Solar Energetic Particle Spectra Measured with PAMELA

James M. Ryan[1],
M. Boezio[2], U. Bravar[1], A. Bruno[3], E. Christian[4], G. de Nolfo[4], M. Martucci[5],
M. Mergé[5], R. Munini[2], R. Sparvoli[5], S. Stochaj[6]
and the PAMELA Collaboration

[1]Space Science Center, University of New Hampshire, Durham, NH, United States
[2]INFN, Sezione di Trieste, Trieste, Italy
[3]University of Bari, I-70126, Bari, Italy
[4]Heliophysics Science Division, NASA/GSFC, Greenbelt, MD, United States
[5]Department of Physics, University of Rome “Tor Vergata,” I-00133, Rome, Italy
[6]Electrical and Computer Engineering, New Mexico State University, Las Cruces, NM, United States

Are GLEs fundamentally different from other SEP events? (Is there a distinct GLE process?)

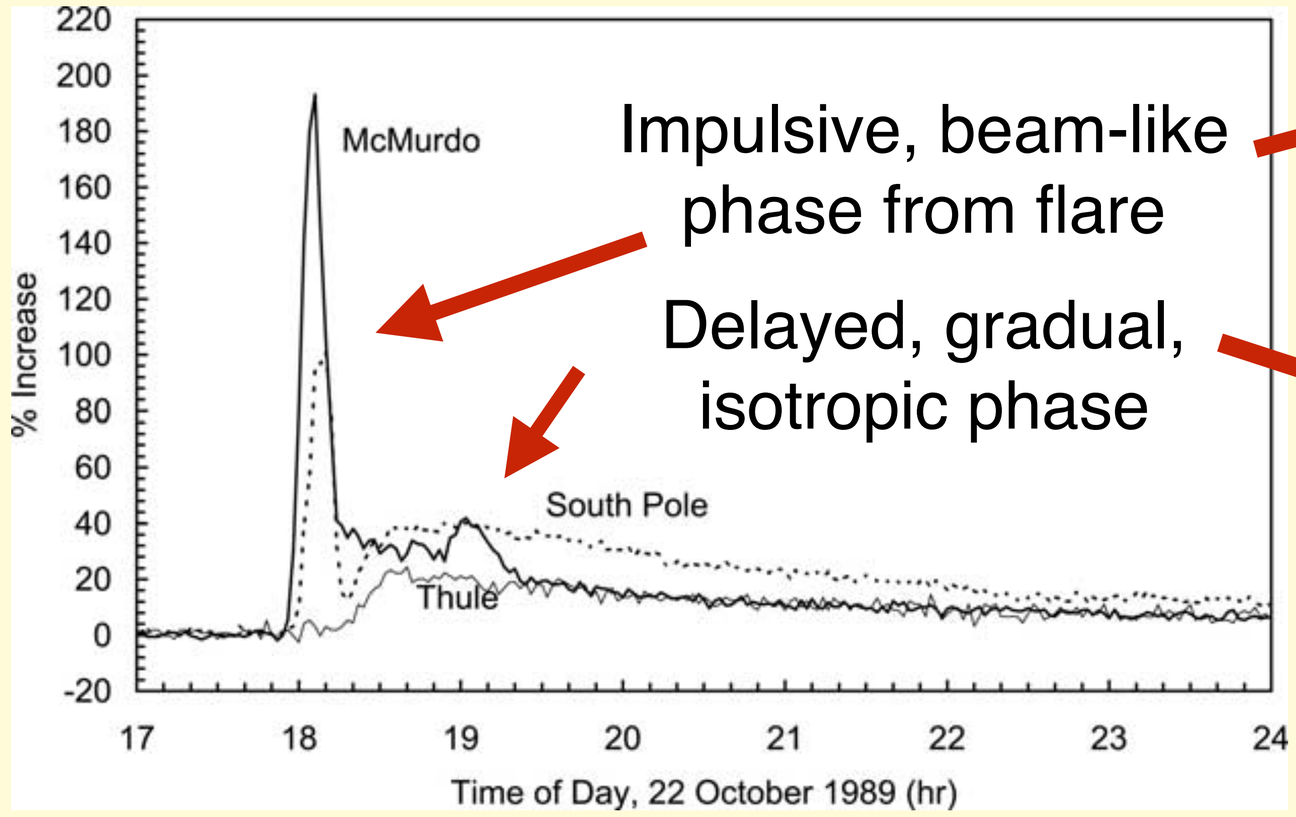
- **A separate interplanetary process, separate from the shock that accelerates the lower energy particles.**

- **A separate flare component with greater energies, more impulsive behavior.**

- **Ground Level Enhancement events are morphologically different from others. Is there an accompanying spectral signature.**

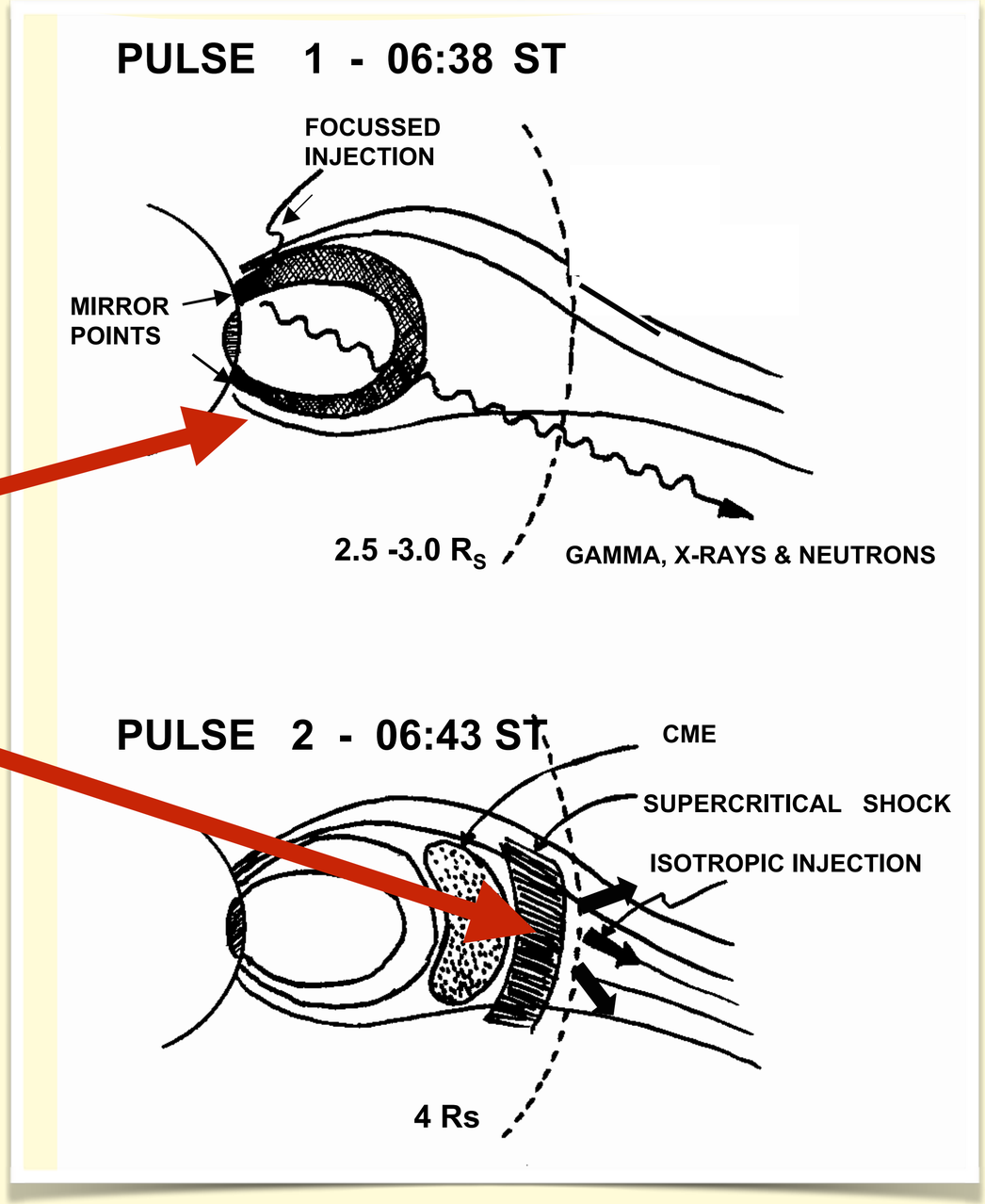
McCracken, Moraal and Stoker 2008

2005 January 20 ***Ground Level Enhancement***
Model for two phases of particle accelertion



Impulsive, beam-like phase from flare

Delayed, gradual, isotropic phase



What might we expect if we have a separate GLE process?

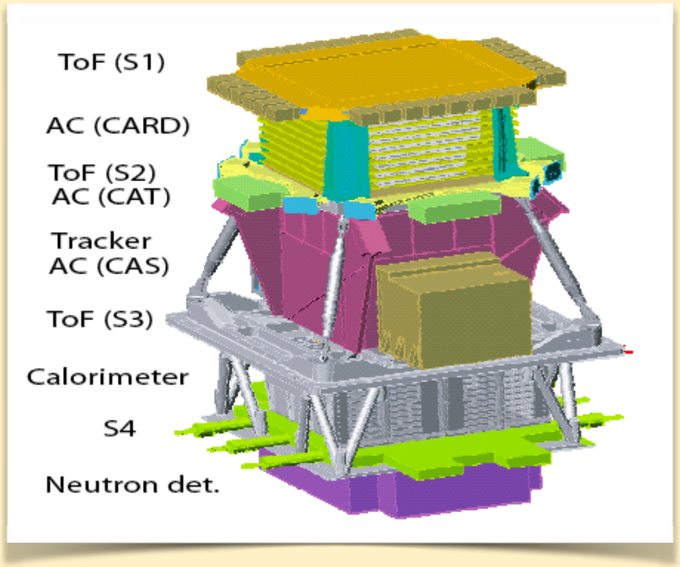
- A hardening of the spectrum above normal SEP energies.
- “Power laws” for GLEs with softer spectra for most SEPs.
  - Ideally, soft at low E with an upward break before ~500 MeV.
- High-E flare signature at the right energies with the right duration and the right time.

What do we need for this assessment?

- Full spectral coverage. Historically, we have measured the lower energies via s/c and deduce the higher energies from the NM data.
- Exposure to the full duration of the event to observe the rise and decay of GLE “component.”

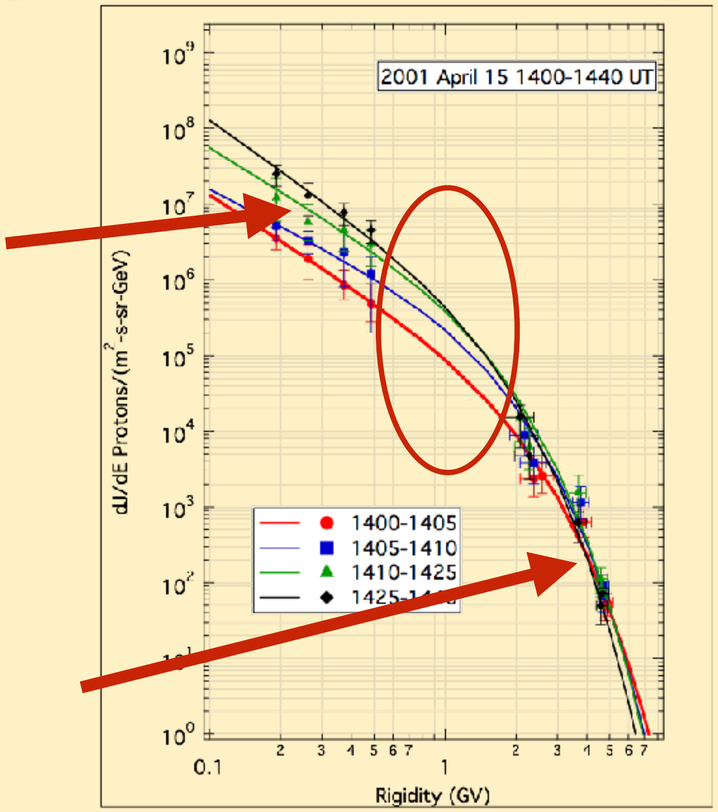
PAMELA Study Objective

- A major objective: produce event-integrated spectra of major SEP events.
- PAMELA spans the energy range of interplanetary space missions and neutron monitors—a nagging gap in spectral coverage.
- **Are there spectral signatures of two components to Ground Level Enhancements?**



IMP-8

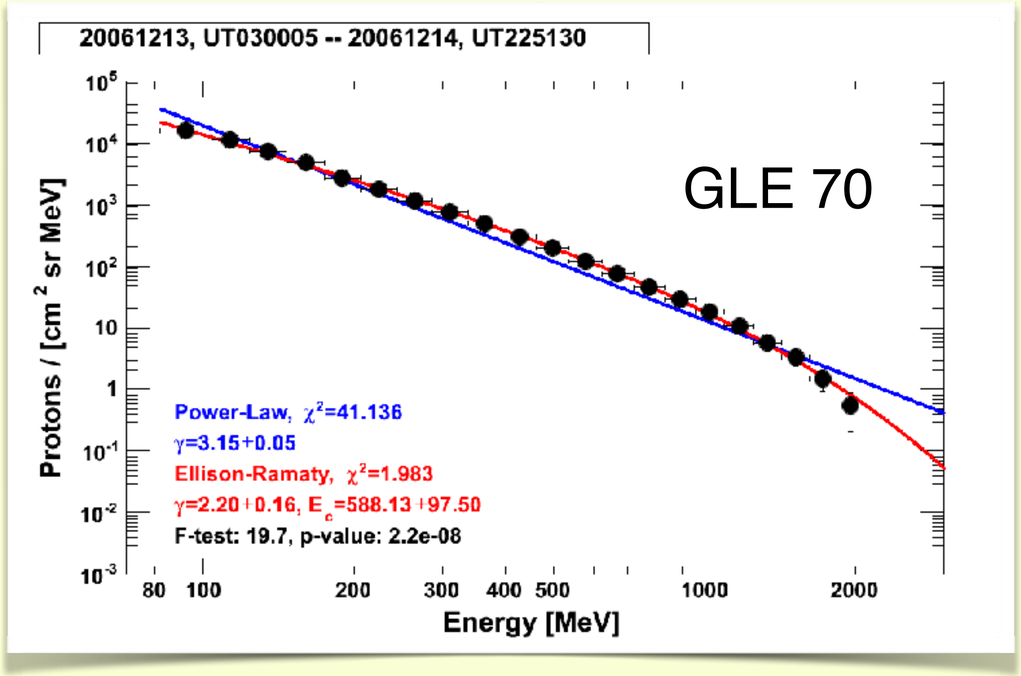
Climax/Milagro



Data Details

- PAMELA measurements take place at high latitudes in low Earth orbit. Data intervals are fragmented into “polar passes.” Incomplete coverage.
- Corrections were performed for live time and exposure factor (time above cutoff rigidity).
- Spectra are event-averaged, including any anisotropic or beamed phase with appropriate solid angle correction.

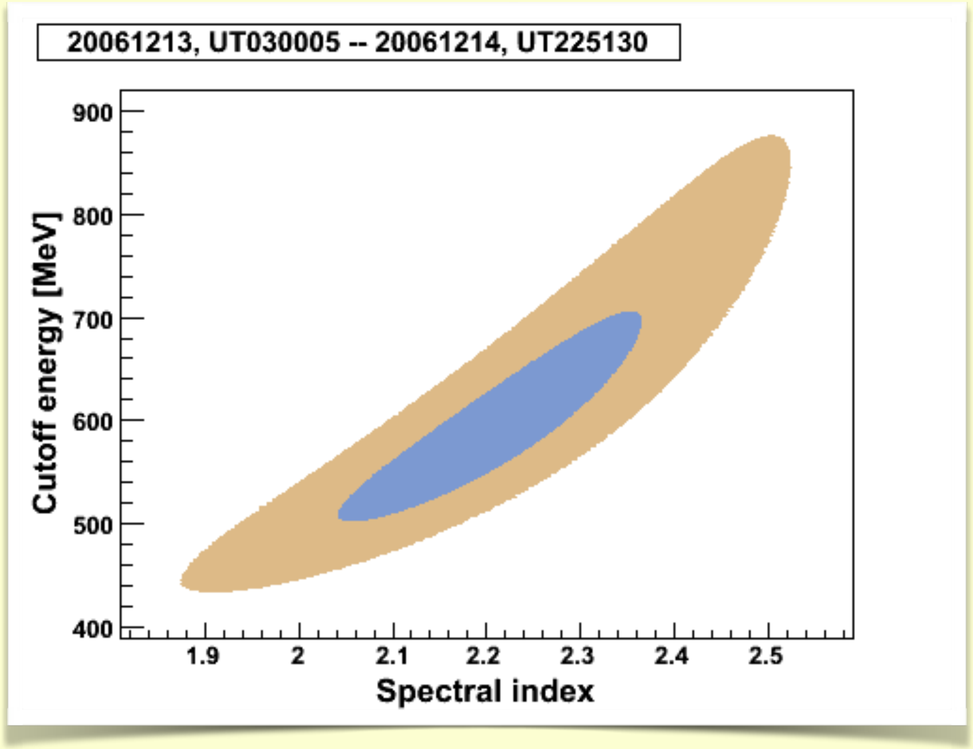
Spectral Fitting Process



2006
December
13

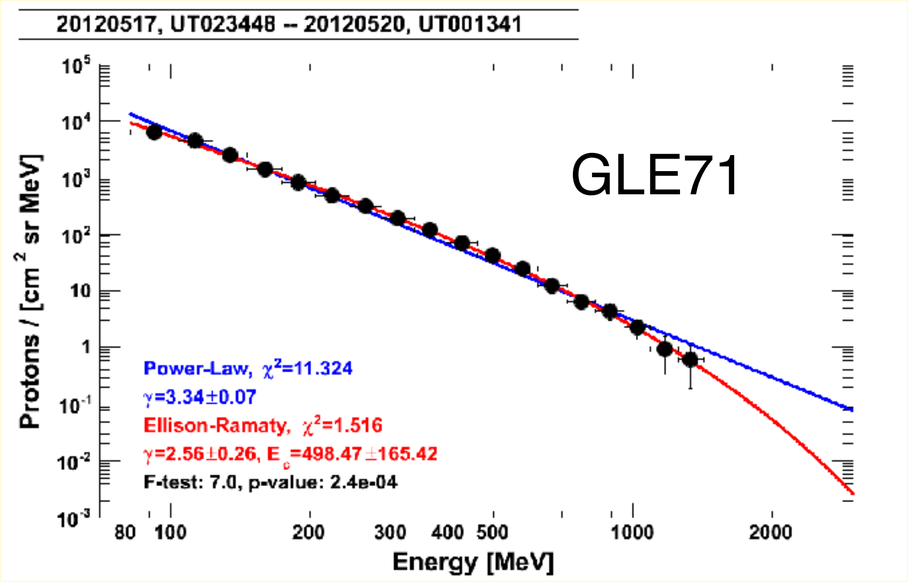
- Data were fit to both a single power law and an Ellison-Ramaty spectrum (1986), $\Phi(E)=N_0\,(E/\,80\ \mathrm{MeV})^{-\gamma}\,e^{-E/E_c}$
- An F-test was performed on each spectrum.
  ➪Unless statistics are poor, each event requires an “exponential” roll over

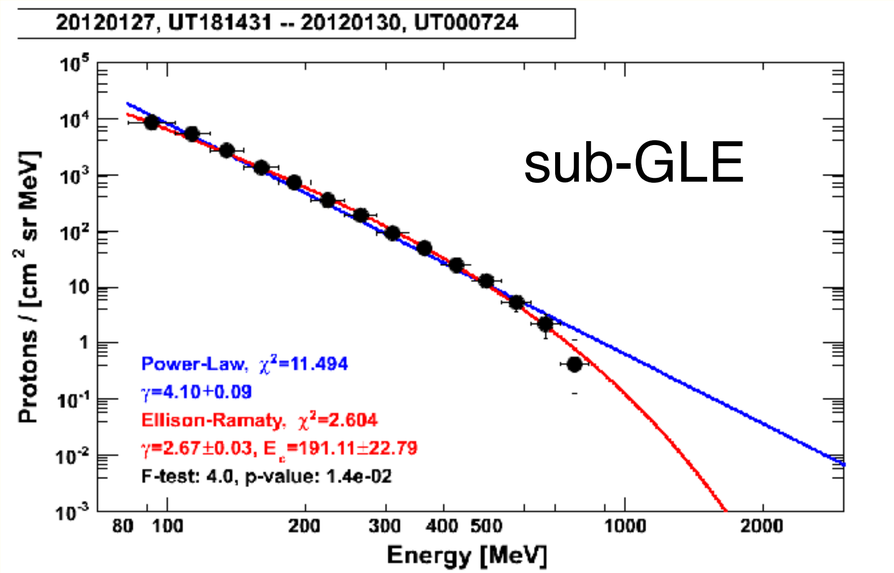
Statistical Cross Correlation

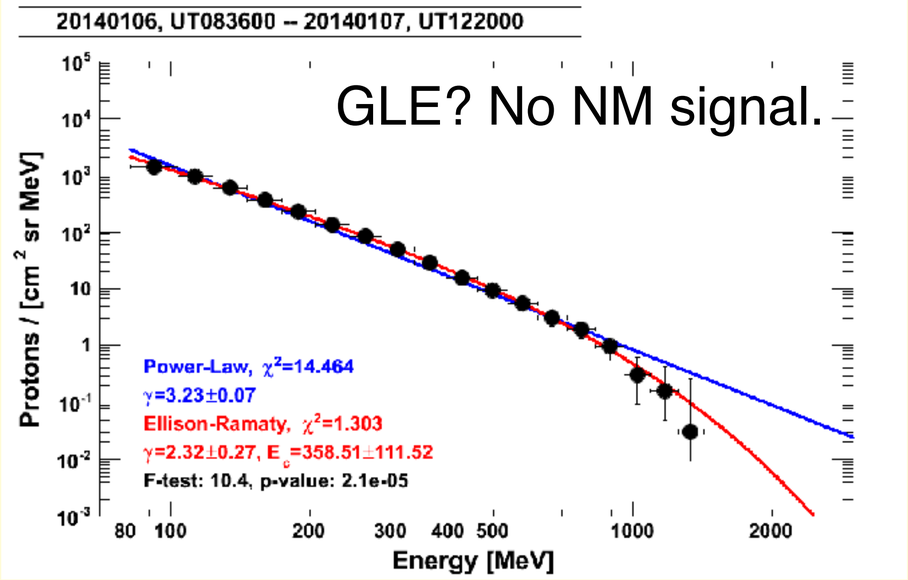


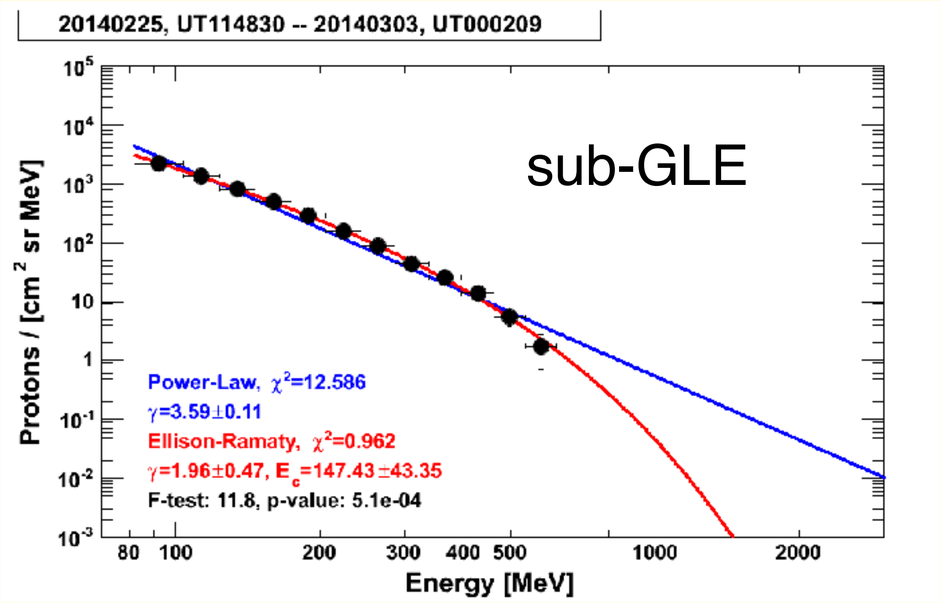
2006 December 13

- In fitting the spectra, a cross correlation between the power law index and the cutoff energy is unavoidable. Care must be exercised in interpreting error bars for either parameter.
- This does not affect the results of the F-test.

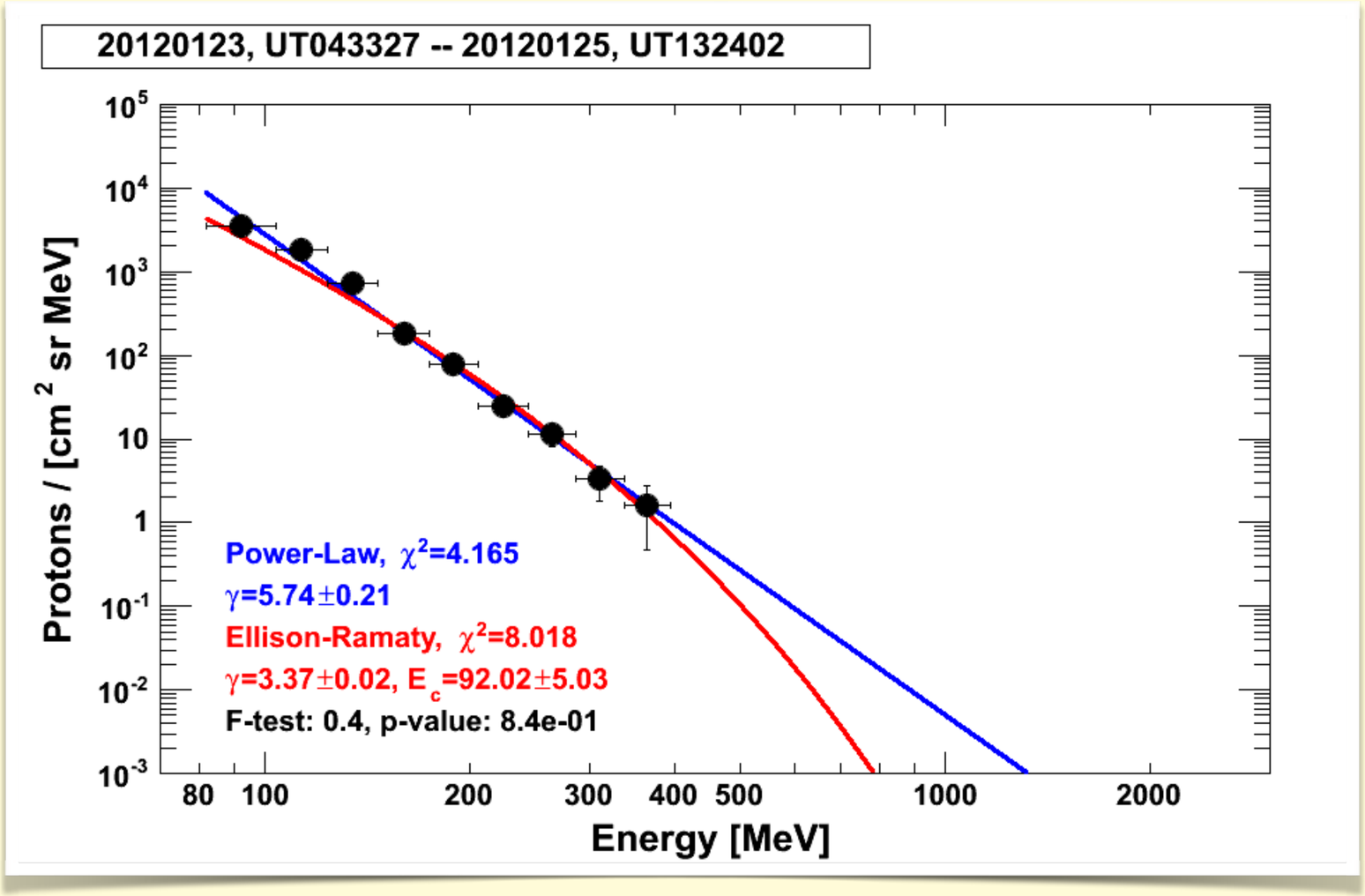

20120517, UT023448 -- 20120520, UT001341
GLE71
Protons / [cm 2 sr MeV]
Energy [MeV]
Power-Law, χ²=11.324
γ=3.34±0.07
Ellison-Ramaty, χ²=1.516
γ=2.56±0.26, E_c=498.47±165.42
F-test: 7.0, p-value: 2.4e-04


20120127, UT181431 -- 20120130, UT000724
sub-GLE
Protons / [cm 2 sr MeV]
Energy [MeV]
Power-Law, χ²=11.494
γ=4.10+0.09
Ellison-Ramaty, χ²=2.604
γ=2.67±0.03, E_c=191.11±22.79
F-test: 4.0, p-value: 1.4e-02


20140106, UT083600 -- 20140107, UT122000
GLE? No NM signal.
Protons / [cm 2 sr MeV]
Energy [MeV]
Power-Law, χ²=14.464
γ=3.23±0.07
Ellison-Ramaty, χ²=1.303
γ=2.32±0.27, E_c=358.51±111.52
F-test: 10.4, p-value: 2.1e-05


20140225, UT114830 -- 20140303, UT000209
sub-GLE
Protons / [cm 2 sr MeV]
Energy [MeV]
Power-Law, χ²=12.586
γ=3.59±0.11
Ellison-Ramaty, χ²=0.962
γ=1.96±0.47, E_c=147.43±43.35
F-test: 11.8, p-value: 5.1e-04

Example of Indeterminate Spectral Shape
Insufficient statistics

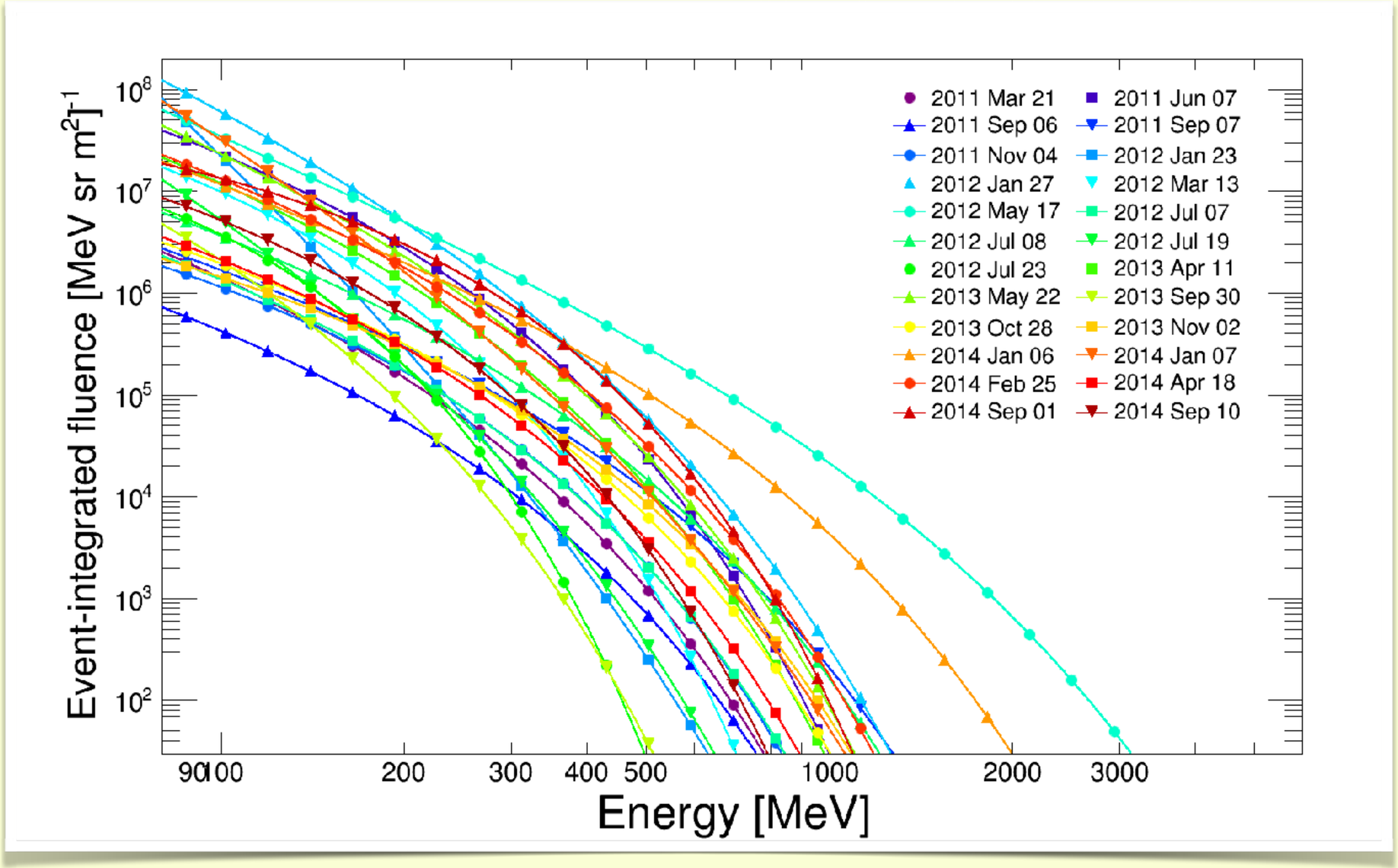


Only slight improvement introducing cutoff energy

Date	γ	Cutoff Energy (MeV)
March 21, 2011	1.7	94
June 7, 2011	1.4	87
September 6, 2011	1.5	102
September 7, 2011	1.7	177
November 4, 2011	1.2	91
January 23, 2012	5.1	132
January 27, 2012	2.6	147
March 13, 2012	**0.9**	**55**
May 17, 2012	**2.5**	**583**
July 7, 2012	1.5	99
July 8, 2012	1.8	153
July 19, 2012	3.1	86
July 23, 2012	0.0	34
April 11, 2013	1.7	99

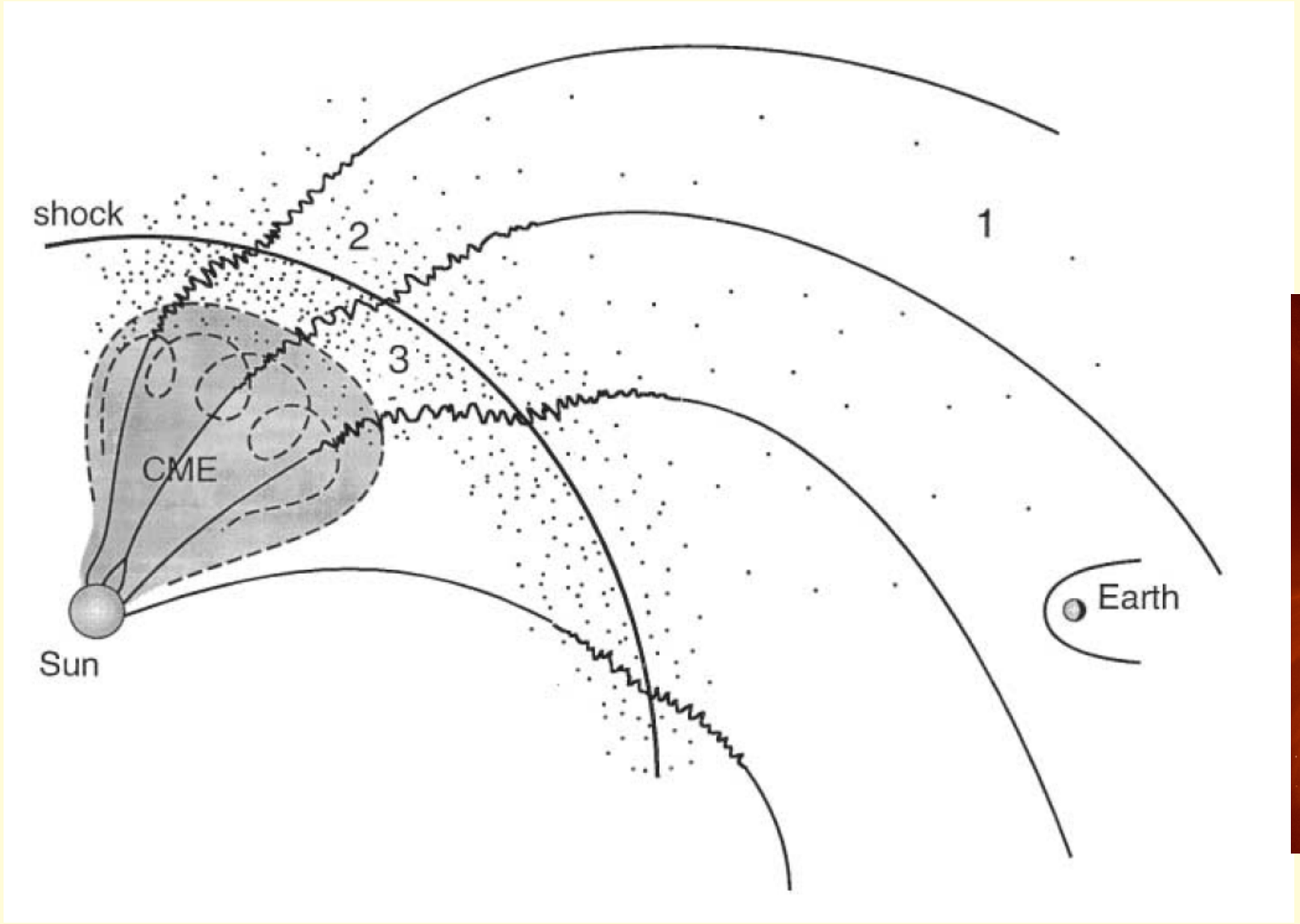
May 22, 2013	2.1	119
September 30, 2013	2.0	53
October 28, 2013	1.4	114
November 2, 2013	1.1	122
January 6, 2014	**2.0**	**280**
January 7, 2014	3.4	166
February 25, 2014	1.7	124
April 18, 2014	1.4	98
September 1, 2014	0.4	82
September 10, 2014	1.0	69

Summary of Spectrum Fits



Conclusions

1. In each case where statistics allow, **pure power-law spectra are consistently rejected.**
2. SEP spectra, over the current PAMELA mission database, exhibit a **terminus to the spectrum**, indicative of the limits of the acceleration process.
3. For interplanetary shocks, such a terminus will result from the three-dimensionality of the shock front (curvature), limited acceleration time and/or vanishing amplitude in the wave spectrum (κ increases rapidly at some large heliocentric radius), releasing the particles from the shock.
4. **Cutoff energies fall above and below the GLE threshold (~1 GV).** Three GLEs are among the group, but also some events falling above 1 GV that were not registered as GLEs, but might have.
5. From the spectrum perspective, we see ***no qualitative distinction*** **between those events that are GLEs, those that could be, or those that are not.**



Lee (2005)