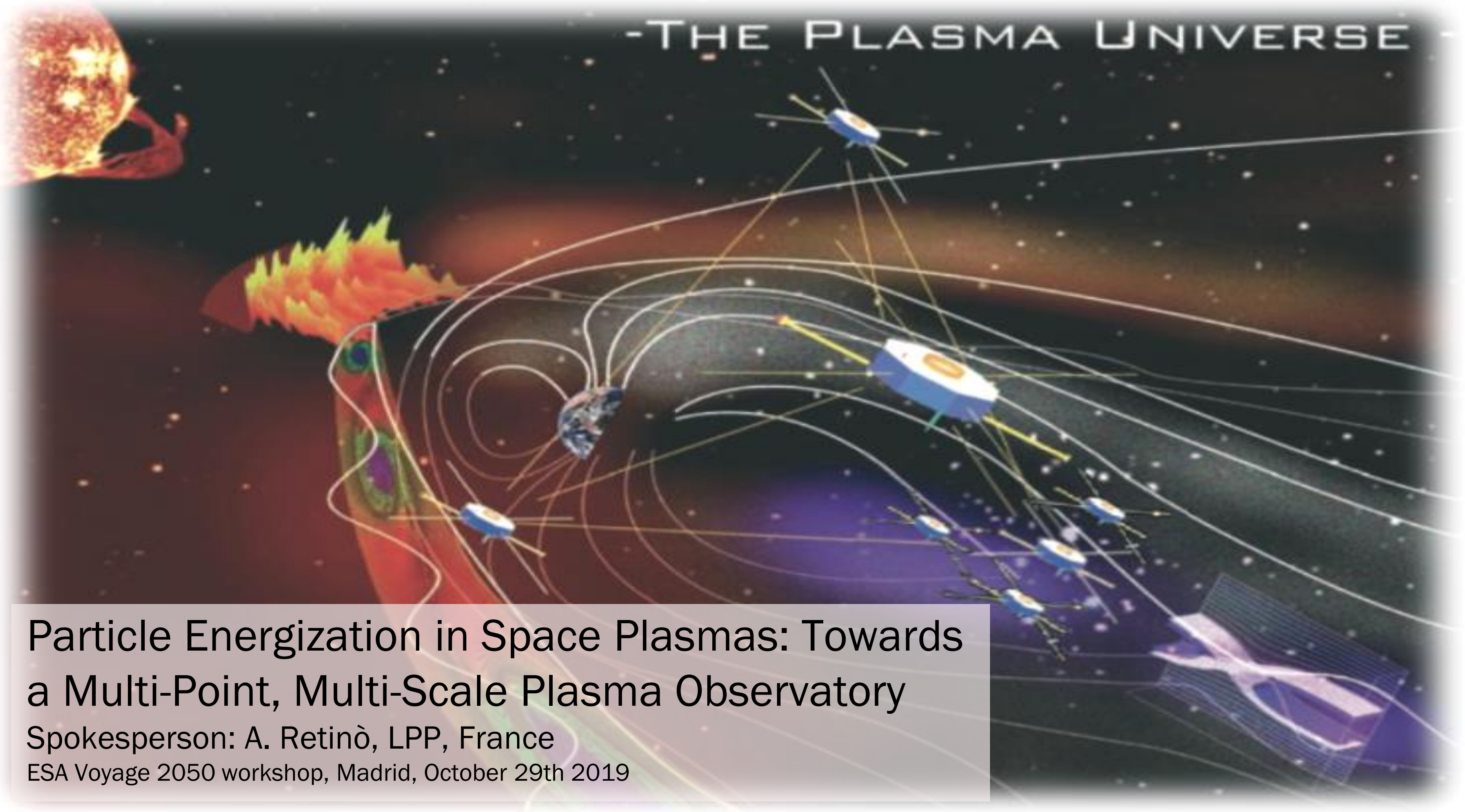


Particle Energization in Space Plasmas: Towards a Multi-Point, Multi-Scale Plasma Observatory

Spokesperson: A. Retinò, LPP, France

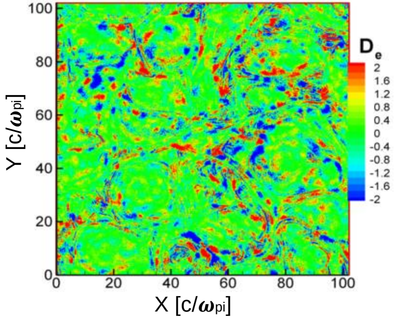
ESA Voyage 2050 workshop, Madrid, October 29th 2019

How are charged particles energized in space plasmas?

A grand challenge and unsolved problem of fundamental importance for plasma astrophysics, that can only be answered in the laboratory of near-Earth space with multi-point in situ measurements.

Fundamental plasma physics in near-Earth space

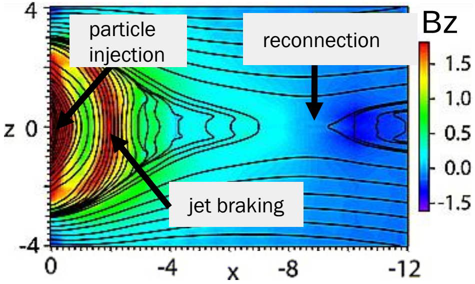
Energy dissipation and particle heating in turbulence (in situ)



[Wan+, PoP, 2016]

Sun-Earth interaction (space weather)

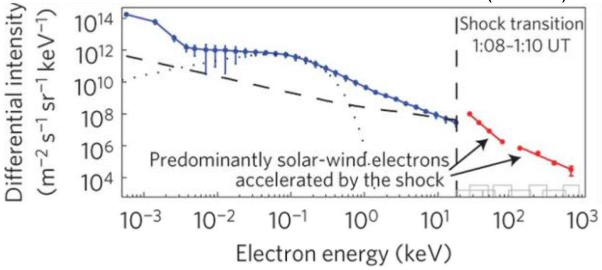
Energetic particle injection into radiation belts (in situ)



[Birn+, 1998; Birn+, 2011]

Other planets

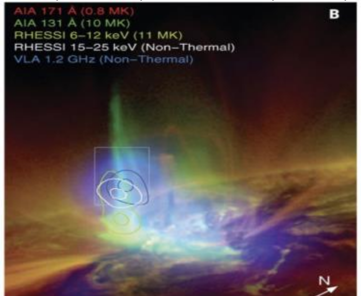
Electron acceleration at Saturn’s shock (in situ)



[Masters+, Nature Physics, 2013]

Solar corona and wind

Flares (remote) and SEPs (in situ)



[Chen+, Science, 2015]

Distant astrophysical objects

Radio image of galaxy jet and lobes (remote)

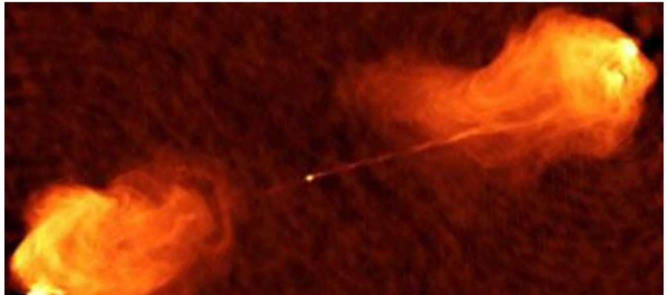


Image credit: NRAO/AUI

Big open questions

Major particle energization is associated with fundamental processes:

- shocks,
- magnetic reconnection,
- turbulence and waves,
- plasma jets,
- Interplay between such processes.

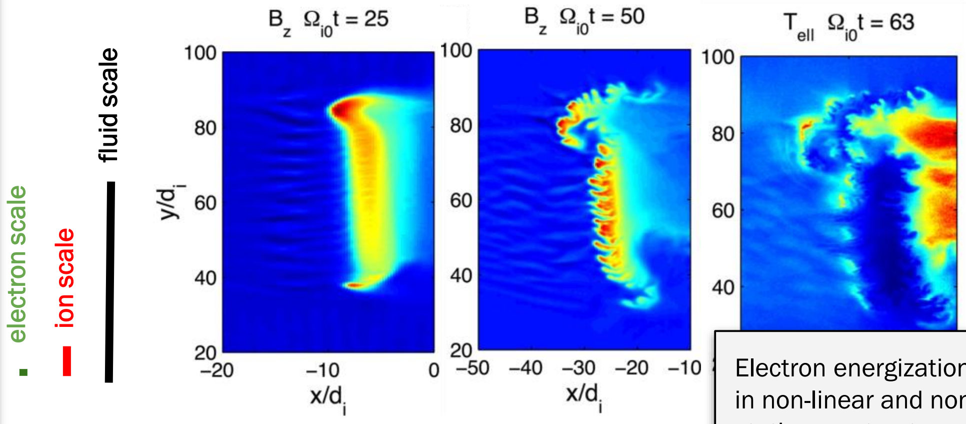
How does energization take place during these fundamental processes?
What is the quantitative contribution of each of these processes?

Solving open questions requires assessing:

1. **non-linearity and non-stationarity** at given scale (electron, ion, fluid),
2. **cross-scale coupling.**

Exploratory science: discover unknown energization mechanisms and new plasma physics.

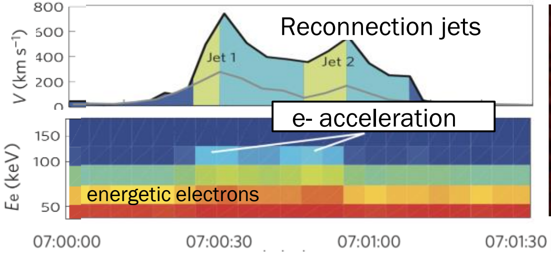
Jet interacting with ambient plasma



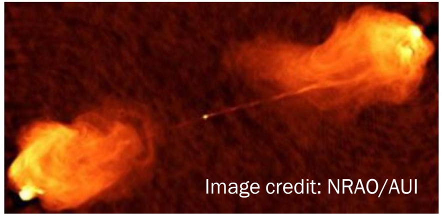
PIC simulations [Pritchett, JGR, 2016]

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

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



Cluster data [Fu+, Nature Physics, 2013]



Radio image of galaxy Cygnus A showing the jet and radio lobes.

Limitations of current multi-point measurements

4 point measurements: Cluster and MMS:

- designed for studying one scale at a time (Cluster: fluid or ion, MMS ion or electron)
- measurement capability at each of these scales allowed important discoveries

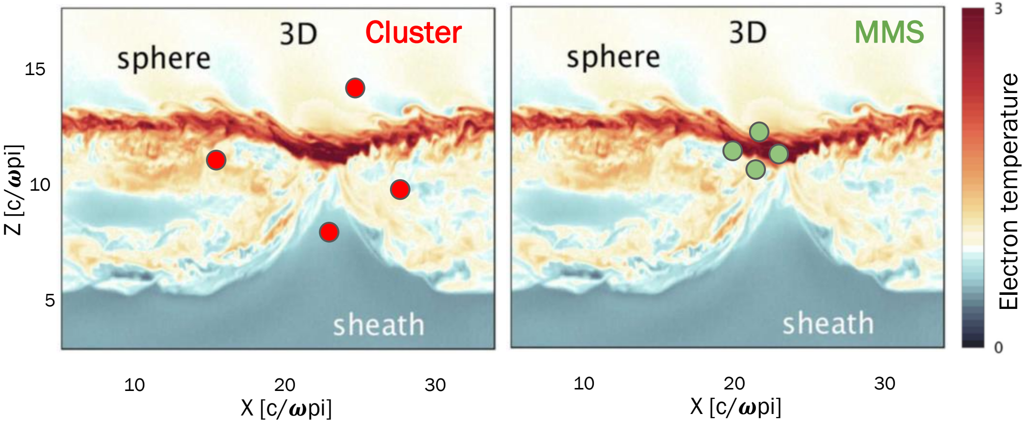
However Cluster and MMS:

- cannot resolve **non-linearity and non-stationarity** of energization structures
- cannot resolve **cross-scale coupling**

These critical limitations hinder significant advances in particle energization and discovering new plasma physics.

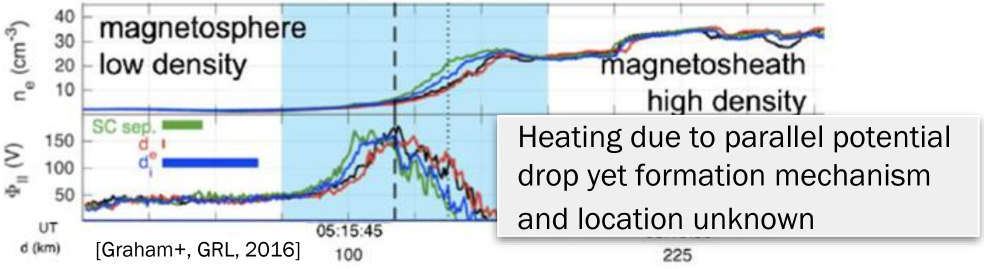
Electron heating during reconnection

PIC simulations [Le+, PoP, 2018]



Heating in 3D only within non-linear and non-stationary electron-scale structures embedded in ion-scale reconnection region

MMS data



Heating due to parallel potential drop yet formation mechanism and location unknown

[Graham+, GRL, 2016]

Need for new multi-point, multi-scale measurements

- Particles and fields measurements from at least 7 points (4+3) are required to resolve:
  - **non-linearity and non-stationarity**
  - **cross-scale coupling**

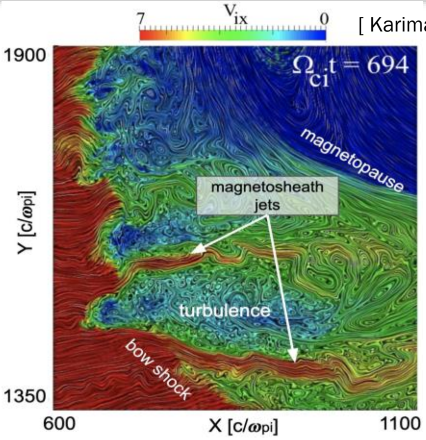
- Need for an L-Class *Plasma Observatory* (PO) with at least 7 spacecraft and improved instrumentation

- PO next logical step following Cluster, THEMIS and MMS

- ESA has expertise

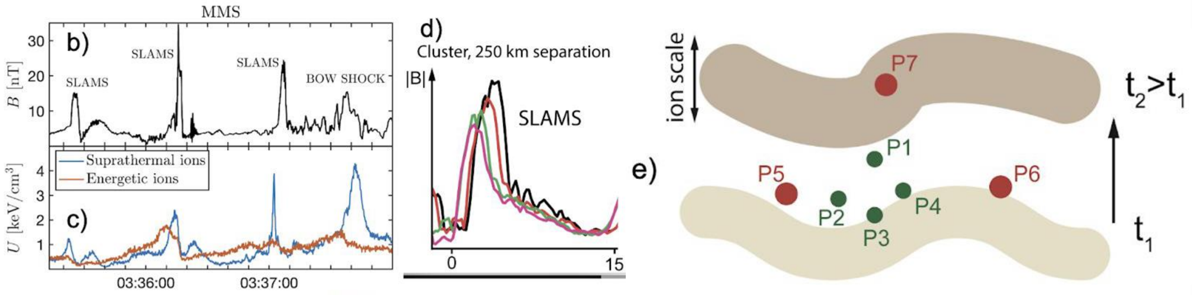
Ion energization at quasi-parallel shocks

Strong turbulence responsible for ion energization, e.g. injection into diffusive shock acceleration



[Karimabadi+, PoP, 2014]

Non-linear and non-stationary ion-scale turbulent fluctuations (Short Large-Amplitude Magnetic Structures) embedded in fluid-scale shock dynamics



[Johlander+, 2019]

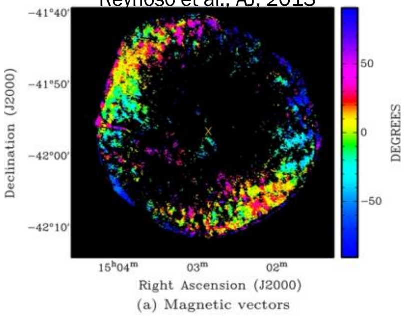
Impact

- Paradigm shift in our comprehension of particle energization in space plasmas
- Interpret observations not accessible with high-quality multi-point in situ measurements
- Additional major impact on understanding:
  - magnetosphere-ionosphere coupling
  - space weather science
- European leadership in space plasma physics for both science and hardware
- Very large and active European and international community

Relativistic electron acceleration at quasi-parallel shocks

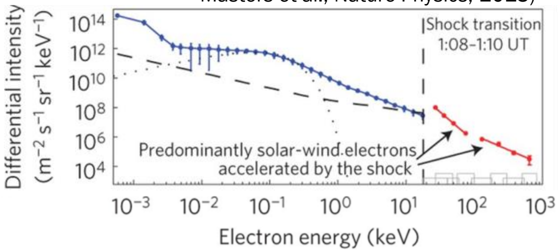
Supernova remnant shock

Reynoso et al., AJ, 2013



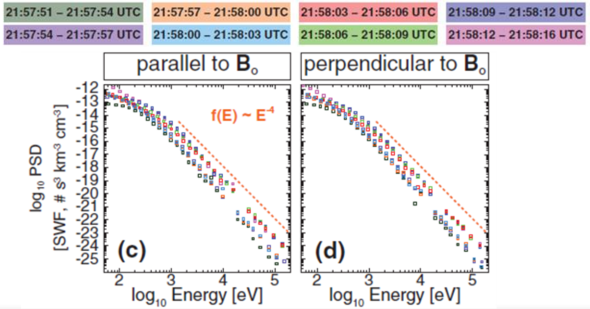
Saturn's bow shock

Masters et al., Nature Physics, 2013)



Earth's bow shock

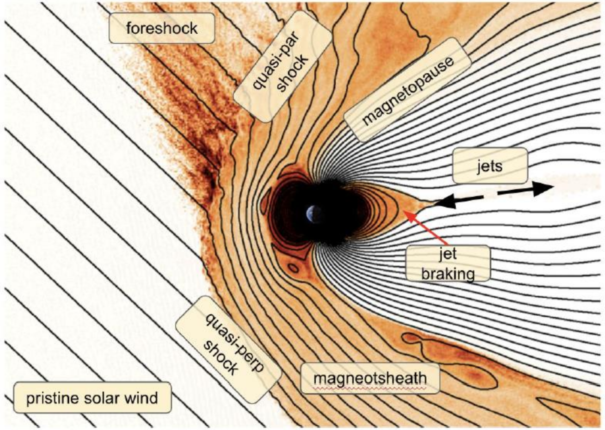
(Wilson et al., PRL, 2016)



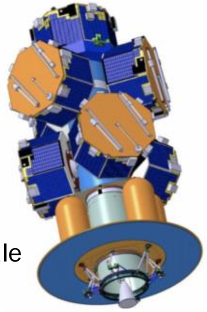
Mission profiles and technological developments

- Equatorial orbits through Key Science Regions:
  - pristine and shocked solar wind, bow shock, magnetopause and magnetotail
- Two L-class constellation options:
  - 7 identical spacecraft (Cross-Scale like)
  - 1 Mother + 6 smaller identical daughter spacecraft (Scope-like)
- Technological developments:
  - use of smallsats
  - constellation management (ISL, ranging, ...)
  - payload miniaturization, new instruments (e.g. particles) and industrial production and testing
  - more autonomous spacecraft and science operations

Key Science Regions

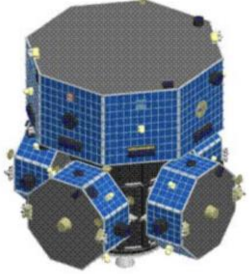


Option 1)
7 identical spacecraft
Heritage:
ESA Cross-Scale phase A



ESA
Cross-Scale

Option 2)
Mother + 6 identical daughters
Heritage:
JAXA SCOPE phase A
ESA THOR phase A (Mother)



JAXA
SCOPE

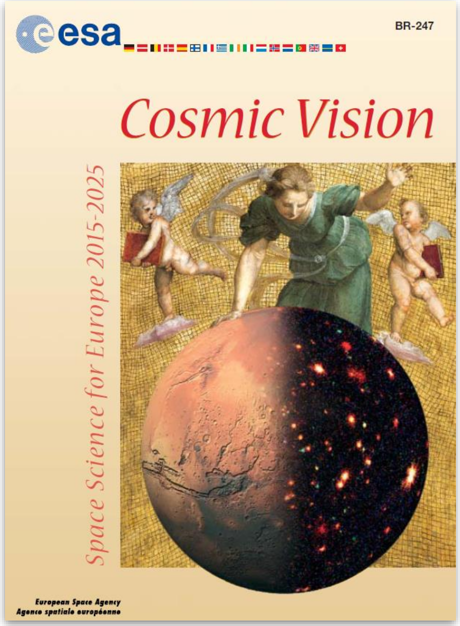
Worldwide context

- The need for a multi-point, multi-scale constellations to study space plasmas is recognized as important by ESA, NASA, JAXA, CSA, CAS-NSSC, Roscosmos, CNES

- Contributions by other agencies would enhance the science return of the Plasma Observatory

- Synergies with coordinated measurements from other near-Earth missions and ground observatories -- coverage of near-Earth space from kinetic to global scales.

- Plasma Observatory has strong support form international science community

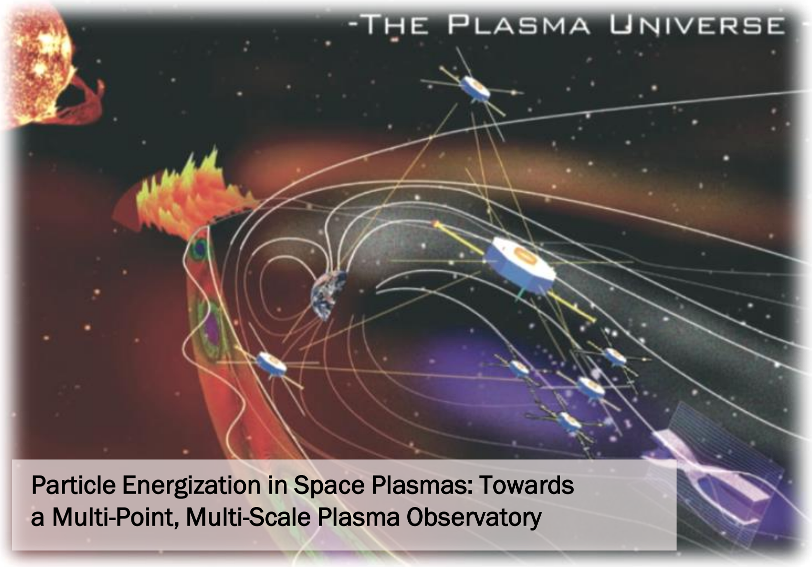


...it is now vital to move on from Cluster, which has four satellites operating in company at relatively large distances, to simultaneous observations at a much larger number of points... (page 31)

Summary

- Science theme: " *How are charged particles energized in space plasmas ?* " Unsolved problem of fundamental/astro plasma physics

- Open questions related to shocks, reconnection, waves and turbulence, jets and the interplay between these. Require resolving cross-scale coupling, nonlinearity and nonstationarity, which is not possible with existing observations.



Particle Energization in Space Plasmas: Towards a Multi-Point, Multi-Scale Plasma Observatory

https://arxiv.org/abs/1909.02783

- Science closure requires a new multi-point, multi-scale L-class Plasma Observatory with at least 7 spacecraft.

- Will enable a paradigm shift in particle energization with very important impact on solar and astrophysical plasmas.

- Next logical step after Cluster, THEMIS and MMS. ESA has expertise.

- European scientific and technical leadership in the space plasma research field.