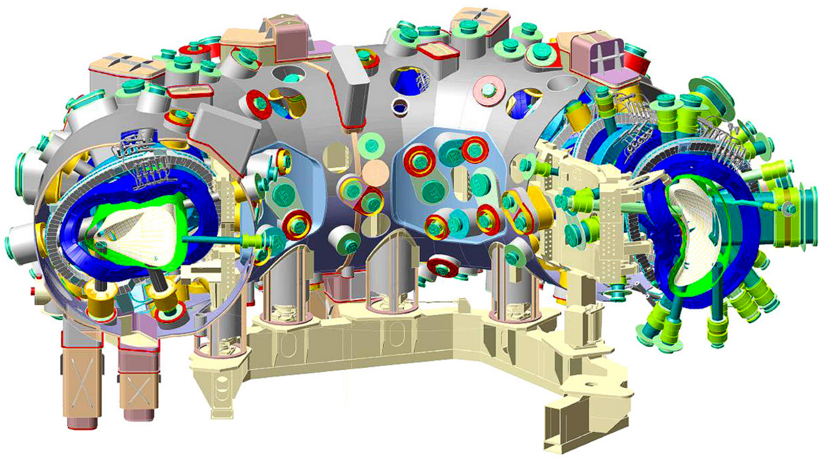
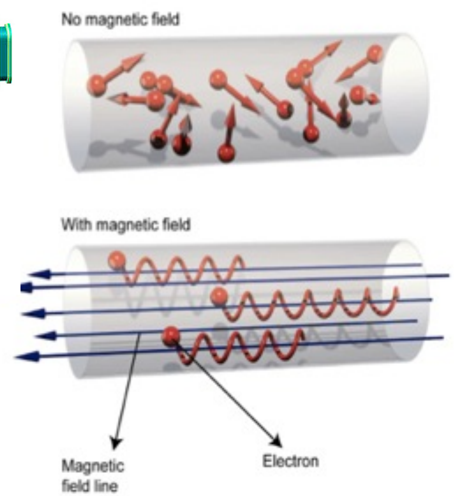
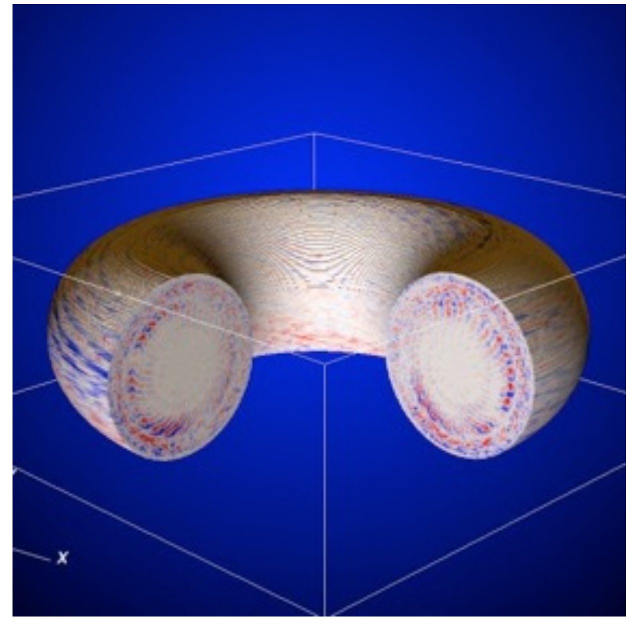
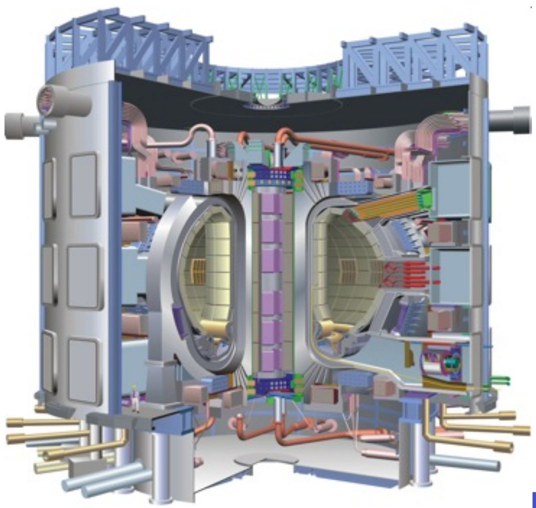
DYNAMICS OF TURBULENT TRANSPORT IN TOKAMAKS AND STELLARATORS









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RES Scientific Seminar 2014: Engineering
October 15, 2014, Barcelona, SPAIN

A very large team effort.....

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PLASMAS

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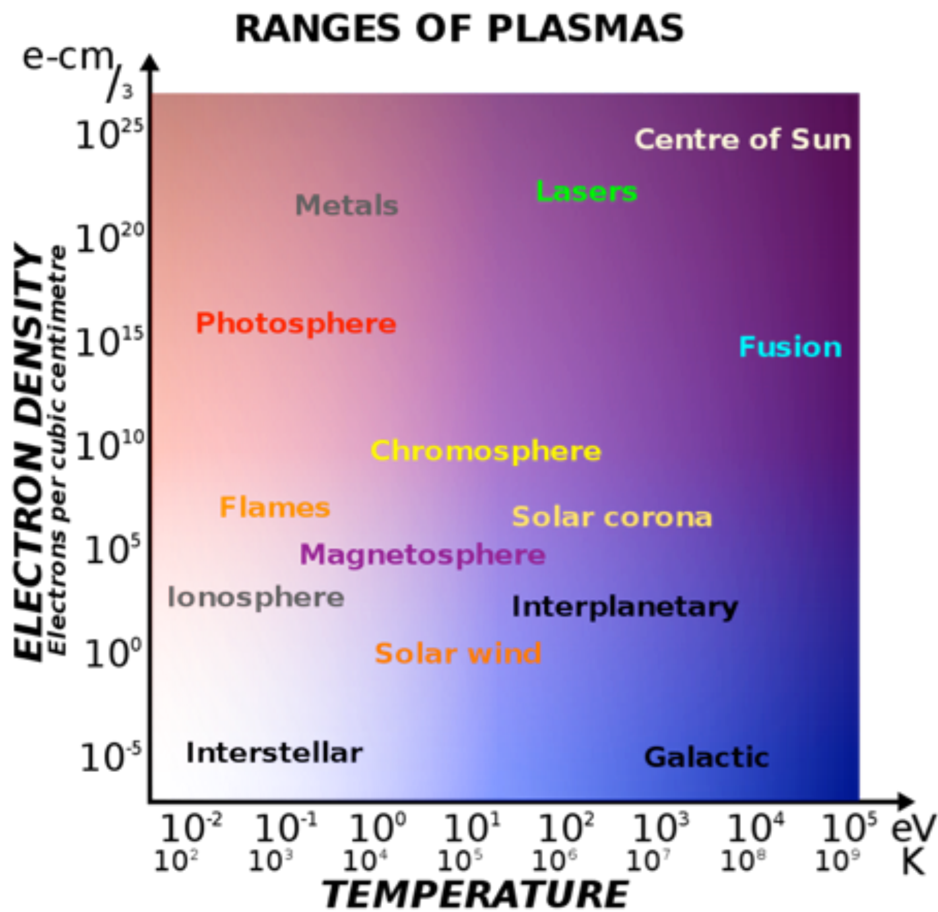
Plasma is loosely described as an electrically neutral medium of positive and negative particles.

Although particles are unbound, they **are not ‘free’**. When the charges move they generate electrical currents with magnetic fields, and as a result, they are affected by each other’s fields. These nonlinear interactions govern their collective behavior with many degrees of freedom.



PLASMA TURBULENCE

	Typical ranges of plasma parameters: orders of magnitude	
Characteristic	**Terrestrial plasmas**	**Cosmic plasmas**
Size in meters	10^{-6} m (lab plasmas) to 10^{2} m (lightning) (~8 OOM)	10^{-6} m (spacecraft sheath) to 10^{25} m (intergalactic nebula) (~31 OOM)
Lifetime in seconds	10^{-12} s (laser-produced plasma) to 10^{7} s (fluorescent lights) (~19 OOM)	10^{1} s (solar flares) to 10^{17} s (intergalactic plasma) (~16 OOM)
Density in particles per cubic meter	10^{7} m^{-3} to 10^{32} m^{-3} (inertial confinement plasma)	1 m^{-3} (intergalactic medium) to 10^{30} m^{-3} (stellar core)
Temperature in kelvins	~0 K (crystalline non-neutral plasma[12]) to 10^{8} K (magnetic fusion plasma)	10^{2} K (aurora) to 10^{7} K (solar core)
Magnetic fields in teslas	10^{-4} T (lab plasma) to 10^{3} T (pulsed-power plasma)	10^{-12} T (intergalactic medium) to 10^{11} T (near neutron stars)

TURBULENCE IN PLASMAS

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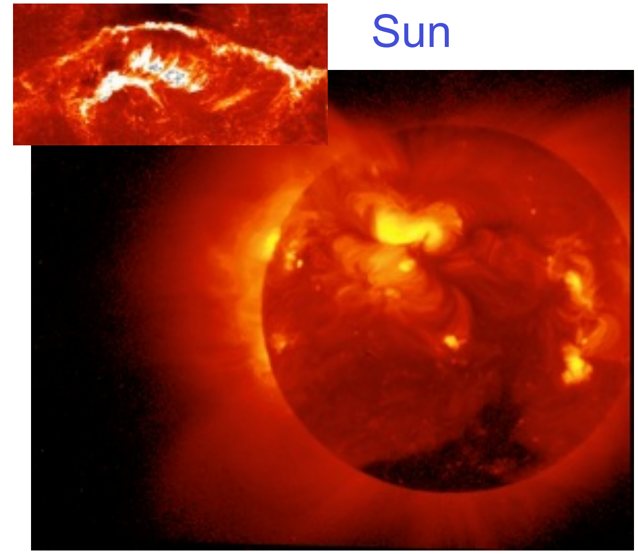
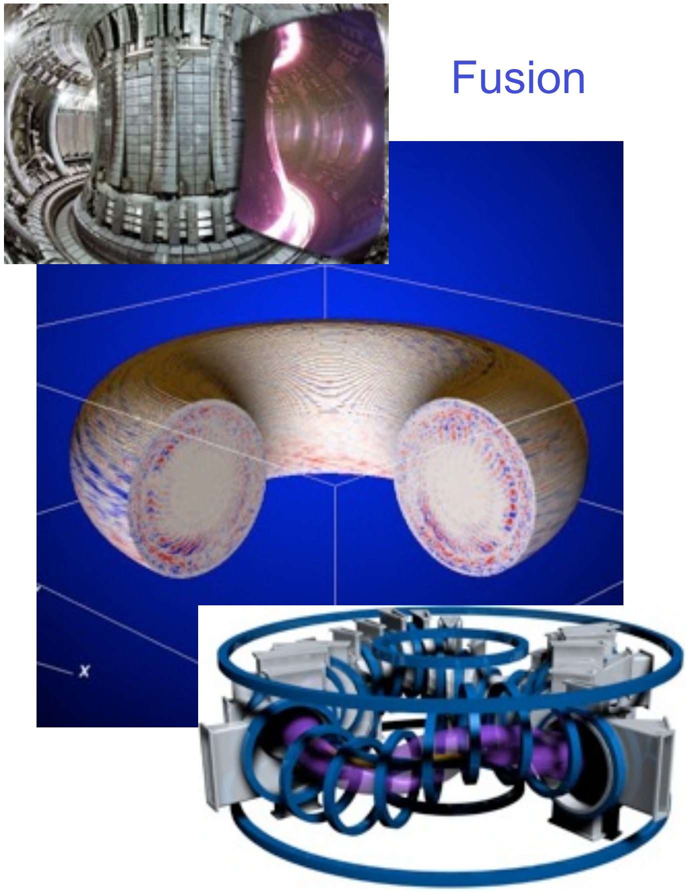
Space

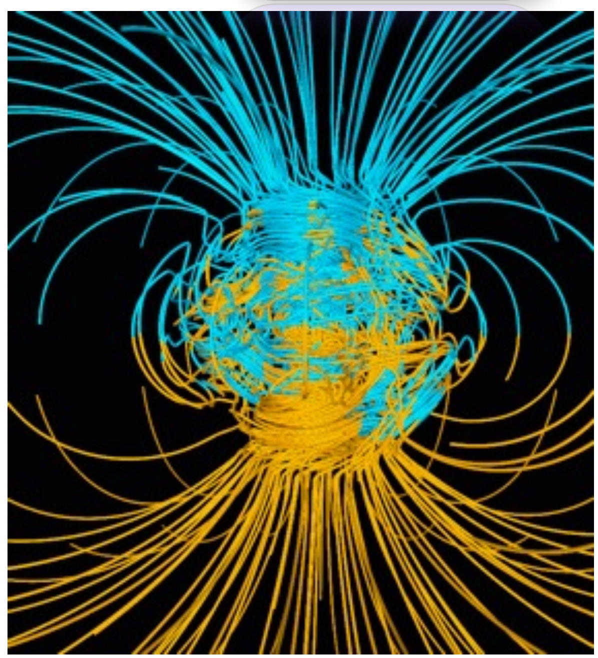
Sun



Fusion



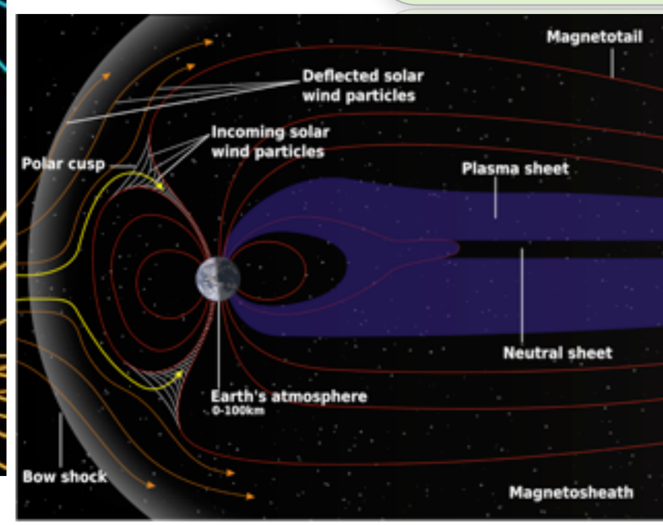
DYNAMOS



Earth

SELF-SIMILARITY

MEMORY



SELF-ORGANIZATION

PATTERNS

FUSION ENERGY: ITER and beyond

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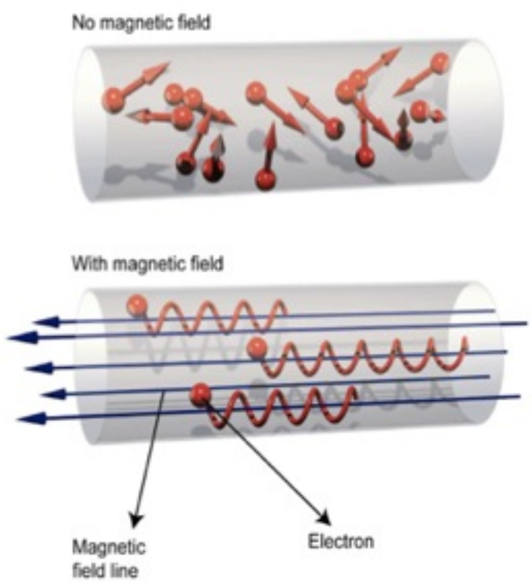
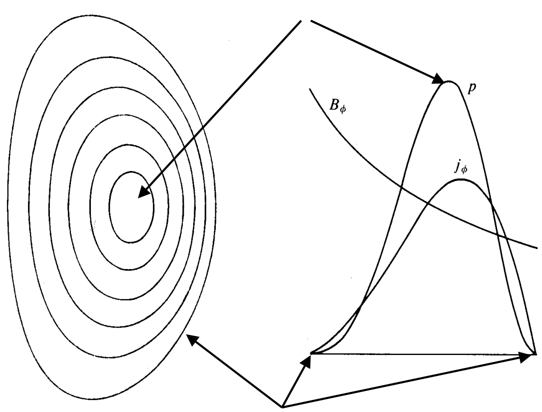
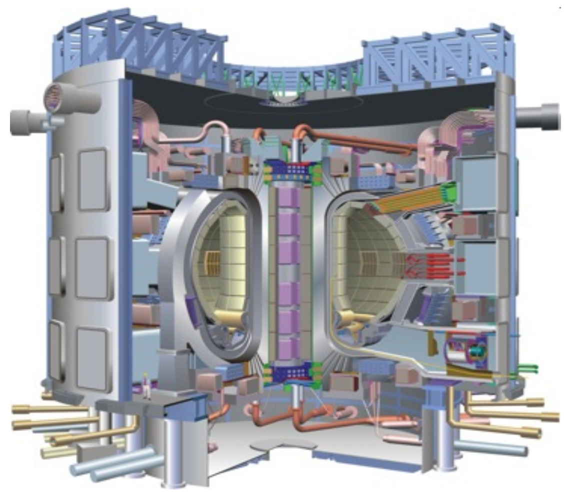


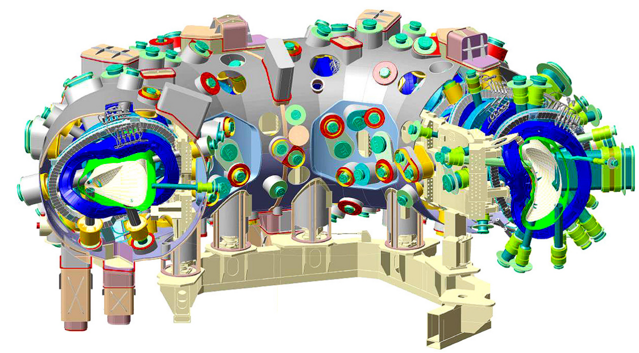
Helical magnetic fields can be used to confine hot plasmas long enough to produce energy



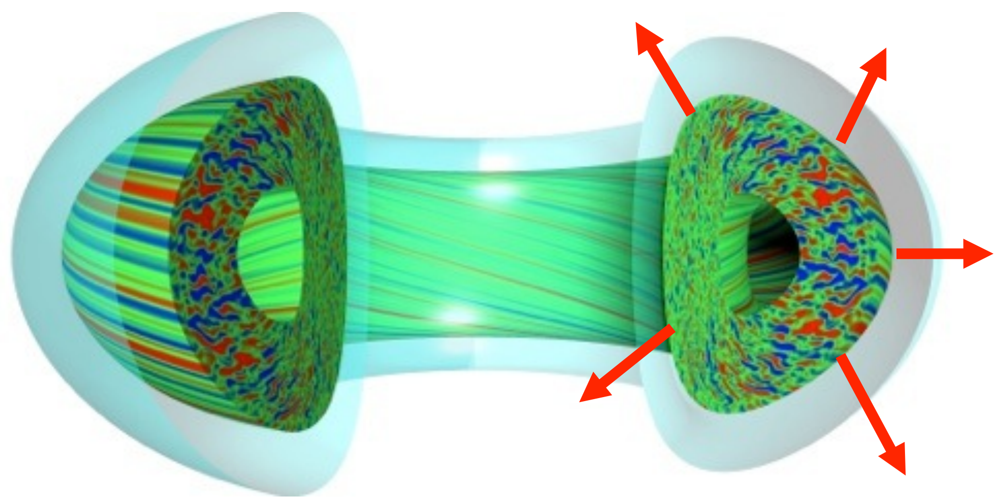
Turbulence dominates radial losses of energy and particles



ITER



W7-X



GYRO, General Atomics

MOTIVATION

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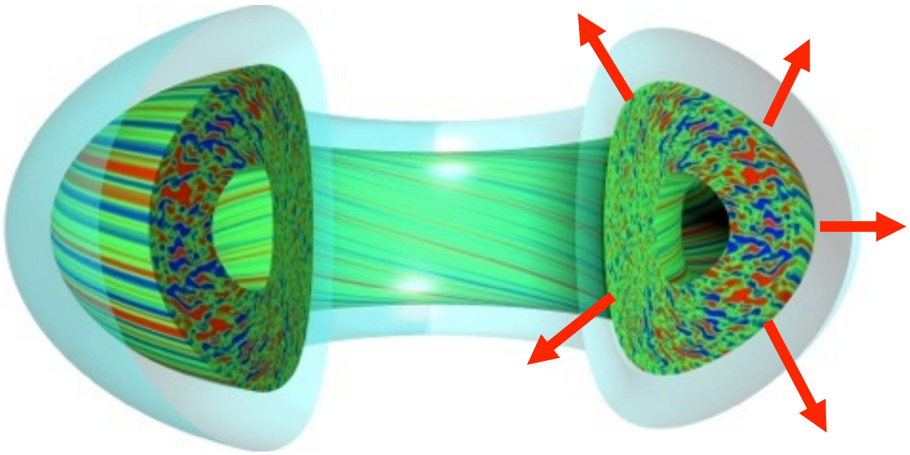
FACT: Turbulence dominates radial transport in tokamaks and stellarators. Thus, it determines how large a device must be to produce energy by fusion in an economically attractive way.



GYRO, General Atomics

FACT: Traditionally, one simply estimates effective transport coefficients that encapsulate the overall effect of turbulence on confinement, while ignoring the smaller/shorter scale physics of turbulence.

FACT: Most first-principle turbulent simulations are run for short periods of time, assuming that profile modification (i.e., transport) is irrelevant to calculate these coefficients.

Engineering QUESTION: is this the optimal way to design a reactor?
Physics QUESTION: do we really understand what is going on?

EFFECTIVE TURBULENT DIFFUSION: when does it work?

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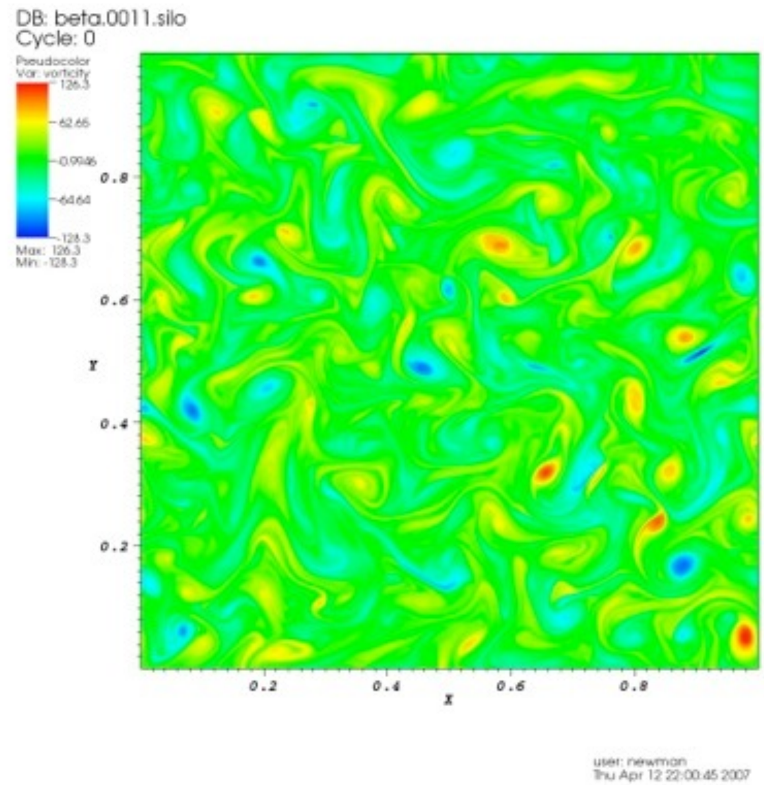
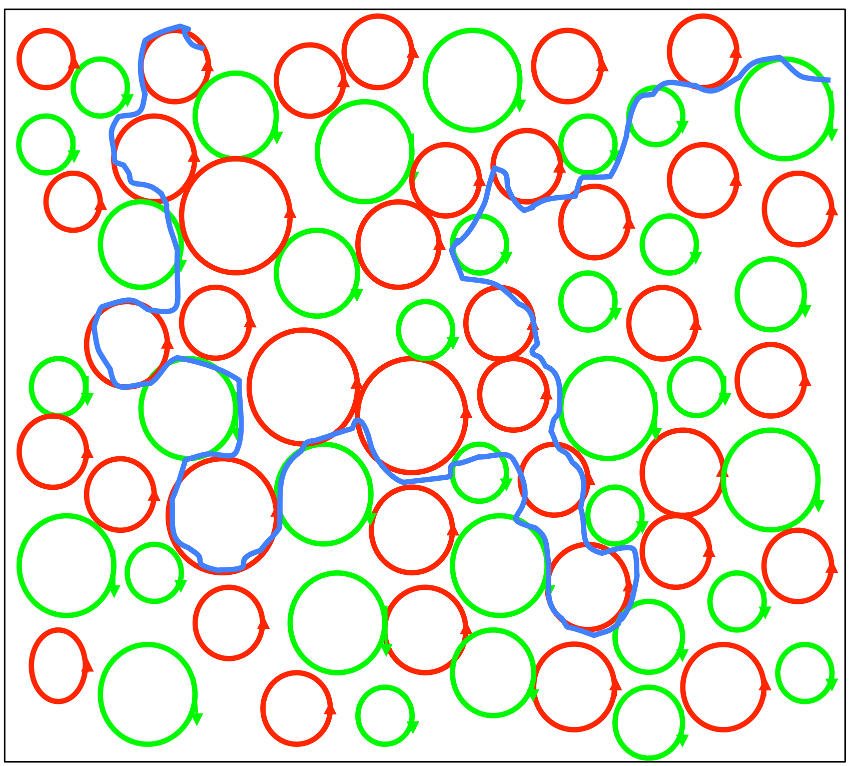
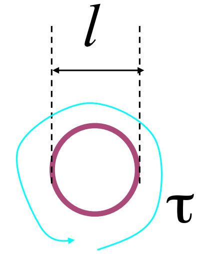
Assumes:

- Characteristic scales
- Lack of memory







$$D \sim \frac{l^2}{\tau}$$

EFFECTIVE TURBULENT DIFFUSION: mathematical assumptions

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[See: R. Balescu, "Aspects of Plasma Turbulent Transport", IOP, Bristol (2005)]

$$\frac{\partial n}{\partial t} + (\mathbf{V}\cdot\nabla)\, n = 0$$

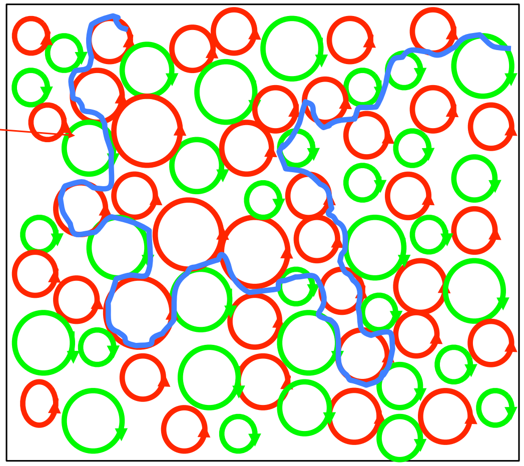
$$\frac{\partial n_0}{\partial t} = -\left\langle \tilde{\mathbf{V}} \cdot \nabla \tilde{n} \right\rangle$$

$$\frac{\partial \tilde{n}}{\partial t} + \tilde{\mathbf{V}} \cdot \nabla \tilde{n} = -\tilde{\mathbf{V}} \cdot \nabla n_0 + \left\langle \tilde{\mathbf{V}} \cdot \nabla \tilde{n} \right\rangle$$

$$\frac{\partial n_0}{\partial t} = \nabla \cdot \int_0^t \left\langle \tilde{\mathbf{V}}(\mathbf{r},t)\tilde{\mathbf{V}}(\mathbf{R}(t'|\mathbf{r},t),t)\nabla n_0(\mathbf{R}(t'|\mathbf{r},t),t) \right\rangle$$

Lagrangian trajectories

$$\frac{d\mathrm{R}}{d\tau} = \tilde{\mathrm{V}}(\mathrm{R},\tau), \quad \mathrm{R}(t) = \mathrm{r}$$



REDUCTION TO DIFFUSIVE DESCRIPTION: Lagrangian view

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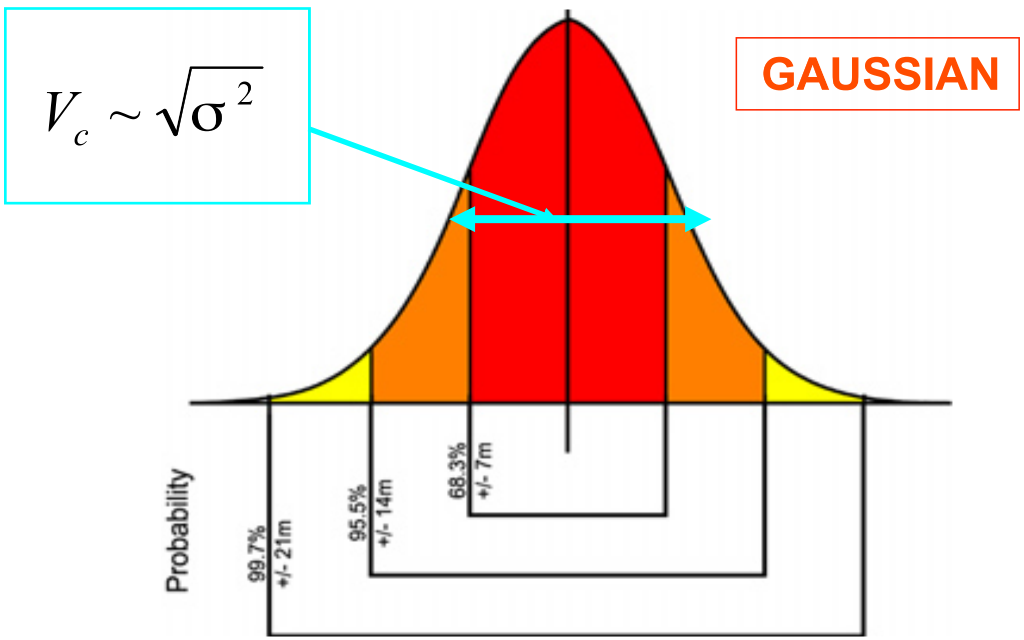
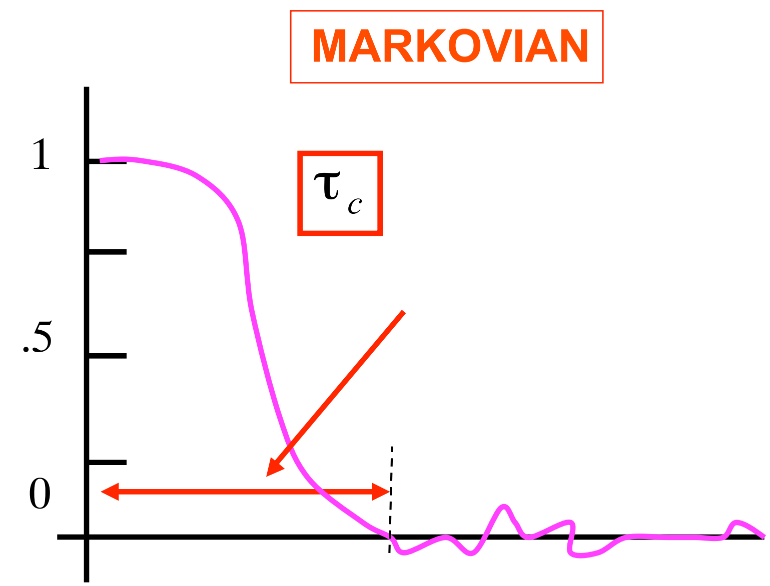
$$\frac{\partial n_0}{\partial t} = \nabla \cdot \int_0^t \left\langle \tilde{\mathbf{V}}(\mathbf{r},t)\tilde{\mathbf{V}}(\mathbf{R}(t'|\mathbf{r},t),t)\nabla n_0(\mathbf{R}(t'|\mathbf{r},t),t) \right\rangle$$

- Characteristic Scales
- Lack of Memory

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2}$$

$$D \simeq \tilde{V}_c^2 \tau_c$$





Transport scales are not necessarily turbulent decorrelation scales!

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[See: G.R. McKee et al, IEEE Tran. Plasma Sci. (2002)]

From point (Eulerian) probe data, both a finite decorrelation length (i.e., typical length scale) and a finite decorrelation time (i.e., typical time scale and thus no long-term memory) are obtained for turbulence.

But are turbulent decorrelation scales the ones characteristic of the transport process?

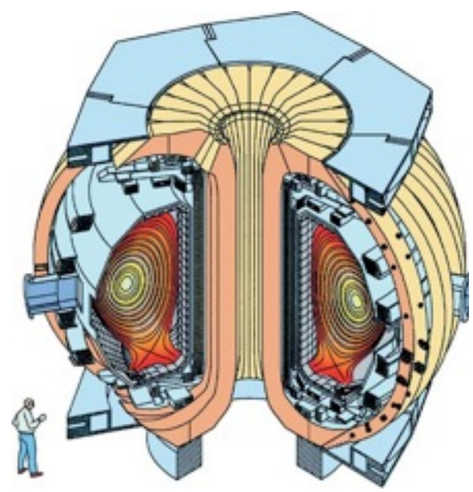
Apparently not always.

Two cases have been identified:

Near-marginal turbulence

With strong sheared flows present

Both relevant in reactor conditions!



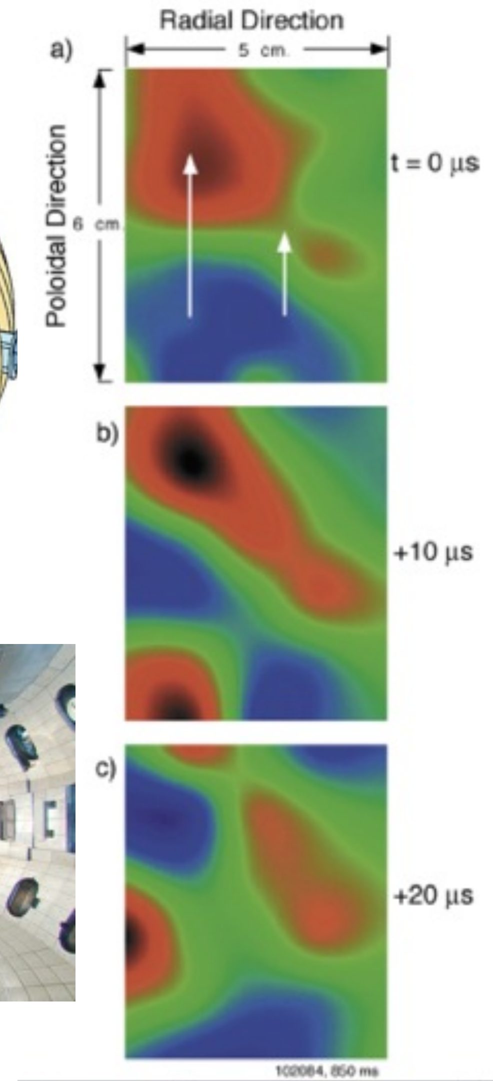
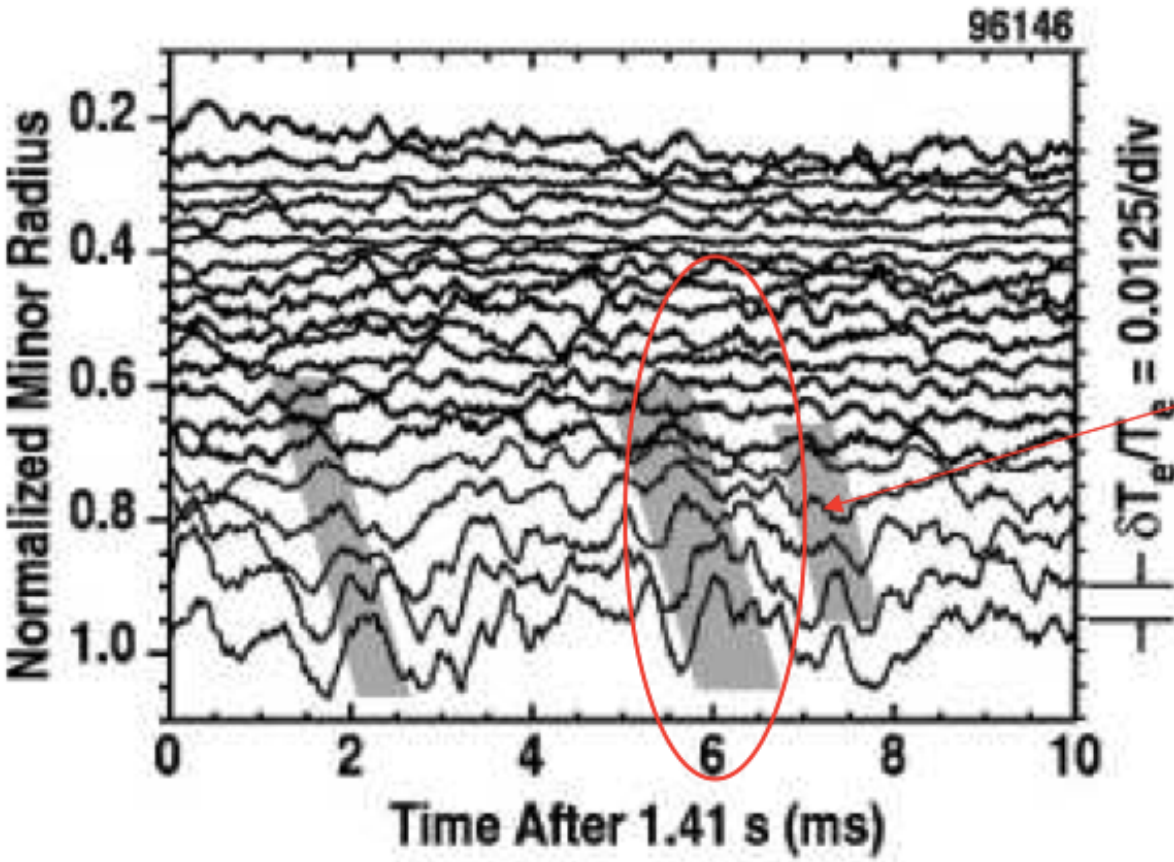
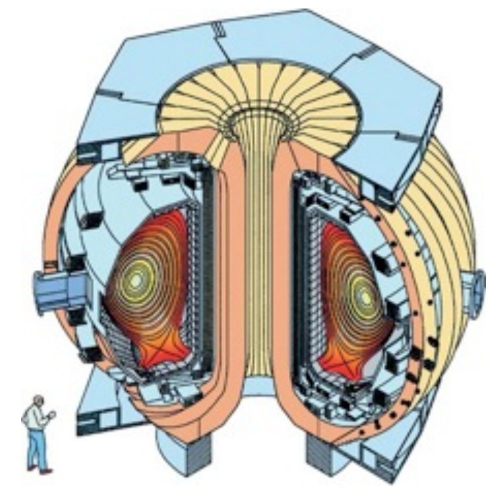


Fig. 1. Images of density fluctuations at 10-μs intervals, obtained over a 5-cm (radial) × 6-cm (poloidal) region at the outer plasma midplane, $\rho = 0.9$–1.05, in a low-confinement (L-mode) discharge. White arrows in (a) qualitatively indicate average flow direction and magnitude.

Is there any evidence from the experiments?



[See: P. Politzer et al, Physics of Plasmas 9,1962 (2002)]



Radial avalanches whose size is limited by the tokamak minor radius seem to be present in the ECE diagnostic?

Is there any evidence from the experiments?

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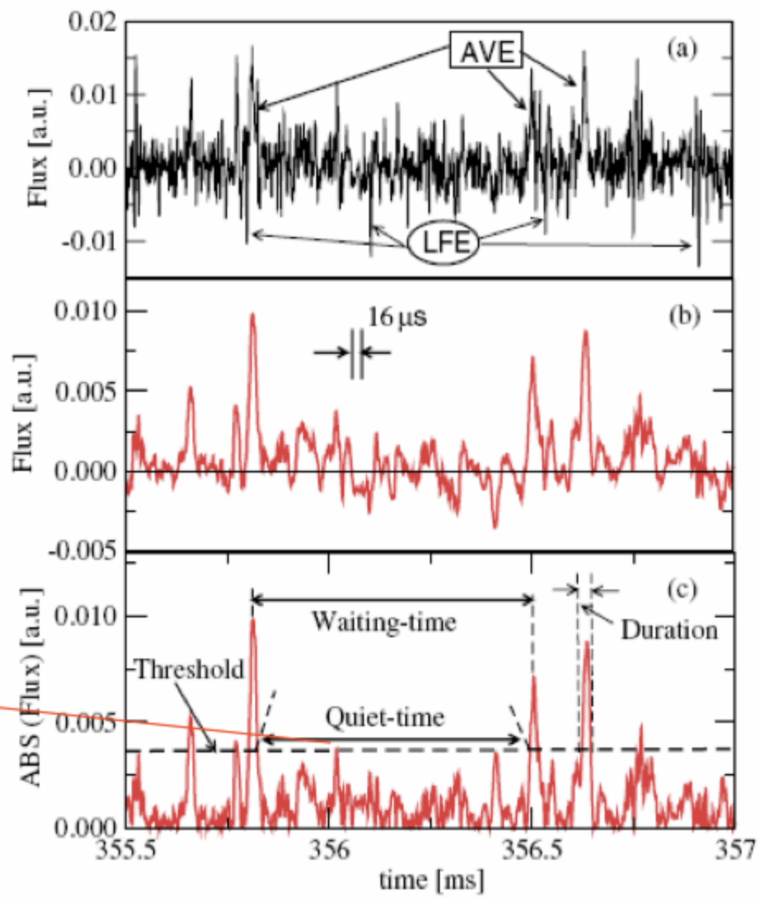


FIG. 1 (color online). (a) Detail of raw W7-AS flux signal; (b) same signal averaged with $m = 32$; (c) absolute value of averaged signal together with a sketch of relevant definitions.

Temporal correlations beyond local turbulent timescales seem apparent in Langmuir probe data.

[See: R. Sanchez, B.Ph. van Milligen, et al, Physical Review Letters 90,185005 (2003)]

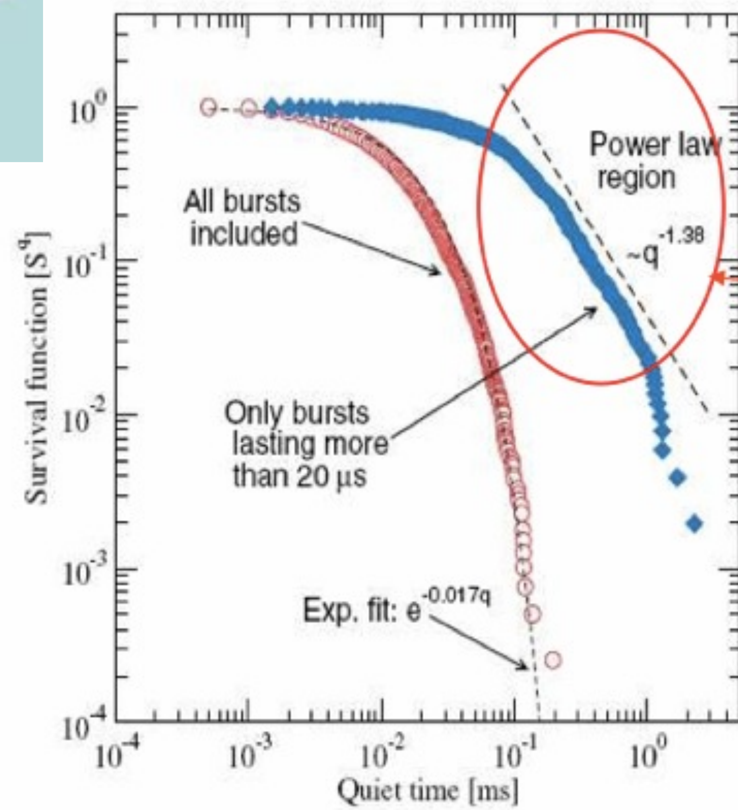


FIG. 2 (color online). Examples of quiet-time survival functions for W7-AS shot No. 35427.

Stable distributions: Levy pdfs

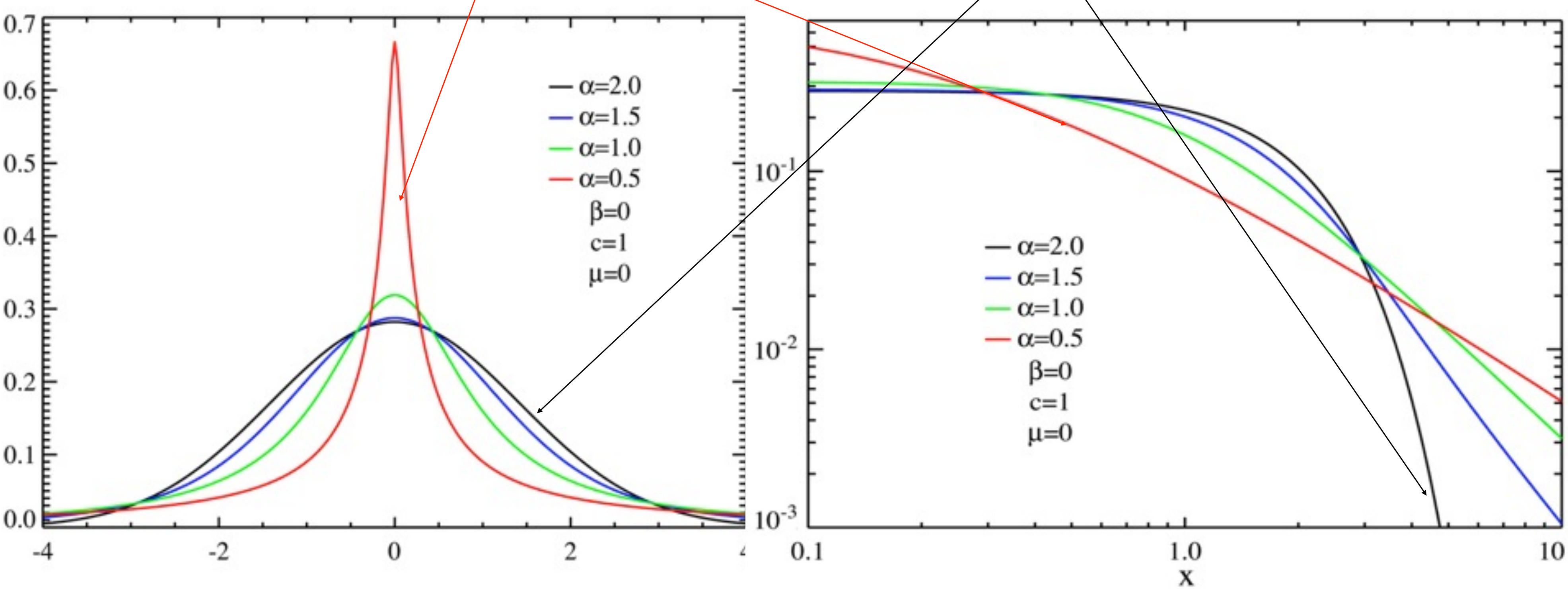
$$\frac{\partial n_0}{\partial t} = \nabla \cdot \int_0^t \left\langle \tilde{\mathbf{V}}(\mathbf{r},t)\tilde{\mathbf{V}}(\mathbf{R}(t'|\mathbf{r},t),t)\nabla n_0(\mathbf{R}(t'|\mathbf{r},t),t) \right\rangle$$

$$P_{\{\alpha,0,\sigma\}} \sim |x|^{-(1+\alpha)}(k) = \exp(-\sigma^\alpha |k|^\alpha), \quad \alpha \leq 2$$

[See: G. Samorodnitsky and M. Taqqu, "Stable non-Gaussian distributions", Chapman and Hall, New York (1994)]

$$P_{\{\alpha,0,\sigma\}} \sim |x|^{-(1+\alpha)}$$

Gaussian: $\alpha = 2$

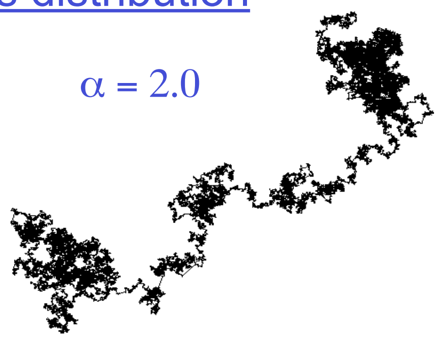


LAGRANGIAN MEMORY

$$\frac{\partial n_0}{\partial t} = \nabla \cdot \int_0^t \left\langle \tilde{\mathbf{V}}(\mathbf{r},t)\tilde{\mathbf{V}}(\mathbf{R}(t'|\mathbf{r},t),t)\nabla n_0(\mathbf{R}(t'|\mathbf{r},t),t)\right\rangle$$

Gauss distribution

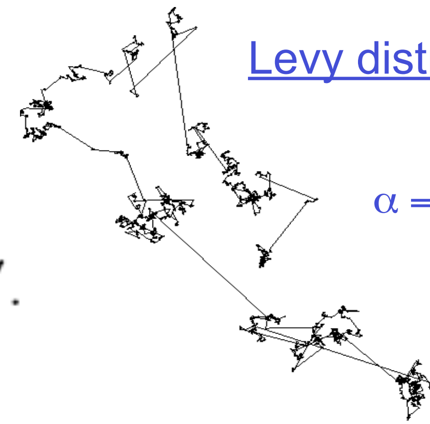
$\alpha = 2.0$



$$x(t) = x_0 + \int_0^t \xi_2(t')dt'.$$

Levy distribution

$\alpha = 1.2$



[See: B.B. Mandelbrot and J.W. van Ness, SIAM Review 10, 422 (1968); I. Calvo and R. Sanchez, J. Phys. A 32, 055003 (2009)]

H, Hurst exponent

$$x(t) = x_0 + \frac{1}{\Gamma\left(H - \frac{1}{\alpha} + 1\right)} \int_0^t dt'(t-t')^{H-1/\alpha}\xi_\alpha(t')$$

$H=1/\alpha$, random; $H > 1/\alpha$, correlated positively; $H < 1/\alpha$, correlated negatively

[See: H.E. Hurst, Trans. Am. Soc. Civ. Eng. 110, 770 (1951)]]

"Complex" EFFECTIVE TRANSPORT

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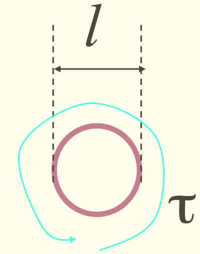
Typical scales

Lack of memory

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2}$$

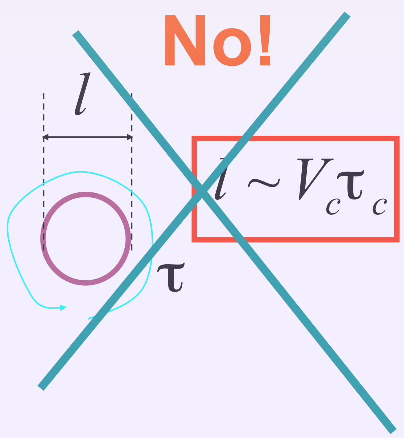
Standard Transport equations

Yes!



$l \sim V_c \tau_c$

No!



$$\frac{\partial n}{\partial t} = {}_0D_t^{1-\alpha H}\left[D \frac{\partial^\alpha n}{\partial |x|^\alpha} \right]$$

Fractional Transport equations

Lack of typical scales

Spatio-temporal correlations

[See: R. Sanchez, B.ph. van Milligen, B.A. Carreras and D.E. Newman, Physical Review E 74, 016305 (2006)]

SPATIAL FRACTIONAL DERIVATIVES: NONLOCAL OPERATORS

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[See: I.Podlubny, *Fractional Differential Equations*, Academic Press (1998)]

$$\frac{\partial n(x,t)}{\partial t} \approx \frac{\partial^{\alpha}}{\partial |x|^{\alpha}} \left[D_{\alpha} n(x,t) \right]$$

G.W. Leibnitz (1646-1716)

G.F. Riemann (1826-1866)

J. Liouville (1809-1882)

RIESZ fractional derivative

$$\frac{\partial^{\alpha}}{\partial |x|^{\alpha}} \left[D_{\alpha} n \right] = \frac{\cos^{-1}(\pi\alpha/2)}{2\Gamma(p-\alpha)} \left[\frac{d^p}{dx^p} \left\{ \int_{-\infty}^{x} \frac{D_{\alpha}(x')n(x',t)dx'}{(x-x')^{\alpha-p+1}} \right\} - \frac{d^p}{d(-x)^p} \left\{ \int_{x}^{\infty} \frac{D_{\alpha}(x')n(x',t)dx'}{(x'-x)^{\alpha-p+1}} \right\} \right]$$

x' < x

x' > x

RIEMANN-LIOUVILLE fractional derivative

TURBULENT TRANSPORT ACROSS STABLE SHEARED FLOWS

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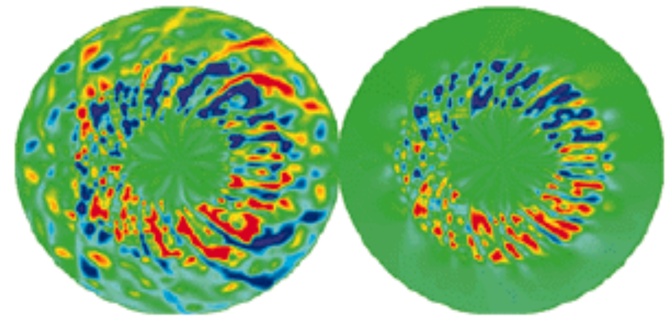
The appearance of stable sheared flows driven by turbulence is an example of self-organization and emergence of complex dynamics in many systems.

In plasmas, (mostly) poloidal flows with radial shear appear naturally at the plasma edge beyond a certain threshold power.

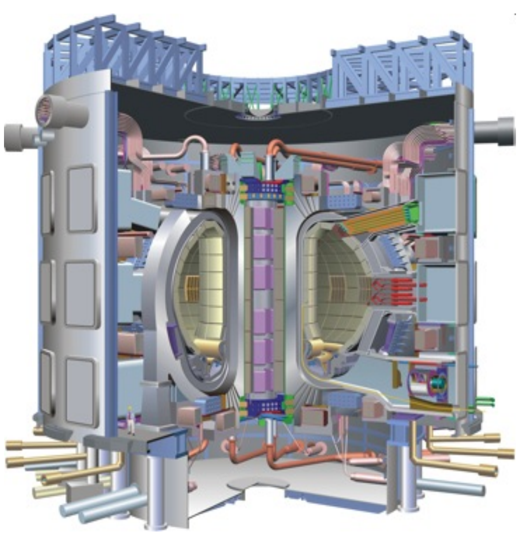
These flows allow access to enhance confinement regimes (H-mode). ITER will operate in this regime.

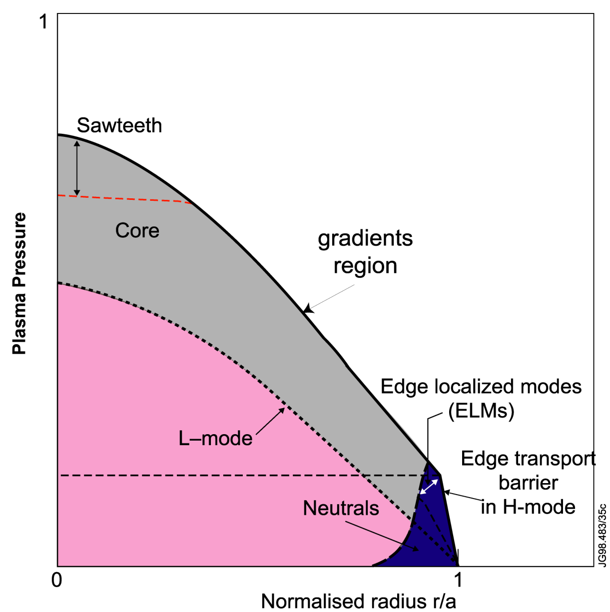
Fluid resistive interchange turbulence (cylinder)



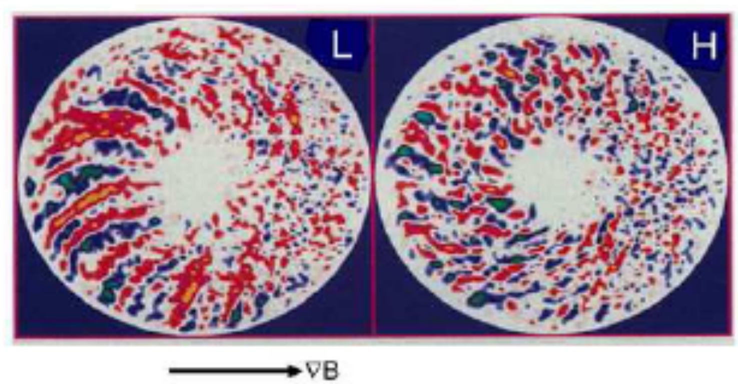
[See: B.A. Carreras et al, Phys. Fluids B 5 (1993) 1491]

ITER tokamak, CEA, France





Toroidal ITG gyro-kinetic simulations



[See: Z. Lin et al, *Science* **281** (1998) 1835]

REDUCTION OF TURBULENT TRANSPORT ACROSS RADIALLY-SHEARED POLOIDAL FLOWS

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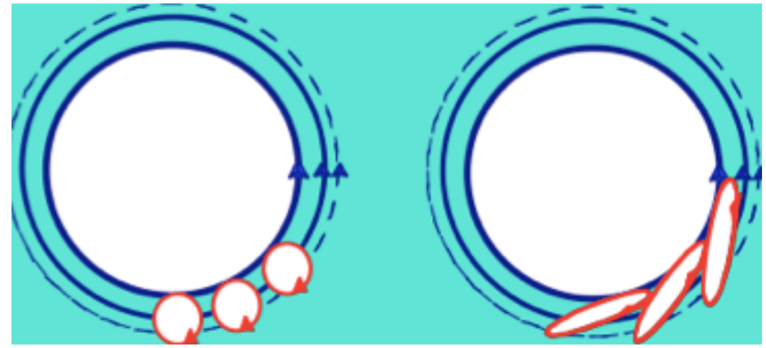
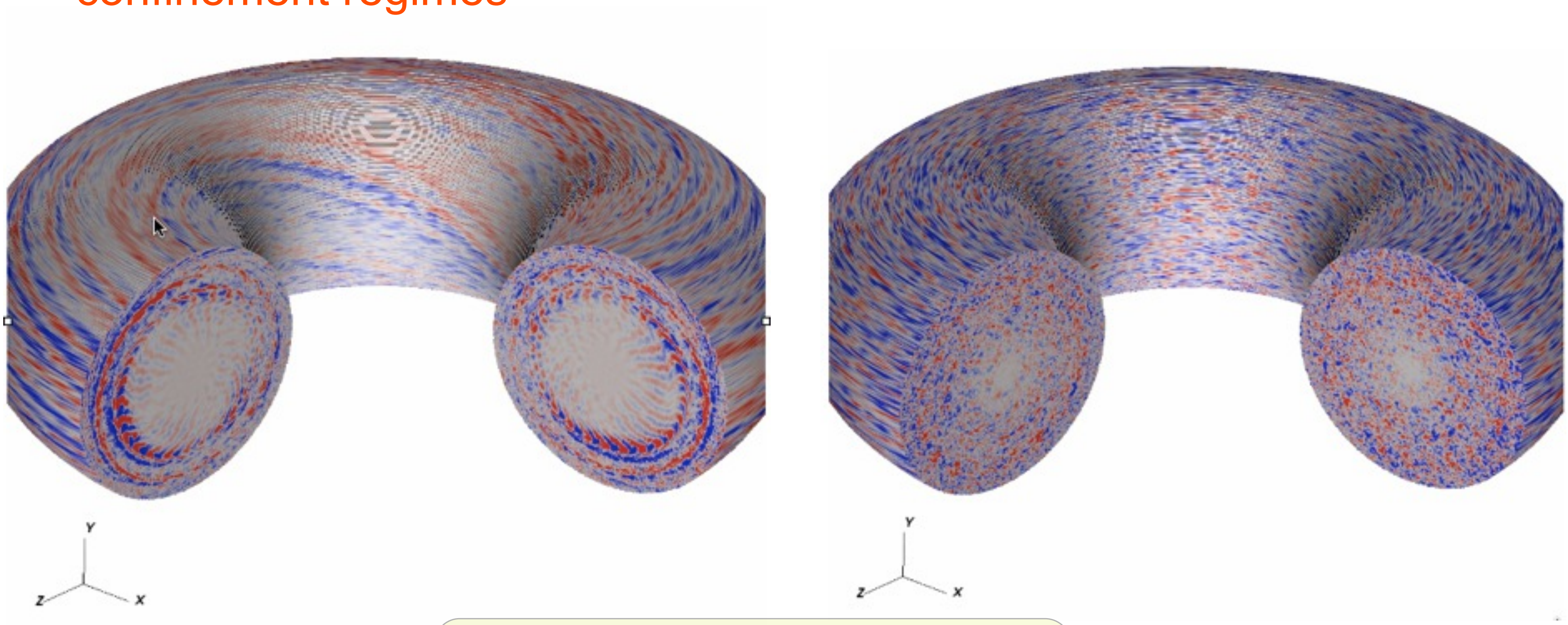


ITER and other devices rely on sheared flows to tame turbulence and access enhanced confinement regimes



Can reduced transport coefficients describe this process?

NATURE OF TURBULENT TRANSPORT ACROSS RADIALLY-SHEARED POLOIDAL FLOWS

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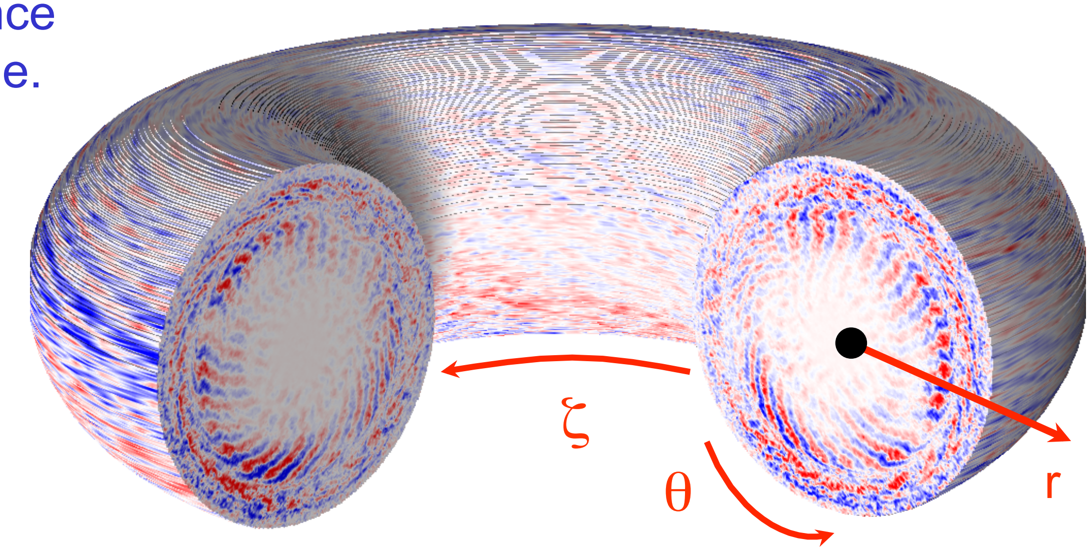
Ion-temperature-gradient (ITG) turbulence simulations realized with the UCAN code.



UCAN characteristics:

- δf-method
- Particle-in-Cell (PIC)
- kinetic ions, adiabatic electrons
- global, toroidal geometry
- collisionless
- electrostatic
- low-β

[See: R. Sydora et al, Pl. Phys. Contr. Fusion 38, A281 (1996)]

RUN parameters:

- **512x512x256 ions**
- 256x256x128 spatial grid points
- 8 particles/cell

PHYSICAL PARAMETERS (DIIID–like):

- Central ion/electron temp [Kev]: 0.68/0.68
- Magnetic field [T]: 1.8
- Axis density [$x10^{20}m^{-3}$]: 0.2
- Major/minor radius [m]: 2.5/0.56
- Ion Larmor radius [mm]: 2.85
- Temporal length of simulation [ms]: 5.56

Most of the results shown have been obtained at the AMD–Penguin Computing Cluster 'Pacman' at the Arctic Region Supercomputer Center in Alaska, as well as the IBM iDataPlex with Intel Sandy Bridge processors 'Mare Nostrum III' at the Barcelona Supercomputer Center in Spain.

GYROKINETIC EQUATIONS IN UCAN

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Ion distribution function equation

$$\frac{\partial \delta f}{\partial t} + \frac{d\vec{R}}{dt}\cdot\vec{\nabla}\delta f + \frac{dv_{\parallel}}{dt}\frac{\partial \delta f}{\partial v_{\parallel}} = -\frac{d\vec{R}^{(1)}}{dt}\cdot\vec{\nabla} f_0 - \frac{dv_{\parallel}^{(1)}}{dt}\frac{\partial f_0}{\partial v_{\parallel}} \qquad f = f_0 + \delta f \qquad (2.1)$$

$$\frac{\partial w}{\partial t} = -(1-w)\left[\frac{d\vec{R}^{(1)}}{dt}\cdot\vec{\nabla} f_0 + \frac{dv_{\parallel}^{(1)}}{dt}\frac{1}{f_0}\frac{\partial f_0}{\partial v_{\parallel}}\right] \qquad w = \frac{\delta f}{f} \qquad (2.2)$$

Method of characteristics: follow ion markers in phase space

$$\frac{d\vec{R}}{dt} = v_{\parallel}\hat{b} + \vec{v}_E + \frac{c}{qB}\mu\hat{b}\times\vec{\nabla}B + \frac{v_{\parallel}^2}{\Omega}\hat{b}\times(\hat{b}\cdot\nabla)\hat{b} \qquad \rho_i = \frac{v_{\perp}}{\Omega} \quad \mu = \frac{Mv_{\perp}^2}{2B} \quad \Omega = \frac{qB}{Mc} \qquad (2.5)$$

$$\frac{dv_{\parallel}}{dt} = \frac{q}{M}E_{\parallel} - \frac{1}{M}\mu(\hat{b}\cdot\vec{\nabla}B) \qquad (2.6)$$

Poisson equation: electrostatic potential

$$\frac{1}{\lambda_{Di}^2}\phi[1-\Gamma_0(k_{\perp}^2\rho_i^2)] = 4\pi|e|(n_i - n_e) \qquad \lambda_{Di}^2 = \frac{T_i}{4\pi n_0 e^2} \qquad (2.7)$$

$$n_i = \oint\frac{d\varphi}{2\pi}N_i(\vec{R}+\rho_i) \qquad (2.8)$$

$$n_e = n_0\frac{|e|}{T_e}[\phi - \langle\phi\rangle] \qquad (2.9)$$

PARALLELIZATION IN UCAN

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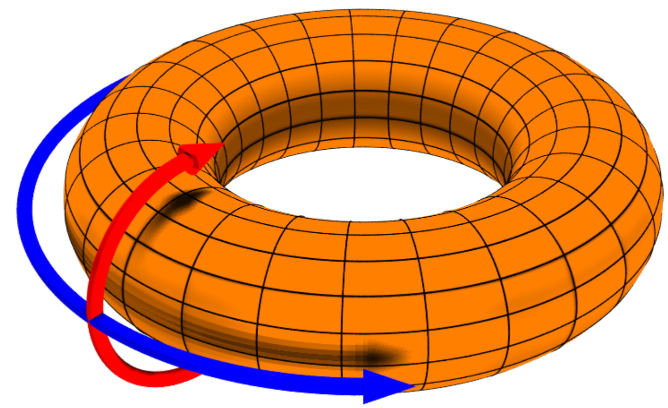
UCAN parallelizes spatially, not over particles.

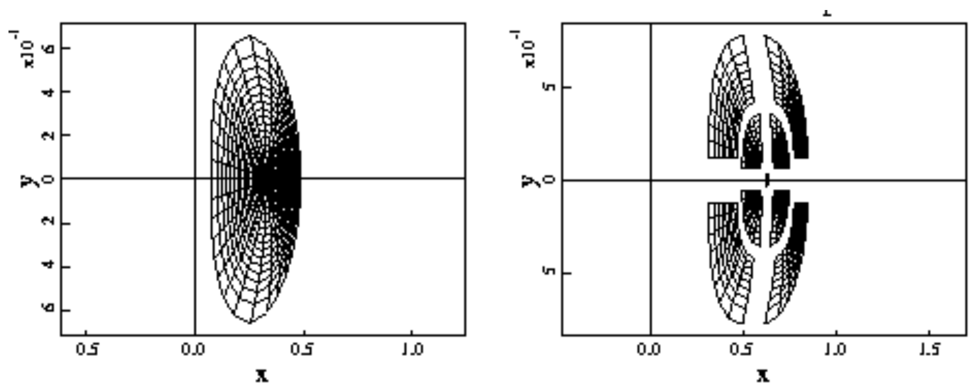
First version, UCAN, only parallelized toroidally, so that each processor handled a toroidal section.



UCAN2 applies domain decomposition techniques to each toroidal section, that can be now divided among processors

Marker ions are passed from one processor to another, as they exit the spatial region controlled by the first processor and enter the region controlled by the second processor

Communication happens mostly whenever particles change spatial domains, or when Poisson solves are done.



UCAN2 Parallel Scaling Studies

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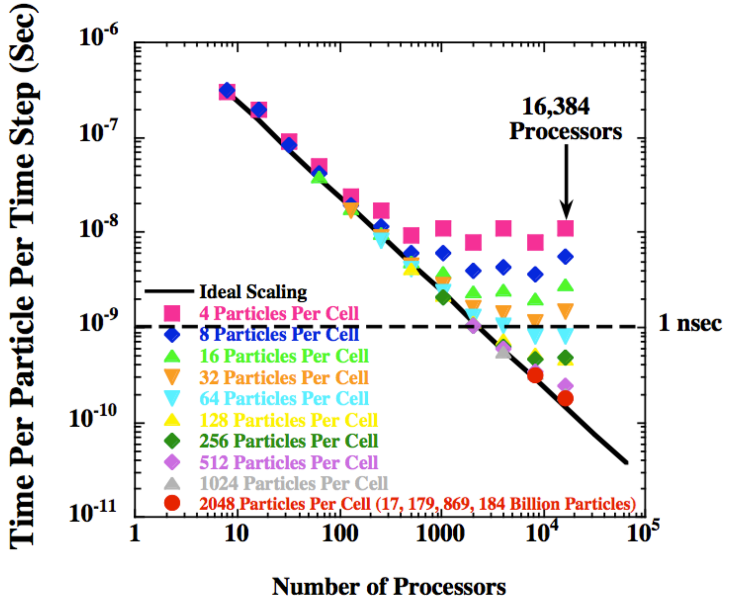

Fig. 4: Time per particle per time step versus number of processors for a system size of 256 x 256 x 128 and from 4 to 2048 particles per cell for a maximum of 17,169,869,184 particles.

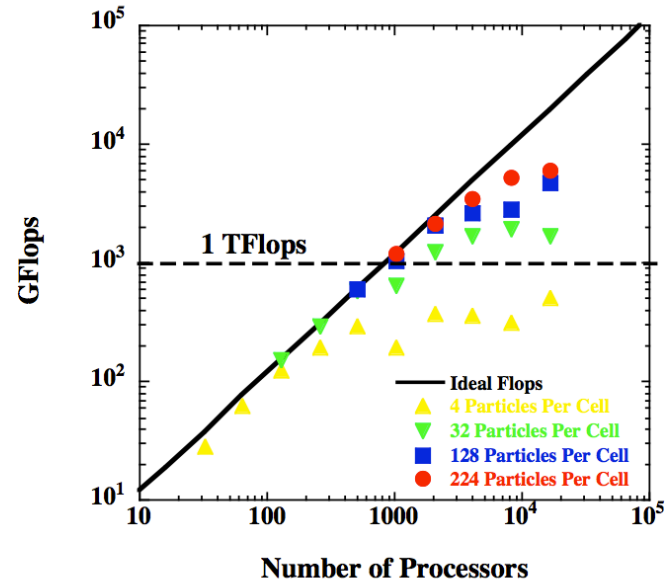

Fig. 5: Floating point operations per second in GFlops versus number of processors for a system size of 256 x 256 x 128 and from 4 to 224 particles per cell for a maximum of 2,046,820,352 particles.

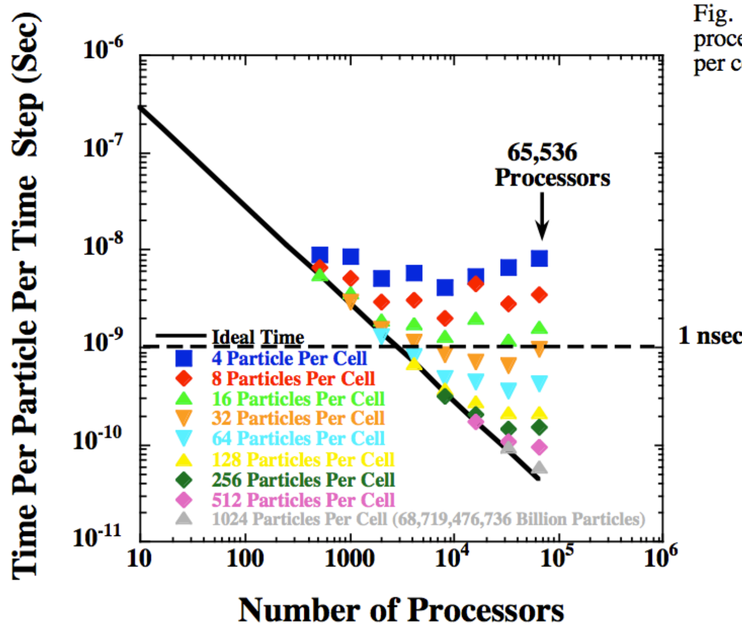

Fig. 6: Time per particle per time step in seconds versus number of processors up to 65,536 processors. The system size for these calculations is 512 x 512 x 256 with 4 up to 1024 particles per cell for a maximum of 68,719,476,736 particles.

Scaling results have been obtained mostly on the Cray XC30 'Edison' at NERSC, but also on the Cray XE6 and the IBM iDataPlex at NERSC, as well as the IBM iDataPlex with Intel Sandy Bridge processors 'Mare Nostrum III' at the Barcelona Supercomputer Center in Spain.

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Ion trajectories

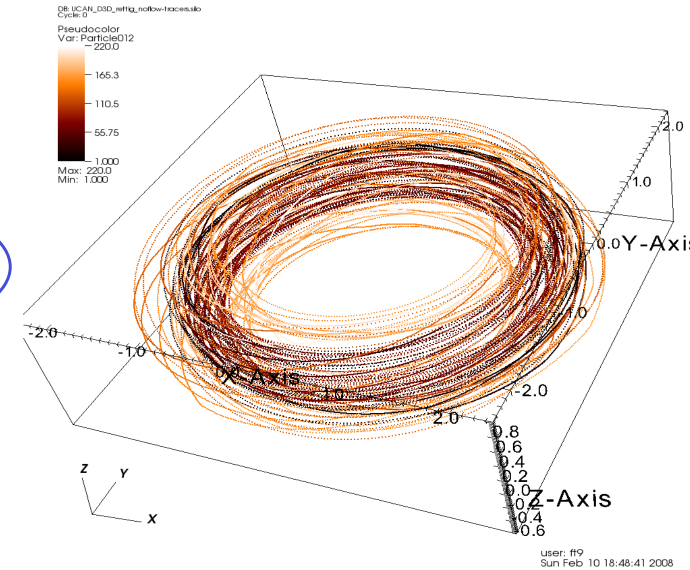
The spatial part of the characteristic along which markers are pushed gives the gyro-averaged ion orbit in real space:

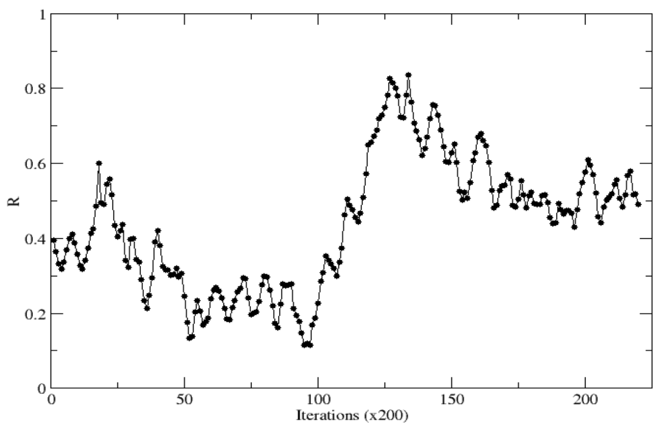
$$\dot{\mathbf{R}} = v_{\parallel}\vec{b} - \frac{c}{B}\nabla_R\varphi\times\vec{b} + \frac{1}{\Omega}\vec{b}\times\left[\mu\nabla B + v_{\parallel}^2\frac{\vec{b}\cdot\nabla B}{B}\right]$$

Parallel motion

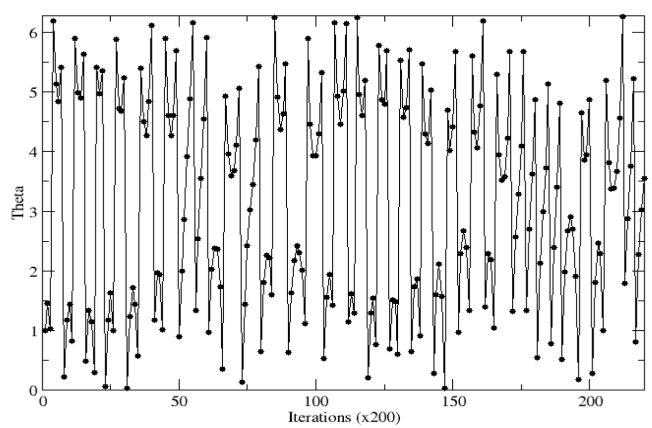
ExB drifts

magnetic drifts

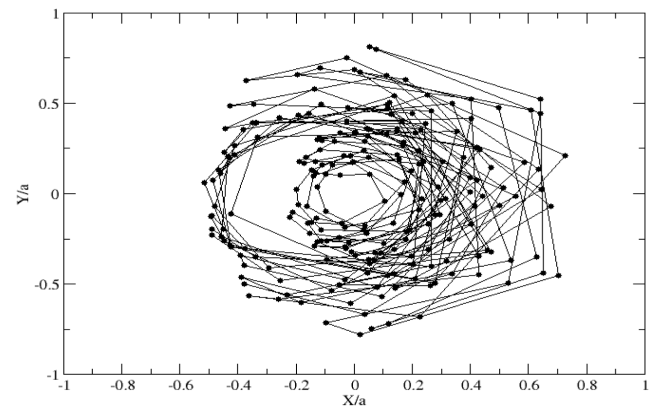




r vs time

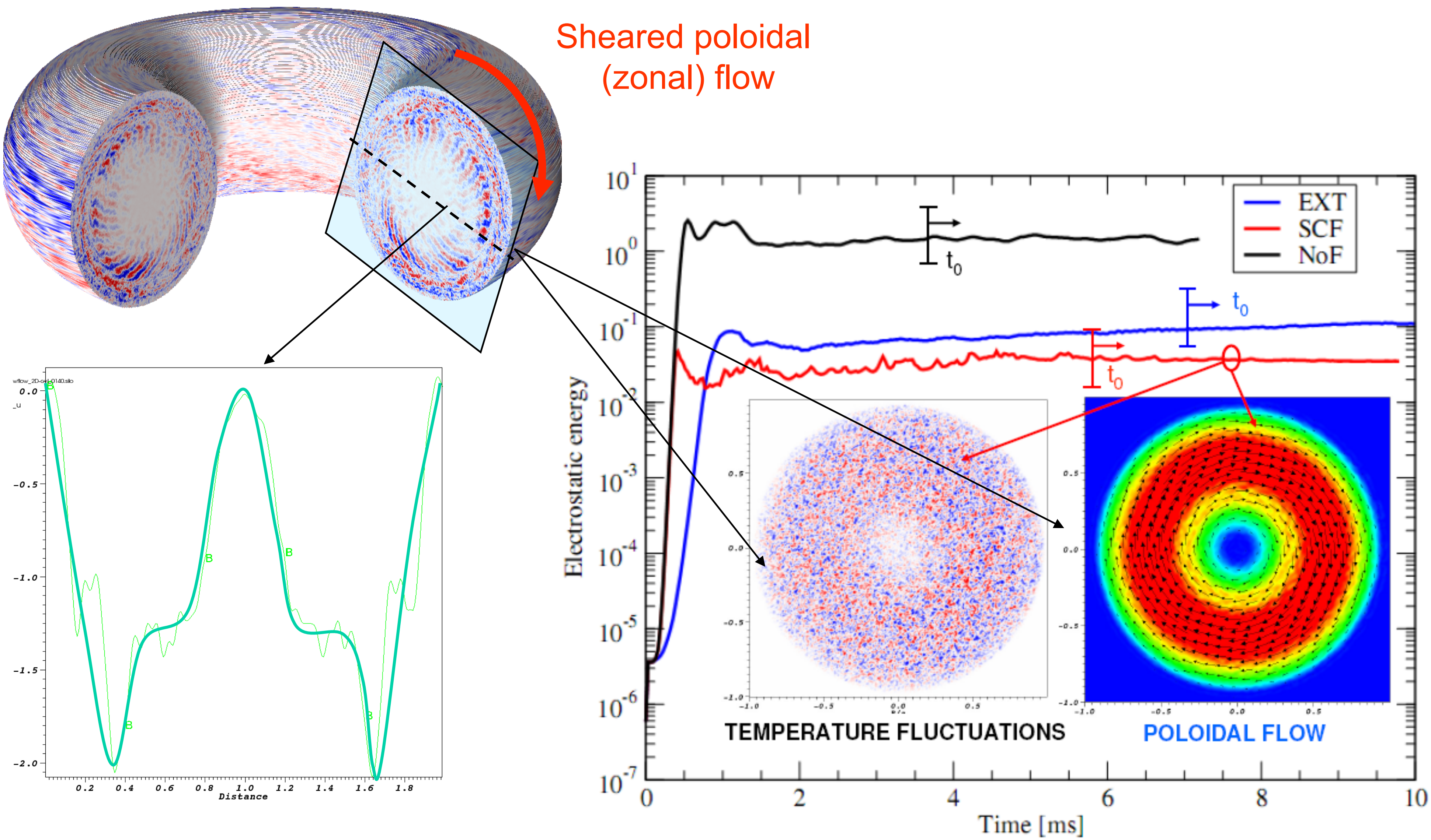


θ vs time



r-θ Poincare plot

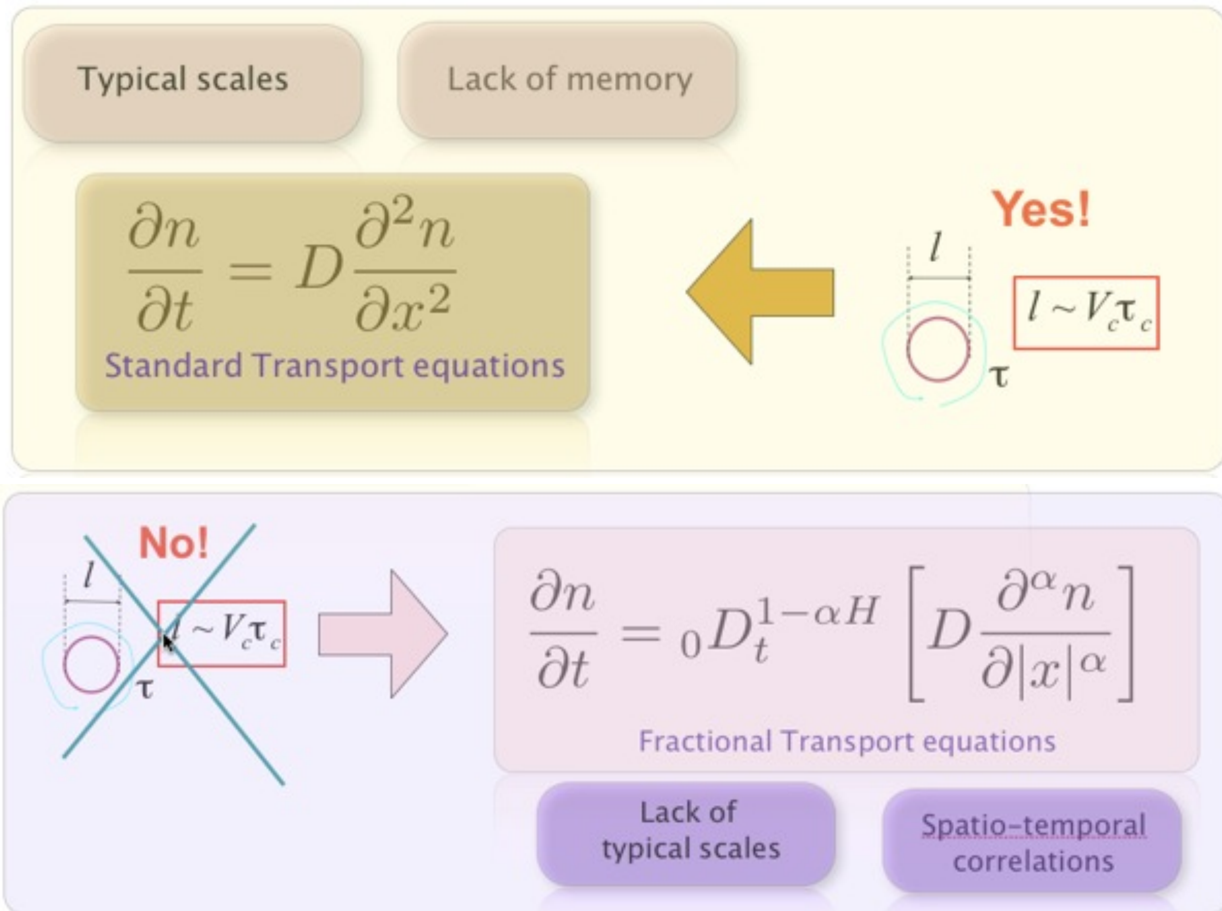
SATURATED PHASE

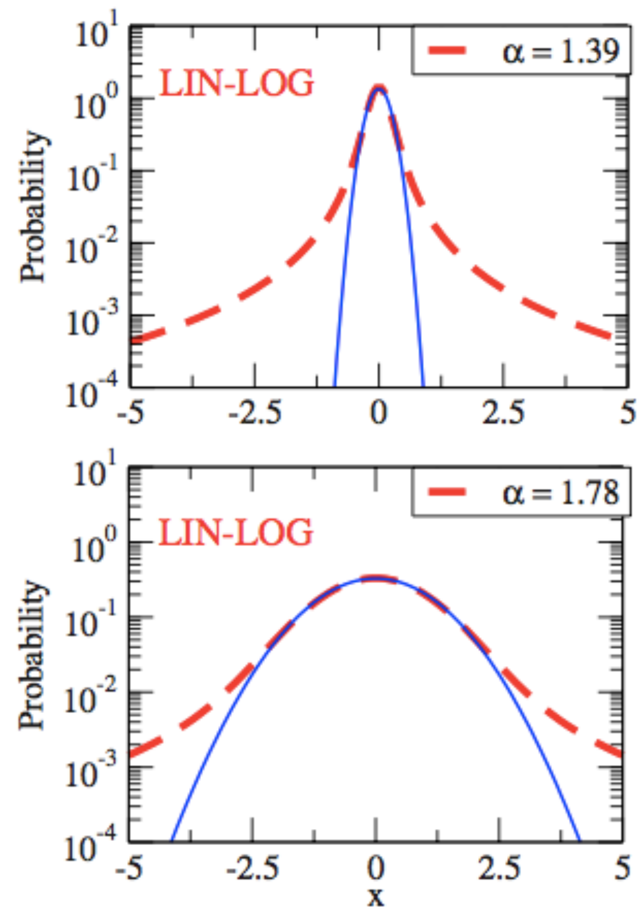


PROPAGATORS AS DIAGNOSTICS

Propagators are the solutions of any differential equation starting from a δ–function initial condition.

Propagators are very easy to construct numerically by using particles/tracers/markers. Comparison with analytic expressions may yield transport exponents.





COMPLEX CROSS-FLOW TRANSPORT

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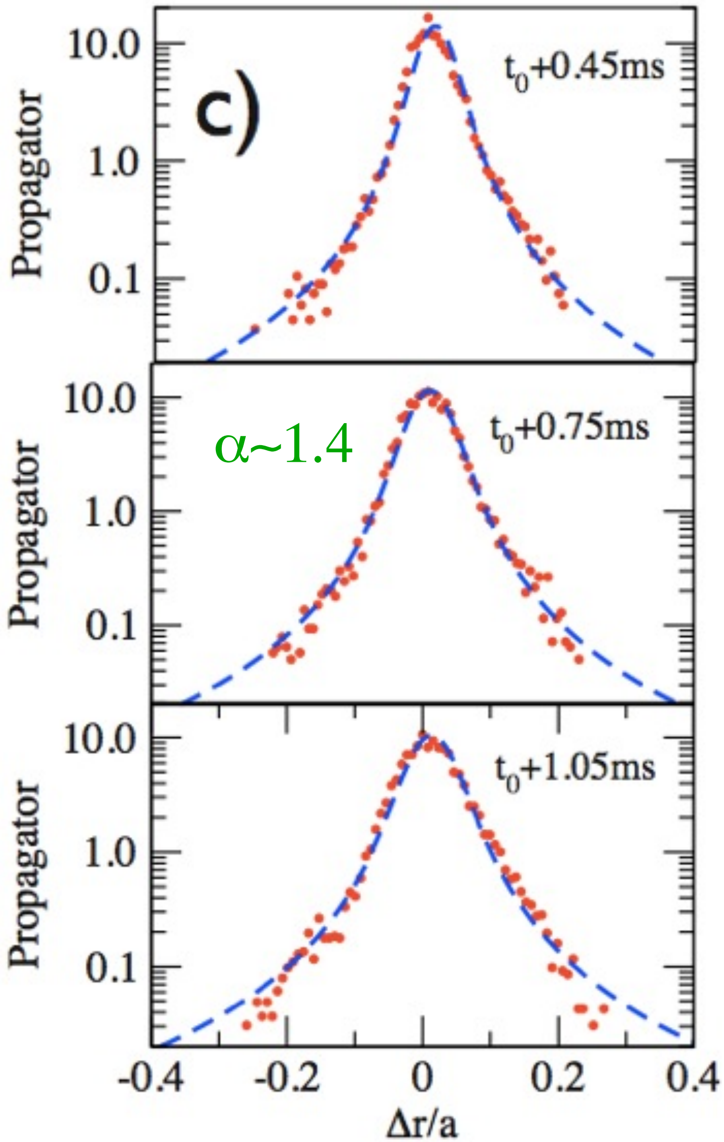
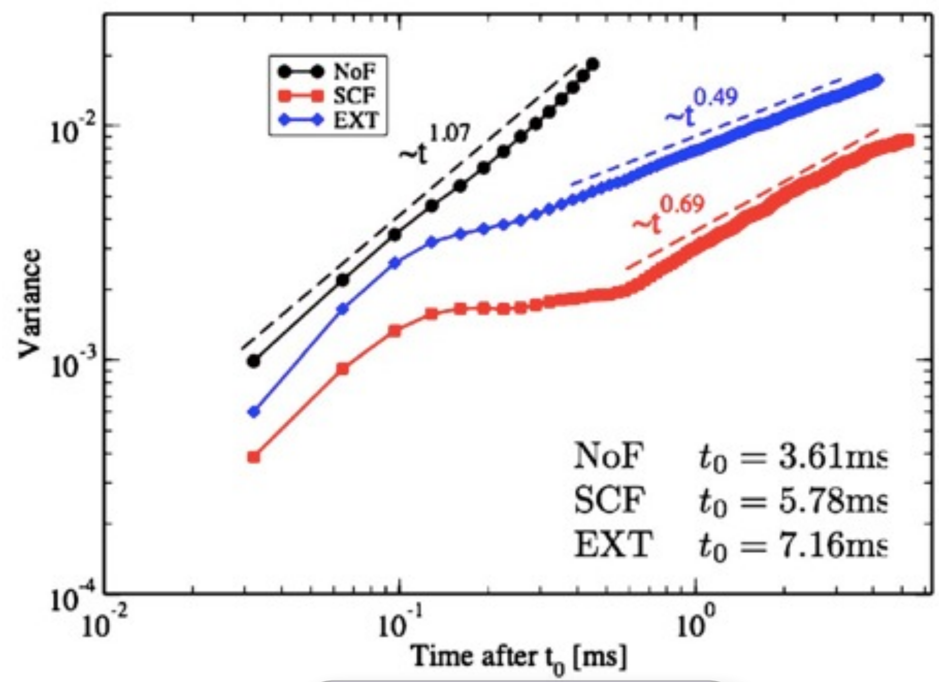


Lack of typical scales



Spatio-temporal correlations

PHYSICS OF SUBDIFFUSION

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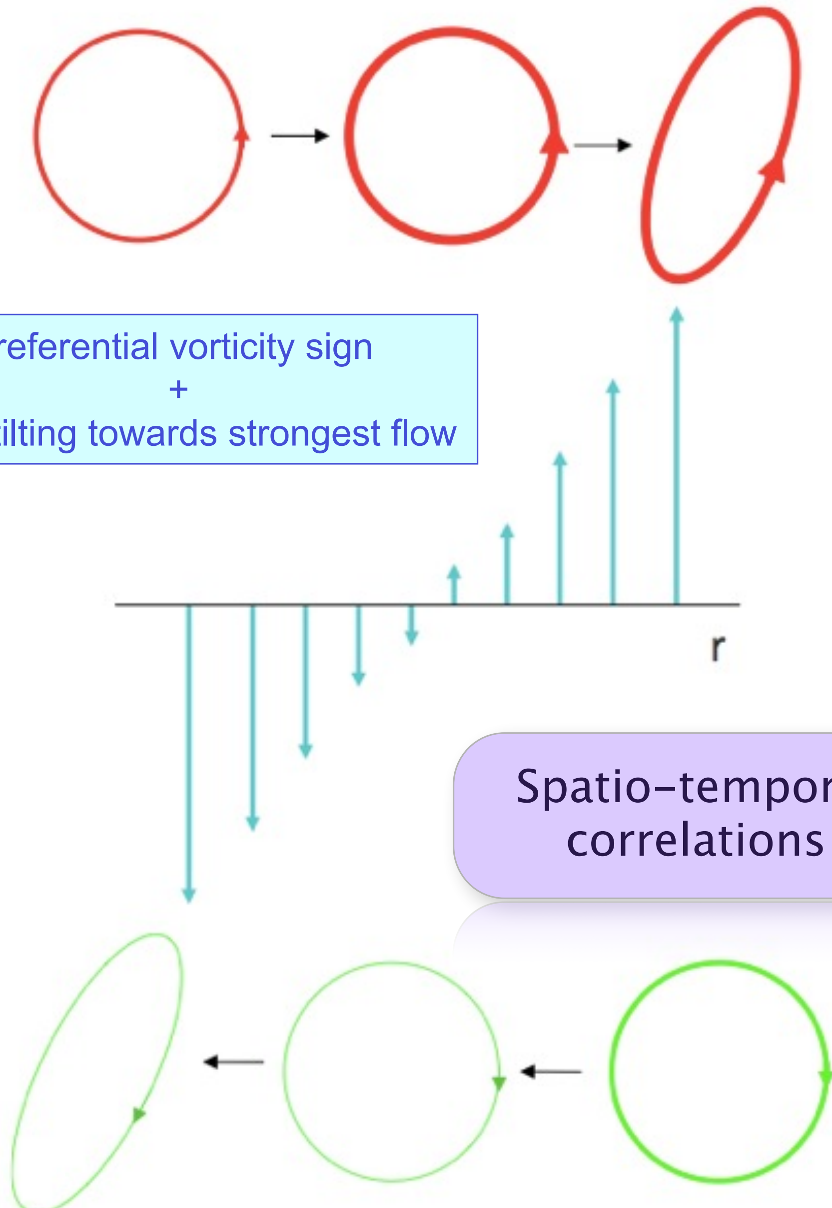
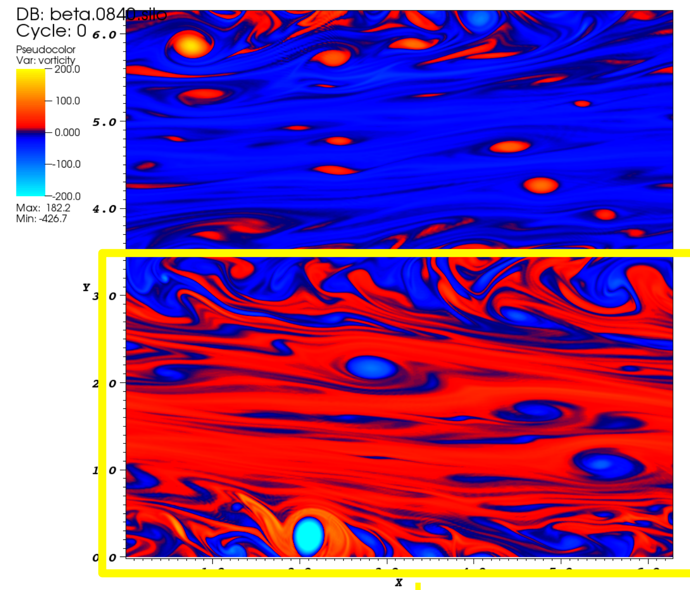
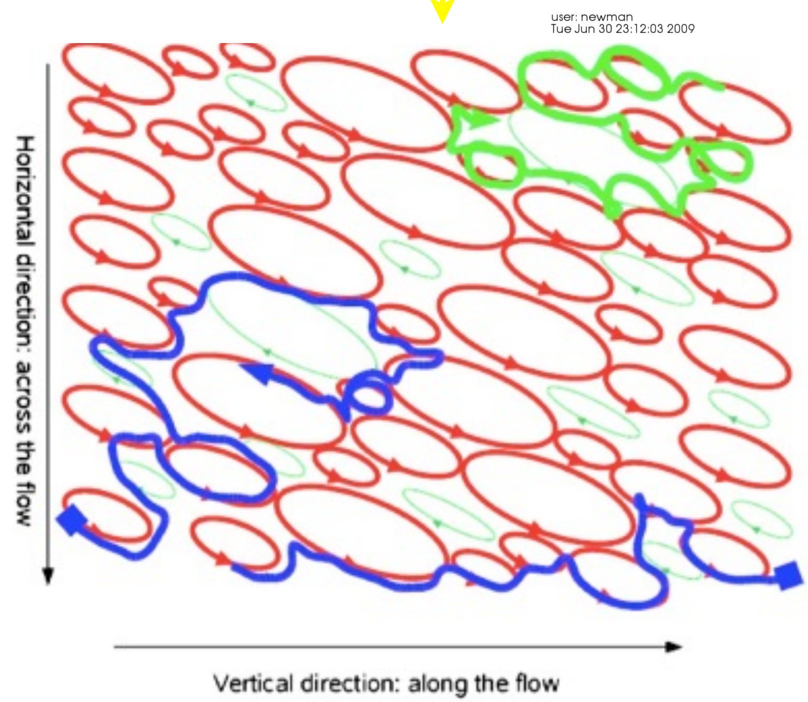


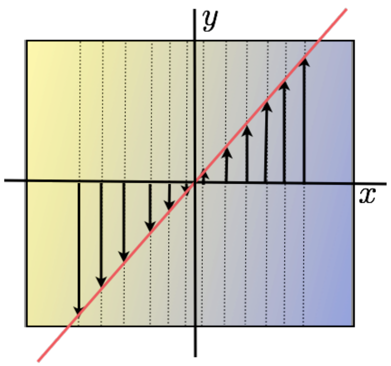
preferential vorticity sign
+
eddy tilting towards strongest flow

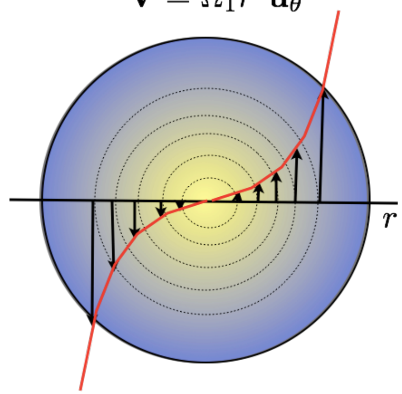
Spatio-temporal correlations



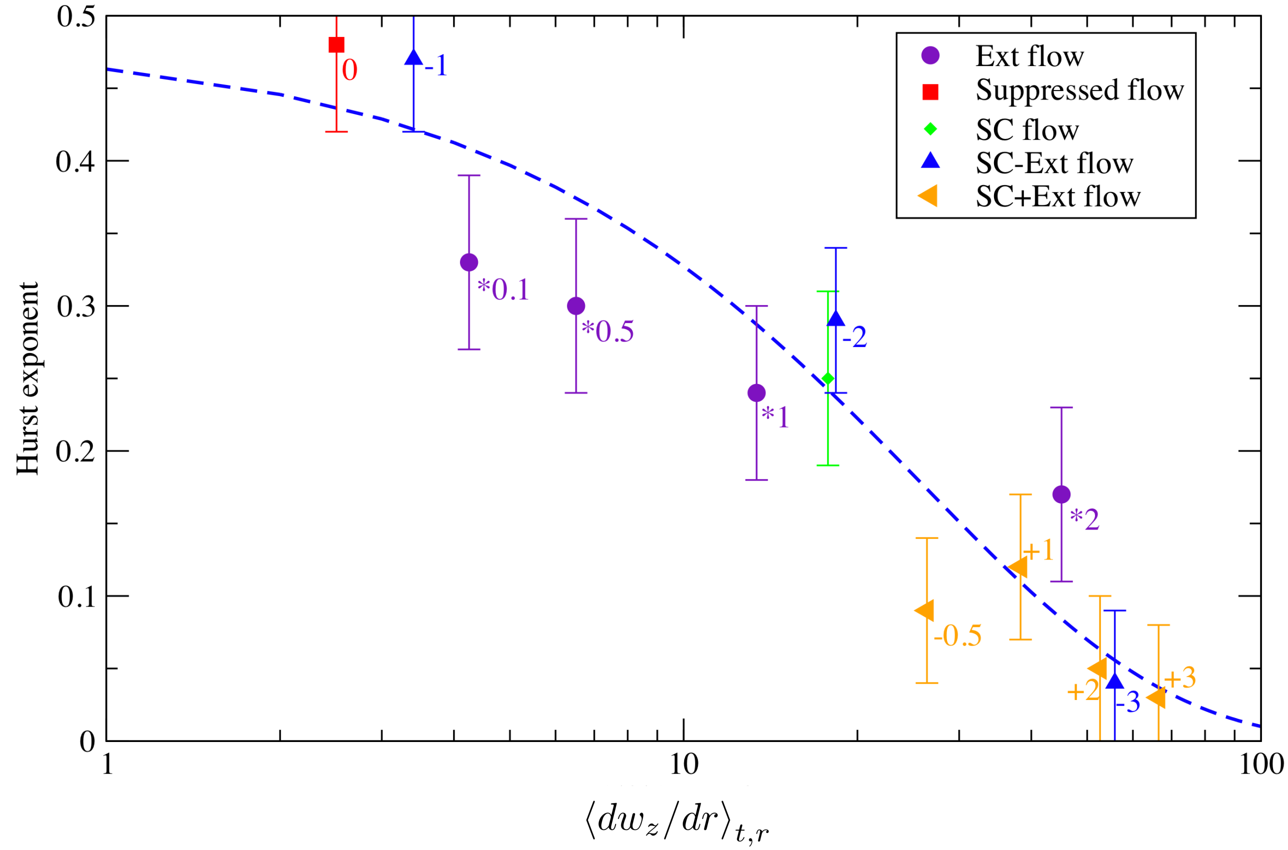


PHYSICS OF SUBDIFFUSION





Subdiffusion set by mean shear profile, not a complex phenomenon in a dynamical sense. It is caused by the underlying landscape in which particles move.



PHYSICS OF NON-GAUSSIANITY

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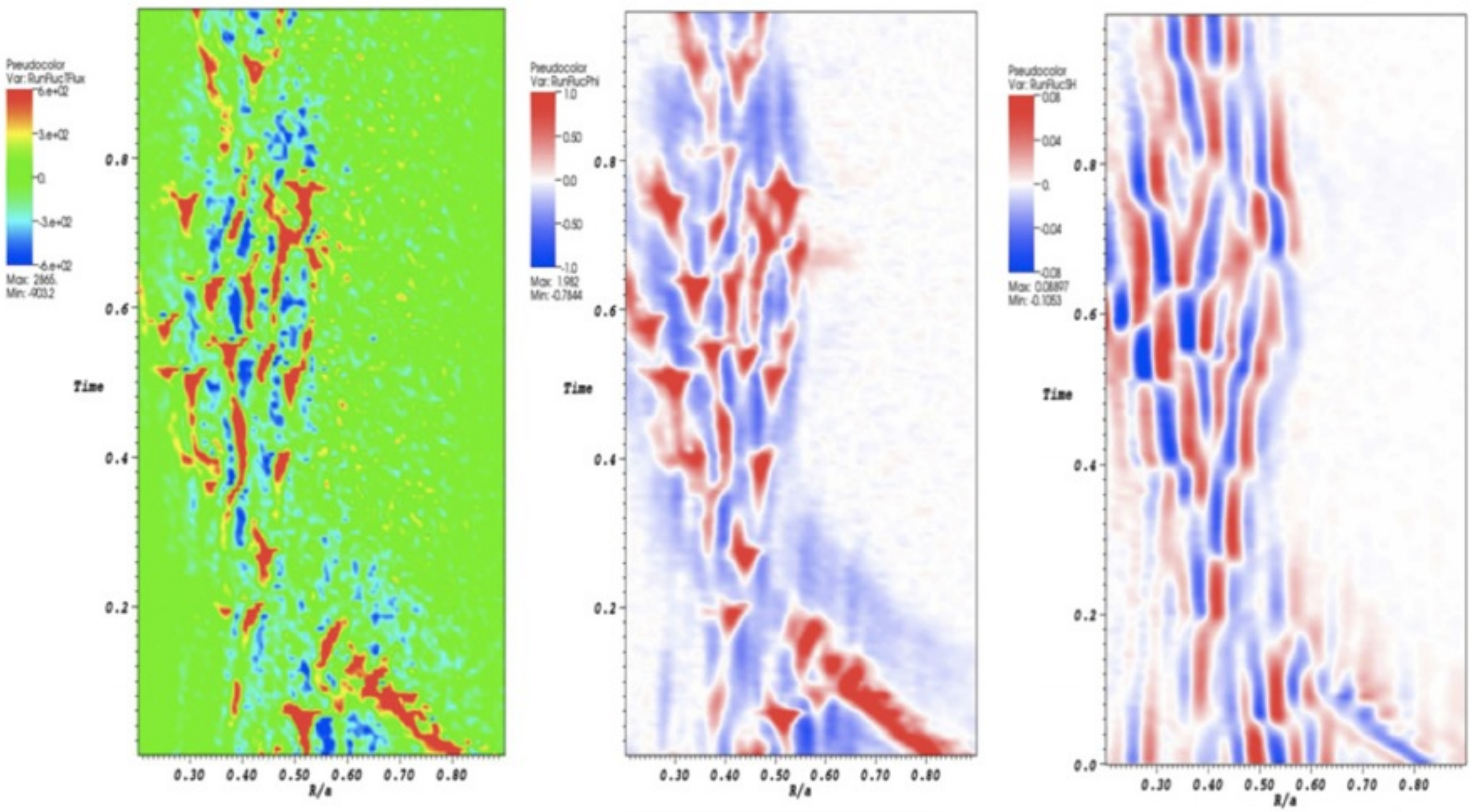
Predator-prey dynamics between fluctuations of turbulence and fluctuations in the shear of the flow



Lack of
typical scales

PHYSICS OF NON-GAUSSIANITY (II)

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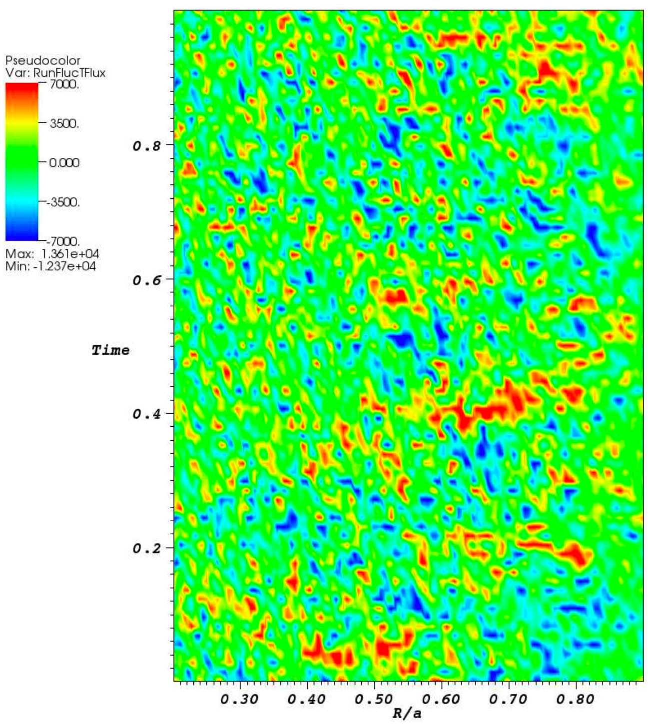
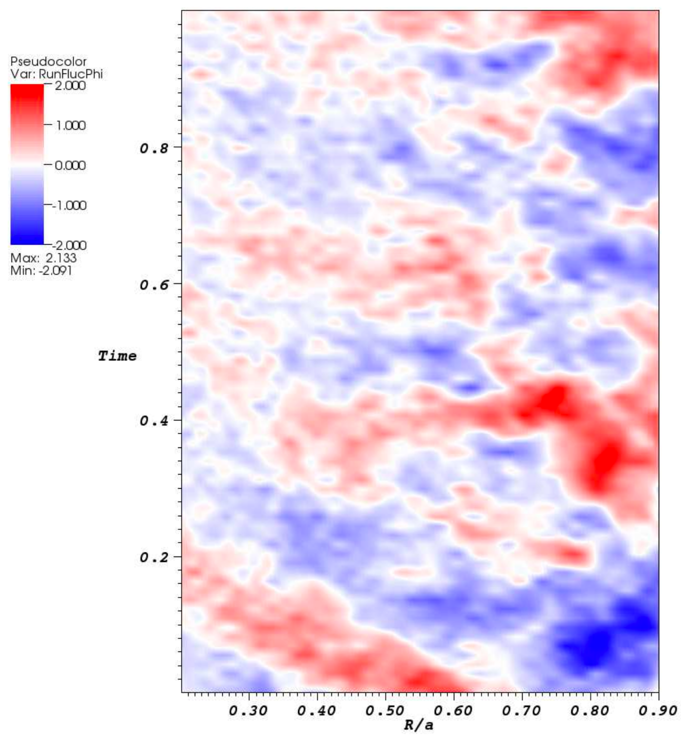
Effective diffusion provides good description when coupling between zonal flow and fluctuations artificially suppressed.

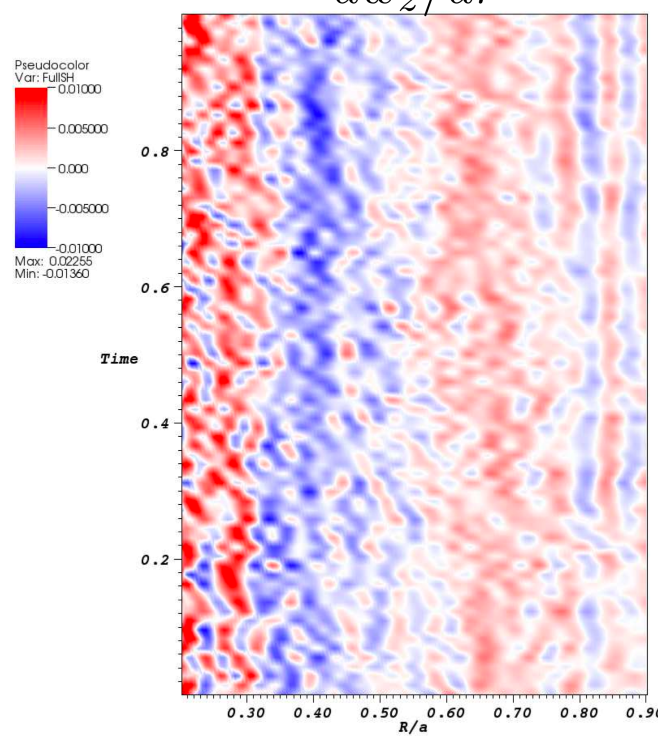
Ion Heat flux



$\phi - \phi_{00}$



dw_z/dr



Typical scales DO exist

Publications

Universidad Carlos III de Madrid

PRL 101, 205002 (2008) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2008

Nature of Transport across Sheared Zonal Flows in Electrostatic Ion-Temperature-Gradient Gyrokinetic Plasma Turbulence

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(Received 6 May 2008; published 12 November 2008)

It is shown that the usual picture for the suppression of turbulent transport across a stable sheared flow based on a reduction of diffusive transport coefficients is, by itself, incomplete. By means of toroidal gyrokinetic simulations of electrostatic, collisionless ion-temperature-gradient turbulence, it is found that the nature of the transport is altered fundamentally, changing from diffusive to anticorrelated and subdiffusive. Additionally, whenever the flows are self-consistently driven by turbulence, the transport gains an additional non-Gaussian character. These results suggest that a description of transport across sheared flows using effective diffusivities is oversimplified.

DOI: 10.1103/PhysRevLett.101.205002 PACS numbers: 52.35.Ra, 05.40.Fb, 52.55.Fa, 52.65.Tt

PHYSICS OF PLASMAS 16, 055905 (2009)

On the nature of radial transport across sheared zonal flows in electrostatic ion-temperature-gradient gyrokinetic tokamak plasma turbulence[a)]

R. Sánchez,[1,b)] D. E. Newman,[2] J.-N. Leboeuf,[3] B. A. Carreras,[4] and V. K. Decyk[5]
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(Received 7 December 2008; accepted 15 April 2009; published online 7 May 2009)

It is argued that the usual understanding of the suppression of radial turbulent transport across a sheared zonal flow based on a reduction in effective transport coefficients is, by itself, incomplete. By means of toroidal gyrokinetic simulations of electrostatic, ion-temperature-gradient turbulence, it is found instead that the character of the radial transport is altered fundamentally by the presence of a sheared zonal flow, changing from diffusive to anticorrelated and subdiffusive. Furthermore, if the flows are self-consistently driven by the turbulence via the Reynolds stresses (in contrast to being induced externally), radial transport becomes non-Gaussian as well. These results warrant a reevaluation of the traditional description of radial transport across sheared flows in tokamaks via effective transport coefficients, suggesting that such description is oversimplified and poorly captures the underlying dynamics, which may in turn compromise its predictive capabilities.
 [DOI: 10.1063/1.3129727]

IOP PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION
Plasma Phys. Control. Fusion 53 (2011) 074018 (10pp) doi:10.1088/0741-3335/53/7/074018

Nature of turbulent transport across sheared zonal flows: insights from gyrokinetic simulations*

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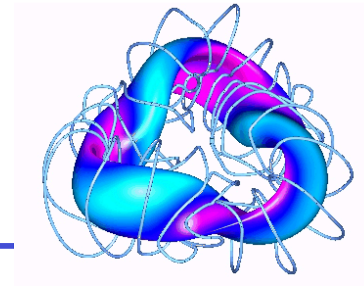
Abstract
The traditional view regarding the reduction of turbulence-induced transport across a stable sheared flow invokes a reduction of the characteristic length scale in the direction perpendicular to the flow as a result of the shearing and stretching of eddies caused by the differential pull exerted in the direction of the flow. A reduced effective transport coefficient then suffices to capture the reduction, that can then be readily incorporated into a transport model. However, recent evidence from gyrokinetic simulations of the toroidal ion-temperature-gradient mode suggests that the dynamics of turbulent transport across sheared flows changes in a more fundamental manner, and that the use of reduced effective transport coefficients fails to capture the full dynamics that may exhibit both subdiffusion and non-Gaussian statistics. In this contribution, after briefly reviewing these results, we propose some candidates for the physical mechanisms responsible for endowing transport with such non-diffusive characteristics, backing these proposals with new numerical gyrokinetic data.

On-going project: stellarators and quasi-symmetries @ BSC



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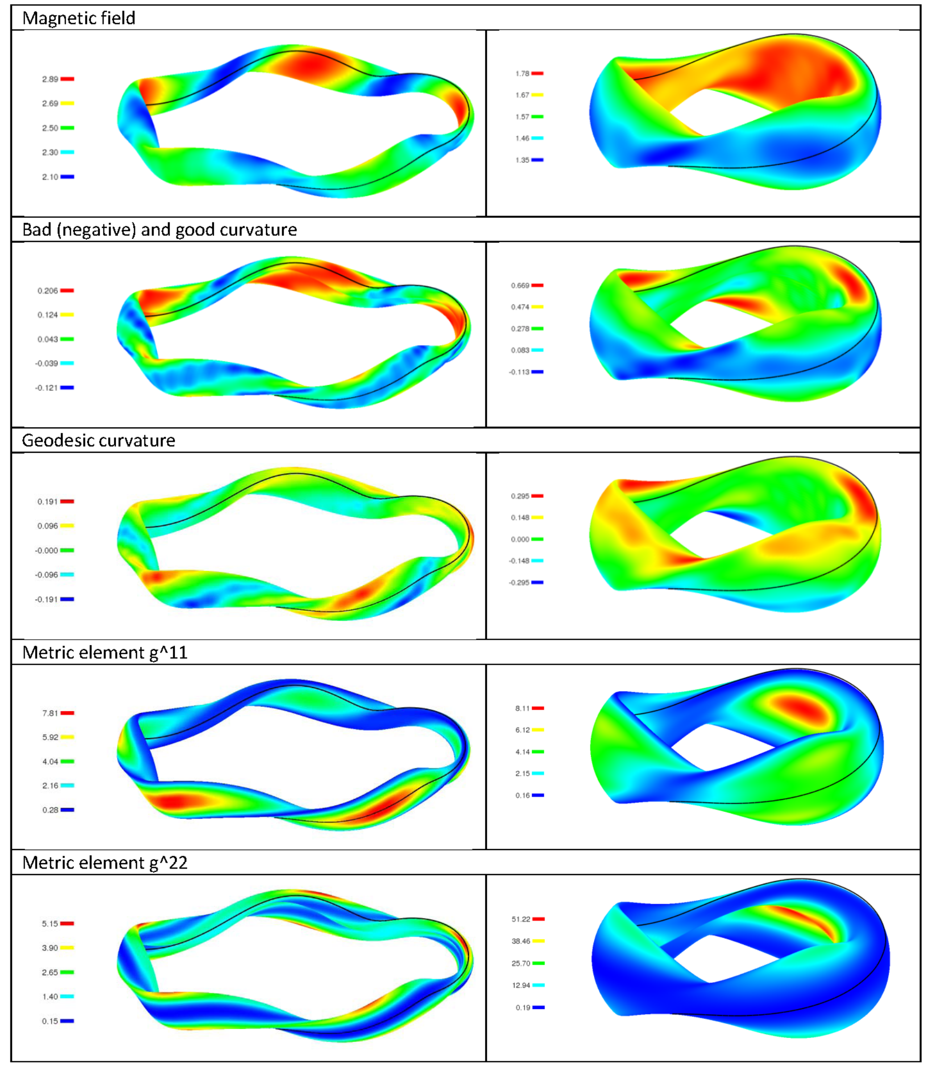
Stellarator design strategies are currently based on reducing neoclassical collisional transport by numerically looking for quasi-symmetries of the confining magnetic field.

Quasi-symmetries are hidden symmetries of the magnitude of the magnetic field when written in Boozer coordinates. These are non-geometrical coordinates, so QS configurations do not look symmetric to the naked eye.

Turbulent transport has been theorized to improve in QS configurations, mostly due to the reduced neoclassical viscosities that should allow for the self-consistent generation of poloidal flows.

On-going project tries to determine the nature of transport as a function of the degree of QS of the configuration.

IPP's GENE/GIST code is used, since it can handle a general 3D geometry.



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- Oak Ridge National Laboratory, Tennessee, USA
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