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Energy conversion and dissipation in nearly-collisionless, turbulent space and astrophysical plasmas

Oreste Pezzi

Institute for Plasma Science and Technology (ISTP/CNR)

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ISTP Istituto per la Scienza e Tecnologia dei Plasmi

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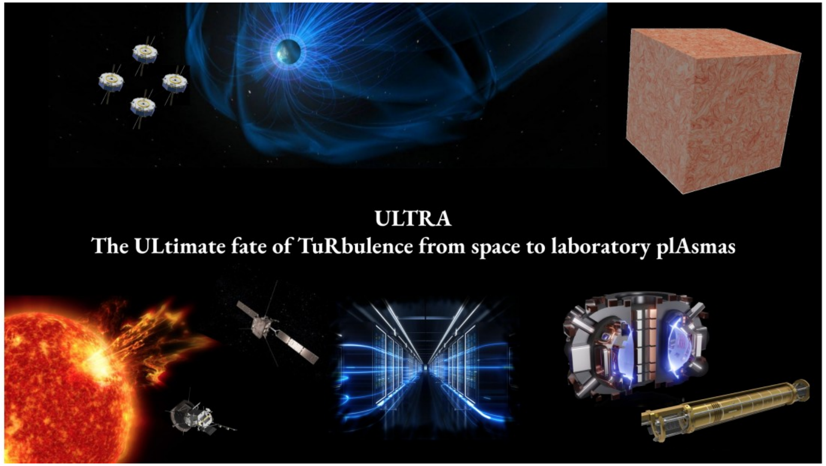
People and projects acknowledgements

Results here collected have been obtained thanks to vivid and friendly scientific collaborations, also formalized through funded research projects.

- **PRIN 2022** *"The Ultimate fate of Turbulence from space to laboratory plasmas (ULTRA)"*, with ASI and UNICAL
- **Bilateral Project CNR & UK Royal Society** *Multi-scale Electrostatic energization of plasmas: Comparison of Collective Processes in Laboratory and Space*, led together with Prof. D. Verscharen
- **ISSI Bern International team** *"Unveiling Energy Conversion and Dissipation in Non-Equilibrium Space Plasmas"*, led together with Prof. P. Cassak (Clemson University):
  ~20 researchers from >10 nations working on these topics through three funded one-week workshops
- **FIS2 Starting Grant** *"PhAse-sPAce cOmplexity in turbulent nearly-reversible plasmas (PAPAO)"*



Main collaborators:

Italy: L. Sorriso-Valvo & M. Zuin (CNR), S. Servidio and F. Valentini (UNICAL), D. Perrone (ASI), S. Benella (INAF), F. Califano (UNIPI)
UK: D. Verscharen (UCL), J. Stawarz (Northumbria)
France: S. Cerri, A. Retino' and G. Cozzani (CNRS)
Sweden: E. Yordanova and L. Richard (IRF)
Spain: D. Trotta (ESAC)
US: P. Cassak (Clemson), W.H. Matthaeus (Delaware), A. Chasapis (Boulder)

Outline

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- **Introduction:**
  - ✓ Turbulence in space and astrophysical plasmas
  - ✓ The "issue" of weak collisionality: plasma dynamics in the entire six-dimensional phase space
  - ✓ Kinetic-scale turbulence and its links with energy conversion and dissipation, plasma heating, and particle energization
  - ✓ Main methodologies: in-situ observations and numerical simulations

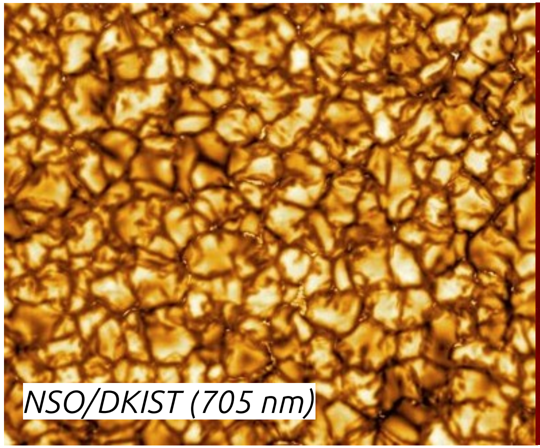
- **An emergent level of complexity: plasma turbulence in phase space**
  - ✓ Theoretical predictions and overview of previous results
  - ✓ Latest outcomes: in-situ spacecraft probes and kinetic Vlasov-Maxwell simulations

- **Irreversibility in nearly-reversible plasmas**
  - ✓ Inter-particle collisions and "friends"
  - ✓ Collisionality enhancement due to fine velocity-space structures
  - ✓ Kinetic Boltzmann-Maxwell simulations

- **Conclusions and future efforts**

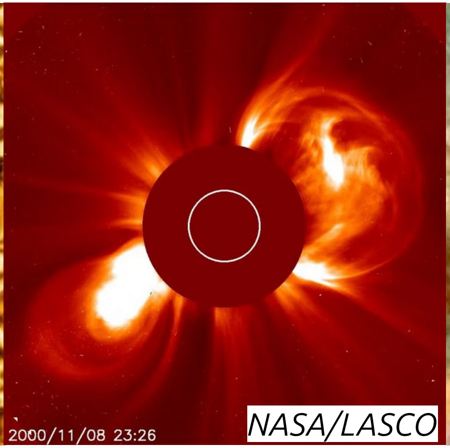
Plasma turbulence… across the Universe

- The **"Plasma Universe"**: nearly all the visible matter in the Universe is a plasma!
- **Turbulence** is the key phenomenon bridging the vast scale separation between injection and "dissipative" scales



Solar granulation

$l \sim 1000$ km $\tau \sim$ 5-10 min



Coronal mass ejection

$v_{CME} \sim 200 - 2000$ km/s

$M_{CME} \sim 10^{12}$ kg

Protostellar cloud (Carina nebula)

$l \sim 80$ pc

Stirring driven by stellar winds and SN explosions.

Relativistic MHD turbulence thought to occur near black holes

Plasma turbulence… across the Universe

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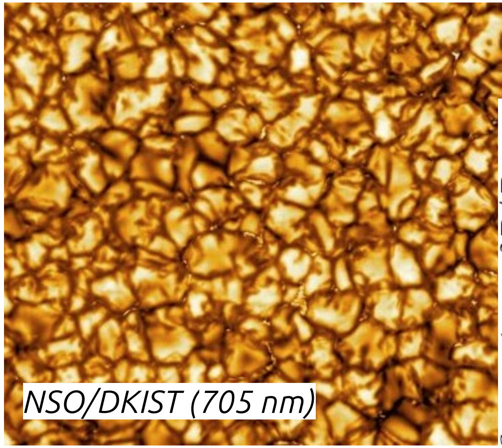
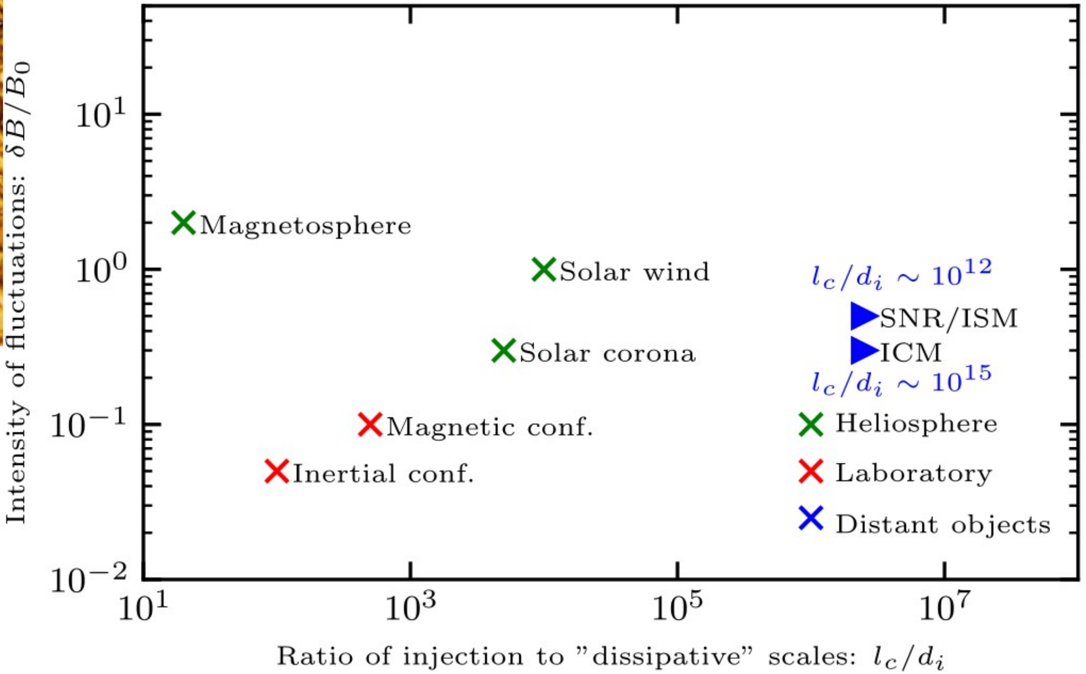


Solar granulation

l ~ 1000 km τ ~ 5-10 min



(Reynolds number proxy)

Relativistic MHD turbulence thought to occur near black holes

Plasma turbulence… across the Universe

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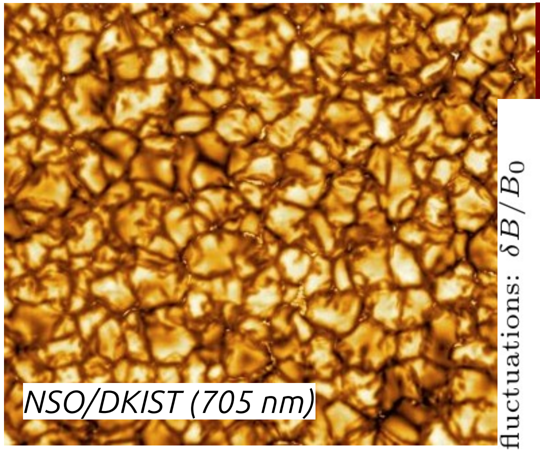
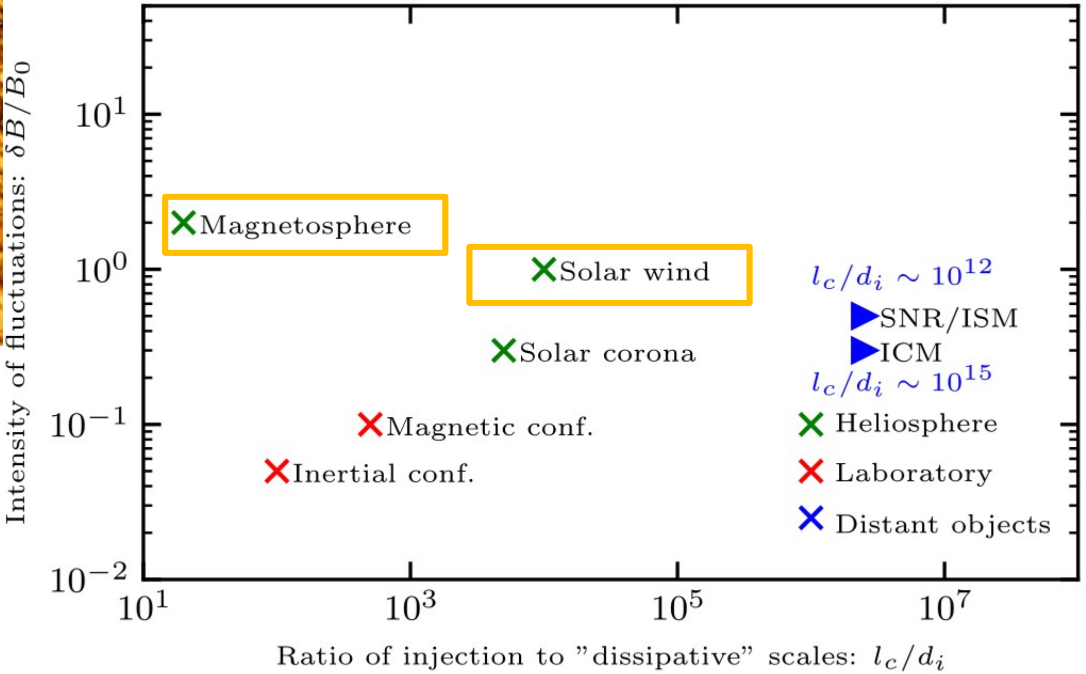


Solar granulation
l ~ 1000 km τ ~ 5-10 min



(Reynolds number proxy)

Relativistic MHD turbulence thought to occur near black holes

The heliosphere: an excellent lab for plasma physics

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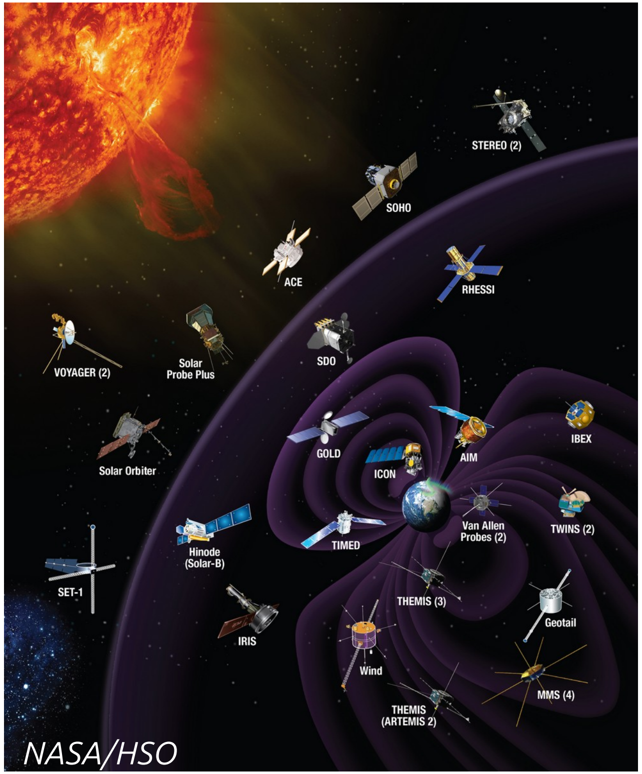
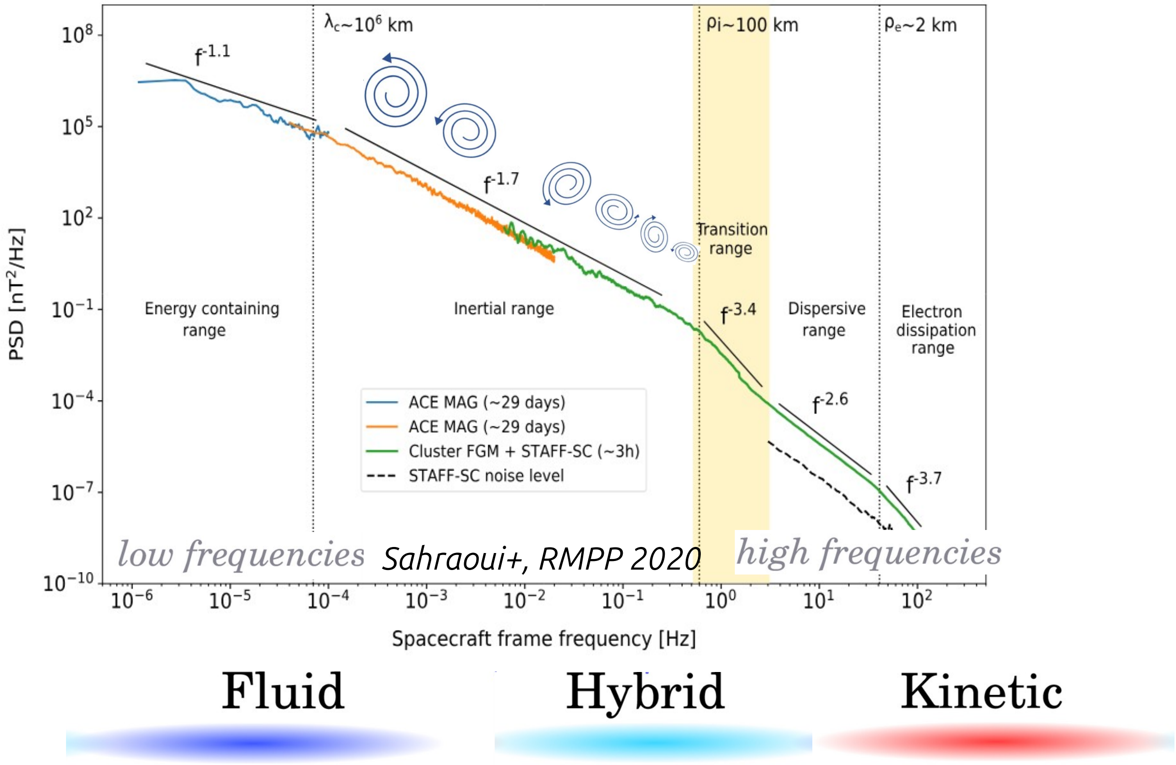
- Thanks to the possibility of **probing in situ the electromagnetic field and the plasma variables**, space plasmas represent an excellent lab for investigating fundamental mechanisms, such as turbulence, occurring in space and astrophysical plasmas.
- The synergy with numerical simulations is decisive to interpret in-situ observations.



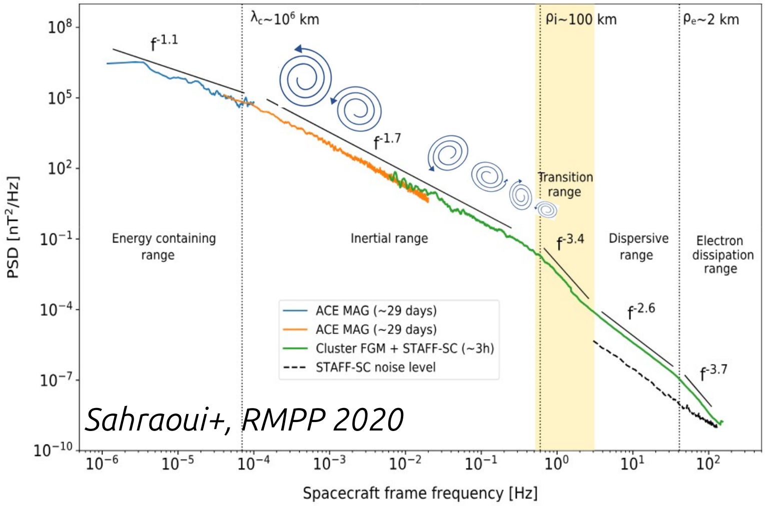
Heliospheric flotilla



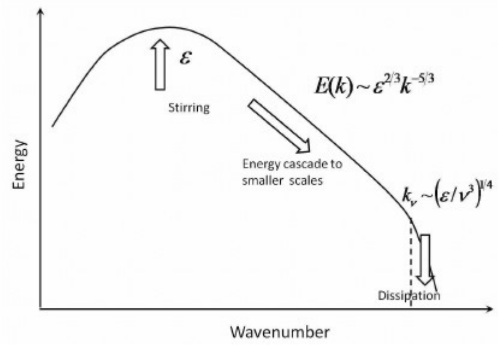
Collisional flows vs space and astrophysical plasmas

Turbulence in collisional flows (neutral or charged) and space and astrophysical plasmas show **important similarities**

CROSS-SCALE ENERGY TRANSFER



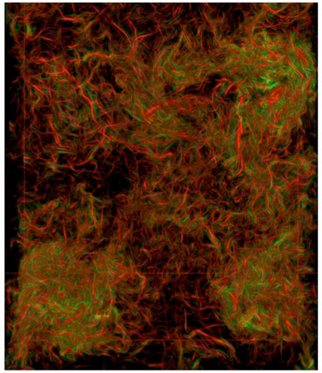
Sahraoui+, RMPP 2020



INTERMITTENCY/COHERENT STRUCTURES

j=∇ x **B**

Pezzi et al. ApJ 2022



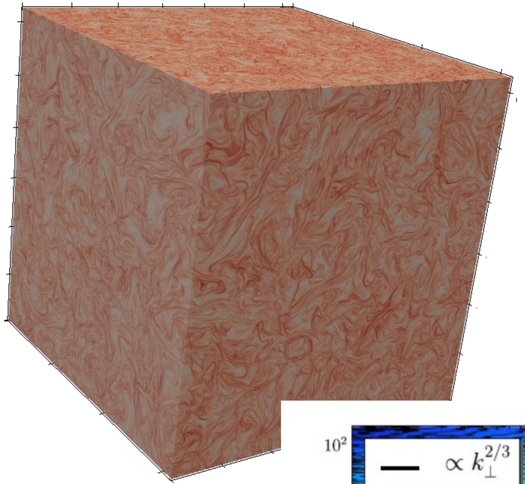
Vorticity $\nabla \times \mathbf{u}$

JH Turb. database

Collisional flows vs space and astrophysical plasmas

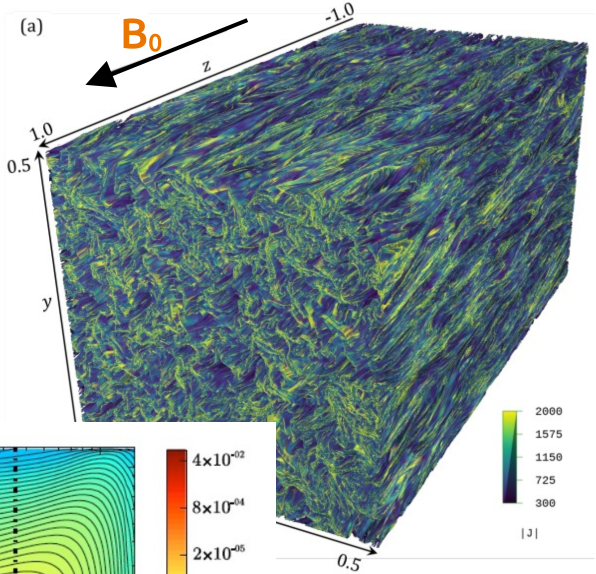
The ordered (background) magnetic field induces an **anisotropic cascade**

$B_0=0$

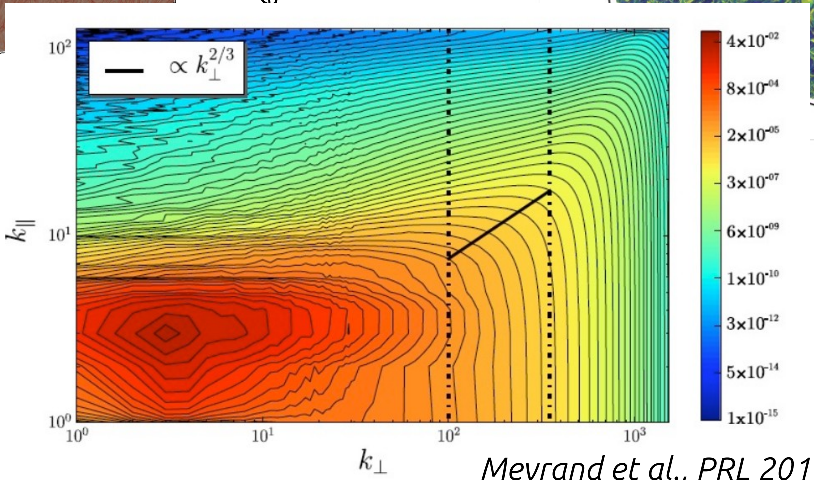


...ezzi et al. ApJ 2022

$B_0\neq0$



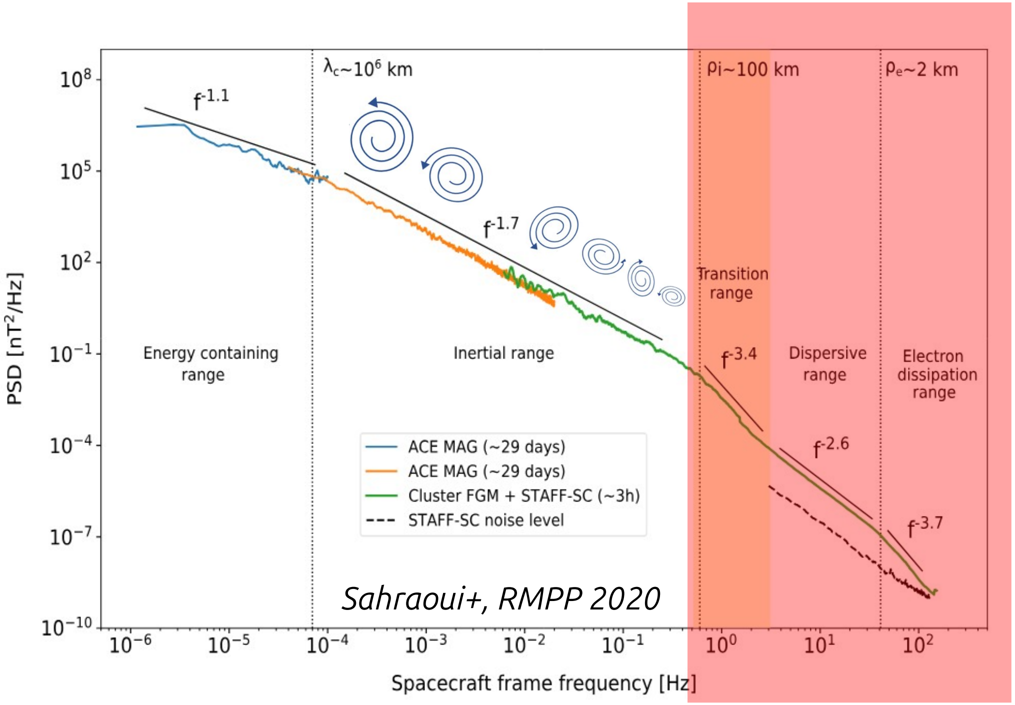
Dong et al., Sci Adv 2022



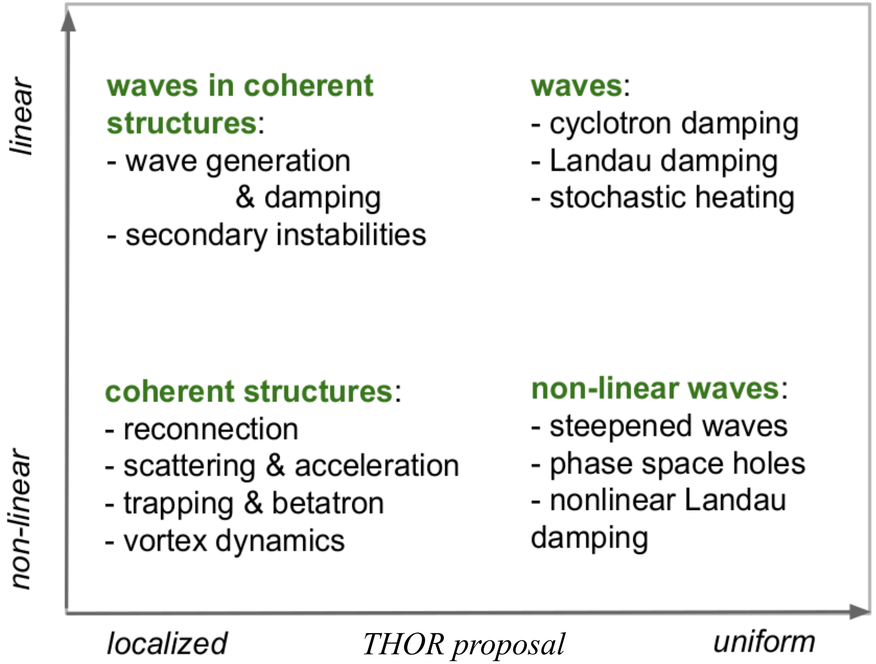
Meyrand et al., PRL 2016

Collisional flows vs space and astrophysical plasmas

Inter-particle collisions, responsible for dissipation in collisional flows, **are very weak in space and astrophysical plasmas: the dissipation function cannot be modeled through viscous-resistive effects!**



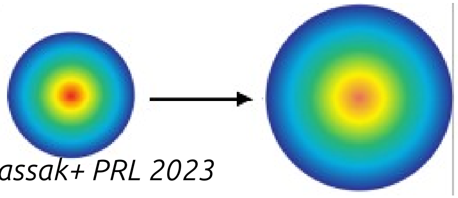
Energy conversion is mediated by diverse plasma phenomena and generally occurs in **entire phase space.**



Phase-space dynamics and energy conversion/dissipation

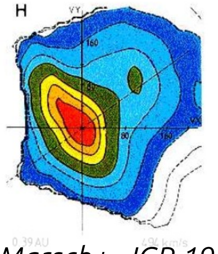
Different perspectives in the community:

a) Thermal energy conversion mechanisms:



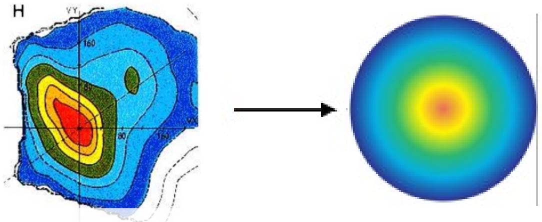
Cassak+ PRL 2023

b) Non-LTE conversion leading to non-equilibrium VDFs:



Marsch+, JGR 1982

c) Irreversible dissipation:



Marsch+, JGR 1982

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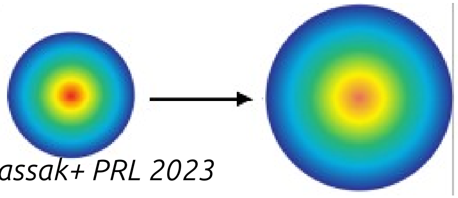

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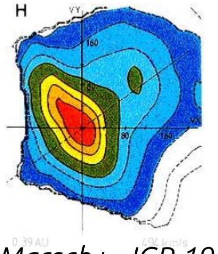

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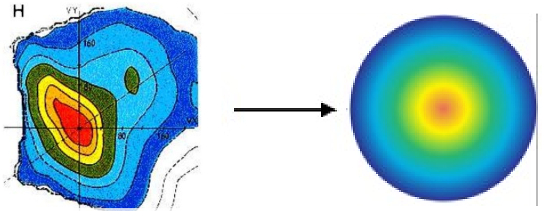
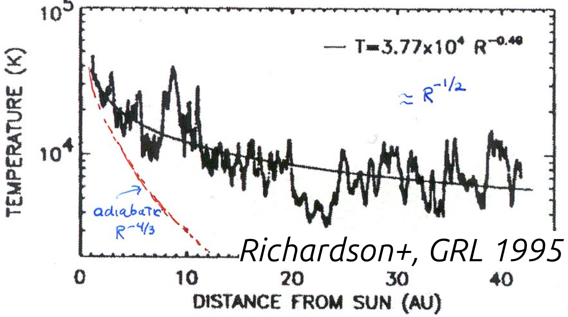


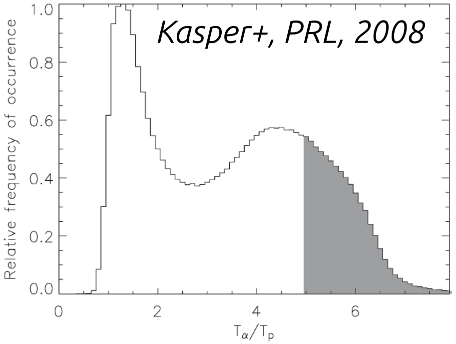
Marsch+, JGR 1982

PLASMA HEATING



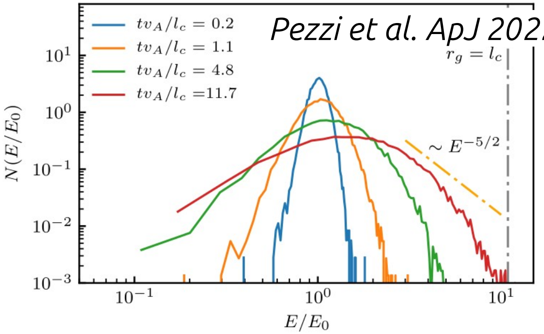
Richardson+, GRL 1995

ENERGY PARTITION



Kasper+, PRL, 2008

PARTICLE ENERGIZATION



Pezzi et al. ApJ 2022

Phase-space dynamics and energy conversion/dissipation

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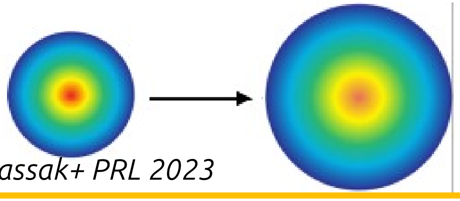

Cassak+ PRL 2023

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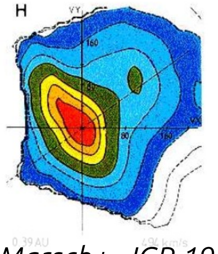

Marsch+, JGR 1982

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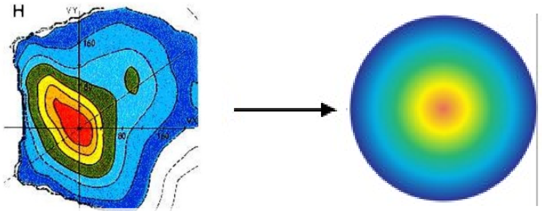
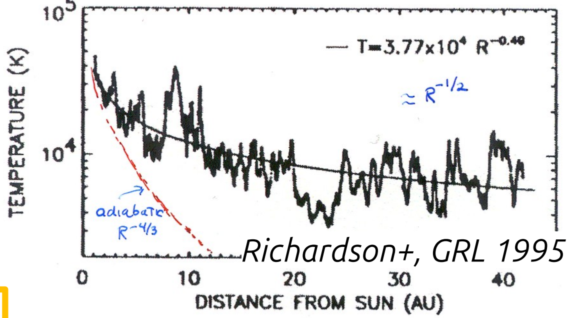


Marsch+, JGR 1982

PLASMA HEATING



Richardson+, GRL 1995

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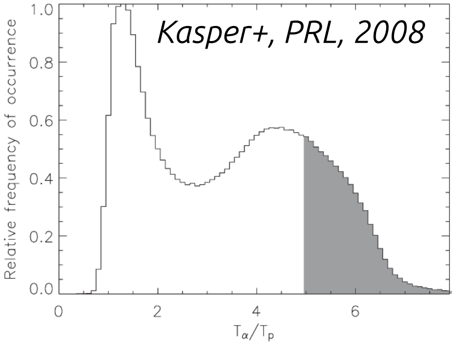

Kasper+, PRL, 2008

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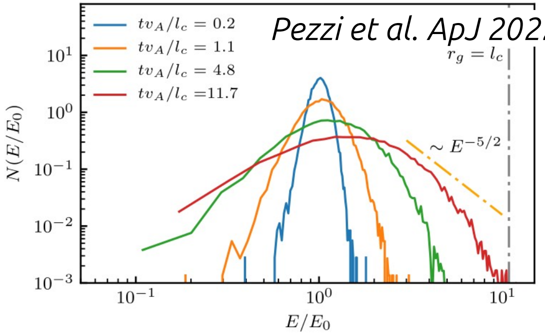

Pezzi et al. ApJ 2022

Phase-space dynamics and energy conversion/dissipation

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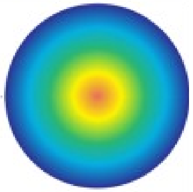
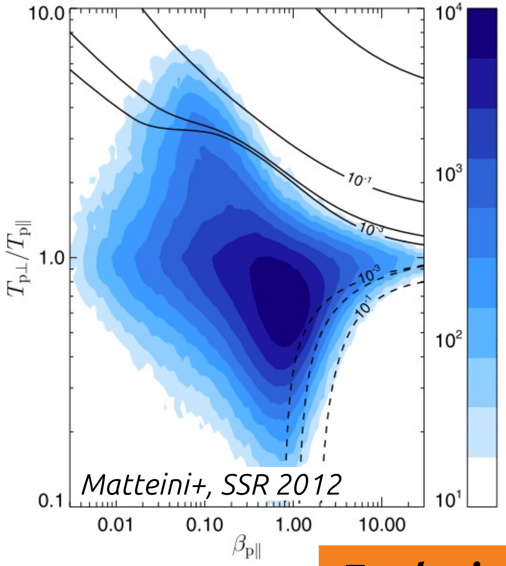
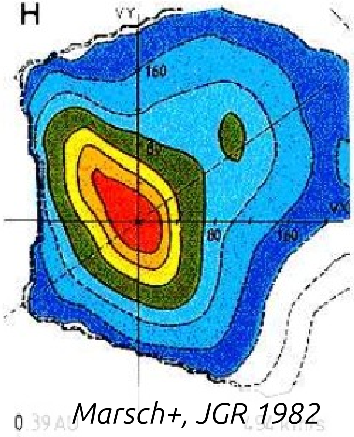
LTE plasmas are luckily a rarity in nearly-reversible space and astrophysical plasmas. We routinely deal with non-LTE plasmas showing distorted non-equilibrium velocity distribution functions (VDFs).



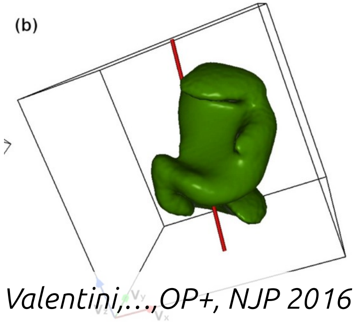
LTE Maxwellian



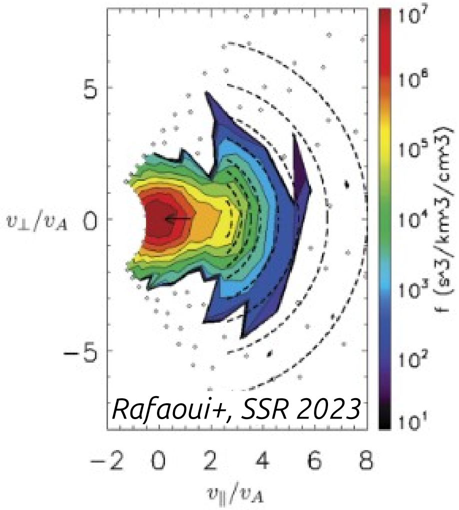
Matteini+, SSR 2012



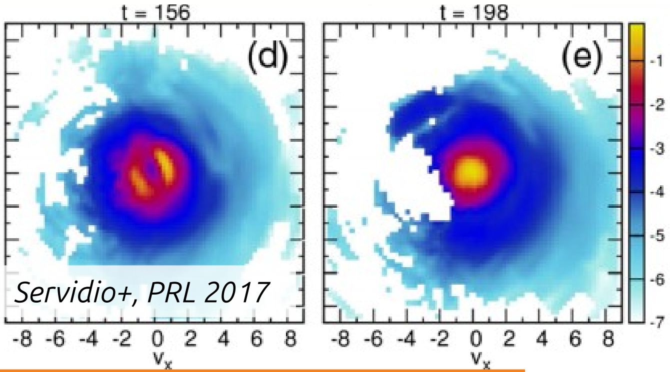
Marsch+, JGR 1982



Valentini,…,OP+, NJP 2016



Rafaoui+, SSR 2023



Servidio+, PRL 2017

Exploring velocity space is the next frontier in kinetic heliophysics!

Howes, Pop 2017

Phase-space plasma turbulence

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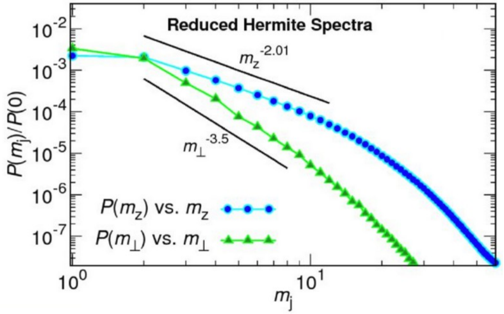
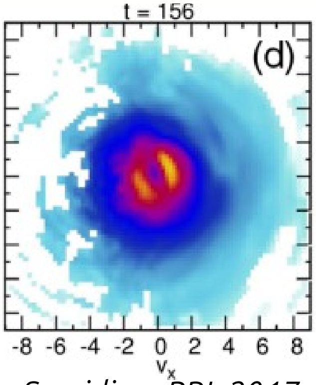
The production of non-LTE **velocity-space structures** is interpreted as a **turbulent cascade.**
At small phase-space scales, **collisions irreversibly dissipate energy.**

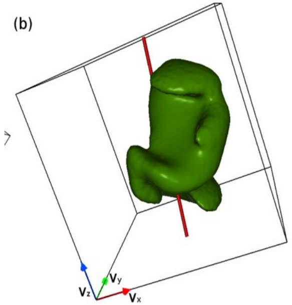
VELOCITY SPACE

f(**v**, t)
+
Hermite

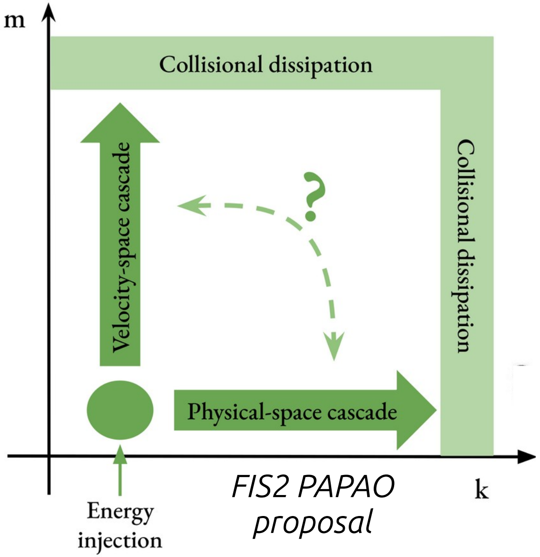




Servidio+, PRL 2017



Valentini,...Pezzi+, NJP 2016

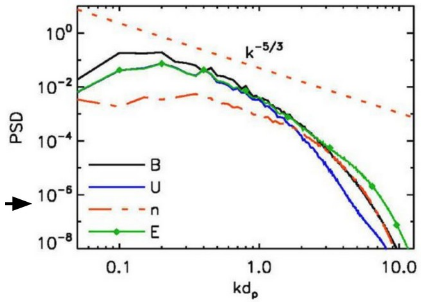


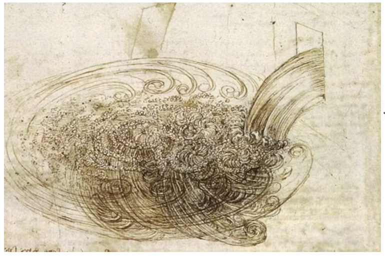
FIS2 PAPAO proposal

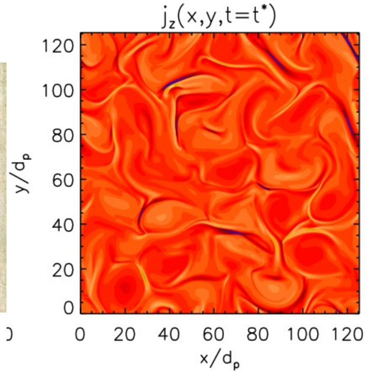
Pezzi+ PRL 2016, PoP 2018, ApJ 2019, MNRAS 2021, SSR 2021

PHYSICAL SPACE

B(**r**, t)
+
Fourier







Grad 1949; Tatsuno+ PRL 2009; Schekochihin+ JPP 2016; Eyink PRX 2017; Servidio+ PRL 2017; Meyrand+ PNAS 2019; Nastac+ JPP 2023; Cassak+ PRL 2023; [...]

Phase-space plasma turbulence

An efficient tool to explore cascades in velocity space is the Hermite decomposition of the particle VDF.
"Energy" associated with different Hermite modes (different velocity-space perturbations with respect to the Maxwellian equilibrium shape) cascades from small to large m (Hermite modes)

$$f(\mathbf{v}) = \sum_m f_m \psi_m(\mathbf{v}) \quad \leftrightarrow \quad \begin{cases} f_m = \int_{-\infty}^{+\infty} f(\mathbf{v}) \psi_m(\mathbf{v}) d^3 v \\ \psi_m(v) = \dfrac{H_m\left(\dfrac{v-u}{v_{th}}\right)}{\sqrt{2^m m! \sqrt{\pi} v_{th}}} e^{-\frac{(v-u)^2}{2 v_{th}^2}} \end{cases}$$

$\{\psi_m\}$ is an orthonormal basis built through Hermite polynomials

Enstrophy (or free-energy)

$$\Omega(\boldsymbol{x}) \equiv \int_{-\infty}^{\infty} \delta f^2(\boldsymbol{x}, \boldsymbol{v}) d^3 v = \sum_{m>0} [f_{\boldsymbol{m}}(\boldsymbol{x})]^2$$

Servidio+, PRL 2017

$$\mathcal{F} = -\sum_s T_s \delta S_s = \sum_s T_s \delta \int \mathrm{d}^3 \boldsymbol{v} \langle f_s \ln f_s \rangle = \sum_s \int \mathrm{d}^3 \boldsymbol{v} \frac{T_s \langle \delta f_s^2 \rangle}{2 F_{Ms}}$$

Schekochihin et al., JPP 2016

In absence of collisions, the enstrophy is preserved in the (phase-space) cascade process!

Phase-space plasma turbulence

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Theoretical efforts:

Reduced frameworks (gyrokinetics, drift-kinetic):
Tatsuno+ PRL 2009; Schekochihin+ JPP 2016; Adkins+ JPP 2018

$$C_m = \frac{A(k_\parallel)}{\sqrt{m}} e^{-(m/m_c)^{3/2}}, \quad m_c = \left(\frac{3|k_\parallel| v_{th}}{2\sqrt{2}\nu} \right)^{2/3}$$

Schekochihin+, JPP 2016

Kolmogorov-like full-Vlasov phenomenological theories:
Servidio+ PRL 2017

$$P(m) \sim m^{-2}$$

(very magnetized)

or

$$P(m) \sim m^{-3/2}$$

(Dominated by advection or electric field)

Servidio+, PRL 2017

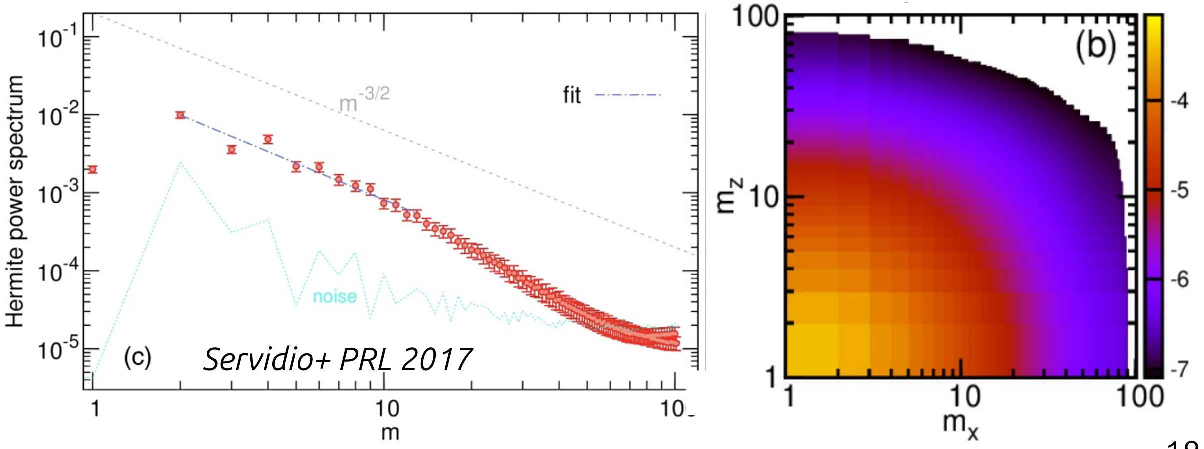
Simulations efforts:

Pezzi+, POP 2018, ApJ 2019, SSR 2021, Cerri+ ApJ 2018, 2021, Meyrand+ PNAS 2019; Celebre+ PoP 2023; Nastac+ PRE 2024

Observational efforts:

MMS: *Servidio+, PRL 2017*
Solar Orbiter: *Wu+ ApJ 2023*
PSP: *Bowen+ PRL 2022; Larosa, Pezzi+, ApJL 2025*

HERMITE POWER SPECTRUM



Phase-space plasma turbulence

Theoretical efforts:
Reduced frameworks (gyrokinetics, drift-kinetic):
Tatsuno+ PRL 2009; Schekochihin+ JPP 2016; Adkins+ JPP 2018

Kolmogorov-like full-Vlasov phenomenological theories:
Servidio+ PRL 2017

Simulations efforts:
Pezzi+, POP 2018, ApJ 2019, SSR 2021, Cerri+ ApJ 2018, 2021, Meyrand+ PNAS 2019; Celebre+ PoP 2023; Nastac+ PRE 2024

Observational efforts:
MMS: *Servidio+, PRL 2017*
Solar Orbiter: *Wu+ ApJ 2023*
PSP: *Bowen+ PRL 2022; Larosa, Pezzi+, ApJL 2025*

$$C_m = \frac{A(k_\parallel)}{\sqrt{m}} e^{-(m/m_c)^{3/2}}, \quad m_c = \left(\frac{3|k_\parallel| v_{th}}{2\sqrt{2}\nu}\right)^{2/3}$$

Schekochihin+, JPP 2016

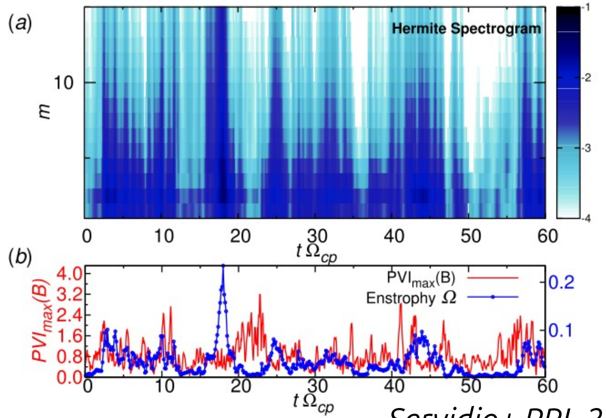
$$P(m) \sim m^{-2}$$
(very magnetized)

or

$$P(m) \sim m^{-3/2}$$
(Dominated by advection or electric field)

Servidio+, PRL 2017

HERMITE SPECTROGRAM



Servidio+ PRL 2017

The near-Sun solar wind: phase-space turbulence

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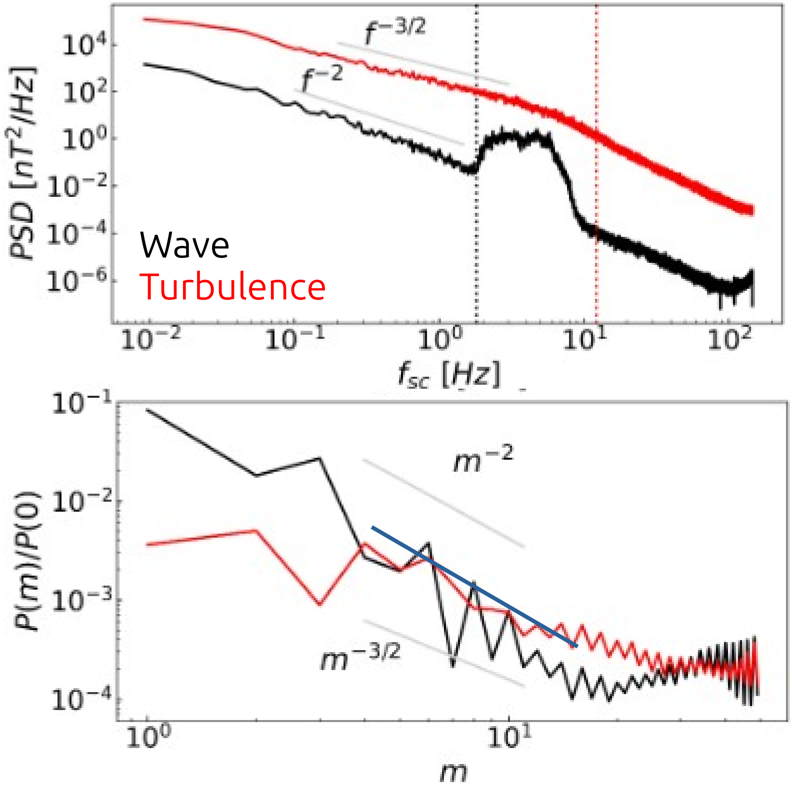
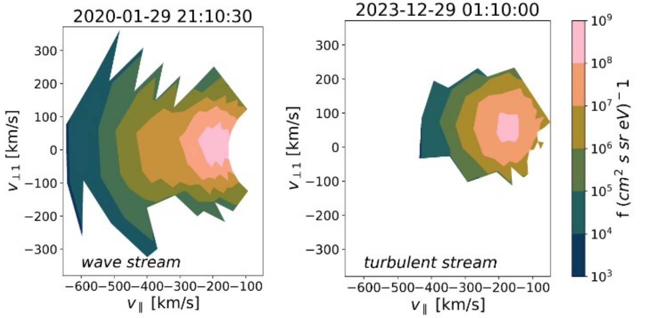
Consiglio Nazionale delle Ricerche

We provided the first observations of dual phase-space cascade in the near-Sun solar wind, by focusing on two intervals:

- **Wave** (|| sampling)**:** wave activity at ion scales and hammerhead distribution (beam at large speeds)
- **Turbulent** (⊥ sampling): classical turbulence phenomenology and complex VDFs with small-scale distortions

Quantity	*wave*	*turbulent*
B_{rms} $[nT]$	9.83	95.81
$B_{rms}/\langle B\rangle$	0.08	0.12
$\langle\beta_p\rangle$	0.6	0.1
$\langle\theta_{BV}\rangle^{\circ}$	168	116
$\langle\sigma_c\rangle$	0.69	0.79
R $[R_{sun}]$	28.0	11.4
M_A	2.6	0.5
f_c $[Hz]$	1.8	12





Hammerhead **⊥ anisotropy**

- Qualitative agreement, in both cases, with Servidio's prediction in the magnetized case (~m^{-2});
- More developed spectra in the turbulent case as a result of the cascade process.

Larosa, Pezzi+, ApJL 2025

The near-Sun solar wind: non-LTE energy conversion

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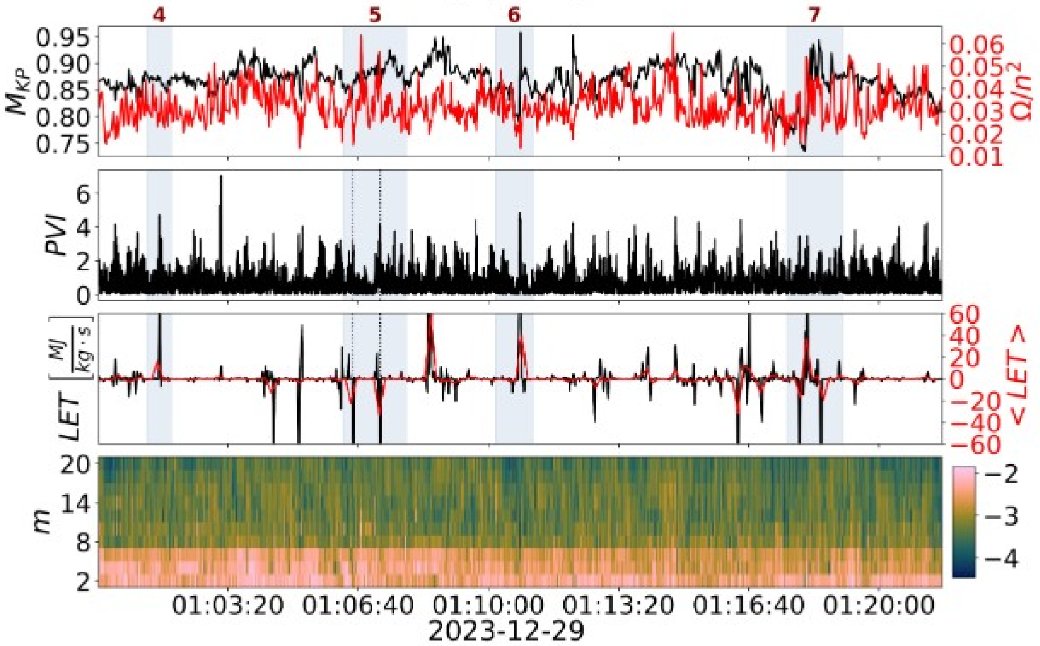
Turbulence



$$s_\alpha(\boldsymbol{r}, t) = -k_B \int d^3v f_\alpha(\boldsymbol{r}, \boldsymbol{v}, t) \log f_\alpha(\boldsymbol{r}, \boldsymbol{v}, t)$$

$$\bar{M}_{\mathrm{KP},\alpha}(\boldsymbol{r}, t) = \frac{s_{\mathrm{M},\alpha}(\boldsymbol{r}, t) - s_\alpha(\boldsymbol{r}, t)}{(3/2) k_B n_\alpha(\boldsymbol{r}, t)}$$

$$\mathrm{PVI}_{s,\tau} = \frac{|\Delta \mathbf{B}(s, \tau)|}{\sqrt{\langle |\Delta \mathbf{B}(s, \tau)|^2 \rangle}} \qquad \Delta \mathbf{B}(s, \tau) = \mathbf{B}(s + \tau) - \mathbf{B}(s),$$

$$\epsilon_{p,\ell} = \left(|\Delta \boldsymbol{u}_p|^2 + |\Delta \boldsymbol{b}|^2\right) \frac{\Delta u_{p,\ell}}{\ell} - 2(\Delta \boldsymbol{u}_p \cdot \Delta \boldsymbol{b}) \frac{\Delta b_\ell}{\ell}$$

- Qualitative correlation between non-Maxwellian diagnostics (e.g., M_{KP}), the local-energy transfer (LET) rate measuring the available turbulent energy at ion scales, and pronounced Hermite spectra (elongation with m in the Hermite spectrogram).
- Hermite spectrogram is generally intermittent (Pezzi+, SSR 2021).

Larosa, Pezzi+, ApJL 2025

The Earth's magnetosheath: phase-space turbulence

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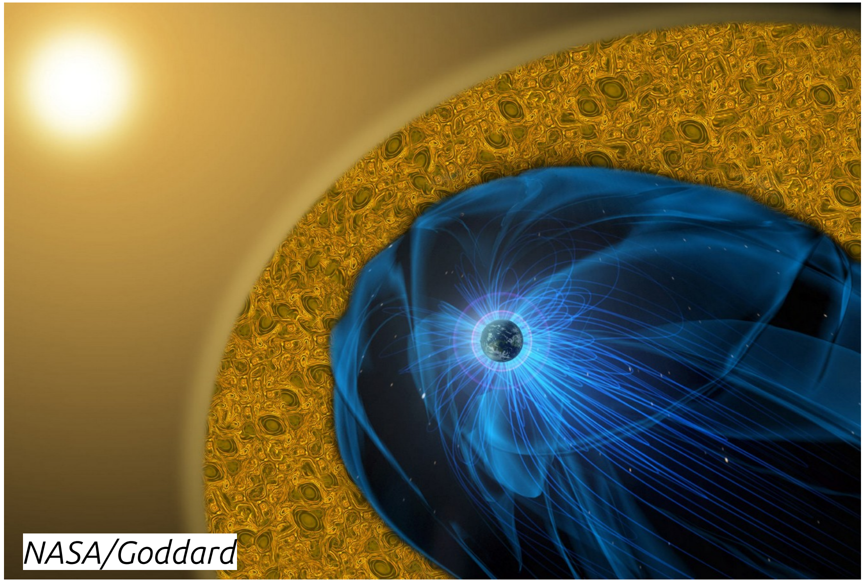
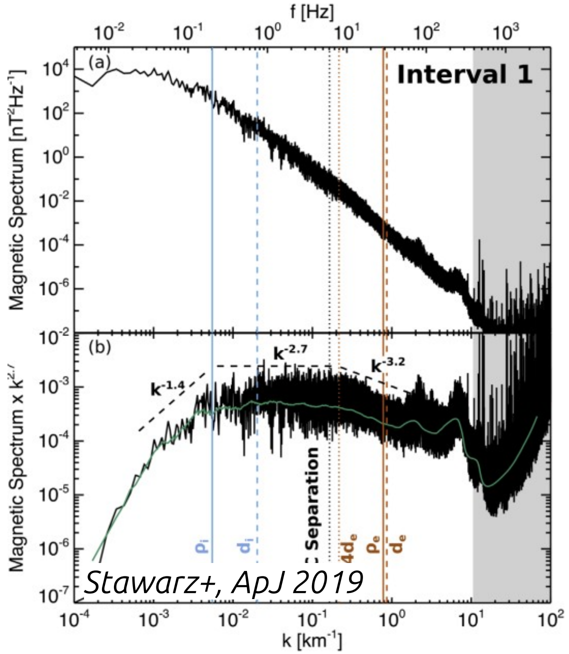
The magnetosheath is the bounded plasma (high β) between the bow shock and the magnetopause.
It is turbulent but, due to the boundaries and the solar wind pushing, the inertial range is usually rather small.

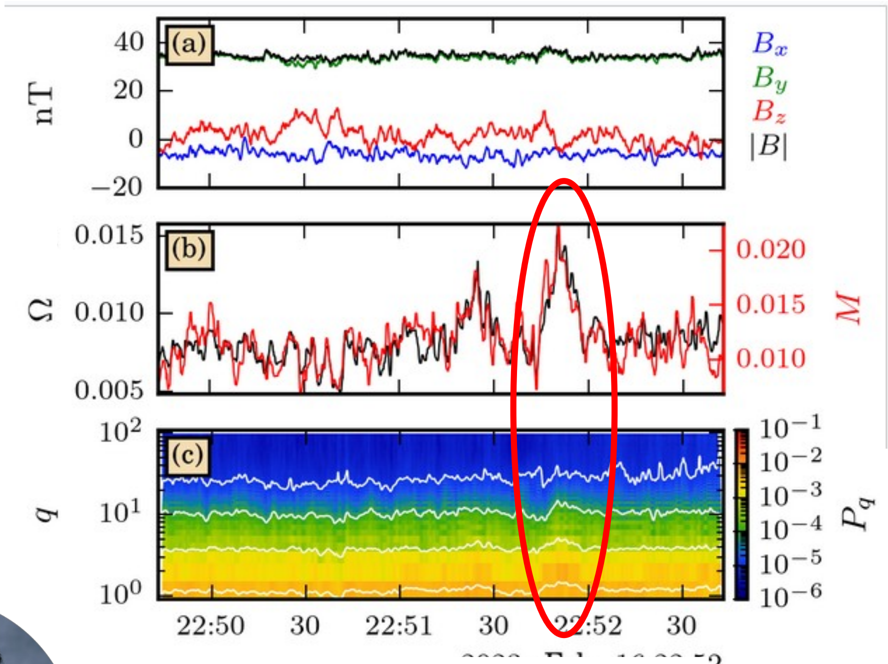

NASA/Goddard



Stawarz+, ApJ 2019

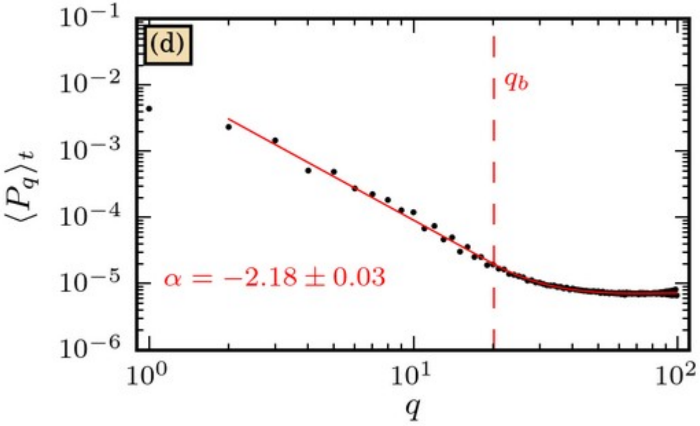
Tetrahedron of four spacecraft allowing to measure wavevector at one scale at unprecedented resolution
Main goal: **magnetic reconnection** up to smallest electron scales.

The Earth's magnetosheath: phase-space turbulence



HERMITE SPECTROGRAM

HERMITE POWER SPECTRUM



Vo, Pezzi,+ in prep 2026

The Earth's magnetosheath: phase-space turbulence

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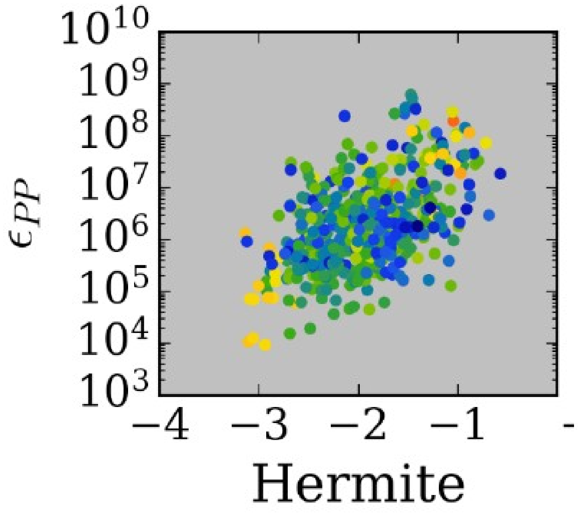
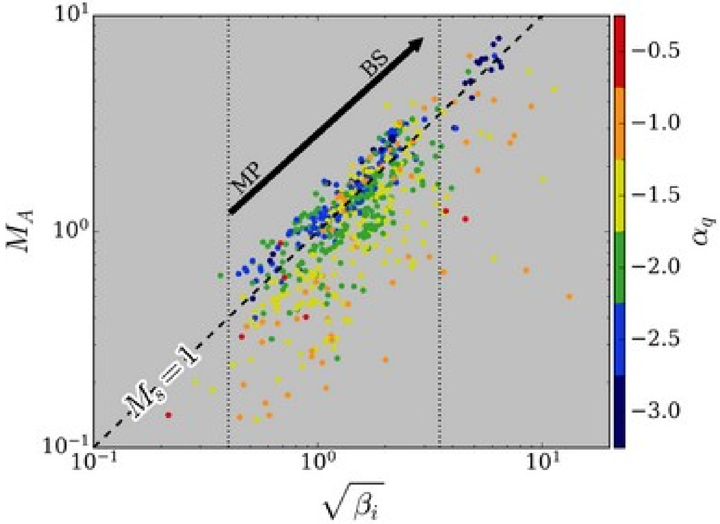
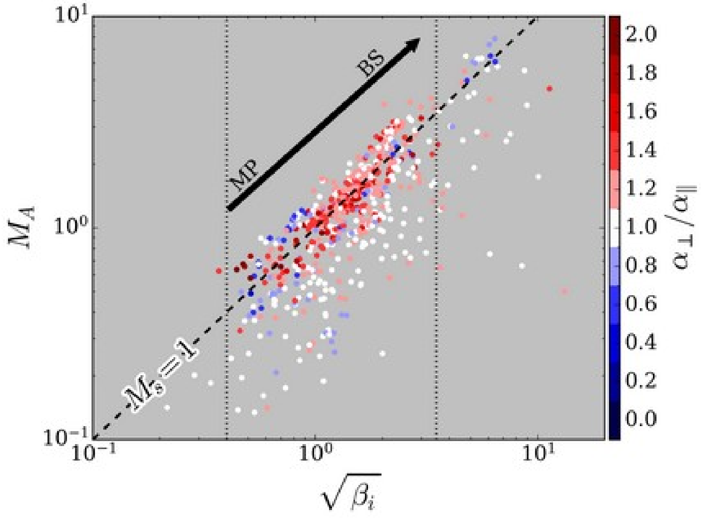
We are performing a deep statistical analysis of phase-space turbulence in the Earth's magnetosheath exploiting the unbiased campaign by MMS.



HERMITE SPECTRAL SLOPE



HERMITE SPECTRAL ANISOTROPY



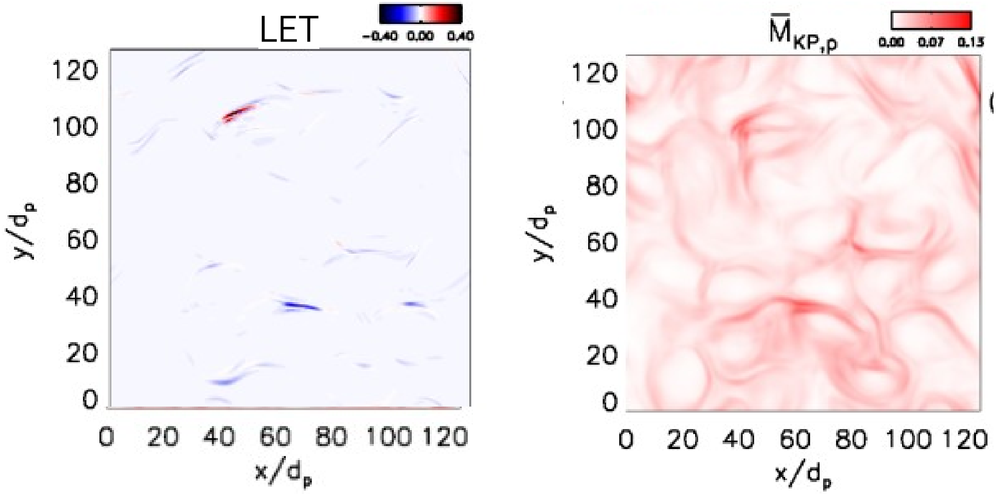
Vo, Pezzi,+ in prep 2026

- Excellent correlation between the turbulent energy estimated with the Politano Pouquet law and the Hermite spectral slope!
- The sonic Mach number is regulating the spectral slope and the anisotropy:
  - ✓ **M_s<1**: -3/2 slope – NO spectral anisotropy (Servidio+, PRL 2017)
  - ✓ **M_s>1**: -2 (Pezzi+, PoP 2018) and -5/2 (Schekochihin+, JPP 2016) slopes + anisotropy
  - ✓ No evidence of the -1/2 slope (Schekochihin+, JPP 2016)

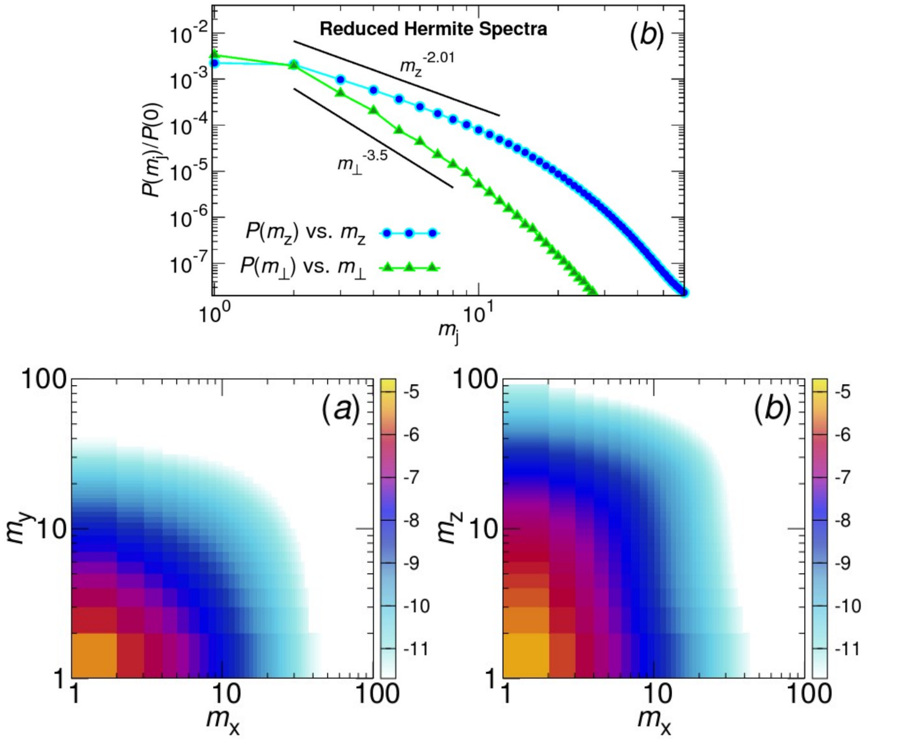
What about simulations?

Simulations are important to complement in-situ observations and investigate the dynamics of other species:

- **Hybrid Vlasov-Maxwell (HVM) code** (Valentini+, JCP 2007) for ions: protons and alpha particles, He^{++}



Non-Maxwellianity, correlated with LET, is intense in regions of intense magnetic stresses:
Intermittent energy conversion/dissipation!



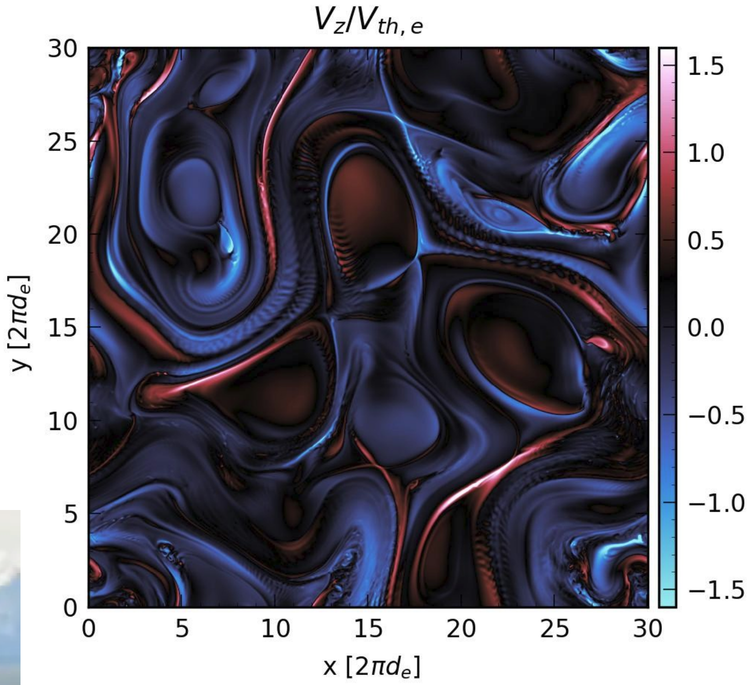
Anisotropic Hermite cascade, preferential along the background magnetic field.

Pezzi et al., PoP 2018, MNRAS 2021

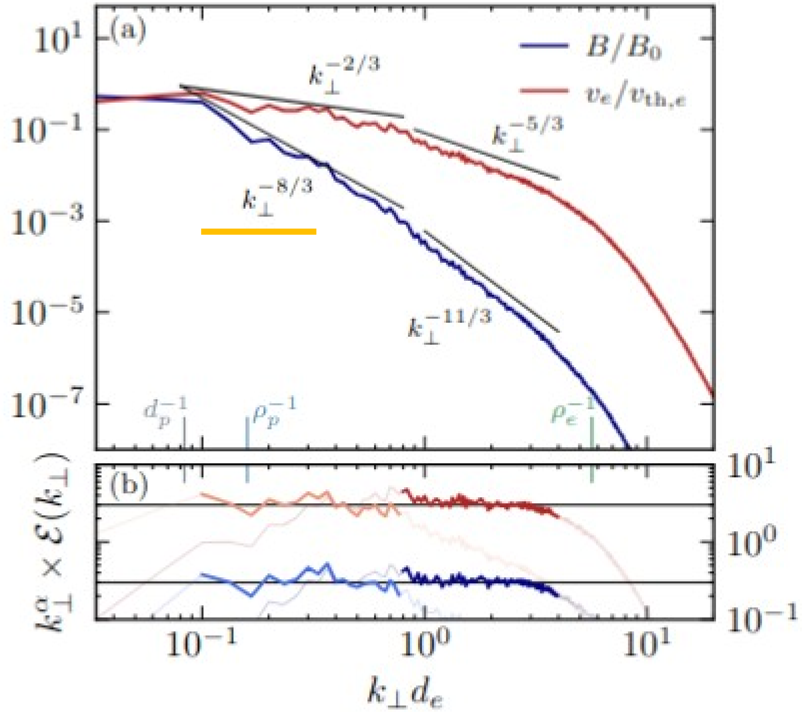
What about simulations?

Simulations are important to complement in-situ observations and investigate the dynamics of other species:

- **Fully-kinetic Vlasov-Darwin (ViDA) code** (Pezzi+, JPP 2019) for electrons



KAW turbulence *Chen&Boldyrev, 2017*



Manzini, Pezzi et al., in prep 2026

What about simulations?

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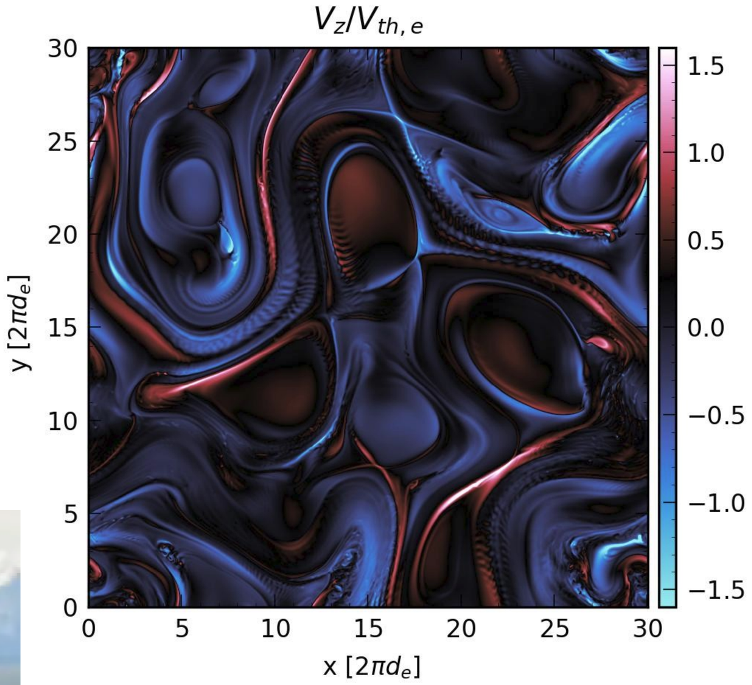
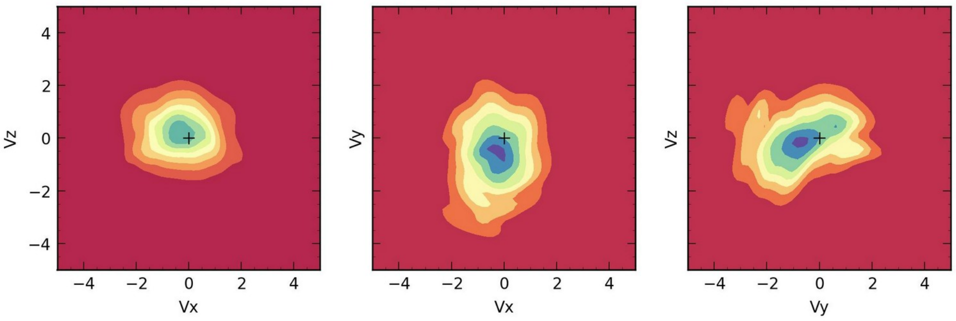
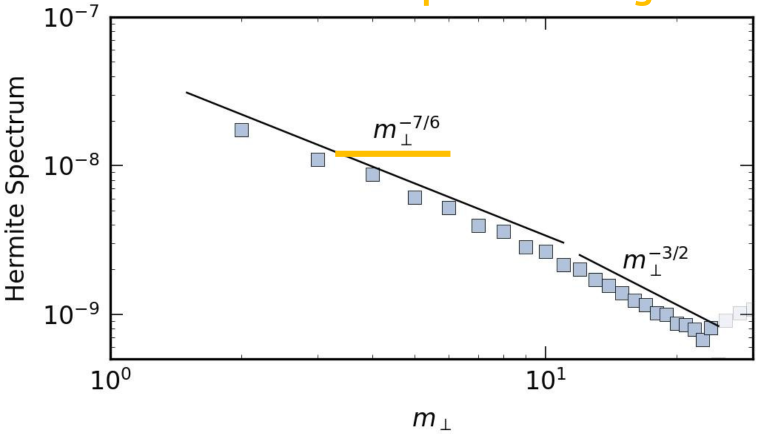




Nonlinear phase-mixing



Manzini, Pezzi et al., in prep 2026

Tatsuno+, 2009, Schekochihin+ 2016

Conclusions and future efforts

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- **Plasmas**, often very far from LTE, are ubiquitous in the Universe and rather accessible in the heliosphere.
- Through their study we can investigate fundamental physical processes, such as **turbulence** and **non-equilibrium statistical mechanics**
- **Turbulence evolves in the entire phase space:**
  - **Anisotropy:** spectra are more developed in the direction of the background magnetic field
  - **Intermittency:**
- **In-situ spacecraft observations and Eulerian Vlasov-Maxwell simulations** enable addressing the questions:
  - ***How does phase-space complexity change as overall parameters vary (β, δB/B0) and for diverse species?***
  - ***How does phase-space complexity change in different systems (expanding solar wind vs bounded magnetosheath)?***

- **Future questions:**
  - ***How different irreversible effects contribute to irreversible dissipation?***
  - ***Are large-scale plasma dynamics, energy budget, and transport properties influenced by phase-space complexity?***

"PhAse-sPAce cOmplexity in turbulent nearly-reversible plasmas (PAPAO)"

- Funding (Oct 2025-Oct 2028):
- **2 temporary researchers** under selection
- **3 2-year post-docs** (call in March/April 2026)
- Site: **Rome**

Ministero dell'Università e della Ricerca
FIS
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Extra: How to turn irreversible a nearly-reversible system?

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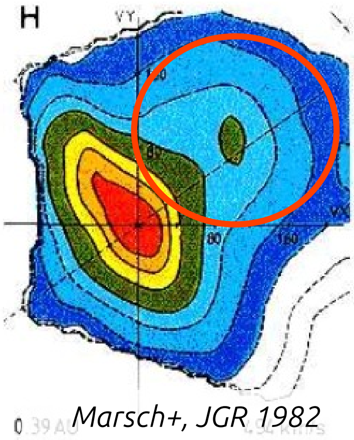
A key question in weakly-collisional (nearly-reversible) space and astrophysical plasmas concerns the **mechanisms regulating the transition to irreversible dynamics and dissipation**.



Marsch+, JGR 1982

a) **Thermal energy conversion mechanisms: not enough!**
It fails in describing phase-space complexity.

b) **Non-LTE conversion leading to non-equilibrium VDFs: not enough!**
The energy (information) stored in non-LTE features of the plasma VDF is a form of ordered energy, e.g., they can lead to secondary electromagnetic instabilities.

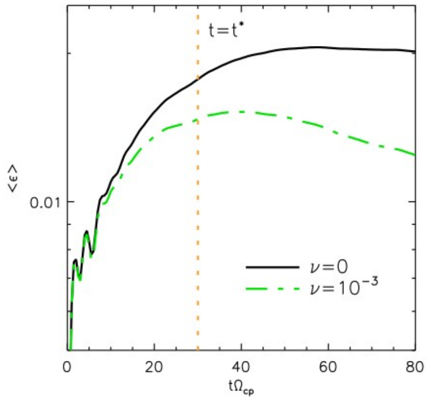
c) **Irreversible dissipation:**
   I. **Long-range inter-particle collisions** (Schekochihin PPCF 2008, Pezzi+, PRL 2016)
   II. **"Collisionless" effective collisionality** (Arzamasskiy+, PRX 2023, Bandyopadhyay+, PoP 2023, Richard,...Pezzi, PRE 2025)
   III. **Dissipative anomalies** (Eyink, PRX 2018)
   IV. **"Complex-systems-inspired" methods** (Garrido+, PRL 2004, Kanekar+, JPP 2015, Yao et al., JFM 2023, Stumpo,…, Pezzi et al., ApJL 2023)

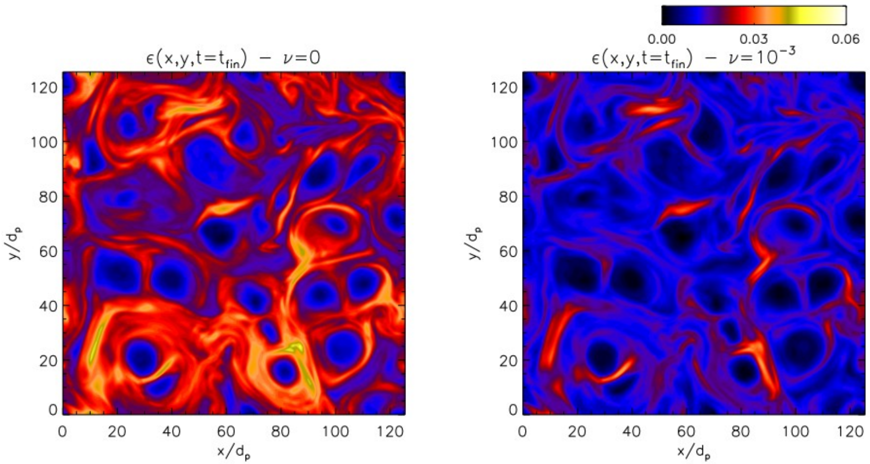
Tackling the non-equilibrium statistical mechanics and thermodynamics of turbulent nearly-reversible plasmas!

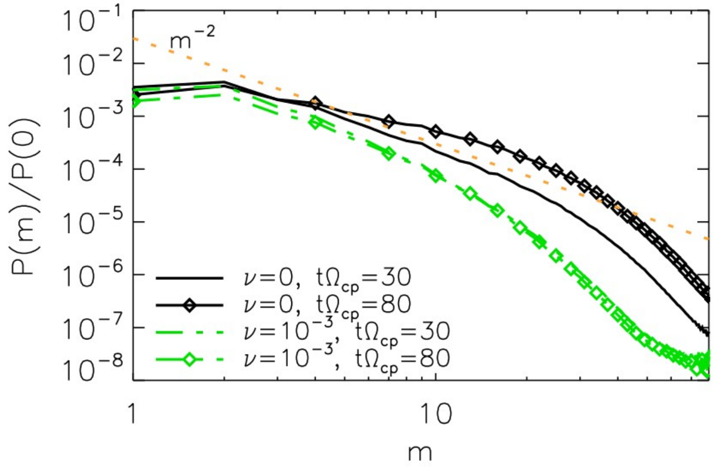
Extra: Collisional enhancement in non-LTE plasmas

We explored this scenario by means of hybrid Boltzmann-Maxwell simulations explicitly taking into account inter-particle collisions.

$$\varepsilon(x,y,t) = \frac{1}{n}\sqrt{\int \left[f(\mathbf{x},\mathbf{u},t) - f_M(\mathbf{x},\mathbf{u},t)\right]^2 d^3\mathbf{u}}$$



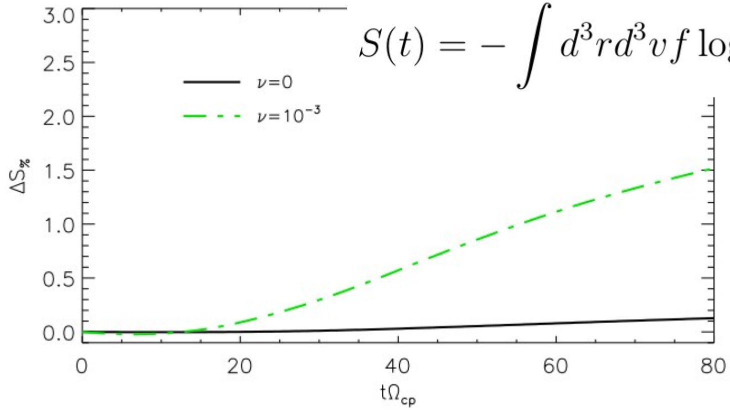




Collisions prevent the formation of non-LTE features in the plasma distribution function, dissipating faster smaller scale non-LTE features.

The development of phase-space turbulence is hence inhibited, causing an irreversible increase of Boltzmann-Gibbs entropy.

$$S(t) = -\int d^3r d^3v f \log f$$



Extra: The Hybrid Vlasov-Maxwell model

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$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{e}{m}\left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right] \cdot \nabla_v f = 0$$

$$\mathbf{E} = -\frac{\mathbf{u} \times \mathbf{B}}{c} + \frac{1}{nec}(\mathbf{j} \times \mathbf{B}) - \frac{1}{ne}\nabla P_e$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c}$$

$$n_e \simeq n_i \simeq n$$

$$P_e = P_e(n)$$

Valentini+, JCP 2007

- **Low-frequency approximation** of the Maxwell system:
  - ✓ Displacement current is neglected
  - ✓ Quasi-neutrality is assumed
- The proton Vlasov equation is solved numerically while electrons are a massless fluid: useful to describe up to **sub-proton scales**.
- **Eulerian method:**
  - The Vlasov equation is integrated in the whole phase-space: **six-dimensional (3D-3V)** grid!
  - **Noiseless** description of the plasma dynamics but **more computational demanding** with respect to Lagrangian (PIC) methods:

    … 3D-3V DF ~ 10 Terabytes
  - Massively parallelized strategy:

    i) Domain decomposition with MPI;

    ii) OpenMP and/or GPU computing on each node

Extra: ViDA: a tool for electron-scale dynamics

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Vlasov

$$\partial_t f_\alpha + \mathbf{v}\cdot\nabla f_\alpha + \frac{q_\alpha}{m_\alpha}\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\nabla_{\mathbf{v}} f_\alpha = 0, \quad \alpha = p, e$$

$$\mathbf{E} = \mathbf{E}_L + \mathbf{E}_T \qquad \nabla\times\mathbf{E}_L = 0,\ \nabla\cdot\mathbf{E}_T = 0$$

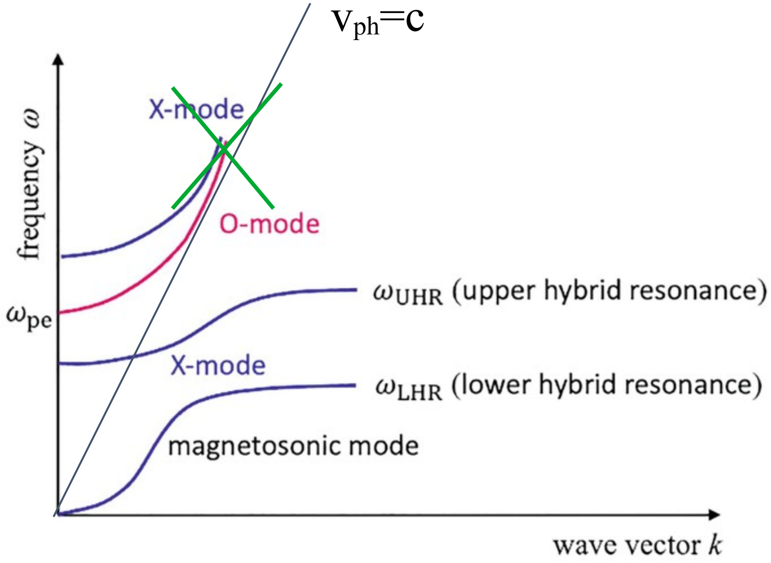
Maxwell

$$\nabla\cdot\mathbf{E}_L = 4\pi\rho_c \qquad \nabla\times\mathbf{E}_T = -\frac{1}{c}\partial_t\mathbf{B}$$

$$\nabla\times\mathbf{B} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\partial_t\mathbf{E}_L + \frac{1}{c}\partial_t\mathbf{E}_T$$

$$\rho_c = \sum q_\alpha \int f_\alpha(\mathbf{v})d\mathbf{v} \qquad \mathbf{j} = \sum q_\alpha \int f_\alpha(\mathbf{v})\mathbf{v}d\mathbf{v}$$

Darwin approximation. The transverse displacement current in the Ampere law is neglected. The propagation of light waves is inhibited, while all other modes are properly retained! *Pezzi et al., JPP 2019*

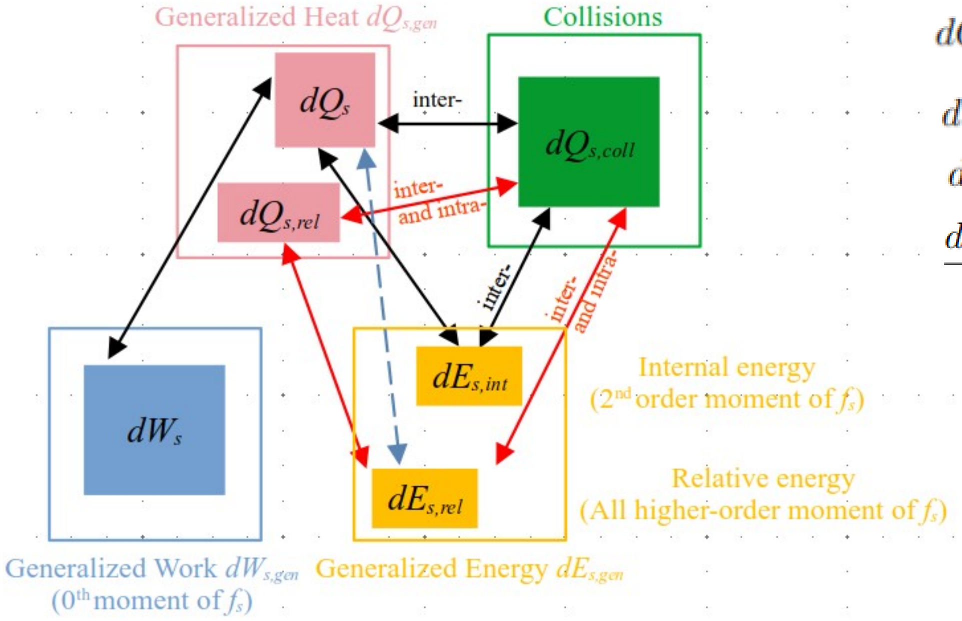


- Massively-parallelized (**CPUs and GPUs**) Eulerian fully-kinetic code
- The **3D-3V** plasma DF f(**r**,**v**) is directly discretized on grid
- **Pro:** Detailed and clean description up to small scales and in velocity space
- **Cons**: computationally demanding and generally small box wrt PIC

ViDA simulations can be a powerful tool to complement PIC methods!

The first law of kinetic theory highlights energy conversion to non-thermal (>2) moments of the plasma VDFs. Channels highlighted with the red arrows "emerge" in non-LTE plasmas.

$$\frac{dW_s}{dt} + \frac{dE_{s,gen}}{dt} = \frac{dQ_{s,gen}}{dt} + \dot{Q}_{s,coll}$$



Cassak+, PRL 2023

$$dW_s = P_s d(1/n_s)$$

$$dE_{s,gen} = dE_{s,int} + dE_{s,rel},$$

$$dQ_{s,gen} = dQ_s + dQ_{s,rel}$$

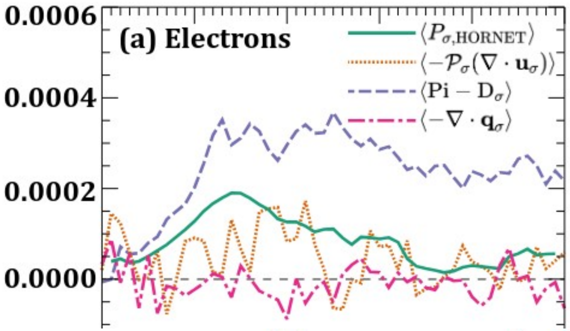
$$dE_{s,int} = 3/2 k_B \, dT_s$$

$$dE_{s,rel} = T_s \, d\left(s_{s,rel}/n_s\right)$$

$$\frac{dQ_{s,rel}}{dt} = \frac{k_B T_s}{n_s}\int [\nabla\cdot((\mathbf{v}-\mathbf{u}_s)f_s)]\ln\left(\frac{f_s}{f_{s,M}}\right)d^3v$$

Relative entropy density

$$s_{s,\mathrm{rel}} = -k_{\mathrm{B}}\int d^3v f_s \ln\left(\frac{f_s}{f_{M,s}}\right)$$



$$P_{s,\mathrm{HORNET}} = -n_s\frac{dE_{s,rel}}{dt} = -n_s T_s \frac{d}{dt}\left(\frac{s_{s,rel}}{n_s}\right)$$

Barbhuiya+, PRE 2025

Extra: Dissipation diagnostics

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Several diagnostics have been implemented to identify kinetic-scale energy conversion and dissipation in weakly-collisional plasmas. We categorize them in: ***energy-based*** and ***VDF-based*** parameters

OP+, MNRAS 2021

Energy-based diagnostics: energy transfers between bulk, thermal and magnetic energy

$$\frac{\partial \mathcal{E}_\alpha^f}{\partial t} + \nabla \cdot \left(\boldsymbol{u}_\alpha \mathcal{E}_\alpha^f + \boldsymbol{u}_\alpha \cdot \boldsymbol{P}_\alpha \right) = (\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha + n_\alpha q_\alpha \boldsymbol{u}_\alpha \cdot \boldsymbol{E}$$

$$\frac{\partial \mathcal{E}_\alpha^{th}}{\partial t} + \nabla \cdot \left(\boldsymbol{u}_\alpha \mathcal{E}_\alpha^{th} + \boldsymbol{h}_\alpha \right) = -(\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha$$

$$\frac{\partial \mathcal{E}^m}{\partial t} + \frac{c}{4\pi} \nabla \cdot (\boldsymbol{E} \times \boldsymbol{B}) = -\boldsymbol{j} \cdot \boldsymbol{E}$$

Work done by EM field
(Zenitani+, PRL 2011; Wan+, PRL 2015)

$$D_\alpha = \boldsymbol{j}' \cdot \boldsymbol{E}' = \boldsymbol{j} \cdot \left(\boldsymbol{E} + \frac{\boldsymbol{u}_\alpha}{c} \times \boldsymbol{B} \right) - \rho_c \left(\boldsymbol{u}_\alpha \cdot \boldsymbol{E} \right)$$

Local Energy Transfer (LET) rate
(Sorriso-Valvo,...,OP,+, JPP 2018, PRL 2019)

$$\epsilon_{p,\ell} = \left(|\Delta \boldsymbol{u}_p|^2 + |\Delta \boldsymbol{b}|^2 \right) \frac{\Delta u_{p,\ell}}{\ell} - 2(\Delta \boldsymbol{u}_p \cdot \Delta \boldsymbol{b}) \frac{\Delta b_\ell}{\ell} - \frac{d_p}{2} |\Delta \boldsymbol{b}|^2 \frac{\Delta j_\ell}{\ell} + d_p (\Delta \boldsymbol{b} \cdot \Delta \boldsymbol{j}) \frac{\Delta b_\ell}{\ell}$$

Pressure-strain interaction (Pi-D and P-θ)
(Yang+, PRE 2017, POP 2018, MNRAS 2020; OP+, POP 2019)

$$-(\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha = -P_\alpha \theta_\alpha - \boldsymbol{\Pi}_\alpha : \mathcal{D}_\alpha$$

Extra: Dissipation diagnostics

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Several diagnostics have been implemented to identify kinetic-scale energy conversion and dissipation in weakly-collisional plasmas. We categorize them in: ***energy-based*** and ***VDF-based*** parameters

OP+, MNRAS 2021

VDF-based diagnostics: non-equilibrium features in the particle VDF

Pressure agyrotropy
(Scudder+, POP 2008; Aunai+, POP 2013; Swisdak+, GRL, 2016)

$$Q_\alpha = \frac{P^2_{\alpha,12} + P^2_{\alpha,13} + P^2_{\alpha,23}}{P^2_{\alpha,\perp} + 2P_{\alpha,\perp}P_{\alpha,\parallel}}. \quad \boldsymbol{P}_\alpha = \begin{pmatrix} P_{\alpha,\perp} & P_{\alpha,12} & P_{\alpha,13} \\ P_{\alpha,12} & P_{\alpha,\perp} & P_{\alpha,23} \\ P_{\alpha,13} & P_{\alpha,23} & P_{\alpha,\parallel} \end{pmatrix}$$

Non-Maxwellianity parameter ξ
(Greco+, PRE, 2012; ***OP****+, JPP 2017, POP 2018)*

$$\xi_\alpha(\boldsymbol{r},t) = \frac{v^{3/2}_{th,\alpha}(\boldsymbol{r},t)}{n_\alpha(\boldsymbol{r},t)} \sqrt{\int d^3v \, [f_\alpha(\boldsymbol{r},\boldsymbol{v},t) - g_\alpha(\boldsymbol{r},\boldsymbol{v},t)]^2} \, .$$

g is the Maxwellian associated with the local VDF f

Entropy density-based parameters
(Kaufmann+, JGR 2009; Liang,…,**OP**+, JPP 2020)

$$\bar{M}_{\mathrm{KP},\alpha}(\boldsymbol{r},t) = \frac{s_{\mathrm{M},\alpha}(\boldsymbol{r},t) - s_\alpha(\boldsymbol{r},t)}{(3/2)k_B n_\alpha(\boldsymbol{r},t)}$$

$$\bar{M}_\alpha(\boldsymbol{r},t) = \frac{\bar{M}_{\mathrm{KP},\alpha}(\boldsymbol{r},t)}{1 + \log\left(\frac{2\pi k_B T_\alpha}{m_\alpha(\Delta^3 v)^{2/3}}\right)}$$

$$s_\alpha(\boldsymbol{r},t) = -k_B \int d^3v \, f_\alpha(\boldsymbol{r},\boldsymbol{v},t) \log f_\alpha(\boldsymbol{r},\boldsymbol{v},t) \qquad s_{\mathrm{M},\alpha} = \frac{3}{2} k_B n_\alpha \left[1 + \log \frac{2\pi k_B T_\alpha}{m_\alpha n_\alpha^{2/3}}\right]$$