Additional acceleration of solar wind particles in the heliosphere and diagnostics from space observations

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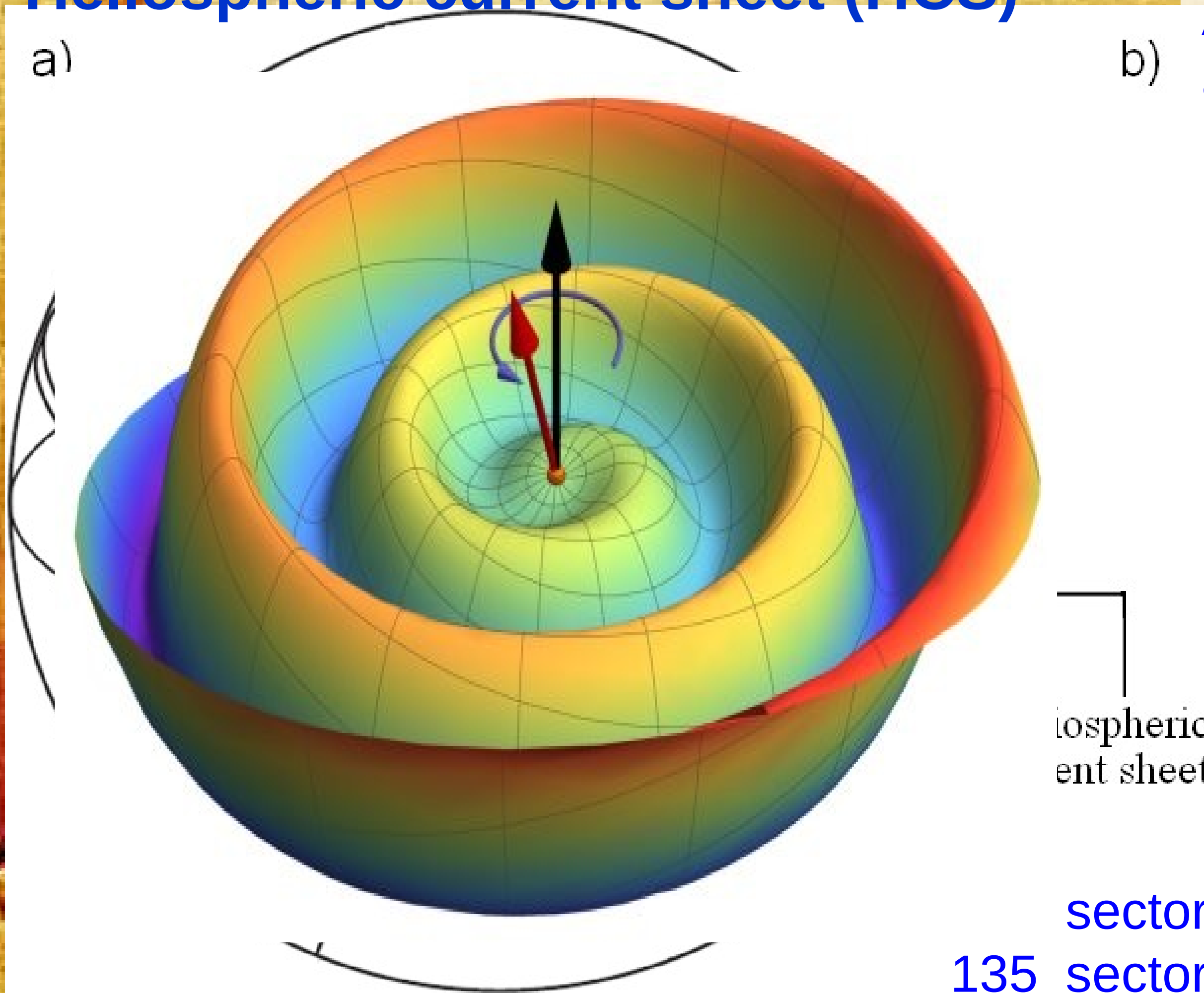
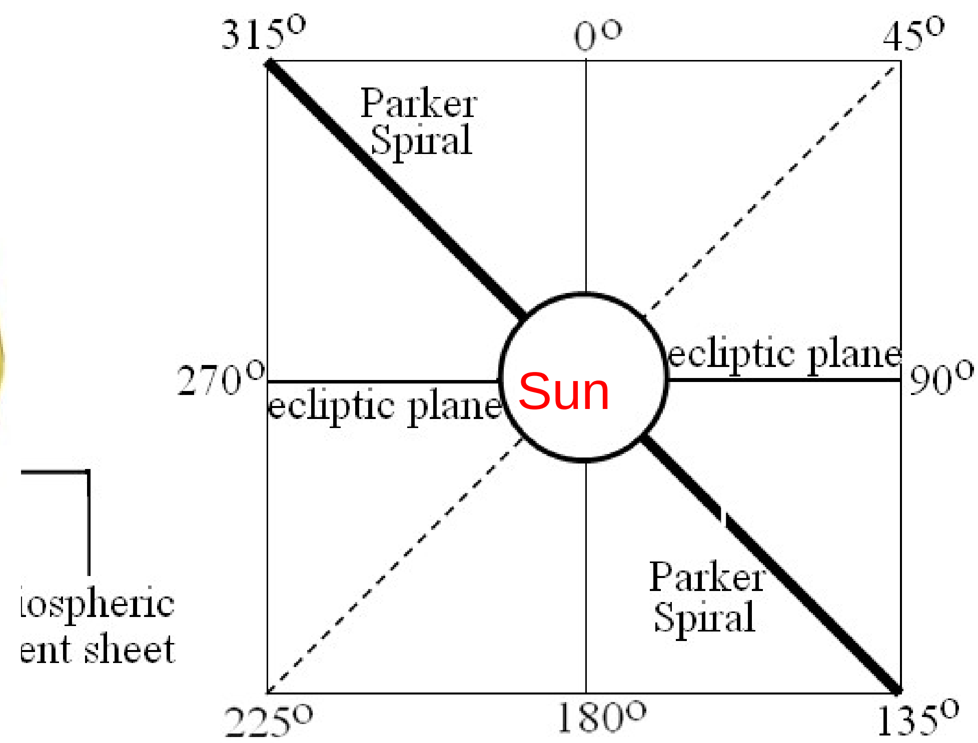
Problems in identification of sector boundaries

Heliospheric current sheet (HCS)



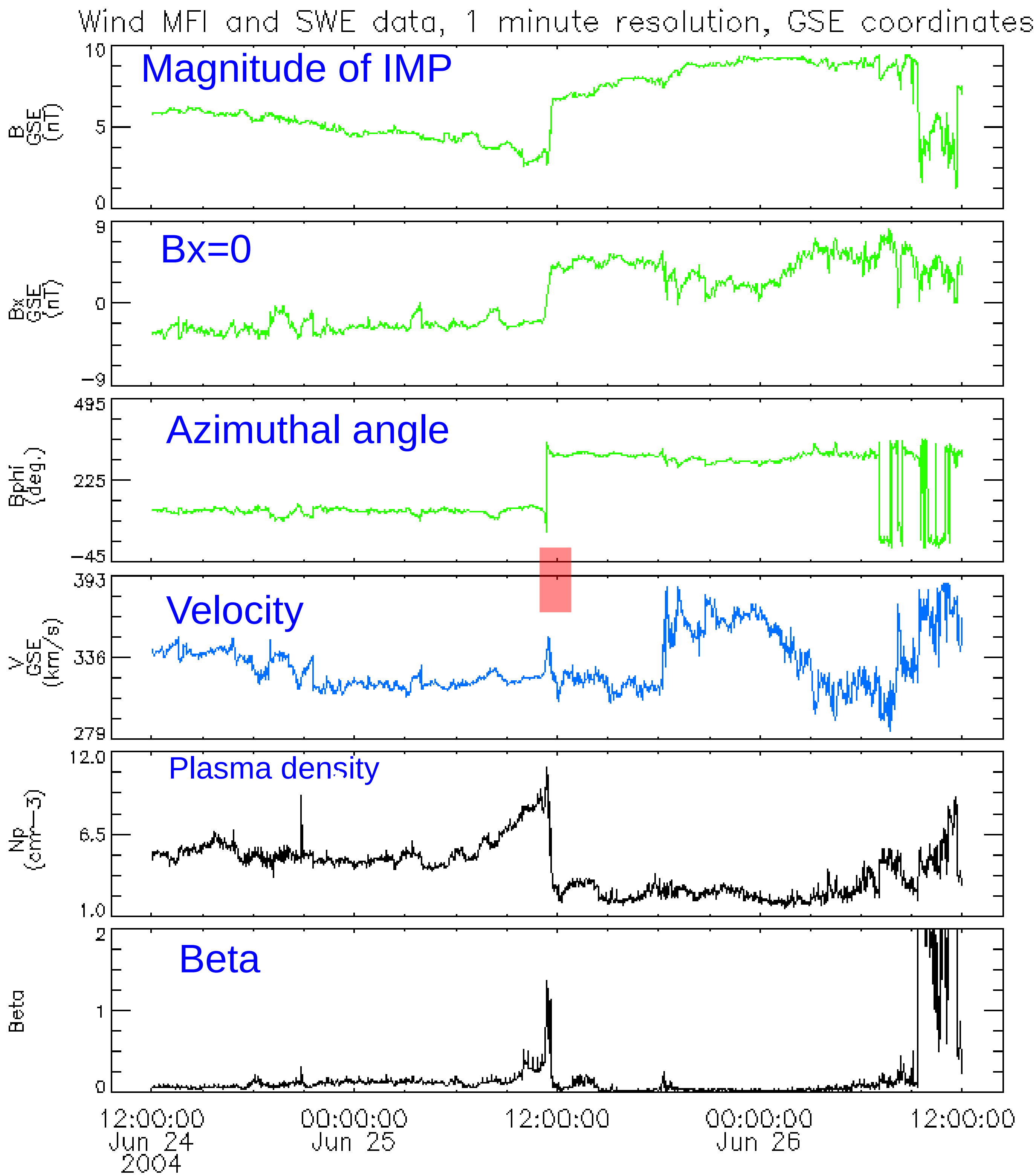
Azimuthal angle of magnetic field at 1 a.e. - B



sector – toward the Sun

135 sector – outward the Sun

- **Using B (if crosses 45 or 225 - change of IMP from or to the Sun).**
- Using components of IMP
- Using change of direction of electron propagation



IMP magnitude sharply drops or increases

Horizontal component(Bx, GSE) = 0 nT;

Azimuthal angle (φ_B) changes by180 ;

Problem 3 –ion velocity profile is asymmetric over the HCS

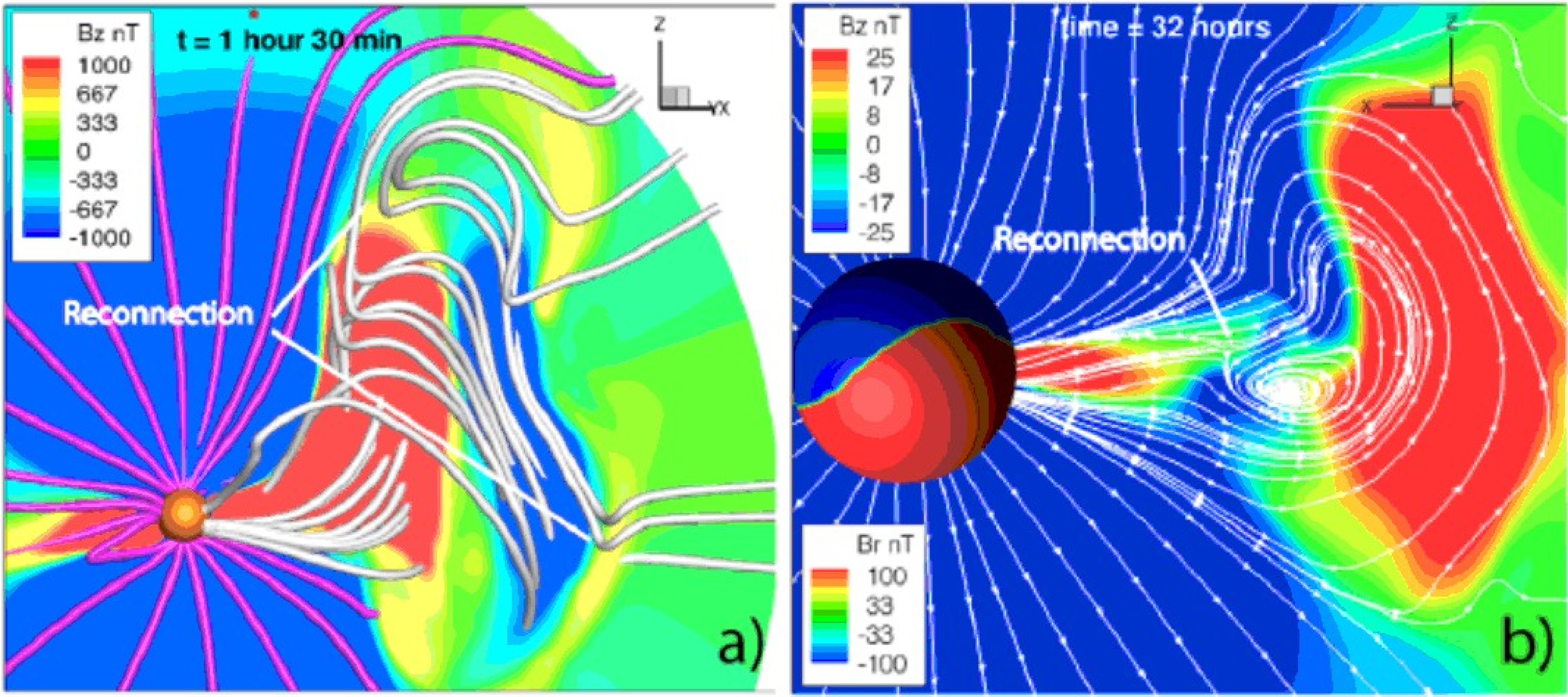
Problem 4 -Density is sharply increased about the HCS

Beta is also sharply increased

Zharkova and Khabarova, 2012, ApJ

ICME current sheets

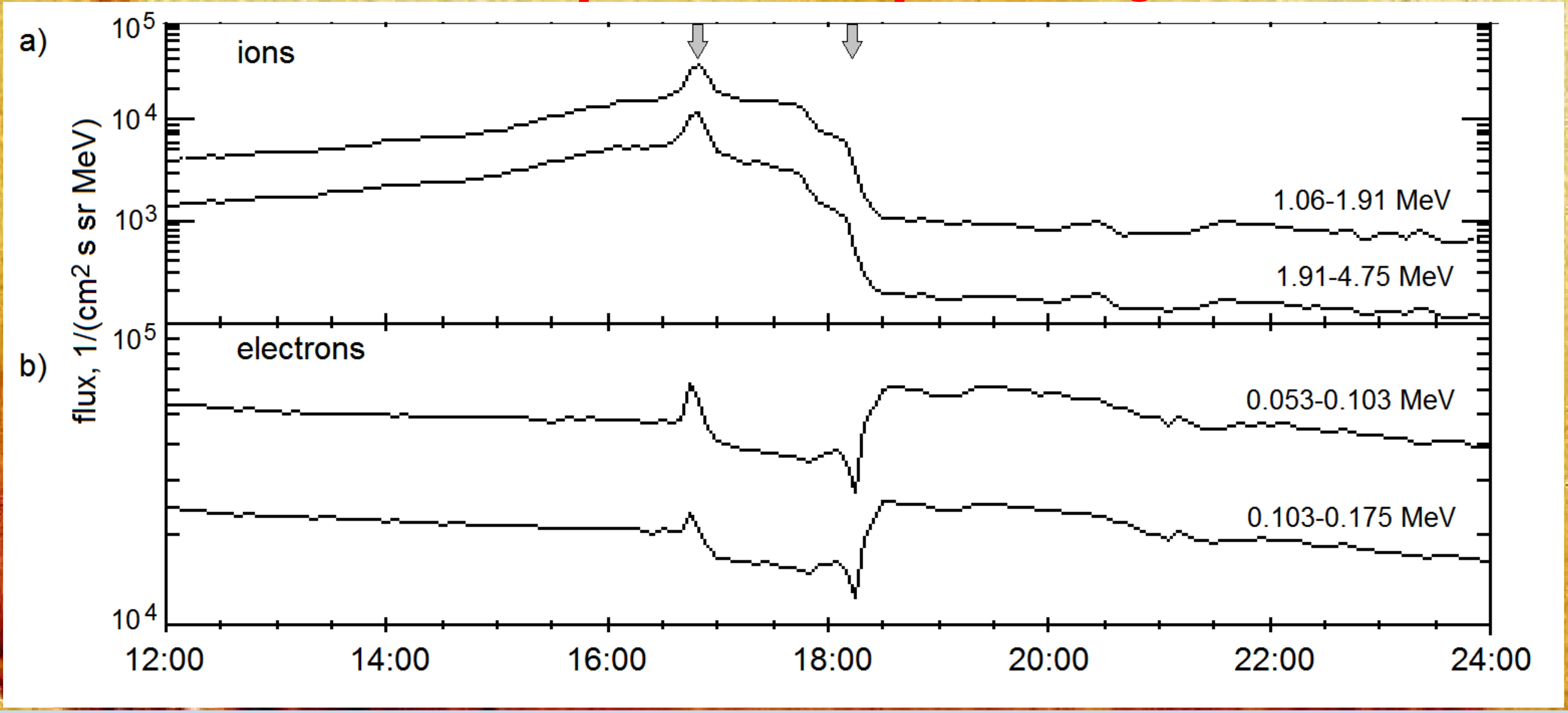
W B Manchester IV *et al* Plasma Phys. Control. Fusion 56 (2014)



Magnetic reconnection

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

Solar wind particles passing ICME



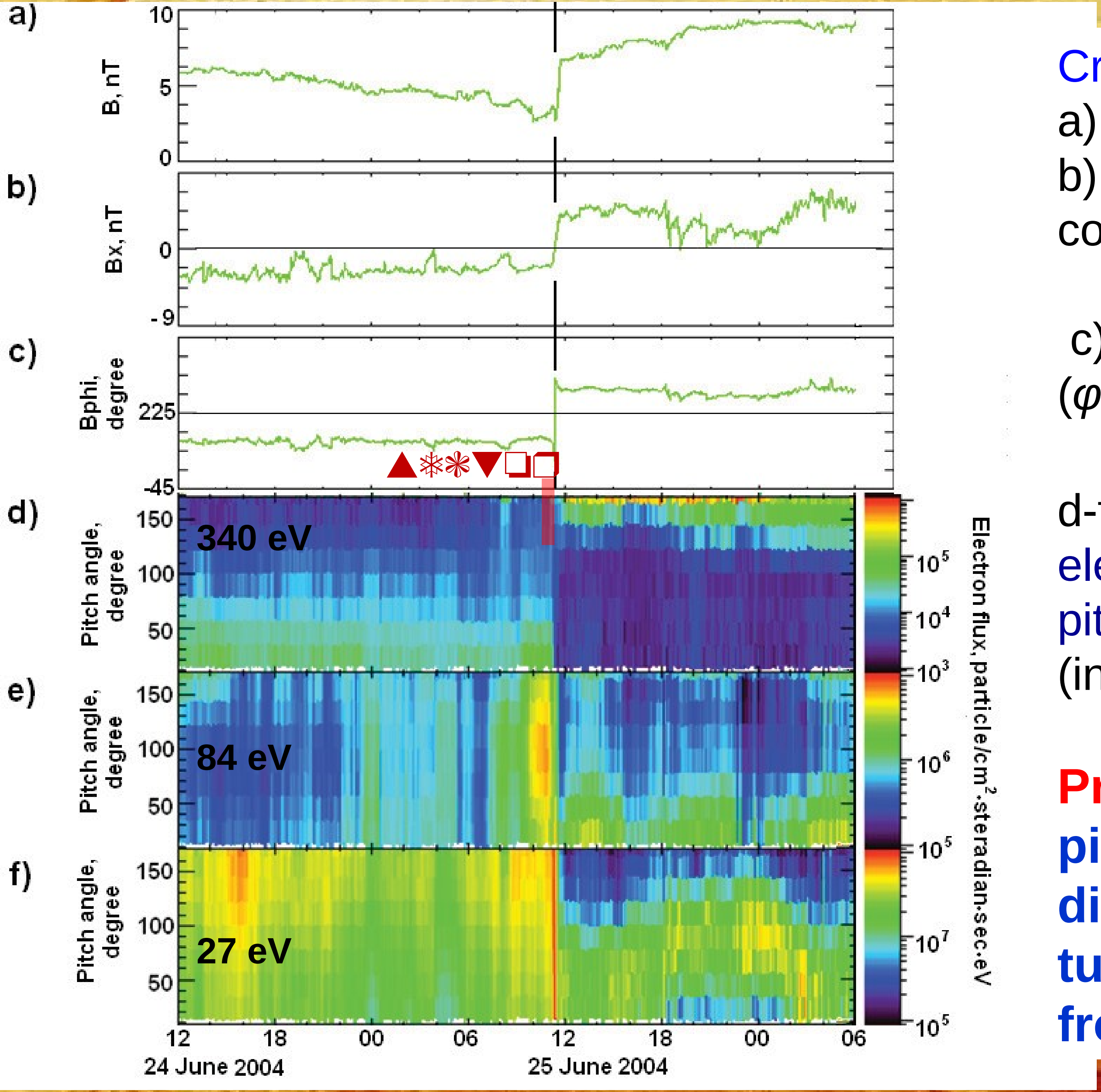
<u>Problems with particles in the interplanetary magnetic field</u>

<u>Problem 1:</u> What makes particles to move perpendicular to the IMF in a vicinity of ICME

<u>Problem 2 :</u> 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?

Problems in identification of sector boundaries

Zharkova&Khabarova, 2012 https://iopscience.iop.org/article/10.1088/0004-637X/752/1/35/pdf



Crossing of a thin SB:

a) IMP magnitude;

b) IMP horizontal component (Bx, GSE);

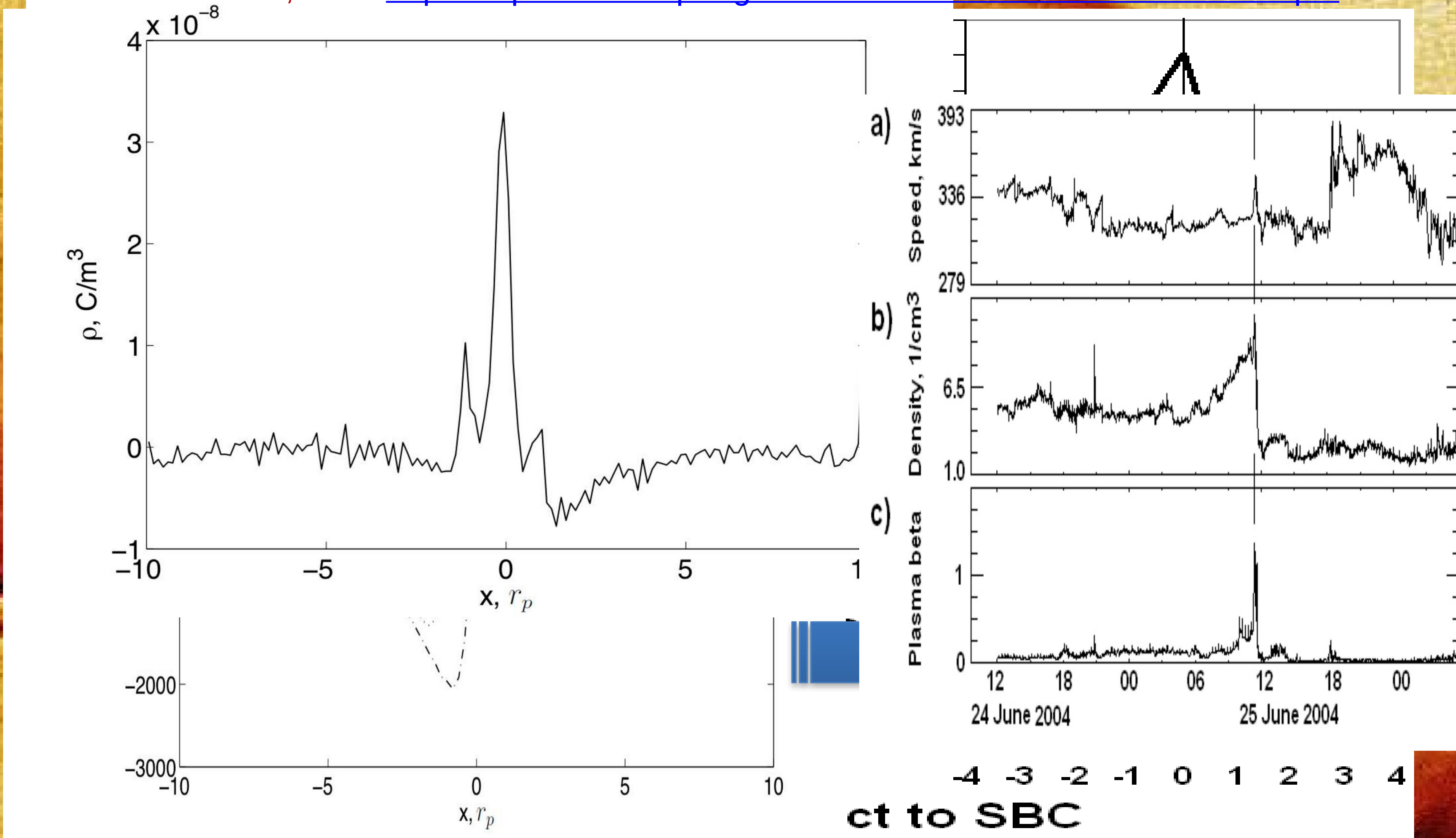
c) IMP azimuthal angle (φ_B);

d-f) Spectrograms of electron distribution in pitch angles (in 3 energy channels)

Problem 3– Electron pitch angle distribution with turning point far away from HCS

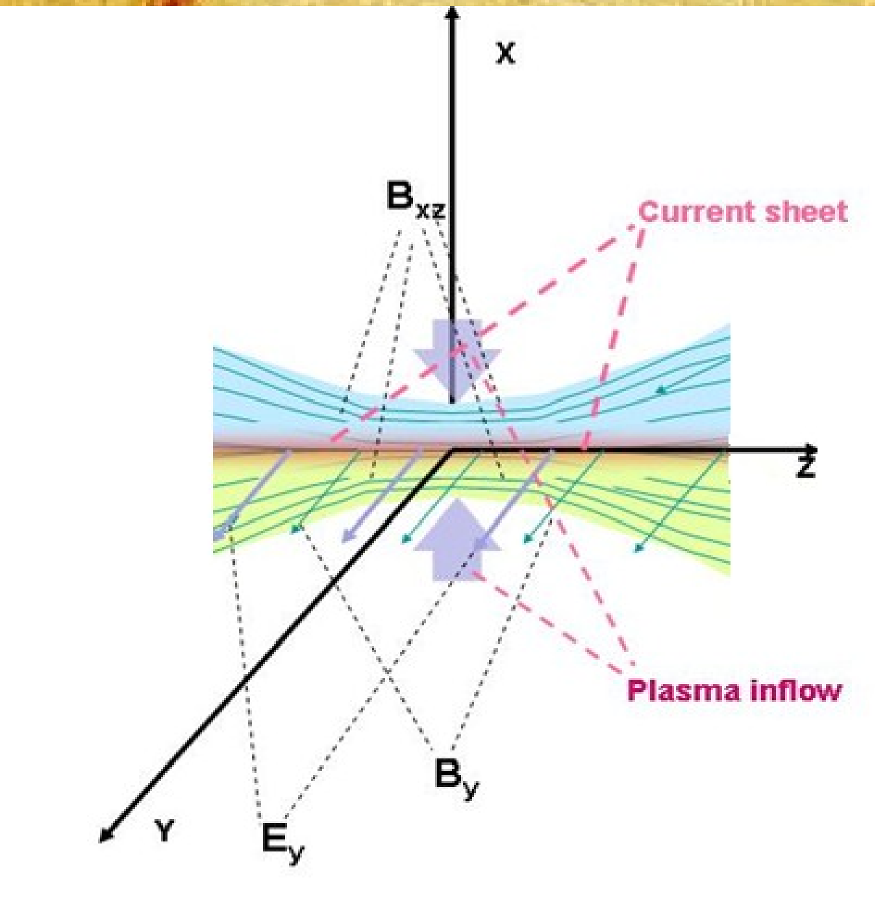
Averaged SB observations

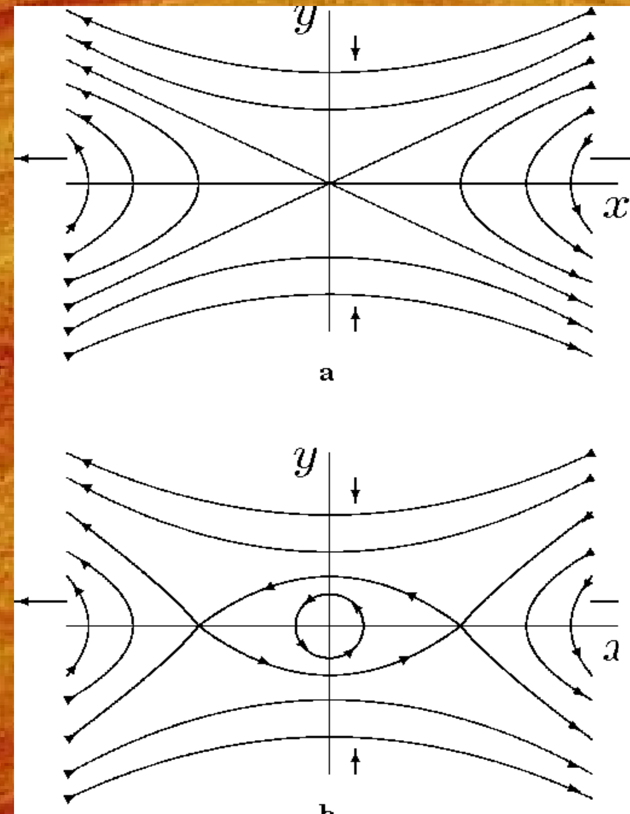
Zharkova&Khabarova, 2012 https://iopscience.iop.org/article/10.1088/0004-637X/752/1/35/pdf



Problem 4– Ion densities about the SB – sharp peak and two smaller peaks

Problem 5 – unusual Ion velocities across SB





A single X-null

O-type
(magnetic island)

Verboncoeur, et al 1995 – 2.5D XOOPIC
Bower et al, 2008 – 3D VPIC

Siversky and Zharkova, 2009, JPP, 75,
Zharkova and Khabarova, 2012, ApJ, 752, 35;
2015, Ann Geo, 33, 457;
Khabarova et al, 2020, ApJL, 894, L12
Xia and Zharkova, 2018, 2020, 2021a,b, A&A, Frontier

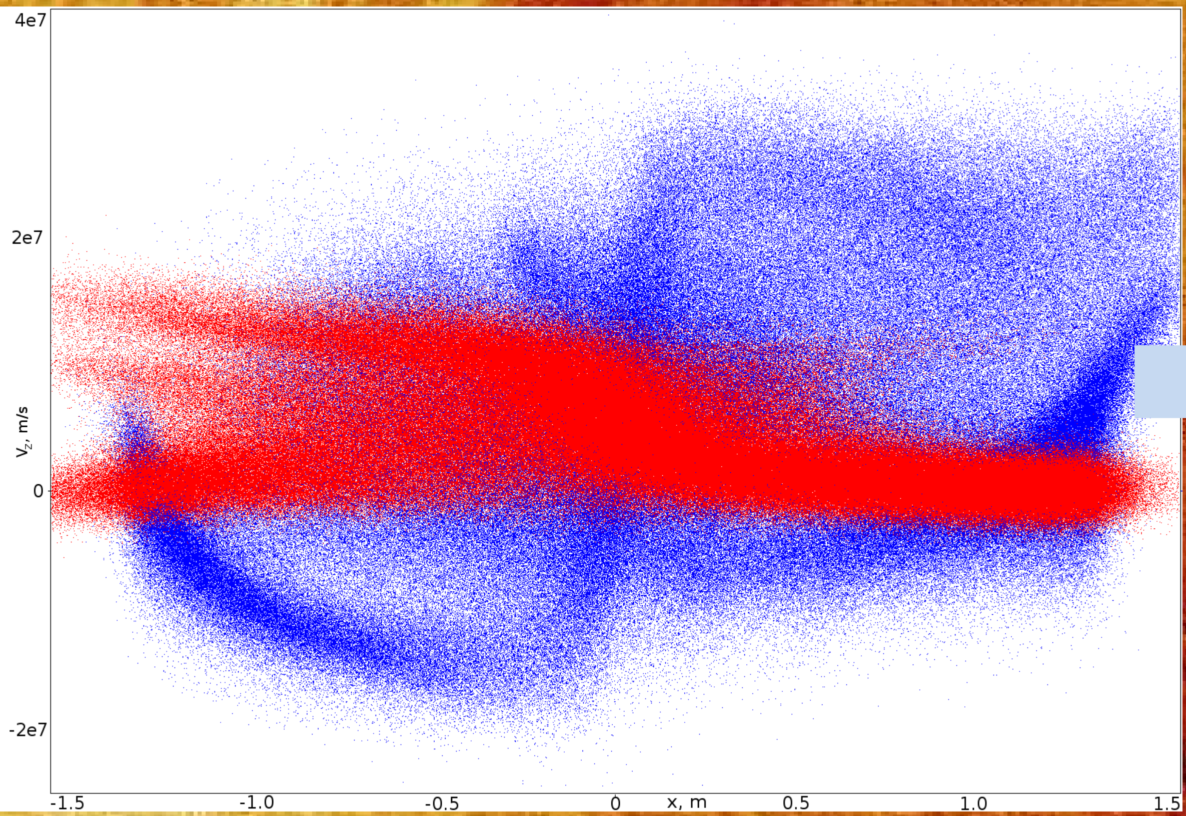
PIC – velocity/energy and PADs

$$B_0 = 10\text{G} \qquad B_y = 1\text{G}$$

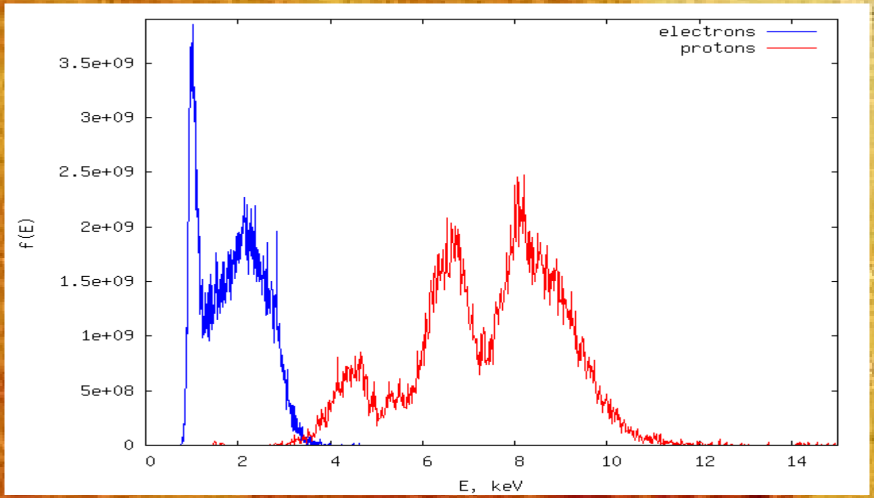
$$B_x = 0.4\text{G} \qquad \frac{m_p}{m_e} = 10$$

$$n = 10^6 \text{cm}^{-3}$$

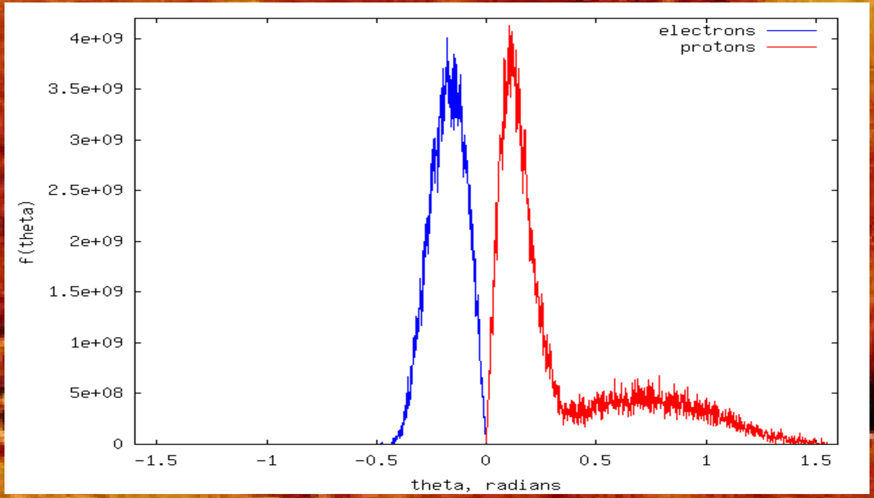
x-V_z phase space



Energy distributions

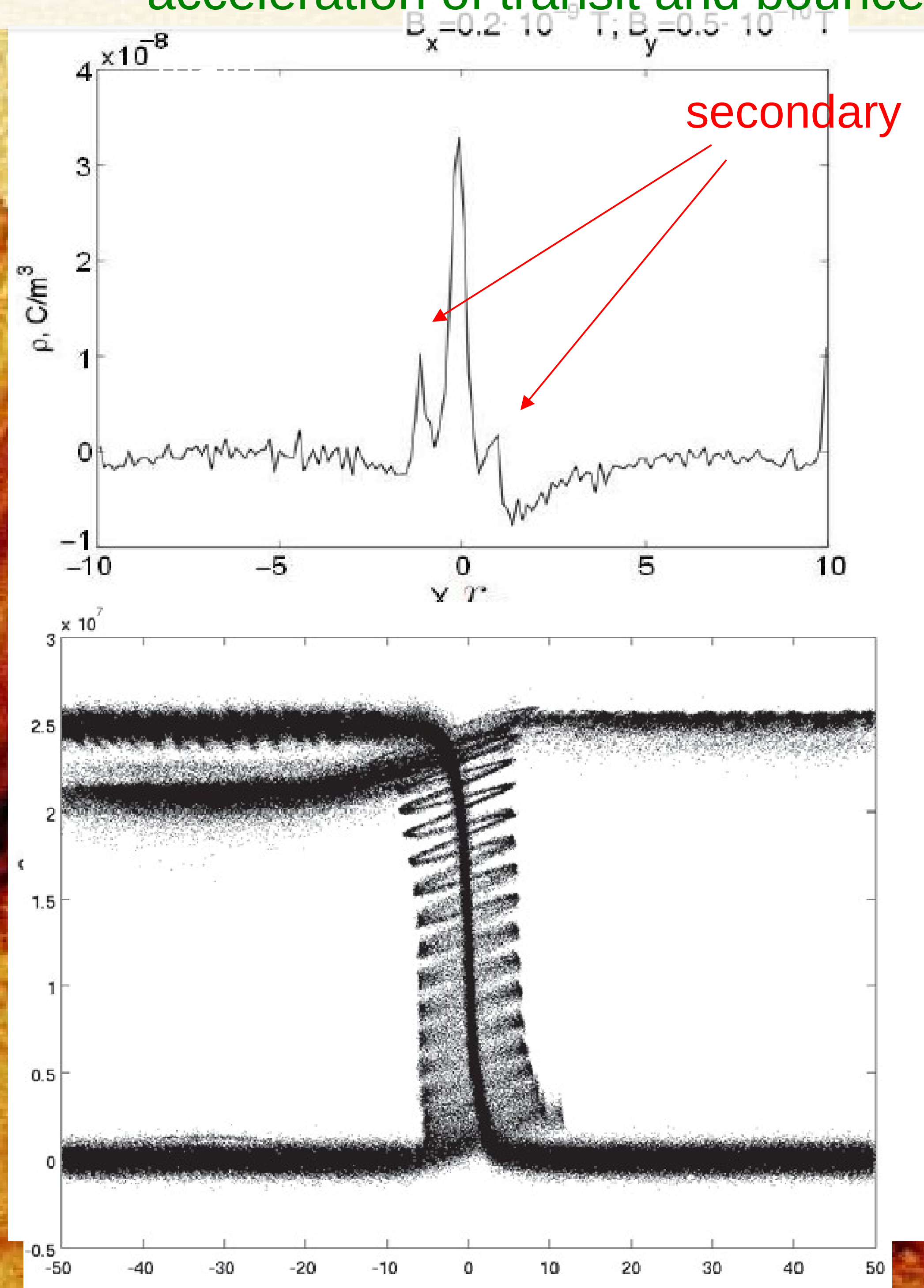


Pitch angle distributions

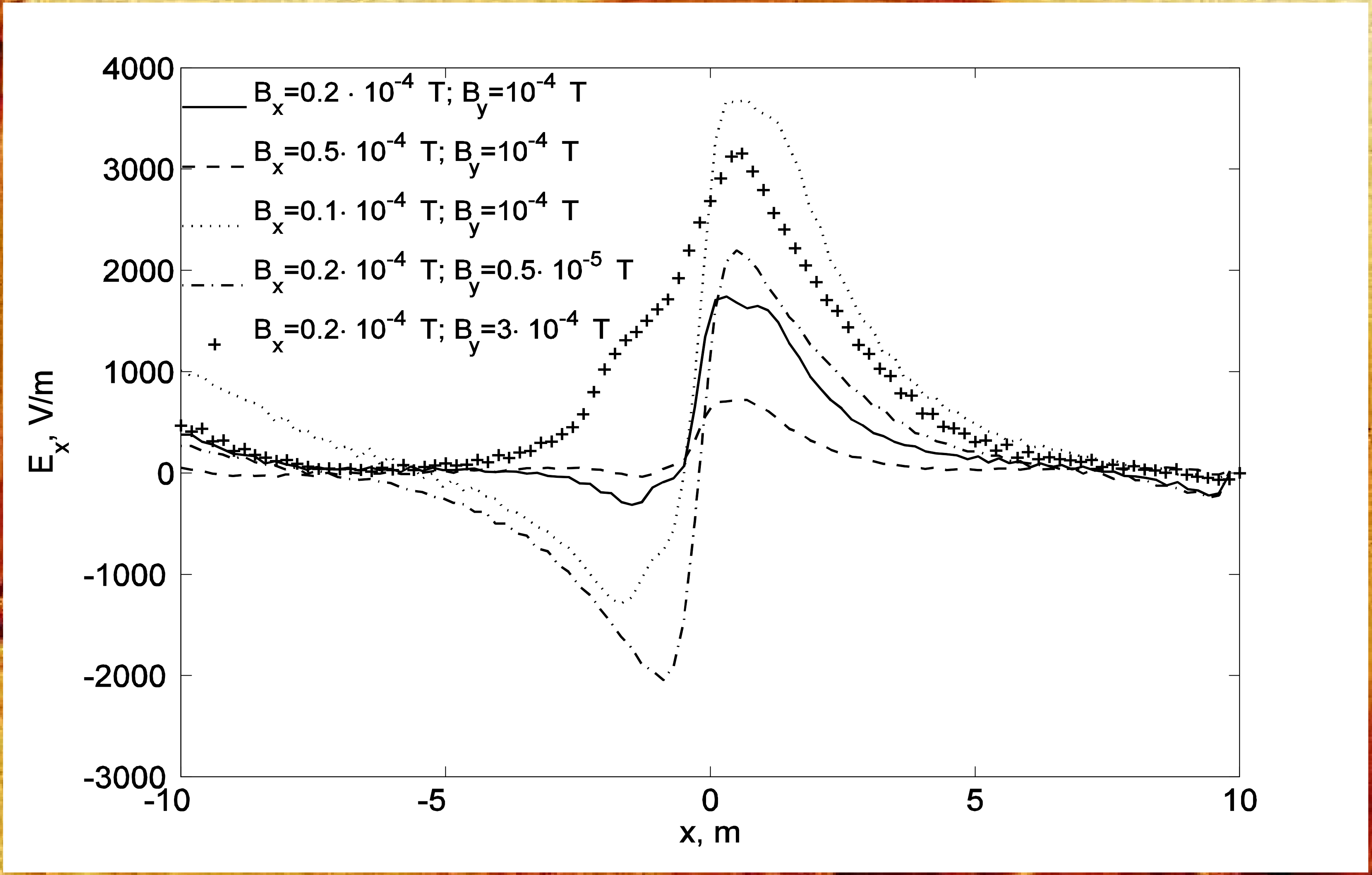


Siversky & Zharkova, 2009, JPP, 75

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

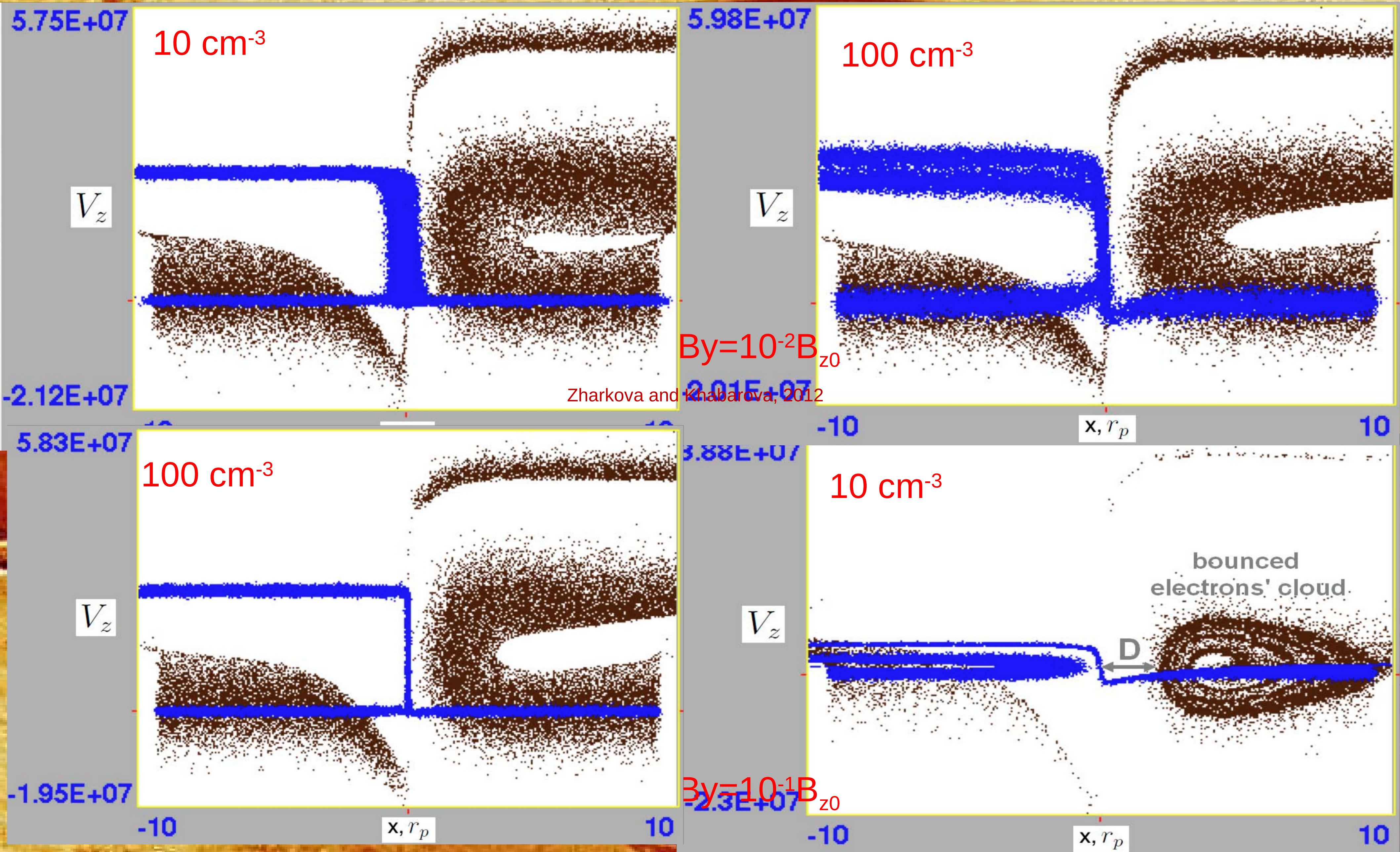


Polarization electric field E_x across a current sheet



plasma density n=10-100 cm^{-3}

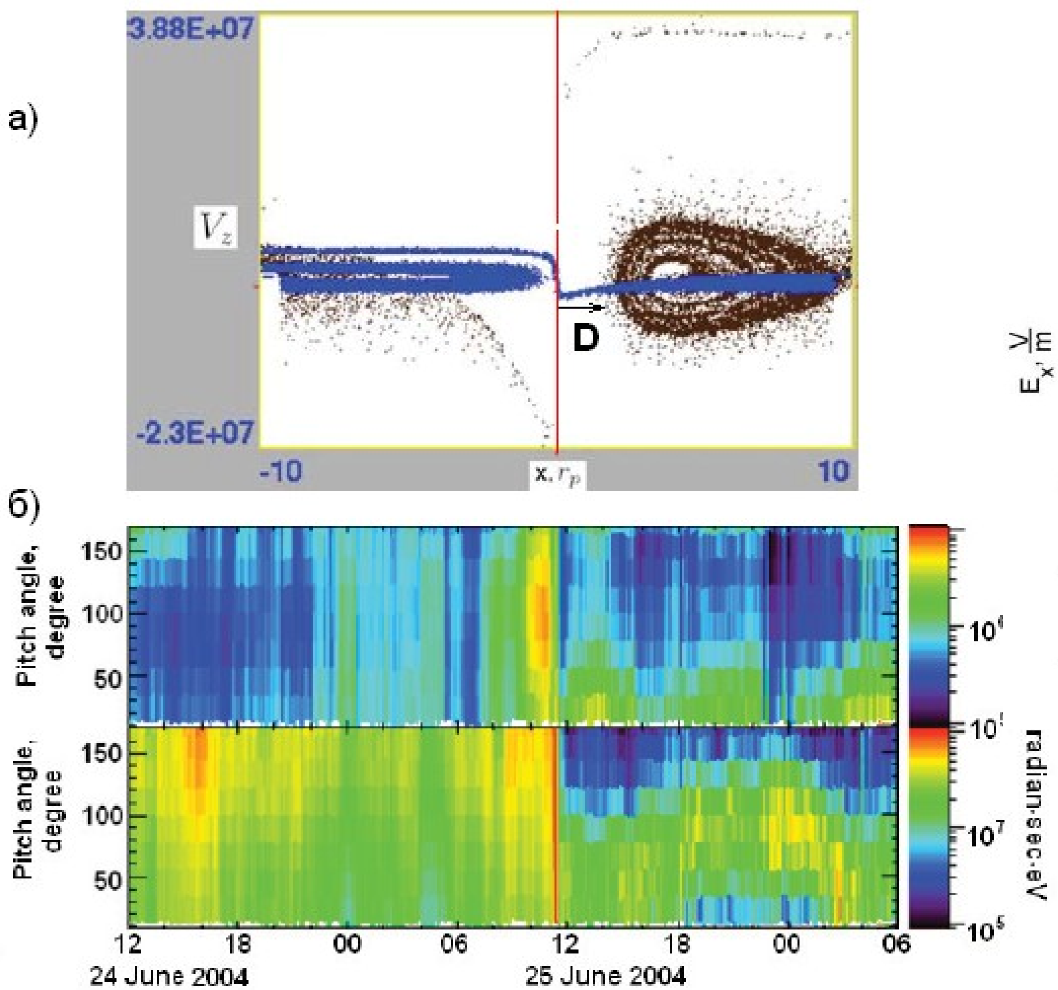
Zharkova&Khabarova, 2012 https://iopscience.iop.org/article/10.1088/0004-637X/752/1/35/pdf

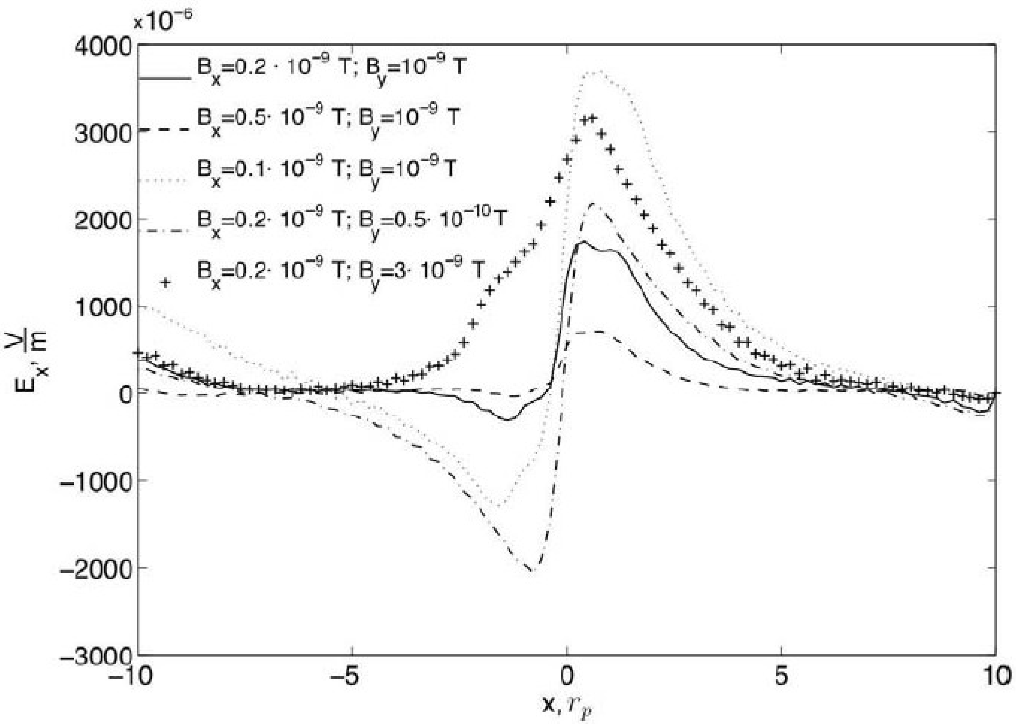


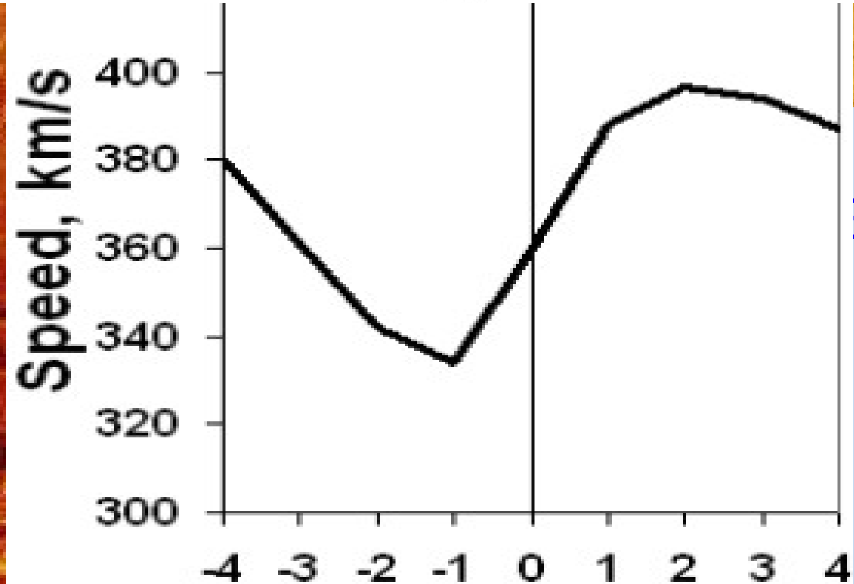
Blue - -protons, black –electrons: h/shoe like –bounced lower energy e top – transit high energy e

Heliospheric current sheet

Zharkova&Khabarova, 2012 https://iopscience.iop.org/article/10.1088/0004-637X/752/1/35/pdf





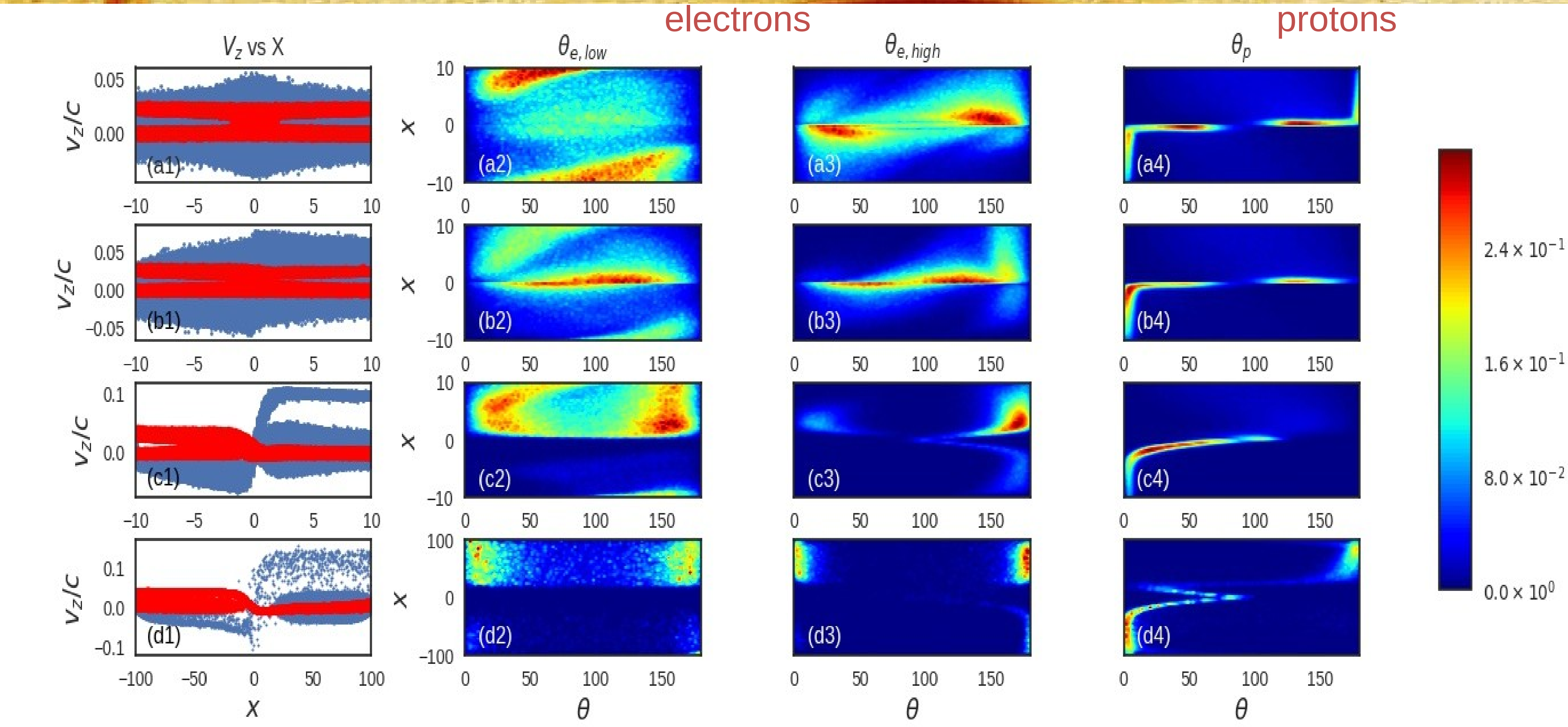


T. Siversky, V.Zharkova, 2009, JPP, 75, 5

V. Zharkova et al, 2011, SSRv, 157, 359

V.Zharkova, O. Khabarova,2012, ApJ, 752, 35

Magnetic topology effects on particle energy and pitch angle distributions (XZ2020)

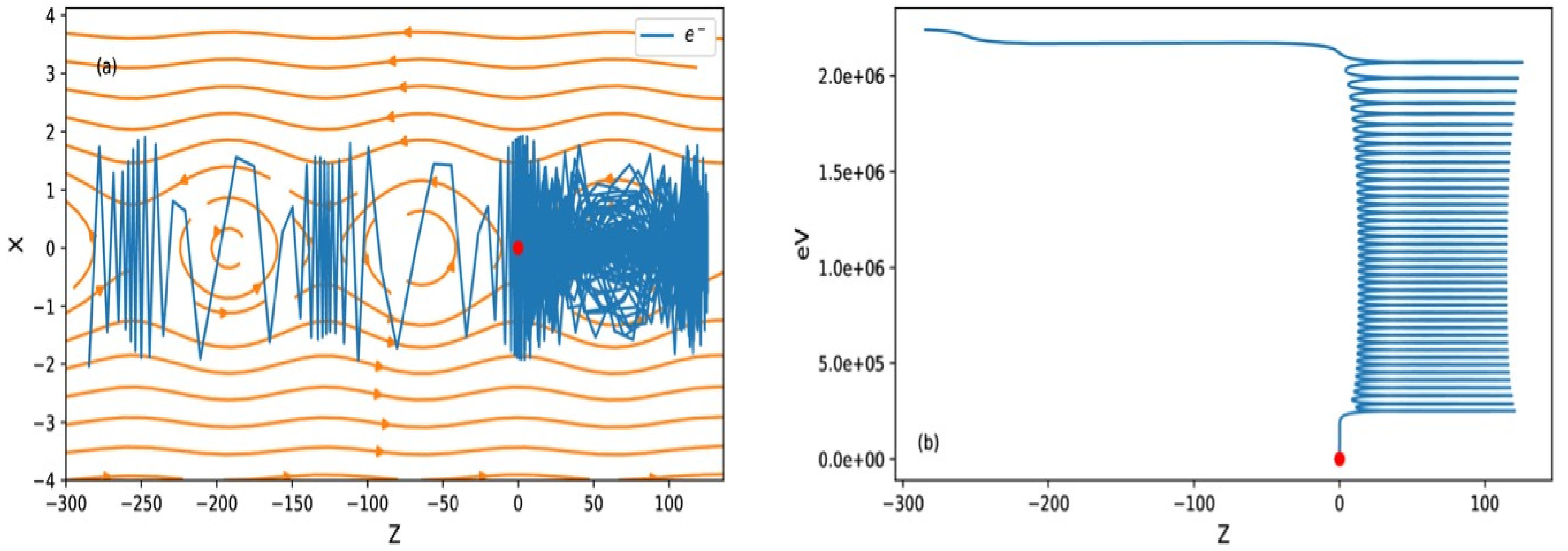


By/B0 = 0 (a-first row), 0.1(b-second row), 1.0 (c-third row), and 1.0 with d = 10 m (d-fourth row)

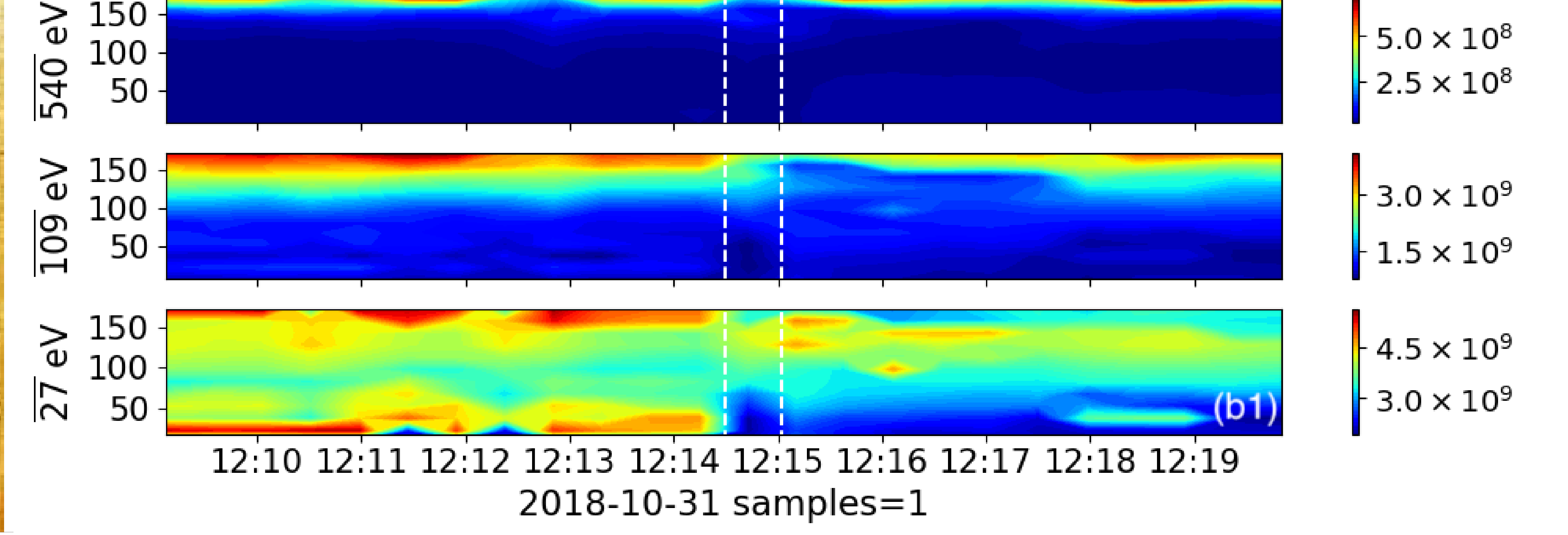
$B_0 = 10^{-3}$ T, $E_{y,0} = 250$ V/m

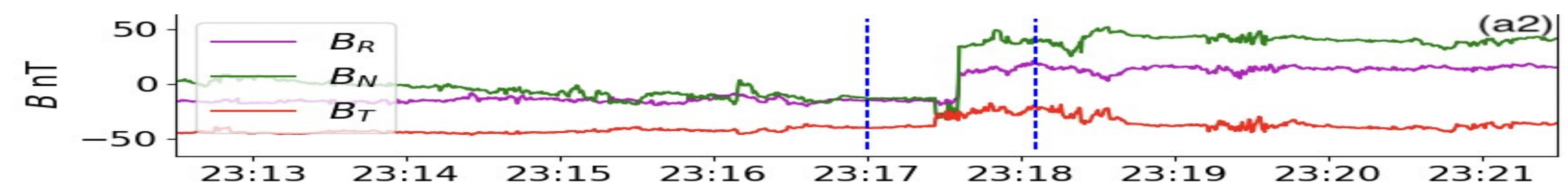
1. Asymmetric ejection with respect to the current sheet midplane in a strong guiding field– separation of electrons from protons
2. Particle of the same charge – transit and bounced particles - with different energies and pitch-angle distributions

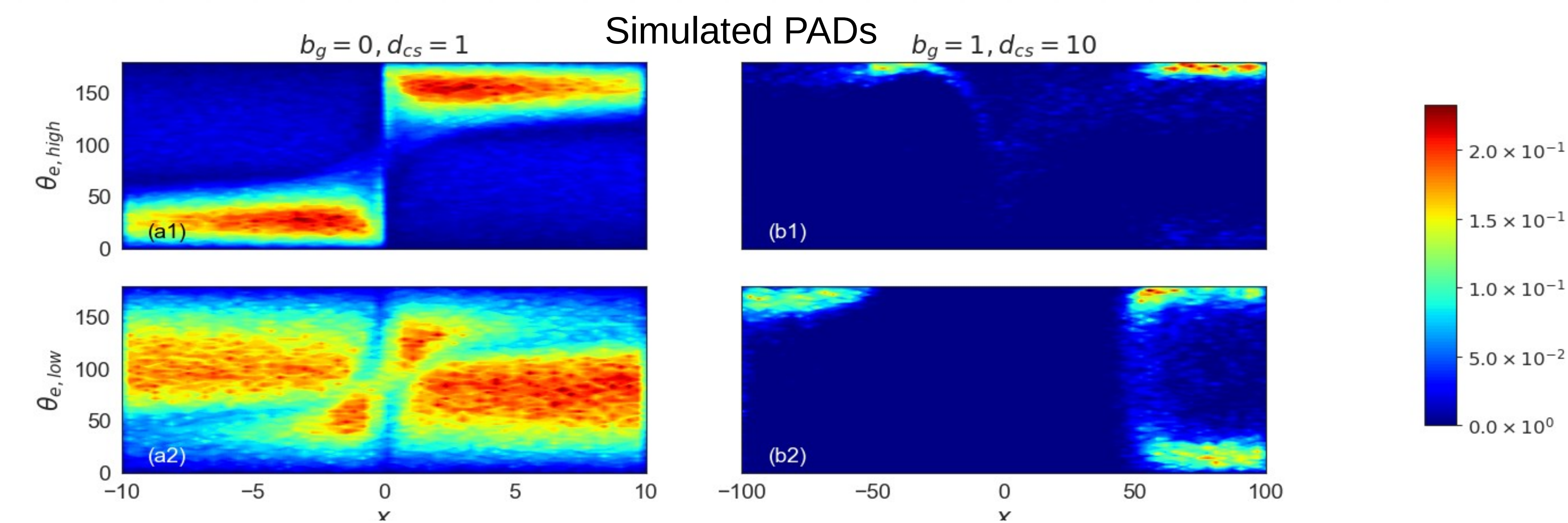
Xia and Zharkova, 2018
https://solargsm.com/wp-content/uploads/2020/03/xia_zharkova_tp_islands_aa18.pdf



Electrons can be accelerated in a single squashed island to relativistic energy. They circle about the O-point and are ejected from X-nullpoint.



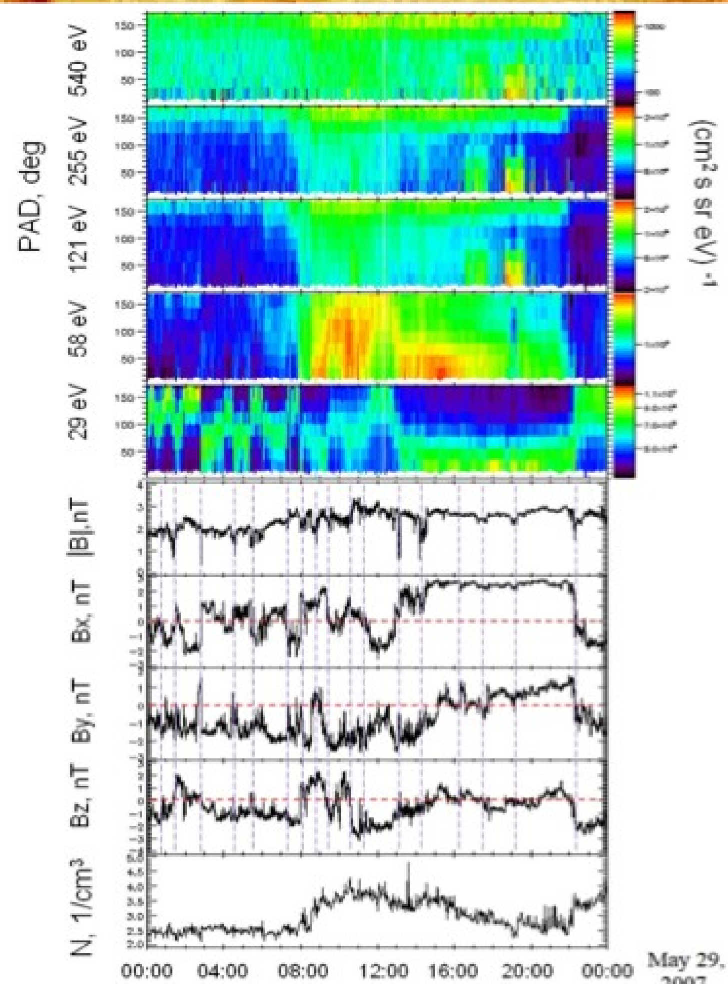




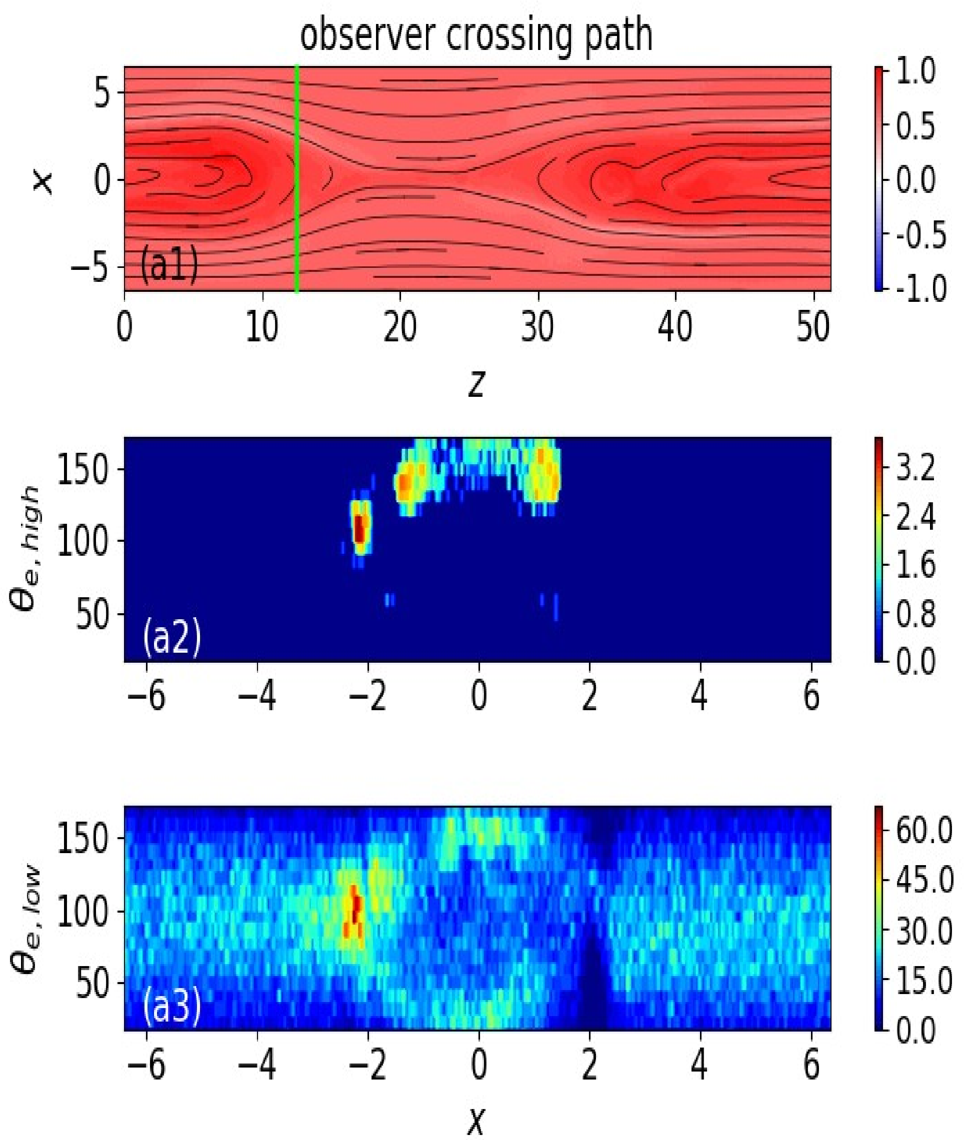
https://solargsm.com/wp-content/uploads/2021/02/zharkova_xia_PADs_aa21.pdf

and simulated by PIC (right)

https://solargsm.com/wp-content/uploads/2020/04/Khabarova_PAD_features_apjl20.pdf

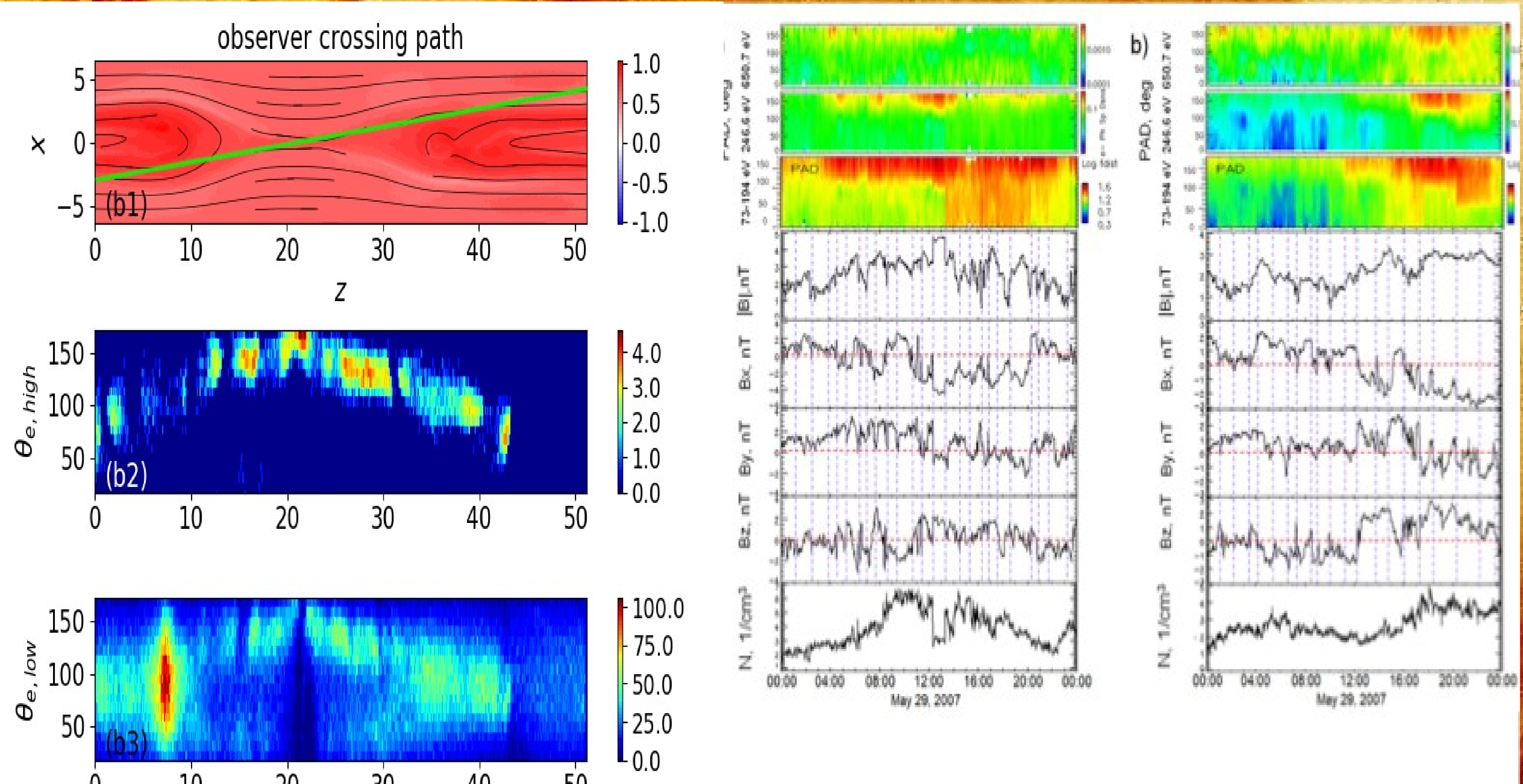


Electrons of different energies, the IMF, and the density in the region filled with MIs as observed by the WIND spacecraft on 2007, May, 29.



650.7, 246.6, and 73-194 eV energy channels from STEREO A (a) and STEREO B (b)

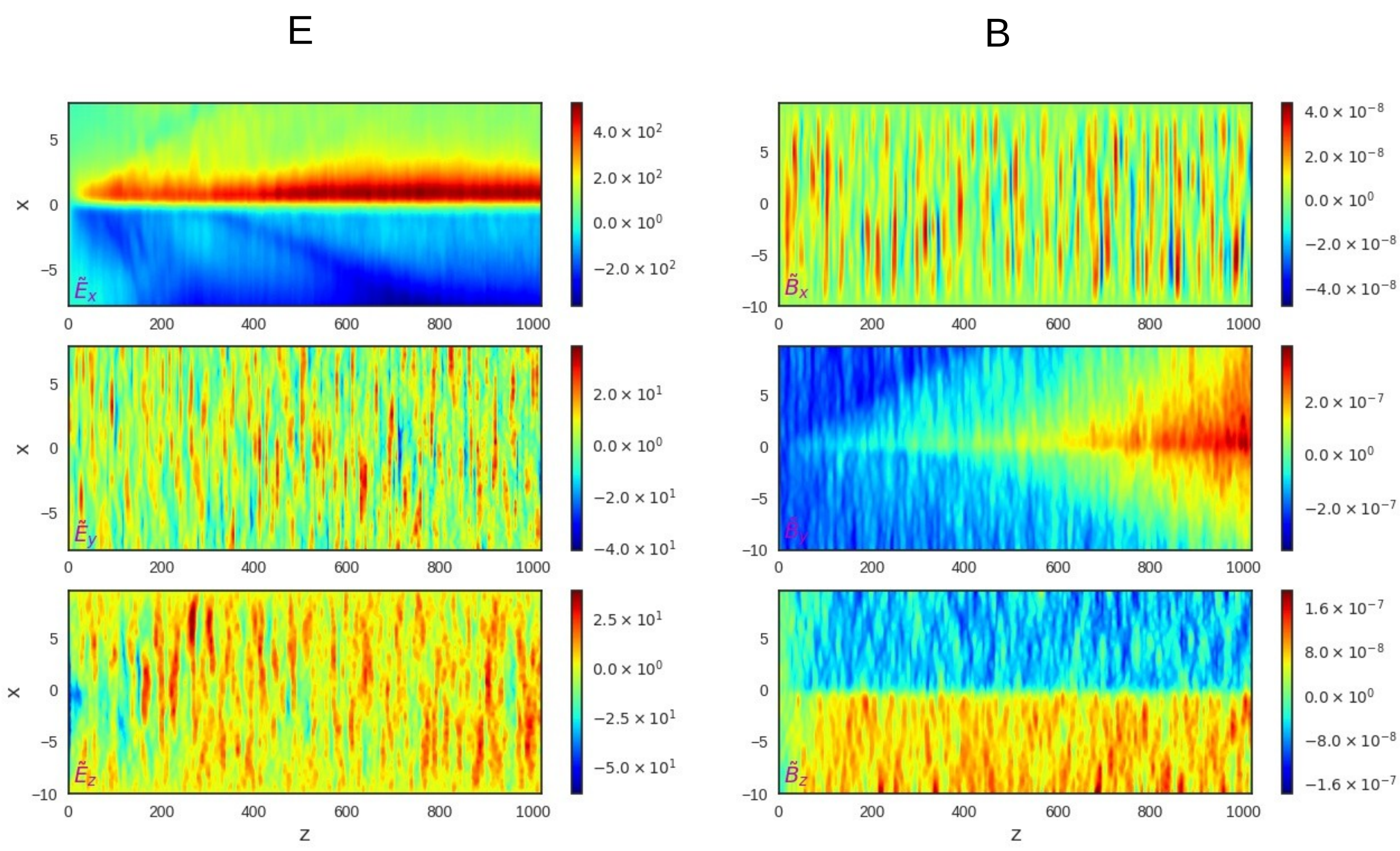
https://solargsm.com/wp-content/uploads/2020/04/Khabarova_PAD_features_apjl20.pdf



The highest-energy 650.7 eV STEREO PAD is completely different from the other PADs. It shows signatures of intermittent bi- directionality, following the location of MIs and CSs

Turbulent electric and magnetic fields induced by accelerated particles

(Siversky& Zharkova, 2009, JPP; Xia and Zharkova, 2020, A&A)



Conclusions

- There is the separation of electrons from protons in RCSs with respect to the midplane (sector boundary – SB in the HCS), which generates a polarization electric field across the current sheet

- Magnetic field imposes its signatures on pitch-angle and energy distributions on particles entering a current sheet from the opposite (transit) and the same side (bounced particles)

- Particles accelerated in magnetic islands still have the populations of transit and bounced particles leading to two beam instabilities often reported in observations and PIC models,

- Particle energy gains in coalescent islands are lower than in squashed ones

- PADs of accelerated particles are shown to reflect magnetic topology of current sheets and can be compared with in-situ observations accounting for energetic strahls (transit electrons) and diffusive drop-offs (bounced electrons) often observed in solar wind

- Bump-in-tail velocity distributions of transit and bounced particles of the same charge induce turbulence in different parts of current sheets – see Zharkova and Xia, 2021, Frontier paper.