The Third Class of Solar Energetic Particles

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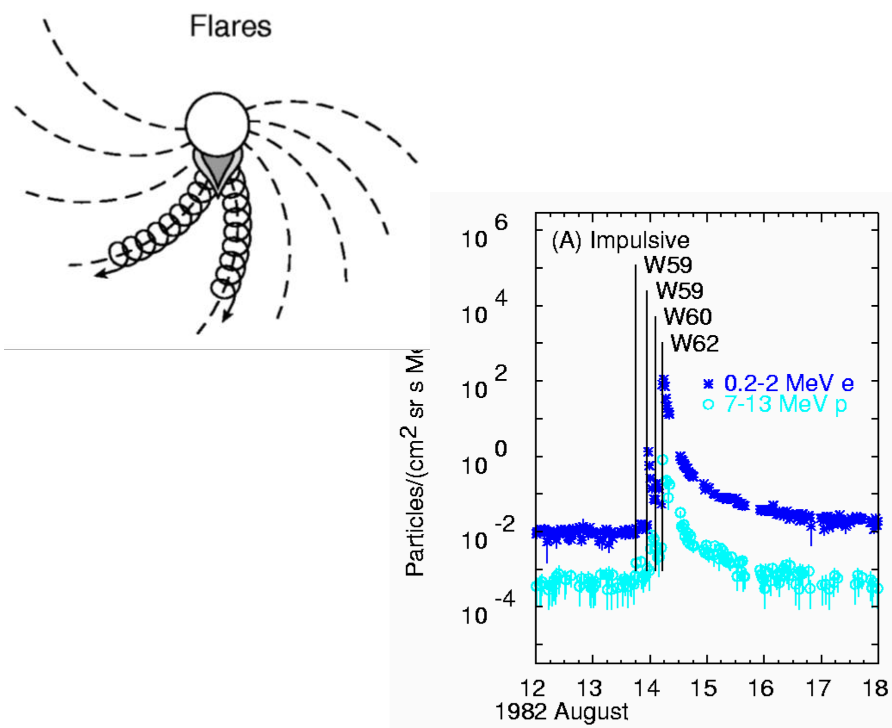
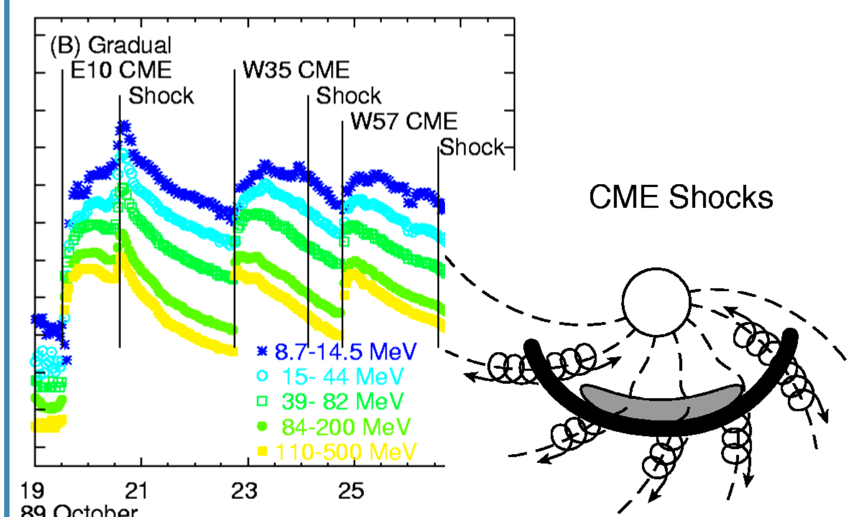
Conventional Classification of SEPs

- **Impulsive events**
  - Associated with impulsive Hα and X-ray flares or jets and mostly occurred in the western region.
  - Short durations (~several hrs).
  - Electron-, 3He-rich events



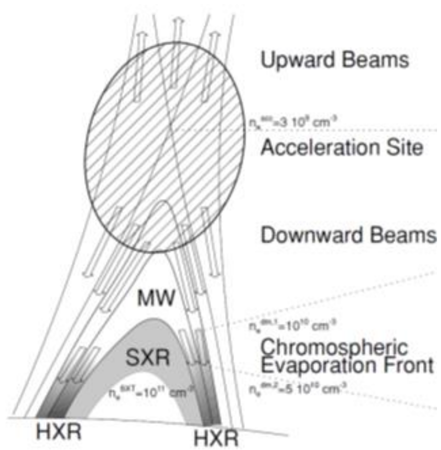
- **Gradual events**
  - Associated with fast CMEs and occurred in broad range of longitude.
  - Long durations (~several days).
  - Proton-rich, and normal coronal abundance and charge states corresponding to typical quiet coronal temperatures.

Reames (1999)

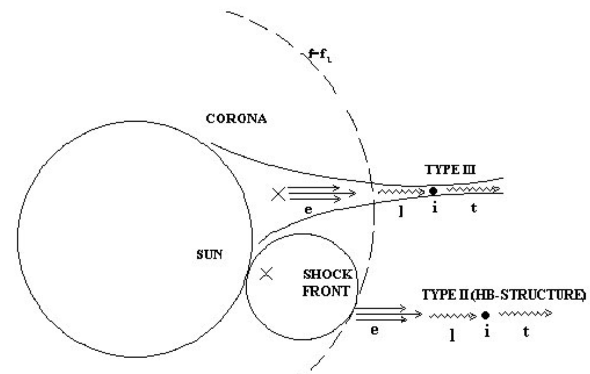


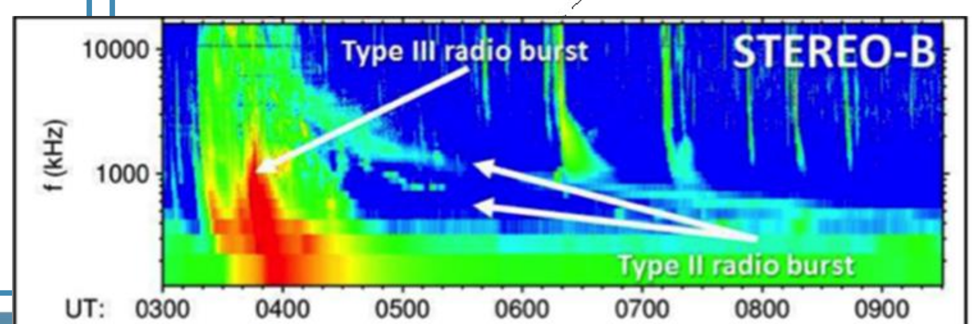
Conventional Classification of SEPs

- **Impulsive events**
  - Magnetically well-connected events with type III radio bursts
  - Type III bursts: Ideal tracers of the escape of energetic electrons (Reames, Dennis, Stone, & Lin).
  - Flare-accelerated particles were likely able to escape from the corona when microwave bursts occurred with simultaneous type III bursts



- **Gradual events**
  - Type II and type IV radio bursts.
  - IP shock theory –self-amplified waves (Lee, 1983)
  - Large SEP events 96% associated with CMEs (Kahler et al., 1984)
  - SEP intensities correlated with CME speed (Kahler, 2001)



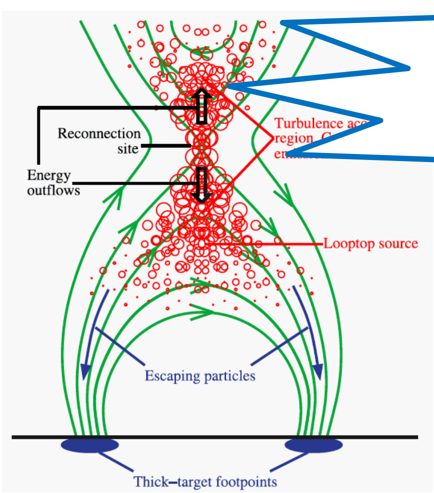


Acceleration Patterns according to Related Mechanisms

- **In the flare sites**
  - Magnetic reconnection in solar flare
  - Rapid acceleration of particles to high energies within short timescale (Miller et al., 1990)
  - → Acceleration starts from the lower energy.

- **In the CME-driven shocks**
  - Fast mode MHD shocks formed by CME
  - Gradual acceleration in which energetic particles are dominant in the initial stage, and low energy particles arise later as the shock propagates further into the solar wind (Zank et al., 2000).
  - → Acceleration starts from the higher energy.

Acceleration patterns are opposite to each other.



Liu 2013

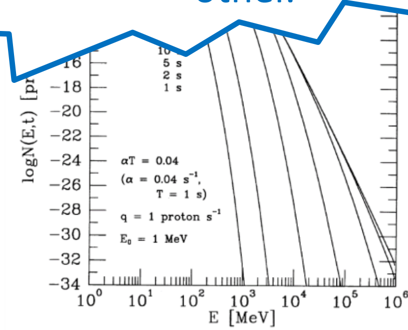
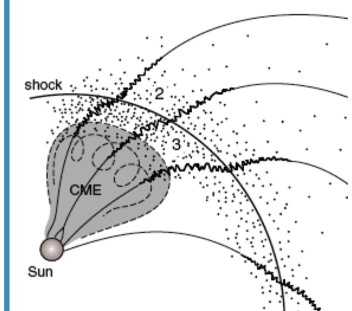


FIG. 4.—Proton energy spectra at various times t after the start of a continuous injection pf protons at energy E_0, showing the approach to equilibrium. Here $\alpha T_{esc} = 0.04$ with $\alpha = 0.04\ s^{-1}$ and $T_{esc} = 1$ s. The lowest curve corresponds to $t = 1$ s, and the highest curve corresponds to $t = 50$ s.

(Miller et al., 1990)



Lee 2005

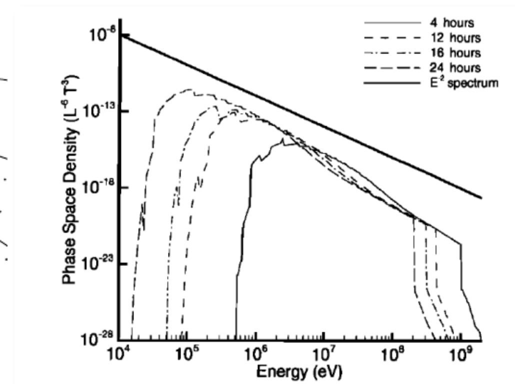


Figure 11. Particle distributions observed at 1 AU, at different times, prior to the shock arrival. Time is measured with respect to the initiation of the shock at 0.1 AU. An E^{-2} spectrum is included to guide the eye.

(Zank et al., 2000)

Acceleration Patterns according to Related Mechanisms

- **Acceleration mechanisms and condition**
  - Reconnection or MHD shock
- **Key factors to determine the strength of SEPs**
  - Strength of related solar eruptive event
    - ✓ Flare intensity and source location
    - ✓ CME angular width and expanding speed

- **Our approach**
  - Time sequence of related phenomena
    - ✓ Flare peak time, CME appearance time, type II radio burst
  - Acceleration patterns
    - ✓ Proton flux

Velocity Dispersion Analysis

Multi-channel energy evolution

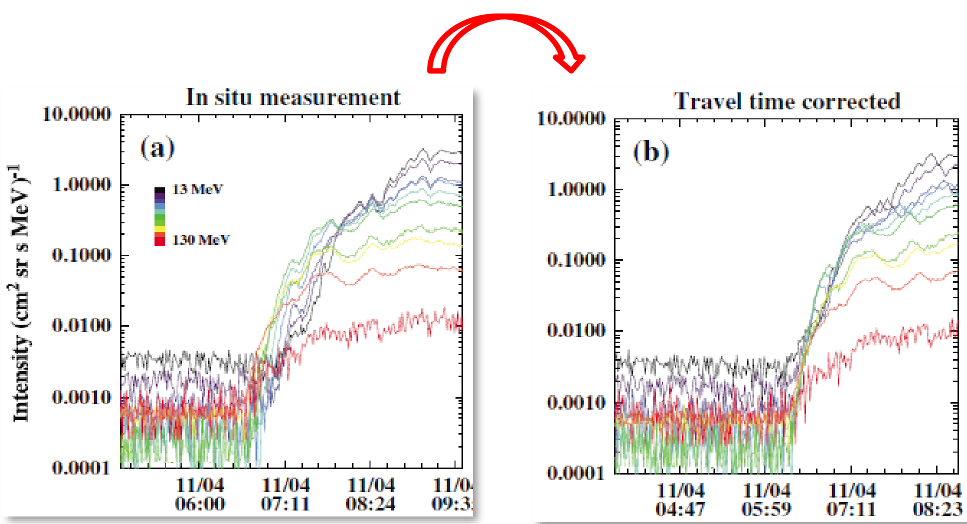
→ Analysis of onset timing and energy evolution for corresponding events

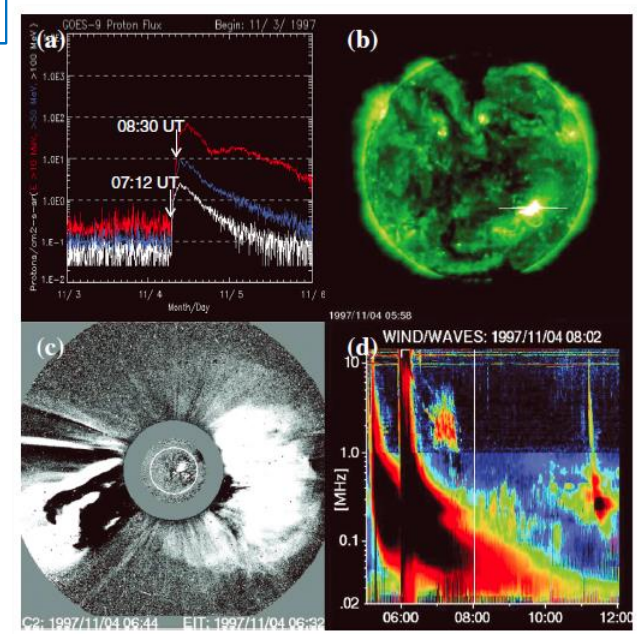
Refined Classification of SPEs (Kim et al., 2014)

- **Data and methods**
  - 42 SPEs observed with SOHO/ERNE multi-energy channel detector from 1997 to 2012
  - Velocity dispersion analysis: estimation of the SPE onset times at the solar vicinity
  - Onset time comparison: SPEs, and associated flares, CMEs, and type II radio bursts.

$$t_{onset} = t_{obs} - t_{tr} + t_c$$

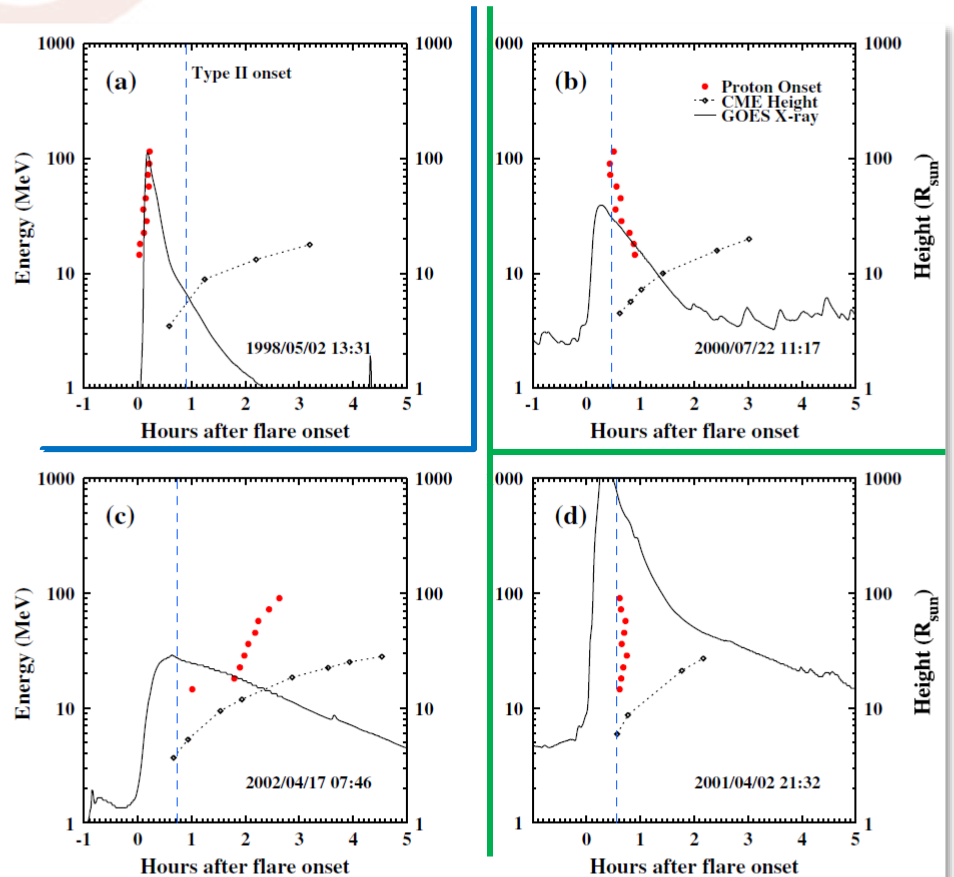
t_c → 8.3 min
L → Path length (Magnetic-field-line length)
v → Proton velocity corresponding each energy channel
$t_{tr} \propto \beta^{-1} = \frac{c}{v} \rightarrow t_{tr} = t_c$, where v=c

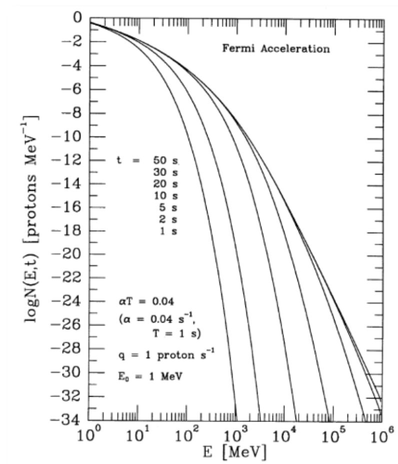


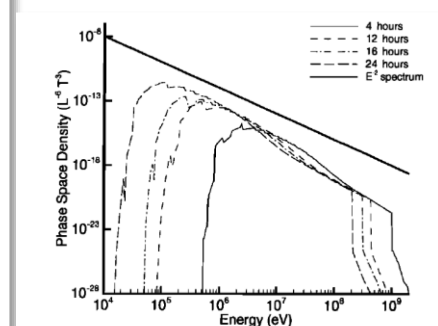


Refined Classification of SPEs (Kim et al., 2014)

- **SPE classification by two criteria of**
  - SPE onset timing relative to flare peak time
  - Flux enhancement sequences ($T_H - T_L$) according the energy levels



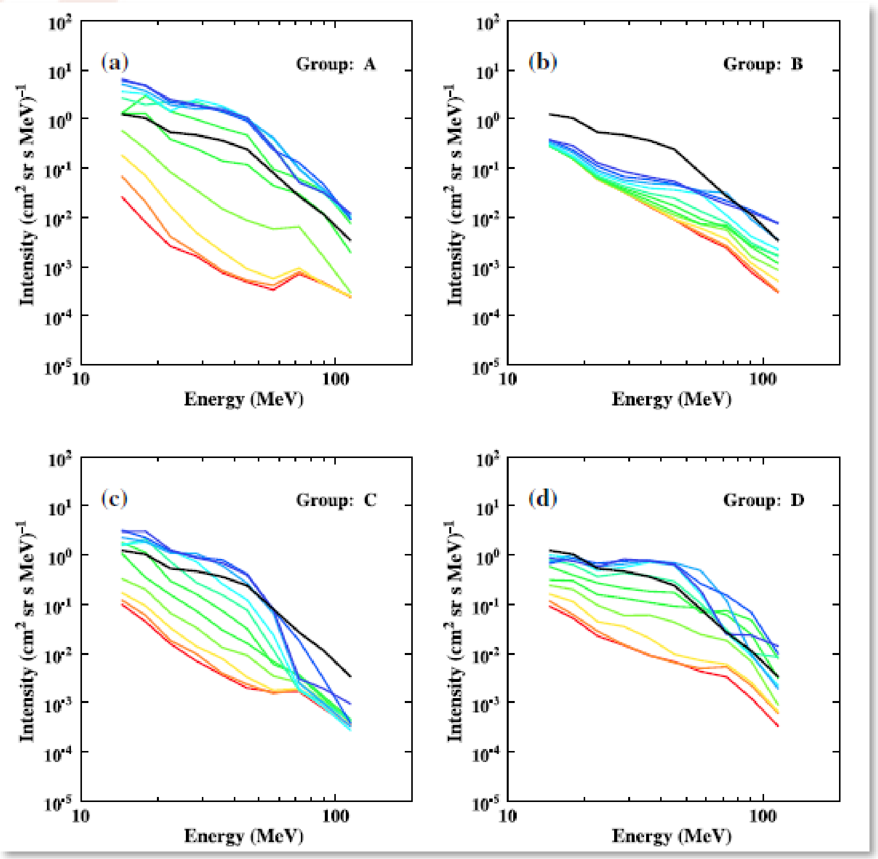




Group	Event #	Association	Acceleration: Direction	Acceleration: $T_H - T_L$ (Average)
A	13 (31%)	Flare	Low → High	17 min
B	13 (31%)	CME	High → Low	−26 min
C	9 (21%)	CME	Low → High	35 min
D	7 (17%)	CME	Simultaneous	−1.8 min

Refined Classification of SPEs (Kim et al., 2014)

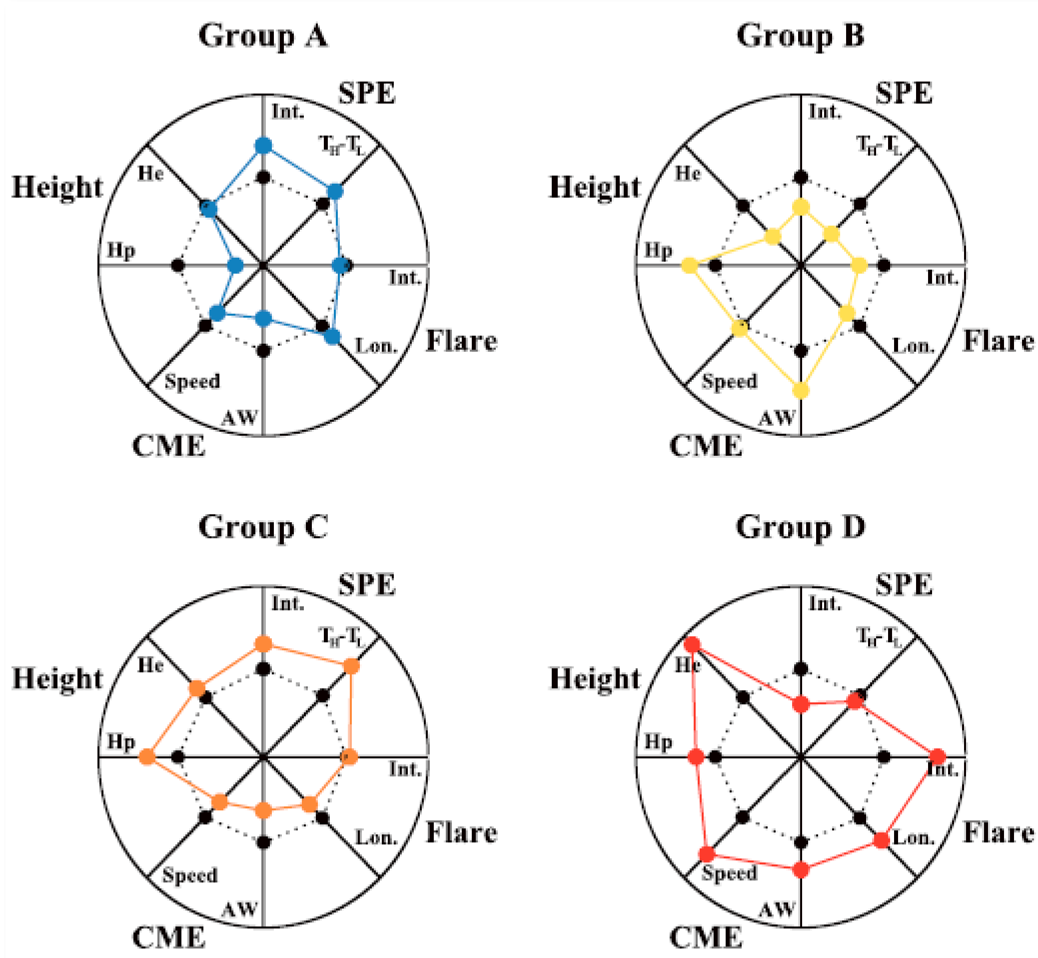
- **Dominant enhancement in energy evolutions**



Group	Event #	Association	Energy Spectrum: Dominant Energy Band	Energy Spectrum: Enhancement
A	13 (31%)	Flare	Low and Middle	$\sim 10^4$
B	13 (31%)	CME	High	$> 10^2$
C	9 (21%)	CME	Low	$\sim 10^3$
D	7 (17%)	CME	Middle and High	$\sim 10^2$

Characteristics of Four SPE Groups (Kim et al., 2015)

- **Considering parameters**
  - SPE: intensity and energy evolution pattern
  - Flare: intensity and source location
  - CME: angular width and speed
  - Acceleration heights
    - ✓ Proton (interpolated H_{CME})
    - ✓ Electron (Type II)
    - ✓ Group A: H_p is lower than 1 Rs
    - → No or less relation with CME



- **General**
  - Group A and C include strong SPEs
  - Group D has weak SPEs

Characteristics of Four SPE Groups (Kim et al., 2015)

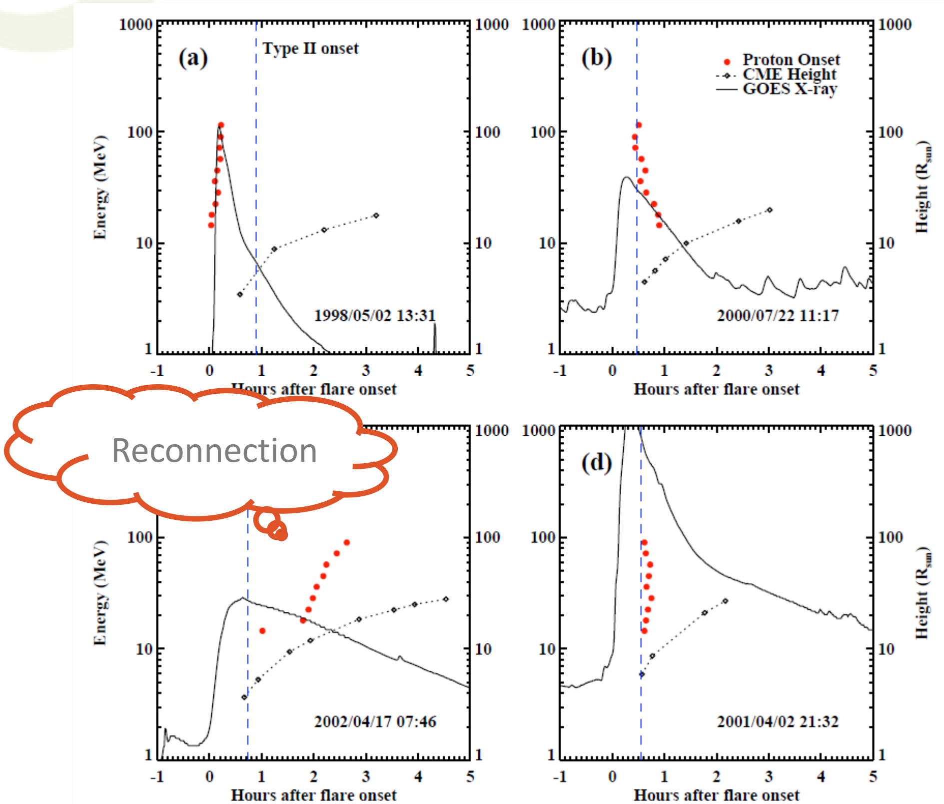
- **If the proton acceleration starts from a lower energy (Group A and C),**
  - → A SPE has a higher chance to be a strong event (> 5000 pfu) even if the associated flare and CME are not so strong.
  - Group A: acceleration sites are very low (~1 Rs) and close to the western limb.
  - Group C: relatively higher (mean=6.05 Rs) and wider acceleration sites.

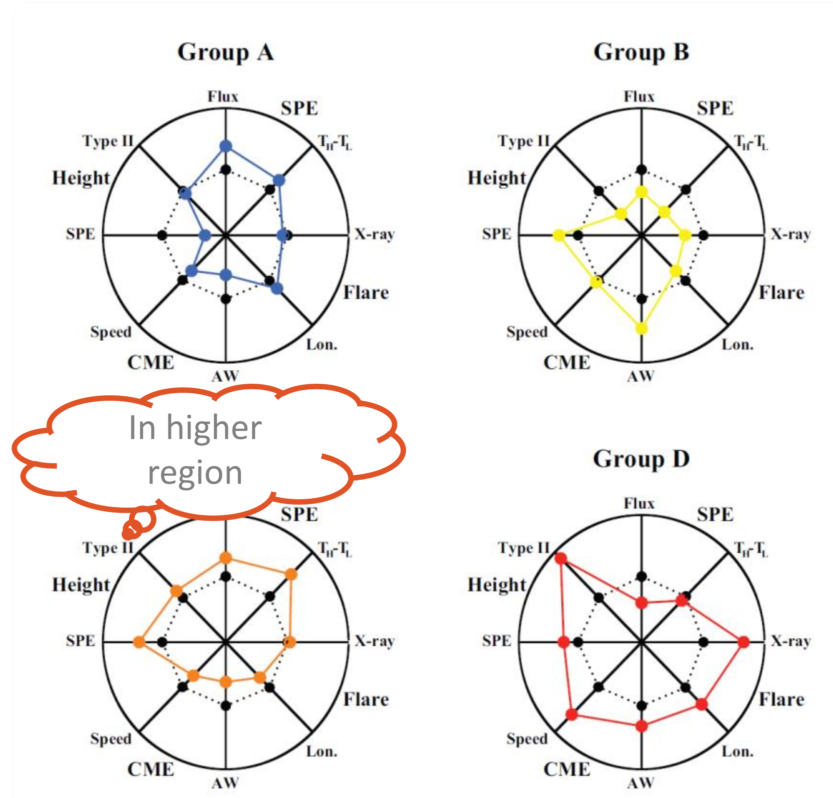
- **When the proton acceleration starts from the higher energy (Group B),**
  - → A SPE tends to be a relatively weak event (< 1000 pfu), in spite of its associated CME is relatively stronger than previous group.

- **SPEs with simultaneous acceleration in whole energy range within 10 minutes (Group D)**
  - → Acceleration heights are very close to the locations of type II radio bursts.
  - → Weakest proton flux (mean=327 pfu) in spite of strong related eruptions.

Hybrid Events as the Third Class of SEPs

- **Reconnection process in higher region**

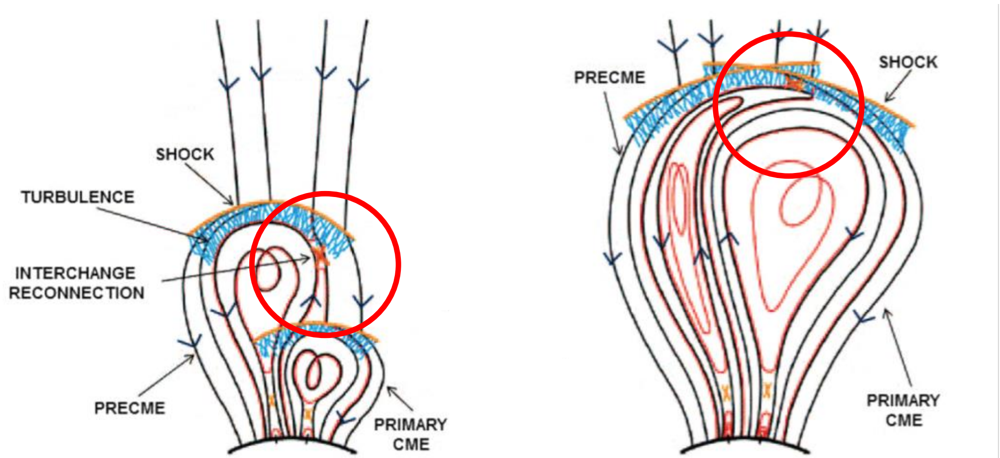




Hybrid Events as the Third Class of SEPs

- **Hybrid or mixed events (Kallenrode, 2003)**
  - Observations have indicated that there are ‘hybrid’ or ‘mixed’ event cases, where both mechanisms appear to contribute, with one accelerating mechanism operating in the flare while the other operates at the CME-driven shock.

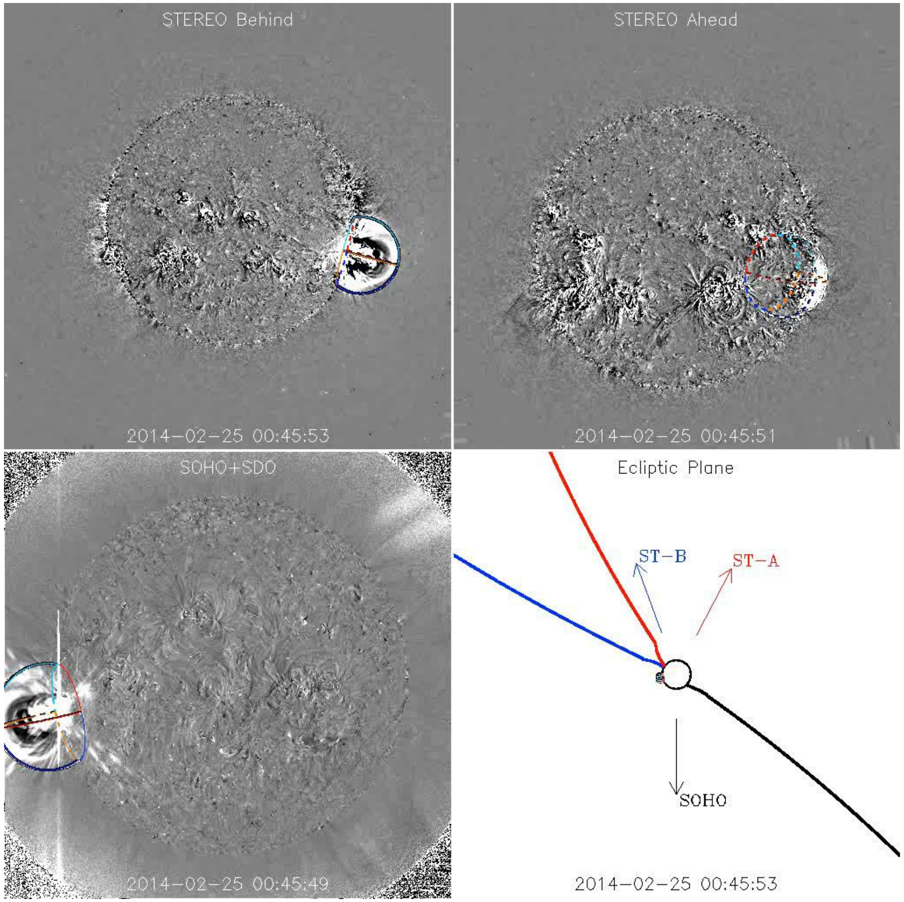
- **Possible scenarios**
  - Re-acceleration
    - ✓ Of remnant flare supra-thermals by shock waves (Mason et al., 1999; Desai et al., 2006)
    - ✓ From the interaction of CMEs (Gopalswamy et al., 2002)
    - ✓ In a magnetic interchange reconnection region of multi-CMEs (Ding et al., 2013)



Li et al., (2012)

Recent Research

- How does magnetic connectivity affect the peak intensity and delay time for each individual SPEs?

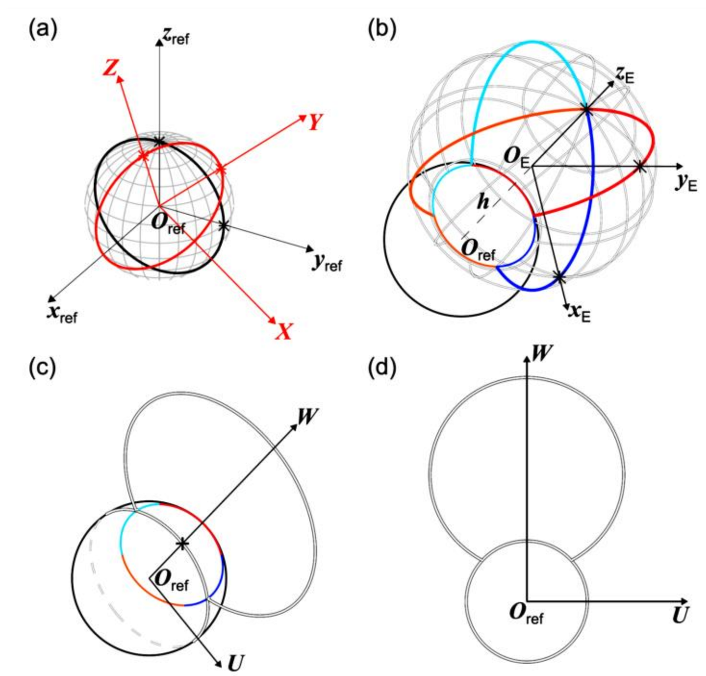


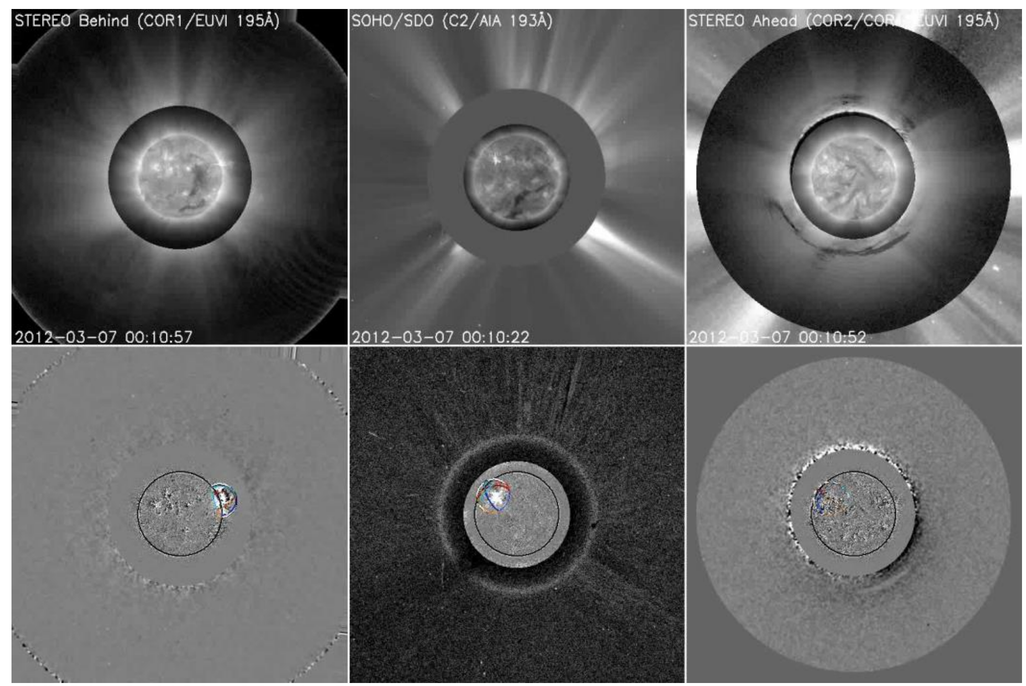
CME and Associated Shock in 3D Structure

- Multi-viewpoint observations from STEREO-A, -B and SOHO coronagraphs

→ 3D structure and kinematics of halo envelopes and driving CMEs

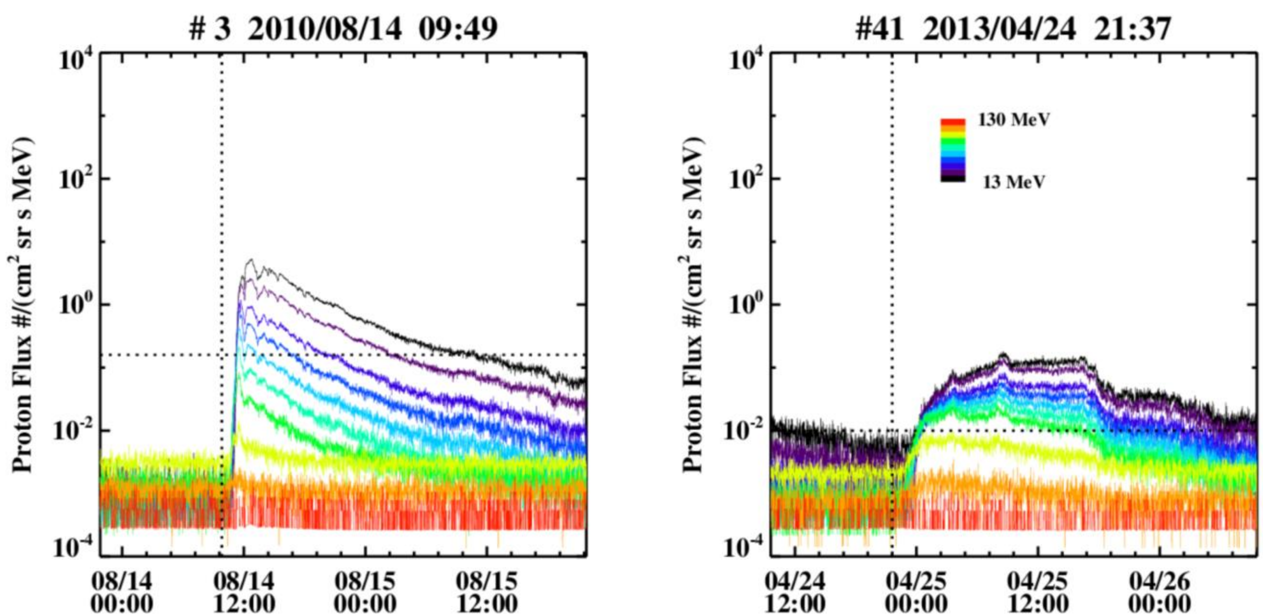
  - The ellipsoid model (Kwon et al. 2014) for halo
  - GCS model (Thernisien et al. 2006) for magnetic flux rope





SPEs Observed at Multi-Position

- **49 events from 2010 to 2013**
  - From the catalog of >25 MeV SPEs observed by the STEREO and/or at Earth (Richardson et al. 2014) at least 2 positions
- **Analysis**
  - Particle acceleration: Onset time and evolution pattern
  - Magnetic connectivity: Connecting time between the CME-driven shock and the Sun-Earth magnetic field line based on ellipsoid model



TOWARD NEXT GENERATION SOLAR CORONAGRAPH

COMPACT DIAGNOSTIC CORONAGRAPH ON ISS

LAUNCH AND OPERATIONS

CODEX 2021

COronagraph Diagnostic EXperiment

Diagnose temperature and velocity of the solar corona

Understand the corona heating and solar wind acceleration

FoV: 2.5 – 15 Rs

Wavelength: 3934 Å/4025 Å (Temperature)
3990 Å/4249 Å (Velocity)

Time cadence: 15 sec (Dynamic mode)
90 min (Diagnostic mode)

Launch to be installed on the ISS in 2021, operation > 2 years

TECHNOLOGY DEMONSTRATION

BITSE 2019

Balloon-born Investigation of Temperature and Speed of Electrons in the corona

Validate the scientific performance of the occulter, electronic and mechanic parts

Pointing system: NASA Wallops Arc Second Pointer

Altitude: Stratosphere (~ 40 km)

Duration: 6 – 8 hours

Launch from New Mexico by NASA CSBF in 2019

RESEARCH TO PROVE FEASIBILITY

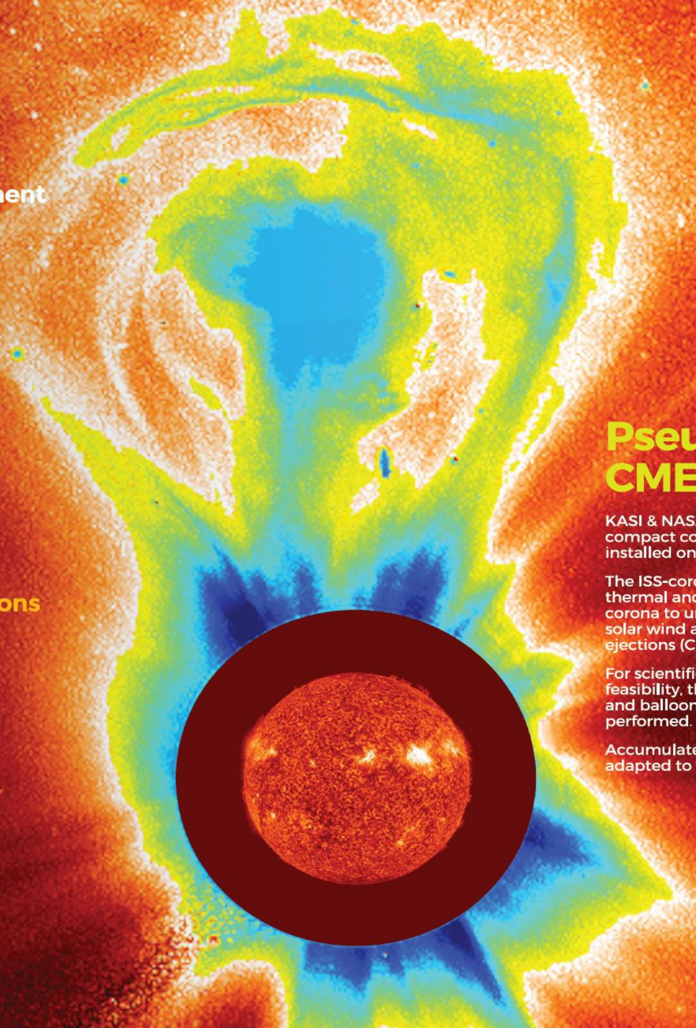
DICE 2017

Diagnostic Coronal Experiment

Verify fundamental technology on filter system and sensor

Total solar eclipse experiment (duration: 137 sec) in Jackson Wyoming, 2017

Twin cameras for high signal-to-noise ratio of faint corona



Pseudo Map of CME Temperature

KASI & NASA are developing the next generation compact coronagraph that is planned to be installed on the International Space Station (ISS).

The ISS-coronagraph is designed to diagnose thermal and dynamic properties of the solar corona to understand the acceleration of the solar wind as well as evolution of coronal mass ejections (CMEs).

For scientific justification and key technology feasibility, the experiment of total solar eclipse and balloon-borne coronagraph will be performed.

Accumulated technique and experience will be adapted to the ISS-coronagraph.