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Connecting the geoelectric field to its magnetospheric sources in a global hybrid-Vlasov simulation

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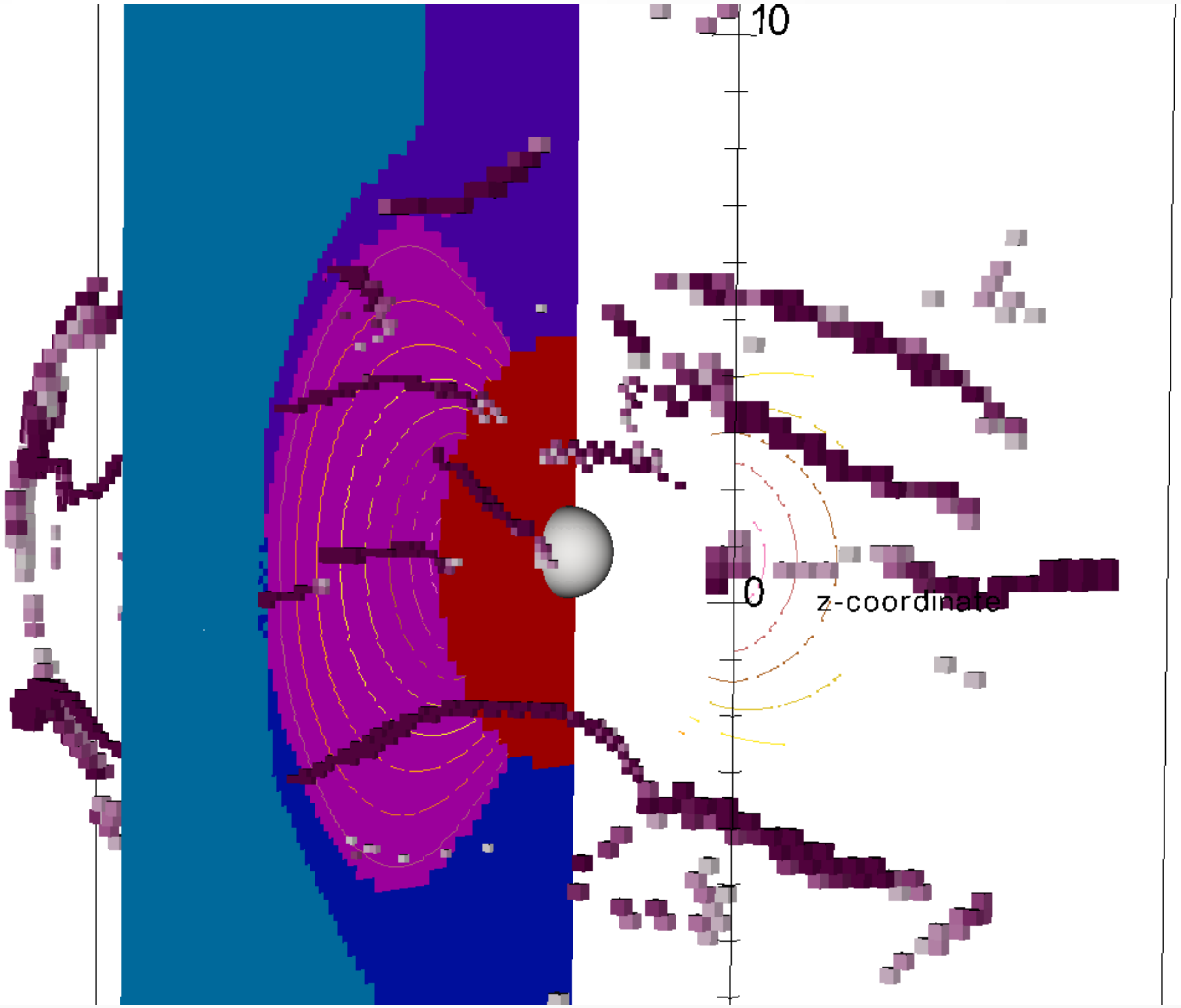
and the Vlasiator Team

VLASIATOR

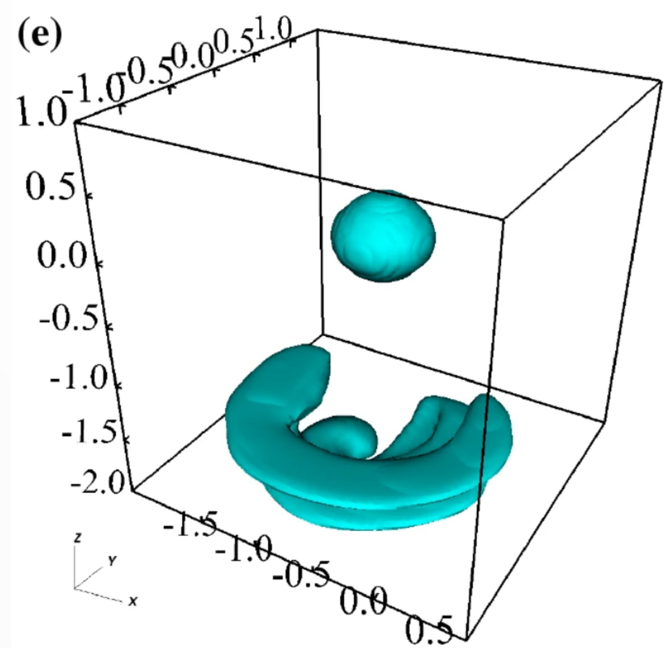
Talk outline

- 1. Vlasiator description and recent results
- 2. Current study: Flux Transfer Events (FTEs) and the geoelectric field
- 3. Future perspectives

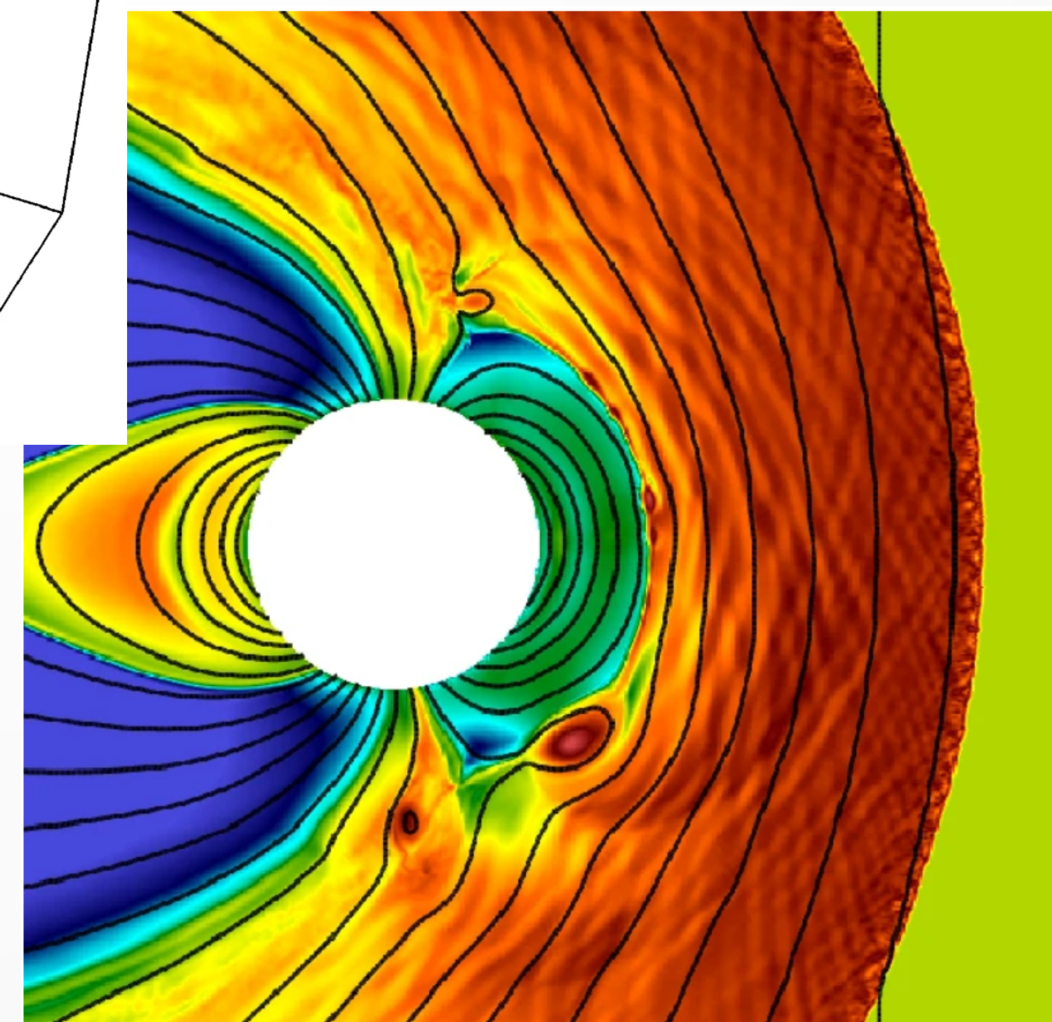


Vlasiator Simulations

- Hybrid-Vlasov
  - kinetic p^+
    - Vlasov equation
  - fluid e^-
    - $\gamma = 5/3$



2D3V (pre-2021)



For details:

- ***M. Palmroth et al., (2018)***
  “Vlasov methods in space physics and astrophysics”

3D Vlasiator Simulations

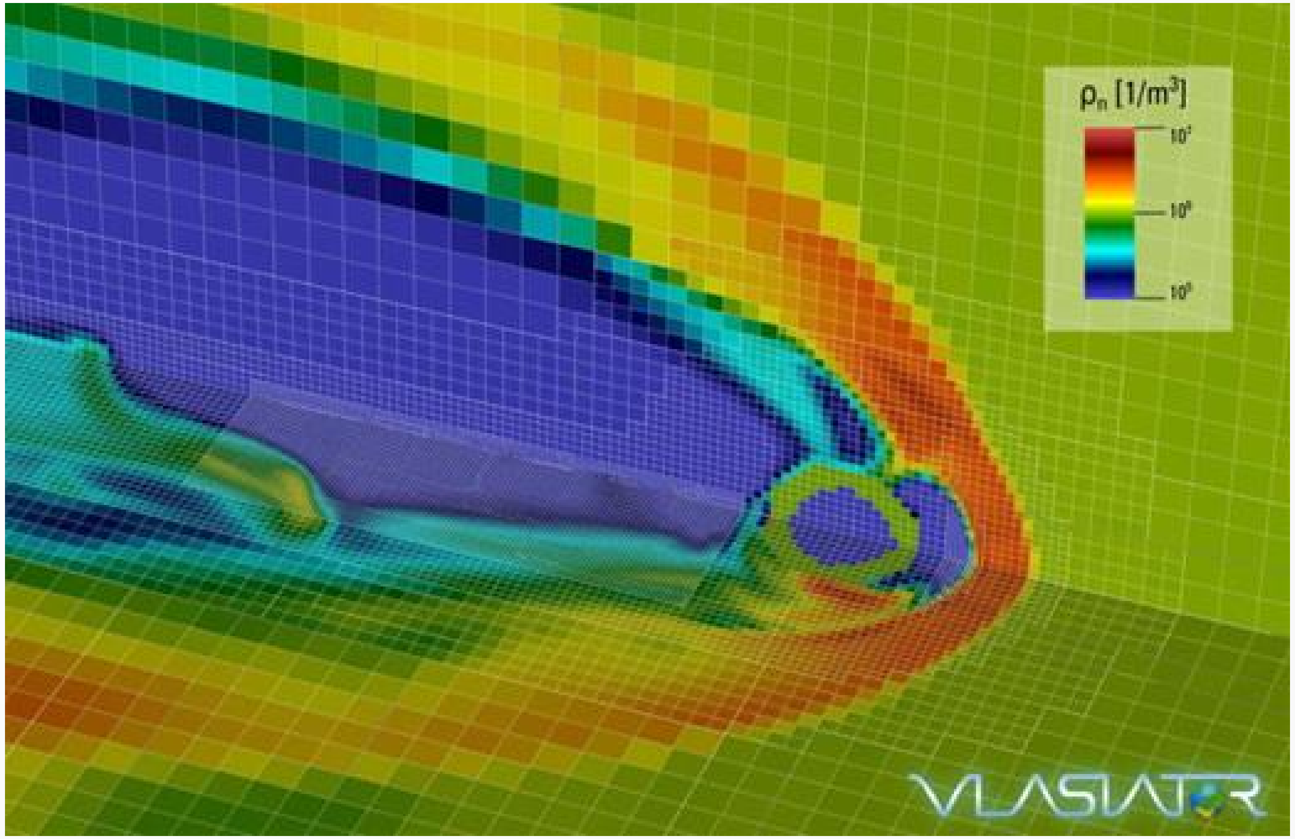
- 3D box (side length ~100 R_E)
- Inner boundary: **r=4.8 R_E**
- **Adaptive mesh**

For details:

- ***U. Ganse, et al. (2023)***

*“Enabling technology for global **3D + 3V** hybrid-Vlasov simulations of near-Earth space.” PoP*

3D3V



Magnetopause Identification

- Magnetopause is an **isocontour** of the ***β**** parameter (S. Xu et al. 2016).

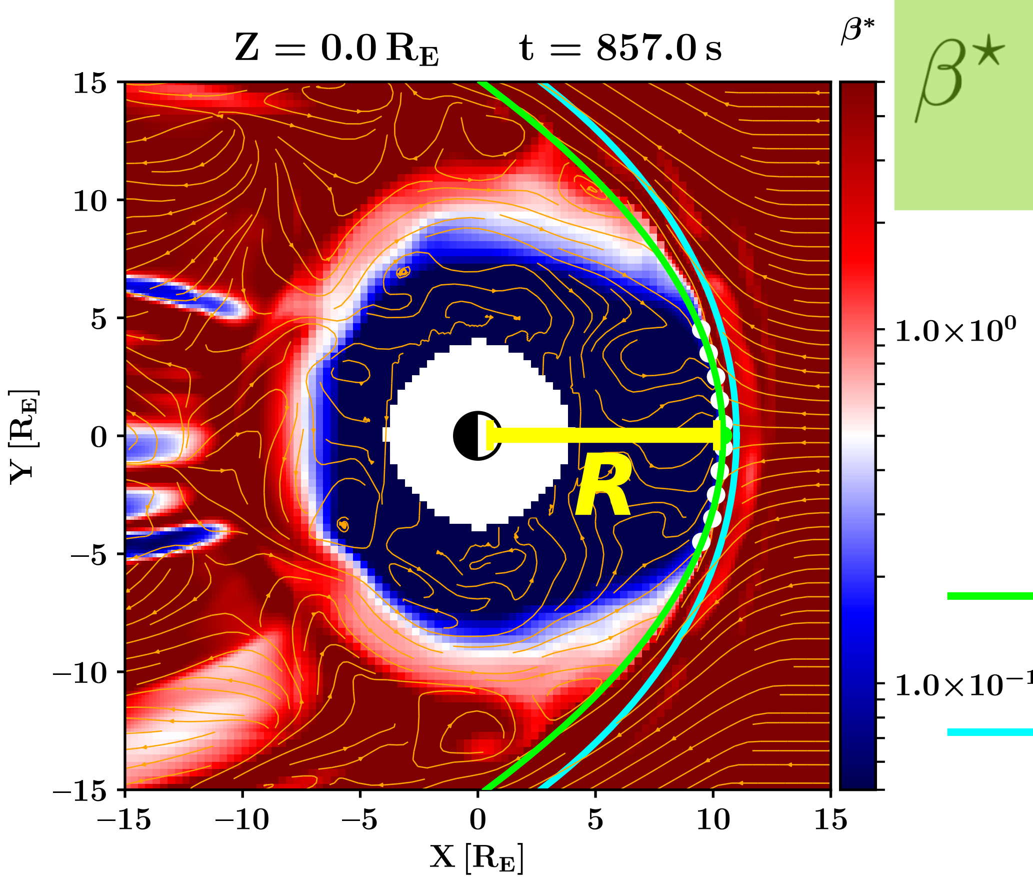
P_d: dynamic pressure

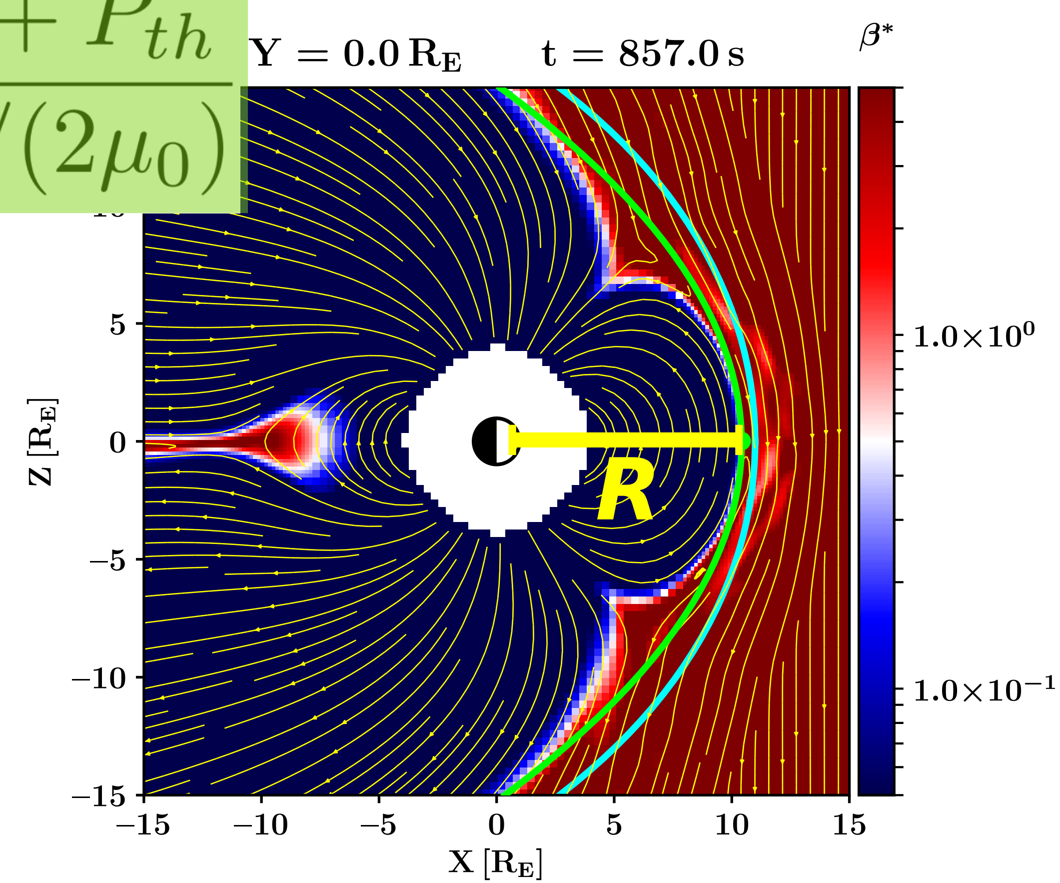
P_{th}: thermal pressure

B: Magnetic field

$$\beta^\star \equiv \frac{P_d + P_{th}}{B^2/(2\mu_0)}$$

Horaites et al., 2023

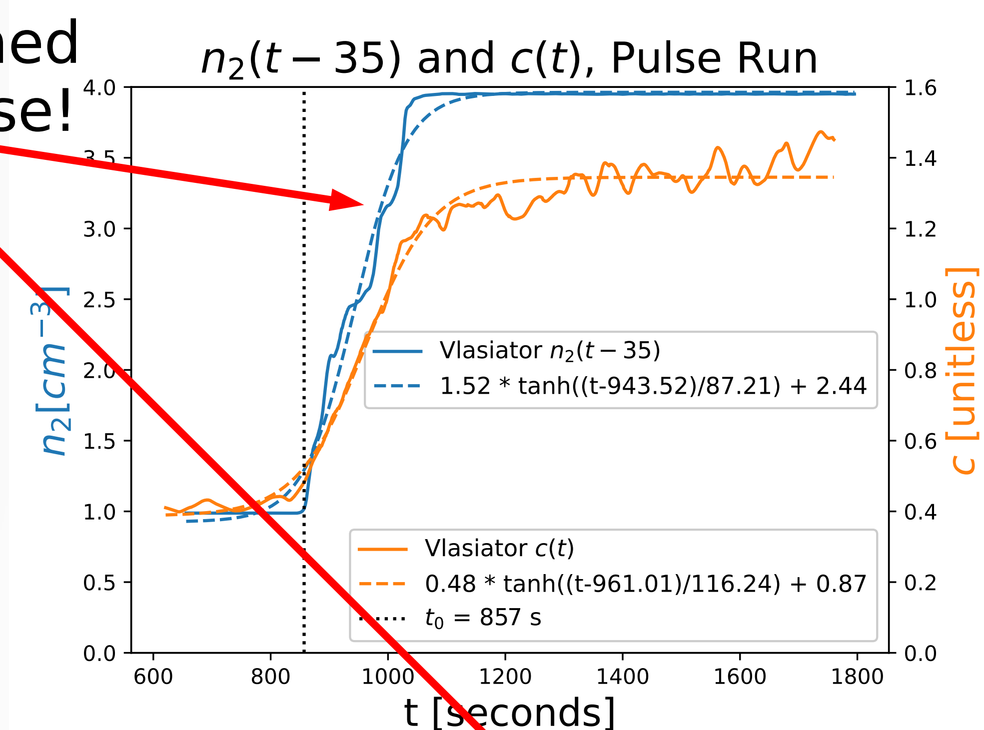


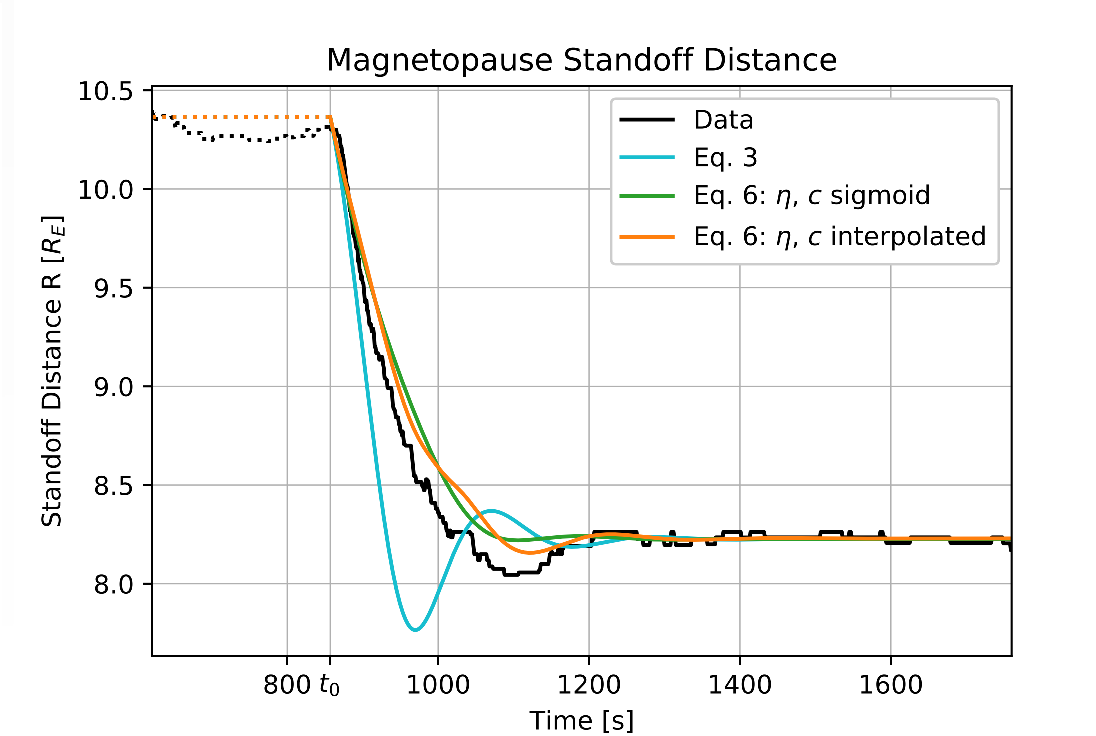


Fit

Shue [98]

Smoothed out pulse!





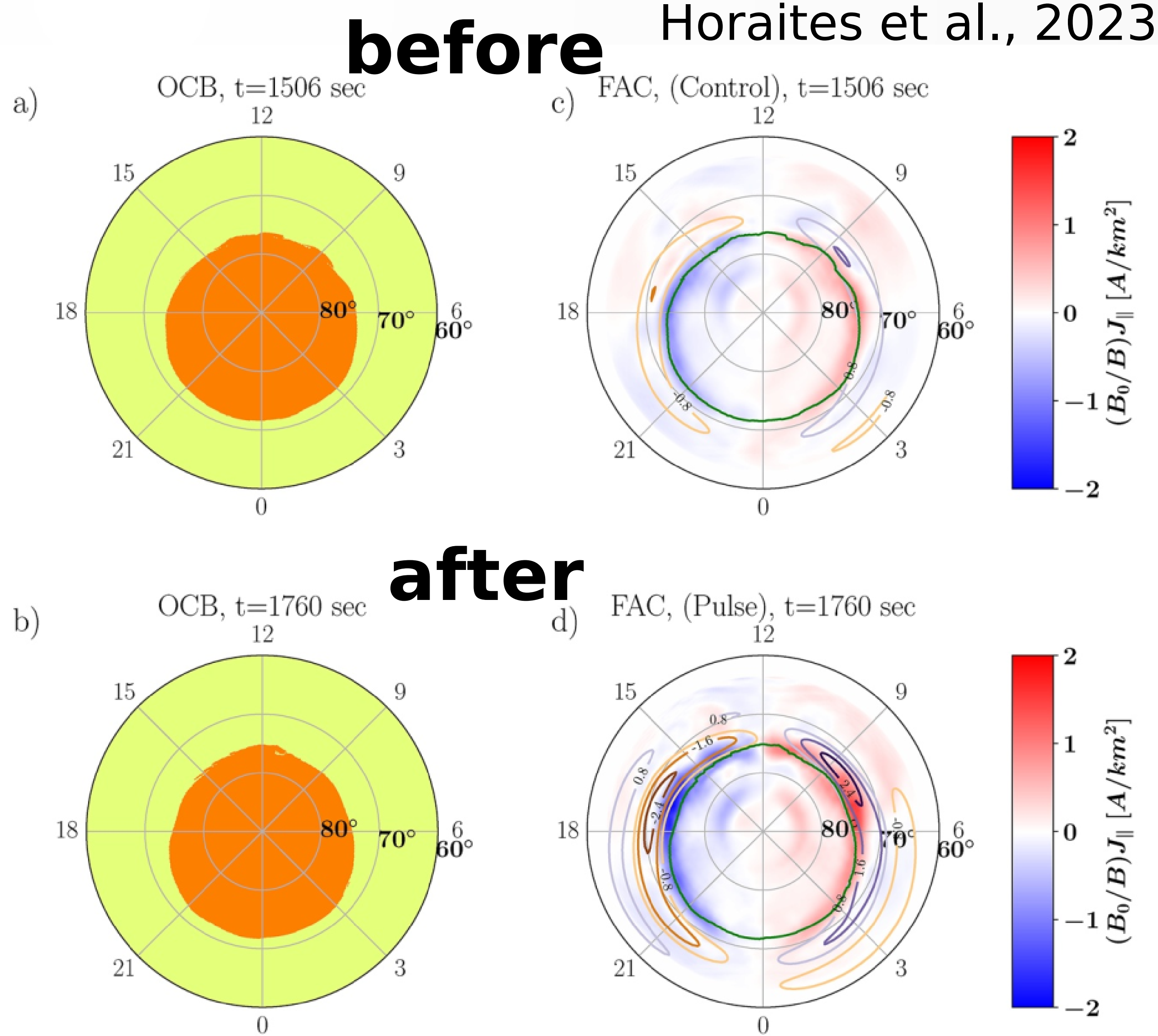
$$\frac{d^2R}{dt^2} + \frac{1}{c(t)R_F}\left\{\eta(t)\left(v_F + \frac{dR}{dt}\right)^2 - v_F^2\left(\frac{R_F}{R(t)}\right)^6\right\} = 0$$

- ***Freeman et al., 1998*** (cyan) predicts the magnetopause is pushed to its mininum standoff distance too rapidly.
- **GENERALIZE**: allow time-dependent mass loading ***c(t)*** and solar wind density ***η(t)***, evaluated directly from Pulse run.

Field-Aligned Currents (FACs)

- **Ionospheric signatures**, before and after a pressure pulse.
- Region 1 FACs compare well with pyAMPS model (panels c-d)
- **Region 2 currents not consistently observed.**

Horaites et al., 2023



FAC closure

- Region 1 and 2 FACs are connected by Pedersen currents.
- Ignored in original 3D3V Vlasiator inner boundary condition (at $r \sim 5R_E$).

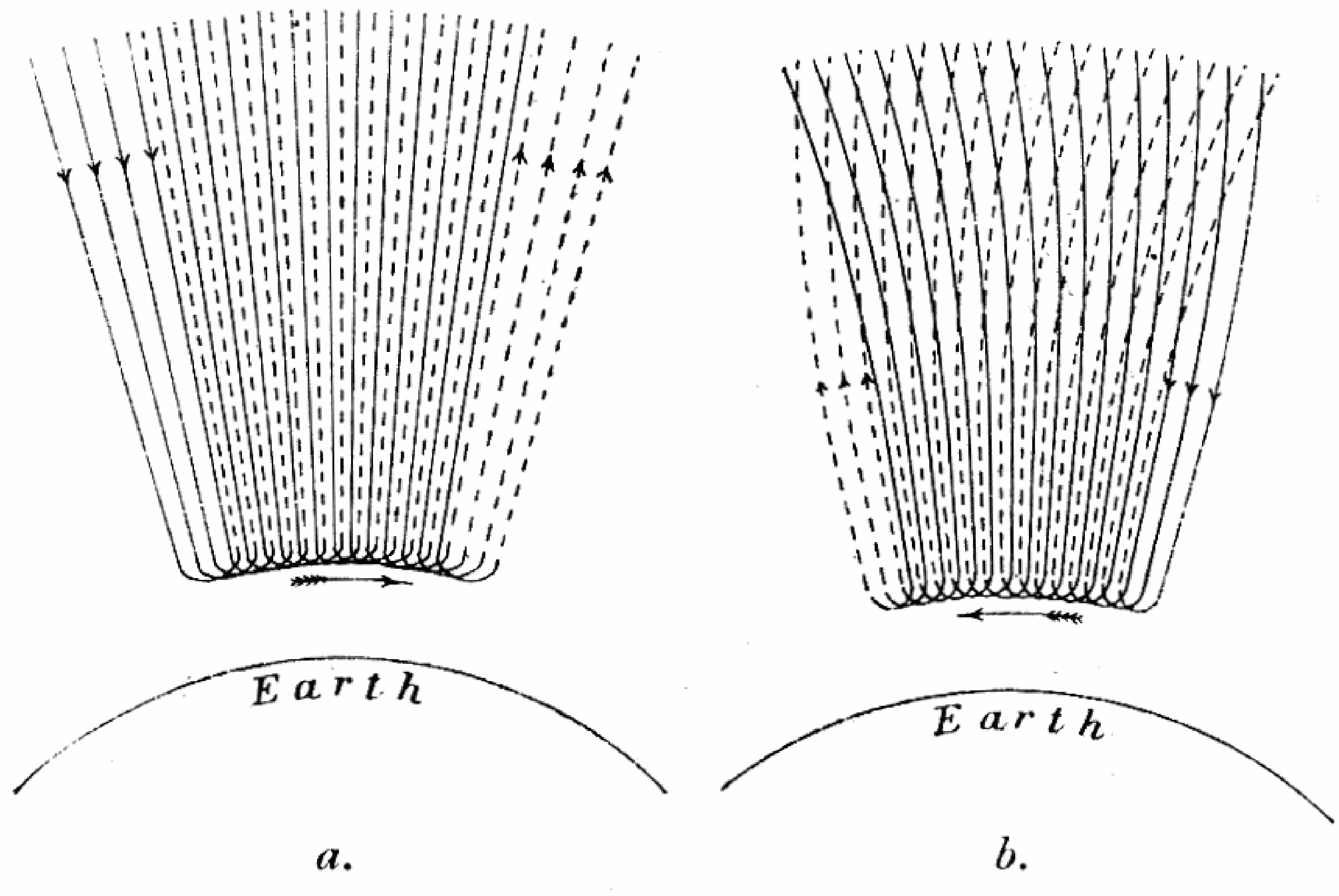
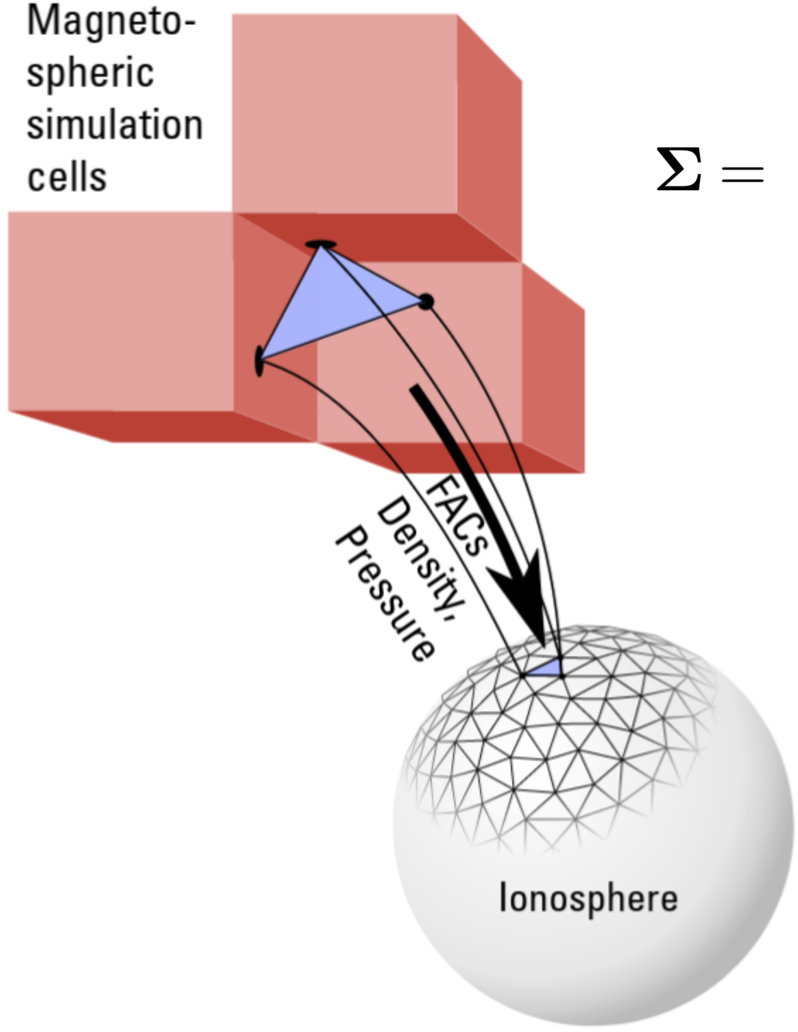


Fig. 50.

Birkeland (1908)

NEW! Ionosphere (Ganse et al., submitted to GMD)

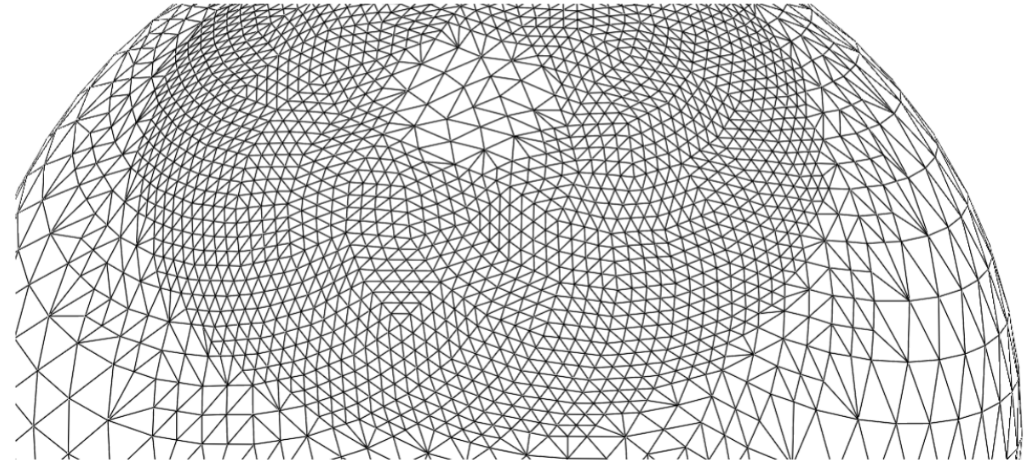


Downmapping

$$\mathbf{\Sigma} = \begin{pmatrix} \Sigma_P & \Sigma_H & 0 \\ -\Sigma_H & \Sigma_P & 0 \\ 0 & 0 & \Sigma_{\|} \end{pmatrix}$$

- Ionosphere ↔ magnetosphere
- Height-integrated conductivity $\mathbf{\Sigma}$ modeled, input FACs ($J_{\|}$) used to solve for ionospheric potential Φ @100 km altitude.
- E-field maps to magnetosphere (field lines are equipotentials)

$$\nabla \cdot [\mathbf{\Sigma} \cdot (-\nabla\Phi)] = -J_{\|}$$

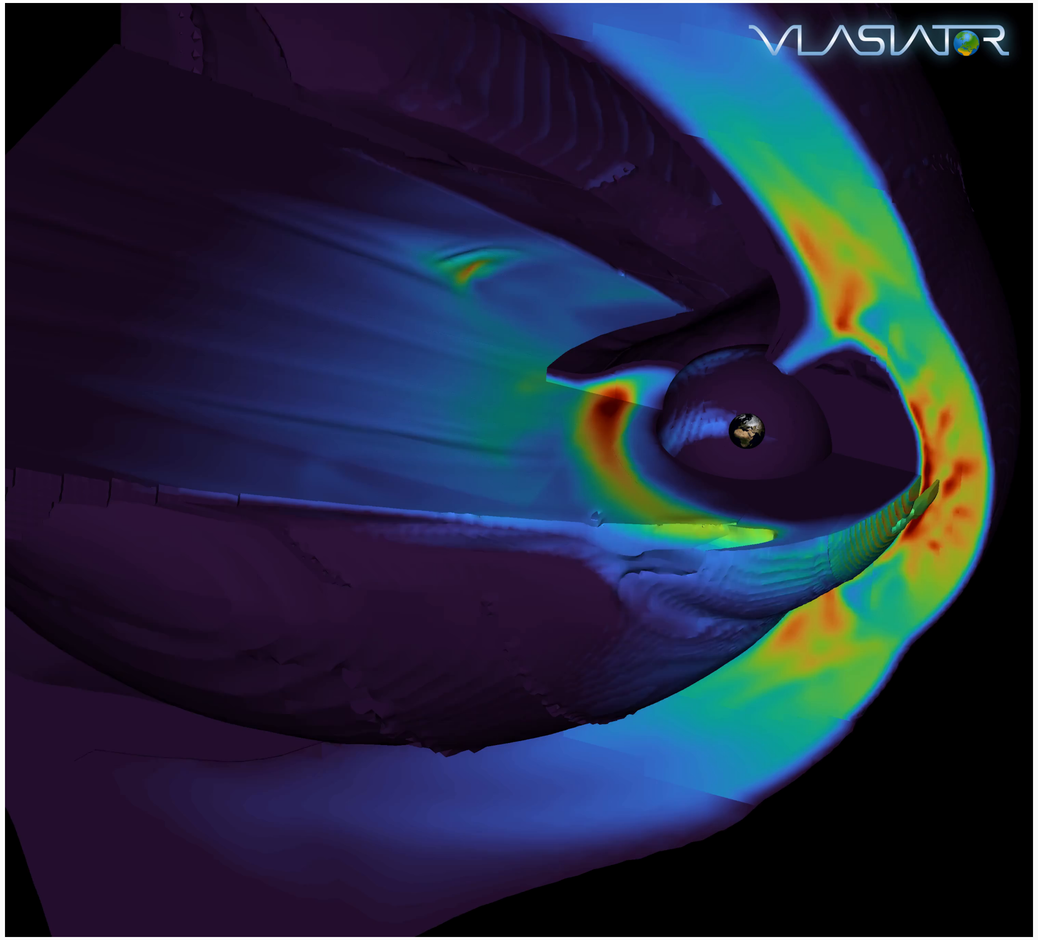


(Ganse et al., unpublished)

Ionospheric mesh refinement

Ionosphere-coupled run

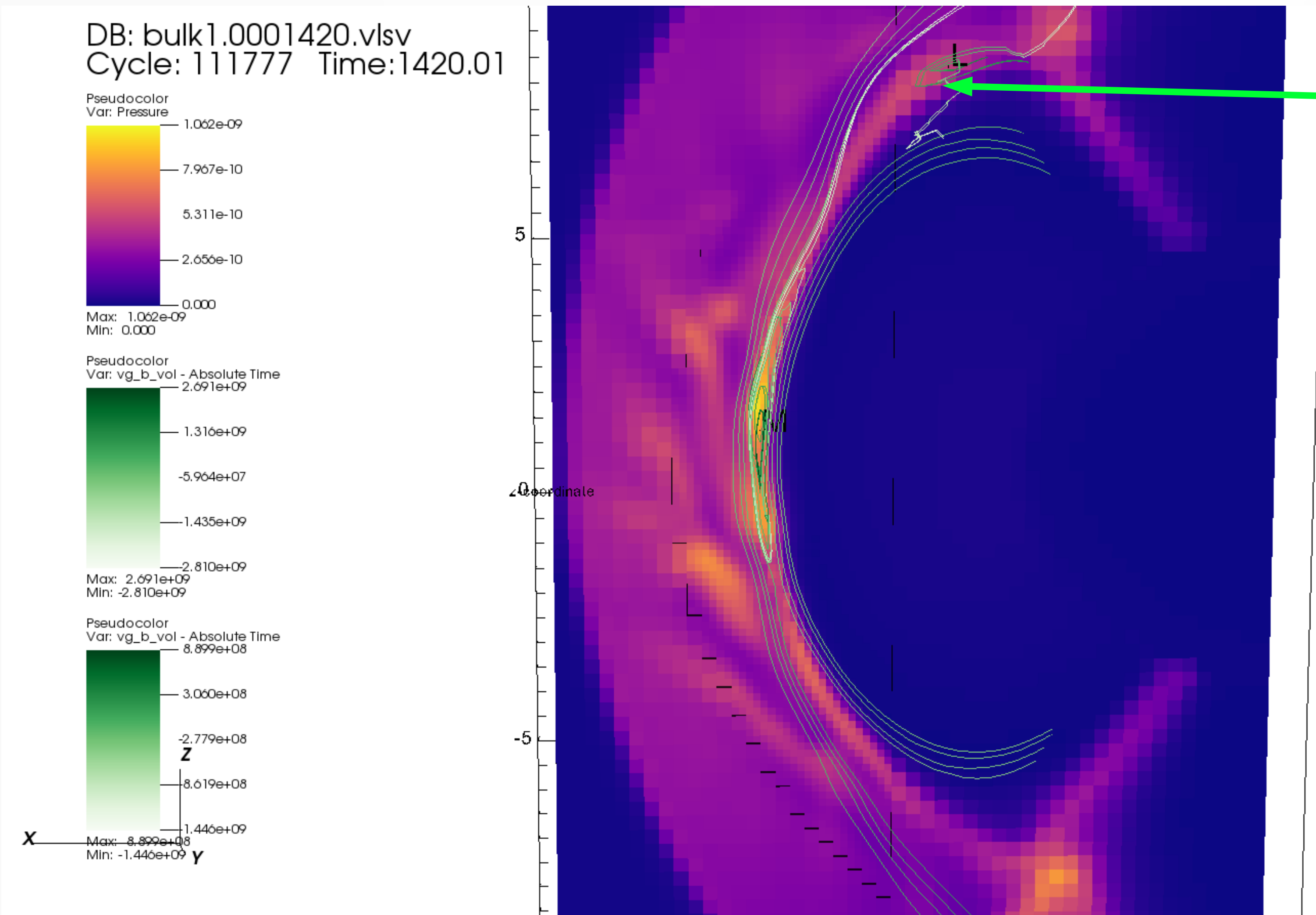
- Right: Plasma pressure
- Regions of enhanced pressure observed near magnetopause
- Structures migrate towards the cusps



Solar wind driving:

B	[0, 0, **-5**] nT
v_{sw}	750 km/s
n	1 cm^{-3}

Flux Transfer Events (FTEs)

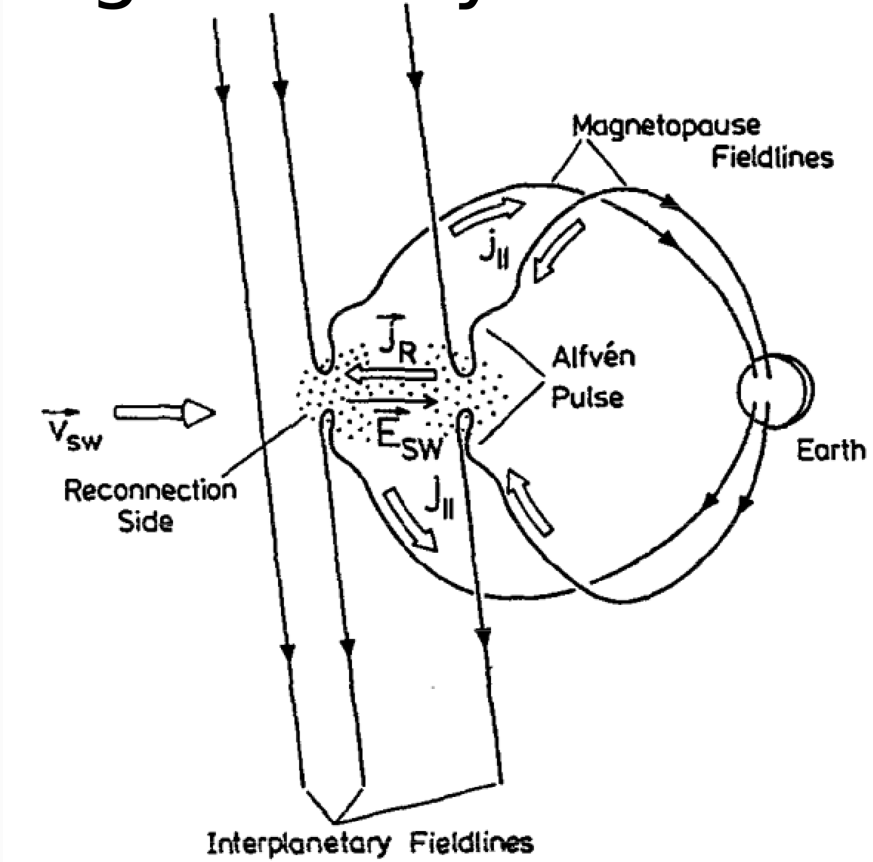


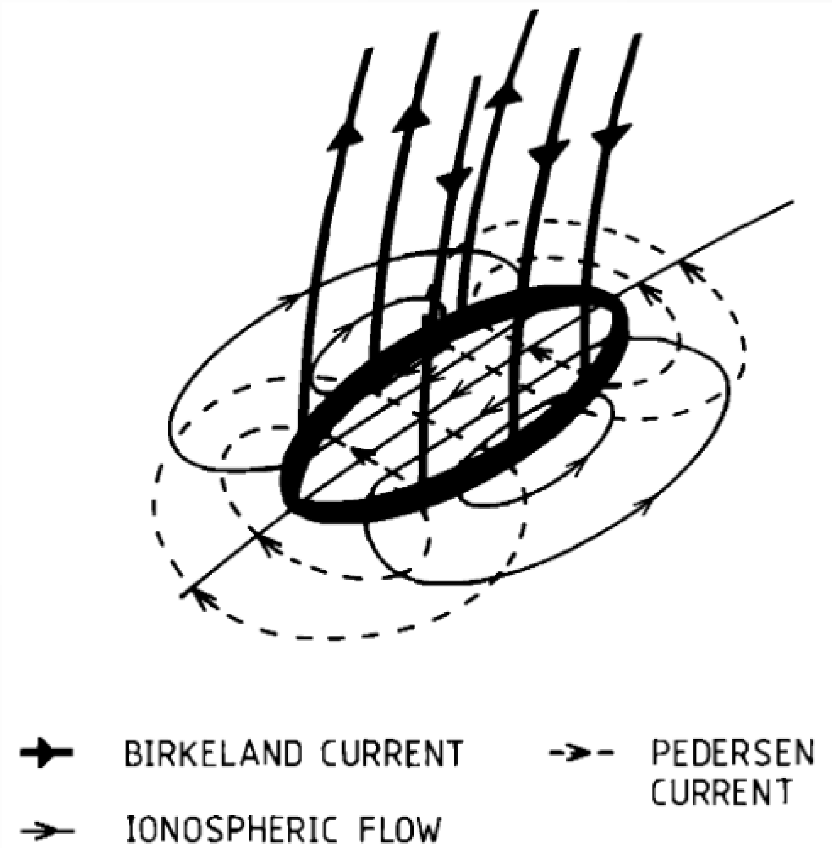
Cusp FTE at
~(6.76, 0, 8.20) R_E

Maps to ionosphere:
~(0.19, 0, 0.98) R_E
(79 deg. north)

Also, equatorial FTE at
~(10.67, 0, 0.52) R_E

Study motivation: Demonstrate the connection between **Flux Transfer Events (FTEs)** and Geomagnetically Induced Currents **(GICs)**





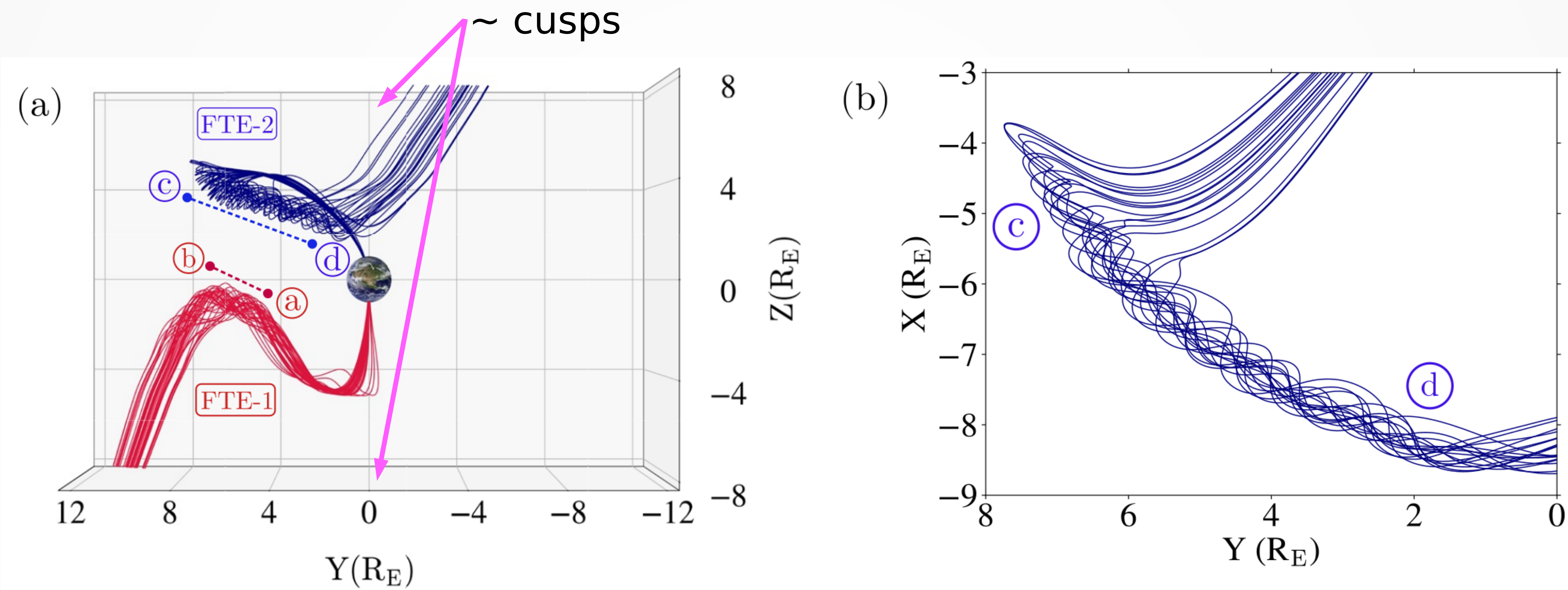
Alfvenic FAC signal

Glassmeier & Stellmacher, 1995

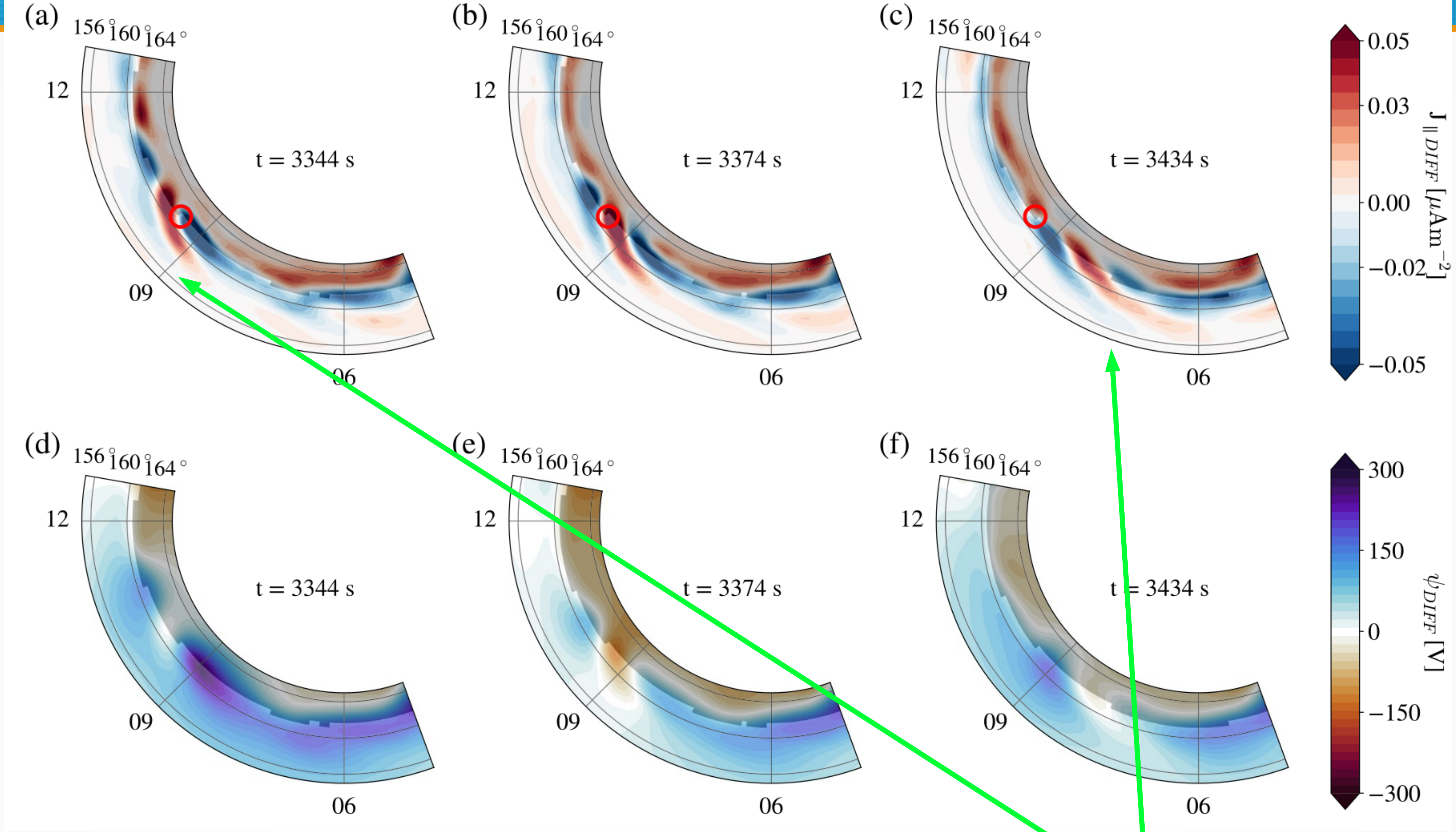
Convection pattern

Southwood, 1987

Recent progress: MagPIE simulations ***(Paul et al, 2023)***

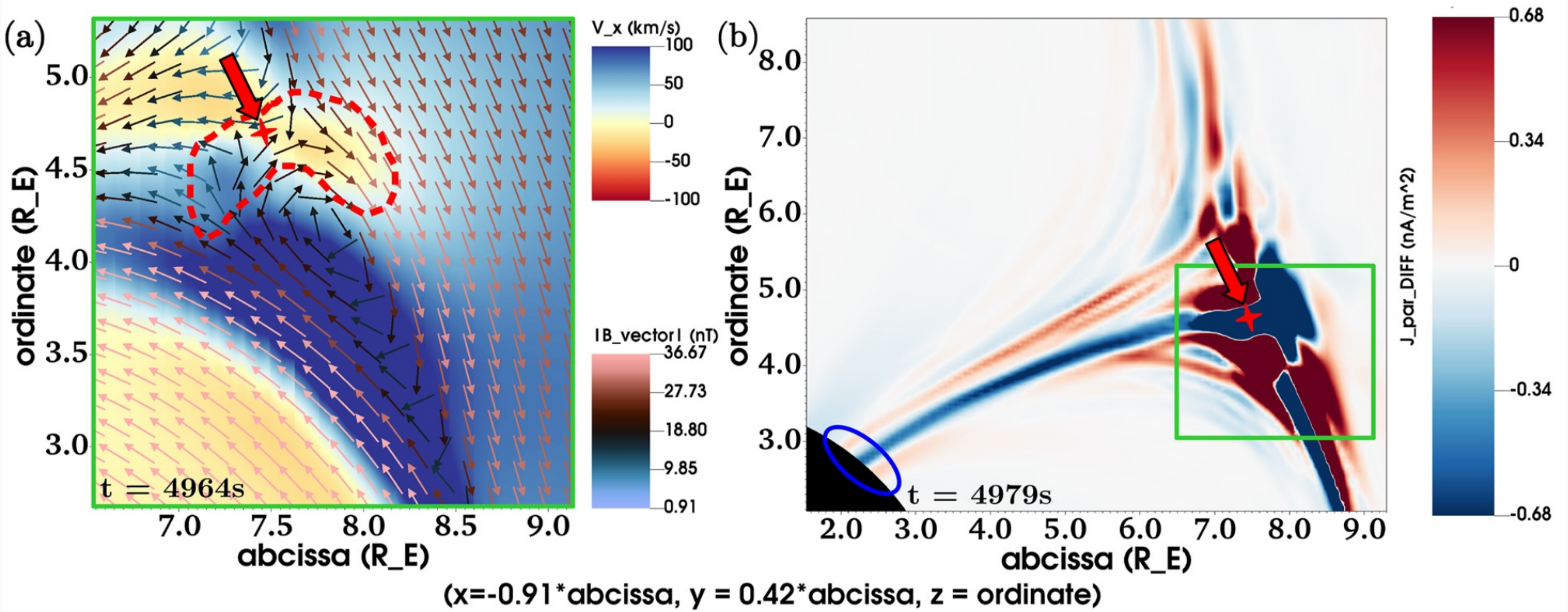


- MagPIE: resistive MHD in magnetosphere (PLUTO code), with electrostatic ionosphere
  - Similar to Vlasiator's ionosphere-coupling scheme
- FTEs (pictured) advect poleward around magnetopause



- FTE-2 ground signature:
  - “tripolar” FAC structure
  - Moves azimuthally

Signal follows the FTE-cusp interaction region



- X-line observed in ~(-x)-z plane
- v_x reversal: reconnection outflows? (---- region)
- Right: $J_{||}(t)$ – $J_{||}(t\text{-}15s)$, strong cusp signal
- Magnetospheric FACs travel at Alfven speed **(not shown)**

Open Questions

Following Paul et al., this study considers FTEs' **space weather impacts**:

- Do the FACs from the cusp-FTE interaction generate a significant geoelectric field?
- What geographical regions are affected?

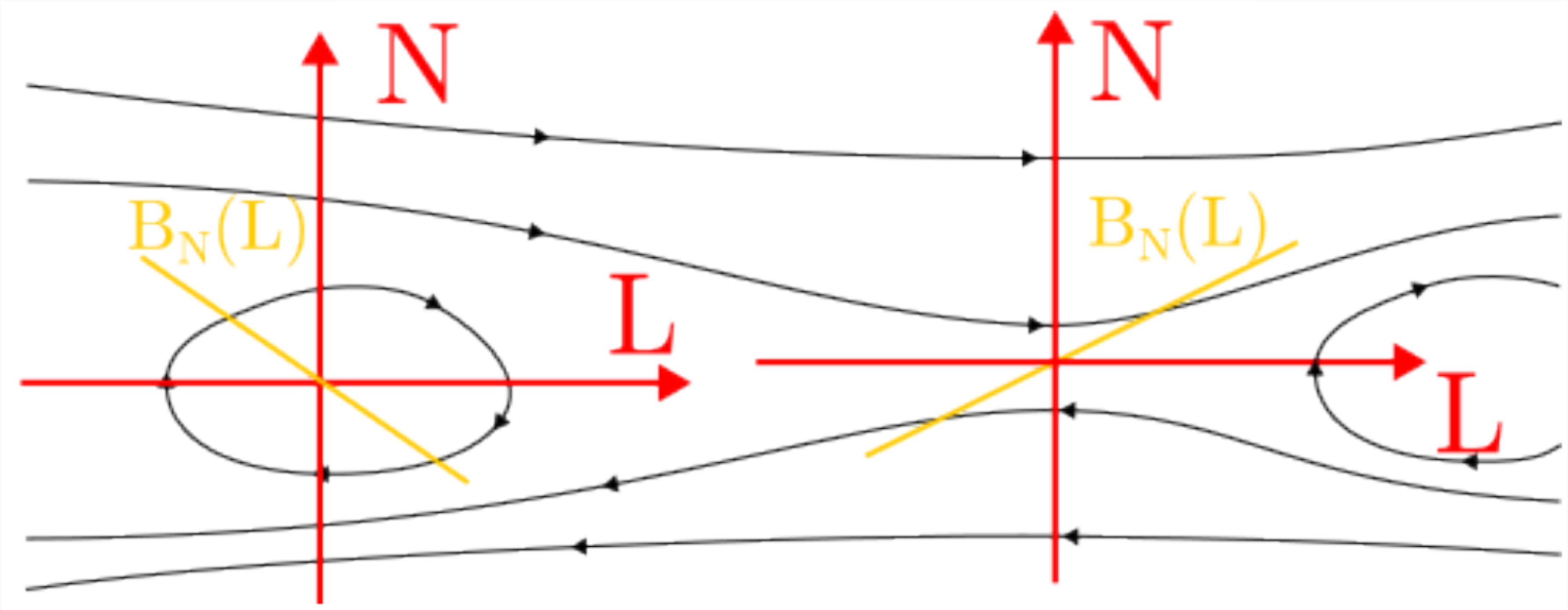
We utilize **recent technical developments:**

- Vlasiator ionosphere
- Automated FTE identification

FTE (O-line) identification

Classification of magnetic null lines (Where **B**=0)
In **LMN** coordinate system:

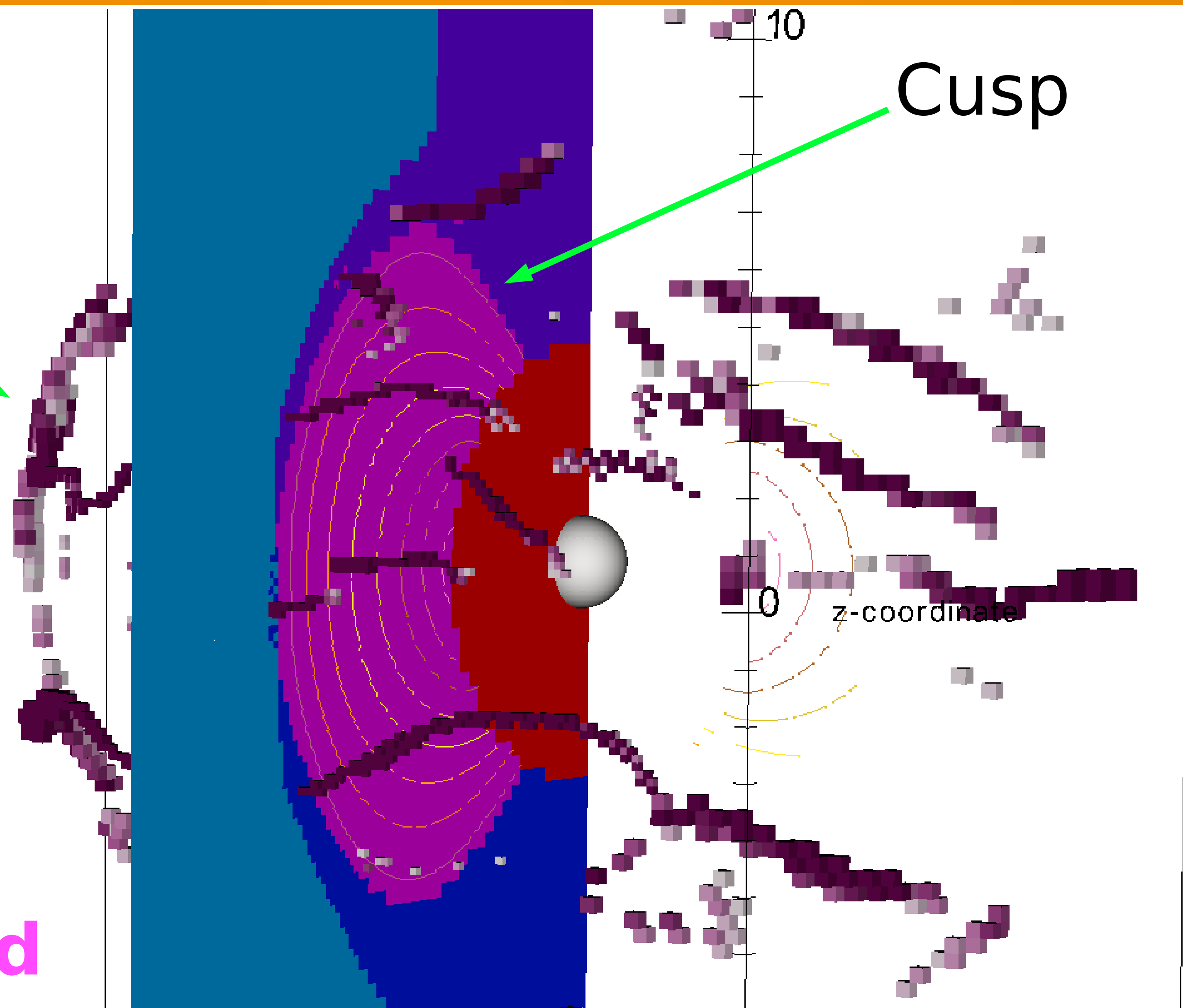
- **“O-lines”: $dB_N/dL < 0$**
- “X-lines”: $dB_N/dL > 0$



Alho et al, 2023

FTE Identification

O-lines



Topology:

open-open

closed-open

closed-closed

Ground magnetic field

Ground magnetic field **B(r)** from Biot-Savart law:

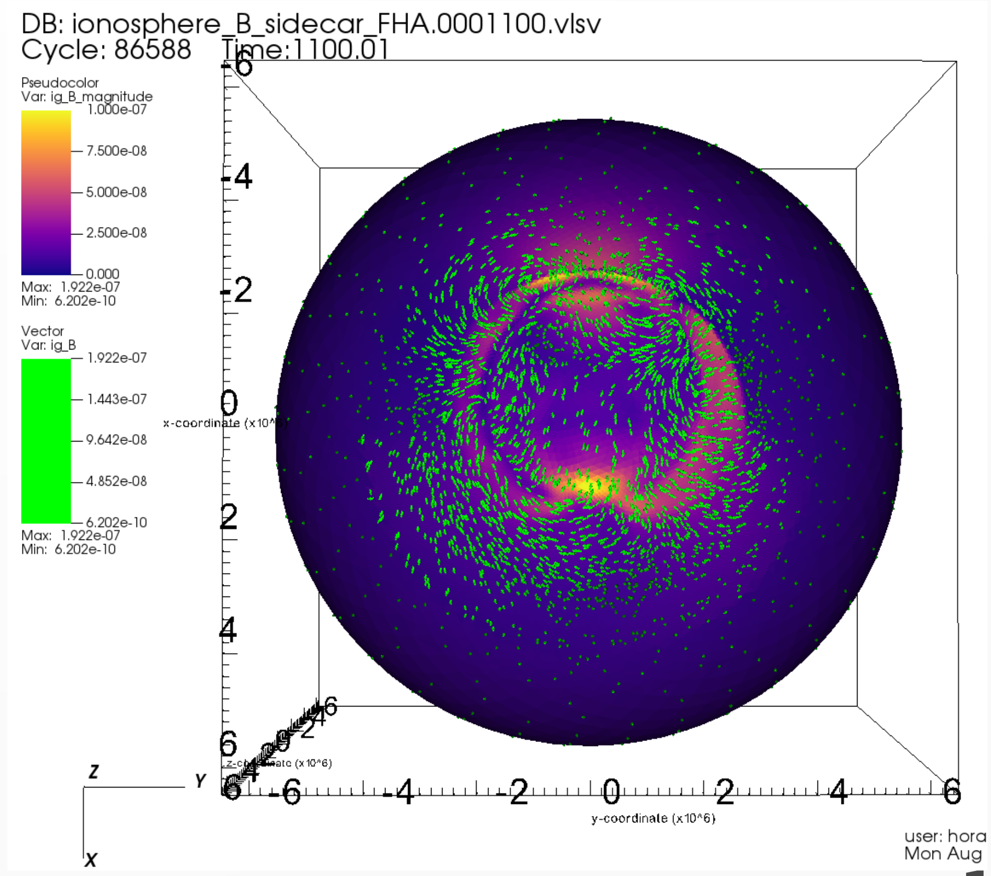
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \iiint_V \frac{(\mathbf{J}\, dV) \times \mathbf{r}'}{|\mathbf{r}'|^3}$$

Integrate over 3 domains:

- **Magnetosphere** ($r > 5R_E$)
- **FACs** ($1R_E < r < 5R_E$)
- **Ionosphere** ($r \sim 1R_E$)

→ *as Welling et al. (2020)*

→ *ignore finite wave speeds*

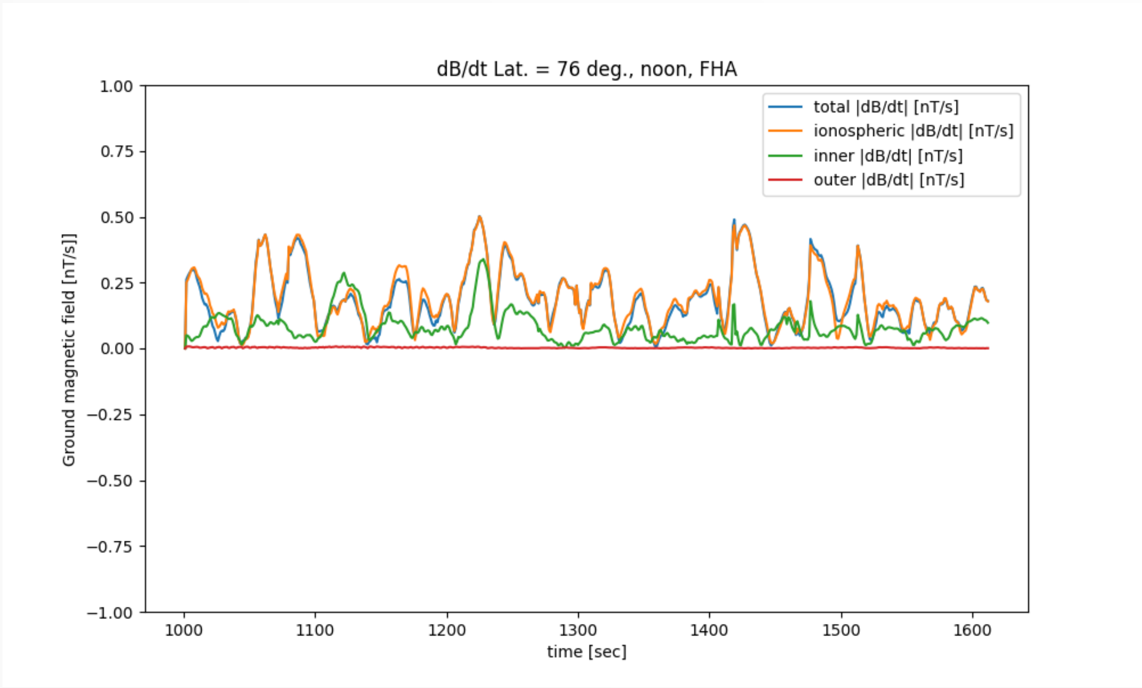


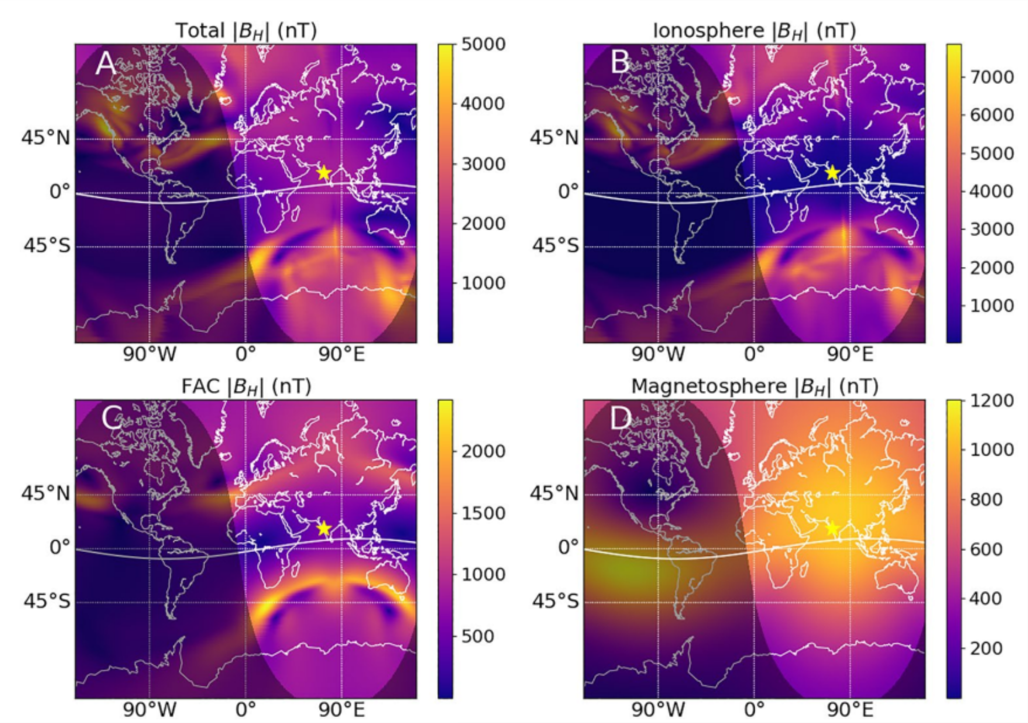
ground **B**-field

Geoelectric Field

Time series of the magnetospheric (outer), FACs (inner), and ionospheric contributions:

- 76° N, MLT=12hr, run “FHA” (weak driving)



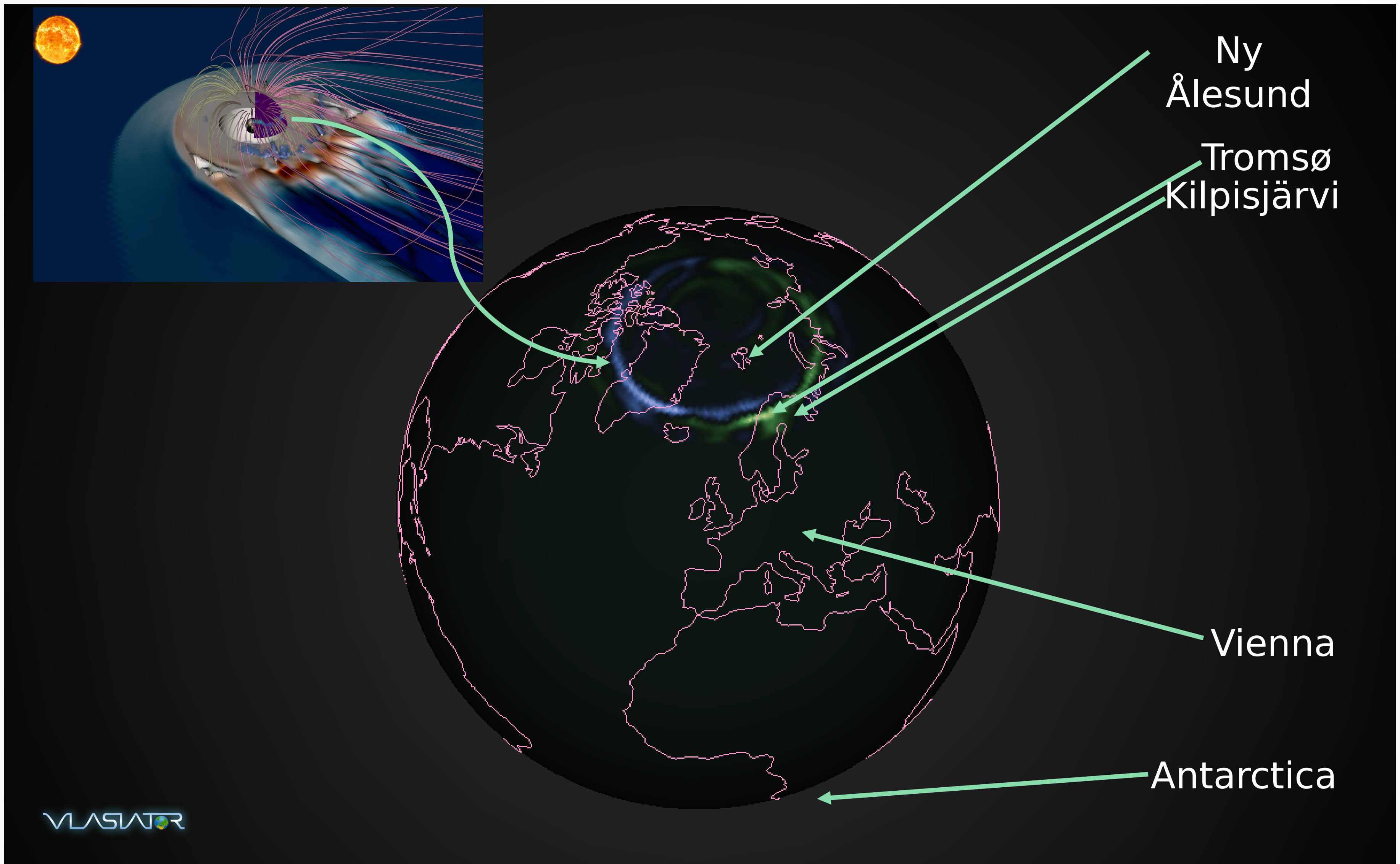


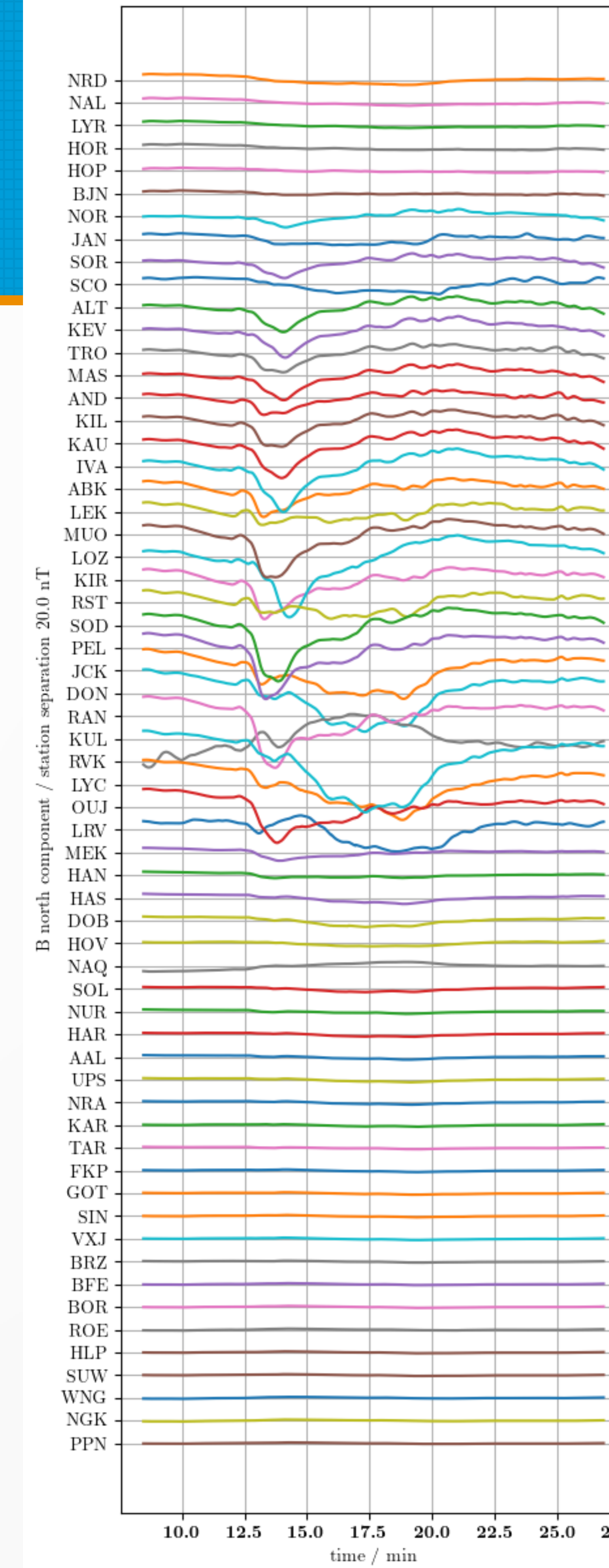
Ionospheric contribution dominates

Outer magnetosphere negligible

Blake+ 2021 (fig. 5)

Virtual Magnetometers





Geoelectric Field (**E**)

- $E_y(t)$ can be calculated as (Cagniard, 1953):

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}}\int_0^{\infty}\frac{dB_x(t-t')}{dt'}\frac{1}{\sqrt{t'}}dt'$$

- And similarly $E_x(t)$ can be calculated from integral of dB_y/dt
- Assume constant conductivity $\sigma=10^{-3}$ S/m

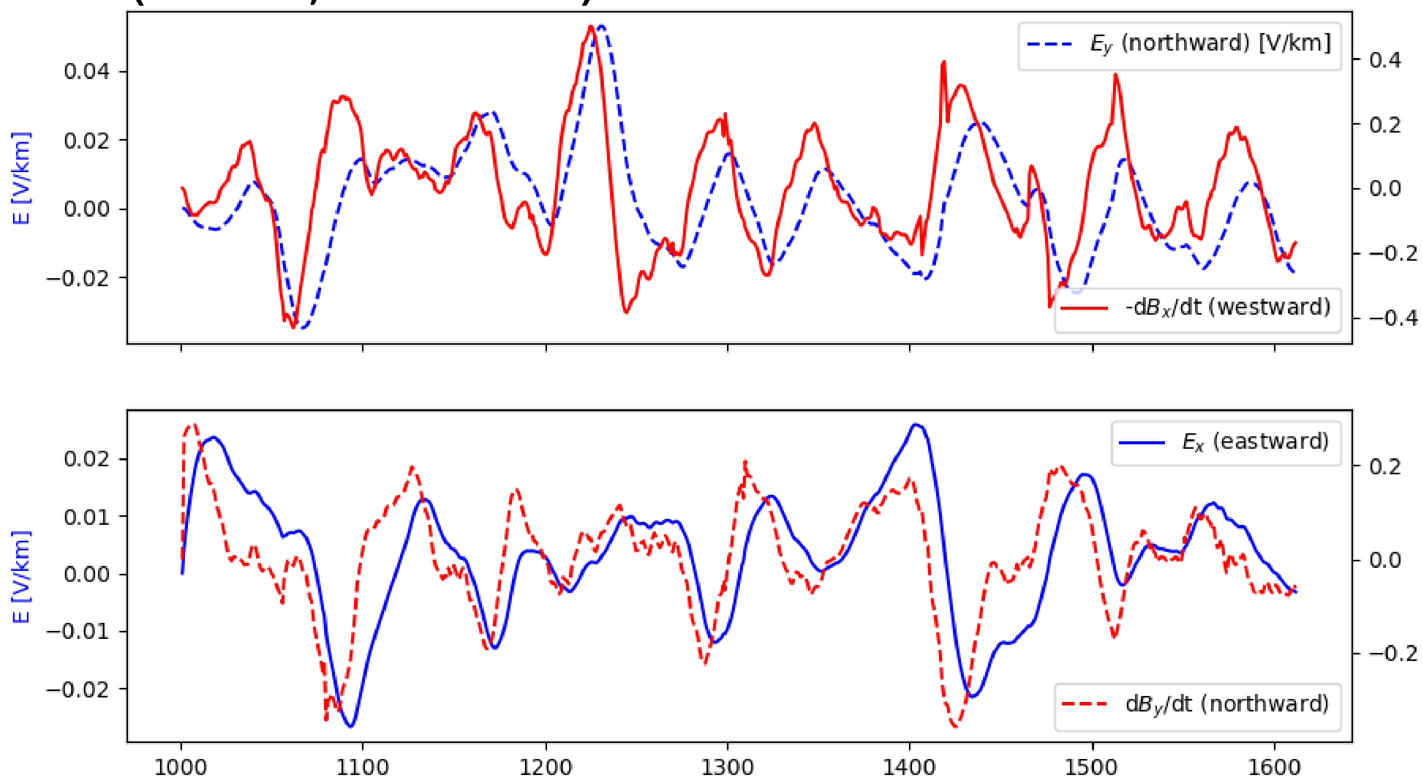
Note: given **E**, Geomagnetically Induced Currents (**J**$_{GIC}$) can be calculated as:

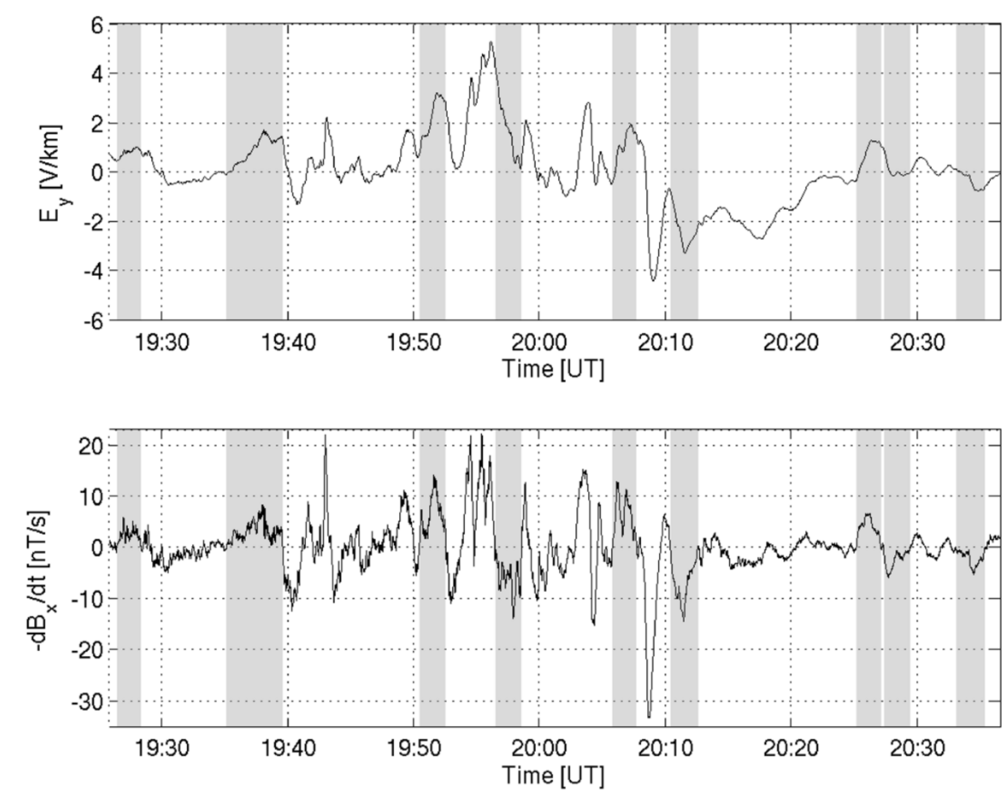
$\mathbf{J}_{GIC} = \sigma\mathbf{E}$

Geoelectric Field

Time series **E** and d**B**/dt components:

(76° N, MLT=12)



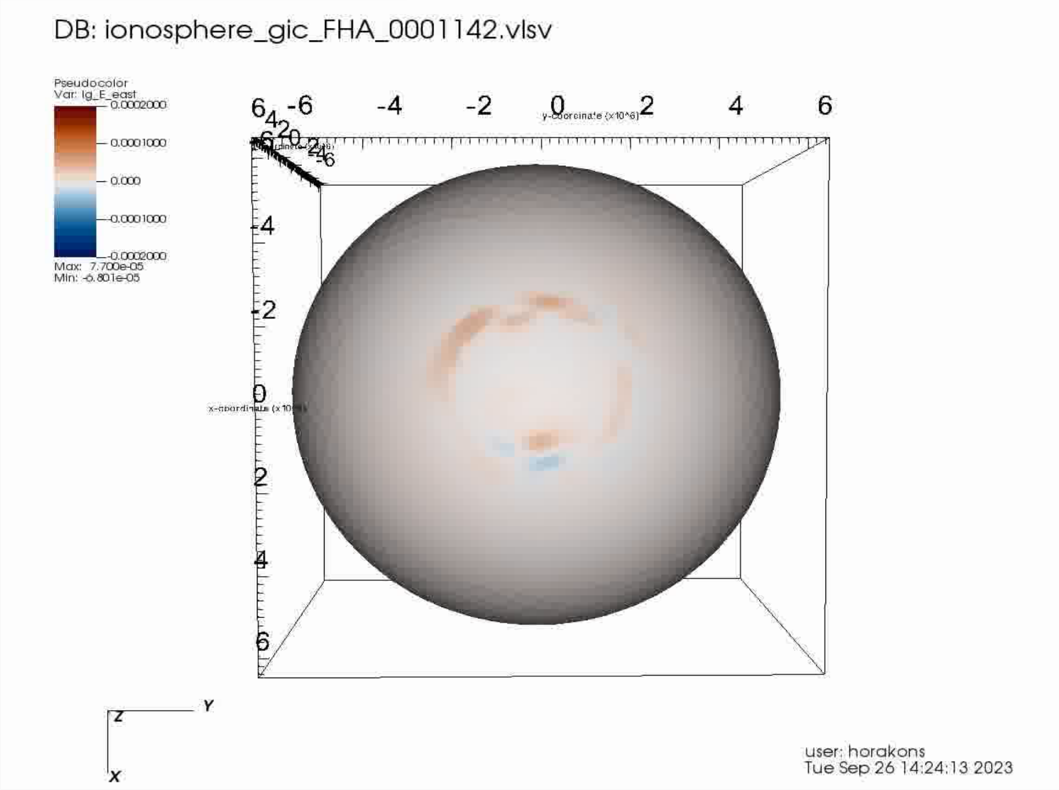


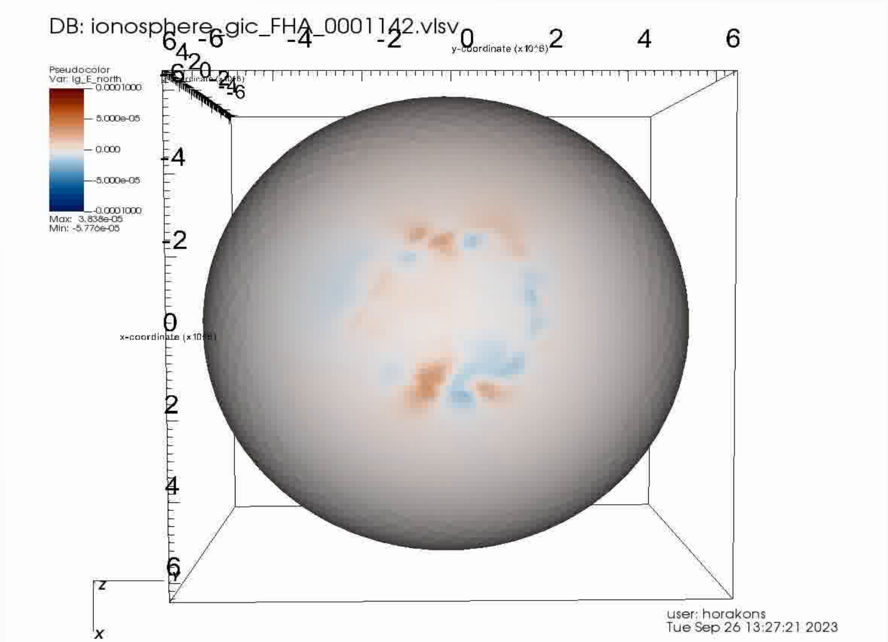
$E_y \leftrightarrow -dB_x/dt$ correlation

$E_x \leftrightarrow dB_y/dt$ correlation

Pulkkinen et al. (2006)

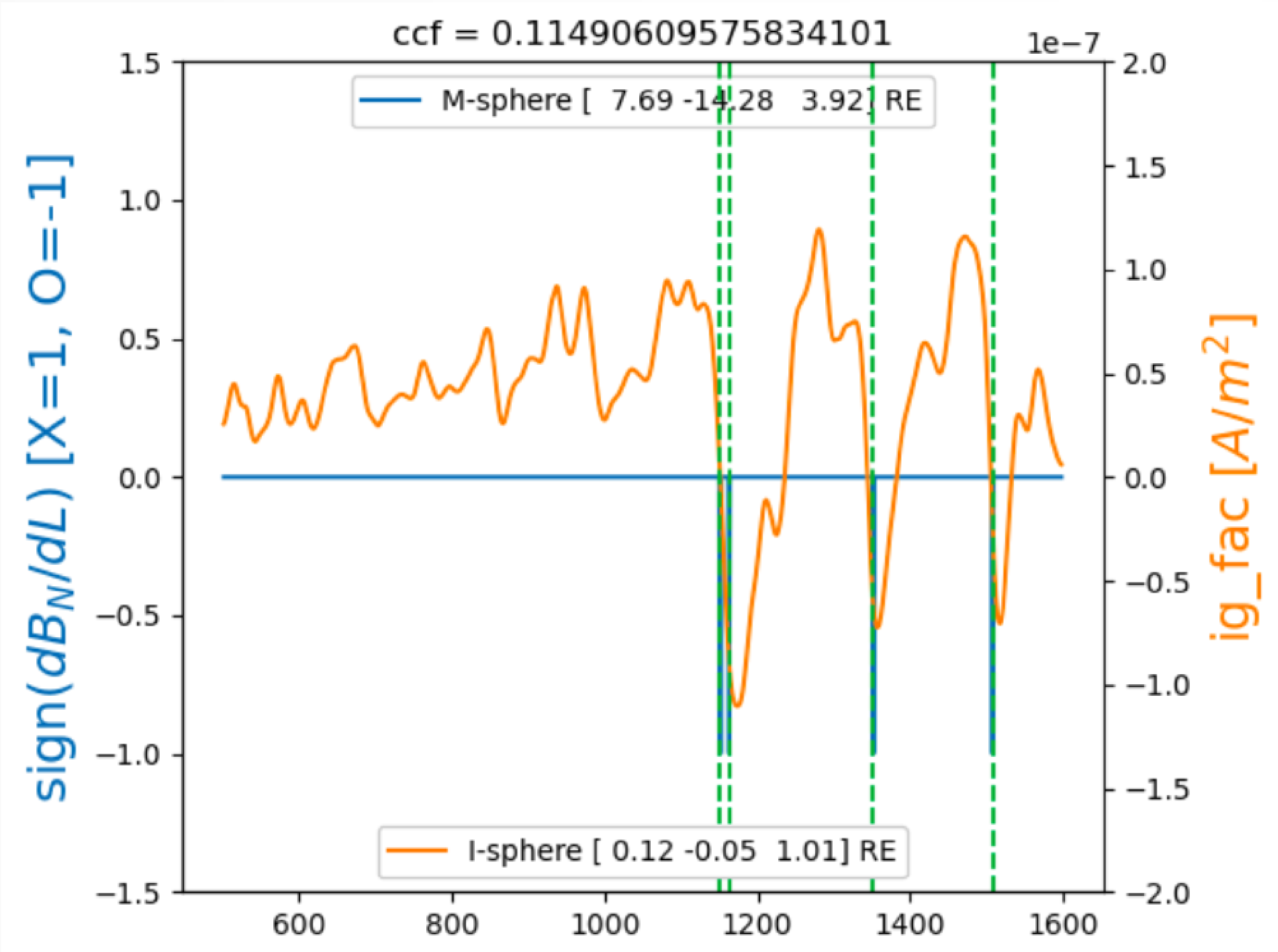
Geoelectric Field

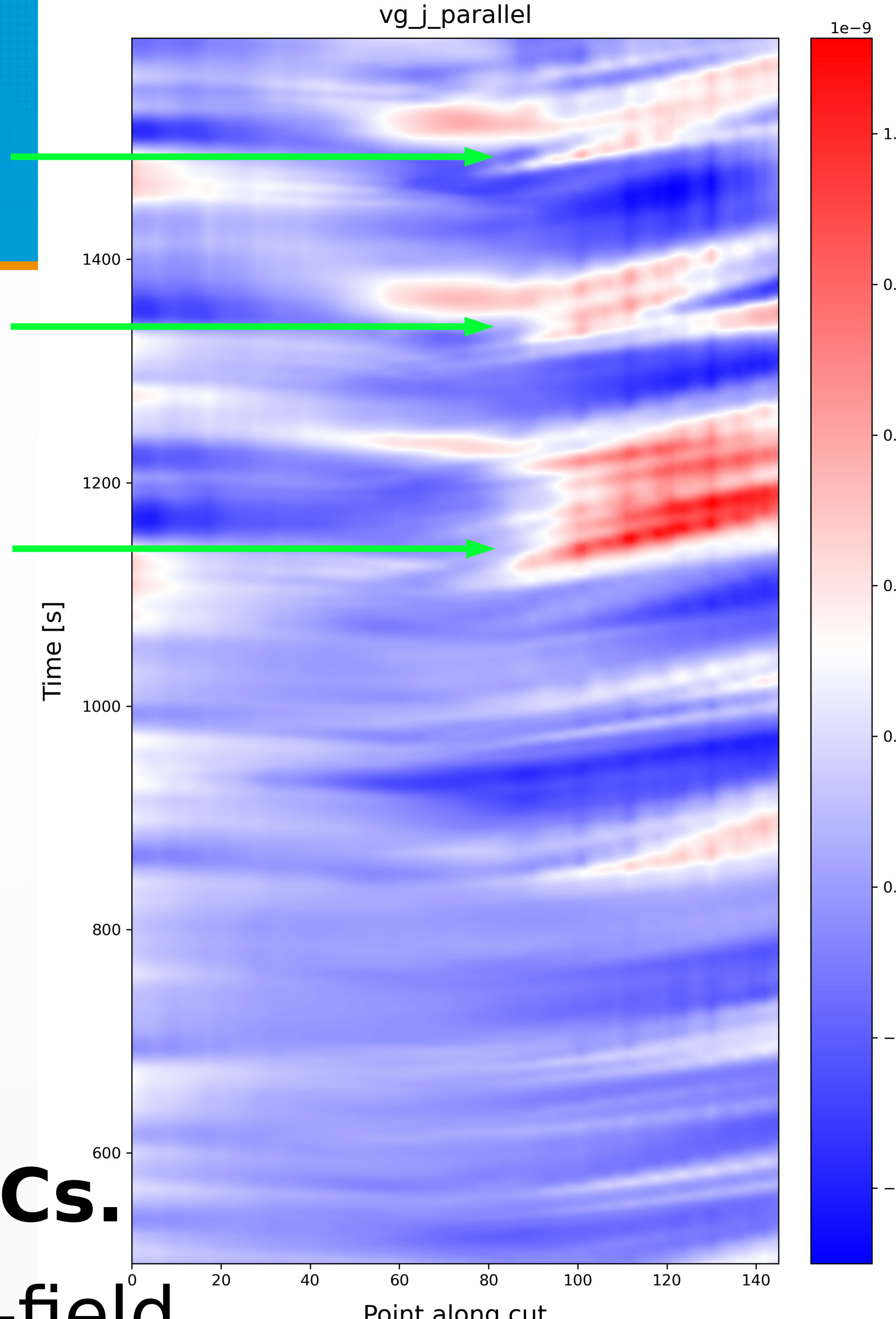




E_{east} E_{north}

FTEs ↔ FACs

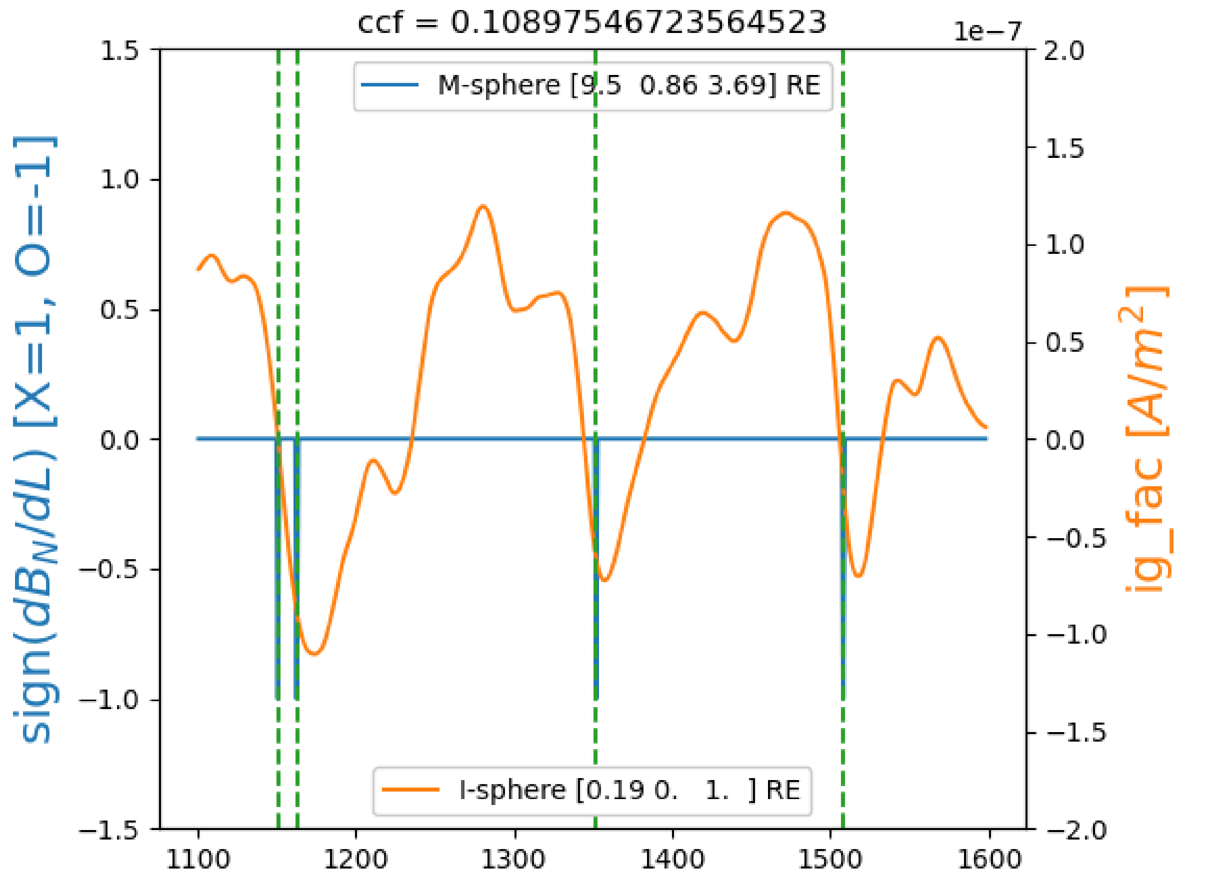


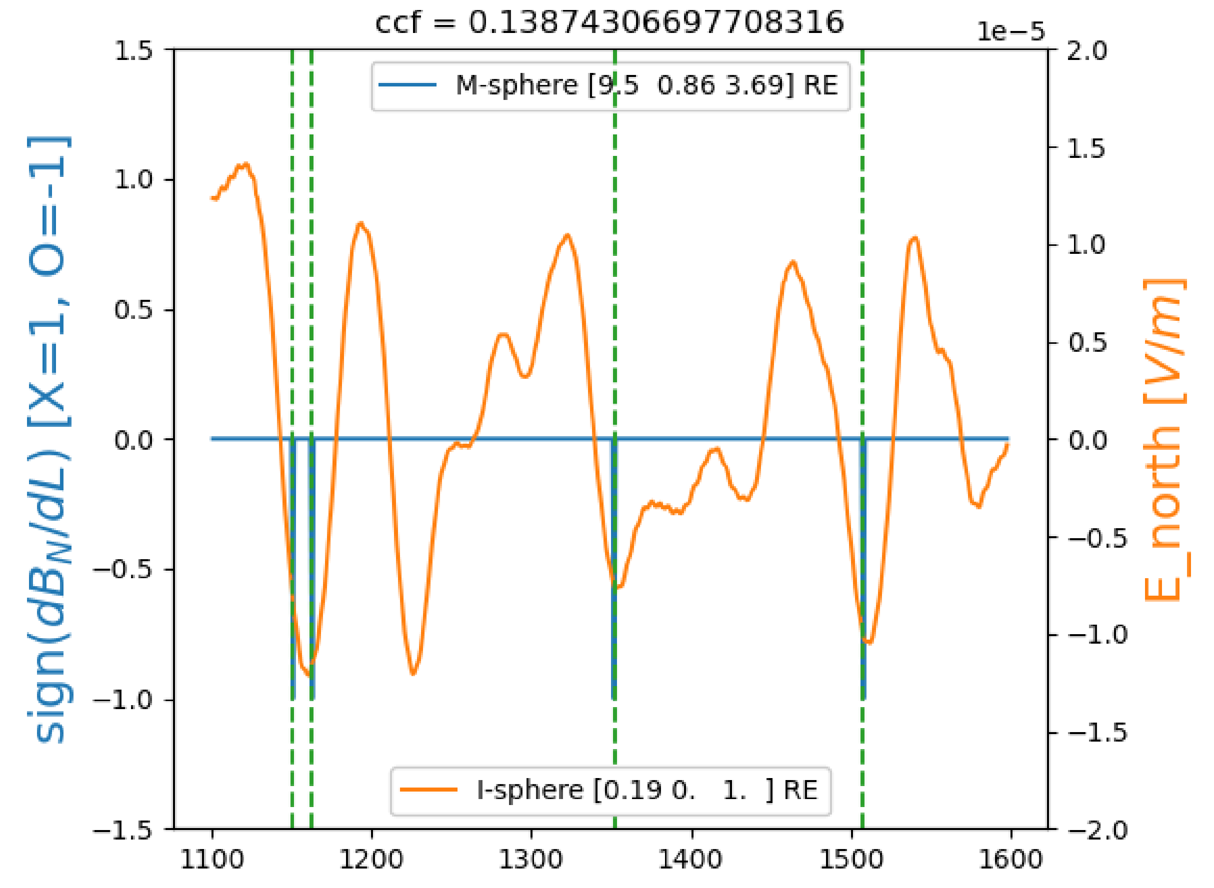


- FTEs correlate w/ ionosphere **FACs.**
- Wave pulse transmitted along B-field.

FTEs ↔ FACs

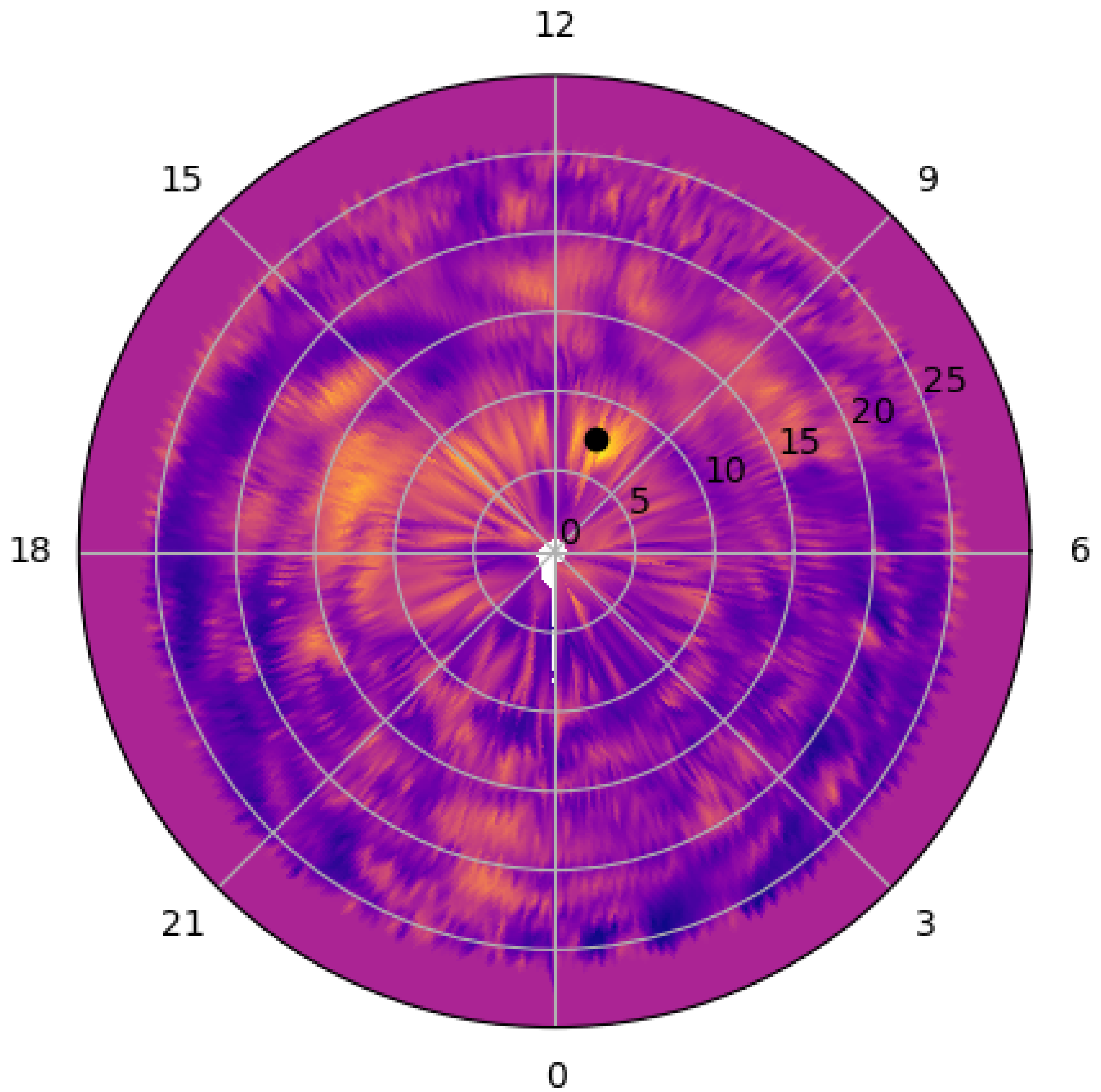
- FTEs correlate closely with FACs,
- Similar, but weaker correlation observed for **E$_{north}$**.





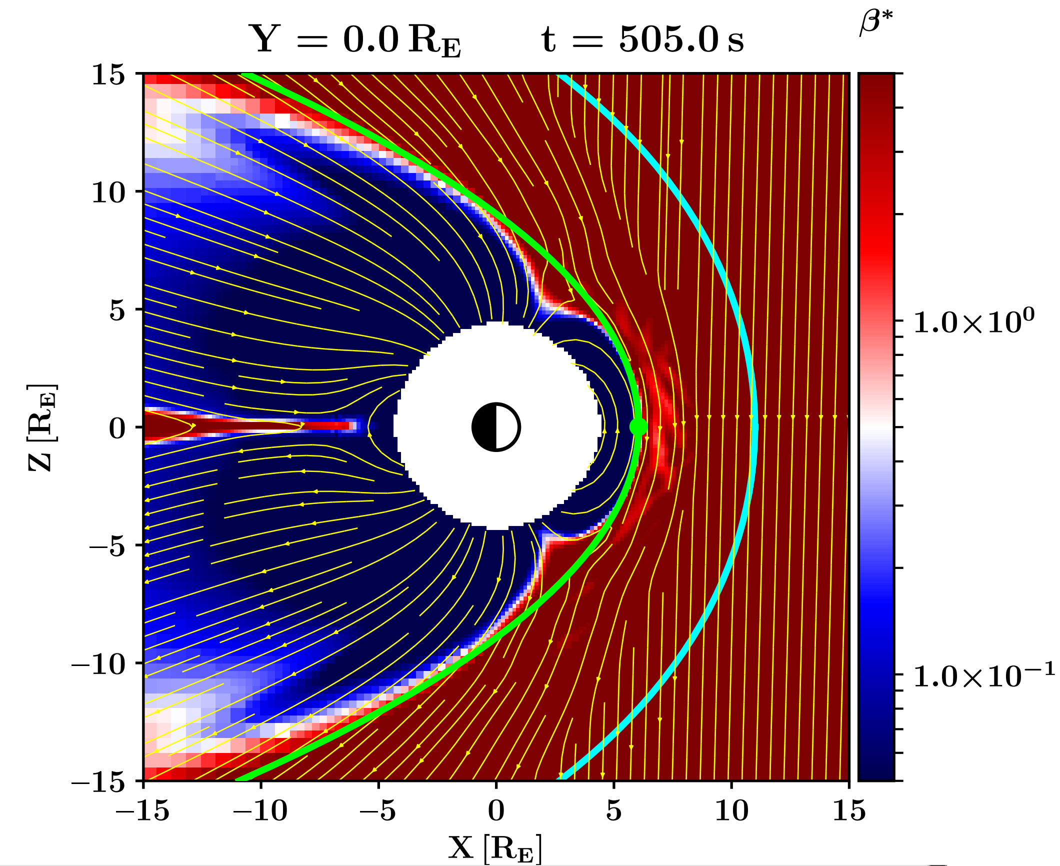
Region of correlated FACs

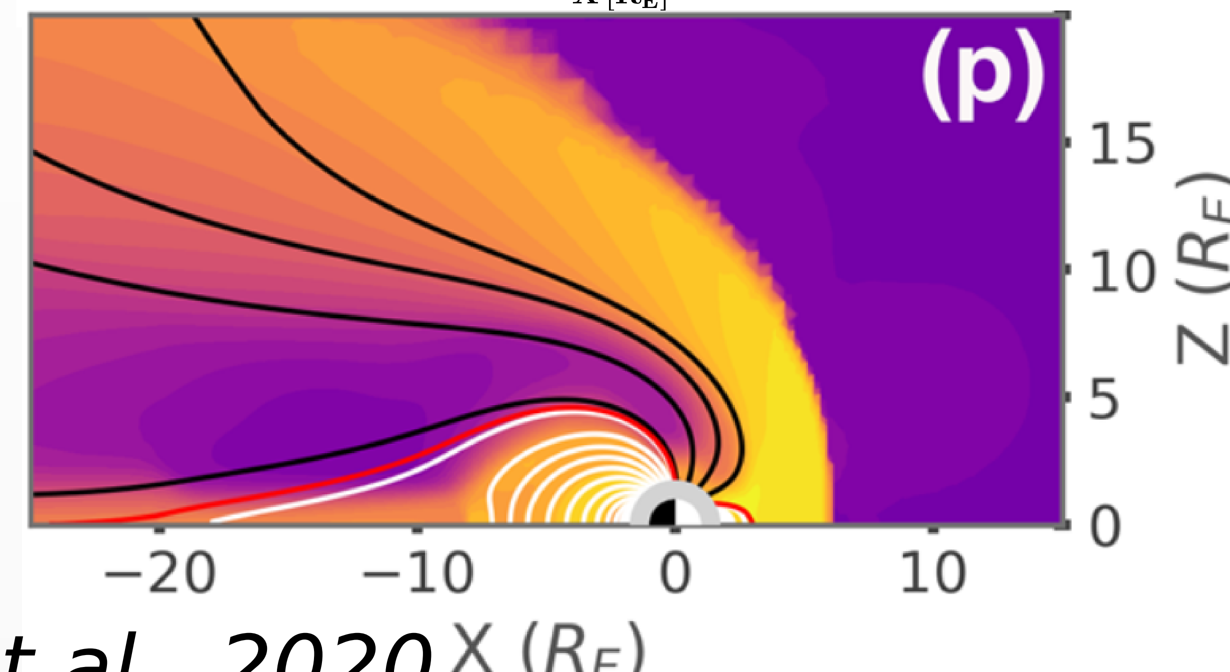
- Pictured: cross-correlation of FACs wrt the marked cusp footpoint.
- FTE-generated FACs sweep out a broad MLT region on Earth’s dayside.



Future work

- We would like to use Vlasiator to study intense CMEs, on the scale of the Carrington event of 1859.
- Magnetopause standoff: R ~ 2-3R_E
- First global hybrid-kinetic simulation of such events.
- **Driving conditions best informed by observations!**

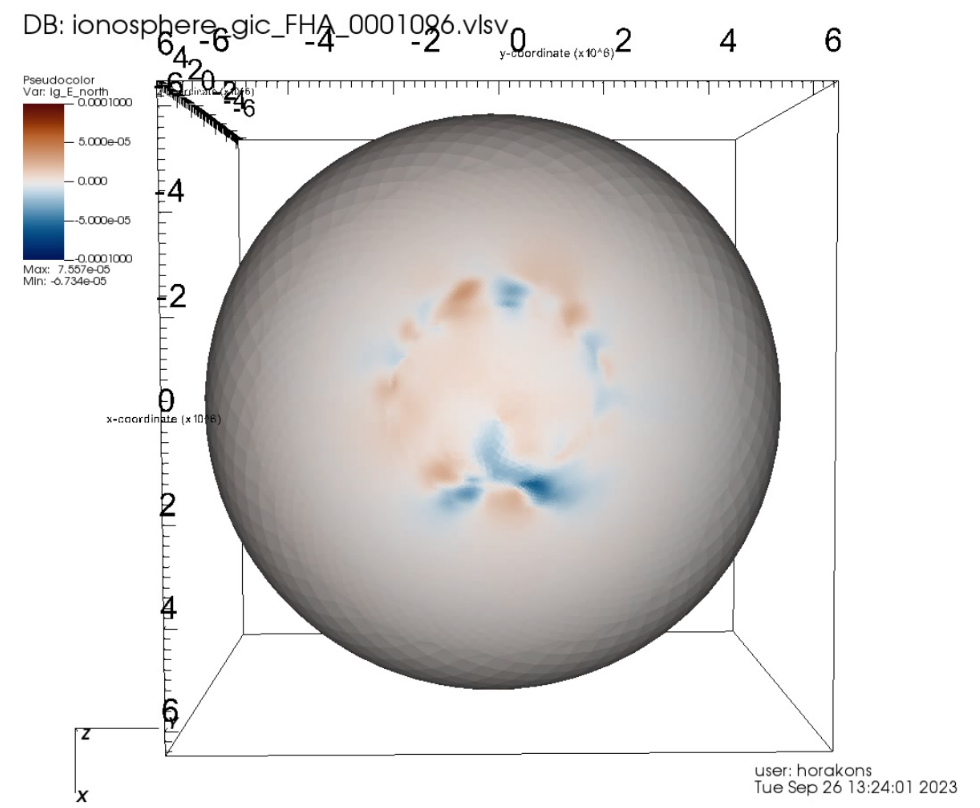




Welling et al., 2020

CONCLUSIONS

- **Vlasiator's new ionosphere** improves physical realism and enables the study of space weather.
- **FTEs are a significant driver of Earth's geoelectric field** at the footpoints of dayside cusp field lines (near auroral latitudes).



Paper in preparation

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