# PLASMA OBSERVATORY

ESA M7 candidate mission
Selection June 2026
Launch 2037

**Maria Federica Marcucci, INAF-IAPS, Italy**
*on behalf of the Plasma Observatory team and ESA team*

# Alessandro Retinò

LPP, France

M. G. G. T. Taylor, T. Amano , Y. K. Khotyaintsev, C. Norgren, 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, G. Giono, L. Griton, L. Kistler, H. Kucharek, K. Issautier, B. Lavraud, O. Le Contel, I. Mann, L. Matteini, M. Maksimovic, E. Panov, F. Plaschke, Y. Saito, M. Yamauchi, R. Vainio, R. F. Wimmer-Schweingruber, M. Alho, S. Benella, A. Chasapis, L. Comisso, G. Cozzani, J.-L. Ripoll, O. Pezzi, D. Trotta, U. Derz, A. Stankov, T.-M. Bruendl, A. Carpentier, T. James, B. Ordoubadian, A. Walsh

*& the Plasma Observatory Science Team*

# Plasma Observatory DNA

Plasma energization and energy transport

A seven-point Observatory

Ion-fluid scale coupling

The Magnetospheric System laboratory

Two ESA M-class Voyage 2050 themes

A long lasting European community effort

# Outline

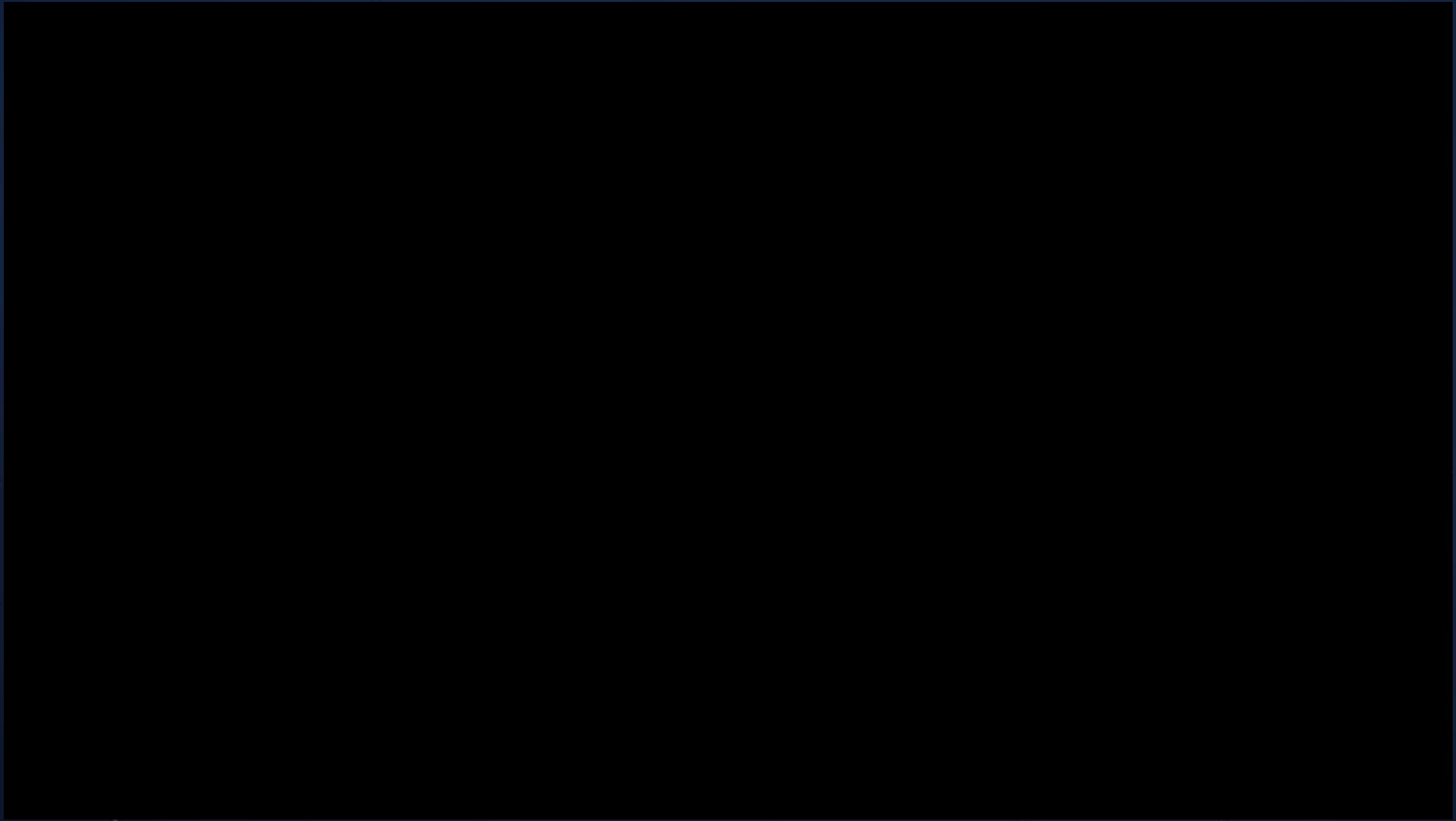
## First part

- Motivation
- The challenge
- Science Questions and Objectives

## Second part

- Scientific requirements
- Mission profile and payload
- The team
- Programmatic aspects

# How our planet works



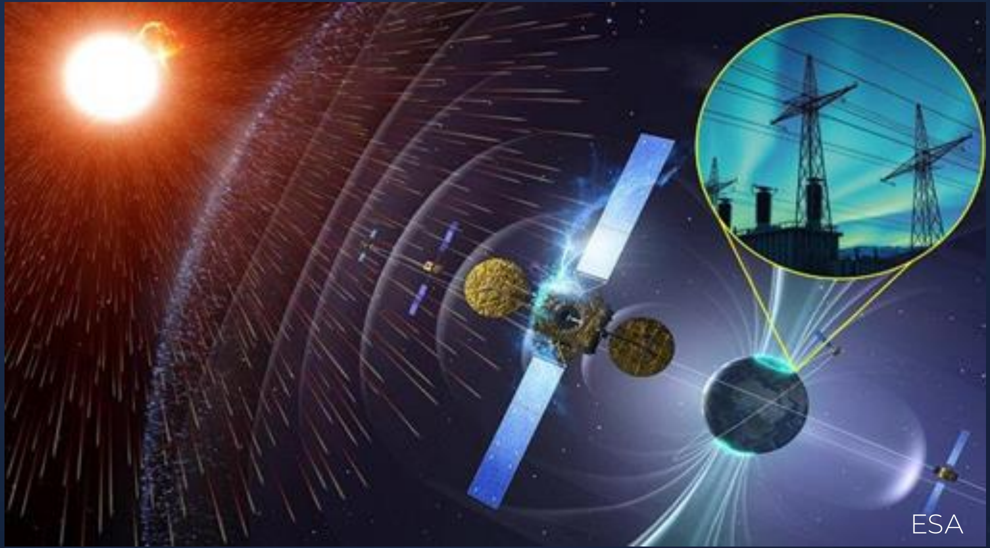
Vlasiator and M. Alho (ECR, GIANNI WG Lead)

# Plasma energization and energy transport underpins space weather

Power grids

Satellites

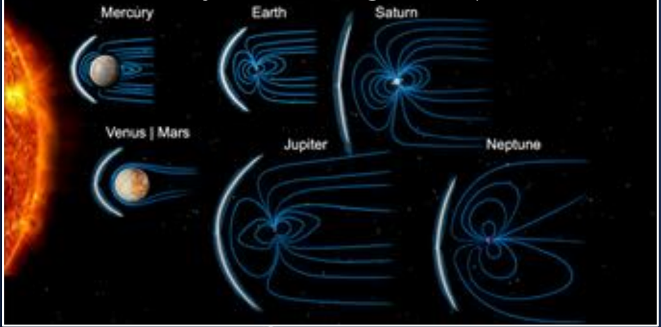
GPS and communications




**A worst-case solar storm today: $0.6–2.6 trillion in damages — we still cannot forecast which storms are dangerous**

# We live in a Plasma Universe

Solar system magnetospheres




Supernova remnant shocks

SN 1006 Shock (NASA/Spitzer) and X-ray Emission (NASA/Chandra and IXPE)

Solar flares

Remote observations of a solar flare (NASA/SDO)

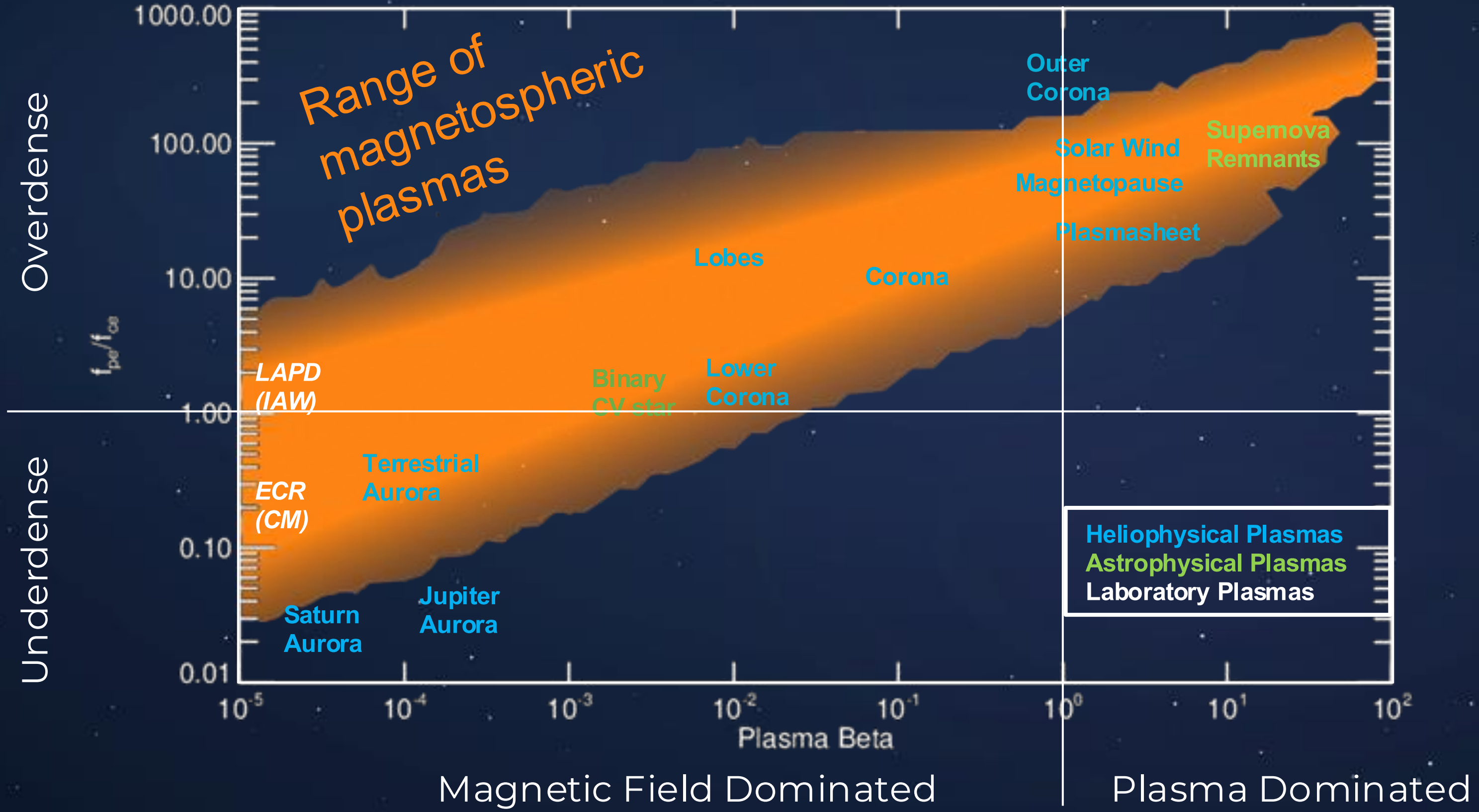
Starburst activity

Visible: NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI), and P. Puxley (NSF). Infrared: NASA/JPL-Caltech/C. Engelbracht (University of Arizona).

Particle **energization** is universal

Fundamental plasma physics governs it

# Diversity of plasma – universal physics




Diverse plasmas – similar properties in terms of dimensionless parameters

# Two grand science questions

How are particles energized in space plasmas?

How is energy transported in the Magnetospheric System?

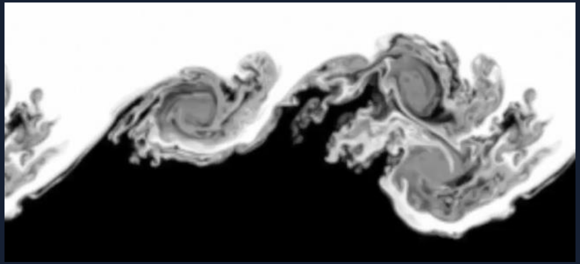
# It is all about scales

## Fluid scale

~1000s km
~minutes

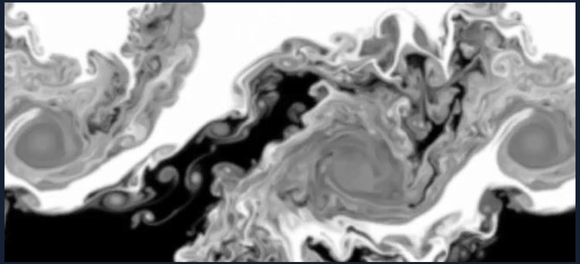
## Ion scale

~100s km
~1s



## Electron scale

~1–10 km
~100ms



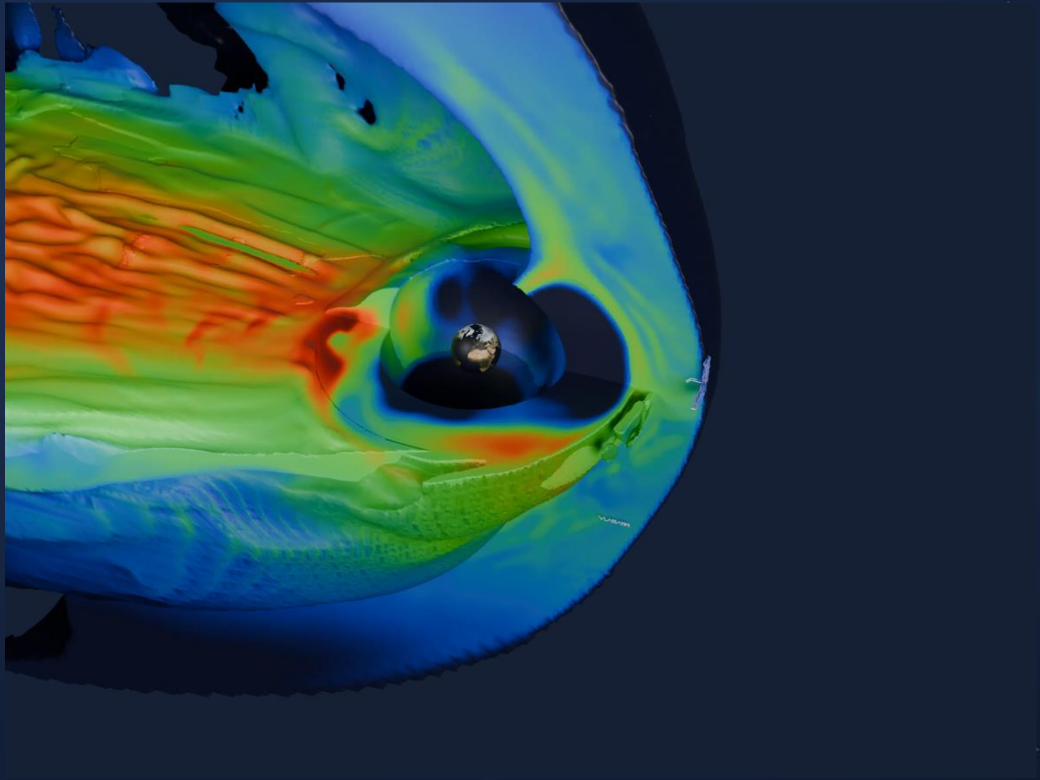
Energy couples across all three scales — but how?

K

# The challenge

Natural plasmas
are inherently
**3D, time dependent** and
**multi-scale**

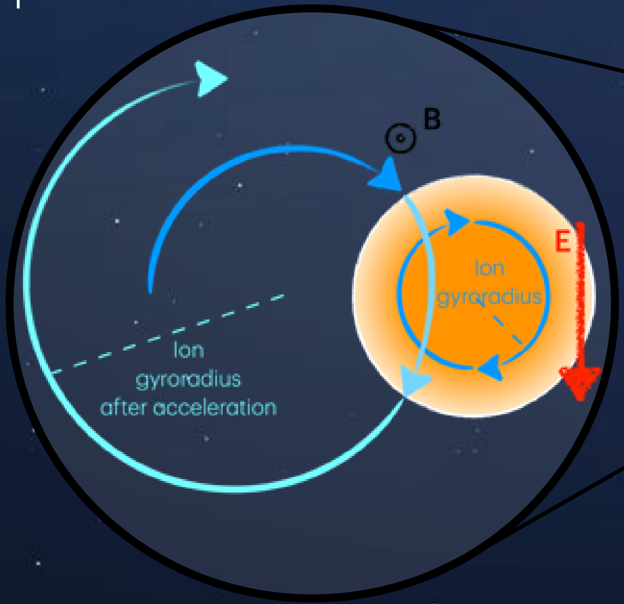
Understanding scale
coupling is essential

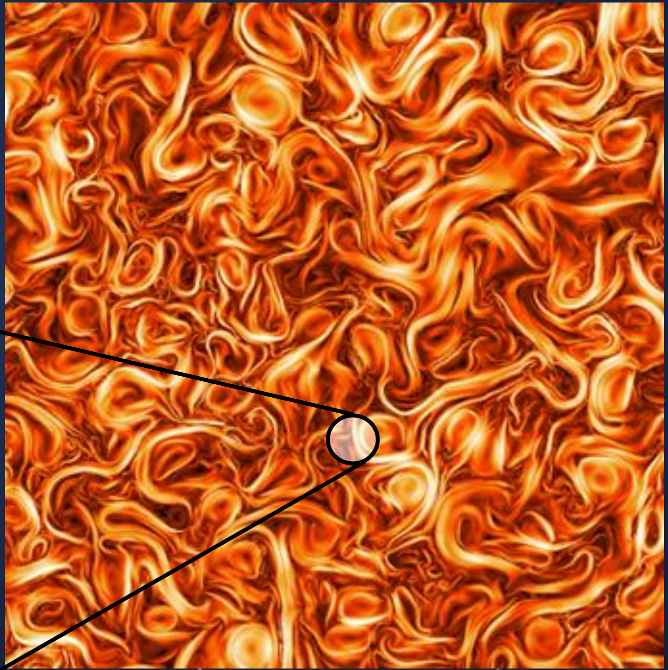


M. Alho *(ECR)*, D. Trotta *(ECR) GIANNI WG Leads*

# The ion-fluid scale connection

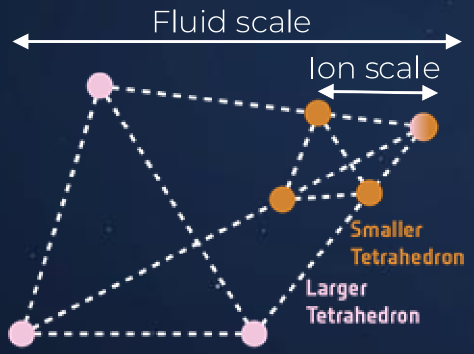
Strongest plasma energization and transport is enabled where ion and fluid scales couple



Franci et al., 2022

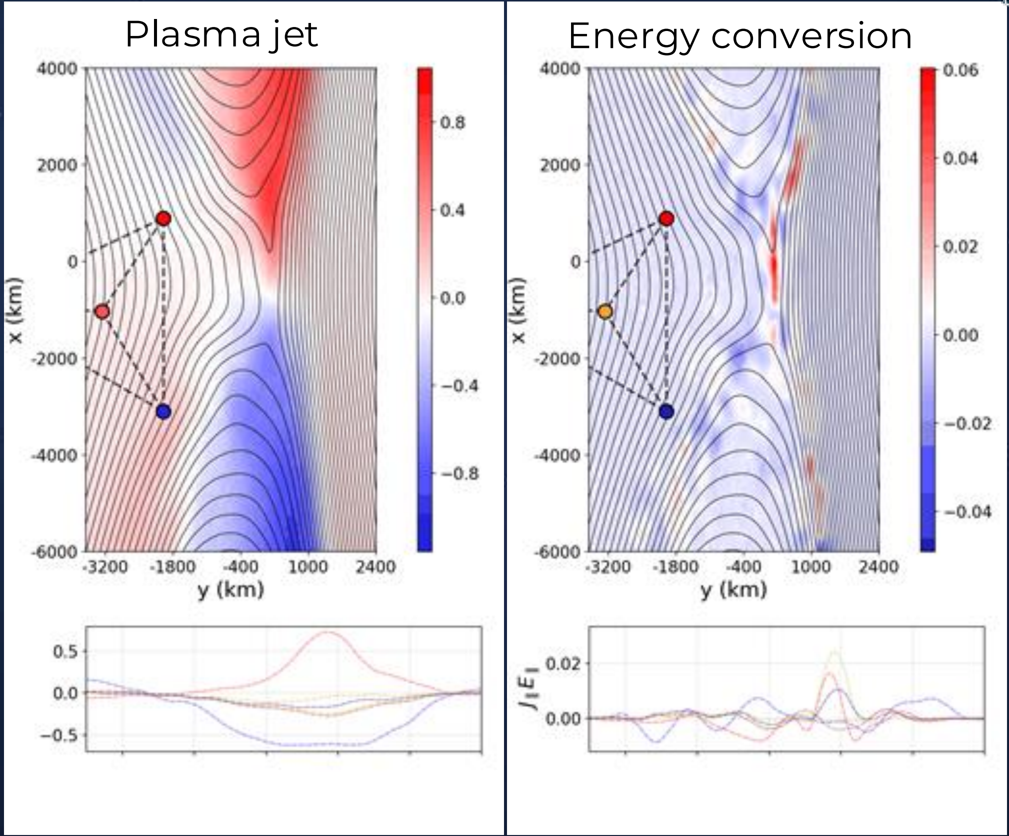
# How many points do we need?




**What would we see?**

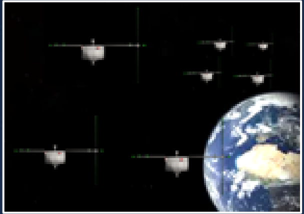
**7 points:** two scales in 3D

**4 points:** single scale in 3D



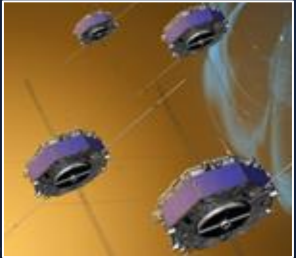

M. Baraka *(ECR)*

# Standing on the shoulders of giants

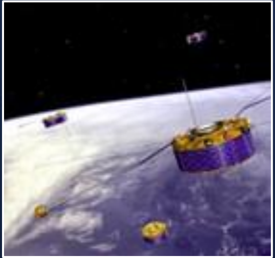


***Plasma Observatory***
*Connecting the dynamics across scales*

First simultaneous multi-scale measurements

***MMS** (2015-)*
*Revolutionary measurements of electron-scale dynamics*



***Cluster** (2000-2026)*
*First 3D view of space plasma dynamics*

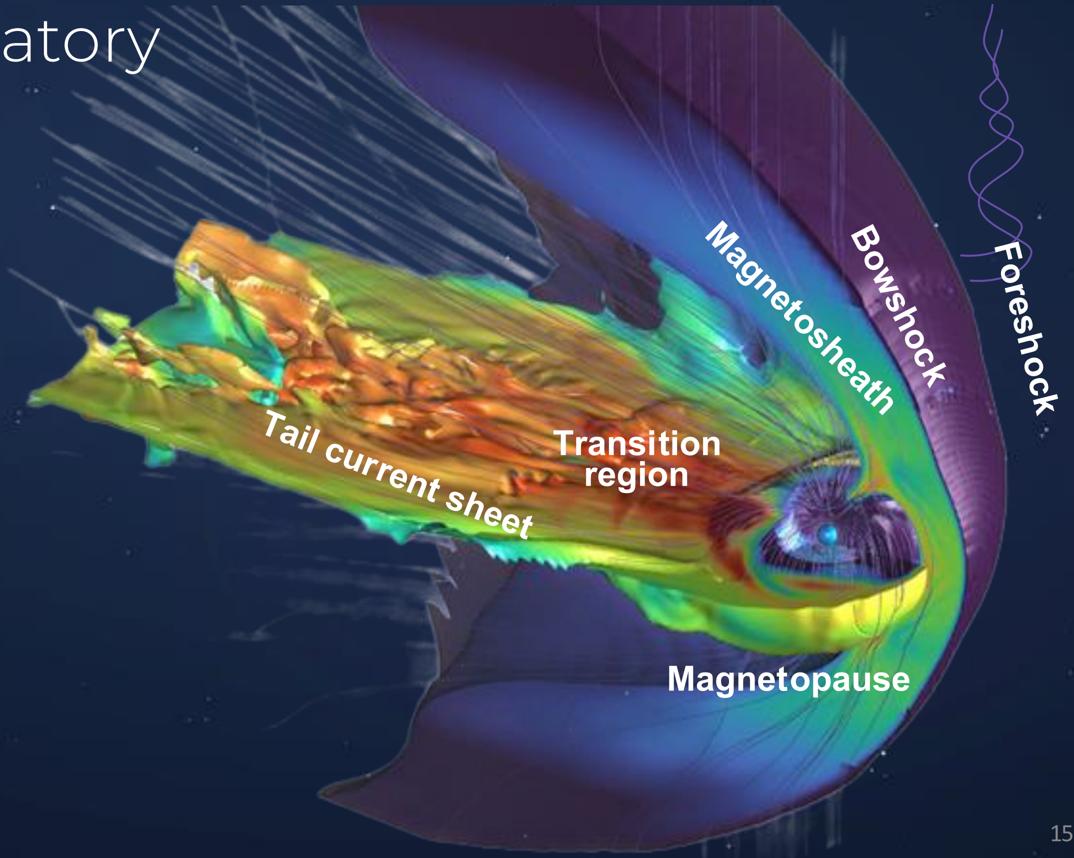
Multi-point has been transformative

One scale at a time

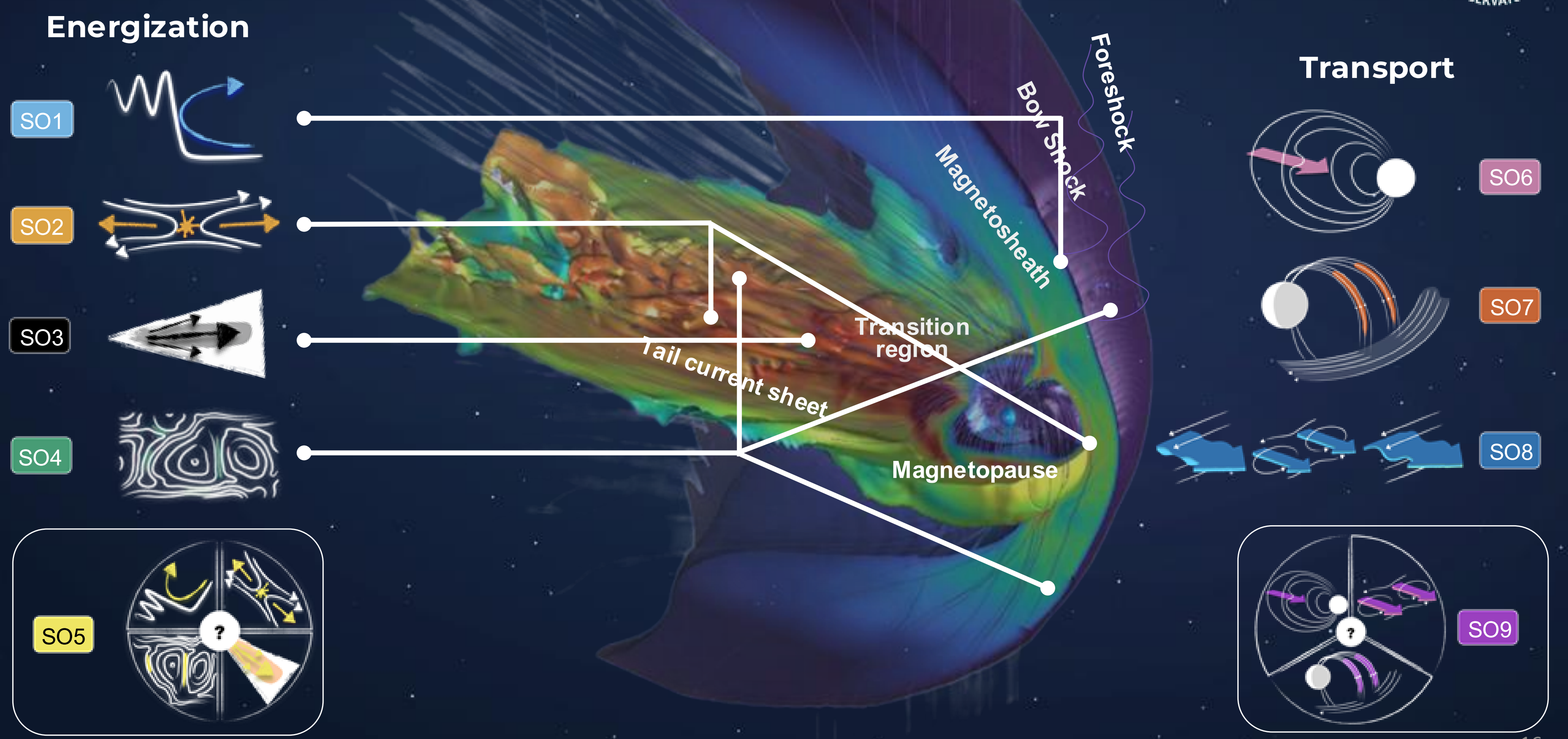
# Earth's Magnetospheric System

## Our best plasma laboratory

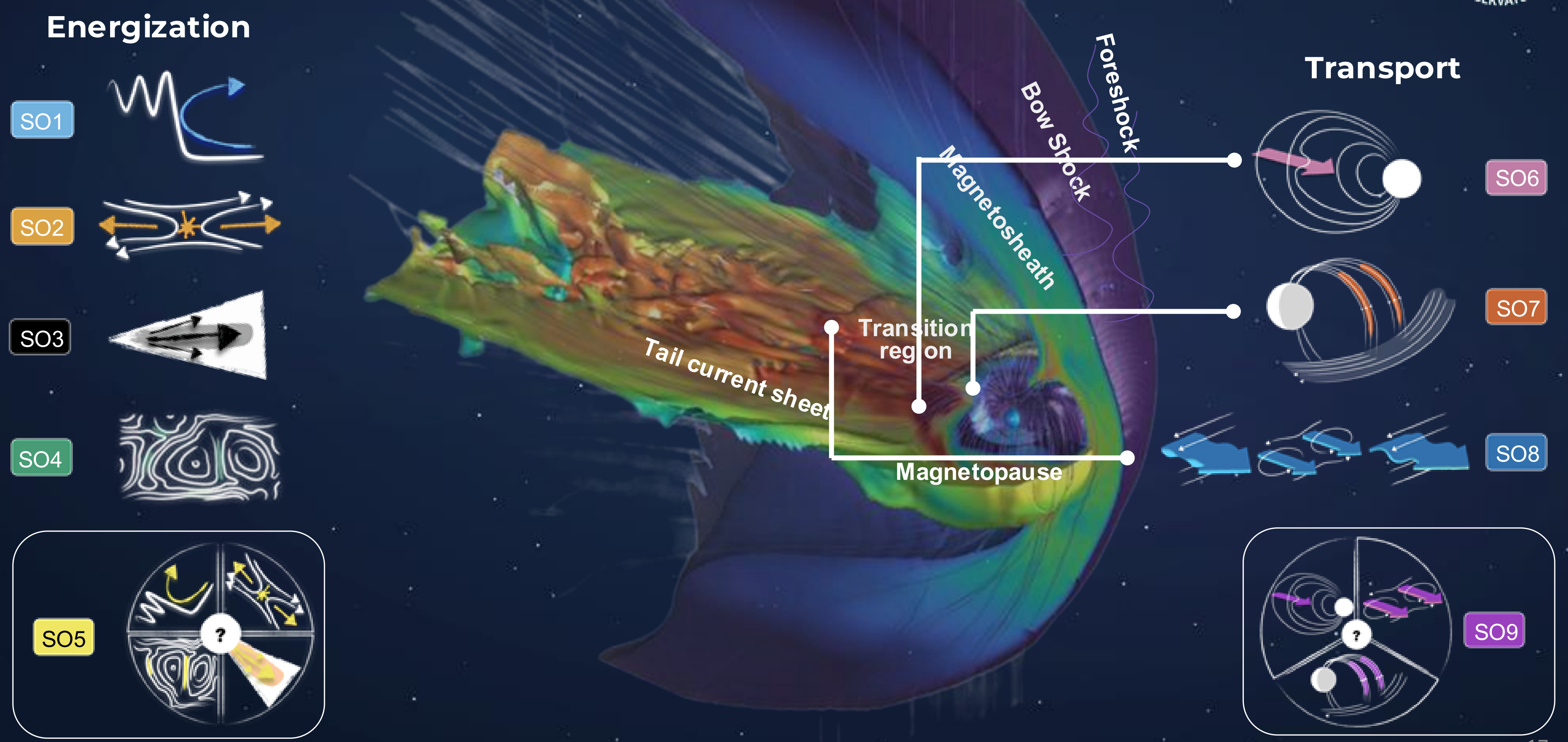
- In situ measurements
- Repeatable and variable conditions
- Strong energization and transport in key science regions



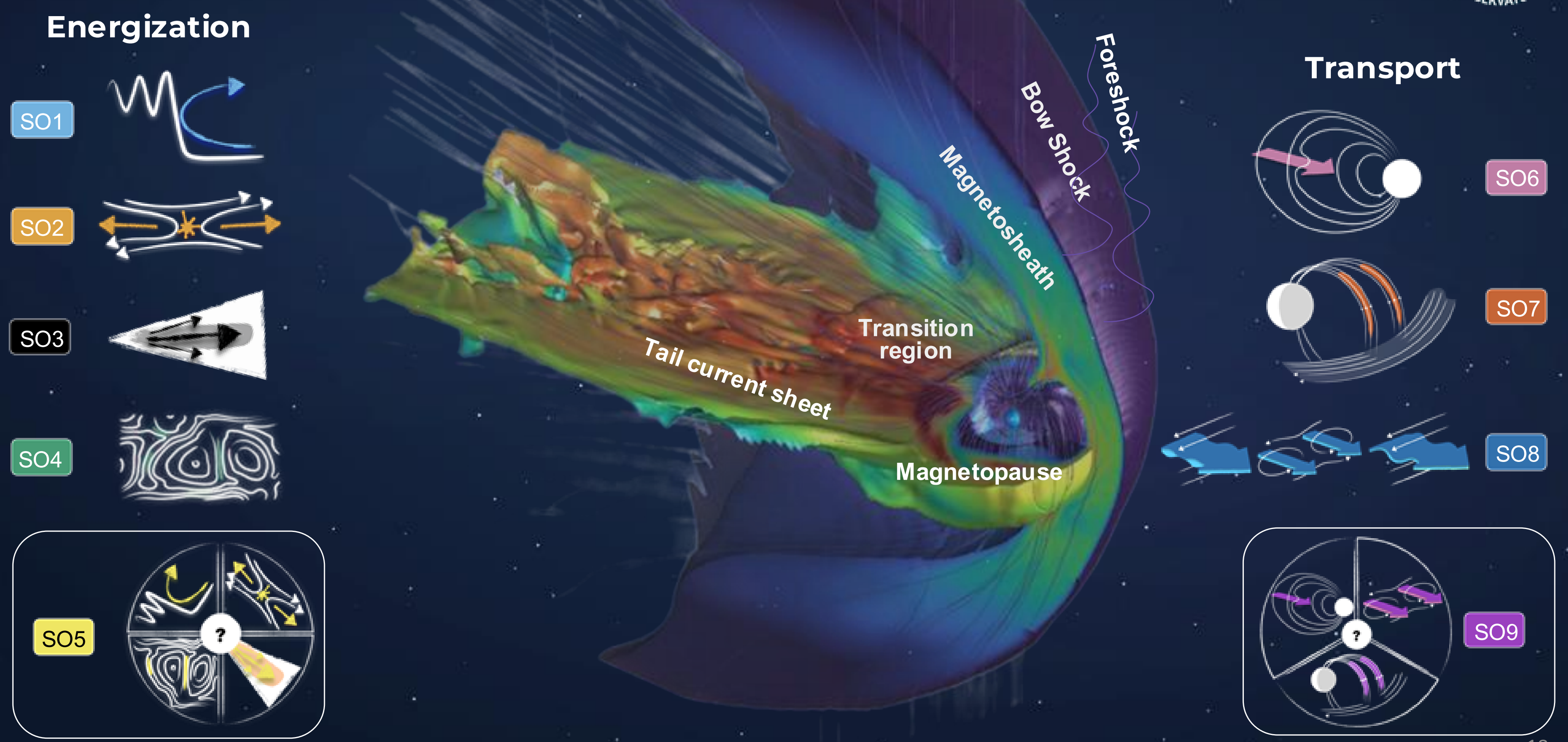
# Science objectives



# Science objectives



# Science objectives

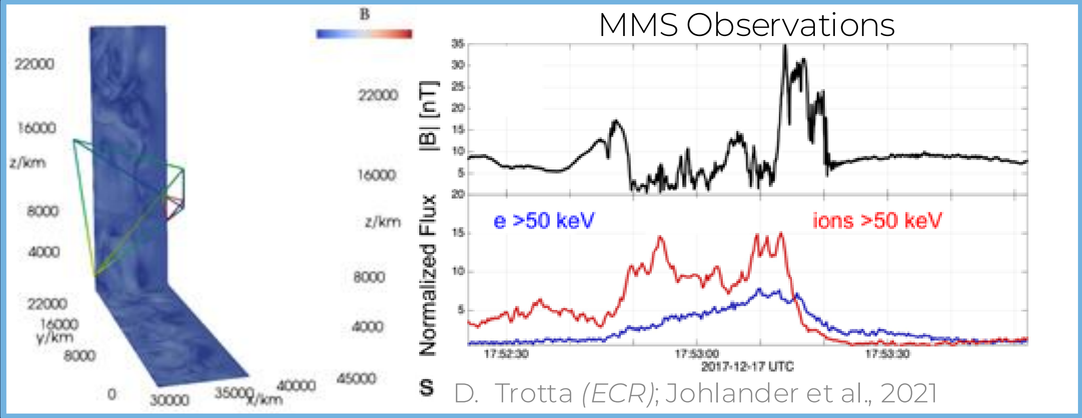


# How are particles energized at shocks?

SO1

**Shock transition:** a patchwork of complex ion- and fluid-scale structures.

**Key unknowns:** Electrons, protons, and heavier ions interact differently with multi-scale structures.




D. Trotta *(ECR)*; Johlander et al., 2021

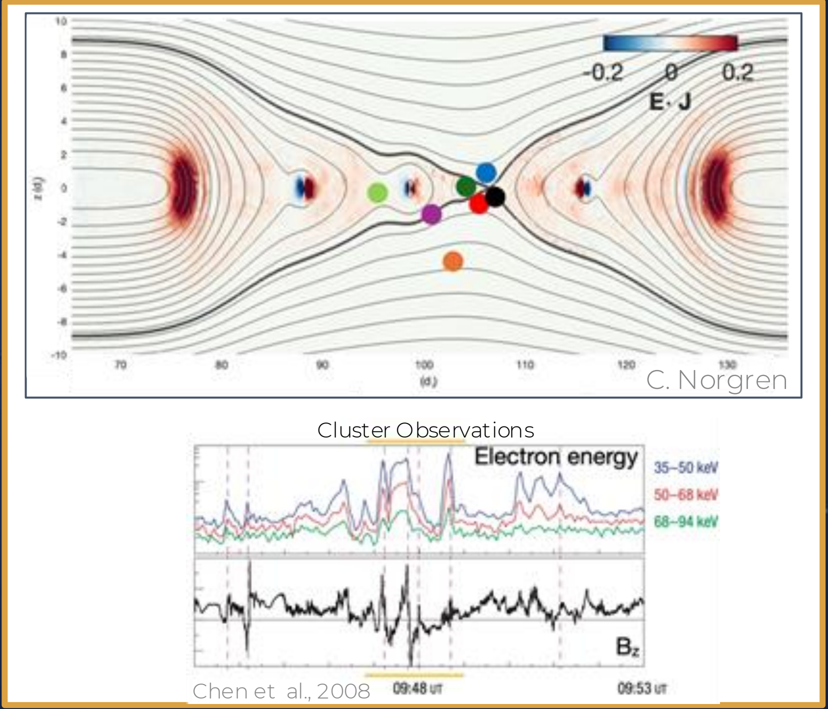
*PO first: will resolve the spatio-temporal shock dynamics simultaneously at ion and fluid scales giving a* ***unified description of plasma energization & injection***

# How are particles energized during magnetic reconnection?

SO2

**Reconnection regions:** inherently multi-scale structures from kinetic to fluid scales.

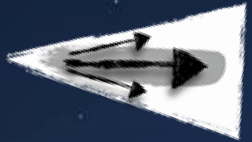
**Key unknowns:** multi-step particle acceleration




*PO first: Provide **quantitative, cross-scale description** of the drivers and processes of electron, proton and heavy ion energization.*

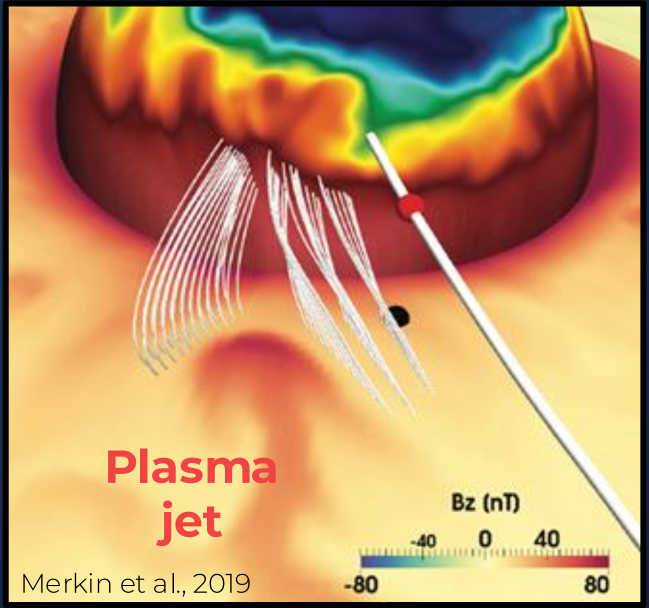
# How are particles energized in plasma jets?

SO3



Multi-step energization: low energies – local interaction with ion scales, high energies – with entire fluid-scale jet

Key unknowns: acceleration processes at different scales, adiabatic vs non-adiabatic



Merkin et al., 2019

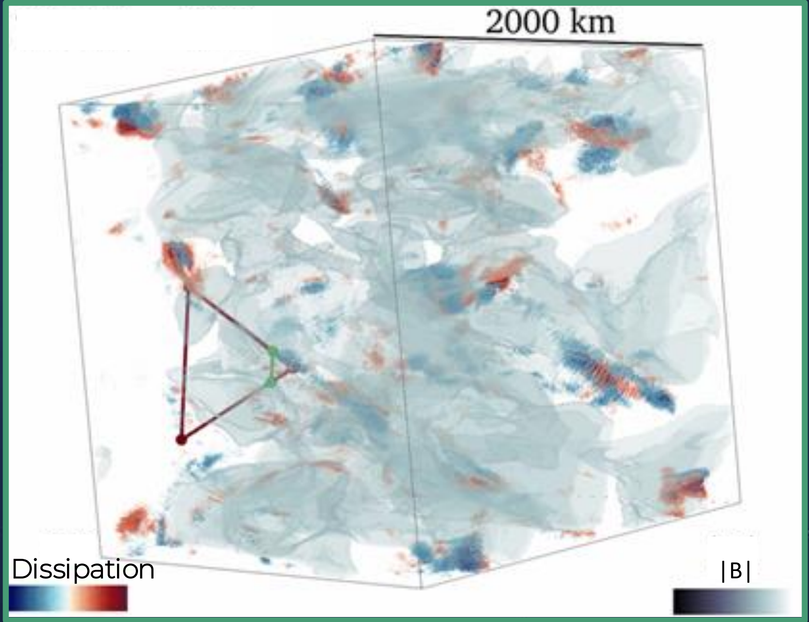
*PO first:* ***Unified description of plasma energization*** *by resolving jet fronts and jet body concurrently at fluid and ion scales for the first time.*

# How are particles energized by waves and turbulence?

SO4

**Turbulence & Waves:** mediate energy transfer across scales — dissipation on ion kinetic scales.

**Key unknowns:** resonant vs. non-resonant heating; thermal heating vs non-thermal acceleration




J. Agudelo Rueda *(ECR)*

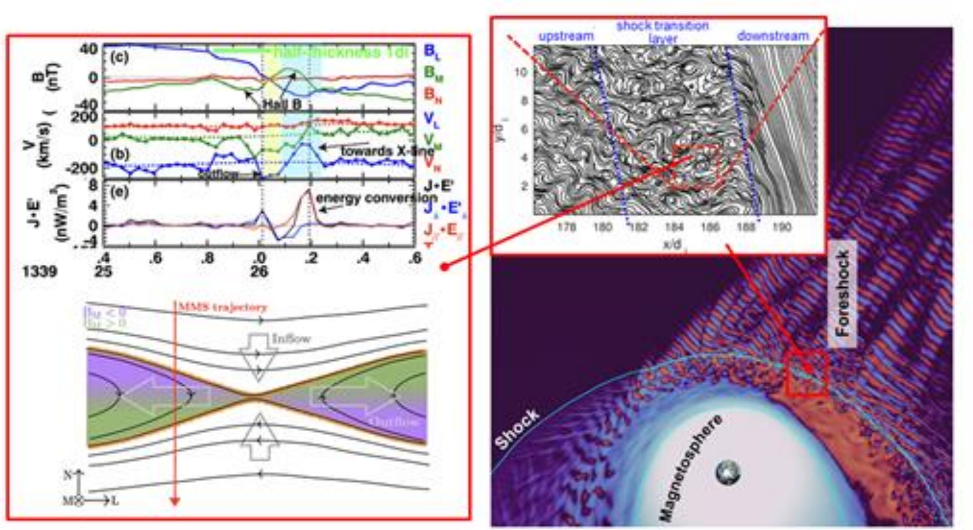
***PO first:*** *7-points will resolve the cross-scale structure of turbulence, uncovering* ***energy transfer mechanisms, particle energization, and driving factors***

# How do different processes combine to energize particles?

SO5

**Multi-process coupling:** shocks, reconnection, turbulence, and jets coexist and interact

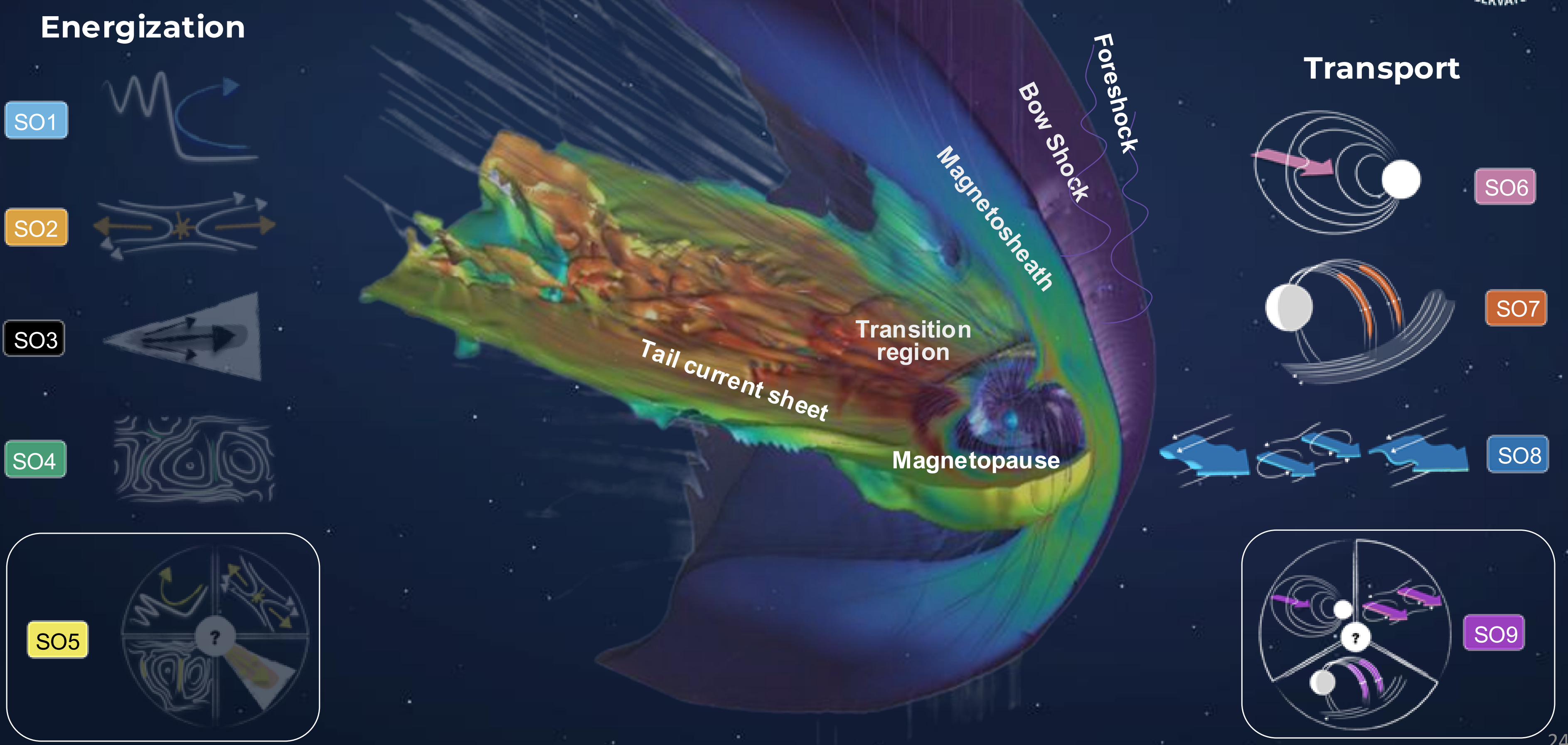
**Key unknowns:** combined energization exceeds any single process.




Gingell et al., 2019; Wang et al., 2019; L. Turc

*PO first: Provide a **unified, multi-scale view of combined energization** — quantifying how interacting processes shape particle energy distributions.*

# Science objectives

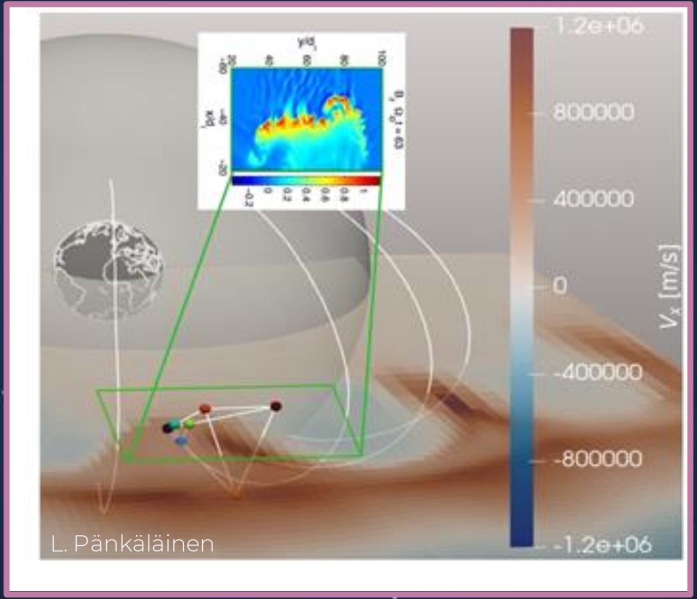


# How do jets interact with the transition region?

**SO6**

**Transition region:** the gateway where magnetotail energy is diverted into the inner magnetosphere.

**Key unknowns:** role of jets vs. interchange in driving structure; mechanisms of particle transport.



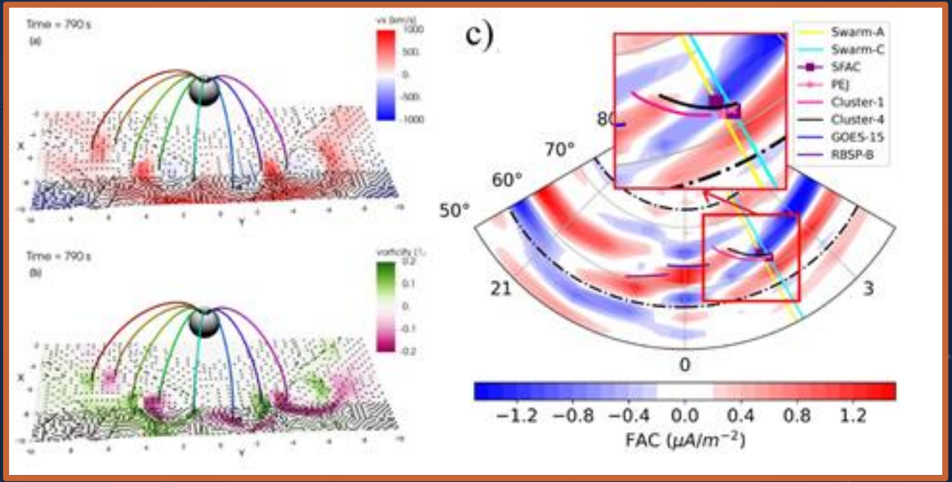

*PO first: Separate 3D spatial and temporal variability concurrently at fluid and ion scales to reveal coupling between jet and substructure.*

# How do field-aligned currents connect regions?

SO7

**Field Aligned Currents:** the primary coupling between the magnetosphere and atmosphere

**Key unknowns:** how large-scale currents close and evolve



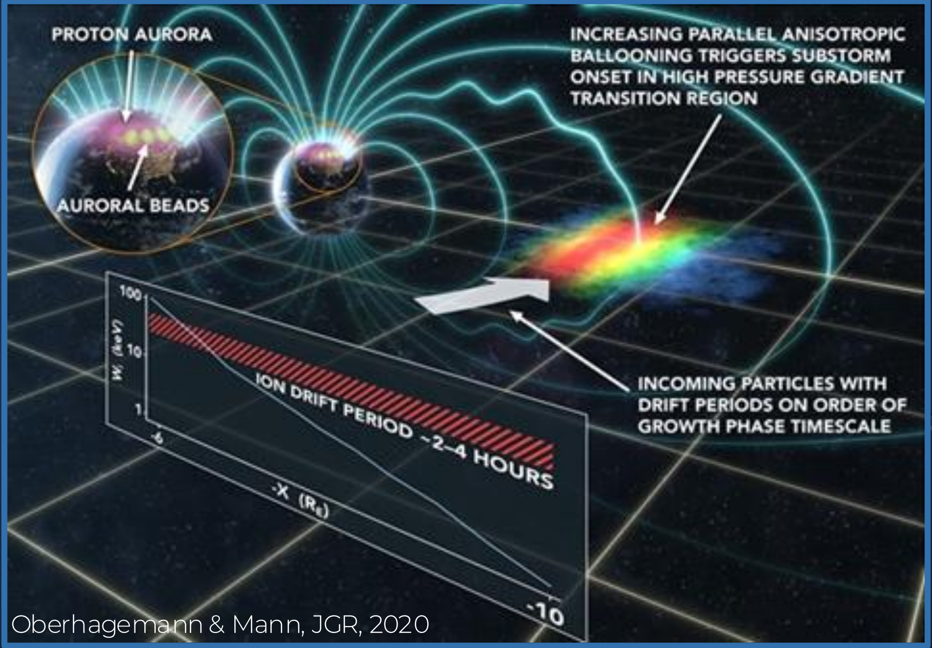

***PO first:*** *Estimate FACs at multiple scales simultaneously, dramatically improving on single-scale Cluster/THEMIS/MMS.*

# Which plasma instabilities drive energy transport?

SO8

**Transition region:** a maelstrom where kinetic instabilities and reconnection interact explosively.

**Key unknowns:** what detonates explosive energy release; how instabilities transfer energy



Oberhagemann & Mann, JGR, 2020

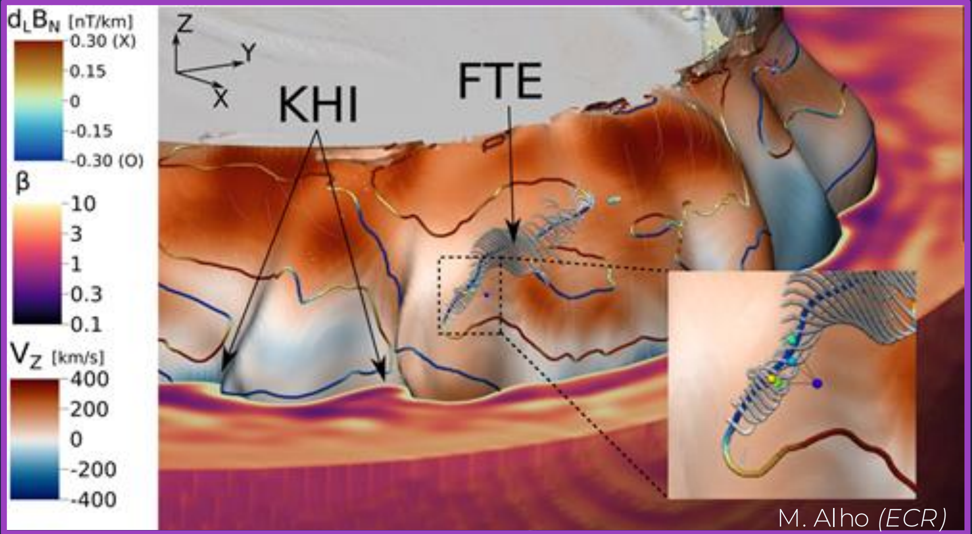
***PO first:*** *Multi-scale wave measurements will provide true diagnosis of instability initiation and evolution.*

# How is energy partitioned among transport processes?

SO9

**Energy pathway:** solar wind energy processed through all regions, and is explosively released over 15–30 min.

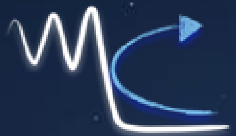
**Key unknown:** how energy flux is partitioned between jets, waves, and instabilities



M. Alho *(ECR)*

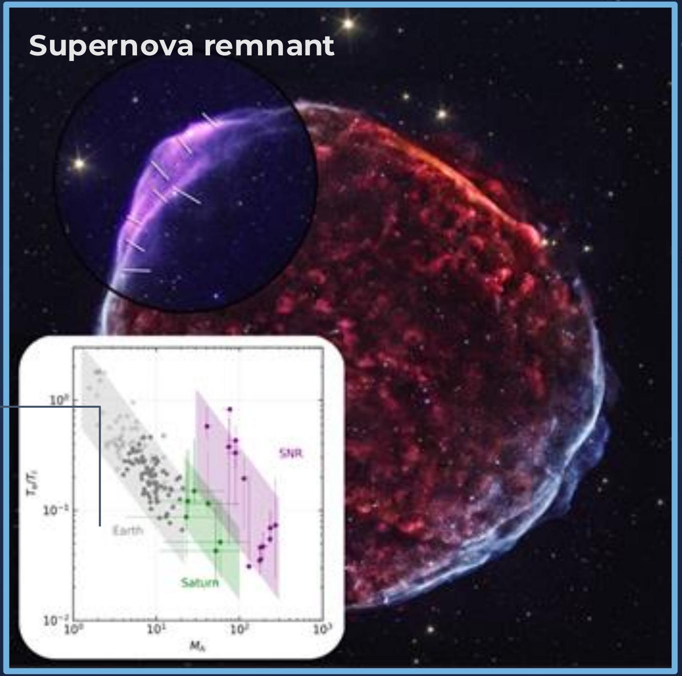
*PO first: 7 points will simultaneously measure fluid-scale drivers and multi-scale response — first quantitative system-wide energy partitioning.*

# From the Earth to the Universe

**SO1**  an example

**Astrophysical impact:** the physics we measure is the unresolved physics at astrophysical shock

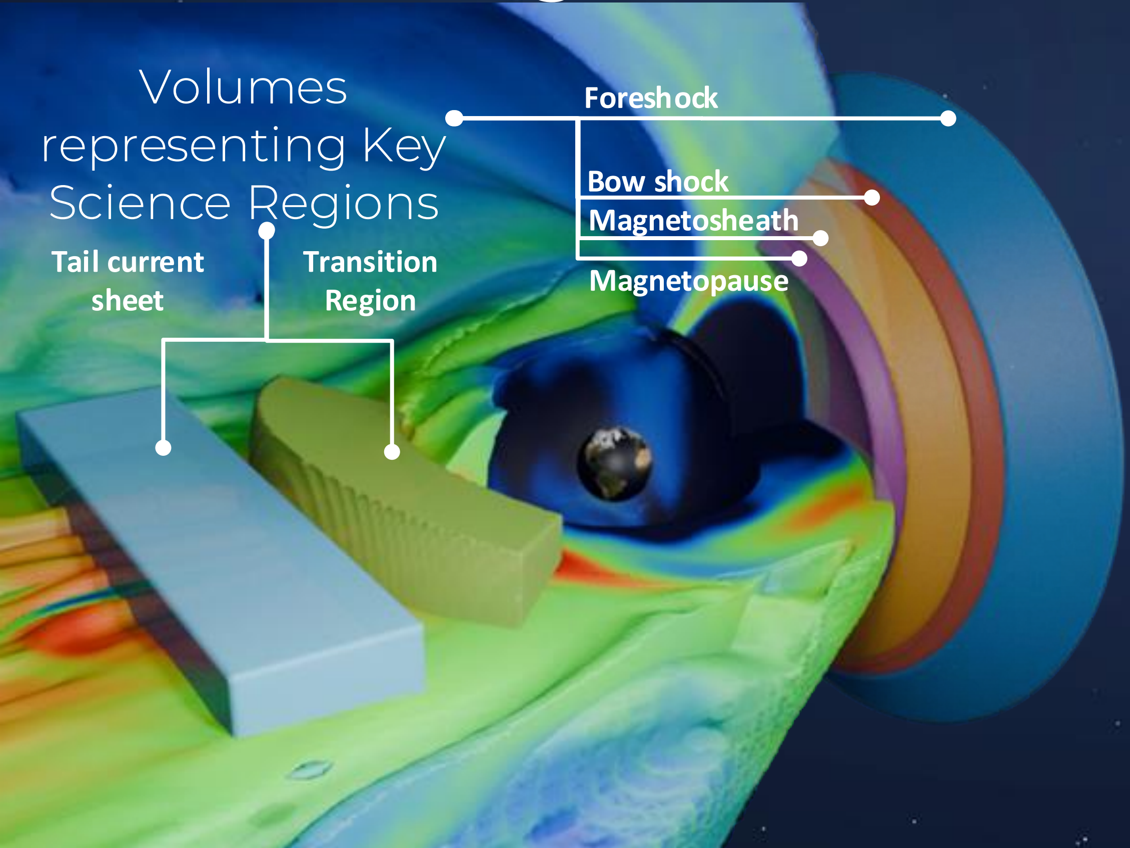
**Key Unknown:** How are particles initially injected into the acceleration process?



NASA/Chandra and IXPE

*PO first: describe how particles are injected at shocks in near-Earth space across a range of parameters and inform theories of astrophysical shock injection*

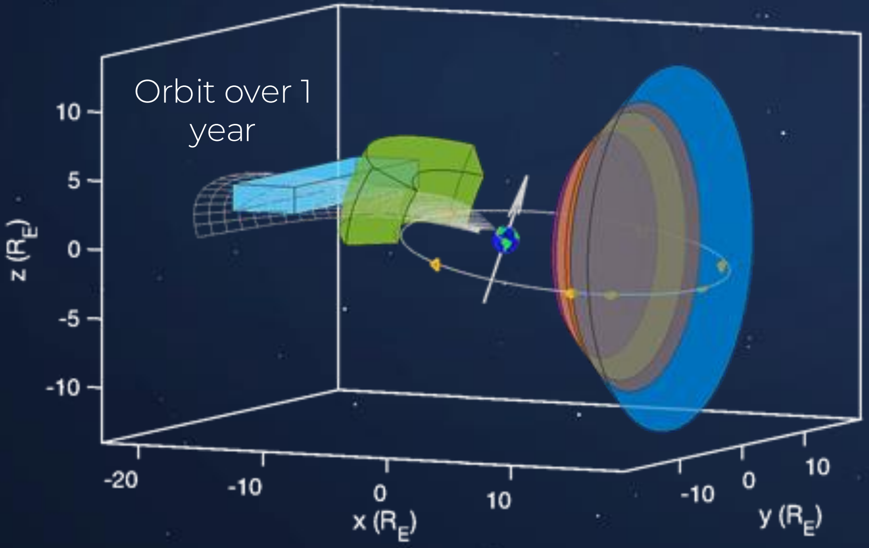
# Multipoint observations in the Key Science Regions




- Measurements from many regions of the magnetosphere
- **Observation time** to guarantee a statistically meaningful sampling
- Simultaneous fields and particles data
- High-resolution observations
- Constellation enabling multi-scale analysis

*Drive orbit, payload and s/c*

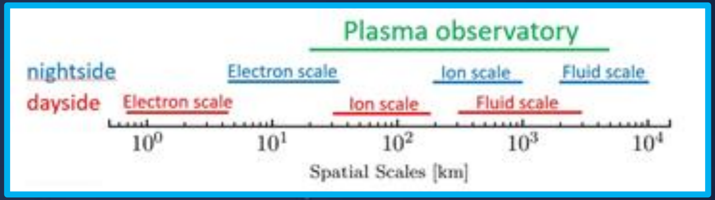
# Spacecraft orbit and constellation




Inclination within 15° | Apogee: 17 $R_E$ | Perigee: 7.2 $R_E$
3 Science Phases each lasting 11 months
High-quality tetrahedra

Simultaneous coverage of scales in all Key Science Regions

Constellations adapted for multi-spacecraft analysis



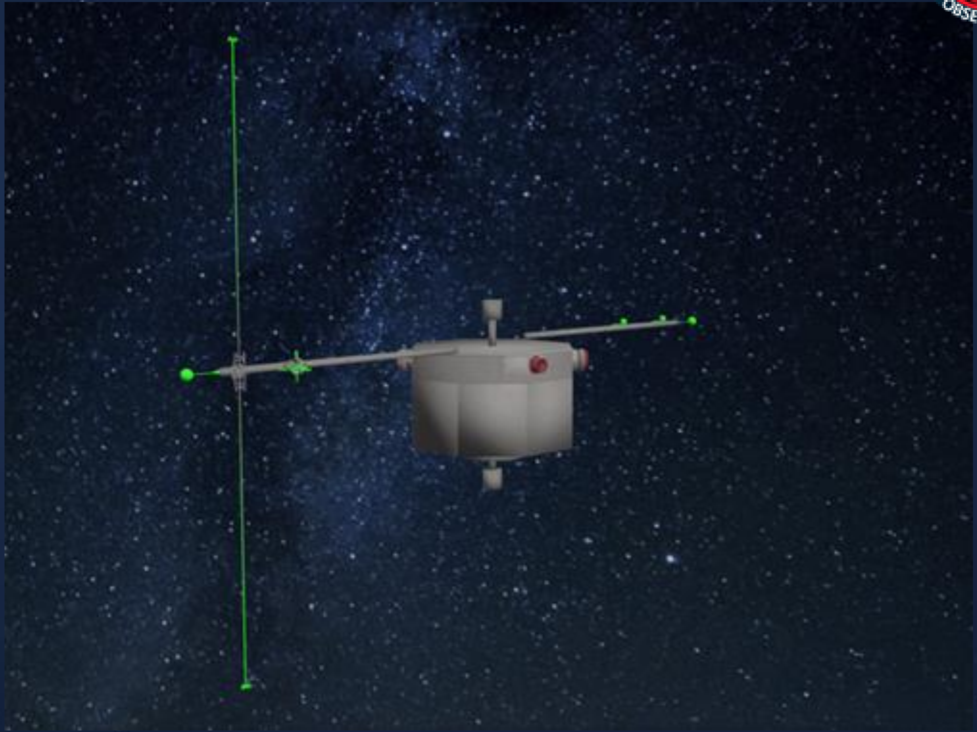

# Payload

## Electromagnetic Fields

Magnetic fields (MAG, SCM)
Electric fields (EFI)

## Particles

3D electron + ion distributions (iEPC)
Ion Composition (IMCA)
Energetic particles (EPE)

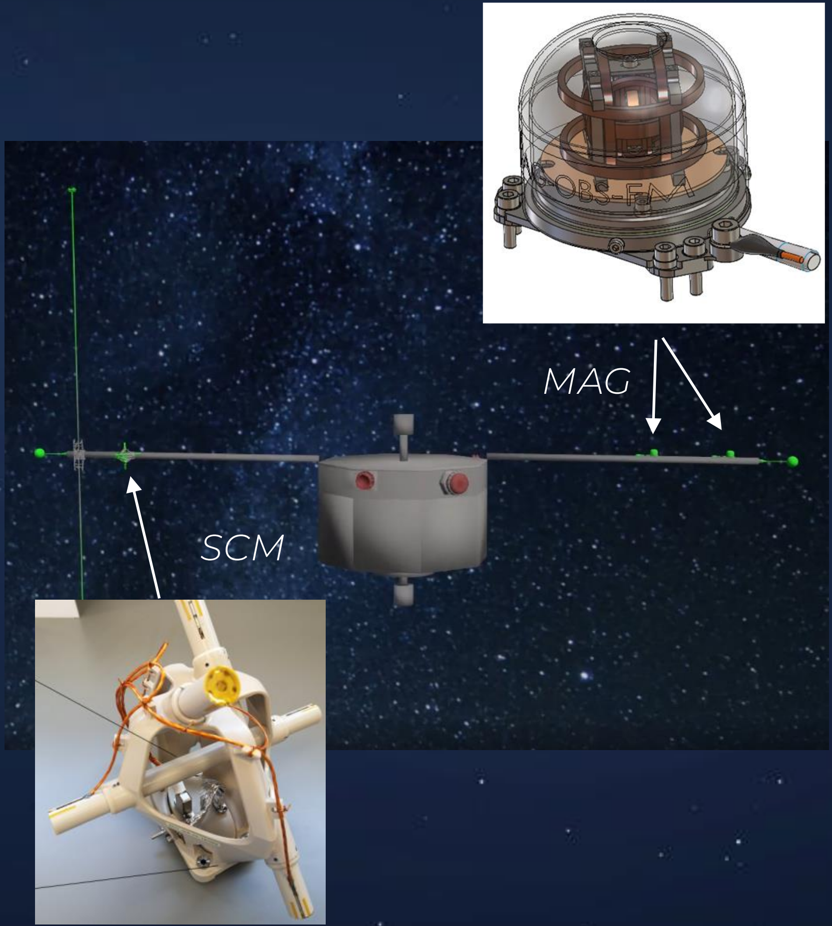


Fields + Particles → Plasma description

# Magnetic Field

*Fluxgate Magnetometer (MAG)*
DC measurements up to 128 Hz

*Search Coil Magnetometer (SCM)*
covering AC magnetic fluctuations from 1 Hz to 8 kHz.

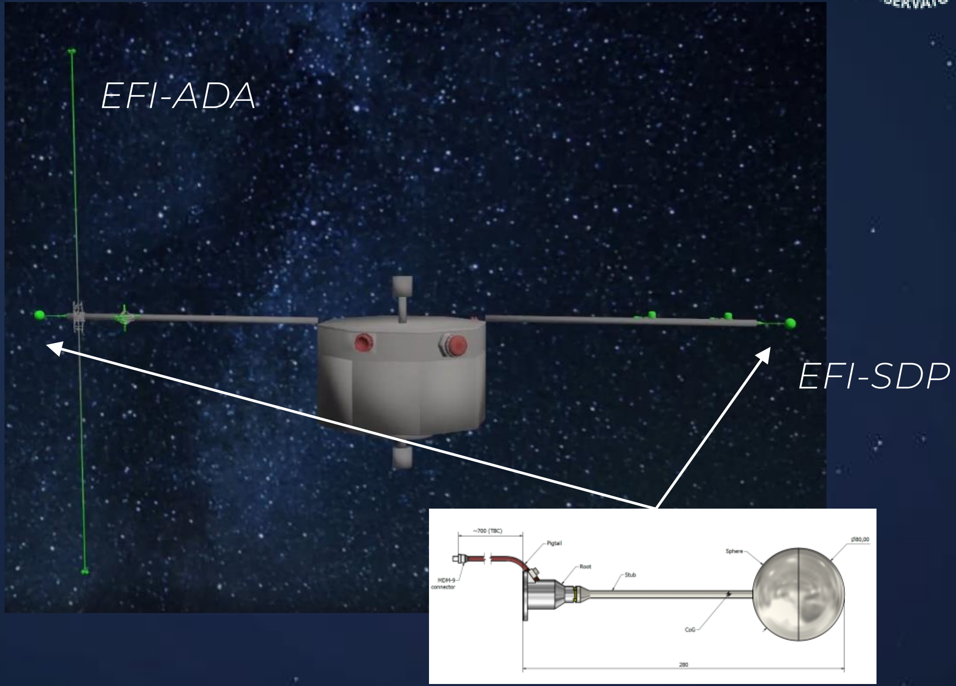


# Electric Field

The Electric Field Instrument will provide electric fields and spacecraft potential measurements.

*EFI-SDP spherical double-probe sensor*
providing DC to 100 kHz coverage, and the

*EFI-ADA axial dipole antenna*
extending sensitivity to electric fluctuations between 10 Hz and 100 kHz.



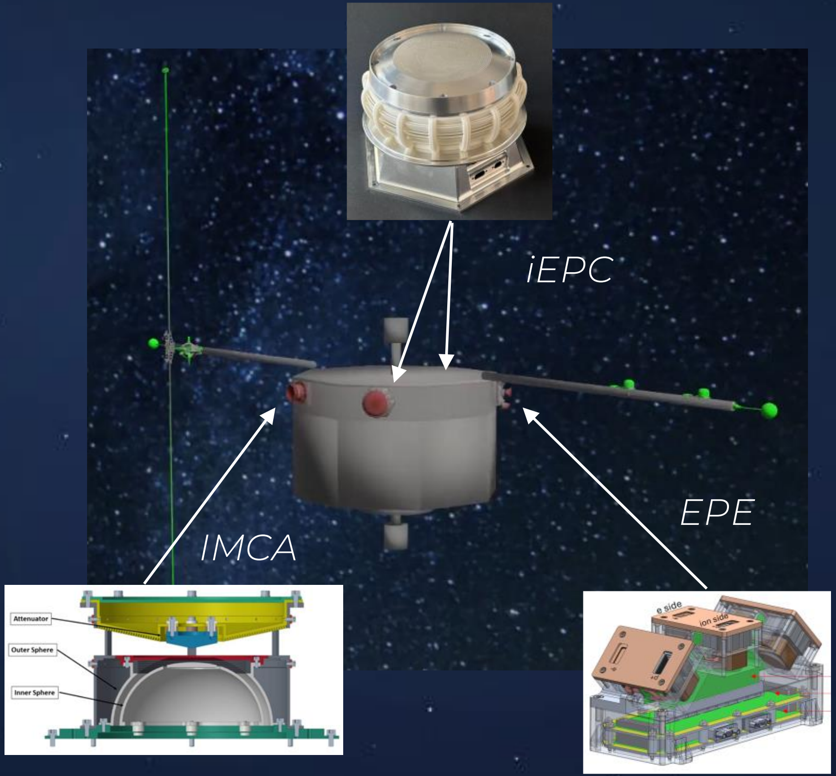

Waveform and spectral products from electric and magnetic sensors are processed by the BOX-W wave electronics unit

# Particles

*IMCA ion mass composition analyser* resolving H+, He++, and O+ distributions at 2 s cadence

*EPE energetic particle detector* measuring energetic electrons and ions from 20 to 600 keV

*iEPC ion–electron analyser*, delivering three-dimensional distribution functions of ions and electrons at 250ms cadence




Particle data processing is performed by the BOX-P electronics unit.

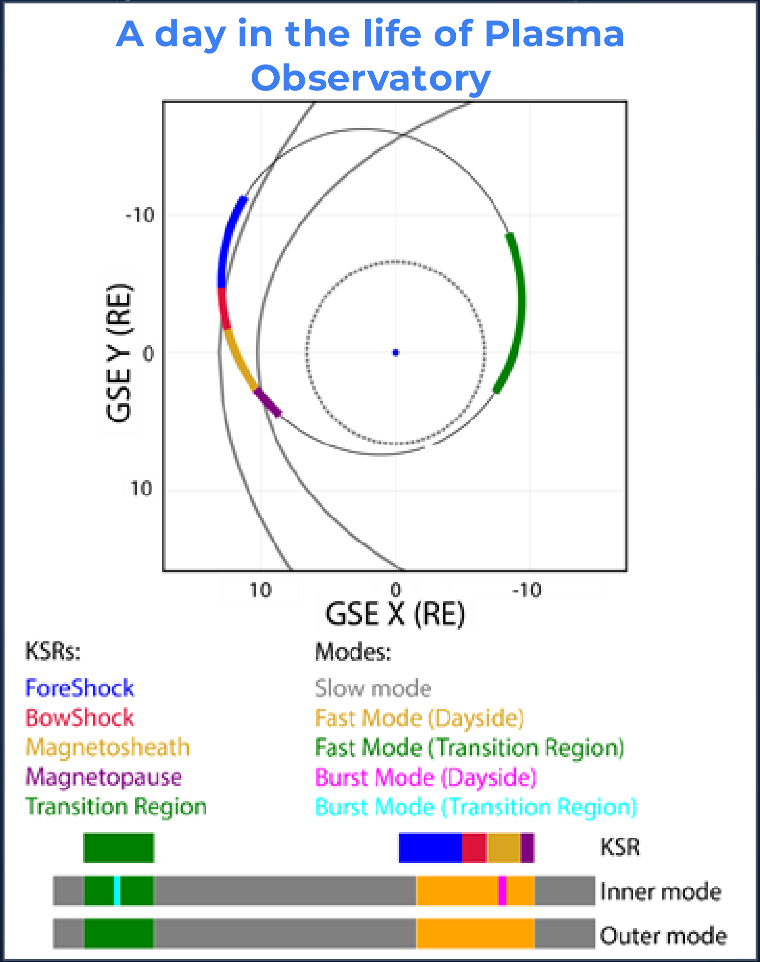
# Science operations

**Coordinated observations** from the seven sister spacecraft:

- **Slow, Fast, and Burst** modes
- Instruments settings tuned to specific science target

Consistent and coherent set of data products

The mission **has the capability** to provide all the data needed to address the science objectives.



# A community ready for discovery

## 10+ Payload teams' ESA countries

with key US and Japanese contributions

## 7 Working Groups

- Numerical Simulations
- Advanced Analysis Methods
- Plasma Astrophysics
- Synergy Science
- Ground Based
- Education and Outreach
- Early Career Networking Group

## 400+ Science Team members

from 25 countries worldwide

## Open Data

Via HelioPhysics Archive


# European leadership – global community

# A Community ready for discovery

## GIANNI
## Group on sImulAtioN NumerIcal support

*in honor of the late Giovanni Lapenta*

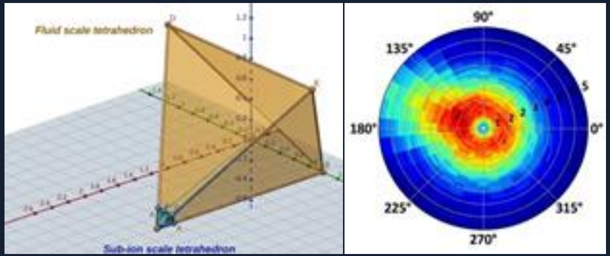
Integrating diverse geospace plasma models

Advancing models, studies, and tools

Enabling data interpretation and mission design

https://plasma-observatory-simulations.github.io/

Virtual Spacecraft Toolkit




Contact: M. Alho, D. Trotta

## Multi-point Data Analysis Methods

Multipoint data and advanced analysis methods leveraging and going beyond Cluster and MMS legacy (synergy with HelioSwarm)

A portfolio of state-of-the-art methods:

Wave Telescope and Magnetic Field Reconstruction
LPDE (Lag-Polyhedra Derivative Ensemble)
Cross correlation methods
Magnetic and velocity field topology reconstruction
Magnetic field curvature
Wave Telescope and Curlometer
Pressure strain interaction
Error calculation on Pi-D


Contact: G. Cozzani, A. Chasapis

# A Community ready for discovery

## Plasma Astrophysics

Bridging heliospheric plasmas and far astrophysical systems by tackling the following question:

How could the measurements performed by Plasma Observatory in the near-Earth environment improve our knowledge of particle energization in astrophysical systems?

- Star-planet interaction and heliospheric physics;
- Galactic cosmic rays and supernova remnants;
- Large-scale cosmic-ray-driven structures (winds, halos) in the inter-stellar medium;
- Intra-cluster medium and galaxy clusters;
- Compact objects

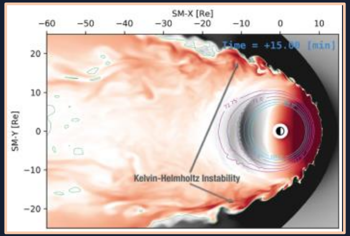
Contact: O. Pezzi, L. Comisso

## Synergy Science

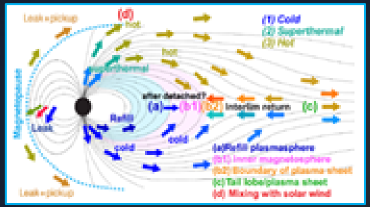
investigating the scientific opportunities enabled by Plasma Observatory beyond the core science enhancing the overall scientific return of the mission and serving a broader the PO science community

The working group fosters scientific discussion with experts from different fields:

- solar wind physics
- ionospheric physics
- inner magnetospheric dynamics
- radiation belt physics
- solar wind–magnetosphere interactions
- Space Weather




Sorathia et al., GRL 2020




Yamauchi, Ann. Geophys., 2019

Contact: S. Benella, J.-L. Ripoll

# A Community ready for discovery

## Ground Based

Supporting the coordination of Plasma Observatory multipoint measurements in the magnetosphere with ground based observations of the ionosphere, building on the heritage of the Cluster Ground-based Working Group

EISCAT-3D (European Incoherent Scatter - 3D)
SuperDARN (Super Dual Auroral Radar Network)
TREx (Transition Region Explorer) all-sky imagers
SuperMAG
IMAGE (International Monitor for Auroral Geomagnetic Effects)

Photo by Ashton Reimer

EISCAT 3D site in Skibotn, Norway in January 2023
Photo: EISCAT Scientific Association

Contact: J. Rae

## Early Career Networking Group

The ECR Networking Group for Plasma Observatory provides a dedicated space for early career colleagues to connect, collaborate, and stay informed about the mission.

ECR representation within the mission team has been established from the outset, and the network facilitates pathways for meaningful involvement.

Contact: S. Lautenbach

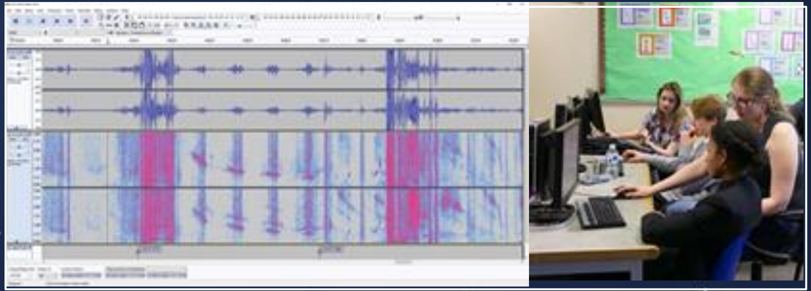
# Reaching people, sharing knowledge

Public Outreach. Contact: C. Forsyth, V. Mangano

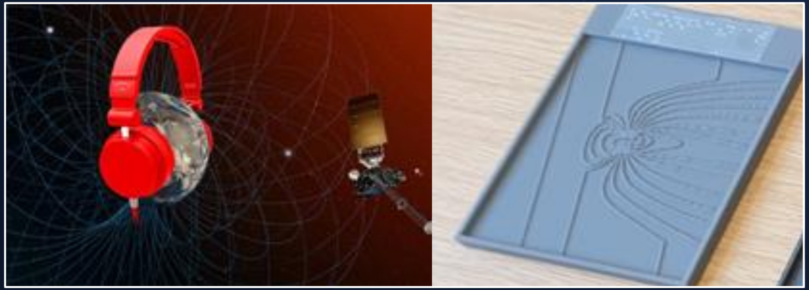
Combining traditional outreach with innovative sensory approaches (e.g., sonification) to engage broad audiences in a non-visual science.

- multi-sensory approach to space science

- understandable data for citizen science

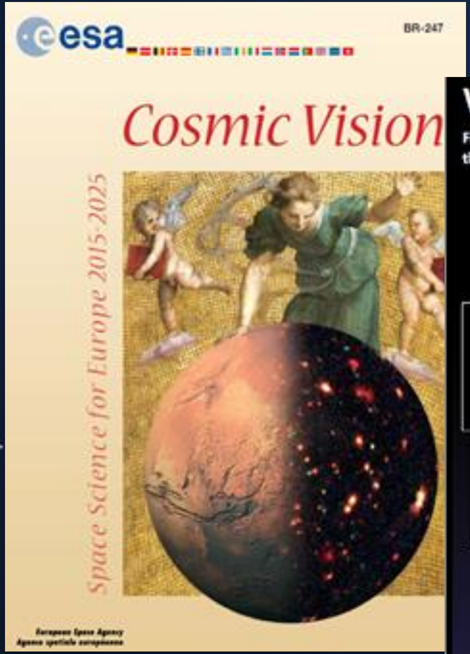


- accessible engagement for a wider audience



- direct engagement with performing arts

# Multi-scale physics is a science priority





***It is vital now to evolve and build on the success of the ground breaking Cluster mission***

The time is now!

# Multi-scale physics is the next frontier

**1-POINT ERA**

1978-2000

ESA GEOS-2
AMPTE
Equator-S
Polar
Wind
Geotail

→ *3D structure*

**1-SCALE ERA**

2000-2010s

ESA Cluster
THEMIS
MMS

→ *scale coupling*

**MULTI-SCALE ERA**

2030s

ESA PLASMA OBSERVATORY

## Re-establishing and boosting European Leadership

# The Plasma Observatory Family

*Reinstating European Leadership in Space Plasma Science for generations to come*

# PLASMA OBSERVATORY

Re-establishing and boosting European Leadership

# Backup slides

The ESA Science Programme provides Europe with the tools to be a world leader in space science.

The Science Programme is populated by different types of missions, each of which fulfil a clearly defined role:

Large (L-class) missions are European-led flagship missions with a launch cadence of approximately one every decade. JUICE (L1), Athena (L2), and LISA (L3) have been selected within this category.

Medium (M-class) missions may be ESA-led or carried out with international partners. These provide flexibility within the programme and have an expected launch cadence of two per decade. Current M missions are: Solar Orbiter (M1), Euclid (M2), PLATO (M3), Ariel (M4), and EnVision (M5).

Small (S-class) missions are a relatively new concept that allow Member State agencies to play a leading role in missions. The first S-class mission is CHEOPS.

Fast (F-class) missions focus on innovative implementations, follow a fast development path, and are intended to be launched alongside an M-class mission. Comet Interceptor and ARRAKIHS are F-class missions.

https://sci.esa.int/web/cosmic-vision/-/59977-missions-of-opportunity
https://www.science.esa.int/web/cm25/about

# Summary of SSCs measurement capabilities

| Instrument | Measurement performance requirements |
|---|---|
| Ion and Electron Plasma Camera (iEPC) | **3D ion and electron distribution functions**<br>Energy range: 10 eV-25 keV<br>Time resolution: 250 ms<br>Angular resolution: 22.5°<br>Energy resolution ΔE/E = 20% |
| Ion Mass Composition Analyser (IMCA) | **3D mass-resolved ion distribution function (H+, He+, He++, O+)**<br>Energy range: 10 eV-30 keV<br>Time resolution: 2s<br>Angular resolution: 22.5°<br>Energy resolution ΔE/E = 20%<br>Mass resolution m/Δm: $H^+$ >8, $He^{++}$ >8, $O^+$ ≥3 |
| Energetic Particle Experiment (EPE) | **Ion and electron distribution functions**<br>Energy range: 30-600 keV<br>Time resolution: 4s<br>Angular resolution: ≥ 22.5°<br>Energy resolution ΔE/E 20 % |
| BOX-Particles | Unique interface to SSC for MAG, EPE, iEPC and IMCA |
| Magnetometer (MAG) | **3D magnetic field**<br>Frequency range: DC to 128 Hz<br>Dynamic range: up to1000 nT<br>Accuracy: 0.5 nT.<br>Sensitivity: < 10^2 pT^2/Hz. |
| Search Coil Magnetometer (SCM) | **3D magnetic field fluctuations**<br>Frequency range: 1 Hz - 8 kHz<br>Sensitivity: [10^-3, 3.6 *10^-6, 10^-8, 2*10^-9, 2*10^-9] nT^2/Hz @ [1,10, 10^2, 10^3, 8*10^3] |
| Electric Field Instrument (EFI) | **3D electric field (via E·B=0)**<br>Frequency range: DC to 0.25 Hz (4s spin period)<br>Dynamic range: up to 1 V/m<br>Accuracy: 1.5 mV/m for \|E\|<5 mV/m and 30% for \|E\|>5 mV/m |
| | **2D/3D electric field fluctuations**<br>Frequency range: 1 Hz to 100 kHz<br>Dynamic range: up to 0.5 V/m<br>Sensitivity: [2*10^-11,3*10^-12,3*10^-12,3*10^-13,3*10^-14] (V/m)^2/Hz @ [10,10^2,10^3,10^4,10^5] Hz (higher in spin plane) |
| | **Spacecraft potential @ 128 Hz** |
| BOX-Waves | Unique interface to SSC for EFI and SCM |