Solar Energetic Particle: origin and space weather relevance

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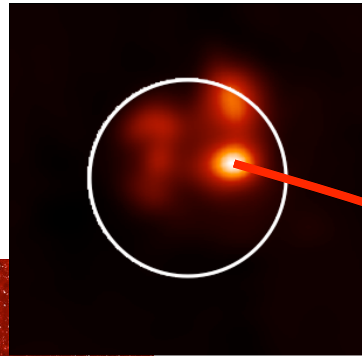
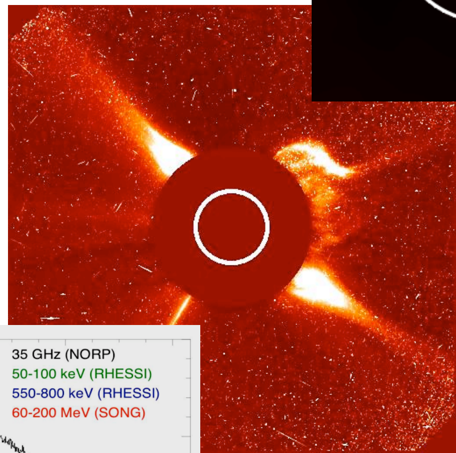
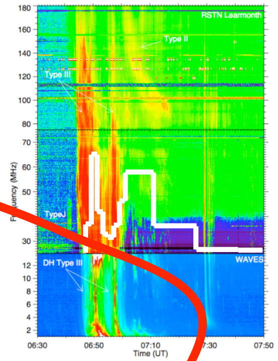
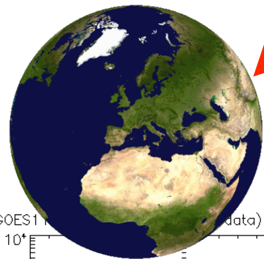
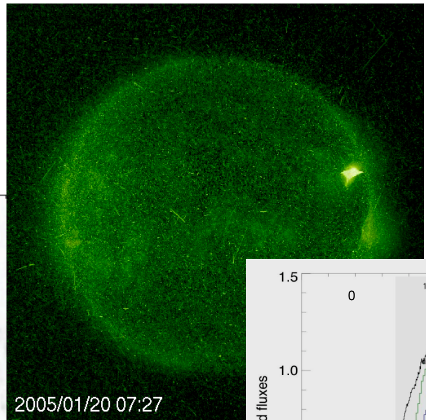
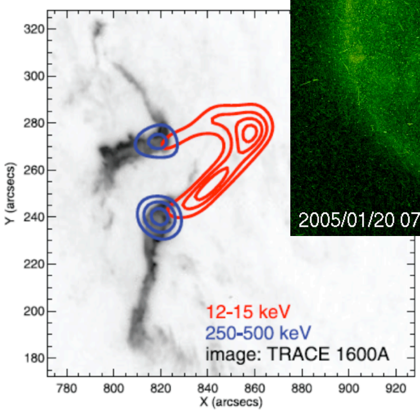


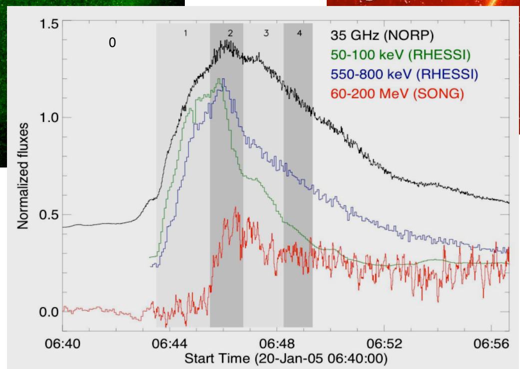


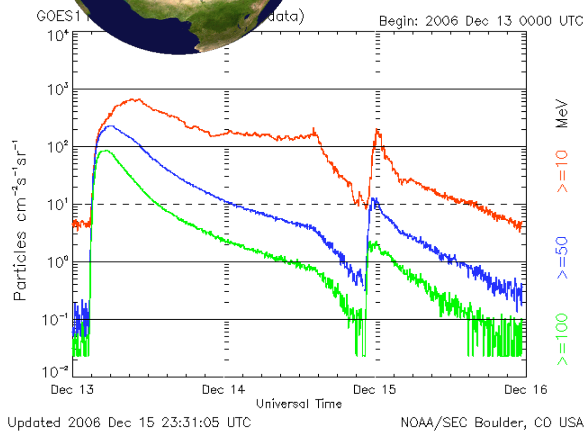












ISWI Quito 8-12 October 2012

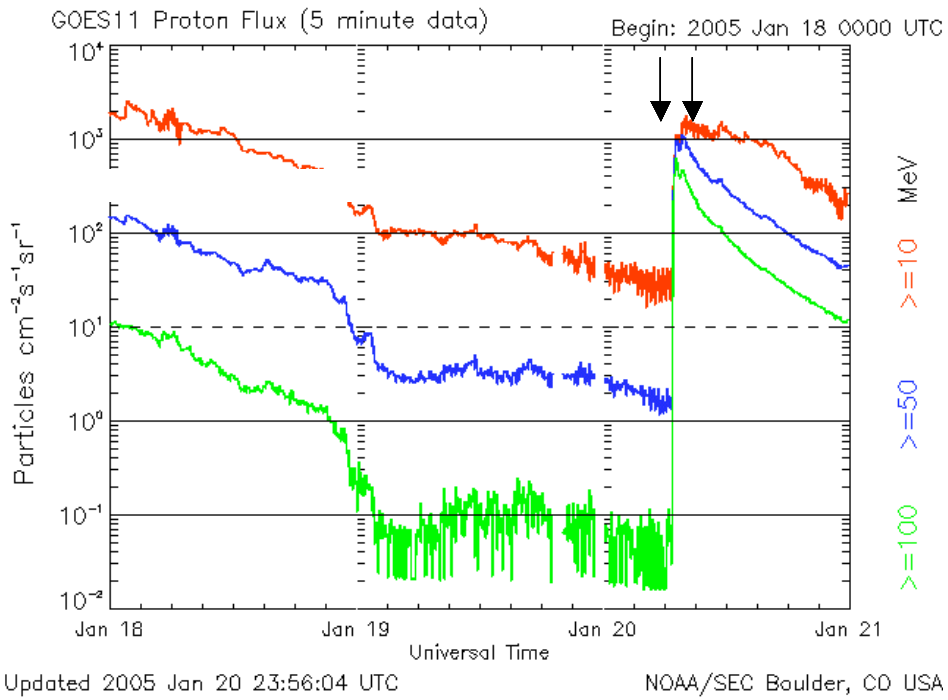
Outline

- Detection of SEPs
- Reasons to study SEPs
- Relevance of SEPs for SW
- Scenarios of particle acceleration
- Particle transport
- Where are SEP accelerated?
- Concluding remarks

Example of SEP + GLE event

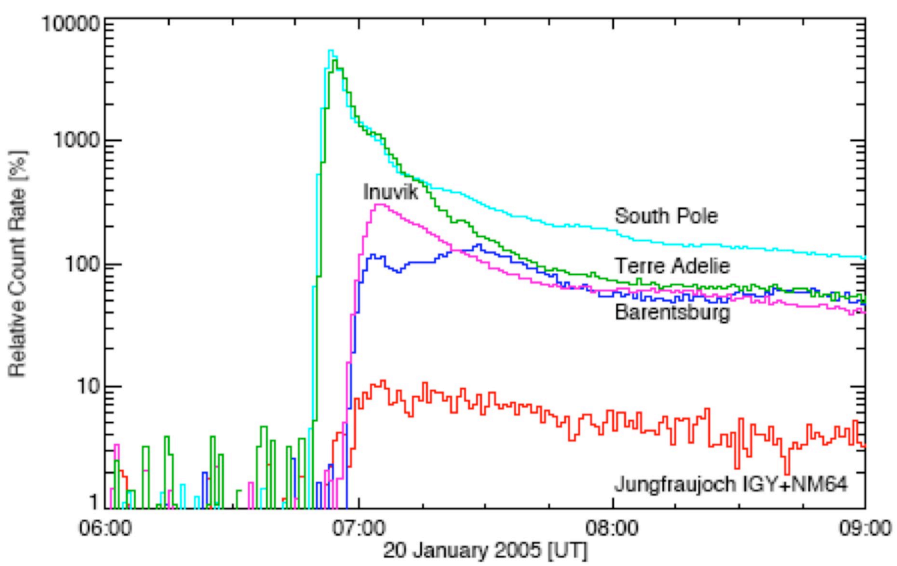
Enhanced fluxes of energetic particles above the GCR associated with solar activity first reported by Forbush in 1946

SEP



GLE

Bütikofer et al. 2009

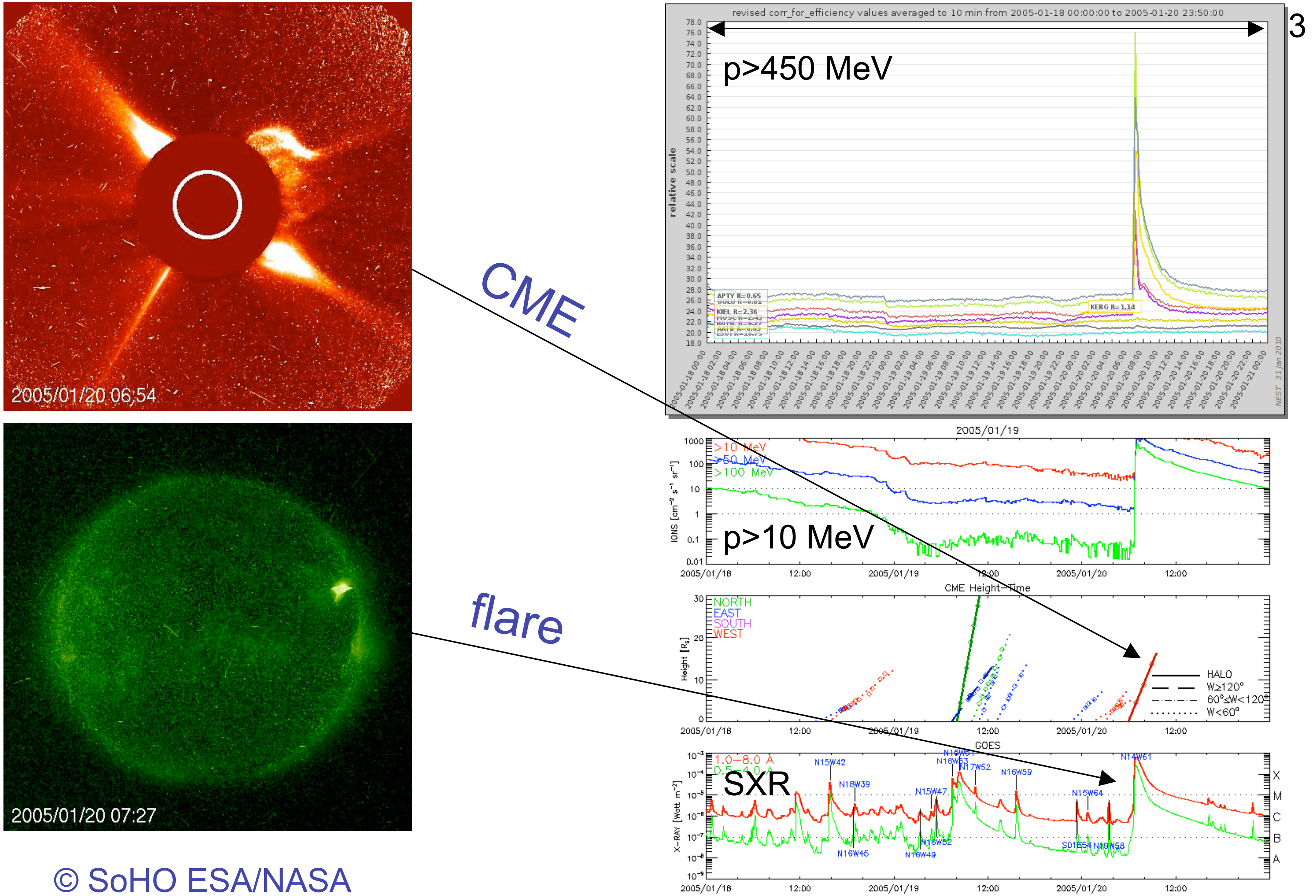


Detection of SEP + GLE (protons and ions)

- In situ measurements by space born instruments (SEP):
  - Time profile and differential energy spectrum in the ~ 1-100s MeV range
  - Elemental composition
  - Charge states
  - Pitch angle distribution
- Measurements at ground level (GLE):
  - Neutron monitor network: time profile and integral energy (rigidity) spectrum in the ~ 0.45 -17 GeV range, anisotropy of incident particles.

  www.nmdb.eu (K-L; Klein and N. Fuller for Paris observatory). Data base at Kiel University: ~40 NM stations (Europe, Asia, US,…). Visualization and data retrieval; on line help in 12 languages.
  - Muon telescopes: integral flux at higher energies (ground level and under ground)
  - VLF measurements

Solar energetic particle (SEP) events
Protons at 1 AU and associated coronal activity



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www.nmdb.eu

cdaw.gsfc.nasa.gov/CME_list/

Particle acceleration in flares and CMEs

Solar Energetic particles: protons, ions from 100s of keV to 10s of GeV:

- carry a major fraction of the energy released during a flare or a CME
- are an ubiquitous component of the Universe and a key to understanding its radiative signatures
- can be studied at the Sun by an otherwise unavailable combination of observations, including remote sensing and *in situ* measurements.
- are an important element of space weather

Relevance of SEPs for SW

- PCA: ionization of the D layer of the polar ionosphere:
  - Can last several days
  - Alter mid and long distance communications in the HF band, blackout
  - GPS: false position, no reception of satellite signal
  - Eruptions October-November 2003: several flights over the pole have lost communication with ground and could not use GPS for > 1 hour
- Satellites and launchers
  - Degradation of on board electronic (worst orbits IP space no magnetospheric protection)
  - Risk of an Ariane 5 failure during an SEP can be > 1%.
- Human being:
  - In the atmosphere **GCR** and SEP (30-200 MeV, A≤ 2): received doses increase with latitude (magnetic cut-off) and altitude (atmospheric cut-off):

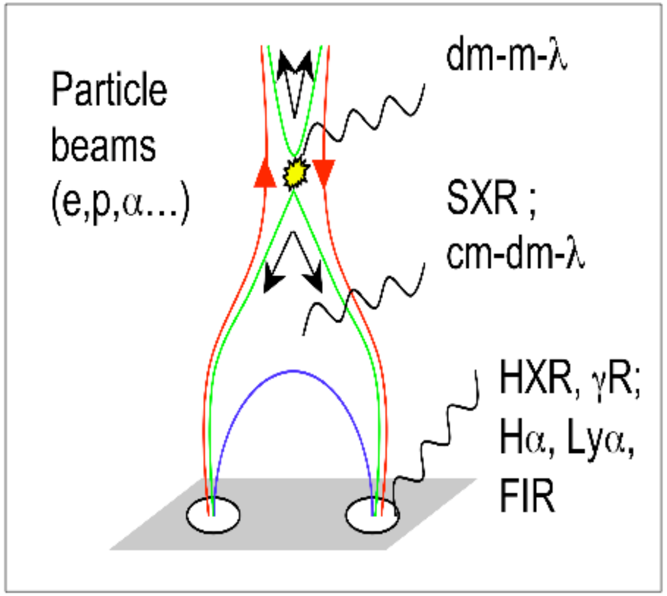
    www.sievert-system.org: computation of received radiation doses during air flights, empirical models for SEP
  - Mission to Moon or March: SEP dangers depend on characteristics of the event (total fluence, spectral hardness, composition) but can be extreme (e.g. Turner 2006)

SEP forecast

Particle acceleration by flares

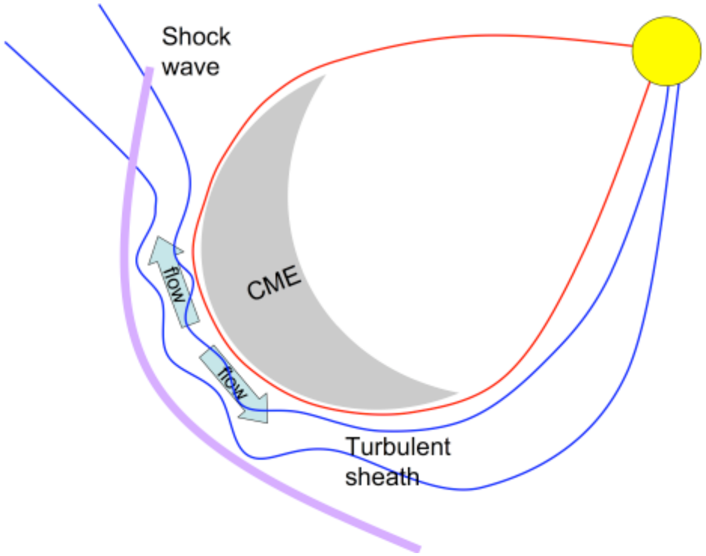
"Flare acceleration":

SEP accelerated in the corona together with the particles radiating γR, HXR, radio; release into open flux tubes, escape towards IP space.



after K.-L. Klein., Sol Orbiter Workshop, Athens, ESA-SP

Particle acceleration by CMEs

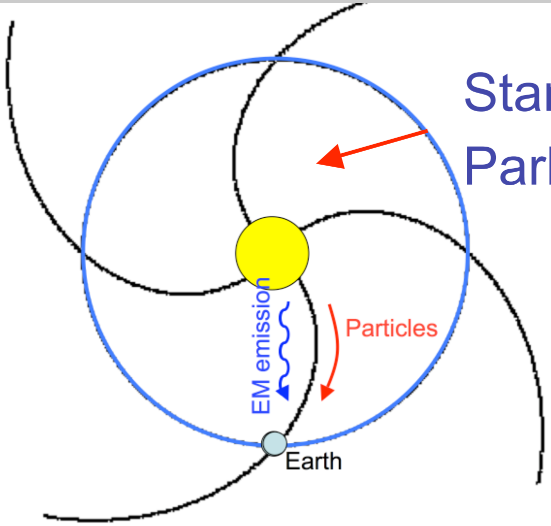


after Y. Liu et al., J. Geophys. Res., 111, A09108

- CME shock acceleration: SEP accelerated at the bow shocks of fast CMEs (corona and IP space).

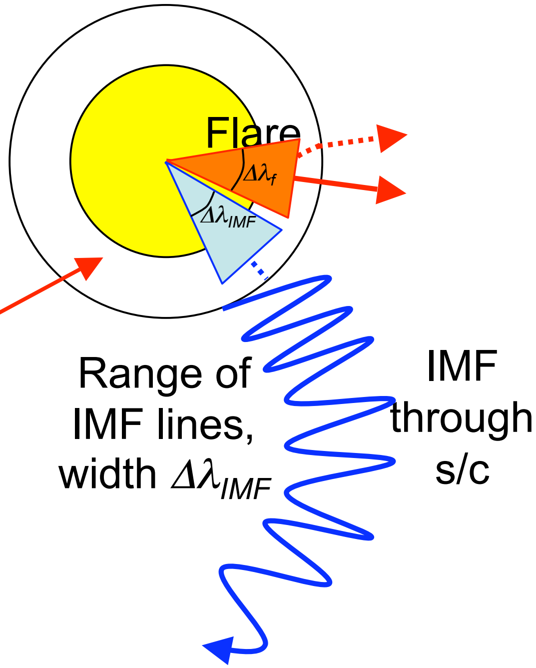
- Site(s) of SEP acceleration in the magnetically stressed post-CME corona (cf. Litvinenko SP 1996, ApJ 2006;
  Craig & Litvinenko ApJ 2002) → GeV ?
- Consistent with earlier analyses of relativistic SEP events (Akimov et al. 1996 SP; Klein et al. 1999, 2001 A&A) and mildly relativistic electrons (Maia et al. 2007 ApJ)

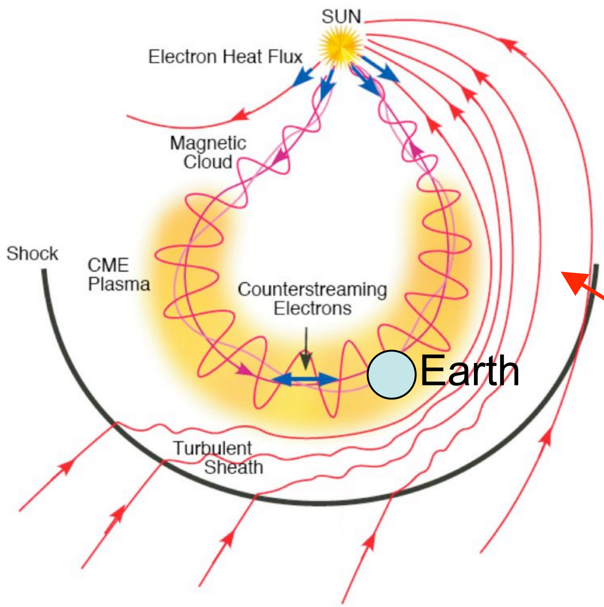
Transport: SEP events and IMF configuration
The IP path of SEP



Standard picture:
Parker spiral IMF connection

More complex picture





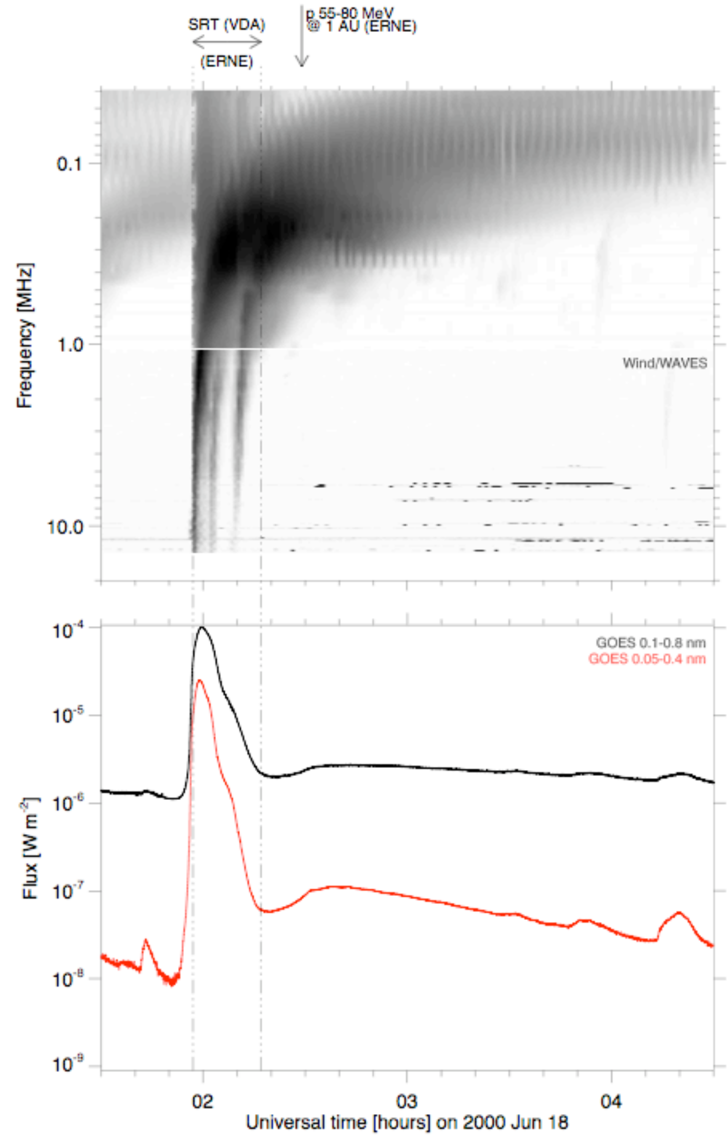
From Zurbuchen & Richardson 2006 SSR

Alternative: ICME ⇒ SEP released onto field lines of an earlier CME whose front has reached the Earth

70% of GLE detected during cycle 23 where in the vicinity of an ICME (Masson et al. 2011)

Why SEP acceleration by flares?

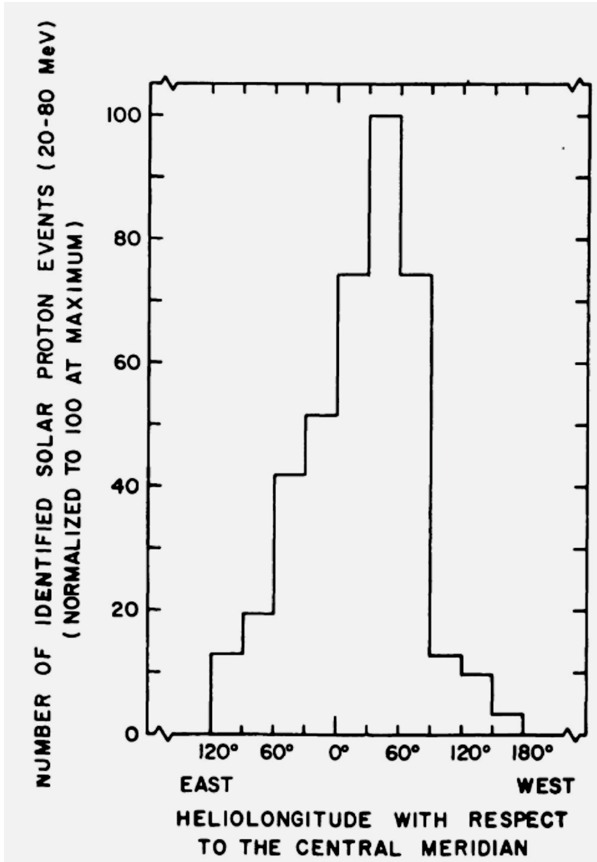
- Flares accelerate e and ions in the corona (X, γ, radio) up to energies consistent with measurements at 1 AU
- Flare accelerated particles may be confined in the corona without associated CME on occasion (Klein et al. 2010, 2011) but not in general (Cane et al. 2010)
- Particles escaping in IP space can be observed at Earth provided magnetic connection.



Courtesy E. Valtonen (Turku)

Why SEP acceleration at CME shocks?

- CME shocks accelerate particles in IP space (in situ observations). But radio quiet CMEs no SEP (Marqué et al.2006; Gopalswamy et al. 2008)
- Long durations of large SEP events (several days) at energies up to deka-MeV, much longer than flare energy release. Consistent with acceleration as CME + shock propagate from Sun to Earth
- Association of some large SEP events with active regions far from the Earth-connected IMF line. CME shocks are broad accelerators that may establish a connection to the Earth and explain SEP onset delays at separated spacecraft (cf. Rouillard et al. 2011 ApJ 735, 7; 2012 ApJ 752, 44).

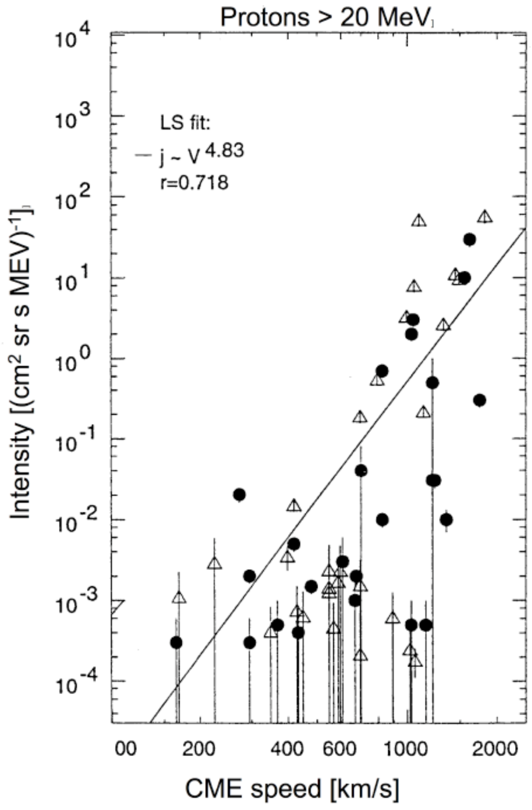


Van Hollebeke et al. 1975 Solar Phys. 41, 189

Reasons valid for protons at MeV to deka-MeV energies, not necessarily for relativistic protons.

Correlation SEP intensity - solar activity

- Intensities of protons>10 MeV in SEP events correlate with CME speed (V_{CME}) and SXR peak flux (I_{SXR}) (Gopalswamy et al.2004, JGR 109, A12105)
- All correlations are noisy:
  - Kahler (2001, JGR 106, 20947): pre-event particle intensity (=seed population for CME shock acceleration ?)
  - Gopalswamy et al. 2004: CME interaction
  - Garcia (2004, Spa Wea 2, S0202): combination of SXR parameters (I_{SXR}, EM, duration)
- Problem: SEP measured in a single point, after a long IP travel (scattering, …): IP transport, magnetic connection
- Influence of the IMF configuration ?



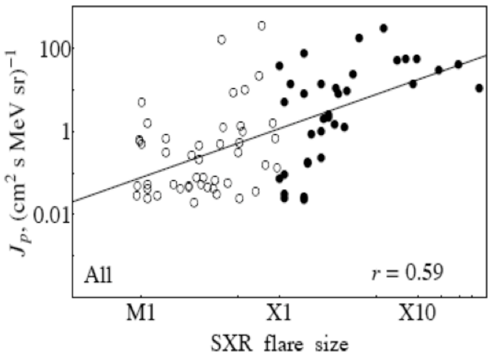
Kahler 2001 JGR 106, 20947

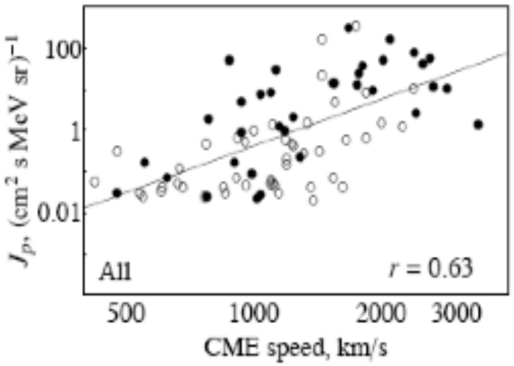
J(SEP)-I_{SXR}-V_{CME} correlation
SEPs in the solar wind (SoWi events) and in ICMEs

All SEP events:

- J(p)/V_{CME}= 0.63±0.05
- J(p)/I_{SXR} = 0.59±0.07

Miteva et al. 2012





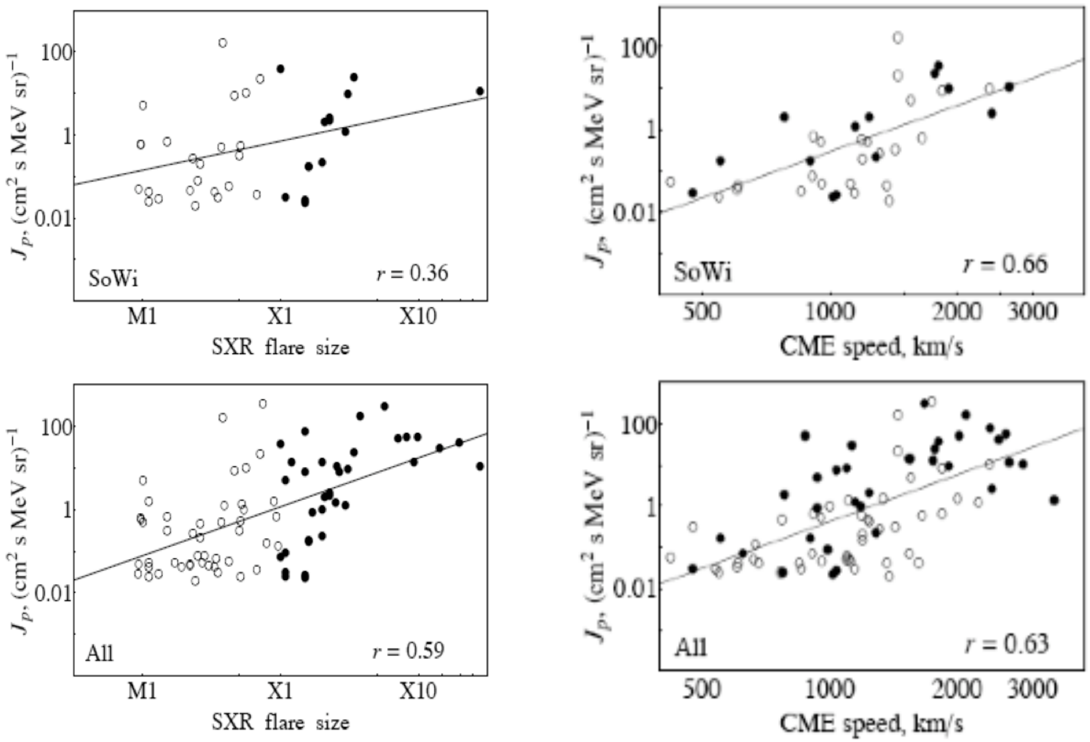
J(SEP)-I_{SXR}-V_{CME} correlation
SEPs in the solar wind (SoWi events) and in ICMEs

SoWi events:

- J(SEP) / V_{CME} unchanged
- J(p)/I_{SXR} = 0.36±0.13

All SEP events:

- J(p)/V_{CME}= 0.63±0.05
- J(p)/I_{SXR} = 0.59±0.07



Miteva et al. 2012

J(SEP)-I_{SXR}-V_{CME} correlation
SEPs in the solar wind (SoWi events) and in ICMEs

ICME events:

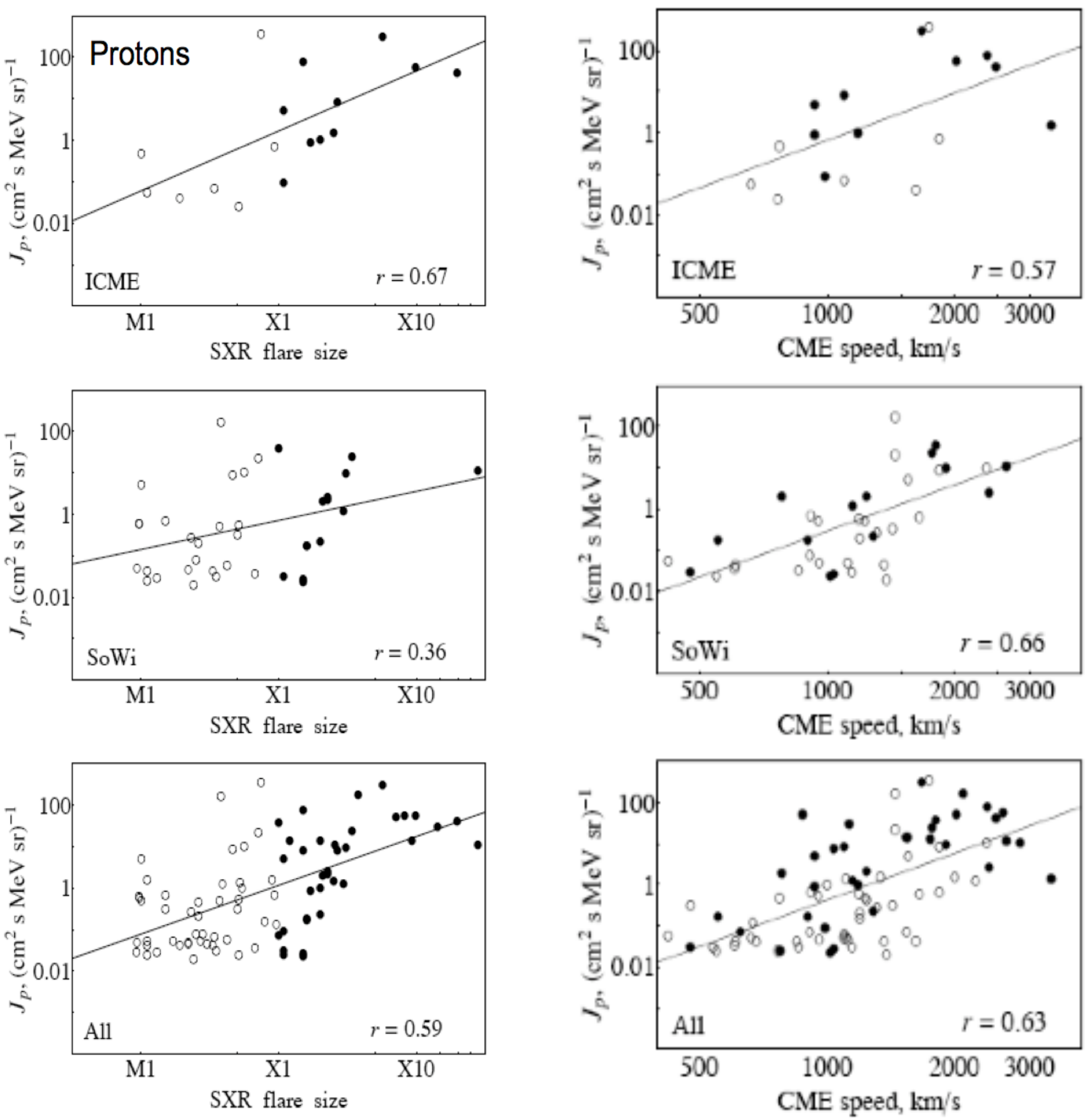
- J(SEP) / V_{CME} unchanged
- $J(p)/I_{SXR}$ = 0.67±0.13

SoWi events:

- J(SEP) / V_{CME} unchanged
- $J(p)/I_{SXR}$ = 0.36±0.13

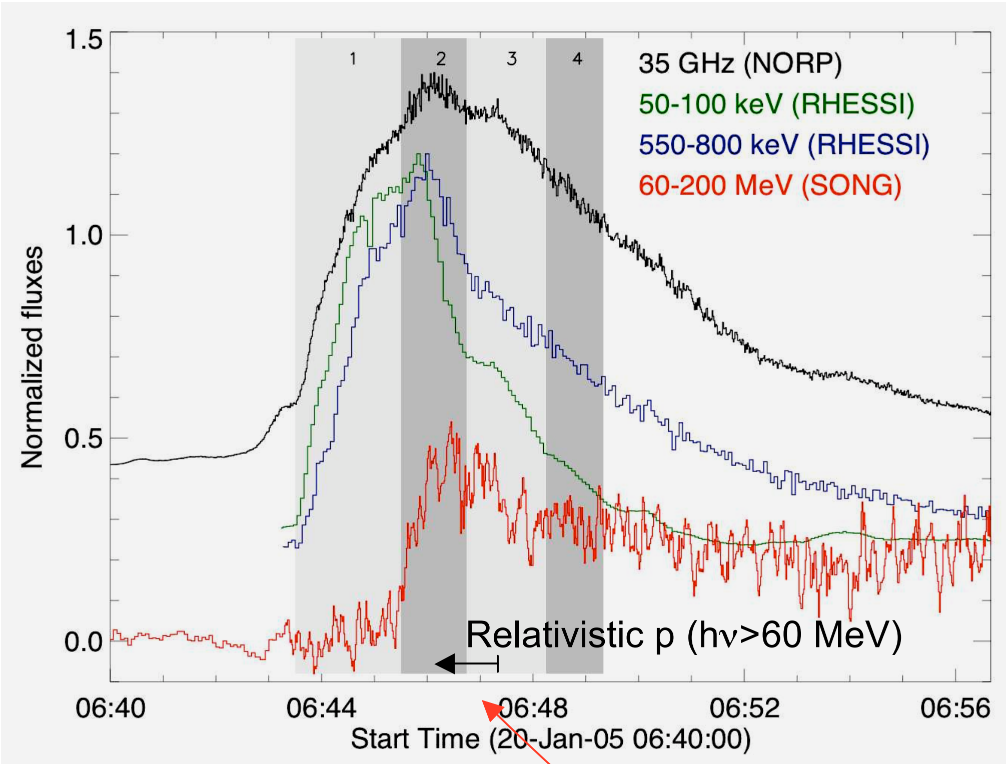
All SEP events:

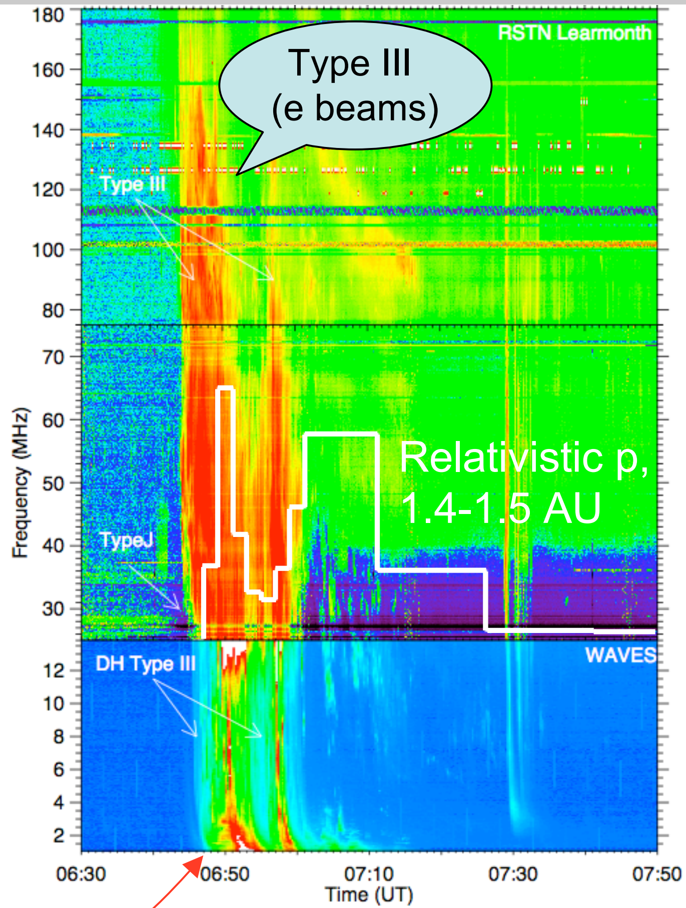
- $J(p)/V_{CME}$= 0.63±0.05
- $J(p)/I_{SXR}$ = 0.59±0.07



Miteva et al. 2012

Case study: GLE on 2005 Jan 20
Interacting and escaping relativistic protons





Masson et al. 2009 SP 257, 305

- Arrival at Earth if relativistic protons escape together with type III electrons
  ⇒ s = 1.4 - 1.5 AU (ICME; Masson et al 2012 A&A 538, A32)
  - Solar release near time of onset hν>60 MeV
  - Similar durations of the release of relativistic p and radio emitting e
- Closely related acceleration of first interacting and escaping relativistic p (see also Simnett 2006 A&A, Grechnev et al 2009 SP, McCracken et al. 2009 JGR)

High-energy particles at and from the Sun
Summary

- Flare acceleration is expected to release SEP to space (confinement in the corona is rare !) that are detectable at Earth when a magnetic connection exists.
- There are clear indications (timing) that relativistic protons detected at 1 AU may be related to the impulsive flare phase
- CME shock acceleration is an attractive explanation of broad injection cones and long durations of SEP, but is not the only means by which a CME can contribute to SEP. Acceleration of relativistic SEP at CME shocks is not demonstrated by the observations.
- **Future:**
  - Exploit 23rd & 24th cycle (in situ +RS); FERMI
  - We need to go close to the Sun: *Solar Orbiter*, *Solar Probe* +
    - shock acceleration close to the Sun, seed populations
    - time evolution of SEP events with less smearing by IP transport

Thanks for your attention

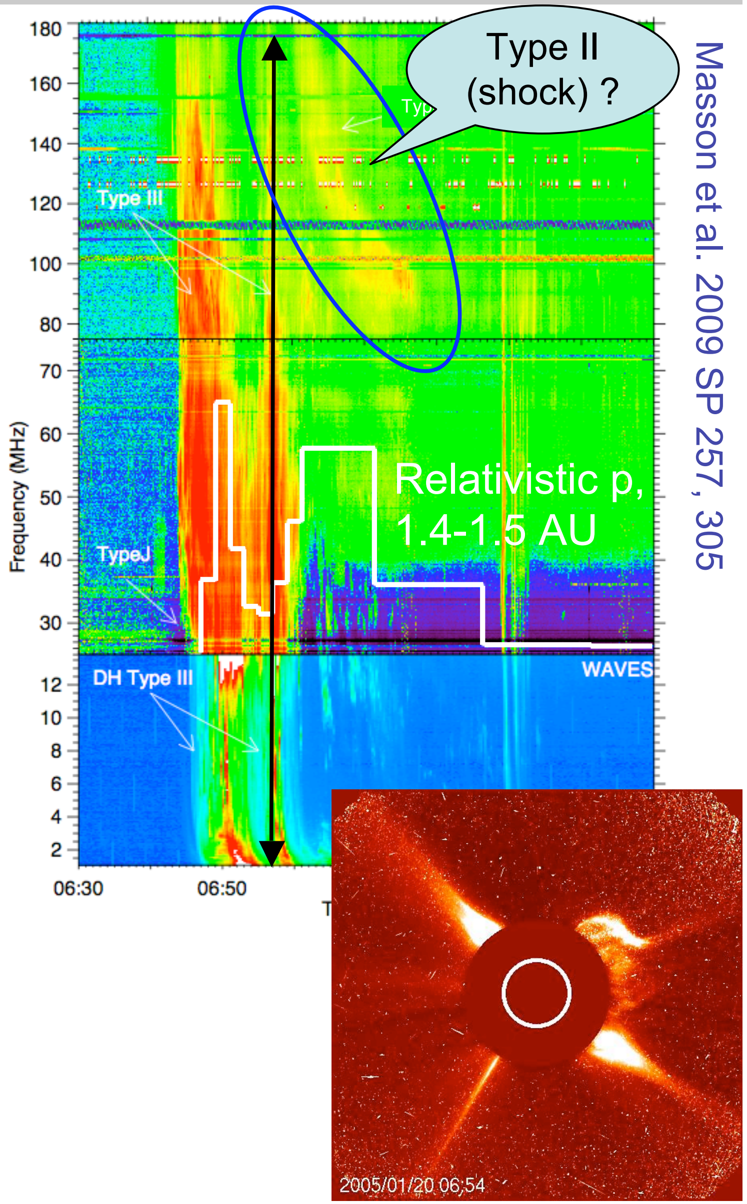
Relativistic SEP, flares and shocks: 2005 Jan 20
Escaping relativistic protons 2

- 2^{nd} peak of relativistic p profile
  - not related with conspicuous HXR/μ wave emission
  - at the time of a new m-Dm-λ type III, a drifting narrow-band m-λ burst (type II=shock wave ???) and broadband synchrotron emission.

- Origin of slowly drifting radio burst :
  $r < 2\ R_0$ (well below CME front)

- If shock acceleration (type II burst): not in front of the CME, where it is generally expected.

- Is the radio burst really a shock signature (= type II) ?

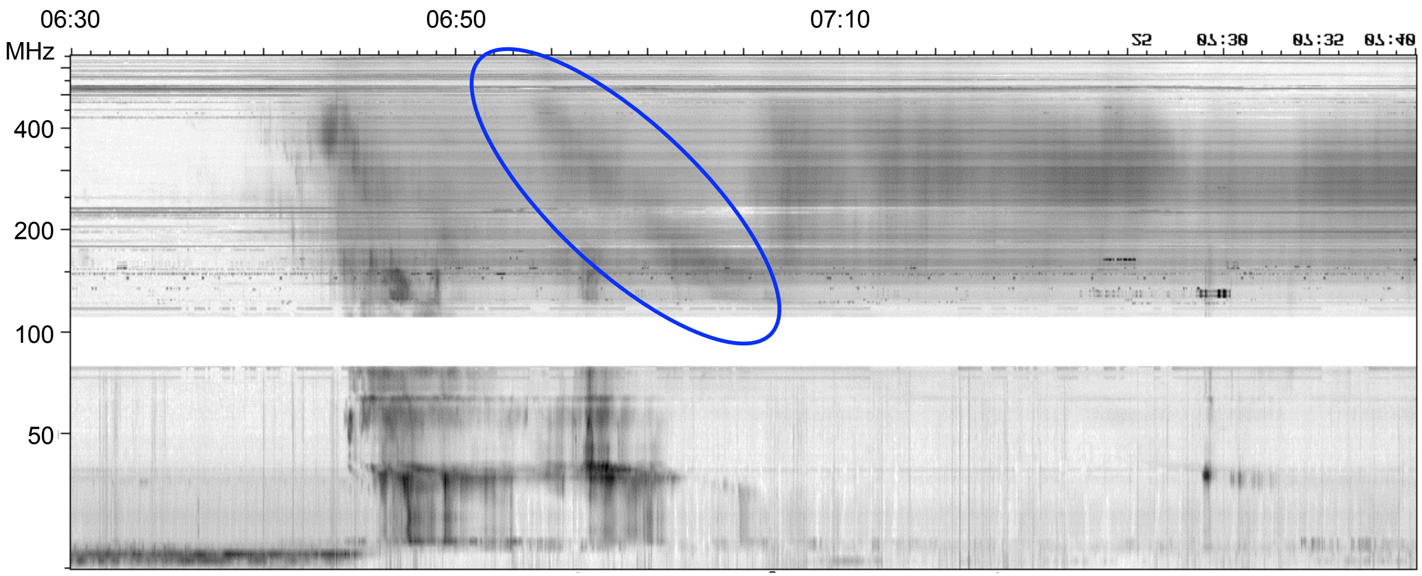


Masson et al. 2009 SP 257, 305

Relativistic SEP, flares and shocks: 2005 Jan 20
Escaping relativistic protons 2

- ARTEMIS (Univ. Athens) radio spectrum:
  - type II = shock wave?
  - But: none of the typical II fine structures
- Type IV burst: reconnection in current sheet behind CME (cf. Cliver at al. 1986, Kocharov et al. 1994, Akimov et al. 1996, Klein et al. 1999, 2001, Aurass et al. 2009 A&A 506, 901)
- Accompanied by new energy release in the low corona (brightening of UV ribbons; Grechnev et al. 2008)

Distinct acceleration from previous impulsive one; related to magnetic reconnection in the post-CME corona.



Bouratzis et al. 2010 Solar Phys 267, 343

Klein, Masson et al., work in progress

Particles at the Sun and in space

Estimated numbers vary widely from event to event

$R_p = N_p(\text{Interacting}) / N_p(\text{escaping})$

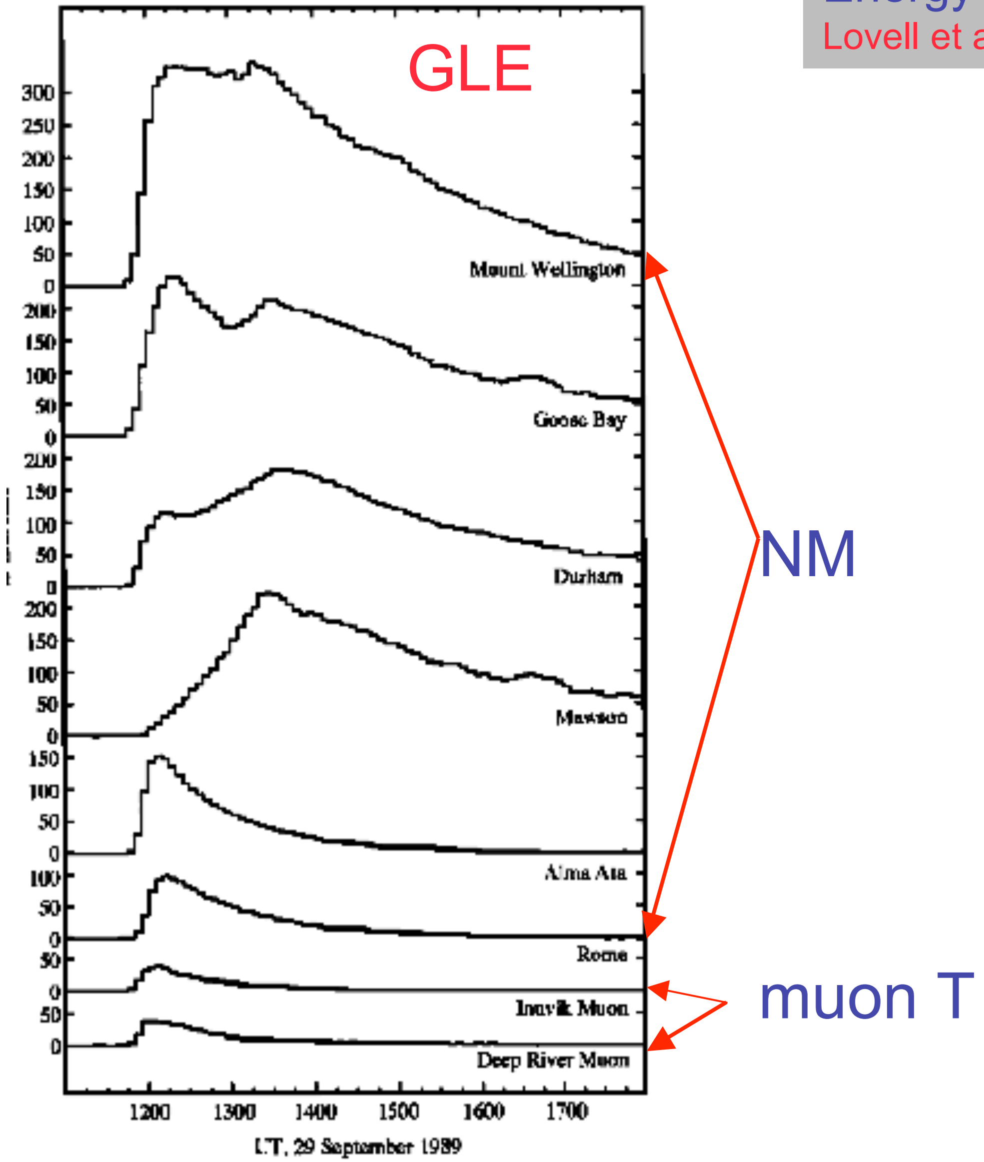
R_p <1 or >1 for protons > 30 MeV (Ramaty et al. 1993)

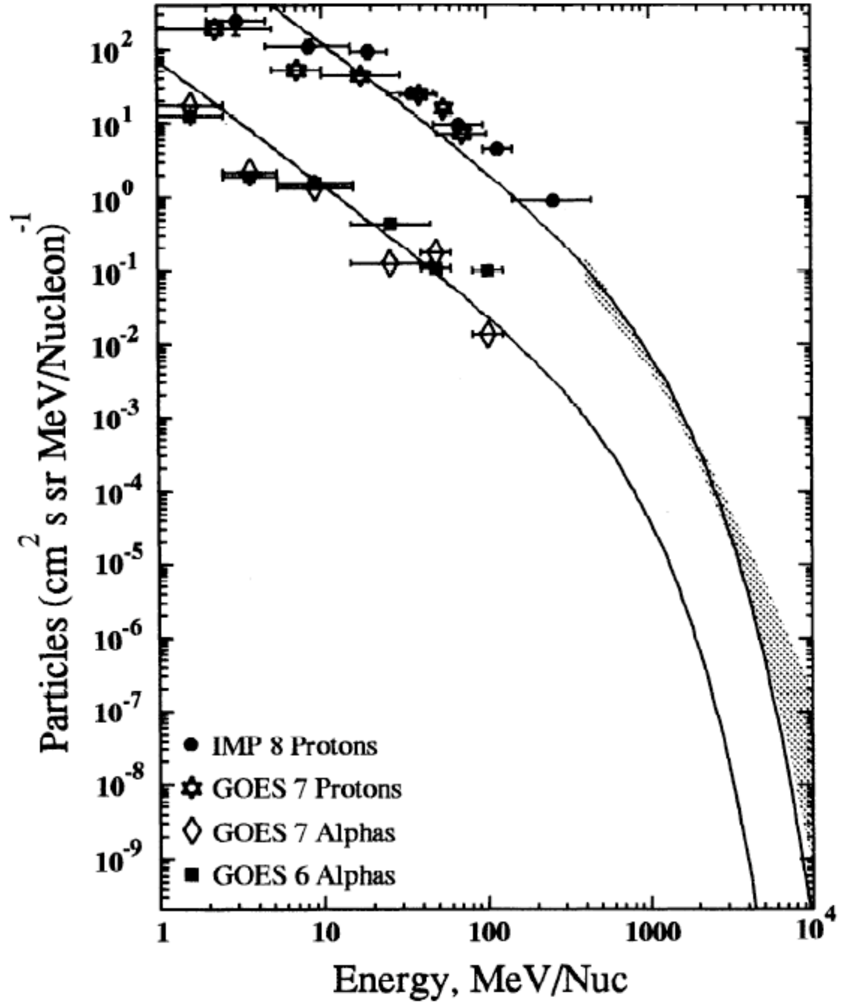
Interacting and escaping protons have accelerators of comparable efficiency (on average)

SEP event: example 2

Energy spectrum (SEP + GLE) 1989 Sep 29

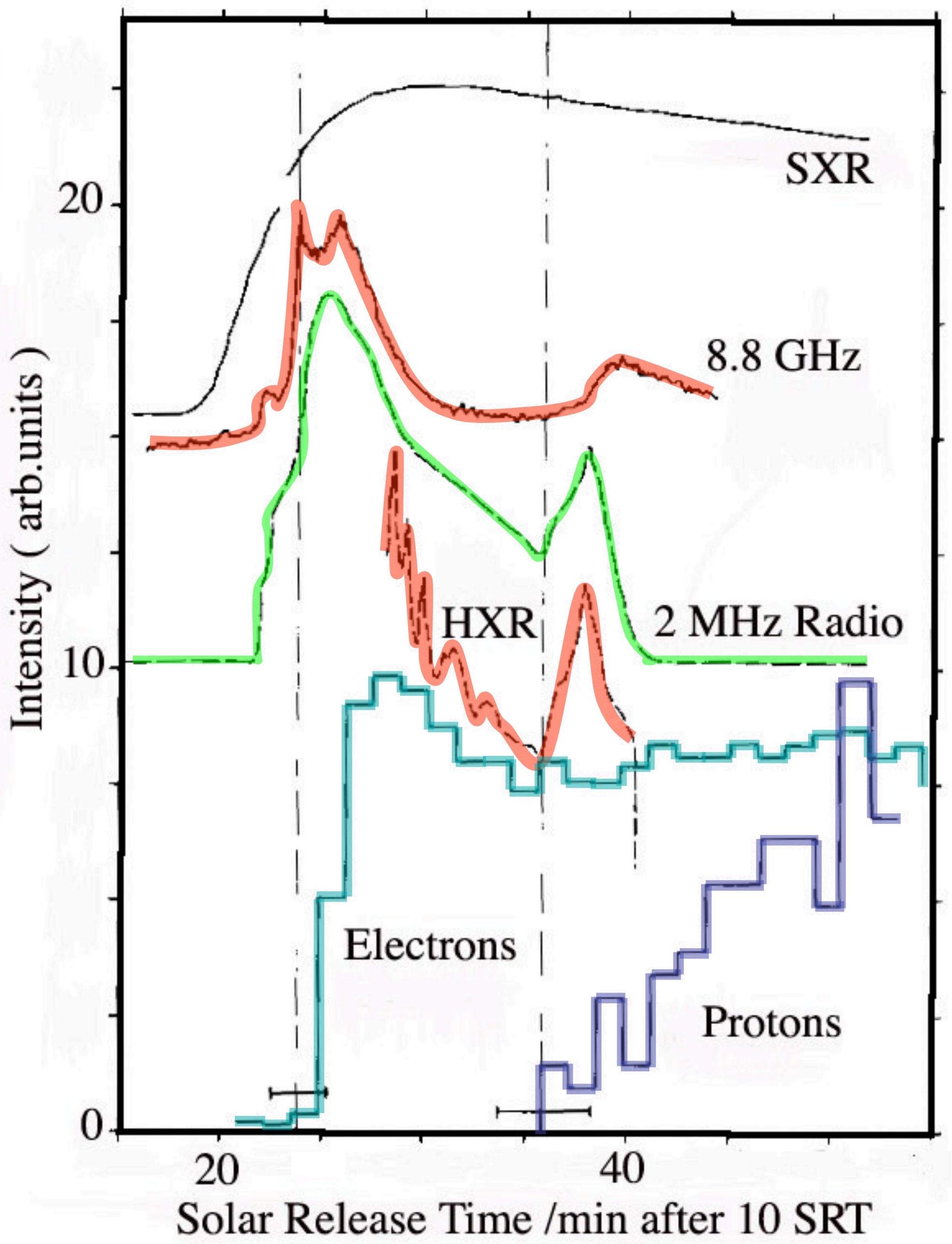
Lovell et al. 1998





HELIOS measurements of SEP at 0.38 AU

- SEP release : e first, p ~10 min later
- e acceleration in the corona (HXR, μ waves) : 2 groups of peaks
- e escape from corona (type III) : with the 2 episodes of coronal acceleration
- Close time correspondence coronal acceleration / SEP
- e/p ratio closely related with coronal acceleration
- ⇒ separate « flare » and « CME » contributions



Kallenrode & Wibberenz 1991 ApJ 376, 787

Impulsive and gradual SEP (Reames, 1999)

Impulsive (flare)	Gradual (CME)
Fe/O ~1	Fe/O ~0.1
^{3}He/^{4}He ~0.1-1	^{3}He/^{4}He ~0.01
Q_{Fe} ~20	Q_{Fe} ~10-14

Oversimplified picture (see Klecker et al. 2006)

- Particles may originate in dense plasma in the low corona even in gradual SEP
- Enrichment in 3He common in IP shock accelerated SEP
- Enrichments in heavy ions often observed in large events at high energies

Explanations:

- Supra thermal population from previous impulsive SEP (Mason et al. 1999)
- Interplay of shock geometry and different seed populations (Tylka et al. 2005)
- Direct injection from the flare (Klein & Trottet 2001; Cane et al. 2003)