MAJOR SOLAR ENERGETIC PARTICLE EVENTS IN THREE DIMENSIONS

L. Kocharov, E. Valtonen, and O. Saloniemi
University of Turku, Finland

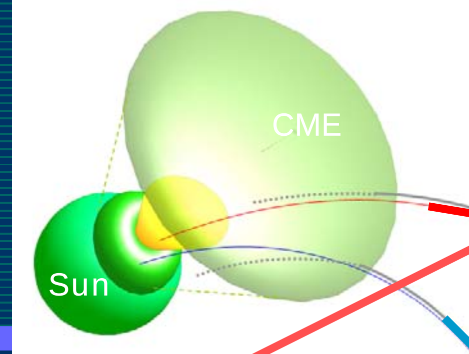
B. J. Thompson and M. J. Reiner
NASA/GSFC, U.S.A.

A. Klassen
Christian-Albrechts-Universität Kiel, Germany

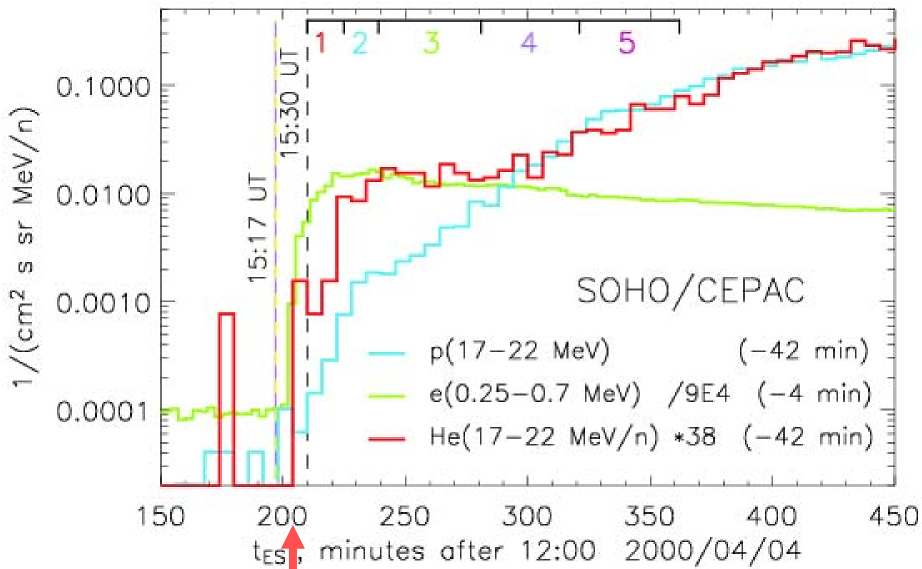
22nd European Cosmic Ray Symposium

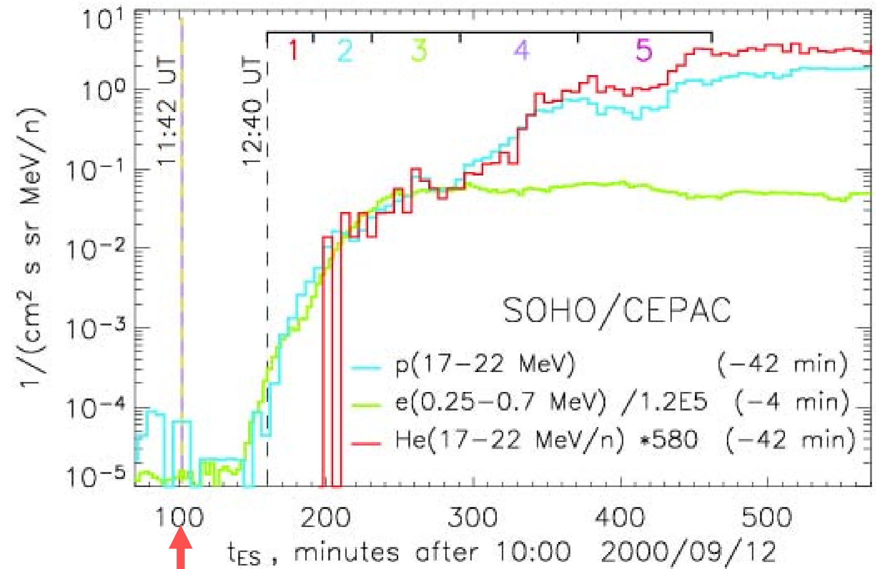
Turku, 5 August 2010

4 Apr 2000: N16 W66



12 Sept 2000: S19 W08





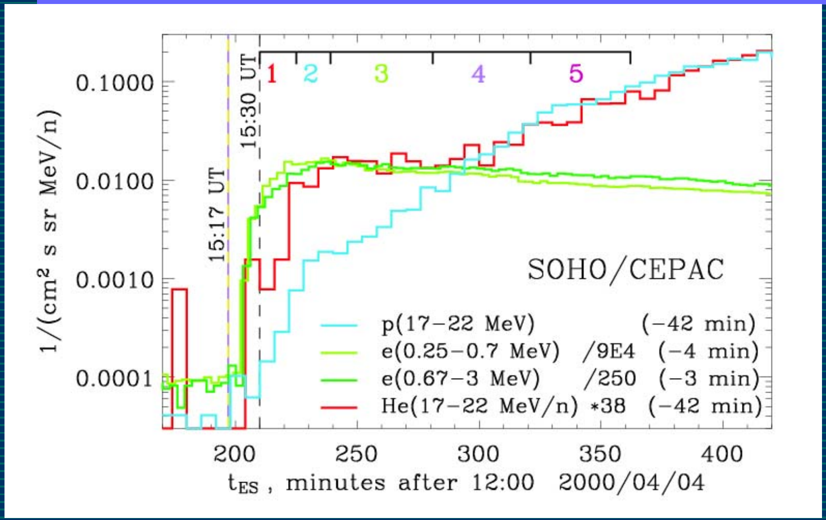
Type II m start

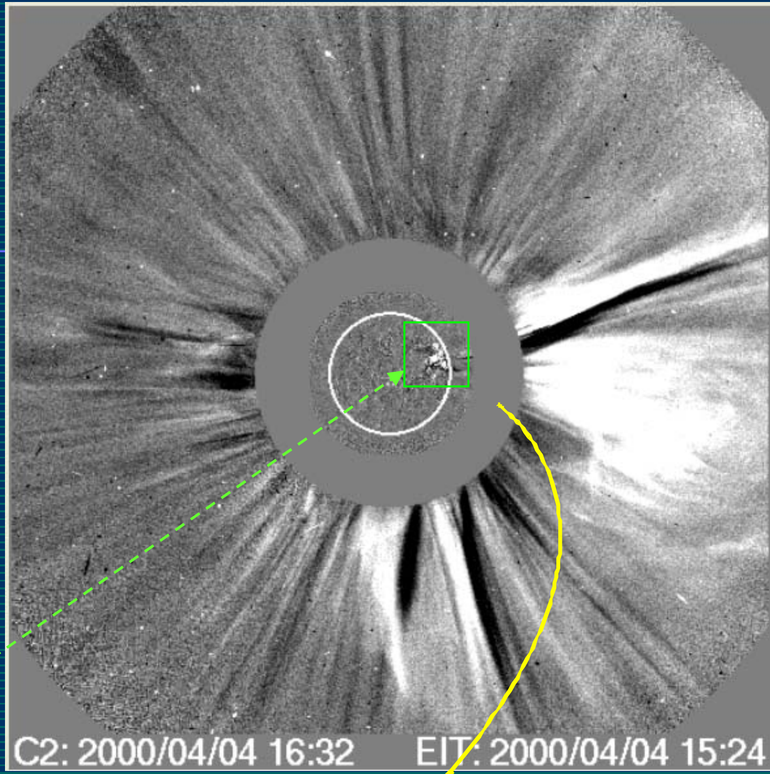
Type II m start

Shifted time: $t_{ES} = t_{OBS} - [1.2\mathrm{AU}] / V + 8\mathrm{min}$

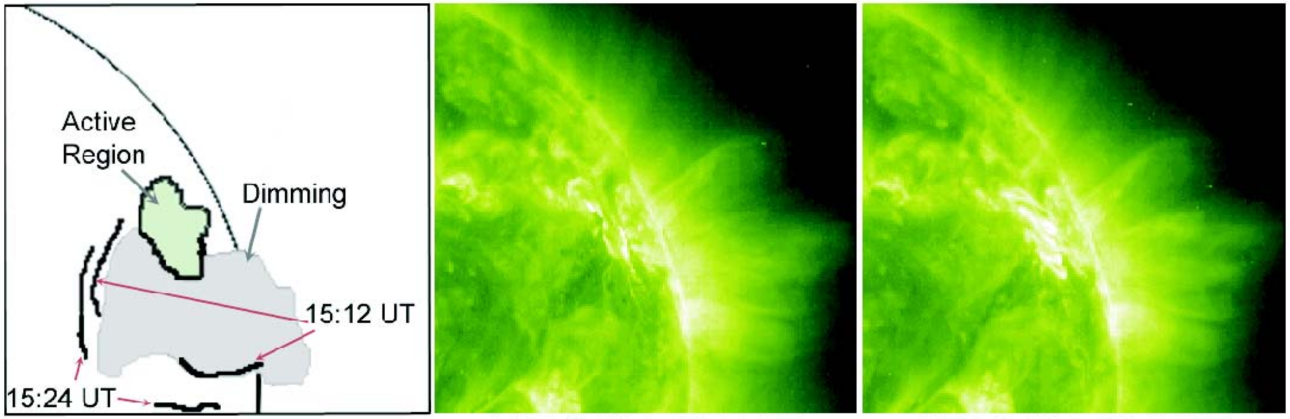
The 4 April 2000 event

Flare: N16 W66



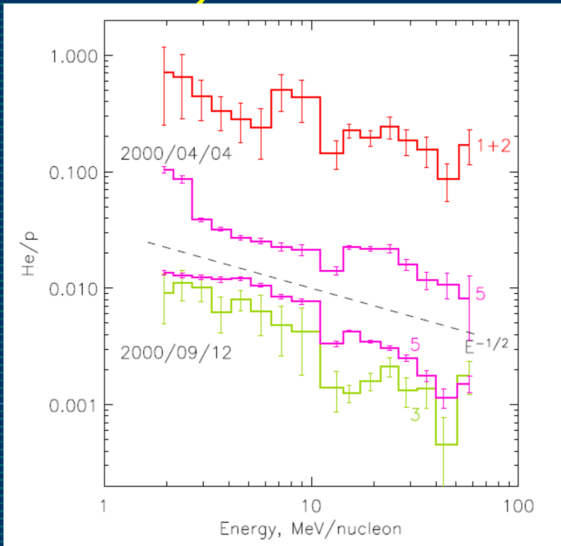


SEPs

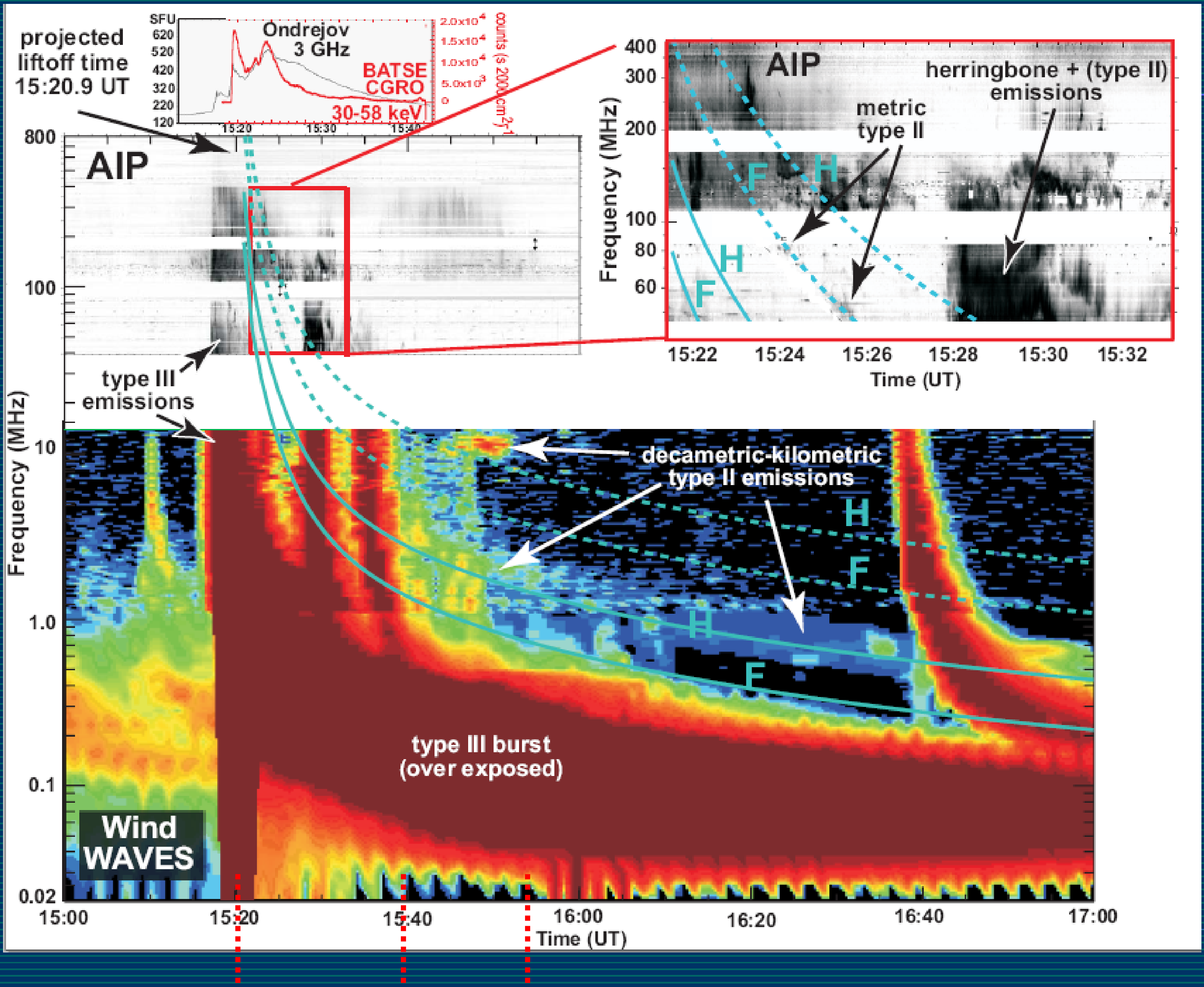


2000/04/04 15:24 UT

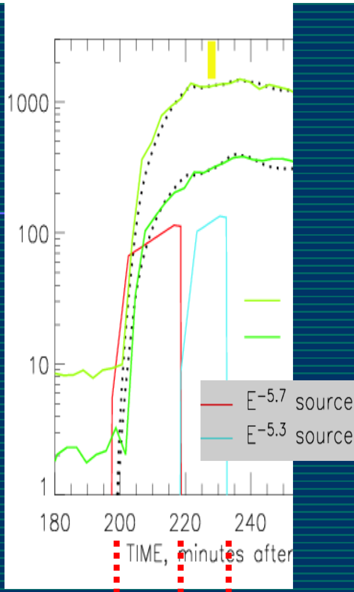
2000/04/04 16:37 UT



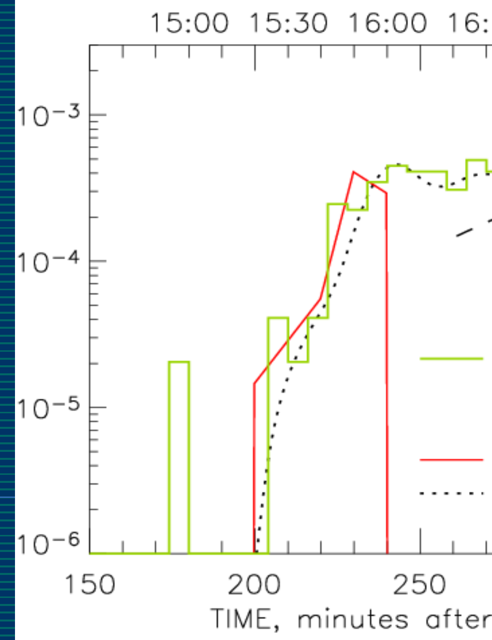
The 4 April 2000 event



~1 MeV electrons



~20 MeV helium



The 4 Apr 2000 SEP event:

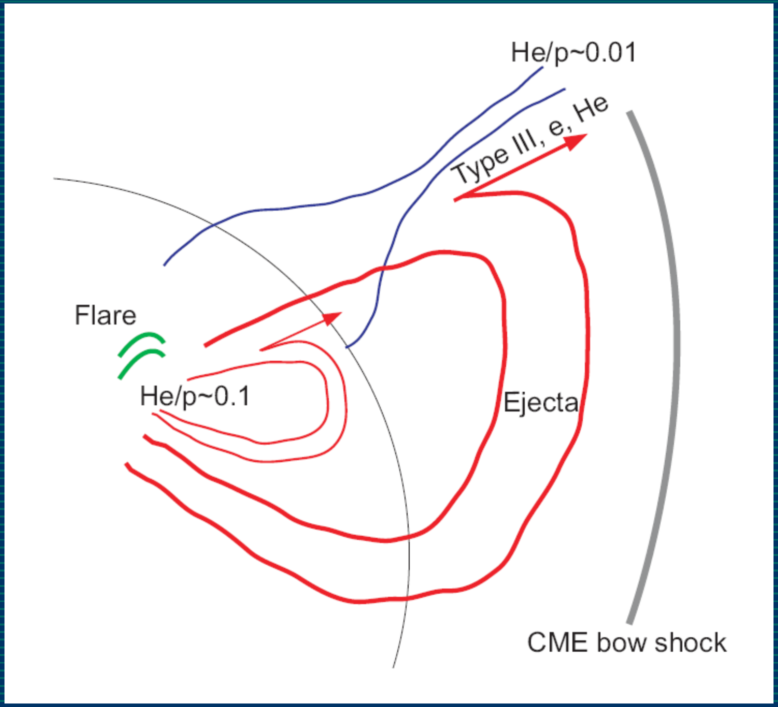
Helium-rich first phase associated with type III L

➢ Solar atmospheric and accelerated helium abundances *at the flare site* can be determined with methods of γ-ray spectroscopy. These studies suggest either accelerated ^{4}He/proton ratios >~50% and/or a higher He/H abundance in the subcoronal regions than in the photosphere. [Kozlovsky, B. & Ramaty, R. 1974, ApJ, 191, L43; Mandzhavidze, N., Ramaty, R., & Kozlovsky, B. 1997, ApJ, 489, L99; Murphy, R. J., et al. 1997, ApJ, 490, 883; Share, G. H., & Murphy, R. J. 1997, ApJ, 485, 409; Share, G. H., & Murphy, R. J. 1998, ApJ, 508, 876]

➢ High helium abundance is observed in the interplanetary space during the passage of the Interplanetary counterparts of Coronal Mass Ejections (ICMEs or ejecta) and especially in the ICME's *magnetic clouds*, He/H> 0.08 , which is indicative of the solar environment of the CME origin [e.g.,Neugebauer, M., & Goldstein, R. 1997, in Coronal Mass Ejections, ed. N. Crooker, J. A. Joselyn, & J. Feynman (Geophys. Monograph 99) p.245; Lynch, B. J., Zurbuchen, T. H., Fisk, L. A., et al. 2005, J. Geophys. Res., 108, A6, 1239].

➢ In a correlative study between >20 MeV solar proton events, coronal mass ejections, flares, and radio bursts, Cane et al. (2002) found that essentially all of the proton events are preceded by groups of type III bursts, with the type III's starting frequencies decreasing as a function of time – *type III L* [Cane, H. V., Erickson, W. C., & Prestage, N. P. 2002, J. Geophys. Res., 107, A10, 1315].

The multiwavelength analysis and modeling of the 2000 April 4 event has revealed:



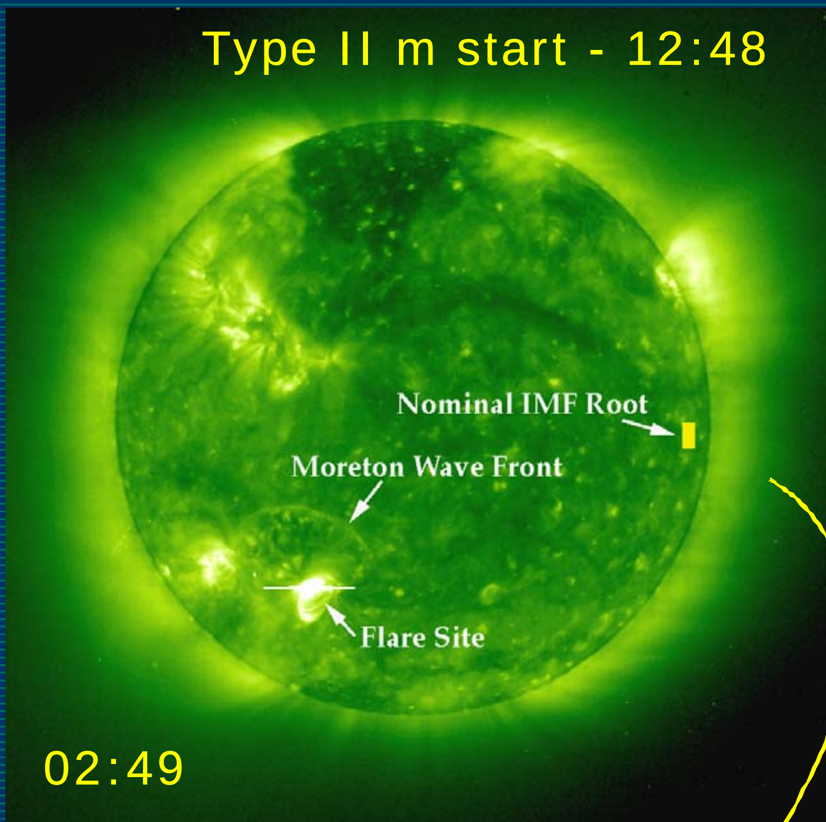
- ❑ A remarkable time coincidence between (i) the timing of the type III bursts, (ii) the release profiles of relativistic electrons and (iii) the release profile of helium-rich SEPs.

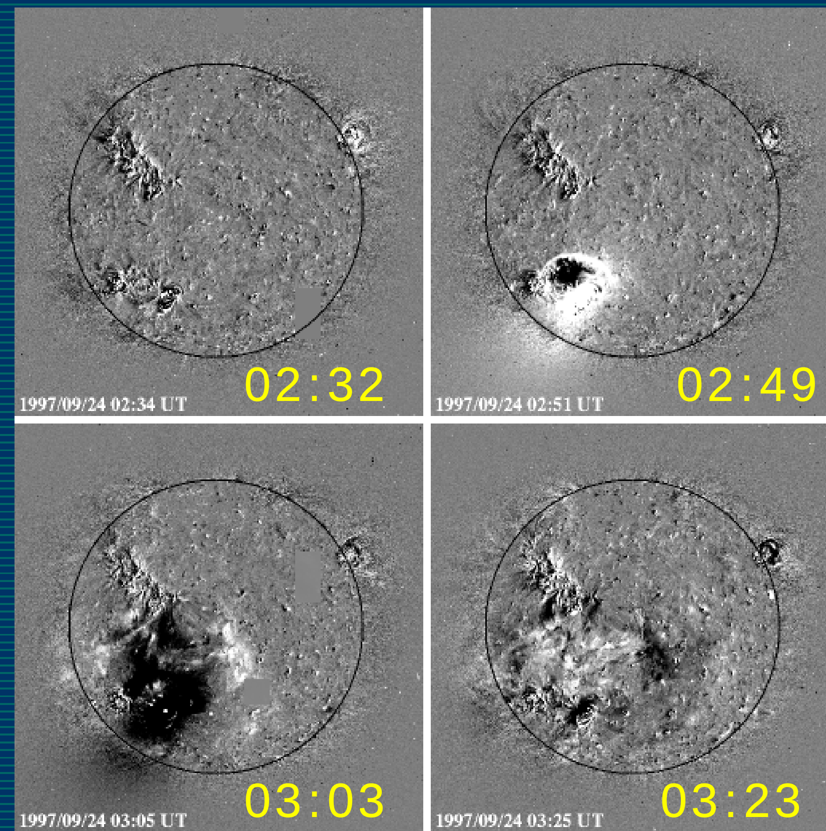
- ❑ A straightforward interpretation is that the SEP event started with particle emission originating from the CME's helium-rich core and that those coronal particles escaped into the interplanetary medium before the start of the second, interplanetary shock-acceleration phase of this major SEP event.

SEP events associated with large-scale coronal waves

- Kocharov, L. G., Lee, J. W., Zirin, H., Kovaltsov, G. A., Usoskin, I. G., Pyle, K. R., Shea, M. A., Smart, D. F. (1994), Neutron and Electromagnetic Emissions During the 1990 May 24 Solar Flare, *Solar Phys.,* 155, 149-170.
- Torsti, J., Kocharov, L. G., Teittinen, M., Thompson, B. J. (1999), Injection of ~10 MeV protons in association with coronal Moreton wave, *Astrophys. J.*, 510, 460-465.
- Krucker, Säm; Larson, Davin E.; Lin, Robert P.; Thompson, Barbara J. (1999) On the Origin of Impulsive Electron Events Observed at 1 AU, *Astrophys. J.*, 519, 864-875.
- Torsti, J., Kocharov, L., Innes, D. E., Laivola, J., and Sahla, T. (2001) Injection of energetic protons during solar eruption on 1999 May 9: Effect of flare and coronal mass ejection, *Astronomy and Astrophysics*, 365, 198-203.

24 September 1997



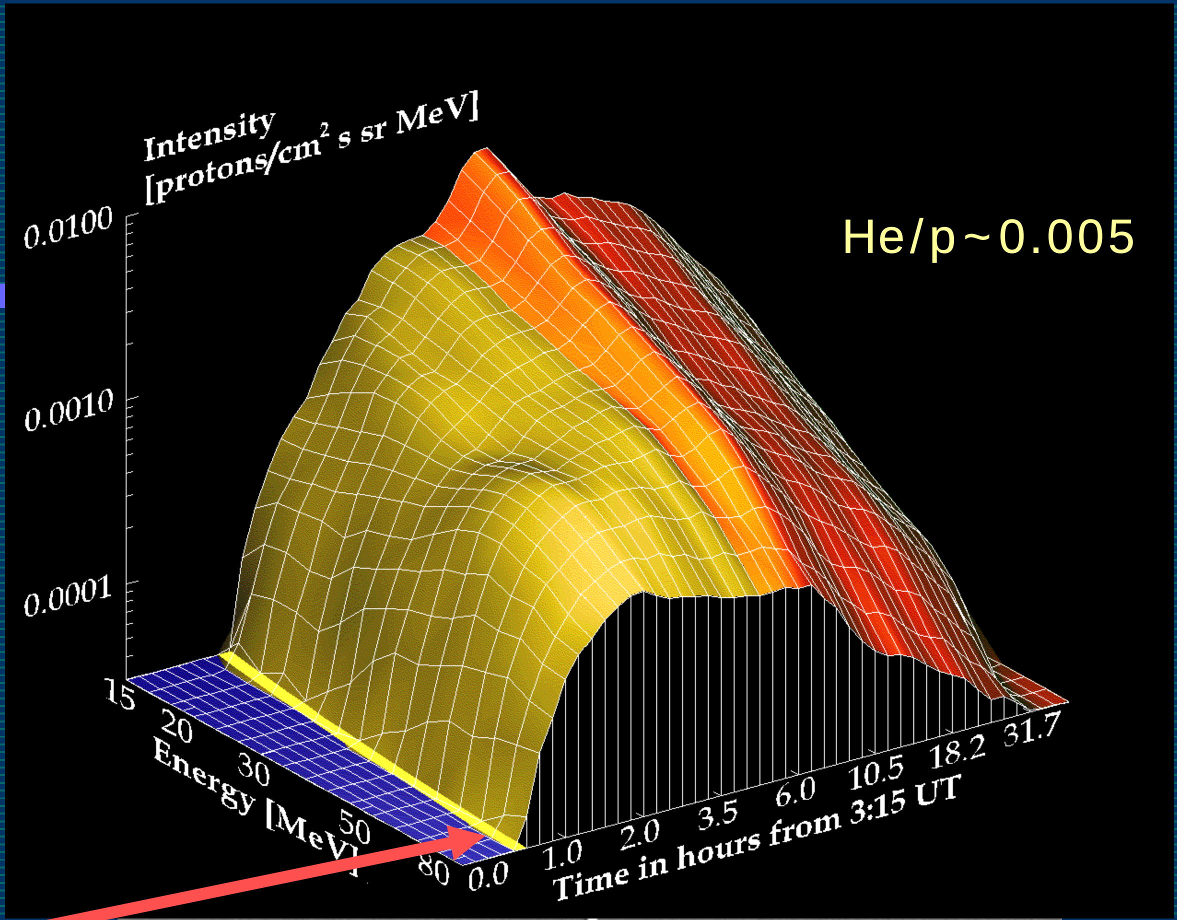


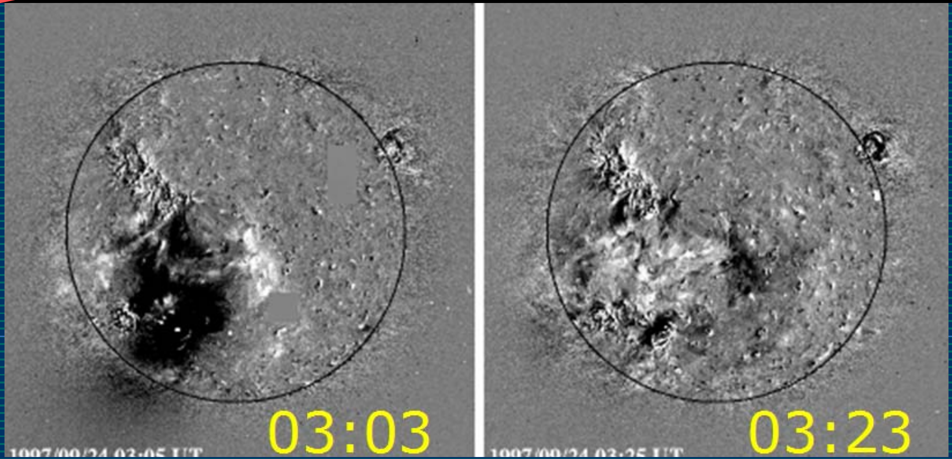
SEPs

J. TORSTI, L. KOCHAROV, M. TEITTINEN, & B. J. THOMPSON (1999) ApJ, 510, 460.

24 September 1997

- Proton intensity-time profiles observed by ERNE in different energy channels.
  The timescale is linear up to 2.0 hr and is logarithmic beyond this point.
- The bright yellow strip indicates arrival of the first protons if injected from the at 3:15 UT [+8 min].





Type II m start - 12:48

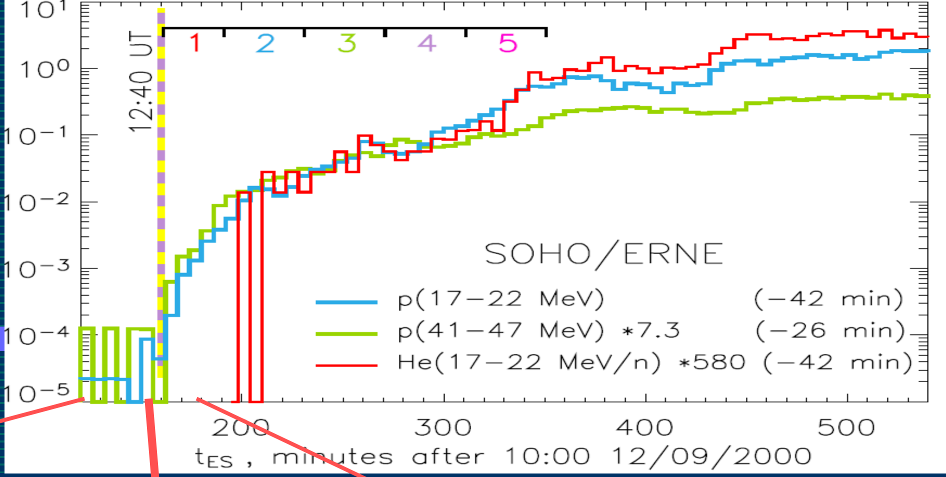
J. TORSTI, L. KOCHAROV, M. TEITTINEN, & B. J. THOMPSON (1999) ApJ, 510, 460.

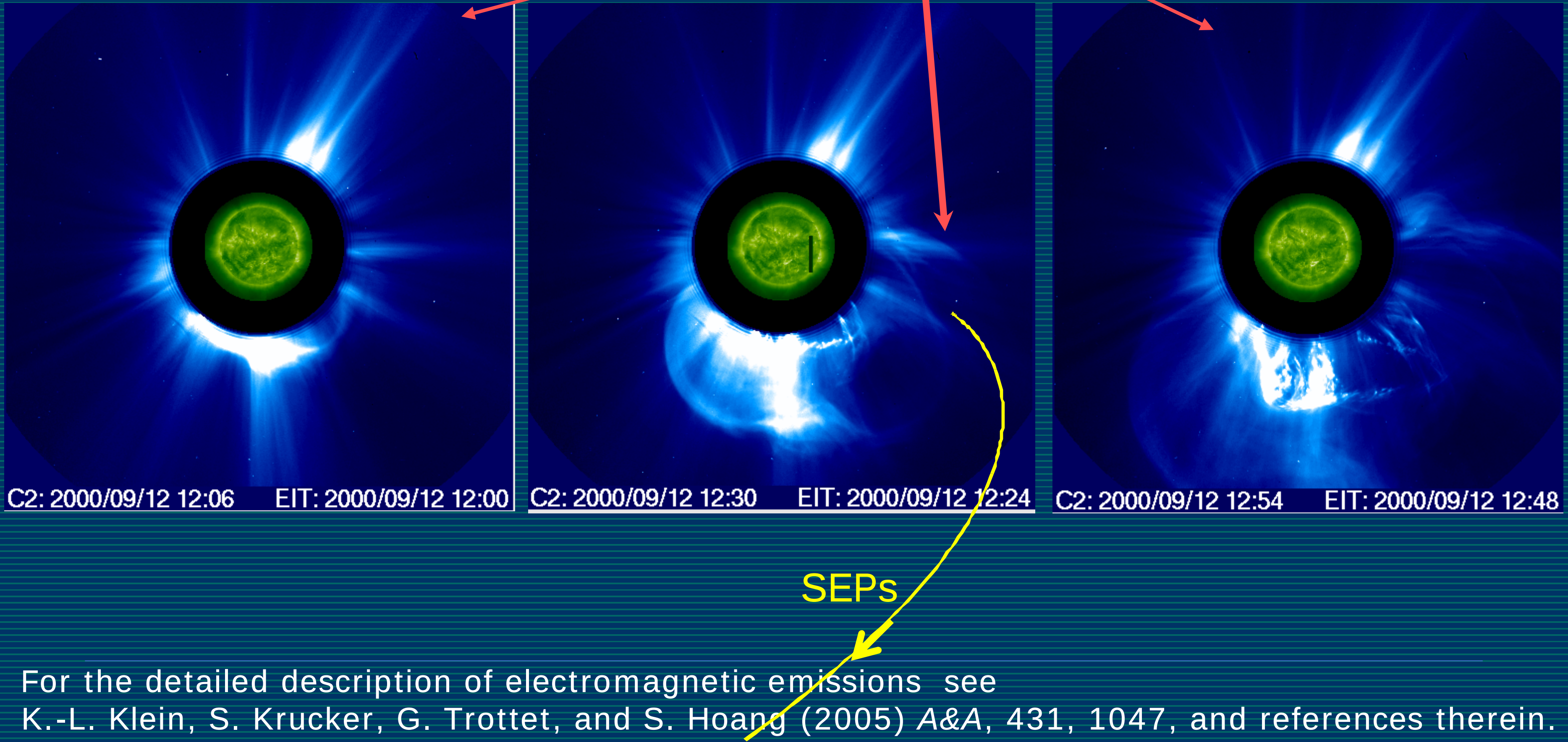
The Physical Nature of Large-Scale Coronal (EIT) Waves

- The MHD wave/shock models.
- Magnetic reconfiguration scenarios.
- Both global wave and magnetic reconnection.

A. Warmuth (2007) *Large-scale waves and shocks in solar corona*, Lect. Notes Phys., 725, 107-138; O. Cohen et al. (2009) *Numerical simulations of a EUV coronal wave based on the 2009 February 13 CME event observed by STEREO*, ApJ, 705, 587-602; and references therein.

12 Sept 2000: S19 W08

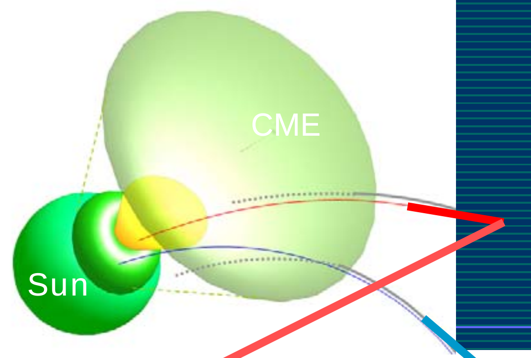


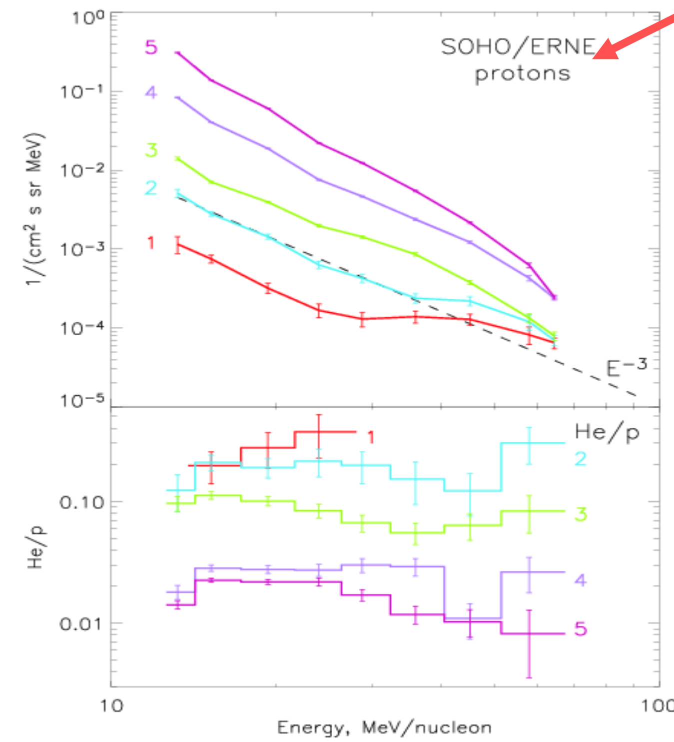


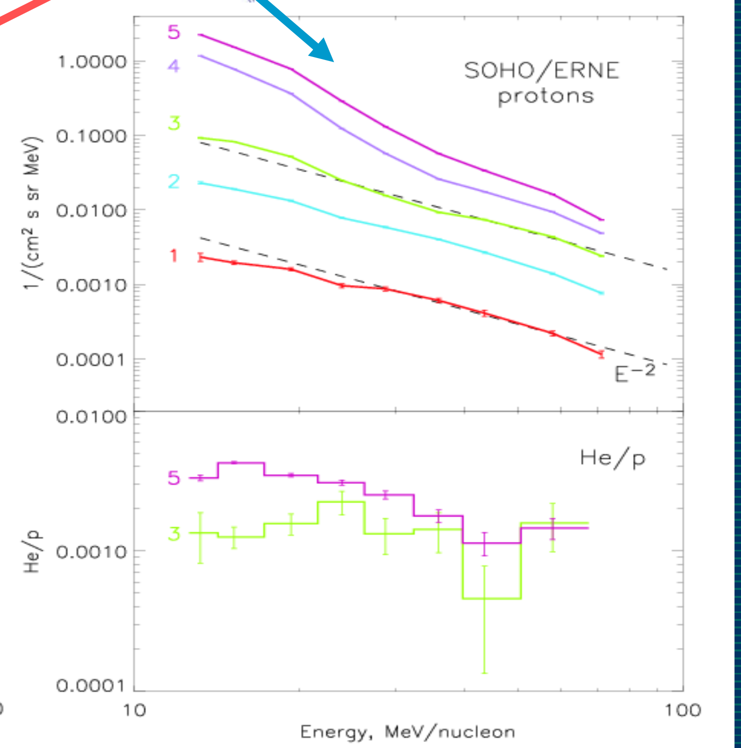
For the detailed description of electromagnetic emissions see
K.-L. Klein, S. Krucker, G. Trottet, and S. Hoang (2005) *A&A*, 431, 1047, and references therein.

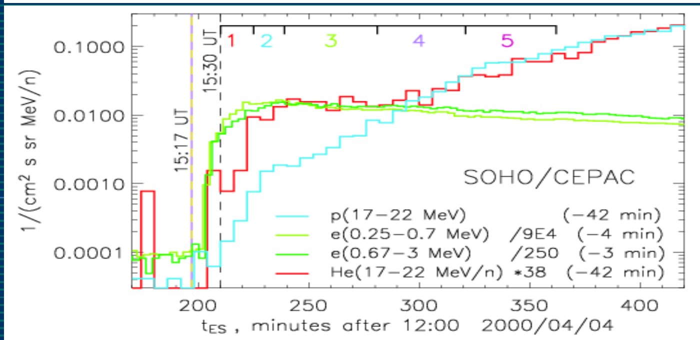
4 Apr 2000: N16 W66

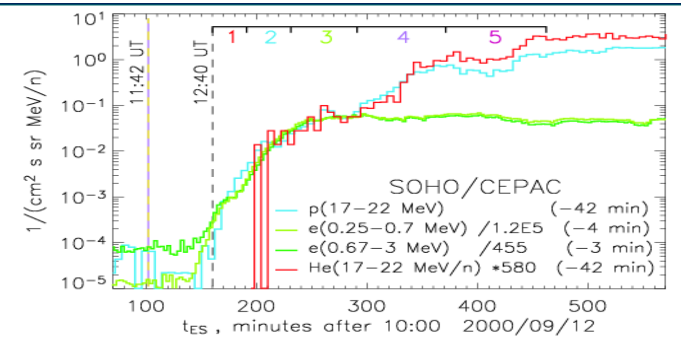
12 Sept 2000: S19 W08

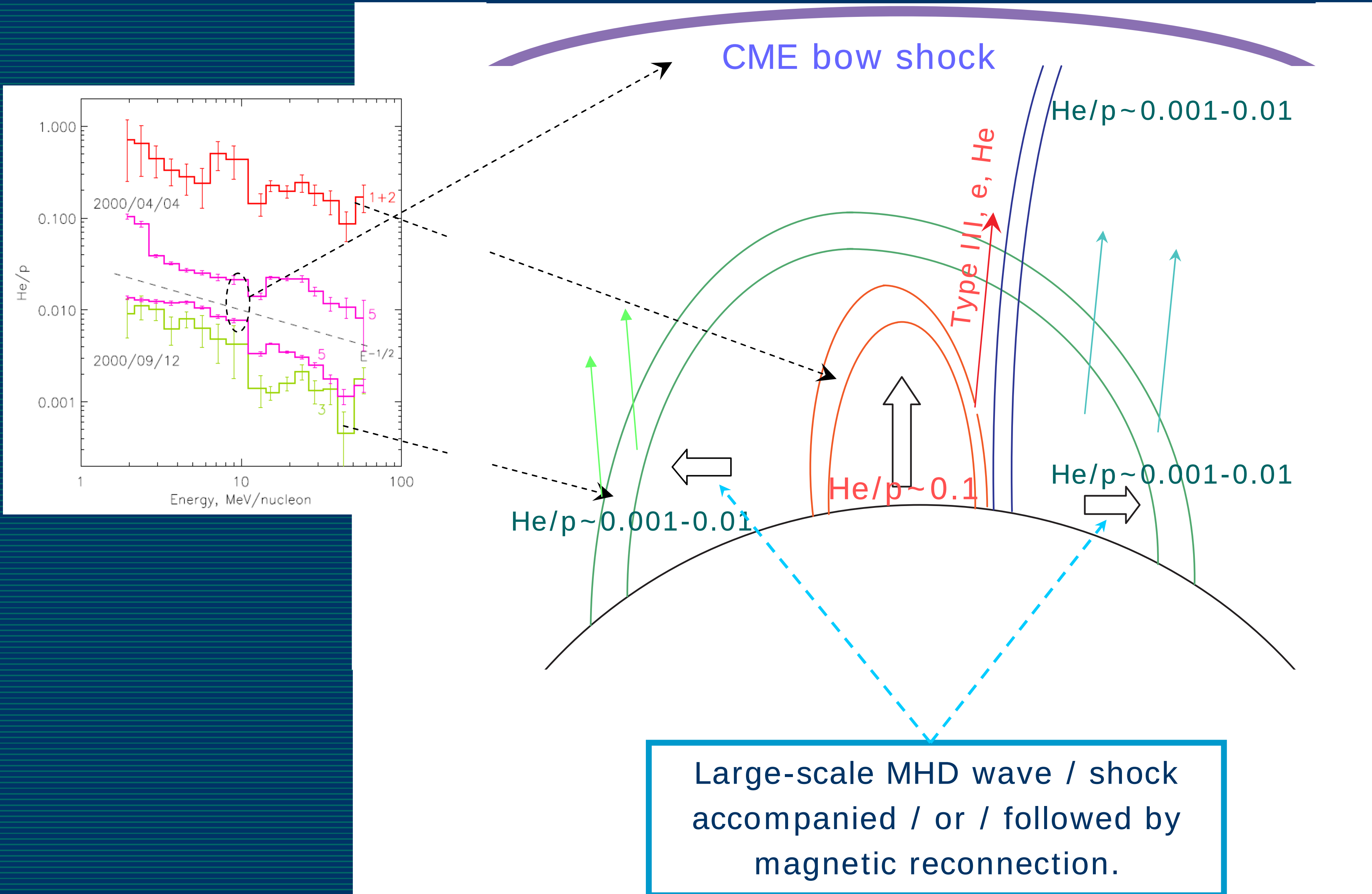











1.000
0.100
0.010
0.001
He/p
2000/04/04
2000/09/12
1+2
5
5
3
E$^{-1/2}$
1
10
100
Energy, MeV/nucleon
CME bow shock
He/p~0.001-0.01
Type III, e, He
He/p~0.1
He/p~0.001-0.01
He/p~0.001-0.01
Large-scale MHD wave / shock
accompanied / or / followed by
magnetic reconnection.

Conclusions

- Major SEP events start with particle accelerations in solar corona, and those coronal components dominate during first 1-2 hours.

- At magnetic connection to the eruption's center, the first-phase SEPs originate from the CME core.

- When observed at magnetic connection to aside from the eruption's center, onset of the SEP release is delayed for about coronal-wave transit time to the connected point. The first-phase SEPs originate neither from the CME core nor from its bow shock.

- During the first hour after the CME launch, the coronal particle populations are not shielded by the CME-bow shock in solar wind, and thus the seed particles for the event's second (main) phase could also come from the solar corona.