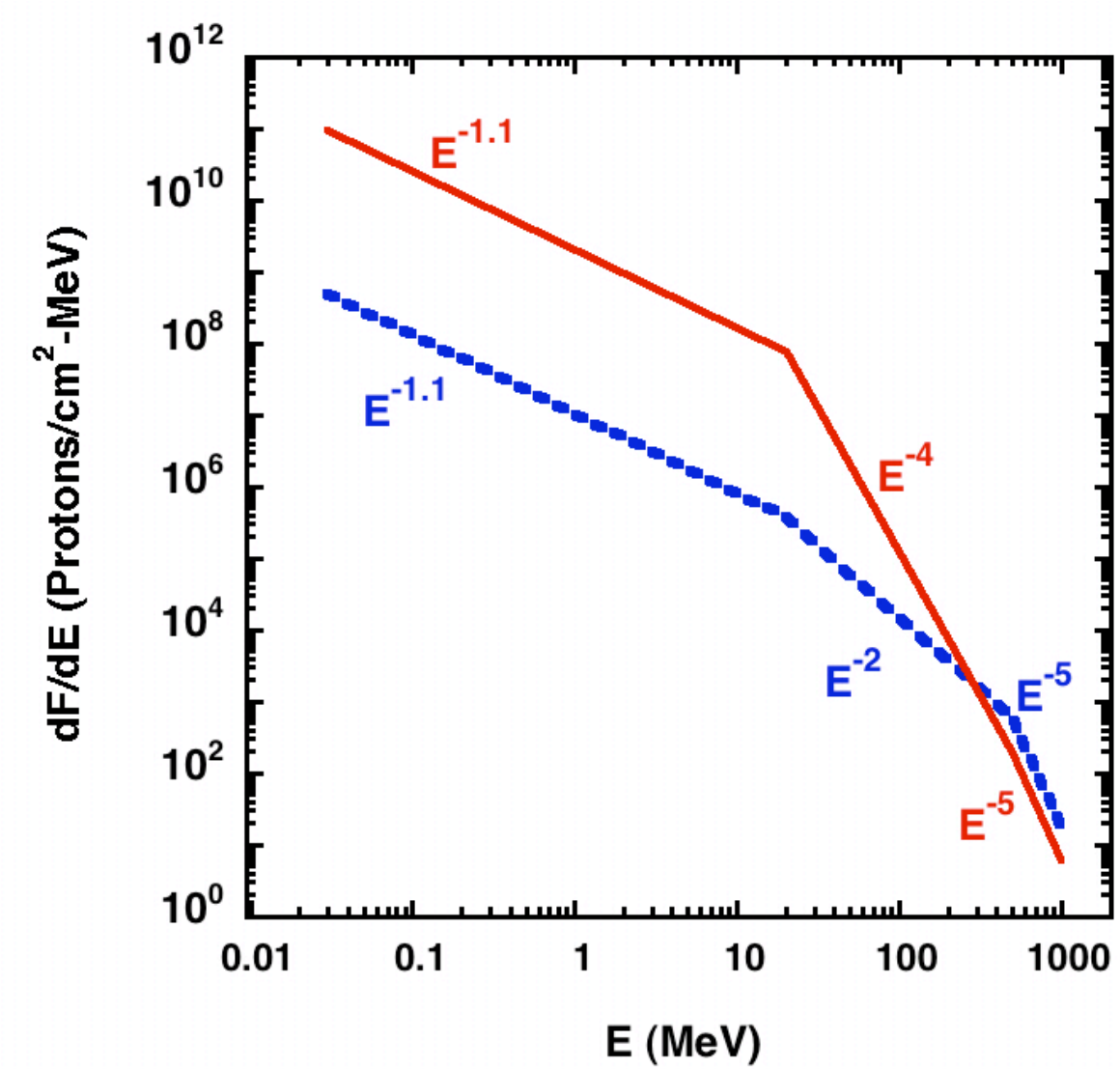
Comparing Fits to Neutron Monitor and Spacecraft Data

Fits from Tylka & Dietrich and from Mewaldt et al. 2009





Exploring the Relations between Spectral Slope, Fluence, and Energy Content

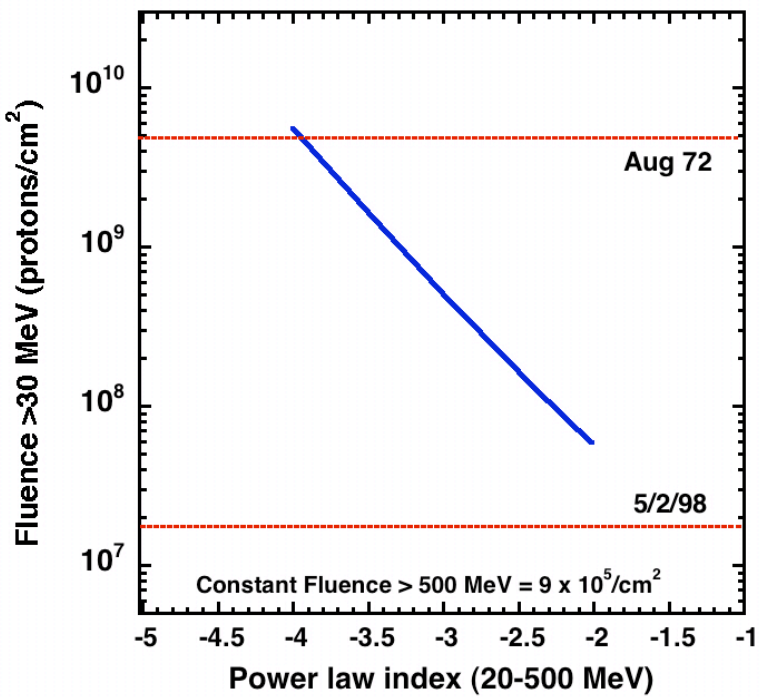


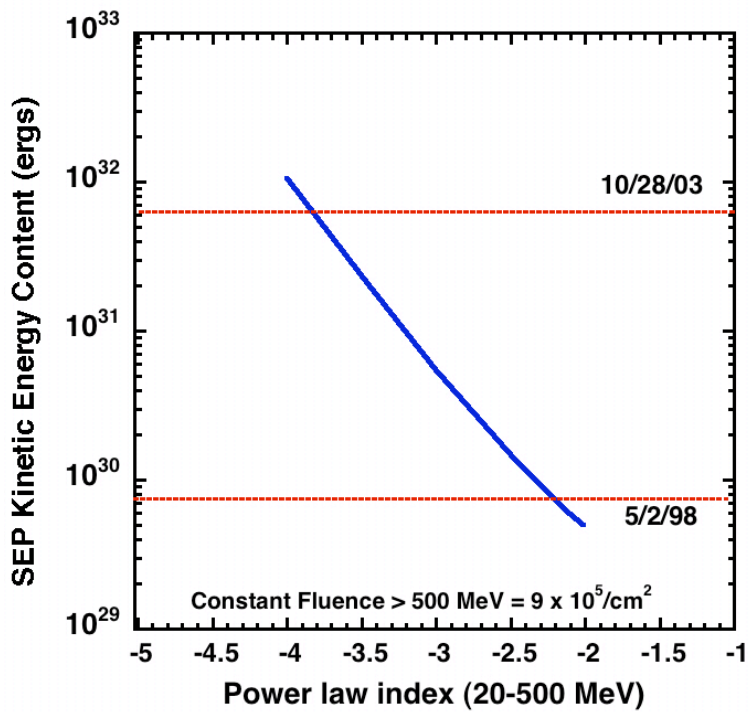
Both events have about the same proton fluence >500 MeV

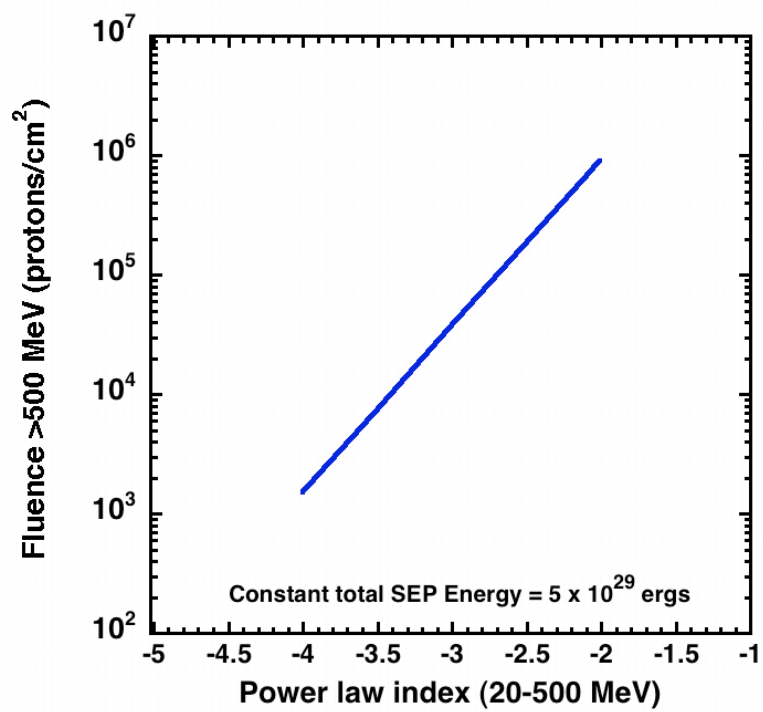
The top one accelerated ~200 times more particles and required ~200 times more kinetic energy

Exploring the Relations between Spectral Slope, Fluence, and Energy Content

In these plots we hold one observable constant and explore the relation of other observables with the proton spectral index between ~20 and 500 MeV

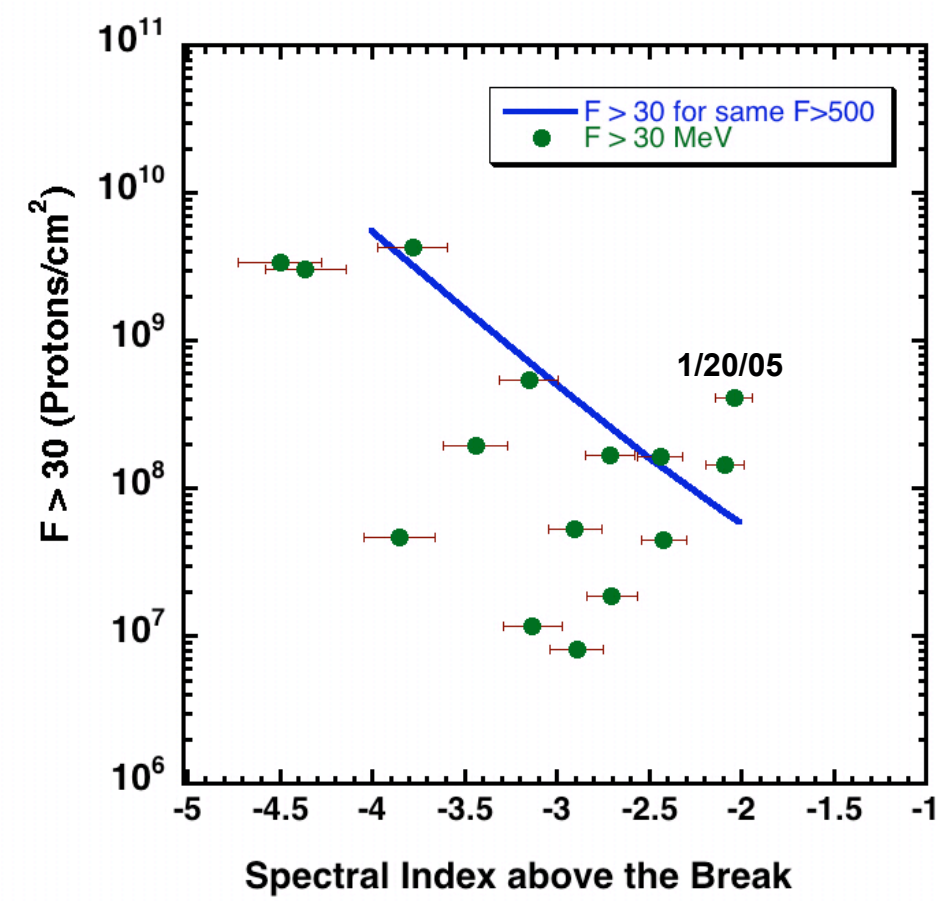


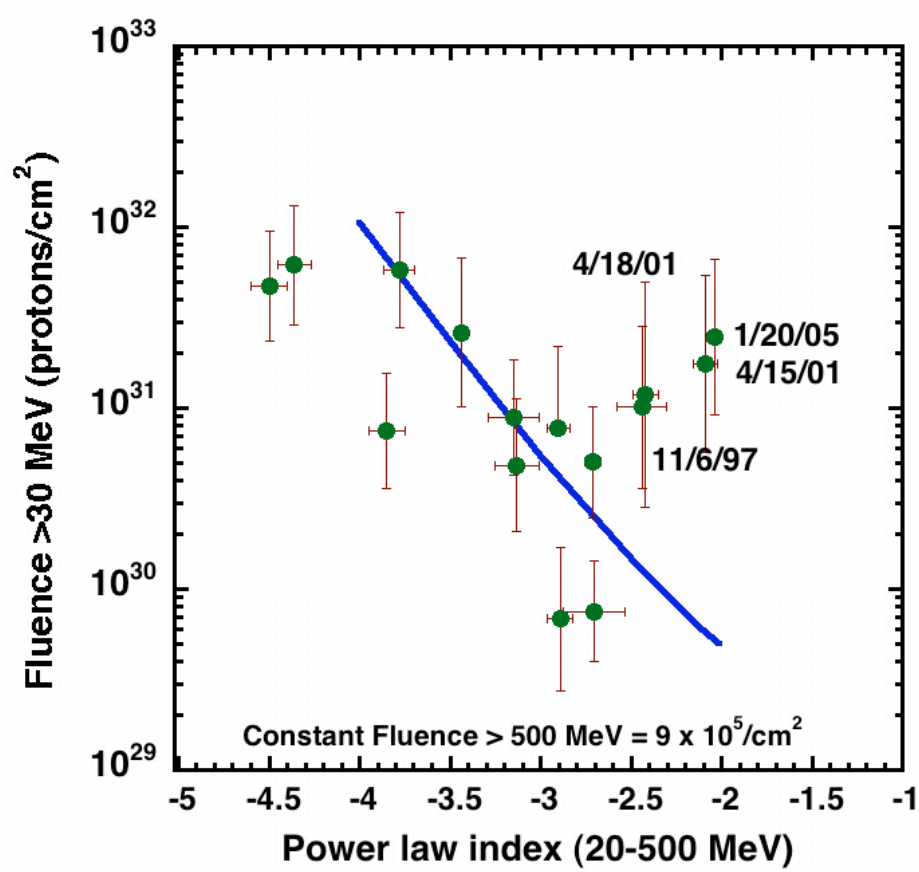




Exploring the Relations between Spectral Slope, Fluence, and Energy Content

Here we add measured values from solar cycle 23. Note, however, that the Observable held constant for the curves was not constant for the events.





Summary

• On average, GLEs appear to include more "flare material" than typical events (Fe, Ne, ^{22}Ne, and highly ionized Fe). However, the abundance distribution of these species in GLE events is similar to that in non-GLE events. The difference in the mean abundance "flare-like material"in GLE events is due mainly to a few GLEs that are greatly unriched in all these species. Some of these are also enriched in ^{3}He (e.g., 11/6/97, 5/2/98, 5/6/98)

• The ACE/SIS data (25-80 MeV/nucleon) do not support the claim that almost all GLEs are Fe-rich, but, on average, we do find that GLEs are more Fe-rich than average. There could also be increased Fe/O at energies >80 MeV/nuc

• All 16 GLE events have double power-law spectra. The most significant difference between GLEs and non-GLEs is that GLEs, on average, have harder spectra above the break. Alternatively, they exhibit smaller changes in slope at the break.

• On average, GLEs appear to have a higher acceleration efficiency.

• The energy content of (and therefore fluence) of an SEP event is inevitably limited by the energy released in the CME and/or flare. Events with hard spectra ($\sim E^{-2}$) from ~20 to 500 MeV/nuc can produce a GLE with a much lower energy requirement than those with softer spectra (e.g., $\sim E^{-4}$)

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