Unveiling plasma energization and energy transport in the Earth's magnetospheric system through multi-scale observations

— The science of the Plasma Observatory mission

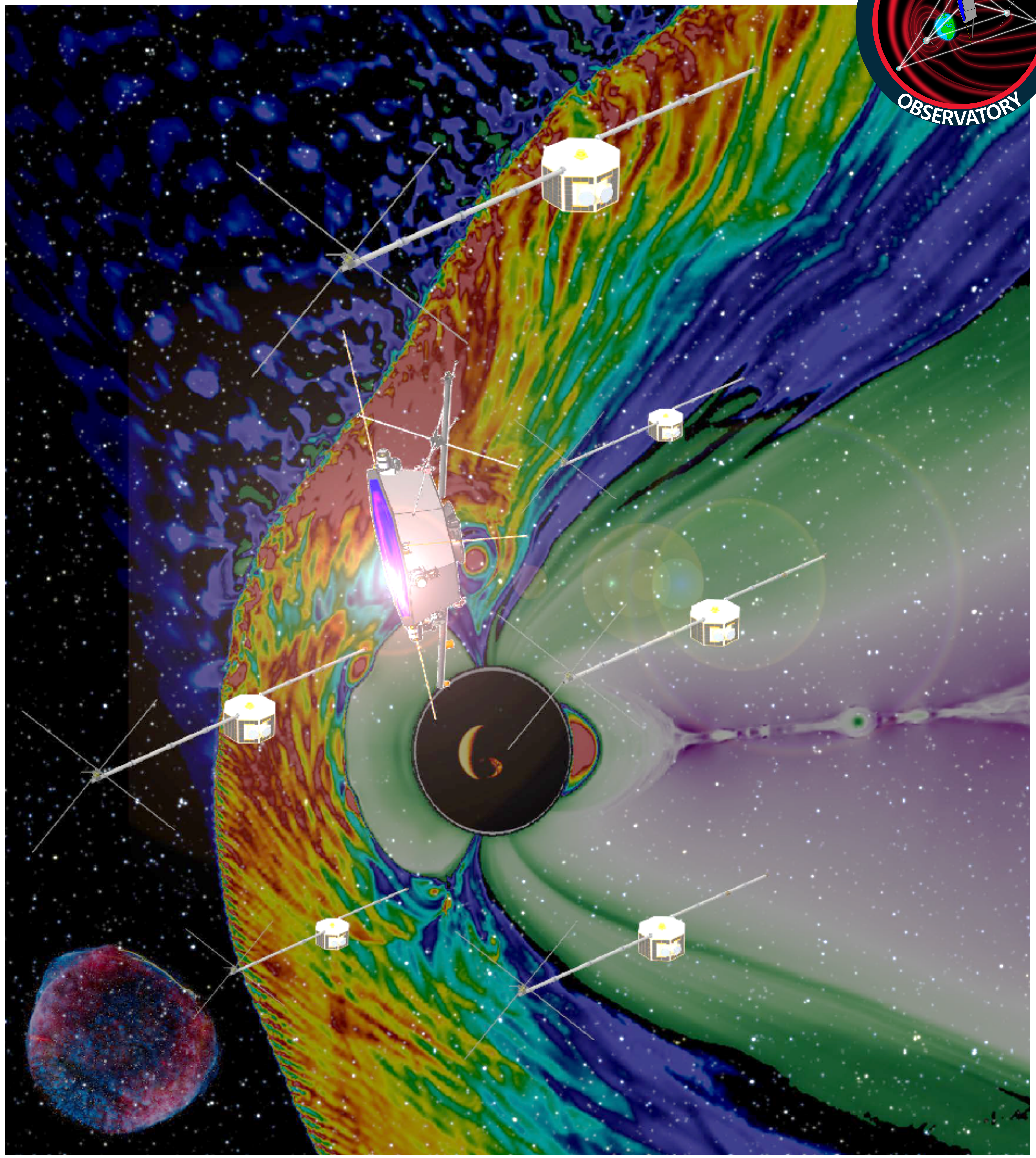
C. Norgren, M.F. Marcucci, A. Retinò, M. G. G. T. Taylor, T. Amano, Y. K. Khotyaintsev, A. Simionescu, J. Soucek, J. Stawarz, F. Valentini, M. Berthomier, M. Dunlop, M. Fraenz, H. Hietala, M. Kretzschmar, R. Nakamura , M. Palmroth, J. Rae, H. Rothkaehl, A. Vaivads, V. Angelopoulos, S. Bale, R. D'Amicis, J. De Keyser, A. Dimmock, C. Forsyth, H. Fu A. Galli, L. Griton, K. Kauristie, L. Kistler, H. Kucharek, K. Issautier, B. Lavraud, O. Le Contel, I. Mann, L. Matteini, K. McWilliams, M. Maksimovic, E. Panov, O. Pezzi, F. Plaschke , Y. Saito, M. Steller, M. Yamauchi, R. Vainio, R. F. Wimmer-Schweingruber, U. Derz, A. Stankov, T.-M. Bruendl, A. Carpentier, T. James, B. Ordoubadian, A. Walsh and the Plasma Observatory Team

European Conference on Magnetic Reconnection, 2025, Torino

Plasma Observatory

Science theme

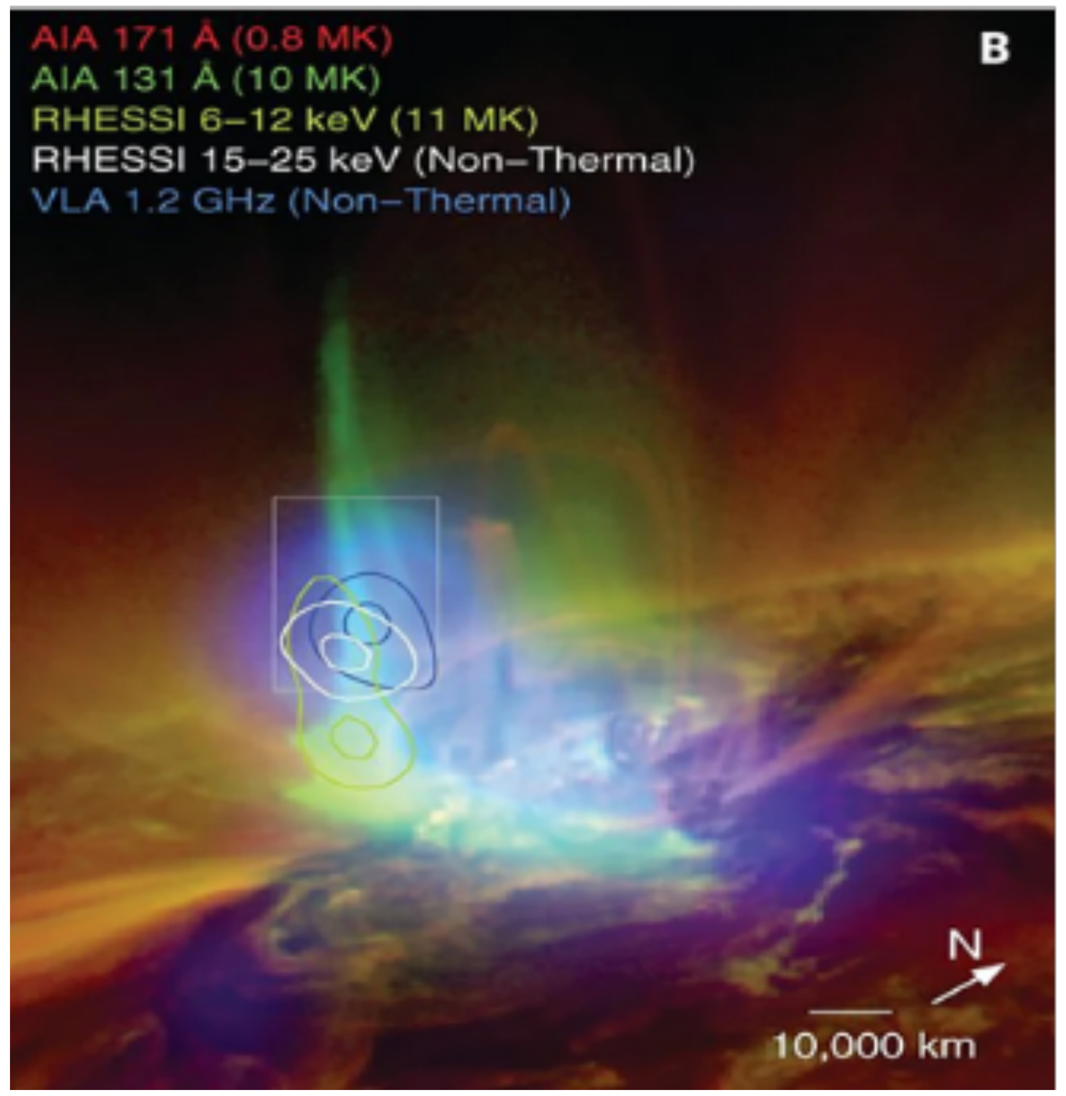
- Unveiling plasma energization and energy transport in the Earth's Magnetospheric System through multi-scale observations.
- ESA M7 candidate in competitive Phase A. Final selection in June 2026. Launch 2037. M = medium = 750 million euro = 0.5 MMS
- Targets two ESA Voyage 2050 themes for ESA-led M Mission:
  - Magnetospheric Systems
  - Plasma Cross-scale Coupling
- ESA Science Study Team (SST): M.F. Marcucci (Lead), A. Retinò (coLead), T. Amano, Y. Khotyaintsev, C. Norgren, A. Simionescu, J. Soucek, J.Stawarz, F. Valentini
- Large scientific community: 370+ researchers from 25 countries (17 in Europe) including US, Japan and China
- Payload team including 10+ ESA countries with key US and Japanese contributions

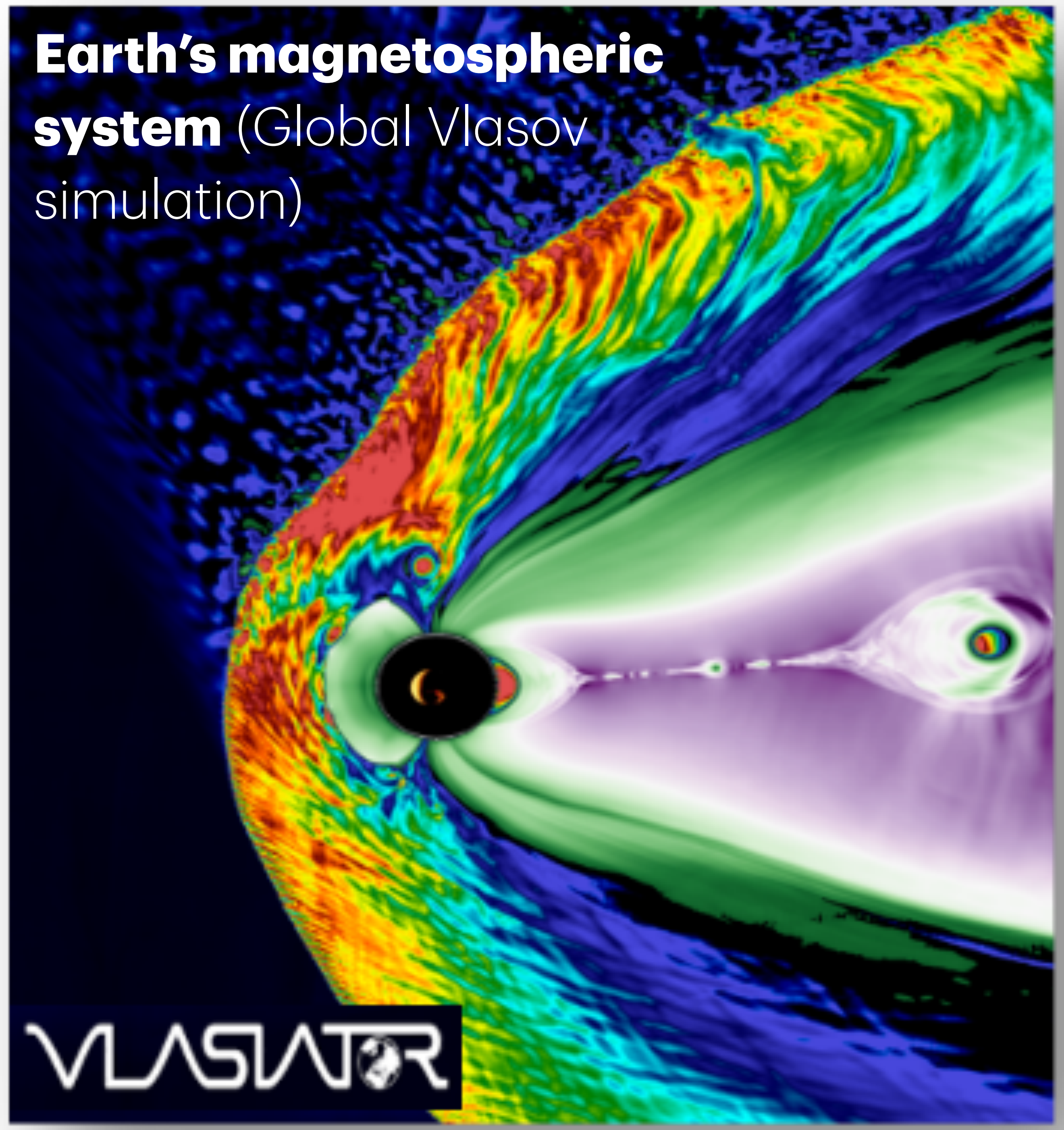


Why Plasma Observatory?

Plasma is the main state of visible cosmic matter but fundamental plasma energization and energy transport processes are still not understood. These processes are inherently driven by coupling of plasma scales.

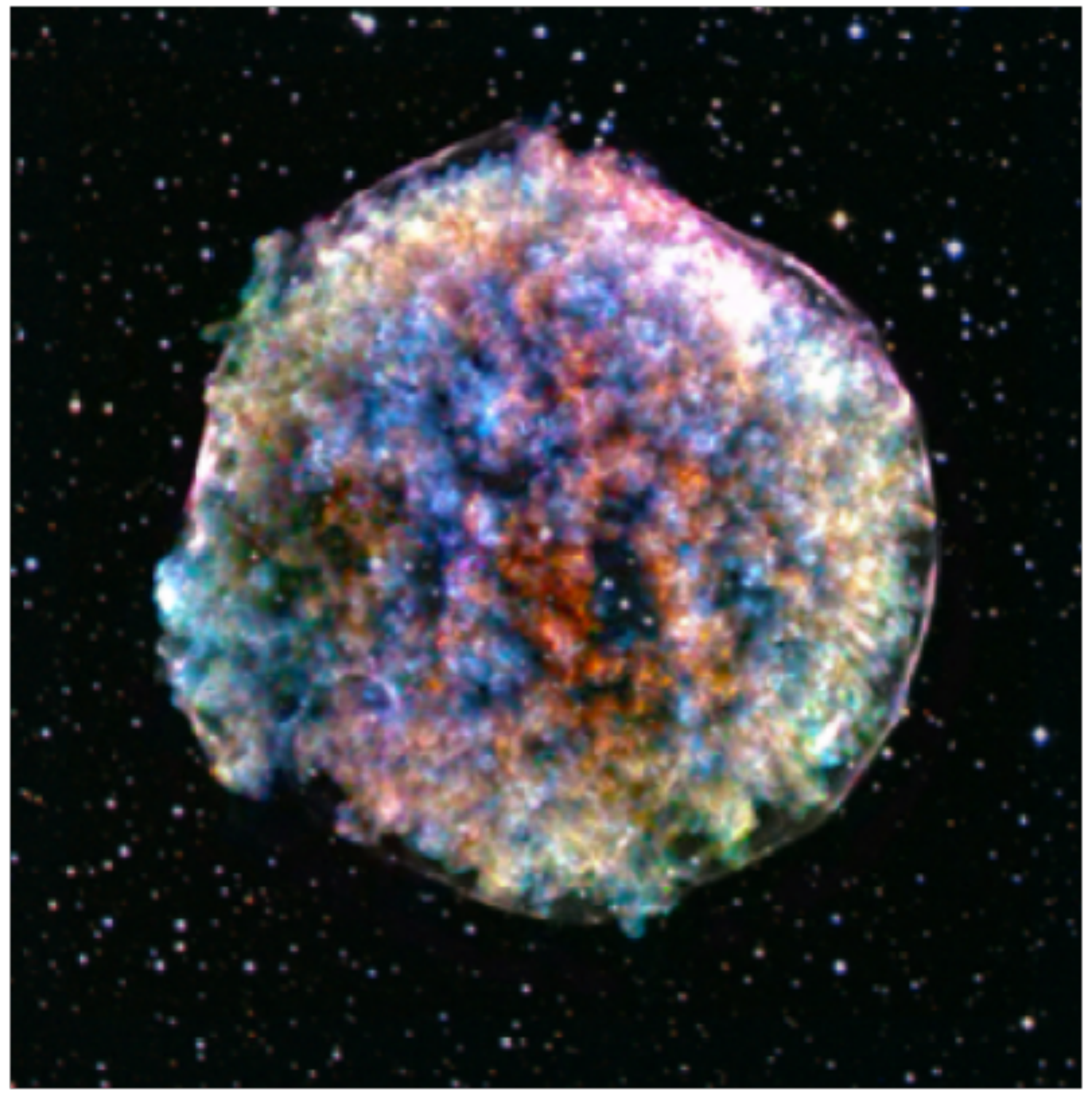
Solar corona. Radiation emitted by energized particles in a solar flare. From Chen+, Science, 2015.





Earth's magnetospheric system (Global Vlasov simulation)

Tycho supernova remnant shock Composite image. X-ray NASA/CSC/RIKEN&GSF C/T. Optical: DSS



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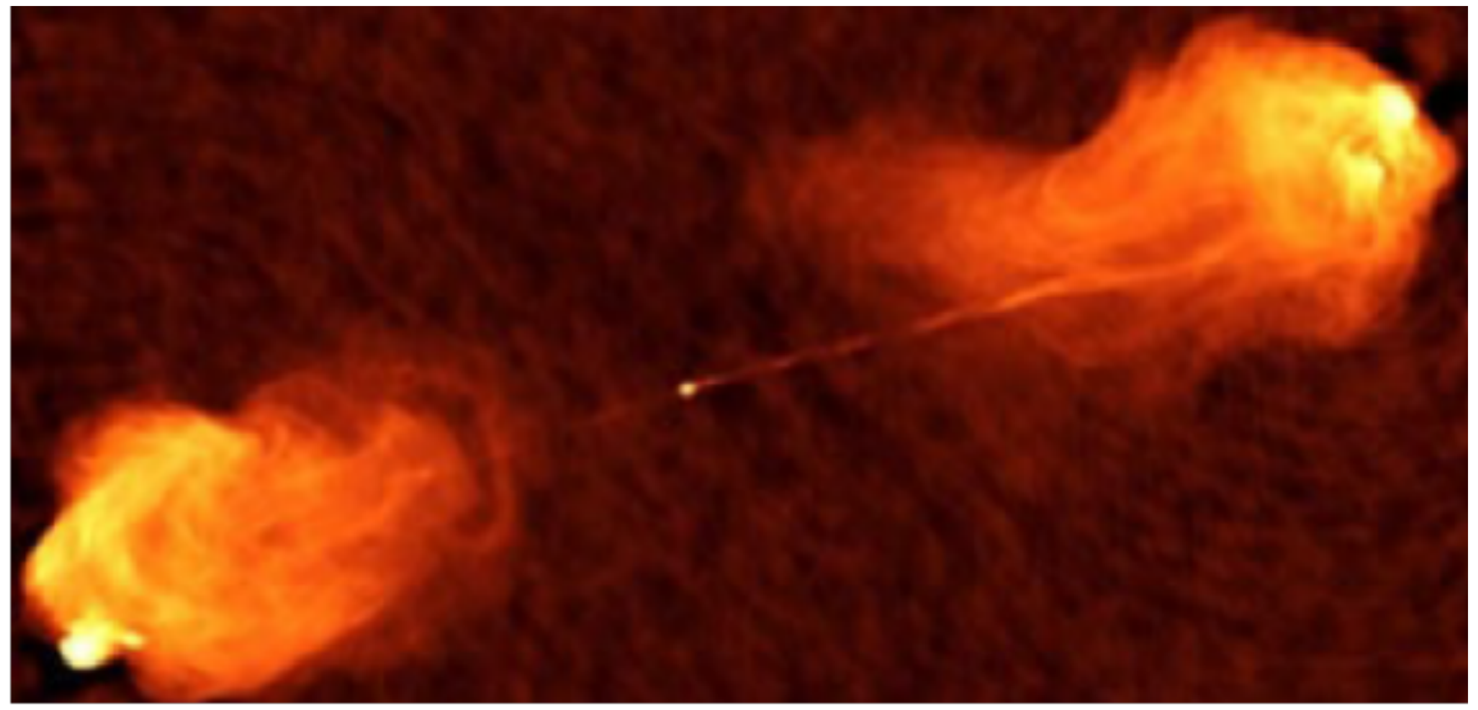
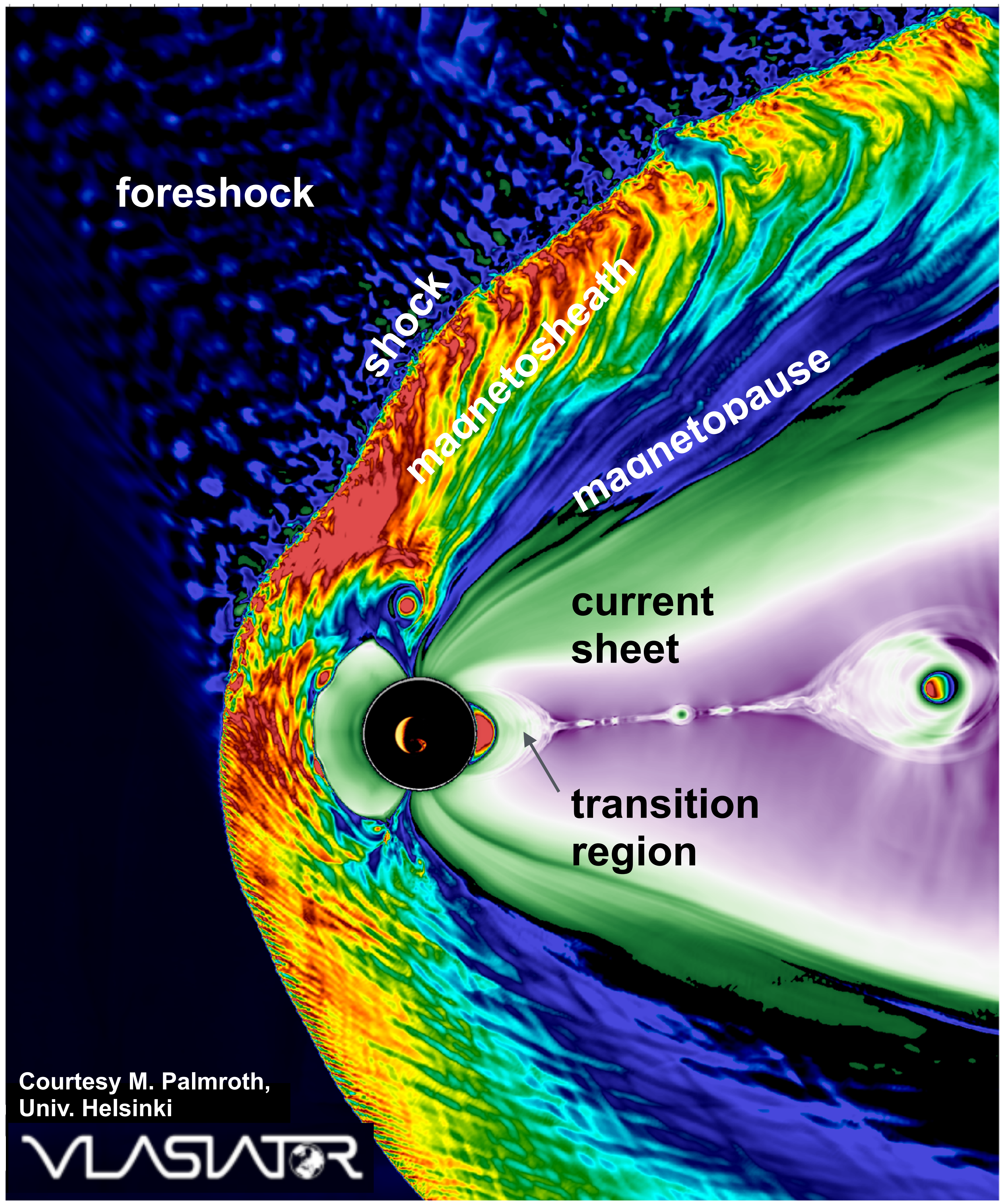


Strong plasma energization and energy transport produced by fundamental plasma processes!

The Earth's Magnetospheric system

- Complex and highly dynamic with massive energy transport and particle energization occurring at boundaries and boundary layers
- Multi-scale processes within non-planar and non-stationary 3D structures governed by field-particle interactions.
- Largest energization when fluid scales couples with smaller ion kinetic scales
- Essential to ultimately understand how our planet works. Contributing to the Space Weather comprehension and understanding of distant astrophysical plasma environments and laboratory plasmas



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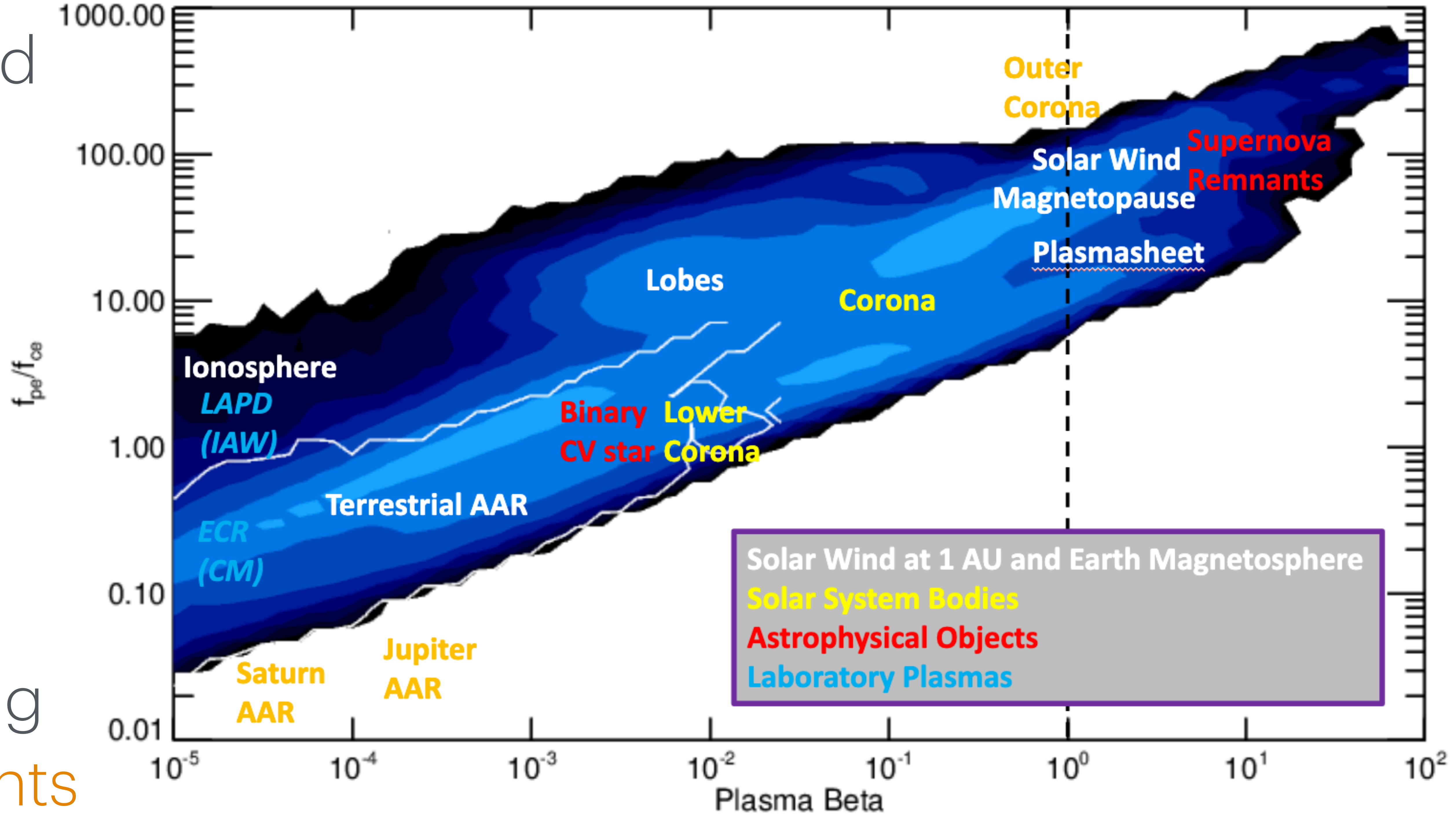
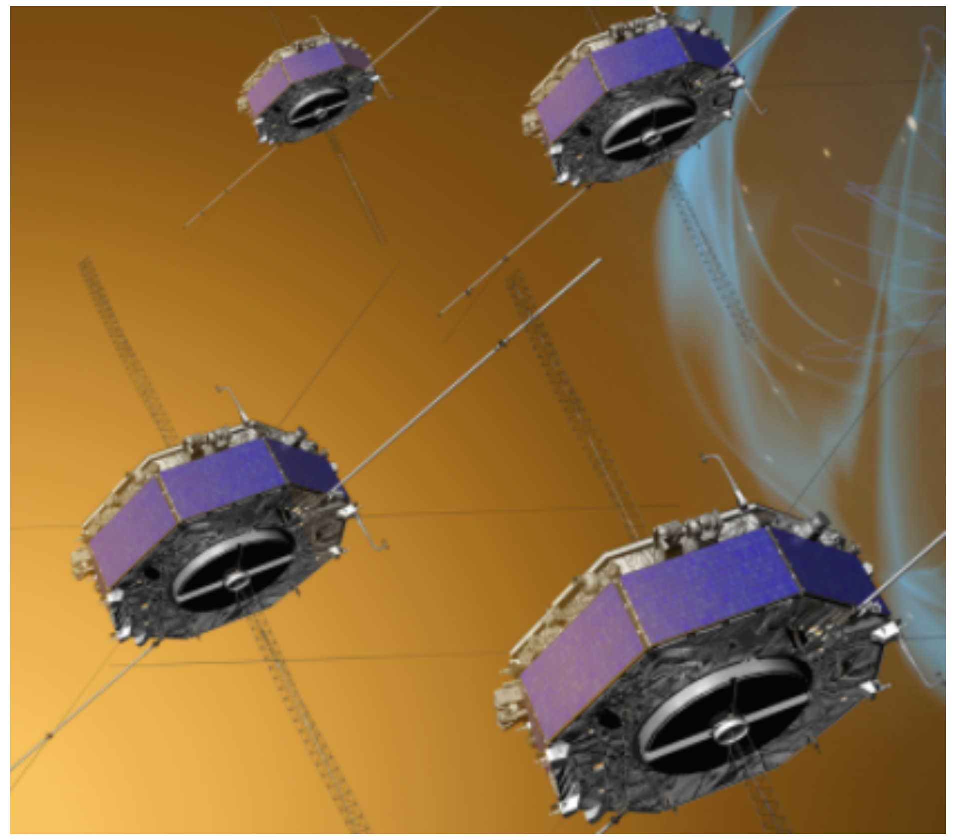
Parameter space covered by the Cluster satellites.

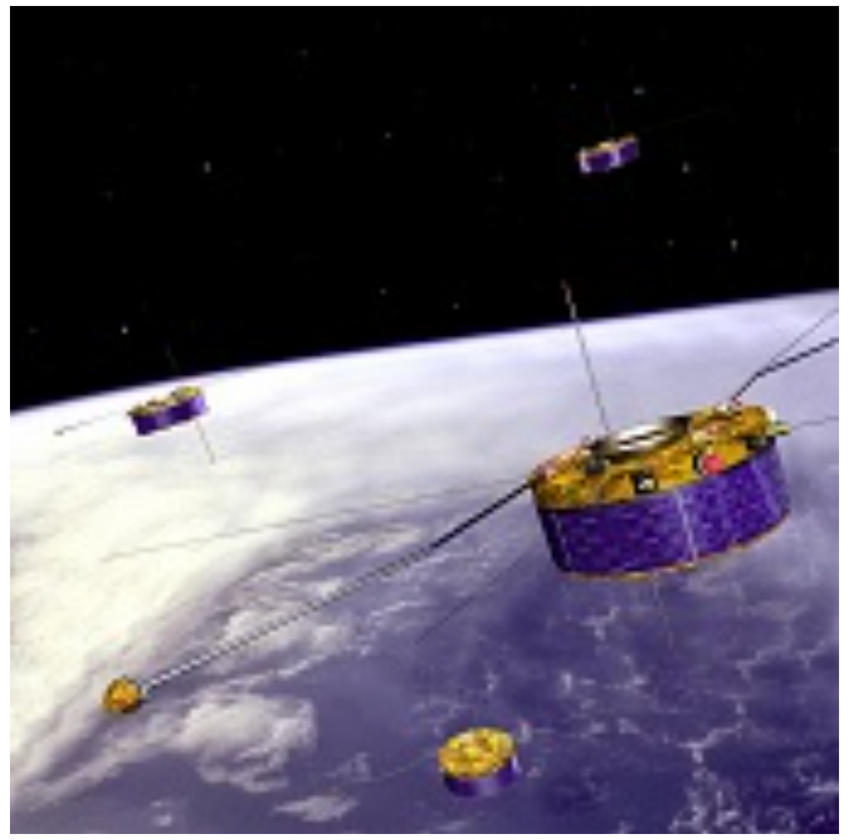


Courtesy of Colin Forsyth.

Plasma Observatory vs. State-of-the art

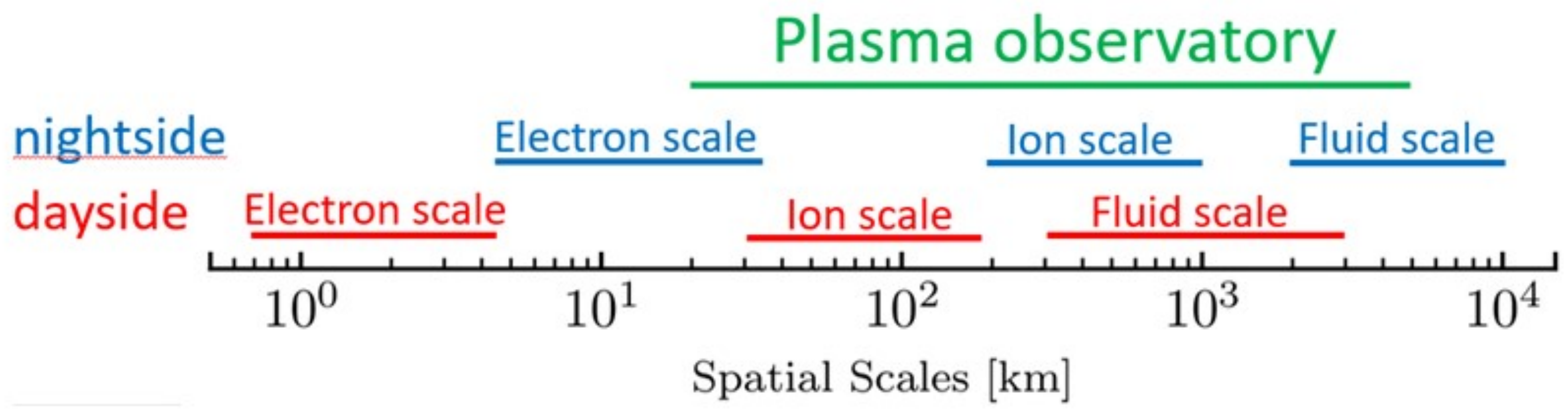
Electron scale — Ion scale — Fluid scale → Log scale

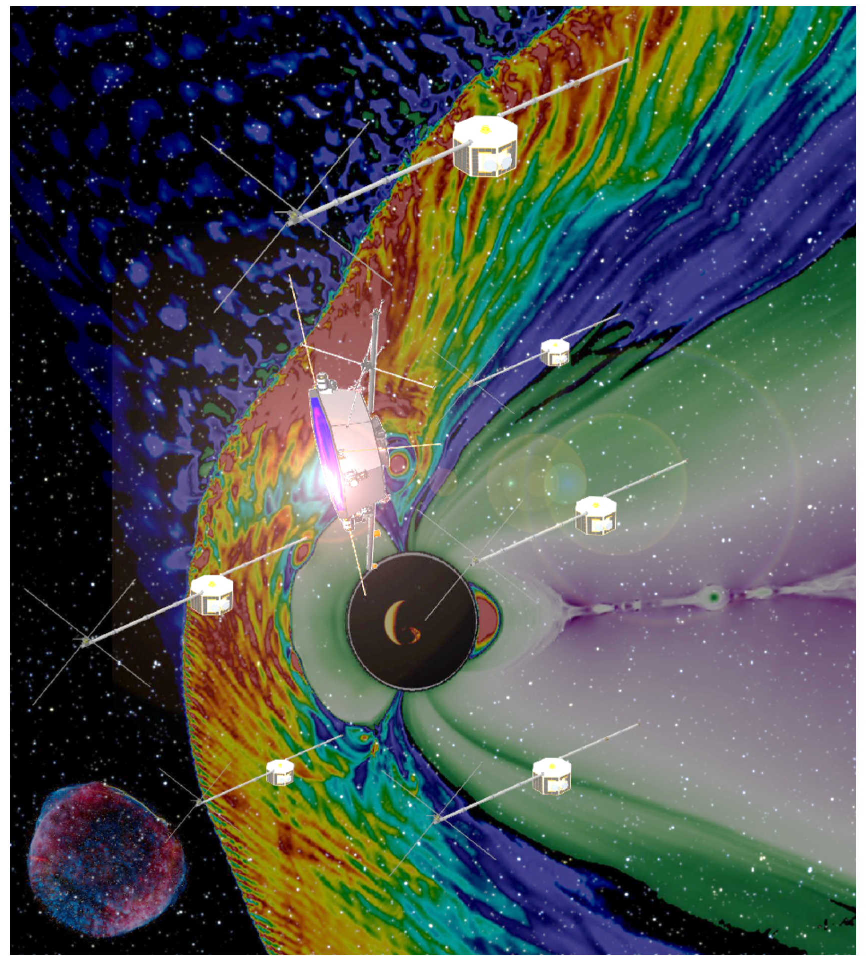




4-point measurements enable to study:

- 1 scale at a time
- 3D planar and stationary structures





7-point measurements required to study:

- Coupling between ion and fluid scales in 3D
- 3D non-planar and non-stationary structures

Plasma Observatory will allow this!

Science questions

Plasma energisation (Voyage 2050 theme: Plasma Cross-scale coupling)

SQ1. How are particles energised in space plasmas?

SQ1-1 At shocks?
SQ1-2 During magnetic reconnection?
SQ1-3 By waves and turbulent fluctuations?
SQ1-4 In plasma jets?
SQ1-5 How do different processes combine to energise particles?

Energy transport (Voyage 2060 theme: Magnetospheric Systems)

SQ2. Which processes dominate energy transport and drive coupling between different regions of the Earth's Magnetospheric System?

SQ2-1 How do plasma jets interact with the Earth's dipole field in the transition region?
SQ2-2 How do field-aligned currents connect different regions of the Magnetospheric System?
SQ2-3 Which are the key plasma instabilities involved in energy transport?
SQ2-4 How is energy flux partitioned in different energy transport processes?

See also: ESA Voyage 2050 White Papers by A. Retinò et al. and by J. Rae et al.
D. Verscharen, ..., A. Retinò, A. Simionescu et al., The Plasma Universe: A Coherent Science Theme for Voyage 2050, Front. Astron. Space Sci., 2021

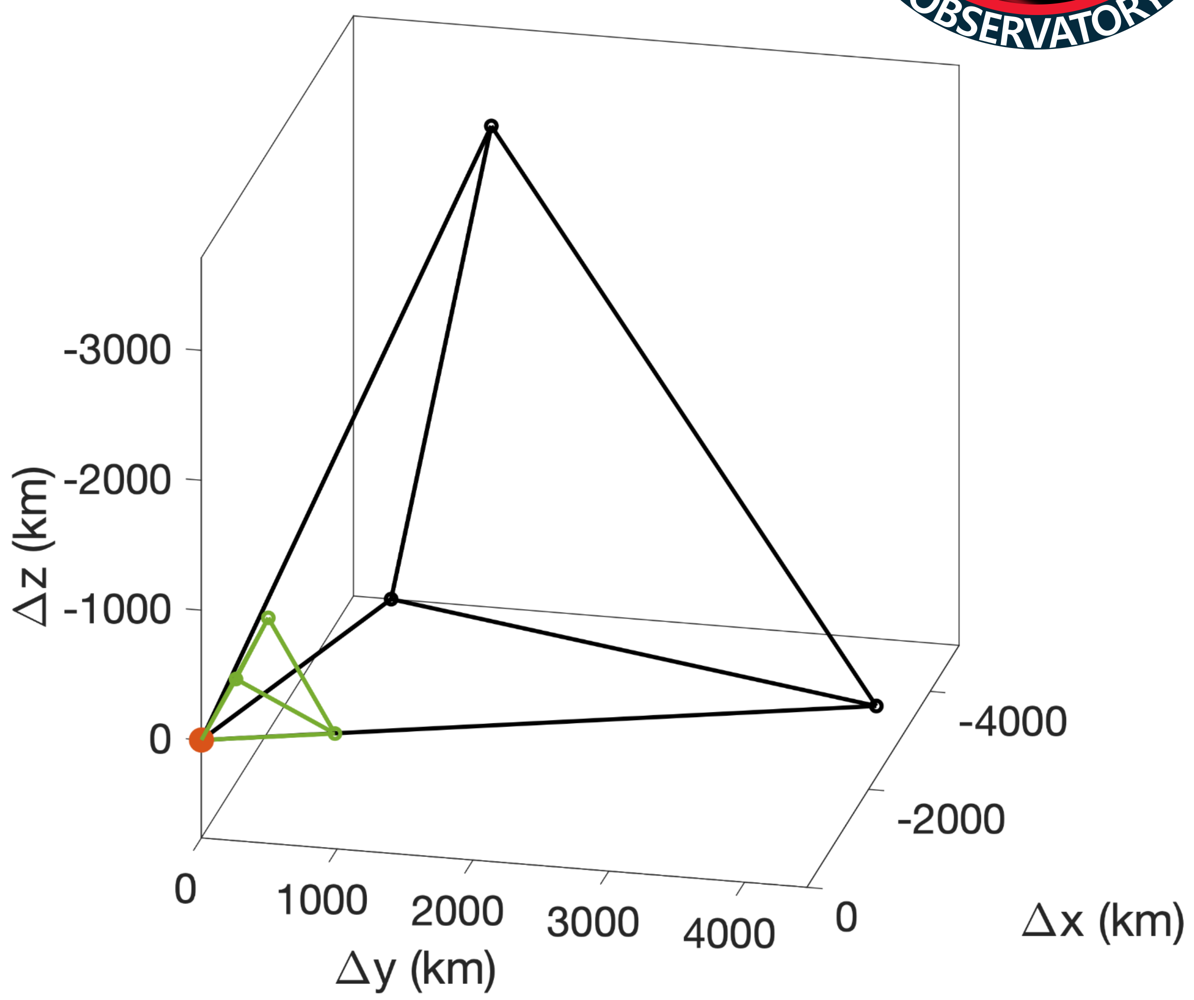
Plasma Observatory: Mission profile

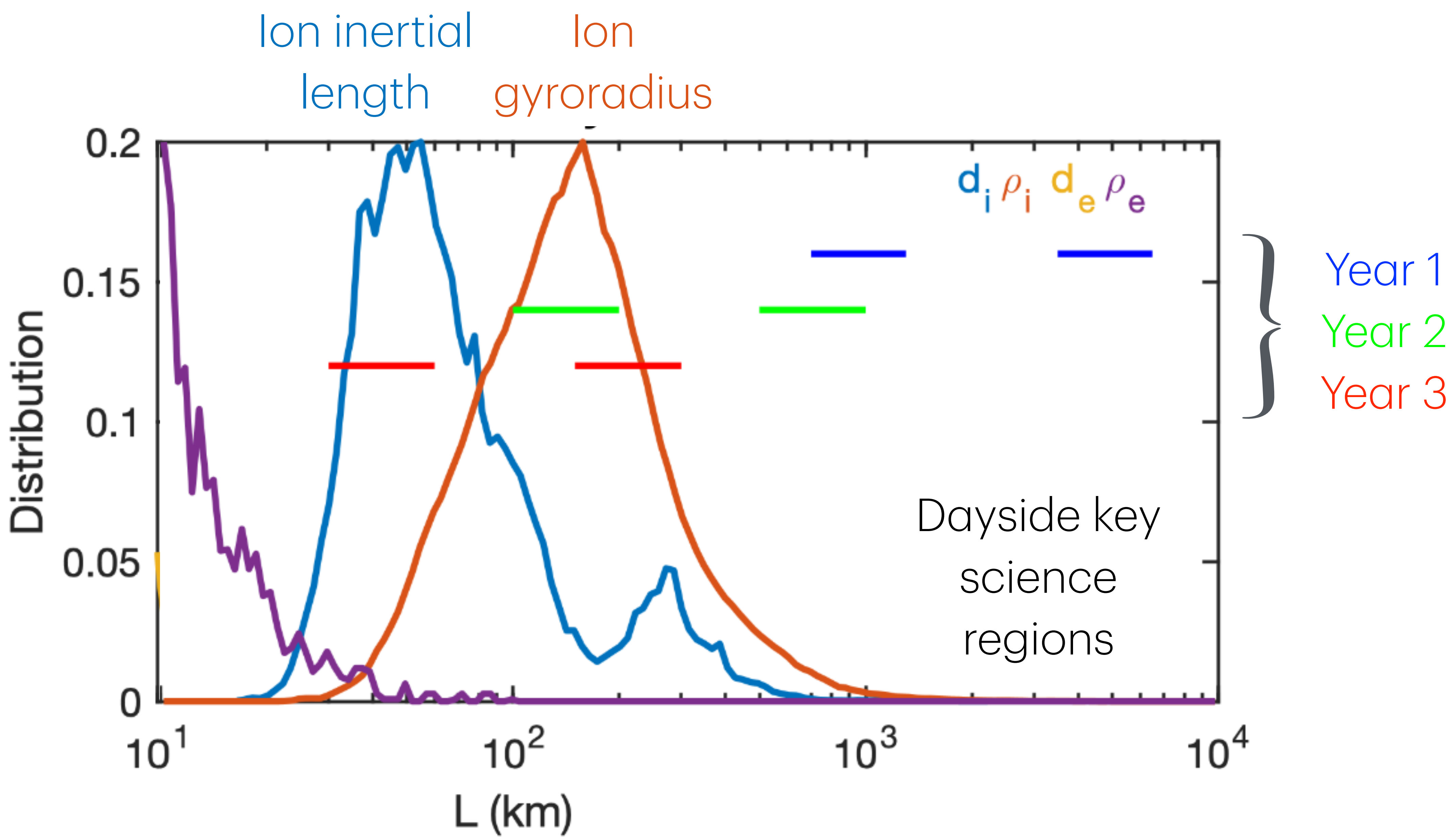
Orbit (baseline). Equatorial HEO 8 x 17 RE with 15° inclination

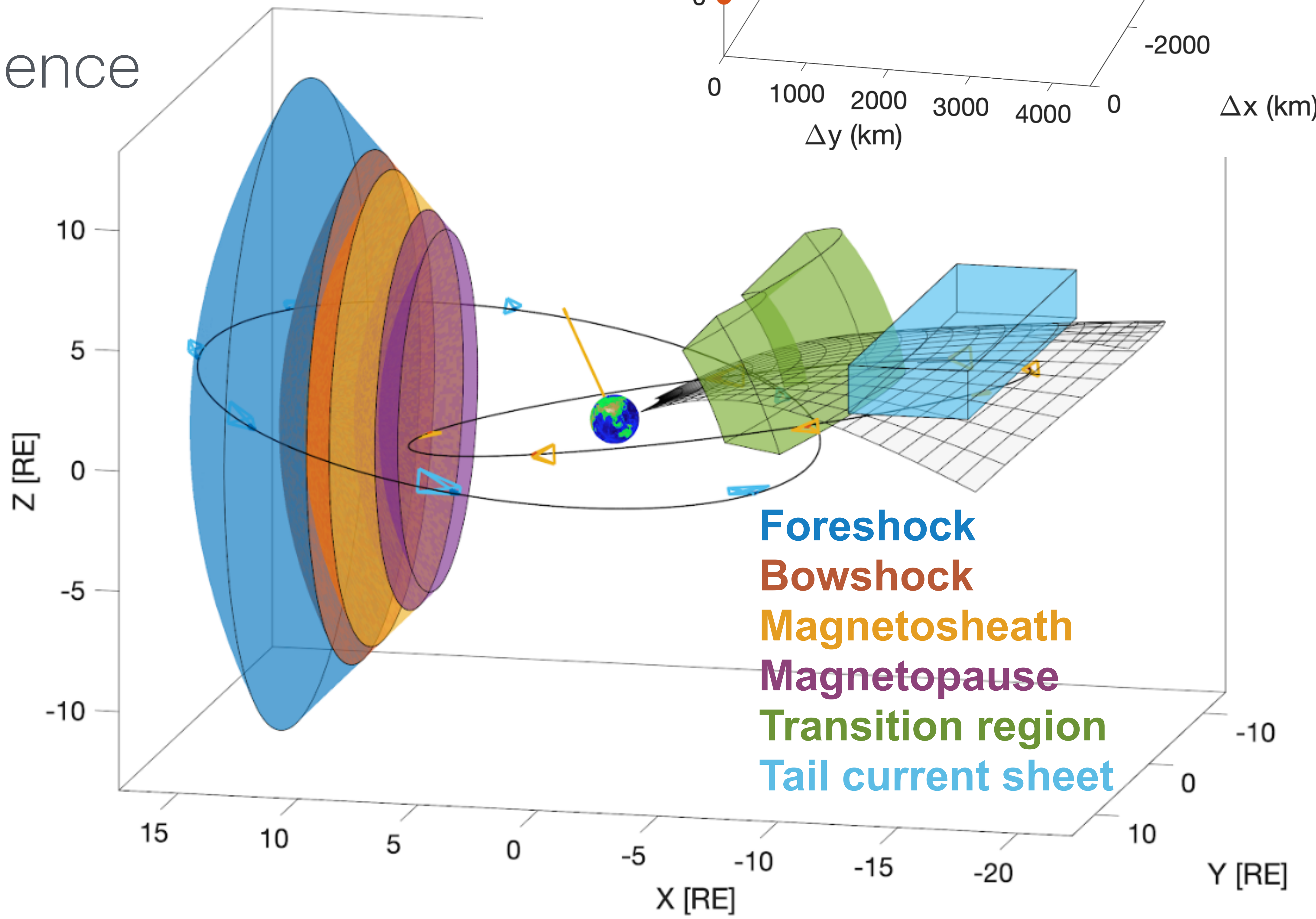
Number of spacecraft. 7 identical smallsats.

Constellation. Two nested tetrahedra sharing one corner.

Mission nominal duration and phases. 3 Nominal Science Phases (NSPs) of 11 months duration.







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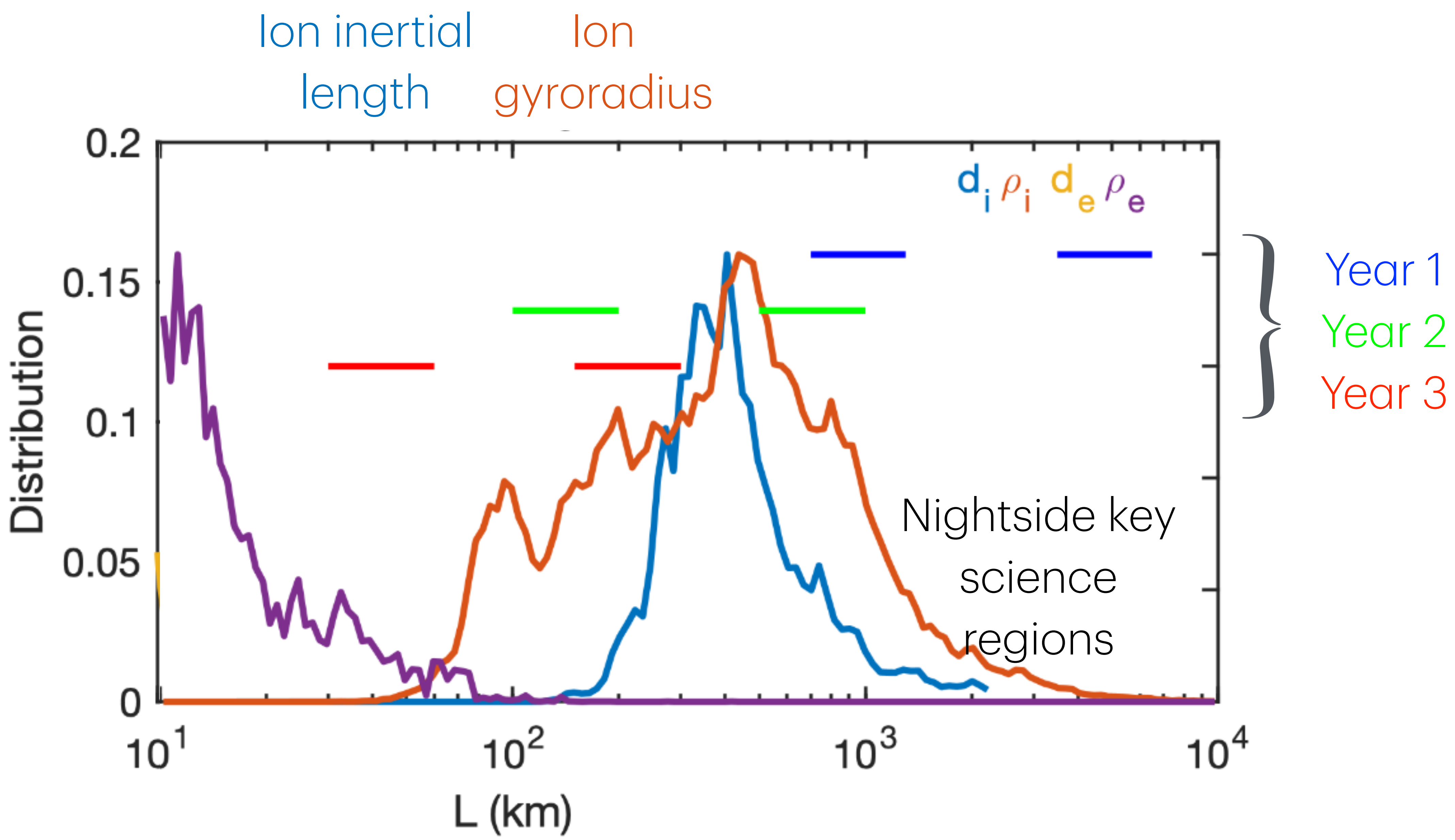
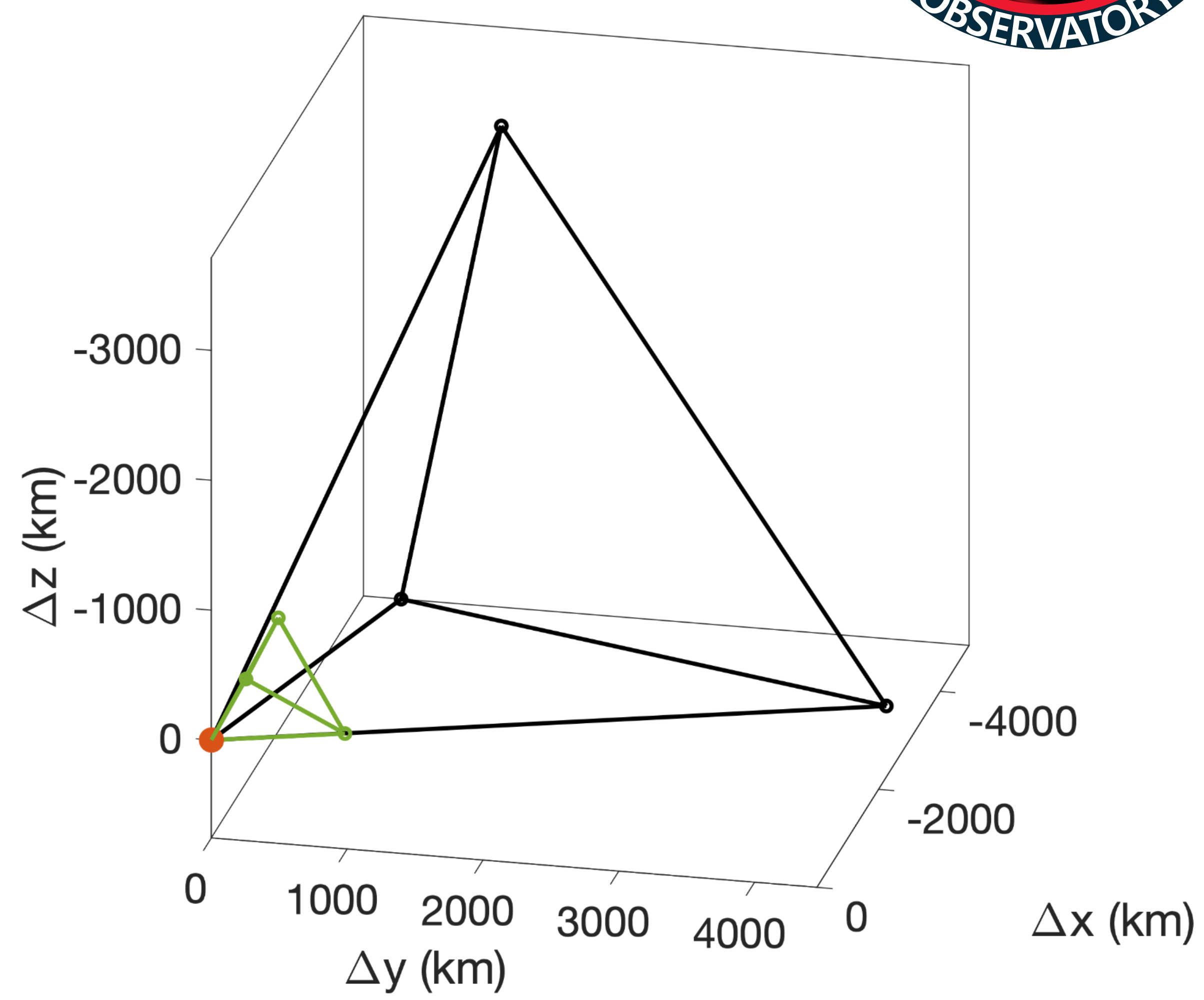
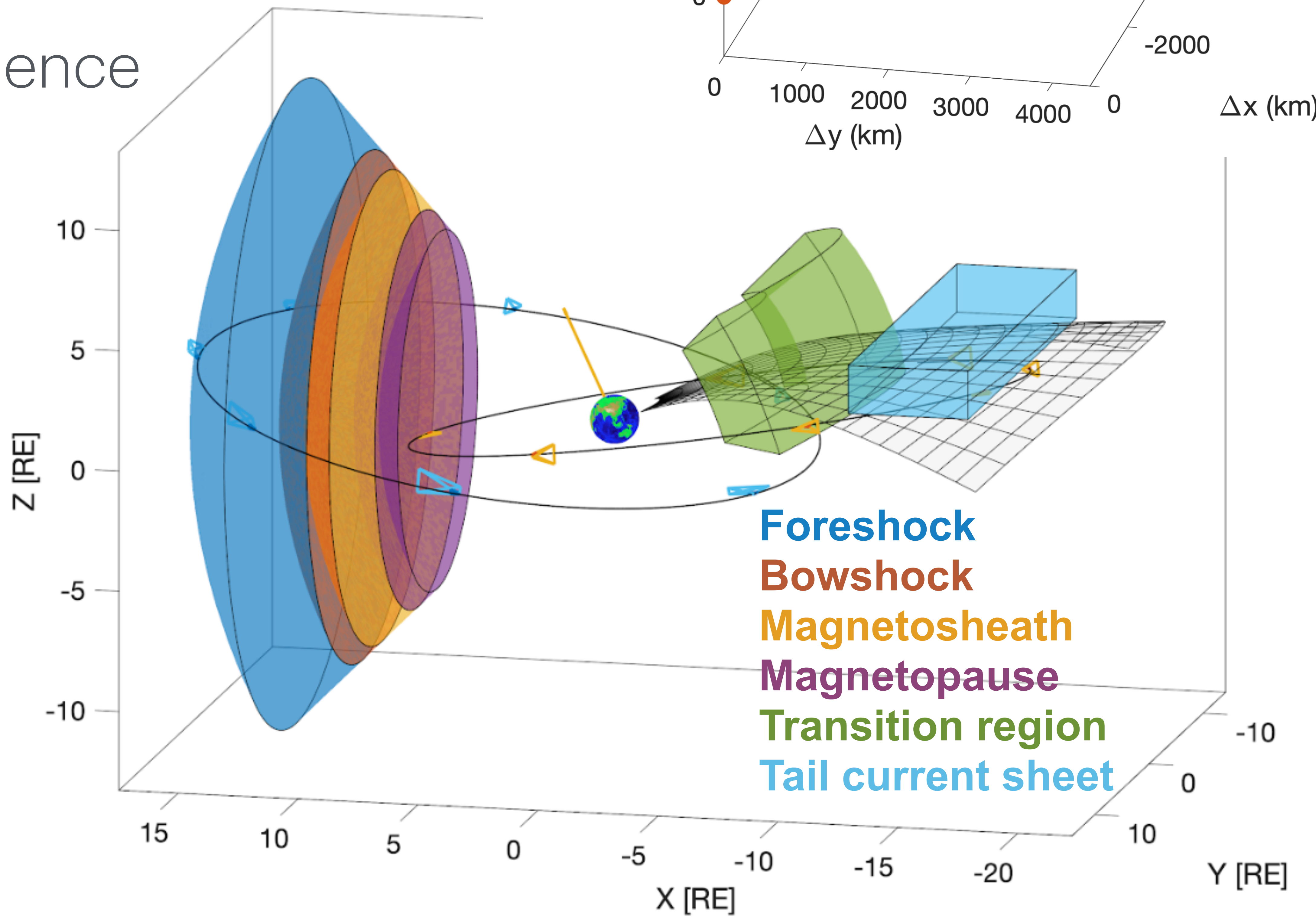






Unresolved questions regarding multi-scale physics of magnetic reconnection

Ion-electron coupling — e.g. Hall dynamics inside and outside of the diffusion regions

Reconnection **intermittency** — onset and cessation, dissipation of islands

Reconnection in **turbulence** — What large-scale structures (boundary conditions) do magnetic reconnection have to adapt to

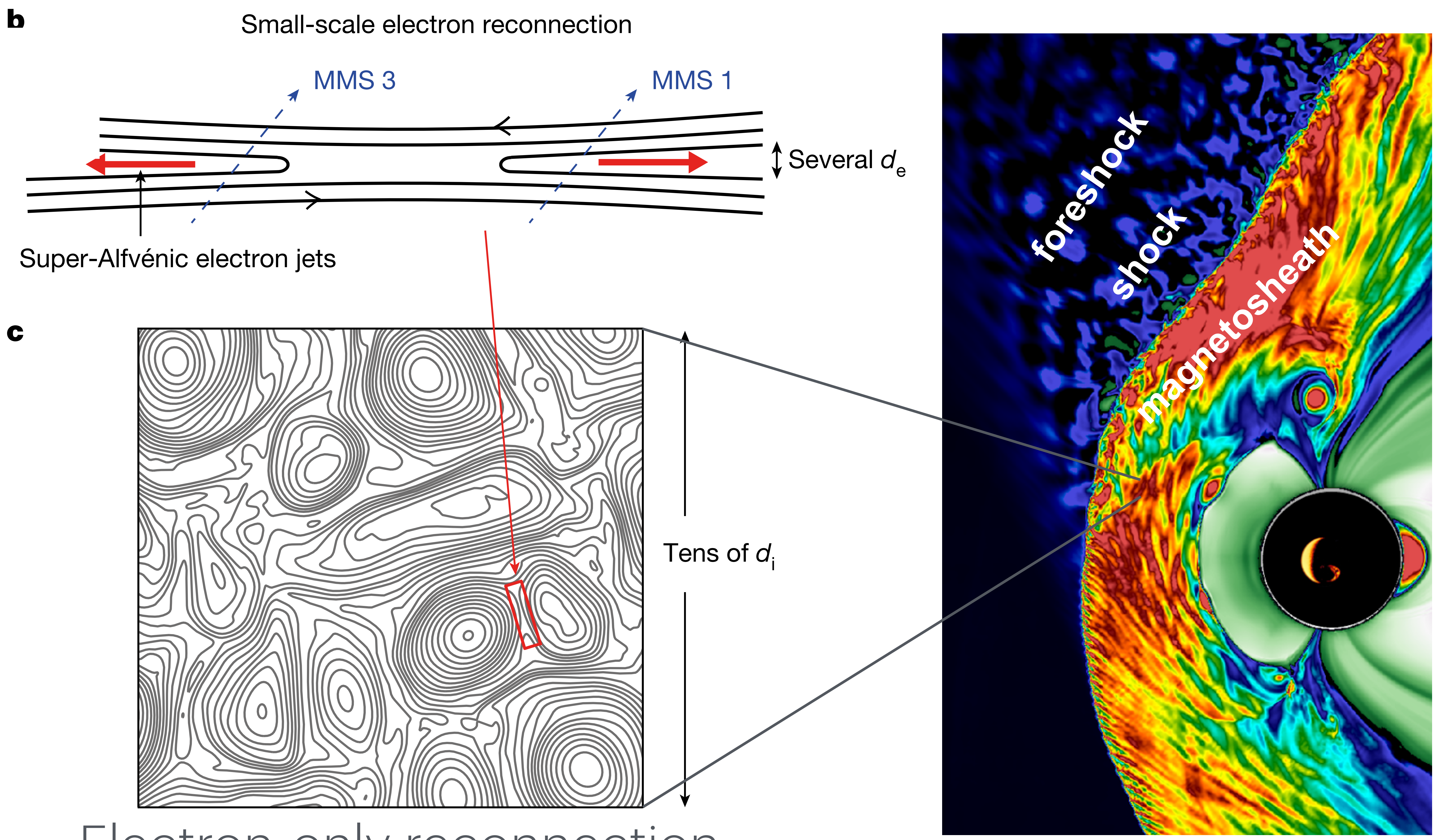
Dependence on **upstream conditions** — temporal scales in the magnetosheath can be as low as 1s to a fraction of a second — we need multiple points to know the upstream and downstream simultaneously

Energisation in dynamic and quasi-stationary structures — plasma jets, islands/flux ropes, magnetic bottles

Reconnection in turbulence

(in a constrained environment)

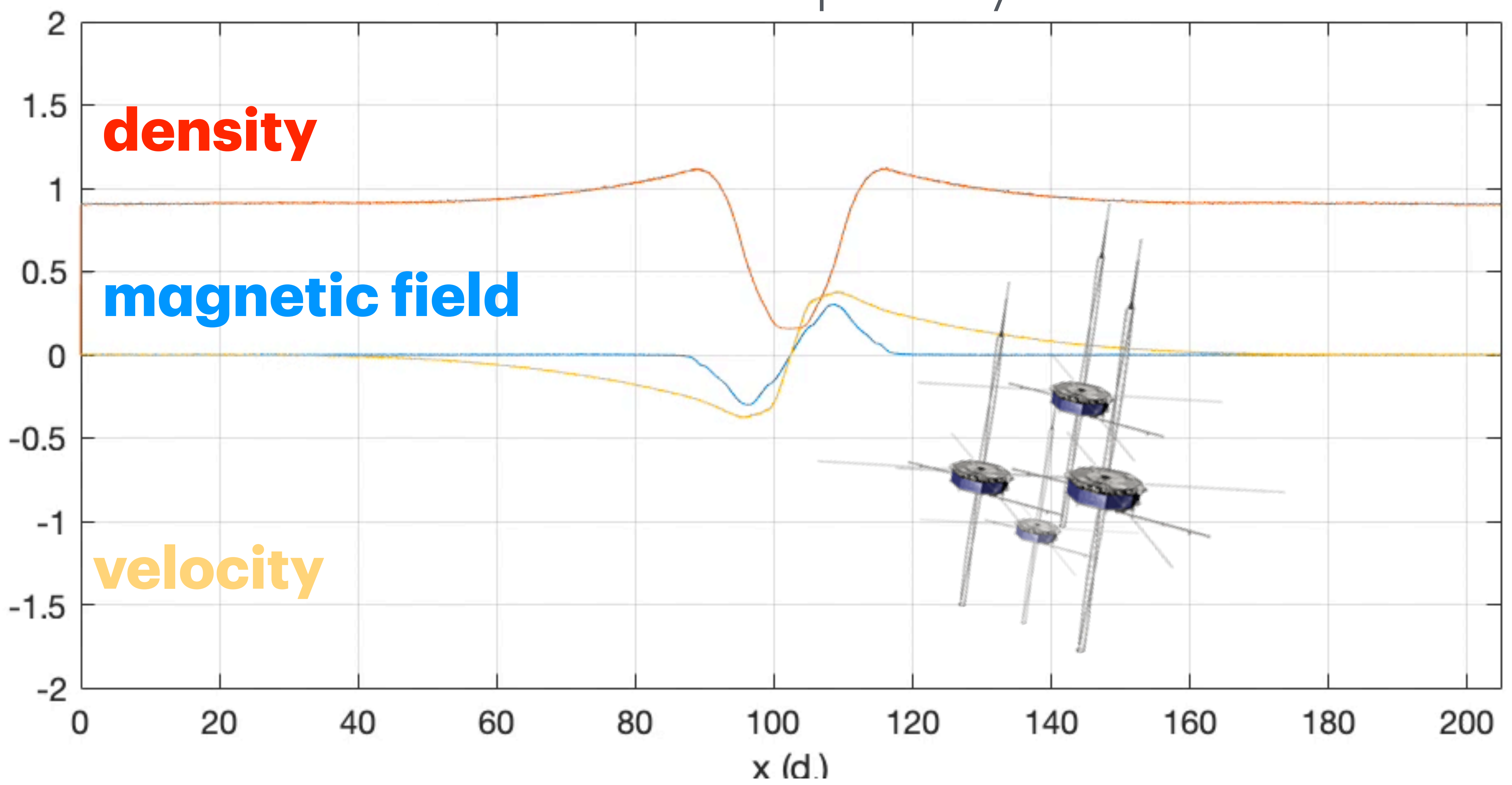
- Magnetic reconnection could account for 20% of turbulent dissipation in the magnetosheath (Stawarz et al., 2022).
- What large-scale structures (boundary conditions) do magnetic reconnection have to adapt to?



Electron-only reconnection
Phan et al., 2018

Ion-electron coupling and temporal evolution

Formation of reconnection jet fronts in an open system



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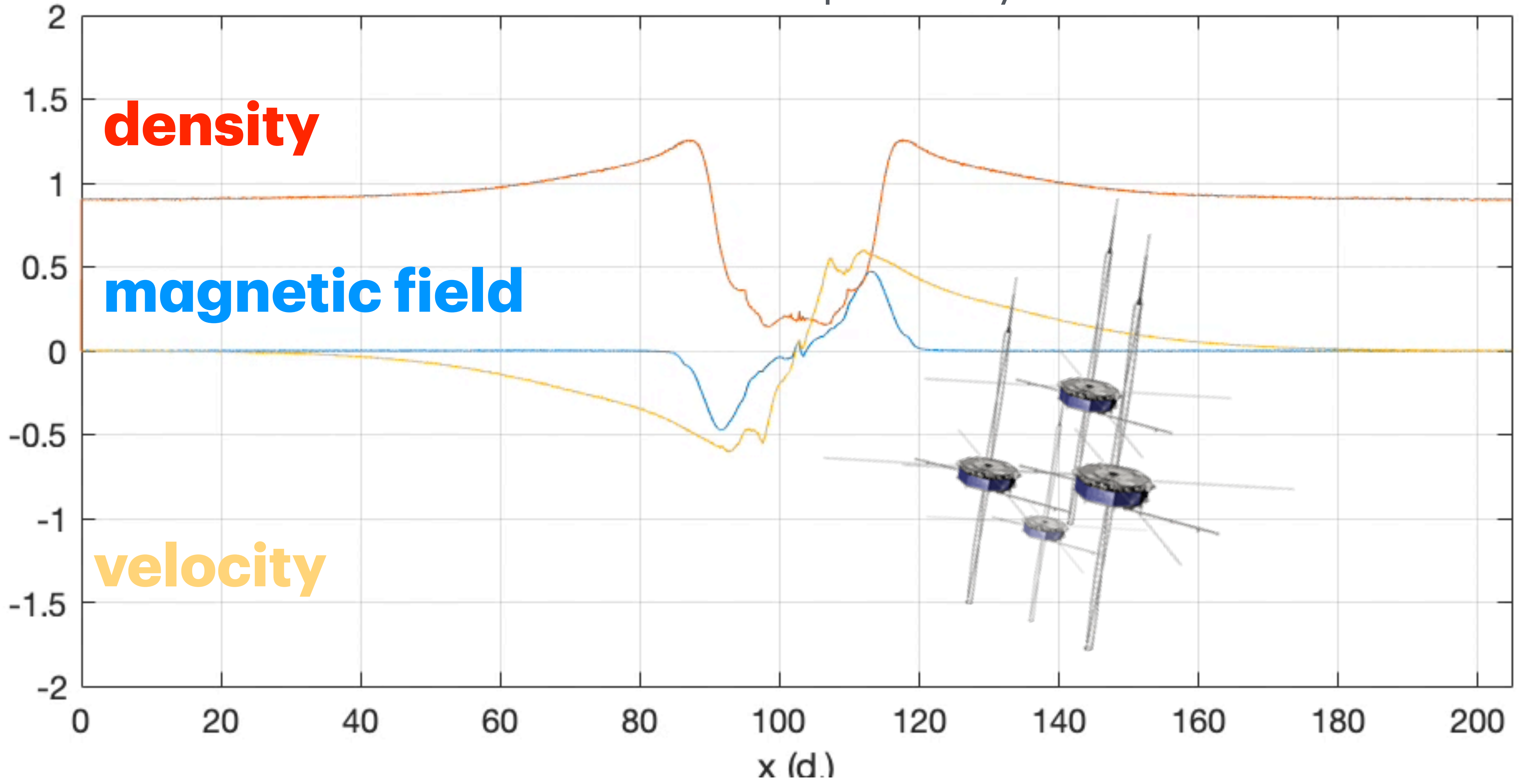

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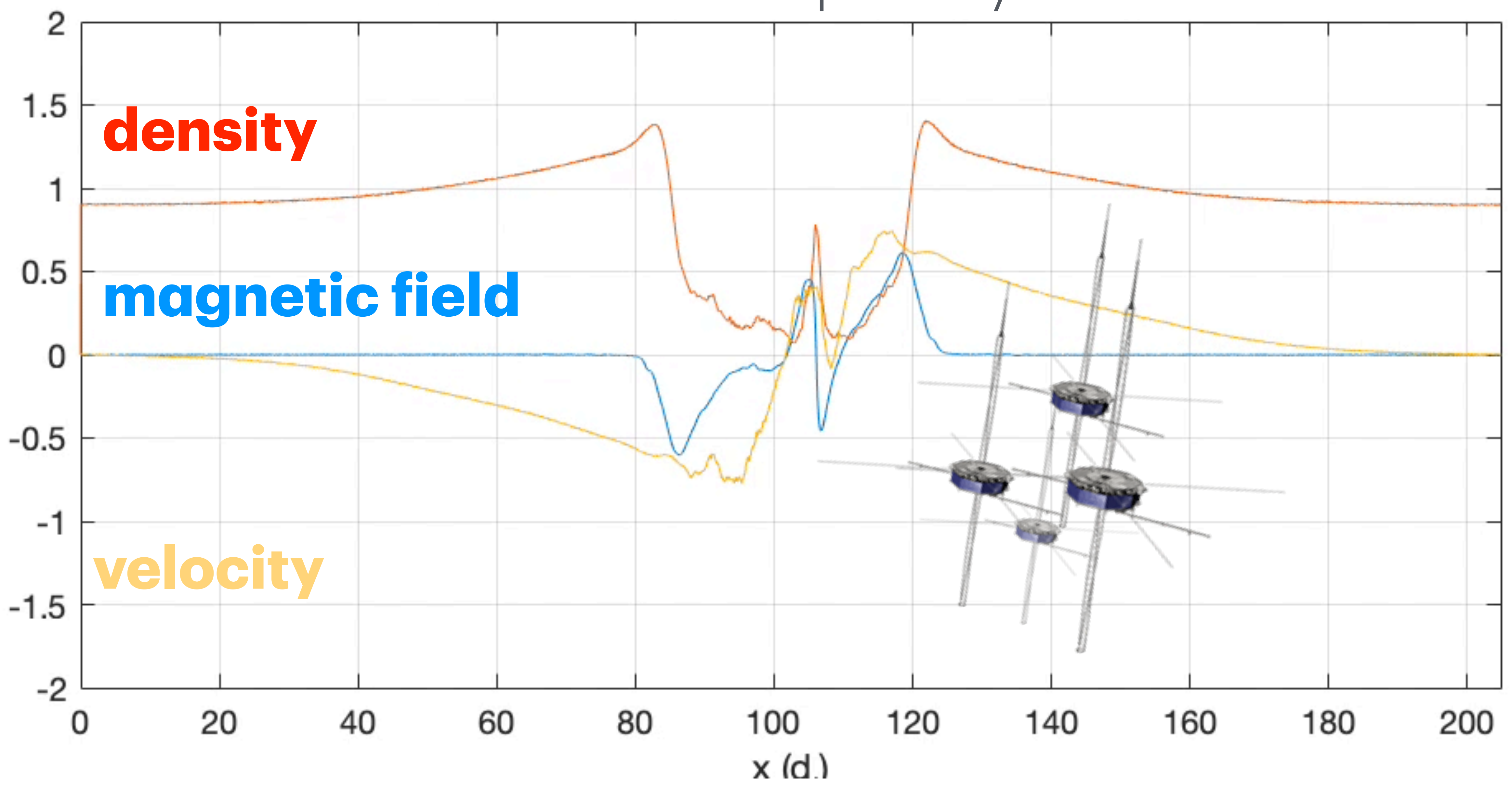

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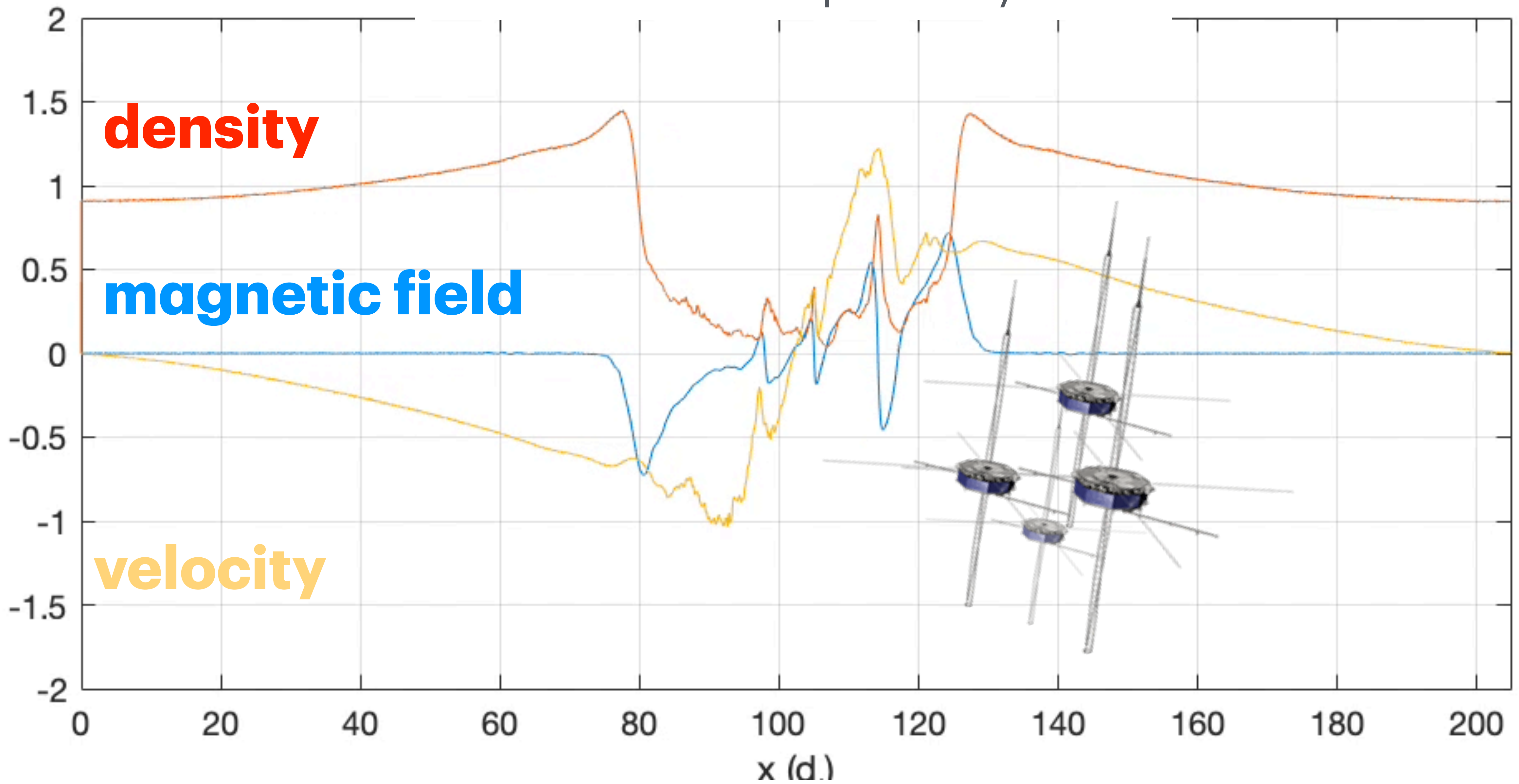

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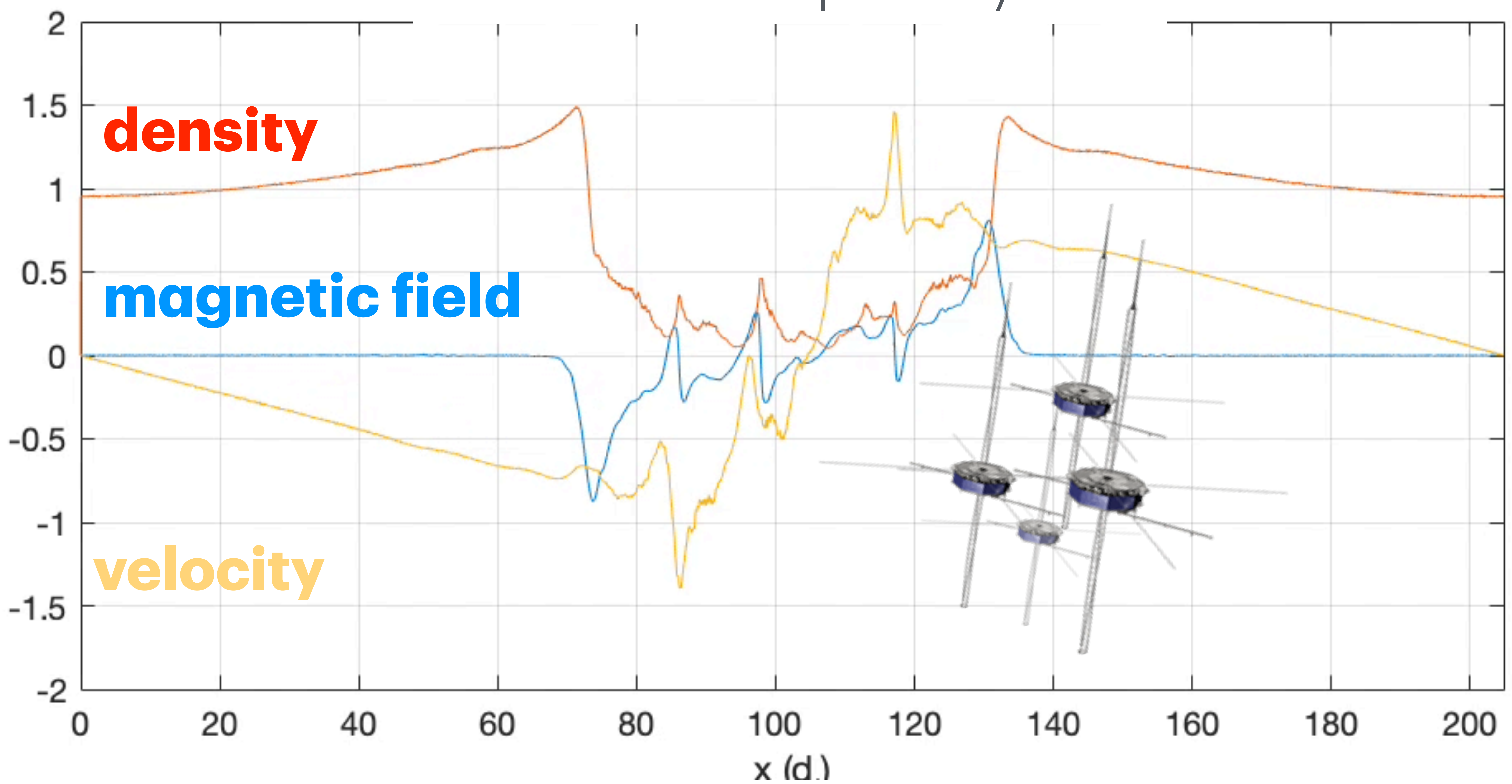

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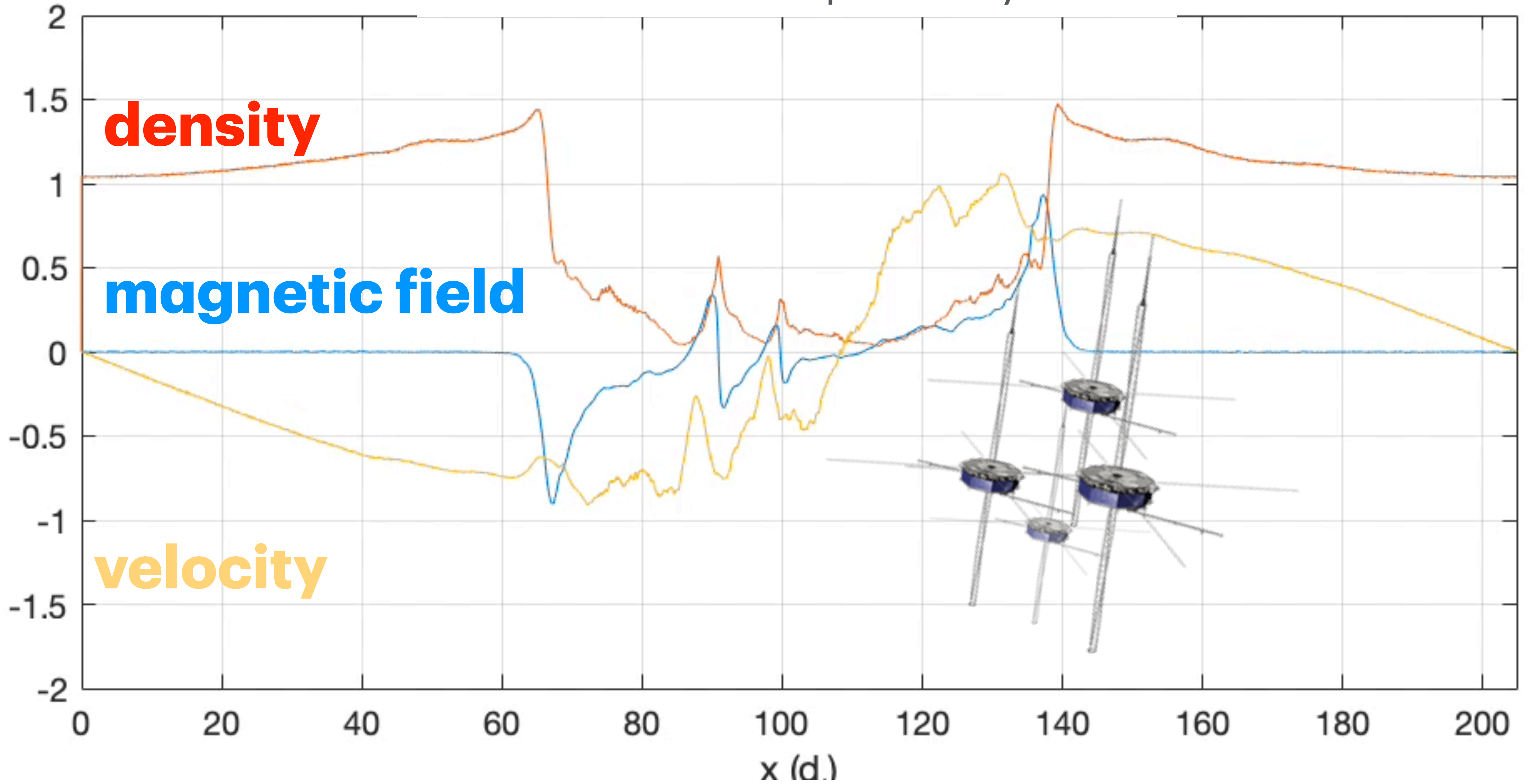

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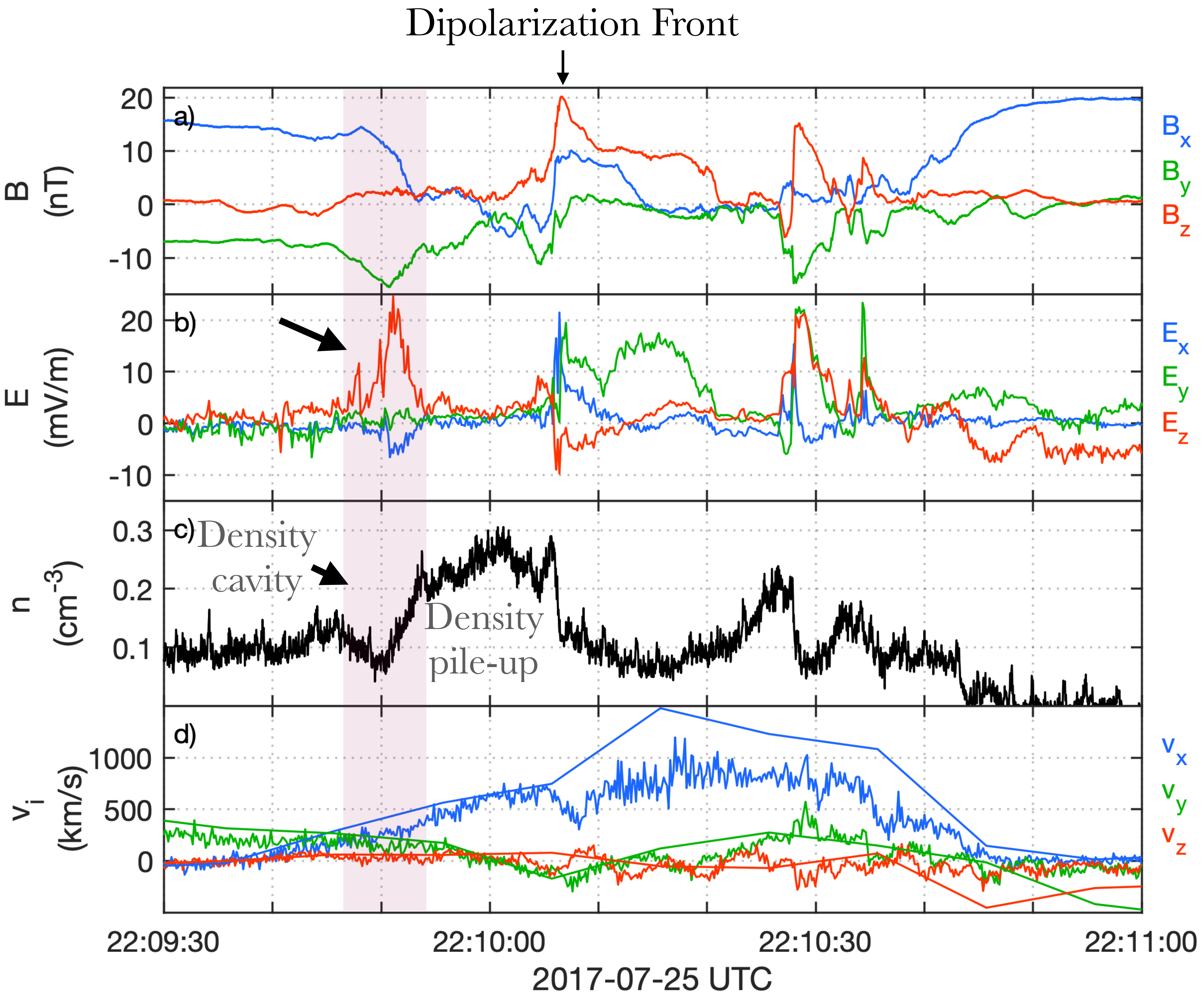

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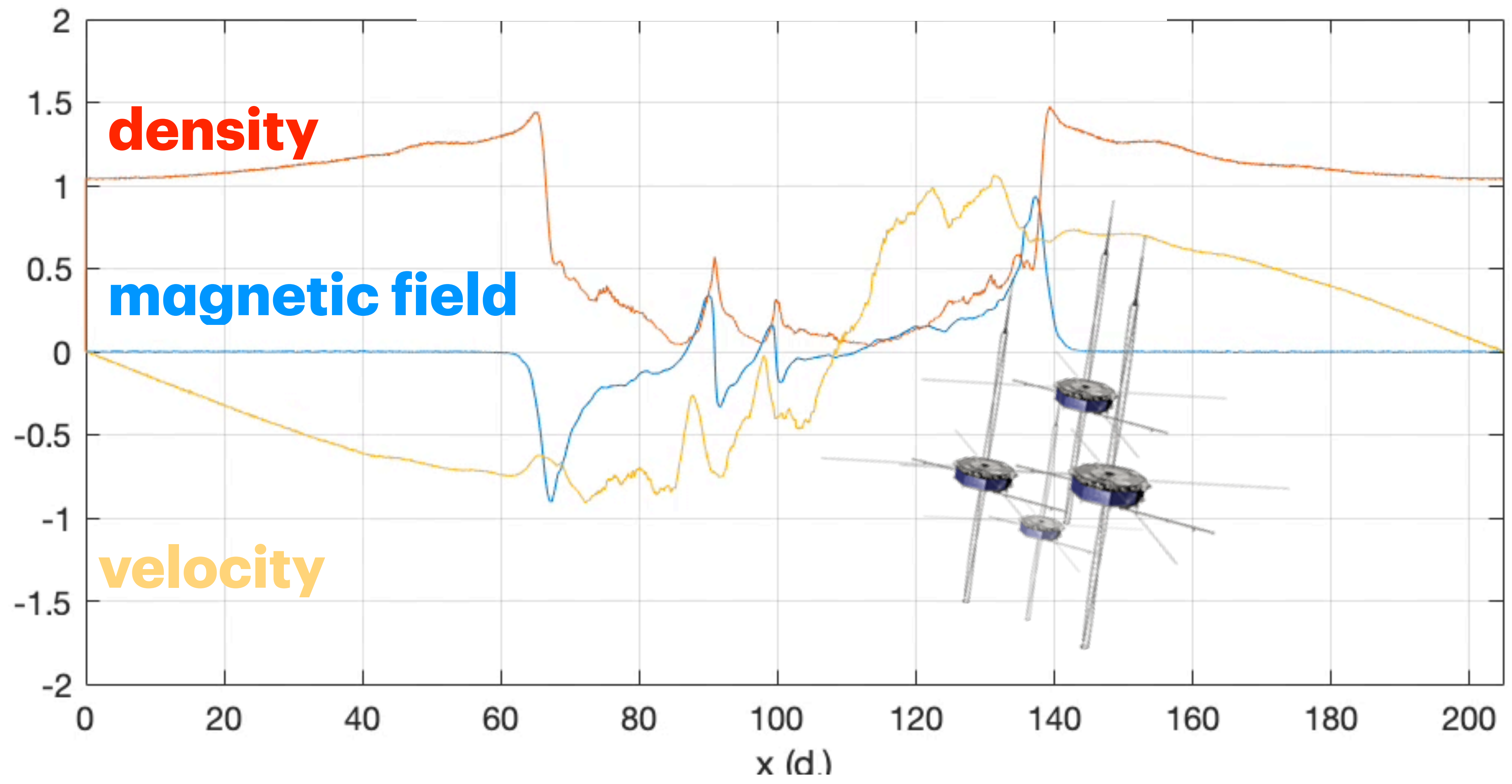

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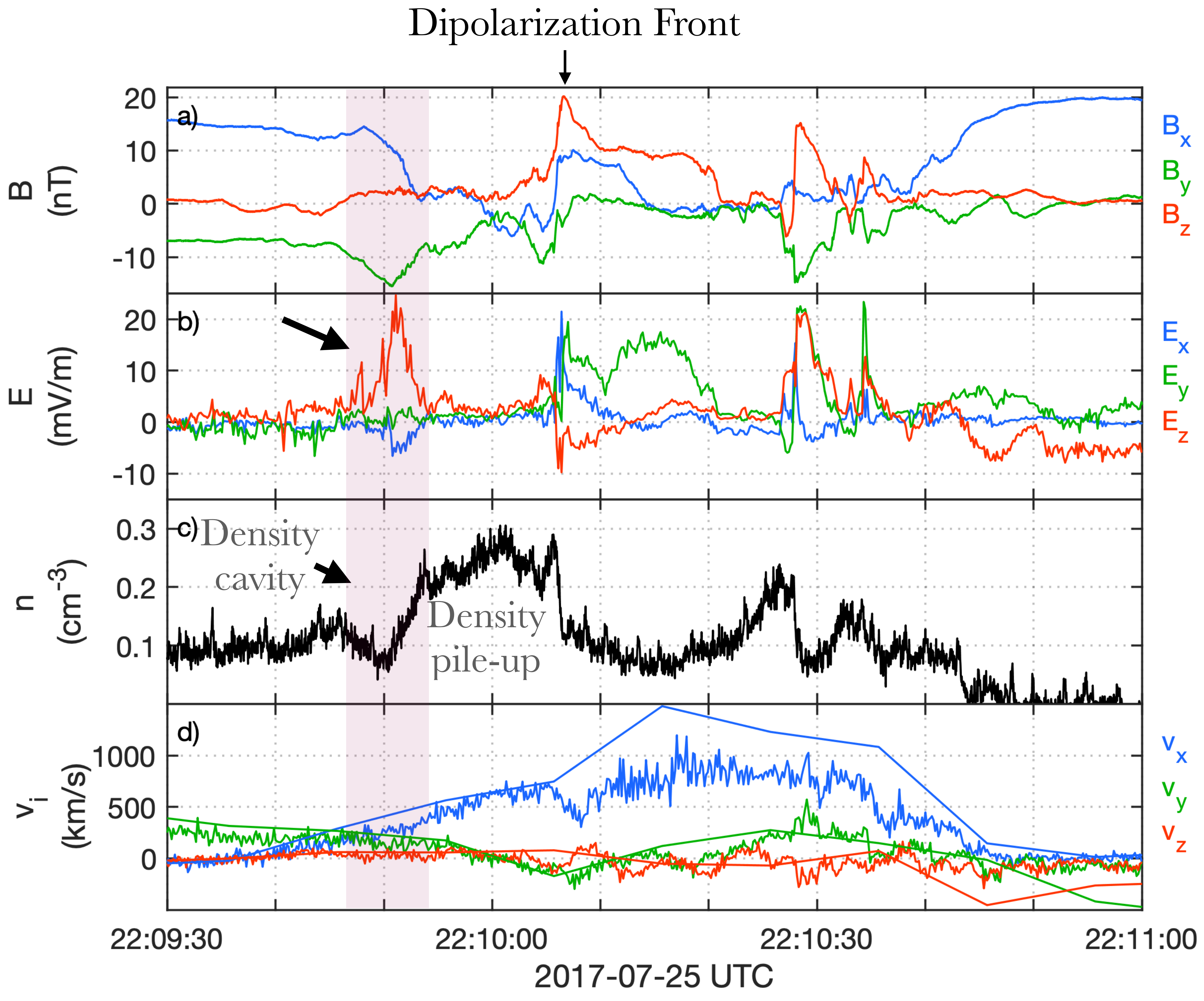
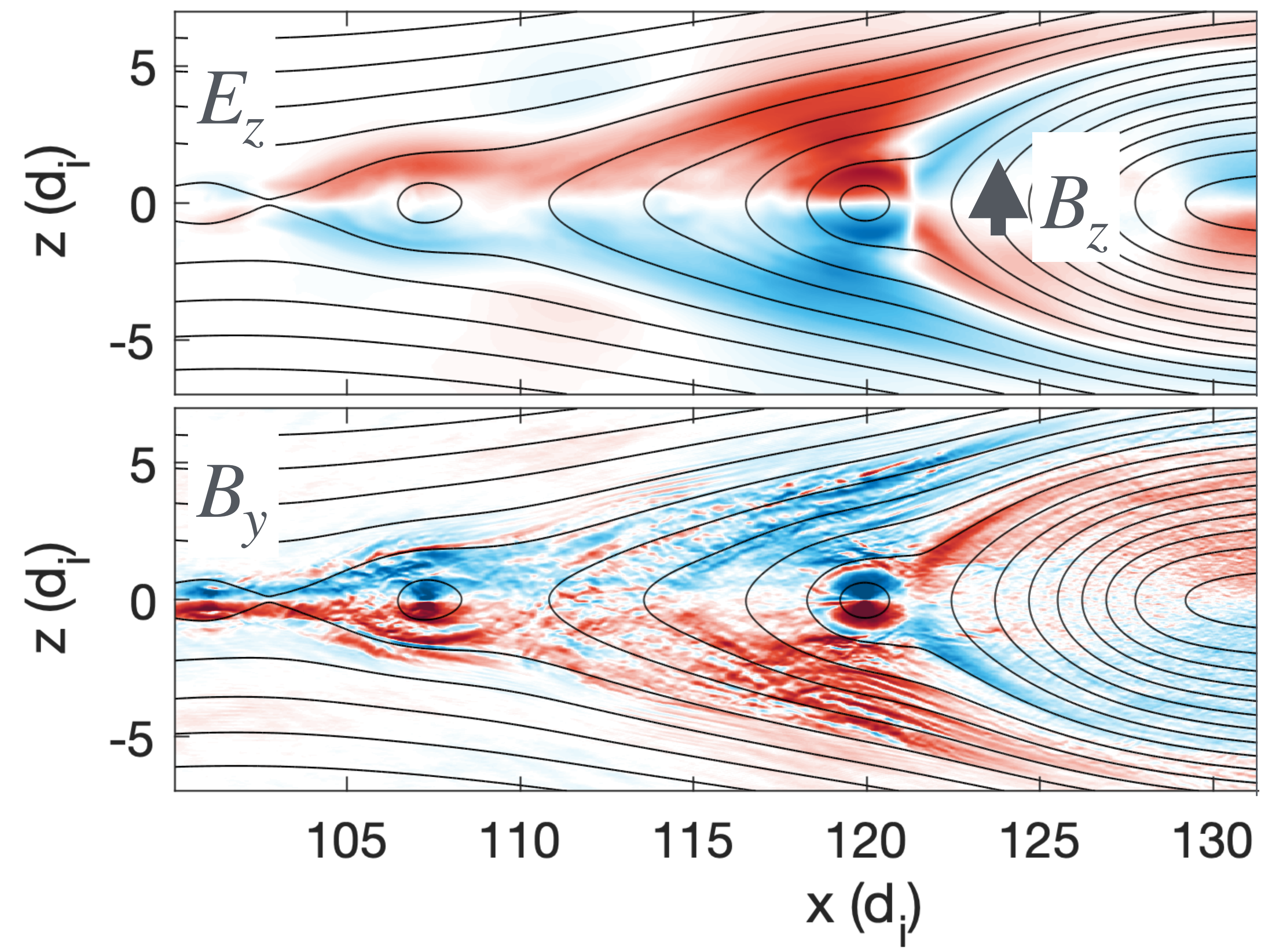


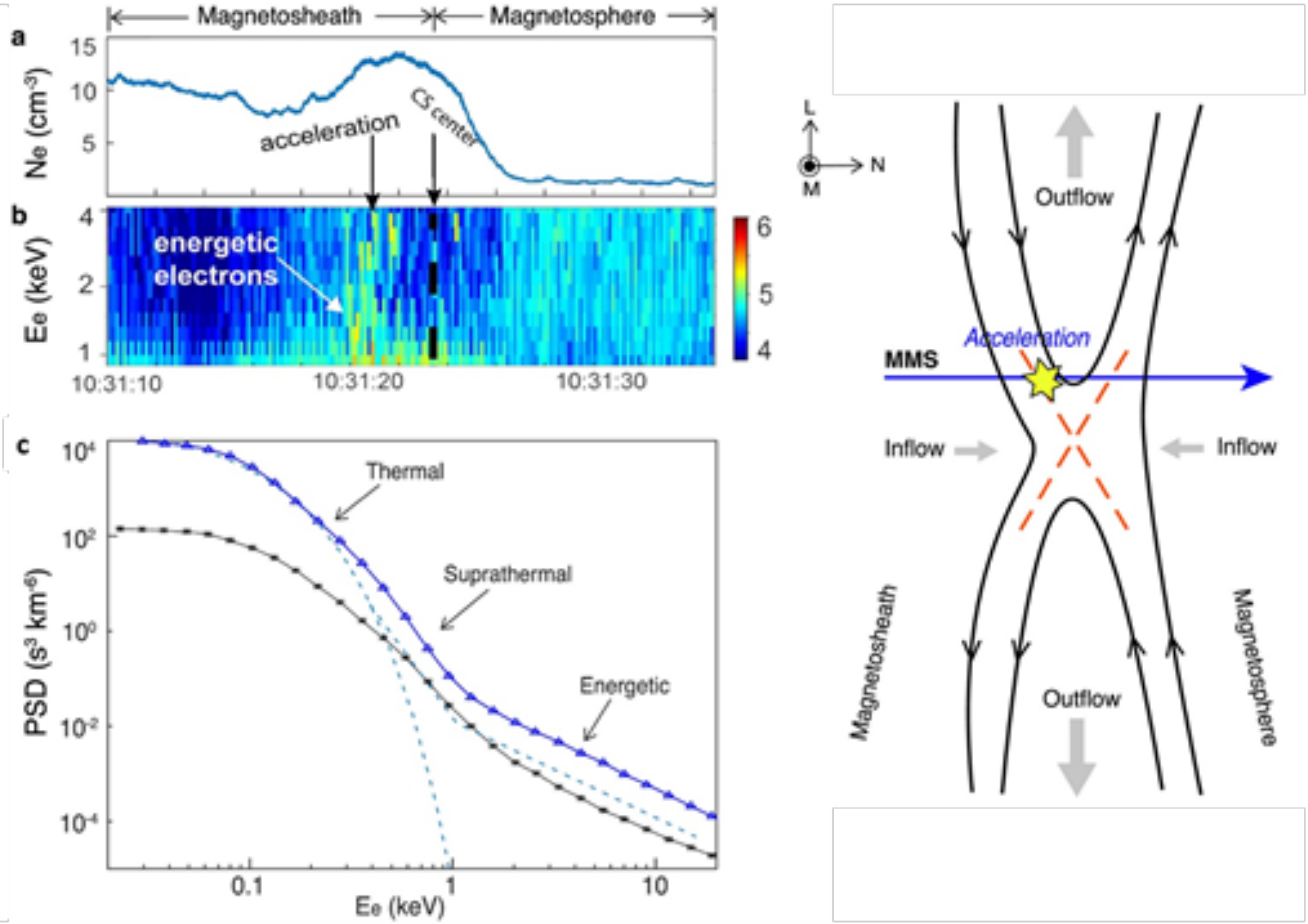
- E.g. Hall dynamics inside and outside of the diffusion regions
- Here, E_z and B_y have the 'wrong' sign — what is the fluid/ion-scale structure of this region?



Energetic electron acc. at X-points

- Energetic energisation is more common during unsteady magnetotail reconnection than steady magnetopause reconnection.
- Is steady reconnection efficient to accelerate energetic electrons and which are the acceleration mechanisms ?
- MMS observations are essentially single point: $\rho_e^{energetic} \sim L_i$,
- Cluster could only access a single scale, and often with insufficient time resolution
- Simultaneous **7-point measurements at ion and fluid scales** required to resolve the large-scale conditions of acceleration while identifying the acceleration mechanisms at small scales.

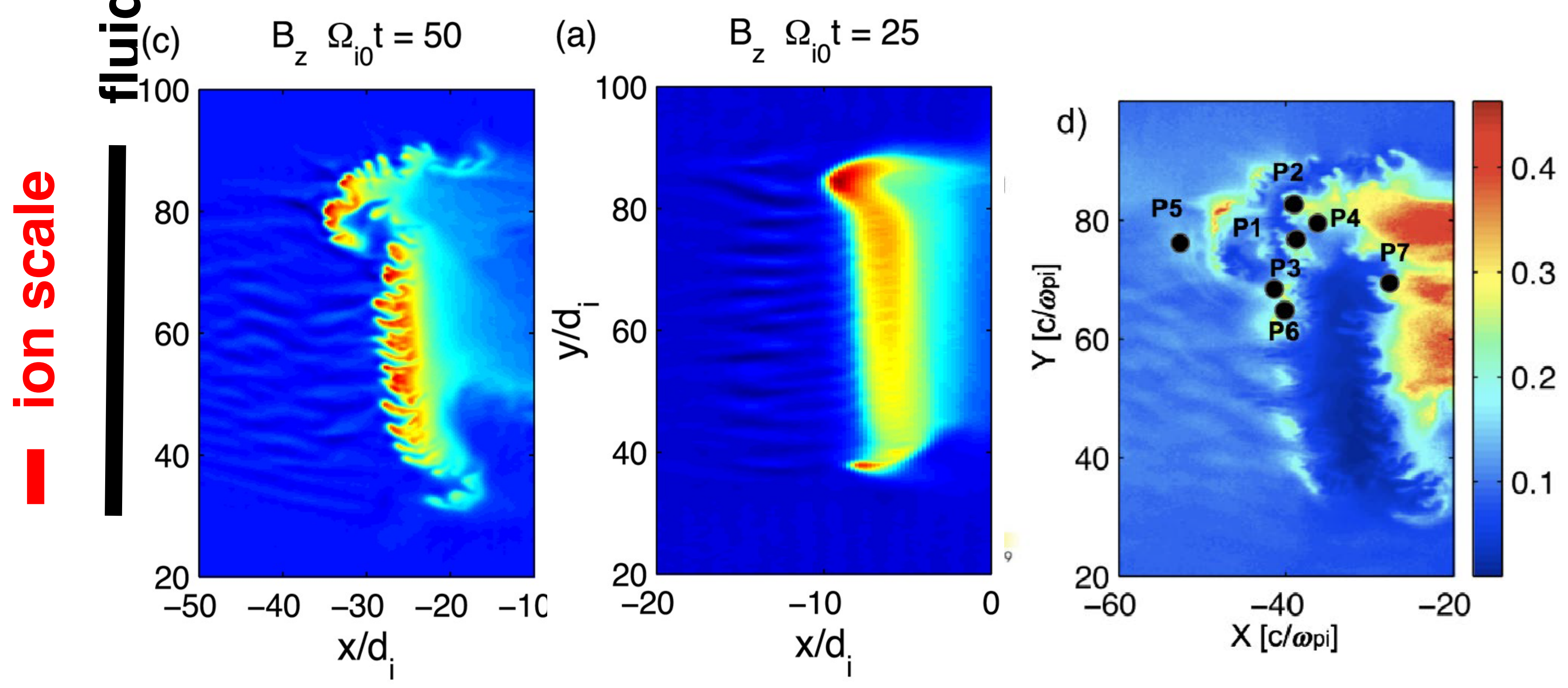
Energetic electron acceleration during magnetopause reconnection. Adapted from Fu et al., GRL, 2019



Astro implication: advance significatively in our understanding of electron acceleration in reconnection regions. Relevant for solar and stellar flares.

Electron energization at plasma jets

Spatio-temporal evolution of jet



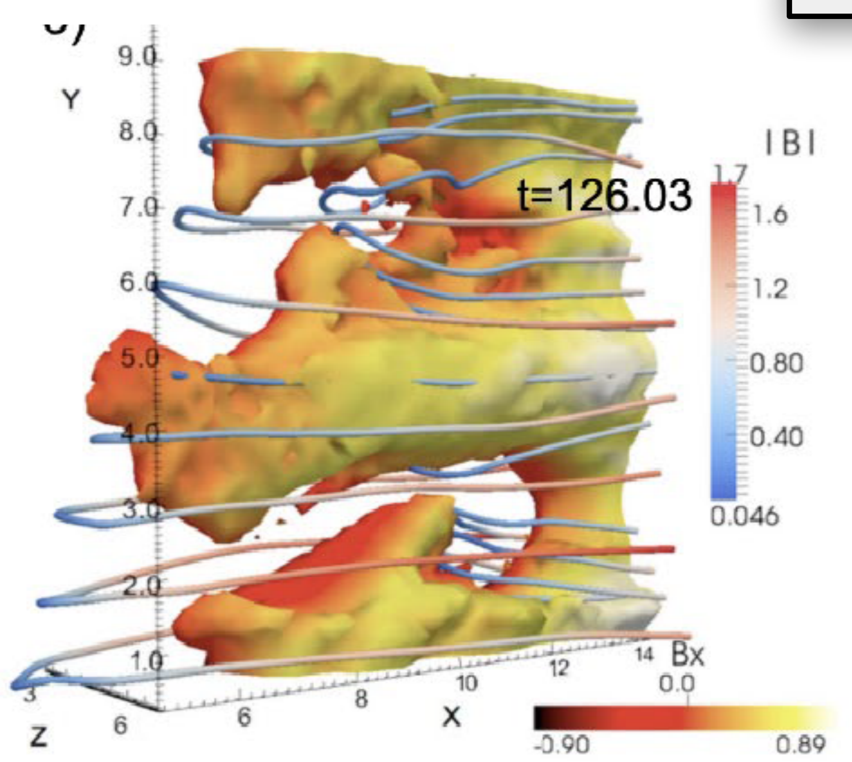
PIC simulations [Pritchett, JGR, 2016]

Electron energization in non-linear and non-stationary 3D structures at ion kinetic scales driven by dynamics at fluid scales.

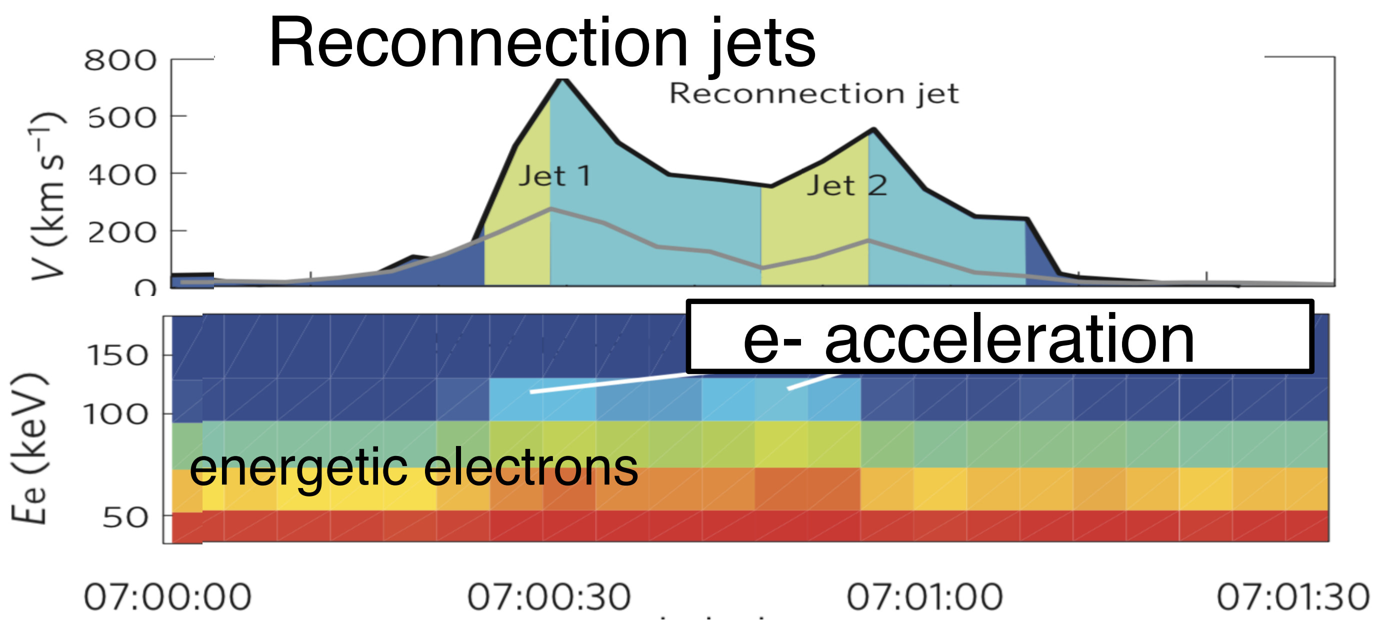
- Large-scale electron energization at jet fronts from adiabatic betatron and Fermi mechanisms.
- Jet fronts can be very structured due to instabilities and can become turbulent. 3D structures at ion kinetic scales, including reconnection sites, are also important sites of energization.

Jet structure

Qualitative evidence of Fermi and betatron mechanisms at fluid scales yet scale coupling between fluid and ion kinetic scales not understood

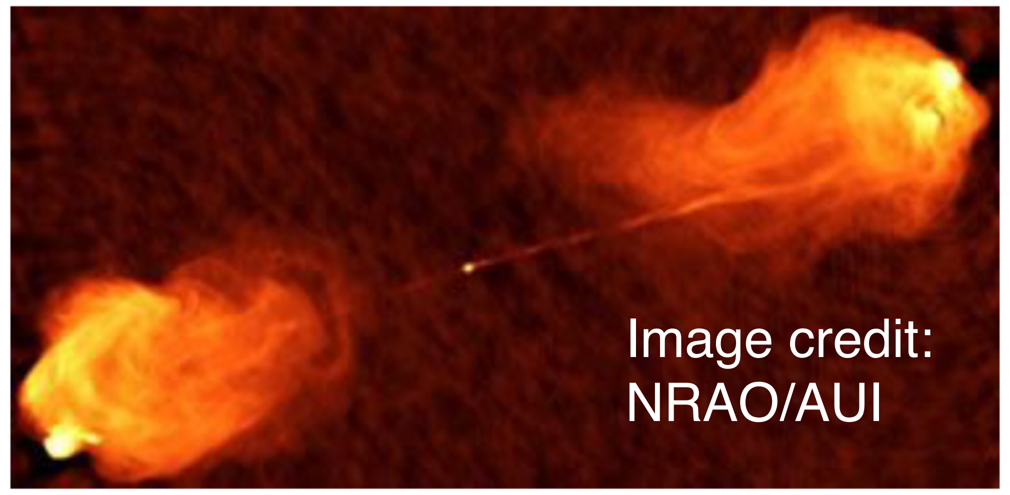


MHD simulations [Lapenta+, GRL, 2019]



Cluster data [Fu+, Nature Physics, 2013]

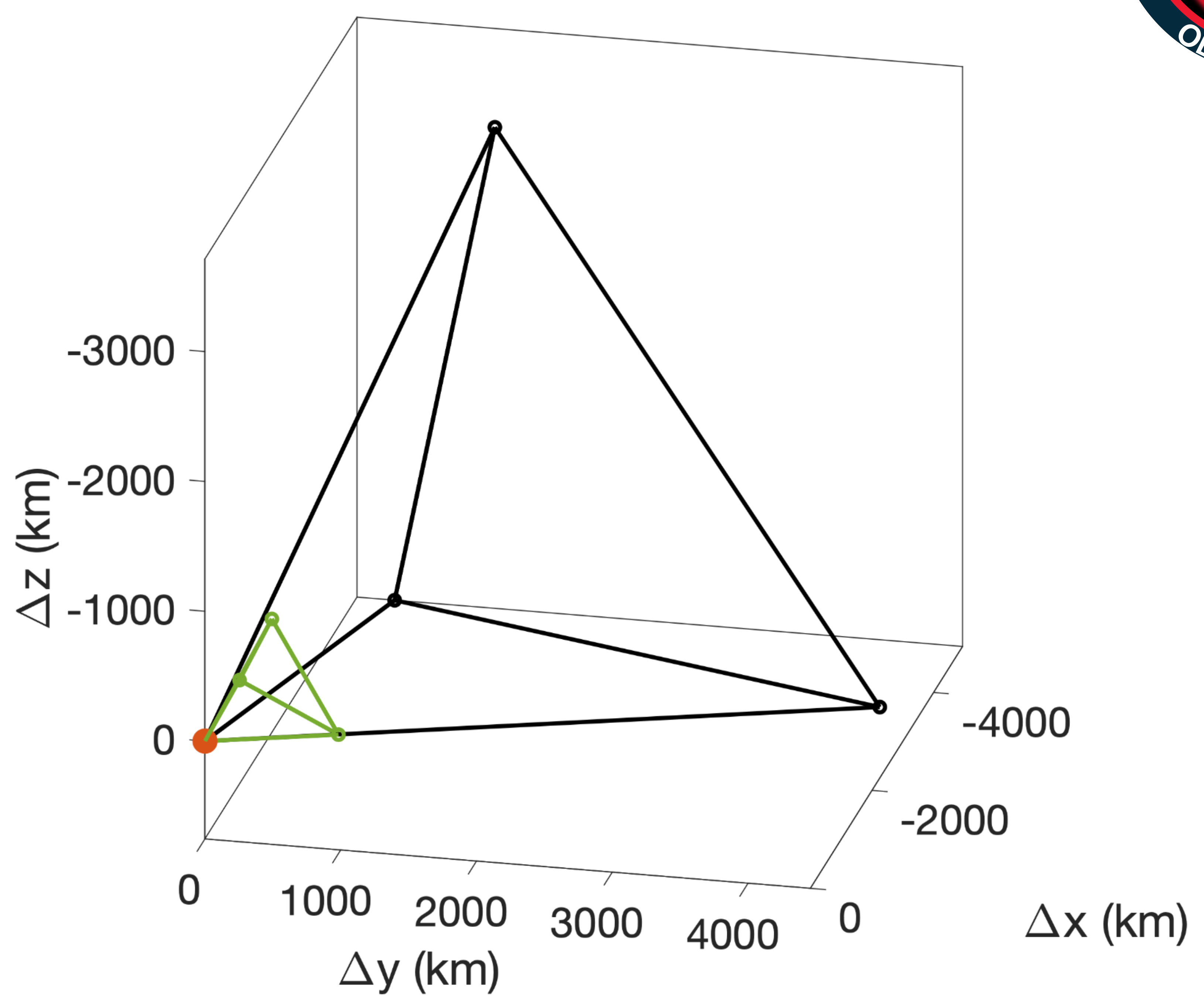
Astro implication: advance significatively in our understanding of electron acceleration at jets. Relevant for solar and astro jets.



Spacecraft and payload

7 (almost) identical spacecraft

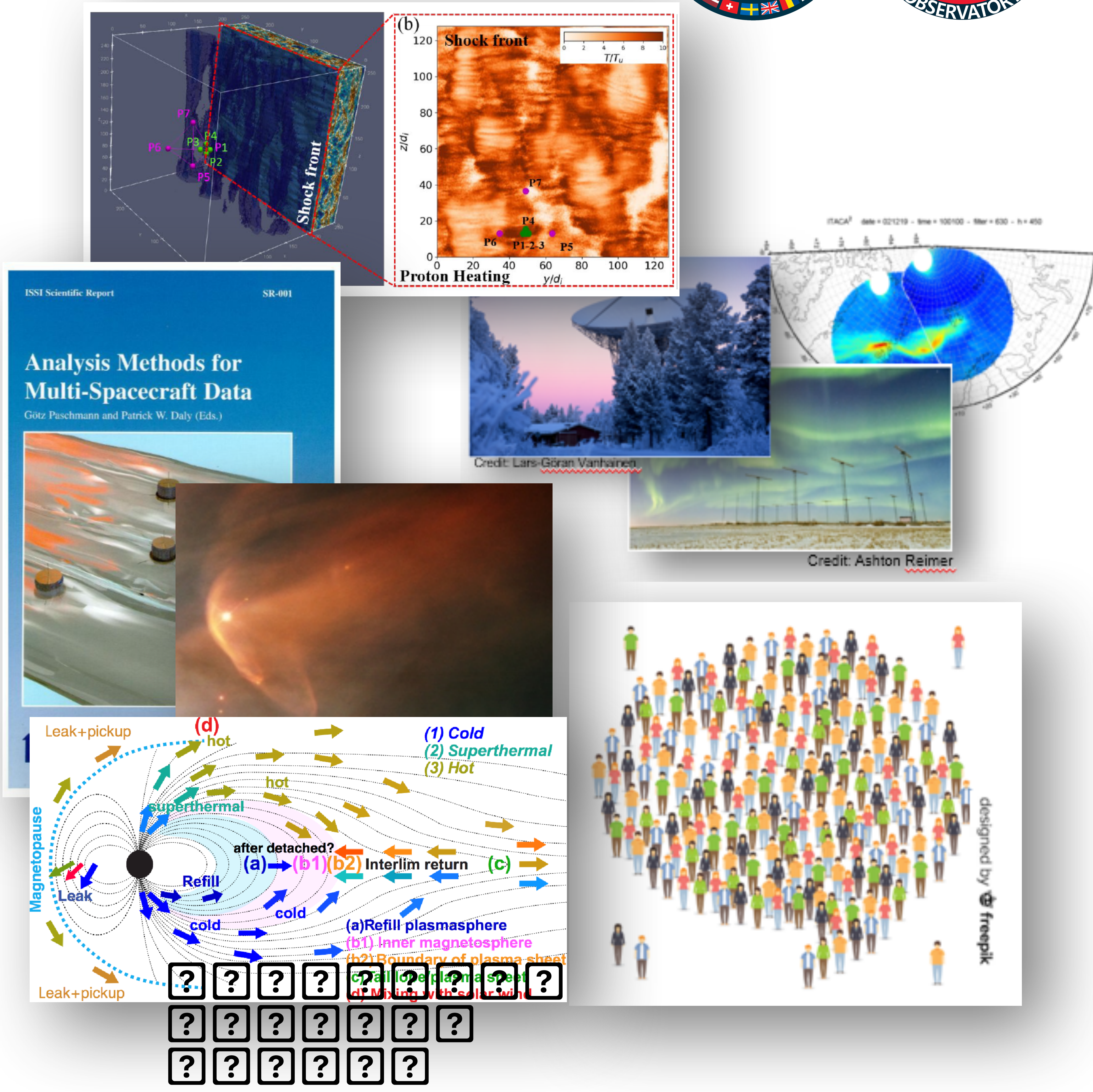
- Spinning (4s)
  - IEPC - thermal ion and electron plasma — 250 ms
  - Energetic particles — 4s
  - IMCA - mass-resolved ions — 2s
  - DC magnetic field — DC-128 Hz
    AC magnetic field — 1-8 kHz
  - DC 3D electric field — DC-2s
    AC 2D electric field — DC-100 kHz, with higher-freq. snapshots



Scientific organisation

PO thematic Working Groups to expand PO specific and crucial themes:

- Numerical Simulations (A. Markku, D. Trotta)
- Multi-Point Data Analysis Methods (G. Cozzani, A. Chasapis)
- Plasma Astrophysics (O. Pezzi, L. Comisso)
- Scientific synergies/Additional science (S. Benella, J.-L. Ripoll)
- Ground-based observations (SST Contact: J. Rae)
- Public Outreach (C. Forsyth)
- Early Career Scientists



New PO members, especially young scientists, are welcome to help us for the Phase A study! Please spread the PO word and contact us: maria.marcucci@inaf.it, alessandro.retino@lpp.polytechnique.fr

PO will lead to transformative advances in both fundamental plasma and magnetospheric physics

PLASMA OBSERVATORY

Important implications for planetary, solar and astrophysical plasmas

Targets two Voyage 2050 themes "Magnetospheric Systems" and "Plasma Cross-scale Coupling"

Next major quantitative leap needed after Cluster and MMS single-scale measurements

Key component of the current international framework towards a new era of magnetospheric physics in mid 2030s (e.g. NASA, JAXA)

Very large scientific community

Strong international science support from US, Japan and China

Strong payload team (10+ ESA countries, US, JP)

Will form the next generation of European space plasma scientists and engineers after ESA pioneered multi-point measurements with Cluster

Will leverage European current new space and smallsat technologies for science applications