Particle Acceleration in 3D magnetic islands and their diagnostics from the heliosphere

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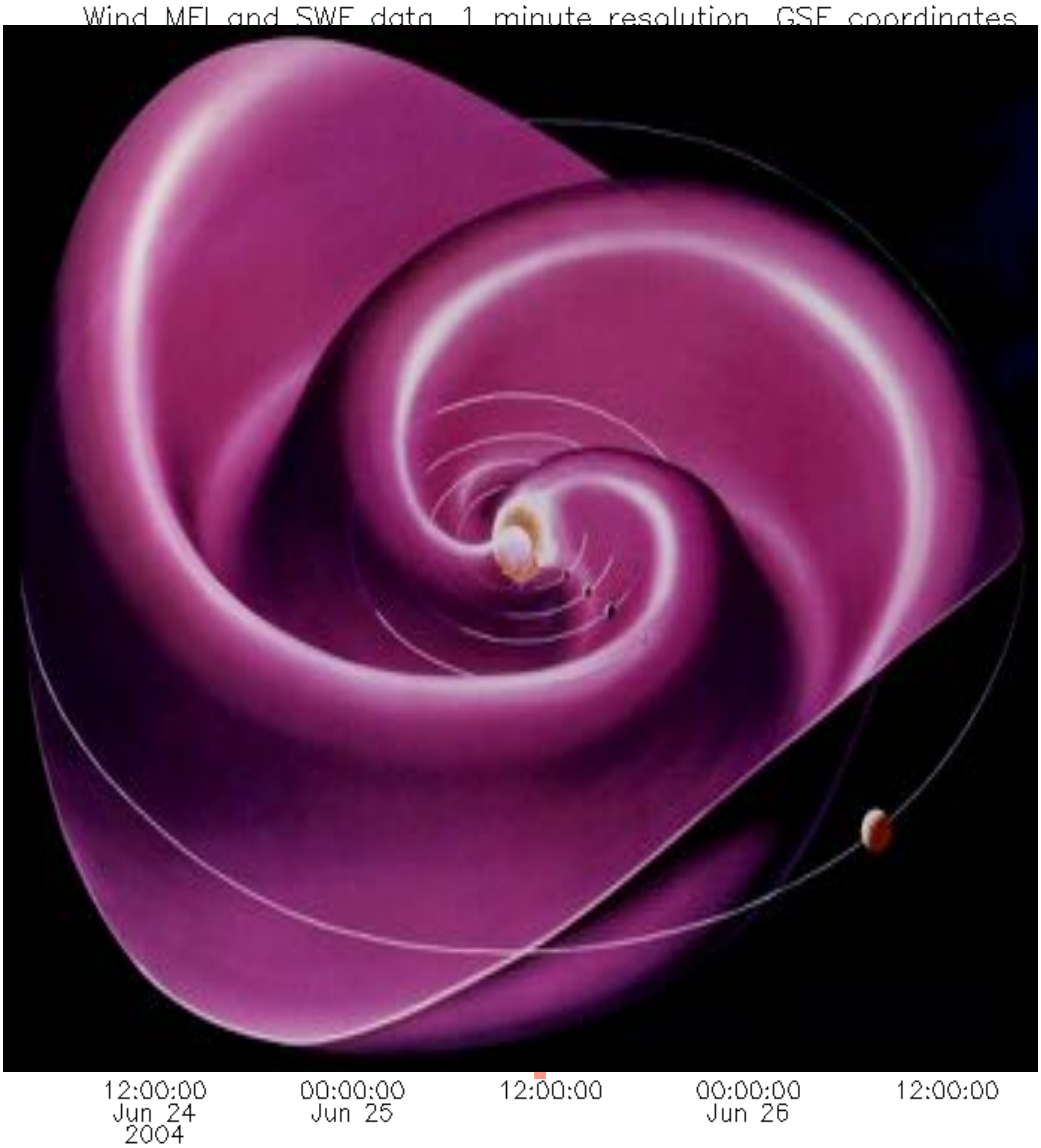
Zharkova and Gordobskyy, 2004, ApJ; 2005a,b MNRAS & SSRv; Zharkova et al, 2011, SSRv; Siversky and Zharkova, 2009, JPP; Zharkova and Agapitov, 2009, JPP; Zharkova and Khabarova, 2012, Khabarova et al, 2015, Zharkova & Khabarova, 2015; Zharkova and Siversky, 2016

Xia and Zharkova, 2018



Zharkova & Khabarova, 2012

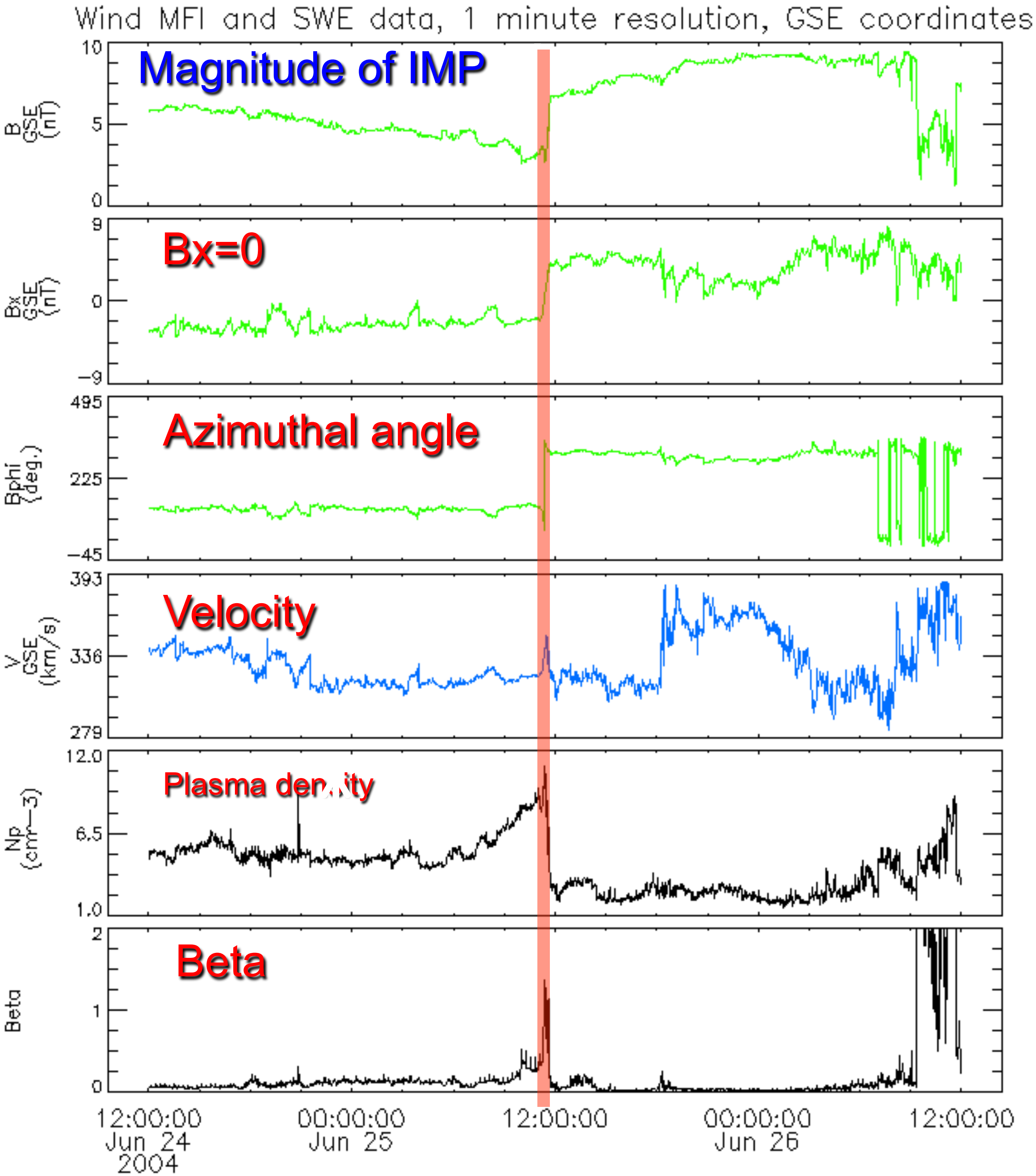
IMP magnitude sharply drops or increases

Horizontal component(Bx, GSE) = 0 nT;

Azimuthal angle (φ_B) changes by180°;

Velocity is slightly increased

Density is sharply increased



In the heliosphere

IMP magnitude sharply drops or increases

Horizontal component(Bx, GSE) = 0 nT;

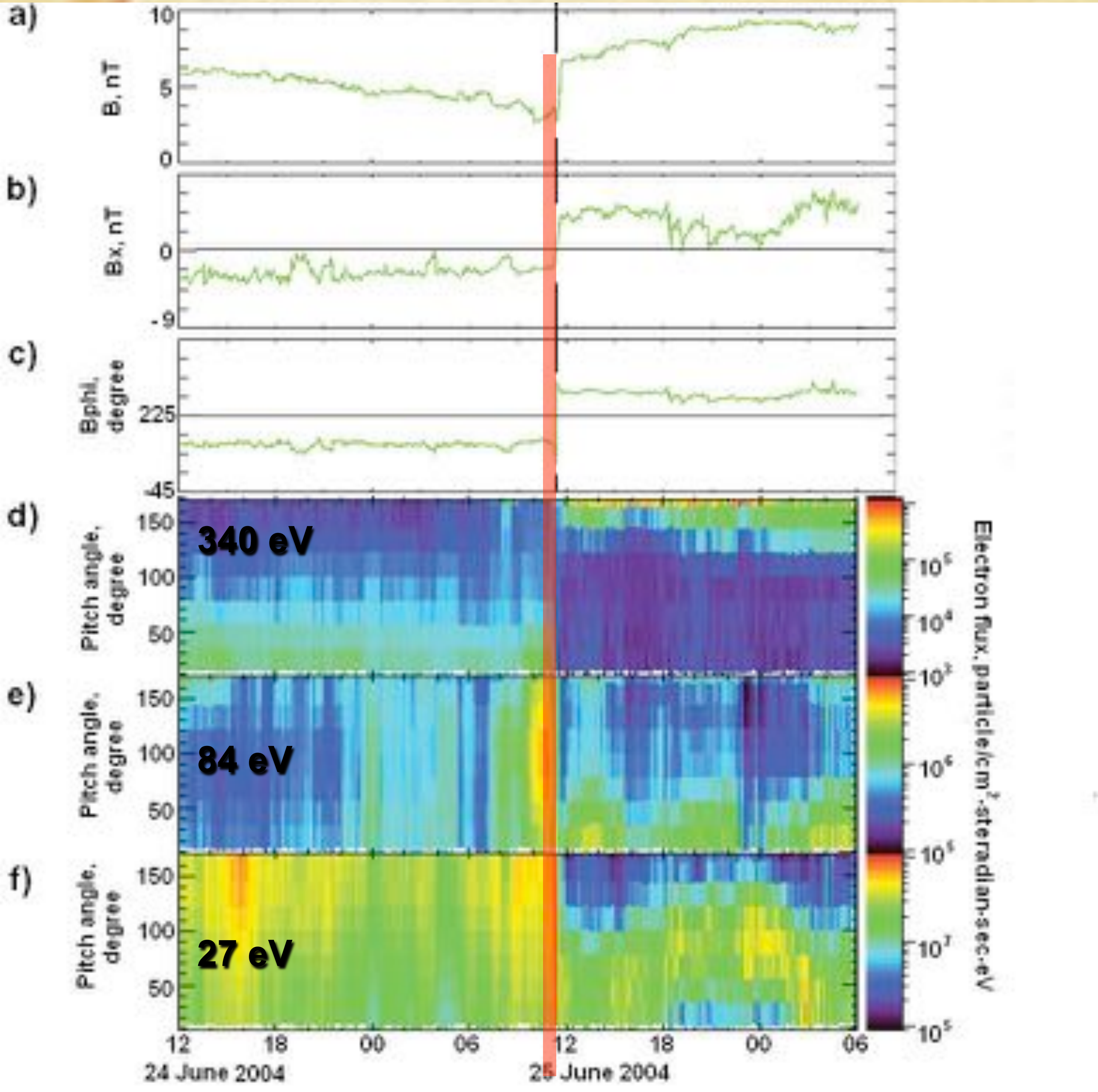
Azimuthal angle (φ_B) changes by180°;

Velocity is slightly increased

Density is sharply increased

Beta is also sharply increased

Problems in identification of sector boundaries



Crossing of a thin SB:

a) IMP magnitude;

b) IMP horizontal component (Bx, GSE);

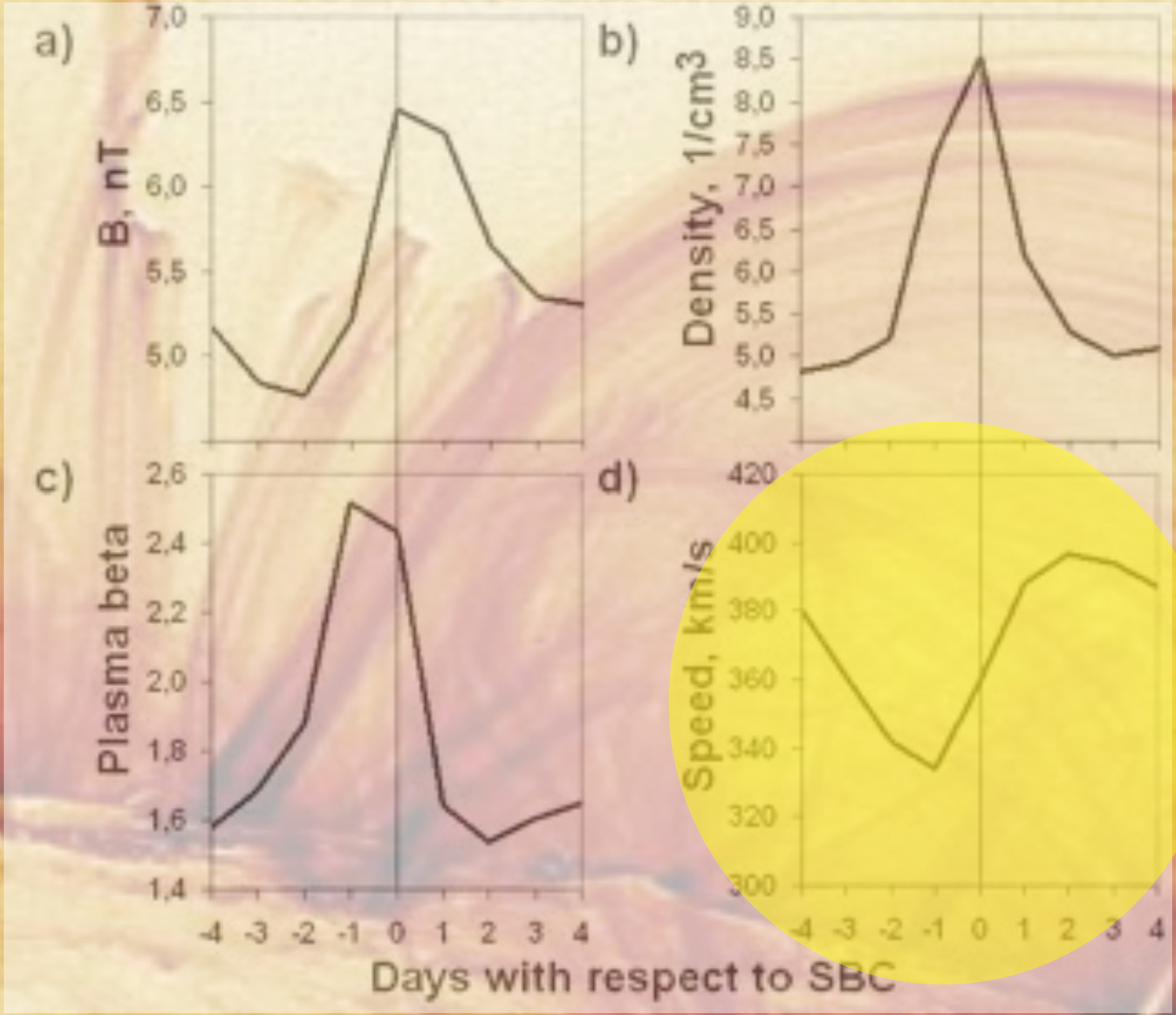
c) IMP azimuthal angle (φ_B);

d-f) Spectrograms of electron distribution in pitch angles (in 5 energy channels)

Kahler, S., and R. P. Lin (1994),, Geophys. Res. Lett., 21, 1575– 1578.

Crooker, N. U., S. W. Kahler, D. E. Larson, and R. P. Lin (2004), J. Geophys. Res., 109, A03108.

Problems in identification of sector boundaries



IMP magnitude, density and beta are quasi-symmetric with respect to the day of sector boundary crossing while the ion velocity is not (?!)

Averaged magnitude obtained for 1322 case from the list by L.Svalgaard, 1964 – 2011, OMNI2).

Problem 1:

Why the electron pitch angle is changed by 180^o occurs well before or after the sector boundary (SB)?

Problem 2:

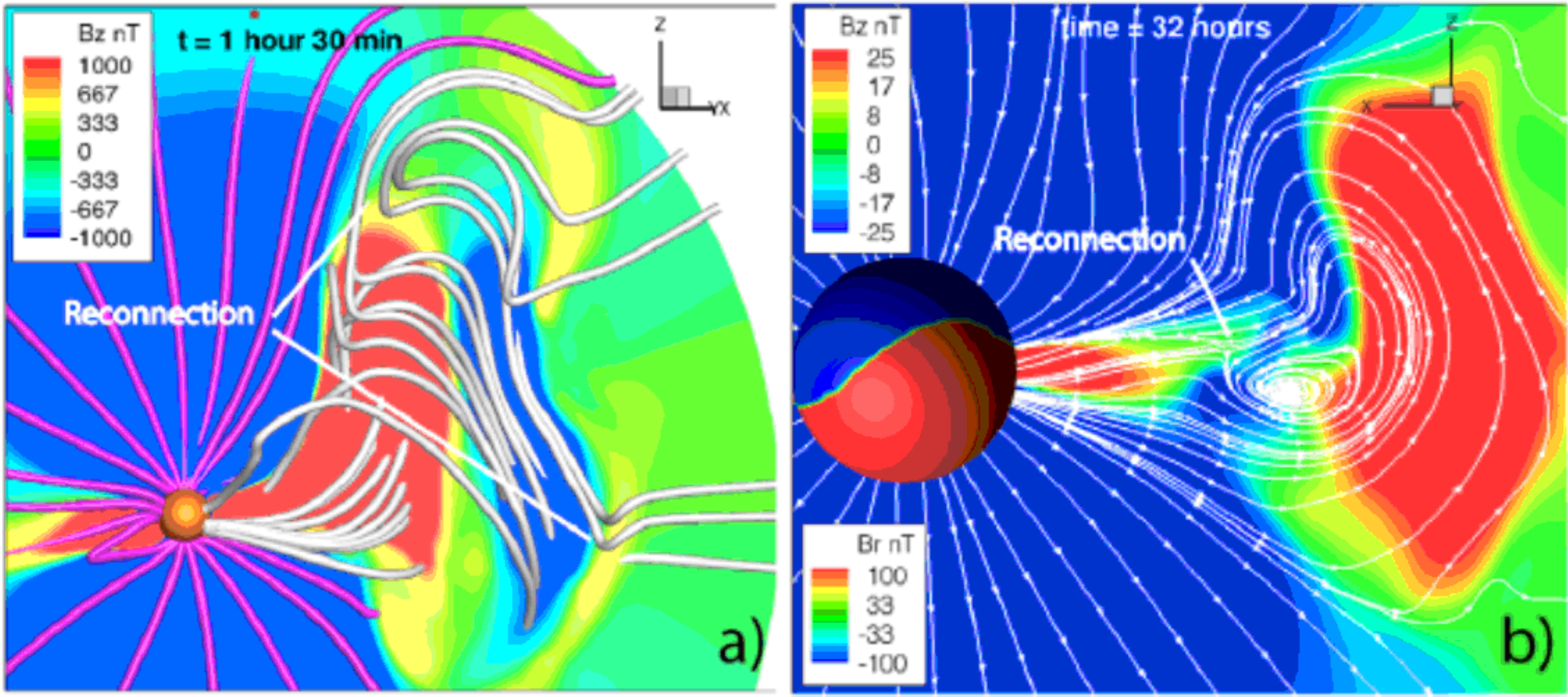
Why the density, magnetic field and beta are quasi symmetric across the SB while the ion (proton) velocity profiles are not?

Problem 3:

Why the plasma density has three symmetric peaks across the SB: the larger central one and two smaller ones from each sides

ICME current sheets

W B Manchester IV *et al* Plasma Phys. Control. Fusion **56** (2014)



Magnetic reconnection

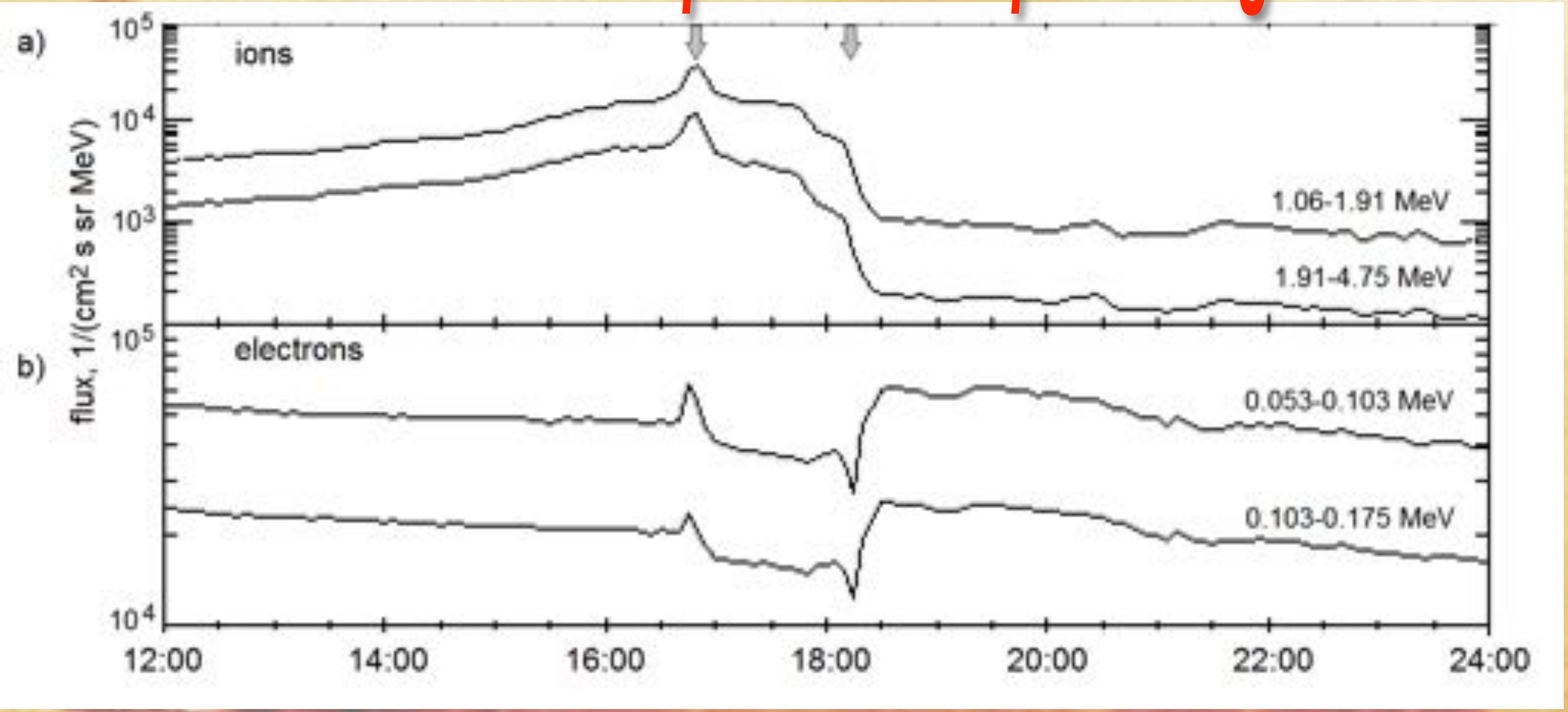
a) at the leading edge of an ICME; b) behind the ICME

Sometimes

Energetic particles stream perpendicular to IMF

Electrons travels towards the Sun

Solar wind particles passing ICME

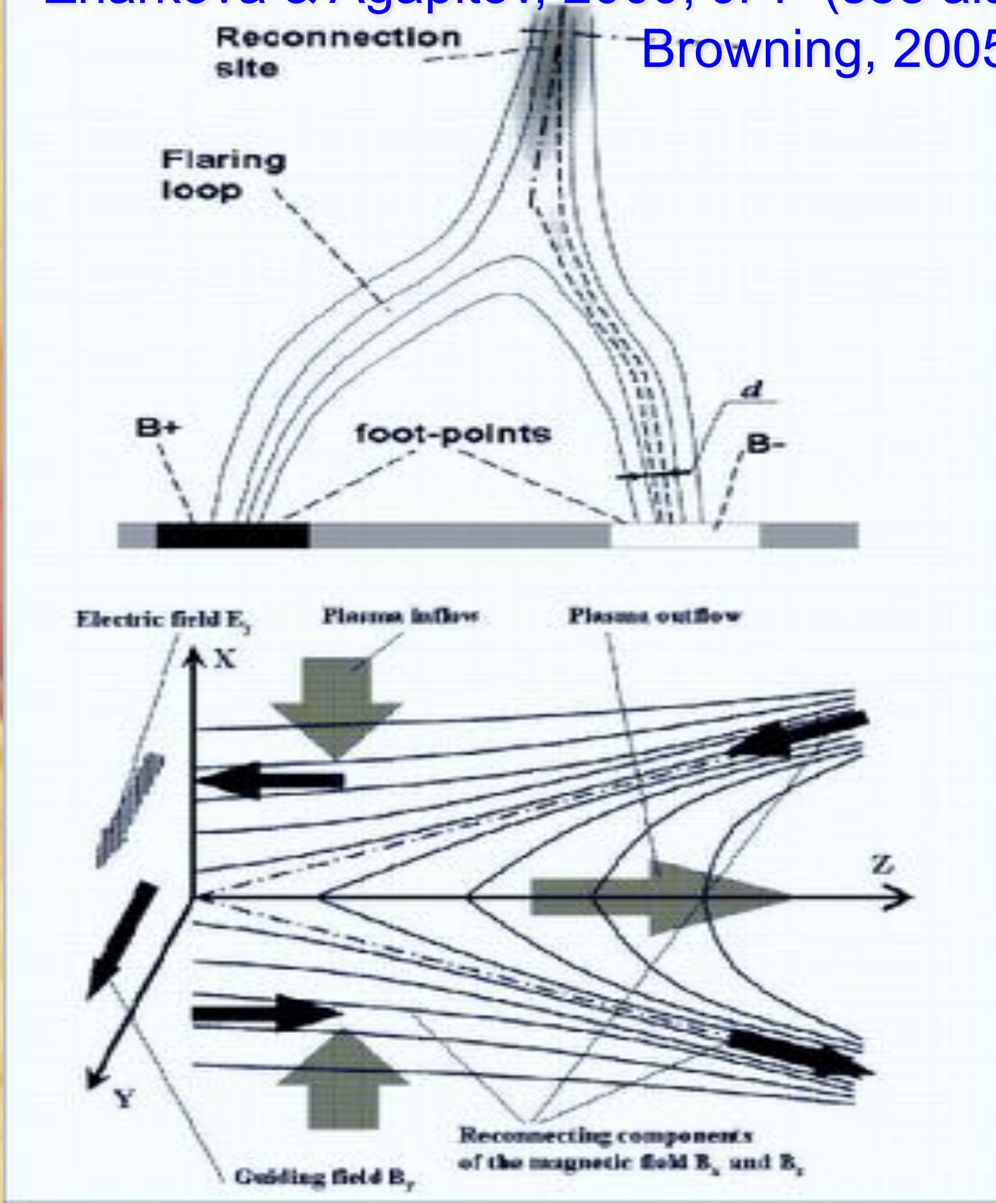


Problem 4: What makes particles to move perpendicular to the IMF in a vicinity of ICME

Problem 5 : Why there is asymmetry in motion of ion and electron flux about ICMEs? Why high energy strahls of electrons are often observed in anti-parallel direction?

Test particle approach –solar corona

Zharkova&Gordovskyy, 2004, ApJ; 2005, A&A; SSRv;
Zharkova & Agapitov, 2009, JPP (see also Wood &Neukirch, 2005, Dalla & Browning, 2005, 2010; Browning et al, 2010...)



$B_z = B_0 \tanh(-x/d)$
$B_x = B_0 (z/a)^{\alpha}$

$B_y = +/- By_0 = 1\text{-}10$ G

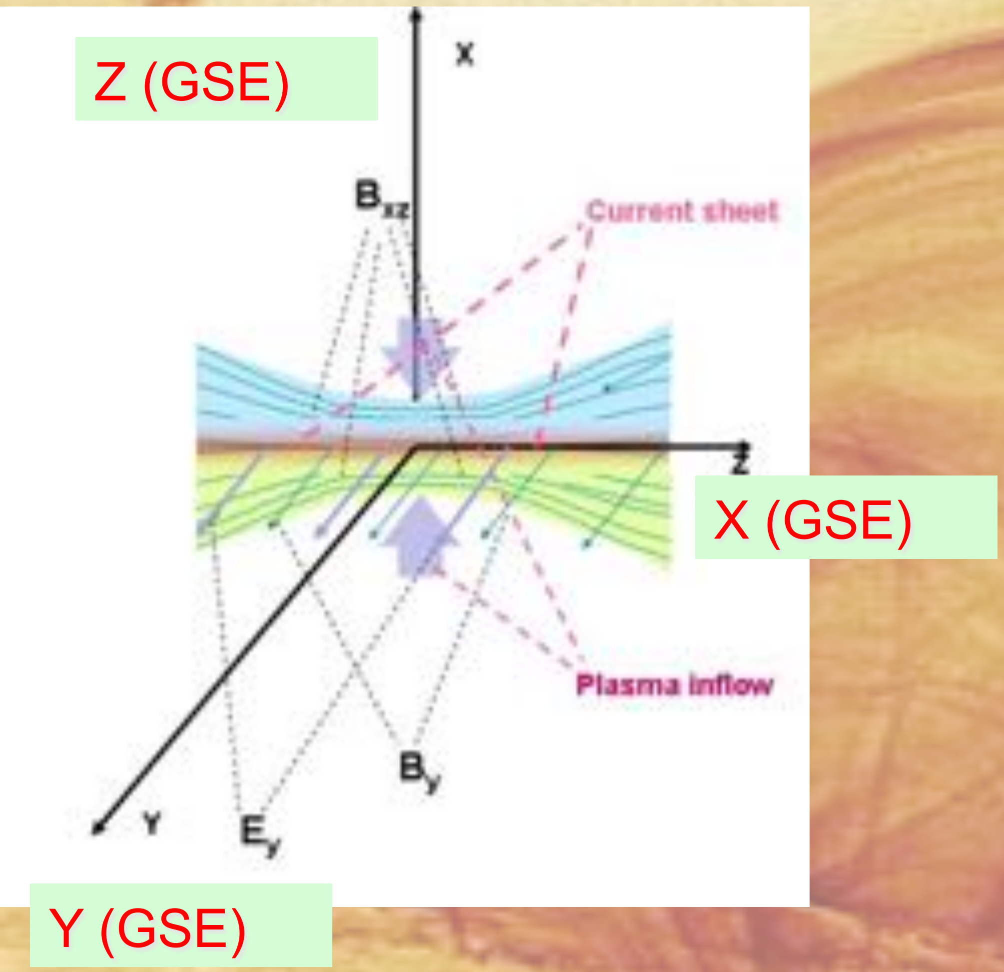
$B_0 = 10\text{-}100$ G

$E_{y0} = B_0 V_{inflow} - 1/\sigma\mu \, dB_z/dx$

$V_{inflow} \approx 0.01 \, V_{alfven} \approx 10^4$ m/s

$E_{y0} = 100\text{-}250$ V/m

Physical model of current sheet (HCS or front ICME)



Zharkova and Khabarova, 2012, ApJ, 752, 35; 2015, Ann Geo, 33, 457

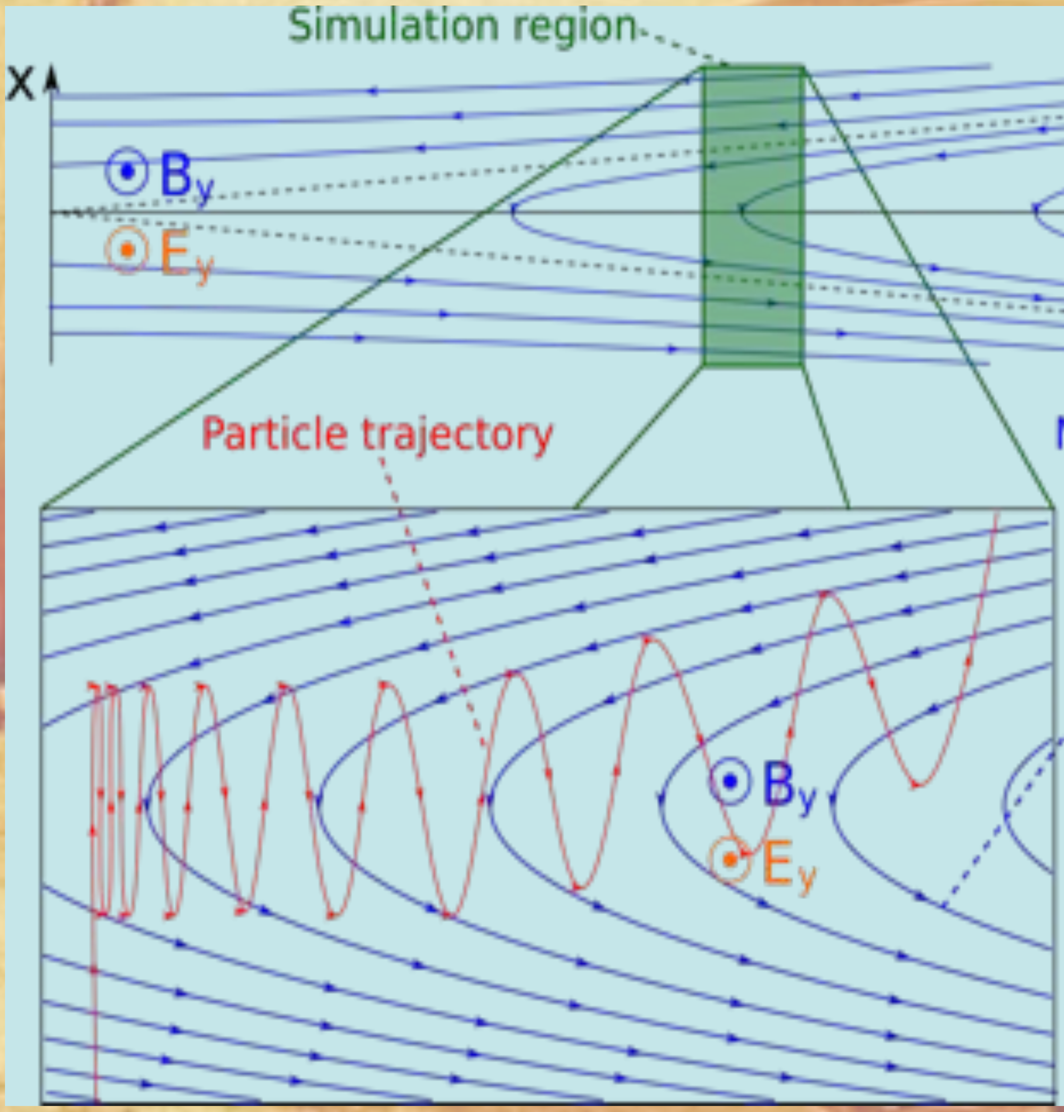
- Consider the HCS with ongoing a magnetic reconnection, which creates a reconnection electric field

- current sheet thickness ~ proton gyroradius (10^4 km for HCS, as B_0 is reduced to from 10^{-2} to 10^{-9} T)

- Model region - 10-100 proton gyroradii from the both sides of the HCS

- Consider plasma feedback to presence of accelerated particles – induced electric and magnetic fields

Physical model for PIC



$$B_z(x) = B_0 \tanh\left(\frac{x}{d}\right)$$

$$E_y, B_y, B_x = const$$

Plasma feedback in 2.5D PIC simulations (Verboncouer & Gladd, 1995)

- $\partial E/\partial t = c^2 \ \nabla \mathrm{x} B - 1/\varepsilon_0 \ (J_e + J_{p)}$
- $\partial B/\partial t = \ \nabla \ \mathrm{x} \ E$

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{p}}{m\gamma}$$

$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{1}{c}\frac{\mathbf{p}}{m\gamma} \times \mathbf{B}\right)$$

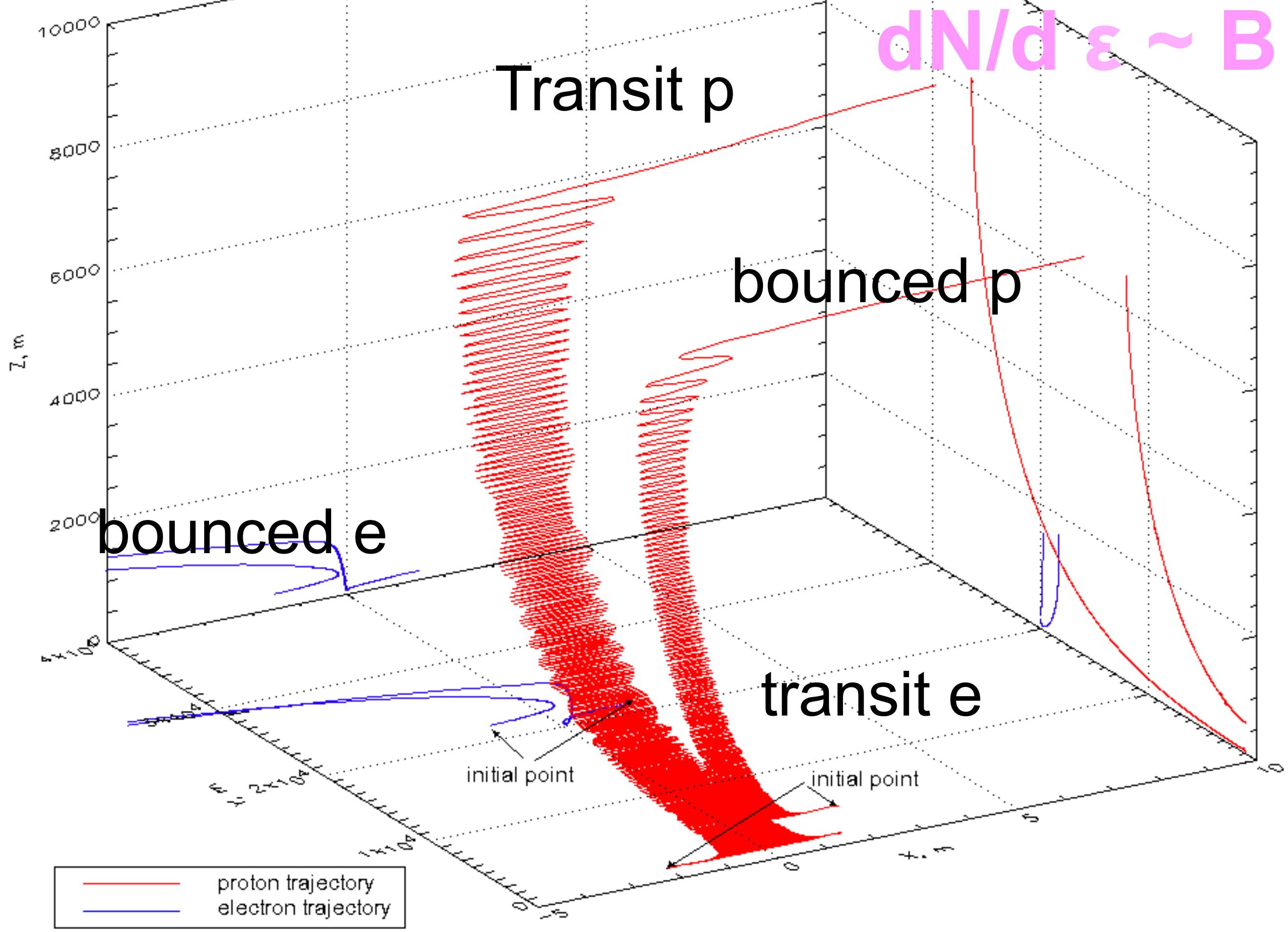
$$d_e \equiv L^{-1}\left(c/\omega_{pe}\right)$$ Electron's skin depth

$$d_i \equiv L^{-1}\left(c/\omega_{pi}\right)$$ Ion's skin depth

Single X-nullpoint

$dN/d\varepsilon \sim A\,\varepsilon^{-1.5}$

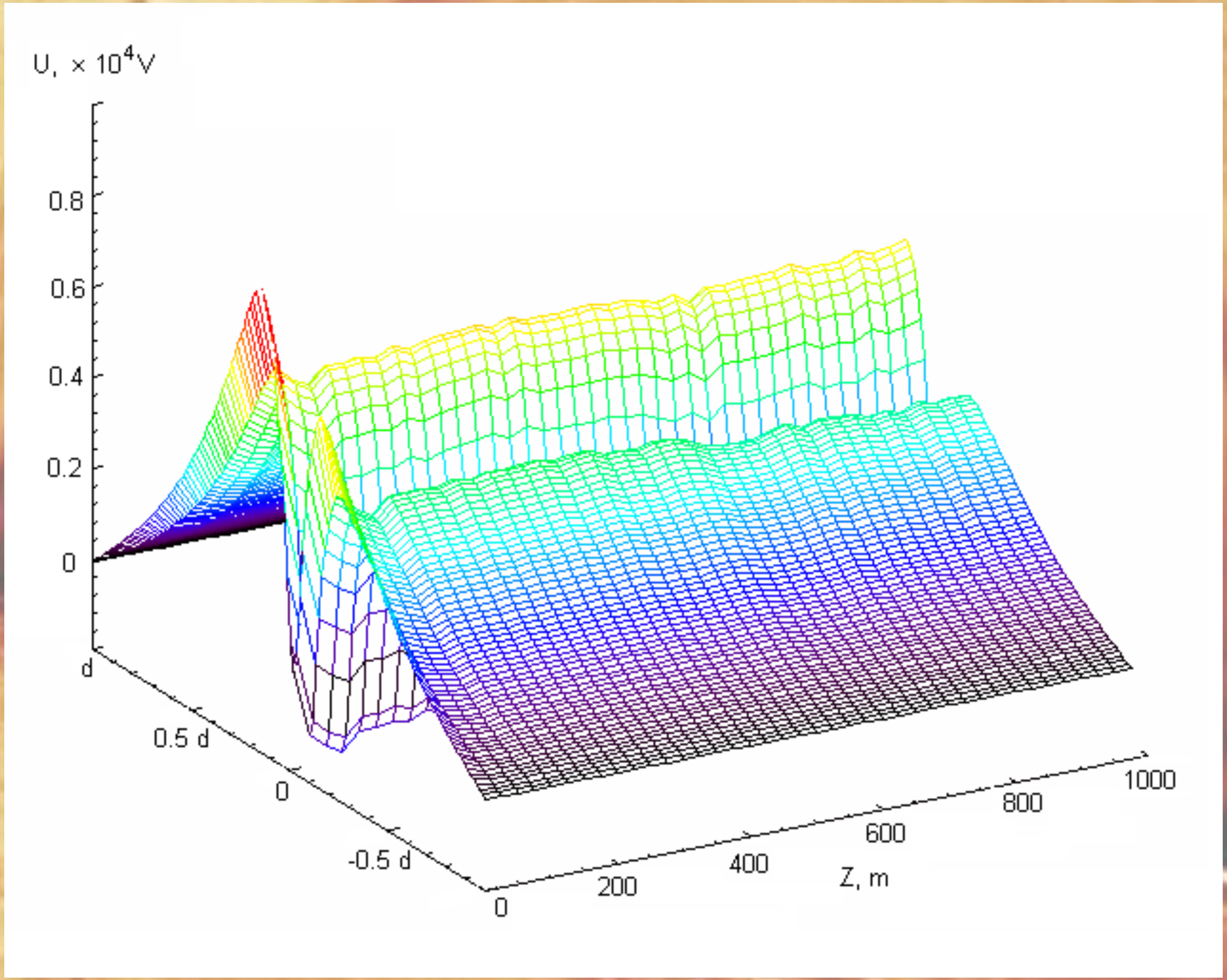
$dN/d\varepsilon \sim B\,\varepsilon^{-2.0}$



Zharkova& Agapitov 2009, JPP, 75/2, 159

Single X-nullpoint

Polarization electric field



In RCS with single X-nullpoint

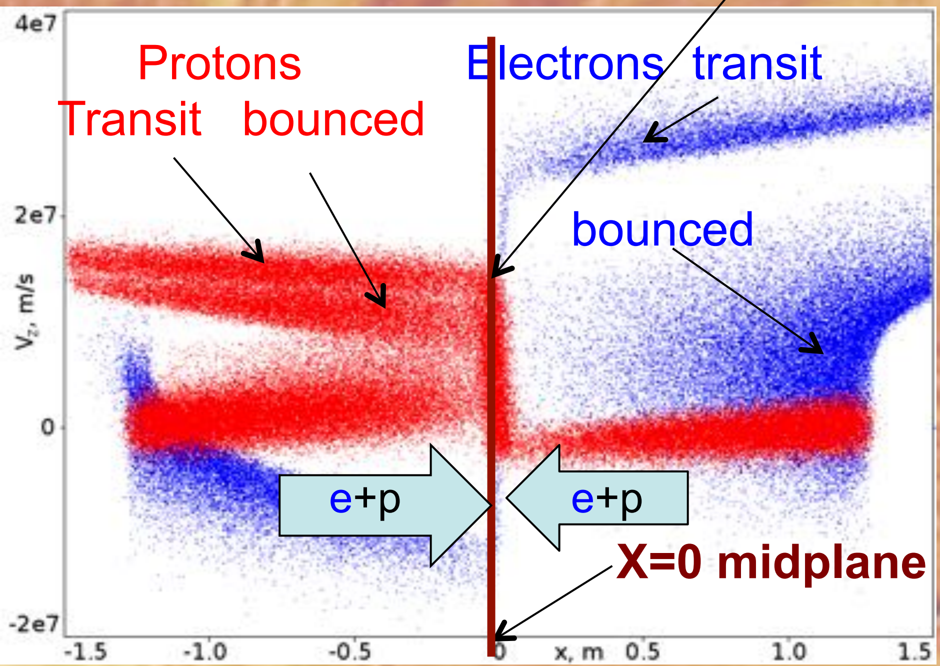
$n = 10^4 \mathrm{cm}^{-3}$

Electrons and protonss are separated with respect to RCS midplane

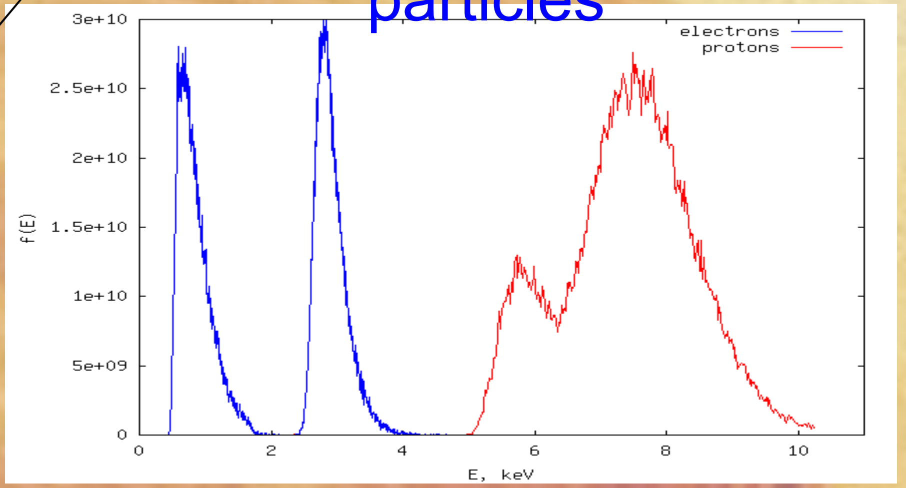
$B_0 = 100\mathrm{G} \qquad B_y = 1\mathrm{G}$

$B_x = 0.4\mathrm{G} \qquad \frac{m_p}{m_e} = 10$

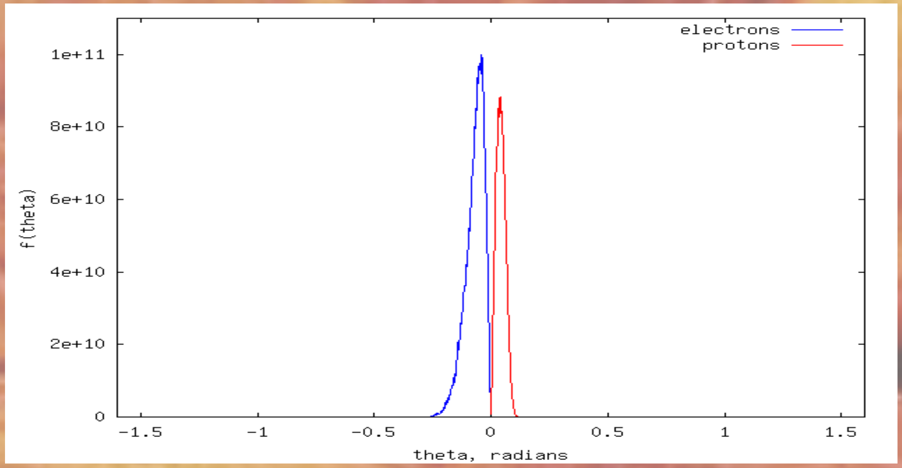
x-V_z phase space



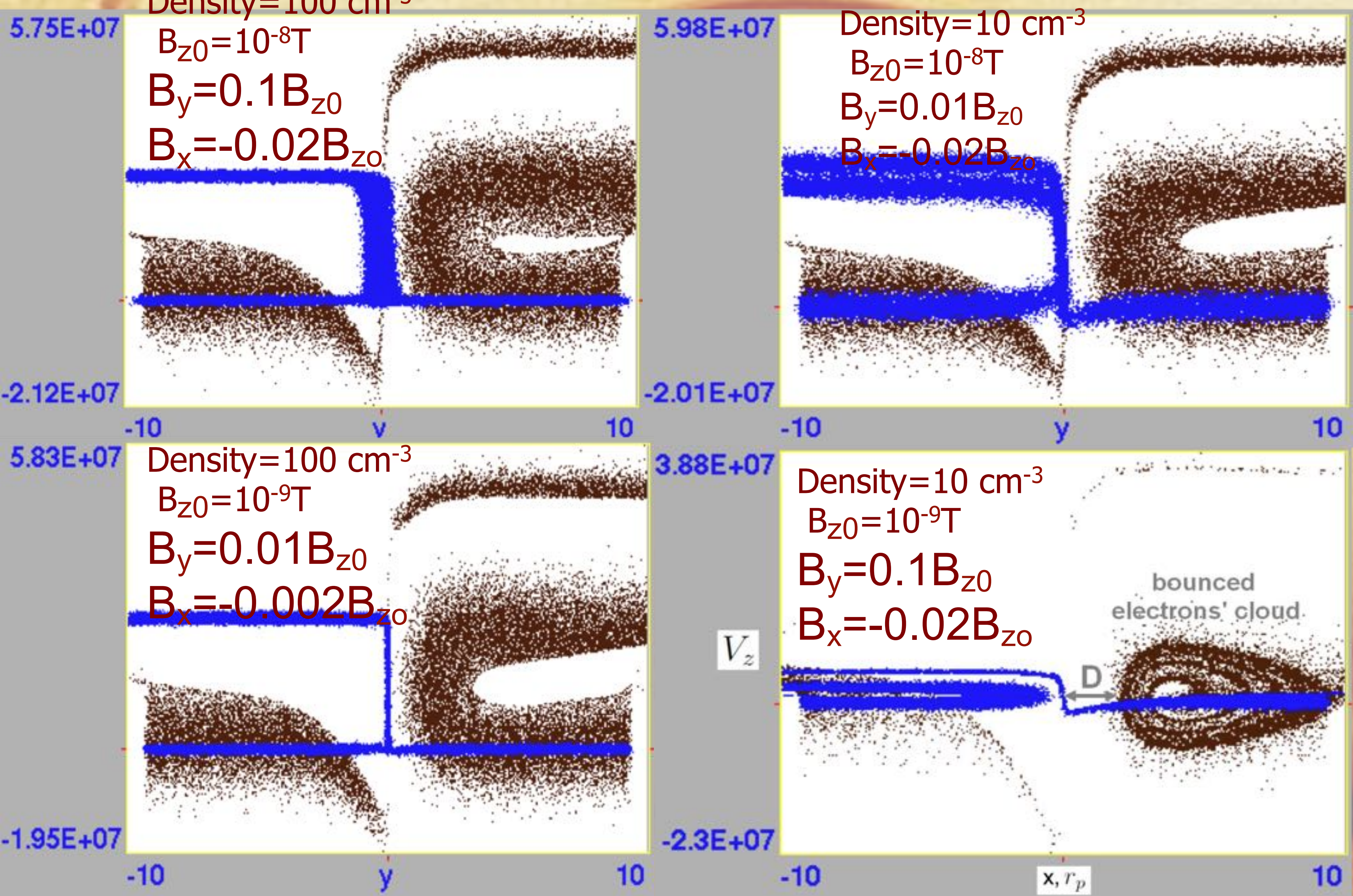
Energy distributions of ejected particles



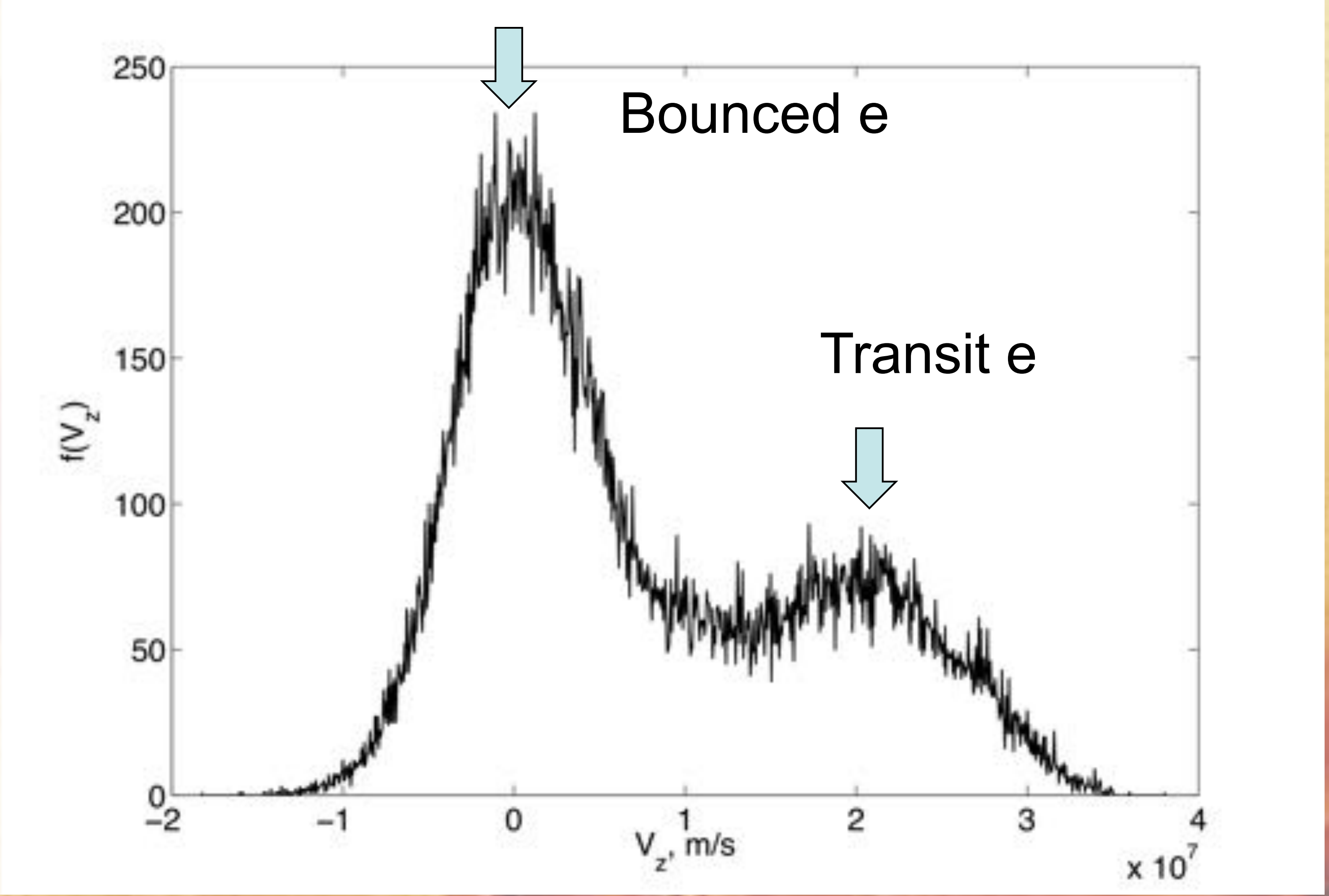
Pitch angle distributions



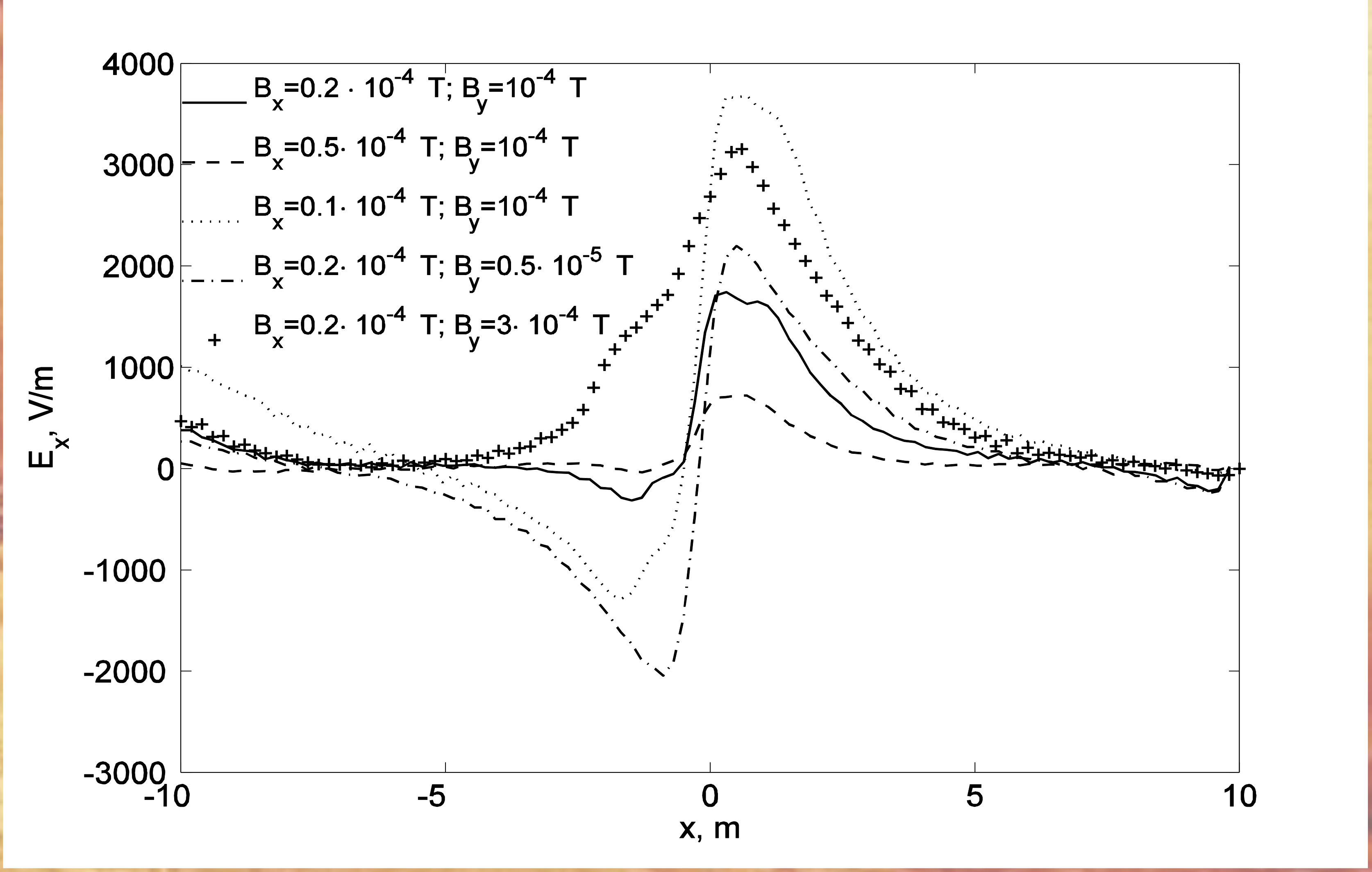
Heliospheric current sheet density = 10-100 cm^{-3} – formation of electron cloud

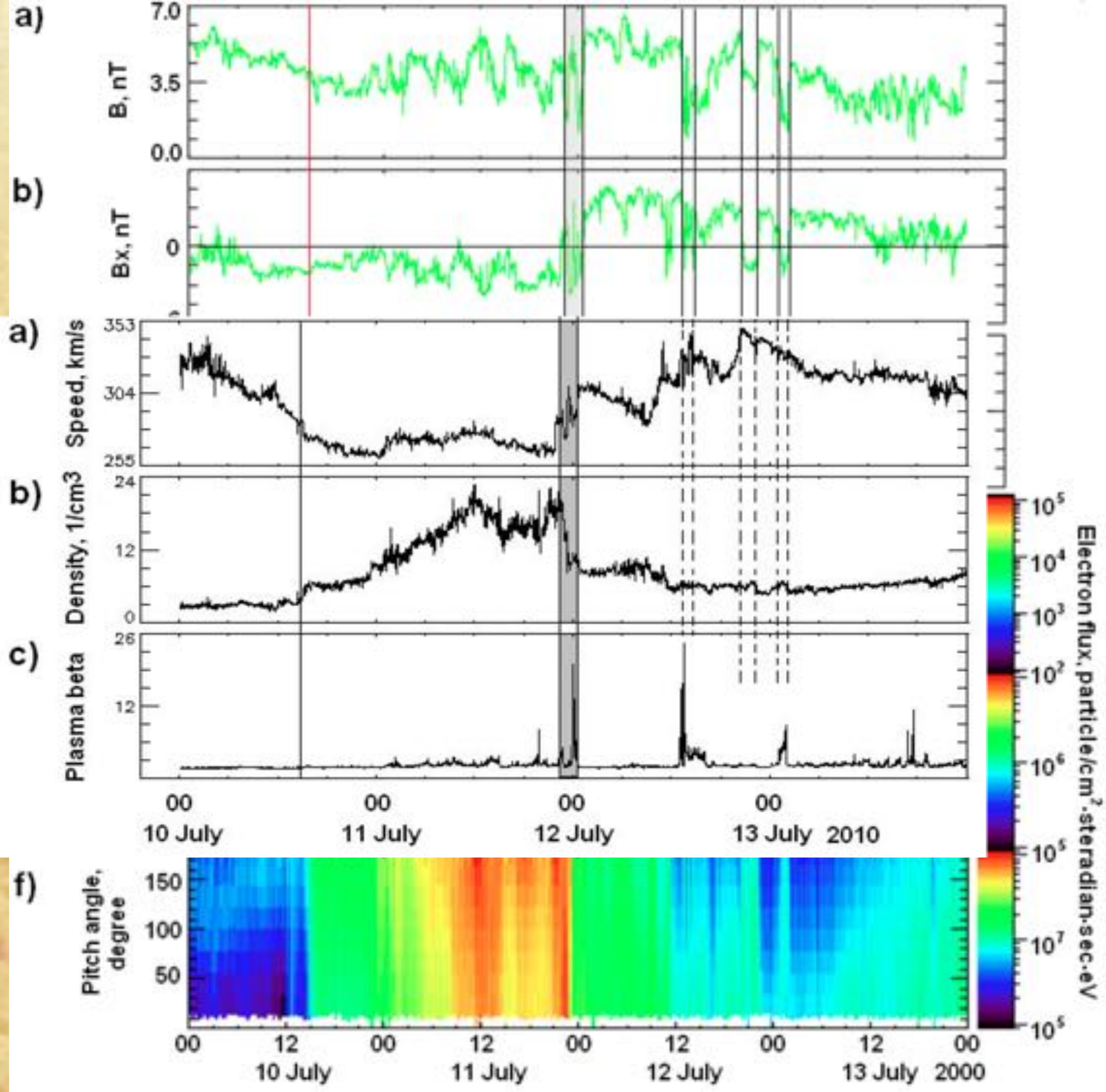


PIC: electron distribution in RCS



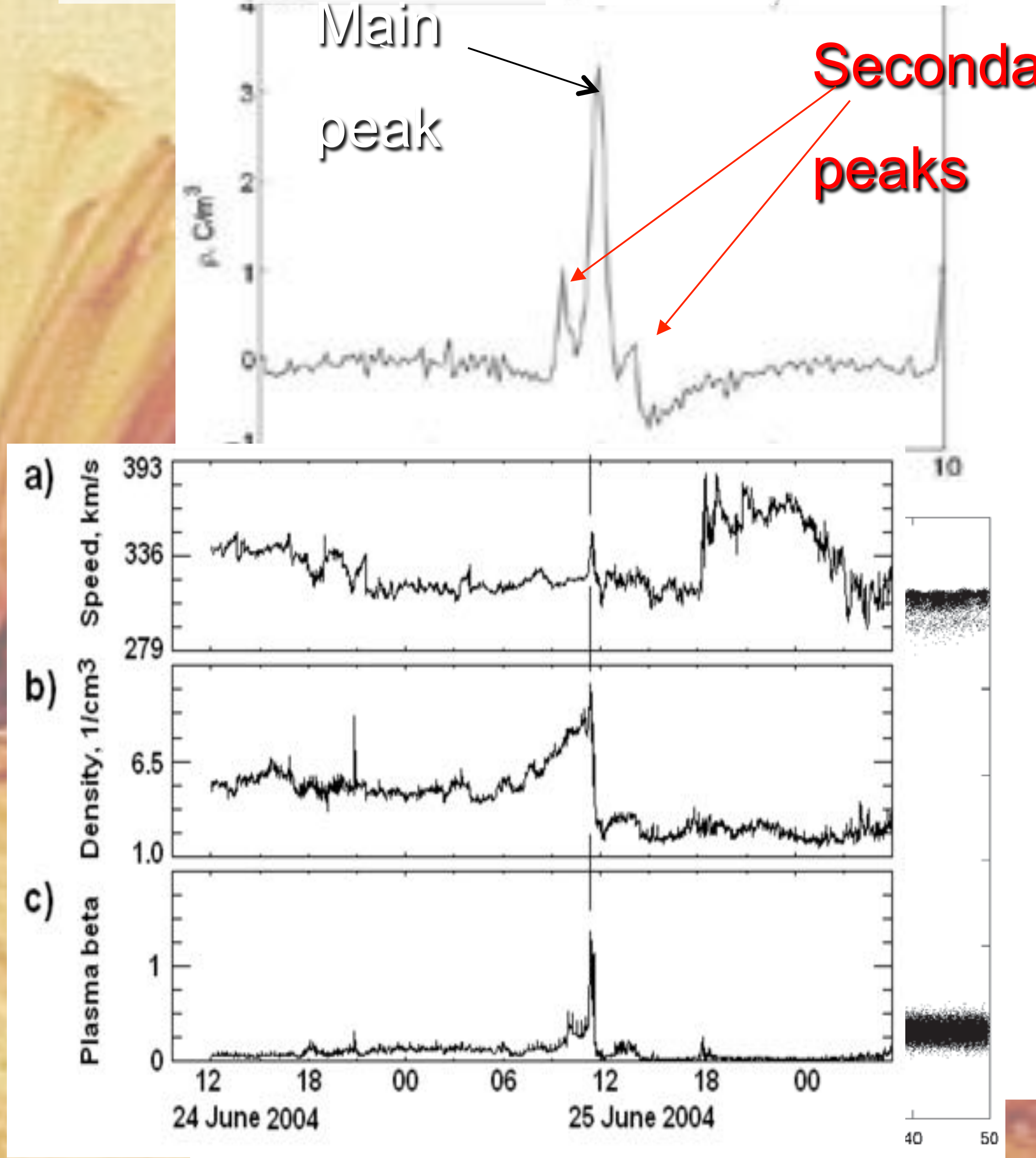
Polarization electric field E_x– across current sheet ($B_0=10^{-2}$ T)



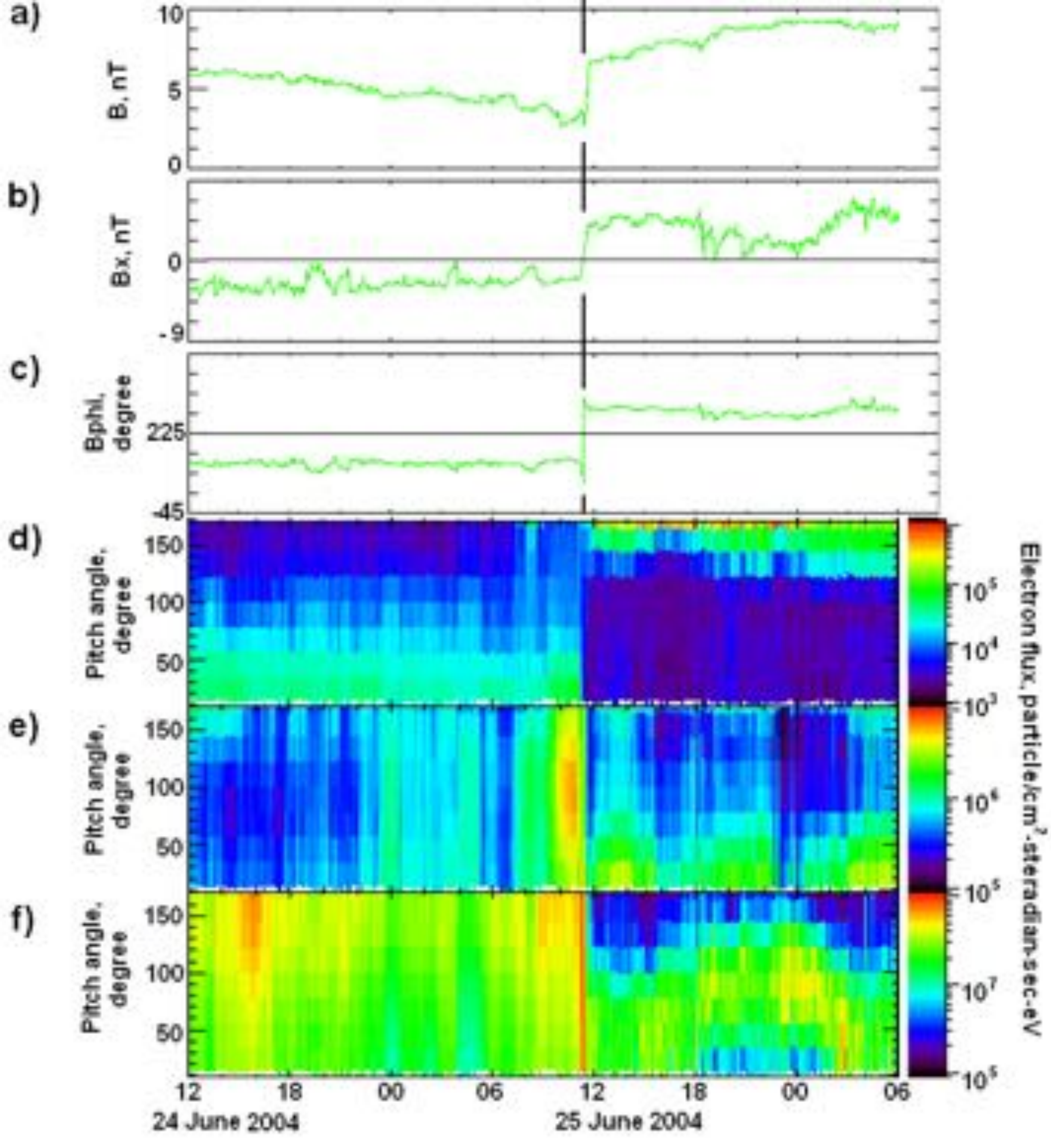


a)
B, nT
7.0
3.5
0.0
b)
Bx, nT
0
a)
Speed, km/s
353
304
255
b)
Density, 1/cm3
24
12
0
c)
Plasma beta
26
12
00
10 July
11 July
12 July
13 July 2010
f)
Pitch angle, degree
150
100
50
00
12
10 July
11 July
12 July
13 July
2000
Electron flux, particle/cm^2·steradian·sec·eV

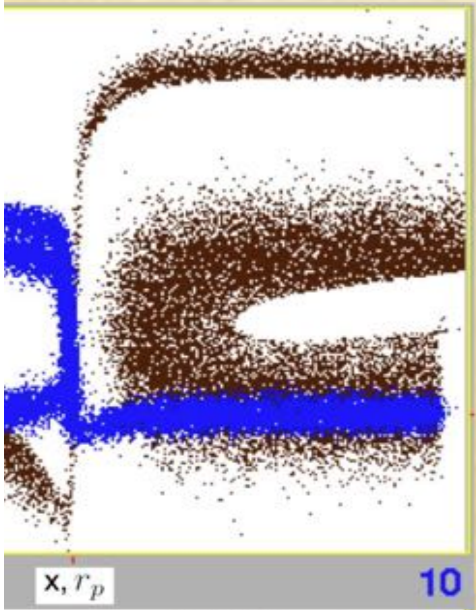
Secondary density peaks about the sector boundary – acceleration of transit and bounced protons



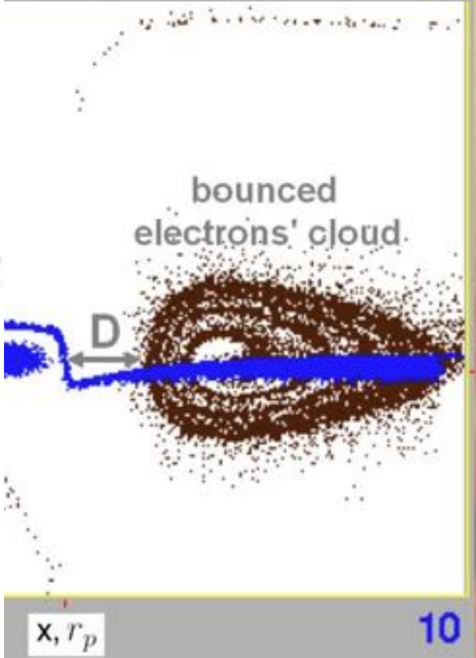
0-100 cm^{-3}



a)
b)
c)
d)
e)
f)
B, nT
Bx, nT
Bphi, degree
Pitch angle, degree
Electron flux, particle/cm^2-steradian-sec-eV
12
18
00
06
24 June 2004
25 June 2004



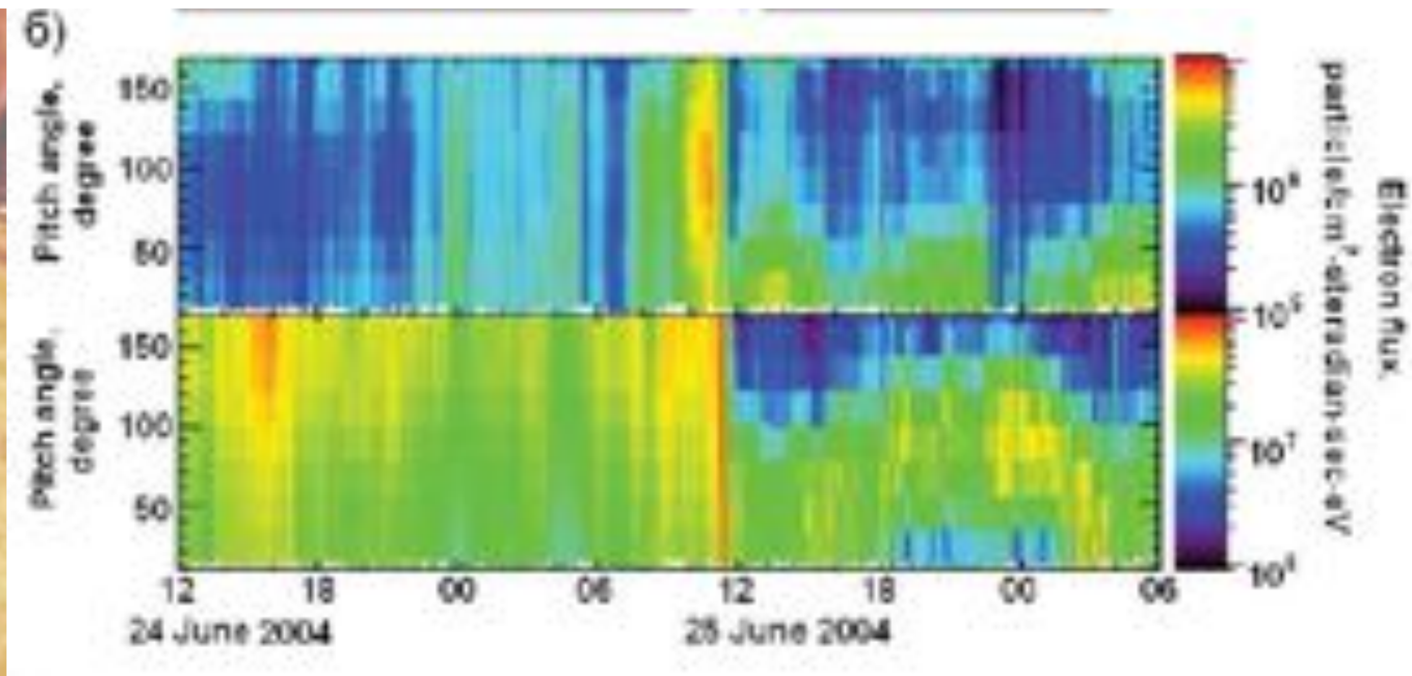
x, r_p
10



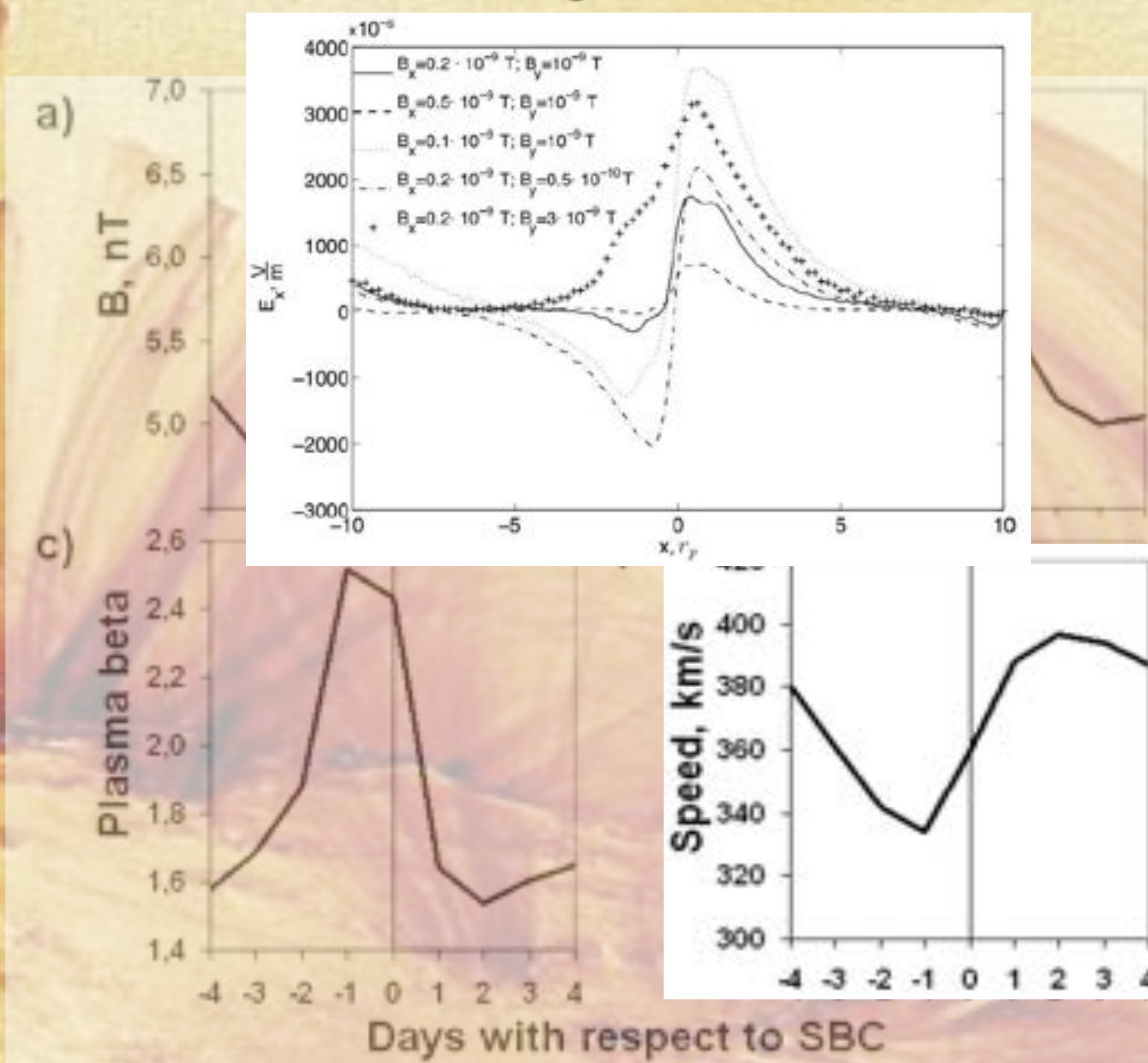
bounced electrons' cloud
D
x, r_p
10

Disagreement of the HCS SB (midplane) and electron turn by 180º (electron cloud) depends on magnitude of

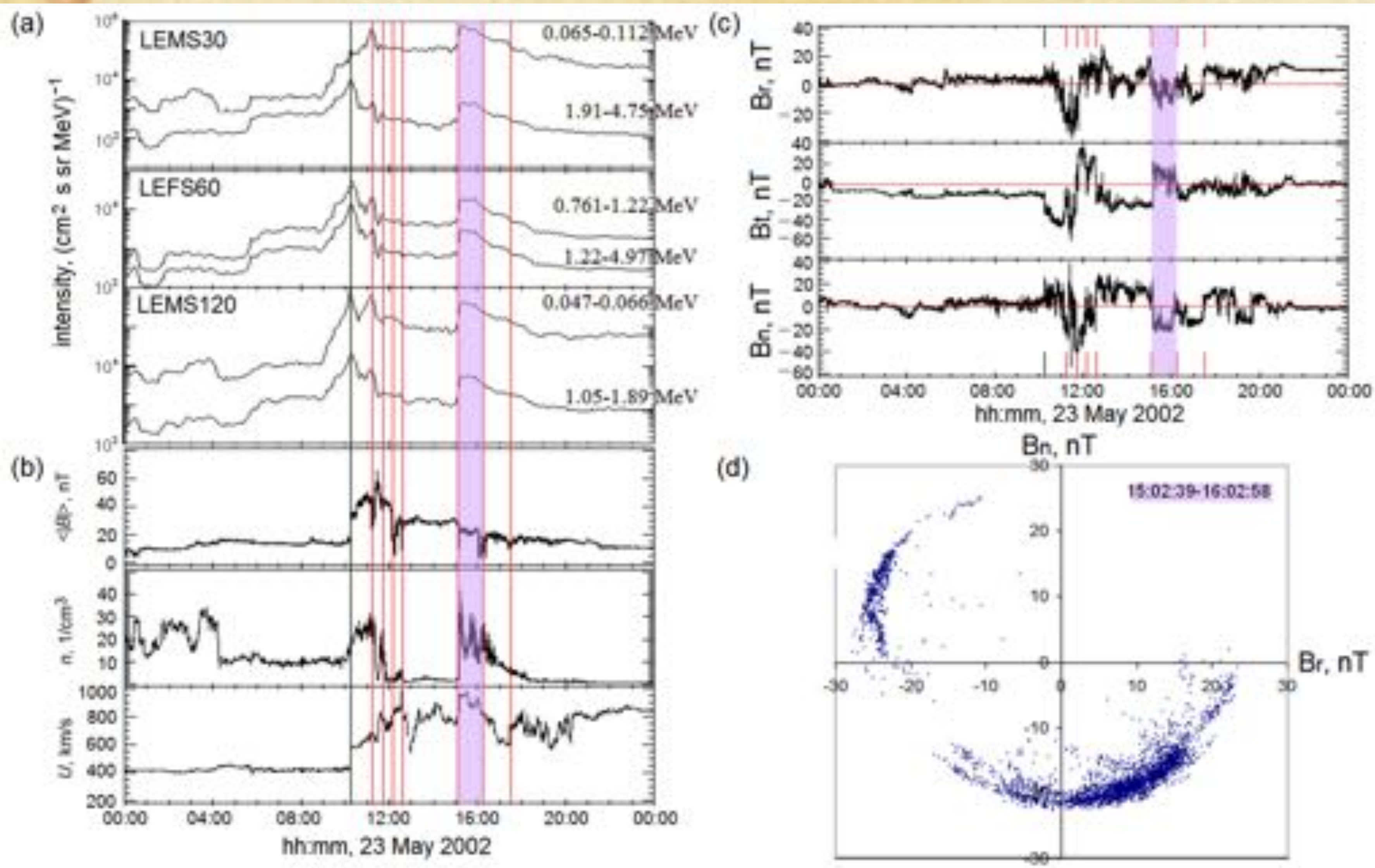
No	Event	Distance D from the main SB, km	Density, cm^{-3}	B_z, nT GSE
1	24-26 June 2004	$4.0 \cdot 10^6$	11	3.5
2	10-13 July 2010	$5.8 \cdot 10^7$	22	6.0
3	28-31 May 1995	$4.0 \cdot 10^7$	36	8.0



Polarisation electric field guides motion of ions and protons

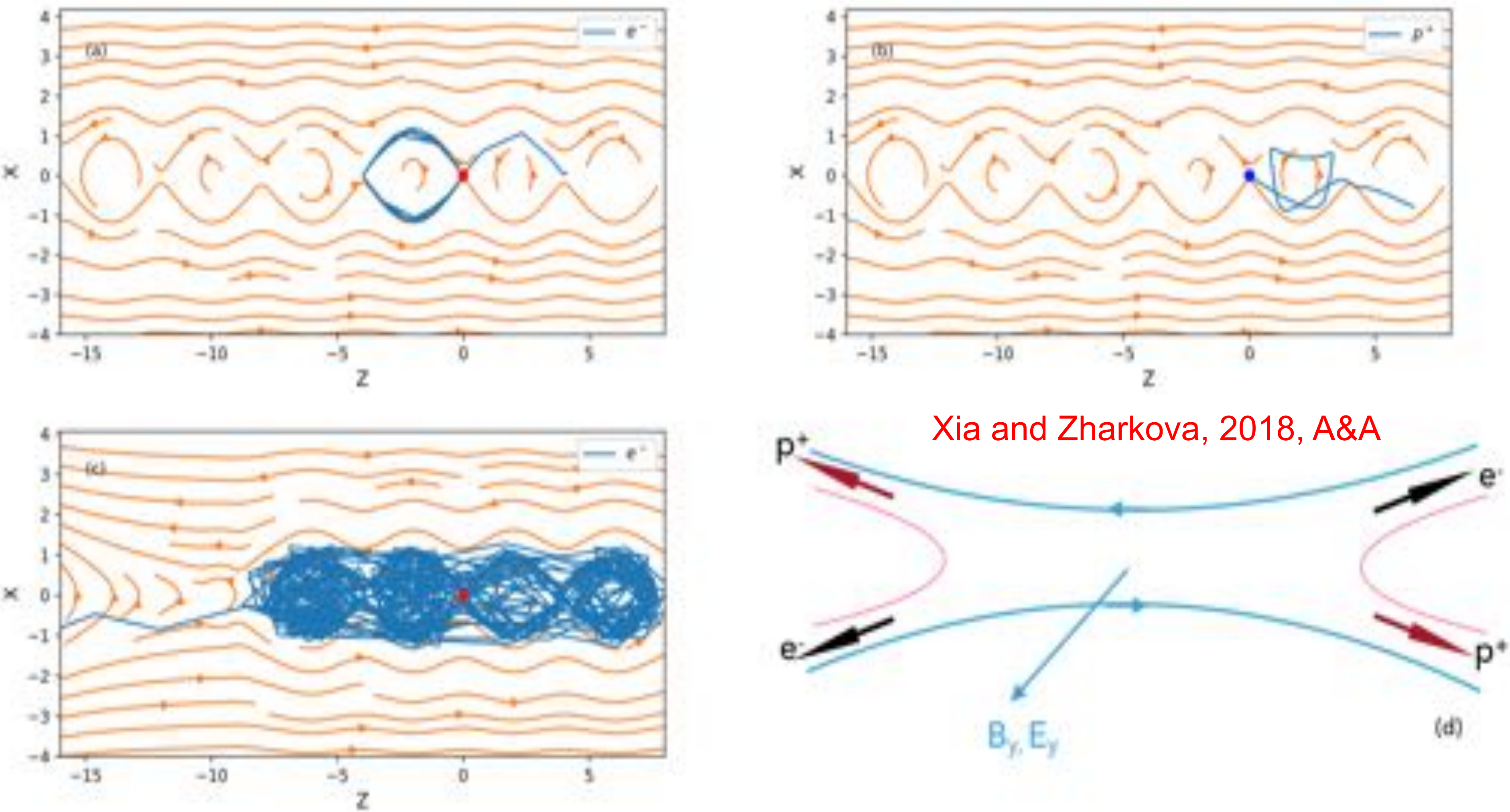


Future work: re-acceleration of particles in magnetic islands



Particle acceleration associated with islands near the HCS (after - ICME event)

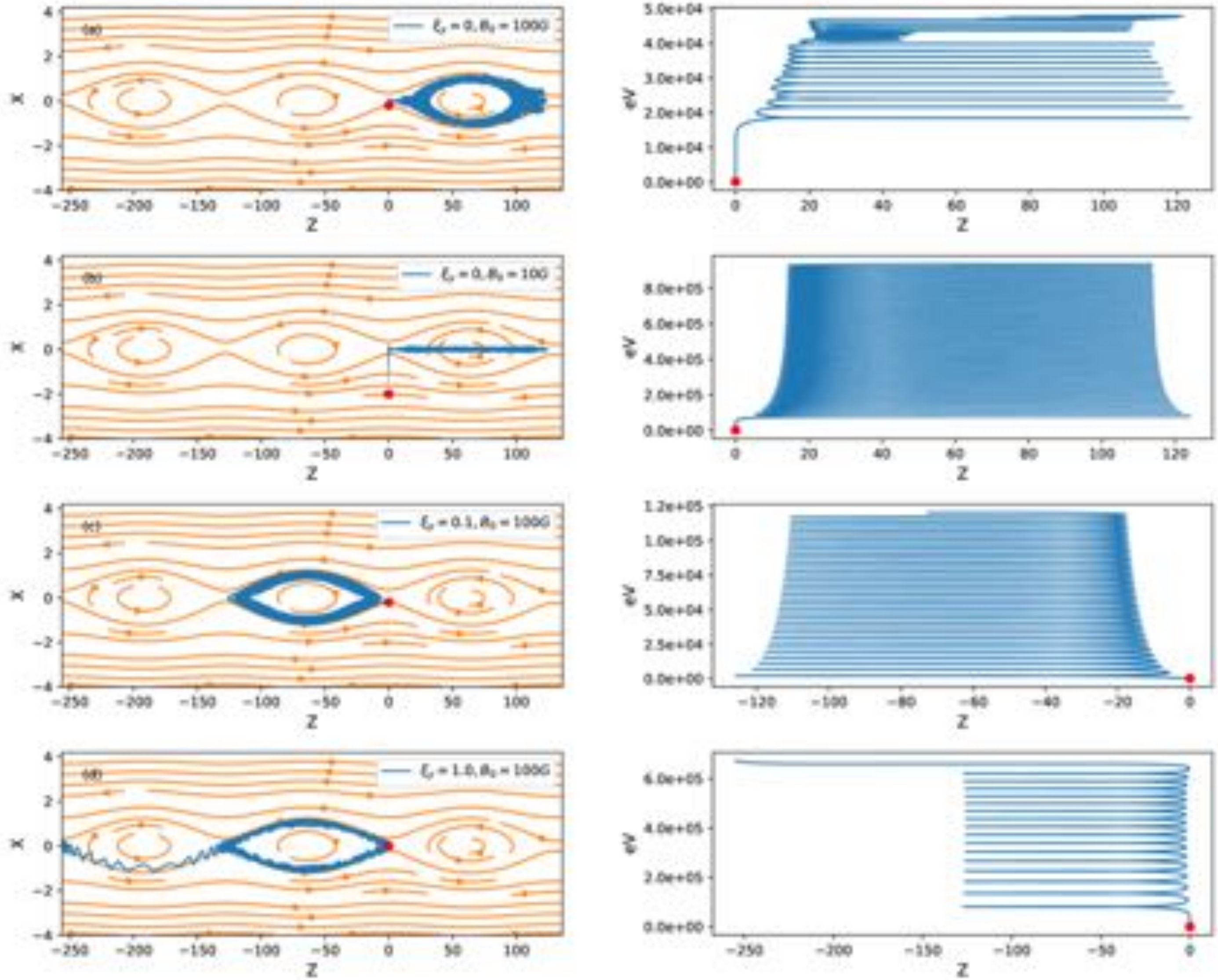
Khabarova, Zank, Li, le Roux, Webb, Dosch, ApJ 2015,



The trajectories of the electrons and protons in magnetic islands with different magnetic topologies. (c) has an open field topology at |z|>10.

The ejection directions of the particles are compared with the ones in a single X-nullpoint.

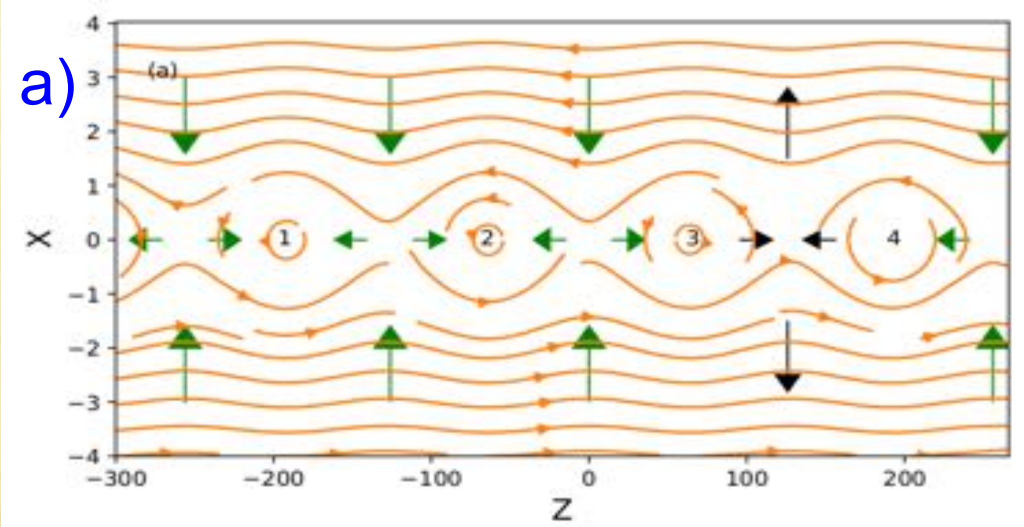
Xia and Zharkova, 2018, A&A



Left panels: test particle orbits (in blue lines); right panels: corresponding energy gains versus z-coordinate

Xia and Zharkova, 2018, A&A

a)

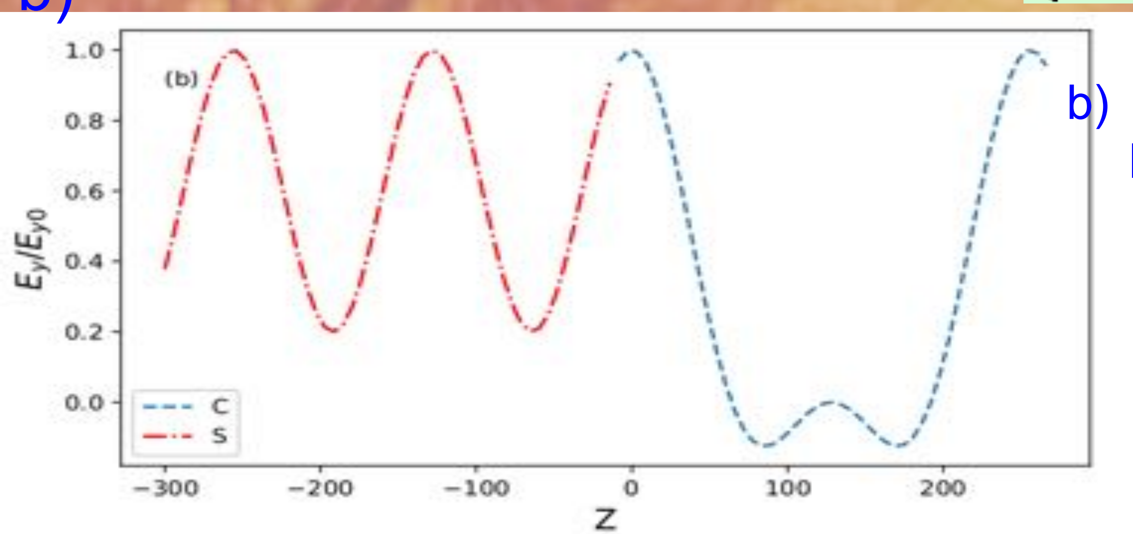


a) The plasma inflow (green arrows) and outflow (black arrows) directions in a coalescent magnetic island chain.

The solid orange lines show the magnetic field in the X−Z plane [Fadeev et al. 1965].

$$\begin{cases} B_z = -\frac{\sinh(x/d)}{\cosh(x/d)+\epsilon\cos(kz/d)} B_0, \\ B_x = -\frac{\epsilon\sin(kz/d)}{\cosh(x/d)+\epsilon\cos(kz/d)} B_0, \end{cases}$$

b)



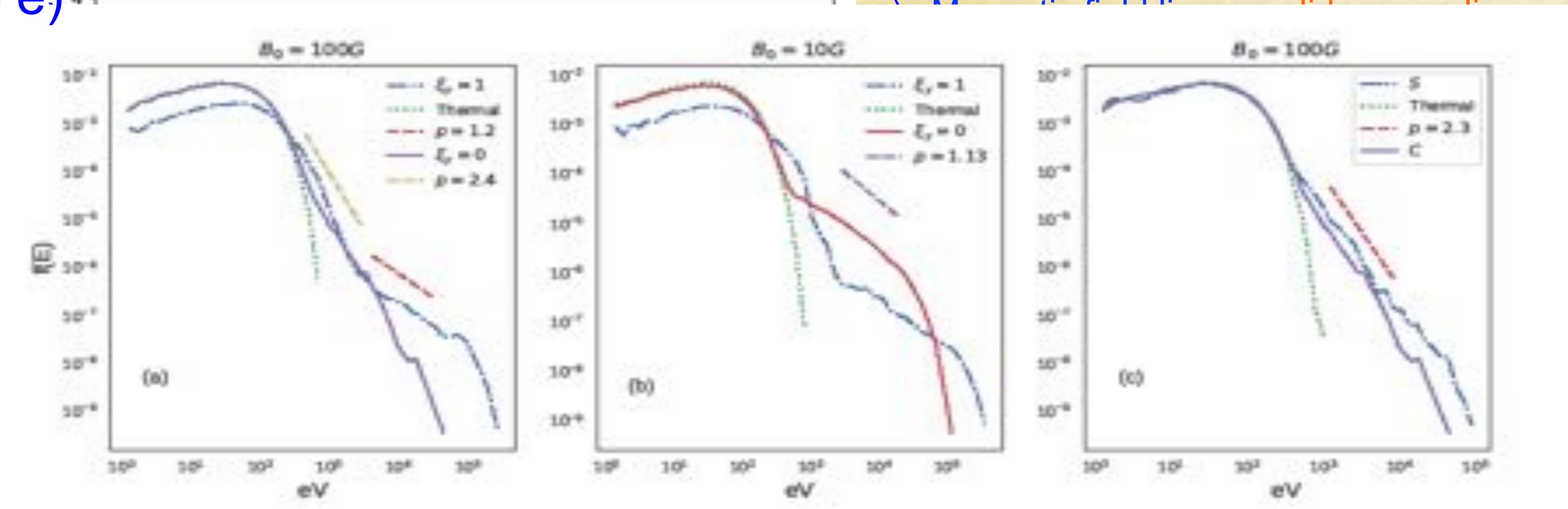
b) The blue dash line and red dash-dot line show the E_y from coalescent and squashed islands on the midplane.

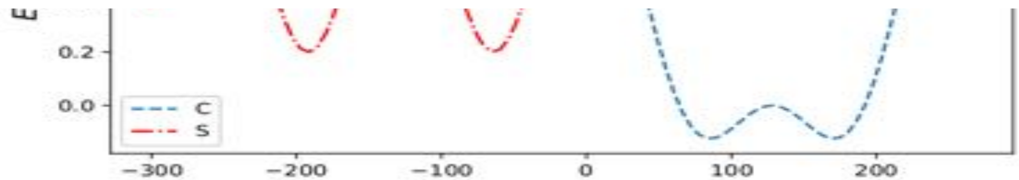
$$C: E_y = E_{y0}\cos(\frac{kz}{2d})\cos^2(\frac{kz}{4d}),$$

$$S: E_y = E_{y0}[0.6 + 0.4\cos(z/d)],$$

Particle acceleration in magnetic islands -TP, Xia&Zharkova, 2018, A&A

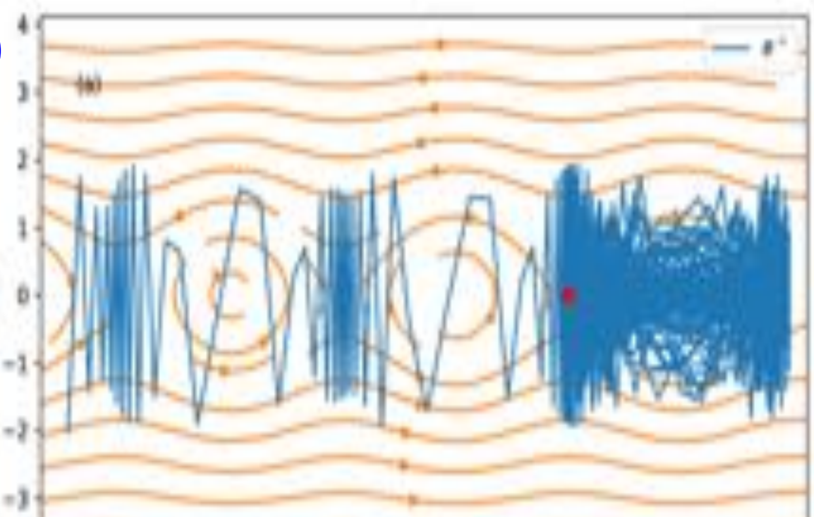
e)

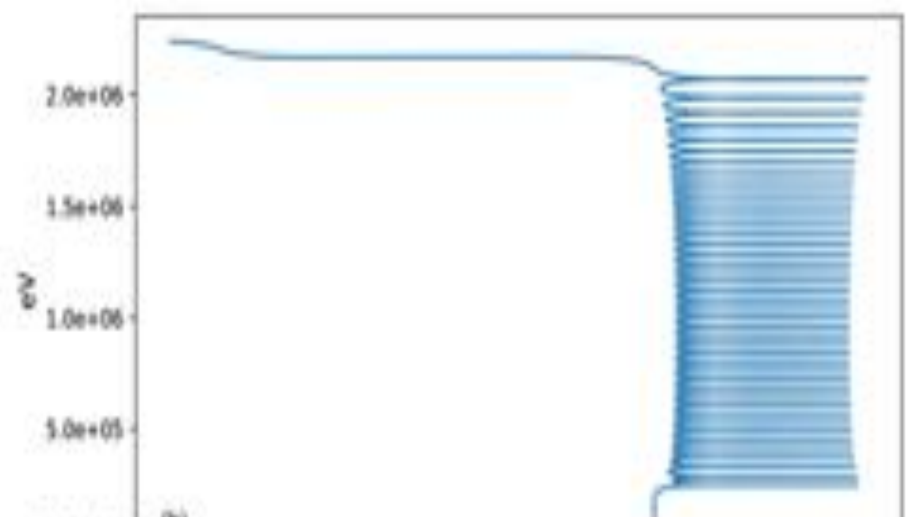




d) Electrons can be accelerated in single island to relativistic energies, they circle about and are ejected from X – nullpoints

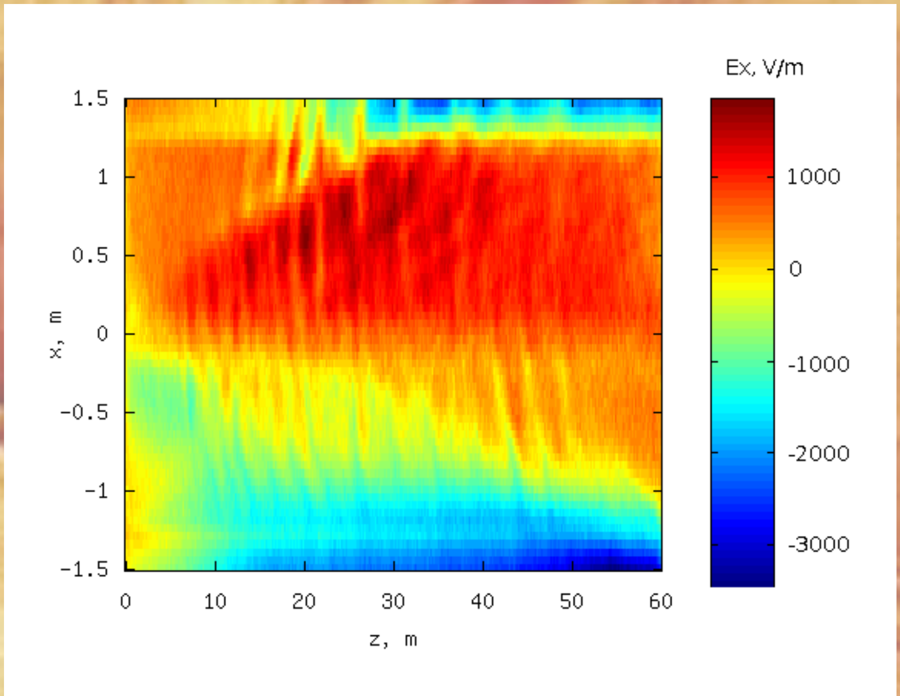
d)



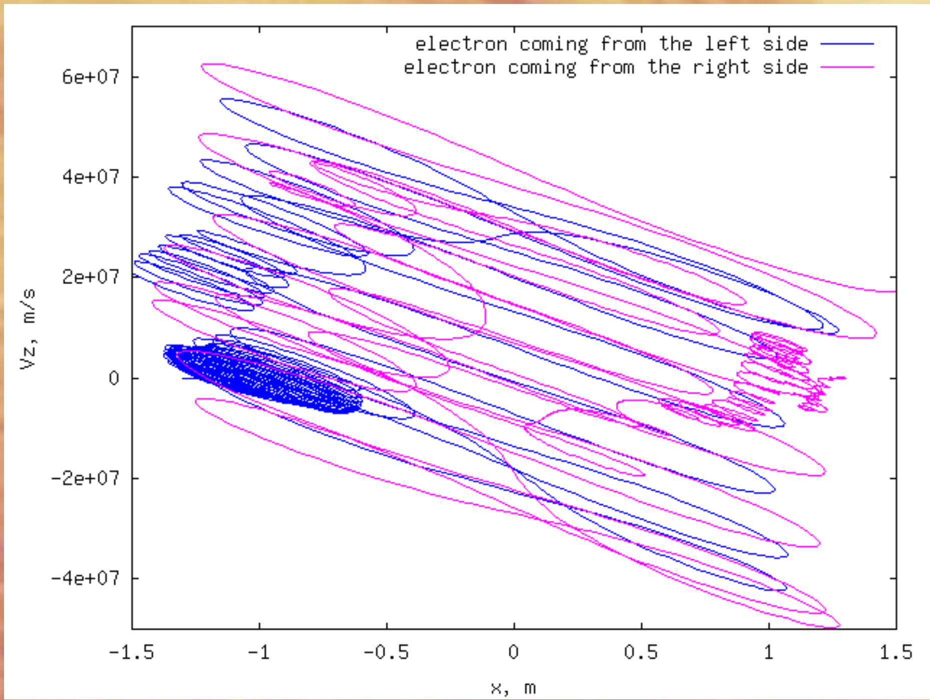


PIC – turbulence generation
(see the talks before and after)

Induced electric field E_x



Test particle trajectories in this field



Conclusions

- Acceleration of particles in 3D current sheets (either with single X or multiple X- and O-nullpoints) strongly depends on a magnetic field topology
- For strong guiding field it leads to separation of electrons from protons with respect to the midplane (corona, or sector boundary – SB in the HCS)
- This separation leads to formation of polarisation of electric field across current sheet 2 orders of magnitude larger than reconnection electric field
- Magnetic field imposes different pitch-angle distributions and energy spectra of particles entering a current sheet from the opposite (transit) and the same side (bounced).
- Proton beams are often ejected well directed at 30-40^o to the Bz while electrons have wider pitch angle distributions
- 3D RCSs with multiple O-nullpoints (magnetic islands still reveals the separation of electrons from protons to the opposite semiplanes of X.
- In some conditions electronsprior ejection are accelerated to subrelativistic energies in a single magnetic island, in other they pass through a few islands while forming clouds about neighbouring X-nullpoints.
- Particle energy gains in coalescent islands are lower than in squashed ones; the higher is squashed island aspect ratio the higher is gained energy.
- Proton and electrons accelerated in islands still have populations of transit and bounced particles leading to two beam instabilities often reported in observations and PIC models