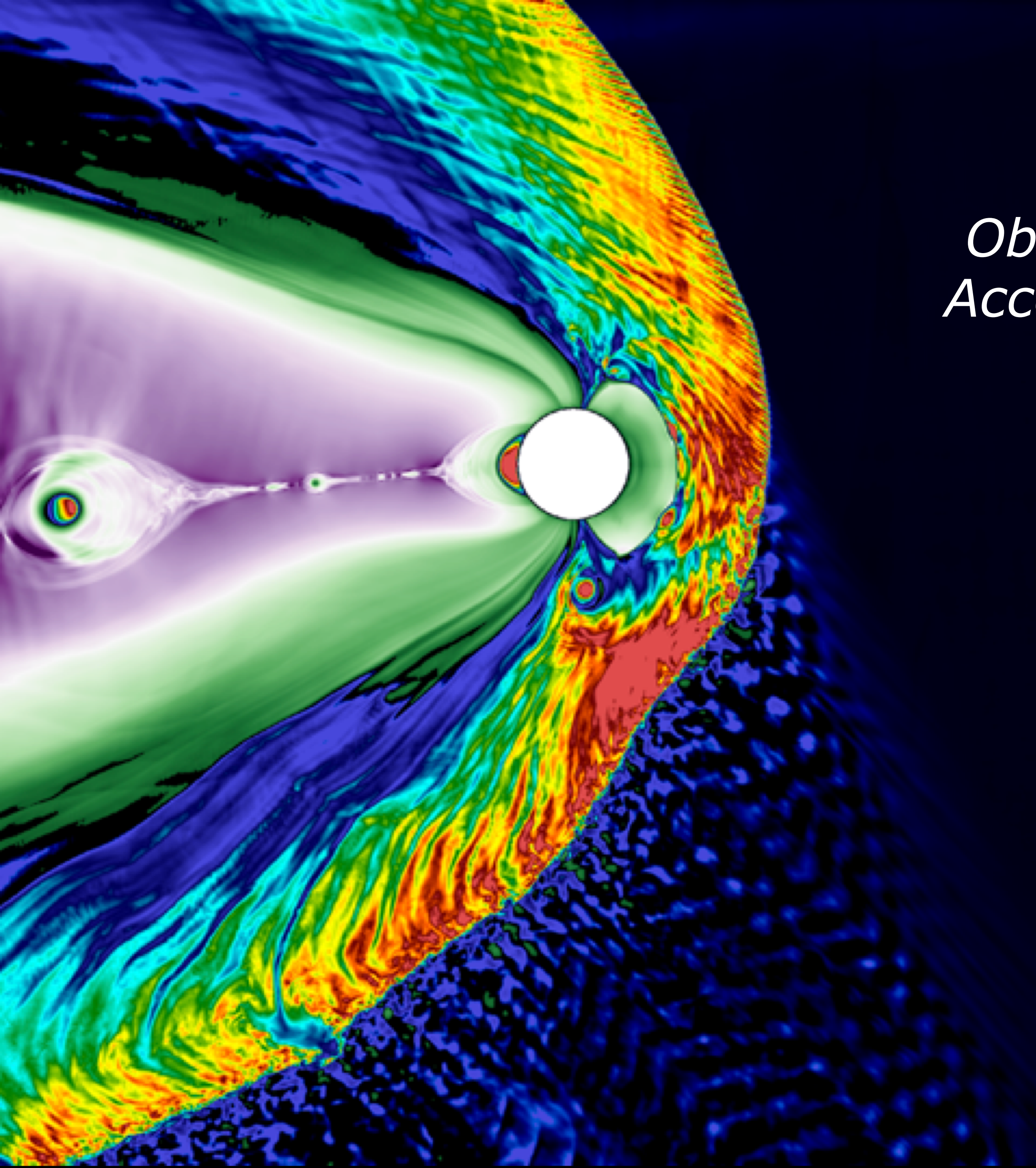


Observations and Simulations of Ion Acceleration at the Earth's Bow Shock

Andreas Johlander

University of Helsinki

Battarbee, M., Pfau-Kempf, Y., Turc, L., Ganse, U., Brito, T., Grandin, M., Dubart, M., Vaivads, A., Khotyaintsev, Yu V., Caprioli, D., Haggerty C., Schwartz, S. J., Palmroth, M., et al.

VLASIATOR

MMS MAGNETOSPHERIC MULTISCALE NASA GODDARD SPACE FLIGHT CENTER SWRI

UNIVERSITY OF HELSINKI FACULTY OF SCIENCE

European Research Council Established by the European Commission

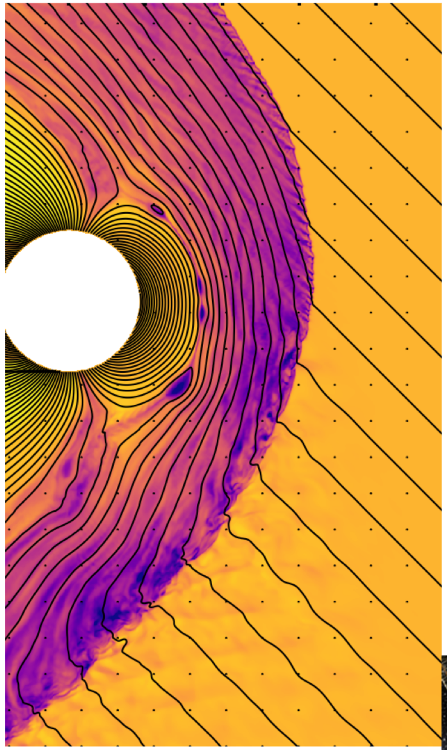
Connecting Micro and Macro Scales: Acceleration, Reconnection, and Dissipation in Astrophysical Plasmas

KITP, Santa Barbara, 2019-09-12

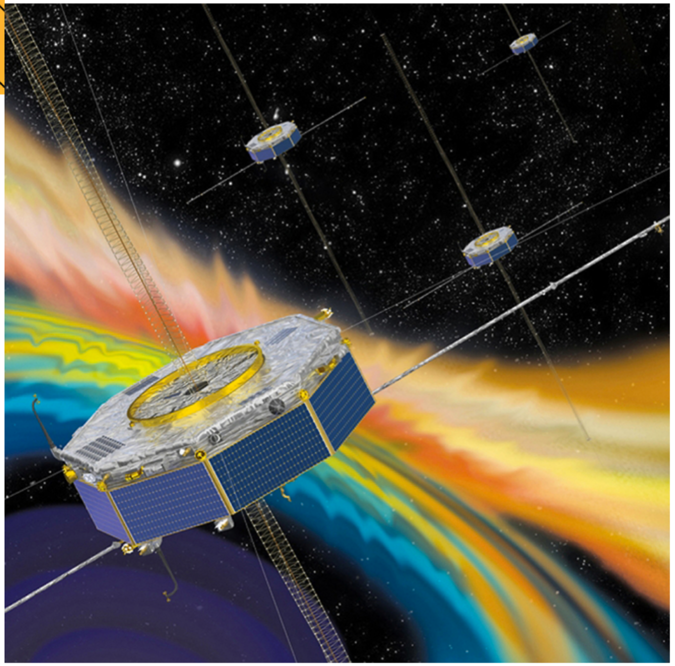
Outline

- Introduction to the Vlasiator code
  - Science being done using Vlasiator
- Ion acceleration at the bow shock
  - Observations by MMS
  - As seen in Vlasiator

Vlasiator



Magnetospheric Multiscale (MMS)



- Ions are represented as a distribution function and follows Vlasov's eq.

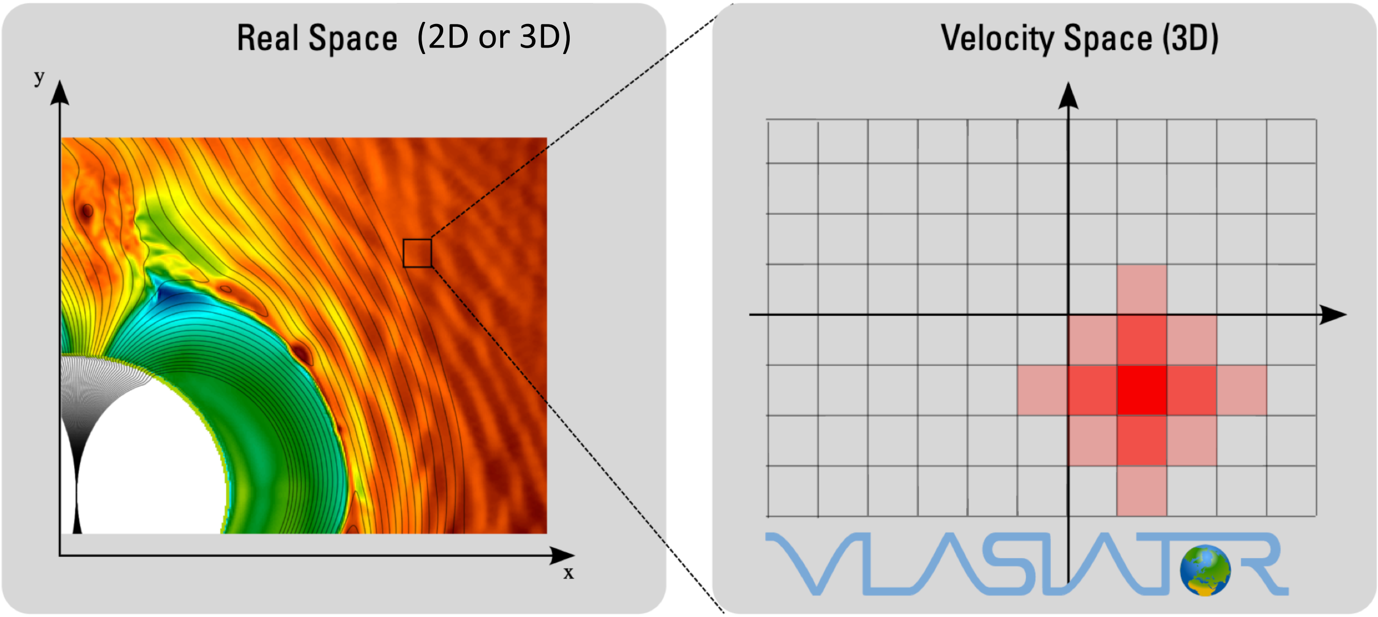
$$\frac{\partial}{\partial t}f(\mathbf{r},\mathbf{v},t) + \mathbf{v}\cdot\nabla_r f(\mathbf{r},\mathbf{v},t) + \mathbf{a}\cdot\nabla_v f(\mathbf{r},\mathbf{v},t) = 0$$

- Maxwell's equations

- Electrons are treated as a cold, neutralizing fluid

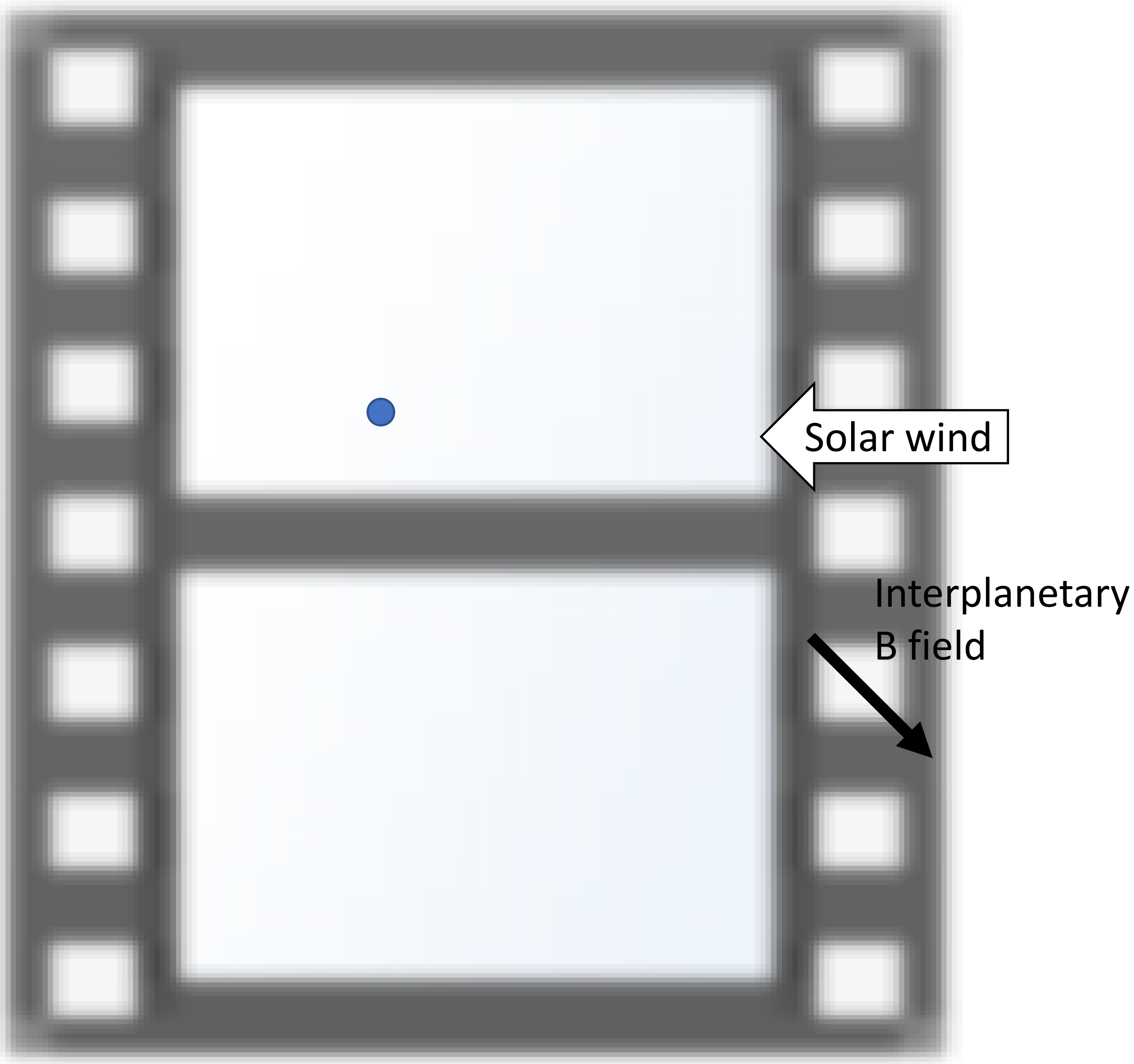
- The electric field is closed by Ohm's law

$$\mathbf{E} = -\mathbf{V}_i\times\mathbf{B} + \frac{1}{en_i}\mathbf{j}\times\mathbf{B}$$



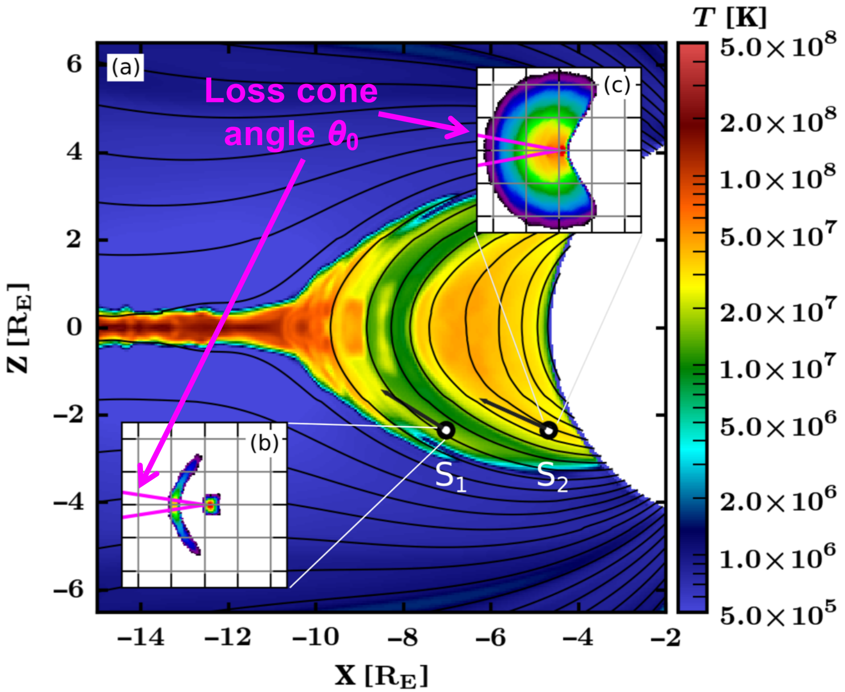
2D global simulation

$$\Delta x = 220 \text{ km}$$
$$\Delta v = 30 \text{ km/s}$$

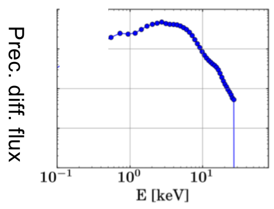


Ongoing science with Vlasiator

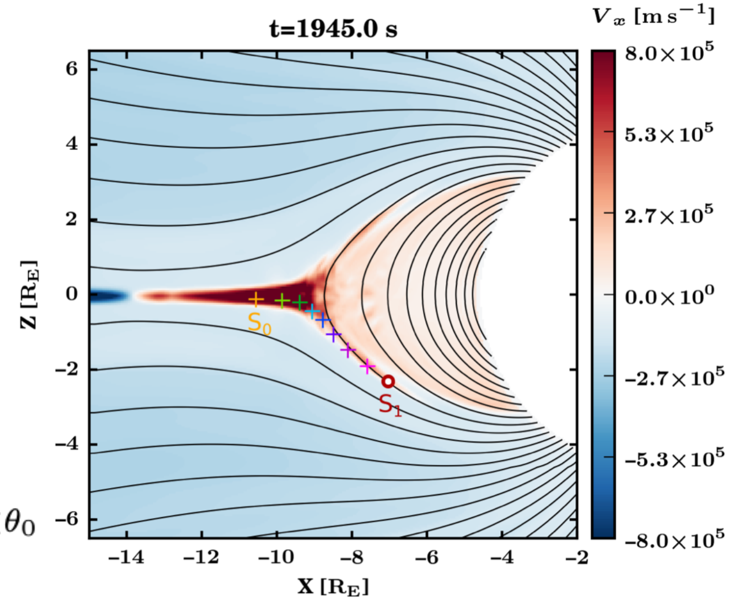
Nightside auroral proton precipitation in Vlasiator



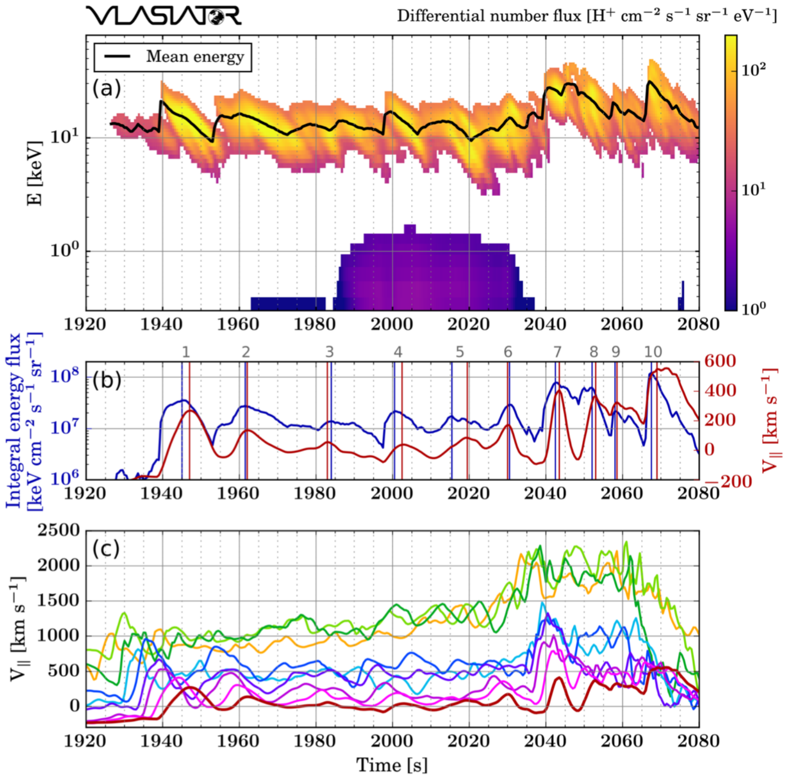
At locations $\mathbf{r}_0$ where the full VDFs are saved, the **precipitating proton differential flux** can be evaluated as a function of energy $E = m_p v^2/2$ by

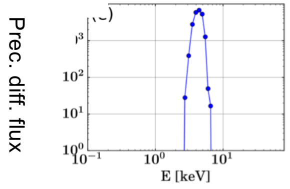


$$\mathcal{J}(E, \mathbf{r}_0) = \frac{v^2}{m_p} \langle f(\mathbf{r}_0, v, \theta, \varphi) \rangle_{\theta < \theta_0}$$



- During active tail reconnection, virtual spacecraft S1 observes short-lived bursts of precipitation
- Integral energy flux of precipitation correlates well with parallel plasma velocity (available everywhere contrary to VDFs)
- Parallel velocity bursts cannot always be traced back to current sheet, suggesting that the transition region can regulate precipitation bursts

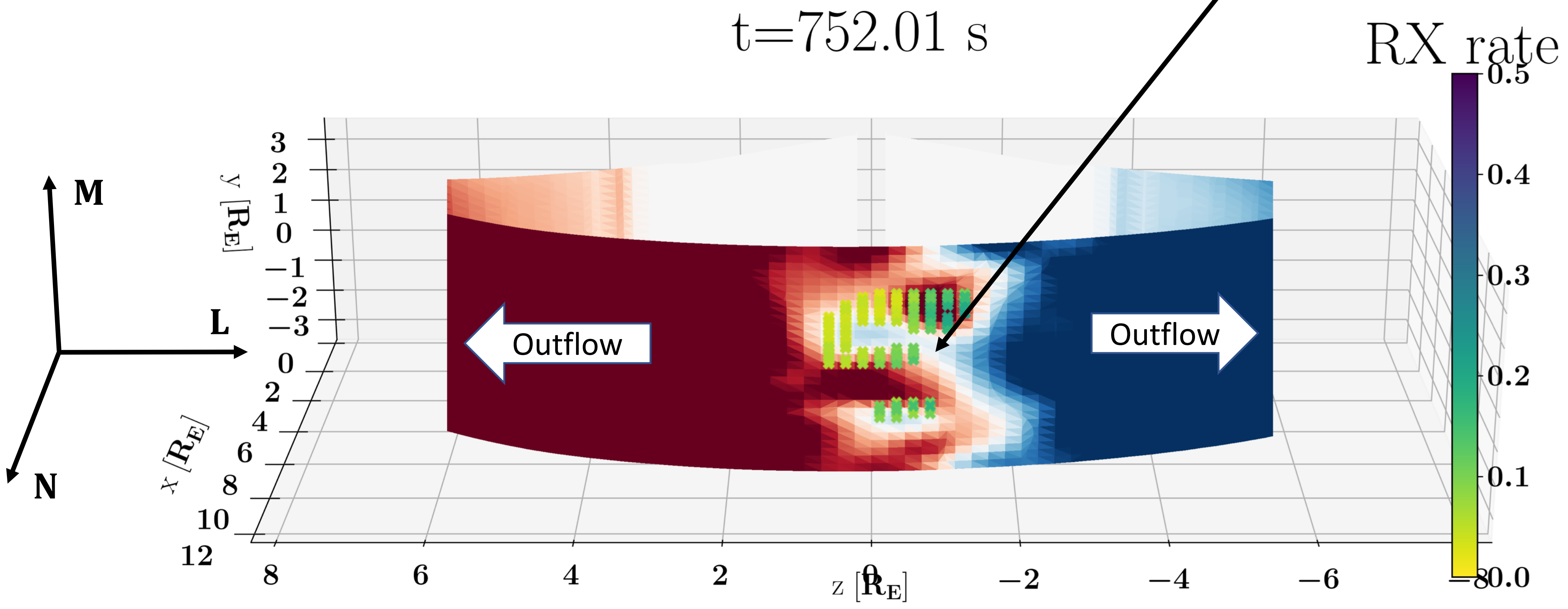




Accepted paper: Grandin et al. (2019), Hybrid-Vlasov modelling of nightside auroral proton precipitation during southward interplanetary magnetic field conditions, *Annales Geophysicae*, https://doi.org/10.5194/angeo-2019-59.

Dayside reconnection in 2.9D

When extended into the 3rd dimension, the reconnection line curves and becomes unsteady

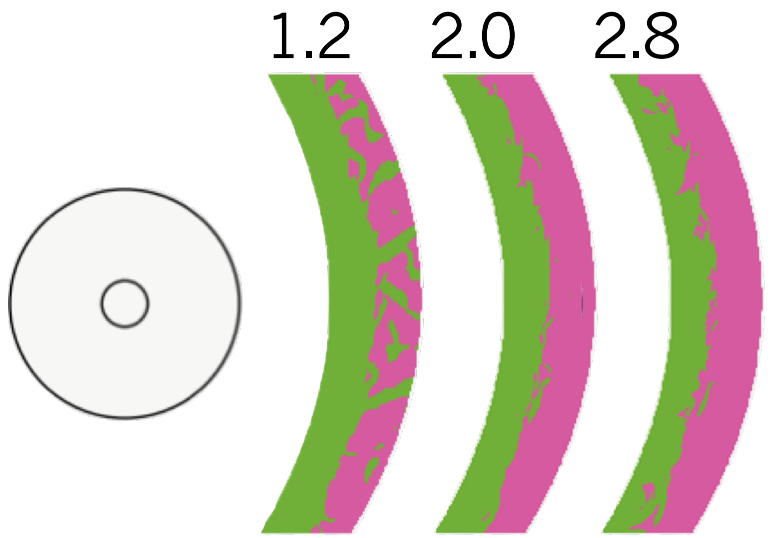


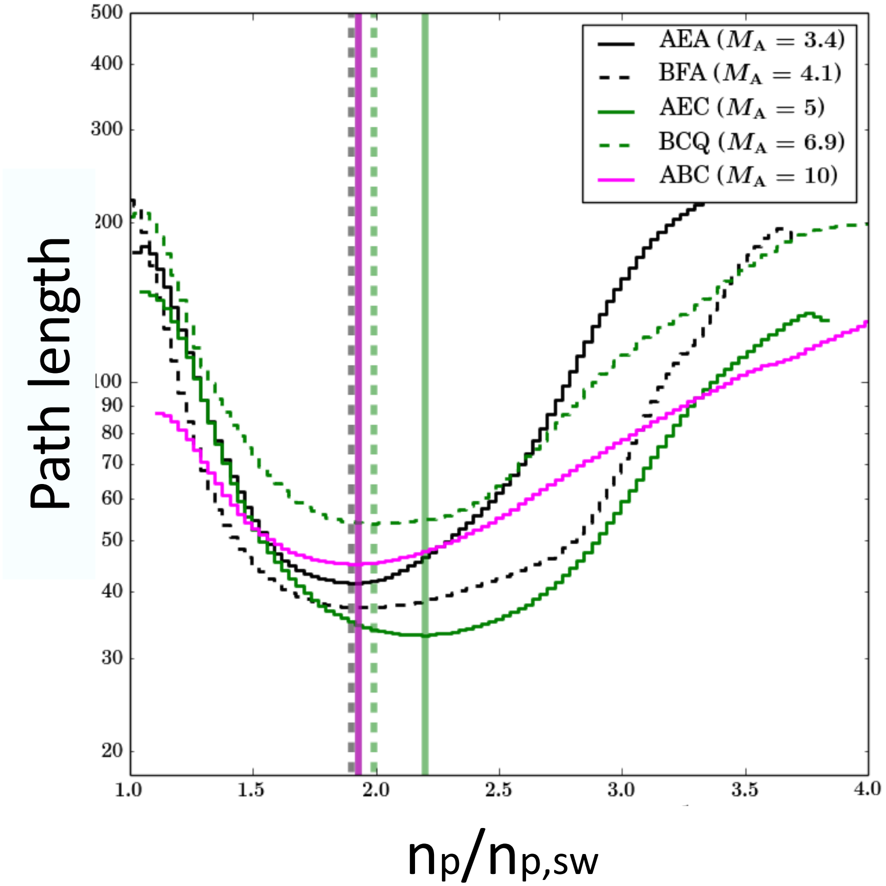
(Phau-Kempf et al., *in prep*)

Bow shock structure

Hypothesis: A good metric for where the bow shock is will *minimize the path length* of the contour delineating the upstream and the downstream.

Examples of quasi-parallel shock contour with different required compression ratios $n_p/n_{p,sw}$



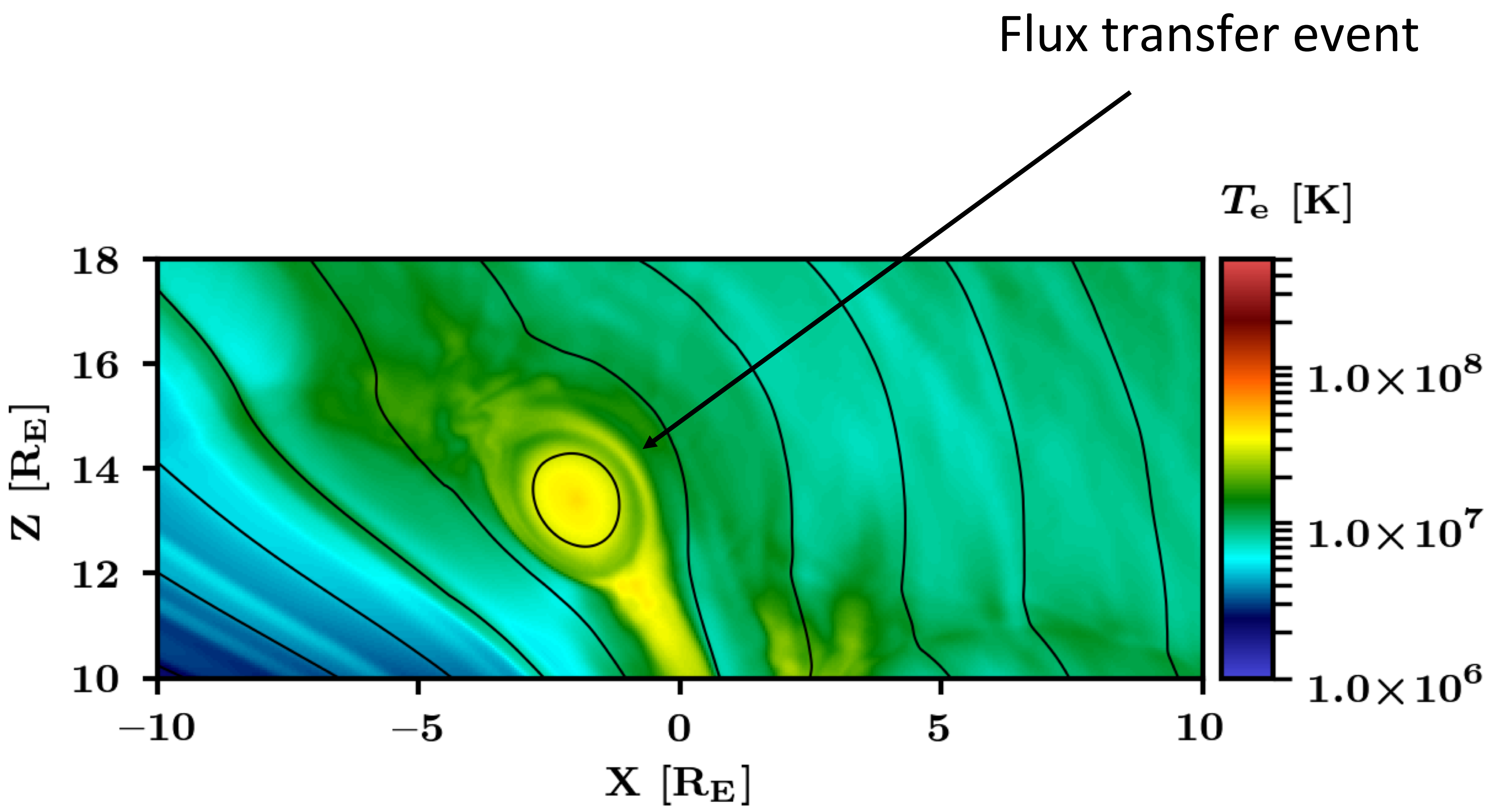


Statistically averaged path lengths minimize!

(Battarbee et al, in prep.)

Adding electrons to Vlasiator

- Goal: understand the evolution of the electron distribution functions with the Vlasov simulation
- Simulations can be done both globally and locally
- Challenges: resolve small spatial-temporal scales and capture high velocity regions of VDF



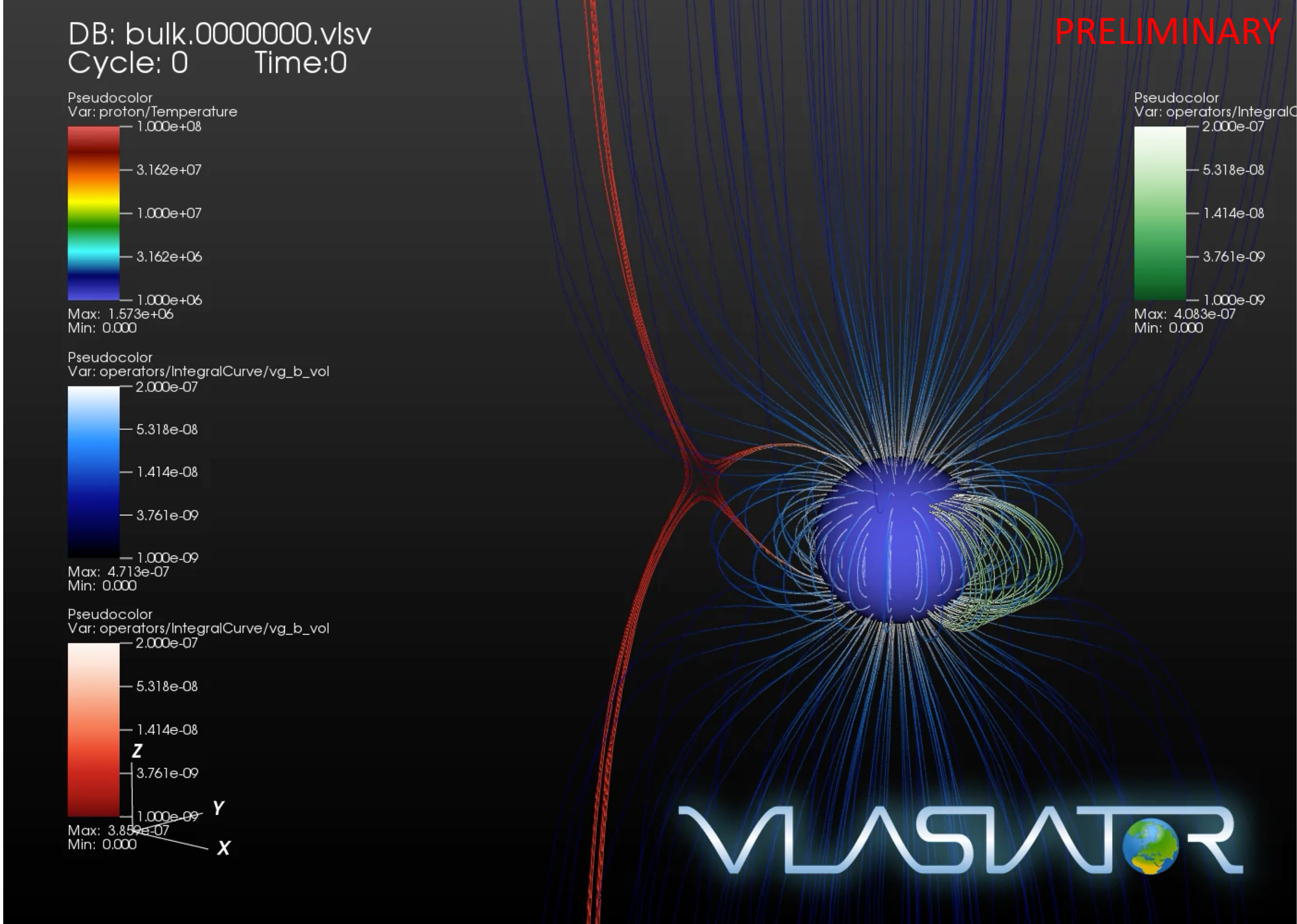
(Brito et al., *in prep.*)

3D simulation of the magnetosphere and solar wind

Southward IMF

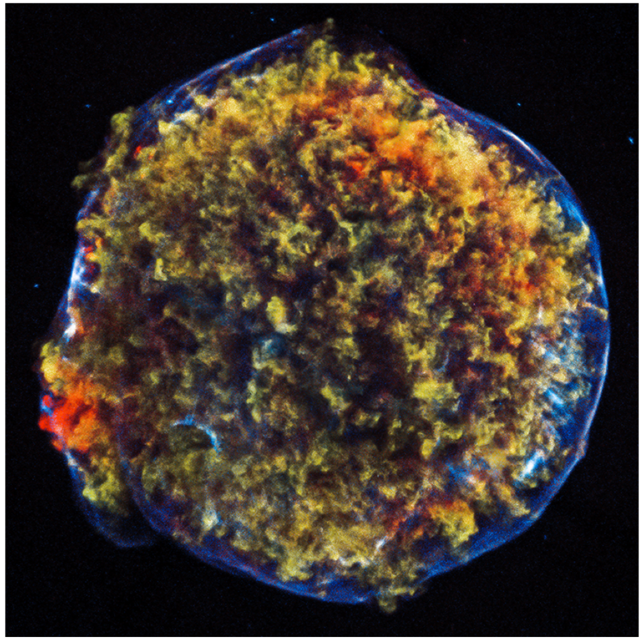
Adaptive mesh refinement in 4 levels

Smallest resolution: 2250 km



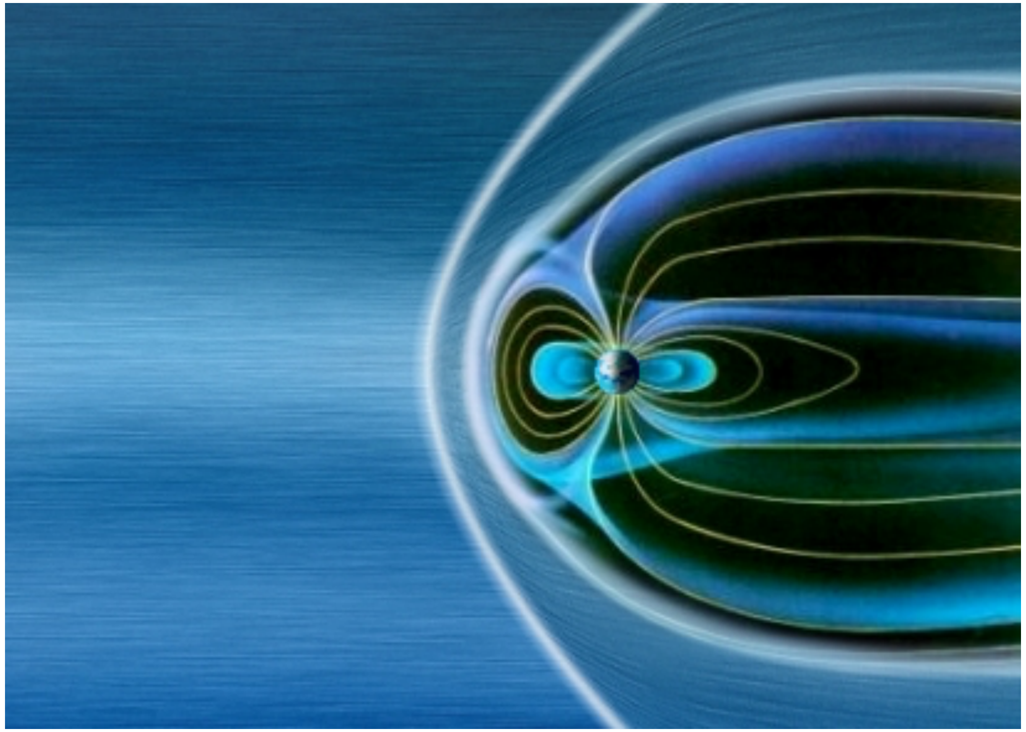
Collisionless shock waves

Supernova remnant shock



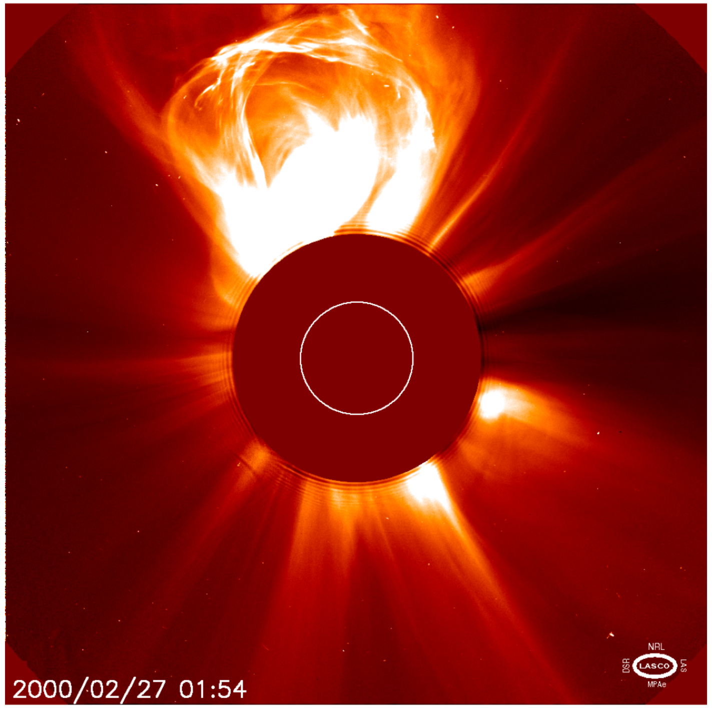
NASA/CXC/SAO

Planetary bow shocks



ESA

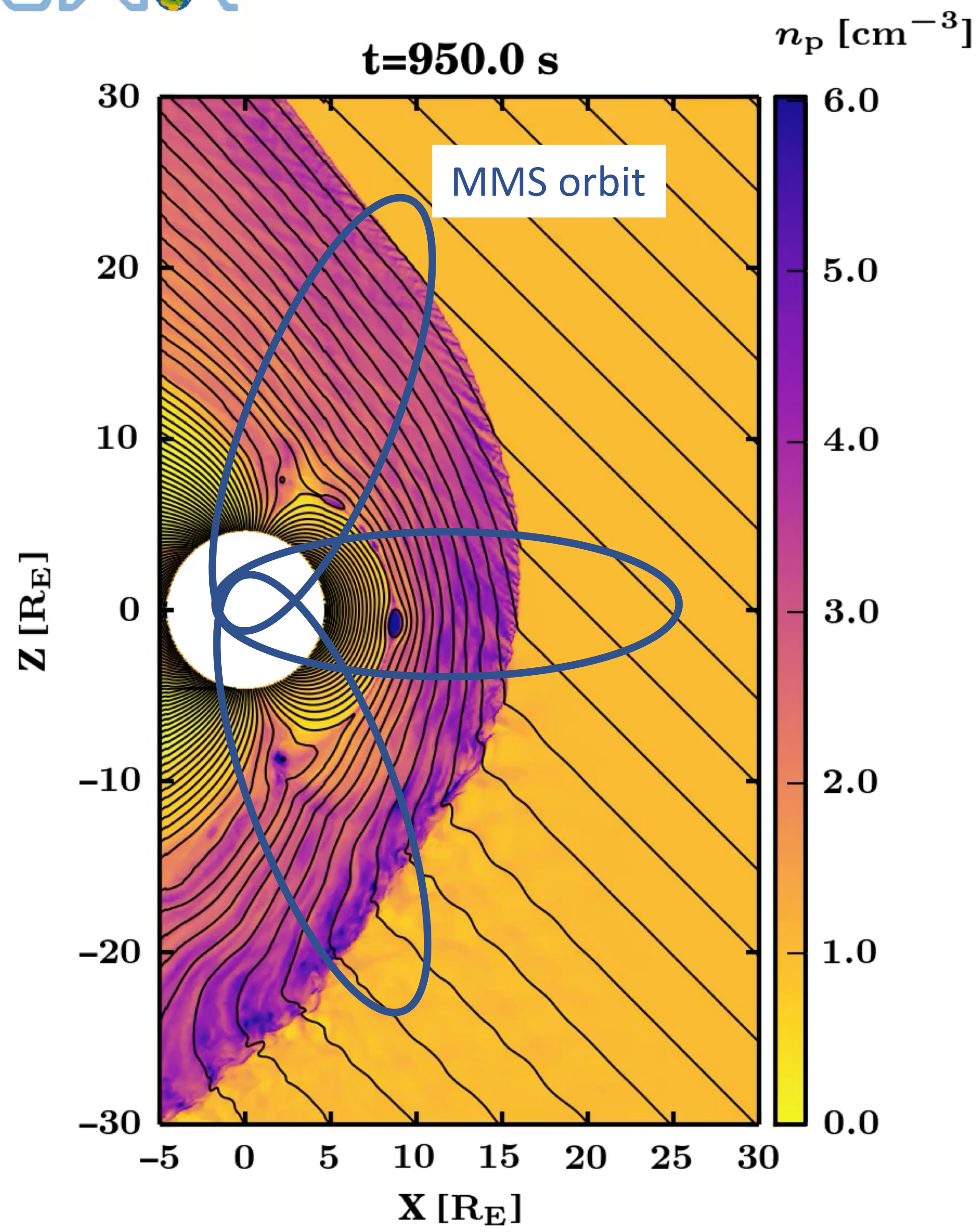
Interplanetary shock waves



NASA

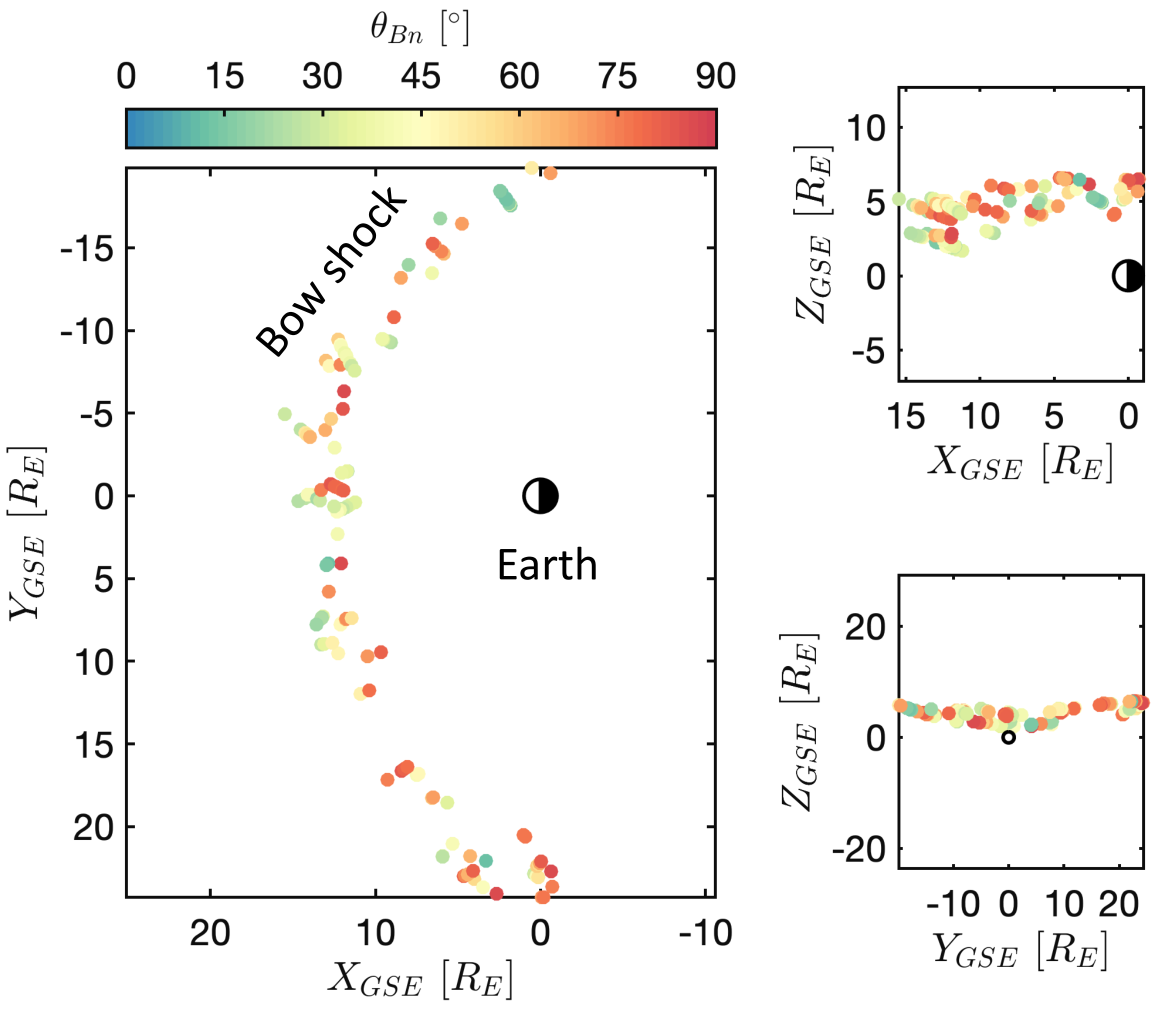
Earth's bow shock

- Shocks can be very efficient ion accelerators, e.g. **galactic cosmic ray**
- **The Earth's bow shock is the best collisionless shock laboratory for in situ studies**
- But the bow shock is relatively **weak, small, and short lived**
- Goal: compare ion acceleration efficiency with MMS and Vlasiator to SNR shock simulations by **(Caprioli & Spitkovsky, 2014, ApJ)**

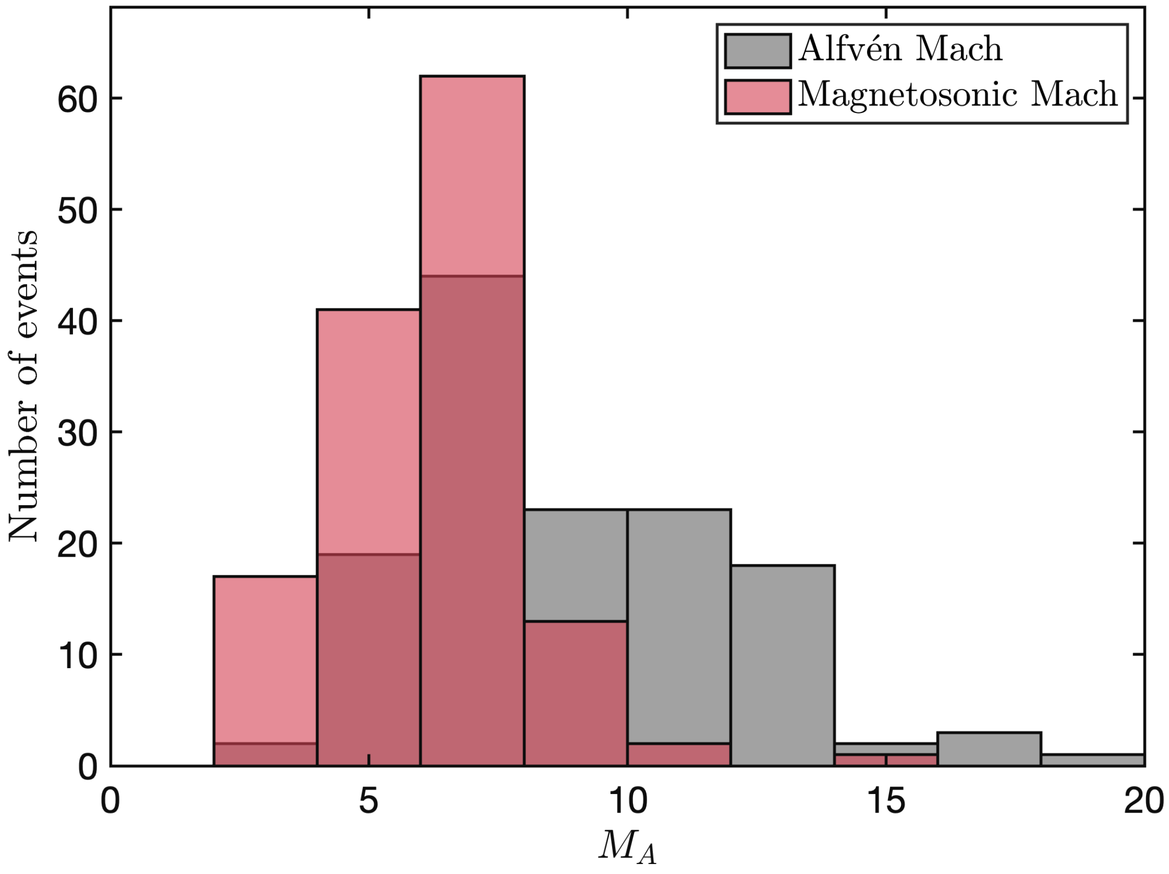


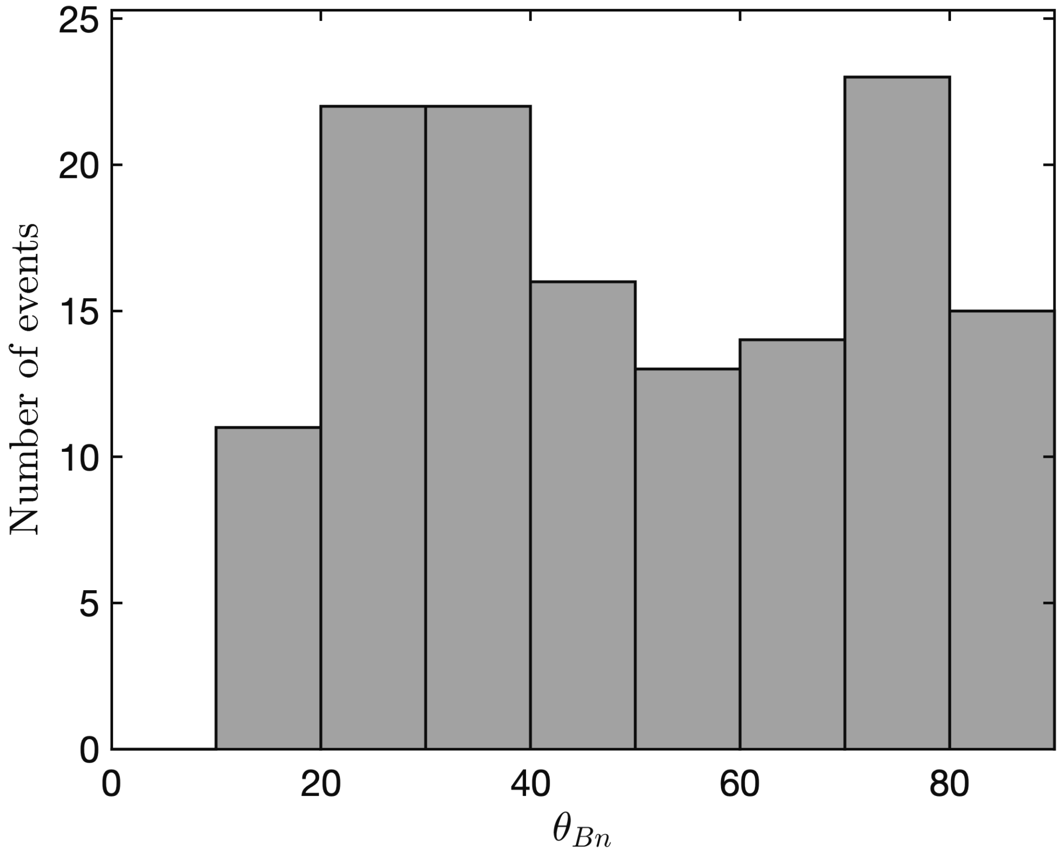
Bow shock observations

- Selected **136 bow shock crossings** by MMS
- Shock parameters determined by another spacecraft far upstream
- Goal is to study ion distributions measured just downstream of the shock

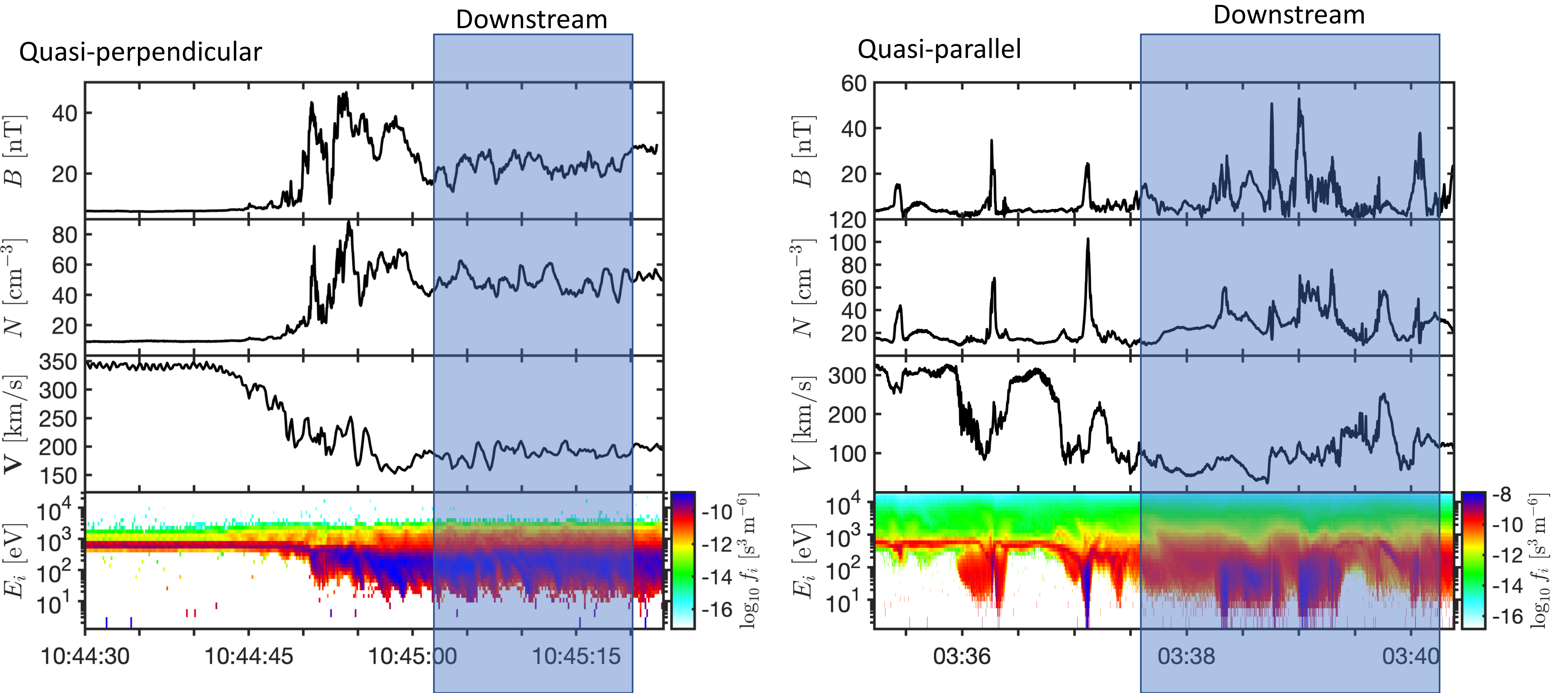


Bow shock observations

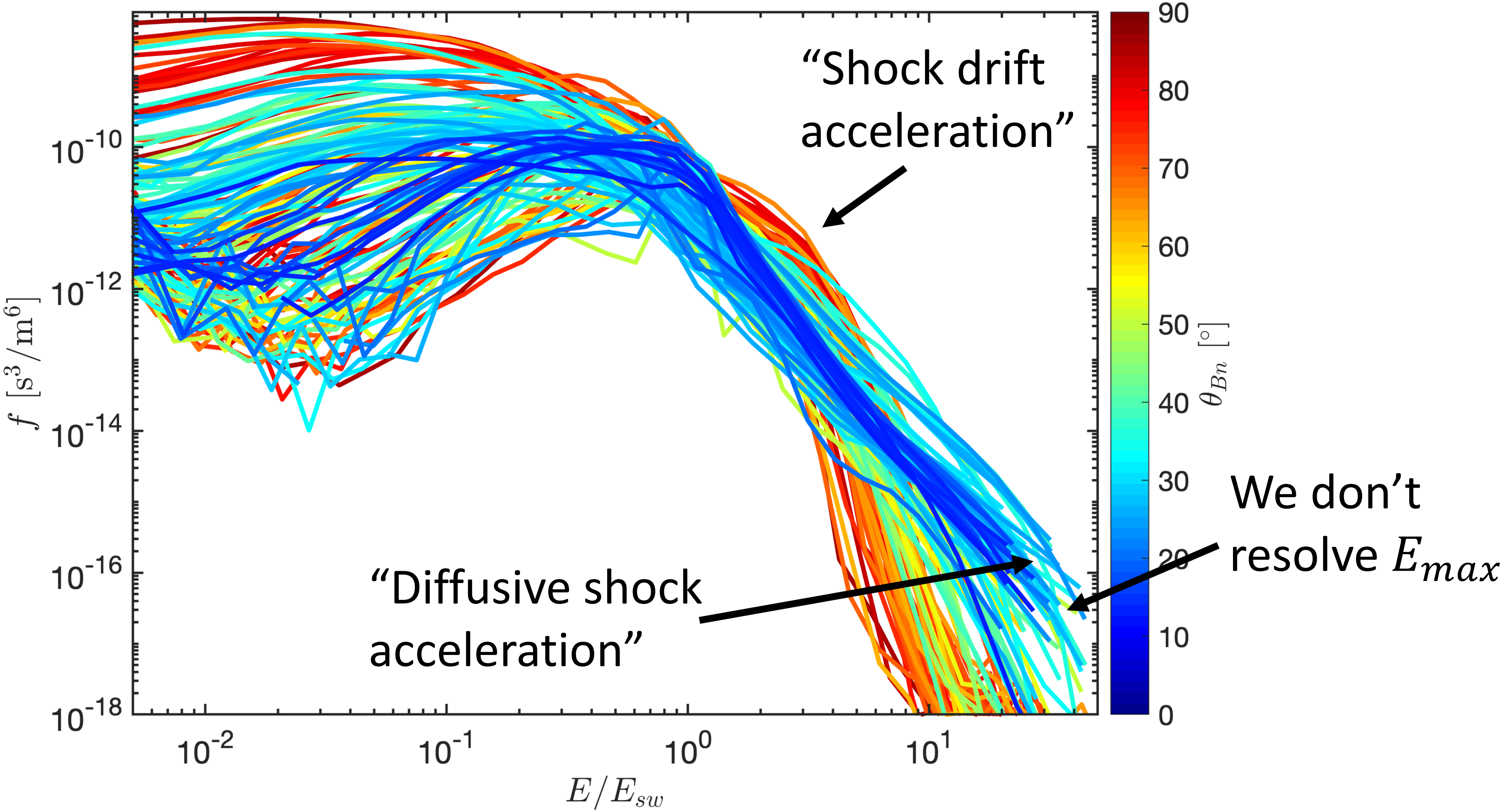




Example MMS shock crossings

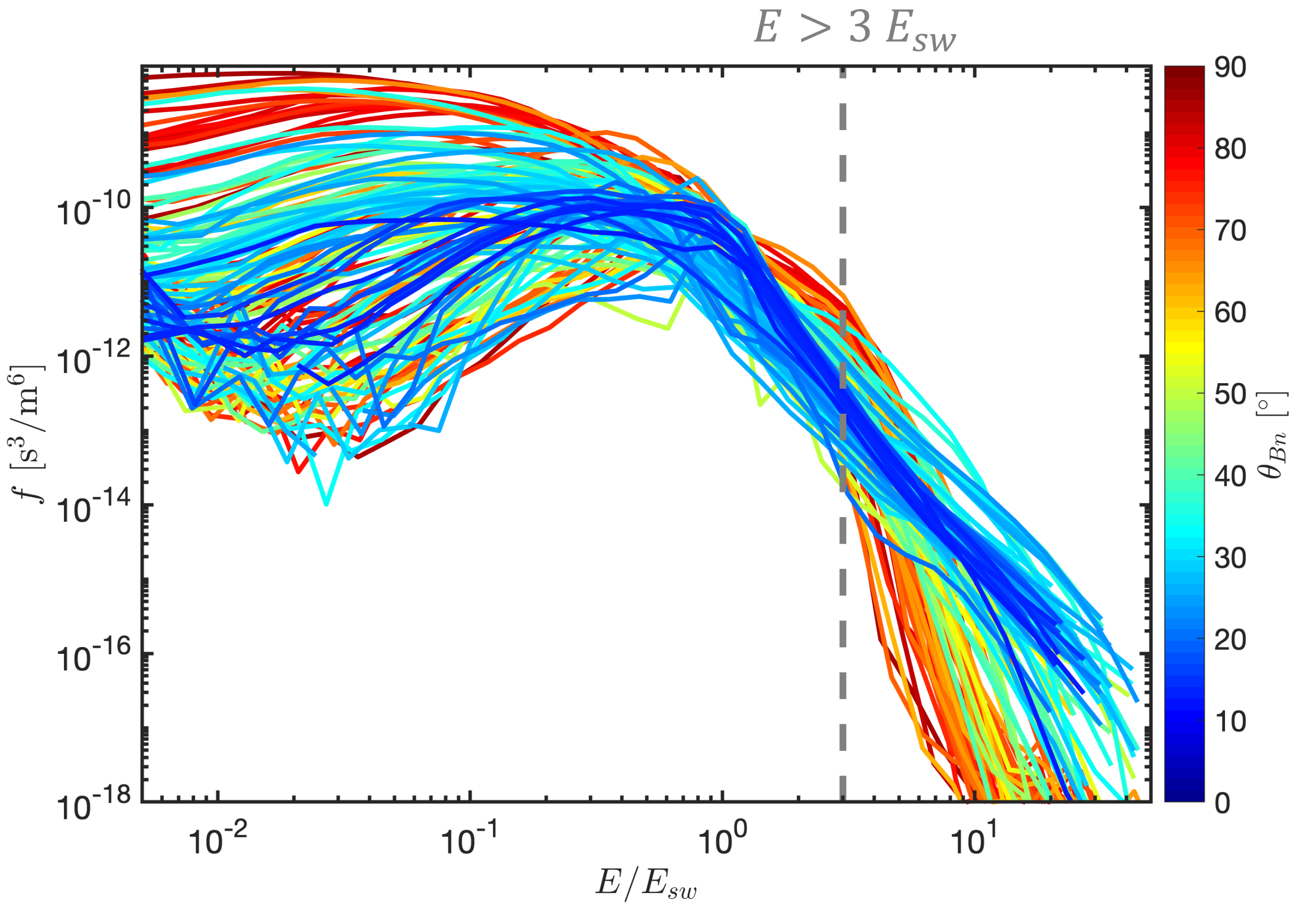


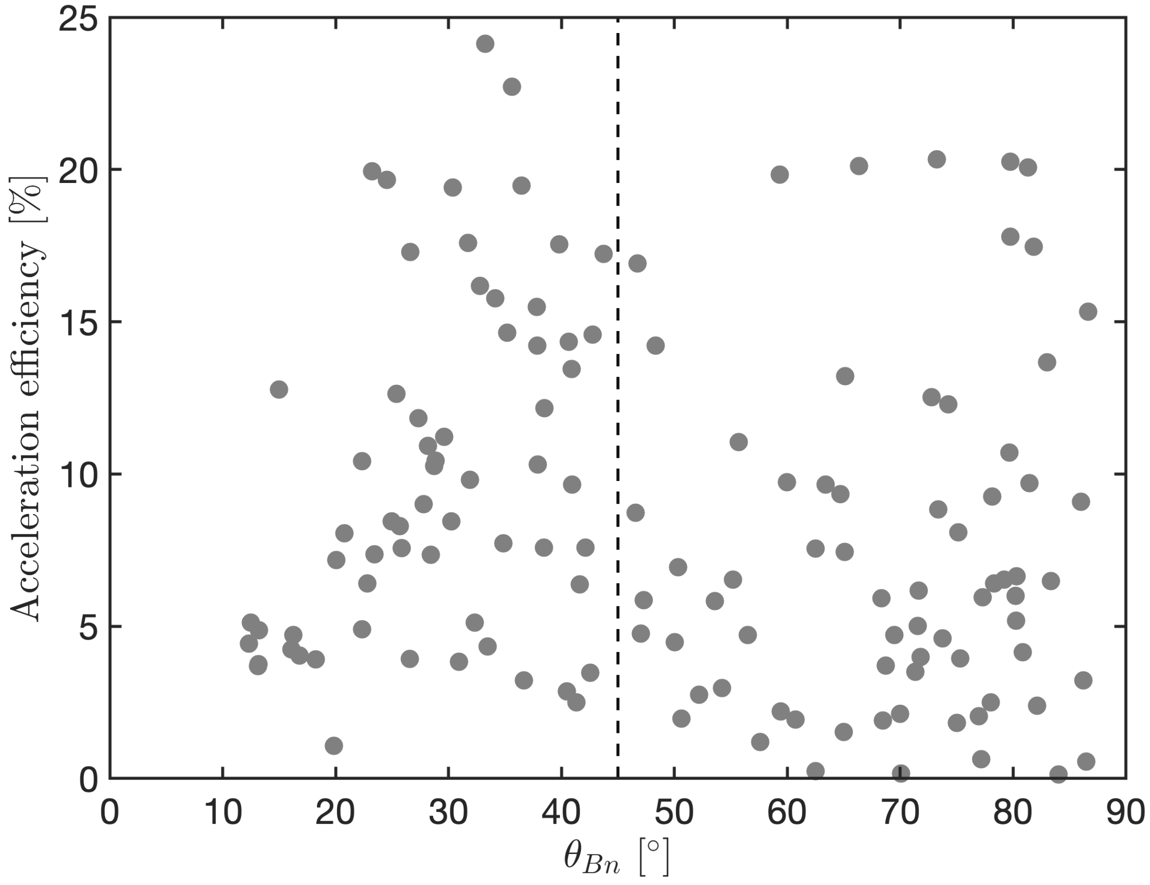
All downstream ion distributions



Acceleration efficiency

Defined as: $\frac{\text{Energy density above threshold}}{\text{Total energy density}} = \frac{U_{E>E_{thr}}}{U_0}$





Acceleration efficiency

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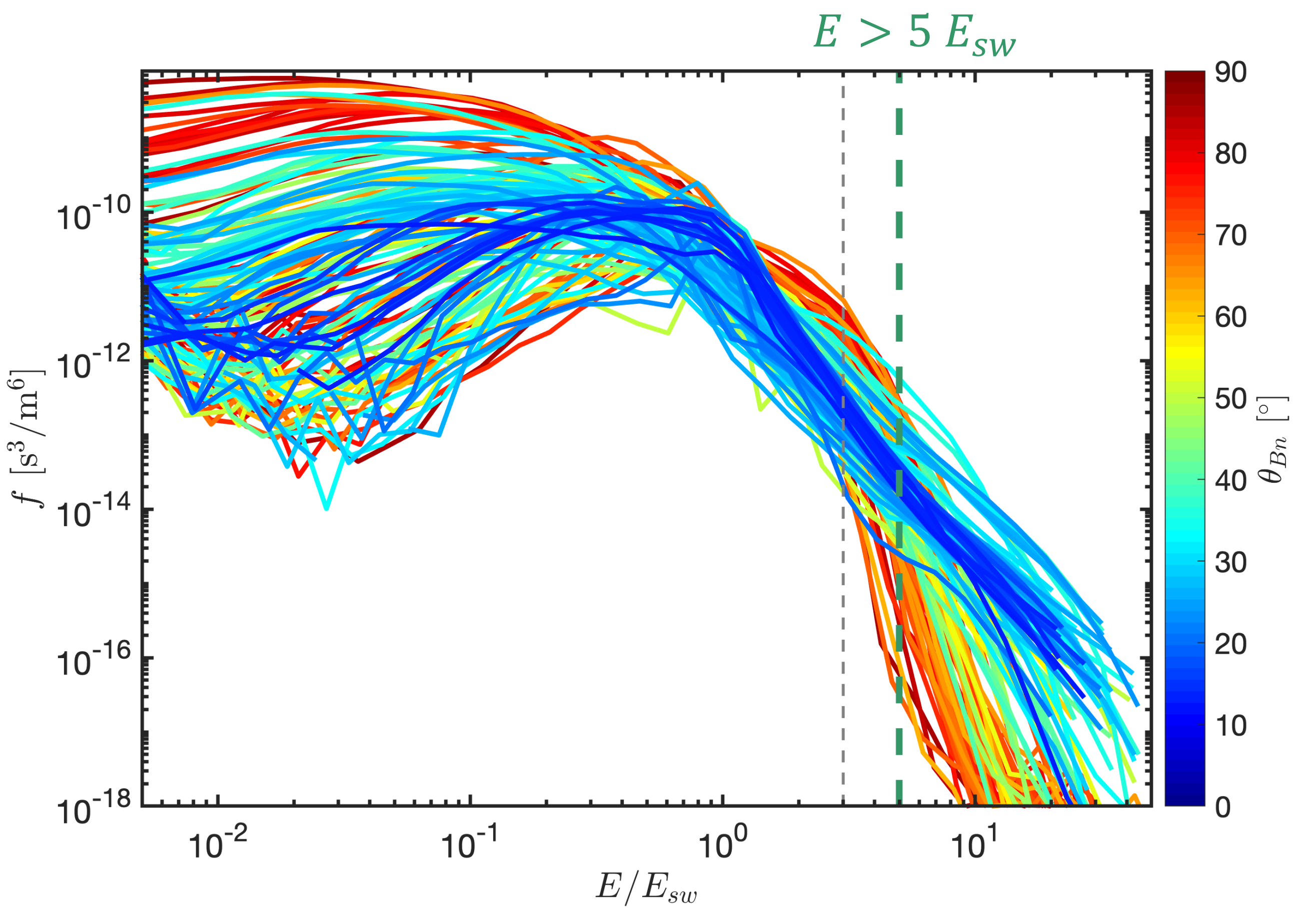
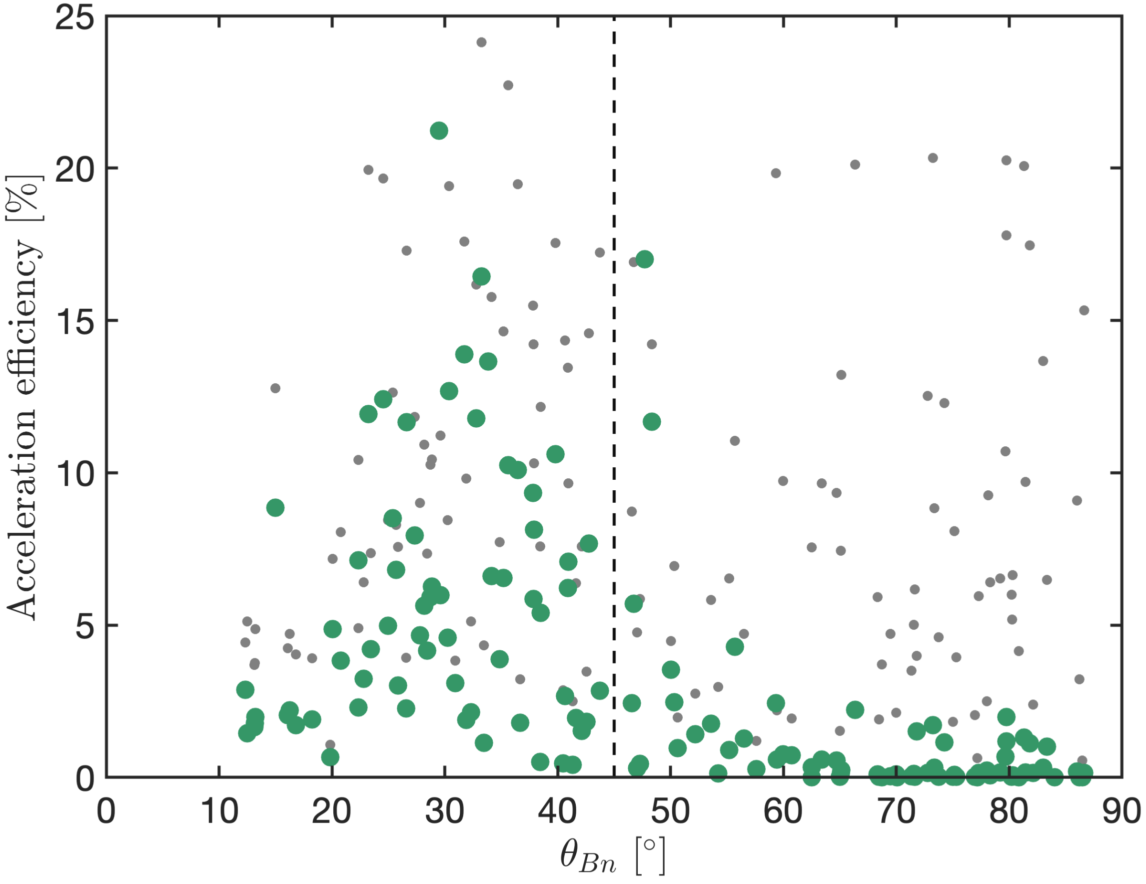
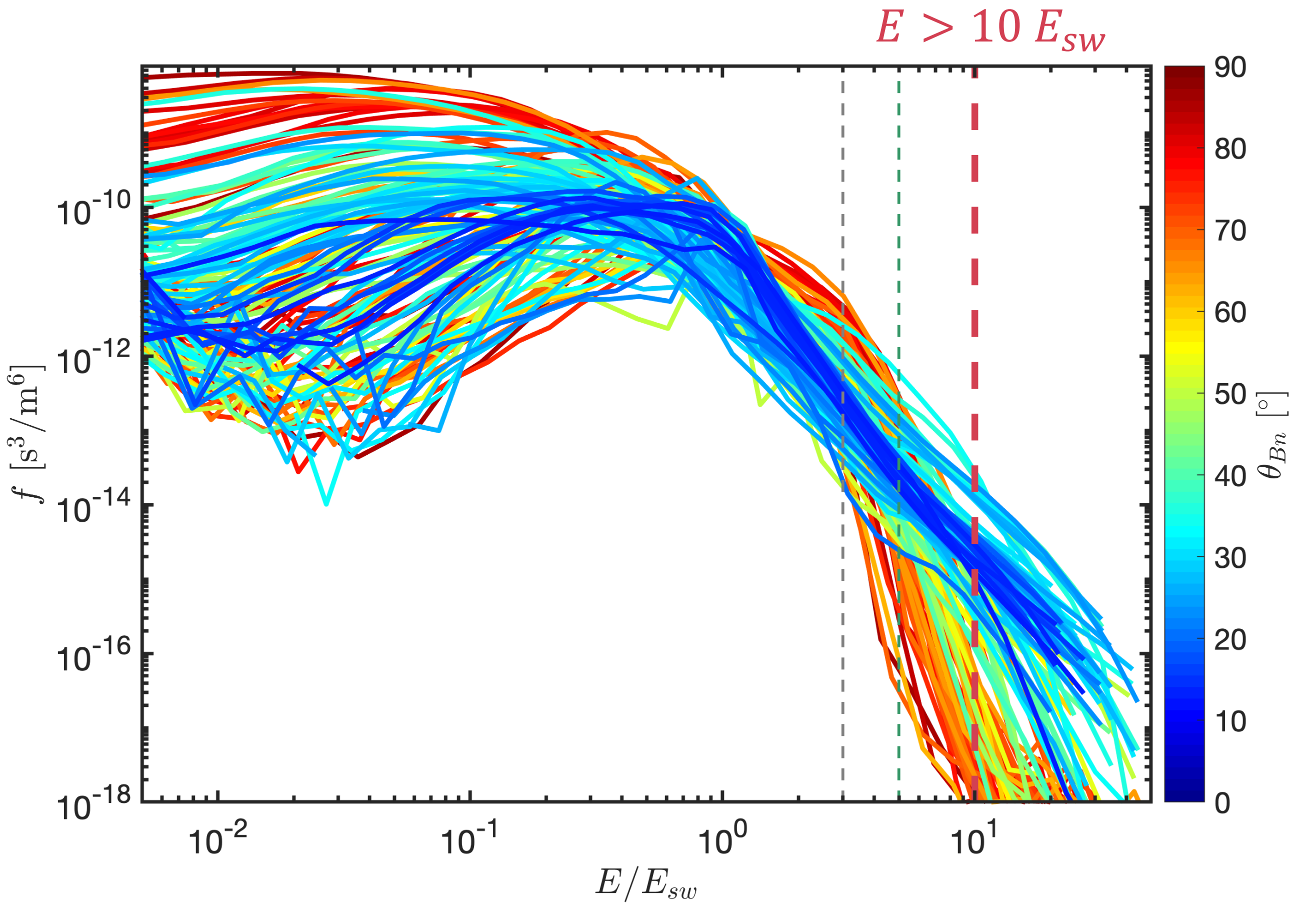
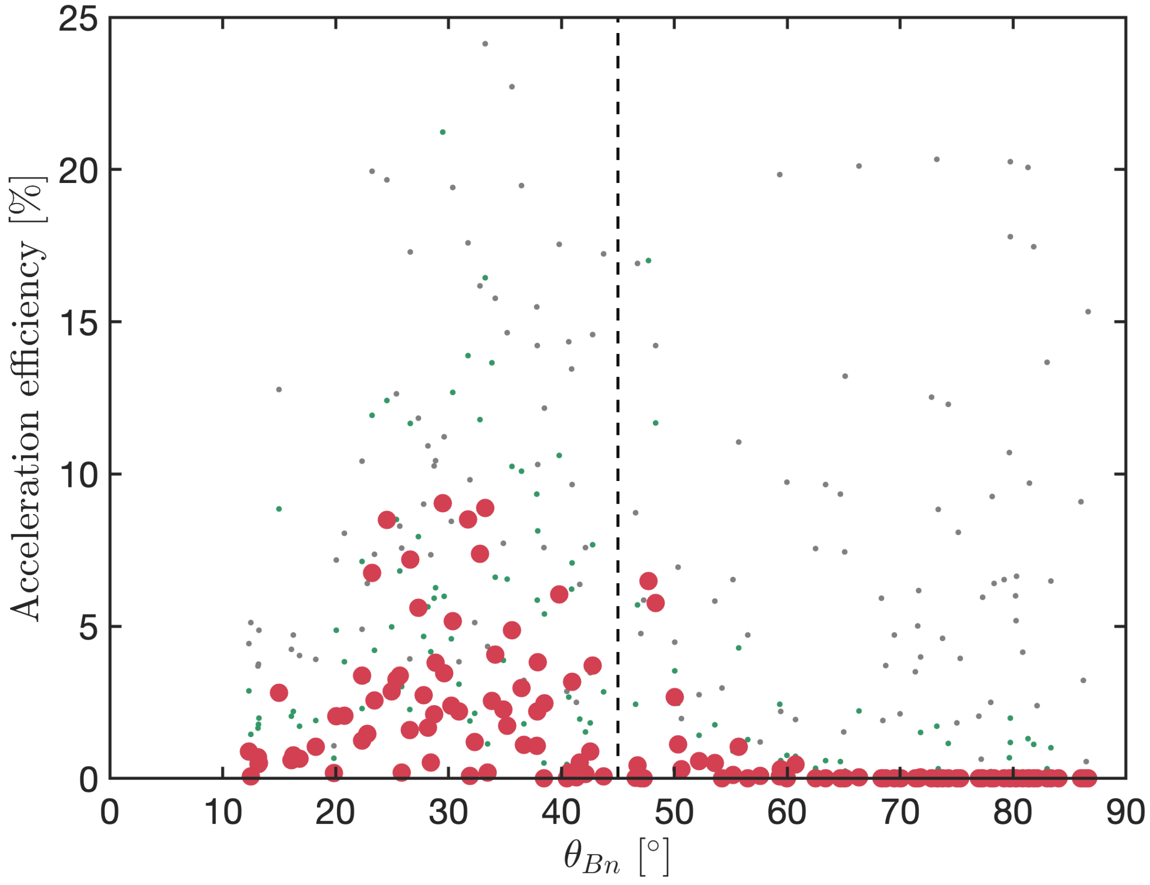




Acceleration efficiency

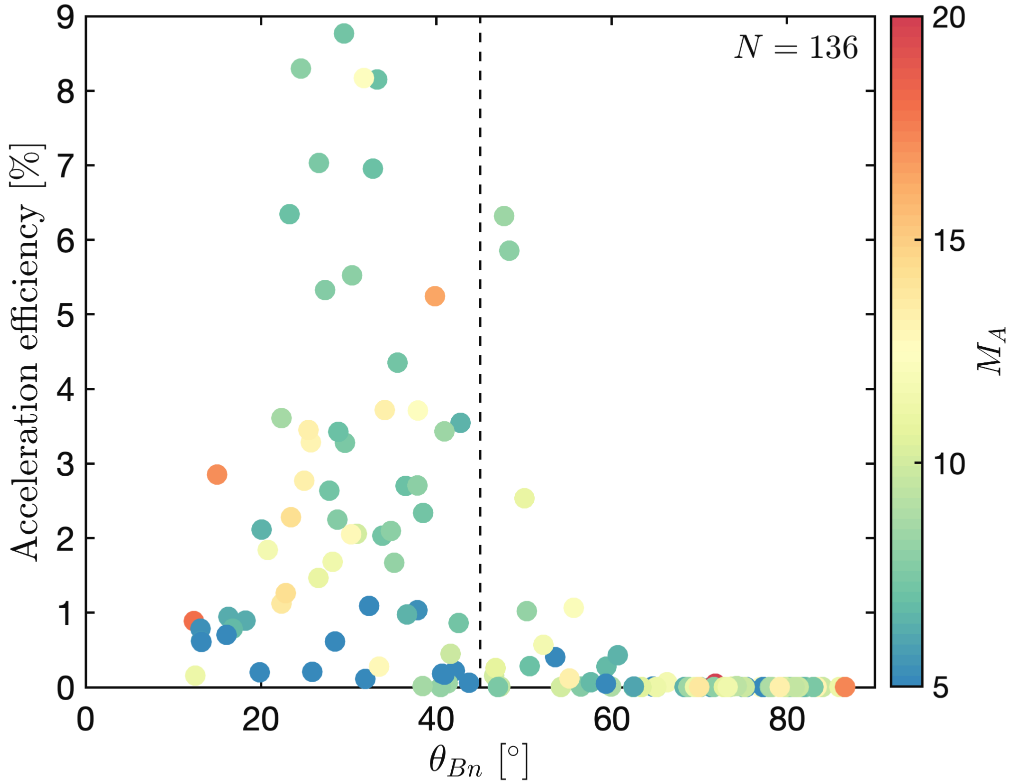
Defined as: $\frac{\text{Energy density above threshold}}{\text{Total energy density}} = \frac{U_{E>E_{thr}}}{U_0}$

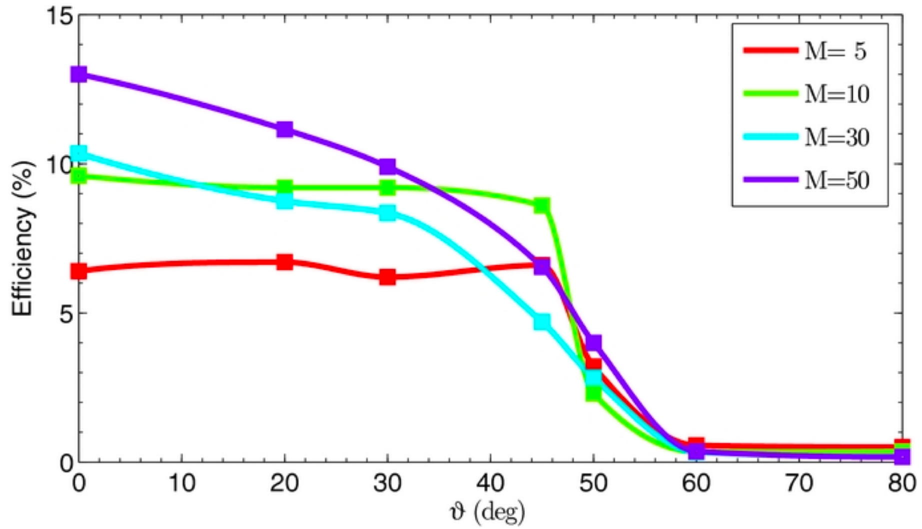




Results

- Shock angle and Mach number are important for ion acceleration
- The acceleration efficiency at the bow shock is similar to simulations of larger shocks

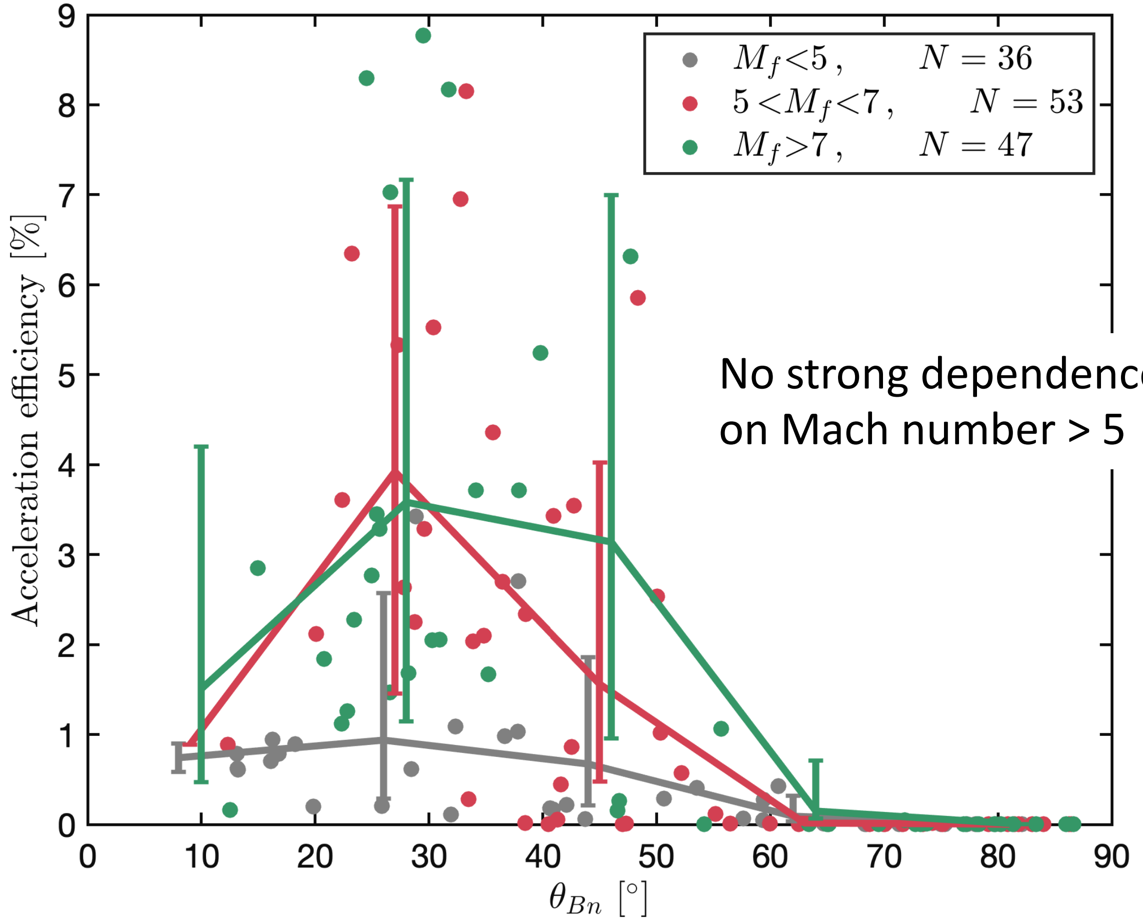




(Caprioli & Spitkovsky, 2014, ApJ)

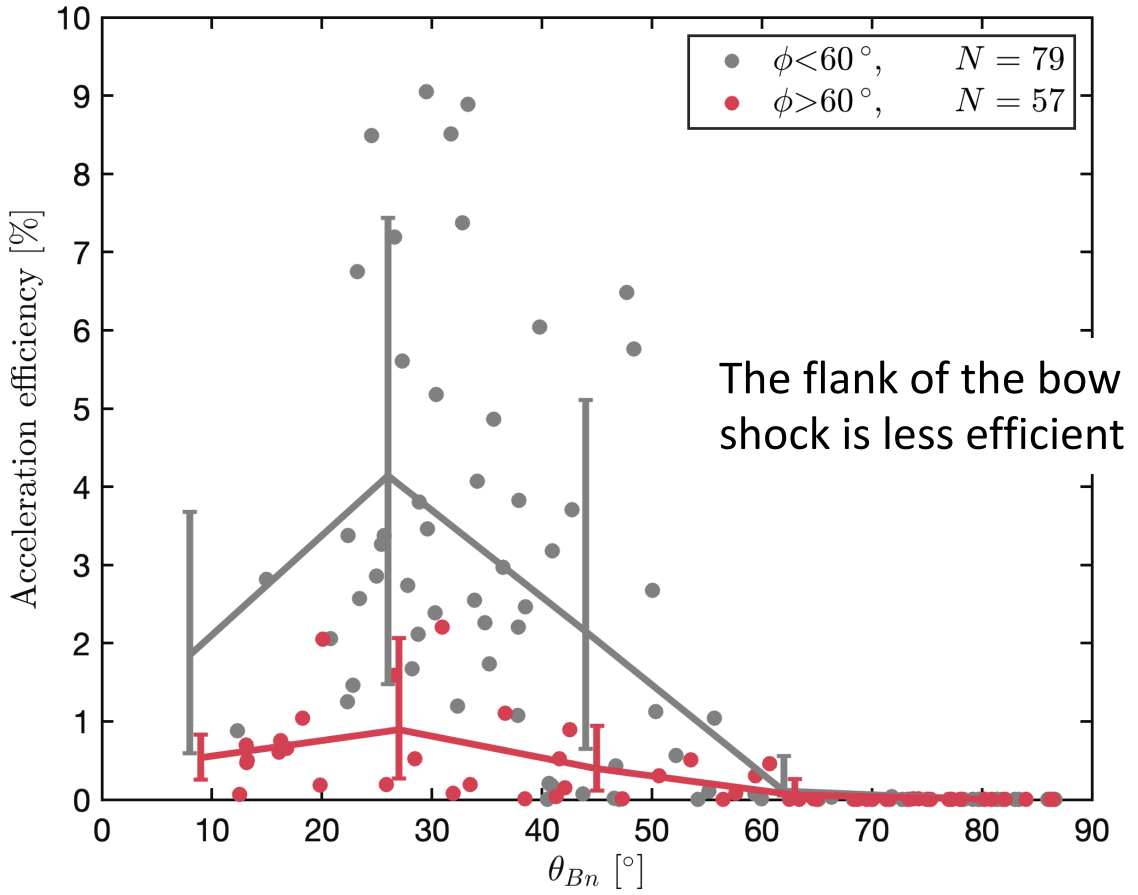
Mach number or spacecraft position?

Ordered after fast magnetosonic Mach number



No strong dependence on Mach number > 5

Ordered angle to Sun-Earth line

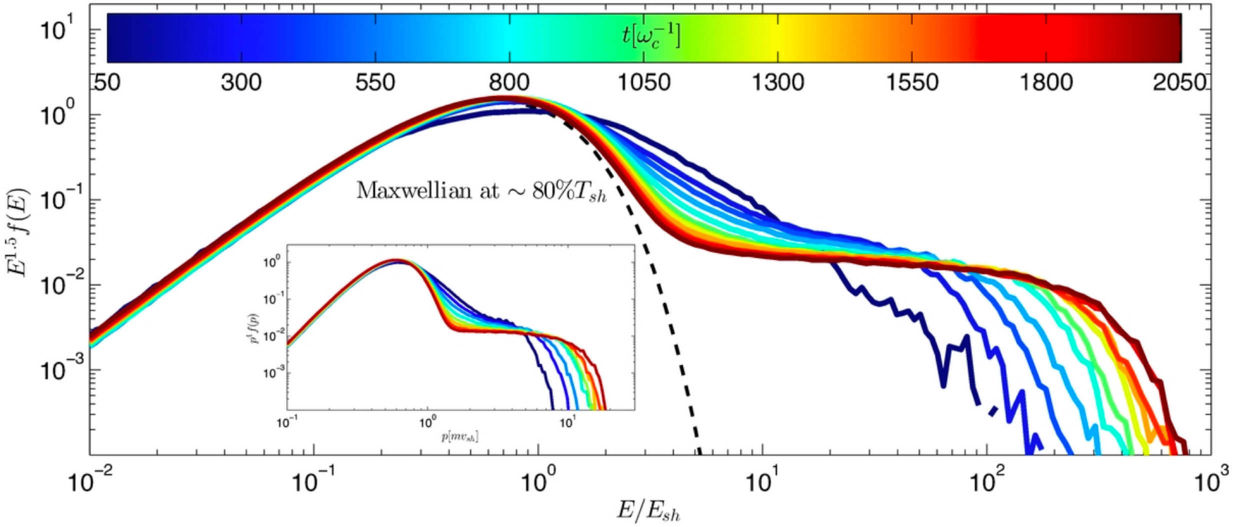


The flank of the bow shock is less efficient

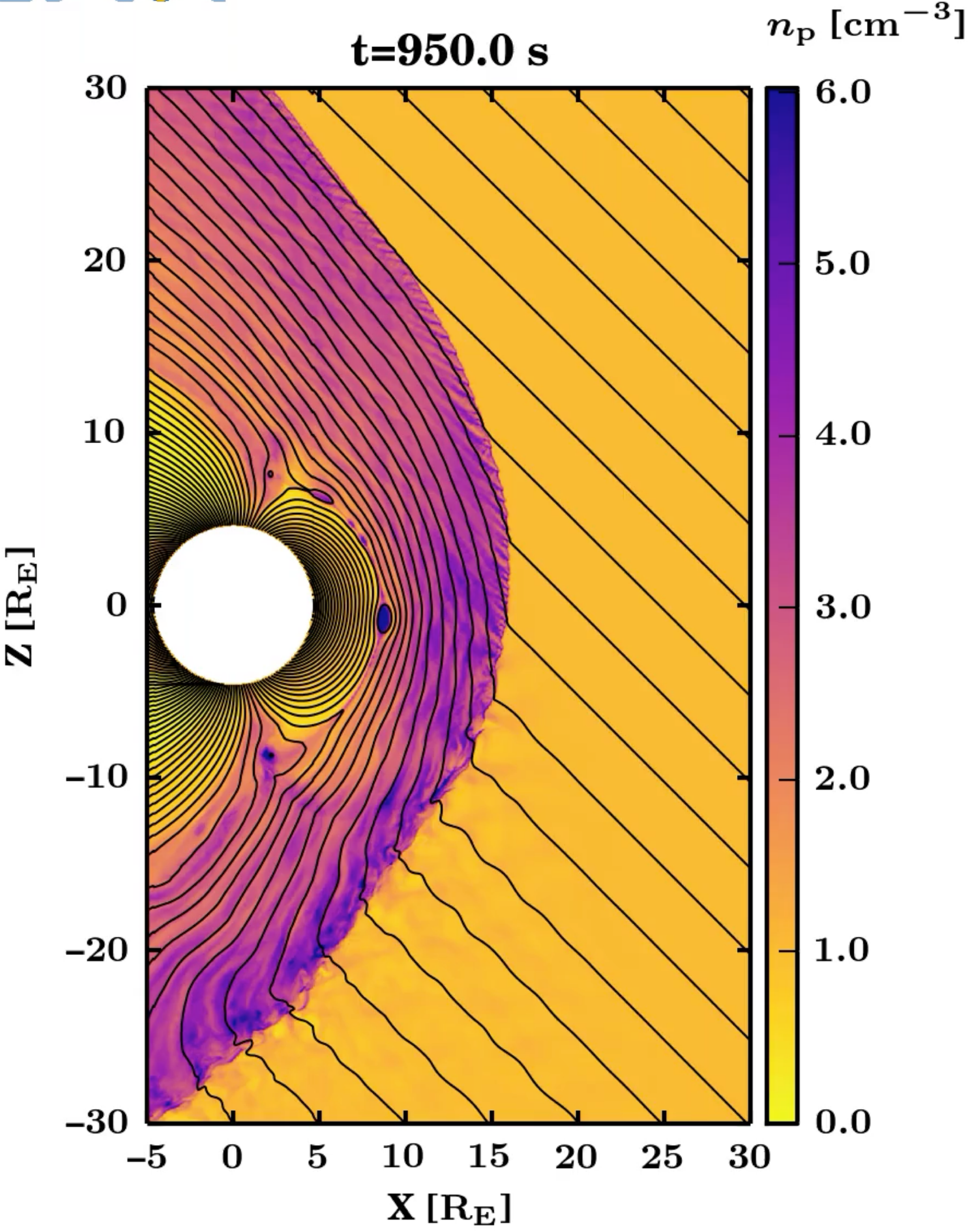
Shock age

- A field line connects to the bow shock at $\theta_{Bn} = 90°$ and then moves across the shock
- **The position on the shock corresponds to the age of the shock**

Box-simulations show ion acceleration changing with shock age:

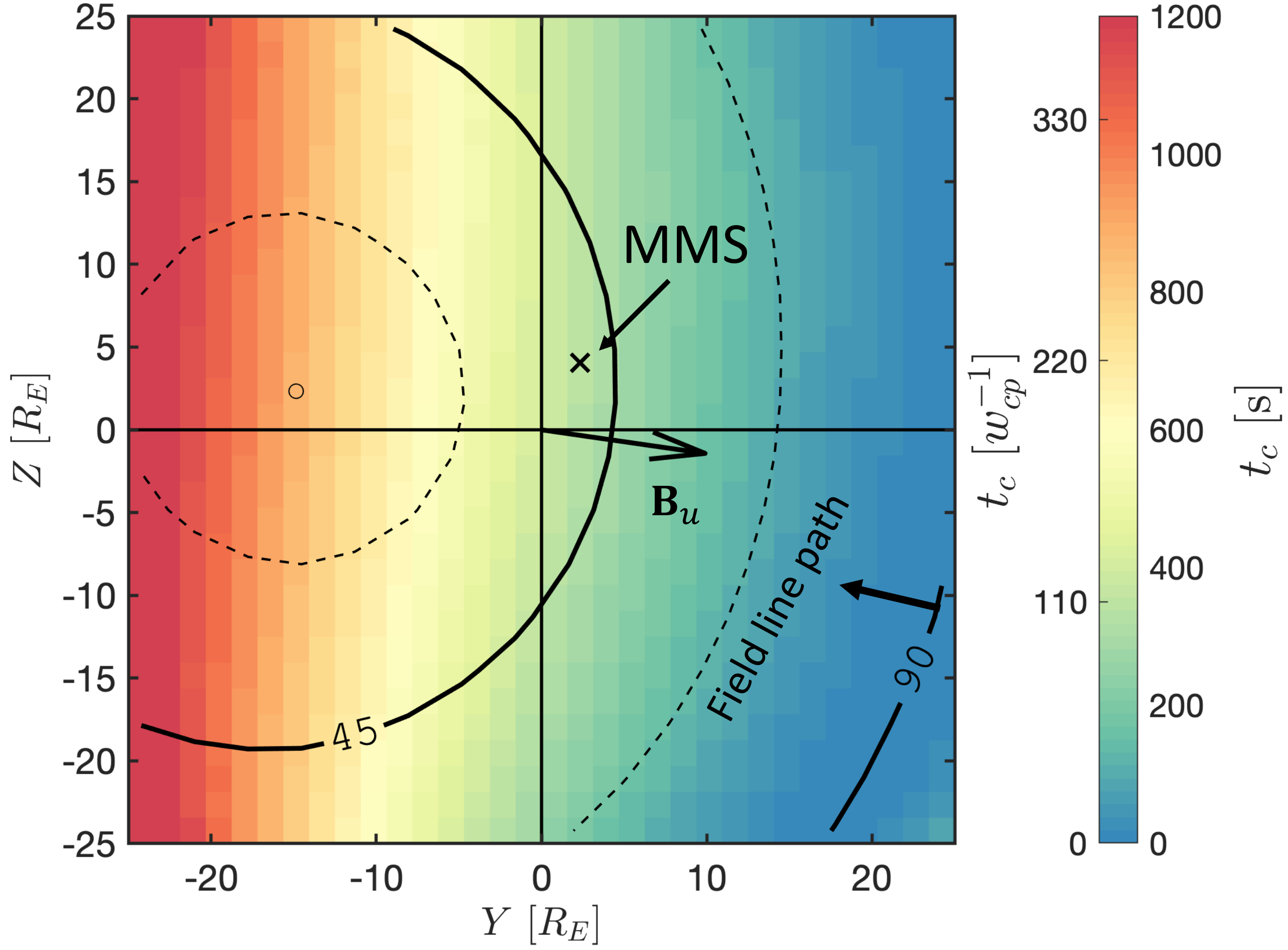


(Caprioli & Spitkovsky, 2014, ApJ)



Ion acceleration and shock age

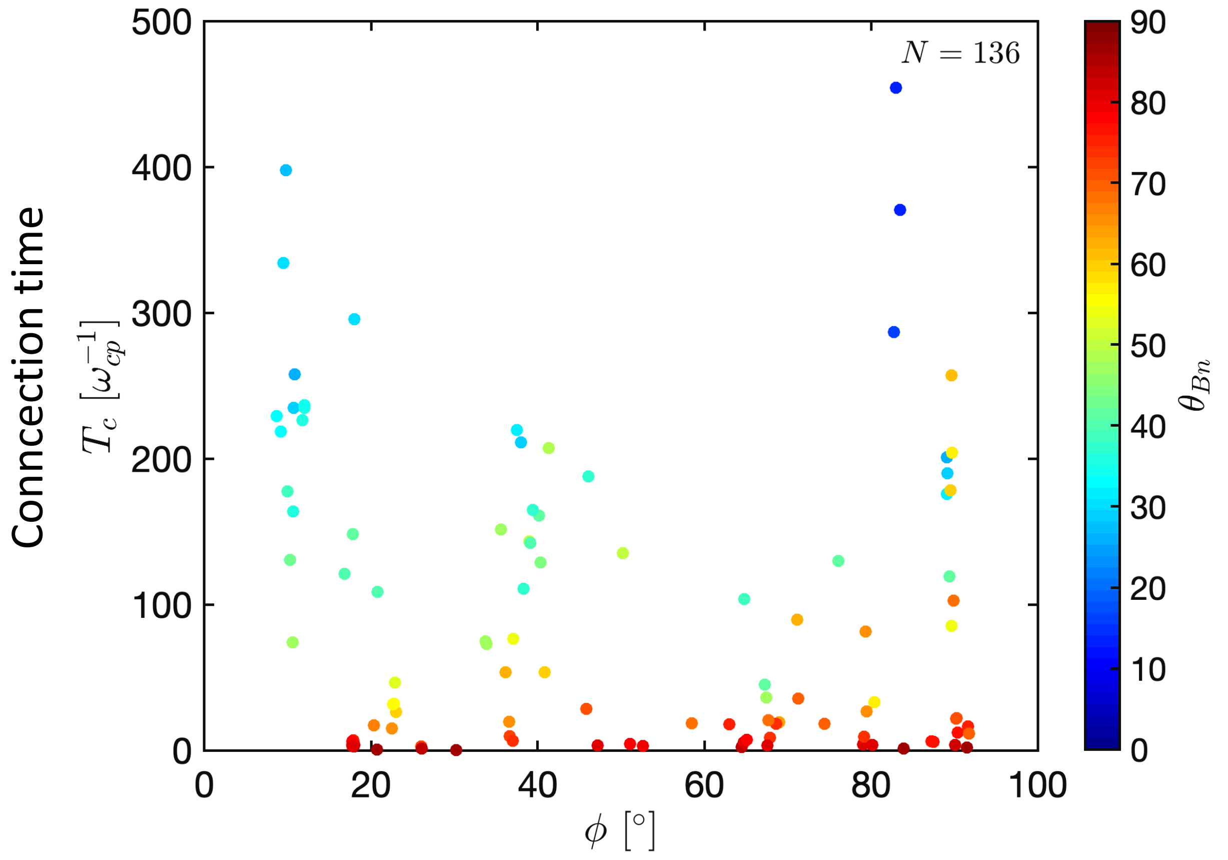
The bow shock seen from the Sun



Shock age

- In 3D, there is no correlation between spacecraft position and age of the shock

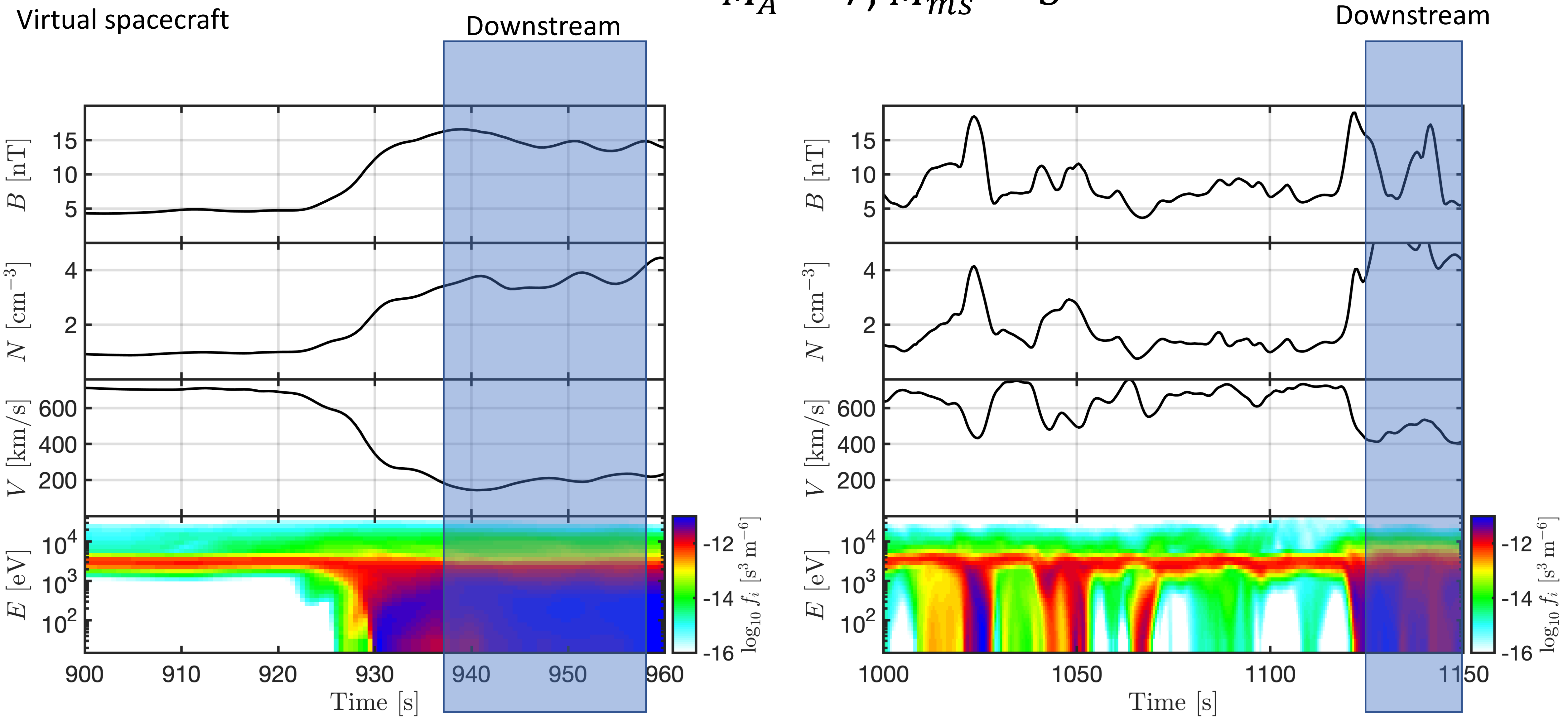
- **The age of the shock does not seem to impact acceleration efficiency**



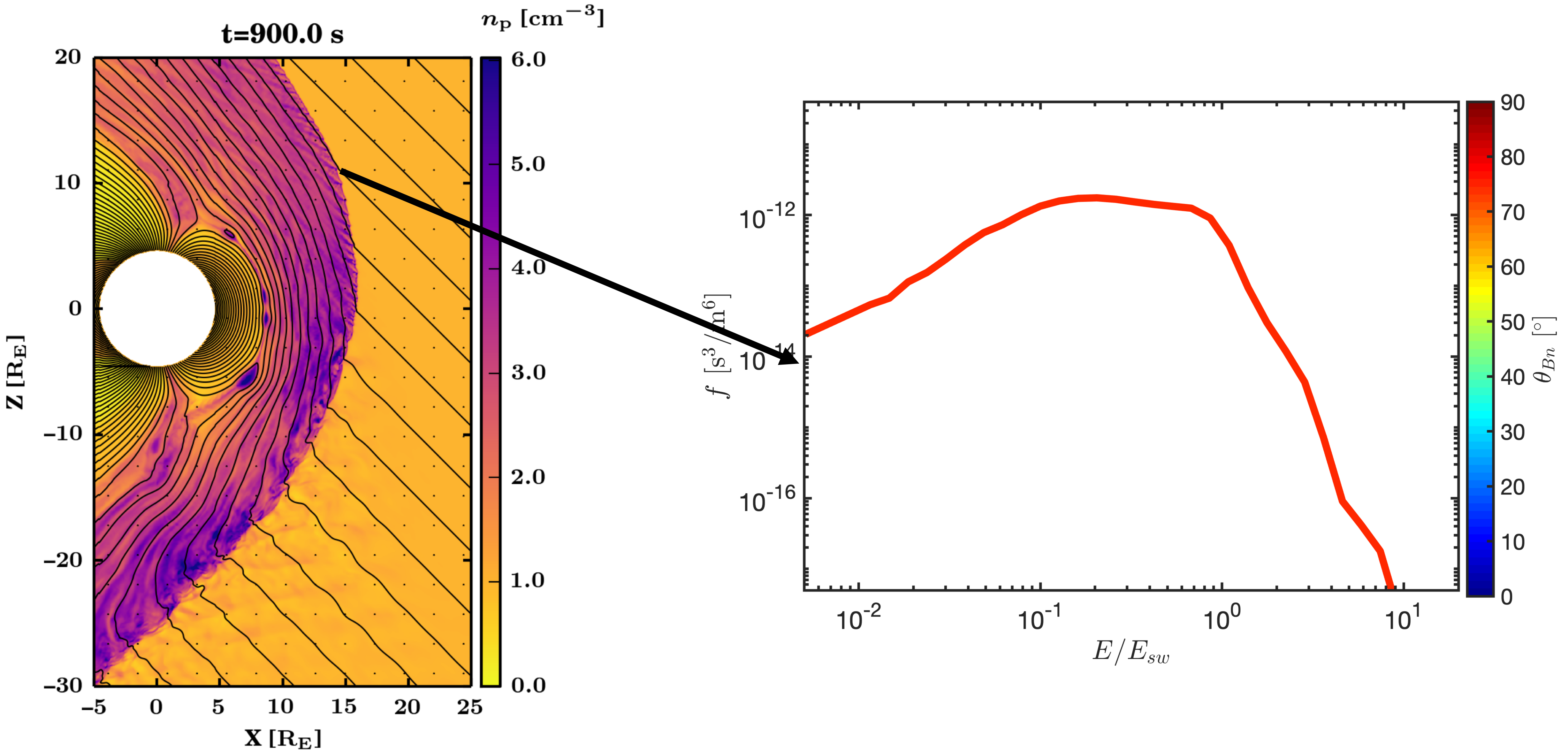
Angle to Sun-Earth line

Now to Vlasiator

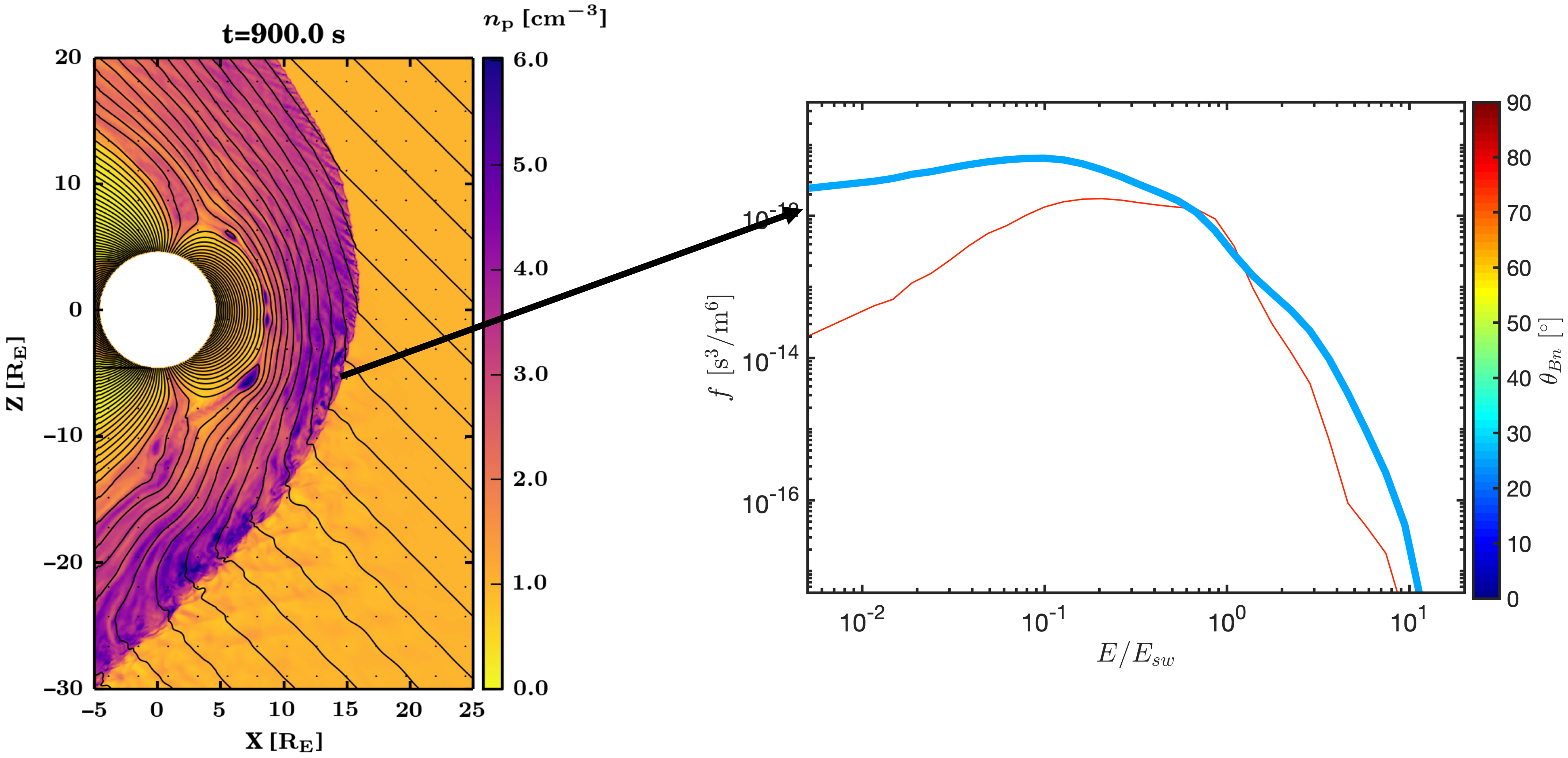
$M_A \approx 7, M_{ms} \approx 5$



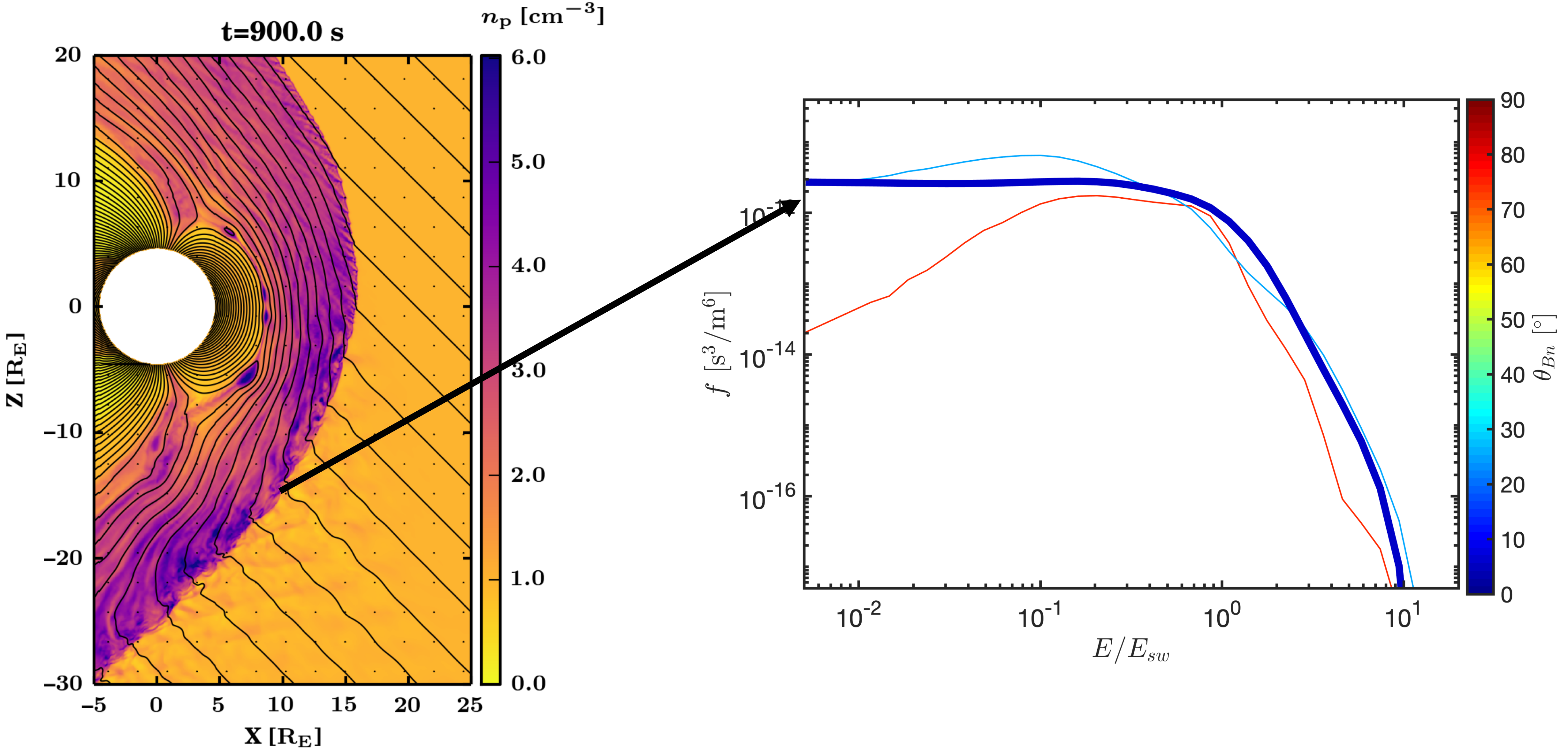
Vlasiator results



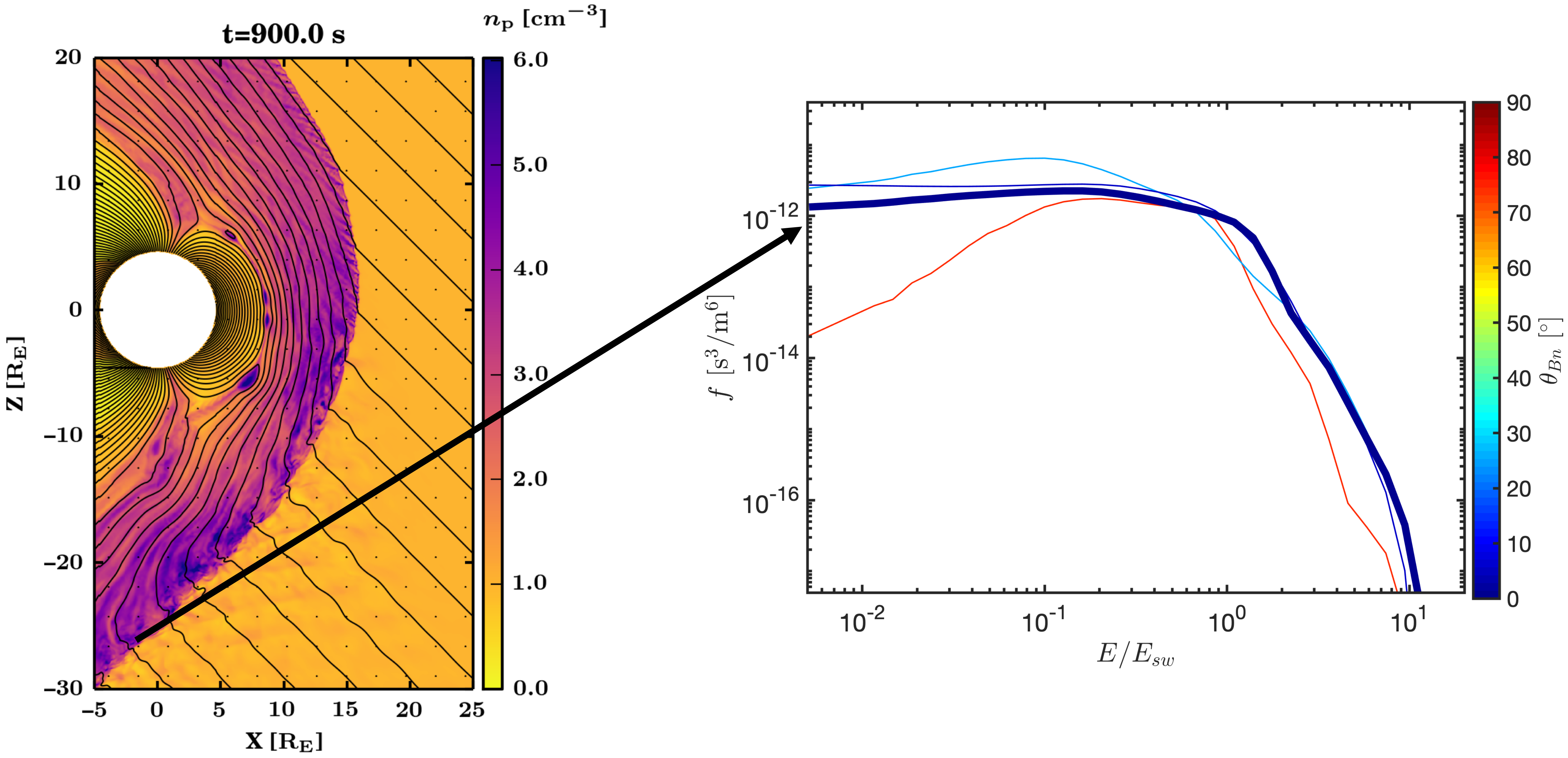
Vlasiator results



Vlasiator results

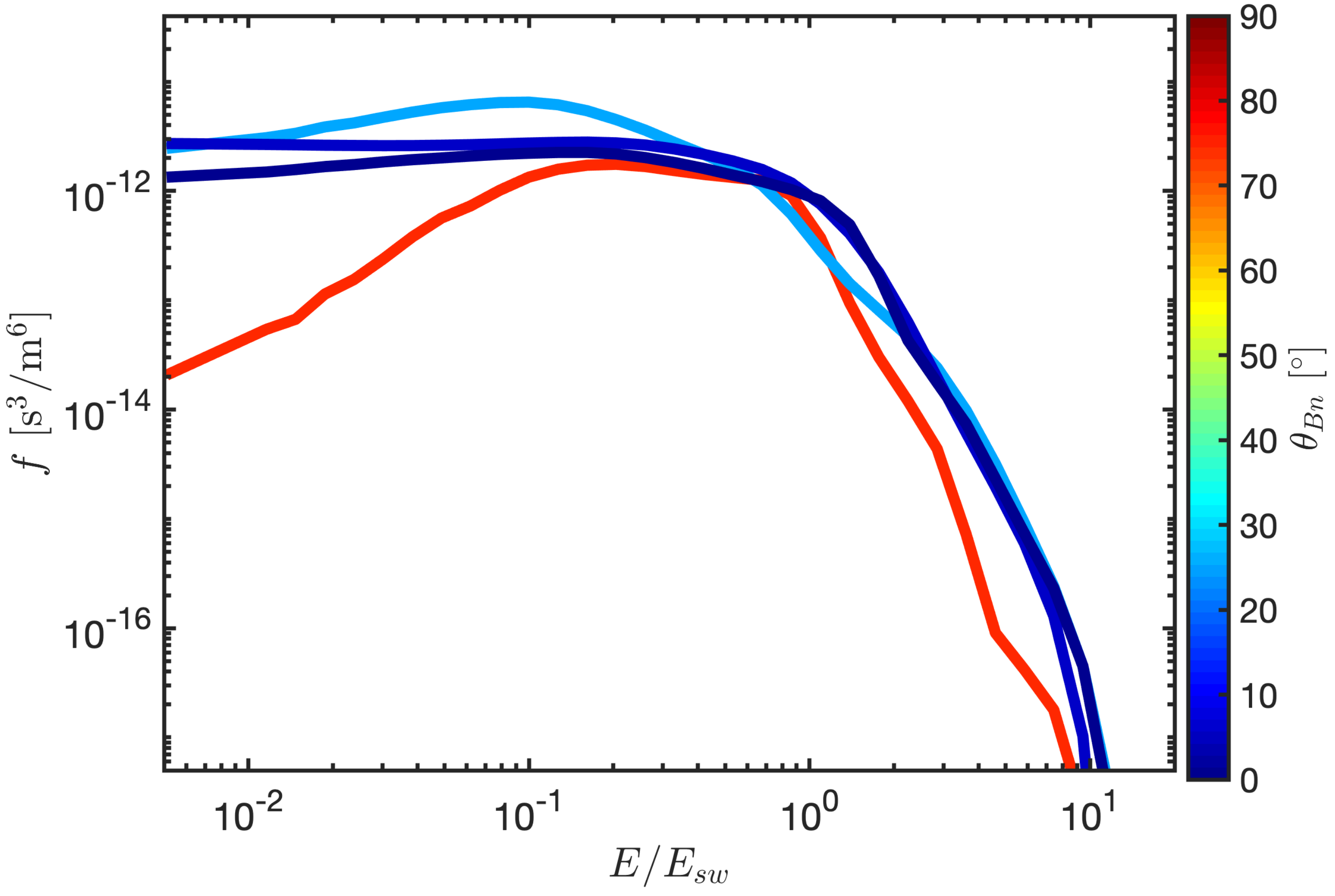


Vlasiator results



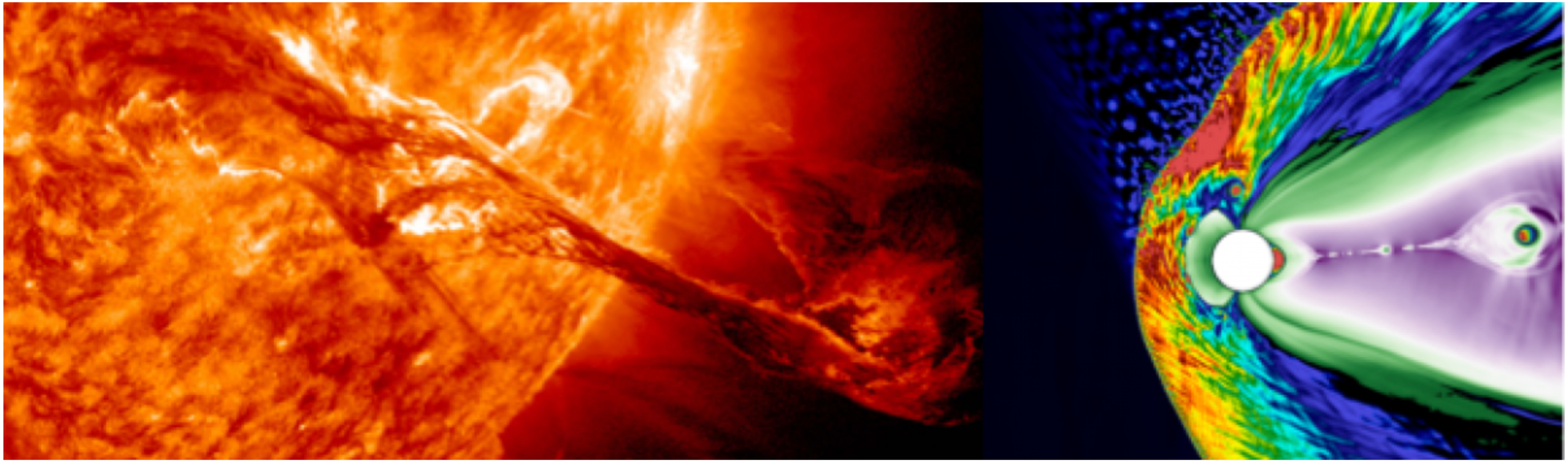
- Similar to MMS observations
  - Somewhat lower acceleration efficiency

- Again, no clear dependence on shock age



Summary

- The quasi-parallel bow shock is much more efficient at accelerating ions
  - This can qualitatively be replicated in Vlasiator
- Up to $5\text{-}10\%$ of the energy can go to energetic ions
  - Quantitative match with simulations of SNR shocks
- Higher Mach number leads to more acceleration
- The time a field line has been connected to the bow shock is not important for ion acceleration
  - Limited size more important?

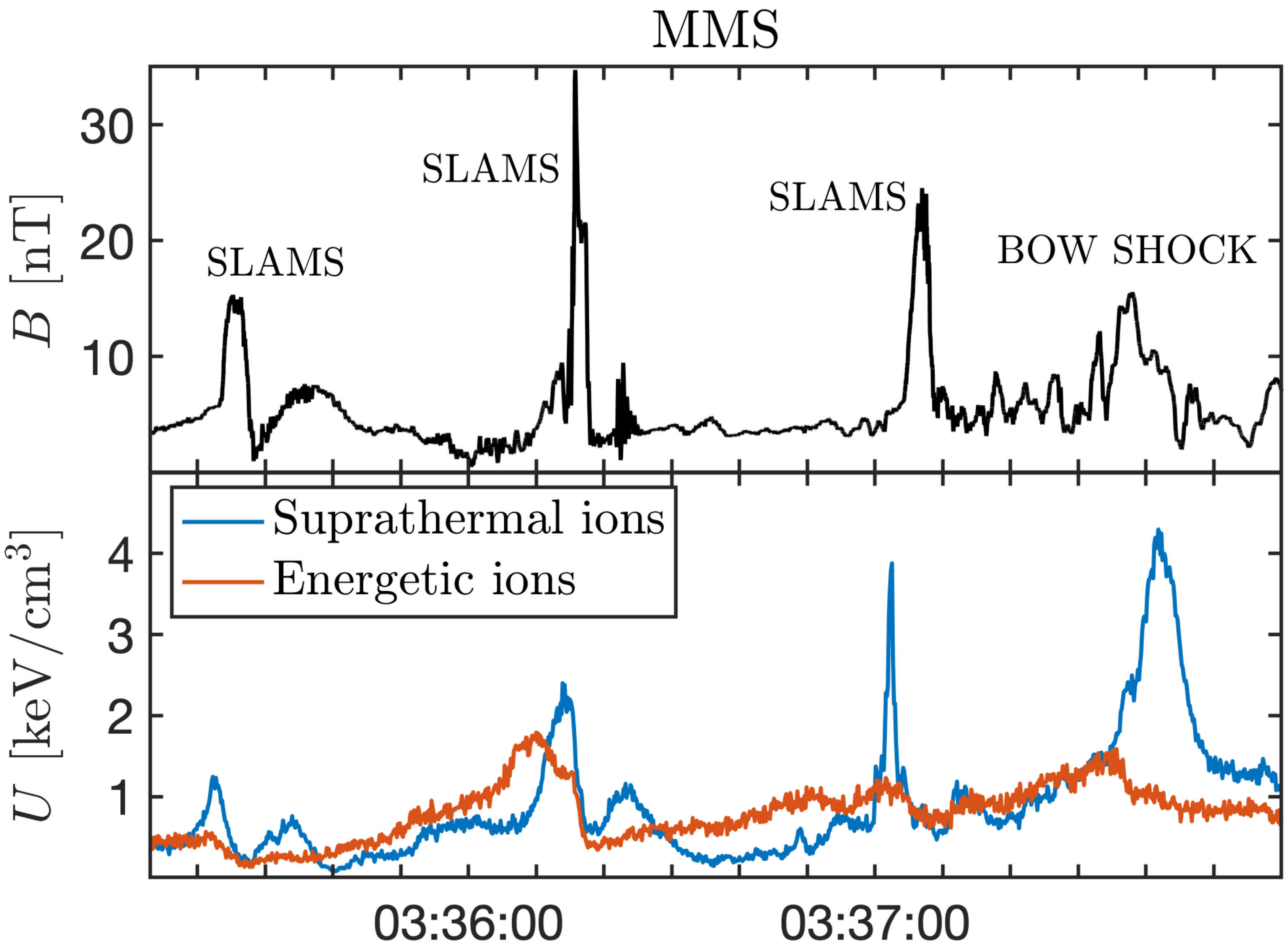


JOB OPENINGS: Postdoctoral Fellow Positions at the University of Helsinki, Space Physics Group, Finland

https://blogs.helsinki.fi/spacephysics/

Additional slides

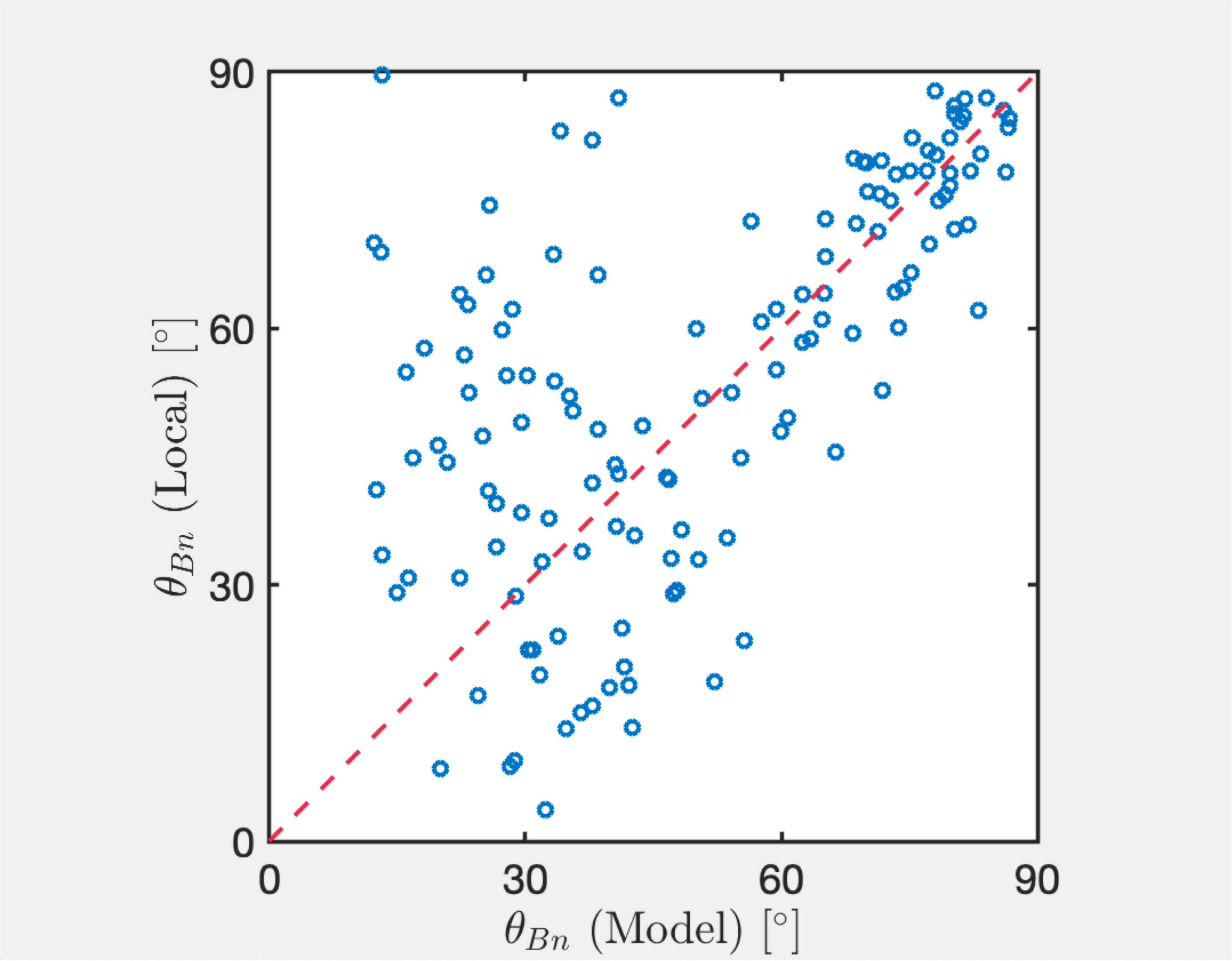
SLAMS



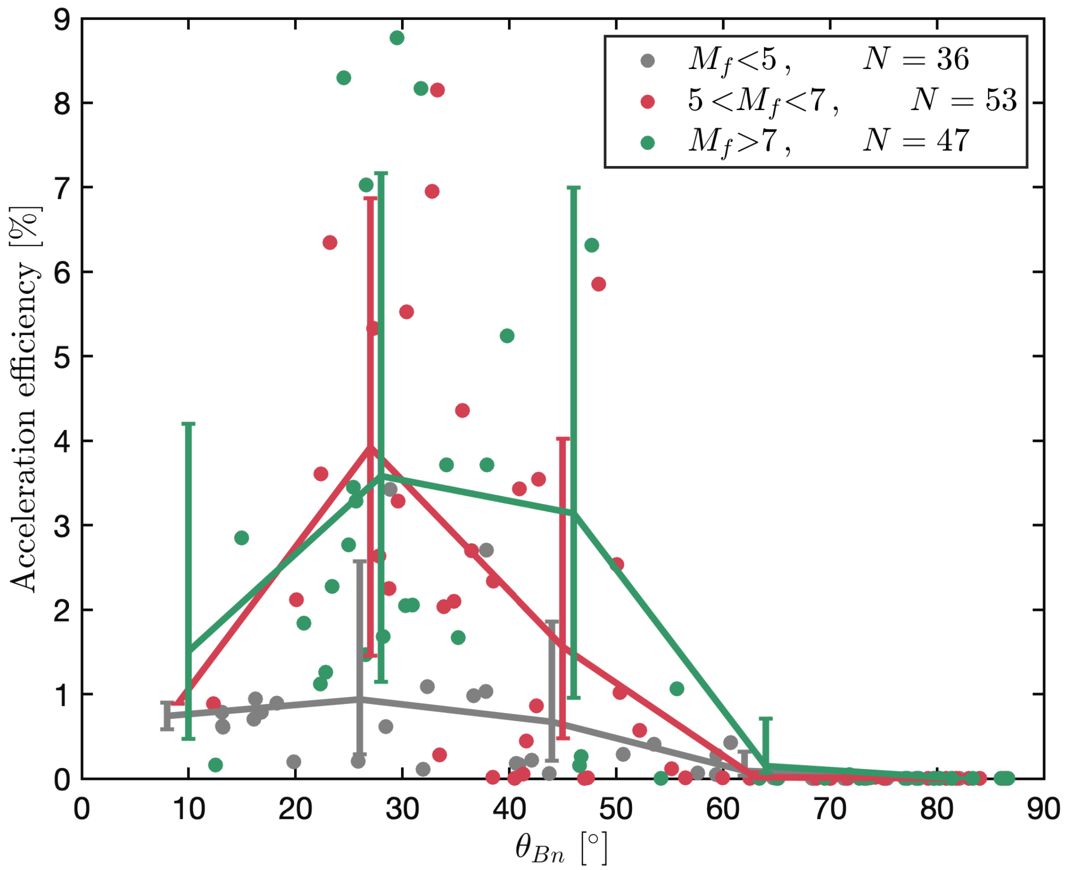
$3E_{sw} < E < 10E_{sw}$

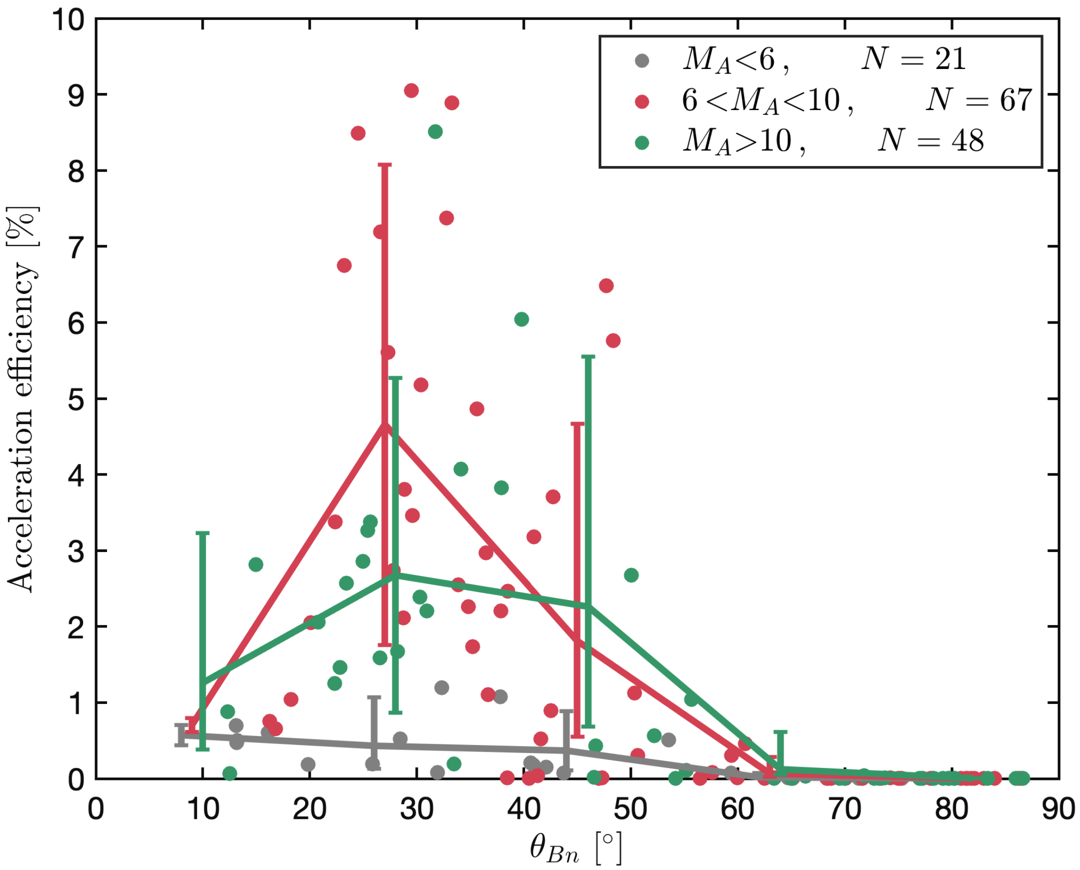
$E > 10E_{sw}$

Local normal determination

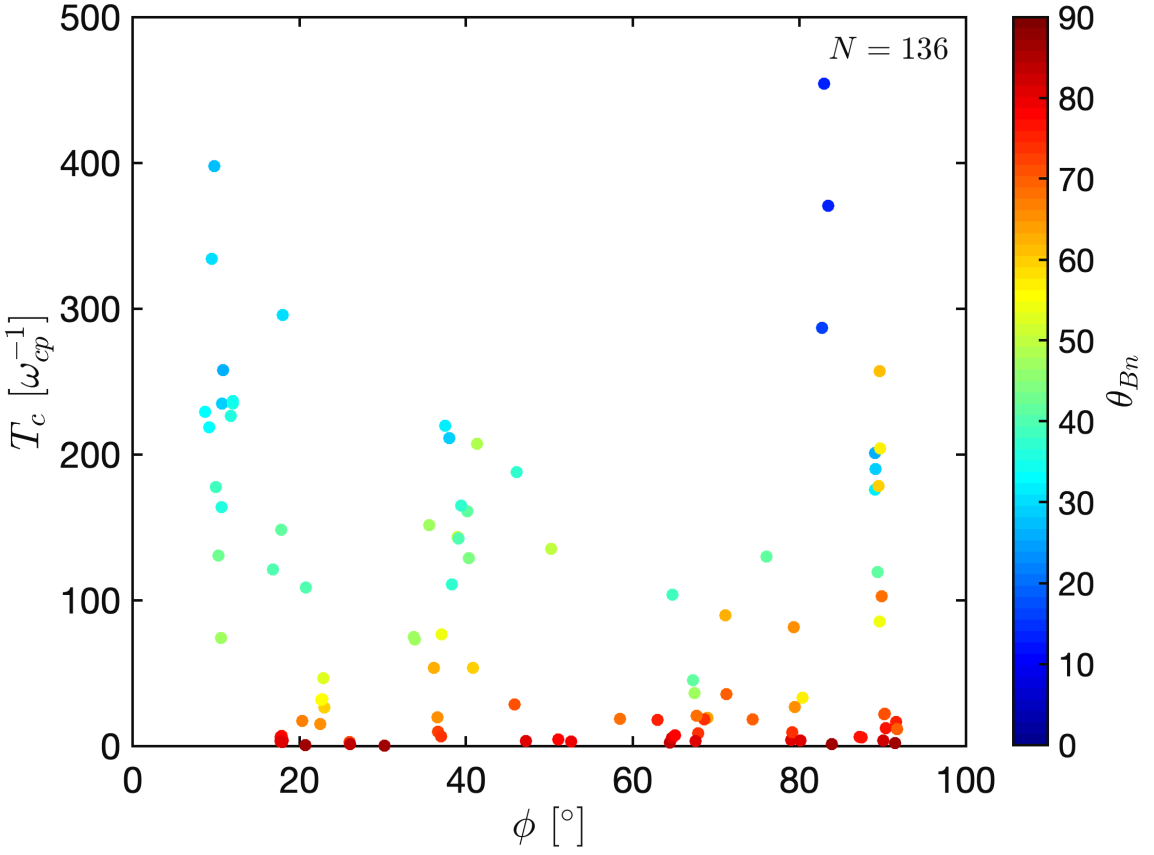


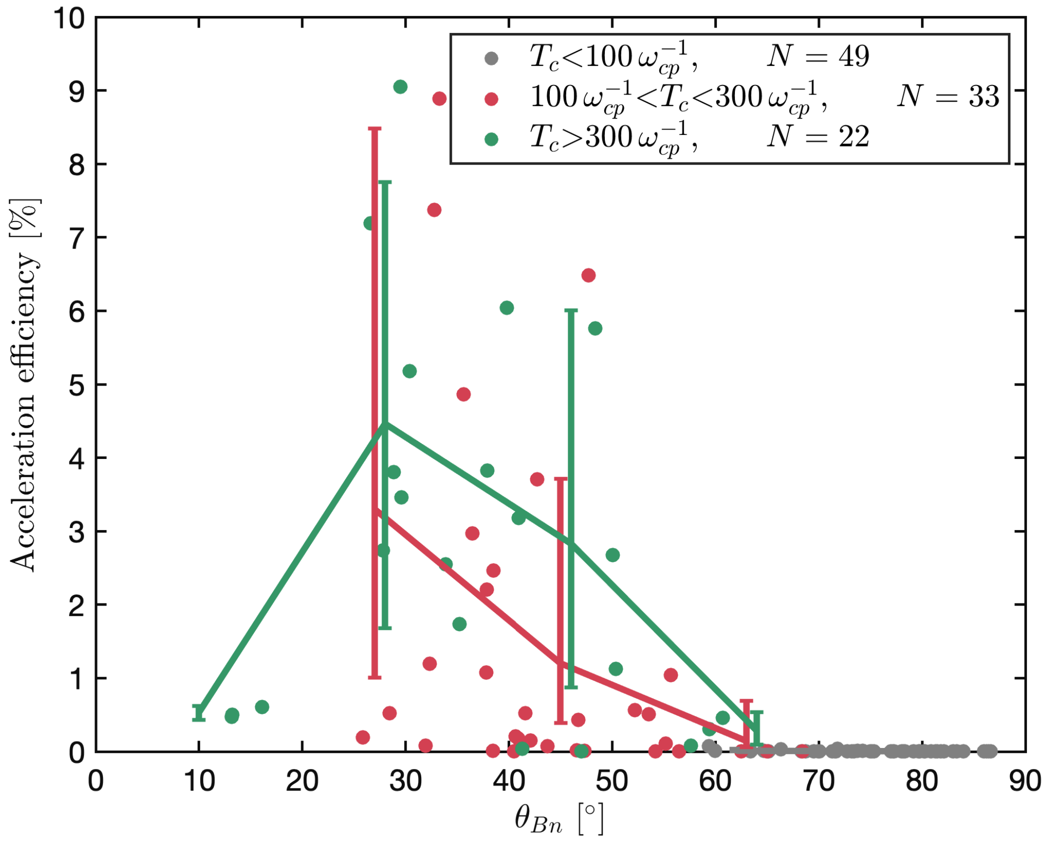
Additional slides

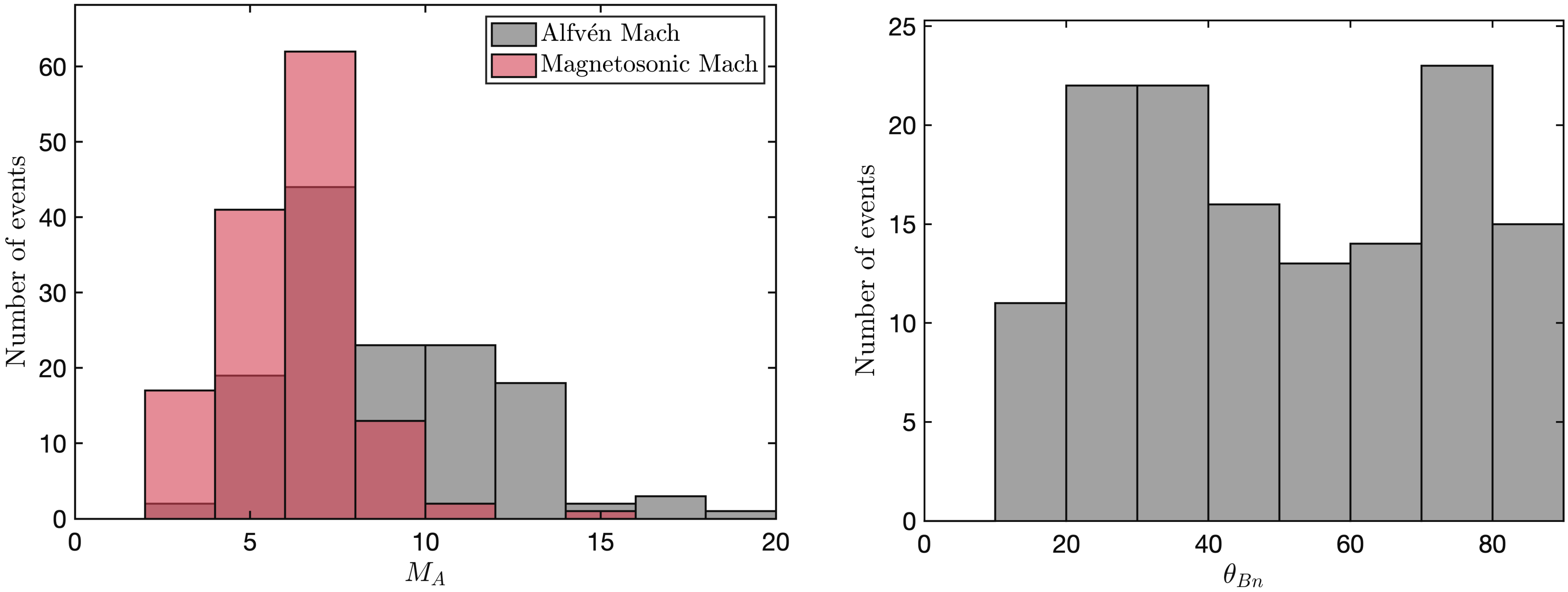




Additional slides





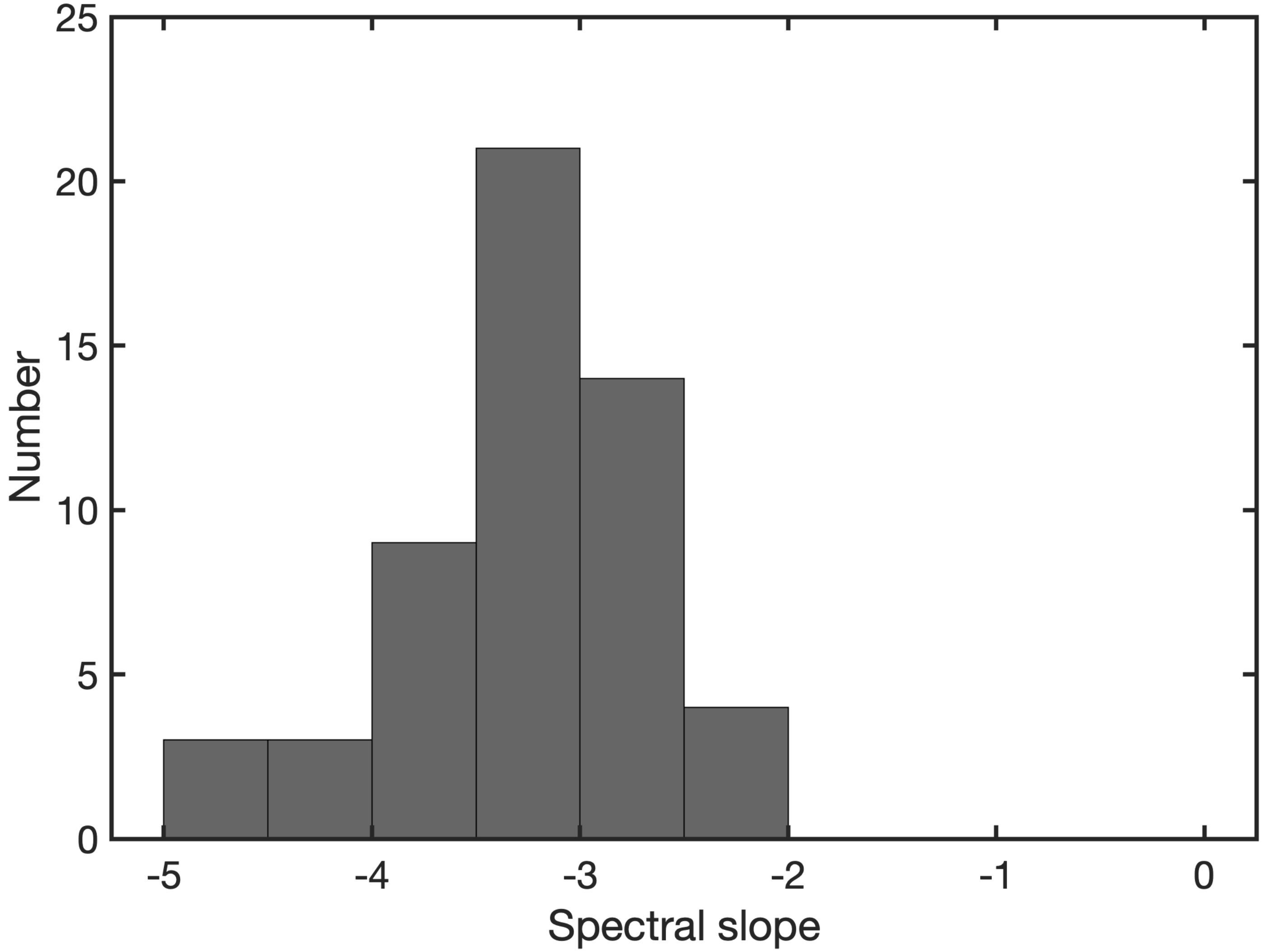


Alfvén Mach
Magnetosonic Mach
Number of events
M_A
0
5
10
15
20
0
10
20
30
40
50
60
Number of events
θ_{Bn}
0
20
40
60
80
0
5
10
15
20
25

Spectral slopes

$f \sim E^q$

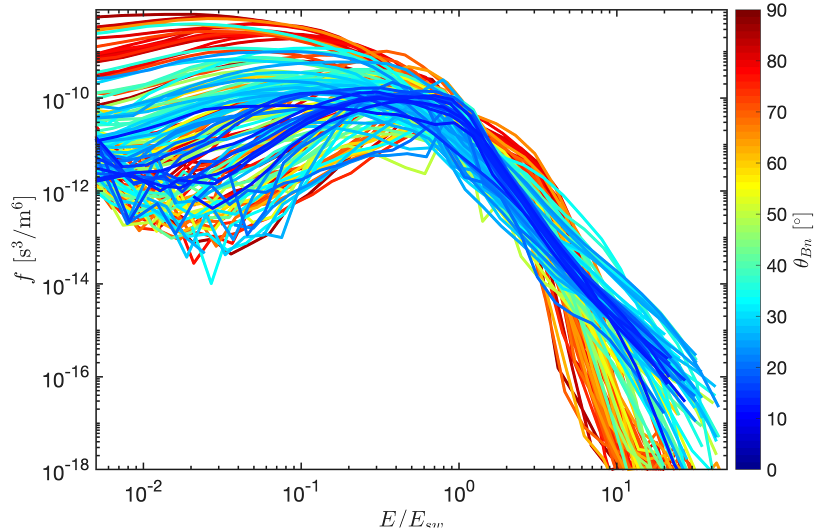
Only for $\theta_{Bn} < 45°$

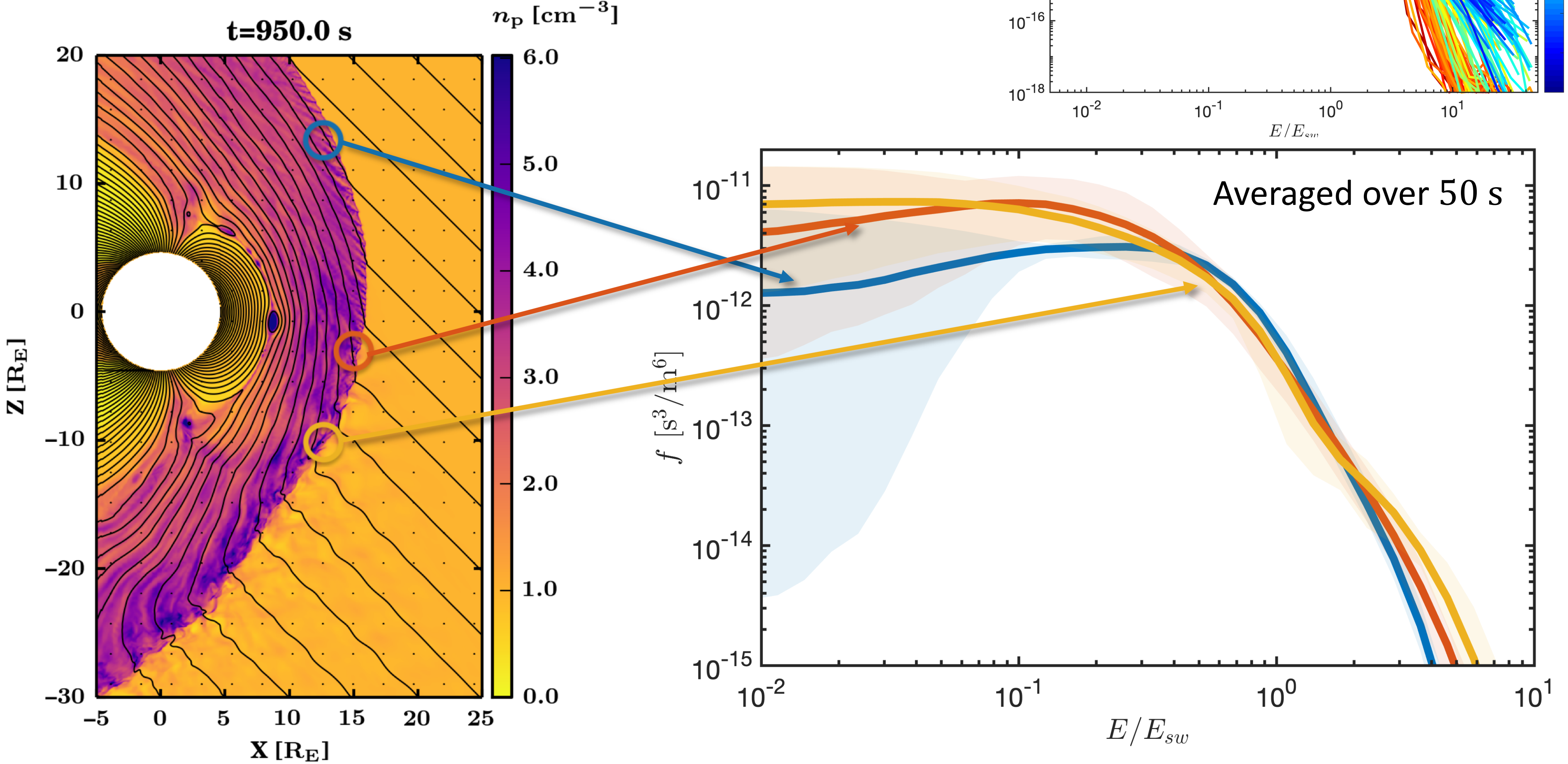


Preliminary Vlasiator results

Vlasiator is largely able to replicate the observed ion distribution functions

MMS observations





Sparse velocity grid

Not all veclocity space is represented in the memory