Modeling Mission-Specific Worst-Case Solar Energetic Particle Environments

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Abstract: To plan and design safe and reliable space missions, it is necessary to take into account the effects of the space radiation environment. The environment during large solar energetic particle events poses the greatest challenge to missions. As a starting point for planning and design, a reference environment must be specified representing the most challenging environment to be encountered during the mission at some confidence level. The engineering challenge is then to find plans and mission design solutions that insure safe and reliable operations in this reference environment. This paper describes progress toward developing a model that provides such reference space radiation environments at user-specified confidence levels.

Modeling Mission-Specific Worst-Case Solar Energetic Particle Environments

by J. H. Adams, Jr.[a], W.F. Dietrich[b] and M.A. Xapsos[c]

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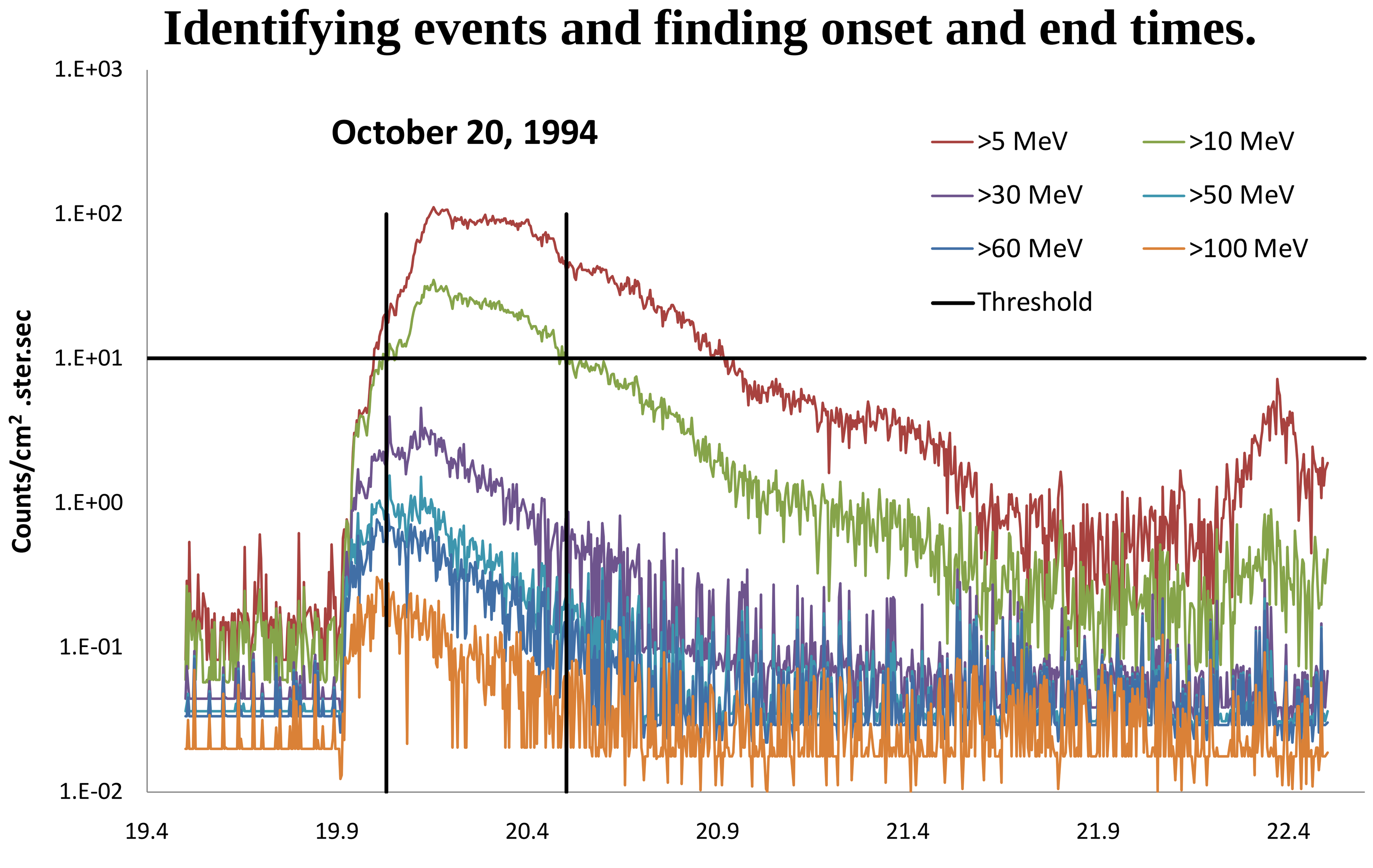
Abstract: To plan and design safe and reliable space missions, it is necessary to take into account the effects of the space radiation environment. The environment during large solar energetic particle events poses the greatest challenge to missions. As a starting point for planning and design, a reference environment must be specified representing the most challenging environment to be encountered during the mission at some confidence level. The engineering challenge is then to develop plans and mission design solutions that insure safe and reliable operations in this reference environment. This poster describes progress toward developing a model that provides mission-specific reference space radiation environments at user-specified confidence levels. The examples shown here are for episode-integrated proton fluence spectra.

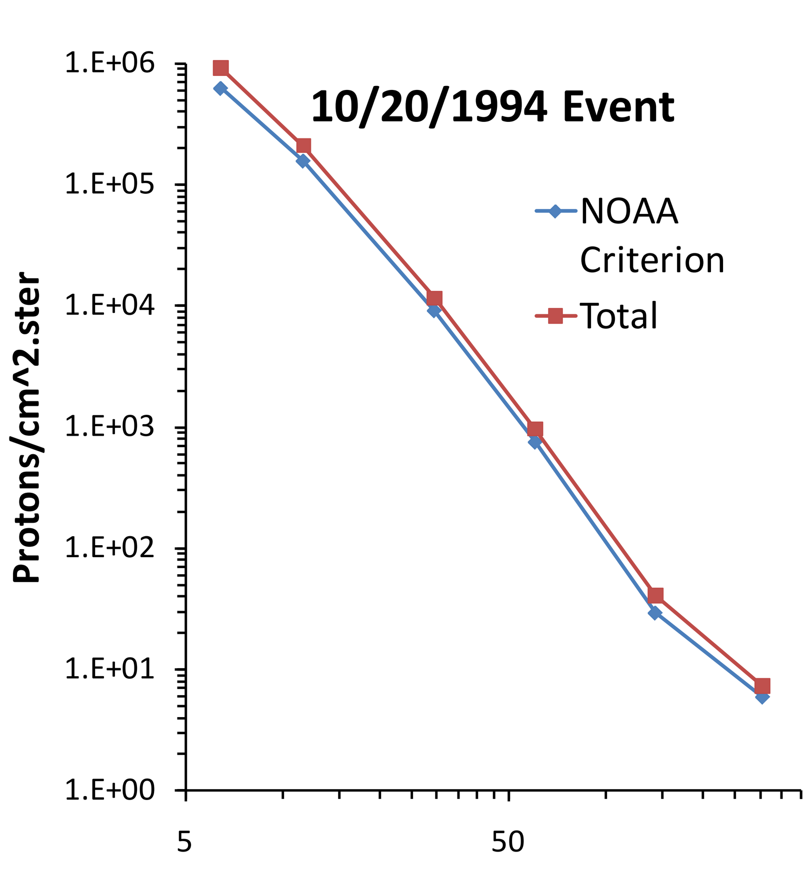
Step 1: Select solar energetic particle events for the data base

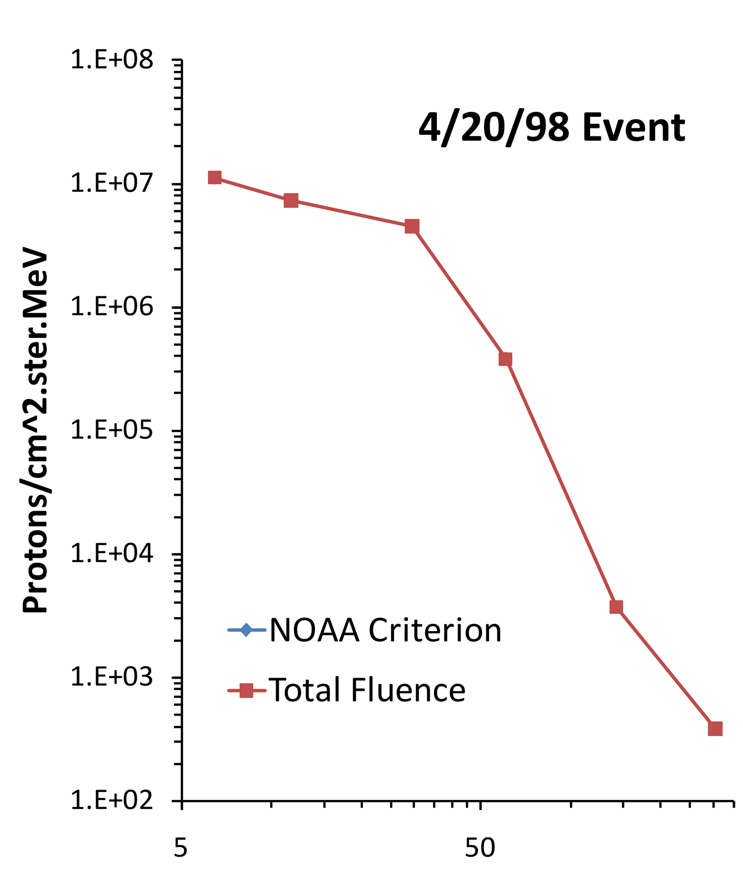
- **NOAA Criterion**
  - o Onset: *The first of 3 consecutive data points with >10 MeV proton fluxes ≥ 10 PFU (protons/cm2.ster.sec).*
  - o **End:** *The last data point ≥ 10 PFU*.*

Identifying events and finding onset and end times.

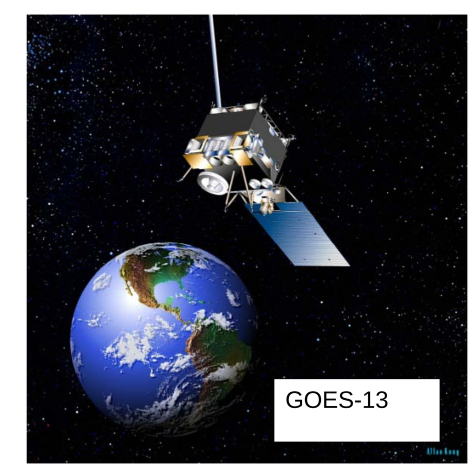


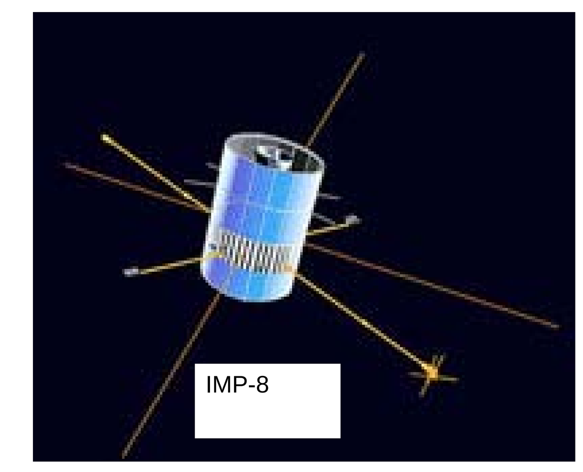
The smallest events are affected most by the NOAA criterion.





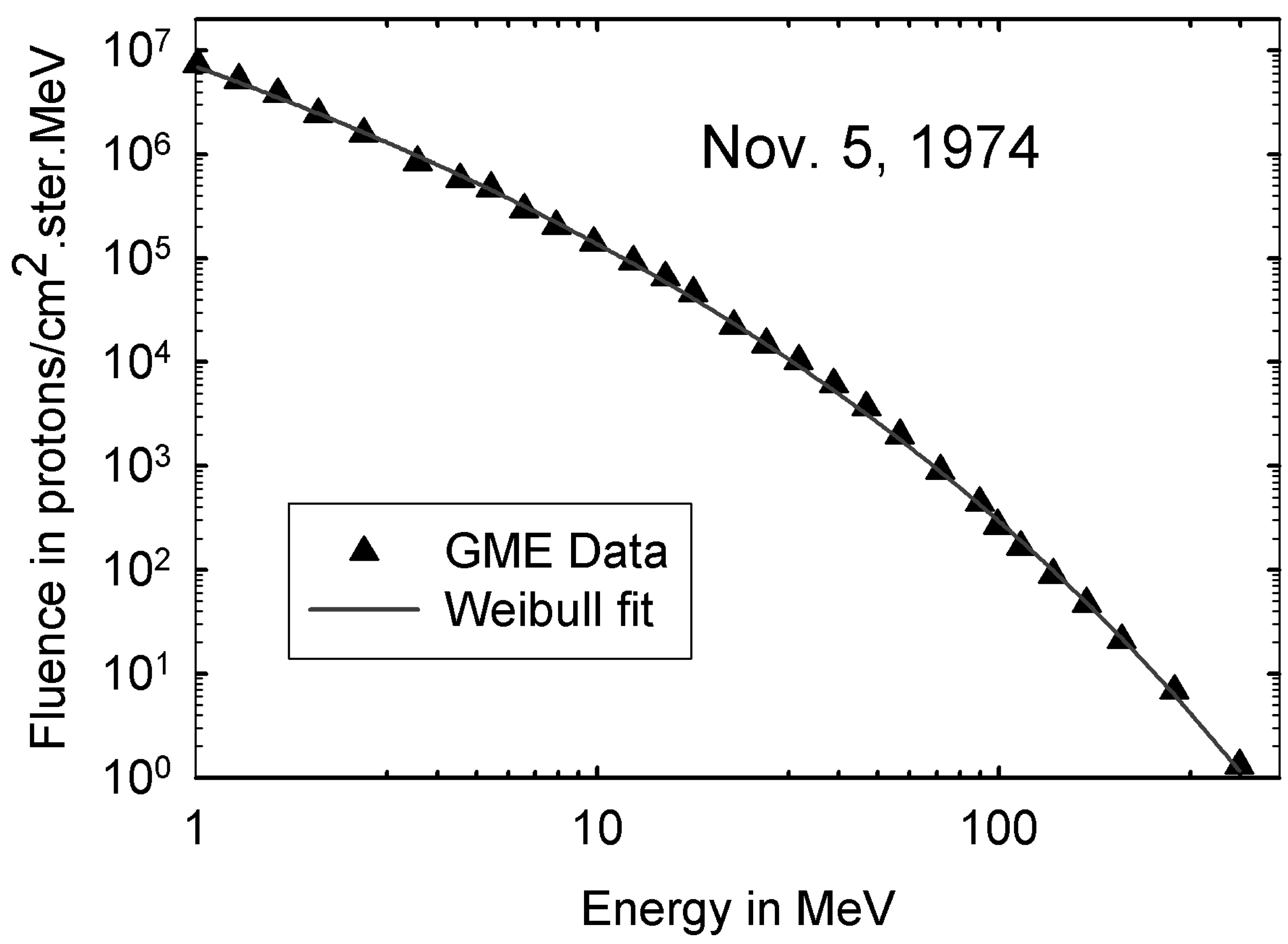
Data Sources:

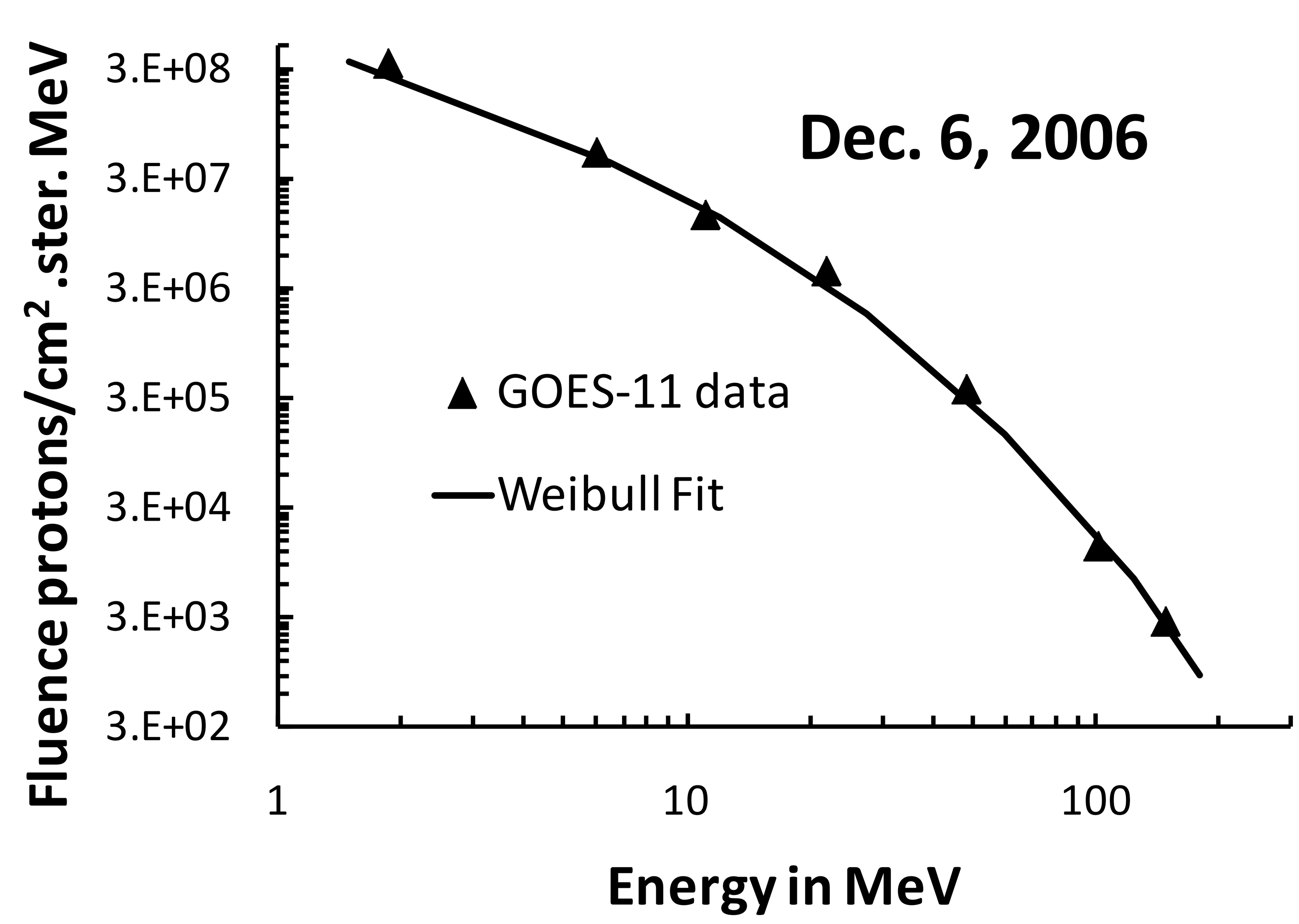




Step 2: Determining the energy spectra for each event

- **Determine the spectra in the instrument-defined energy bins**
- **Convert the spectra to a common set of energy channels.**
  - o requires spectral fitting to redistribute the energy into the common set of energy bins





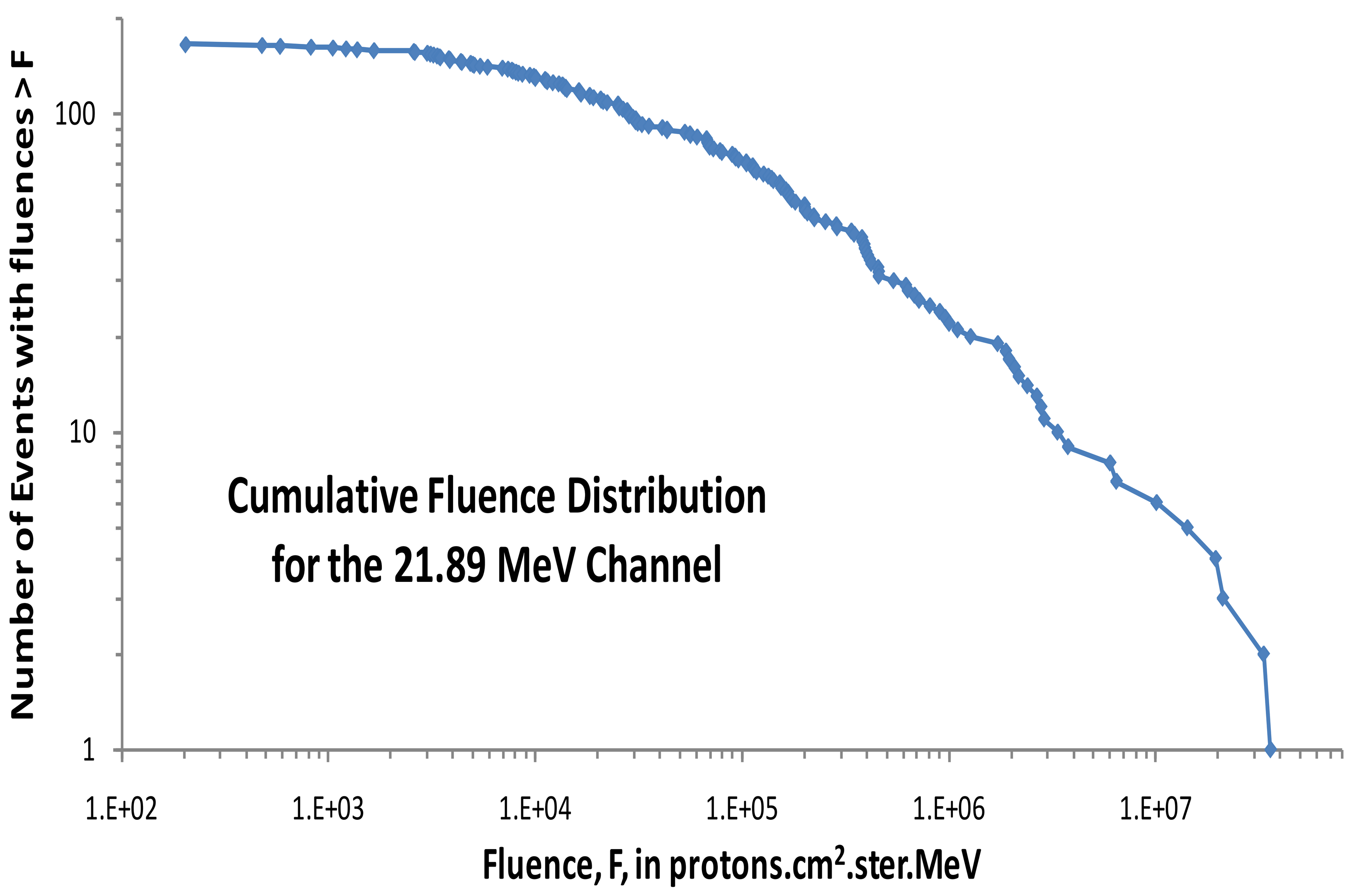
- **We have fit 214 episodes with:**
  - The Ellison-Ramaty Model (90)
  - The Band Function (116)
  - The Weibull Function (136)
- **In many cases two or three of these models gave good fits.**

Step 3: Construct cumulative distributions of the fluxes for each energy channel.

• Below is an example of the cumulative distribution for the 21.89 MeV energy channel

• Each cumulative distribution must be fit by a Fréchet Distribution

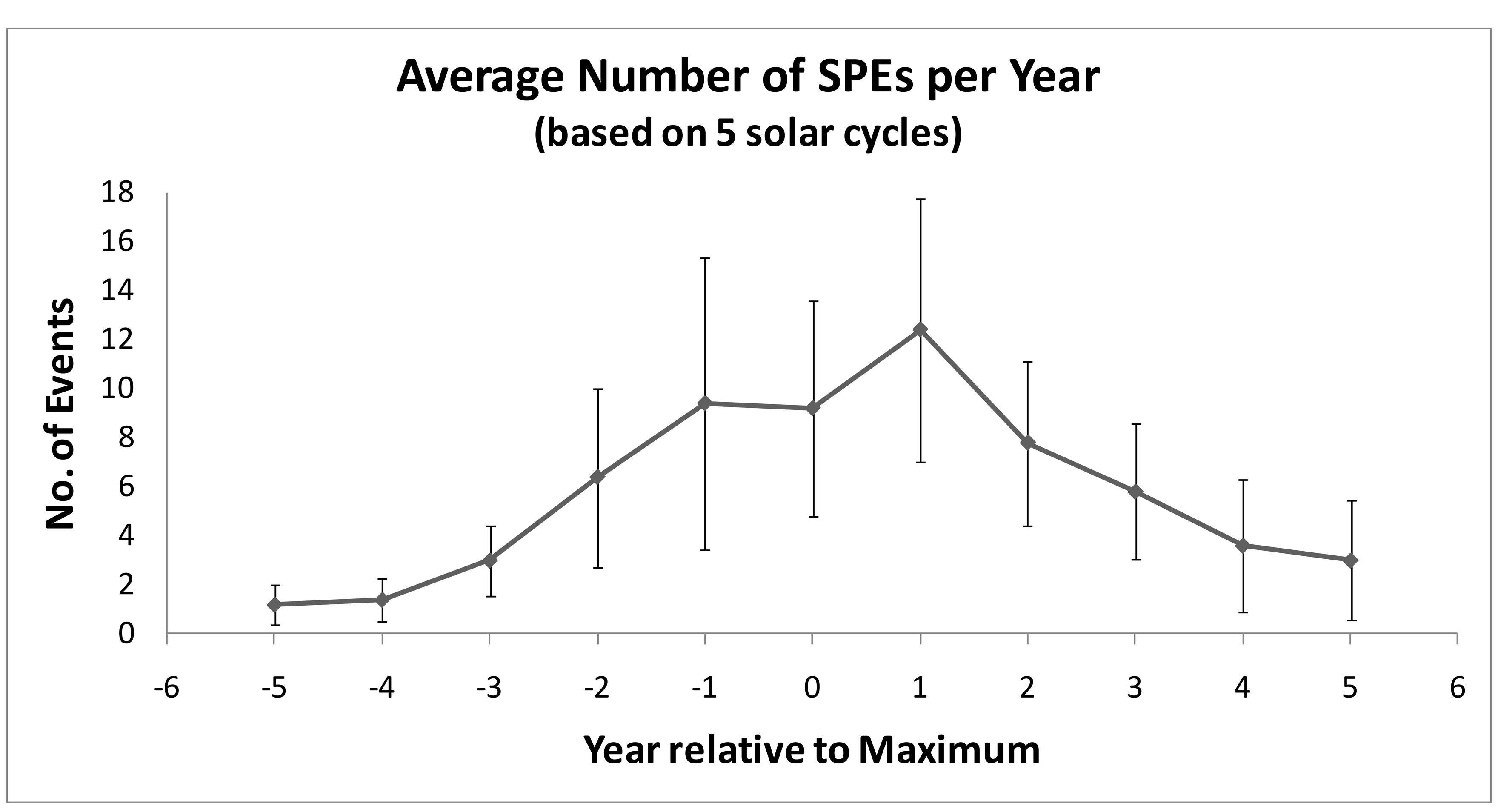
$$P(\phi) = (\phi_{min}^{-b} - \phi^{-b})/(\phi_{min}^{-b} - \phi_{max}^{-b})$$



Step 4: Convolve the cumulative distributions with a Poisson distribution to create an extreme value distribution for the fluence in each energy channel.

$$F_T(\phi) = \exp\{-\mu T[1 - P(\phi)]\}$$

• The event frequency varies over the solar cycle so extreme value distributions must be constructed for each year of the solar cycle.



Step 5: Construct the Worst Case Spectrum

• Using the user-supplied launch date and mission duration, determine from the figure above, the average number of SPEs expected during the mission.

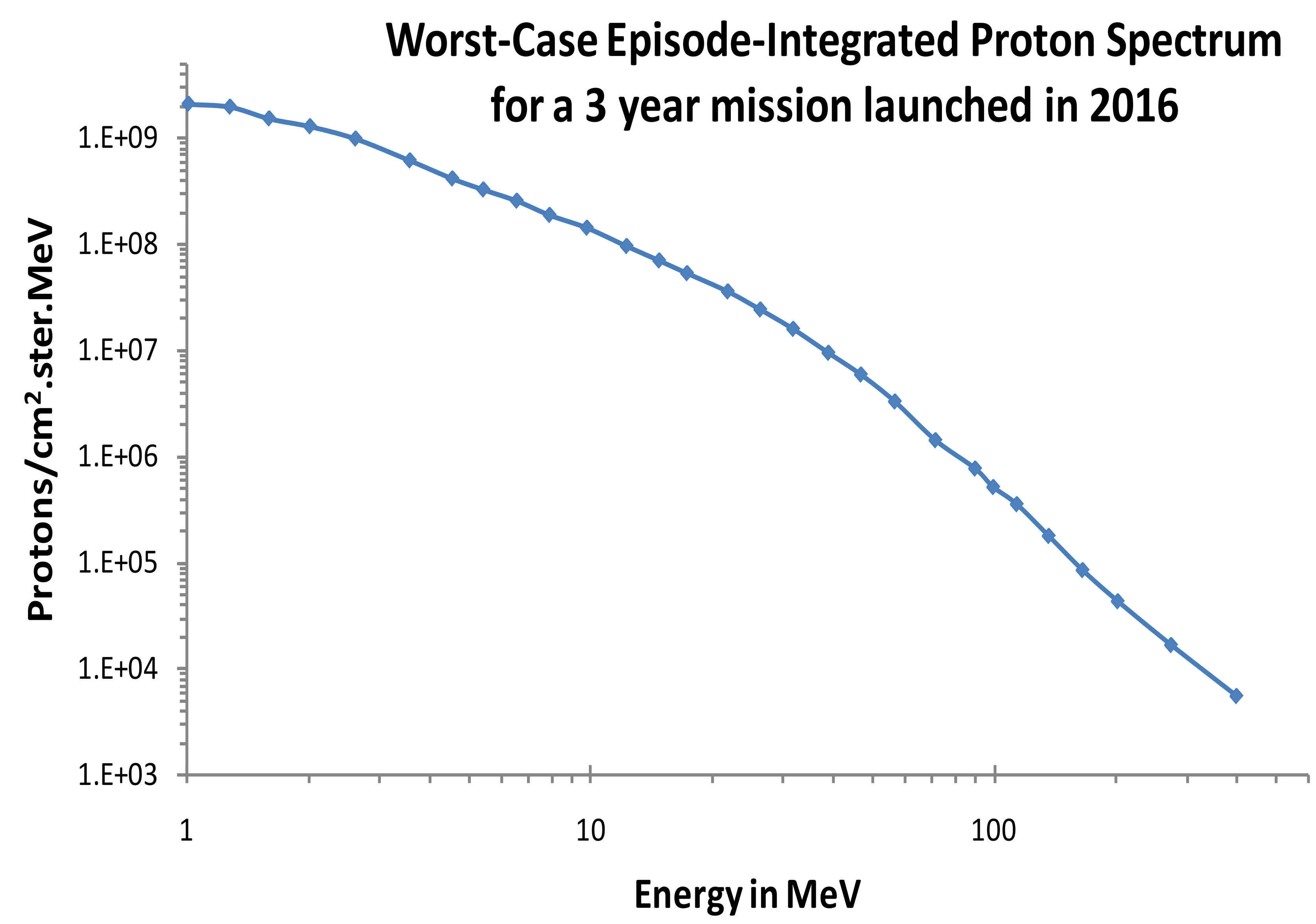
• Use the mission-average number of SPEs to construct the extreme value distribution for each energy bin.

• Use the user-supplied confidence level to determine the fluence in each energy bin that corresponds to this confidence level.

• Construct the mission-specific worst-case fluence spectrum.

• An example is shown in the next column.

o It is for a three-year mission launched in 2016 at a 90% confidence level.



Summary

- **We have developed a model for estimating the worst-case episode-integrated proton spectrum that is:**

  o Specific to the mission start date and duration

  o At a user-specified confidence level

- **<u>Limitations</u>: Can't obtain high confidence level reference environments for long missions that are supported by data.**

- **We plan to extend this model to:**

  o Alpha particles and Heavy ions

  o We plan to construct similar models for peak fluxes and mission-integrated fluences.

References:

[1] J. Feynman et al., JGR, **98**, 13,281 (1993).

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[3] M. A. Xapsos et al., MSFC SEE Program, http://see.msfc.nasa.gov.

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[8] J.N. Kapur, *Maximum Entropy Models in Science and Engineering*, John Wiley and Sons, Inc., NY (1989).

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[11] E.C. Stone et al., Space Science Reviews, 86, 285 (1998)

[12] M.O. Burrell, in NASA TM X-2440, 310-323 (1972)

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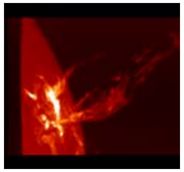
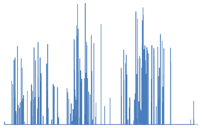
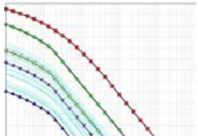
Outline



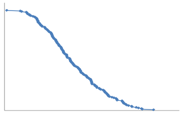
Determining a reference worst-case environment.



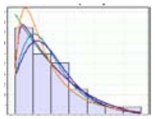
Selecting the SPEs.



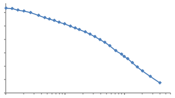
Determining the energy spectra for each event.



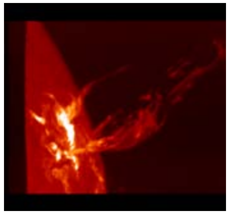
Constructing the cumulative spectra.



Finding the extreme-value distributions.

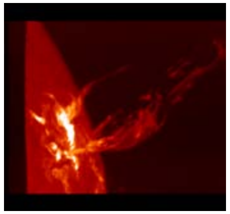


Finding the worst-case energy spectra.



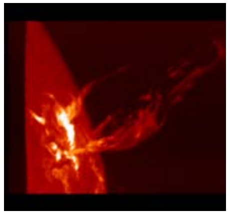
What is a reference environment and why do we need one?

- A Reference Worst-Case Environment in the local interplanetary medium is needed for:
  - Spacecraft design
  - Mission planning
- Objective: Determine an environment that:
  - Won't be exceeded at a specified confidence level
  - For a user-specified mission, e.g.
    - Launch date, mission duration, heliospheric location
- <u>This talk focuses on the proton component of the Reference Worst-Case Environment</u>



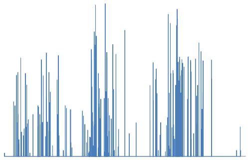
Past work on reference environments

- JPL Model Objective:
- Xapsos Models
- Rosenqvist Model
- Jiggens Model



How is the Reference Worst-Case Environment determined?

- Build a database of SPEs with measured elemental spectra and time-histories.
- Decide how to treat solar cycle dependence of SPE.
- Form cumulative frequency distributions for each differential energy channel.
- Construct extreme value distributions for each channel.
- Using the user-supplied orbit, launch date mission duration and confidence level, construct the worst case elemental spectra.



The first step: Event Selection

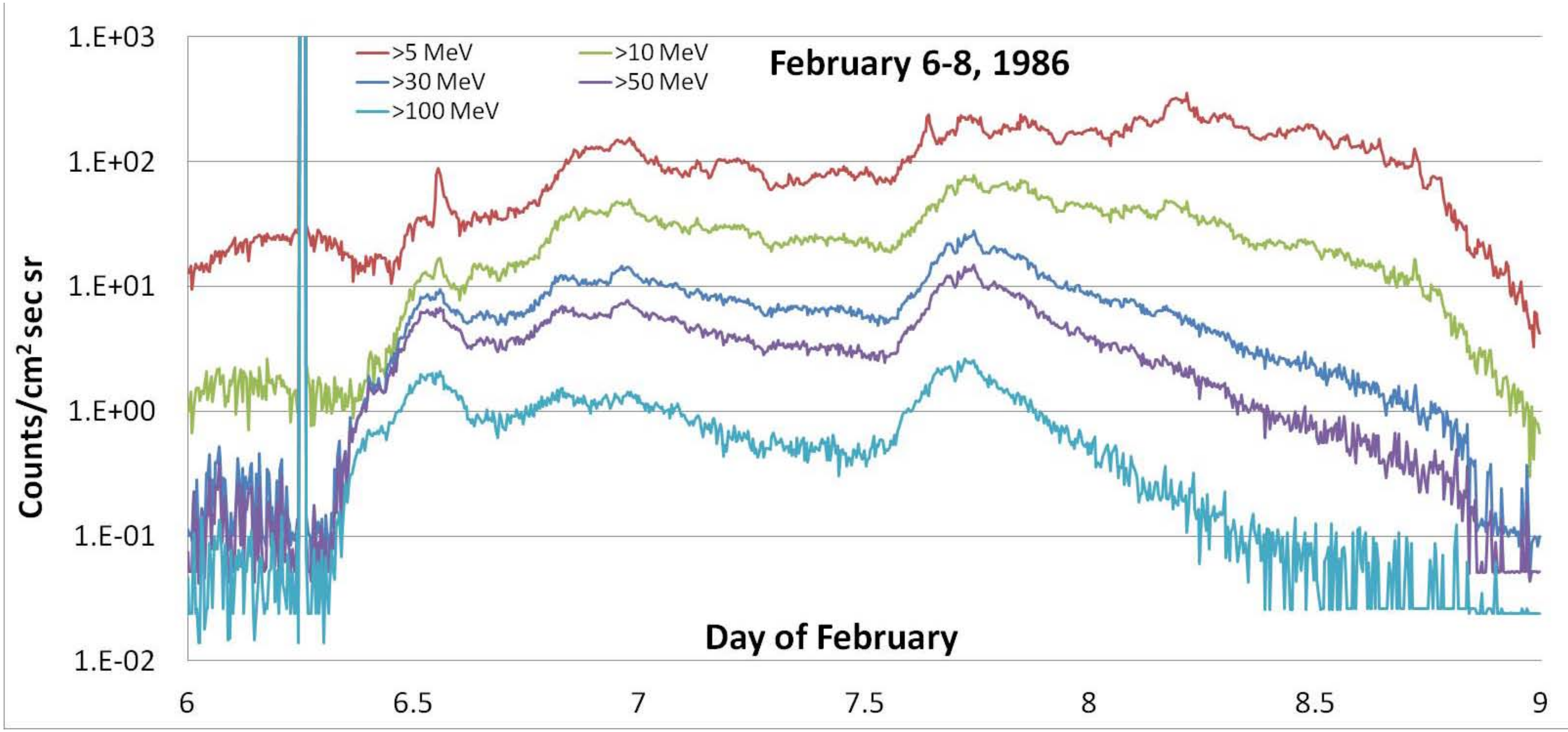
- Use a consistent selection criterion that can be applied over the broadest time span $\Rightarrow$ Use GOES data (1974-present)
- Group sequences of events that appear to be correlated into episodes (same active region, sympathetic triggering, etc.)
- Minimize biases due to how onset and ending times are determined.

We have chosen to use the NOAA criterion:

- **Onset:** *The first of 3 consecutive data points with >10 MeV proton fluxes ≥ 10 PFU*.*
- **End:** *The last data point ≥ 10 PFU*.*

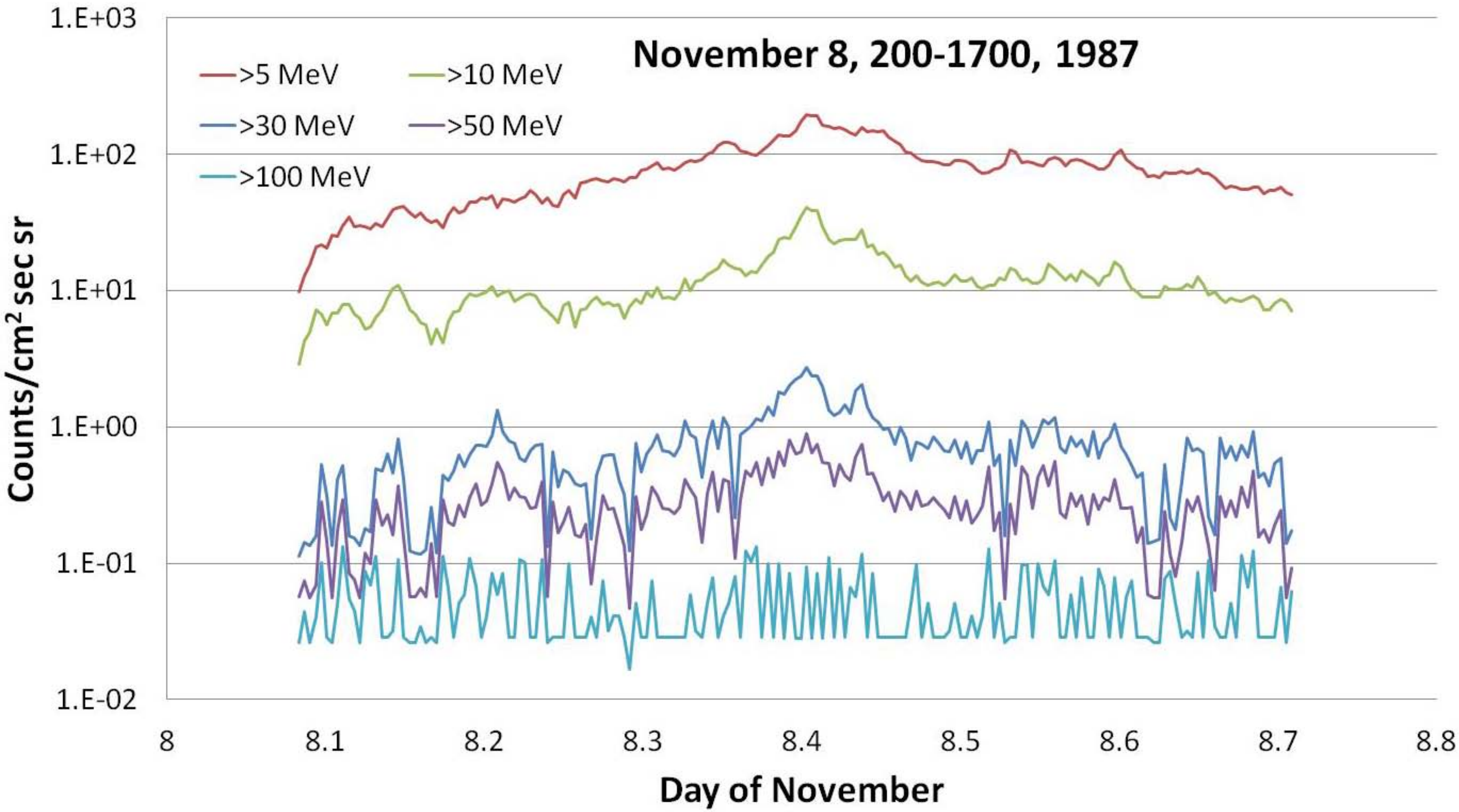
*protons/cm^2.ster.sec.

Applying the NOAA Criterion, example 1



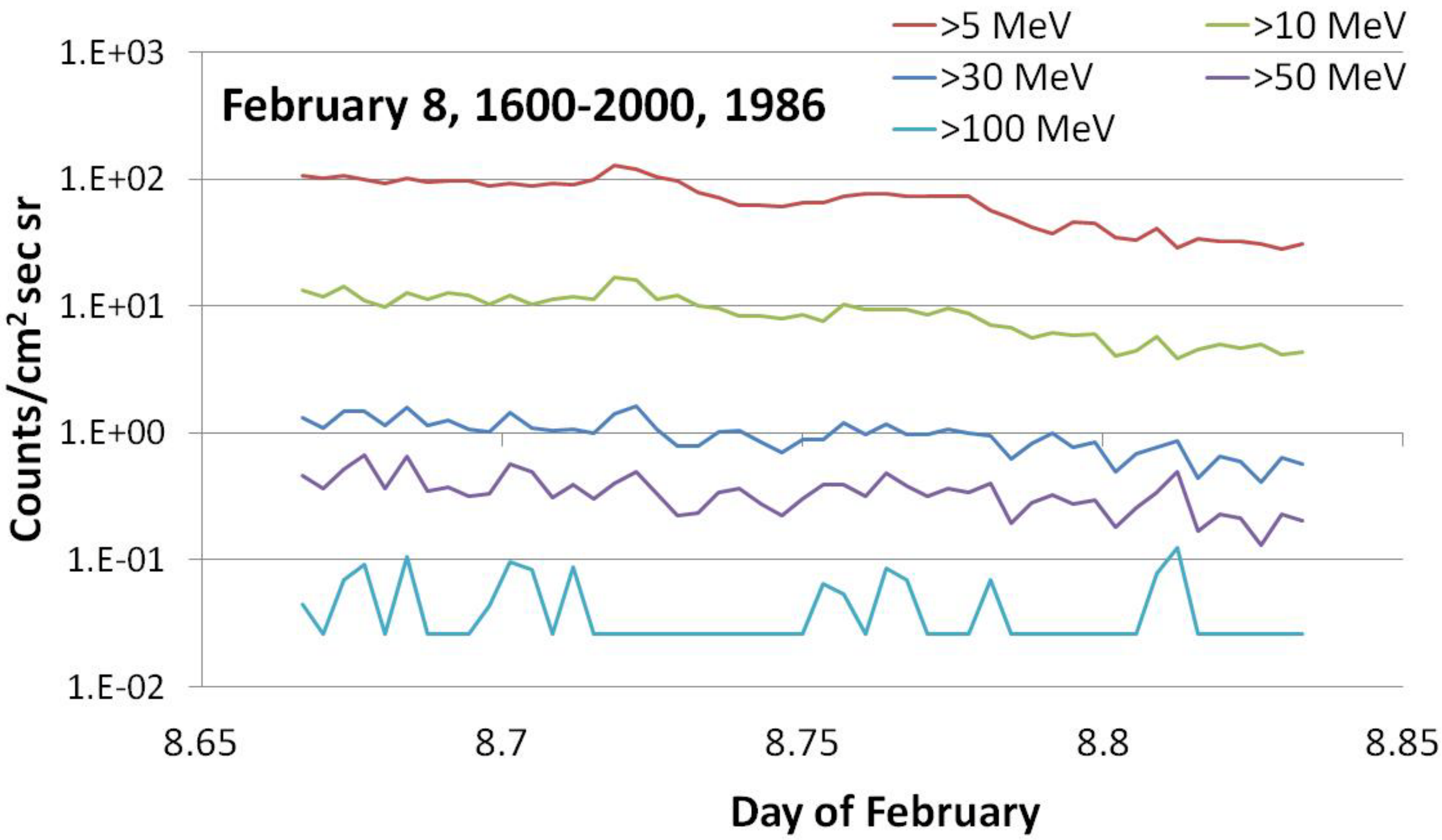
- **Missing or bad data:** 6:00-6:15 on 2/6
- **Multiple events:** There appears to be an episode of ≥2 correlated events
- **1 or 2 Events:** Strictly applying the criterion, the first event ends at 14:00 on 2/6, but this is not really the end of the episode.

Applying the NOAA Criterion, example 2



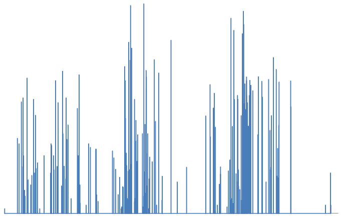
- **Where is the onset?** Strictly, at 7:50 but The event started much earlier at ~3:25.

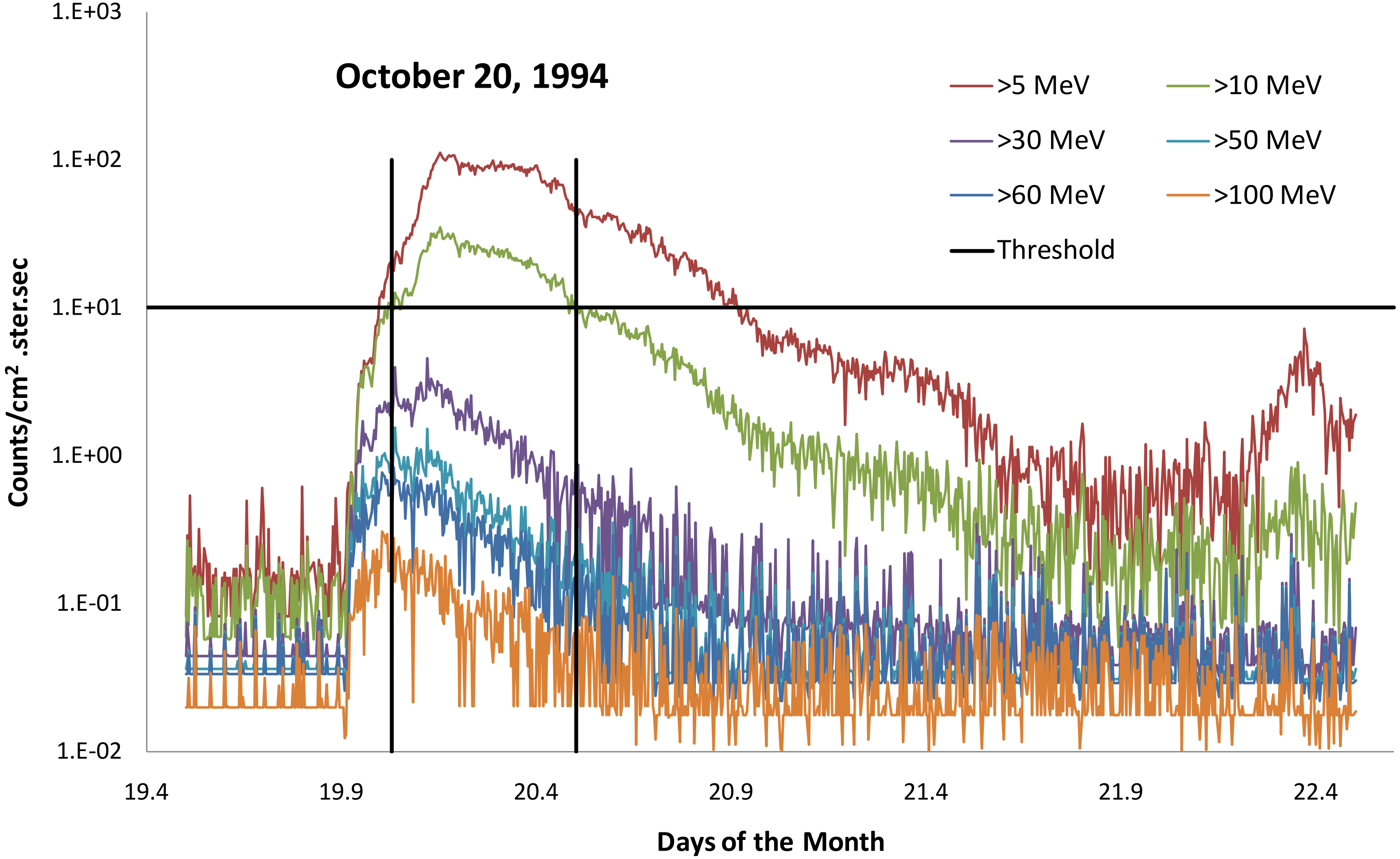
Applying the NOAA Criterion, example 3

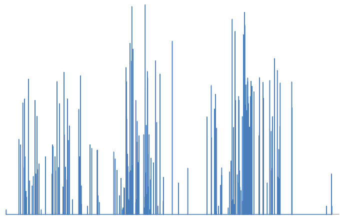


- **Where does it end?** Strictly, at 16:20 but the trend falls below 10 PFU at about 17:30.

Time-of-flight delay and energy-dependent recovery







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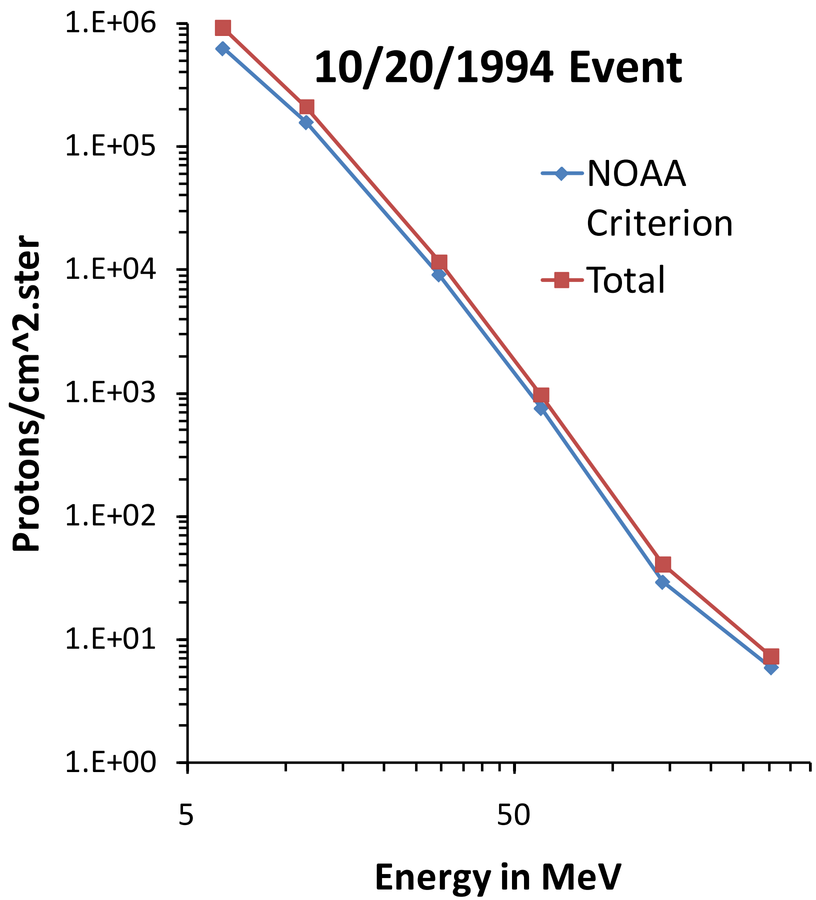
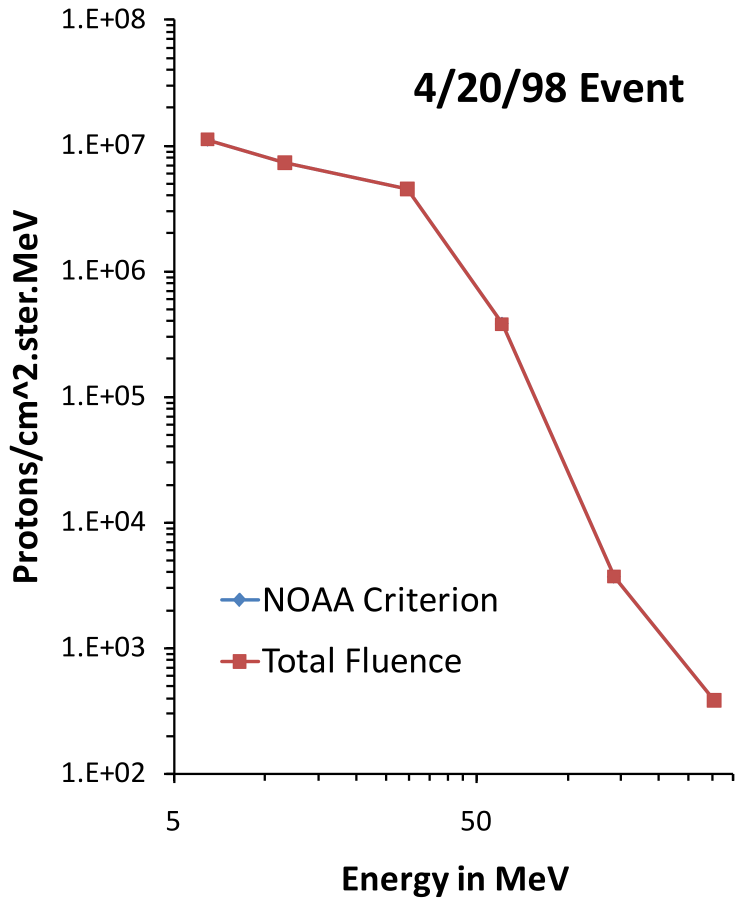
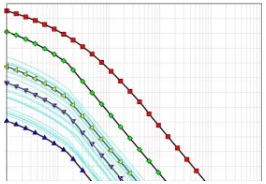
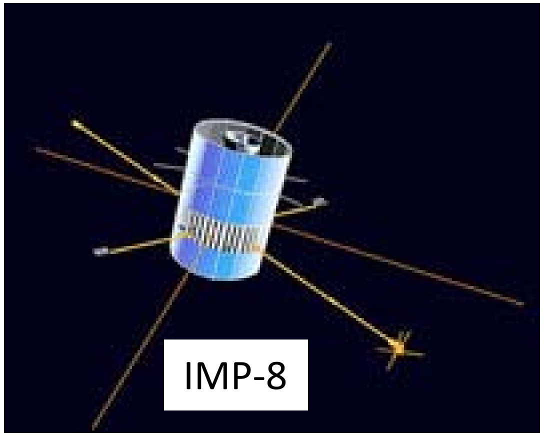


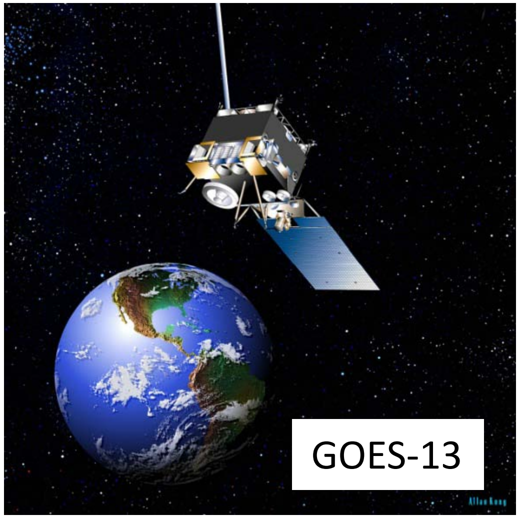


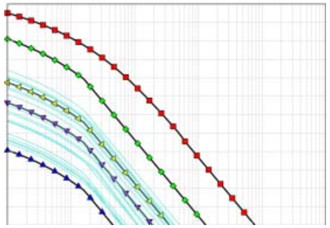


Episode-integrated proton spectra

- Proton Data Sources
  - 7/74 – 10/01: IMP-8 GME
    - 167 episodes
  - 11/02 – Present: GOES
    - 47 episodes
- Common spectral binning
  - Adopted 29 GME channels
- Redistribute GOES data into GME channels
  - Fit GOES spectra with a spectral form, e.g. double power law
  - Distribute flux into GME channels

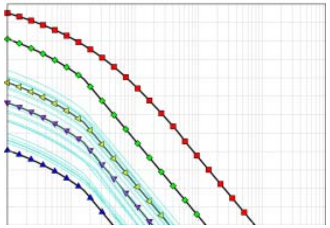






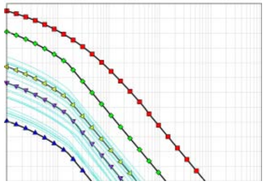
Data sources for other elemental spectra.

- **Helium**
  - 7/1974 - 10/2001: IMP-8 GME
  - 11/2001 – present: GOES
- **Heavy Ions**
  - 7/1974 - 10/2001: IMP-8 CRNE
  - 11/2001 – present: ACE SIS

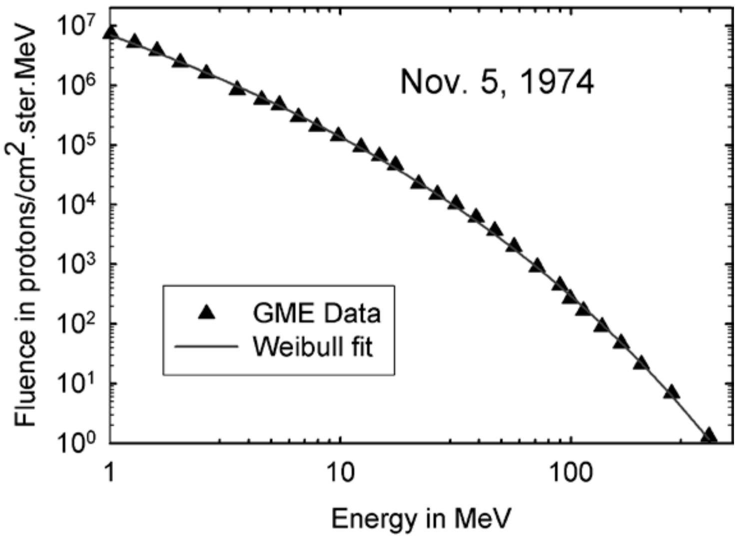


Putting all the proton spectra in a standard format

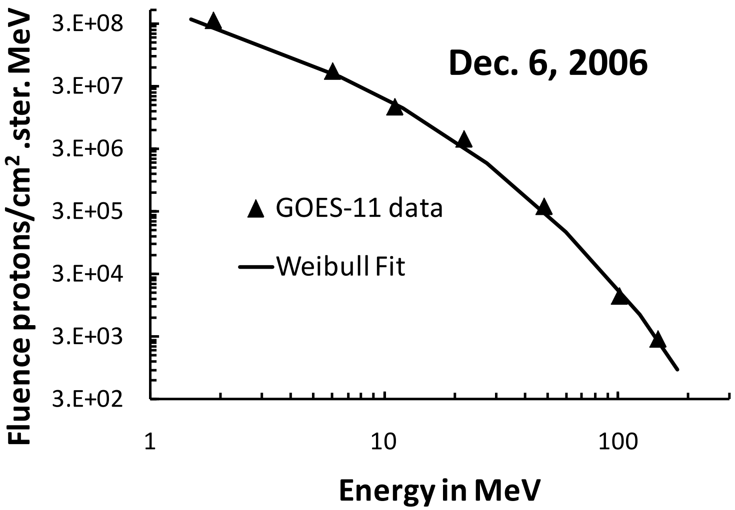
- The IMP-8 GME format with 29 energy bins was chosen as the standard format.
  - The spectra for the events before Nov. 2001 are taken from GME measurements.
- For events after October 2001, GOES data were used.
  - The 7-energy-bin GOES spectra were fitted.
  - The best spectral fits were used to re-bin the data into the GME format with 29 bins

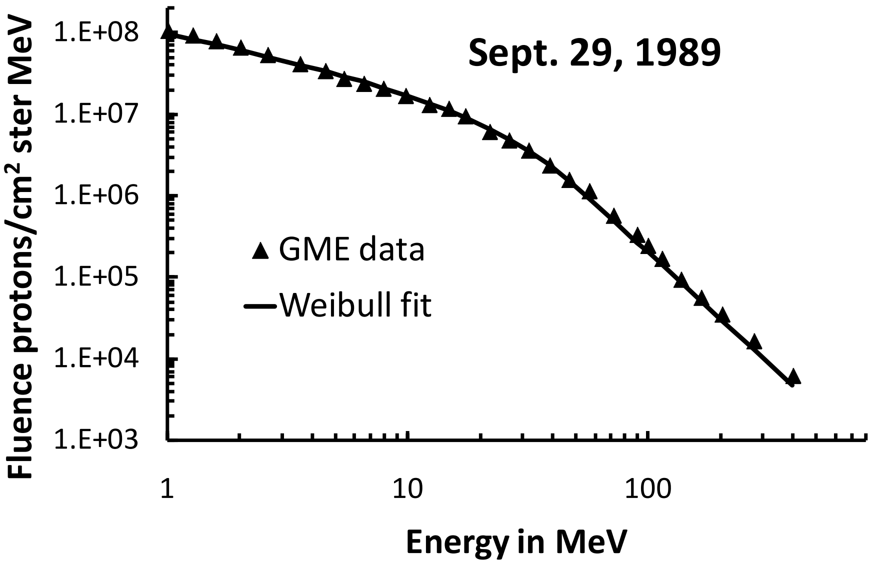


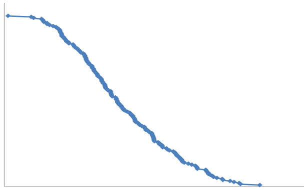
Measured proton spectra and fits



- We have fit 214 episodes with:
  - The Ellison-Ramaty Model (90)
  - The Band Function (116)
  - The Weibull Function (136)
- In many cases two or three of these models gave good fits.

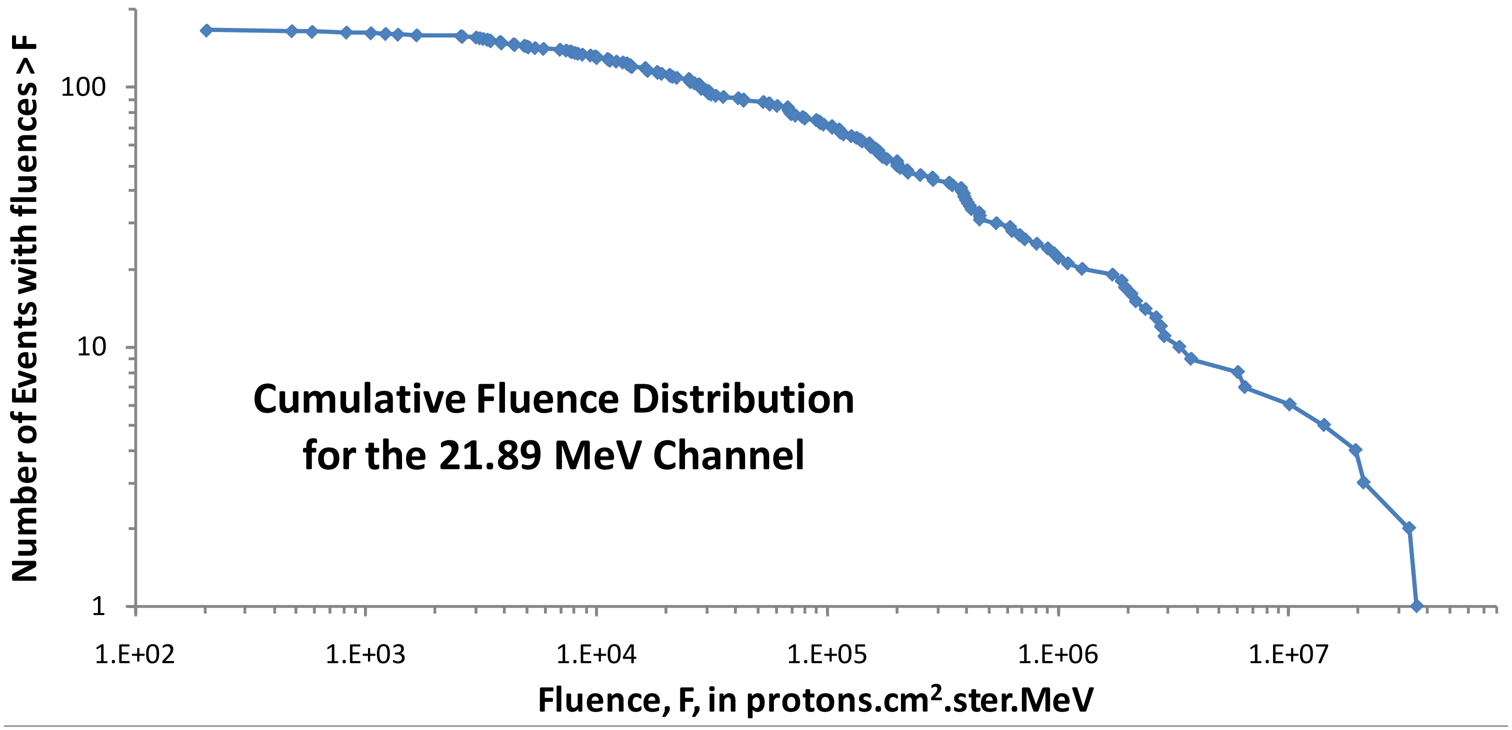


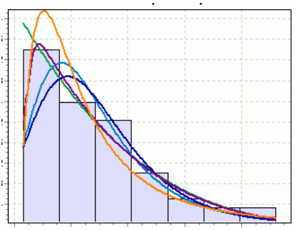




Cumulative spectra

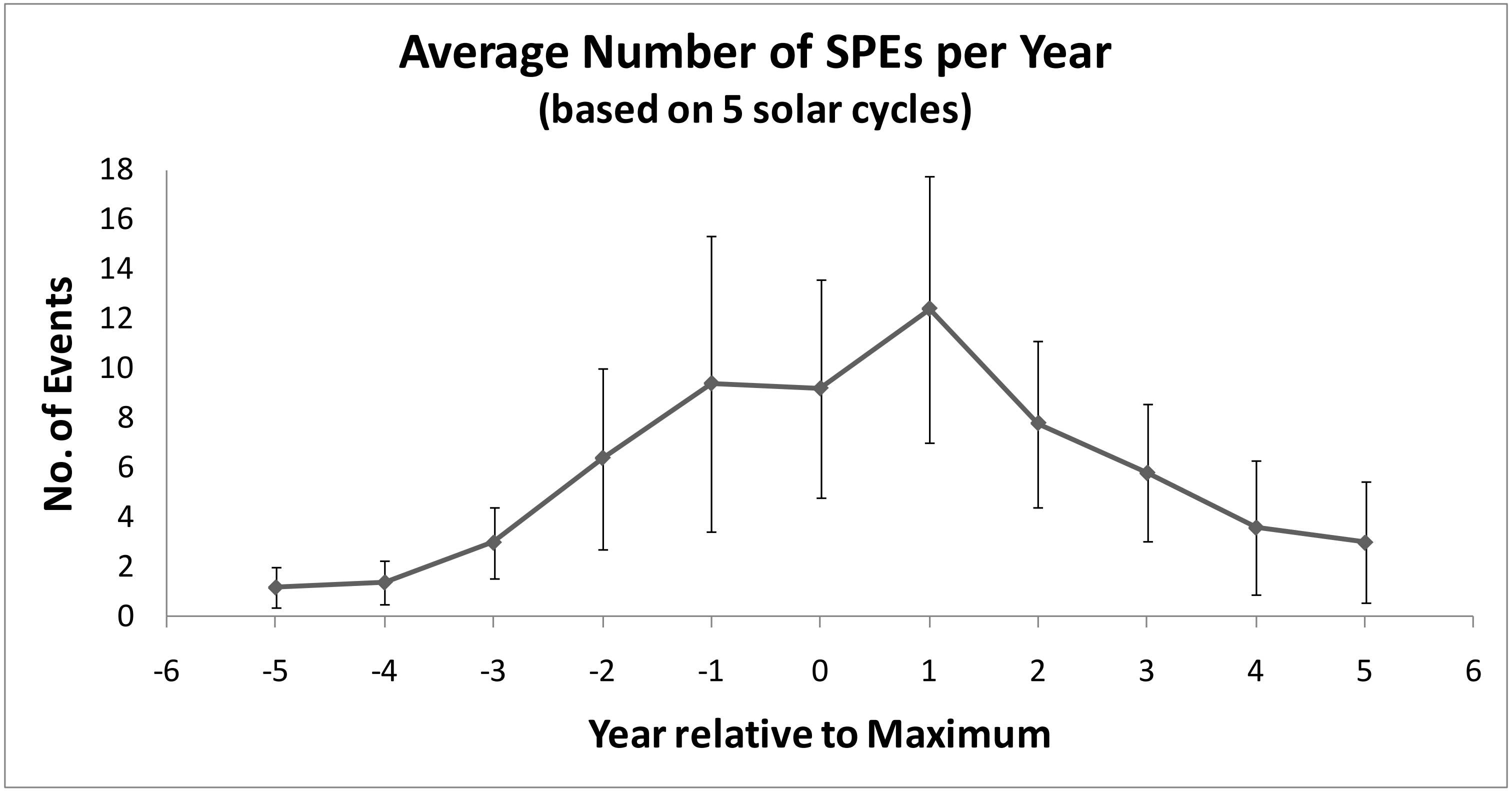
- Cumulative spectra were constructed for each energy bin.
  - An example is shown below.

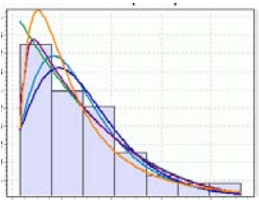




Solar Cycle variation is SPE probability

- The probability of occurrence of solar particle events varies over the 11-year solar cycle as shown below.





Extreme Value Model

- The number average number of SPEs, N, expected during the mission is found by summing over the part of the solar cycle covered by the mission.
- N is used to construct a Poisson distribution, $P(n)$.

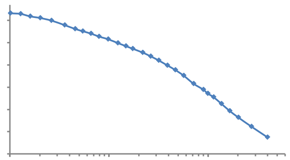
$$P(n) = [e^{(-N)}(N)^n]/n!$$

- The cumulative distributions, $C(\phi)$, are fit with the following function (Xapsos et al., 1998):

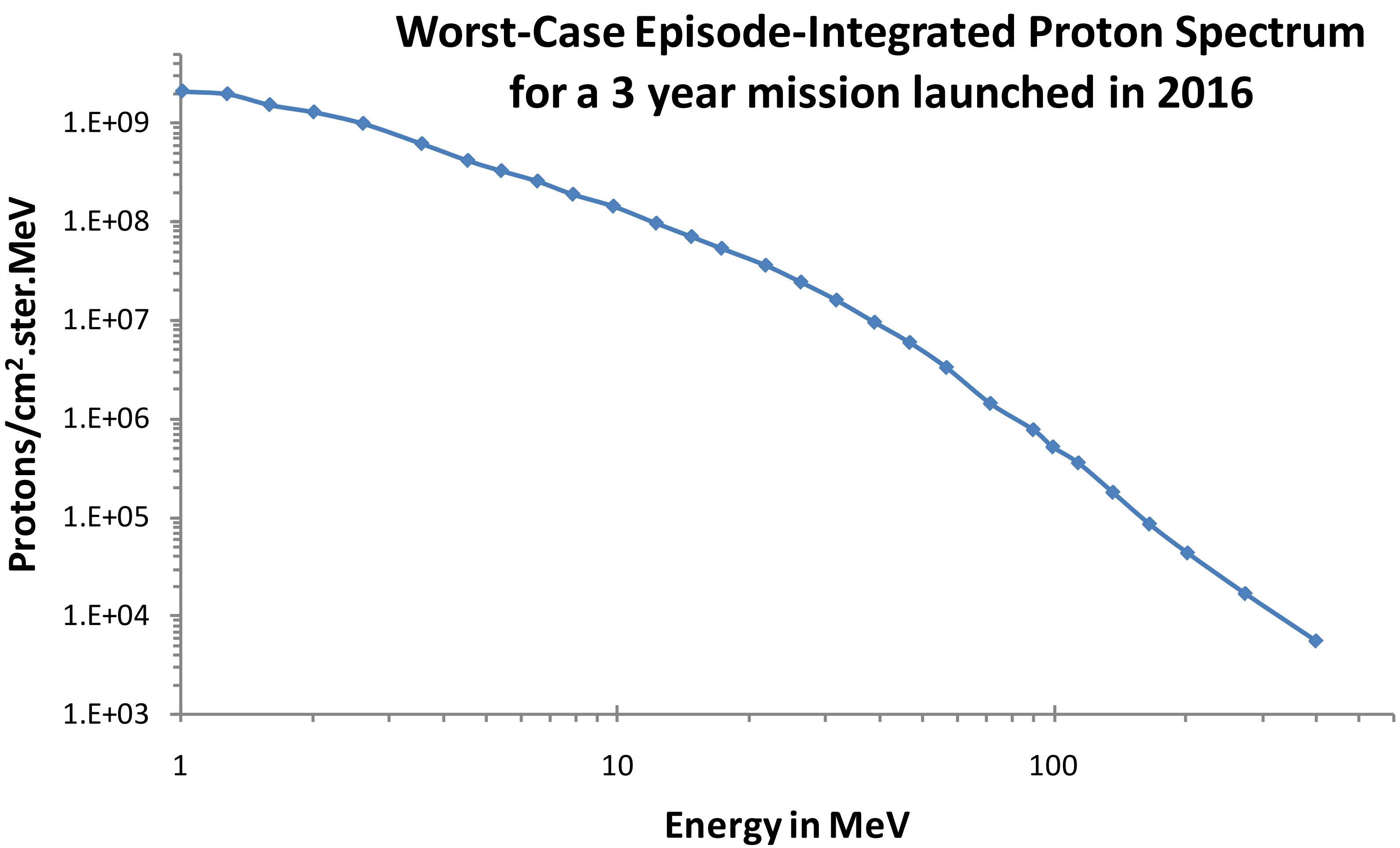
$$C(\phi) = (\phi^{-b} - \phi_{max}^{-b})/(\phi_{min}^{-b} - \phi_{max}^{-b})$$

- These distributions are convolved to get extreme value distributions for each energy bin:

$$F_i(\phi) = \exp\{-NP_i(\phi)\}$$



Worst-Case Proton Spectrum



Summary

- We have developed a model for estimating the worst-case episode-integrated proton spectrum that is:
  - Specific to the mission start date and duration
  - At a user-specified confidence level
- Limitations: Can't obtain high confidence level reference environments for long missions that are supported by data.
- We plan to extend this model to:
  - Alpha particles and Heavy ions
- We plan to construct similar models for peak fluxes and mission-integrated fluences.