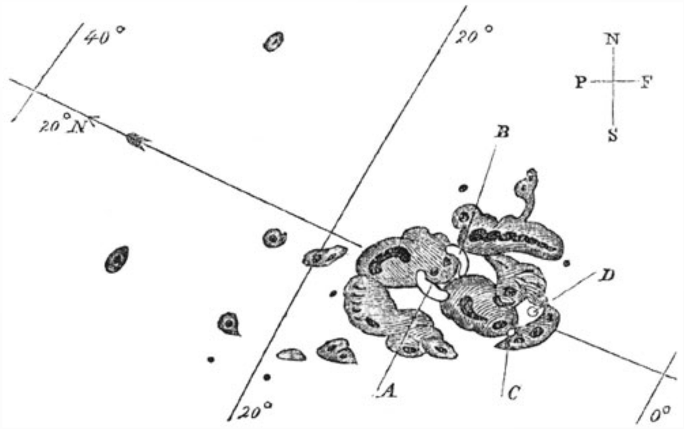
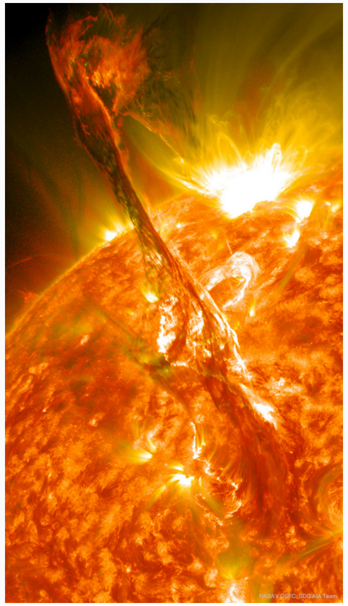
Calm Before the Storm: Preparing for the first Carrington-scale hybrid-Vlasov simulations of Earth's Magnetosphere

Konstantinos Horaites
University of Helsinki

Carrington Event: 1859

- **September 1, 1859**: British astronomer Richard Carrington observes a bright spot on the sun...
- ...18 hours later, aurorae are observed as equatorward as Colombia

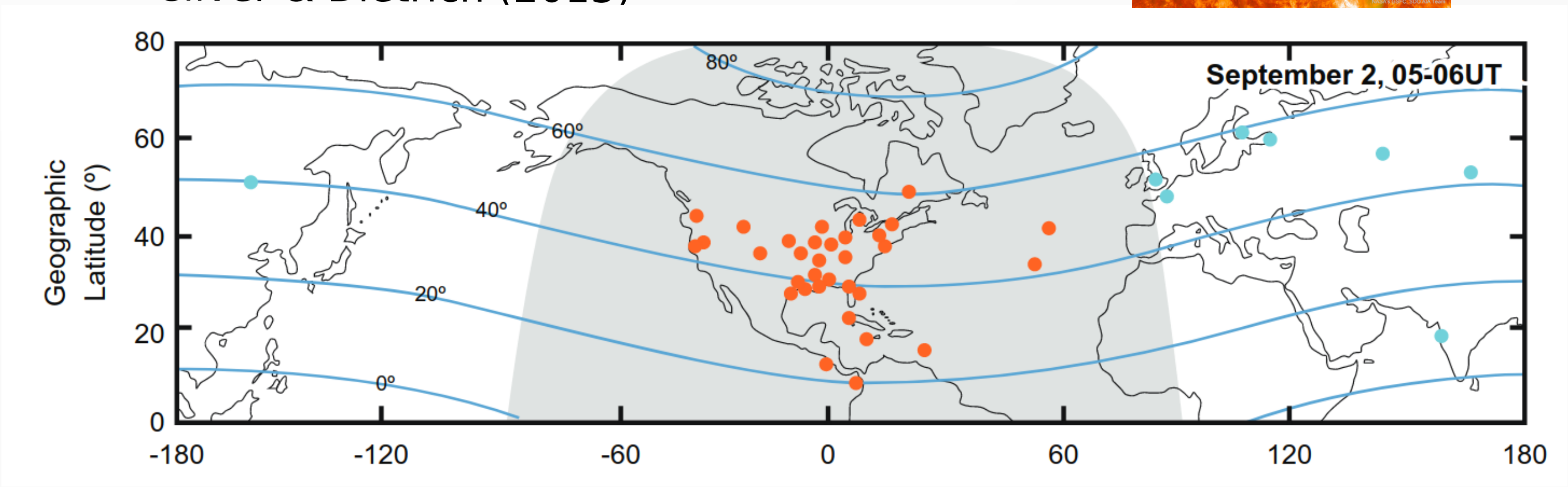




Source: NASA SDO AIA

c. Mia Stålnacke

Cliver & Dietrich (2013)



Carrington Event: 1859

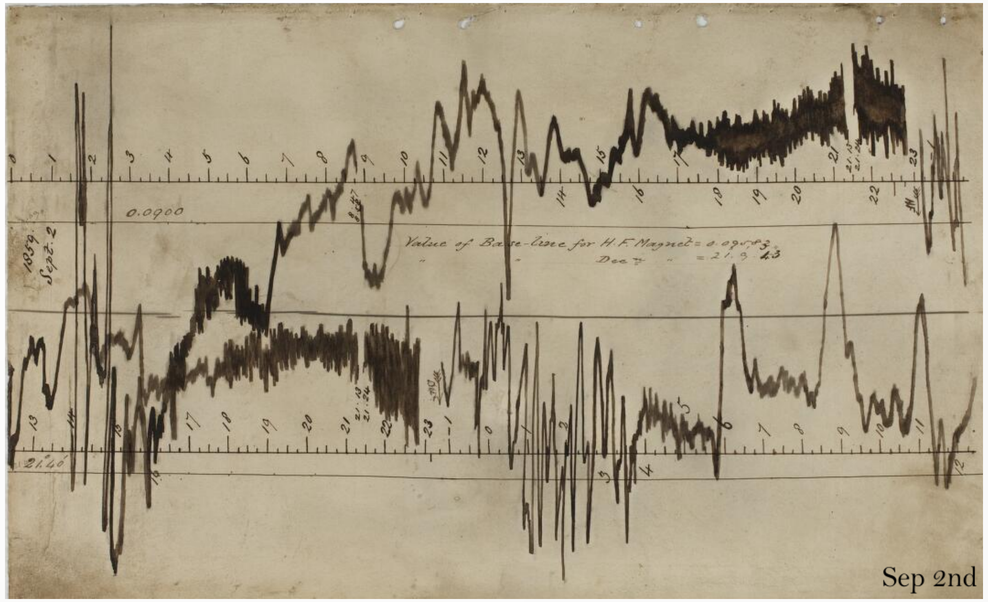
- Large induced (~100nT) magnetic fields are recorded
- Power grids and electrical systems fail

Boston to Portland telegraph communication:

- "**Please cut off your battery entirely** from the line for fifteen minutes."

Portland operator - "Will do so. **It is now disconnected**."

Boston - "Mine is disconnected, and **we are working with the auroral current**. How do you receive my writing?"



Magnetogram, Greenwich Observatory (source: British Geological Survey)

Geomagnetic Storms

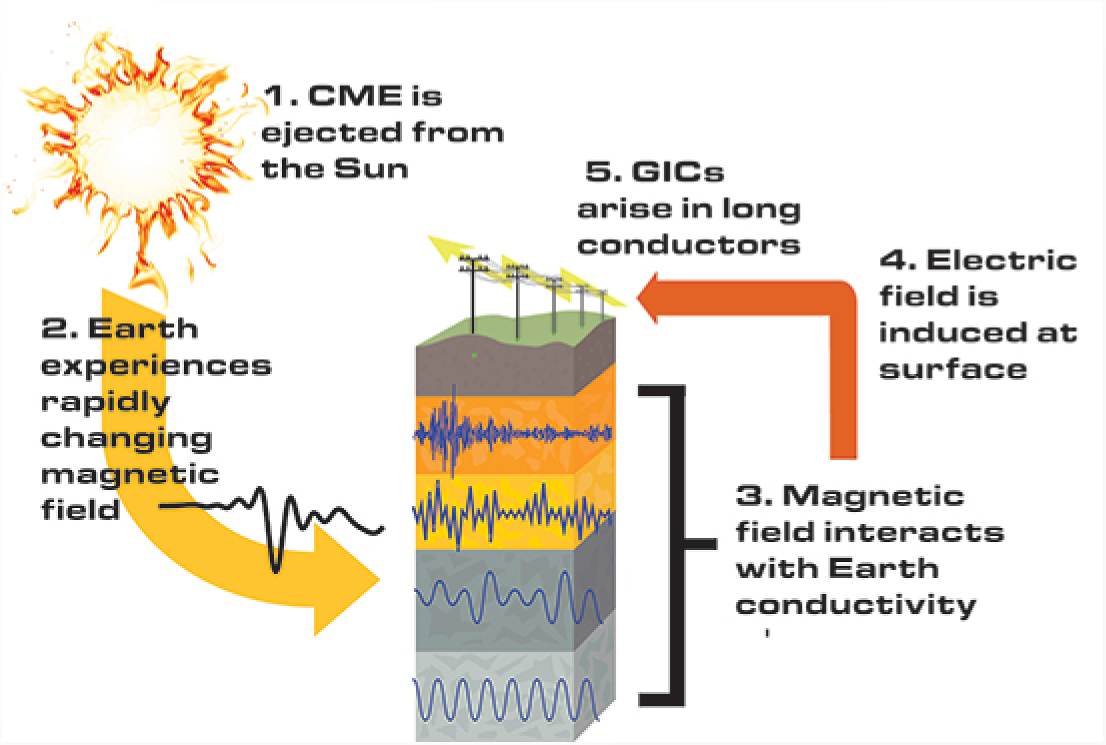
When a Coronal Mass Ejection (CME) hits Earth:

- dB/dt in the conducting crust induces an E-field
- ~1V/km over thousands of km… ~1000 volts!

$$\frac{1}{\mu_0}\nabla \times \mathbf{B} = \sigma\mathbf{E} + \mathbf{j}^{ext},$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

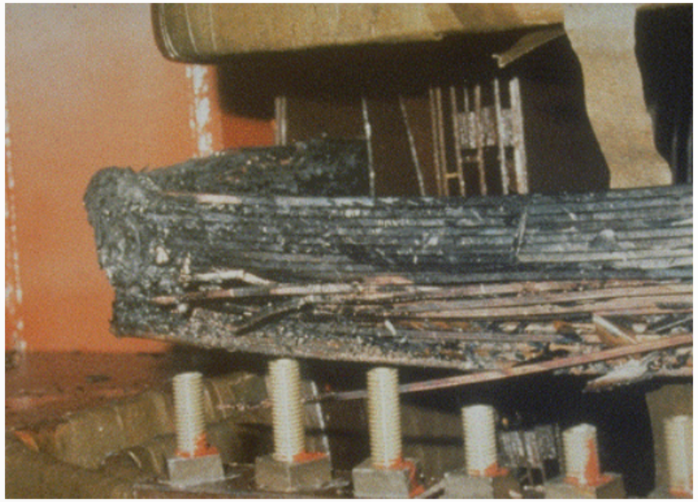
Marshalko et al. (2021)



Gannon (2016)

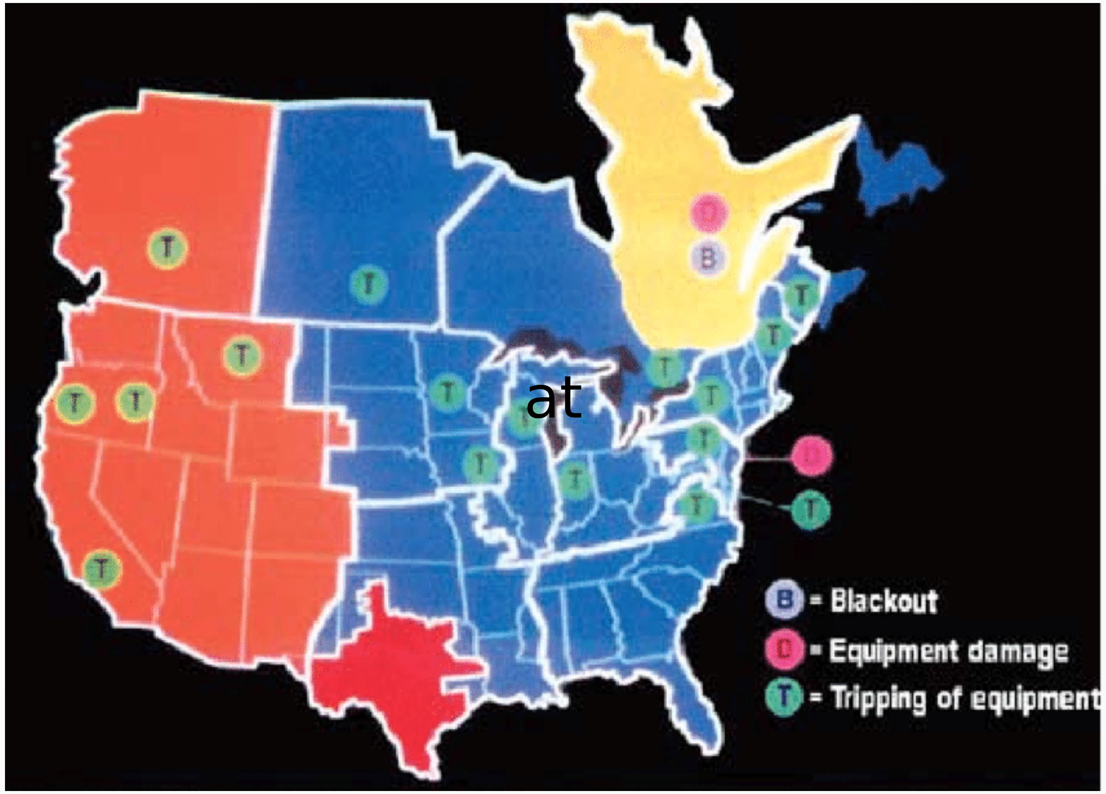
Geomagnetically Induced Currents (GICs)

Impacts (Earth)



Metatech report, 2010

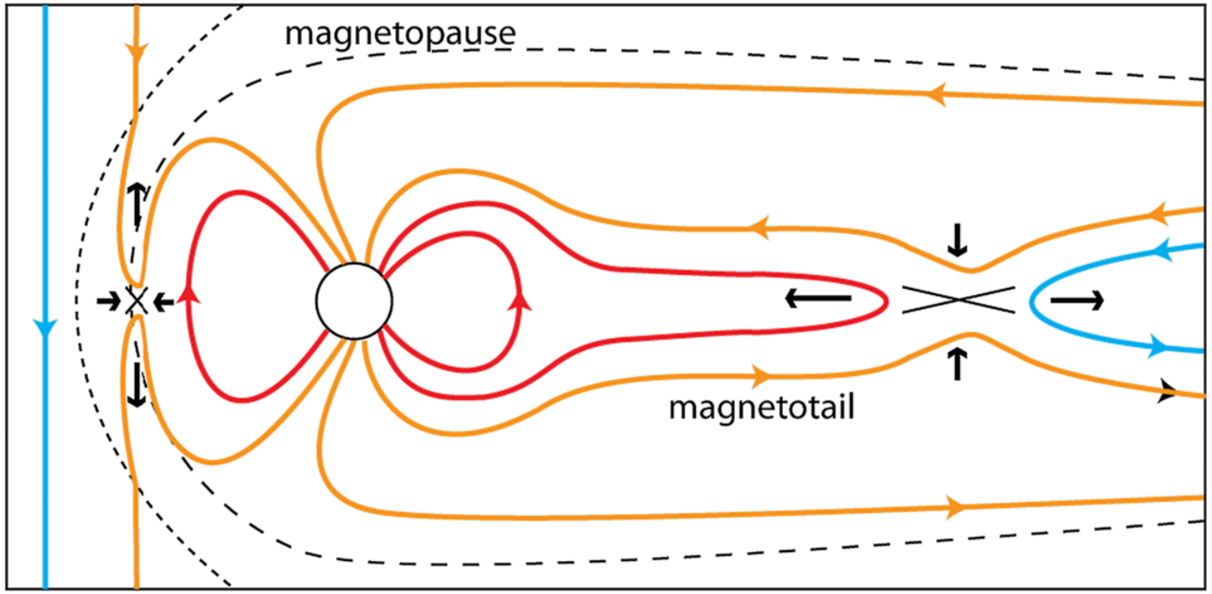
- Disruption of power systems
  - Blackouts
  - Transformer damage
- Natural gas pipelines
  - Currents quicken pipe corrosion
- Communication/Aviation
  - Radio signal disruption



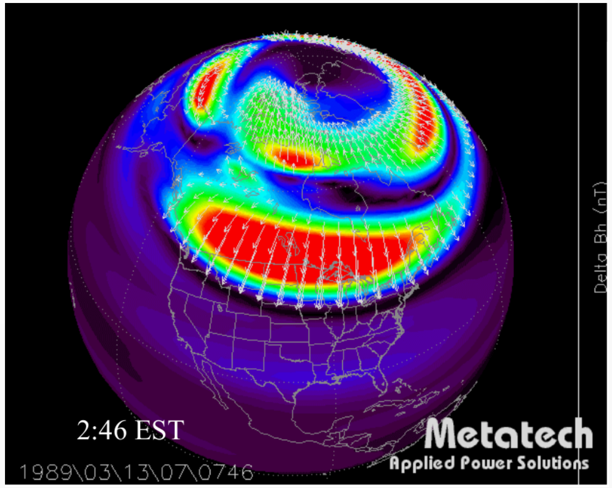
March 13, 1989: Quebec experiences 9-hour blackout enabled by low ground conductivity (image: Baker et al, 2008)

What makes a CME Geoeffective?

- **Bz < 0**
  - Enables dayside reconnection,
    energy/particle transfer to magnetosphere
  - Horizontal dB/dt leads to induced currents
  - Intensity evaluated by **Dst index:** average of dBz/dt at 4 equatorial magnetometers



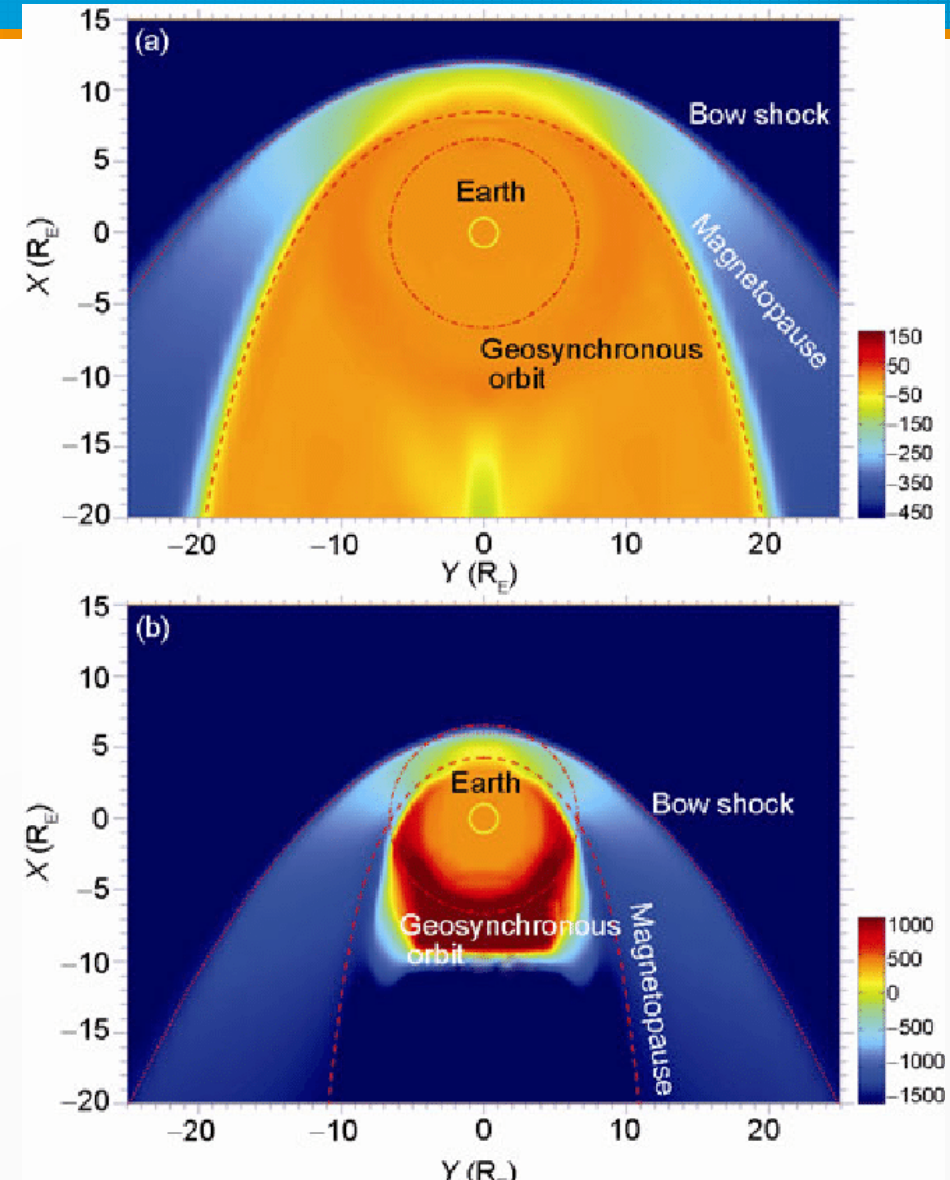
Eastwood et al., 2017



Horizontal dB/dt and electrojet formation in 1989 storm (Kappenman 2010)

Impacts (Space)

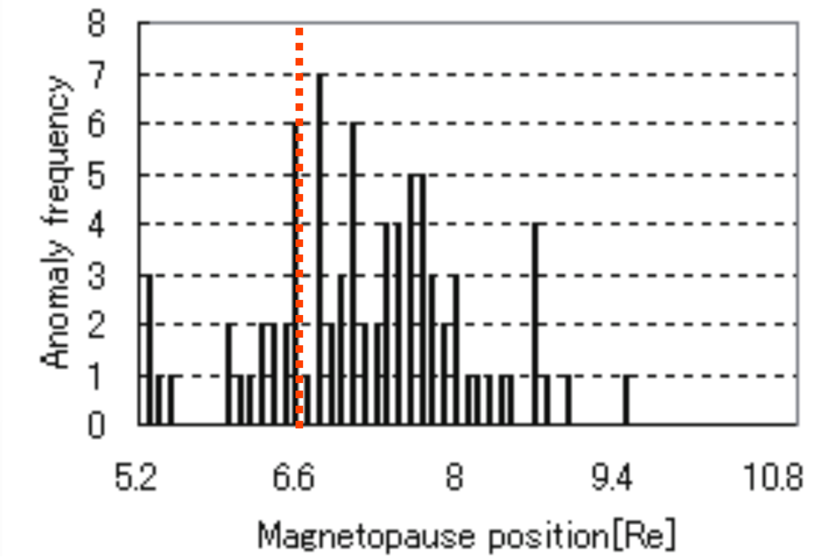
- Radiation Belts
  - High energy e- and p+ lead to spacecraft charging which causes damage when discharged
- Storm-time magnetopause compression can place geosynchronous satellites ($r = 6.6\ R_E$) in the solar wind
  → Geosynchronous Magnetopause Crossing (GMC)



Compression of magnetopause—simulations (Wang, 2012)

Impacts (Space)

- GMCs are quite rare: occurrence ratio 0.6%
- Yet, 30% of geosynchronous spacecraft anomalies occur during GMCs



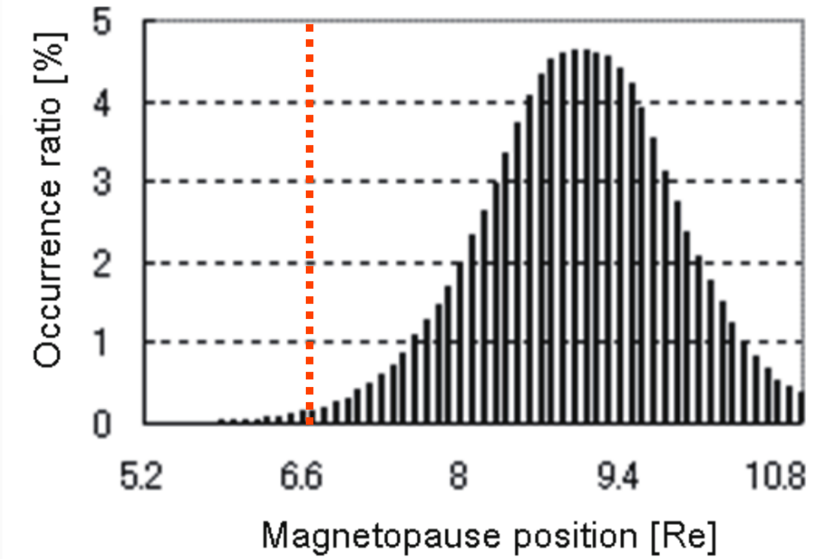


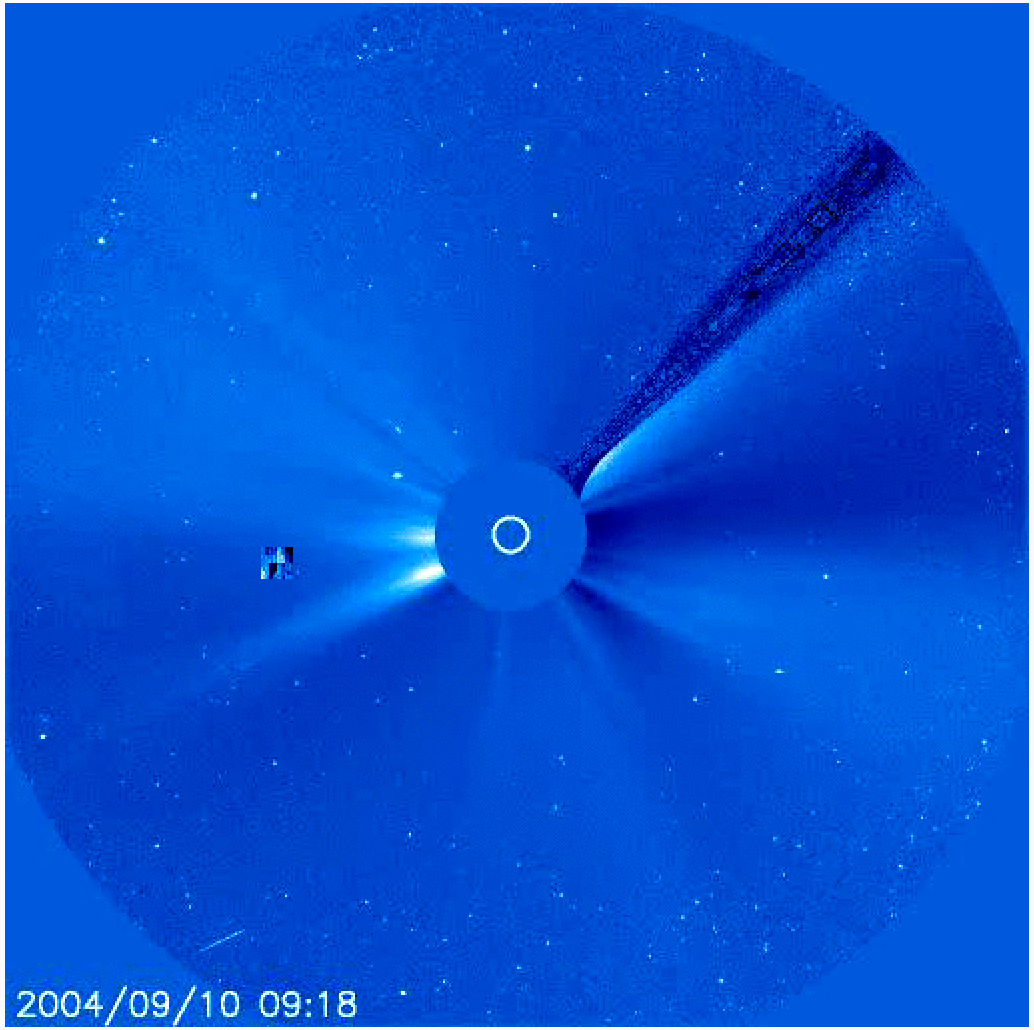
Table 3. Satellite anomaly outline and GMC occurrence date.

Satellite name	GMC Date (UT)	Anomaly Date (UT)	Anomaly outline
Telstar 401	11 Jan 1997	11 Jan 1997	Electrostatic discharge; total loss
Tempo 2	11 Apr 1997	11 Apr 1997	Solar flare zapped three transponders, DC power loss

Tamaoki et al., 2010

Studying Extreme Events

- Solar storms can have a big impact on Earth
- ...But, we may only have a matter of hours to respond to a fast-moving CME
- How can we prepare for the impact of a 1-in-100-year event?
  - Simulations!

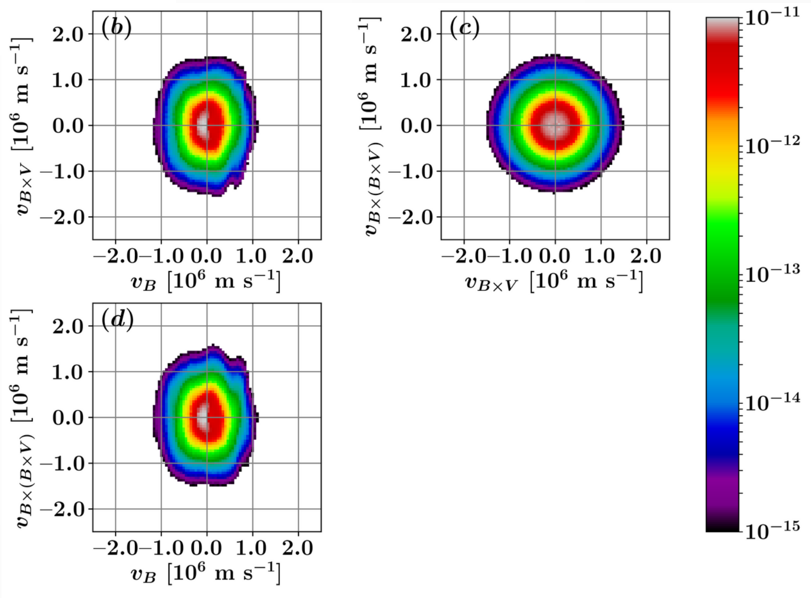


Full Halo CME coronagraph (SOHO)

- Vlasiator is a **hybrid-Vlasov** code that is now performing the first 6D (3 spatial, 3 velocity) simulations of the global magnetospheric system
- Hybrid: Kinetic protons, fluid (adiabatic) electrons

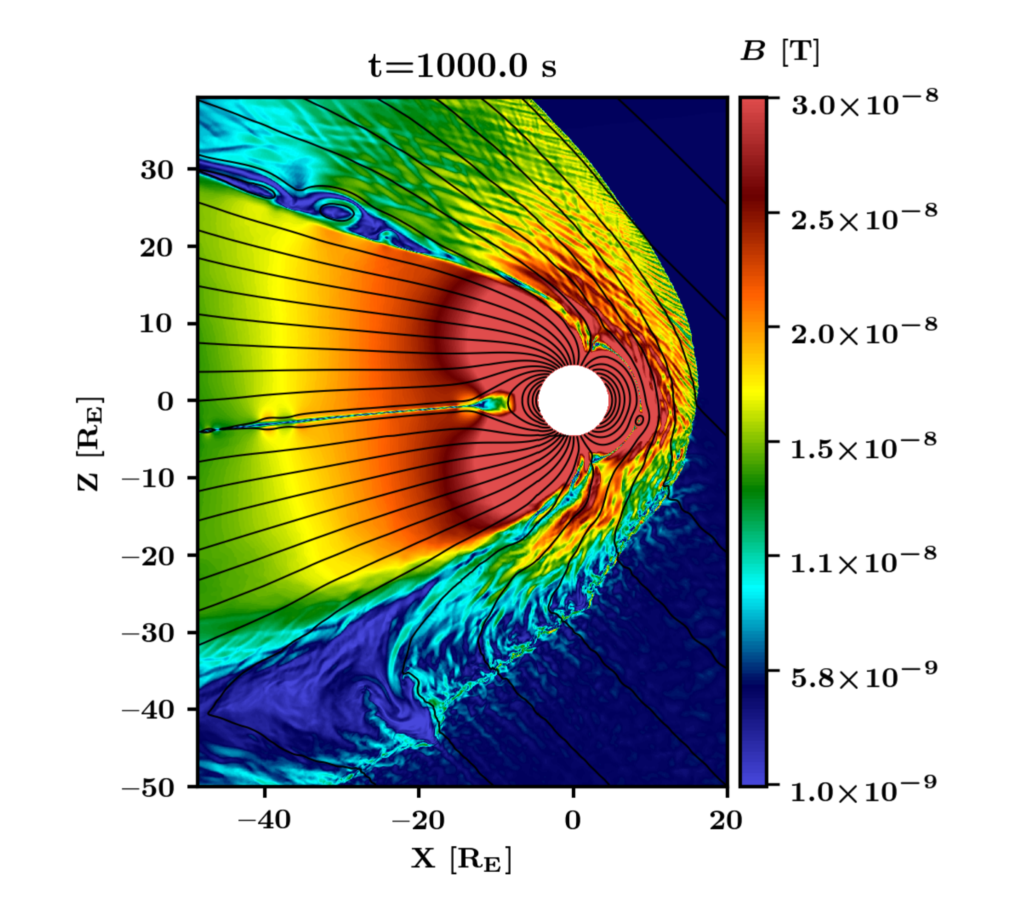
$$\frac{\partial f(\mathbf{r},\mathbf{v},t)}{\partial t} + \mathbf{v}\cdot\nabla_r f(\mathbf{r},\mathbf{v},t) + \mathbf{a}\cdot\nabla_v f(\mathbf{r},\mathbf{v},t) = 0$$

- E-field: convective + Hall + ∇P_e
- Inner boundary (ionosphere) implemented as perfectly conducting sphere

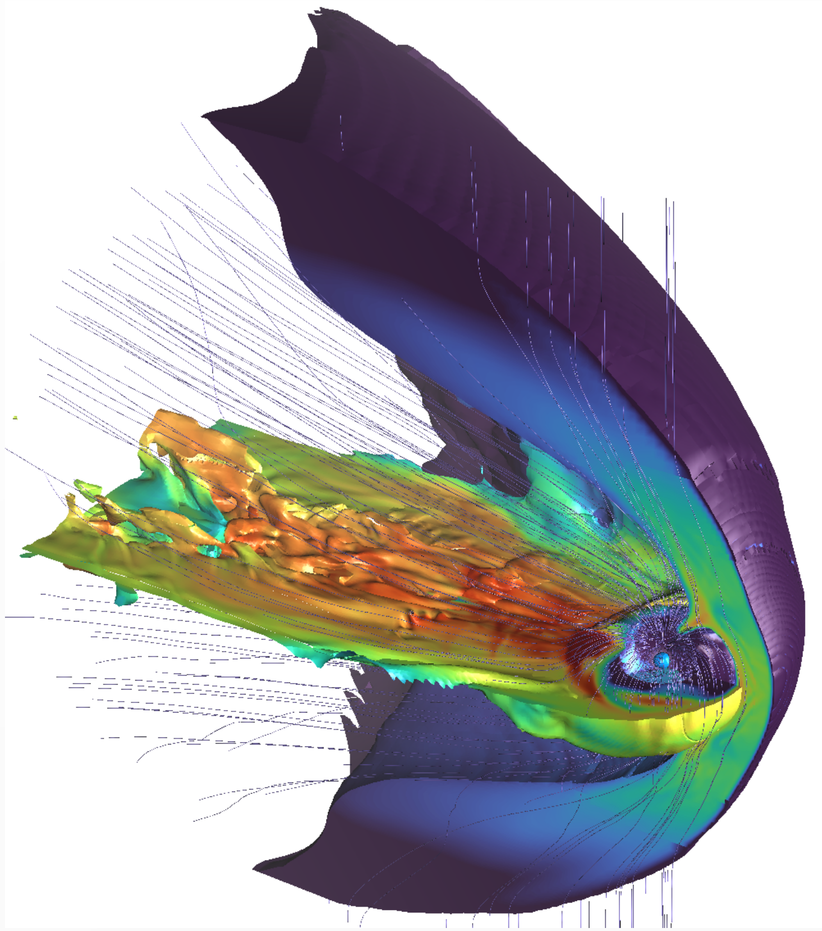


6D runs

2D3V



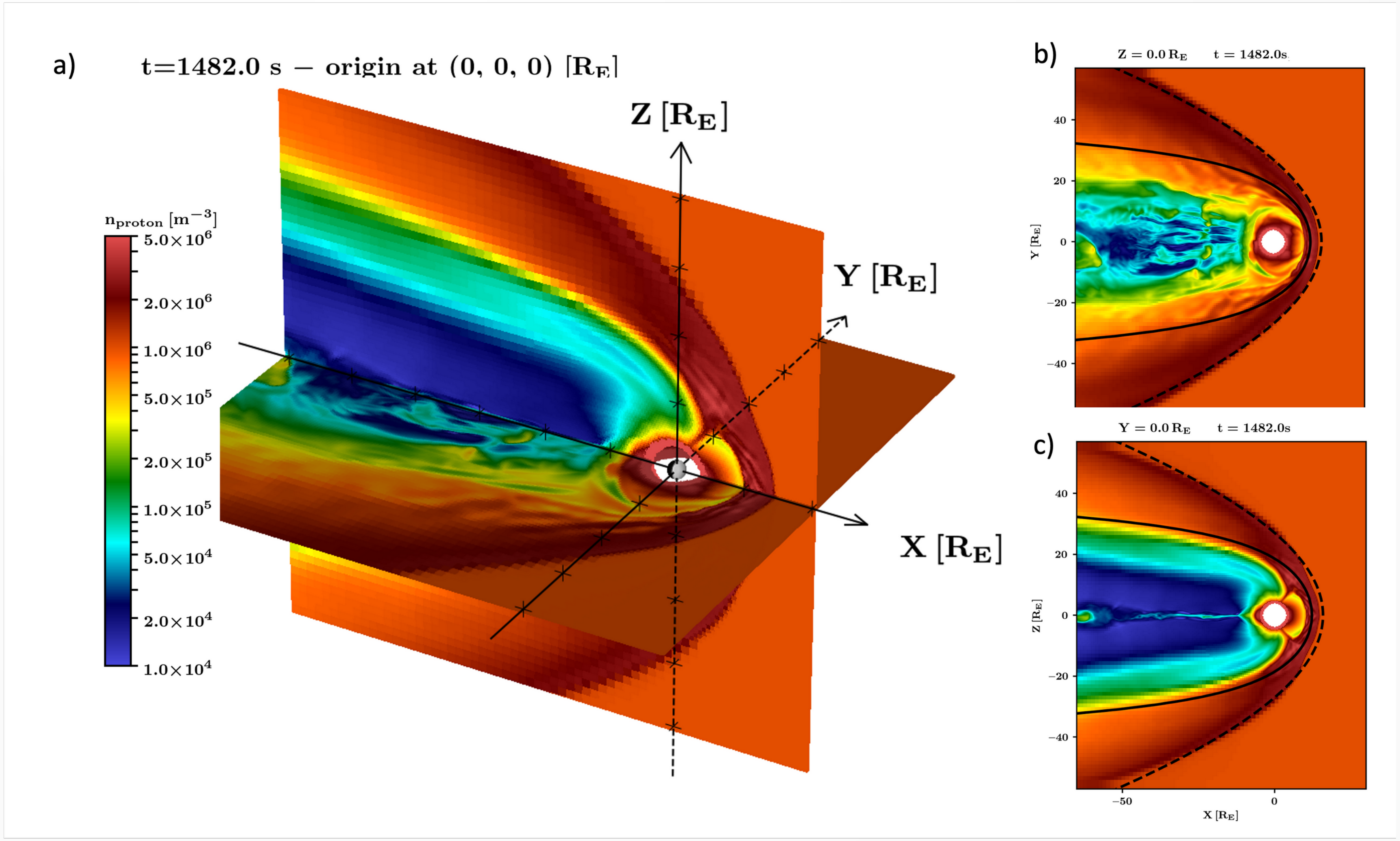
3D3V



6D simulations

- 6D enabled by adaptive mesh refinement (AMR)
  - Finer mesh near Earth
- Simulation box

  ~100 R_E per side
- Realistic magnetic dipole!
- New results on the onset of substorms and current sheet flapping in the magnetotail



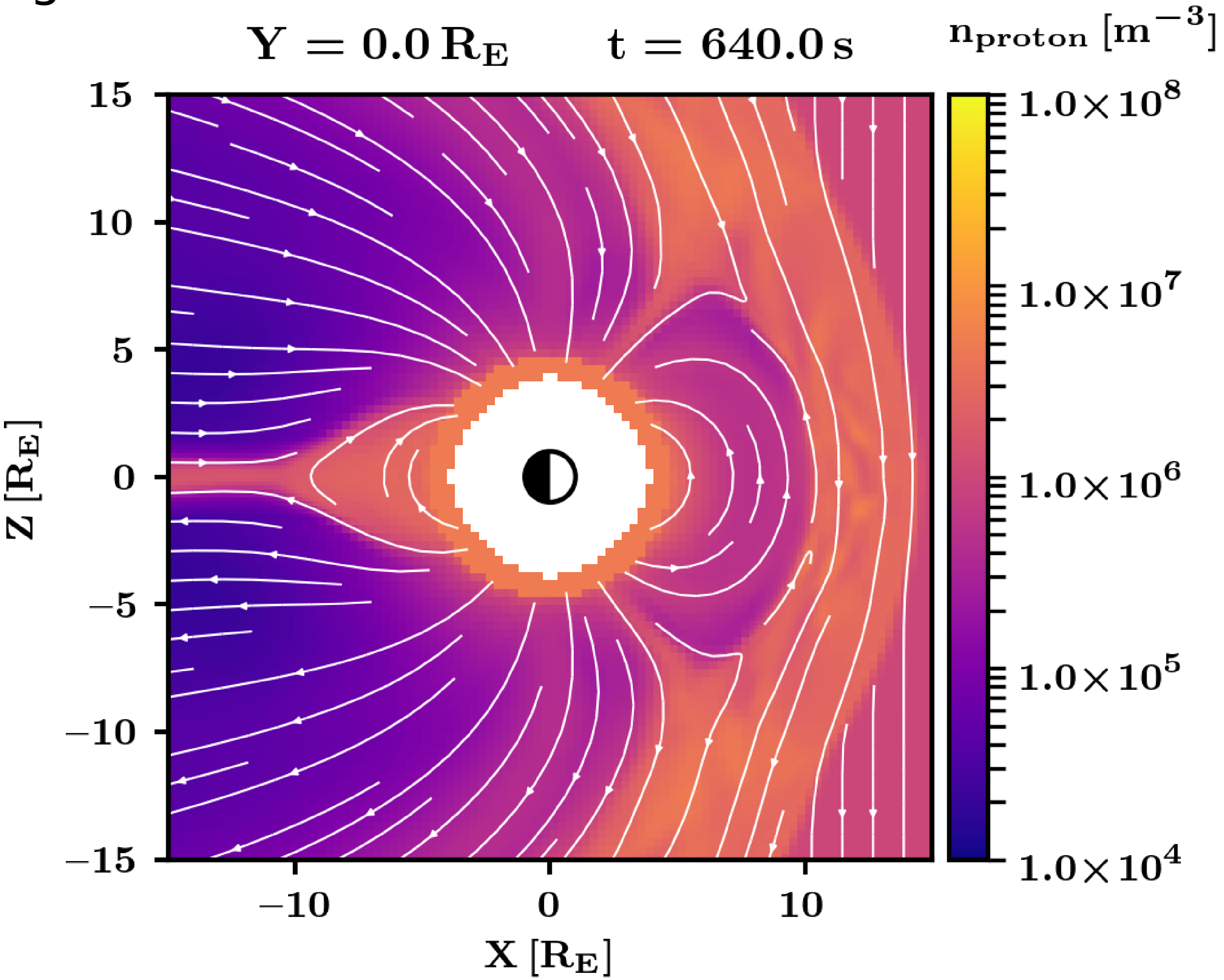
Palmroth et al. (2021, submitted)

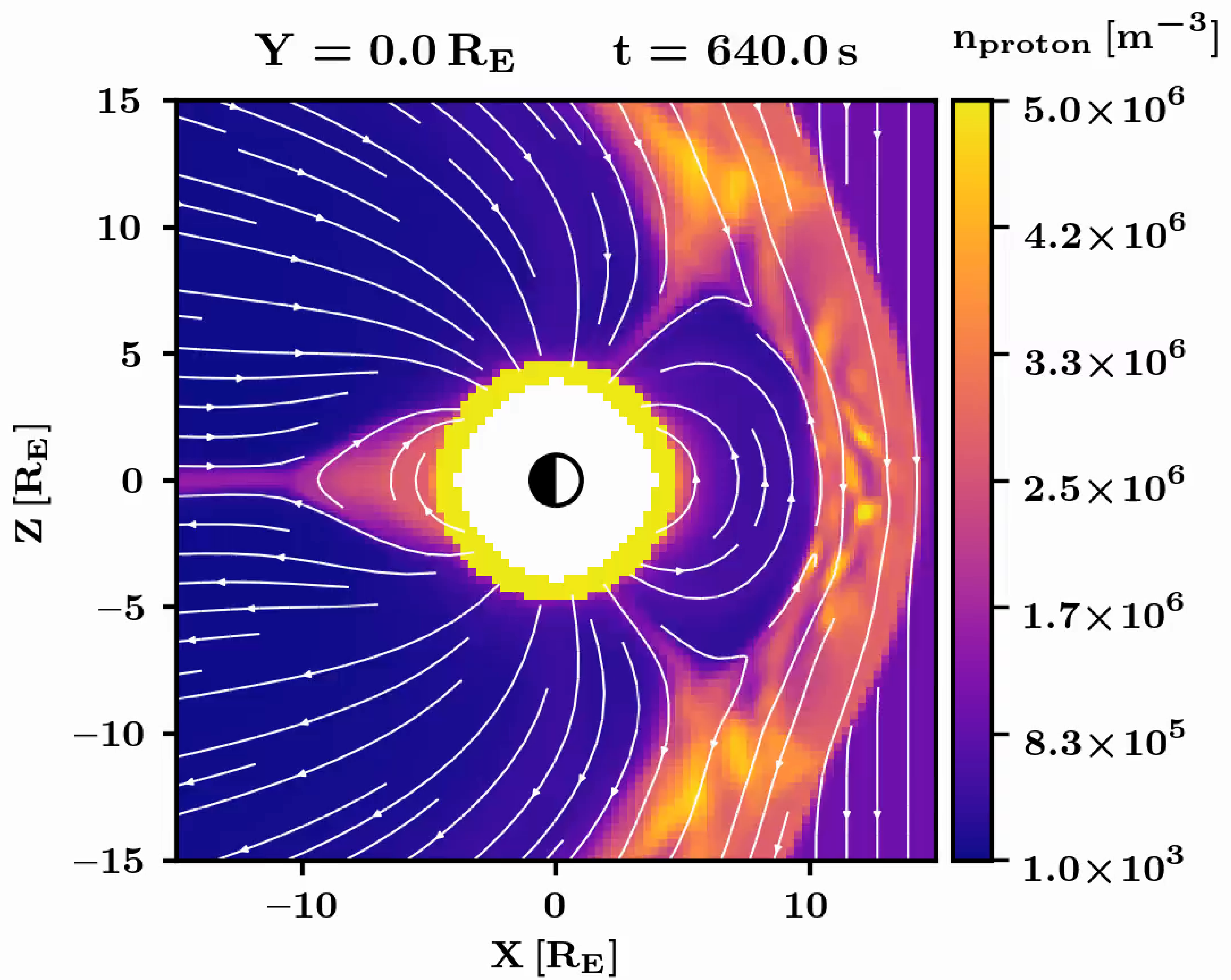
Carrington test run setup

- Solar wind $B_z<0$
- High pressure pulse impacts Earth mid-simulation

Driving	B [nT]	v_{sw} [km/s]	n [cm^{-3}]
normal	[0, 0, -10]	750	4
moderate	[-0.5, 0, -20]	1000	7
1859 storm (Wang et al, 2012)	[x, x, -60]	1500	40

Normal driving




Y = 0.0 R_E   t = 640.0 s
n_proton [m^-3]
15
10
5
0
−5
−10
−15
Z [R_E]
−10
0
10
X [R_E]
5.0×10^6
4.2×10^6
3.3×10^6
2.5×10^6
1.7×10^6
8.3×10^5
1.0×10^3

What space weather impacts can we observe in Vlasiator simulations?

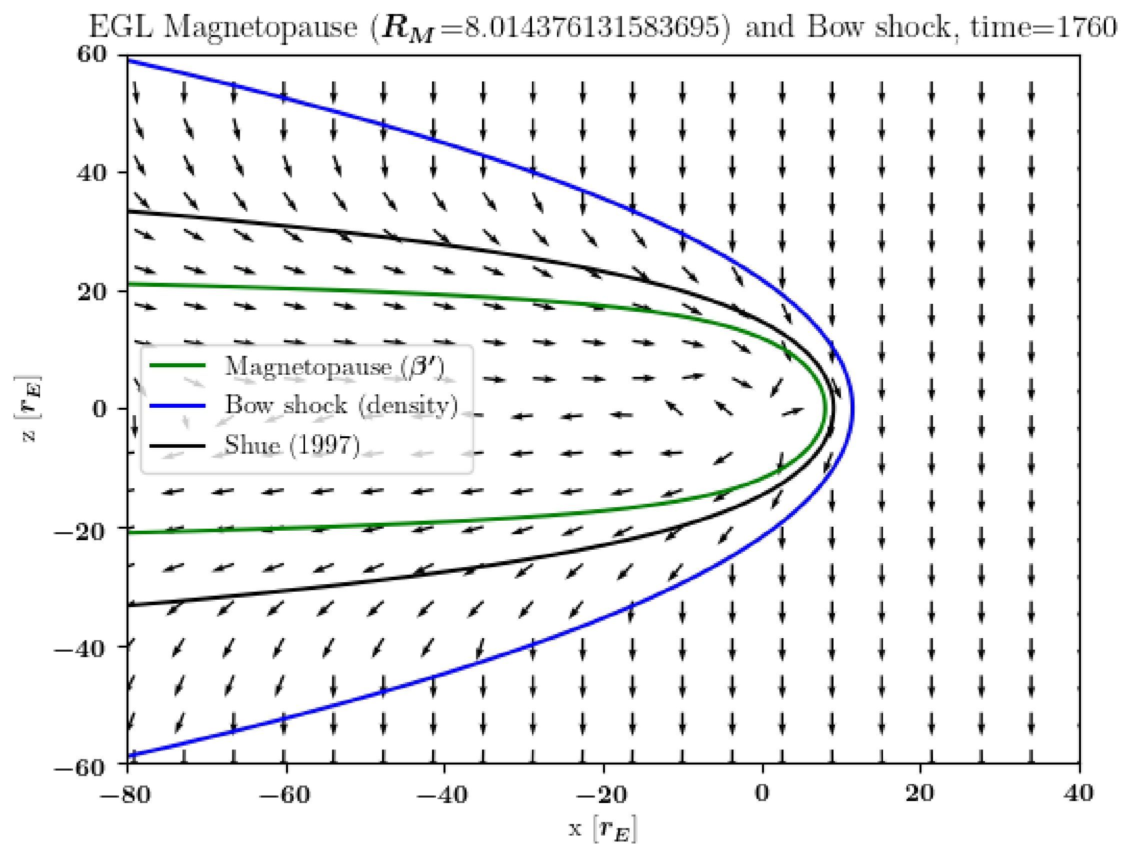
- Magnetopause compression
- Expansion of auroral oval
- Field-aligned currents near polar cusps
- Proton precipitation

TBD:

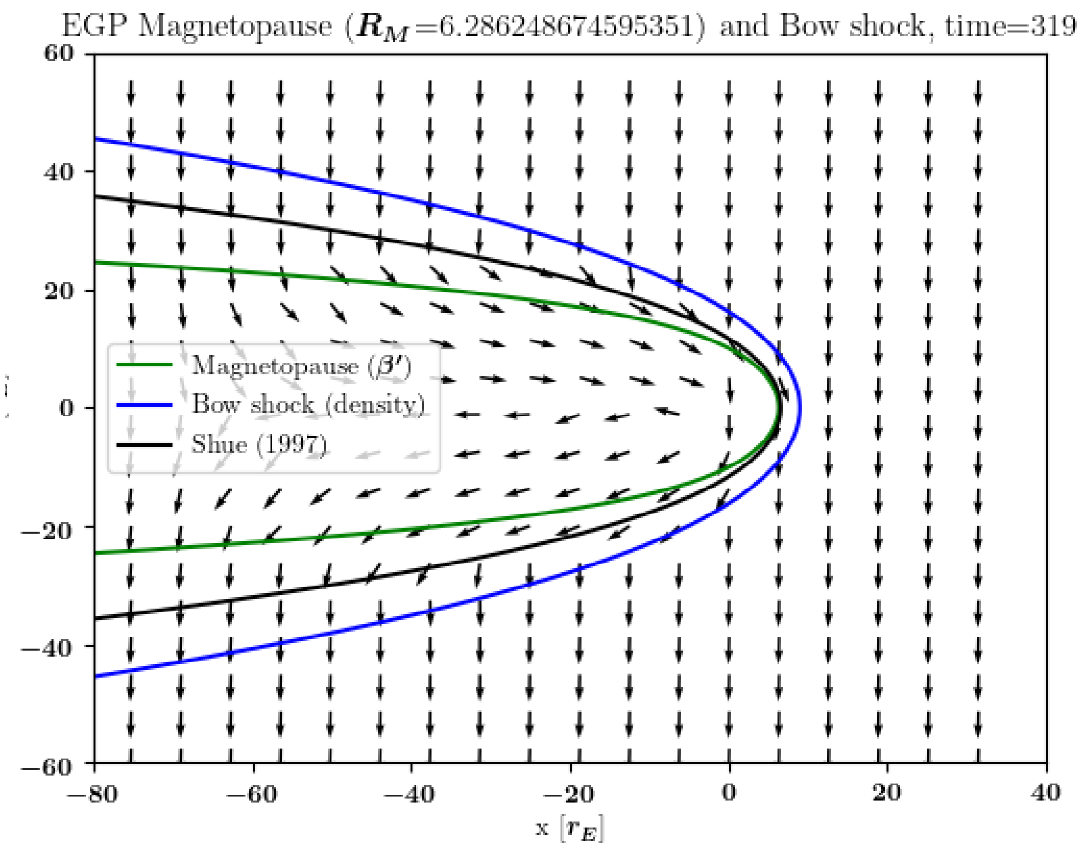
- dB/dt at $r=1R_E$
  - Ring current

Magnetopause Compression

Normal driving



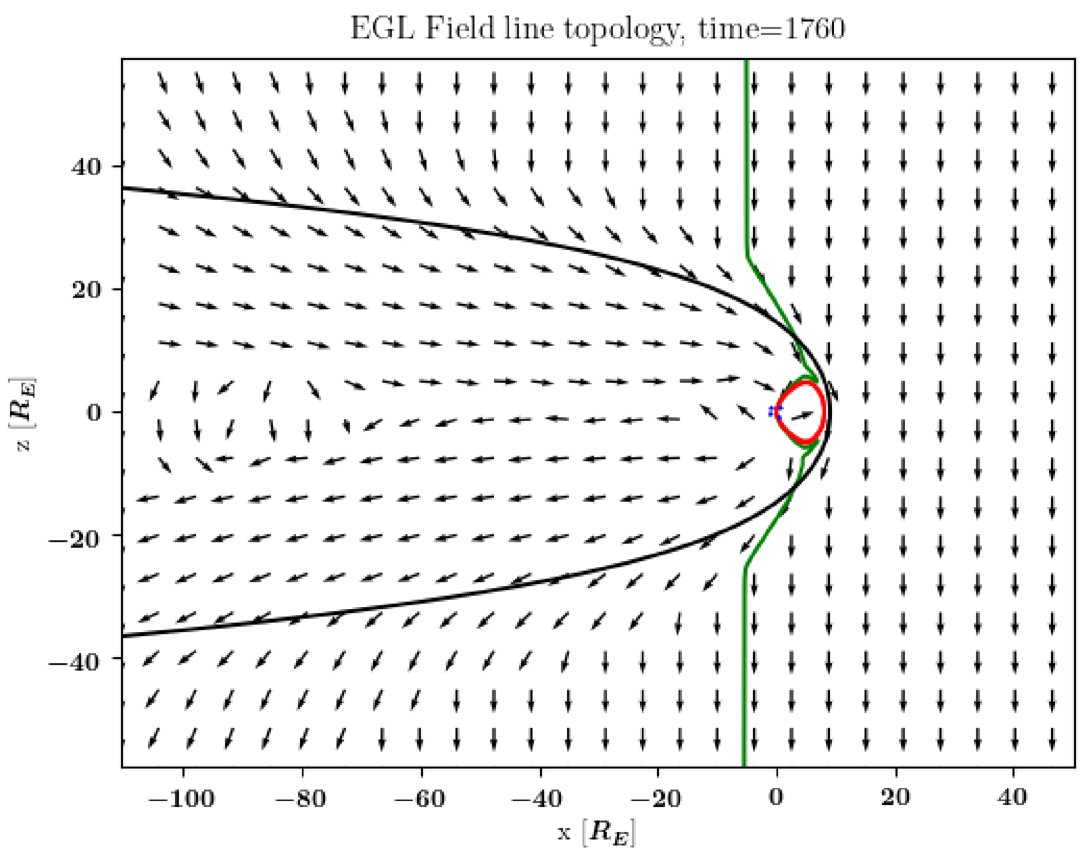
Moderate driving



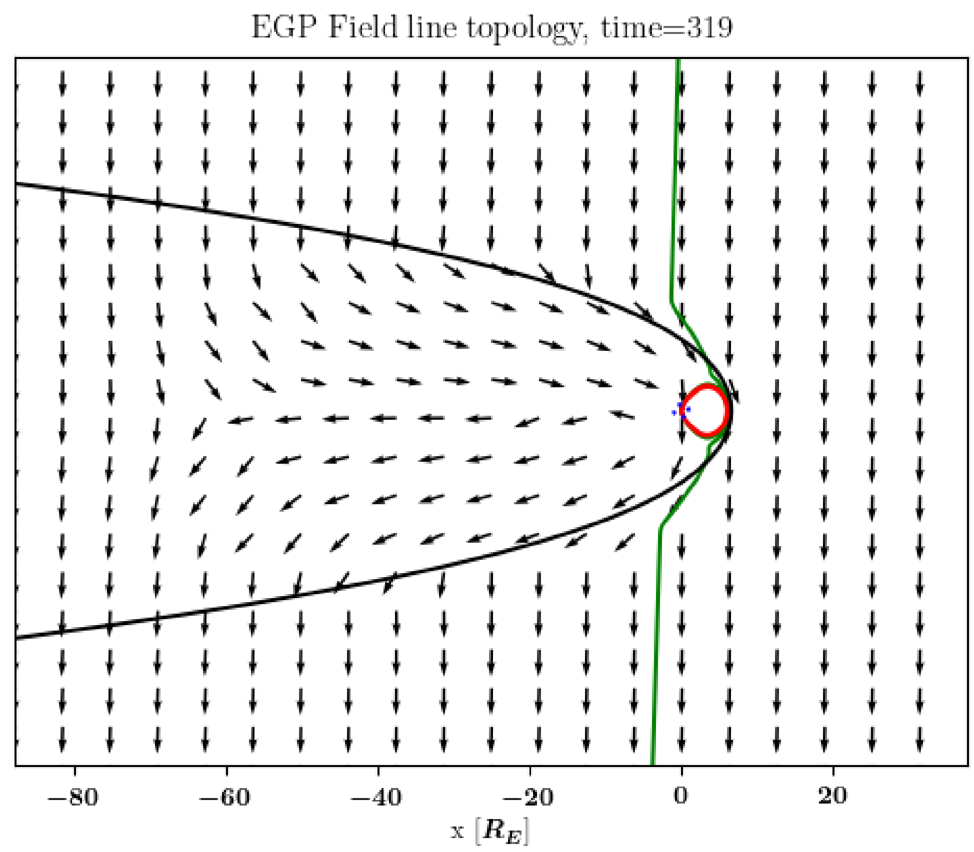
R_M<6.6 R_E !

Open/Closed field line boundary

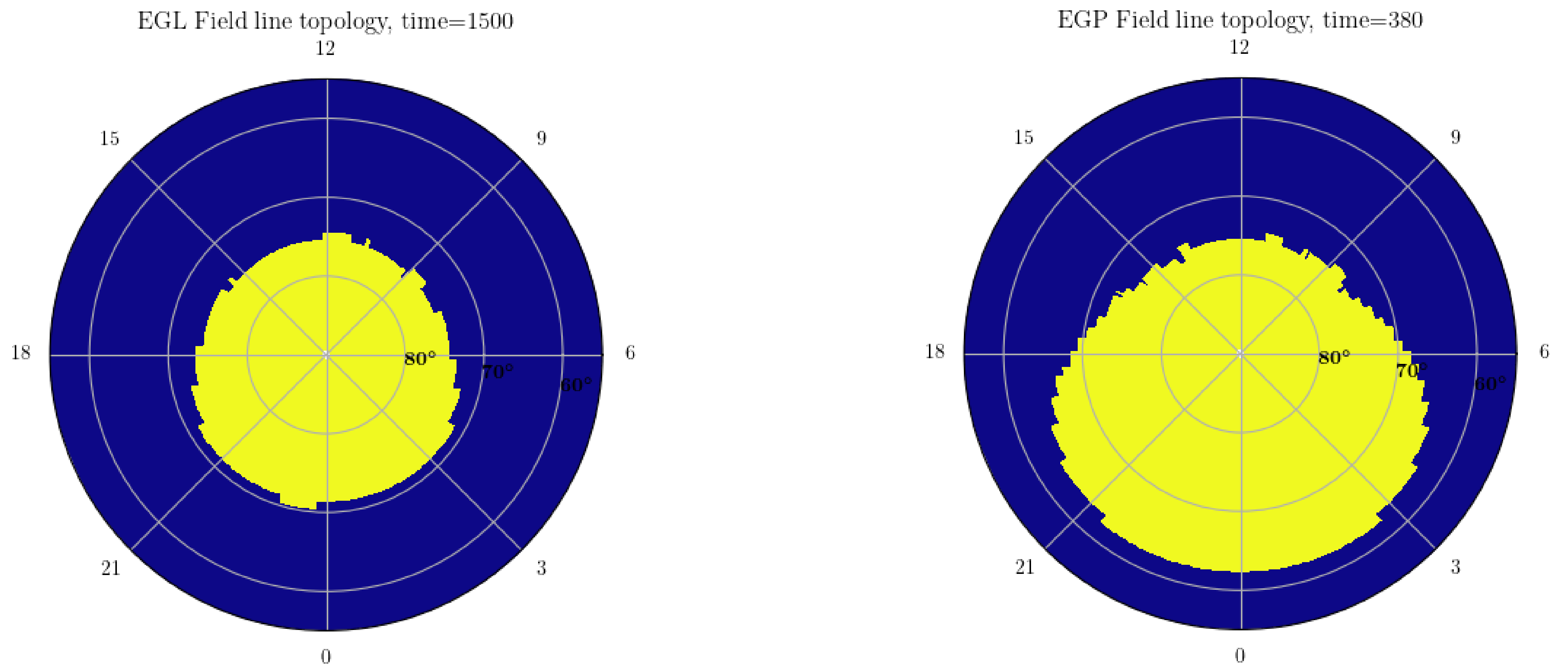
Normal driving



Moderate driving

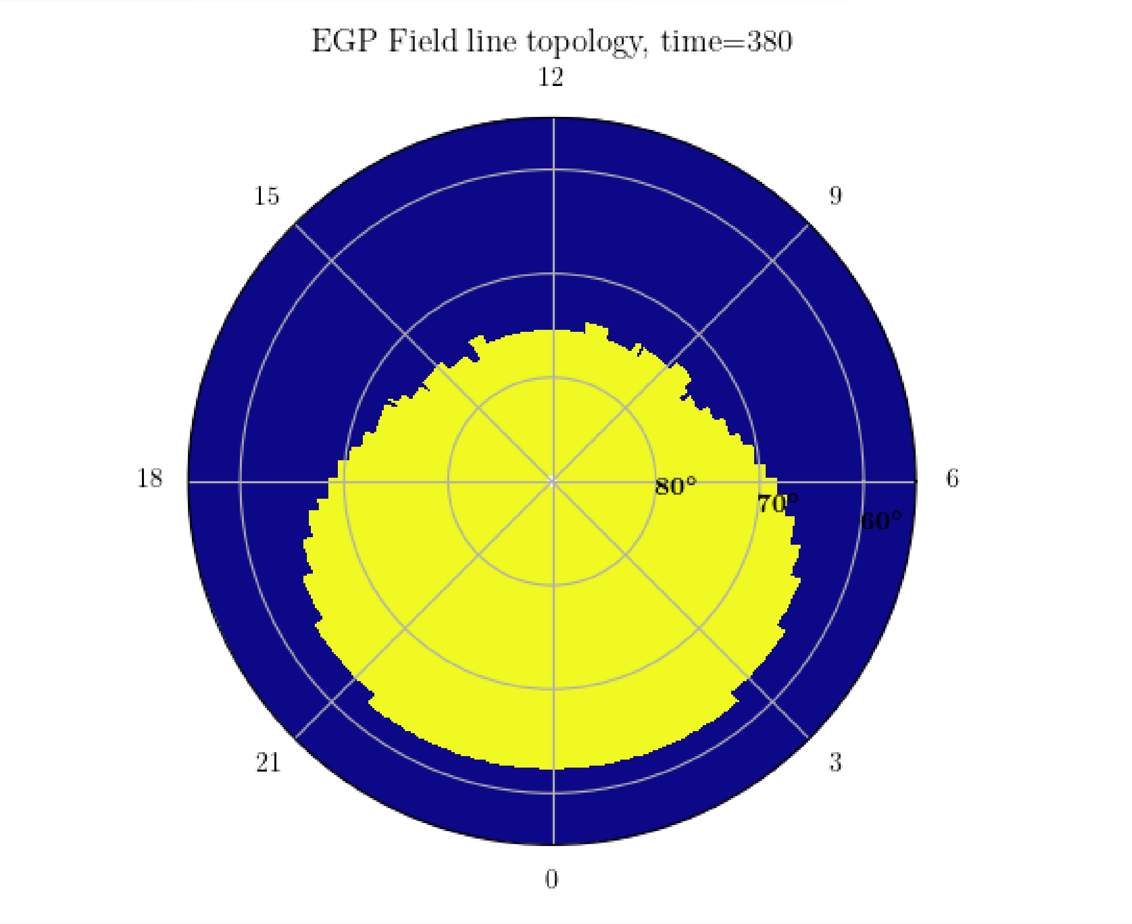


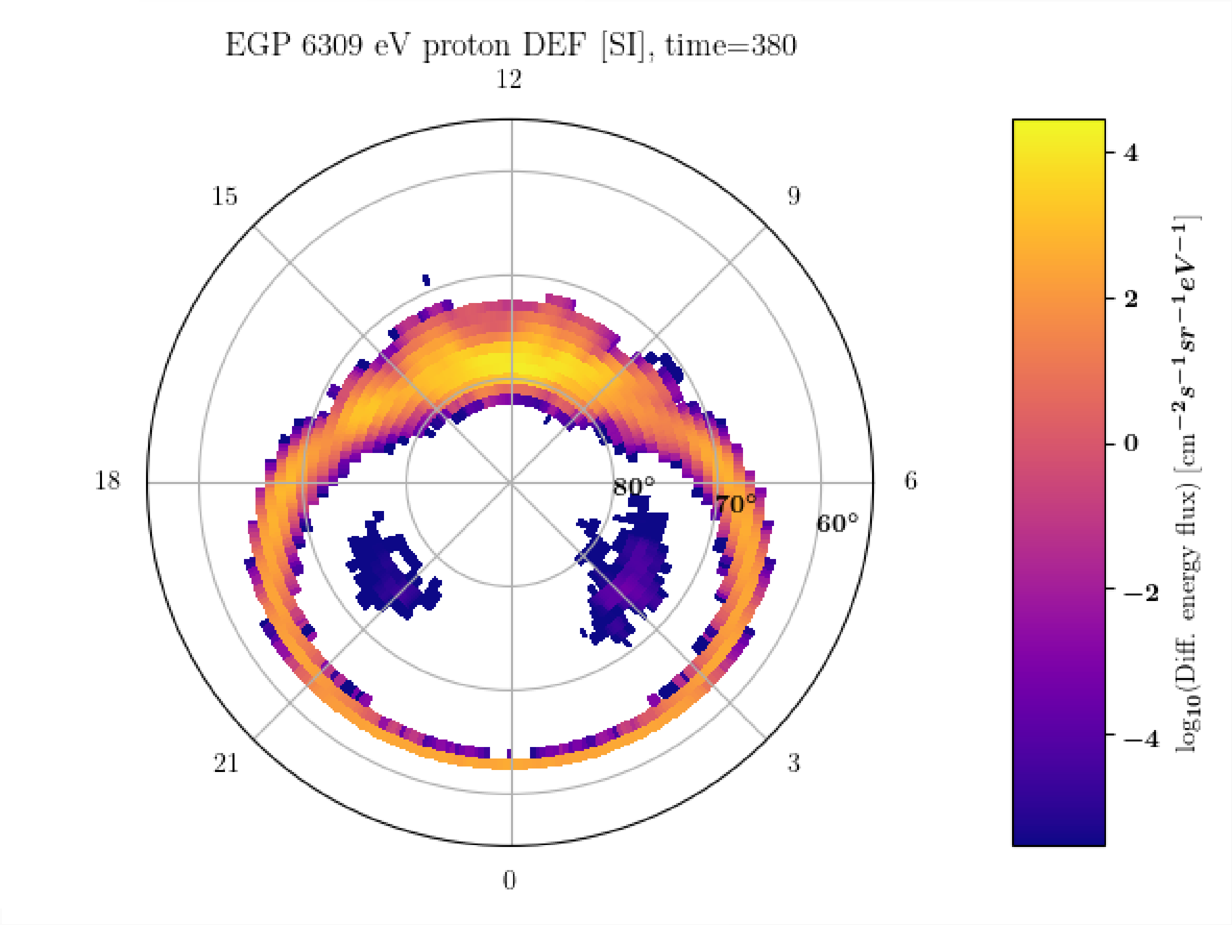
Observed Expansion of Auroral Oval



Note: tilt of Earth’s magnetic axis not yet accounted for

Particle Precipitation



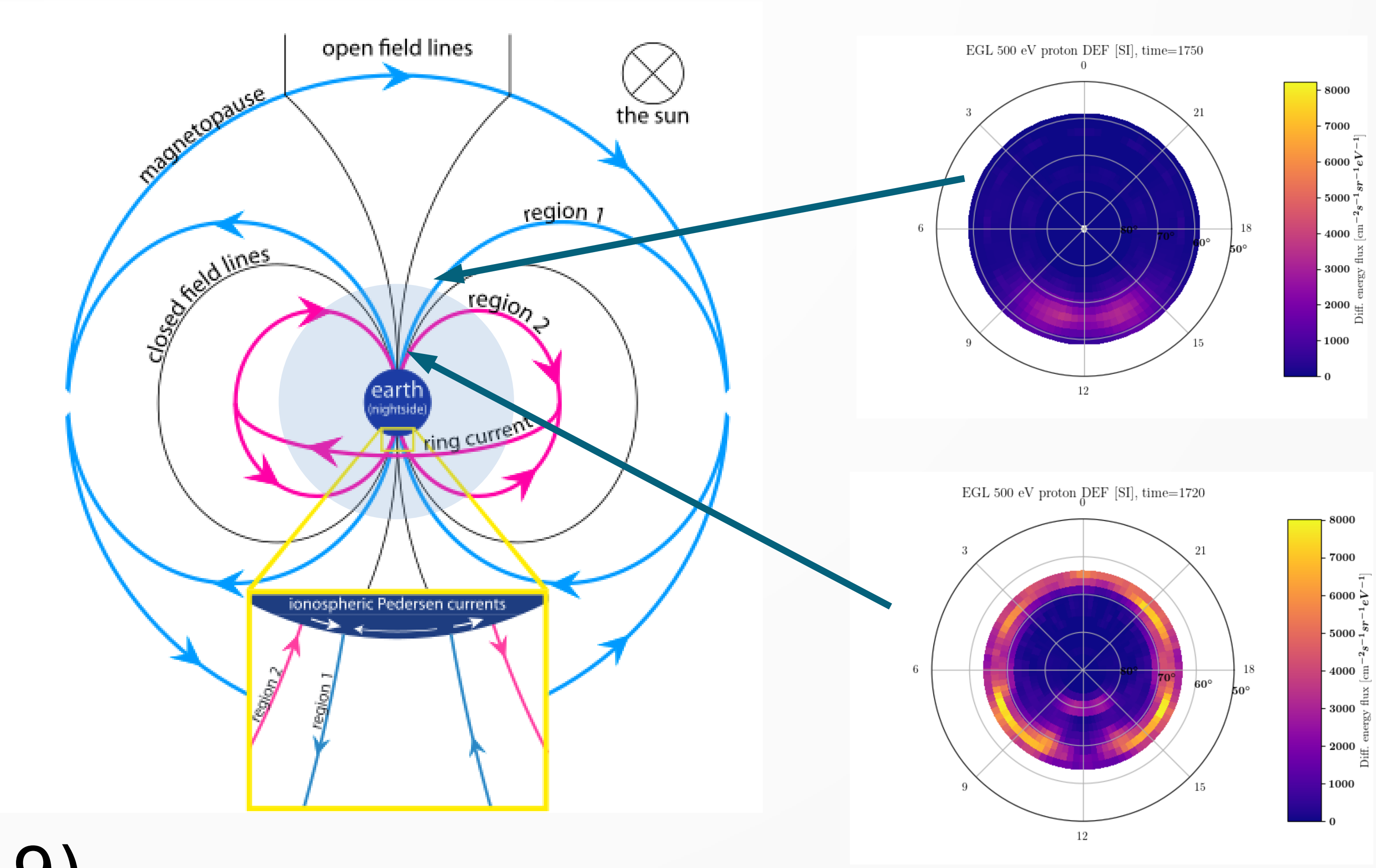


Moderate Driving

High particle fluxes near the open/closed boundary

Field Line Mapping: Precipitation

- Proton precipitation inferred by mapping the flux along magnetic field lines



- For detailed analysis, see Grandin et al. (2019)

Field Line Mapping: field aligned currents (FACs)

Region 1 currents clearly seen!

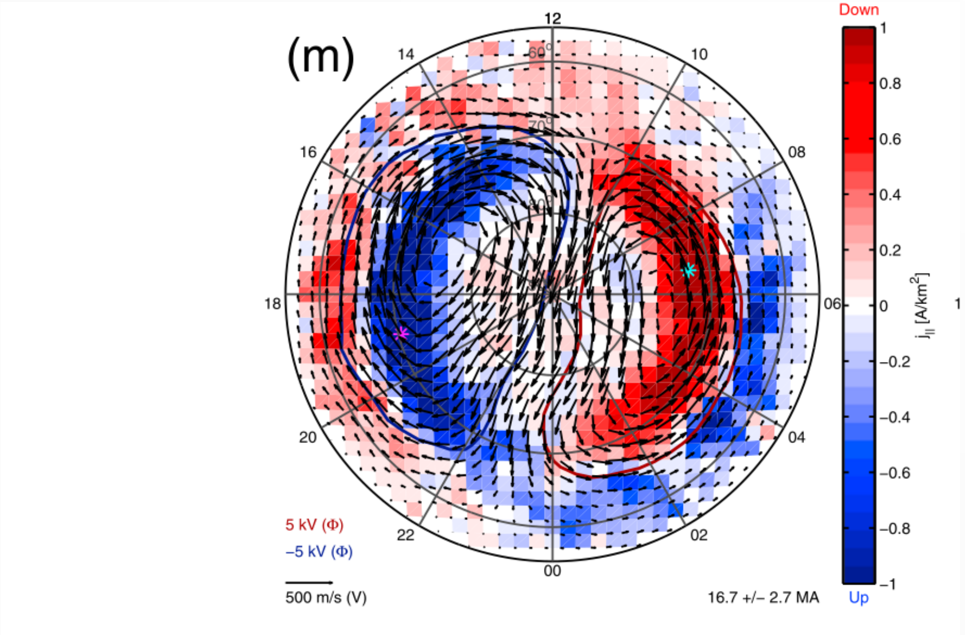
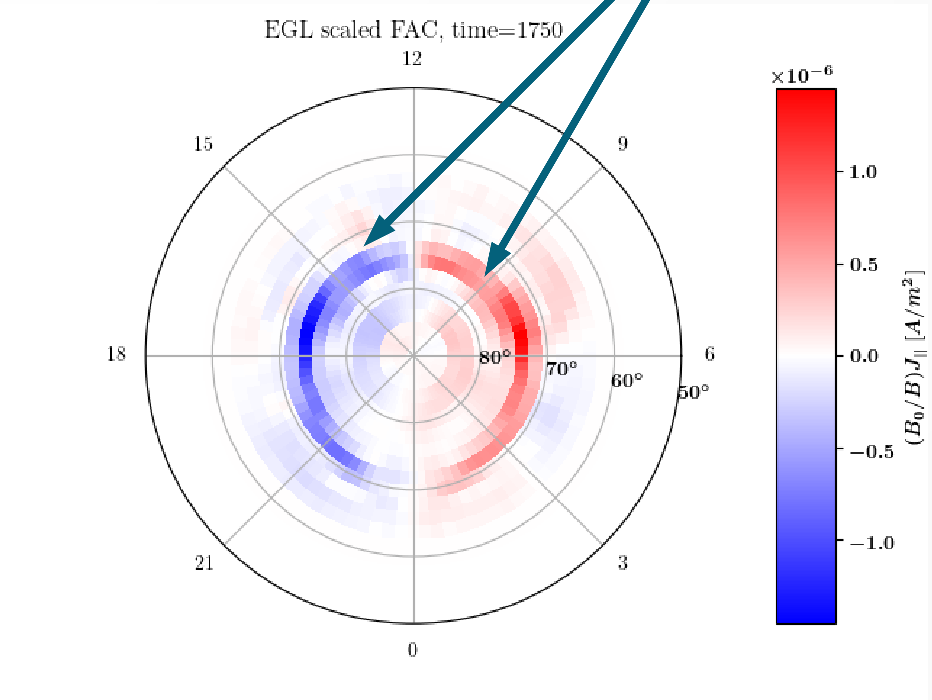


Figure 8. Figure 7 continued.

Auroral FACs (B_z<0)

Juusola et al (2013)

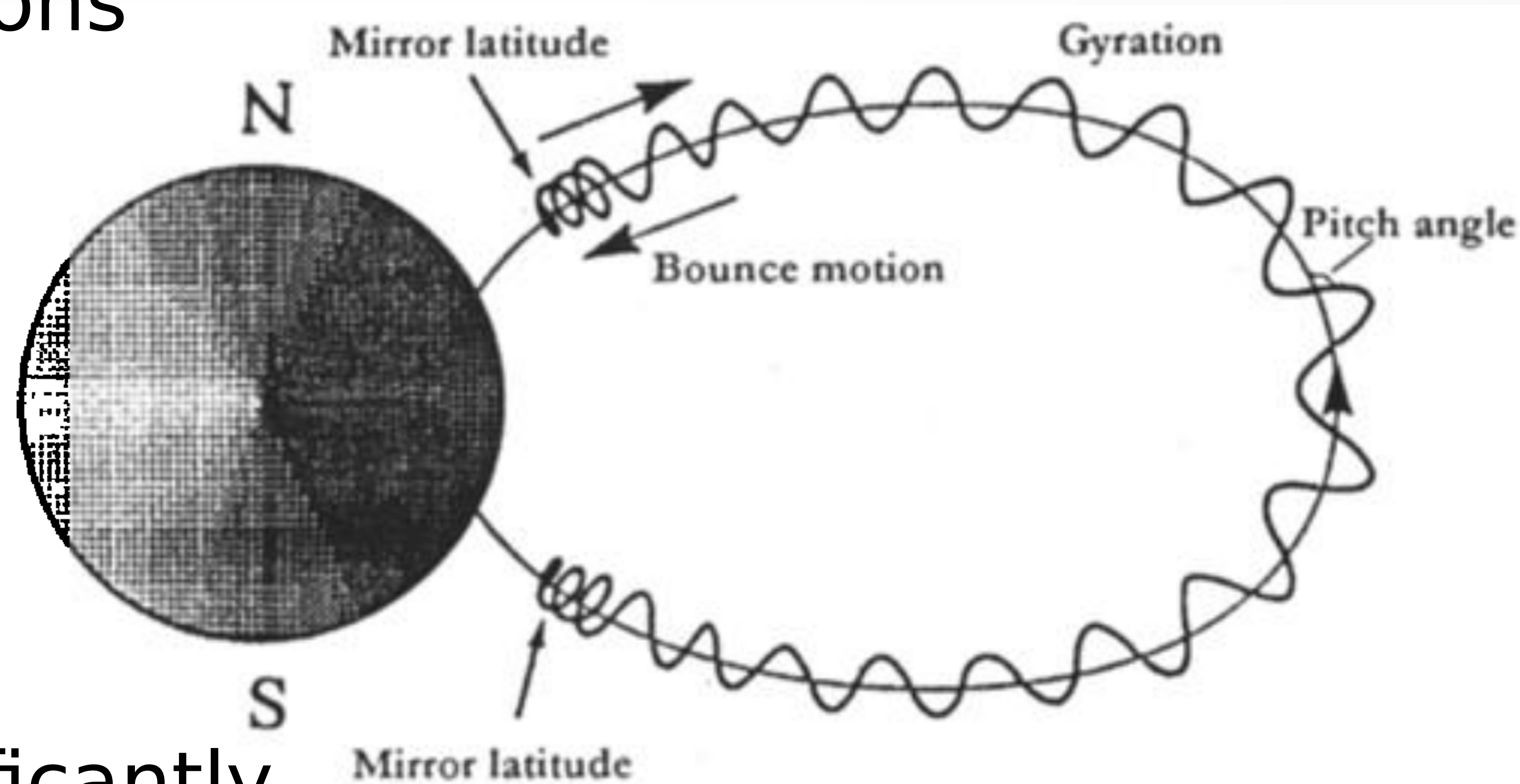


Vlasiator FACs (normal driving)

FACs mappped from inner boundary $r=5R_E$ to $r=1R_E$, assume $J_{||} \alpha B$

Ring Current

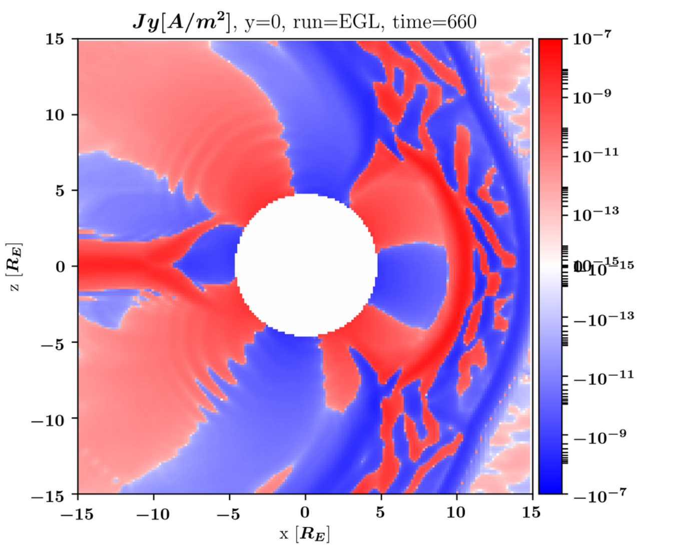
- Magnetospheric ions bounce along B-field lobes
- Drift motion causes a westward current
- Contributes significantly to dB/dt

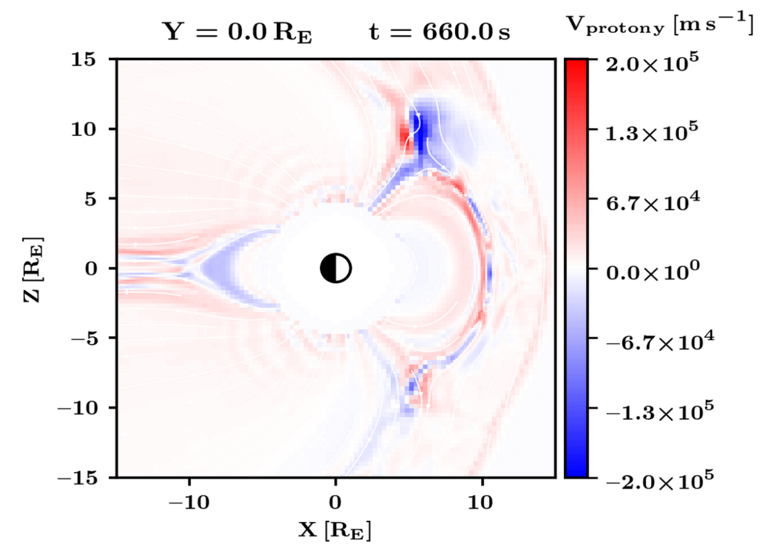


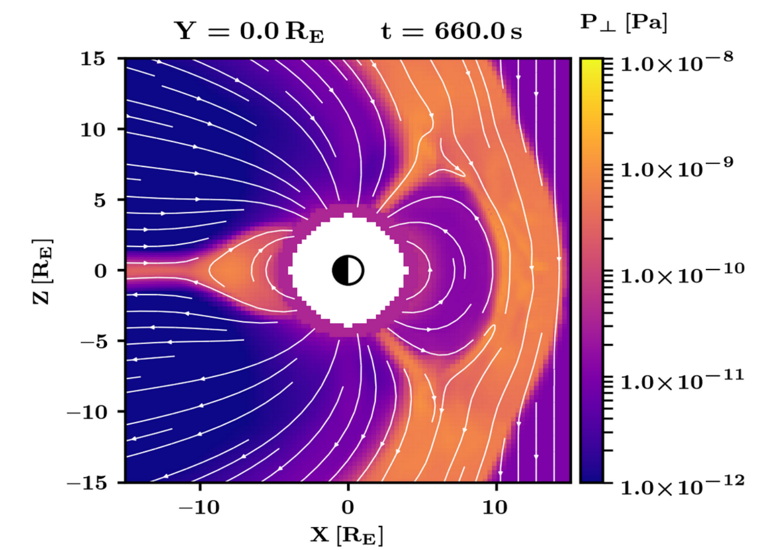
Daglis (1999)

Ring Current (pre-storm) normal driving

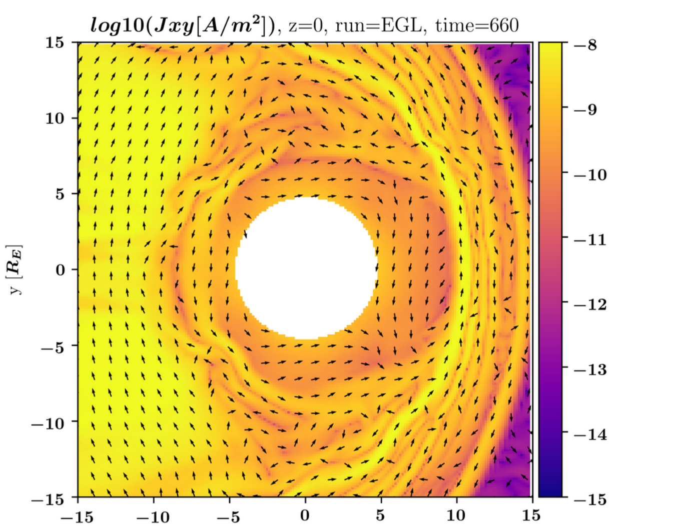
y=0 cut

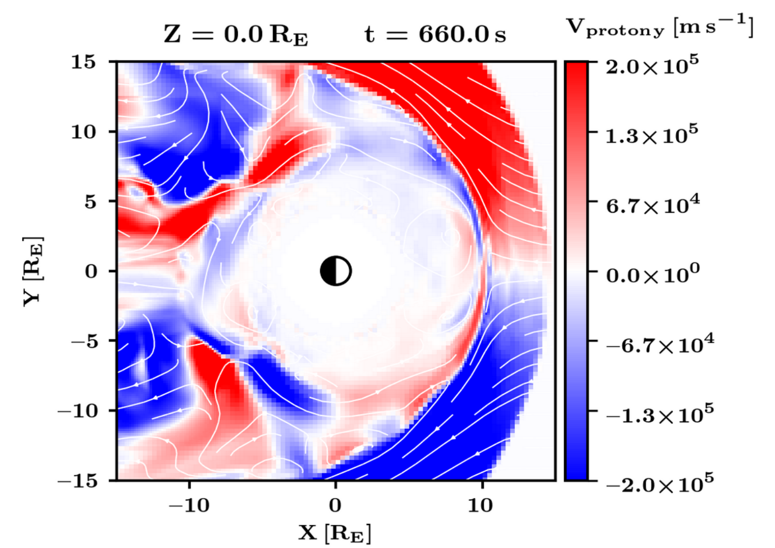


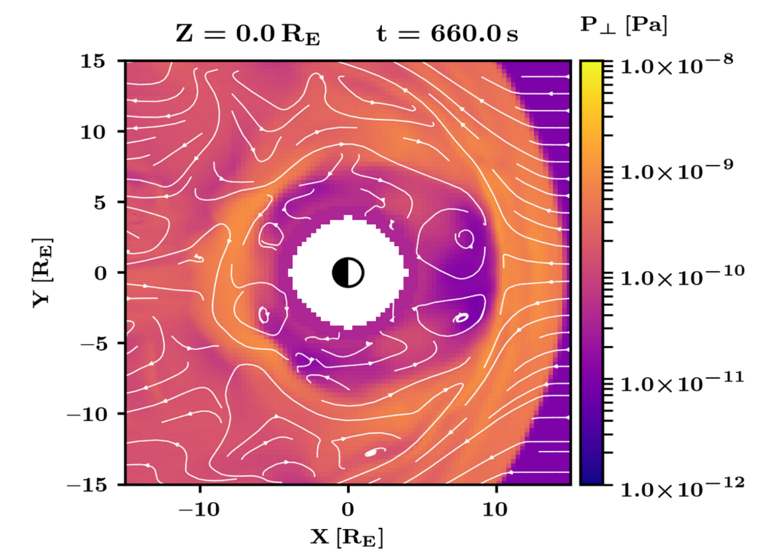




z=0 cut



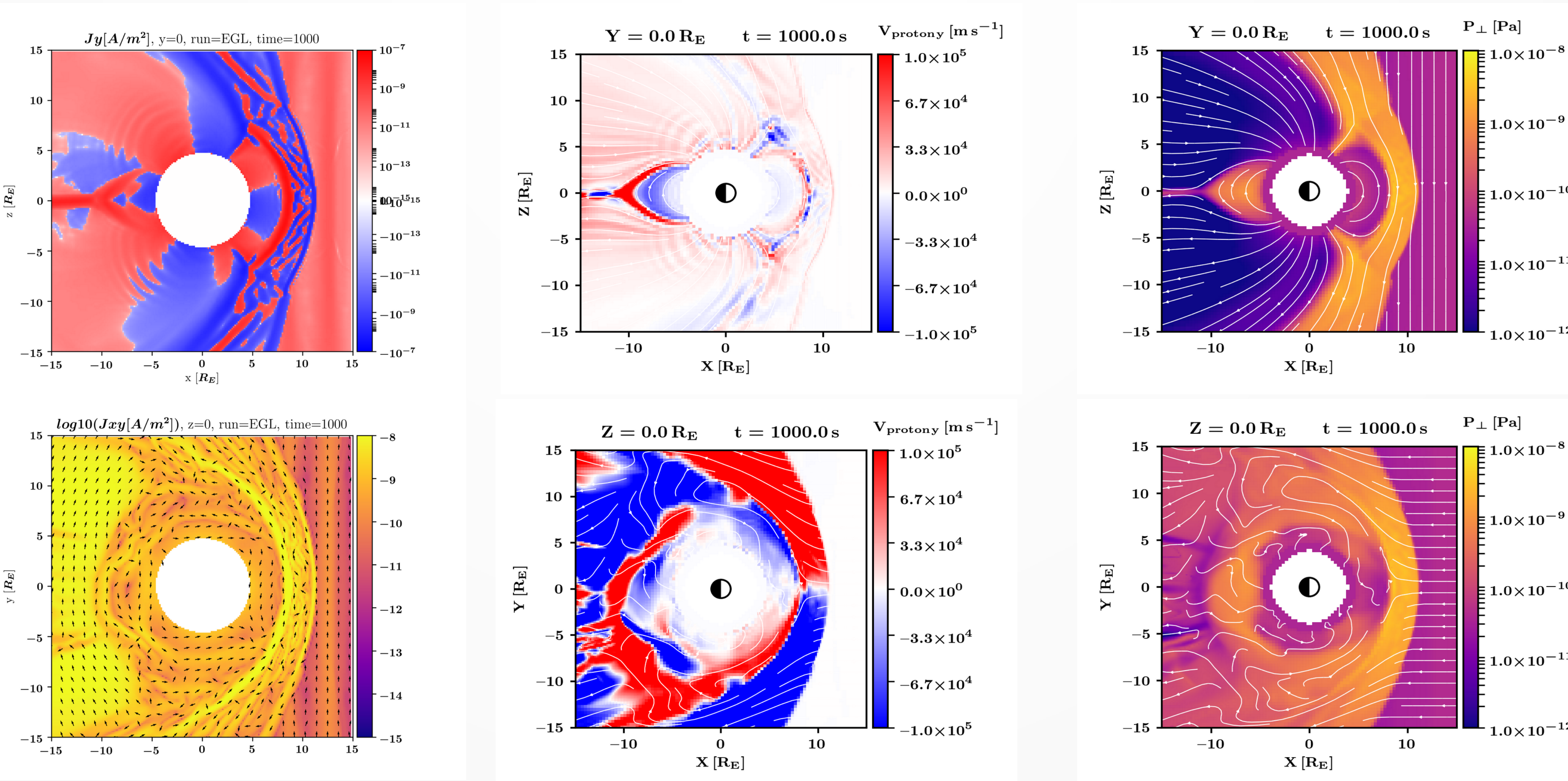




Ring Current (storm onset) normal driving

y=0 cut

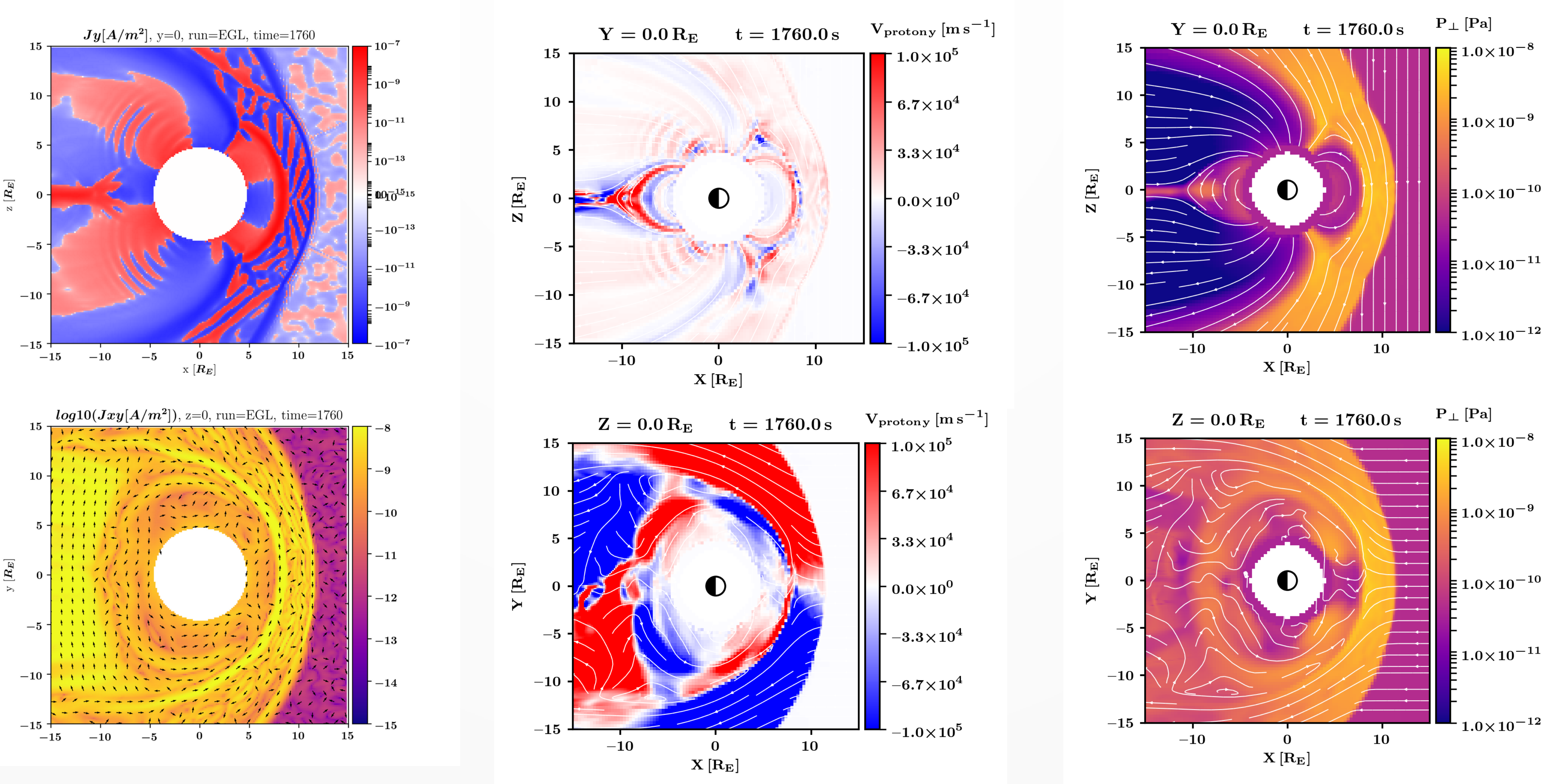
z=0 cut



Ring Current (after onset) normal driving

y=0 cut

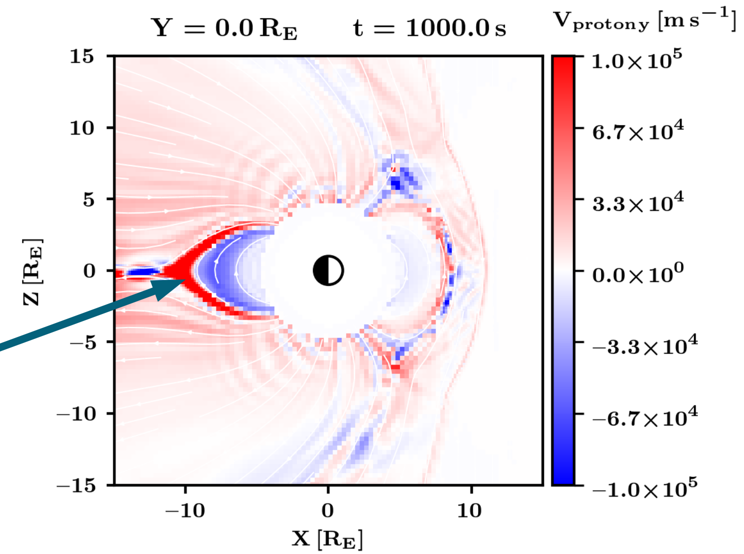
z=0 cut

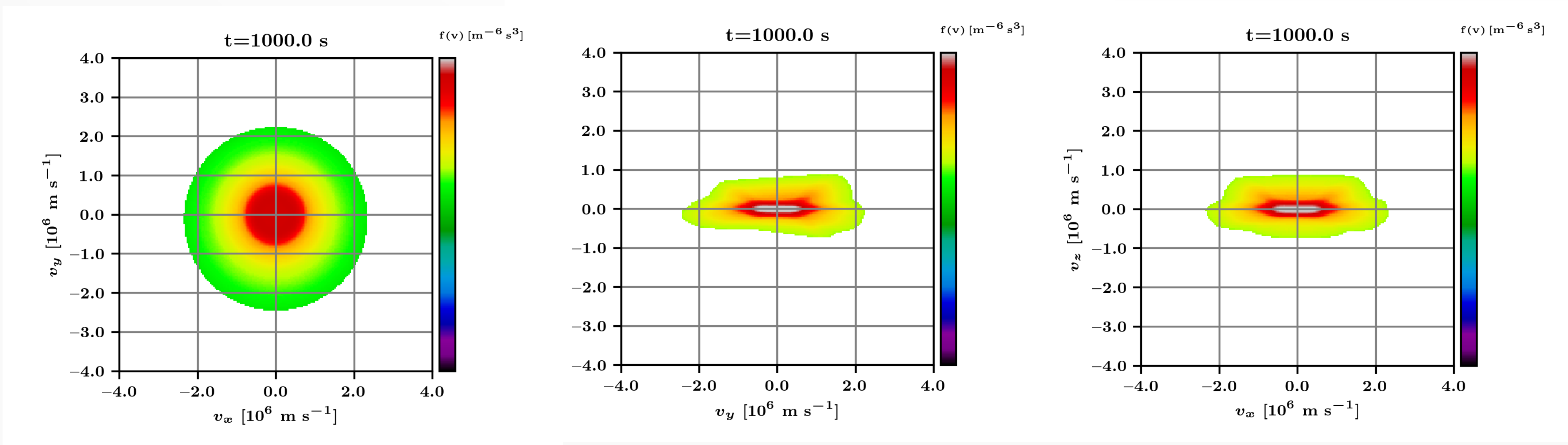


Ring Current (storm onset) normal driving

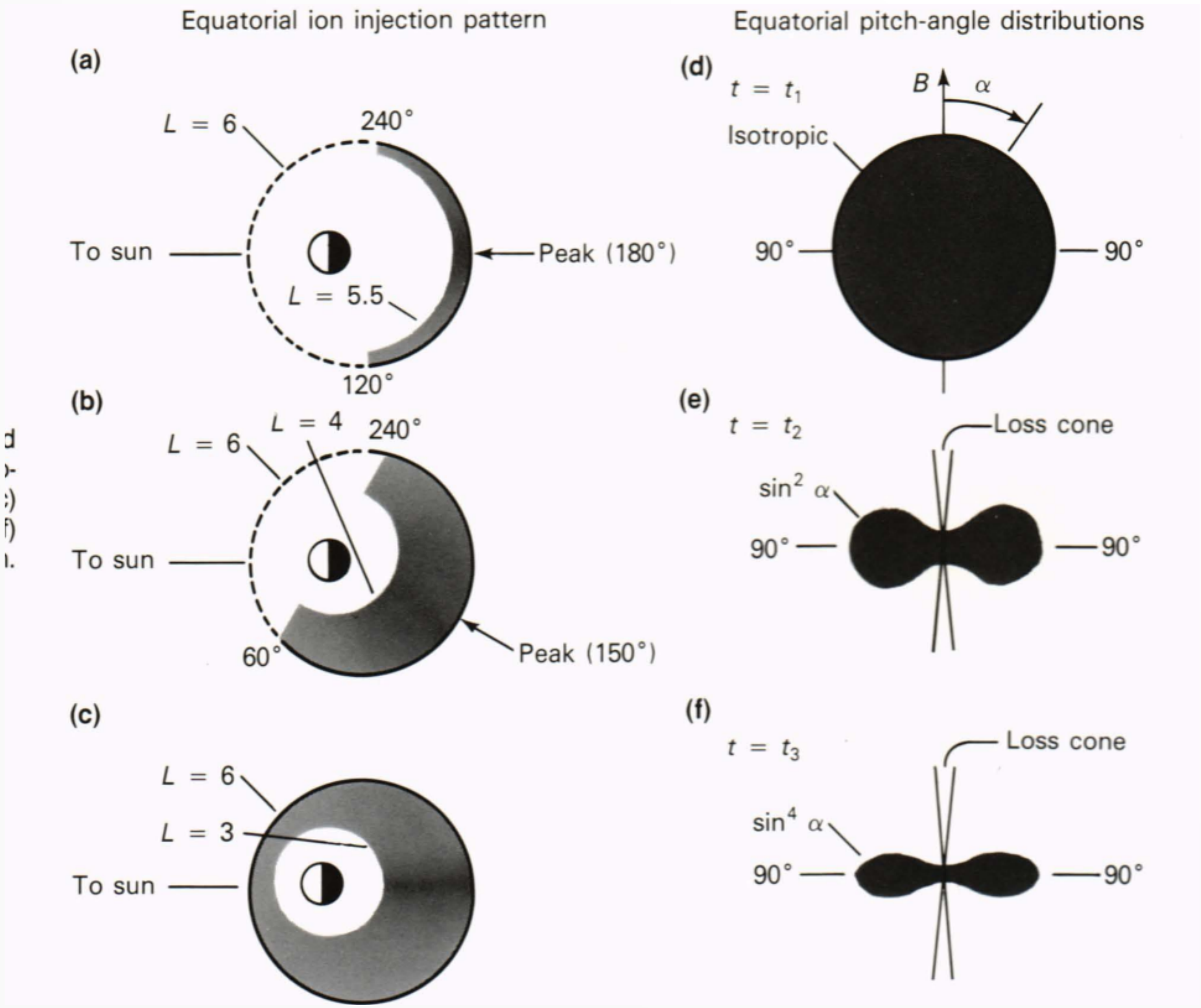
Plot VDFs

[X,Y]= [-10,0]

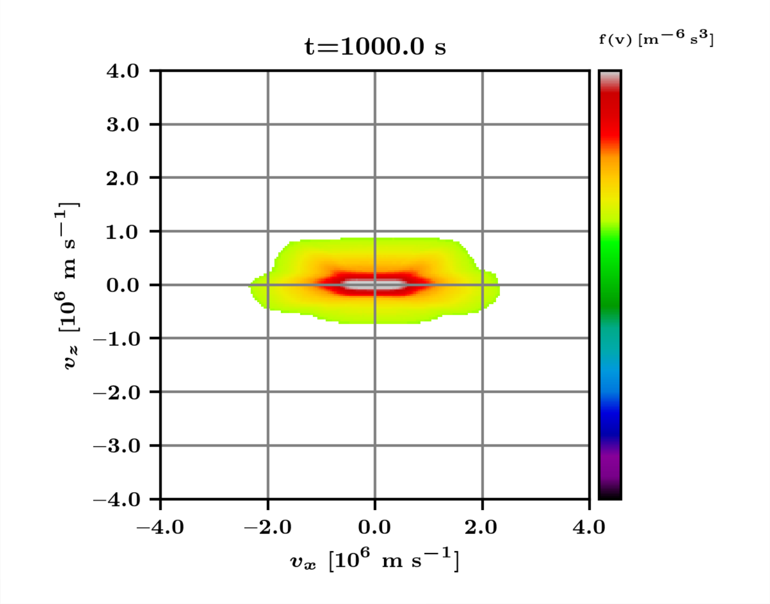




Ring Current (storm onset)



Roelef (1988)

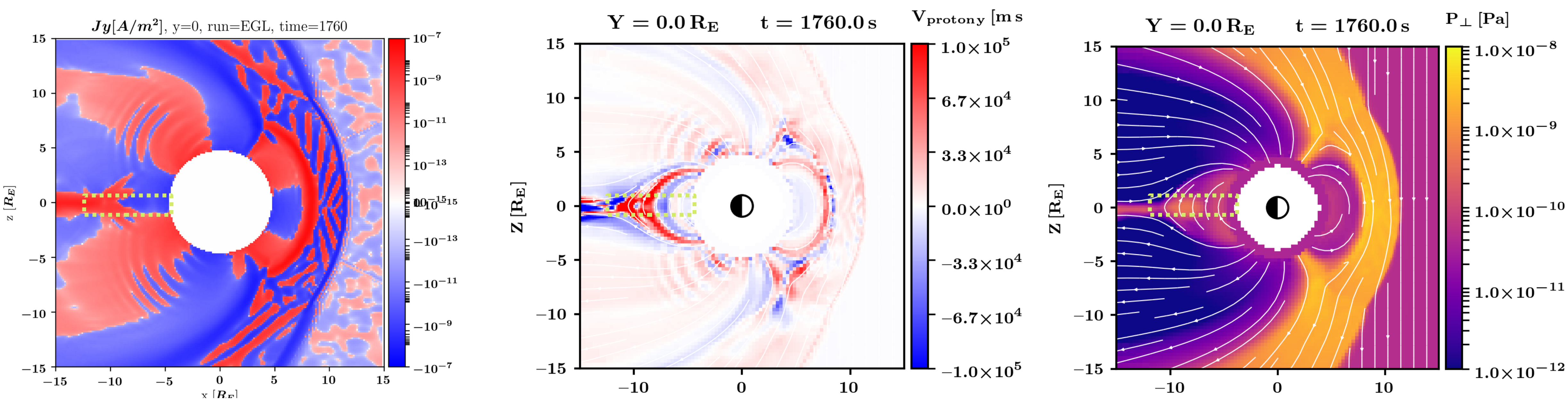


Ring Current: Summary

- Arc of +Jy is seen on the nightside
- Region of +Jy fills out the local magnetic field lobes
- +Jy (westward current) region correlates with +vy region
- Drift velocity ~100km/sec
- VDFs have flat donut shape (loss cone)

- +Jy does not match 1-to1 with +vy
- Region of westward current is very small and short-lived
- Strange rib-like structure in +vy seen at y=0

Ring Current (after onset)



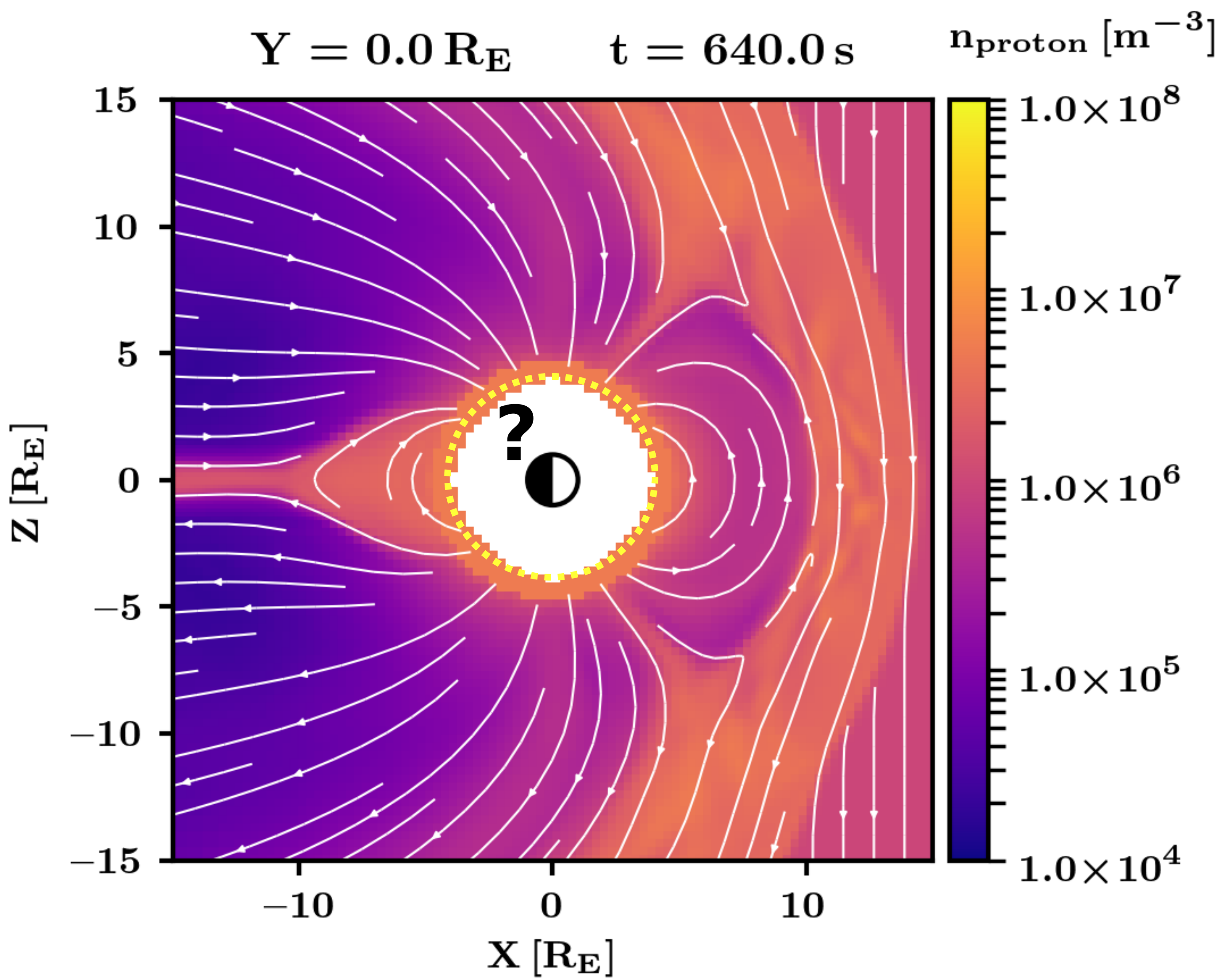
$$\mathbf{j} = \mathbf{j}_\nabla + \mathbf{j}_C + \mathbf{j}_G = \frac{\mathbf{B}}{B^2} \times \left(\nabla P_\perp + \frac{P_\parallel - P_\perp}{B^2} (\mathbf{B} \cdot \nabla)\mathbf{B} \right)$$

(<0)

(Daglis, 1999)

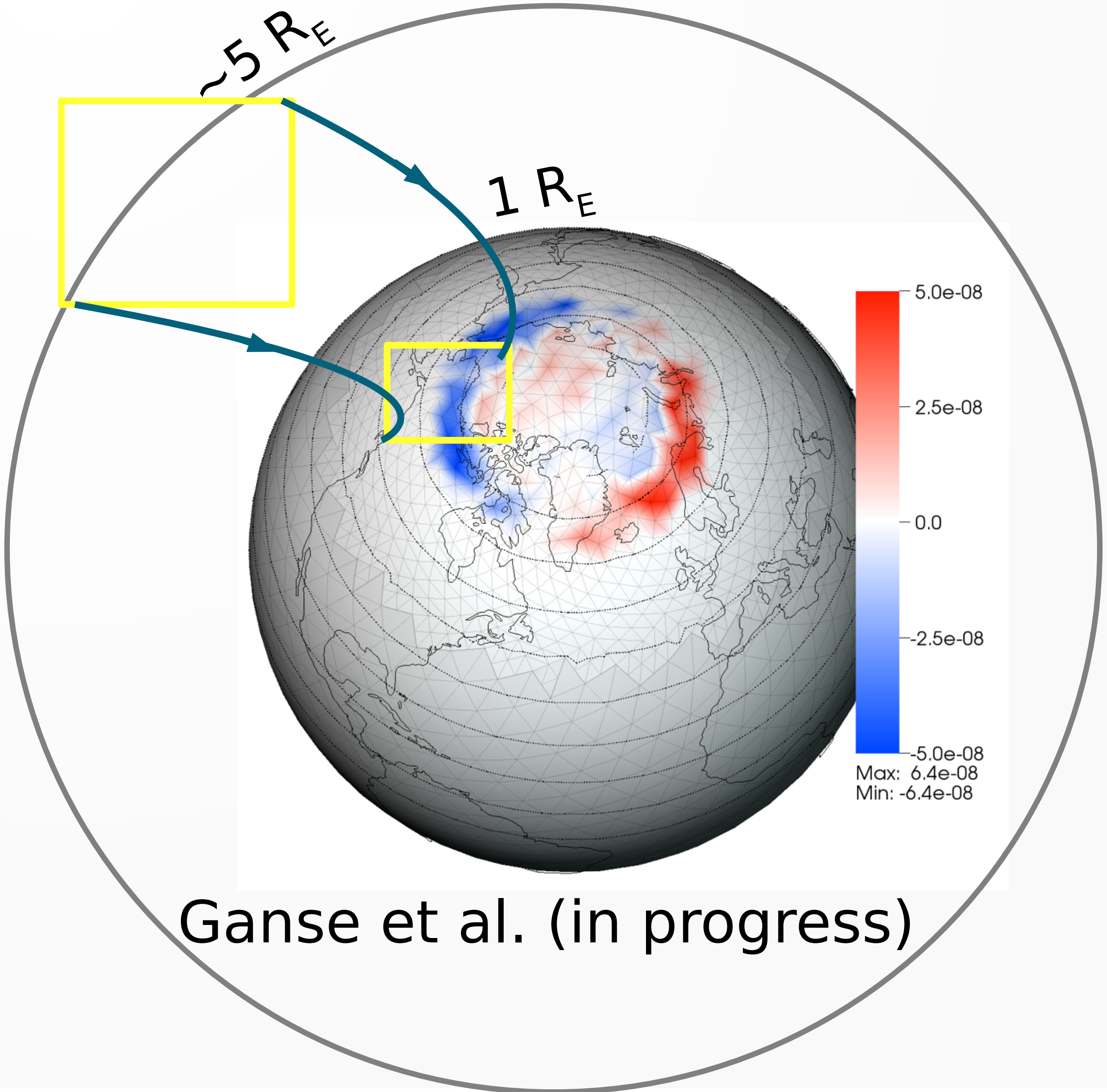
Back to Earth

- Construction of the geoelectric field and GICs depends on the ionosphere
- Too expensive to run full Vlasiator simulations at small r (finer plasma scales requires finer mesh)



Ionosphere

- Adapting GUMICS-4 MHD (Janhunen et al., 2012) coupling between magnetosphere and ionosphere
- Combines Vlasiator input with empirical data
- Outputs:
  - FACs, ionospheric Φ, σ
- Once implemented, will allow analysis of dB/dt that causes GICs



Ganse et al. (in progress)

UNIVERSITY OF HELSINKI

Department of Physics

Matti Ala-Lahti
Markku Alho
Markus Battarbee
Marja Bussov
Giulia Cozzani
Maxime Dubart
Urs Ganse
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Lucile Turc
Yann Pfau-Kempf
Ivan Zaitsev
Hongyang Zhou

Carrington Consortium:

Finnish Meteorological Institute

Change in Momentum (Roope Siirtola et al.)

Email: konstantinos.horaites@helsinki.fi

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www.physics.helsinki.fi/vlasiator