Particle Transport in the Heliosphere:
Part 1

Gaetano Zimbardo

Universita’ della Calabria, Cosenza, Italy

with contributions from S. Perri, P. Pommois, P. Veltri

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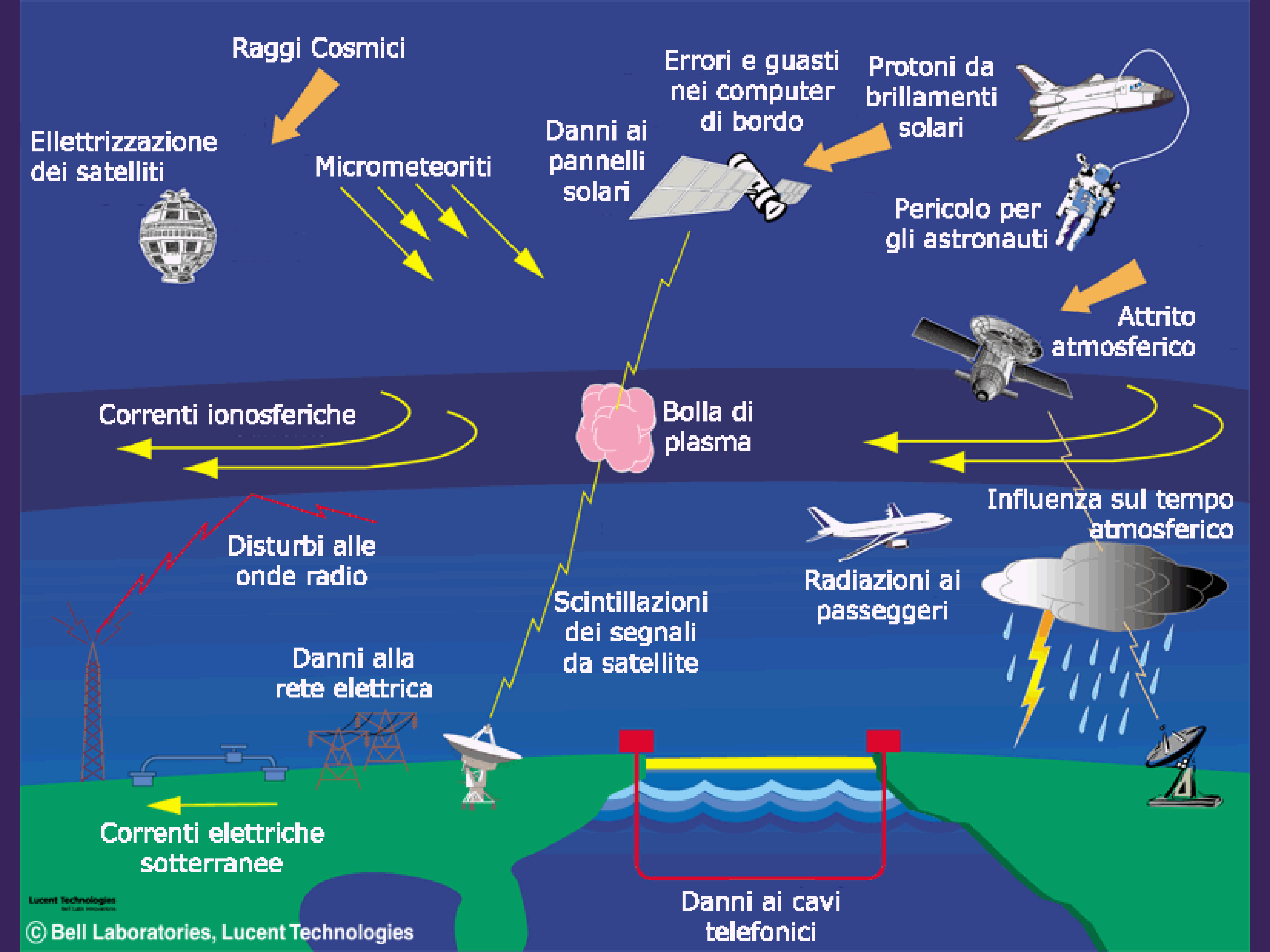

Raggi Cosmici
Errori e guasti nei computer di bordo
Protoni da brillamenti solari
Elettrizzazione dei satelliti
Micrometeoriti
Danni ai pannelli solari
Pericolo per gli astronauti
Attrito atmosferico
Correnti ionosferiche
Bolla di plasma
Influenza sul tempo atmosferico
Disturbi alle onde radio
Radiazioni ai passeggeri
Scintillazioni dei segnali da satellite
Danni alla rete elettrica
Correnti elettriche sotterranee
Danni ai cavi telefonici
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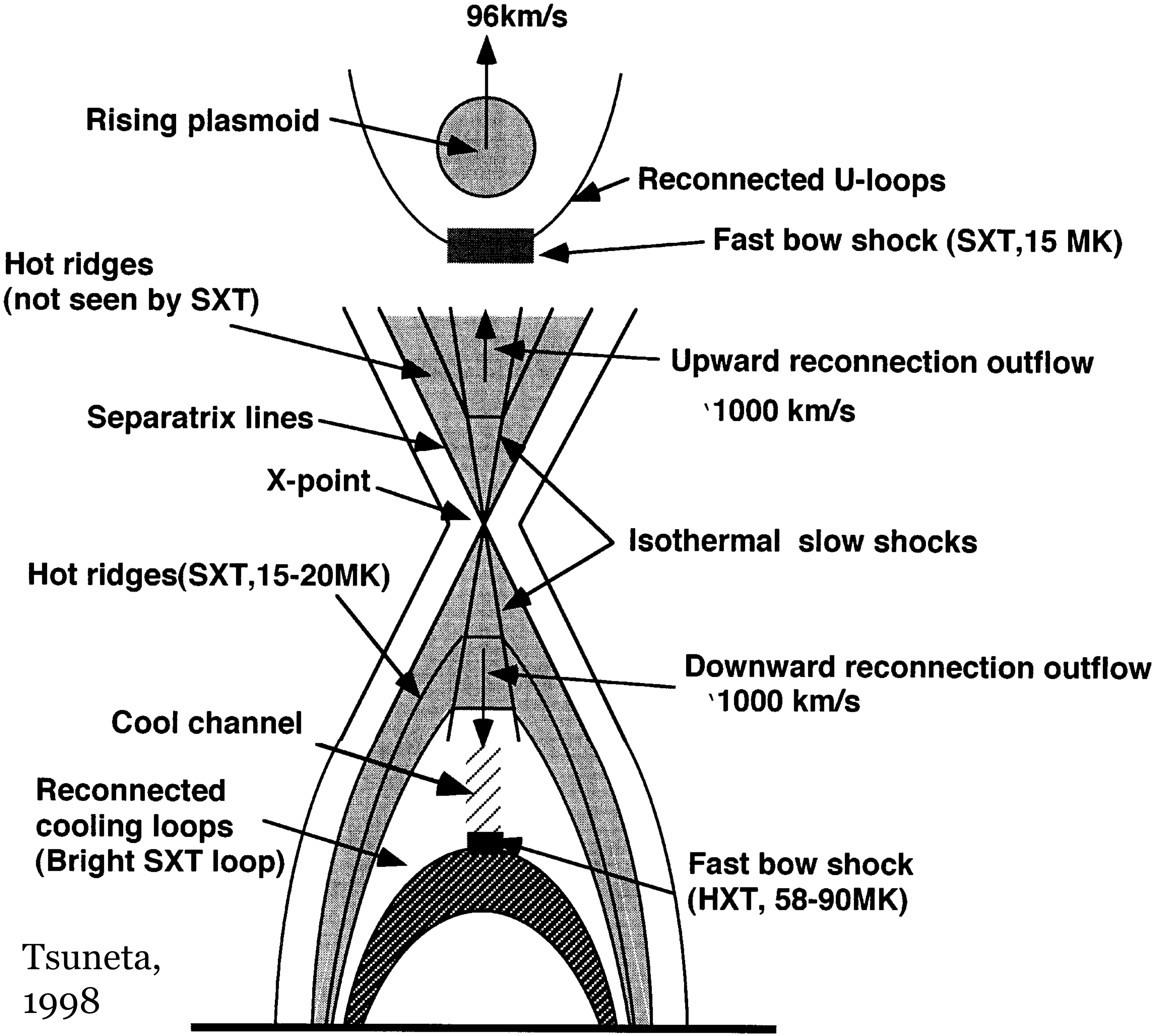
Energetic particles with energies well above the thermal energy are observed everywhere in space:

- In the solar corona
- In the Earth's magnetosphere
- At heliospheric shocks
- At the solar wind termination shock
- From supernova remnants (galactic cosmic rays)
- Extragalactic cosmic rays

- For instance ...

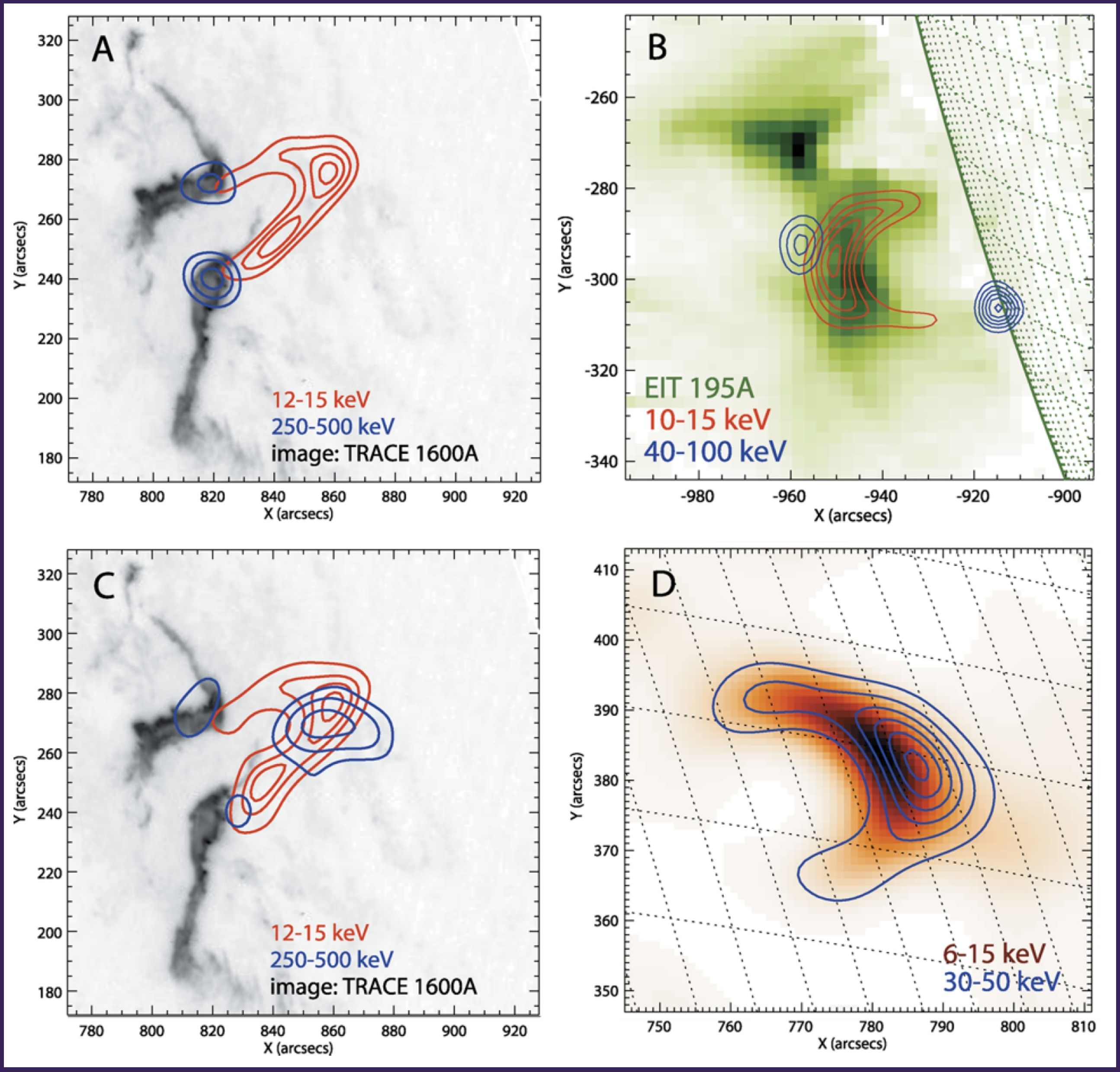


Tsuneta,
1998

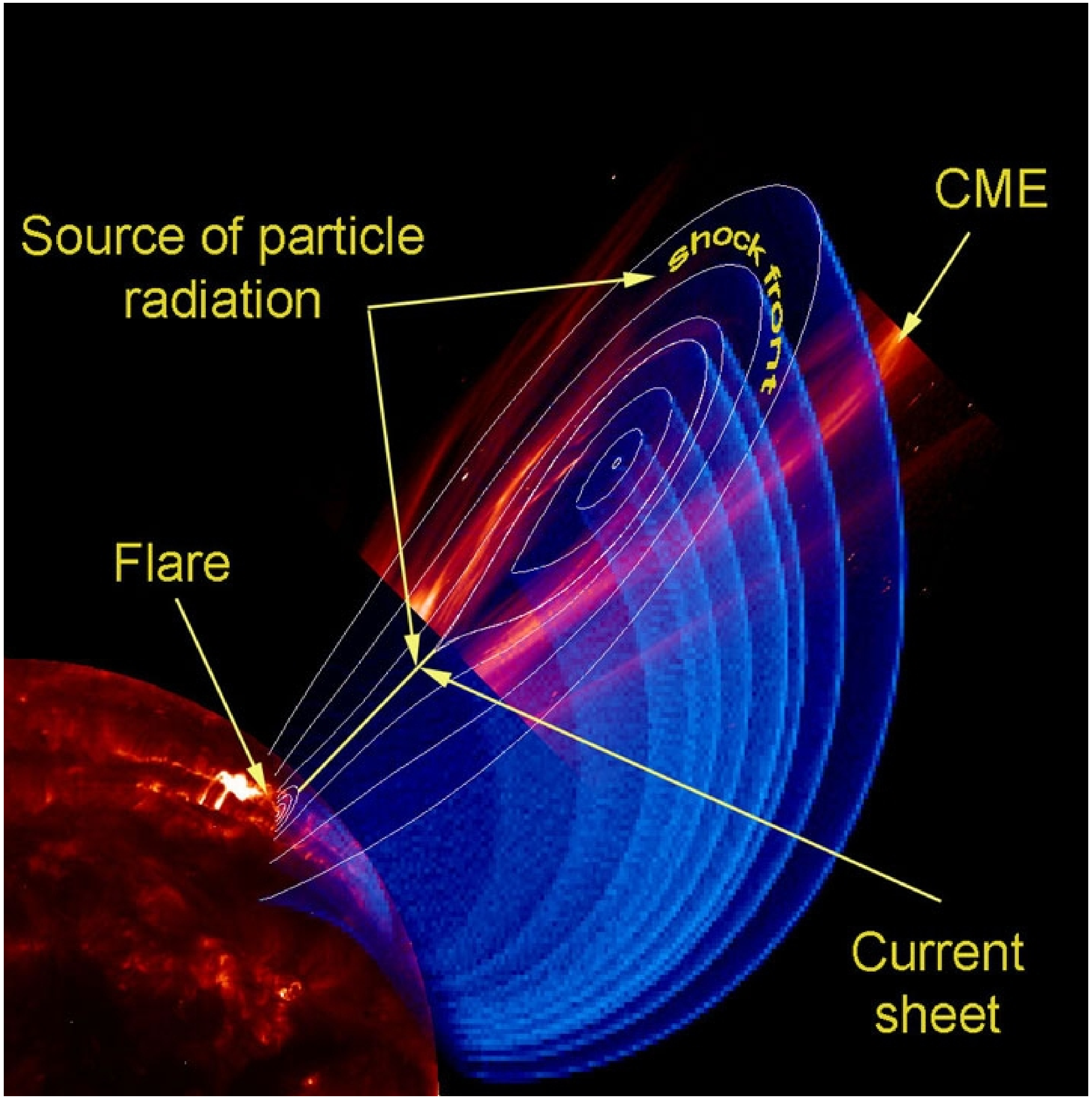
Hard X rays from RHESSI spacecraft:

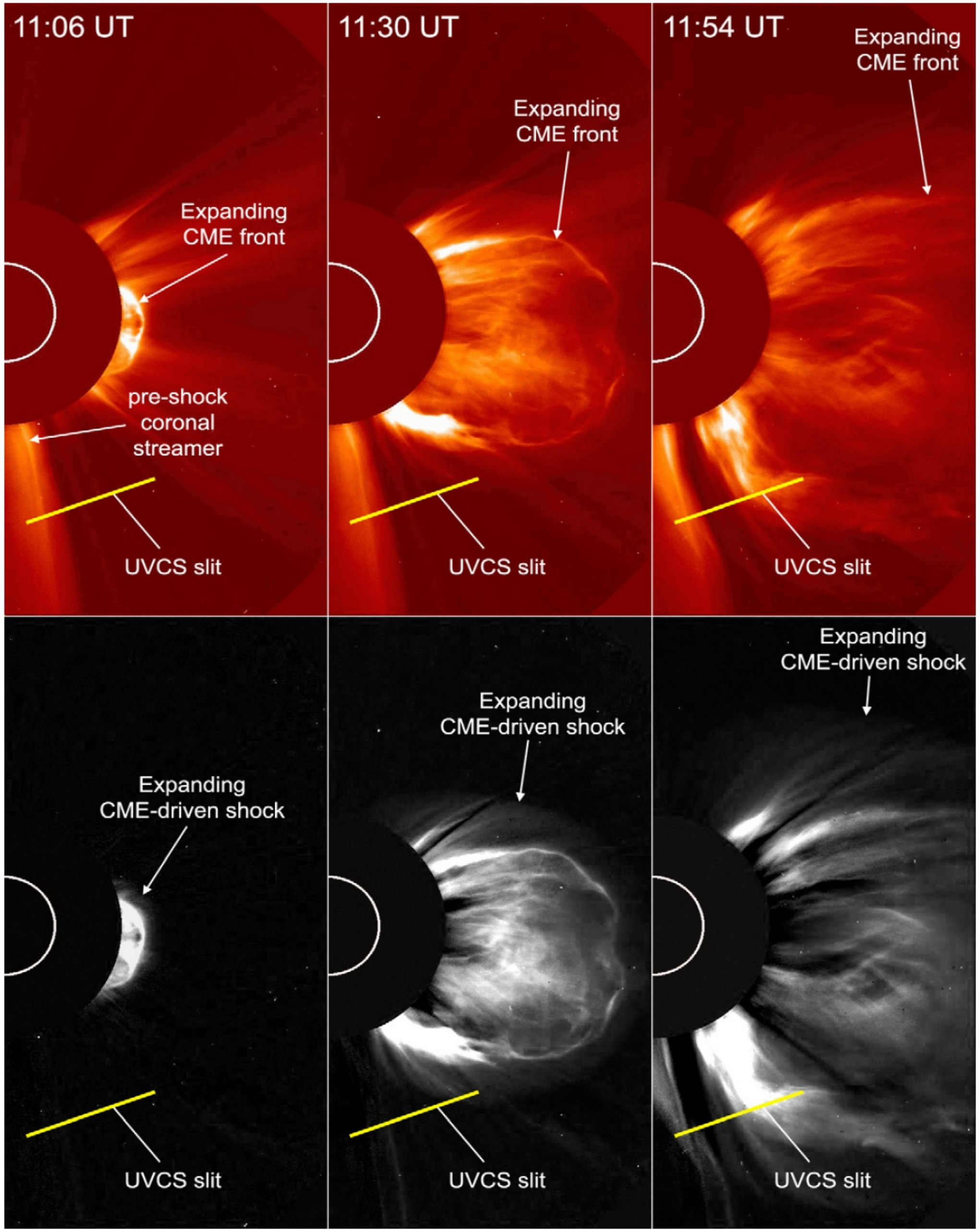
Hard X rays imply energies of several MeV for electrons and ions.

Acceleration times are about 0.1 seconds – big challenge for models!



CME shocks are the main source of solar energetic particles





CME shocks have been studied in detail by Bemporad and Mancuso, ApJ (2010, 2011) and Bemporad et al., ApJ (2014). All the shock parameters have been determined using SoHO white light and UVCS instruments.

SoHO data

Propagation of solar energetic particles (SEPs):

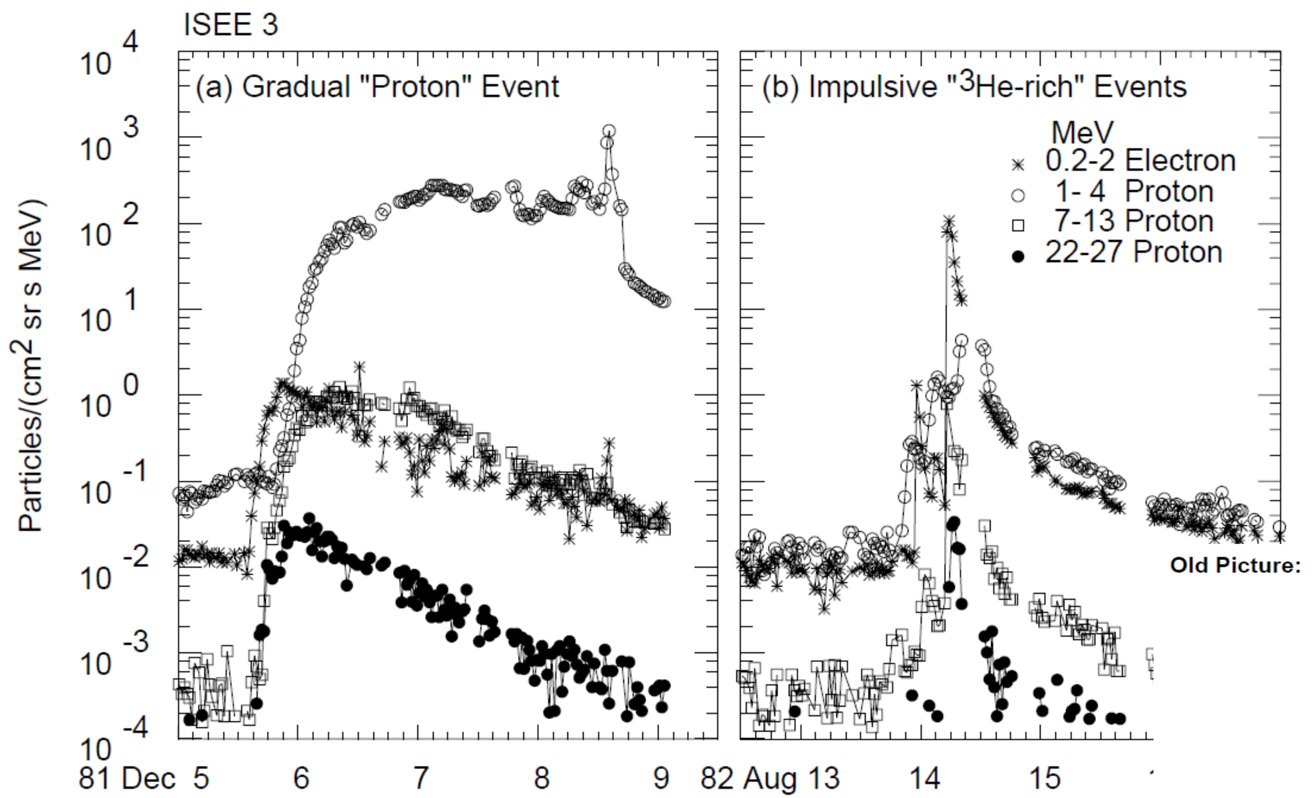
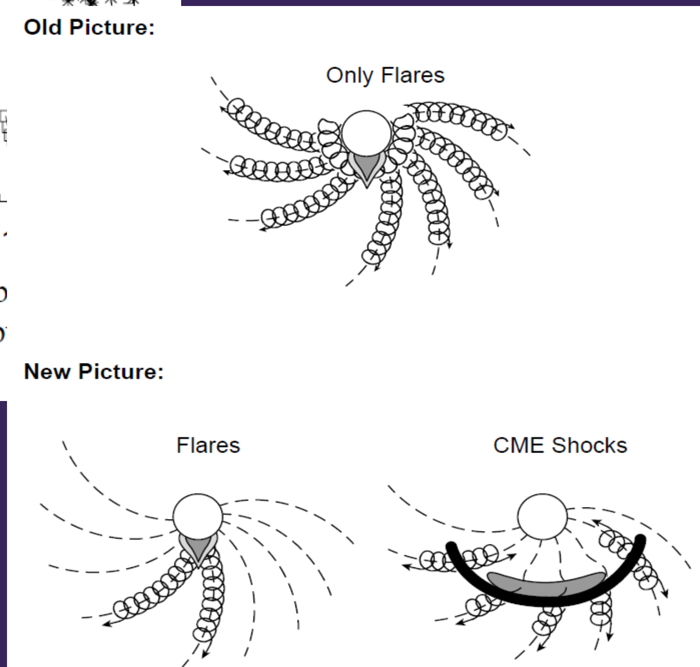
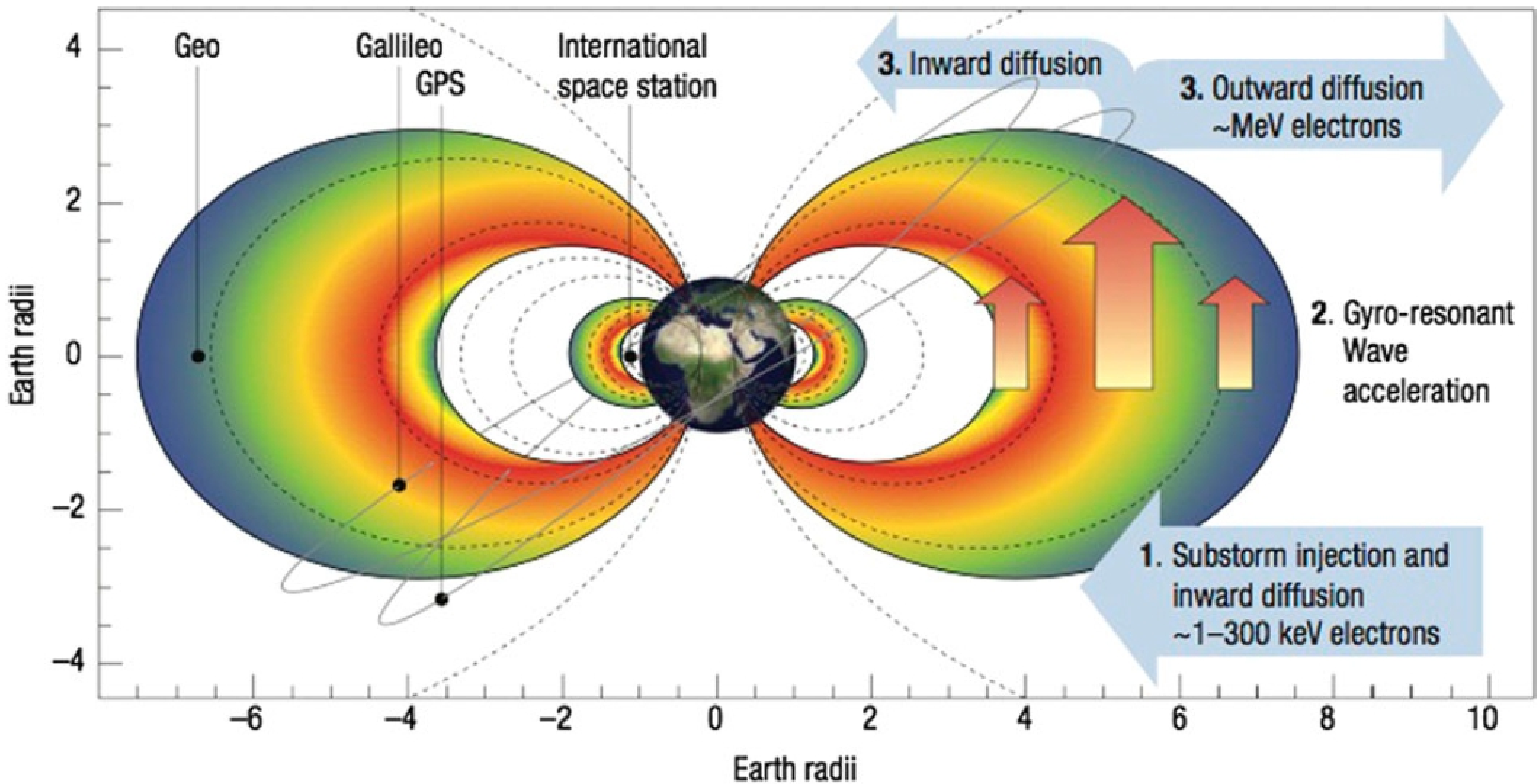


Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b
SEP events. The gradual event is a disappearing-filament event with a CME but no imp
The impulsive events come from a series of flares with no CMEs.



Reames, Space Sci. Rev. (1999)

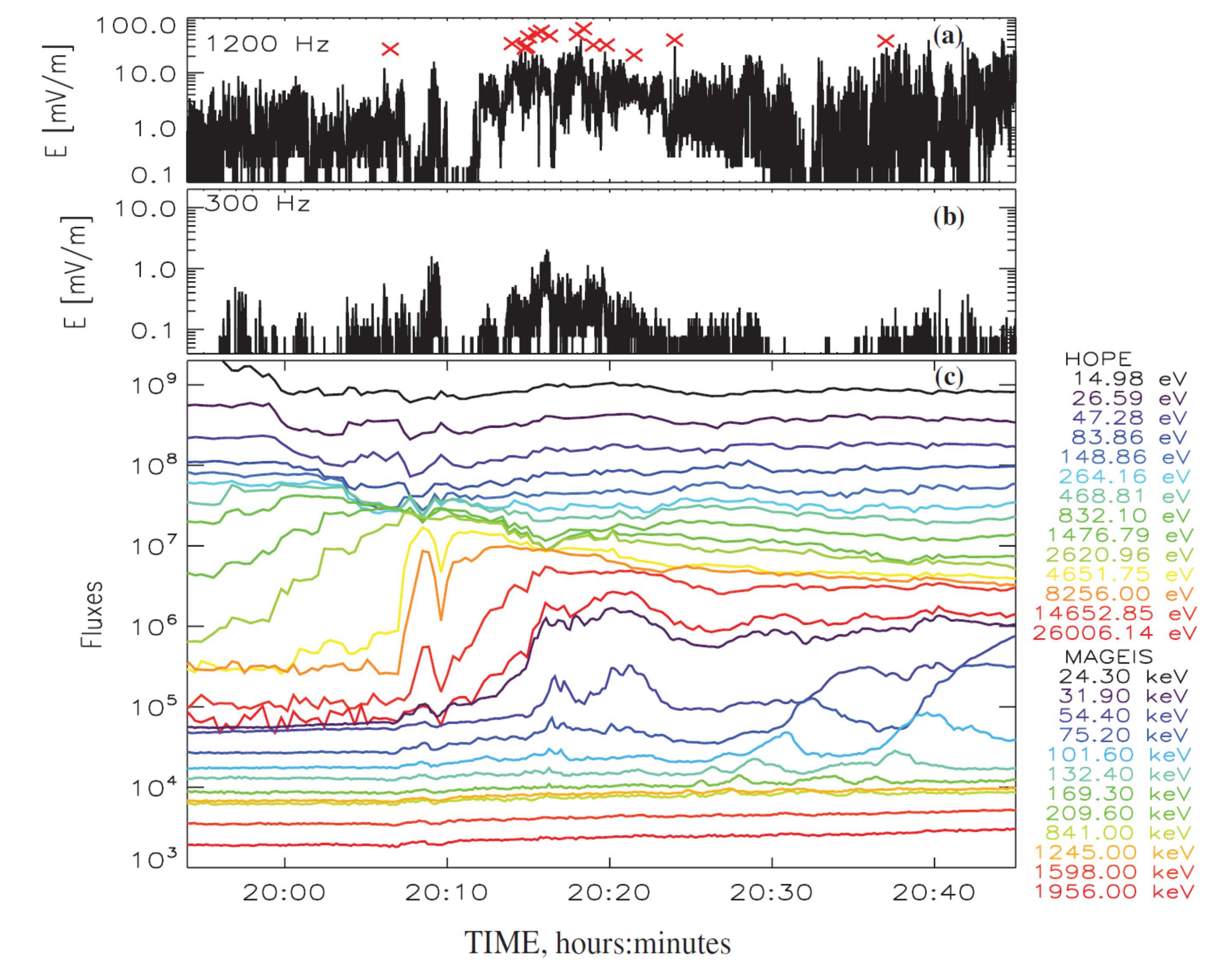
MeV particles are observed in the Earth's radiation belts:



Horne, Nature Phys., 2007

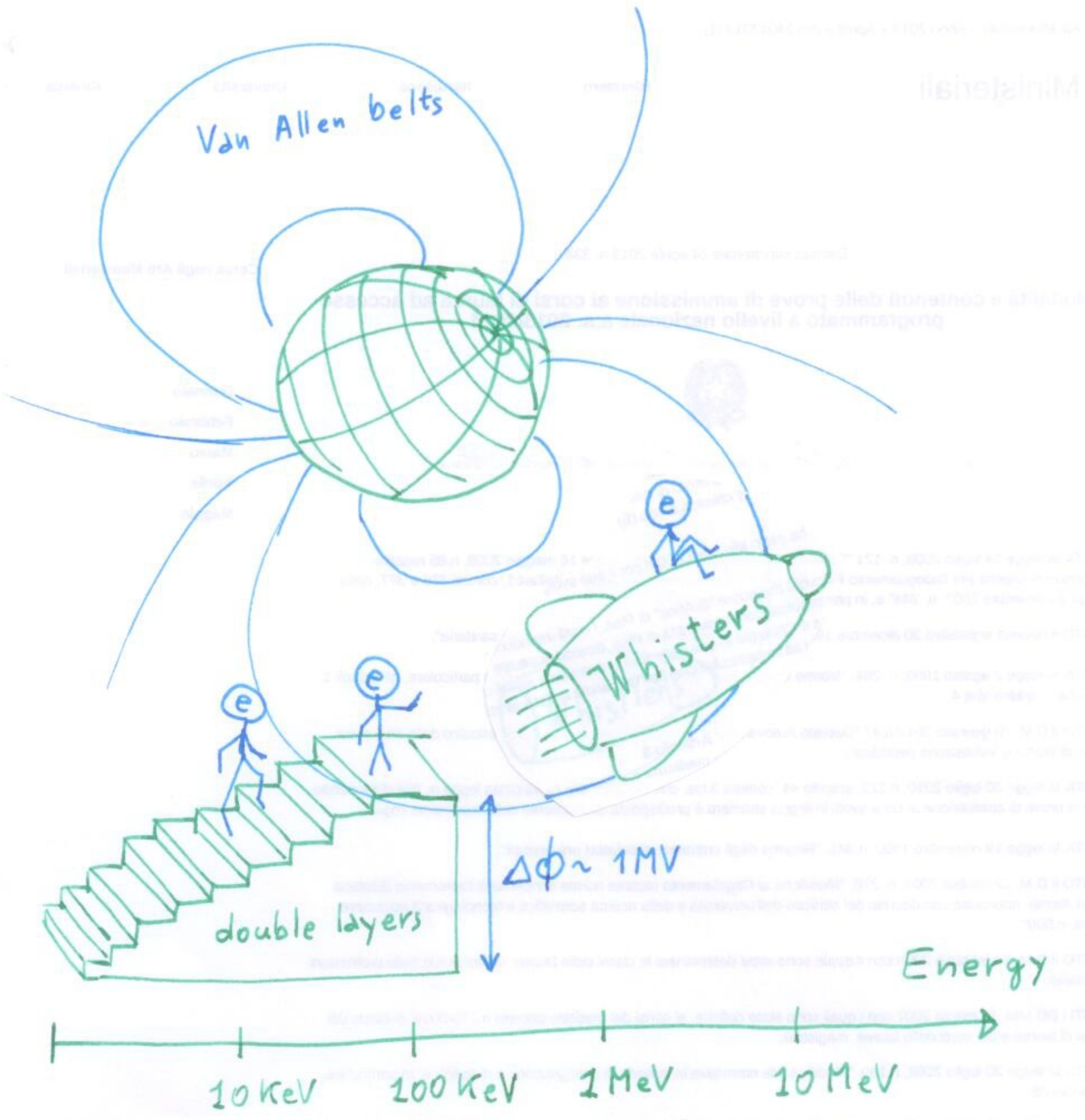
Local electron acceleration in the radiation belts as seen by the Van Allen Probe B

Mozer et al., PRL, 2014

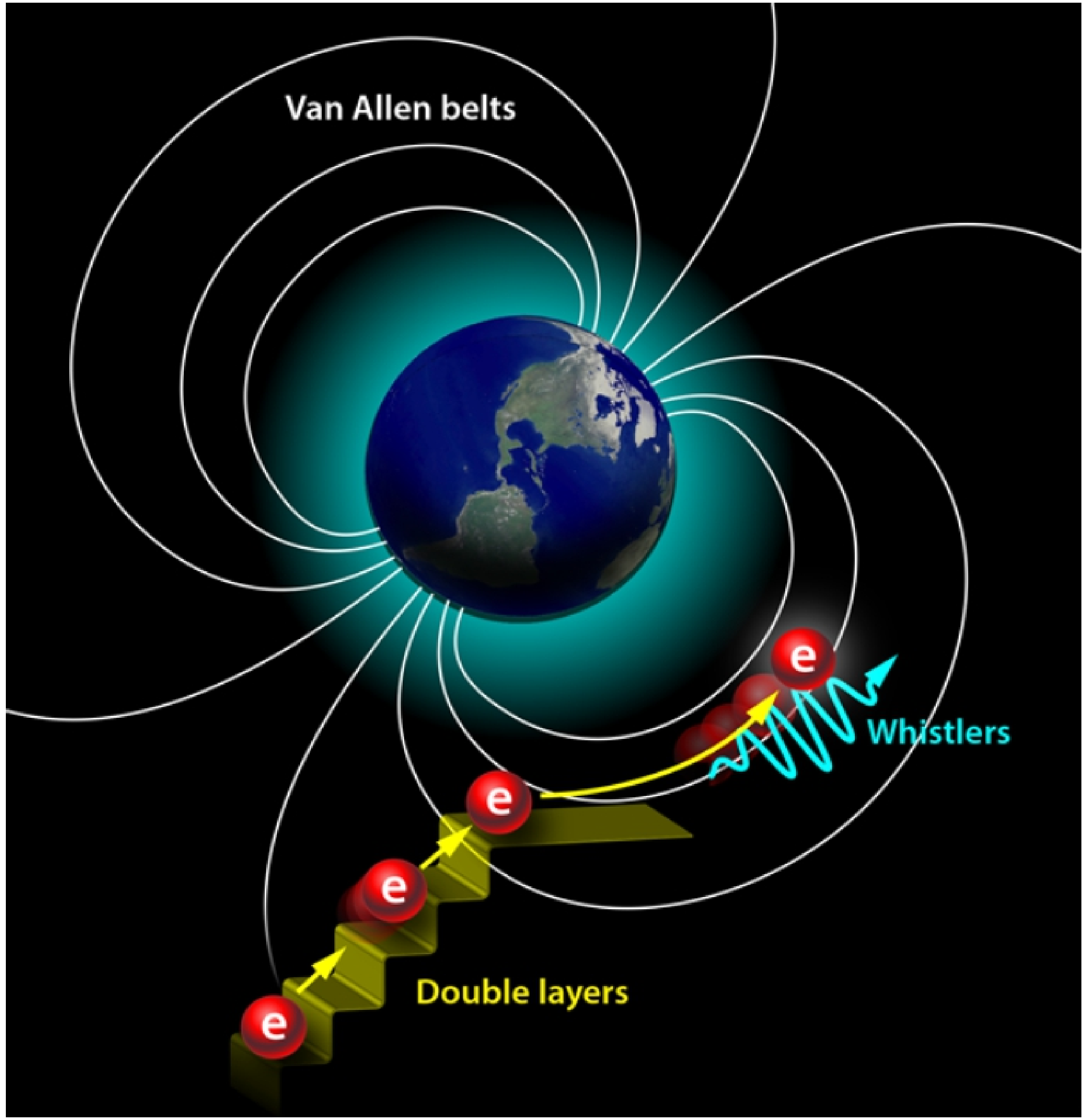


Two step acceleration process!

Multi step processes also possible!



Physics

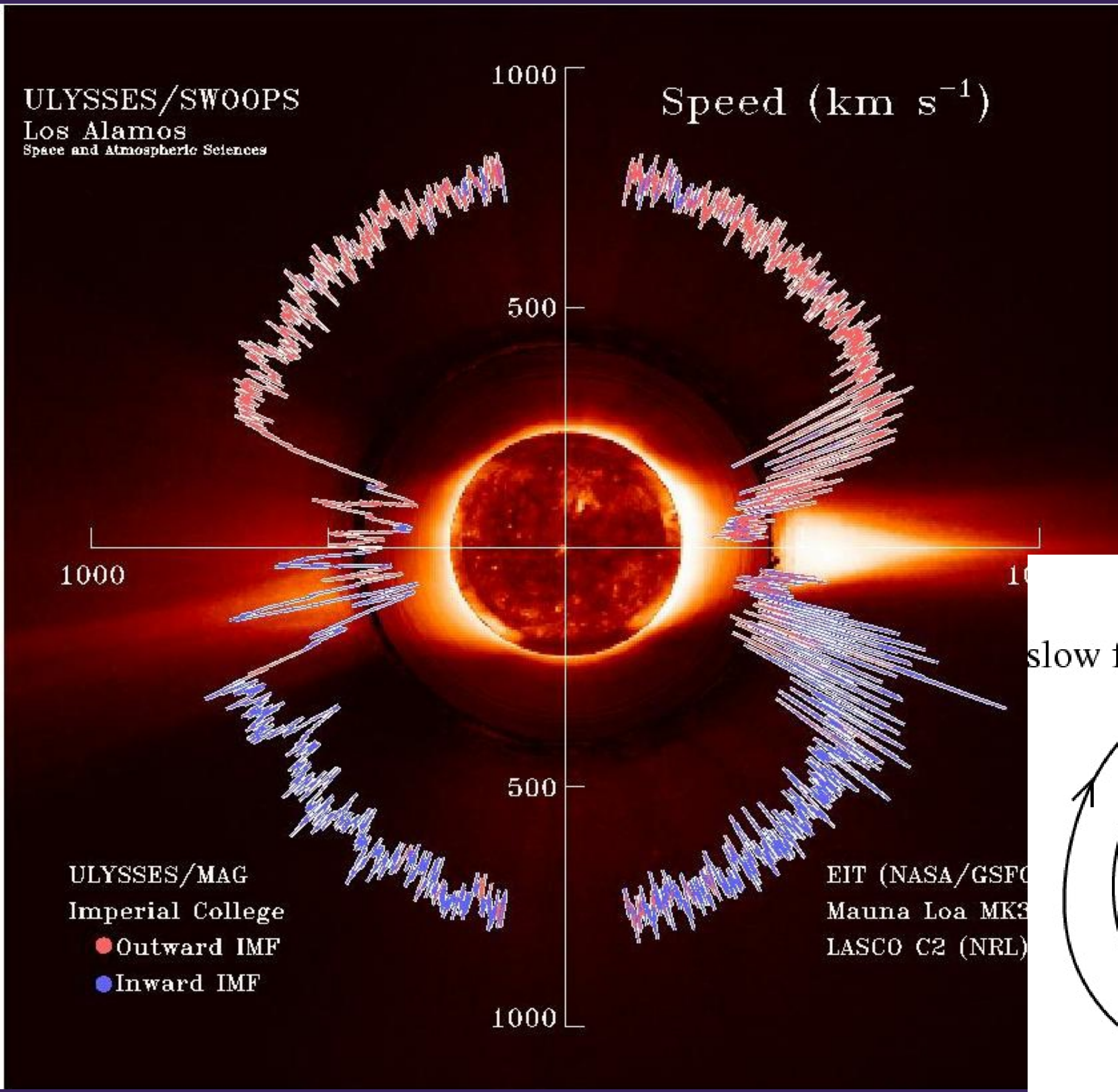


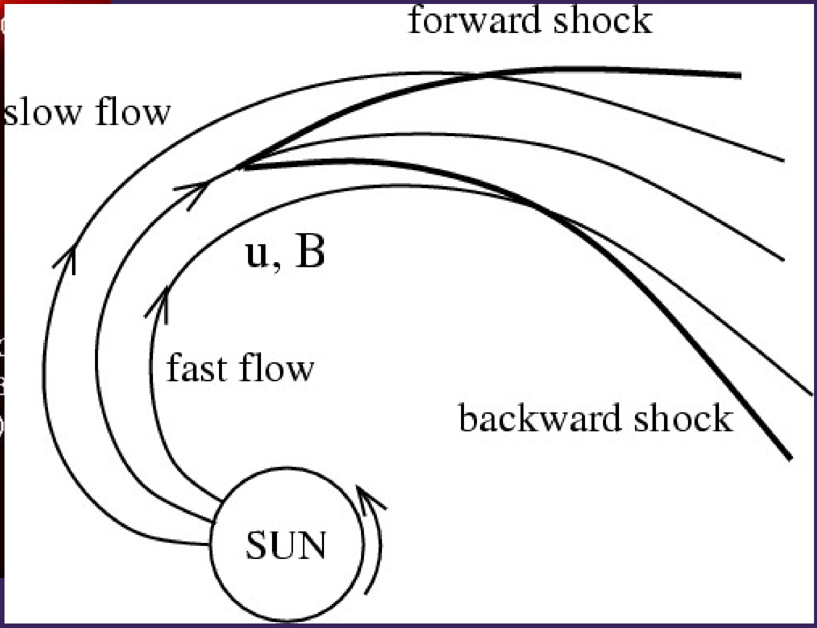
Viewpoint

A Particle Accelerator in the Radiation Belts

Gaetano Zimbardo

Fast and slow streams in the solar wind lead to corotating interaction regions (CIRs) shocks





Protons and electrons are accelerated at heliospheric shocks

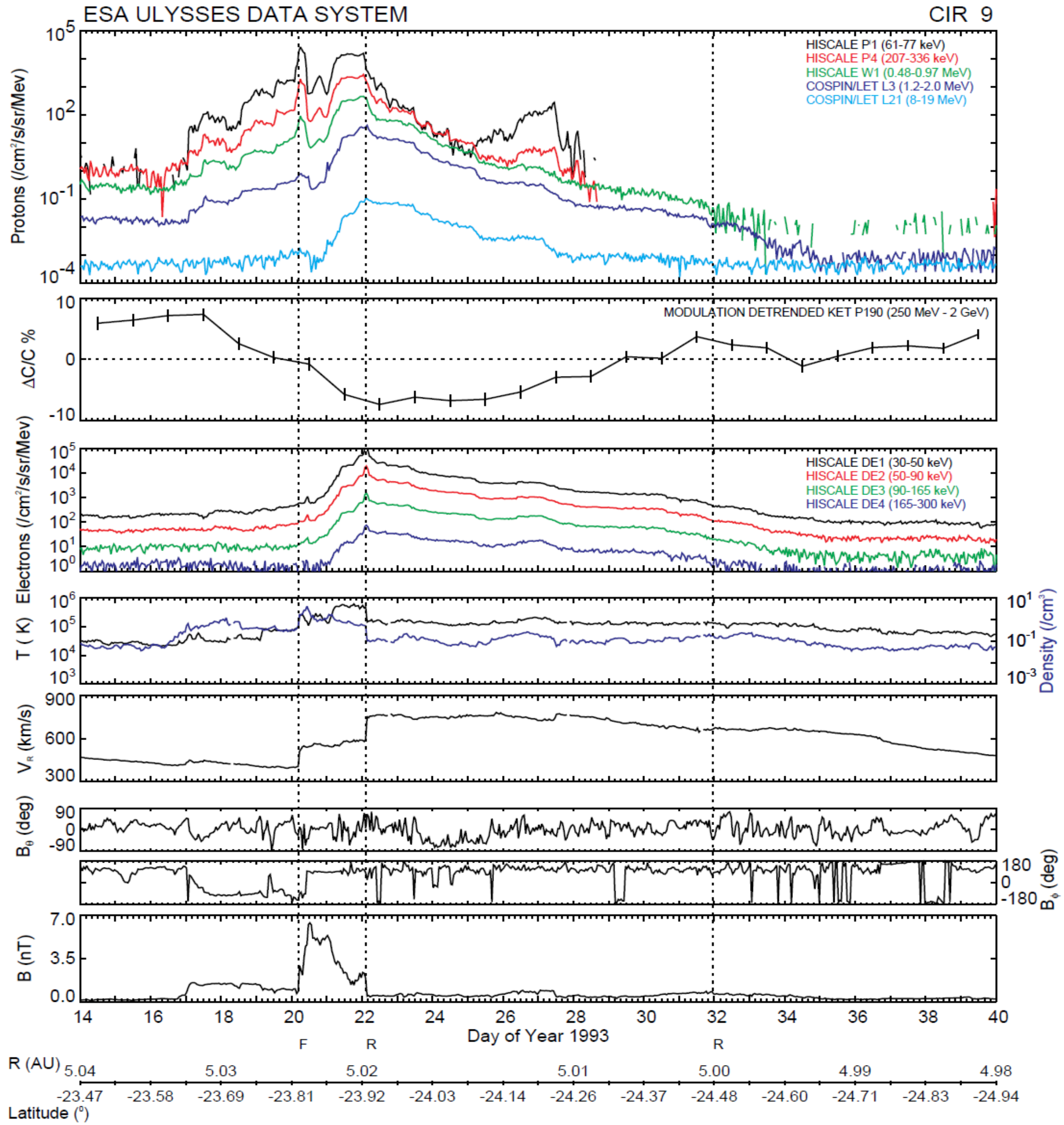
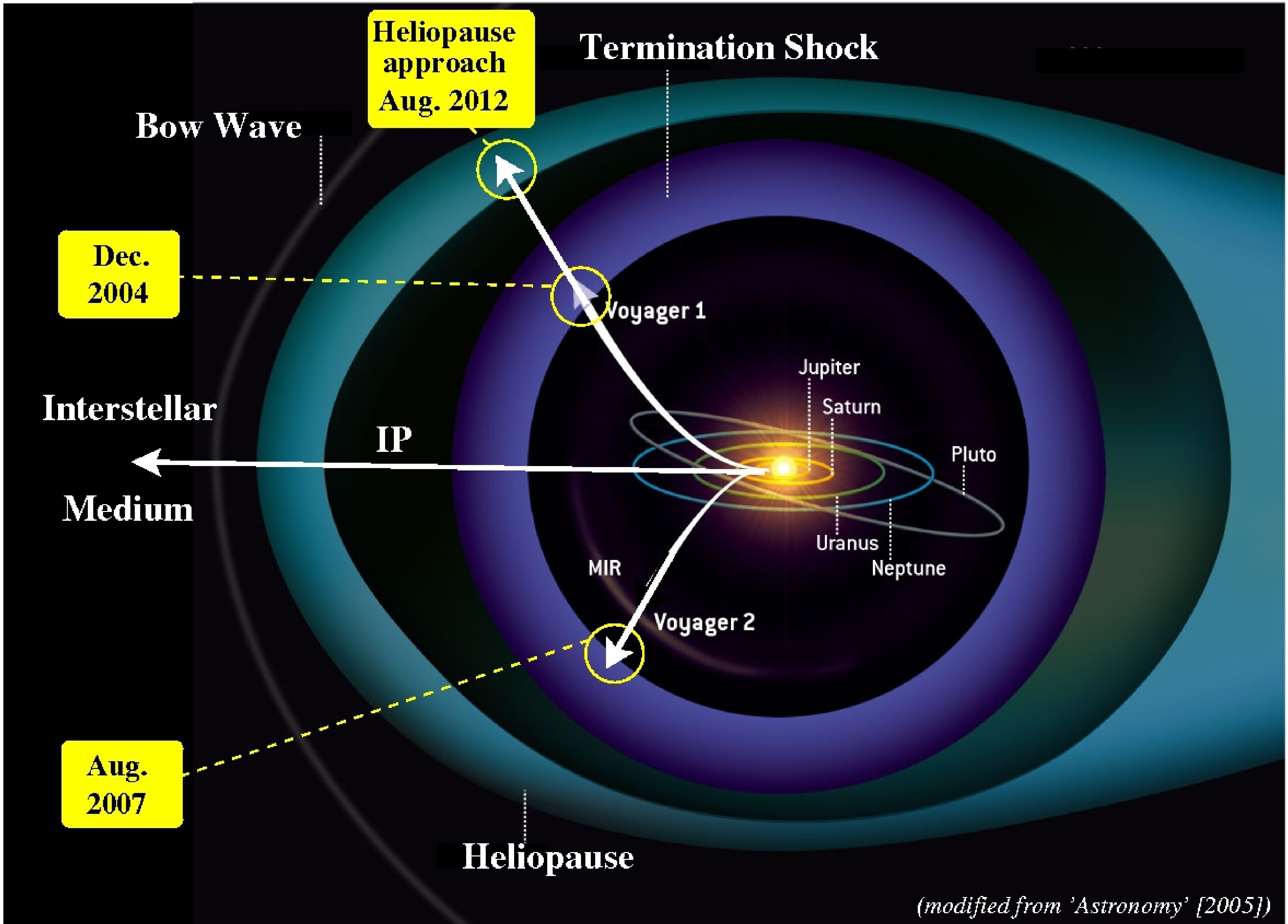


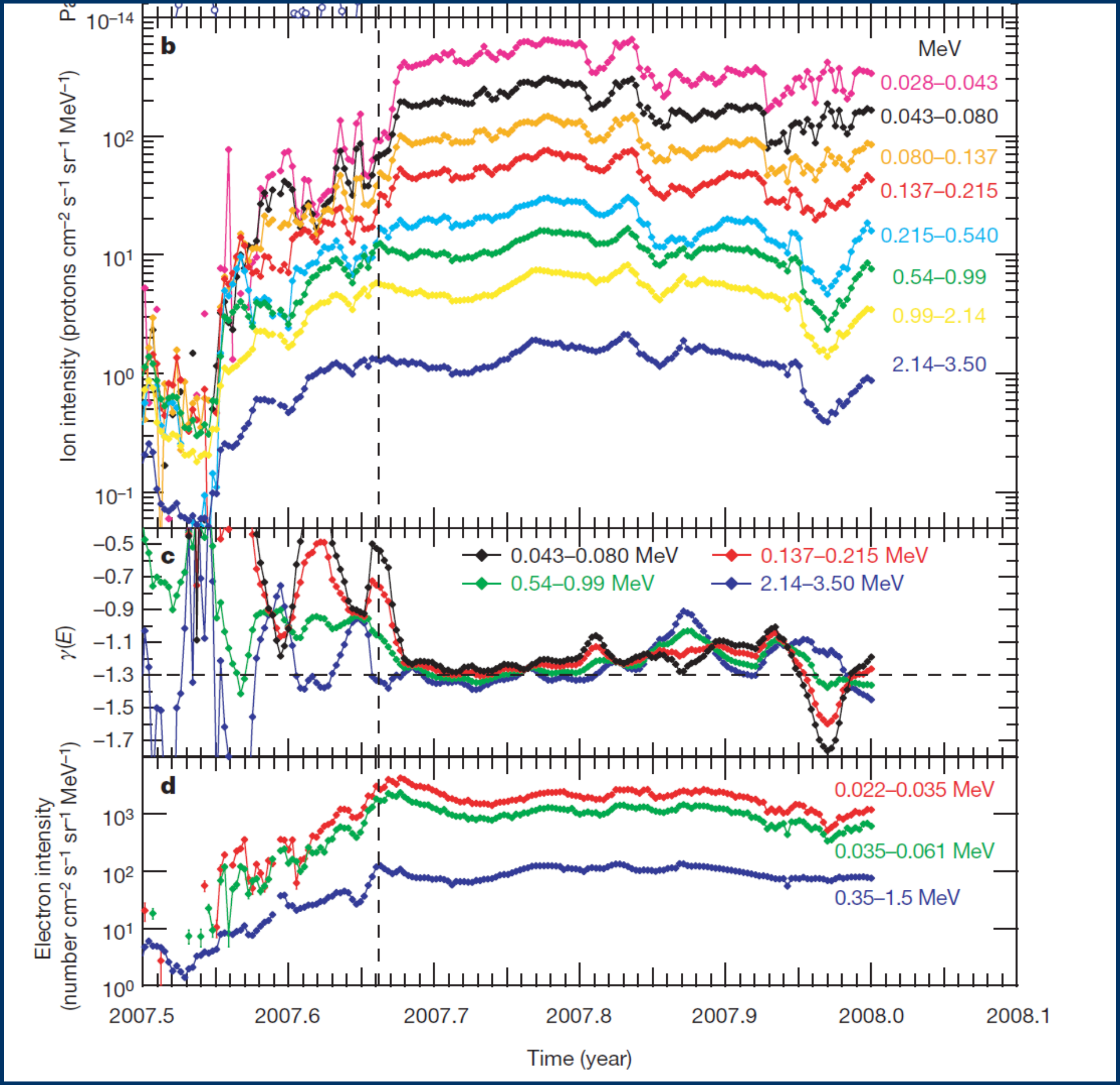
Figure 1. CIR 9 as observed by Ulysses in January 1993 at a distance of ~5 AU and 24° heliolatitude.

Kunov et al., 1999



(modified from 'Astronomy' [2005])

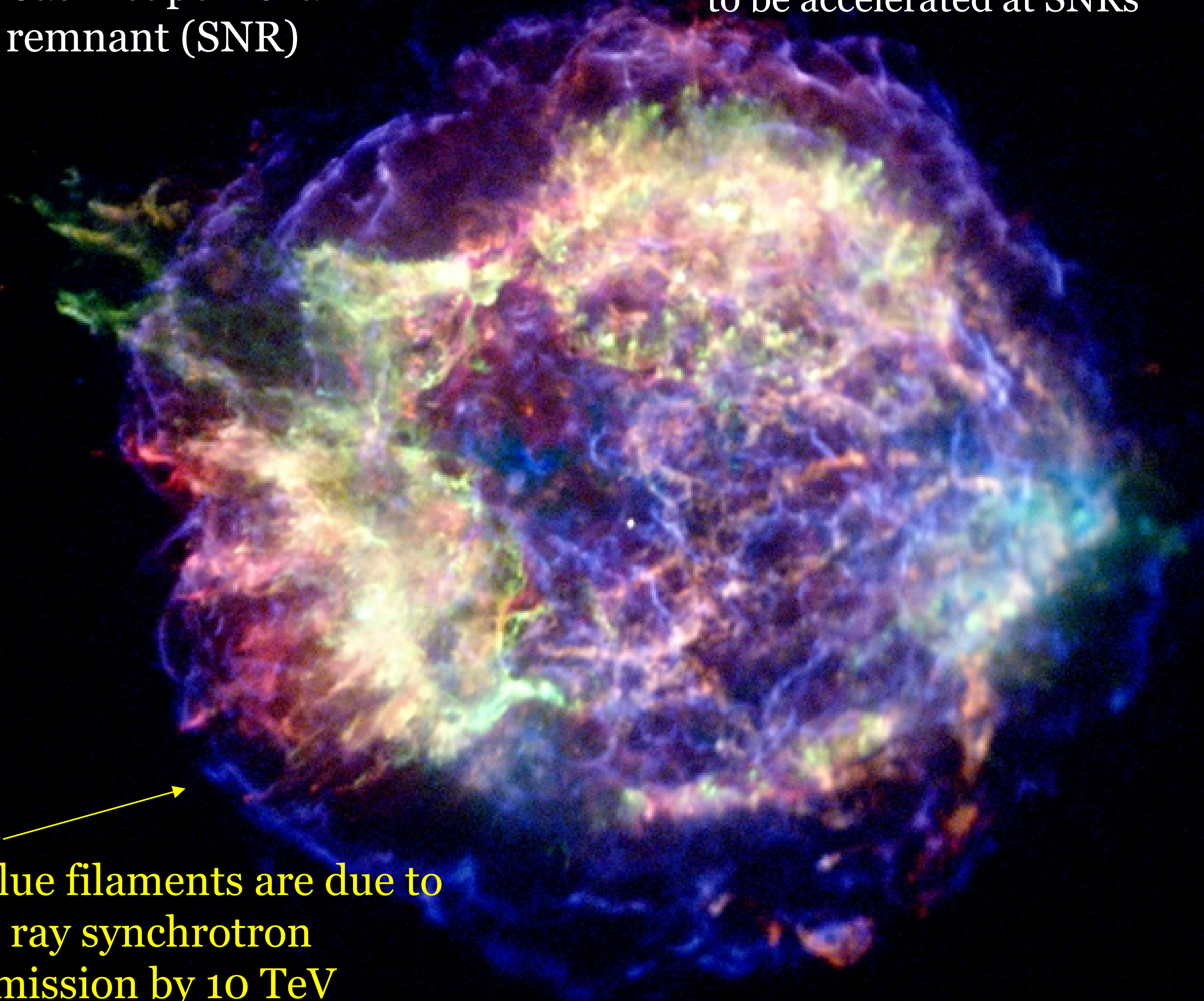
Observations at the solar wind Termination Shock



Ion data from LECP onboard Voyager 2, at the termination shock crossing of 2007 (from Decker et al., Nature, 2008)

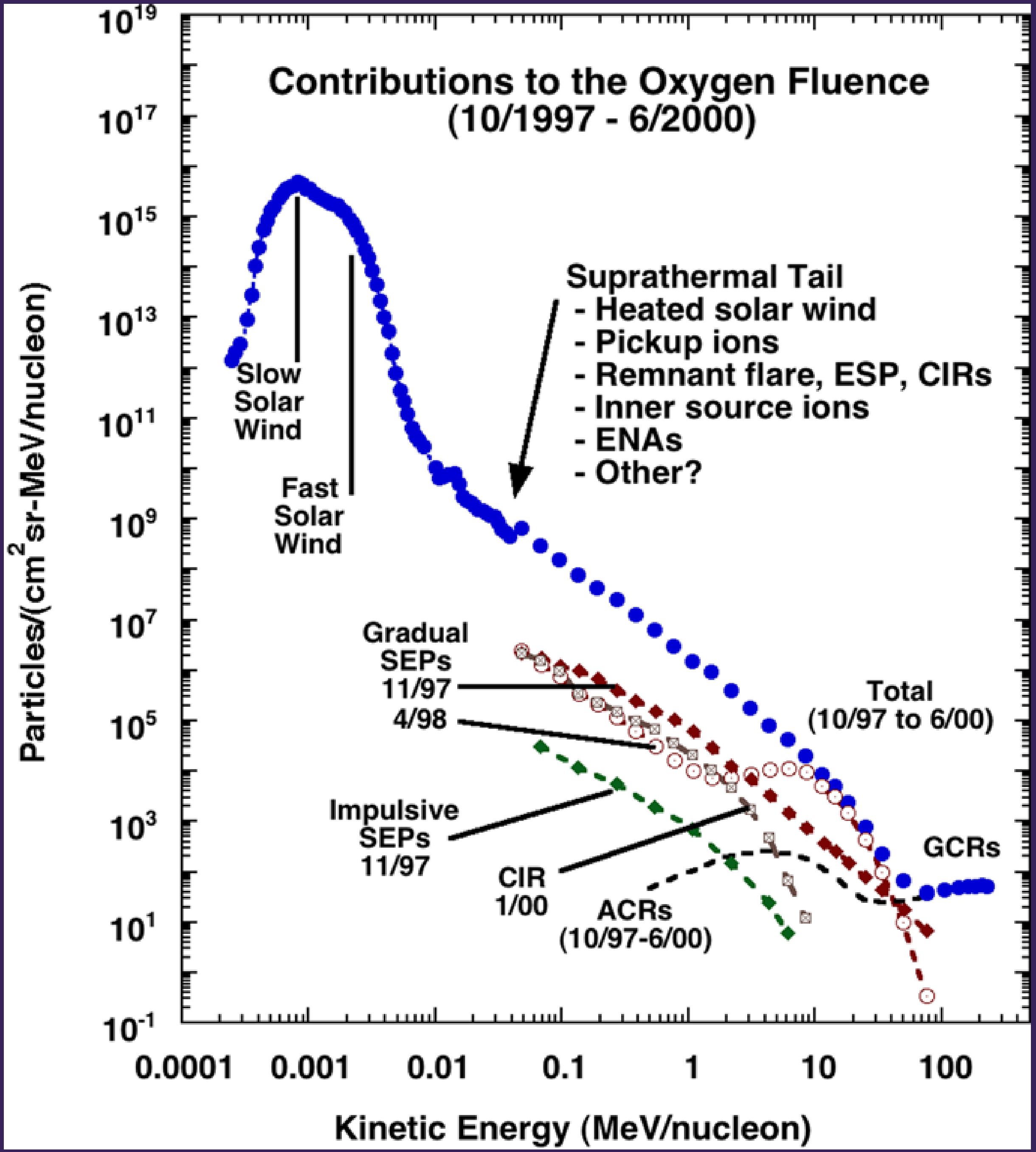
Cas A supernova remnant (SNR)

Galactic cosmic rays are thought to be accelerated at SNRs



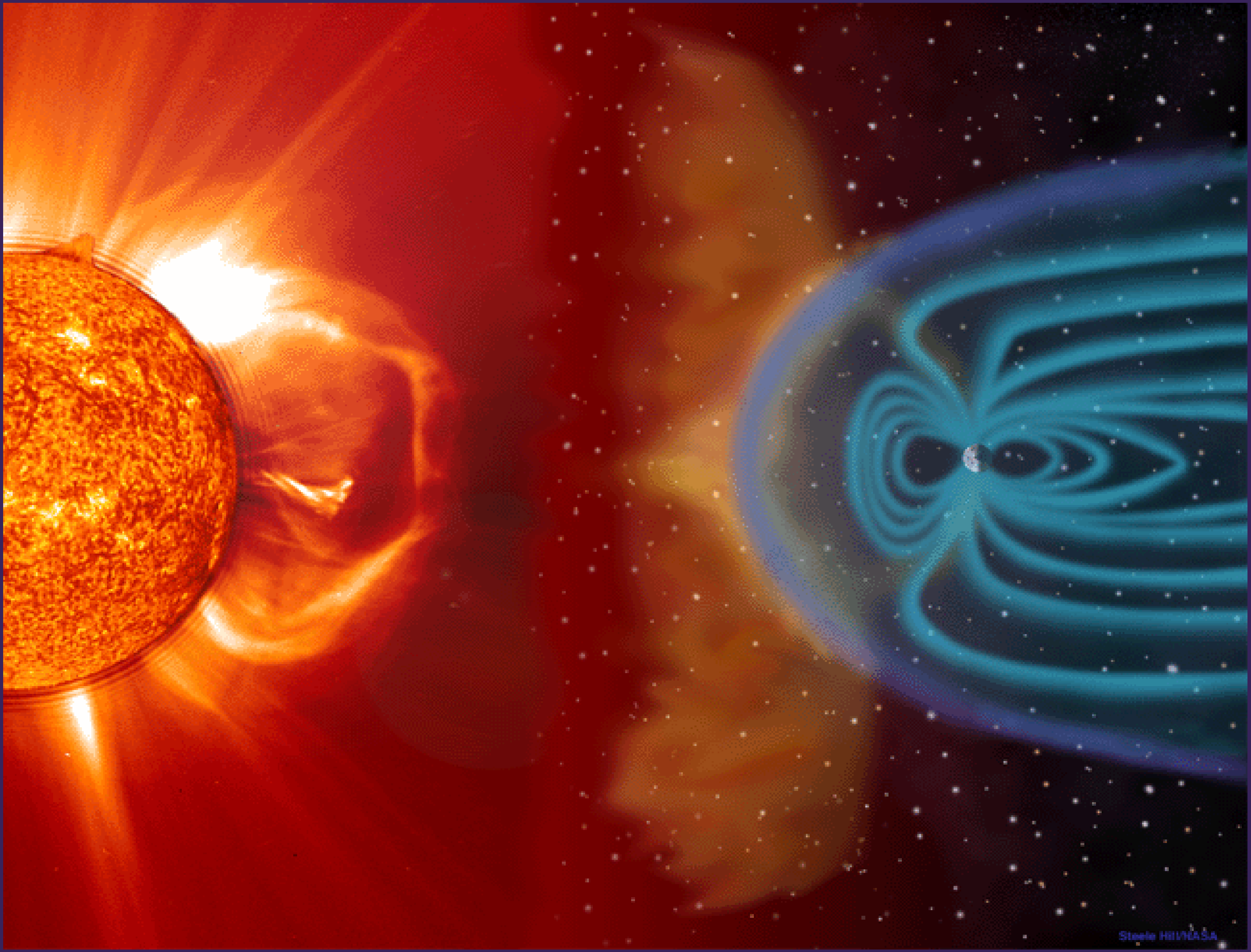
Blue filaments are due to X ray synchrotron emission by 10 TeV electrons

Intensity of energetic particles observed in the solar system:

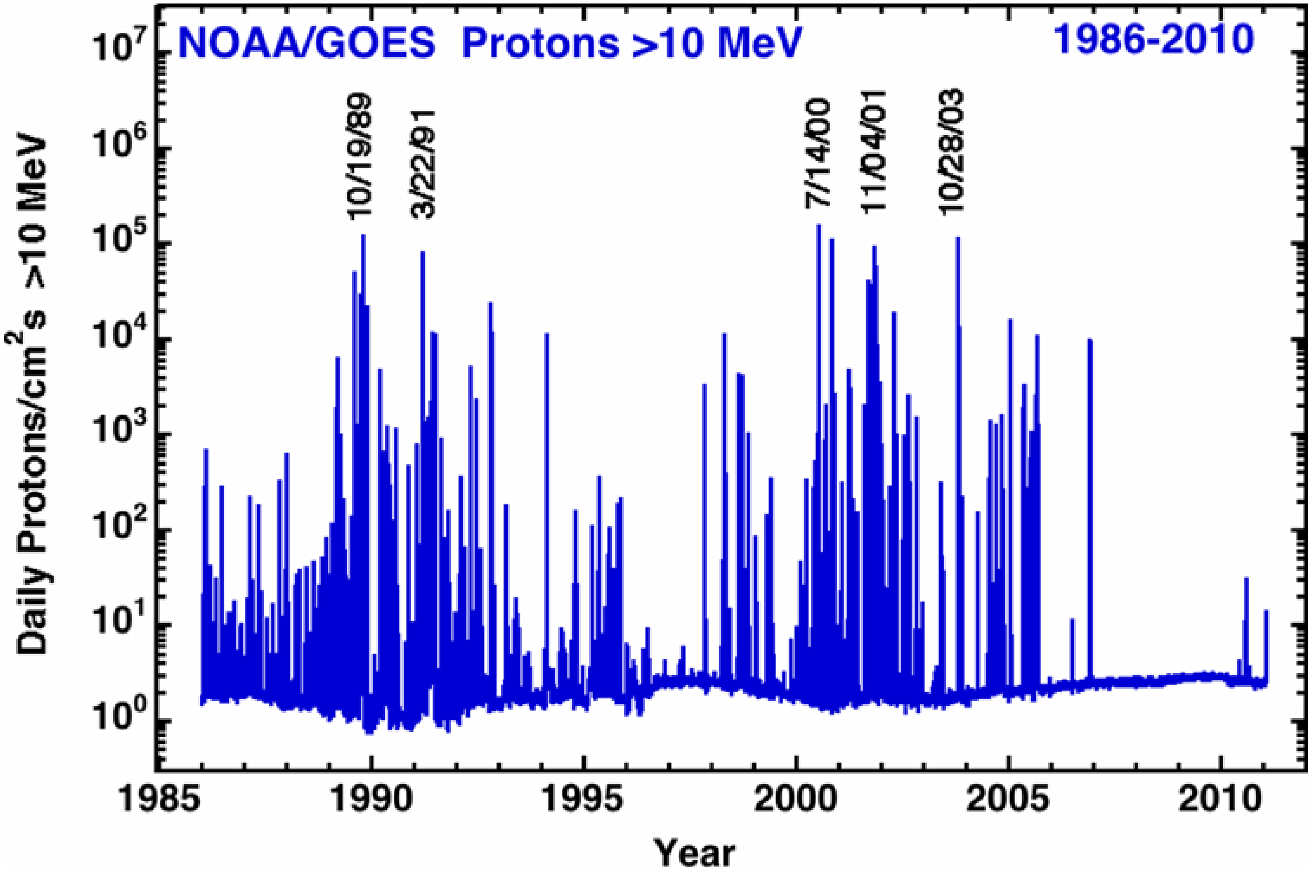


Possible acceleration mechanisms:

- Fermi acceleration: first order (shock), second order (stochastic);
- Wave particle interaction: ion cyclotron heating, electron-whistler acceleration;
- Reconnection electric fields, reconnection jets;
- Turbulence
- Betatron effects
- Shock surfing
- Drift shock acceleration
- Pump acceleration (Fisk and Gloecker)
- …

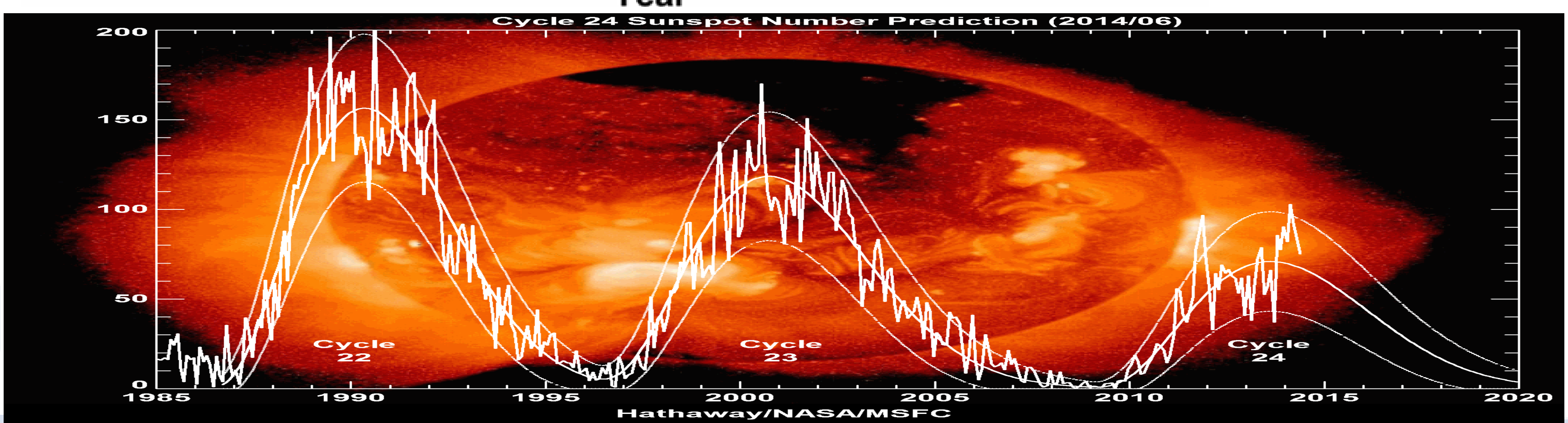

Steele Hill/NASA

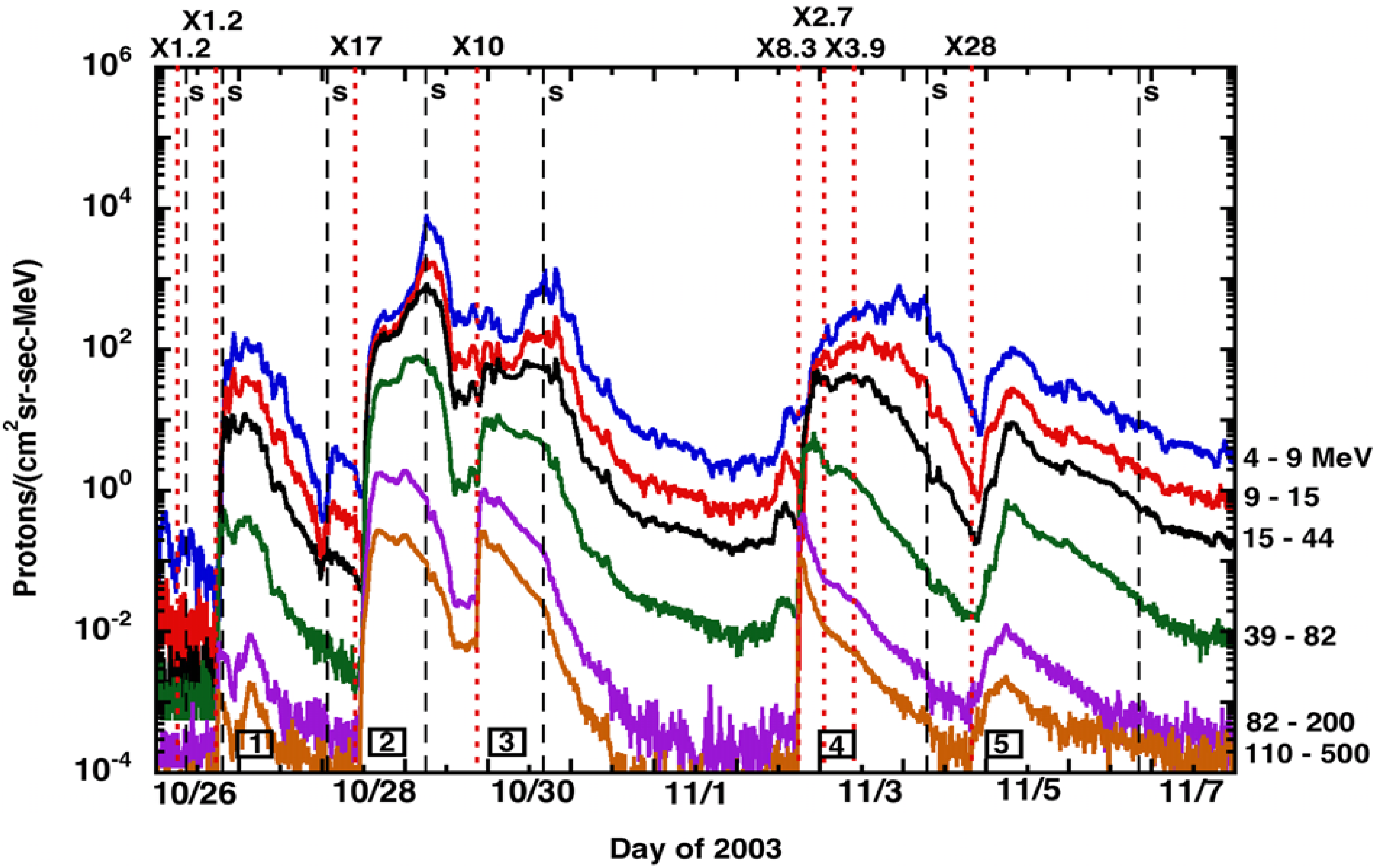
Solar Energetic Particles (SEPs)



From Lee et al., SSRv, 2012

Clear association with solar cycle





“Halloween” 2003 SEP event. Particles are accelerated both by flares and by shocks, but mostly close to the Sun. From Mewaldt et al., 2005.

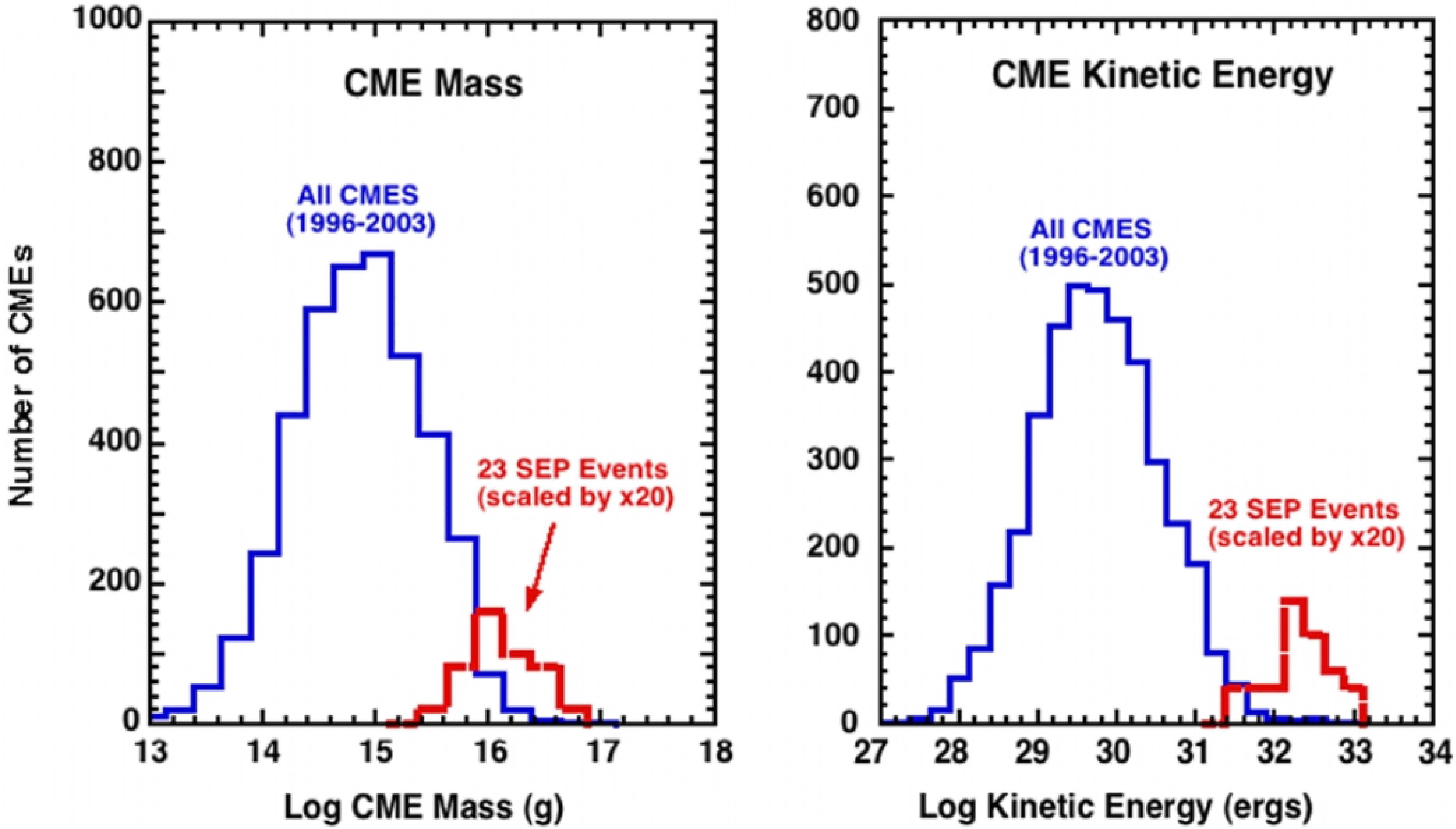
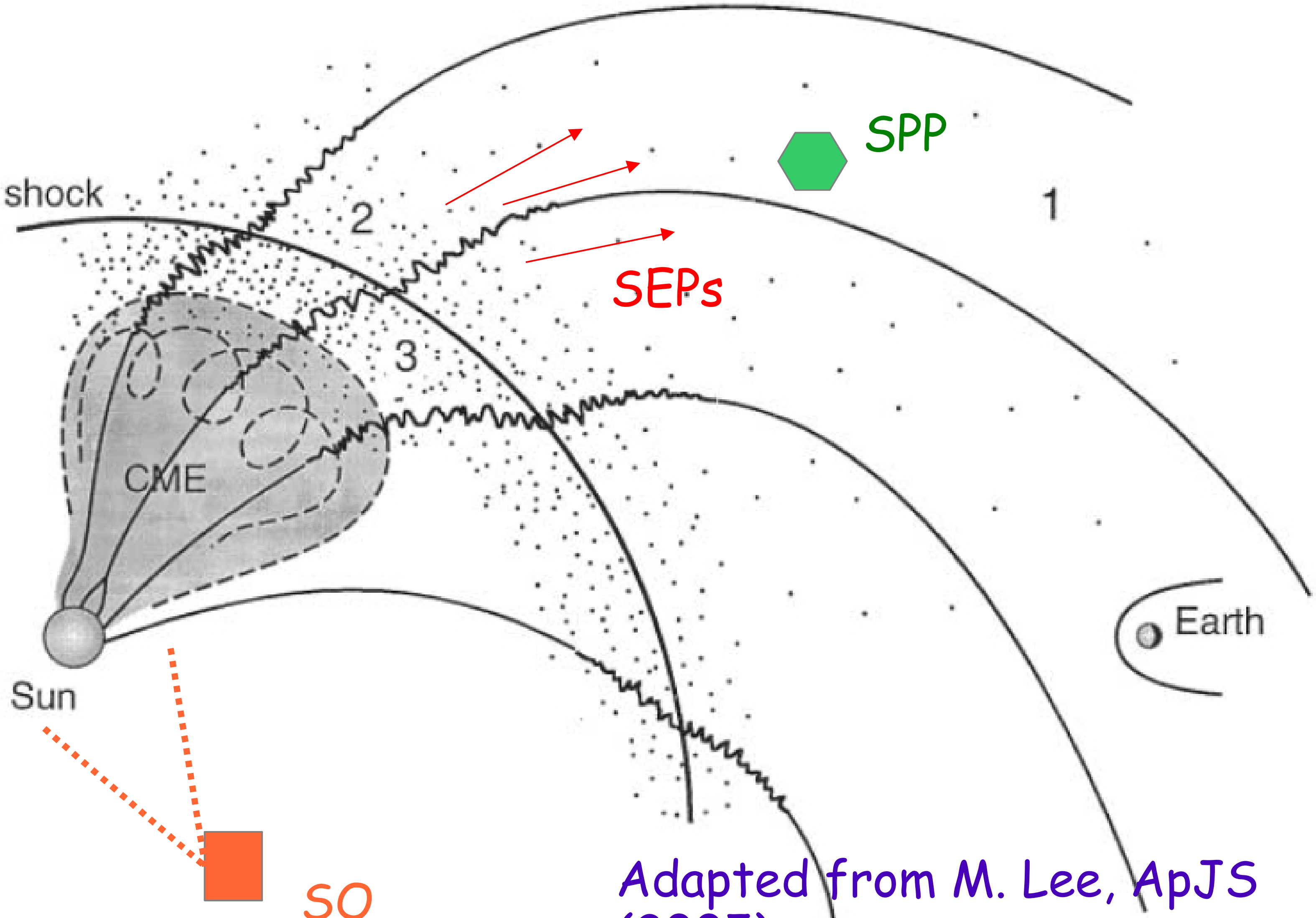


Fig. 8 (*Left*) A histogram of all CME masses from 1997–2003 (Gopalswamy 2006) is compared to the mass of CMEs associated with 23 of the 50 largest SEP events of Solar Cycle 23 (scaled up by × 20). (*Right*) Here the 1997–2003 CME kinetic energy distribution is compared to the kinetic energy of CMEs associated with the same 23 large SEP events (from Mewaldt et al. 2008)

SEPs acceleration depends on the physical parameters **local to the shock**



Adapted from M. Lee, ApJS (2005)

Particle transport in the presence of magnetic fluctuations:

For magnetic field lines:

$$\frac{dx}{dz} = \frac{\delta B_x}{B_0}$$
$$\frac{dy}{dz} = \frac{\delta B_y}{B_0}$$

$$\left\langle (\Delta x)^2 \right\rangle = \frac{1}{B_0^2} \int_0^z \int_0^z \langle \delta B_x[x(z'), y(z'), z'] \times \delta B_x[x(z''), y(z''), z''] \rangle dz' dz''.$$

For particles following the magnetic field lines:

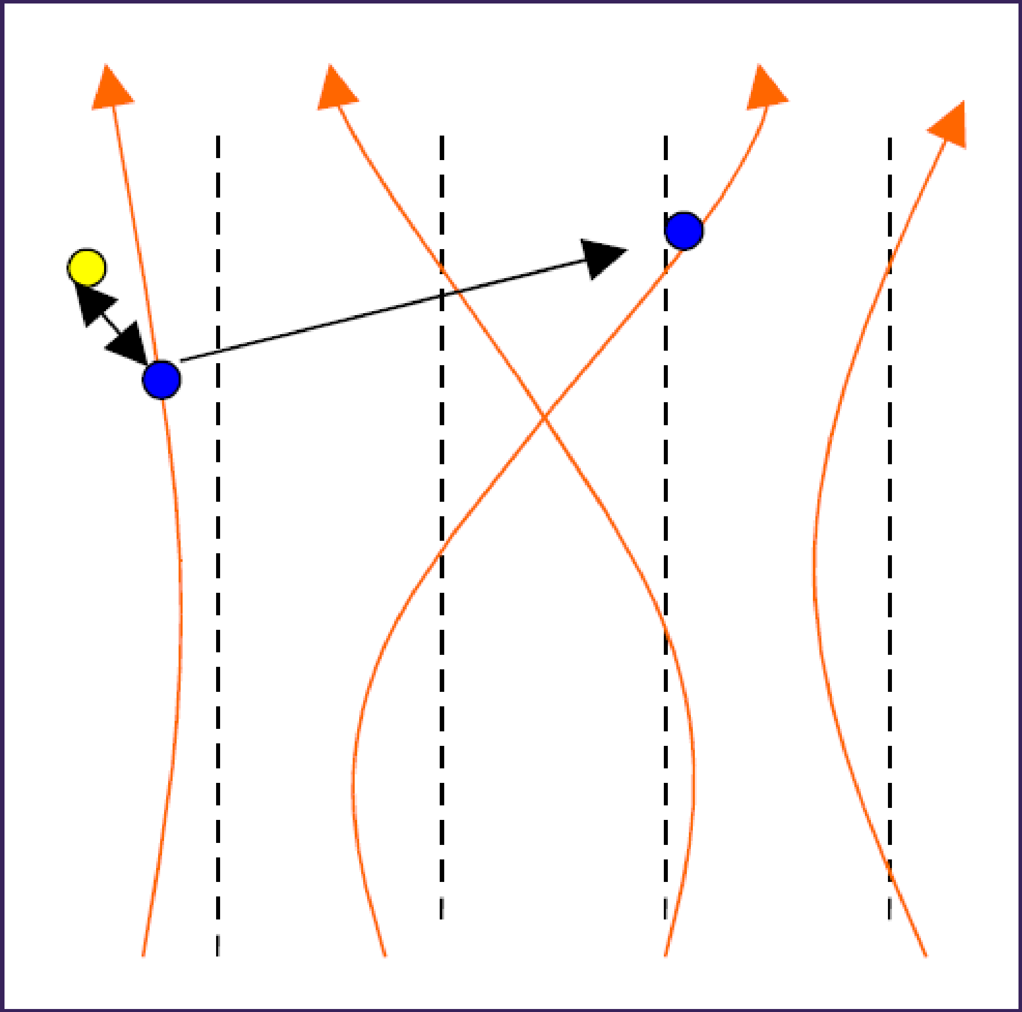
$$\kappa_{xx} = \int_0^\infty \langle v_x(0) v_x(t') \rangle dt'$$

$$\tilde{v}_x \equiv a v_z b_x / B_0$$

From Matthaeus et al., ApJL 2003

Perpendicular transport due to magnetic turbulence:

- Particles perpendicular transport induced by magnetic fluctuations
- Parallel transport can be either scatter free or not
- Numerical simulation of particle transport in the presence of magnetic turbulence



Numerical Simulation

The magnetic field is represented as a superposition of a constant field and a fluctuating field

$$\mathbf{B}(\mathbf{r}) = \mathbf{B_0} + \delta\mathbf{B}(\mathbf{r})$$

where

$$\mathbf{B}_0 = B_0 \hat{e}_z \qquad \delta\mathbf{B}(\mathbf{r}) = \sum_{\mathbf{k},\sigma} \delta B(\mathbf{k})\, e^{(\sigma)}(\mathbf{k}) \exp i\left[\mathbf{k}\cdot\mathbf{r} + \phi_{\mathbf{k}}^{(\sigma)}\right]$$

with

$$e^1(\mathbf{k}) = i\frac{\mathbf{k}\times\mathbf{B}_0}{|\mathbf{k}\times\mathbf{B}_0|}, \qquad e^2(\mathbf{k}) = i\frac{\mathbf{k}}{|\mathbf{k}|}\times e^1(\mathbf{k})$$

Numerical Simulation

Wave vectors on a cubic lattice 128x128x128

$$\mathbf{k} = \frac{2\pi}{L}\left(n_x + n_y + n_z \right)$$

Anisotropic power law spectrum:

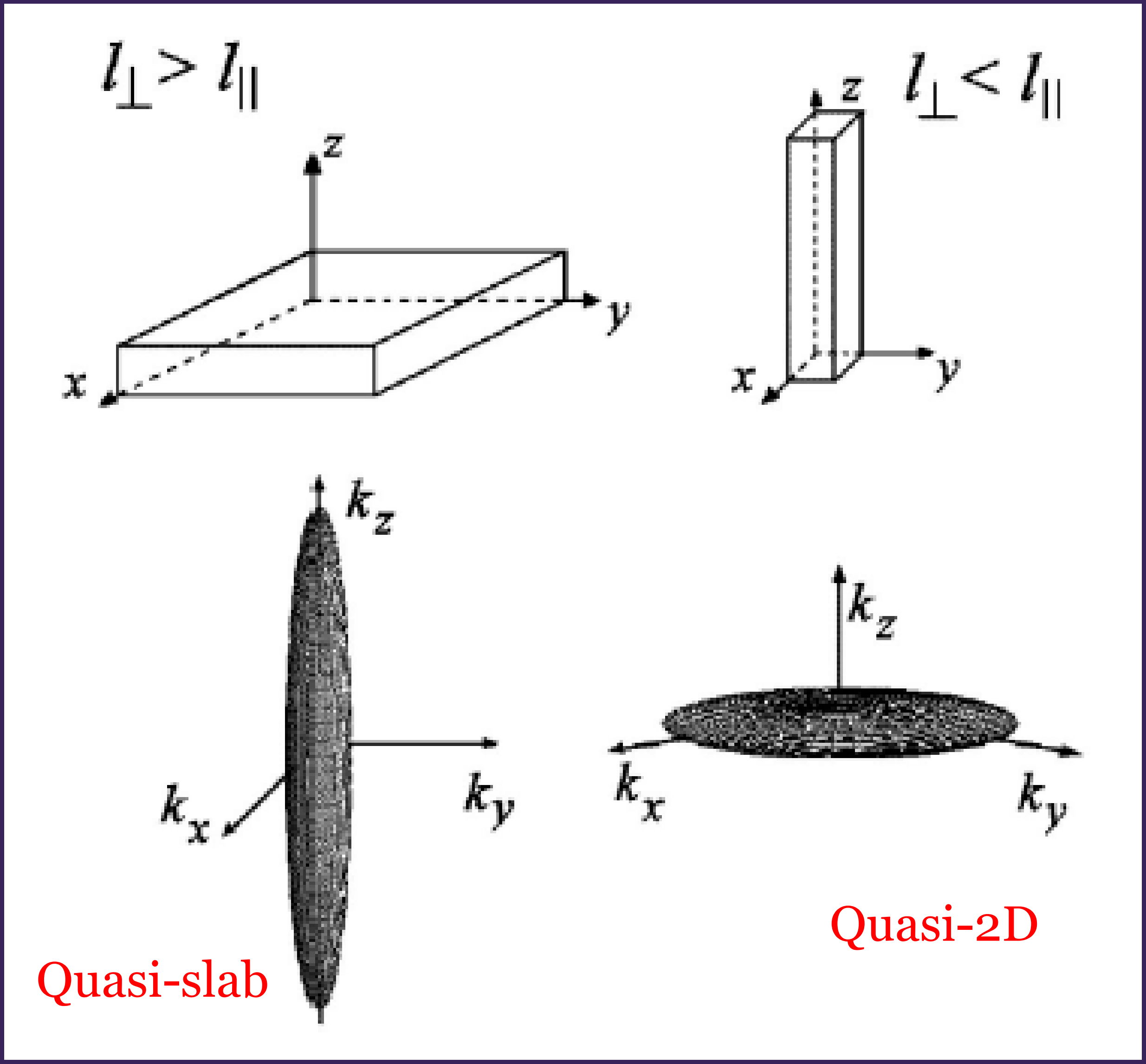
$$\delta B\left(\mathbf{k}\right) = \frac{C}{\left(k_x^2 l_x^2 + k_y^2 l_y^2 + k_z^2 l_z^2 \right)^{\frac{\alpha}{4}+\frac{1}{2}}}$$

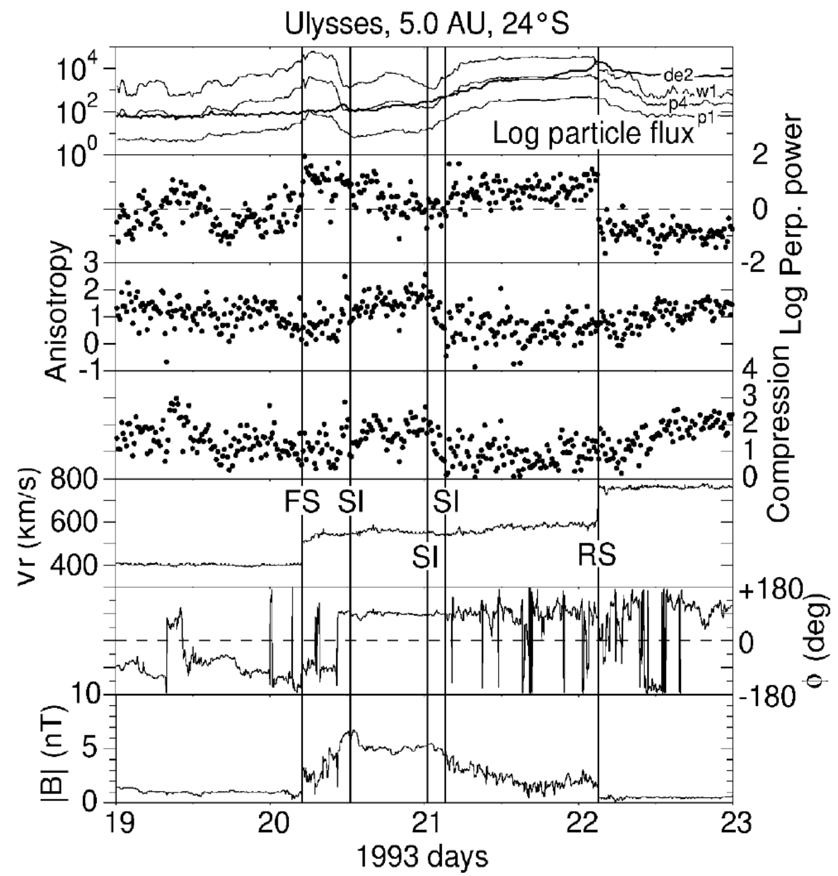
Band spectrum:

$$N_{\min}^2 \leq n_x^2 + n_y^2 + n_z^2 \leq N_{\max}^2$$

Here N_{min}= 4, N_{max}= 16. Future simulations with longer spectrum (see work by Francesco Pucci)

Anisotropy in physical and phase space





Crooker et al., 1999

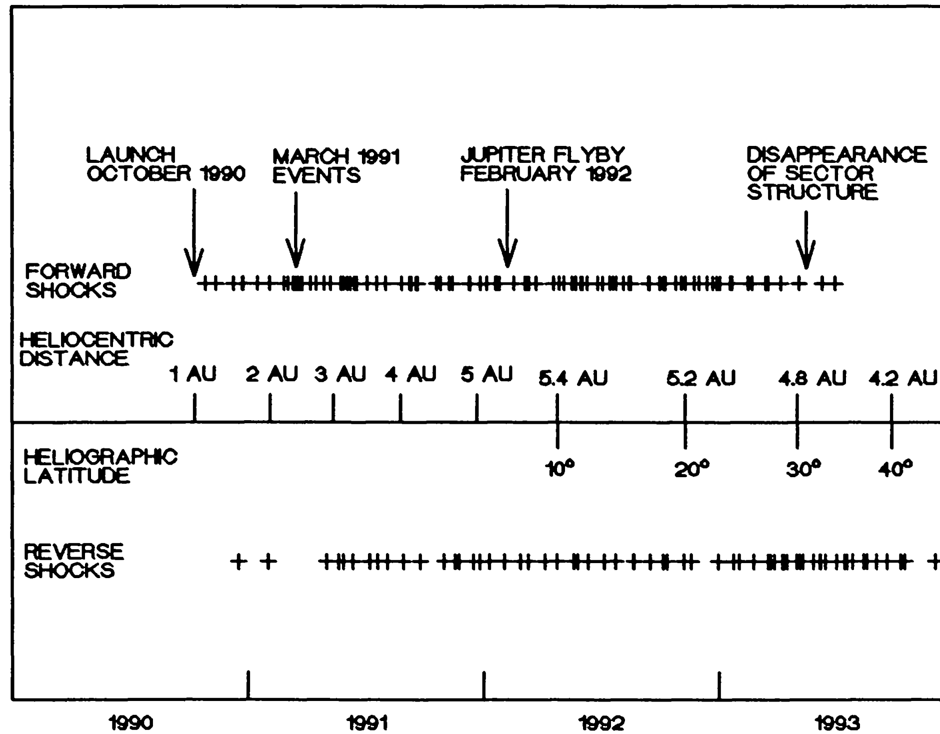
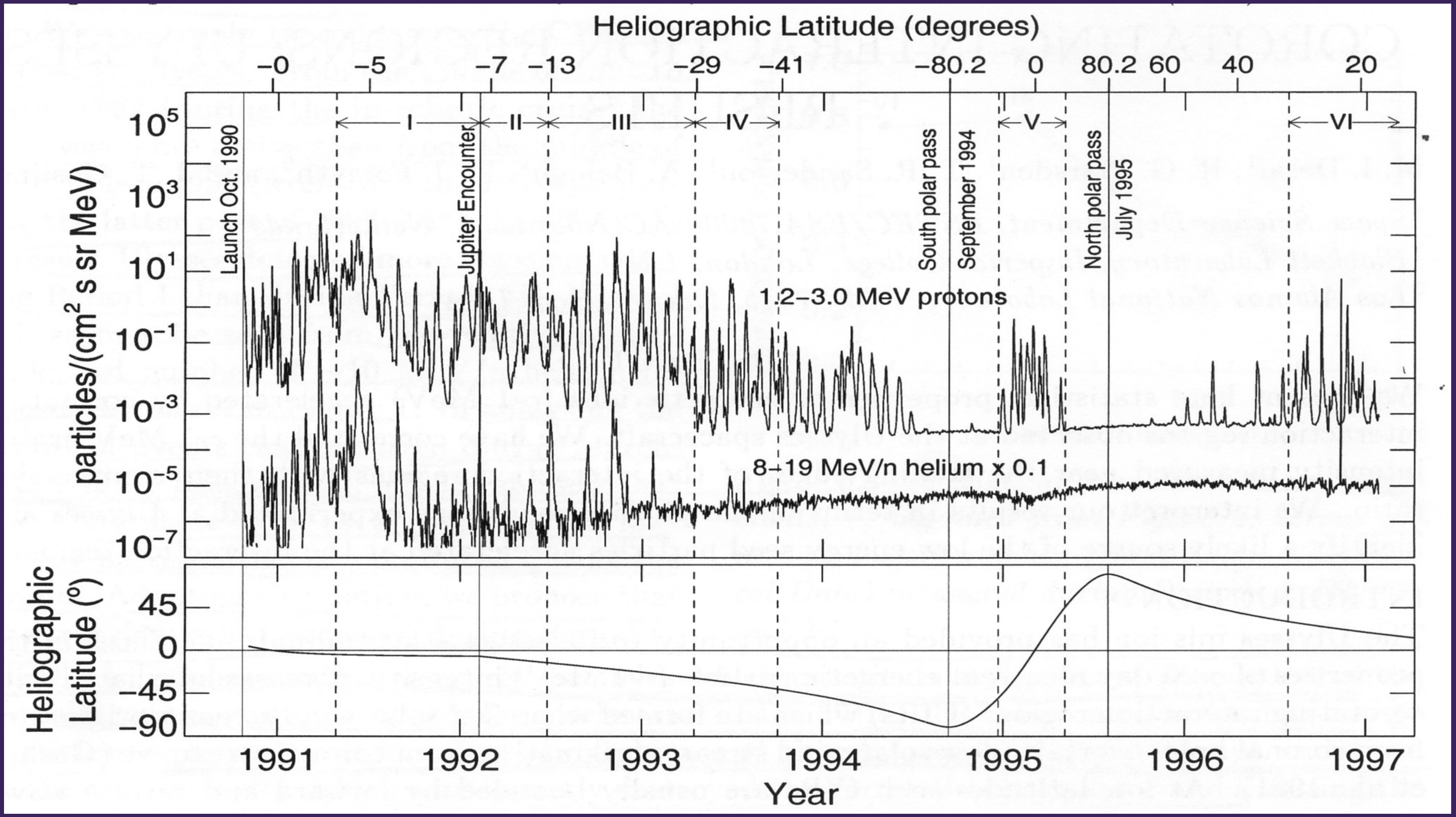


Fig. 1: Overview of shock waves seen by Ulysses from 1990 to 1993.

Balogh et al, 1995

We performed analyses of Ulysses data who observed particles accelerated at CIR shock



- Ulysses observed a series of Corotating Interaction Regions in 1992-1993; both protons and electrons are accelerated at CIR shocks:

Among the others, model by Zimbardo, Pommois, Veltri (2001)

$$\frac{d\mathbf{r}}{d\xi} = \frac{\langle \mathbf{B}(\mathbf{r})\rangle + \delta \mathbf{B}}{|\langle \mathbf{B}(\mathbf{r})\rangle|} = \hat{e}_B + \frac{\delta \mathbf{B}(\mathbf{r})}{B_0(\mathbf{r})}$$

$$\langle B_r \rangle = B_{r\mathrm{E}} \left(\frac{r_\mathrm{E}}{r}\right)^2 ,$$

$$\langle B_\theta \rangle = 0 ;$$

$$\langle B_\varphi \rangle = -B_{r\mathrm{E}} \left(\frac{r_\mathrm{E}}{r}\right)^2 \frac{\Omega\, r}{V_\mathrm{SW}} \sin\theta$$

$$\frac{\delta B_i(\mathbf{r})}{B_0(\mathbf{r})} = \eta_i(\xi) A_i(\mathbf{r})$$

$$A_x(\mathbf{r}) = \sqrt{6 D_x(\mathbf{r})}$$

Cross latitude transport of CIR accelerated particles detected by Ulysses:

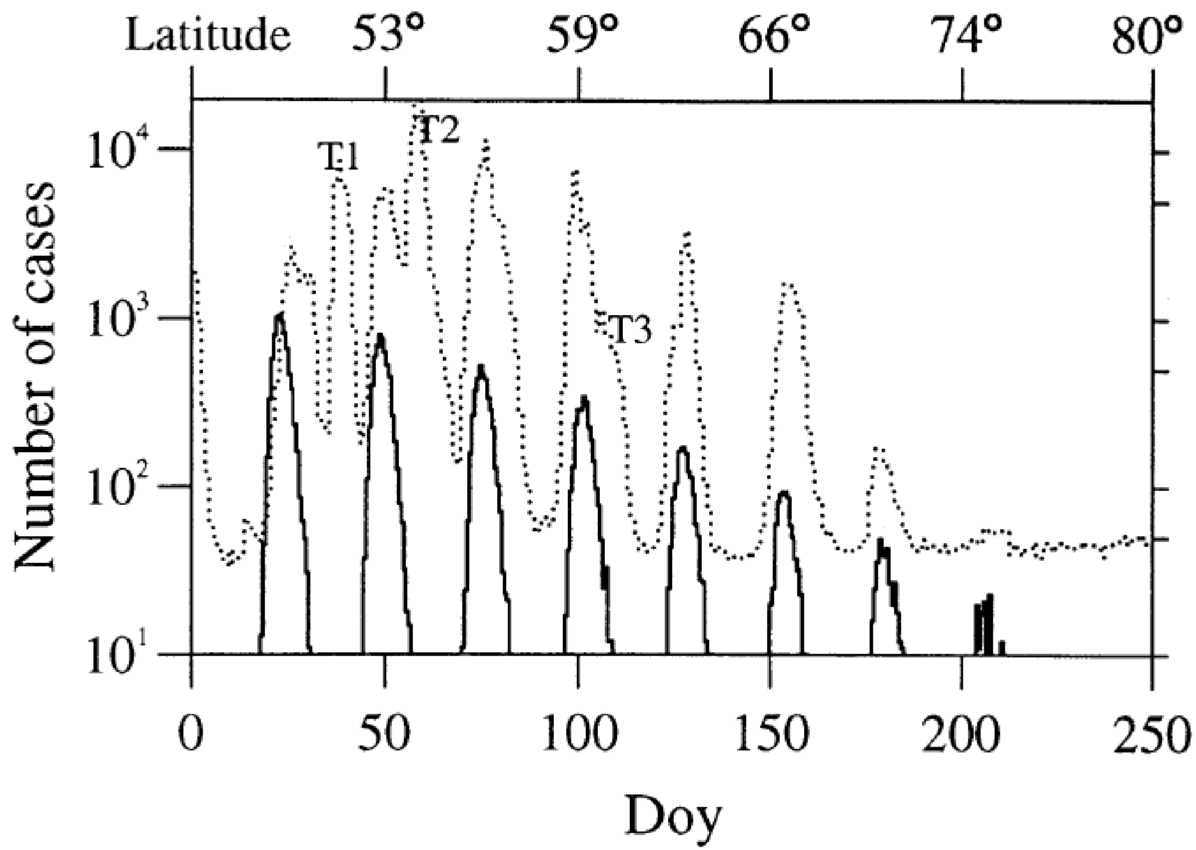
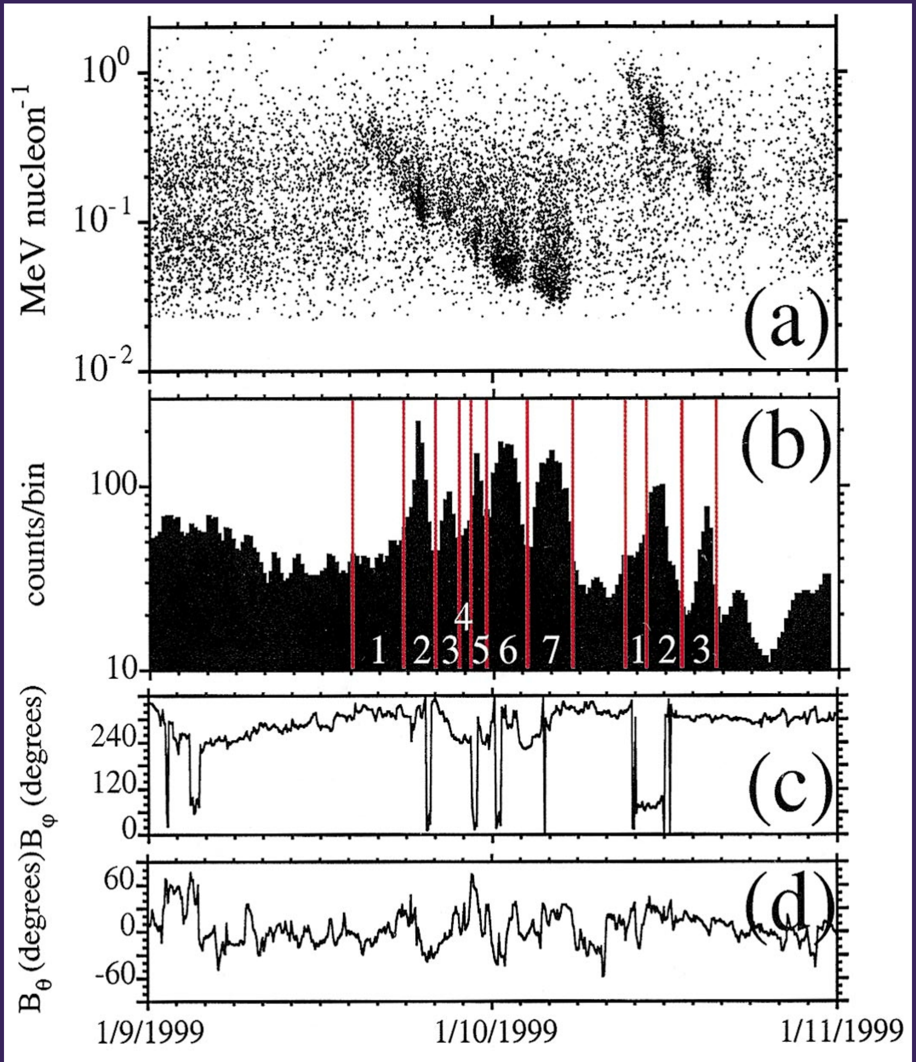


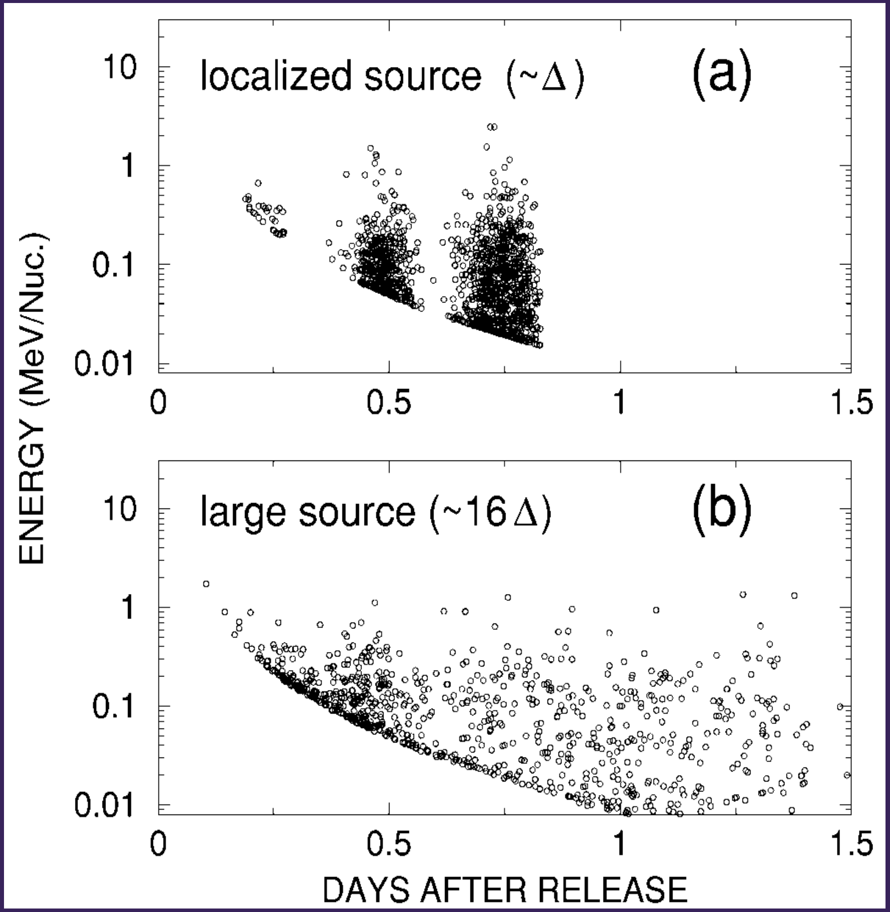
Figure 9. Comparison between the simulation results for $\delta B_E/B_E = 0.5$, $l_x/l_y = 3$, and $r_0 = 8$ AU (solid line) and Ulysses data in the 1.2–3.0 MeV proton channel (dotted line) (arbitrary units). Transient events are indicated by a T [*Bothmer et al.*, 1995].

Pommois et al., JGR, 2001.

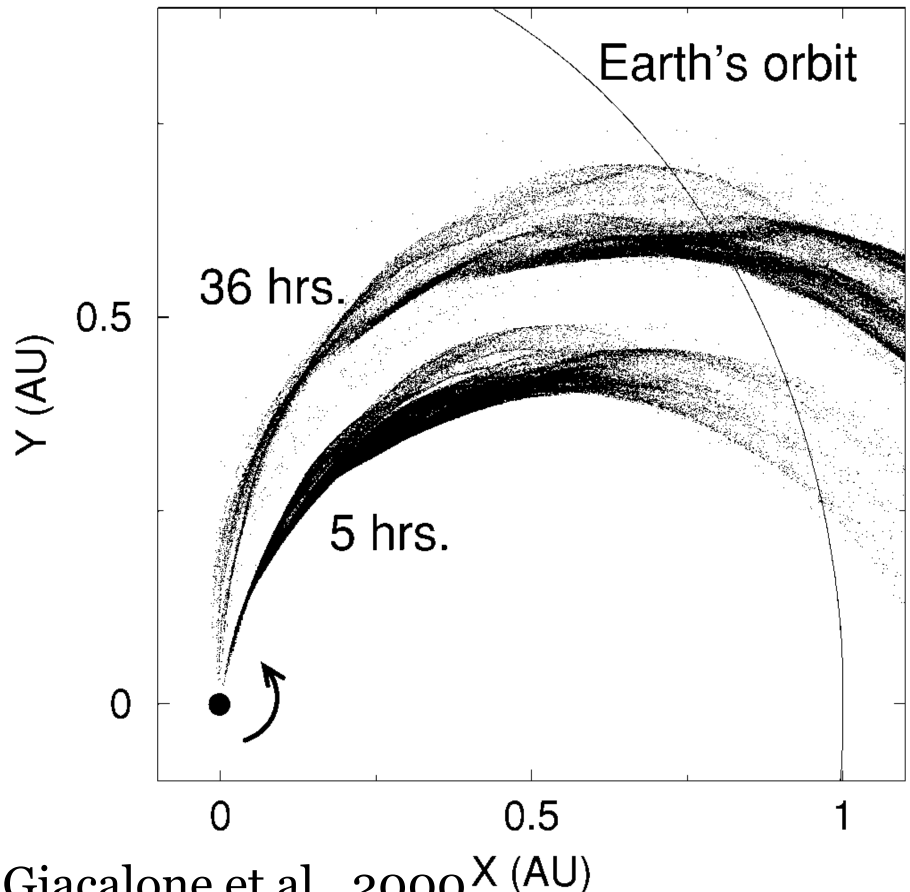
Solar energetic particle drop outs for impulsive events:



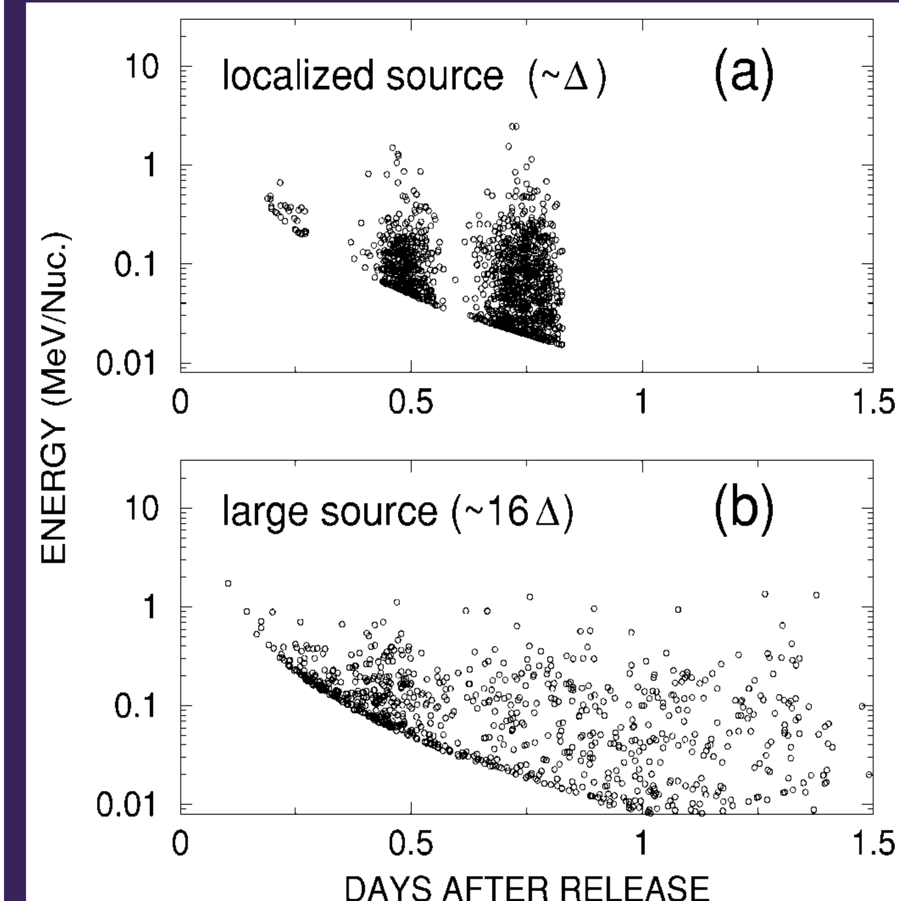
ACE data, Mazur et al., 2000

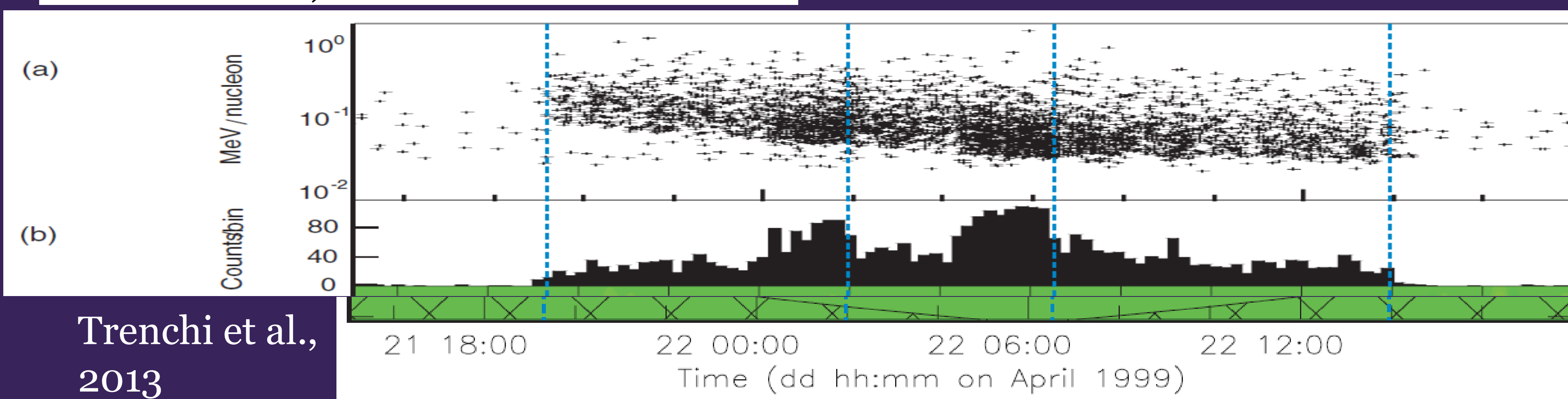


Simulation in turbulence model, Giacalone et al., 2000



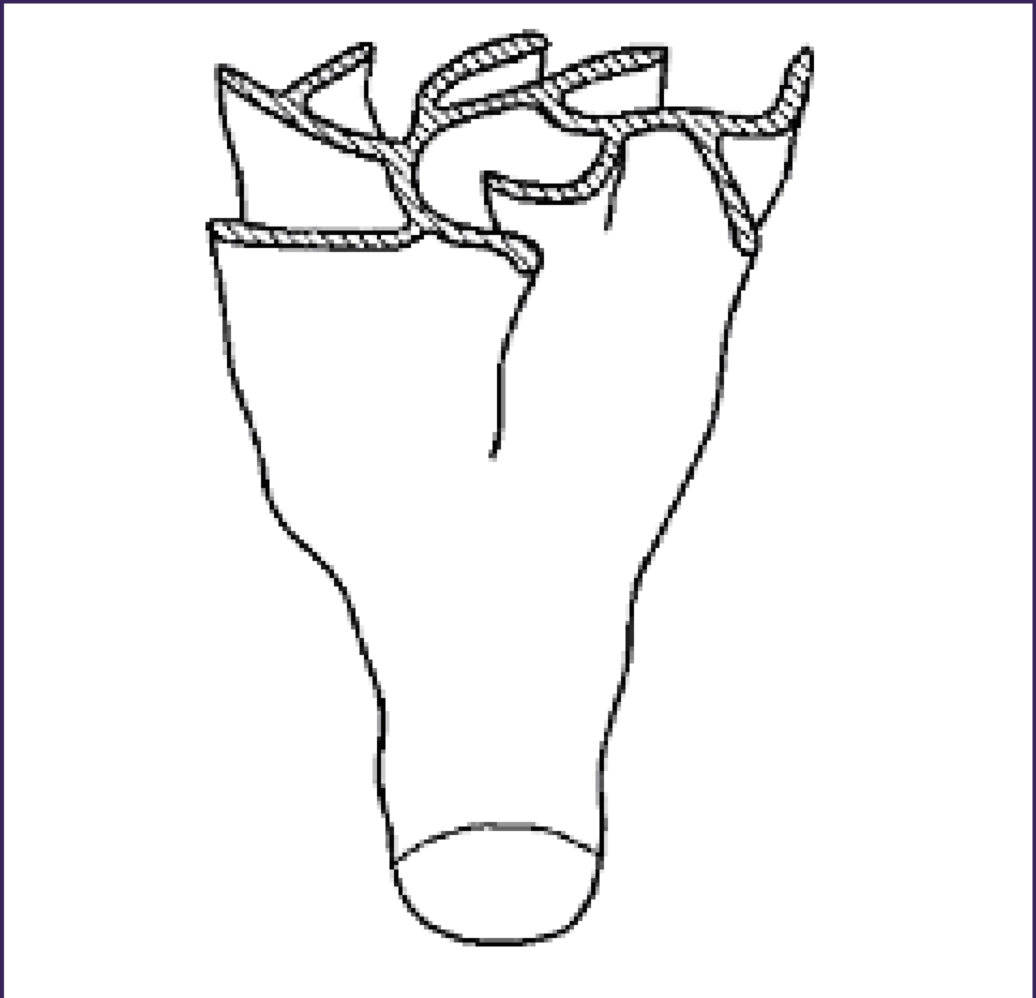
Giacalone et al., 2000





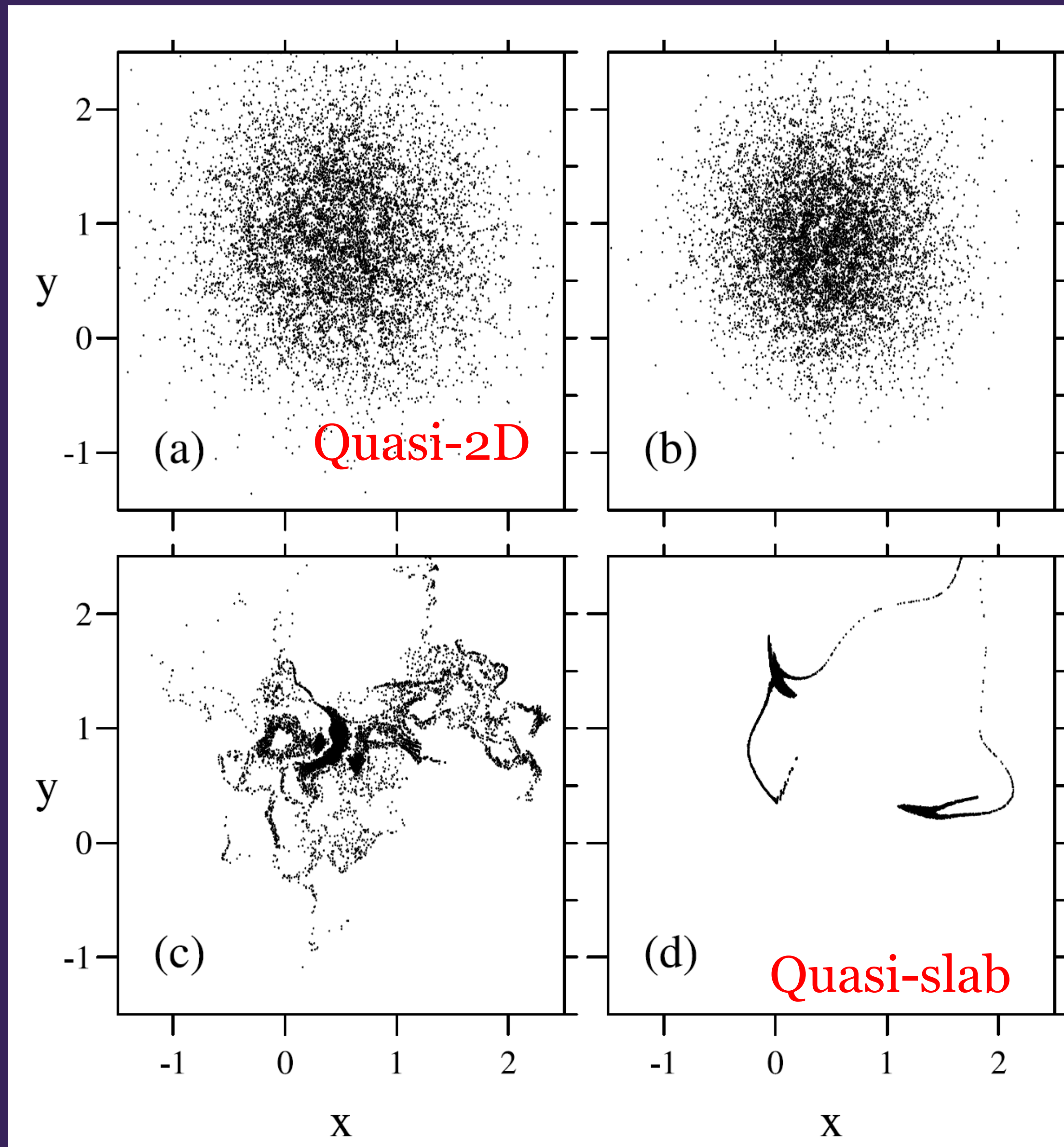
Trenchi et al., 2013

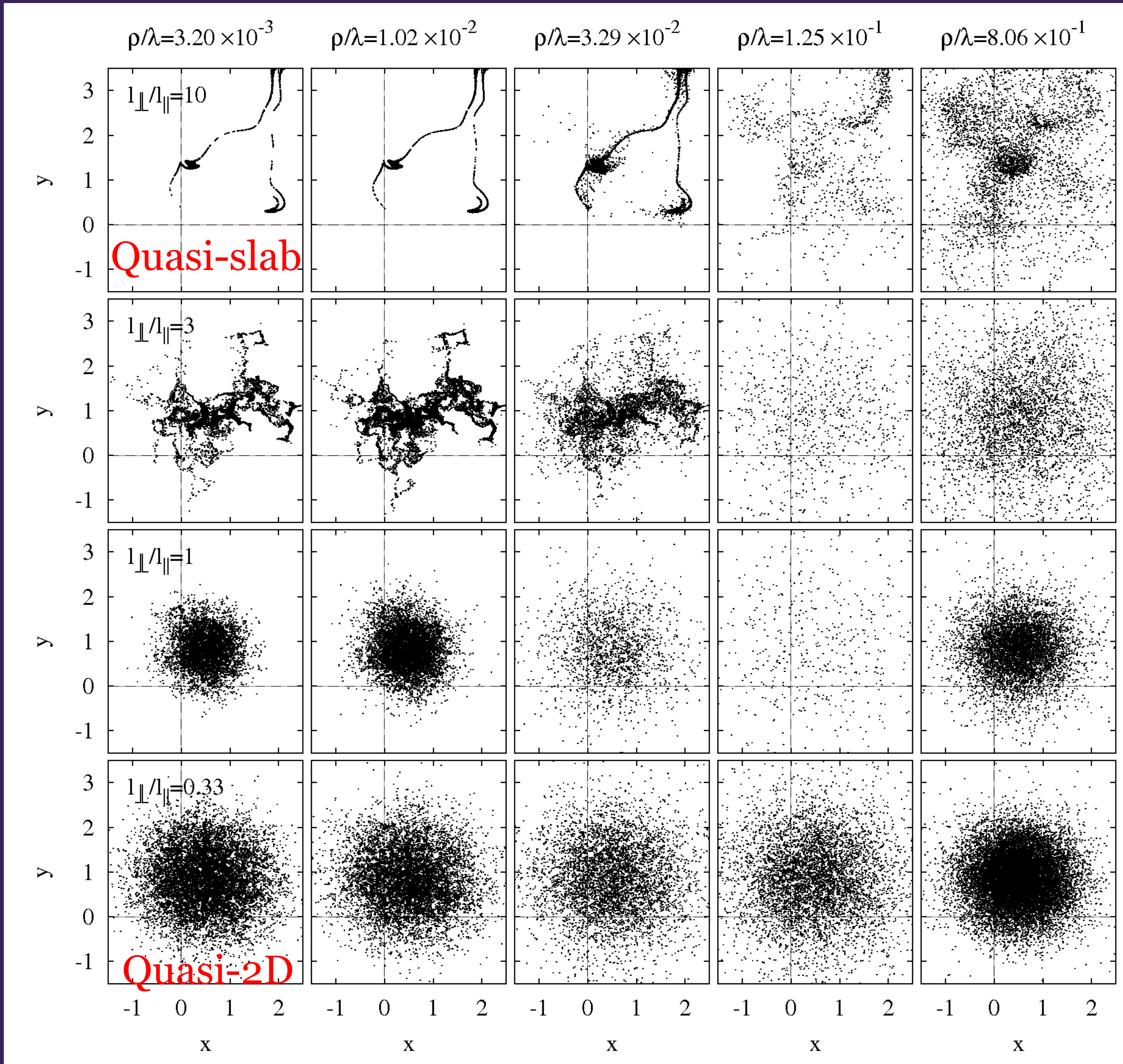
The structure of magnetic flux tubes is influenced by magnetic turbulence:



From Isichenko, PPCF, 1991

Magnetic flux tube cross section for axisymmetric anisotropies and $\delta B/B = 0.5$ at 1 AU (Zimbardo et al., JGR 2004)

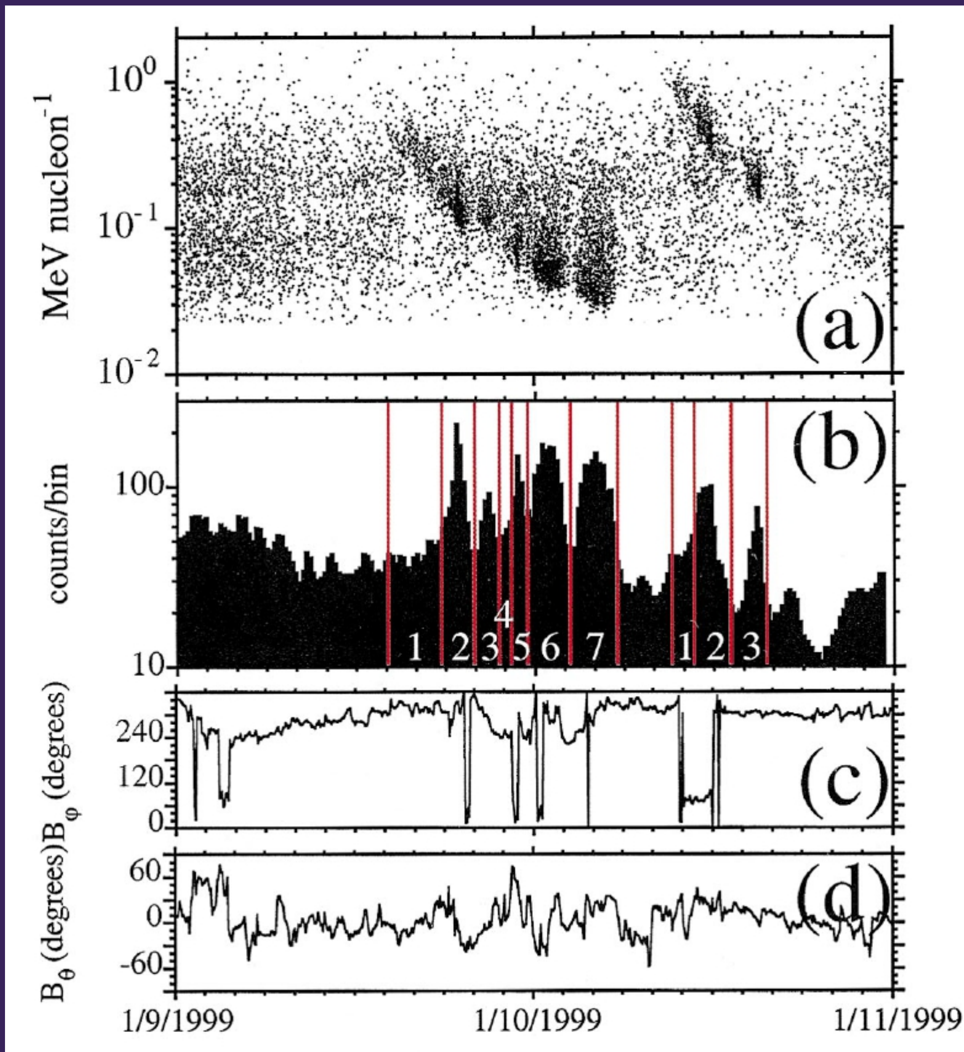




Injecting particles with different Larmor radii ‴ ḿḿḿ

(Pommois et al., Ph.Pl. 2007; Zimbardo et al., IEEE Trans. Plasma Sci., 2008)

Space observations of energetic particles dropouts reveal the complex structure of magnetic flux tubes in solar wind



Mazur et al., Astrophys. J. 2000

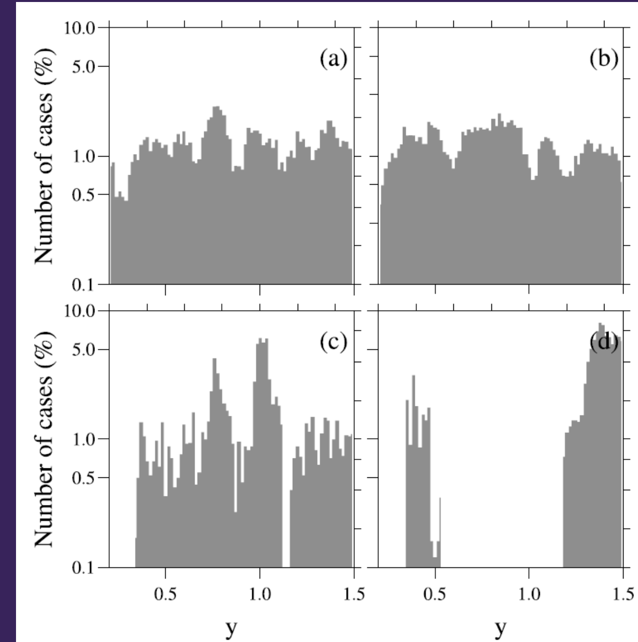


Figure 6. Histograms representing a y-slice of the distributions of field lines shown in Figure 5.

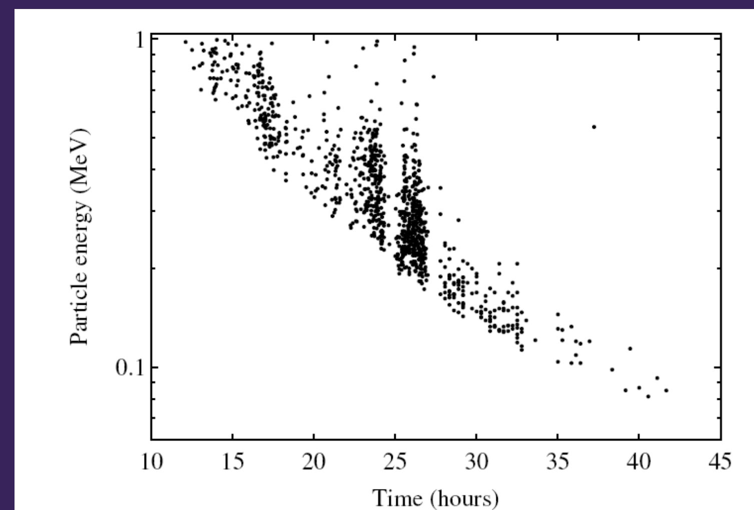
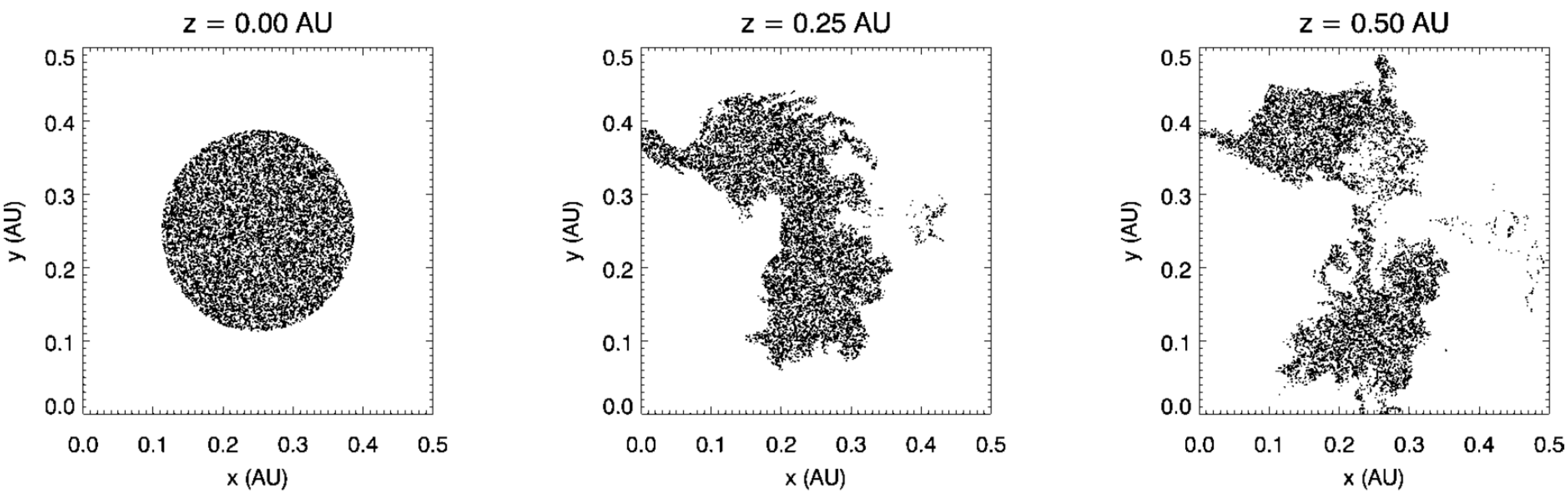
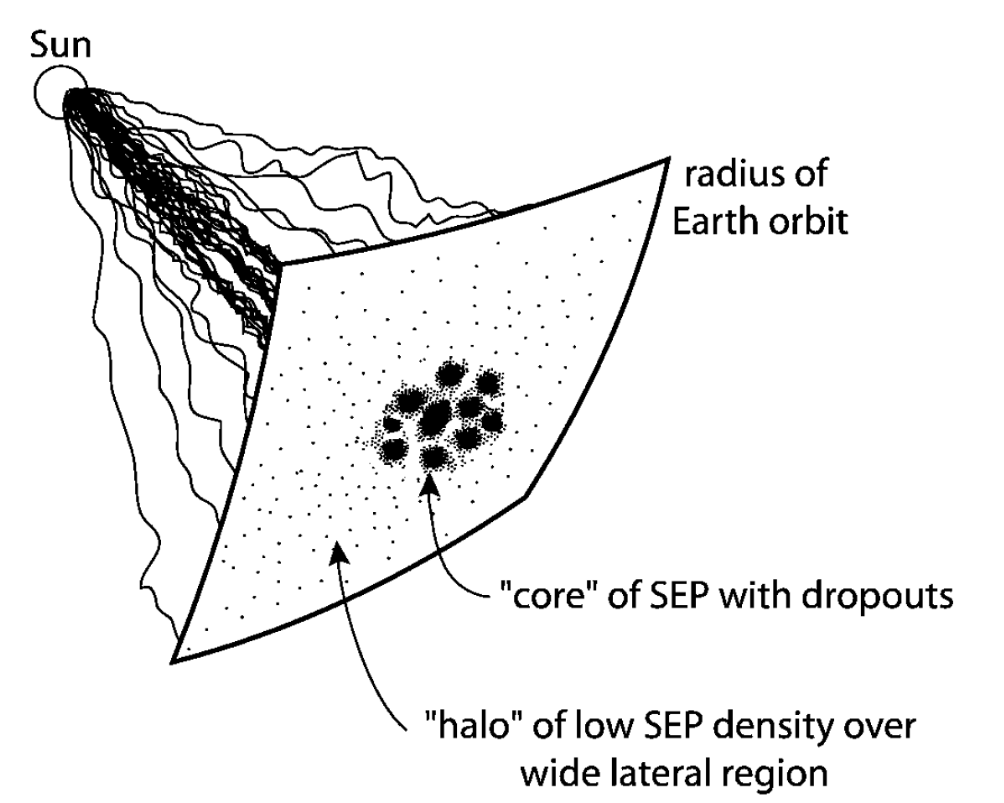


Fig. 2. Particle as observed by spacecraft. The turbulence level is $\delta B/B_0 = 0.5$ and spectrum is with $l_x/l_z = l_y/l_z = 3$.

Pommois et al., Adv. Spa. Res. 2005



Similar study by Ruffolo, Matthaeus and Chuychai (2003)



Conclusions – Part 1

We have illustrated the different energetic particle populations which are found in space

- Solar energetic particles are most dangerous for space weather
- Numerical simulation of perpendicular transport can help to understand energetic particle transport to large heliographic latitudes as well as SEP dropouts
- The forthcoming Solar Probe Plus and Solar Orbiter spacecraft will boost our understanding of both SEP acceleration and transport