



THE NATURE OF TURBULENCE IN SPACE PLASMAS

*Leveraging Multi-point, Multi-scale Observations to
Uncover the Nature of Turbulence in Space Plasmas*

Kristopher Klein, University of Arizona

EGU 2021

On behalf of the HelioSwarm MIDEX Mission Proposal Team



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New Hampshire



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THE NATURE OF TURBULENCE IN SPACE PLASMAS

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Roadmap for Talk

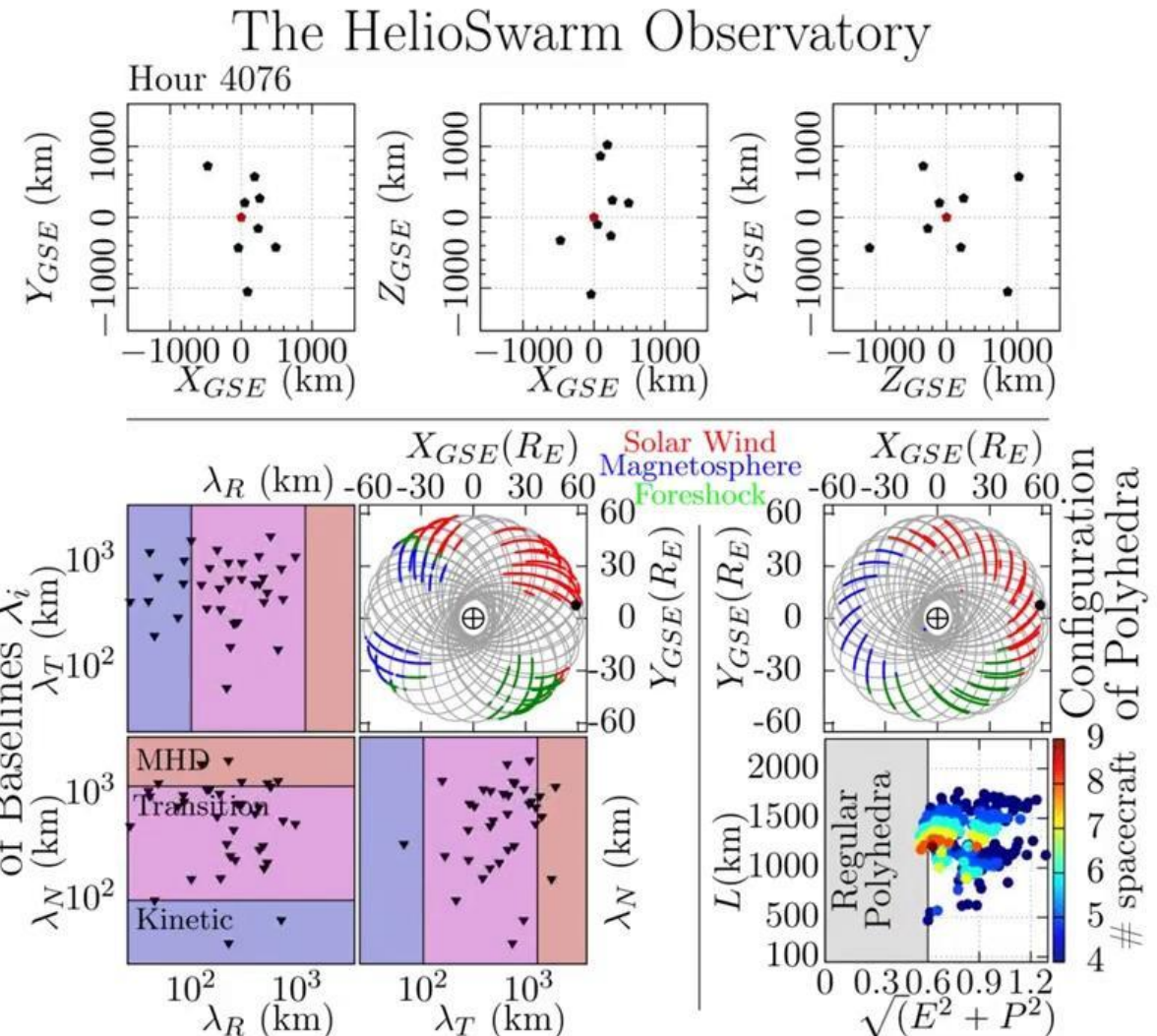


Scientific motivations – What is turbulence and Why is it important?

Outstanding science questions – What do we know about turbulence and what do we not know about it?

HelioSwarm mission goals and objectives- How will a multi-spacecraft mission advance our understanding of the outstanding questions?

HelioSwarm mission implementation- How do we go from concept to launched mission?



What is Turbulence?



Turbulence is Multiscale Disorder

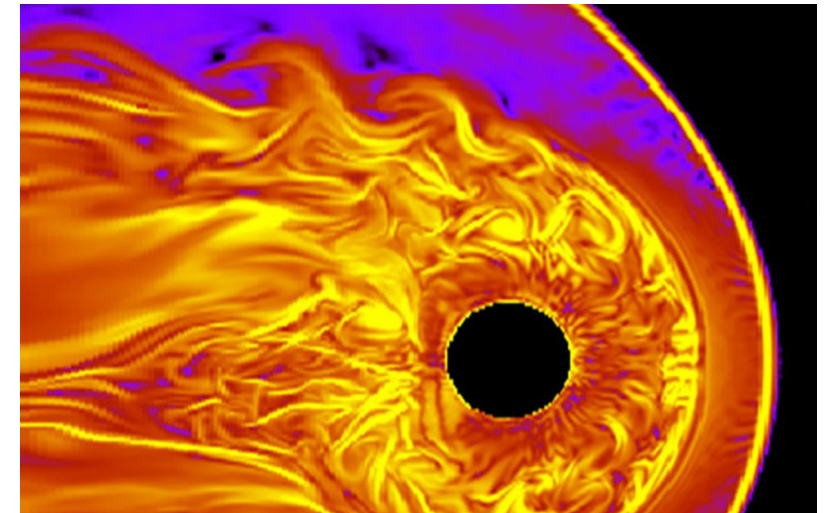
- Turbulent flow is one in which a gas, fluid, or plasma undergoes irregular fluctuations and mixing
- Turbulent flows are multiscale; energy injected at largest size scale cascades to smaller scales, eventually converting the kinetic energy in the flow into thermal energy of the constituent medium
- Turbulence is considered by many to be the last unsolved mystery of classical physics

Turbulence plays a fundamental role driving the transport of mass, momentum, and energy in a wide variety of kinds of plasmas

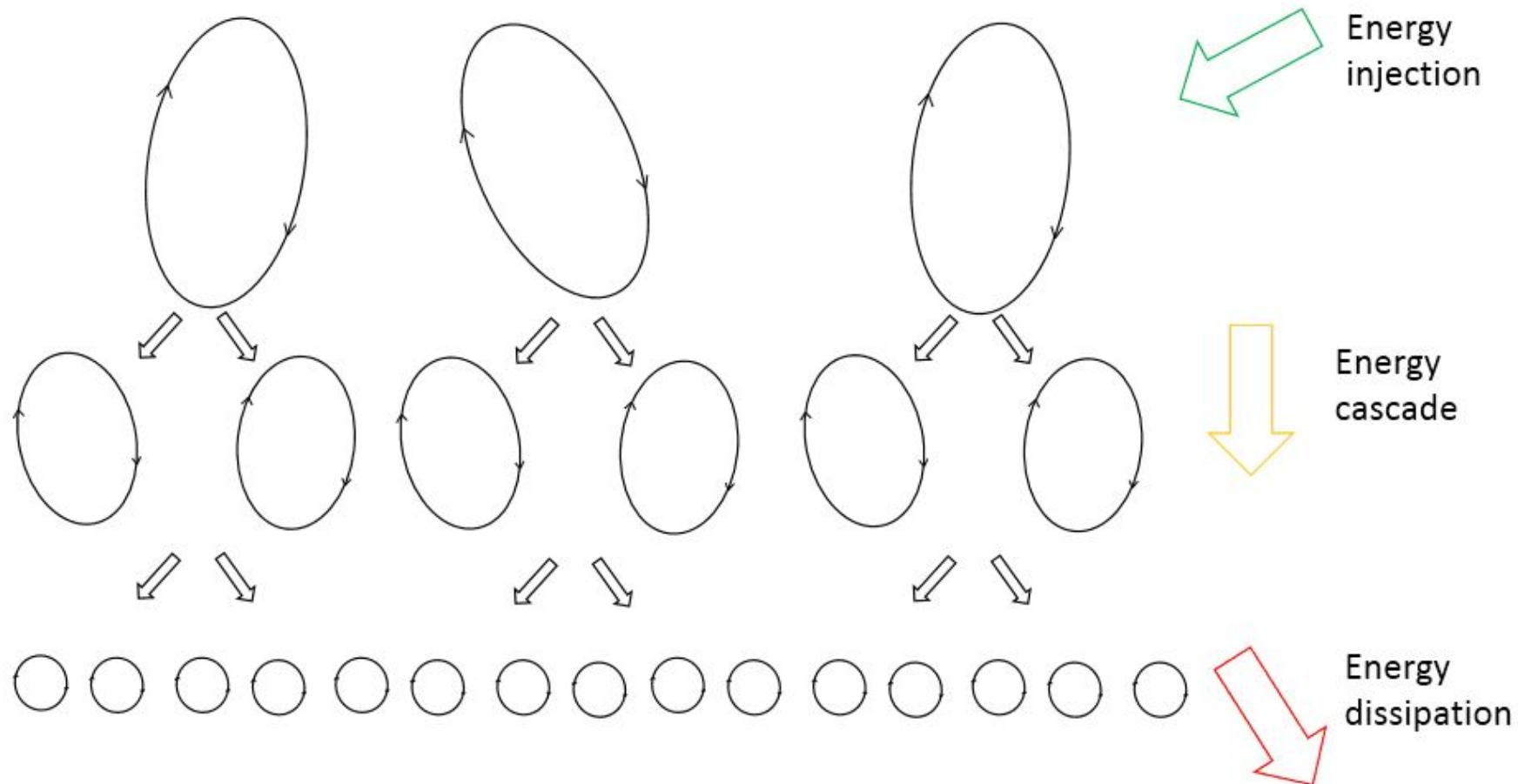


Katsushika Hokusai,
Thirty-six views of Mt. Fuji.

OpenGGCM MHD simulation of Earth's
magnetosphere, S. Kavosi, J. Raeder



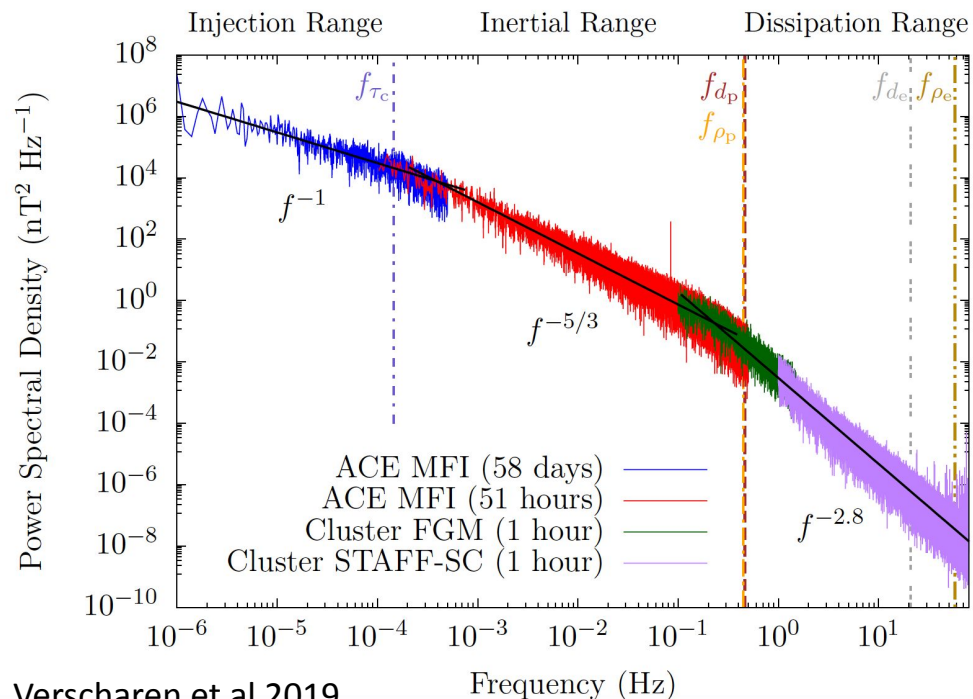
Injection, Cascade, Dissipation



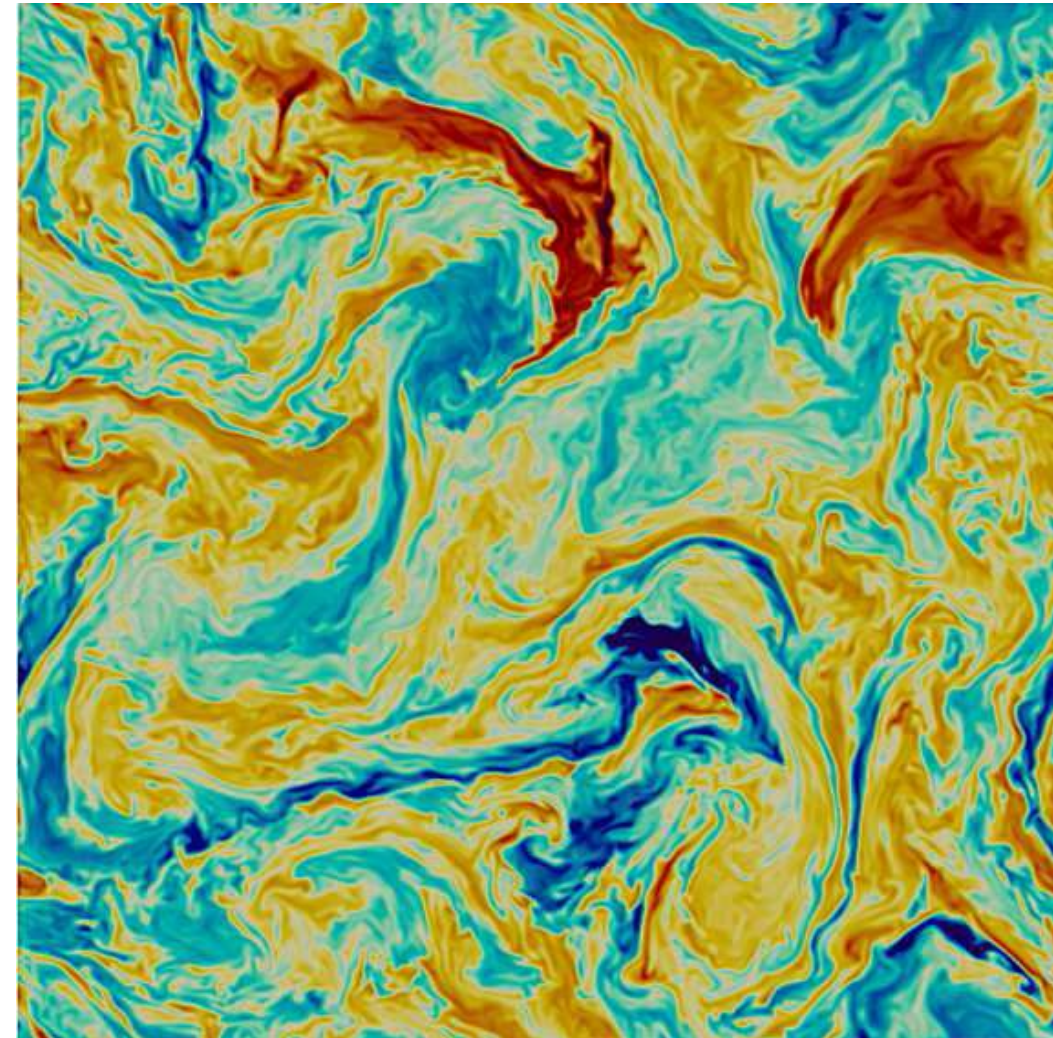
Turbulence sets the background state that influences the dynamics of shocks, reconnection, heating, and particle acceleration in plasmas throughout the Universe.

A More Detailed Picture

- Nonlinear couplings produce ranges with power-law scalings
- Intermittent Structures are also naturally formed and are associated with enhanced dissipation



Verscharen et al 2019



Meyrand et al 2019

Turbulence Plays a Fundamental Role in Universal Plasmas



Turbulence plays a key role in regulating the thermodynamics of many environments:

- Enables angular momentum transport in accretion disks (e.g. Balbus & Hawley 1998)
- Creates Galactic magnetic field amplification (e.g. Kulsrud & Zweibel 2008)
- Limits thermal conduction in galaxy clusters (e.g. Kunz et al 2011)
- Determines the dispersal and mixing of elements in the ISM (e.g. Scalo & Elmegreen 2004)
- Establishes high temperatures in galaxy cluster (e.g. Zhuravleva et al 2018)
- Regulates the heat flux in the intracluster medium (e.g. Roberg-Clark et al 2016)
- Plays a key role in star formation (e.g. McKee & Ostriker 2007)
- Drives Stellar and Solar Wind Acceleration (e.g. Cranmer et al 2015)
- Governs heating and dissipation in the Solar Wind (e.g. Bruno & Carbone 2013)

Turbulence theories can be tested in near-earth space:

'Local' measurements of heliospheric plasma provide in-situ observations of this universal process.

Open Questions

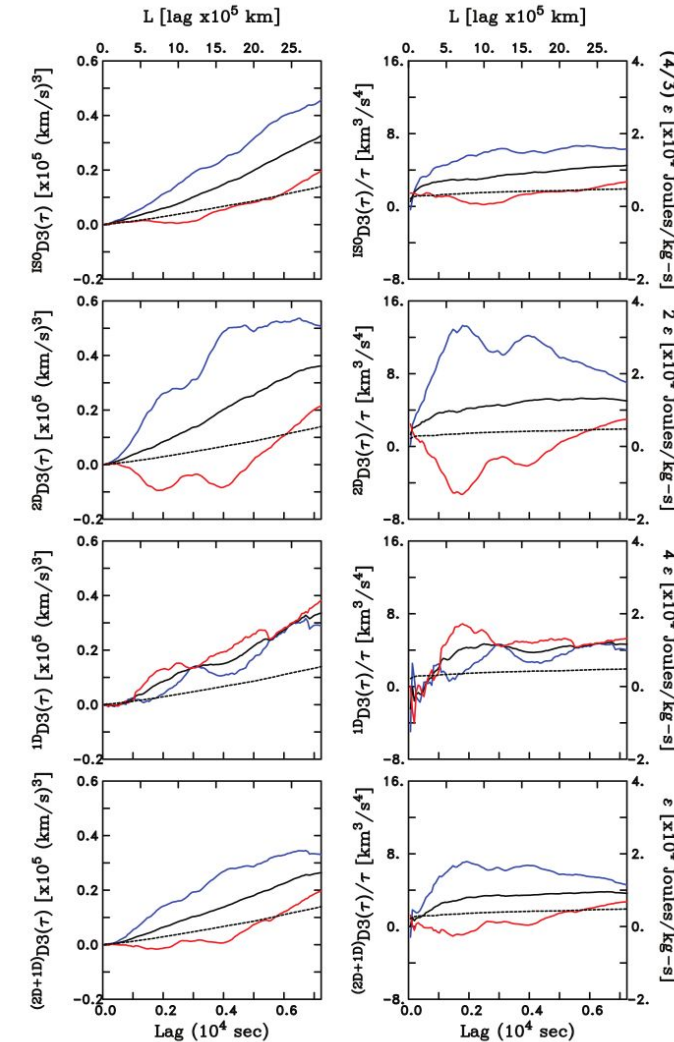


What is the Turbulence Cascade Rate?

What is the Energy Distribution in Space and Time?

What is the Nature of Intermittency?

What Dynamics Drive the
Spectral Distribution of Turbulent Energy?



See white papers by

TenBarge et al (arxiv.org/abs/1903.06890) and **Matthaeus et al** (arxiv.org/abs/1903.06890)

for more in depth discussion for how multipoint, multiscale measurements will improve our understanding of these questions

MacBride et al 2008

Open Questions

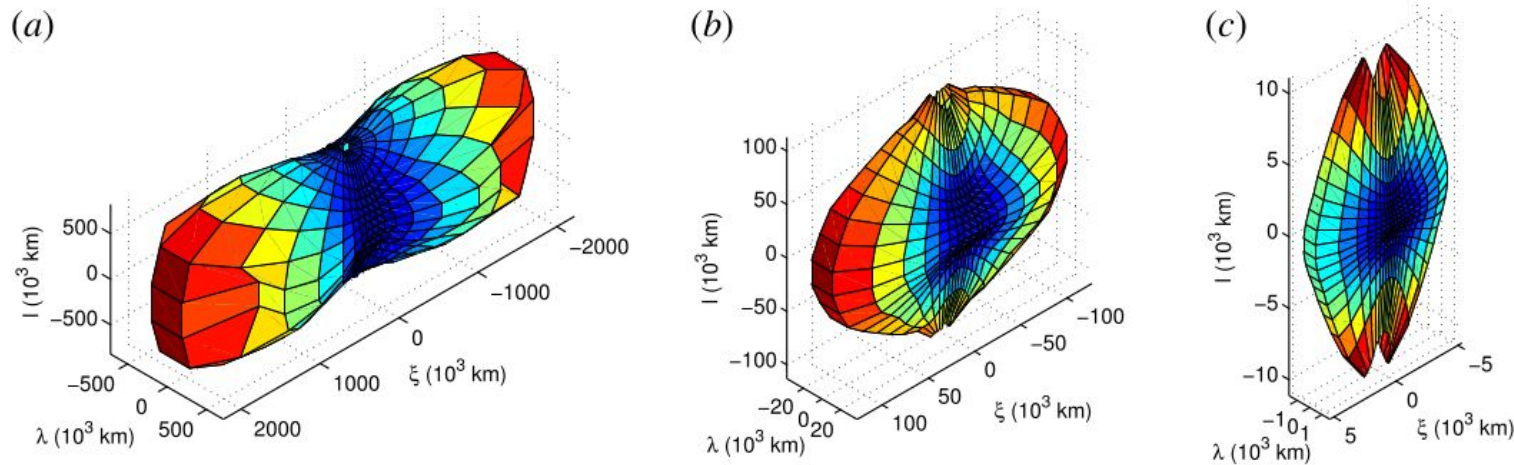


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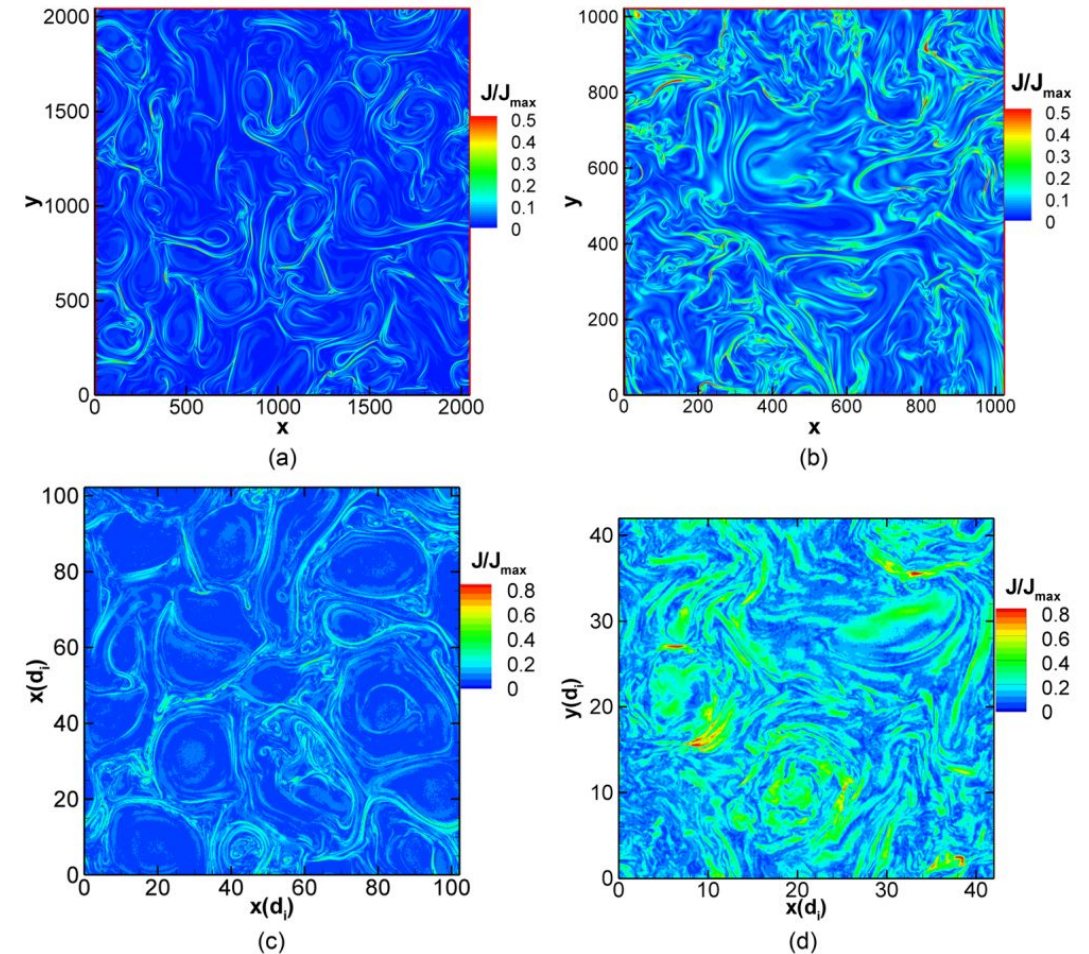
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Chen et al 2012

Open Questions



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Wan et al 2016

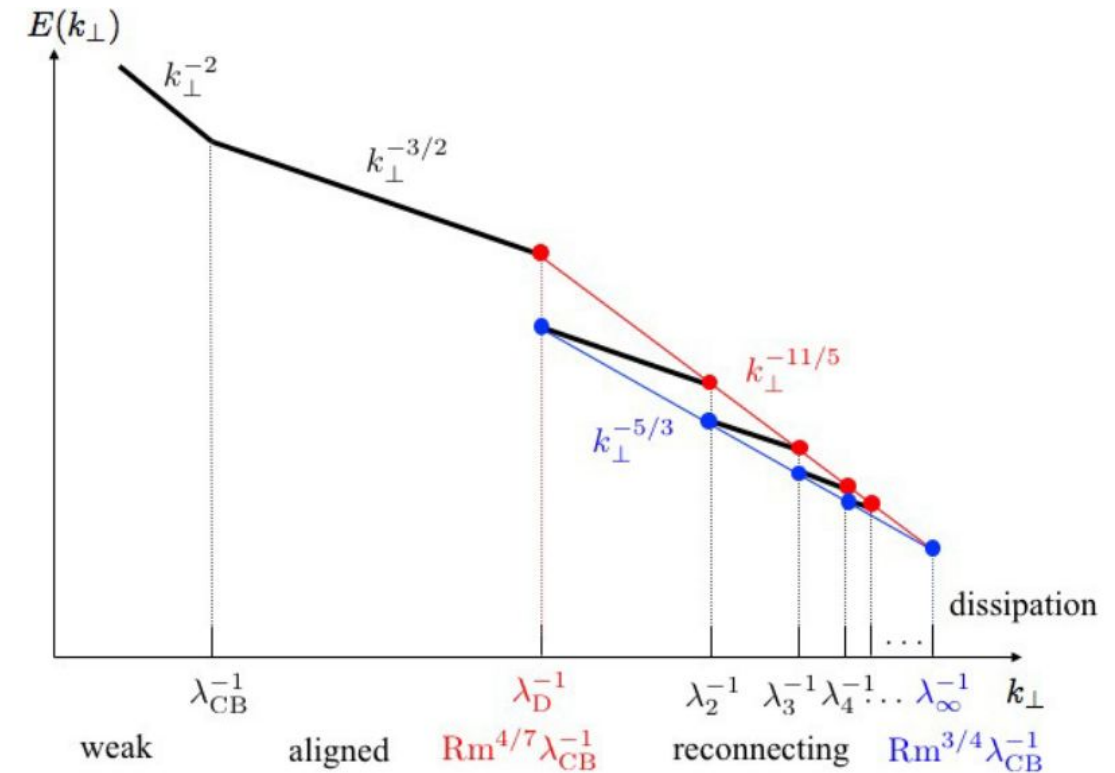
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Open Questions



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Schekochihin 2020 (After Mallet et al 2017)

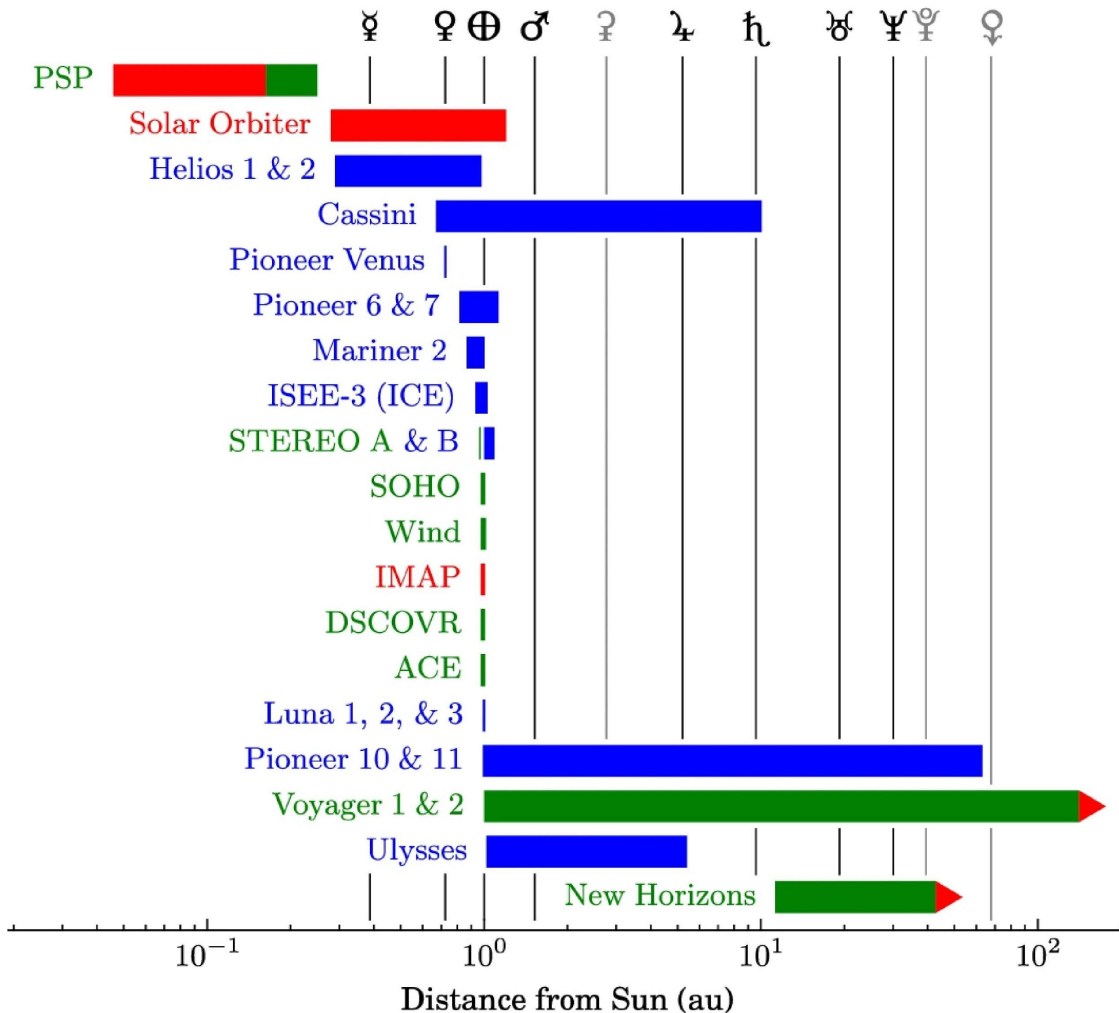
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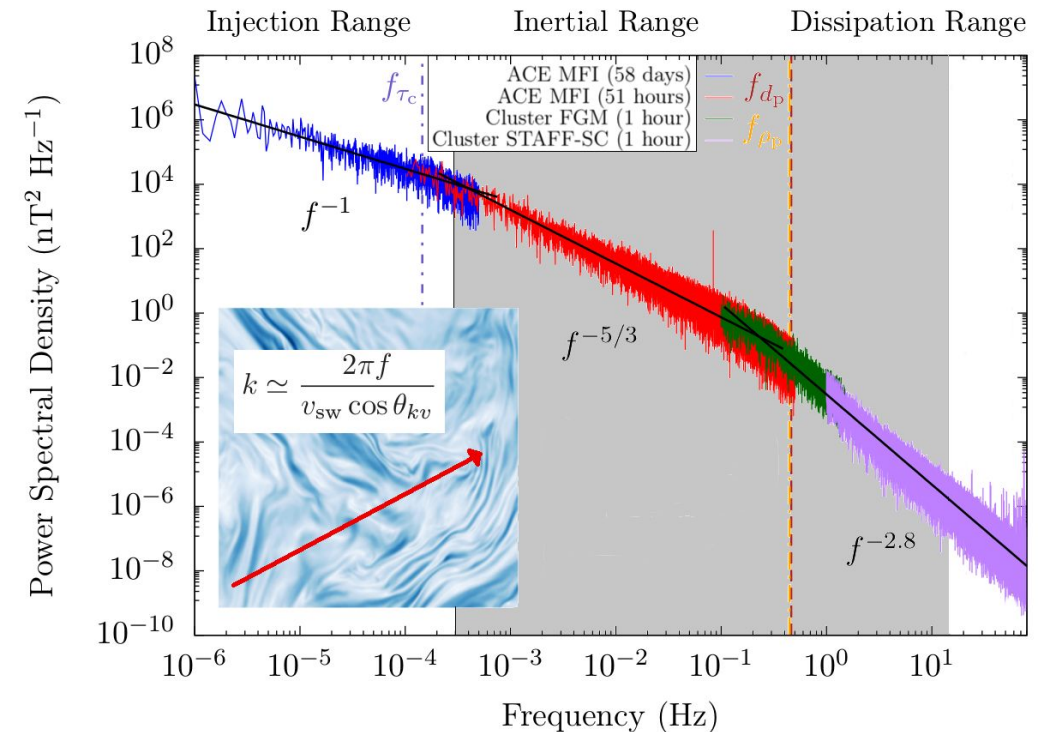
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The Solar Wind as a Natural Laboratory for Studying Plasmas



Verscharen et al 2019 LRSP

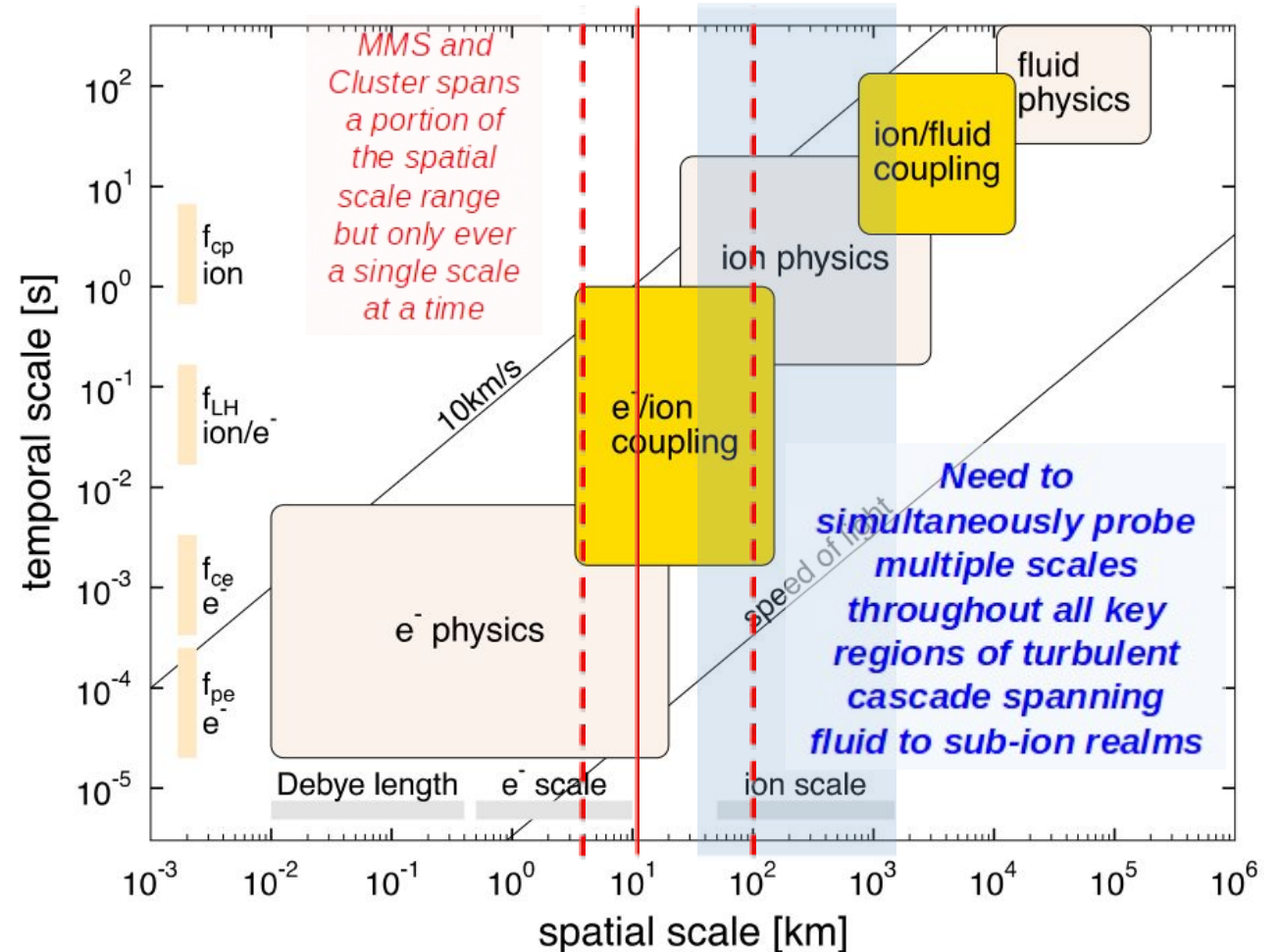
Our understanding of such systems is limited to single point (ACE, Wind) or single scale (Cluster, MMS) observations, requiring assumptions to map between temporal and spatial structures.



Multipoint, Single Scale Studies- isn't this already solved?



- Multi-spacecraft missions revolutionized an approach by measuring quantities over finite volumes rather than at a point, however 4-spacecraft missions (MMS, Cluster) probe only a single scale size at a time
- MMS optimized for probing single scales from ~ 5 to ~ 100 km, exploring only single points at a time within a limited portion of the turbulent regime; excellent for electron microphysics of reconnection and final endpoint heating of electrons by turbulent cascade



Cross-scale Mission Proposal

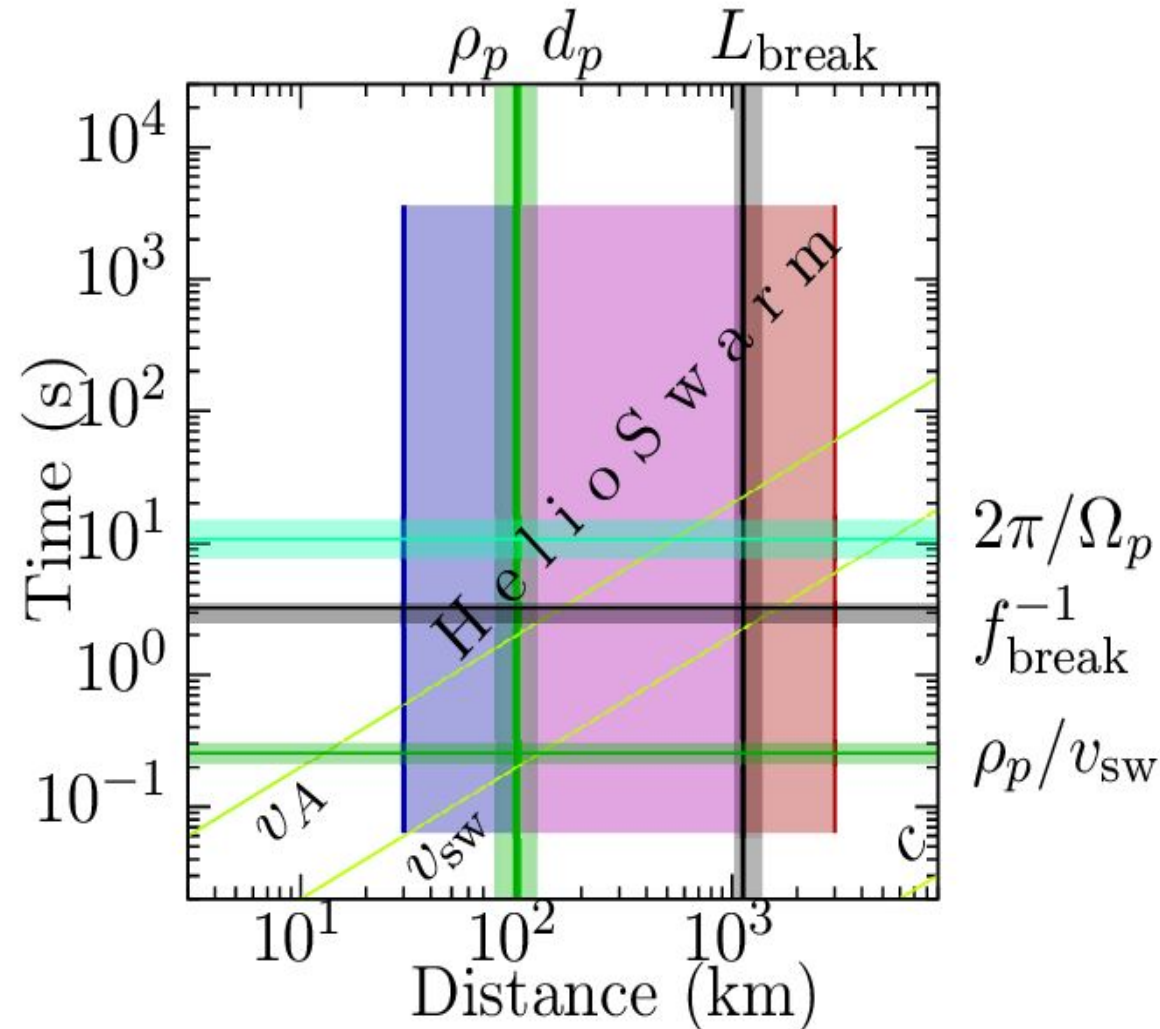
Characteristic Length and Time Scales



In order to transform our understanding of the underlying physical processes, we need to simultaneously measure the solar wind plasma at many points, with separations between the spacecraft spanning MHD and ion scales, as well as the transition region in between.

These measurements must be made sufficiently rapidly to capture ion scale structures advecting over the observatory, while simultaneously hours long, low-frequency processes.

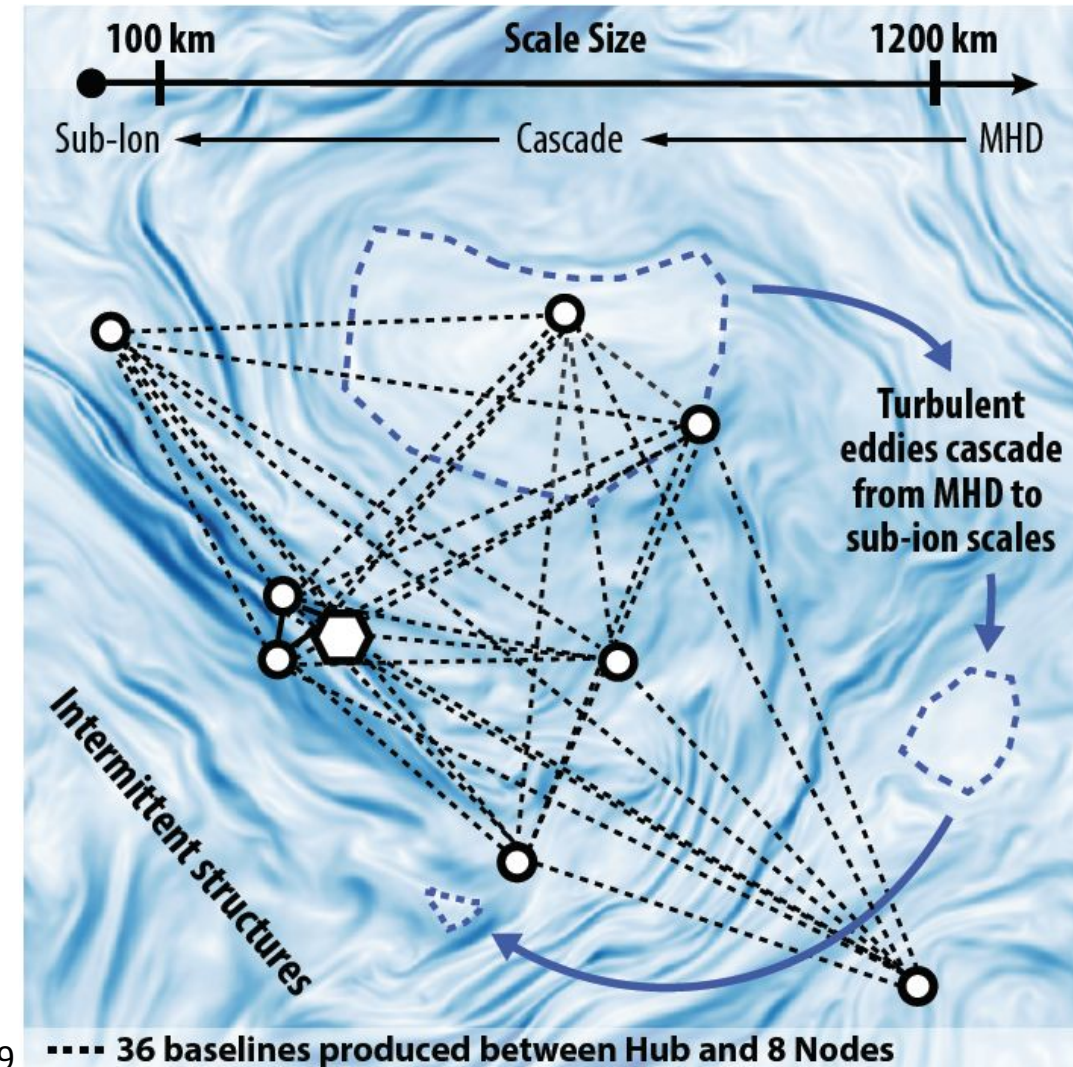
Such measurements can be made by a multipoint observatory in near-Earth space.



The HelioSwarm Mission Concept



Recently selected for phase A study for NASA's Heliophysics MidEx Announcement of Opportunity, the HelioSwarm Observatory proposes to transform our understanding of the physics of turbulence in space and astrophysical plasmas by deploying nine spacecraft to measure the local plasma and magnetic field conditions at many points, with separations between the spacecraft spanning MHD and ion scales.



Arzamasskiy et al 2019

HelioSwarm Science Goals and Objectives



Science

HelioSwarm science is tightly aligned with NAS 2013 Heliophysics Decadal Survey and NASA SMD Priorities: Turbulence identified as a Decadal Science Goal ("Understand the origins and effects of turbulence") and a Decadal Imperative ("Implement ... a multispacecraft mission to address cross-scale plasma physics")

Goal #1:

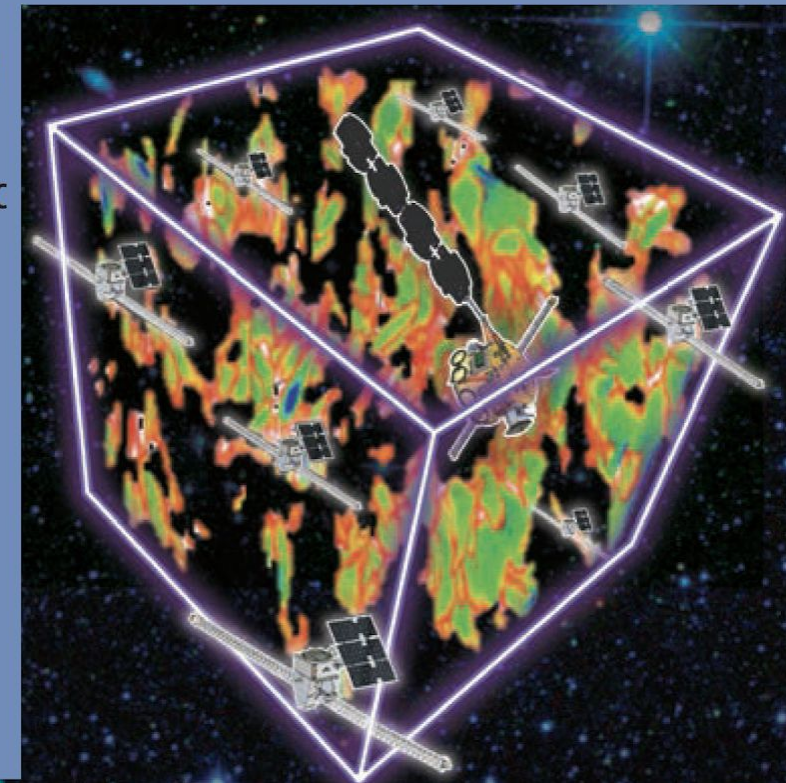
Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma.

- 1: Reveal how turbulent energy is transferred in most probable, undisturbed solar wind plasma and distributed as a function of scale and time.
- 2: Reveal how turbulent cascade of energy varies with background magnetic field and plasma parameters in different environments.
- 3: Quantify transfer of turbulent energy between fields, flows, and protons.
- 4: Identify thermodynamic impacts of intermittent structures on proton distributions.

Goal #2:

Ascertain the mutual impact of turbulence near boundaries and large-scale structures.

- 1: Determine how solar wind turbulence affects and is affected by large-scale structures.
- 2: Determine how strongly driven turbulence in the foreshock, magnetosheath, and magnetosphere differs from that in the undisturbed solar wind.



HelioSwarm's first-ever simultaneous multipoint, multiscale measurements disentangle spatial and temporal variations in solar wind plasmas that connect MHD scale turbulence with sub-ion scale heating.

Spatial Configurations Enabled by Robust Orbit Design



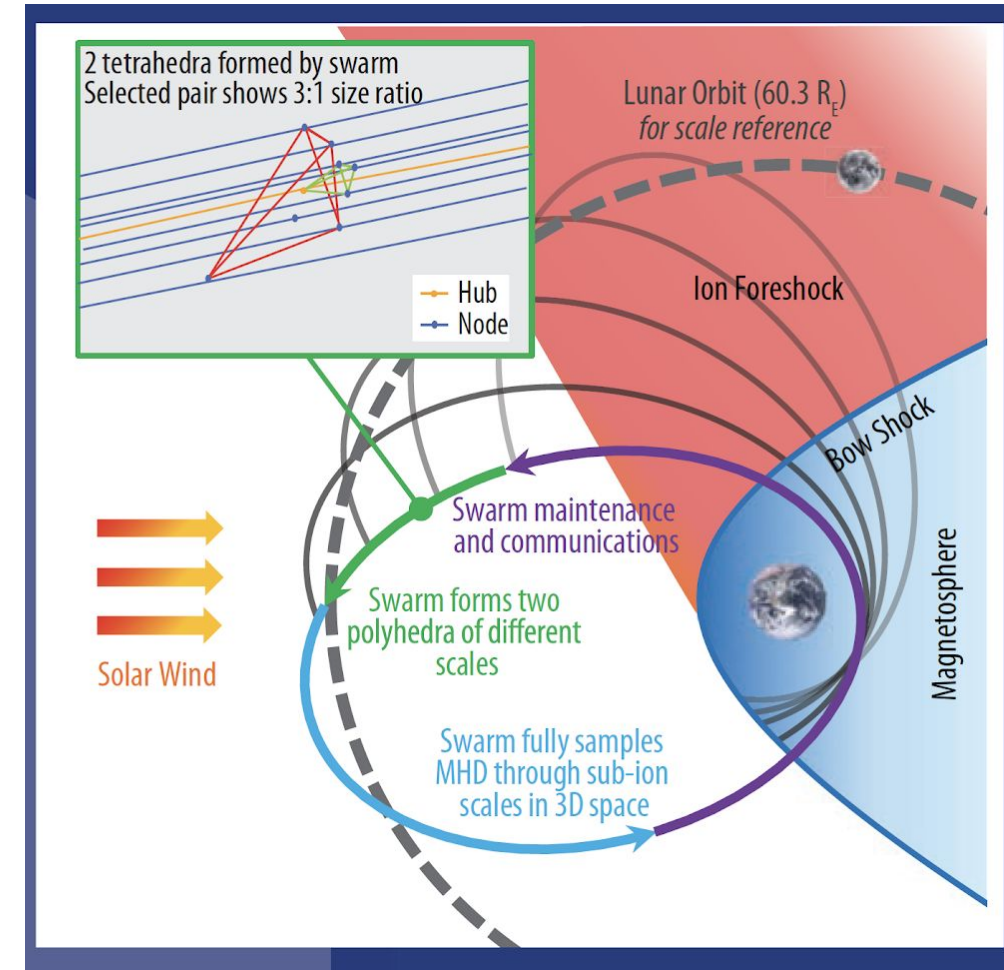
Duration: One Year Science Mission

Launch Readiness Date: October 2026 (December 2028)

Flight System: One hub and Eight co-orbiting node spacecraft

Science Orbit: P/2 Lunar Resonant Orbit (14 day period)

Enables Access to Pristine Solar Wind, Foreshock, and Magnetospheric Plasma (apogee at 60 Re) and robust data downlinks (perigee at 15 Re).

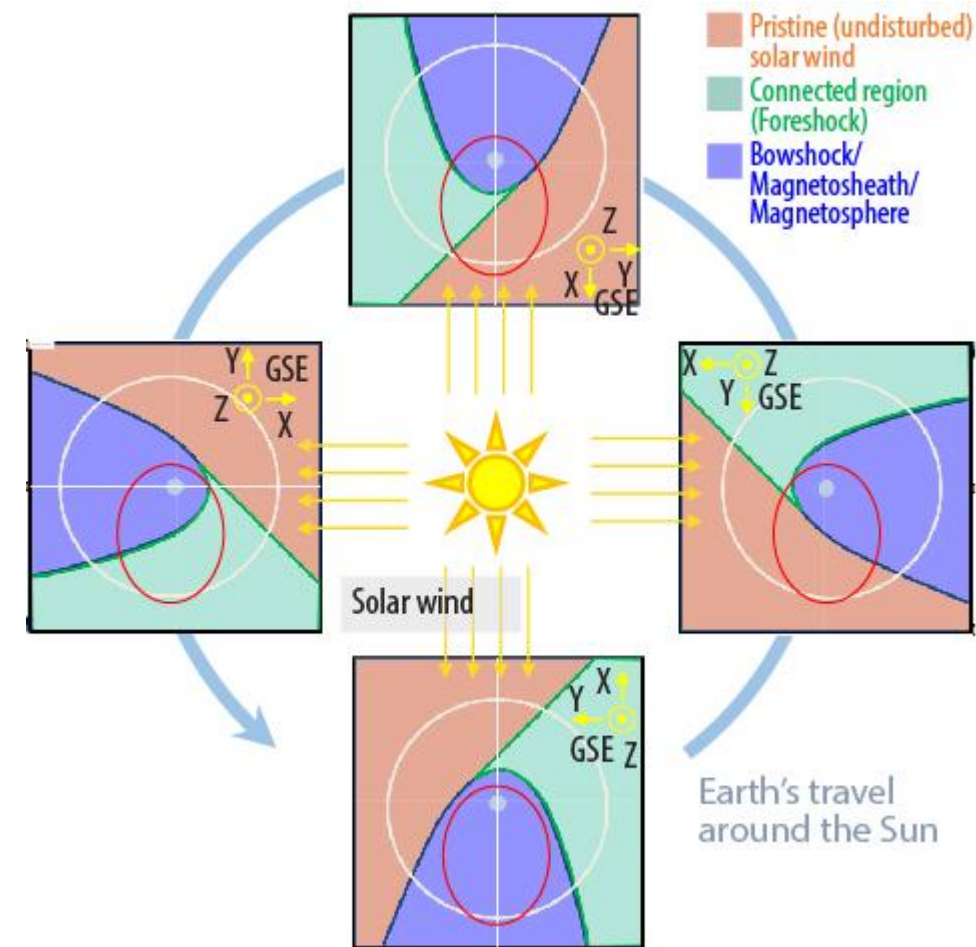
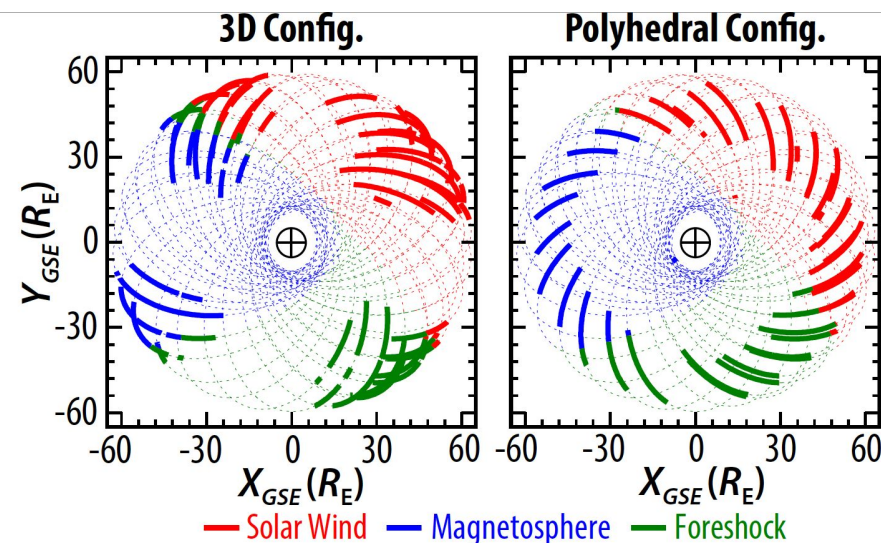


Both Pristine and Strongly-Driven Turbulence will be Observed



The orbit of the hub will remain fixed in inertial space, enabling the sampling of the solar wind, the foreshock, and the magnetosphere over a year.

The node orbits are designed to provide good polyhedral and 3D configurations (solid lines) in all of these regions.



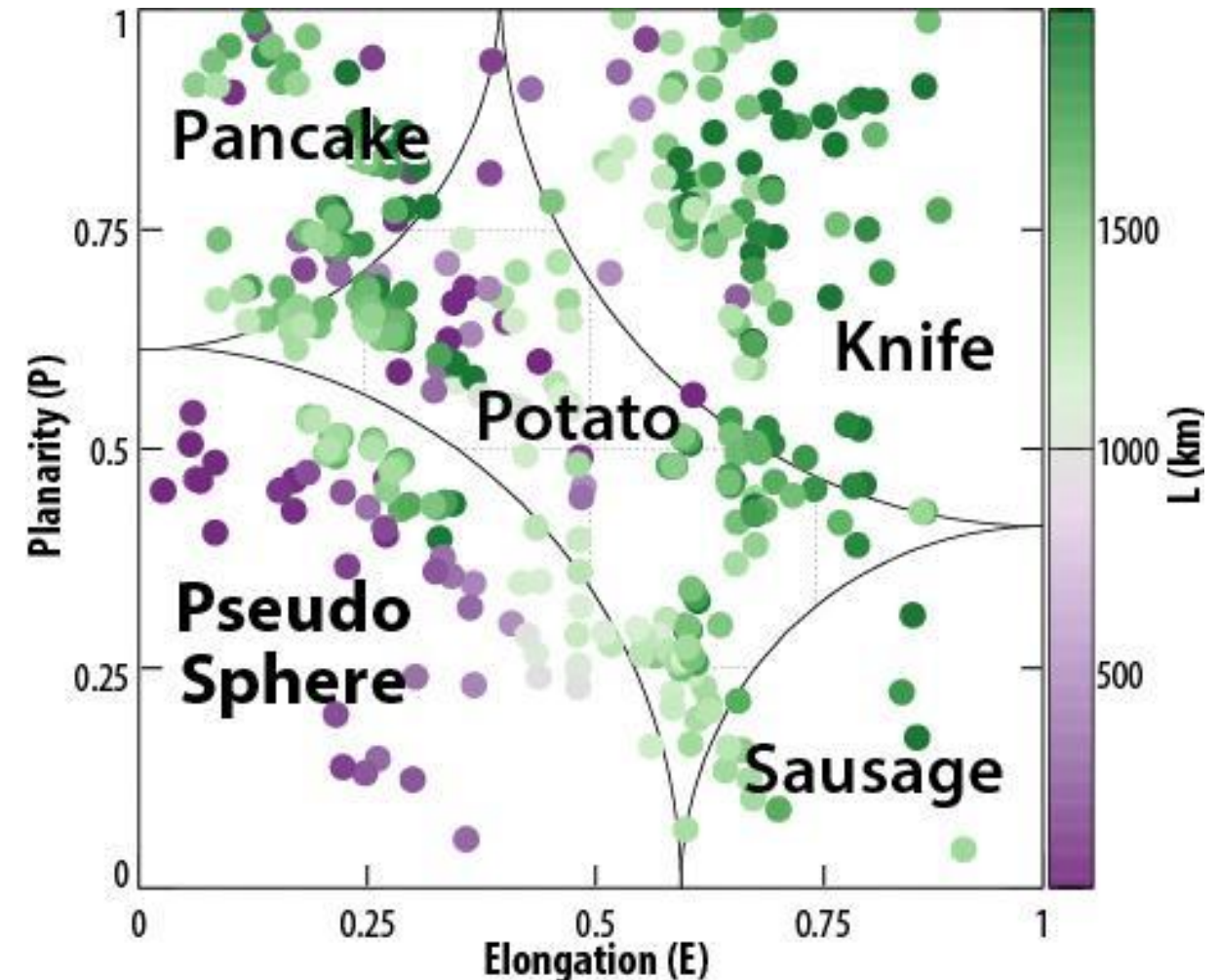
Polyhedral Configurations Enable the Study of Spatial Structure



Given N spacecraft, $C(N,M)$ polyhedra with M vertices can be constructed, each with varying degrees of Elongation and Planarity, as well as an average spacing L .

The 9 HelioSwarm spacecraft produce 382 polyhedra with at least 4 vertices necessary for the application of many three dimensional analysis techniques.

The observatory is configured such that there will simultaneously be pseudospherical polyhedra with $L_i > 3 L_j$ to allow the reconstruction of spatial structure of turbulent fields and flows at multiple scales.

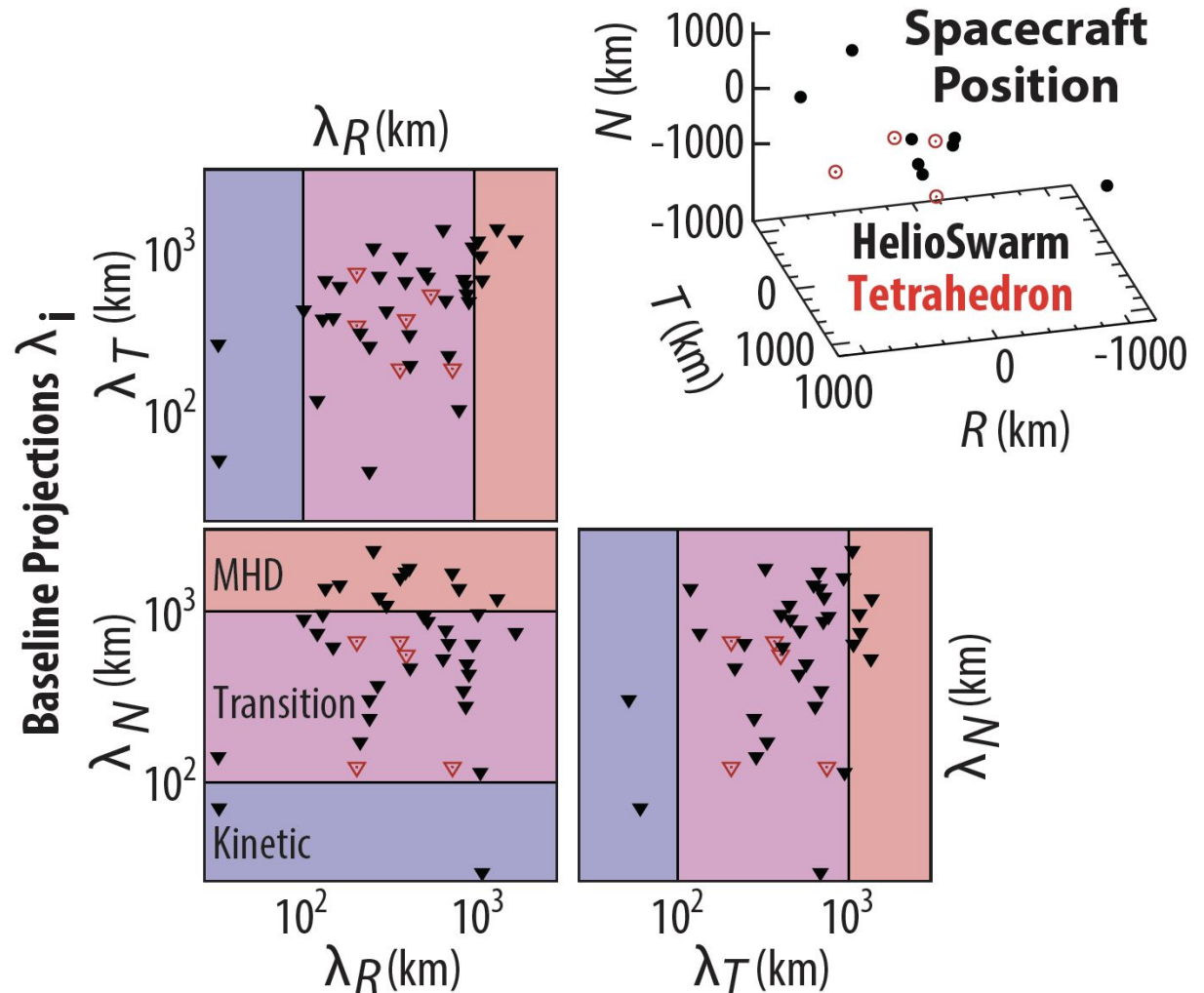


HelioSwarm's 3D Configuration Spans MHD and Ion Scales



Given N spacecraft, $N(N-1)/2$ baseline separations between can be constructed between each point of measurement.

The 9 HelioSwarm spacecraft will be situated so that the components and magnitudes of the 36 baselines will simultaneously span MHD and ion scales, and the transition range between, enabling the study of correlations and structure functions.



HelioSwarm's 4-Instrument, High-TRL Suite Meets Mission Requirements



Science Instruments High-TRL, high-heritage instrument suite optimized for solar wind turbulence measurements.

HUB & NODE

Fluxgate Magnetometer (FGM)

- Vector DC magnetic fields
- Solar Orbiter post-environmental heritage and JUICE design heritage



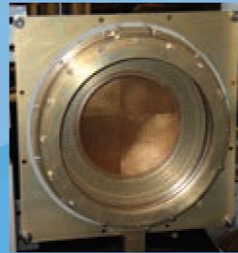
Search Coil Magnetometer (SCM)

- Vector AC magnetic fields
- JUICE design heritage



Faraday Cup (FC)

- Solar wind plasma density and velocity
- Parker Solar Probe, WIND, DSCOVR flight heritage



HUB ONLY

Ion Electrostatic Analyzer (iESA)

- Ion velocity distributions
- Solar Orbiter post-environmental heritage and MAVEN flight heritage



Tim Horbury (Lead)

Imperial
College
London

Olivier Le Contel
(Lead)

LPP/CNES

Tony Case
(Lead)

Smithsonian
Astrophysical
Observatory

Benoit Lavraud
(Lead)

IRAP/CNRS

Robust Analysis Approaches



Cascade Rate: Measure of the transfer of a turbulent fluctuation energy from one spatial scale to another.

2-point correlation: Measure of the temporal and spatial scale over which a spectral element is remade by nonlinear processes.

Structure Functions: Statistics of two-point increments of turbulent fields to reveal scale-dependent, intermittent turbulence.

Wave telescope: Multipoint method for determining the wavevectors of plasma waves and their associated 3D power distributions.

Pressure-strain interaction (Pi-D): Measurement of the dilation, $-(P \cdot \nabla) \cdot \mathbf{v}$, describing the local conversion between flow and thermal energy.

Curlometer & Gradient Methods: Multipoint methods for constructing current density/intermittent structures from spatially distributed measurements.

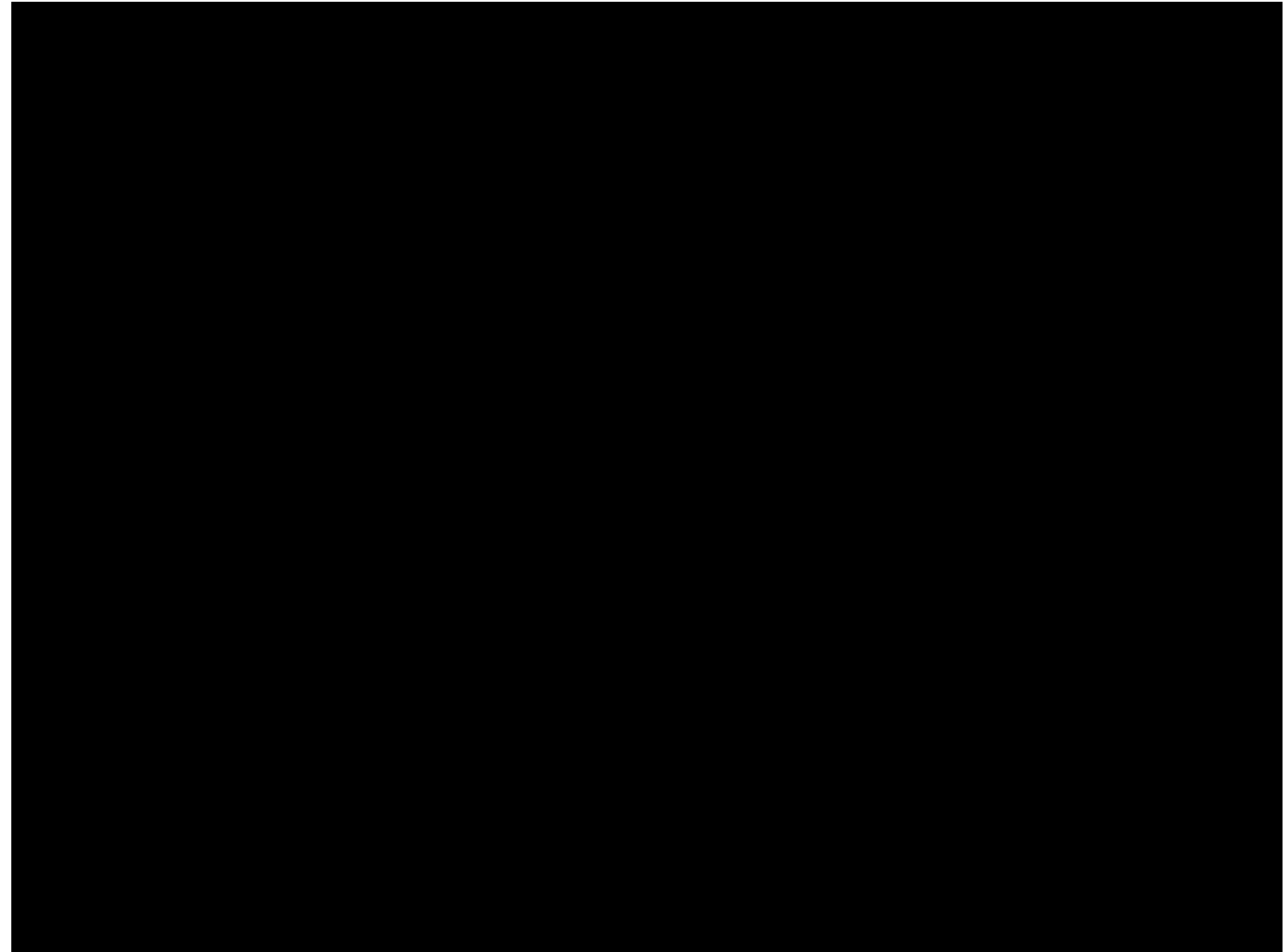
- HelioSwarm leverages heritage analysis techniques for studying turbulence.
- These techniques have been developed for earlier single and multipoint missions (e.g., MMS, Cluster, THEMIS)
- All of these have already been extended for application in missions with “N” spacecraft

Applying Analysis Approaches



We apply these analysis approaches to synthetic time series generated using HS configurations passing through numerical simulations of turbulence (e.g. Gkeyll and Pegasus ++)

Arzamasskiy et al 2019



Analysis Approach: Structure Functions

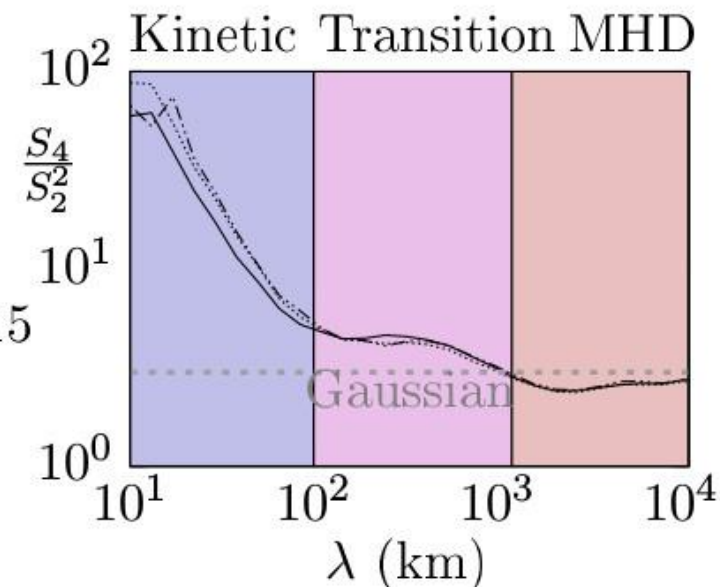
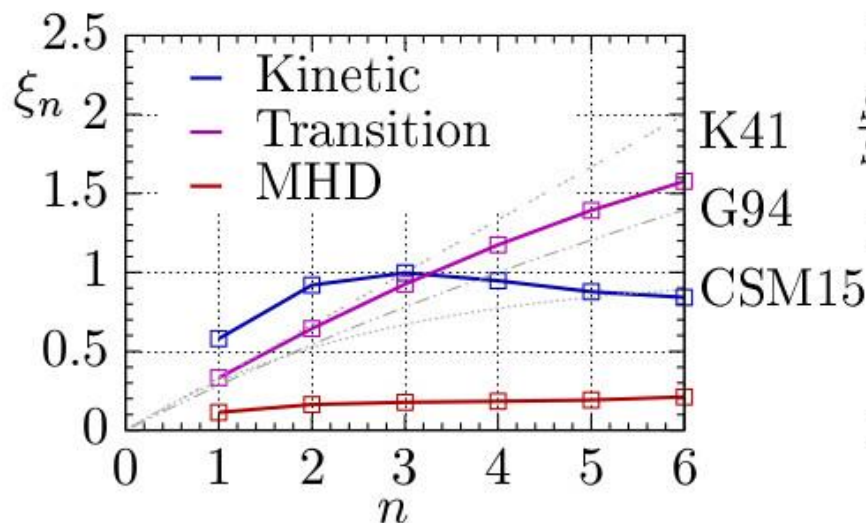
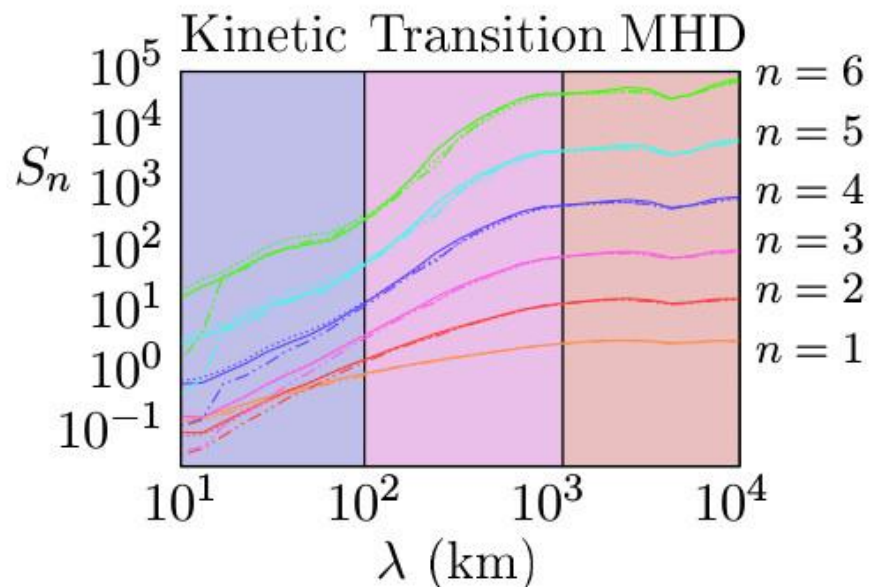


Structure functions characterize the intermittent nature of turbulence by averaging power of two-point increments. With a time series from a single spacecraft, this calculation relies on converting temporal lags into spatial scales:

$$S_n(\lambda = v_{sw}\tau) = \langle [\delta B(t + \tau) - \delta B(t)]^n \rangle$$

With multiple spacecraft, we have orders of magnitude more increments that can be used for this calculation, yielding a more statistically robust coverage of spatial scales with sufficient increment samples to resolve higher orders:

$$S_n(\lambda = \mathbf{x}_i(t + \tau) - \mathbf{x}_j(t)) = \langle \{ \delta B[\mathbf{x}_i(t + \tau), t + \tau] - \delta B[\mathbf{x}_j(t), t] \}^n \rangle$$



Analysis Approach: Cascade Rate



Politano & Pouquet (1998a,b) extended the HD expression for the cascade rate to

$$-4\epsilon^{\pm} = \nabla \cdot \mathbf{D}^{\pm}(\lambda)$$

with the 3rd order product of increments of the Elsasser fields

$$\mathbf{z}^{\pm} = \mathbf{v} \pm \frac{\mathbf{B}}{\sqrt{4\pi n_p m_p}}$$

$$\mathbf{D}^{\pm}(\lambda) = \langle \Delta \mathbf{z}^{\mp}(\lambda) |\Delta \mathbf{z}^{\pm}(\lambda)|^2 \rangle$$

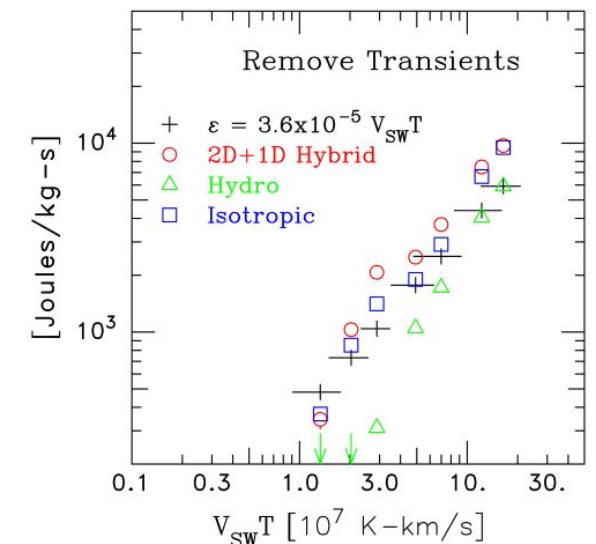
From a single spacecraft timeseries, the spatial scale is approximated by using temporal lags,

$$\lambda = v_{sw} \tau$$

Producing increments defined as

$$\Delta \mathbf{z}^{\pm}(\lambda) = \mathbf{z}^{\pm}(t + \tau) - \mathbf{z}^{\pm}(t)$$

This leads to estimates for the cascade rate from the solar wind (Stawarz et al 2009)



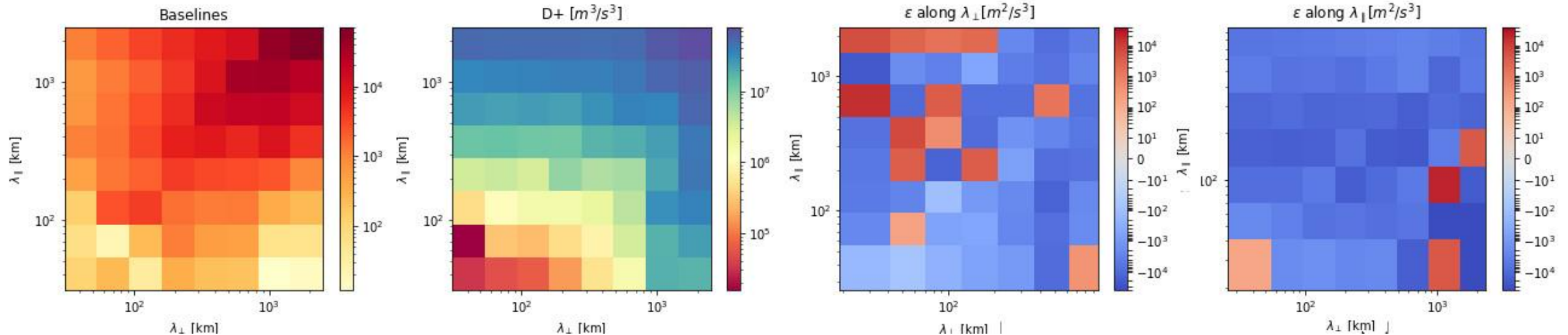
Analysis Approach: Cascade Rate



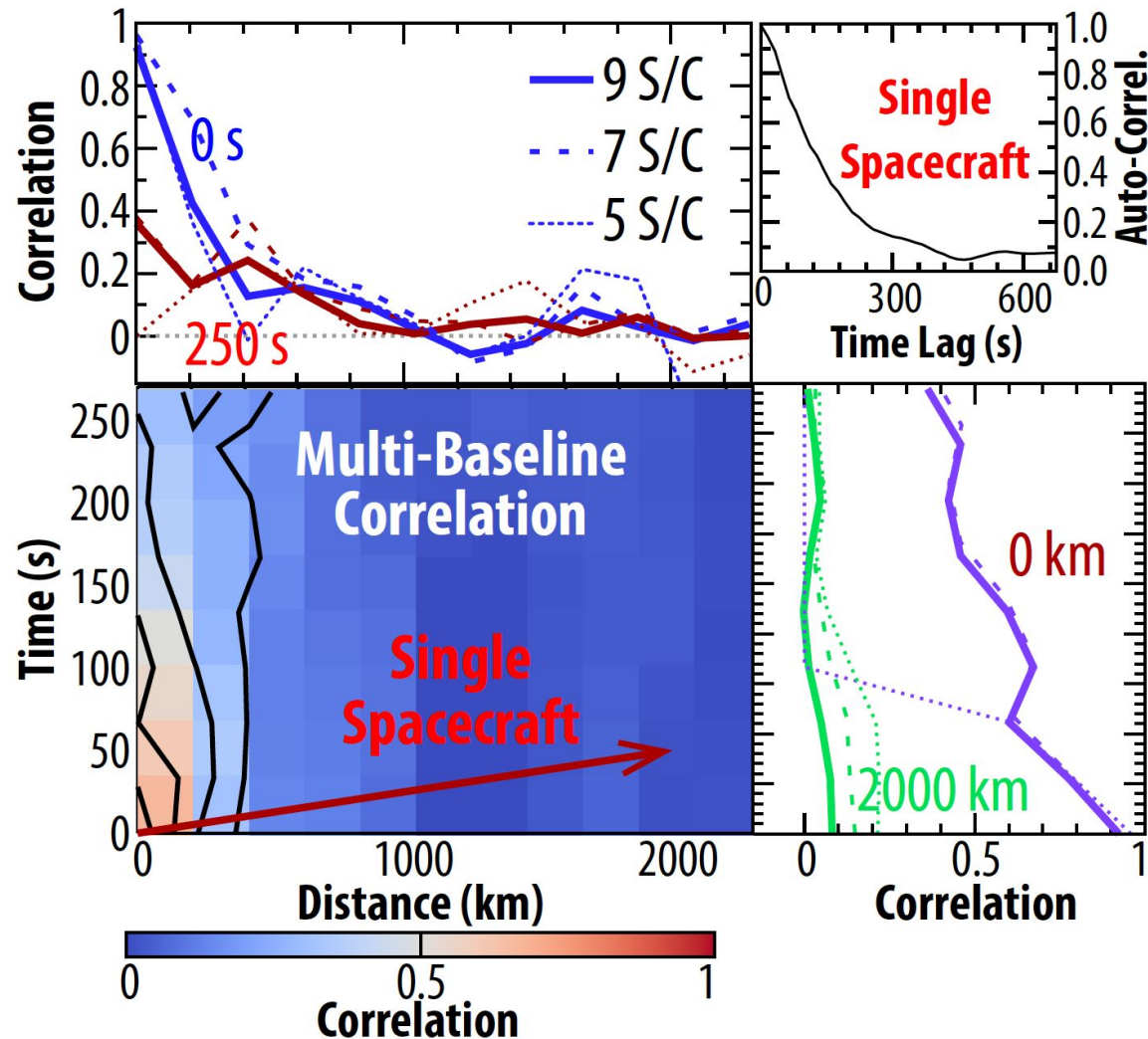
As with any increment-based calculation, using HS's 36 baselines enables the calculation of orders of magnitude more increments both along and across the local field, enabling the investigation of anisotropic cascades.

Assuming cylindrical symmetry, this can be simplified to (e.g. Stawarz et al 2009)

$$-4\epsilon^{\pm} = \left(\frac{1}{\lambda_{\perp}} \right) \frac{\partial}{\partial \lambda_{\perp}} (\lambda_{\perp} D_{\perp}^{\pm}) + \frac{\partial}{\partial \lambda_{\parallel}} (D_{\parallel}^{\pm})$$



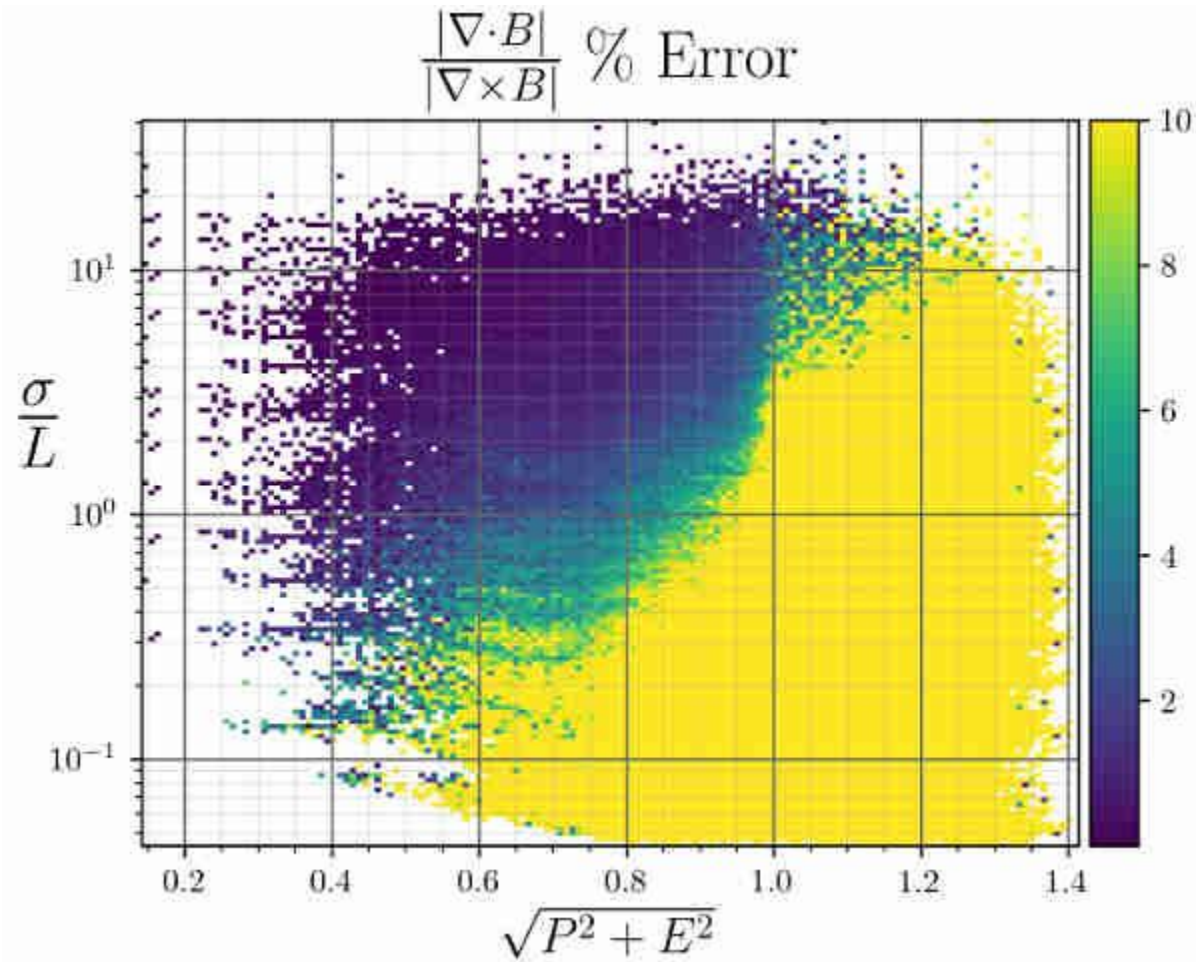
Analysis Approach: Time-Space Correlation



The autocorrelation of a time series measured by a single spacecraft with a lagged copy of said series fundamentally can not deconvolve the decorrelation of a turbulent signal as a function of time and space independently; see red arrow in lower left hand corner.

By performing two-point correlations between timeseries measured by all nine HelioSwarm spacecraft, we can separately measure the decorrelation times and length scales, accessing fundamental characteristics of the underlying turbulence.

Analysis Approach: Curlometer



By applying the Curlometer technique (a numerical estimate of $\nabla \times B$ e.g. Dunlop et al 2002) to synthetic timeseries drawn from HelioSwarm-like observations of numerical models, we can reconstruct the spatial structure of the current.

Shown here is the relative error in the magnetic field reconstruction for all tetrahedra drawn from a two-week orbit as a function of the regularity of the polyhedra and the relative size of the polyhedra L compared to the width of the input current sheet σ .

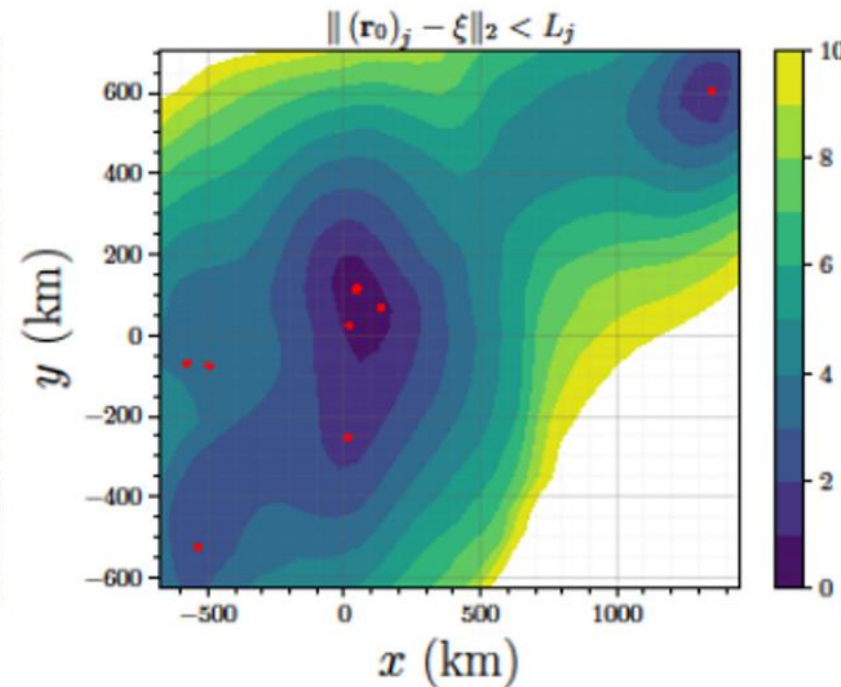
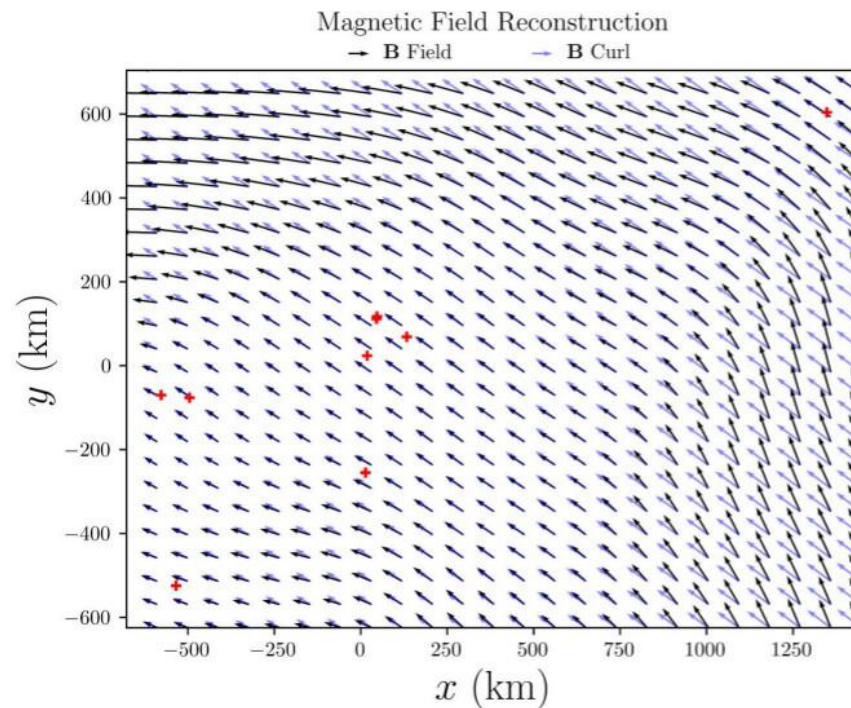
Analysis Approach: Magnetic Field Reconstruction



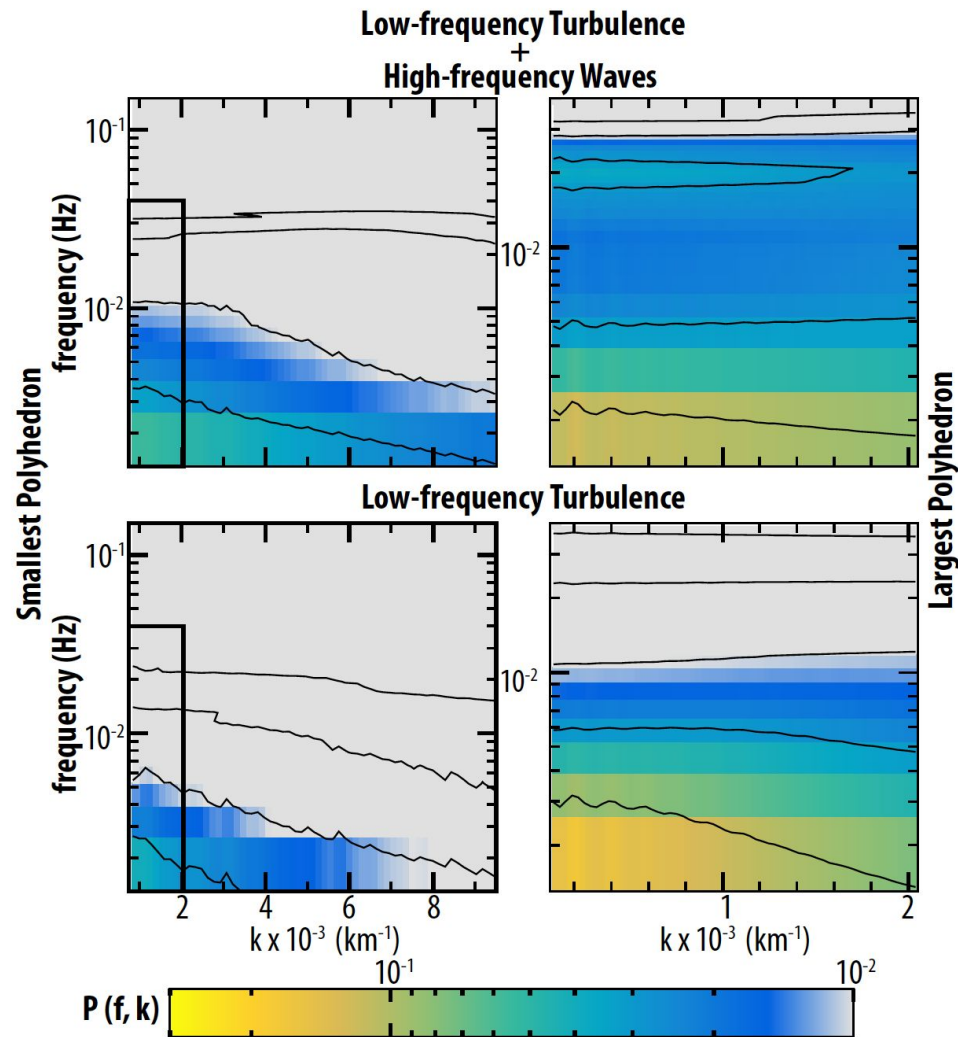
A 1st order Taylor Expansion can be combined with an estimate for the spatial gradient in the magnetic field drawn from a single tetrahedra

$$\hat{\mathbf{B}}(\mathbf{x}_i) \approx \mathbf{B}(\mathbf{r}) + \sum_{k \in \{x, y, z\}} \partial_k \mathbf{B}(\mathbf{x}_i - \mathbf{r})_k$$

Averaging these estimates over a subset of the 126 tetrahedra constructed from the 9 Spacecraft yields an accurate representation of large volumes of numerical simulations of turbulence.



Analysis Approach: Wave-telescope Technique



Applying the Wave-Telescope Technique (e.g. Narita et al 2011) to HelioSwarm-like time series derived from numerical models of turbulence measured at the vertices of large and small regular polyhedra, we can differentiate between different spatial and temporal distributions of power.

Shown at left is the derived distribution of power as a function of frequency and wavenumber for both a model of purely low-frequency Alfvénic turbulence, lower plots, and for low-frequency turbulence with an additional high-frequency component. The high-frequency component is not distinguishable when only using the smallest polyhedra, but can be clearly observed when using timeseries from the larger polyhedra.

Flight Dynamics is Complicated

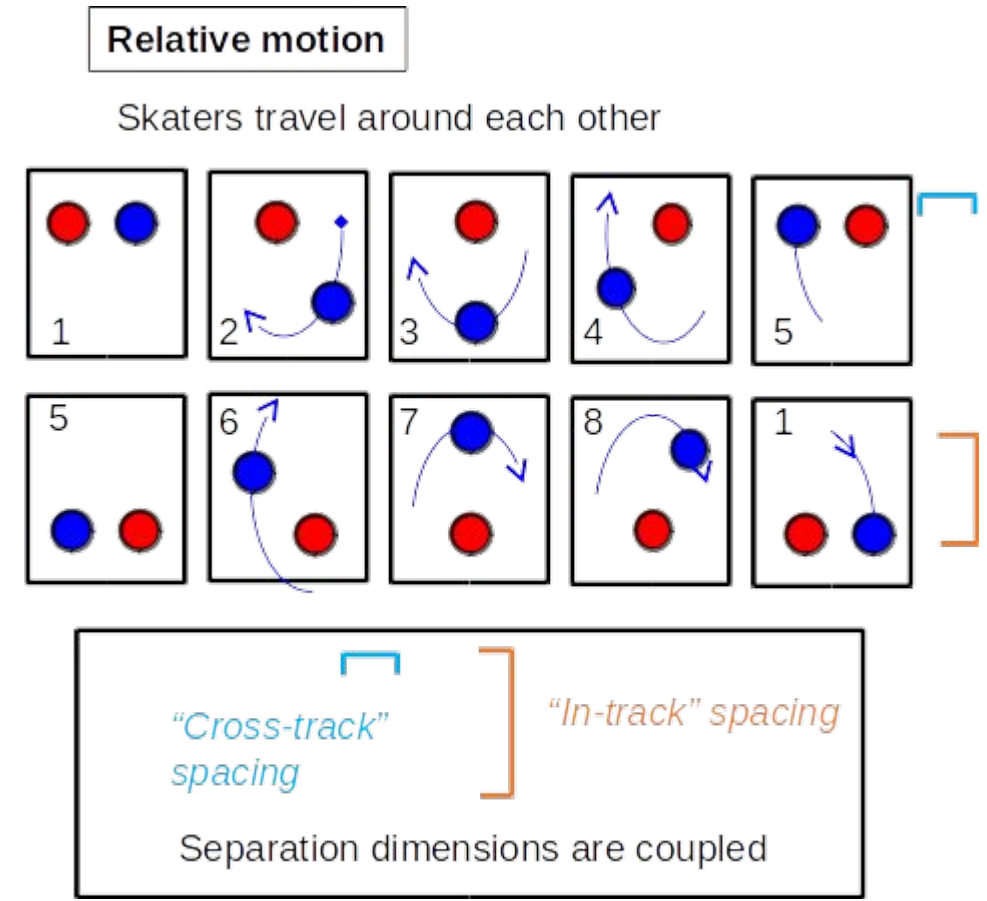
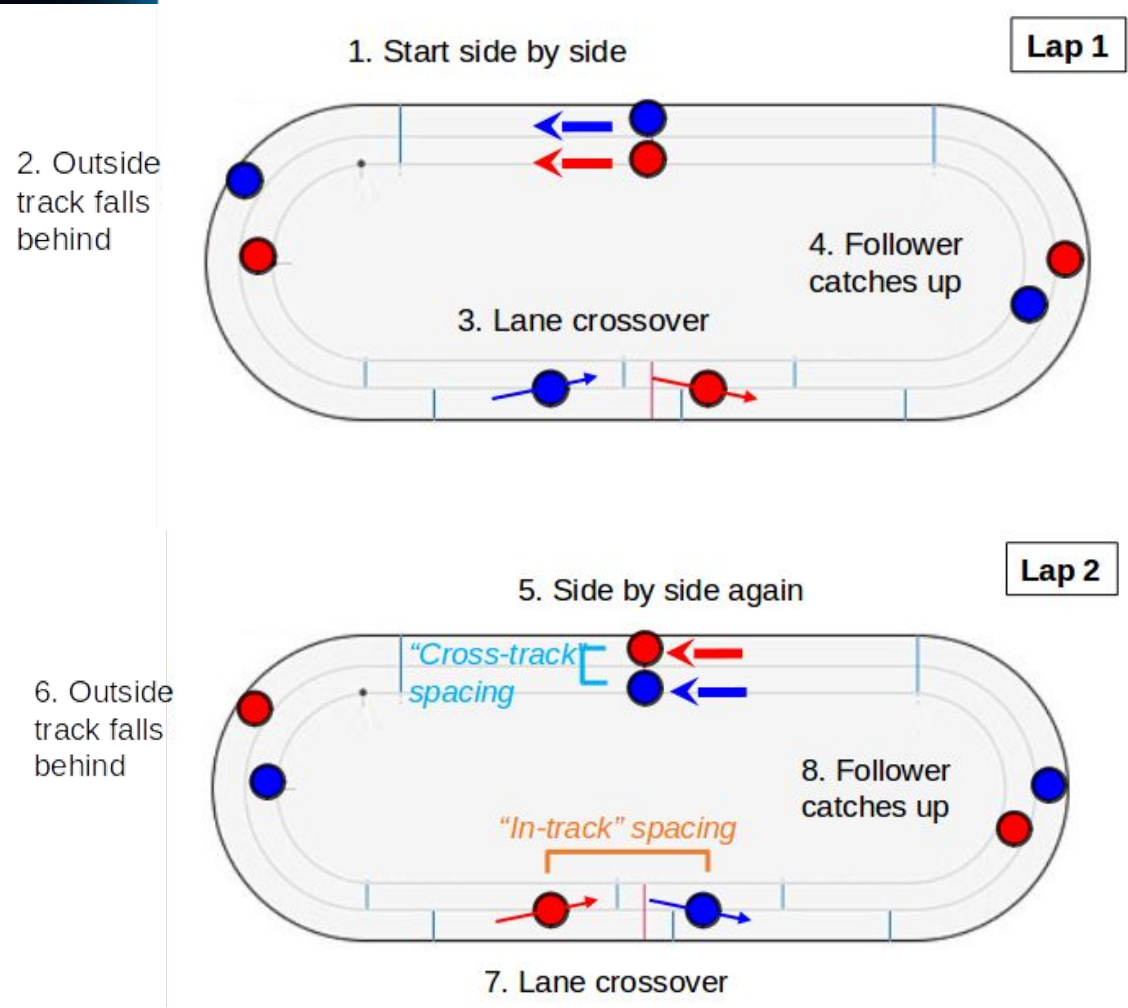


- Let me acknowledge Laura Plice and her NASA/ARC flight dynamics team at this juncture! She inspired what follows!
- It is natural to envision a satellite swarm as freely directed members, analogous to a hockey team, with players independently skating to where they need to be.
 - That's not how it works.
- In orbit, a closer analogy would be an imaginary time trial in speed skating, where two identical skaters are moving at exactly the same speed.
 - On an elliptical track.



You Can't Just Drive or Fly Spacecraft Where You Want Them – They Orbit!

Relative Motion 'in Orbit'

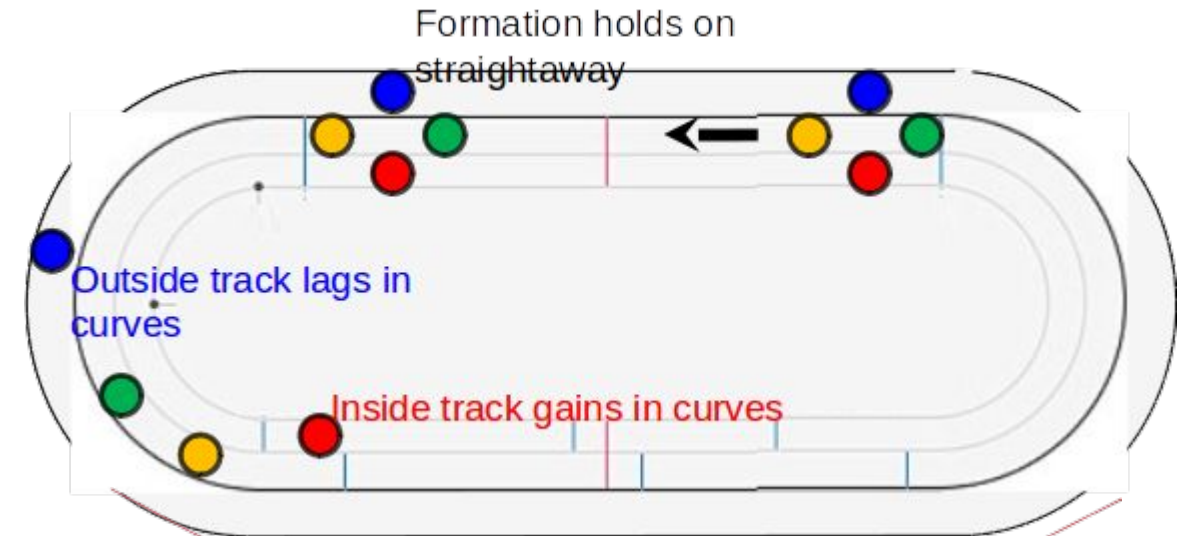


You Can't Just Drive or Fly Spacecraft Where You Want Them – They Orbit!

Adding More Elements Creates a Swarm



- Formation appears static in straight line flight
- For curvilinear motion, secular drift can occur unless “lane occupancy” averages out
- Orbits don’t have straight portions so all configurations are dynamic
- Spacecraft don’t propel themselves through space (like in science fiction or like aircraft); other than rare adjustments, satellites coast through space (especially with conventional propulsion)

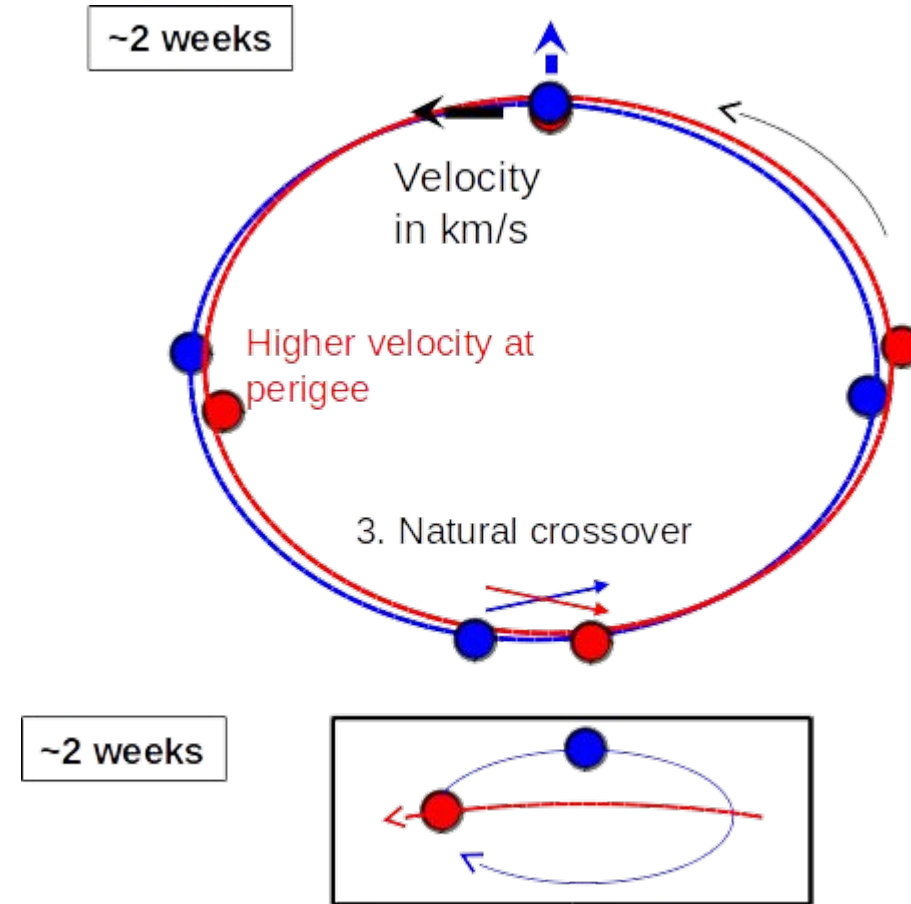


You Can't Just Drive or Fly Spacecraft Where You Want Them – They Orbit!

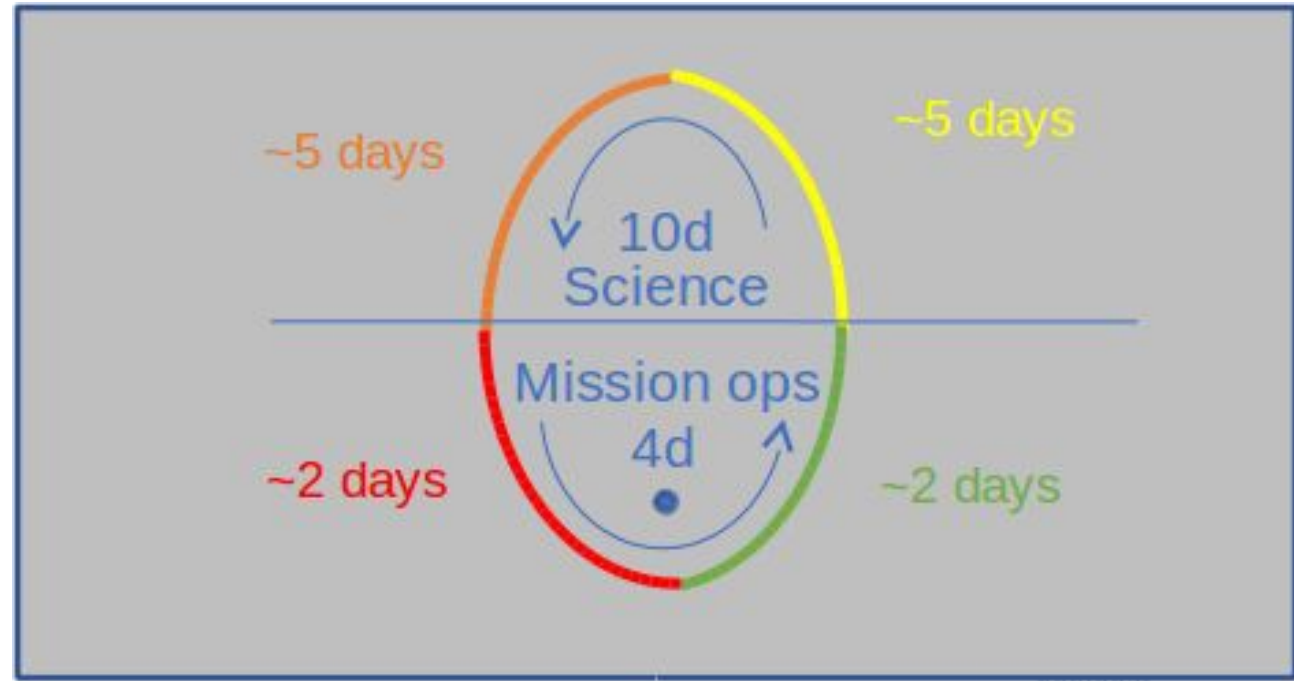
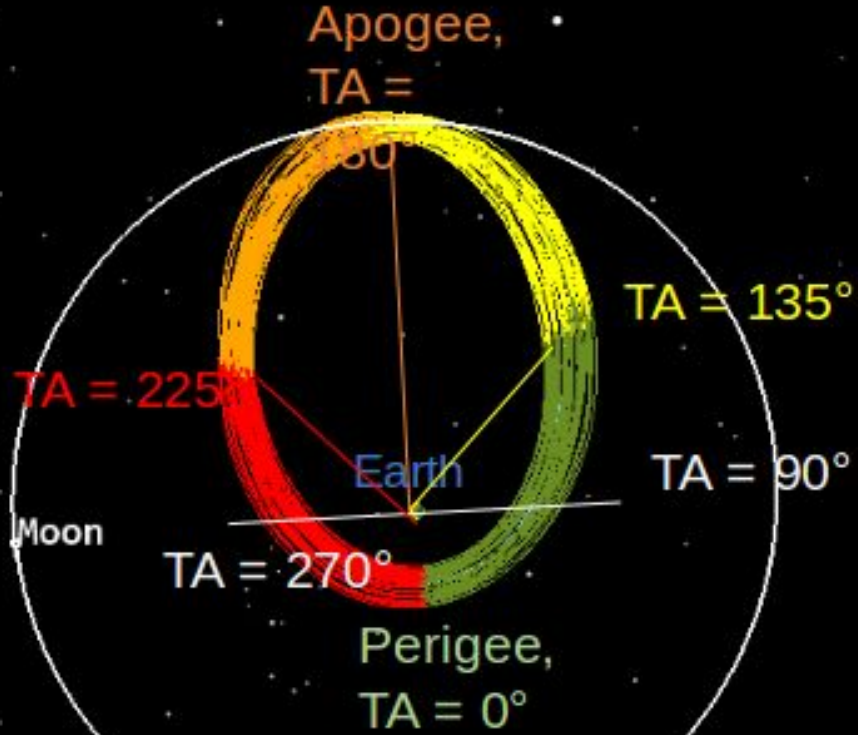
Orbit Period Equals the Swarm Period



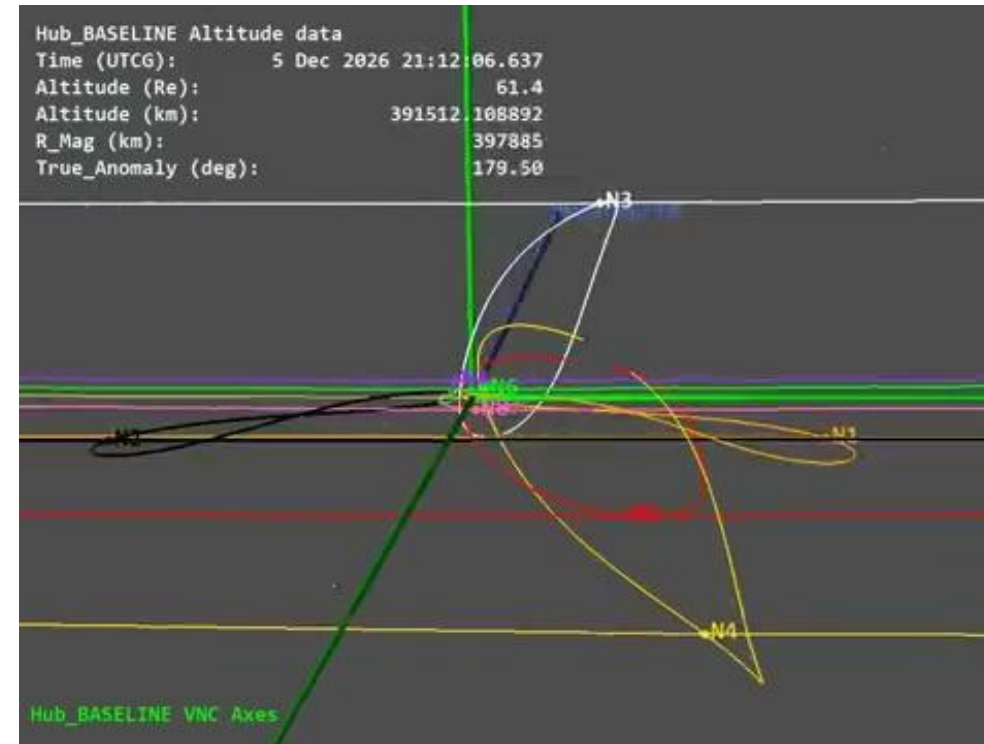
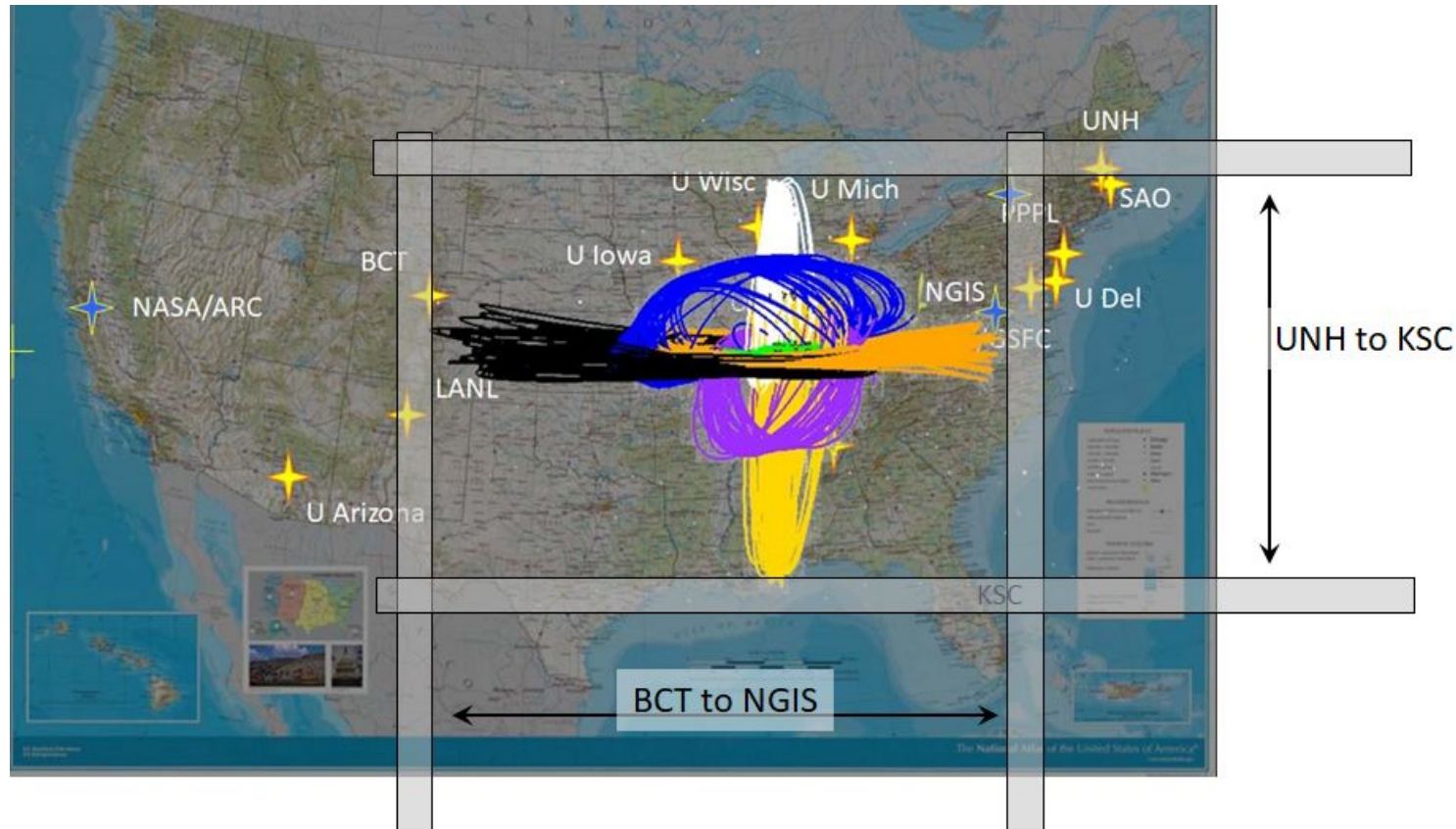
- Because the relative configuration results from subtle variations in the travel around the orbit, both types of motion have the same period
- They have to, or one satellite will fall farther and farther behind
- In the skating analogy, it took two laps to complete a cycle of relative motion – but one lane was larger than the other and one skater went all the way around the other
- In orbit, we draw from Kepler's laws to show that the orbital and relative motion have the same cycles.



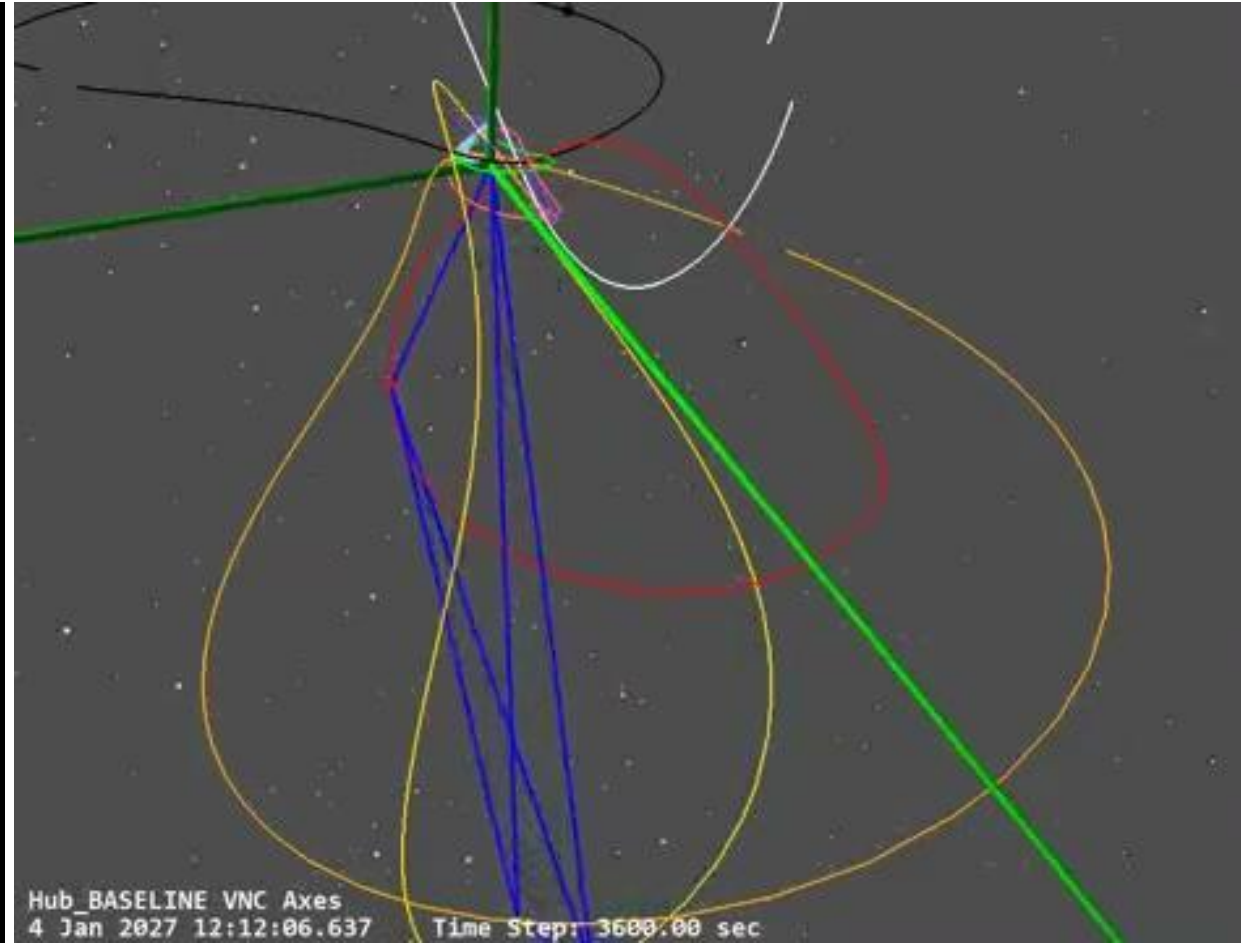
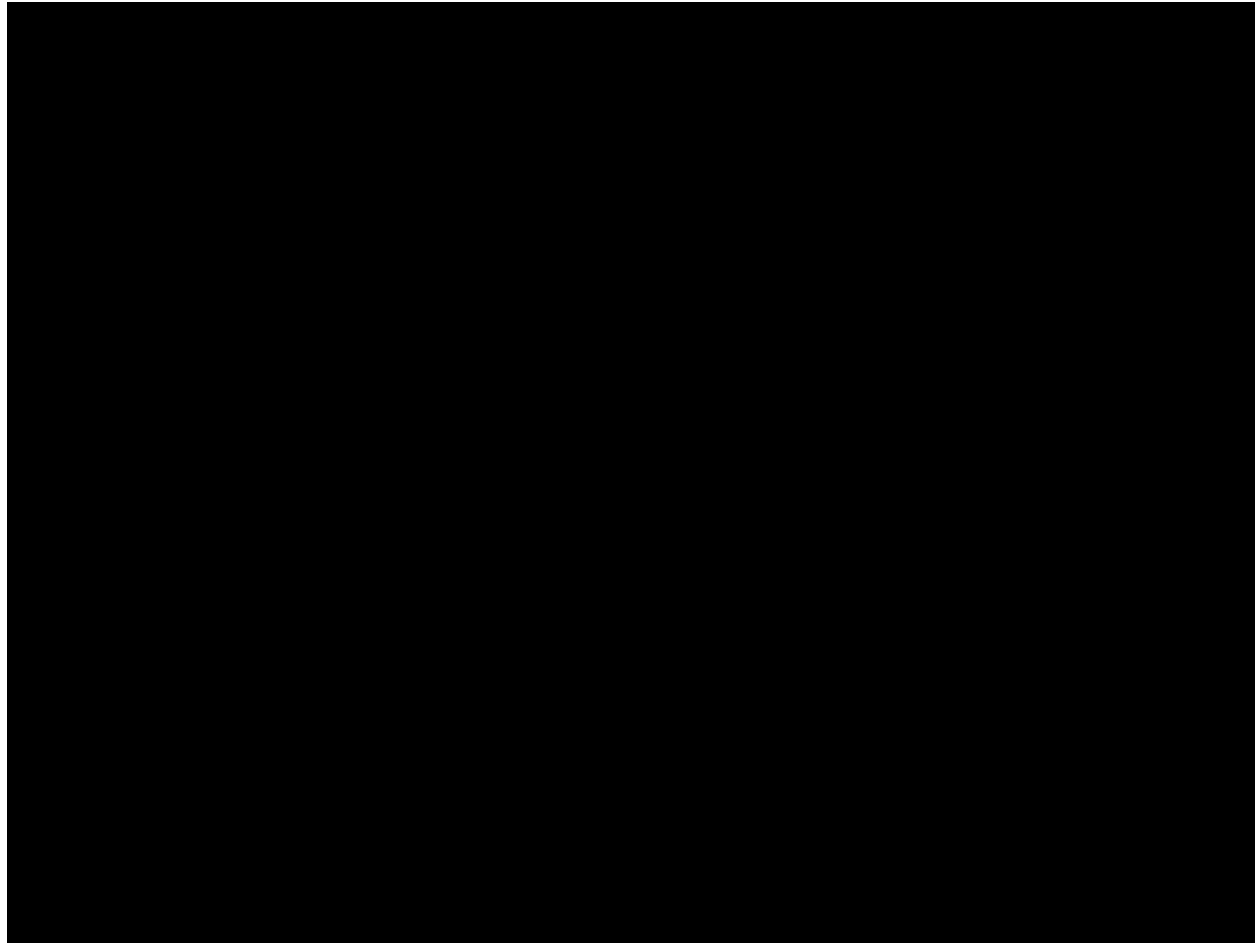
HelioSwarm Orbit Achieves Mission Science



Observatory Configuration in Relative Terms



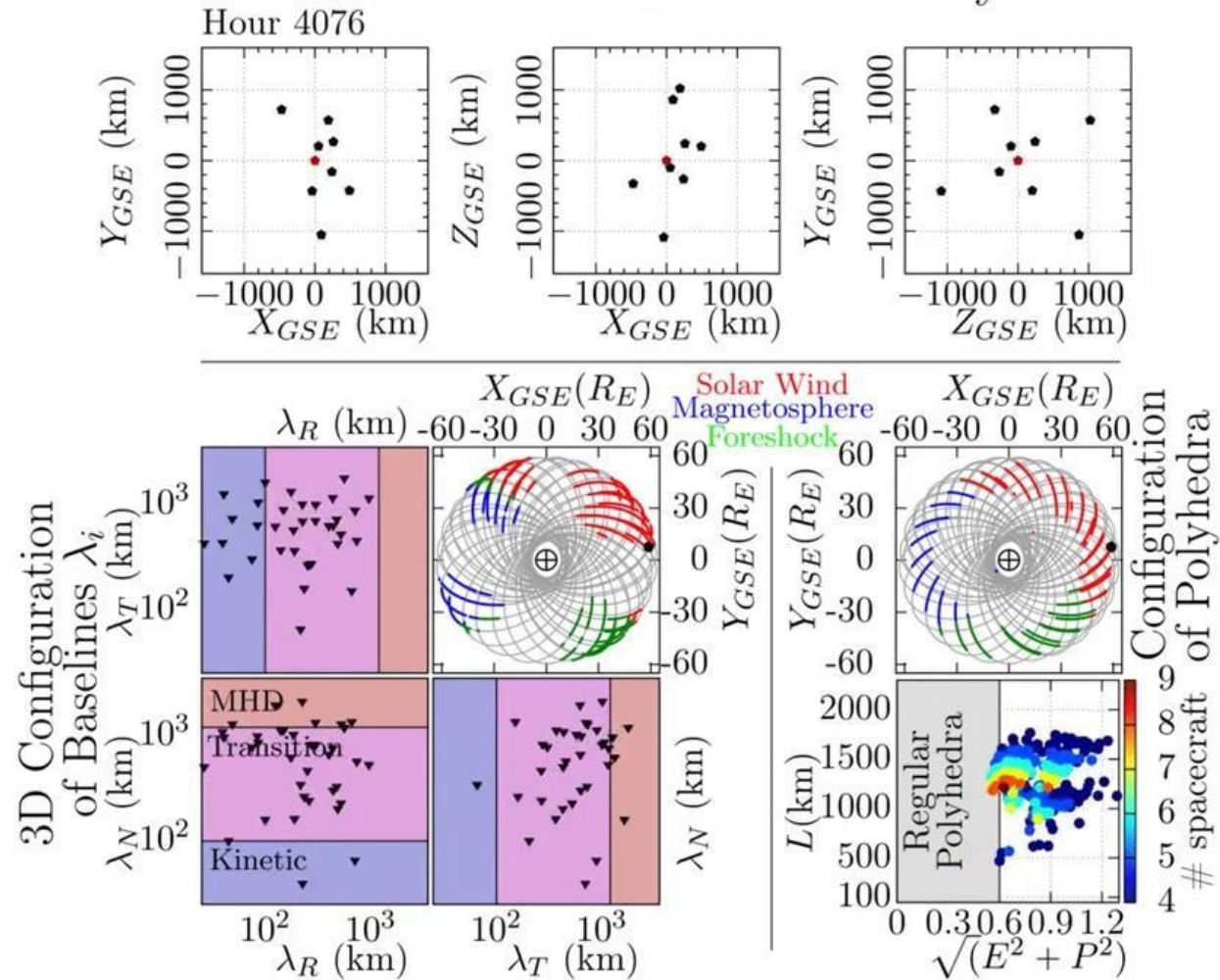
HelioSwarm Observatory Designed w/ Multiscale Baselines and Polyhedra



HelioSwarm Orbit Covers Our Needed Configurations



The HelioSwarm Observatory



HelioSwarm: A MDEX Proposal Under Phase A Study



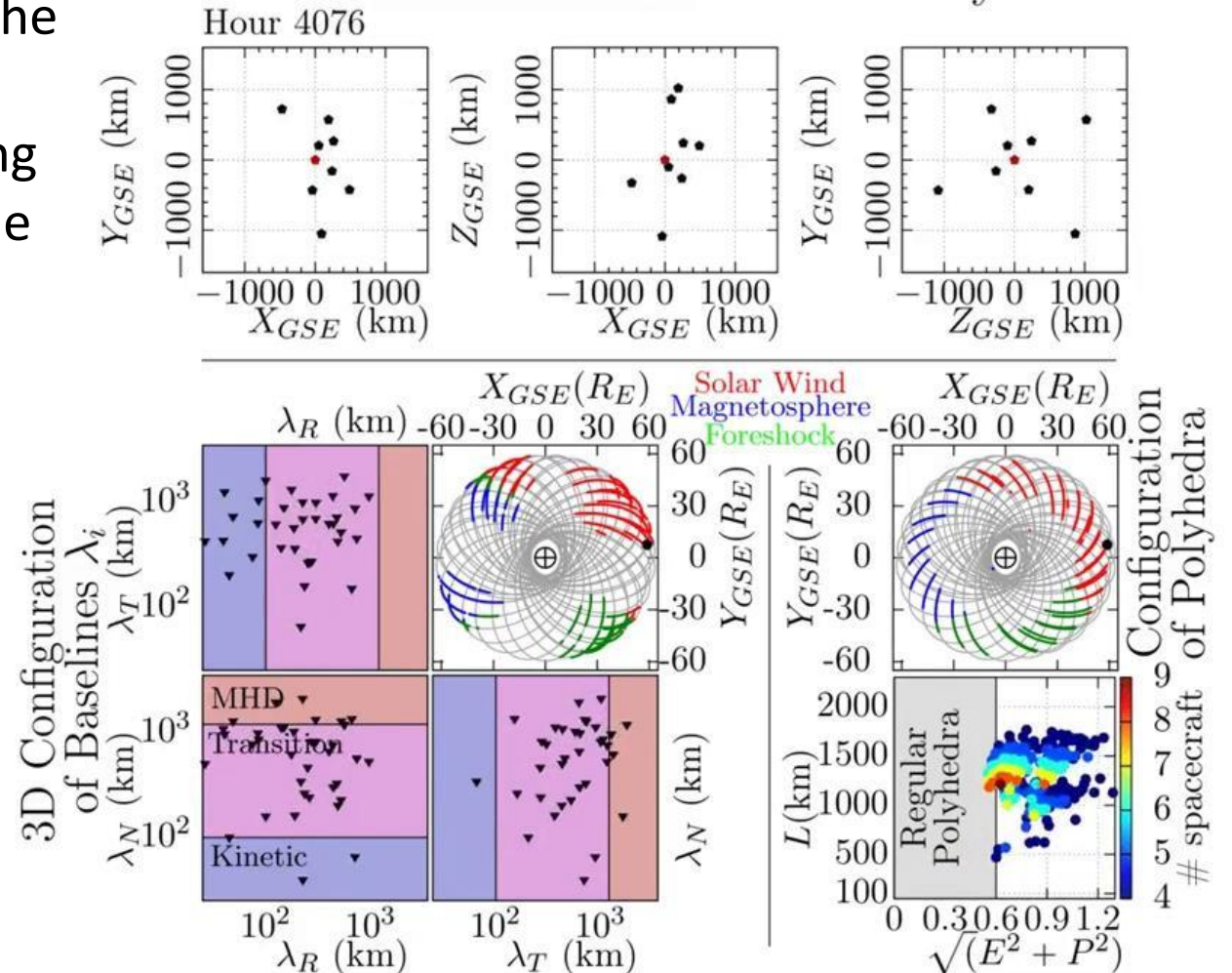
HelioSwarm transforms our understanding of the physics of space plasma turbulence.

The solar wind is the only laboratory for probing the universal turbulence processes that cascade energy from larger to ever smaller scales, ultimately heating space and astrophysical plasmas.

For More Information, See White Papers at:

- arxiv.org/abs/1903.05710
- arxiv.org/abs/1903.05740
- arxiv.org/abs/1903.06890
- arxiv.org/abs/1908.04192

The HelioSwarm Observatory



Backup Slides



Are you unaware that the true astronomer must be a person of great wisdom? Here there will be a need for several sciences. The first and most important is that which treats of pure numbers. To those who pursue their studies in the proper way, all geometric constructions, all systems of numbers, all duly constituted melodic progressions, the single ordered scheme of all celestial revolutions should disclose themselves. And, believe me, no one will ever behold that spectacle without the studies we have described, and be able to boast that they have won it by an easy route.

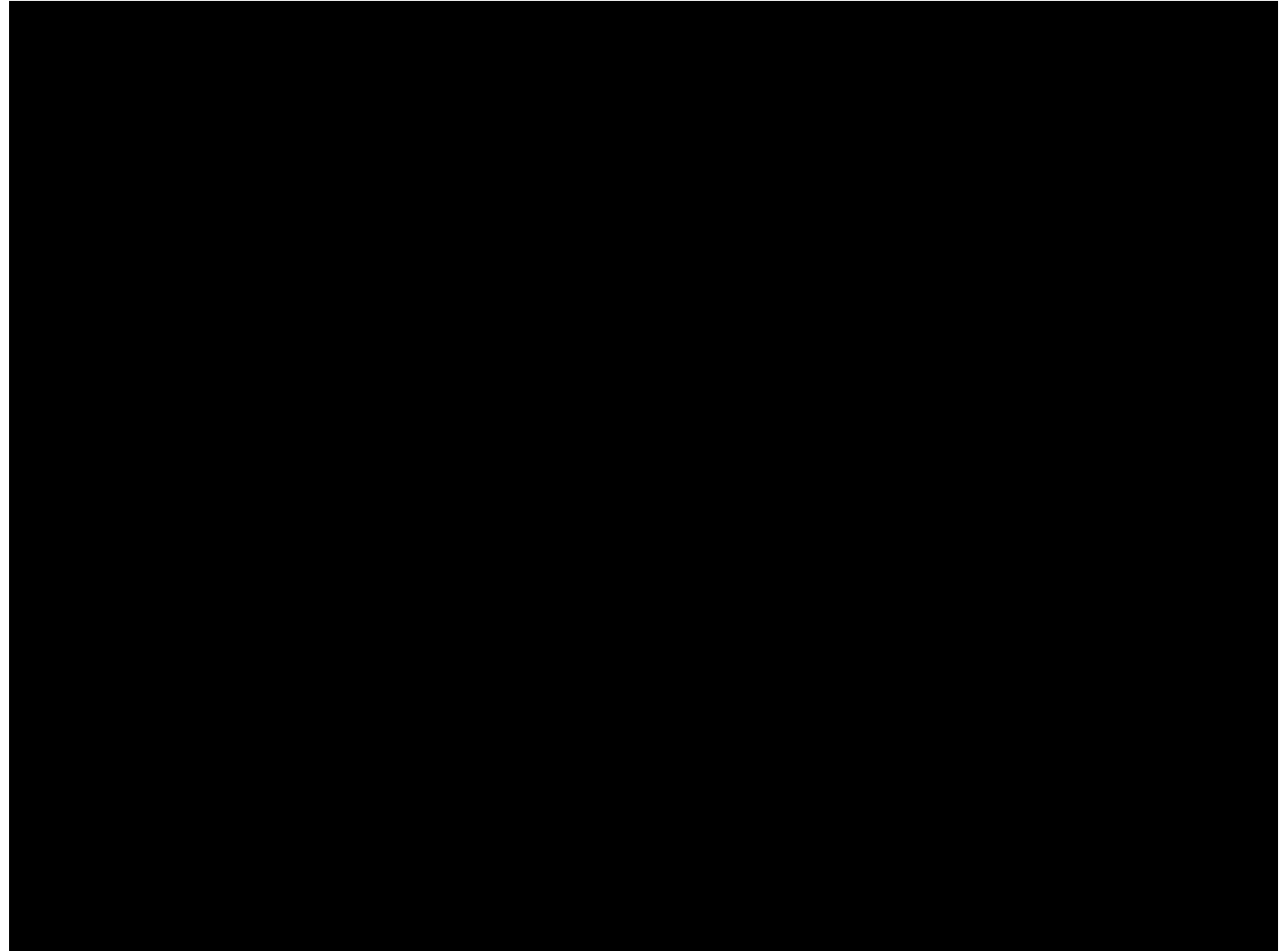
Plato *Epinomis*

Comparison to Previous Missions

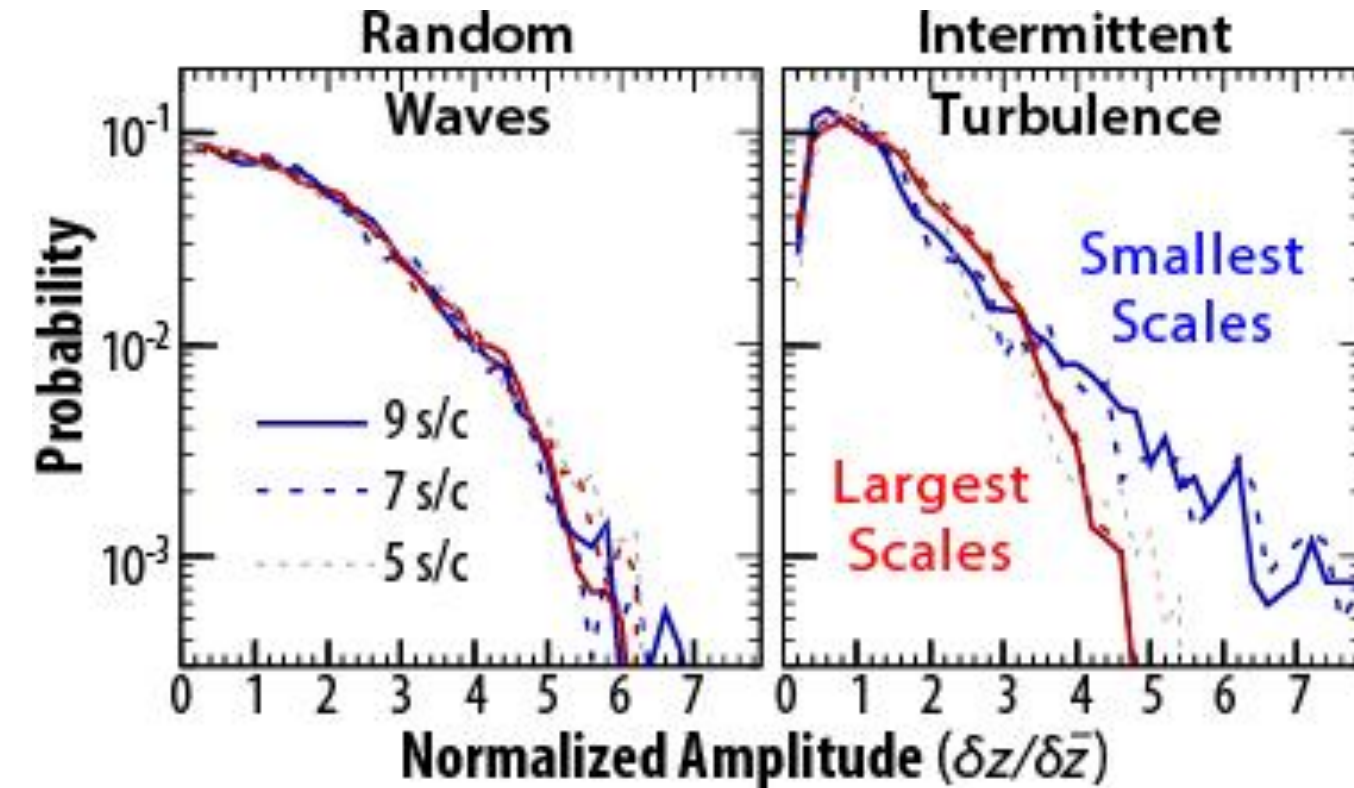


HelioSwarm's Science Orbit places it further from the Earth than previous missions such as Cluster, yielding longer residences in the pristine solar wind.

The longer period also produces more stable good geometric configurations, enabling statistical studies over longer periods of time.



Analysis Approach: Structure Functions

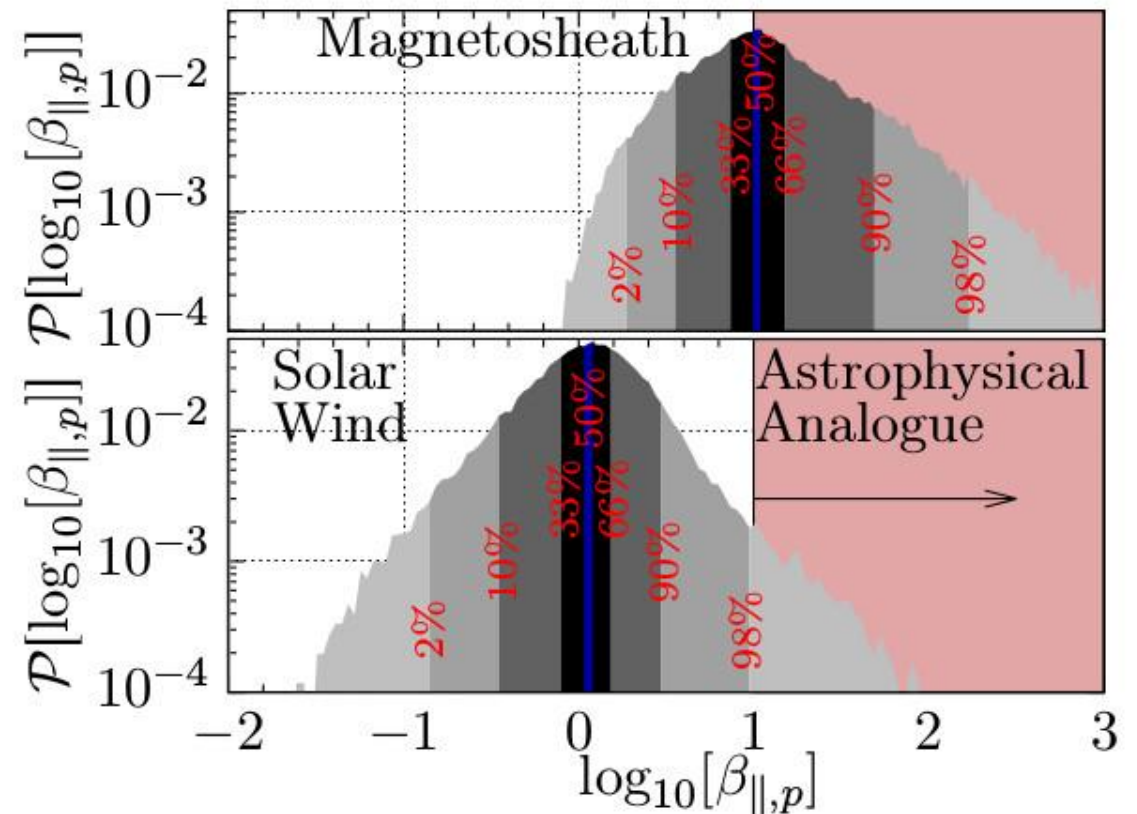
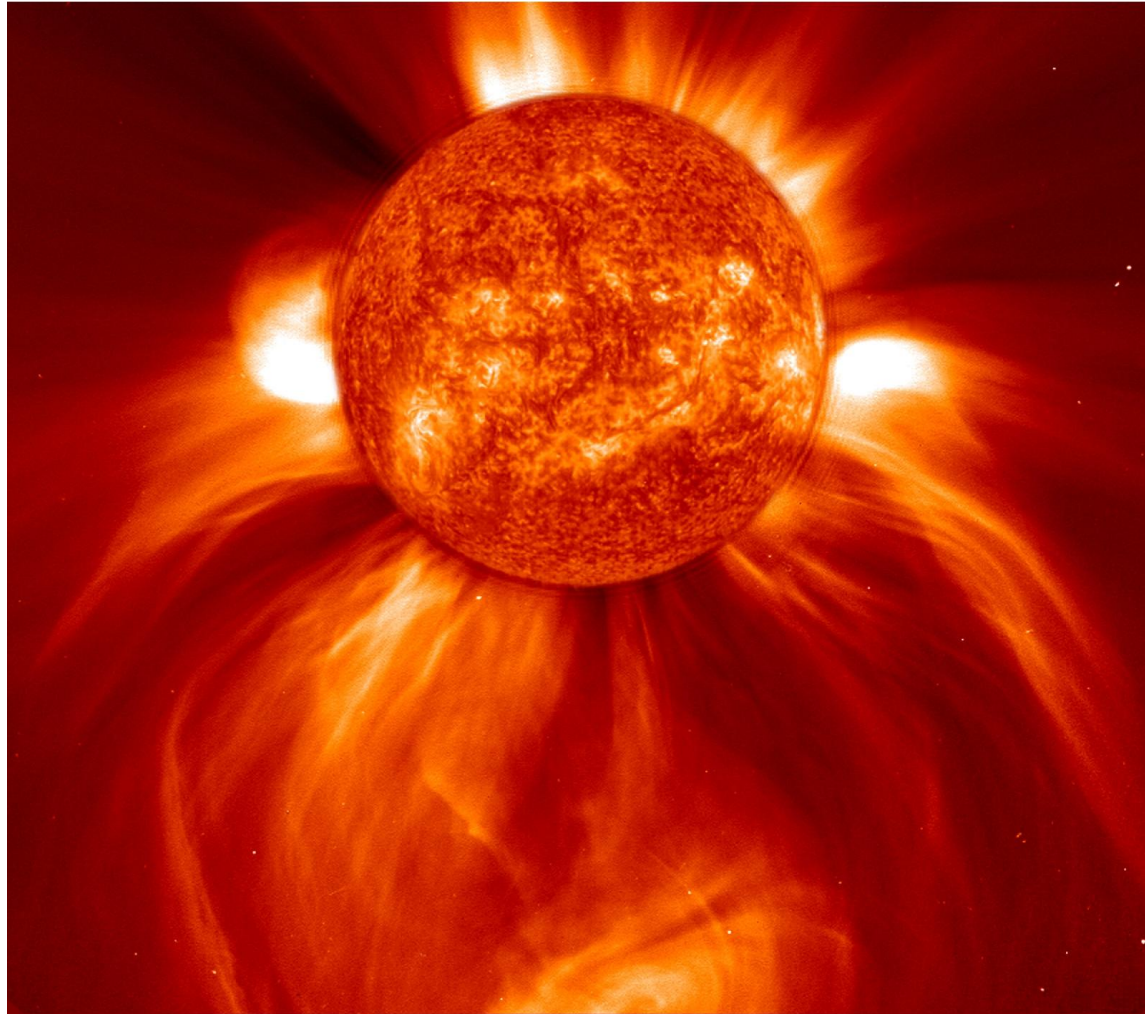


Calculating structure functions of measurements of plasma reveals variations in the statistical characteristics of the underlying turbulence, for instance how does the intermittent nature of the turbulence change for larger or smaller scale separations. This is typically done using an autocorrelation with a single time series.

HelioSwarm's 36 baseline separations between spacecraft will enable the calculation of such structure functions at both larger and smaller separations simultaneously, rather than needing to wait hours or days to collect sufficient data, potentially mixing different kinds of turbulence into a single calculation.

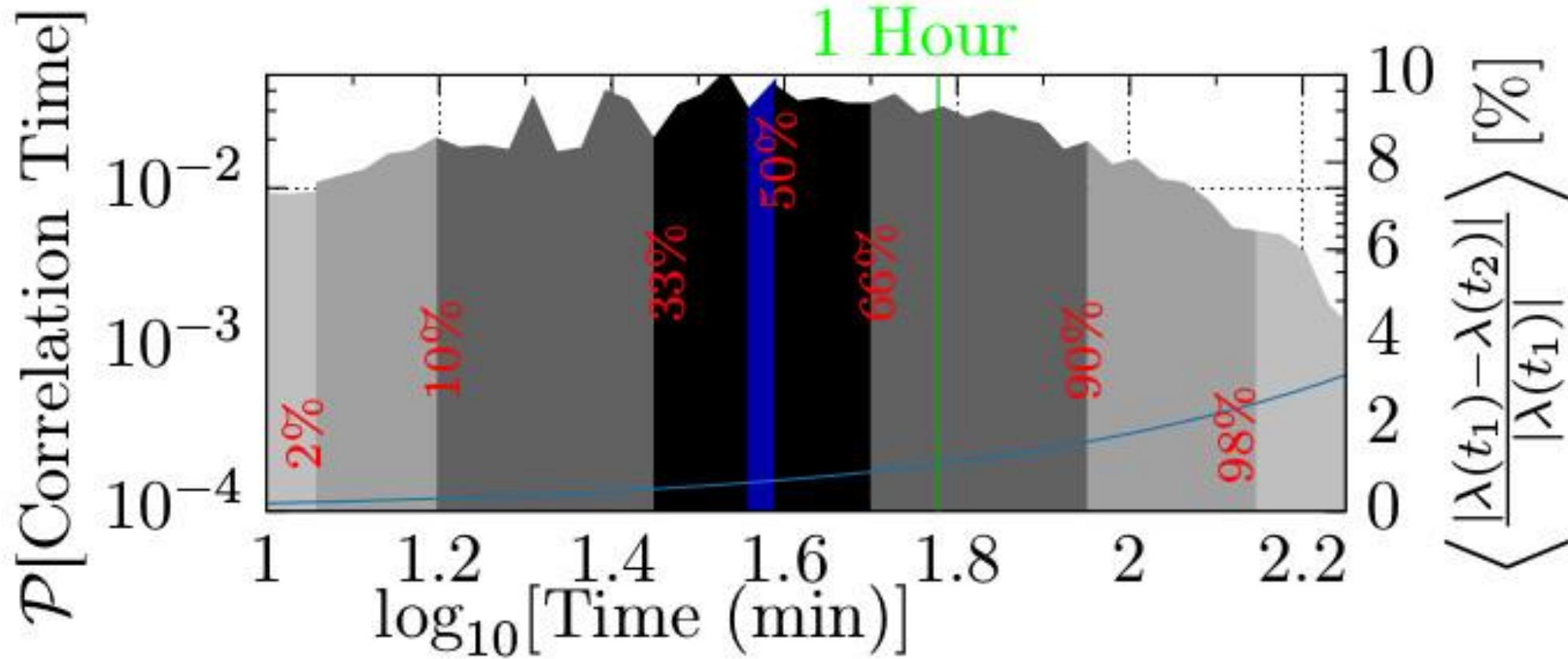
Shown is the calculation of the probability distribution function of the amplitude of the normalized Elsasser fluctuations for both large MHD and small ion kinetic scales (red and blue respectively, following Mallet et al 2015) drawn from HelioSwarm-like measurements of random waves, left, and a hybrid numerical simulation of turbulence, right.

The Solar Wind as a Natural Laboratory for Studying Plasmas

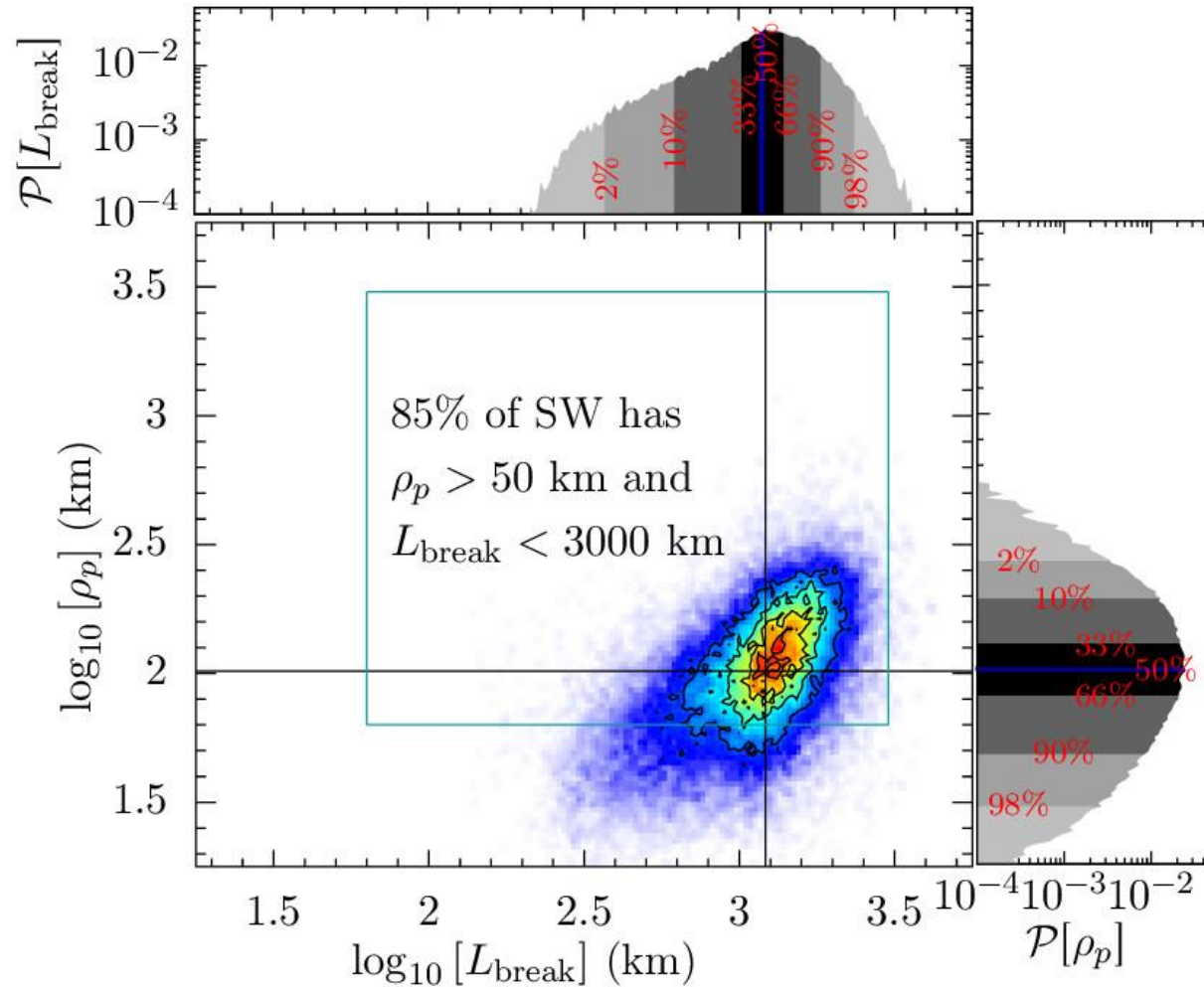


PDFs from Magnetosheath (Maruca et al 2018) and Solar Wind (Klein & Vech 2019) illustrate natural variability.

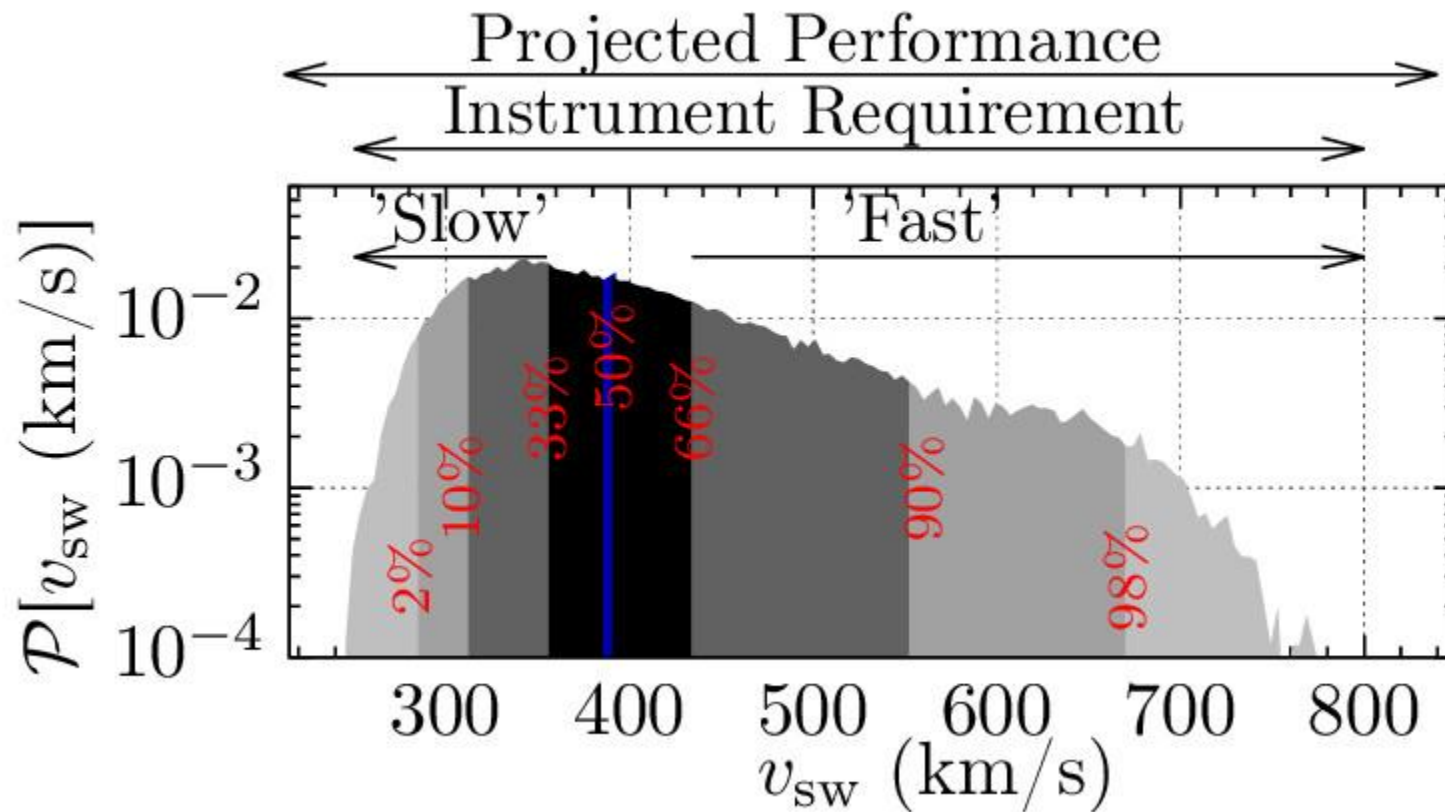
HelioSwarm Configurations Are Stable over Correlation Timescales



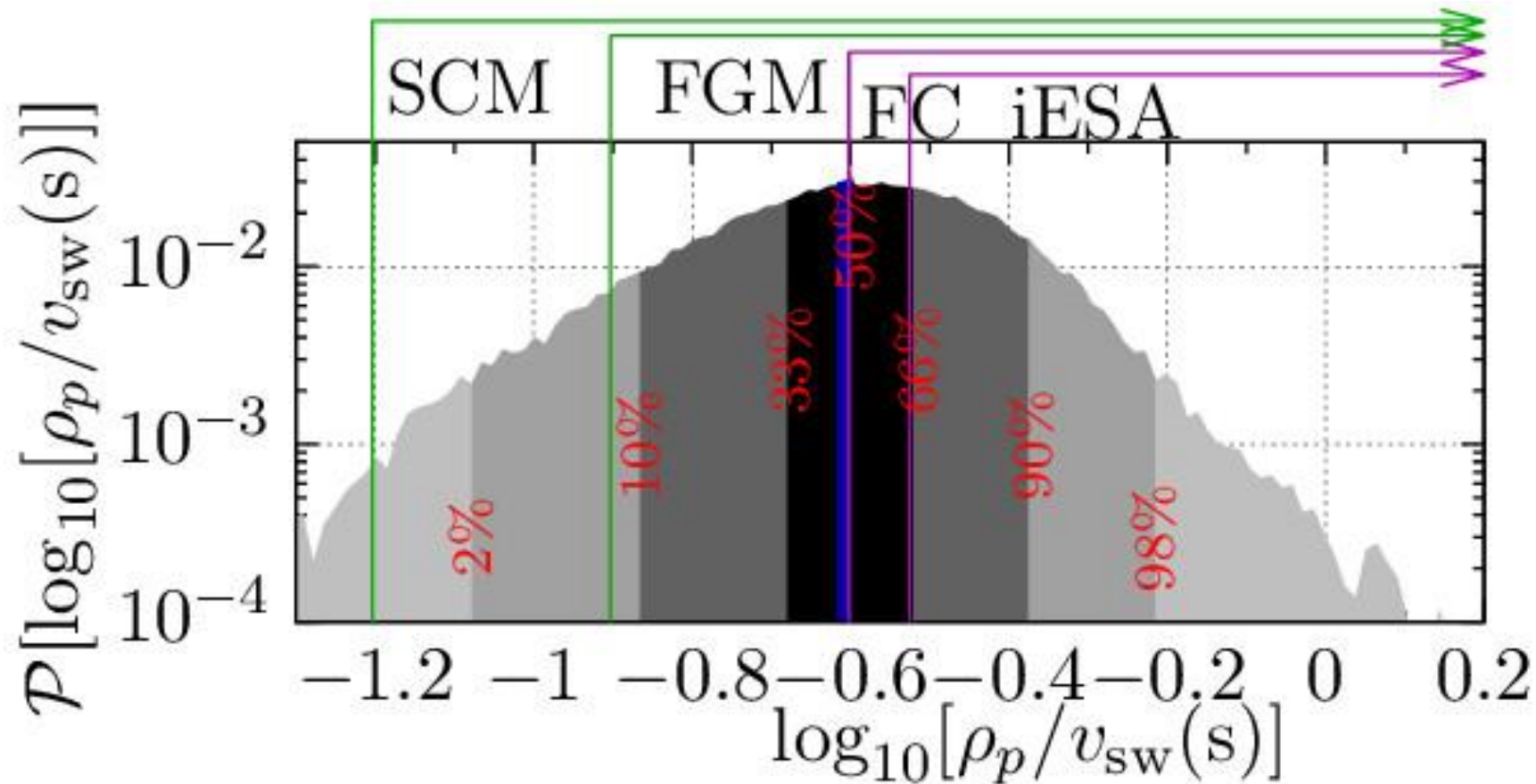
HelioSwarm Configurations Resolve Fluid and Proton Kinetic Scales



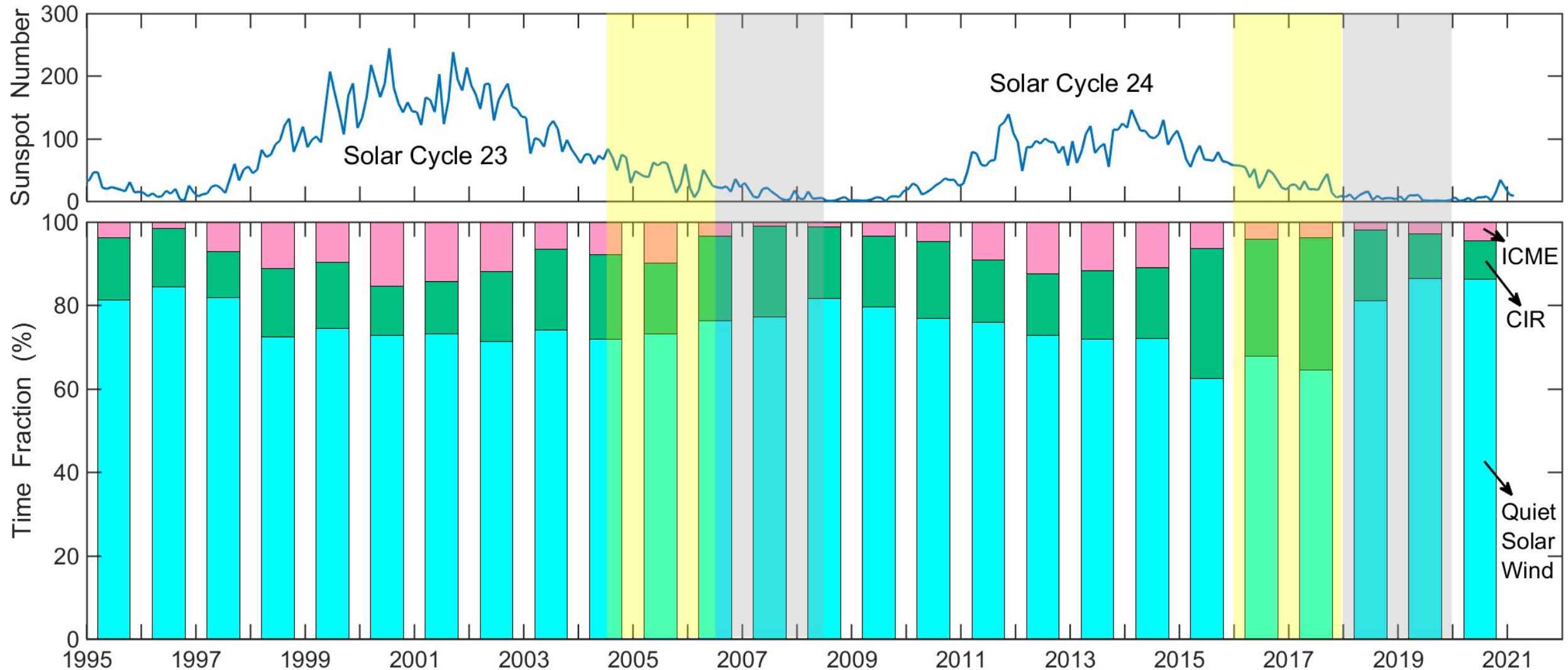
HelioSwarm Measures Full Range of Solar Wind Speeds



HelioSwarm Measures Advection Ion-Scale Structures

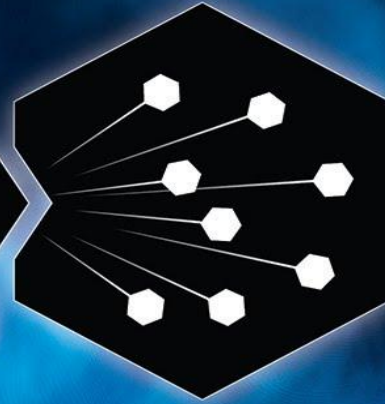


HelioSwarm Science Phase will Encounter ICMEs and CIRs





HELIO SWARM



THE NATURE OF TURBULENCE IN SPACE PLASMAS



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