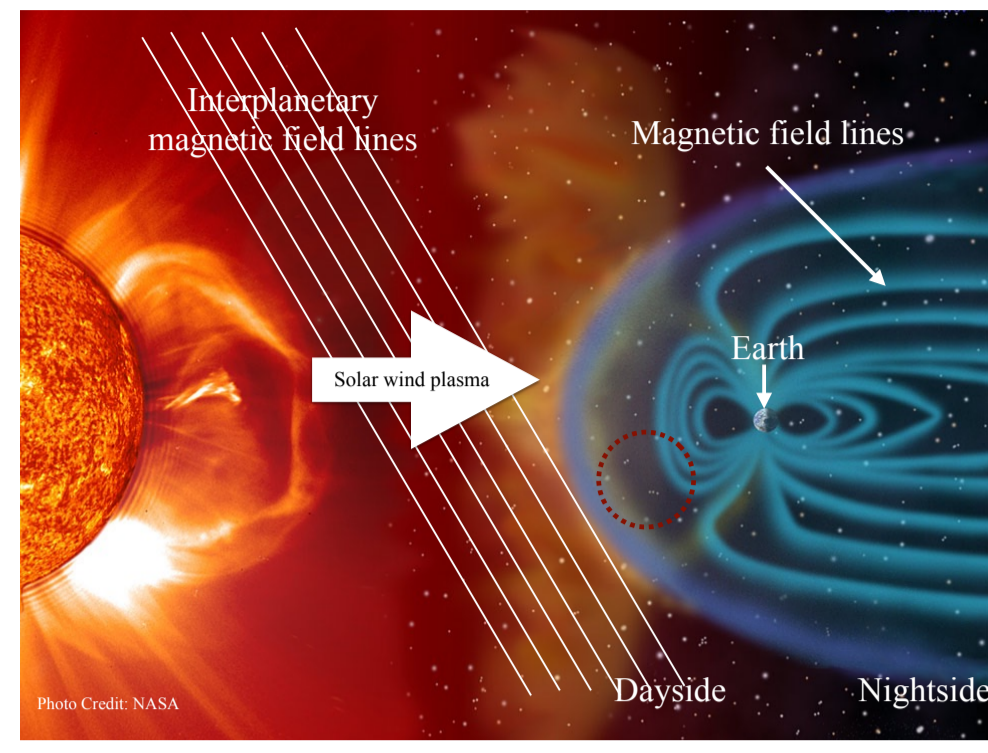


Nonlinear Evolution of Mirror Instability into Magnetic Holes

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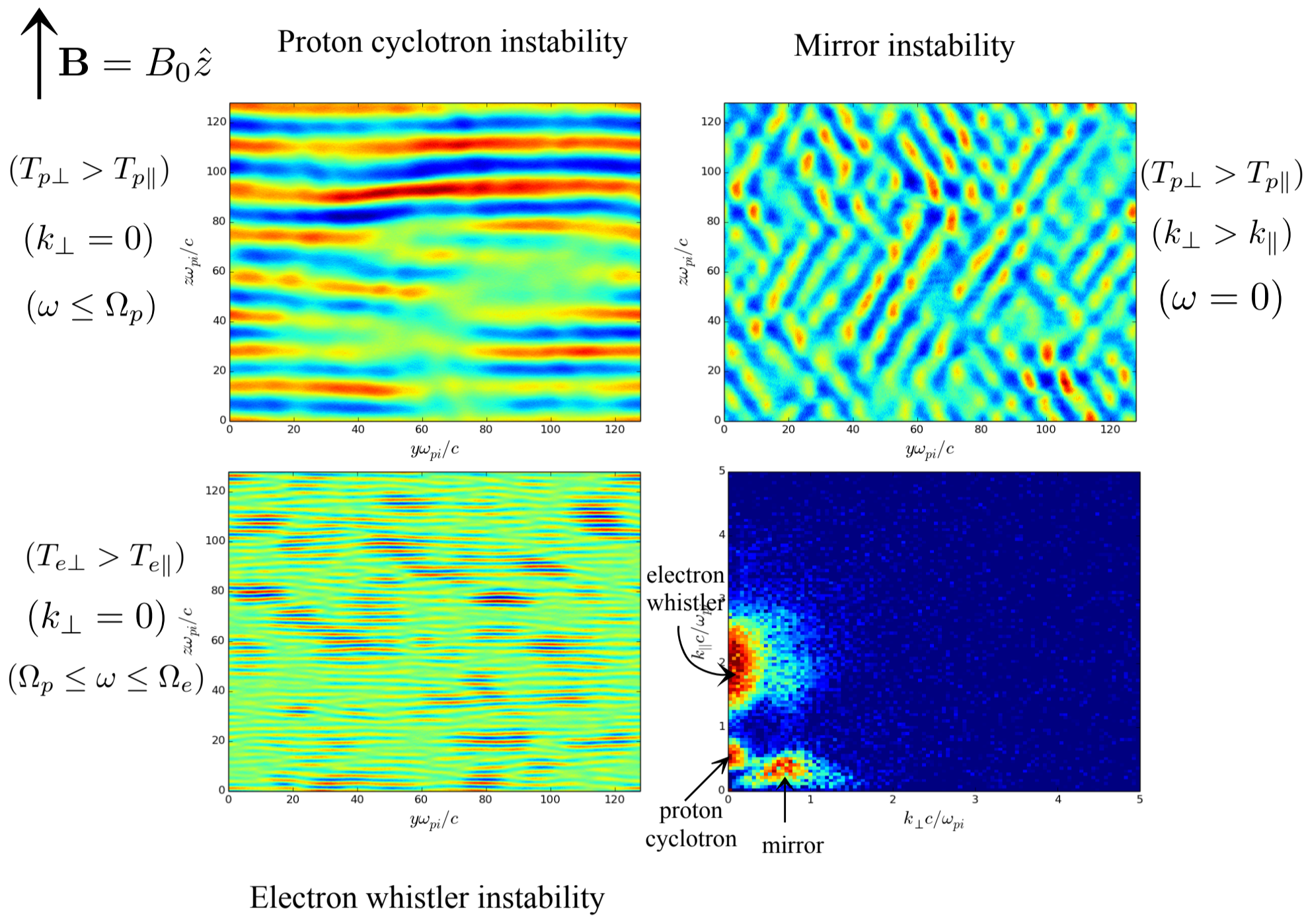
MOTIVATION

- Frequent observations of magnetic holes in planetary magnetosheath, solar wind and comets with $\delta B/B \sim 1$.
- It is believed that nonlinear saturation of mirror instability leads to magnetic holes.
- Does mirror instability evolve to magnetic hole structures?



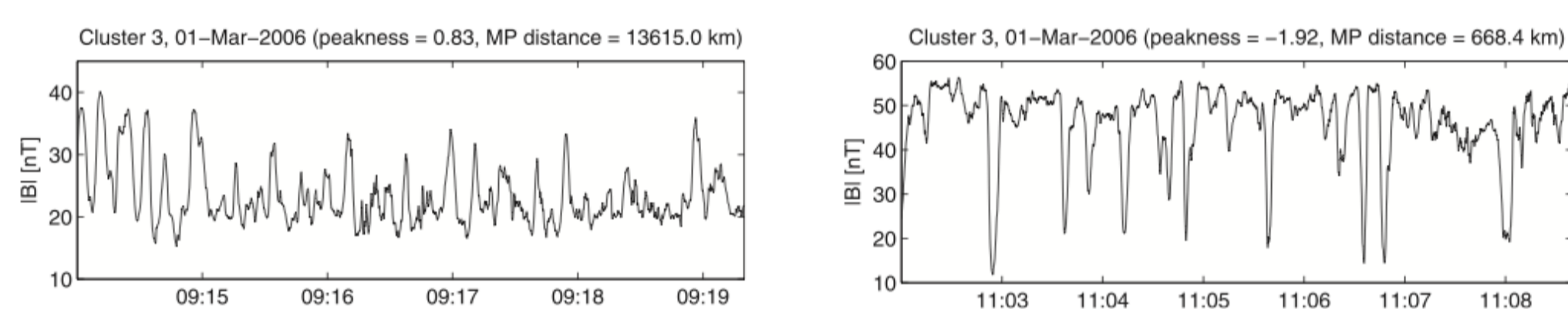
TEMPERATURE ANISOTROPY INSTABILITIES

Figures show our particle-in-cell (PIC) simulations of instabilities that are generated at the presence of temperature anisotropy of larger than one.



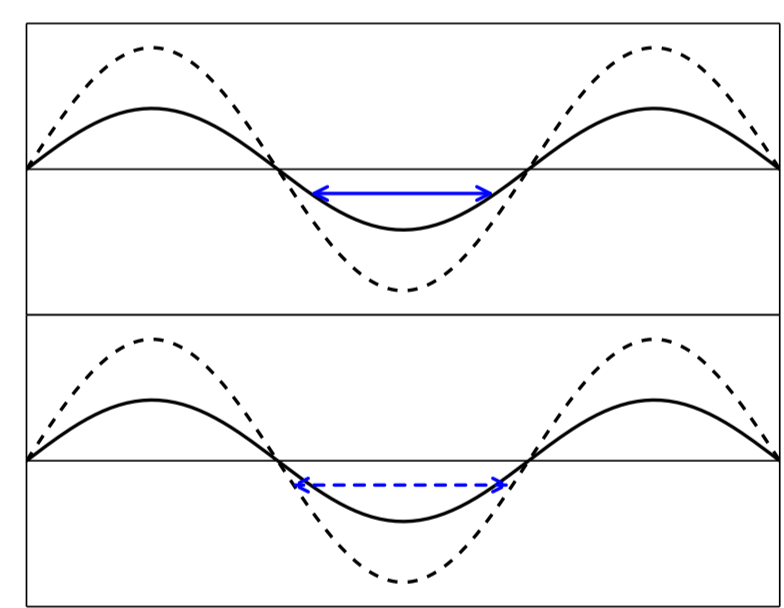
NONLINEAR SATURATION

Mirror structures have been observed in the form of magnetic peaks and magnetic holes in the magnetosheath. (Figures from Soucek et al. [2008])



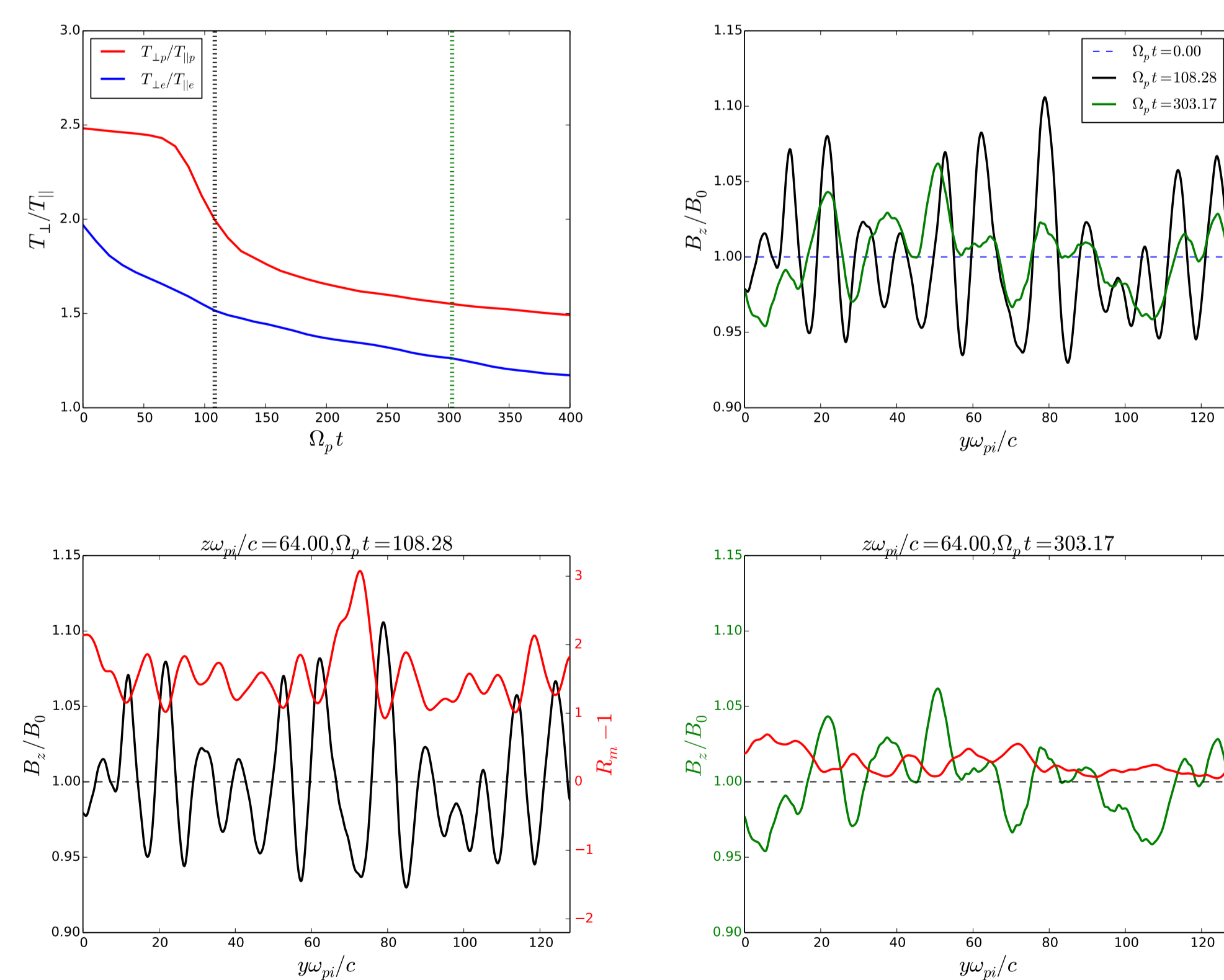
Kivelson and Southwood [1996] predict that plasma becomes mirror stable in magnetic holes if the holes get deeper. They proposed two different saturation mechanisms, one that operates in magnetic peaks and another one for magnetic holes.

- At the peaks, the density and pressure will drop as trapped particles are excluded from the rising field region.
- The cooling for the trapped particles in the hole can be produced by moving magnetic mirrors. If magnetic mirrors move apart, deceleration occurs.



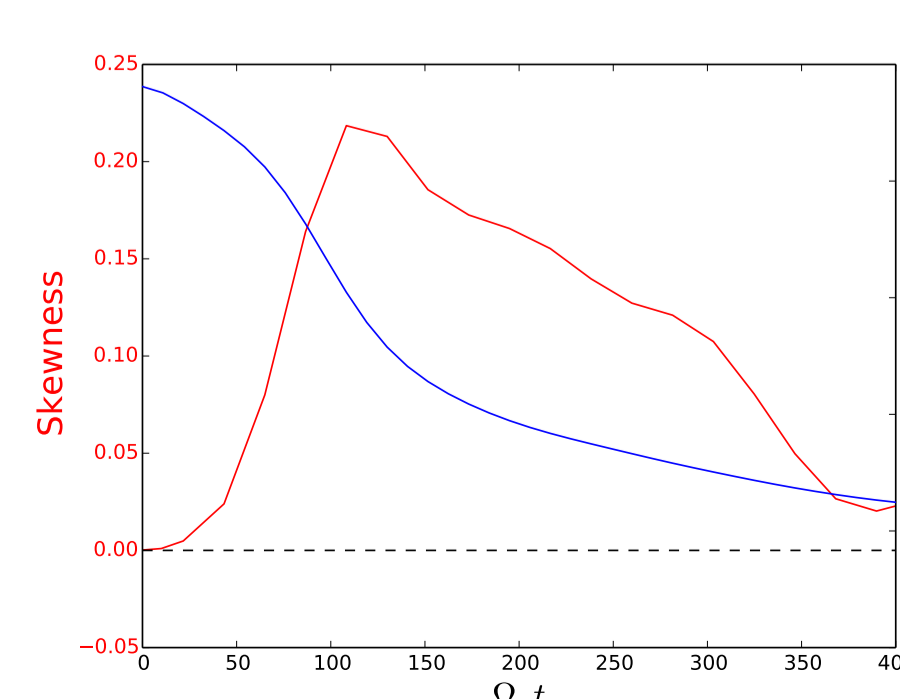
We perform 2D PIC simulation to study the evolution of the mirror structures. Simulation parameters are:

$$l_y = l_z = 128d_p, n_y = n_z = 4096, T_{p\perp}/T_{p\parallel} = 2.5, T_{e\perp}/T_{e\parallel} = 2, \beta_{p\parallel} = \beta_{e\parallel} = 1$$



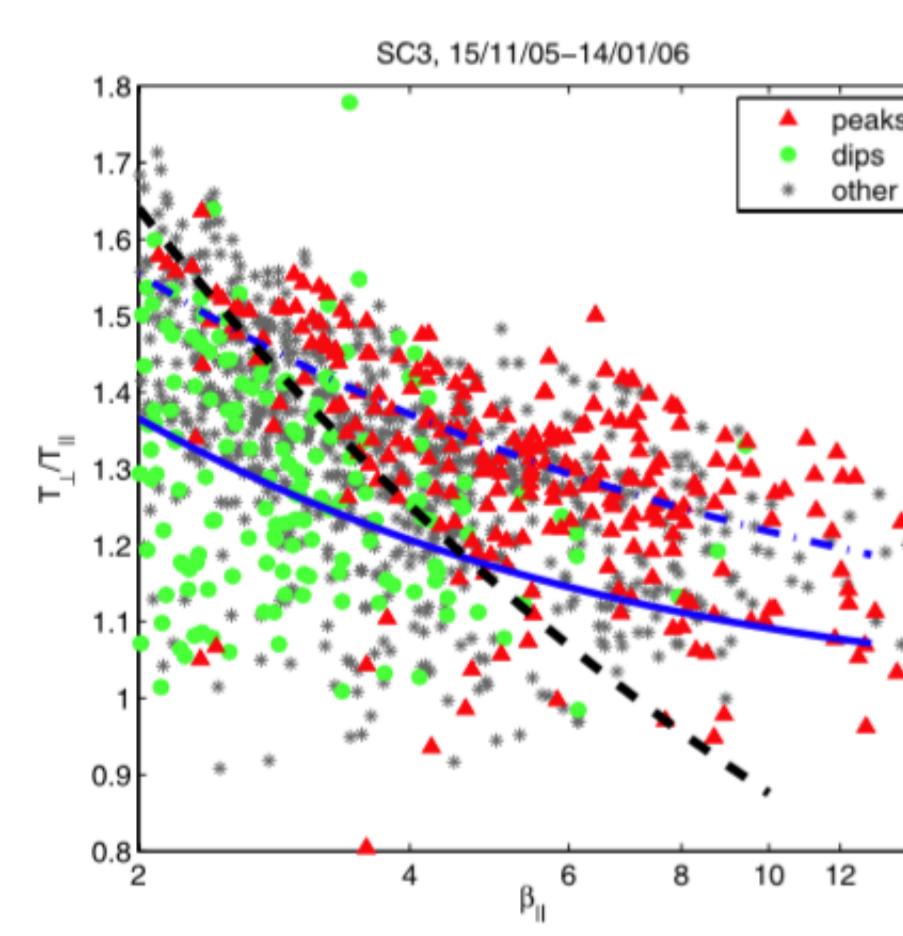
Magnetic holes get shallower and plasma becomes more mirror stable. This contradicts the Kivelson and Southwood prediction.

- Skewness measures the asymmetry of a distribution about its mean. Positive skewness means magnetic peaks are dominant and when magnetic holes are dominant, skewness is negative.
- Skewness is positive and mirror structures are dominated by magnetic peaks.



OBSERVATIONS

- Solid blue line shows mirror instability threshold with cold electron limit.
- Statistical analysis of magnetic fluctuations associated to mirror structures in the magnetosheath show that magnetic holes are observed when plasma is mirror stable or marginally mirror unstable.

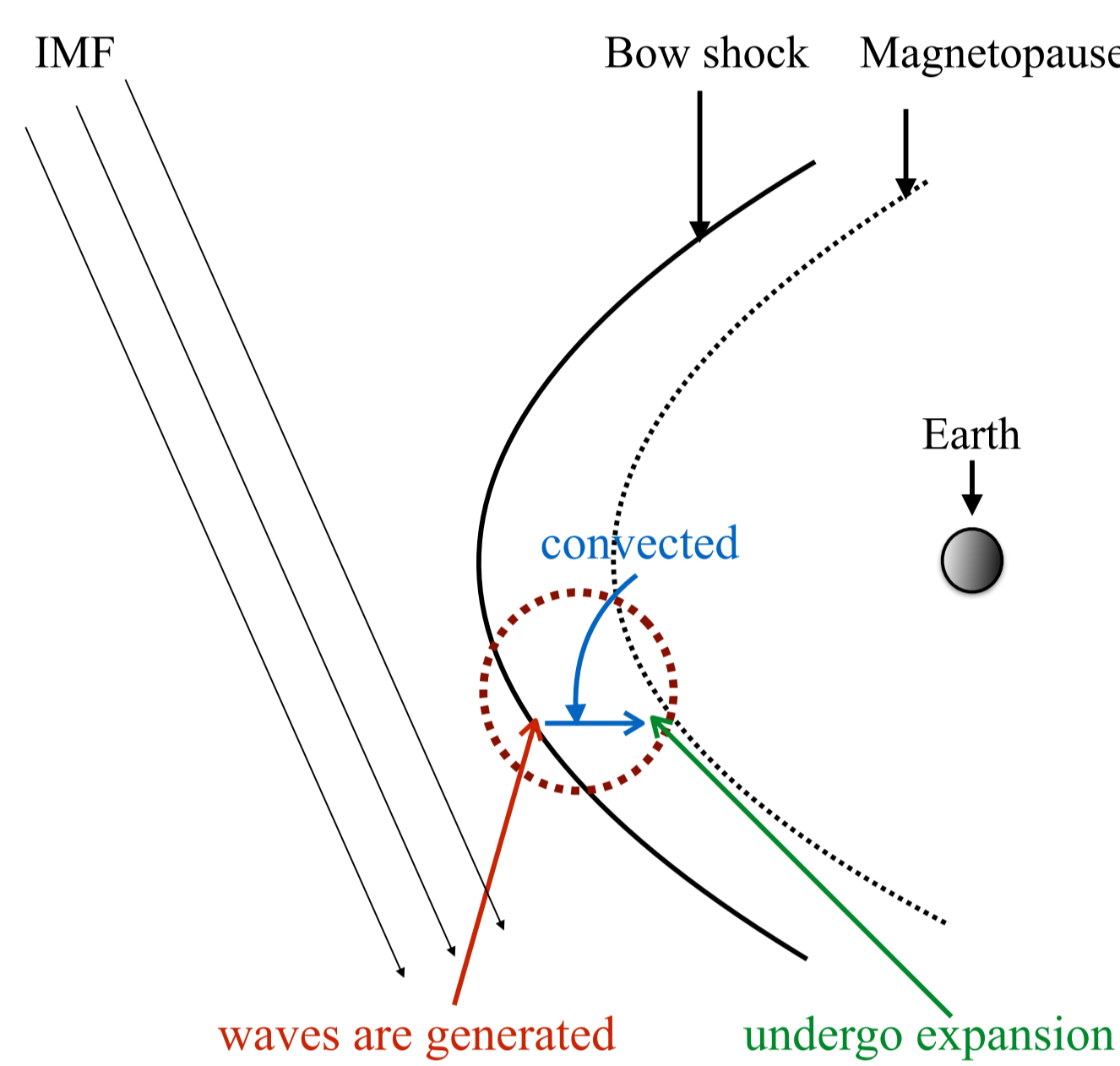


After Soucek et al. (2008)

- Magnetic peaks are observed when plasma is mirror unstable.

Mirror instability threshold ($\gamma_m = 10^{-3}\Omega_p$) is given by:

$$R_m = \beta_{p\perp} \left(\frac{T_{p\perp}}{T_{p\parallel}} - 1 \right) + \beta_{e\perp} \left(\frac{T_{e\perp}}{T_{e\parallel}} - 1 \right) - \frac{1}{2} \frac{\left(\frac{T_{p\perp}}{T_{p\parallel}} - \frac{T_{e\perp}}{T_{e\parallel}} \right)^2}{1/\beta_{e\parallel} + 1/\beta_{p\parallel}} \geq 1 \rightarrow \begin{cases} \text{unstable} & \text{if } R_m - 1 > 0 \\ \text{stable} & \text{if } R_m - 1 < 0. \end{cases}$$



- With an expanding box simulation, we resemble the magnetosheath plasma to study the mirror structures in a mirror stable plasma.

THE PIC METHOD IN AN EXPANDING BOX

We solve the basic equations of the PIC method in the fluid comoving frame, which is related to the laboratory frame by a Lorentz boost, with velocity U . We only consider the non-relativistic limit $U/c \ll 1$ since the compression and expansion velocities in the magnetosheath are nonrelativistic. Compression or expansion are described by a diagonal matrix:

$$L = \begin{pmatrix} a_x & 0 & 0 \\ 0 & a_y & 0 \\ 0 & 0 & a_z \end{pmatrix}, a_j = 1 + q_j t \text{ (expansion)}, a_j = 1/(1 + q_j t) \text{ (compression)}$$

- The plasma density evolves as $n(t) = \frac{n(0)}{L_x(t)L_y(t)L_z(t)}$ and the magnetic field evolves as $\vec{B}(t) = \frac{\sum_j L_j(t)(B_j(0) - \vec{e}_j^T \cdot \vec{e}_j)}{L_x(t)L_y(t)L_z(t)}$
- For a slow expansion or compression, when there are no waves present in the system, the first and second adiabatic invariants would be conserved, based on CGL condition,

$$\text{First adiabatic invariant: } \frac{d}{dt} \left(\frac{p_{\perp}}{nB} \right) = 0 \rightarrow T_{\perp} \propto B$$

$$\text{Second adiabatic invariant: } \frac{d}{dt} \left(\frac{p_{\parallel} B^2}{n^3} \right) = 0 \rightarrow T_{\parallel} \propto \frac{n^2}{B^2}$$

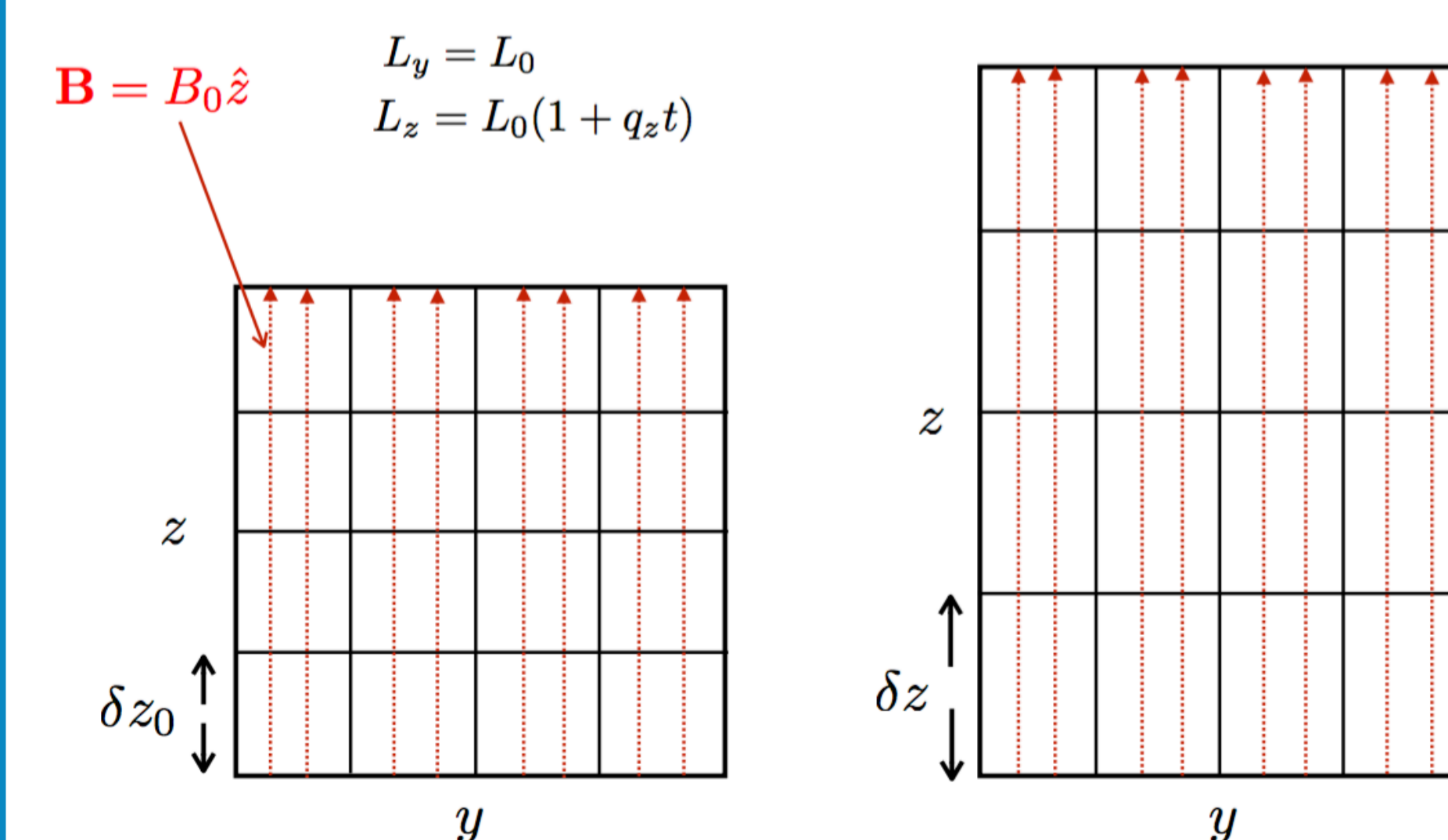
PARALLEL EXPANSION IN THE MAGNETOSHEATH

For an adiabatic expansion parallel to the background magnetic field:

$$a_x = a_y = 1, a_z = (1 + q_z t) \rightarrow L_y = L_0, L_z = L_0(1 + q_z t)$$

$$B \propto \text{constant}, n \propto 1/L_z, T_{\perp} \propto \text{constant}, T_{\parallel} \propto 1/L_z^2,$$

$$T_{\perp}/T_{\parallel} \propto L_z^2 = (1 + q_z t)^2, \beta_{\perp} \propto 1/L_z = 1/(1 + q_z t), \beta_{\parallel} \propto 1/L_z^3 = 1/(1 + q_z t)^3$$



- For a parallel expansion, temperature anisotropy increases and plasma beta decreases. If we expand the simulation box long enough, plasma becomes mirror stable.

CONTACT

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MAGNETIC HOLES IN THE MAGNETOSHEATH

We perform parallel expansion simulation to study the evolution of the mirror structures in a mirror stable plasma. Simulation parameters are:

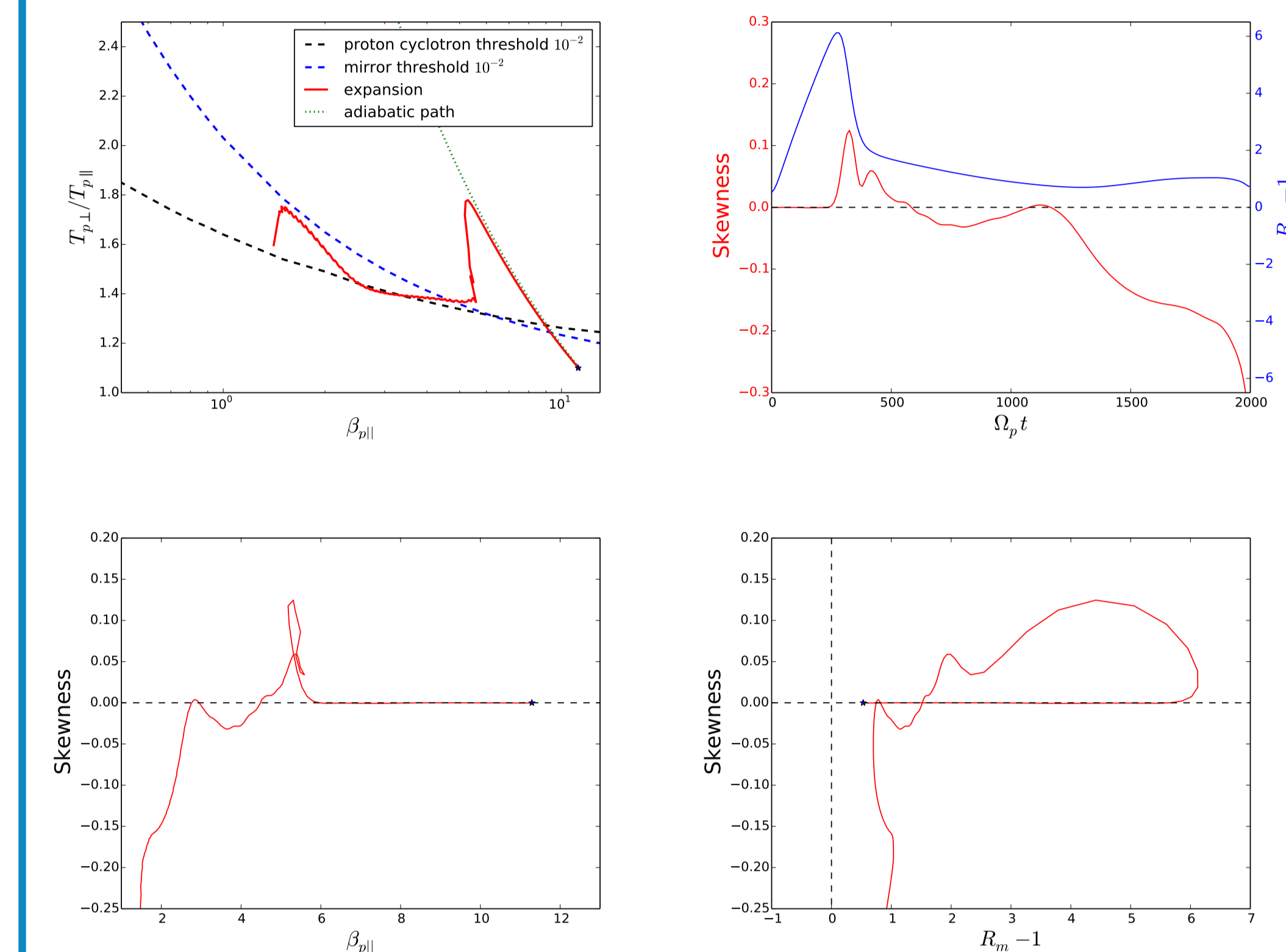
$$B = v_A/c \hat{z} = 0.1 \hat{z}, \omega_p/\Omega_p = 10, q_z = 10^{-4} \omega_p = 10^{-3} \Omega_p$$

$$\tau_c = 1000 \Omega_p^{-1} \rightarrow \text{Expansion characteristic time}$$

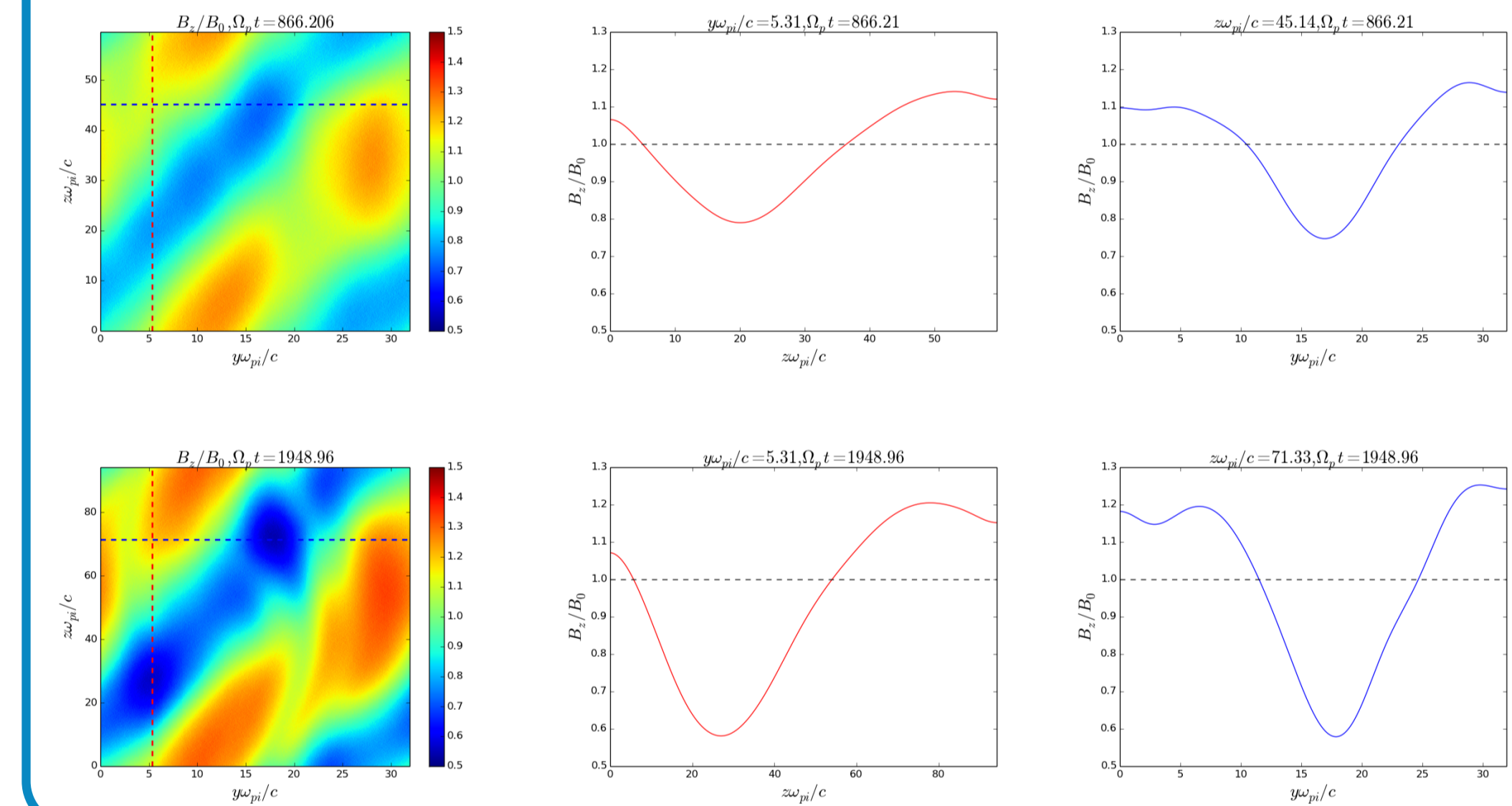
$$L_y = 32d_p, L_z = 32d_p(1 + q_z t), n_y = n_z = 2048, m_p/m_e = 25$$

$$T_{p\perp}/T_{p\parallel} = 1.1, T_{e\perp}/T_{e\parallel} = 1, \beta_{p\parallel} = 13, \beta_{e\parallel} = 1$$

At the end of the simulation, simulation box has become 3 times larger.



- First proton cyclotron instability is the dominant instability since protons follow the proton cyclotron instability threshold. but later plasma deviates from proton cyclotron threshold.
- When plasma becomes marginally mirror unstable ($R_m \sim 1.75$), skewness becomes negative and magnetic holes are dominant.
- Magnetic holes are dominant in low plasma beta $\beta_{p\parallel} \leq 2.7$.

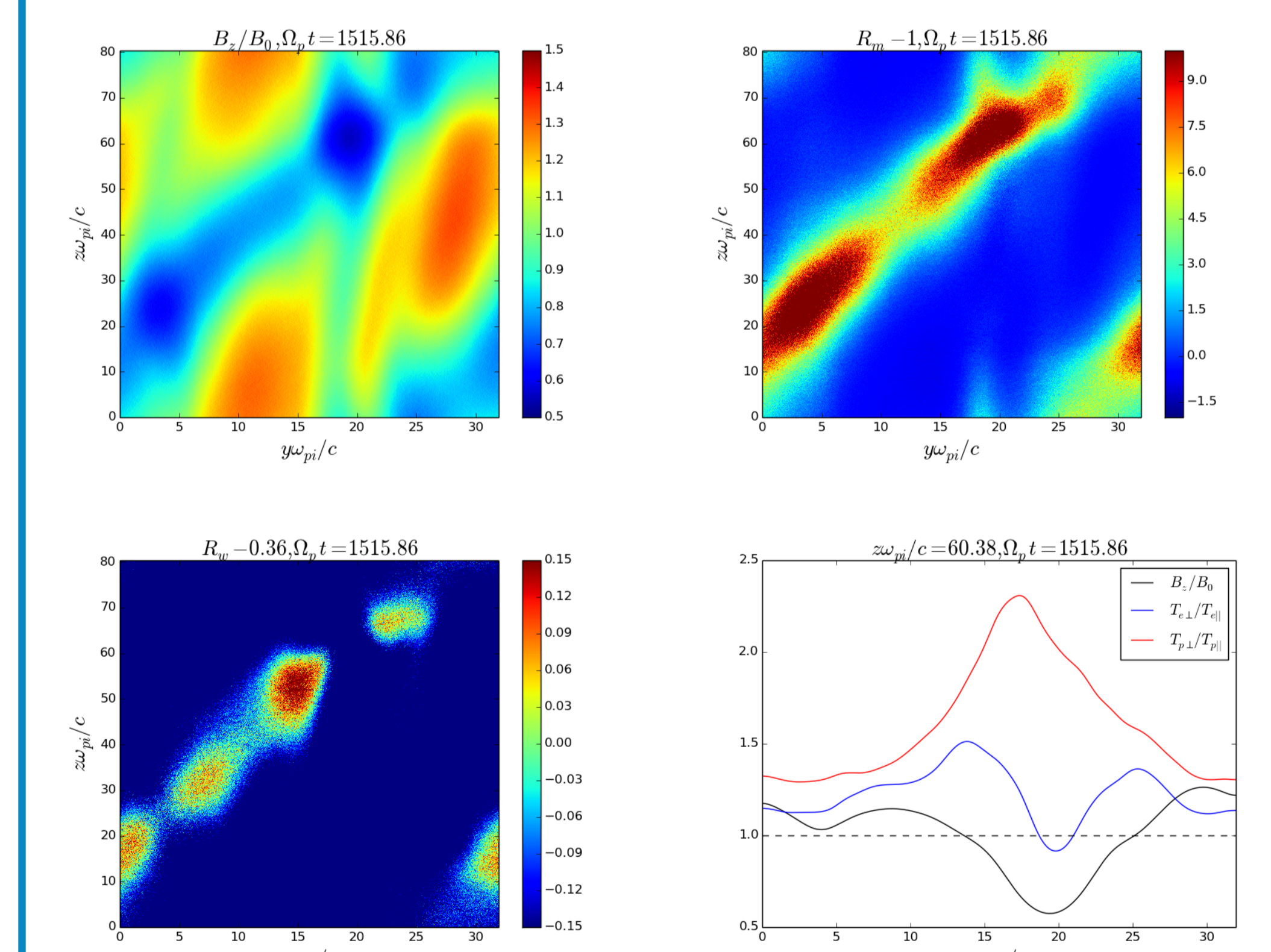


CHORUS WAVES SIGNATURES

- Plasma is mirror unstable in magnetic holes and mirror stable in magnetic peaks.
- Plasma is electron whistler unstable at the gradients of magnetic holes.

Electron whistler instability threshold is given by:

$$R_w = \beta_{e\parallel}^{0.55} \left(\frac{T_{e\perp}}{T_{e\parallel}} - 1 \right) \geq 0.36$$



CONCLUSIONS

- Direct nonlinear saturation of mirror instability leads to magnetic peaks which contradicts the Kivelson and Southwood prediction.
- Statistical analysis of mirror structures in the magnetosheath showed that magnetic holes are observed when plasma is mirror stable or marginally mirror unstable.
- With an expanding box simulation, we mimicked the magnetosheath plasma to study the mirror structures in a mirror stable plasma and we produced the magnetic holes.
- Plasma is electron whistler unstable at the gradients of magnetic holes.