Solar Energetic Particles

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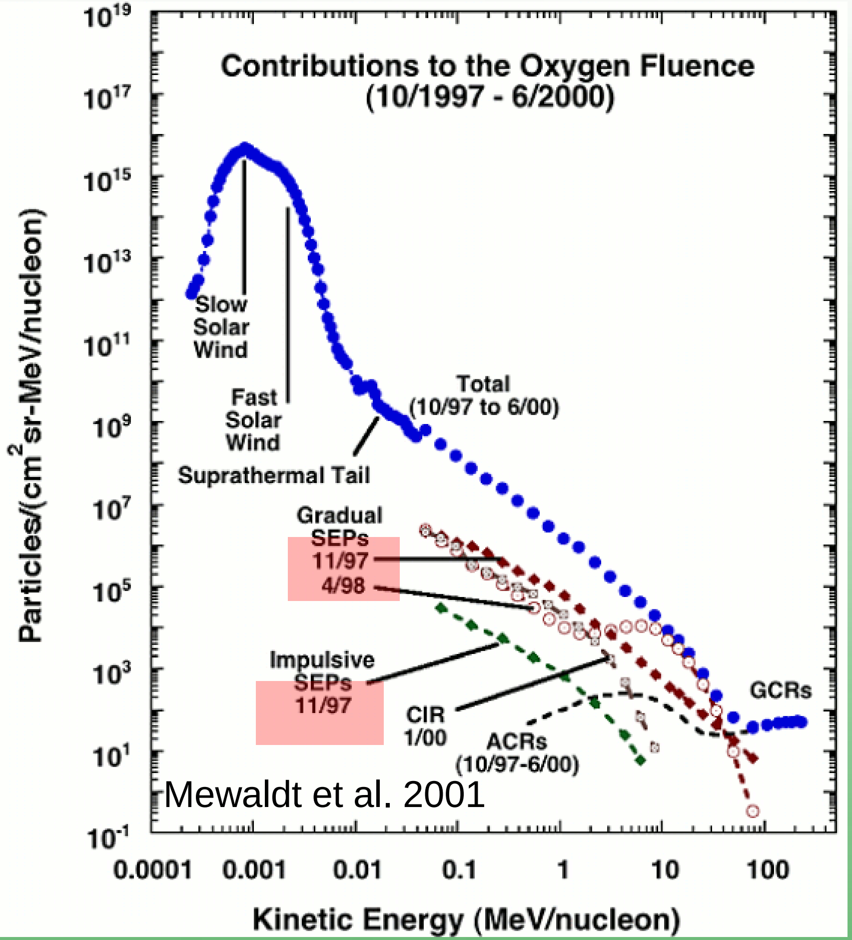
SEP Event Characteristics

- Energy range from few tens of keV/nucleon to over GeV/nucleon
- Duration from hours to days
- Mostly protons (He, heavy ions, electrons)
- Large event-to-event and during event variability:
  1. Intensity and duration
  2. Energy spectrum
  3. Elemental and isotopic composition
  4. Ionic charge states
- Everything is energy dependent

Reflects variability in source particle population, in particle acceleration mechanisms and IP particle transport conditions



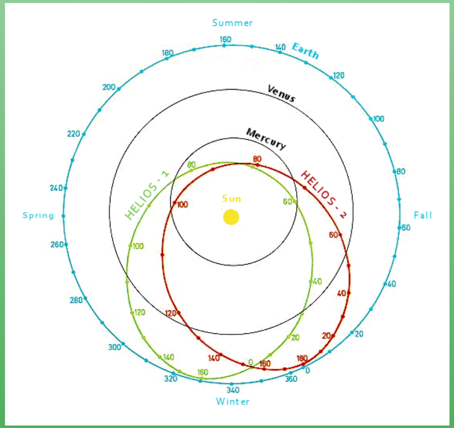
eV = electron volt = energy gain of electron in 1 Volt potential

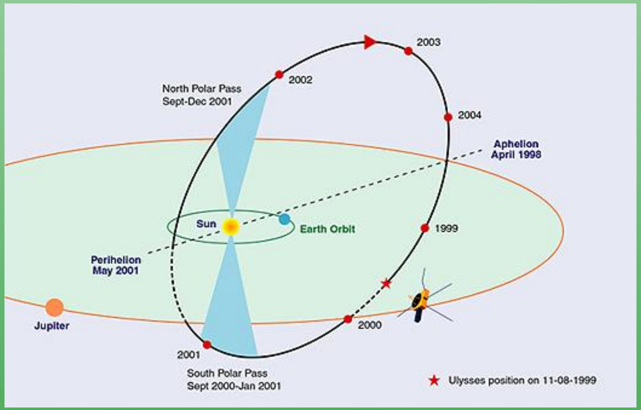
Significance

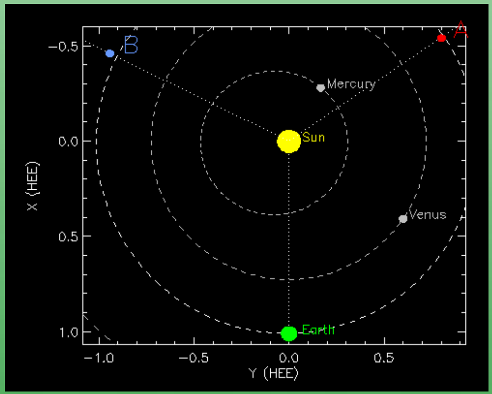
- A sample of solar material (processed and multiple sources?)
- Information about particle acceleration and transport processes in magnetized plasma
- Major hazard for human space exploration (increased radiation dose) and space borne systems (instrument anomalies and failures)

Observations

- Observed with instruments on spacecraft or on the ground (neutron monitors)
- Spacecraft observations mostly at ecliptic plane near Earth
- Exceptions: Helios 1&2 (min. distance ~0.3 AU, 1970s); Ulysses (high latitude up to 80°, 1990-2009); STEREO (2006->)







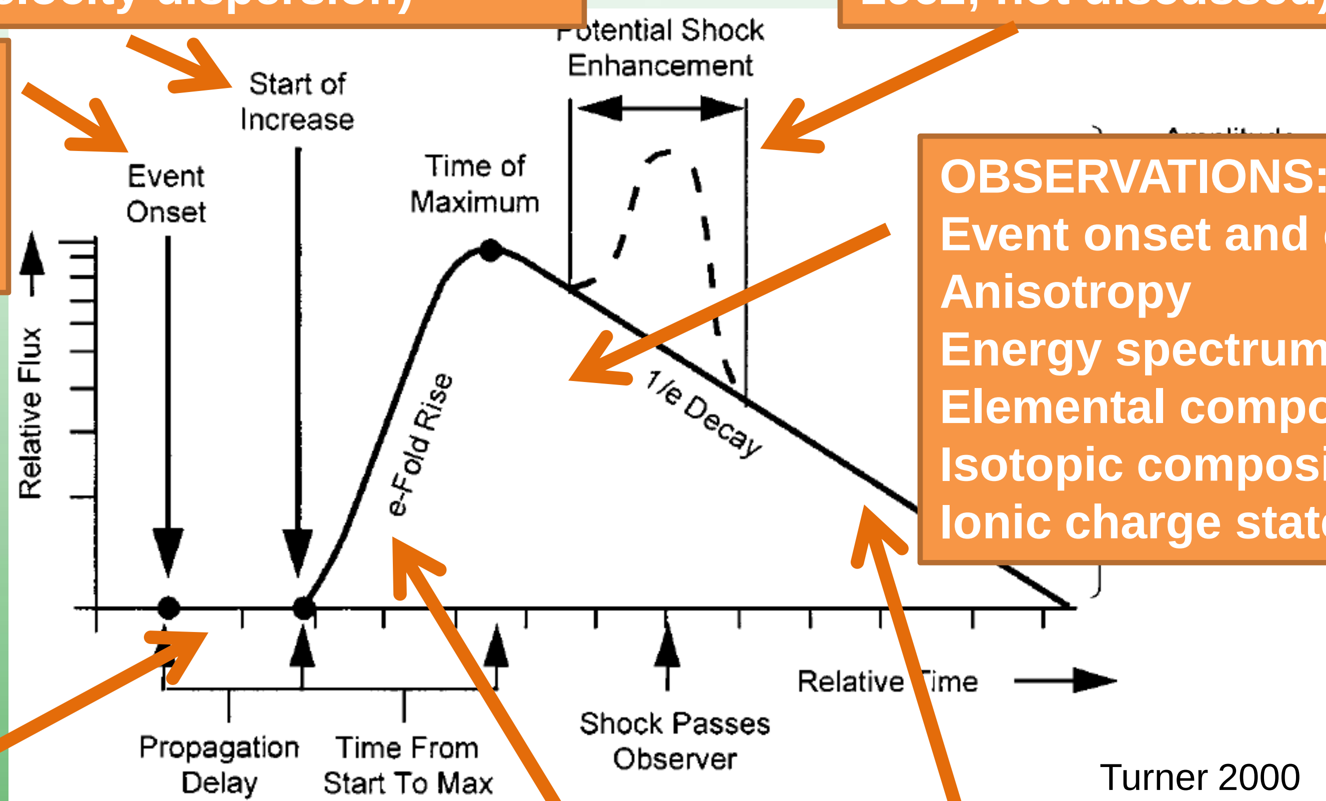
Typical SEP Event

Energy dependent arrival: fastest particles arrive first (velocity dispersion)

Energetic Storm Particle (ESP) event (Bryant et al. 1962; not discussed)

Acceleration and release
How? What? Where?

OBSERVATIONS:
Event onset and evolution
Anisotropy
Energy spectrum
Elemental composition
Isotopic composition
Ionic charge states



Turner 2000

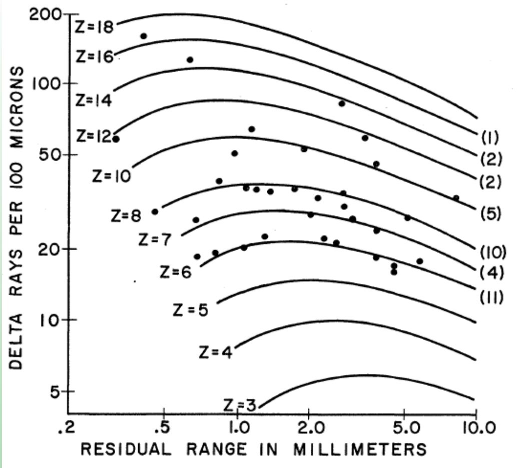
Particle transport along Archimedean spiral field (scattering and other effects)

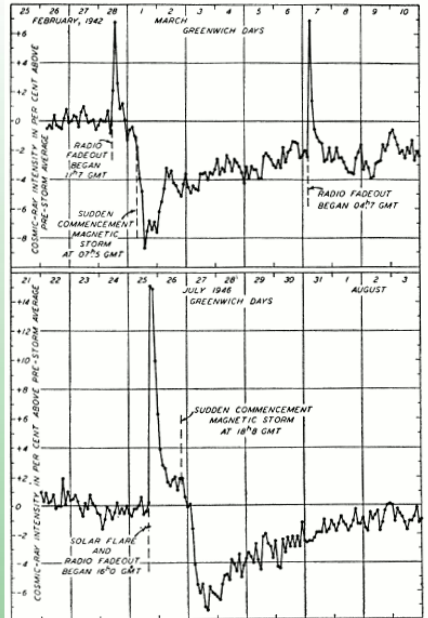
Fluxes of higher-energy particles evolve faster

Early SEP Observations

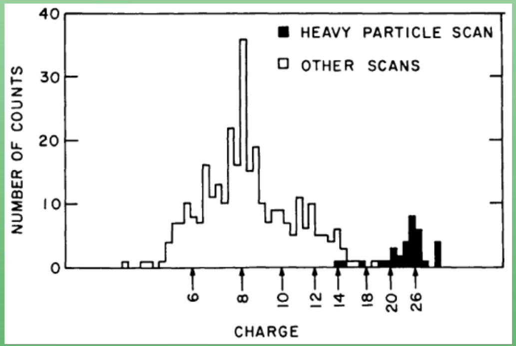
- Particles originally assumed to be flare-accelerated
- First reports based on observations of Ground Level Enhancements (GLEs) by Forbush (1946) and Meyer et al. (1956)
- Heavy ion SEPs (Fichtel & Guss 1961, rocket experiment)
- Evidence of ^{3}He-rich events (Shaeffer & Zäringer 1962; Hsieh and Simpson 1970; Anglin et al. 1973, Garrard et al. 1973; Serlemitsos & Balasubrahmanyan 1975)
- Fe enhancements (Bertsch et al. 1969; Price et al. 1971; Lanzerotti et al 1972; Mogro-Campero & Simpson 1972; Teegarden et al. 1973)

Fichtel & Guss 1961

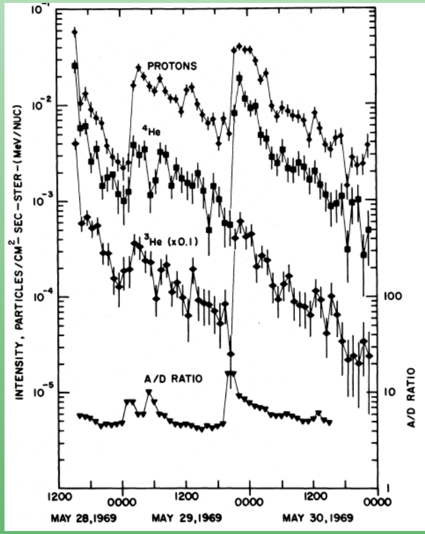




Forbush 1946



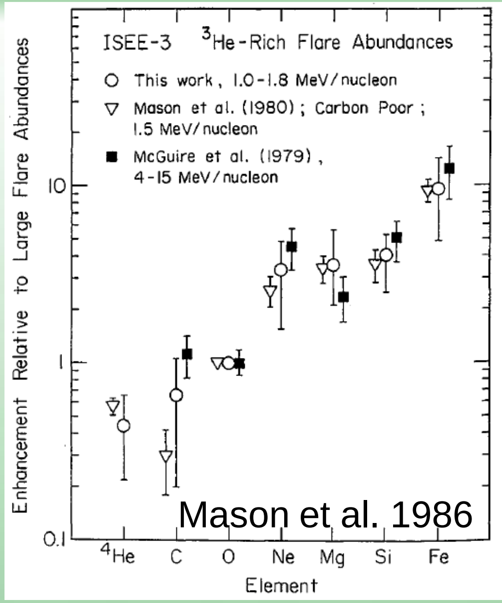
Bertsch et al.1969

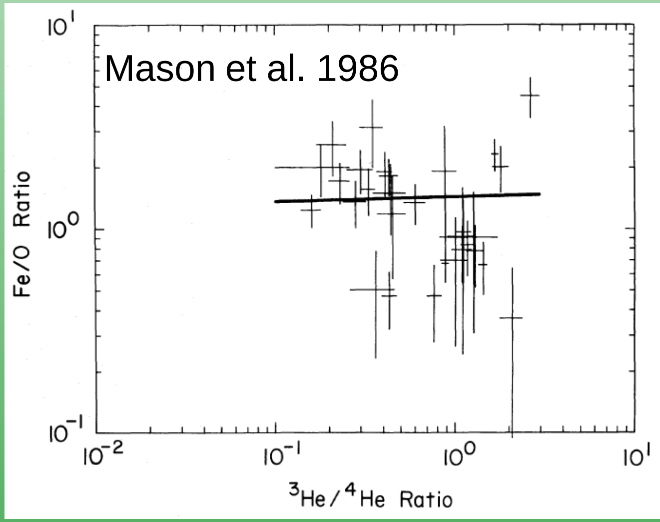


Serlemitsos & Balasubrahmanyan 1975

^{3}He-Rich Events

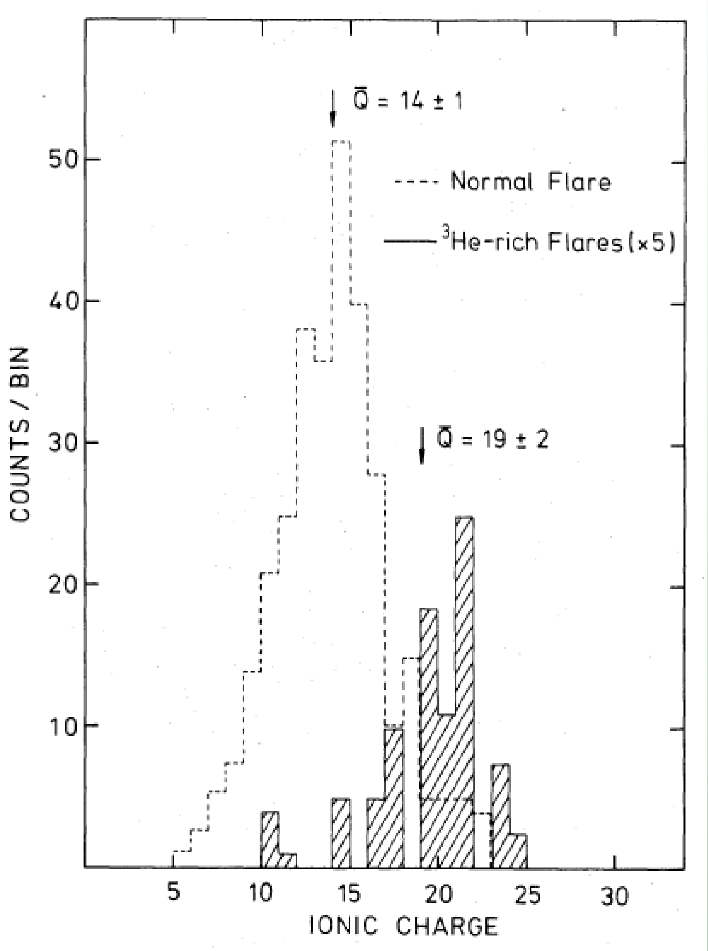
- Other heavy ions enhanced (Hurford et al. 1975)
- No CME association with ^{3}He-rich events (Kahler et al. 1985)
- ^{3}He-rich events associated with electron events (Reames et al. 1985)
- ^{3}He-rich events associated with metric (Kahler et al. 1987) and km (Reames et al. 1988) type III radio bursts
- ^{3}He-rich events associated with impulsive flares (Reames & Stone 1986)
- Enhancements of other heavy ions uncorrelated with ^{3}He/^{4}He (Mason et al. 1986)





Early Ionic Charge State Observations

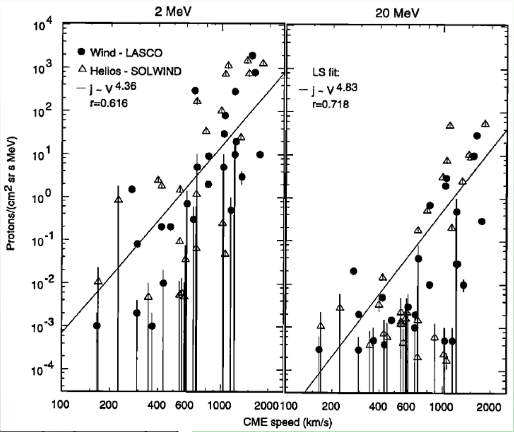
- C and O nearly fully ionized (Gloeckler et al. 1973)
- First direct Q_{Fe} measurements (Gloeckler et al. 1976; Sciambi et al. 1977; Hovestadt et al. 1981; Klecker et al. 1984; Luhn et al. 1984)
- High Q_{Fe} in ^{3}He-rich event (Ma Sung et al. 1981; Klecker et al. 1984)
- Ions up to Si fully stripped in ^{3}He-rich events (Klecker et al. 1984; Luhn et al. 1987)



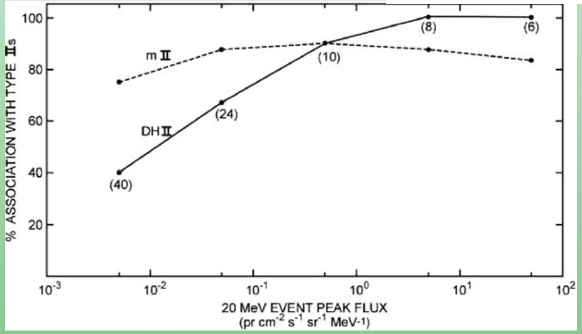
Klecker et al. 1984

CMEs, Type IIs and SEPs

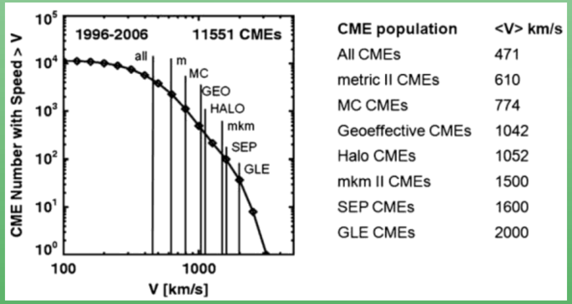
- Proton events associated with metric type II radio burst (Lin 1970) and coronal mass ejections (CMEs; Kahler et al. 1978)
- Modest correlation between CME speed and maximum intensity of SEPs (Kahler et al. 1984)
- Large SEP events associated with IP shocks (Cane et al. 1988)
- SEP events associated with DH type IIs (Gopalswamy et al. 2002; Cliver et al. 2004)
- CME interaction important for SEP production (Gopalswamy et al. 2002)



Kahler 2001



Cliver et al. 2004

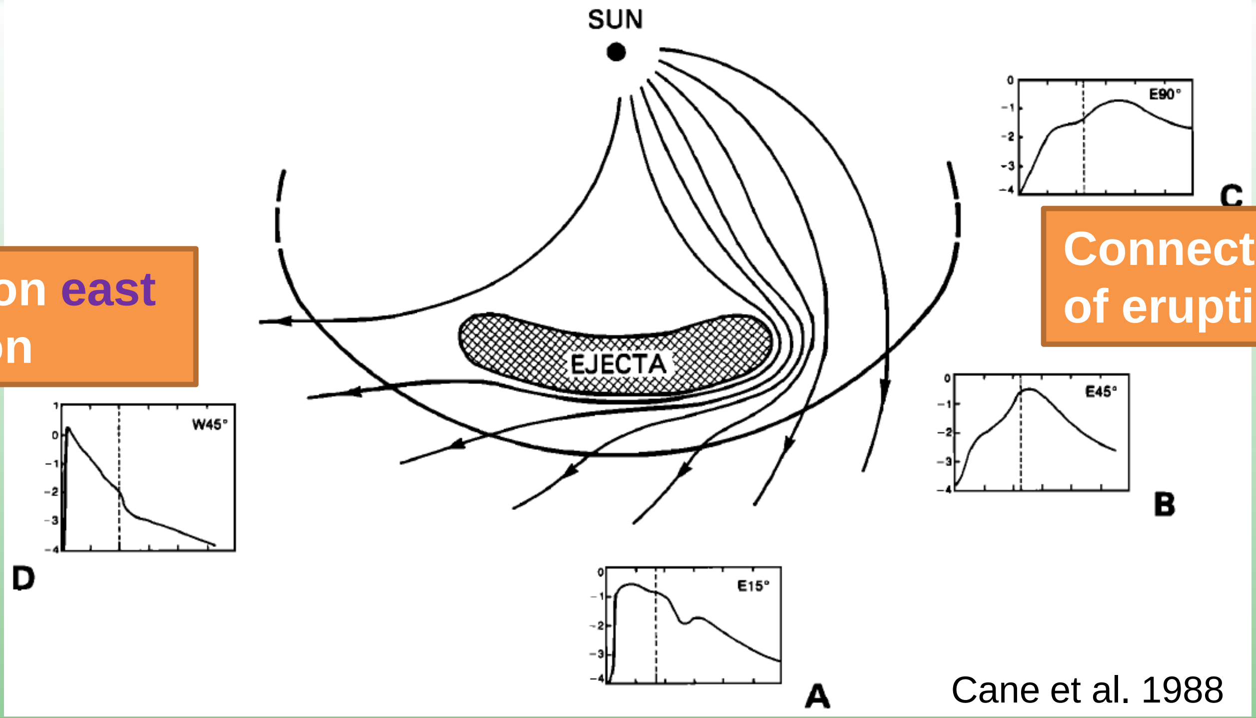


Gopalswamy 2010

Magnetic Connection

Connection **east** of eruption

Connection **west** of eruption



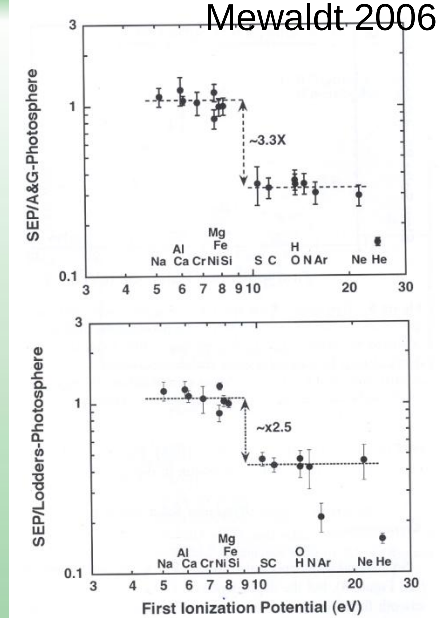
Cane et al. 1988

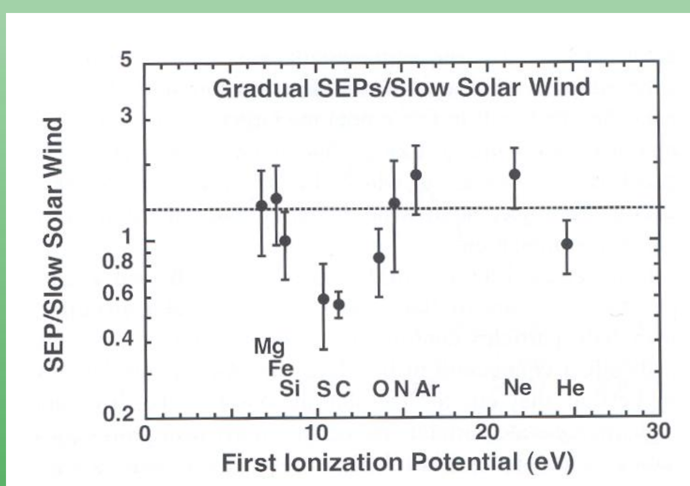
1. Time profiles are organized by the longitude of the solar source (Cane et al. 1988): it depends on where the observer's magnetic field line connects at the shock and how the connection point moves along the shock front.
2. Nominal solar wind: Earth connected to heliographic longitude ~W60°.
3. Acceleration most efficient at the shock nose, decreases towards flanks.

PROBLEM: IP field configuration not know accurately (disturbances change IP magnetic field)

First Ionization Potential (FIP) Effect

Mewaldt 2006

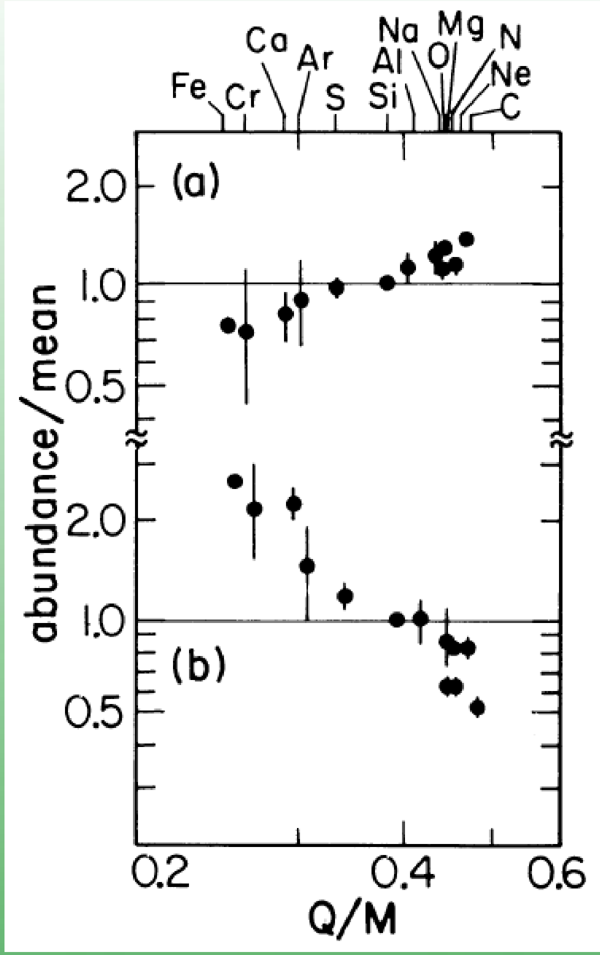




Mewaldt 2006

- Coronal, solar wind (SW), SEP elemental abundances differ from those of photospheric values (Meyer 1985ab)
- Ratios of SEP abundances relative to photospheric abundances are organized by FIP: low first ionization potential (FIP < 10 eV) are enhanced relative to those with high FIP
- Recently photospheric abundances revised (Lodders 2003)
- FIP fractionation results from a separation of ions and neutrals, taking place between the photosphere and the corona (e.g. Schmelz et al. 2012)
- SEP abundances do not show simple relation with slow SW indicating that SEPs do not originate from bulk SW (e.g. Mewaldt 2006)

Q/A Fractionation

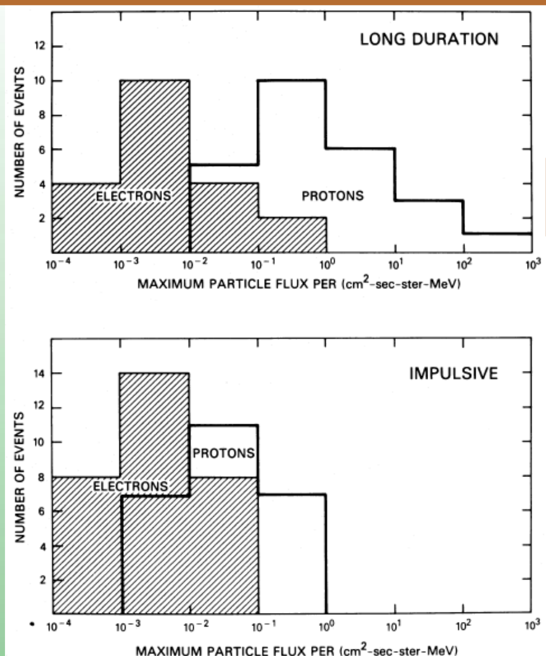


Breneman & Stone 1985

- Breneman & Stone (1985) showed that elemental enhancements are described by a power law $(Q/M)^{-\beta}$
- Large variability of the power-law index β from event to event
- Expected as acceleration and propagation processes depend on rigidity:
  $$\boldsymbol{R = p/Qe \propto M/Q}$$
- Recent observation do not always show similar simple dependence (Reames 1999)

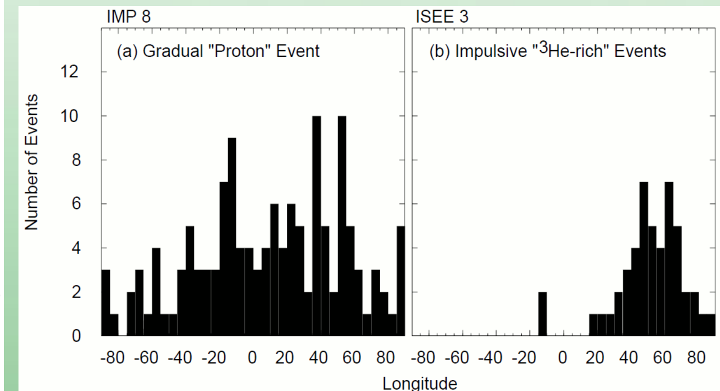
Two Populations of Events

Proton-poor and –rich events



Cane et al. 1986

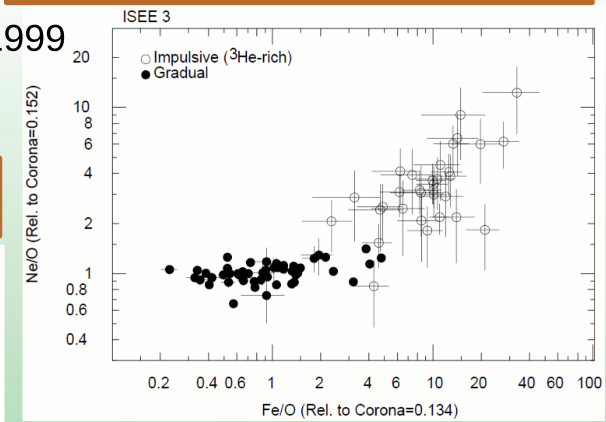
Source longitude difference

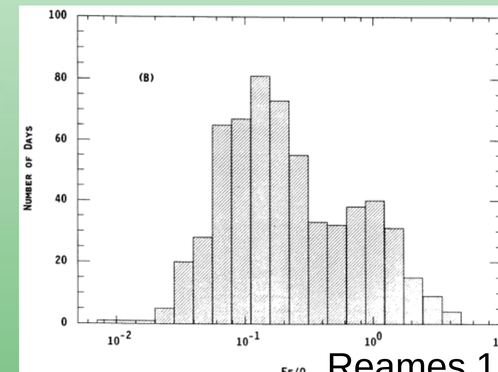


Reames 1999

Composition difference

Reames 1999



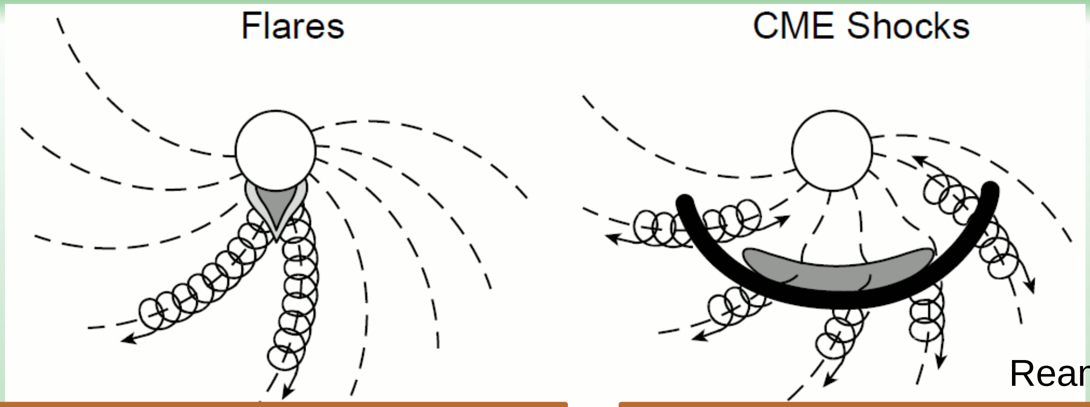


Reames 1988

SEP events with different characteristics divided into impulsive and gradual events based on the duration of the associated solar flare (Cane et al. 1986)
Bimodal distribution of abundances (Reames 1988):

1. **shock accelerated coronal material**
2. **flare heated and accelerated material with heavy-ion enhancements**

Two-Class Paradigm



Reames 1999

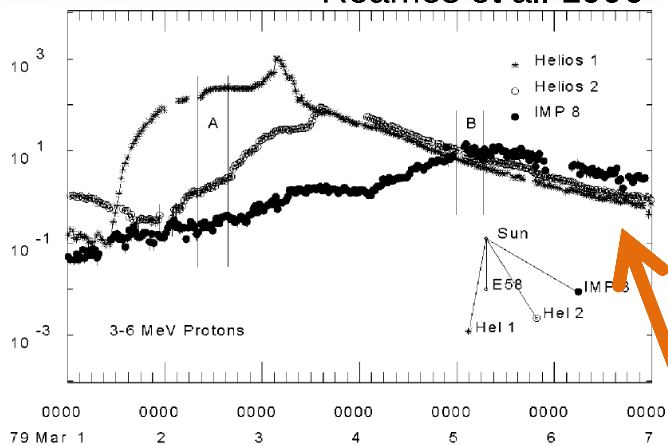
IMPULSIVE (flare) events:
- Narrow longitudinal range
- Short-duration
- Low intensities (small events)
- Electron rich
- He^3/He^4 ~1-10
- Fe/O ~1
- H/He ~10
- Q_{Fe} ~ +20 (Temp. ~10 MK)
- Type III radio bursts
- Flare heated material

GRADUAL (CME shock) events:
- Wide longitudinal range
- Long-duration
- High intensities (large events)
- Proton rich
- He^3/He^4 ~10^{-4}
- Fe/O ~0.1
- H/He ~100
- Q_{Fe} ~ +14 (Temp. ~1-2 MK)
- Type II radio bursts
- Coronal or SW material

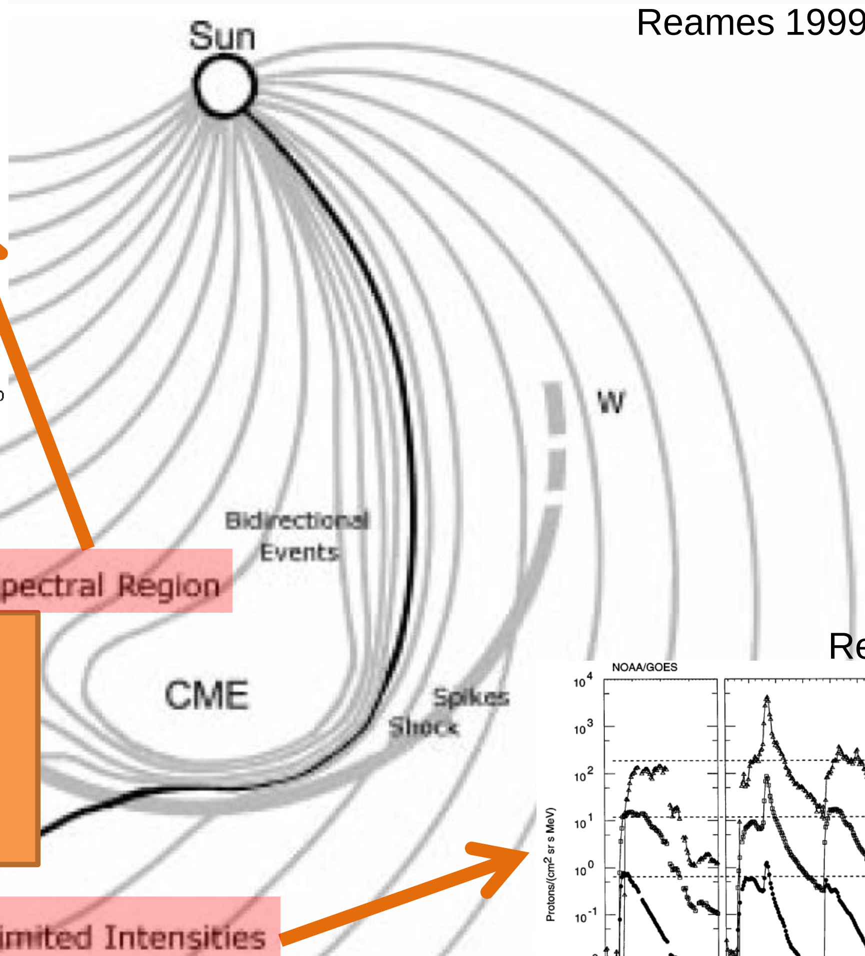
Paradigm revised because observations have revealed in gradual events characteristics typical of impulsive events

Particle Reservoir and Streaming Limit

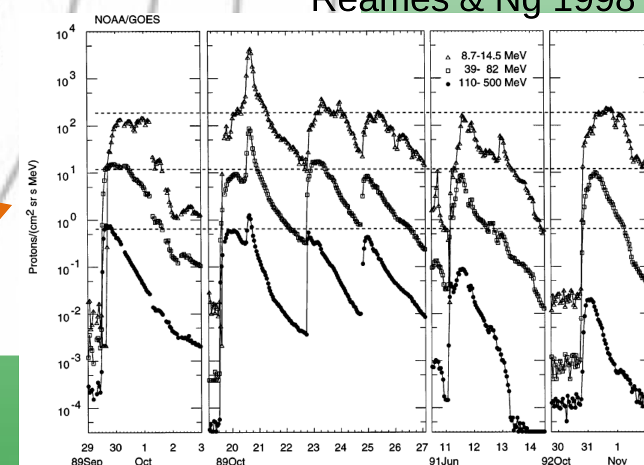
Reames et al. 1996



Reames 1999



Reames & Ng 1998

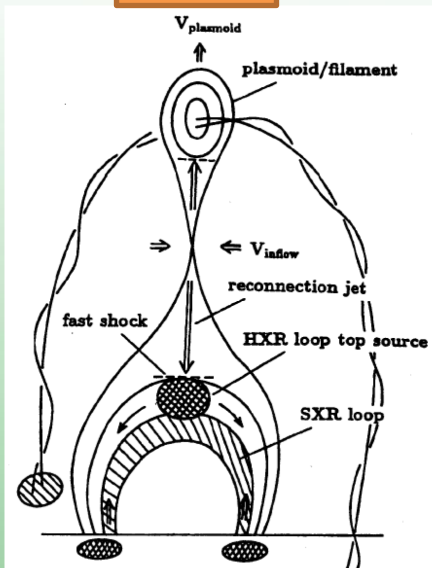


Widely separated spacecraft detect similar particle spectra: Seeing same large particle reservoir

All events show same maximum-intensity plateau: self-generated waves restrict particle escape from the shock

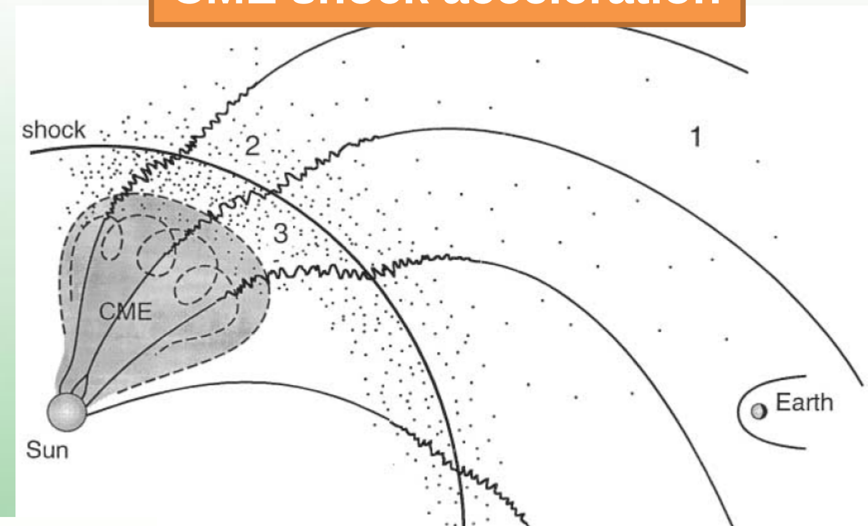
Acceleration Site

Flare



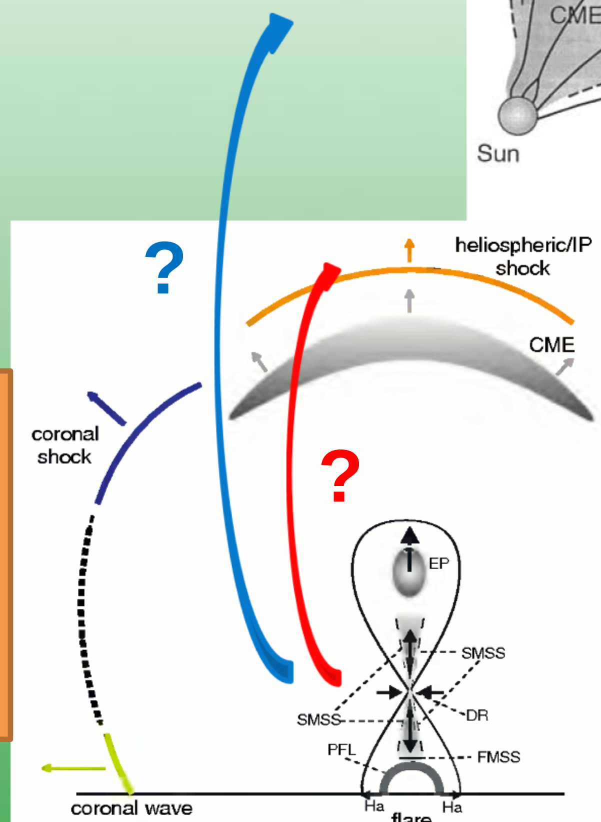
Shibata et al. 1995

CME shock acceleration



Lee 2005

IP space

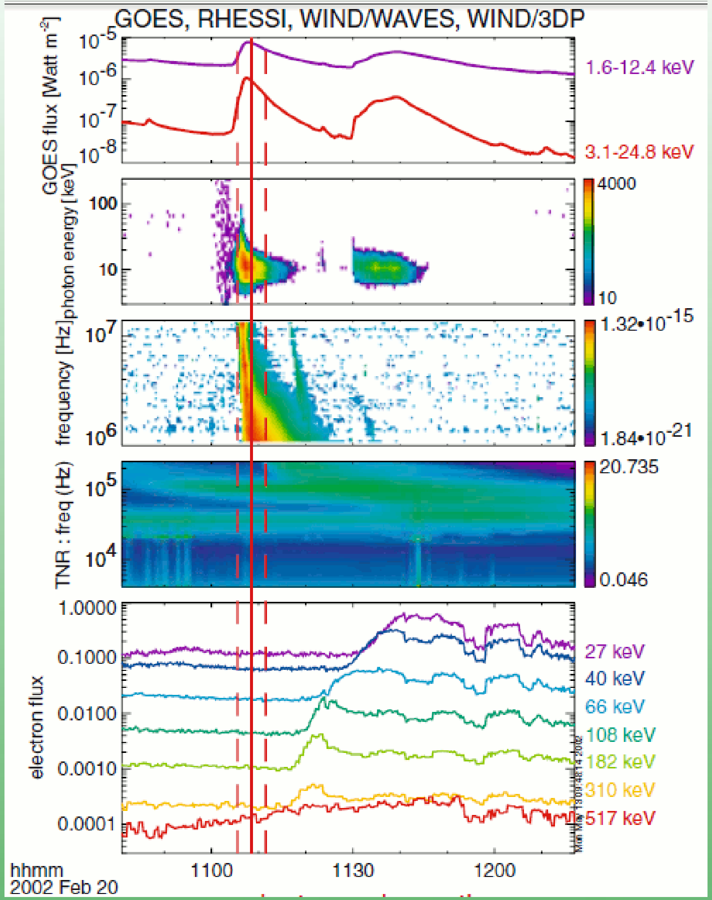


Aurass et al. 2002

Does CME shock accelerate flare particles? Flare occurs low in the corona: How particles escape to IP space?

Where and when the shock forms? Is there enough time for the shock to form and accelerate particles to explained the first observed IP particles?

Electron Events

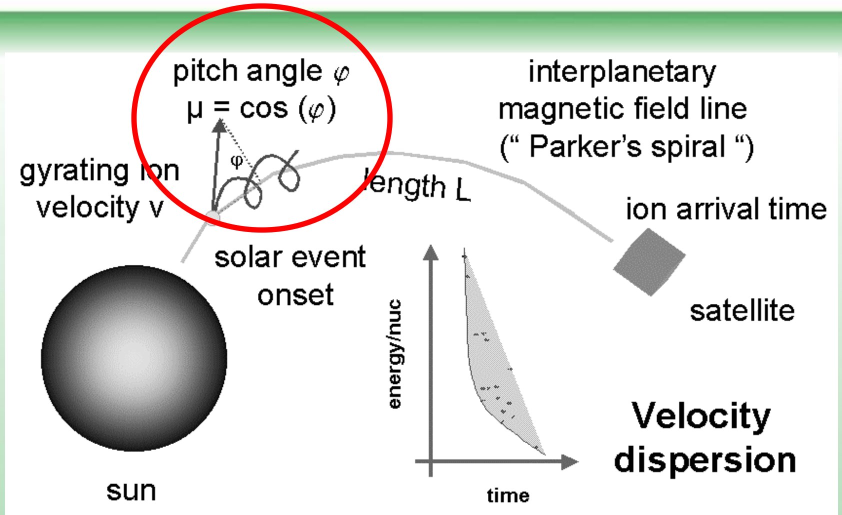


Krucker & Lin 2002

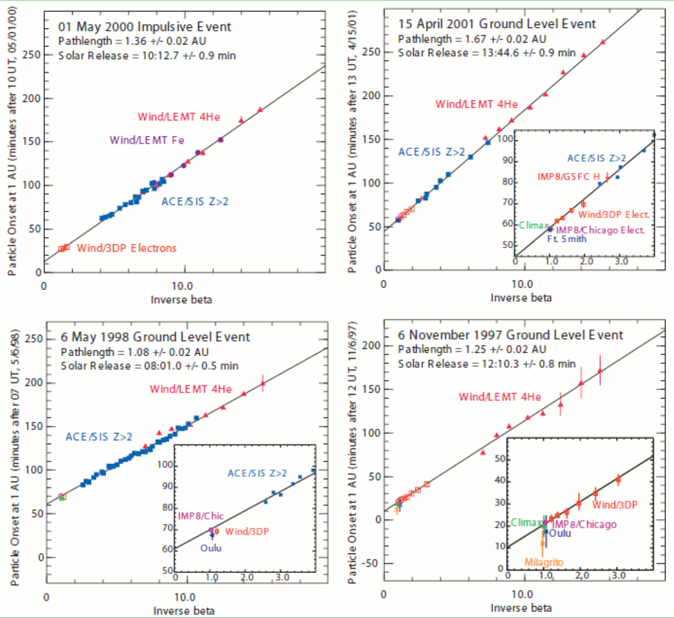
- Origin of near-relativistic (E≥30 keV) impulsive electron events remains uncertain
- Known to be associated with type III solar radio bursts (Lin 1970)
- But injection delayed by ~10-30 min from the type III bursts (Krucker et al. 1999; Haggerty & Roelof 2002)
- Propagation effect, i.e. electrons are accelerated in flare processes (Cane 2003)
- Accelerated by reconnection processes during the CME aftermath (Maia & Pick 2004; Klein et al. 2005)
- CME shock acceleration (Simnett et al. 2002)
- Modeling shows all three options possible (Agueda et al. 2009)
- Evidence suggests that CME-driven shocks are statistically the dominant acceleration mechanism of relativistic (E ≥0.3 MeV) events, but most near-relativistic events result from flares (Kahler 2007)

Particle Release Time

- From velocity dispersion of the SEP event onset one can estimate particle release time at the Sun $t_{obs} = \frac{L}{\sqrt{2E/m}} + t_{rel}$, where L is path length, E kinetic energy, t_{obs} is arrival time and t_{rel} release time (add 8.3 min to compare with electromagnetic emissions)
- Assumes scatter-free propagation of first particles (see Lintunen & Vainio 2004; Saiz et al. 2005)
- Estimated SEP release heights: ≥5 $R_\odot$ (Kahler 1994); in GLEs ~3.1 $R_\odot$ (Gopalswamy et al. 2012)



Hilchenbach et al. 2003



Tylka et al. 2003

IP Transport

During propagation from the source to observer particles experience:

1. convection with solar wind (low-energy particles)
2. interactions with the turbulent IP magnetic field (pitch angle scattering)
3. focusing in large-scale magnetic field (diverting Archimedean spiral field)
4. energy change

Transport effects change observed in-situ distributions of accelerated particles

→ Harder to resolve original acceleration processes

Basic Transport Equations

Parker (1965) diffusion-convection equation:

$$\frac{\partial F}{\partial t} - \nabla \cdot (K \cdot \nabla F) - v_{SW} \cdot \nabla F - \frac{1}{3}(\nabla \cdot v_{SW}) p \frac{\partial F}{\partial p} = Q$$

- assumes that particle distribution (*F*) is nearly isotropic
- mean free path λ *(average distance traveled between scattering)* depends on diffusion coefficient (small λ = strong scattering)

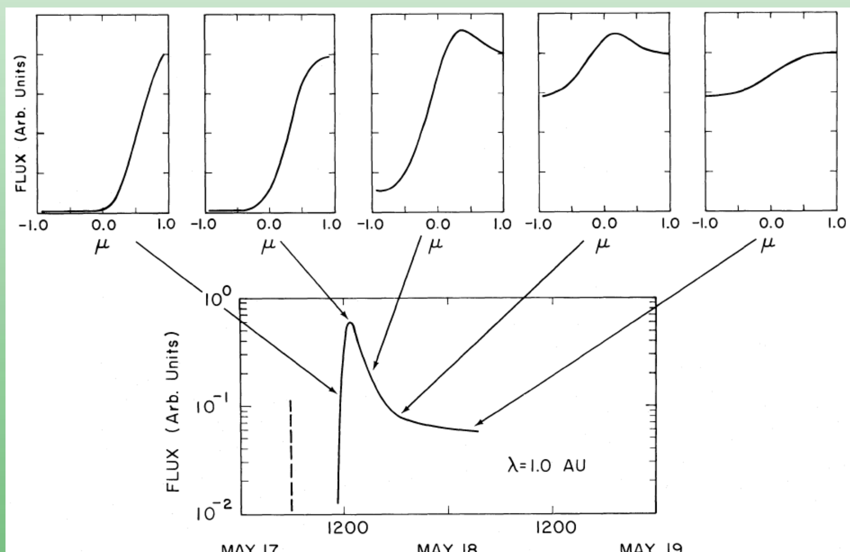
Focused transport equation (Roelof 1969):

$$\frac{\partial F}{\partial t} + \mu v \frac{\partial F}{\partial s} + \frac{1-\mu^2}{2\vartheta} v \frac{\partial F}{\partial \mu} - \frac{\partial}{\partial \mu}\left(K \frac{\partial F}{\partial \mu}\right) = Q$$

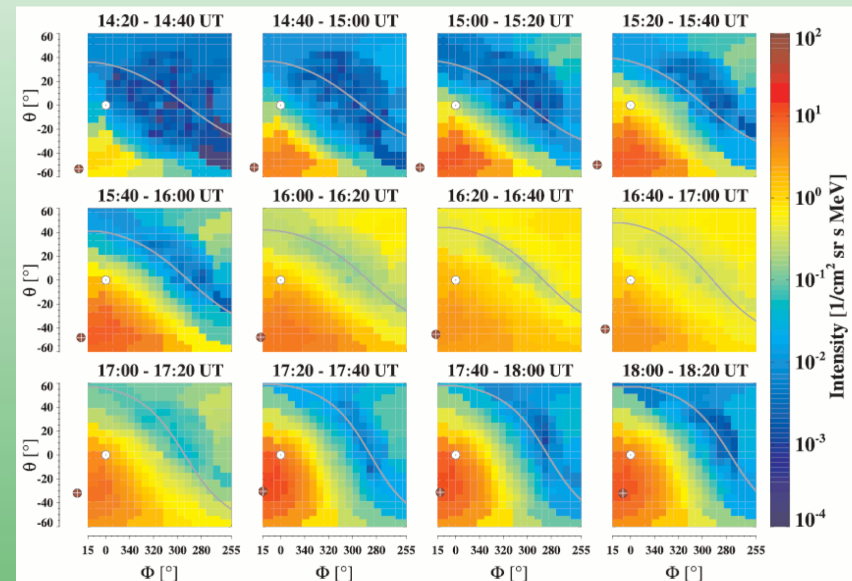
- *F* may be anisotropic

Particle Flux Anisotropy

At the beginning of a SEP event particle fluxes could be anisotropic
Diffusive approximation not valid if fluxes are highly anisotropic, i.e. if particle mean free path *λ* is long (weak scattering)

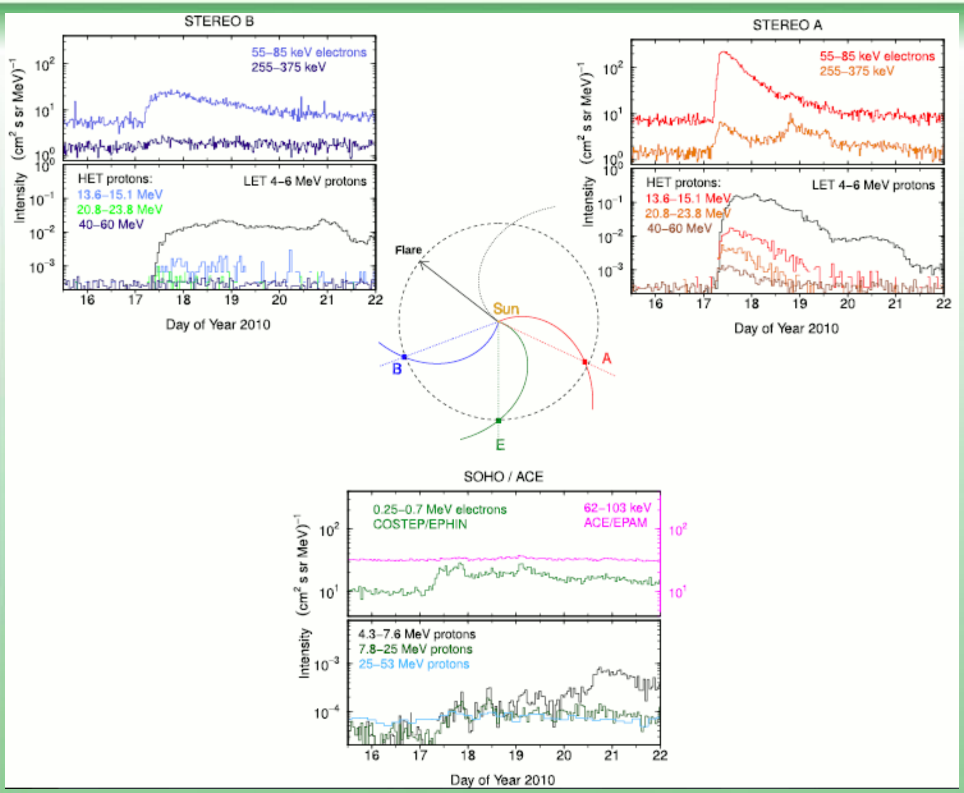


Mason et al. 1989



Extremely long mean free paths (*λ*≳10 AU) observed inside magnetic cloud 2 May 1998 (Torsti et al. 2004)

Perpendicular Diffusion



Perpendicular diffusion across magnetic field lines **not well understood**

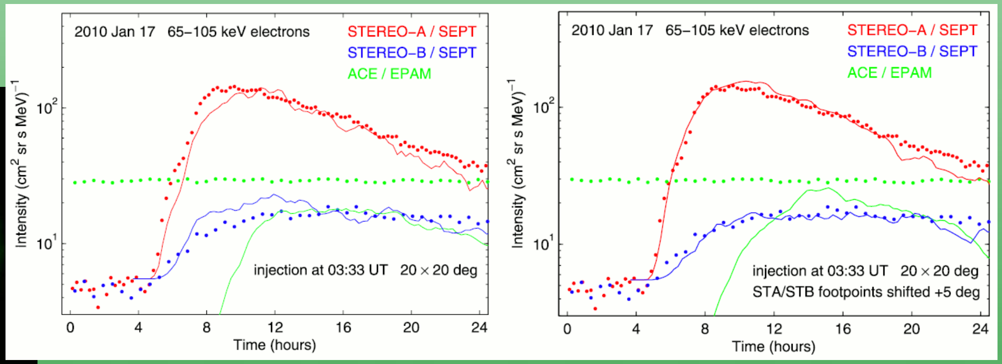
Example by Dresing et al. (2012)

1. fluctuations scatter particles from one field line to another
2. field line mixing

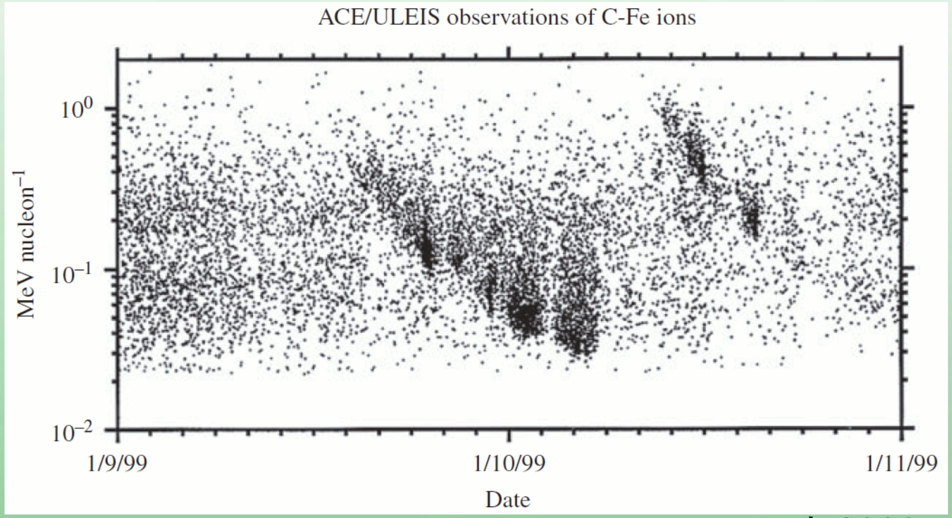
Propagation model:

Source: flare pos ± 20° in lon/lat

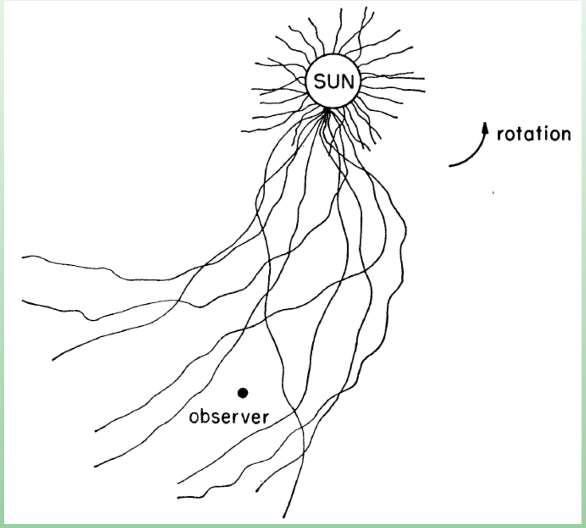
lateral particle transport due to perpendicular diffusion and corotation



Perpendicular Diffusion



Mazur et al. 2000



Jokipii 1966

- **Mazur et al. (2000) reported sharp dropouts of heavy ion flux during an impulsive SEP event**
- **Evidence of irregular IP magnetic field lines**

Shock Acceleration

- Power-law energy spectrum in downstream region (Axford et al. 1977; Blandford & Ostriker 1978; Bell 1978; Lee 1983):

$$dJ/dE \propto E^{-\gamma}$$

- Exponential turnover due to finite shock lifetime and size (Ellison & Ramaty 1985)

$$dJ/dE \propto E^{-\gamma}\exp(E/E_0)$$

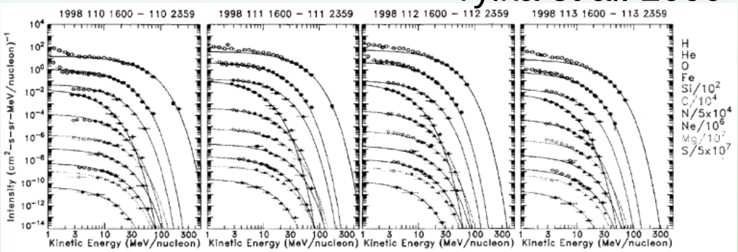
Quasi-parallel shock ($\theta_{BN} \leq 45°$)

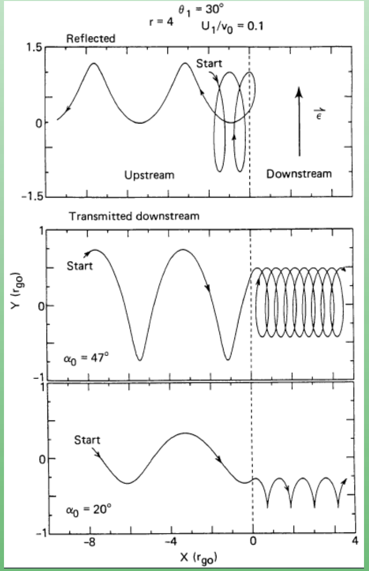
- **Diffusive shock acceleration (DSA):** particles scattering between up- and downstream magnetic fluctuations (1st order Fermi acceleration)
- Slower acceleration rate
- Efficient particle scattering requires enhanced level of turbulence/waves

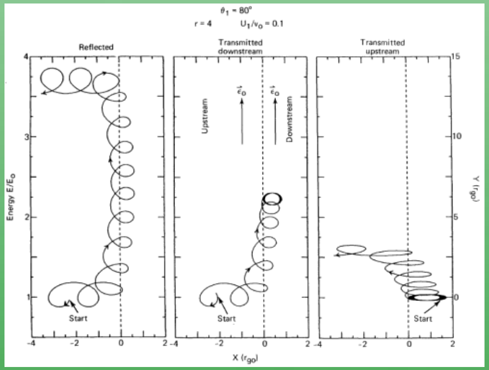
Quasi-perpendicular shock ($\theta_{BN} \geq 45°$)

- **Shock drift acceleration (SDA)**: Induced electric field **E**=**V**×**B** at shock front
- Fast acceleration rate
- Higher maximum energy

Tylka et al. 2000





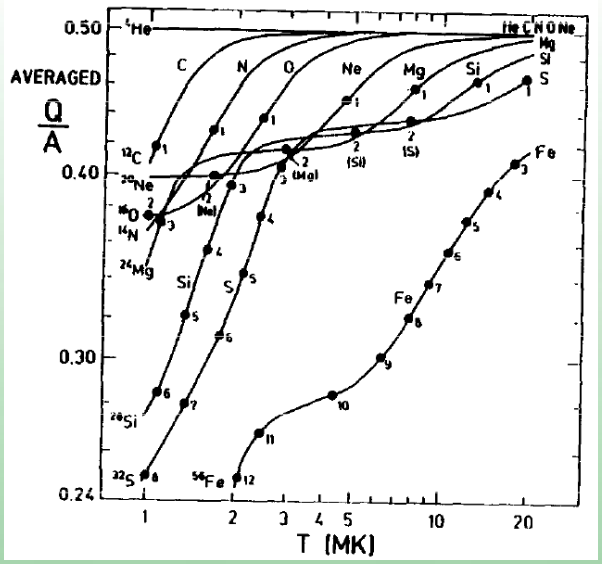


Decker 1988

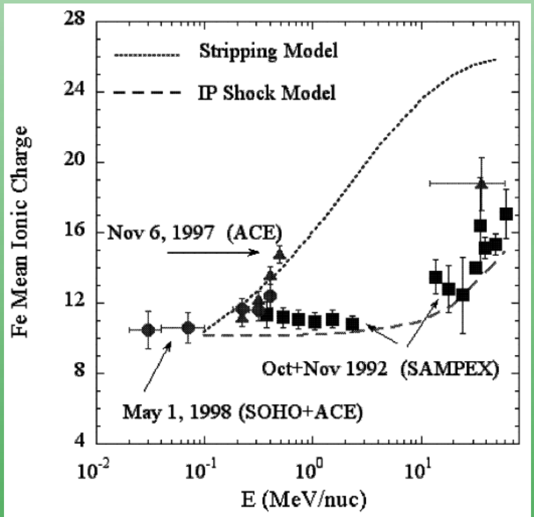
Flare Acceleration

- Stochastic acceleration based on wave-particle resonance
  - Fisk (1978) suggest that ^{3}He is preferential heated by oscillations near ^{3}He gyrofrequency due to its unique Q/M (> 0.5) ratio (also Temerin & Roth 1992, Zhang 1995)
  - Can explain enhanced ^{3}He/^{4}He, but what about other heavy ions?
  - Cascading turbulence models (Miller & Vinas, 1993; Miller 1997,1998; Liu et al. 2006)
  - Waves cascade up to higher frequencies, first accelerating Fe (Q/M < 0.5) , then Ne, Mg, and Si group ions, then waves accelerate ^{4}He, C, N, and O (Q/M=0.5). As waves accelerate ions they lose energy and are damped, so Fe ions are enhanced most, then Ne, Mg, and Si.
- Other possible mechanism:
  1. Acceleration in electric fields
  2. 2nd order Fermi acceleration (stochastic acceleration mechanism suggested by Fermi 1949)
- Form of energy spectrum uncertain

Ionic Charge States



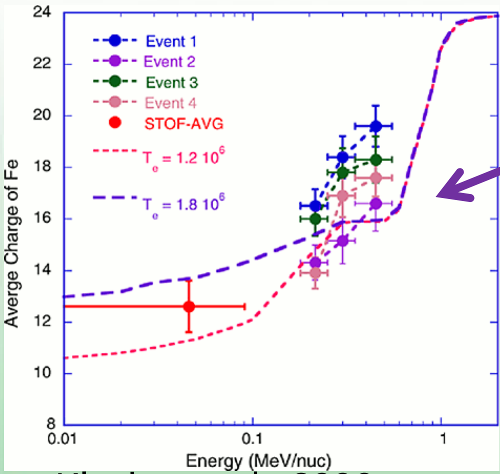
Reames 1995



Klecker et al. 2001

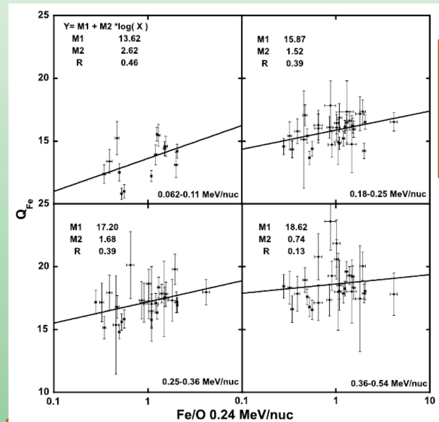
- Ionic charge states changed by recombination and ionization processes
- Q_{Fe} important: Fe ions are relatively abundant and only partially ionized
- Charge states reflect source region temperature and effects of collisional processes (Popecki 2006)
- Energy dependence due to:
  1. charge-changing processes during acceleration near the Sun, where ions are traversing through dense enough plasma (electron stripping, see e.g. Kocharov 2006)
  2. Shock acceleration processes in IP space (e.g., Klecker et al. 2001)

Q_{Fe} in Impulsive Event



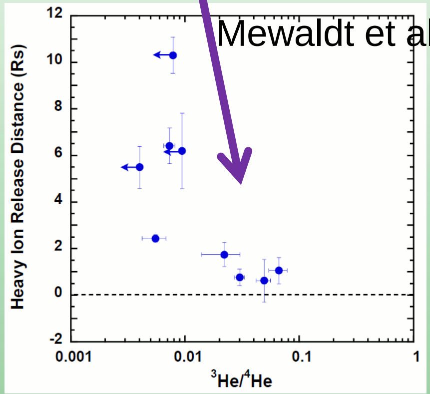
Klecker et al. 2006

Lines show charge states calculated with model of Kocharov et al. 2000 (Klecker et al. 2006): charge states at low-energy reflect source temperature, at high-energy electron stripping low in corona

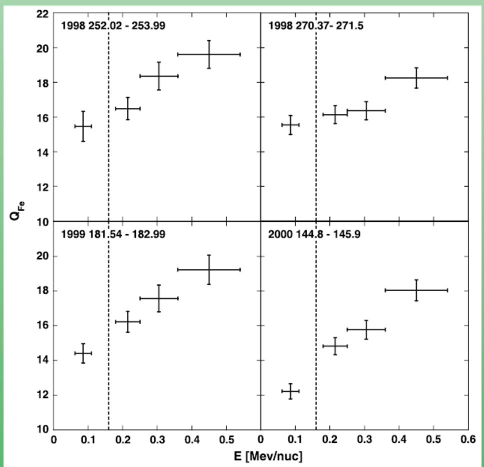


DiFabio et al. 2008

Weak energy dependence



Mewaldt et al. 2003



DiFabio et al. 2008

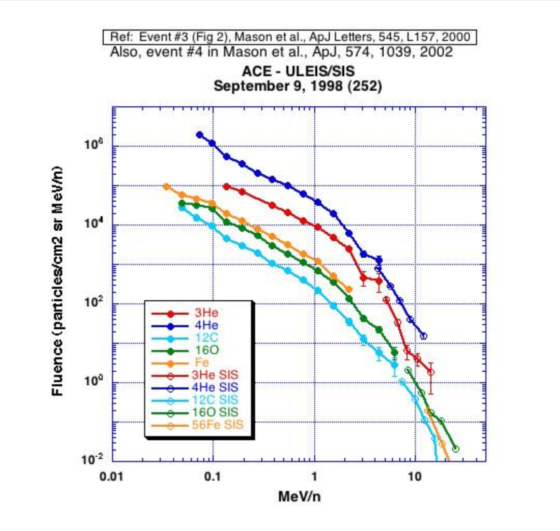
Iron charge state Q_{Fe} increases with energy and correlates with heavy ion abundance ratios (Möbius et al. 2000)

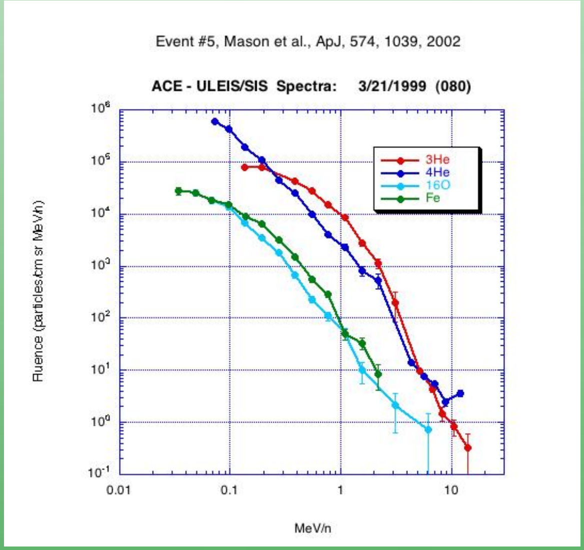
Why heavy ions more enhanced when charge state increases (theory: Q/M -> 0.5 -> weaker enhancement)?

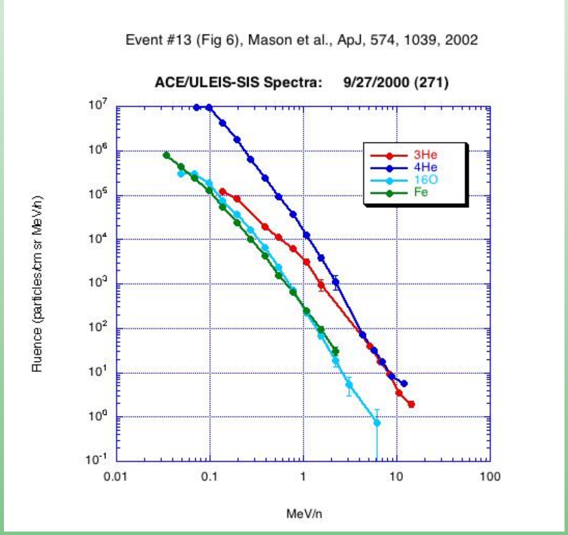
Acceleration of 1-3 MK plasma and stripping during acceleration (e.g. Klecker et al. 1994; Kartavykh 2006,2007; DiFabio et al. 2008)

Energy Spectra in Impulsive Events

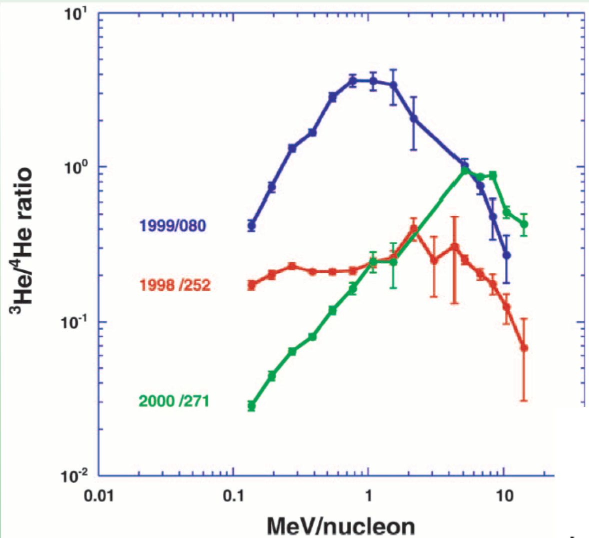
Shape of energy spectrum varies from event to event but shapes similar between elements
^{3}He spectral shapes differ



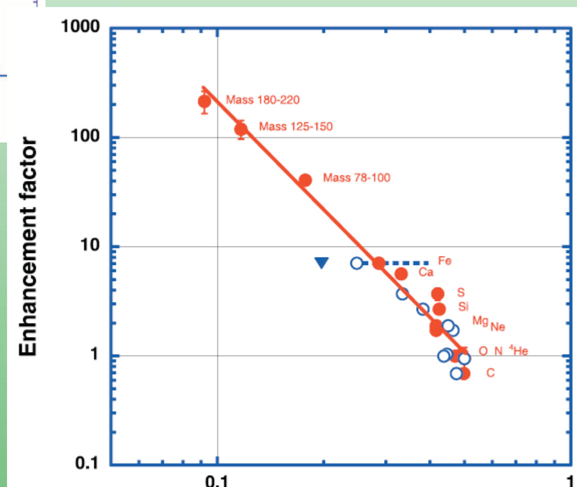




Abundances in Impulsive Events



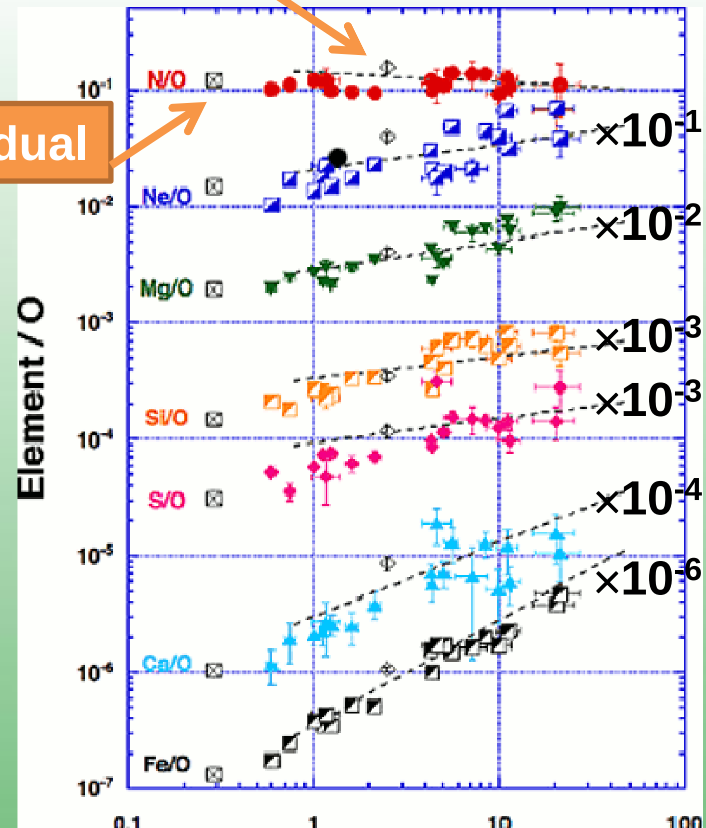
Mason et al. 2002



Mason et al. 2004

Average impulsive

Average gradual

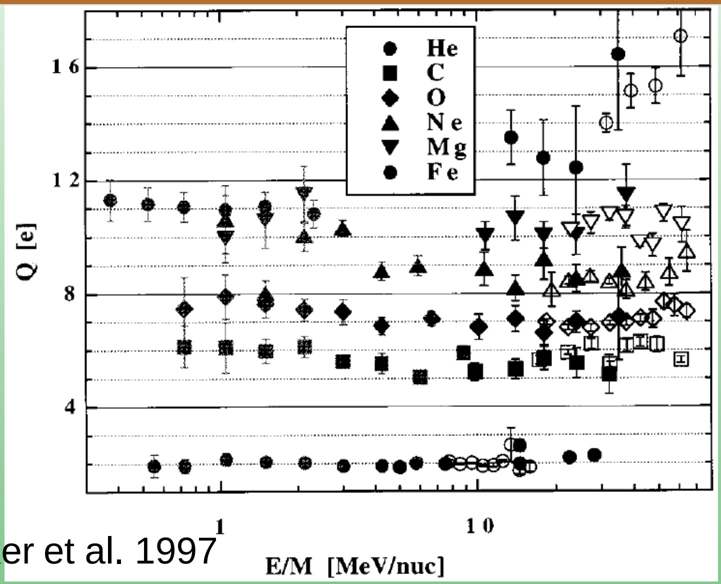


Mason et al. 2004 Fe / C

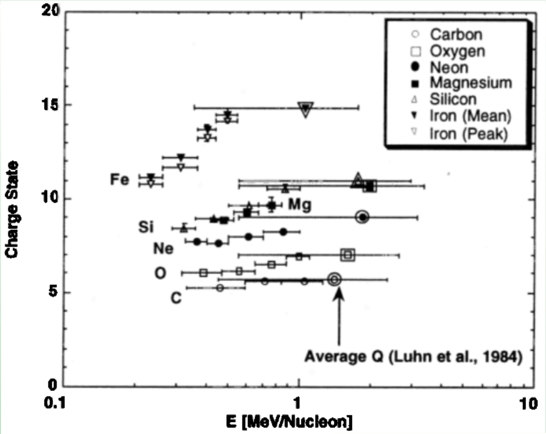
Mason et al. (2002, 2004): Heavy-ion enhancement correlate and increase with Q/M, except N/O; ^{3}He/^{4}He ratio varies with energy and event to event

Charge States in Gradual Events

Earlier view : Fe charge states between 10 to 14 indicate ~1 MK solar source plasma, i.e. coronal material

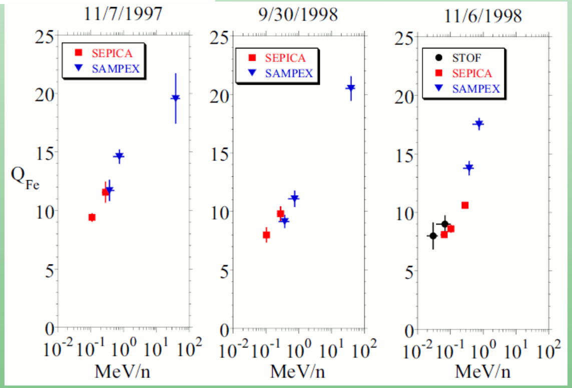


Oetliker et al. 1997



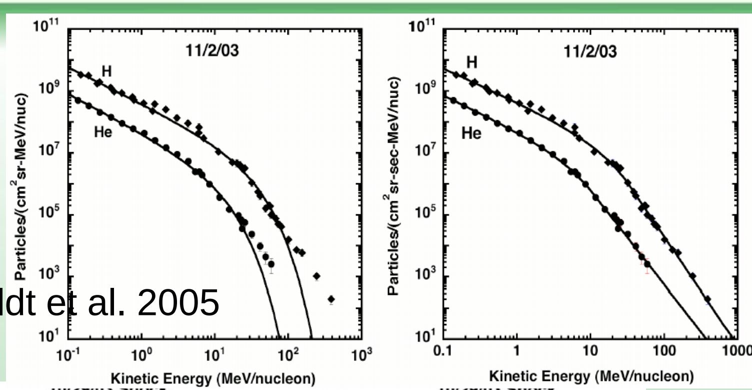
Möbius et al. 1999

Popecki et al. 2003

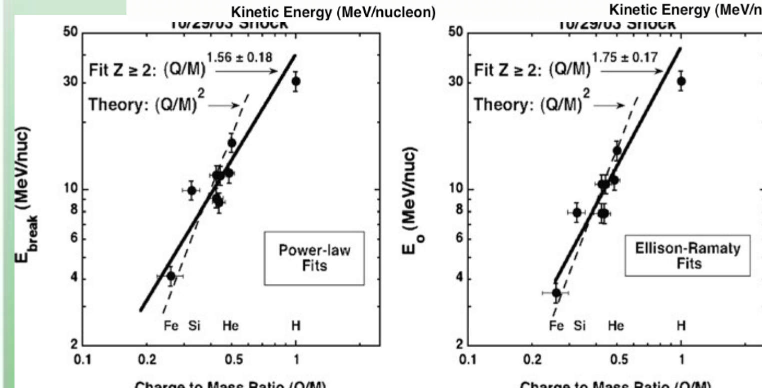


Oct and Nov 1992 and 6 Nov 1997 gradual events: higher charge states as energy increases (Oetliker et al. 1997; Mazur et al. 1999)
no simple correspondence with source temperature possible

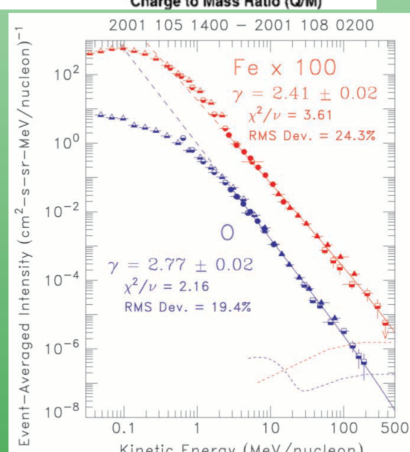
Energy Spectra in Gradual Events



Mewaldt et al. 2005



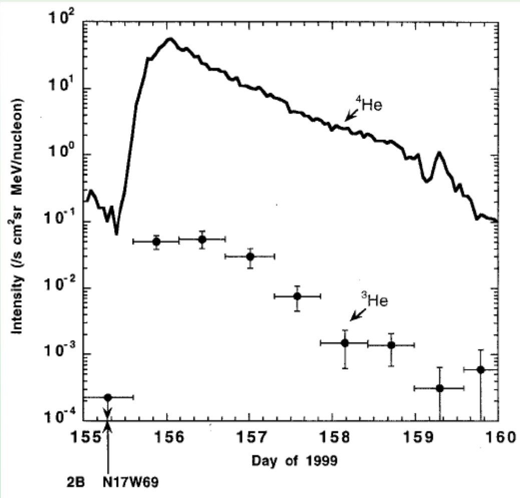
Mewaldt et al. 2005



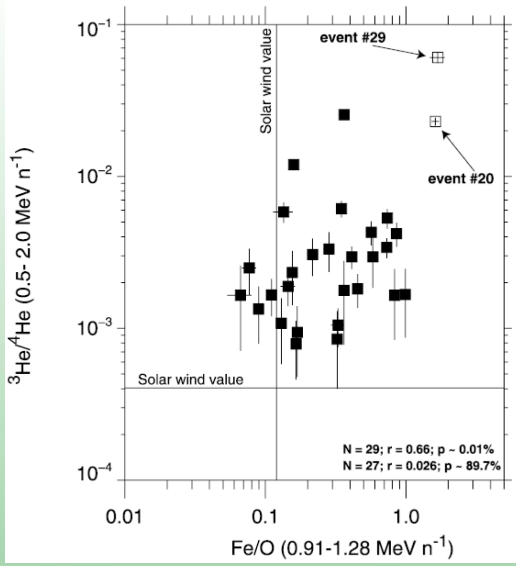
Tylka et al. 2002

- Exponential rollover (Ellison & Ramaty 1985) form used often to fit spectra (e.g. Tylka et al. 2000)
- E_0 differs between species (e.g. $E_{0,Fe} < E_{0,O}$): high-energy Fe/O ratio is affected by the difference
- Tylka et al. (2000) $E_{0i} \propto E_0 (Q_i/A_i)^{\delta}$; Li et al. (2005) $E_0 \propto (Q/M)^2$
- Reasonable consistency with observations (Mewaldt et al. 2005)
- Some events are better fit with double power-law
- High-energy power-law indices differ between species (e.g. Tylka & Dietrich 1999; Tylka et al. 2002)
- Simple shock acceleration predicts independence of Q/M (Tylka & Lee 2006)

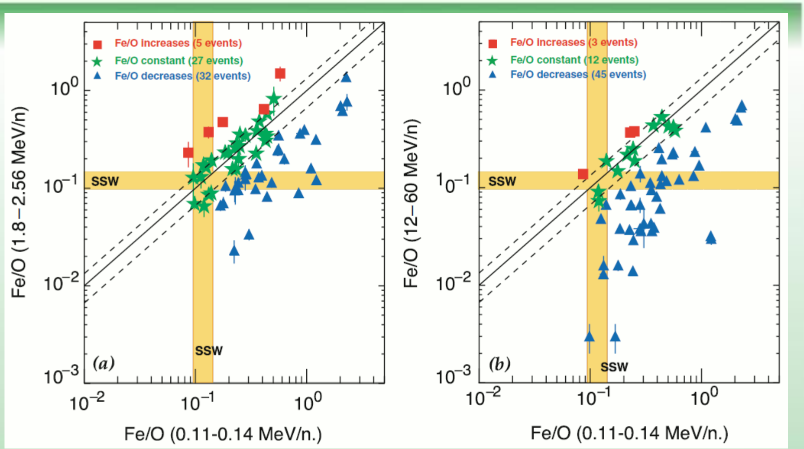
^3He and Fe Abundance in Gradual Events



Mason et al. 1999



Desai et al. 2006



Desai et al. 2006

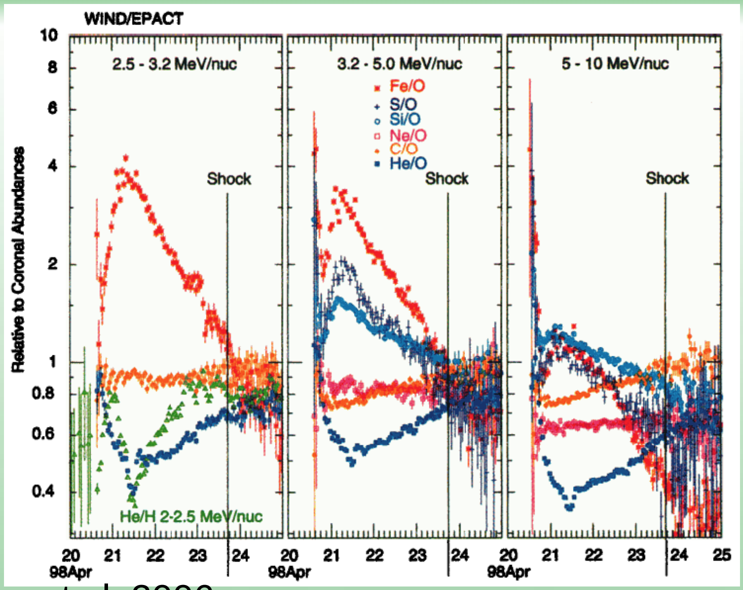
$^3He/^4He$ (e.g. Mason et al. 1999) and Fe/O (e.g. Reames 1990) enhancements typical to impulsive events observed also during gradual events
Assumed to indicate the presence of flare-accelerated particle populations
Fe/O ratio decreases with increasing energy in most of events, show large even-to-event variation and poor correlation with $^3He/^4He$ ratio (Desai et al. 2006)

Seed Particle Population

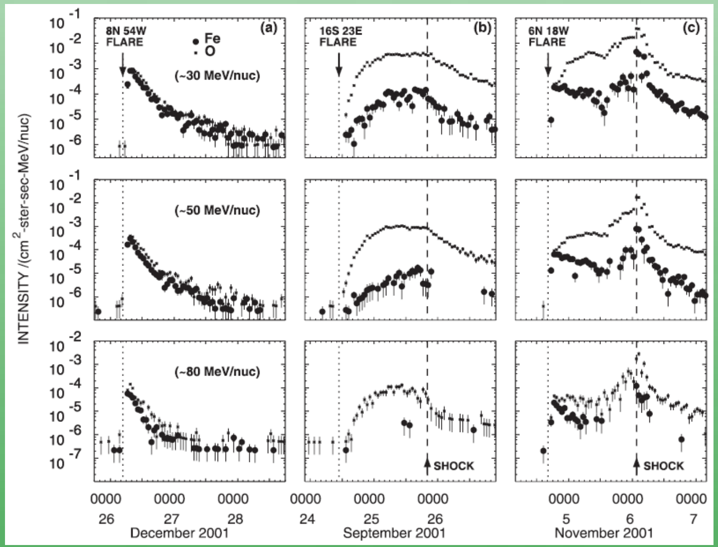
Suggested explanations for mixed composition in gradual SEP events:

1. shock acceleration of remnant suprathermal ions from previous impulsive SEP events or particles from associated flare (Mason et al. 1999; Tylka et al. 2005; Mewaldt et al. 2003; Tylka and Lee 2006)
2. Mixture of flare-accelerated particles and CME shock-accelerated particles (Cane et al. 2003, 2006)

Time Variation of Elemental Ratios—Flare or CME?



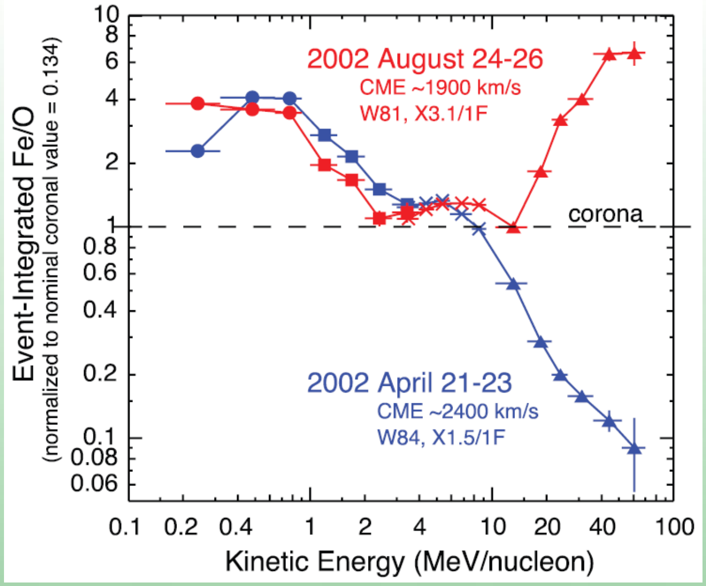
Tylka et al. 2006

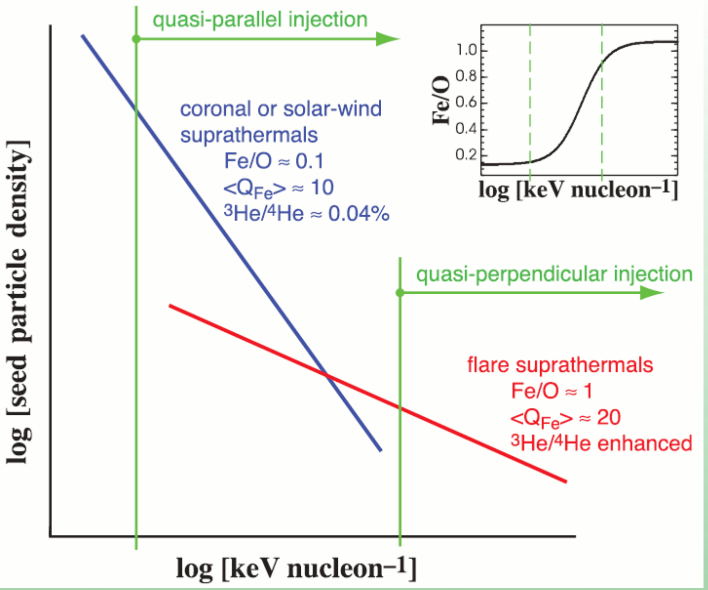


Cane et al. 2003

- Elemental ratios vary during SEP events (e.g. 1990Tylka et al. 1999)
- Cane et al. (2003) suggested that high Fe/O ratio at the beginning of the well-connected SEP events indicates direct flare particles
- Fe/O increase clear in well-connected events
- Ng et al. (1999) suggest that variation caused by transport effects: Q/M-dependent interactions with waves generated by escaping protons cause Fe ions (higher rigidity $R \propto M/Q$) to arrive before O ions, which are delayed by stronger scattering
- Different temporal behavior of F e/O and He/H ratios indicates that a dynamic wave spectrum generated by the streaming particles themselves is fundamental not scattering from background wave spectrum

Variation of High-Energy Fe/O Ratio in Gradual Events



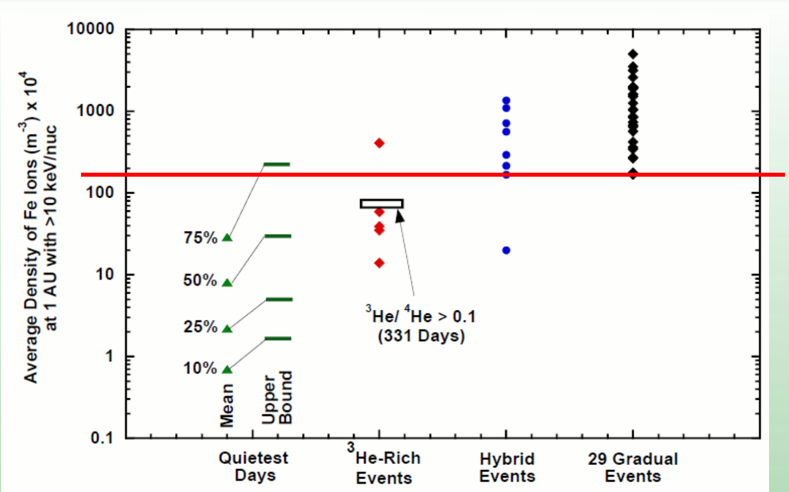


Two similar gradual SEP events but high-energy Fe/O varies dramatically
Variability due to **shock geometry** (quasi-parallel vs quasi-perpendicular) that affects the injection energy of particles. Therefore shocks accelerated seed particle populations with differing composition (Tylka et al. 2005; Tylka and Lee 2006)

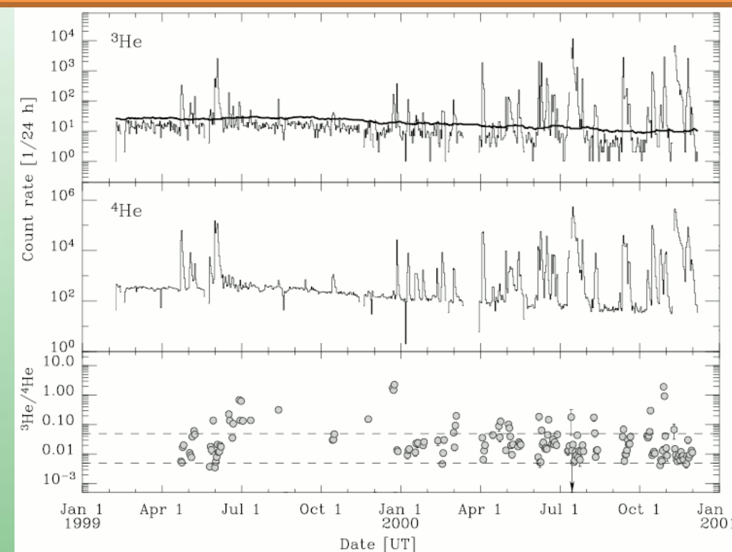
PROBLEM 1: Shock geometry unknown near the Sun

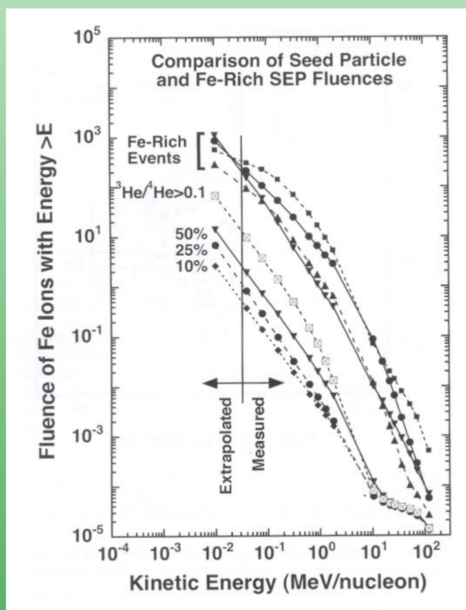
PROBLEM 2: Injection energy might not depend on shock geometry (Giacalone 2005)

Are There Enough Suprathermal Particles?



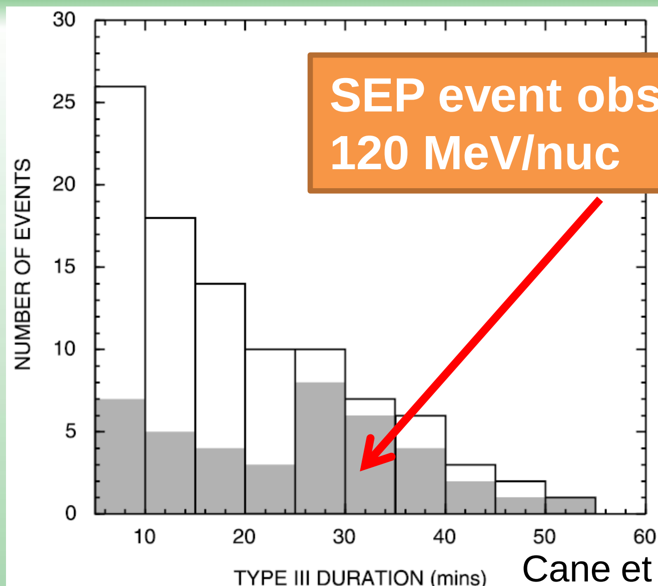
Periods of enhanced ^{3}He/^{4}He ratio are relatively common (Torsti et al. 2003, Wiedenbeck et al. 2003)





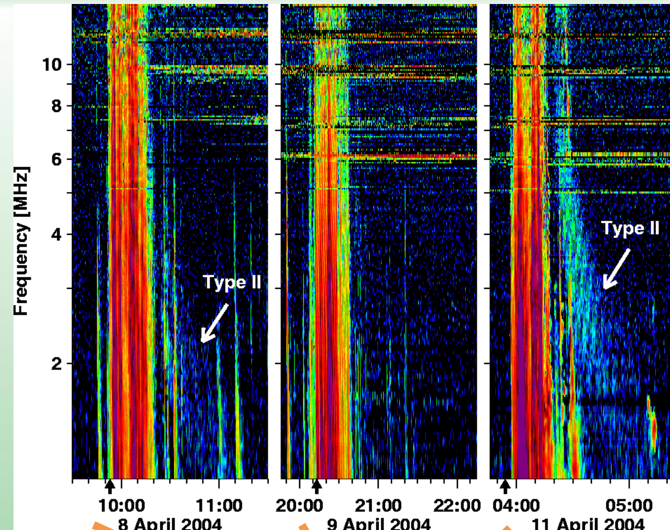
Mewaldt et al. (2003) estimated that there might not be enough suprathermal remnant particles available, another source is required (reaccelerated particles from CME-associated flare, <10 keV solar wind particles?, see also Mewaldt 2006)

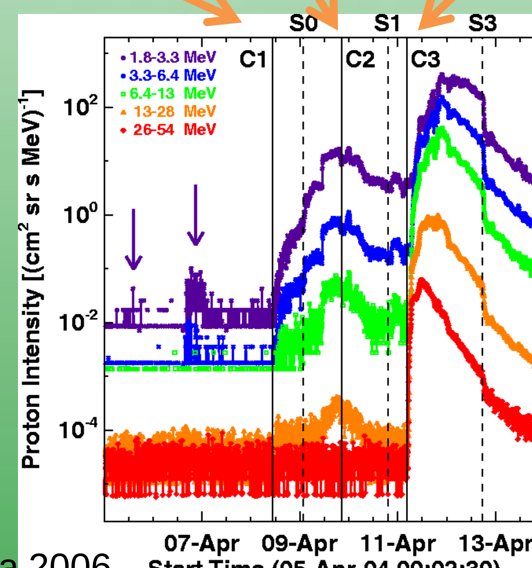
Direct Flare Particles and Type III Radio Bursts



SEP event observed above 120 MeV/nuc

Cane et al. 2002





Cane et al. (2002):

1. long-duration, low-lasting, low-frequency type III radio bursts associated with SEP events
2. Type IIIs indicate open magnetic field lines for electrons to escape, hence flare-accelerated ions have access to IP space too

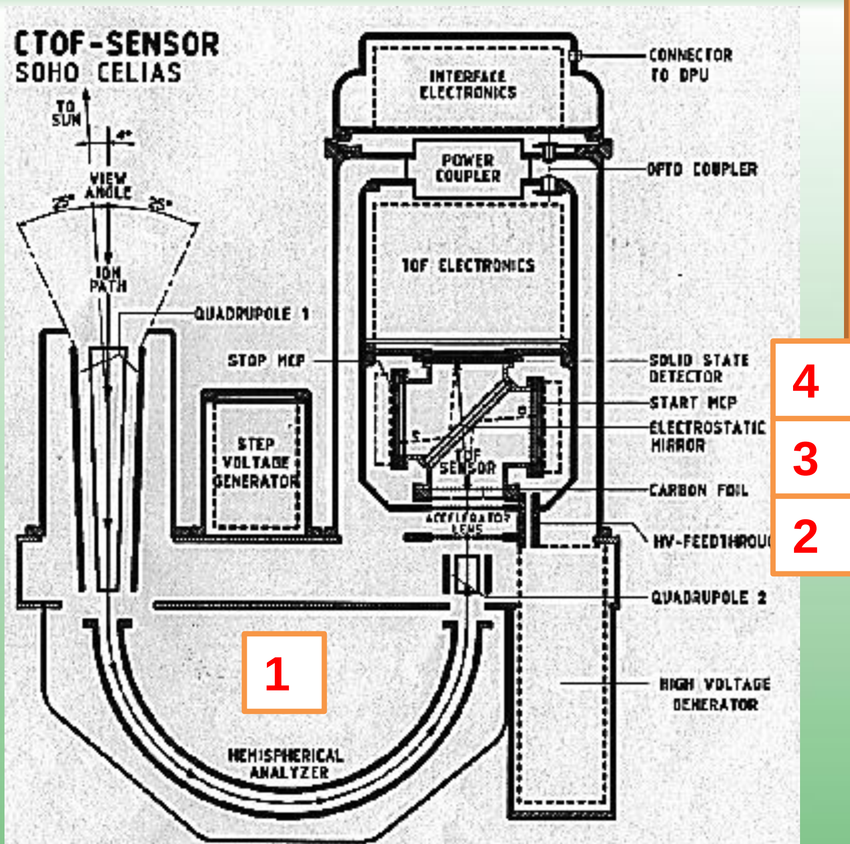
Gopalswamy & Mäkelä (2010) showed that SEPs produced only if type II burst is observed

Gopalswamy & Makela 2006

Summary

- Early observations resulted in the two-class paradigm of impulsive and gradual SEP events
- Recent observations of energy dependent charge states and impulsive-like particle populations during gradual SEP events indicate more complex SEP events.
- Electron stripping in low corona important for ionic charge states
- Suggested seed particle populations of gradual events include suprathermal remnant particles from previous flares accelerated selectively depending on shock geometry, direct flare particles, and reaccelerated particles from the CME-associated flare
- STEREO observations show perpendicular diffusion of particles but it’s not well understood

Electrostatic Deflection Time-of-flight



Incident ion (*E*, *q*, *m*):

1. Electrostatic deflector selects ions with (*E*/*q*), selection can be stepped
2. Acceleration by voltage V_a
3. TOF gives the time τ particle used to travel the distance *d*
4. Residual energy measurement gives the kinetic energy E_{res}

$$m = 2(\tau/d)^2 E_{res}$$
$$m/q = 2(\tau/d)^2 (V_a + bE/q)$$
$$q = E_{res}/(V_a + bE/q)$$
$$E = q(E/q)$$

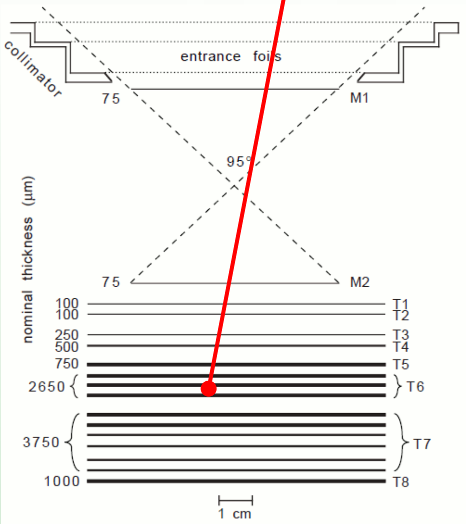
bE/q takes account a small energy-loss in the carbon foil

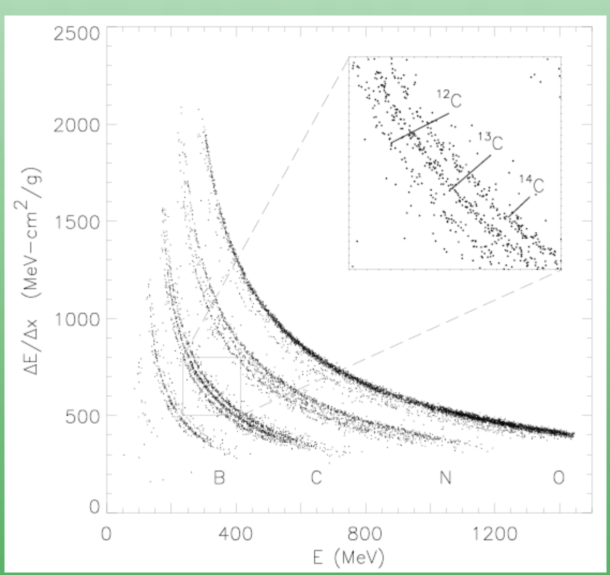
Technical limitations of high voltages used for the electrostatic deflection limit energies below a few MeV/nuc at most

dE/dx vs E Technique

$$dE/dx \approx \Delta E/\Delta x \propto Z^2 m/E$$

- Measure energy deposited in detector layers
- Particles must stop in the detector stack
- Anticoincidence detectors surrounding detector stack “veto” non-stopping particles
- Measure particle arrival direction using position sensitive detectors or restrict arrival directions by collimator to improve element/isotope resolution
- Commonly used detectors:
  - Solid-state silicon detectors (charge proportional to deposited energy)
  - Scintillators (light pulse proportional to deposited energy)





Stone et al. 1998

Data Resources

SOHO Data Archive: http://soho.nascom.nasa.gov/

- COSTEP: http://www.ieap.uni-kiel.de/et/ag-heber/costep/
- ERNE: http://www.srl.utu.fi/erne_data/main_english.html

ACE Science Center: http://www.srl.caltech.edu/ACE/

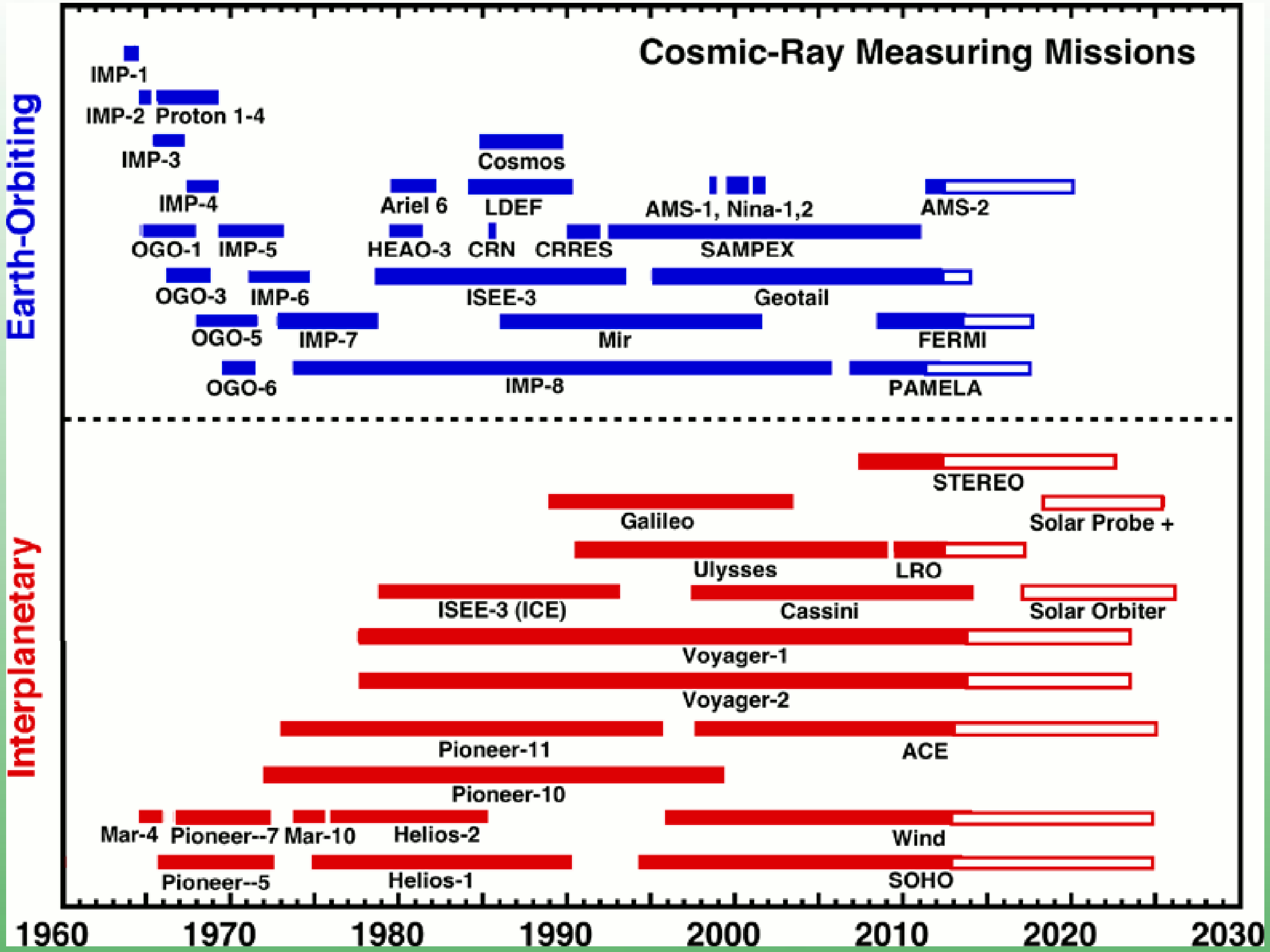
STEREO Science Center: http://stereo.gsfc.nasa.gov/

NEW Virtual Energetic Particle Observatory (VEPO): http://vepo.gsfc.nasa.gov/

Space Physics Interactive Data Resource (SPIDR): http://spidr.ngdc.noaa.gov

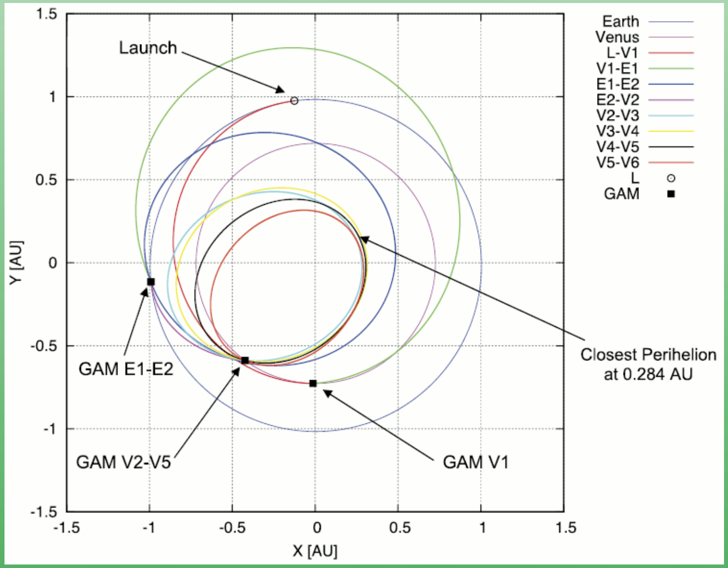
Read data caveats and papers describing instrument

Cosmic-Ray Missions



Mewaldt et al. 2012

Solar Orbiter
http://www.solarorbiter.org/



Launch date: Jan 2017 (Mar 2017 and Sep 2018 back-ups)

Nominal mission duration: 7 years (+3 years)

Closest perihelion: 0.28 AU

Max. latitude 25° (34°–36°)

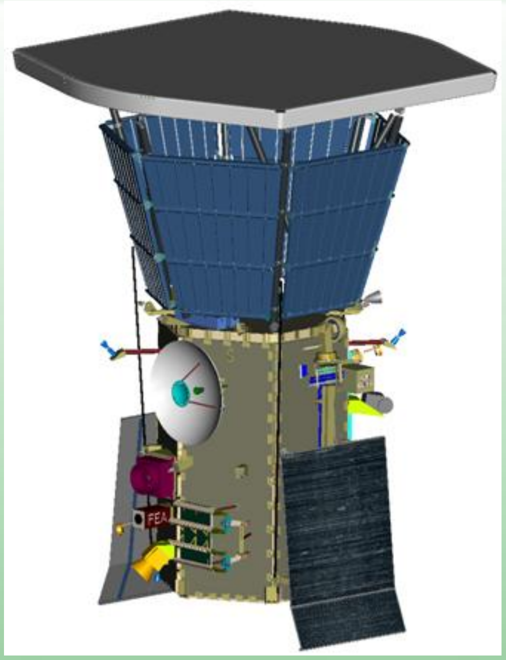
In-Situ Instruments:

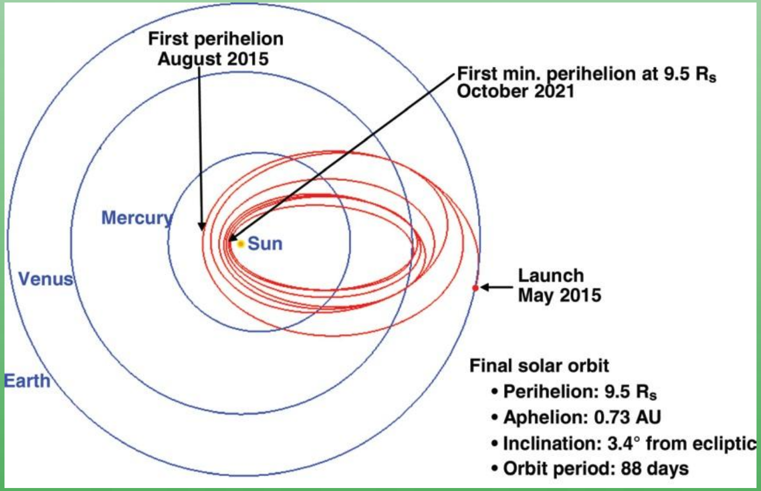
- Energetic Particle Detector (EPD)
- Magnetometer (MAG)
- Radio and Plasma Wave analyser (RPW)
- Solar Wind Analyser (SWA)

Remote-Sensing Instruments:

- EUV full-Sun and high-resolution Imager (EUI)
- Coronagraph (METIS)
- Polarimetric and Helioseismic Imager (PHI)
- Heliospheric Imager (SoloHI)
- EUV spectral Imager (SPICE)
- X-ray spectrometer/telescope (STIX)

Solar Probe Plus
http://solarprobe.jhuapl.edu/





Launch date: No later than 2018

Nominal mission duration: Will orbit the Sun 24 times

Closest perihelion: 9.5 solar radii (final three orbits)

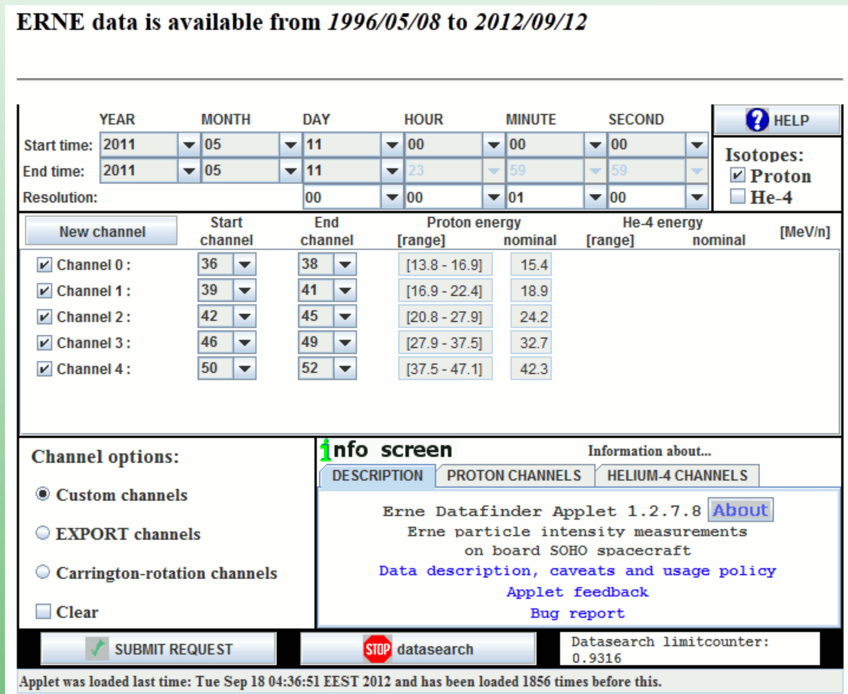
Science objectives:

1. Coronal heating and solar wind acceleration
2. Production, evolution and transport of solar energetic particles

Example of Velocity Dispersion Analysis

- http://www.srl.utu.fi/erne_data/datafinder/df.shtml
- Start time: 2001 May 11 00:00 UT
- End time: 2001 May 11
- Resolution: 1 Minute
- Select Isotope: Proton
- Click first Carrington-rotations channels, then Custom channels
- Set start and end channels numbers: 36-38; 39-41; 42-45; 46-49; 50-52
- Average energies should be now: 15.4; 18.9; 24.2; 32.7; 42.3 MeV

Example of Velocity Dispersion Analysis



- Click submit request and wait data window to open
- In data window select one channel at a time
- Zoom in on the onset by dragging a box around onset in the intensity plot until you see the separate data points
- Select data point where you think the event starts
- Draw a small box around the data point to change the time axis so that you can read the time

Example of Velocity Dispersion Analysis

- Calculate speed (m/s) of particles in each energy channel from the average energy of the channel:
  1 eV=1.60×10^{-19} J m=1.67×10^{-27} kg
- Select t_0 and calculate $(t_i - t_0)$ in seconds, where t_i is onset time in the energy channel i
- Fit data with line, i.e. $t_{obs} = a + b(^1/_v)$, where $a = t_{rel}$ is release time relative to t_0, b is the particle path length in meters
- You can use online fitting sites like http://www.alcula.com/calculators/statistics/linear-regression/
  - First line space separated list of X-values $(^1/_v)$
  - Second line space separated list of Y-values $(t_i - t_0)$
- Change unit: $s = \frac{b}{1.5\times10^8}$ [AU]
- If you want to compare t_{rel} to electromagnetic radiation shift it 8.3 min (~500 s) later

Example of Velocity Dispersion Analysis

t_{obs} [UT]	t_i-t_0 [s]	E [MeV]	v [10^7 m/s]	1/v [10^{-8} s/m]
03:46:30	32*60	15.4	5.4	1.8
03:38:30	24*60	18.9	6.0	1.7
03:28:30	14*60	24.2	6.8	1.5
03:27:30	13*60	32.7	7.9	1.3
03:14:30	0*60	42.3	9.0	1.1

$y = -2648 + 2.462\times10^{11}x$
$s = 2.462\times10^{11}/1.5\times10^{11}$ AU = 1.64 AU
t_{rel}= 02:30:30 UT (~44 min before t_0)
t_{rel} + 8.3 min = 02:38:30 UT
LASCO CME catalog:
CME observed 02:48 UT , 745 km/s