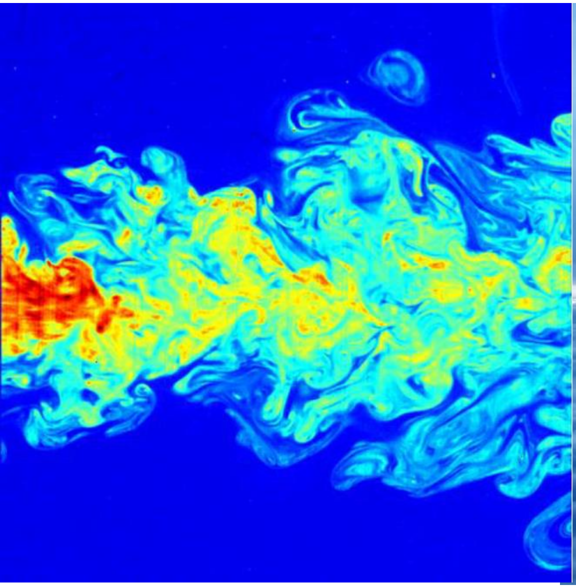
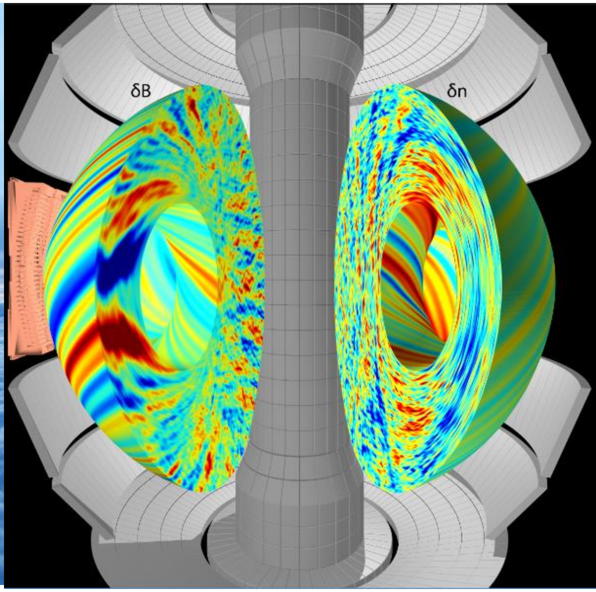
Turbulence Lecture #1: Introduction to turbulence & general concepts





Walter Guttenfelder

Graduate Summer School 2018
Princeton Plasma Physics Laboratory
Aug. 13-17, 2018

This week's turbulence lectures

1. **Turbulence basics** (*Guttenfelder*)

2. **Plasma turbulence, tokamak turbulence** (*Hammett*)

3. **Drift waves, gyrokinetics, astrophysical turbulence** (*Hammett*)

4. **Zoology of magnetized plasma turbulence (illustrated with experiment & simulation)** (*Guttenfelder*)

5. **Modeling turbulence & transport** (*Guttenfelder*)

Today's lecture outline

- Definition and examples of turbulence
- Length and time scales (Navier-Stokes Eq., Reynolds #)
- Energy cascades (Kolmogorov scaling)
- Transport (Reynold's stress, mixing length estimates)
- Energy drive for turbulence (linear & nonlinear instability)
- 2D turbulence (atmospheric, plasmas)

$\Rightarrow$ Outline ways plasma impacts turbulence

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$\Rightarrow$ Outline ways plasma impacts turbulence

- As a starting point, this lecture is predominantly based on neutral fluids – *but plasma turbulence has analogous behavior for all of the topics we'll cover*
- *For this lecture I've drawn a lot from books by Frisch (1995) and Tennekes & Lumley (1972), notes from Greg Hammett's turbulence class lectures, and Wikipedia & Google*

What is turbulence?

Why do we care?

What is turbulence? *I know it when I see it (maybe)…*

- M. Lesieur (2004) gives the following tentative definition:

(Hammett class notes)

  - "Firstly, a turbulent flow must be *unpredictable*, in the sense that a small uncertainty as to its knowledge at a given initial time will amplify so as to render impossible a precise deterministic prediction of its evolution". [I.e, turbulence is "chaotic", it may occur in a formally deterministic system, but exhibits apparently random behavior because of extreme sensitivity to initial/boundary conditions.]

  - "Secondly, it has to satisfy the increased mixing property", i.e., turbulent flows "should be able to mix transported quantities much more rapidly than if only molecular [collisional] diffusion processes were involved." This property is of most interest for practical applications to calculate turbulent heat diffusion or turbulent drag.

  - "Thirdly, it must involve a wide range of spatial wave lengths"

- Also, turbulence is not a property of the *fluid*, it's a feature of the *flow*

Why do we care?

- Transport → pipe flow, heat exchangers, airplanes, sports, weather & climate predictions, accretion in astrophysics, fusion energy confinement

- It's cool! "Turbulence is the most important unsolved problem in classical physics" (~Feynman)

Three themes throughout this introductory talk

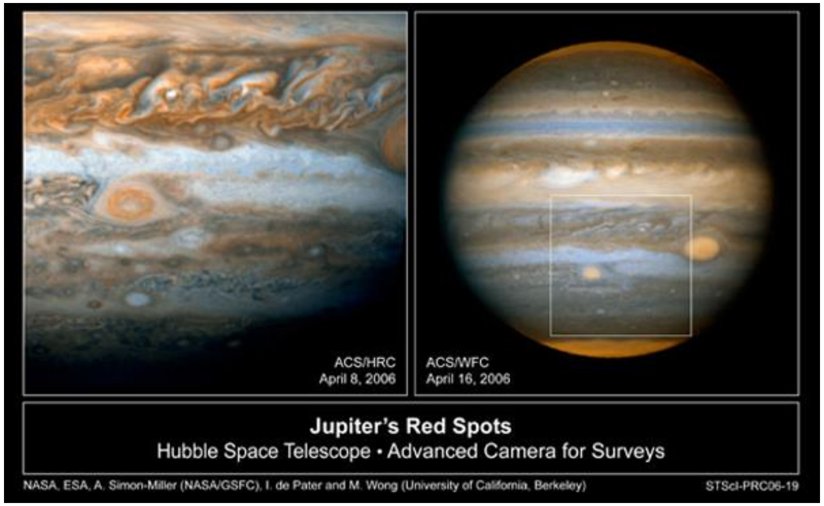
- Turbulence is deterministic yet unpredictable (chaotic), appears random
  - We often treat & diagnose statistically, but also rely on first-principles direct numerical simulation (DNS)

- Turbulence causes transport larger than collisional transport

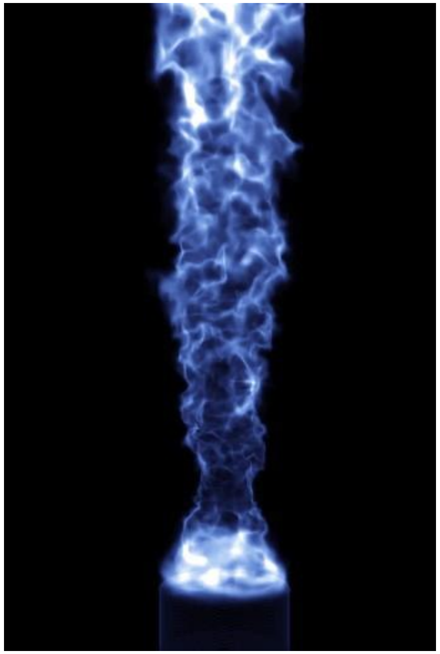
- Turbulence spans a wide range of spatial and temporal scales
  - Or in the case of hot, low-collisionality plasma, a wide range of scales in 6D phase-space (**x**,**v**)

Examples of turbulence

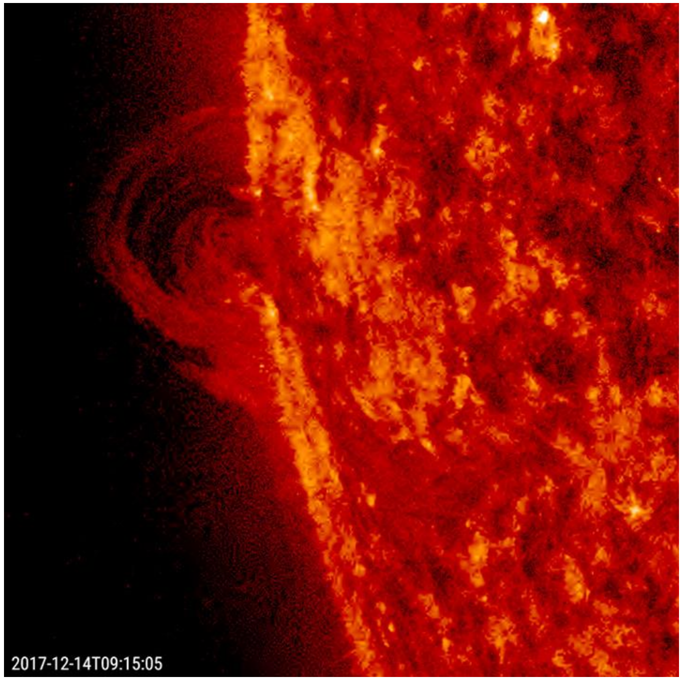
Turbulence found throughout the universe



Steve Morr



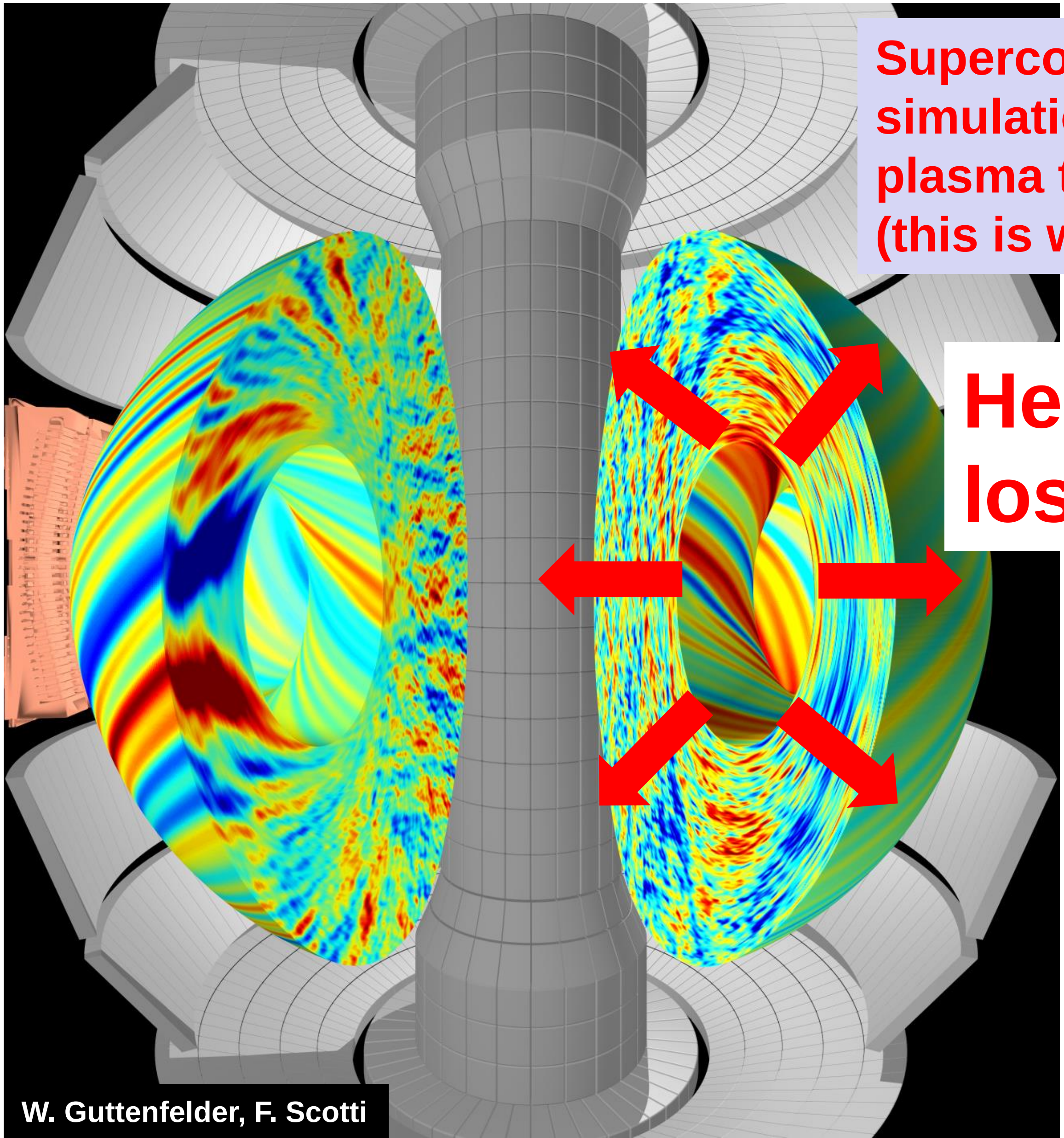
Universität Duisburg-Essen



https://sdo.gsfc.nasa.gov/gallery

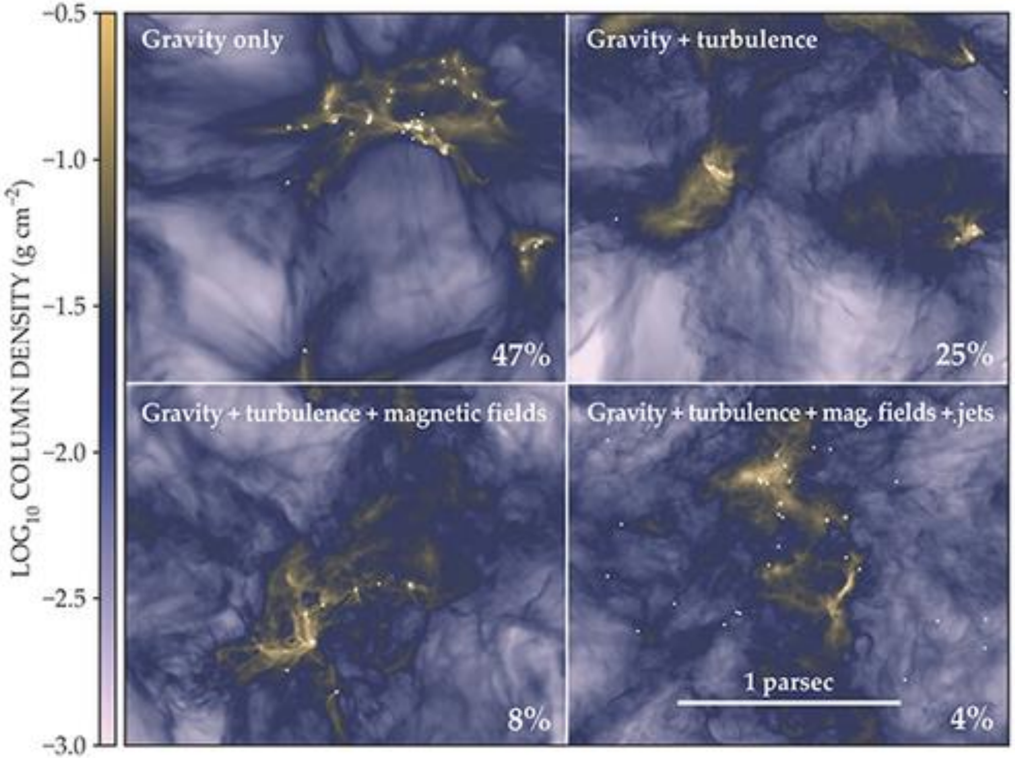
Turbulence is ubiquitous throughout planetary atmospheres

Plasma turbulence degrades energy confinement / insulation in magnetic fusion energy devices

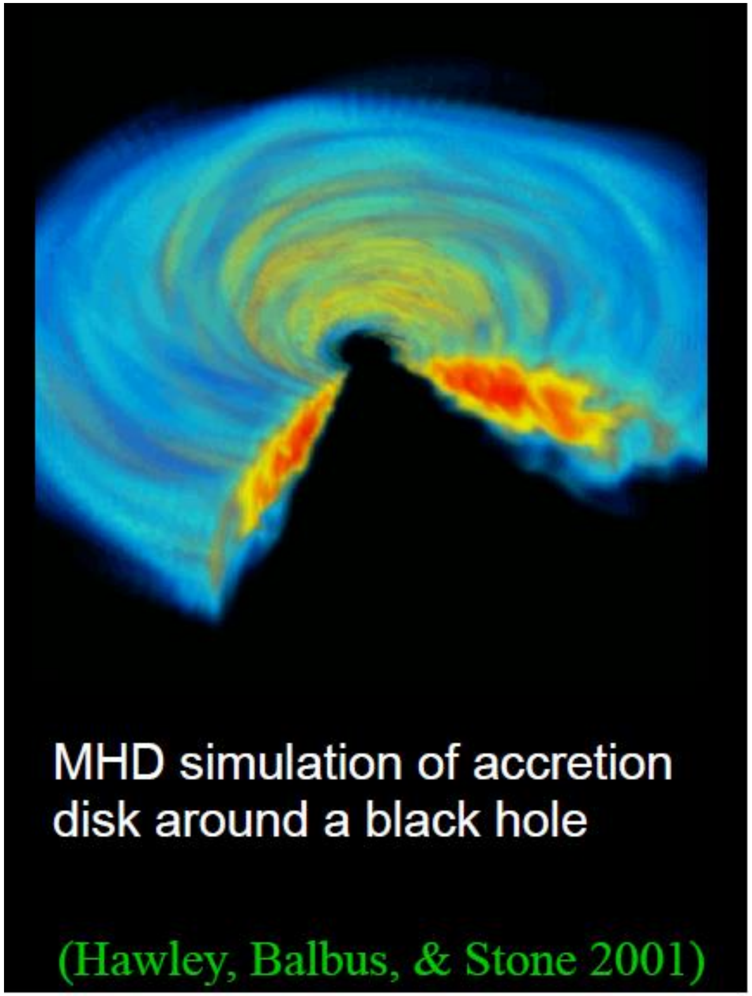


Supercomputer simulation of plasma turbulence (this is what I do 🙂)

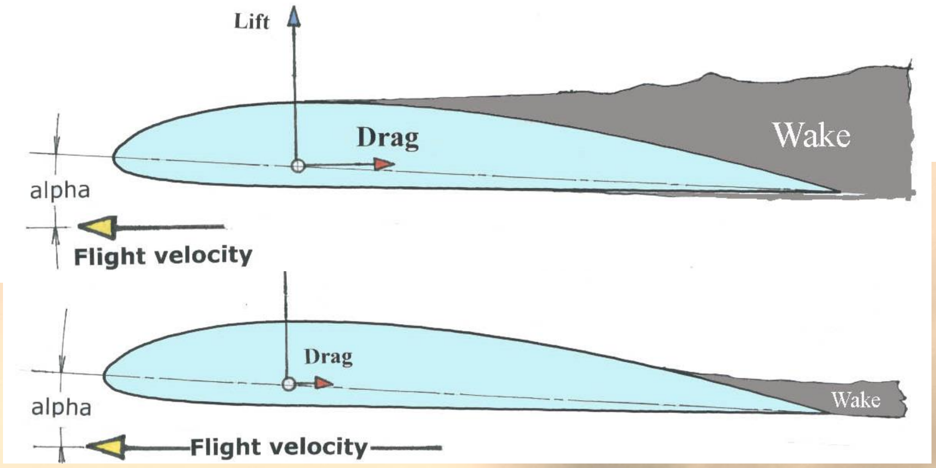
Turbulence is important throughout astrophysics



- Plays a role in star formation (C. Federrath, Physics Today, June 2018)

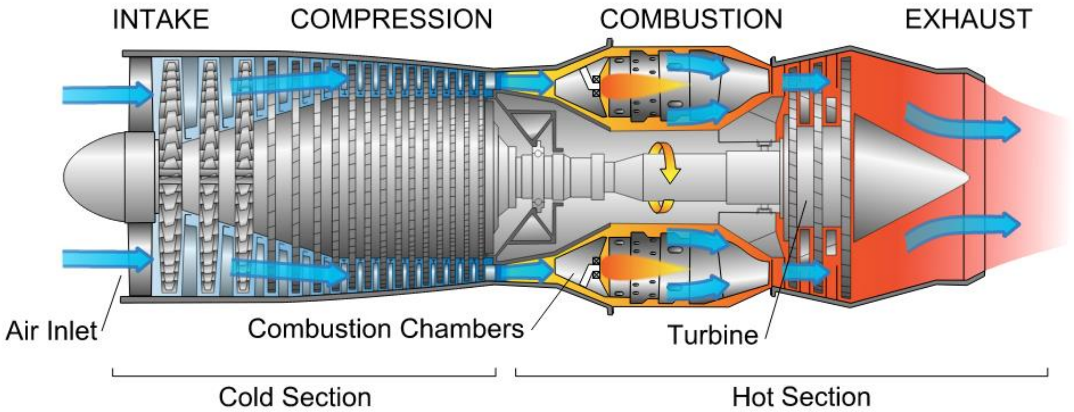


Turbulence is crucial to lift, drag & stall characteristics of airfoils



Increased turbulence on airfoil helps minimize boundary-layer separation and drag from adverse pressure gradient

Turbulence generators



Turbulent mixing of fuel and air is critical for efficient & economical jet engines

Turbulence in oceans crucial to the climate, important for transporting heat, salinity and carbon

Perpetual Ocean (NASA, MIT)

nasa.gov

mitgcm.org

Fun with turbulence in art

Starry Night, Van Gogh (1889)

Leonardo da Vinci (1508), *turbolenza*

The Great Wave off Kanagawa, Hokusai (1831)

Why such a broad range of scale lengths?
(Enter the Reynolds number)

Incompressible Navier-Stokes

- Momentum conservation law:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{v} + \mathbf{f}_B$$

Unsteady flow	Convective acceleration	Pressure force	Viscosity	Body forces (g, $J \times B$, qE)

- Assuming incompressible, from mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) \rightarrow \nabla \cdot \mathbf{v} = \mathbf{0}$$

Consider externally forced flow, no body forces or pressure drop

- Momentum conservation law:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{v} + \mathbf{f}_B$$

Unsteady flow | **Convective acceleration** | **Pressure force** | **Viscosity** | **Body forces (g, J×B, qE)**

- Assuming incompressible, from mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) \rightarrow \nabla \cdot \mathbf{v} = \mathbf{0}$$

Use dimensionless ratios to estimate dominant dynamics

- Reynolds number gives order-of-magnitude estimate of inertial force to viscous force

$$\frac{\mathbf{v}\cdot\nabla\mathbf{v}}{\nu\nabla^2\mathbf{v}} \rightarrow \frac{V^2/L}{\nu V/L^2}$$

$$\boxed{\mathrm{Re} = \frac{VL}{\nu}}$$

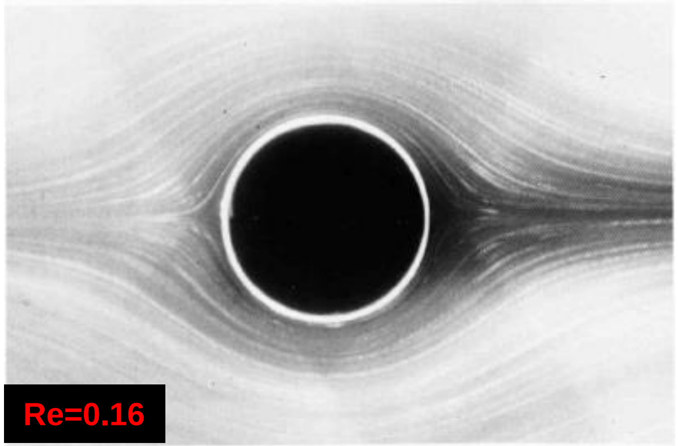
Viscosities (m^2/s)

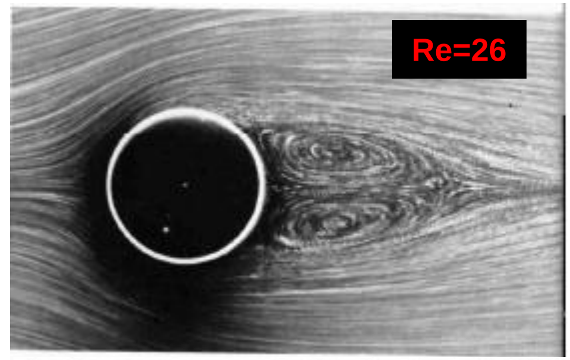
Air	**$\sim 1.5\times10^{-5}$**
Water	**$\sim 1.0\times10^{-6}$**

For $L\sim1$ m scale sizes and $V\sim10$ m/s, $Re\sim10^6$-10^7

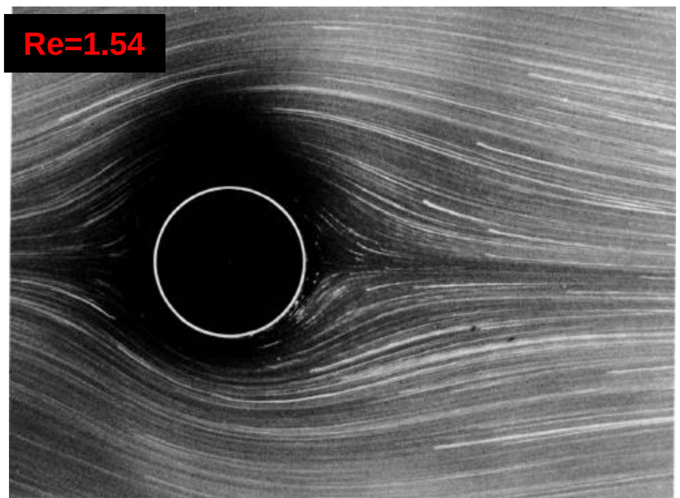
- For similar Reynolds numbers, we expect similar behavior, regardless of fluid type, viscosity or magnitude of V & L (as long as we are at low Mach #)

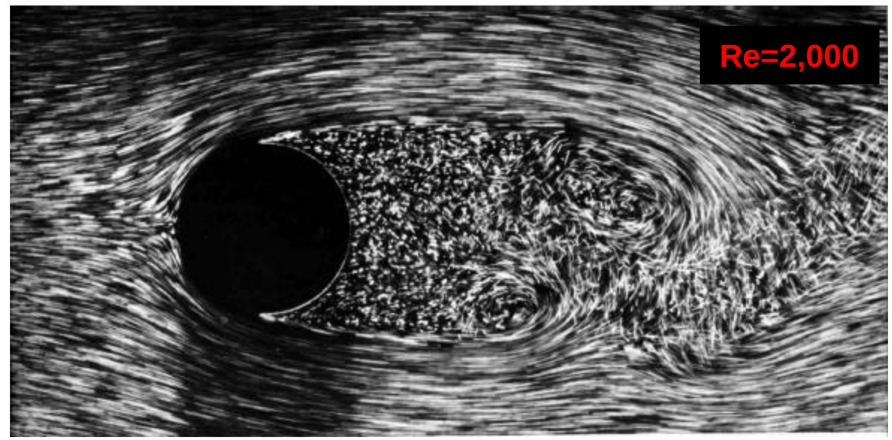
Transition from laminar to turbulent flow with increasing Re

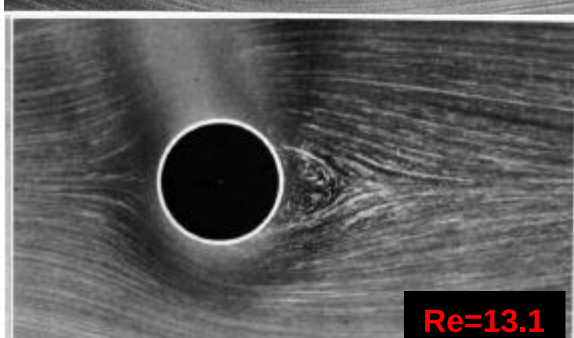


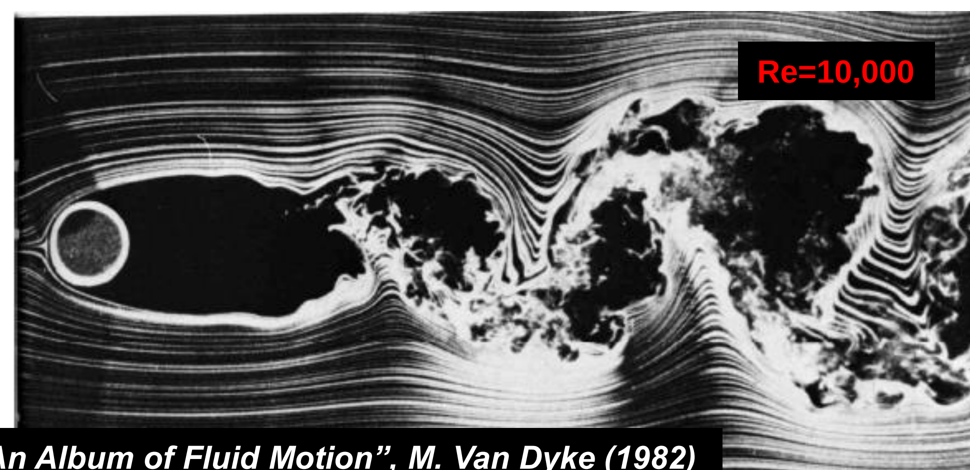


Cylinders or spheres



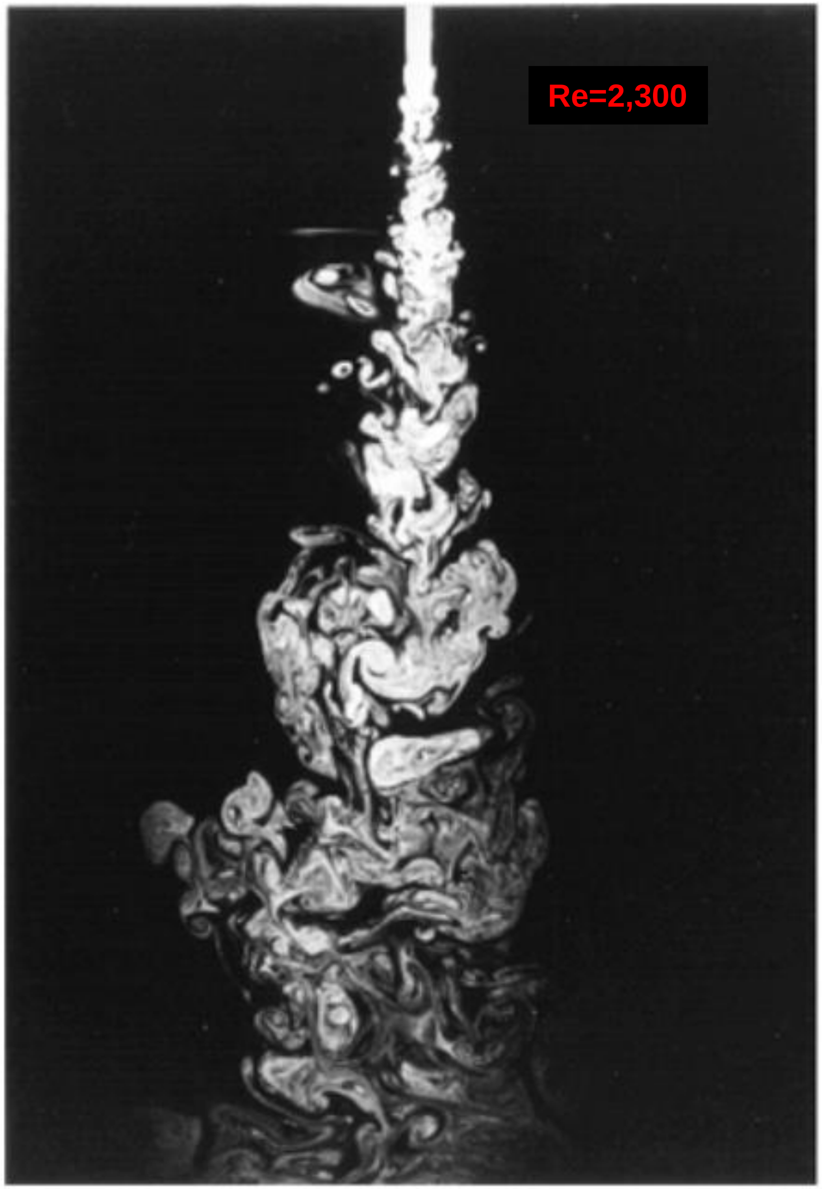


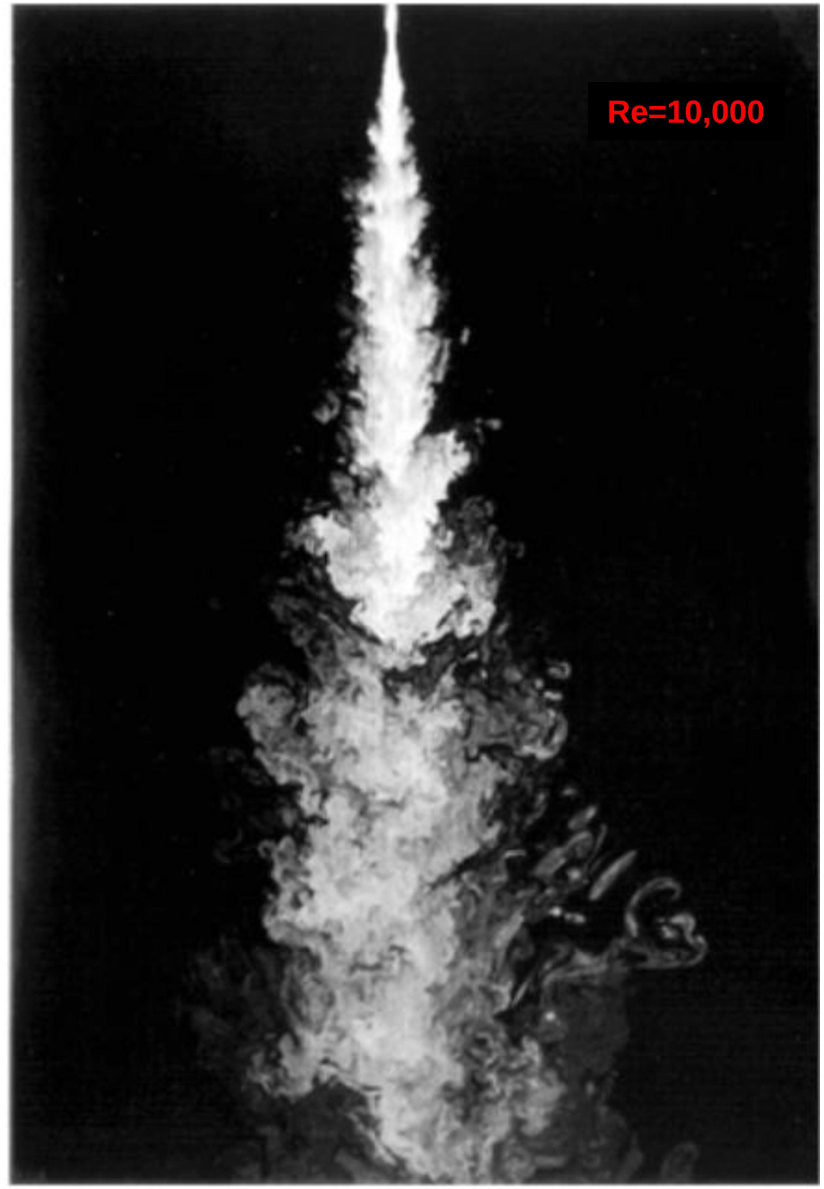




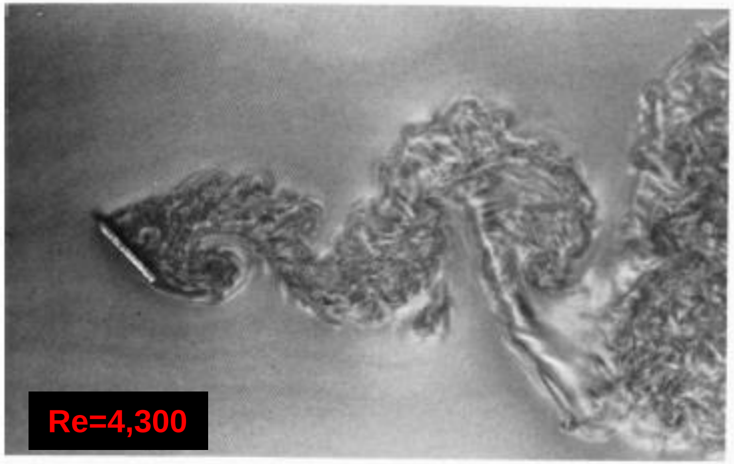
"An Album of Fluid Motion", M. Van Dyke (1982)

Increasing Re # in jet flow (what is changing?)





P. Dimotakis, J. Fluid Mech (2000)



172. Wake of an inclined flat plate. The wake behind a plate at 45° angle of attack is turbulent at a Reynolds number of 4300. Aluminum flakes suspended in water show its characteristic sinuous form. *Cantwell 1981. Reproduced, with permission, from the* Annual Review of Fluid Mechanics, *Volume 13. © 1981 by Annual Reviews Inc.*

173. Wake of a grounded tankship. The tanker *Argo Merchant* went aground on the Nantucket shoals in 1976. Leaking crude oil shows that she happened to be inclined at about 45° to the current. Although the Reynolds number is approximately 10^7, the wake pattern is remarkably similar to that in the photograph at the top of the page. *NASA photograph, courtesy of O. M. Griffin, Naval Research Laboratory.*

"An Album of Fluid Motion", M. Van Dyke (1982)

For large Reynolds #, we expect a large range of scale lengths

- Viscosity works via shear stress, $\nu\nabla^2\mathbf{v} \sim \nu v/\ell^2$

- For the energy injection scales (L_0, V_0), viscosity dissipation is tiny compared to nonlinear dynamics, ~1/Re

- Effects of viscosity will become comparable to rate of energy injection at increasing smaller scales $\ell \ll L_0$

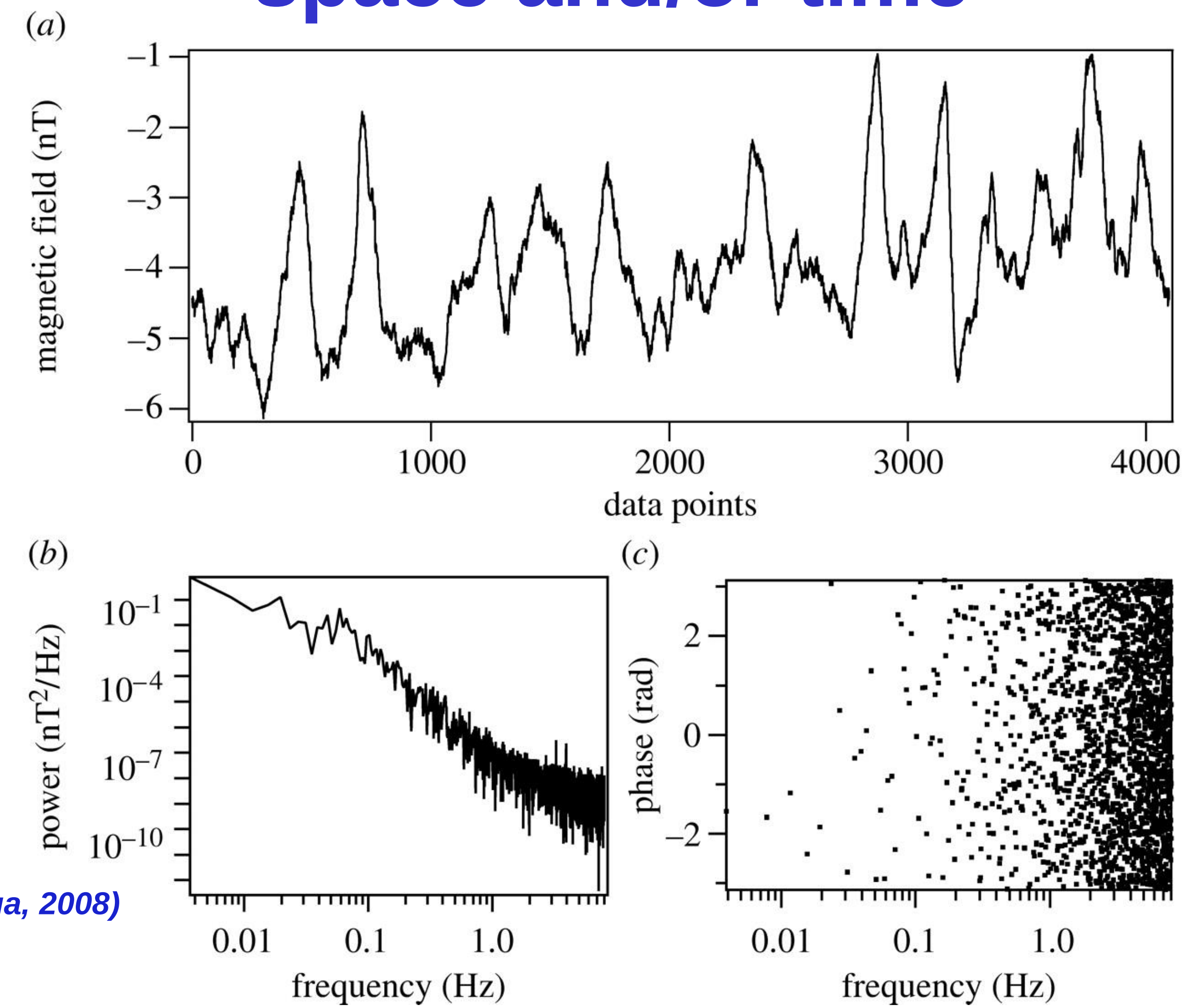
  $\ell/L_0 \sim Re^{-1/2}$ (for laminar boundary layer)

  $\ell/L_0 \sim Re^{-3/4}$ (turbulent flow)

$\Rightarrow$ **What sets the distribution of fluctuations?**

Kolmogorov scaling
(energy cascade through the inertial range)

Aside: Commonly use Fourier transforms in space and/or time

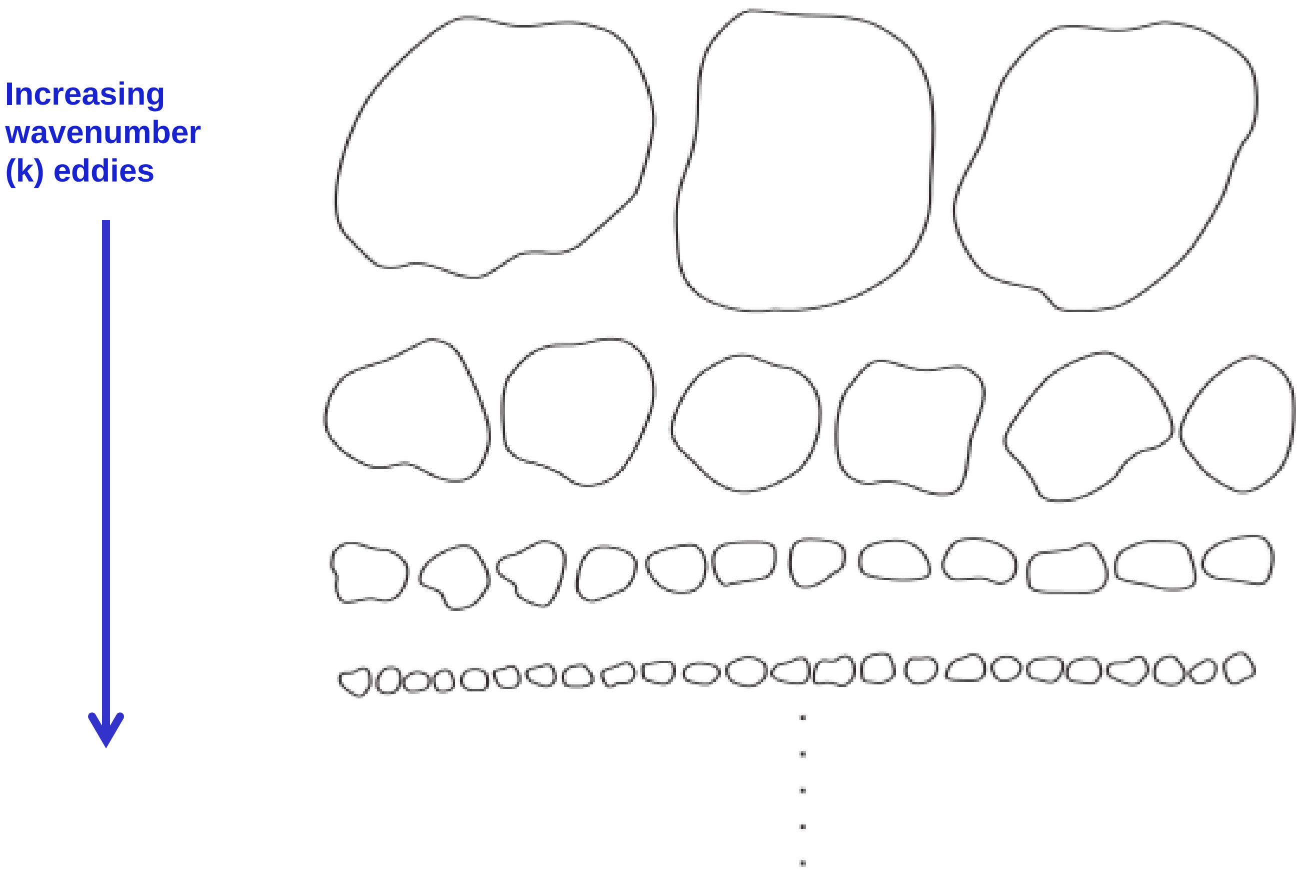


MHD turbulence (Koga, 2008)

- We freely interchange between real space (**x**) and wavenumber space (**k**) in the following, e.g. $k \sim 1/\ell_k$ for a characteristic eddy size ℓ_k

E.g., imagine there are eddies distributed at various scale lengths

- Of course these different wavenumber eddies are not spatially separated but co-exist in space



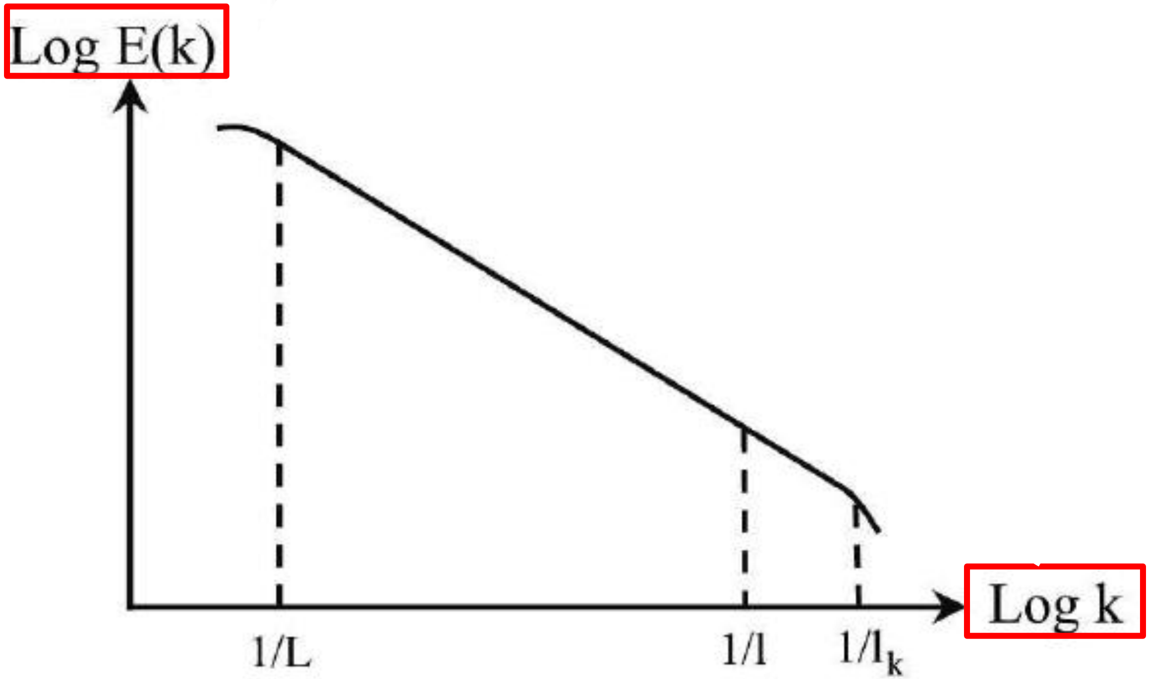
Want to predict distribution of energy with scale length (or wavenumber)

Turbulent energy spectrum

$$\langle \frac{v^2}{2} \rangle = \int E(k)dk$$

$$E(k) \sim v_k^2/\Delta k$$

$$v_k^2 \sim \Delta k \, E(k)$$

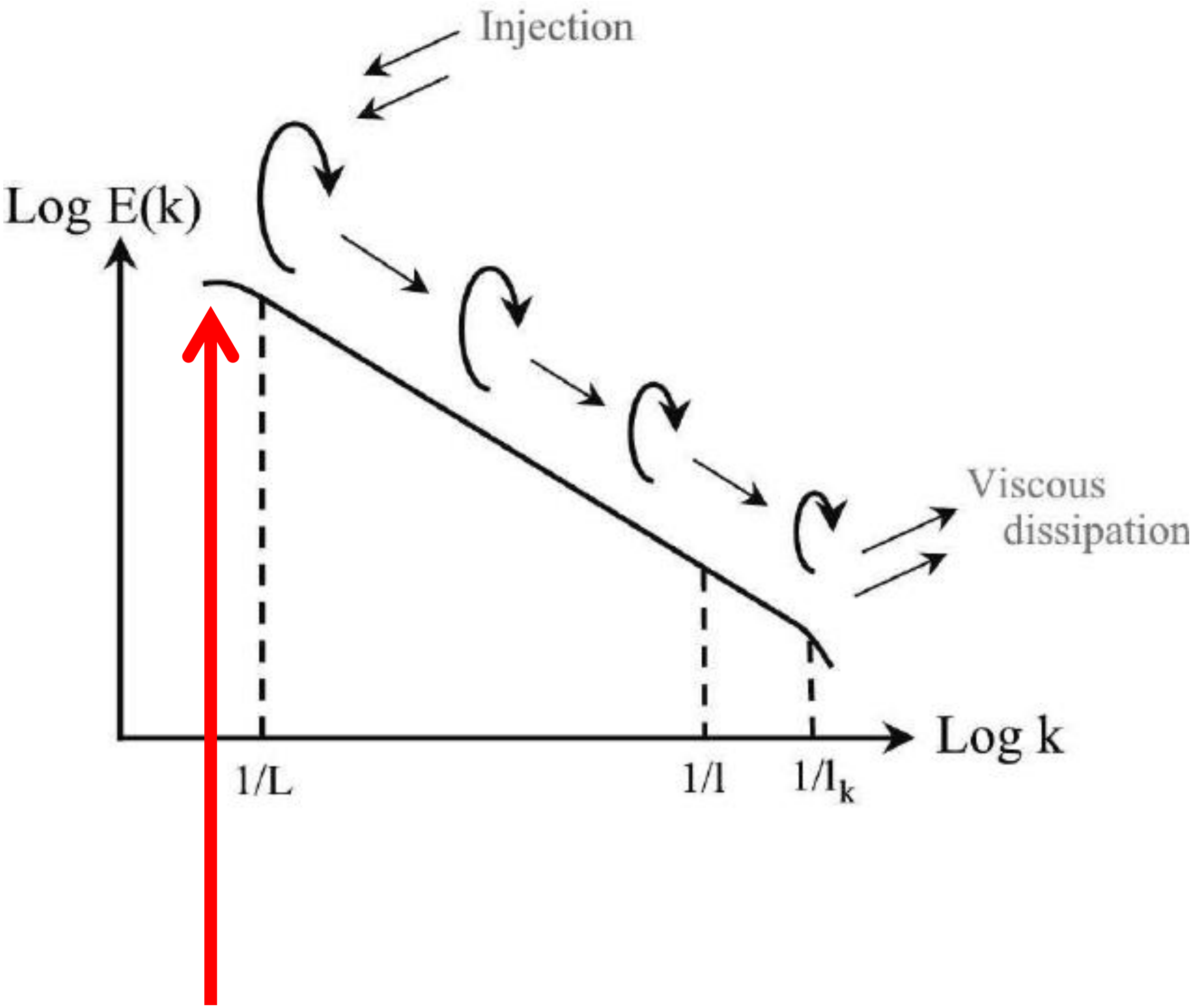


A.N. Kolmogorov (1941) provides a well known derivation of turbulent energy spectrum

Assumptions

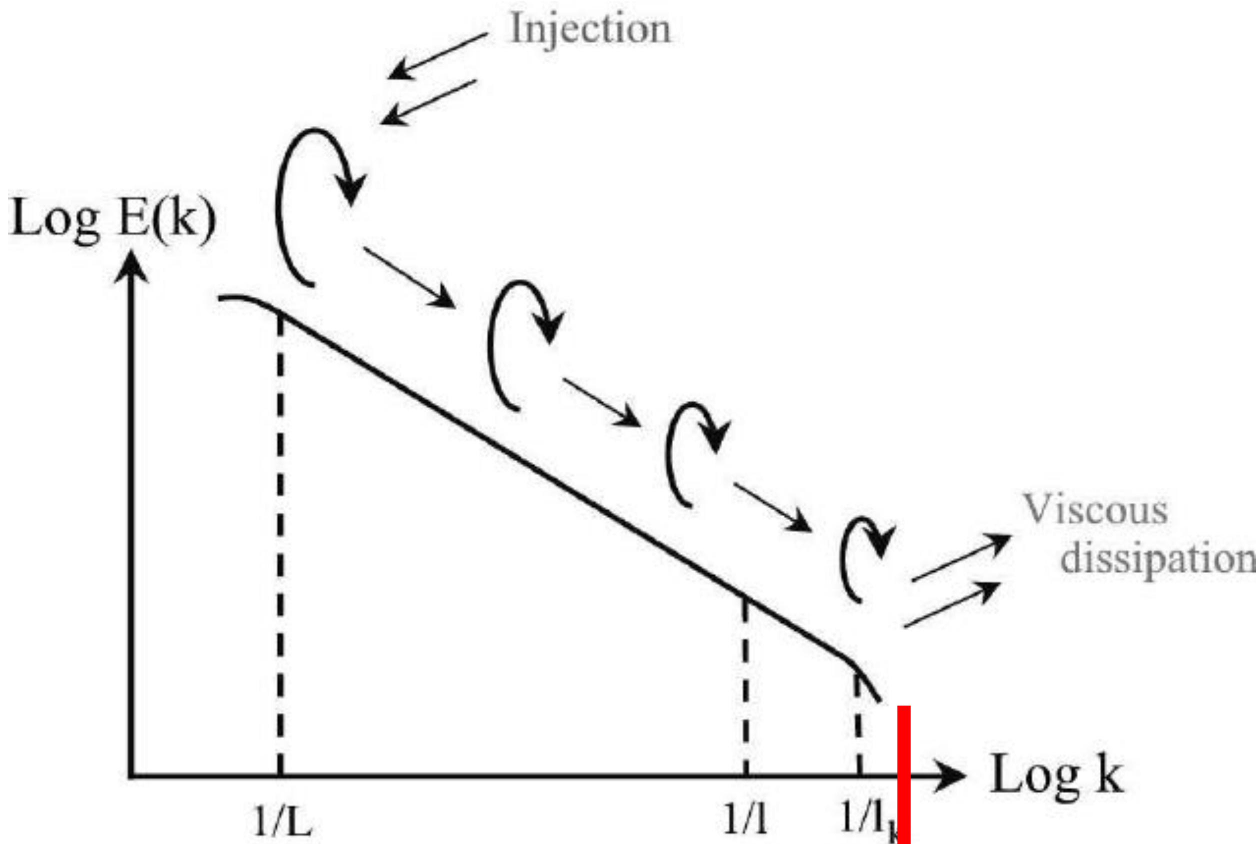
- Energy injected at large scales ~ L_0 ($k_{forcing}$ ~ $1/L_0$)
- Viscosity only matters at very small scales ~ ℓ_ν ($k_\nu \sim 1/\ell_\nu$)
- For sufficient separation of scales ($L \gg l \gg \ell_\nu$, i.e. Re >>>> 1), assume non-linear interactions independent of energy injection or dissipation (so called “inertial range”)
- Turbulence assumed to be homogeneous and isotropic in the inertial range
- Assume that interactions occur locally in wavenumber space (for interacting triads $\mathbf{k}_1+\mathbf{k}_2=\mathbf{k}_3$, $|\mathbf{k}_1|\sim|\mathbf{k}_2|\sim|\mathbf{k}_3|$)

Energy injection occurs at large scales (low k)



$$\epsilon_{inj} = \frac{d}{dt}(U_0^2) \sim \frac{U_0^3}{L_0}$$

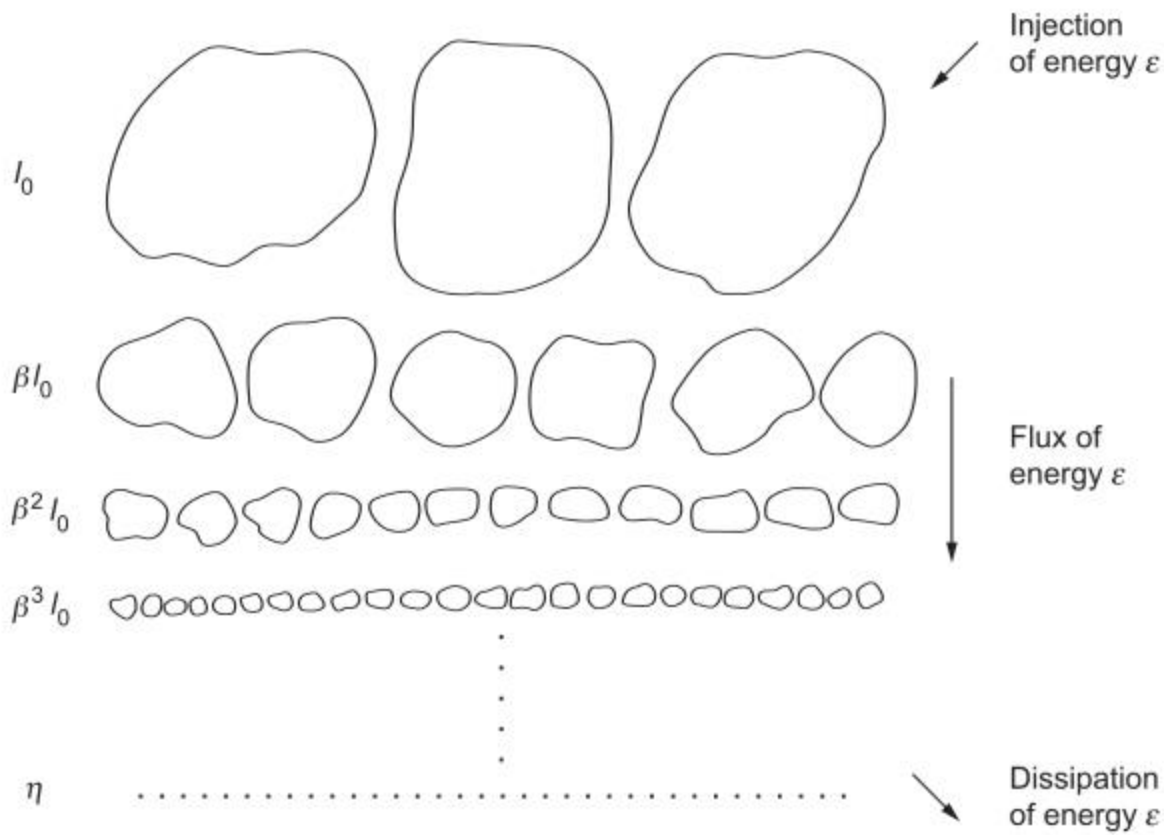
Viscous dissipation strong at small scales (high k)



$$\epsilon_{diss} = -\nu k_\nu^2 E(k)$$

Energy cascade: energy transferred from large eddies down through successively smaller eddies

- Occurs locally in k-space (e.g. between ~k/2 < ~2*k)
  - Very large eddy will not distort smaller eddy very much (~rigid translation/rotation, no shearing); smaller eddies will not distort much larger eddies as they don't act coherently
- "Space filling" at every scale (i.e., not intermittent)



Frisch (1978)

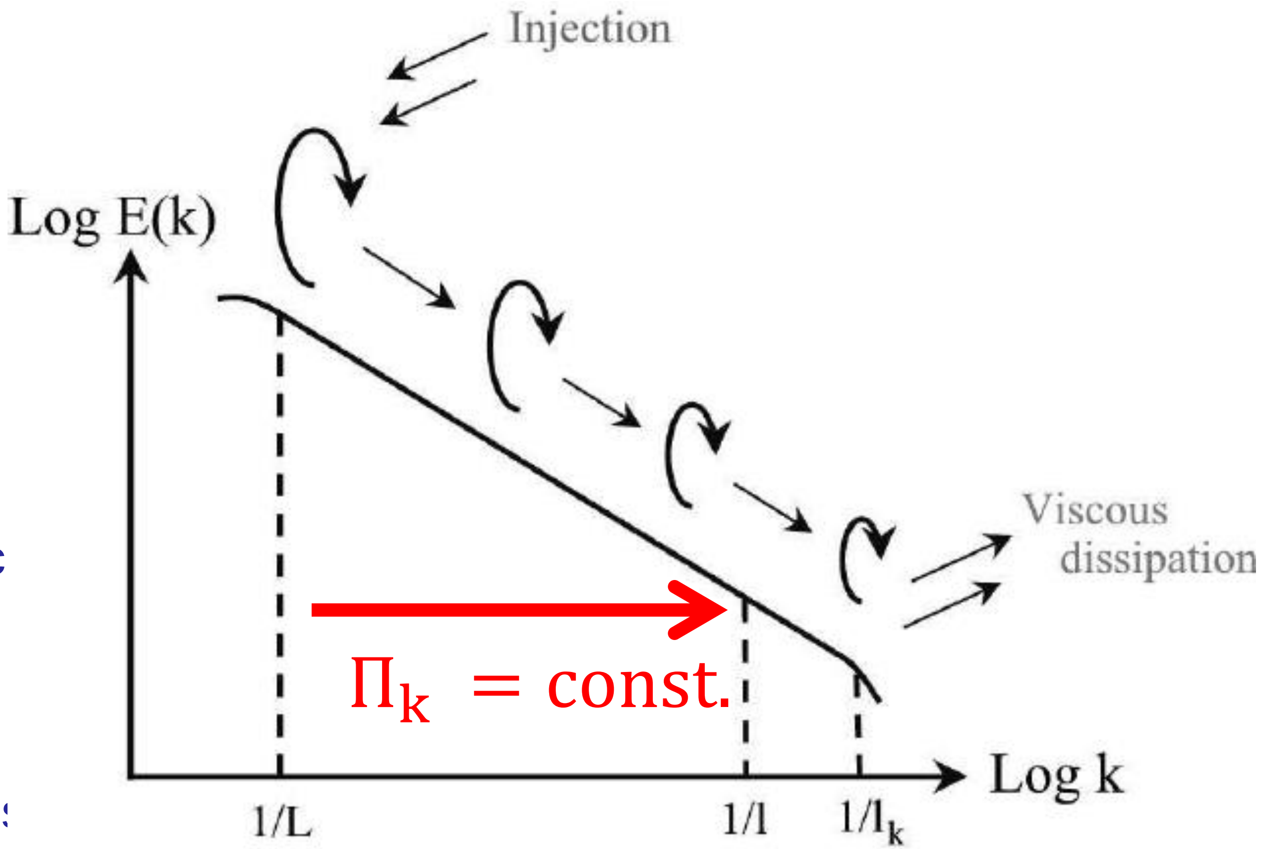
Constant energy cascades through the "inertial range"

- With sufficient separation between forcing and viscous scales (**Re>>>1**), assume "universal" behavior in the inertial range

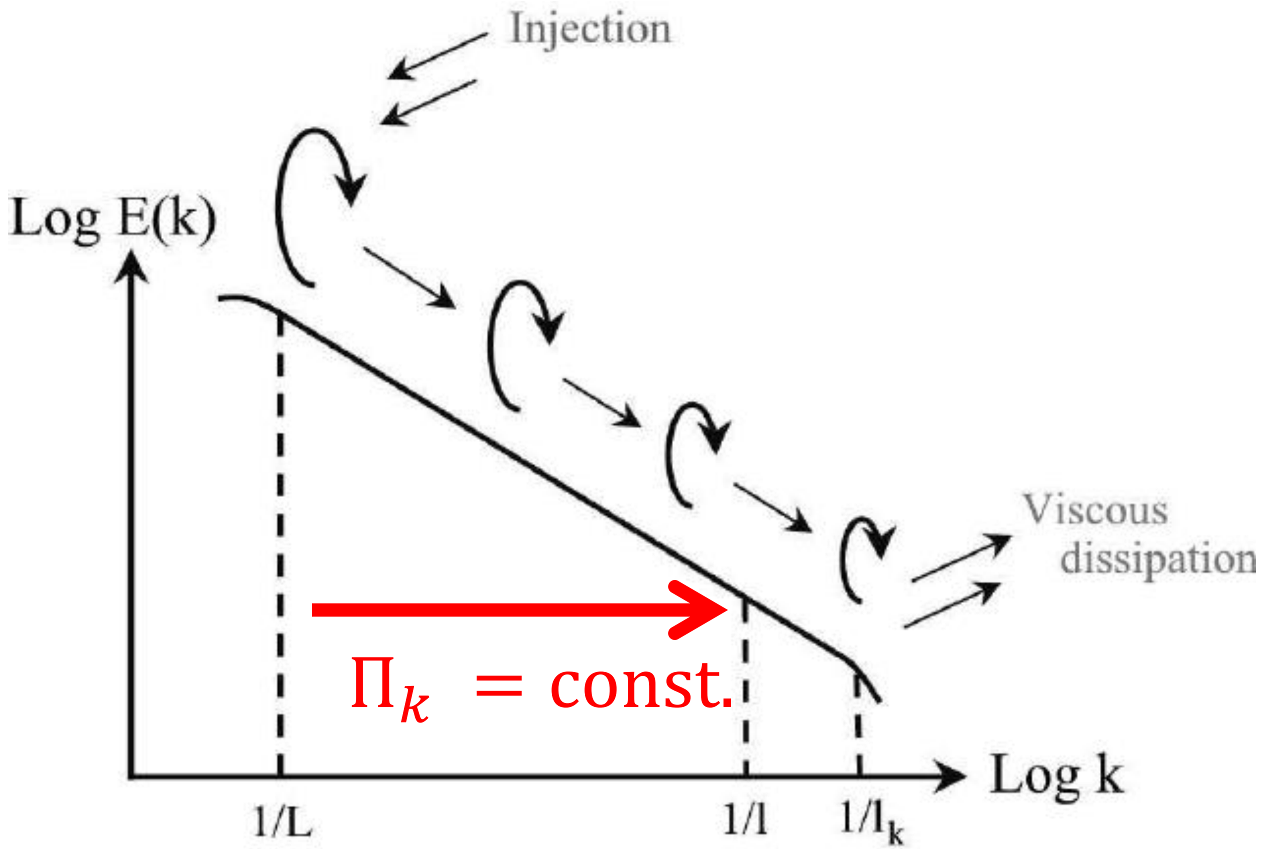
- Turbulence assumed homogenous and isotropic

- Energy cascades through wavenumber space via nonlinear $v \cdot \nabla v$ interactions

- Assume energy cascade to be constant (conservative, viscous dissipation negligible until smallest scales reached)



Consider a Fokker-Plank / advection equation for energy transfer through k-space

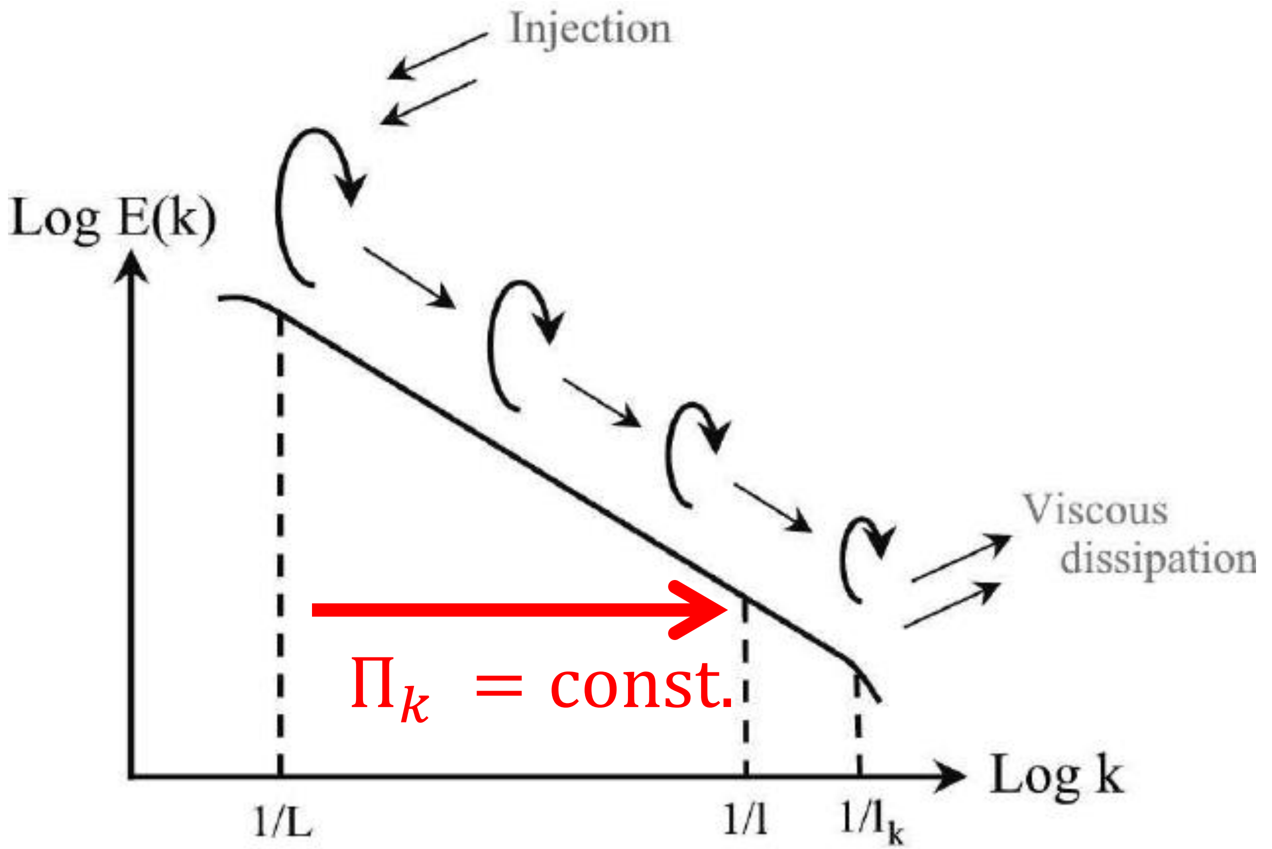


$$\Pi_k = \frac{\langle \Delta k \rangle}{\Delta t} E(k)$$

$$\frac{d}{dt} E(k,t) = \epsilon_{inj} \delta(k - k_f) - \frac{\partial}{\partial k} [\Pi_k] - \nu k^2 E(k) = 0$$

(Hammett class notes)

Consider a Fokker-Plank / advection equation for energy transfer through k-space



$$\Pi_k = \frac{\langle \Delta k \rangle}{\Delta t} E(k)$$

$$\epsilon_{inj} = \epsilon_{diss} = \epsilon \approx \underline{\Pi_k = \frac{\langle \Delta k \rangle}{\Delta t} E(k)} = const$$

Constant cascade of energy through the inertial range gives Kolmogorov spectrum $E(k) \sim \varepsilon^{2/3} k^{-5/3}$

$\Delta t \sim \frac{\ell_k}{v_k} \sim \frac{1}{k v_k}$ eddy turn-over time for scale ℓ_k

$v_k^2 \sim \Delta k\, E(k) \sim k\, E(k)$ ($k \sim \Delta k$ for "local-k" interactions)

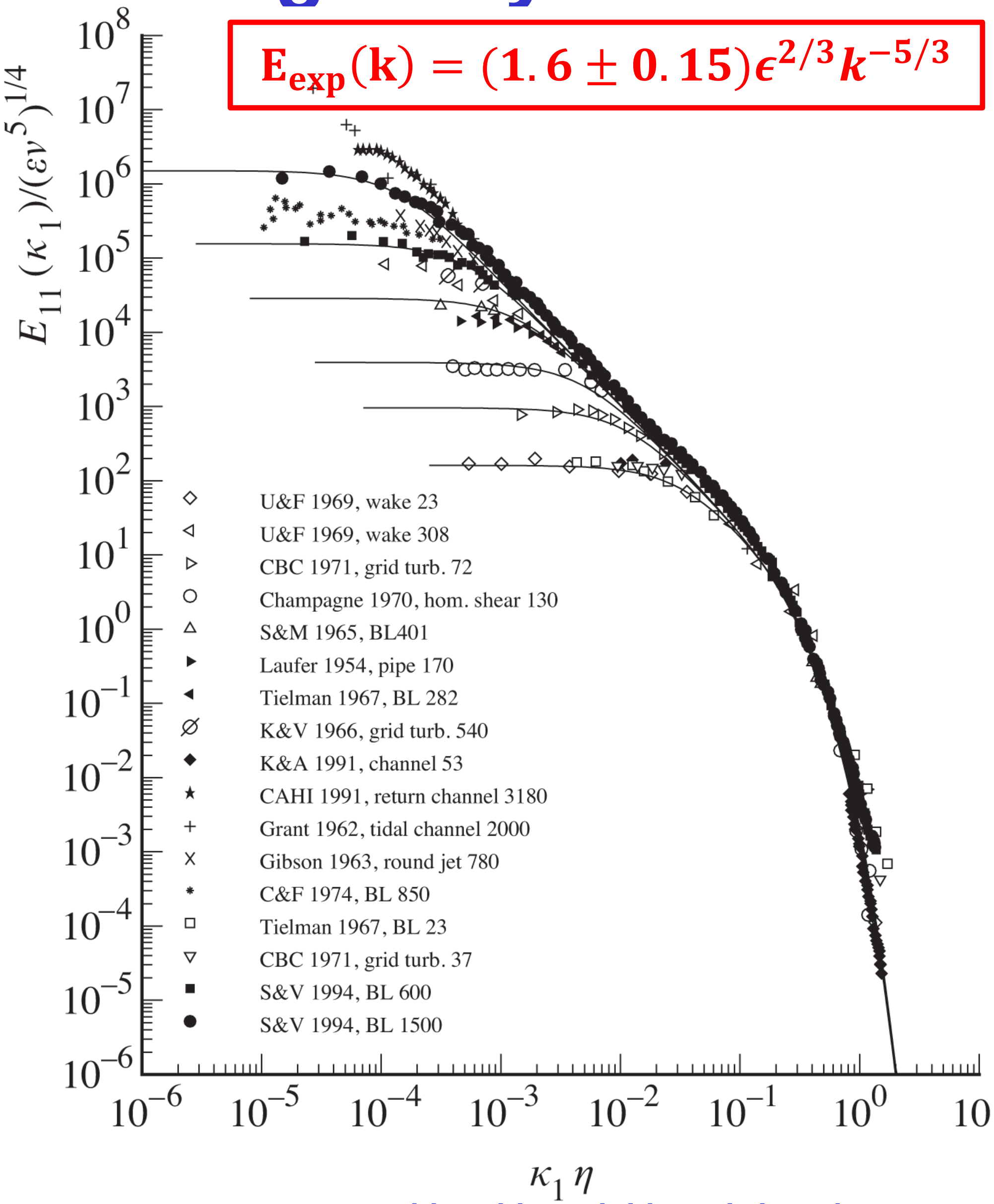
$$\Delta t \sim \frac{1}{k\sqrt{kE(k)}} \sim \frac{1}{k^{3/2} E^{1/2}}$$

$$\epsilon \sim \frac{\langle \Delta k \rangle}{\Delta t} E(k) \sim k^{5/2} E^{3/2}$$

$$\boxed{\mathbf{E(k) \sim \epsilon^{2/3} k^{-5/3}}}$$

Energy cascades will also be seen to be important in plasma turbulence

Significant experimental evidence supports inertial cascade at large Reynolds



<u>Kolmogorov scales</u>

$\ell_K = (\nu^3/\varepsilon)^{1/4}$

$\tau_K = (\nu/\varepsilon)^{1/2}$

$v_K = (\nu\varepsilon)^{1/4}$

Ratio of Kolmogorov / <u>integral scales</u>

$\ell_K/\ell_{int} \sim Re^{-3/4}$

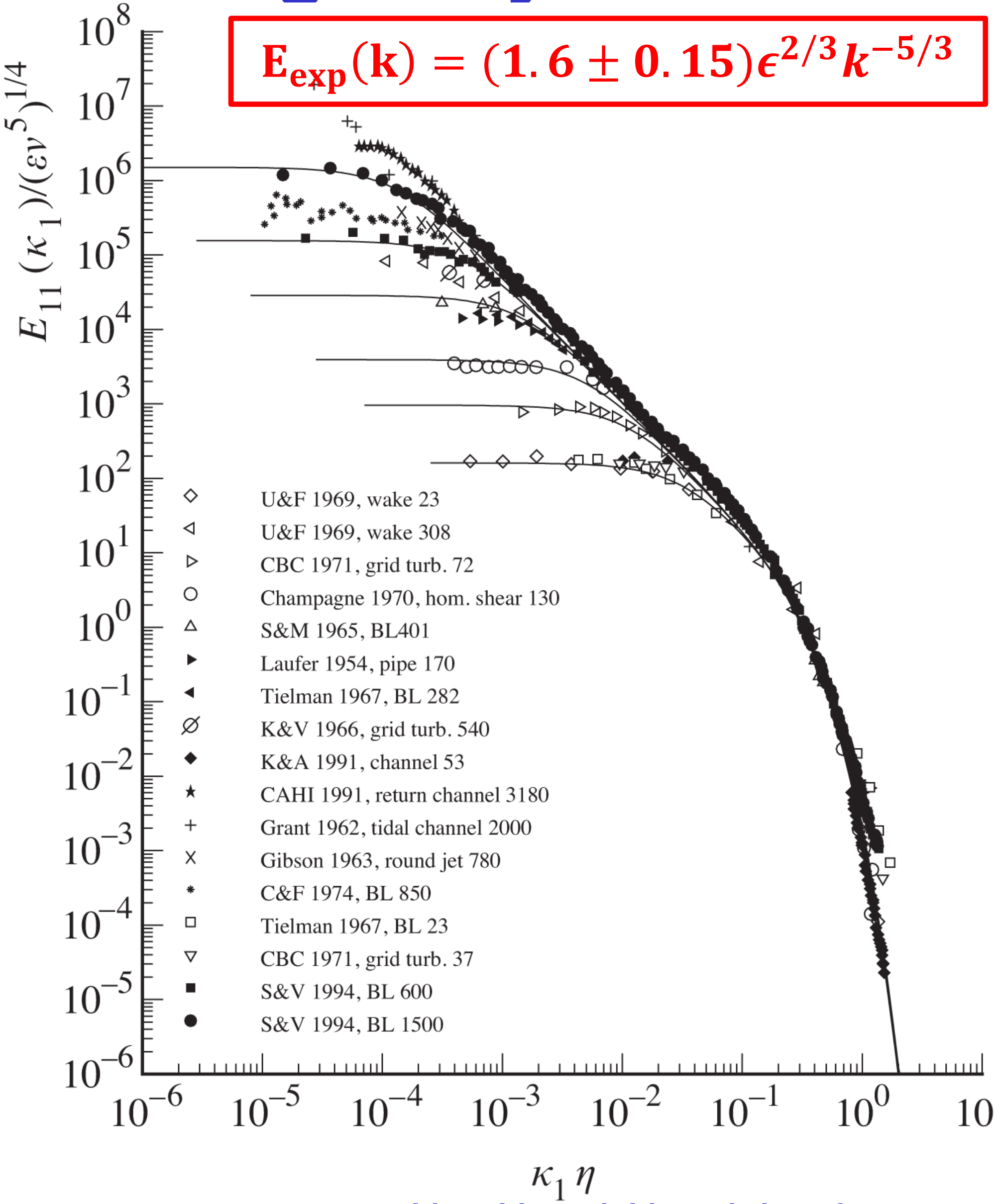
$\tau_K u/\ell_{int} \sim Re^{-1/2}$

$v_K/u \sim Re^{-1/4}$

S.G. Saddoughi, J. Fluid Mech (1994)

Significant experimental evidence supports inertial cascade at large Reynolds

$$\mathbf{E_{exp}(k) = (1.6 \pm 0.15)\epsilon^{2/3}k^{-5/3}}$$



S.G. Saddoughi, J. Fluid Mech (1994)

<u>Kolmogorov scales</u>

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Ratio of Kolmogorov / <u>integral scales</u>

$\ell_K/\ell_{int} \sim Re^{-3/4}$

$\tau_K u/\ell_{int} \sim Re^{-1/2}$

Too expensive to do direction numerical simulation (DNS) of N-S for realistic applications → look to modeling

A poem to help remember the inertial cascade

Big whorls have little whorls
Which feed on their velocity,
And little whorls have lesser whorls
And so on to viscosity

Lewis F. Richardson (1922)

Analysis can be done equivalently in real space with structure functions

- 2^{nd} order structure function observed to follow “two-thirds law”

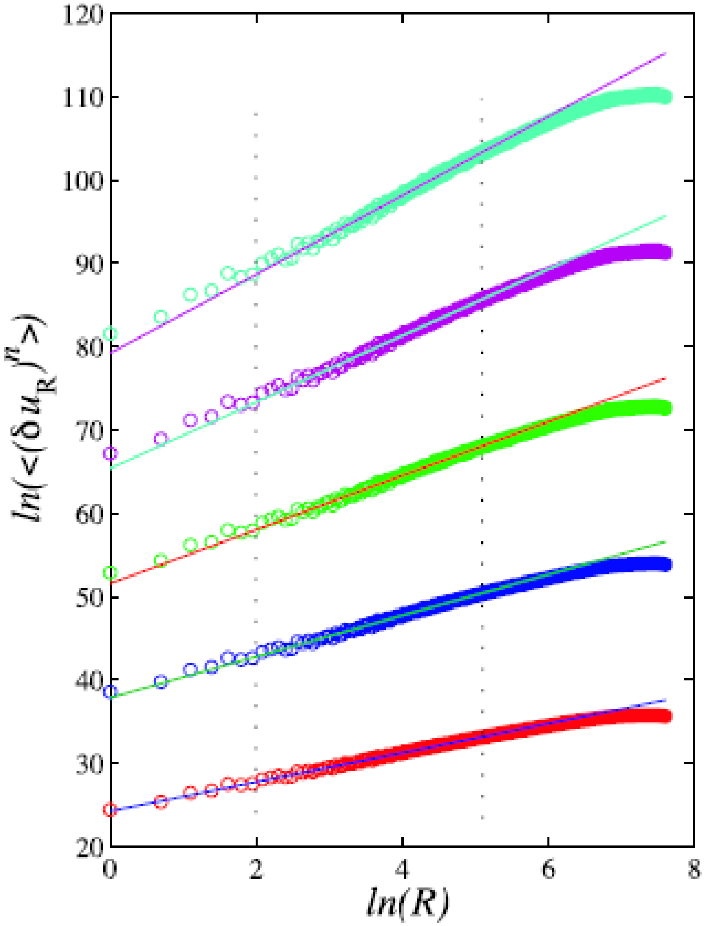
$$\left\langle \left(v_{||}(r+\ell) - v_{||}(r) \right)^2 \right\rangle \sim \ell^{2/3}$$

- One of the only exact analytic results (“four-fifths law”) is given in terms of 3^{rd} order “structure function”

$$\left\langle \left(v_{||}(r+\ell) - v_{||}(r) \right)^3 \right\rangle = -\frac{4}{5}\epsilon\ell$$

Let's revisit van Gogh's turbulent mind

- Distribution of luminance in "Starry Night" matches Kolmogorov expectations
  - Not true of his other paintings



Aragón et al., J. Math Imaging Vis. (2008) "Turbulent Luminance in Impassioned van Gogh Paintings"

Additional interesting notes on Kolmogorov phenomenology

- Energy cascade from large (forcing) scales to small (viscous dissipation) scales occurs in ~2.7 large-scale eddy turnover times *regardless of Reynolds # or viscosity!* (Frisch,

- Large scale dynamics doesn't depend sensitively on details of dissipation at small scales, offers potential route to reduce computational demands

➢ Large Eddy Simulations (LES) with Sub-Grid Scale (SGS) models
  – Direct numerical simulation of large scales (sensitive to geometry / boundary conditions) coupled to model of cascade to dissipation (but not resolved)

What about the transport?

Use Reynolds decomposition to write expression for mean flow

- Decompose velocity into mean and fluctuating components

$$\mathrm{u} = \overline{\mathrm{U}} + \mathrm{u}'$$

- Take a time-average → Reynolds-averaged Navier-Stokes

$$\rho\frac{\partial\bar{u}_i}{\partial t} + \rho\bar{u}_j\frac{\partial\bar{u}_i}{\partial x_j} = \rho\overline{f_i} + \frac{\partial}{\partial x_j}\left[-\bar{p}\delta_{ij} + 2\mu\bar{S}_{ij} - \rho\overline{u_i'u_j'}\right]$$

$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)$ ← mean rate of strain tensor

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- $\overline{u_i' u_j'}$ is the Reynolds stress (a turbulence-advected momentum flux)

Use Reynolds decomposition to write expression for mean flow

- Decompose velocity into mean and fluctuating components

$$u = \overline{U} + u'$$

- Take a time-average → Reynolds-averaged Navier-Stokes

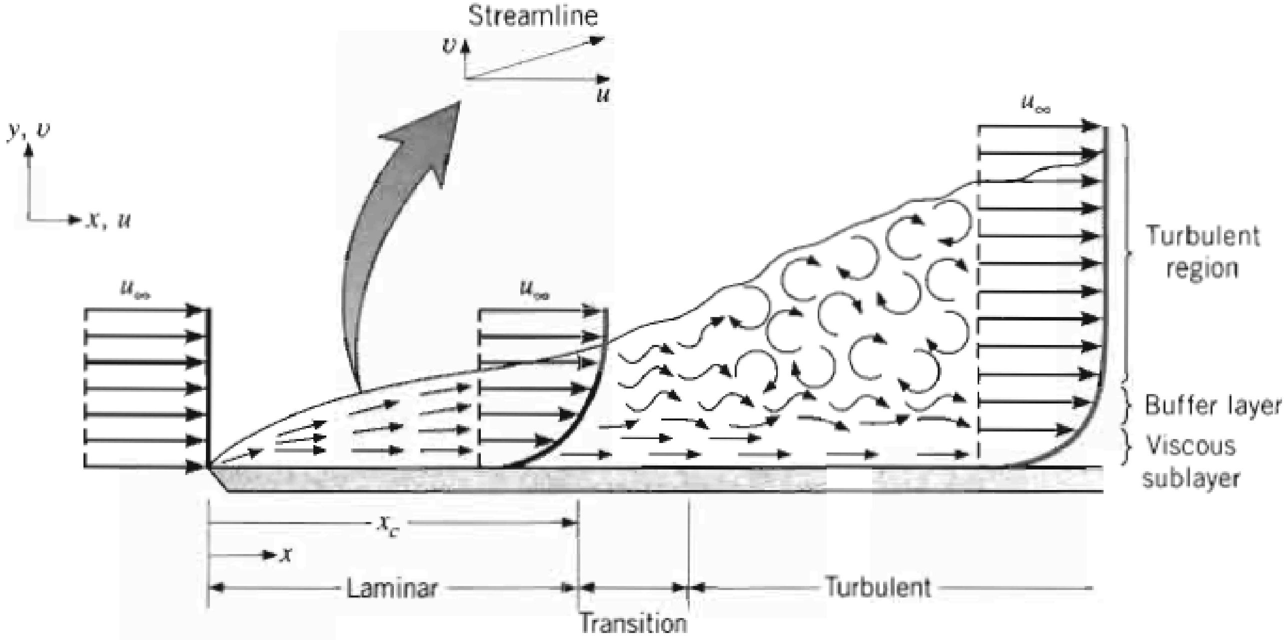
$$\boxed{\rho \frac{\partial \bar{u}_i}{\partial t}} + \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \bar{f}_i + \boxed{\frac{\partial}{\partial x_j}}\left[-\bar{p}\delta_{ij} + 2\mu \bar{S}_{ij} - \boxed{\rho \overline{u_i' u_j'}}\,\right]$$

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$ ← mean rate of strain tensor

- $\overline{u_i' u_j'}$ is the Reynolds stress (a turbulence-advected momentum flux)
- $\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\,\right) + \bar{f}_i$ ... → like a transport equation with turbulent momentum flux ($\overline{u_i' u_j'}$) adding to diffusive viscous flux ($\sim \nu \frac{d\bar{u}}{dx}$)
- Larger turbulent flux → reduced mean velocity gradient

Example: flow over a surface

- Expanding boundary layer, leads to momentum deficit (drag)

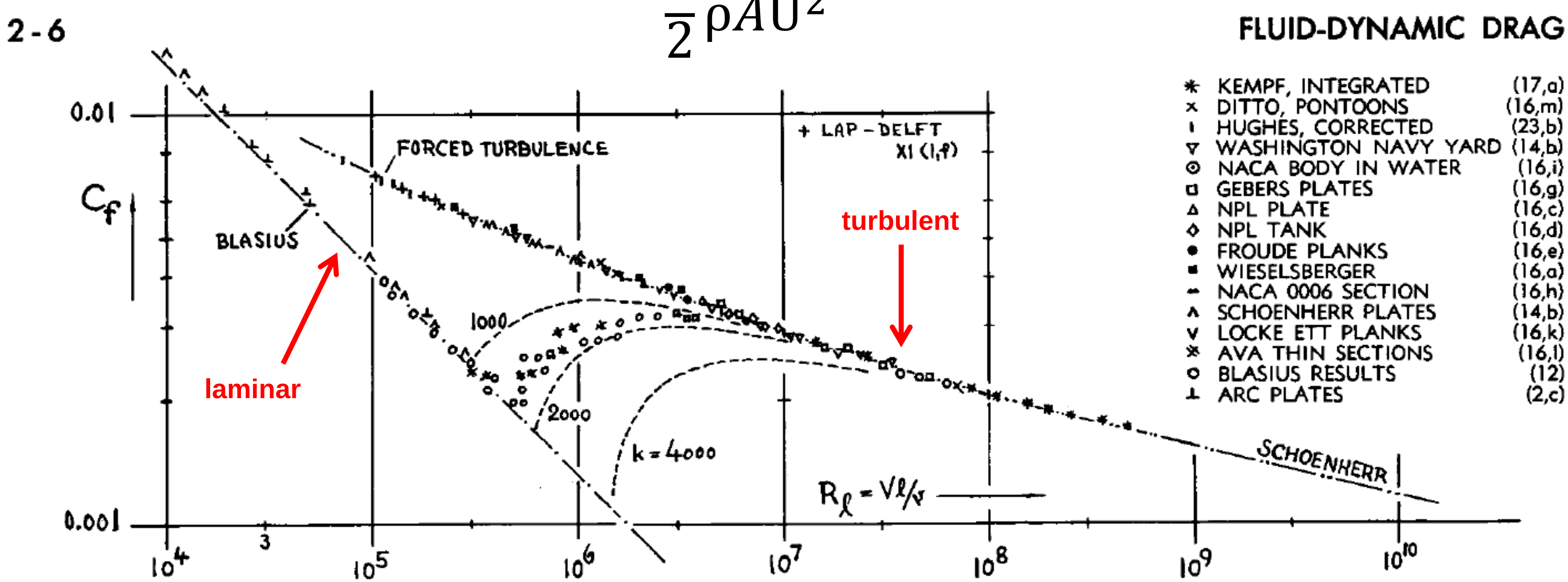


- Where does momentum go
  - Some cascades to small scales and viscosity
  - Transport momentum to near-wall viscous sublayer, loss through viscosity in enhanced by increased sheared flow
  - A component of drag also comes from adverse pressure gradient ($p_0=p_\infty + 1/2\rho u^2$, Bernoulli, incompressible)

Turbulence increases drag coefficient compared to projected laminar coefficient

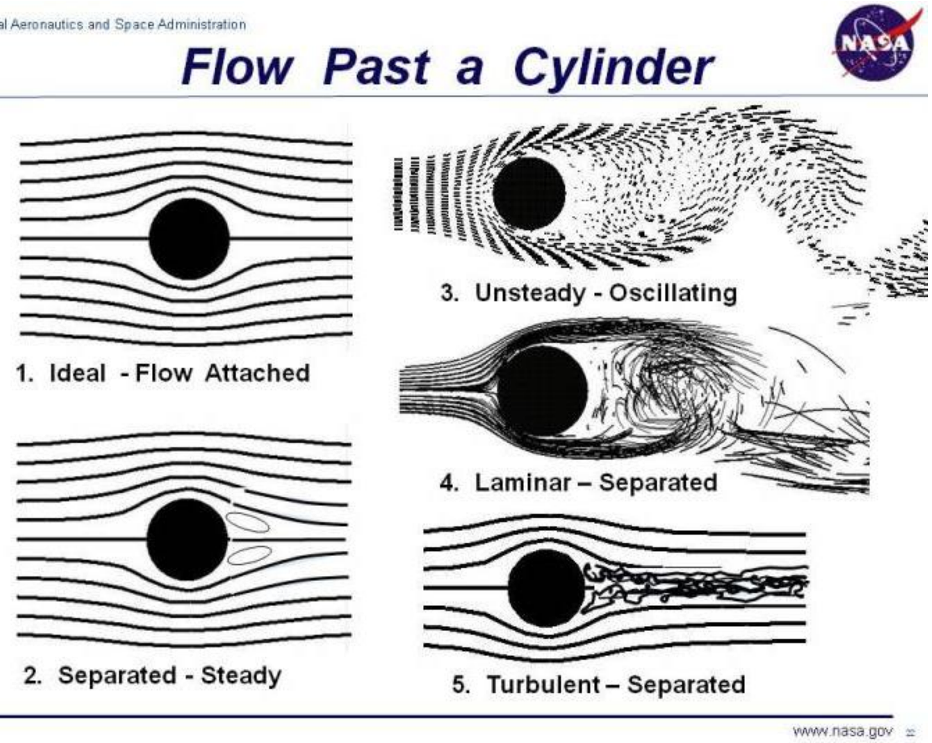
- Transition point changes with surface roughness & geometry

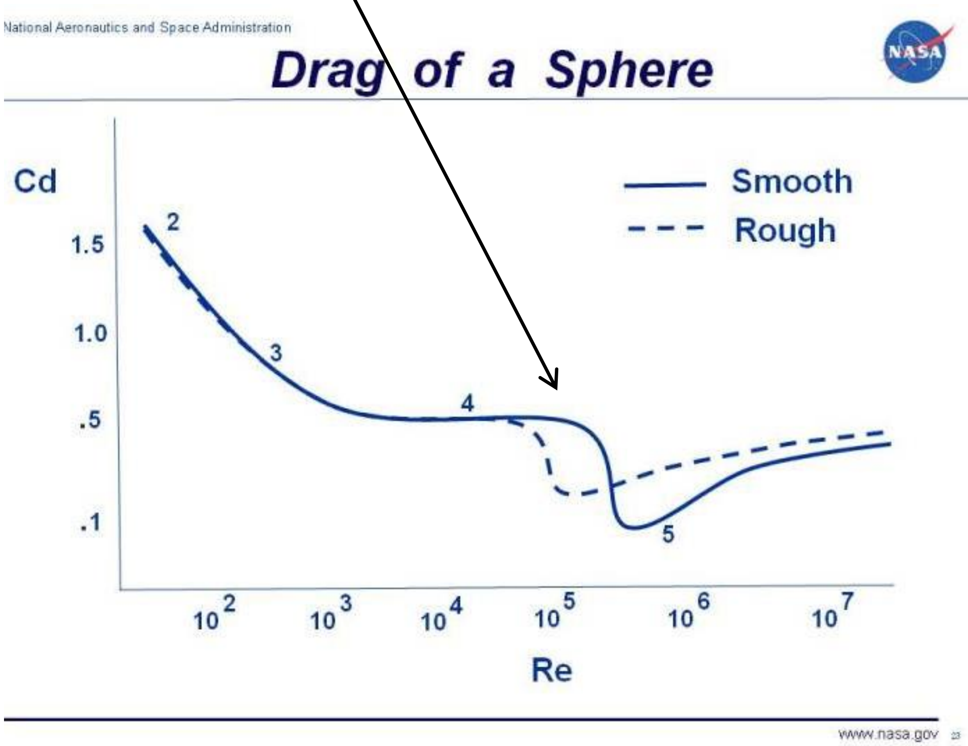
$$c_D = \frac{F_{drag}}{\frac{1}{2}\rho A U^2}$$



Horner, "Fluid Dynamic Drag" (1965)

Sudden drop in c_D with Reynolds # for sphere transitioning to detached turbulence



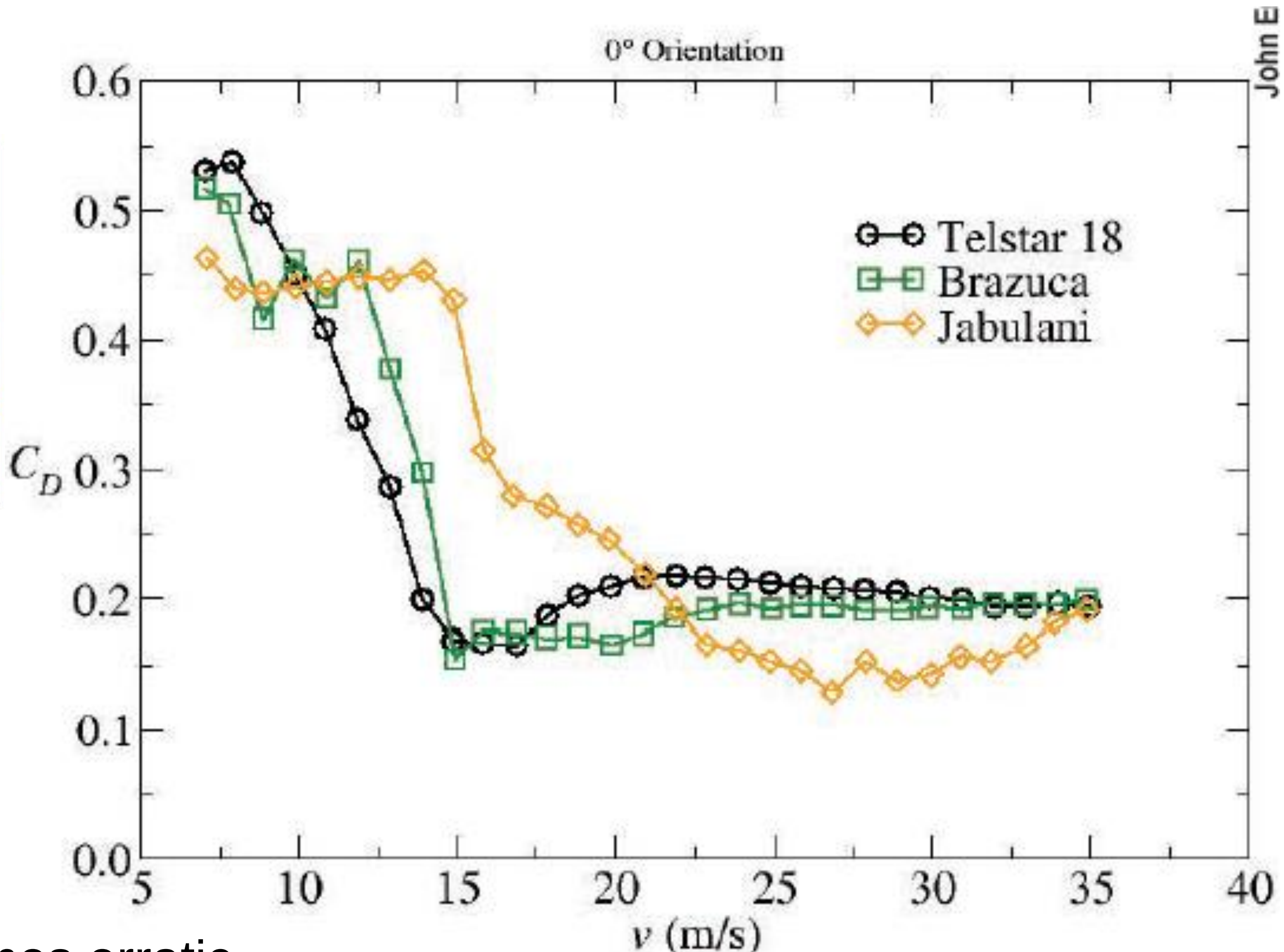


https://www.grc.nasa.gov/www/K-12/airplane/dragsphere.html

Drag coefficient and transition to turbulence important to World Cup players

Physicist John Eric Goff studies the aerodynamics of soccer balls.

APS News (July 2018)



- Ball trajectory becomes erratic around transition – has varied for different World Cups (different balls), can lead to unhappy players

Speed of free kicks / corner kicks

Modeling turbulence (eddy viscosity, mixing length estimates)

Would like solutions for Reynolds stresses (fluxes) without expense of direct numerical simulation

- Could write equations for evolution of 2nd order Reynolds stresses, but will then depend on 3rd order terms → closure problem
- Generally, models try to relate Reynolds stresses to lower order moments

- One example: eddy viscosity (ν_T) (Boussinesq, 1870s)

$$\overline{u_i' u_j'} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} + \cdots \right)$$

- where $\nu_t \sim \overline{u'}\ell$, i.e. treat analogous to molecular diffusion (**danger**: turbulence is advective in nature, not diffusive!!!!!)

- Interesting historical summary by Frisch
  - Barré de Saint-Venant (1850), Boussinesq (1870) – interest in water flow in canals; before Maxwell work on kinetic theory of gases
  - Taylor (1915), Prandtl (1925) – boundary layer flows (e.g. airfoils)

Prandtl (1920s) proposed a mixing length model for eddy viscosity

$$u_x' = \ell_m \frac{\partial \overline{u_x}}{\partial y}$$

<u>Interpretation:</u>

- Deviation from the mean after traversing a mixing-length ℓ_m
- Or, roughly a balance between characteristic turbulent gradient ($\nabla u' \sim u'/\ell_m$) and mean-flow gradient ($\nabla \bar{u}$) → gives order-of-magnitude estimate for fluctuation amplitude $\left(\frac{u'}{\bar{u}} \sim \ell_m \nabla\right)$

⇒ Corresponding turbulent eddy viscosity:

$$\nu_t = u_x' \ell_m = \ell_m^2 \frac{\partial \overline{u_x}}{\partial y}$$

- Still have to pick (or fit to data) a suitable mixing length, e.g. ~ integral scale length (average correlation length)
- Magnetized plasma turbulent transport models have used eddy viscosity / mixing length estimates (now with much added sophistication, Lec. 5)

Why is turbulence everywhere?
(Linear vs. non-linear stability)

Energy gradients can drive linear instabilities → turbulence

- Free energy drive in fluid gradients (∇V, $\nabla\rho$ ∇T) or kinetic gradients $\nabla F(\mathbf{x},\mathbf{v})$ in the case of plasma
- We will uncover multiple analogous instabilities in magnetic plasmas

Kelvin-Helmholtz instability ~ ∇V

Rayleigh-Taylor instability ~ $\nabla\rho$

Rayleigh-Benard instability ~ ∇T

- Generally expect large scale separation remains between linearly unstable wavelengths and viscous damping scale lengths (*often not the case in kinetic plasma turbulence*)

Nonlinear instability important for neutral fluid pipe flow

Pipe flow is believed linearly stable for all Re (not rigorously proven). Nevertheless: Laminar for Re < 2300, turbulent for Re>4000 (both possible in transition region). Due to nonlinear instabilities: with large-enough amplitude becomes self-sustained turbulence (transient growth by non-normal modes (Trefethen)). Turbulent drag depends (weakly) on surface roughness.

From http://en.wikipedia.org/wiki/Reynolds_number From Moody (1944), Princeton Prof. of Hydrolic Eng.

(Hammett notes)

- Nonlinear instability (subcritical turbulence) may be important in some plasma scenarios

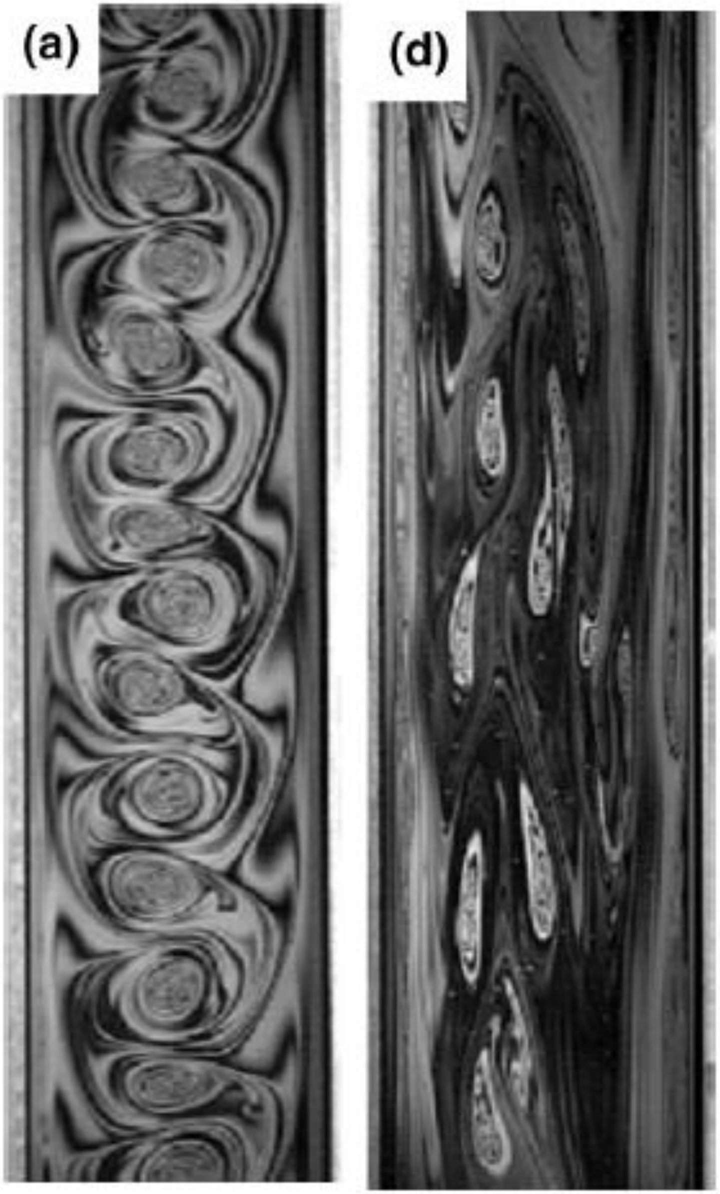
2D turbulence (atmospheric, soap films, magnetized plasma)

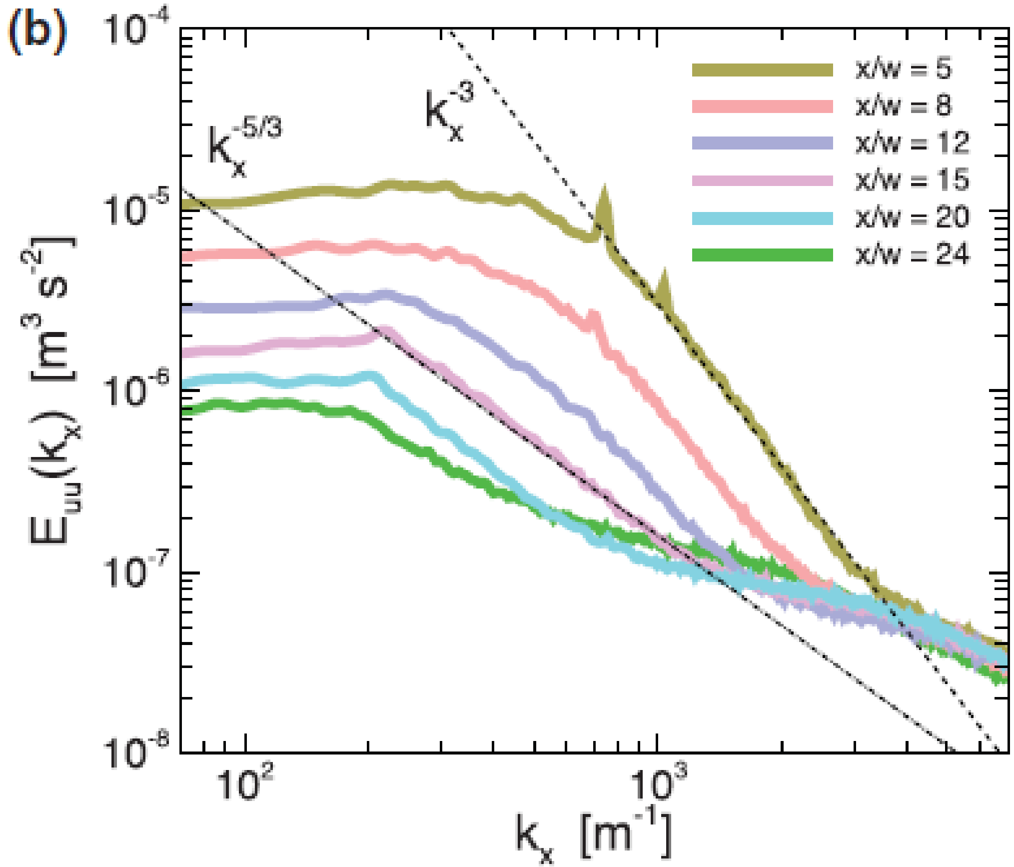
Quasi-2D turbulence exists in many places

- 2D approximation for geophysical flows like ocean currents (Charney, 1947), tropical cyclones, polar vortex, chemical mixing in polar stratosphere (→ ozone hole)
- Strongly magnetized plasma turbulence is 2D in nature

- Loss of vortex stretching, vorticity is conserved → change in non-linear conservation properties
  - ***Inverse*** energy cascade $E(k) \sim k^{-5/3}$
  - Forward enstrophy $[\omega^2 \sim (\nabla \times v)^2]$ cascade $E(k) \sim k^{-3}$ (at larger wavenumbers, smaller scales)
  - Non-local wavenumber interactoins can couple over larger range in k-space (e.g. to zonal flows)

Soap film images have been used to measure variation in energy spectrum in 2D

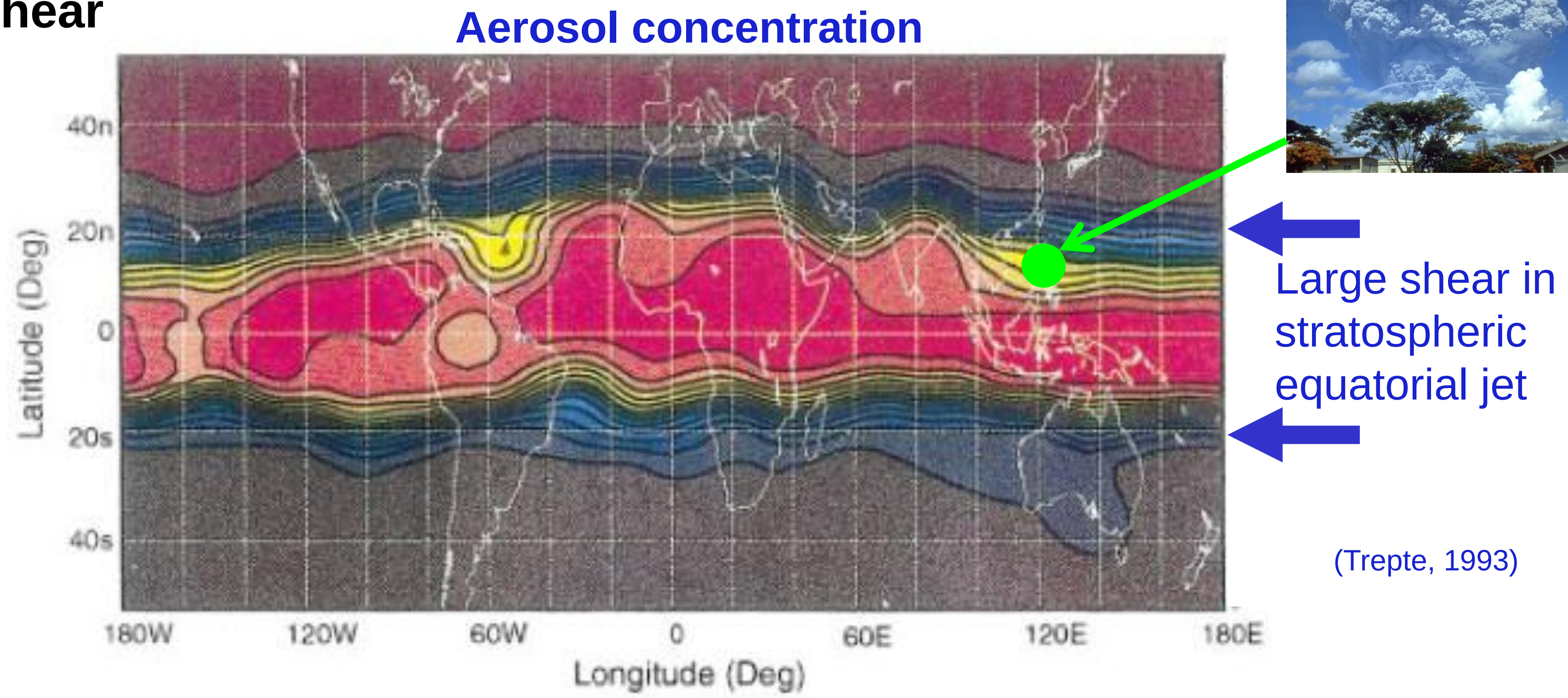




Liu et al., PRL (2016)

Mean velocity shear flow can suppress turbulence & transport in quasi-2D!

- In contrast to flow shear *drive* in 3D turbulence
- Stratospheric ash from Mt. Pinatubo eruption (1991) spread rapidly around equator, **but confined in latitude by flow shear**

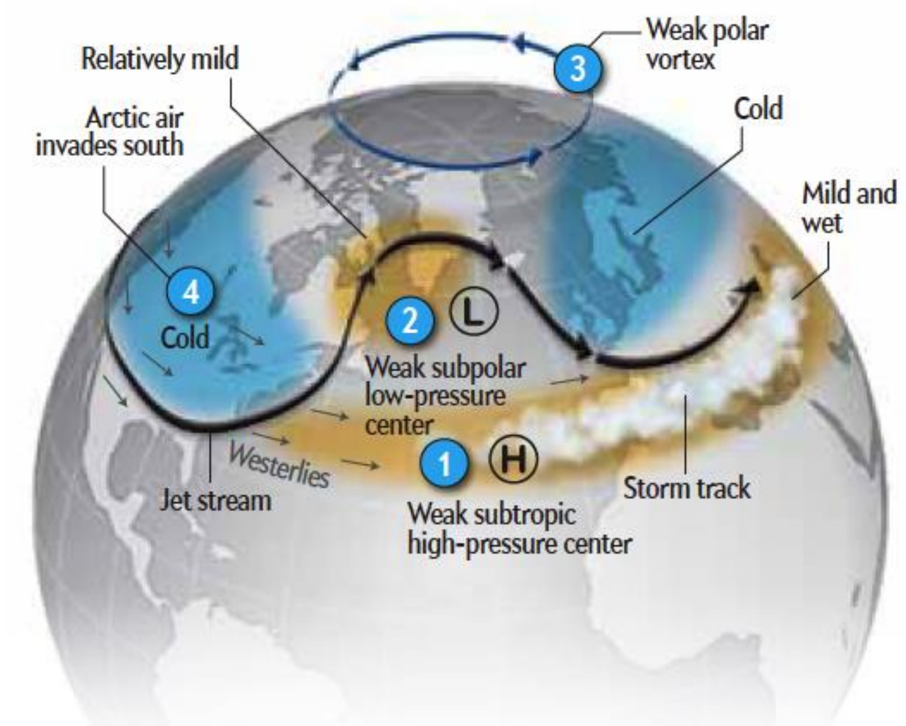


(Trepte, 1993)

- *Flow shear suppression of turbulence important in magnetized plasmas*
  - See lengthy review by P.W. Terry, Rev. Mod. Physics (2000)

The Jet Stream (zonal flow) occurs as a consequence of 2D dynamics

- NASA/Goddard Space Flight Center Scientific Visualization Studio



- *Similar zonal flow development is critical element in magnetized plasma turbulence*
  - Driven by non-local wavenumber interactions

How does plasma change N-S, inertial cascades?

New dynamics arise in plasma turbulence

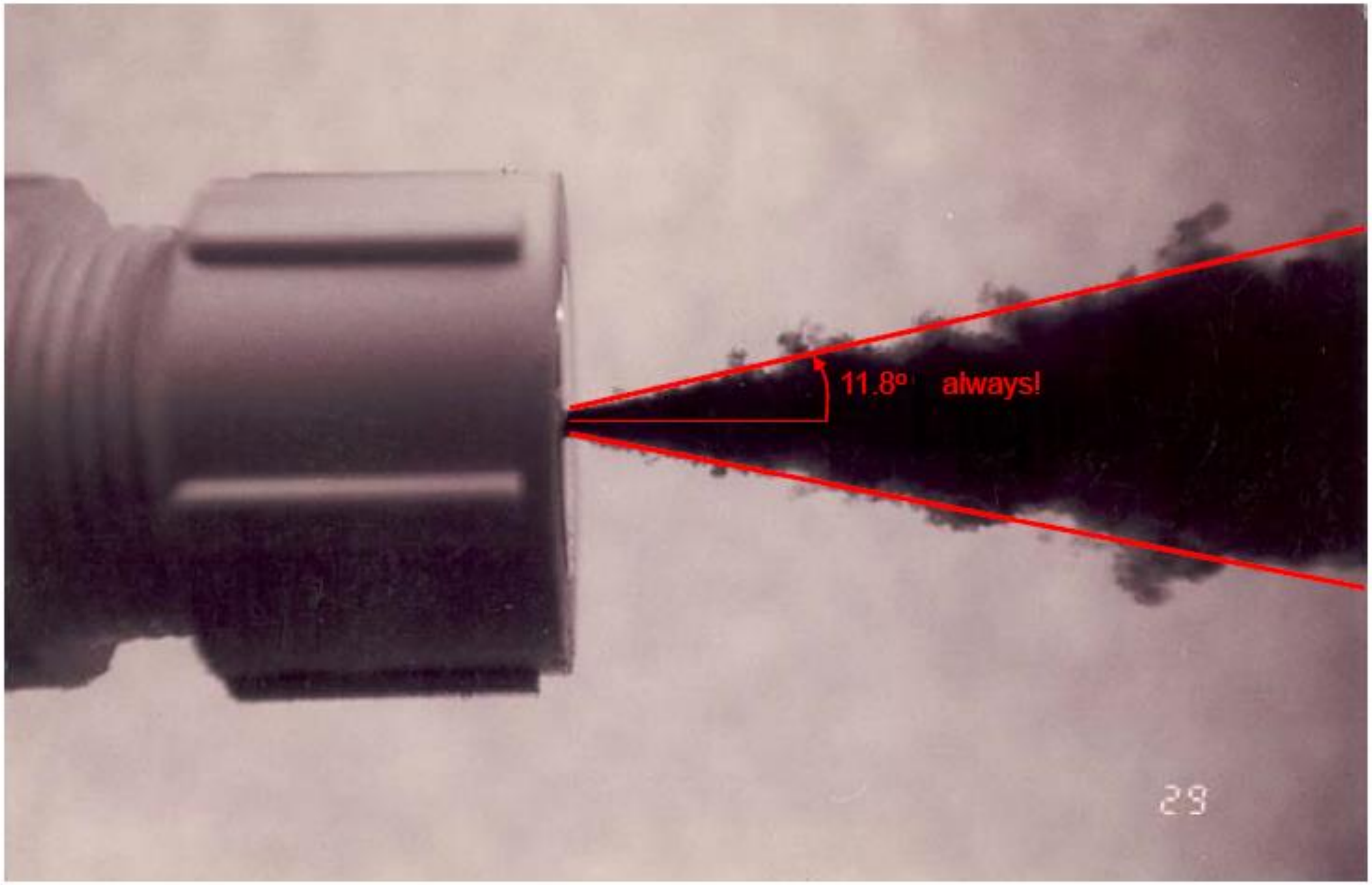
- New forces & interactions through charged particle motion
  - $\delta n_{e,i}$ & $q\delta v_{e,i} \rightarrow \delta E, \delta j, \delta B \rightarrow q[E+\delta E + (v+\delta v)\times(B+\delta B)]$
  - Turbulent dynamos jxB
  - New body forces, e.g. neutral beam injection & RF heating
- Manipulated by externally applied E & B fields
  - Strong guide B-field → quasi-2D dynamics, changes inertial scaling
  - Variation in equilibrium E field → can suppress turbulence through sheared V_{ExB} flows (in 2D)
- Introduces additional scale lengths & times
  - $\rho_{i,e}$, $(\rho/L)v_T$, c/ω_{pe}
- High temperature plasma → low collisionality → kinetic effects, additional degrees of freedom
  - New sources of instability drive / energy injection (can occur over broad range of spatial scales)
  - Different interpretation of spatial scale separation / Reynolds # → phase-space (**x**,**v**) scale separation / Dorland #
  - Different cascade dynamics & routes to dissipation (that still occurs through collisions / thermalization, but can occur at all spatial scales)
- *You will learn more about all of these as the week progresses*

Summary of turbulence basics

- Turbulence is deterministic yet unpredictable (chaotic), appears random, often treat & diagnose statistically
- Turbulence causes transport larger than collisional transport
- Turbulence spans a wide range of spatial and temporal scales
  - In neutral fluids, there is an energy cascade through the inertial range (direction depends on 3D vs. 2D)
- Plasmas introduce many new turbulence dynamics, but we are constantly drawing from neutral fluid experience

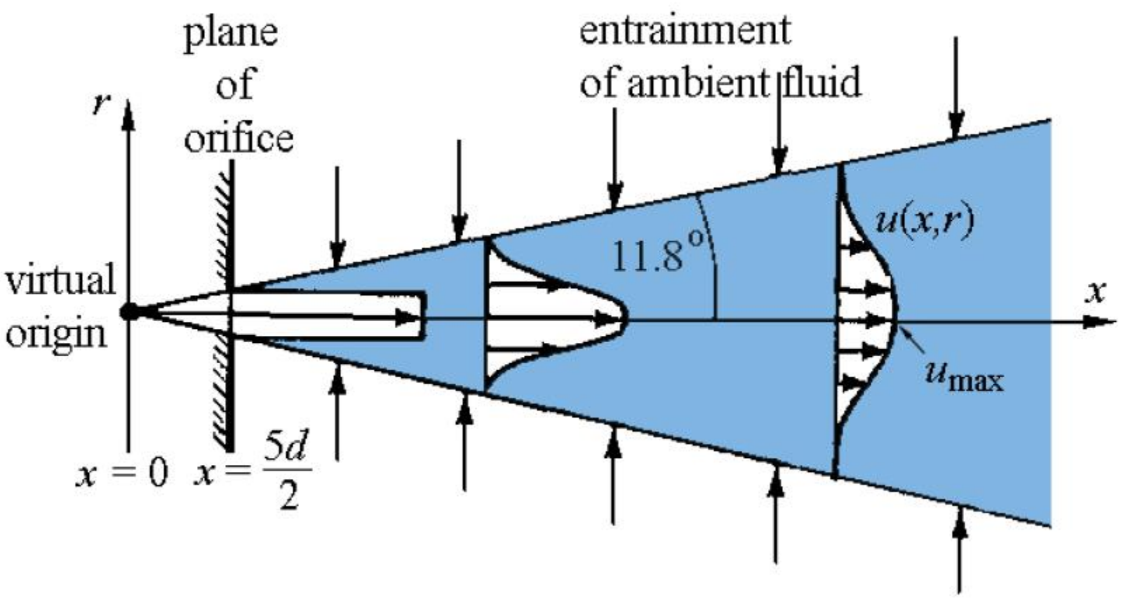
EXTRA SLIDES

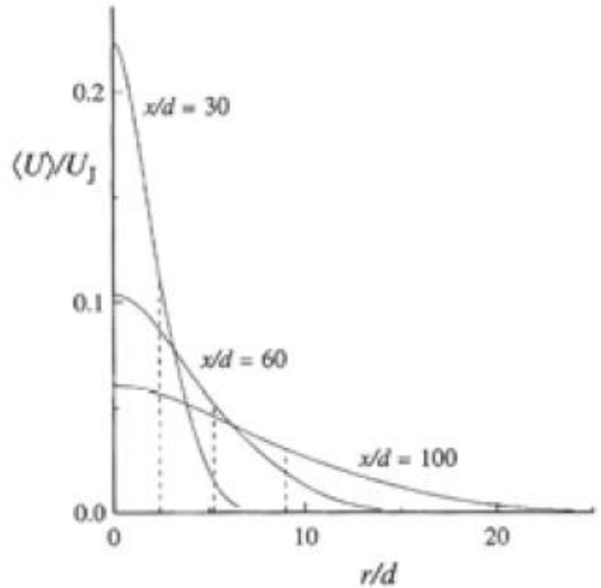
Momentum transport in turbulent jet



A fully developed turbulent round jet (Photo taken in Thayer School Fluid's Lab)

Momentum transport in turbulent jet

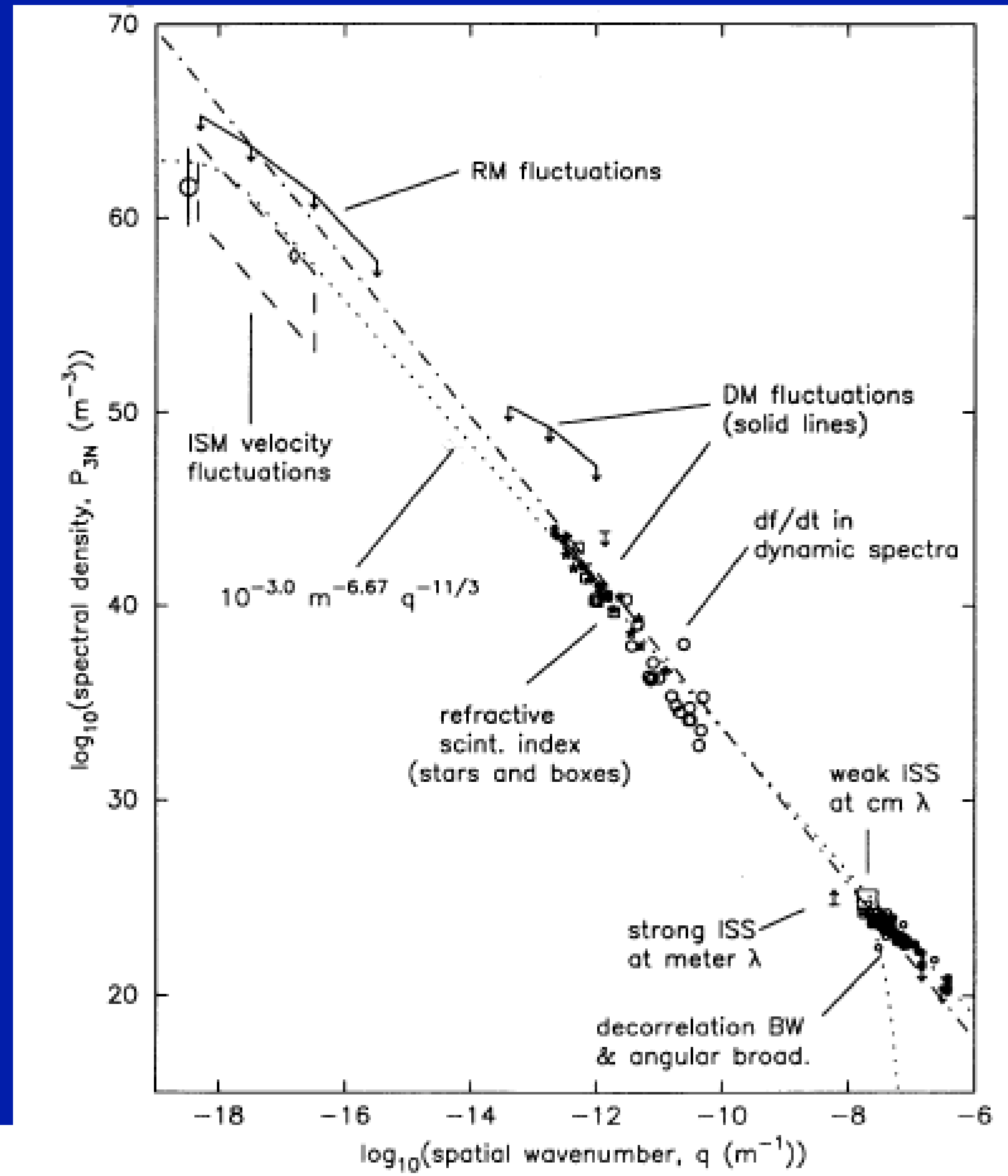




5.2. Radial profiles of mean axial velocity in a turbulent round jet. The dashed lines indicate the half-width, $r_{1/2}(x)$, of the profiles. (Ada data of Hussein et al. (1994).)

Scintillations → Big Power Law in Sky

- Armstrong, Cordes, Rickett 1981, Nature
- Armstrong, Rickett, Spangler 1995, ApJ



(from Spangler astro.physics.uiowa.edu/~srs/AAS_07.ppt)

NL interactions

- $\mathrm{v}(\mathrm{x},\mathrm{t}) \rightarrow \mathrm{v}_{\mathrm{k}}(\mathrm{t}) \exp(\mathrm{ik}\cdot\mathrm{x})$
- $\mathrm{v}\cdot\nabla\mathrm{v} \rightarrow \mathrm{v}_{\mathrm{k}_1}(\mathrm{t})\cdot\mathrm{k}_2\mathrm{v}_{\mathrm{k}_2}(\mathrm{t}) \exp[\mathrm{i}(\mathrm{k}_1+\mathrm{k}_2)\cdot\mathrm{x}]$

$$\Rightarrow \frac{\partial \mathrm{v}_{k_3}}{\partial \mathrm{t}} = -\mathrm{v}_{\mathrm{k}_1}\cdot\mathrm{k}_2\mathrm{v}_{\mathrm{k}_2} \qquad k_3=k_1+k_2$$

What is turbulence? *I know it when I see it (maybe)…*

- **(Enc. Britannica) Turbulent flow**, type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to **laminar flow**, in which the fluid moves in smooth paths or layers. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.
- Deterministic yet unpredictable (chaotic)
- We predominantly rely on statistical analysis or big supercomputer direction numerical simulation (DNS) to develop understanding

• Why do we care?

- Transport → pipe flow, heat exchangers, airplanes, sports, weather & climate predictions, accretion in astrophysics, fusion energy confinement
- Also, it's cool! And it's one of the hardest physics problems! "Turbulence is the most important unsolved problem in classical physics" (~Feynman)

Who am I
(my turbulent academic path)

- Studied electrical engineering at Milwaukee School of Engineering (*loved analog circuitry, I was a wannabe audiophile*)

- Studied turbulent flames at Purdue University (*enjoyed analogous math between thermo/fluids and E&M*) → my first intro to turbulence (*I was hooked*)

- Finally realized plasmas was the place to be (*thermo/fluids + E&M!*), so I went to U. Wisconsin-Madison to study fusion plasma physics

- Low and behold, plasma turbulence is a hugely important topic in fusion (and other) plasmas →*I'm in the right place!*

- My expertise – validating super-computer simulations of gyrokinetic drift wave turbulence with experiments