



# Solar energetic particle (SEP) events and associated solar phenomena: statistical studies in solar cycle 23

**Rositsa Miteva**

research associate

Space Research and Technology Institute

Bulgarian Academy of Sciences

[rmiteva@space.bas.bg](mailto:rmiteva@space.bas.bg)

*In collaboration with:*

*K.-L. Klein (France), O. Malandraki (Greece), S. W. Samwel (Egypt), H. A. S. Reid (Scotland),  
A. Nindos (Greece), A. Kouloumvakos (Greece)*

## **Outlook**

- I. SEP events – overview**
- II. SEP origin – the debate**
- III. Interplanetary conditions – a new parameter?**
- IV. Two work topics: SEP statistics and SEP-radio signatures**
- V. Remarks**

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# I. SEP events: definition, instruments, measurements

## Definition

*Solar energetic particles are transient enhancement of the intensity of charged particles: electrons with energies > 10s keV, protons and ions > 100s keV, observed at instruments onboard spacecraft or at Earth*

## Instruments

- space
  - L1 (ACE/EPAM, Wind/EPACT, SOHO/EPHIN)
  - geostationary orbit (GOES)
  - along Earth orbit (STEREO A&B)
- ground
  - network of neutron monitors [www.nmdb.eu](http://www.nmdb.eu)

## Measurements

- space: primary particles
  - particle 'intensity'*
  - units: *particles/(cm<sup>2</sup> s sr MeV)* or **particle flux units**, *particles/(cm<sup>2</sup> s sr)*
  - flux**
  - units: *particles/ (cm<sup>2</sup> s)*
  - fluence**
  - units: *particles/cm<sup>2</sup>*
- ground: secondary particles
  - count rates**

# I. SEP events: species, energy ranges, profiles

protons

electrons

**ACE/EPAM** 38–53/175–315 keV

(<http://www.srl.caltech.edu/ACE>)

**SOHO/EPHIN** 250–700 keV

(<http://www2.physik.uni-kiel.de/SOHO>)

**GOES (ONERA database)** 15–40 MeV

(courtesy D. Boscher)

**Wind/EPACT** 19–28 MeV

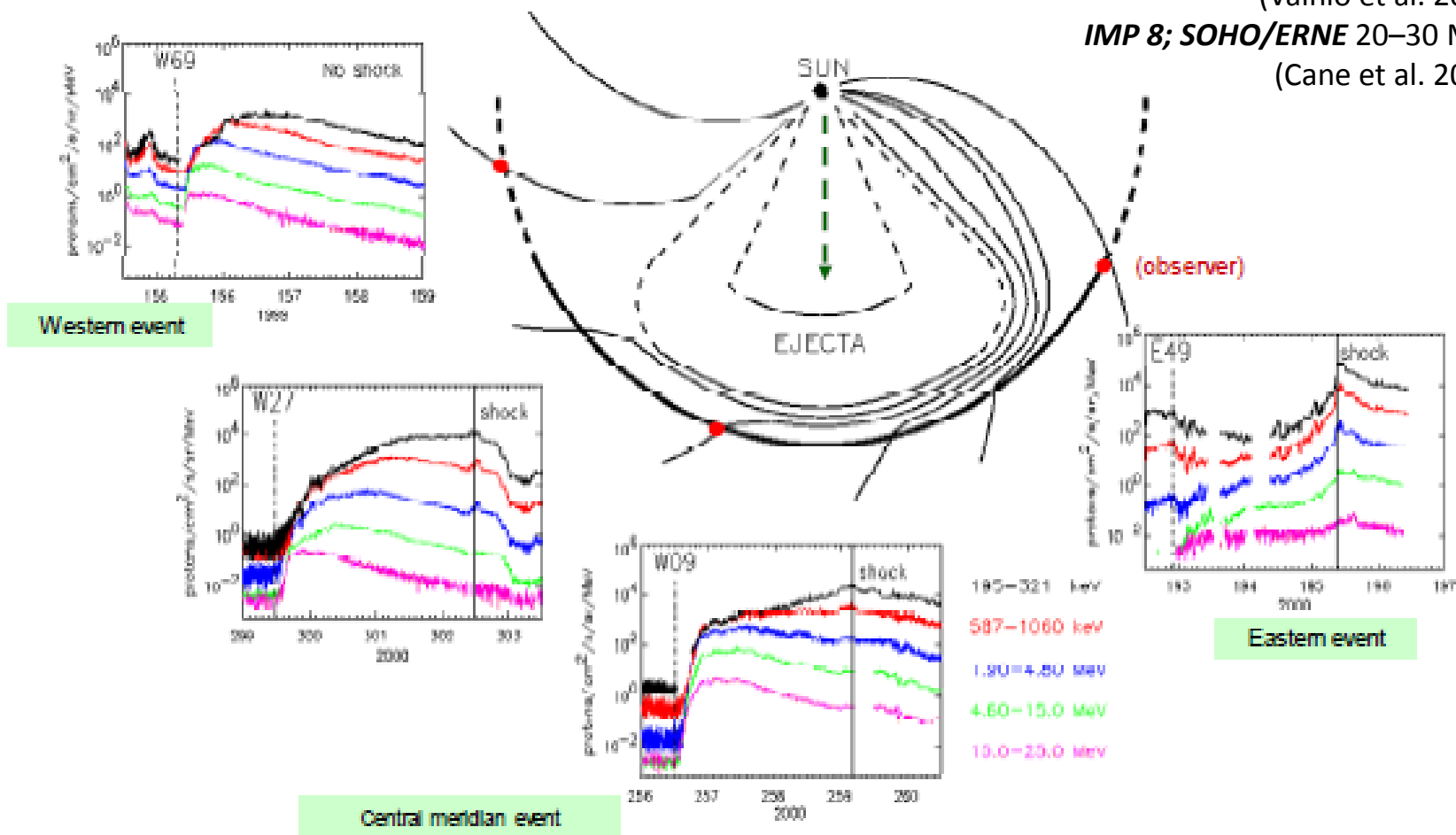
(<http://cdaweb.gsfc.nasa.gov>)

**SOHO/ERNE** 25–41 MeV

(Vainio et al. 2013)

**IMP 8; SOHO/ERNE** 20–30 MeV

(Cane et al. 2010)

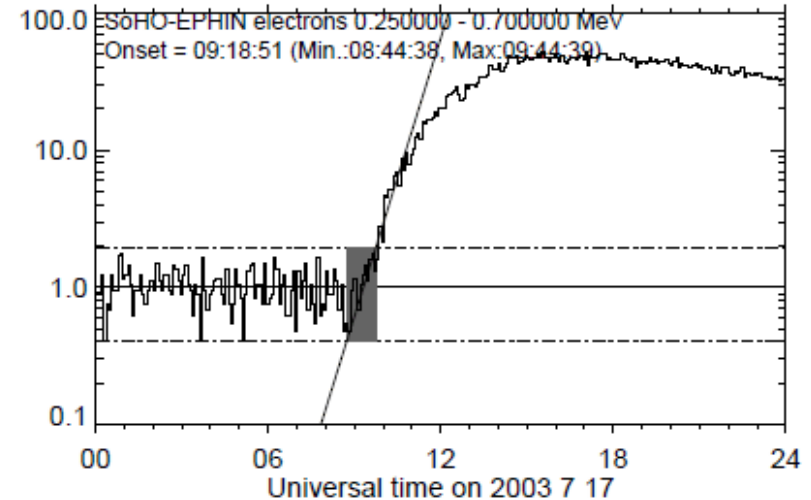


cartoon adapted from Lario and Simnett (2004)

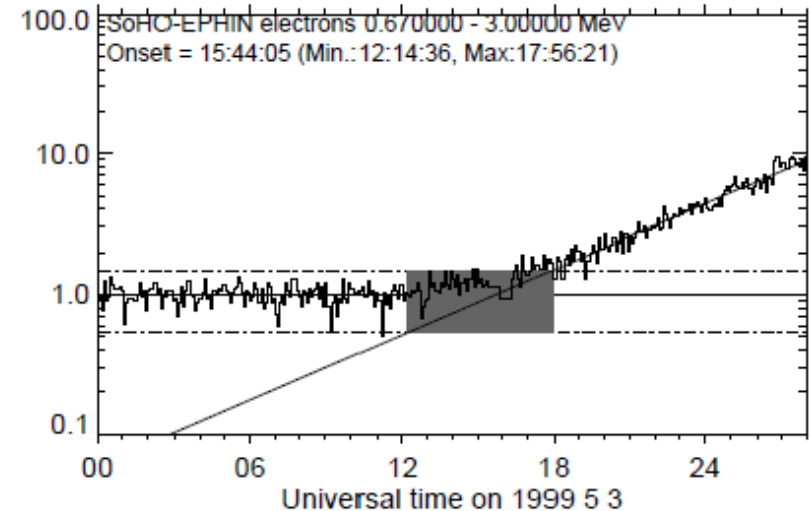
# I. SEP events: times, assumptions and uncertainties

## Scheme to determine the SEP parameters

- onset at 1AU:  $t_{1AU}$ 
  - depends on the method
  - depends on the steepness of the intensity curve
  - ex.:  $bg \pm 3\sigma$ : uncertainties vary  $\pm(1-150)$  mins
- solar wind speed
  - data from SOHO/CELIAS-MTOF-Proton Monitor
  - e.g., averaged over 12h before proton onset at 1AU
- Parker spiral (PS) length for each event
  - depends on the solar wind speed only
  - 'classical value': 1.2 AU
- Travel time:  $t_{travel} = PS \text{ length} / \text{particle speed}$ 
  - ex.:  $\sim 10$  min for the electrons (ACE/EPAM low energy),
  - $\sim 30$  min for the protons (Wind/EPACT)
- release time at the Sun:  $t_{rel} = t_{1AU} - t_{travel}$ 
  - assuming scatter-free propagation of the first arriving particles
  - always a subject to approximations and assumptions



Ex.: flare at E21



Ex.: flare at E32

## II. The SEP accelerators in the solar corona: flares vs. CMEs

### Solar eruptive phenomena (what we observe)

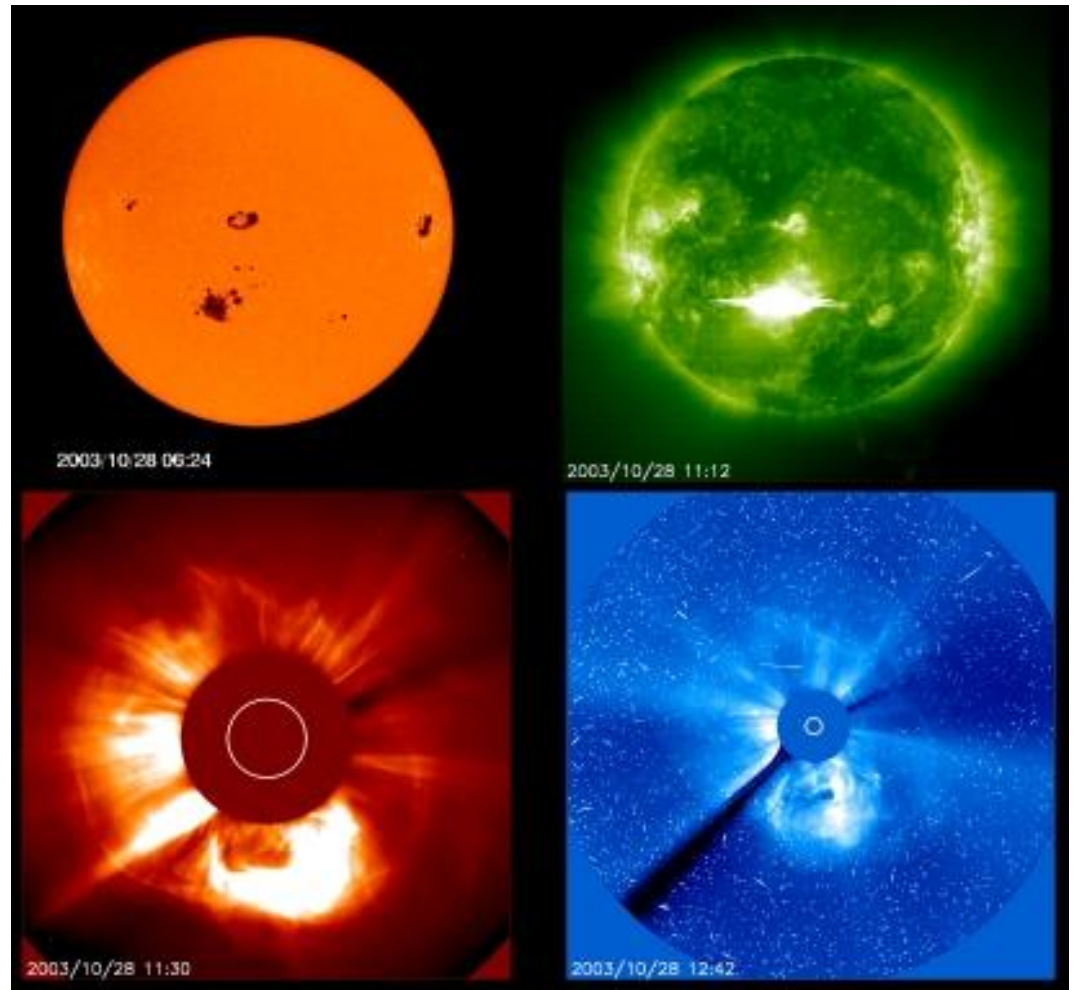
- Flares – ‘a flash of light’, e.g., see the EIT image (right); major magnetic reconstruction in the solar corona, leading to plasma heating, mass motion and EM radiation
- Coronal Mass Ejections – ‘a bubble’ on white-light LASCO images (right); part of the corona is ejected into the IP space

### Physical mechanisms for particles acceleration (what we believe happens)

- Magnetic reconnection (the process triggering flares)
- Shock waves (ahead of CMEs)

### Signatures of energetic particles (what is the result)

- EM emission
- in situ detection

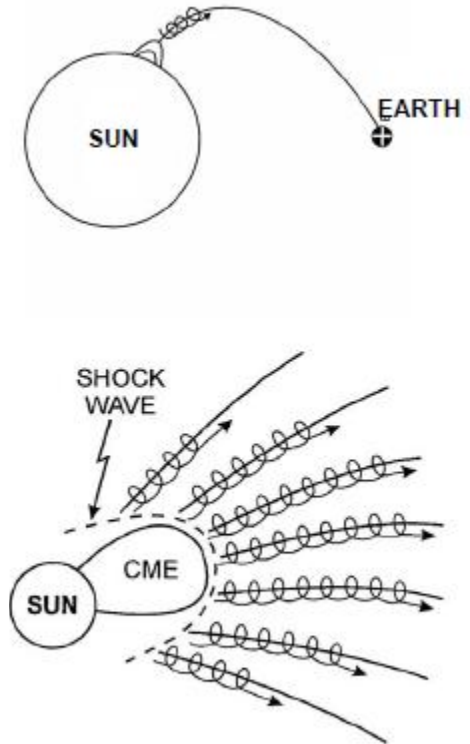


images from SOHO satellite

## II. SEP events: classification – implication for their solar origin

- Single-class type: flare only (before the CME discovery in the 70s)
- Two-class picture: impulsive vs. gradual SEP events (flare vs. CME contribution)  
Reames 1999
- Plateau-like SEP distribution (flare and CME contribution)  
Kocharov and Torsti (2002), Cane et al. (2003, 2006, 2010), Klein and Posner (2005)...

	Impulsive events	Gradual events
Particles	Electron-rich	Proton-rich
$^3\text{He}/^4\text{He}$	$\approx 1$	$\approx 0.0005$
Fe/O	$\approx 1$	$\approx 0.1$
H/He	$\approx 10$	$\approx 100$
Duration of X-ray flare	Impulsive (minutes, hard X-rays)	Gradual (hours, soft X-rays)
Duration of particle event	Hours	Days
Radio bursts	Types III and V <sup>b</sup>	Types II and IV
Coronagraph	Nothing detected	Coronal mass ejections, 96%
Acceleration site	Solar flares	Interplanetary shocks
Solar wind	Energetic particles	Very energetic particles
Longitudinal extent	$< 30^\circ$	$\approx 180^\circ$
Events per year	$\approx 1,000$	$\approx 100$



<sup>a</sup>Adapted from Gosling (1993) and Reames (1997)

<sup>b</sup>Impulsive type III and V bursts can be followed by type II and IV

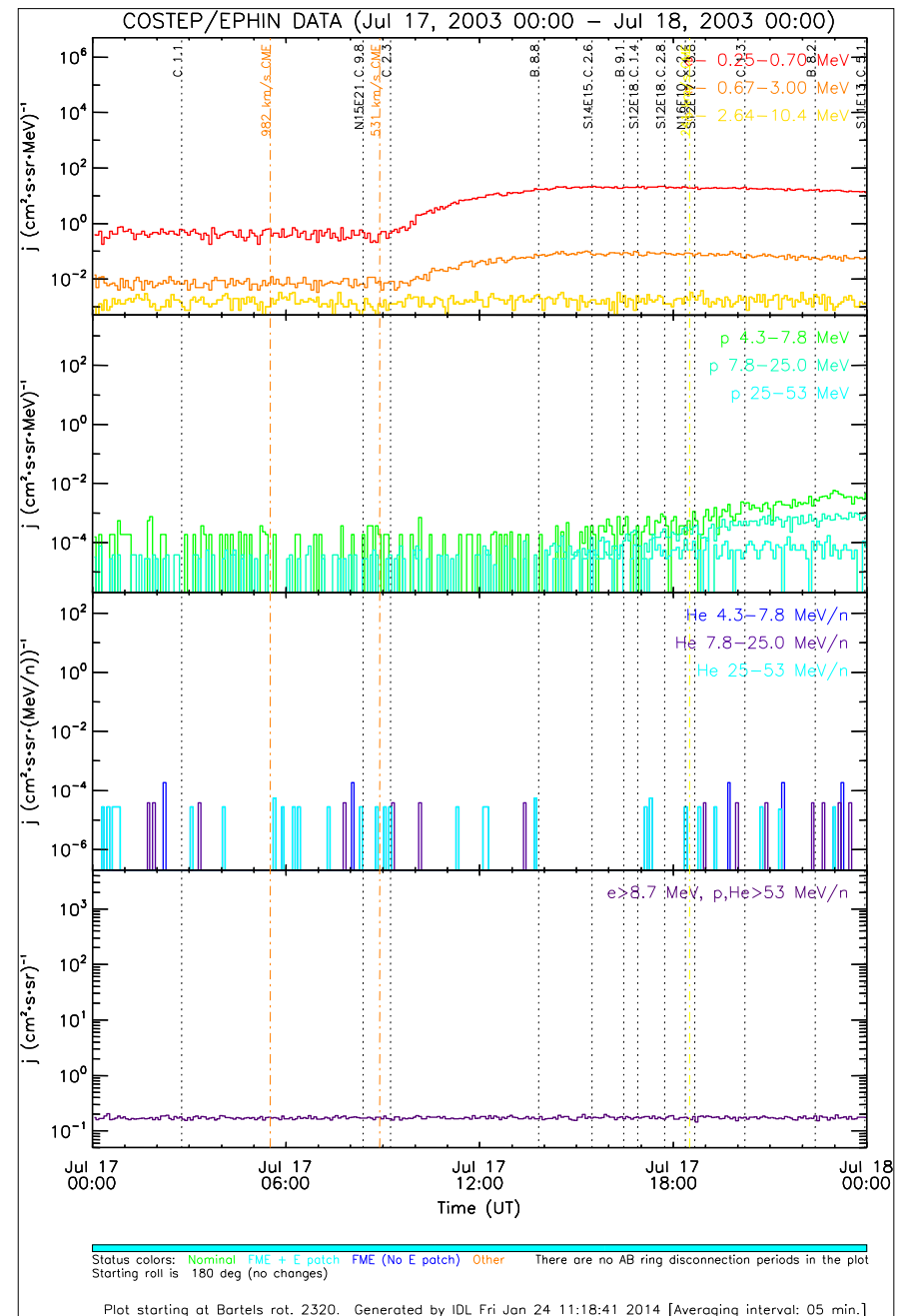
from 'The Sun from Space', Lang 2009

### Note:

- **charges particles (SEPs) propagate only along IP magnetic field (IMF) lines**
- **in order to be detected close to Earth, SEPs need to be injected initially on the field lines connected to the observer (flare scenario) or some time later in the IP space (CMEs)**

## II. On the solar origin of SEP events: Timing analysis I

- It is an observational fact that SEP events follow in time solar eruptive phenomena (flares and CMEs)
- Identifying eruptive phenomena as SEP-solar origin (solar source) entails (subjective!):
  - flares/CMEs to precede the SEP onset;
  - preference is given to flares with CMEs from western longitudes;
  - usually a pair of flare and CME is identified as solar origin, because w.r.t. SEPs:
    - = CMEs without flares have SEPs but are rare cases if any  
Kahler et al. 1986; Marque et al. 2006
    - = flares without CMEs have confined particles  
Klein et al. 2010, 2011
- Any delays could be due to travel time of the accelerator to the field lines connected to the spacecraft and/or particle transport (in the corona and the IP space)



## ***II. On the solar origin of SEP events: Timing analysis II*** ***SEP onset at 1 AU in relation to flare/CME onset (median values)***

### ***In the present analyses***

#### ***(observations at $\approx 1$ AU):***

- onset time + uncertainties
- peak SEP intensity
- flare class, CME projected speed:  
both from western and eastern longitudes
- time coverage: 1997–2006

### **Data sources**

- **Flares:** *onset of GOES SXR curve*  
*(note: SXR emission due to thermal plasma)*  
Solar Geophysical Data reports  
ILD/SolarSoft goes-routine
- **CMEs:** *time of first appearance in*  
*LASCO-C2*  
*(note: later time that 'true' onset time)*  
LASCO CDAW online catalog

### **To construct (histograms on next slide)**

- time offsets between the proton/electron onset at 1 AU and the proxy onset of the flare and CME at the Sun
- results for eastern, western and all SEPs

### **Results**

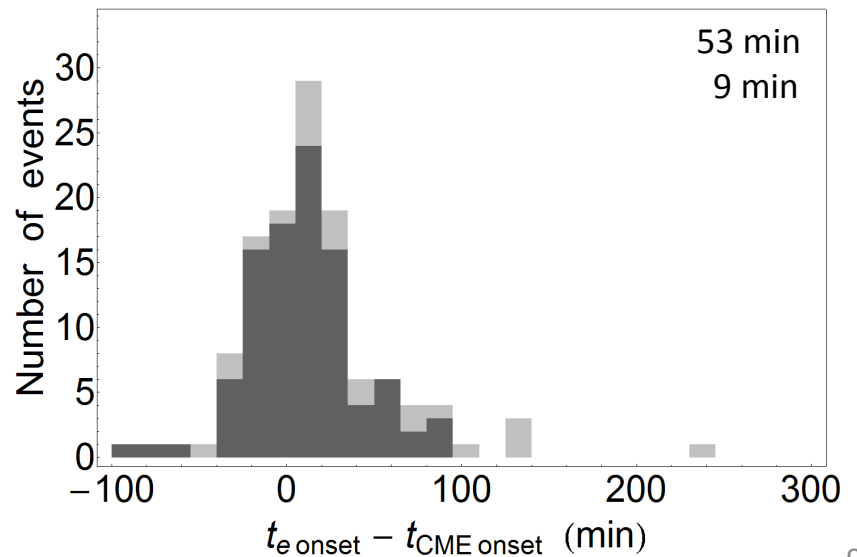
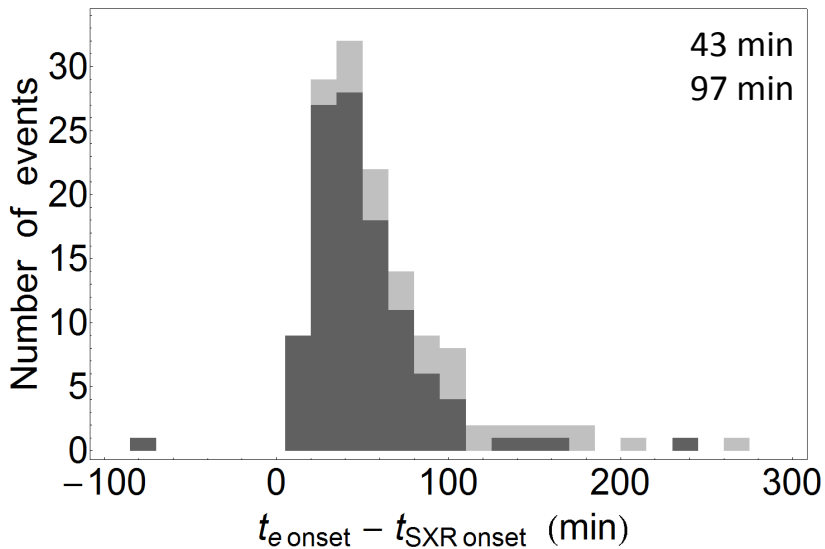
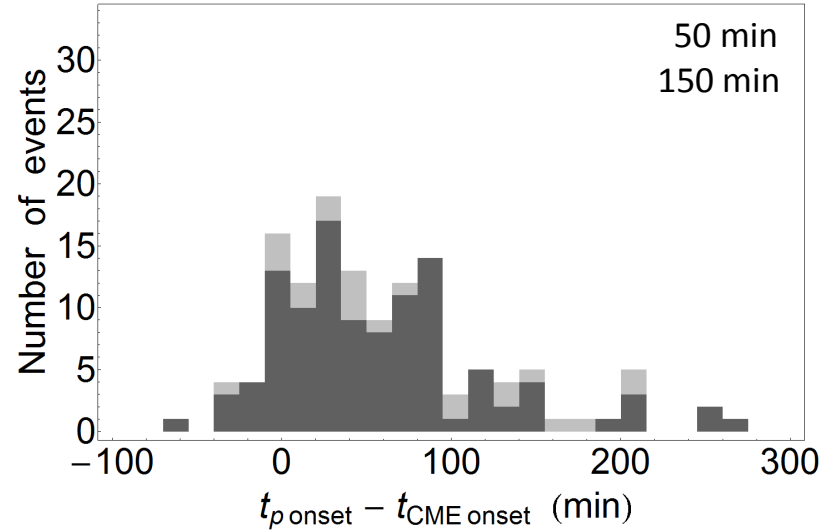
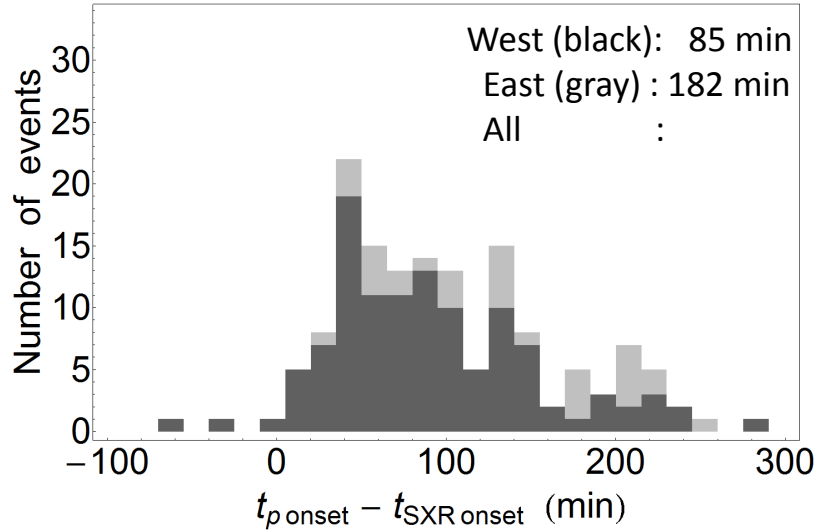
- distribution of values, no uncertainties taken into account!
- the median values of the time offsets is smaller for electrons
- no conclusion on whether SEP onset is linked more to the flare vs. CME onset



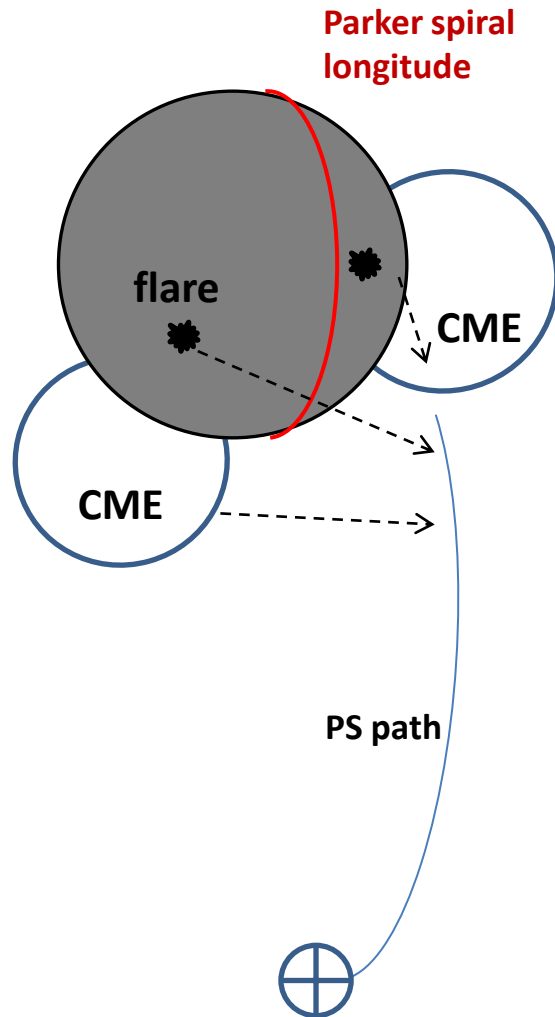
## II. On the solar origin of SEP events: Timing analysis II

### SEP onset at 1 AU in relation to flare/CME onset (median values)

- examples: p-data Wind/EPACT (19–28 MeV); e-data ACE/EPAM (38–53 keV)



## II. On the solar origin of SEP events: flares or/and CMEs



Ways towards identifying the SEP origin

- Timing analysis → SEP origin  
particle onset at 1 AU → particle release at the Sun  
using occurrence and timings of: flares, CMEs,  
radio bursts, waves...

- Observations **this work**  
Correlation studies  
particle peak intensity vs. SXR flare size/CME speed  
Timing arguments using EM emission  
flare vs. CME contribution to the particle flux

- Theoretical efforts  
Modeling  
injection, propagation...

## ***Statistical studies on SEP events***

### **Statistical studies on solar energetic particles**

- larger number of events
- limitation: considering the overall properties only
- evaluation of the statistical significance of the results is needed!

### ***Solar cycle 23 (1997–2006)***

Cane et al. (2010) *JGR*: 1997–2006, 280 proton events > 25 MeV

Laurenza et al. (2009) *Space Weather*: 1995–2005, 93 proton events > 10 MeV

many other partial coverage lists

- **different SEP intensity thresholds used**
- **no uncertainties estimated**

### ***Solar cycle 24 (2007–ongoing): status 2013***

**GOES SEP event list** (<http://umbra.nascom.nasa.gov/SEP/seps.html>)

< 30 events, none during 2007–2009

**SEPServer SEP lists** ([server.sepserver.eu](http://server.sepserver.eu))

~130 events in STEREO-A (2007–2013)

~50 events in STEREO-B (2007–2013)

## Topic 1. Correlation analysis between peak particle intensity and CME speed/flare class

- calculated SEP peak intensity (background subtracted) vs. SXR flare size/CME projected speed
- observational bias for events < longitude West 60: focus on limb events
- calculated uncertainties on the correlations

Selection criteria:

all SEP events in solar cycle 23 (1997–2006) associated with flares/CMEs from western longitudes  
~100 events

work based on Cane et al. (2010) SEP list

*Miteva, Klein, Malandraki, Dorrian, Solar Physics (2013) 282: 579*

### Statistical study with uncertainties

using ‘bootstrap method’ (Wall and Jenkins 2003)

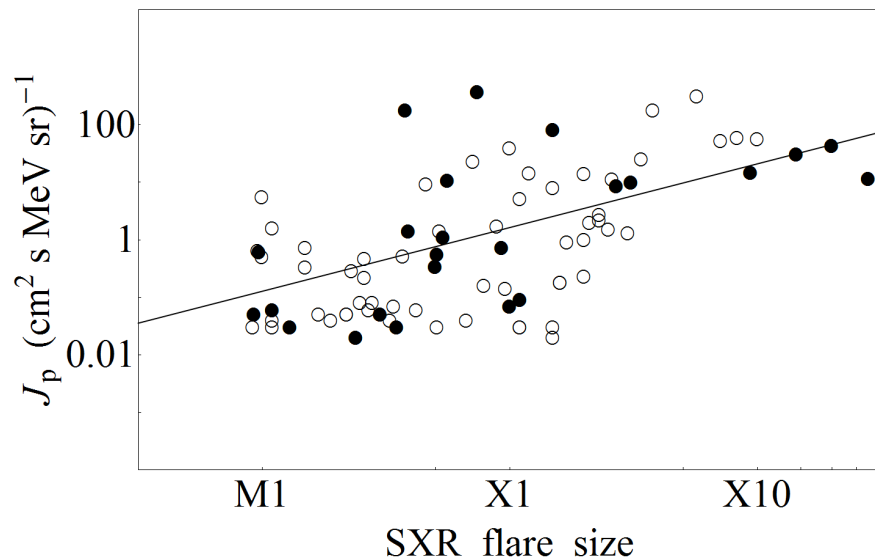
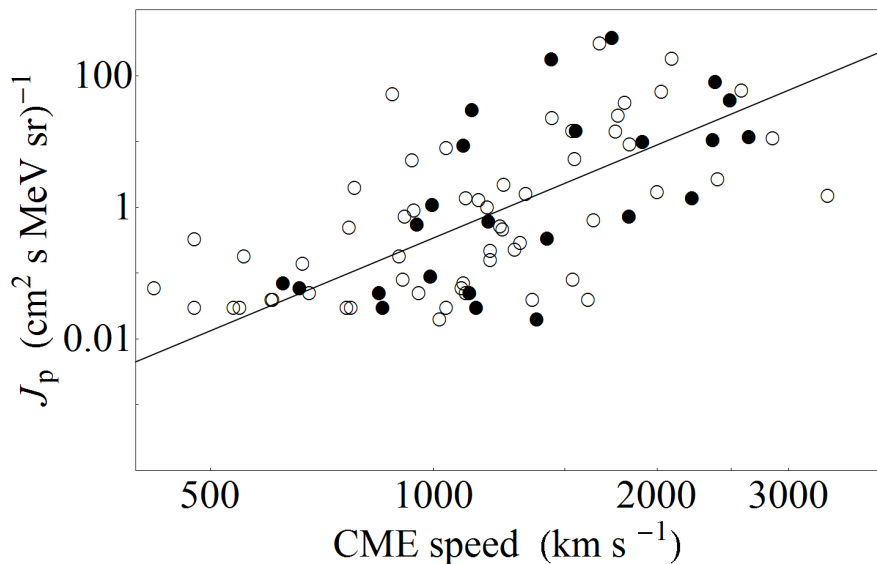
*method description:*

*i.* taking from a sample of N events – N events in random and computing the cc of the new sample

*ii.* the procedure is repeated 1000 times: calculated value of ccs and the standard deviation of the sample (used as the uncertainty measure)

**Goal: to discriminate between the influence of different particle accelerators (flares vs. CMEs) on the SEP intensity in a statistical sense**

## **Correlation analysis between peak particle intensity and CME speed/flare class: results Western events**



open circles: all events; filled circles: limb events > W60

### **Results: Protons (GOES 15–40 MeV)**

All SEPs (81 events): **cc = 0.63±0.05** for CME speed; **cc = 0.59±0.07** for SXR flare class

>W60 (24 events): **cc = 0.64±0.09** for CME speed; **cc = 0.60±0.11** for SXR flare class

### **Earlier studies:**

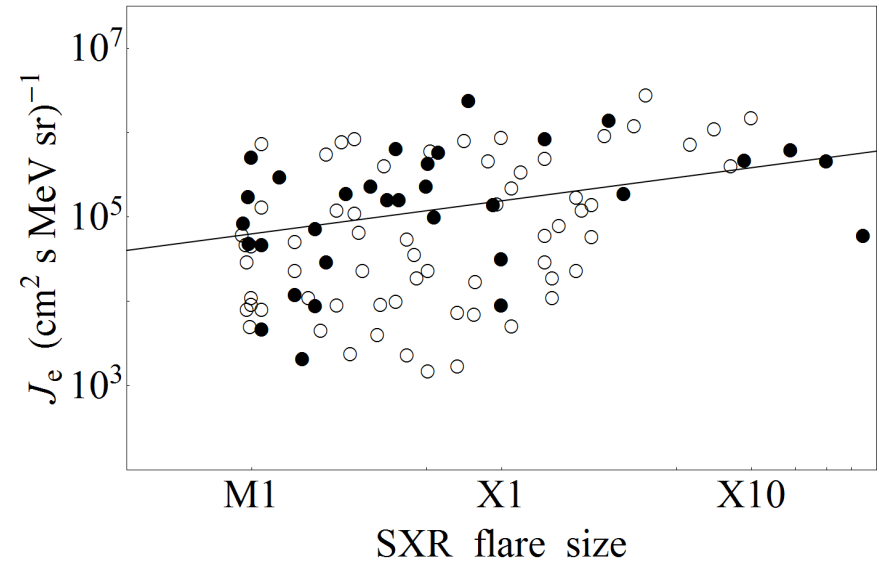
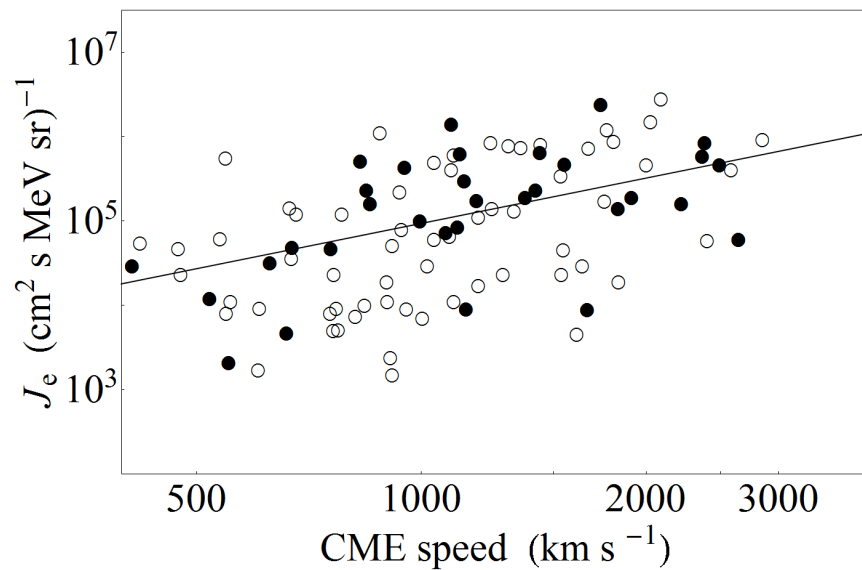
Cane et al. (2010)            cc = 0.6 for CME speed and for SXR flare class

Gopalswamy et al. (2003) cc = 0.6 for CME speed , cc = 0.4 for SXR flare class

Kahler (2001,1982)        cc = 0.7 for CME speed, cc = 0.5 for SXR flare class

**→ differences probably due to small number of events, different intensity thresholds, no uncertainties given**

## Correlation analysis between peak particle intensity and CME speed/flare class: results Western events



open circles: all events; filled circles: limb events > W60

### Electrons (ACE/EPAM 38–53 keV)

All SEPs (96 events): **cc = 0.53±0.07** for CME speed; **cc = 0.40±0.08** for SXR flare class

>W60 (32 events): **cc = 0.52±0.13** for CME speed; **cc = 0.38±0.13** for SXR flare class

**Same cc obtained for the relationship between:**

**peak proton (electron) intensity with SXR size and CME speed: ≈ 0.6 (0.5)**  
**and for proton data from different spacecraft (GOES, Wind, IMP-8)**

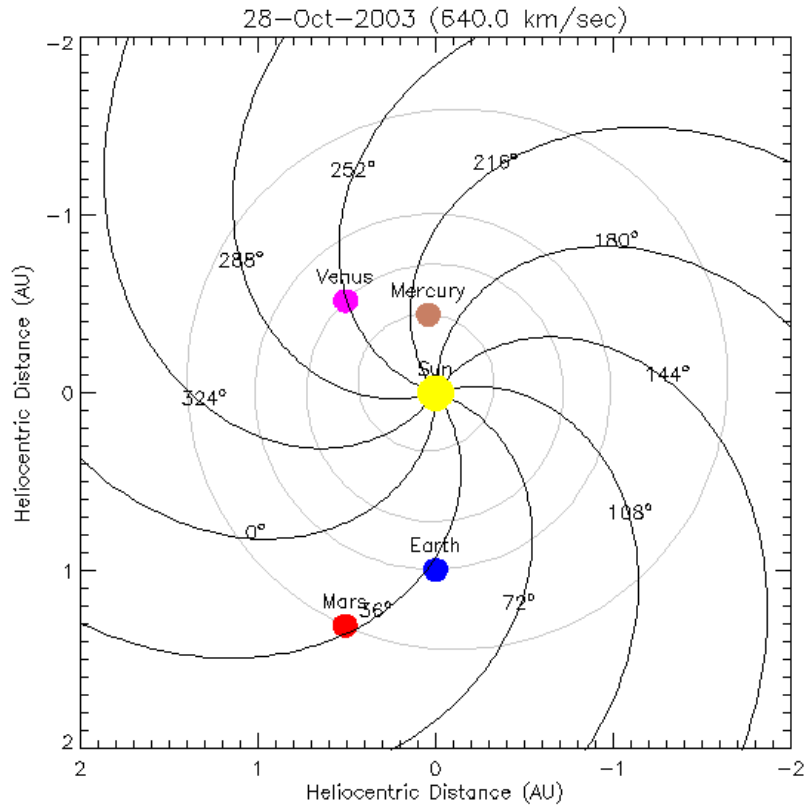
**→ no clear answer by looking at the entire SEP sample**

**→ A need for a new parameter**

# Considering the IP conditions: a new ordering parameter?

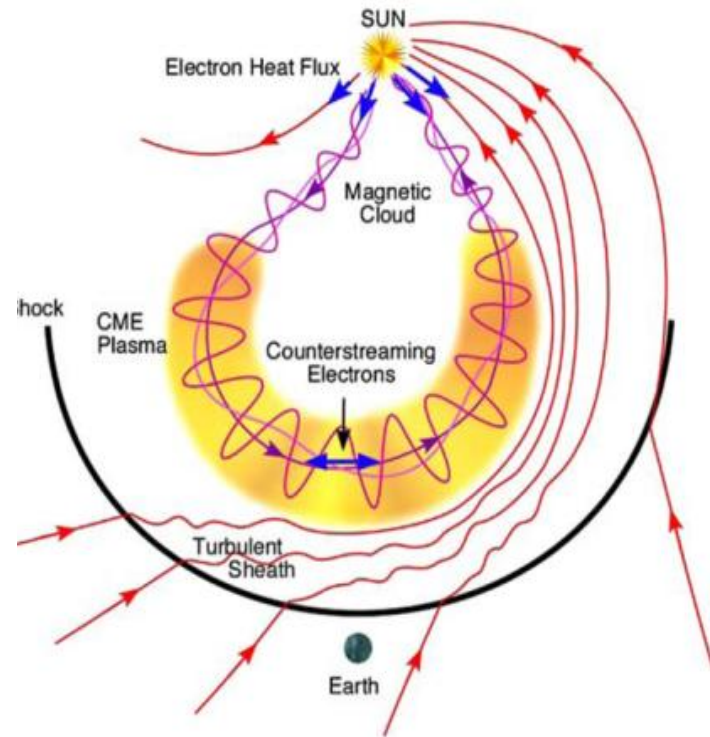
## A. 'quiet' solar wind

plot: HELIOS service tool



## B. ICME disturbance

cartoon: Zurbuchen and Richardson (2004)  
catalog: Richardson and Cane (2010)



## ***Considering the IP conditions: as a new ordering parameter***

**SoWi events:** SEP particles propagating in quiet solar wind conditions along IMF that can be approximated by Parker spiral

~50 % West

~70 % East

**ICME events:** SEP particles propagating inside an interplanetary CME (ICME)

~20 % West

~17 % East

**Vicinity events:** SEPs propagating in the ICME sheath region or behind the ICME where the IMF is strongly disturbed

**Criterion used to place the SEPs in the above categories:**

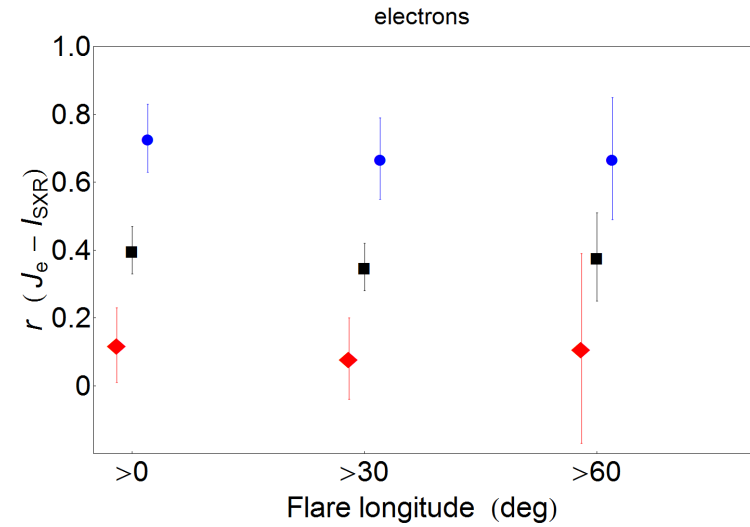
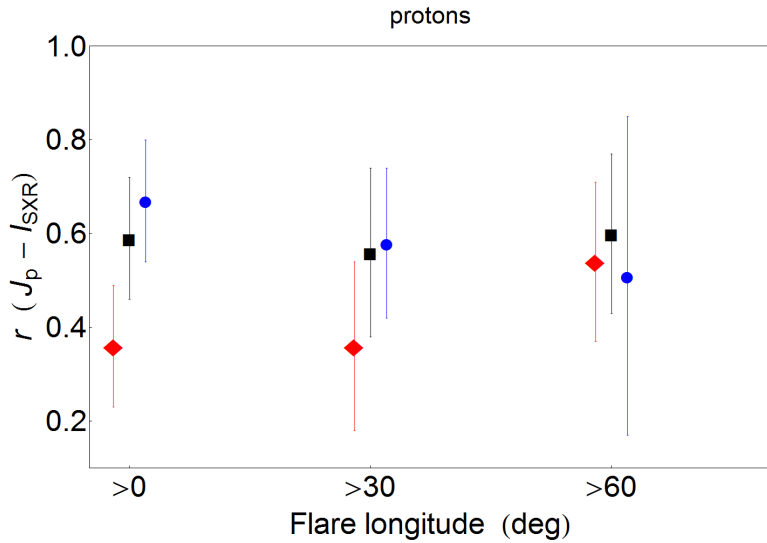
***at 1 AU, the SEP onset is compared to the borders of the ICME (in time)***

- If the SEP onset is within the ICME borders: ICME events
- If any ICME border is at least 1 day apart in time from the SEP onset: SoWi events
- For mixed cases, namely less than 1 day: Vicinity events

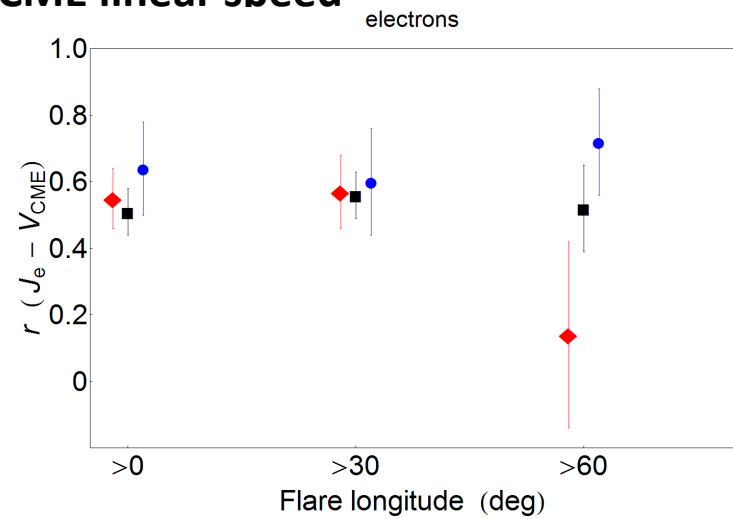
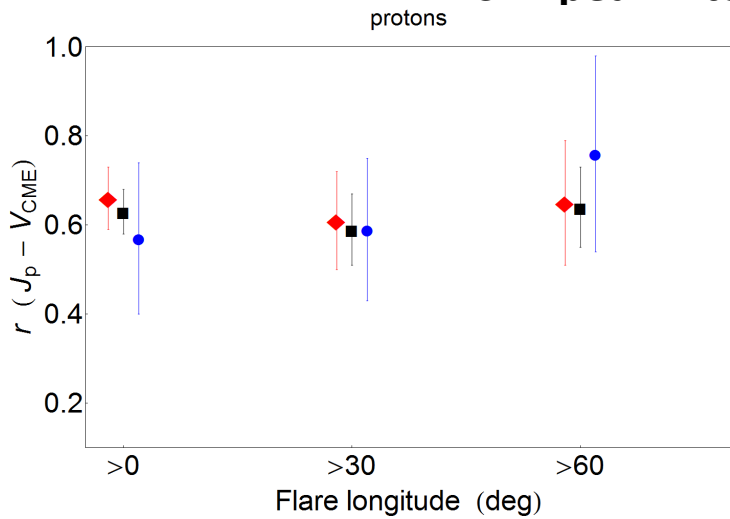


# Considering the IP conditions: results

## SEP peak intensity vs. SXR flare size



## SEP peak intensity vs. CME linear speed



Color code: All, SoWi, ICME

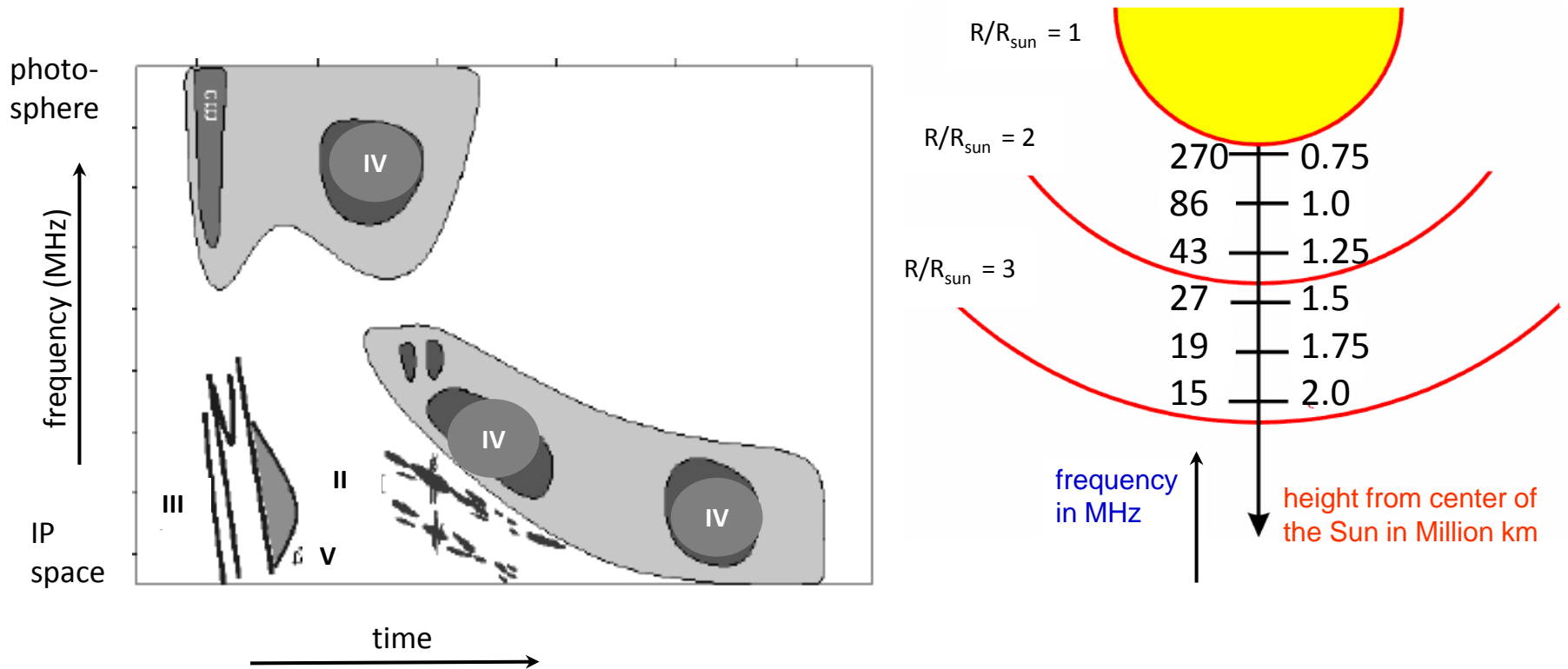
## ***Considering the IP conditions: some conclusions***

- **IP conditions are not a clear parameter to quantify the flare vs. CME influence on the SEP intensity**
- observational bias exists for SEP events associated with solar activity close to the disk center
- limitation to limb events reduces the original sample and increases the uncertainties
- **Taking the entire sample as such and considering the uncertainties we obtained the same correlation coefficient for SEP peak intensity with flare class or CME projected speed**
- this is valid for electrons (0.5) and protons (0.6)
- independent on the instrument: checked for protons only
- **When considering IP conditions we obtain the ICME vs. SoWi events differences, valid both for protons and electrons**
- the correlation of  $J_{\text{peak}}-I_{\text{SXR}}$  is weaker for SoWi events
- the correlations of  $J_{\text{peak}}-V_{\text{CME}}$  is the same for ICME and SoWi events
- **When limiting the sample to limb events (proton vs. electron difference)**
- protons: the correlation of  $J_{\text{p}}-I_{\text{SXR}}$  and  $J_{\text{p}}-V_{\text{CME}}$  is the same for ICME and SoWi events
- electrons: the correlations of  $J_{\text{e}}-I_{\text{SXR}}$  and  $J_{\text{e}}-V_{\text{CME}}$  is weaker for SoWi events compared to ICME events

**Statistical studies cannot give the final answer: a need for other means to discriminate between the flare vs. CME contribution to the particle flux**

# Solar radio emission signatures of SEP events: providing additional information?

Dynamic radio spectrum  $\leftrightarrow$  height-time diagram (density vs. height model needed)



adapted from Warmuth and Mann (2005)

## Notes

**radio emission:** is an indirect diagnostic for the presence and propagation path of energetic electrons in the corona (and by inference also protons)

**dynamic radio spectrum:** gives no positions of the radio emission on the solar disk

## ***Solar radio emission signatures***

### **Phenomenology (Wild and McCready 1950; McLean and Labrum 1985)**

*Type I: called noise storm; < 1 s; bandwidth few 10s MHz; not assoc. with flares*

*Type II: due to shock waves (m-DH); few min; few MHz emission lanes – F and H; CMEs and flares*

*Type III: due to electron beams (0.3 c); seconds; from 1 GHz to 10 kHz; flares (and CMEs?)*

*Type IV: stationary (dm) and moving (m) broad-band continua due to trapped electrons in coronal loops or plasmoid; long-lasting; follow major flares and CMEs*

*Type V: continua after group of type III, 10s sec*

### **Emission mechanisms in solar corona (Melrose 1980, 1985)**

m- $\lambda$  and DH- $\lambda$  (300 MHz–30 kHz): radio emission mechanism  
(at local plasma frequency ( $\omega \sim \text{density}^{1/2}$ ) and harmonics)

dm- $\lambda$  (300 MHz–3 GHz): gyrosynchrotron emission  
(at electron gyrofrequency,  $\omega \sim \text{magnetic field}$ )

$\mu$ - $\lambda$  (> 3 GHz): free–free emission/gyrosynchrotron (< 0.1  $R_{\text{Sun}}$ ; flare related)

## Topic 2. Solar radio emission signatures (as proxy for particle escape)

catalog of all SEP-associated single frequency radio signatures (RSTN data);

catalog of dynamic radio spectra;

timing analysis between microwave and escaping (DH-type III bursts) radio emission

*Miteva, Klein, Samwel, Nindos, Kouloumvakos, Reid, Central European Astroph. Bulletin (2013) 37, 2: 541*

### The scheme

From a SEP event onset times towards:

→ associated flares/CMEs

→ radio emission signatures

### Completed (SolarSoft/IDL)

1. catalog of SEP-associated single frequency

radio signatures (data from RSTN network of stations)

2. catalog of SEP-associated dynamic radio spectra

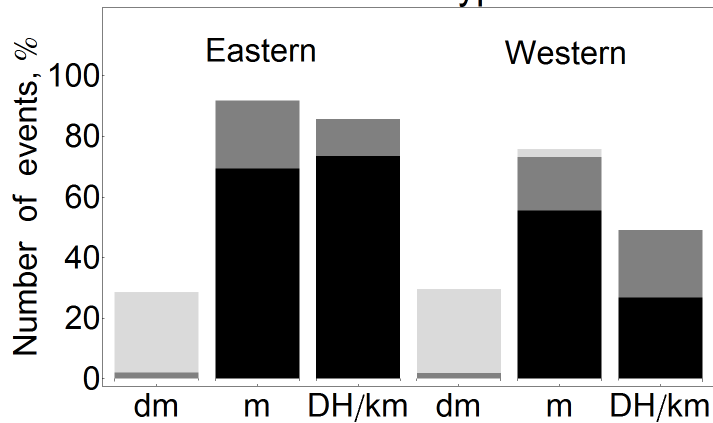
(data from more than 10 ground-based radio observatories and one in space)

Quick-look radio spectral plots and observatory reports (1997–2006)

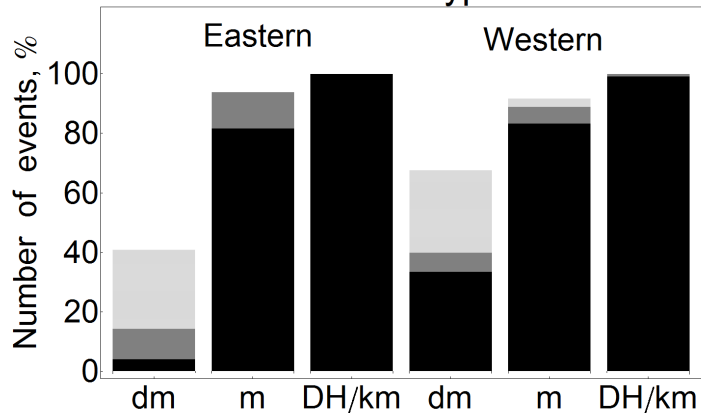
• Ondrejov	800–4500 MHz
• Phoenix-2	100–4000 MHz
• HiRAS	25–2500 MHz
• Culgoora	18–800 MHz
• Potsdam	40–800 MHz
• Artemis	20–650 MHz
• Izmiran	25–270 MHz
• Learmonth	18–180 MHz
• RSTN	18–180 MHz
• DAM	20–75 MHz
• Green Bank	18–70 MHz
	170–1070 MHz
• Wind/WAVES	0.02–14 MHz

SEPServer related studies  
Vainio et al. (2013)

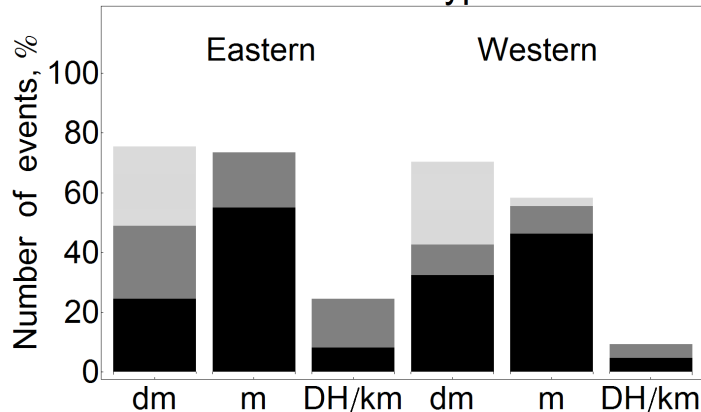
## SEP-associated type II bursts



## SEP-associated type III bursts



## SEP-associated type IV bursts



## Radio burst occurrence: results

Our final event list:

selection of **~180** particle events

associated with  $\geq C9$  flares, located  $\pm 90^\circ$

Western activity: **~70 %**

Eastern activity: **~30 %**

SEPs are always related to radio emission

**Miteva et al. CEAB (2013)**

*Other results*

**All (Eastern+Western) SEPs**

• **~75% with DH-IIIs**

*63% Cliver et al. 2004*

*100% Gopalswamy 2003*

• **~80% with m-IIIs**

*82% Cliver et al. 2004*

• **~100% with DH-IIIs**

*~90% MacDowall et al. 2003*

• **~90% with m-IIIs**

*100% Cane et al. 2002*

• **~40% with dm-IIIs**

• **~60% with m-IVs**

*88% Kahler 1982*

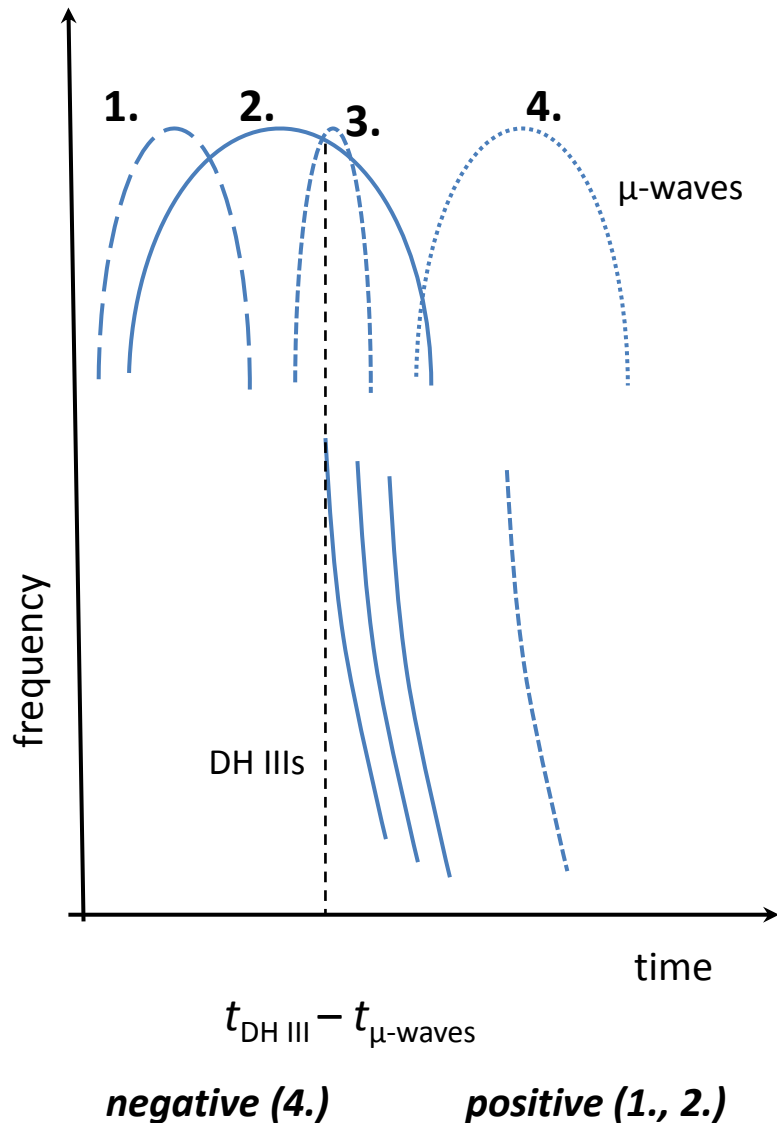
• **~60% with dm-IVs**

black – dynamic radio spectra

dark gray – observatory reports only

light gray – data gap

## Solar radio emission signatures (DH type IIIs as proxy for particle escape)



### The idea

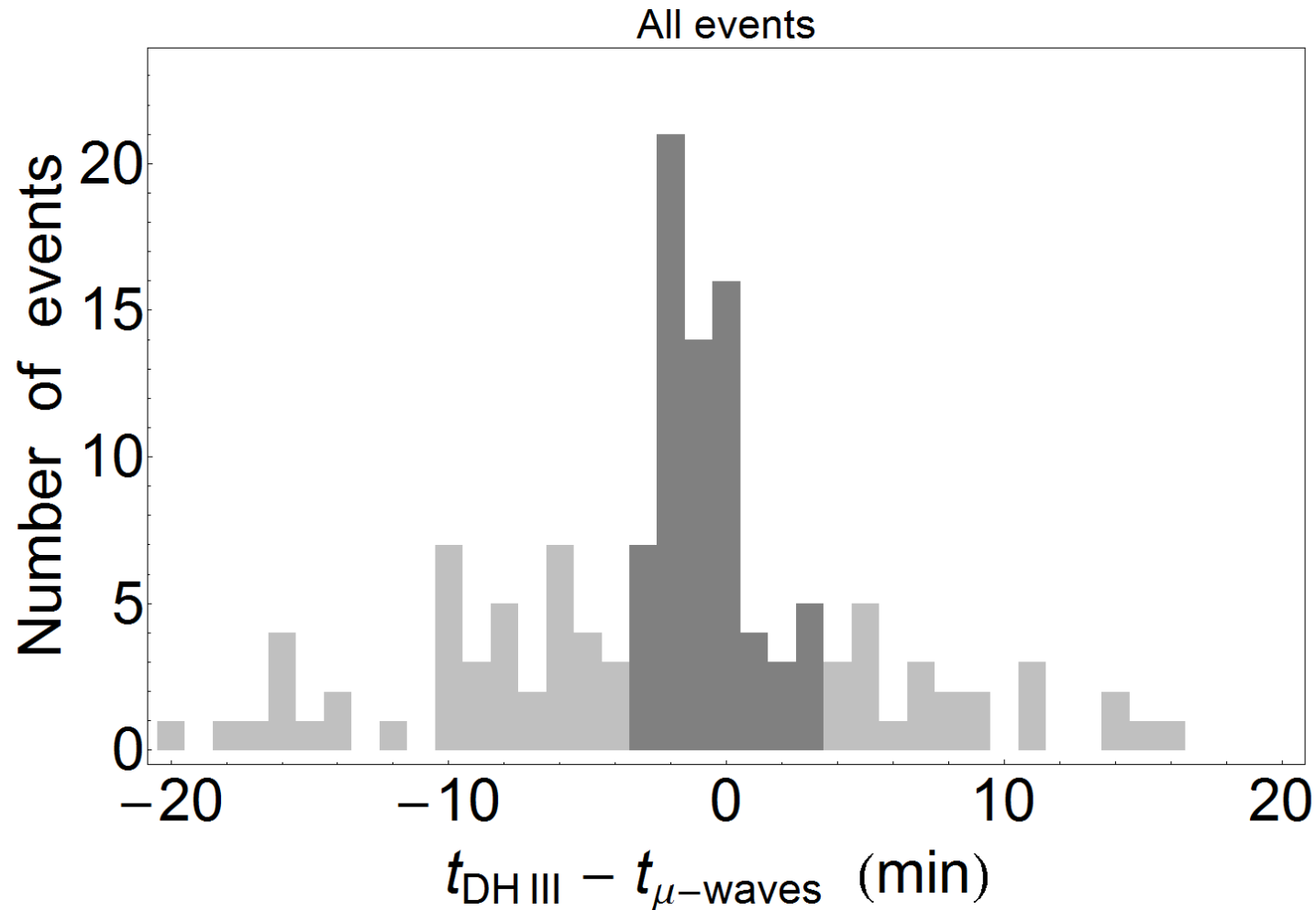
Time comparison between microwave radio emission and DH type III in order to evaluate the flare contribution

### Selection criteria:

Evaluate from the radio data the time of the first prominent peak at 15 GHz (RSTN) and first type III in 1–14 MHz (WAVES RAD2)

### **Flare-accelerated particles: scenarios**

1. Confinement
2. Partial Confinement
3. Direct Escape
4. Late Contribution or Confinement



**Negative offsets**

DH IIIs before  $\mu$ -waves

Escape from low corona

*(Late flare contribution if any)*

34 %

**No offset** within

the unc.:  $\pm 3$  min

Direct Escape

*(flare contribution)*

49 %

**Positive offsets**

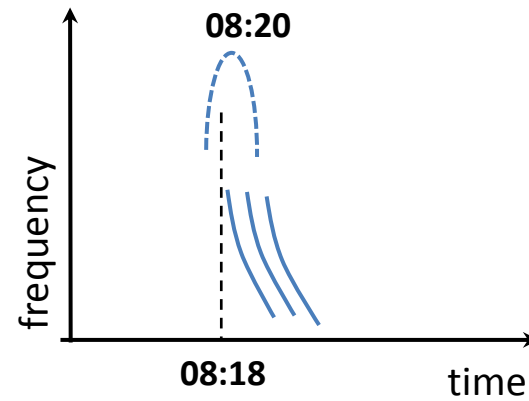
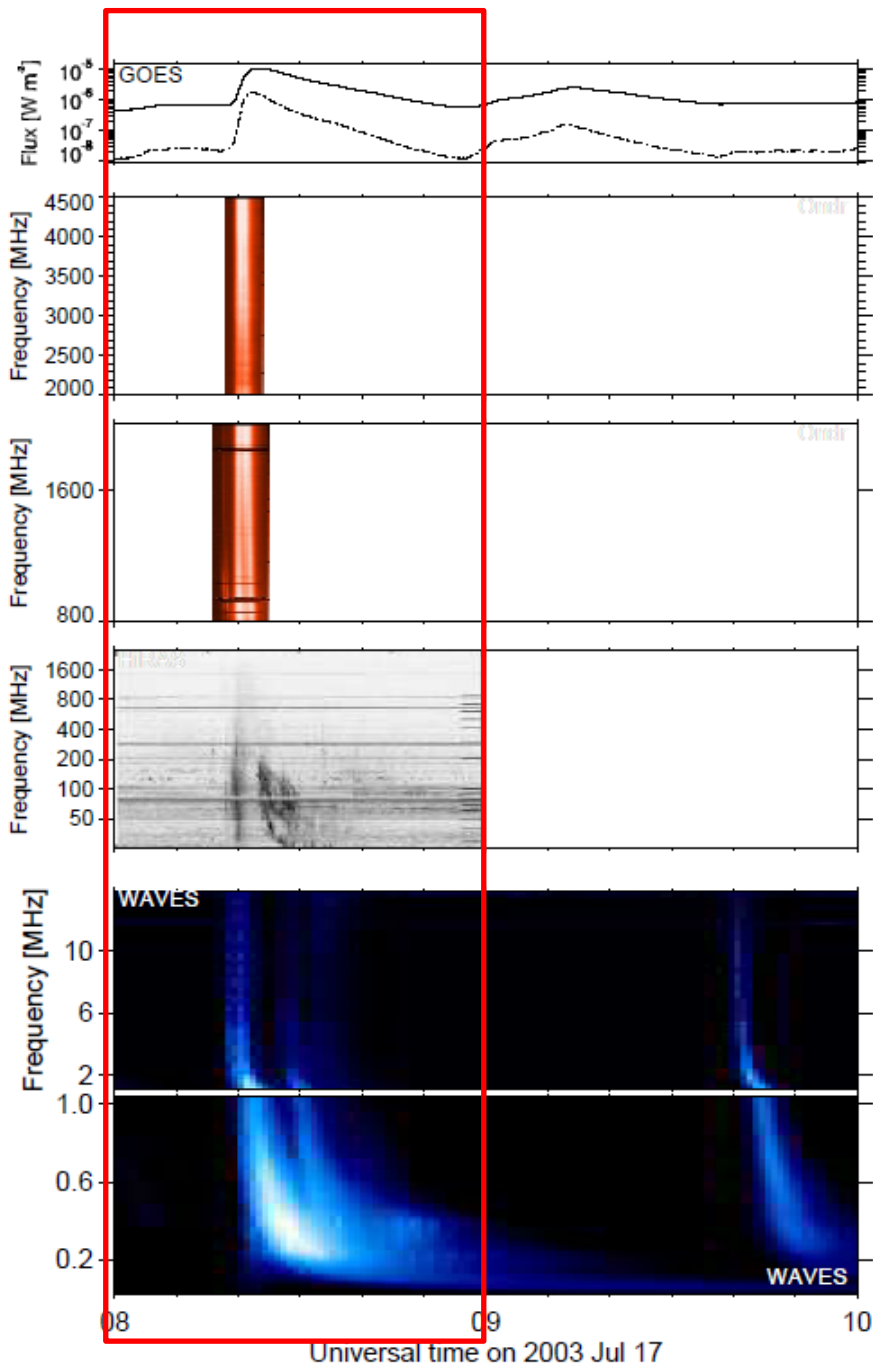
DH IIIs after  $\mu$ -waves:

Confinement/Partial Confinement

*(early flare contribution if any)*

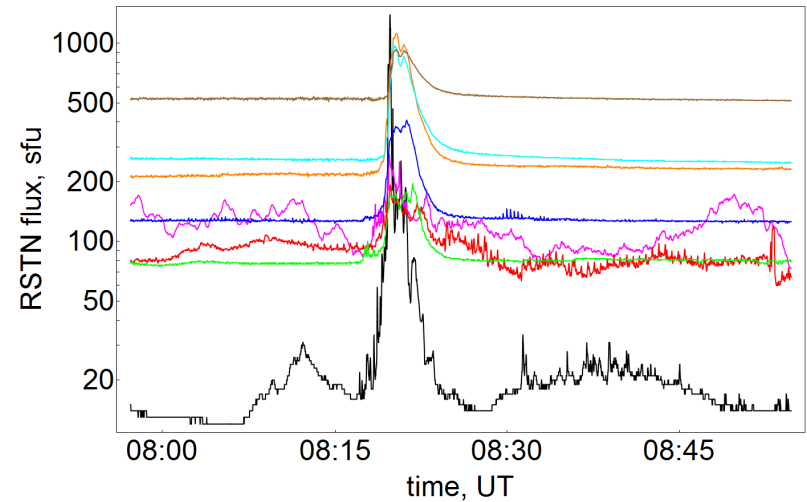
17 %





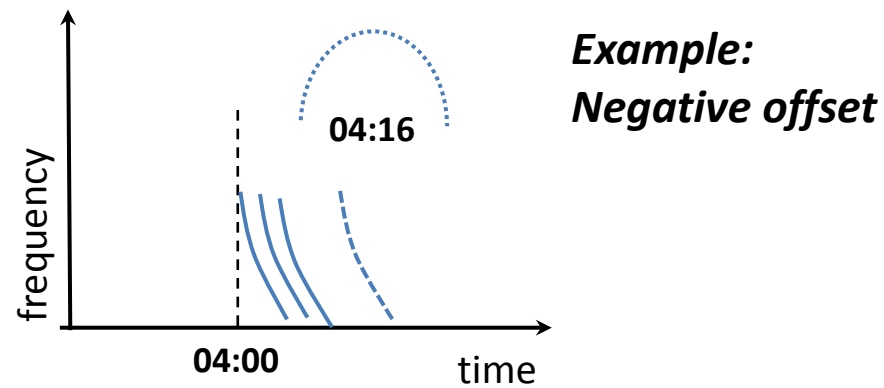
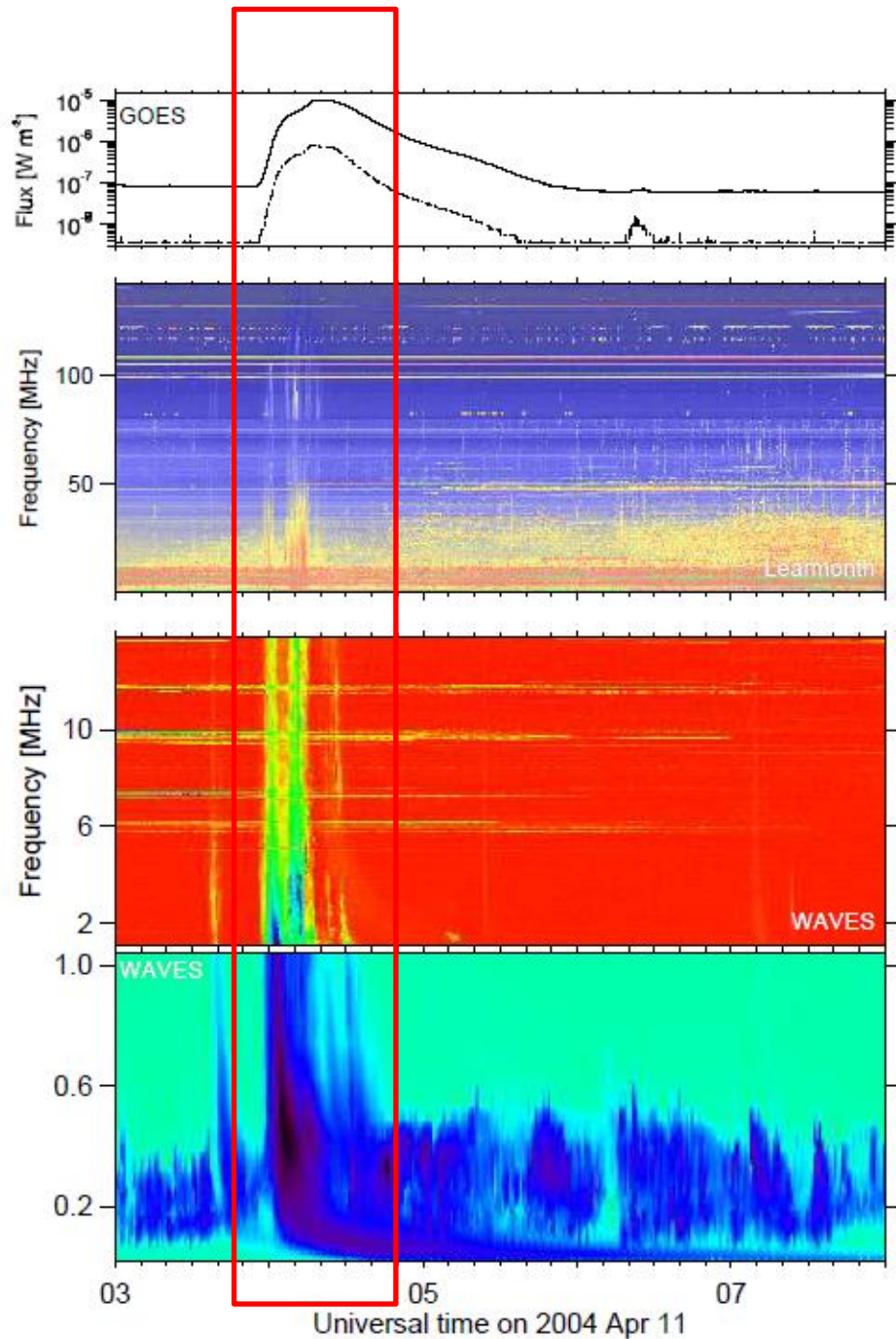
*Example:  
No offset*

2003-07-17 (San Vito)

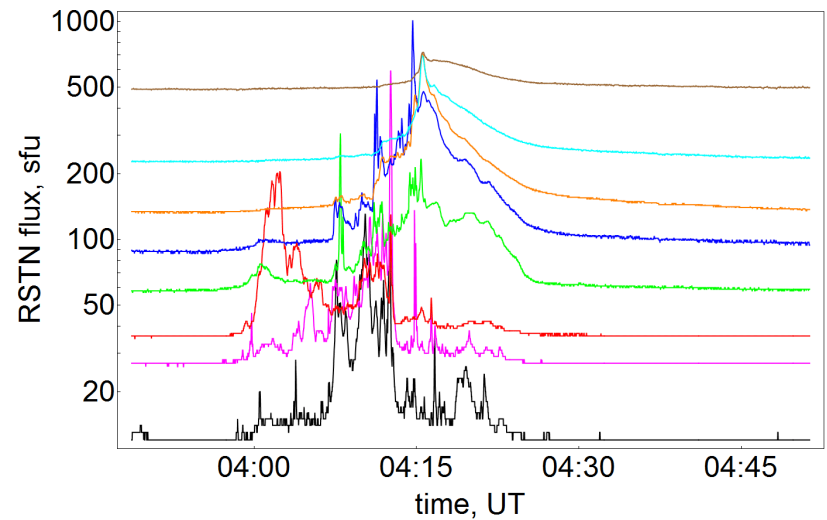


245 MHz (black)  $\rightarrow$  15 GHz (brown)

Direct escape of flare related particles (3.)  
Late CME contribution (type IIs, low corona)

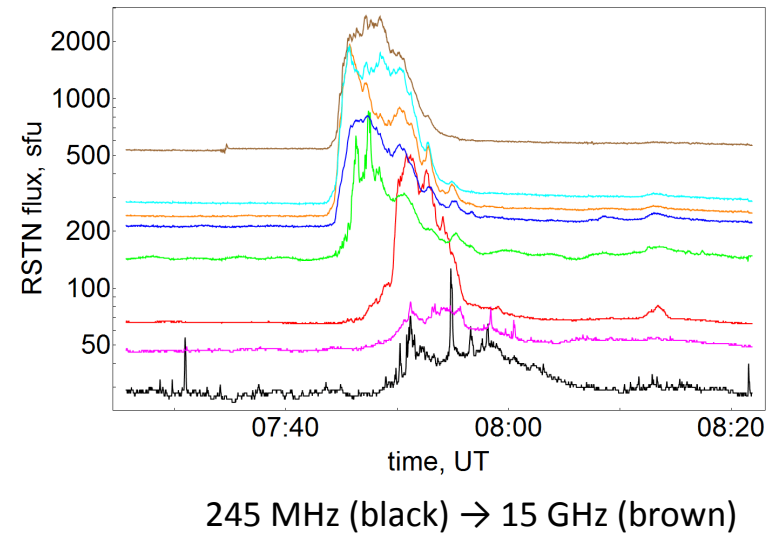
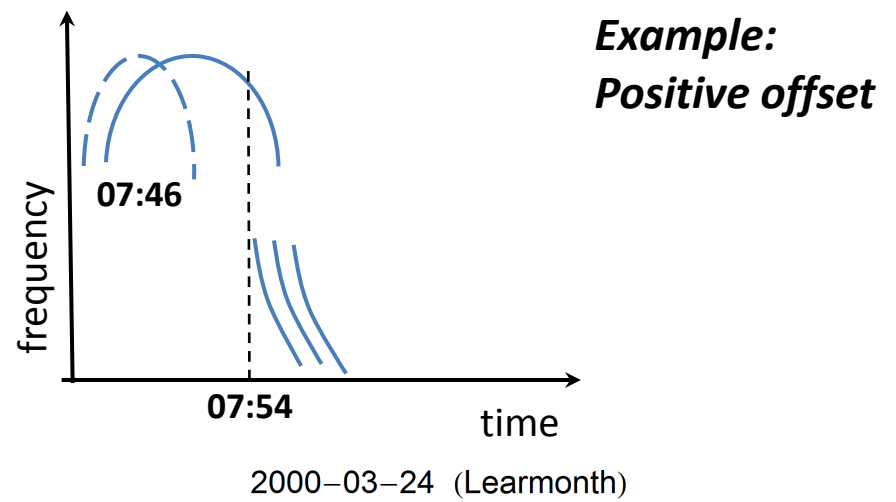
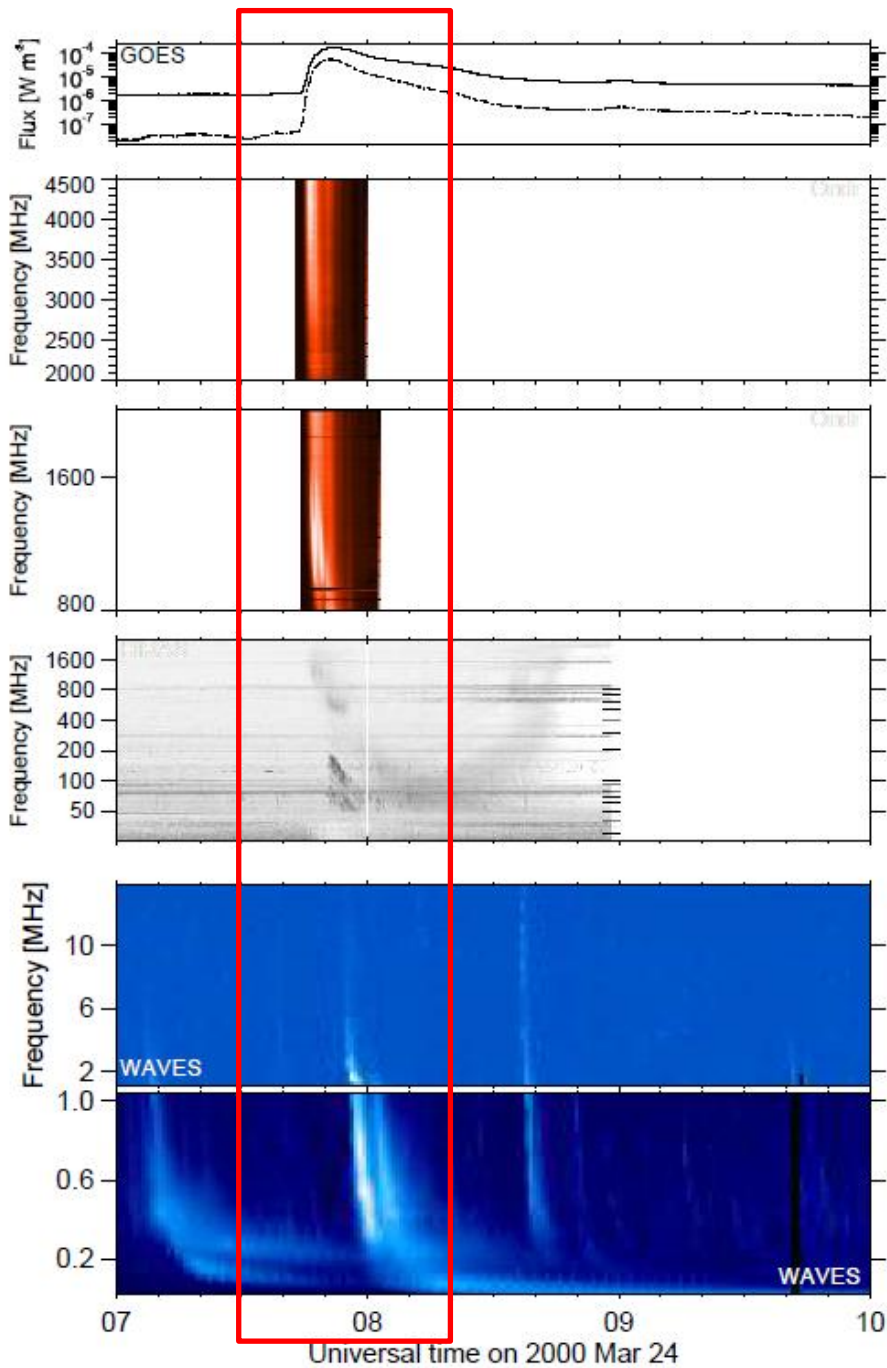


2004-04-11 (Learmonth)



245 MHz (black) → 15 GHz (brown)

CME related particles (from high corona)  
Late flare contribution (4.)



CME related particles (IIs, high corona)  
flare confinement (1.)

## Summary

### IP conditions as a new parameter (but not a final answer to the debate on the SEP origin)

(1) SEP peak intensity and SXR flare class  $\leftrightarrow$  (2) SEP peak intensity and CME speed

- entire data set, both for protons and electrons
  - correlation (1) is weaker for SoWi events compared to ICME events,
  - correlation (2) has the same value
- considering limb cases (to minimize the observational bias)
  - for electrons correlation (1) is kept weaker, but also (2) becomes weaker for SoWi compared to ICME events
  - for protons correlation (1) is now the same for the different IMF categories

### Radio signatures of SEP events (~130, 50 have no RSTN data/data issues)

#### ***preliminary results:*** main particle accelerator

49 % flare-related particles (late CME contribution is not excluded)

34 % CME-related particles (flare contribution later in the event if any)

17 % CME-related particles (flare contribution is confined or in some cases partially confined)

### Future task on the radio work

evaluation of the duration of the microwave emission:

in order to obtain the final proportion of confinement, partial confinement and direct escape of particles