The Geomagnetic Cusps: Magnetic Topology and Physical Processes

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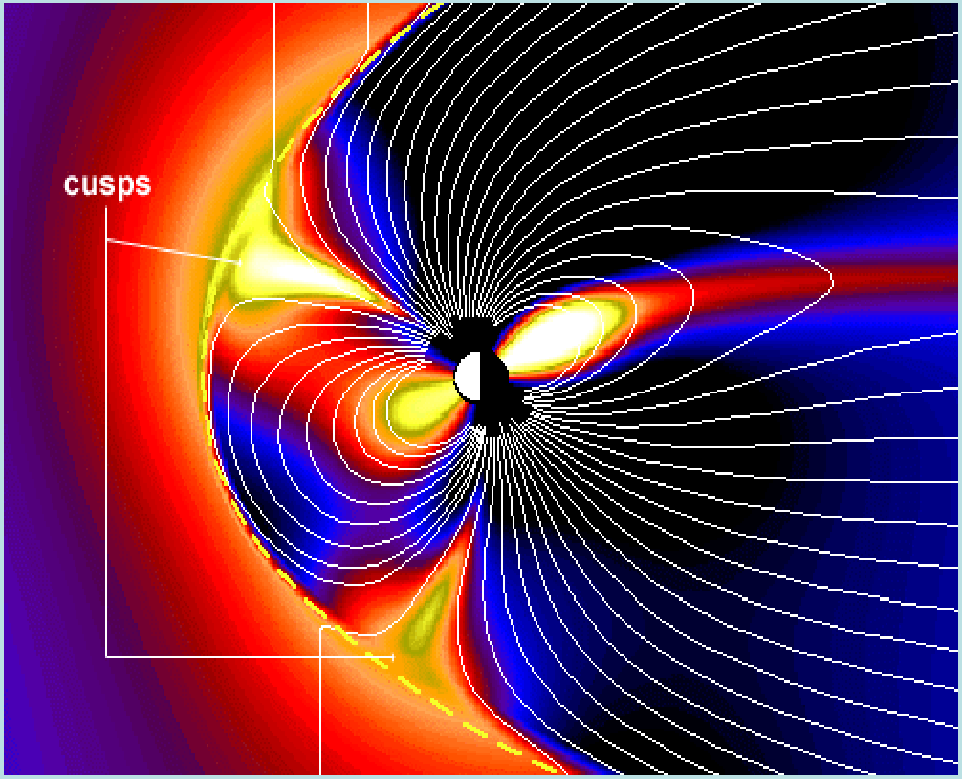
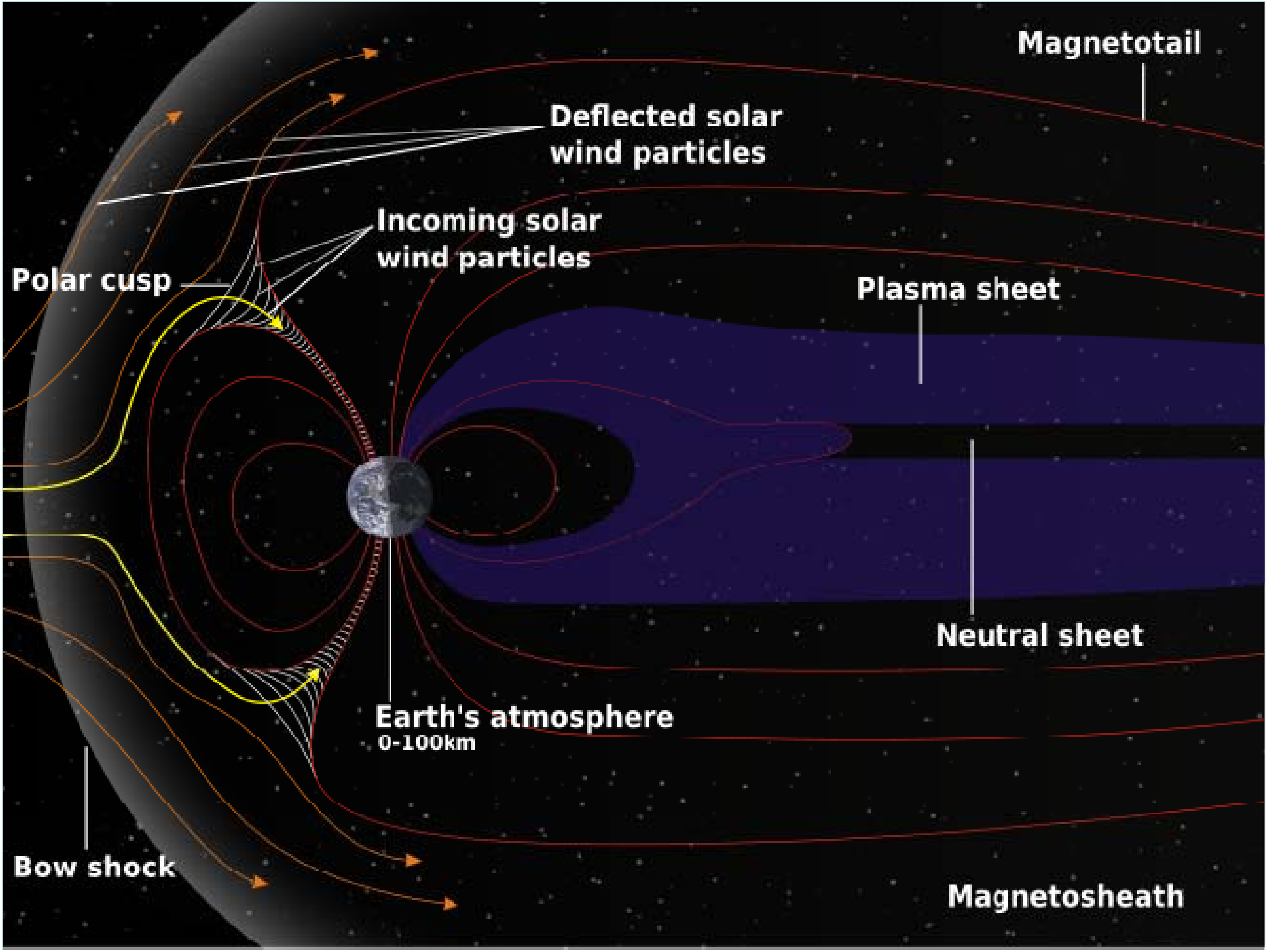


http://pluto.space.swri.edu/IMAGE/glossary/cusp.html

Thanks to: Eric Adamson, Katariina Nykyri, Julia Pilchowski, Jason McDonald


Magnetotail
Deflected solar
wind particles
Incoming solar
wind particles
Polar cusp
Plasma sheet
Neutral sheet
Earth's atmosphere
0-100km
Bow shock
Magnetosheath

The Geomagnetic Cusps

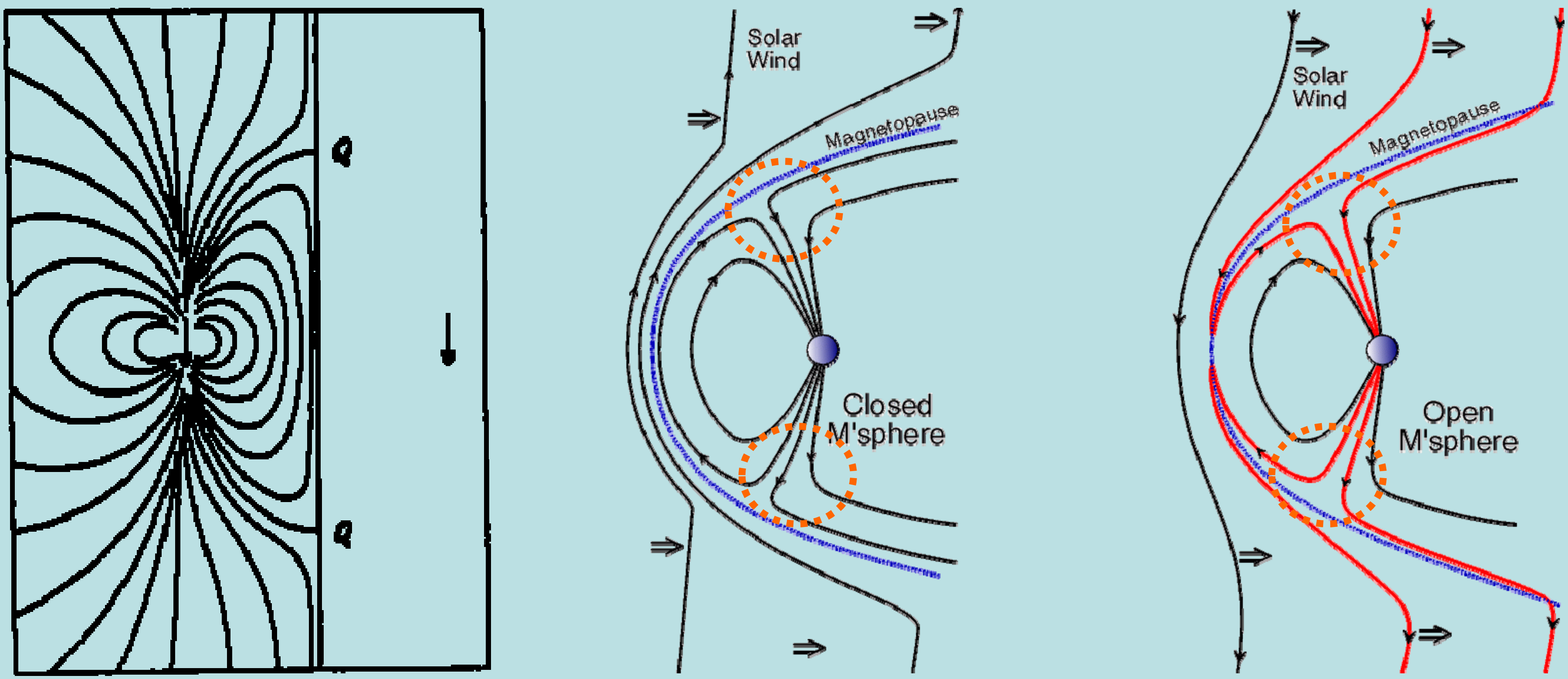
Structure:
Magnetic structure (topology) – Magnetic null point => B=0
Magnetic boundary maps to cusp point!
Identification

Topics:
Structure, Morphology
Location, size, formation
Geomagnetic significance
- Plasma entry
- Precipitation
- Ion outflow
- Waves and Turbulence
- Particle trapping

Physical processes
- Magnetic reconnection
- (Kelvin Helmholtz instability
- Turbulence)

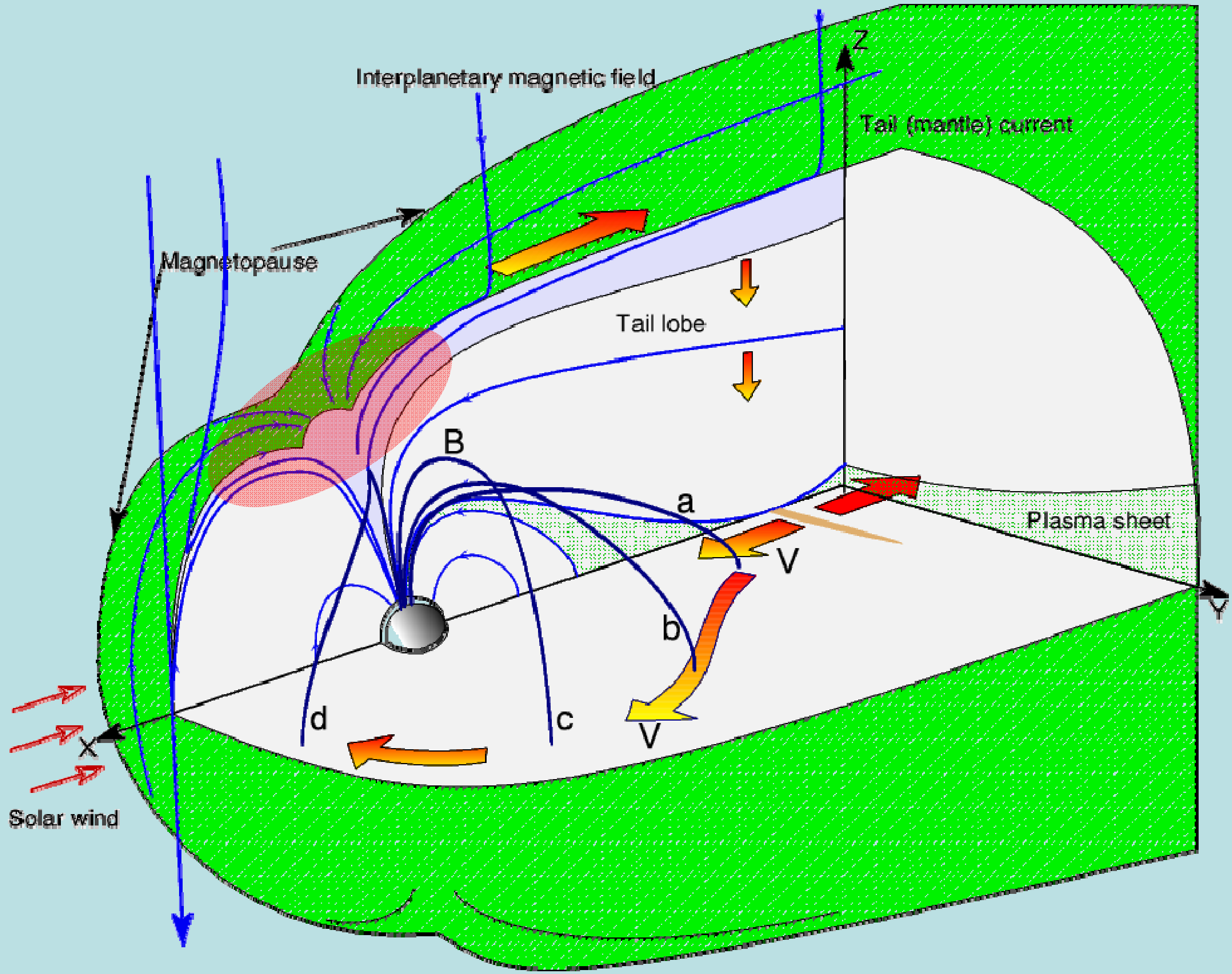
Diamagnetic Cavities and Cusp Energetic Particles
Formation
Particle source and acceleration
Summary

The Geomagnetic Cusps

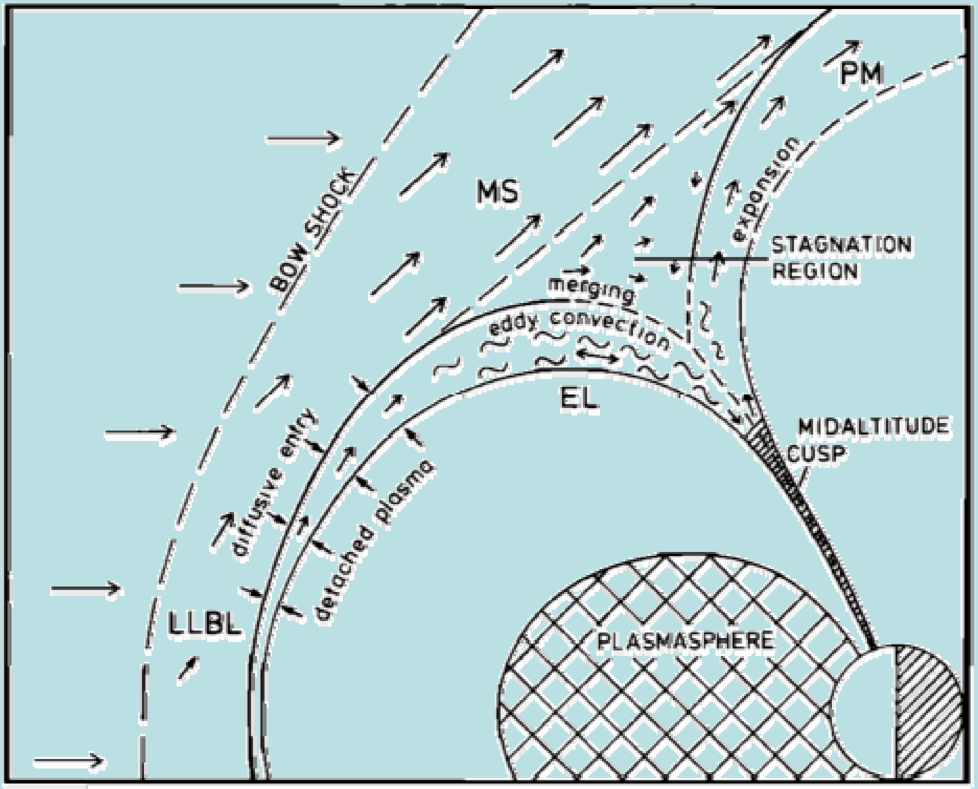


Chapman and Ferraro (1931)

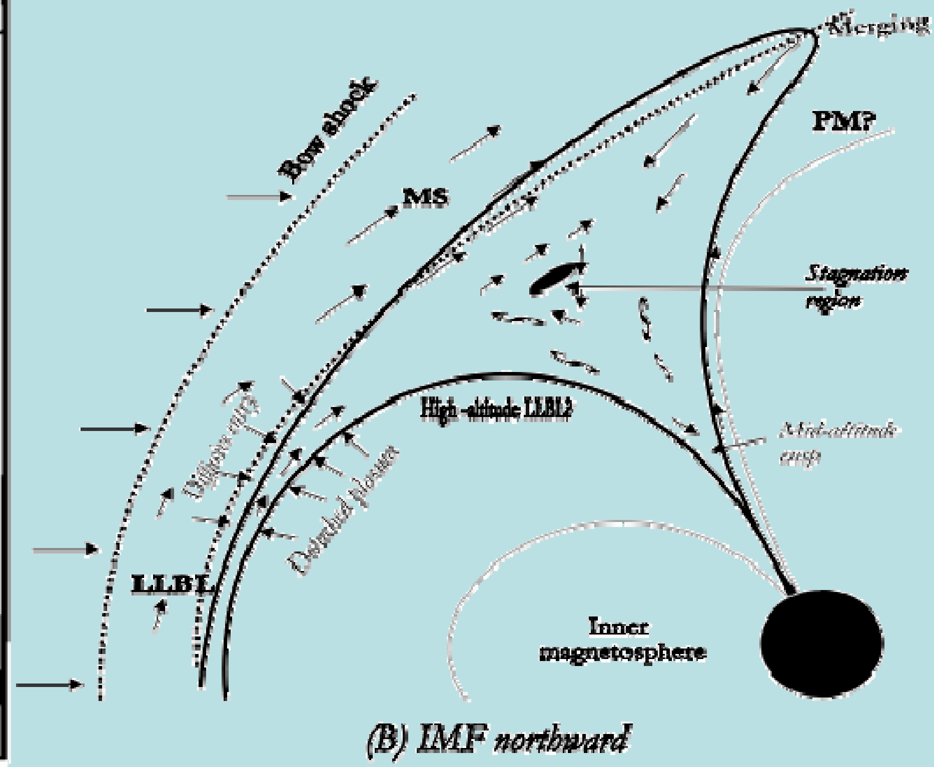
Role of the cusps in magnetospheric physics



The Geomagnetic Cusps - Structure



Haerendel et al., 1978

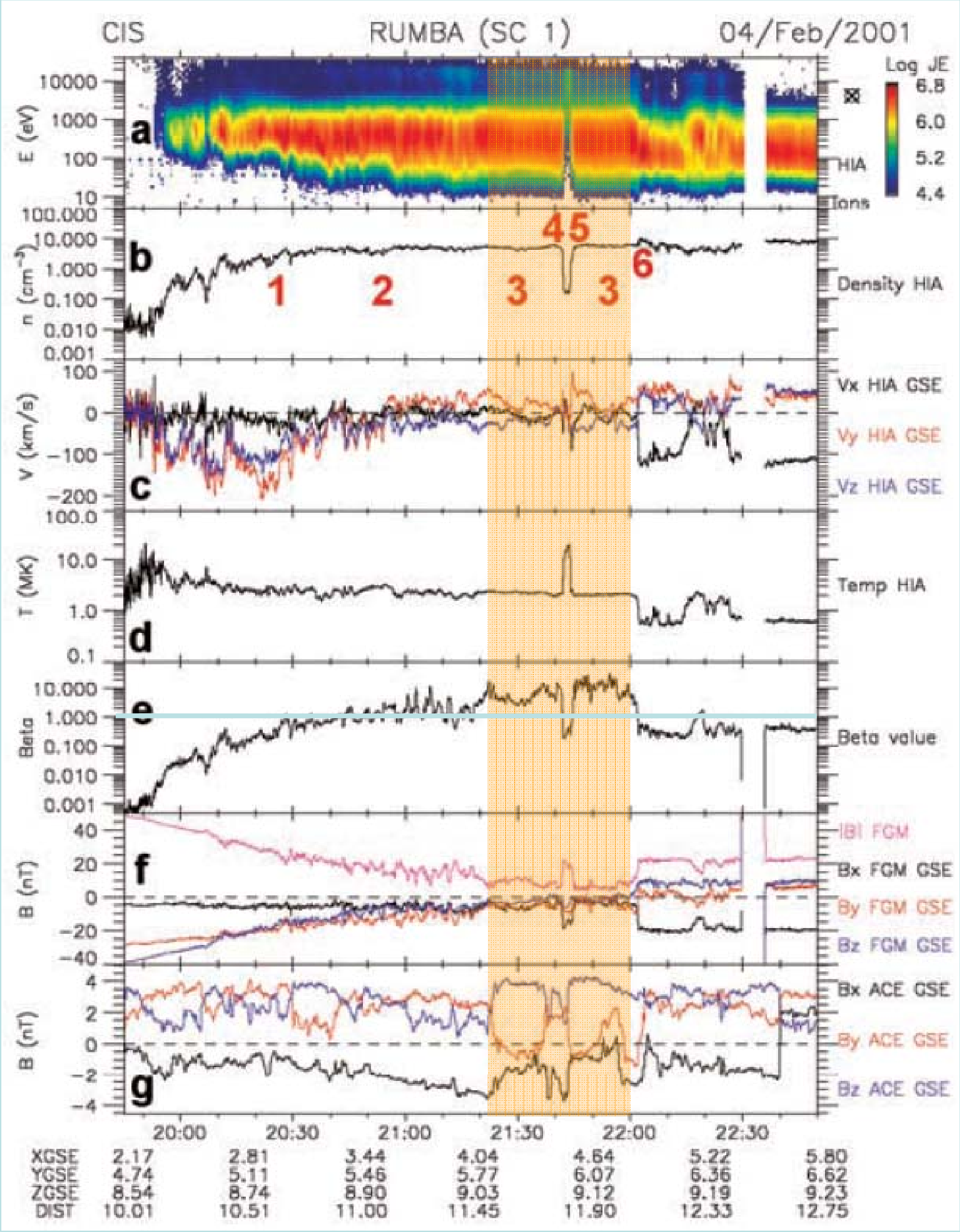


Zong et al., 2005

Structural Elements:

- Stagnation region
- Entry Layer (HLBL - High Latitude Boundary Layer)
- Midaltitude cusp
- LLBL (Low Latitude Boundary Layer)
- Plasma Mantle

Cusp Observations and Properties



n

V

T

β

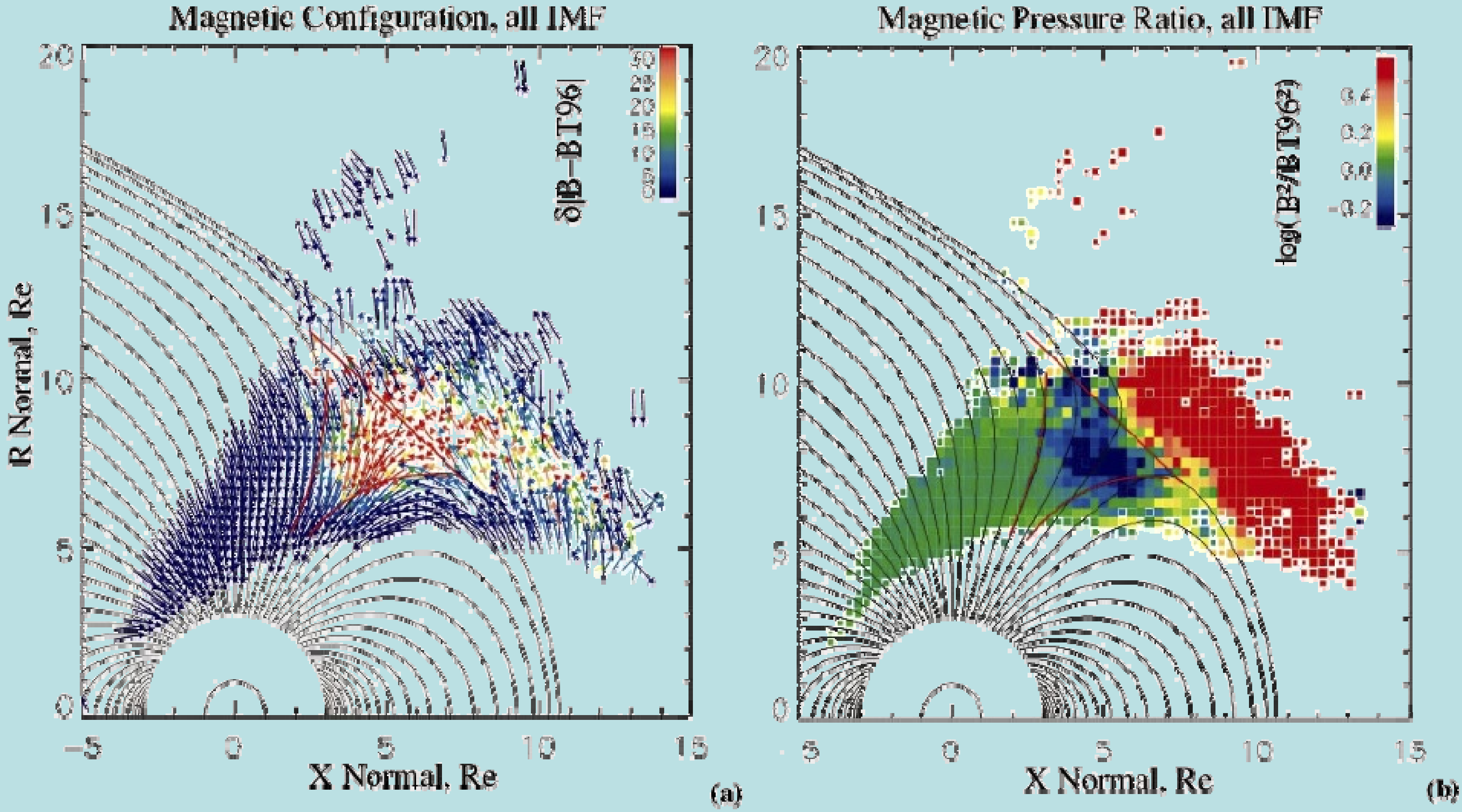
B

Exterior Cusp

- **Stagnant flow**
- **Weak magnetic field**
- **High plasma β**
- **Plasma properties different from magnetosheath**
- **Thin boundaries**

Cluster Observations:
Lavraud et al., 2002

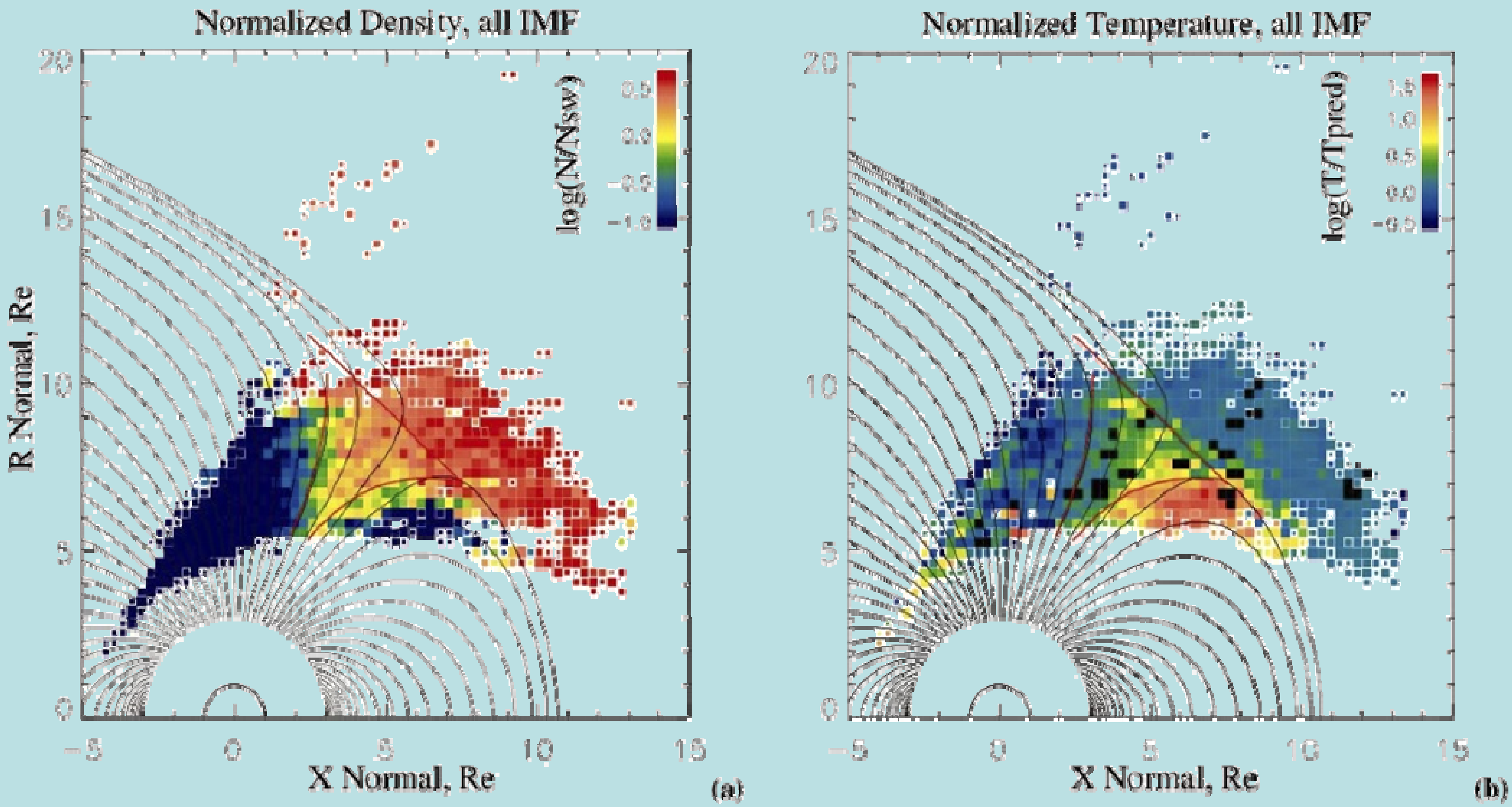
The Geomagnetic Cusps - Structure



Lavraud et al. (2004)

Exterior Cusp: Region with strong magnetic field variation and depression!

The Geomagnetic Cusps - Structure

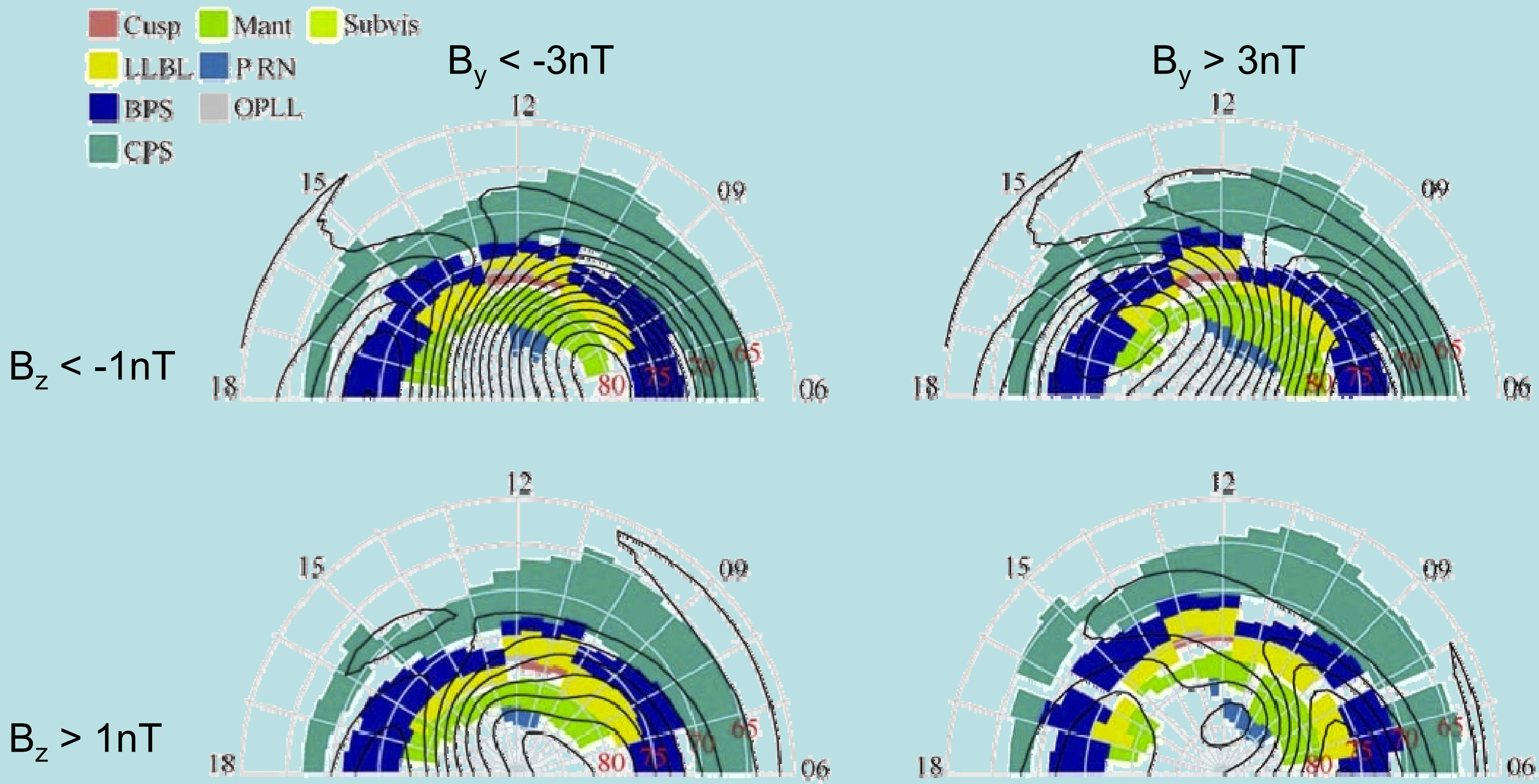


Lavraud et al. (2004)

Exterior cusp:

- Boundaries: Lobes, dayside plasma sheet, and magnetosheath
- Stagnant plasma (particularly for $B_z > 0$)
- Total pressure balance

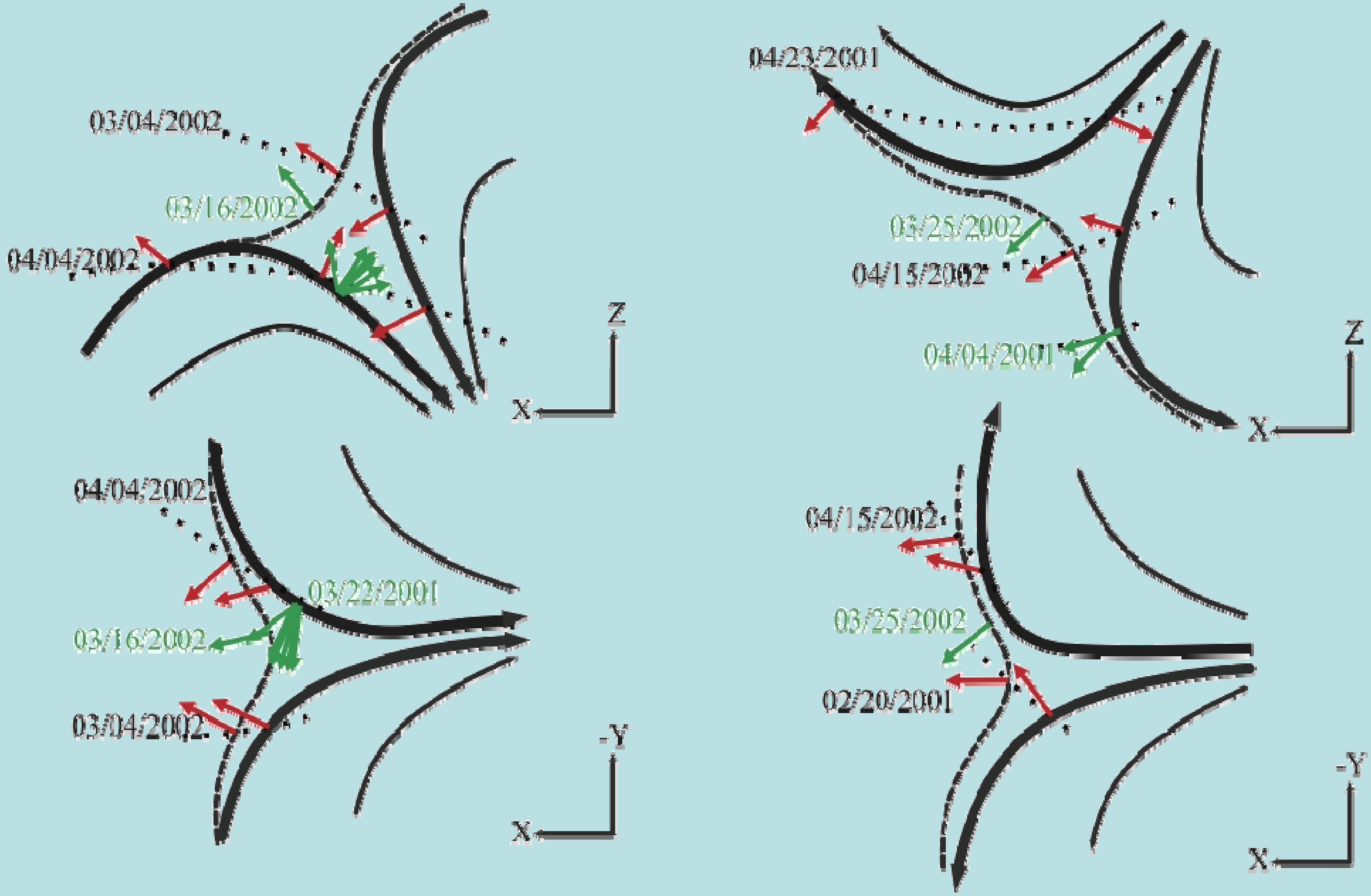
The Geomagnetic Cusps - Structure



Newell et al. (2005)

Cusp Precipitation:
Low energy, high number density flux (e.g. Burch, 1968; Heikkila and Winningham, 1971; Frank, 1971; Newell et al., 2004 …)
Ion precipitation (Proton aurora;

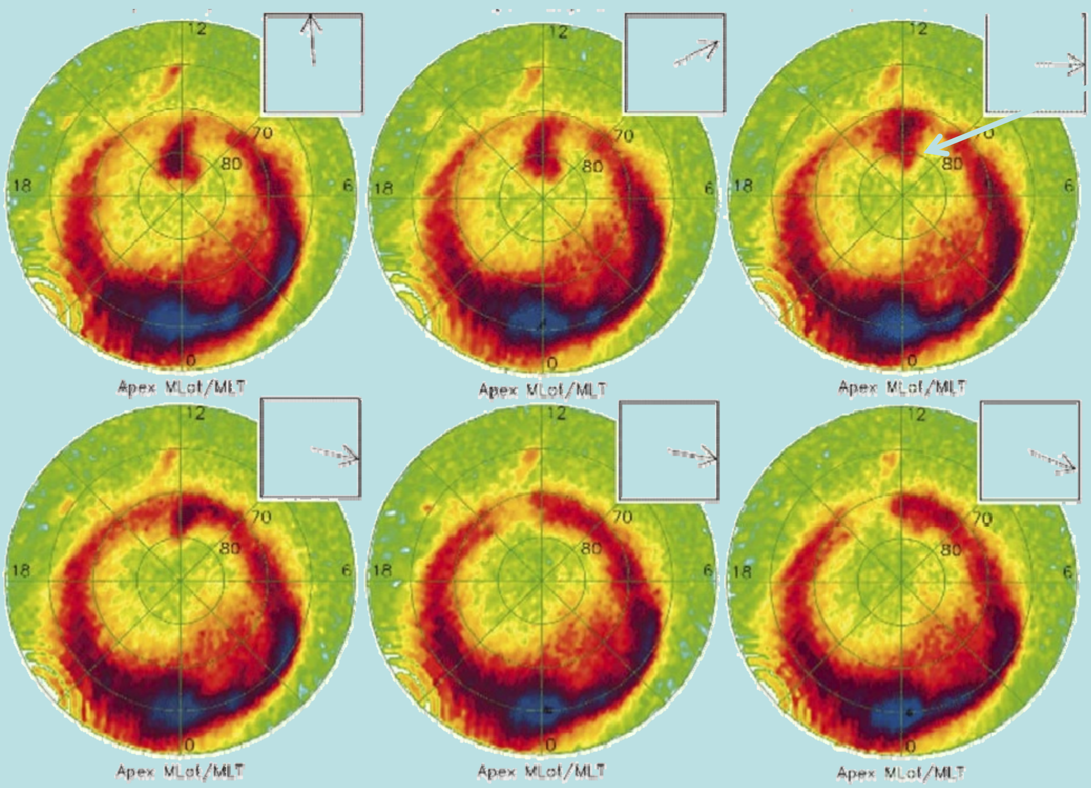
The Geomagnetic Cusps - Boundaries



Zhang et al. (2006), also Dunlop (2005), Nykyri (2010)

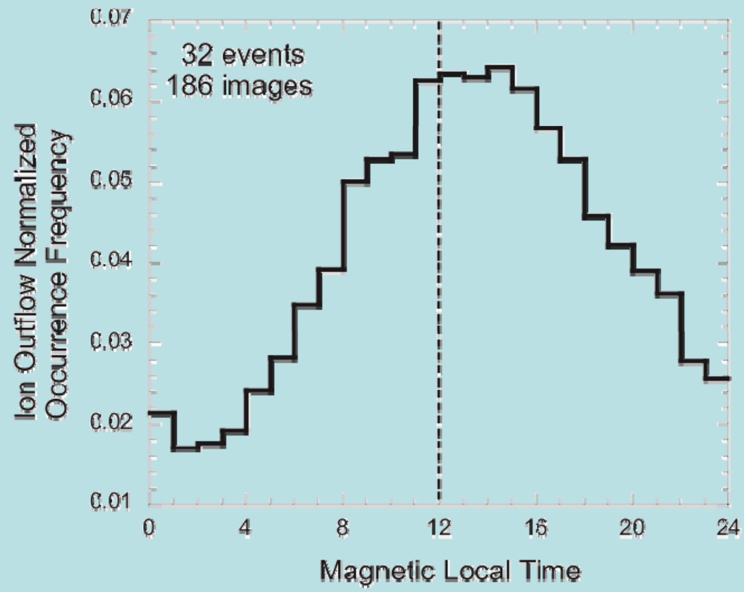
The Geomagnetic Cusps – Precipitation + Ion outflow

Cusp aurora for changing IMF orientation



Cusp aurora

Ion outflow distribution



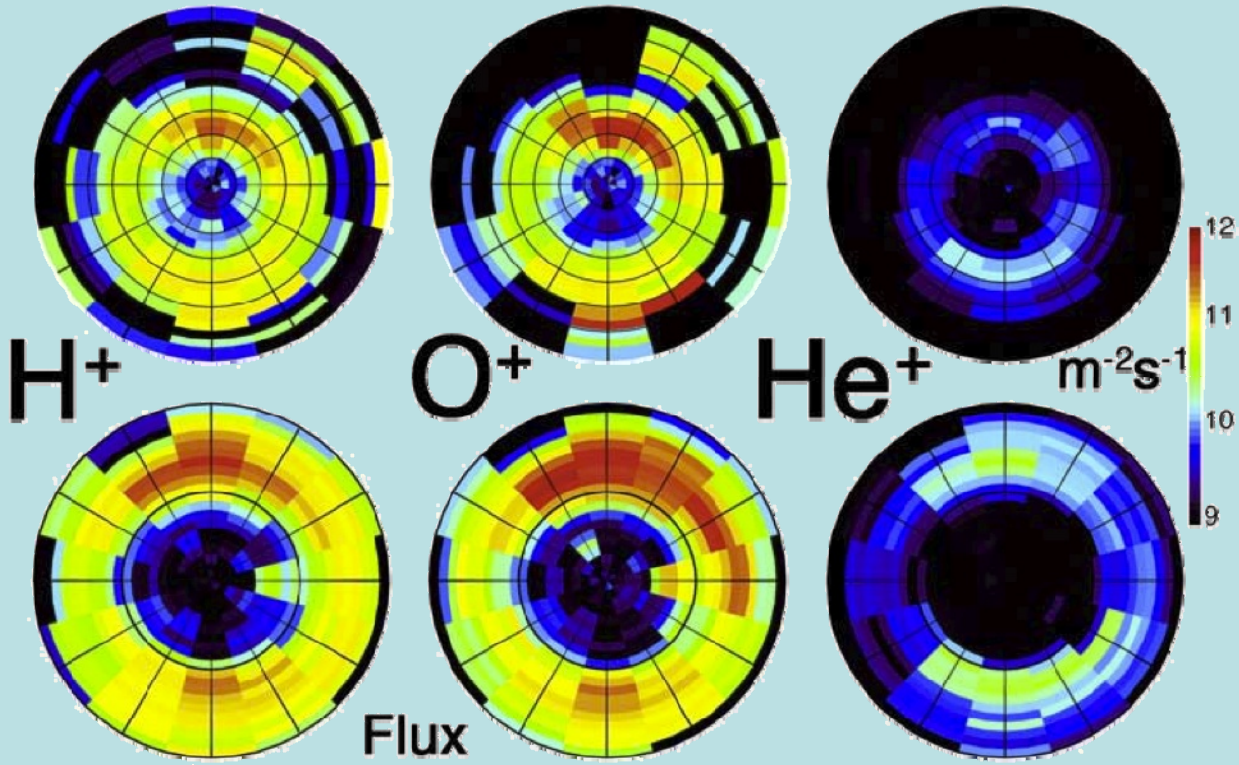
Fuselier et al. (2003)

Fuselier et al. (2008)

Also! Relation between upflow and poleward moving auroral transients (and intermittent reconnection)

(e.g., Moen et al., 2004)

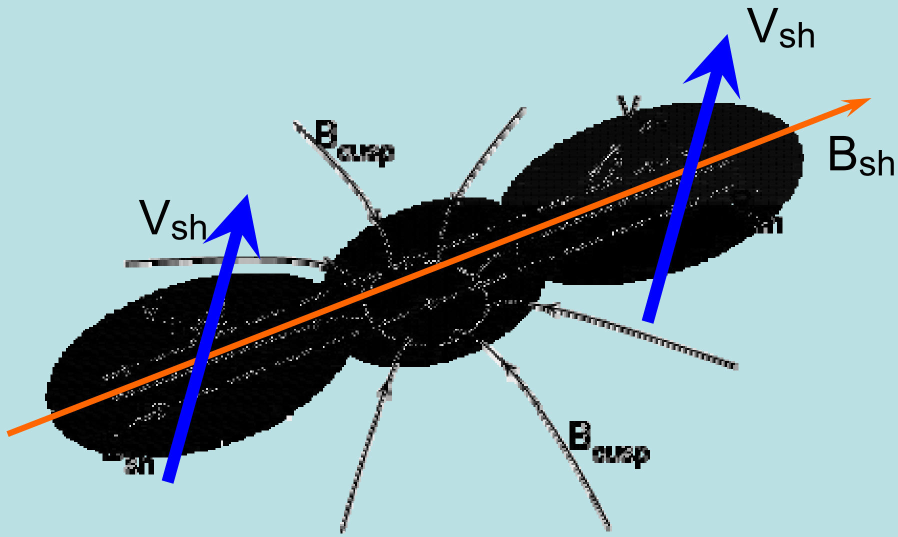
The Geomagnetic Cusps – Precipitation + Ion outflow



Net hemispheric outflow during quiet times (Peterson et al., 2008)

Ionosphere major plasma source for magnetosphere (e.g. Chappell et al, ‘87, Lockwood et al., ’85; Horwitz and Moore, ’97)

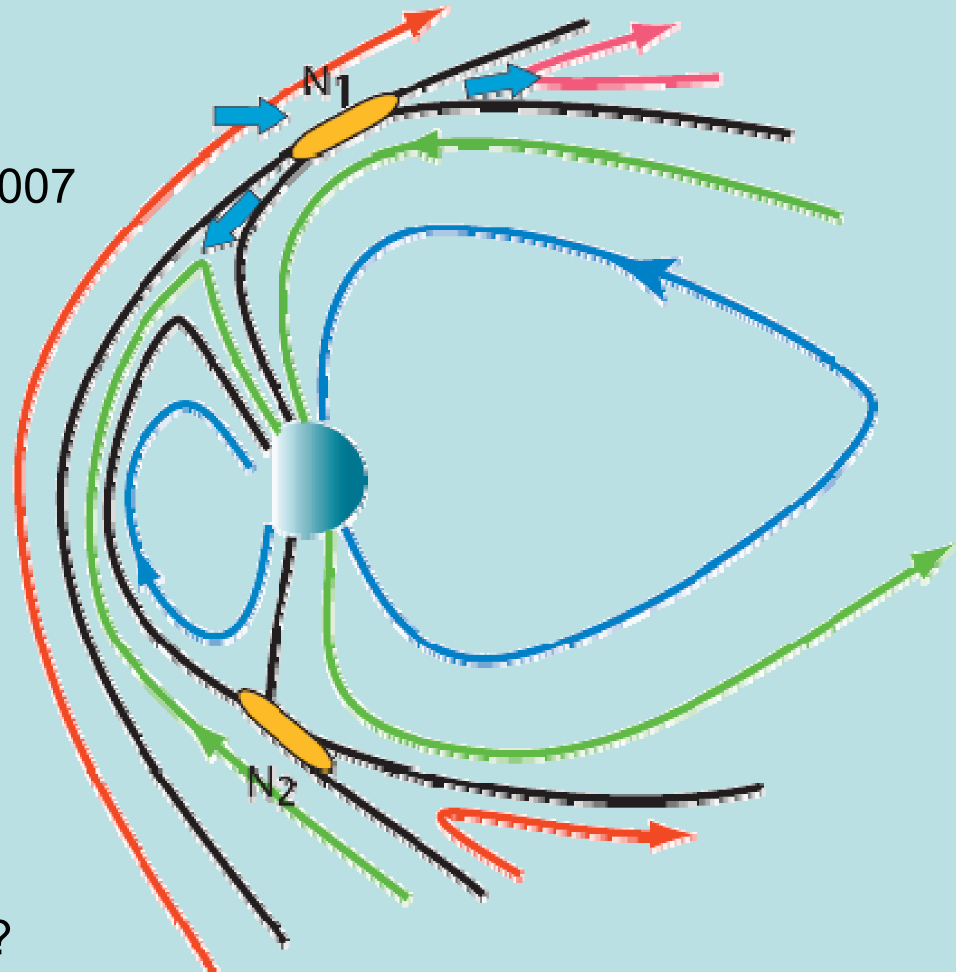
Expected Cusp Processes



- Local magnetic shear varies 360 degrees:
  - Antiparallel magnetic field => Magnetic Reconnection
  - Parallel and antiparallel field => Kelvin Helmholtz
  - Fast (superfast) flow past an obstacle => Turbulence
  - Low magnetic field strength
- Issue: Difficult in local models

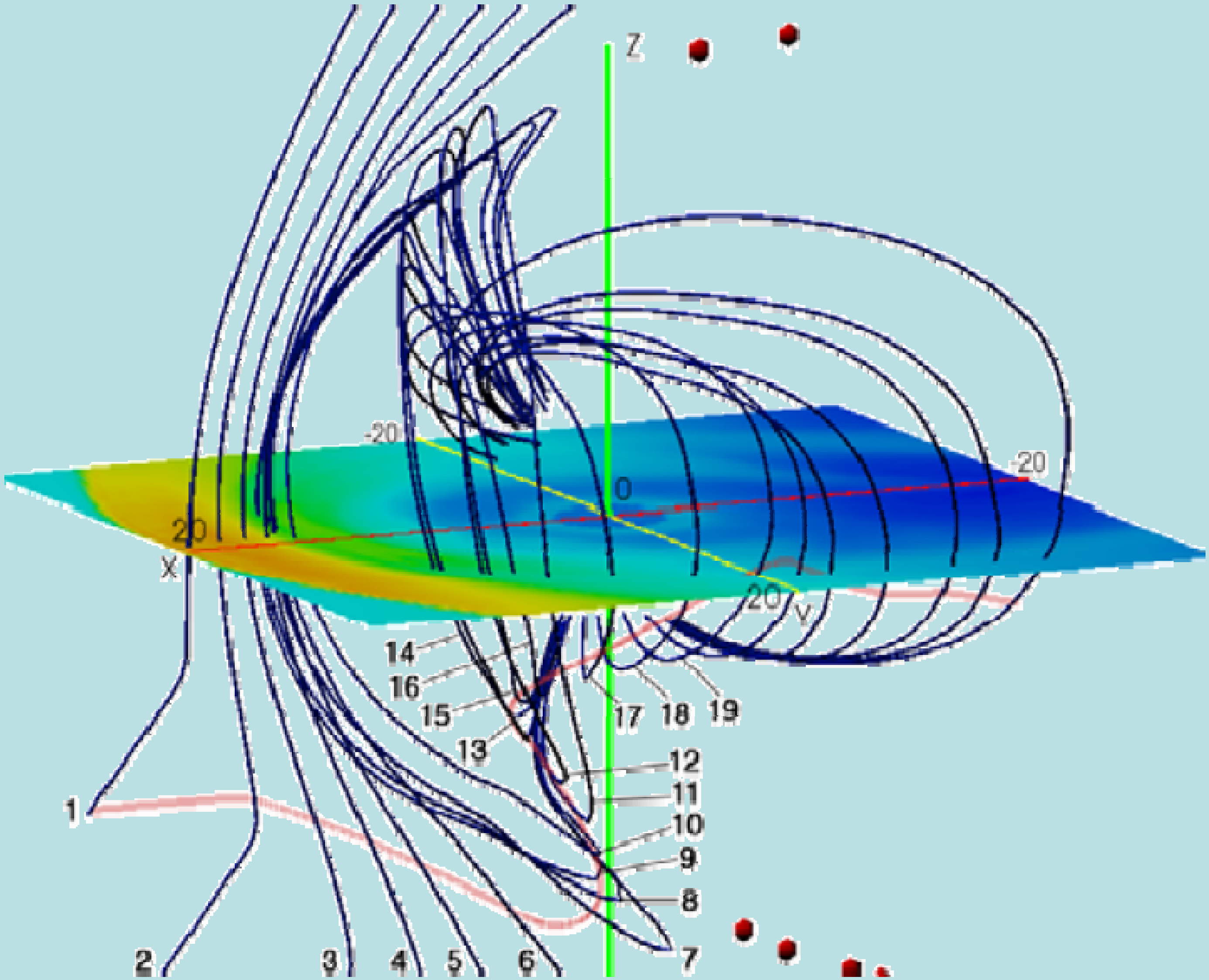
Cusp Reconnection (Crooker, '79; Song and Russell, '92; ..)

Dorelli et al, 2007



Importance of magnetic null points?
Antiparallel vs. component reconnection?
Sash (White et al., 1998)

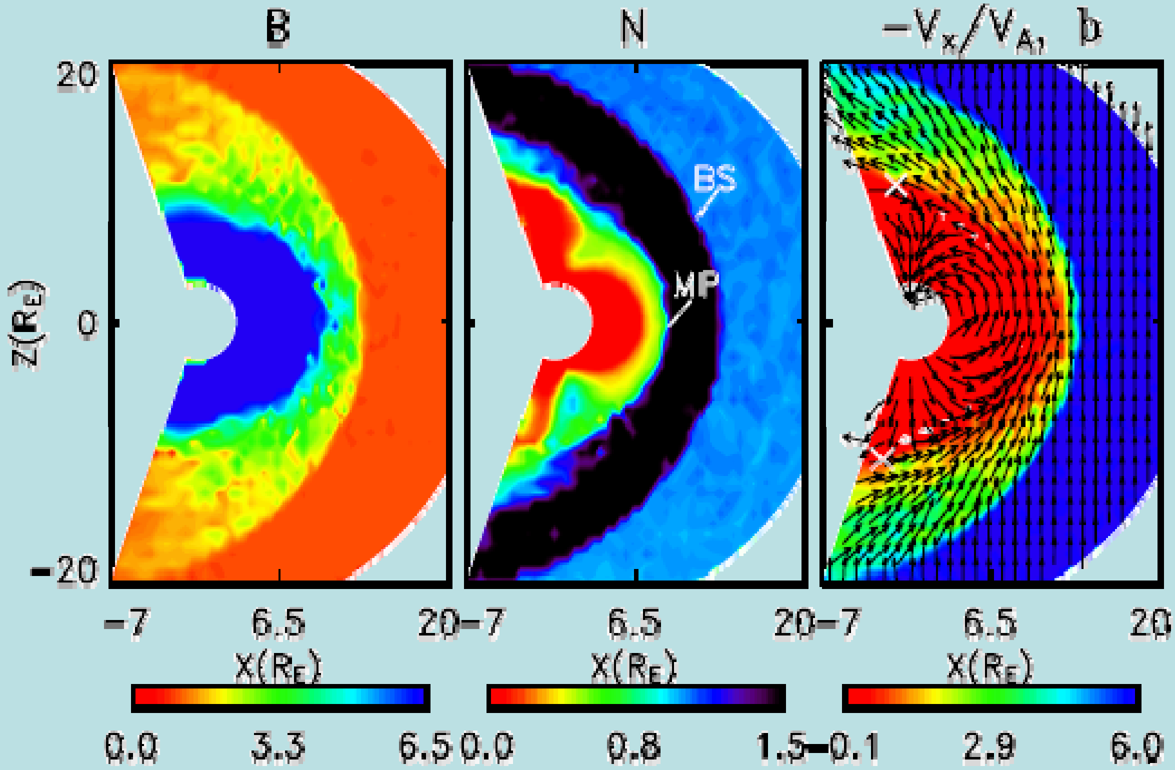
Cusp Reconnection – Global simulation



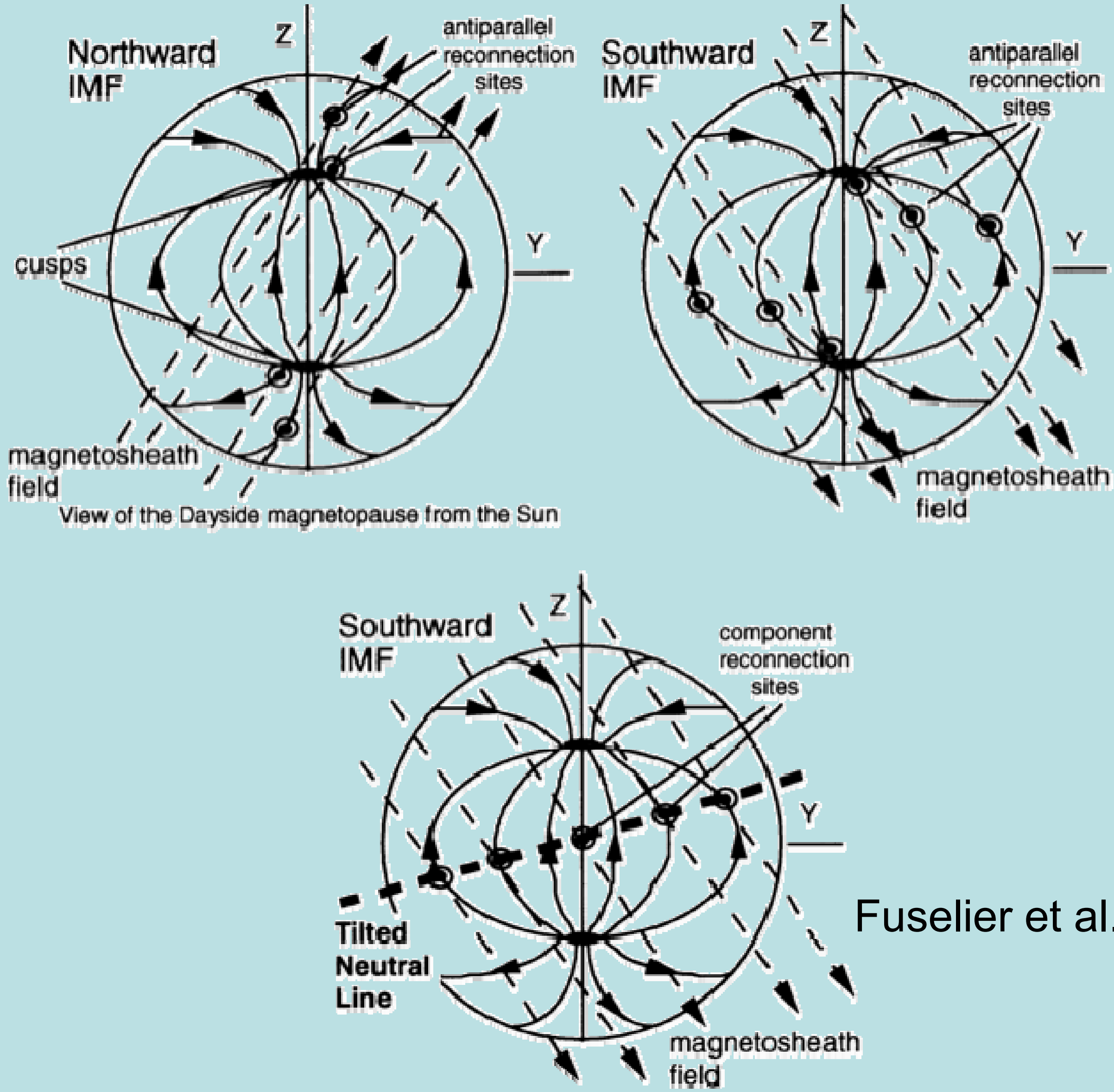
Li et al., '05

Cusp Reconnection

Dayside Hybrid Simulations (Lin and Wang, '06)



Cusp Reconnection - antiparallel vs component?

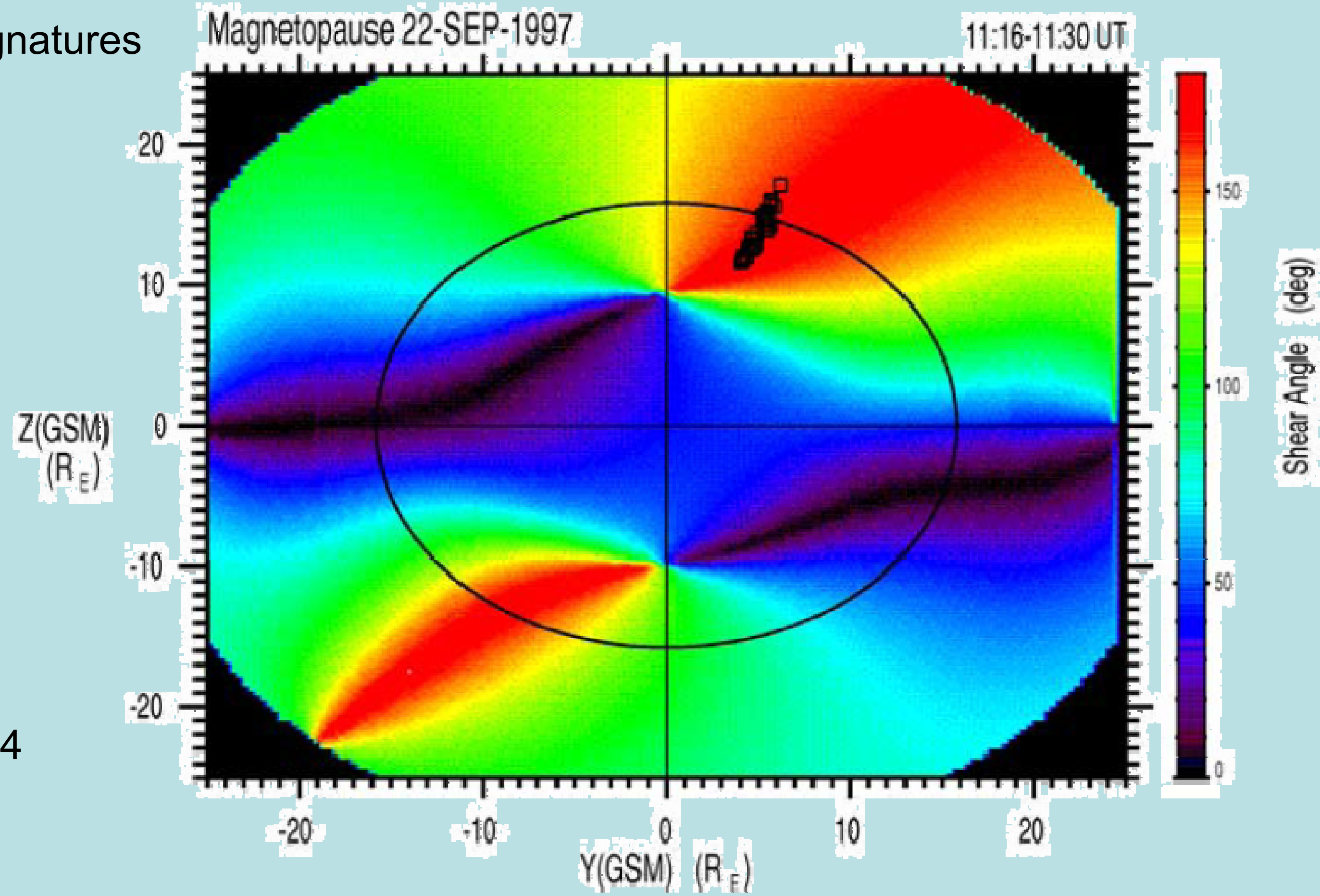


Fuselier et al.

Cusp Reconnection

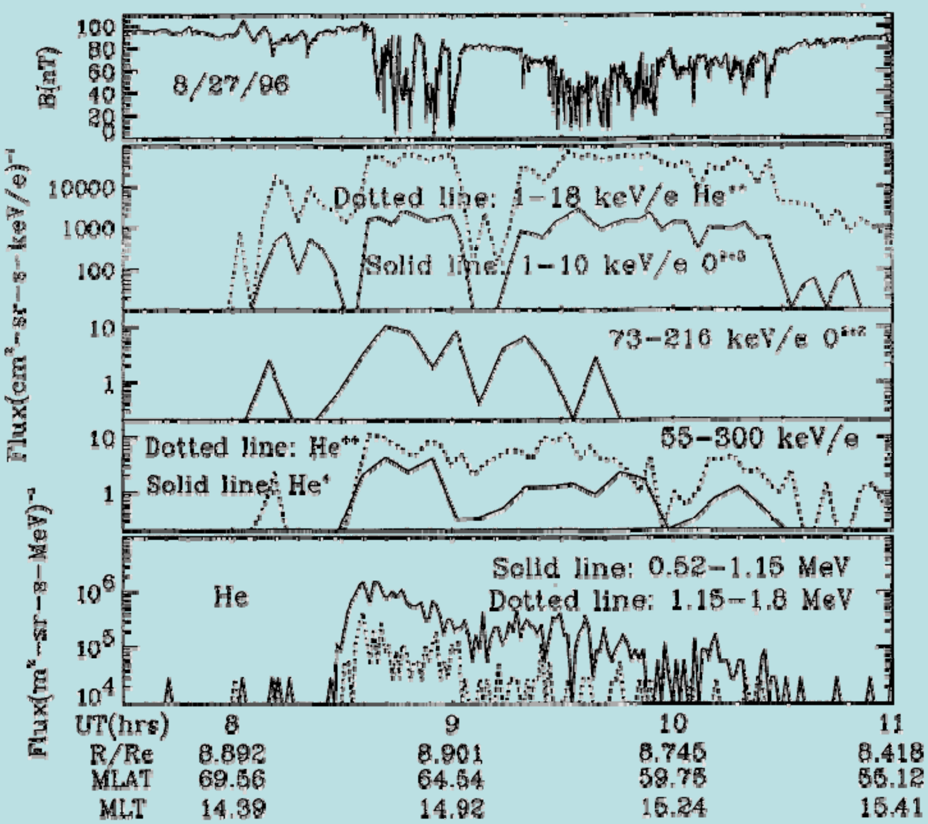
Observations (Fuselier, Phan, Trattner, Wang, Lavraud, ..)

- Ground based (lobe reconnection cells, particle signatures)
- In-situ spacecraft observations
- Remote particle signatures

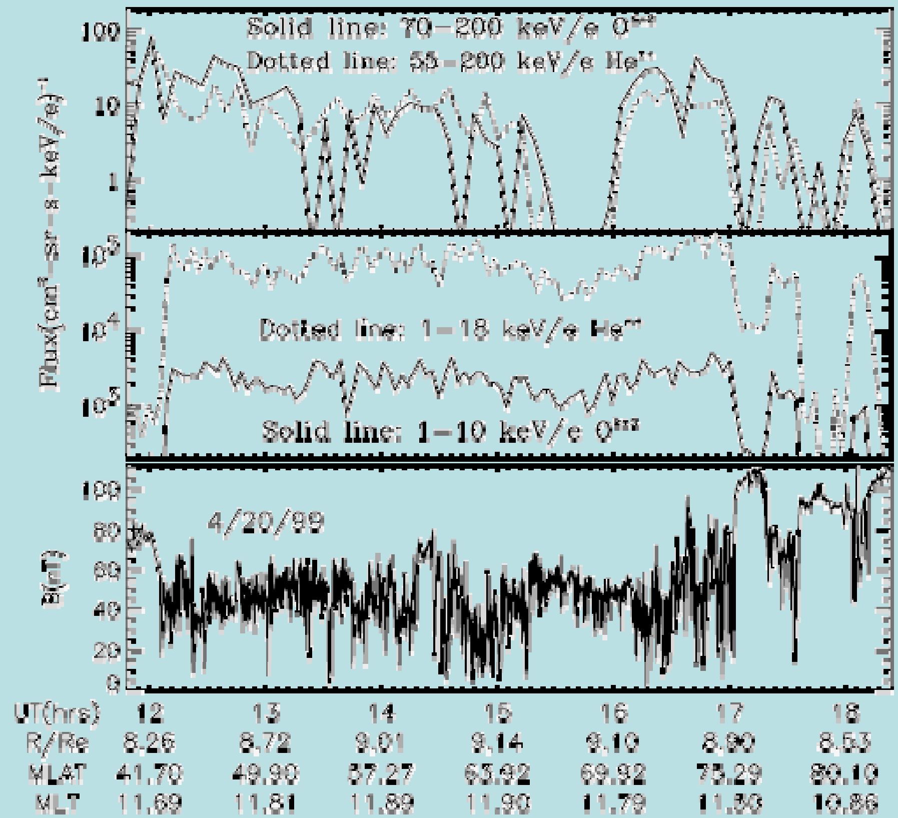


Trattner et al, 2004

Polar Magnetic Field and Particle Observations – 1



Fritz and Chen, 2001



Fritz and Chen, 2003

Diamagnetic cavities:

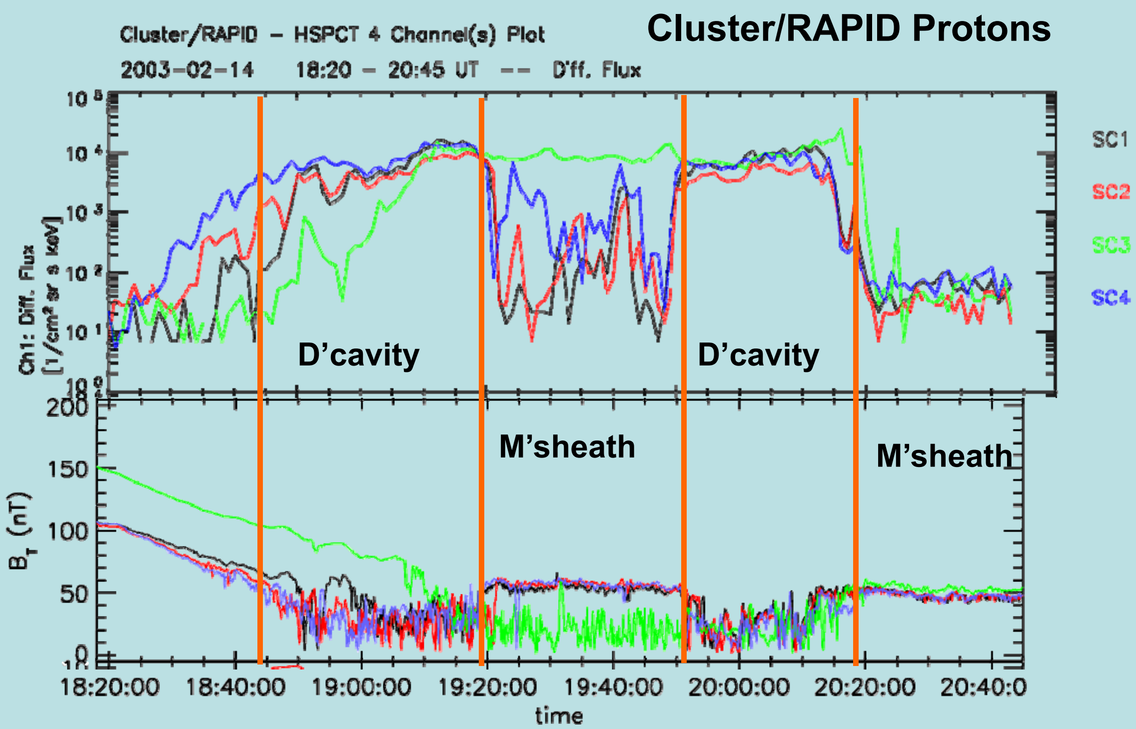
- High level of magnetic and density fluctuations
- Frequently associated with strongly enhanced fluxes of energetic particles

(Also Chen et al., 1997, 1998; Sheldon et al., 1998; ...)

Magnetic Field and Particle Observations – 2

CEP's - Cusp Energetic Particle Events:

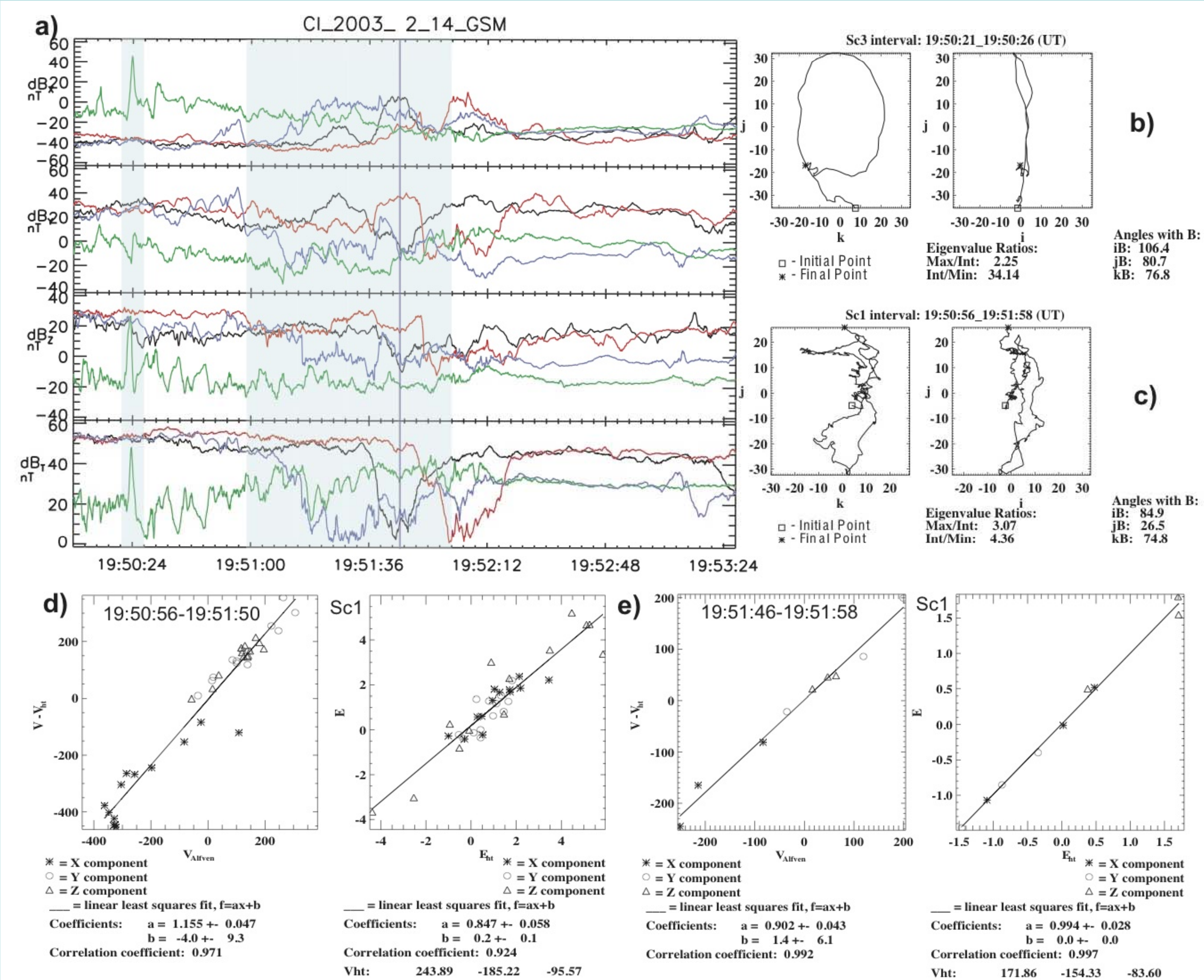
- Regions of `turbulent' weak magnetic field
- Enhanced energetic particle fluxes at/above 10 keV
- Particle energy proportional to charge
- Magnetic moment consistent with ring current/ radiation belt

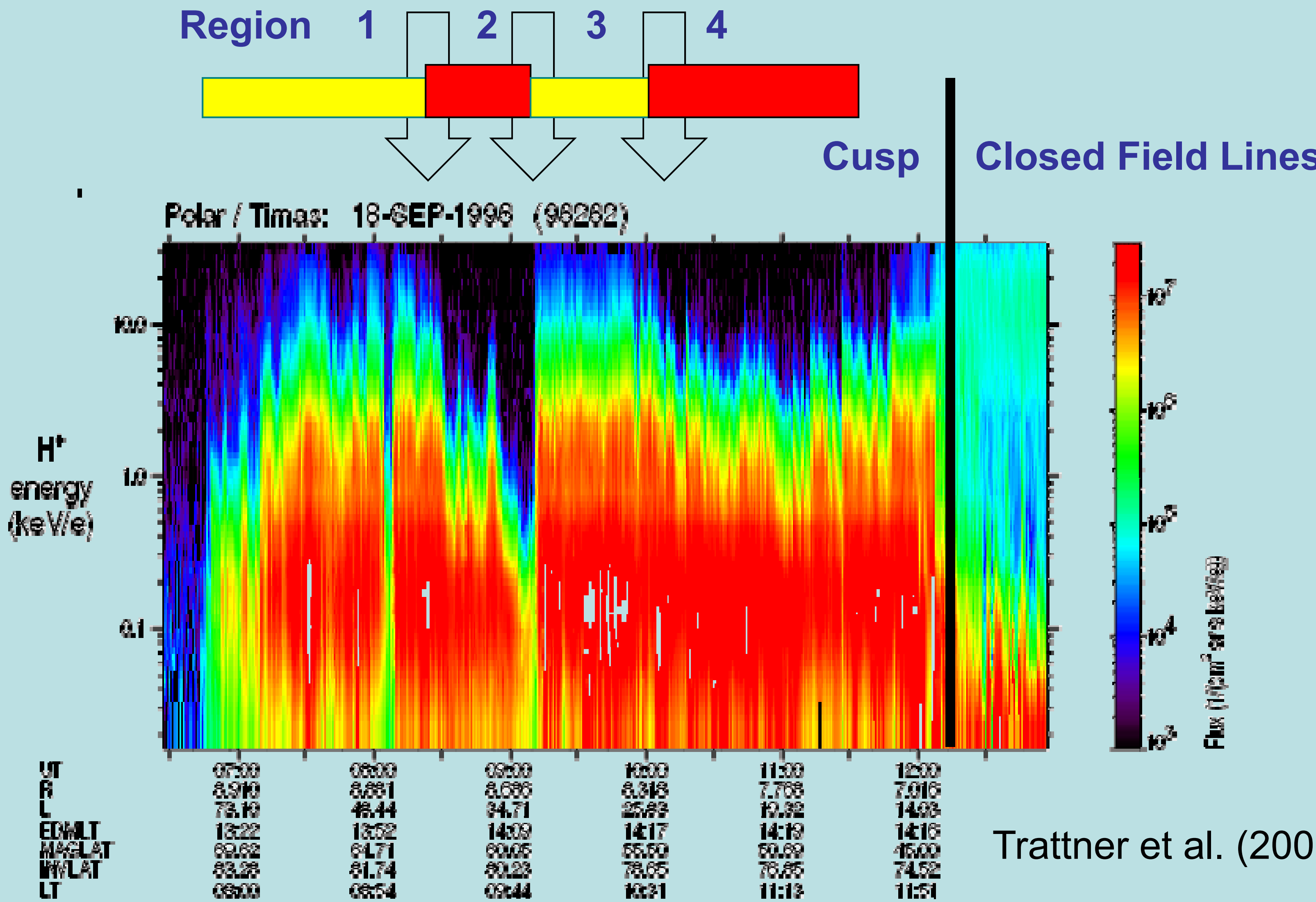


Nykyri et al., 2008

Turbulence or structure

Nykyri et al. (2010)





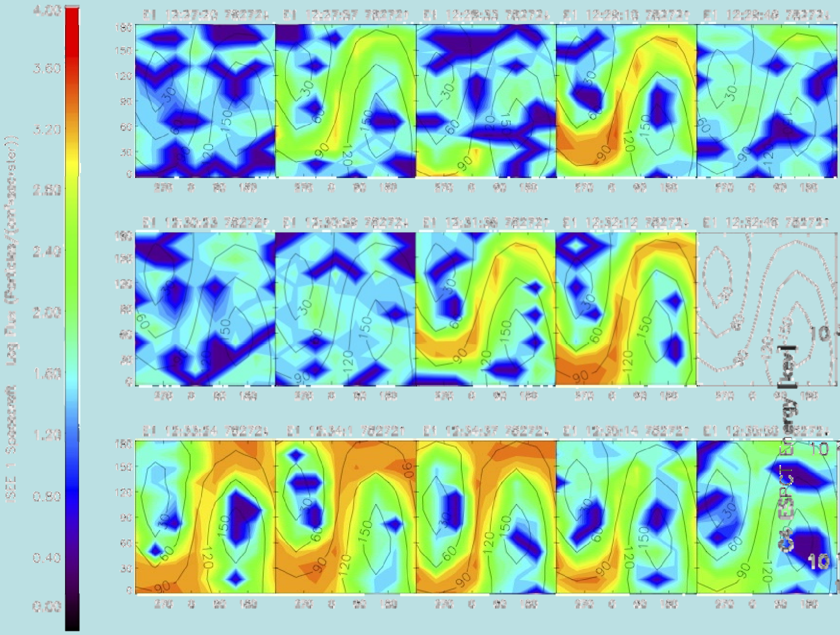
Trattner et al. (2009)

- Sharp Transitions between Regions with and without CEP’s
- Regions with CEP’s map to quasi-parallel bow shock.

Questions:

- Local Acceleration?
- Quasi-parallel bow shock source?
- Magnetospheric source (Aiskainen and Mursula, 2006)?
- What is the acceleration mechanism?

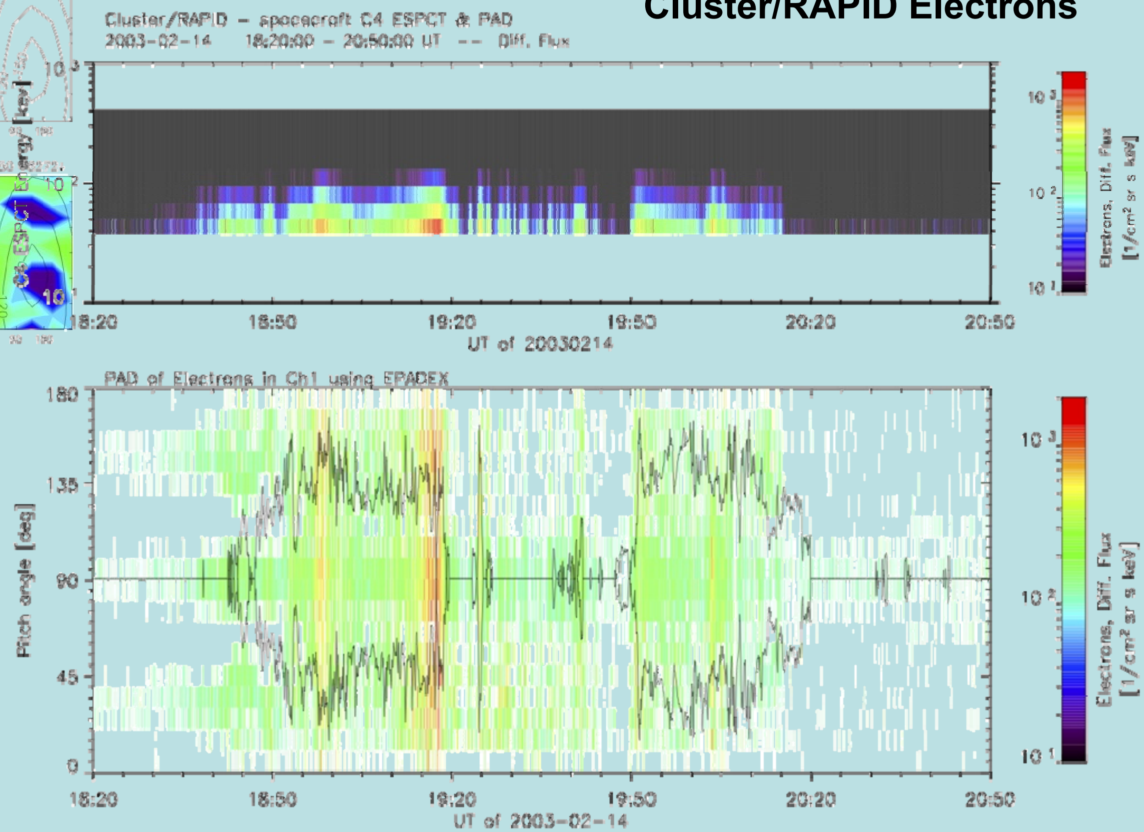
    Turbulence, Betatron, Fermi, Potential, Other?



ISEE 1

Walsh et al. (2007)

Cluster/RAPID Electrons



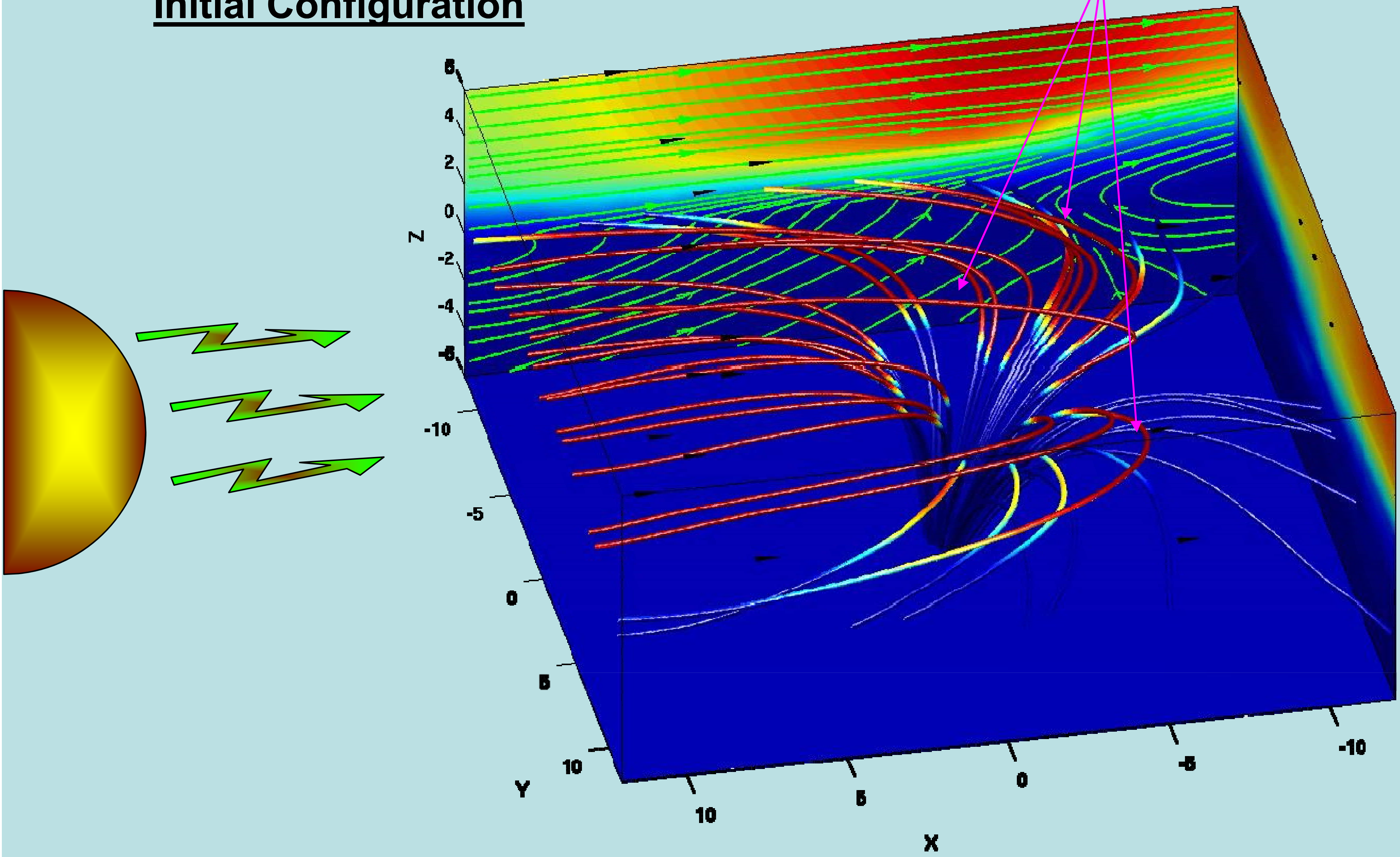
Nykyri et al. (2010)

- Presence of energetic electron in cavities.
- Only small fraction of distribution in the loss cone (to the magetosheath)

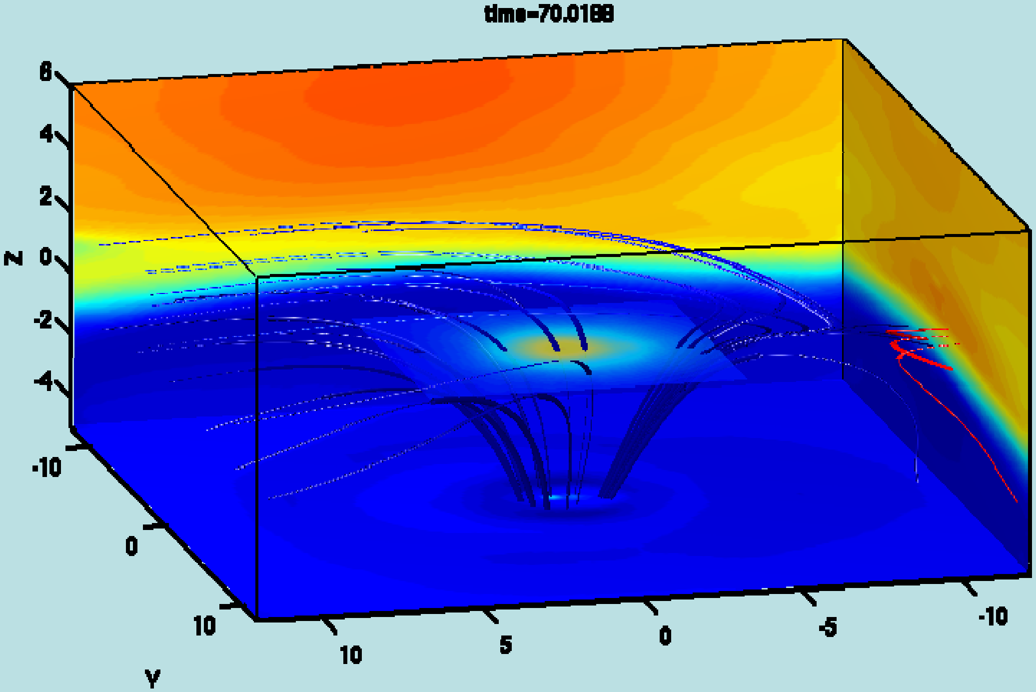
Local MHD + Test Particle Simulations

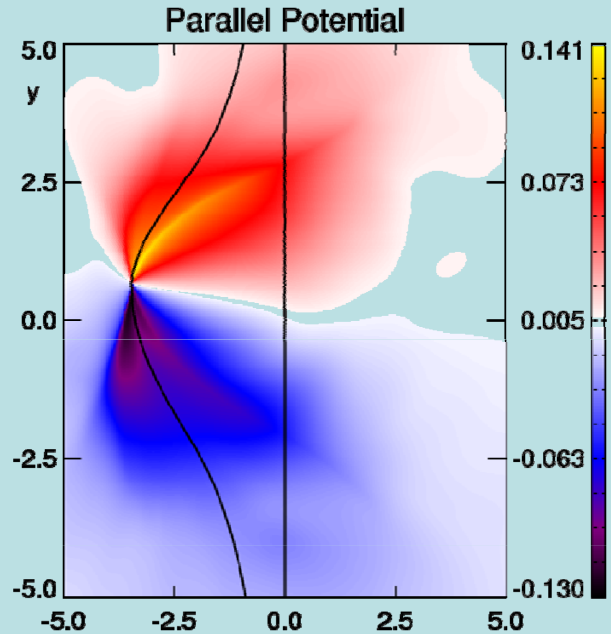
IMF-connected
Magnetospheric field lines

Initial Configuration



3D Cusp-like Reconnection



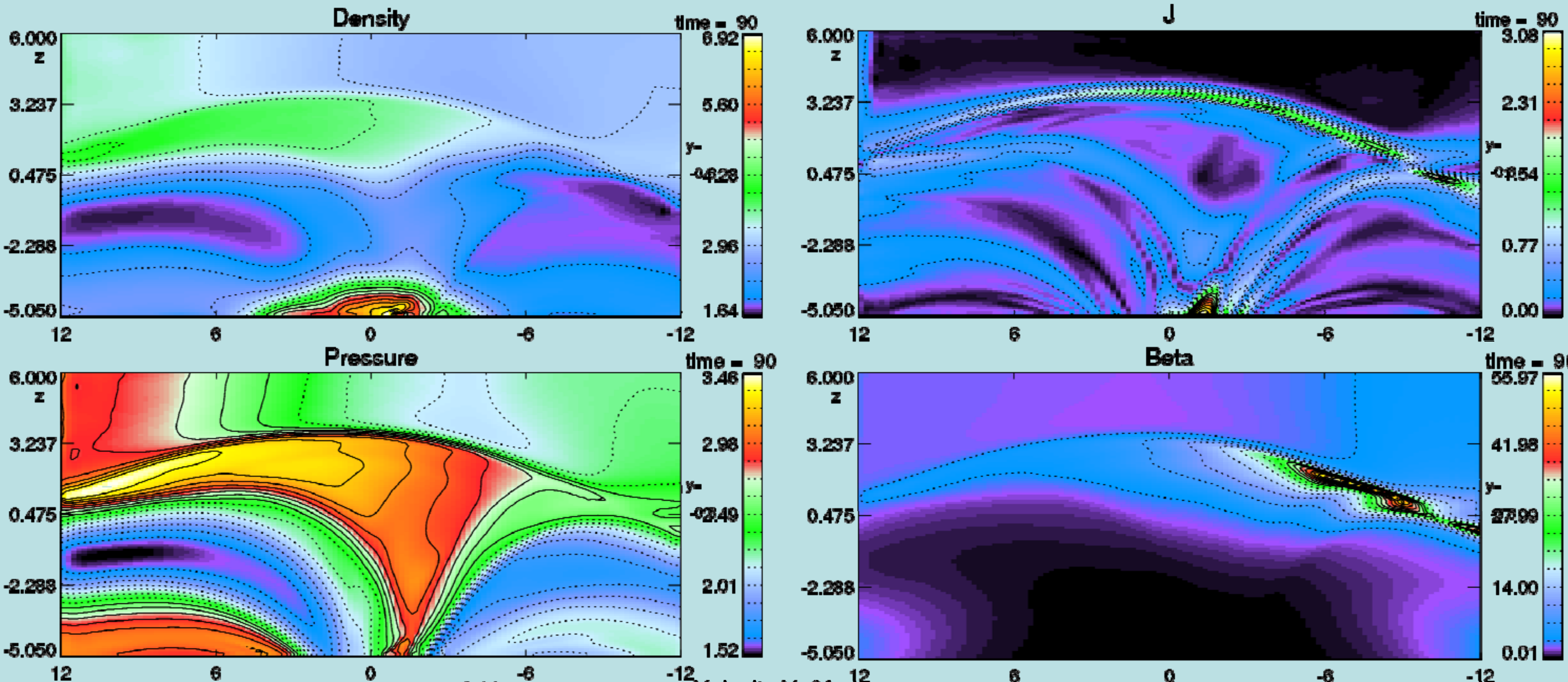


$$v_0 = 1090 km / s$$

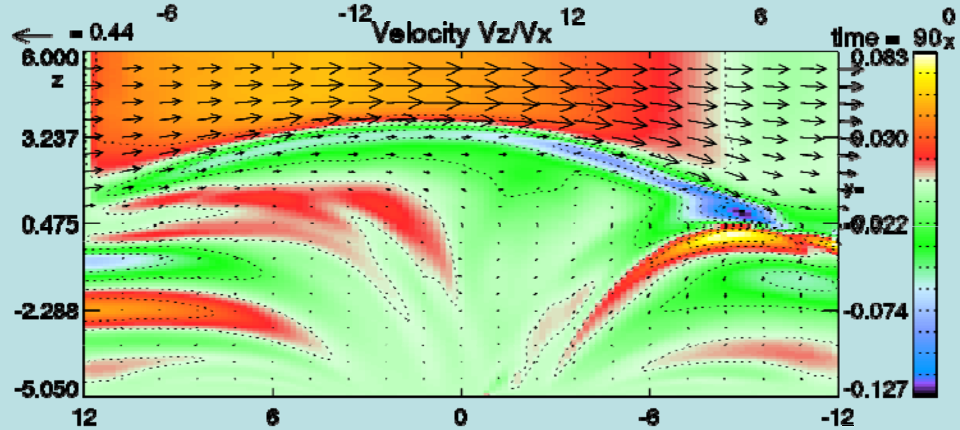
$$B_0 = 50 nT$$

$$L_0 = 6400 km$$

Typical Properties



•Enhanced Density and Pressure

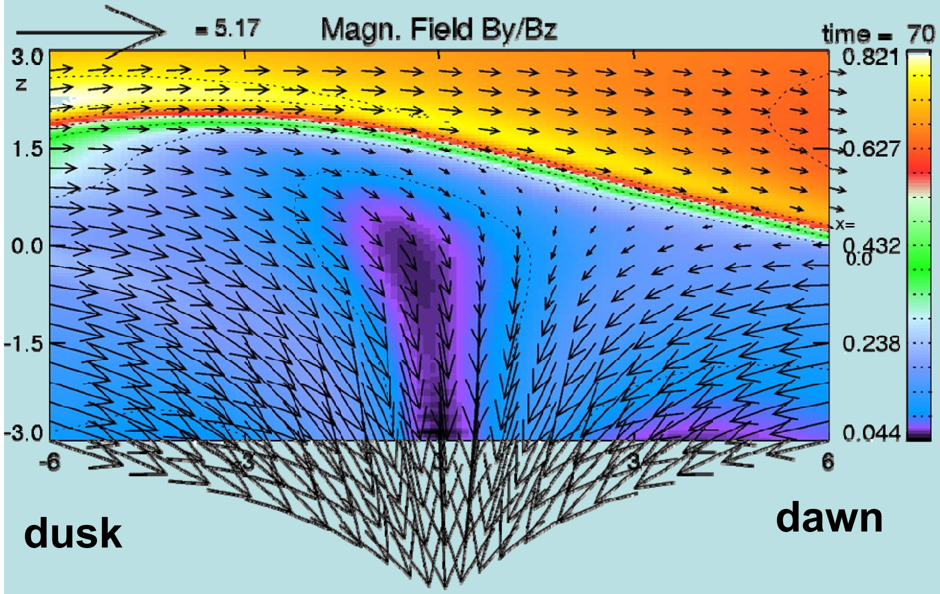


•Thin Current sheet bounding exterior

•High Plasma Beta

•Flows into cusp from reconnection site

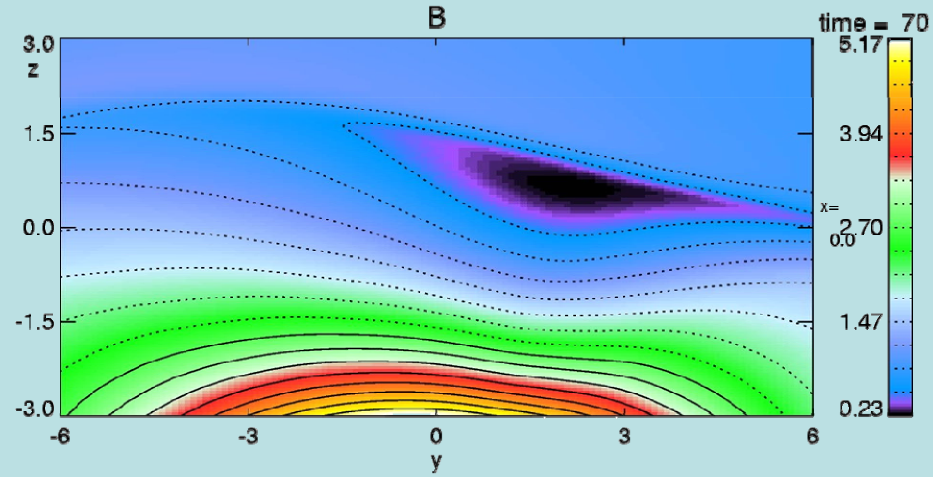
Diamagnetic Cavities

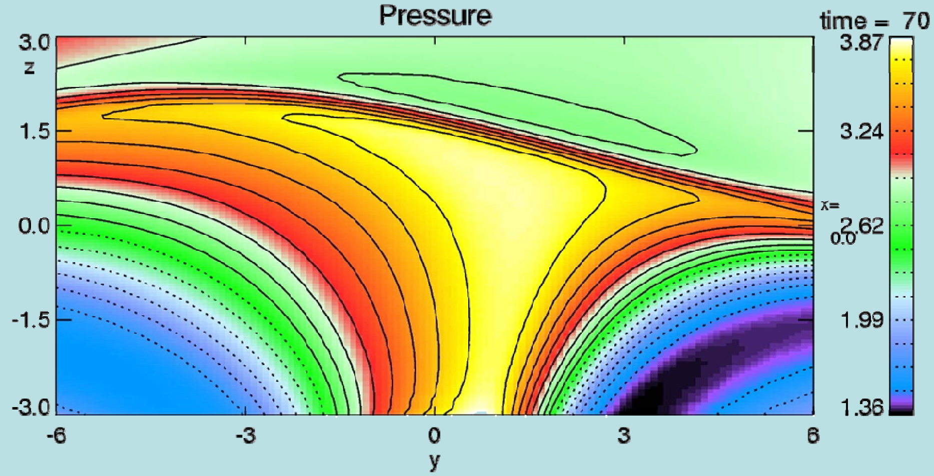


dusk

dawn

- Regions of strongly depressed magnetic field
- Scale: 4 to 6 R_E parallel to boundary; 1 to 2 R_E perpendicular to boundary
- Enhanced pressure and density

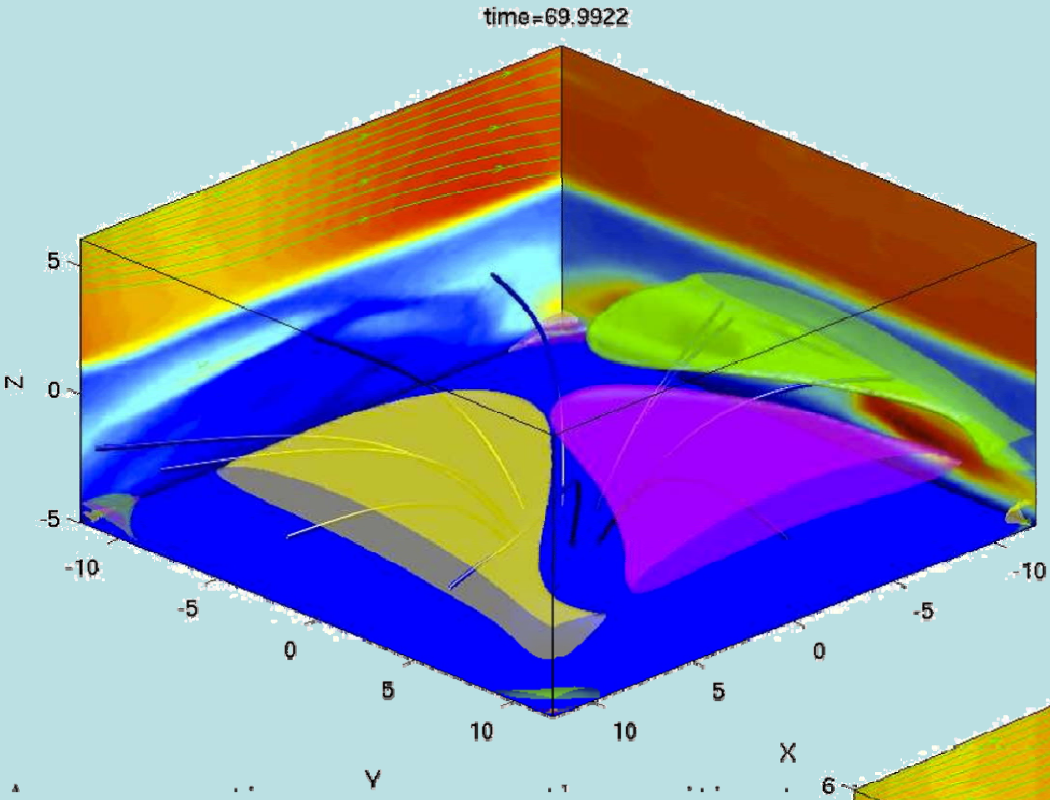


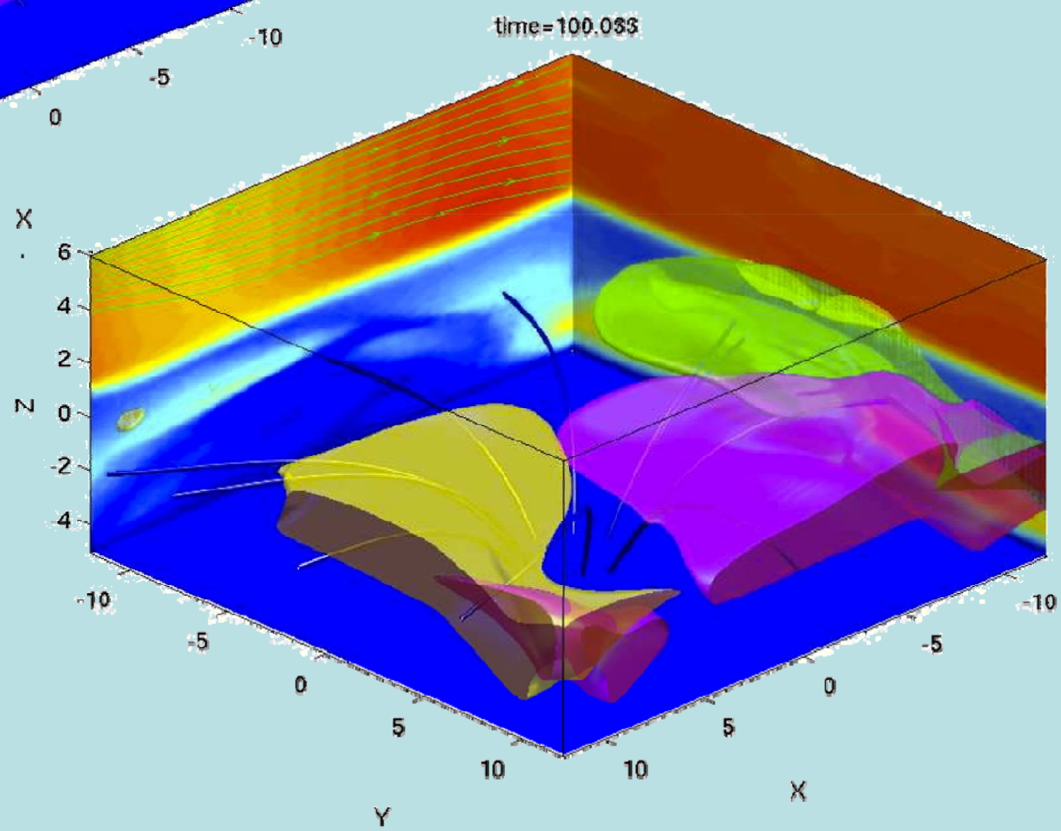


dusk

dawn

Cavity locations superposed for 3 IMF orientations.





Cavities increase in size due to reconnection in region with small guide field.

Test Particle Dynamics –Model:

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i$$

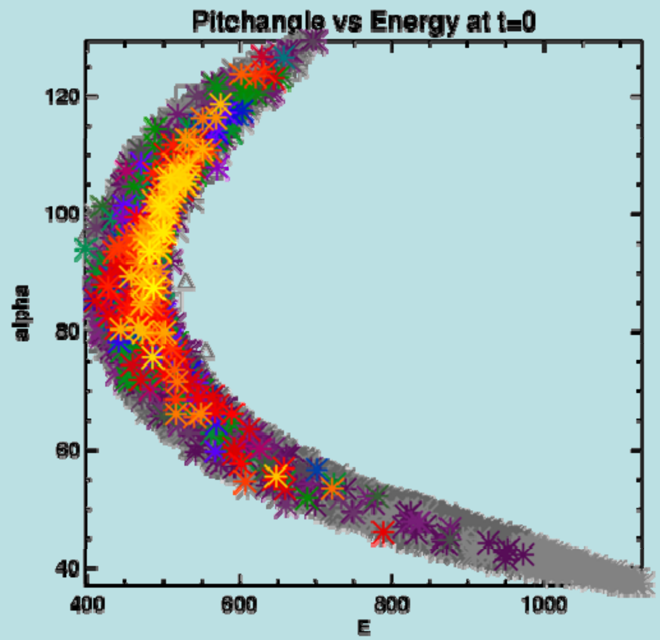
$$\frac{d\mathbf{v}_i}{dt} = \frac{q_i}{m_i}\left(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}\right)_{\mathbf{r}_i,t}$$

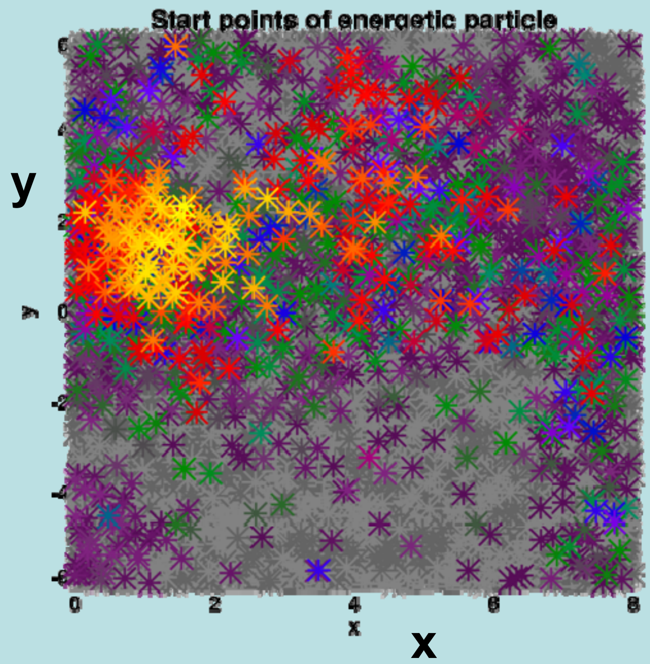
Typical particle properties:

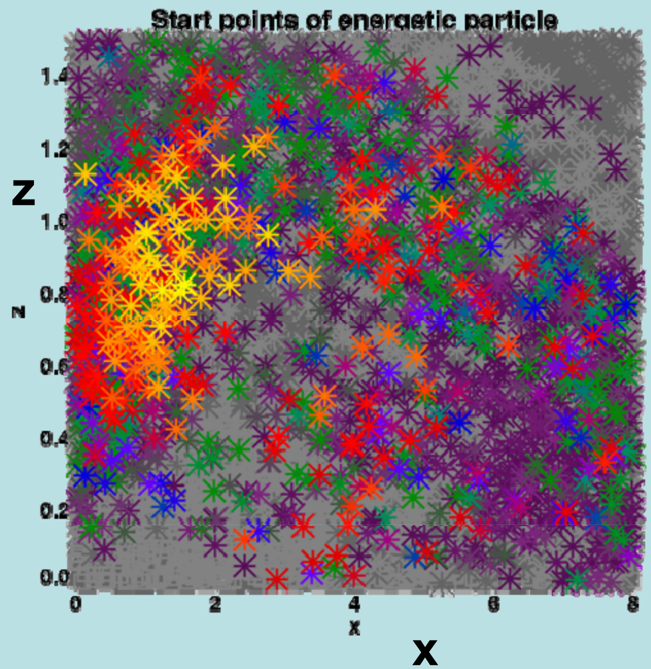
Quantity		Protons	Electrons	He^{++}	O^{+}	O^{++}
Gyro frequency	ω_{cs0}	$3.832\ s^{-1}$	$7025\ s^{-1}$	$1.916\ s^{-1}$	$0.240\ s^{-1}$	$0.479\ s^{-1}$
Gyro time	$t_{cs0} = \omega_{cs0}^{-1}$	0.261 s	$1.423 \cdot 10^{-4}$ s	0.522 s	4.18 s	2.09 s
Gyro period	$2\pi t_{cs0}$	1.640 s	$8.94 \cdot 10^{-3}$ s	3.280 s	26.23 s	13.12 s
Time ratio	t_{cs0}/t_A	$2.51 \cdot 10^{-2}$	$1.371 \cdot 10^{-5}$	$5.03 \cdot 10^{-2}$	0.402	0.201
Gyroradius - v_A	$r_{cs} = v_A/\omega_{cs0}$	161 km	87.8 m	321 km	2575 km	1287 km
Energy[1] for v_A	$m_s v_A^2/2$	1.98 keV	1.081 eV	7.93 keV	31.7 keV	31.7 keV
Thermal speed	$v_{ths} = \sqrt{\frac{k_B T_0}{m_s}}$	309 km/s	13,200 km/s	154 km/s	77.2 km/s	77.2 km/s
Therm. gyrorad.	v_{ths}/ω_{cs0}	80.6 km	1.88 km	80.4 km	322 km	161 km

Particle Dynamics:
Initial conditions

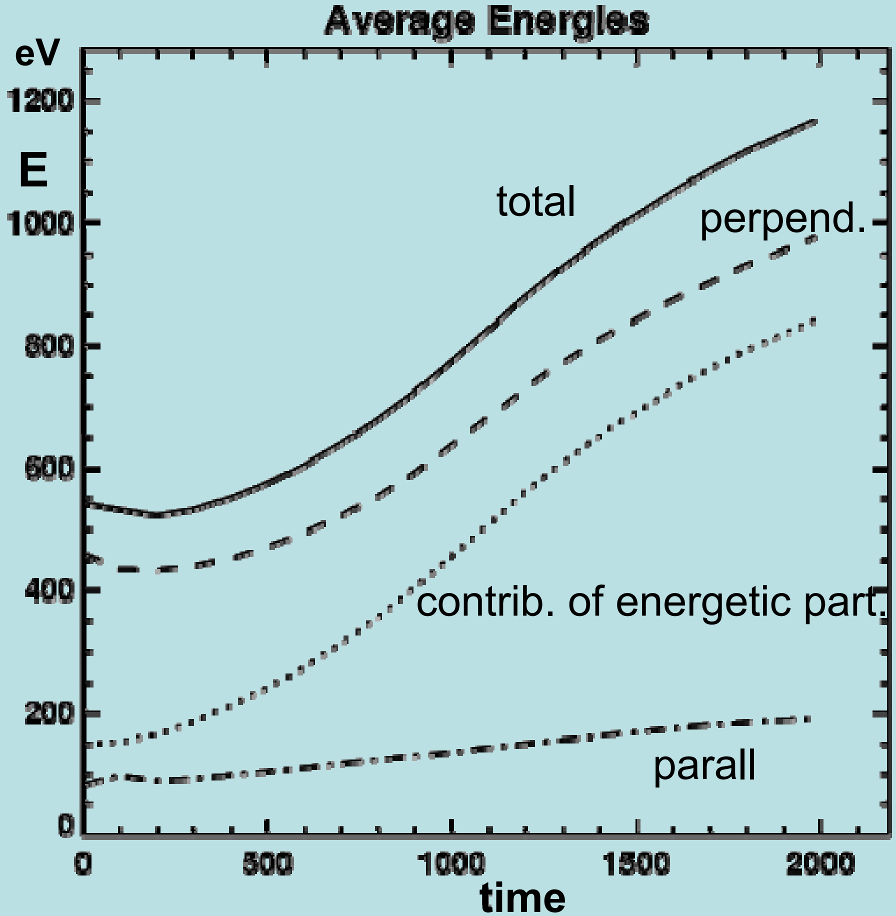
- Shell distributions in velocity (e=500eV)
- Random distribution in space
- Color codes max energy (see next slide)
- Number of particles: here 20000

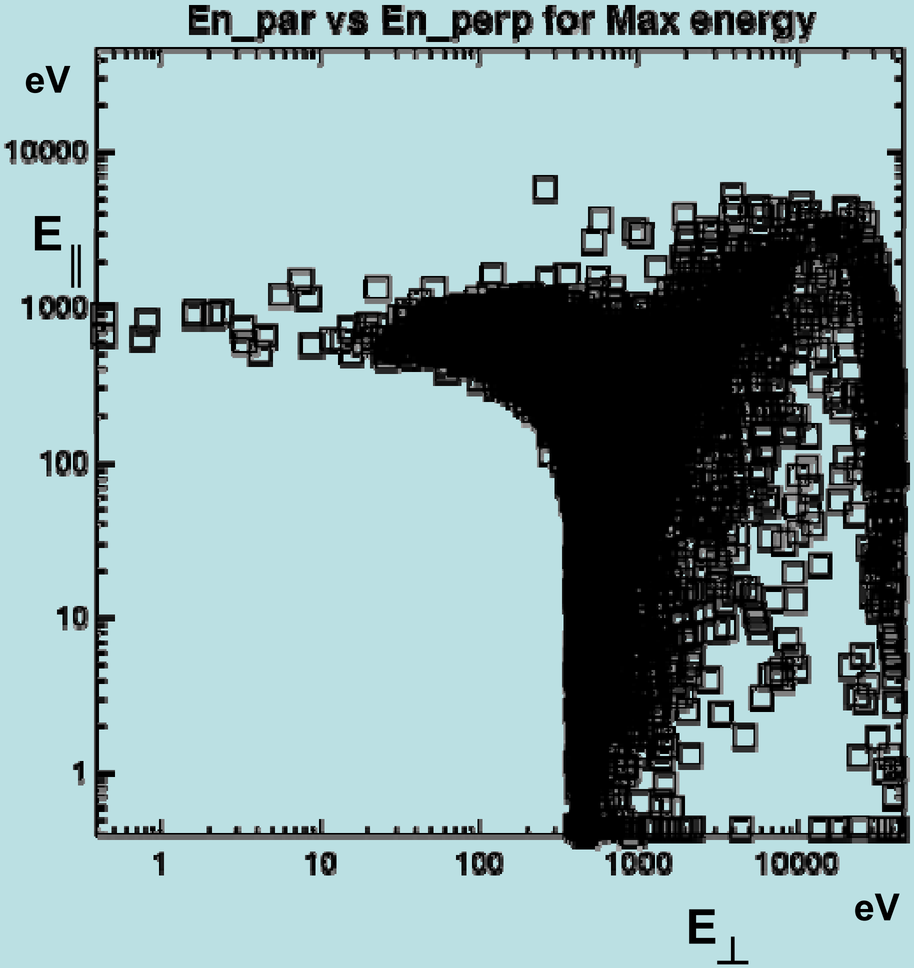






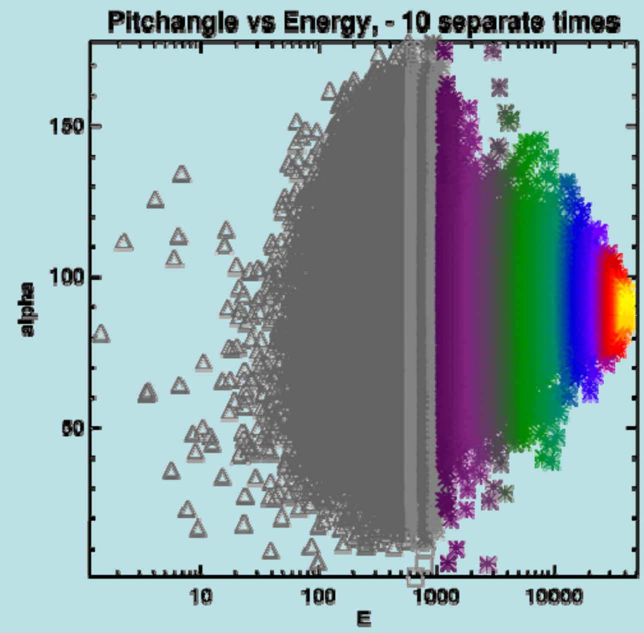
Particle Dynamics:
Total/average energy





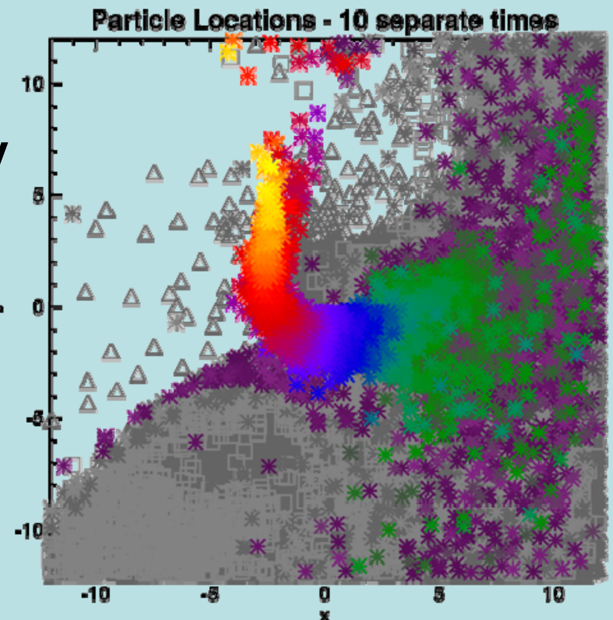
Particle Dynamics:
Evolution inside of simulation domain

Pitch angle



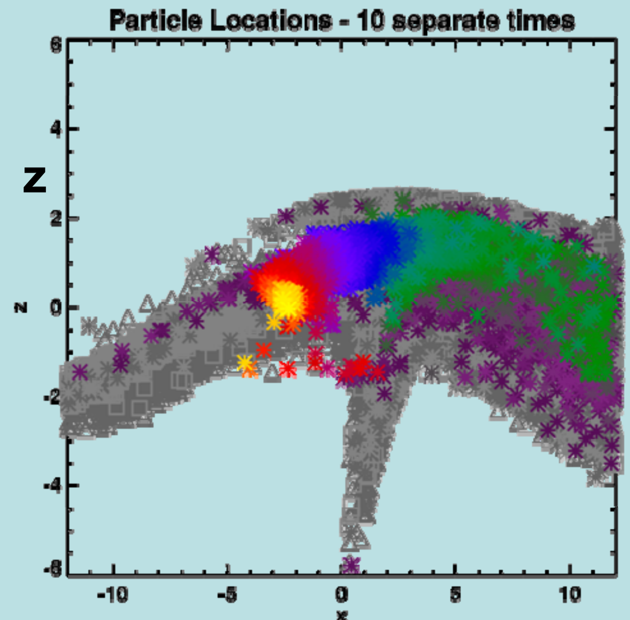
90

y



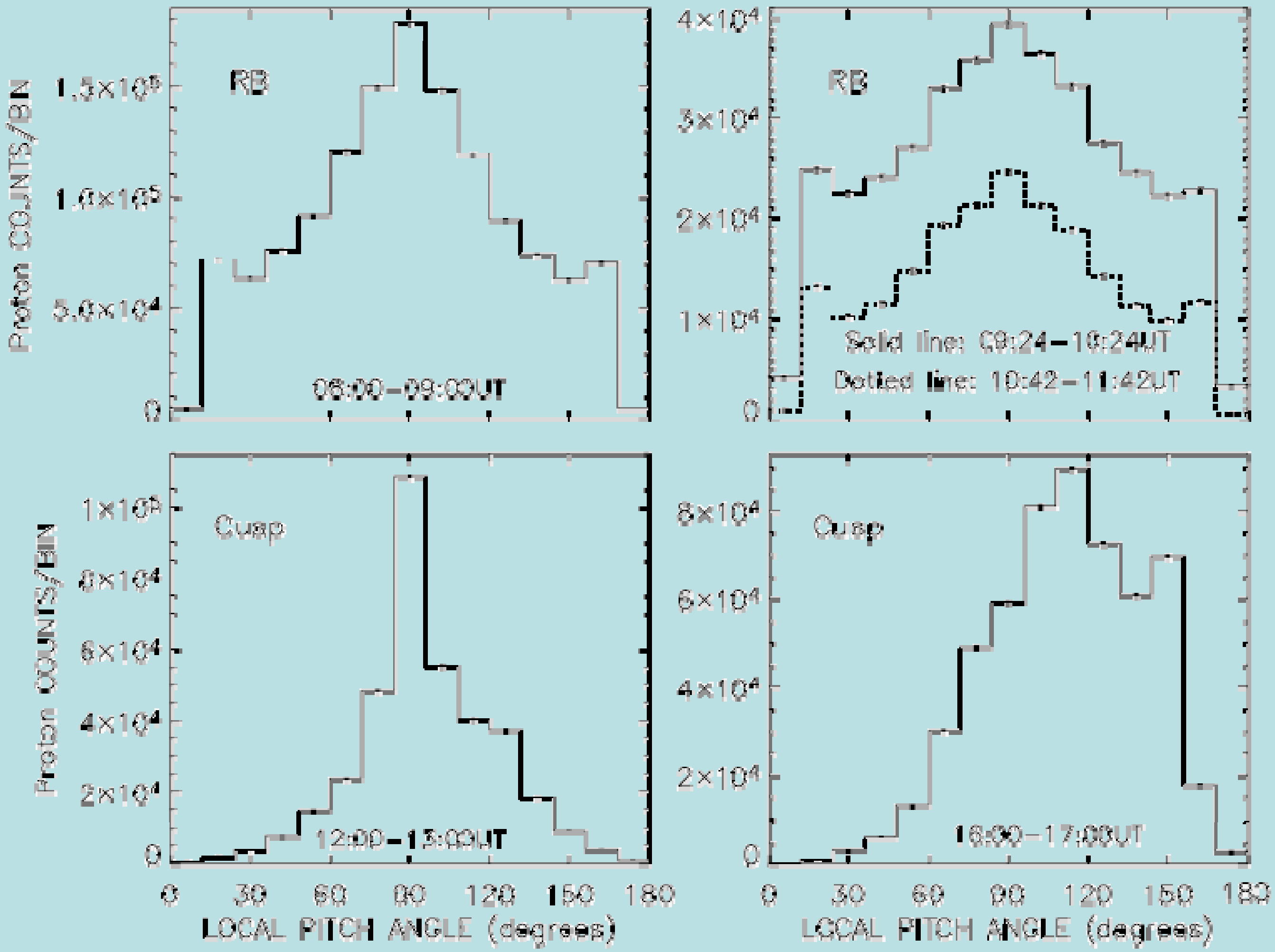
x

z



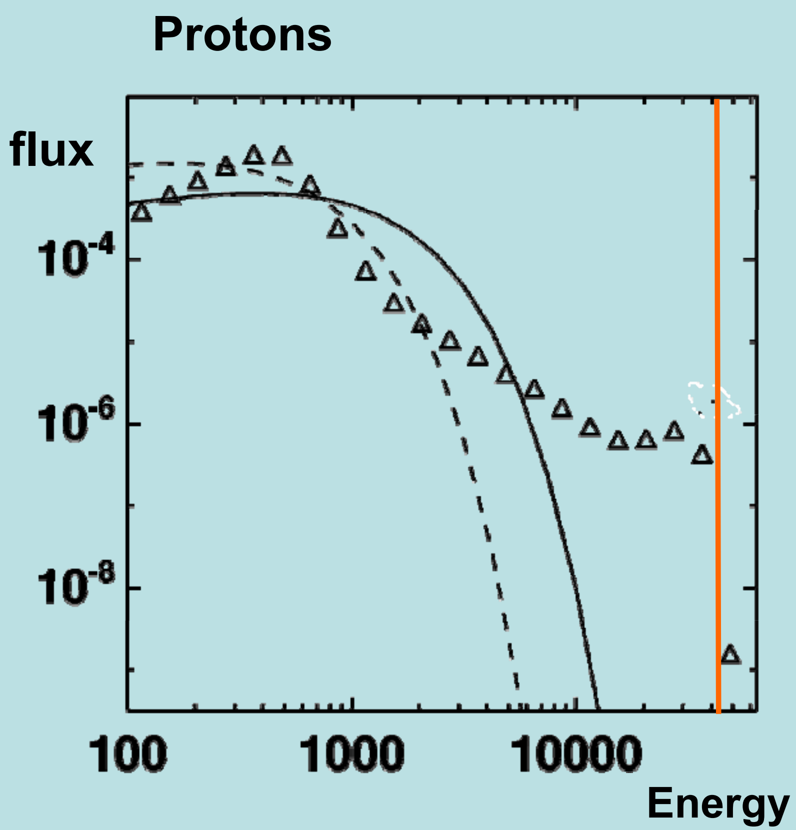
x

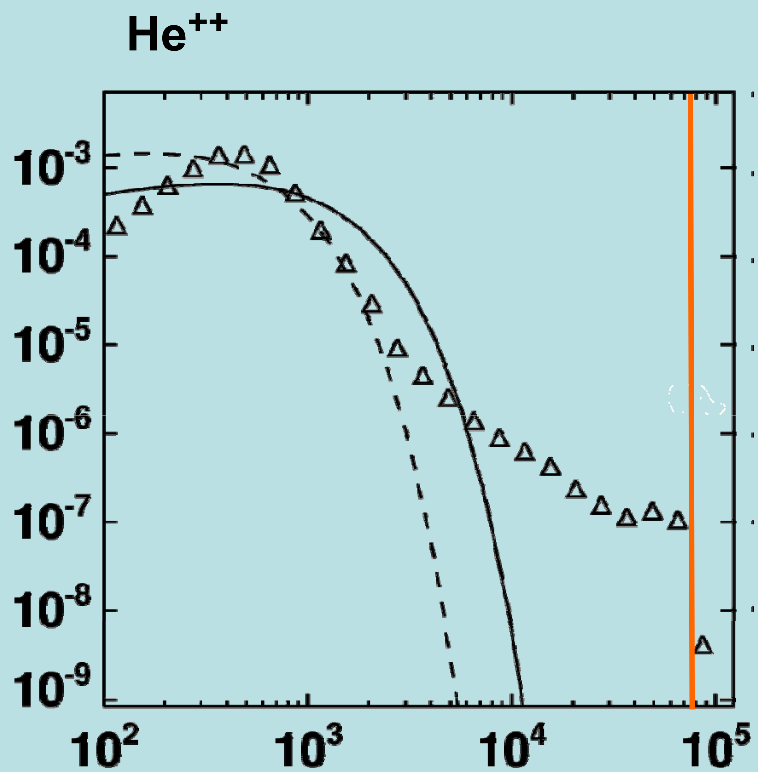
Polar Observations: Pitchangle distribution



Chen and Fritz, 2004

Simulation: Particle Fluxes



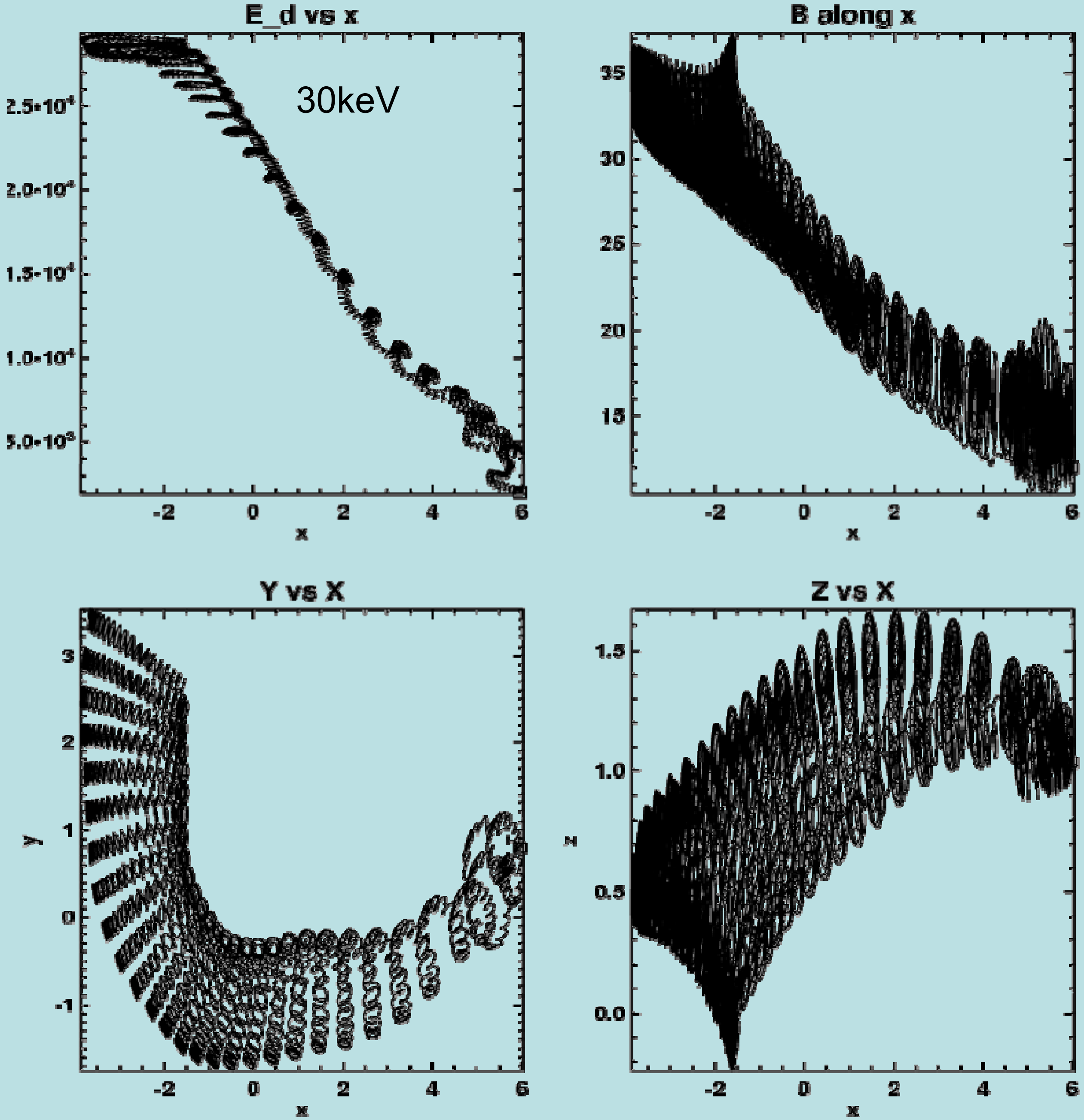


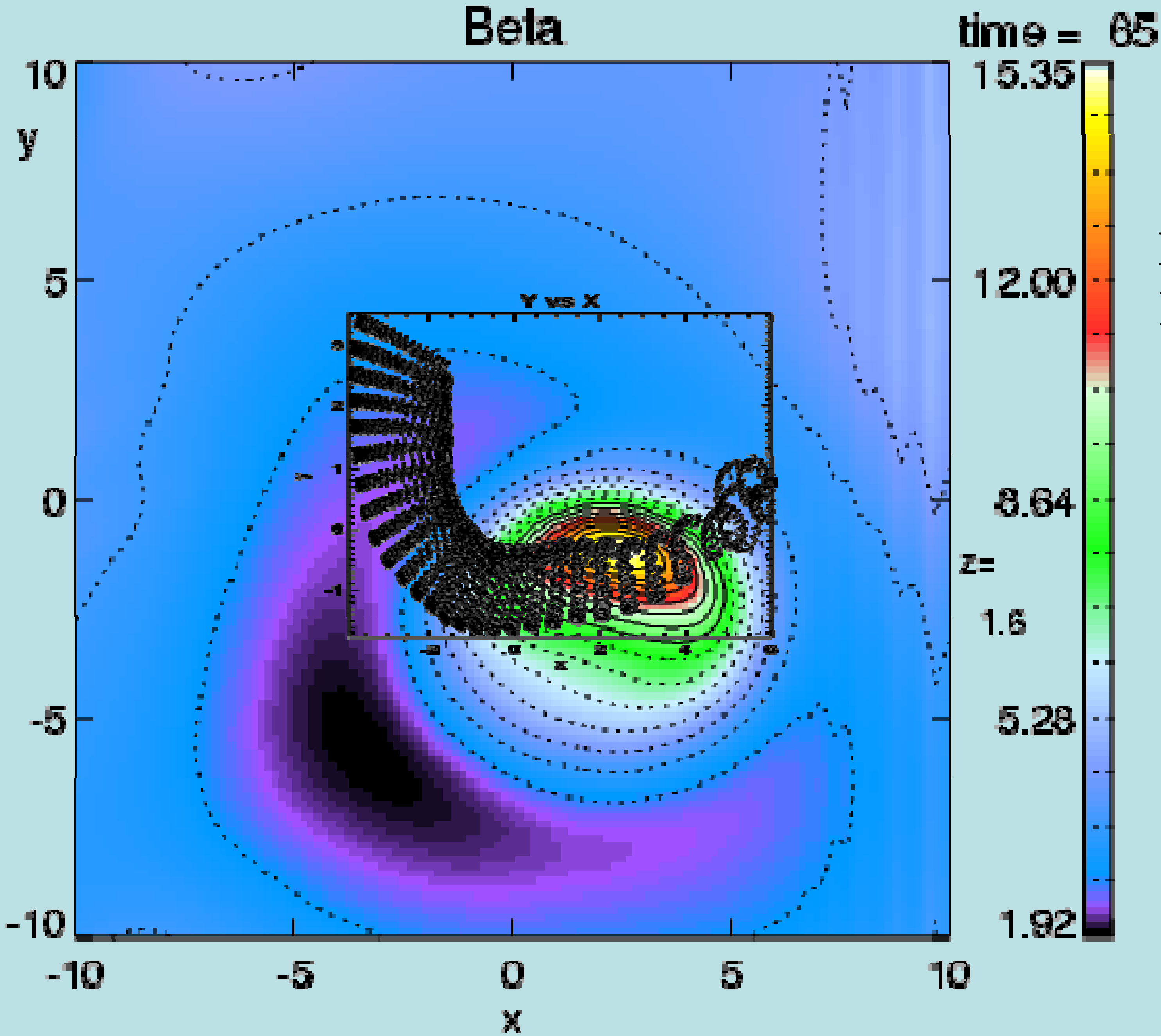
Triangles – flux constructed from test particles in the simulation domain (left) and particles leaving the domain (right)

Dashed – flux corresponding to a Maxwellian with the initial thermal energy

Solid – flux corresponding to a Maxwellian with the maximum thermal energy

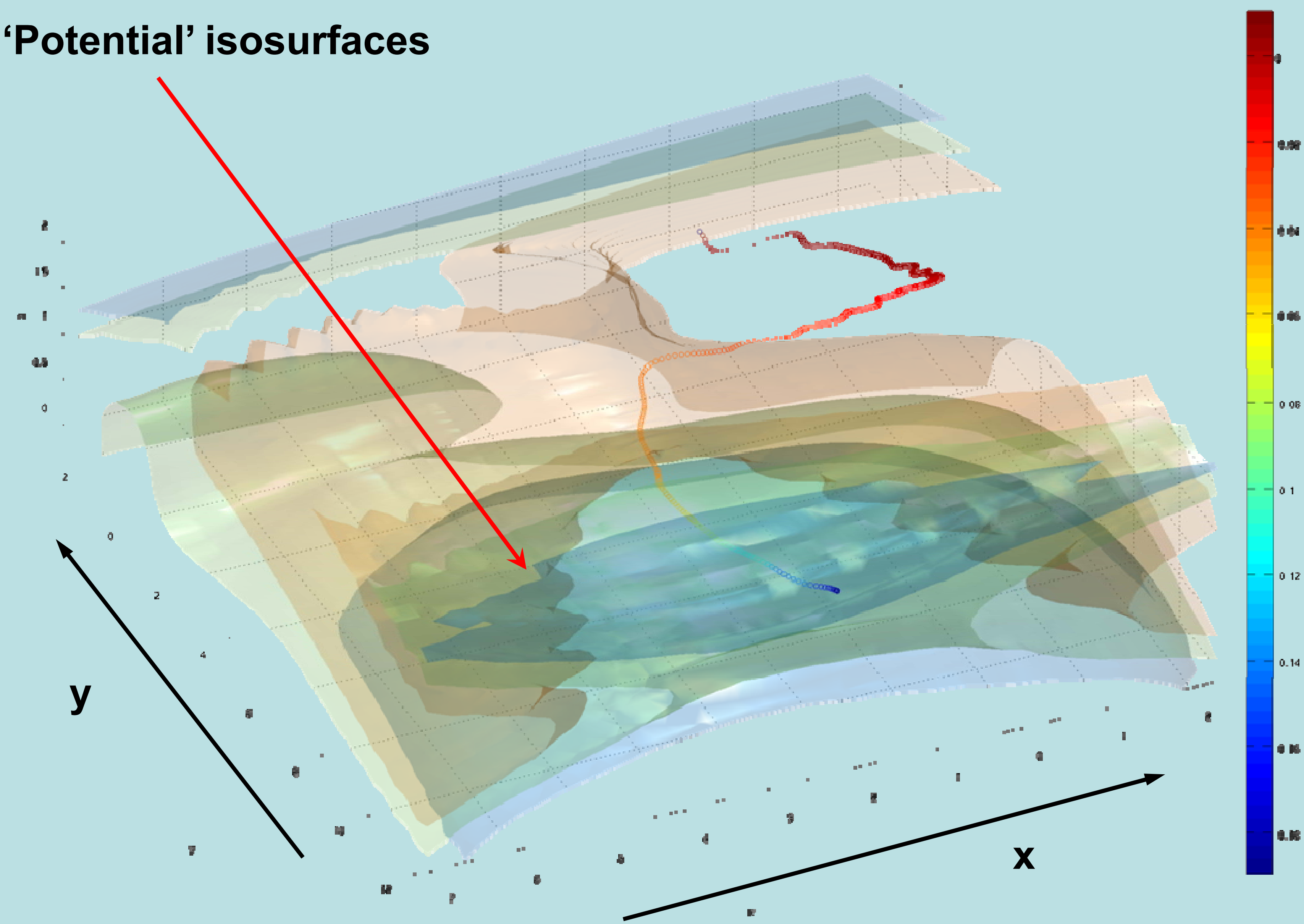
Particle Dynamics: Example 1





Particle Dynamics: Example 1

Particle motion in Cusp ‘potential’



Mechanism:

- **Highly efficient particle trapping.**
- **Particle motion: Combination of gradient curvature and ExB drift.**
- **Gradient curvature drift along the electric field component**

Scaling of the acceleration process:

Drift velocity:

$$v_{gd} = \frac{mv_\perp^2}{2qB^3}\left(\mathrm{B} \times \nabla B\right) \propto \frac{v_\perp r_c}{L_g} \quad \textbf{with} \quad r_c / L_g \propto 1/B$$

Electric field:

$$E \propto v_A B = B^2 / \sqrt{n}$$

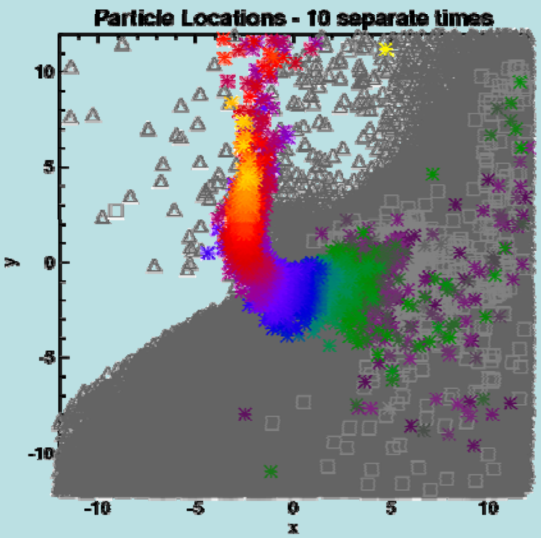
Energy:

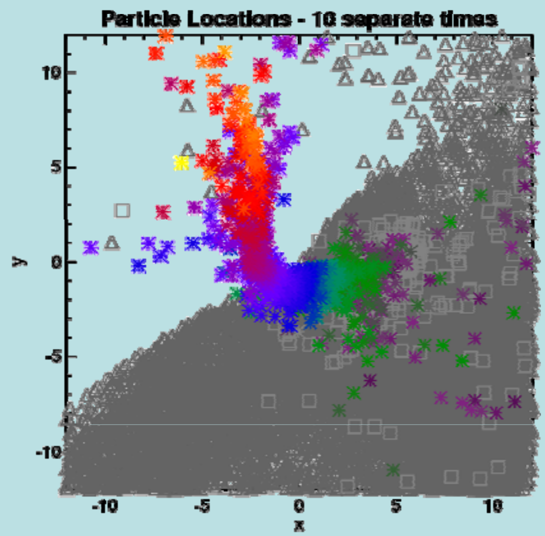
$$W \propto \int E \cdot ds \propto B^2 L_0 / \sqrt{n}$$

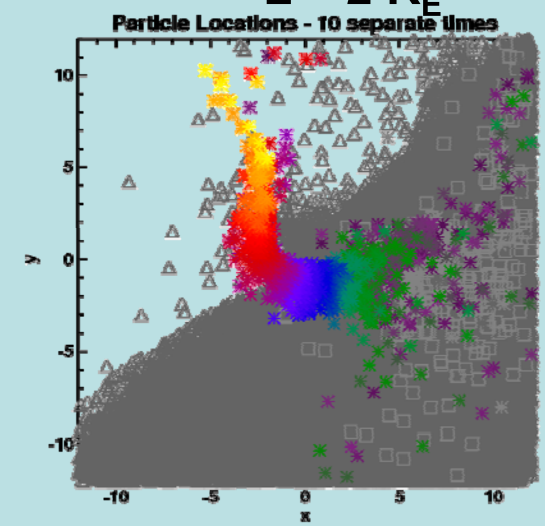
Particle Dynamics: Scaling laws

B_0 = 40 nT, L = 1 R_E | **B_0 = 80 nT** | **L = 2 R_E**

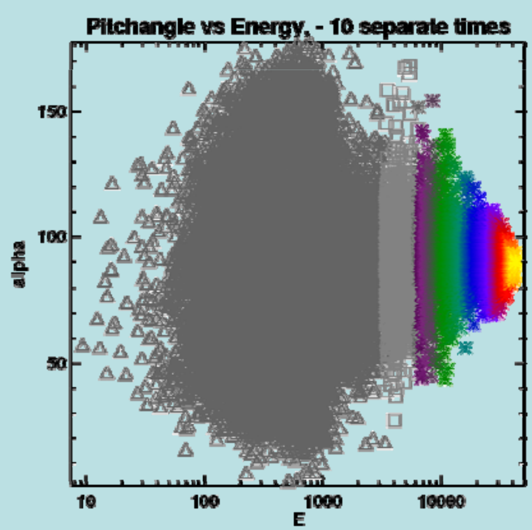
Particle drift paths:

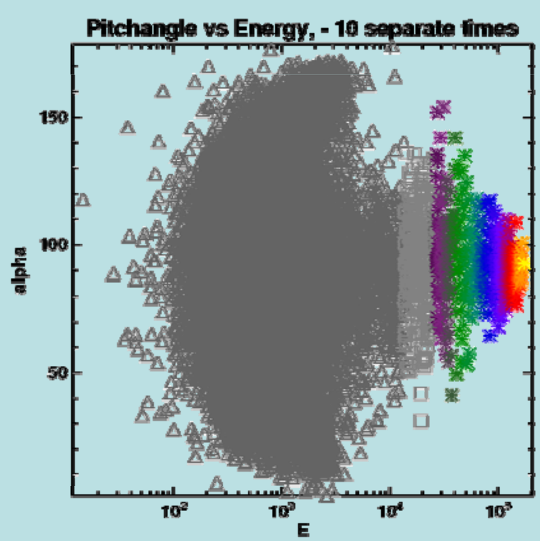


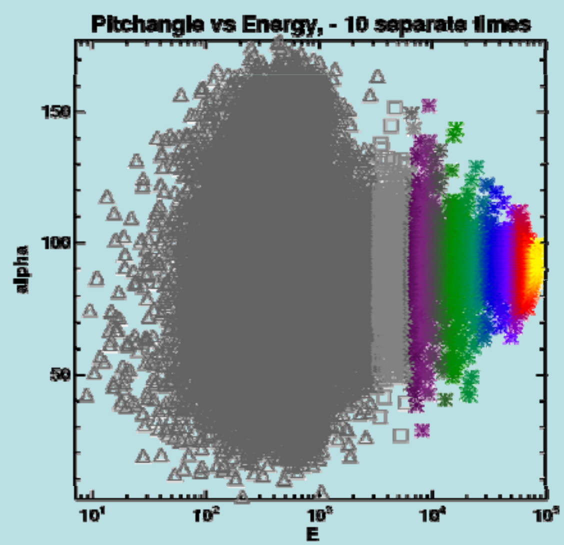




Particle Distrib:

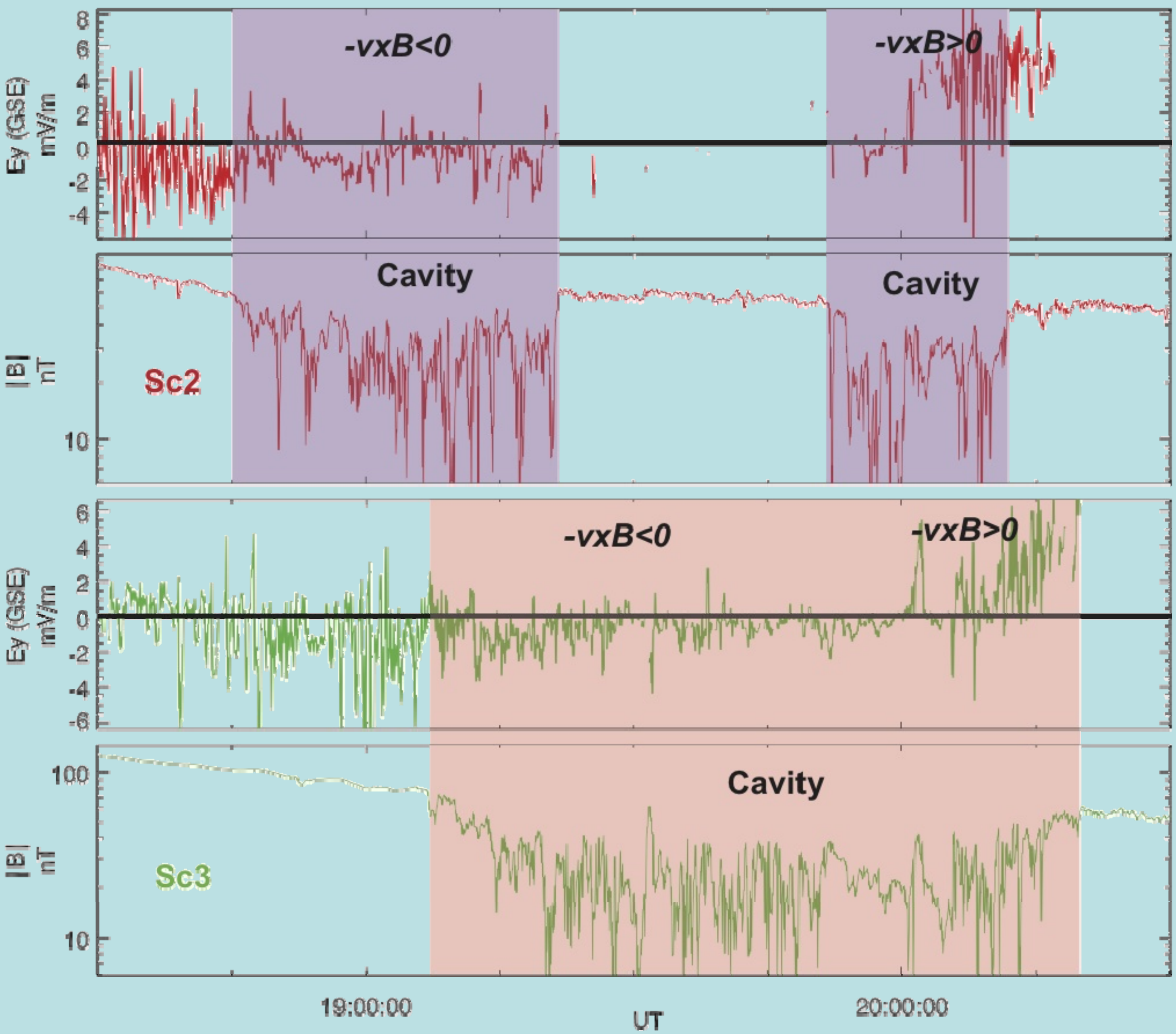






Max. Energy: ~50 keV | ~200 keV | ~100 keV

Model: Energy gain for duskward ion motion and $B_z < 0$
and dawnward ion motion and Bz > 0



Consistent with Cavity E_y in Cluster event!

Summary on Particle Acceleration

Mechanism:

- Highly efficient particle trapping.
- Particle motion: Combination of gradient curvature and ExB drift.
- Gradient curvature drift along the electric field component

Scaling:

- Nonadiabaticity -> less spatially confined distributions, no contrib. to acceleration!
- Energy gain scales proportional to electric field $\sim E \sim B^2$ and length scale $\sim L_0$
- Temporal scale $\sim 1/B$, $\sim L_0$, and $\sim 1/m$

Other:

- Energization not confined to inertial length scales!
- Primary energization in perpendicular direction.
- Parallel electric field = 0!
- Particle trapping + perpendicular electric field natural for high beta regions (magnetic neutral points, diamagnetic cavities, ..)
- Solar particle acceleration
- Particle dynamics and acceleration of key importance in many space plasma systems

Concluding remarks:

- Cusps are rich in physics and play an important role for the magnetosphere
- Important aspects:
    - Magnetic reconnection
    - Particle entry and precipitation
    - Ion outflow
    - Generation or storage of energetic particles
- Unresolved (but progress): Origin of CEP’s
    - Pitch angle distribution
    - Fluxes are higher then in adjacent magnetosheath
    - Presence of Oxygen
    - Presence of energetic electrons