On the link between the solar energetic particles and eruptive coronal phenomena

Statistical study in solar cycle 23

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in collaboration with

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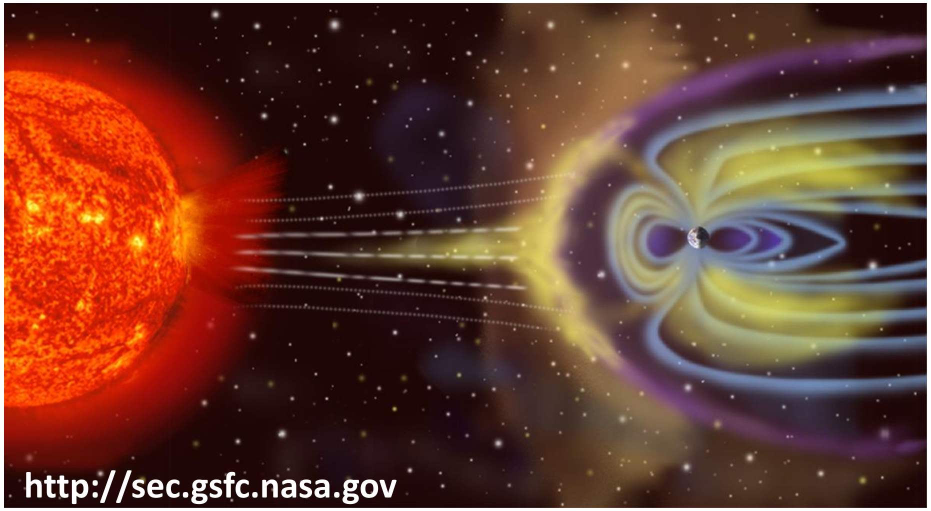
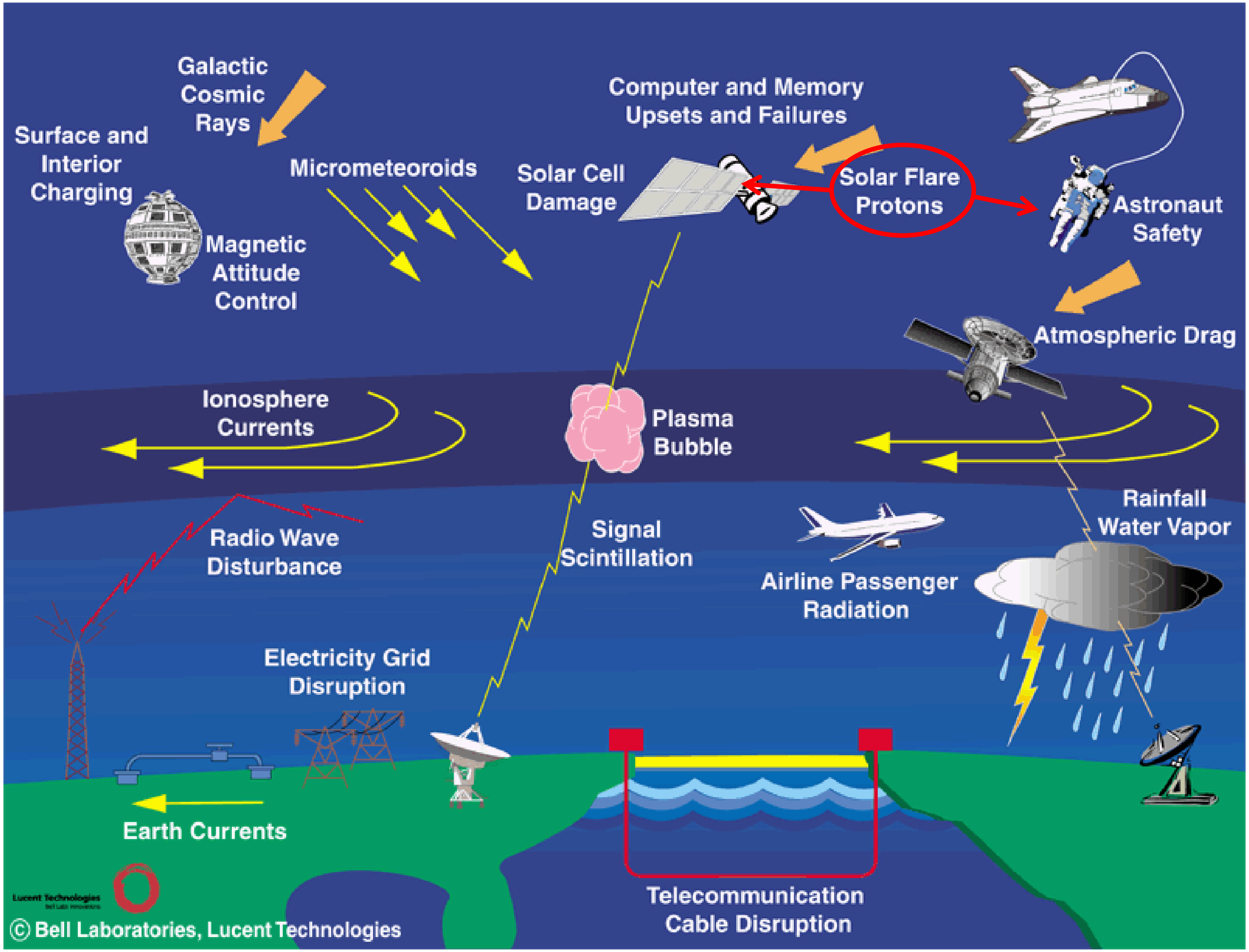
Motivation

Astrophysics
To study the particle acceleration and transport by combined in situ (particle fluxes) and remote observations (radiation signatures from gamma to radio waves)

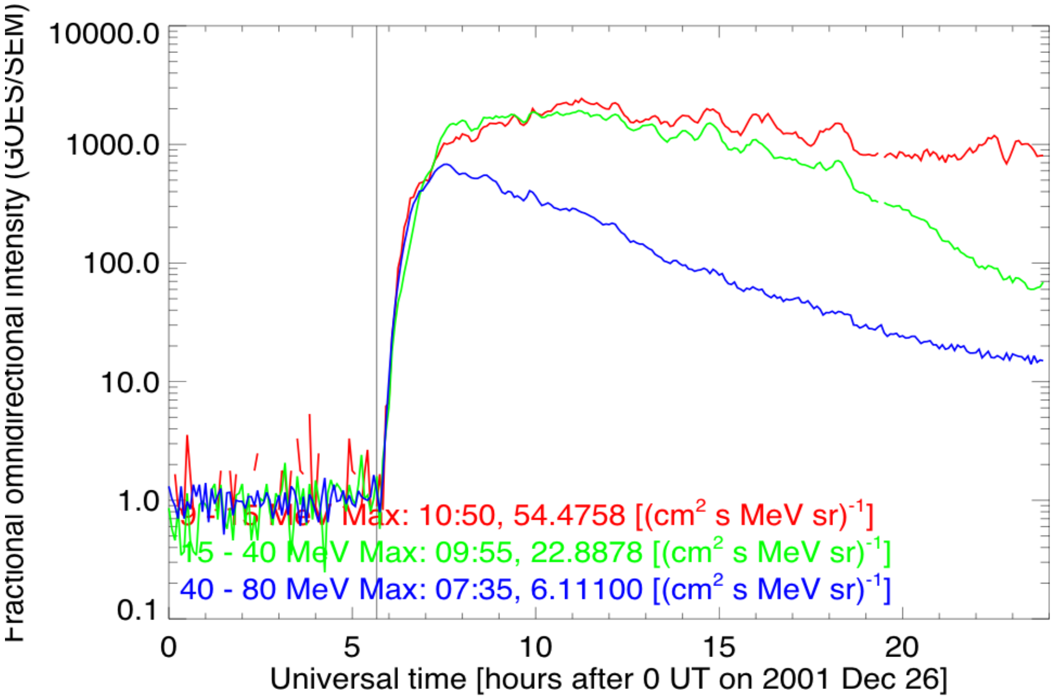
Space weather effects
Refers to the conditions on the Sun, in the solar wind, magnetosphere, ionosphere and thermosphere, which can influence the performance and reliability of space-borne and ground-based technological systems and which can affect human life and health (US National SW plan)



Solar–terrestrial relationship/Space weather



Solar energetic particles (SEPs)



SEP events

flux of energetic particles (protons >10 MeV, electrons > 10 keV) observed in situ

Time coverage: 1997–2006

SEP events: ~100 (with origin in the western heliosphere)

Association: solar flares and CMEs

deka-MeV protons

- **GOES** (~27 MeV)
- **Wind/EPACT** (~23 MeV)
- **Cane et al. 2010** (~25 MeV)

→ peak intensity, J_p (cm^2 s sr MeV)$^{-1}$

→ onset time ±30 (to ~60) min

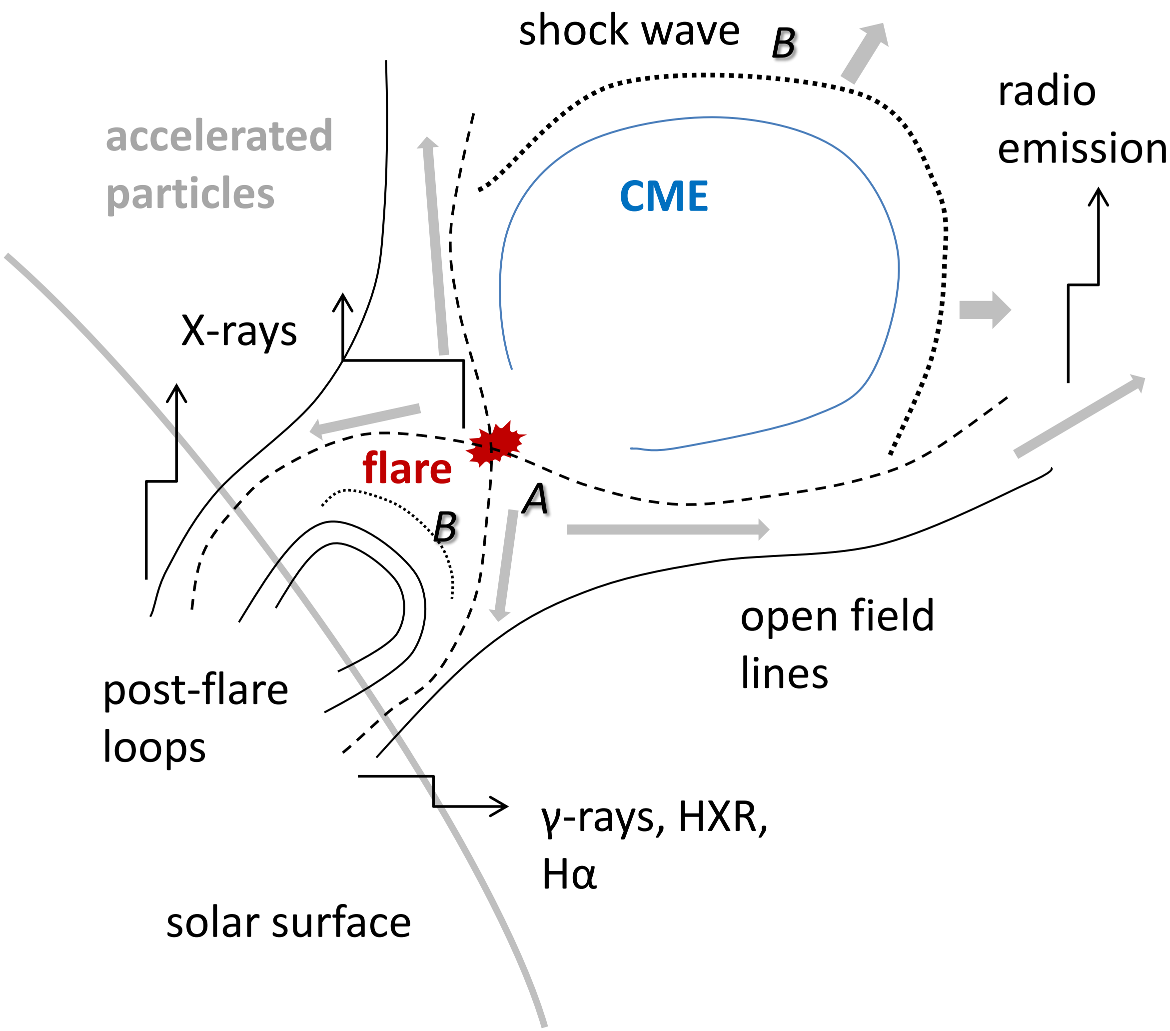
SEP acceleration, connection, transport

I. Particle acceleration
physical relationship between in situ particles and coronal activity/particle accelerator
(flare–CME relationship!)

II. Magnetic connection
particle access to open magnetic field lines
particle access from high corona to Earth

III. Particle transport
scattering

I. Particle acceleration



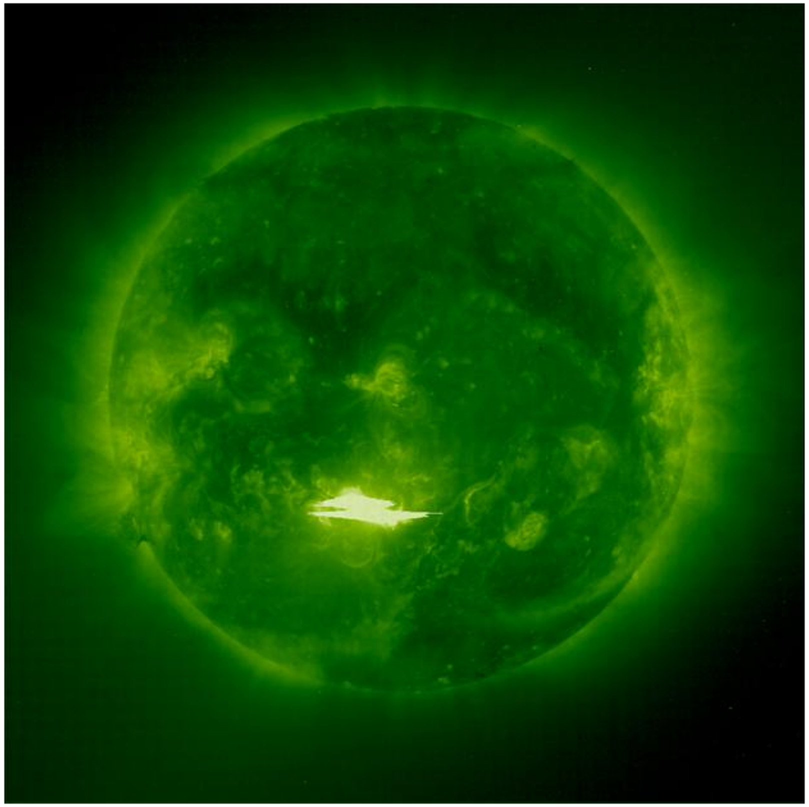
A. Magnetic reconnection (small acceleration site and short timescales)

- flares
- behind CMEs

B. Shock acceleration (broad and long lasting accelerator)

- flare blast shock wave
- CME piston-driven shock

Solar flare

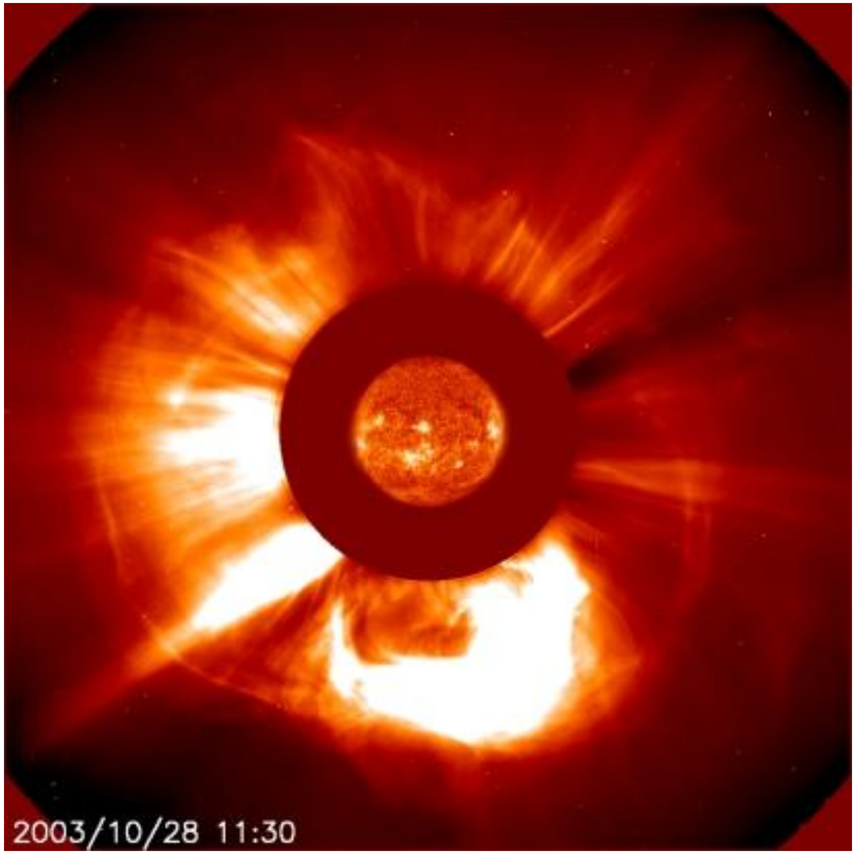


SOHO/EIT 28/10/2003

→ sudden release of the stored magnetic energy in the corona,
~ 10^{25} Joules,
emission covering the entire EM spectrum (from γ- to radio)

X- and M-class
(GOES 1-8 Å; western location)
Solar Geophysical Data reports
→ SXR peak flux ($10^{-4}\ W\ m^{-2}$)

Coronal mass ejection (CMEs)



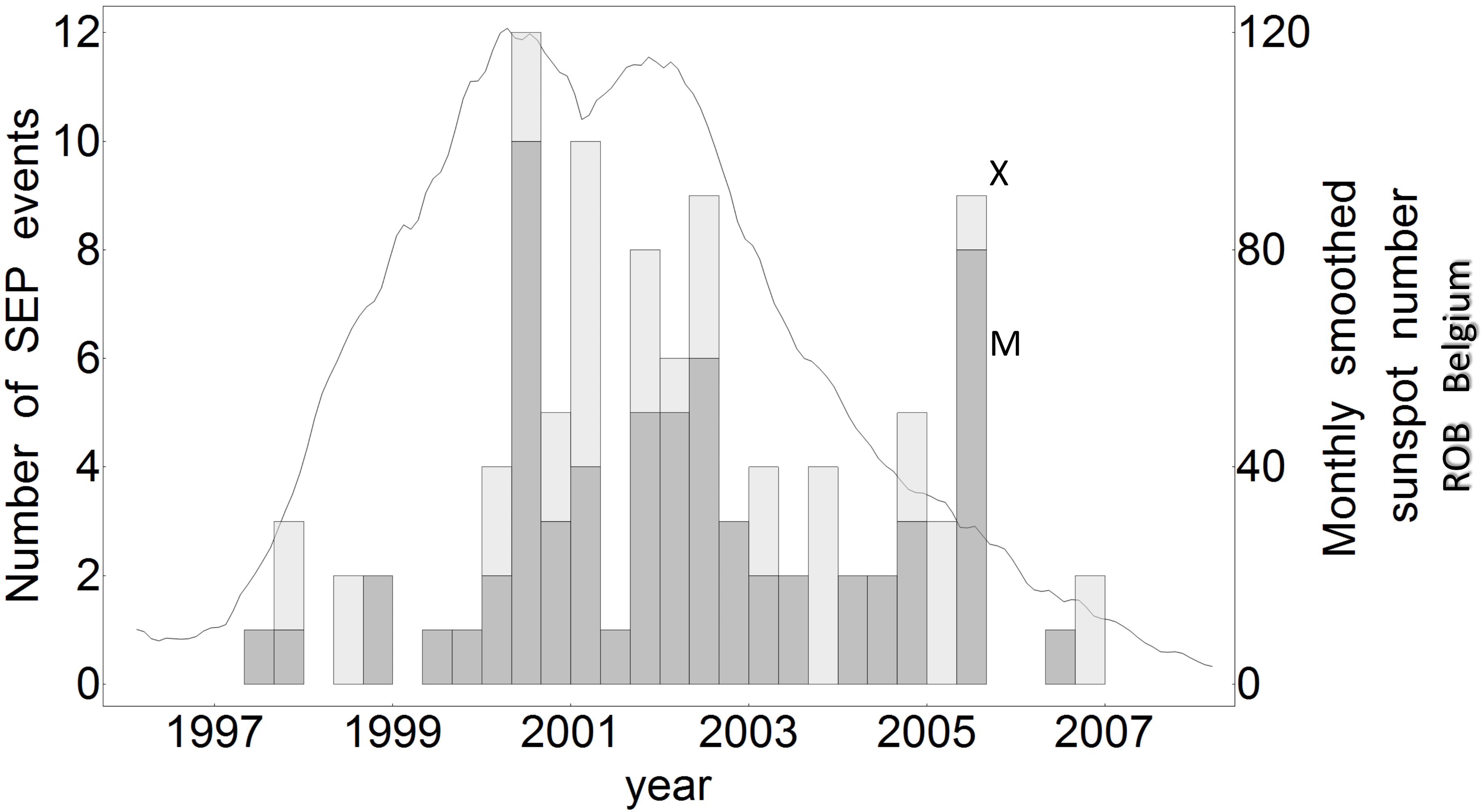
SOHO/LASCO C2 28/10/2003

→ mass (< 10^{13} kg) and embedded magnetic field expelled into the IP space

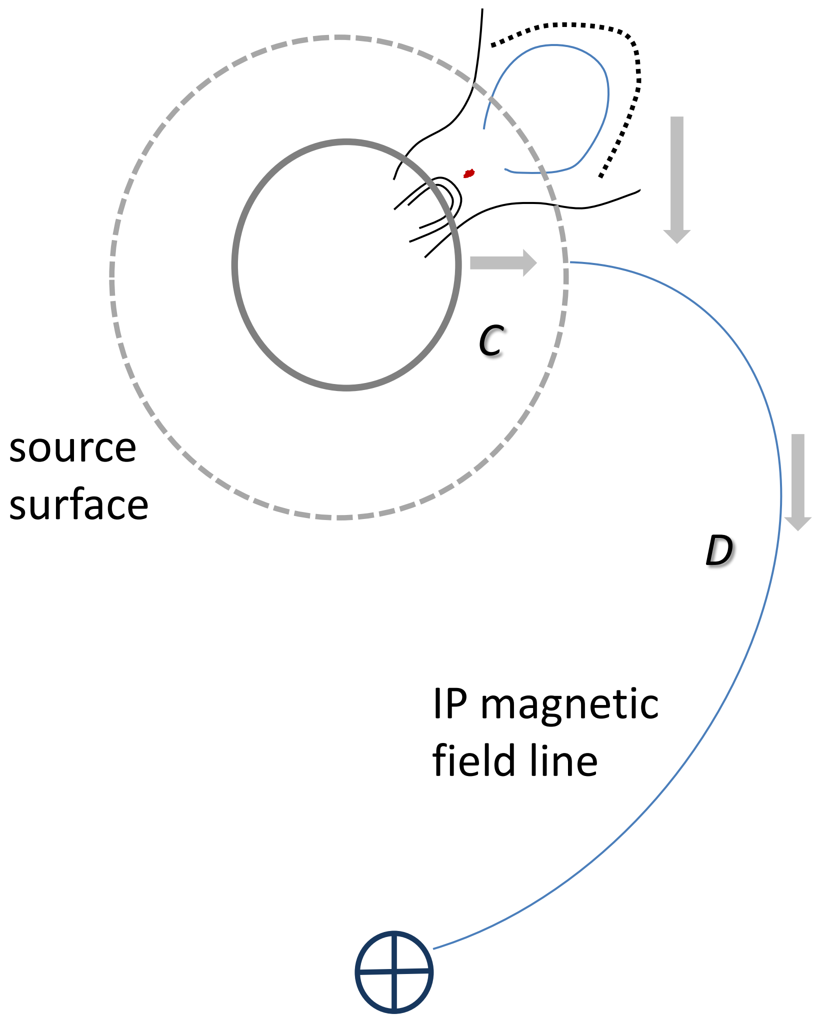
SOHO/LASCO catalogue

→ on-sky projected speed (100s–3000 km s^{-1})

SEPs and solar cycle



II. Magnetic connection to Earth



C. Particle access to open field lines

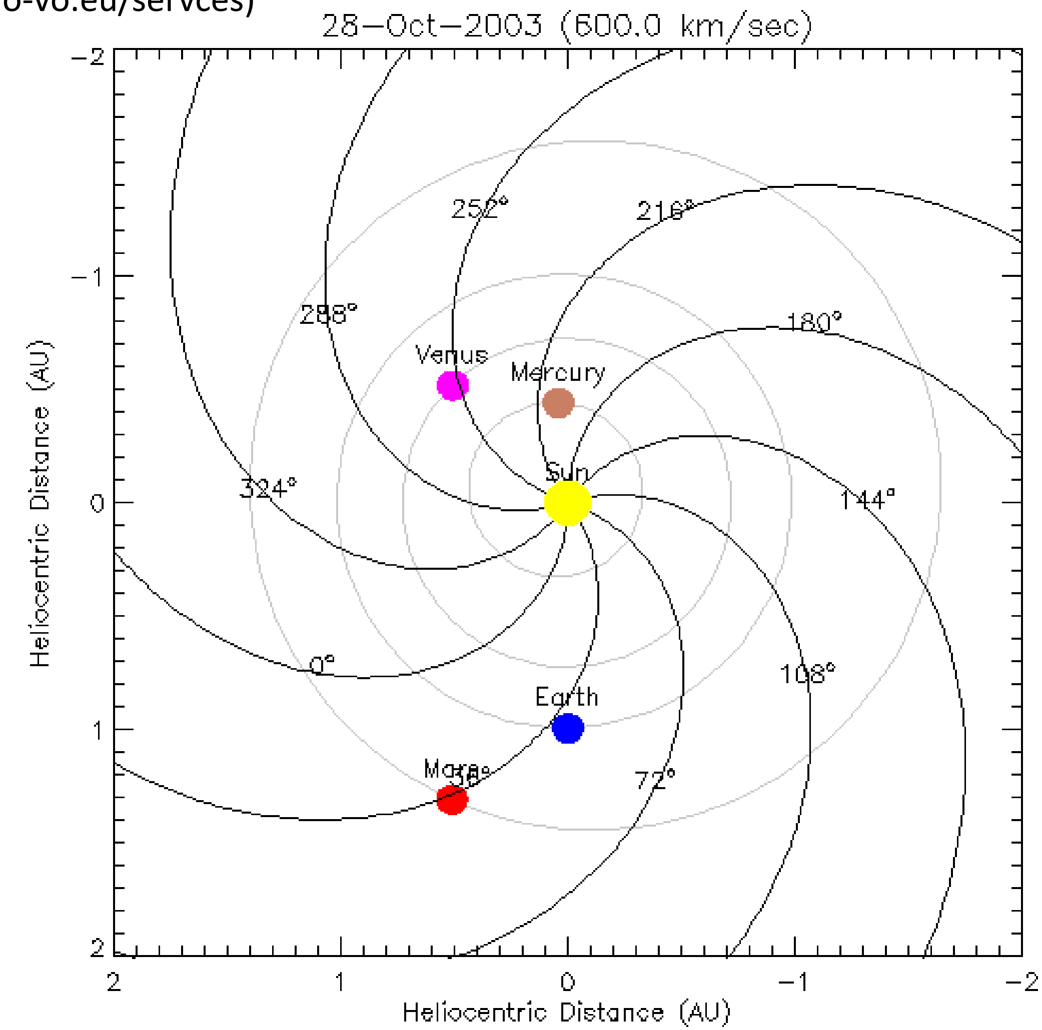
from the acceleration site to to 2.5 R_S

D. Particle access to Earth

access to magnetic field line
connected to 1 AU

D. Parker spiral magnetic field

Calculated with HELIO
(helio-vo.eu/servces)



Parker spiral IMF
(Parker 1963)

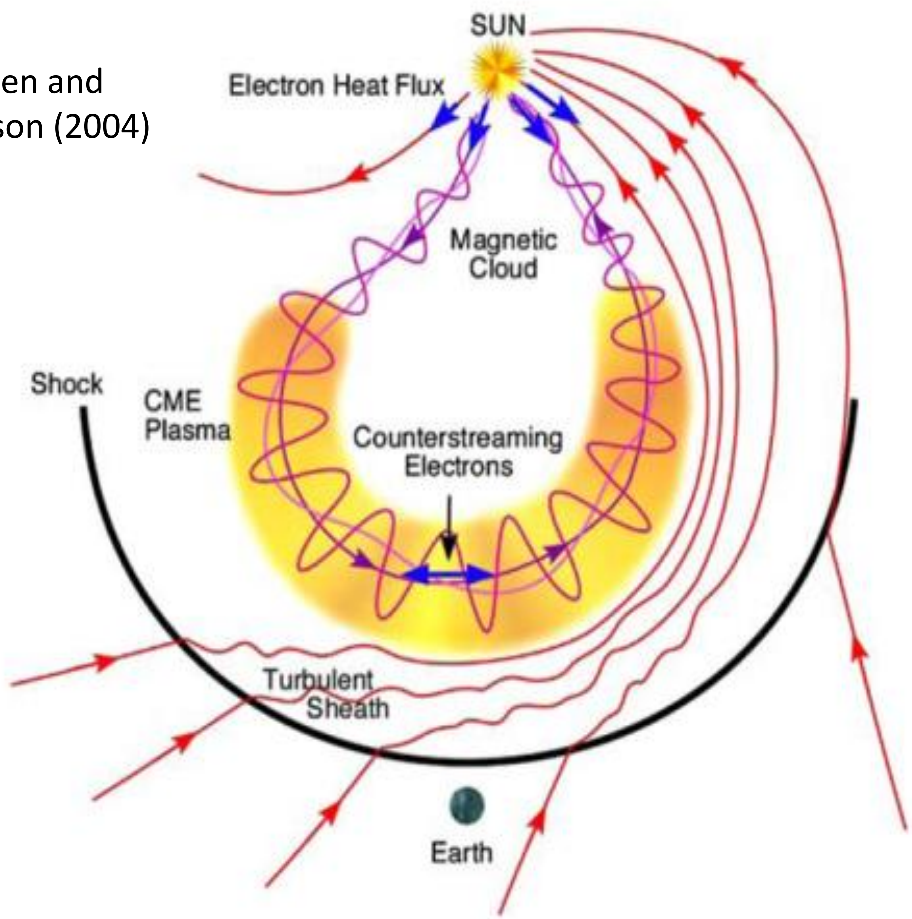
≈ 1.2 AU
45°
depends on solar wind speed

'SoWi' SEP category

50% in solar wind

D. Interplanetary coronal mass ejection (ICME)

Zurbuchen and Richardson (2004)



Case studies on SEP propagation within ICMEs

Torsti et al. (2004), Malandraki et al. (2005), Masson et al. (2012)

Statistical approach: ICME configuration and SEP propagation

present study

ICME catalogue

Richardson and Cane (2010)

'ICME' SEP category

20% within ICME

Aim

To study the physical relationship between in situ particles and coronal activity from a statistical perspective

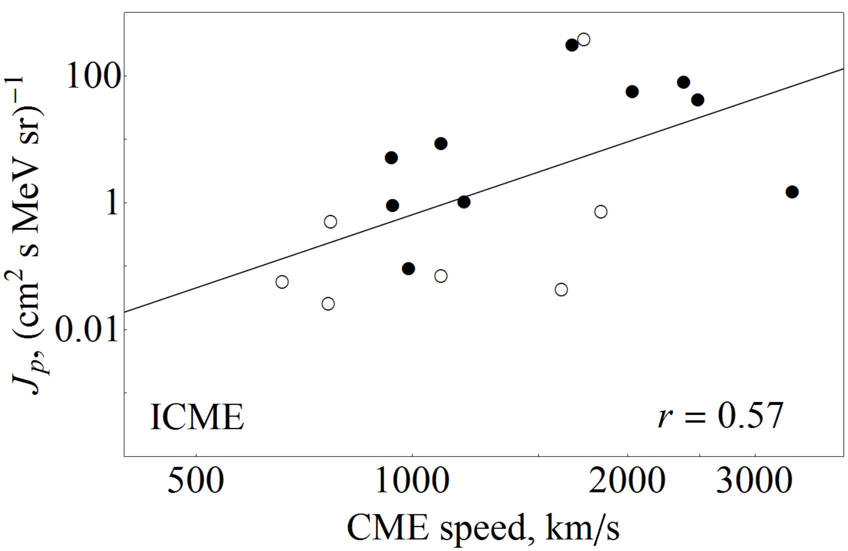
To build the correlations between

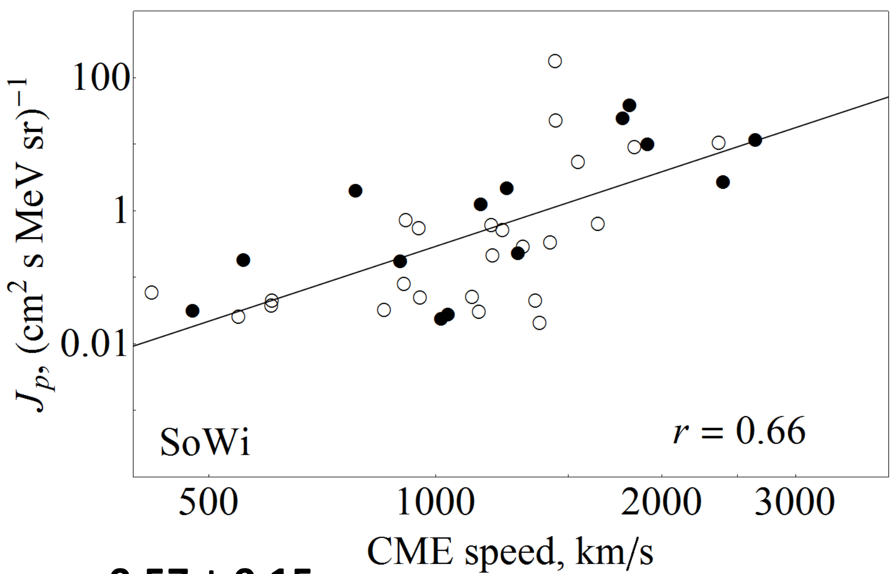
SEP events *(particle intensity)* and
solar activity *(flare SXR flux and CME speed)*

→ taking into account IP magnetic field (IMF) configuration

Statistical analysis

Peak particle intensity vs. CME projected speed





ICME events: ***r* = 0.57 ± 0.15**

SoWi events: ***r* = 0.66 ± 0.07**

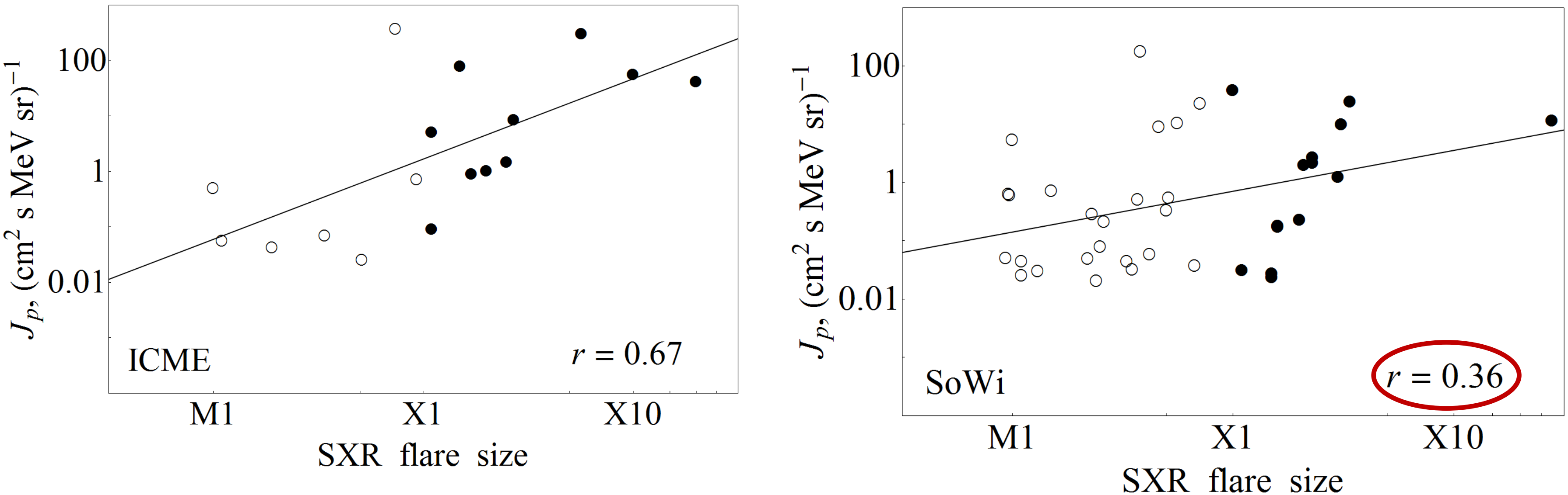
All events: ***r* = 0.63 ± 0.05**

Standard deviation,
method by Wall & Jenkins (2003)

0.6–0.7 (Kahler 2001, Gopalswamy et al. 2003, Cane et al. 2010)

Statistical analysis

Peak particle intensity vs. SXR flux



ICME events: **r = 0.67 ± 0.12**

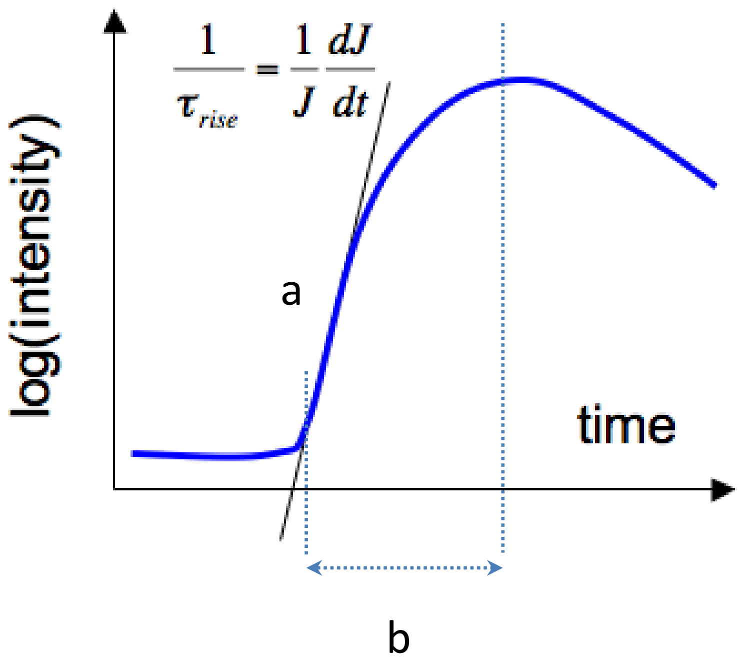
SoWi events: **r = 0.36 ± 0.13**

All events: **r = 0.59 ± 0.07**

weak flare influence
or transport effects?

0.4–0.6 (Kahler 1982, Cane et al. 2010)

III. Particle transport



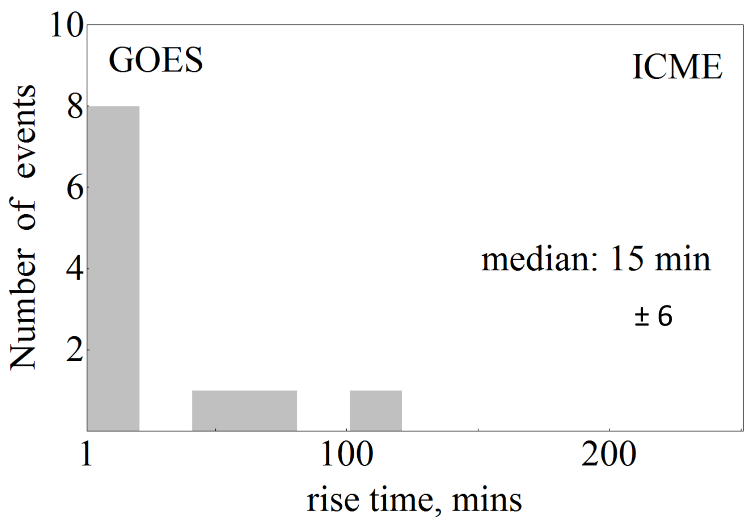
Rise time:
signature of particle transport effects

Methods:
a. steepest slope
b. max–onset
…

subjectivity!

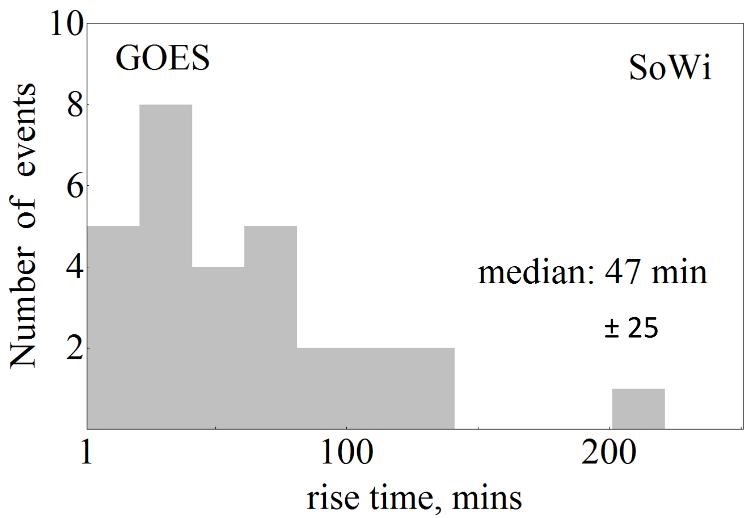
Short rise time: less scattering

SEP rise time



→ *Signature of IP transport effects*

ICME events: weak scattering



SoWi events: stronger scattering

Wind/EPACT protons

ICME events rise time: 11 ± 7 min

SoWi events rise time: 66 ± 35 min

Radio spectral analysis

Diagnostic

electron **acceleration**: flare reconnection vs. shocks

electron **escape**: confinement vs. open field lines

electron **propagation**: from low corona (cm-λ) to IP space (DH/km-λ)

Data

~10 ground-based radio observatories

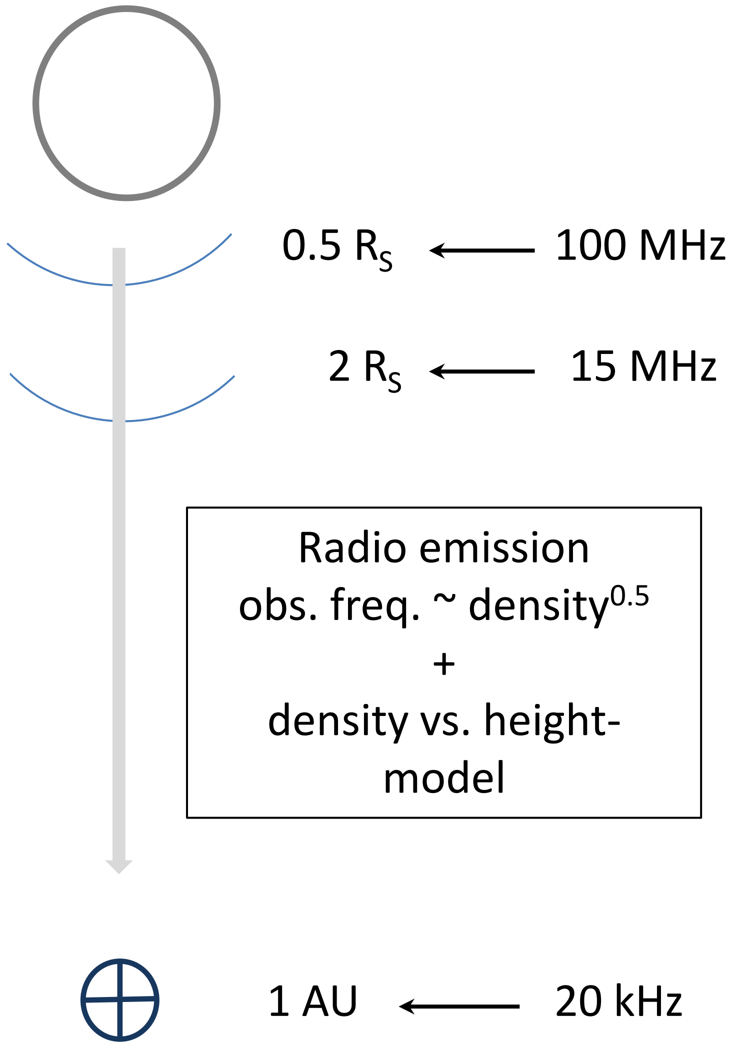
(spectra 20 MHz – 4.5 GHz; single frequency plots 0.2–15 GHz)

Wind/WAVES (3 kHz–14 MHz)

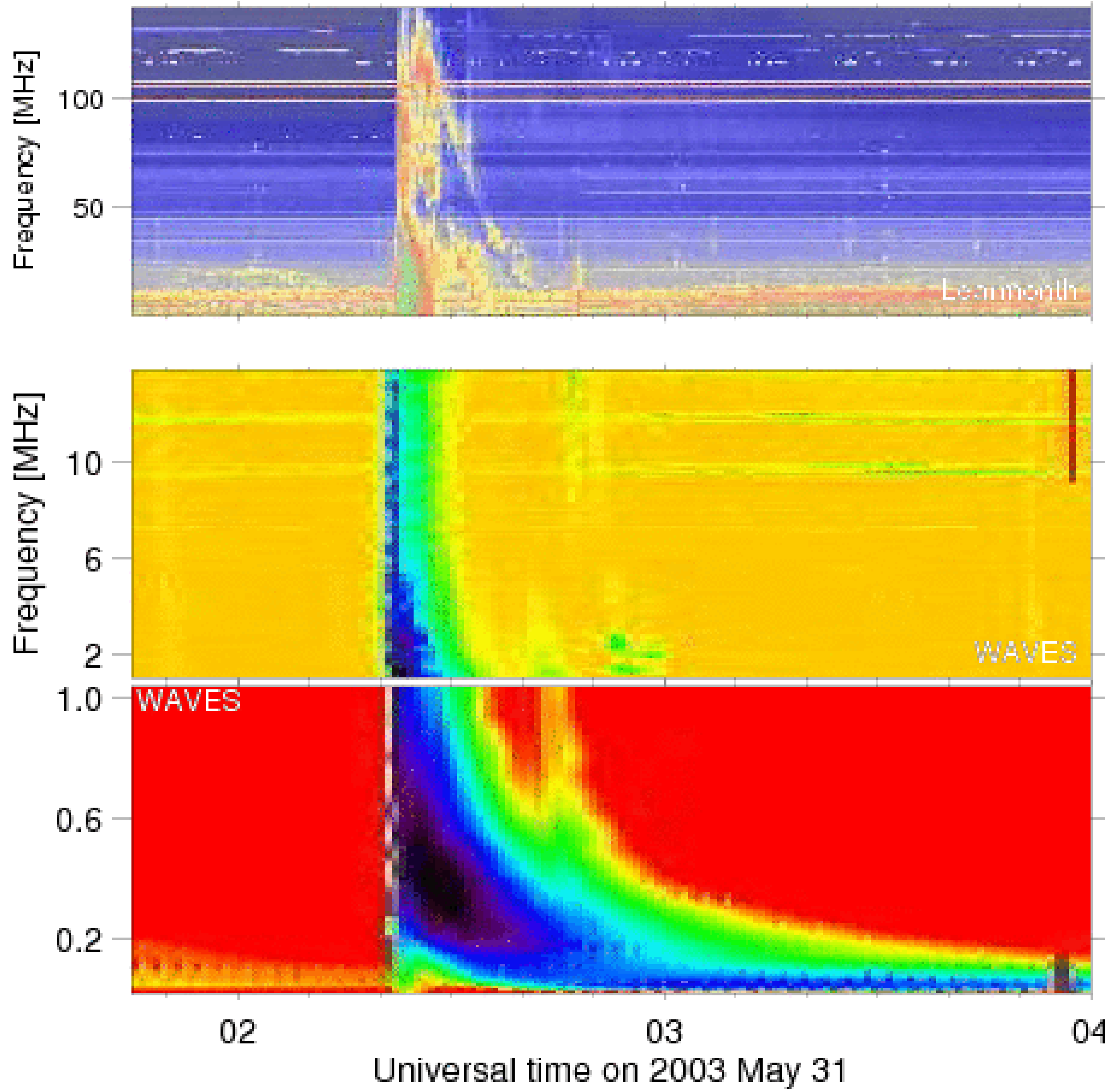
Results

for all ICME and SoWi events

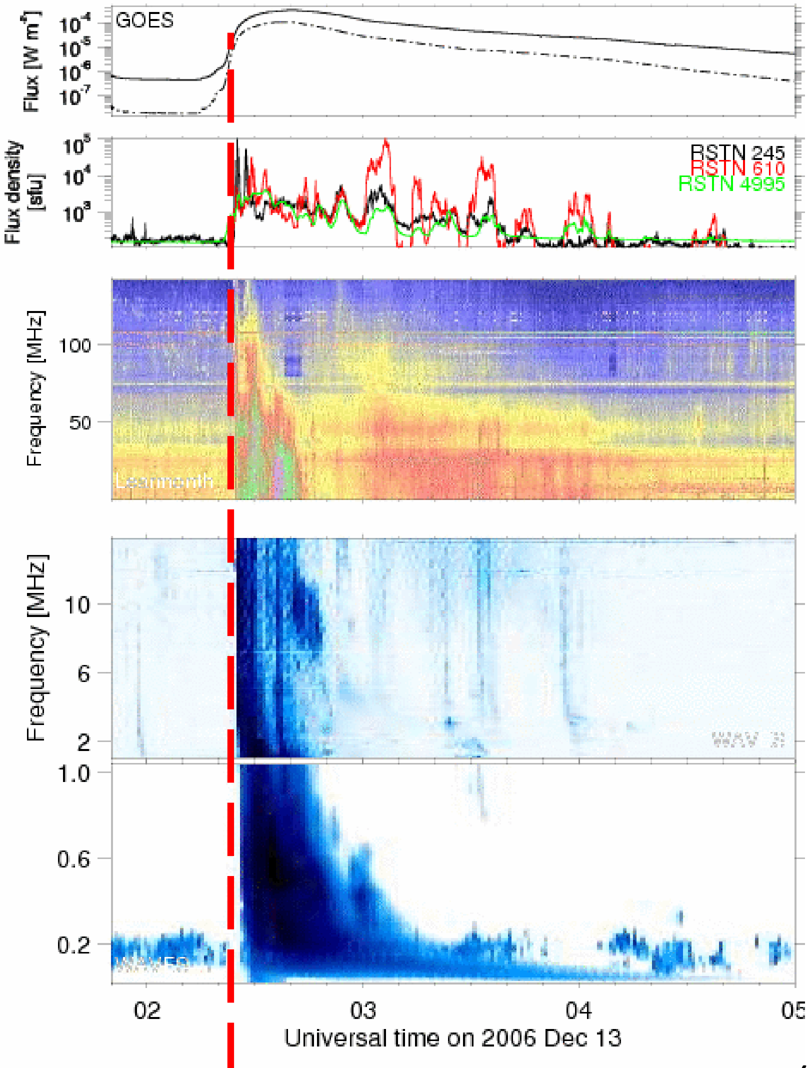
Radio spectral analysis

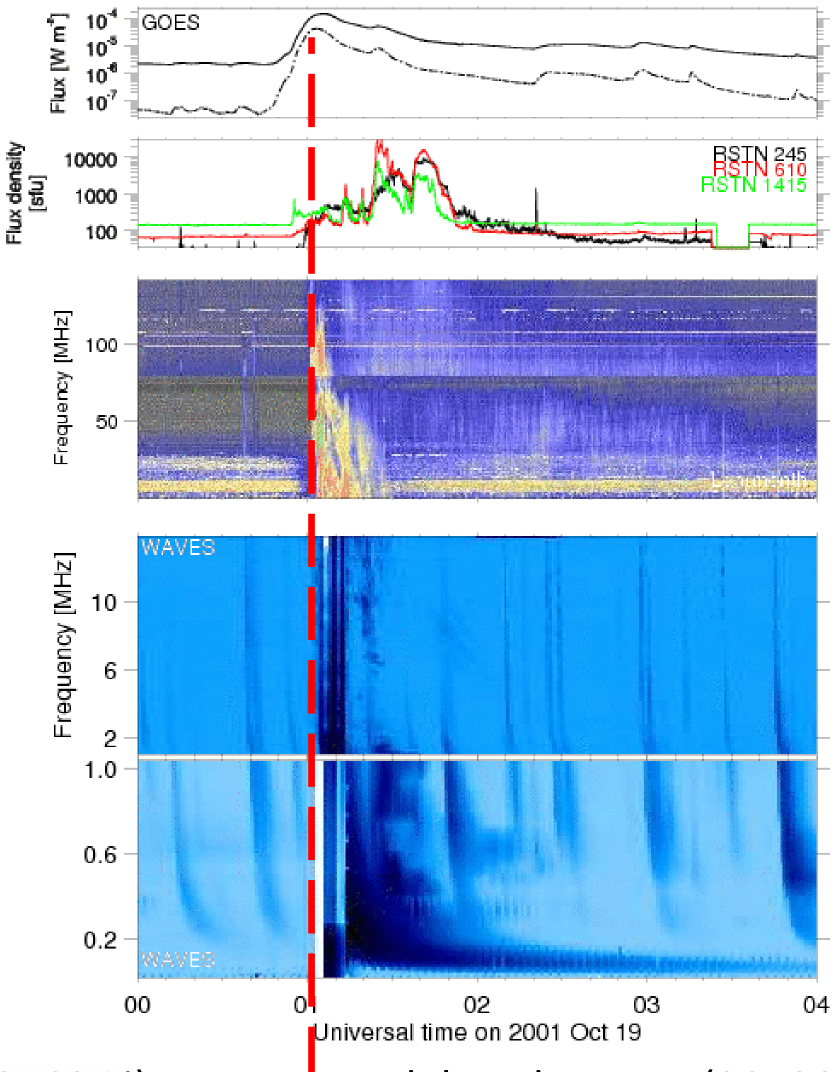


Radio emission
obs. freq. ~ density$^{0.5}$
+
density vs. height-model



Radio spectral analysis





prompt escape (50–60 %)

delayed escape (20–30 %)

Results

I. Particle acceleration + particle escape (radio analysis)

→ good correlation of the particle intensity with **CME** speed for ICME/SoWi category

→ good/poor correlation of the particle intensity with SXR **flare** flux in ICME/SoWi category of SEP events

→ type II (shocks) vs. III (flare) radio bursts: majority vs. all cases

II. Magnetic connection (IMF conditions)

→ *20% of all SEP events propagate within ICME*

→ *30% – in the vicinity of the ICME*

→ *50% – along Parker spiral*

III. Particle transport (rise time analysis)

→ **short/long** rise time for **ICME/SoWi** particle events: **weak/stronger** scattering

Interpretation

I. Particle acceleration + particle escape (radio analysis)

→ **mixed flare/CME contribution to ICME/SoWi particle events**

II.+III. Magnetic connection + particle transport

→ **scattering**

1. SEP amplitude:
acceleration strength;
escape/confinement;
scattering effects

2. SEP duration:
acceleration time;
scattering effects