Probabilistic Model Development

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Objective: Develop a Probabilistic Model for the Solar Energetic Particle Environment

- Develop a tool to provide a reference solar particle radiation environment that:
  - Will not be exceeded at a user-specified confidence level
  - Will provide reference environments for:
    - Peak flux
    - Event-integrated fluence
    - Mission-integrated fluence
  - The reference environments will consist of:
  - Elemental energy spectra
    - For protons, helium and heavier ions

Plan for the SEP Model

- Step 1: Develop a data base of SPE measurements that:
  - Follows consistent selection rules
  - Consists of statistically independent episodes of solar activity
- Step 2: Fit the elemental spectra for each episode with spectral forms such as the Ellison-Ramaty[*] Model
  - This makes it possible to determine the flux (or fluence) above a common set of energy thresholds.

[*]Ellison and Ramaty, Ap.J., **298**, 400 (1985)

Plan- Continued

- Step 3: Construct Cumulative flux (or fluence) distributions for a standard set of energy bins
  - fit these with the Generalized Extreme Value (GEV)[1] distribution to obtain initial distributions for each energy

- Step 4: Determine the frequency of SPE episodes over the solar cycle and use this frequency to:
  - Levy distribution[2].

- Step 5: Convolve the initial distributions with a Levy distribution to obtain extreme value distributions for each energy bin of elemental spectrum

[1] "An Introduction to Statistical Modeling of Extremes" by Stuart Cole (Springer, 2001)

[2] "Time distributions of solar energetic particle events: Are SEPEs really random?" by Jiggens and Gabriel (JGR, **114**, A10105, 2009)

Plan - Continued

- Step 6: Construct reference energy spectra for each element
  - This requires user input on:
    - Mission start date and duration
    - Choice of peak flux, event-integrated fluence or mission-integrated fluence reference spectra
    - Choice of Confidence level
- Step 7: Fit the reference spectra with the best-fit spectral form so that the final result is an energy spectrum for each element.

Other Considerations

- In defining the initial distributions, we must also take into account the uncertainty in the parameters of the initial distributions determined by the fits to the cumulative flux (or fluence) distributions.
  - Xapsos[*] has suggested a bootstrap procedure for this
- We must consider that the episode frequency is variable over the solar cycle so that the theory of 'Extremes of Non-Stationary Sequences' must be used.
- Finally, we must investigate the solar cycle dependence of the SPE spectra to be sure that the initial distribution is valid in all solar cycle phases.

[*]Xapsos et al., IEEE Trans. on Nucl. Sci., **46**, 1481 (1999)

So, where are we?

- We have collected proton episode-integrated differential spectra from 1974 to the present
  - Using IMP-8 GME before Nov. 2001 and GOES afterwards
  - using NOAA's criteria to select events and their starting and ending dates based on GOES >10 MeV fluxes
- We have tested eight functions for fitting spectra and determined the three that are most likely to fit any SPE event spectrum (Weibull[1], Band[2] and Ellison-Ramaty functions).
- We have fit the GOES spectra with these functions and chosen the fit giving the lowest χ^2
- We have constructed cumulative distributions for all differential energy bins (from 206 SPE episodes)

[1]Xapsos et al., IEEE Trans. on Nucl. Sci., **47**, 2218 (2000)
[2]Band et al., ApJ, **413**, 281 (1993)

NOAA Selection Criterion

- NOAA defines the start of a proton event to be the first of 3 consecutive data points with fluxes greater than or equal to 10 pfu. The end of an event is the last time the flux was greater than or equal to 10 pfu.

- 1 pfu = 1 proton/cm^2.sec.ster

Examples of > 10 MeV Proton Flux Plots
(dark green curves)
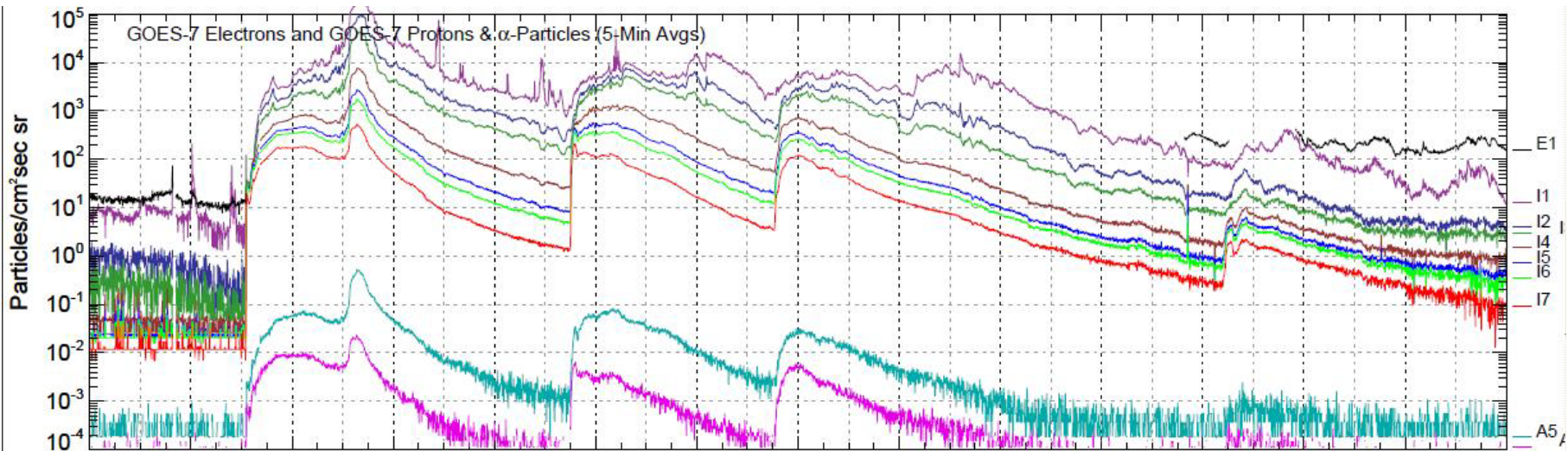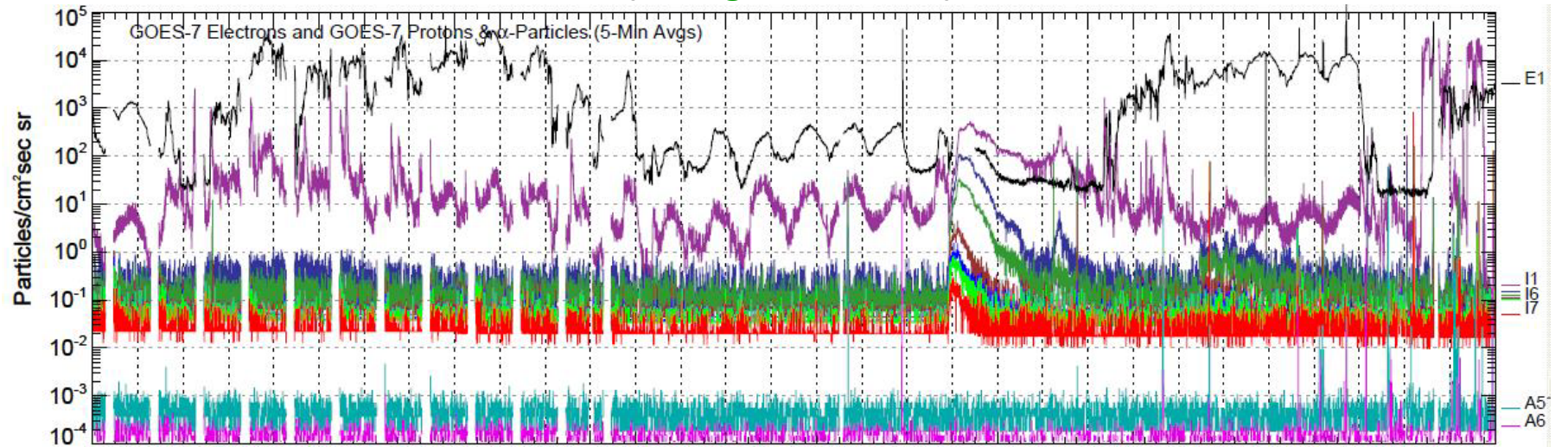
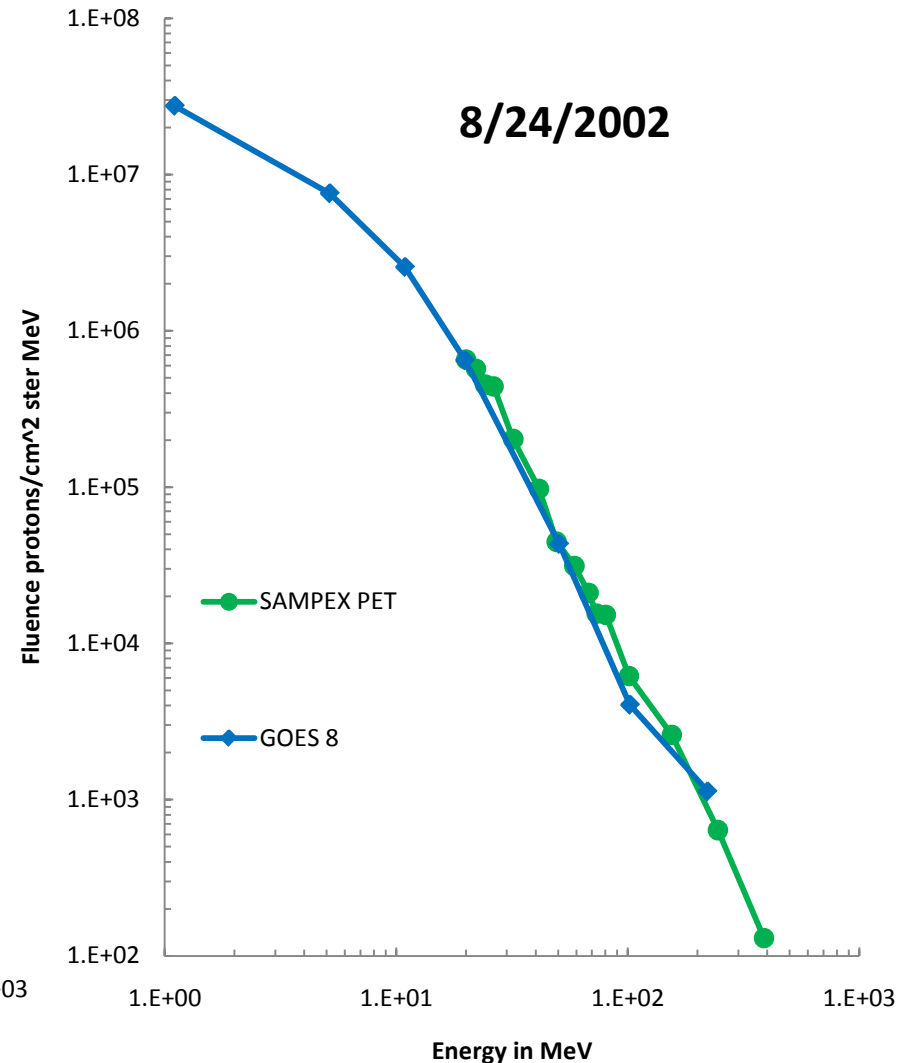# Data Reliability
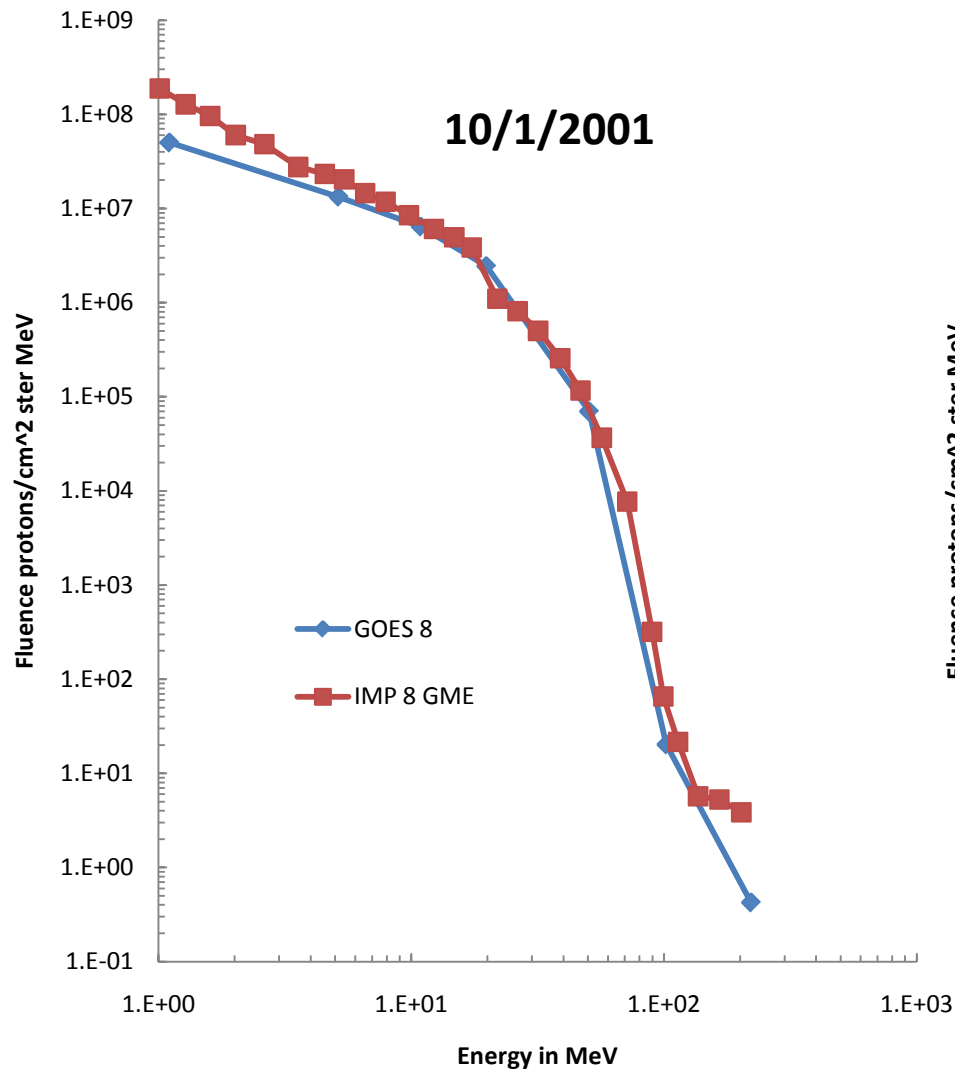
This is a rather sad story

- The best that can be done is to find instruments that agree on the flux consistently within a factor of two
- Some authors have suggested that it is necessary to choose a trusted instrument and renormalize other instruments to it in overlapping time periods.
- For protons, only the GOES instruments cover the entire period after November, 2001.
  - SAMPEX covers the period up through June 30, 2004
  - There is also ERNIE on SOHO, but it saturates in large events.
- For helium and heavy ions we have ACE and it is reasonably consistent with the CRN instrument on IMP-8 that is a trusted reference.
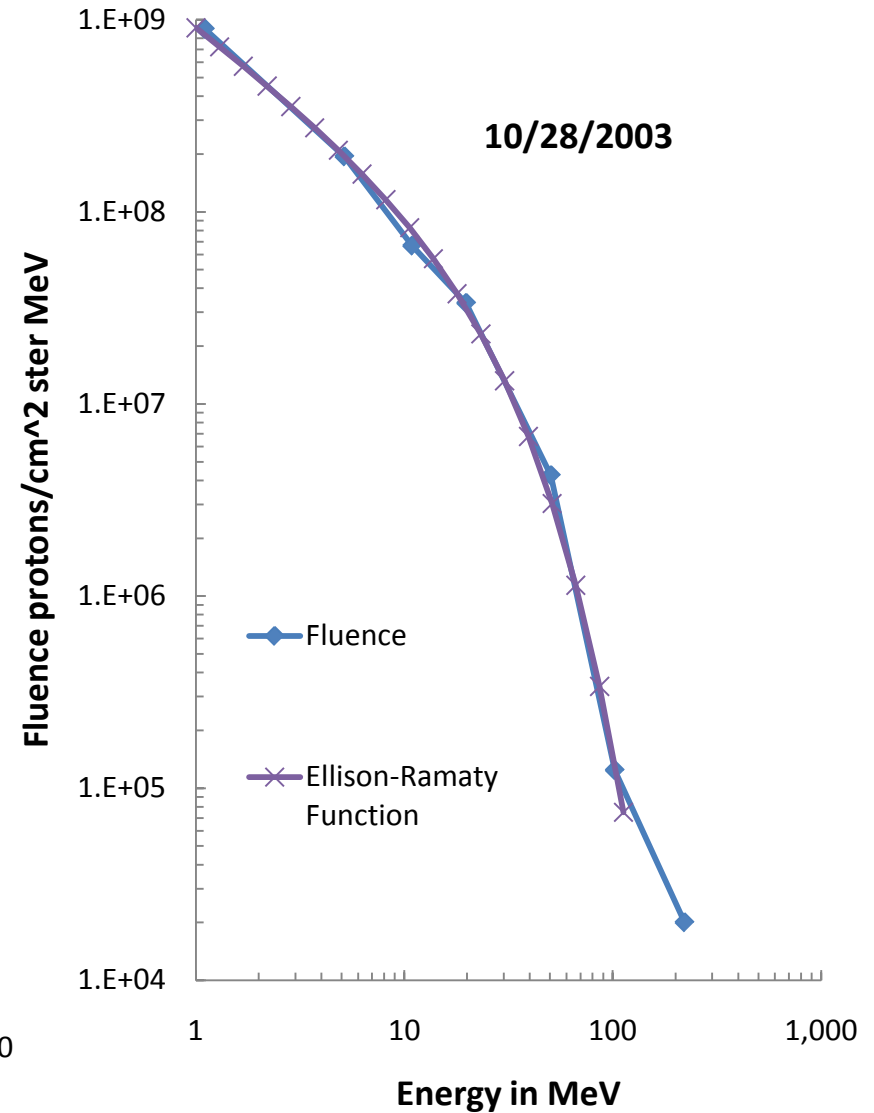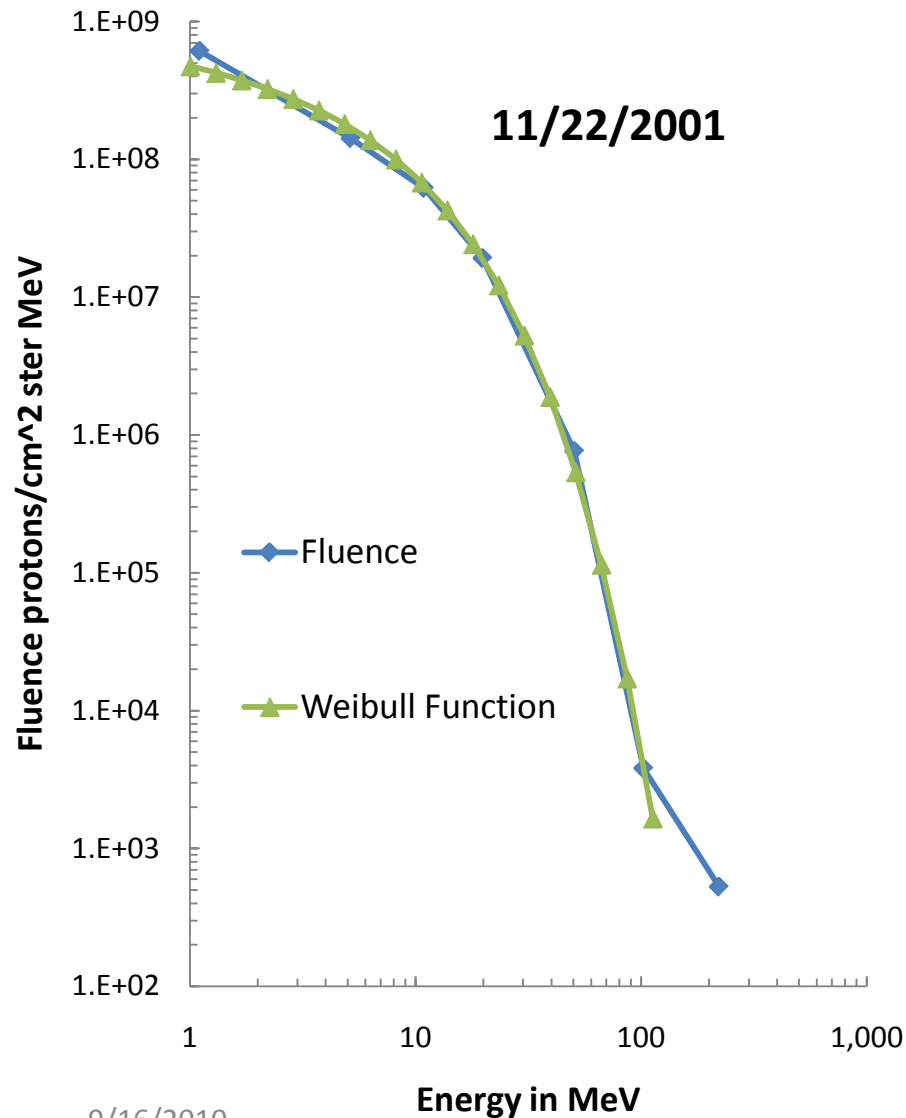
GOES Corrections and Testing

- There are many suggestions for how to correct GOES data. We have chosen:
  - To use the "corrected" data on the GOES FTP site
  - Correct the flux point locations within each energy bin following Mott and Nymmik[*].
- The resulting spectra were tested against:
  - SAMPEX measurements
  - GOES-8 was tested against IMP-8 GME before just November 2001
  - Generally good agreement was found.

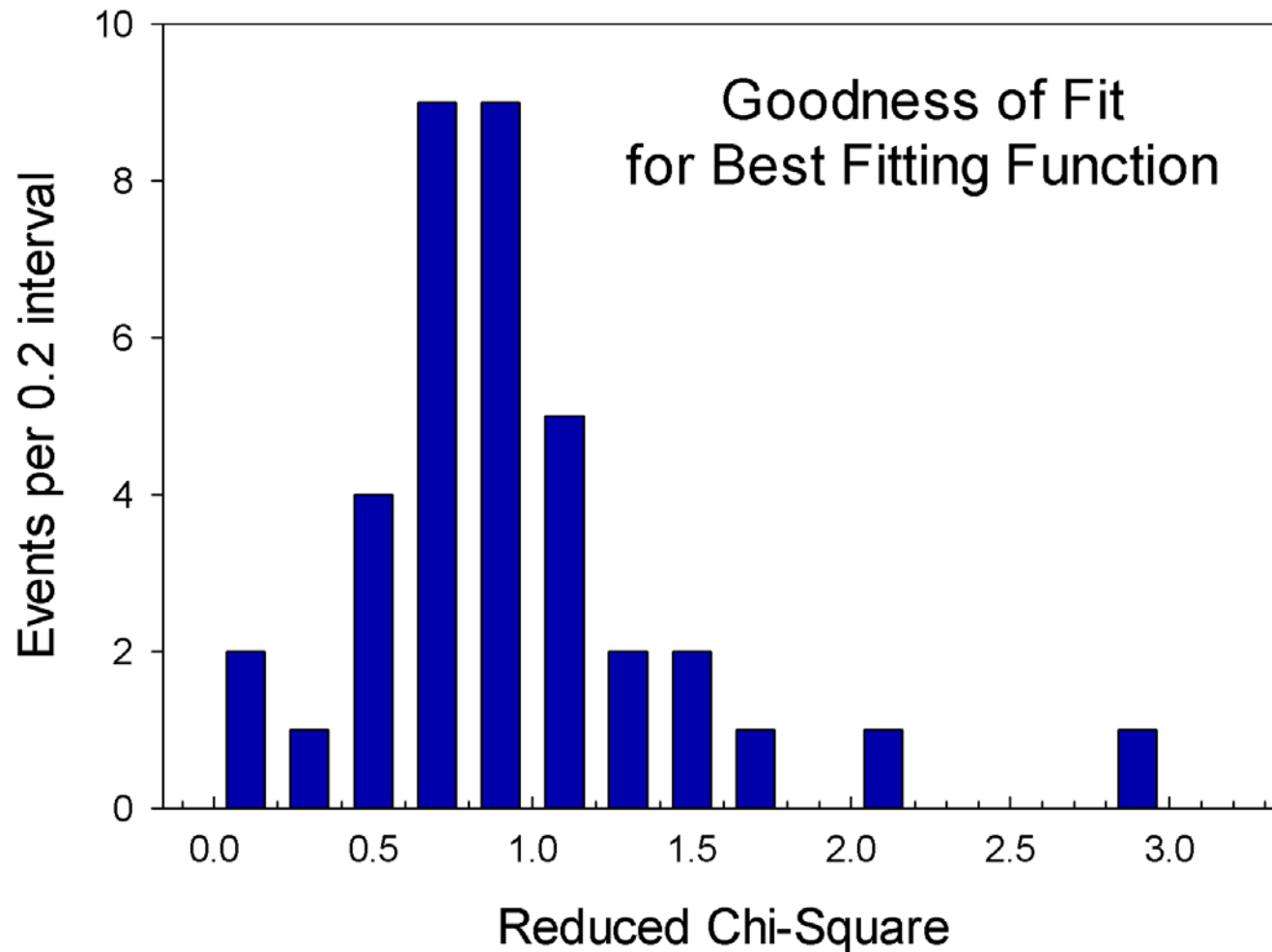[*]Mott and Nymmik, Adv. Sp. Res., **39**, 1355 (2007)

GOES vs SAMPEX PET and IMP8 GME

Spectral Fit Results
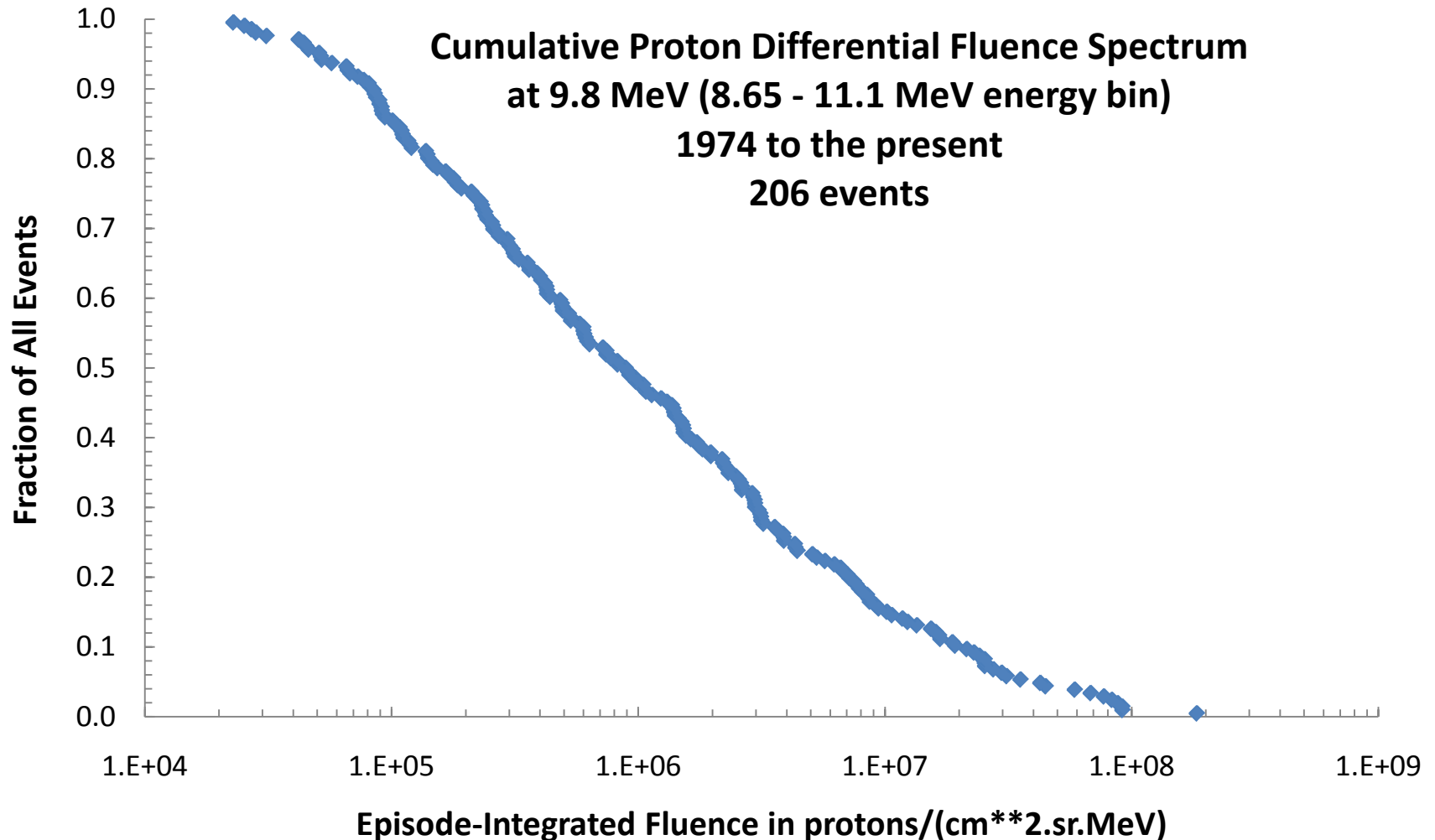
GOES Spectral Fits

Cumulative Spectra

**Cumulative Proton Differential Fluence Spectrum
at 9.8 MeV (8.65 - 11.1 MeV energy bin)
1974 to the present
206 events**

Fraction of All Events

Episode-Integrated Fluence in protons/(cm**2.sr.MeV)

SPE Frequency over the Solar Cycle

**Average No. of Events per Cycle
(1953 – 2006)**

No. of Events / Year relative to Maximum
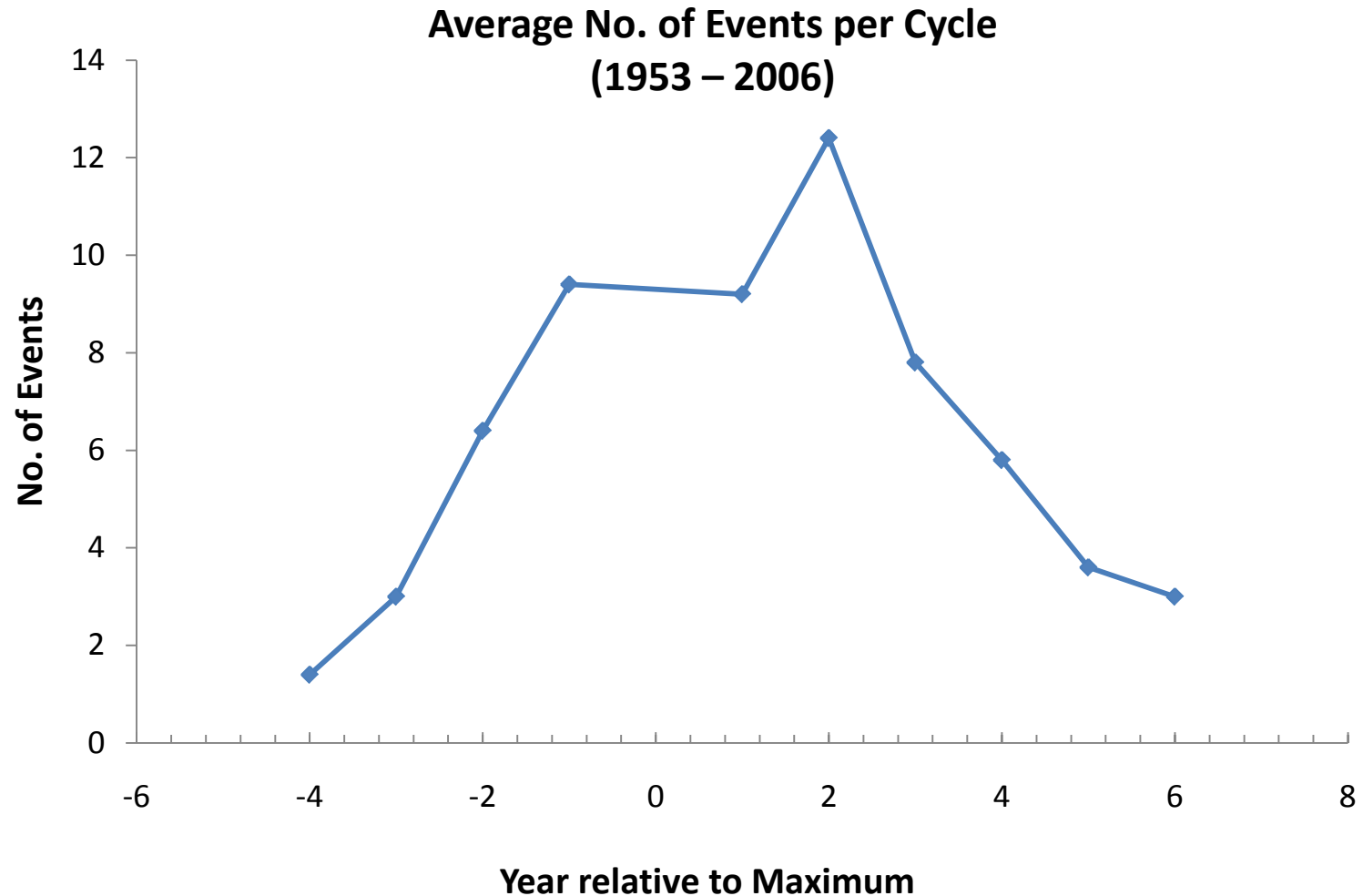
Are SPEs independent of Solar Cycle Phase?

- two sample Kolmogorov-Smirnov tests were used to compare all the SPEs
  - Occurring during solar active periods
  - Occurring during solar quiet periods
- Results: <u>SPE spectra do not depend on solar cycle phase for energies > 5 MeV</u>

Energy cutoff	All Energies	>2.5 MeV	>5 MeV	> 9.7 MeV
K-S Test Value	0.0005	0.114	0.419	0.727

Plans

- Complete Event-integrated Proton Fluence Model
  - Consider extensions
    - Back before 1974
    - To higher energies using GOES HEPAD data and Neutron Monitors
  - Investigate Non-Stationary Extreme Value Models to account for solar cycle variation, e.g.
    - Time-dependent Poission or Burrell distributions
    - Lévy Distribution*
- Repeat for Helium and Heavier Ions
- Repeat to Create a Peak Flux models and Mission Integrated Models.

*Jiggens and Gabriel, JGR, 114, A10105 (2009)

Summary

- **CREME96 is currently available at http://creme.isde.vanderbilt.edu**
  - **Note that the NRL site has closed**
- **The revised model, CRÈME-MC will be released in 2011.**
- **The environmental models described here will become available in CRÈME-MC as they are released**

Thank You

Current Databases

- Peak Proton Flux
  - E > 10 MeV
  - 6/1967 through 12/2006
- Event-integrated Proton Fluences
  - 6/1966 through 10/1995
  - Energy Binning Ranges from:
    - 10 to 150 MeV in 17 energy bins to
    - 1 to 300 MeV in 23 energy bins
- Daily-integrated Proton fluences
  - 11/1973 through 10/2001
  - 1.01 to 398 MeV in 29 energy bins

Initial Distribution

- The initial Distribution is:

$$N(\phi) = N_{tot}(\phi^{-b} - \phi_{max}^{-b})/(\phi_{min}^{-b} - \phi_{max}^{-b})$$

- Where

  - ϕ_{min} = 10
  - N_{tot} = 10
  - b = 0.41 and
  - ϕ_{max} = 1.3X10^5

Initial Distribution for Proton Peak Flux > 10 MeV for May 1967 to Dec 2006