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VLASIATOR

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Hybrid-Vlasov simulation of auroral proton precipitation in the cusps: Comparison of northward and southward IMF driving

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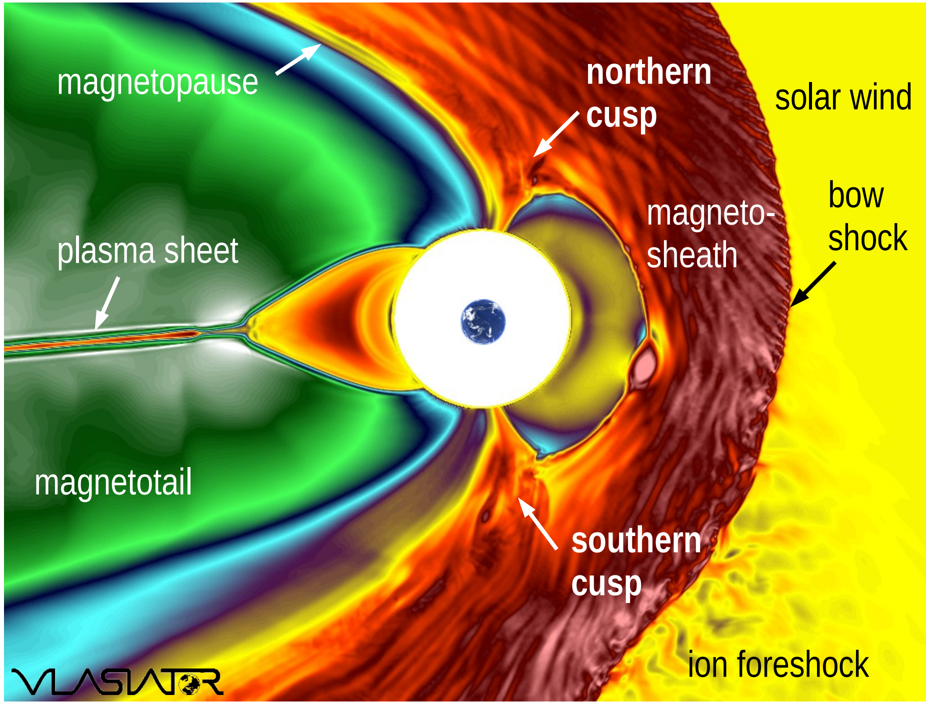
EGU Sharing Geoscience Online – 4–8 May 2020

Outline

Proton precipitation in the cusp



- The cusps are special regions of near-Earth space, where plasma from the magnetosheath can directly enter the upper atmosphere
- The cusp location is affected by the interplanetary magnetic field (IMF), especially the B_z and B_y components
- Precipitation into the cusps comprises electrons and protons of eV–keV energies, whose ionospheric signatures include red and green auroral emissions
- Observations of precipitating energy spectra are limited to spacecraft overpasses (Cluster, DMSP...); ground-based instruments give a wider (spatially and temporally) view but limited information on the precipitating population
- Previous numerical simulations of cusp precipitation have been made with MHD + test particle codes or hybrid-particle-in-cell codes

This study proposes to compare the effect of northward vs southward IMF driving on cusp proton precipitation in global hybrid-Vlasov simulations

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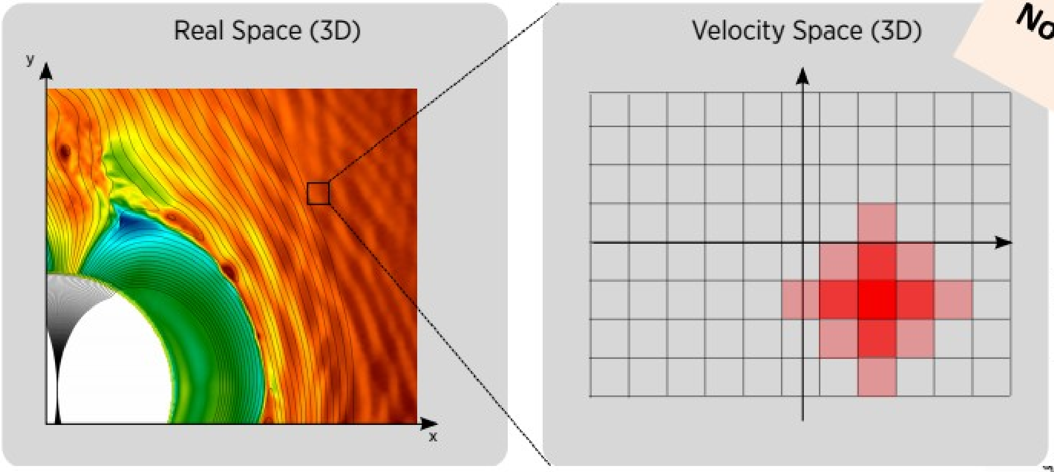
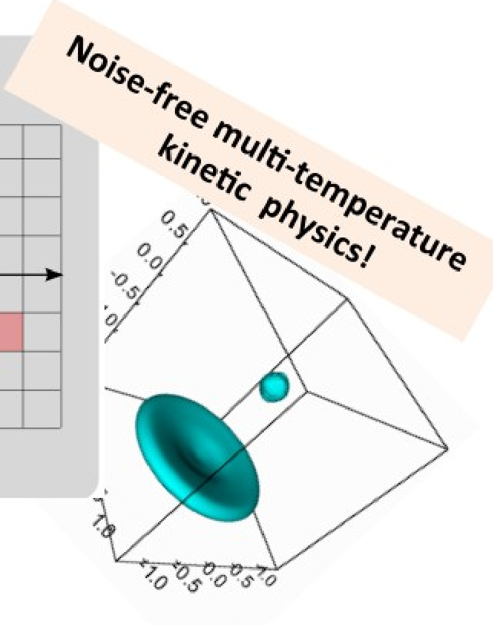
VLASIATOR – Model overview

Vlasiator represents ion-kinetic plasma physics by solving the Vlasov equation for ions. Electrons are massless charge-neutralising fluid.





- Divide real space into grid cells
- Compute **E**, **B** fields in real space
- Each real space cell contains a 3D velocity space
- Self-consistent: In 6D, propagate distribution function using Vlasov equation
  - Couple back to ordinary space to update **E**, **B** field

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(firstname.lastname@helsinki.fi)

Website:
https://www.helsinki.fi/en/researchgroups/vlasiator

More details on hybrid-Vlasov methods in space physics as well as on the Vlasiator code can be found in the *Living Reviews in Computational Astrophysics* paper:

Palmroth et al. (2018, doi: 10.1007/s41115-018-0003-2)

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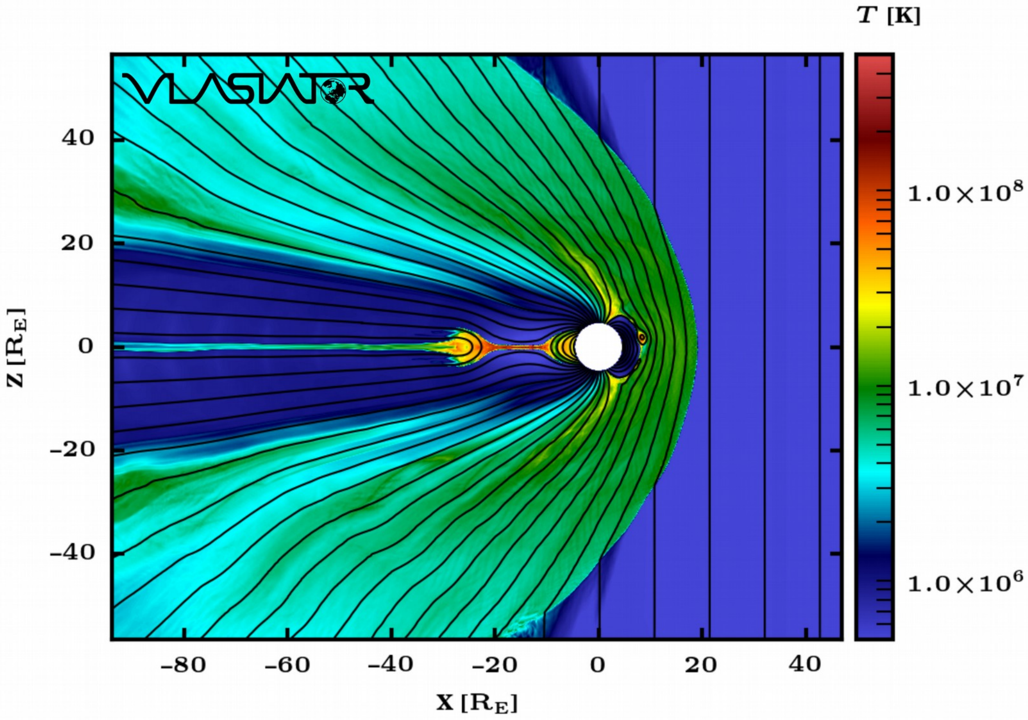
Selected runs for the study

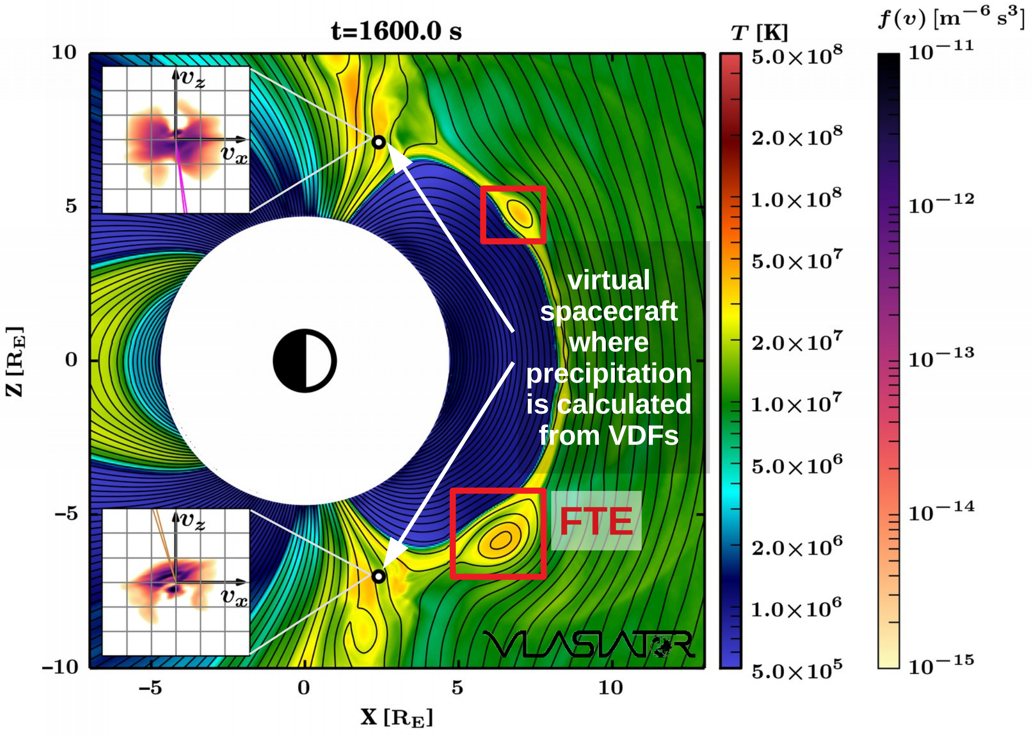
2 almost identical simulations

- 2D in the noon-midnight meridional plane (XZ in GSE coordinate system)
- Resolution: dx = 300 km; dv = 30 km/s, dt = 0.5 s
- Input: steady IMF $|B|$ = 5 nT; V = 750 km/s; n_p = 1 cm^{-3}
  - Run #1: purely southward IMF (B_z = –5 nT)
  - Run #2: purely northward IMF (B_z = +5 nT)
- Full proton VDF saved at each time step every 50 cells in X and Z directions (i.e., every 15,000 km or ~2.35 R_E)



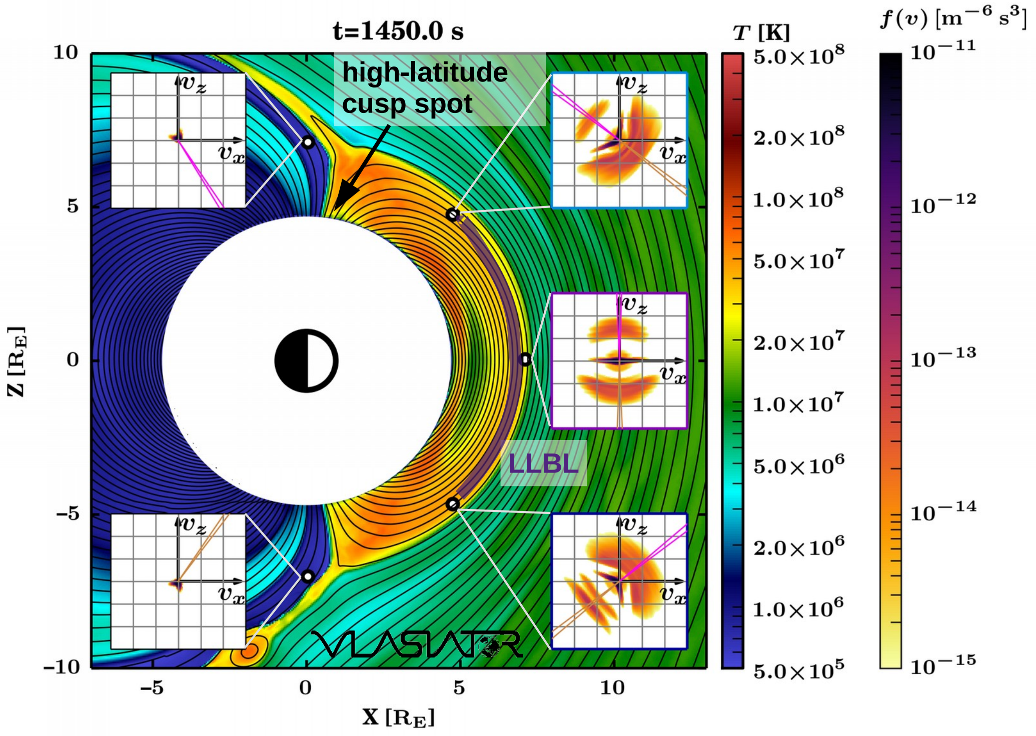
Selected runs for the study

Run #1 (southward IMF; *t* = 1350–2150 s)



Dayside reconnection, formation of flux transfer events (FTEs)

Run #2 (northward IMF; *t* = 1100–1938 s)



Dual lobe reconnection, 2 virtual spacecraft near high-latitude cusp spot + 3 in low-latitude boundary layer (LLBL)

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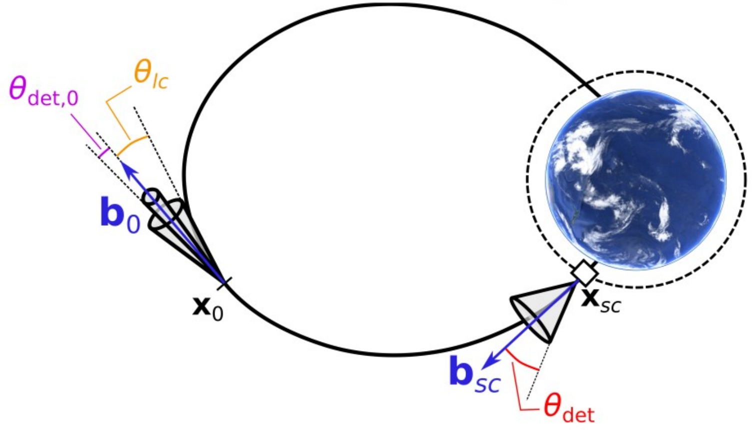
Precipitating proton flux calculation

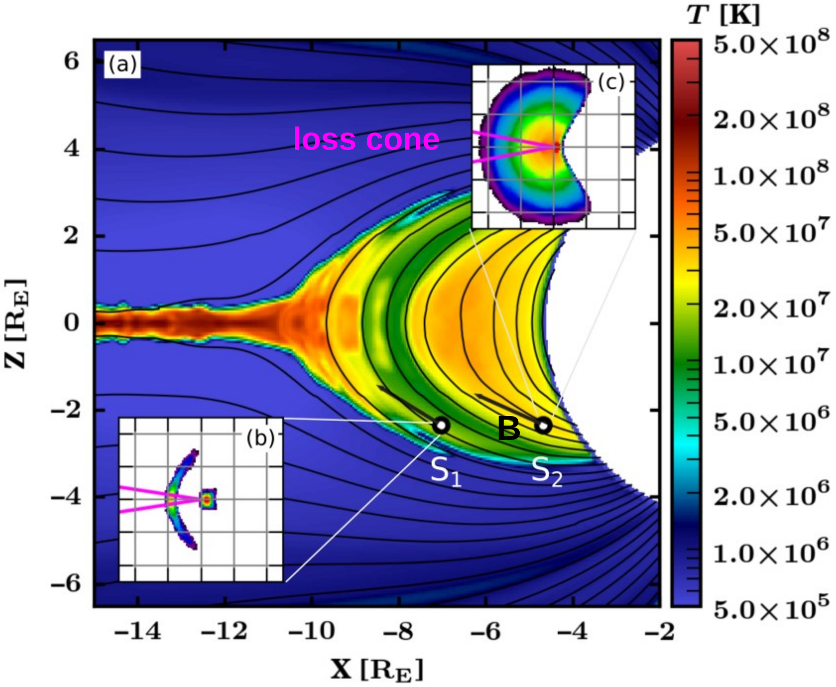
Differential precipitating flux estimation

In ordinary-space cells where the velocity distribution is saved in the output file, we **calculate the value of the loss cone angle**, based on the ratio between the local magnetic field magnitude at the cell and at the topside ionosphere (~600 km altitude).

The directional differential precipitating flux is then estimated by **averaging the phase-space density inside the loss-cone**, at a given velocity v (energy E) value, and calculating (m_p : proton mass)

$$\tilde{\mathcal{F}}(E, \mathbf{b}_{sc}, \mathbf{x}_{sc}) = \tilde{\mathcal{F}}(E, \mathbf{b}_0, \mathbf{x}_0) = \frac{v^2}{m_p} \langle f(\mathbf{x}_0, v, \theta, \varphi) \rangle_{\theta < \theta_0}$$



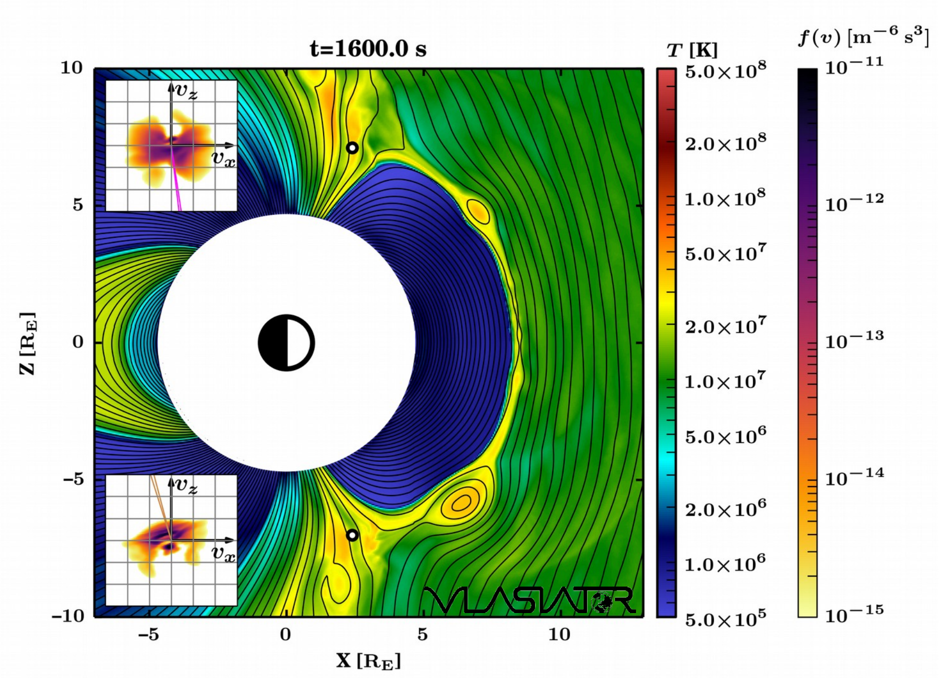


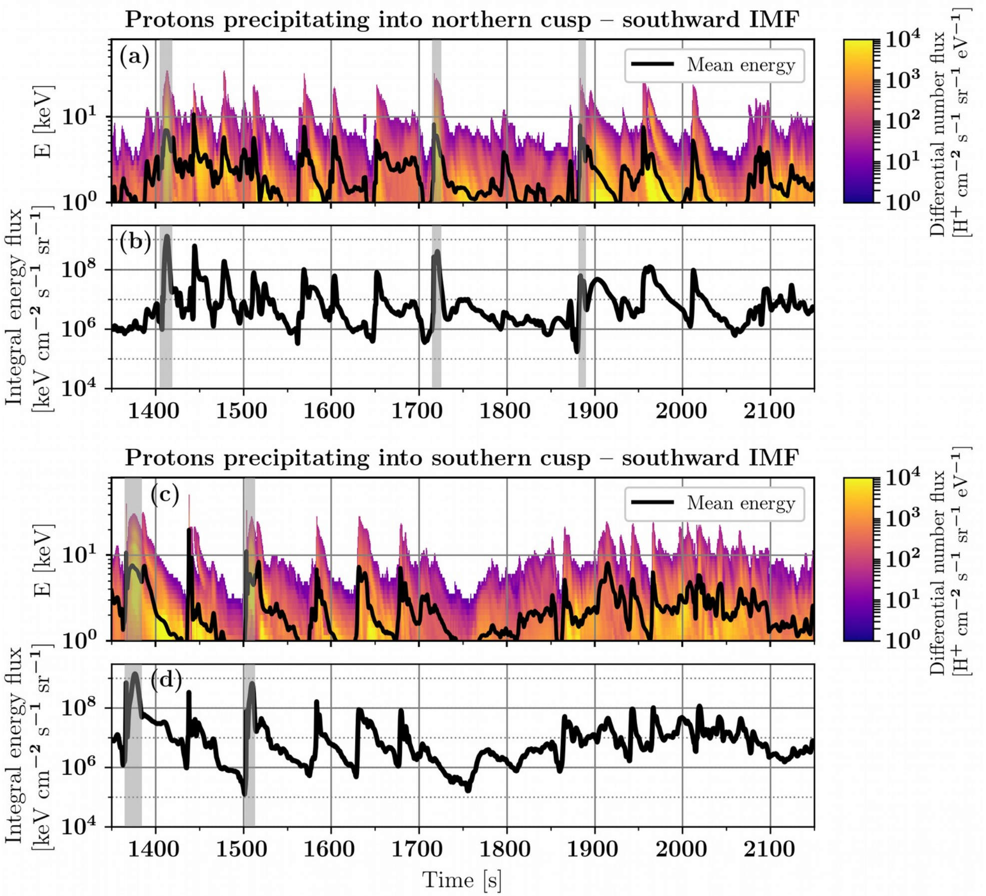
Method introduced and applied to nightside proton precipitation in *Grandin et al.* (2019; doi:10.5194/angeo-37-791-2019)

Outline

1. Proton precipitation in the cusp
2. Vlasiator: brief overview
    2.1. Model overview
    2.2. Selected runs
    2.3. Precipitation flux calculation
3. Results
    3.1. Southward IMF
    3.2. Northward IMF
    3.3. Cusp morphology
    3.4. EMIC wave activity
4. Summary and key points

Results: Southward IMF cusp





- Cusp precipitation is bursty and with northern/southern hemisphere asymmetry
- Proton energies can reach up to ~30 keV during bursts
- Precipitation bursts correspond to the transit of FTEs in the cusp

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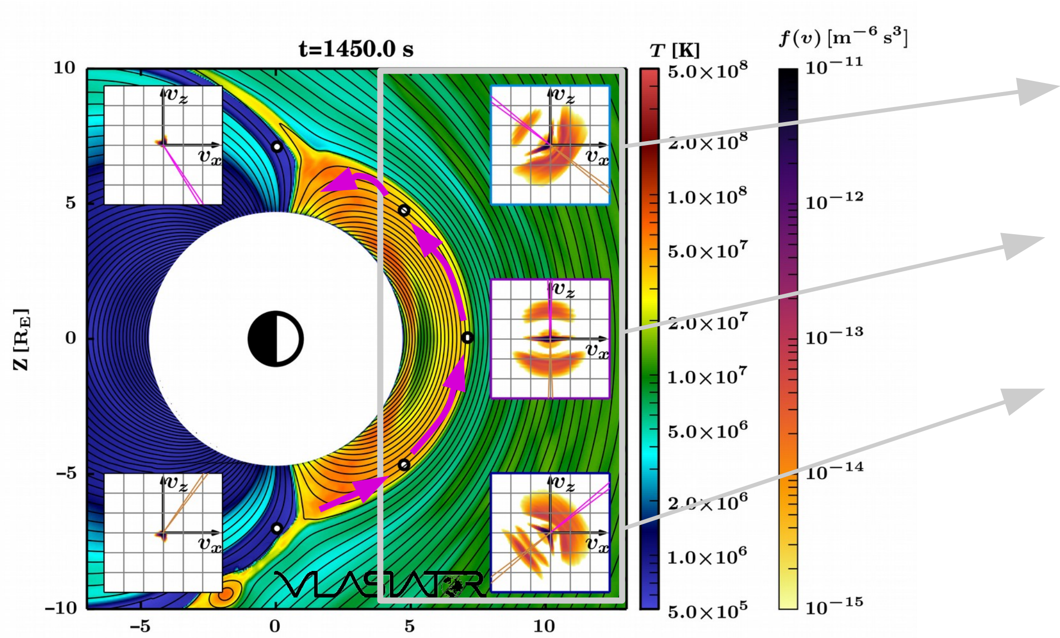
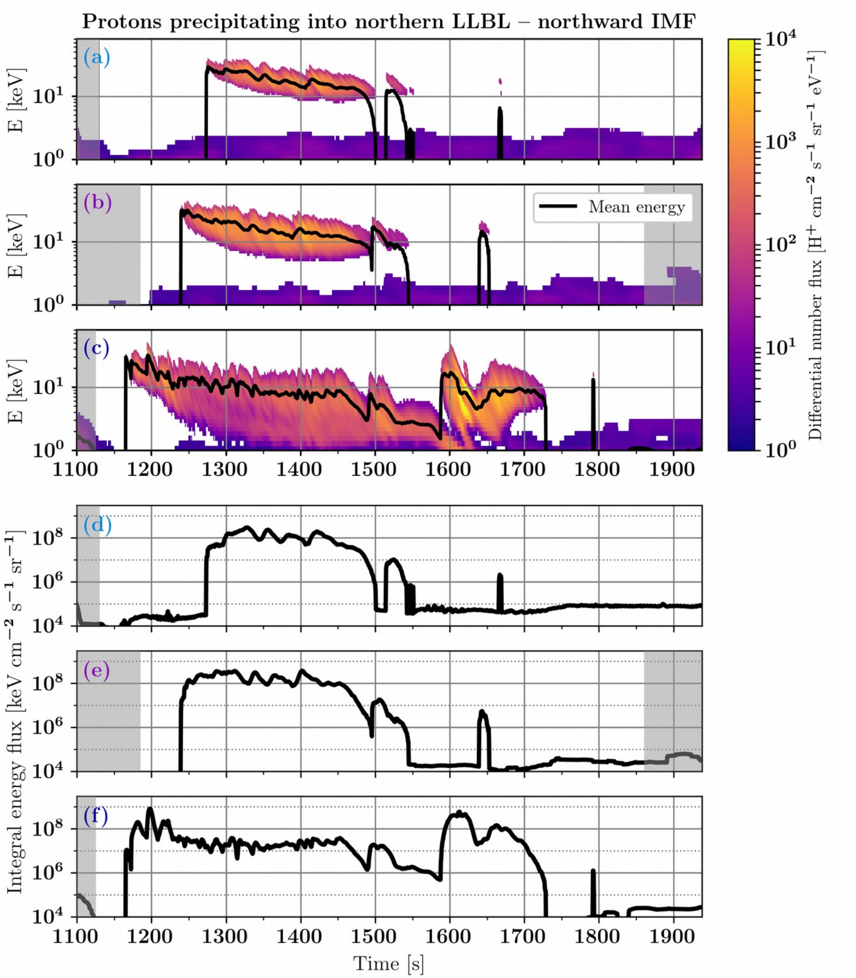
Results: Northward IMF LLBL



northern hemisphere precipitation = magenta loss cones in VDFs



- Southern lobe reconnection produce field-aligned proton beams along the dayside magnetopause, detected at the three virtual spacecraft
- This results in proton precipitation into the northern LLBL
- The same happens into the southern LLBL (from the northern lobe)

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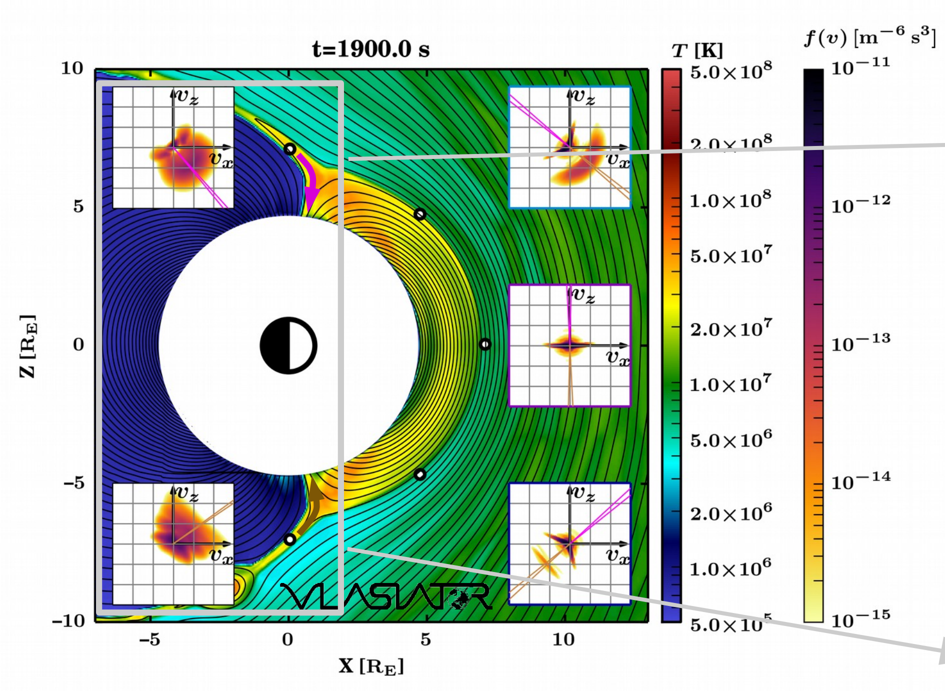
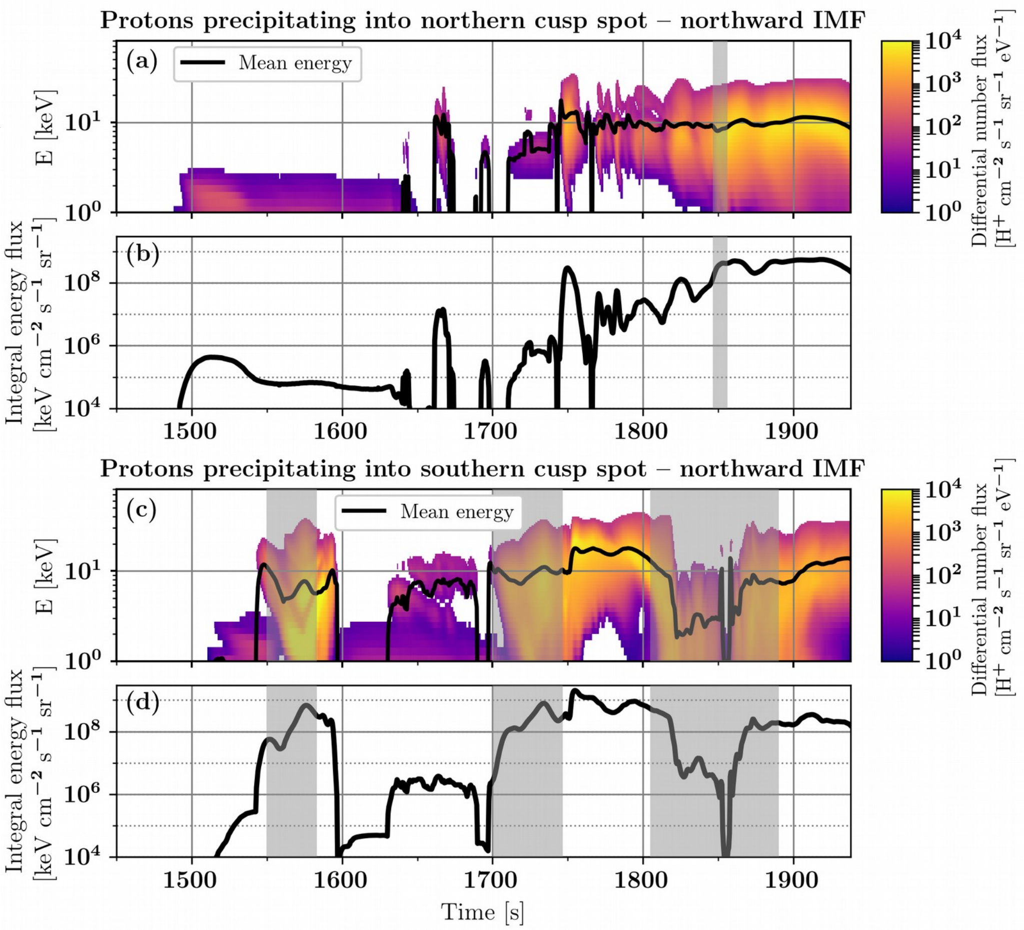
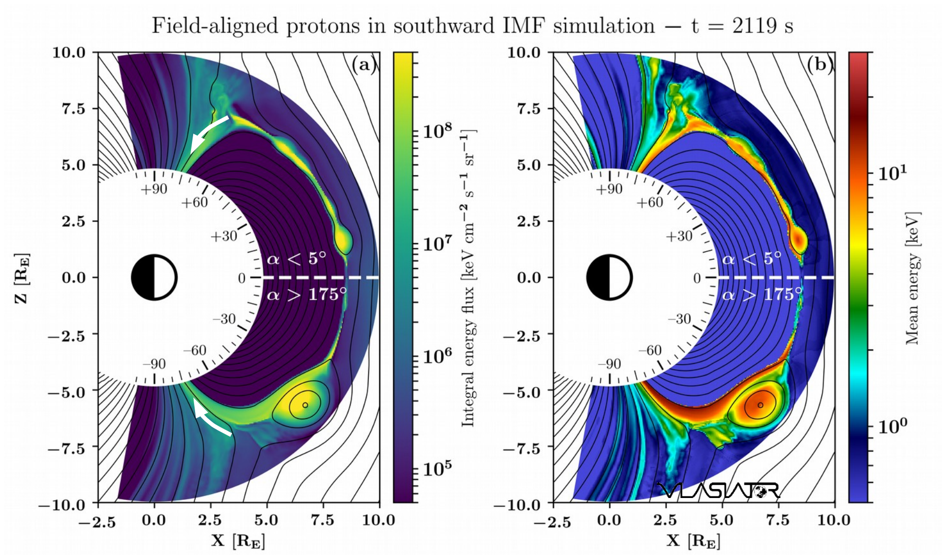
Results: Northward IMF cusp spots

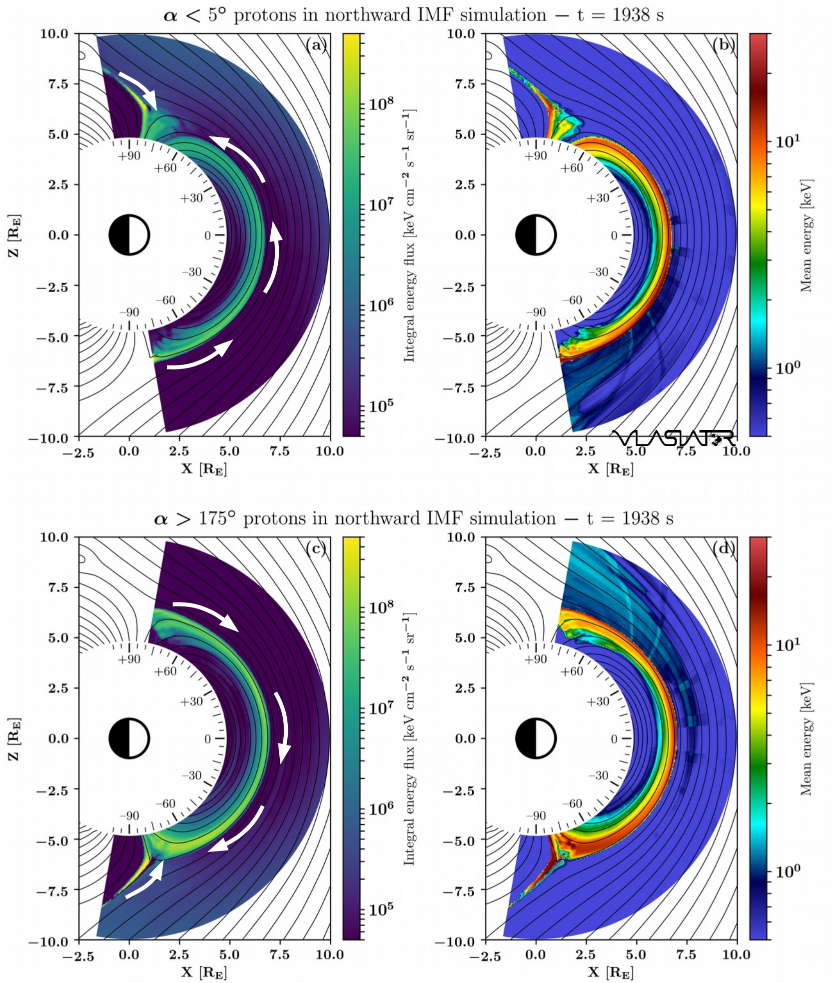




- Lobe reconnection also produces proton precipitation into the high-latitude cusp spots
- Although some FTEs are present, the precipitation is mainly associated with plasma from reconnection exhaust regions

Results: Cusp morphology comparison





- In each run, one special ("restart") file has VDFs saved in all cells
- This allows to produce a 2D snapshot of dayside precipitation
- Southward IMF cusps exhibit a sharp equatorward edge and decreasing mean precipitating energy with increasing latitude
- Northward IMF cusp spots exhibit a sharp poleward edge and a reversed energy dispersion (increasing mean precipitating energy with increasing latitude)
- Northward IMF LLBLs also exhibit a reversed energy dispersion
- Southward IMF cusps are at lower latitude than northward IMF cusp spots

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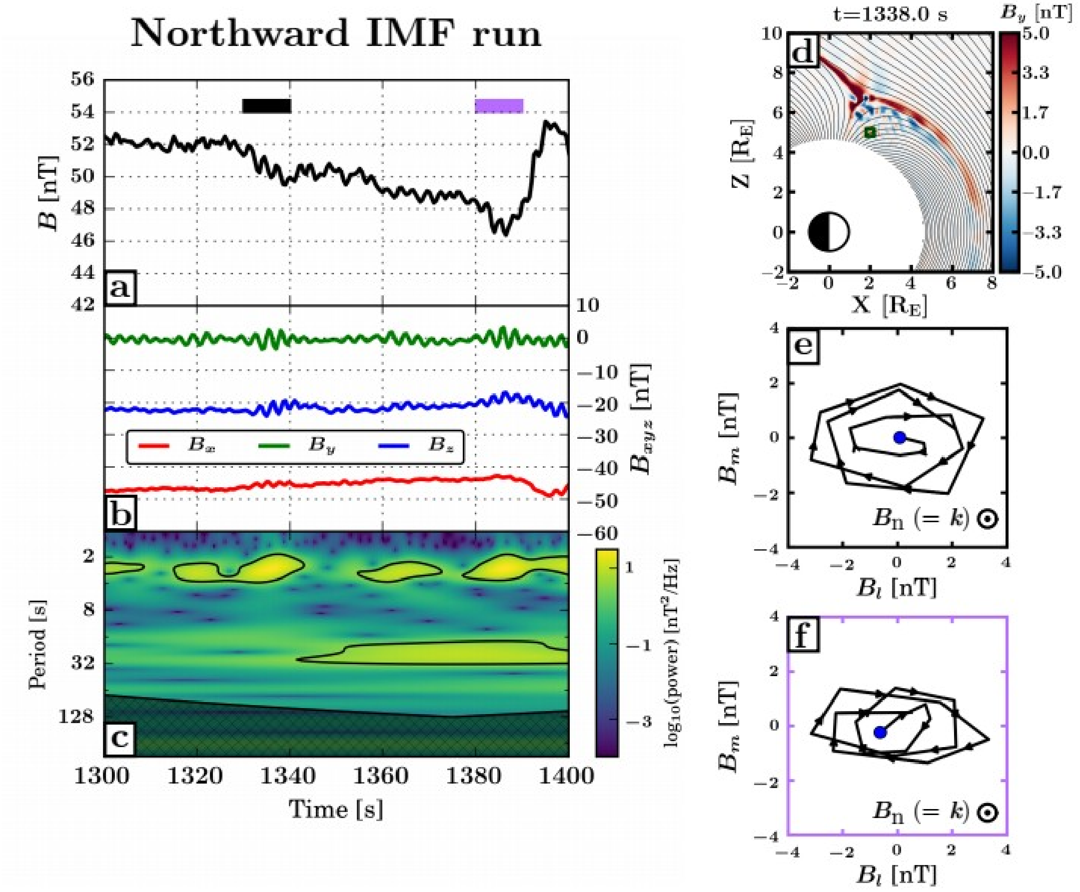
Results: EMIC wave activity



- VDFs seen at the virtual spacecraft and associated with proton precipitation are intrinsically unstable
- The expected dominant ion/ion instability is the **ion cyclotron anisotropy instability, associated with electromagnetic ion cyclotron (EMIC) waves**
- In both runs, wave activity can be identified by looking at, e.g., the out-of-plane component of the magnetic field (B_y)
- Wavelet analysis of B_y at a selected location in the cusp during the northward IMF simulation reveals significant wave power associated with periods of ~3 s
- Minimum variance analysis combined with visual inspection of B_y animation shows that the waves propagate earthwards parallel to the magnetic field direction and have a left-hand polarisation
- **The wave period, propagation direction and polarisation are consistent with EMIC waves**
- EMIC waves are known to be able to contribute to proton precipitation through wave-particle interactions
- **The precipitating fluxes calculated at the virtual spacecraft are therefore likely conservative low estimates of fluxes that could be obtained just above the ionosphere**

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Summary and key points

- Comparison of two Vlasiator simulations with purely southward/northward IMF
- **Bursty cusp precipitation** during southward IMF is associated with **FTEs**
- **Dual lobe reconnection** signatures are seen in VDFs in the northward IMF simulation
- Protons from the lobe reconnection site can precipitate in the **low-latitude boundary layer equatorwards from the opposite hemisphere's cusp**
- High-latitude cusp spot precipitating protons originate from lobe reconnection exhaust regions
- Cusp morphology and latitudinal dependence of precipitating energies agree with published observations for southward/northward IMF
- **EMIC waves** are seen in the cusps in both simulations and are likely to further increase the calculated fluxes between the virtual spacecraft and the ionosphere

Grandin, M., Turc, L., Battarbee, M., Ganse, U., Johlander, A., Pfau-Kempf, Y., Dubart, M., and Palmroth, M., Hybrid-Vlasov simulation of auroral proton precipitation in the cusps: Comparison of northward and southward interplanetary magnetic field driving, under review, 2020.

Discussion via live chat

Tue 5 May 2020 (14:00–15:45 CET)

Remember to also <u>vote</u> for the Photo Competition!

Maxime Grandin (distributed via imaggeo.egu.eu)