Extreme Relativistic Electron Fluxes in GPS Orbit

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British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Sat-Risk

Space Weather

- Modern society is increasingly reliant on satellites for a wide variety of applications including communication, navigation, Earth observation and defence
- This ever growing infrastructure is increasingly vulnerable to the potentially damaging effects of space weather

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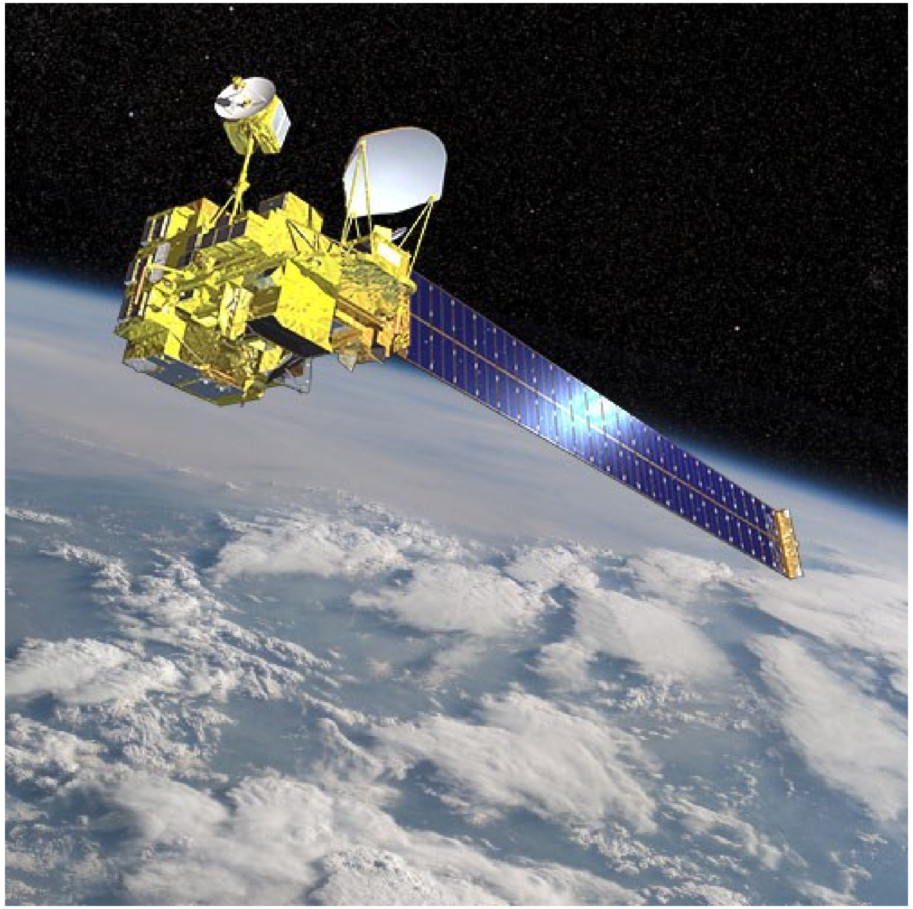
- The likelihood of a reasonable worst case scenario occurring in the next year is estimated to be between 1 in 20 and 1 in 100

Space Weather Effects on Satellites

- The impacts of space weather on satellite operations range from momentary interruptions of service to total loss of capabilities when a satellite fails



Artists impression of Midori-2 satellite

Space Weather Effects on Satellites

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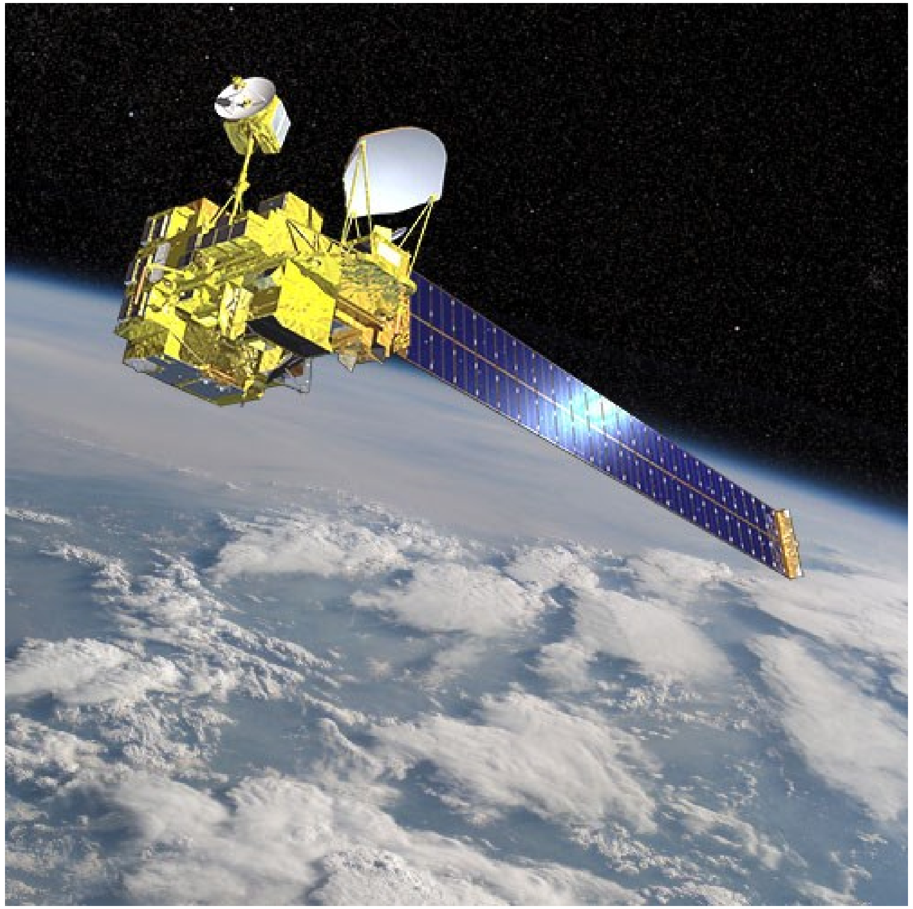
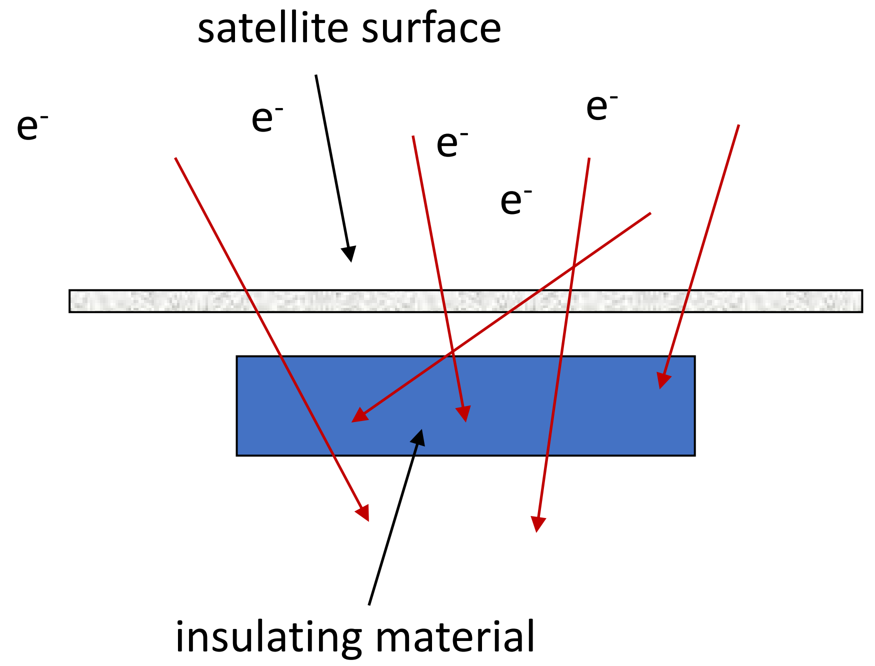
- During a major storm in 2003
  - 47 satellites experienced anomalies
  - more than 10 satellites were out of action for more than 1 day
  - the US$ 640 M Midori-2 satellite was a complete loss

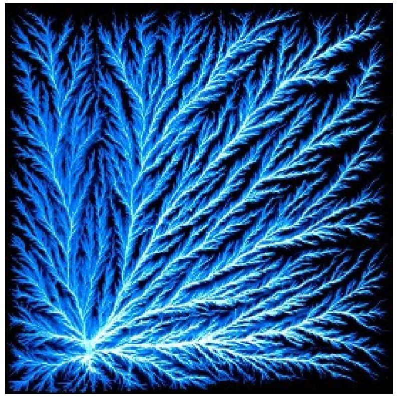


Artists impression of Midori-2 satellite

Radiation Damage

- Relativistic electrons (E > 0.5 MeV) are a major source of radiation damage to satellites
- These, so called ”killer electrons”, can penetrate satellite surfaces and embed themselves in insulating materials





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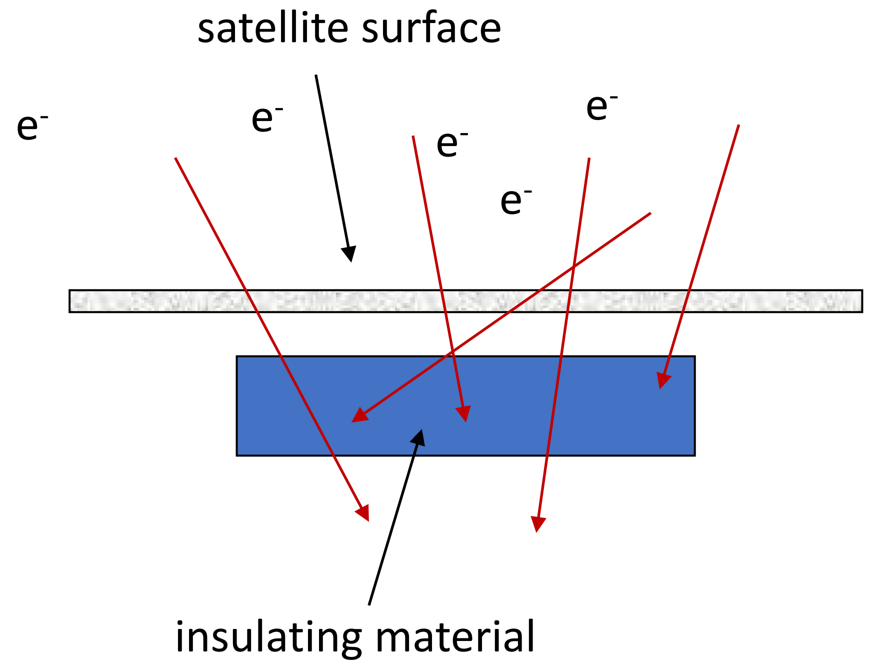
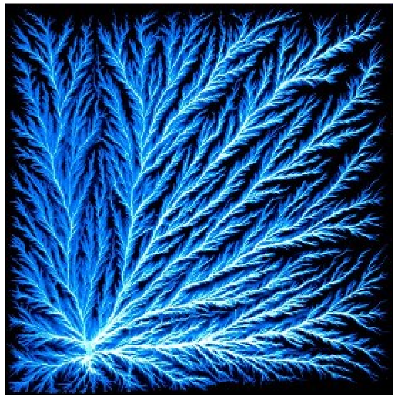
- These, so called ”killer electrons”, can penetrate satellite surfaces and embed themselves in insulating materials

- The charge can accumulate over time resulting in the build up of high electric fields which may eventually exceed breakdown levels

- The subsequent discharge can damage components and even destroy a satellite

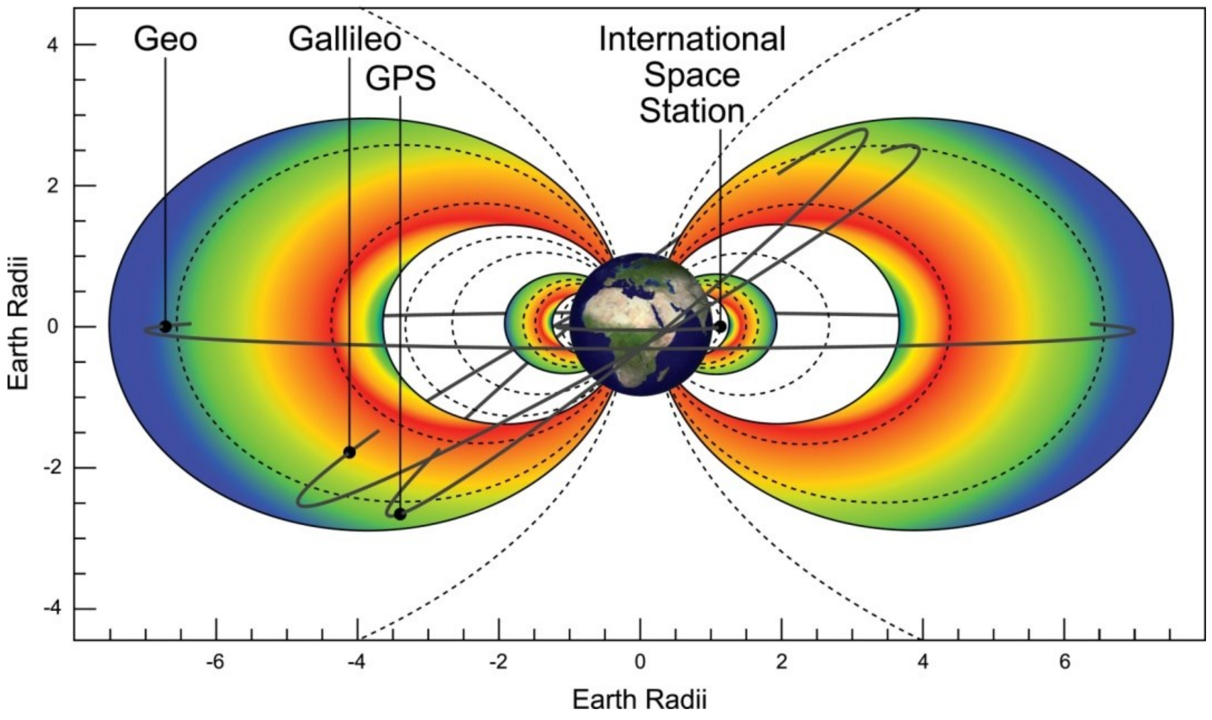




Earth’s Radiation Belts

- Our critical infrastructure extends to 6.6 Earth radii
- Over 6700 operational satellites in Earth orbit including
  - 5900 in low Earth orbit
  - 140 in medium Earth orbit
  - 580 in geostationary orbit
- Most are exposed to relativistic electrons (E > 500 keV) in the Earth’s radiation belts

Satellite orbits and the van Allen radiation belts



GNSS Satellites

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- GNSS enabled devices are used all over the world for navigation, positioning, tracking, mapping and timing

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- GNSS enabled devices are used all over the world for navigation, positioning, tracking, mapping and timing

- It is, therefore, important to have a comprehensive understanding of the environment encountered by satellites in GNSS-type orbits and, in particular, knowledge of the likely extremes of this environment

Objective

- The objective of this study is to calculate the 1 in 10 and 1 in 100 year relativistic electron fluxes throughout the Earth’s outer radiation belt in GPS orbit

Extreme Relativistic Electron Fluxes

- The data used in this study were collected by the Burst Detector Dosimeter IIR (BDD-IIR) on board the GPS satellite NS41

- The satellite was launched on 10th November 2000 and operated in a circular orbit at an altitude of 20,200 km with an inclination of 55^o and a period of 12 hours

- It crossed the magnetic equator around L = 4.2 and sampled higher L shells at higher latitudes

- We use data from 10th December 2000 to 25th July 2020

GPS Block IIR

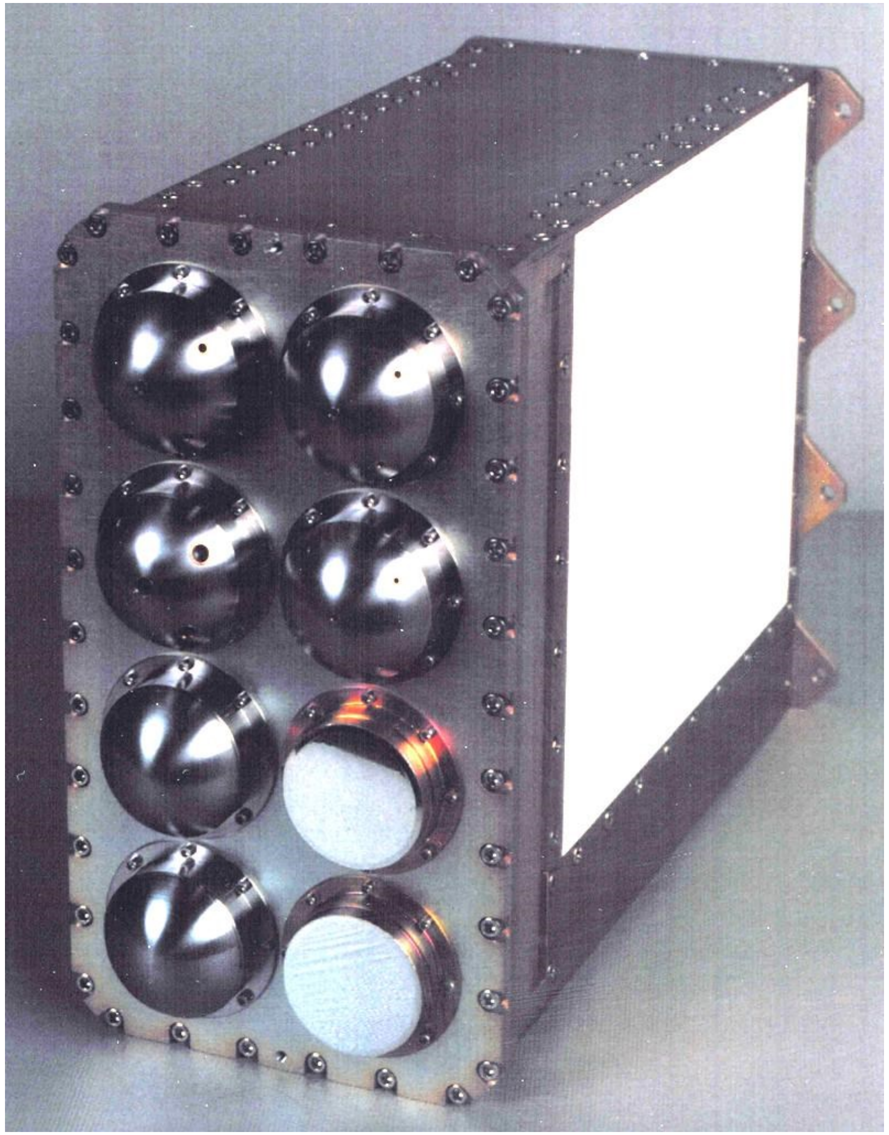
Credit: Lockheed Martin

Orbital Parameters

Altitude:	20,200 km
Inclination:	55^o
Period:	12 h

BDD-IIR

- BDD-IIR is a multi-purpose silicon detector system
- It features 8 individual channels of a ”shield/filter/sensor” design
- Absorbers in front of the sensors determine the energy thresholds for measuring the incident particle fluxes

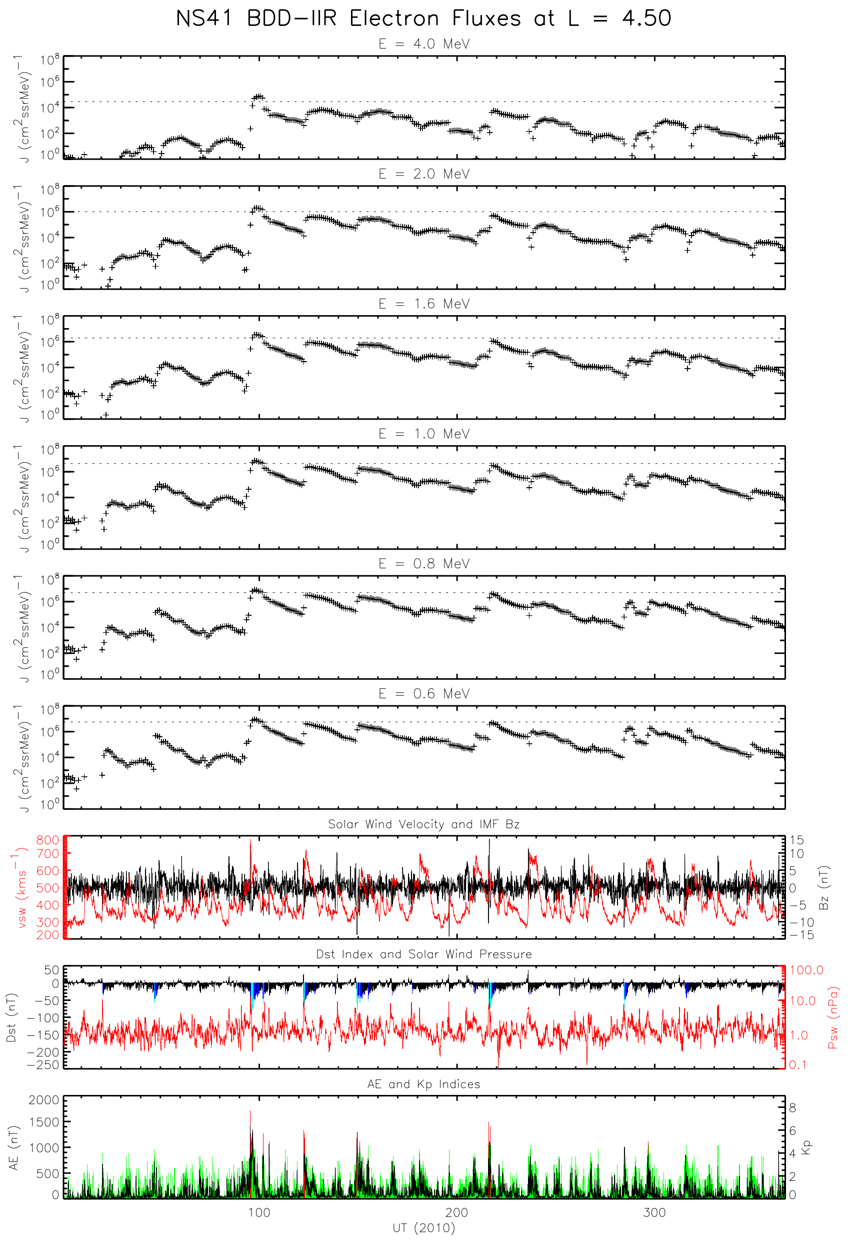


Data Processing

- Differential fluxes at 10 energies in the range $0.6 \leqq E \leqq 8$ MeV were written into separate files for each crossing of 12 equally spaced L shells in the range $4.25 \leqq L \leqq 7.00$
- Daily averaged fluxes were then computed for each energy and L shell
- Here L is the McIlwain L value computed using the IGRF internal field and the Olson-Pfitzer quiet time external field

Annual Plots

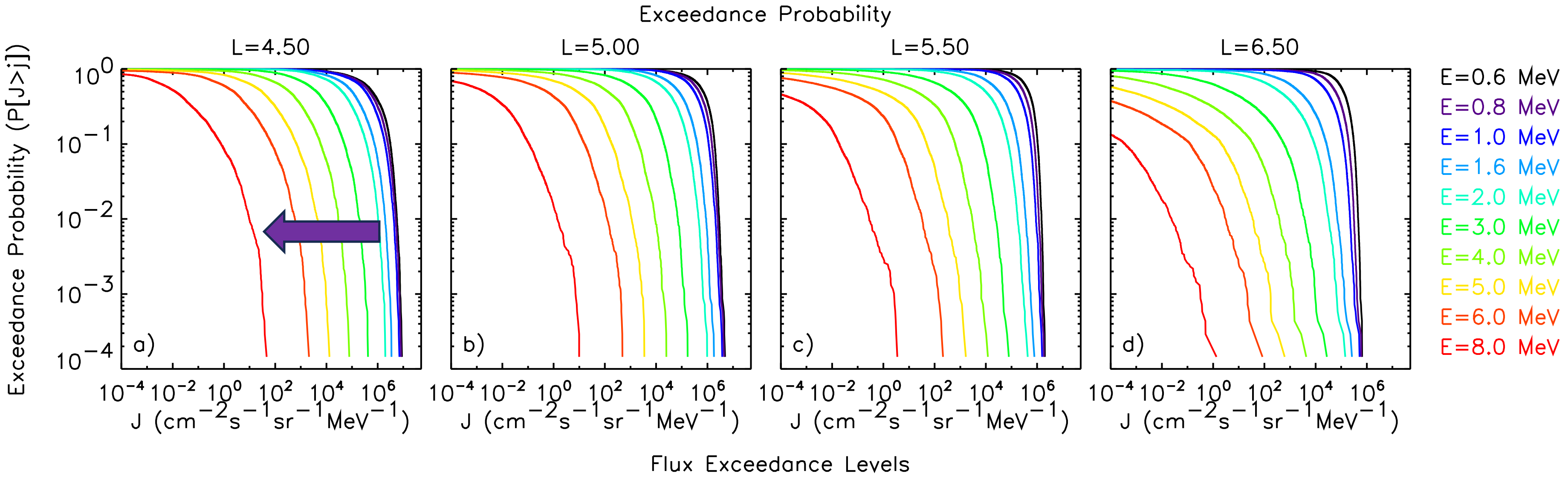
- To inspect the data we produced annual summary plots
- This figure shows the annual summary plot at L = 4.5 for 2010 for six representative energies
- At each energy the fluxes are characterised by relatively rapid increases followed by gradual decays lasting many days



Exceedance Probabilities and Flux Exceedance Levels

- We plotted the exceedance probabilities as a function of electron flux for each energy and for each value of L

Statistical Analysis of NS41 BDD-IIR Fluxes



- The observed flux for any given exceedance probability decreases with increasing energy

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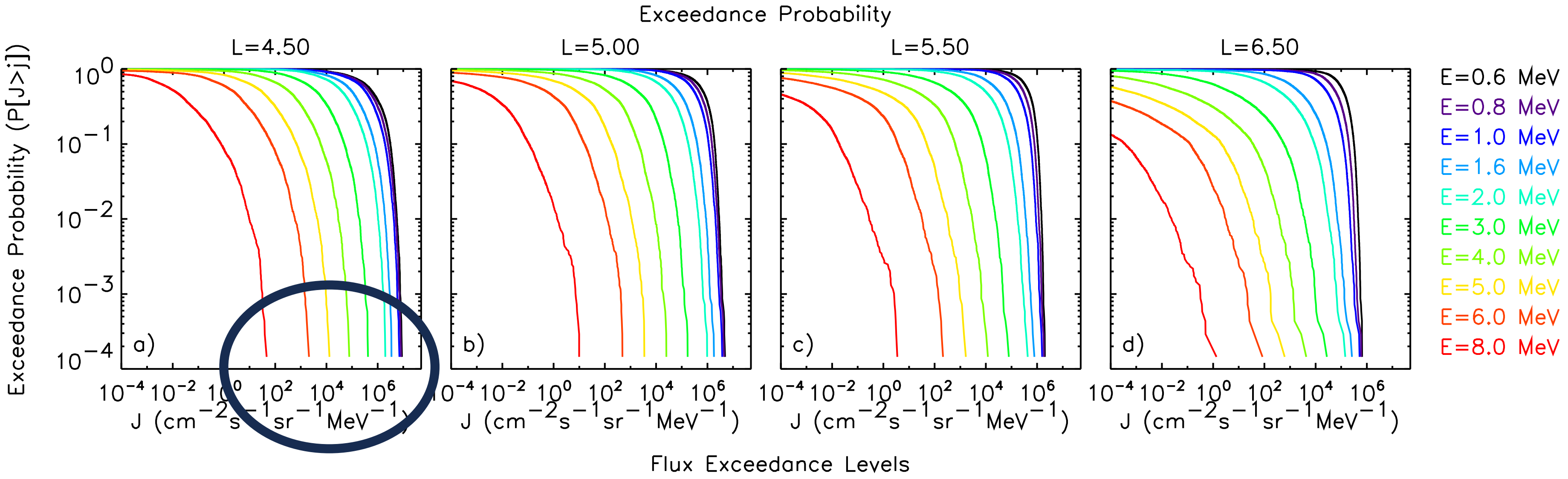

- The observed flux for any given exceedance probability decreases with increasing energy

- In the heart of the outer radiation belt, at L = 4.5, the largest observed fluxes cover over 5 orders of magnitude ranging from 8.9×10^6 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 0.6 MeV to 46 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 8.0 MeV

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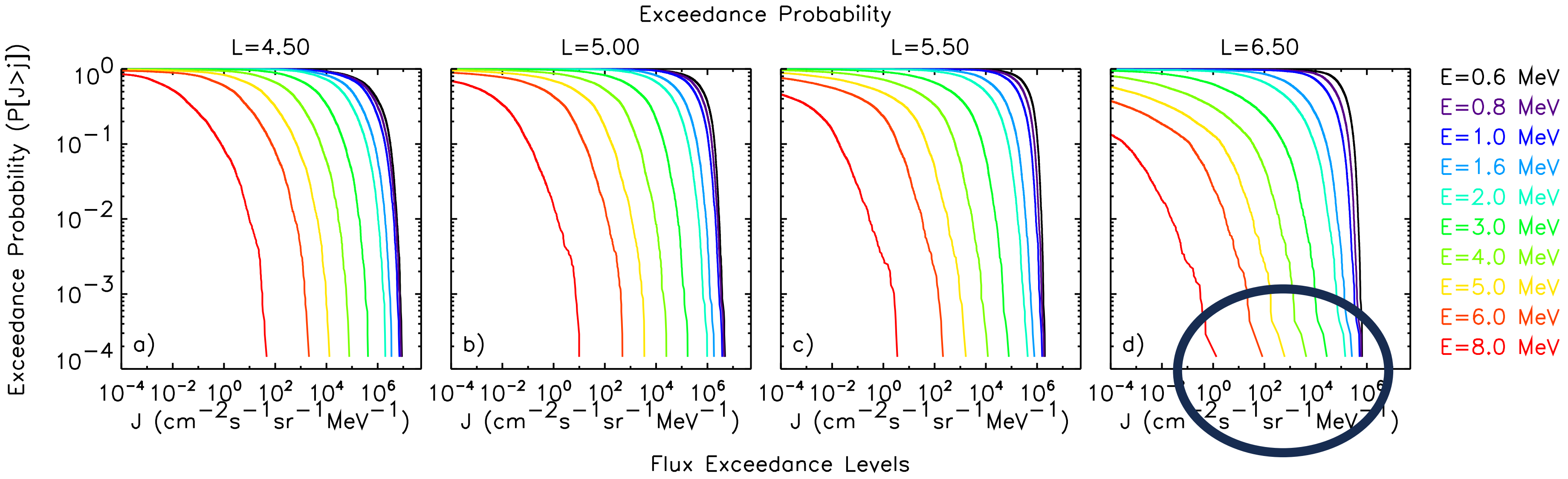

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- At L = 6.5, on field lines that map to geostationary orbit, the largest fluxes are factors of 13 and 34 lower than those at L = 4.5 at E = 0.6 and 8.0 MeV respectively

Extreme Value Analysis

- The main objective of this study is to determine the 1 in 10 and 1 in 100 year daily average electron flux for specified energies and L shells

- Since daily averages are available and to compare with previous studies we use the exceedances over a high threshold method

- For this approach the appropriate distribution function is the Generalised Pareto Distribution (GPD)

Extreme Value Analysis

- Based on experience analysing other satellite datasets we set the threshold at the 1% exceedance level
- We declustered the data to avoid counting individual events more than once by assuming a cluster to be active until the three consecutive daily averages fall below our chosen threshold
- We then fit the GPD to the cluster maxima for each specified energy and L shell

Generalised Pareto Distribution

- The GPD may be written in the form

$$G(x-u) = 1 - (1+ \xi(x-u)/\sigma)^{-1/\xi}$$

where: x are the cluster maxima above the chosen threshold u
ξ is the shape parameter which controls the behaviour of the tail
σ is the scale parameter which determines the dispersion or spread of the distribution

- We fit the GPD to the tail of the distribution using maximum likelihood estimation

Determination of the 1 in N Year Event

- The flux that is exceeded on average once every N years can be expressed in terms of the fitted parameters σ and ξ as:

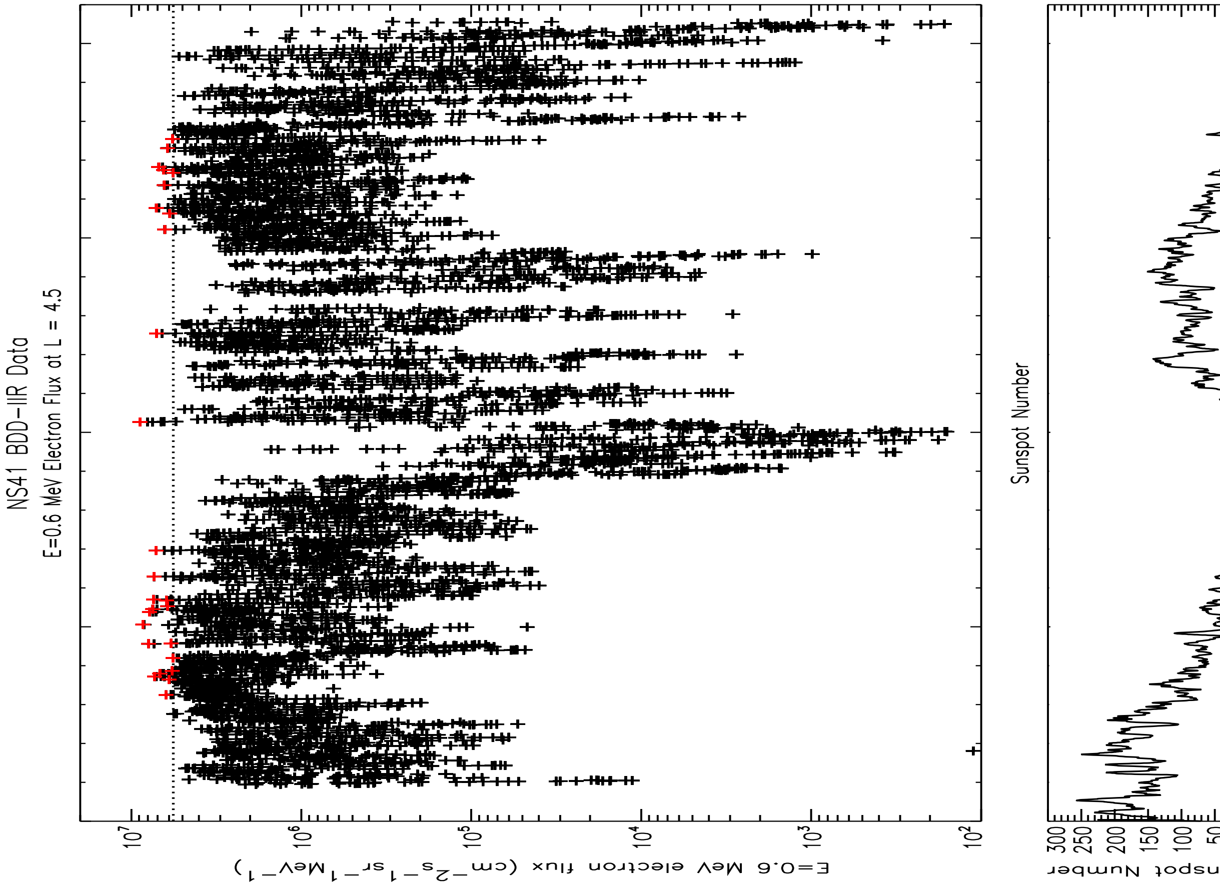
$$x_N = u + (\sigma/\xi)((N n_d n_c/n_{tot})^{\xi} - 1))$$

where n_d is the number of data points in a given year, n_c is the number of cluster maxima and n_{tot} is the total number of data points

- A plot of x_N against N is known as a return level plot

E = 0.6 MeV Electrons at L = 4.5

- This figure shows the E = 0.6 MeV daily average electron flux for the entire mission



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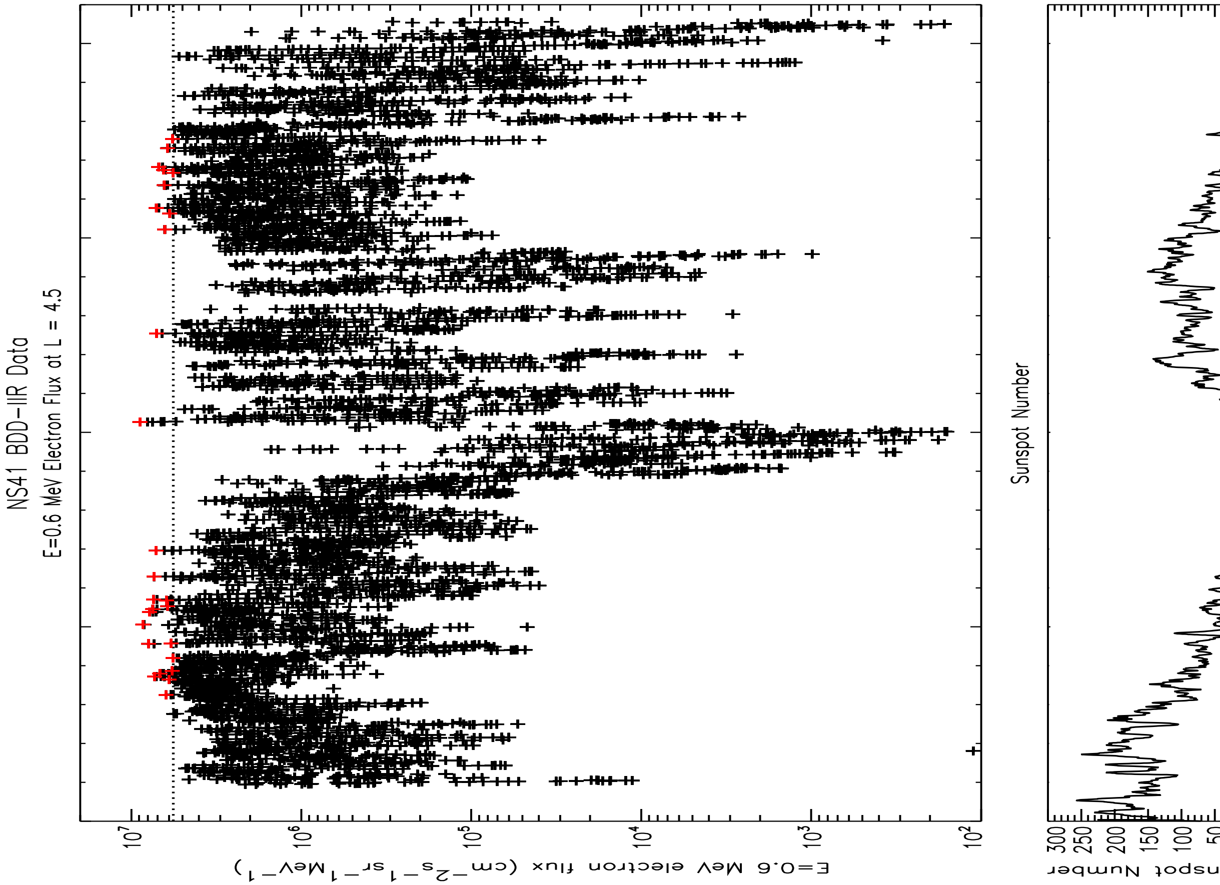

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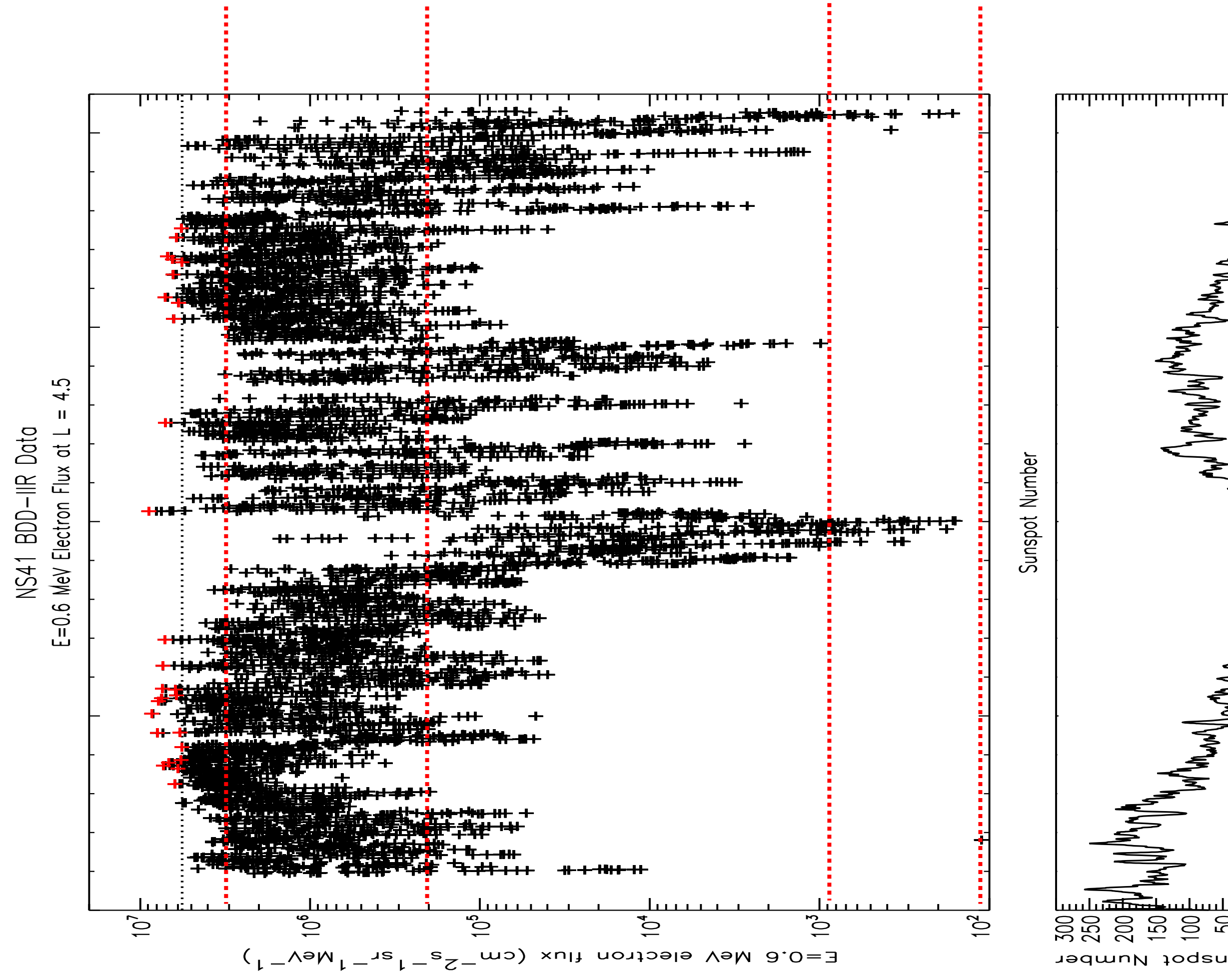
- The largest fluxes of E = 0.6 MeV electrons at L = 4.5 are largely seen from 2003-2008 and 2015-2018, during the declining phases of solar cycles 23 and 24



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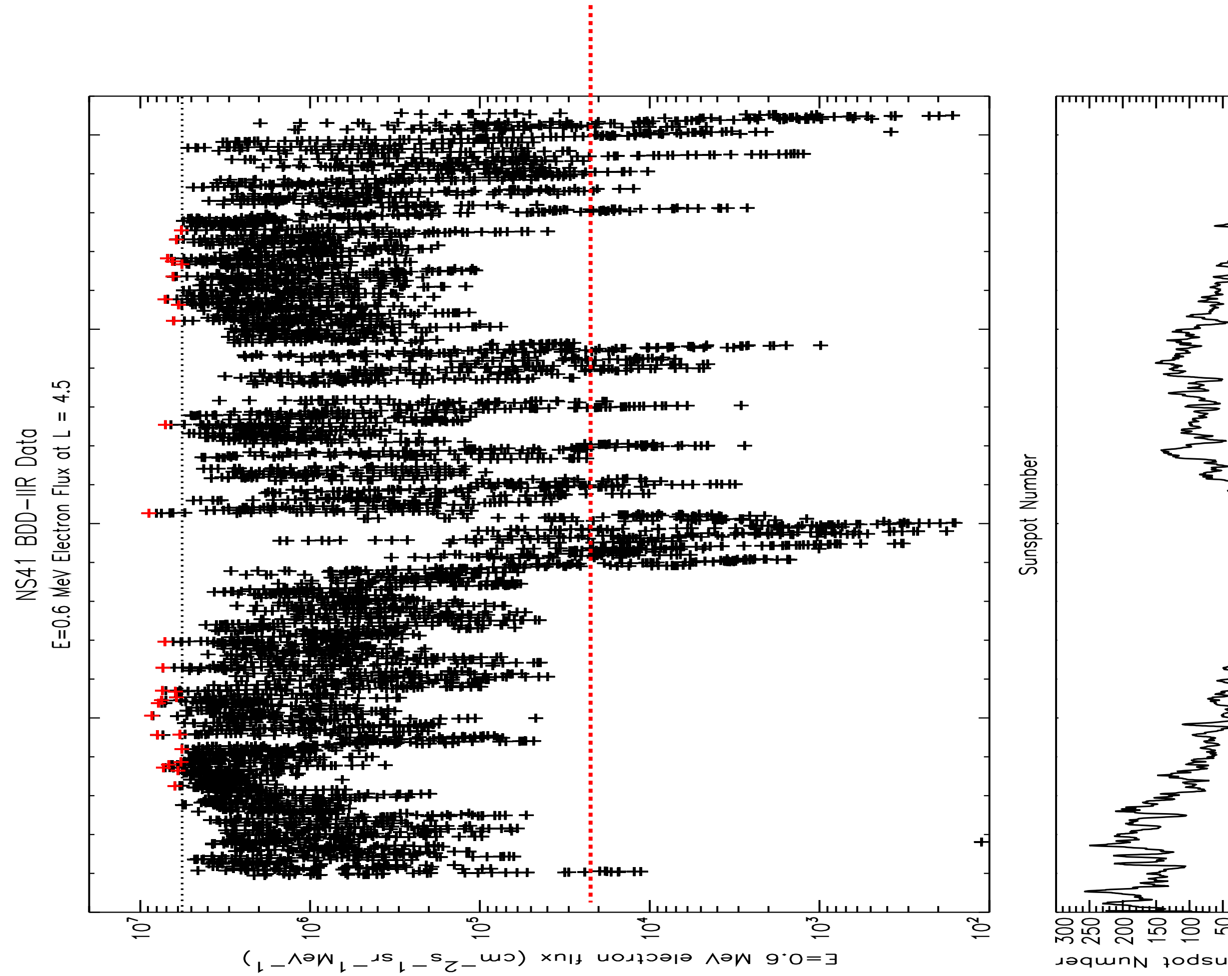
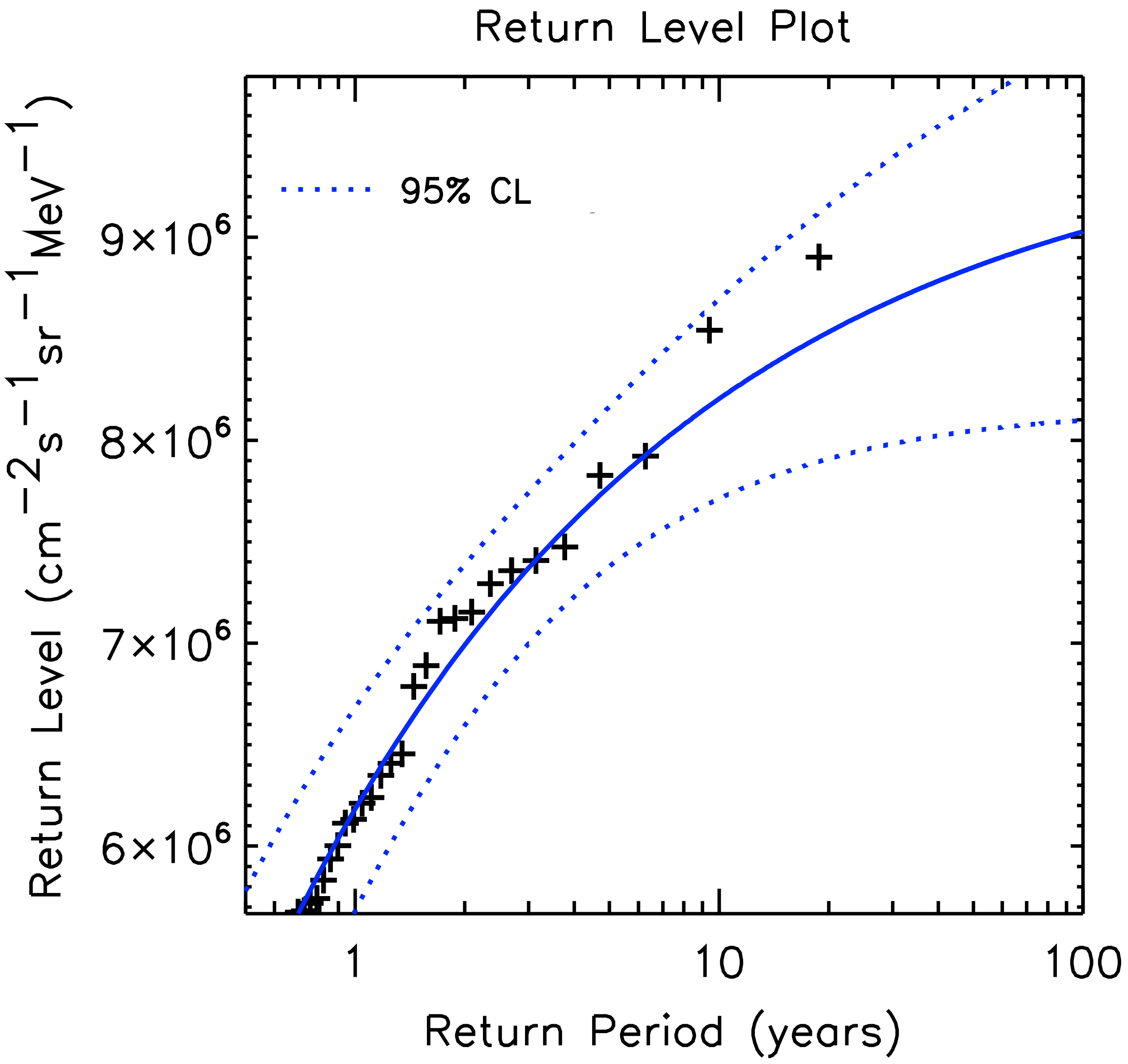
- The 1% exceedance level, chosen as the threshold for the analysis, is shown as the dotted line and the cluster maxima are coded red
- However, the largest event occurred near solar minimum – showing that an extreme event can occur at any time in the solar cycle



Return Level Plot

This figure shows the return level plot for 0.6 MeV electrons at L = 4.5



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- 1 in 10 year daily-average flux
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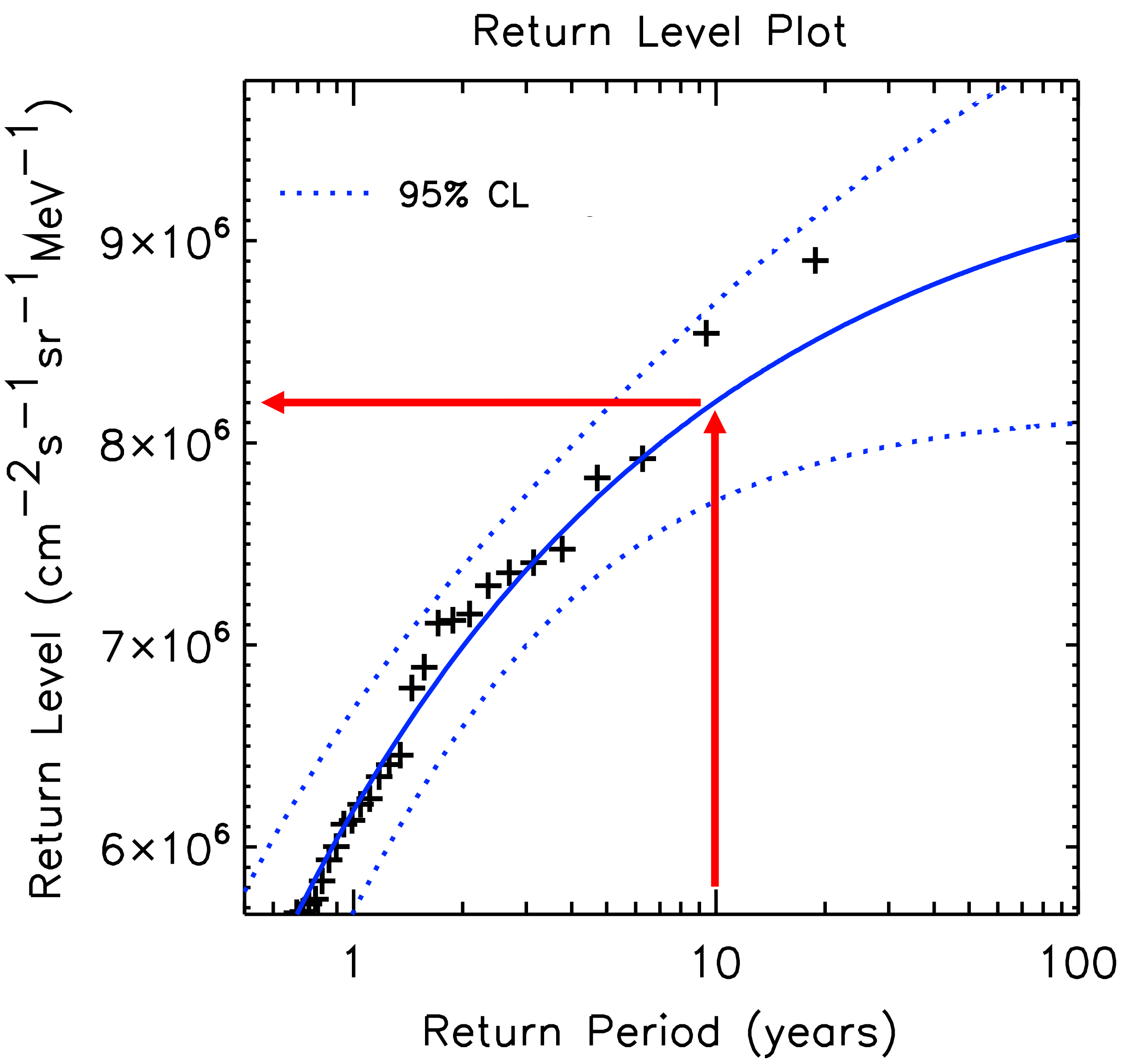

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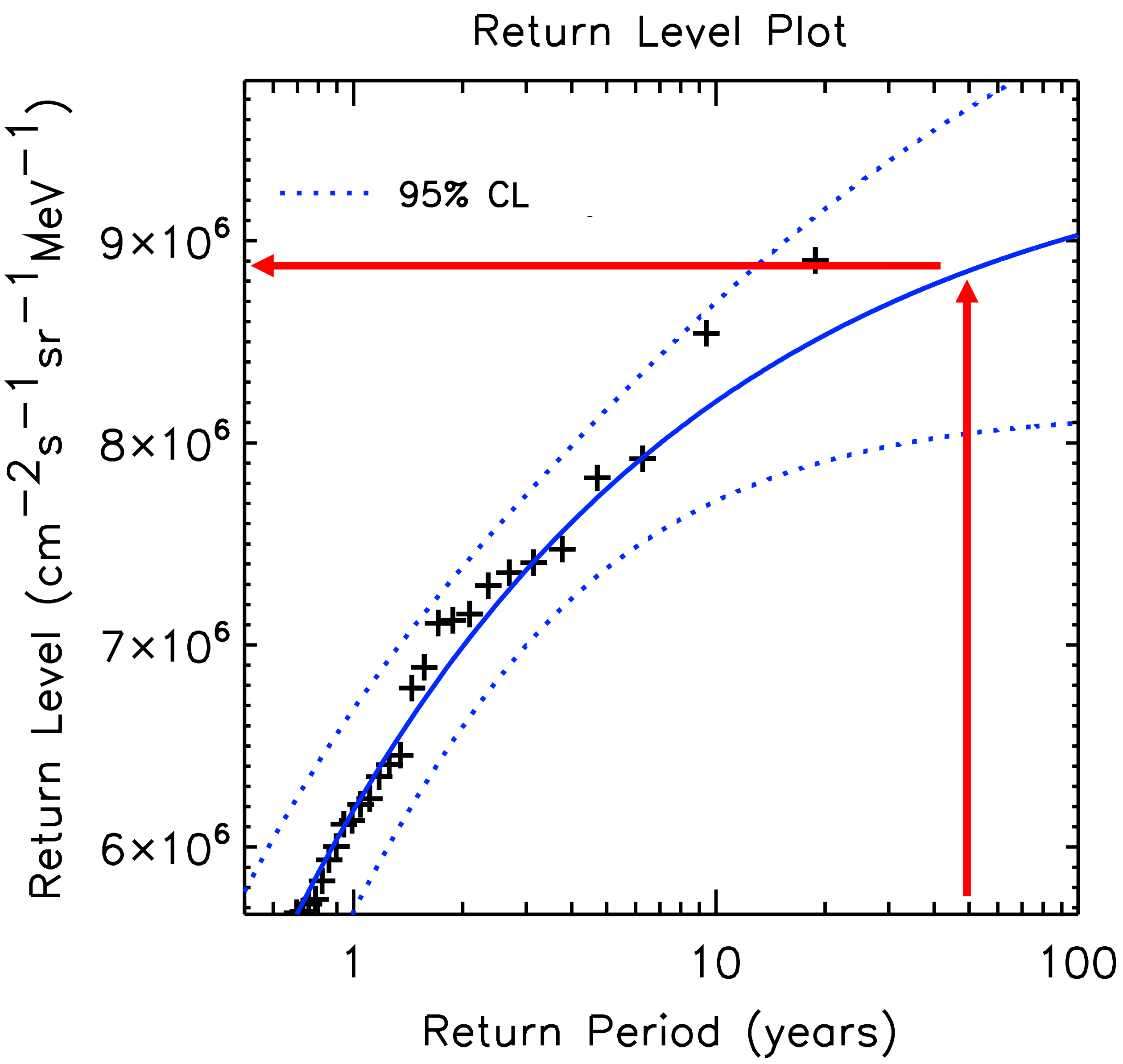

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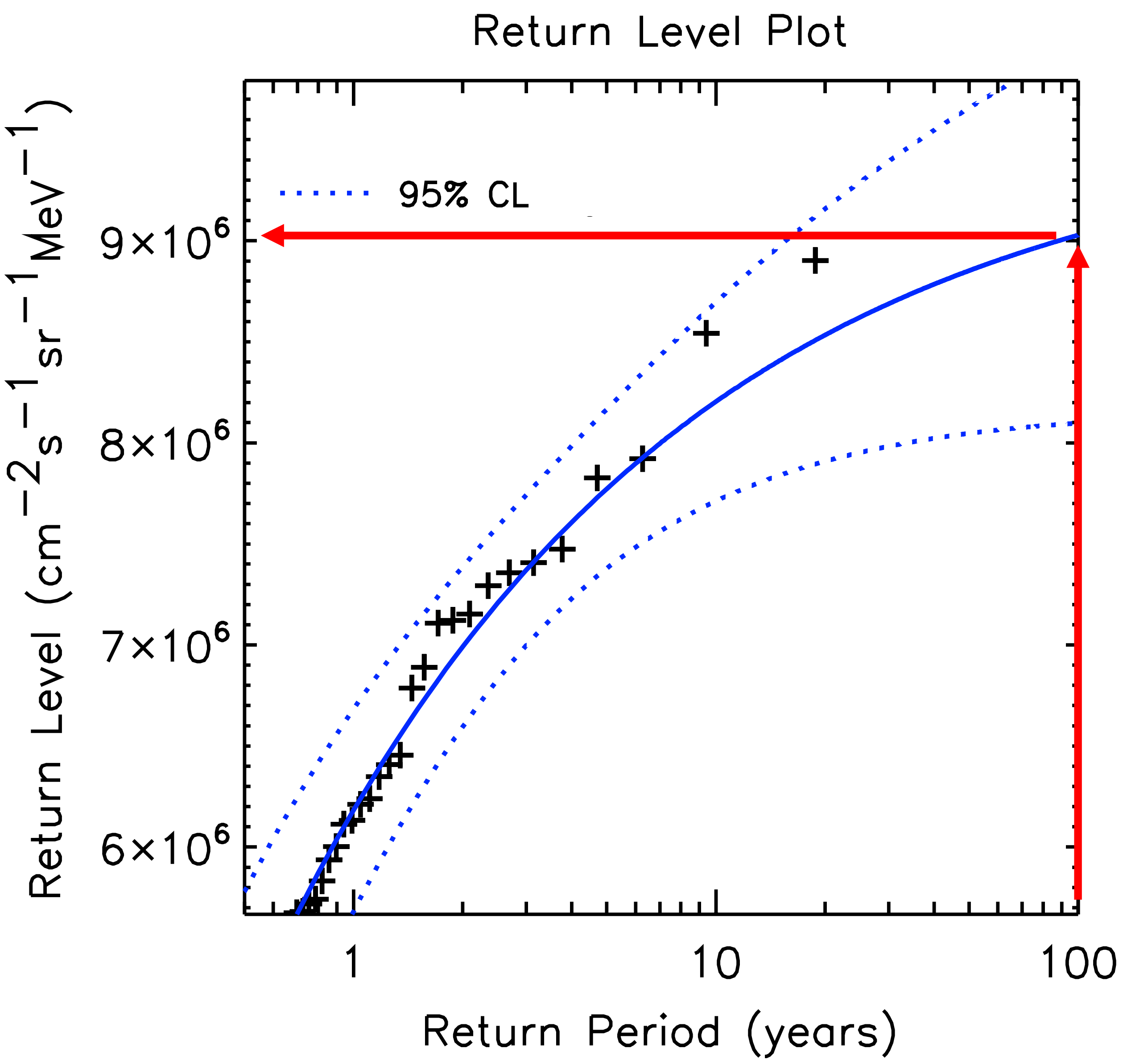
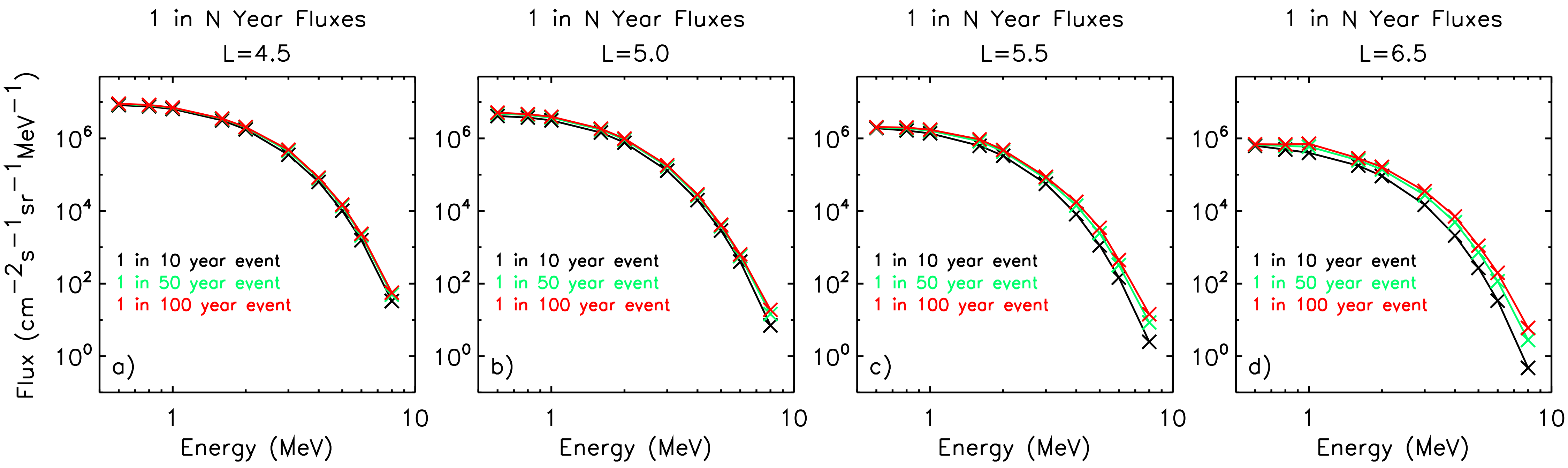
- 1 in 100 year daily-average flux
  - 9.0×10^6 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$

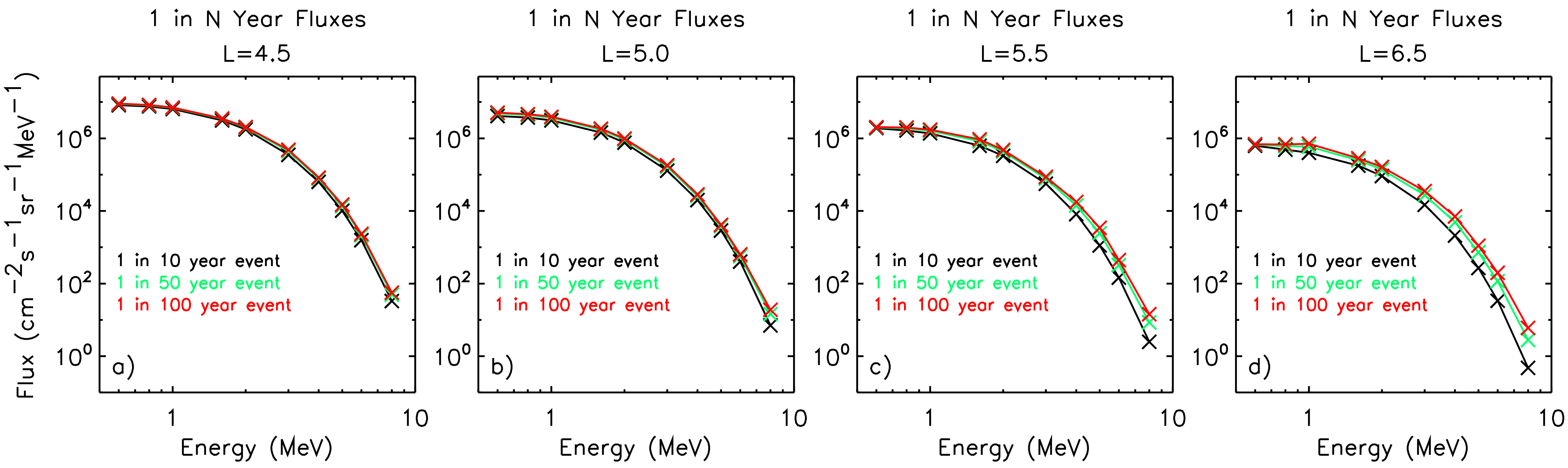


1 in N Year Fluxes



- The 1 in N Year fluxes decrease with increasing energy

1 in N Year Fluxes



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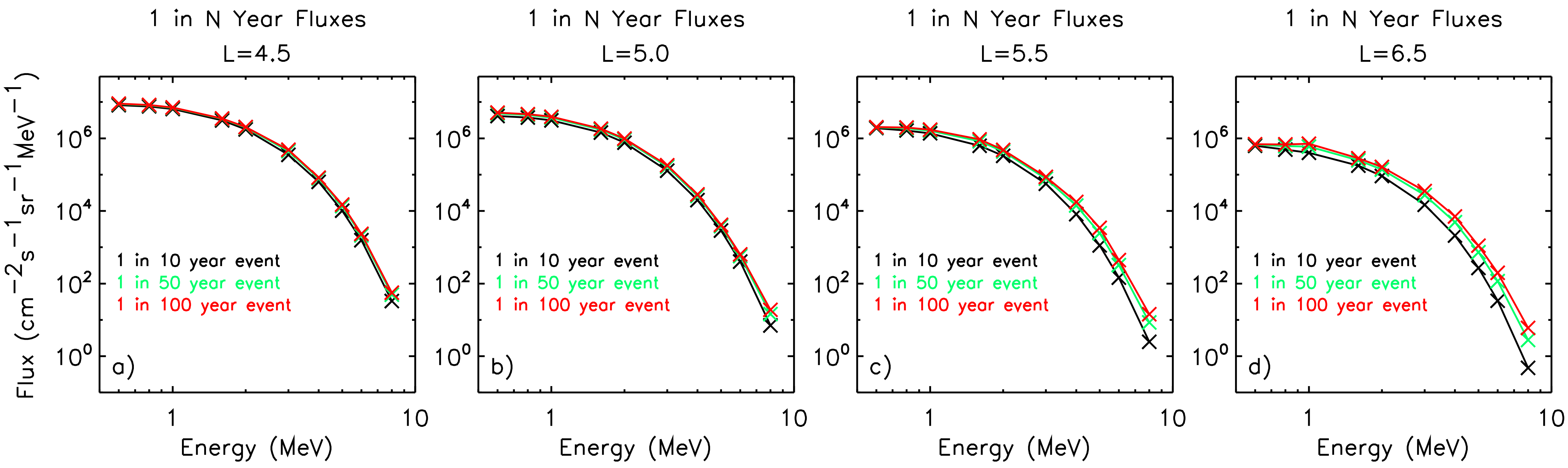
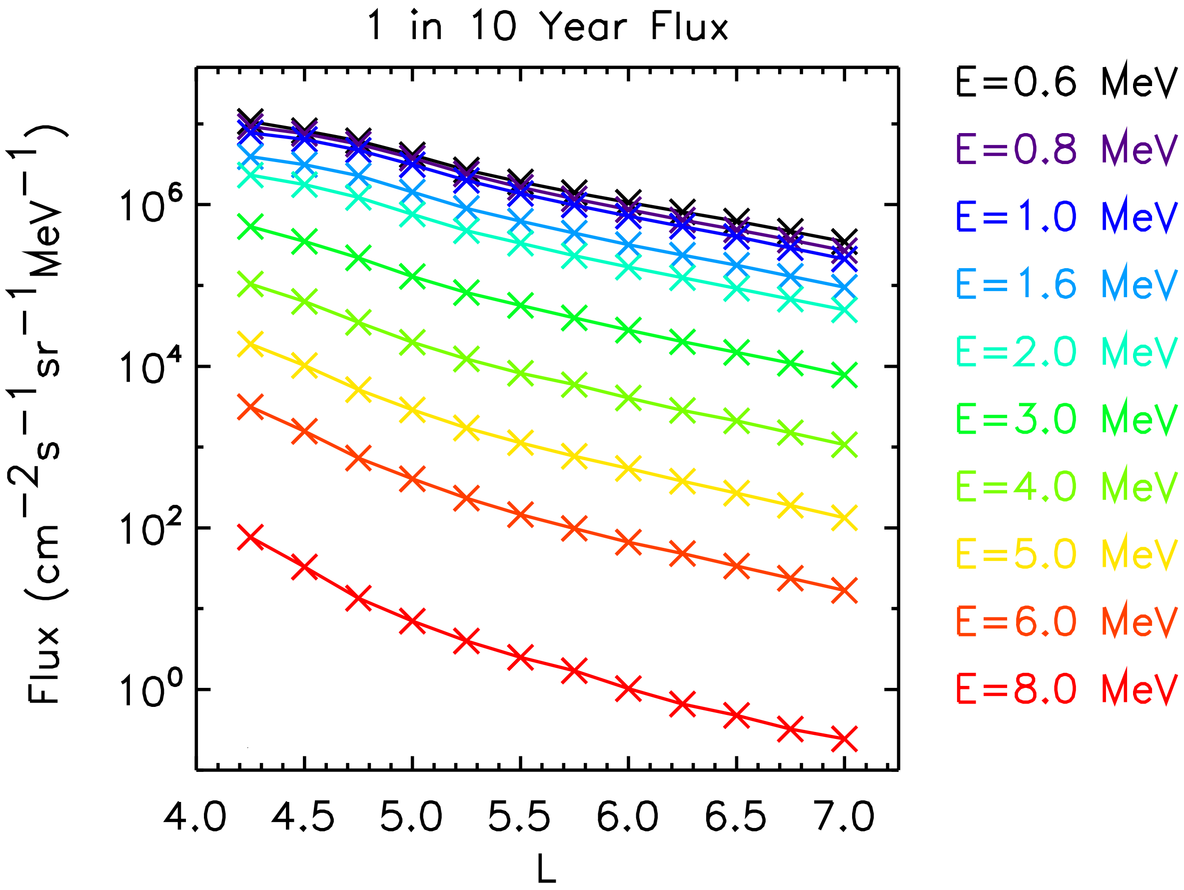


- The 1 in N Year fluxes decrease with increasing energy
- At L = 4.5 there is very little difference between the 1 in 10 and 1 in 100 year events
- Further out there is an increasing tendency for a larger difference between the 1 in 10 and 1 in 100 year events, particularly at higher energies

1 in 10 Year Fluxes as a function of L and Energy

- We can summarise the 1 in N year electron fluxes as a function of L for the different energies



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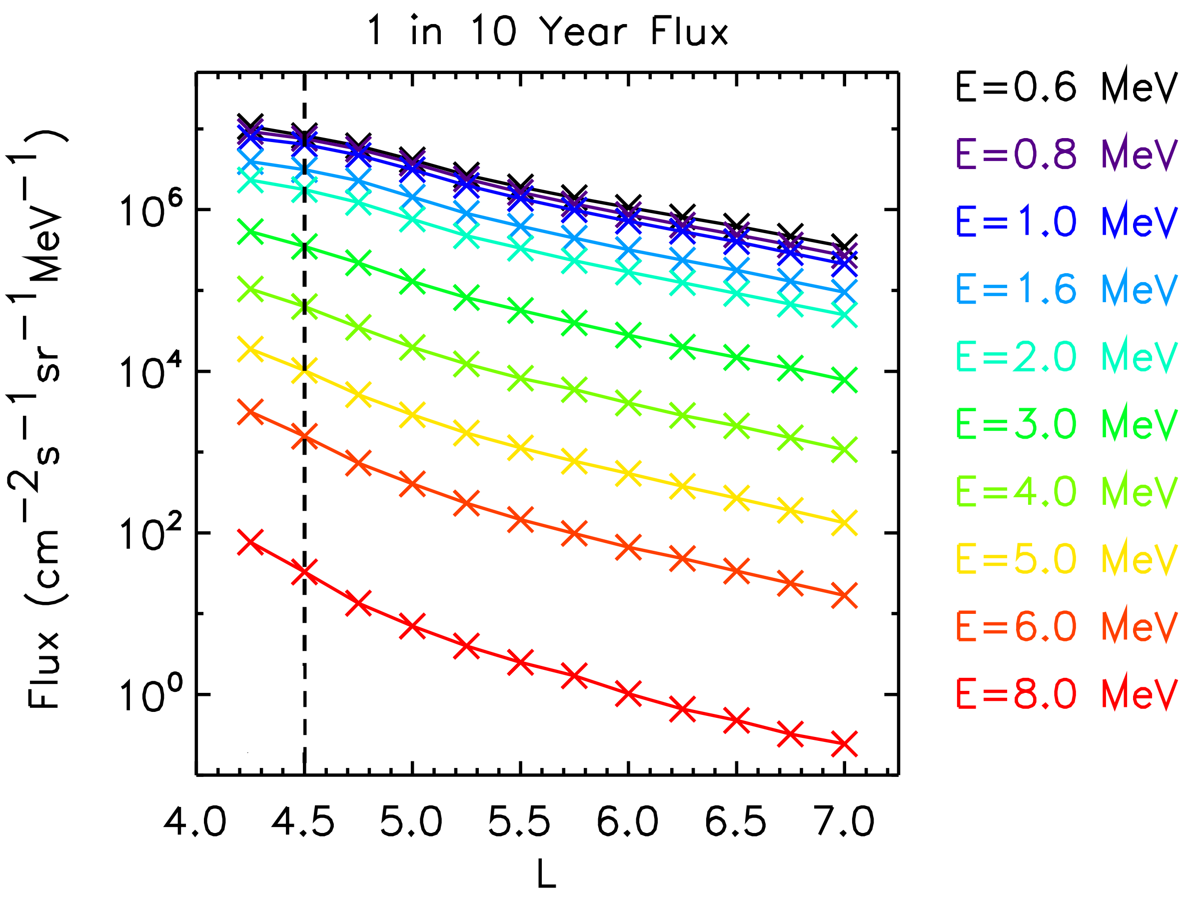

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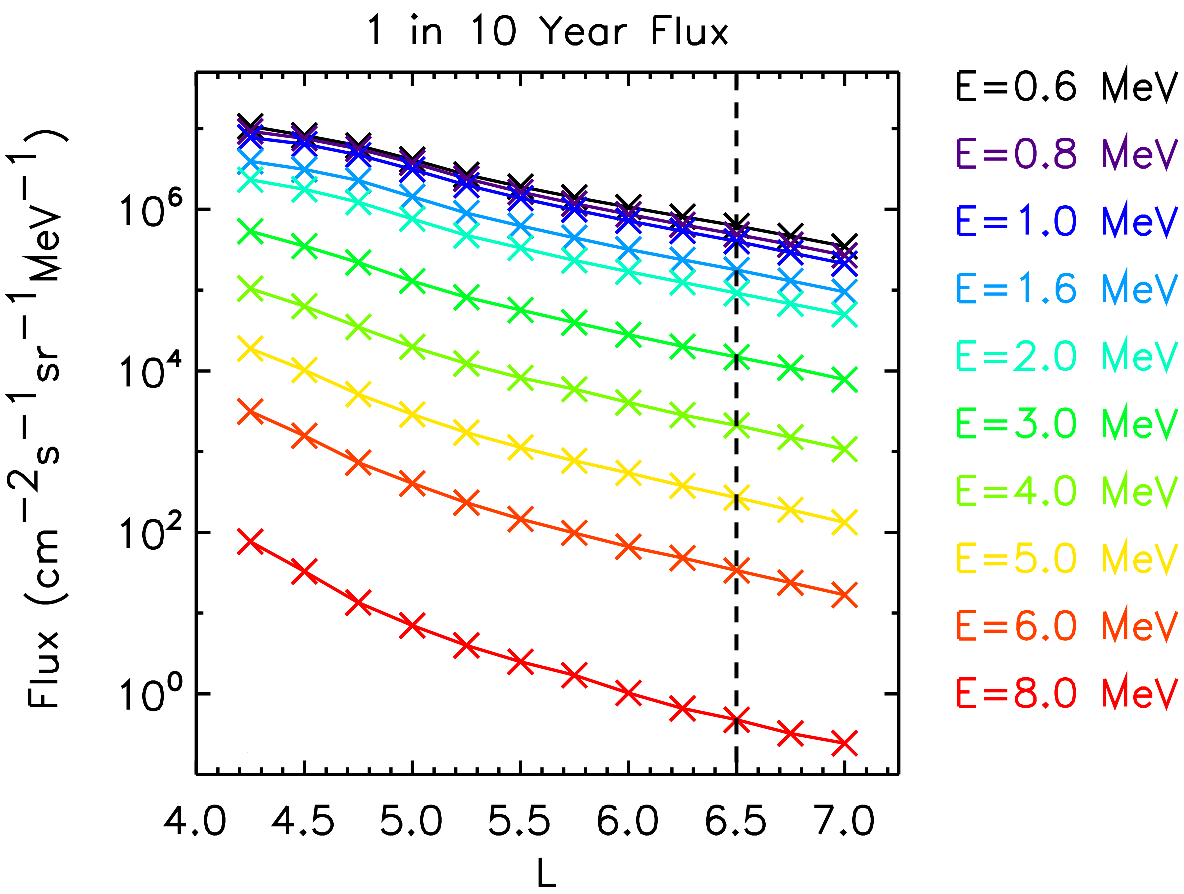
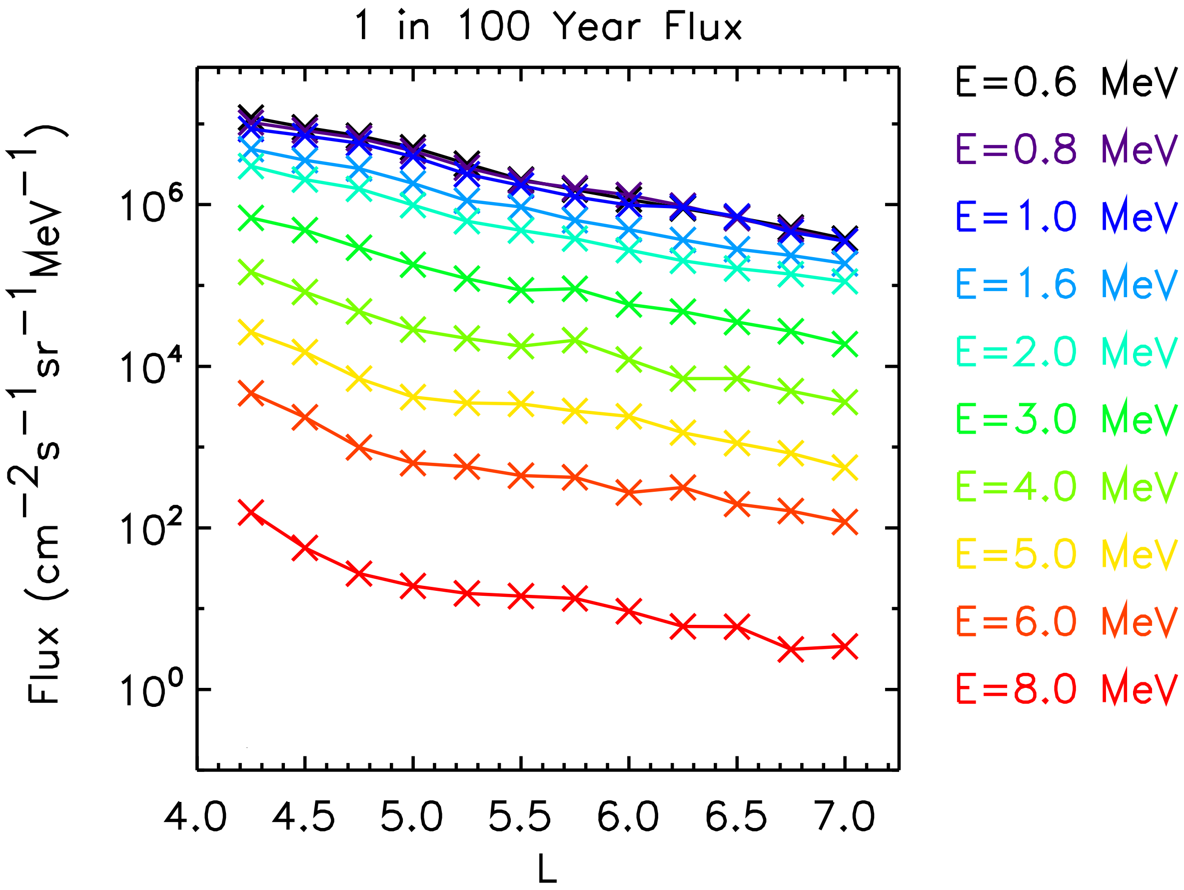
- Further out, at L = 6.5 the 1 in 10 year flux ranges from 6.2×10^{5} $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 0.6 MeV to 0.47 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at 8.0 MeV



1 in 100 Year Fluxes as a function of L and Energy

- This figure shows the 1 in 100 year electron flux as a function of L for the different energies
- The 1 in 100 year fluxes are typically up to a factor of 2 to 10 times larger with the largest differences being at the higher L shells

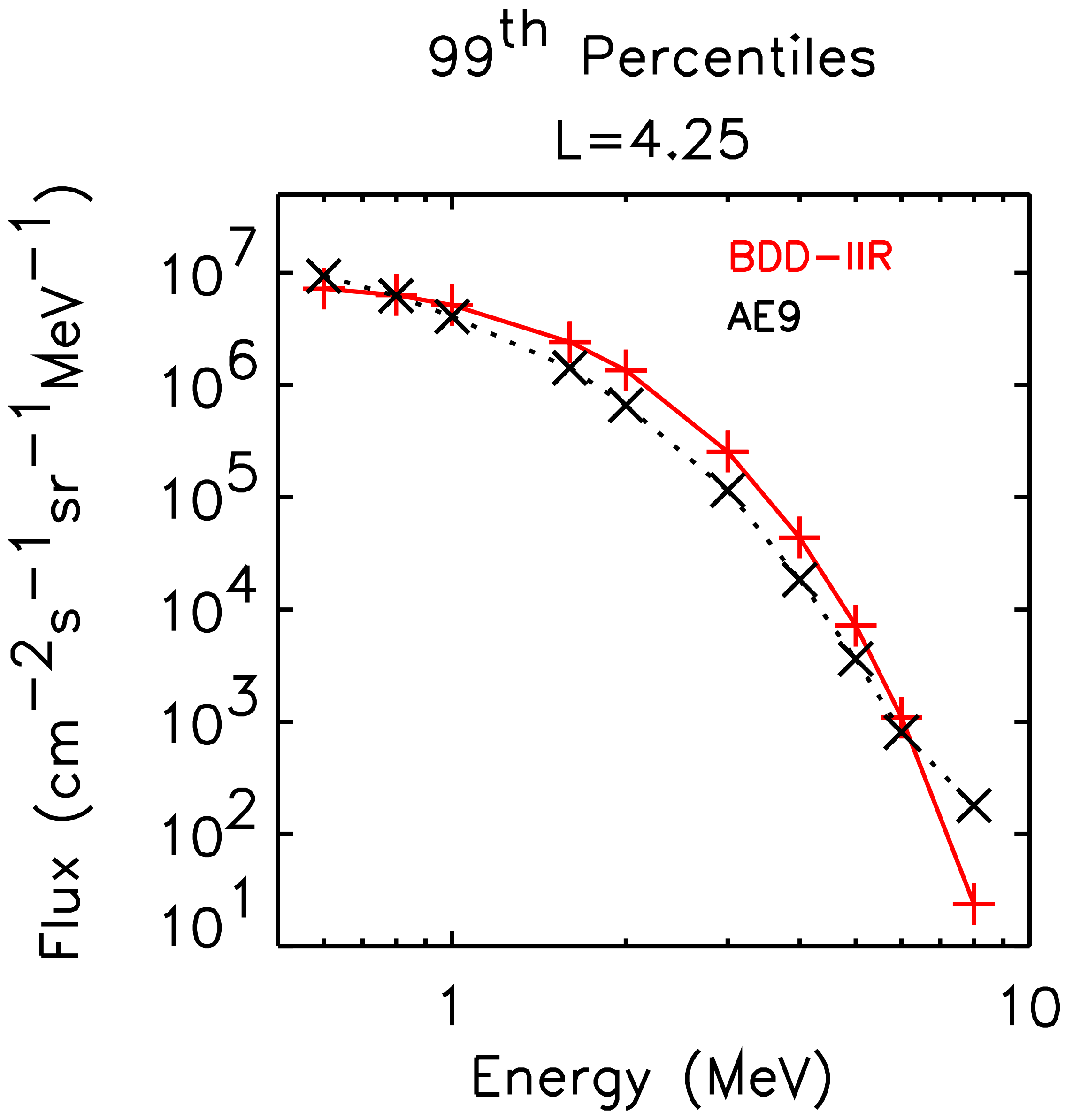


Comparison with the IRENE AE9 Radiation Environment Model

- It is interesting to compare the 99th percentiles of the NS41 fluxes with AE9

- The results are largely in extremely good agreement over the energy range 0.6 – 6.0 MeV

- The 99th percentile fluxes are about an order of magnitude less than AE9 at 8.0 MeV



Comparison with the IRENE AE9 Radiation Environment Model

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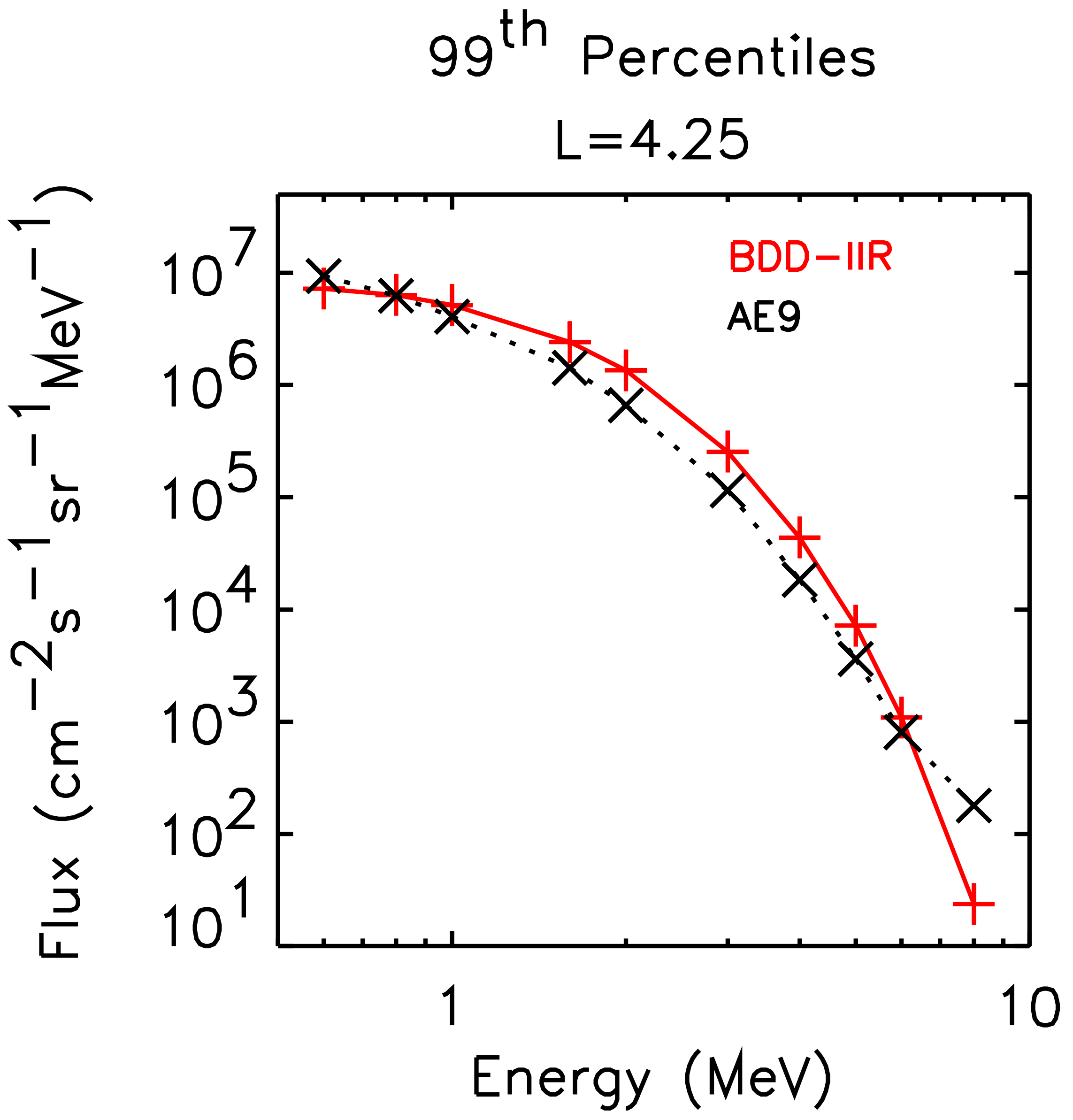
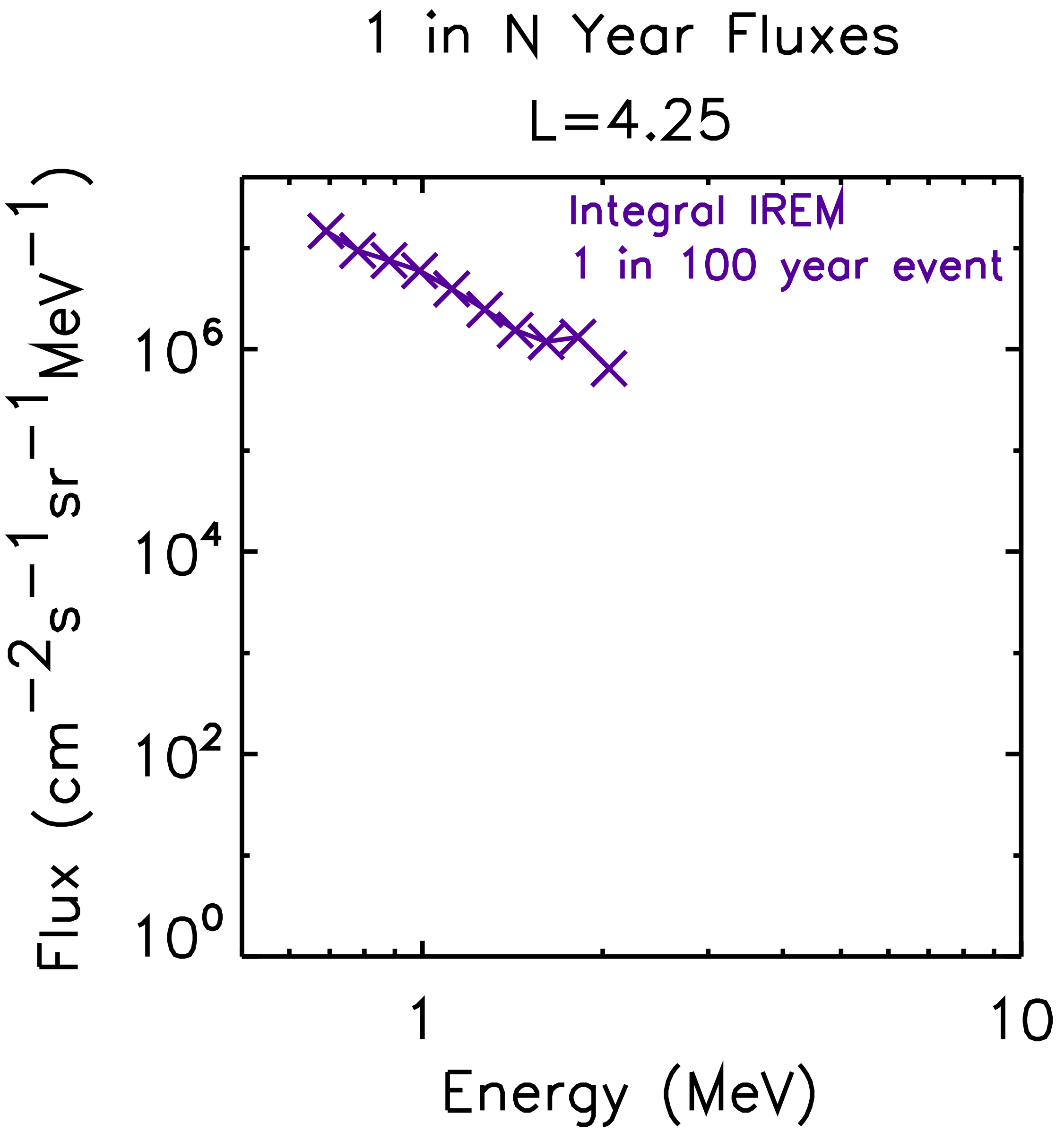
- The results are largely in extremely good agreement over the energy range 0.6 – 6.0 MeV
- This could be due to background counting issues in the data used to construct AE9, especially as the gradient in the AE9 fluxes becomes less steep around 6.0 MeV



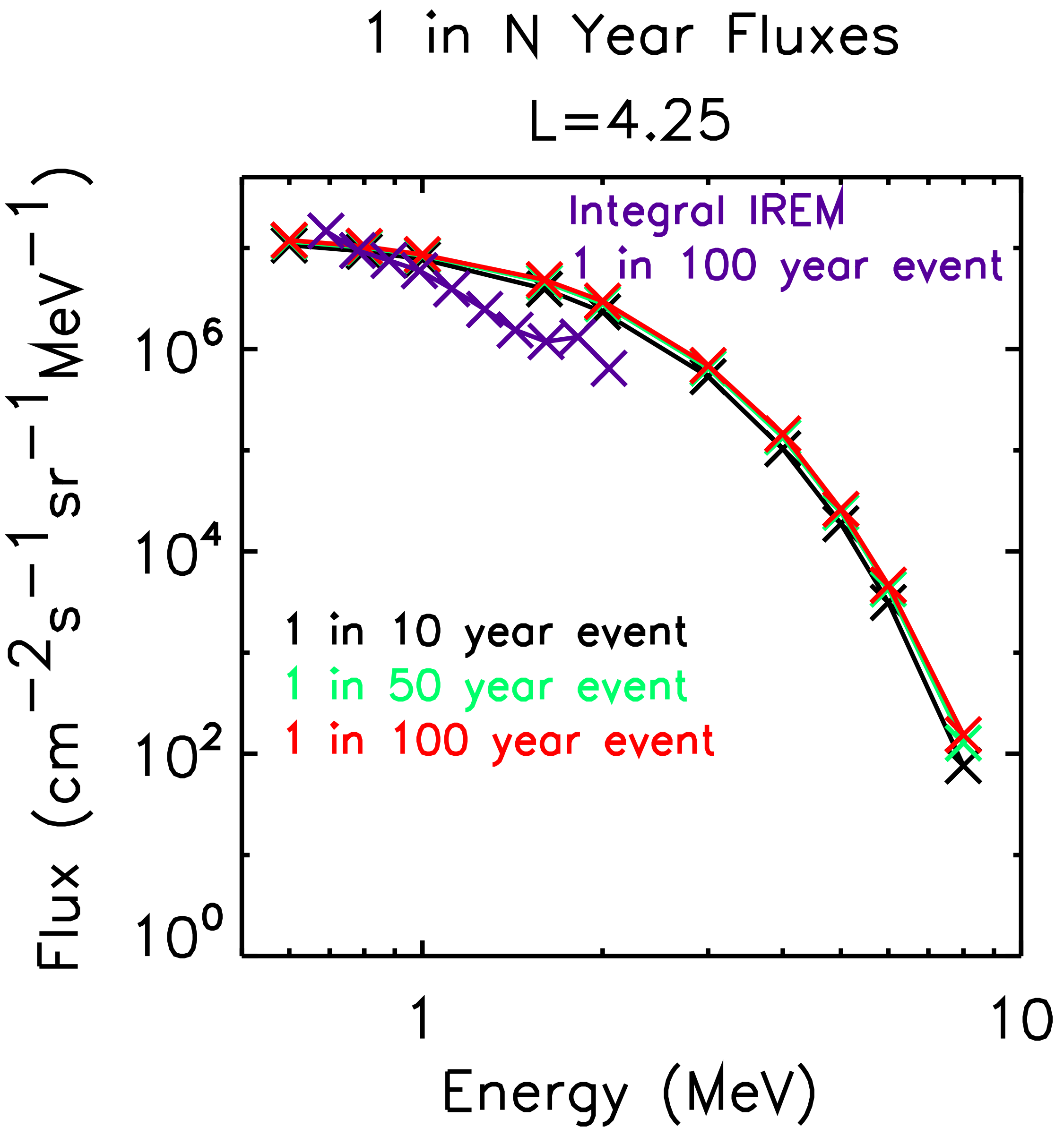
Comparison with Integral IREM Results

- In 2017, we conducted an extreme value analysis using ~ 14 years of data from the Radiation Environment Monitor on board the Integral spacecraft (Meredith *et al.*, 2017)
- We can to compare these findings with the new results from the NS41 BDD-IIR instrument

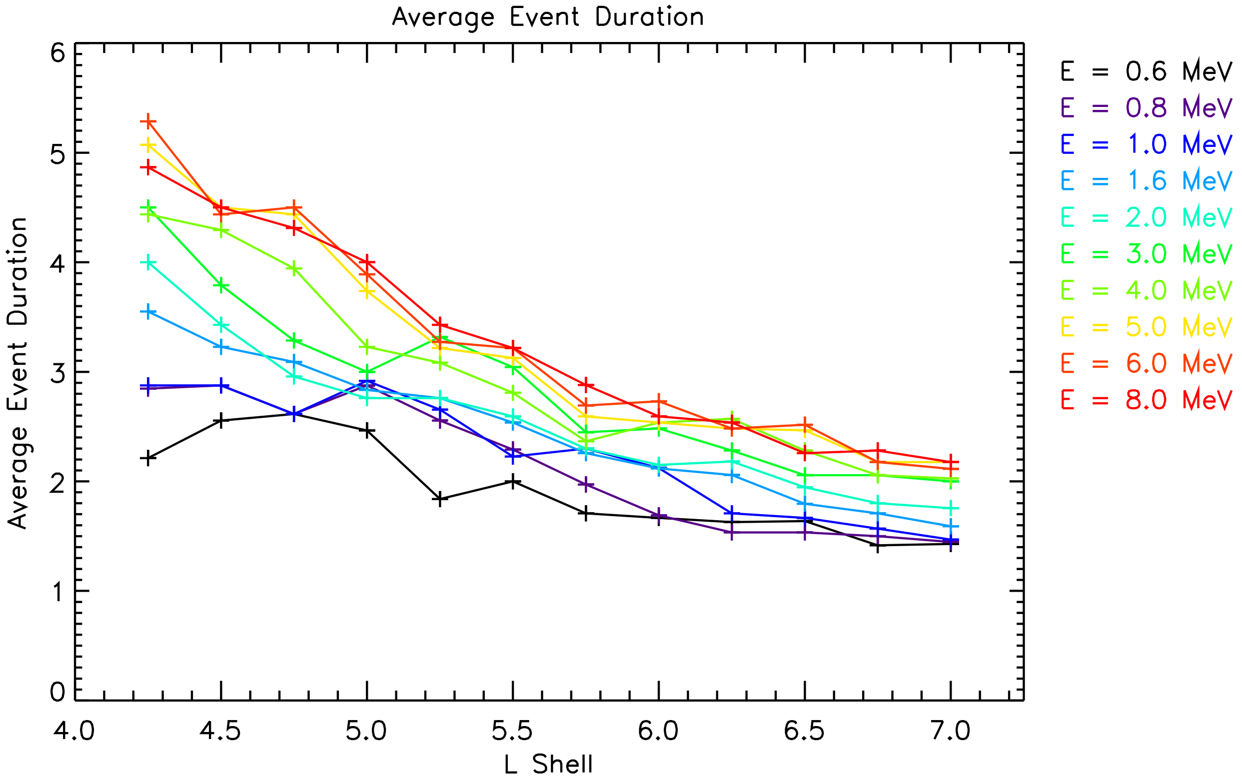


Comparison with Integral IREM Results

- The results are in good agreement at 0.8 and 1.0 MeV, but the Integral results are about a factor of 5 lower at 1.6 and ~ 2 MeV

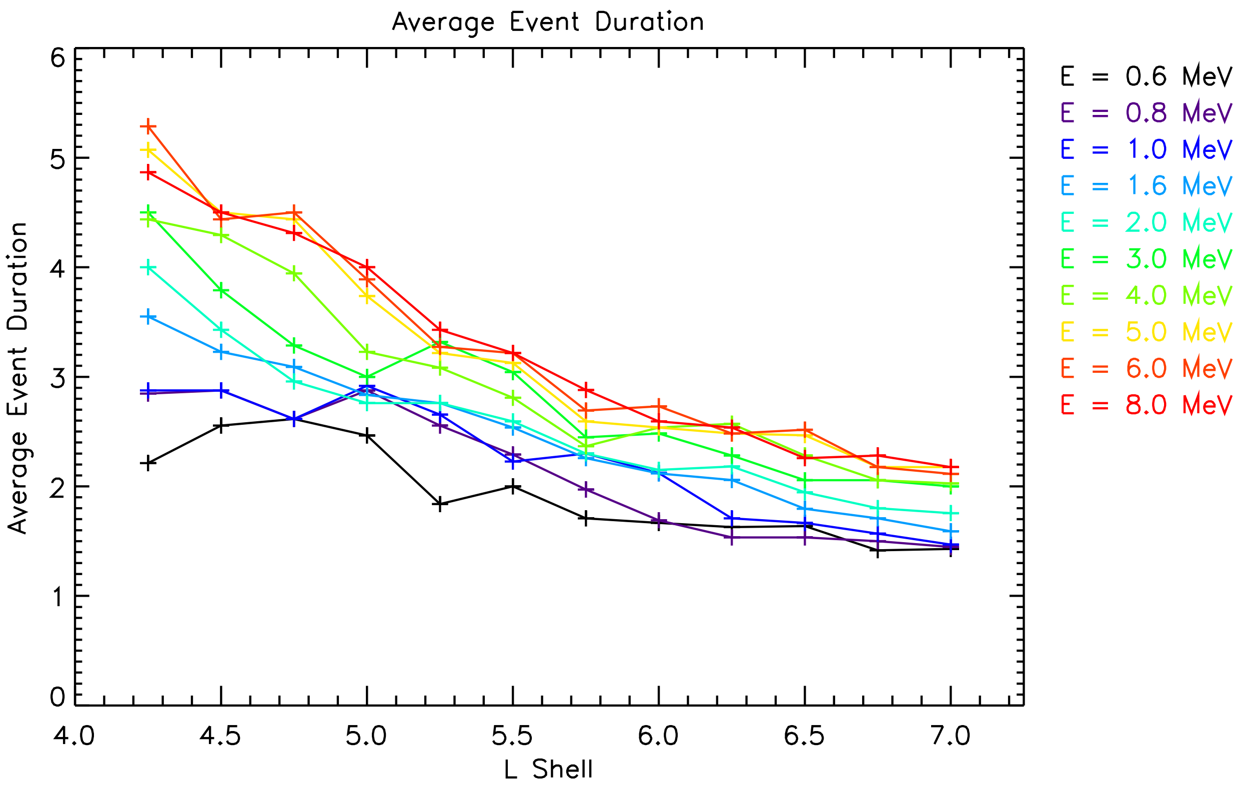


Average Event Duration



- This figure shows the average time the flux exceeds the 1% exceedance level for each of the cluster maxima for each energy as a function of L

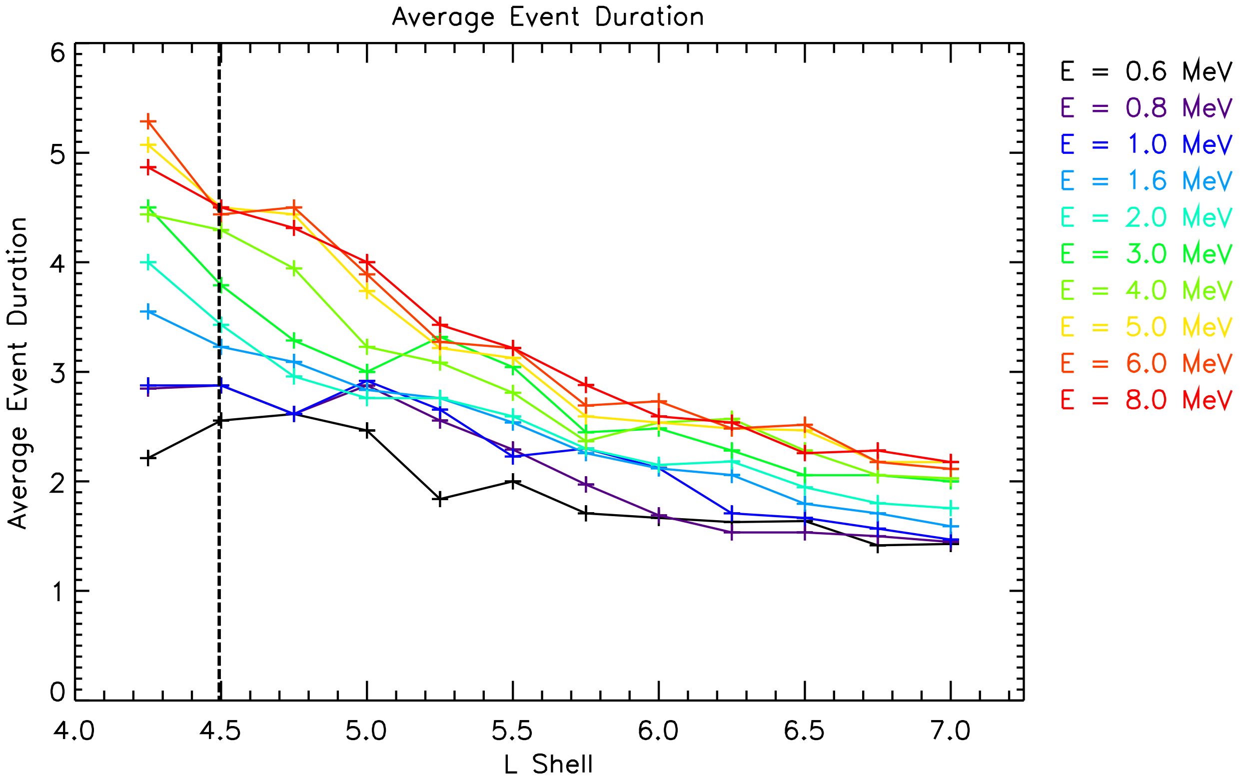
Average Event Duration



- This figure shows the average time the flux exceeds the 1% exceedance level for each of the cluster maxima for each energy as a function of L

- The average event duration increases with increasing energy and decreasing L

Average Event Duration



- Specifically, at L = 4.5, the average event duration increases from 2.5 days at E = 0.6 MeV to 4.4 days at the highest energies

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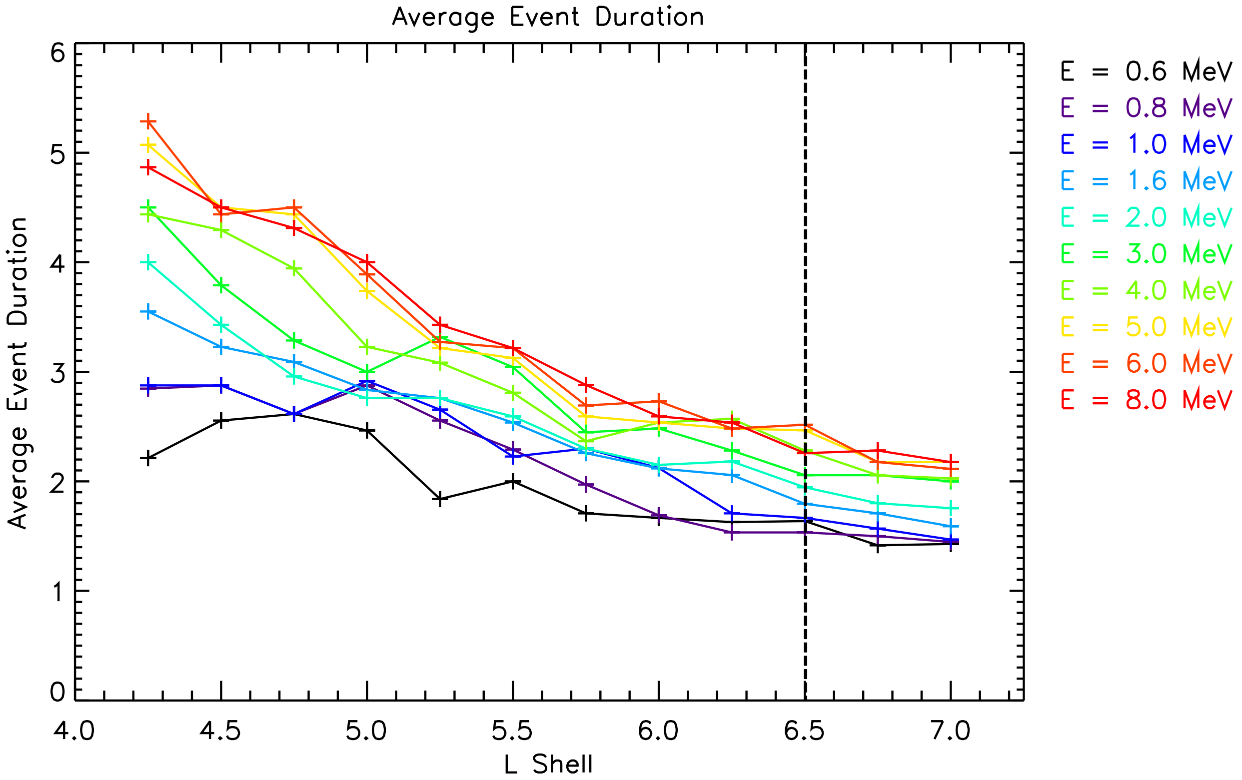
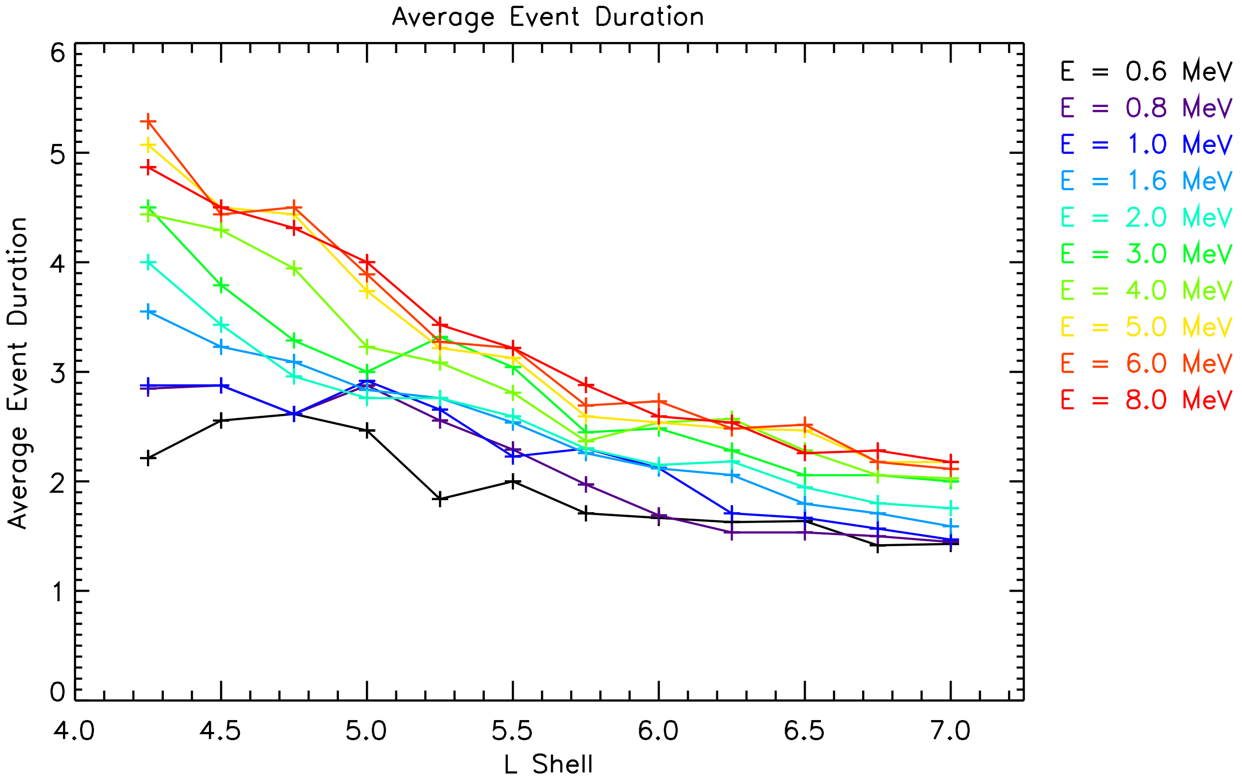


- Specifically, at L = 4.5, the average event duration increases from 2.5 days at E = 0.6 MeV to 4.4 days at the highest energies

- Further out at L = 6.5 we see the same trend, but the average duration is smaller ranging from 1.4 days at E = 0.6 MeV to 2.5 days at E = 8.0 MeV

Average Event Duration

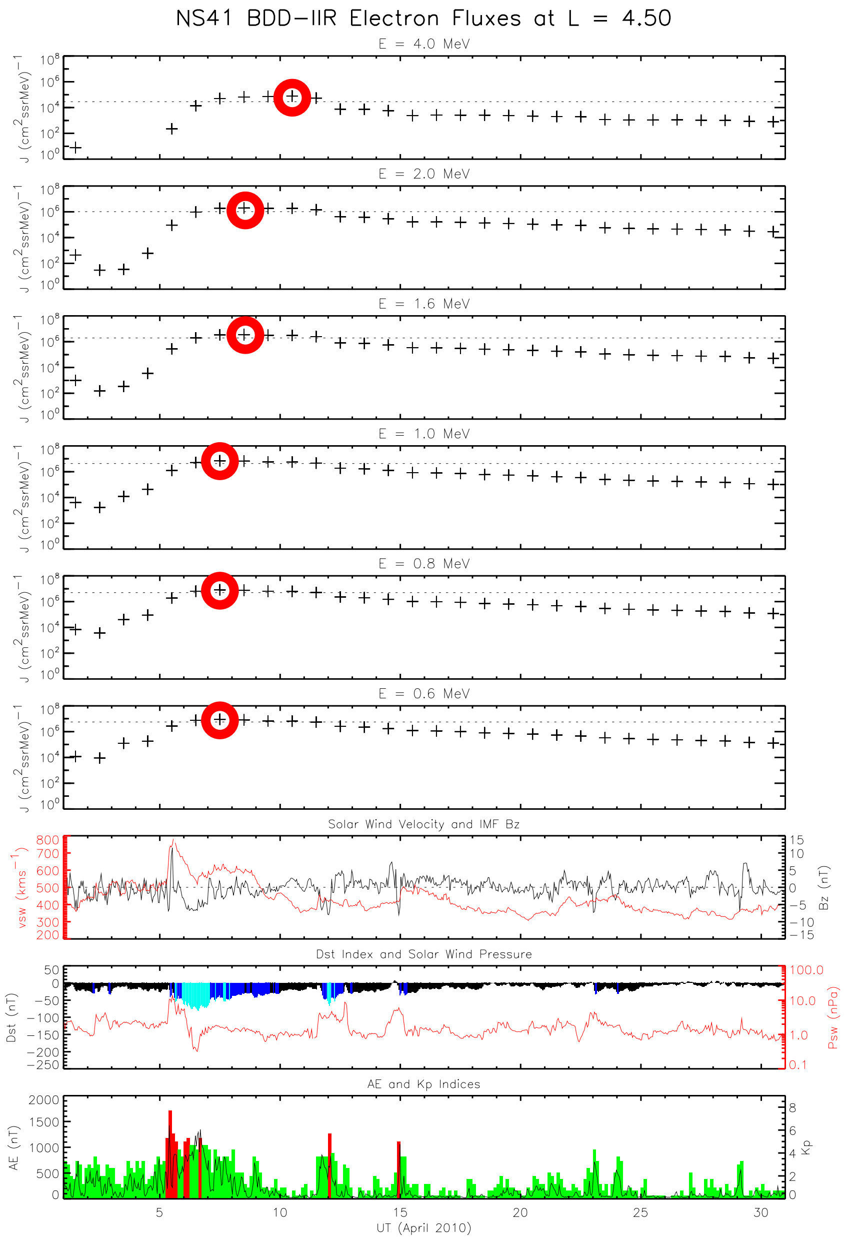


- Although we are not fitting timescales the data indicate that, over the range of energies and L samples, the timescale for loss is generally smaller at lower energies and higher L

Largest Event

- Some of the largest daily average fluxes encountered during the entire mission were observed during the 6 April 2010 geomagnetic storm

- This was a relatively moderate geomagnetic storm with a minimum Dst of -81 nT on 6 April



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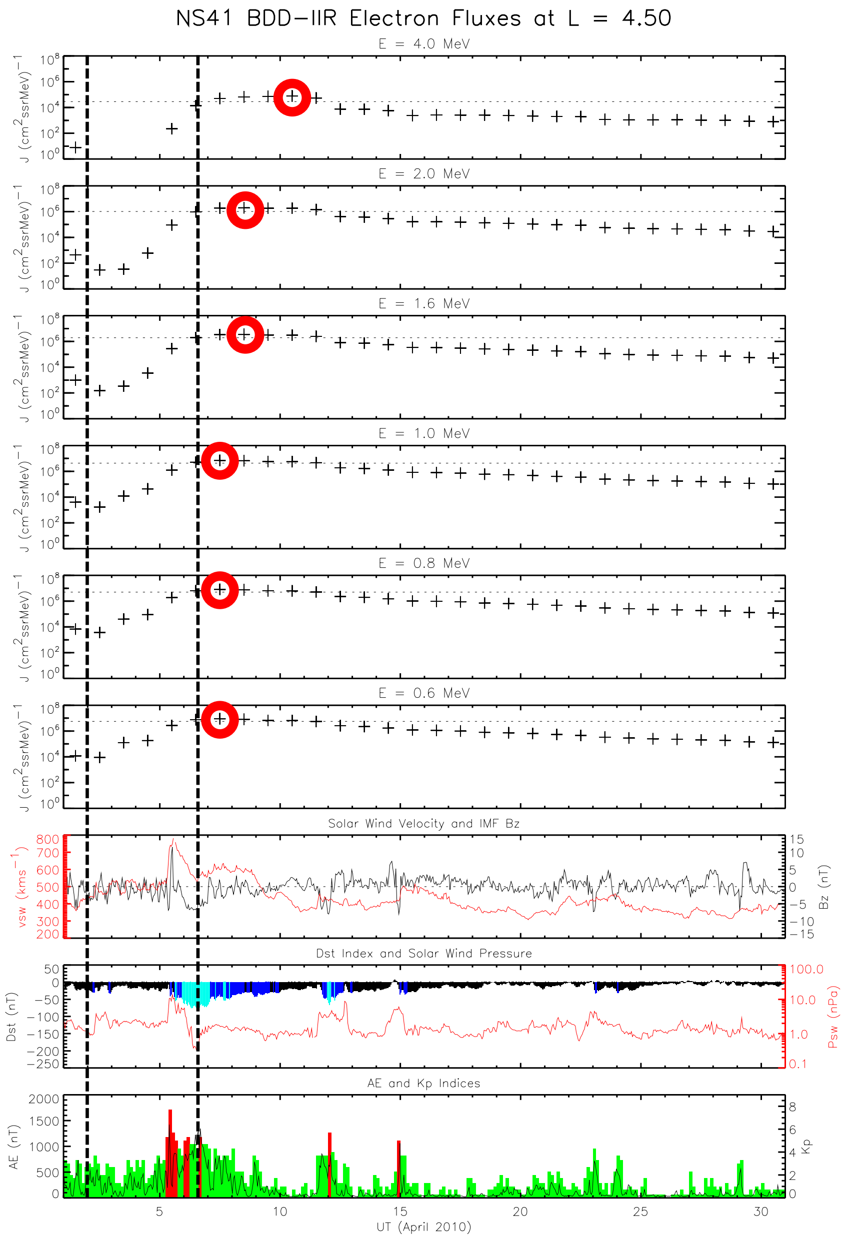
- This was a relatively moderate geomagnetic storm with a minimum Dst of -81 nT on 6 April

- Interestingly the relativistic electron fluxes had started to rise from 2 April, prior to the arrival of the storm due to a period of IMF Bz fluctuating about 0 nT and enhanced geomagnetic activity as monitored by AE

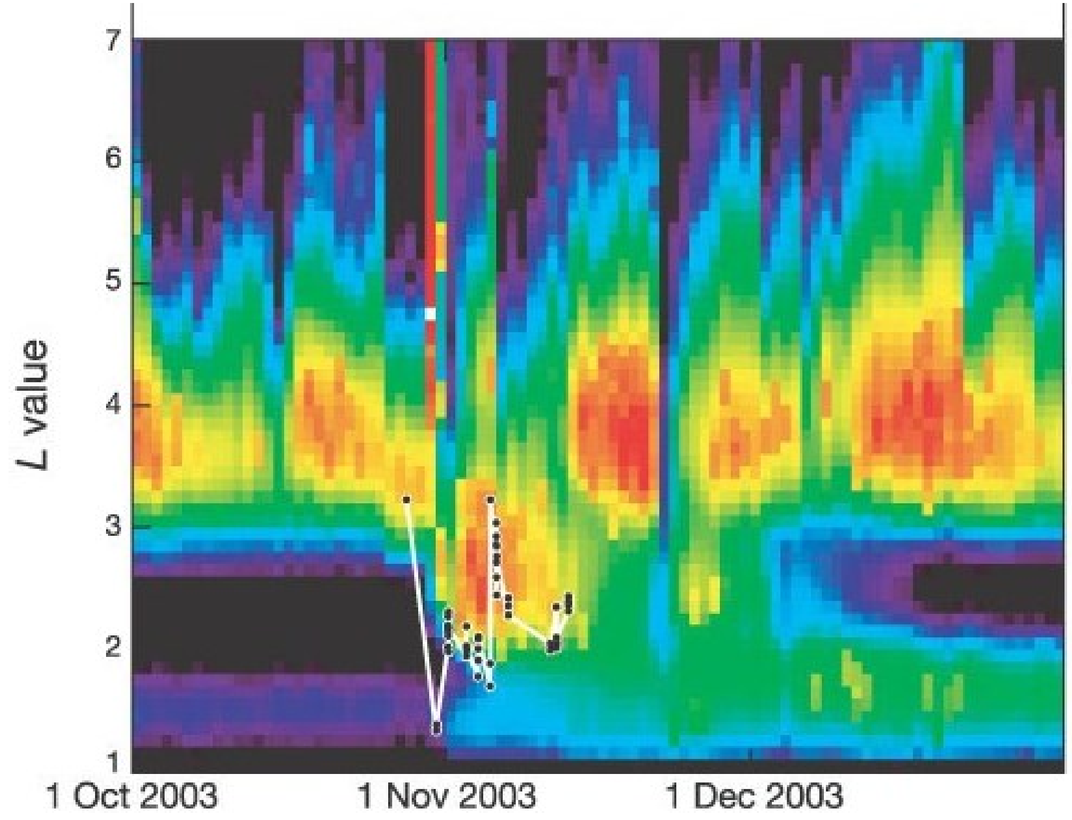


Halloween Storm

- One of the largest geomagnetic storms of the last 20 years was the Halloween storm in 2003, with a minimum Dst of -383 nT on 30th October

- Following the storm a new outer radiation belt formed at low L, peaking in the slot region below L = 3.0

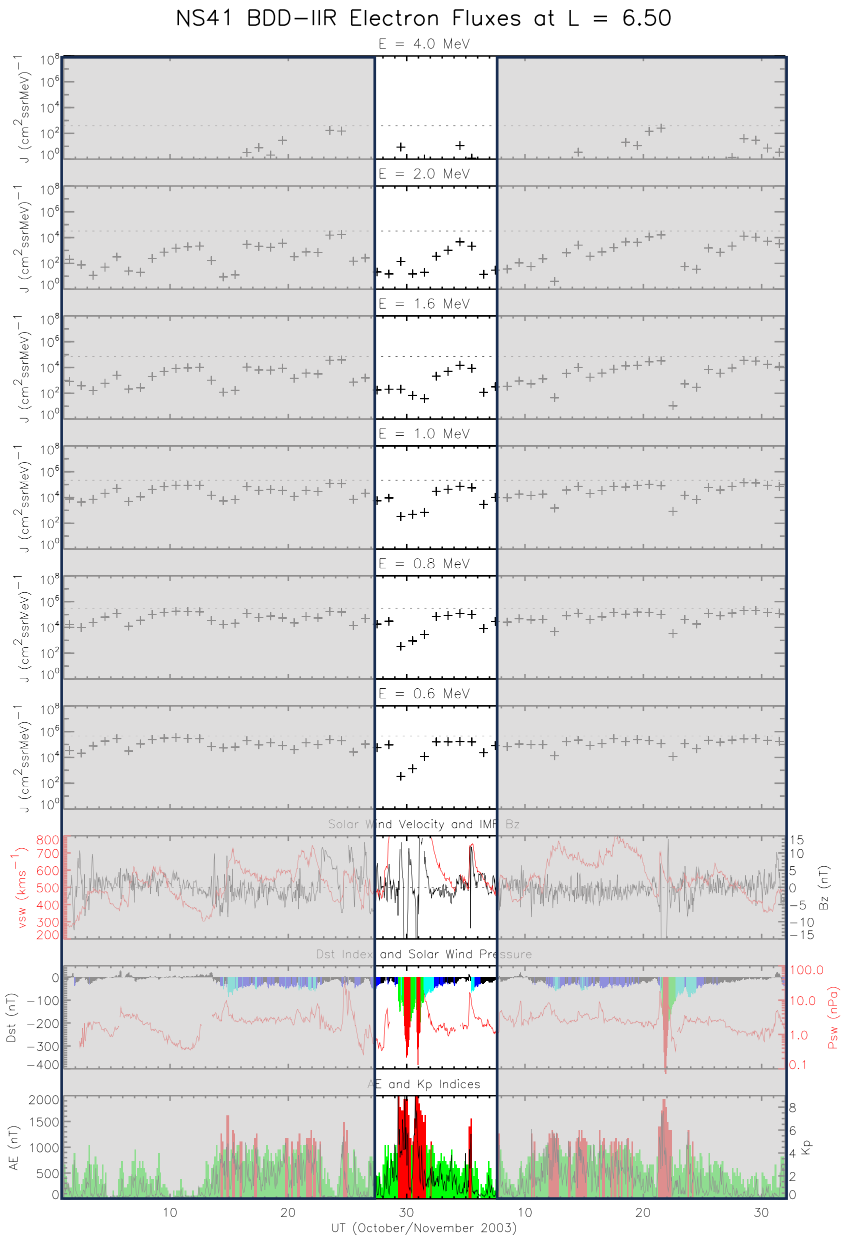
SAMPEX E 2-6 MeV Electrons



Baker et al., Nature, 2004

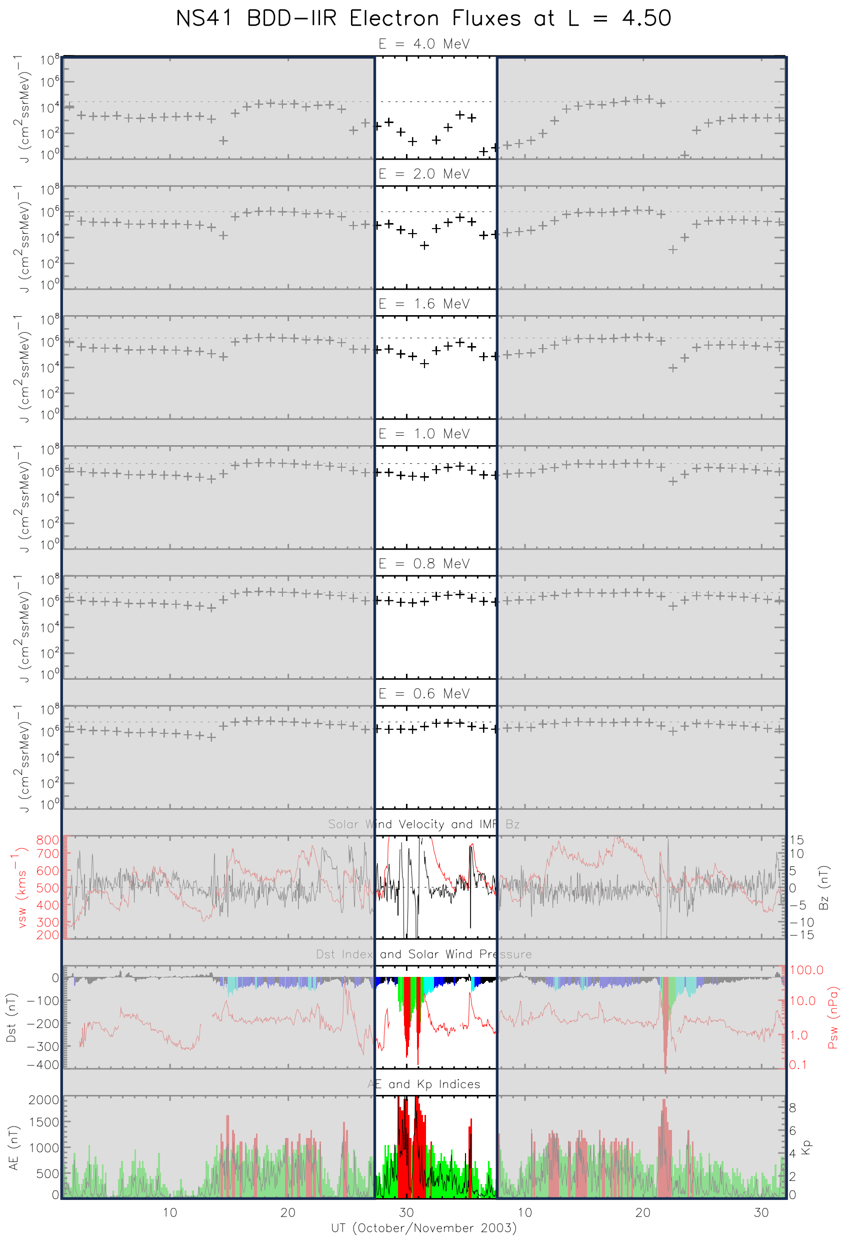
Halloween Storm

- This storm was not associated with large fluxes of relativistic electrons as observed by NS41, either towards the outer edge of the outer radiation belt at L = 6.5



Halloween Storm

- This storm was not associated with large fluxes of relativistic electrons as observed by NS41, either towards the outer edge of the outer radiation belt at L = 6.5 or at the heart of the outer radiation belt at L = 4.5



Preliminary Storm Study

- These results suggests that modest storms may pose more of a risk to satellites in GPS orbit than the largest storms that are more typically associated with extreme space weather

- To examine this finding in more detail we looked at the top 50 E = 2.0 MeV flux events at L = 4.5 and 6.5 and compared them with the largest fluxes associated with the top 15 strongest storms

Storm Categories

- We classify the storm strength by the minimum value of the Dst index associated with the storm, defined by Loewe and Prolss (1997) as follows:

  - **Weak ($-50 < Dst_{min} < -30$ nT)**
  - **Moderate ($-100 < Dst_{min} < -50$ nT)**
  - **Strong ($-200 < Dst_{min} < -100$ nT)**
  - **Severe ($-350 < Dst_{min} < -200$)**
  - **Great ($Dst_{min} < -350$ nT)**

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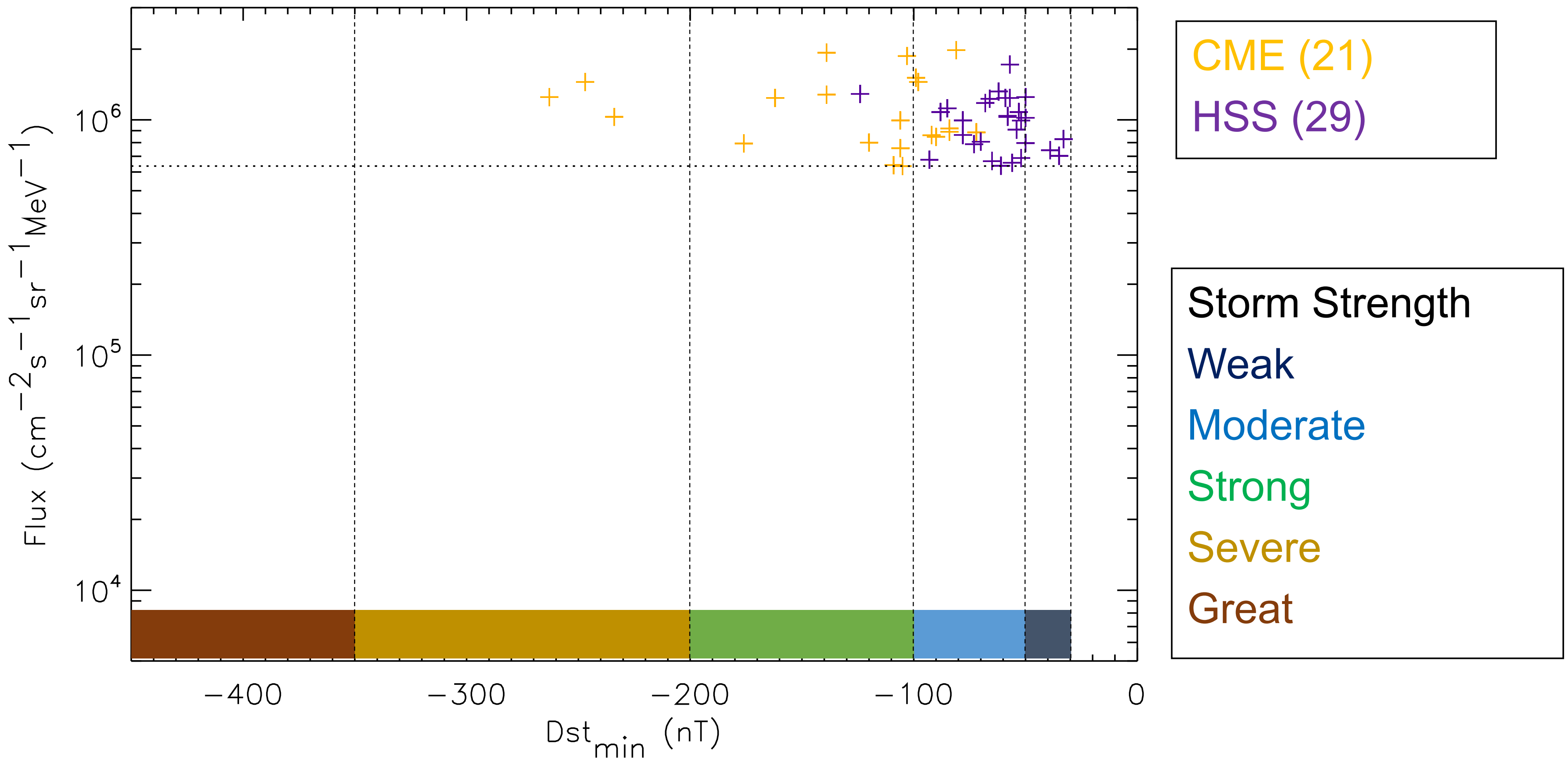
- We further split the storms into two groups:
  - **Coronal Mass Ejections (CME)**
  - **High Speed Solar Wind Streams (HSS)**

Top 50 E = 2.0 MeV Flux Events at L = 4.5



- At L = 4.5 the majority of the largest flux enhancements are associated with weak and moderate geomagnetic storms

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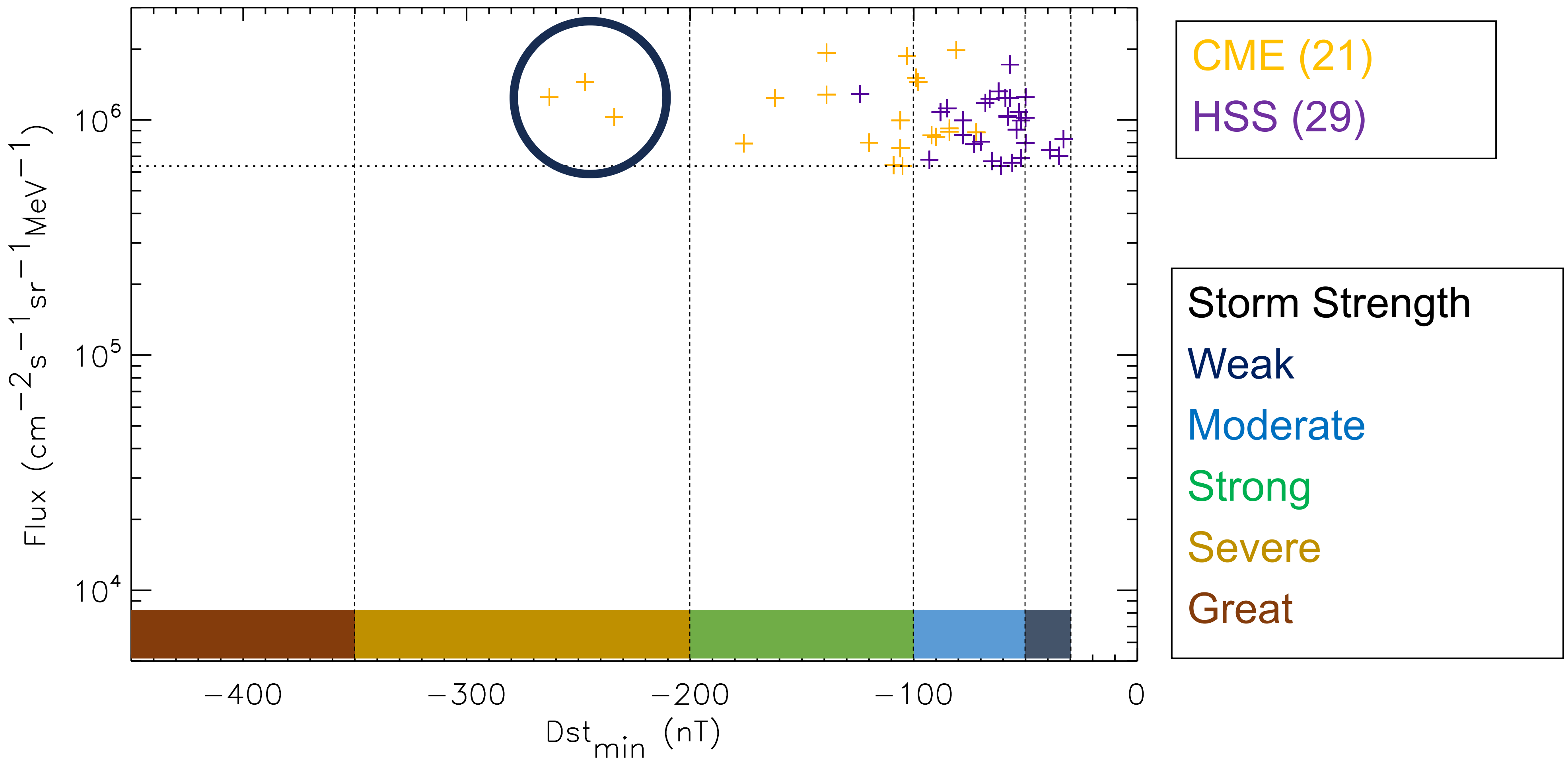
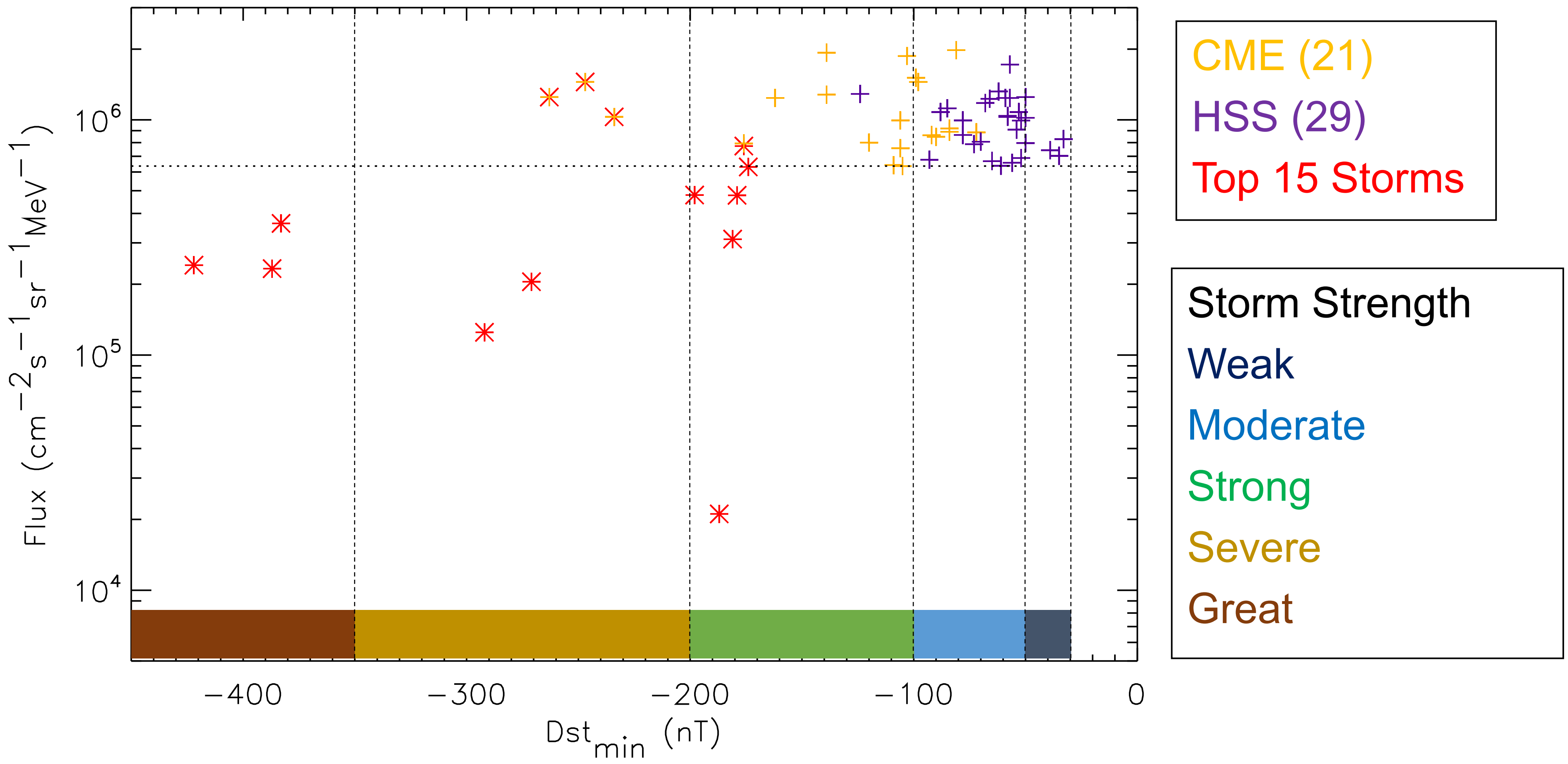


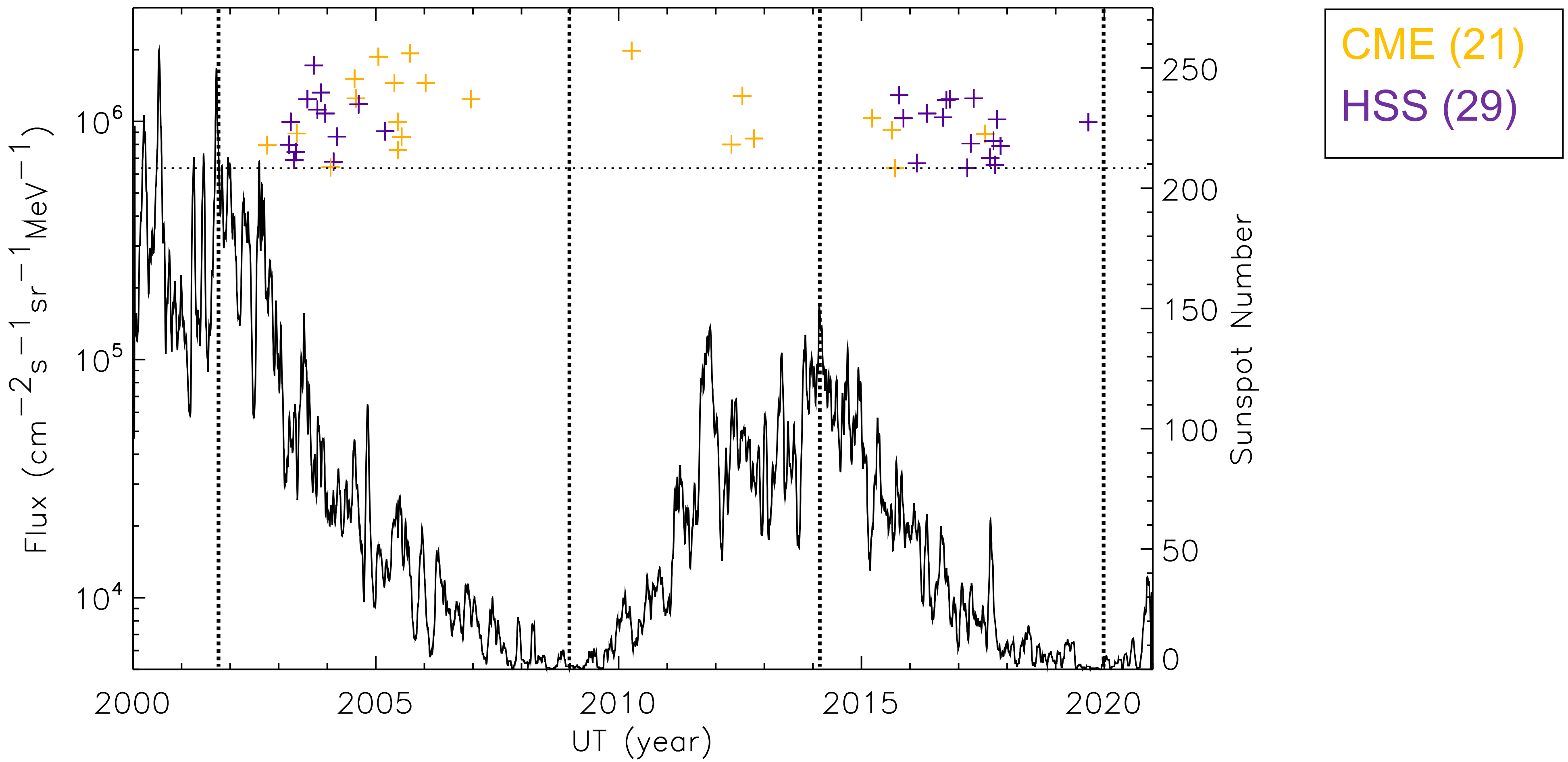
- At L = 4.5 the majority of the largest flux enhancements are associated with weak and moderate geomagnetic storms
- While it is possible to have a large flux associated with a severe storm, the latter is not a requirement for a large flux event

Top 50 E = 2.0 MeV Flux Events at L = 4.5



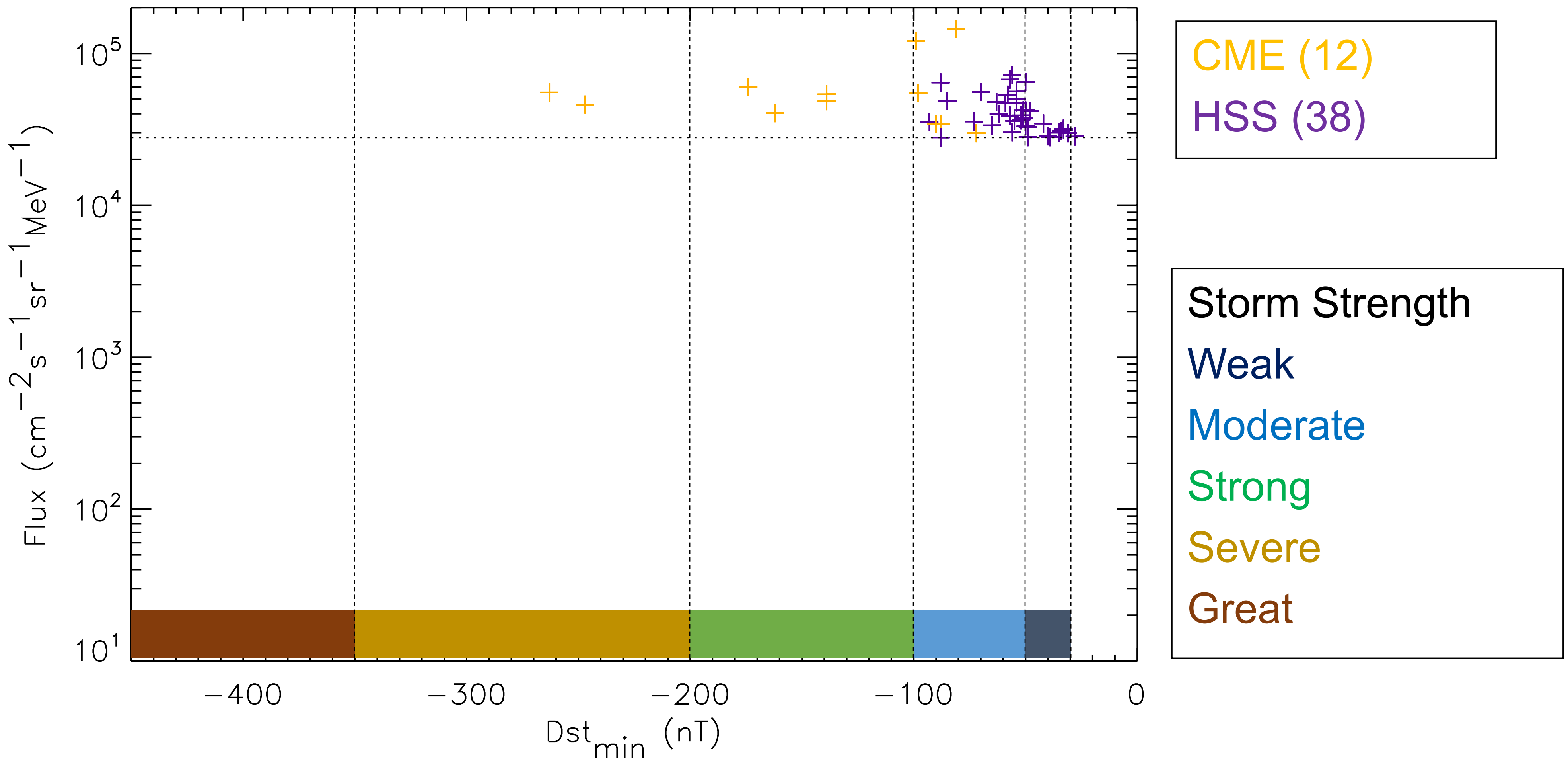
- At L = 4.5 the majority of the largest storms do not lead to significant flux events

Top 50 E = 2.0 MeV Flux Events at L = 4.5



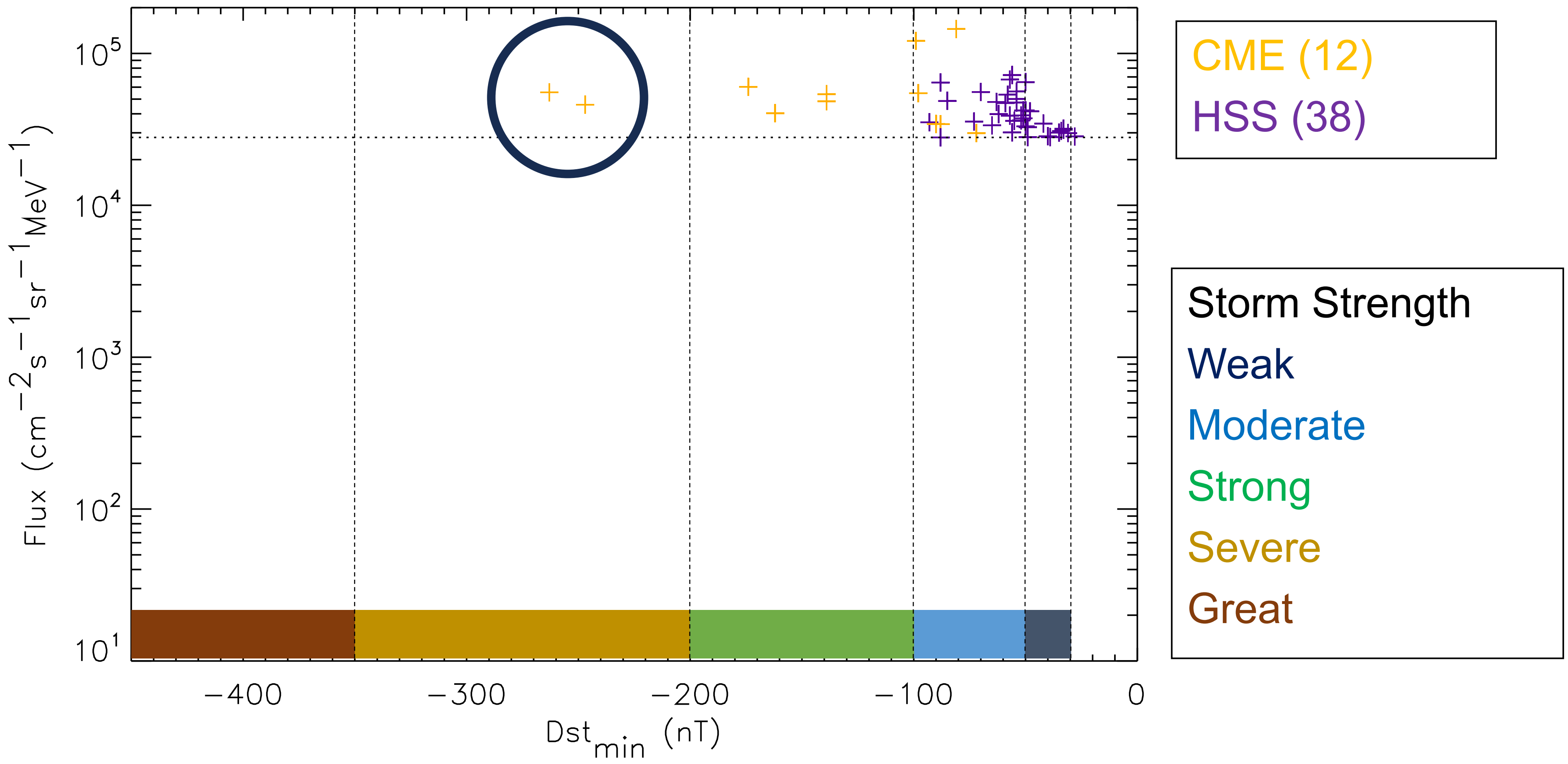
- At L = 4.5 the majority of the largest fluxes are seen during the declining phases of solar cycles 23 and 24

Top 50 E = 2.0 MeV Flux Events at L = 6.5



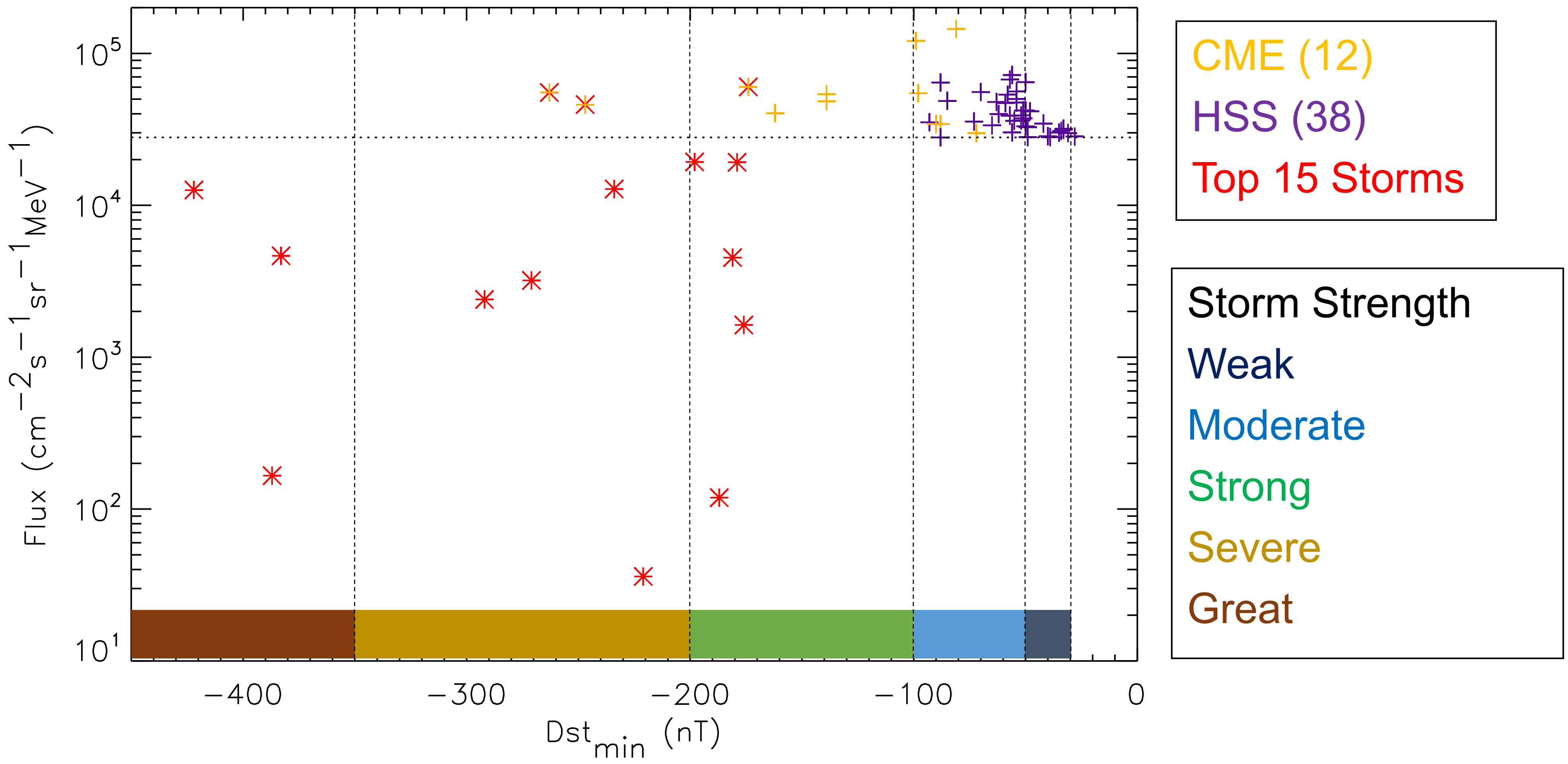
- At L = 6.5 the majority of the largest flux enhancements are also associated with weak and moderate geomagnetic storms

Top 50 E = 2.0 MeV Flux Events at L = 6.5



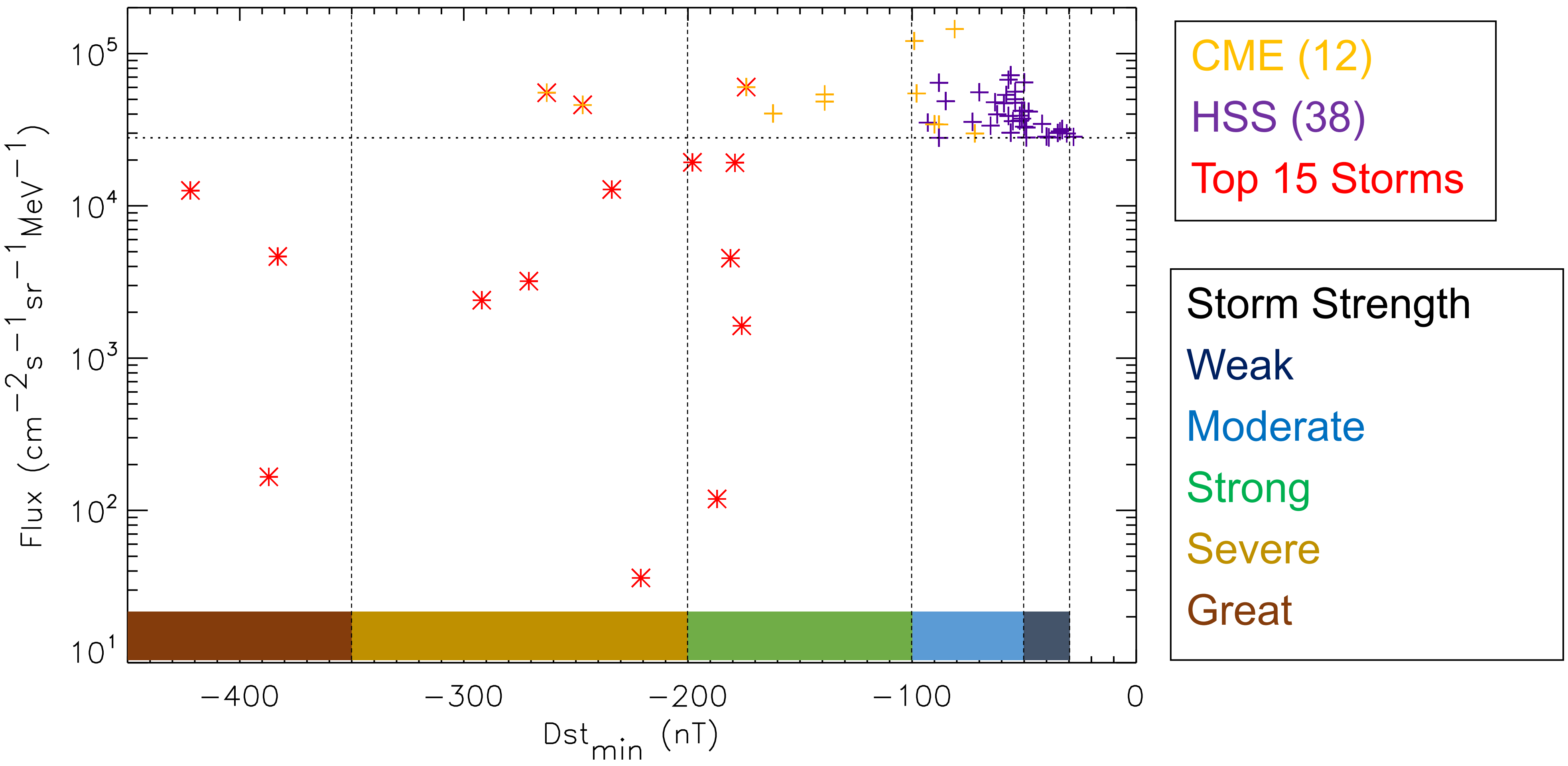
- At L = 6.5 the majority of the largest flux enhancements are also associated with weak and moderate geomagnetic storms
- Again, while it is possible to have a large flux associated with a severe storm, the latter is not a requirement for a large flux event

Top 50 E = 2.0 MeV Flux Events at L = 6.5



- At L = 6.5 the majority of the largest storms do not lead to significant flux events

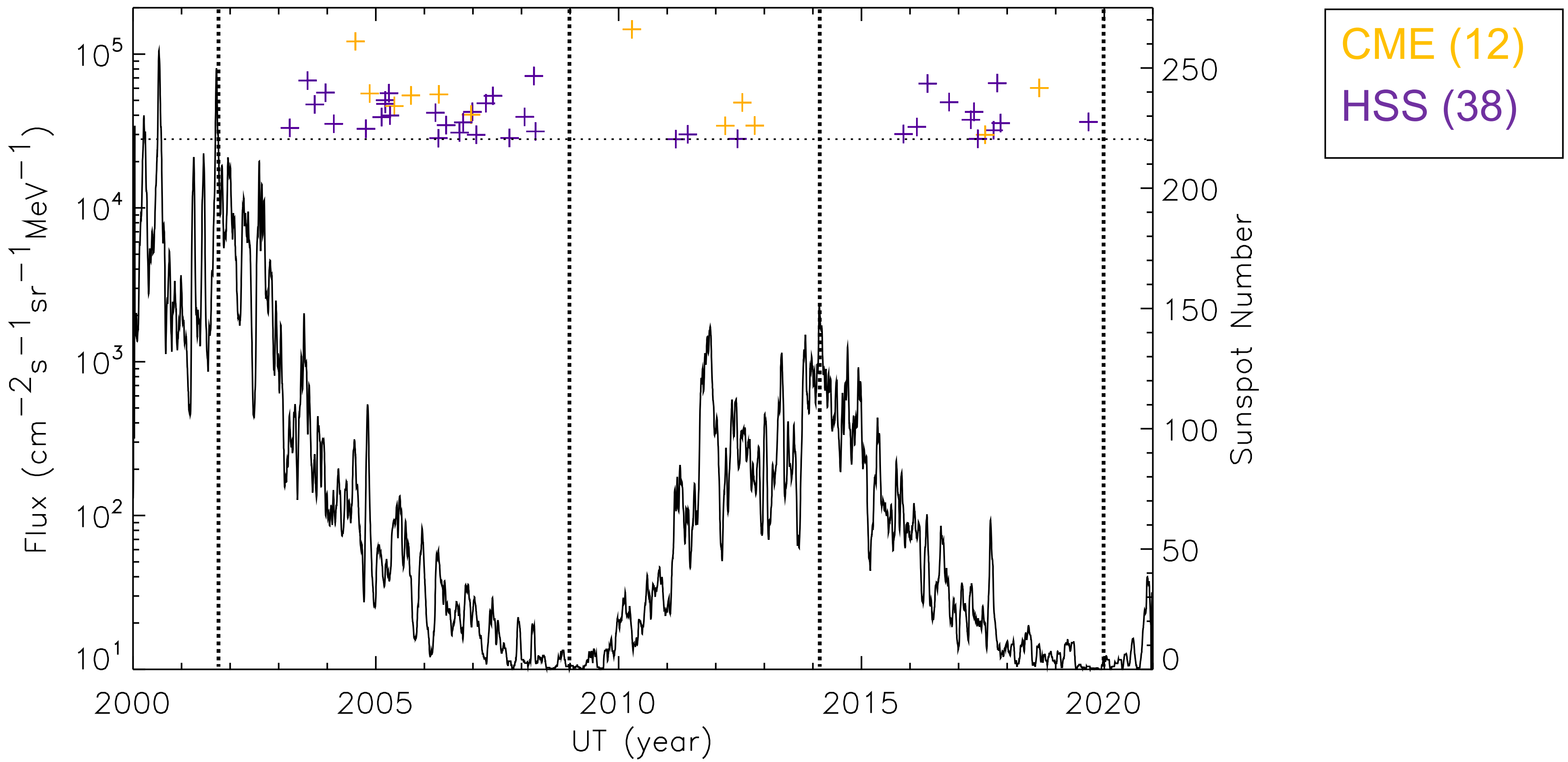
Top 50 E = 2.0 MeV Flux Events at L = 6.5



- At L = 6.5 the majority of the largest storms do not lead to significant flux events

- *This study shows that the largest relativistic electron fluxes in GPS orbit are not related to the most extreme storms as monitored by the Dst index*

Top 50 E = 2.0 MeV Flux Events at L = 6.5



- At L = 6.5 the majority of the largest flux events are seen during the declining phases of solar cycles 23 and 24

Applications

- The 1 in 10 and 1 in 100 year flux levels as a function of energy and L serve as benchmarks
  - to compare against other extreme space weather events
  - to help assess the potential impact of an extreme event
  - to improve the resilience of future satellites
  - to help evaluate realistic disaster scenarios

Conclusions

- The 1 in 10 year flux at L = 4.5, near the heart of the outer radiation belt, decreases with increasing energy ranging from 8.2×10^{6} cm^{-2} s^{-1} sr^{-1} MeV^{-1} at E = 0.6 MeV to 33 cm^{-2} s^{-1} sr^{-1} MeV^{-1} at E = 8.0 MeV. The 1 in 100 year event exhibits a similar trend and is a factor of 1.1 to 1.7 larger than the corresponding 1 in 10 year event.

- The 1 in 10 year flux at L = 6.5, on field lines which map to the vicinity of geostationary orbit, decrease with increasing energy ranging from 6.2×10^{5} cm^{-2} s^{-1} sr^{-1} MeV^{-1} at E = 0.6 MeV to 0.47 cm^{-2} s^{-1} sr^{-1} at E = 8.0 MeV. The 1 in 100 year event exhibits a similar trend and is a factor of 1.1 to 12 times larger than the corresponding 1 in 10 year event.

Acknowledgements

- We would like to acknowledge the skill and attention to detail of Timothy J. Wehner that enabled these measurements at Medium Earth Orbit

- We acknowledge Los Alamos National Laboratory for generating the BDD-IIR data products used in this study, and the National Oceanic and Atmospheric Administration's archive of the data files themselves

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