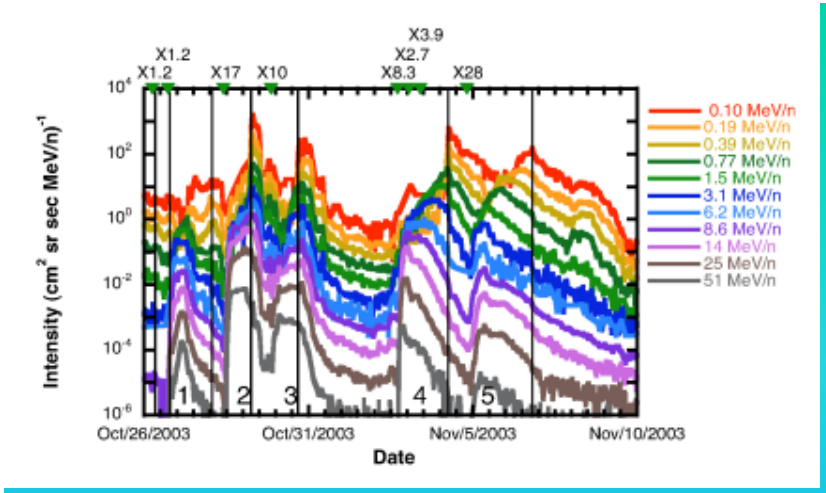
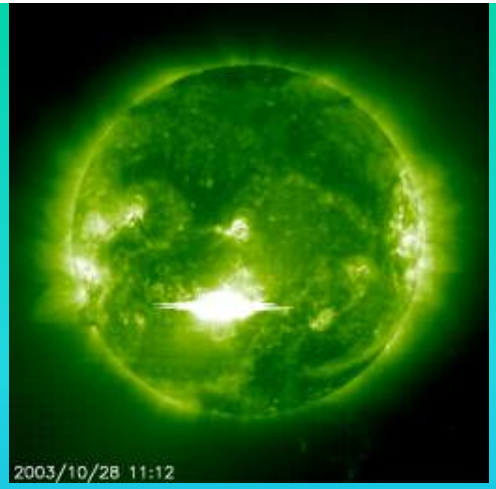
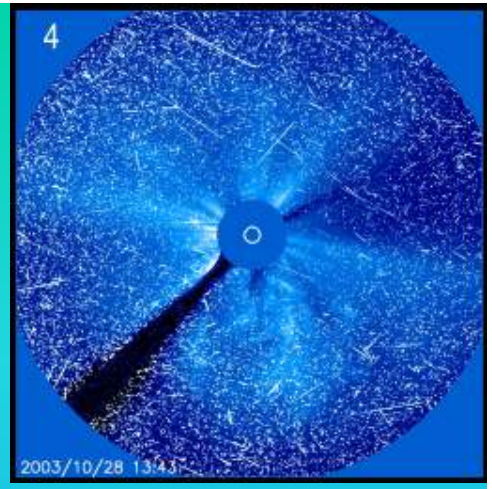


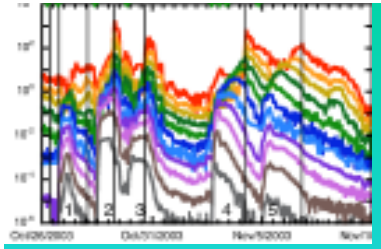




Introduction to SEPs

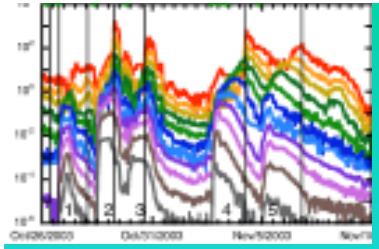
Christina Cohen

Caltech



Outline

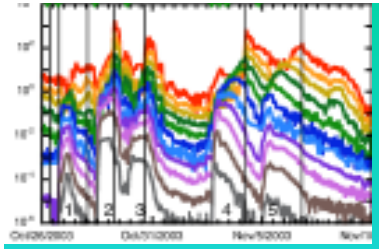
- What are SEPs?
  - And why do we care?
- How are the measured?
  - on the ground
  - in space
- What is the SEP history?
  - pre-1997
  - post 1997
- What is new and exciting about SEPs?
  - in my humble opinion.....



What are SEPs?

- Solar Energetic Particles
  - › Solar = assumed to originate at the Sun
  - › Energetic = historically above a few hundred keV/nuc
  - › Particles = ions (mostly H, He like the Sun) + electrons
- Seen as increases in counting rates of ions (and/or electrons) of energies usually above 0.1 MeV/nucleon

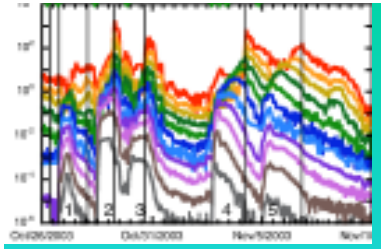
What measure history (old/new) excitement



Why do we care about SEPs?

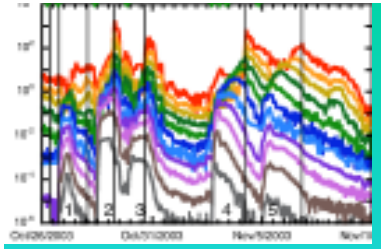
- A sample of the Sun
  - one of the most accurately measured solar samples
  - if we can just figure out the details of creating them and getting them here
- Earth effects
  - energetic particles hitting the Earth's atmosphere excite atoms and create aurora

What measure history (old/new) excitement



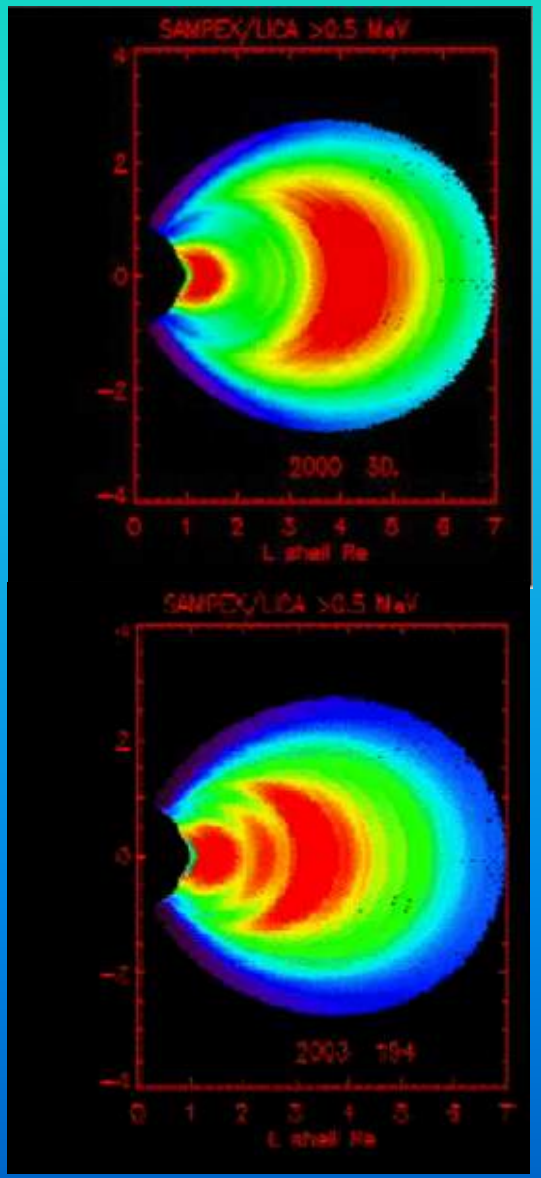
Aurora Examples

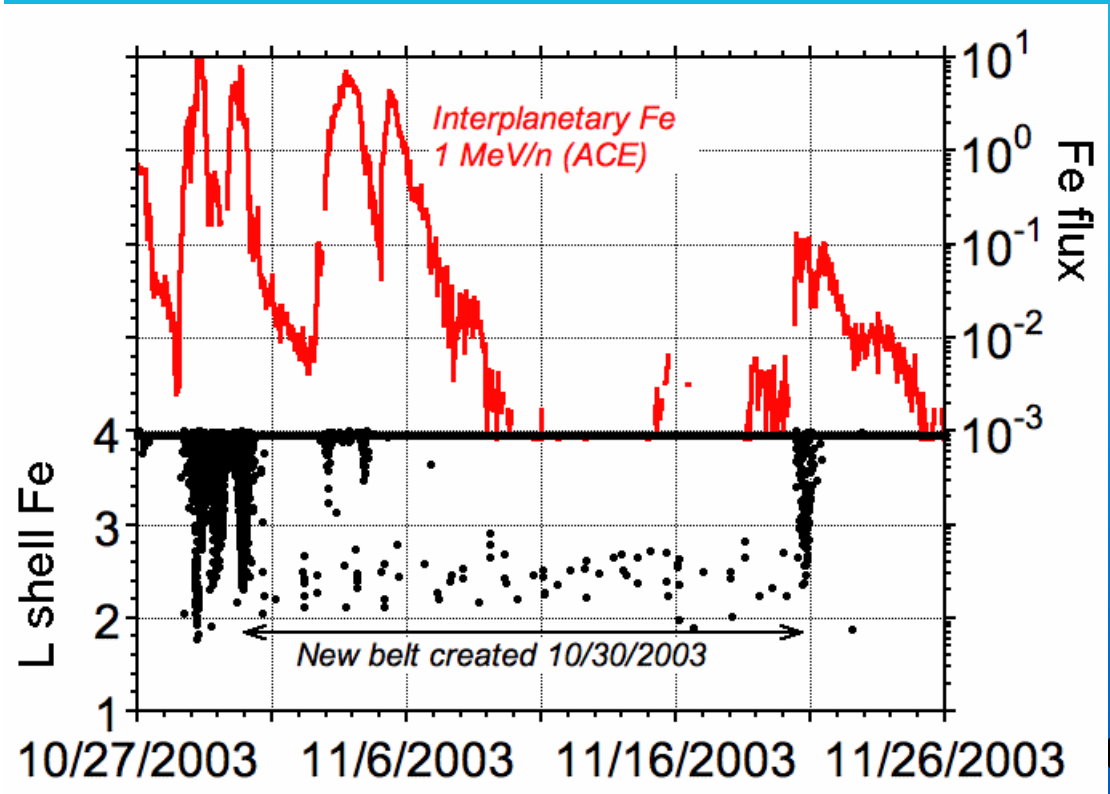
- energetic particles hitting the Earth's atmosphere excite atoms and create a



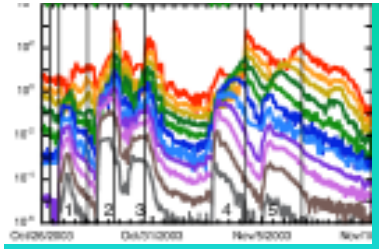
Earth Radiation Belts

- Energetic particles are trapped in belts around the Earth
- Radiation hazard for Earth-orbiting spacecraft





d/new) excitement



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- A sample of the Sun
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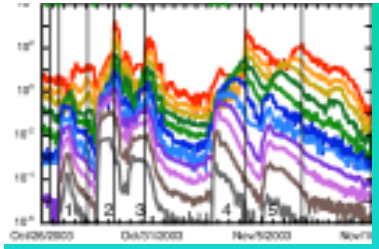
- Earth effects
  - energetic particles hitting the Earth's atmosphere excite atoms and create aurora
  - energetic particles contribute to the radiation belts
  - part of geomagnetic storms which can cause black outs
    - change in Earth's magnetic field induces strong currents in power system
    - Hydro Quebec lost power grid for 9 hours in March 1989

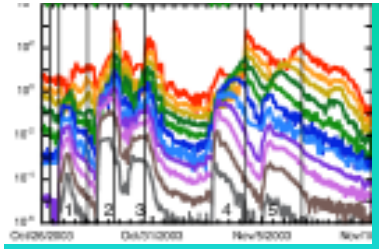
What measure history (old/new) excitement



Why do we care about SEPs?

- Spacecraft Effects
  - Loss of data
  - Spurious signals
    - False alarms, noise strobes, erroneous telemetry values
  - Phantom commands
    - For example gain changes and attitude sensor errors
  - Mission or sensor degradation
  - Solar array degradation
  - Safeholds
  - Latchups
  - Subsystem failure
    - Loss of a redundant system
  - Mission Loss

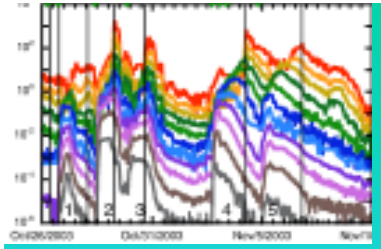
What measure history (old/new) excitement



How are SEPs Measured?

- On the ground
  - › neutron monitors (indirect measurement)
- In space (since early 1960s)
  - › first measurements (scintillation and Geiger counters)
  - › dE/dx vs E technique
    - Proportional counters
    - Solid state detectors
  - › Time of flight
  - › E/q + dE/dx vs E (SEPICA)

What measure history (old/new) excitement



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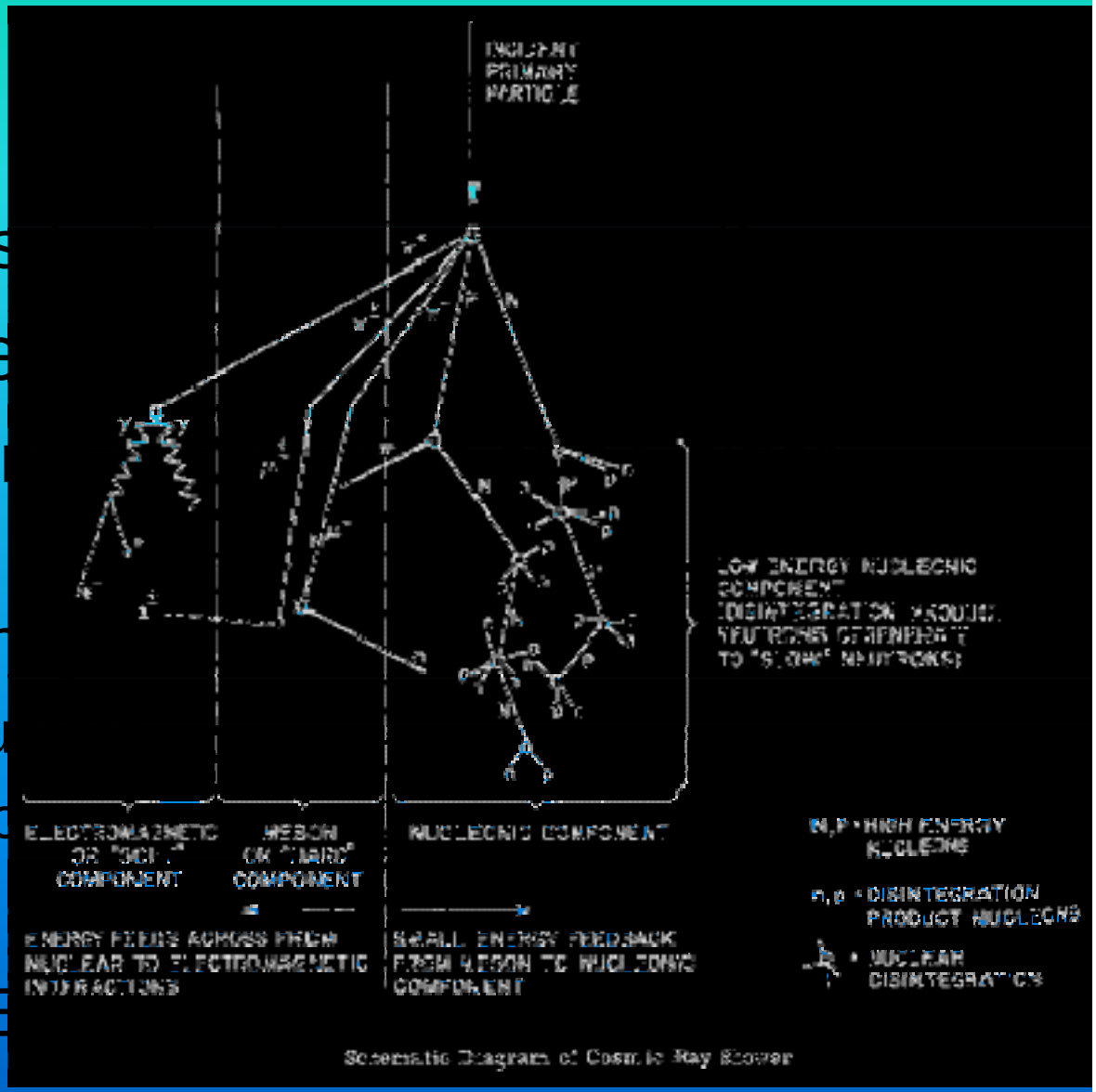
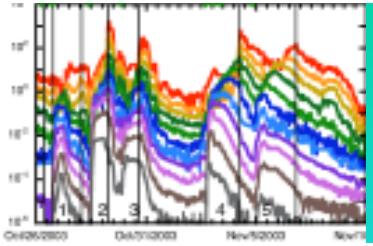


Schematic Diagram of Cosmic Ray Shower

What measure history (old/new) excitement

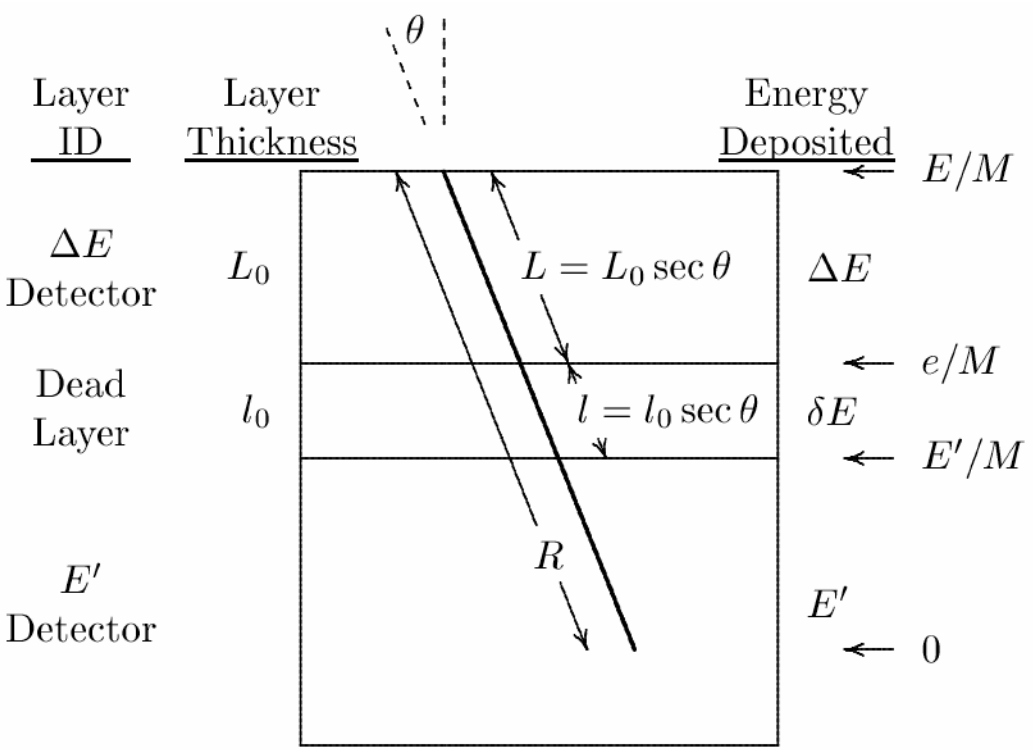


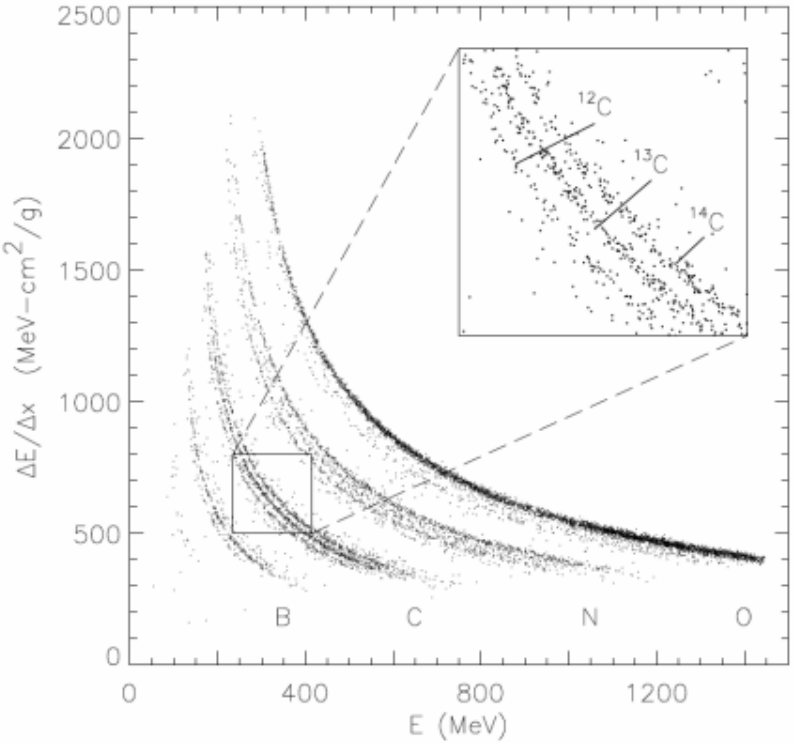
How are SEPs Measured?

$$dE/dx \propto (Z/V)^2 \propto (MZ^2/E)$$

$$E\ dE/dx \propto Z^2M$$

$$dE/dx \sim \Delta E/\ L = \Delta E/(L_0 \sec \vartheta)$$





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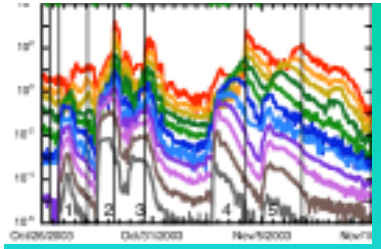

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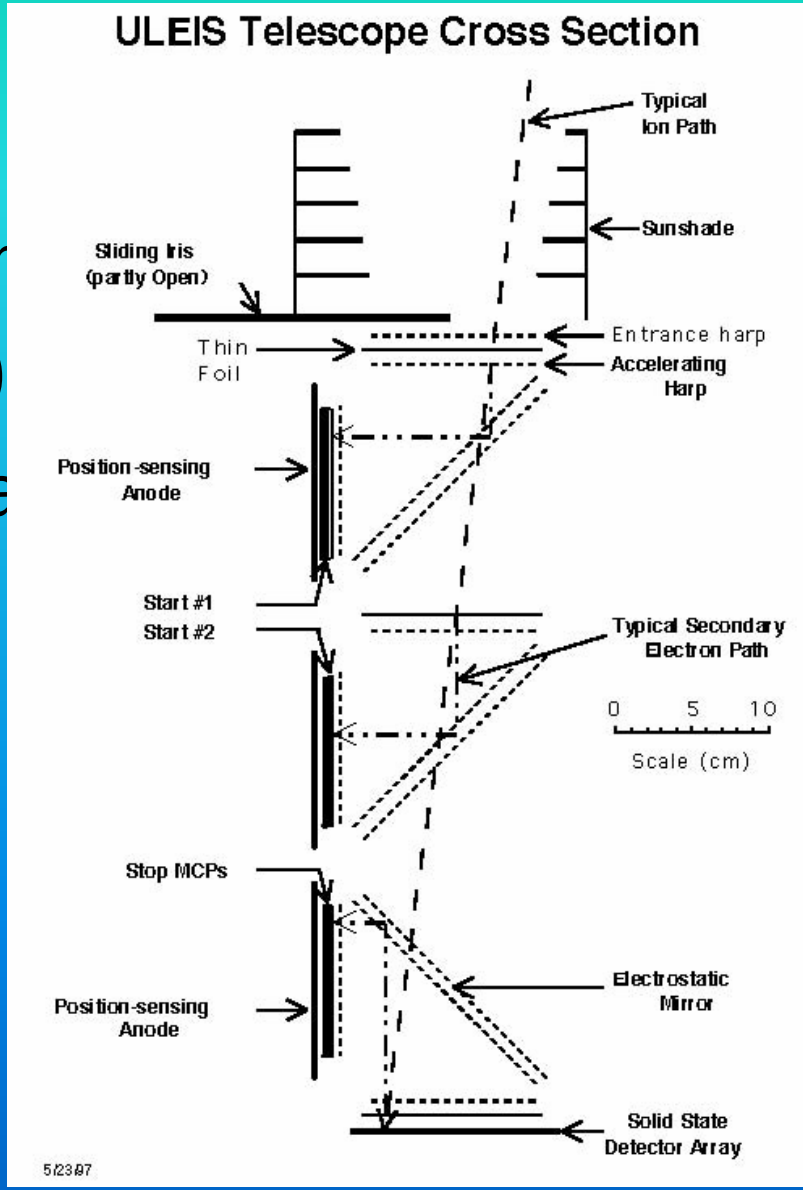

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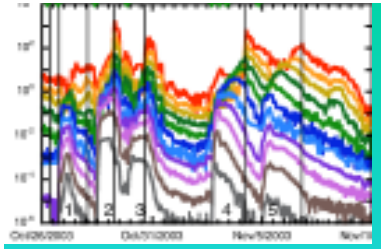

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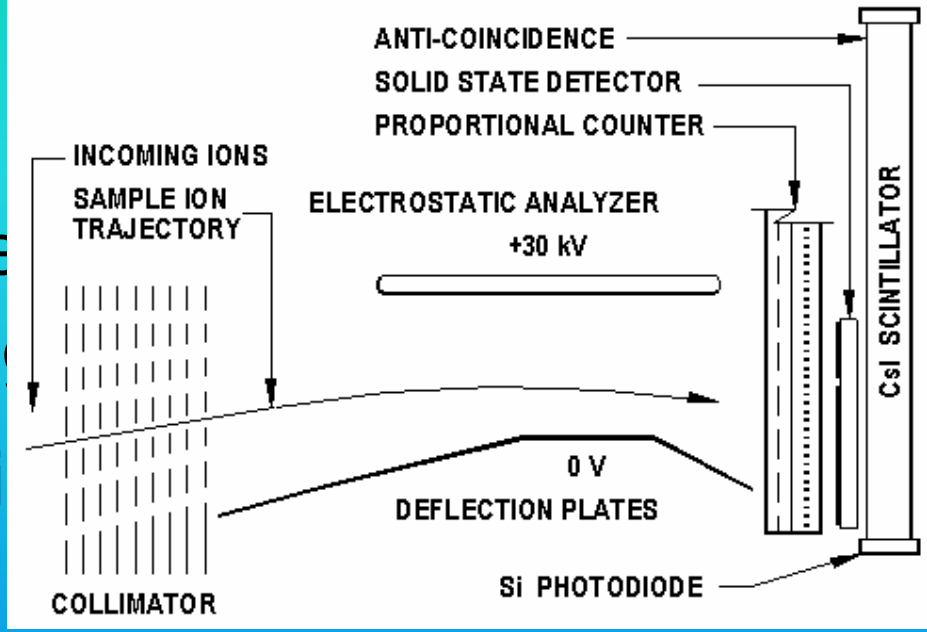

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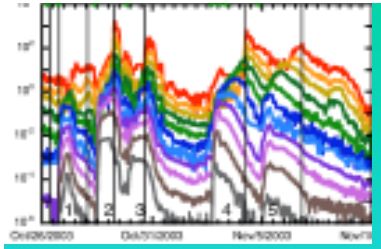


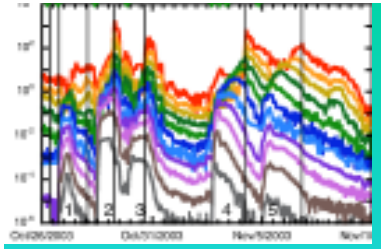
What is the History of SEPs?

(pre-1997)

- First detection with connection to solar flare observation - Forbush 1946 in neutron monitor
- Timing related to gamma ray flare 1956 (most well studied)
- Better in space because can see them directly - space age
  - intensity
  - energy spectra
  - composition

Categorization

What measure history (old/new) excitement



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Categ

What measure history

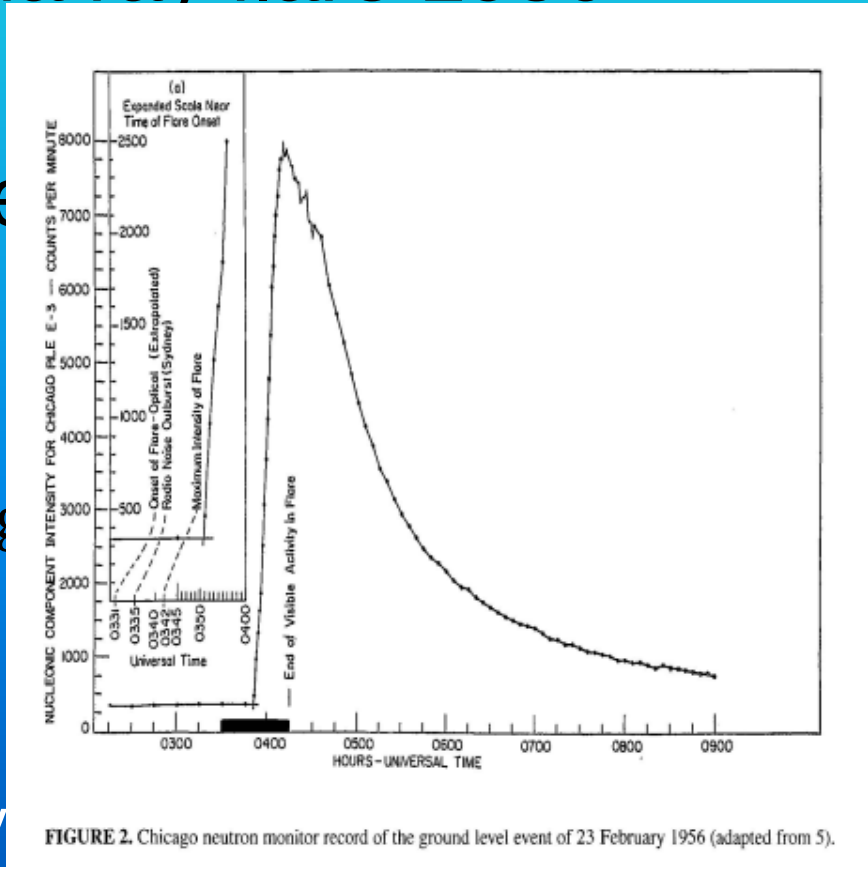
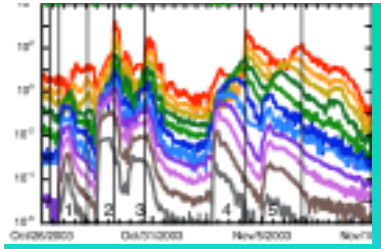


FIGURE 2. Chicago neutron monitor record of the ground level event of 23 February 1956 (adapted from 5).

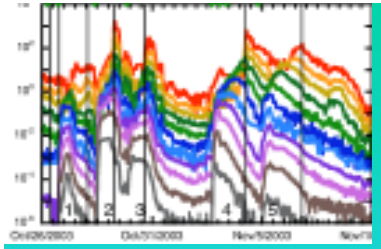


What is the History of SEPs?

(pre-1997)

- At the same time...
  - › flares are being categorized by size, duration, emission wavelength
  - › radio emission is being categorized
  - › flares and radio emission combined to create...
- Two classes of flares
  - › Impulsive
  - › Gradual

What measure history (old/new) excitement



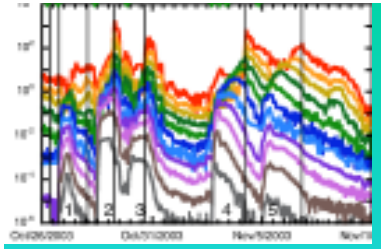
What is the History of SEPs?

(pre-1997)

- Correlations with SEP characteristics results in a 2 class SEP system:

	Impulsive	Gradual
Flare Characteristics	Short duration Compact/Point Source	Long duration Large Source
Radio Characteristics	Type III/V	Type II/IV
Particle Characteristics	^3He, e^-, heavy ion rich short duration, small, limited longitude	SW like composition long duration, large, wide longitude

What measure history (old/new) excitement



What is the History of SEPs?

(pre-1997)

Gradual Impulsive

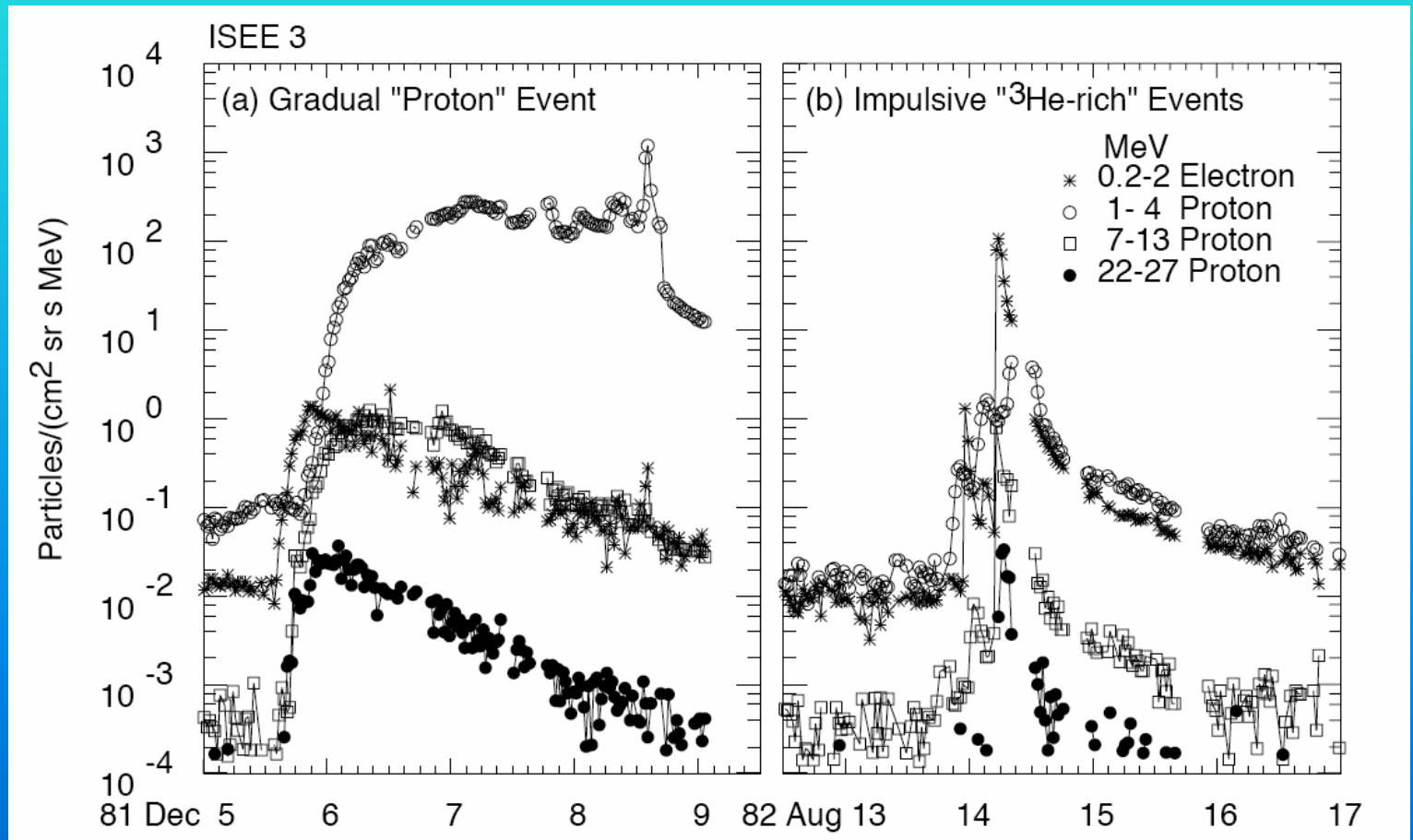
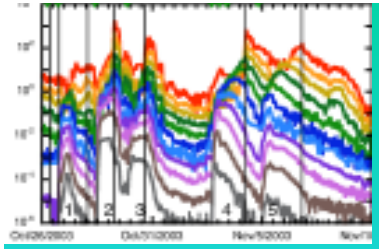


Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.

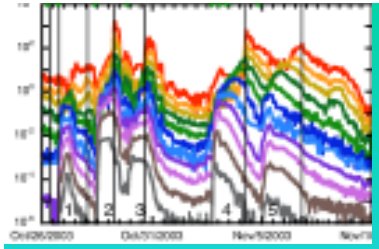


What is the History of SEPs?

(pre-1997)

- All SEPs created by flares
  - › slight problem with longitude distribution of gradual events
  - › ideas of storage, cross-field transport, lots of scattering in the interplanetary medium (not happy about this)
  - › Not a good correlation between interacting protons and SEP protons (SMM allowed gamma-ray measurements in space 1980)
- Enter Skylab and CME observations (1978)
  - › high correlation (96%) between gradual flares and CMEs
  - › CMEs can drive shocks and shocks can accelerate

What measure history (old/new) excitement

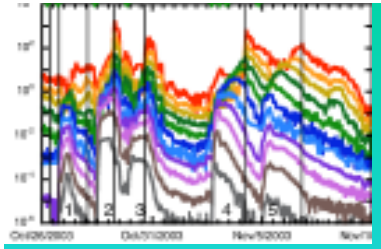


What is the History of SEPs?

(pre-1997)

- Nice things about CME-shock acceleration for gradual SEP events
  - › CME angular size close to longitude distribution of gradual SEP events
  - › Solves the cross-field transport ‘problem’
  - › Correlation between CME size/speed and SEP size
  - › Found a gradual SEP event *with no flare* but with CME
  - › Found CMEs did *not* occur with impulsive SEP events
  - › Long acceleration in the IPM explained long duration of gradual SEP events (compared to

What measure history (old/new) excitement



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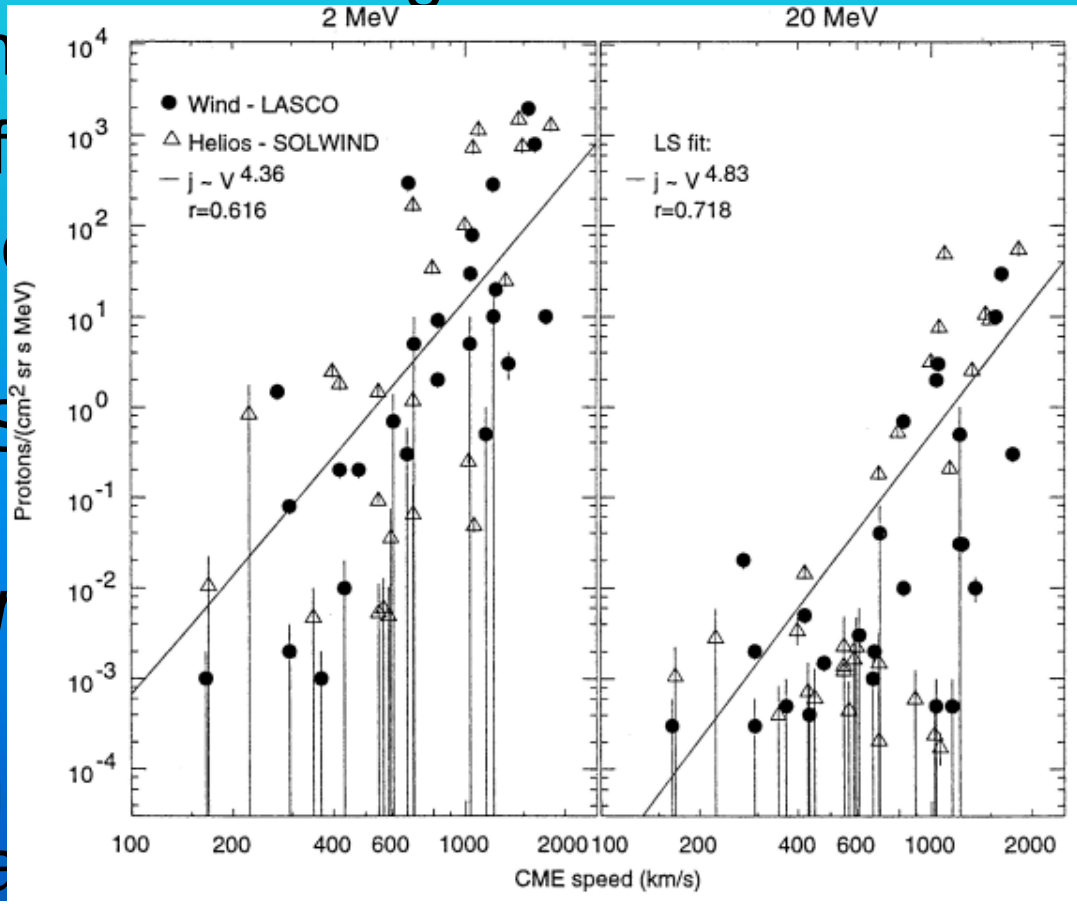
  - › Correlation betwe size
  - › Found a gradual S CME
  - › Found CMEs did *n* events
  - › Long acceleration duration of gradua



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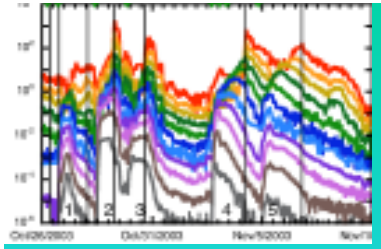


What is the History of SEPs? (pre-1997)

- ‘Paradigm Shift’
  - › Had 1 acceleration mechanism for all SEP events
  - › Now have two independent acceleration mechanisms
    - CME-driven shock acceleration => Gradual SEP events
    - Impulsive flare acceleration => Impulsive SEP events

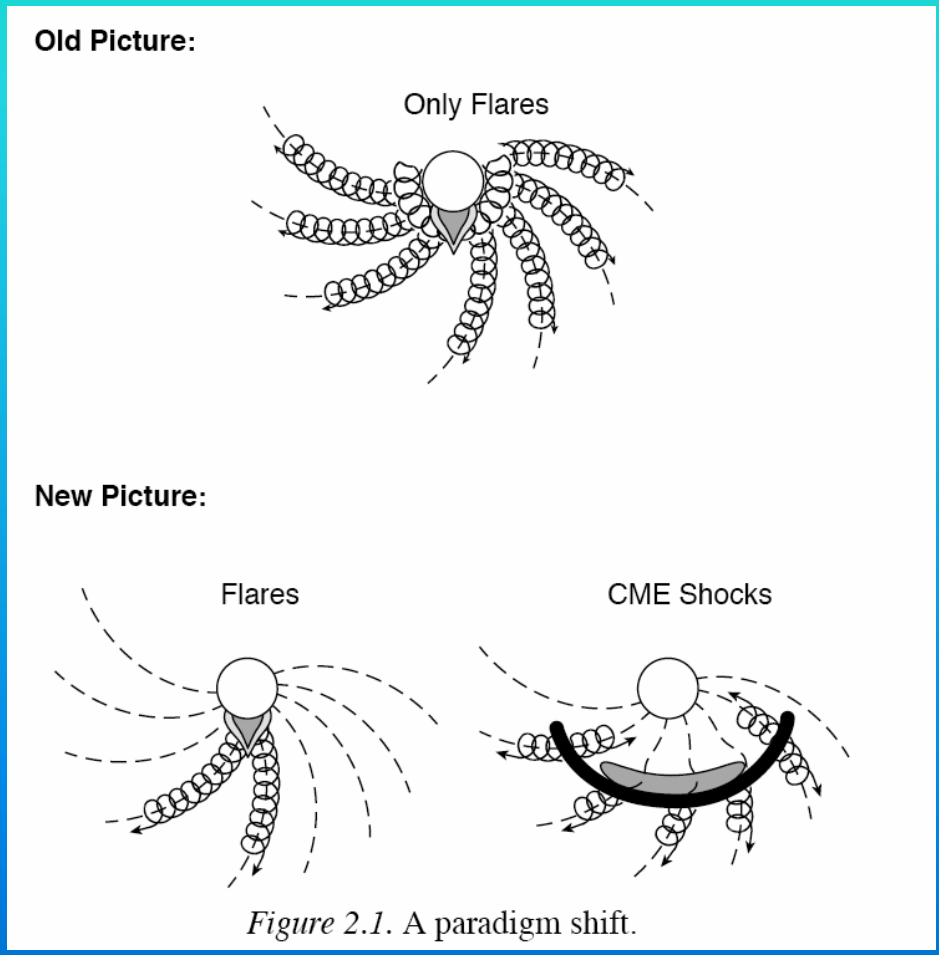
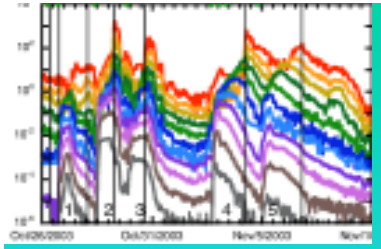


Figure 2.1. A paradigm shift.

Reames 1999

What measure history (old/new) excitement

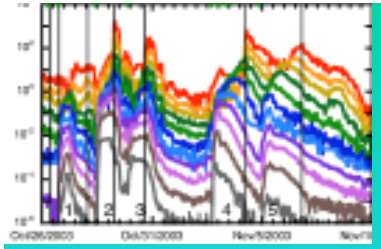


What is the History of SEPs?

(pre-1997)

- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - › Klecker et al. 1984 finds charge state difference
  - › Mason et al. 1986 finds systematic composition difference
  - › Reames explains charge and composition characteristics in terms of low altitude

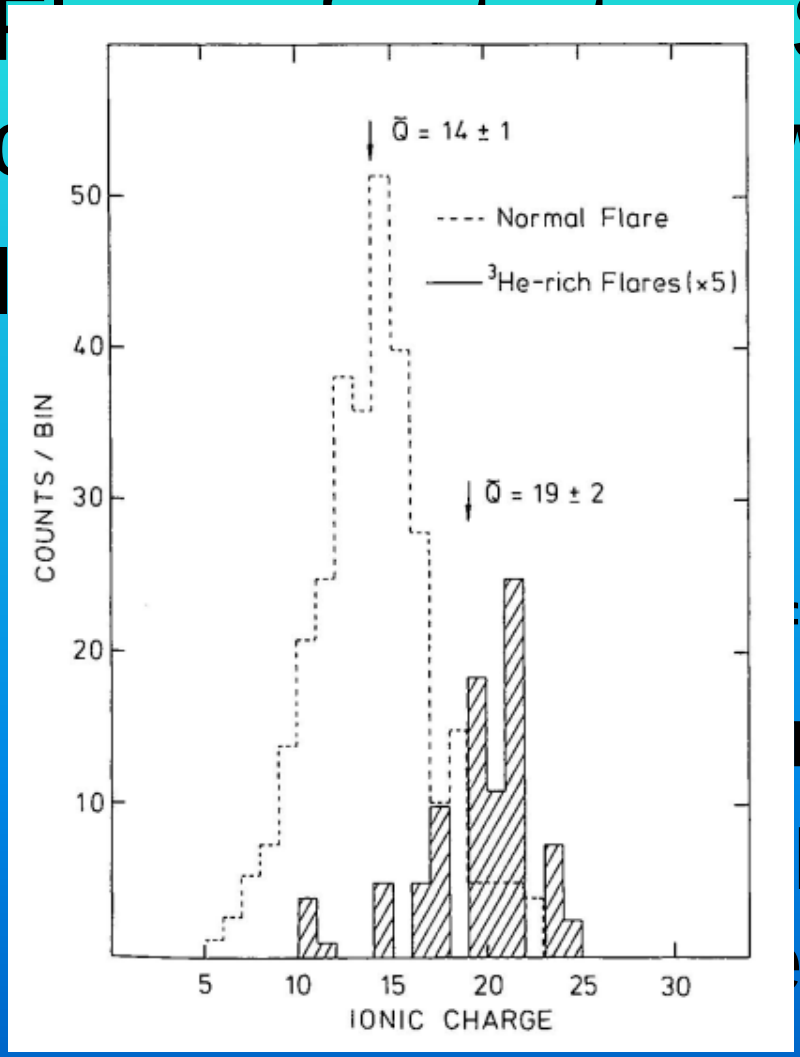
What measure history (old/new) excitement

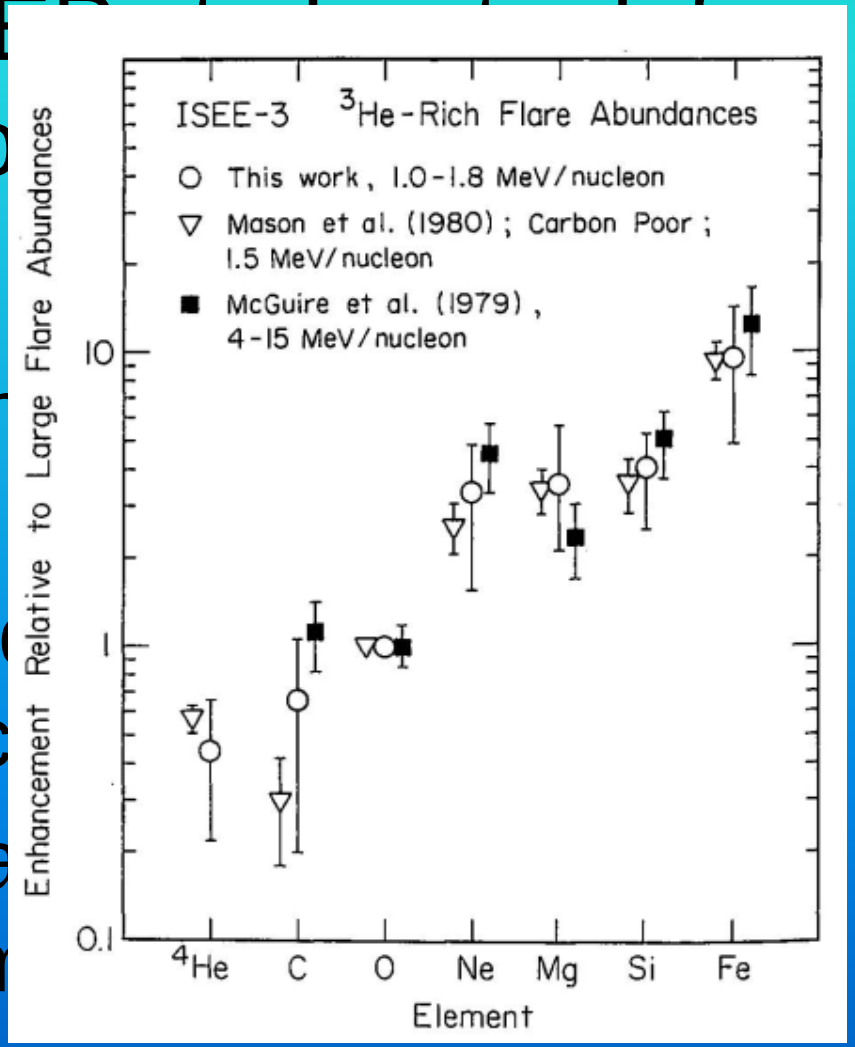


What is the History of SEPs?

(pre-1997)

- F… …SE…
- I… …vo…





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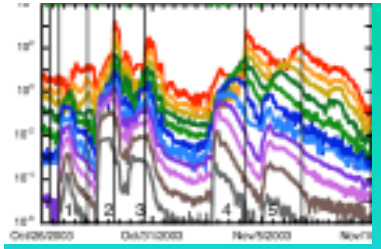

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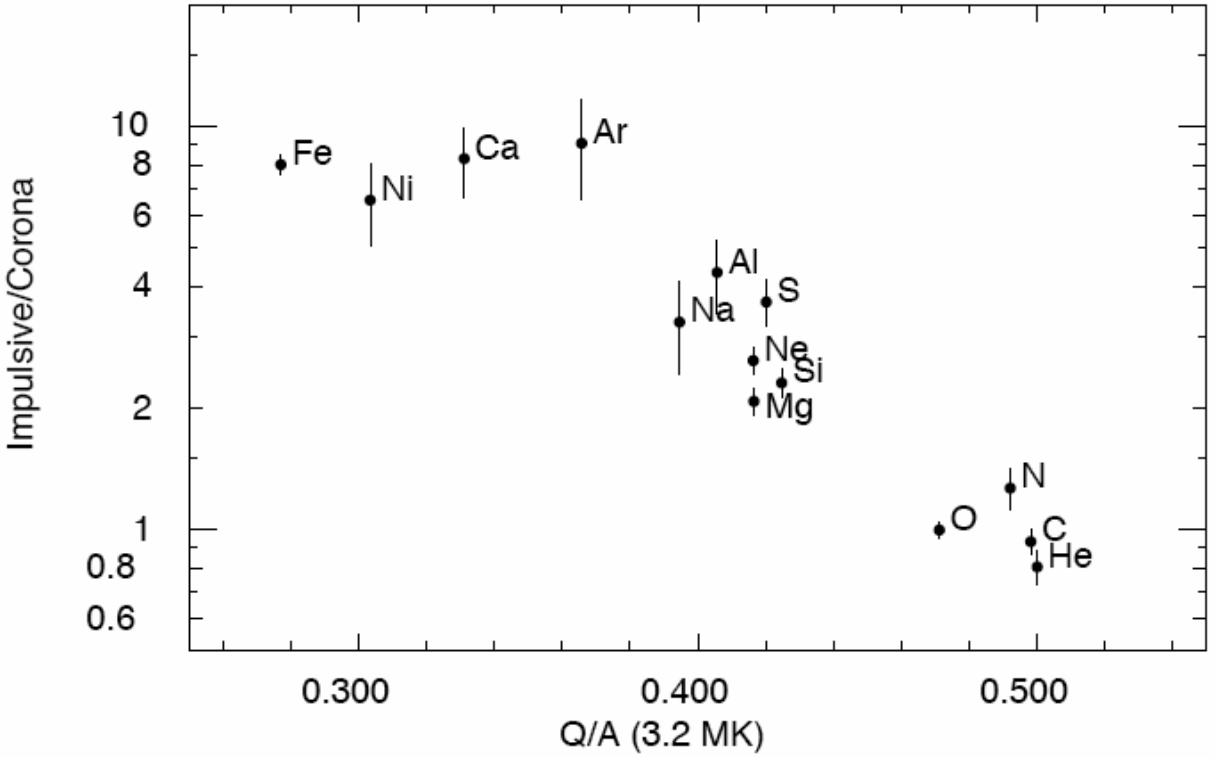

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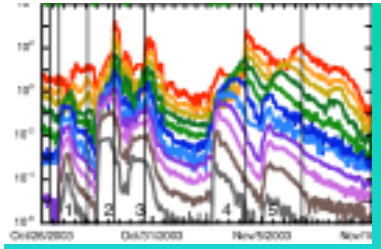
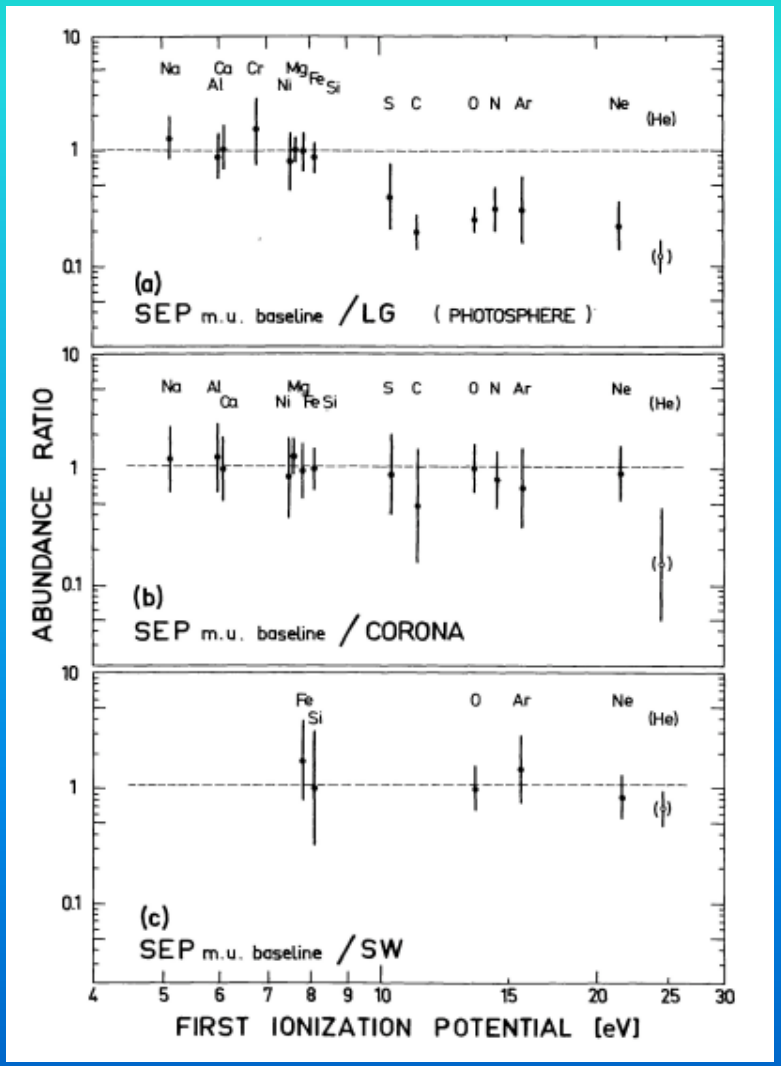


What is the History of SEPs?

(pre-1997)

- Gradual
  - › All flare material is like impulsive SEP material but gradual SEP material looks like the solar wind
    - composition
    - charge states
  - › Roll offs of spectra consistent with diffusion from shock region



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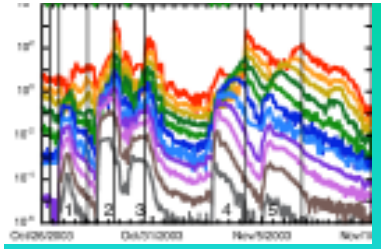
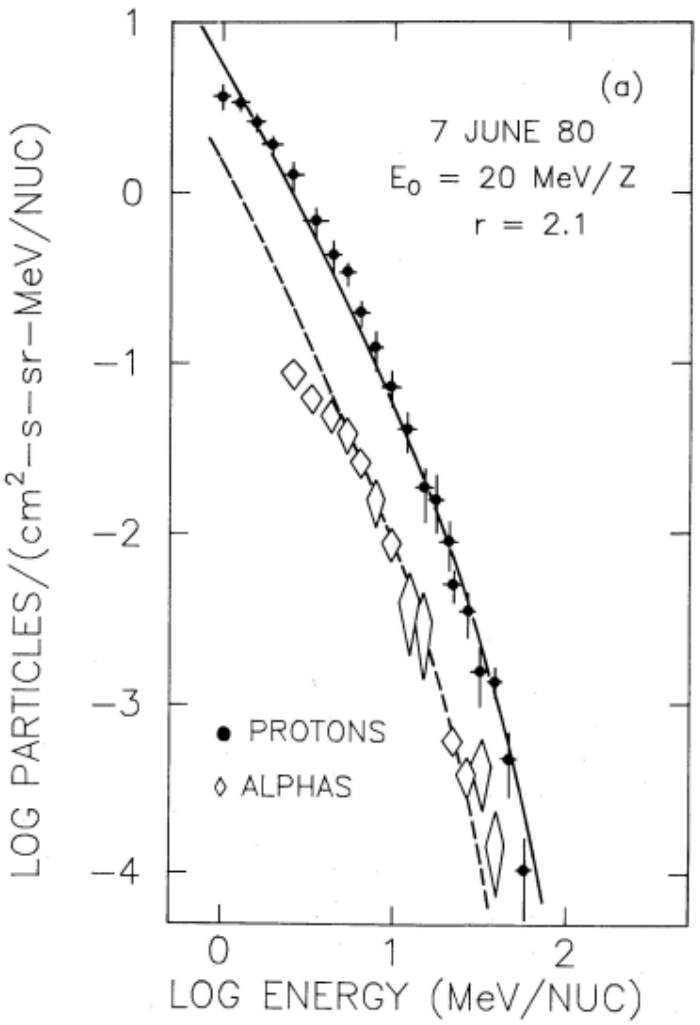


What is the History of SEPs?

(pre-1997)

- Gradual
  - › All flare material is like impulsive SEP material but gradual SEP material looks like the solar wind
    - composition
    - charge states
  - › Roll offs of spectra consistent with diffusion from shock region



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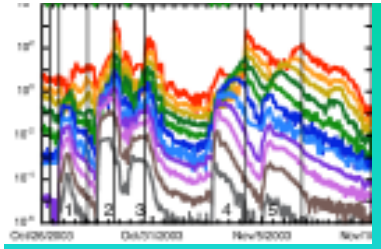

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(pre-1997)

- The 1990s standard 2 class system table

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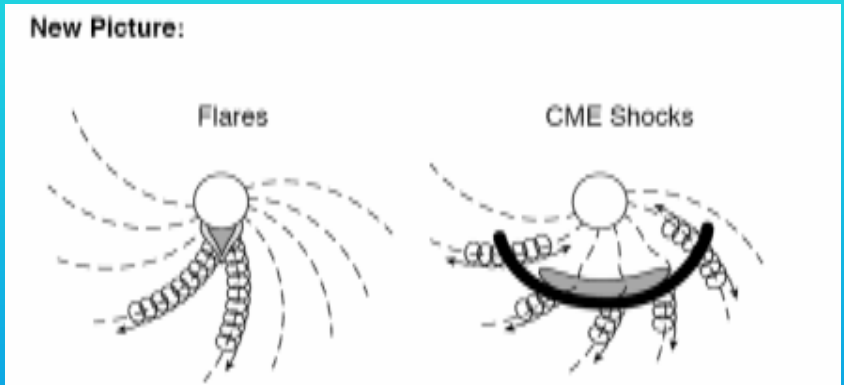
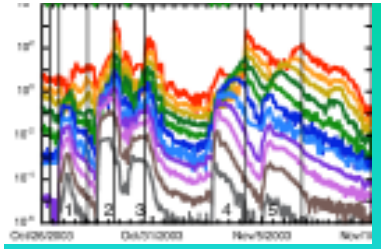


Figure 2.1. A paradigm shift. Reames 1999

Big Point to remember:
» the two classes are *exclusive*

Flare particles in gradual events do not escape into the IPM because of closed field lines behind the CME

What measure history (old/new) excitement



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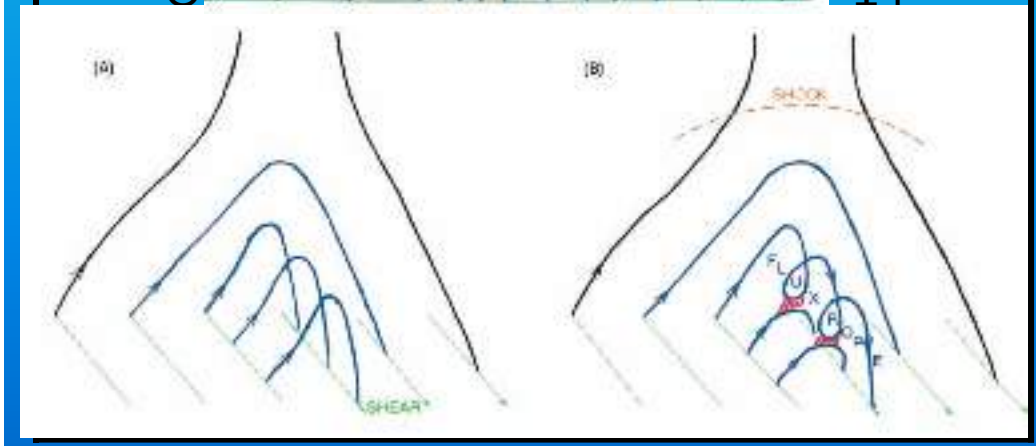

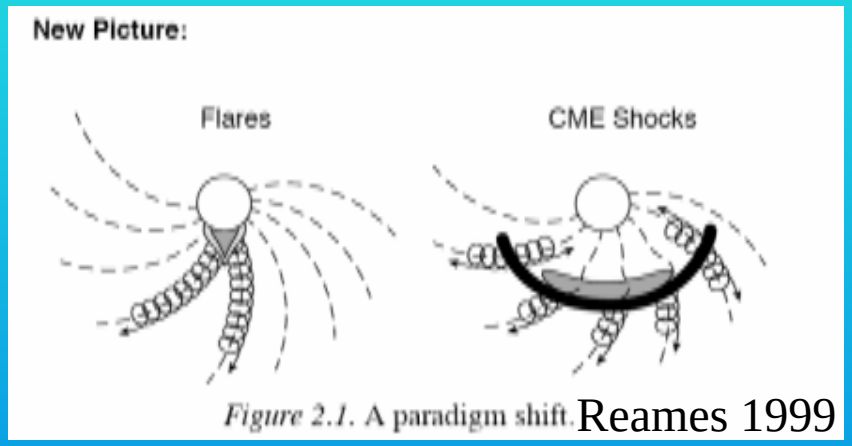

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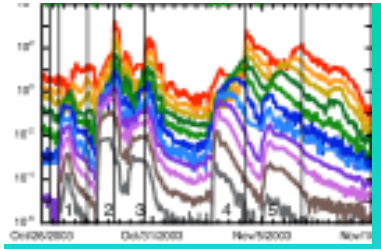
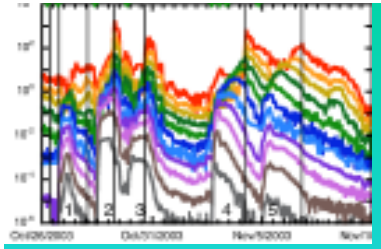


What is the History of SEPs?

(post-1997)

- ACE launches August 1997
  - › Suite of high-tech instruments to study heavy ions in SEP events over 3 orders of magnitude in energy (.1-100 MeV/n)
    - Elemental Composition (ULEIS+SIS)
    - Isotopic Composition (ULEIS+SIS)
    - Charge State Composition (SEPICA)
  - › In November 1997, ACE observes first gradual SEP events
    - Composition does not look as it should...

What measure history (old/new) excitement



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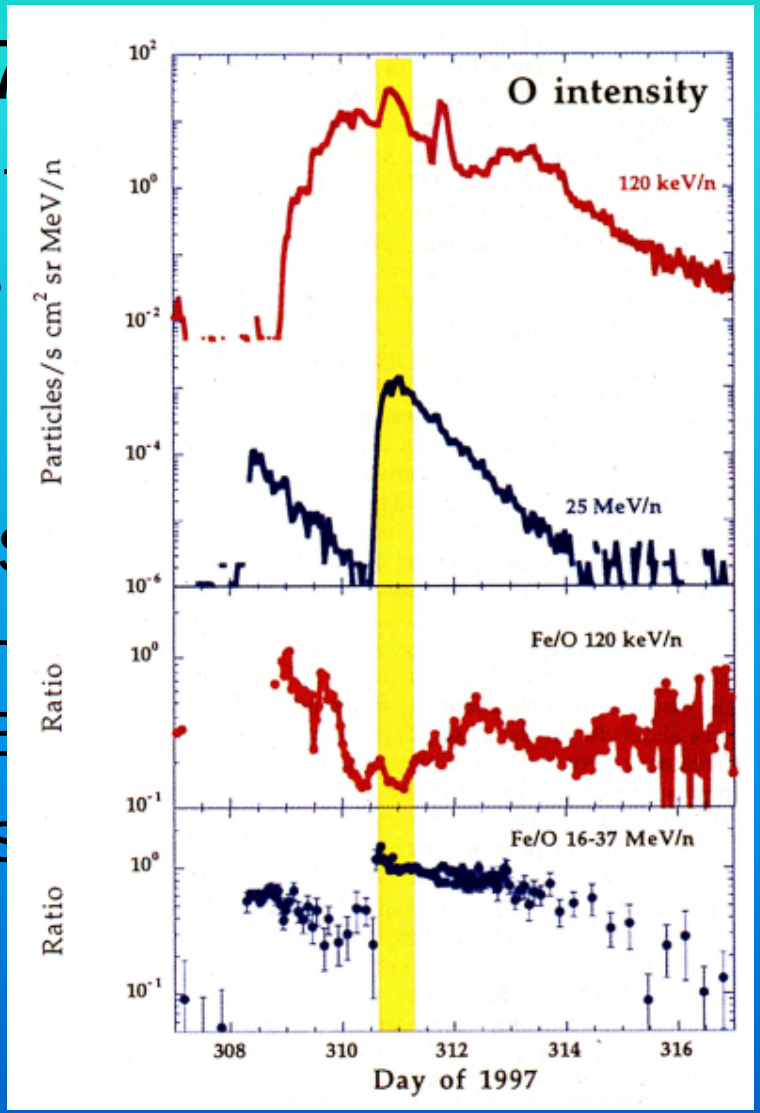

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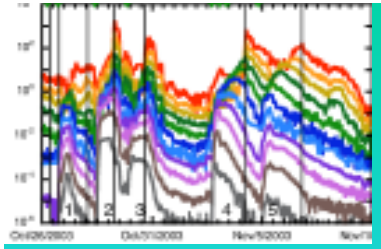
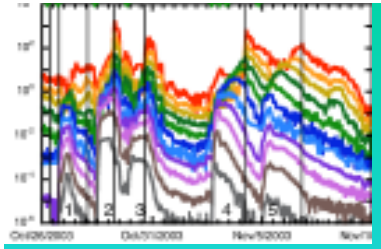


What is the History of SEPs?

(post-1997)

- Within the first year, ACE observes many more of these enriched-Fe events
  - › Composition from C-Ni looks impulsive (12-60 MeV/n)
  - › Enhancements of ^{3}He (not at impulsive levels)
- SAMPEX measures charge states with geomagnetic cutoff technique
  - › At 30 MeV/n Q_{Fe} is ~20 (like impulsive)
  - › Q_{Fe} is *energy dependent*

What measure history (old/new) excitement



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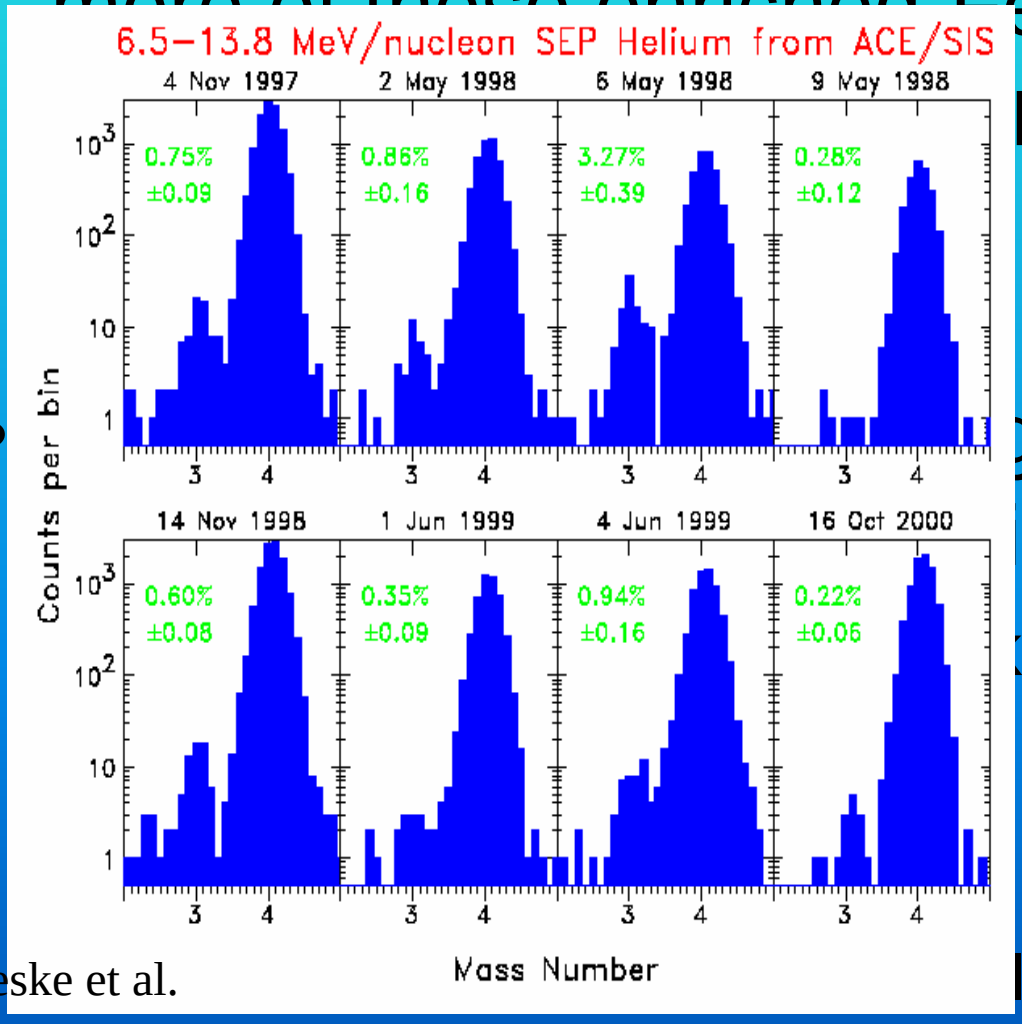
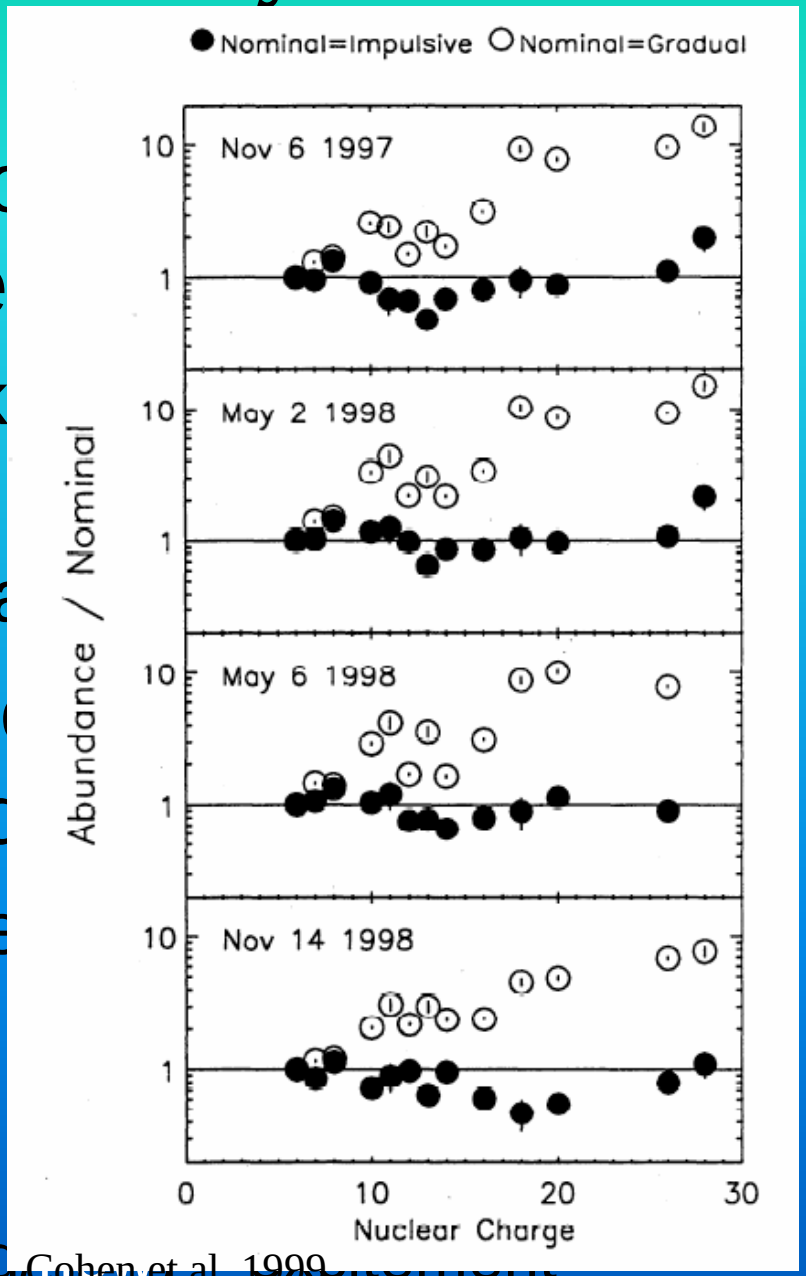


Leske et al.



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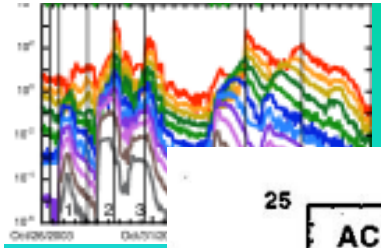

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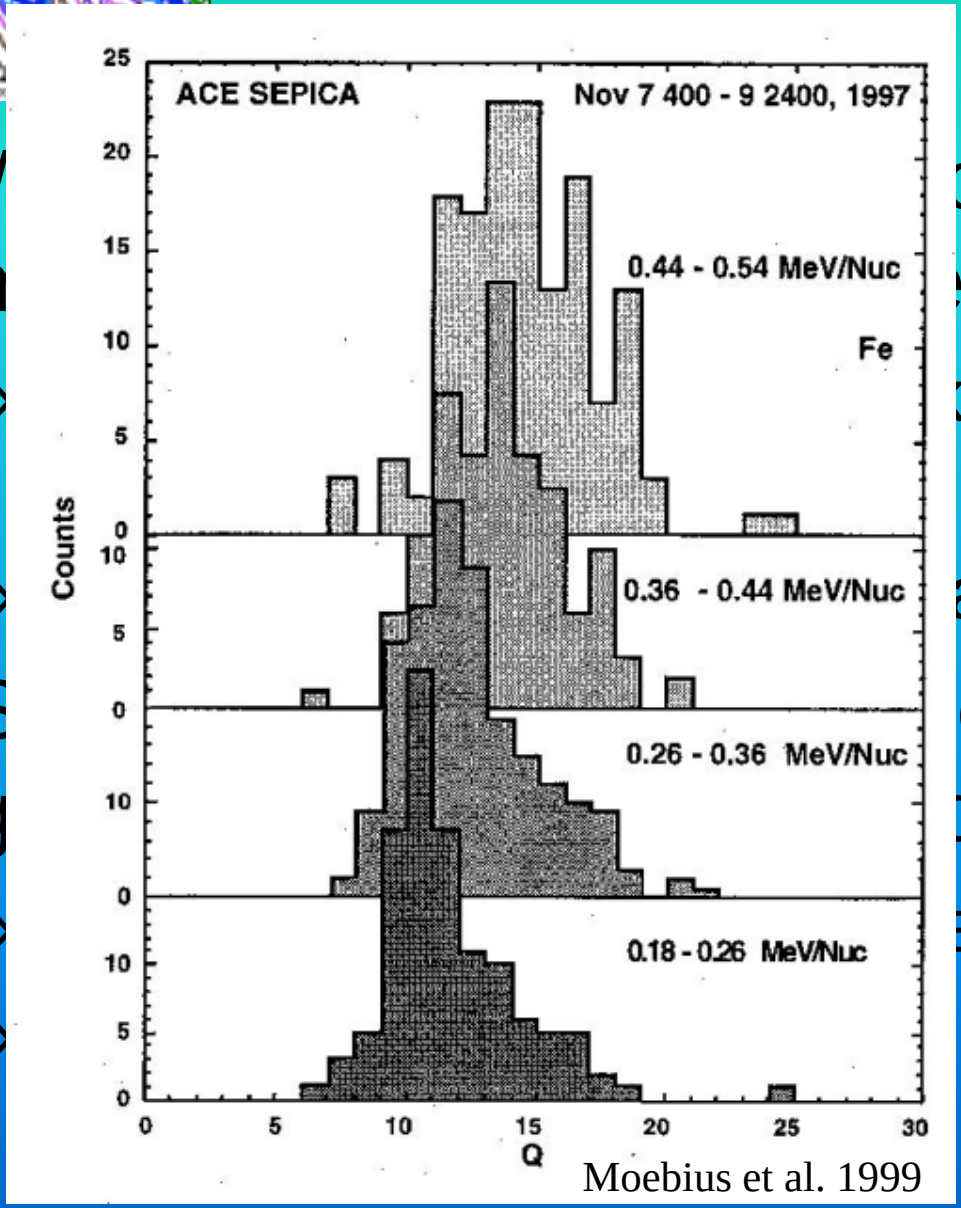
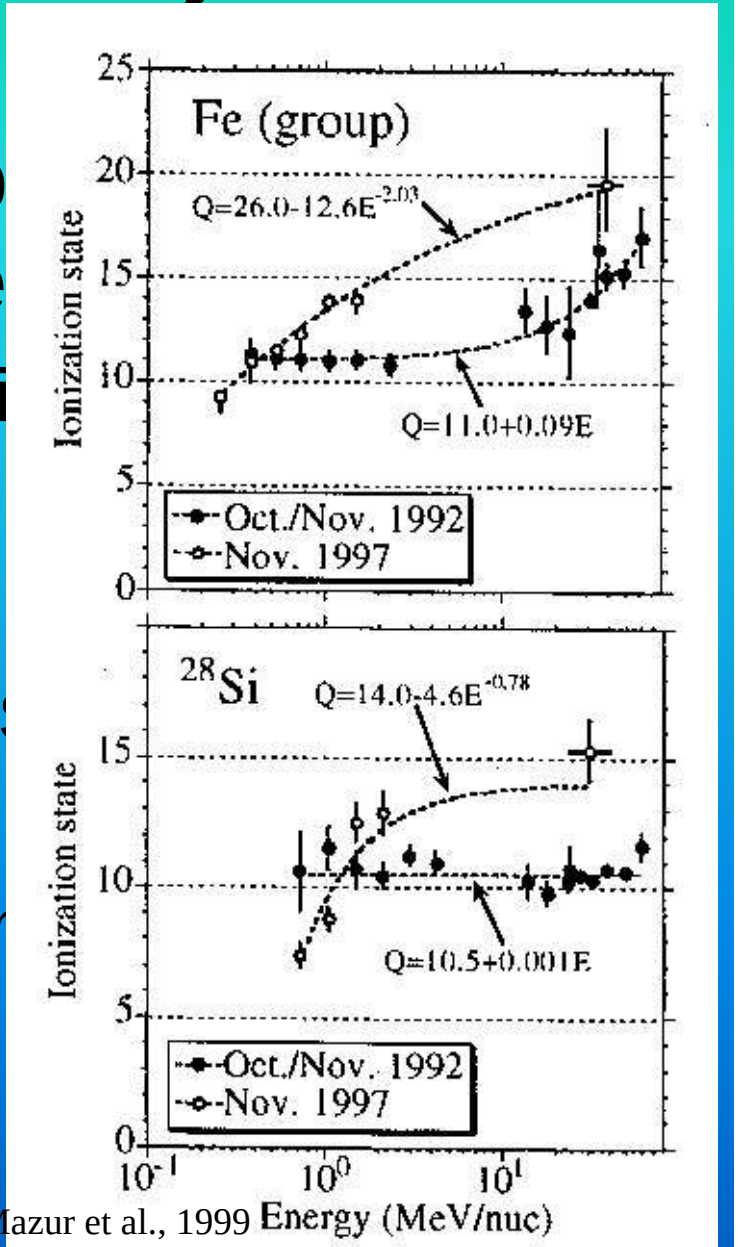


Moebius et al. 1999



Mazur et al., 1999

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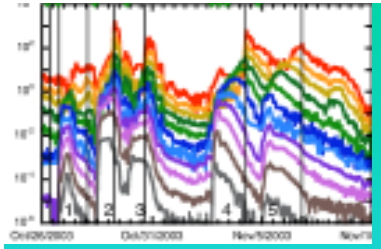

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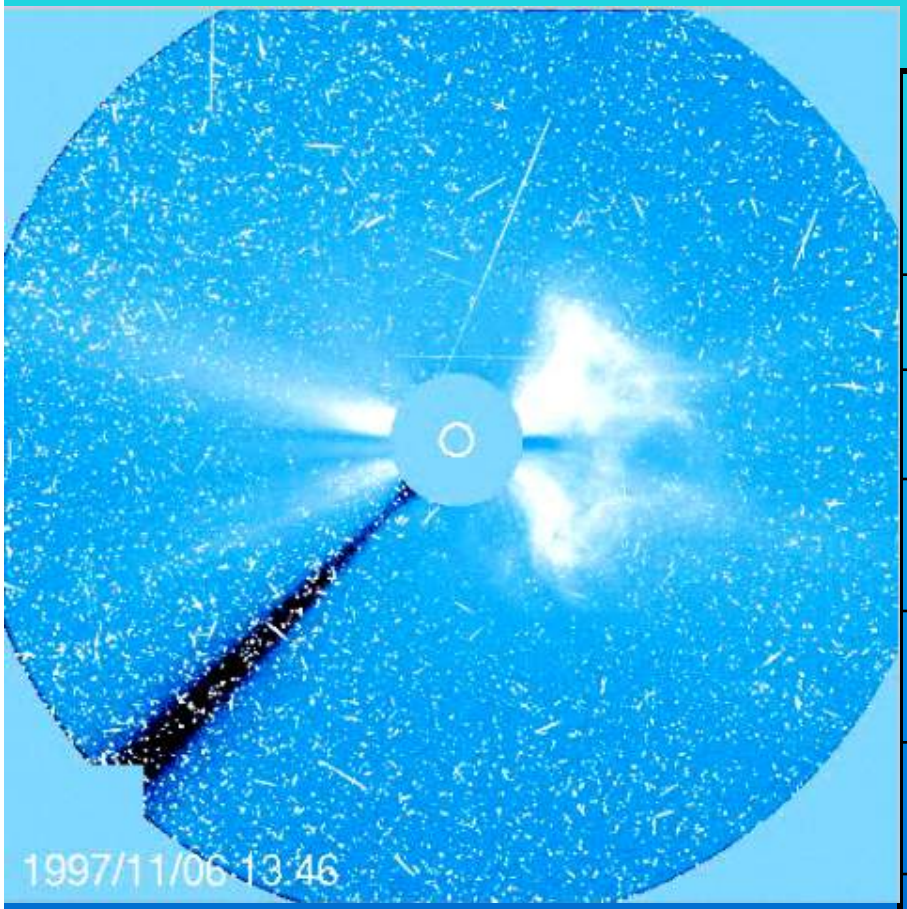

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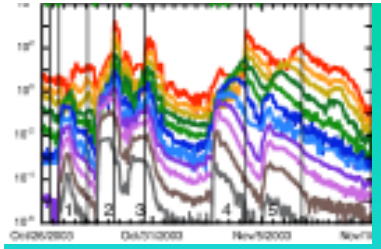

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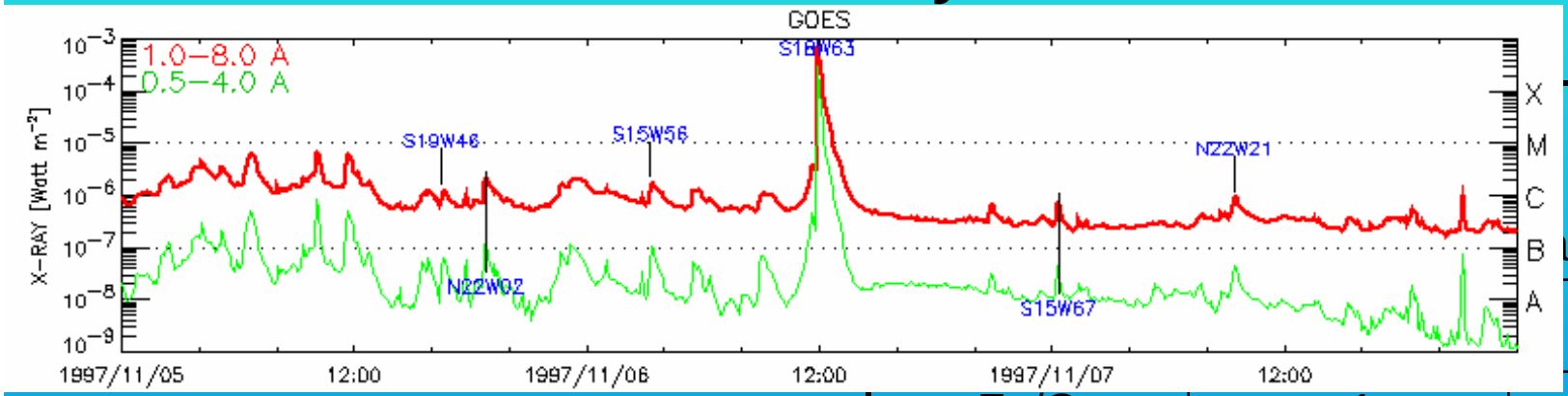

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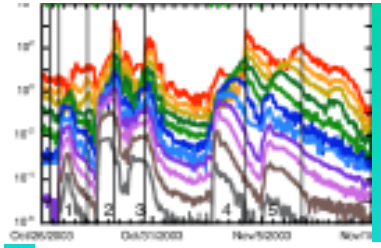

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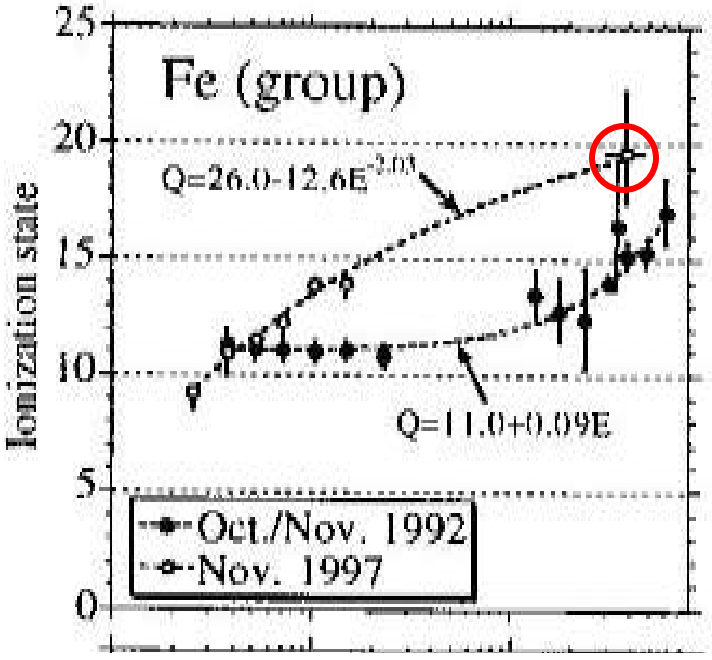

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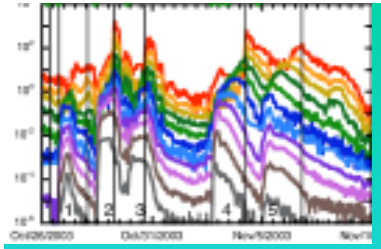

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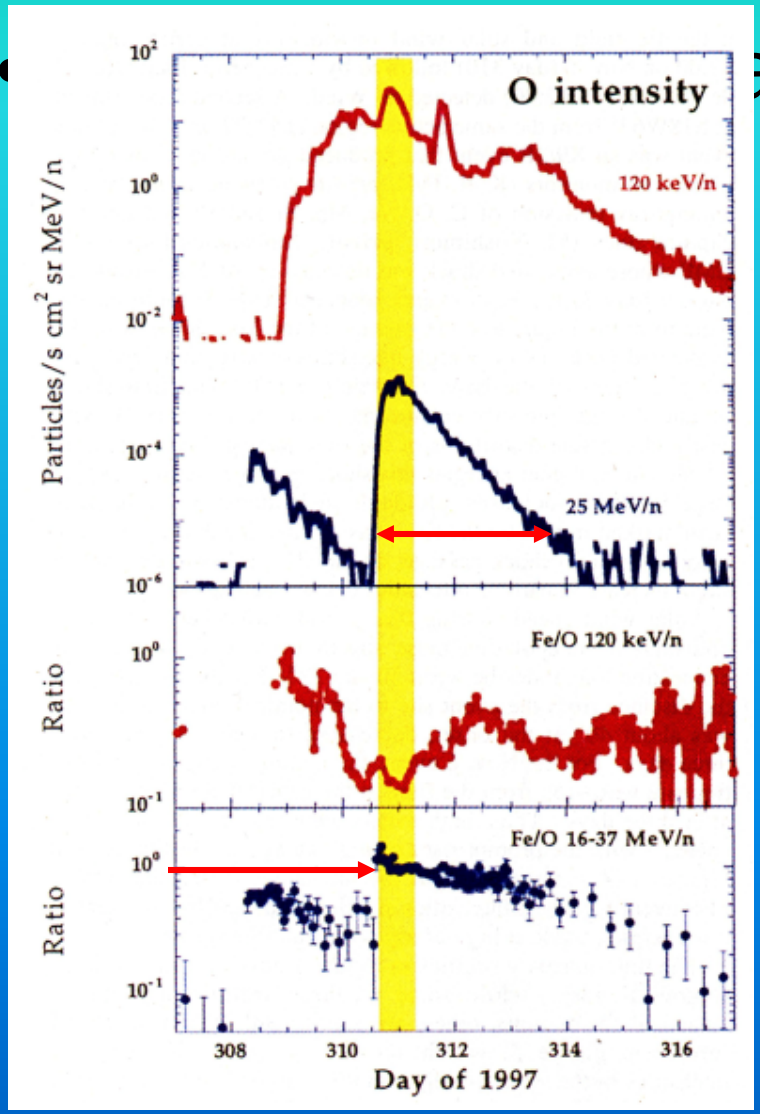

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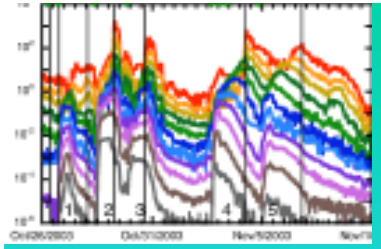

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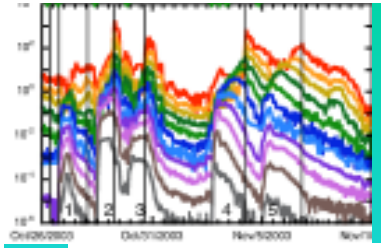

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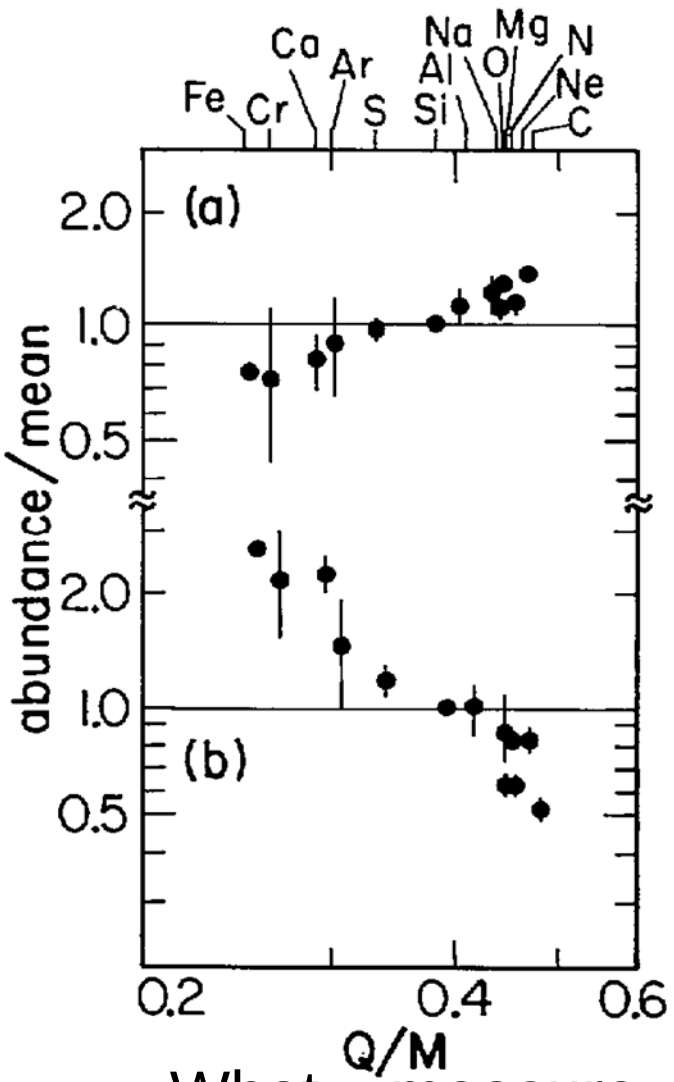

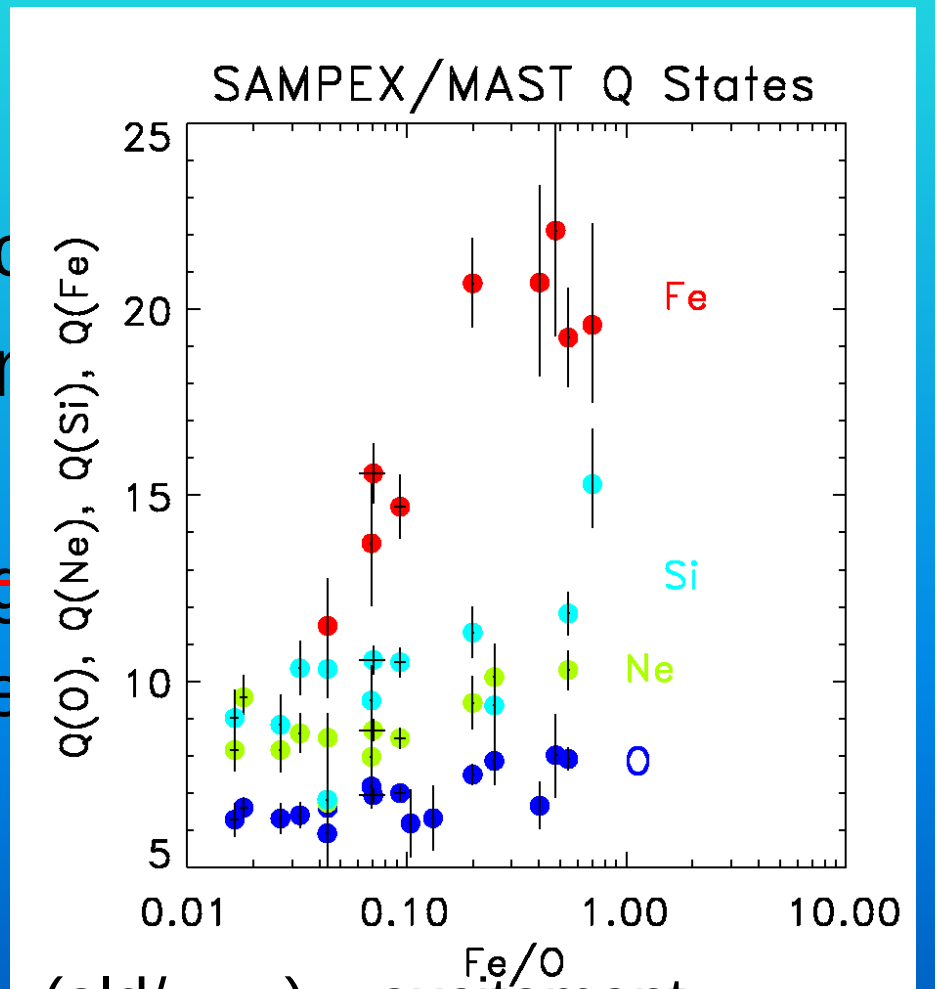

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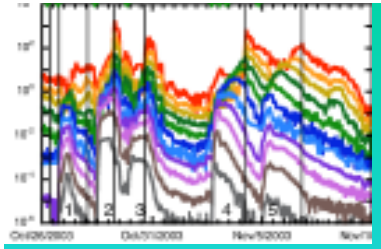

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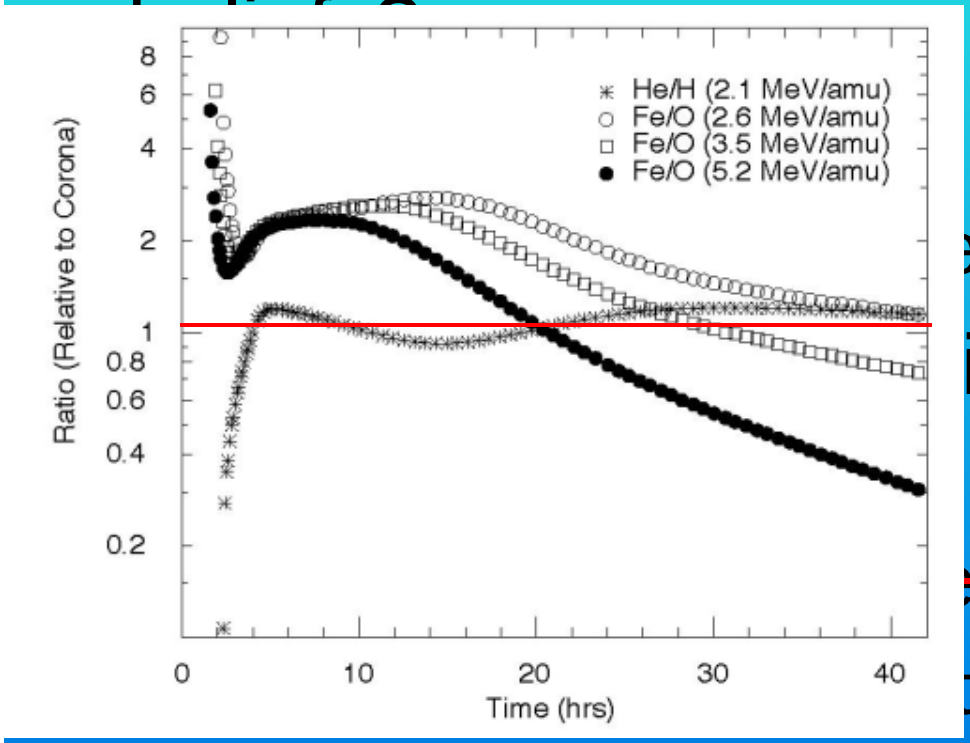

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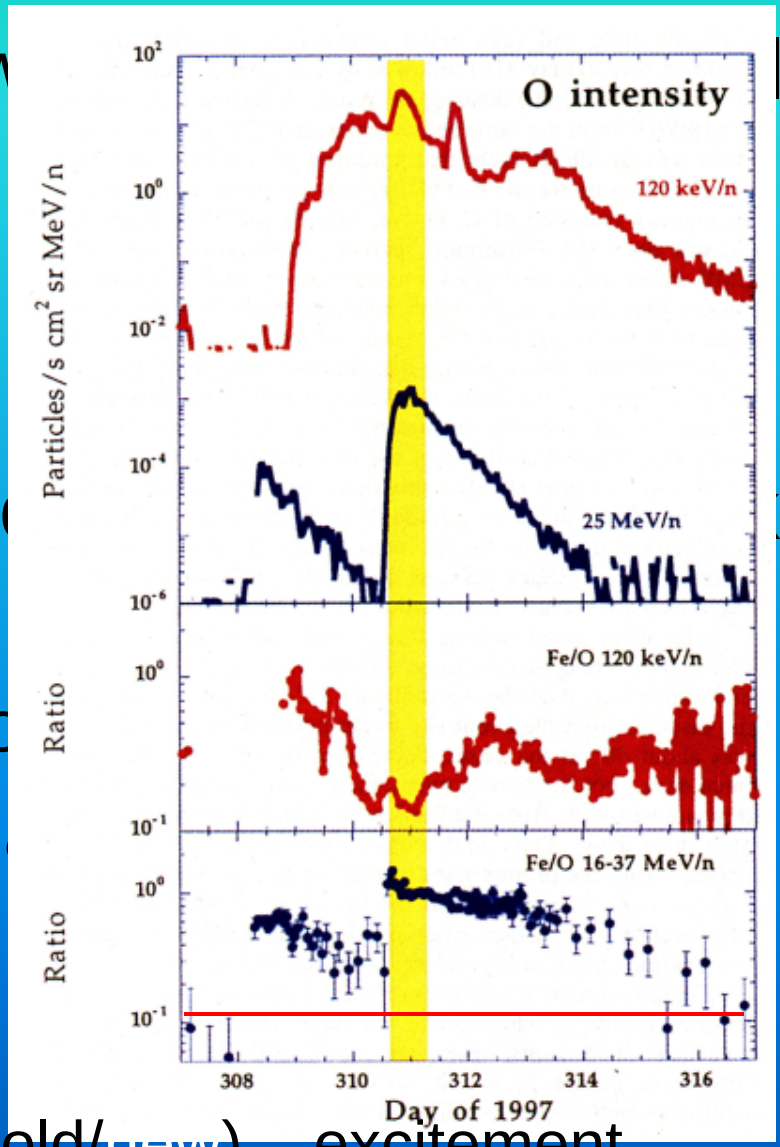

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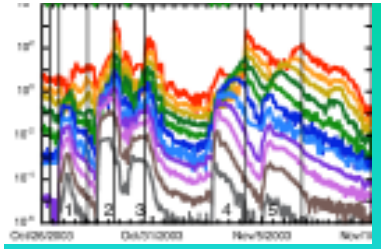

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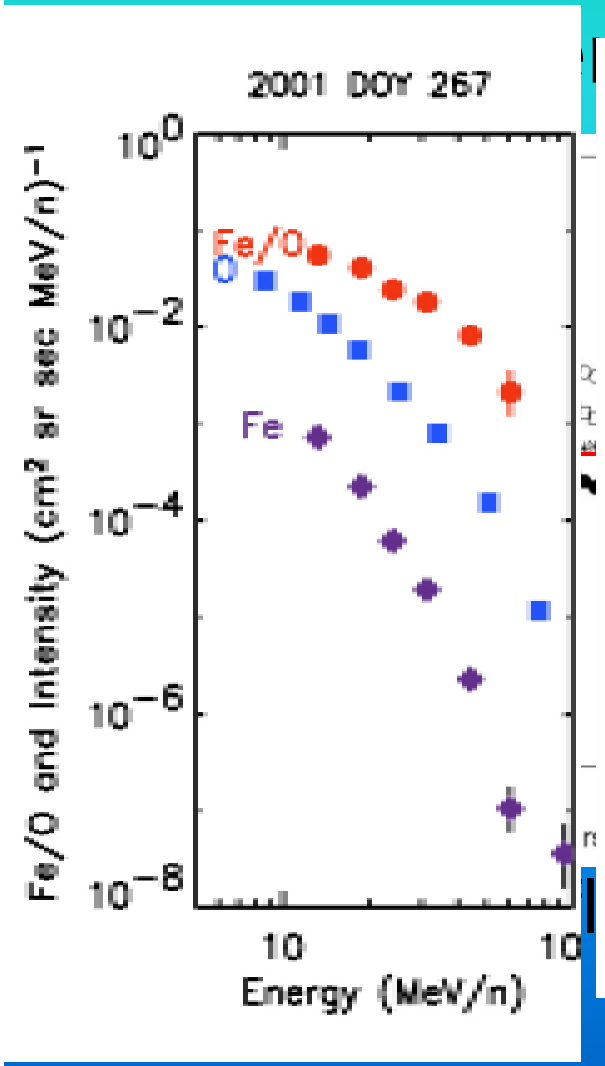

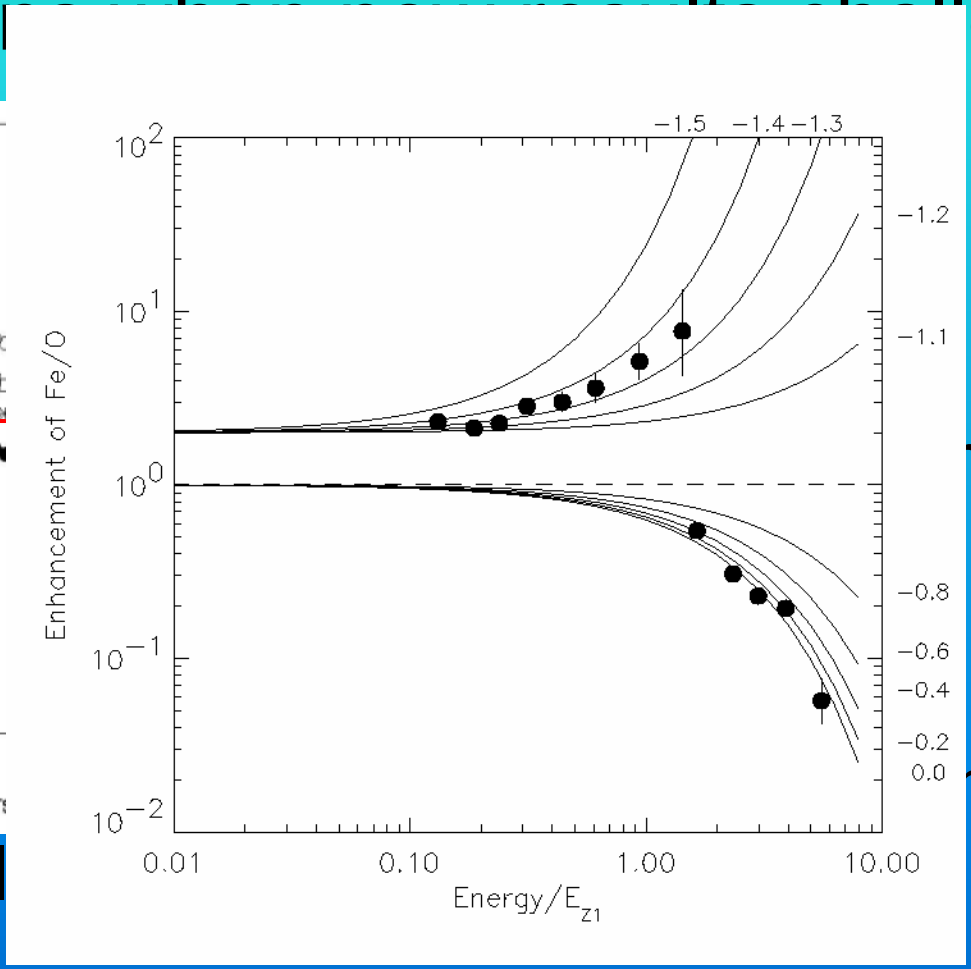

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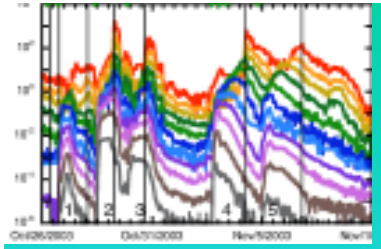

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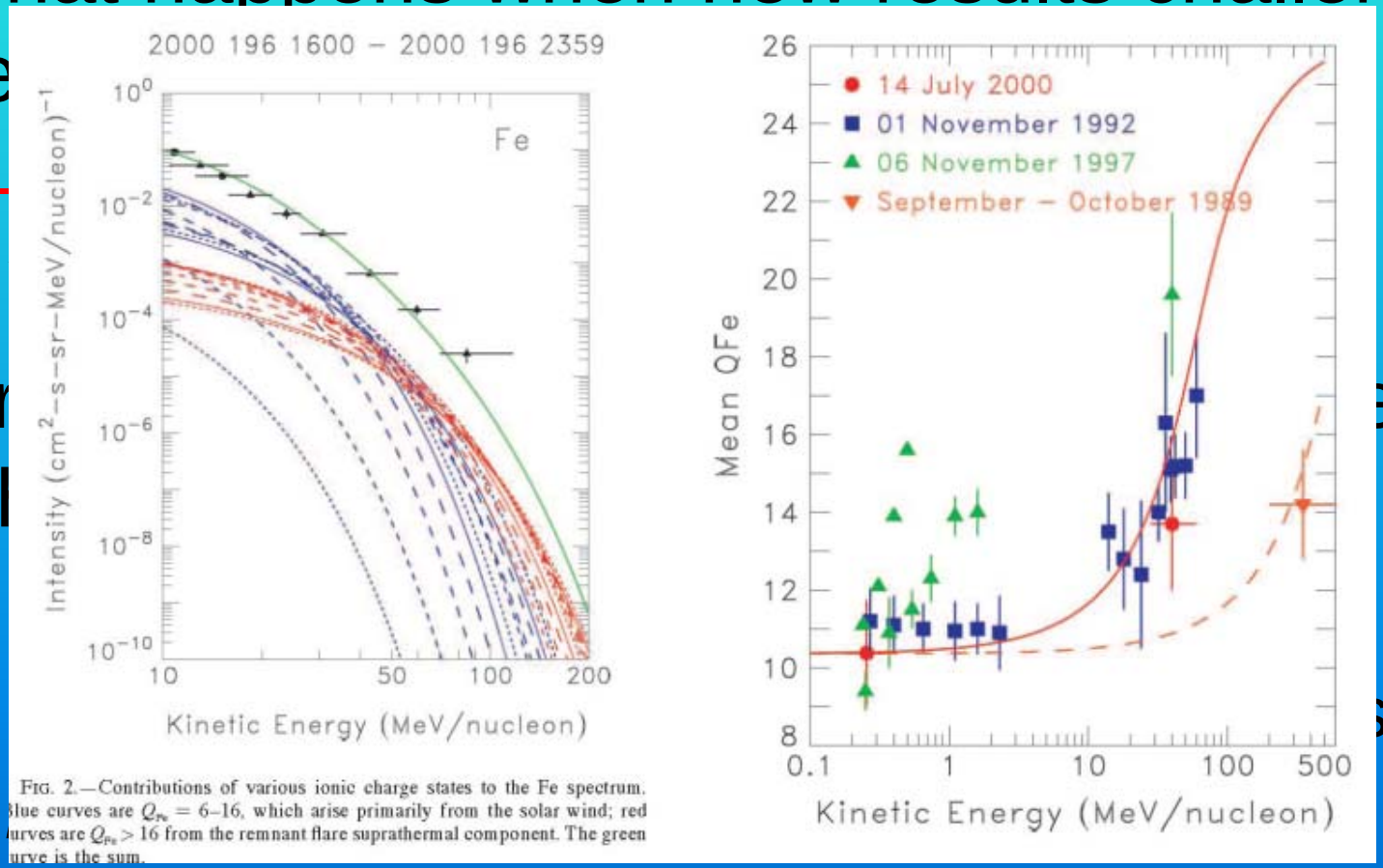

FIG. 2.—Contributions of various ionic charge states to the Fe spectrum. Blue curves are $Q_{Fe} = 6$–16, which arise primarily from the solar wind; red curves are $Q_{Fe} > 16$ from the remnant flare suprathermal component. The green curve is the sum.

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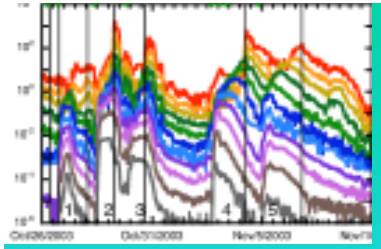

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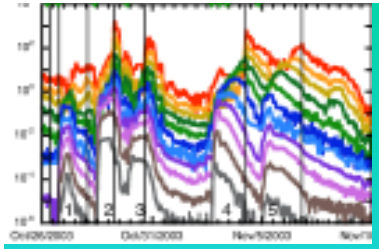

What is New and Exciting About SEPs?

- How do we explain these results?
  - › Flare material in gradual events
  - › Energy dependent charge states and composition
  - › CMEs seen with impulsive SEP events
  - › Type IIIs seen with gradual SEP events
  - › gradual SEP events don't look like solar wind

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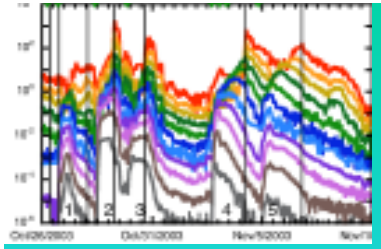

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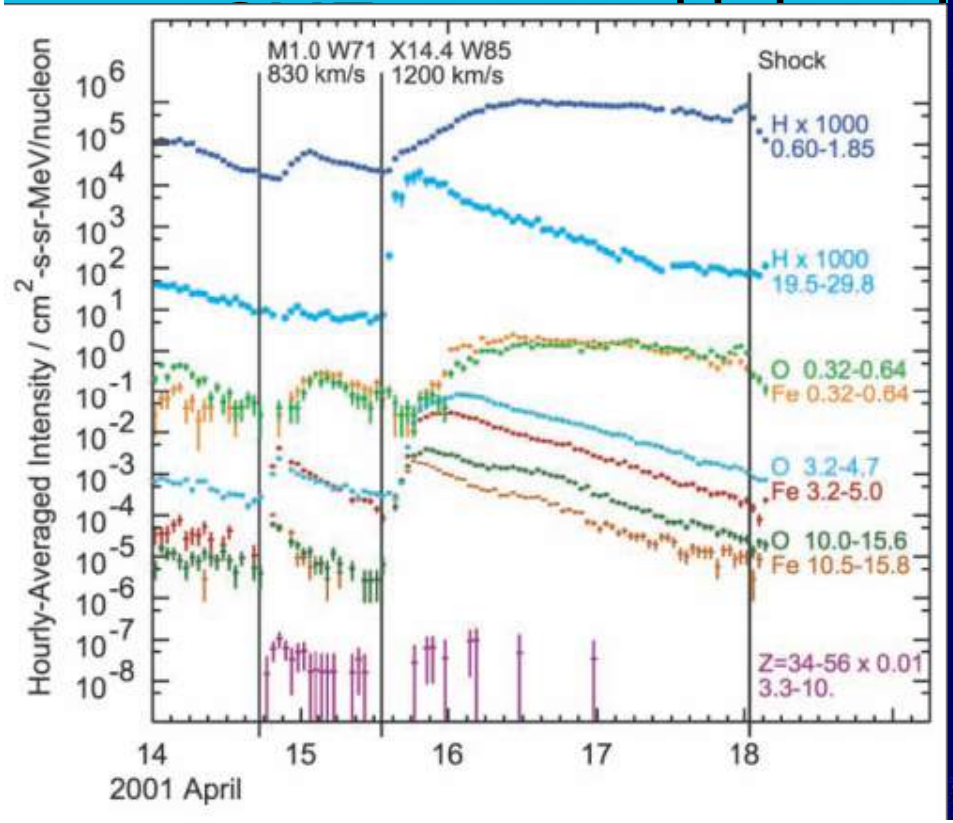

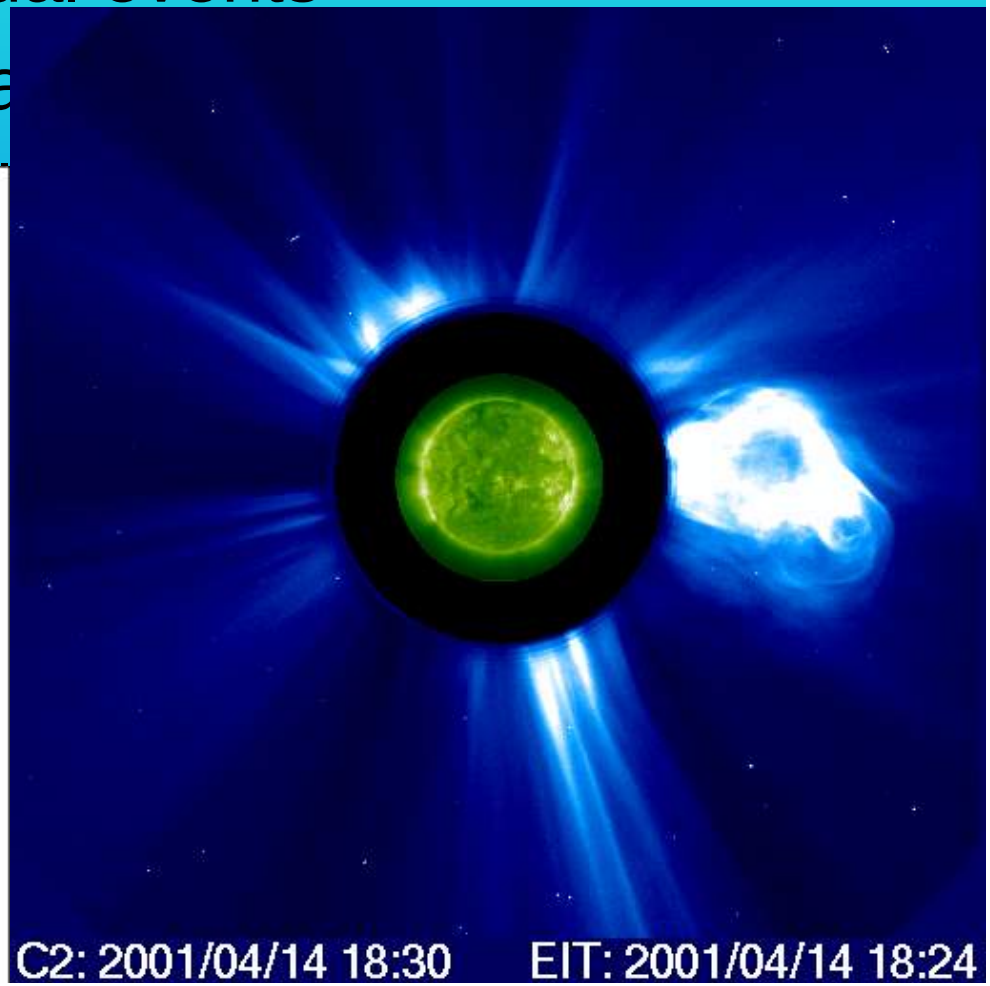

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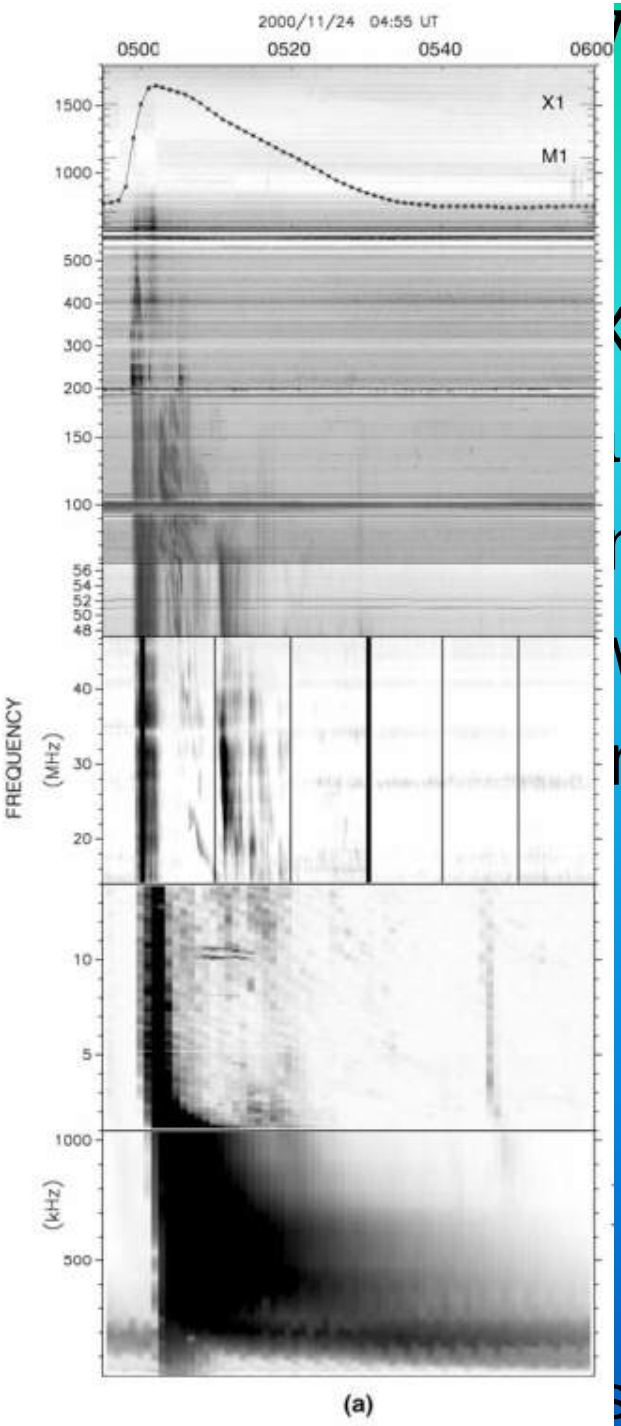
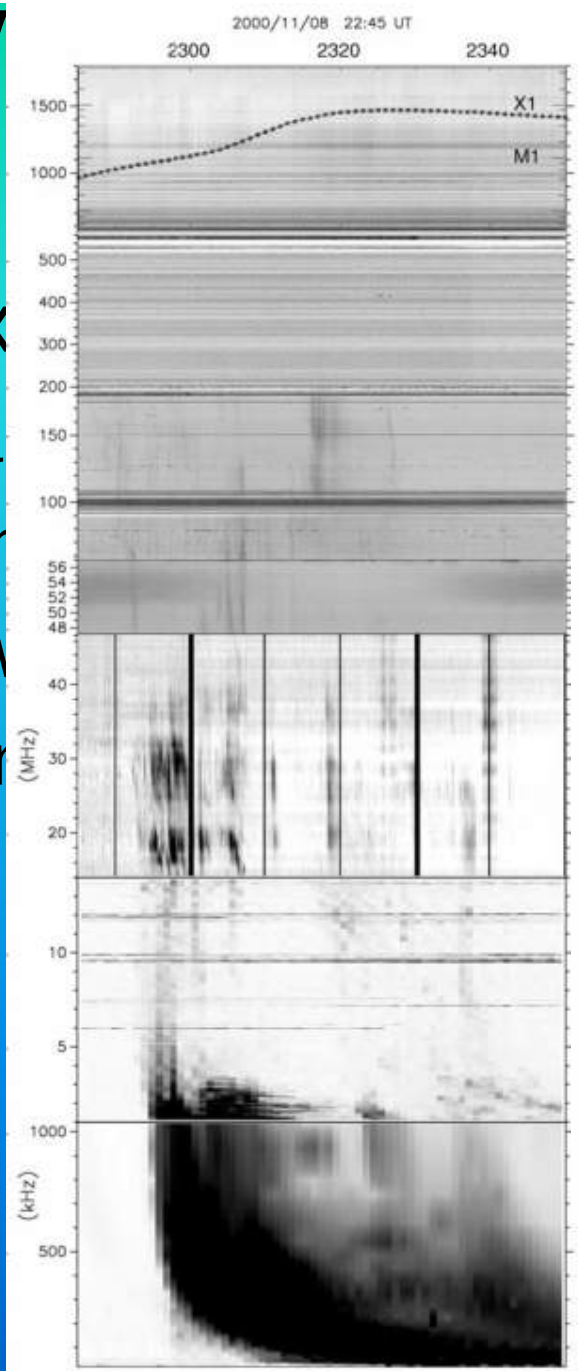
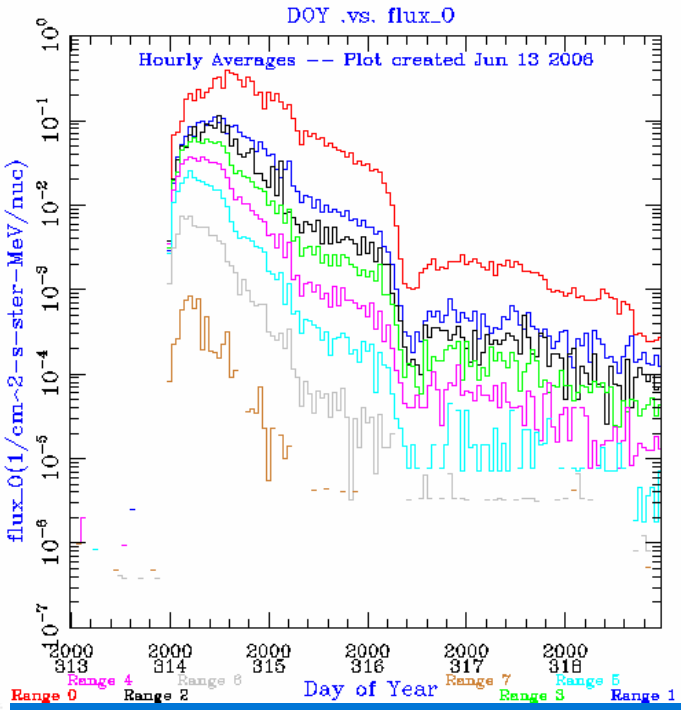
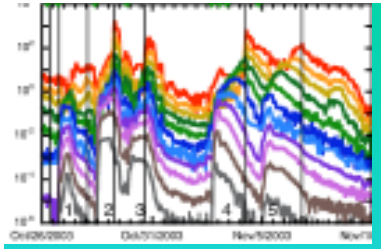




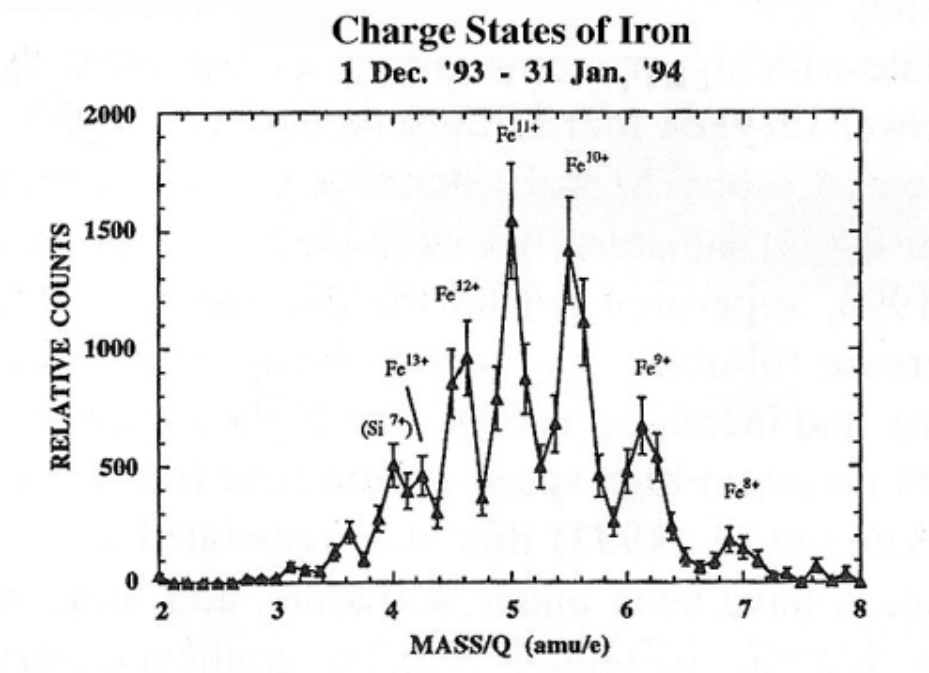


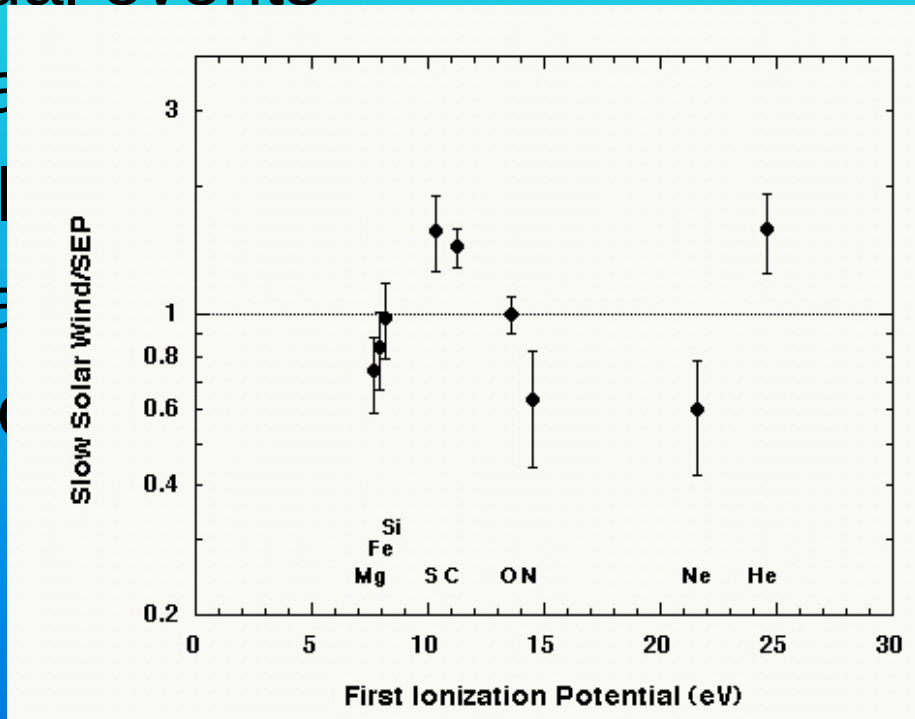
sure history (old/new) excitement



What is New and Exciting About SEPs?

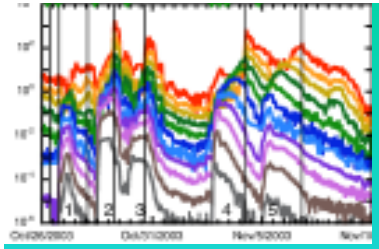
- How do we explain these results?
  - › Flare material in gradual events





Mewaldt et al. 2000

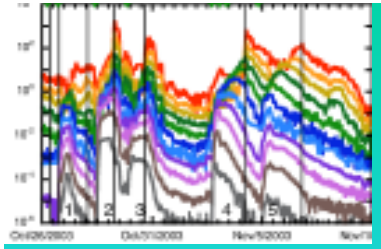
What measure history (old/new) excitement



What is New and Exciting About SEPs?

- Back to the big questions
  - › Are there 2 distinct classes of SEP events??
  - › What is being accelerated?
  - › How is it being accelerated?

What measure history (old/new) excitement



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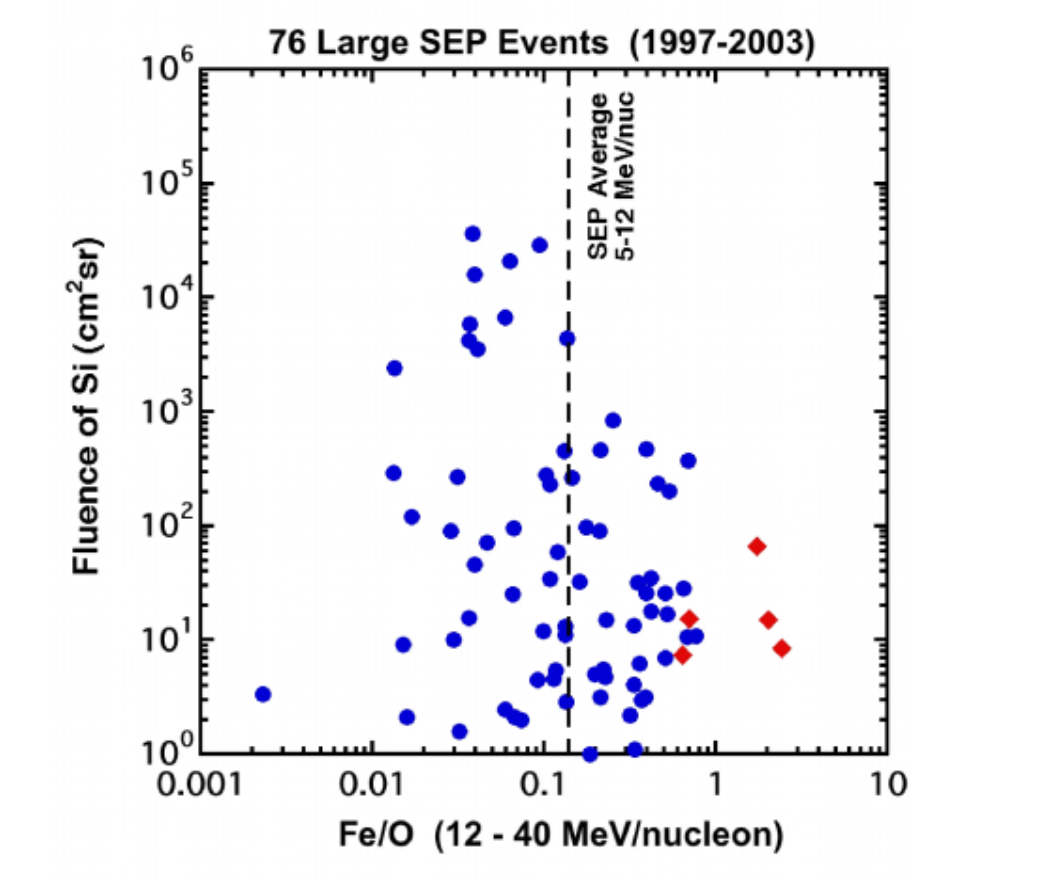

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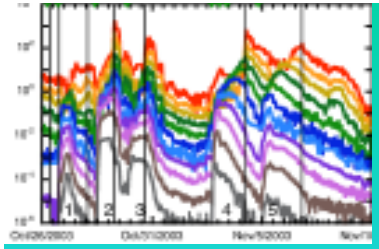

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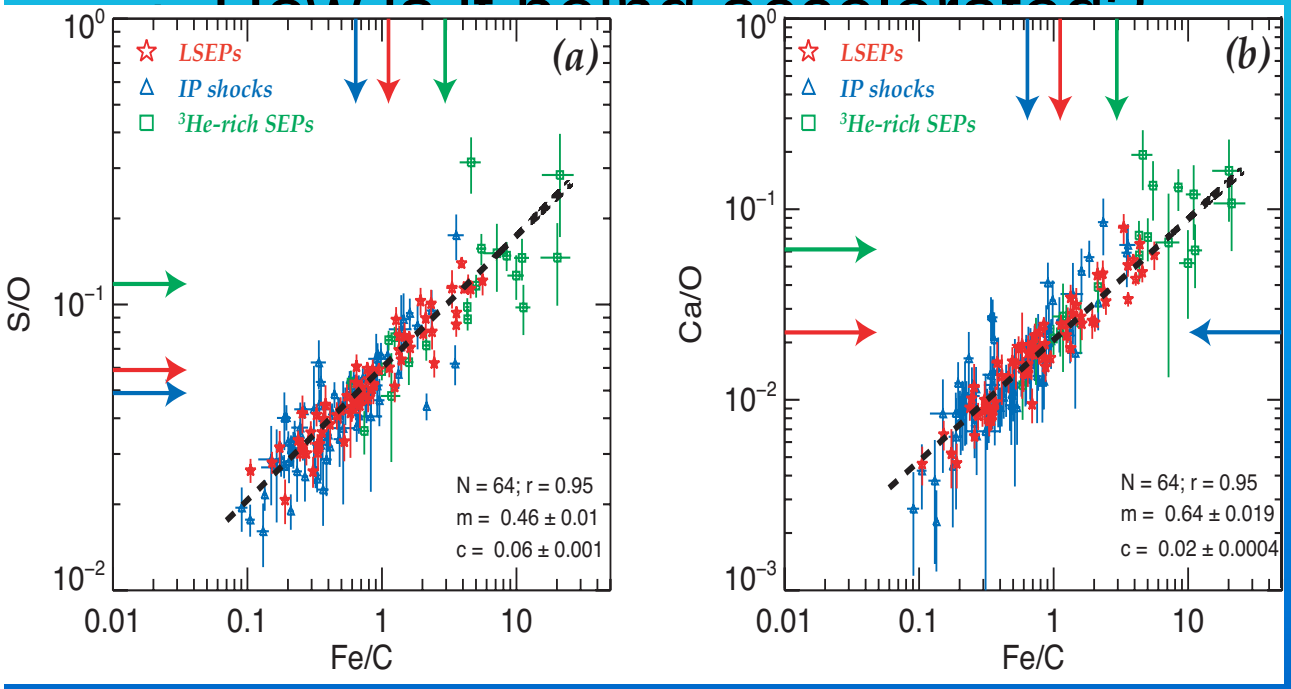

Probably not 2 separate classes of *events*

But 2 acceleration *mechanisms* (the hard part is distinguishing them in SEP observations)

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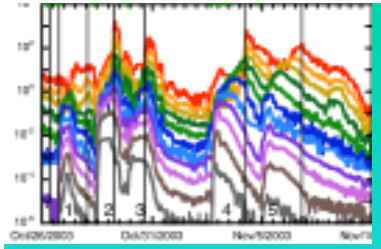
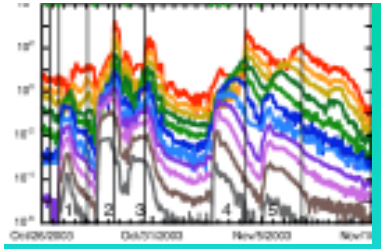


What is New and Exciting About SEPs?

- Two competing theories
  - › Shock orientation
    - flare suprathermals present → energy-dependent composition of the seed population
    - perpendicular vs parallel shock difference
  - › Direct flare contribution
    - flare particles can escape
    - observation depends on
      - » connection to flare
      - » strength of shock
      - » size of flare

What measure history (old/new) excitement



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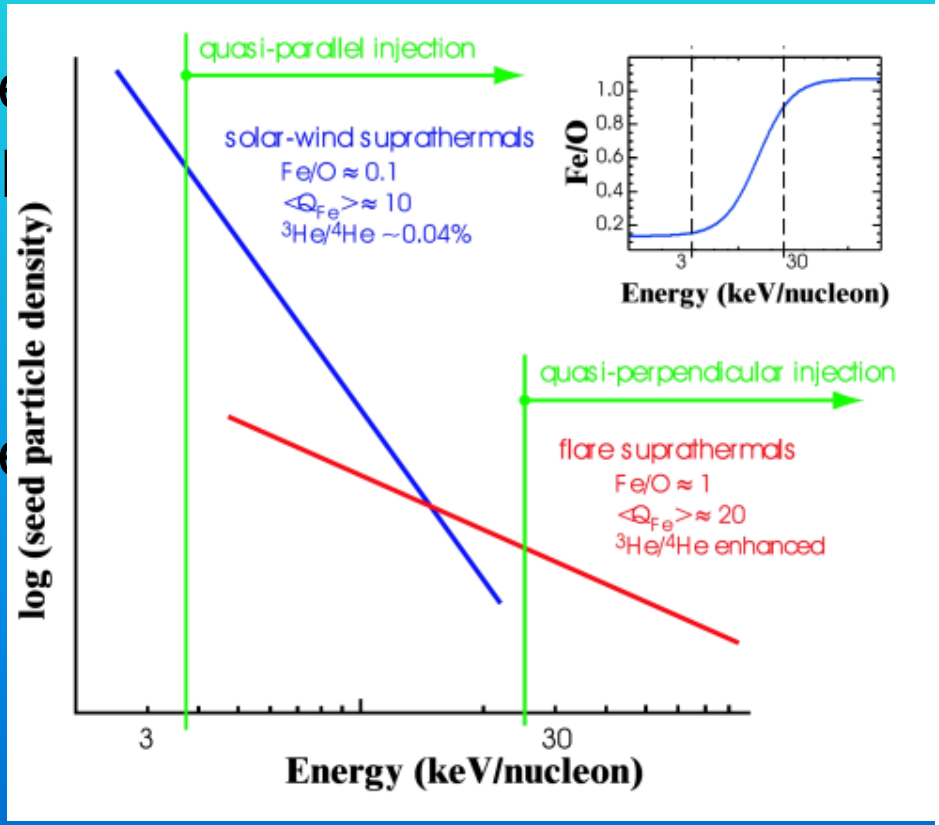

Tylka et al. 2005

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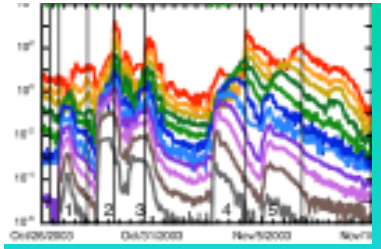

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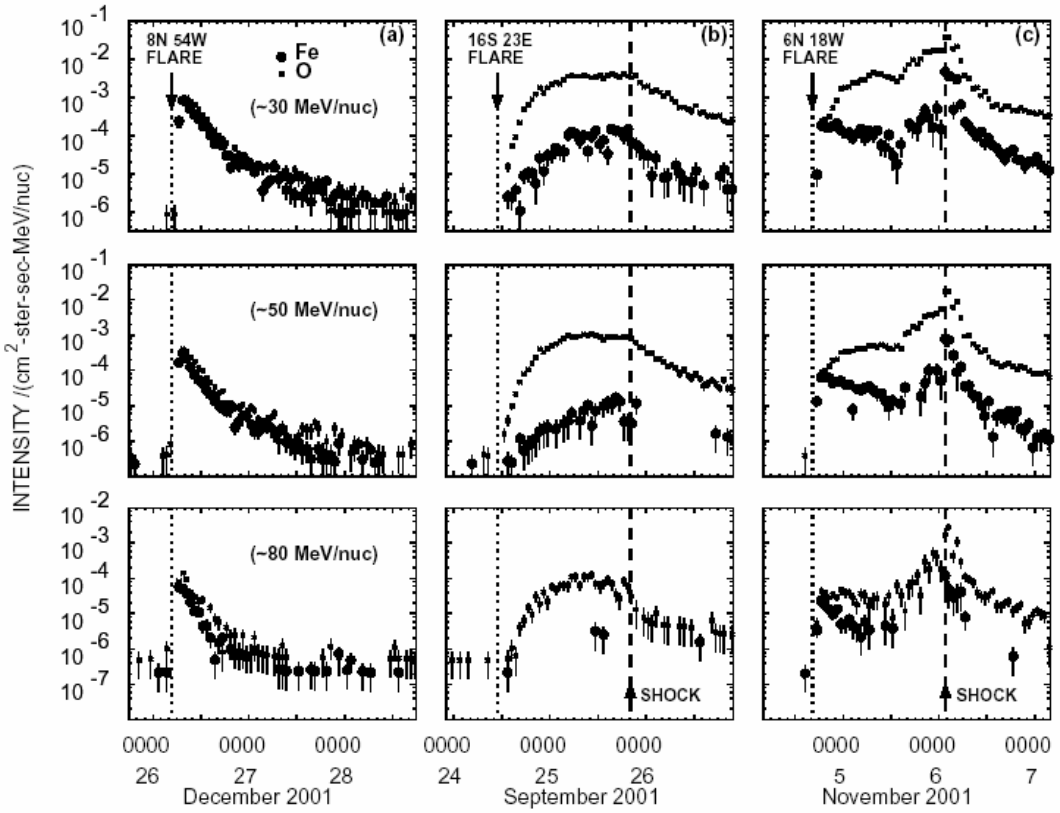

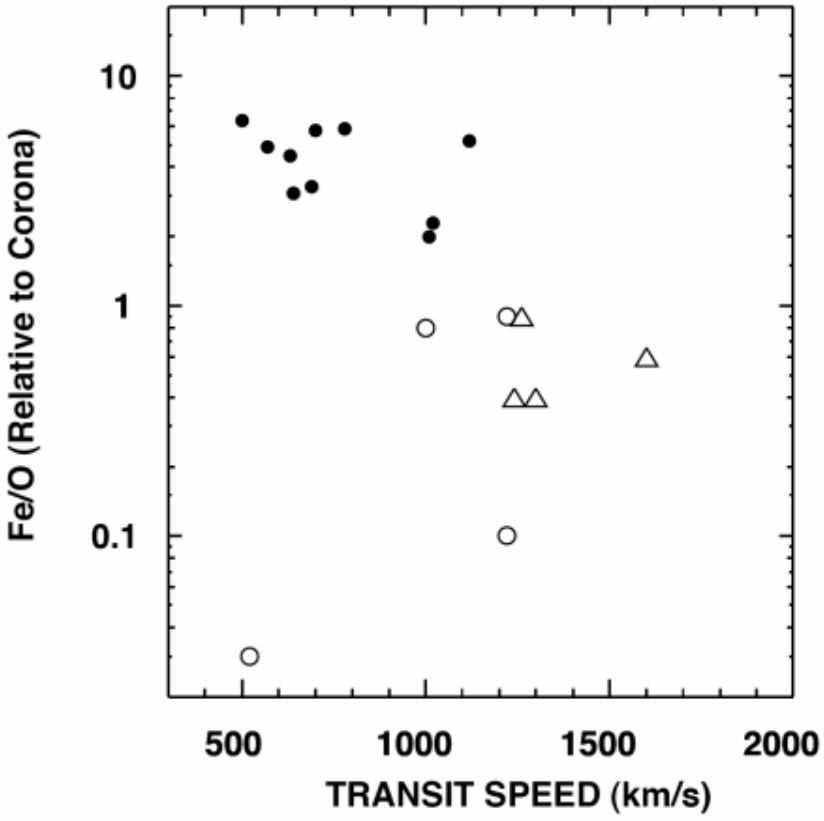

Cane et al. 2003

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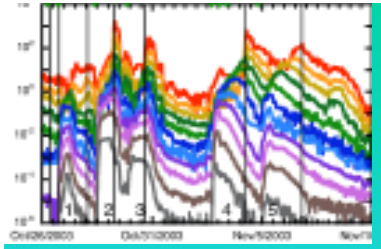

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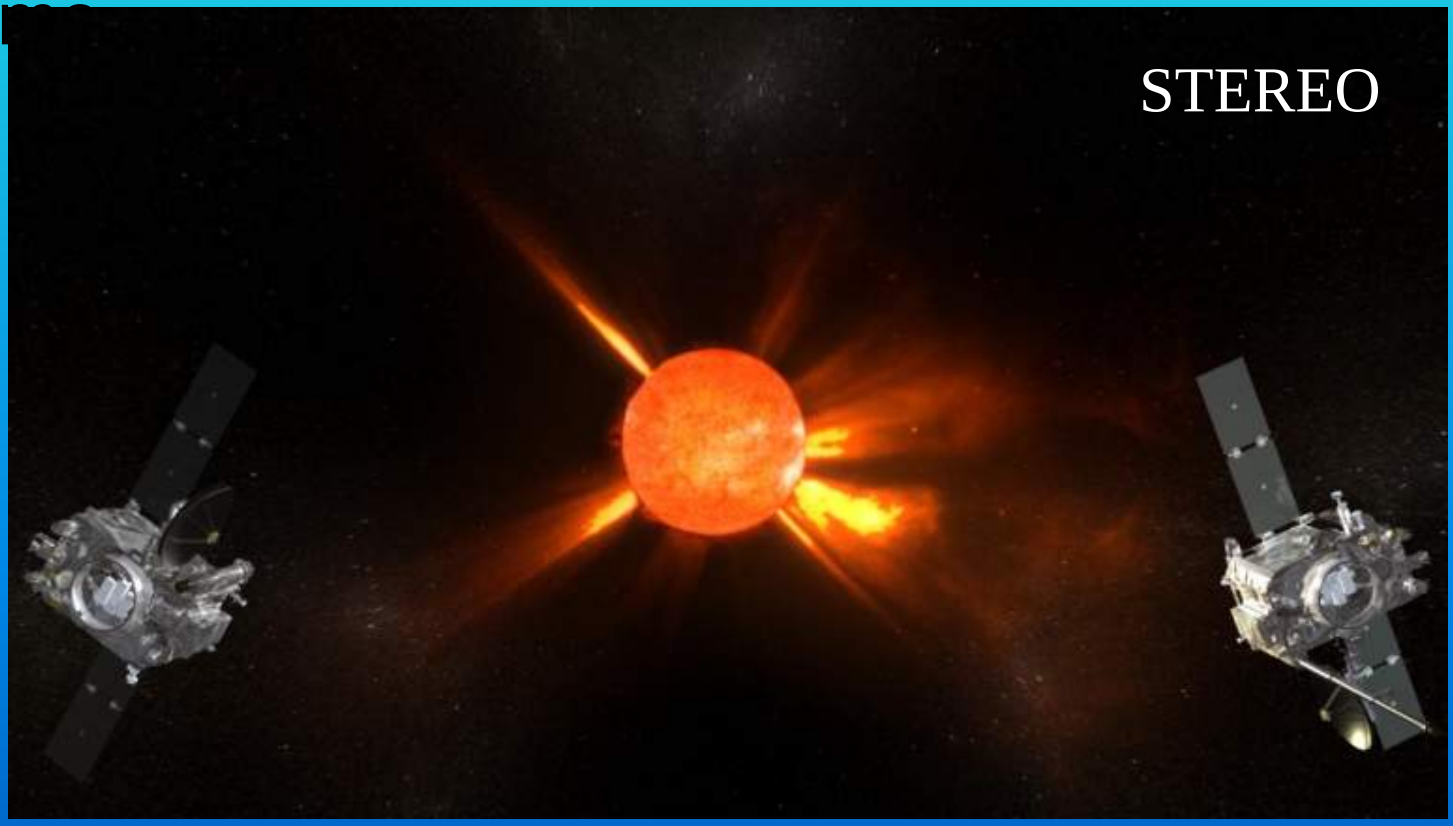
- Two competing theories - How to decide?
  - › Measurements at different longitudes at the same ti



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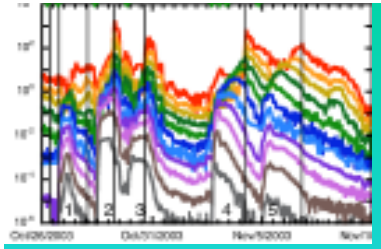
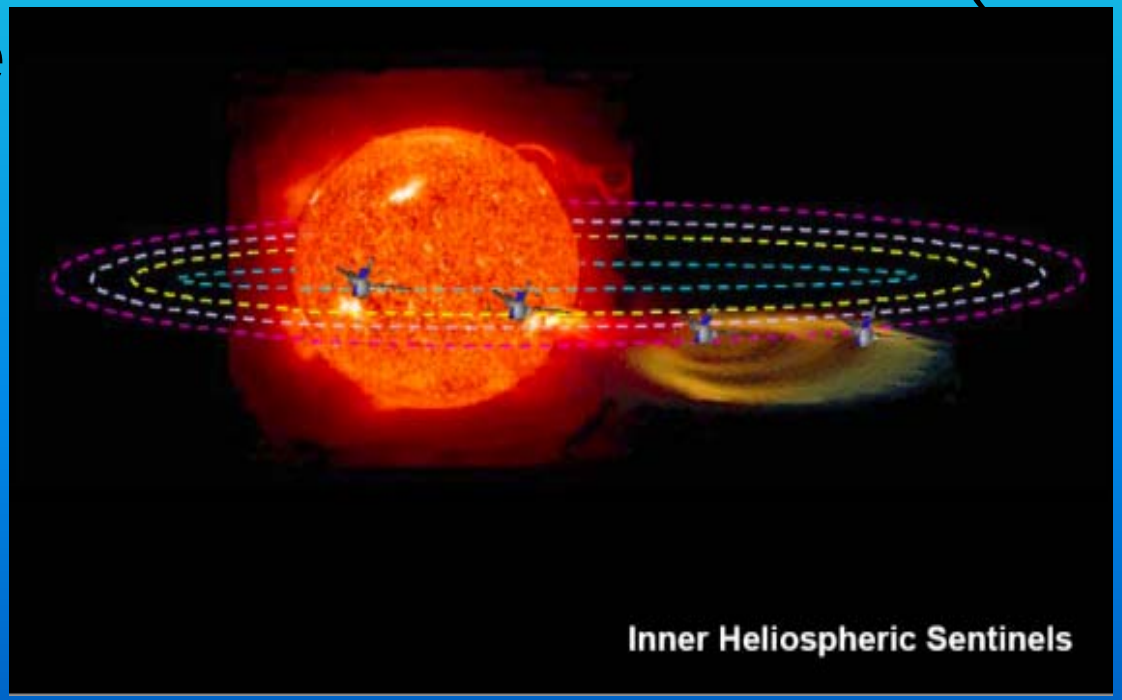


What is New and Exciting About SEPs?

- Two competing theories - How to decide?
  - › Measurements at different longitudes at the same time
  - › Measurements closer to the Sun (and/or at diffe



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