Turbulence driven by Thermal Gradients in Magnetically Confined Plasmas

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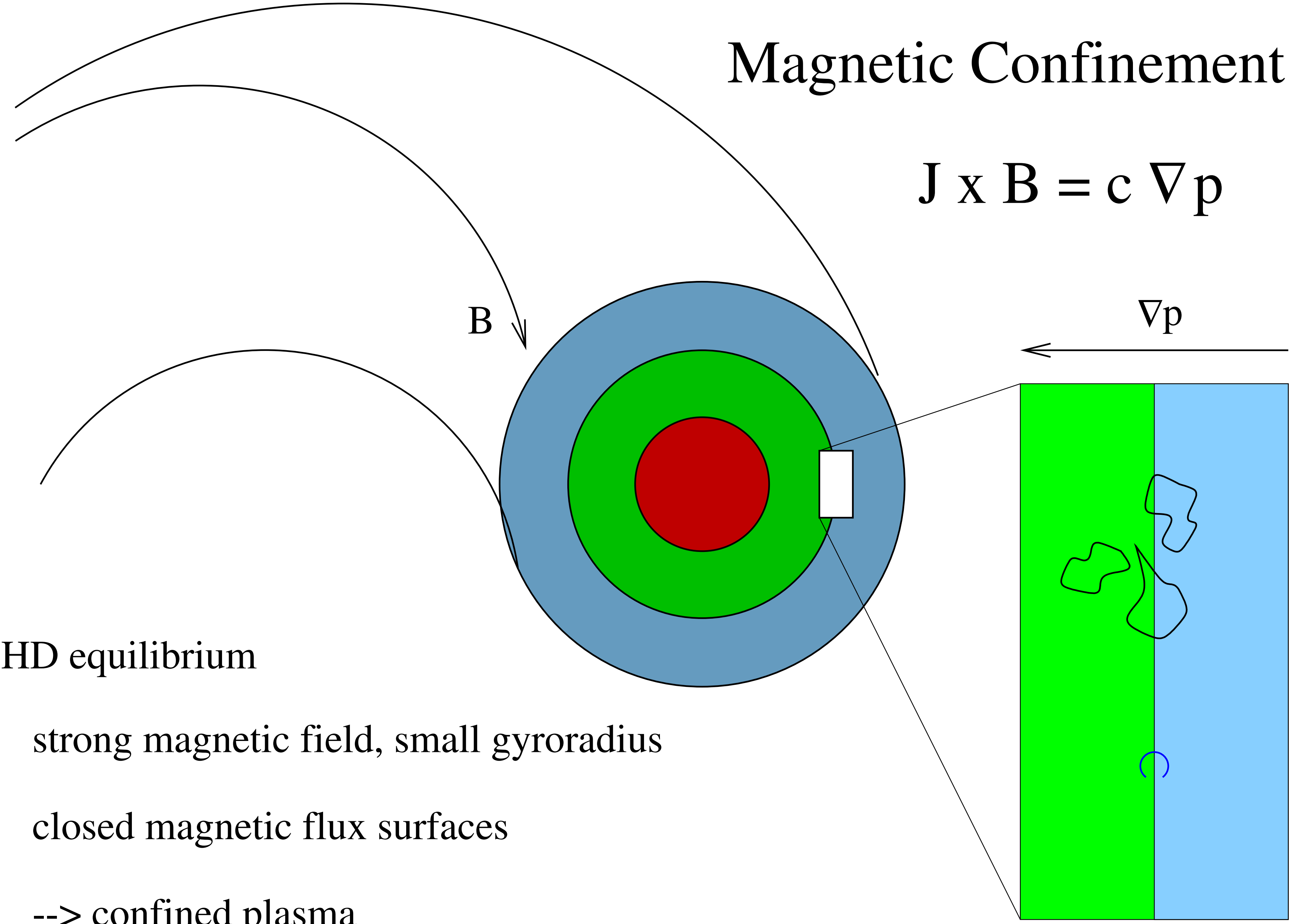
Outline

- **Basic Transfer Dynamics**
  — low frequency basics, energy transfer in turbulence, equilibrium
- **Gyrofluid Core Turbulence**
  — electromagnetic, fully realistic parameters
  — self consistent evolution of MHD equilibrium
- **Gyrofluid Field Theory**
  — fully inhomogeneous equations, necessary for strong spatial parameter variation
  — energy conservation consistency assured
- **Gyrokinetic Edge Turbulence**
  — delta-f model, first application to transcollisional edge
  — strong role for large $v_\perp$, small $v_\|$ electrons (not a trapping effect)
- **Stellarator Edge Turbulence**

Magnetic Confinement

$$J \times B = c \, \nabla p$$



MHD equilibrium

strong magnetic field, small gyroradius

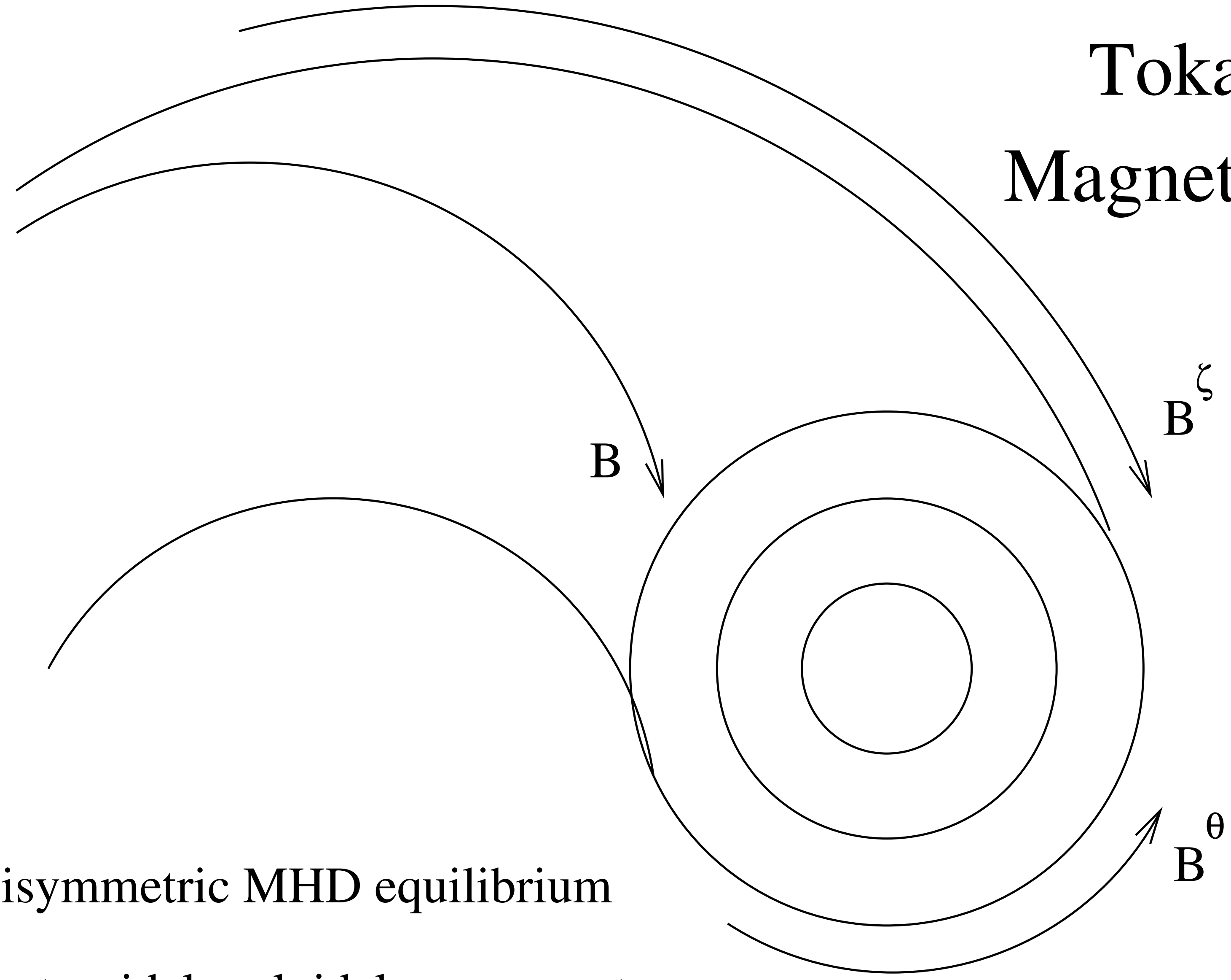
closed magnetic flux surfaces

--> confined plasma

however . . .   turbulence --> losses

eddies, few gyroradii

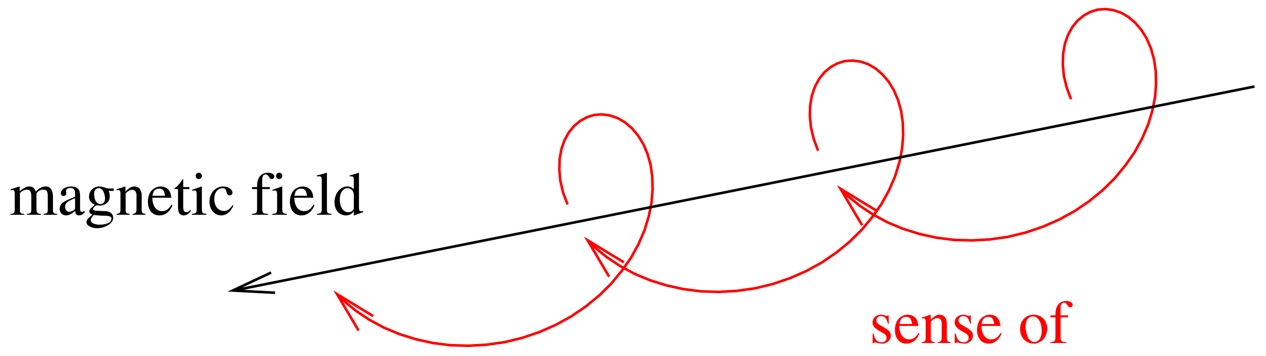
Tokamak Magnetic Field



axisymmetric MHD equilibrium

- toroidal, poloidal components
- mainly toroidal
- ratio of components --> pitch parameter ‘‘q’’ B^ζ / B^θ

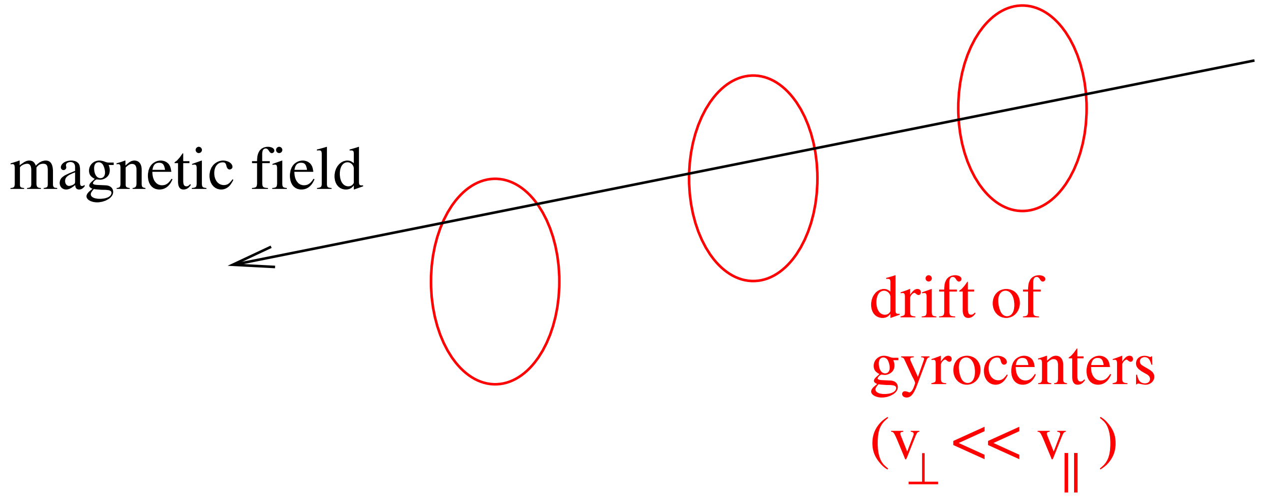
Low Frequency Drift Motion



magnetic field

sense of
gyration
for ions

general



magnetic field

drift of
gyrocenters
($v_\perp << v_\parallel$)

low frequencies

$\omega << \Omega$

v-space details: ‘‘gyrokinetic’’

few moments: ‘‘gyrofluid’’

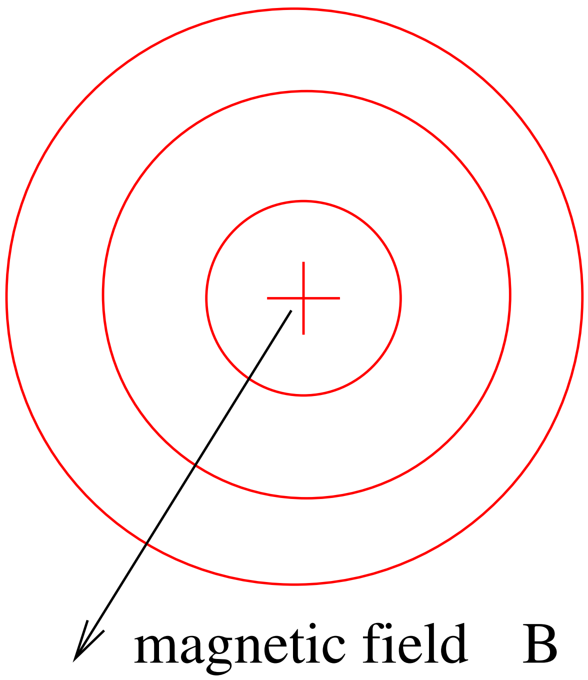
Low Pressure (Beta) Dynamics

low ‘‘beta’’

$p << B^2/8\pi$

low frequencies

$\omega << k_\perp v_A$



pressure disturbance $\tilde{p}$

magnetic disturbance $\tilde{B}$
(parallel to B)

‘‘flute mode’’

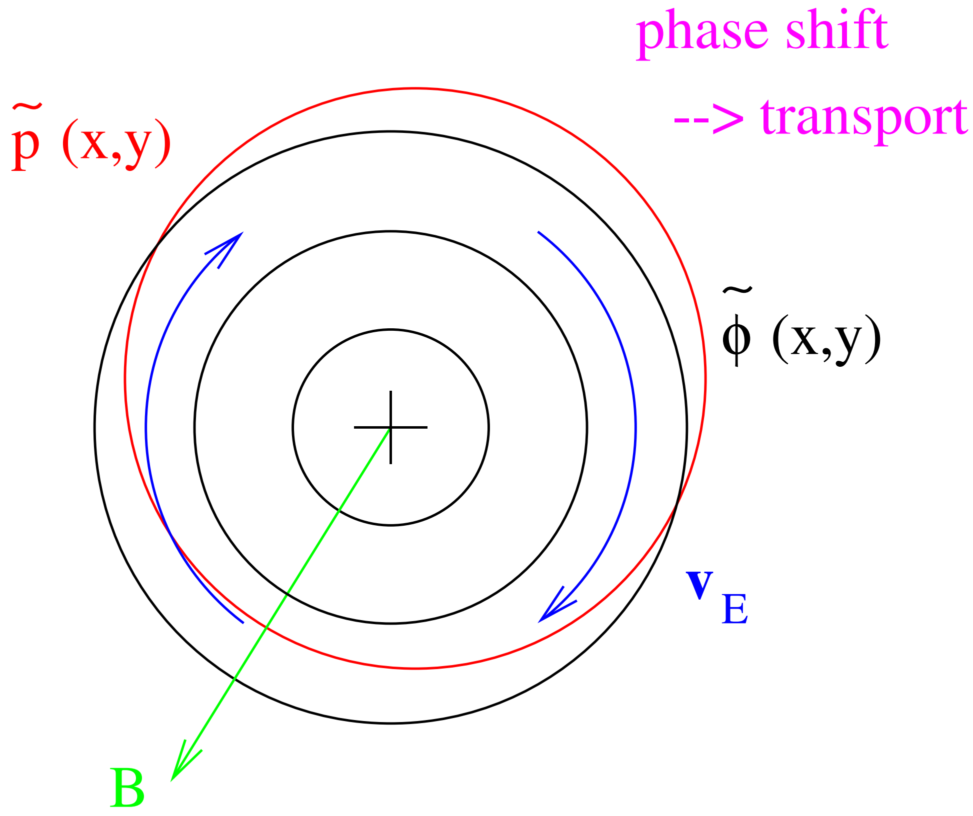
vortices/filaments

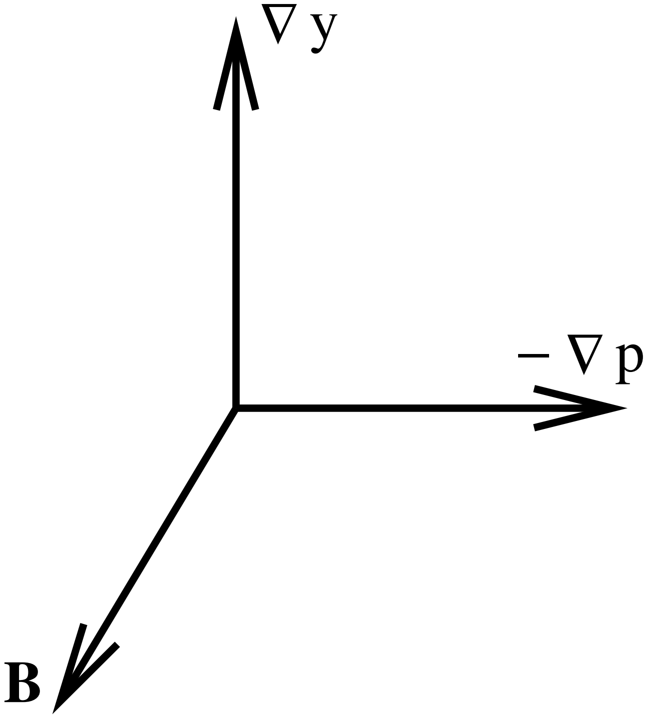
$k_\parallel << k_\perp$

--> strict perpendicular force balance $\nabla(\tilde{p} + 4\pi\ B\tilde{B}) \sim 0$

$\omega \sim k_\parallel v_A$ --> electromagnetic parallel dynamics

Sense of Coordinate Geometry





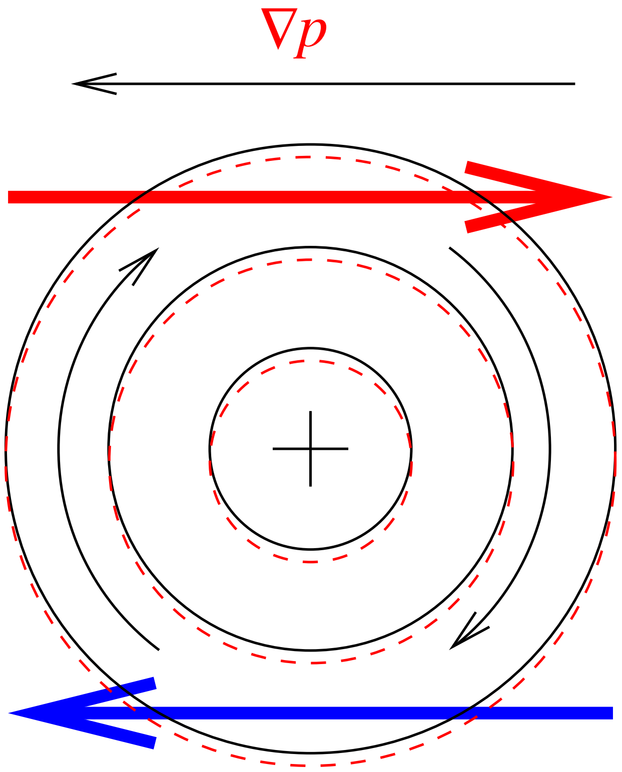
computations: align coordinates to magnetic field (sheared, curved)

(only one contravariant component of B is nonvanishing)

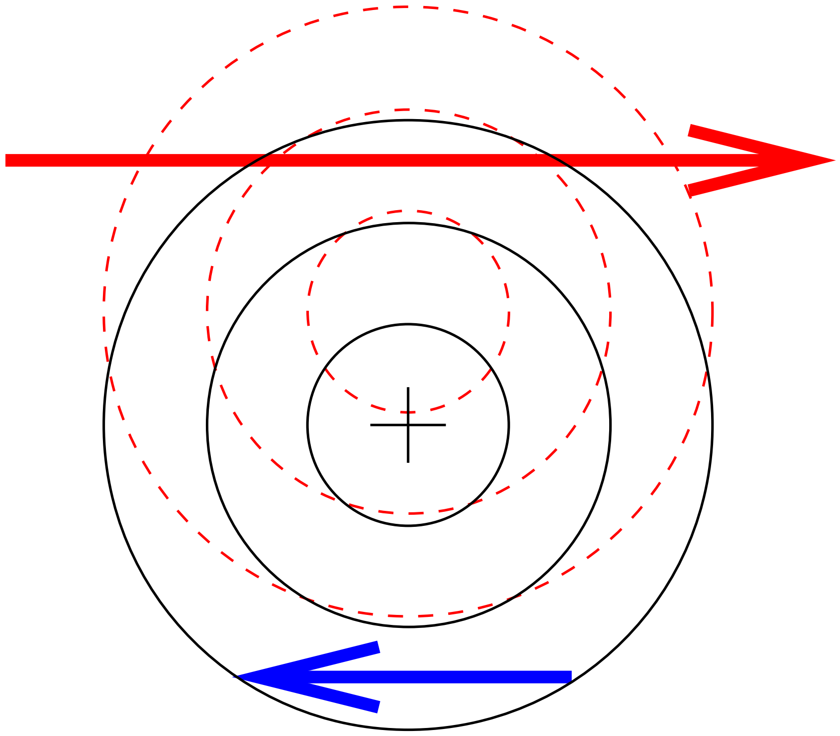
(nonorthogonal, takes advantage of slowly varying B)

(S Cowley et al Phys Fluids B 1991, B Scott Phys Plasmas 1998, 2001)

Phase Shifts and Transport



p and phi in phase
--> no net transport



phase shift --> net transport

phase shift --> net transport down gradient
--> free energy drive

Role of Parallel Forces on Electrons

equation of motion for electrons parallel to B

$$n_e e \left(\frac{1}{c}\dot{A}_{\|} + \nabla_{\|}\phi + \eta_{\|}J_{\|} \right) = \nabla_{\|}p_e + \text{inertia}$$

Alfven (MHD) coupling

adiabatic (fluid compression) coupling

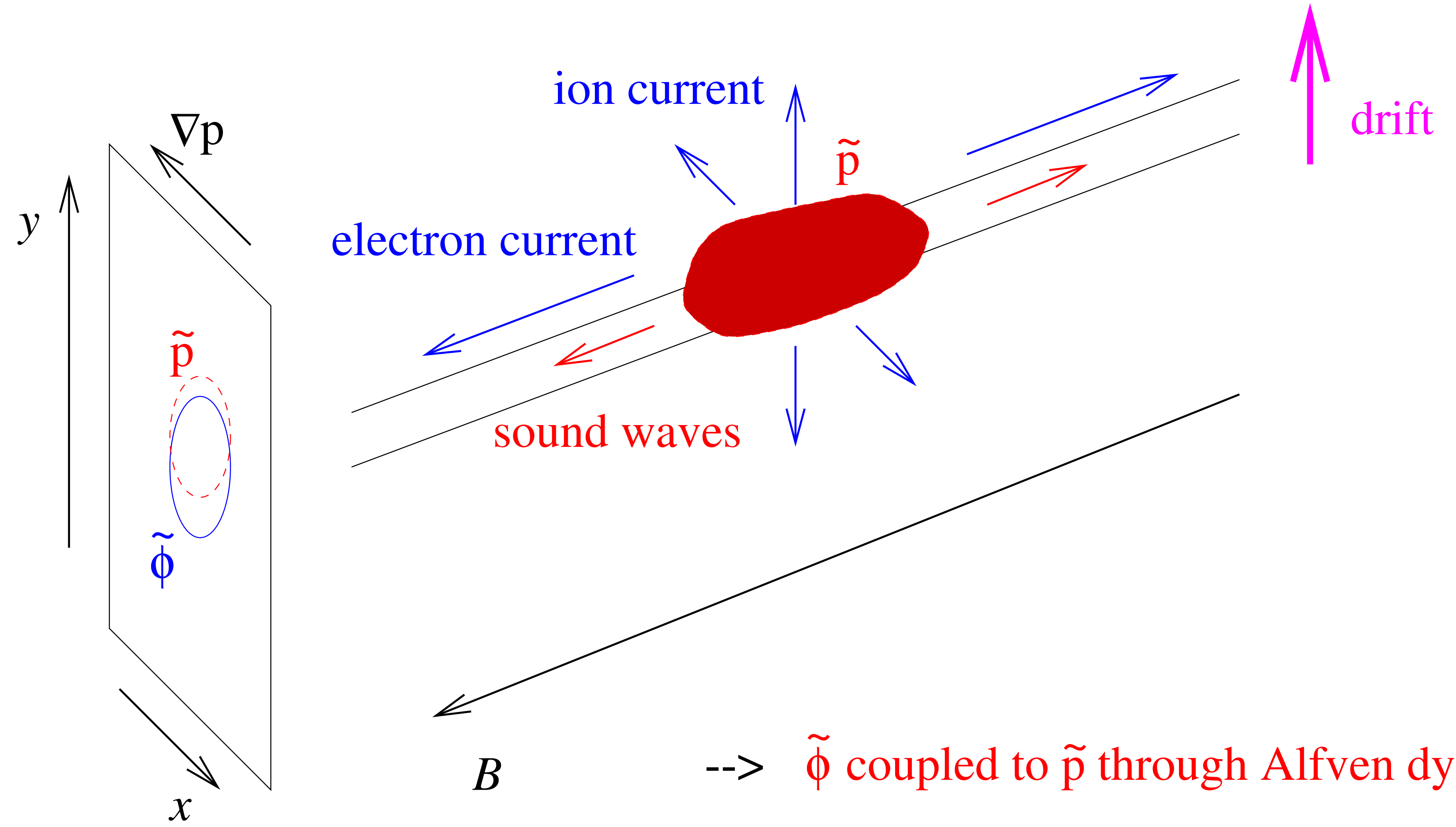
a ‘‘two fluid’’ effect

static balance of gradients --> ‘‘adiabatic electrons’’

general: response of currents to static imbalance

controls possible phase shifts $\tilde{p}_e \quad \texttt{<-->} \quad \tilde{\phi}$

Drift (Alfven) Wave Dynamics



--> $\tilde{\phi}$ coupled to $\tilde{p}$ through Alfven dynamics

--> $\tilde{\phi}$ continually excites $\tilde{p}$ in the gradient

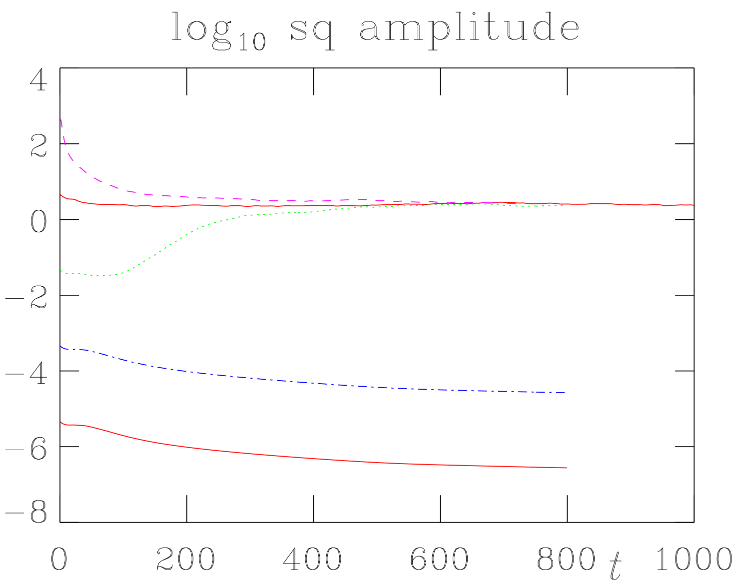
--> structure drifts

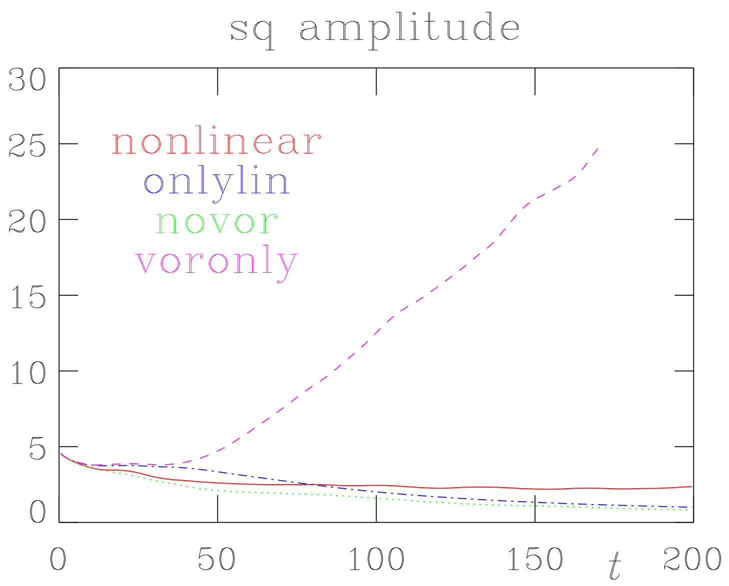
(M Wakatani A Hasegawa Phys Fluids 1984)

(B Scott Plasma Phys Contr Fusion 1997)

Nonlinear Instability

basic feature of drift wave turbulence





amplitude threshold --> linear stability

vorticity nonlinearity --> damped eigenmodes destabilise each other

role of pressure advection nonlinearity --> saturation

edge turbulence --> washes out microinstabilities in toroidal magnetic field

(B Scott Phys Rev Lett 1990, Phys Fluids B 1992, New J Phys 2002)

Energy Transfer

part of energy theorem governed by vorticity equation

$$-\phi_{-k}\left(\dot{\Omega}+v_E\cdot\nabla\Omega+\mathrm{FLR}=\nabla_\parallel J_\parallel+\nabla\cdot\frac{c}{B^2}B\times\nabla p\right)_k$$

Fourier mode k

vorticity $\Omega = (n_e - n_i)\,e$

currents: polarisation parallel diamagnetic

free energy: source in pressure equation, transfer in to vorticity equation

pathways: over parallel dynamics or toroidal compression

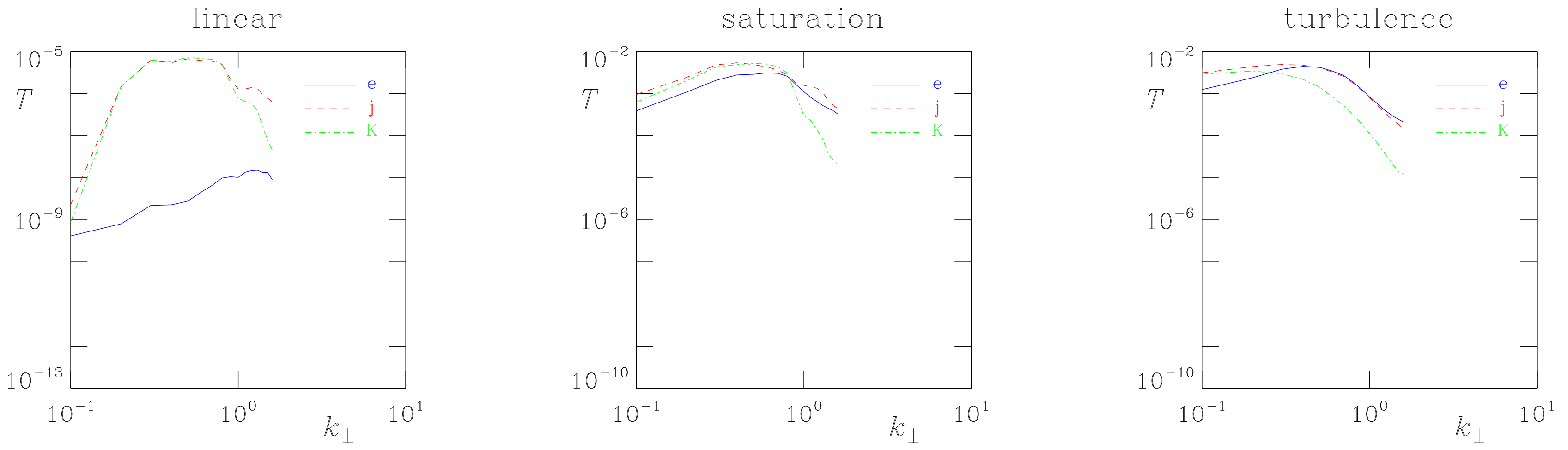
between modes within ExB energy -- nonlinear advection

direct, in-context measurement of physical mechanism supporting turbulence

(B Scott Phys Plasmas 2000)

Vorticity Energetics -- Transition to Turbulence

turbulence imposes its own mode structure on dynamics



linear interchange mode -- balance between diamagnetic/parallel currents

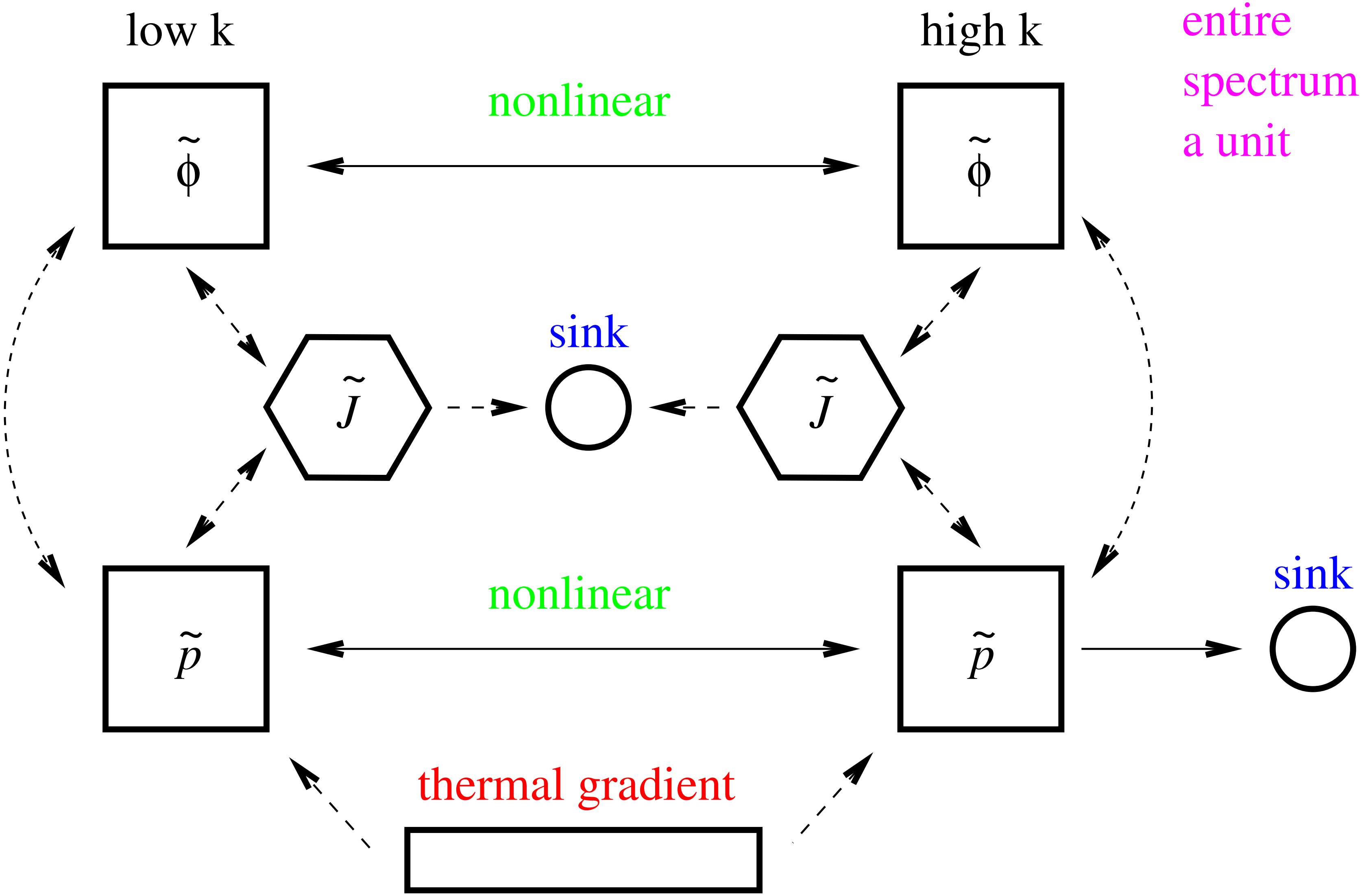
turbulence -- emergence of nonlinear ExB vorticity advection

developed turbulence -- balance between polarisation/parallel currents

basic mechanism supporting eddies in turbulence differs from linear instability

(B Scott Plasma Phys Contr Fusion 2003)

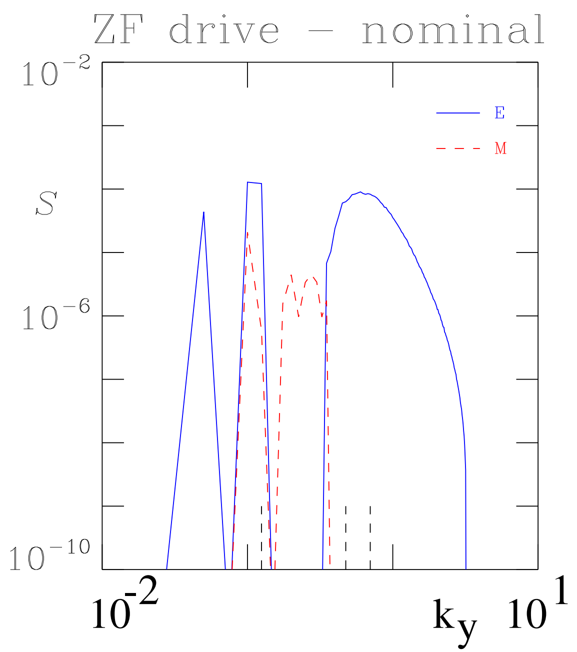
Energy Transfer: electromagnetic turbulence

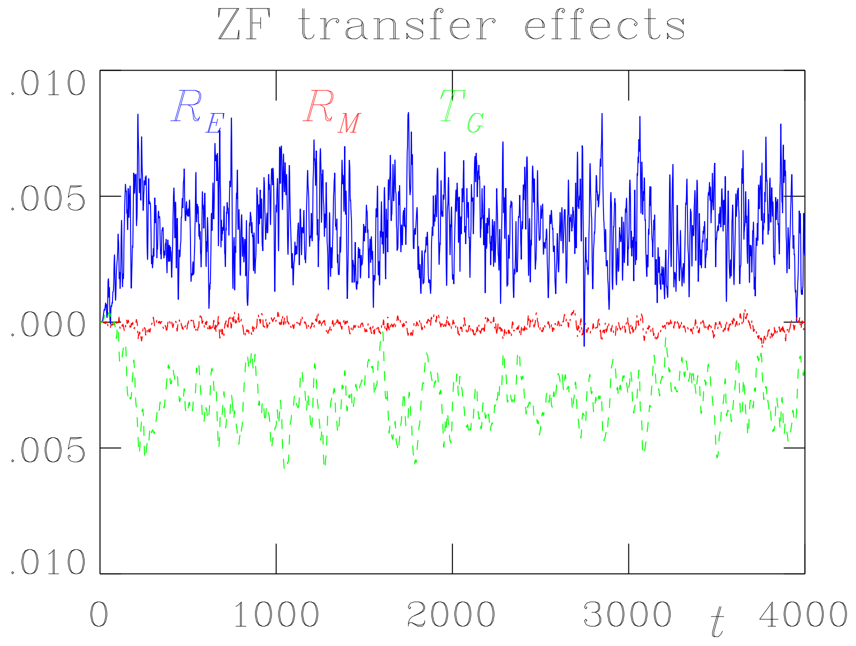


(B Scott Phys Fluids B 1992, Plasma Phys Contr Fusion 1997)

Coupling to Zonal Flows

turbulence regulated by flows, regulated by toroidal compression





eddy Reynolds stress --> energy transfer from turbulence to flows

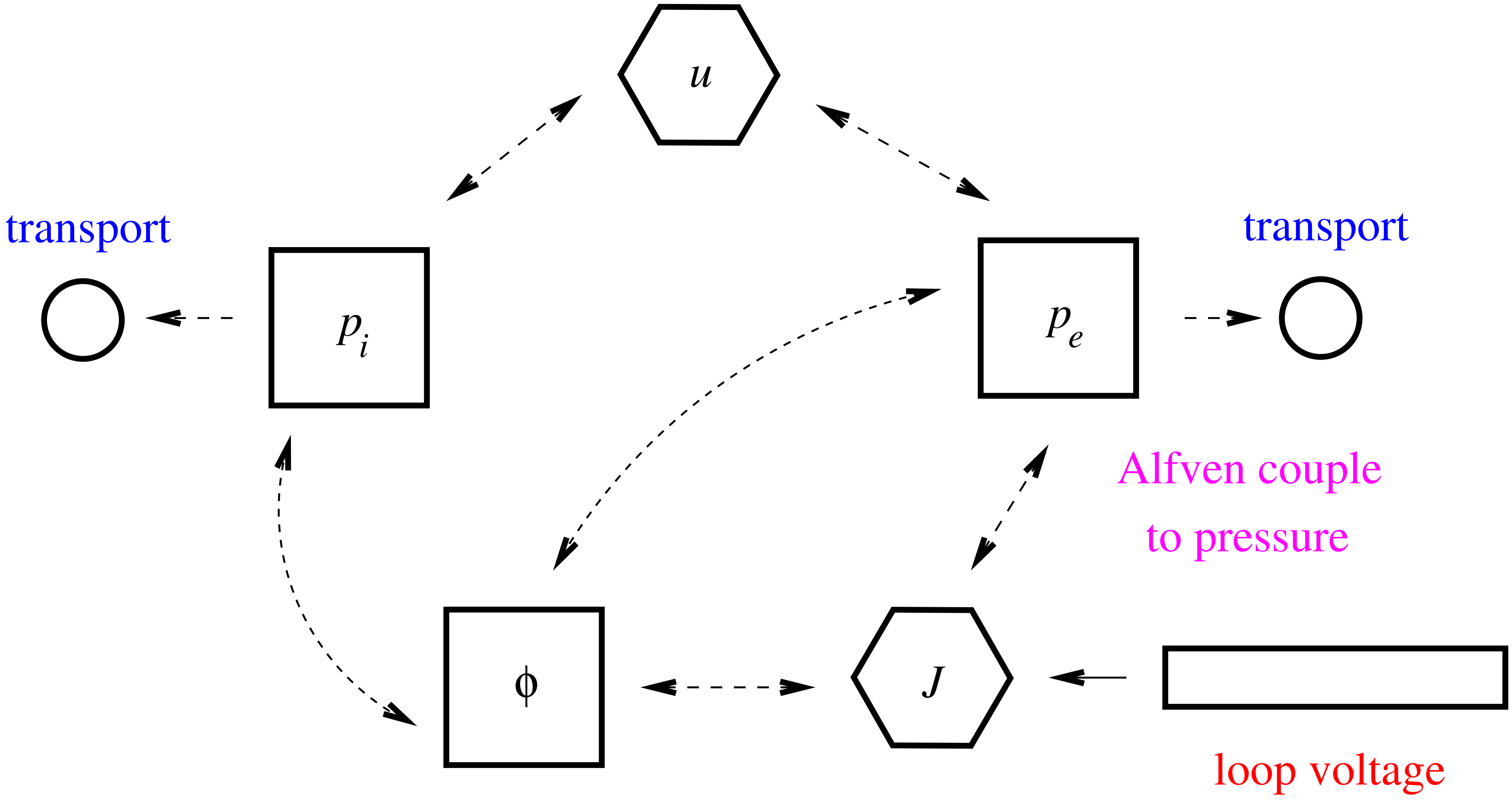
turbulence moderately weakened but not suppressed

toroidal compression --> energy loss channel to pressure, turbulence

entire system in self regulated statistical equilibrium (turb, flows, mag eq)

(B Scott Phys Lett A 2003, New J Phys 2005)

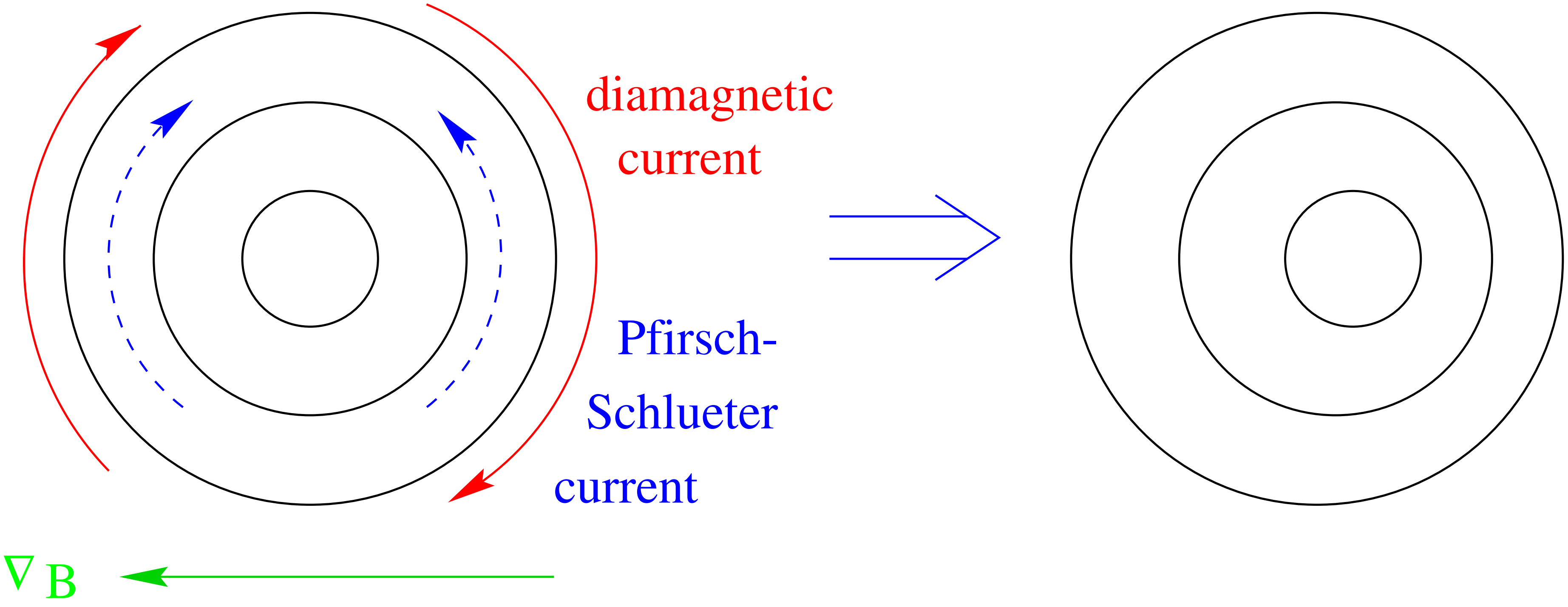
Energy Transfer: equilibrium



(B Scott Phys Plasmas 2003)

Incorporation of Magnetic Equilibrium

toroidal equilibration current <--> Shafranov shift



P-S current equilibrates toroidal diamagnetic compression

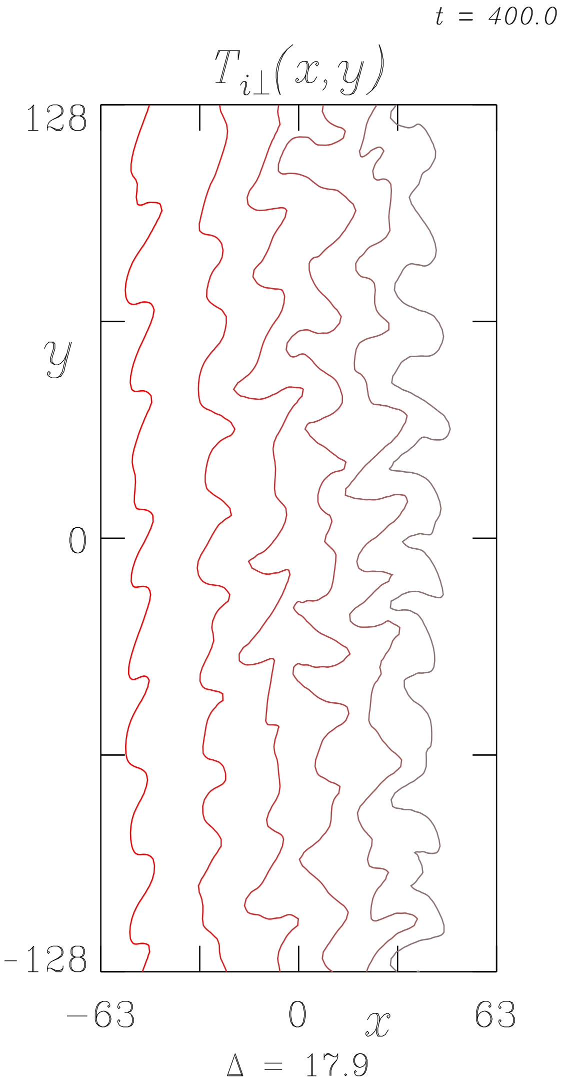
Ampere’s Law --> ‘‘Pfirsch-Schlueter magnetic field’’ --> toroidal shift

current stays in moment variables, magnetic field in coordinate metric

Global Electromagnetic Gyrofluid (GEM):

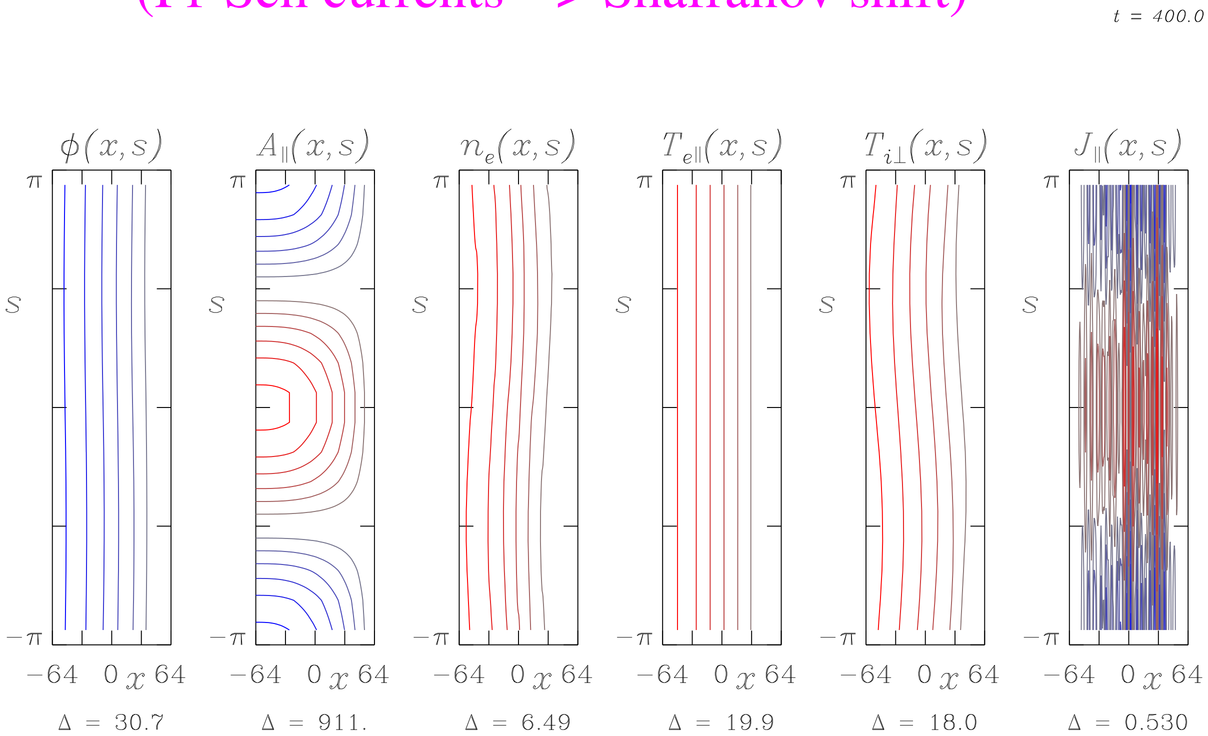
turbulence and transport

(profile + disturbances)



self consistent magn eq, geometry

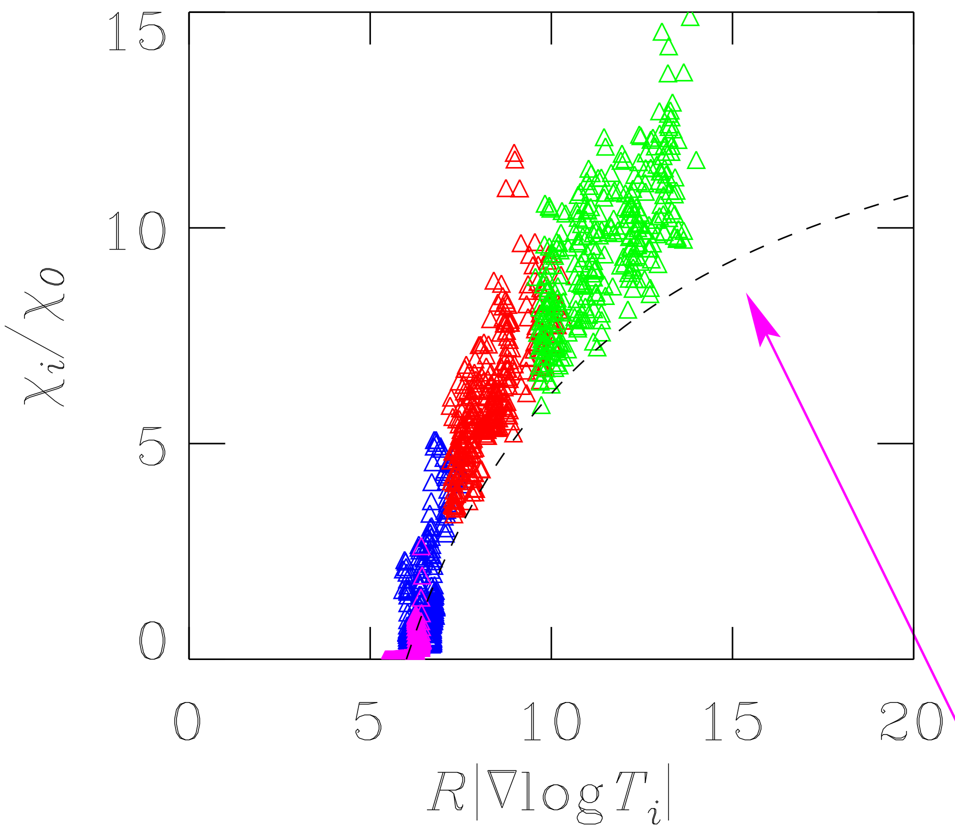
(Pf-Sch currents --> Shafranov shift)



Cyclone Base Case (D-III-D 81499)

correct mass ratio, gyroradius

Global Result, adiabatic electrons



assumes electrons in
parallel force balance

global boundary conds
relaxing profiles

turbulence is
temporally local

gradient, transport
measured in outer
3rd quarter of domain

Cyclone Base Case (D-III-D 81499)

compares well to gyrokinetic result

(A Dimits et al Phys Plasmas 2000)

Gyrofluid Field Theory

–-> inhomogeneous equations, needed for edge + core computations

$$L = \sum_{\mathrm{sp}} \left[ne(\mathbf{A}/c + mv_{\|}\mathbf{b}) \bullet \mathbf{u} - nH \right] - B_{\perp}^{2}/8\pi$$

$$H = e\, G\,\phi - MV_{E}^{2}/2 + p_{\perp} + p_{\|}/2$$

vary displacement field –-> equation of motion (drift velocity **u**)

vary field potentials –-> polarisation and induction (ϕ, $A_{\|}$)

constrained variation –-> continuity equations (n, $T_{\|}$, $T_{\perp}$)

Noether Theorem: conservation, self consistency guaranteed

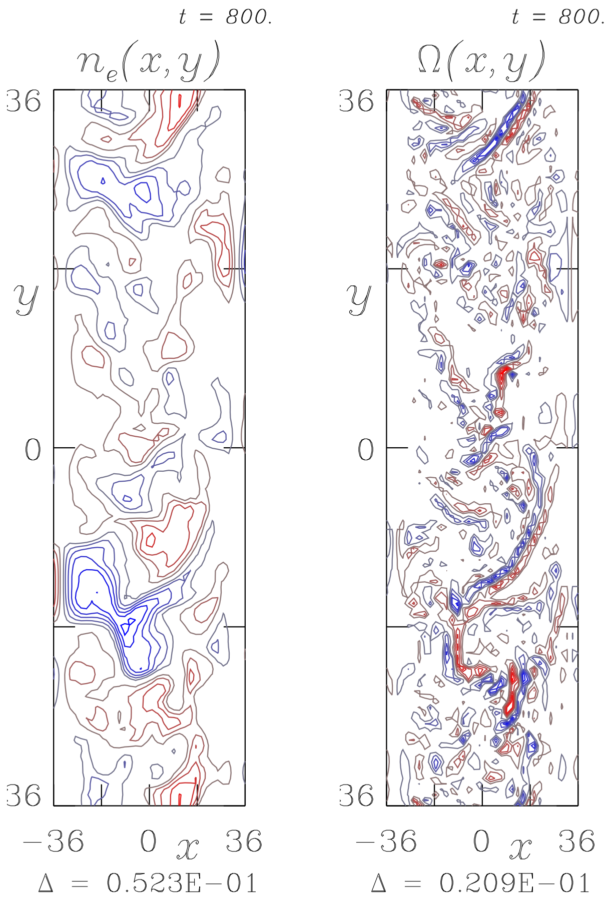
arbitrary disturbance amplitude, parameter variation

required for proper capture of ‘‘pedestal’’ phenomena

(D Strintzi B Scott Phys Plasmas 2004)

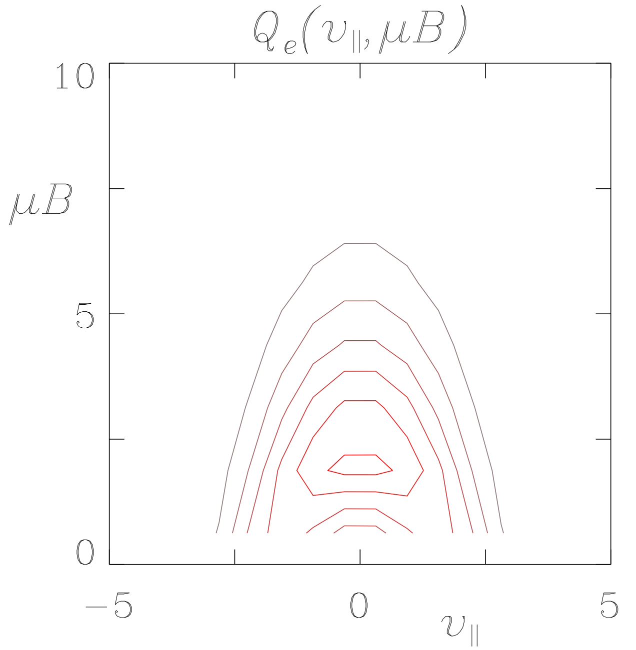
delta-f Gyrokinetic Edge Turbulence (dFEFI):

turbulence morphology
(much like gyrofluid)



(B Scott IAEA Fusion Energy Conf 2004)

velocity space dependence of
electron particle flux



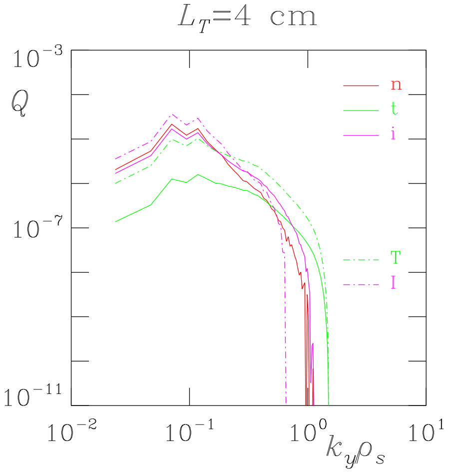
standard L-mode case (AUG)

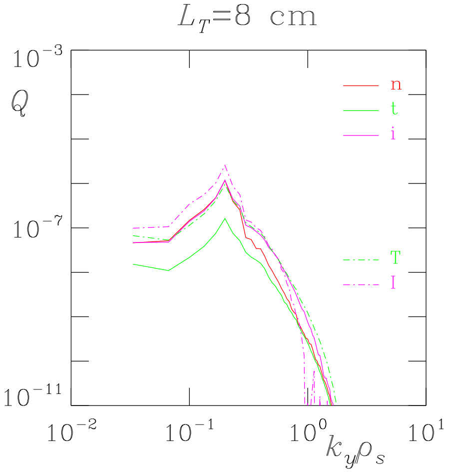
collisions (incl energy scattering)

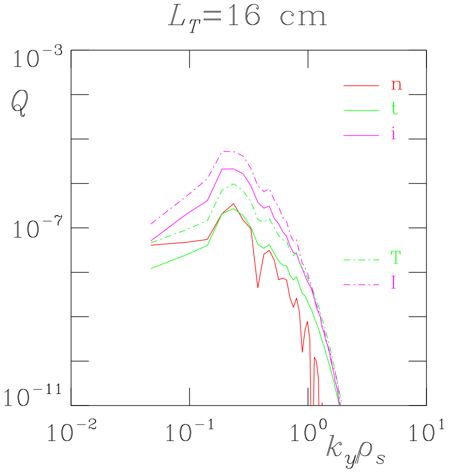
edge geometry (incl slab modes)

delta-f Gyrokinetic Edge Turbulence (dFEFI):

transport spectrum: edge-to-core transition







spectrum sharpens towards core (--> ‘‘weak turbulence’’)

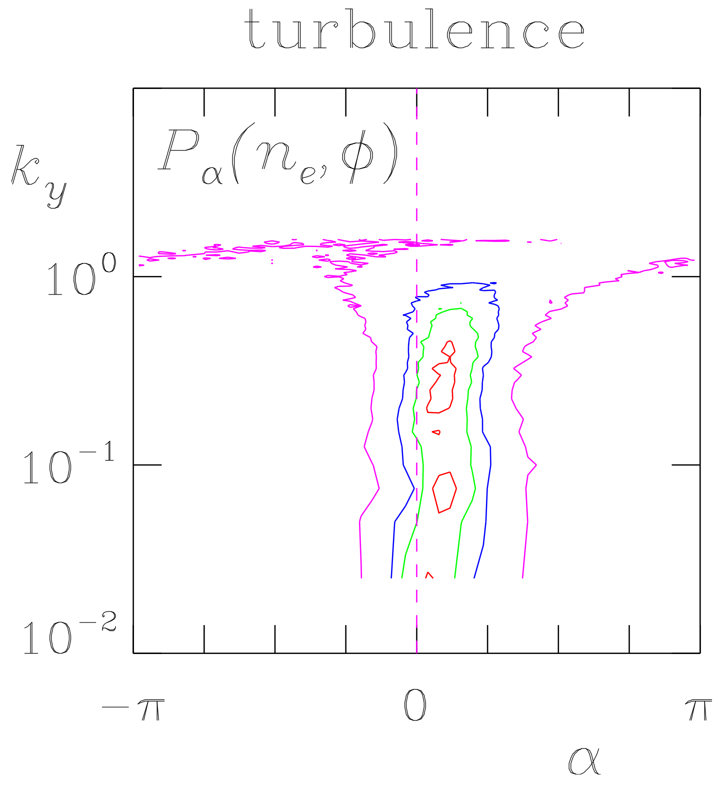
vorticity broader in edge (--> gyroradius even more important there)

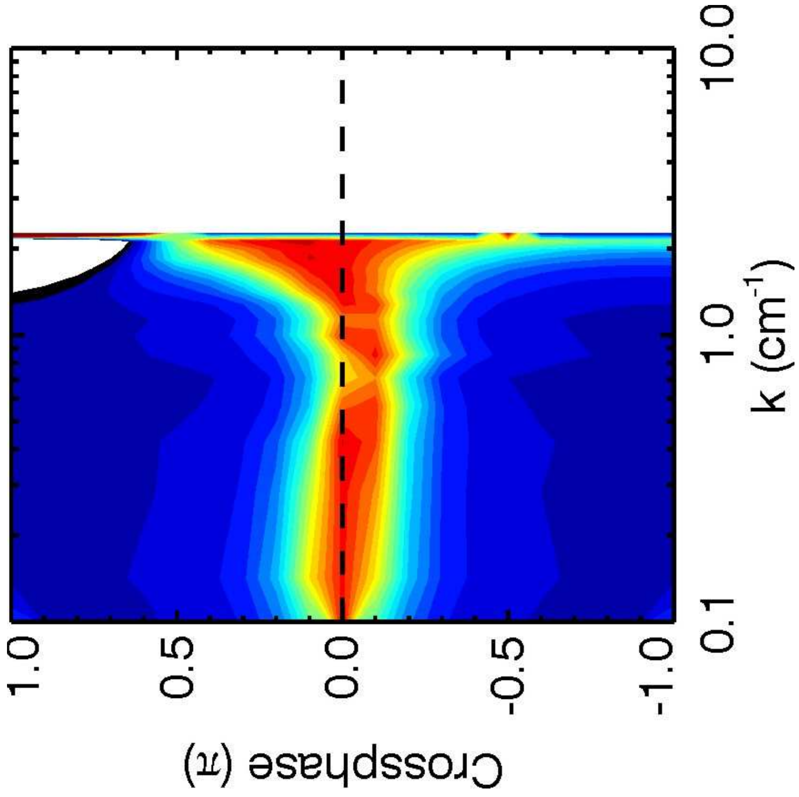
phenomenology same as gyrofluid model

kinetic details mostly in electron anisotropy

(B Scott IAEA Tech Meeting Instabilities, Trieste, 2005)

Comparison -- Fluctuation Statistics





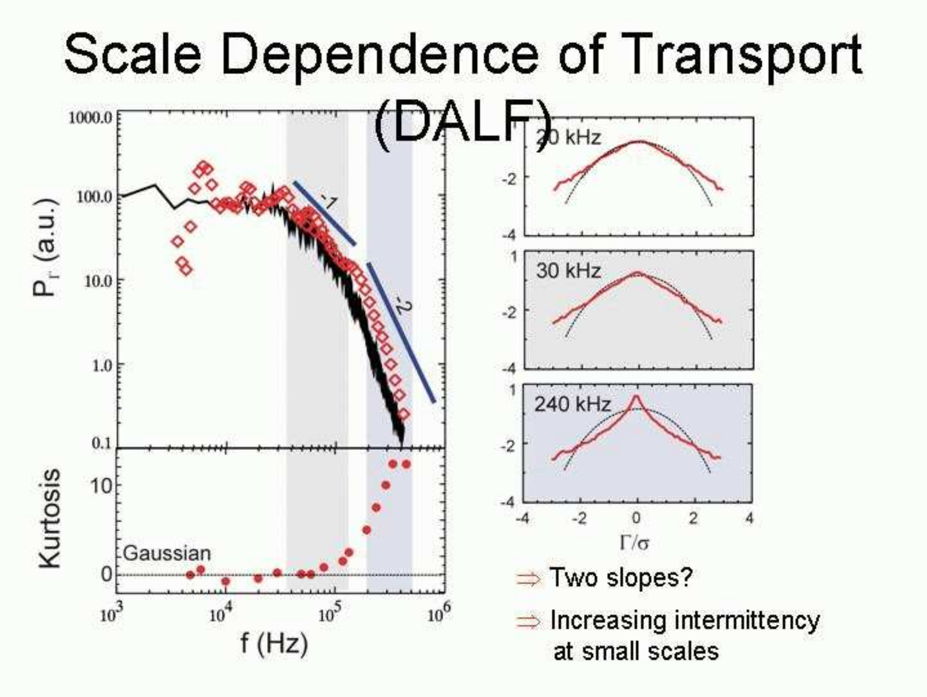
probability distribution of cross phase for each Fourier mode

unified spectrum, phase shifts between 0 and $\pi/4$, in code and TJK experiment

basic signature of drift wave mode structure (parallel current dynamics)

(B Scott Plasma Phys Contr Fusion 2003) (U Stroth F Greiner C Lechte et al Phys Plasmas 2004)

Comparison -- Fluctuation Statistics

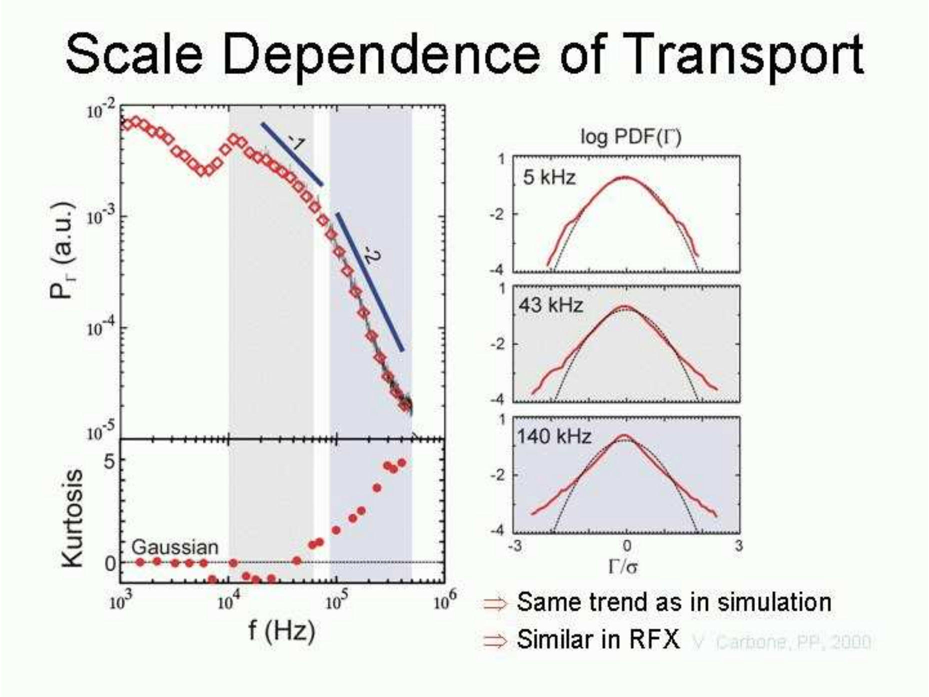


Scale Dependence of Transport

(DALF)

⇒ Two slopes?

⇒ Increasing intermittency at small scales



Scale Dependence of Transport

⇒ Same trend as in simulation

⇒ Similar in RFX V. Carbone, PP, 2000

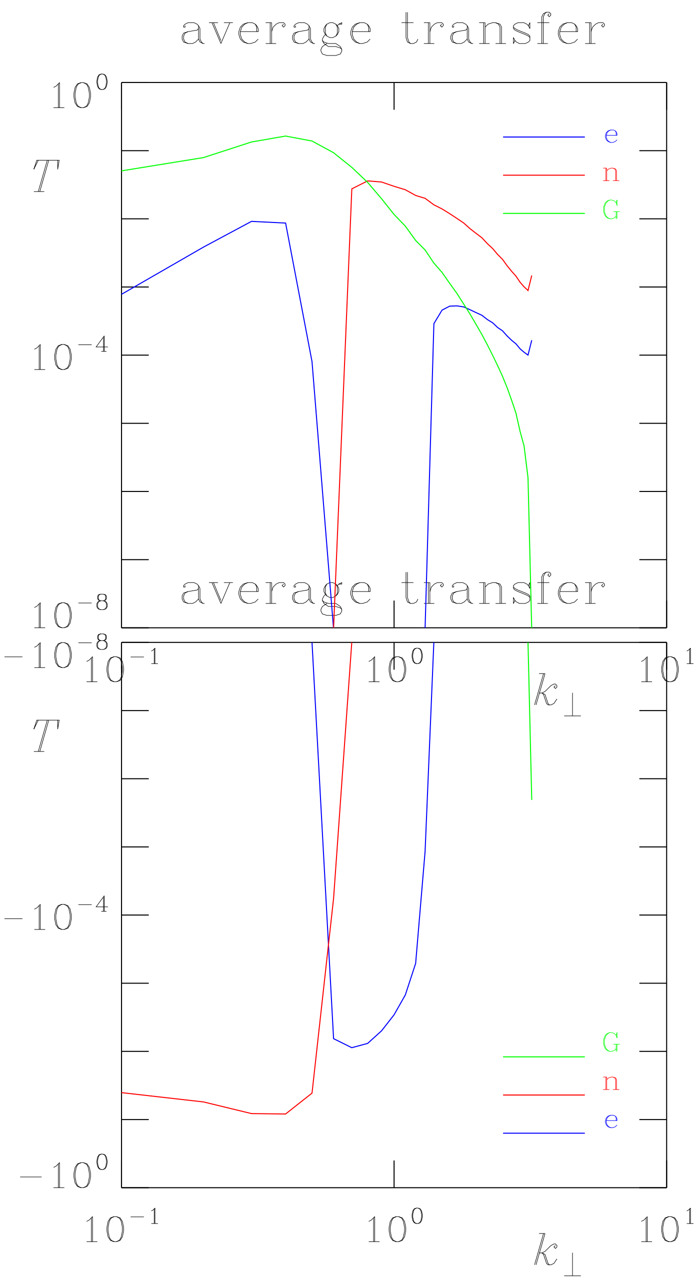
wavelet analysis of fluctuation induced transport in code and TJK experiment

both results show same phenomenology: regime break in spectrum

evidence of nonlinear cascade overcoming drive?

(N Mahdizadeh et al Phys Plasmas 2004)

Nonlinear Free Energy Cascade



direct cascade

--> nonlinear drive at small scales

==> passive scalar regime

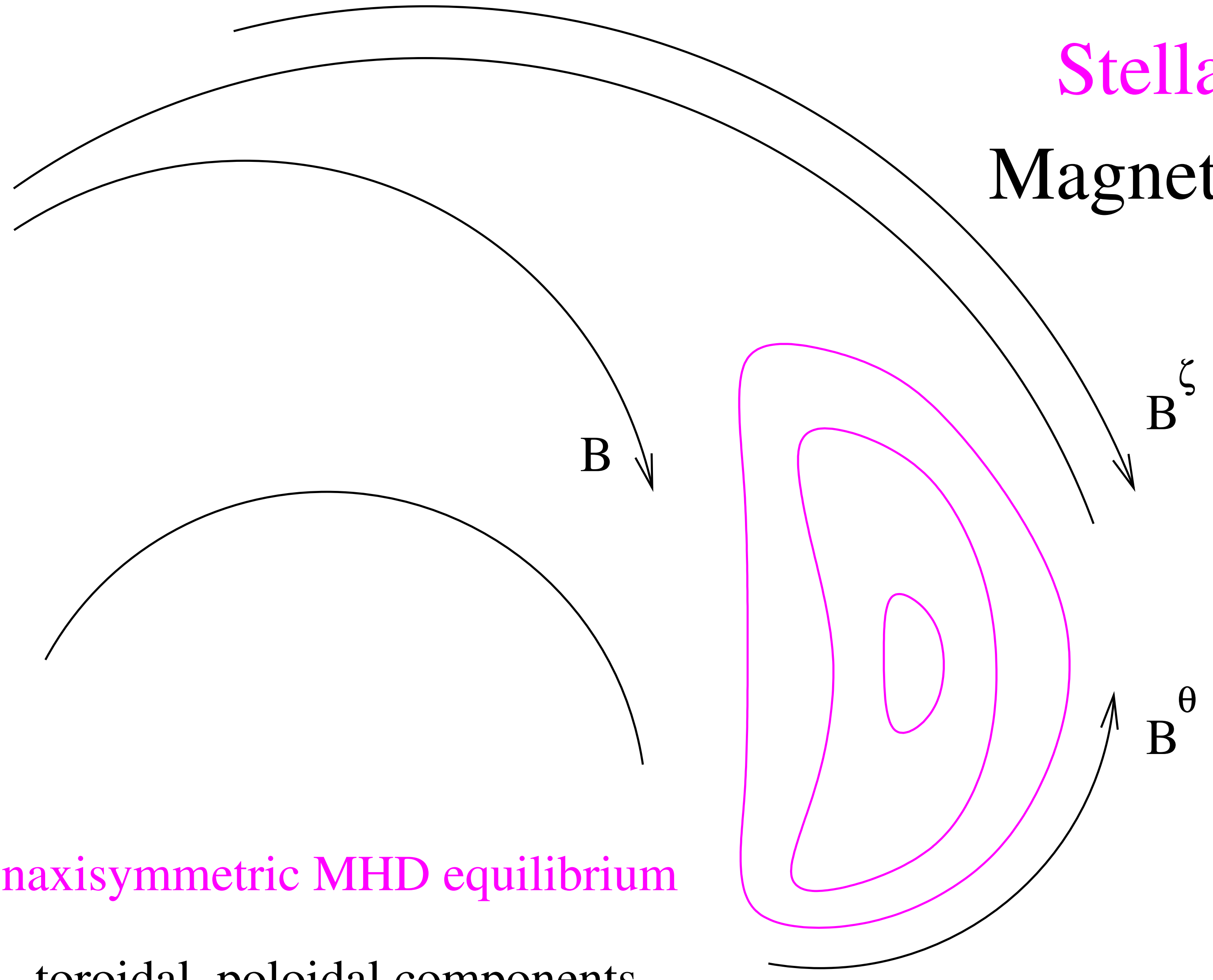
frequency/scale correlation

matches with frequency break

evidence for onset of

passive scalar regime

Stellarator
Magnetic Field



surface shape
depends on
toroidal position

strong
eddy deformation

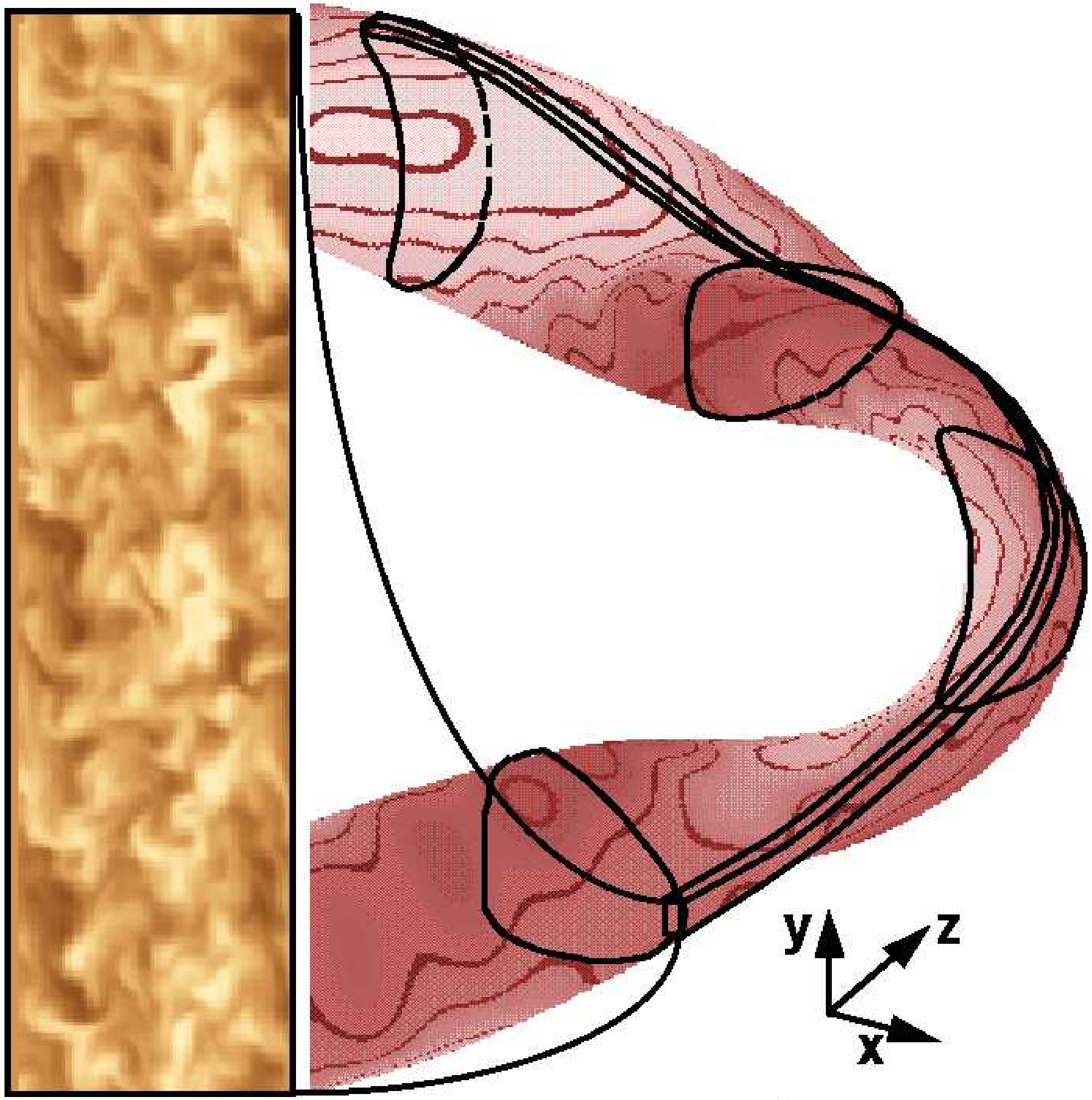
nonaxisymmetric MHD equilibrium

toroidal, poloidal components

mainly toroidal

ratio of components --> pitch parameter “q” B^ζ / B^θ

Edge Turbulence Computation in Stellarator Geometry



field aligned coordinates
in a 3D equilibrium

same methods
as in tokamak

formally, metric
depends also on y

full flux surface
is necessary

similar mode structure
(local shear --> currents)

(A Kendl B Scott Phys Rev Lett 2003)

Themes for Stellarator Theory

apply methodology from tokamak global computation to stellarator equilibria

facilitated by use of covariant magnetic geometry

main problems: deformation, resolution, parallel structure

global gyrokinetic model automatically faces the neoclassical equilibrium

self consistency: do the MHD equilibrium inside the turbulence model

new physics themes:

✷ global electromagnetic computation

✷✷✷ stable reconnection and equilibration currents

incorporation of trapping effects in fluid codes (may be hopeless)

ongoing integration of all the main efforts (forced by numerical issues!)

✷✷ one should expect surprises affecting design of high performance devices