# Observations of cold ion heating in the exhaust region at the Earth's subsolar magnetopause

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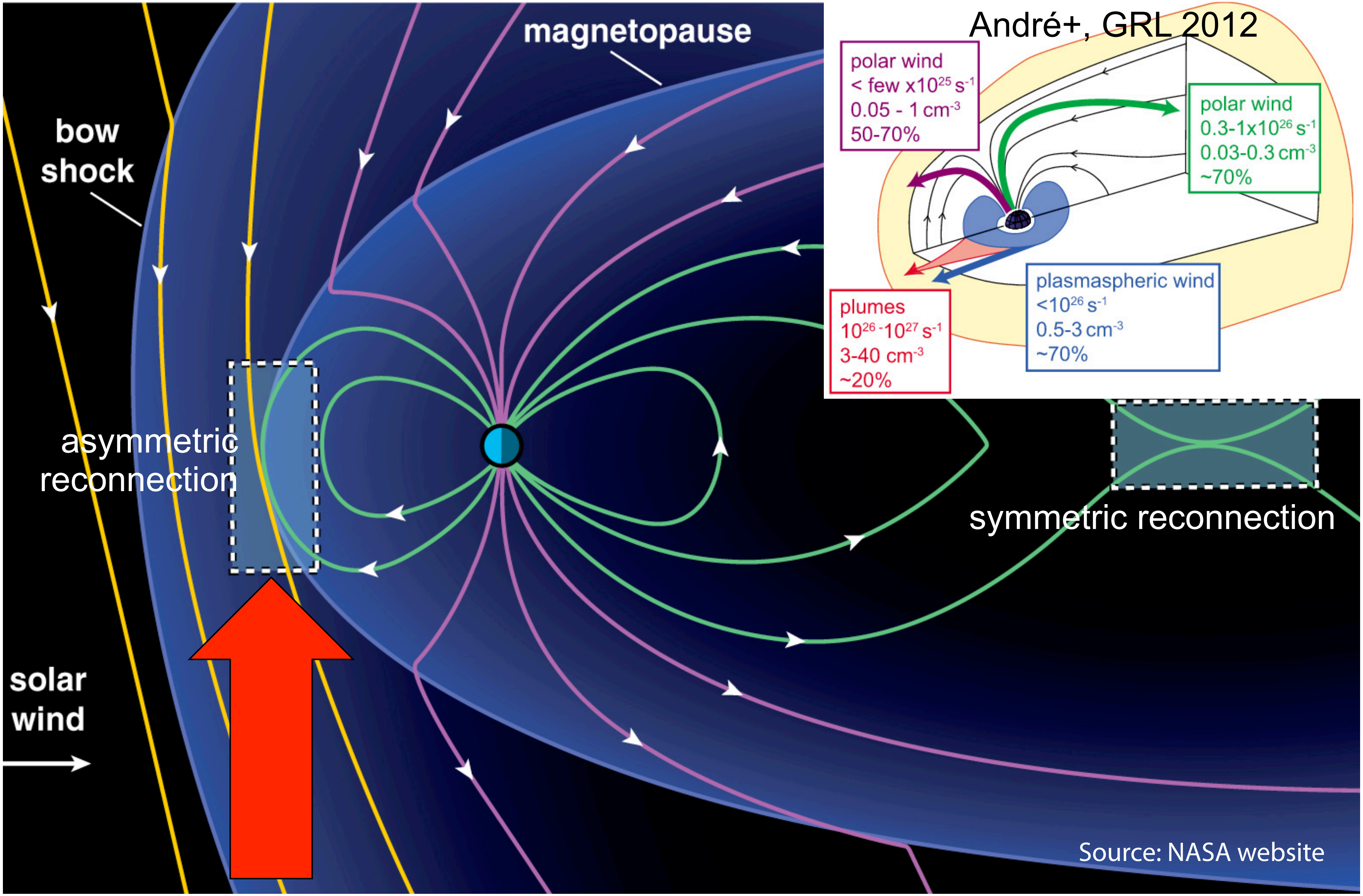
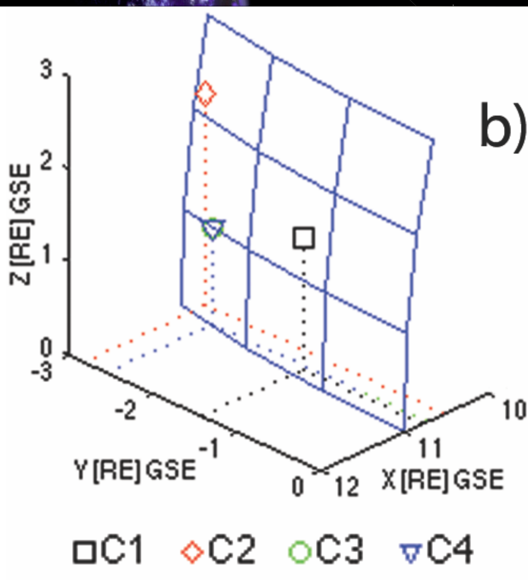
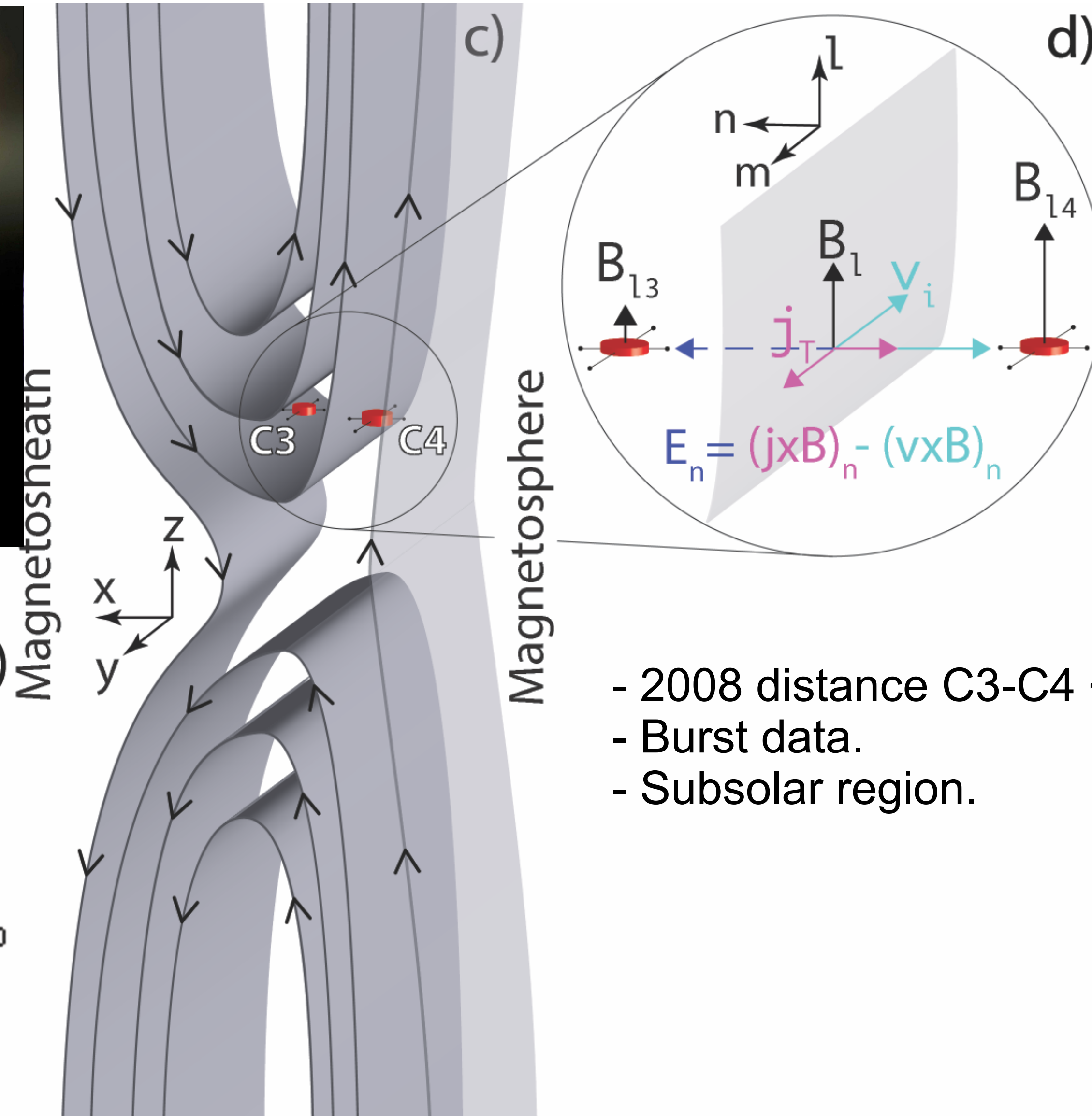
# Magnetic reconnection at the subsolar Magnetopause



# In-situ measurements from CLUSTER


- 2008 distance C3-C4 ~50 km.
- Burst data.
- Subsolar region.

# Outline

**PART I: Cold ions in Magnetic reconnection: current reduction.**

- Three-fluid description.
- Cold ion detection.
- Cold ion reduction of currents in thin boundaries.

**PART II: Heating of cold ions in Magnetic reconnection**

- Overview and detail of two magnetopause crossings.
- Parallel and perpendicular ion velocities.
- Cold ion heating by spatial E gradients.
- Cold ion heating by resonant wave activity.

# PART I

# Or

# “Cold ion effect on reconnection”

# Three-fluid description

Consider plasma composed of electrons, hot ions and cold ions.

$$\vec{J} = e(n_h \vec{v}_h + n_c \vec{v}_c - n \vec{v}_e)$$

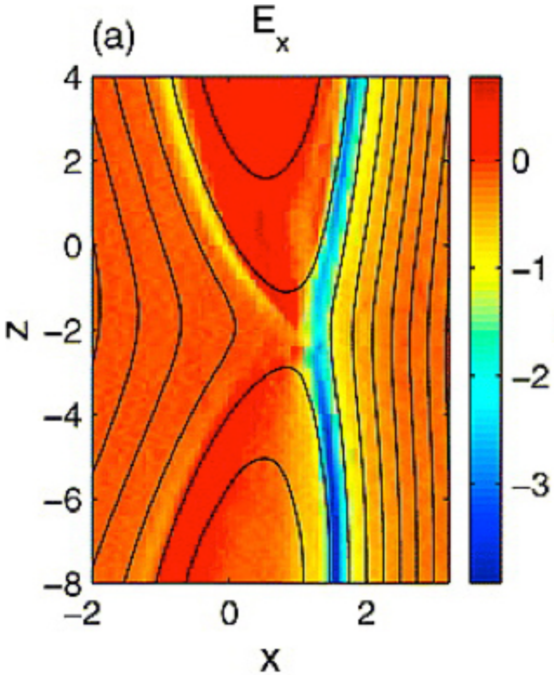
From e$^-$ momentum equation, neglecting *dt* and inertial term:

$$\vec{E} = -\frac{n_h}{n}\vec{v}_h \times \vec{B} - \frac{n_c}{n}\vec{v}_c \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\nabla \overleftrightarrow{P}_e$$

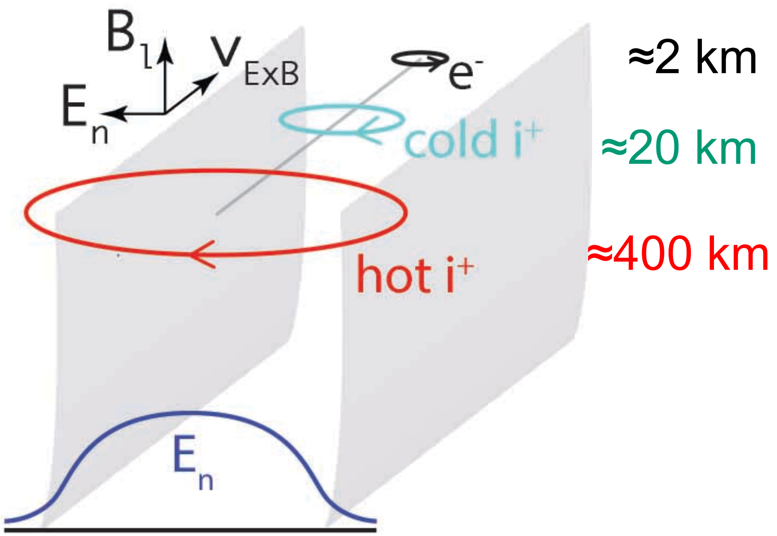
At scales $L>r_h$ it reduces to the frozen-in condition.
**At scales $r_c<L<r_h$, only cold ions and e$^-$ remain magnetized**.
At scales $L<r_c$ the typical Hall physics dominate.

*"**Cold ions** introduce a **new length-scale** where they remain frozen-in, **modifying the Hall effect**."*

# Hall electric field and cold ions

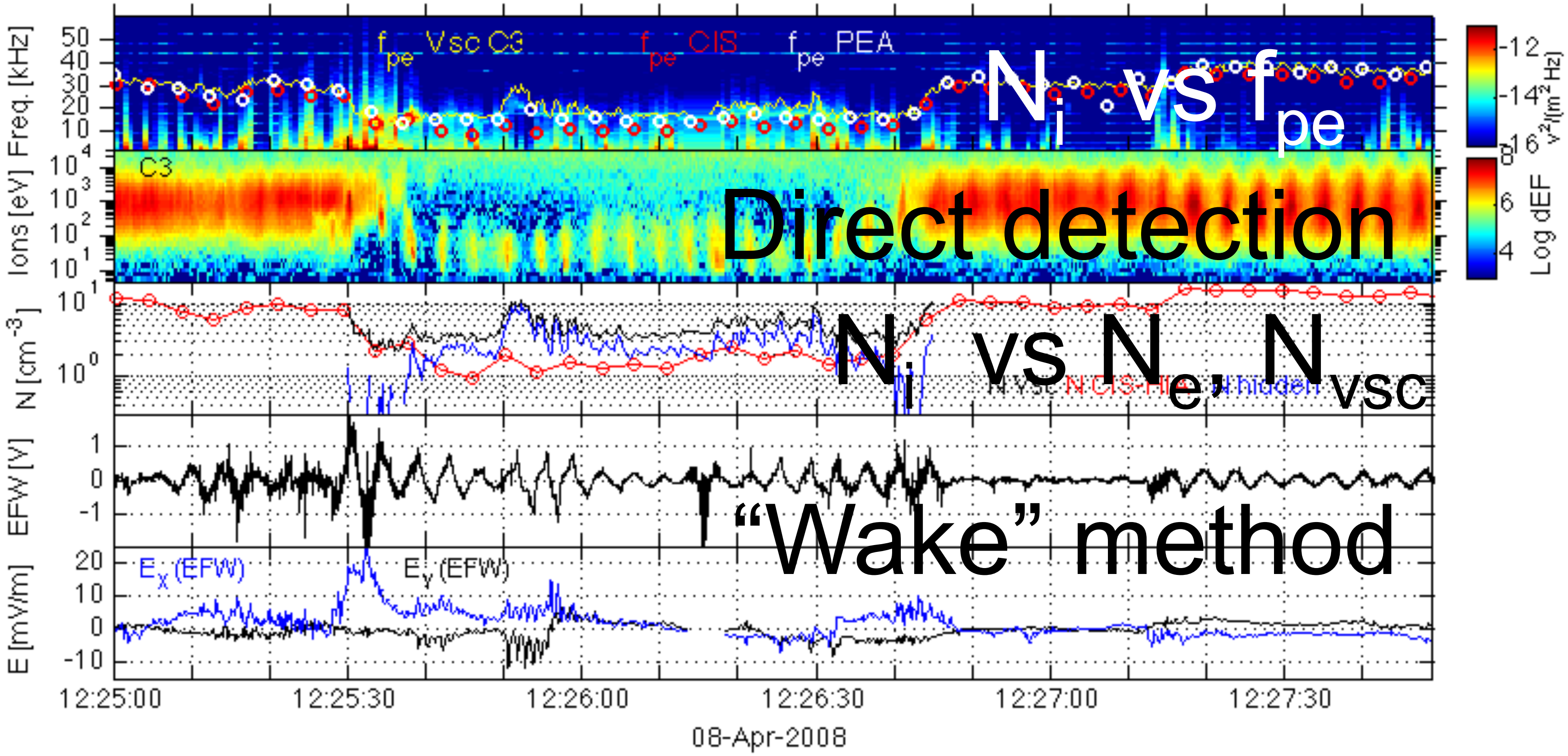


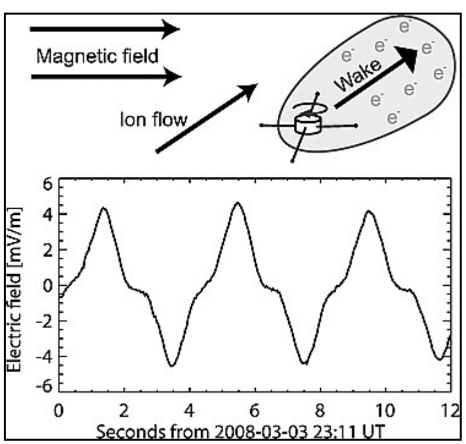

Pritchett+, JGR, [2009]



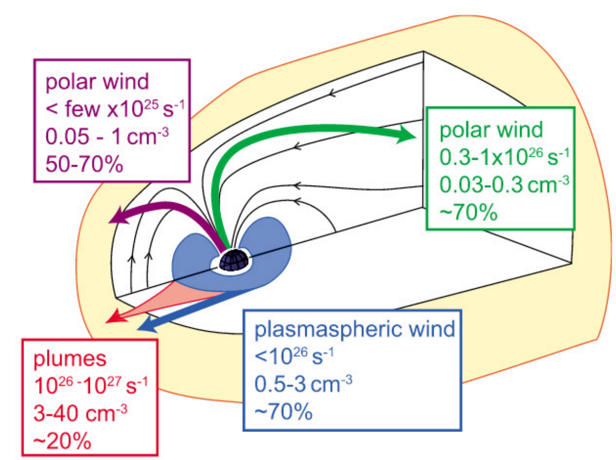

*"**Cold ions** can **ExB** drift in the narrow region of enhanced **Hall electric field** in the **separatrix region**."*

# Cold ion detection




André+, GRL, [2012]
André+, JGR, [2015]



# Estimation of the Ohm's law terms

$$\mathbf{E} = -\mathbf{v}_c \times \mathbf{B} - \mathbf{v}_h \times \mathbf{B} + \mathbf{j} \times \mathbf{B}/ne - \Delta p_e/ne$$

Assume **1D magnetopause** (2SC). Estimation only of **normal components.**

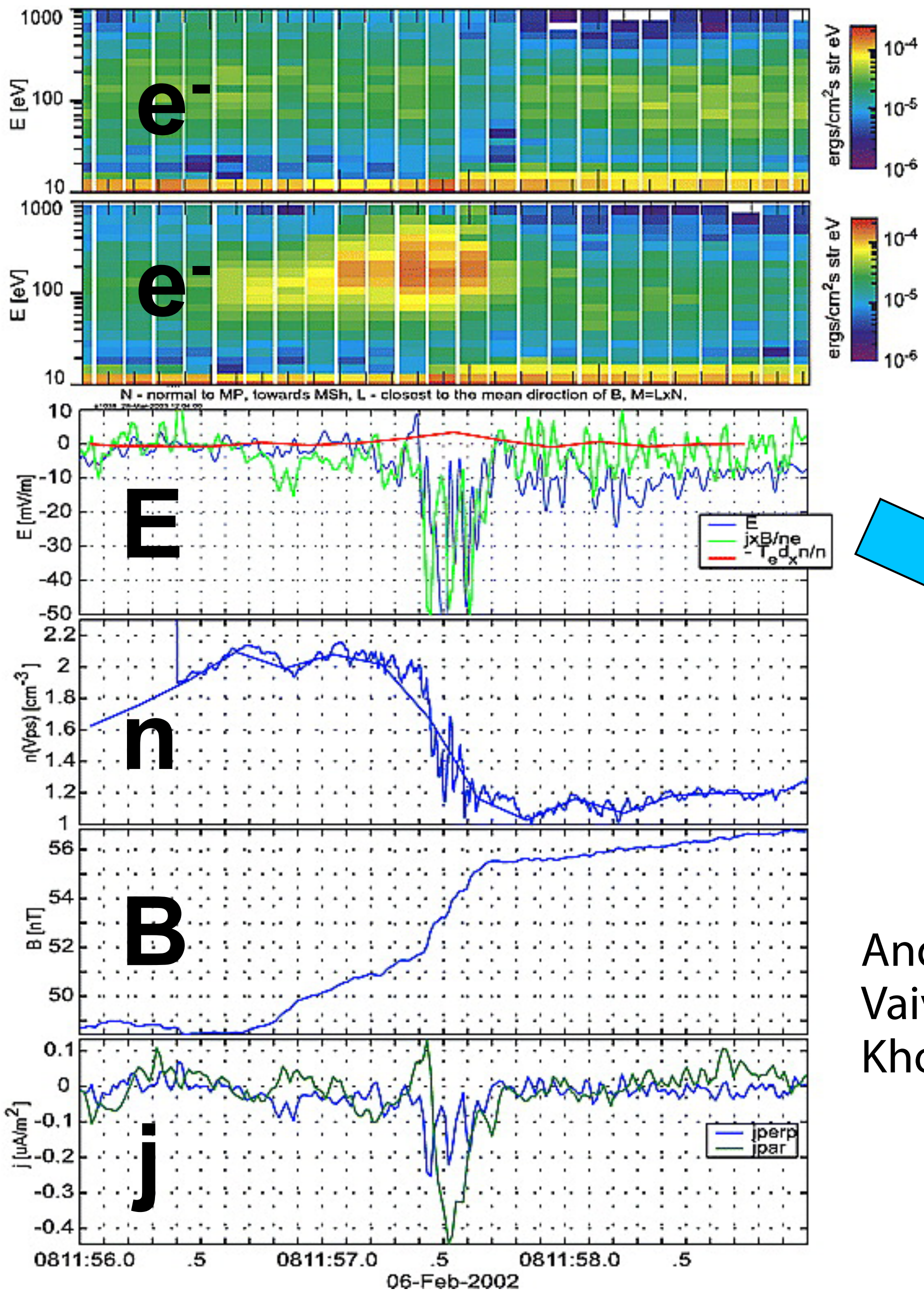
$E_n$ measured by EFW.

jxB/en: B from FGM, j from c3-c4 + 1D MP.

$v_i$xB: B from FGM, $v_c$, $v_h$ from partial CIS moments (4s resolution).

grad($p_e$)/en: $p_e$ from CIS 4s moments, assume constant $V_{mp}$.

# Hall E field balance without cold ions

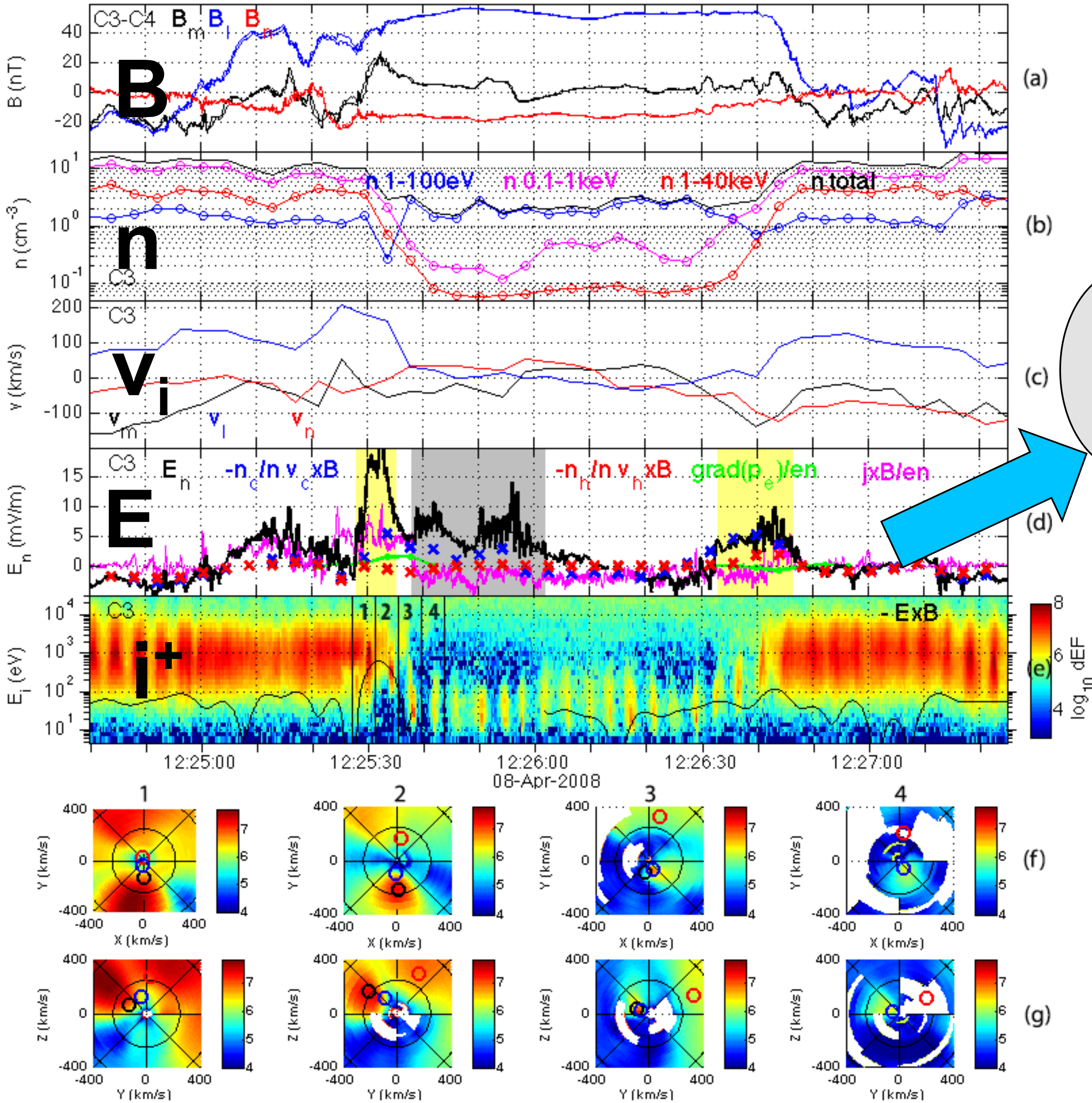



Previous studies at high-latitude magnetopause (**no low-energy ions** expected) showed that **En** is balanced mainly by the **Hall term**.

$$\vec{E}_n \approx \frac{1}{ne}[\vec{J} \times \vec{B}]_n$$

André+, GRL, [2004]
Vaivads+, PRL, [2004]
Khotyaintsev+, PRL, [2006]

# Hall E field balance with cold ions




$$\vec{E}_n \approx -\frac{n_c}{n}[\vec{v}_c \times \vec{B}]_n \quad \frac{1}{ne}[\vec{J} \times \vec{B}]_n$$

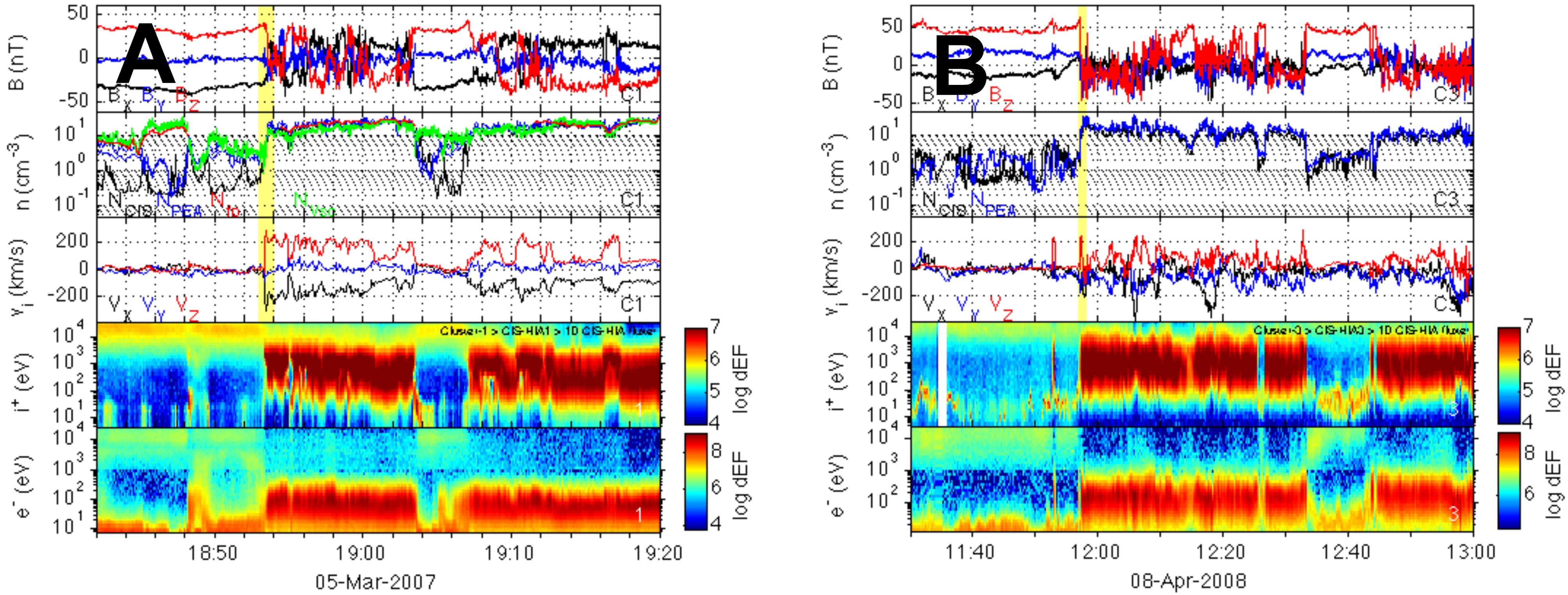
André+, GRL, [2010]
Toledo-Redondo+, GRL, [2015]
and
Poster outside, André+

# PART II

# Or

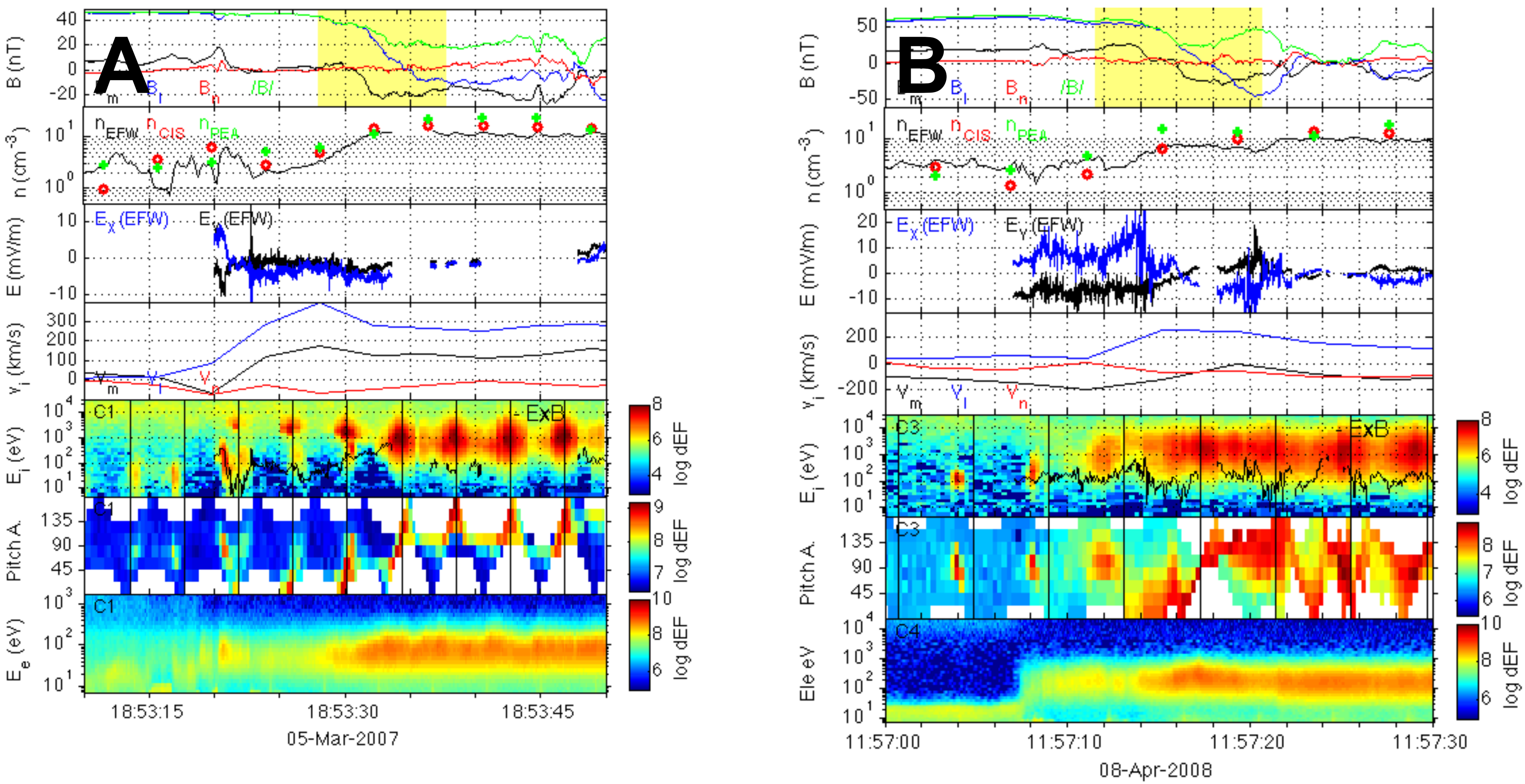
# “Reconnection effect on cold ions”

# Overview of the crossings

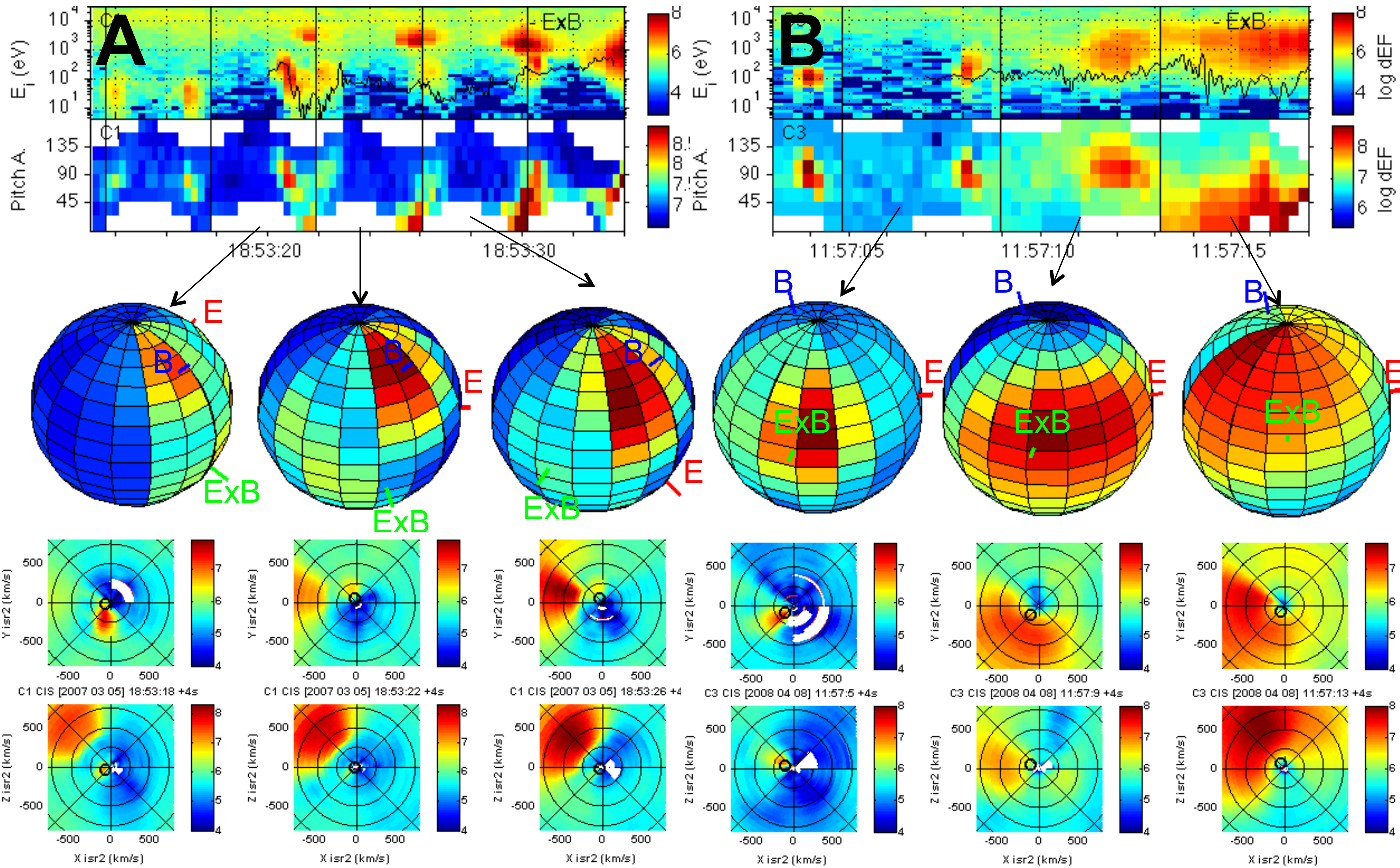



- Magnetopause crossings near the subsolar point.
- Presence of magnetospheric cold ions (dominant).
- Ion jets consistent with reconnection.
- Cold electrons?

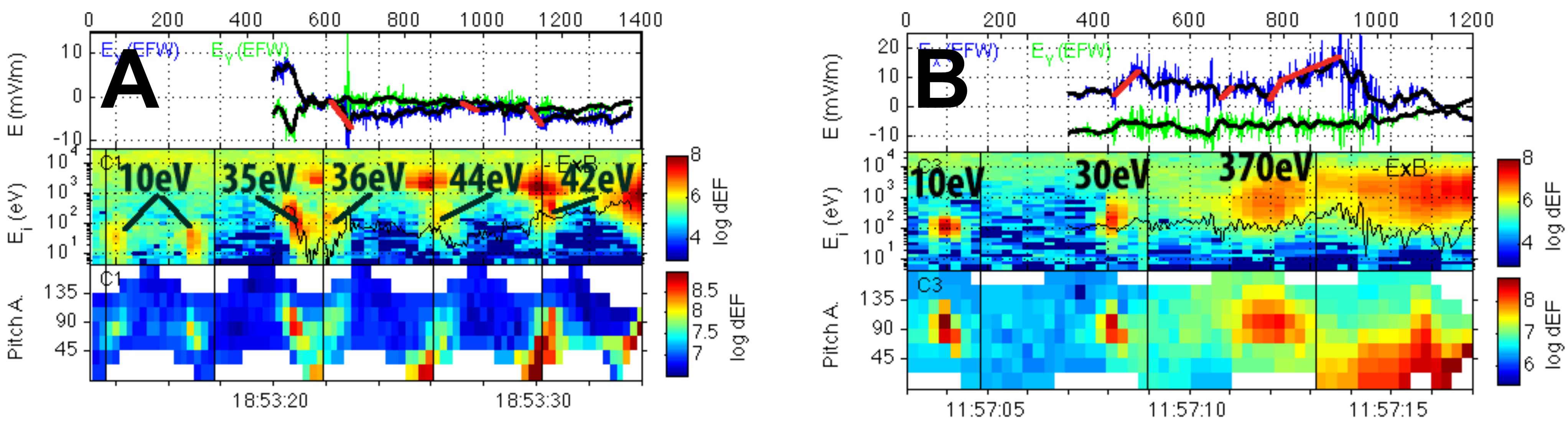
# Detail of cold ion heating



# Direction of ions



## Heating of cold ions

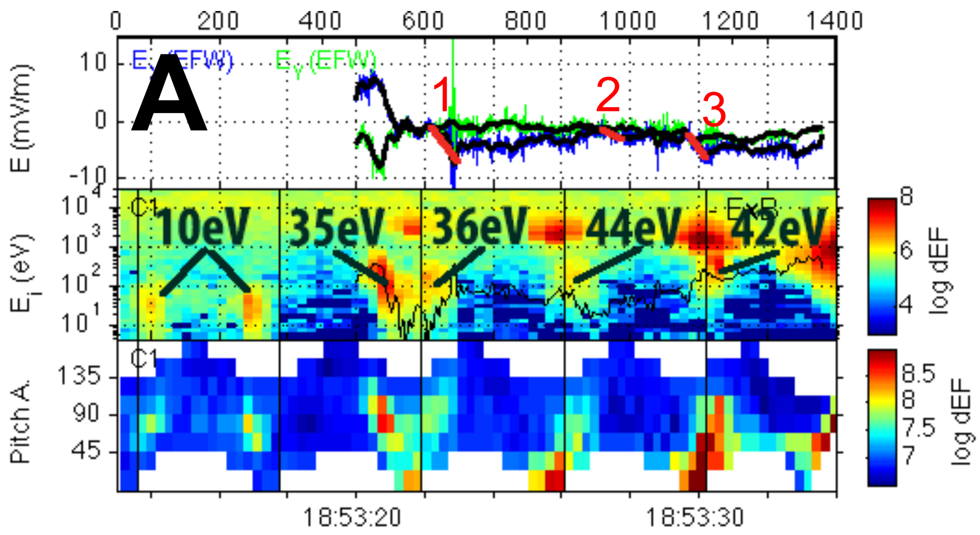


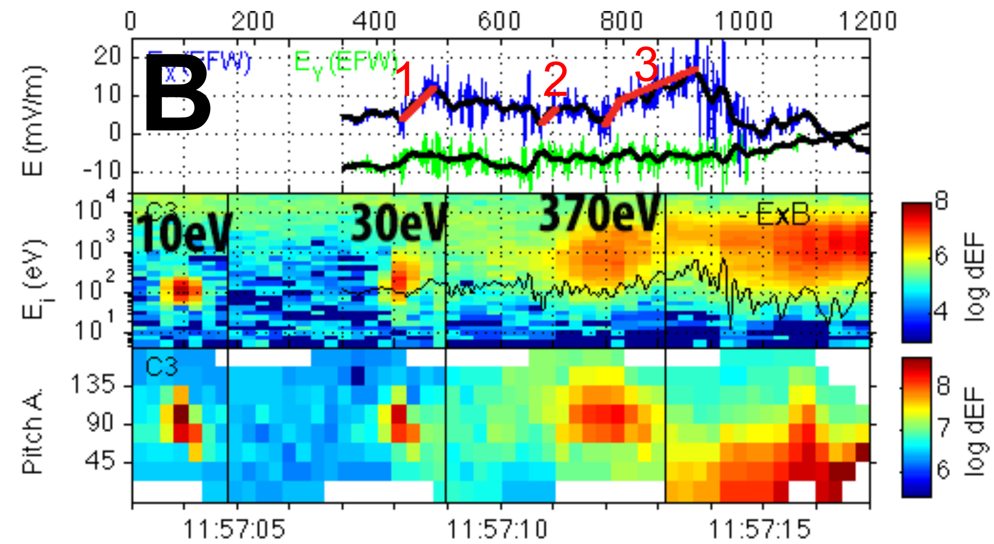

In case A, ions are heated ~30 eV, in case B ~360 eV.

We identify 2 possible mechanisms for cold ion heating:

- Spatial gradients of E field (red lines).
- Resonant wave activity (blue and green).

# Heating by spatial E field gradients



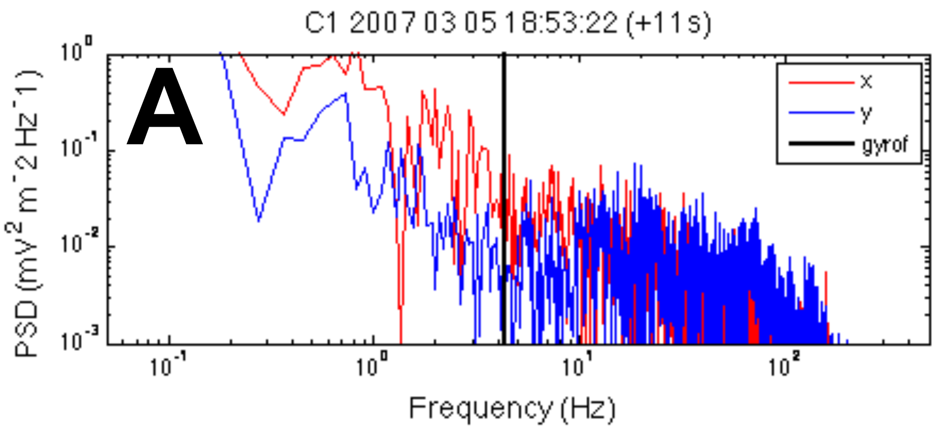

Condition for heating: $\nabla E > qB^2 / m_i$ [Cole, 1976]

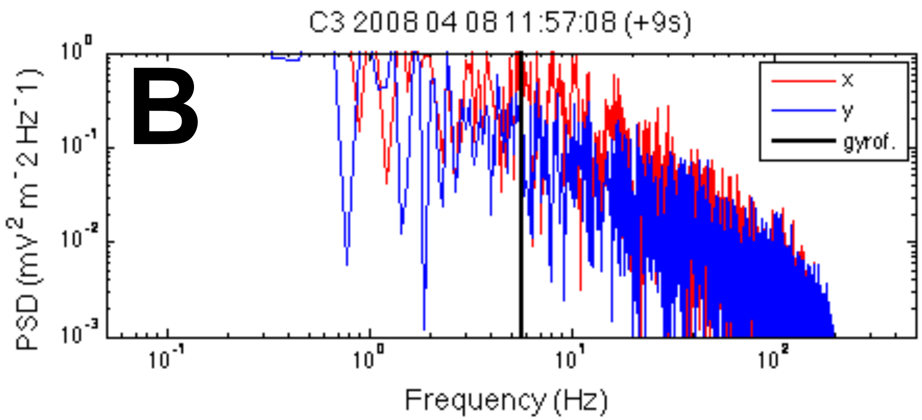
| | Grad(E)[V/km] | qB^2/m [V/km] |
|---|---|---|
| 1 | 0.116 | 0.240 |
| 2 | 0.055 | 0.240 |
| 3 | 0.166 | 0.240 |

| | Grad(E)[V/km] | qB^2/m [V/km] |
|---|---|---|
| 1 | 0.160 | 0.345 |
| 2 | 0.310 | 0.345 |
| 3 | 0.100 | 0.345 |

Condition is not satisfied for the large scale E gradients.

# Heating by resonant wave activity

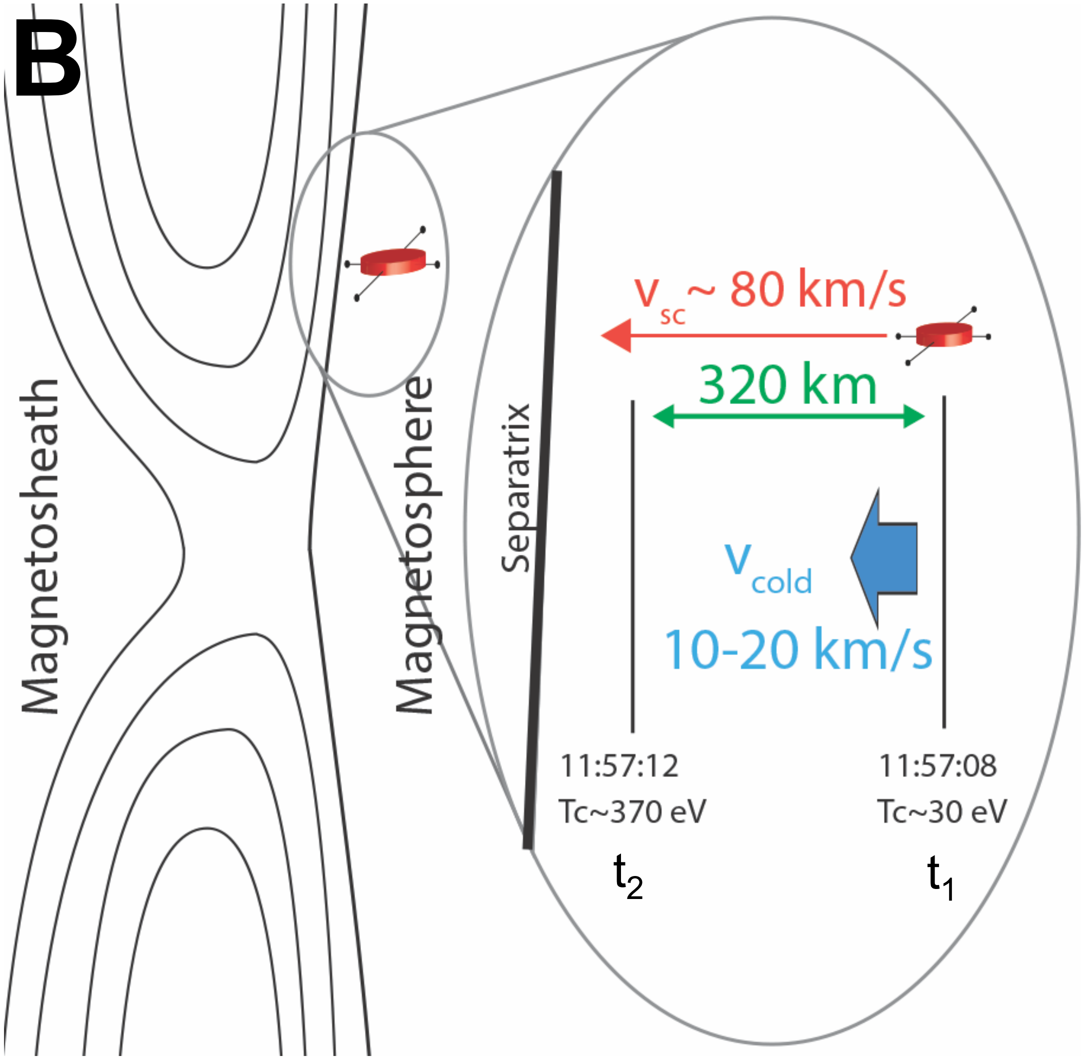



Heating ratio by resonant wave: $\frac{dw}{dt} = S_L \frac{q^2}{m_i}$ [Chang, 1986]

Considering 50% of the power transferred, the cold ions need 17s of interaction to be consistently heated in case B. The same time would provide a heat of ~10eV to case A ions.

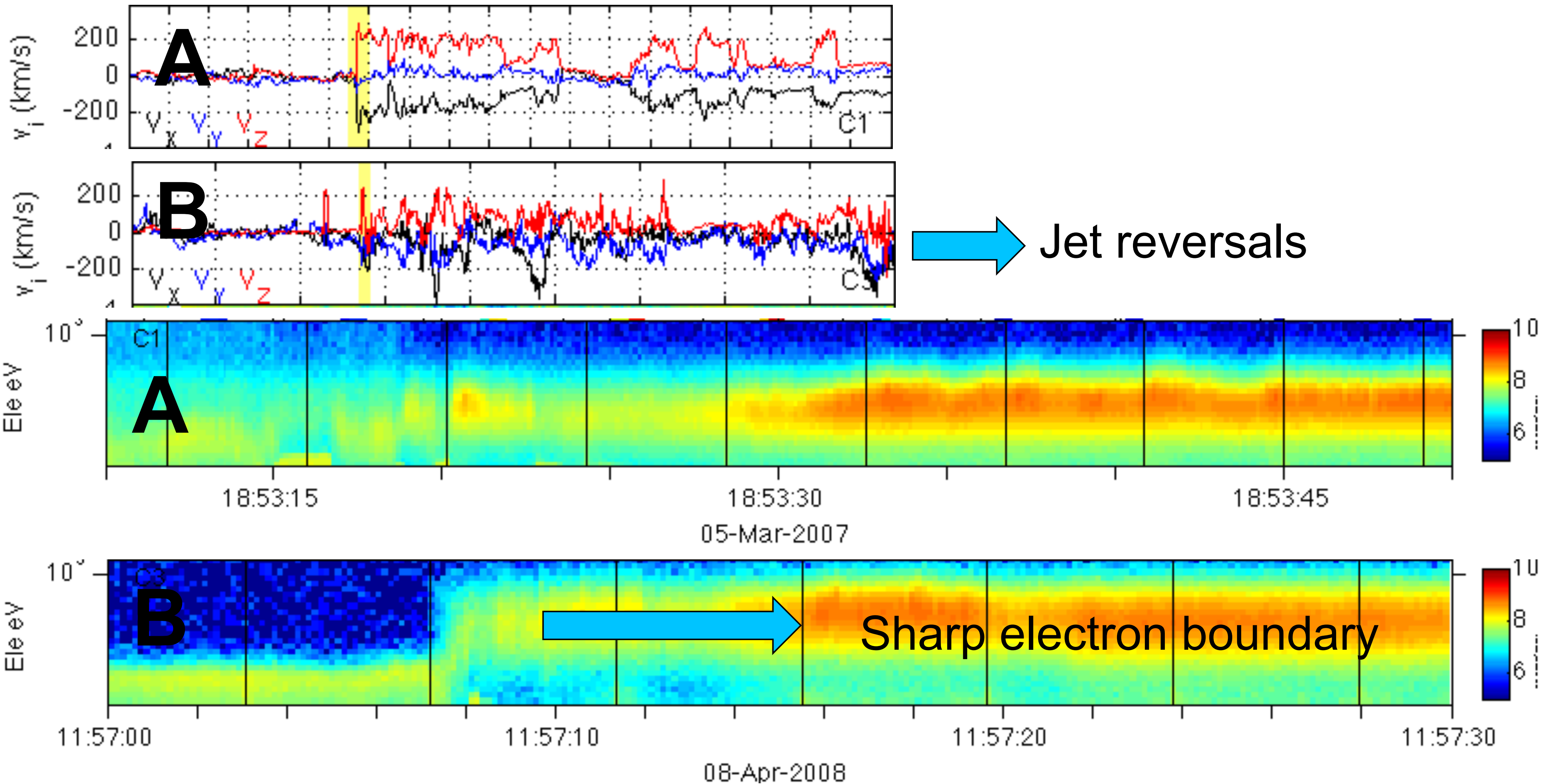
# Heating by resonant wave activity




Convection time of cold ions (16-32 s) is **consistent with wave heating**.

# Distance to X-line

Case B corresponds to a crossing near the X-line.



# Conclusion

- A **new length-scale** ($r_c<L<r_h$) is introduced into reconnection by cold ions, where only $i_c$ and $e^-$ **remain frozen-in**.

- The **perpendicular currents** in the thin layer of strong $E_n$ are **reduced by the presence of cold ions**. Changes in the current must **change B topology.**

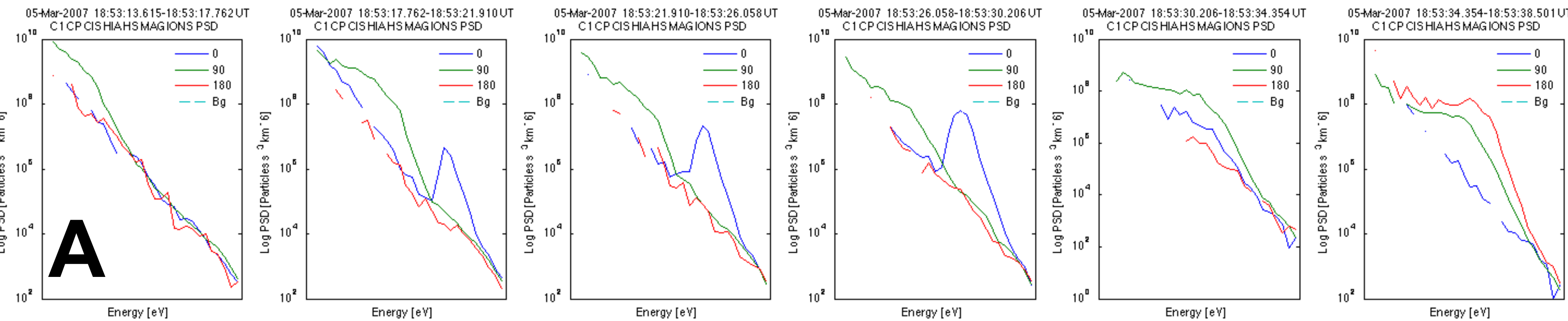
- Effective heating of cold ions near the X-line is consistent with resonant **wave heating**.

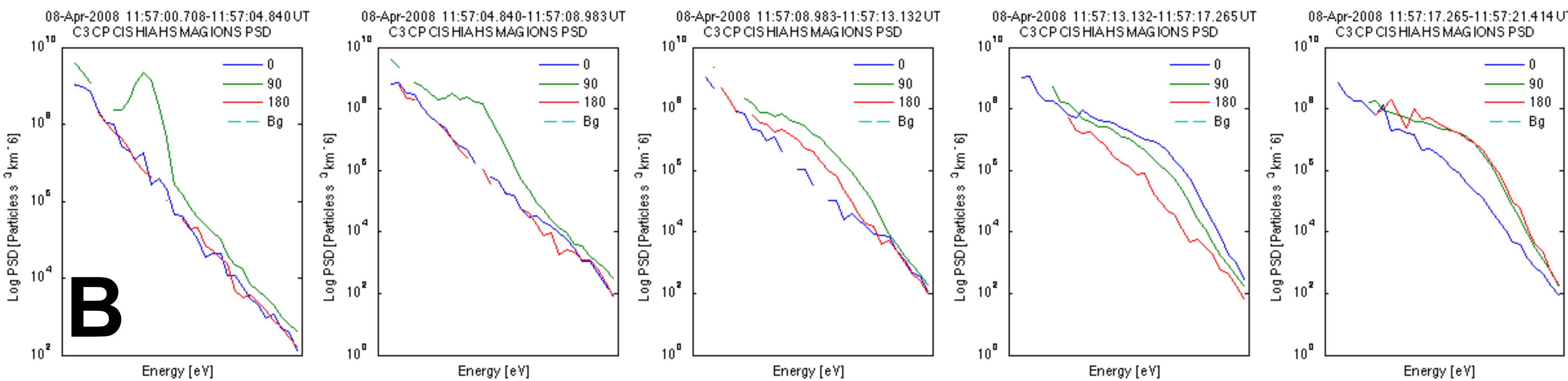
- What comes next:
  - Run simulations including cold ions (collaboration with other teams).
  - MMS measurements with cold ions (equatorial orbit).
  - Link the 2 parts of this talk.

Thank you

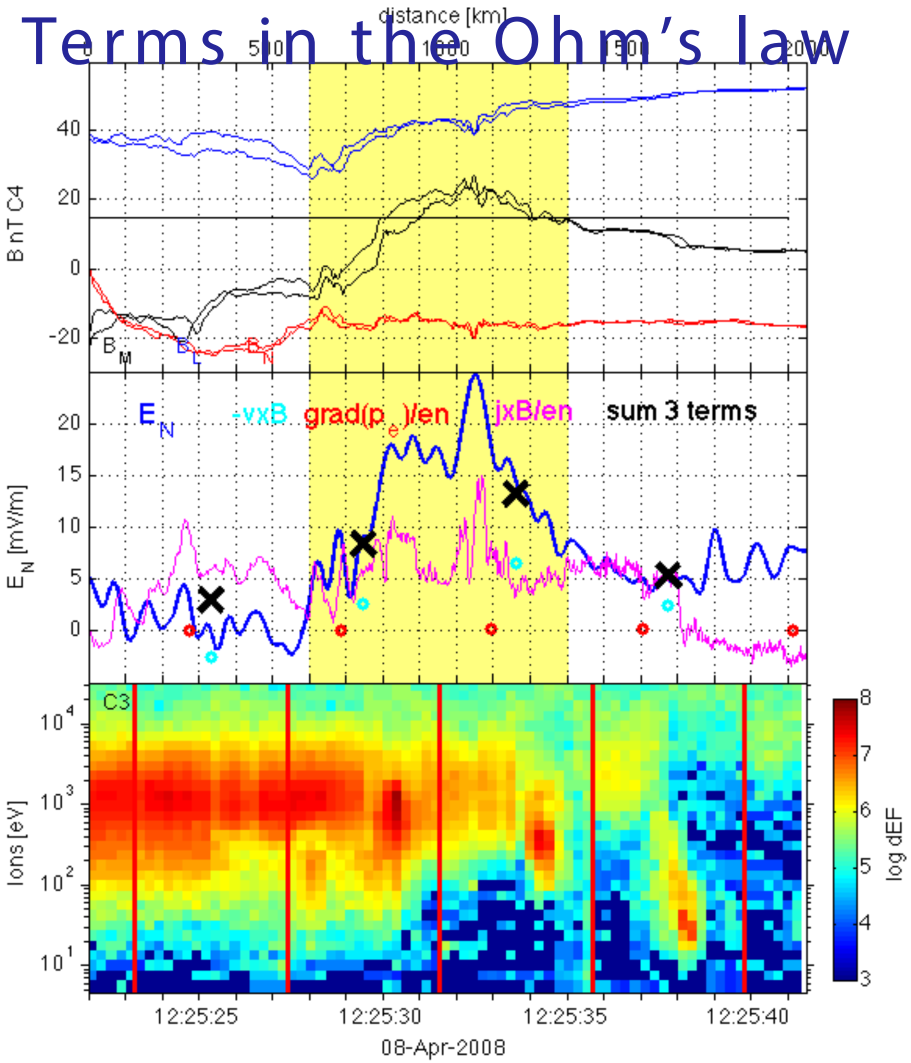
for your attention

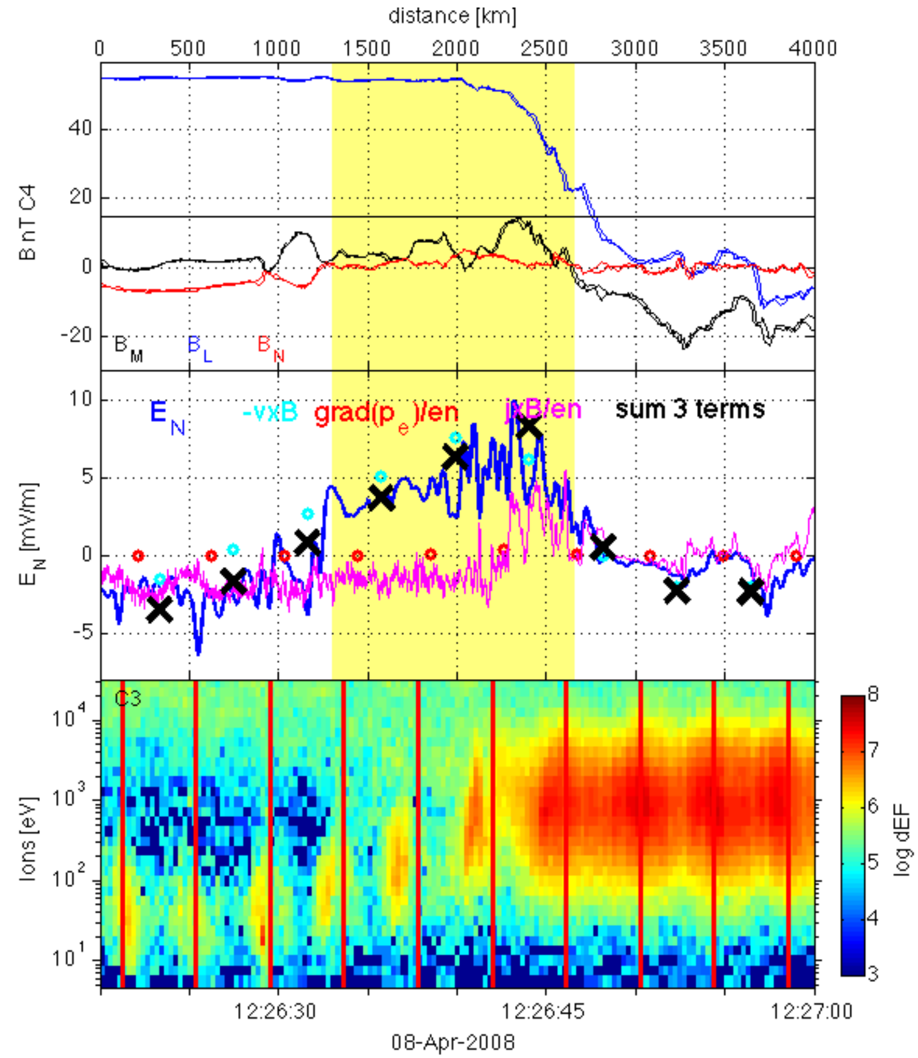
# Ion distributions



# Terms in the Ohm's law

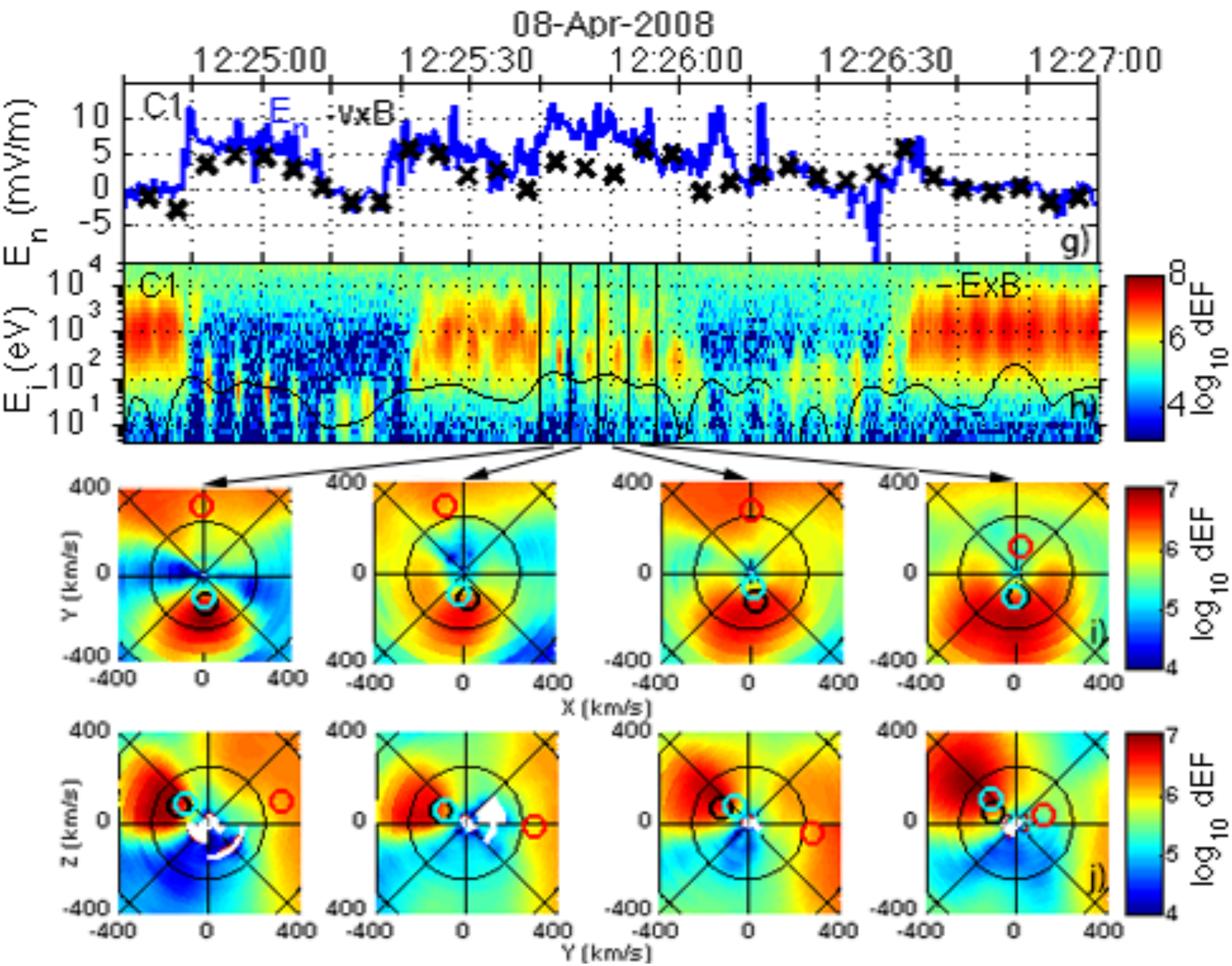


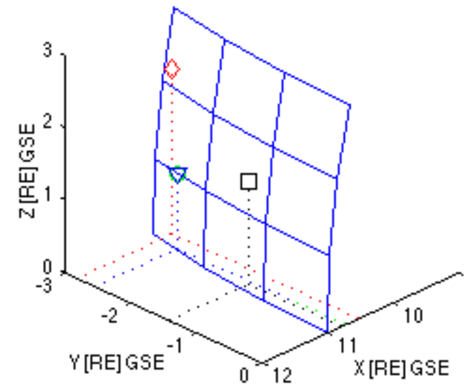




Estimation of terms in the **Ohm's law**. $v_i$xB term must be accounted for in order to balance the equation.

$$\mathbf{E} = -\mathbf{v}_i\times\mathbf{B} + \mathbf{j}\times\mathbf{B}/ne - \Delta p_e/ne$$

# $v_c xB$ supports part of the Hall E field



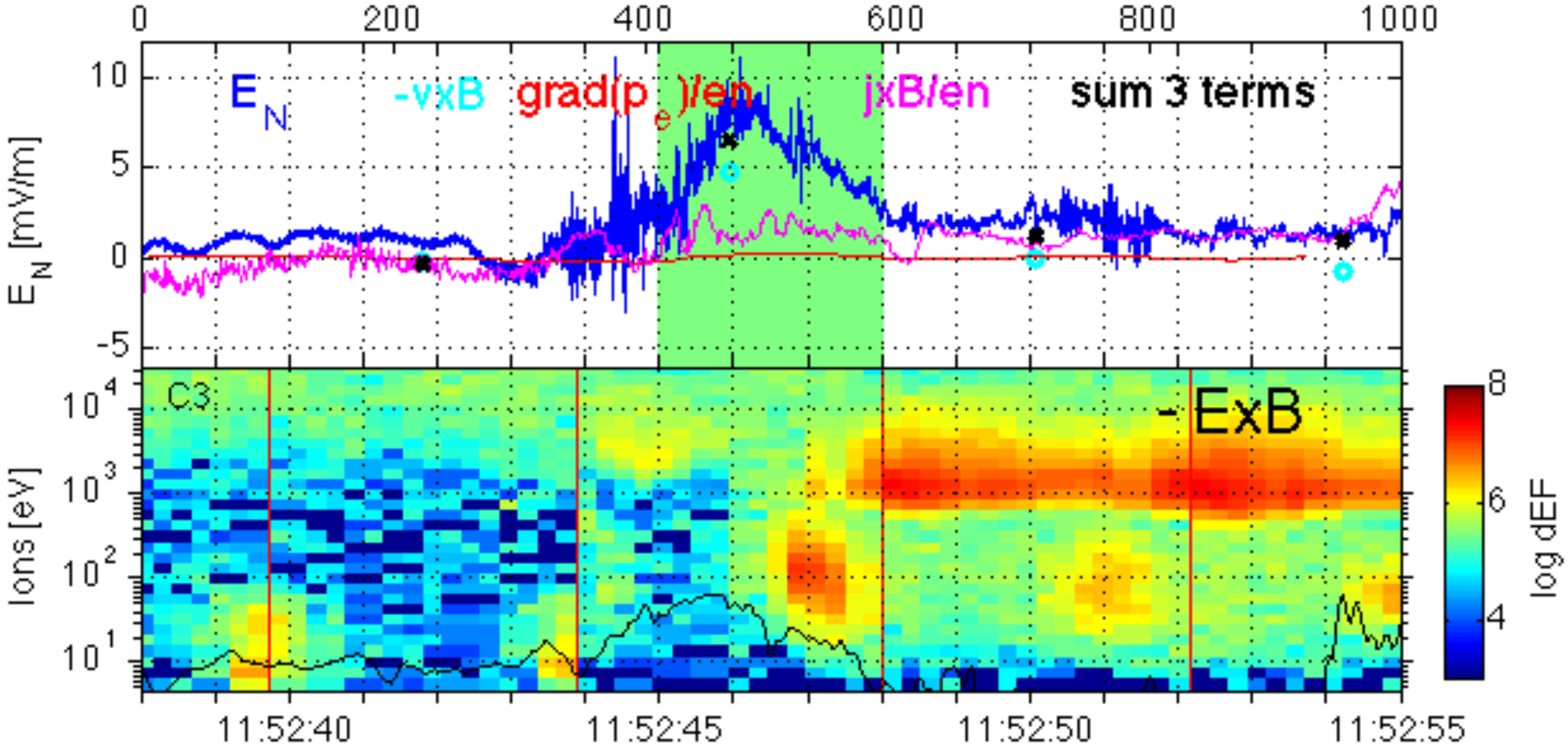




O ExB velocity

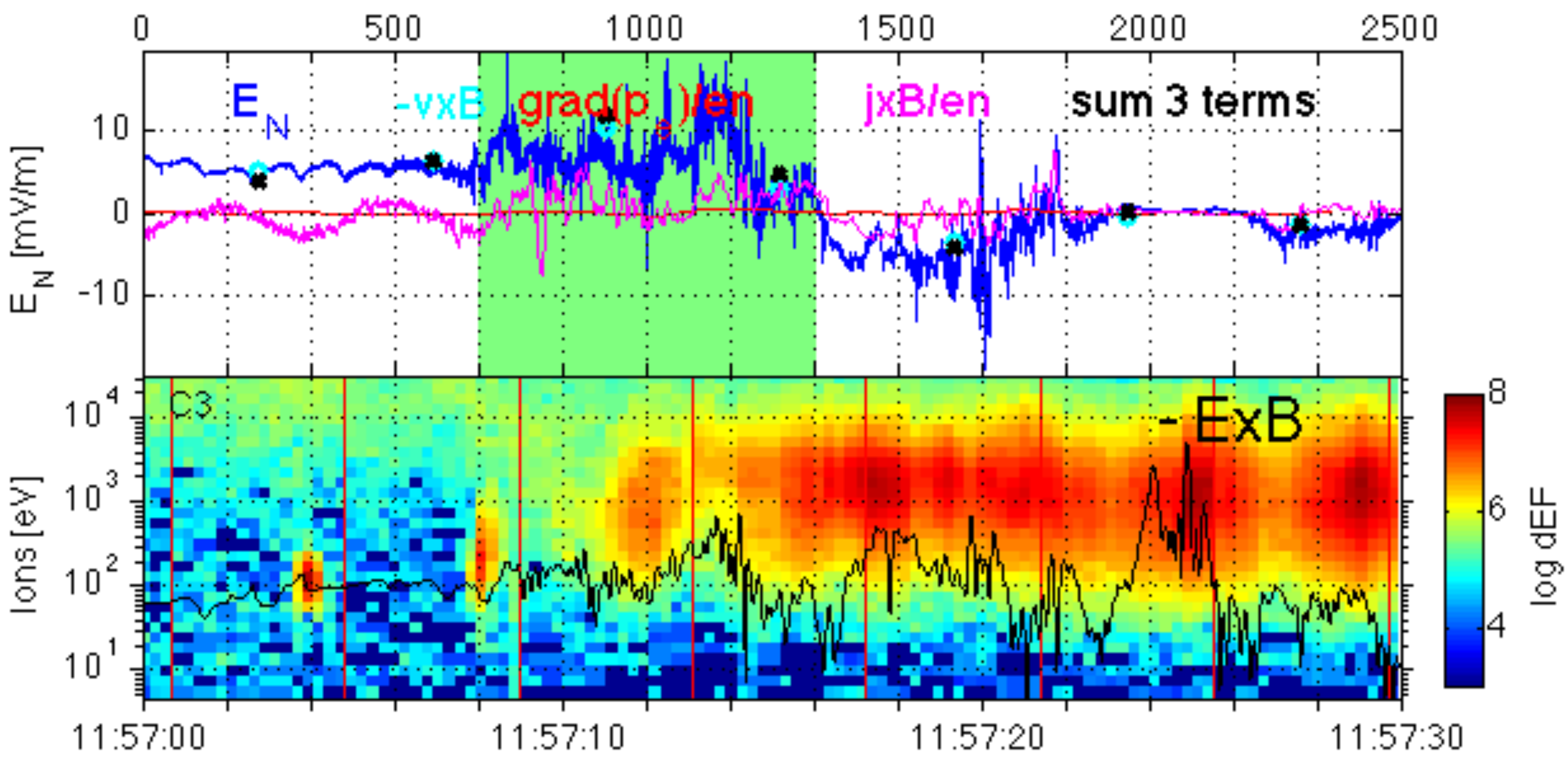
O 0.1-1 keV ion velocity

O 1-10 keV ion velocity

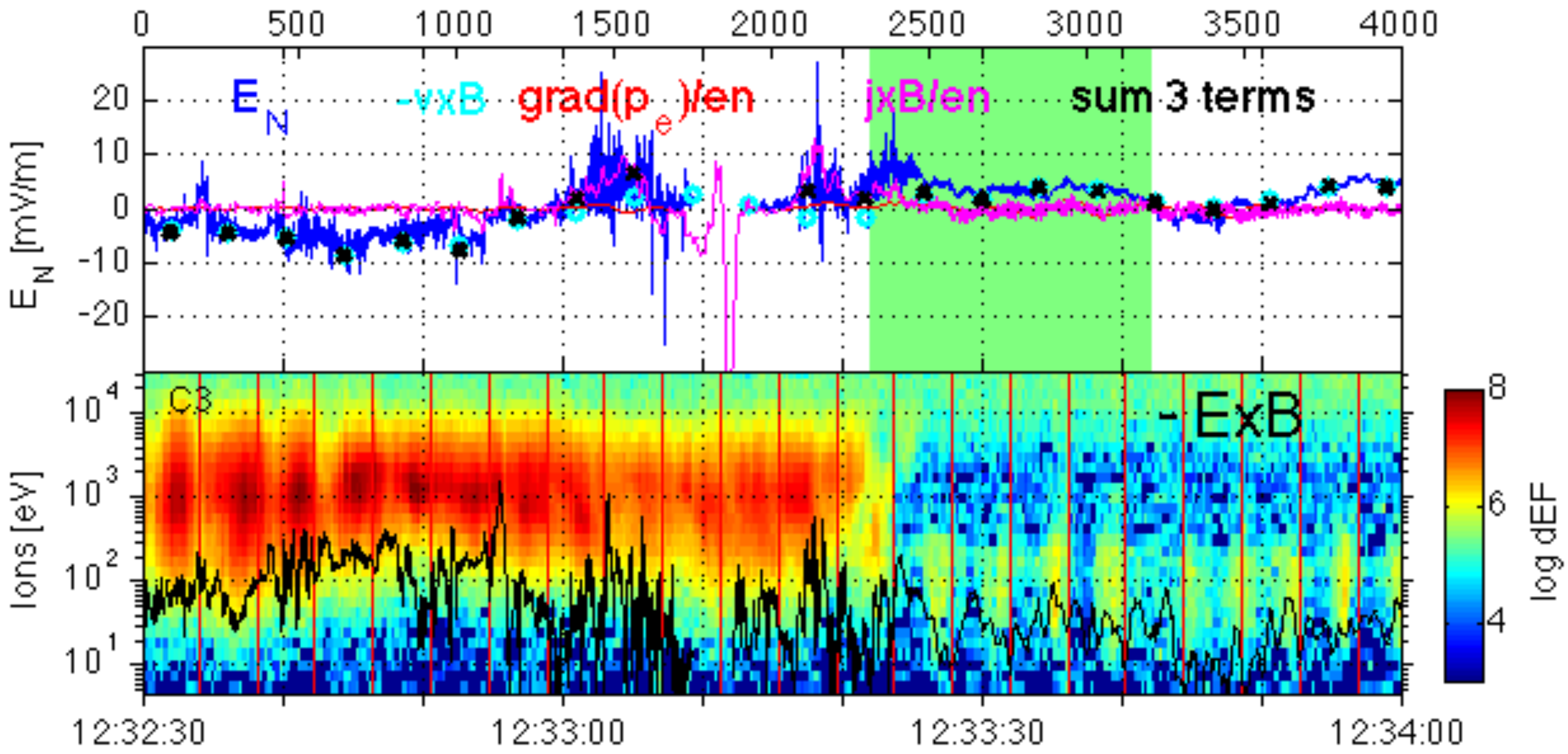
# ExB drift in the narrow layer



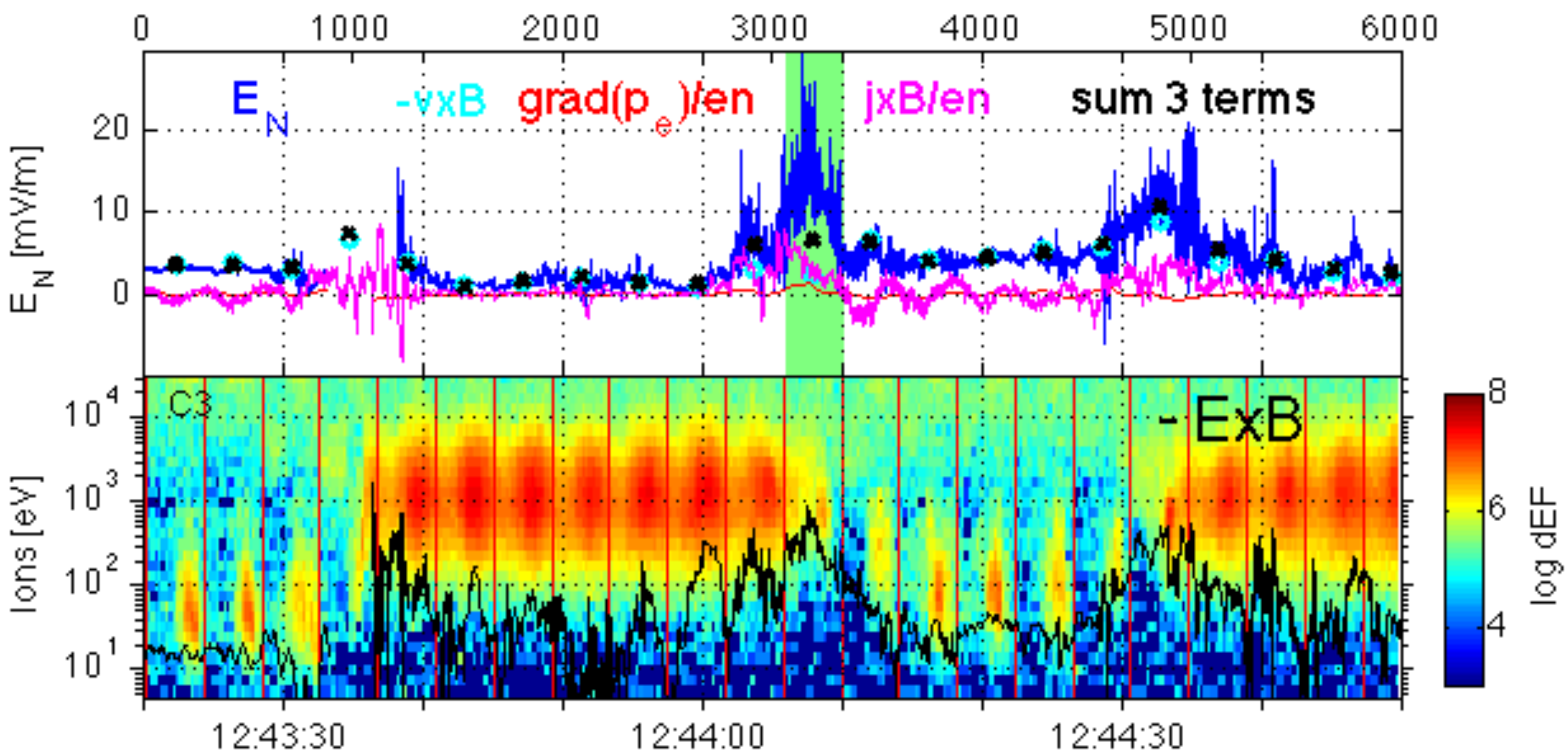
# ExB drift in the narrow layer



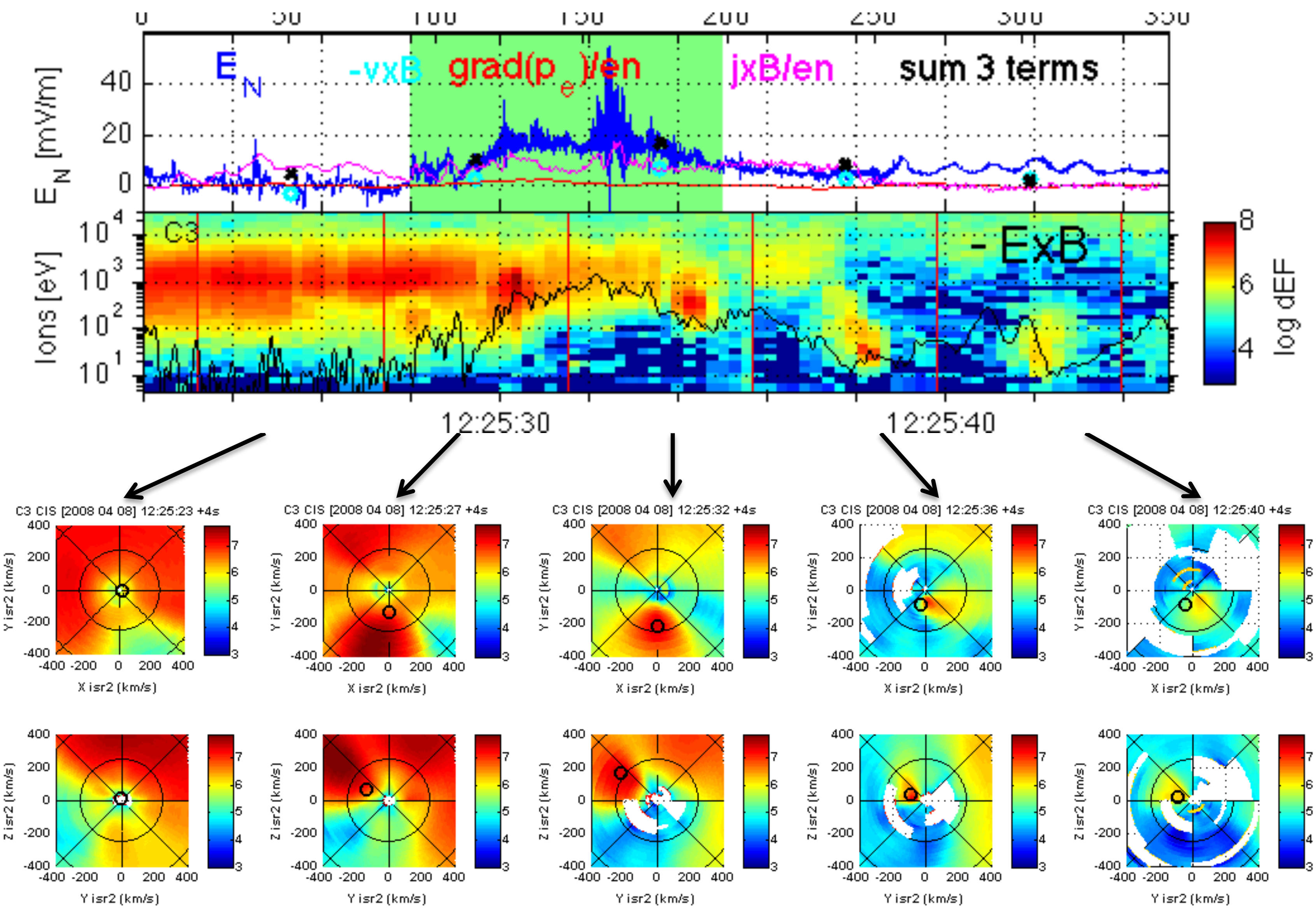
# ExB drift in the narrow layer



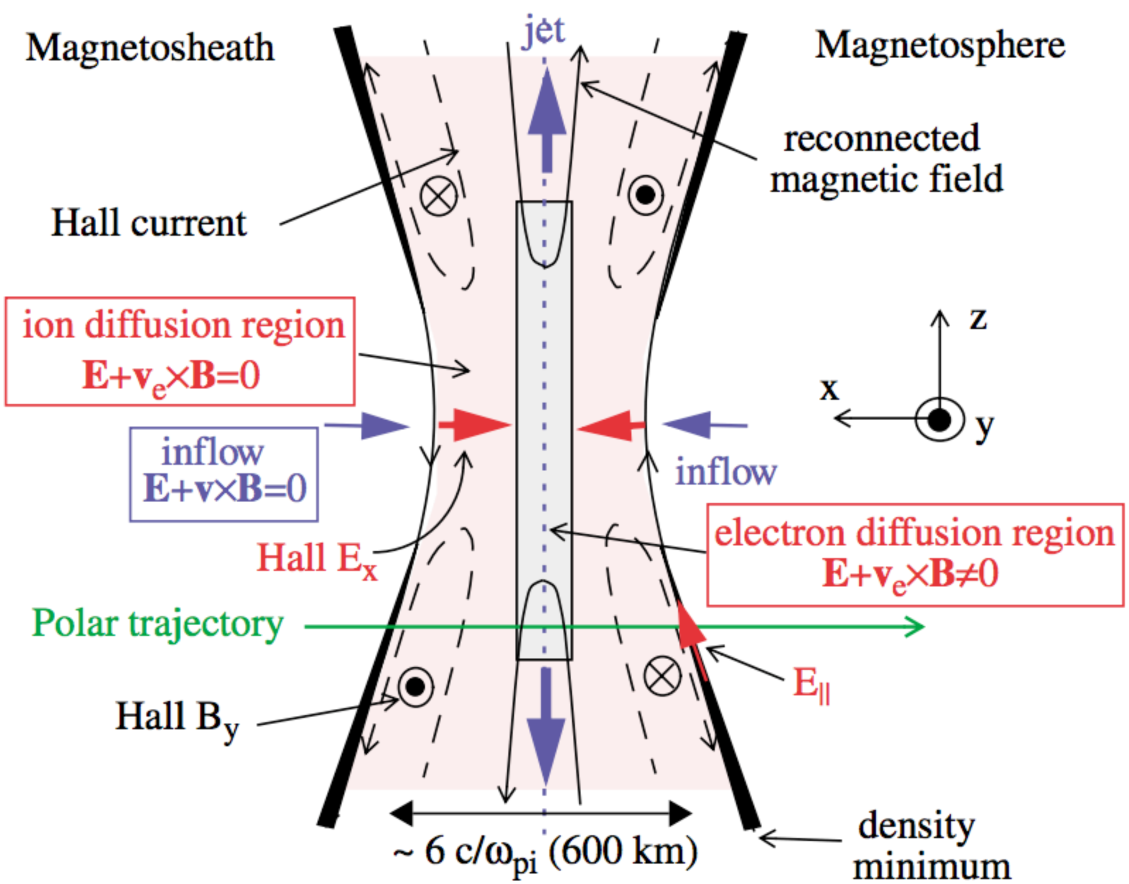
# ExB drift in the narrow layer



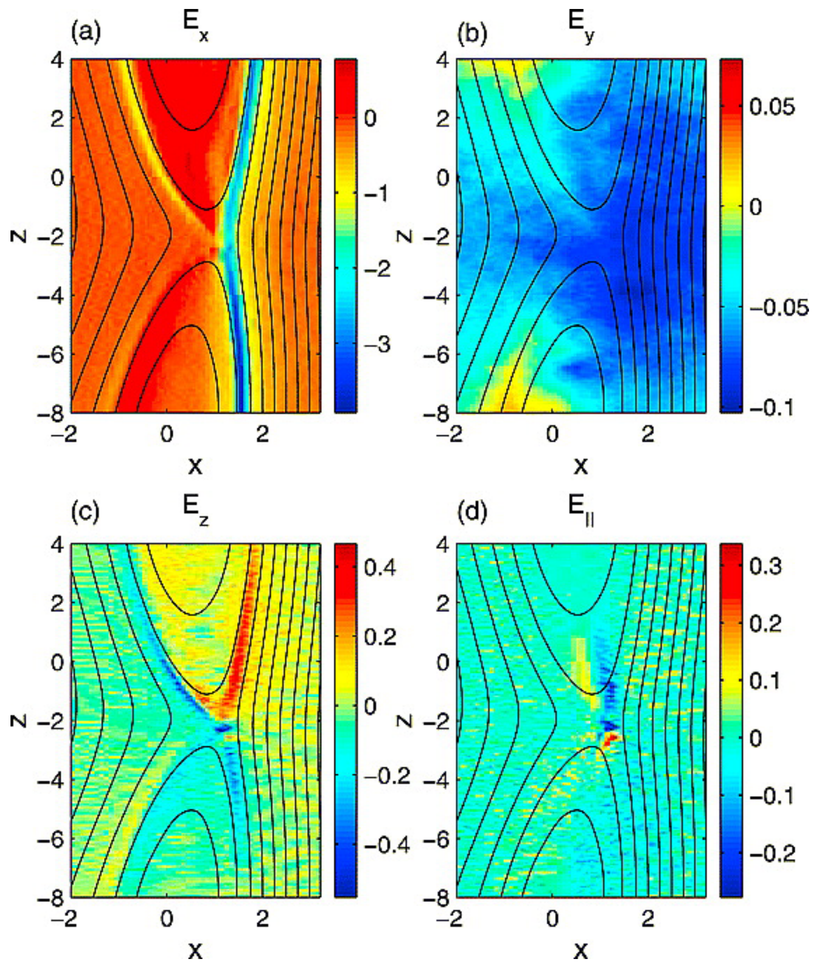
# ExB drift in the narrow layer



# Hall physics in the diffusion region




Mozer+, PRL, [2002]




Pritchett+, JGR, [2009]