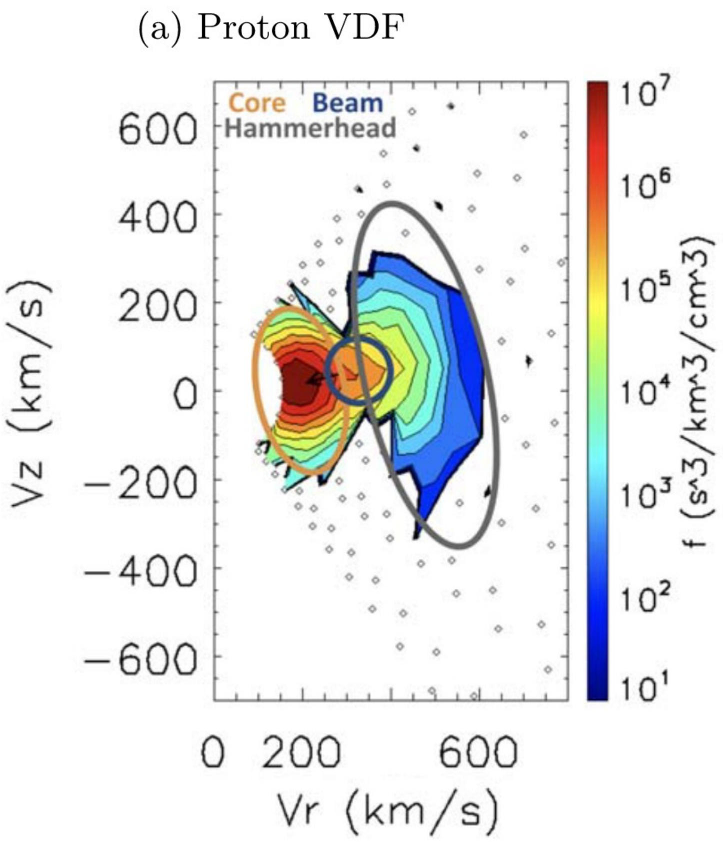
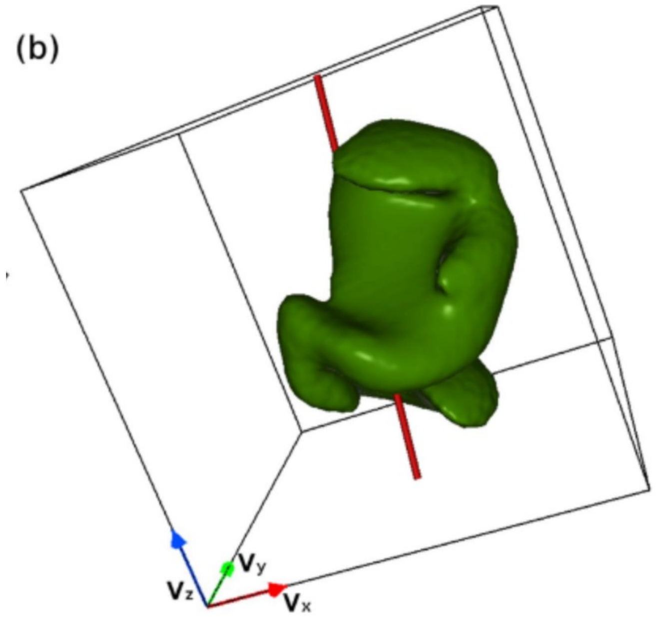
Velocity space cascade

Collisionless Plasmas Are Out of Equilibrium

- Astrophysical plasmas are rarely in local thermal equilibrium. This allows for “fancy” velocity distribution functions (VDFs) shapes
- How energy gets dissipated in weakly collisional plasma is still debated
- Different energy/dissipation proxies in the literature but no definitive consensus (Pezzi+, MNRAS 2021)
- A recent paradigm: **phase space (or velocity space) cascade**



Verniero+2022



Valentini, NJP + 2016.

A route to dissipation: Velocity Space Cascade

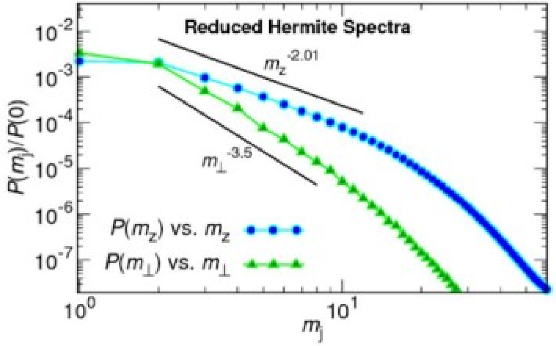
- The generation of velocity space fluctuations at smaller and smaller velocity scales is envisioned as a cascade process
- An effective tool to investigate velocity-space cascades is the Hermite decomposition of the particle VDF. The associated “energy,” distributed across Hermite modes—i.e., velocity-space perturbations relative to a Maxwellian—cascades from low to high m.

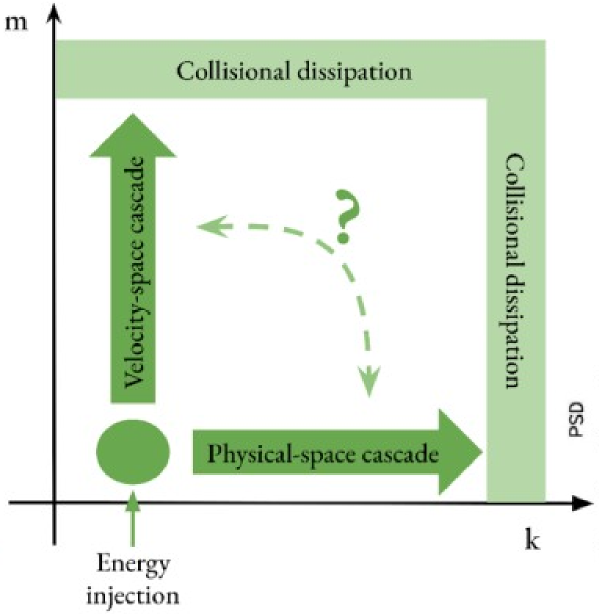
$$f(\boldsymbol{v}) = \sum_{\boldsymbol{m}} f_{\boldsymbol{m}} \psi_{\boldsymbol{m}}(\boldsymbol{v})$$

$$f_{\boldsymbol{m}} = \int_{-\infty}^{\infty} f(\boldsymbol{v}) \psi_{\boldsymbol{m}}(\boldsymbol{v}) d^3 v$$

$$\psi_m(v) = \frac{H_m\left(\frac{v-u}{v_{\rm th}}\right)}{\sqrt{2^m m! \sqrt{\pi} v_{\rm th}}} e^{-(v-u)^2/2v_{\rm th}^2}$$

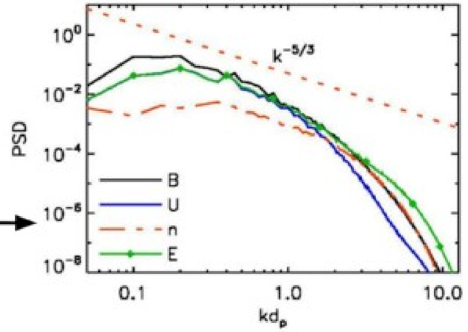
Velocity space





Credits: Oreste Pezzi, central figure adapted from Plunk&Parker 2014 EPJD

Real space



Literature

- **Theory**: Schekochihin+2008, 2016, T. Tatsuno et al. 2009
- **Solar wind**: Wu+2023 (Solar orbiter), Larosa+2025 (Parker Solar Probe)
- **Magnetospheric plasmas**: S. Servidio, PRL 2017, T. Vo+(A. Larosa) submitted)
- **Numerical works** : S. Cerri + 2018, O. Pezzi + 2018, 2019, S. Cerri + 2021, G. Celebre+ 2023

Velocity Space Cascade: Vlasov-Maxwell numerical simulations

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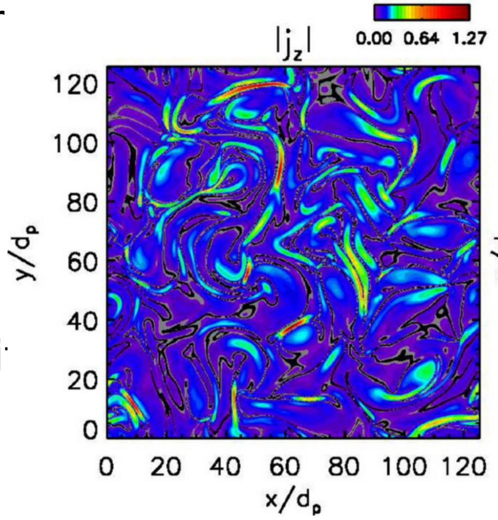
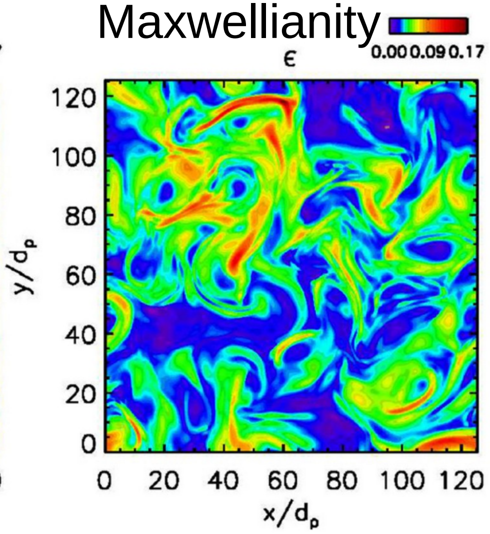
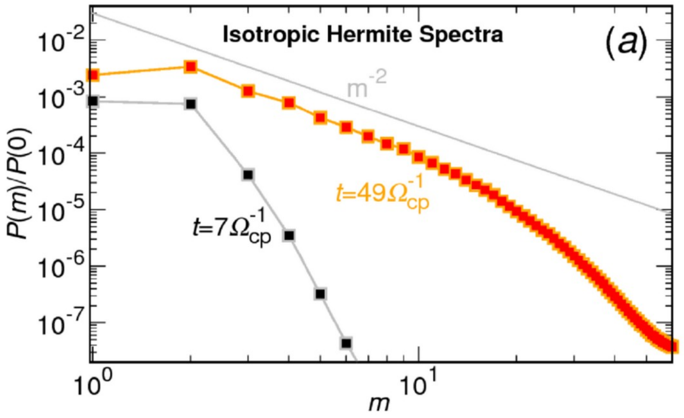
Current density



Deviations from Maxwellianity



Hermite spectrum evolution in time



Pezzi+, PoP 2018

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Velocity Space Cascade: In Situ Measurements

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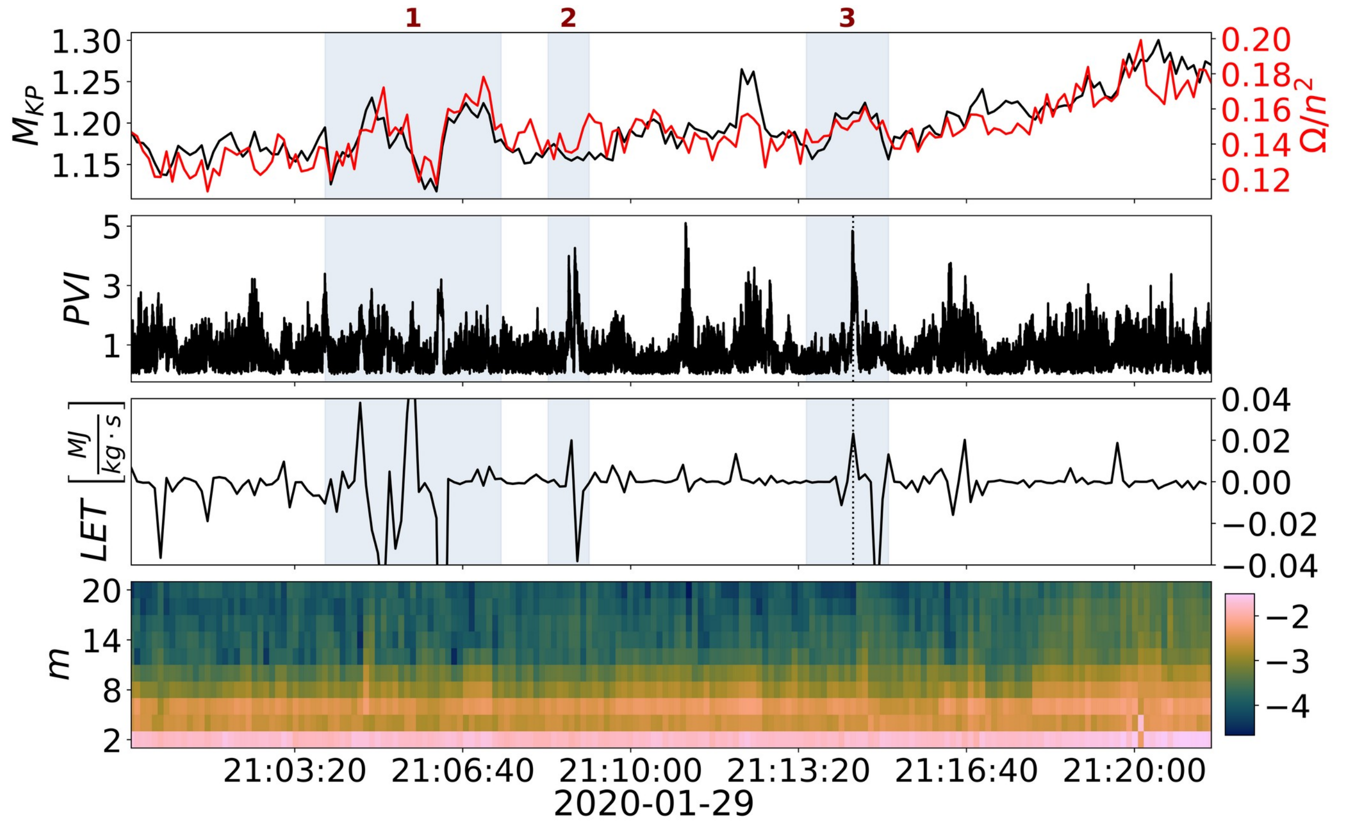

Larosa+2025 ApJL

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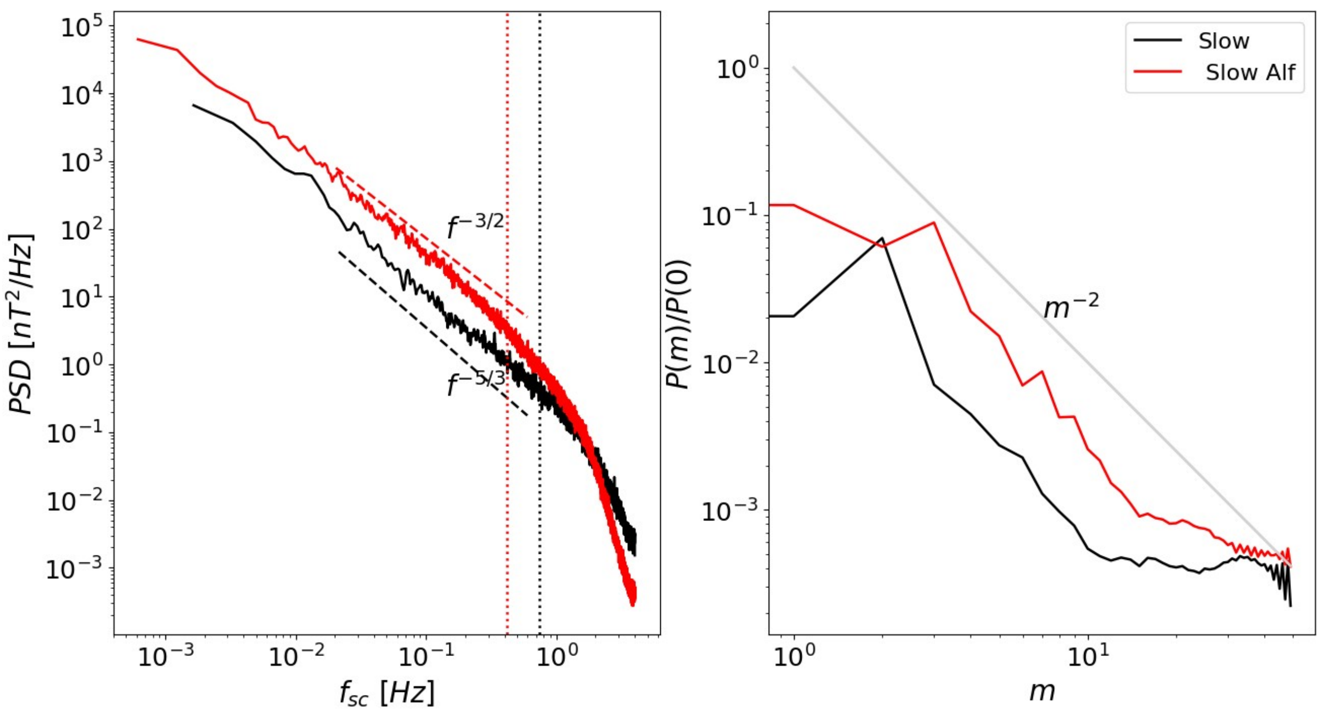
Magnetic field PSD — Hermite transform of the VDFs



Larosa+In Prep

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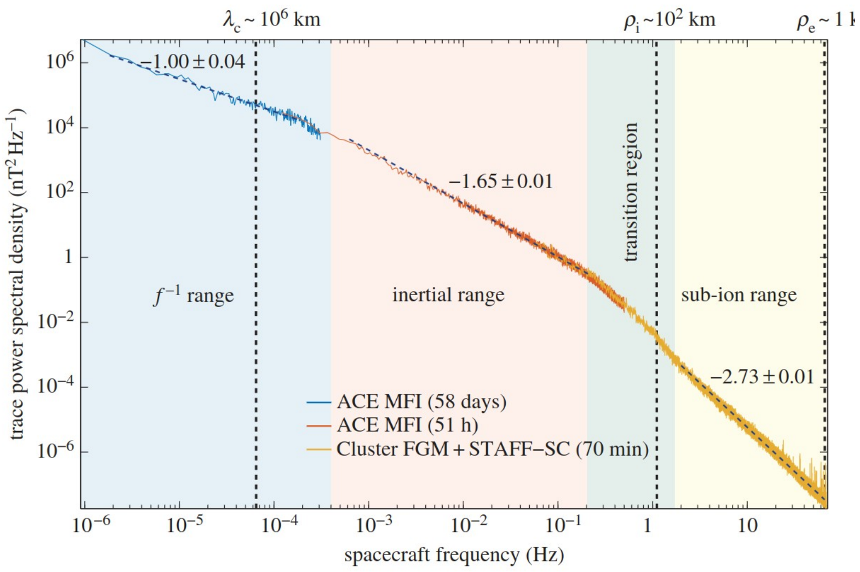
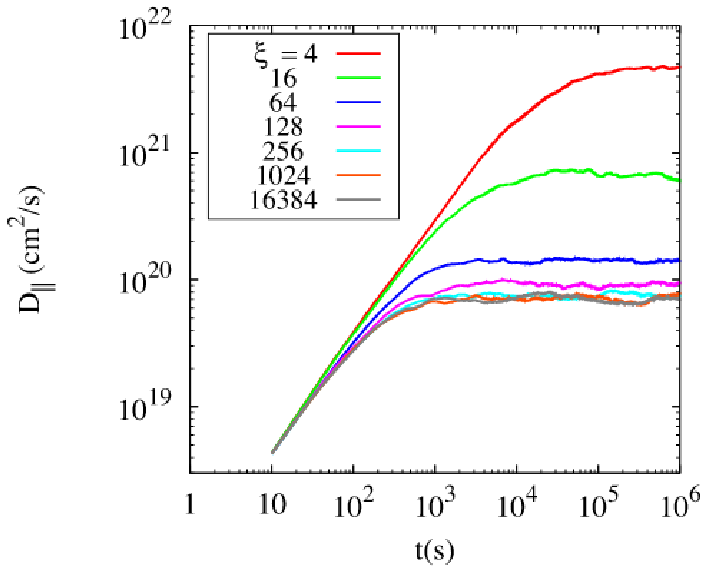
Synthetic turbulence

Synthetic turbulence: Overview

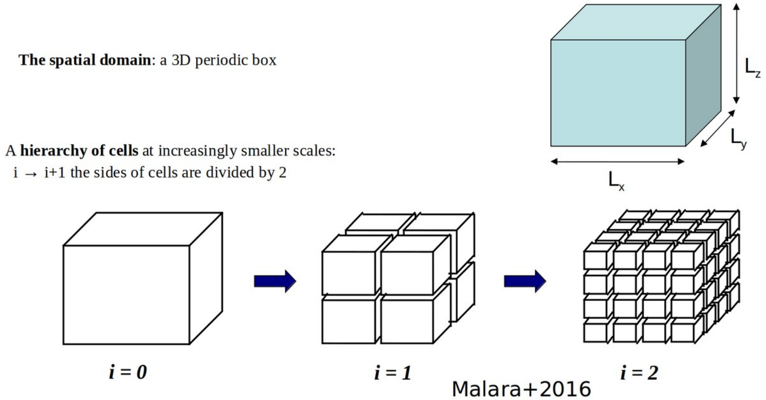
- The solar wind magnetic field inertial range extend for many decades. This is very hard to achieve with direct numeric simulations.
- A limited extension of the inertial range implies an overestimation of the parallel diffusion coefficients.
- The picture is complicated by the evolution of turbulence with distance from the Sun.



Kiyani+2015



Pucci+2016, MNRAS



Malara+2016

Literature

- **Homogeneous Turbulence**: Cametti+1998, Malara+2016, Durrive+2022
- **Heliospheric Turbulence**: Giacalone+2001, Ruffolo+2013, Fraschetti+2018, Laitinen+2023, **Larosa+in prep**
- **Different background geometries** : Maci+2024

Synthetic turbulence: Heliospheric magnetic field

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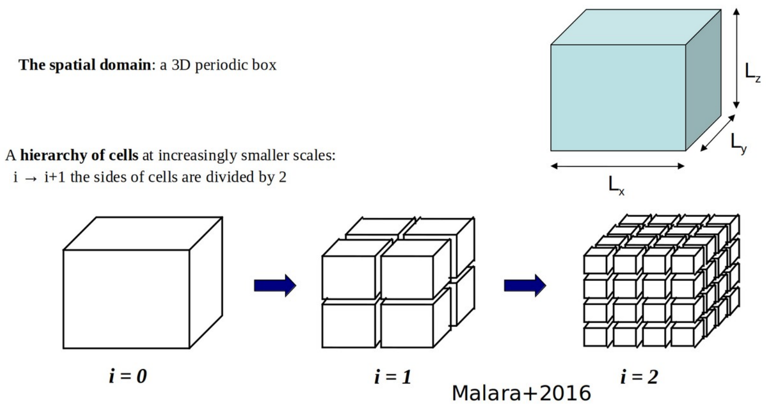
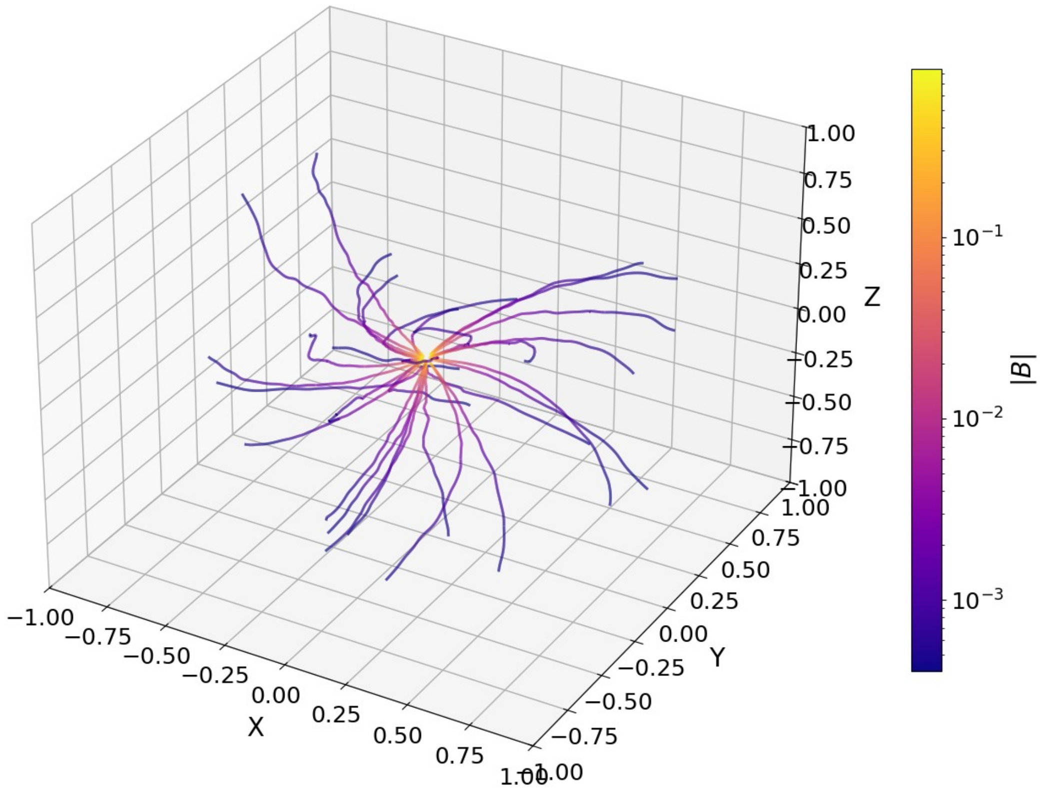


Malara+2016



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Synthetic turbulence: Radial scaling of the fluctuations

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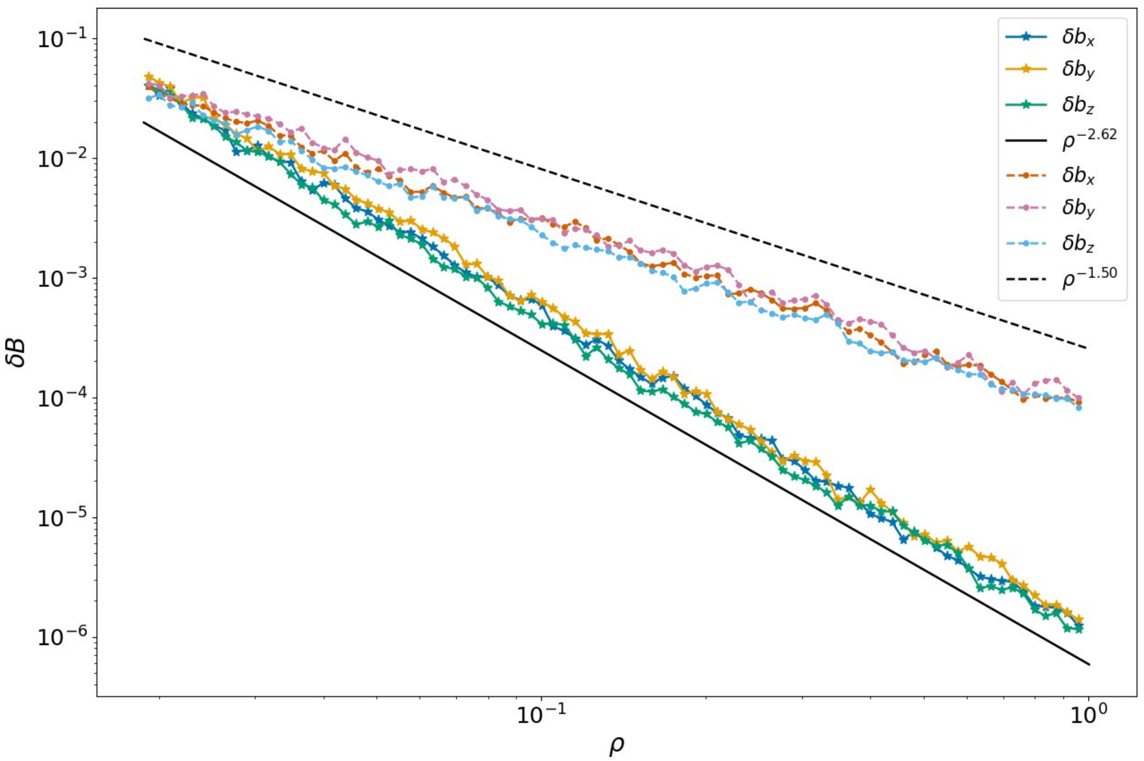

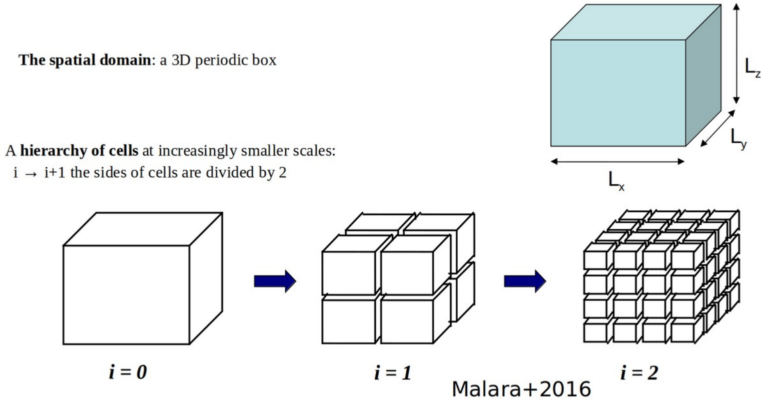

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Synthetic turbulence: Correlation length evolution

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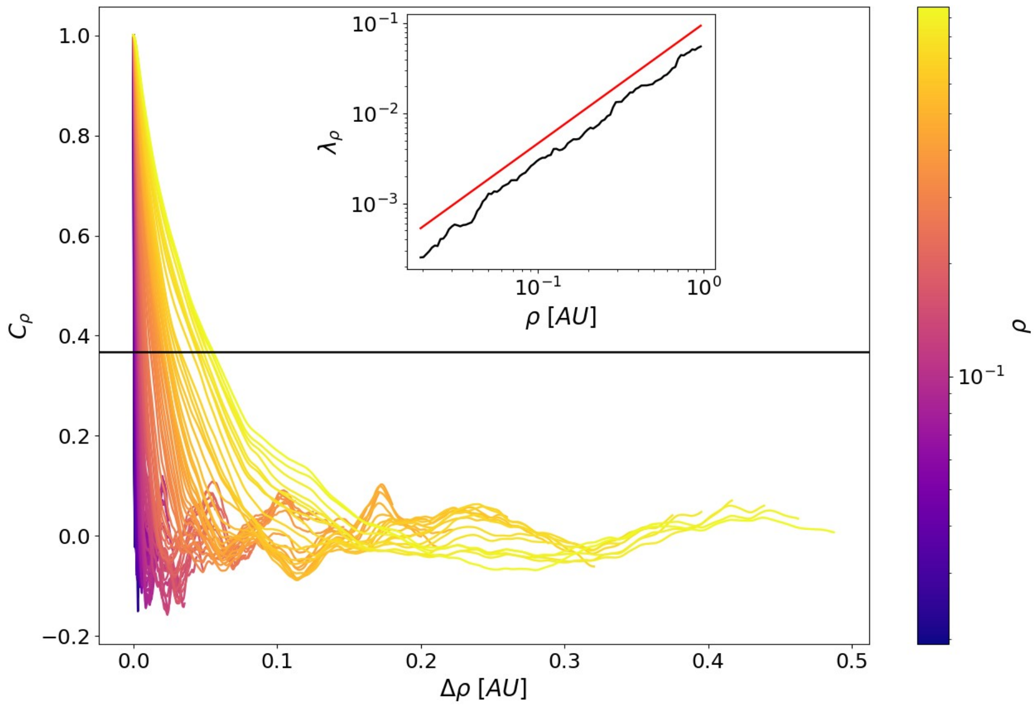

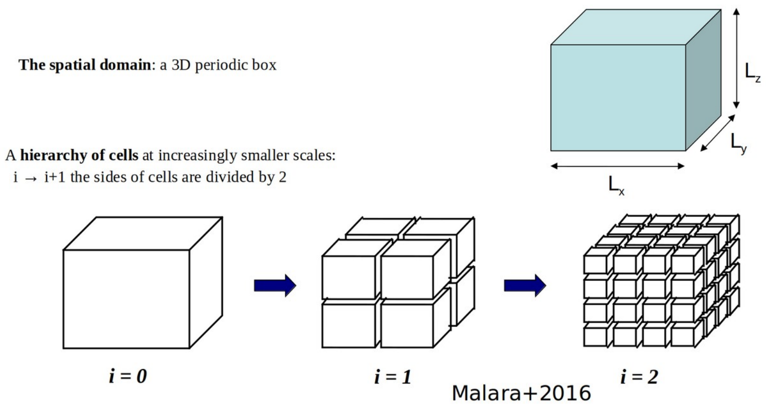

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Synthetic turbulence: Intermittency

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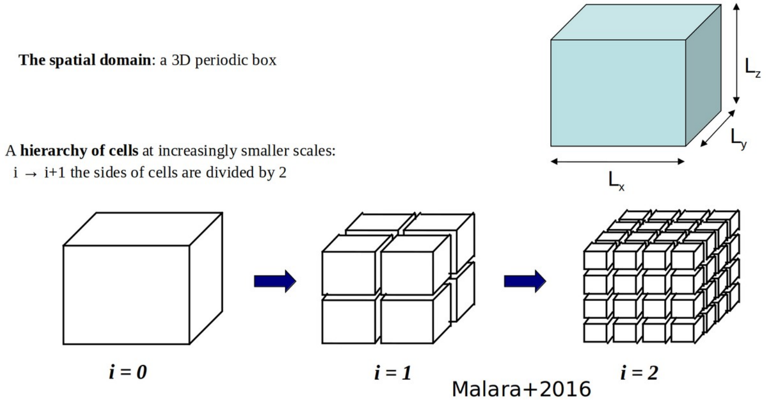
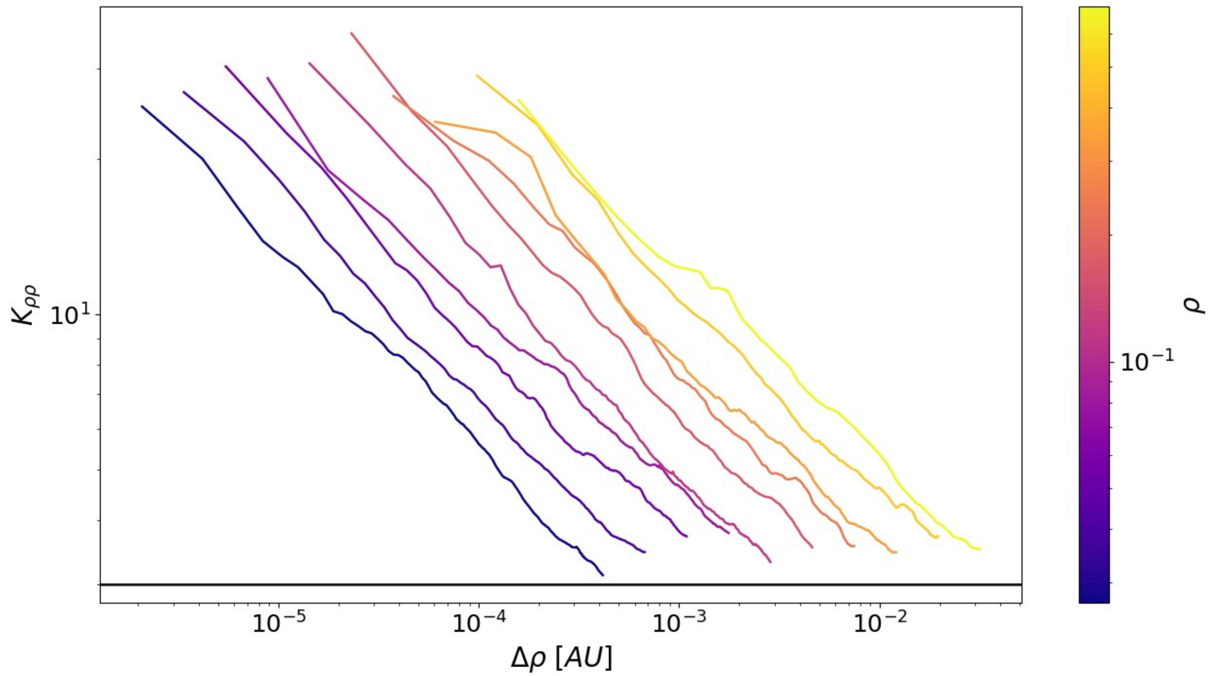


Malara+2016



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Synergies

- Phase space cascade in fusion plasmas? Currently looking at the Velocity distribution functions from Giacomin+, Plasma Phys. Control. Fusion(2024)

- Can the synthetic turbulence model be used to model turbulence in astrophysical environment to study test particle propagation?

- Mode conversion in laboratory plasmas. Can we study the generation of radio burst we commonly observe in the Heliosphere in “the box”?