Some peculiarities of the decay of extreme solar energetic particle events

E.I. Daibog[1], K. Kecskeméty[2], Yu.I. Logachev[1]

1 Skobeltsyn Institute of Nuclear Physics, Moscow State University, Russia
2 KFKI Research Inst. for Particle and Nuclear Physics, Budapest, Hungary

Why decays?

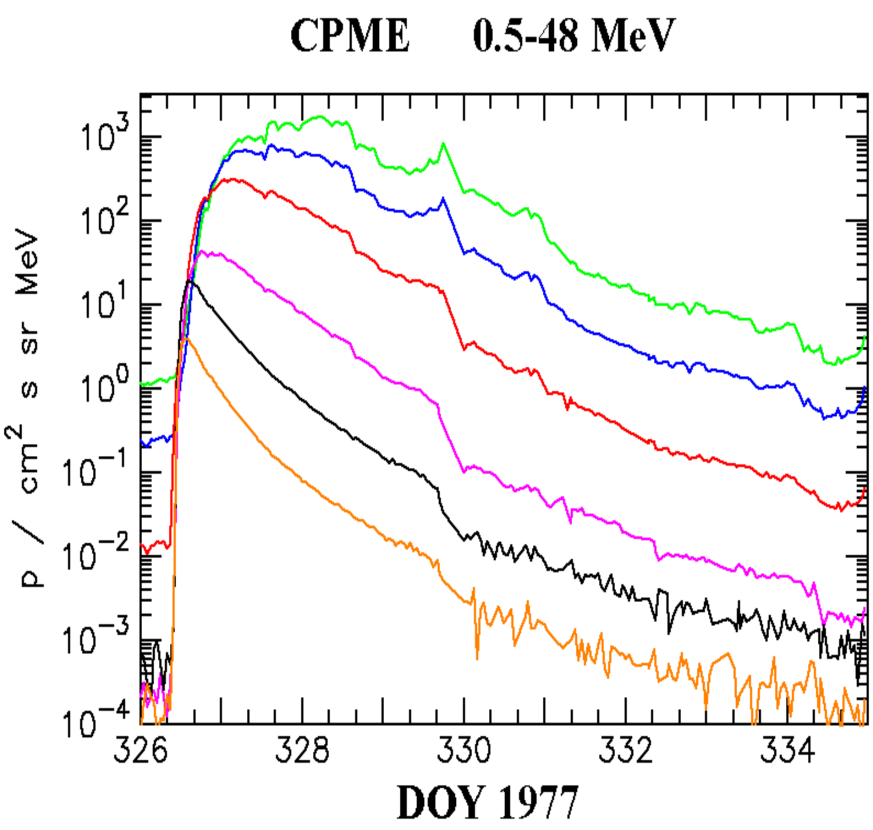
the features and conditions in a source of SEPs at the Sun become unessential during decay phase and effects and peculiarities of particle acceleration and losses in interplanetary space become more important.

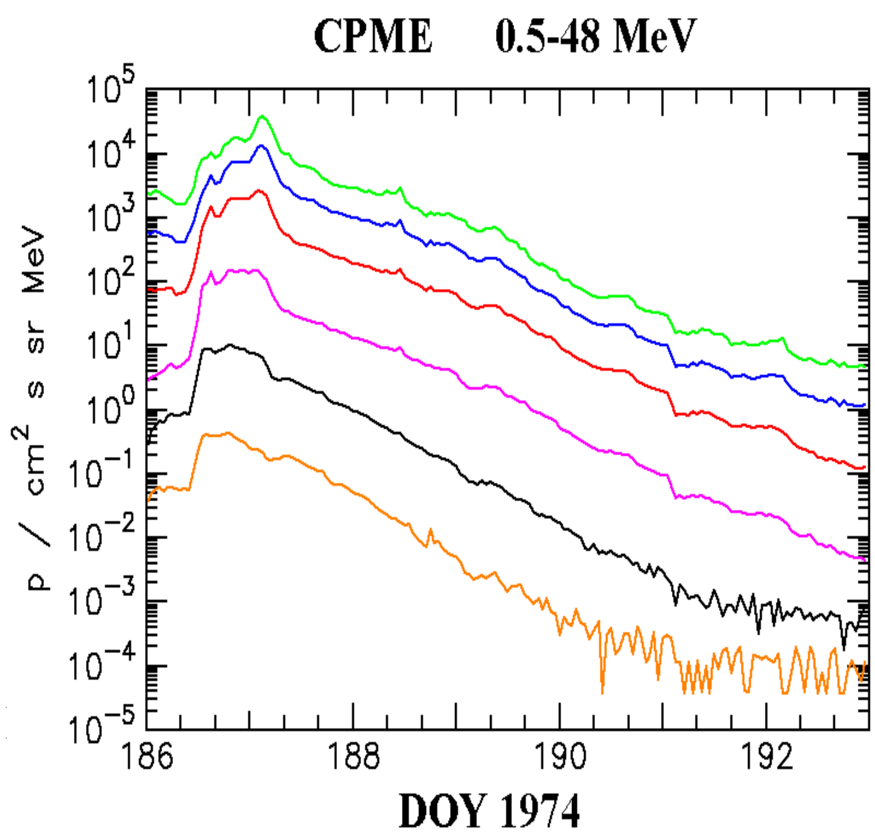
Power-law decay indicates the dominance of diffusive propagation or trapping between converging magnetic field near the Sun and a front of CME initiated shock, whereas exponential-law decay emphasizes convection transport and adiabatic deceleration.

From 700 events of 1-5 MeV proton fluxes from IMP 8 (CPME) between 1974 and 2001 only about 10% of the decays were power-law, 90% were exponential, while a small fraction of exponentials had power-law tails above ~20 MeV.

power- law

exponential





$J(t) \propto t^{-n}$

$J(t) \propto \exp(-t / \tau)$

Observed flux profile is a mixture of temporal and spatial variations.

What factors does τ depend on?

Earlier we analyzed at 1 AU such dependences as:

- **magnetic field strength and disturbance**
- **particle energy**
- **solar wind speed**
- **spectral index γ**
- **radial distance from the Sun**

Here we consider dependences on:

- **relative heliolongitude of the parent flare and the magnetic footpoint**
- **decays of electron events**

If τ = const, some invariant combination of parameters describing particles and/or interplanetary medium must exist.

We use the formula obtained in (Forman, 1970; Jokipii, 1971; Lee, 2000) in supposition of predominance of convection and adiabatic deceleration under diffusive propagation:

$$\tau_{theor} = 3r / 2V\,(2 + \alpha\,\gamma),$$

where $\alpha = T+2mc^2/(T+mc^2) \approx 2$ for non-relativistic energies.

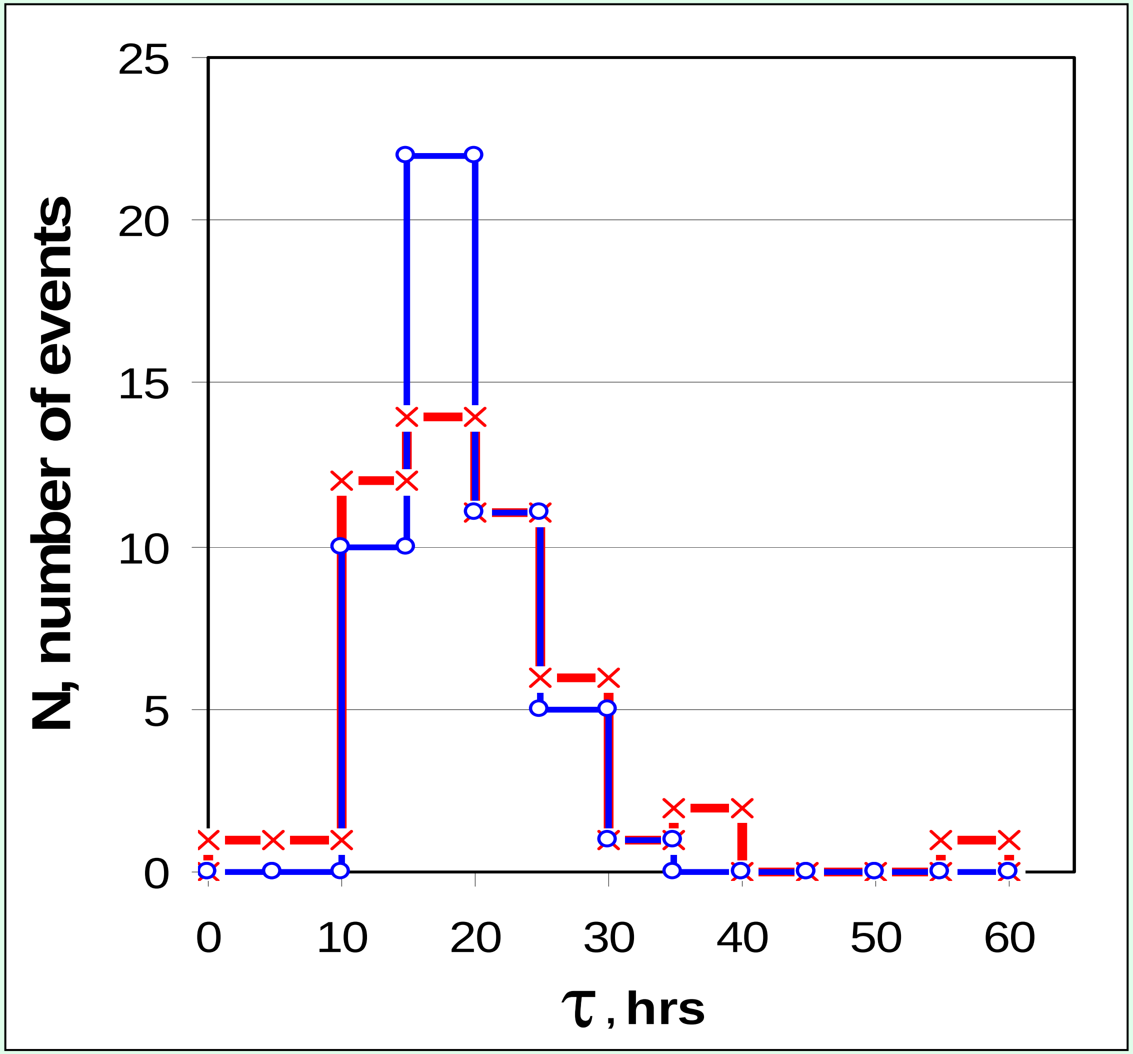
Deviation from theoretical prediction (at fixed r)

- variation of solar wind speed V

- energy dependence (both increase and decrease with E)

- variation of magnetic connection between the observer and a flare site through the decay – dependence on heliolongitude (McCracken, 1971)

That must manifest itself in statistical prevalence of smaller values of decay times τ_{obs} for western flares comparing with eastern ones.



49 decays Ep= 2-4.6 MeV with V=const. Distribution of t_{exp} (red) is wider than t_{theor} (blue). Longitudinal effect.

Longitude effect

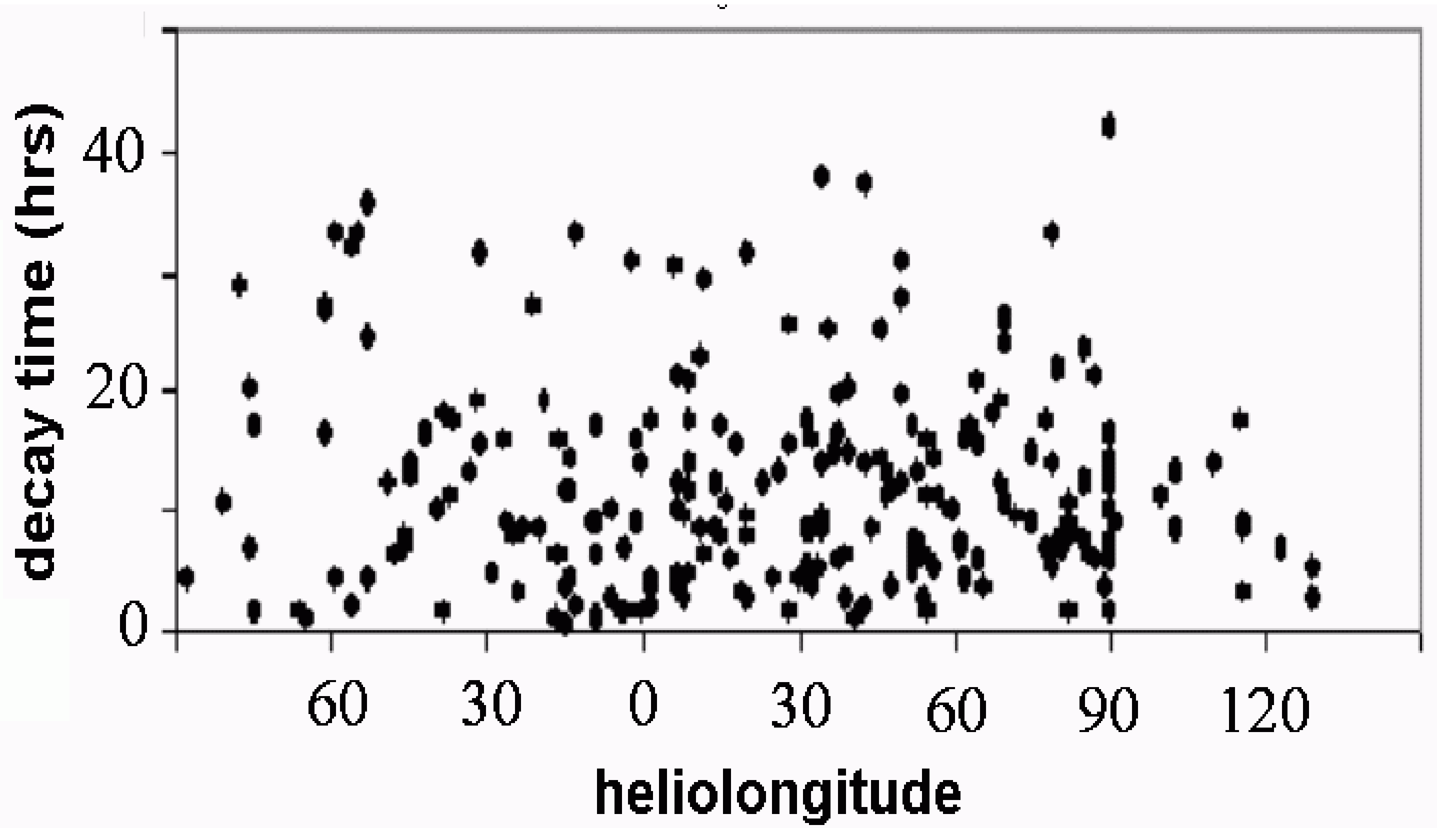
Rising time of most events associated with eastern flares is prolonged in comparison with the western ones.

This is caused by moving of the flare field line toward or away from the observer.

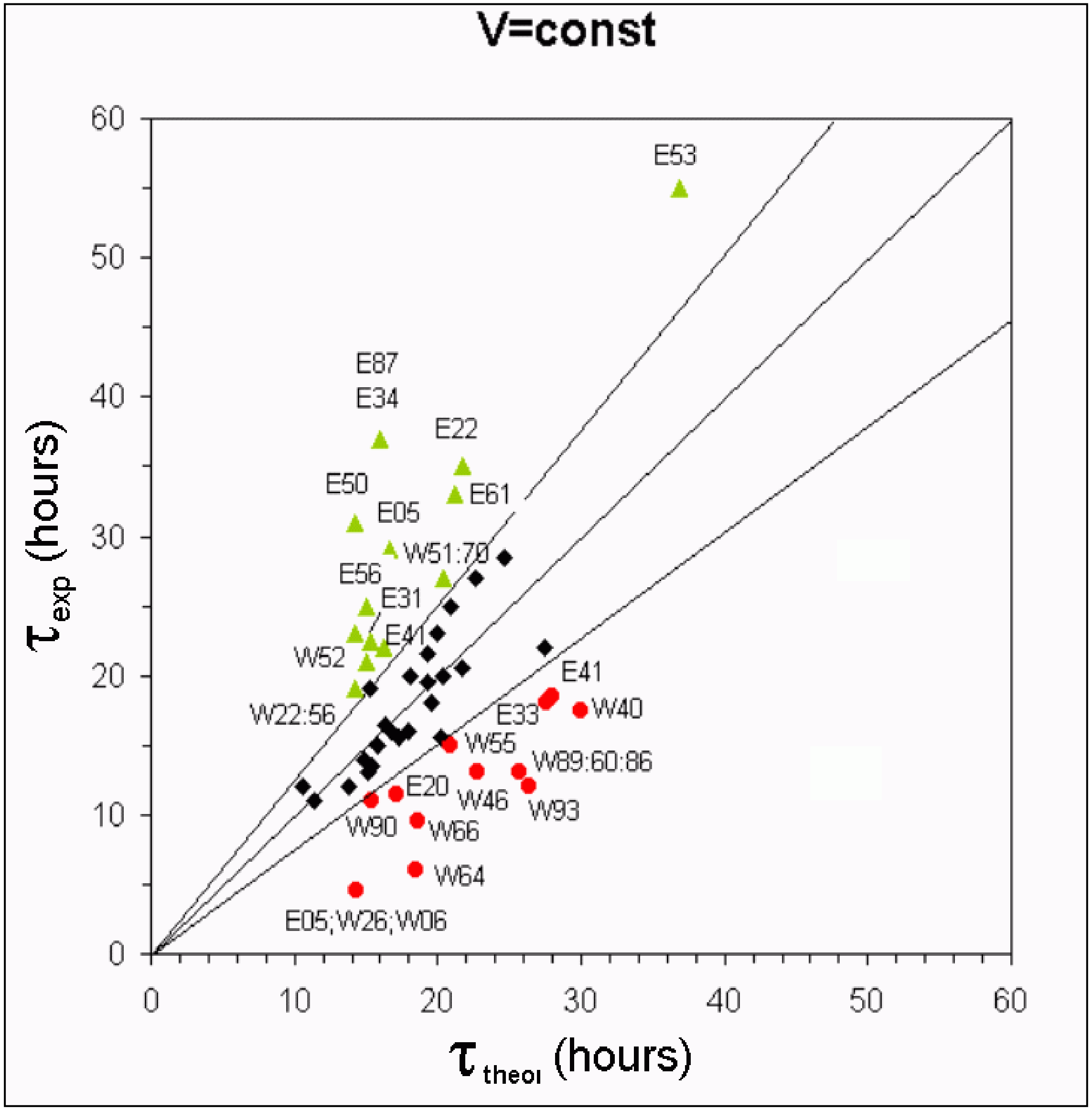
Similar dependence must exist for the decay rate even in absolutely

homogeneous interplanetary medium, and a "step" in the scatter plot $\tau(\varphi)$ must appear.

Decrease of values of τ is observed at φ about 50-60 degs.



decay time (hrs)
40
20
0
60
30
0
30
60
90
120
heliolongitude



V=const
E53
E87
E34
E22
E50
E61
E05
W51:70
E56
E31
E41
W52
W22:56
E41
E33
W40
W55
W89:60:86
E20
W46
W93
W90
W66
W64
E05;W26;W06
0
10
20
30
40
50
60
τ_{exp} (hours)
τ_{theor} (hours)

Exception of some events from the general order might be caused by:

- **Strong difference between flare and observer’s heliolatitudes;**
- **Difference of the flare site and a site of particle escape from the Sun;**
- **Incorrect association between particle event and parent flare.**

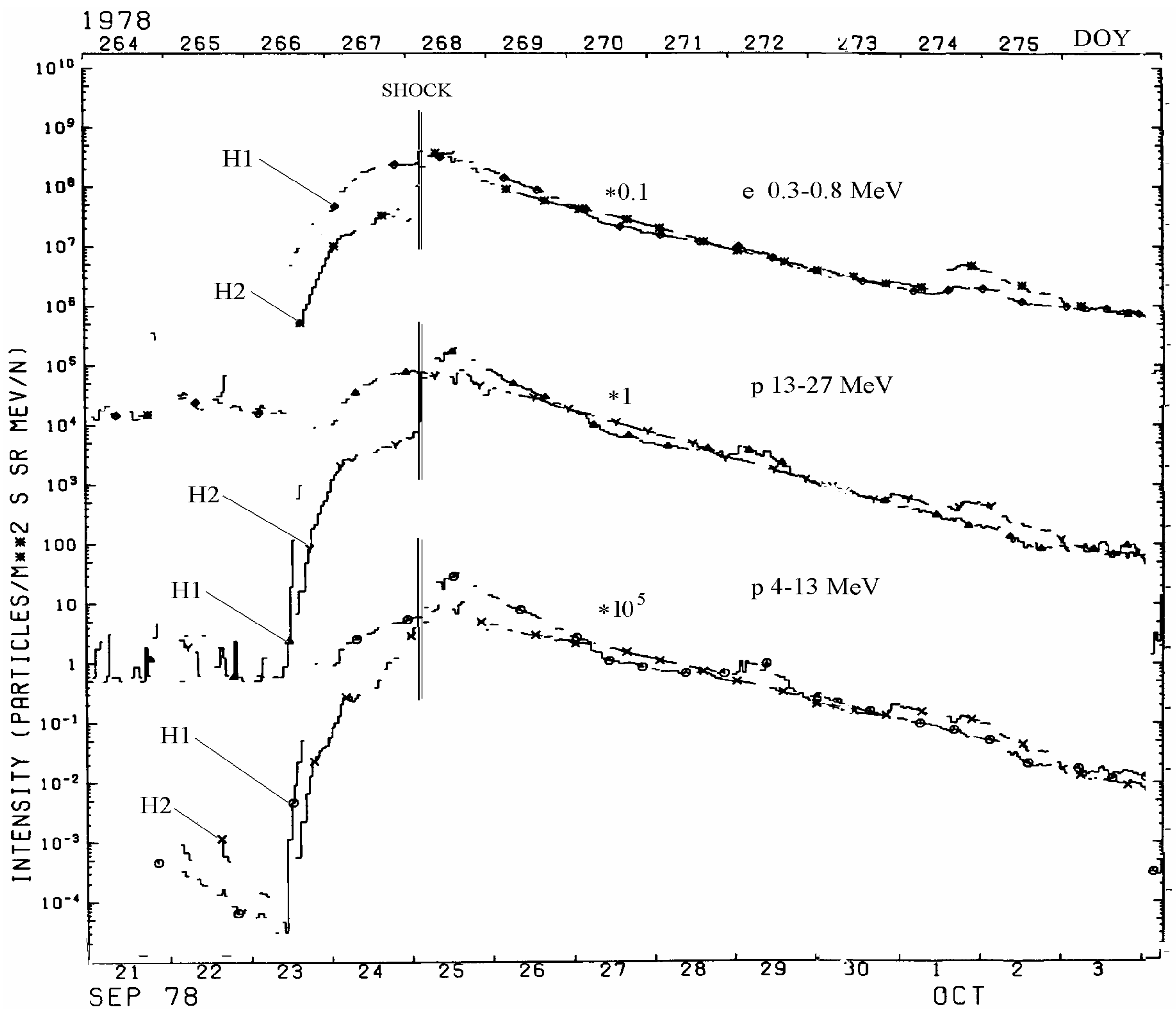
Comparison of electron and proton intensity decays

Correlation between electron and proton rates of decays was examined (Helios 1 and Helios 2) in connection with the spatial and temporal invariance of the energy spectra (Reames et.al, Daibog et.al.) in CME-shock-associated events.

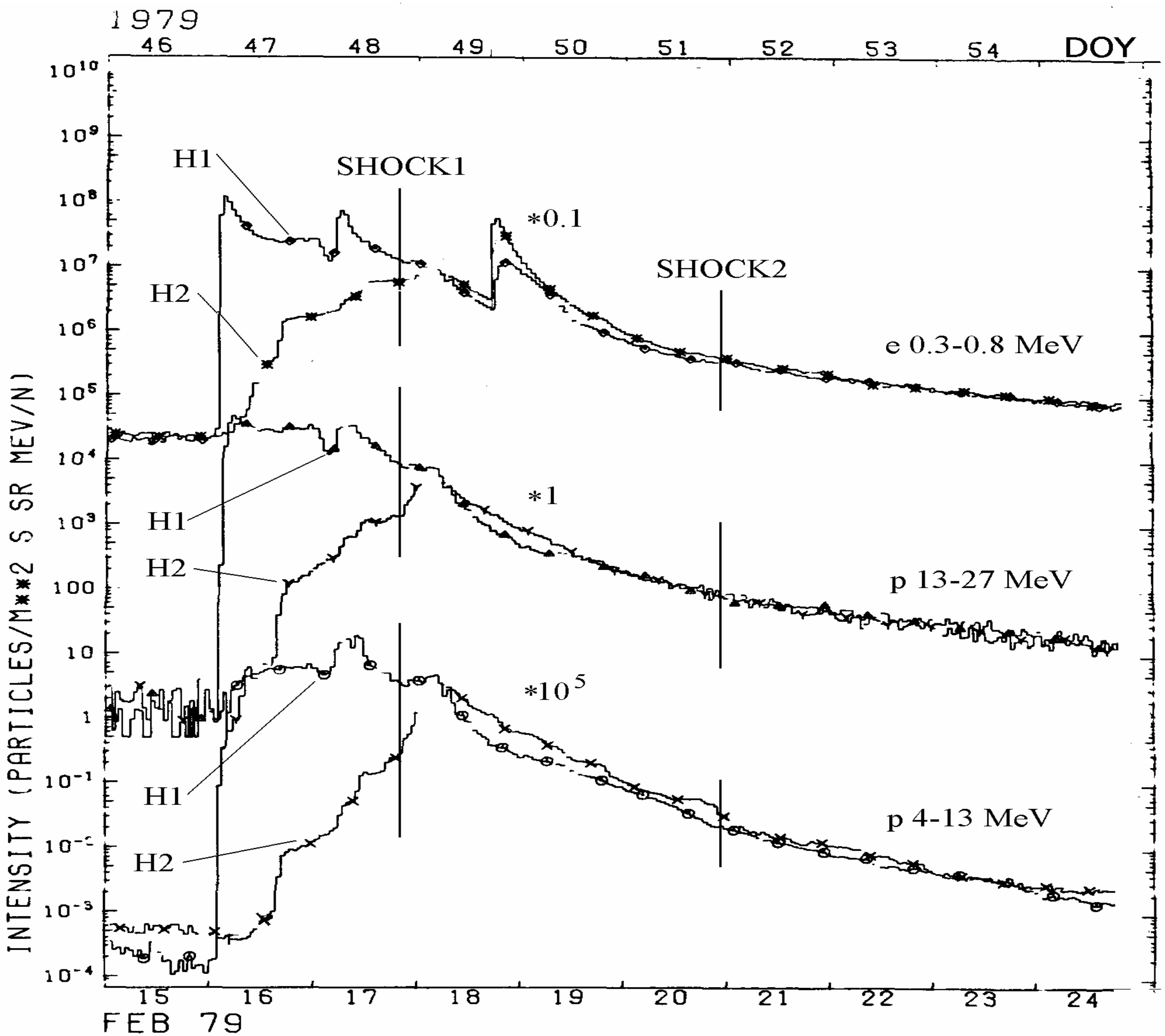
Electrons 0.3-0.8 MeV, protons 13-27 MeV

In most cases shapes of p and e decays were similar and τ_e and τ_p of the same order of magnitude or $\tau_e > \tau_p$

31 decays (16 - $\tau_e = \tau_p$; 15 - $\tau_e > \tau_p$).



1978
264 265 266 267 268 269 270 271 272 273 274 275 DOY
SHOCK
H1
H2
*0.1
e 0.3-0.8 MeV
*1
p 13-27 MeV
H2
H1
p 4-13 MeV
$*10^5$
H1
H2
INTENSITY (PARTICLES/M**2 S SR MEV/N)
10^{10} 10^9 10^8 10^7 10^6 10^5 10^4 10^3 100 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4}
21 22 23 24 25 26 27 28 29 30 1 2 3
SEP 78
OCT



1979
DOY
46
47
48
49
50
51
52
53
54
INTENSITY (PARTICLES/M**2 S SR MEV/N)
H1
H2
SHOCK1
SHOCK2
*0.1
e 0.3-0.8 MeV
*1
p 13-27 MeV
*10^5
p 4-13 MeV
FEB 79
15
16
17
18
19
20
21
22
23
24

SOHO COSTEP EPHIN

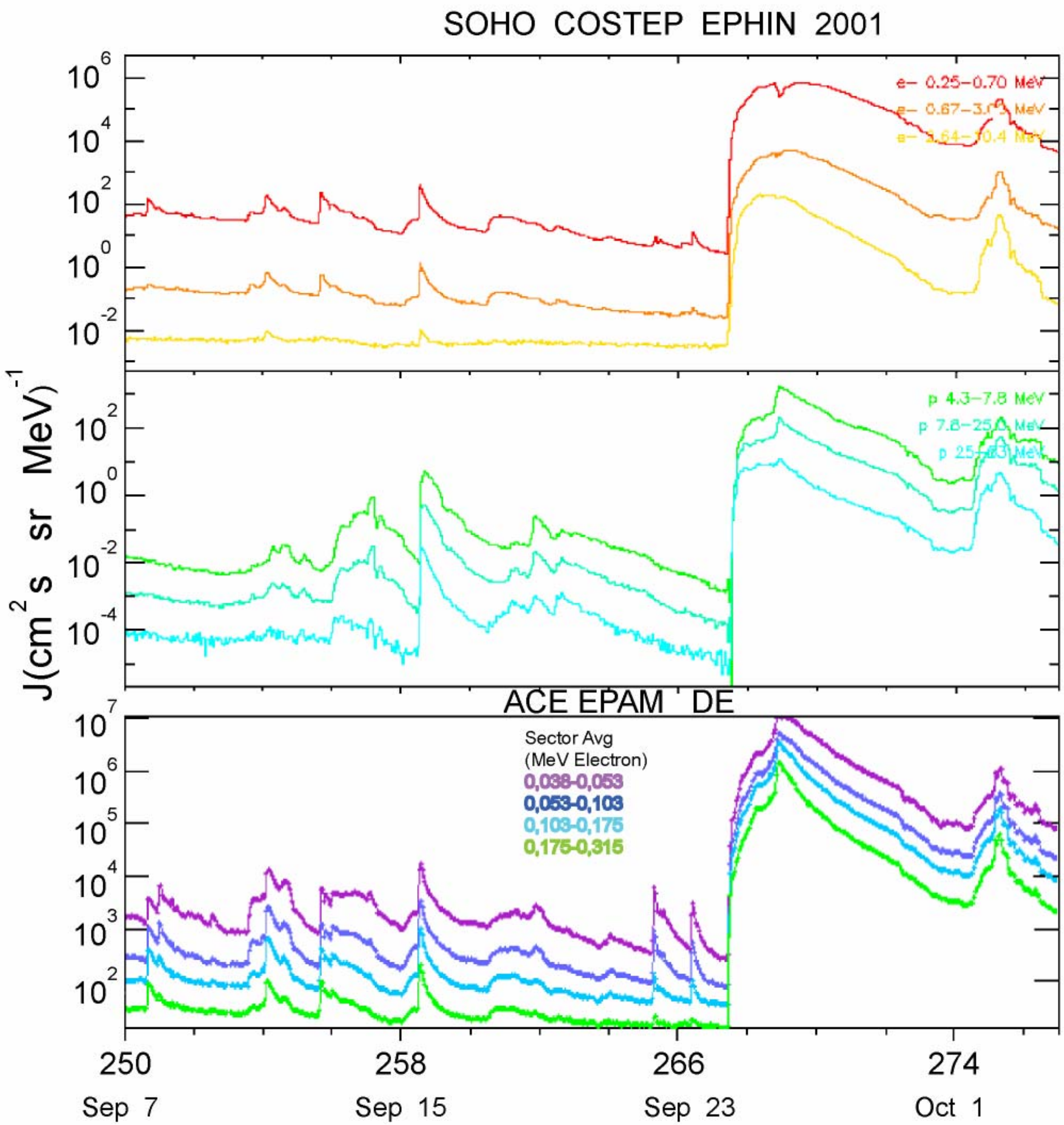
88 clear-shaped decays of p and e of nearly equal velocities (electrons 0.25-0.7 MeV, protons: p1 4.3-7.8, p2 7.8-25 MeV)

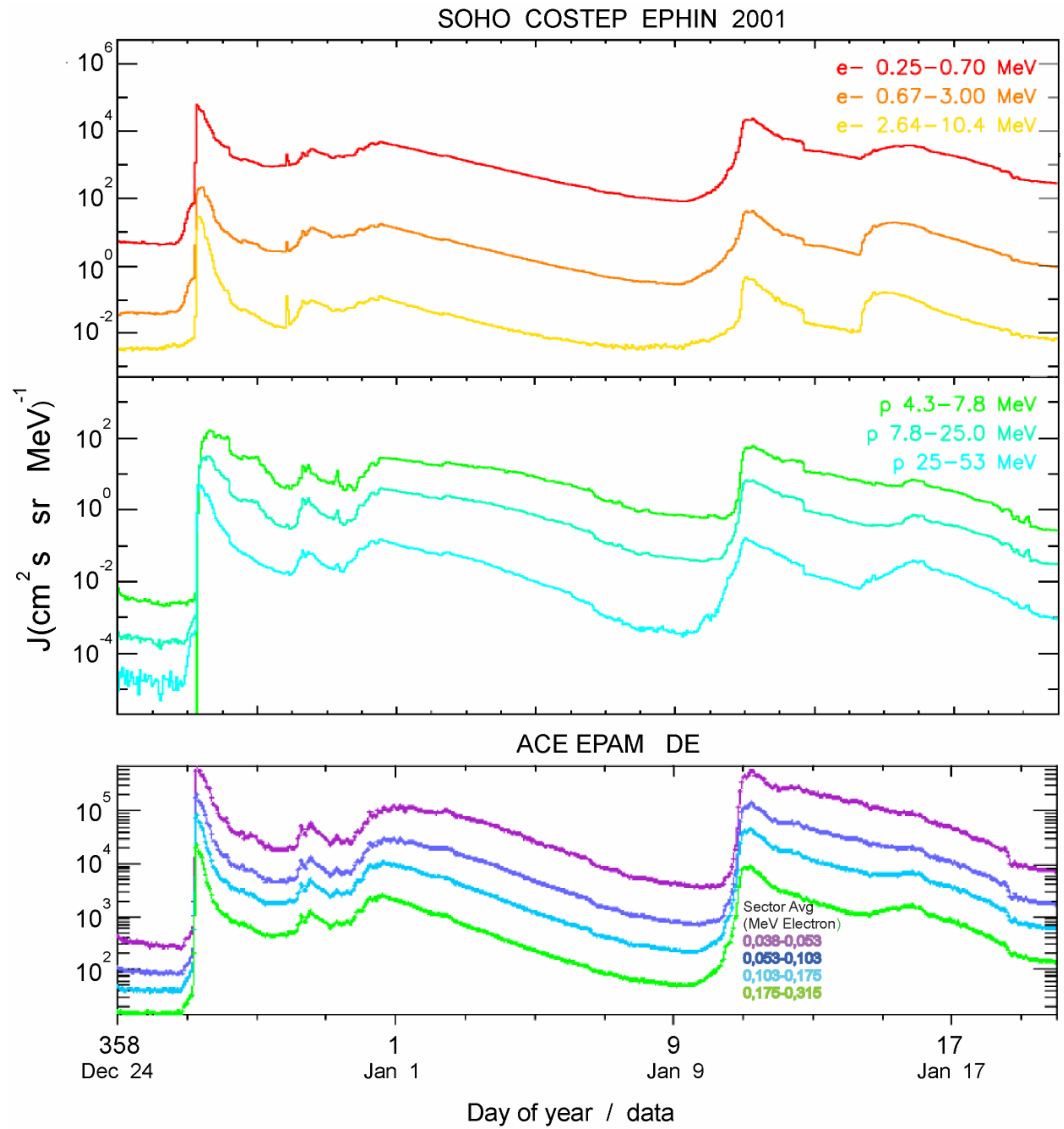
ACE EPAM DE

low energy electrons (0.103-0.178 MeV)

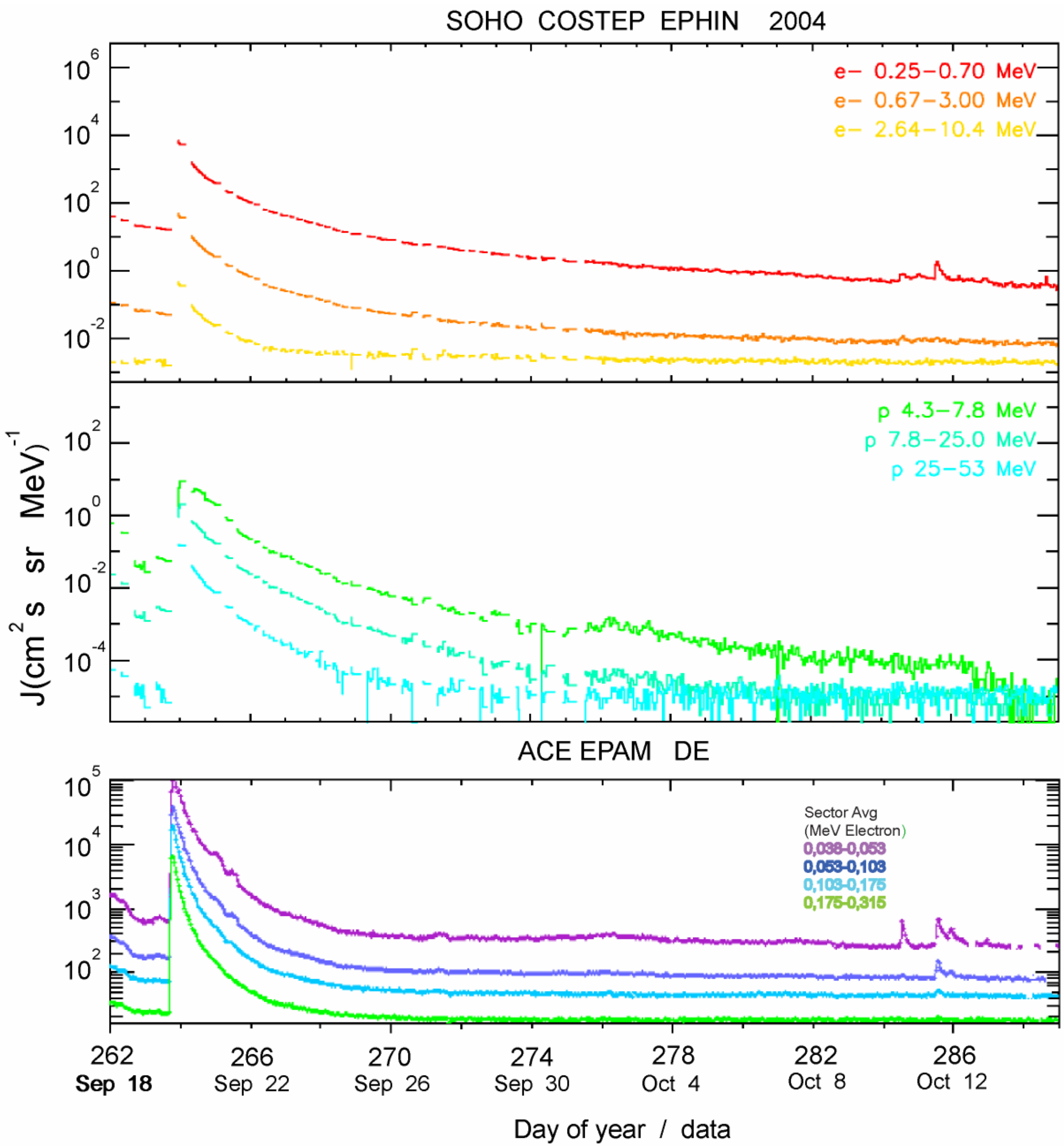
52 electron and proton shapes coincide
30 have different shapes
6 uncertain

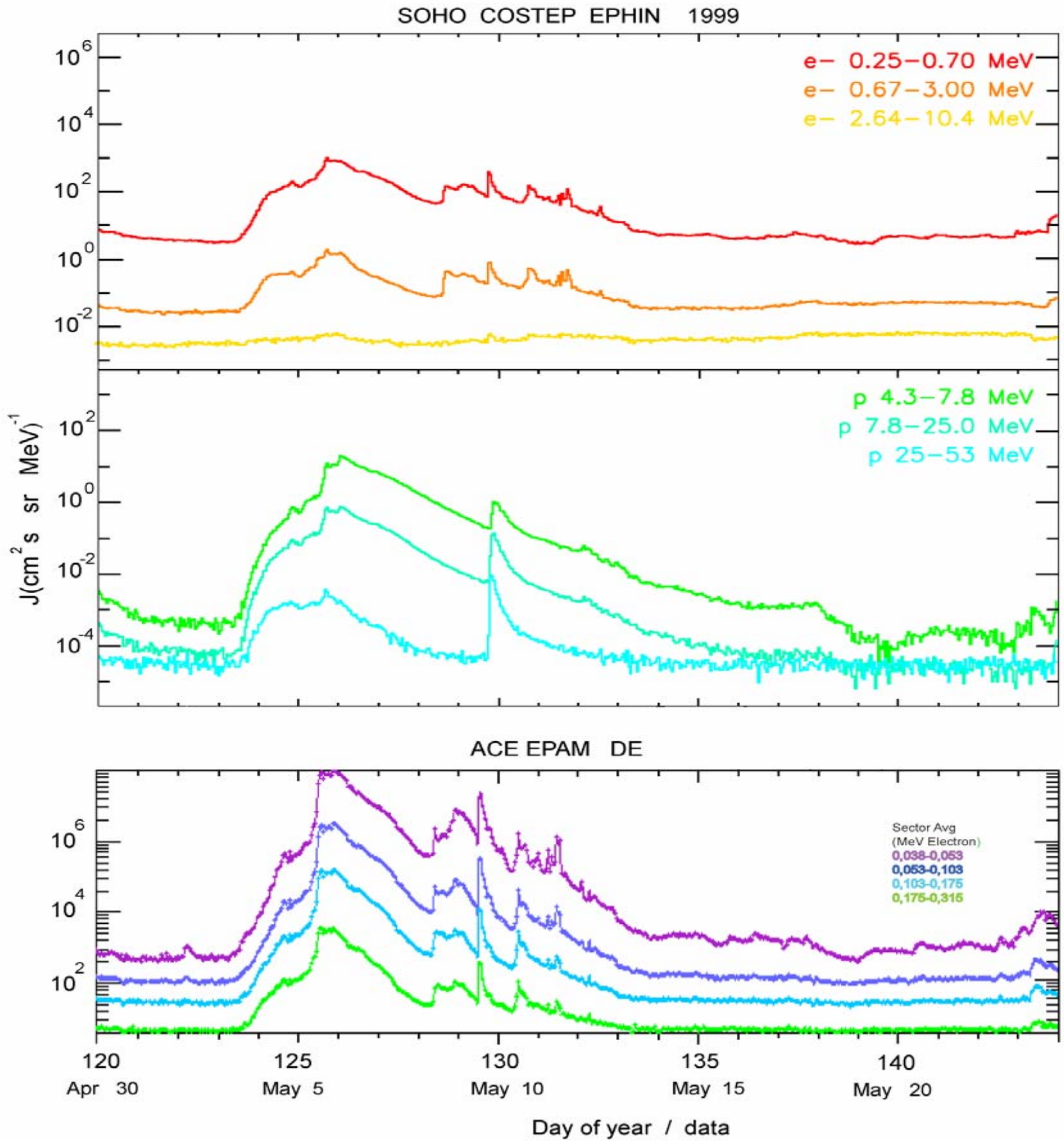
This suggests that electrons can be subjected to the same processes (convection and adiabatic deceleration) as protons.

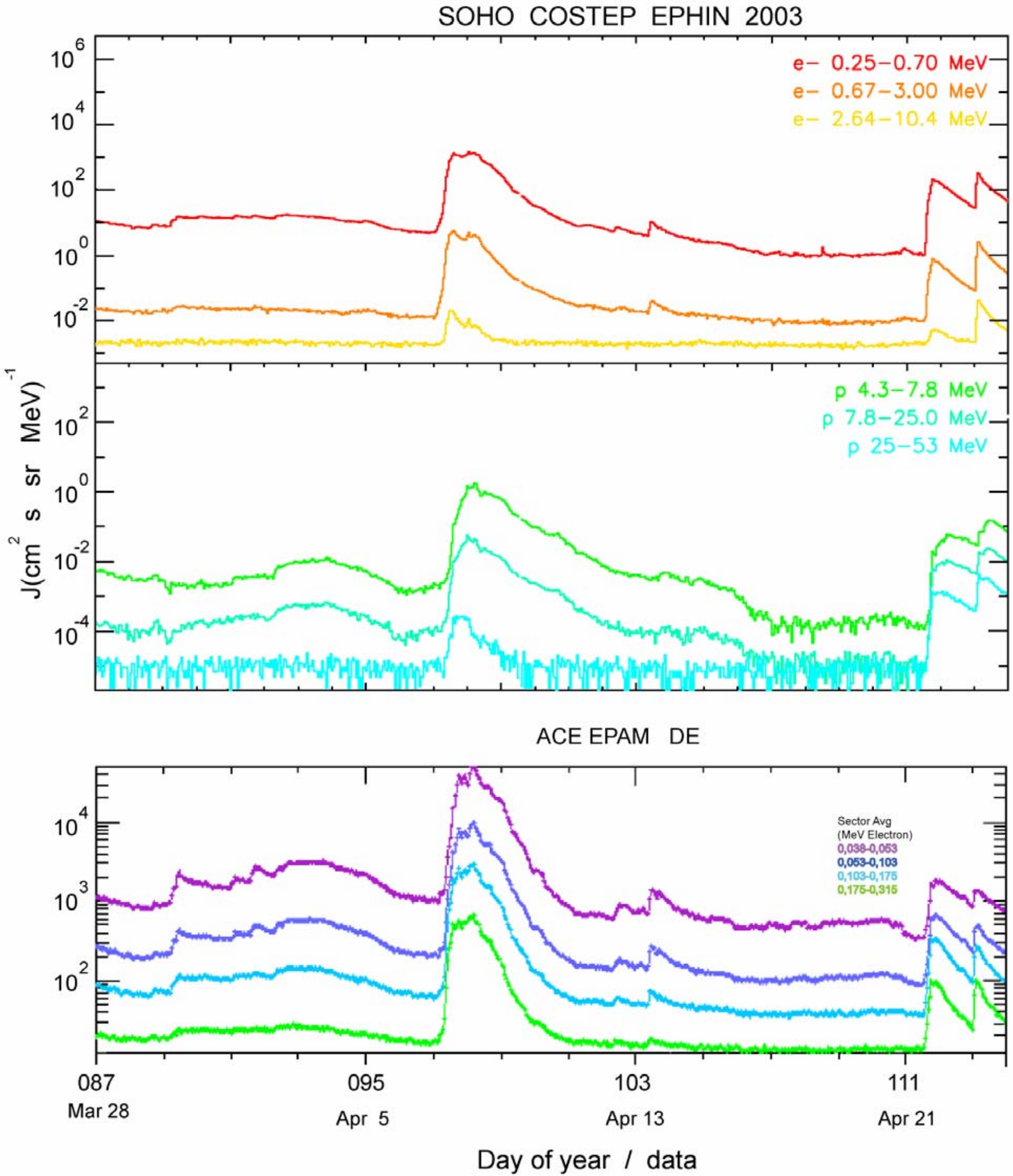

SOHO COSTEP EPHIN 2001
e- 0.25-0.70 MeV
p 4.3-7.8 MeV
J(cm^2 s sr MeV)^-1
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
250
258
266
274
Sep 7
Sep 15
Sep 23
Oct 1



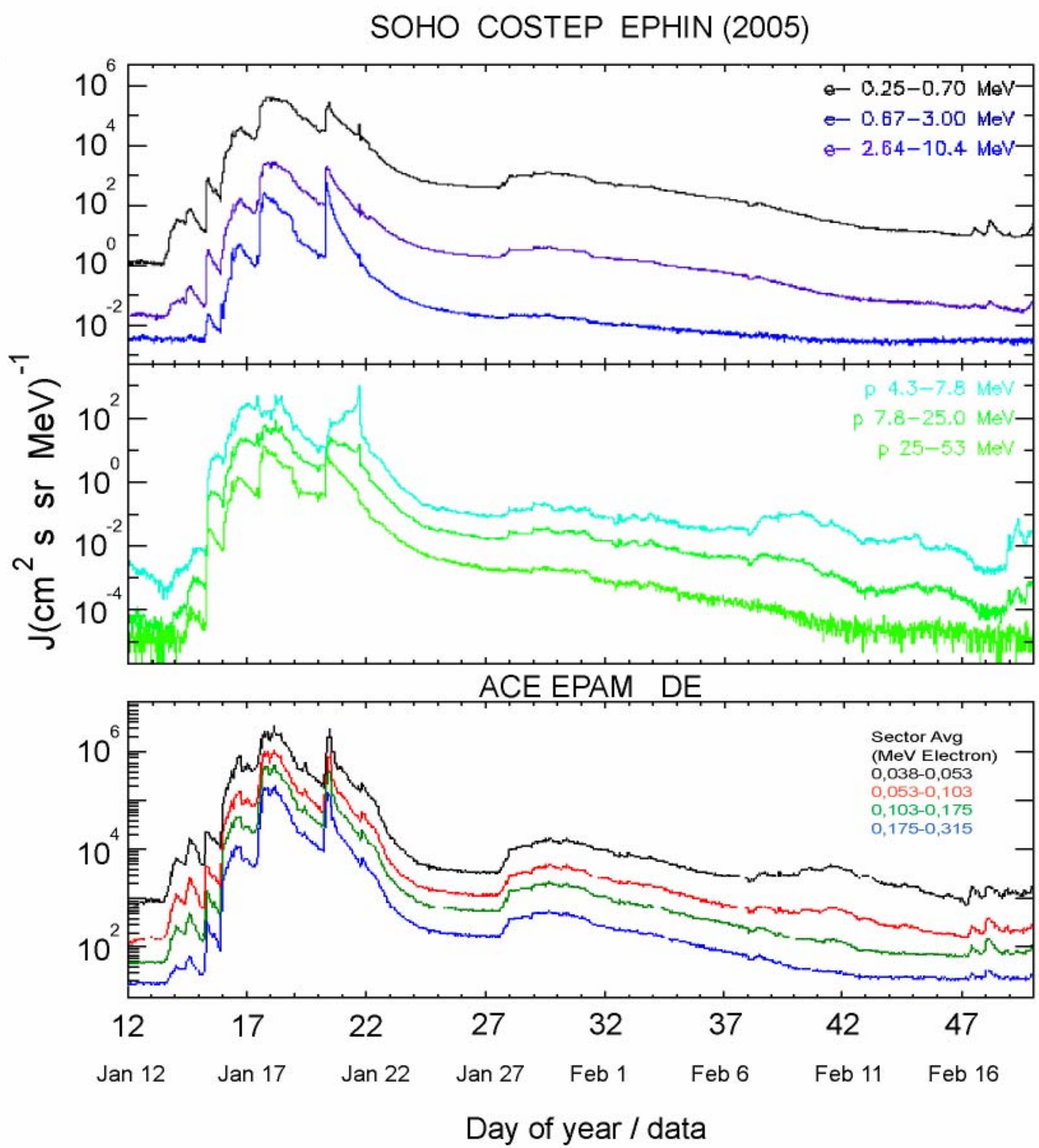
SOHO COSTEP EPHIN 2001
e− 0.25−0.70 MeV
e− 0.67−3.00 MeV
e− 2.64−10.4 MeV
p 4.3−7.8 MeV
p 7.8−25.0 MeV
p 25−53 MeV
J(cm2 s sr MeV)-1
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
358
Dec 24
1
Jan 1
9
Jan 9
17
Jan 17
Day of year / data


SOHO COSTEP EPHIN 2004
e− 0.25−0.70 MeV
e− 0.67−3.00 MeV
e− 2.64−10.4 MeV
p 4.3−7.8 MeV
p 7.8−25.0 MeV
p 25−53 MeV
J(cm² s sr MeV)⁻¹
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
262 Sep 18
266 Sep 22
270 Sep 26
274 Sep 30
278 Oct 4
282 Oct 8
286 Oct 12
Day of year / data


SOHO COSTEP EPHIN 1999
e− 0.25−0.70 MeV
e− 0.67−3.00 MeV
e− 2.64−10.4 MeV
p 4.3−7.8 MeV
p 7.8−25.0 MeV
p 25−53 MeV
J(cm² s sr MeV)⁻¹
10⁶
10⁴
10²
10⁰
10⁻²
10⁻⁴
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
120
125
130
135
140
Apr 30
May 5
May 10
May 15
May 20
Day of year / data



SOHO COSTEP EPHIN 2003
e- 0.25-0.70 MeV
e- 0.67-3.00 MeV
e- 2.64-10.4 MeV
p 4.3-7.8 MeV
p 7.8-25.0 MeV
p 25-53 MeV
J(cm2 s sr MeV)-1
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
087
Mar 28
095
Apr 5
103
Apr 13
111
Apr 21
Day of year / data



SOHO COSTEP EPHIN (2005)
e– 0.25–0.70 MeV
e– 0.67–3.00 MeV
e– 2.64–10.4 MeV
p 4.3–7.8 MeV
p 7.8–25.0 MeV
p 25–53 MeV
J(cm^2 s sr MeV)^-1
ACE EPAM DE
Sector Avg
(MeV Electron)
0,038-0,053
0,053-0,103
0,103-0,175
0,175-0,315
12
17
22
27
32
37
42
47
Jan 12
Jan 17
Jan 22
Jan 27
Feb 1
Feb 6
Feb 11
Feb 16
Day of year / data

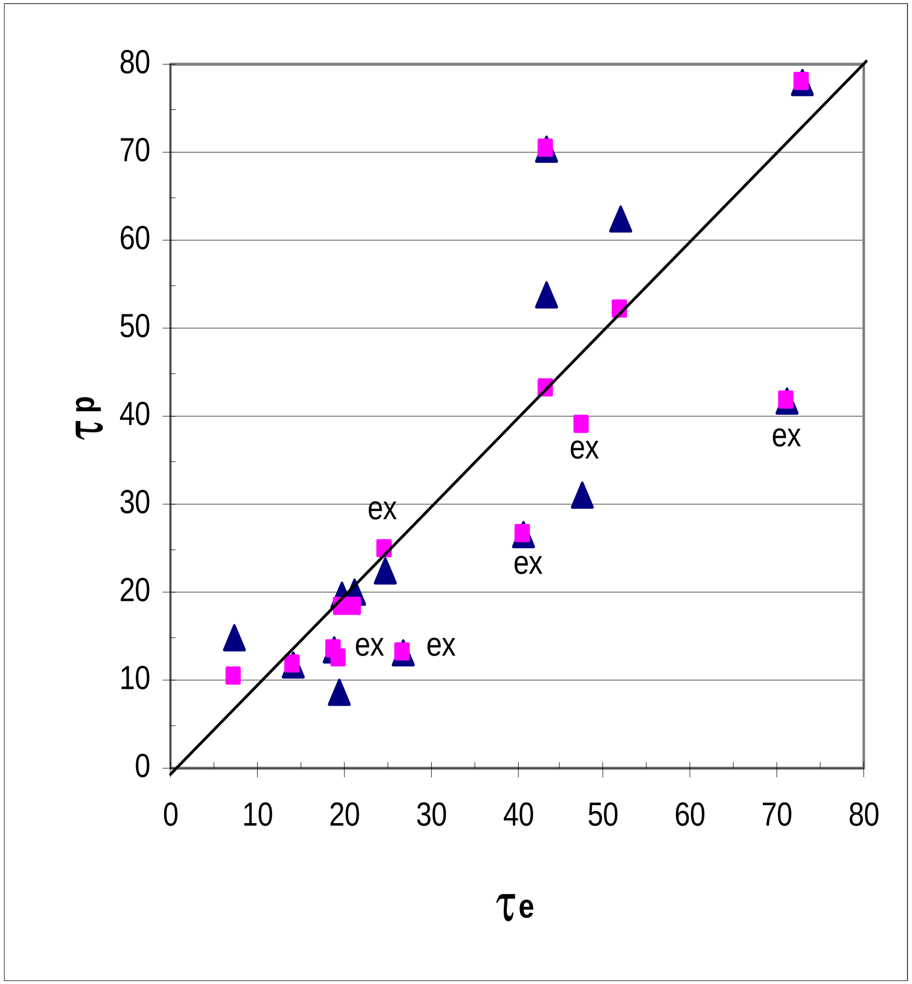
SOHO

15 major flare-associated events with exponential p and e decays far from the background, longer than 1.5-2 days

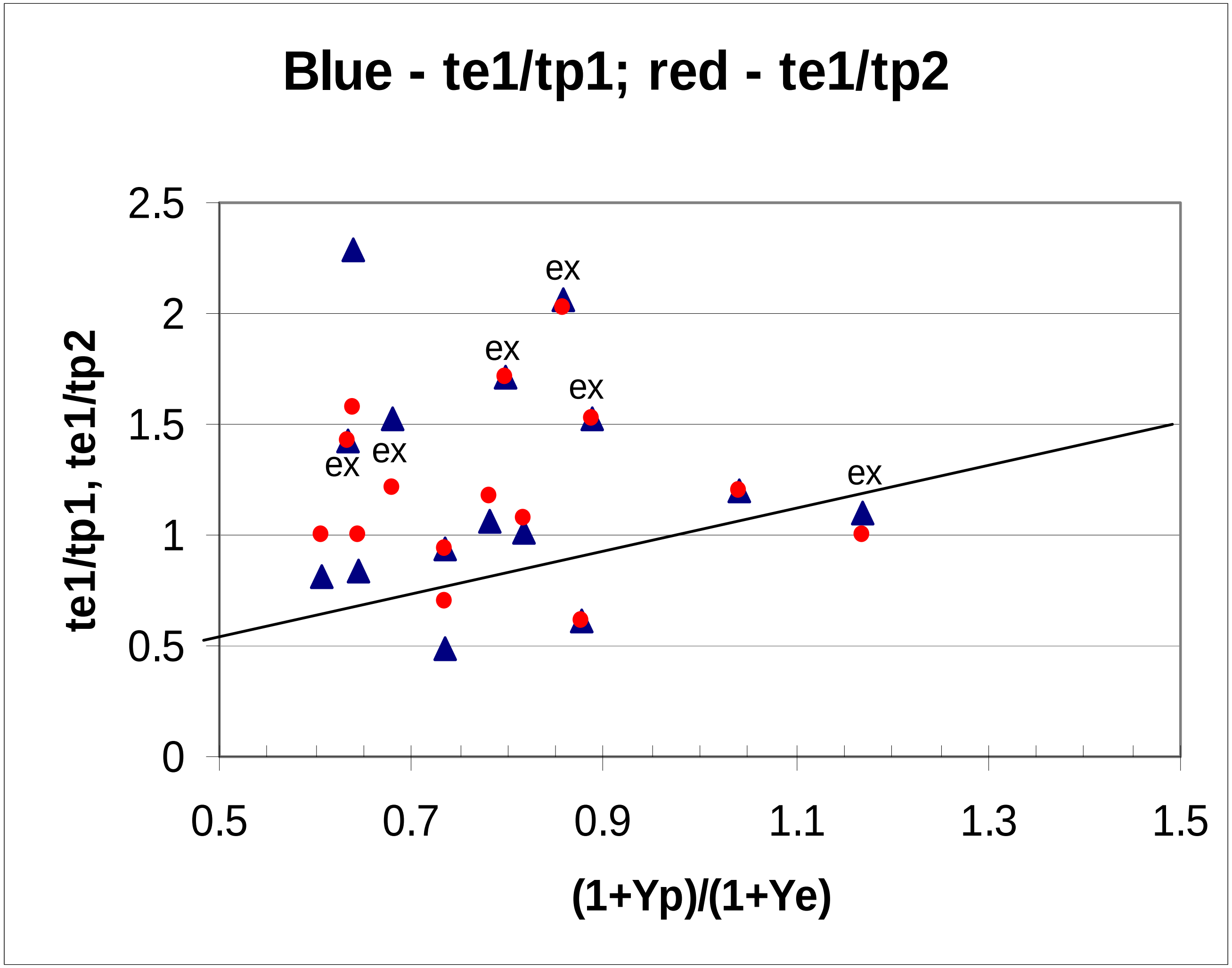
- **Electrons 0.25-0.7 MeV, protons: p1: 4.3-7.8, p2: 7.8-25 MeV.**

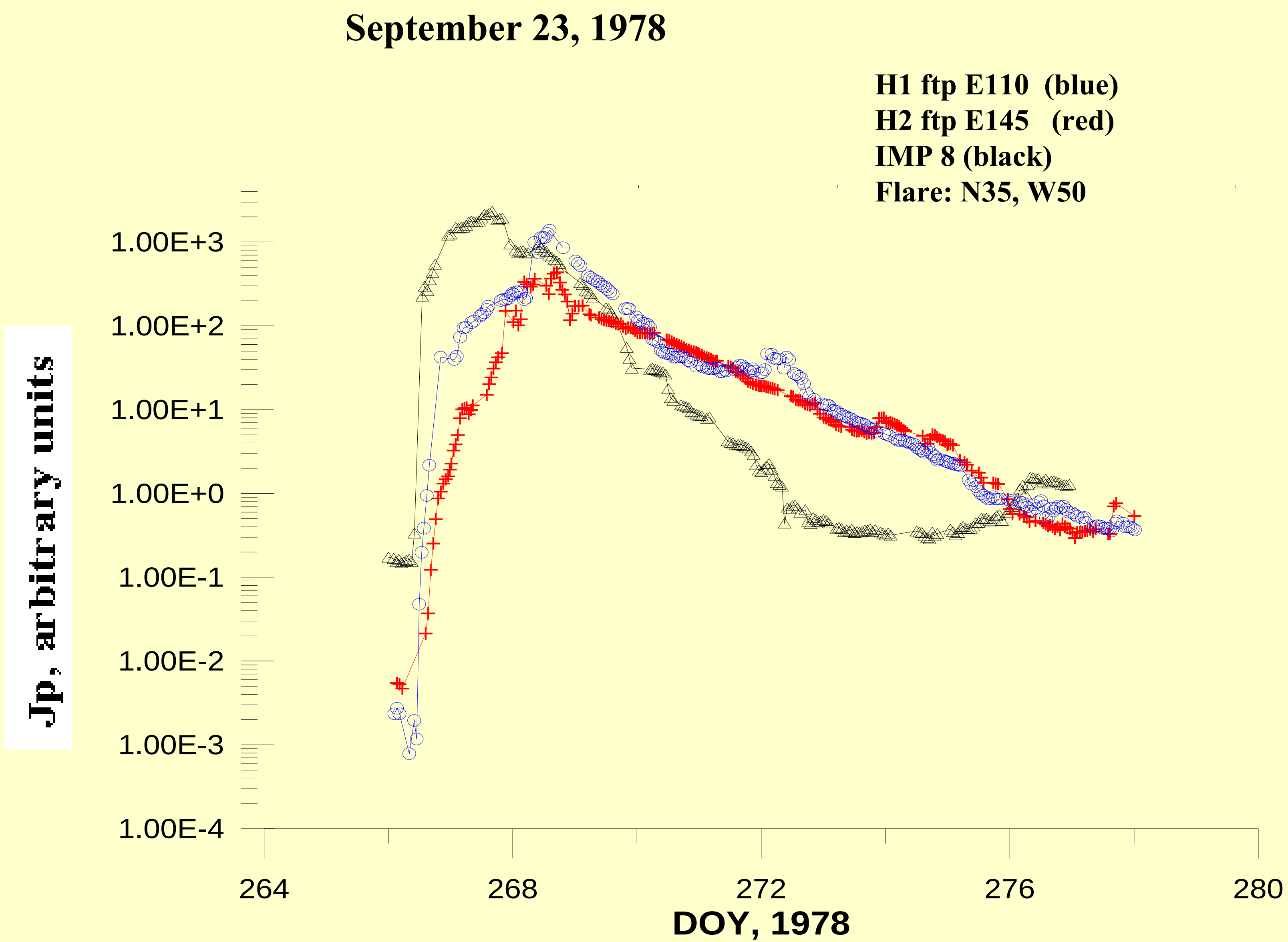
- **Scatterplot $\tau_e - \tau_p$**
- **Forman's formula $\tau_e/\tau_p = (1+\gamma_p)/(1+\gamma_e)$.**

- **Most deviating points belong to "extreme events".**



80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
τ p
τ e
ex
ex
ex
ex
ex
ex


Blue - te1/tp1; red - te1/tp2
te1/tp1, te1/tp2
(1+Yp)/(1+Ye)
2.5
2
1.5
1
0.5
0
0.5
0.7
0.9
1.1
1.3
1.5
ex
ex
ex
ex
ex
ex



September 23, 1978
H1 ftp E110 (blue)
H2 ftp E145 (red)
IMP 8 (black)
Flare: N35, W50
Jp, arbitrary units
1.00E+3
1.00E+2
1.00E+1
1.00E+0
1.00E-1
1.00E-2
1.00E-3
1.00E-4
264
268
272
276
280
DOY, 1978

September, 23, 1978 event, associated with the 3B flare at N35W50.

It was observed simultaneously by IMP 8, Helios 1 and Helios 2.

The flare coordinates relative to the foot points of H1 and H2 magnetic field lines were correspondingly E110 and E145.

Helios 1 and 2 4-13 MeV and IMP 8 >4,6 MeV

H1 and H2 "saw" the flare eastward through the event and $\tau = 30$ hrs.

IMP 8 was optimally connected to the flare site at the start and saw it westward during the decay phase and τ had less value

$\tau = 12$ hrs.

Conclusions. At late phase of decay

1. **In half of events τ_{exp} differ from τ_{theor} not more than 25%.**

2. **Main part of $\tau_{exp} > \tau_{theor}$ decays are associated with East flares, those of $\tau_{exp} < \tau_{theor}$ with West flares.**

3. **Deviation of τ_{exp} from τ_{theor} with a "wrong" sign in some events may be due to the difference of the flare site and a site of particle escape from the Sun or even may cast doubt on traditional flare association of SEPs.**

4. **In most cases the shapes of similar velocity electrons and protons are similar (exponential or power-law).**

5. **As a rule the rate of electron decay is similar or slower than proton one.**

6. **On the limited statistics of 15 major events correlation between τ_e and τ_p : $\tau_e/\tau_p = (1+\gamma_p)/(1+\gamma_e)$ (Forman) within 30-35 % accuracy is valid only for a half of decays. Most deviating points concern "extreme" events.**

More statistics is necessary!!