An Overview of Current Research in Space and Astrophysical Plasmas

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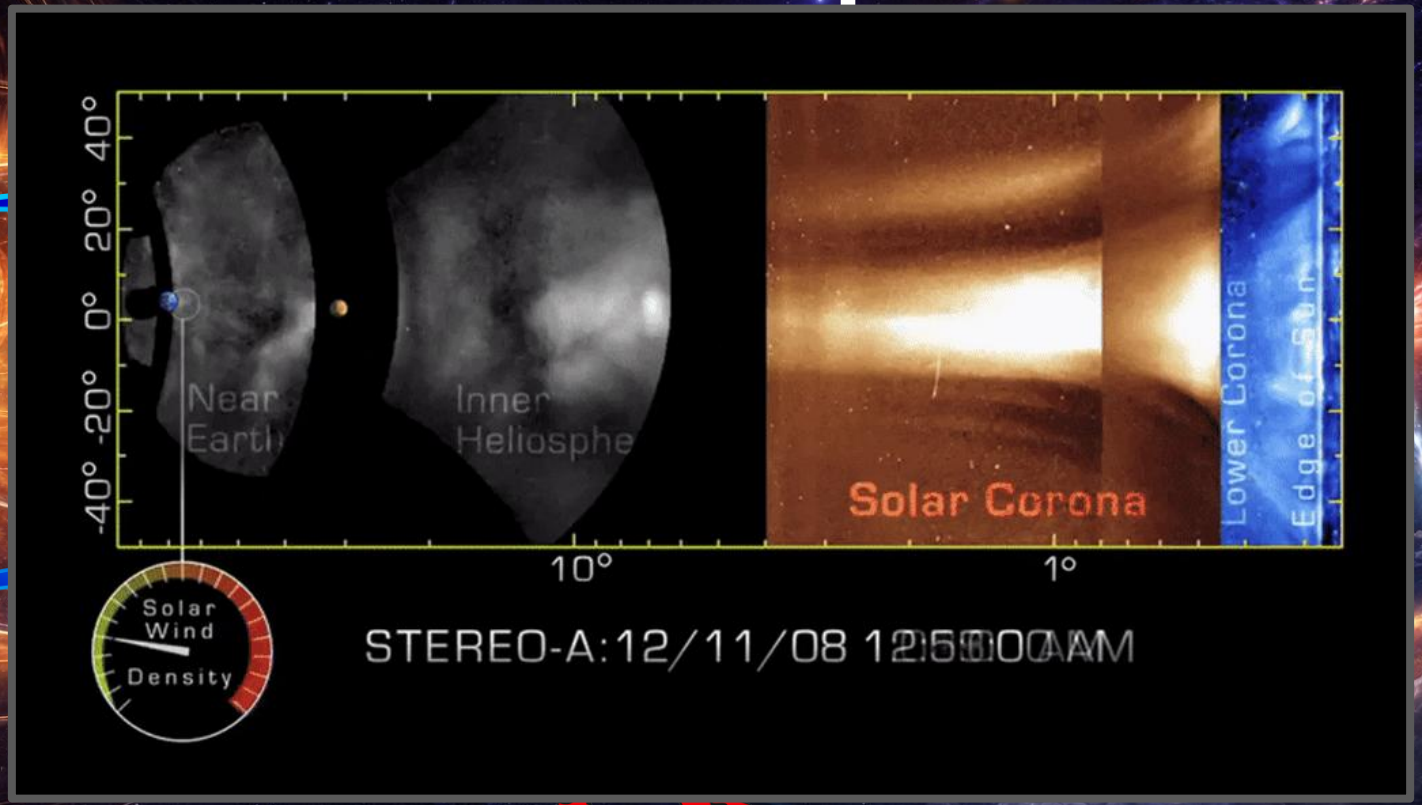
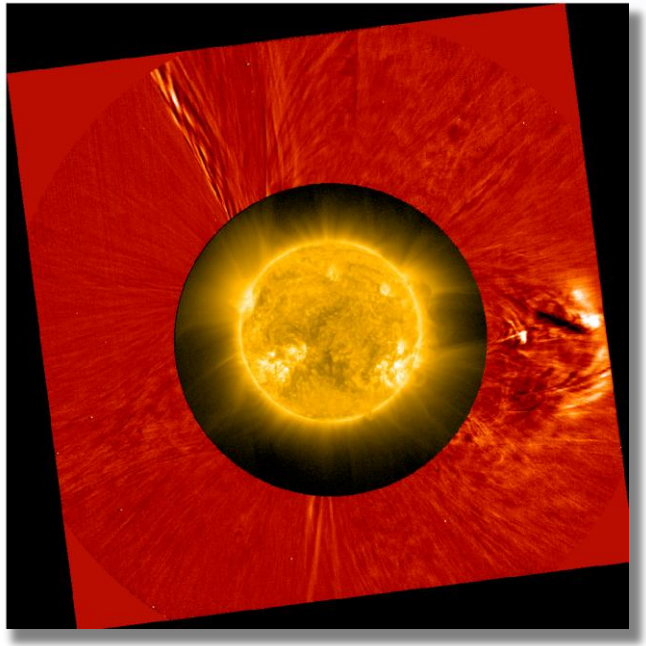
Sergio Servidio, *Università, della Calabria, Cosenza*

S. Servidio acknowledges “Space It Up!”, funded by the Italian Space Agency (ASI), and the Ministry of University and Research, MUR, under contract no. 2024-5-E.0–CUP no. I53D24000060005

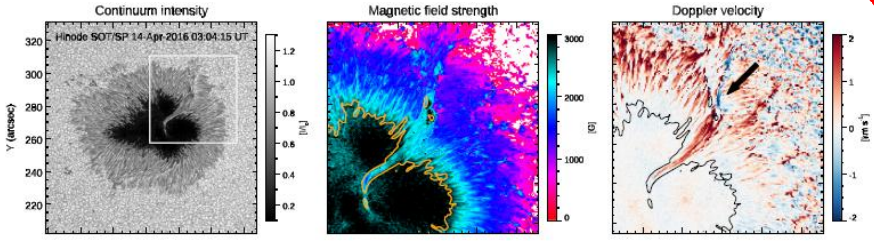
The trip


-40° -20° 0° 20° 40°
Near Earth
Inner Heliosphe
Solar Corona
Lower Corona
Edge of Sun
10°
1°
Solar Wind Density
STEREO-A:12/11/08 12:56:00 AM

New Hints from Observations



Next-generation space observations reveal wealth of complexity:
A zoo of coherent structures, waves, and plasma phenomena that we don't fully understand yet



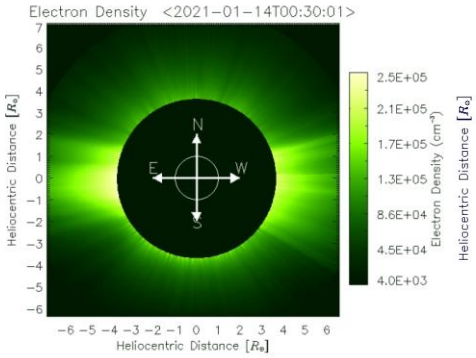
Flux rope hanging above the sunspot and forming penumbral-like filaments within the umbra

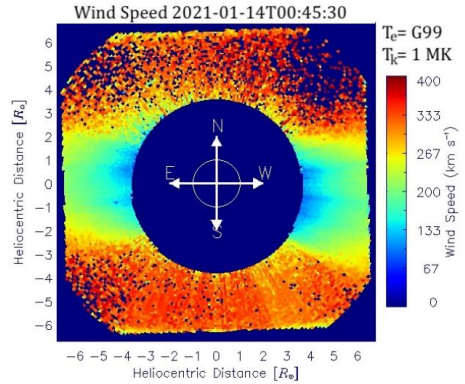
[Romano+, SP, 2019](#)
[Guglielmino+, ApJ 2019](#)

METIS observations of Alfvénic outflows driven by interchange reconnection in a pseudostreamer

Unique, New Plasma Observations

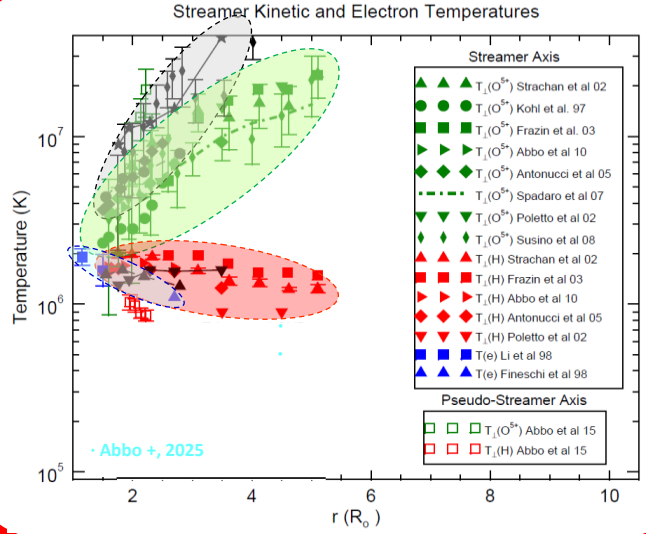
Probing the Solar Wind Acceleration region





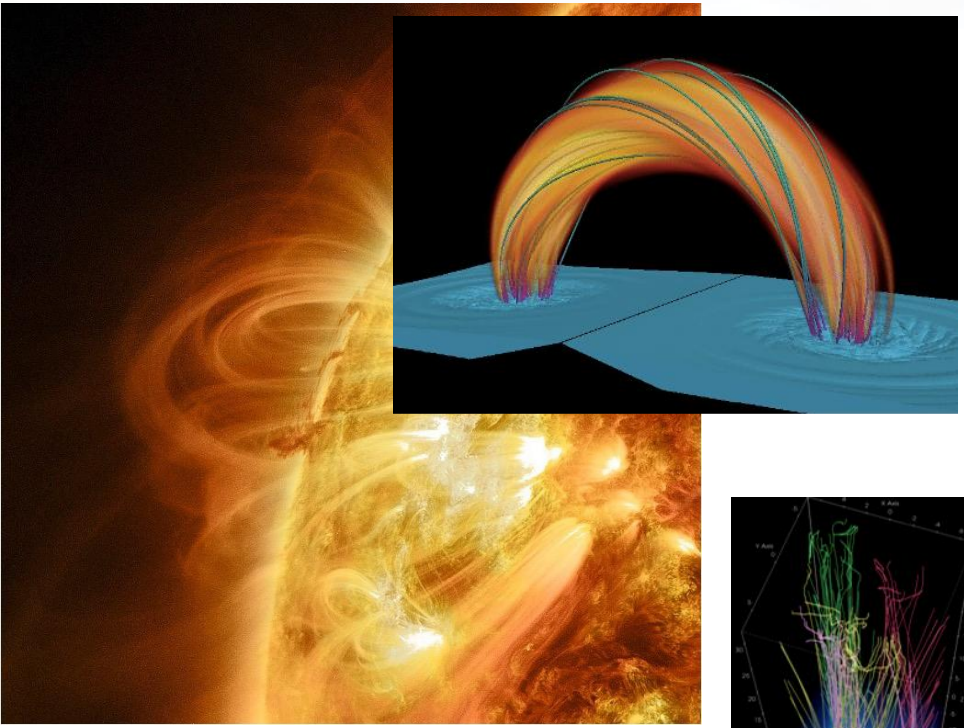
Unique SO/METIS measurements of density and solar wind velocity (via Doppler dimming) in the cradle of the solar wind

Romoli+2021, Antonucci+2023, Giordano+2025



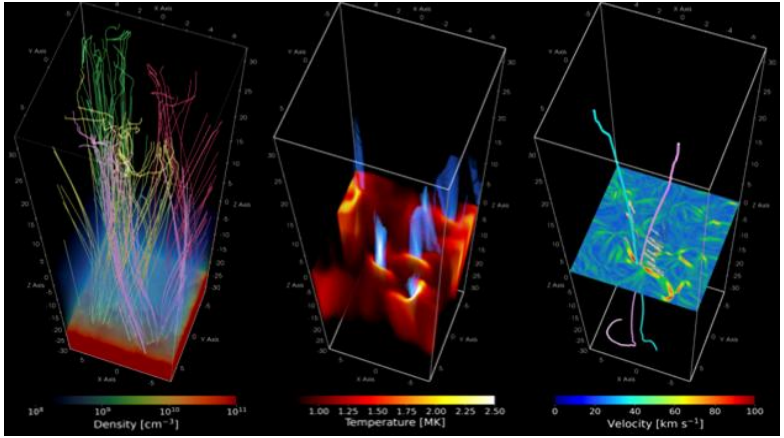
Abbo+, SSRv, 2016

State of the Art Models of Coronal Dynamics



Plasma modeling has achieved remarkable accuracy in simulating coronal dynamics - particularly for plasma confined within closed magnetic loops.

This success mirrors the sophistication of models used for tokamak plasmas, but in a vastly different parameter space



3D MHD model of a complex flux tube: appearance of magnetic reconnection events (nanoflares) and small jets

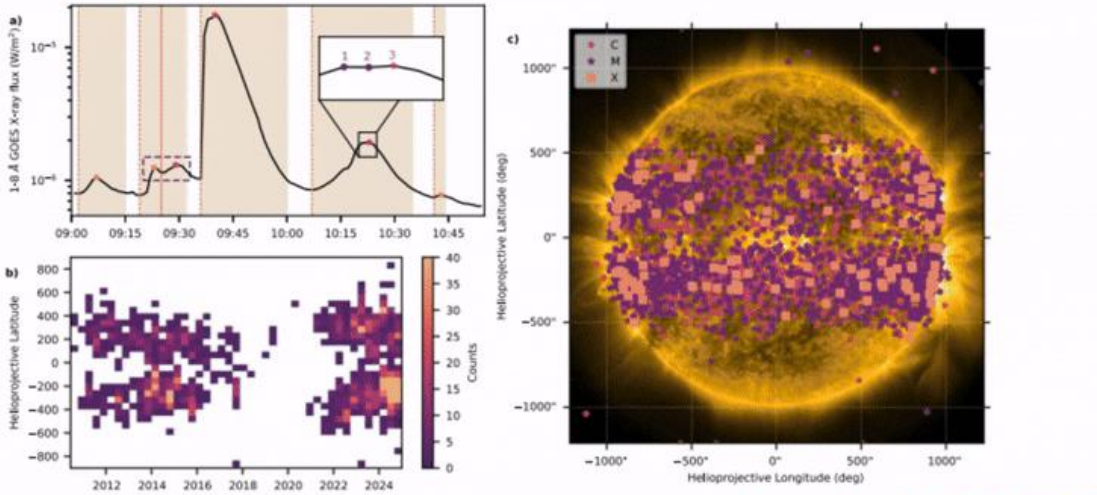
Cozzo+, 2024-2026
Reale, LRSP 2014

- F. Berrilli, D. del Moro, L. Giovannelli, G. Nigro, R. Reda
- M. Berretti, M. Cantoresi, L. Casara, S. Chierichini, A. Chiodini, A. Giri Nair, F. Konow, L. Lucaferri, R. Mugatwala, A. Russo

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

highlights

ASR: Archival Solar Flares Catalog



Beretti+, APJSS, 2025

INAF/OATO

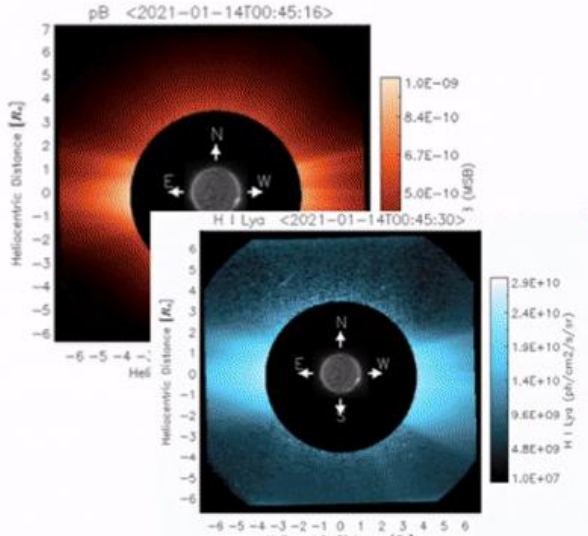
- S. Fineschi, R. Susino, D. Telloni, L. Abbo, A. Bemporad, S. Giordano, L. Zangrilli, S. Mancuso, C. Benna
- F. Frassati, A. Liberatore, R. Biondo, H. Haudemand, E. Amato, R. Chiartano

OSSERVATORIO ASTROFISICO DI TORINO

highlights

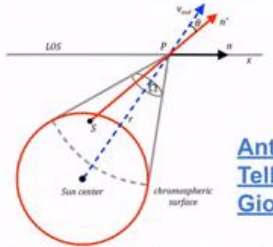
Study of Solar Wind Acceleration With Metis/SO Observations

VL and UV observations + Coronal Model



H I Lyα Intensity is a function of

$I_{ex}(\lambda)$	Specific Intensity of Chromospheric radiation
A_{He}	Helium Abundance
n_e	Coronal Electron Density
T_e	Coronal Electron Temperature
T_p	Coronal Proton Temperature
$K_i = \frac{T_\perp}{T_\parallel}$	Anisotropy factor
u	Outflow Speed



Antonucci+A&A, 2020
Telloni+ A&A, 2023
Giordano+ A&A, 2025

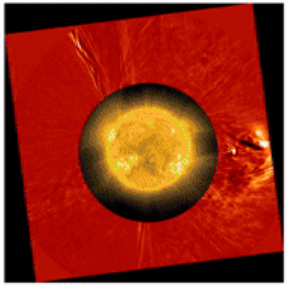
INAF/OACatania

- Paolo Romano, Salvatore Luigi Guglielmino, Lidia Contarino
- Fabiana Ferrente

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI CATANIA

highlights

Study of this wind flying out from the Sun in a twisting, whirling motion



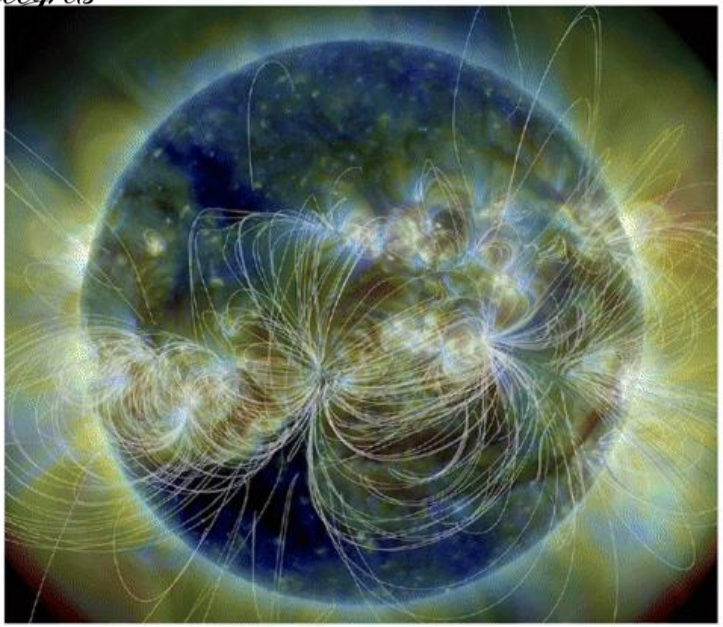
Metis observations of Alfvénic outflows driven by interchange reconnection in a pseudostreamer.

UNIPA & INAF

- Fabio Reale, Paolo Pagano, Costanza Argiroffi, Antonino Petralia (INAF/OAPa)
- Antonio Franco Rappazzo, Gabriele Sano, Gabriele Cozzo (now at Harvard, US)

UNIVERSITÀ DEGLI STUDI DI PALERMO

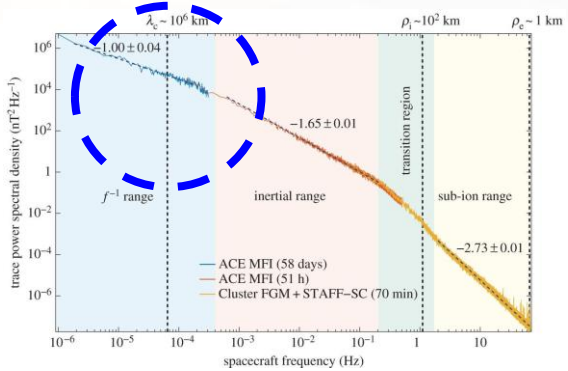
highlights



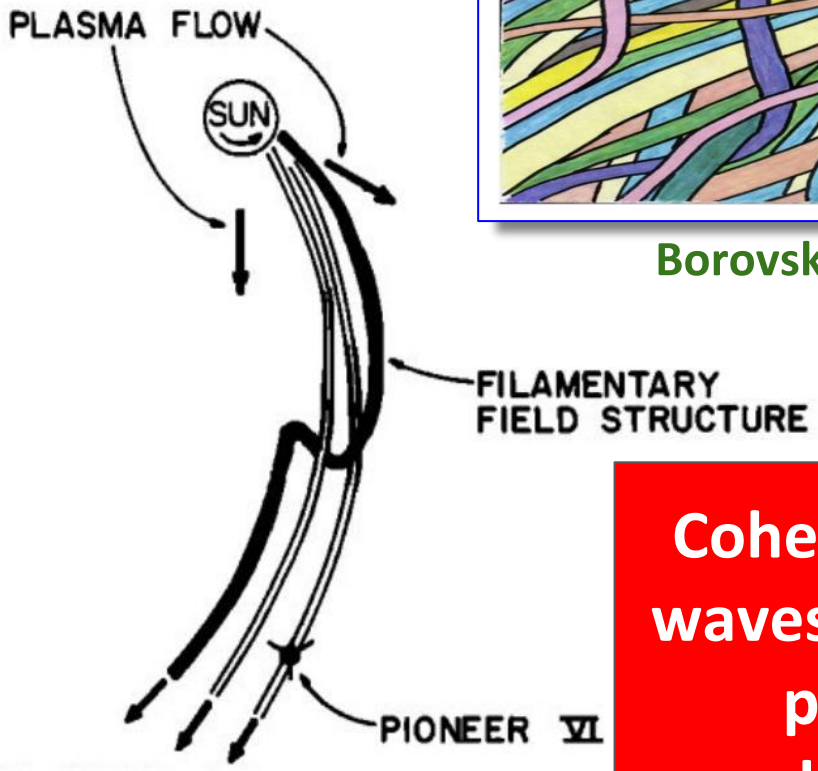
Solar EUV image and magnetic field lines: using three-dimensional MHD simulations of kink-unstable coronal flux tubes, we investigate how the intensity of the ambient magnetic field influences the temperature of coronal loop plasma.

Solar wind & space weather

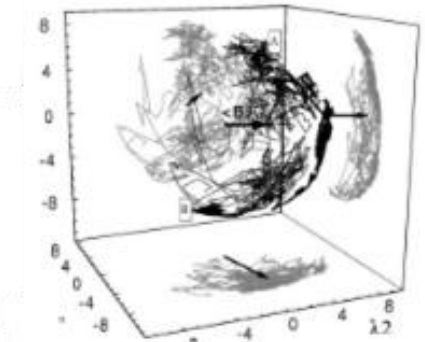
A Very Complex Plasma



Kiyani+, PTRSA (2008)



Borovsky+, JGR (2008)



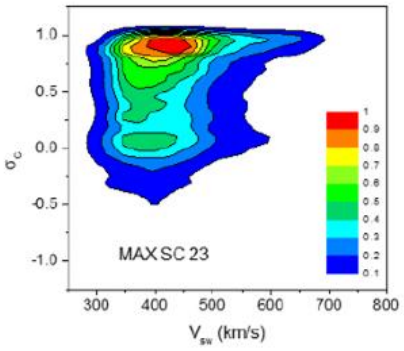
Bruno+, PSS (2001)

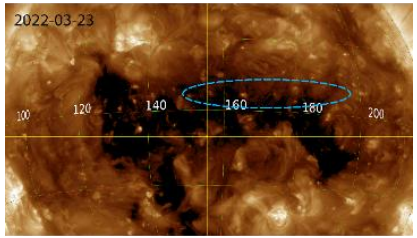
Coherent structures, waves and turbulence populate the heliosphere

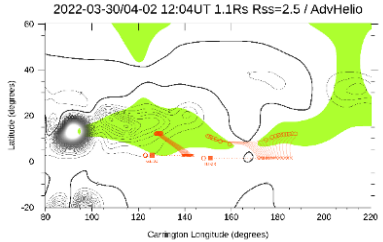
Solar Wind Turbulence

Statistical predominance of the Alfvénic slow wind during maximum of solar activity

(D'Amicis et al, 2011, 2015, 2019)





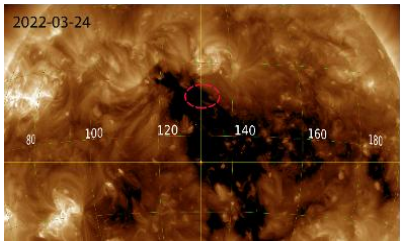


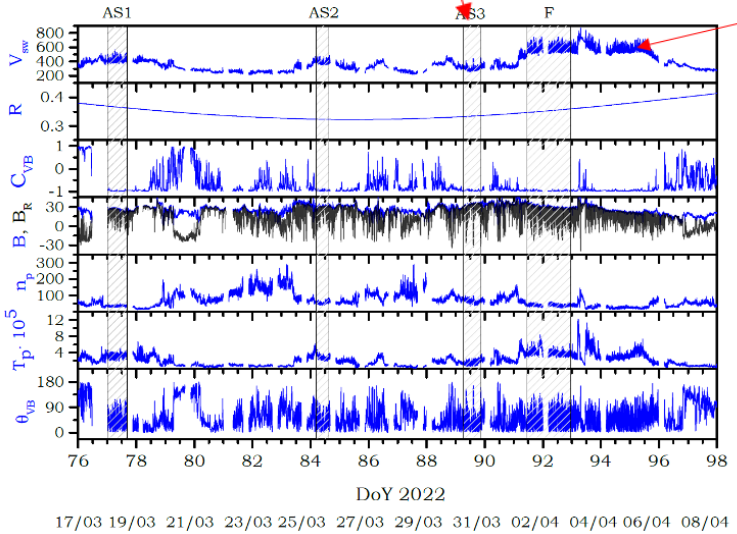
Origin and characterization of the Alfvénic wind

(D'Amicis et al 2021a, 2021b, 2021c)

PFSS extrapolation + imaging

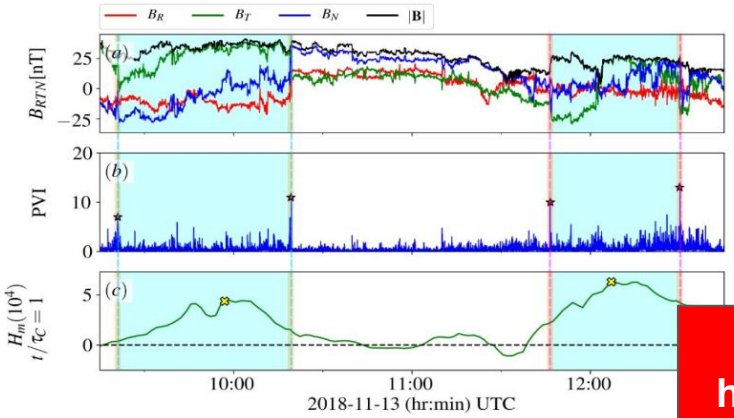
Solar sources with large expansion factors





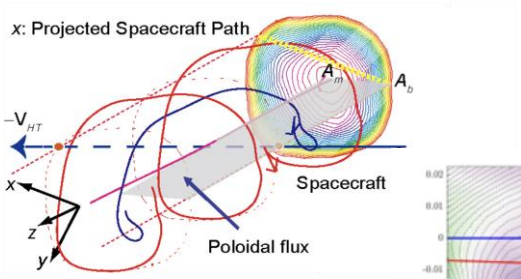
- fast wind closer to equipartition
- lower magnetic compressibility

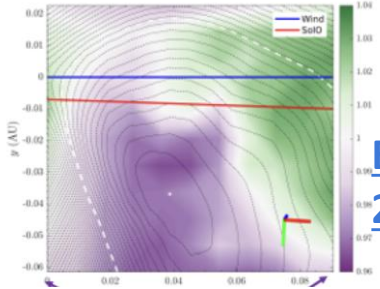
Flux tubes, Reconnection and Particles



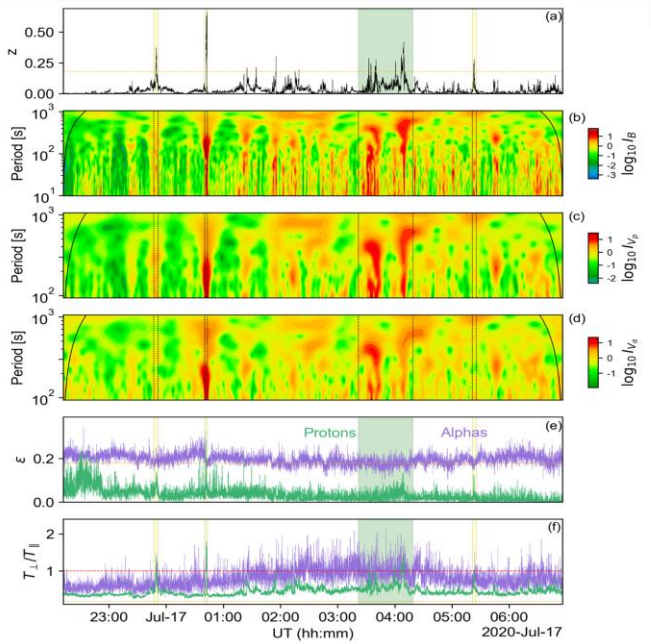
[Pecora+, 2018, 2021]

Large scale helical tubes are bounded by sharp (reconnecting) current layers





[Benella+, 2019, 2021]

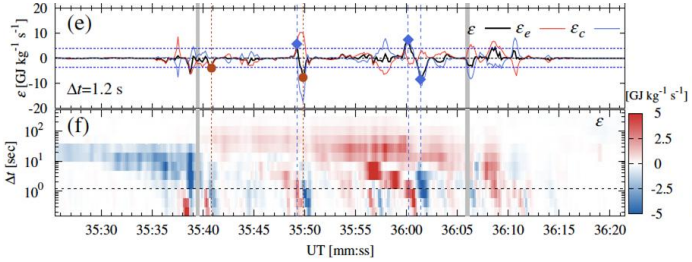


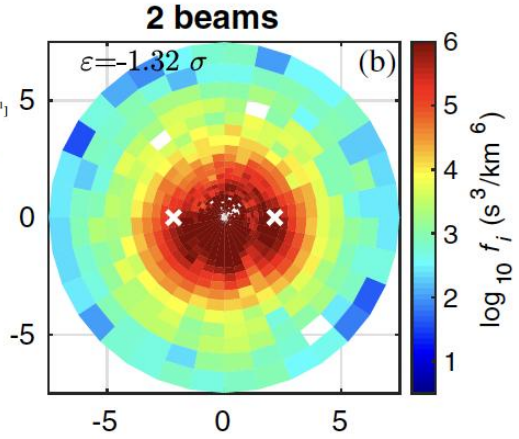
Switchbacks influence the turbulent (kinetic cascade) Perrone+, 2025

Agenzia Spaziale Italiana

Kinetic Effects in the Heliosphere

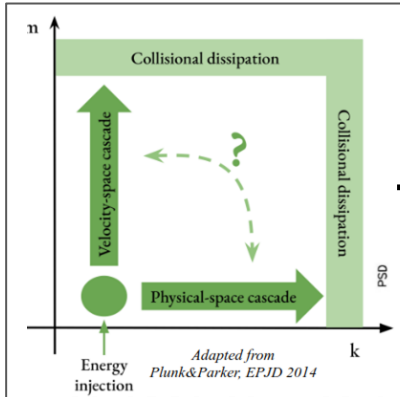
Turbulence-driven ion kinetic processes:





Turbulent intermittent structures and anomalous ion VDFs

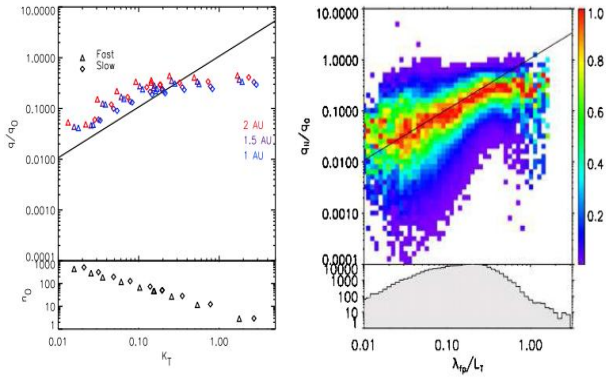
[Sorriso-Valvo+, PRL, 2019]



Phase-space dynamics and dissipation in turbulent nearly-reversible plasmas

[Pezzi+, MNRAS 2021]
[Richard+, PRE 2025]
[Larosa+, ApjL 2025]

Electrons In the Solar Wind



A comparison between electron heat flux measurements in the solar wind (WIND data) and kinetic simulations (Landi et al., ApJL, 2014)

Despite being weakly collisional many properties of the electrons in the solar wind are constrained by their collisional properties

(Landi et al.. ApJ, 2012, Landi et al, ApJL 2014, Bercic et al, JGR, 2021

INAF/IAPS

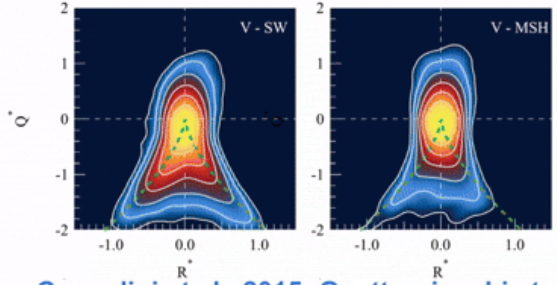
- R. Bruno, G. Consolini, R. D'Amicis, M. Laurenza, R. De Marco, S. Benella, M. F. Marcucci
- D. Belardinelli, N. Chrisaphi, O. S. Dhamane, V. Quattrociocchi, E. Rota, M. Scarabotti

highlights

Topology & Stochastic Processes

Magnetic and velocity field topology in turbulent plasmas

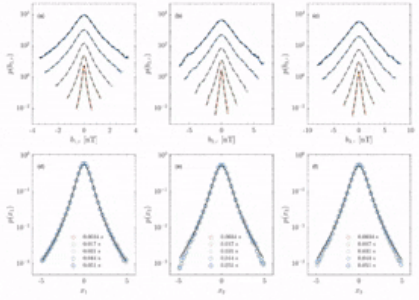
The understanding of turbulent plasma evolution implies the investigation of magnetic and velocity field structures and topologies via the analysis of gradient tensors invariants



Consolini et al., 2015; Quattrociocchi et al, 2019, 2022, 2023, 2025, 2026; Benella et al., 2026

Scaling and stochastic features at sub-proton scales

$$-\frac{\partial}{\partial\tau}p(x,\tau|x',\tau') = \left[-\frac{\partial}{\partial x}D^{(1)}(x,\tau)+\frac{\partial^2}{\partial x^2}D^{(2)}(x,\tau)\right]p(x,\tau|x',\tau').$$



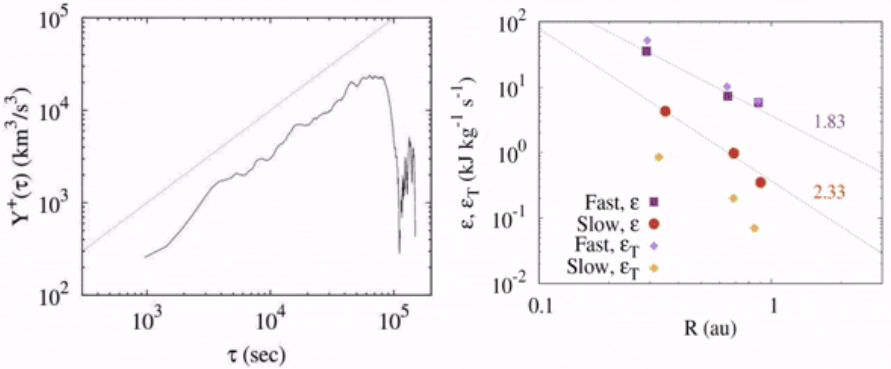
(Benella et al., 2022a, 2022b; Stumpo et al., 2023; Belardinelli et al., 2024)

- Luca Sorriso-Valvo, Oreste Pezzi, Francesco Pucci, Francesco Carbone (IIA)
- Andrea Larosa, more coming!

ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
Consiglio Nazionale delle Ricerche

highlights

Third-order laws and energy cascade rate in solar wind turbulence



Experimental validation of the Politano-Pouquet law for MHD turbulence: observation (left) and applications (solar wind heating, radial decay of turbulence - right)

Sorriso-Valvo et al., PRL 99, 115001 (2007)

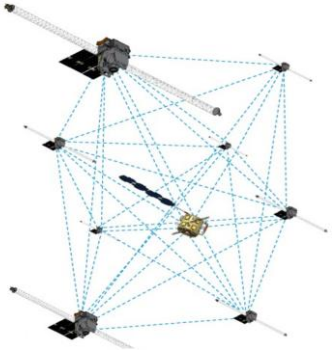
Marino & Sorriso-Valvo, Phys. Rep. 1006, (2023)

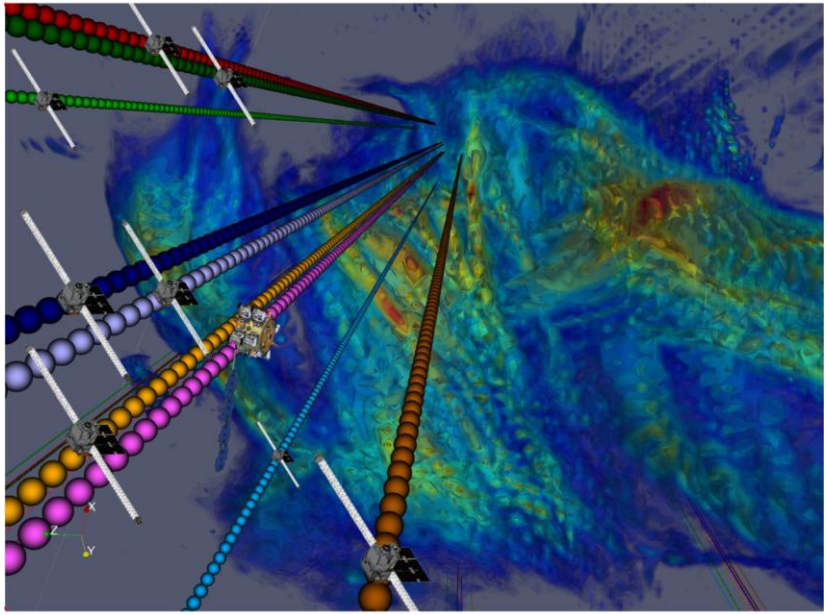
Magnetosphere & Sun-Earth Connection

Multispacecraft Analyses in The Magnetosheath

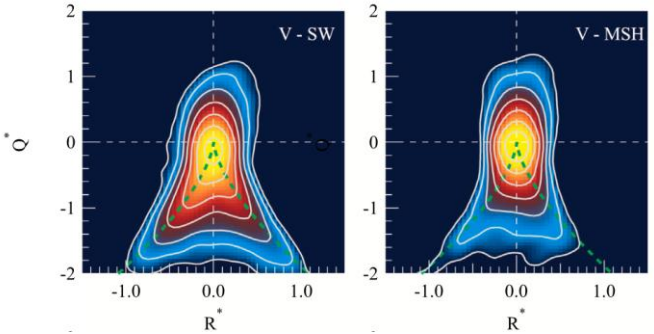
Pecora+, 2023-2025

New techniques for turbulence





New Techniques for structure classification



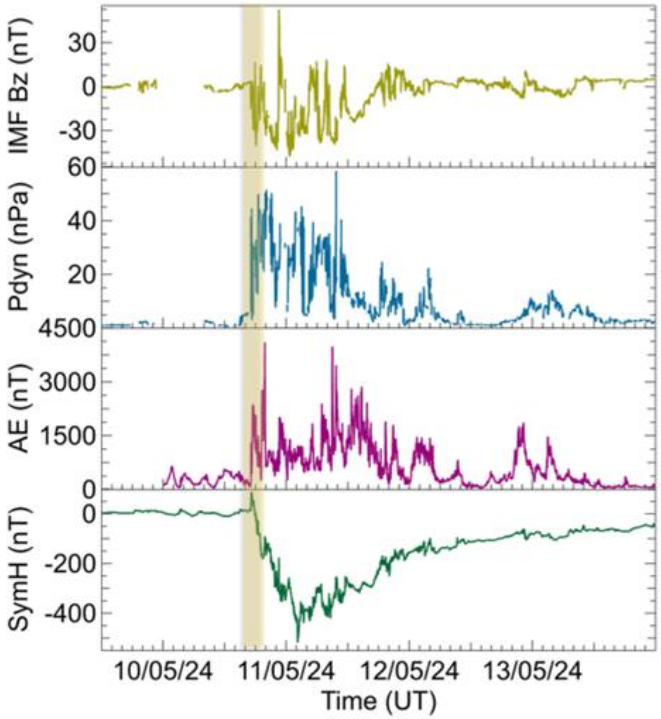
Magnetic and velocity field topology in turbulent plasmas

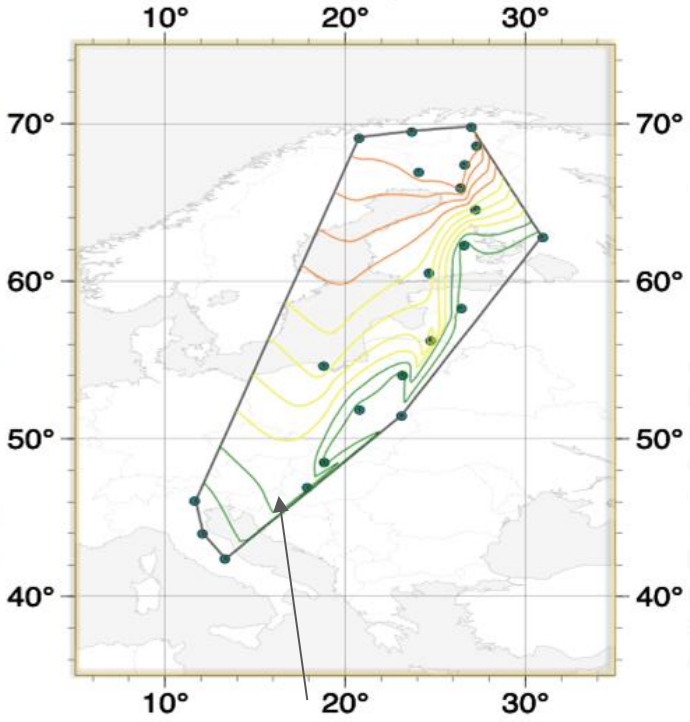
The understanding of turbulent plasma evolution implies the investigation of magnetic and velocity field structures and topologies via the analysis of gradient tensors invariants

Consolinii+
Quattrociocchi+,
Benella+

Plasma Perturbations: from the Sun to us

Geomagnetically Induced Currents Hazard due to geomagnetic Storm!

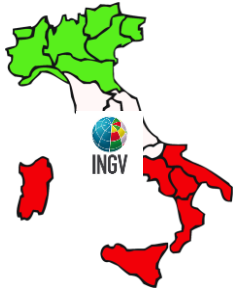




Courtesy of Dario Sabbagh

Contours of maximum treat levels

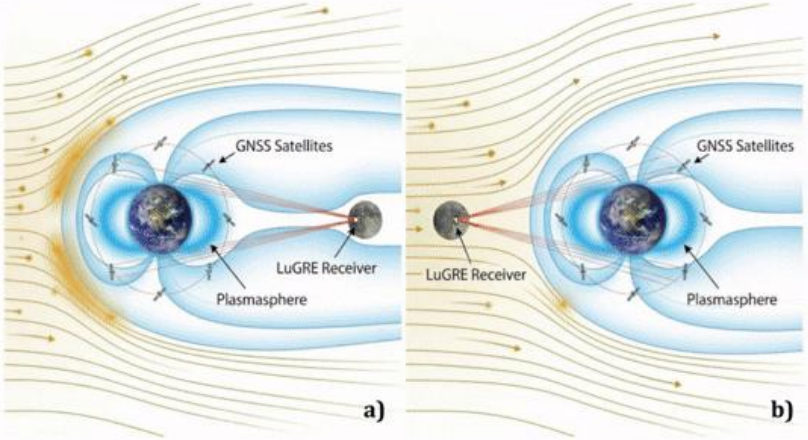
INGV & INAF



- INAF: Giuseppe Consolini, Simone Benella, Anna Milillo
- INGV: Lucilla Alfonsi, Paola De Michelis, Tommaso Alberti, Alessandro Ippolito, Fabio Giannattasio, Alessio Pignalberi, Roberta Tozzi, Michael Pezzopane, Igino Coco, Claudio Cesaroni, Luca Spogli, Vincenzo Romano, Dario Sabbagh, …
- Edoardo Cascio, Manuel Lacal, Emanuele Papini

highlights

Earth's Plasmasphere and Ionosphere from the Moon



First characterization of the Earth's plasmasphere and ionosphere using Global Navigation Satellite Systems signals tracked from the lunar surface by the Lunar GNSS Receiver Experiment (LuGRE).

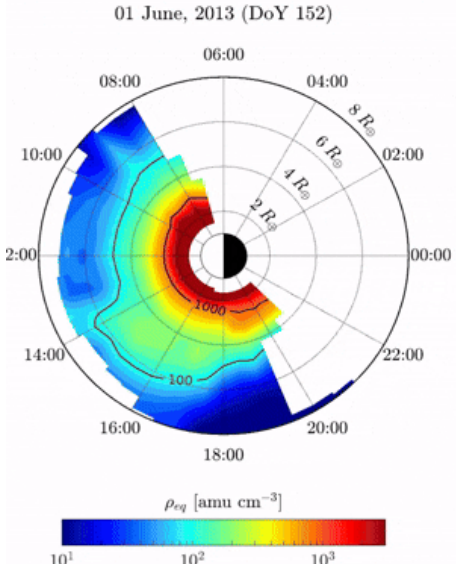
Cesaroni+, 2026

- Mirko Piersanti, Ermanno Pietropaolo, Giulia D'Angelo, Umberto Villante
- Dario Recchiuti, Giulio La Rovere, Stefano Zurzolo

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

highlights

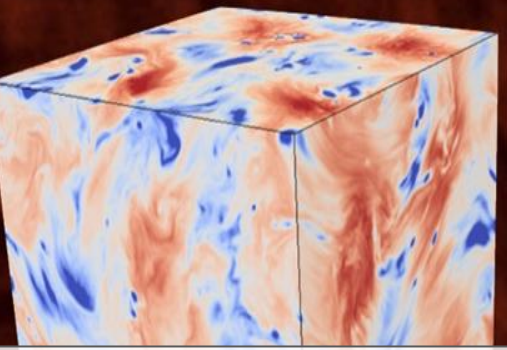
Space Weather: Monitoring of magnetospheric plasma dynamic processes

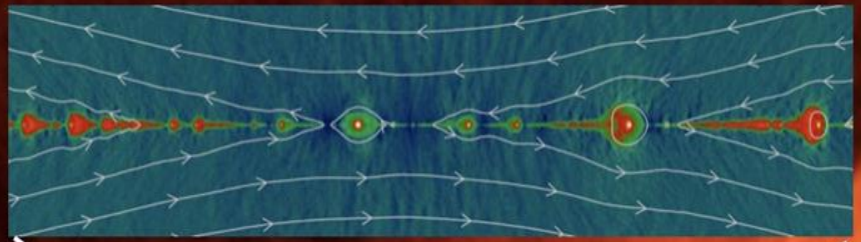


Plasma dynamics reveal how solar wind energy and particles are transferred and redistributed within the magnetosphere.

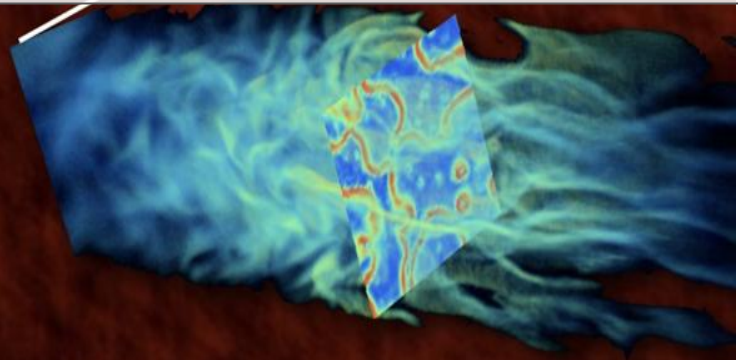
Role of the plasmasphere: plasma density modulates electromagnetic waves that are crucial for the evolution of the radiation belts

UnivAQ:
Remote monitoring of magnetospheric plasma density

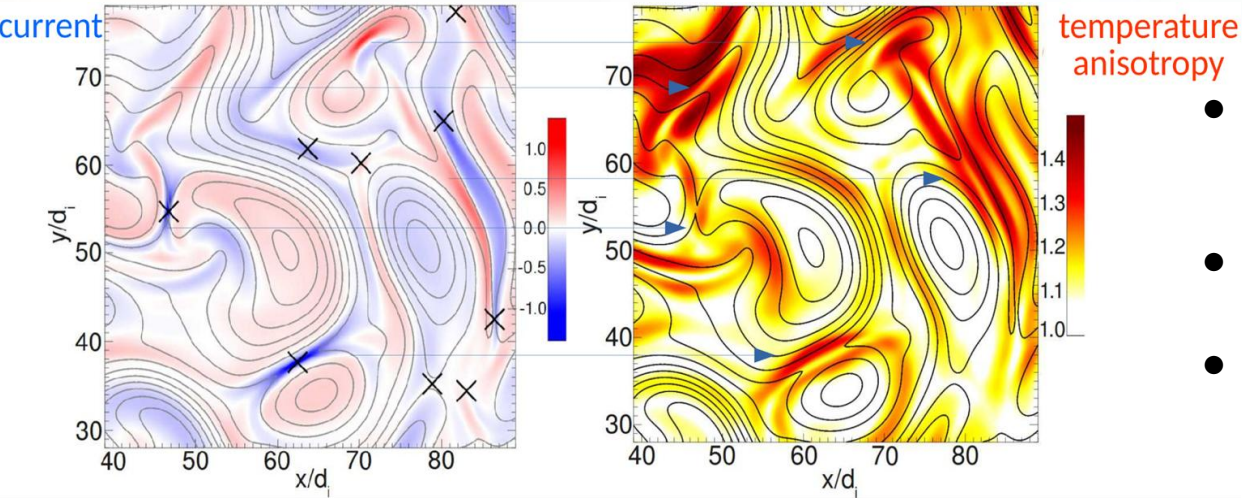




Plasma Theory & Computation

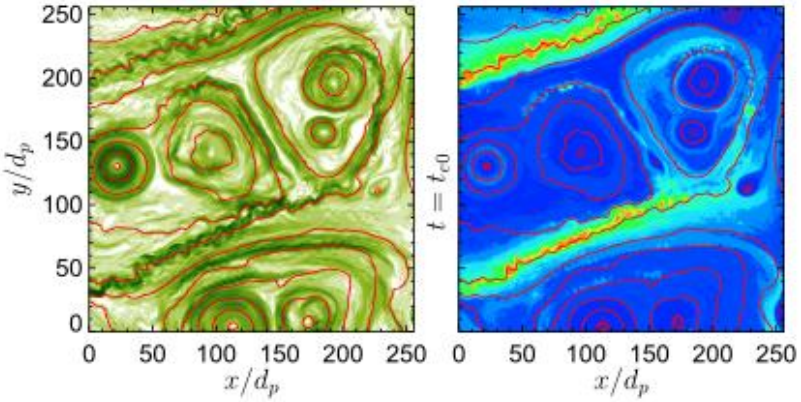


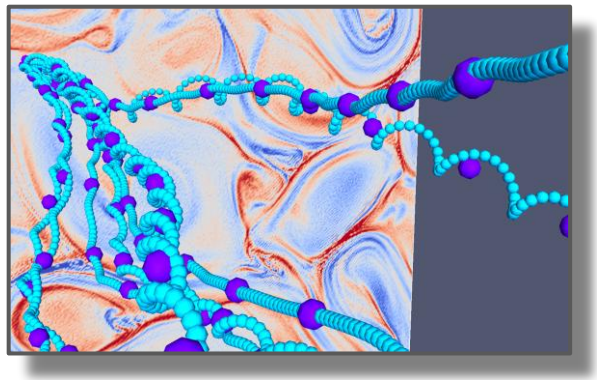
Turbulence, reconnection and much more



- **Magnetic reconnection is a fundamental element of turbulence**
- **Kinetic effects develop at the reconnection regions**
- **Particles get accelerated at these regions**

[Servidio, (2009)](#)
[Verdini, Landi+](#)
[Hellinger+ (2015)](#)

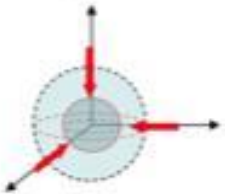




The Novelty

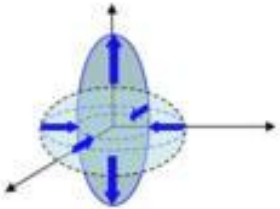
$$\underbrace{\nabla \mathbf{u}}_{\partial_i u_j \; i=x,y,z} = \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{u})\mathbf{I}}_{-\mathcal{C}\delta_{ij}} + \underbrace{\left[\frac{1}{2}\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)-\frac{1}{3}(\nabla\cdot\mathbf{u})\mathbf{I}\right]}_{\mathbf{D}_{ij}} + \underbrace{\frac{1}{2}\left(\nabla\mathbf{u}-(\nabla\mathbf{u})^T\right)}_{\mathbf{W}_{ij}}$$

Rate of Isotropic Compression



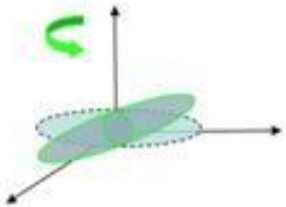
isotropic volume compression

Trace-less Rate of Shear



volume-preserving deformation without rotation

Vorticity



rotation

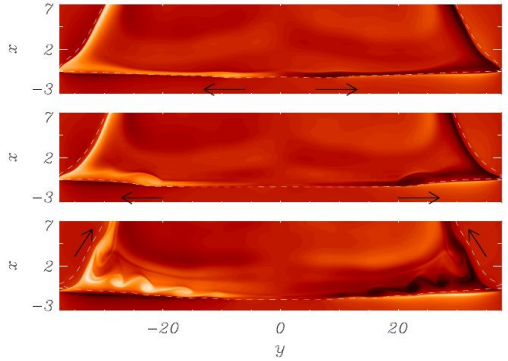
Anisotropization of particle distribution function:
Explains shear-induced pressure anisotropy and correlation with fluid vorticity in a low collisionality plasma

Pegoraro+
Del Sarto, Pegoraro, Califano, 2016

CNR-ISC & POLITO

- Daniela Grasso, Dario Borgogno, Chiara Marchetto
- Victorien Simon

Role of Kelvin-Helmholtz instability in asymmetric reconnection

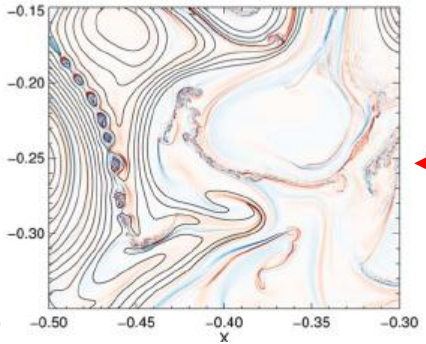


Turbulence develops on the edge of magnetic islands

Grasso+, PoP, 2020

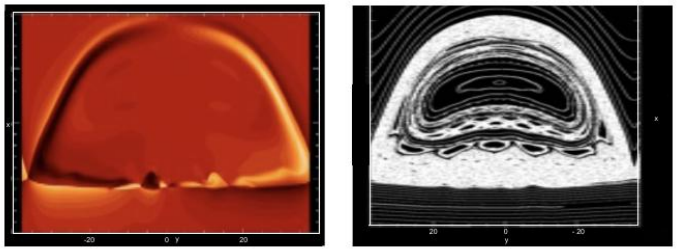
Role of plasmoids in a t

The competition between plasmoids and KH changes the trubulent spectrum



Borgogno+, APJ, 2022

Interaction between magnetic and turbulent chaos

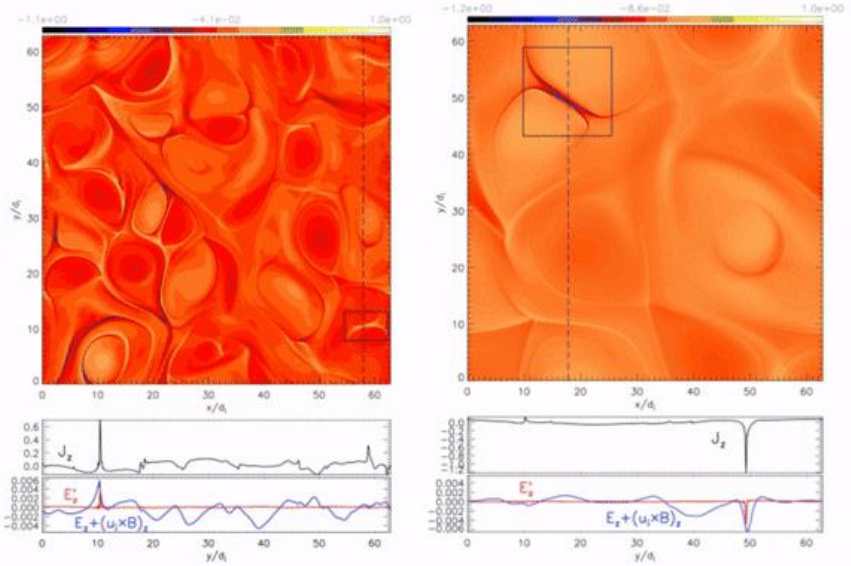


Marchetto+, PoP, 2026

- Francesco Califano, Francesco Pegoraro
- External collaborators & *ex-students*

highlights

Electron-Only Reconnection in Plasma Turbulence



Califano+, Frontiers, 2020

- Luca Del Zanna, Simone Landi, Andrea Verdini, Marco Romoli
- E. Papini (INAF), M. Sangalli, G. Napolitano, A. Celati, A. Burtovoi, P. Kumar, J. Xue

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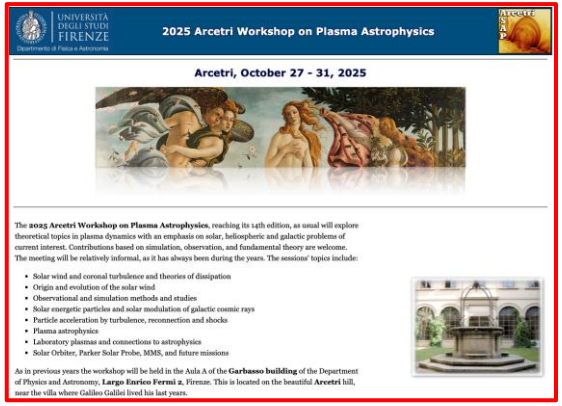

UNIVERSITÀ DEGLI STUDI FIRENZE
Dipartimento di Fisica e Astronomia

2025 Arcetri Workshop on Plasma Astrophysics

Arcetri, October 27 - 31, 2025

The **2025 Arcetri Workshop on Plasma Astrophysics**, reaching its 14th edition, as usual will explore theoretical topics in plasma dynamics with an emphasis on solar, heliospheric and galactic problems of current interest. Contributions based on simulation, observation, and fundamental theory are welcome. The meeting will be relatively informal, as it has always been during the years. The sessions' topics include:

- Solar wind and coronal turbulence and theories of dissipation
- Origin and evolution of the solar wind
- Observational and simulation methods and studies
- Solar energetic particles and solar modulation of galactic cosmic rays
- Particle acceleration by turbulence, reconnection and shocks
- Plasma astrophysics
- Laboratory plasmas and connections to astrophysics
- Solar Orbiter, Parker Solar Probe, MMS, and future missions

As in previous years the workshop will be held in the Aula A of the **Garbasso building** of the Department of Physics and Astronomy, **Largo Enrico Fermi 2**, Firenze. This is located on the beautiful **Arcetri** hill, near the villa where Galileo Galilei lived his last years.

highlights

Expanding Box Model: a tool for studying plasma properties in supersonic flows (e. g. the SW)

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = -(\dot{a}/a) 2\rho,$$
$$\rho(\partial_t + \mathbf{v} \cdot \nabla)\mathbf{v} - (\mathbf{B} \cdot \nabla)\mathbf{B} + \nabla(p + B^2/2) = -(\dot{a}/a)\rho \mathbf{v} \cdot \mathcal{T},$$
$$(\partial_t + \mathbf{v} \cdot \nabla) p + \Gamma p \nabla \cdot \mathbf{v} = -(\dot{a}/a) 2\Gamma p,$$
$$\partial_t \mathbf{B} - \nabla \times (\mathbf{v} \times \mathbf{B}) = -(\dot{a}/a)\mathbf{B} \cdot (2\mathcal{I} - \mathcal{T}).$$

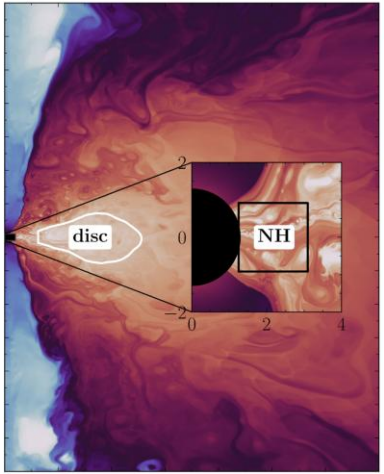
Expansions and compressions can be parametrized with a cosmology-like scale factor a(t) in MHD equations (e.g. Del Zanna et al., JPP, 2015).

The ECHO code for MHD and GRMHD, now on GPUs!

ECHO

Del Zanna+

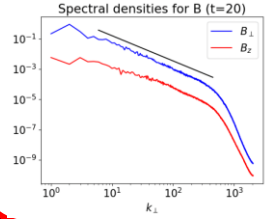
ECHO was born in 2000, with P. Londrillo. Innovative and highly cited methods, classic MHD or GR in any metric. Now on GPUs using standard FORTRAN!

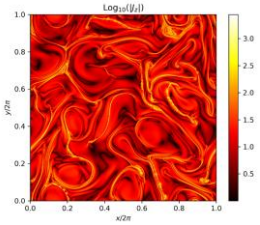


Plasma turbulence near black holes

Megale+, 2025
Ficarra+,2026
Meringolo+,2023
Imbrogno+, 2025

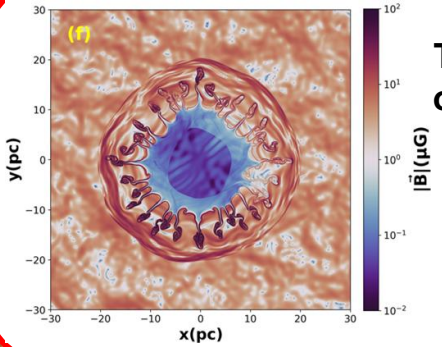
Relativistic plasmas in astrophysical sources





Pulsar wind nebulae can be modeled by relativistic 3D MHD turbulence simulations

Del Zanna+



The Interaction of a Supernova Remnant with Background Interstellar Turbulence

Prete+, 2025

- V. Carbone, P. Veltri
- G. Zimbardo, S. Savaglio, F. Valentini, S. Servidio, F. Malara, L. Primavera, F. Lepreti, A. Greco, S. Perri, G. Nisticò, L. Sorriso-valvo (CNR), O. Pezzi (CNR), F. Pucci (CNR)
- V. Capparelli, G. Prete, F. Chiappetta, L. D'Alessi, G. Ficarra, A. Larosa (CNR), G. Ciardullo, G. Celebre, M. Imbrogno, F. Feraco, A. Dagore, A. Tamburrini, E. Doria Rosales, B. Beniamino, A. Mercuri, L. Scarivaglione, M. Waqas, R. Megale, M. Simone, S. Zanelli, E. M. Fortugno, A. Congacha, S. Bertone

UNIVERSITÀ DELLA CALABRIA

In memory of Vincenzo Carbone

highlights

Movie interrupted : too much data!