Fundamental study of plasma turbulence

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Why and how should we study fundamentals of plasma turbulence

Despite similarities, plasma turbulence differs from Navier-Stokes turbulence.

- Results do not simply carry over from fluids to plasmas.

Although manifestations of plasma turbulence are extremely diverse, they share a common underlying structure, thus general results can find broad practical application.

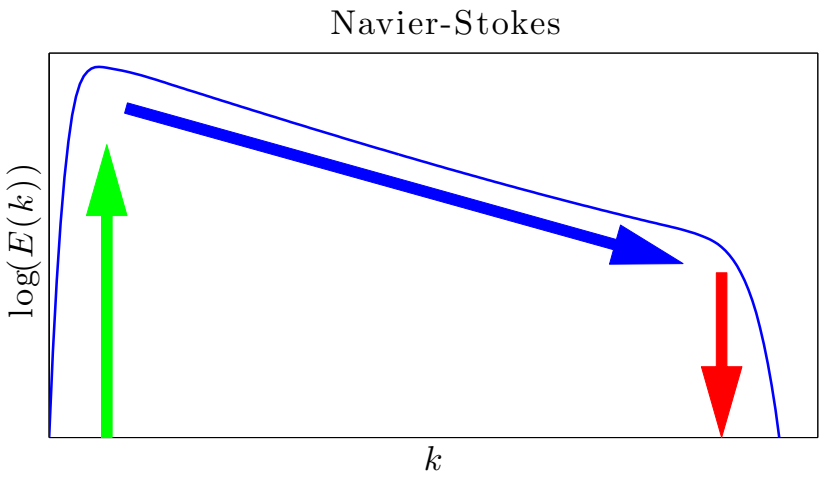
- Example cross-cutting topics:
  - Wave-turbulence interaction
  - Turbulence interaction with large-scale flows and fields
  - Energy cascade in 5- or 6-D phase space

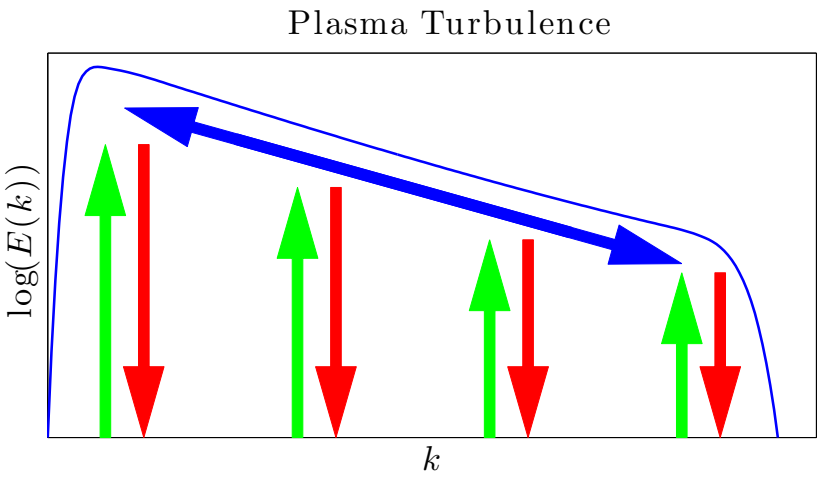
Plasma turbulence is ubiquitous in nature and the lab, so it can be studied with existing devices and codes.

- Funds need to be allocated for turbulence-focused run time and diagnostics.

KEY: This research must be focused and leveraged by input from dedicated analytical and semi-analytical study.

In plasmas, unlike Navier-Stokes, linear terms provide sources and sinks at many scales.





Navier Stokes

- Large-scale stirring.
- Small-scale viscosity.
- Large inertial range: nonlinear transfer only.

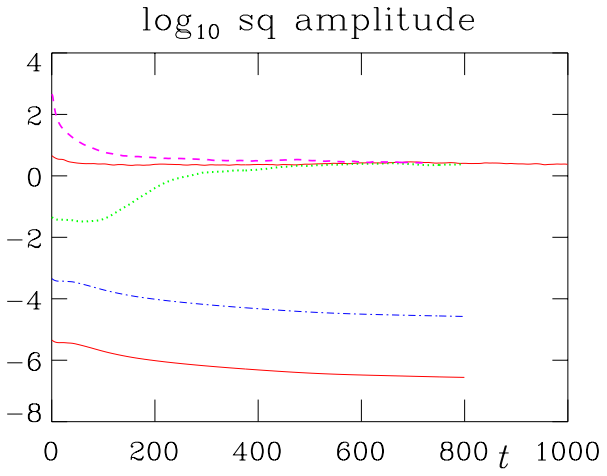
Plasma turbulence

- Instabilities at many scales.
- Damped waves at many scales.
- May be no inertial range.

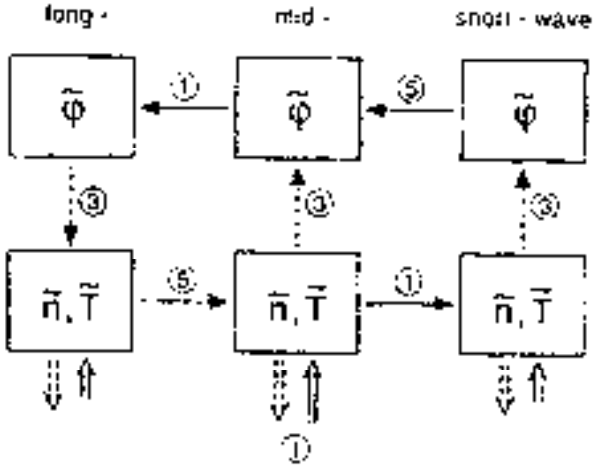
- In plasmas, we must also consider energy transfer between fields (e.g. $n \leftrightarrow u_{\|e} \leftrightarrow \phi$), equivalently between linear eigenmodes.

Energy source is neither outside forcing nor purely linear.

- N-S: Energy source is outside forcing.
- Next step: Energy from linear modes alone.
  - Linear instabilities⇒source
  - Nonlinear terms⇒transfer
  - Damped modes⇒sink
- But in plasmas, the nonlinearities can affect the energy source term:
  - Submarginal turbulence: turbulence without any unstable linear eigenmode.
  - Requires:
    - Non-normal linear operator
    - Favorable nonlinear energy transfer



Scott New J. Phys **4**: 52 (2002)

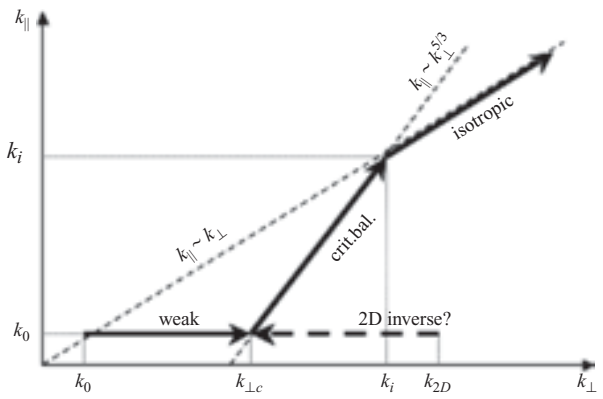


Scott Phys. Fluids B **4**: 2468 (1992)

Linear decorrelation can affect nonlinear energy transfer.

For energy transfer, two quantities must stay correlated for some time τ_c. What sets τ_c?

- Weak turbulence regime: wave dispersion dominates decorrelation
  - Allows rigorous perturbation expansion.
- Strong turbulence: turbulent eddies dominate decorrelation.
  - More common, no rigorous expansion.
  - Linear decorrelation often still matters:
    - Magnetized plasmas:
      Often, physics linear $\parallel$ **B**$\rightarrow$
      e.g. Critical balance
    - Rhines length in geophysics:
      Anisotropic wave dispersion$\rightarrow$ZFs



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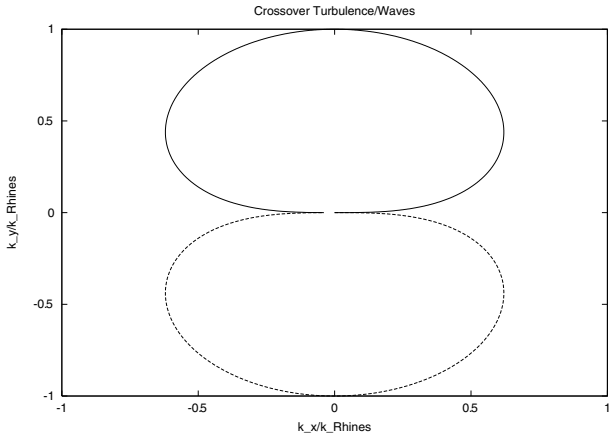


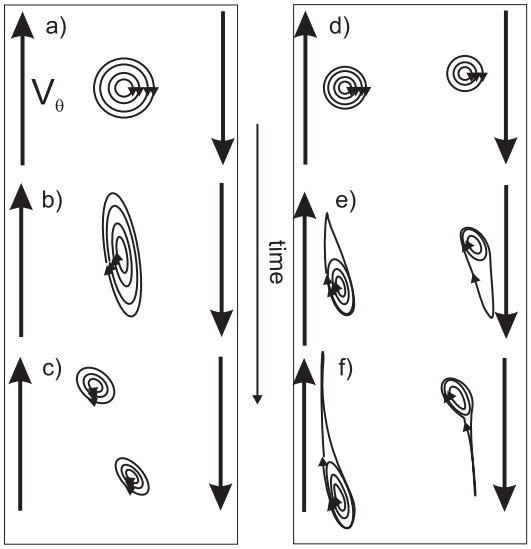
Naulin New J. Phys **4**: 28 (2002)

Interaction of turbulence and large scale flows and fields:

Nonlinear beating of small-scale turbulent fluctuations generates a large scale structure, which often saturates by modifying the turbulence that formed it.

Well-known examples include

- ZFs in tokamaks and geophysics
- Magnetic dynamo
- Intrinsic rotation



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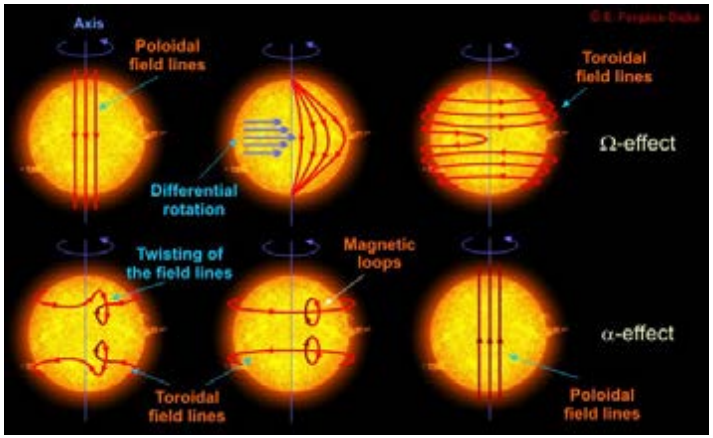
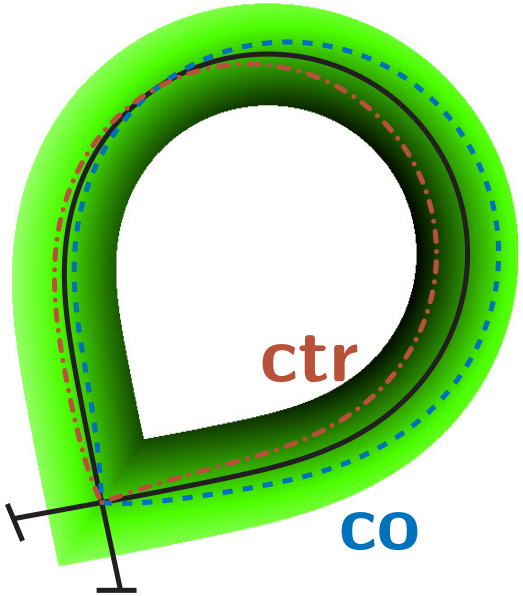


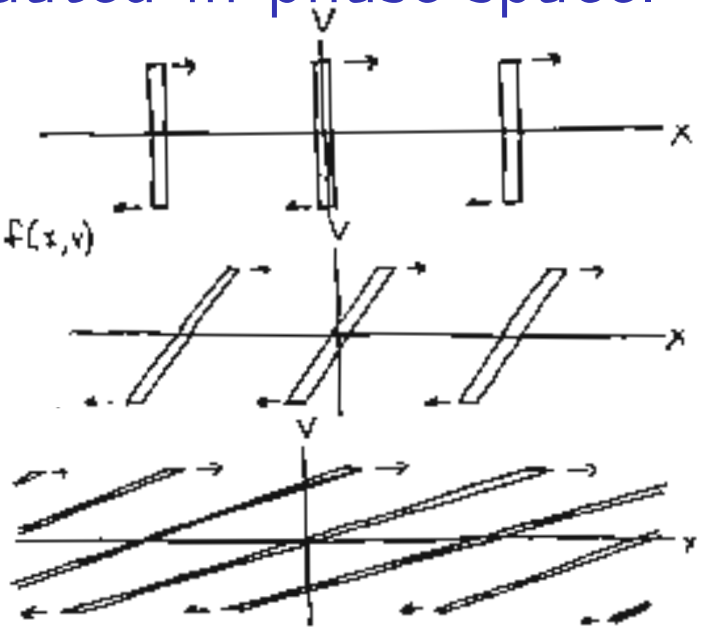


http://www.konkoly.hu/solstart/stellar_activity.html

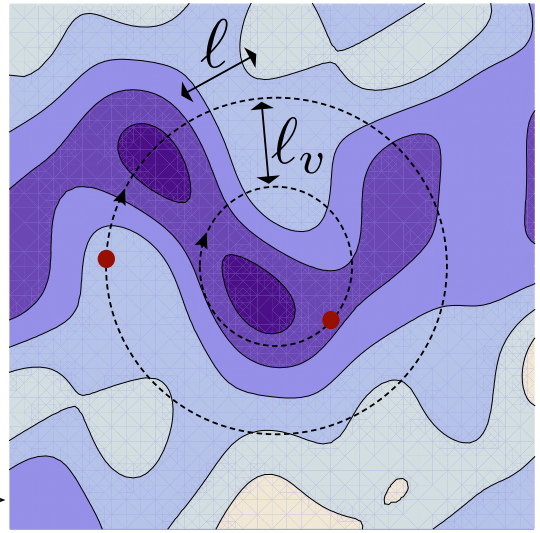
Plasma turbulence is fundamentally situated in phase space.

In both neutral fluid and plasma turbulence, quadratic nonlinearities redistribute conserved quantities across different scales, typically via an incompressible flow. But this flow is located in different spaces, which matters:

- Neutral fluids:
  - In general, 3D: direct cascade
  - Strongly anisotropic, 2D: dual cascade
- Plasmas
  - 2D and 3D spatial descriptions can be useful for certain problems, but:
  - For collisionless plasmas, turbulence rearranges the velocity-space as well as real-space dependence, in a:
    - In general: 6D, Boltzmann or Vlasov eqn
    - Magnetized plasma: 5D, gyrokinetics
  - Landau damping can be seen as a direct cascade in velocity space.



Hammett, U Wisc Summer School (1993)



Plunk et al, J Fluid Mech **664**: 407 (2010)⇒

Plasma turbulence can be studied with existing devices and codes.

Plasma turbulence is ubiquitous, both in nature and in the laboratory, so it's easy to find...

- Many codes exist today that are capable of simulating plasma turbulence
- Small devices are good for fundamental studies:
  - Relatively low cost
  - Good diagnostic access
  - Small size (eases numerical modeling)
  - Many good devices exist today, including:
    LAPD at UCLA, the U Texas Helimak, Pegasus and MPDX at U Wisconsin, and LTX at PPPL
- Larger devices such as NSTX-U and DIII-D can also study plasma turbulence.
- For large or small devices, funds need to be allocated for turbulence-focused run time, possibly also diagnostics.

If you want a better answer, try asking a better question.

Analytical and semi-analytical study is necessary in order to focus and leverage experimental and numerical work.

Analytical and semi-analytical methods can contribute greatly to the fundamental study of plasma turbulence, since they can:

- Identify general trends and scalings
  - Context for numerical and experimental studies, which are always done at specific parameter values.
- Identify general bounds and inequalities.
  - Avoid expensive investigation of questions whose answer turns out to be obvious.
- Find general principles exposed by empirical results from experimental and numerical work.
  - Epicycles formed a good empirical description of the motion of planets, but the central force law generalizes better...

Although any analytical model of turbulence must be incomplete, analytical and semi-analytical theory forms a valuable (and cheap!) partner to experimental and numerical studies of plasma turbulence.

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