SEP observations

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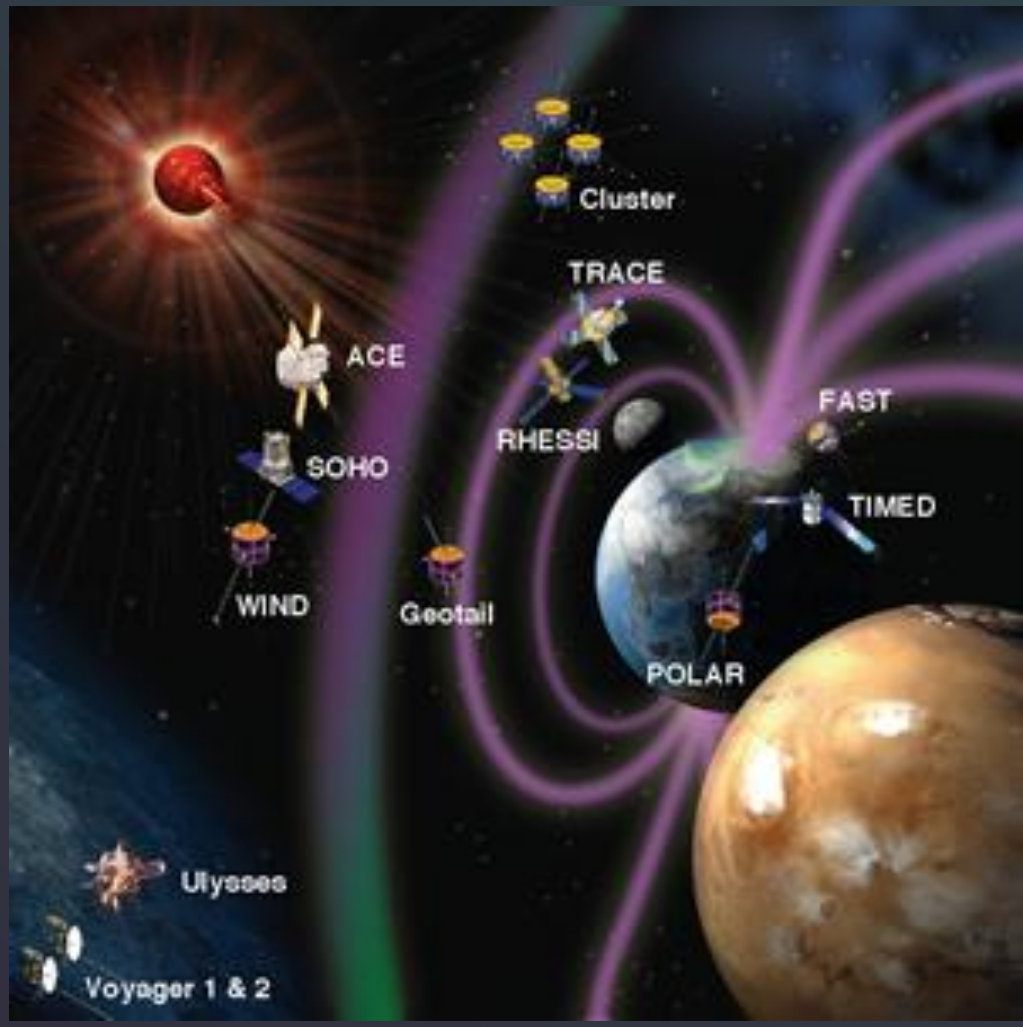
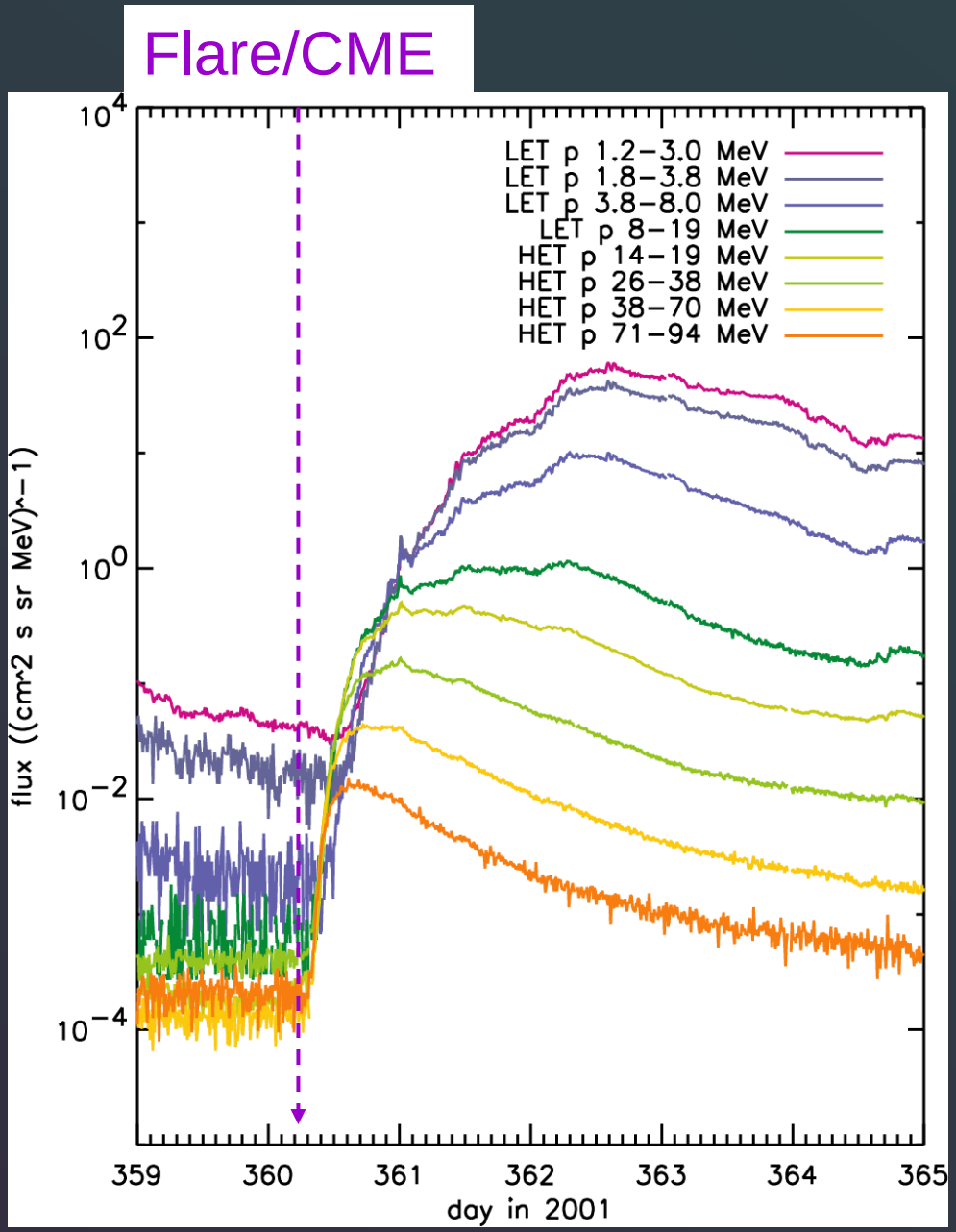
Outline

- SEPs and key observables
- Issues in data analysis
- 2-class low-scattering paradigm
- Challenges from modern observations
- Conclusions



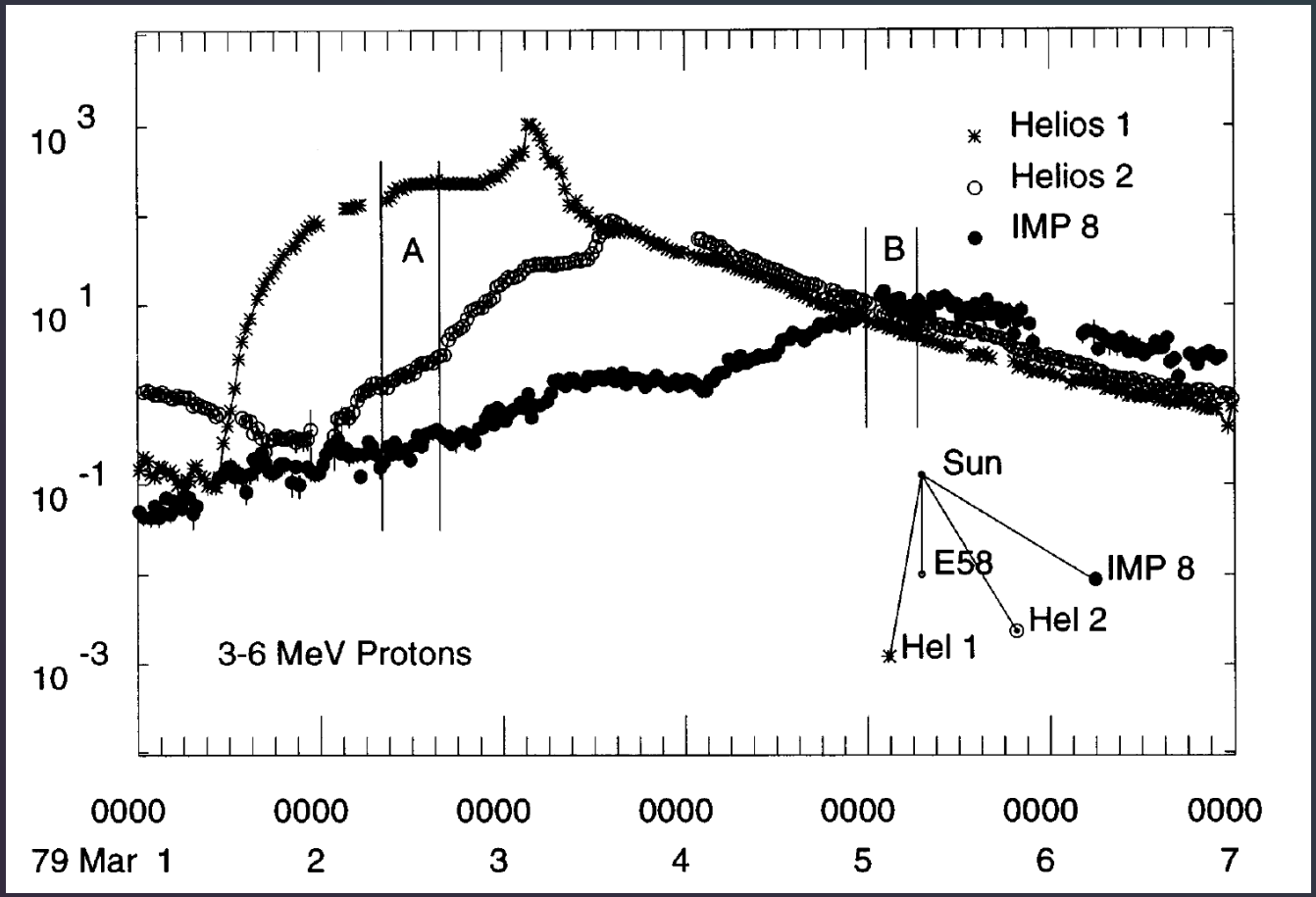
SEP events

- Solar Energetic Particles (SEPs) = the particles accelerated during flares/CMEs that reach a detecting spacecraft in interplanetary space
- Particles include electrons, protons and many ion species including He, O, Fe
- Injection characteristics are not well known



Observables: (1) Intensity profiles

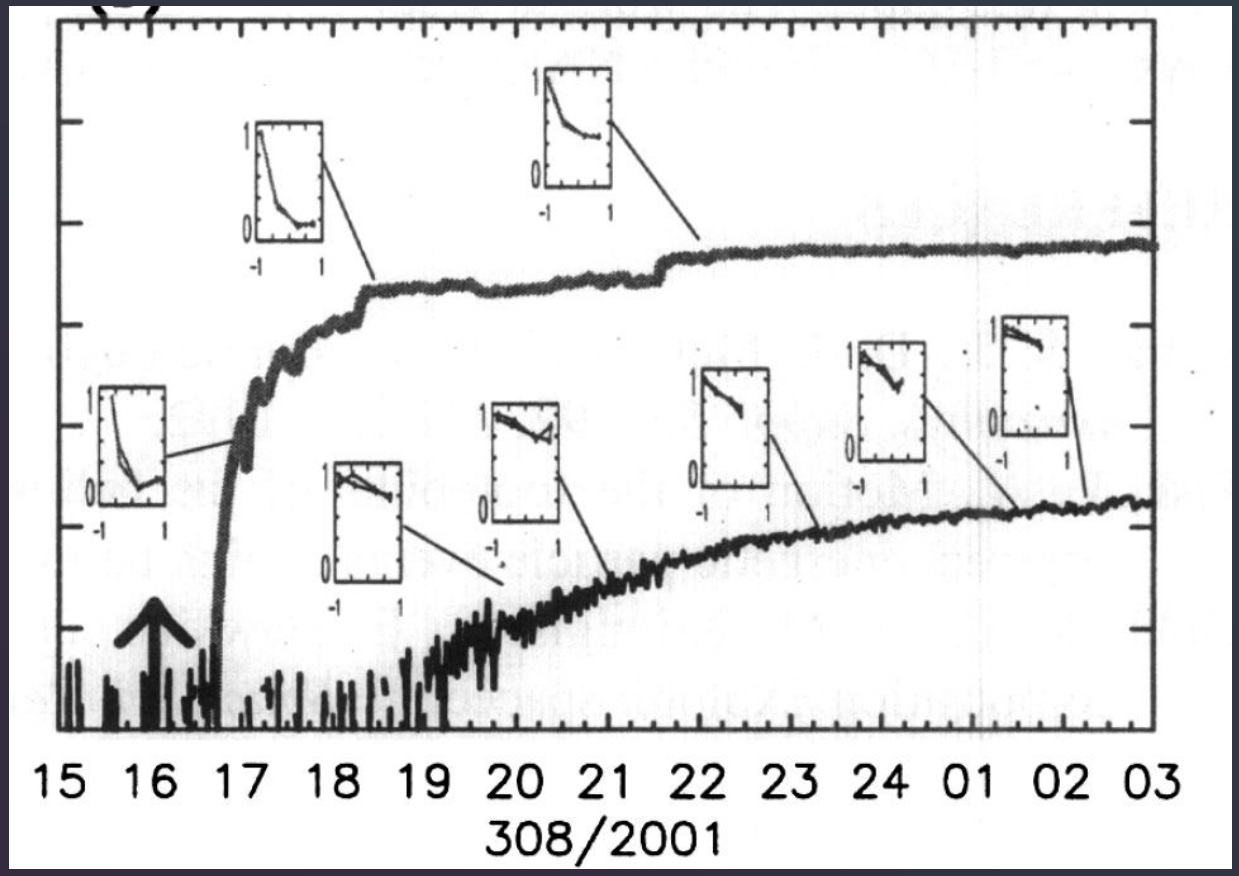
- Particle intensities vs time for a variety of energy channels and particle species
- Multi-spacecraft observations of the same event



Reames et al 1997

Observables: (2) Pitch-angle distributions

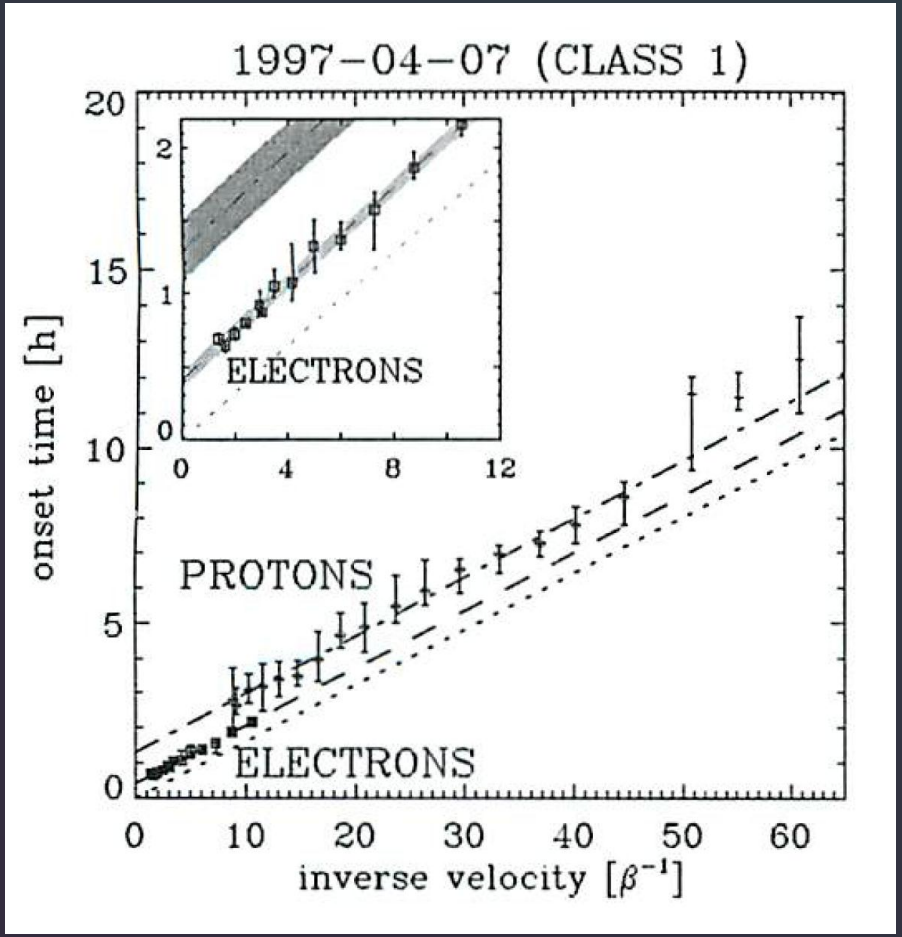
- Multidirectional telescopes / spinning spacecraft, together with magnetic field information
- Directionality expressed as pitch-angle distributions or anisotropies



Lario et al, 2003

Observables: (3) Onset time analysis

- Onset times vs $\beta^{-1}=c/v$
- If propagation is scatter-free, can provide solar release time



Krucker & Lin, 2000

Issues in data analysis

- SEP observables result from the combined effect of:

  (a) acceleration mechanism – injection profile (spatial and time characteristics, spectrum, composition; flare vs CME shock)

  (b) interplanetary transport (structure of IMF, turbulence)

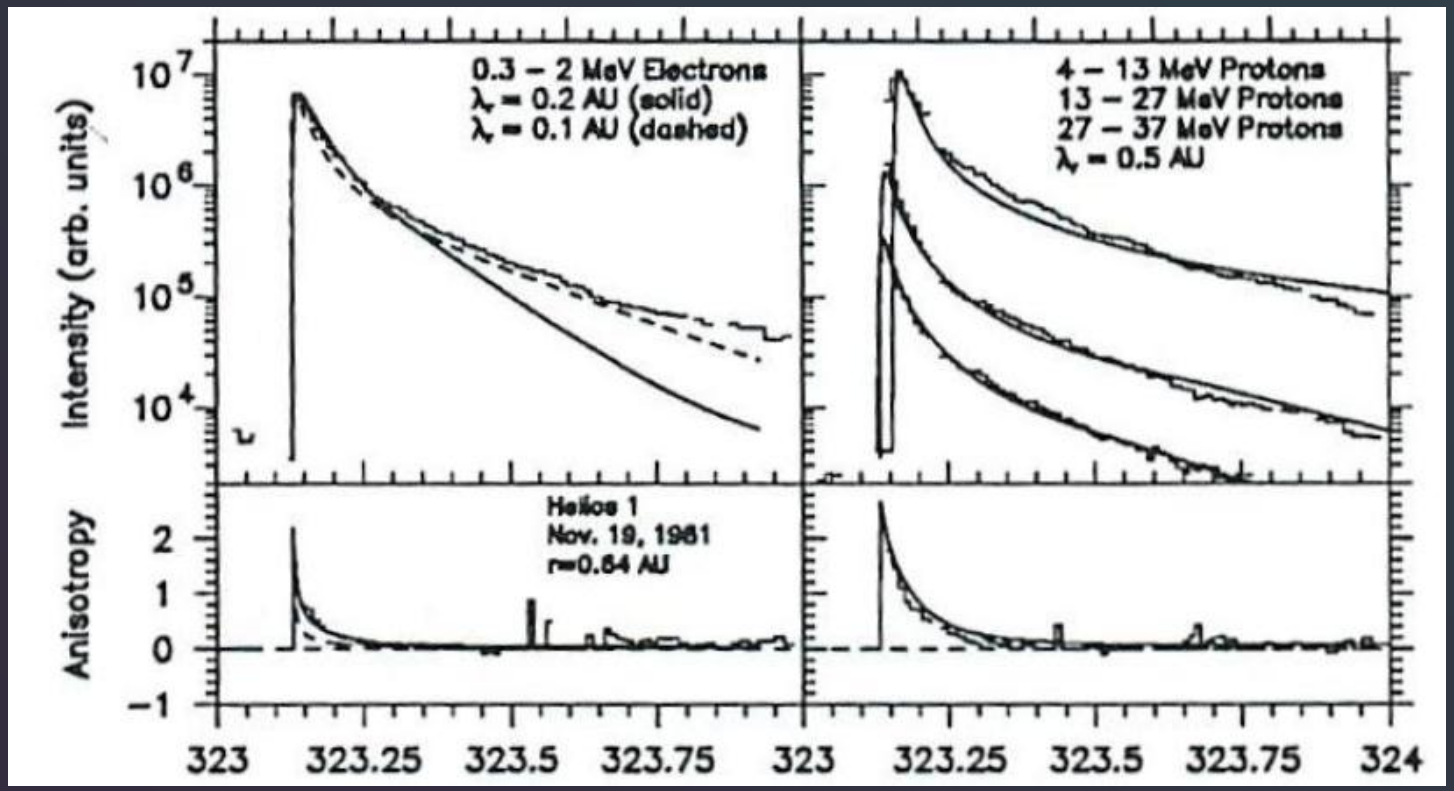
  (c) instrumental detection

- Different models/interpretations tend to assign different weighting to (a) and (b)

Early interpretations
and
2-class paradigm for SEP events

Early interpretations

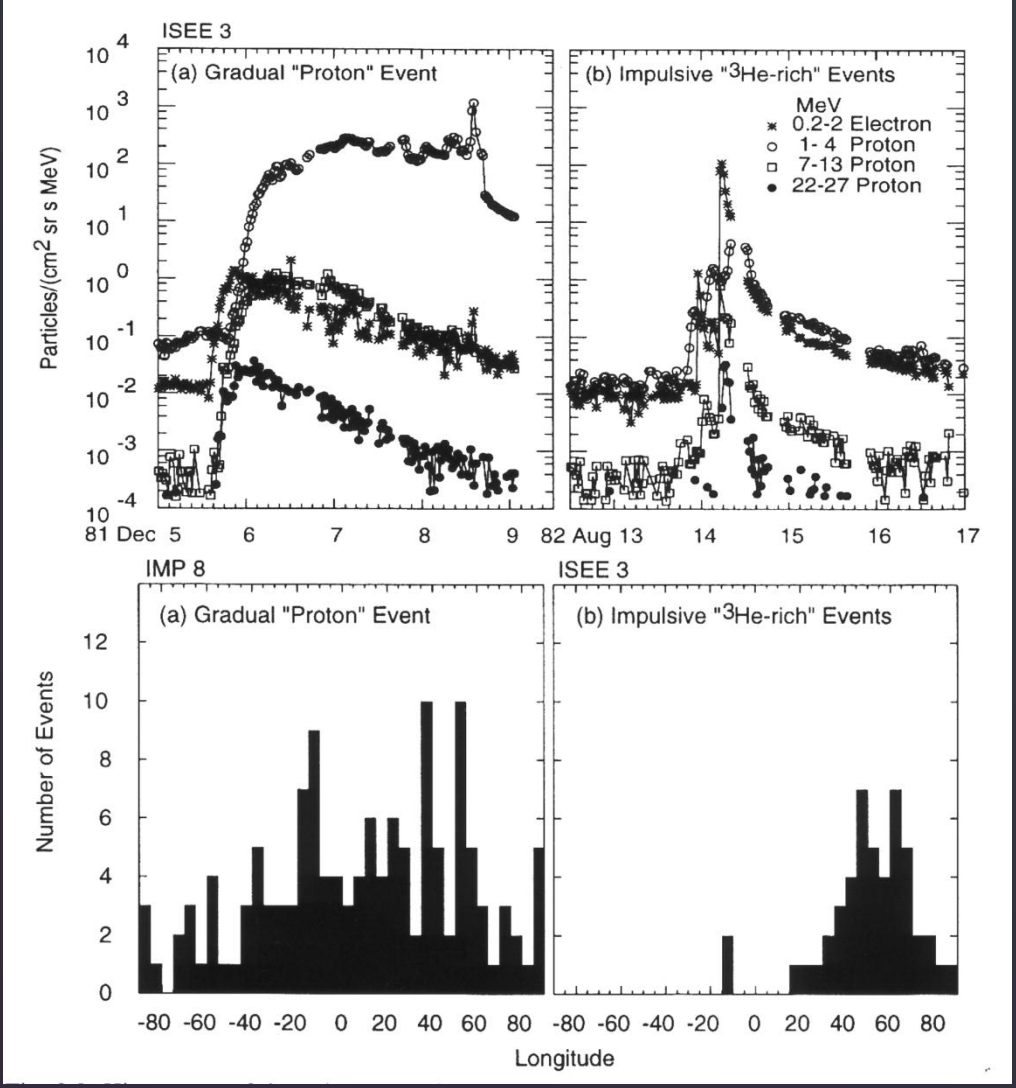
- SEPs propagate from localised source at the Sun through IMF with strong scattering (λ~0.1 AU)



Kallenrode, 1993

2-classes of SEP events?

- Gradual vs impulsive SEP events

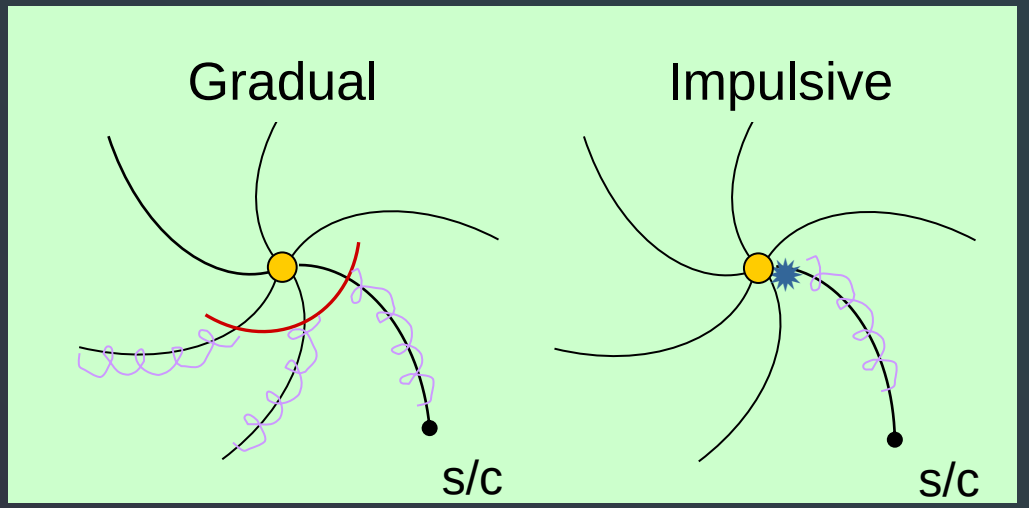


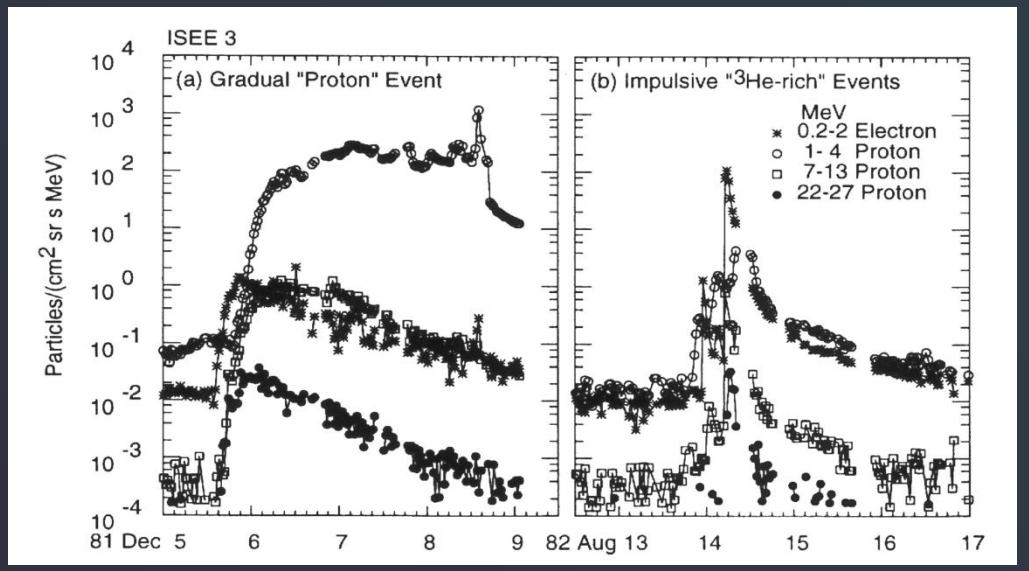
	Gradual	Impulsive
Event duration	days	few hours
Electron/proton	low	high
He 3 / He 4	coronal	coronal*1000
Longitude of solar event	any	W20-W90
Fe/O	coronal	coronal*10
Fe mean charge	15	20
Source of particles	***CME shock***	***Flare***

Reames, 1999

2-class low-scatter paradigm

- Wide spread in longitude results from extended source: travelling CME-driven shock
- Two types of SEP events: impulsive $\leftrightarrow$ flare reconnection gradual $\leftrightarrow$ CME shock acceleration
- In this model, SEP profiles are shaped mostly by acceleration process and the role of propagation is minimal $\lambda_{||}$~1 AU



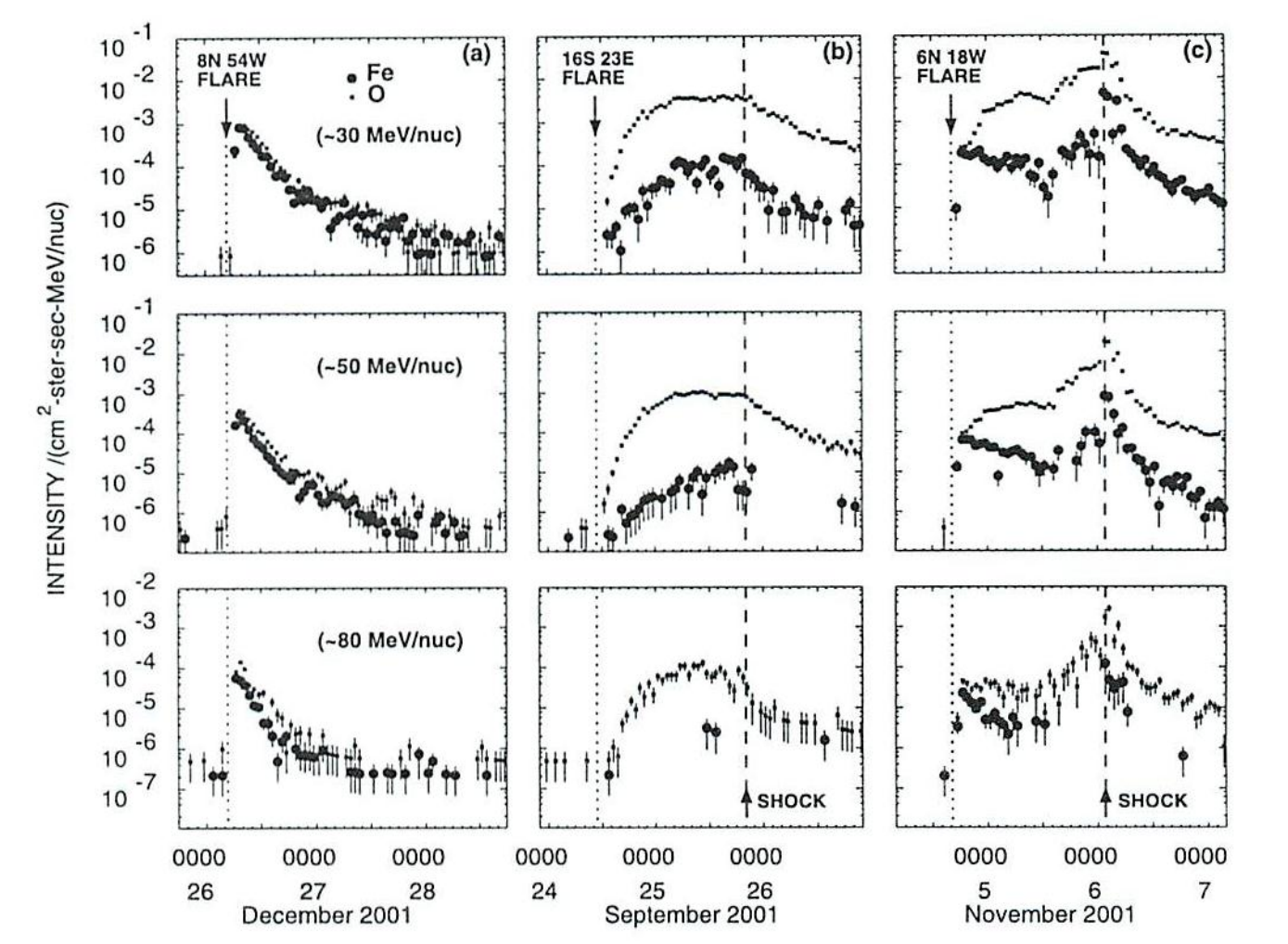


Reames, 1999

Challenges to 2-class low scattering paradigm

Composition

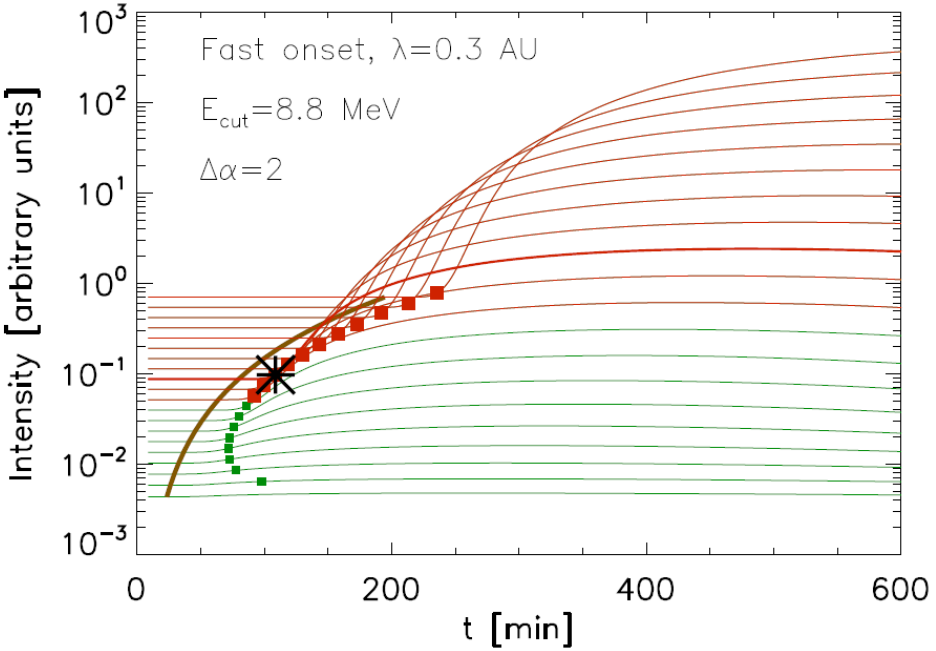
- Difference in composition between impulsive and gradual is not clear-cut

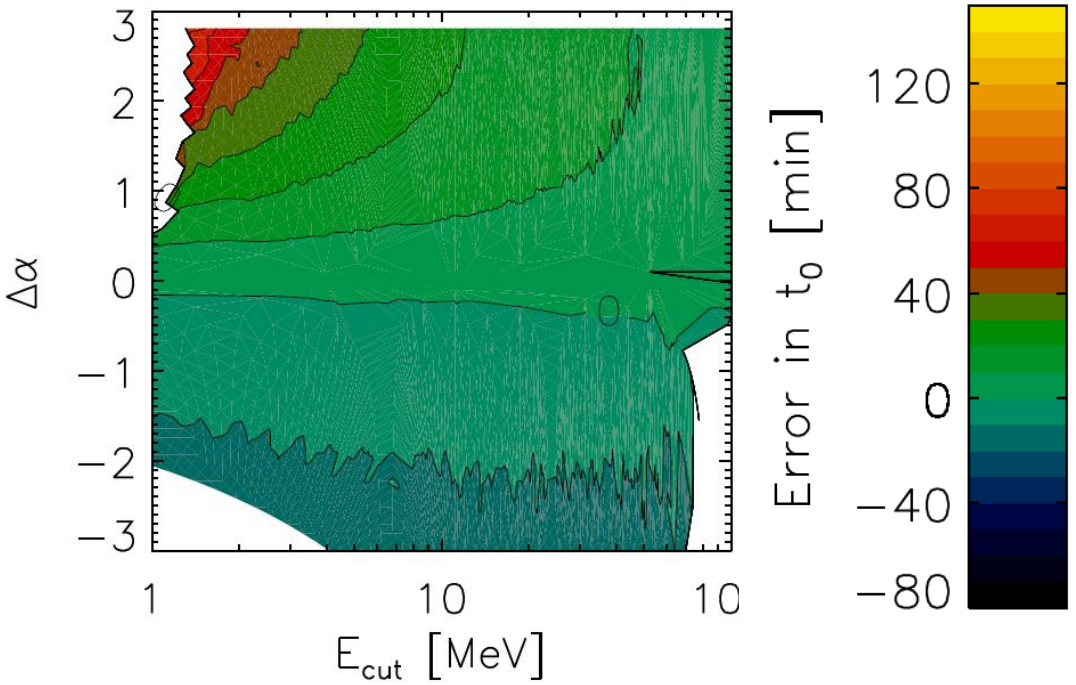


Cane et al, 2003

Onset analysis

- A good linear fit to c/v plot does not imply scatter free propagation (Saiz et al 2005)
- Pre-event background can cause large errors in the determination of release times from c/v plots

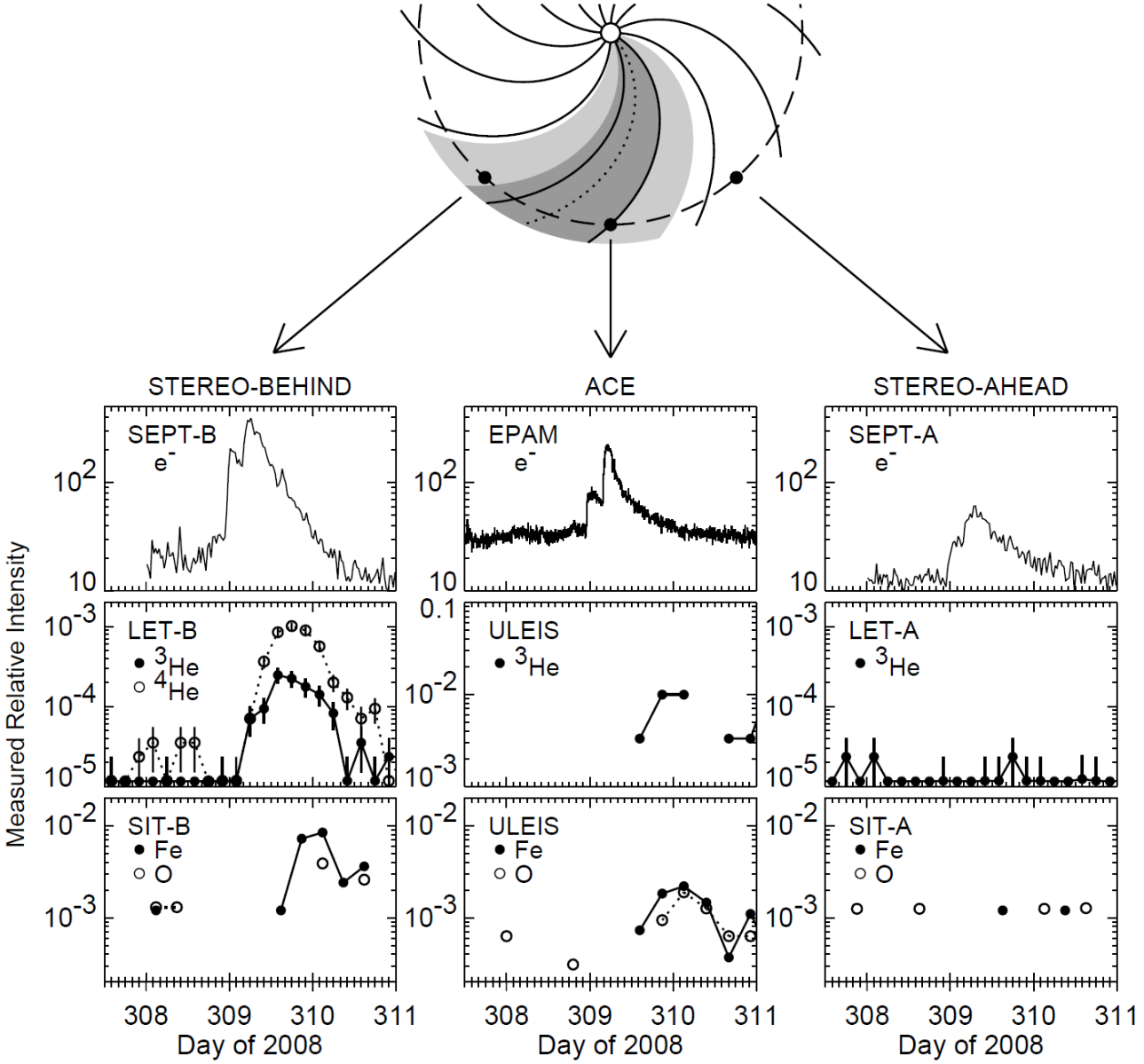




Laitinen et al, 2010

Electrons: longitudinal spread

^{3}He rich event. STEREO A and B separation is 82°.

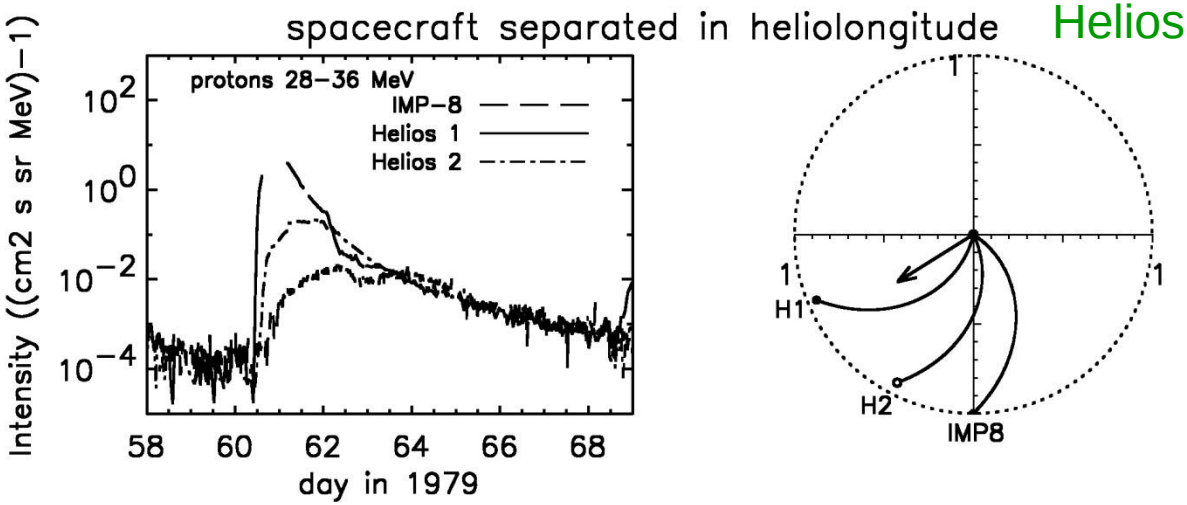


- Longitudinal extent of 'impulsive' flare associated event is larger than previously thought

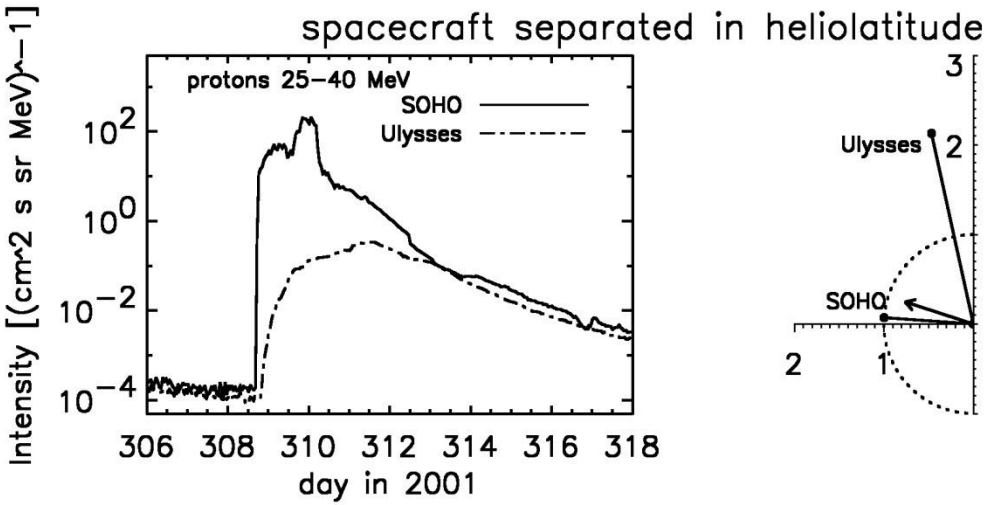
See also talk by Dresing et al.

Wiedenbeck et al, 2010

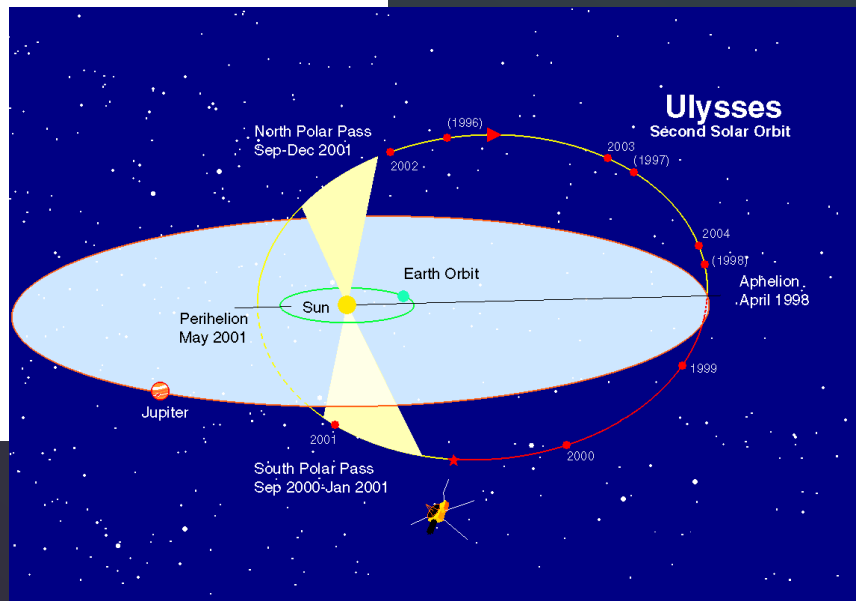
High heliolatitude observations



Helios 1 and 2

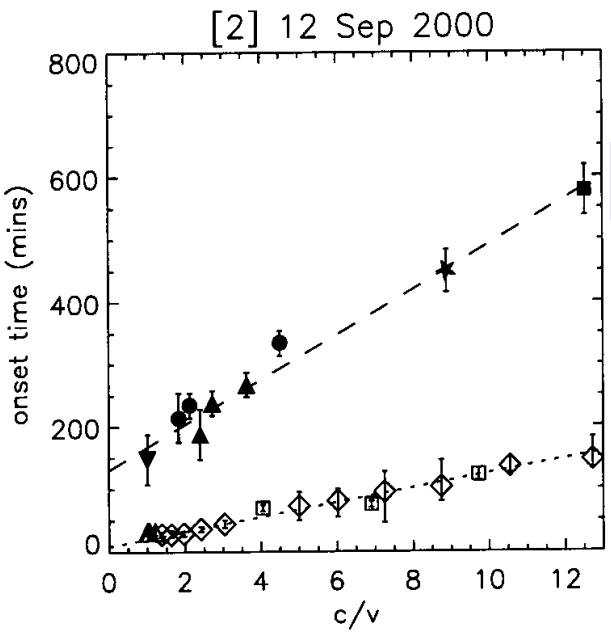


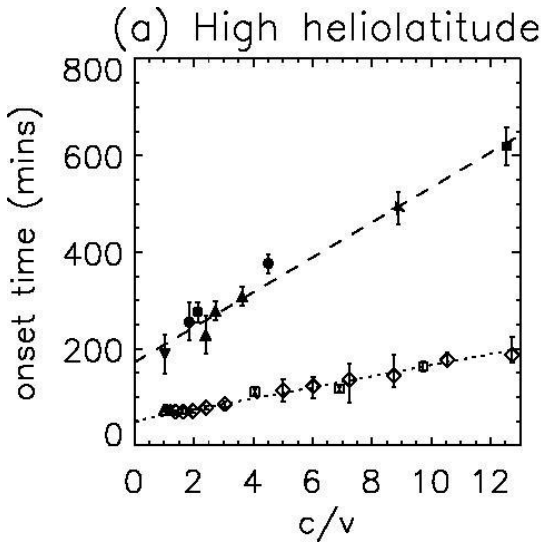
Ulysses

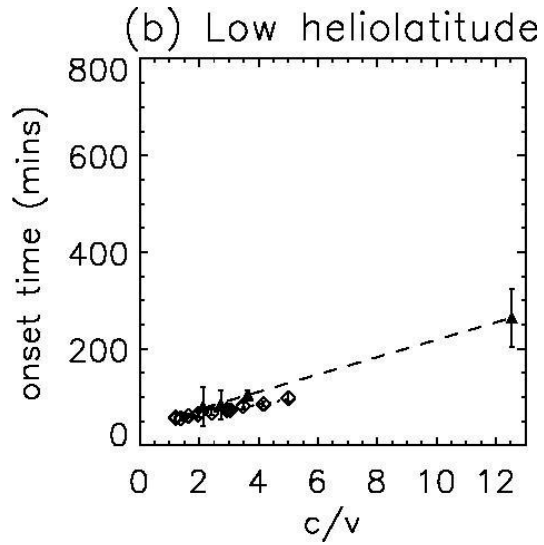


Arrival times to high heliolatitudes

- Study of 9 large SEP events at high heliolatitudes
- Arrival times are consistently much later than to a near-Earth s/c (by 100s of minutes)







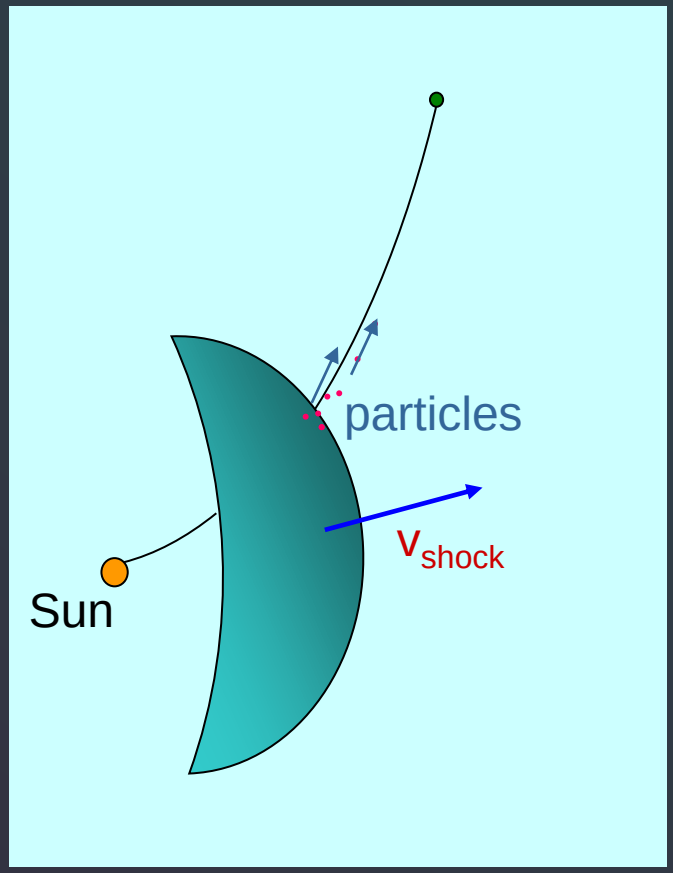
Dalla et al, 2003a

Ulysses data and CME shock acceleration

A) Particles released later to high heliolatitudes

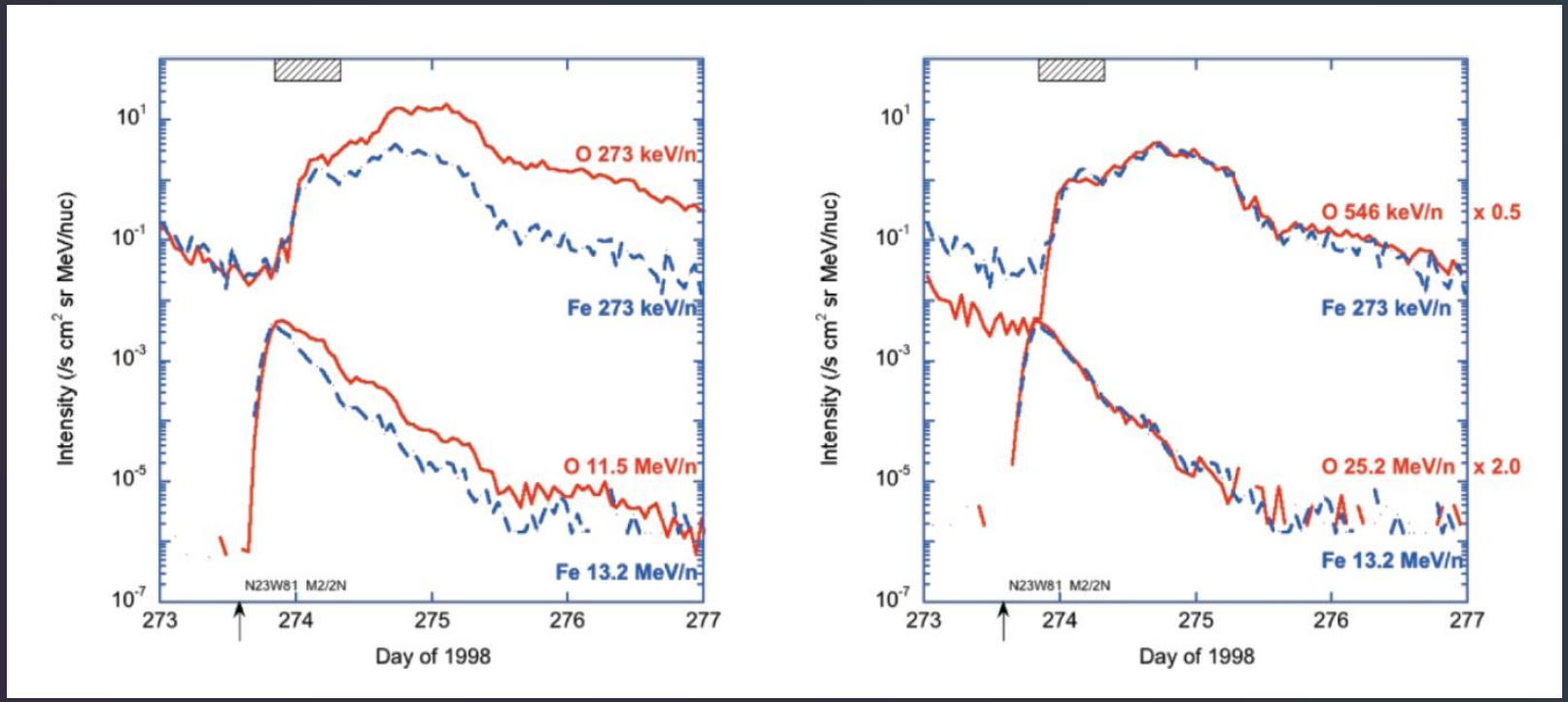
- A shock was observed at Ulysses only in 3/9 events
- No correlation with 1 / v_{CME}
- Times to max are not consistent with shock acceleration model (Dalla et al 2003b)

B) Particles need to scatter to reach field lines to Ulysses – transport across the field



Evidence for scattering

- Compare Fe intensity with that of O at higher kinetic energy per nucleon
- Cannot be explained in a scatter-free scenario



Mason et al, 2006

Summary

- A wealth of SEP data in the 3D heliosphere exists, with new missions such as STEREO providing essential multi-point views
- A number of questions regarding acceleration and propagation remain unresolved (role of flares vs CMEs, scattering properties…)
- Distinction between impulsive/gradual events is becoming less clear cut (eg ^{3}He rich events with large longitudinal spread)
- Clarifying the role of transport (including perpendicular) is a key issue in SEP studies