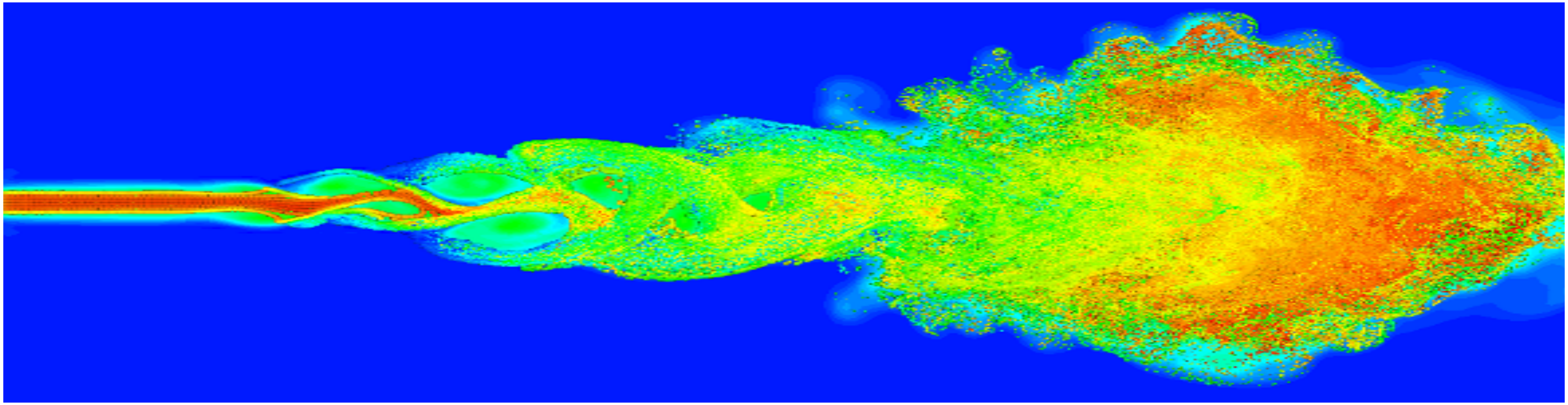
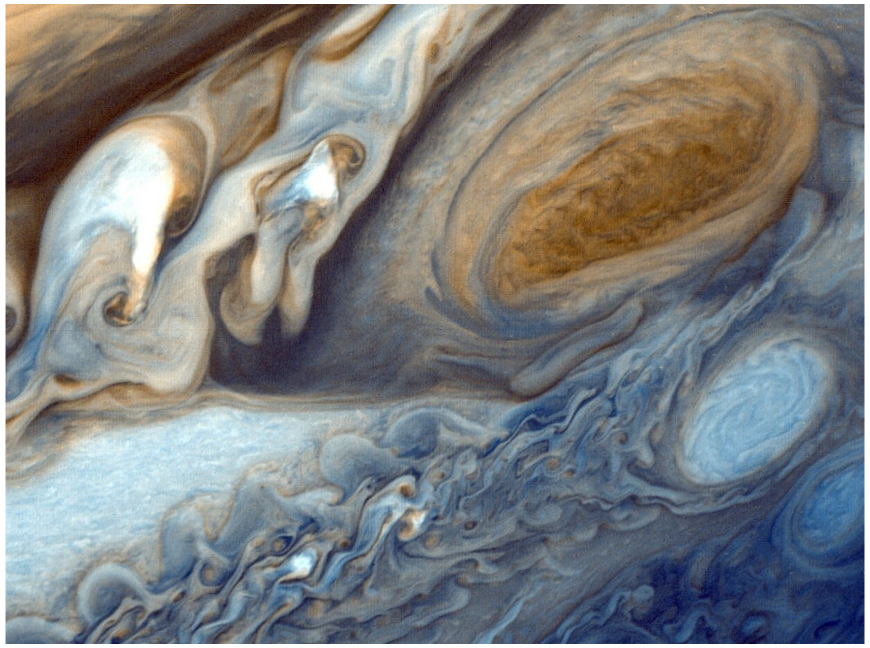
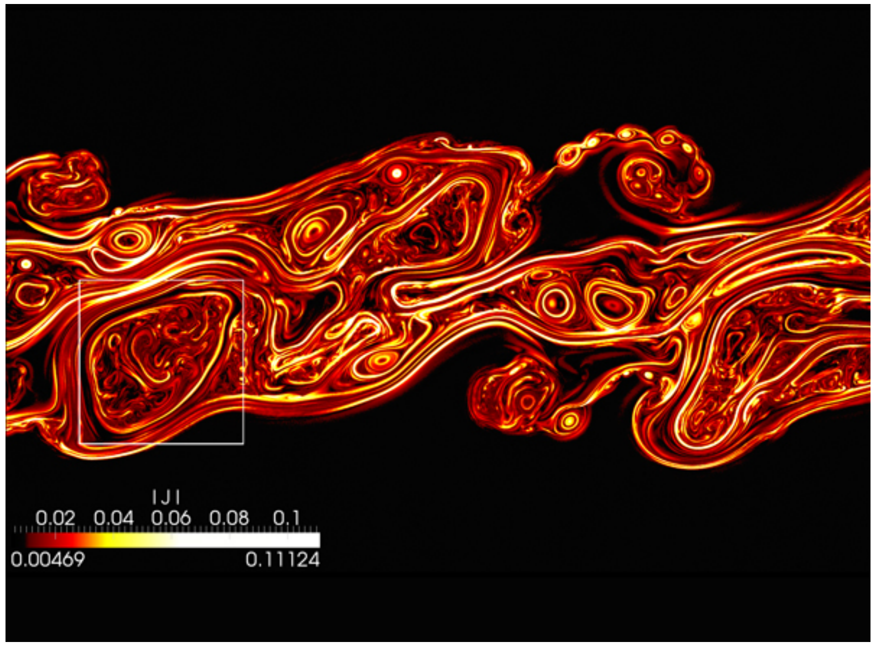


Plasma Turbulence

Natasha Jeffrey, Northumbria University





Lecture contents

- **Part 1: Basics of turbulence**

  - *What is turbulence?*
  - *Properties of turbulent flows.*
  - *Fluid versus MHD plasma turbulence.*

- **Part 2: Turbulence in solar and space plasmas**

  - *Role of turbulence in solar and space plasmas.*
  - *Examples of turbulence in solar plasma.*
  - *Examples of turbulence in space plasma.*

- **Summary and questions**

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What is turbulence?

- What words do you associate with turbulence???

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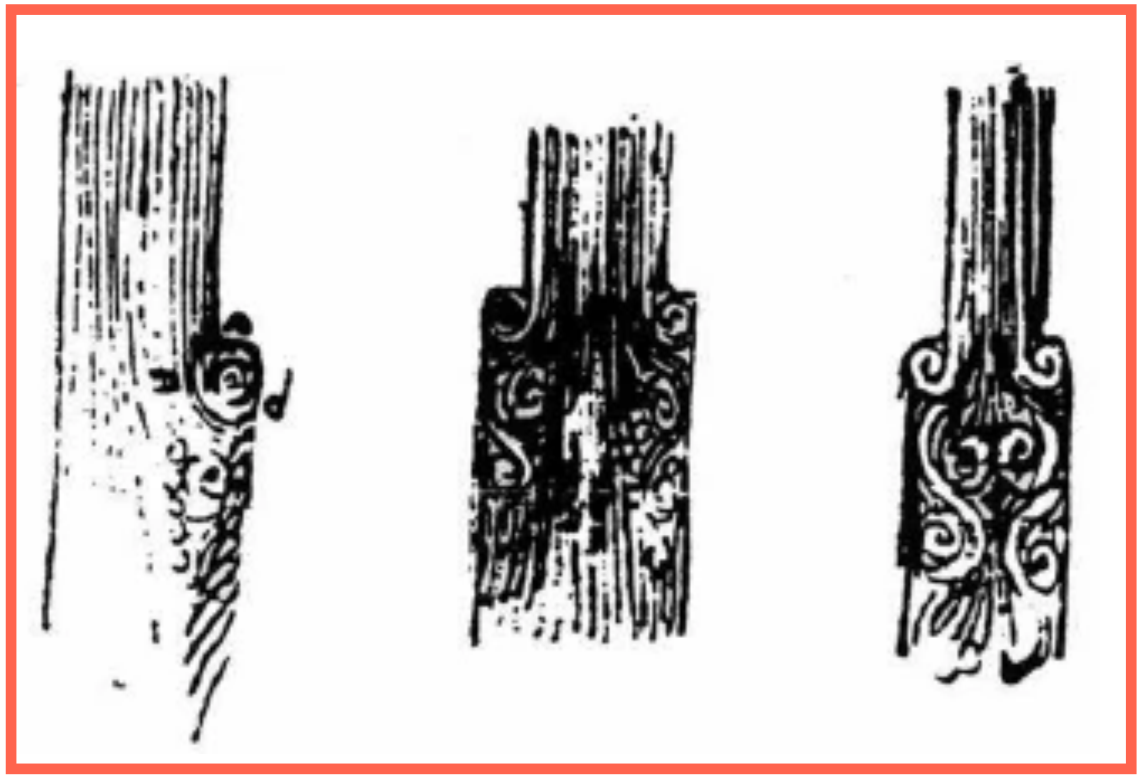
What is turbulence?

- What words do you associate with turbulence???

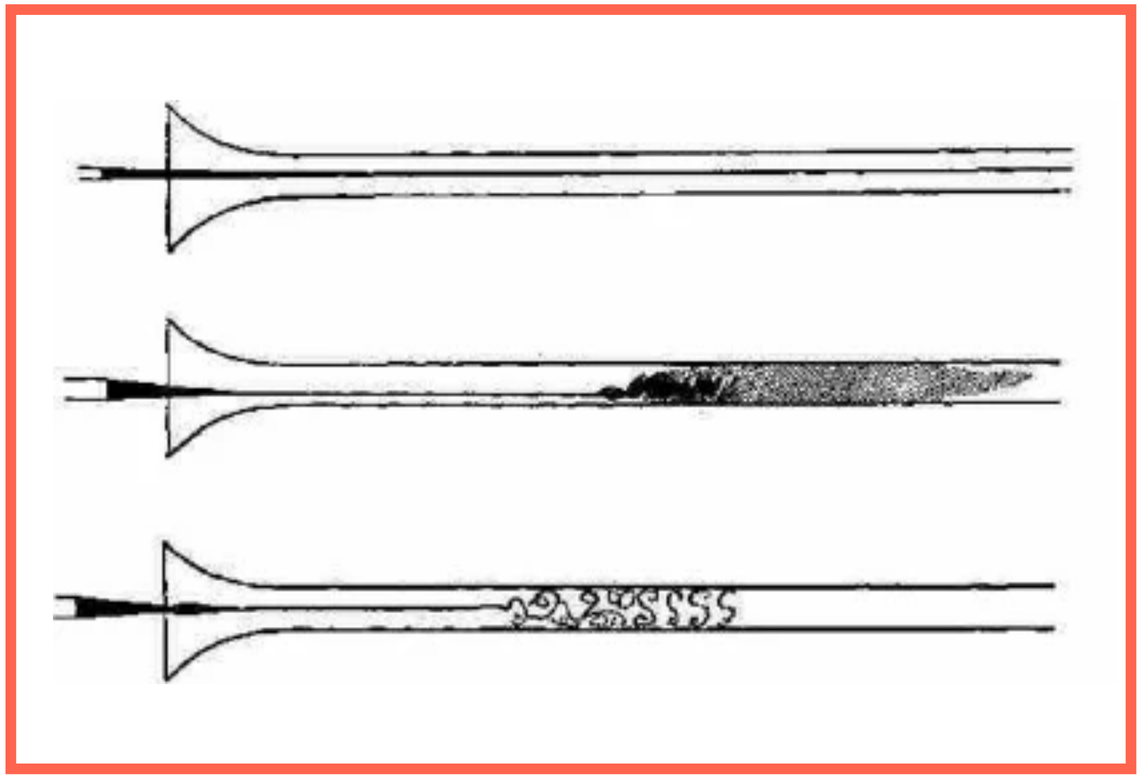
"disturbance" *"disruption"*

"chaotic" *"irregular"* *"unsettled"*

Latin: turba means something confusing or something which does not follow an ordered plan.



Studies of turbulence by Leonardo Da Vinci (Frisch 1995)



Original pictures by Reynolds 1883 (Bruno & Carbone 2013).

What is turbulence?

- What words do you associate with turbulence???

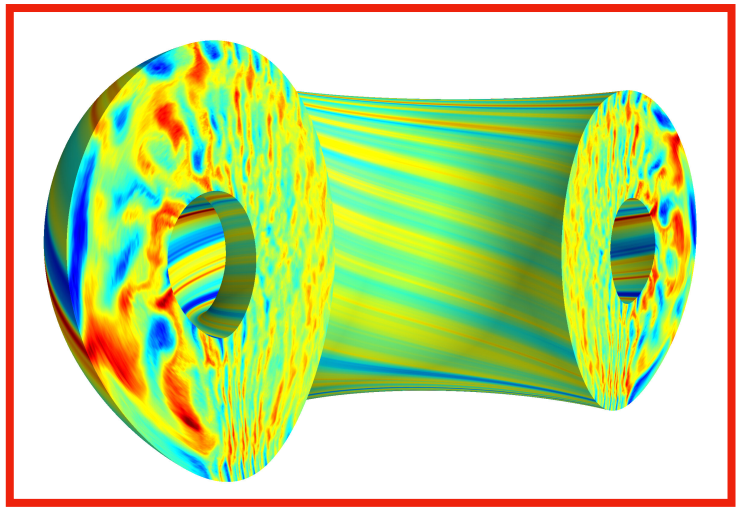
"disturbance" *"disruption"*

"chaotic" *"irregular"* *"unsettled"*

Latin: turba means something confusing or something which does not follow an ordered plan.

- Understanding turbulence is important as it appears everywhere in nature…



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What is turbulence?

- *"While fluids can flow in a variety of ways, turbulence describes the extremely complicated, chaotic motion that fluids frequently exhibit in natural and engineered systems."*

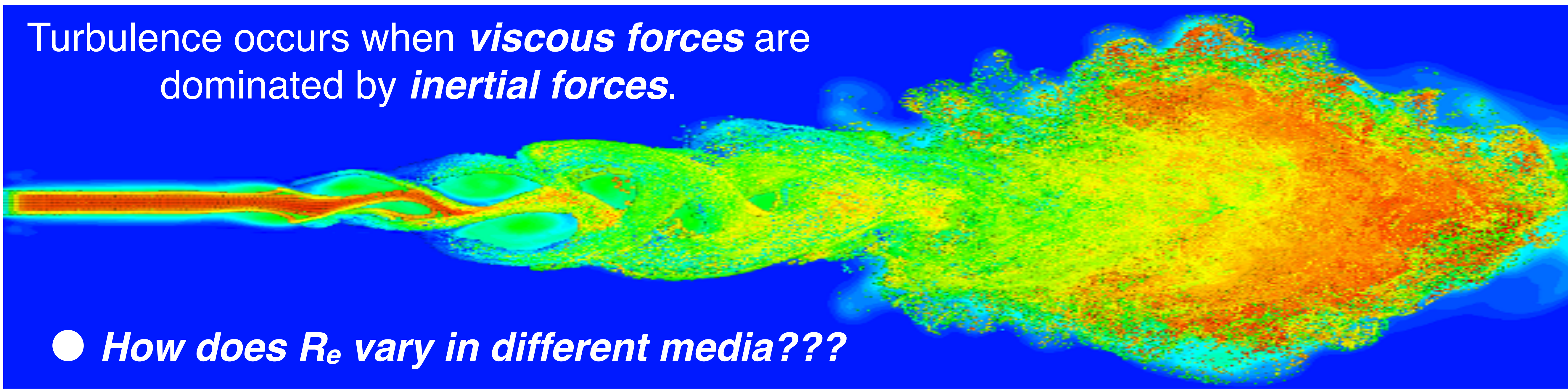
- Fluid flow can be described as **laminar** or **turbulent**:

  - **laminar flow** occurs at <u>low Reynolds numbers</u>, where viscous forces are dominant (leading to smooth, constant motion).

  - **turbulent flow** occurs at <u>high Reynolds numbers</u>, where inertial forces are dominant (leading to chaotic eddies, vortices and other flow instabilities).

$$\mathrm{Re} = \frac{\rho v L}{\mu}$$

ρ is the density of the fluid
v is a characteristic velocity of the fluid with respect to the object
L is a characteristic linear dimension
μ is the dynamic viscosity of the fluid

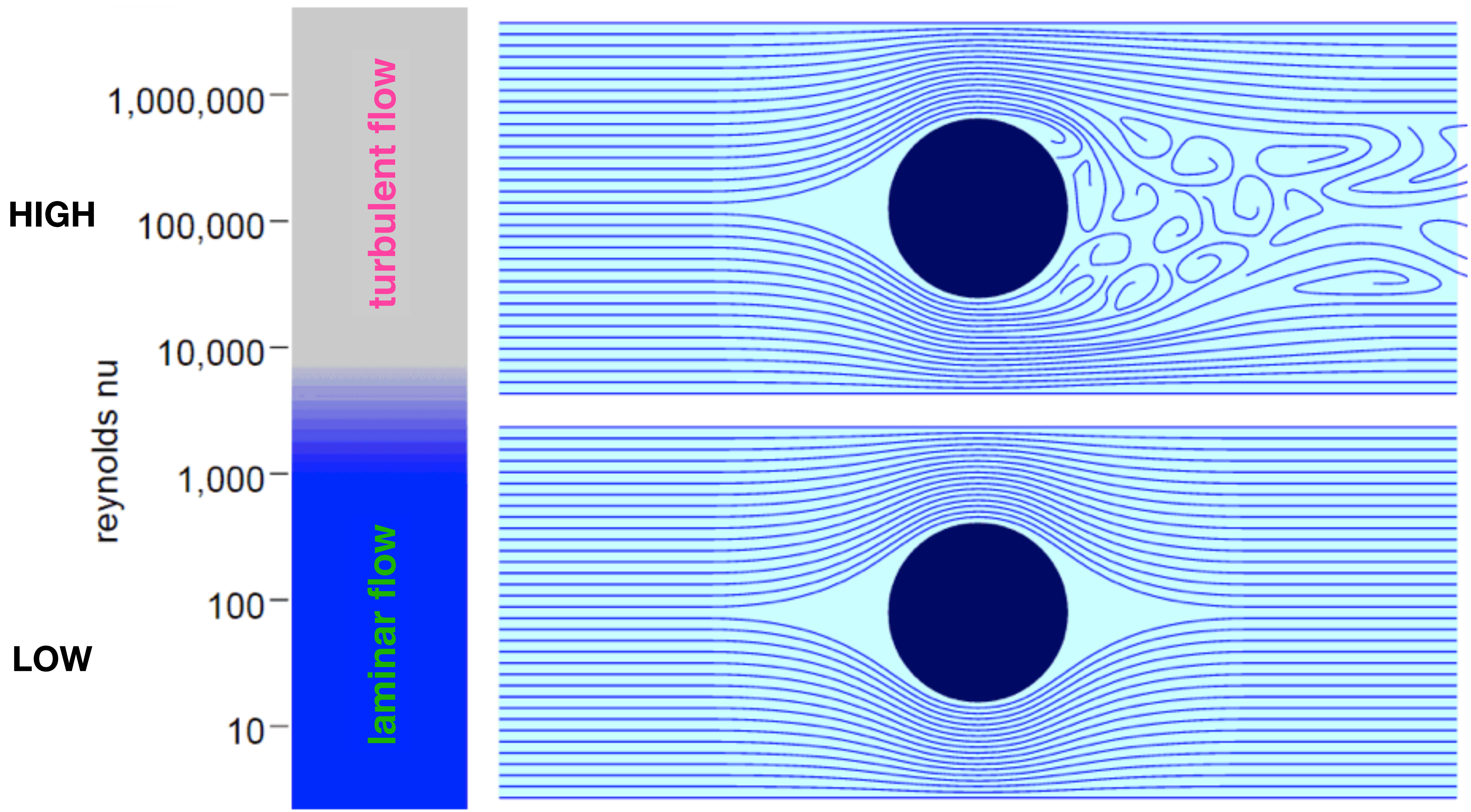


Turbulence occurs when ***viscous forces*** are dominated by ***inertial forces***.

- ***How does R_e vary in different media???***

What is turbulence?

- *"While fluids can flow in a variety of ways, turbulence describes the extremely complicated, chaotic motion that fluids frequently exhibit in natural and engineered systems."*
- Fluid flow can be described as **laminar** or **turbulent**:



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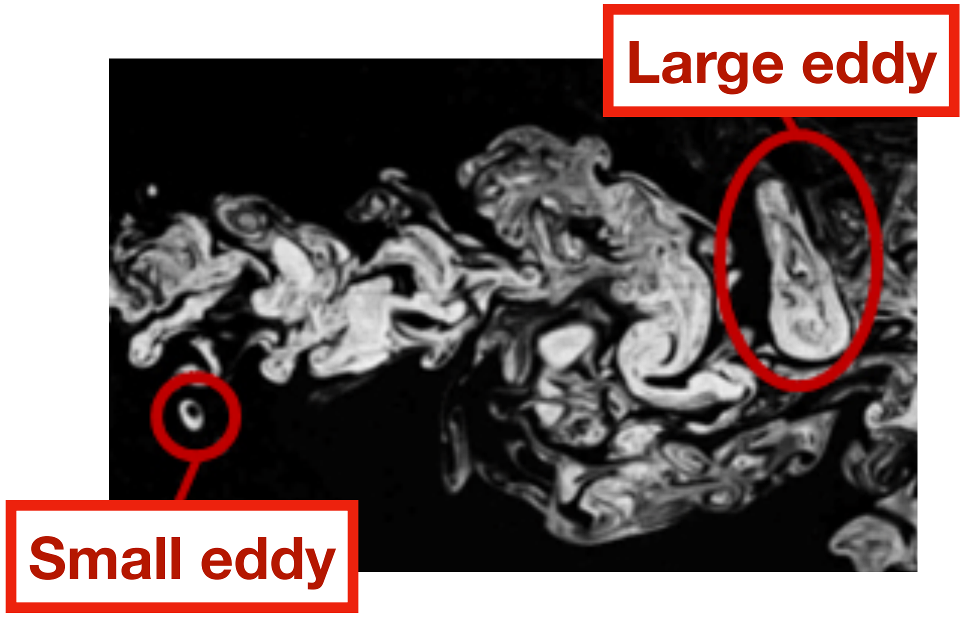
Useful turbulence glossary

- **Eddy** - "rotating fluid element" or a "turbulent motion" localised over a region of size l and ~ coherent over this region.
- **Characteristic quantity** - the length / timescale / velocity etc. over which a process takes place.
- **Turnover time** - the timescale over which an eddy of scale l undergoes significant distortion.
- **Correlation length** - defines a length scale over which the deviations from the average stop being similar / measure of the order of the system / relationship between neighbouring fluctuations.
- **Energy power spectrum** - usually a plot of energy E(k) versus wavenumber k telling us how the energy of the system is distributed amongst the different scales.
- **Energy cascade** - defines the flow of energy between different length scales from injection to dissipation, via the inertial scale.
- **Inner and outer scales** - Scales related to the lengths at which injection and dissipation occur. A Kolmogorov assumption occurs over the inertial range i.e., $1/L \ll k \ll 1/l$.
- **Incompressible** - fluid density is the same everywhere.
- **Viscosity** - measure of a fluid's resistance to flow.
- **Homogeneous** - same properties at every point in space / all points in the fluid.
- **Isotropic / Anisotropic** - no directional preference / directional preference.

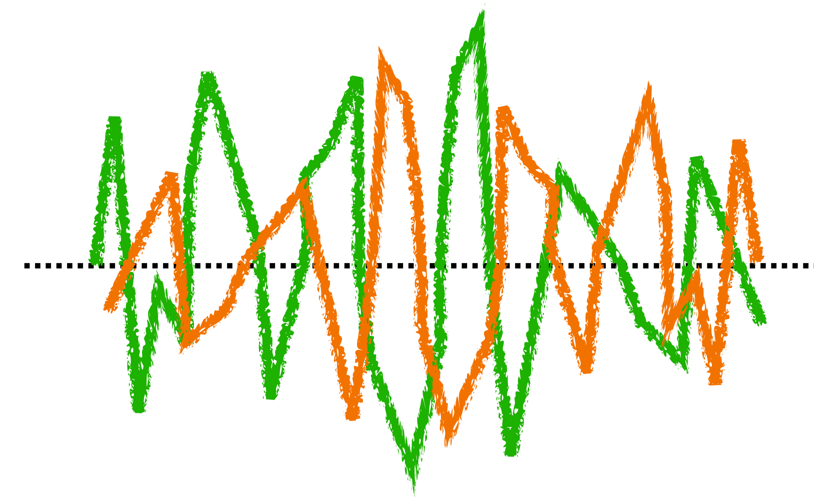
Properties of fluid turbulence

- **Main properties of fluid turbulence:**

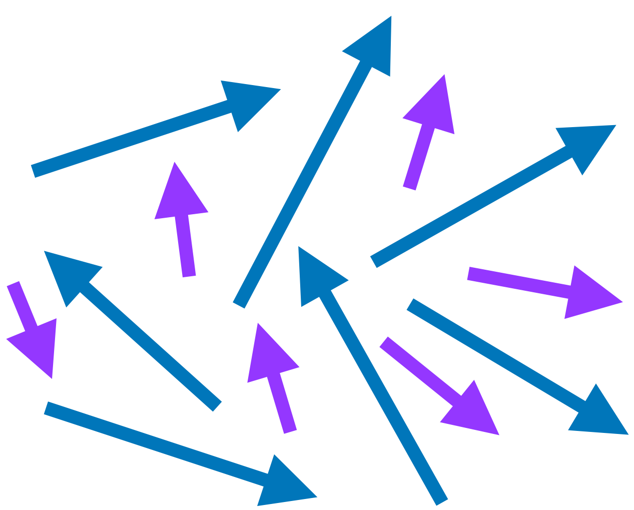


- **Randomly fluctuating parameters** (v, P, T) with erratic motions and different size eddies.

- **Irregularity** (space, time).



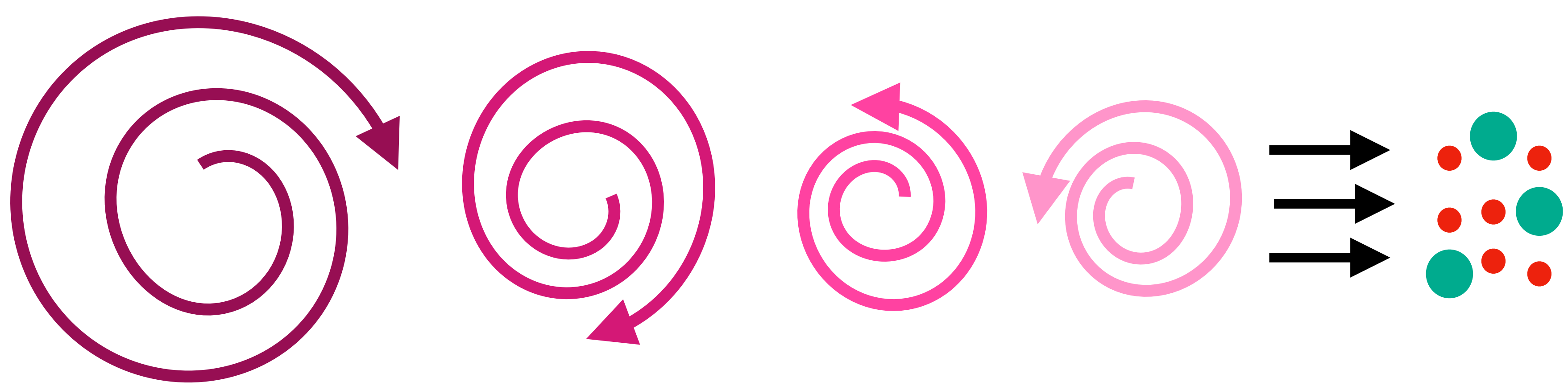
- **High Reynolds number**.



- **Flow pattern is random** (or “stochastic") with no preferred direction.

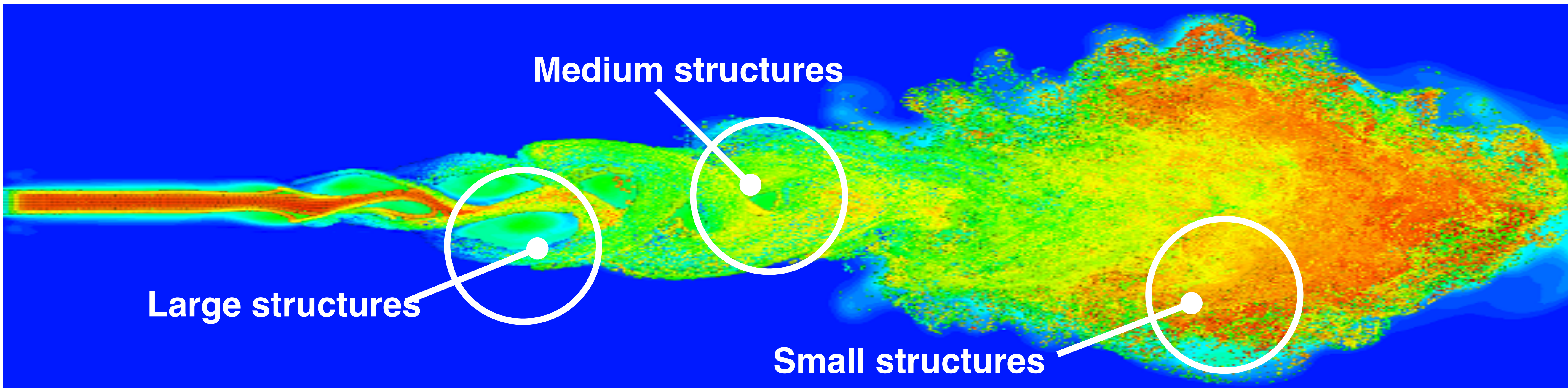
- **Diffusive** nature.

- **Dissipative**.

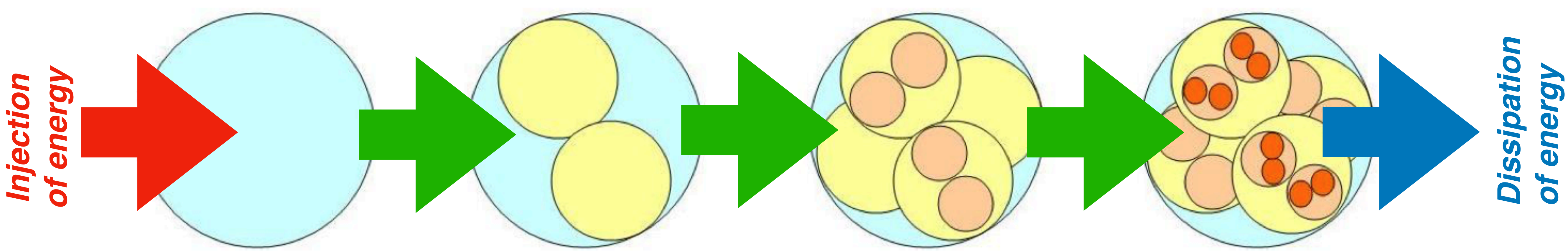


Turbulent energy cascade

- Turbulent motions occur over a wide range of length and time scales.
- Energy is **input at large scales** and energy is **dissipated at small scales**.
- There are three main intervals in the energy cascade: (1) **Generation of energy,** (2) **Inertial range (steady state)**, (3) **Dissipation**.

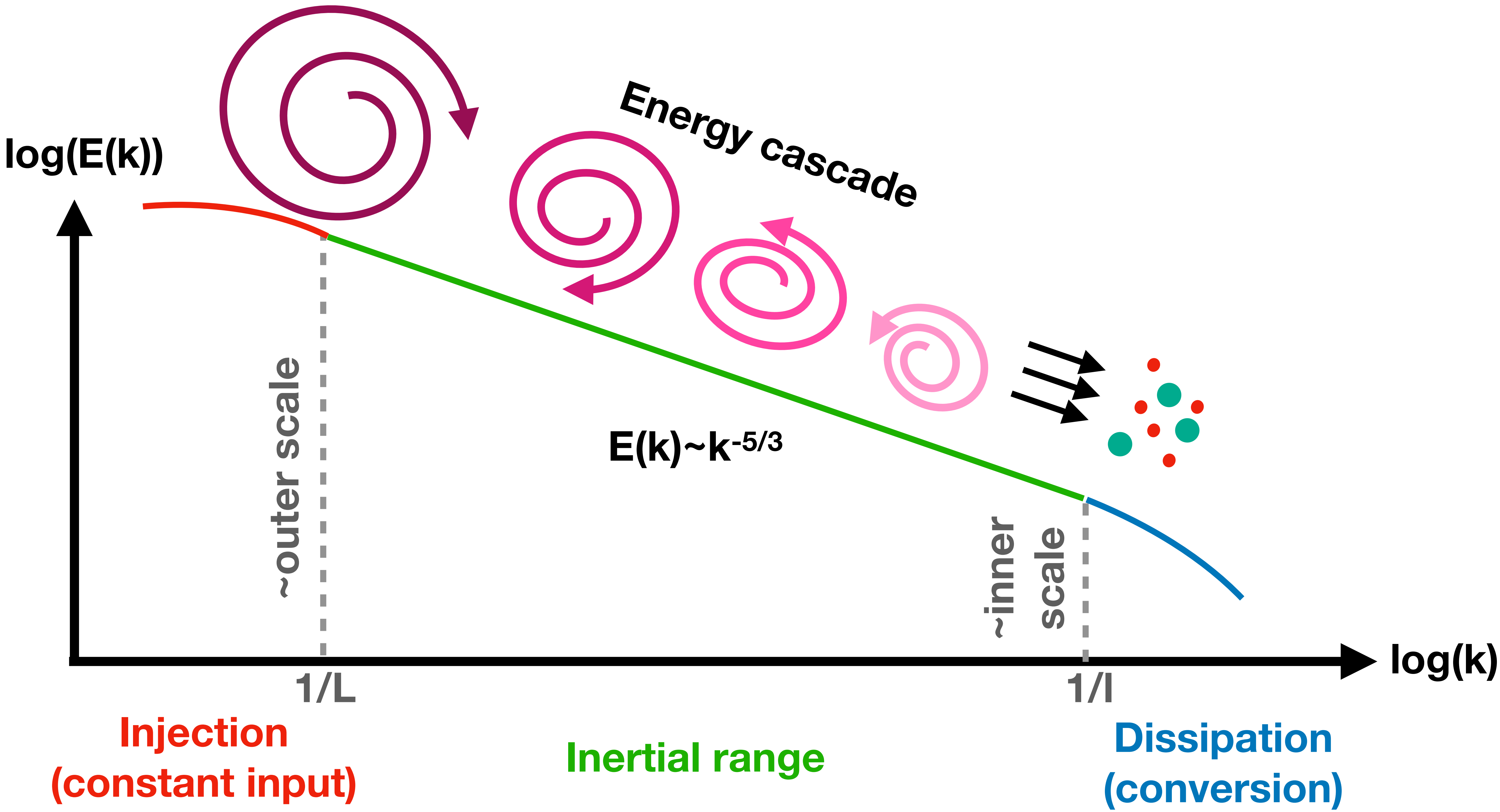


- When energy is supplied at large scales, it gets redistributed over fluctuations of different scales, and removed at small scales where viscosity can finally dominate.



Turbulent energy cascade

- **Hydrodynamic turbulence is universal**, the energy cascade in the inertial range does not dependent on the energy-injection mechanism or on the dissipation mechanism.



- The slope of -5/3 in the inertial range is known as the **Kolmogorov spectrum**.

Kolmogorov spectrum

- ***Assumptions:*** *turbulence is incompressible, homogeneous and isotropic.*
- ***Assumptions:*** *energy transfer rate is constant from large eddies to small eddies.*

Eddy turnover time, t : $t = \frac{l}{u}$ and **wavenumber, k :** $k = \frac{2\pi}{l}$ *small eddies have large k*

Turbulent kinetic energy per unit mass : $u^2 = \int_0^\infty E(k)dk$ *i.e., integral over all scales.*

Energy transfer rate / dissipation rate: $\epsilon = \frac{\text{energy}}{\text{time}} = \frac{u^2}{t} = u^3 k = \text{constant}$

Hence, $u = \epsilon^{1/3} k^{-1/3}$

Energy spectrum E(k) : $E(k) = \frac{u^2}{k} = \frac{\epsilon^{2/3} k^{-2/3}}{k} = \epsilon^{2/3} k^{-5/3}$

$E(k) \sim k^{-5/3}$ is known as the Kolmogorov spectrum, universal amongst all inertial scales between the energy injection (outer) and dissipation (inner) scales, i.e.,

$$1/L << k << 1/l$$

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MHD plasma turbulence

- **Most astrophysical plasmas are magnetised leading to MHD plasma turbulence.**

- **MHD turbulence describes turbulence in an electrically conducting, magnetised fluid**.

- **The presence of a magnetic field at larger scales introduces anisotropy.**

- The energy cascade in different directions is now different (main difference to fluid turbulence with no preferred direction).

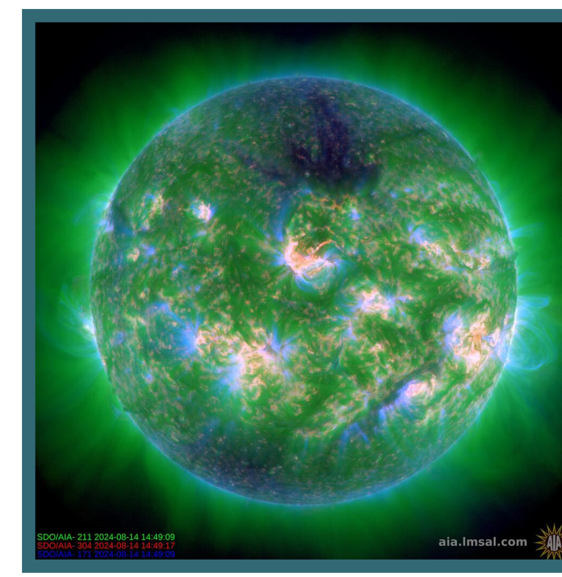
- Astrophysical sources will only be turbulent if there are suitable forces to drive the turbulence.

- We also define the **magnetic Reynolds number:**

$$\mathrm{R_m} = \frac{UL}{\eta} \sim \frac{\text{induction}}{\text{diffusion}}$$

U is a characteristic velocity of the fluid
L is a characteristic linear dimension
η is the magnetic diffusivity

- **Magnetic diffusivity** - rate of magnetic diffusion ("magnetic viscosity").



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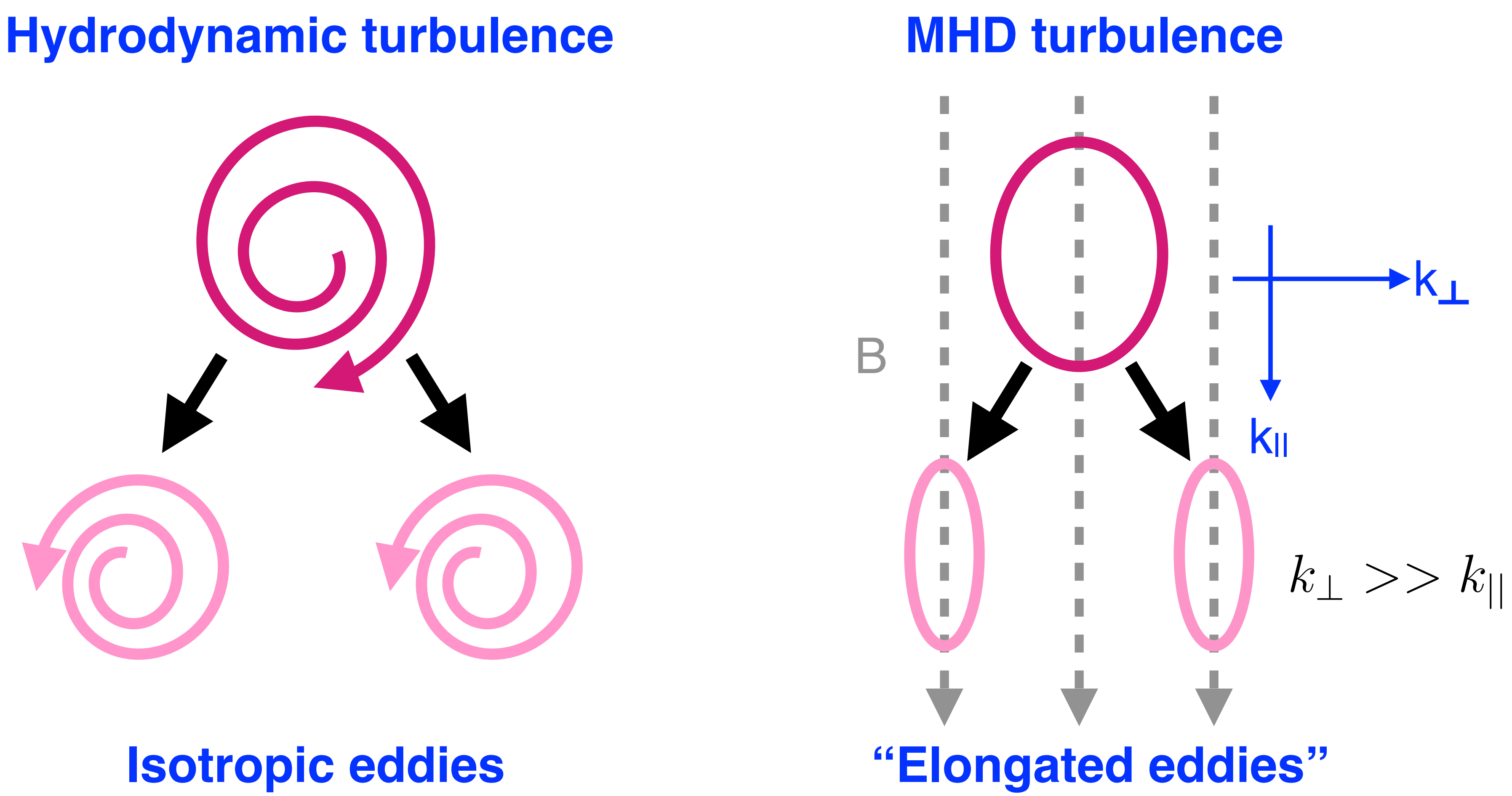
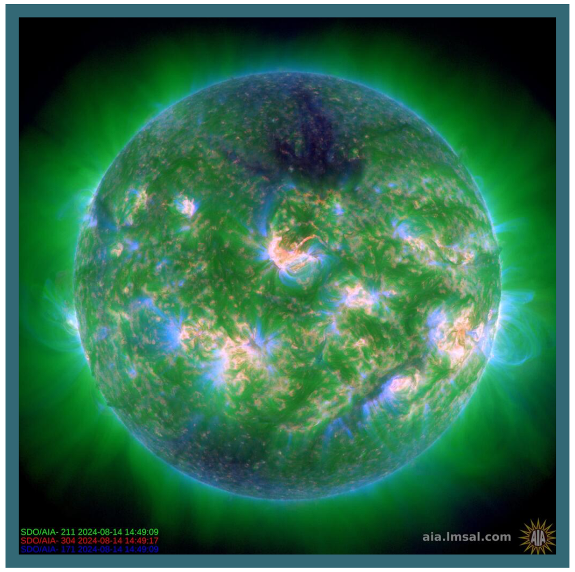
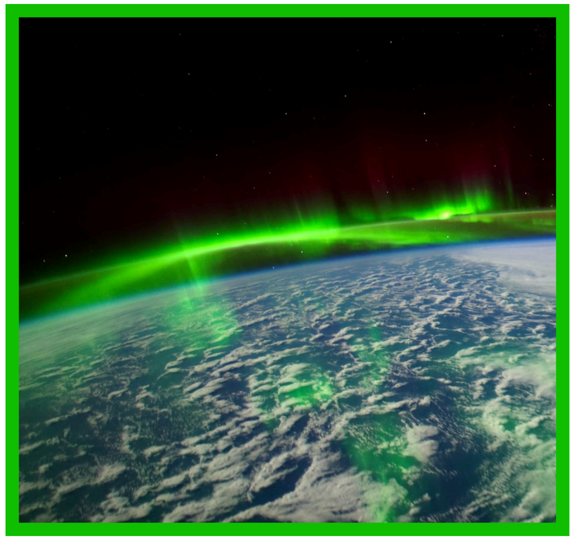


- In MHD, motion along B is free, but it is limited across B.





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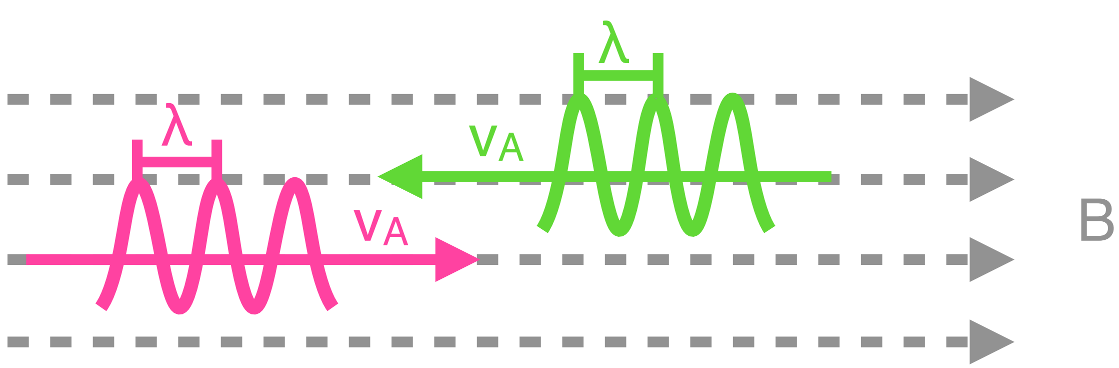
Iroshnikov-Kraichnan spectrum

- Iroshnikov (1963) & Kraichnan (1965) (IK) determined the cascade spectrum in the inertial range for **weak MHD turbulence** with a **strong large-scale magnetic field**.

We will discuss this assumption again later when we look at turbulence in the solar wind!

- A plasma threaded by a straight uniform magnetic field B is considered. It is assumed that the **turbulence is weak**, i.e., many interactions are required to transfer energy to smaller scales.

- MHD turbulence can be created by counter-propagating magnetic disturbances such as **Alfvén waves**.



- In MHD turbulence, a new timescale becomes important and this is the **Alfvén timescale** (~ period of an Alfvén wave).

$$t_A \approx \frac{\lambda}{v_A}$$

The above assumptions lead to a Iroshnikov-Kraichnan spectrum (opposite wave packets interact weakly), which has a flatter spectrum than Kolmogorov (slower energy cascade).

Iroshnikov-Kraichnan spectrum

- Iroshnikov (1963) & Kraichnan (1965) (IK) determined the cascade spectrum in the inertial range for **weak MHD turbulence** with a **strong large-scale magnetic field**.

We will discuss this assumption again later when we look at turbulence in the solar wind!

- Number of interactions N required to deform the packet (*u* now represents components of fluctuating velocity):

$$N = \left(\frac{v_A}{u}\right)^2$$

- Dominant timescale (Alfvénic time):

$$t = N\frac{\lambda}{v_A} = \left(\frac{v_A}{u}\right)^2\frac{\lambda}{v_A} = \frac{v_A}{ku^2}$$

- **Turbulent kinetic energy per unit mass :**

$$u^2 = \int_0^\infty E(k)dk$$

- **Energy transfer rate / dissipation rate:**

$$\epsilon = \frac{\text{energy}}{\text{time}} = \frac{u^2}{t} = u^4 k = \text{constant}$$

- Hence,

$$u = \epsilon^{1/4}k^{-1/4}$$

- **IK energy spectrum E(k):**

$$E(k) = \frac{u^2}{k} = \frac{\epsilon^{1/2}k^{-1/2}}{k} = \epsilon^{1/2}k^{-3/2}$$

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Solar/space physics turbulence

Turbulence is present and plays a key role in the behaviour and evolution of plasma in solar and space physics.

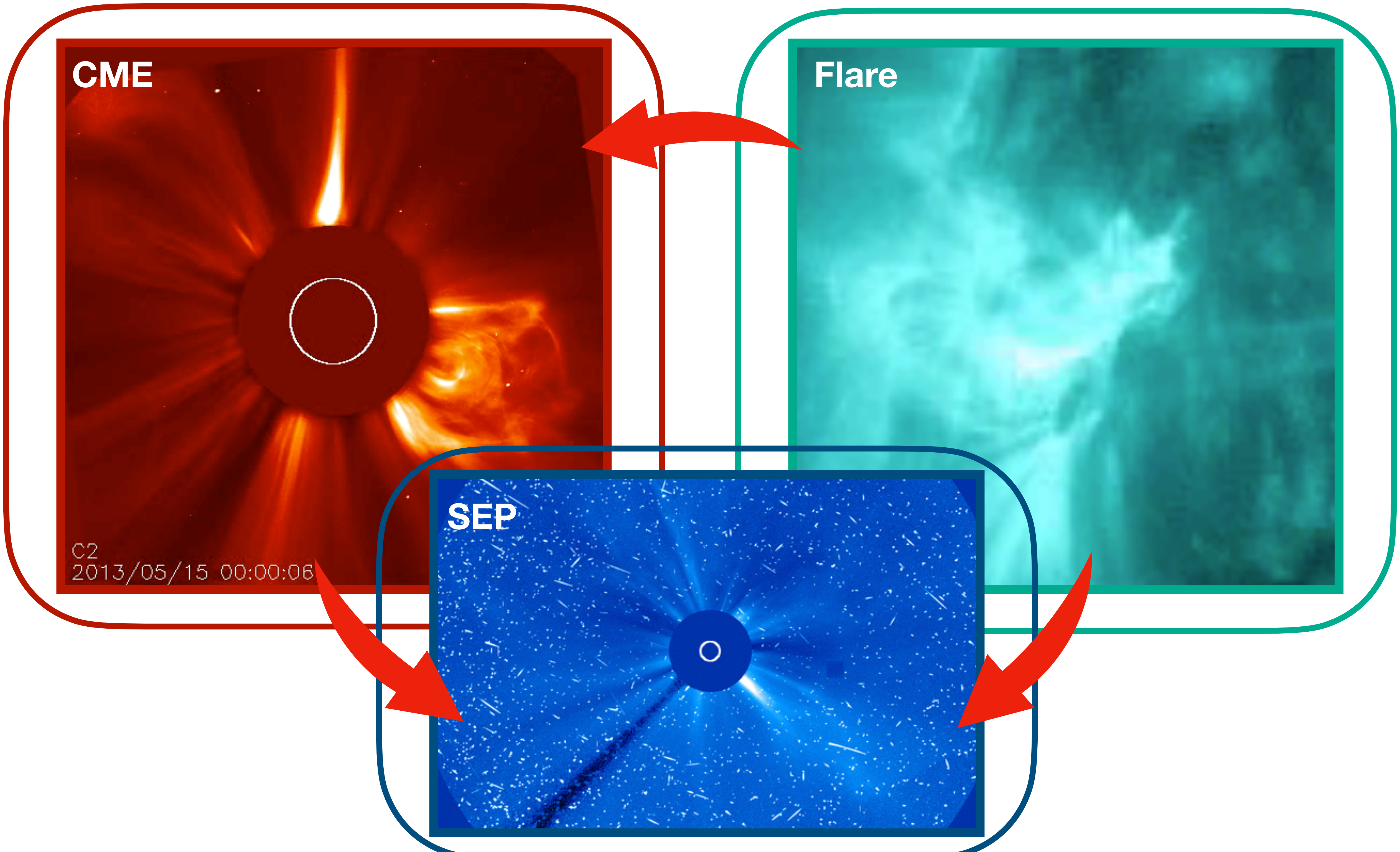
- Here, we will briefly discuss three examples:

1. Spectral line broadening and the role of turbulence in solar flares.
2. In-situ measurements and solar wind turbulence
3. Radio measurements and solar wind turbulence

There are still many challenges associated with understanding MHD plasma turbulence (e.g., development, dissipation)!

Solar Energetic Particles

- The Sun is an efficient particle accelerator producing energetic electrons, protons and ions during transient events e.g., flares and coronal mass ejections (CMEs).



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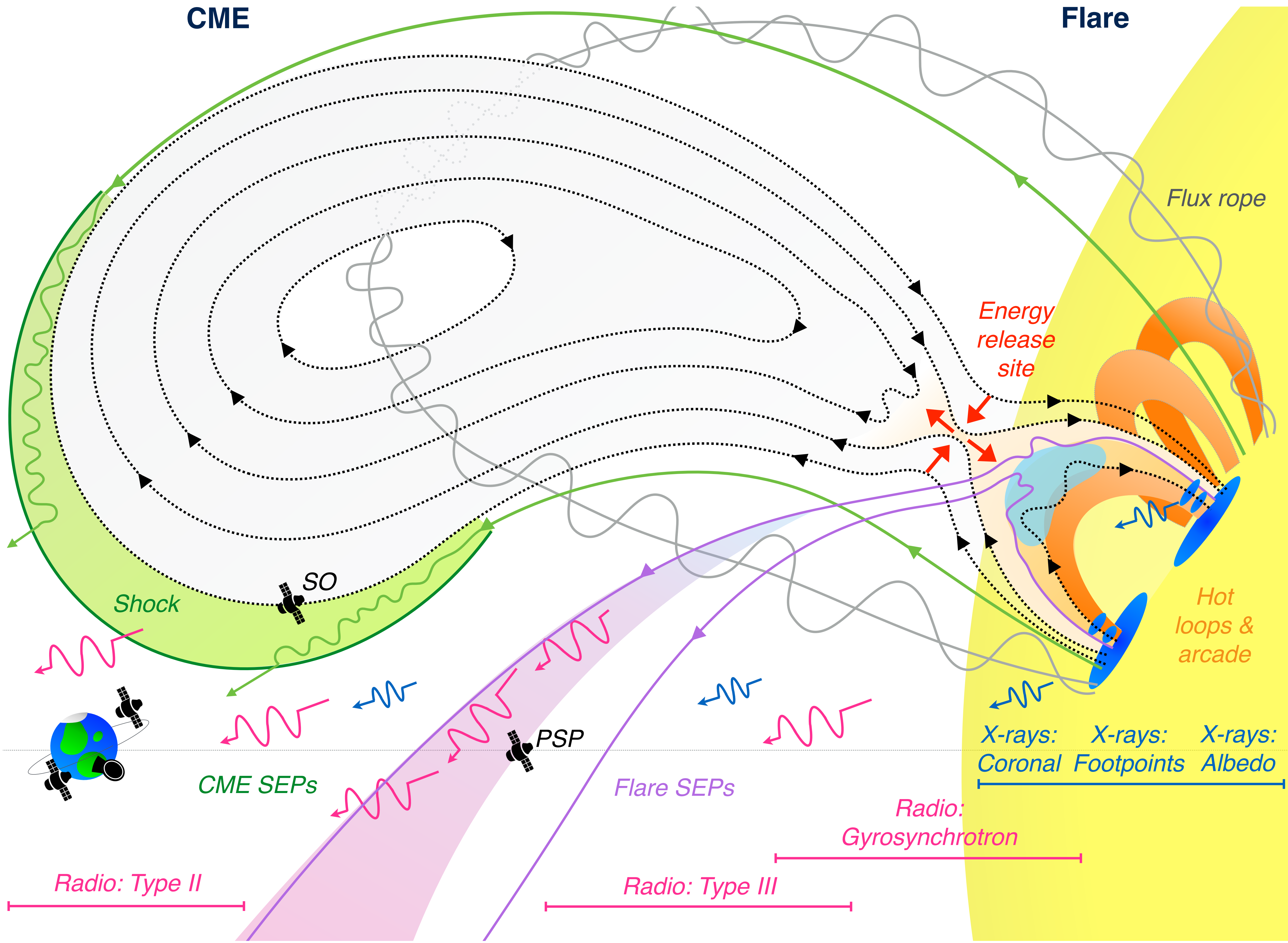
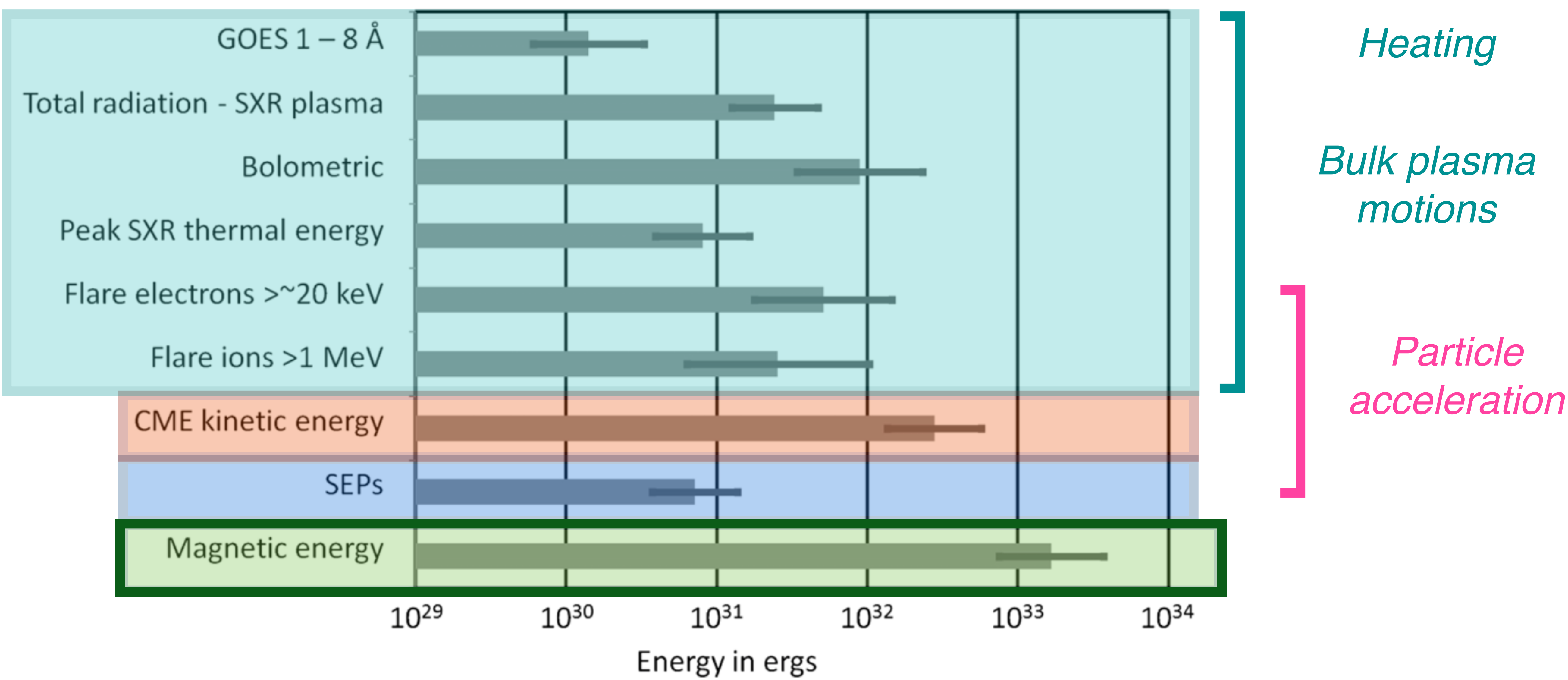
Solar Energetic Particles



Solar Flare Energy Partition

Understanding solar flares means we have to understand how energy is released, dissipated and deposited, at all stages.

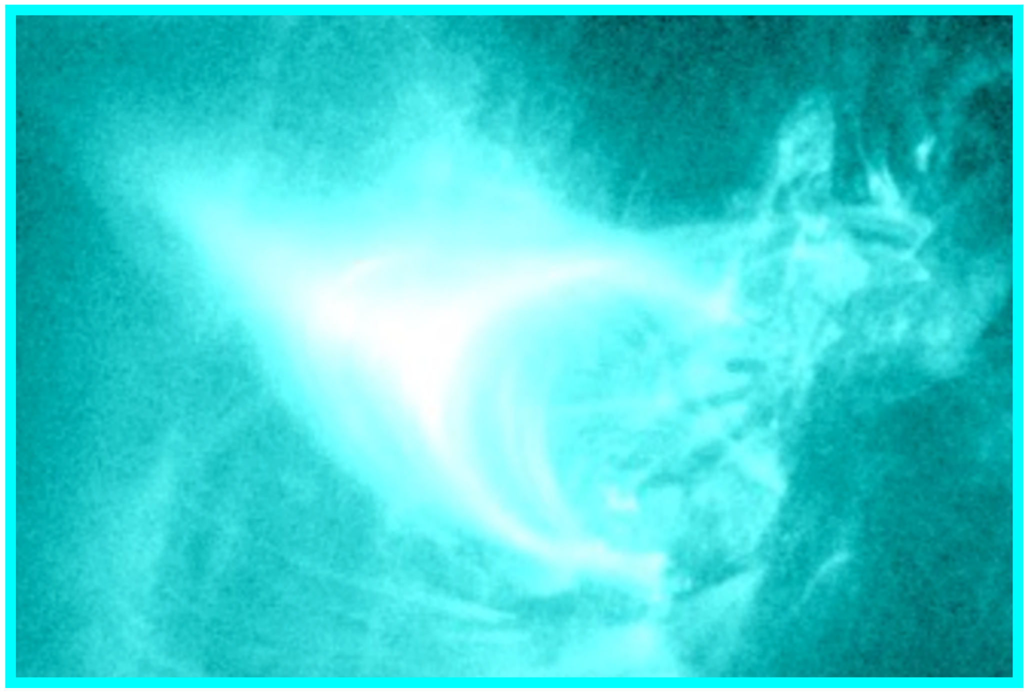
- A medium solar flare releases about 10^{32} erg (where 1 megaton of TNT = 4×10^{22} erg).
- The ***magnetic energy*** is transformed into different energies *e.g. Emslie et al. 2012.*

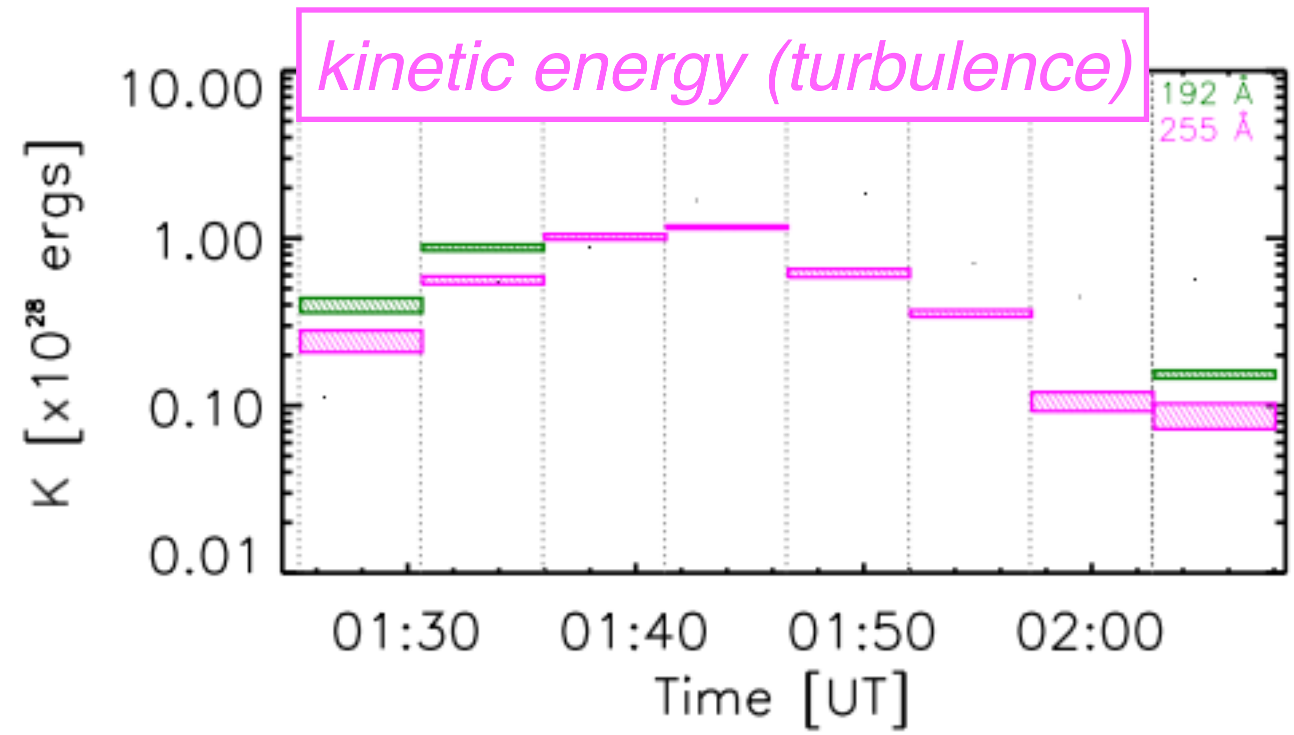


Solar Flare Turbulence

A substantial fraction of the magnetic energy goes into non-thermal electrons.

e.g., **Emslie et al. 2012**, **Warmuth & Mann 2016**, **Aschwanden et al. 2017**.





- **Turbulence** is an important mechanism for the transfer of magnetic energy e.g. **Larosa & Moore 1993, Petrosian 2012, Vlahos et al. 2016, Kontar et al. 2017.**
- **Turbulence** may dissipate energy over multiple fragmented regions during the flare e.g. **Vlahos et al. 2016, Gordovskyy et al. 2016.**
- **Energy is transferred** from large scales (~size of a solar flare loop 10^9 cm) to small scales (particle level).

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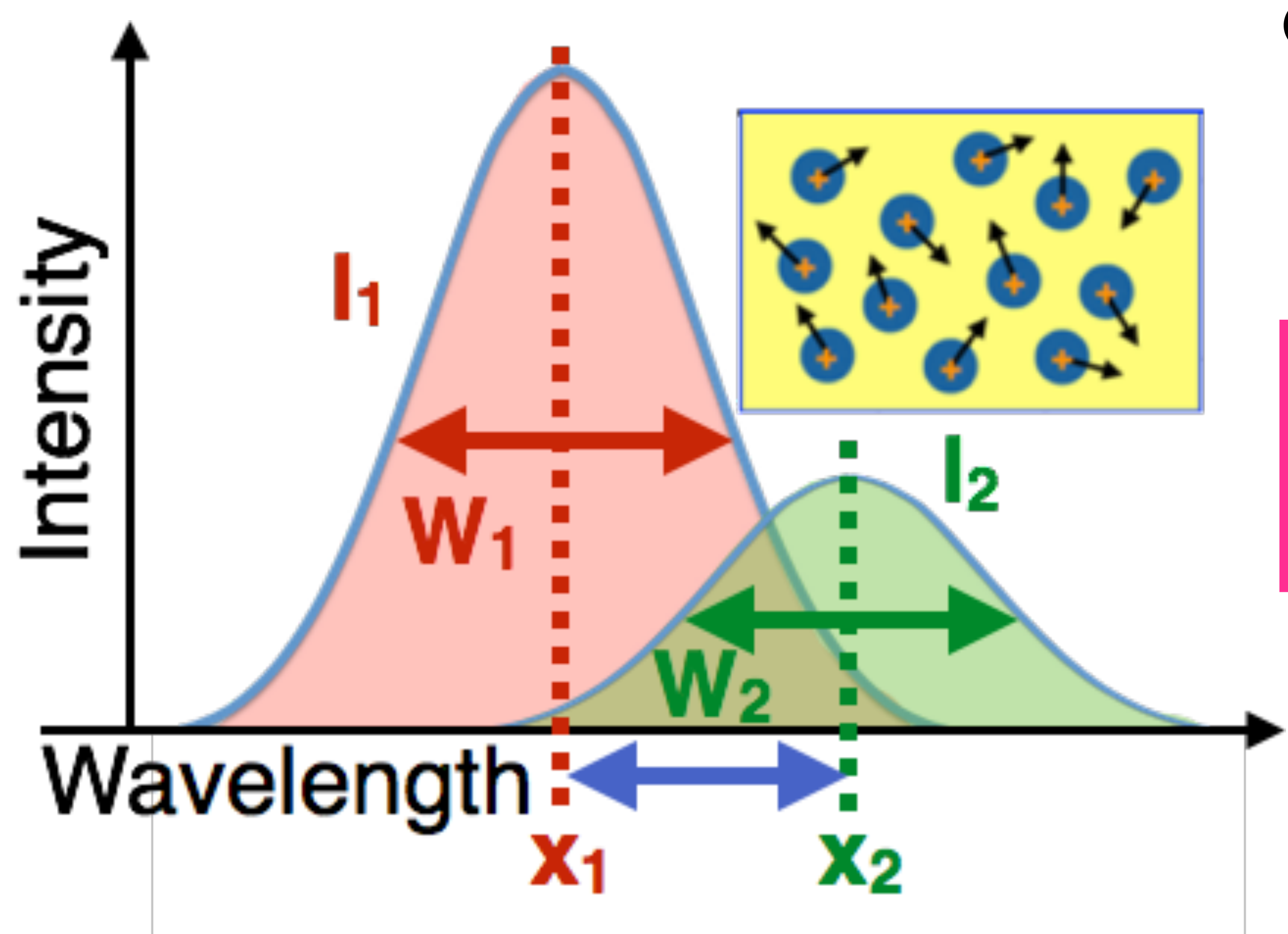
Solar Flare Turbulence

How do we diagnose the presence and properties of turbulence in solar flares?

Spectral line broadening is the main tool

- The properties of the plasma are usually found from Gaussian fitting. The second moment is related to the width of the line (which can be converted to a velocity).
- The ‘expected’ width of a spectral line is related to temperature.
- An excess width may be due to the presence of turbulence.



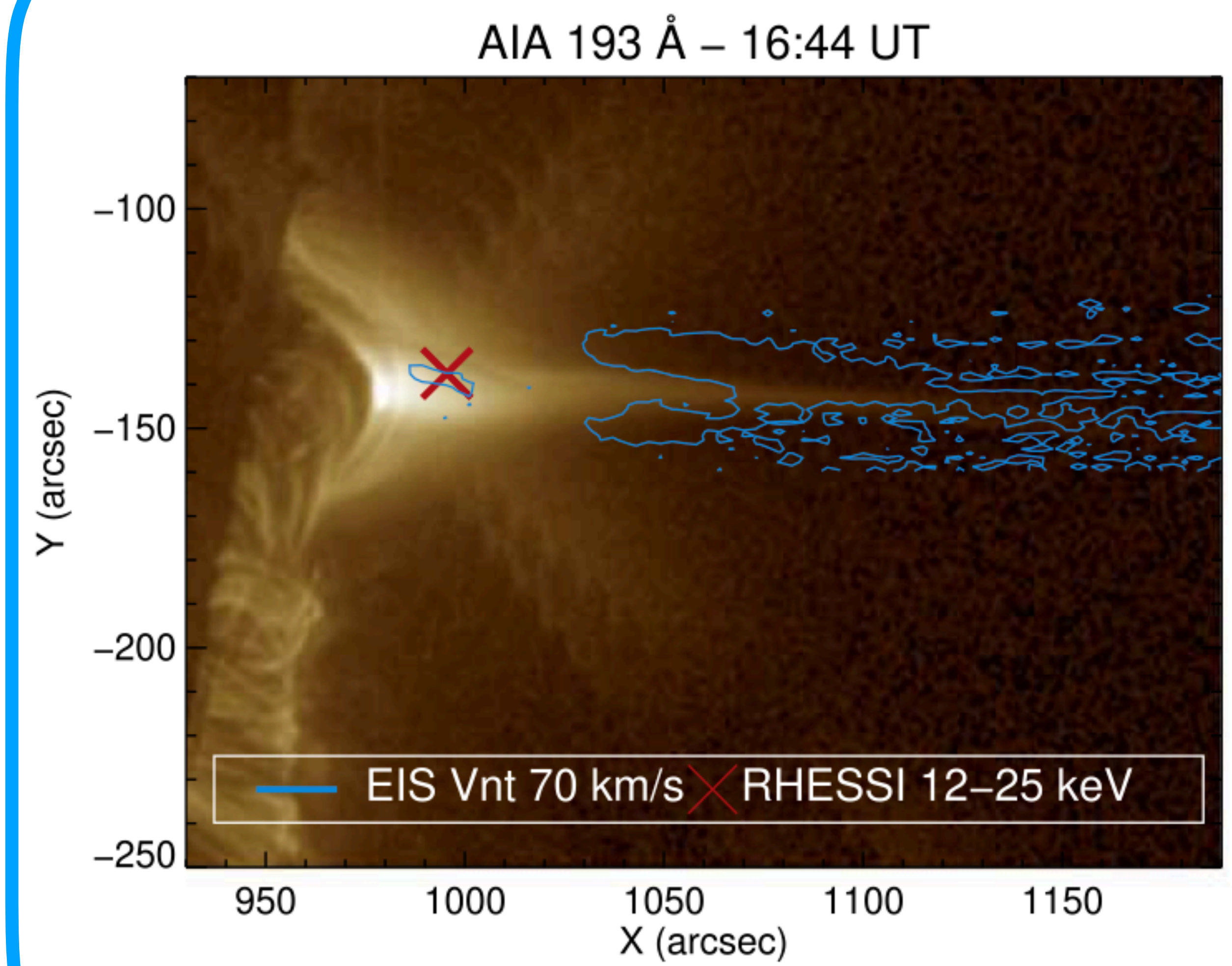
- The **non-thermal velocity** is attributed to **plasma turbulence**.

$$v = \sqrt{v_{\mathrm{th}}^2 + v_{\mathrm{inst}}^2 + v_{\mathrm{nth}}^2}$$

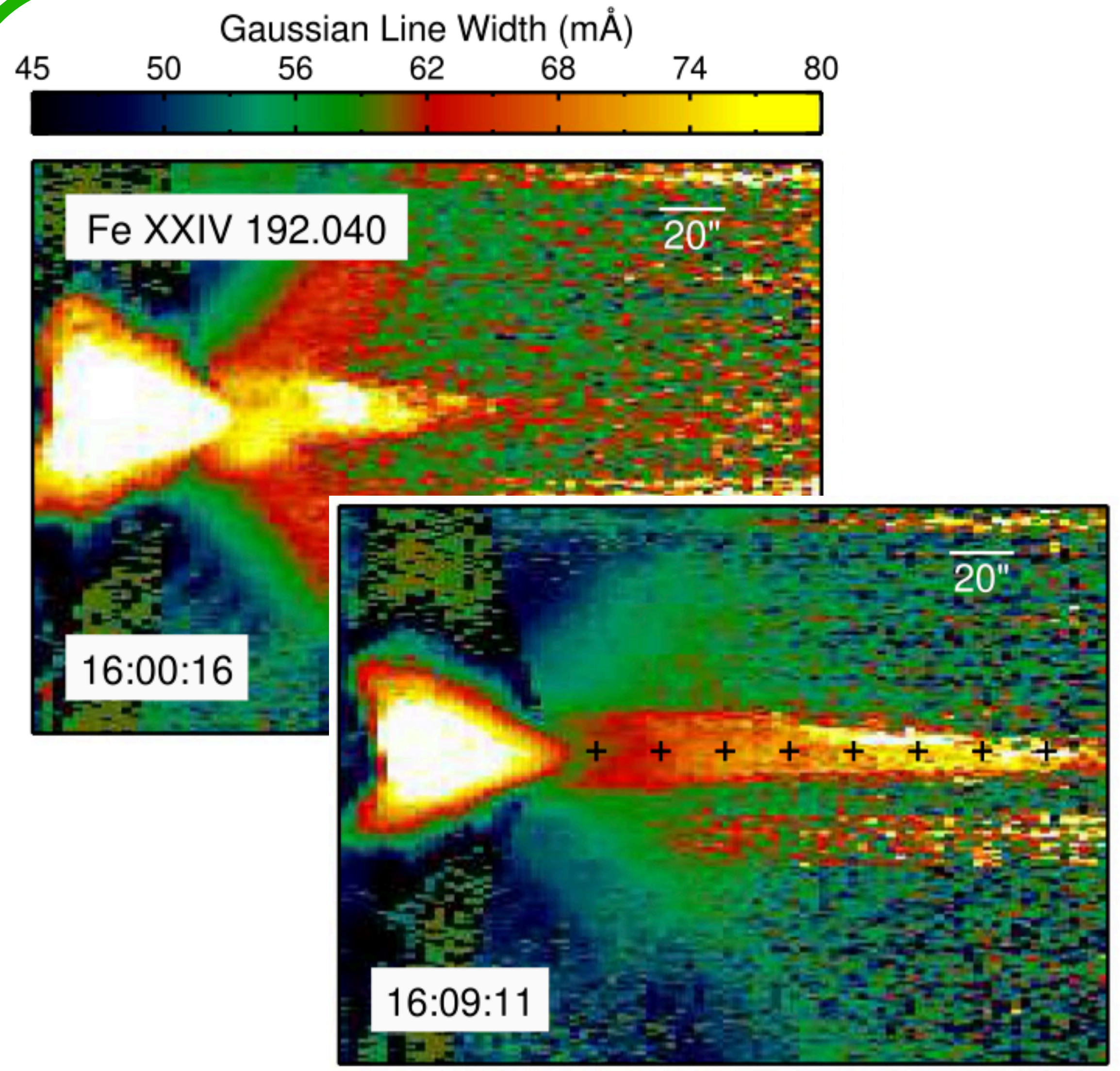
thermal *instrument* *nonthermal*

Solar Flare Turbulence

- **Turbulence** is usually inferred via the presence of non-thermal line broadening.



French, Matthews et al. 2020



Warren, Brooks et al. 2018

Solar Flare Turbulence

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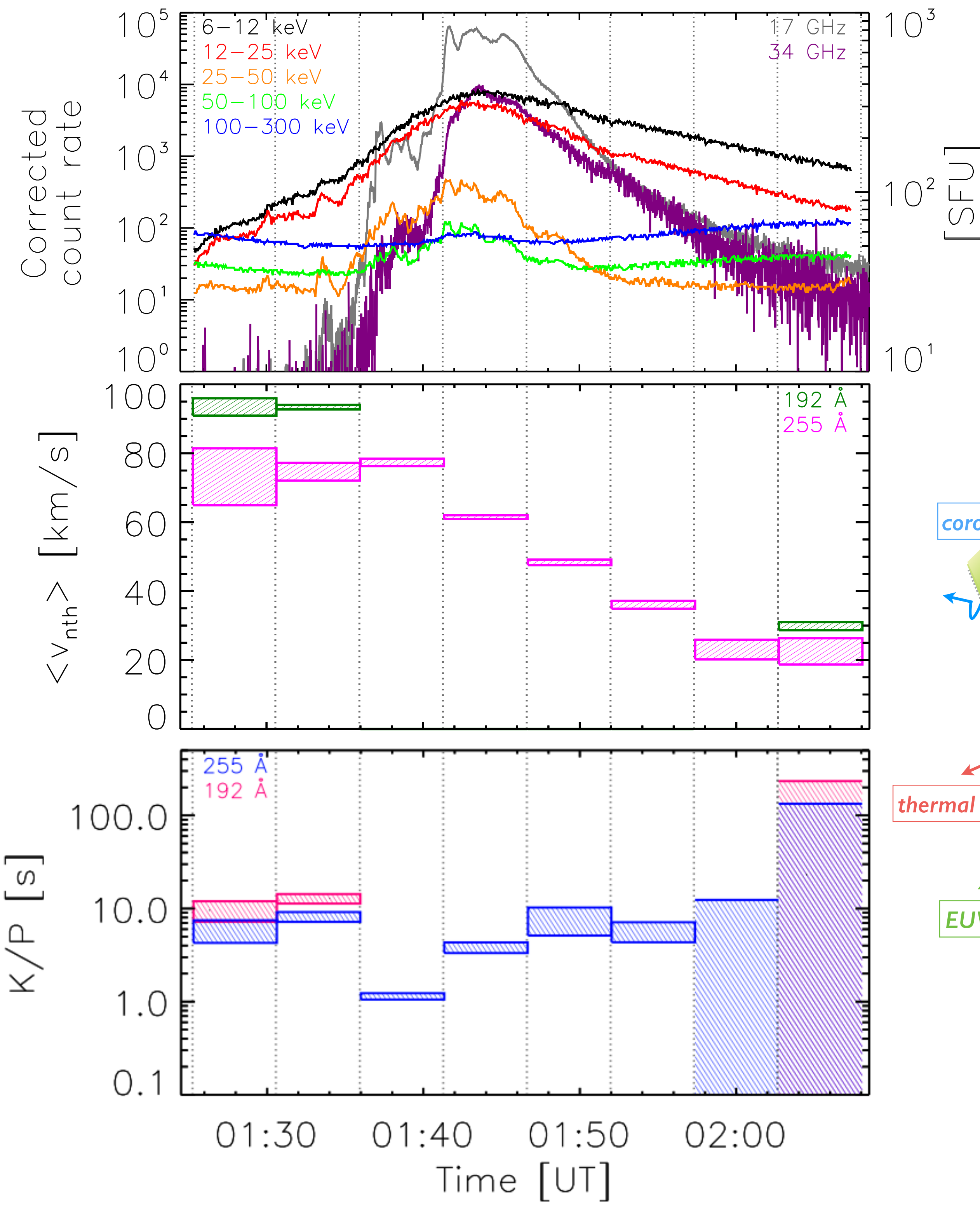
Turbulence plays a vital role in the transfer of energy from magnetic fields.

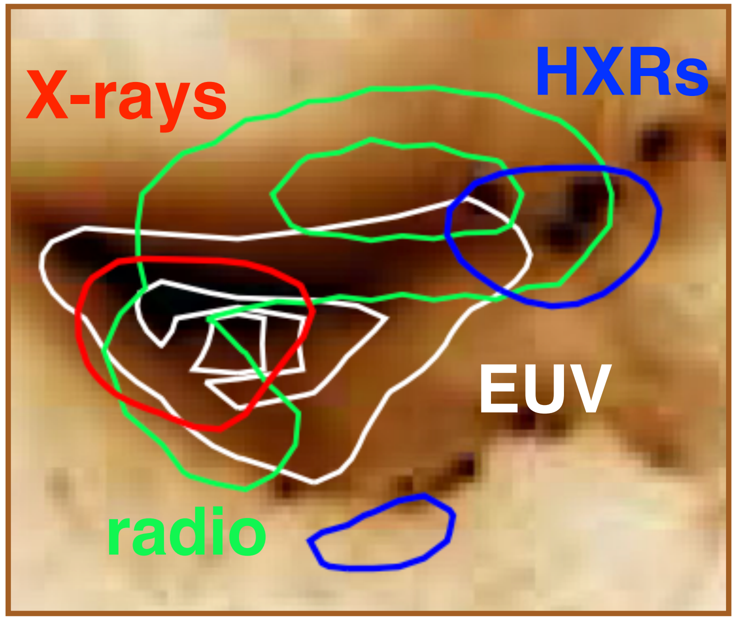
Flare Light curves

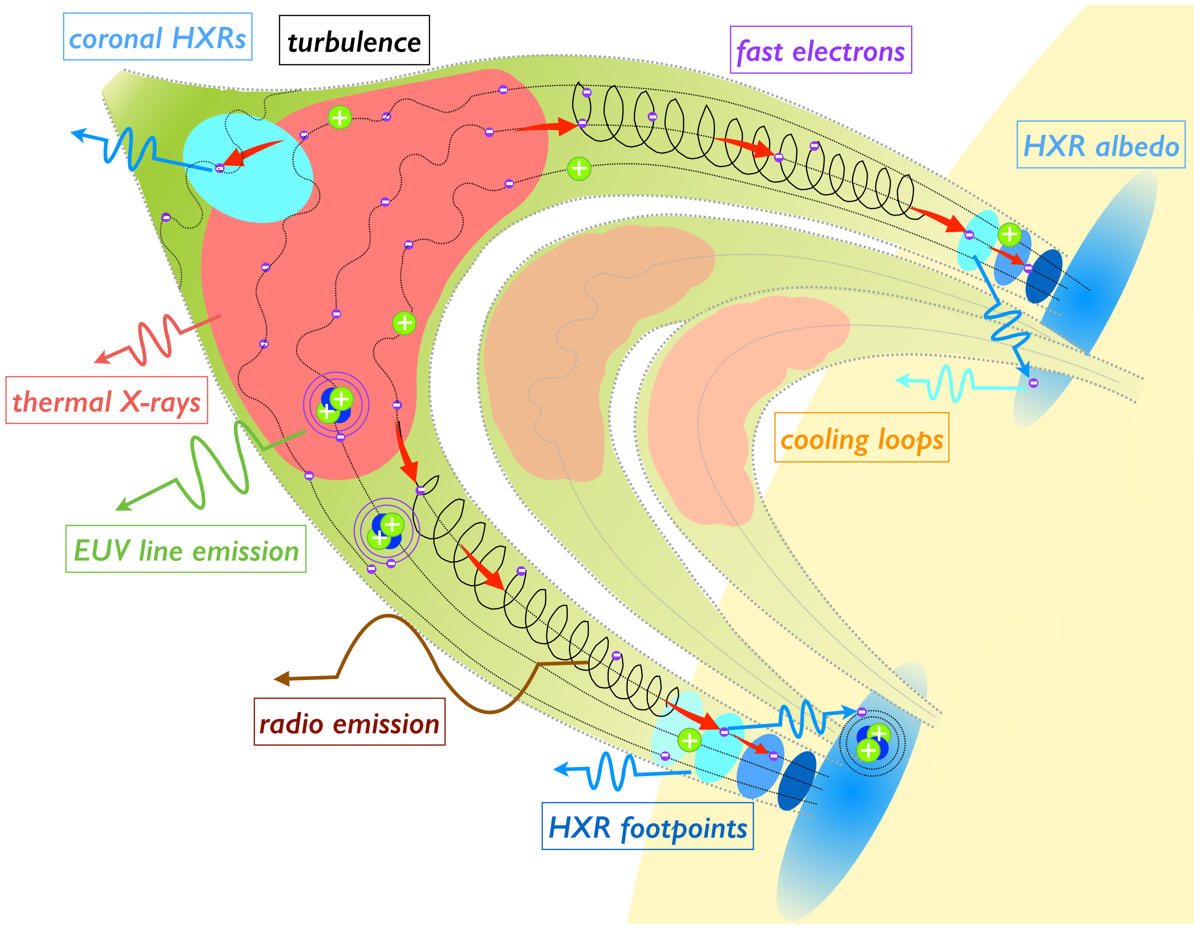
Non-thermal velocity (turbulence)

Turbulent dissipation time



Kontar et al. 2017





Solar Flare Turbulence

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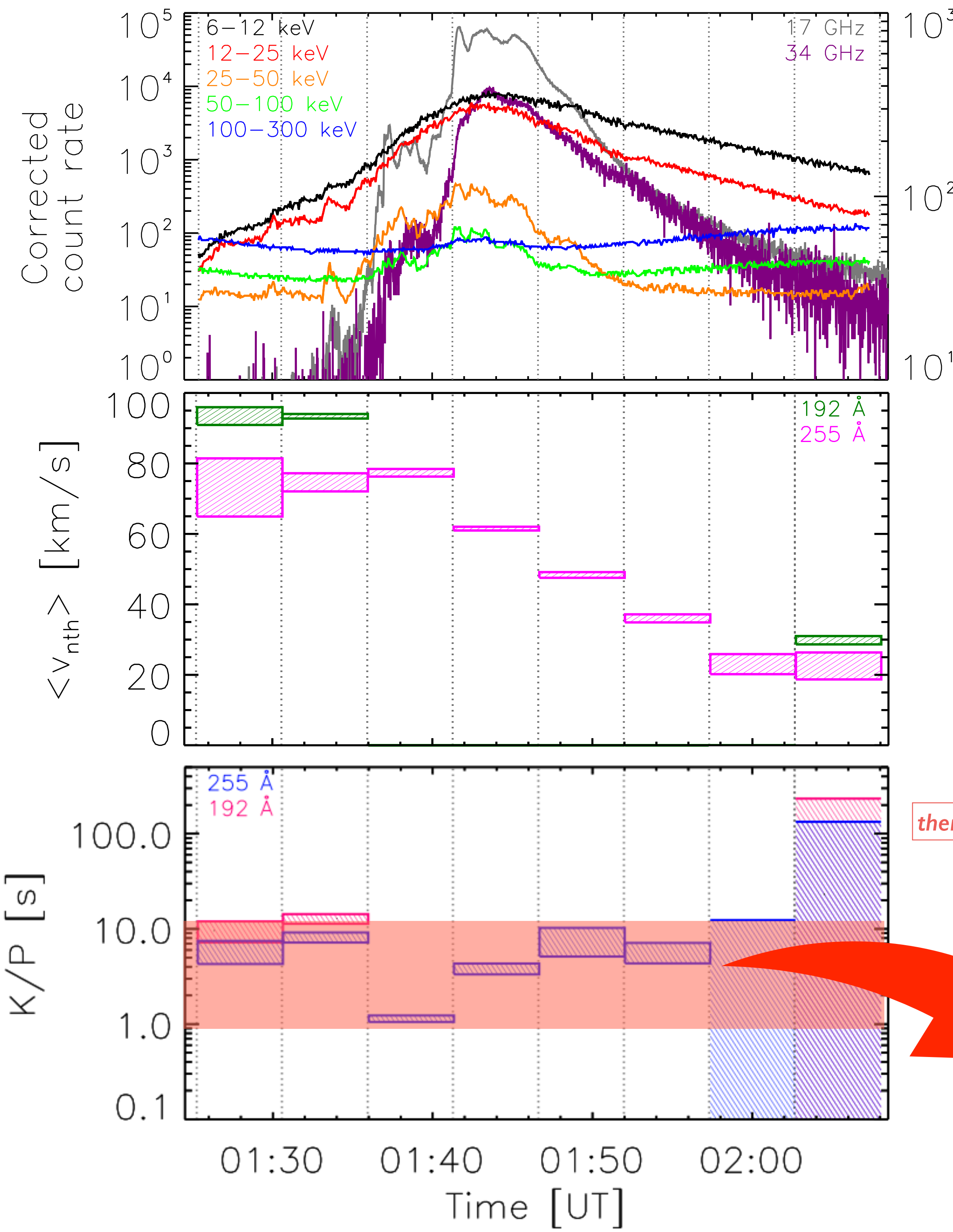
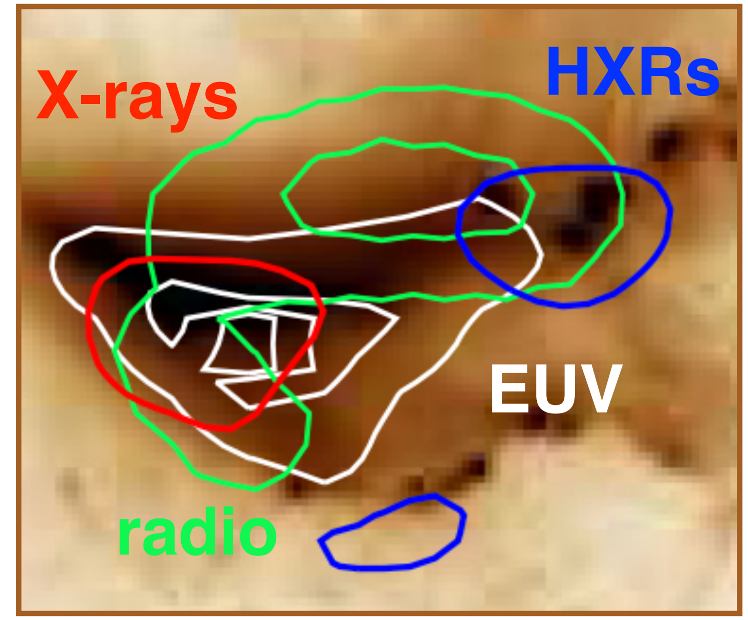
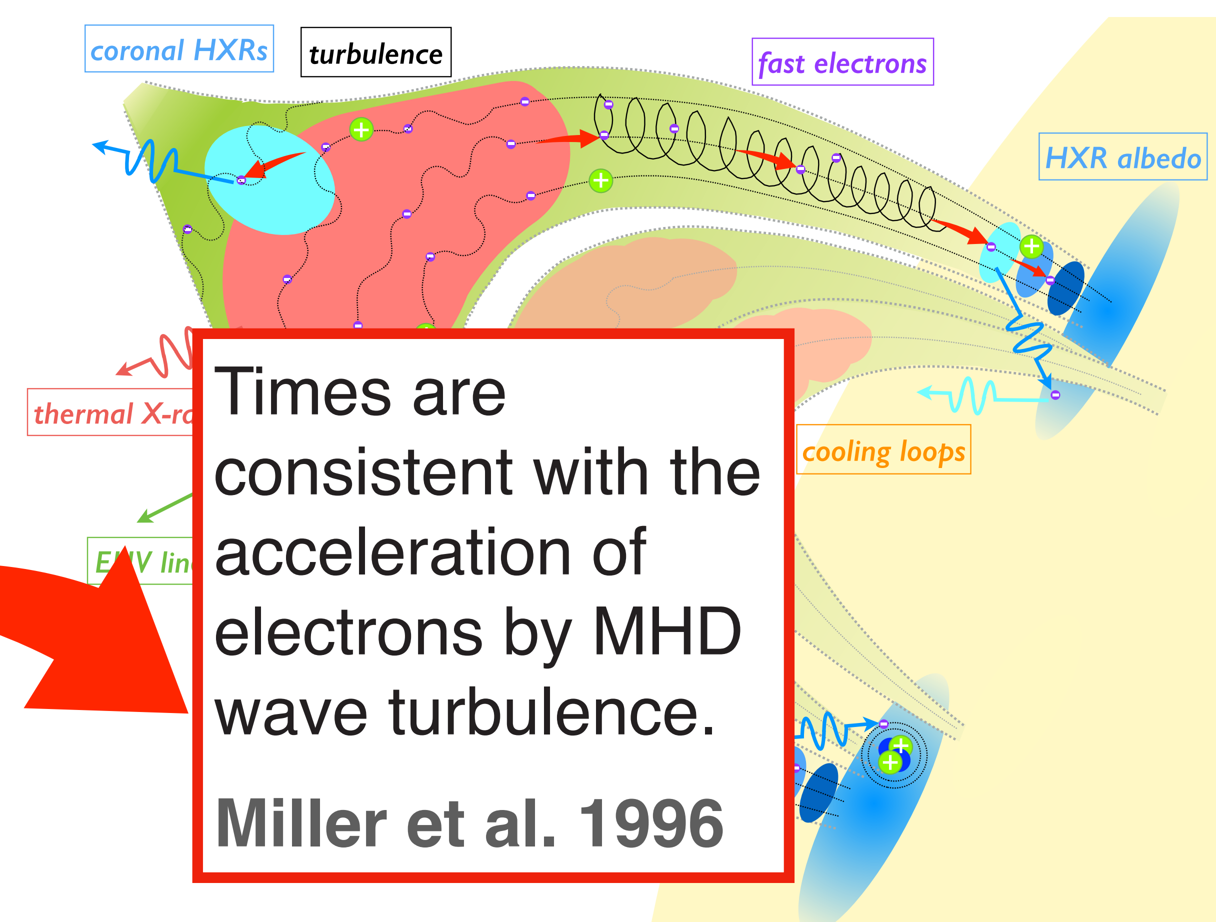


Kontar et al. 2017



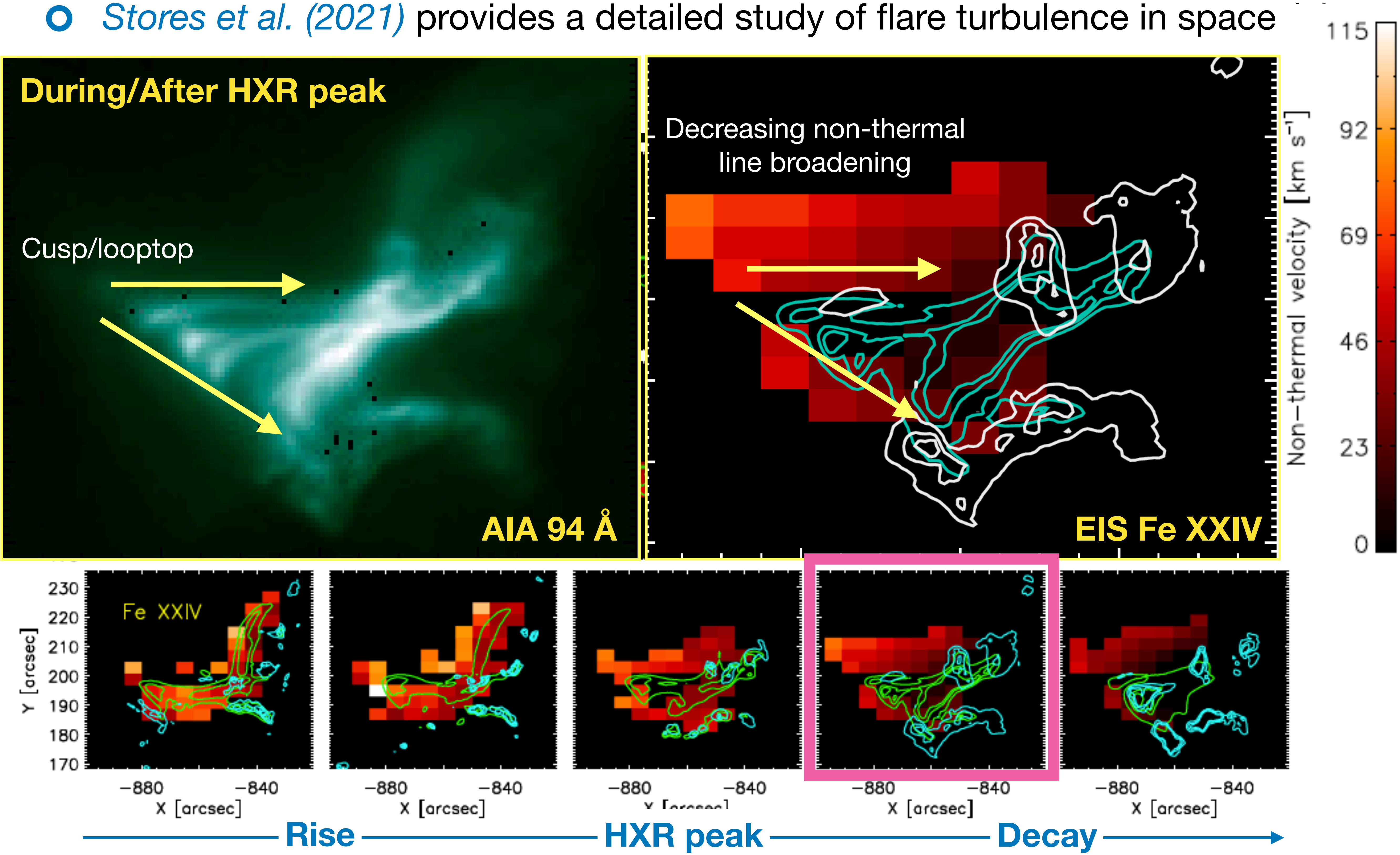


Times are consistent with the acceleration of electrons by MHD wave turbulence.

Miller et al. 1996

Solar Flare Turbulence

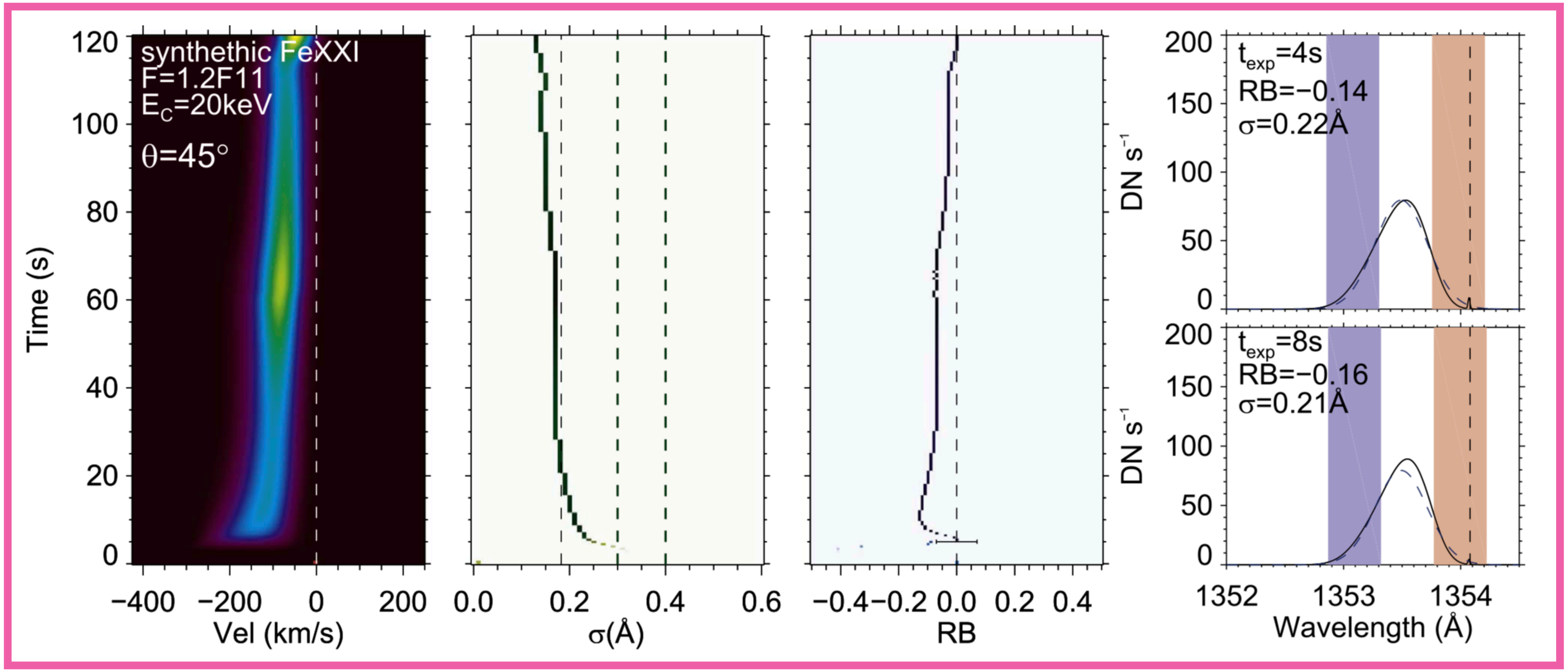
- *Stores et al. (2021)* provides a detailed study of flare turbulence in space

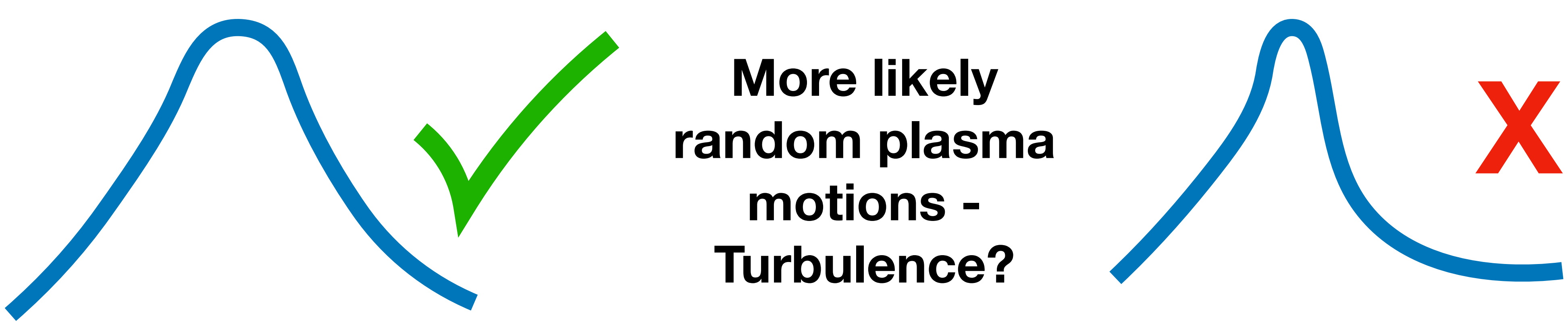


- *Stores et al. (2023)* studies electron acceleration in **extended turbulent regions.**

Solar Flare Turbulence

- Turbulence OR superposition of unresolved plasma flows along the line of sight?
- **Polito et al. 2019** suggest that it is difficult to reconcile symmetrical broadened lines with flows (flows are more likely to produce asymmetrical broadened lines).





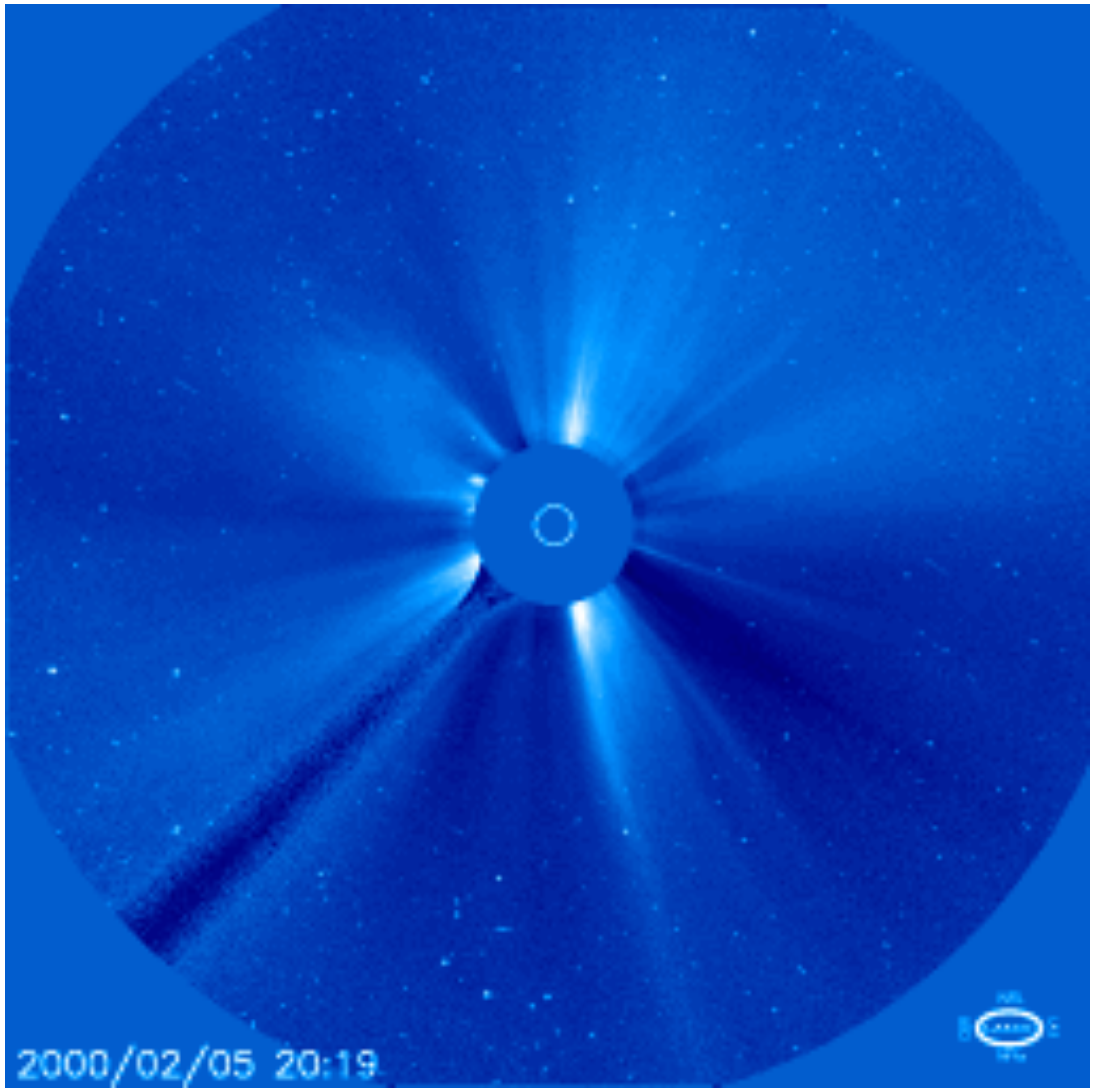
More likely random plasma motions - Turbulence?

More likely superposition of unresolved, independent flows?

Solar Wind Brief Recap

See the slides from Tuesday's lecture "CME's, the Solar Wind and the Heliosphere".

- The whole heliosphere is permeated by the solar wind, a plasma flow of solar origin that expands into the heliosphere.
- The heated corona expands into space, accelerates and forms the solar wind.
- **Solar wind properties (e.g., speed, temperature, density) are highly variable.**
- **The solar wind carries magnetic field, waves and turbulence into the heliosphere.**
- Two states: an irregular slow wind with typical speeds of 400 km/s and a smooth fast wind with a speed of ~750 km/s.

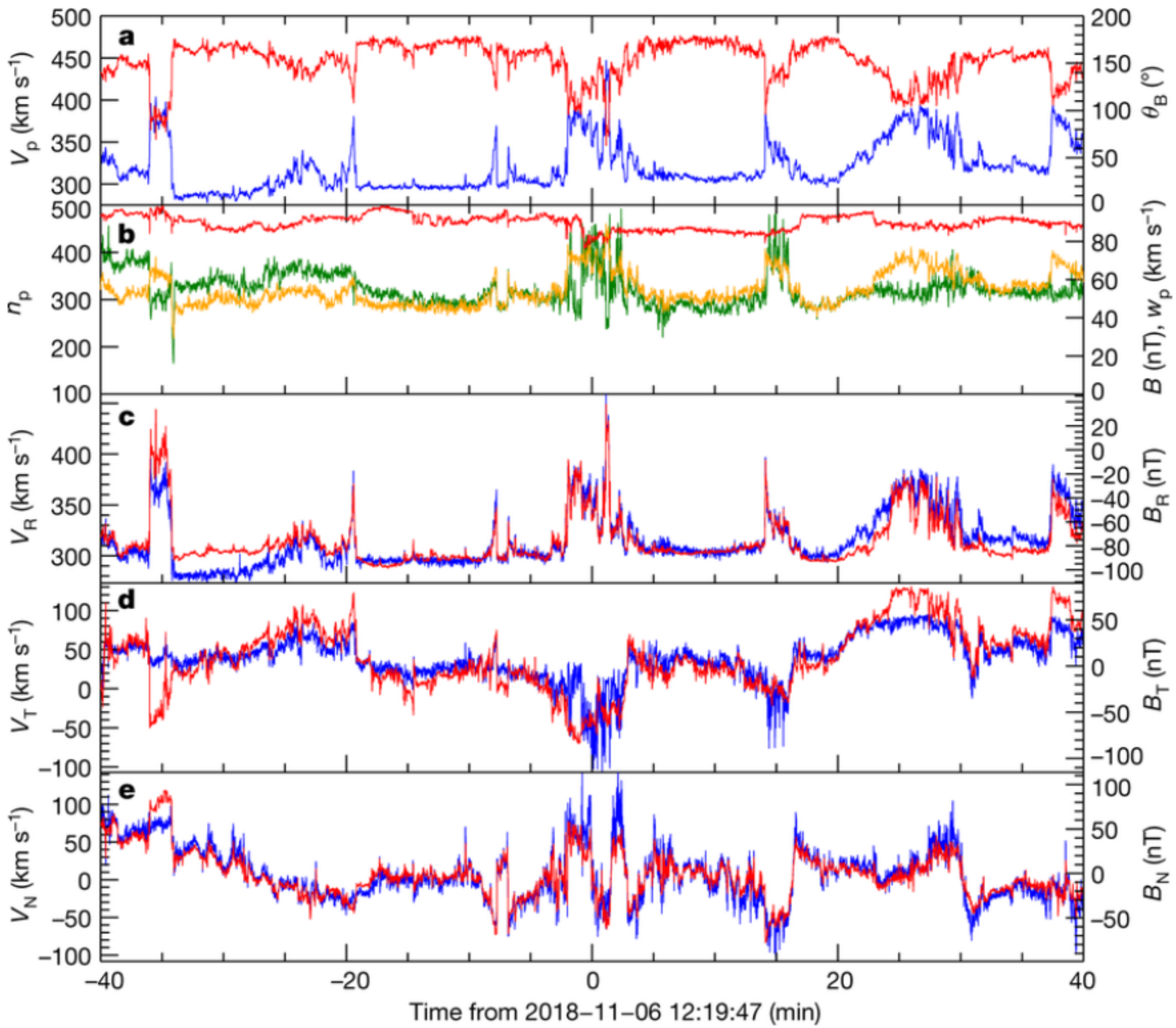


Turbulence in the solar heliosphere plays a relevant role in several aspects of plasma behaviour in space, such as solar wind generation, high-energy particles acceleration, plasma heating, and cosmic rays propagation.

Solar wind turbulence

- The solar wind is a highly turbulent plasma, and hence, an excellent laboratory for studying turbulence!

- In the solar wind, **turbulence can be measured directly via in-situ measurements at different heliospheric locations** e.g., fluctuating B-fields, E-fields.



PSP observations, Kasper et al. (2019), Nature, 576, 228.

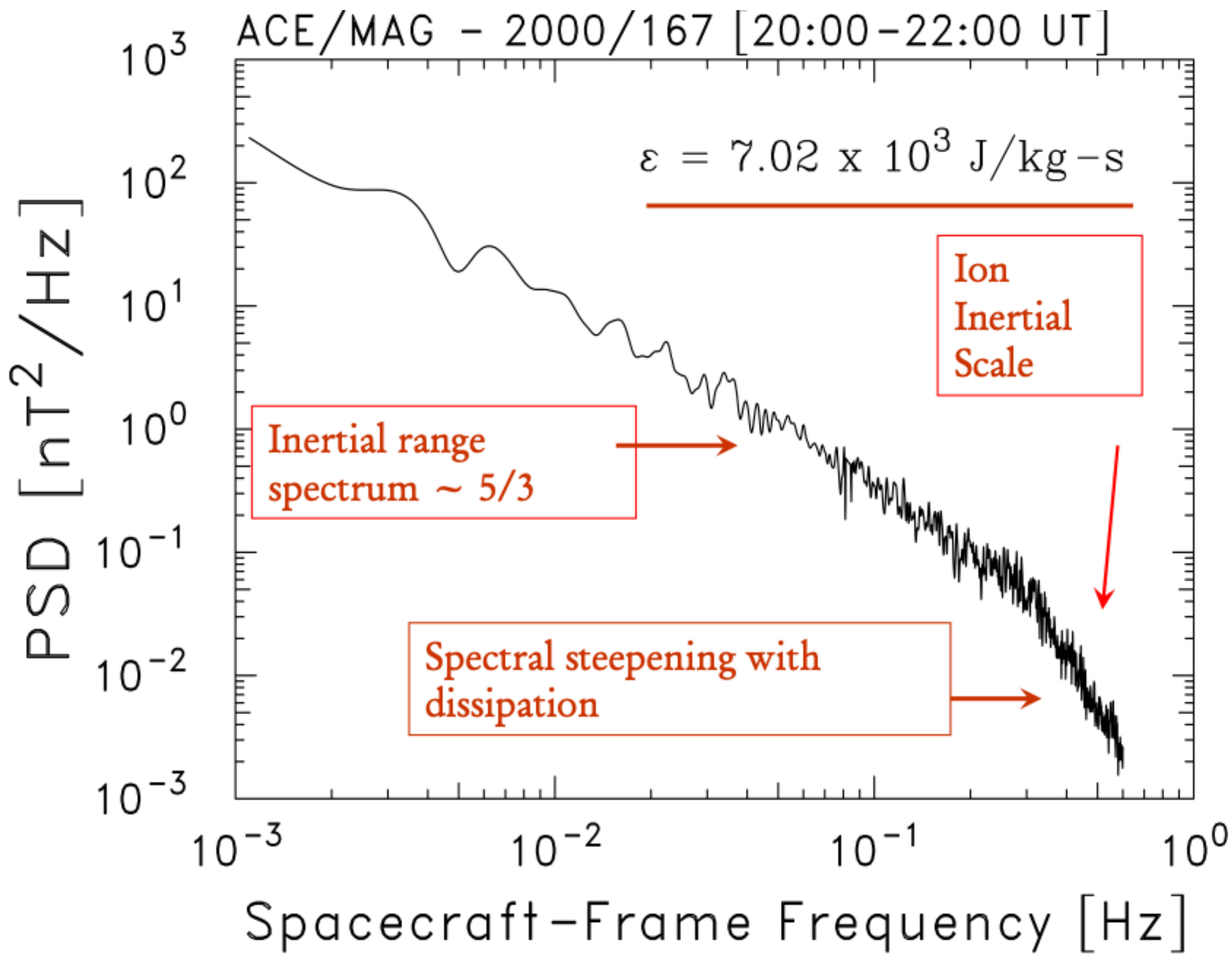
- Real time solar wind: https://www.swpc.noaa.gov/products/real-time-solar-wind

Solar wind turbulent cascade

- **Large-scale disturbances (shocks, ejecta, heliospheric current sheets, stream interactions) provide energy to drive the turbulent cascade.**

- The spectrum (e.g., turbulent magnetic field) displays fluctuations over several decades in scale.

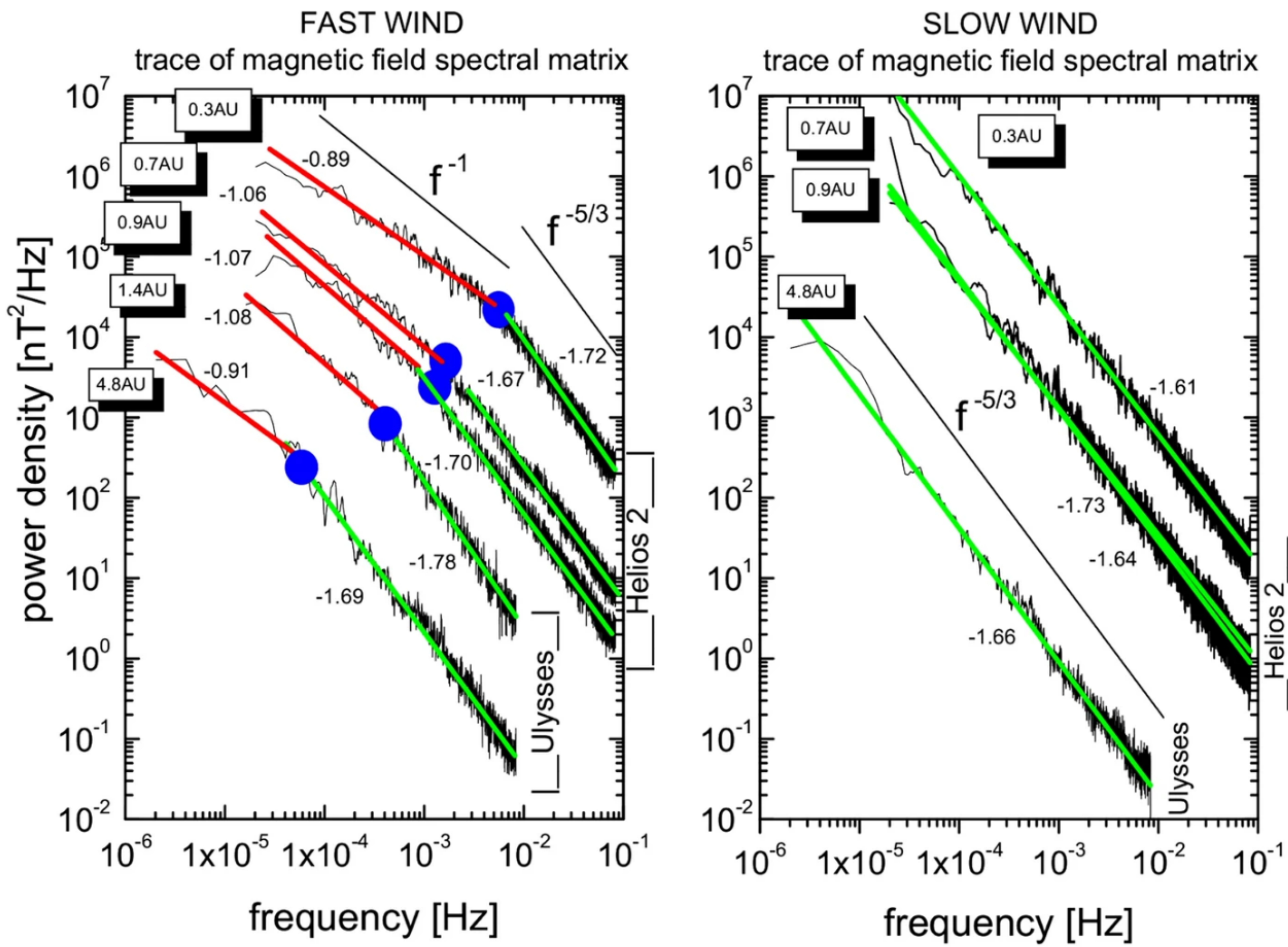
- The spectral break indicates the beginning of the ion kinetic range where the ion scale lengths are of comparable sizes to the magnetic fluctuations.



- How energy is dissipated exactly (e.g., collisionless plasma) is an open question!

Spacecraft measurements

- **Example:** distance differences and fast and slow wind differences.



Bruno & Carbone 2013

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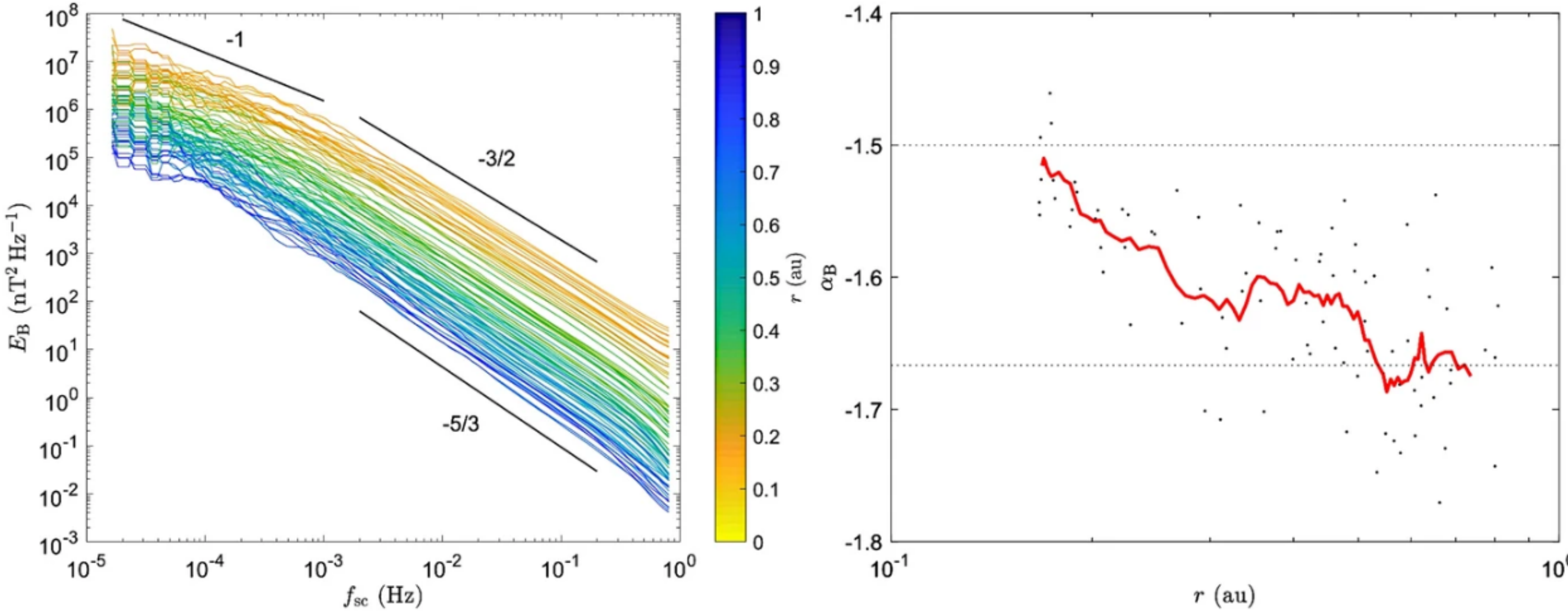
Spacecraft measurements

- **Example:** PSP measurements at different radial distances in the heliosphere.



Chen et al. (2020)

- Net power in the magnetic fluctuations is seen to rise sunwards.
- Most of the spectra show a 1/f range at the largest scales.
- **Inertial range shows a transition (-3/2 to -5/3) as the radial distance increases.**

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Critical balance

- **Why do we see a Kolmogorov-type spectrum in the solar wind??????**

- Although we see IK -3/2 spectra, many solar wind observations (and numerical simulations) show the Kolmogorov –5/3 spectrum.

- The direction of the motion of the solar wind is not constant and the orientation of the wave vectors, i.e., $k_{||}$ (parallel to B) and k (perpendicular to B) with respect to the solar wind velocity should be taken into account.

- **Weak turbulence**: many collisions are required to transfer energy to smaller scales leading to a slower cascade rate (this assumption is used in the IK spectrum).

- **Strong turbulence: energy is transferred to smaller scales in a single collision.**

$$\tau_c \approx \frac{1}{k_{||} v_A}$$

Goldreich & Sridhar (1995) invoke strong turbulence where fluctuations dominate the mean magnetic field (critical balance theory).

Critical balance

- **Why do we see a Kolmogorov-type spectrum in the solar wind??????**
- In Goldreich & Sridhar (1995), the assumption of **strong turbulence is assumed**.
- This leads to a nonlinear transfer time τ_{NL} approximately equal to the collision time τ_C.

$$\tau_{nl} \approx \tau_c \rightarrow \frac{1}{k_{||} v_A} \approx \frac{1}{k_\perp v_\perp}$$

- This is known as **Critical Balance**.
- Perpendicular transfer rate: $\epsilon = \frac{\text{energy}}{\text{time}} \approx k_\perp v_\perp^3$ $\quad v_\perp \approx \epsilon^{1/3} k_\perp^{-1/3}$

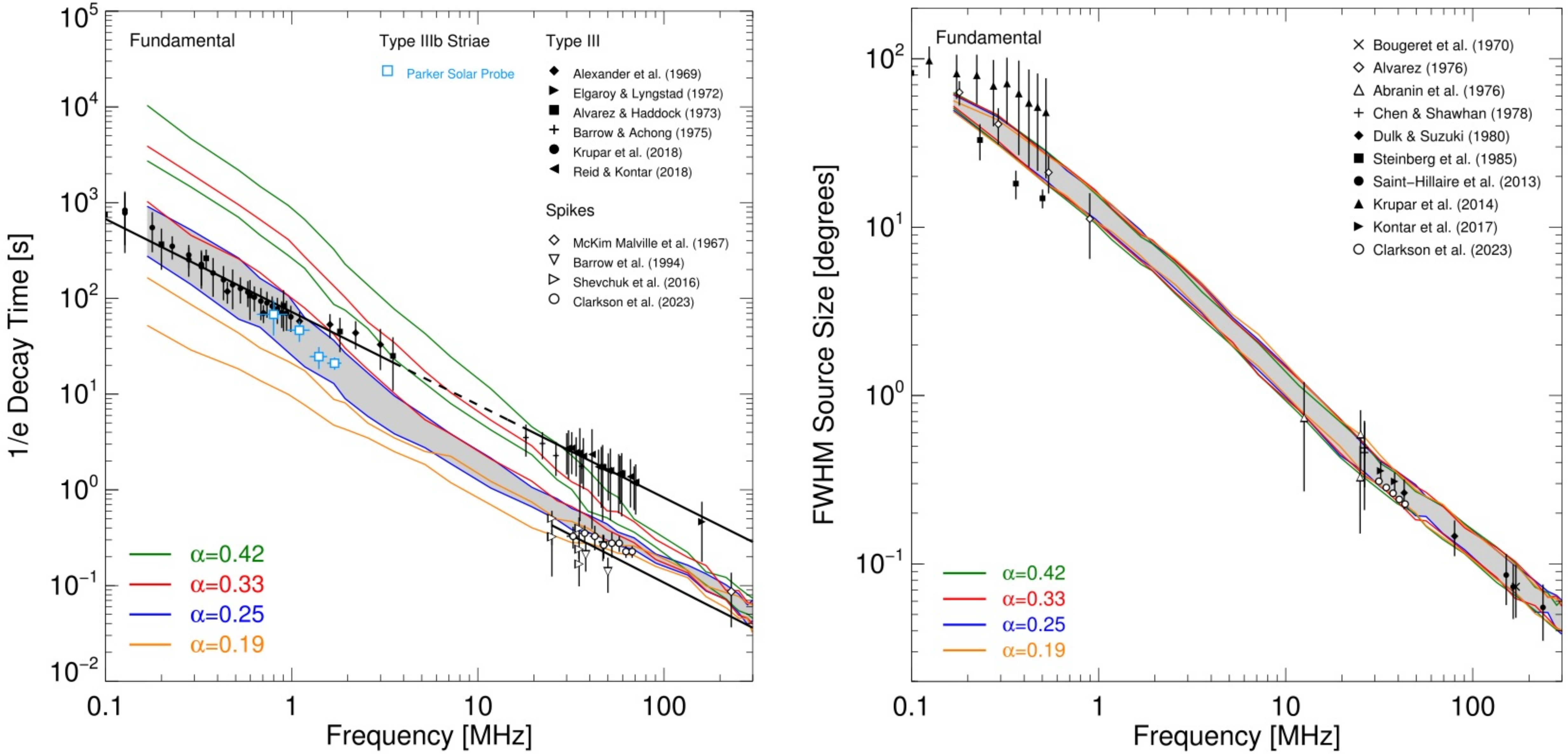
→ **Kolmogorov spectrum** $E(k_\perp) \approx k_\perp^{-5/3}$

- Parallel transfer rate: $k_{||} v_A \approx k_\perp v_\perp \approx k_\perp \left(\epsilon^{1/3} k_\perp^{-1/3} \right) \approx \epsilon^{1/3} k_\perp^{2/3}$ $\quad k_{||} \propto k_\perp^{2/3}$

→ **Parallel spectrum** $E(k_{||}) \approx k_\parallel^{-2}$

Density fluctuations

- Density fluctuations are not as well studied as magnetic field fluctuations.
- Novel radio observations can be used to map turbulence via density fluctuations over large distance in the heliosphere (from the Sun to 1 AU).

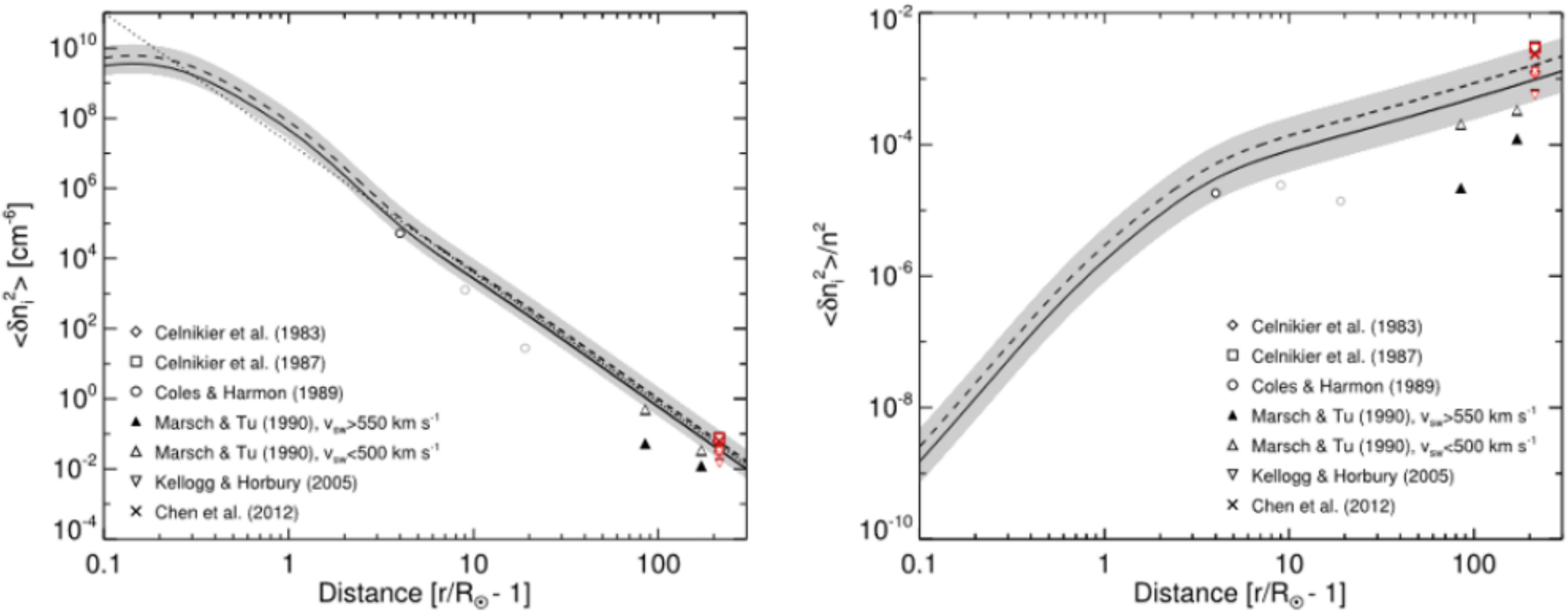


Kontar et al. (2023)

Density fluctuations

- Density fluctuations are not as well studied as magnetic field fluctuations.
- Matching of simulations with radio observations suggests that the turbulence is anisotropic.

$$\overline{q\epsilon^2}(r)R_\odot n^2 \simeq 6.5 \times 10^{14}(r/R_\odot - 1)^{-5.17}$$ where $\overline{q\epsilon^2} \sim$ 0.5-2.



Kontar et al. (2023)

Lecture summary

Turbulence plays an important role in most astrophysical systems including in solar and space physics.

- **Open questions/problems:**

  - MHD turbulence is believed to be important for coronal heating problem and acceleration of the solar wind.

  - MHD turbulence plays a key role in energy transfer in solar flares, coronal mass ejections, magnetic reconnection at the Sun and in a variety of astrophysical phenomena.

  - The details of development and dissipation of MHD turbulence are not fully understood!

Papers used in the lecture

Aschwanden et al. 2017 https://ui.adsabs.harvard.edu/abs/2017ApJ...836...17A/abstract

Bruno & Carbone 2013 https://ui.adsabs.harvard.edu/abs/2013LRSP...10....2B/abstract

Chen et al. (2020) https://ui.adsabs.harvard.edu/abs/2020ApJS..246...53C/abstract

Emslie et al. 2012 https://ui.adsabs.harvard.edu/abs/2012ApJ...759...71E/abstract

French, Matthews et al. 2020 https://ui.adsabs.harvard.edu/abs/2020ApJ...900..192F/abstract

Frisch 1995 https://ui.adsabs.harvard.edu/abs/1995tlan.book.....F/abstract

Goldreich & Sridhar (1995) https://ui.adsabs.harvard.edu/abs/1995ApJ...438..763G/abstract

Gordovskyy et al. 2016 https://ui.adsabs.harvard.edu/abs/2016A&A...589A.104G/abstract

Iroshnikov 1963 https://ui.adsabs.harvard.edu/abs/1963AZh....40..742I/abstract

Kasper et al. (2019) https://ui.adsabs.harvard.edu/abs/2019Natur.576..228K/abstract

Kolmogorov 1941 https://ui.adsabs.harvard.edu/abs/1941DoSSR..30..301K/abstract

Kontar et al. 2017 https://ui.adsabs.harvard.edu/abs/2017PhRvL.118o5101K/abstract

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Kraichnan 1965 https://ui.adsabs.harvard.edu/abs/1965PhFl....8.1385K/abstract

Larosa & Moore 1993 https://ui.adsabs.harvard.edu/abs/1993ApJ...418..912L/abstract

Miller et al. 1996 https://ui.adsabs.harvard.edu/abs/1996ApJ...461..445M/abstract

Petrosian 2012 https://ui.adsabs.harvard.edu/abs/2012SSRv..173..535P/abstract

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Stores et al. 2023 https://ui.adsabs.harvard.edu/abs/2023ApJ...946...53S/abstract

Warmuth & Mann 2016 https://ui.adsabs.harvard.edu/abs/2016A&A...588A.116W/abstract

Warren, Brooks et al. 2018 https://ui.adsabs.harvard.edu/abs/2018ApJ...854..122W/abstract

Vlahos et al. 2016 https://ui.adsabs.harvard.edu/abs/2016ApJ...827L...3V/abstract

UKSP and MIST

- UK Solar Physics are a specialist group affiliated to the Royal Astronomical Society (RAS). The council represents the solar community in the UK and perform tasks beneficial to that community such as providing a newsletter (with workshops, jobs etc.), organising solar sessions at NAM and liaising between the solar community and other similar groups such as MIST (Magnetosphere, Ionosphere and Solar-Terrestrial).

UKSP

https://www.uksolphys.org

- The council has eight members covering different career levels and institutes within all four parts of the UK: Natasha Jeffrey (chair), Marianna Korsos (deputy chair), Karen Meyer, Peter Wyper, Ryan Milligan, Suzana de Souza e Almeida Silva, Rahul Sharma, Matthew Lennard (PhD). A new council is elected every three years.

Please join the mailing list here: https://www.jiscmail.ac.uk/uksp

- MIST (Magnetosphere, Ionosphere and Solar-Terrestrial) is a similar specialist group.

MIST
Magnetosphere, Ionosphere and Solar-Terrestrial

https://www.mist.ac.uk