Solar and Galactic Sources of Precipitating Energetic Particles

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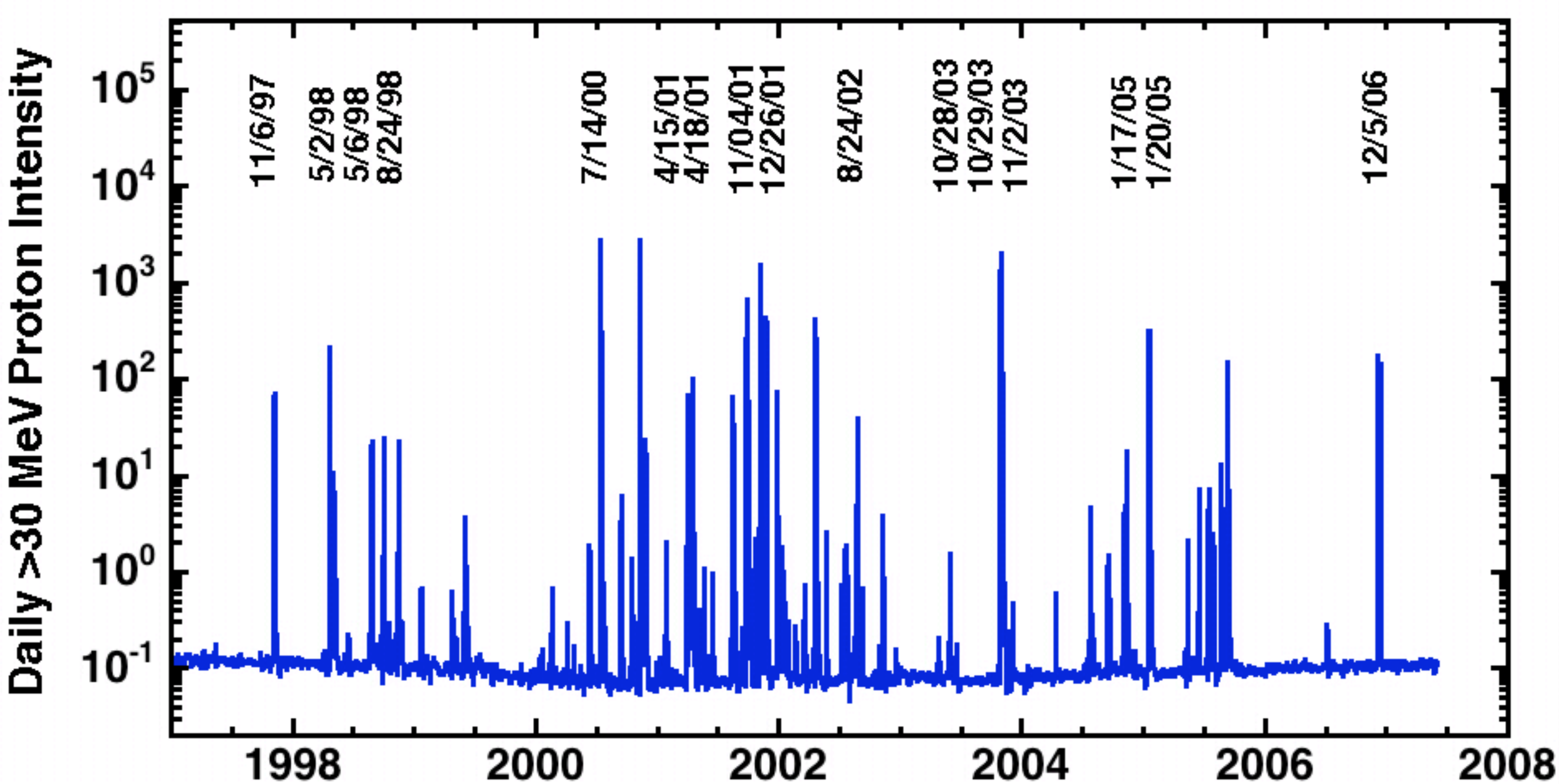
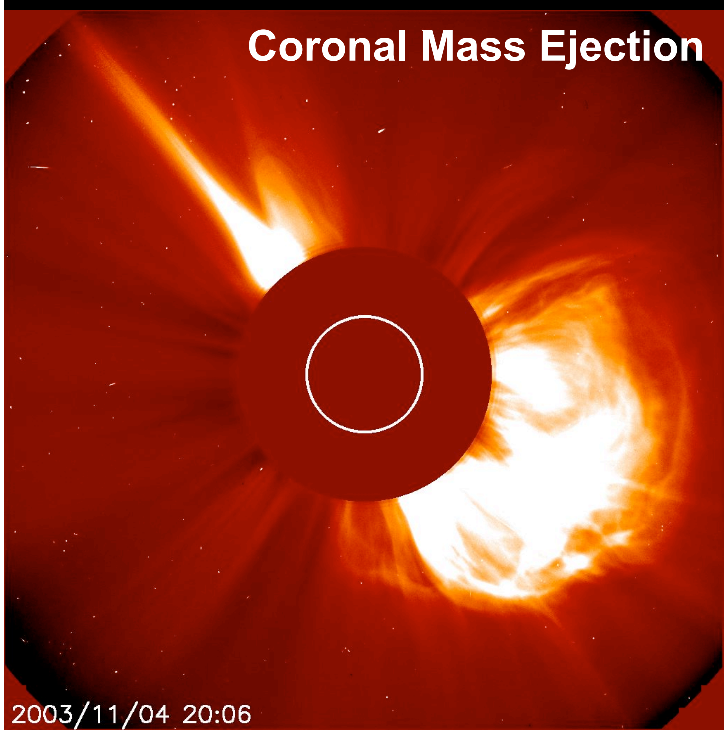
Daily average >30 MeV proton intensity for solar cycle 23
[Ground level events (GLEs) are indicated]



Mewaldt et al. (2007a)

Data from GOES 8, 10, 11, and 12



Galactic Cosmic-Rays (GCRs) are accelerated by shock-waves from supernovae

Their integrated intensity varies by about a factor of 2-3 over the solar cycle

V ~ 10,000 km/s
~10^{52} ergs

Solar Energetic Particles (SEPs) are accelerated by flares and by shocks driven by Coronal Mass Ejections (CMEs)

Their intensity can increase by a million times in hours

V ~ 1500-2500 km/s
~10^{32} ergs

Outline

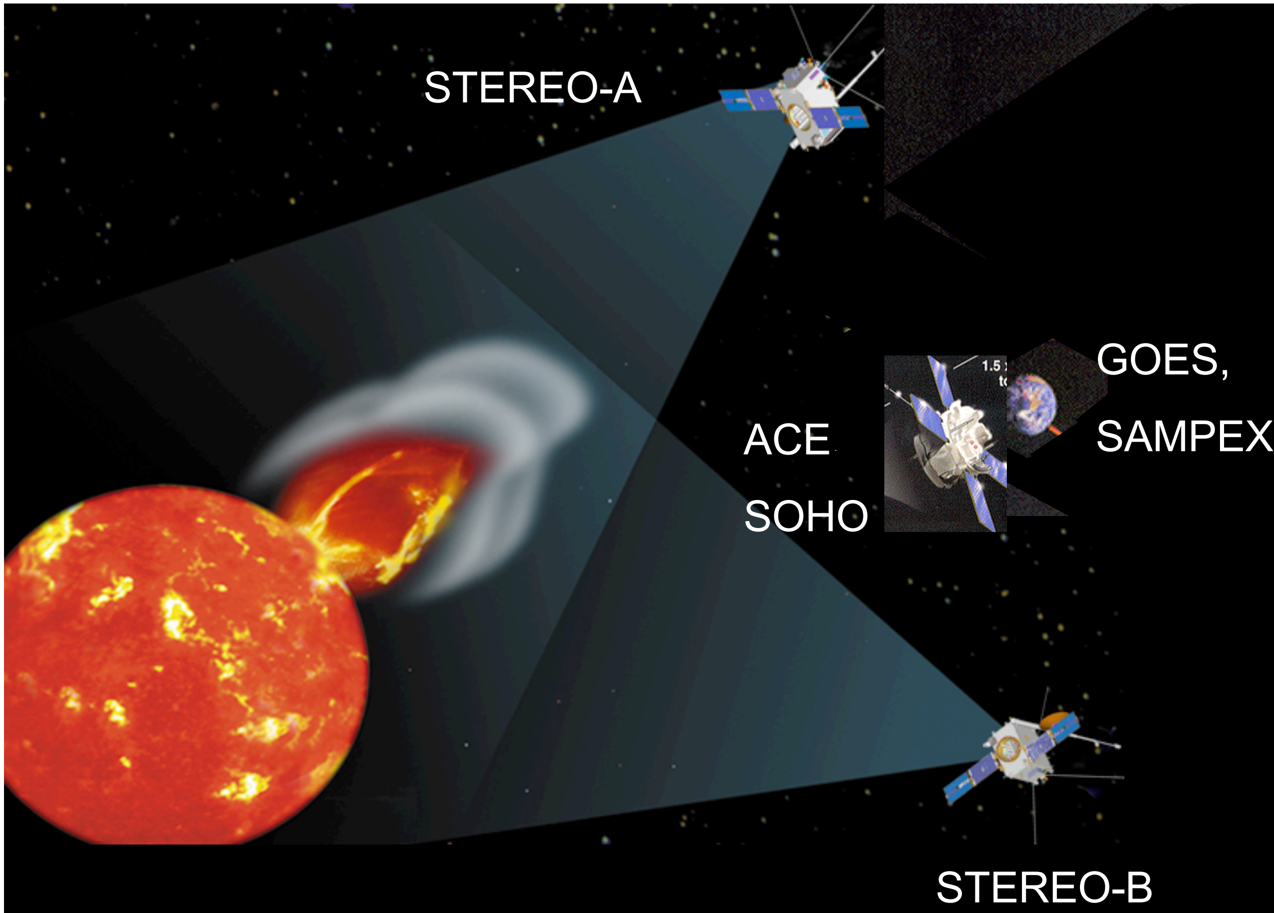
Introduction

Solar Eruptions and SEPs

- Flare and shock acceleration
- Composition and Energy Spectra
- CMEs and SEPs
- SEP access to the Upper Atmosphere

Galactic Cosmic Rays

- Acceleration, access to the Heliosphere
- Composition and energy spectra
- Solar cycle variations
- Record–setting and long-term intensities

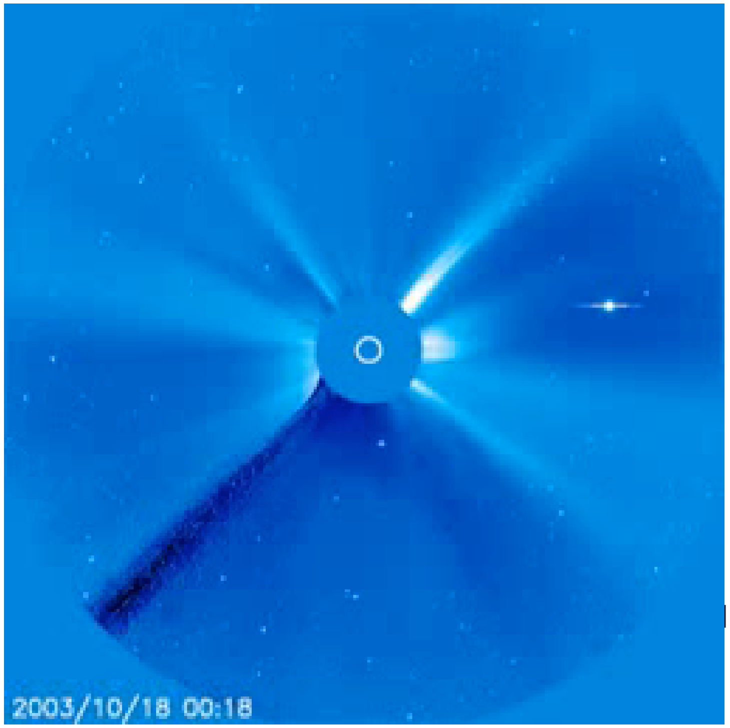


Sources of Data

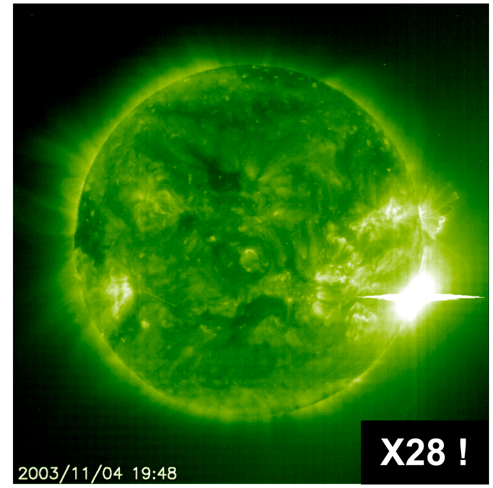
ACE, SOHO, STEREO, SAMPEX, RHESSI, NOAA/GOES

With thanks to the ACE and STEREO teams at Caltech

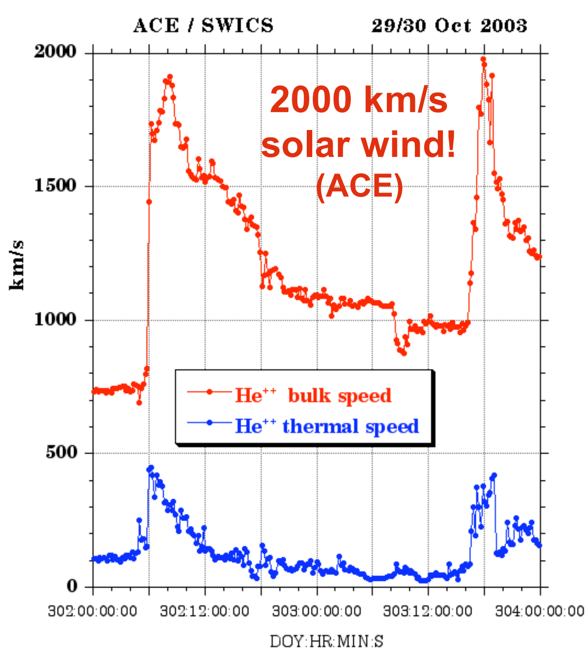
The Oct-Nov 2003 Halloween Events



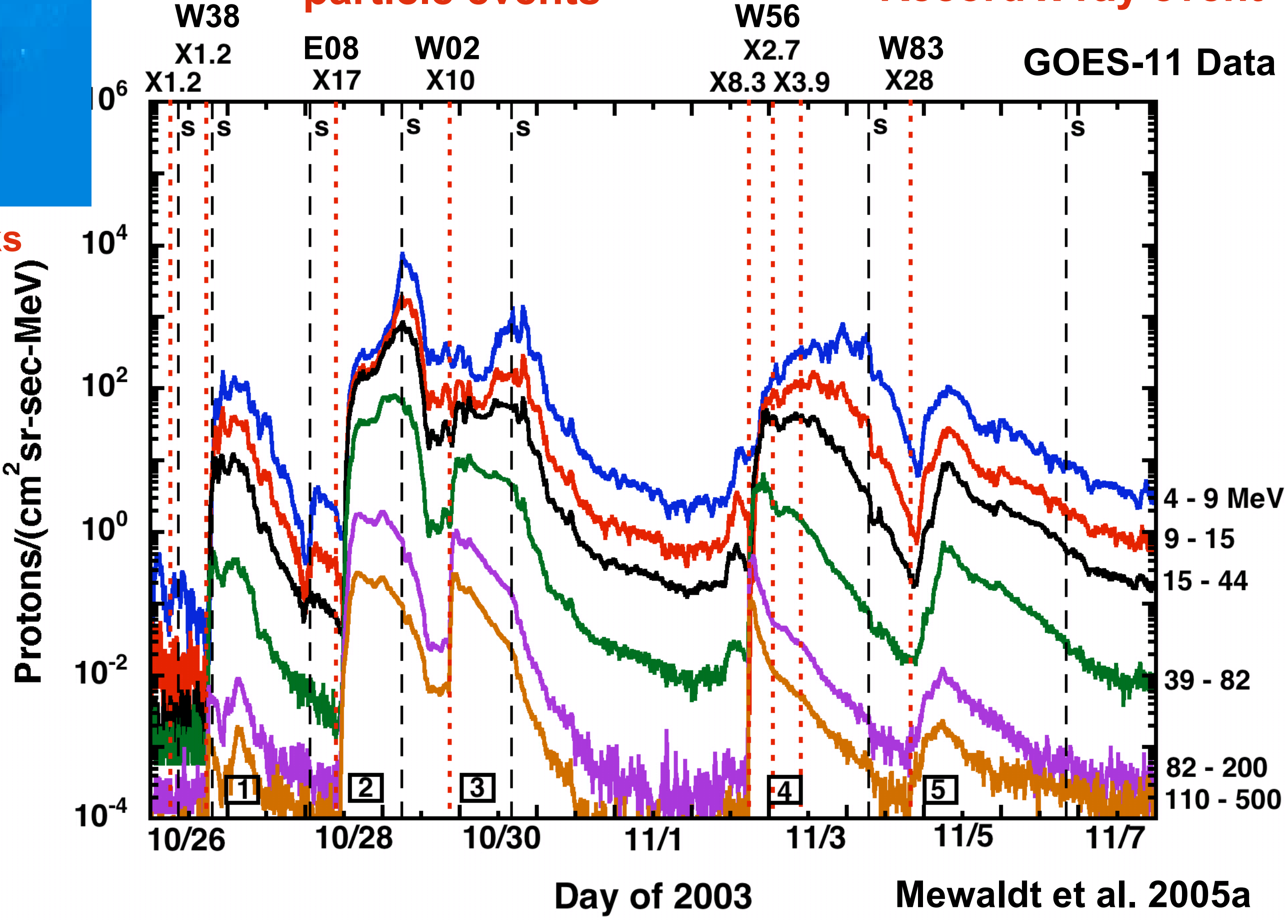
SOHO/LASCO: >50 CMEs in ~2 weeks



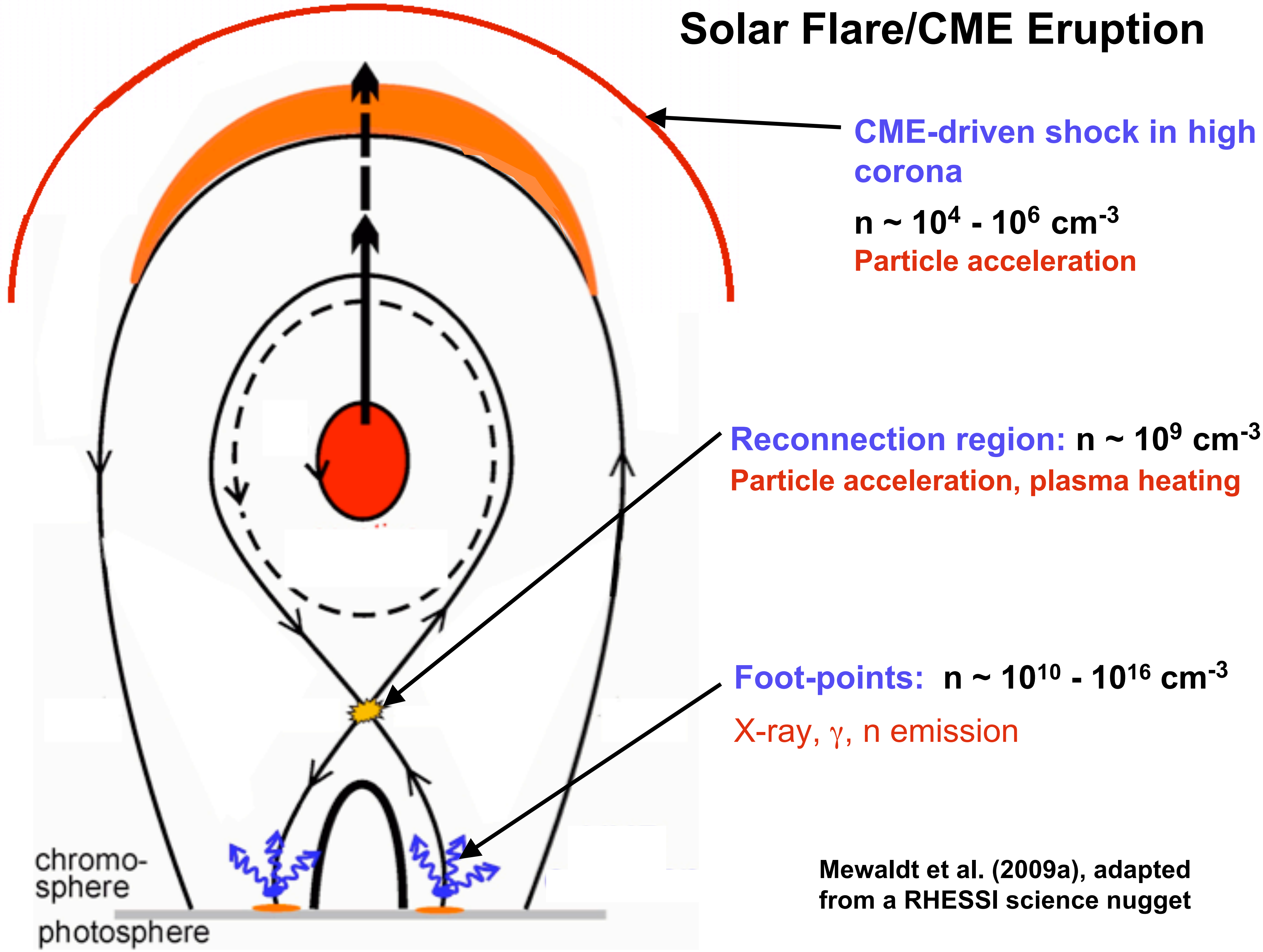
Record x-ray event



5 large solar particle events

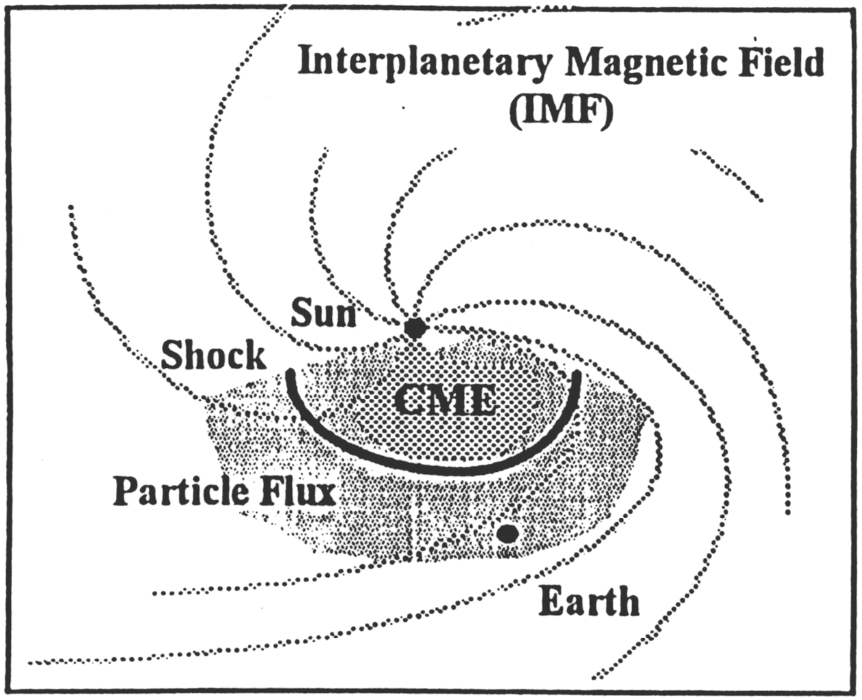


Mewaldt et al. 2005a


Solar Flare/CME Eruption
CME-driven shock in high corona
n ~ 10^4 - 10^6 cm^{-3}
Particle acceleration
Reconnection region: n ~ 10^9 cm^{-3}
Particle acceleration, plasma heating
Foot-points: n ~ 10^{10} - 10^{16} cm^{-3}
X-ray, γ, n emission
chromo-sphere
photosphere
Mewaldt et al. (2009a), adapted from a RHESSI science nugget

The Sun accelerates high-energy particles in at least two different ways

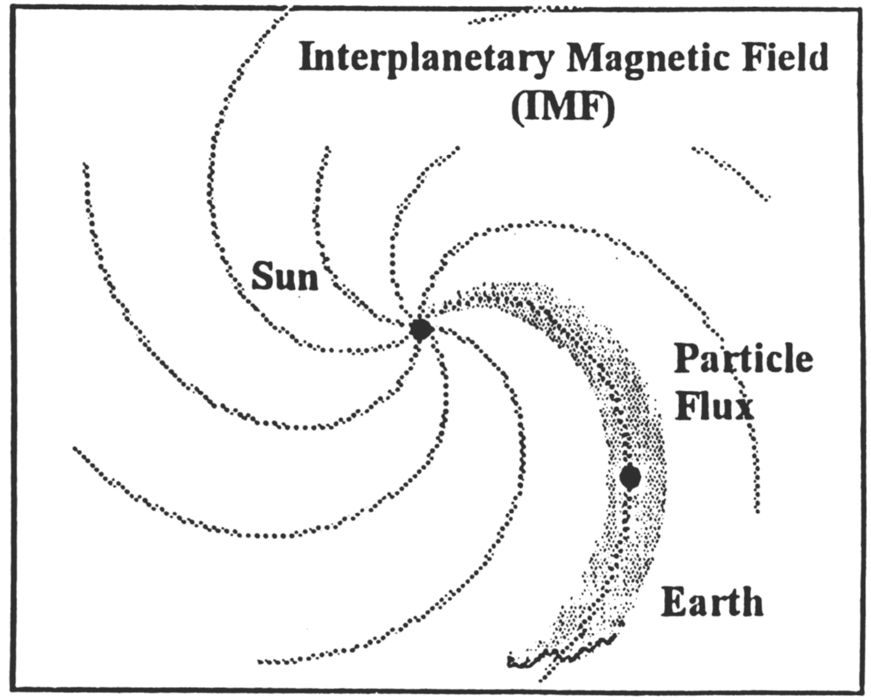
CME-Associated (Gradual Event)



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

~Coronal composition
Shocks accelerate solar wind and suprathermal particles

Impulsive Flare-Associated (Impulsive Event)

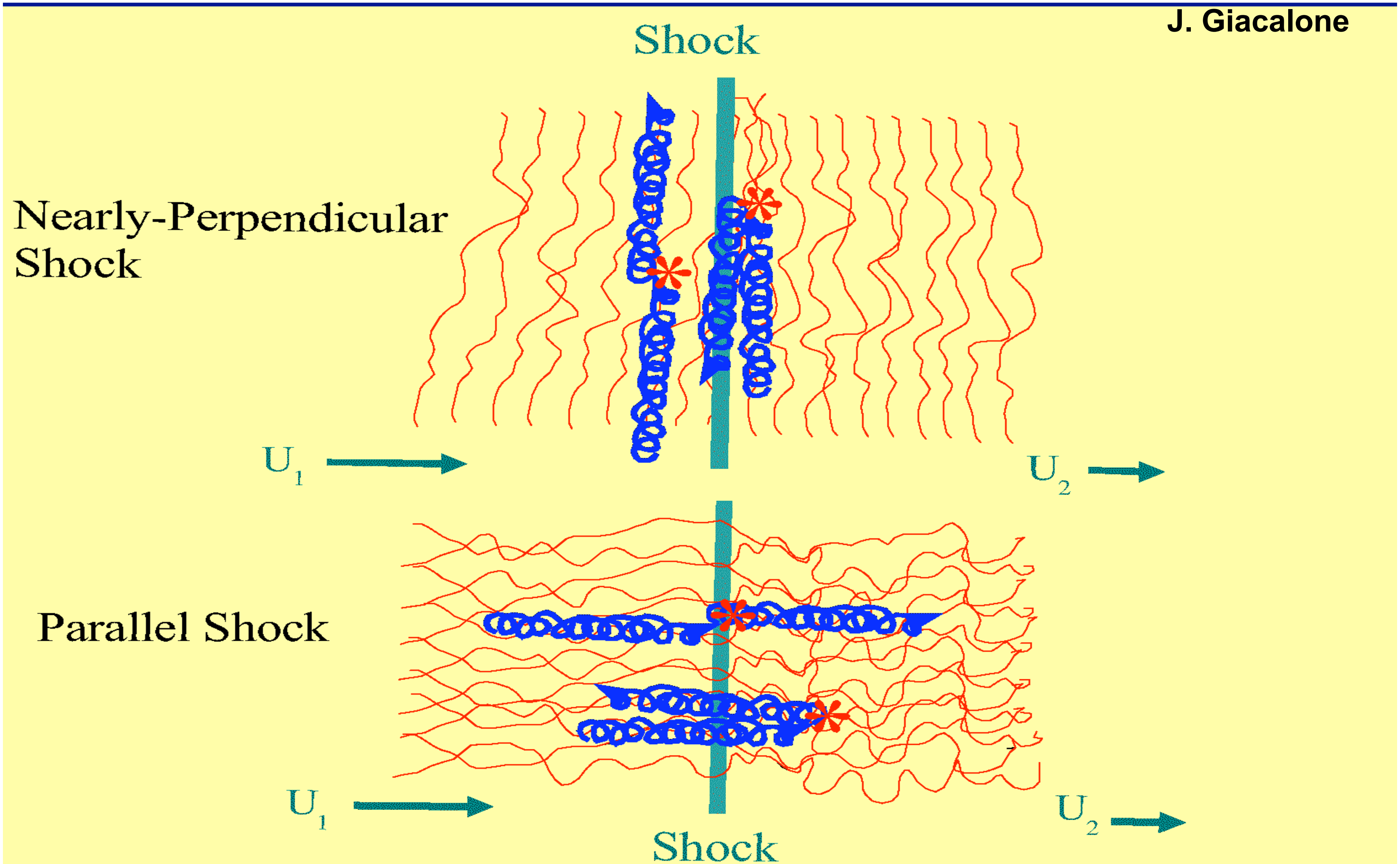


Electron-Rich
Short-Lived (Hours)
30-45 Degrees Solar Longitude

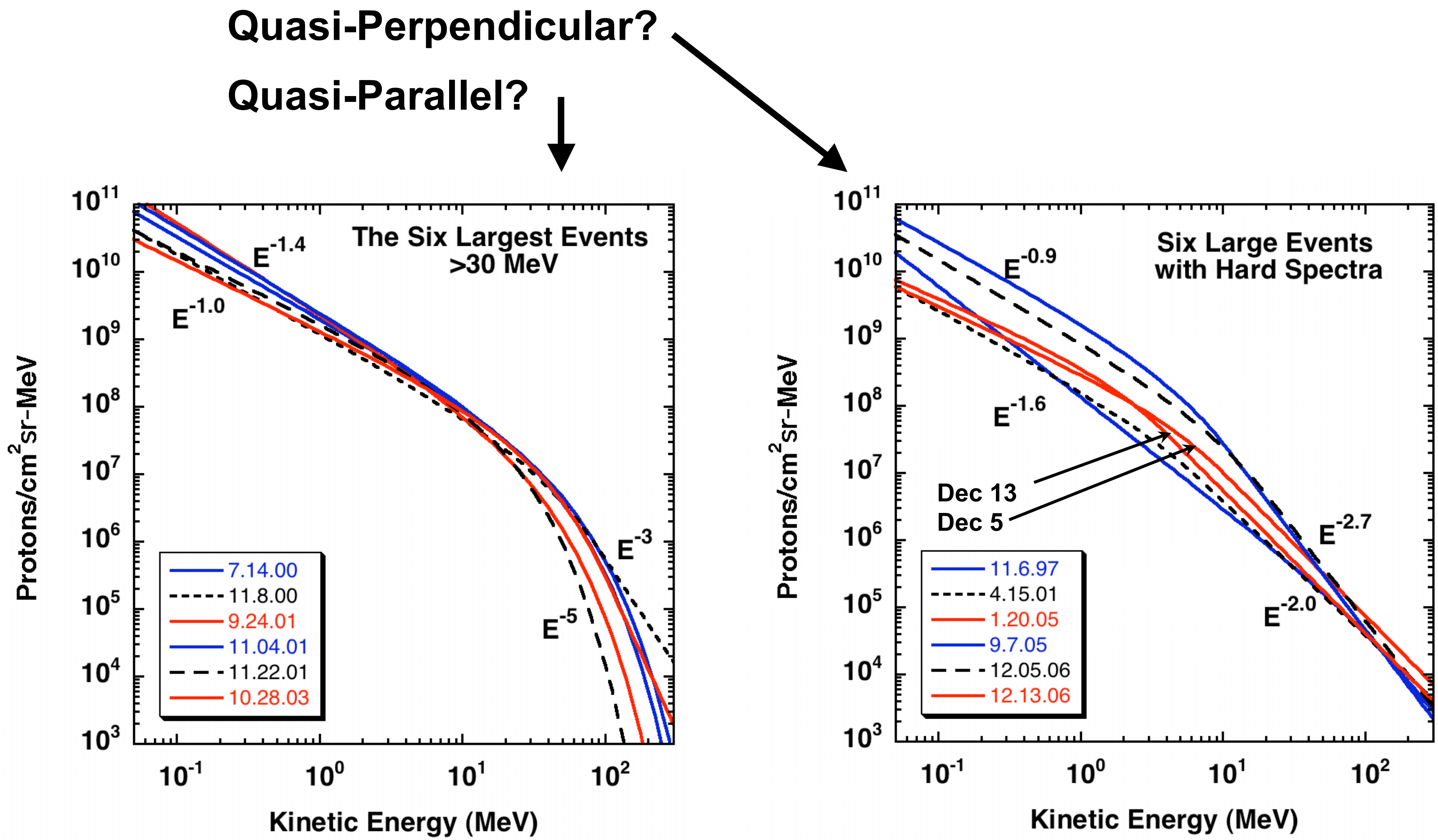
Fe, ^{3}He, and electron rich
Active region material accelerated

What is the role of shock geometry in particle acceleration?

Simulations show that perpendicular shocks can accelerate particles faster, and to higher energy



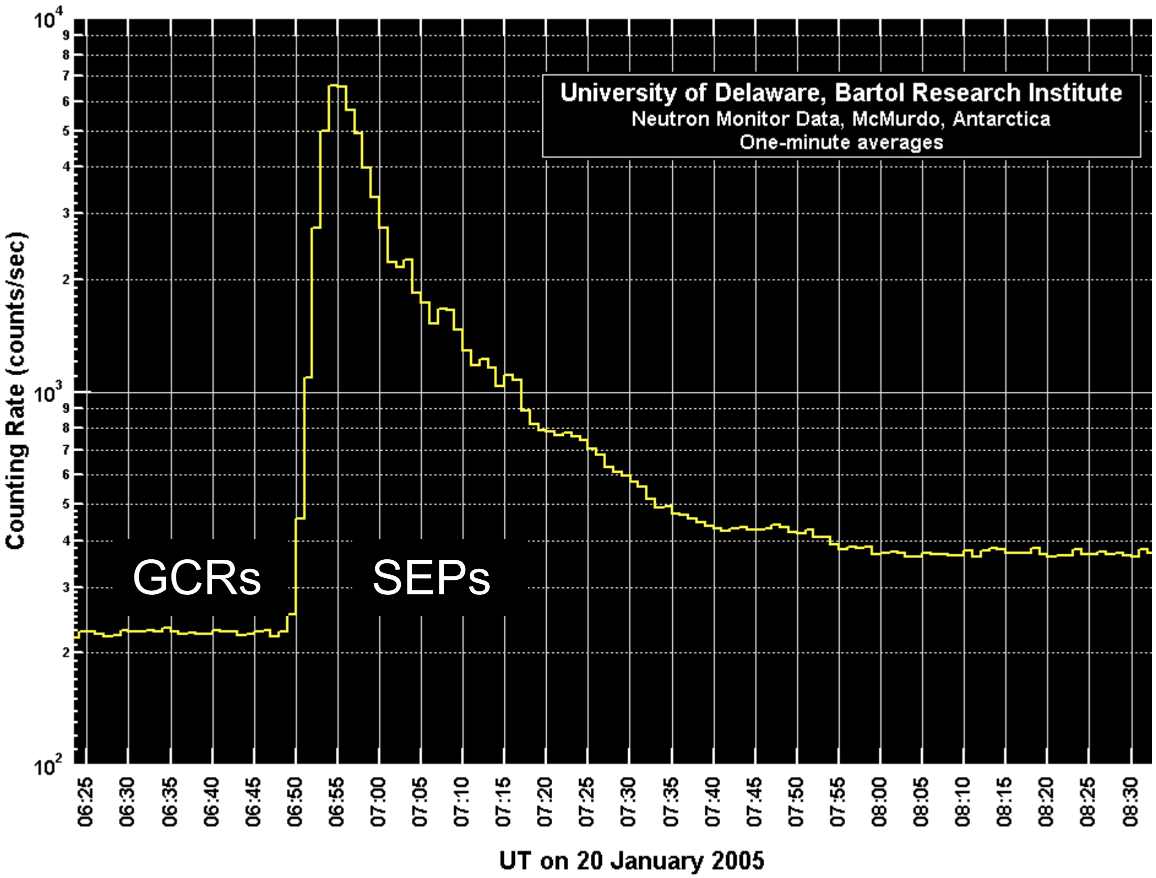
SEP Energy Spectra - Role of Shock Geometry?



Mewaldt et al. (2007b); see also Tylka et al. (2005)

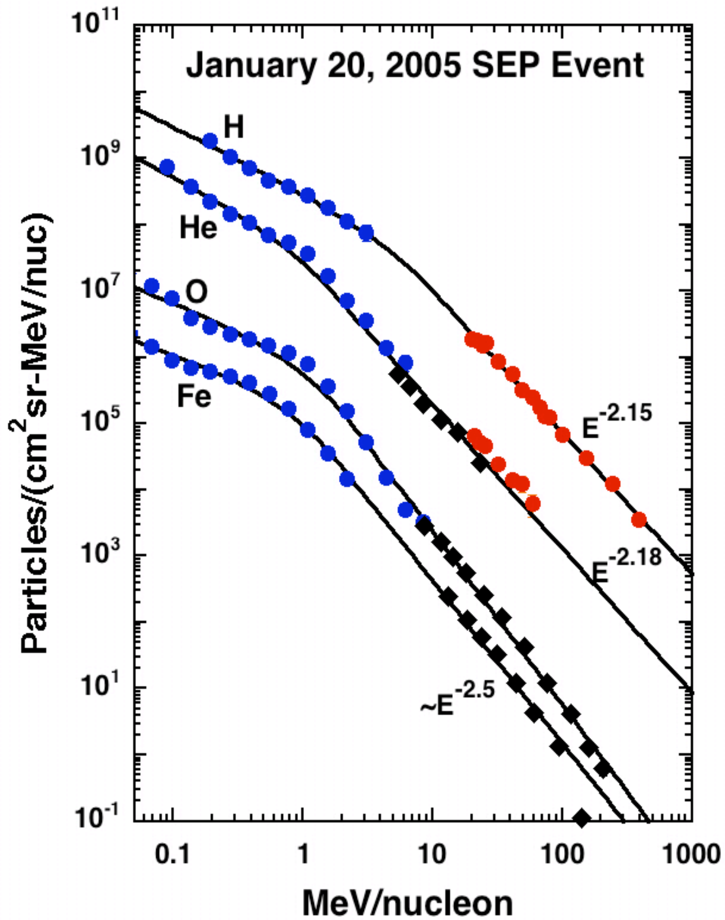
Example of a Ground-Level Event (GLE)
January 20, 2005

Neutron-monitor data from McMurdo, Antarctica



University of Delaware

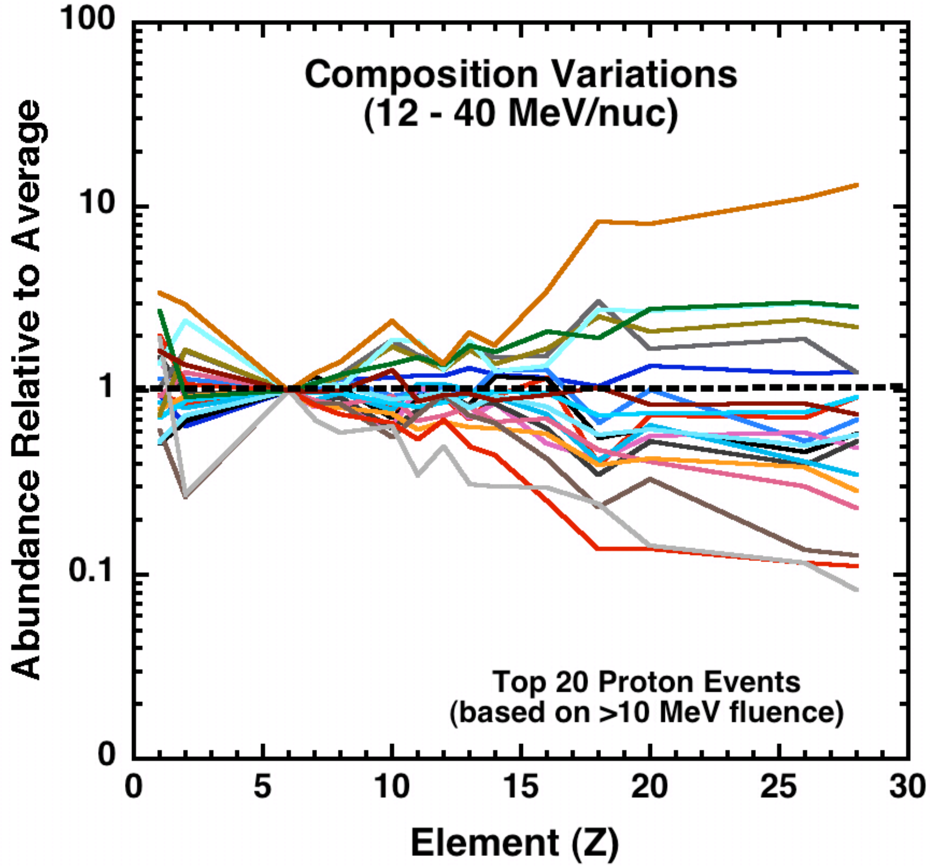
Energy spectra from ACE, and SAMPEX



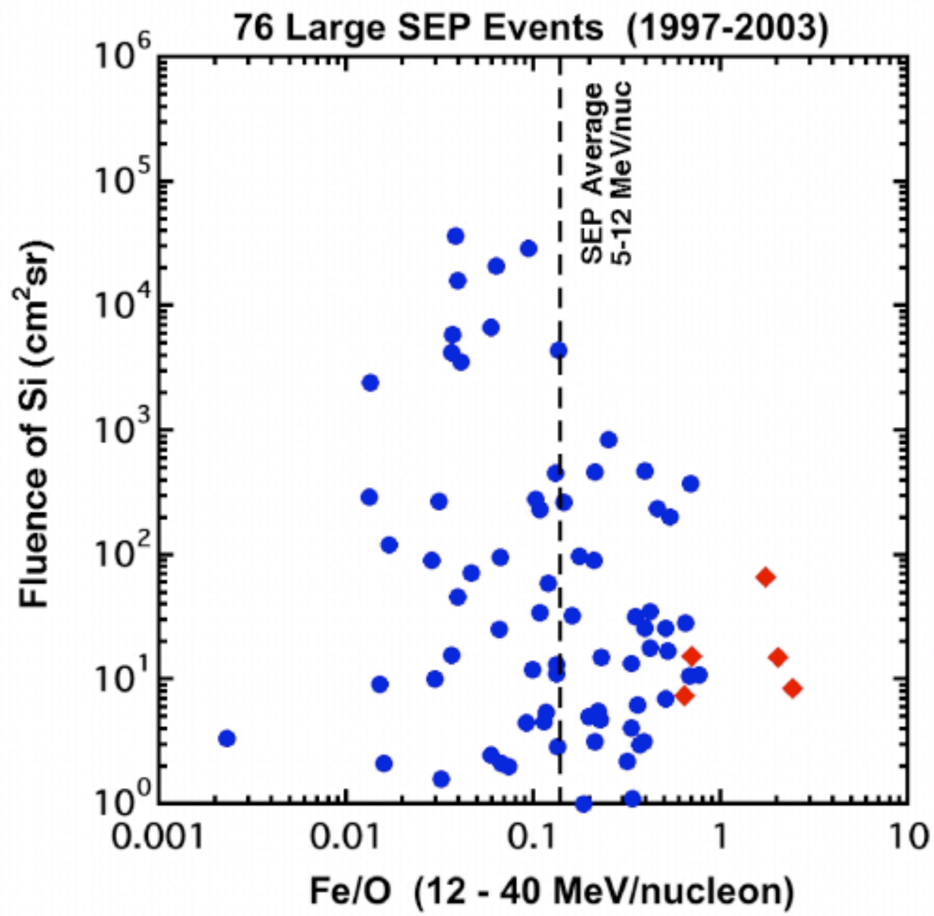
Mewaldt et al., 2005b

Composition Variability

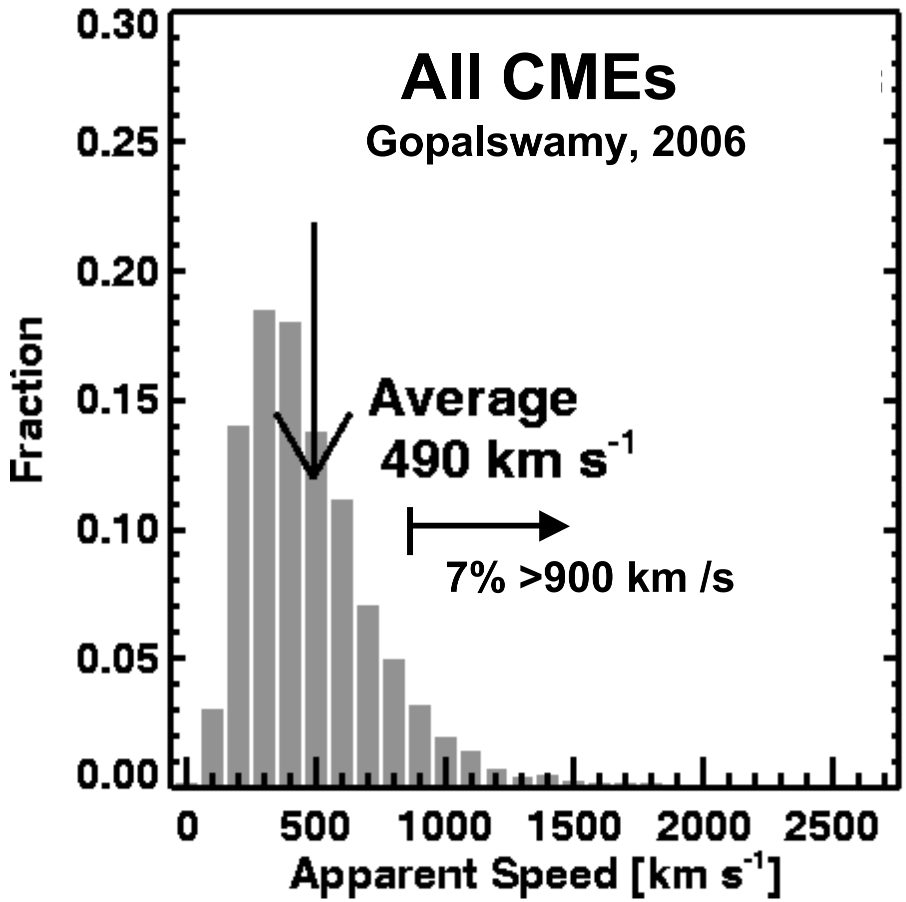
Variations in the top 20 SEP Events



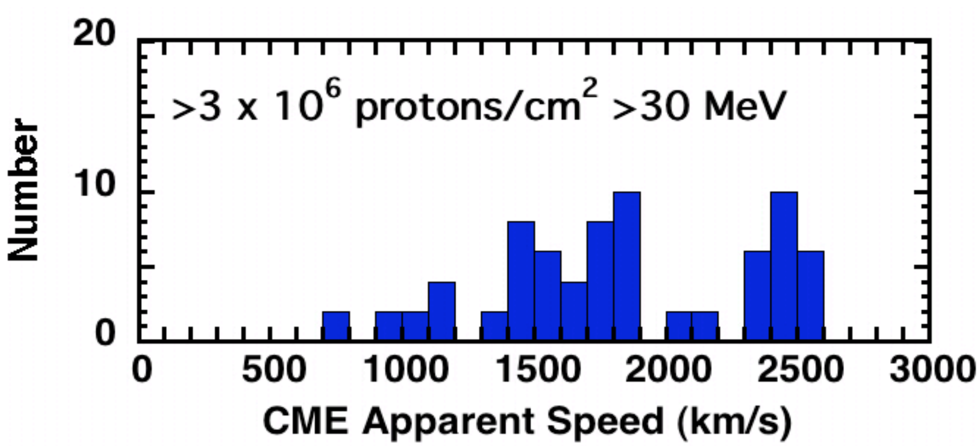
The largest events are Fe-poor



Mewaldt et al. 2006



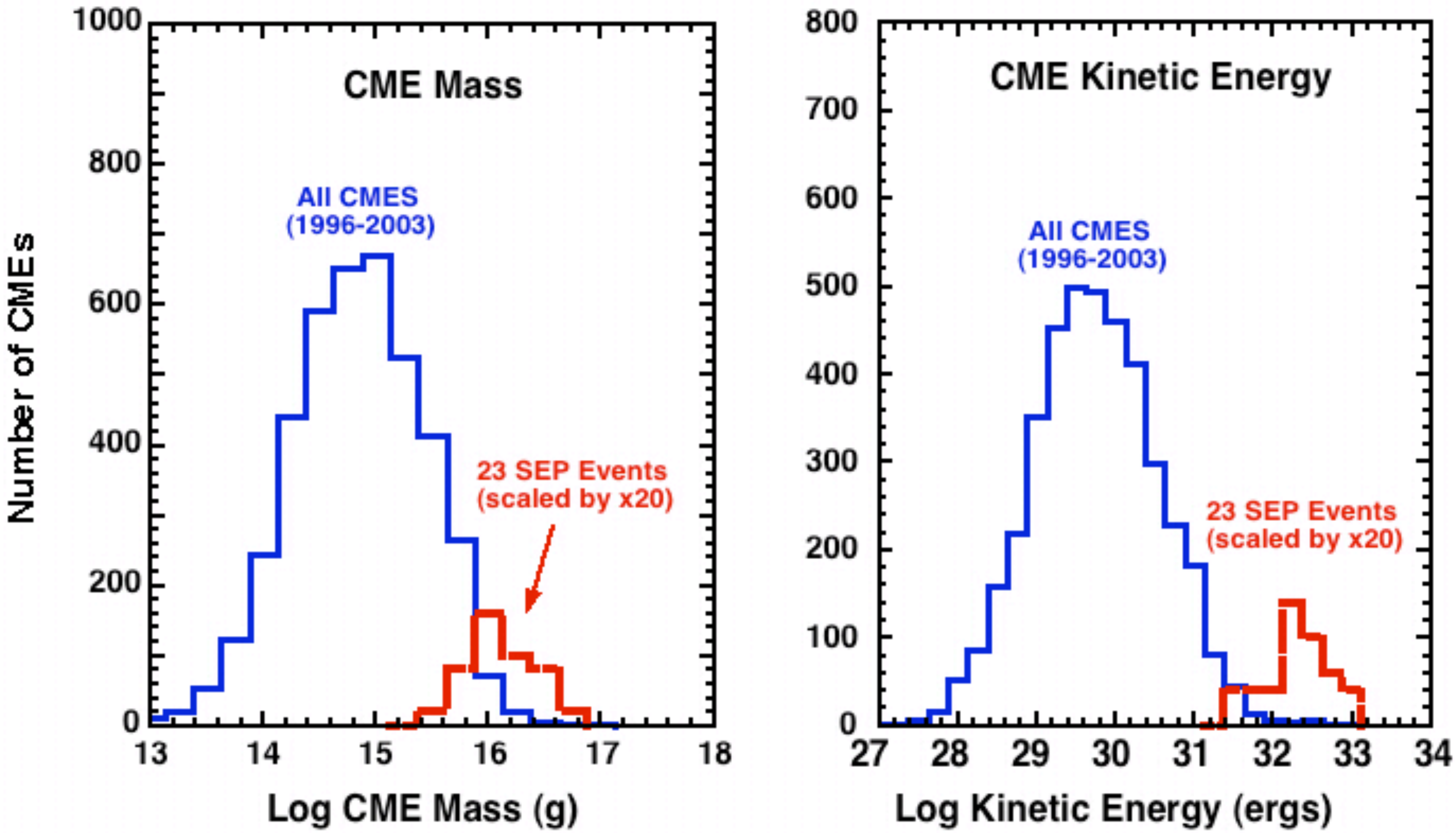
The largest SEP events are due to CMEs with speeds of 1500-2500 km/s



CME apparent speeds for the top 50 SEP events of solar cycle 23

Mewaldt et al. 2008

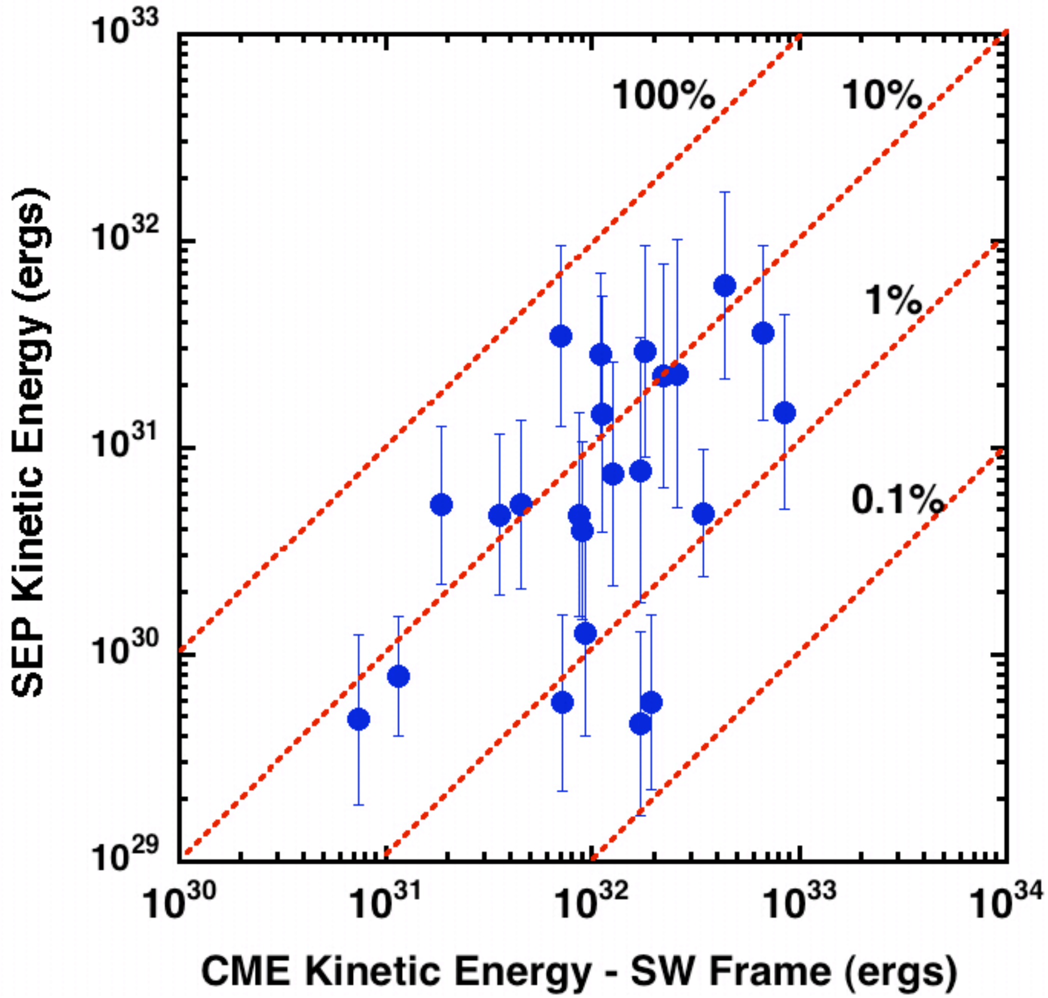
Large SEP events are associated with very massive, energetic CMEs



CME data from Gopalswamy 2006

Mewaldt et al. 2008

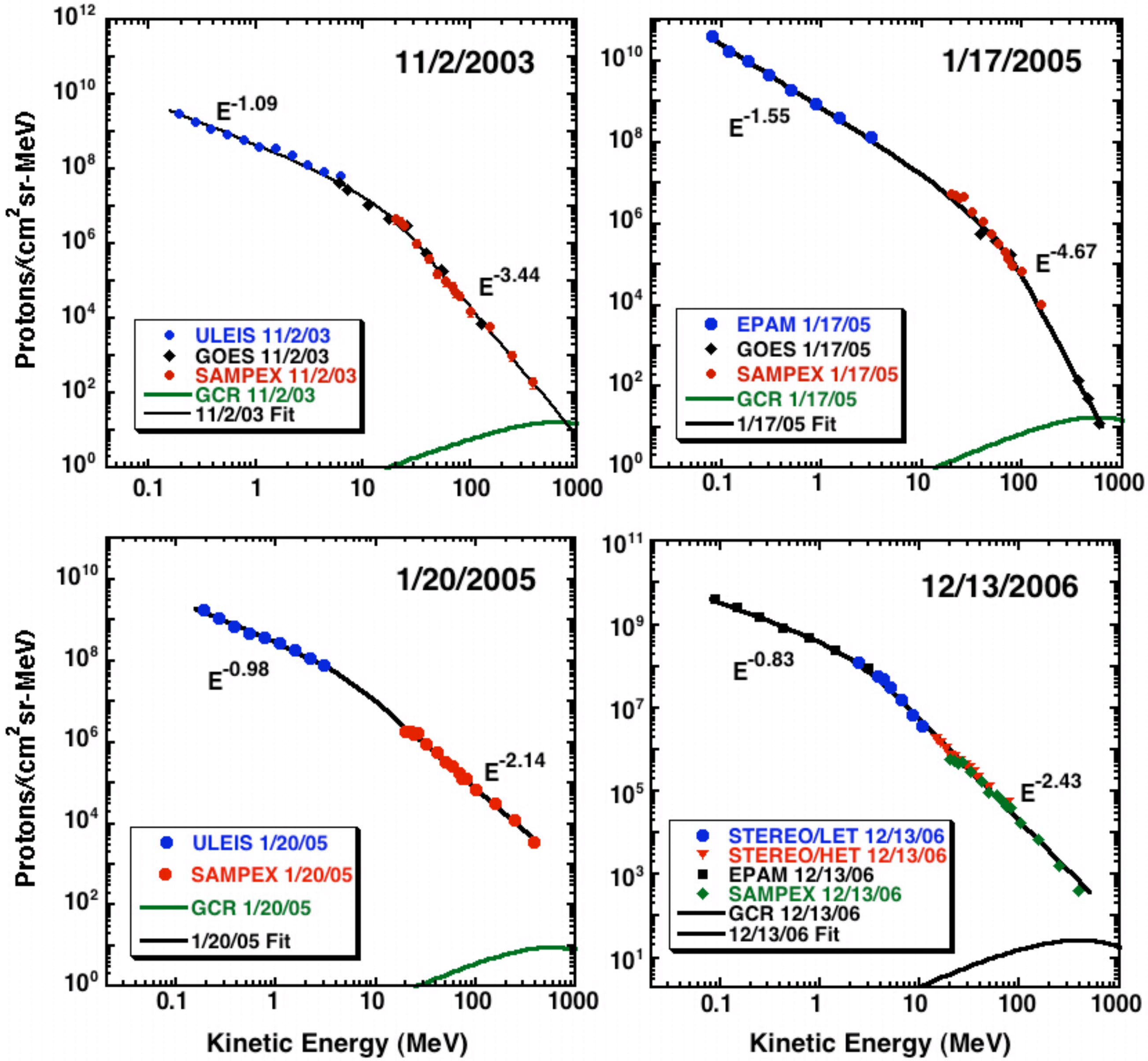
How efficient are CME-driven shocks at accelerating energetic particles?



Apparently, it is not uncommon for ~10% of the CME kinetic energy to go into accelerated particles

Mewaldt et al. 2008

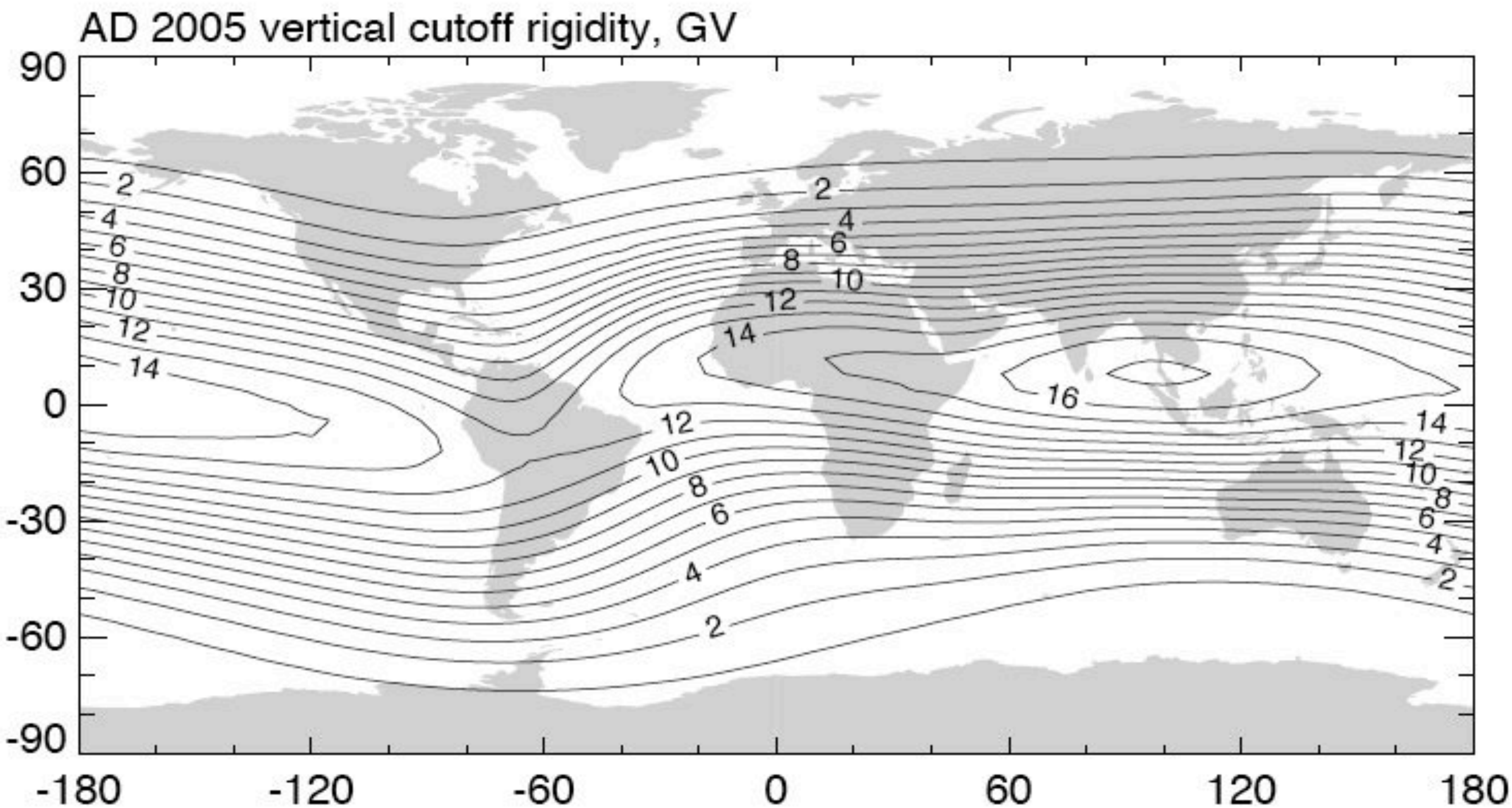
All GLEs from solar cycle 23 appear to be double power-laws in energy



GLEs #13 - #16

Mewaldt et al. (2009b)

For vertically incident particles the minimum rigidity particle that can reach the upper atmosphere of Earth is given approximately by: $R_c = 14.5 \cos^4\lambda$ GV, where R_c is called the geomagnetic cutoff rigidity (in GV) and λ is the geomagnetic latitude. The plot below is based on a more exact calculation.

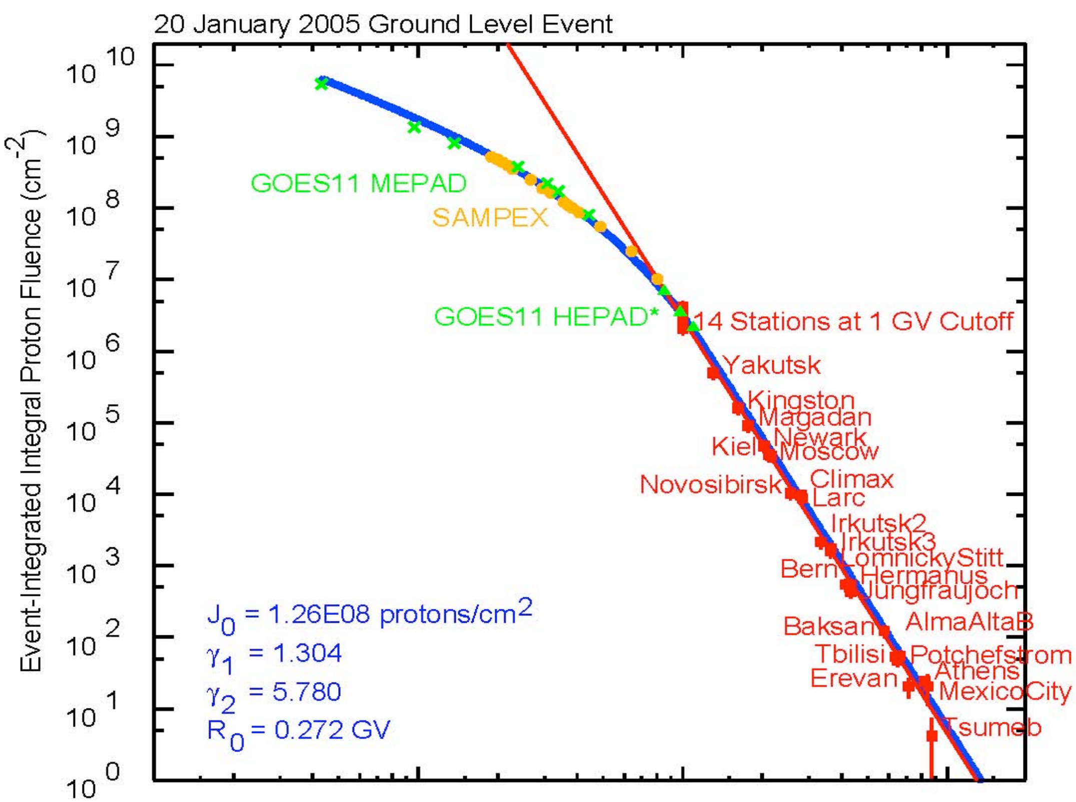


Selesnick et al. (2007)

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

Integral Rigidity Spectra

J(>R) ~ Double power-law



R = Rigidity (momentum/charge in GV)

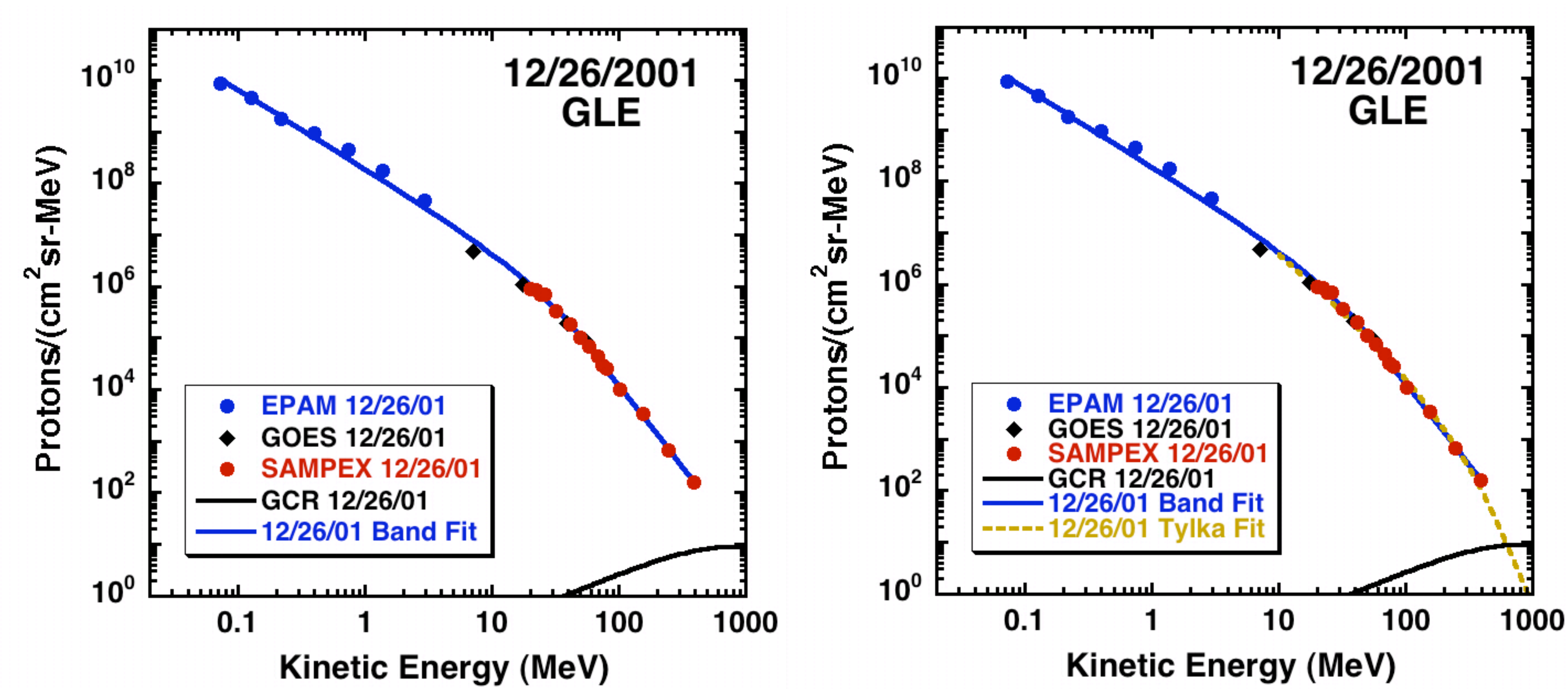
$R = (A/Ze)[E^2 + 2M_PE]^{1/2}$

E in GeV

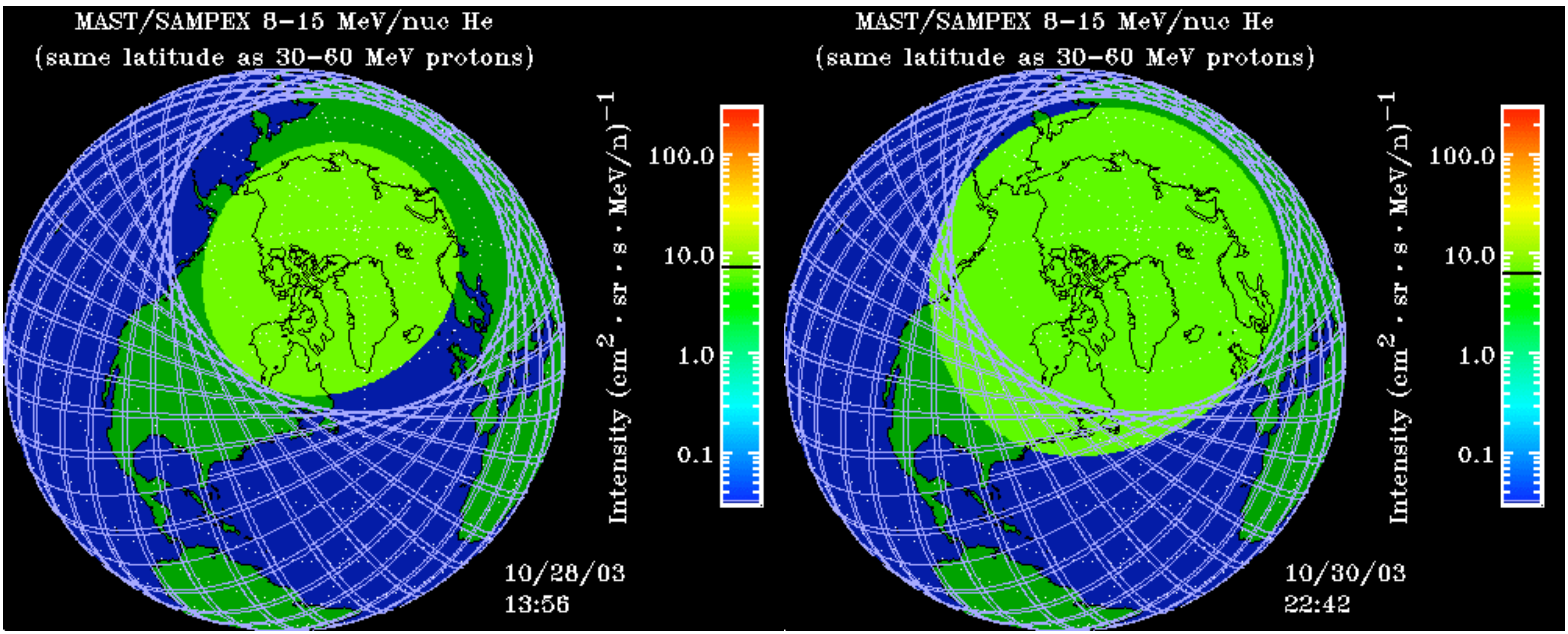
Fit integrated rate at various neutron monitors versus their cutoff rigidity

Comparing Fits to Neutron Monitor and Spacecraft Data

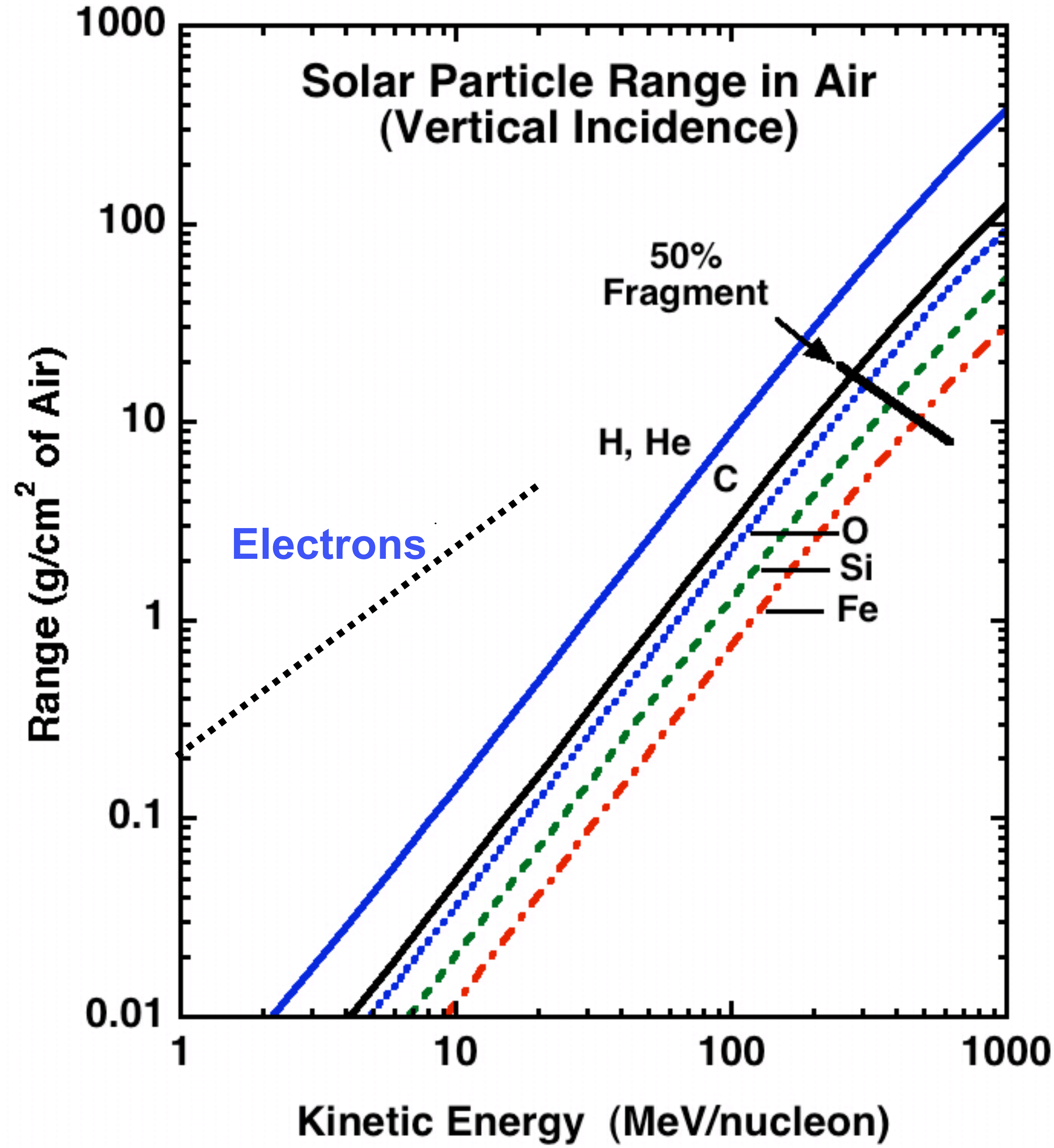
The work by Tylka and Dietrich indicate that there is an additional spectral break at ~400 MeV



During the Halloween solar storms SAMPEX tracked the size of the polar caps by measuring the location geomagnetic cutoff of 8-15 MeV/nuc He (equivalent to 30-60 MeV protons) four times each orbit. As a result of the geomagnetic storms due to the Oct 28 and Oct 29 ICMEs the polar cap was often several times larger in area.

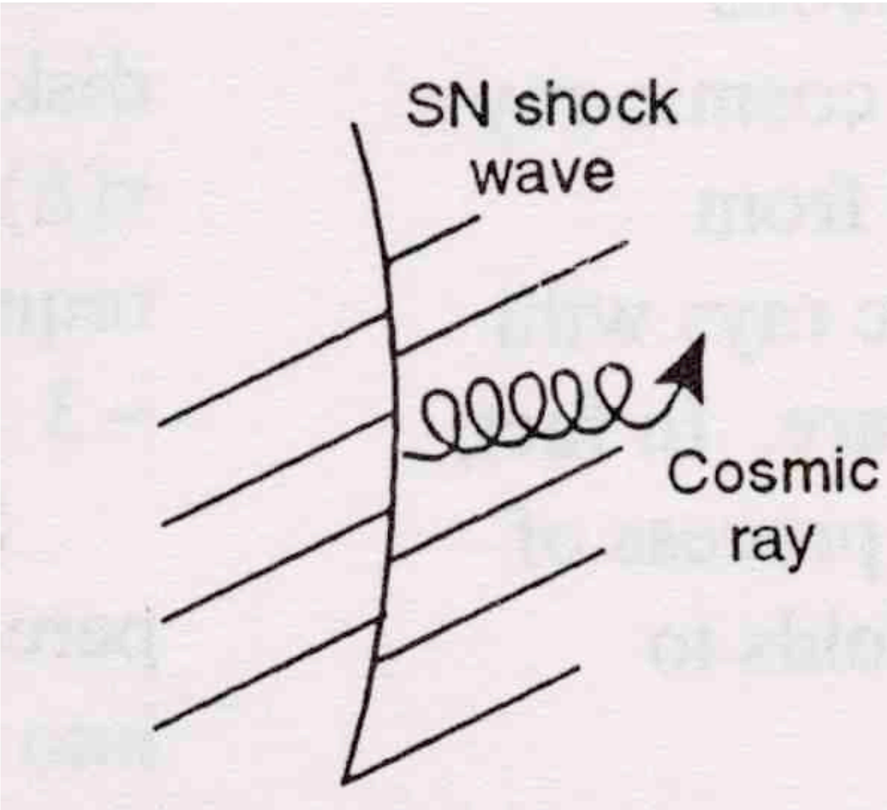


Leske et al. (2004)



Solar Particle Range in Air
(Vertical Incidence)
50%
Fragment
H, He
C
O
Si
Fe
Electrons
Range (g/cm2 of Air)
1000
100
10
1
0.1
0.01
1
10
100
1000
Kinetic Energy (MeV/nucleon)

Acceleration of interstellar material by supernova shock waves produces a power-law spectrum in momentum $dJ/dP \approx P^{\gamma}$, with index $\gamma \approx -(2+\delta)$

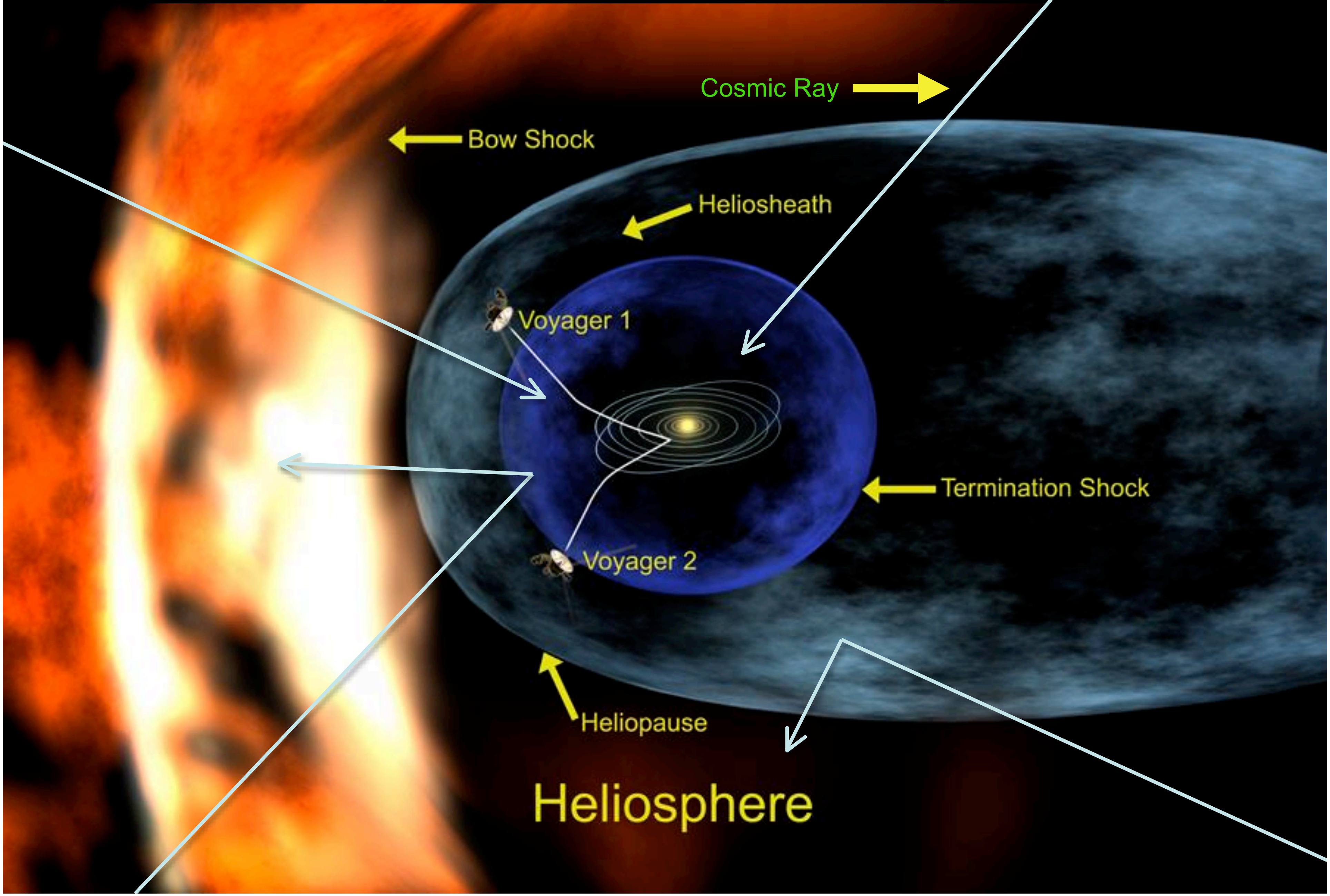


In our cosmic-ray transport and solar-modulation model, the "source spectrum" that best fits the observations has $\gamma = -2.35$

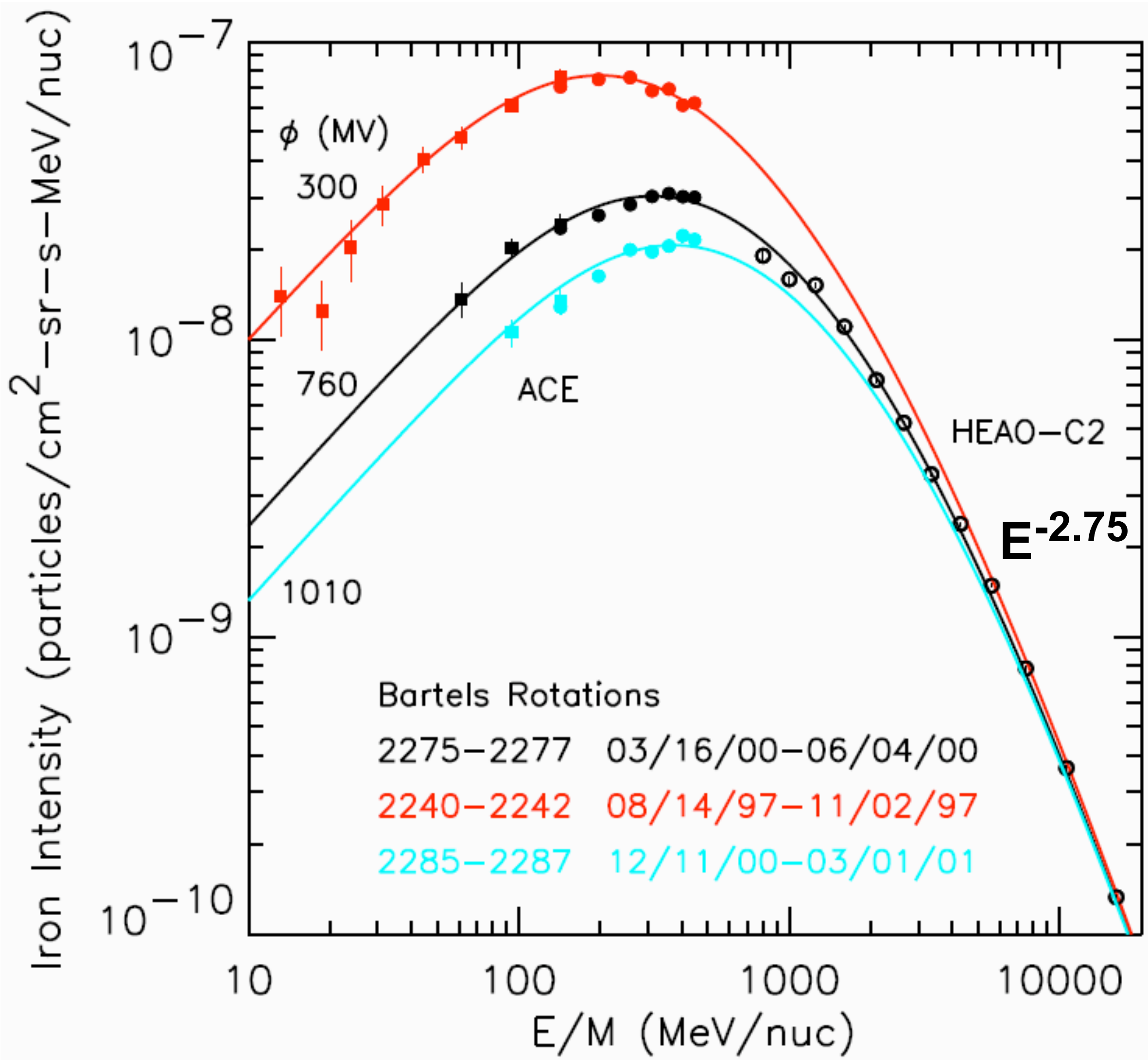
At relativistic energies $Pc \sim E$, which gives a source spectrum of $dJ/dE \approx E^{-2.35}$

The difference between the source and observed spectrum ($dJ/dE \sim E^{-2.75}$) is attributed to higher energy cosmic rays leaking out of the Galaxy more easily

The intensity of cosmic rays that reach in the inner solar system is modulated by the solar wind and its embedded magnetic field



Cosmic-ray spectral variations over the solar cycle

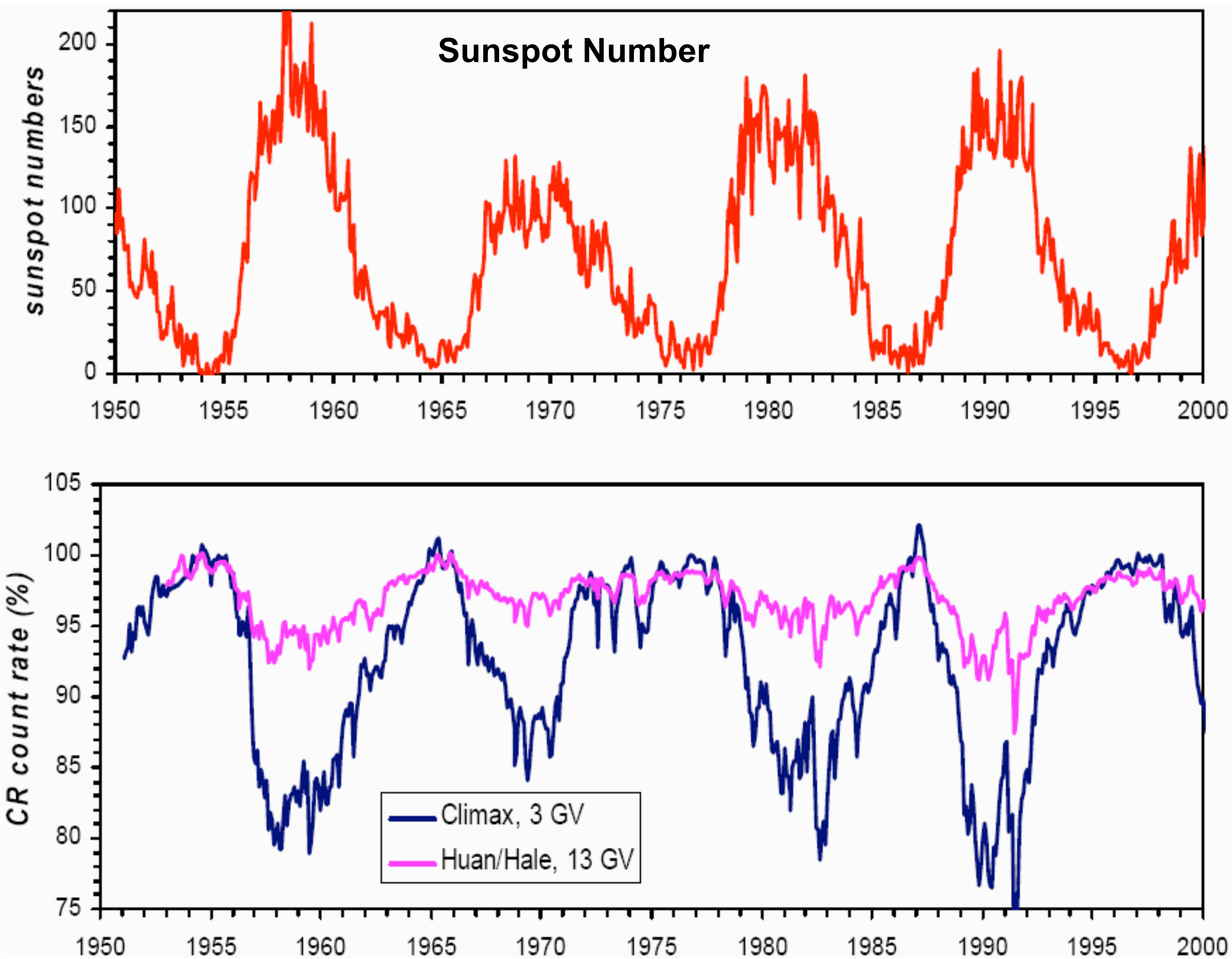


"Solar modulation" changes GCR intensities at low energies by up to an order of magnitude between solar min and solar max.

Wiedenbeck et al. 2007

Cosmic-ray intensity variations are anti-correlated with solar activity

Cosmic-ray modulation is a complex process - it is usually parameterized by changes in the interplanetary diffusion coefficient (K) due to variations in the turbulence in the interplanetary magnetic field (ΔB/B) .

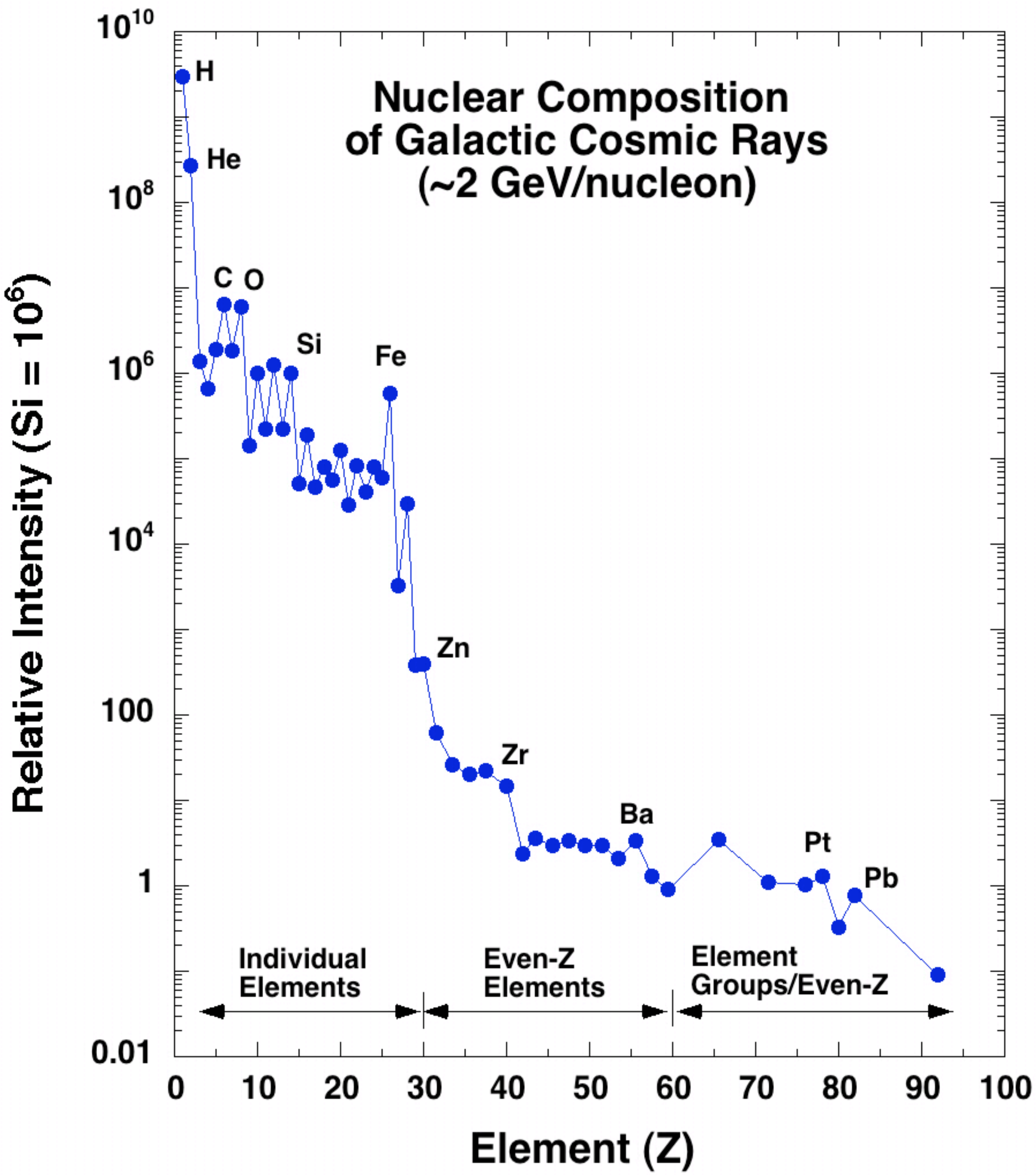


Neutron monitor count rates at 3 and 13 GV cutoff rigidities

Note the 22-year periodicity

Usoskin

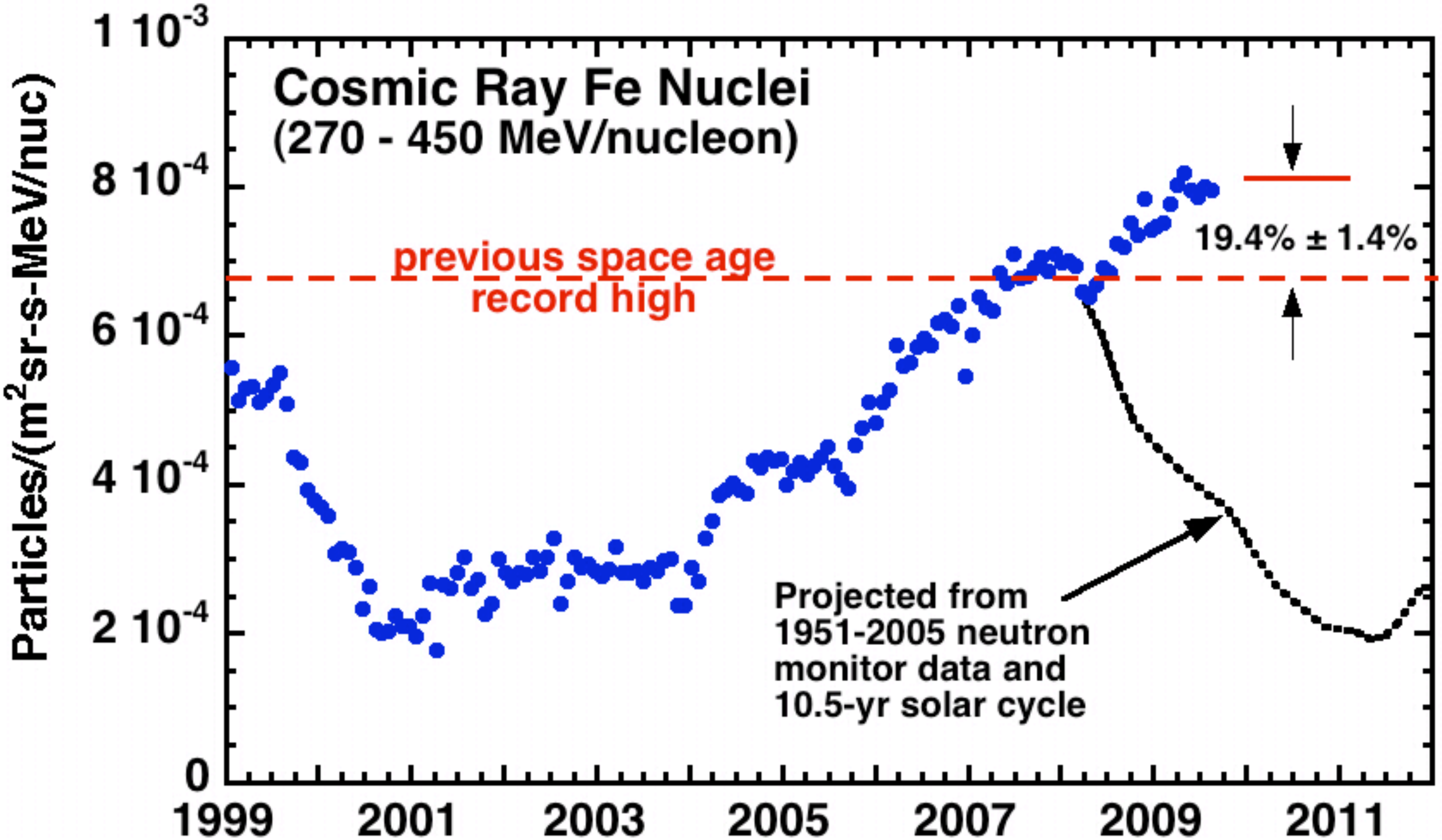
Cosmic Ray Elemental Composition



Cosmic rays include all of the elements in the periodic table thru Th and U

Mewaldt (1999)

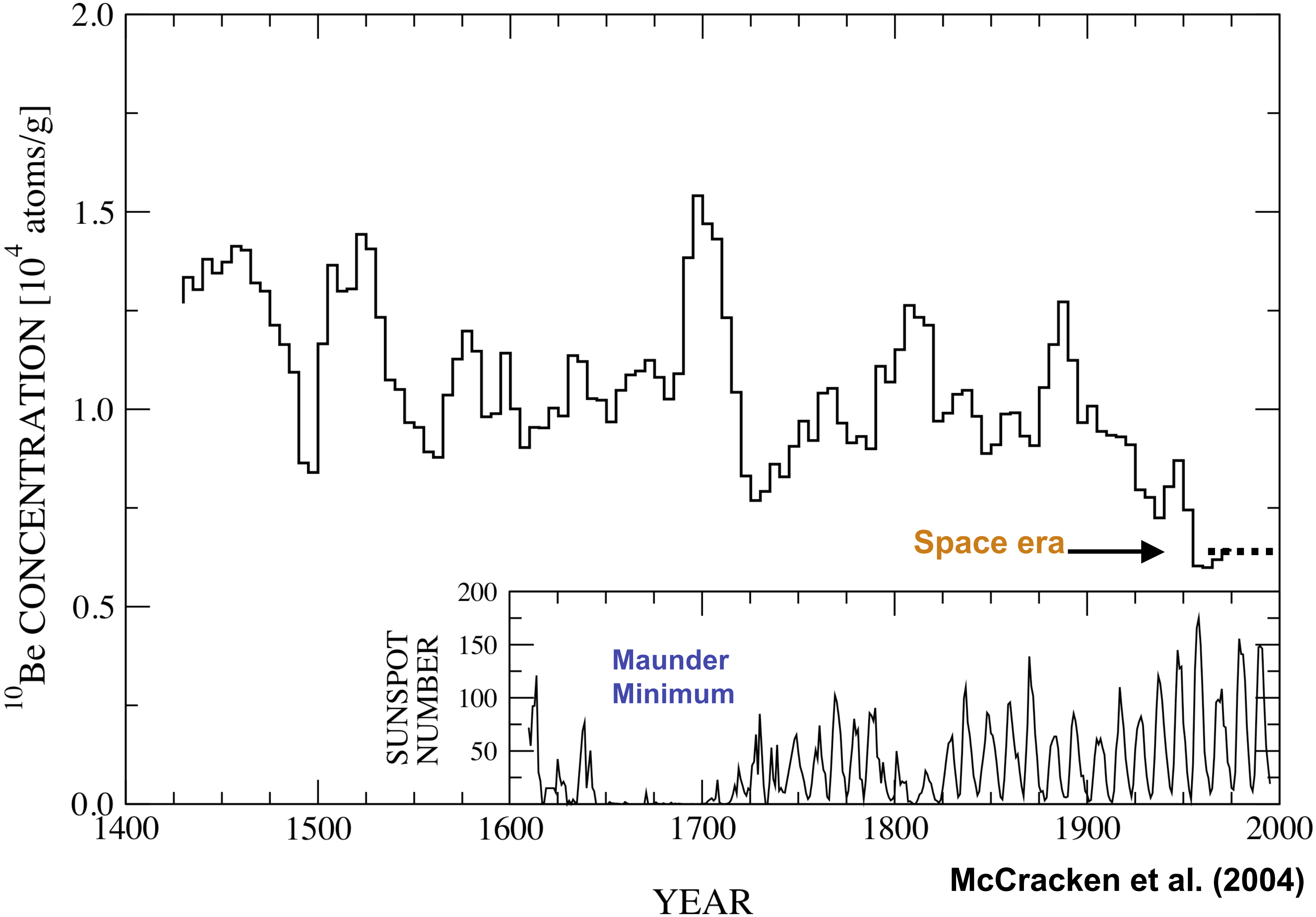
Highest Cosmic Ray Intensities of the Space Age



Why now?
- Weaker interplanetary magnetic field
- Reduced solar wind dynamic pressure
- Prolonged solar minimum

See recent Science@NASA item

The ^{10}Be record in ice cores shows that over the past 600 years the cosmic-ray intensity has been 1.5 - 2.5 times as great as during the space era.



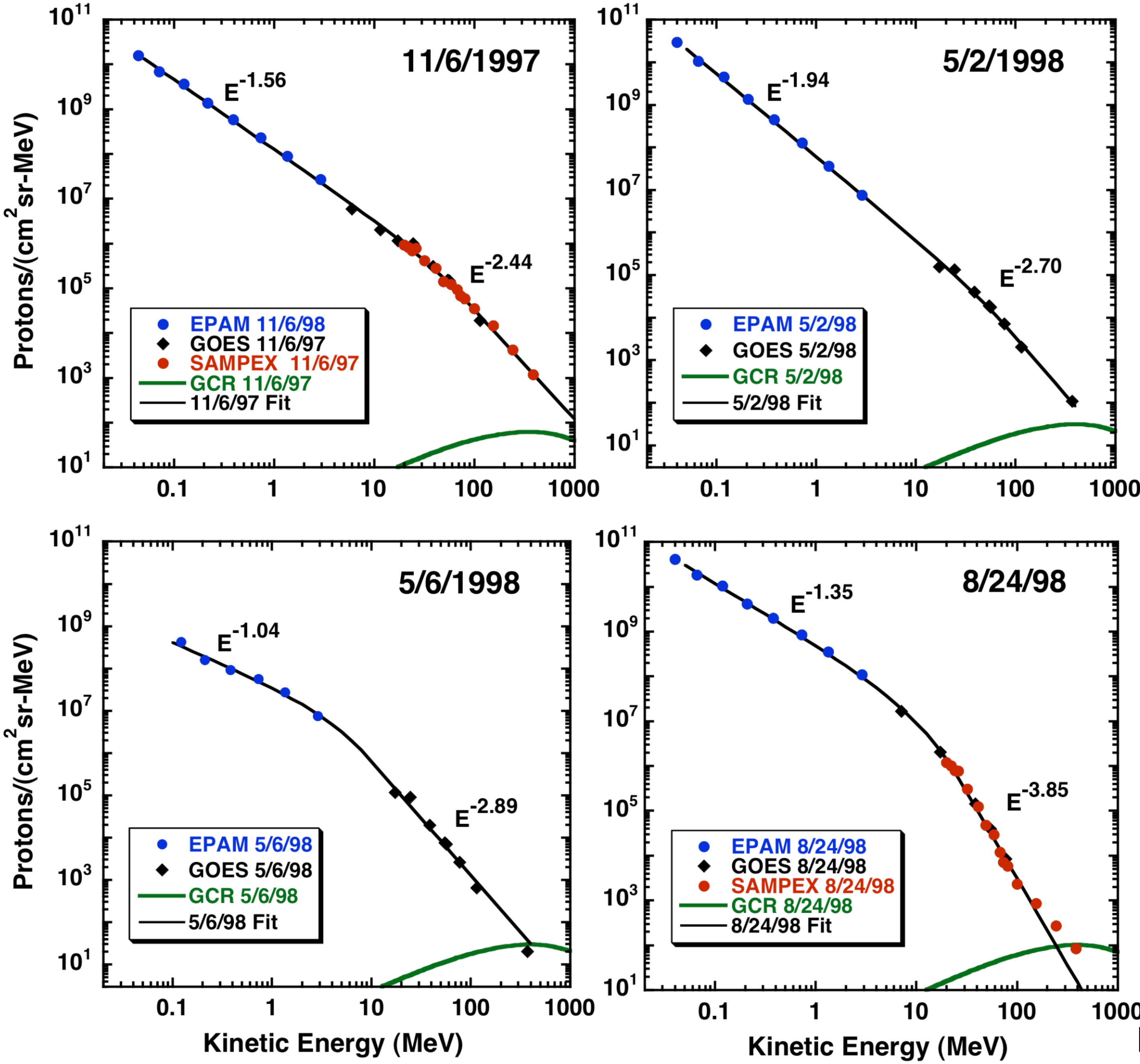
McCracken et al. (2004)

Summary of Key Properties

Property	SEPs	GCRs
Energy Range (MeV)	0.1 to ~10,000	1 to $>10^{14}$
Spectral Slope	-1 to -5	-2.75
Intensity variation	$\sim 10^{5}$	~3 (over space era) ~5 (over last 500 yr)
Sunspot relation	correlated	Anti-correlated
Max intensity >10 MeV (per cm^2sr-s-MeV)	$\sim 5 \times 10^{4}$	~0.5
Energy Content (%)		
H	75 ± 5	~70
He	15 ± 5	~22
Z>2	5 ± 4	~7
Solar Electrons	5 ± 3	~1

Extra Slides

Measured and fit fluence spectra for the first four GLE events

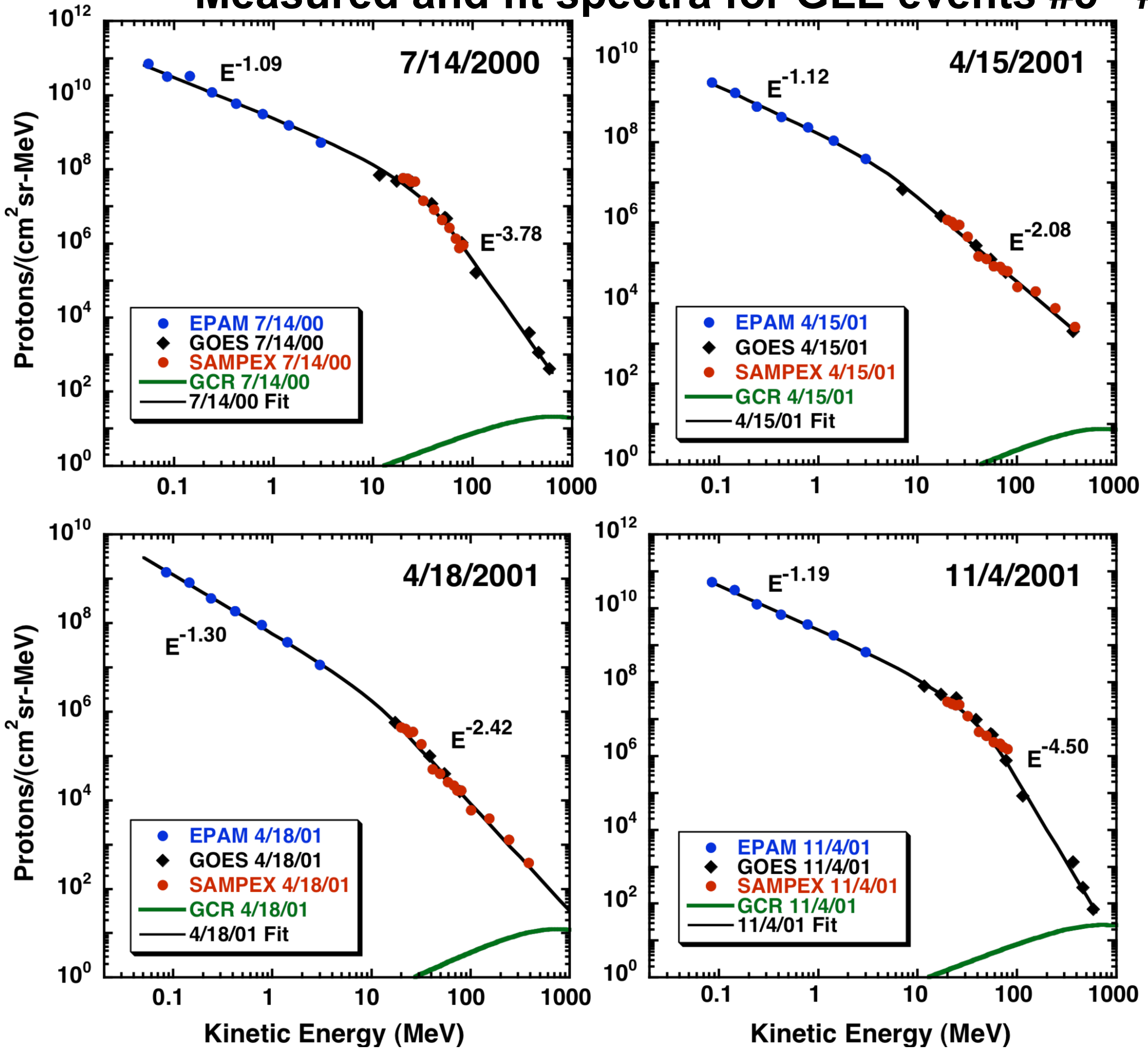


Spectral slopes above and below the break energy are indicated

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

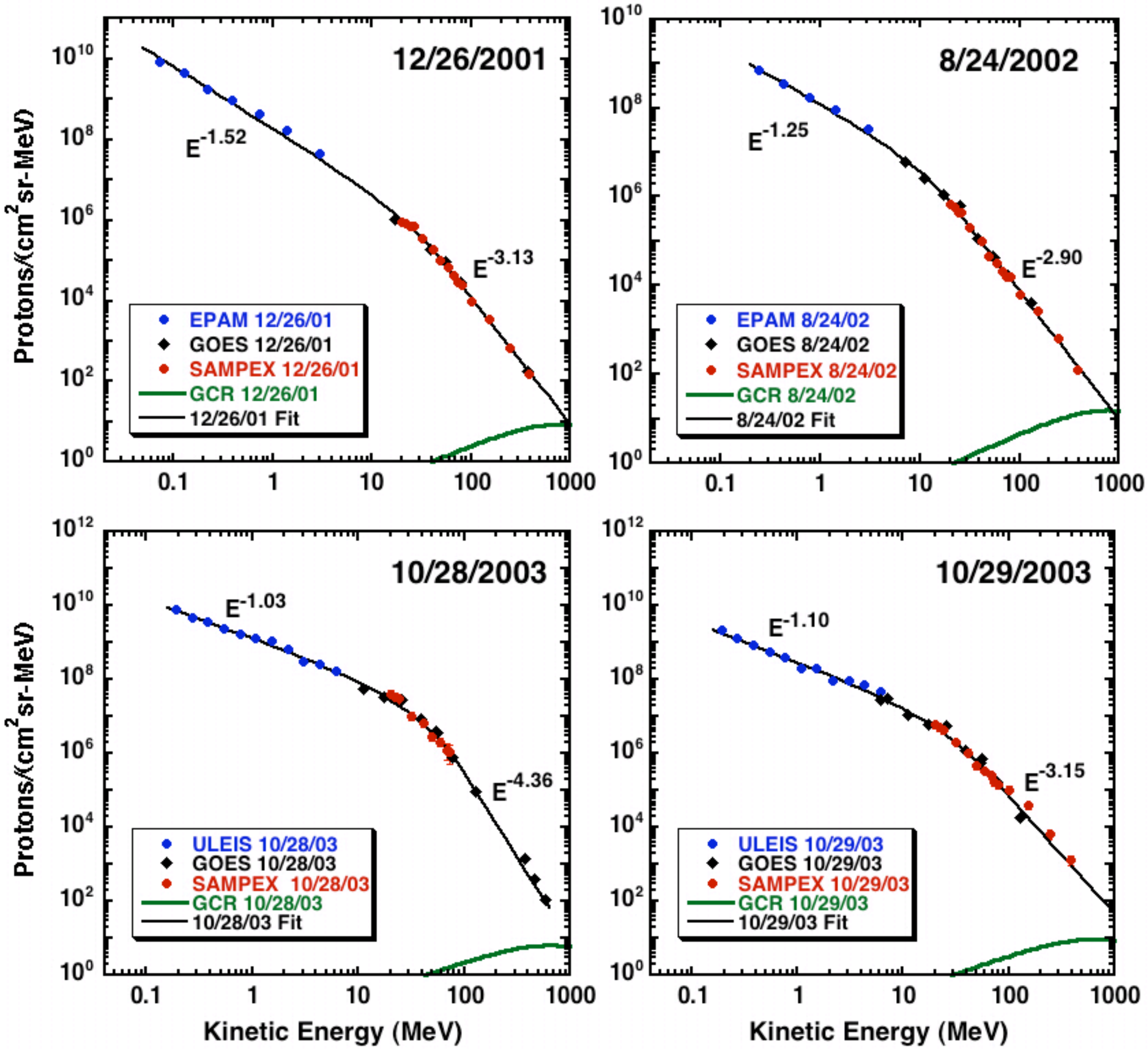
Mewaldt et al. (2009b)

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



Mewaldt et al. (2009b)

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



Mewaldt et al. (2009b)

References

N. Gopalswamy, J. Astrophys. Astron., 27, 243 (2006).
K. G. McCracken, et al., *JGR*, 109 A12103, doi:10.1029/2004JA01085 (2004).
R. A. Leske, R. A. Mewaldt, et al., *J. Geophys. Res.,* 110, doi:10.1029/2005JA011038 (2005a).
R. A. Mewaldt et al., *Proc. 29th Internat. Cosmic Ray Conf.* 1, 111 (2005b)
R. A. Mewaldt, et al., in *Turbulence and Nonlinear Processes in Astrophysical Plasmas*, D. Shaikh and G. P. Zank, eds., AIP Conf. Proc. #932, AIP (2007), pp. 277-282.
R. A. Mewaldt et al. in *Solar Eruptions and Energetic Particles*, AGU Monograph Series, p. 115 (2006).
R. A. Mewaldt et al., Proc 31st Internat Cosmic Ray Conf., Paper 1225 (2009a)
R. A. Mewaldt et al., Proc 31st Internat Cosmic Ray Conf. Paper 783 (2009b)
R. A. Mewaldt (2009c), see http://science.nasa.gov/headlines/y2009/29sep_cosmicrays.htm
R. S. Selesnick, M. D. Looper, & R. A. Mewaldt, *Space Weather* 5, SO4003, doi:10.1029/2006W000275 (2007).
A. J. Tylka, et al., *Astrophysical Journal* 625, 474-495 (2005).
M. E. Wiedenbeck et al., *Space Science Reviews,* 130, 415, doi:10.1007/s11214-007-9198-y (2007).