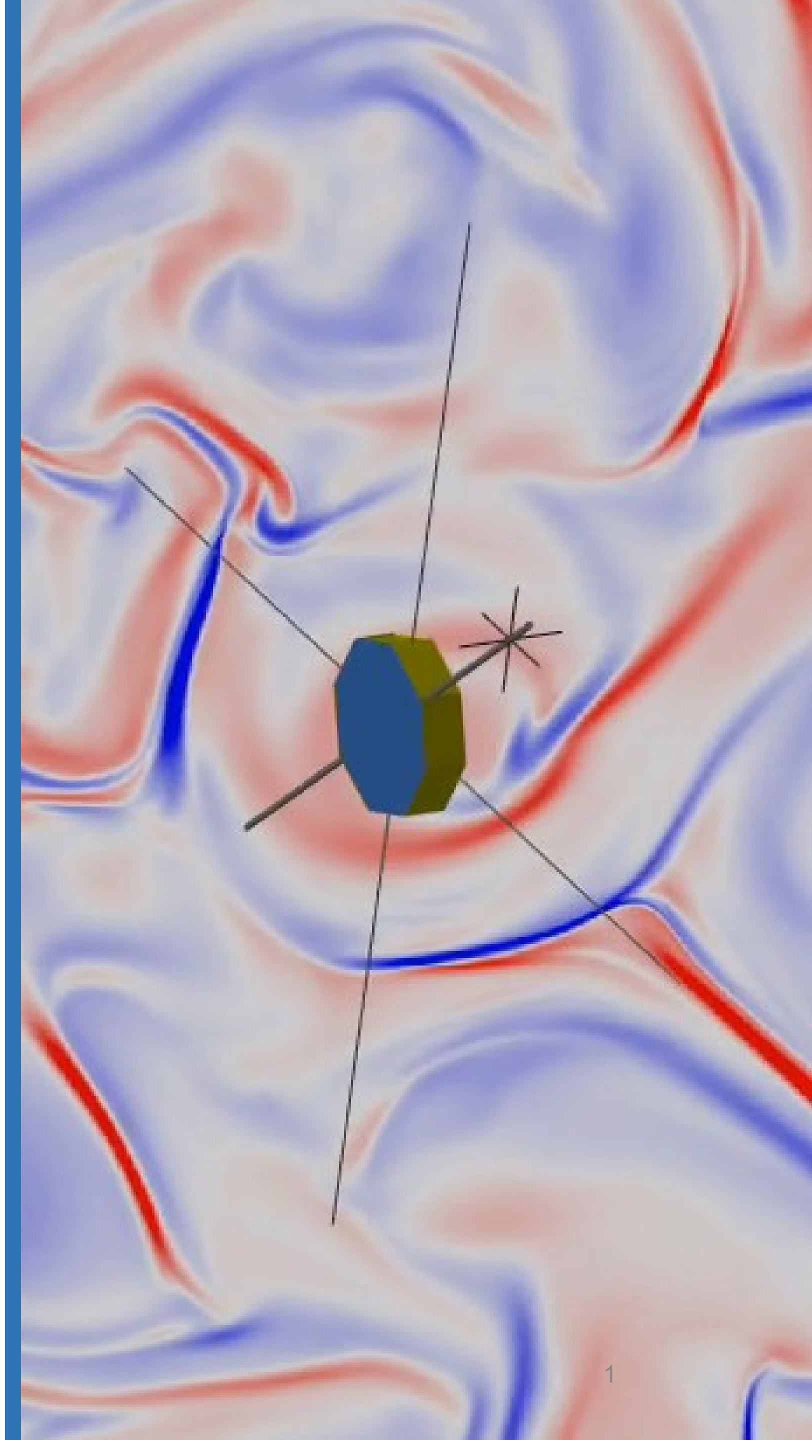
Turbulence Heating ObserveR

THOR team

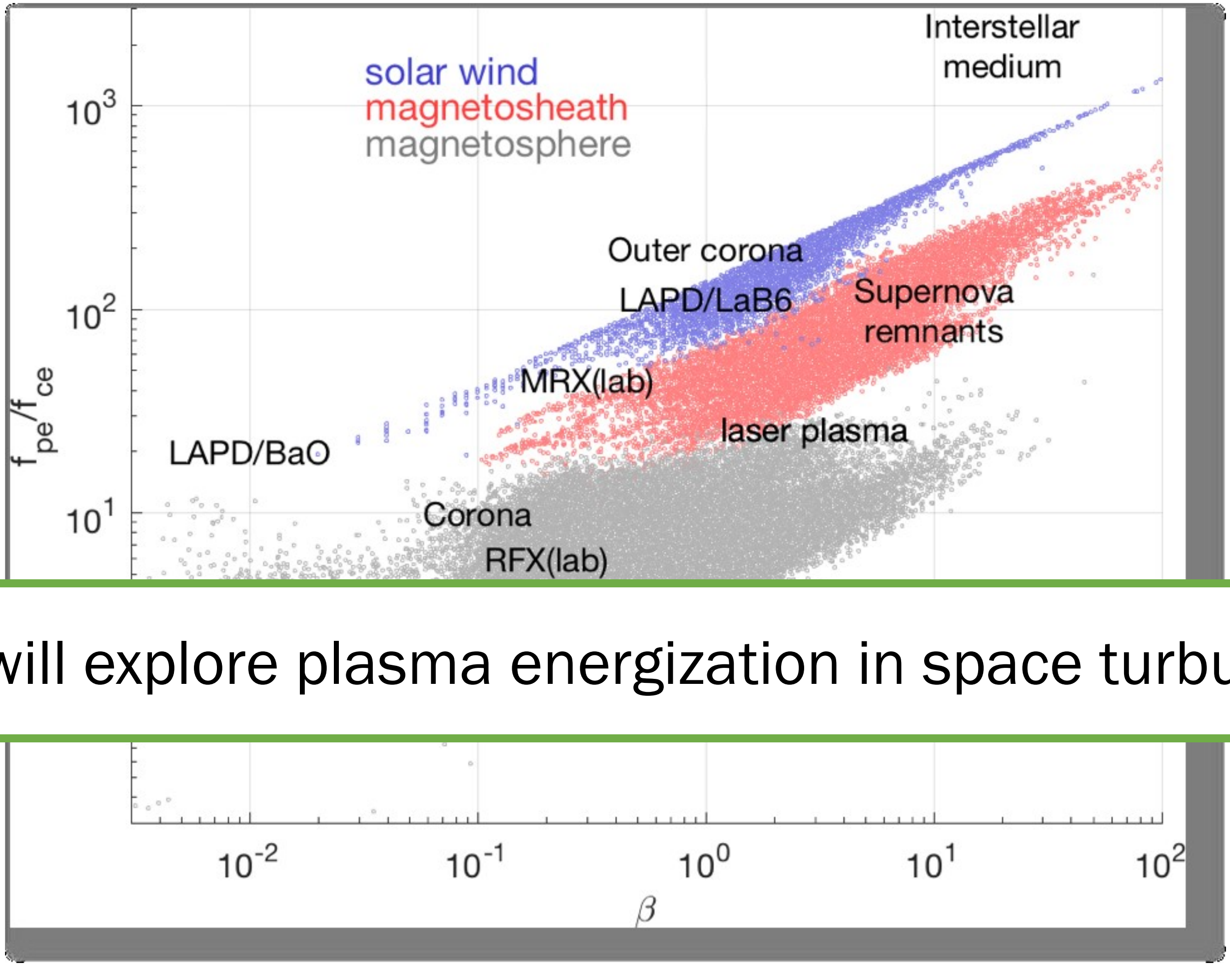
Presenting: Andris Vaivads (Lead Scientist)

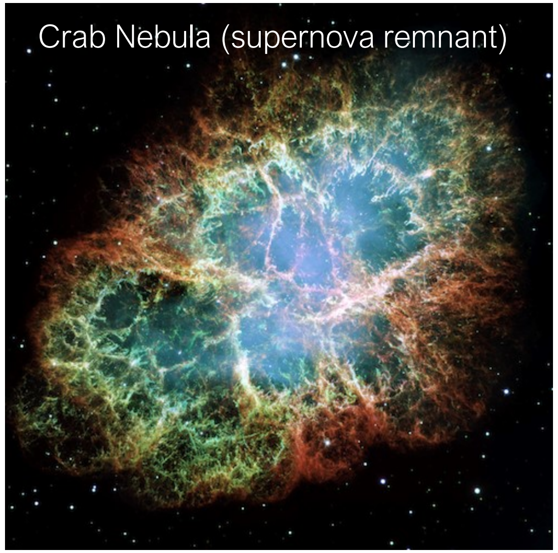
Paris 2017 July 3

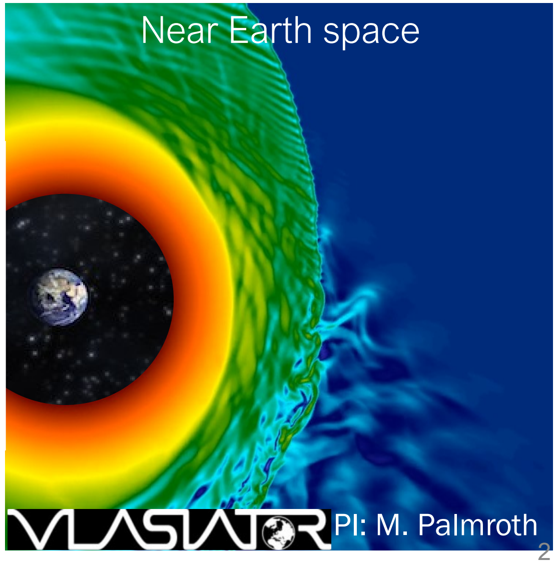


Motivation

How does all the hot plasma in the Universe get heated to high temperatures?







THOR will explore plasma energization in space turbulence

Summary

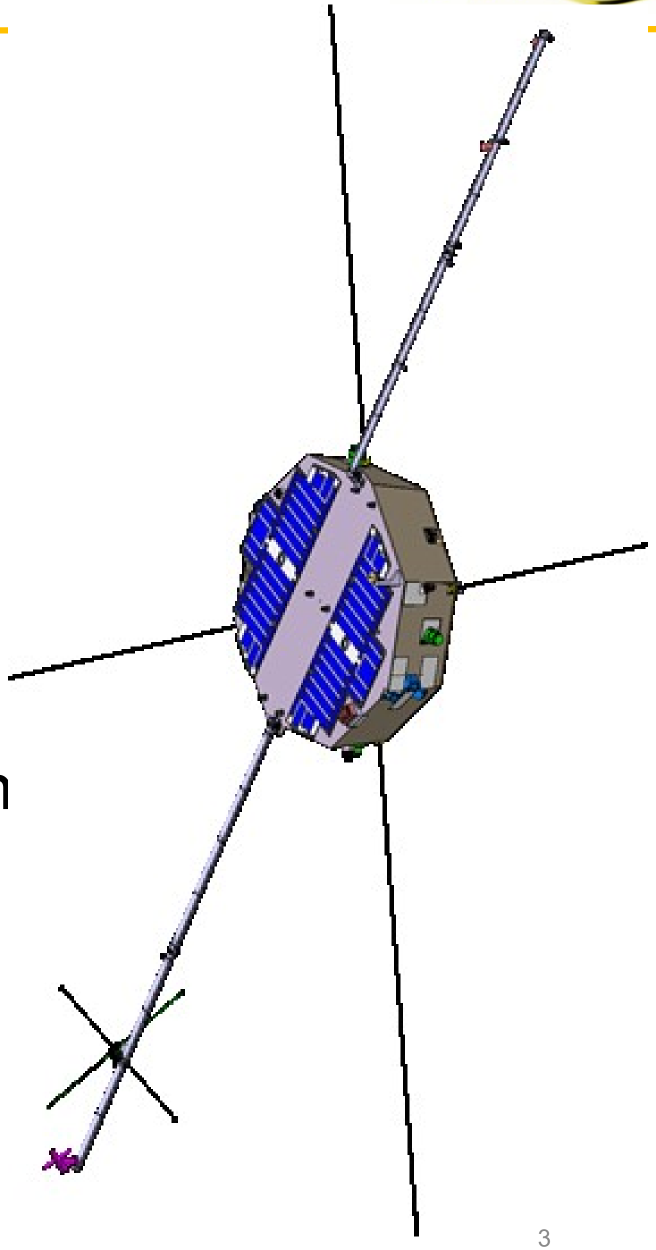
First mission **dedicated to plasma energization by turbulence.**

Using near Earth space as a **unique laboratory for study of fundamental plasma physics** of relevance to astrophysics.

Addresses Cosmic Vision Scientific Question:
“2. How does the Solar System work?”

Comprehensive payload (4 field, 6 particle) - **highest resolution instruments ever flown in near-Earth space**

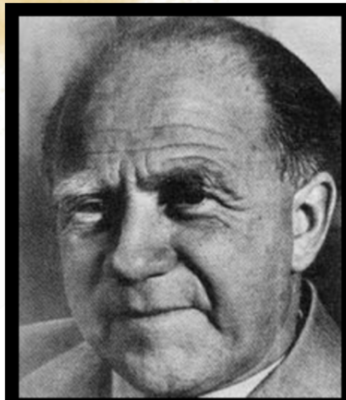
Experienced team supported by large and interdisciplinary community.



SCIENCE

Leonardo Da Vinci
ca 1500, Codice Atlantico, f. 74v:

"Doue la turbolenza dellacqua rigenera,
doue la turbolenza dellacqua simantiene plugho,
doue la turbolenza dellacqua siposa"

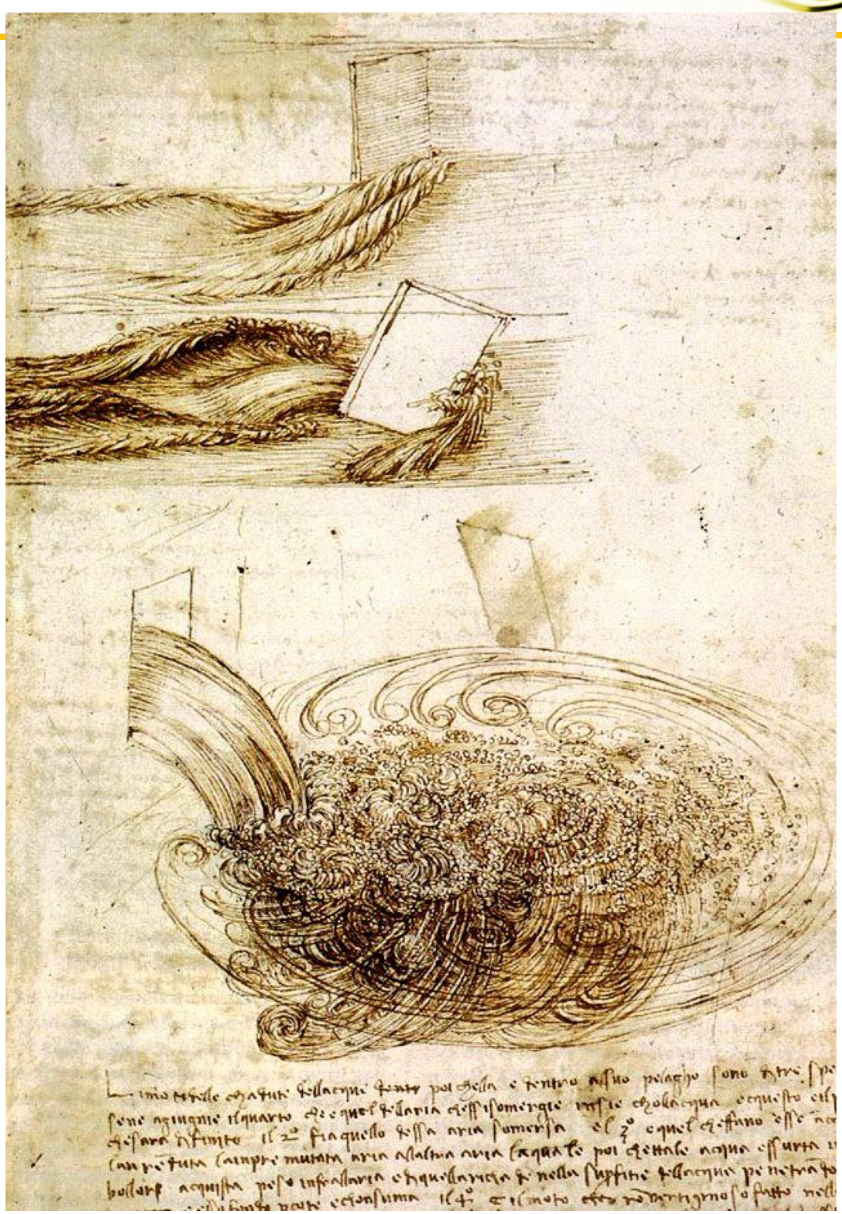


Werner Heisenberg (1901 – 1976)

$$\Delta p \Delta x \geq \frac{\hbar}{2}$$

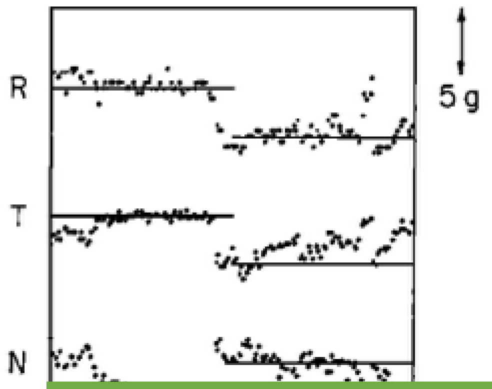
On his deathbed, Heisenberg is reported to have said*:

" When I meet God, I am going to ask him two questions:
Why relativity? And why turbulence?
I really believe he will have an answer for the first. "



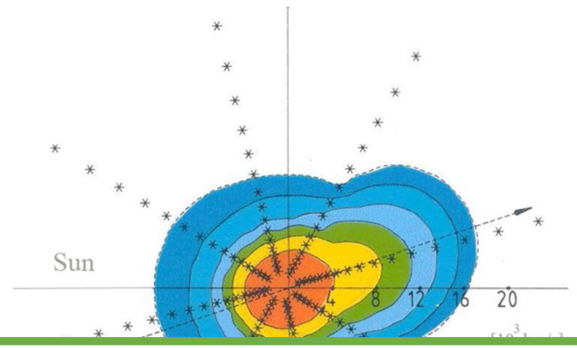
History of in-situ plasma turbulence observations

1971 – Mariner 5



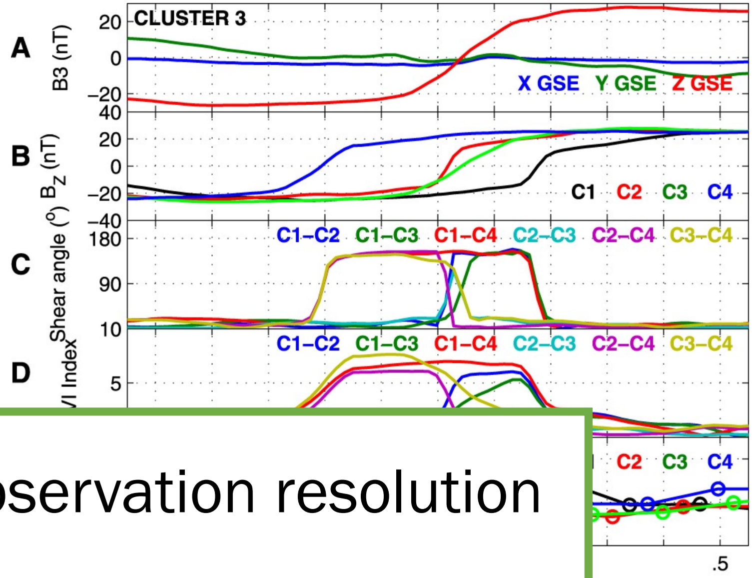
Belcher & Davis, JGR, 1971

1982 – Helios 2



Marsch et al., JGR, 1991

2001 – Cluster



Chasapis et al., ApJL, 2015.

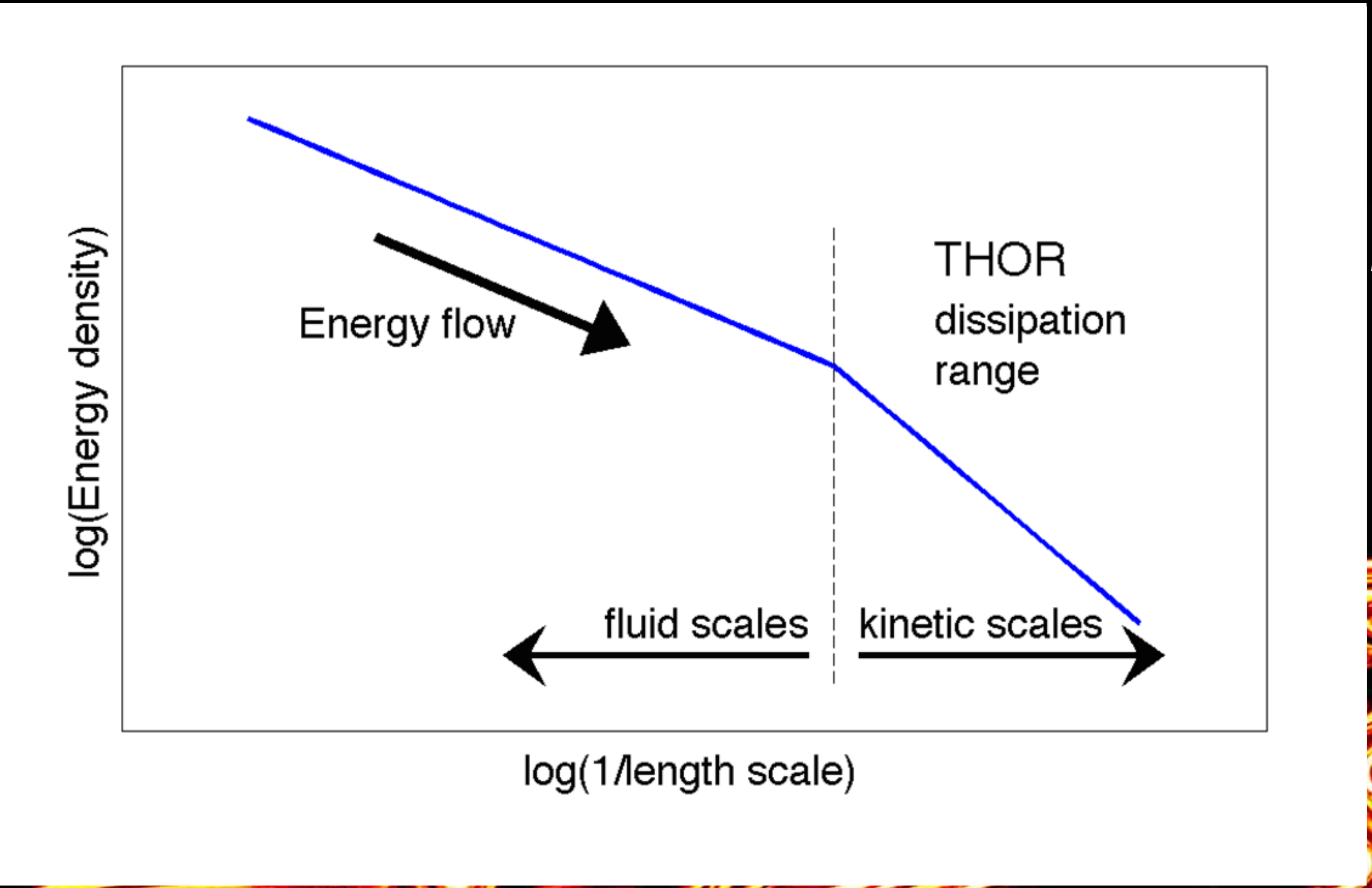
Every time a new space plasma mission increases observation resolution new discoveries are made!

5 minute data: first observation of Alfvén waves, magnetic field (dots) and velocity (lines) correlate

10s data: proton distribution function is anisotropic about the magnetic field suggesting kinetic processes are at work.

0.01s *B* data, 1s electron data: electron heating in very thin magnetic structures suggesting dissipation.

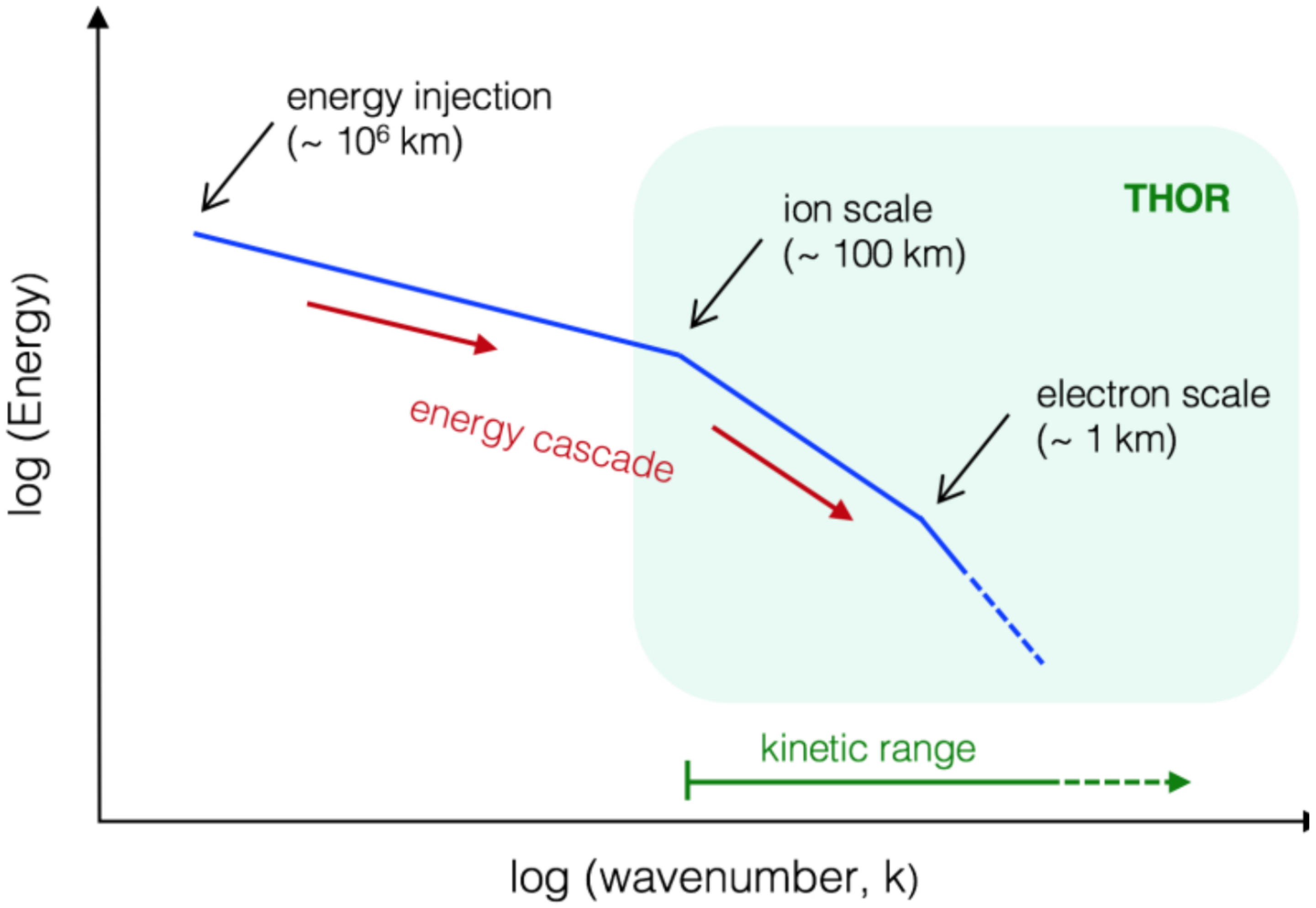
Kinetic scales of plasma turbulence



Karimabadi, H. et al., PoP, 2013

Plasma turbulence dissipates at kinetic scales heating plasma and accelerating particles.

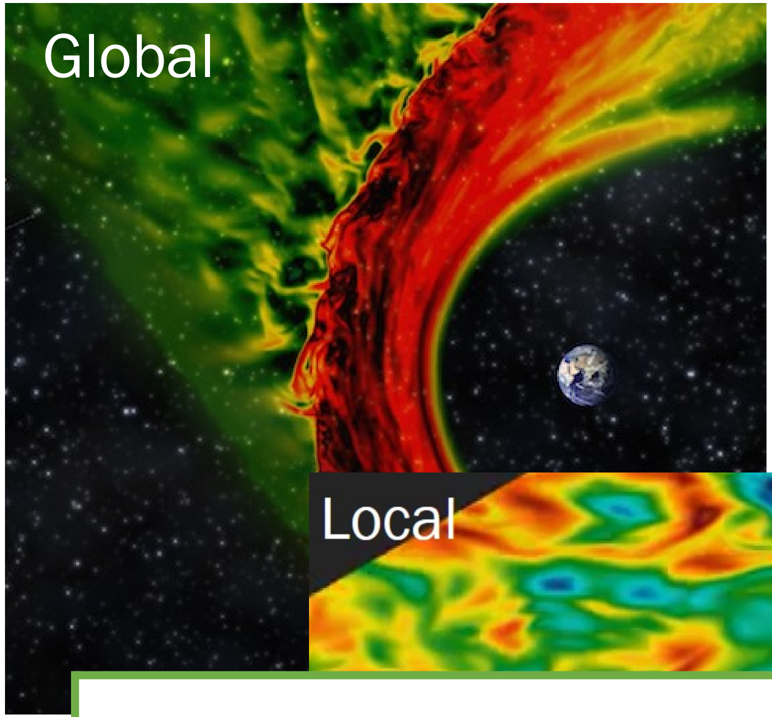
Kinetic scales

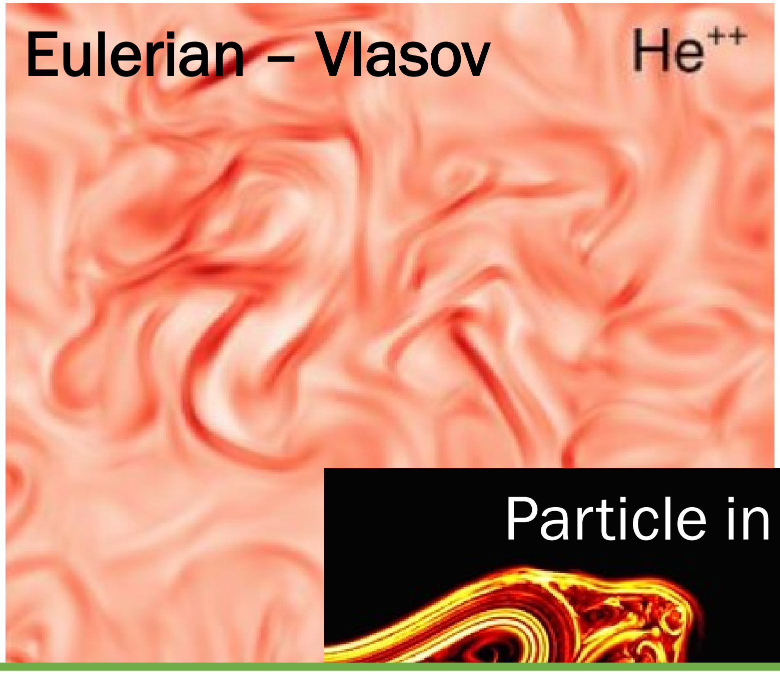


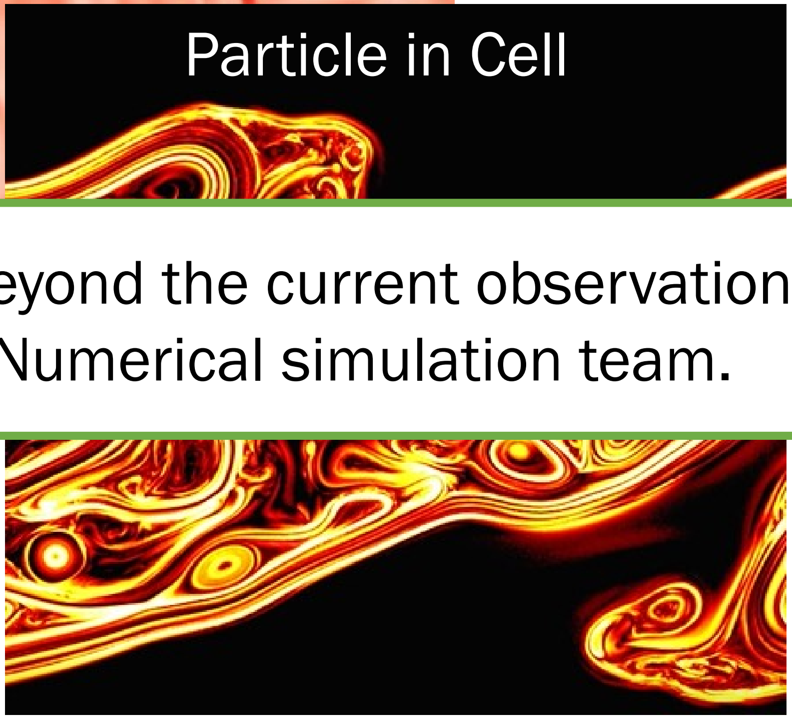
Required THOR measurements:

- Electric and magnetic fields
- Particle distribution functions

Kinetic numerical simulations







Simulations allow to explore part of the physics beyond the current observational capabilities. THOR requires and has a strong Numerical simulation team.

THOR Science

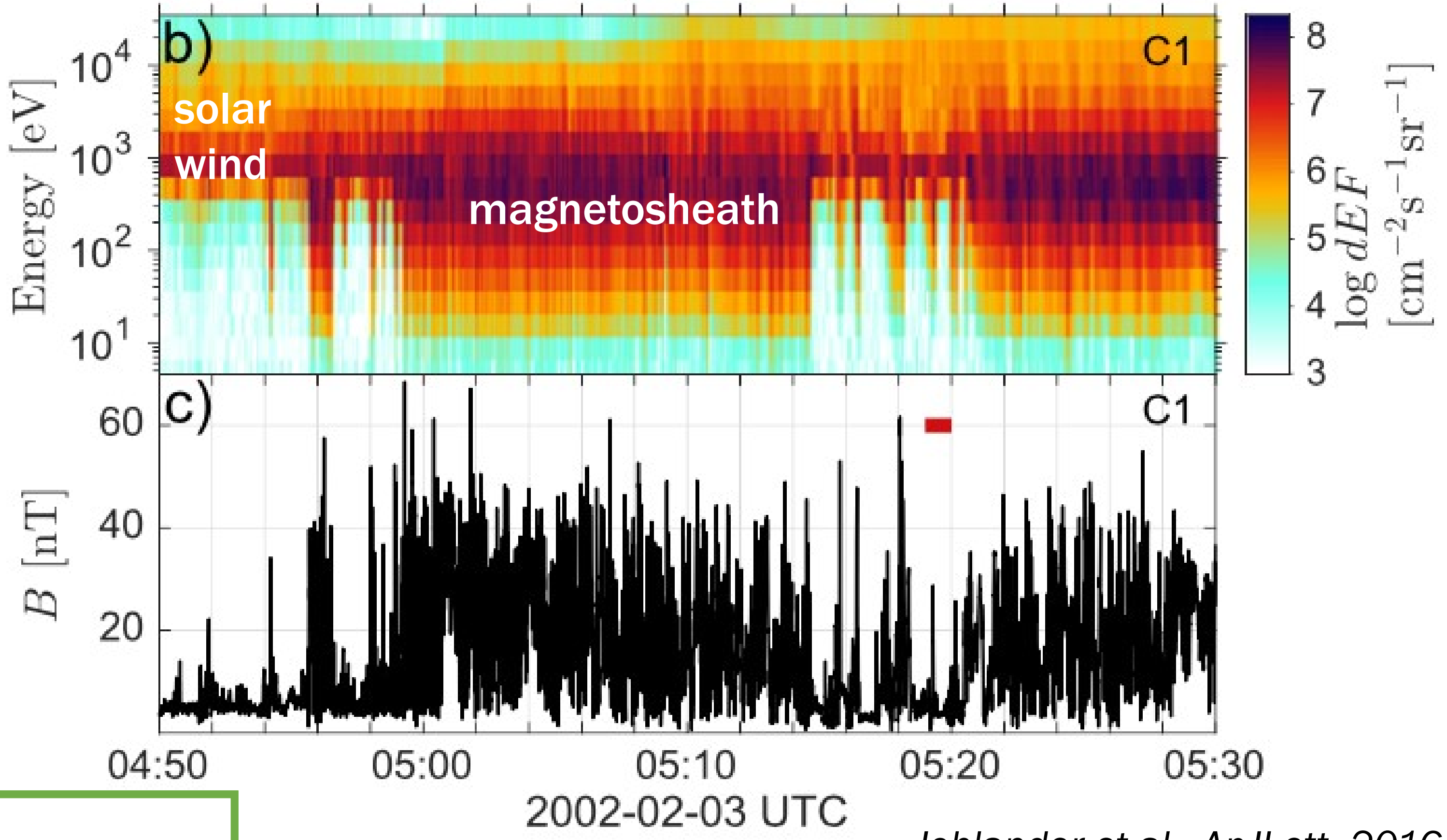
"Exploring plasma energization in space turbulence"

- *Q1: How is plasma heated and particles accelerated?*
  - heating mechanism: resonant, stochastic, reconnection, etc.
  - distribution throughout plasma, e.g. structures
- *Q2: How is the dissipated energy partitioned?*
  - electrons vs protons vs heavy ions
  - particle acceleration vs heating
- *Q3: How does dissipation operate in different regimes of turbulence?*
  - different environments: solar wind, foreshock, shock, magnetosheath
  - different plasma parameters: beta, temperature ratio, imbalance

Q1: How is plasma heated and particles accelerated?

Cluster, bow shock crossing

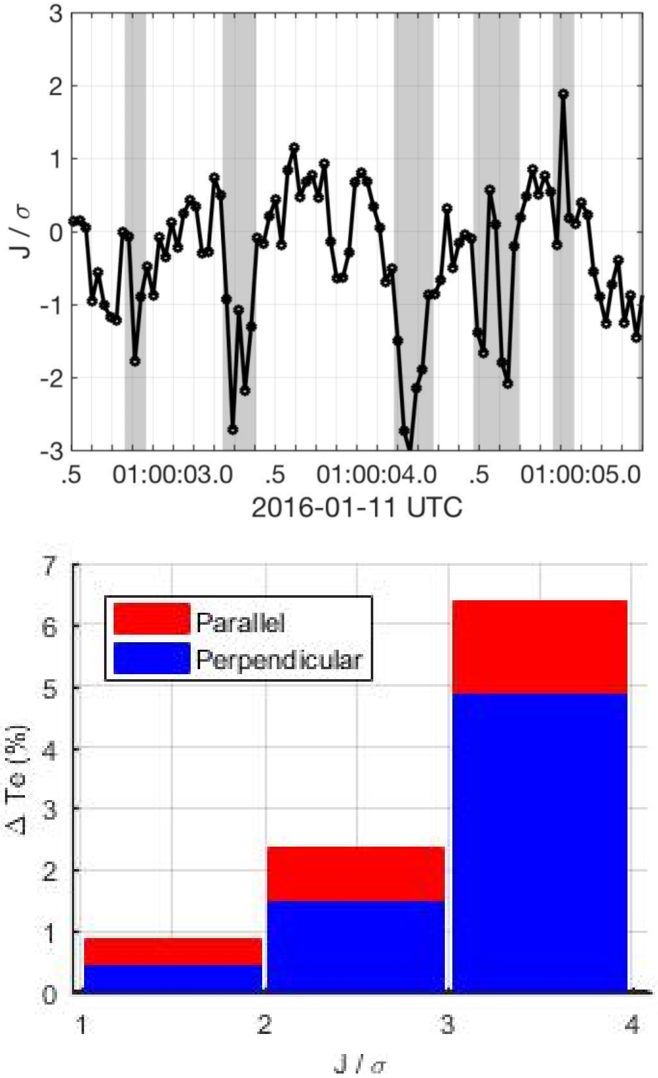
- Heated and accelerated ions observed
- in association with magnetic turbulence (B - magnetic field amplitude)



Johlander et al., ApJLett, 2016

Measurements of electric and magnetic fields and particle distribution functions **at kinetic scales** are required.

Q1: Electron heating at kinetic scales



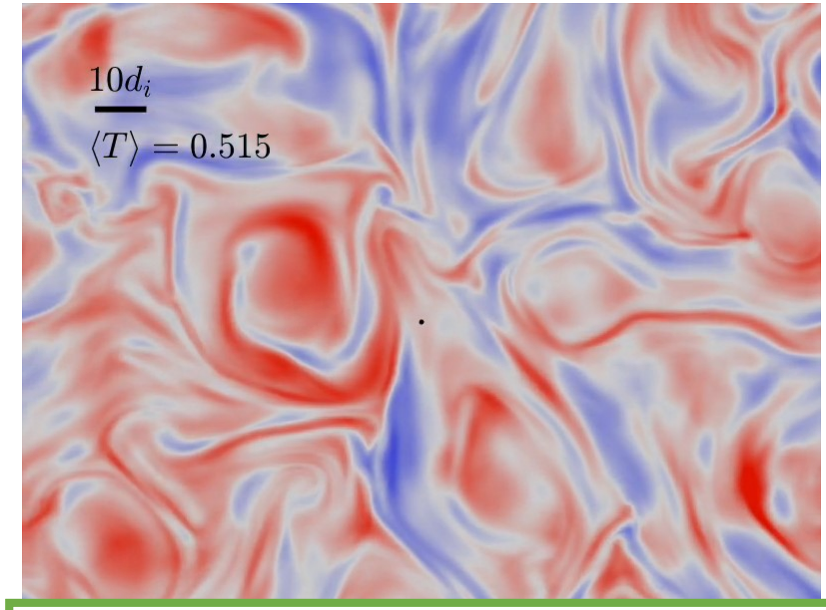
Adopted from Chasapis et al., ApJLett, 2017

- MMS observations of current density (J) and electron temperature (T_e) in the magnetosheath.
- Current density at the smallest scales can only be resolved by single-spacecraft techniques, i.e. it cannot be resolved by multi-spacecraft techniques.

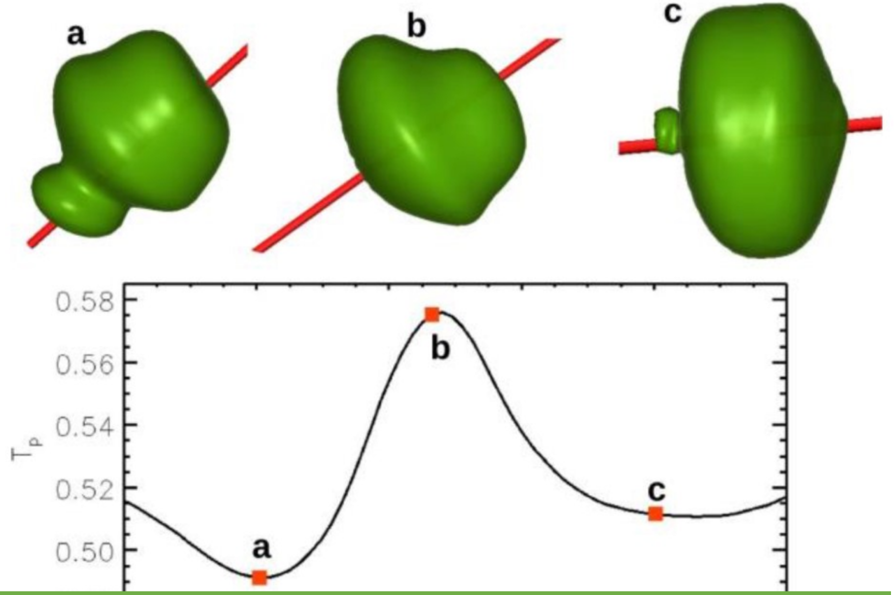
State of art electron measurements are insufficient to resolve electron scales in turbulence.

Q1: Non-maxwellian distributions

Proton temperature



Non-Maxwellian distributions at kinetic scales

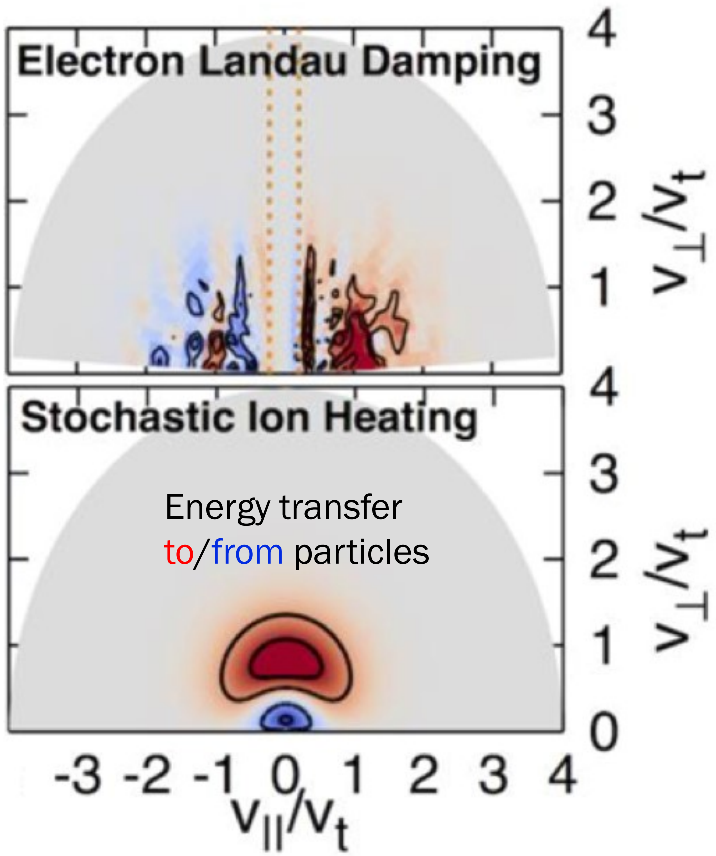


THOR will make measurements of particle distribution functions and electric and magnetic fields **at kinetic scales.**

space plasma show variations in proton temperature at kinetic scales.

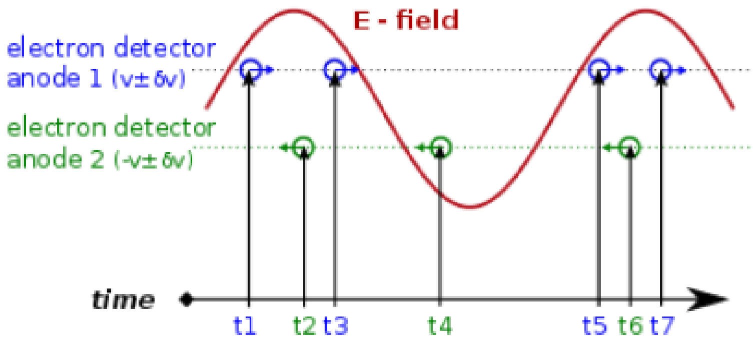
Distribution functions evolve rapidly.

Q1: Field-particle correlations



Klein et al., ApJL, 2016, Howes et al., JPP, 2017

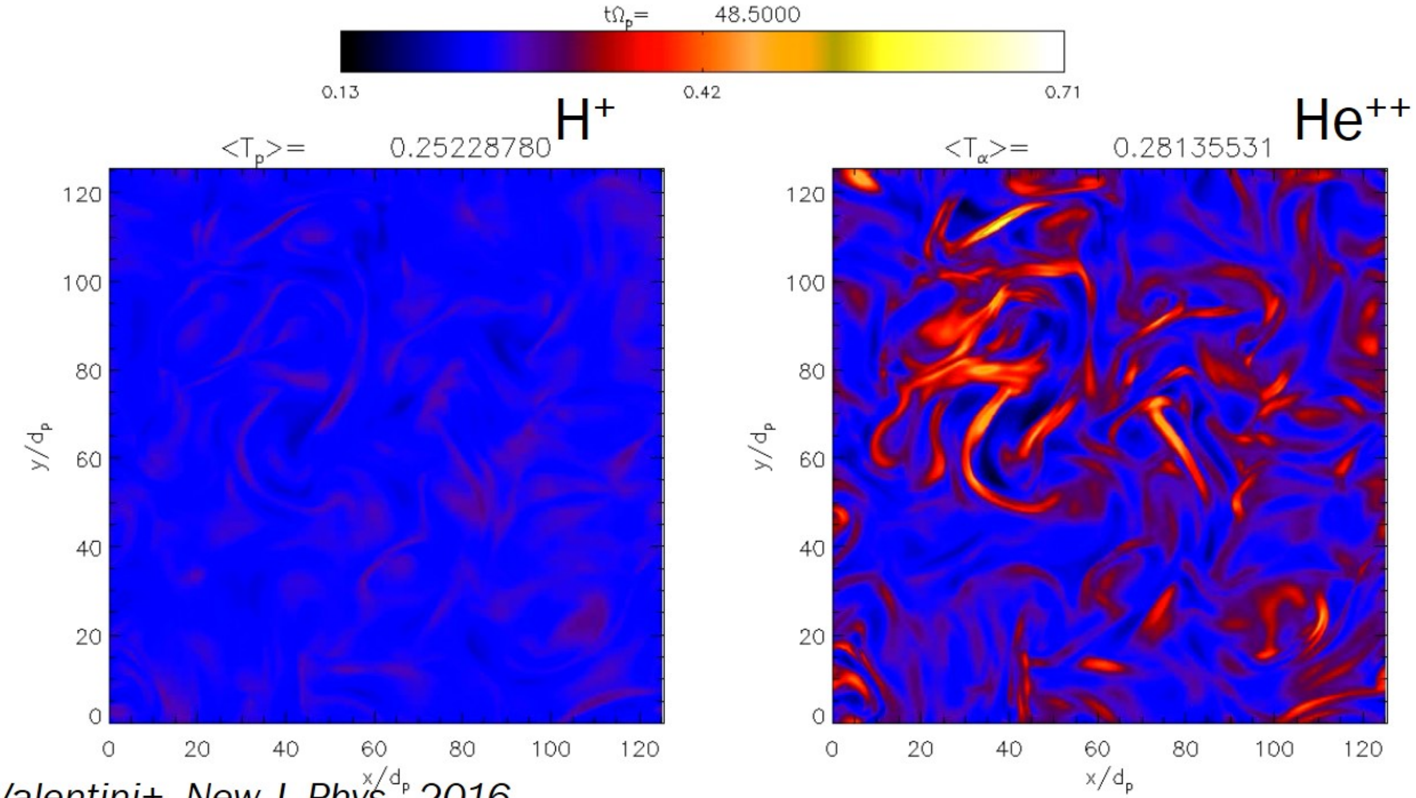
- Simulation predict different heating mechanisms producing unique correlation footprints
- Simultaneous measurement of electric field and individual electron counts up to f_{pe} (superburst).



THOR coordinated fields and particle measurements will allow to distinguish the different heating mechanisms.

Q2: How is the dissipated energy partitioned?

- Localized ion heating by plasma turbulence (intermittency) predicted by simulations
- Alphas are more heated relative to protons

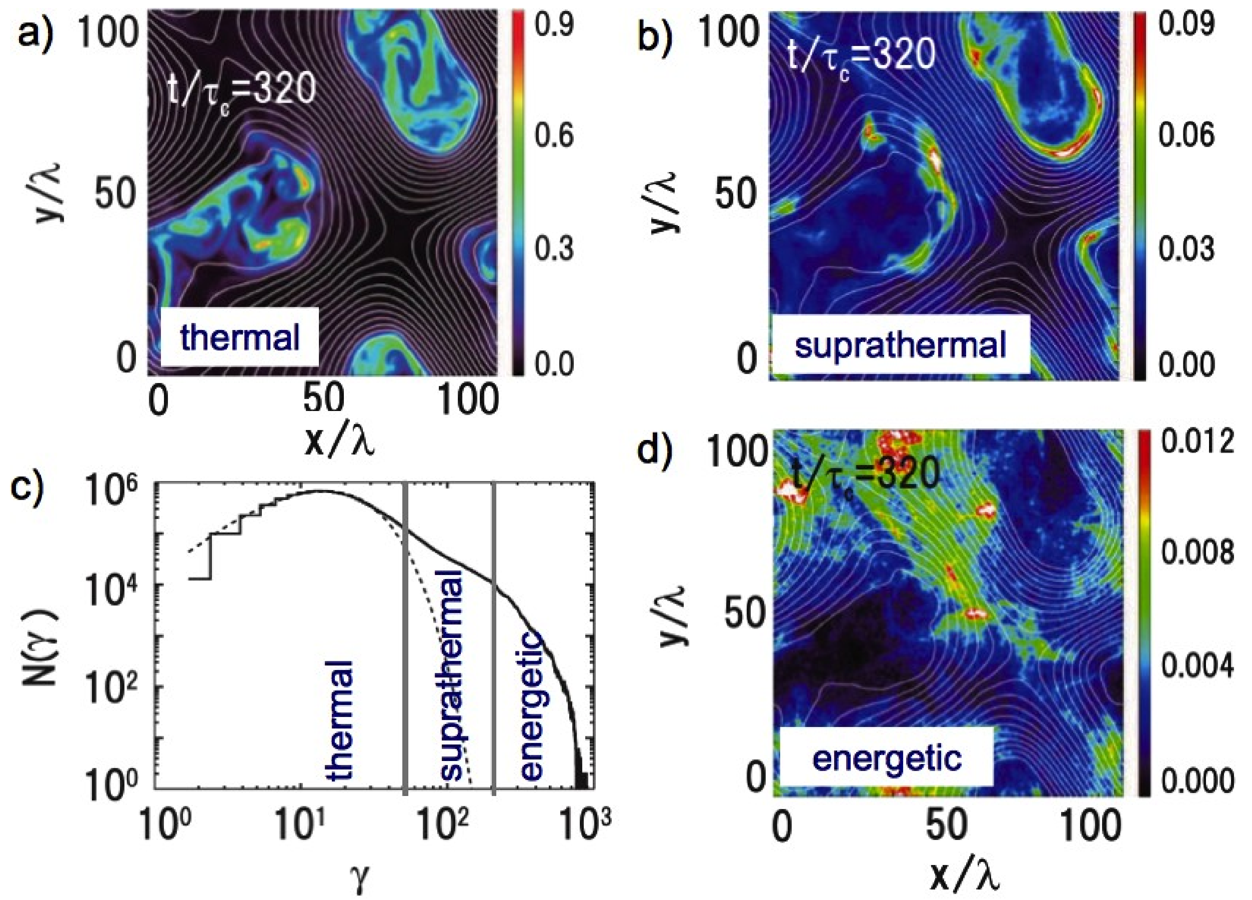


Valentini+, New J. Phys., 2016

Necessary to quantify the **energy partition among protons and alphas** at kinetic scales.

Q2: Energy partition

Hoshino et al., PRL, 2012

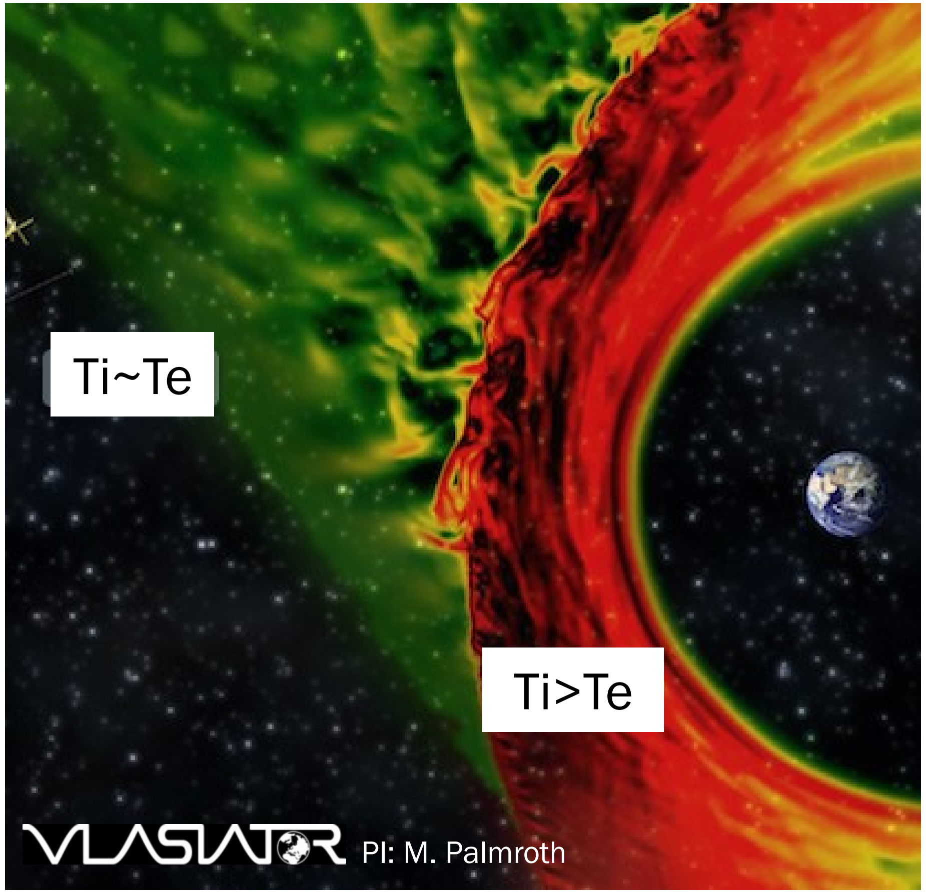


Simulations predict different locations of energization for thermal/suprathermal/energetic electrons.

Necessary to resolve both **thermal and suprathermal** parts of the spectrum.

Q3:Different turbulence regimes

- **spatial regions**
  - fast vs slow pristine solar wind
  - shocks/foreshocks/sheaths
  - interaction regions
- **plasma regimes**
  - β
  - T_i/T_e
  - Mach number
- **turbulence properties**
  - fully developed vs newly generated
  - different amplitude levels
  - intermittency

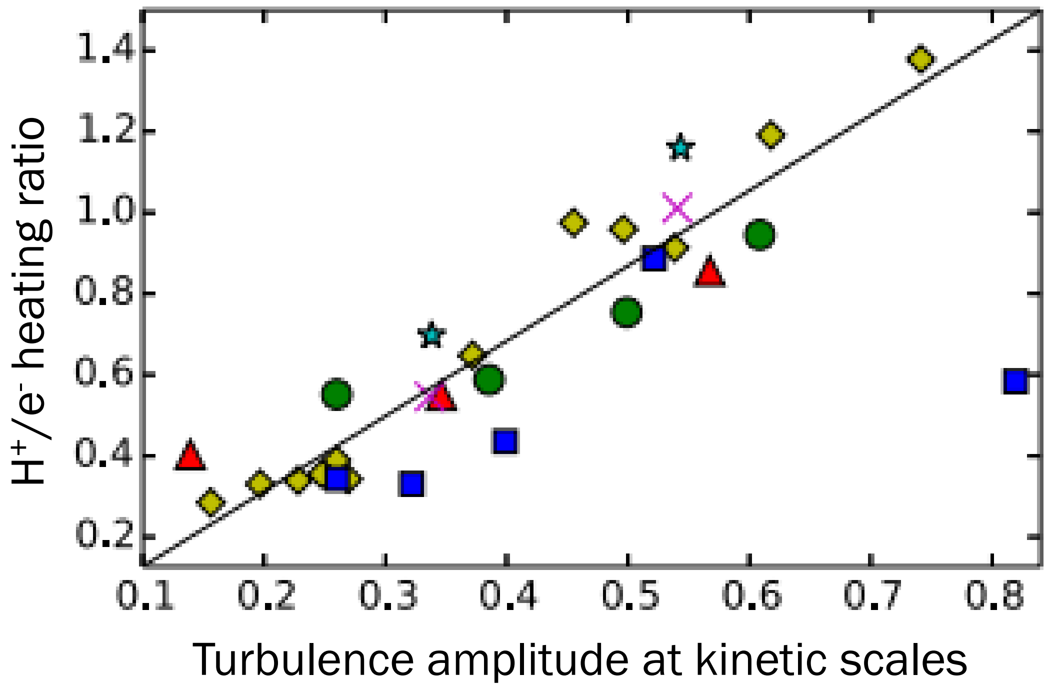


Orbits allowing measurements in different turbulent regions. High telemetry to allow statistical studies.

Q3: Heating dependence on fluctuation amplitude

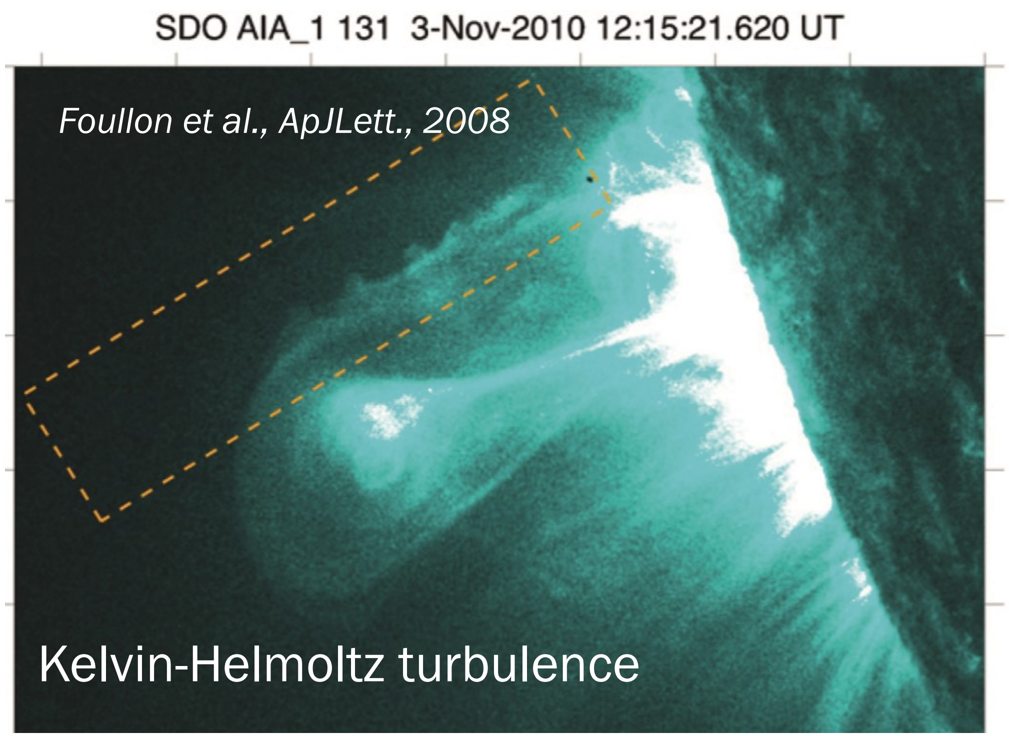
- PIC simulations show that the relative heating of ions and electrons can depend on plasma parameters, like turbulence amplitude at kinetic scales.
- Protons absorb a larger fraction of the cascaded energy when the turbulence is stronger.

Matthaeus et al., ApJLett, 2016

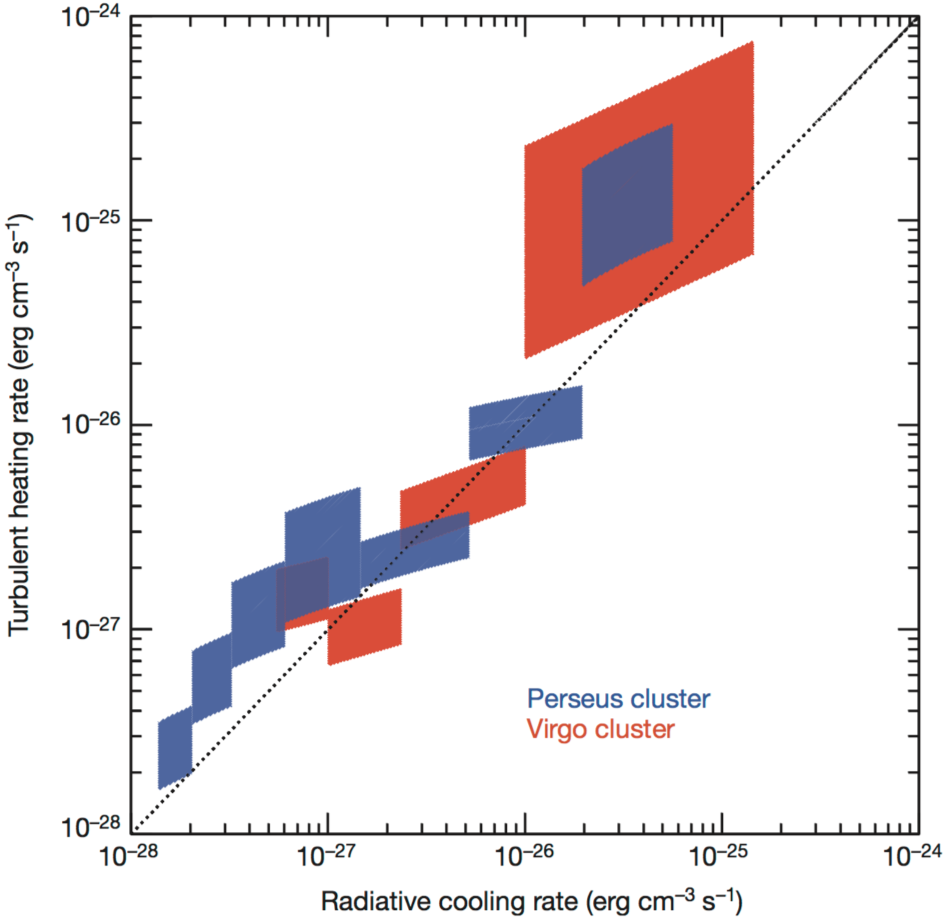


Necessary to explore dependence on amplitude, intermittency and other parameters.

Turbulence in astrophysical plasmas



Turbulent heating in galaxy clusters

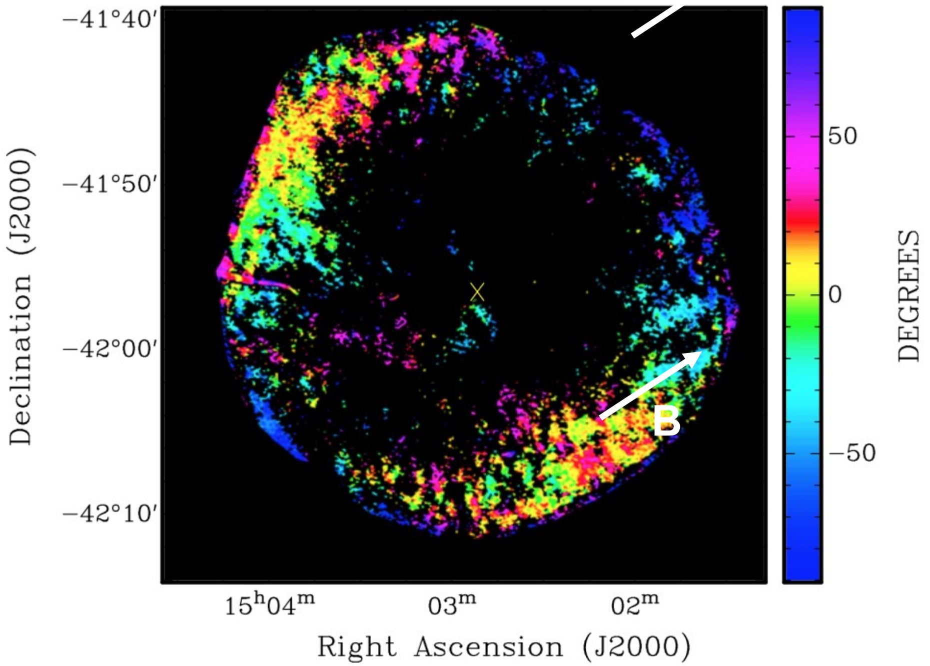


Zhuravleva, Nature, 2014

The injection problem at astrophysical shocks

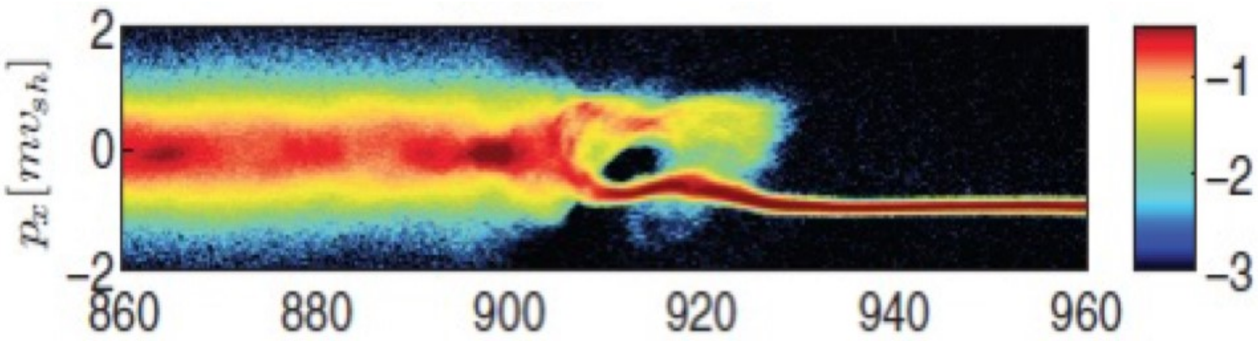
THOR

Remote observations
Supernova remnant shock (SN 1006)



Reynoso et al., ApJ, 2013

Kinetic simulations
Quasi-parallel shock



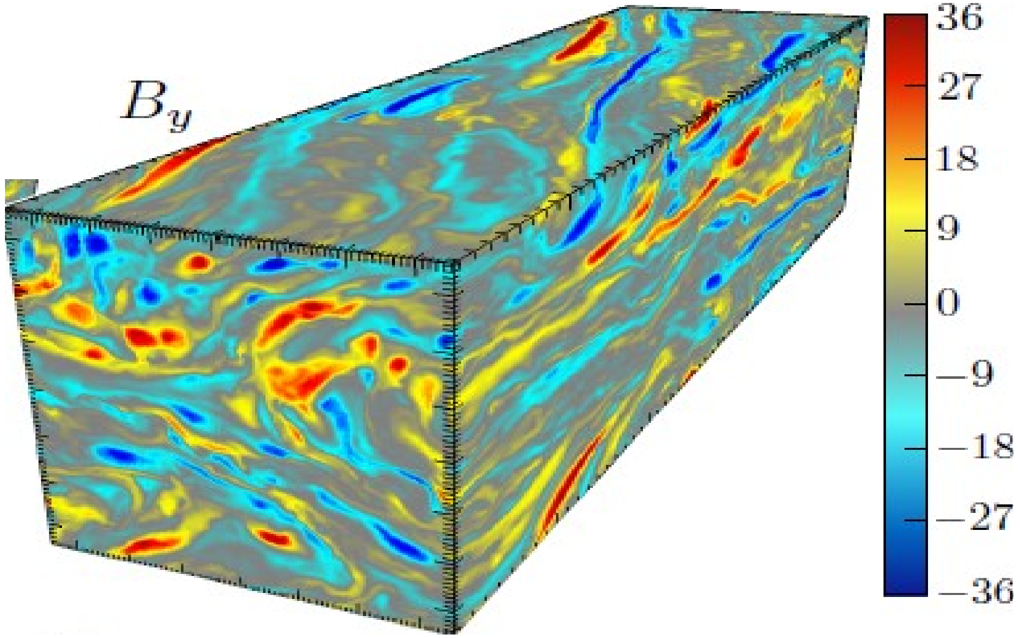
Caprioli et al., ApJ, 2015

- Ion injection to supra-thermal energies necessary for efficient Diffusive Shock Acceleration.
- Injection driven by turbulence at kinetic scales.

THOR high-quality measurements of particle distribution functions can help obtaining a realistic injection model for astrophysical shocks.

Kinetic instabilities in collisionless accretion disks

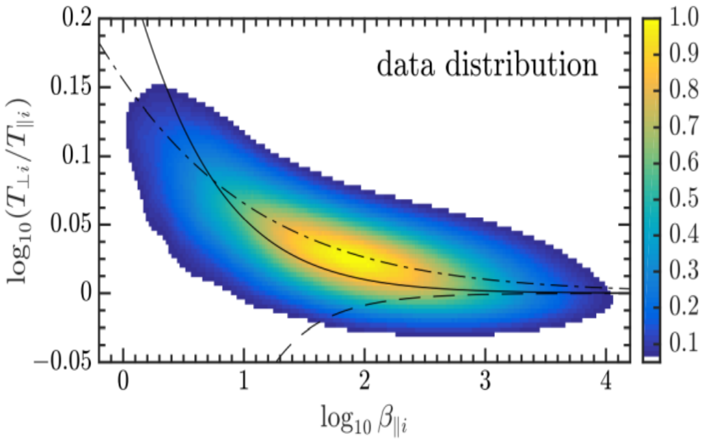
Magneto-Rotational Instability (MRI) responsible for angular momentum transport and particle energization



Kunz et al.,PRL, 2016

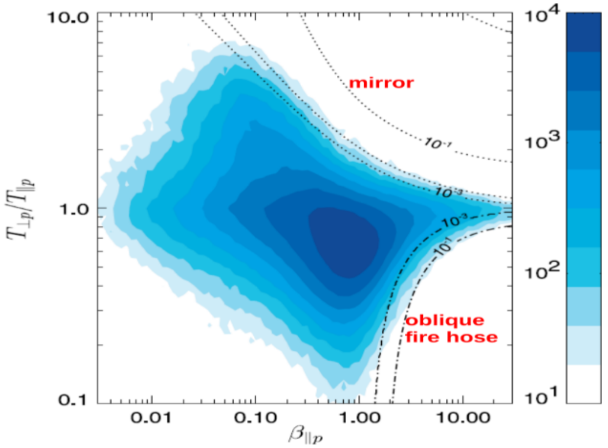
Kinetic-scale plasma instabilities strongly affect MRI

Kinetic simulation



Kunz et al.,PRL, 2016

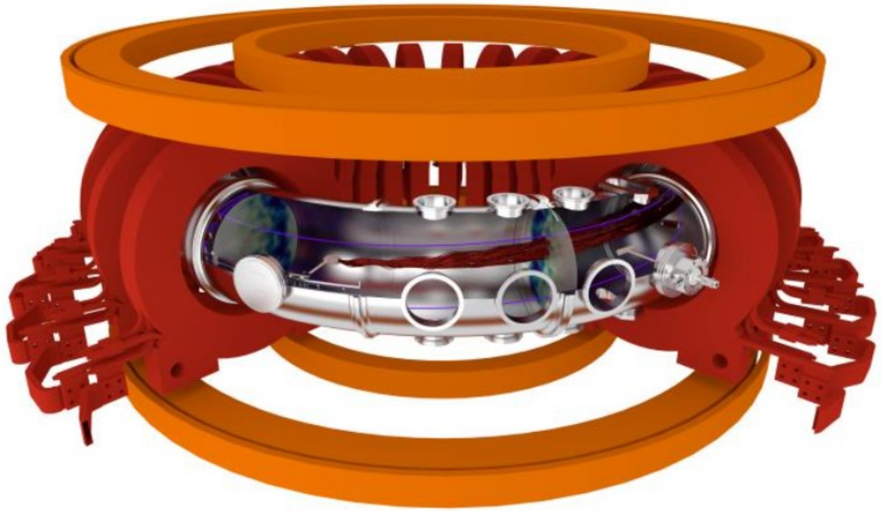
Solar wind in situ observations



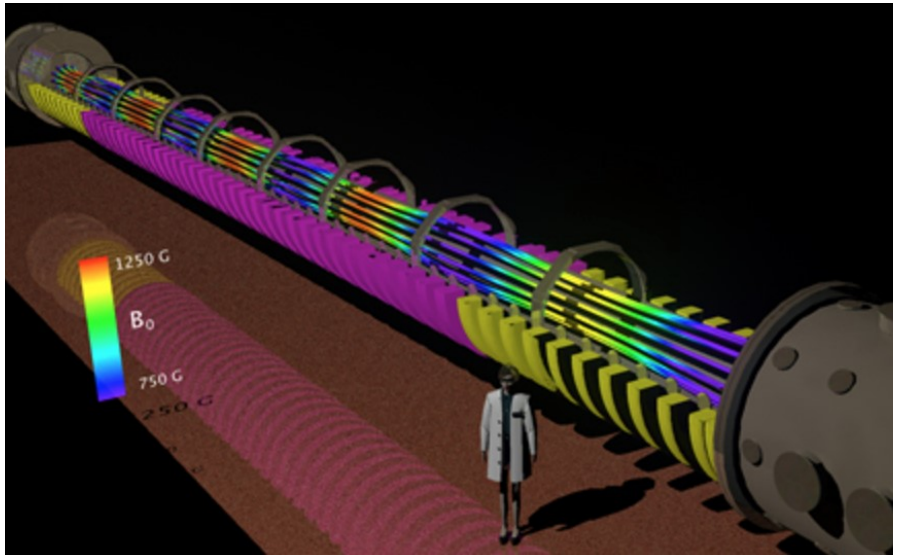
Hellinger et al., GRL, 2006

THOR high-quality measurements of distribution functions can help to more realistically model kinetic-scale instabilities in astrophysical objects.

Laboratory plasma



TORPEX (SPC)

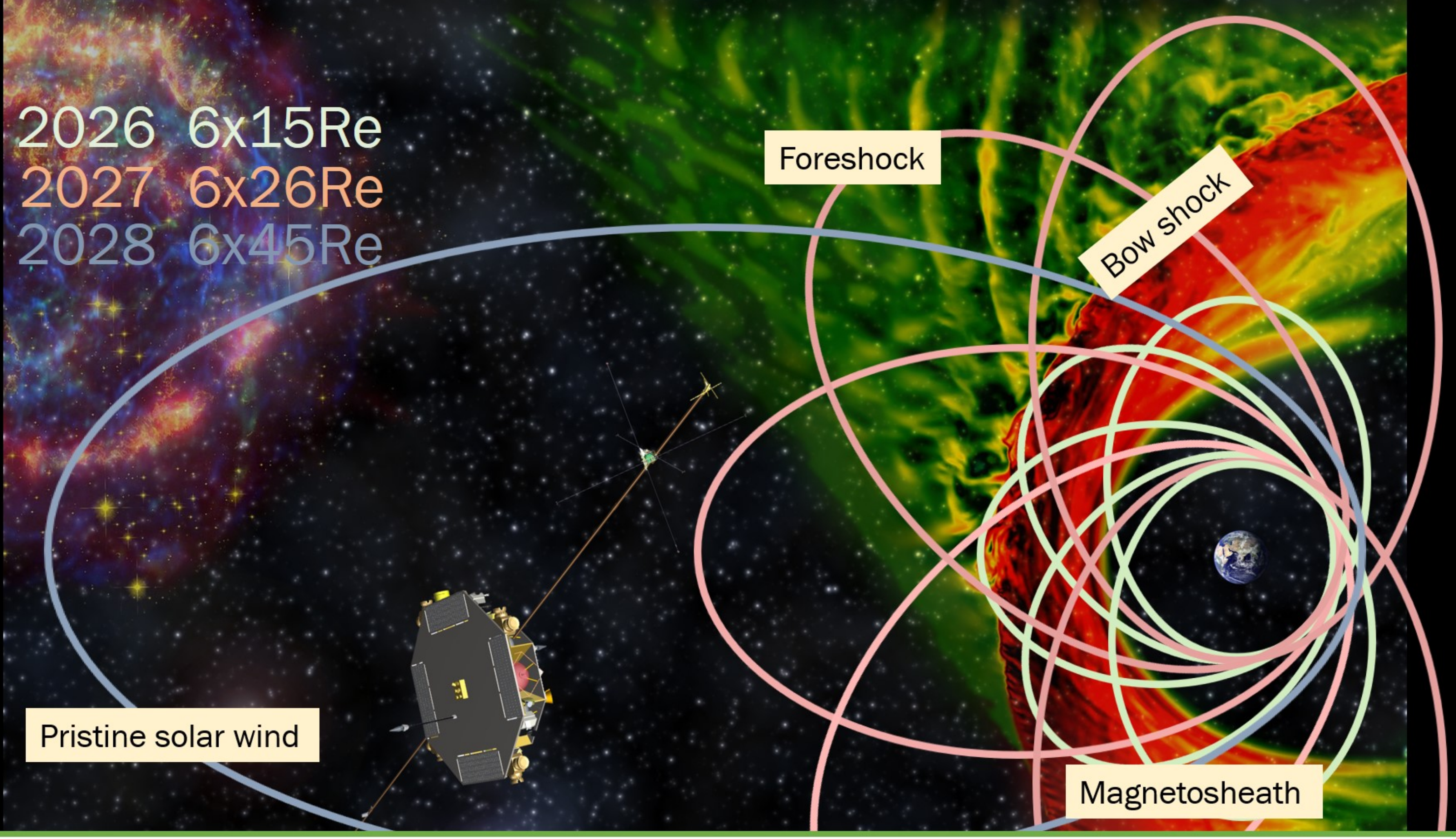


LAPD (UCLA)

- Swiss Plasma Center (SPC), EPFL, Lausanne
- Basic Plasma Science Facility (BaPSF), UCLA
- Princeton Plasma Physics Laboratory
- Max-Planck-Institut für Plasmaphysik, München
- Endorsement from Italian laboratory plasma community (CNR letter)

Laboratory plasma experiments in synergy with the THOR measurements will allow to obtain a more comprehensive pictures of plasma physics at kinetic scales.

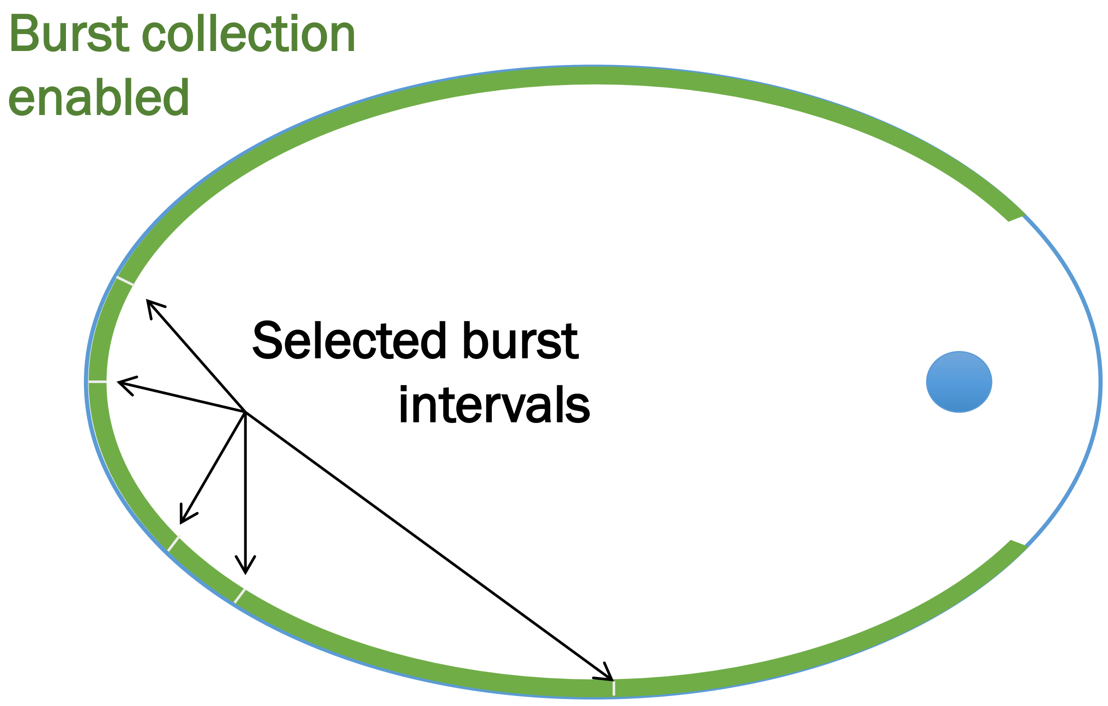
MISSION



Systematic exploration of solar wind and shocked solar wind regions reflecting different types of turbulent environments leads to knowledge of astrophysical importance.

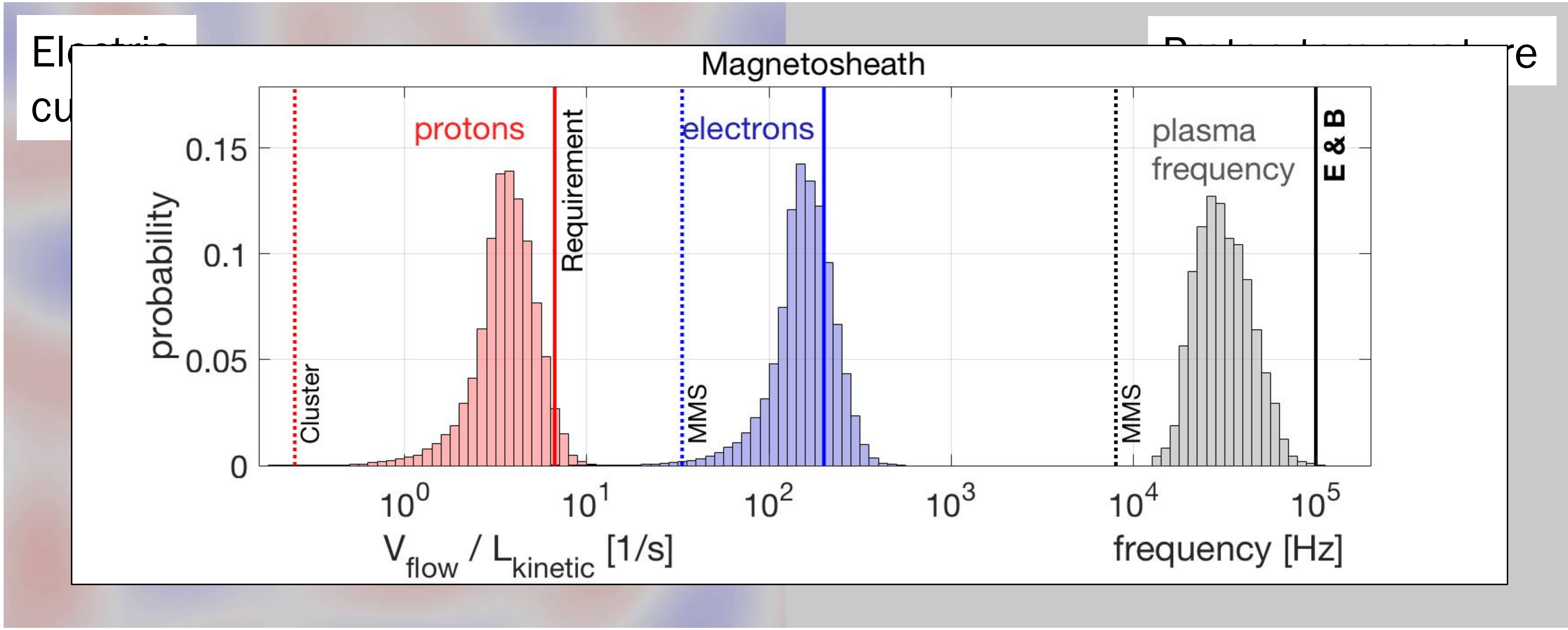
Operations, Scientist in the Loop

- ✓ Survey data (science quality lower resolution) and Burst data (highest resolution) **saved on-board** (~10TB).
- ✓ All Survey data transmitted to ground and used to select Burst data for downlink by **Scientist In The Loop.**
- ✓ **Guest Investigator** program open to other communities.



THOR maximizes science return with efficient and flexible selection of burst data.

Scientific measurement requirements



THOR shall resolve: plasma distribution functions at kinetic scales of electrons and mass-resolved ions, 3D electric and magnetic fields at plasma frequency.

Key required improvements

Mission	Scientific Measurement Requirements								
	Fields				Particles				
	R1	R2	R3	R4	R5	R6	R7	R8	R9
THOR	●	●	●	●	●	●	●	●	●
Cluster	○			○	○				○
MMS	○		○	○	●	○			●
Solar Orbiter	○	●			○				○
SPP	○	●			○				○
Wind	○								●

+ **Wave and electron correlation** up to electron plasma frequency,

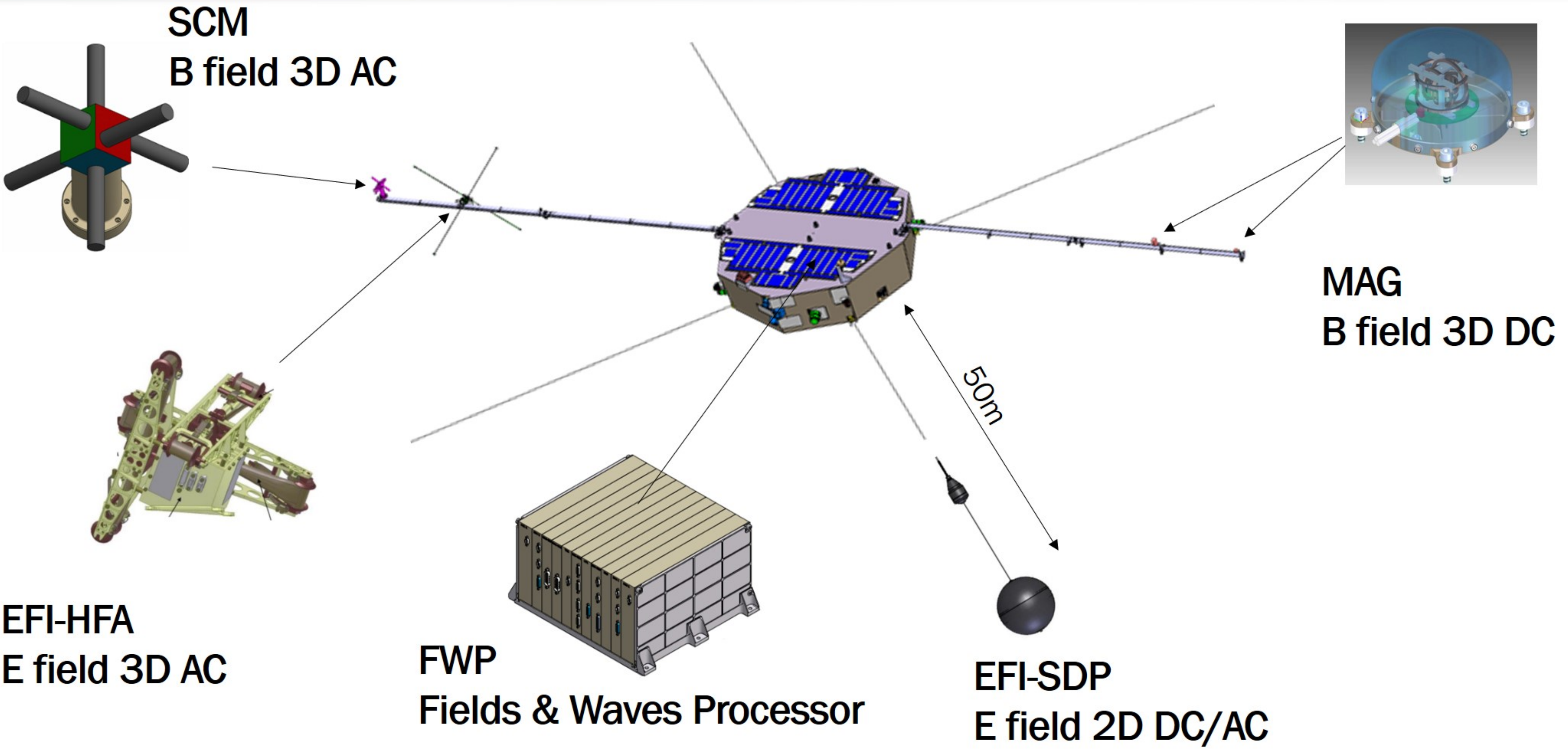
+ Large on-board mass memory for **selective downlink.**

+ **Optimized orbit** for sampling of the key science regions.

R1 – High EM field **cadence**
R2 – High EM field **sensitivity**
R3 – High EM field **accuracy**
R4 – phase velocity

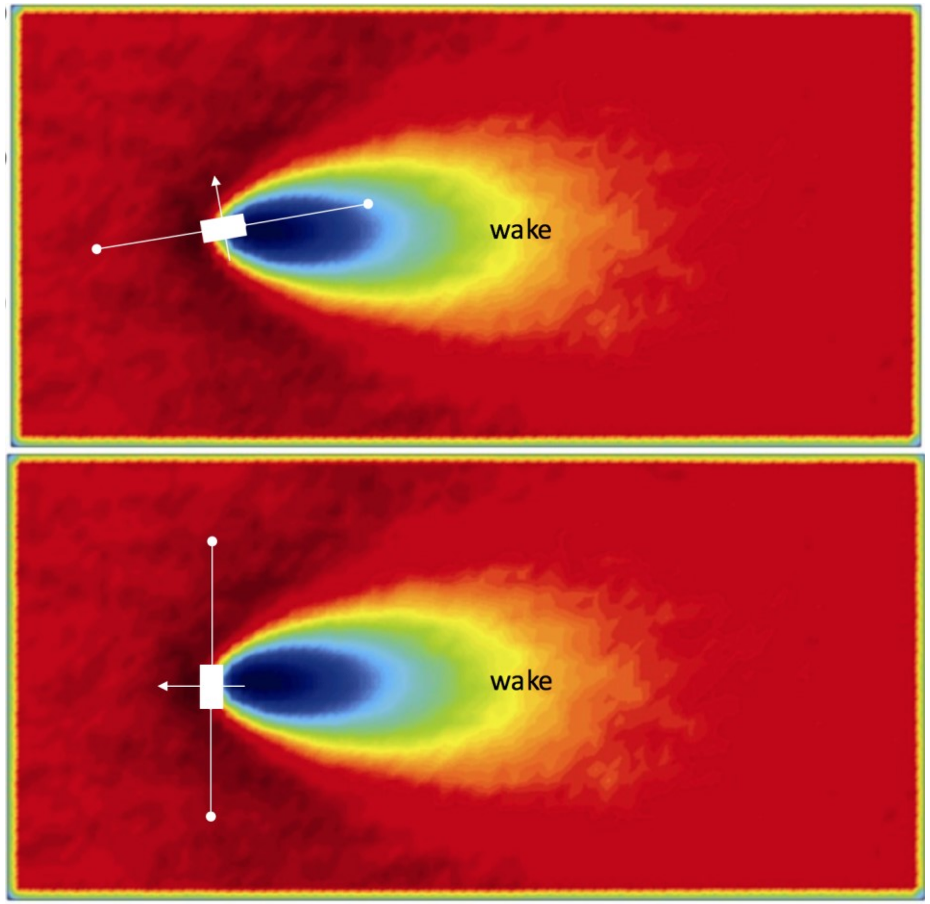
R5 – ion composition at high cadence
R6 – particle moments at high cadence
R7 – thermal distribution functions at high cadence
R8 – suprathermal distribution functions
R9 – energetic particles

Fields instrument consortium



E field accuracy

- Strong contamination by wake effects for spacecraft with spin plane close to the ecliptic plane.
- Sun-pointing spacecraft enables high accuracy measurement of electric field as the E field booms will not pass through the spacecraft plasma wake.



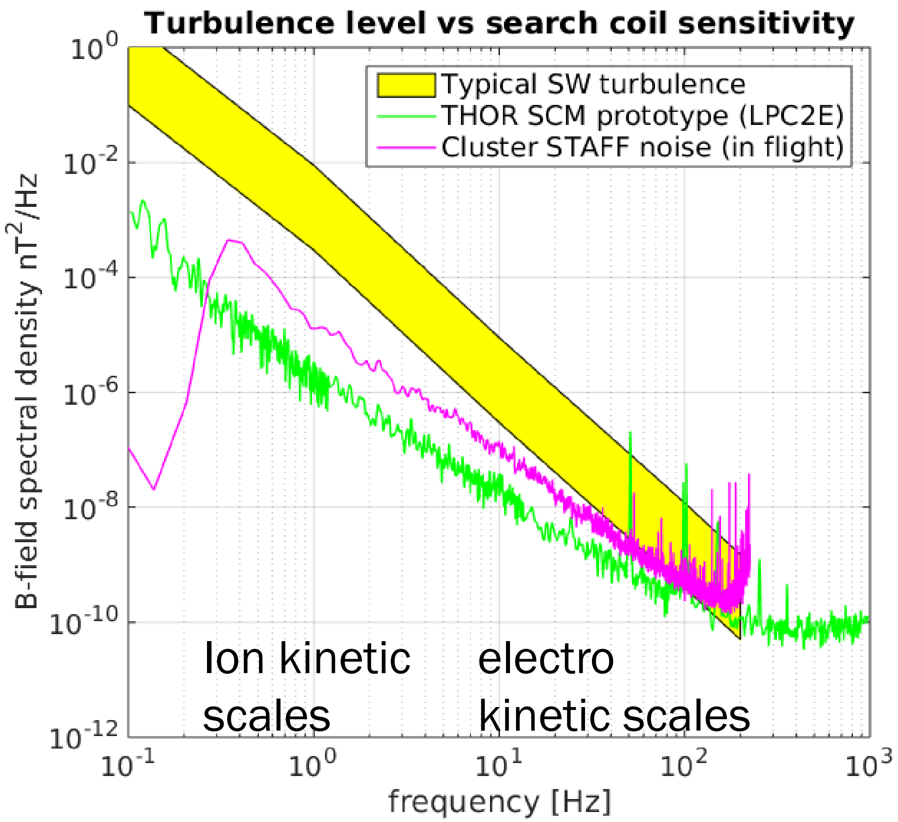
Geotail
Cluster
MMS

THOR

High accuracy electric field measurements are required to quantify energy dissipation in plasmas.

B sensitivity

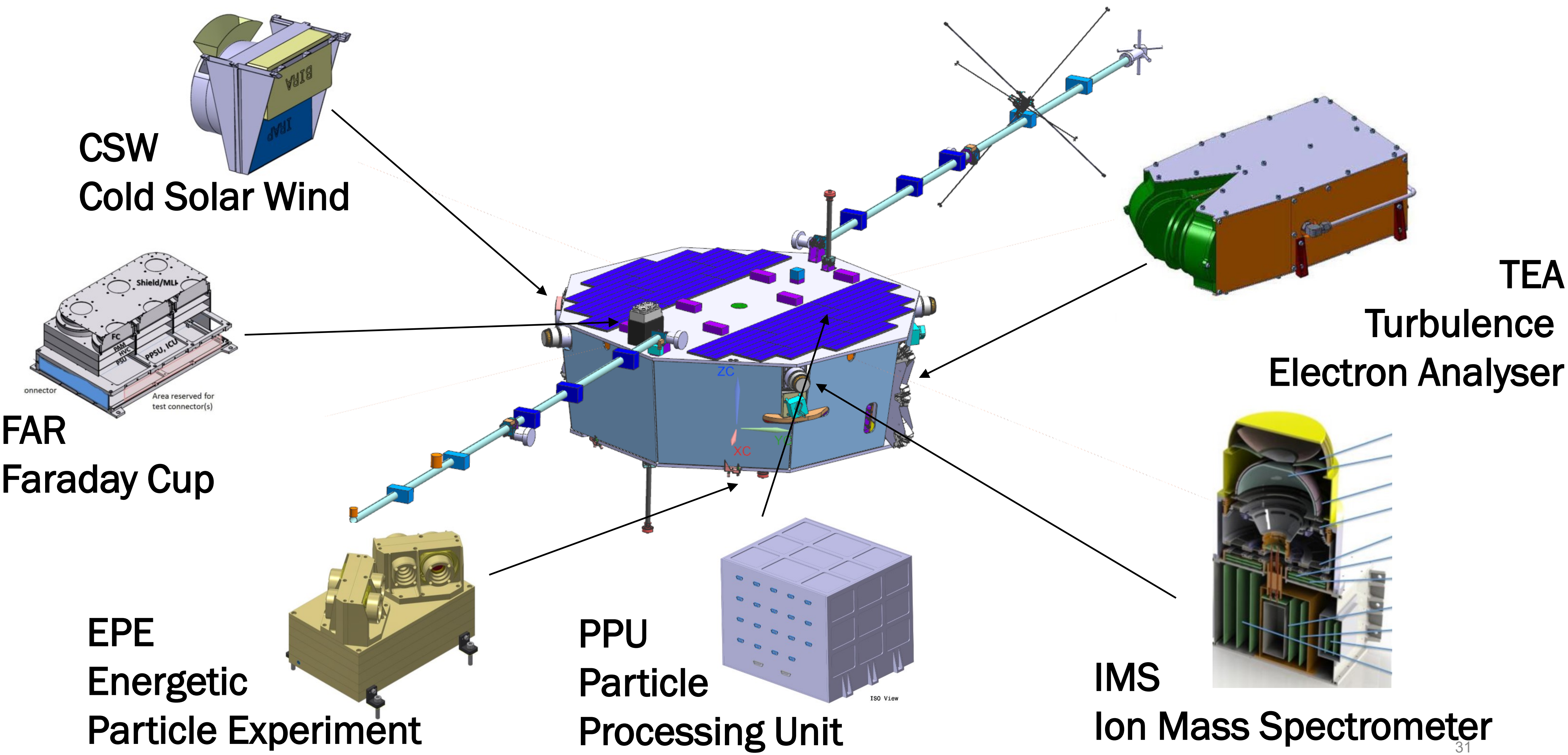
- Cluster has state-of-art search coil magnetometer to measure AC B field.
- It could resolve only the strongest magnetic turbulence at electron kinetic scales in pristine solar wind.
- THOR search-coil magnetometer would be more sensitive.



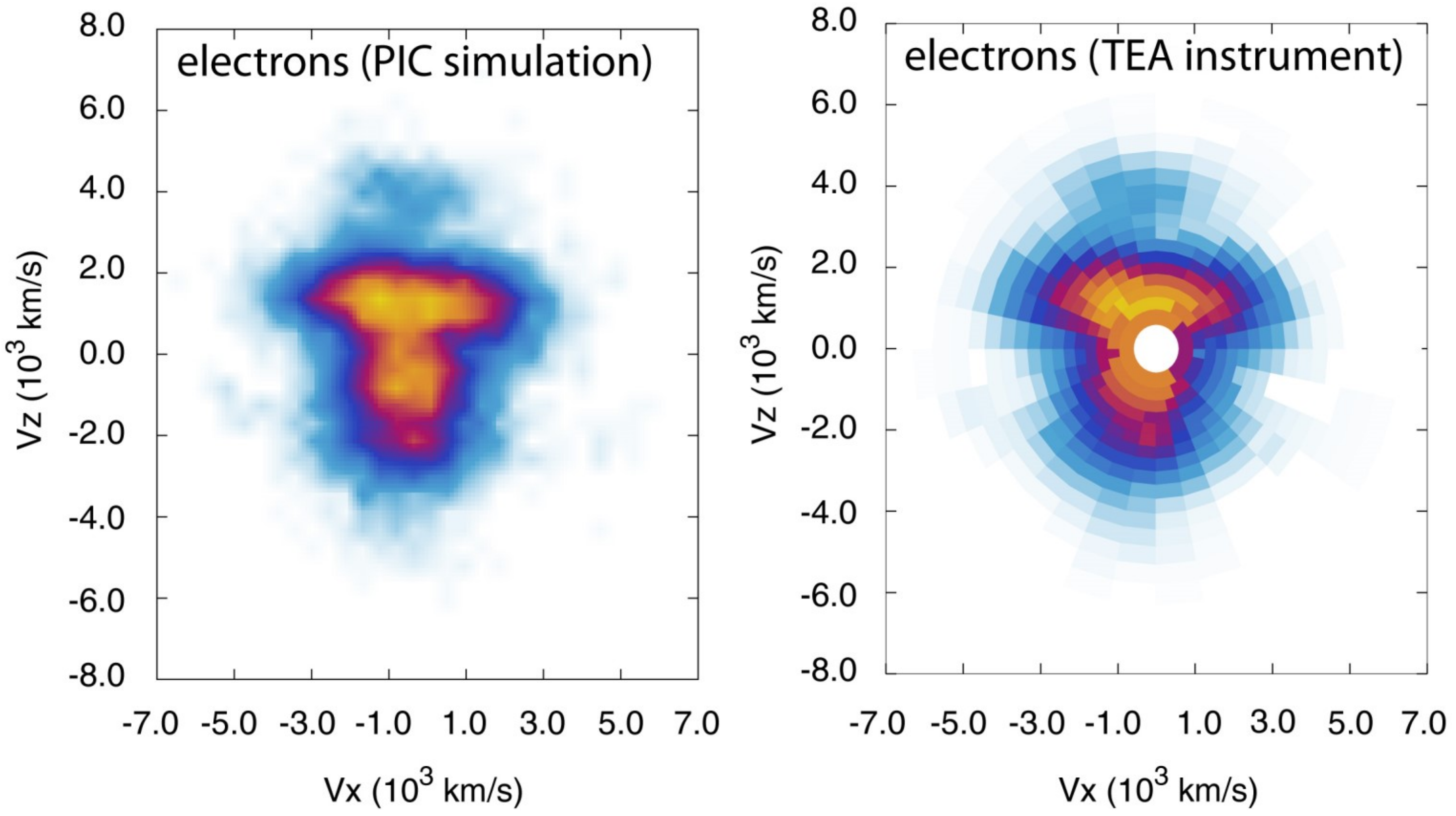
Sahraoui et al., 2010; Alexandrova et al., 2012

High sensitivity search-coil magnetometer enables studies of electron scale turbulence in pristine solar wind.

Particle instrument consortium



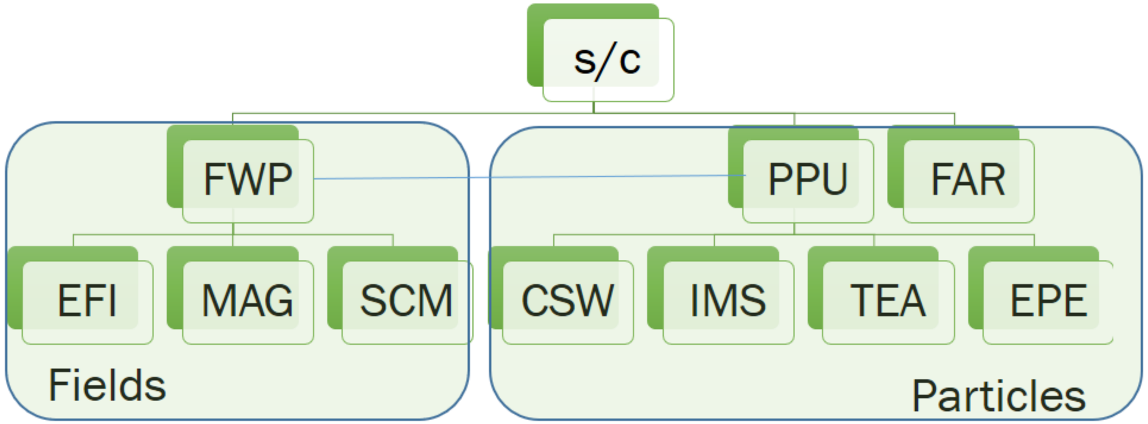
Velocity distributions functions (VDF) by virtual TEA instrument (right) observing VDF of electrons in numerical simulation (left).



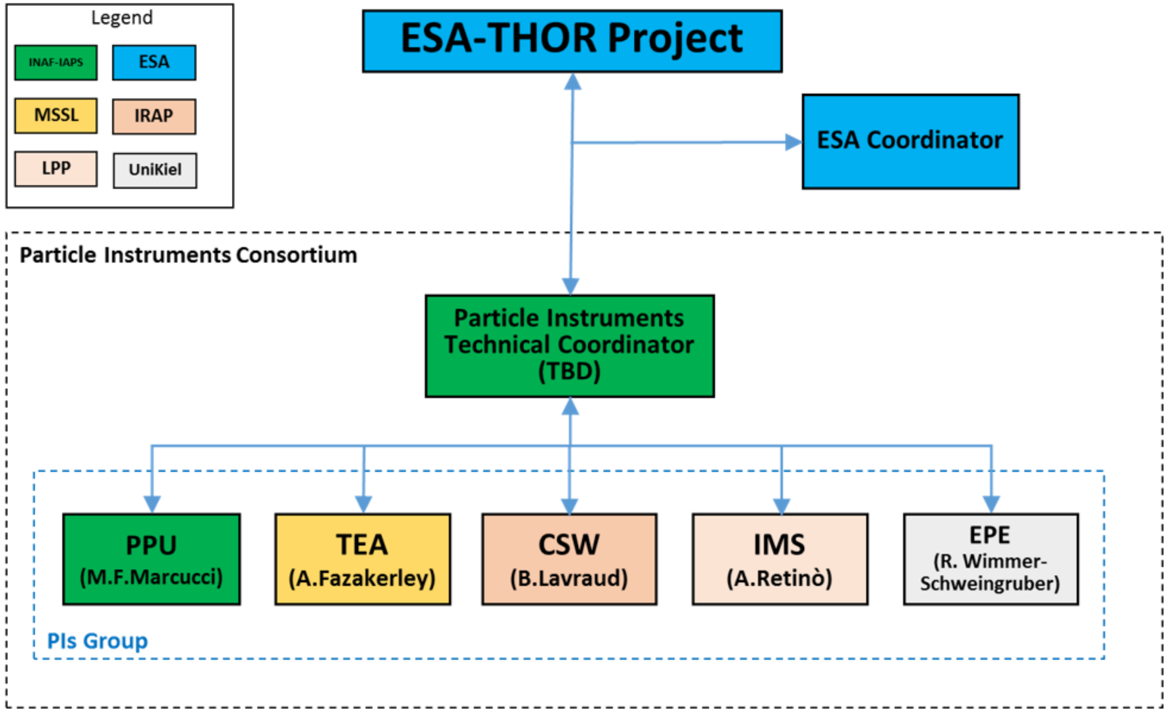
Simulations of instruments TEA, CSW and IMS shows that expected count rates of the instruments are adequate to address the THOR science.

Payload consortium

INTERFACE

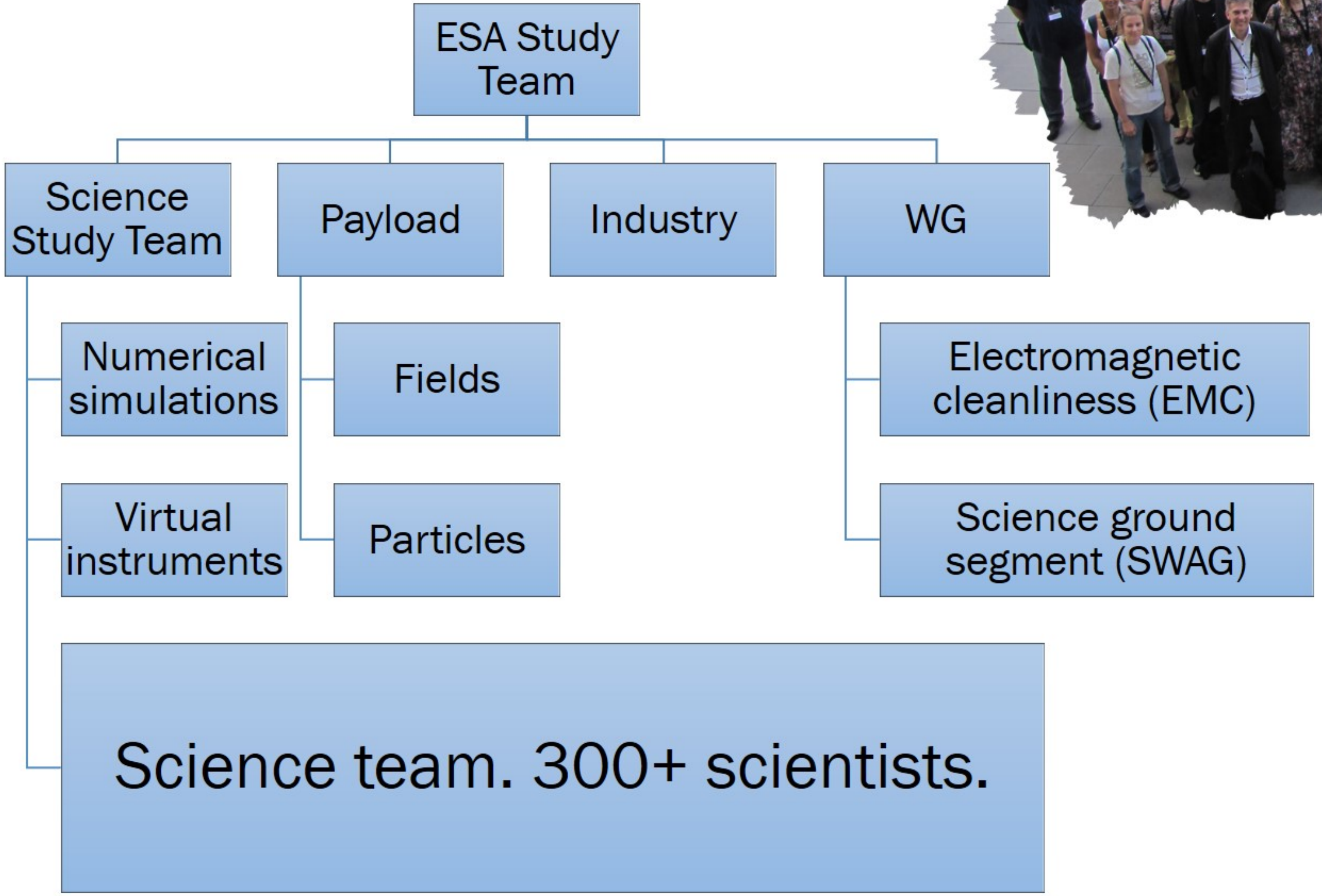


MANAGEMENT OF PARTICLES

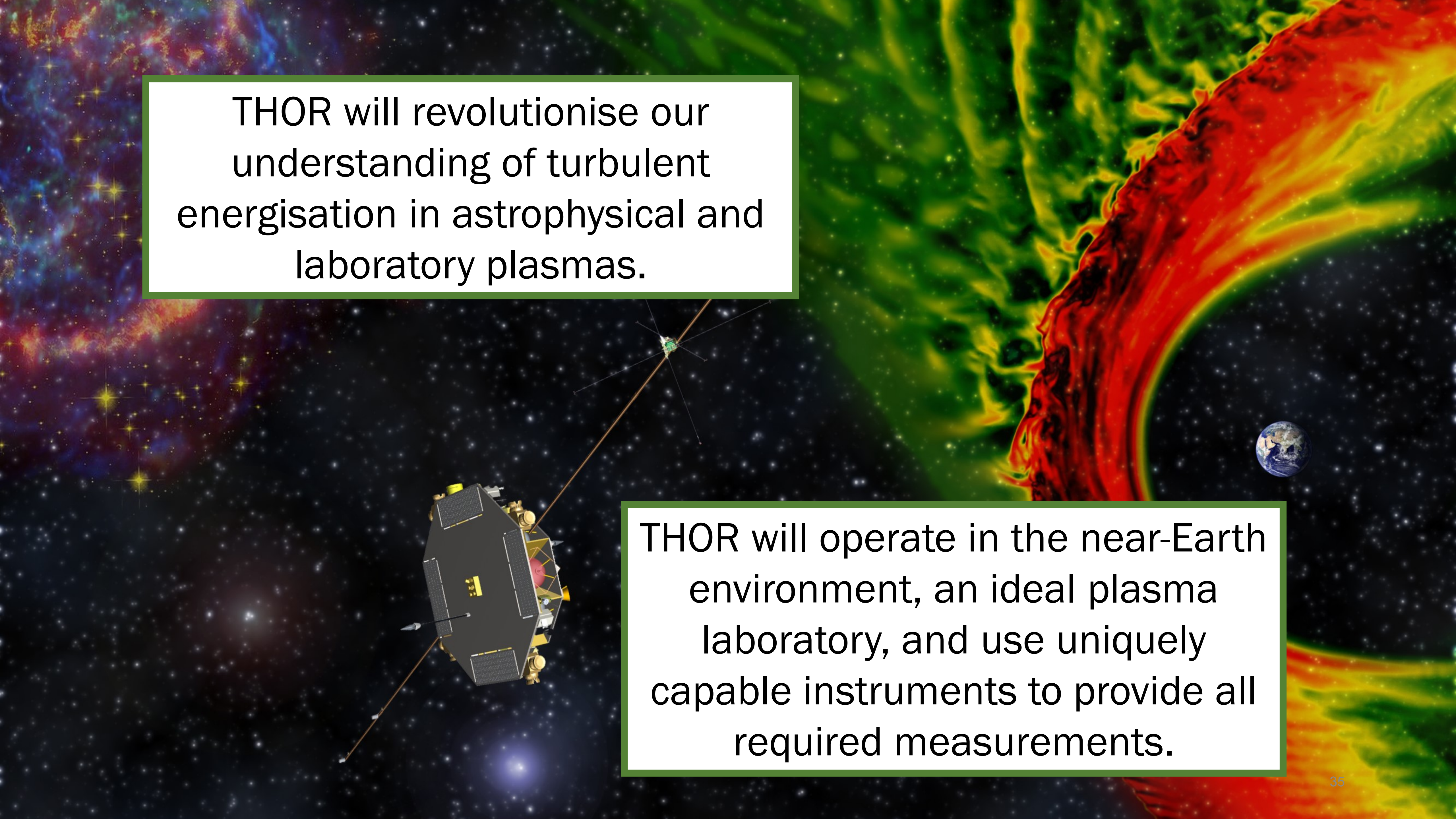


Simple interfaces, simple management and simple operations.
Payload operated as a single experiment

Team



THOR workshop @Barcelona 2016-Sep



THOR will revolutionise our understanding of turbulent energisation in astrophysical and laboratory plasmas.

THOR will operate in the near-Earth environment, an ideal plasma laboratory, and use uniquely capable instruments to provide all required measurements.

Links

- THOR web page: http://thor.irfu.se
- THOR YouTube channel with movies: https://www.youtube.com/channel/UCRnk0yFY-ebM_vCzhZ0QL5Q
- THOR Twitter: @ESA_THOR