Near-Earth space in five and six dimensions
recent results from the Vlasiator model

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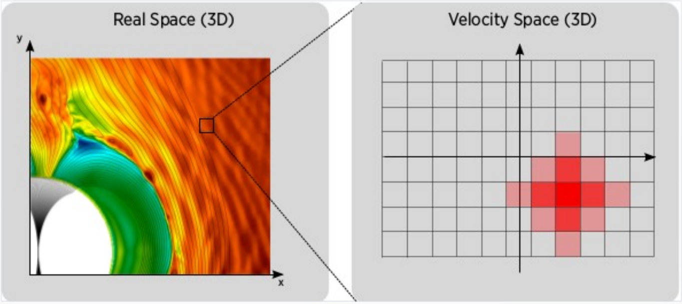
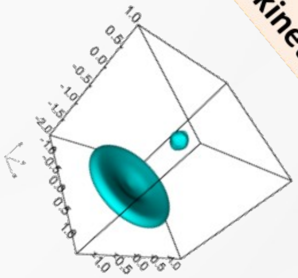
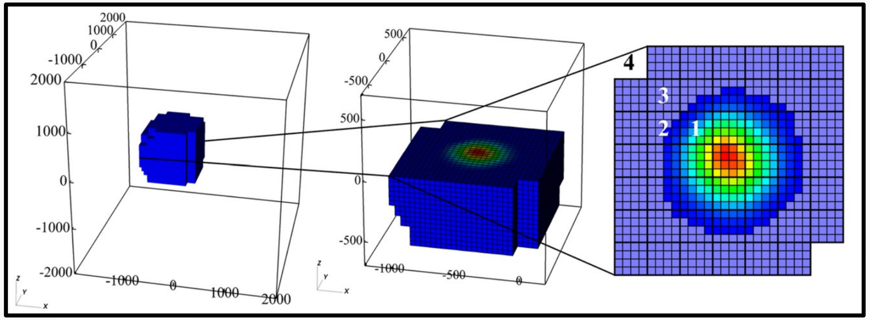
- Hybrid-Vlasov model designed for global magnetospheric simulations [Palmroth et al., 2018], using an unscaled dipole → direct comparison with observations
- Ions treated as velocity distribution functions, electrons are a massless charge-neutralising fluid
- Ion dynamics controlled by Vlasov's equation, coupled with Maxwell's equations
- Closure provided by the generalised Ohm's law → since 2021: electron pressure gradient term





Noise-free multi-temperature kinetic physics!

THE VLASIATOR MODEL

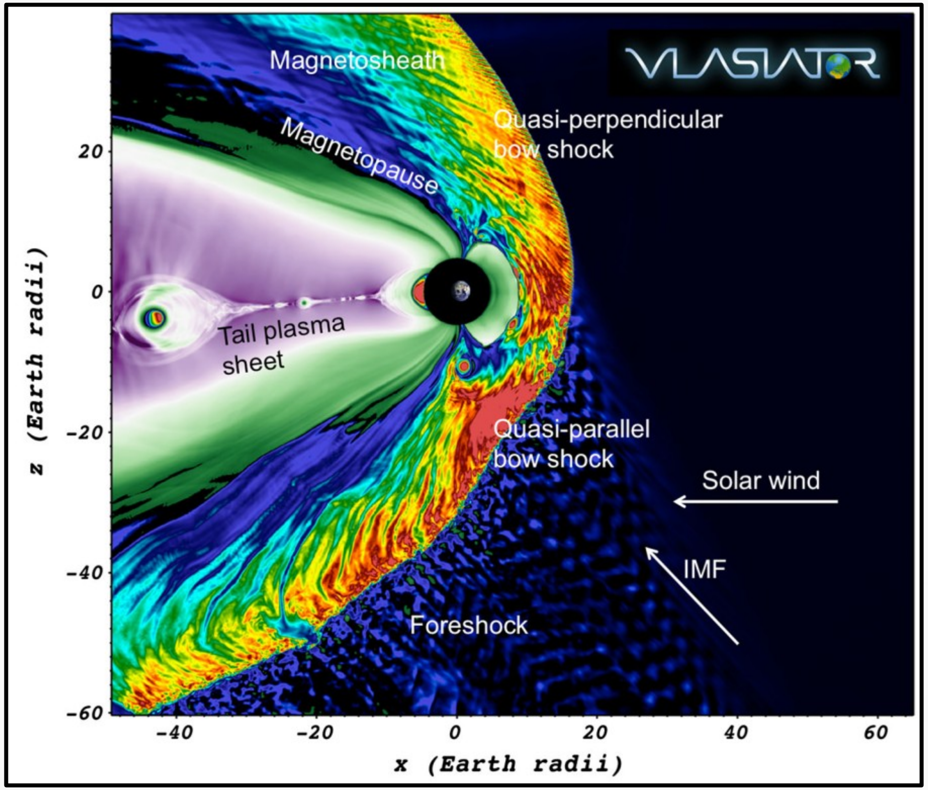


Schematic of sparse velocity space,
from Palmroth et al. [2018],
Living Reviews in Computational Astrophysics

- Spatial grid: cartesian grid, now with (static) **adaptive mesh refinement**
- Velocity grid: **sparse velocity space** to save on memory
- Inner boundary: perfectly conducting sphere
  → WIP: better ionosphere description
- Inflow boundary: Maxwellian distribution + interplanetary magnetic field
  → since 2021: **time-varying input conditions**

VLASIATOR ENABLES STUDYING ION KINETIC PROCESSES IN THEIR GLOBAL CONTEXT

From Palmroth et al. [2018], Living Reviews in Computational Astrophysics

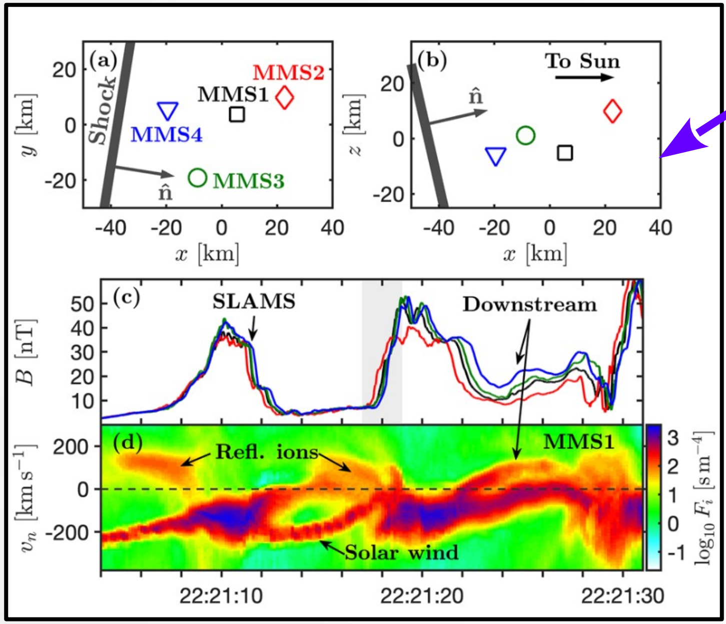


For example:

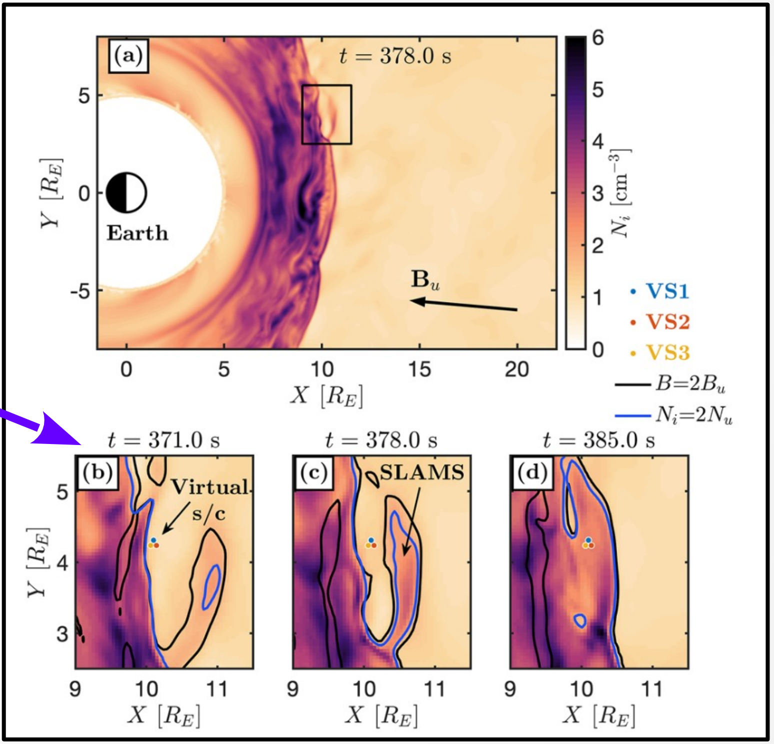
- Shock-foreshock interactions
- Ion acceleration at the curved bow shock
- Ultra-low frequency waves (1 mHz – 1 Hz) and their transmission across different regions
- Ion precipitation linked with tail reconnection or flux transfer events

SIMULATIONS CAN PROVIDE THE GLOBAL CONTEXT FOR OBSERVATIONS OF SHOCK REFORMATION

MMS satellites crossing the shock in the "wrong" order



Signature of shock reformation caused by a SLAMS

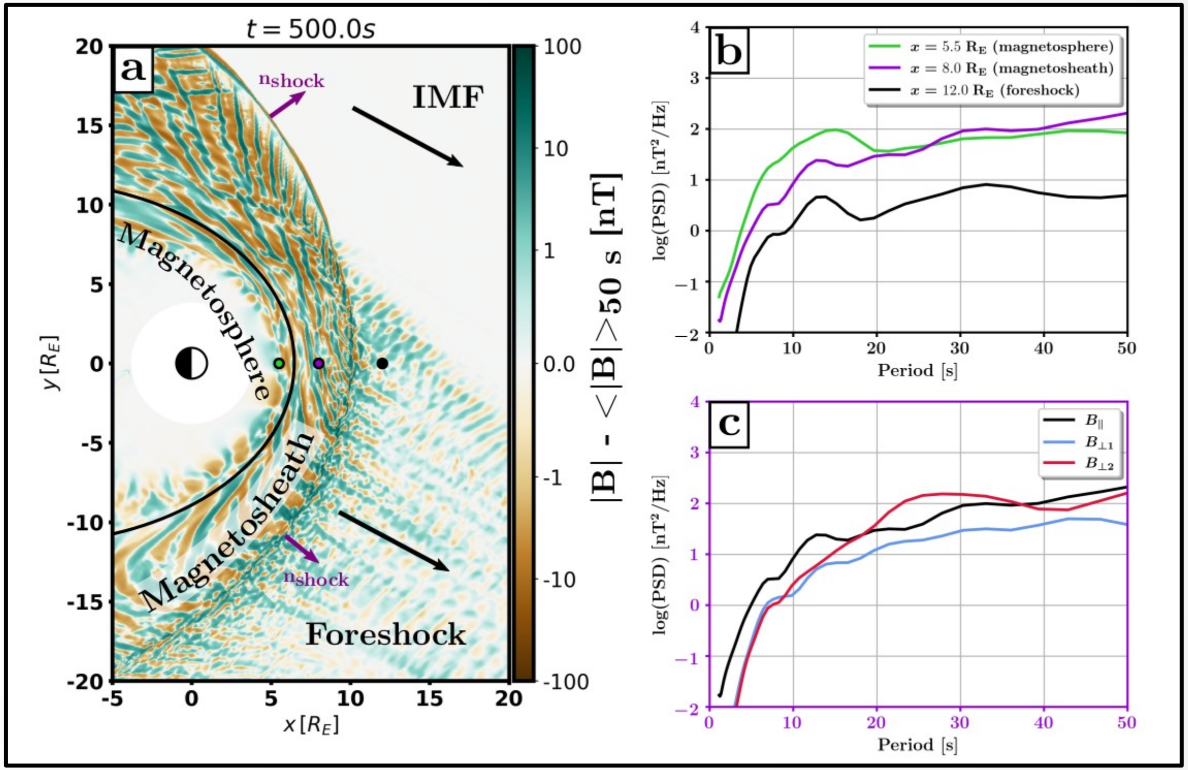


From Johlander et al. [2022], Geophysical Research Letters

HOW DO FORESHOCK WAVES CROSS THE MAGNETOSHEATH TO GENERATE MAGNETOSPHERIC PC3 WAVES?

- **Waves with similar periods** observed simultaneously in the **foreshock** and the **magnetosphere** [e.g., Takahashi et al., 1984; Clausen et al., 2009]

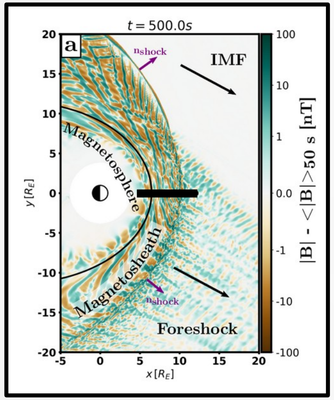
- No direct observations of fast-mode waves inside the magnetosheath

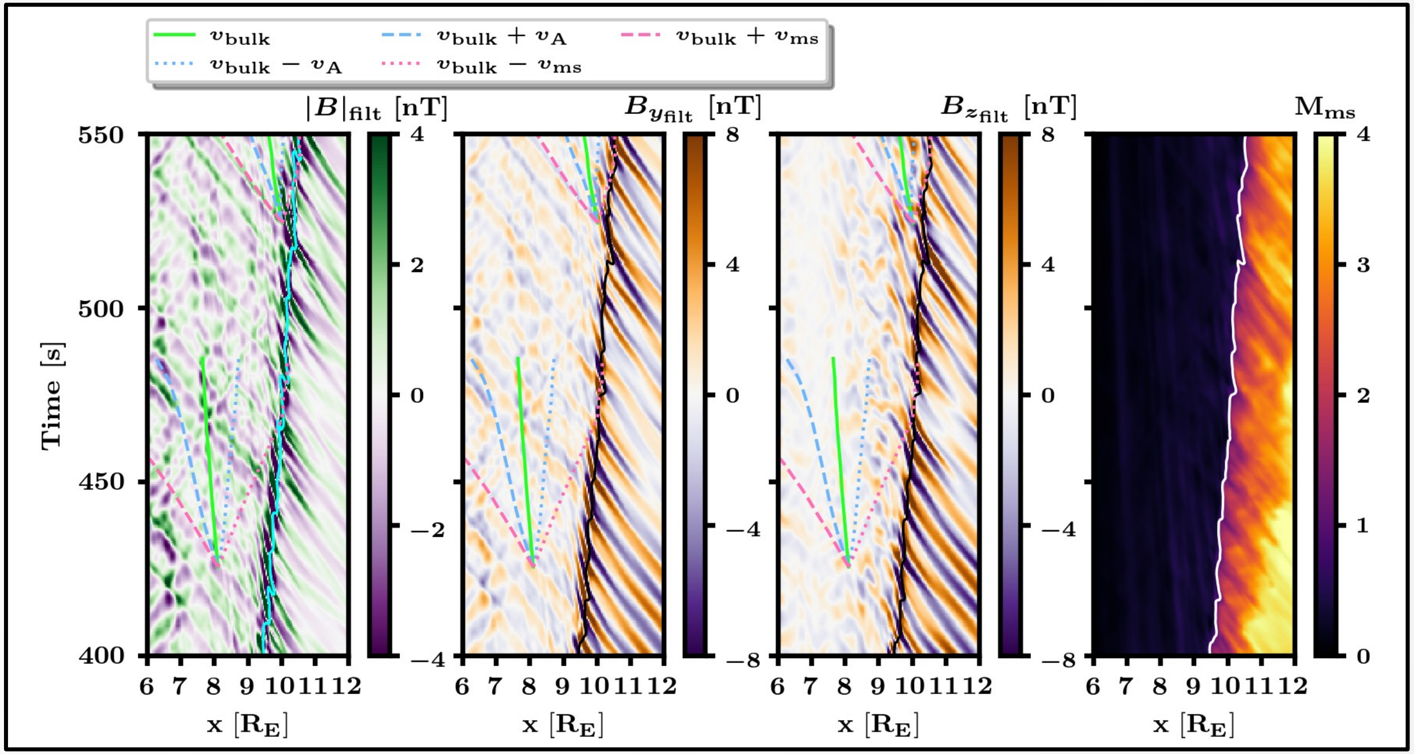


Turc et al., manuscript under review

FORESHOCK WAVES MODULATE THE MACH NUMBER UPSTREAM OF THE SHOCK

Fast-mode signals generated downstream of the shock due to **variations in the compression ratio**





Turc et al., manuscript under review

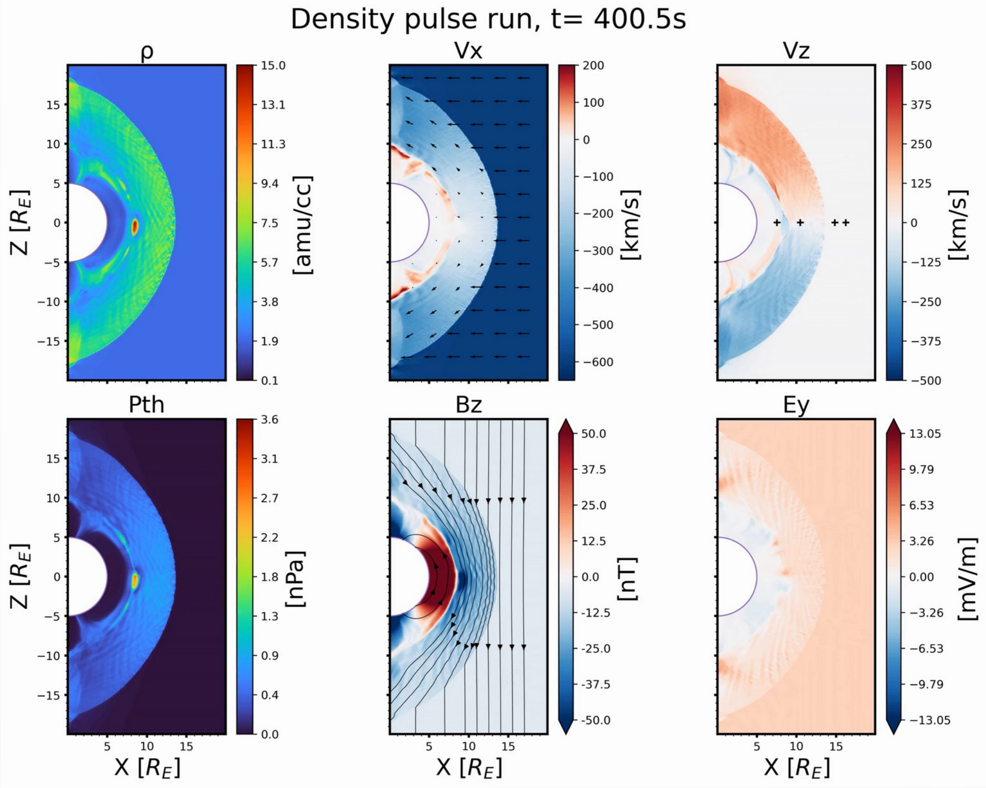
GLOBAL IMPACT OF SOLAR WIND DENSITY FLUCTUATIONS ON THE MAGNETOSHEATH

New time-varying input parameters

Sinusoidal density variations in the solar wind.

Period = 150 s (Pc5 waves)

“Stripes” of modified plasma parameters inside the magnetosheath

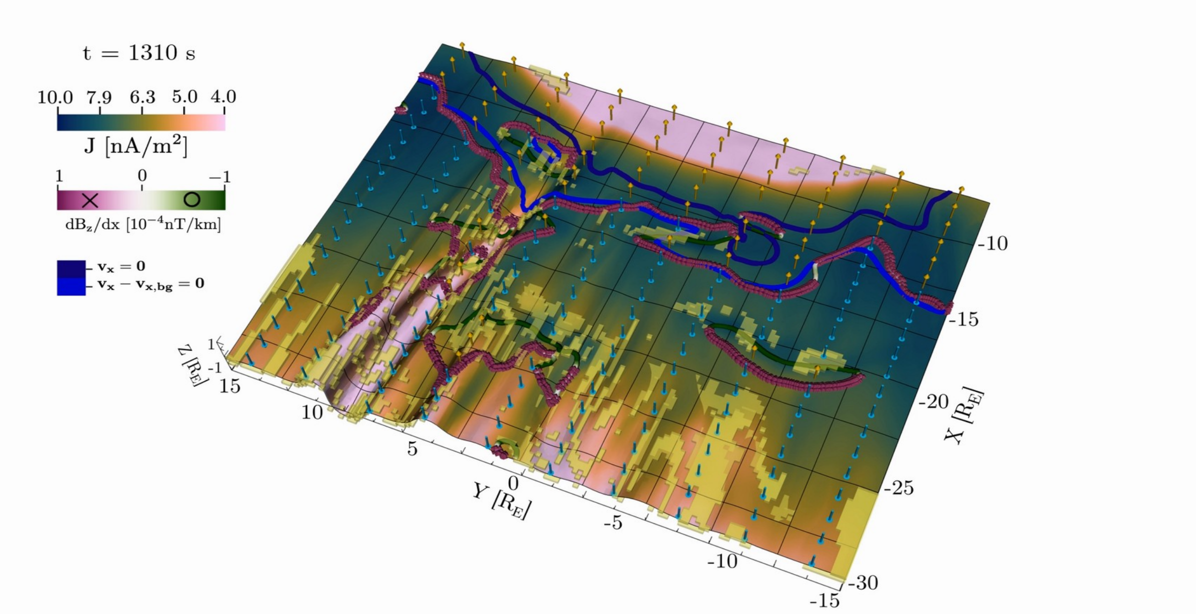


From Zhou et al., manuscript in prep

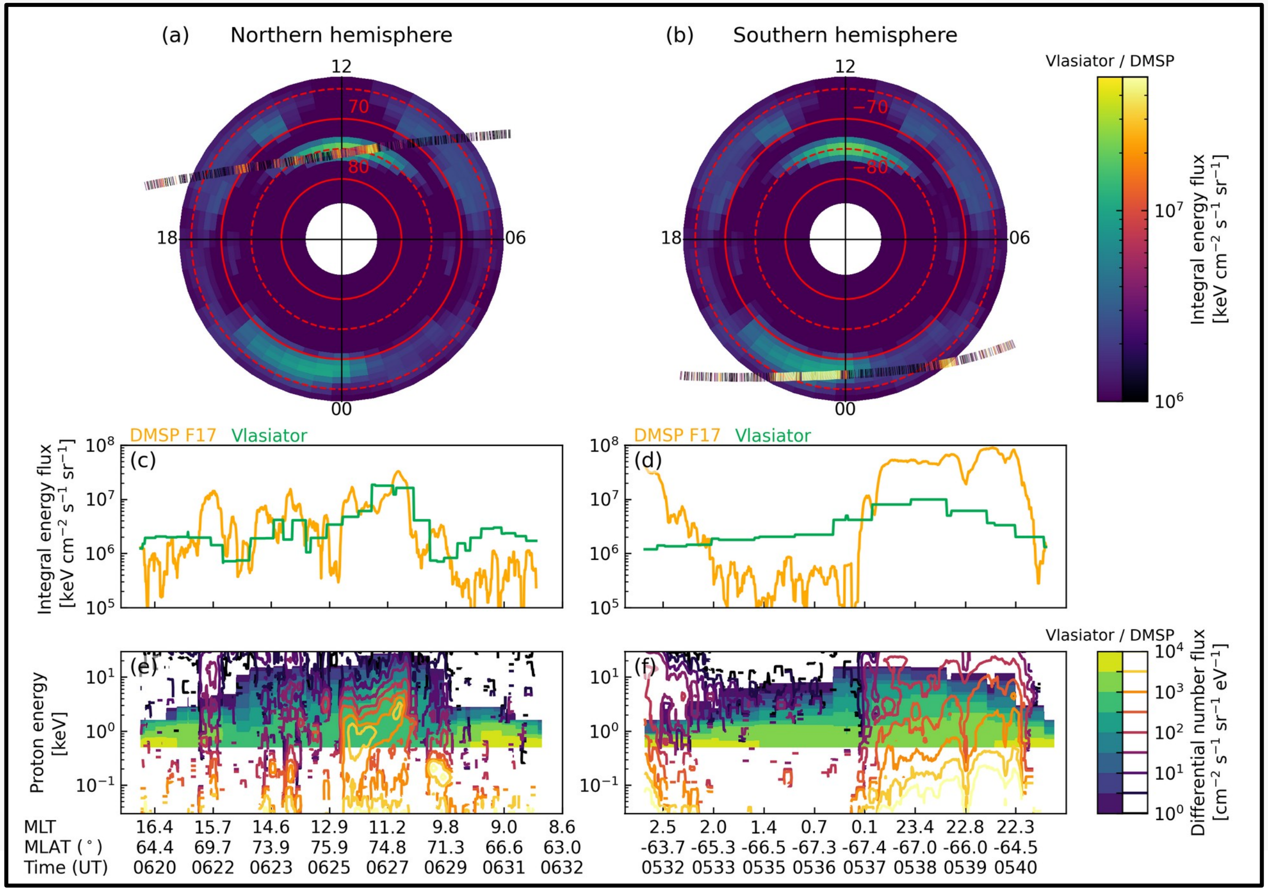
THE MAGNETOSPHERE IN 6 DIMENSIONS

THE MAGNETOTAIL DYNAMICS IS DRIVEN BY A COMPLEX INTERPLAY BETWEEN RECONNECTION, FLAPPING AND INSTABILITIES

Palmroth et al., manuscript under review



ION PRECIPITATING FLUXES SHOW GOOD AGREEMENT WITH DMSP MEASUREMENTS



Grandin et al., manuscript in preparation

CONCLUSIONS

Vlasiator enables studies of **ion kinetic processes in their global context** in near-Earth space, and allows for **direct comparison with observations**.

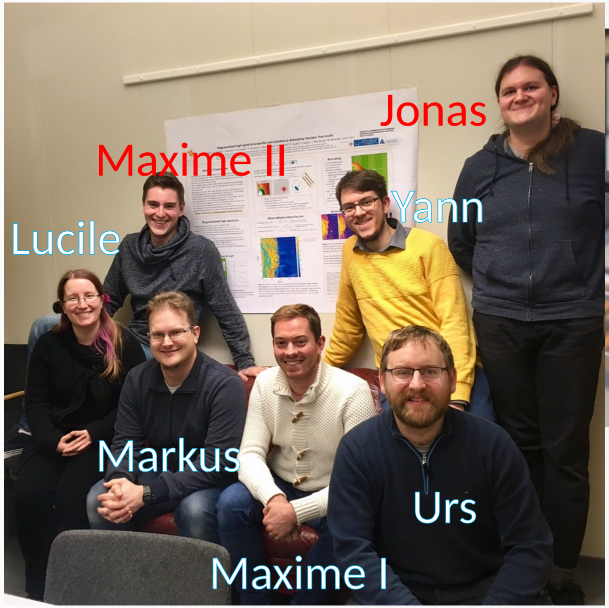
Most Vlasiator publications so far are presenting 5D simulations, but the first 6D runs have been carried out and their analysis is underway.

The first results, reveal a **complex interplay between reconnection and instabilities** in the magnetotail.

THE VLASIATOR MODEL IS CONTINUOUSLY IMPROVING THANKS TO THE EFFORTS OF THE DEVELOPMENT TEAM

Upcoming model developments:

- Addition of a more realistic ionosphere
- Adaptive mesh refinement in velocity space
- Dynamic adaptive mesh refinement



The Vlasiator code is **open-source** and **available on Github**

https://github.com/fmihpc/vlasiator

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