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Physics of Zonal Flows

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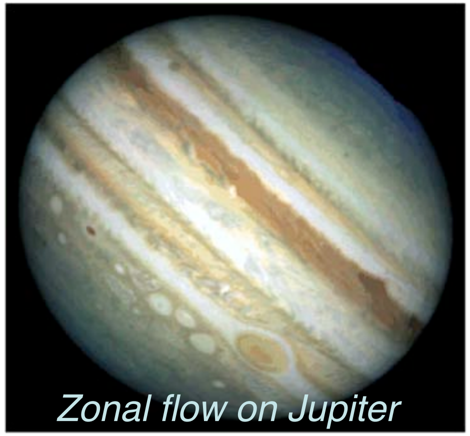
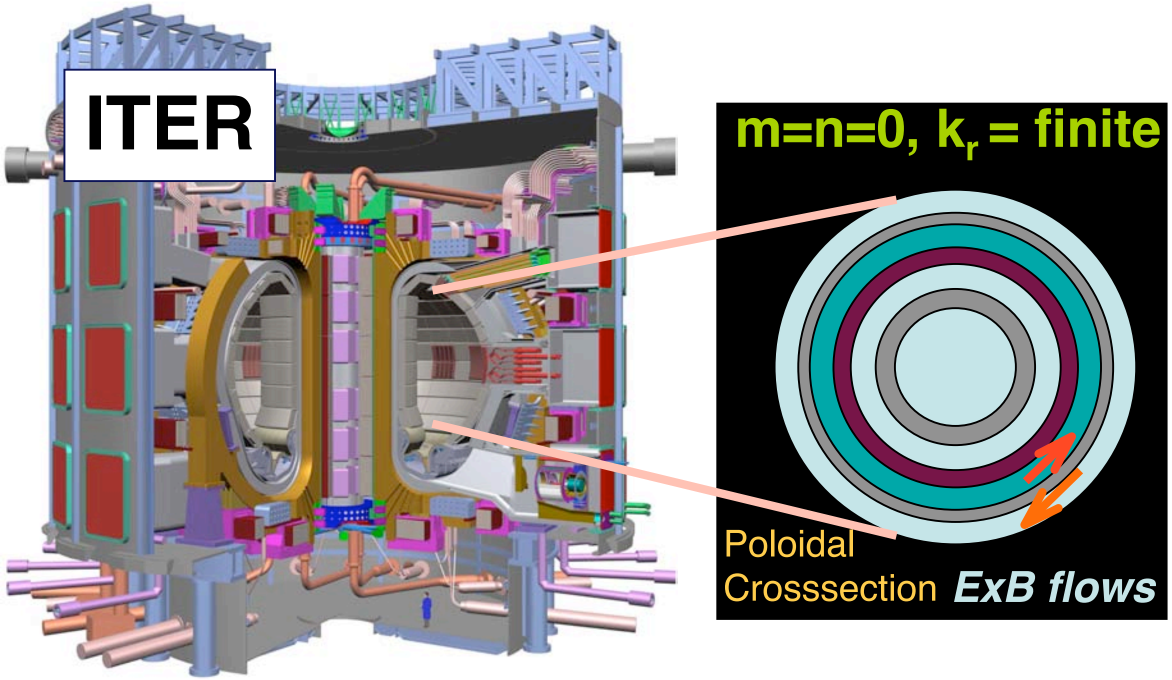
This overview is dedicated to the memory of
Professor Marshall N. Rosenbluth.

Contents

What is a zonal flow?



Zonal flow on Jupiter



Drift Waves

↓

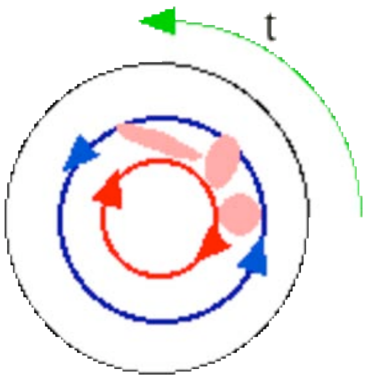
Drift waves
+
Zonal flows

Paradigm Change

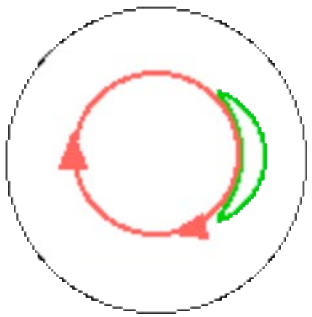
ZFs are "mode", but:

1. Turbulence driven
2. No linear instability
3. No direct radial transport

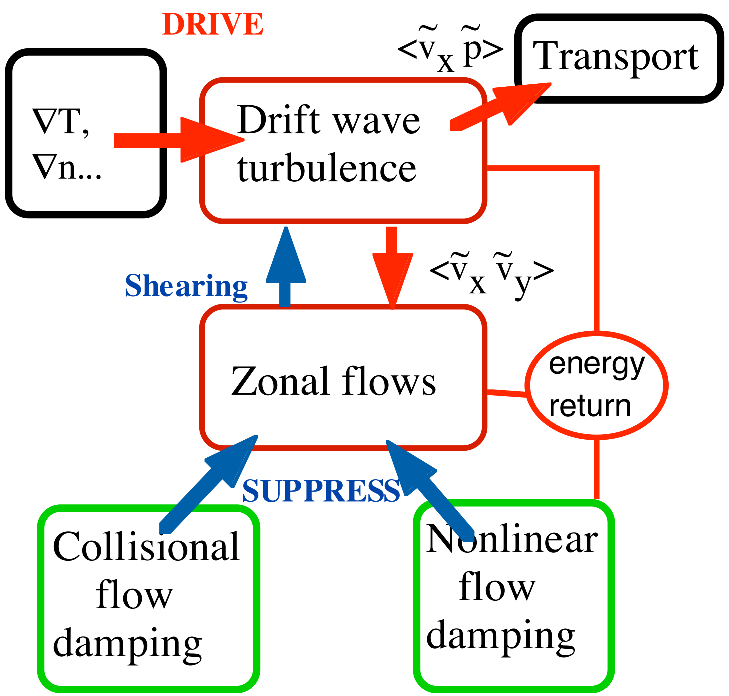
Basic Physics of a zonal flow

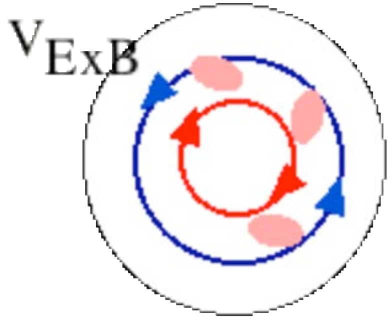


Suppression of DW by shearing



Damping by collisions





Generation By vortex tilting

Tertiary instability

Self-regulation: Co-existence of ZF and DW

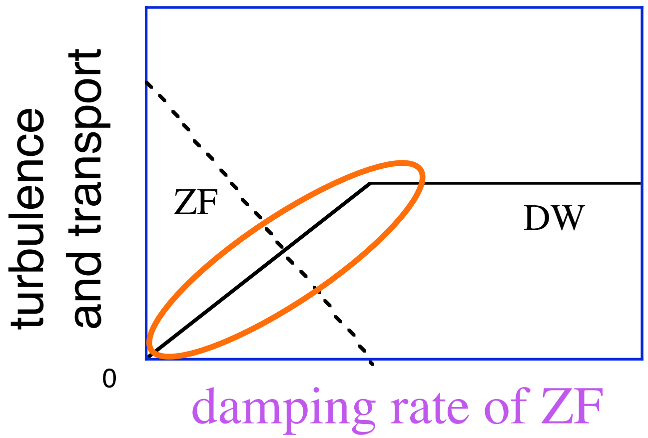
$$\begin{cases} \frac{\partial}{\partial t} W_d = \gamma[\nabla p_0, \cdots] W_d - \alpha W_d W_{ZF} \\ \frac{\partial}{\partial t} W_{ZF} = \gamma_{damp}[\cdots] W_{ZF} + \alpha W_d W_{ZF} \end{cases}$$

W_d : drift wave energy

W_{ZF} : zonal flow energy

(ν_{ii}, q, ε geometry) (+ rf, etc.)

$$W_d \sim \frac{\gamma_{damp}}{\alpha}$$



Transport coefficient

$$\chi_i \sim \frac{\gamma_{damp}}{\omega_{eff}} \chi_{gB} \Rightarrow \chi_i = \mathcal{R} \chi_{gB}$$

"$\mathcal{R}$ – Factor"

Confinement enhancement
Includes other reduction effects
(i.e., cross phase)

Why ZFs are Important for Fusion ?

Issues in fusion

$\tau_E = H \tau_{E,\mathrm{L-scaling}}$

"Intrinsic" H-factor (wo barrier)

$H \propto \mathcal{R}^{-0.6}$

Realizability of Ignition

$\$ \propto \mathcal{R}^{-0.8}$

$\$ \propto H^{-1.3}$

1. Self-regulation

   $\chi = \mathcal{R} \chi_{gB}$

2. Shift for onset of large transport → Operation of ITER near marginality

3. Identify transport control knob → Flow damping ? → P_{LH}- threshold

→ Intermittent flux, e.g., ELMs → Peak heat load

4. Meso-scales and zonal field → Impacts on RWM and NTM → β-limit → Steady state

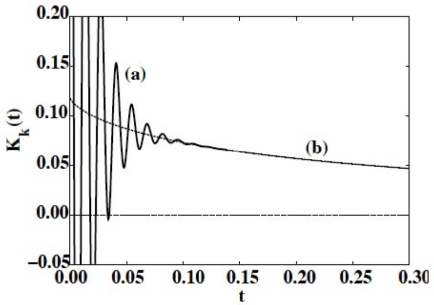
Assessment I "*What we understood*"

ZFs are UNIVERSAL

	Scales	Transport	Role of ZF	This IAEA Conference
ITG	ρ_i c_s/a	core χ_i, χ_ϕ, D	Very important	Falchetto (TH/1-3Rd), Hahm (TH/1-4), Hallatschek (TH/P6-3), Hamaguchi (TH/8-3Ra), Miyato (TH/8-5Ra), Waltz (TH/8-2), Watanabe (TH/8-3Rb)
TEM/TIM	ρ_i c_s/a	core $\chi_i, \chi_e, \chi_\phi, D$	Very important	Lin (TH/8-4), Sarazin (TH/P6-7), Terry (TH/P6-9)
ETG	ρ_e $v_{\mathrm{Th},e}/a$	core χ_e, χ_J	On-going	Holland (TH/P6-5), Horton (TH/P3-5), Idomura (TH/8-1), Li (TH/8-5Ra), Lin (TH/8-4)
Resistive ballooning/ interchange	$\Delta_{\mathrm{resis.\ layer}}$	edge, sol, helical edge	Important	Benkadda(TH/1-3Rb), del-Castillo-Negrette (TH/1-2)
Drift Alfven waves at edge	$\sim\rho_i$	edge, sol	Very important	Scott(TH/7-1), Shurygin(TH/P6-8)

Linear Damping of Zonal Flows

Neoclassical process

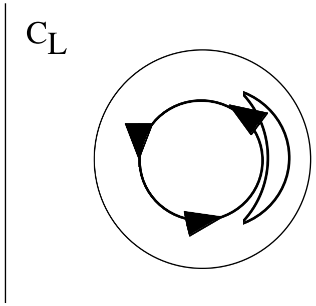


Rosenbluth-Hinton undamped flow - survives for $\tau > \tau_{\text{transport}}$

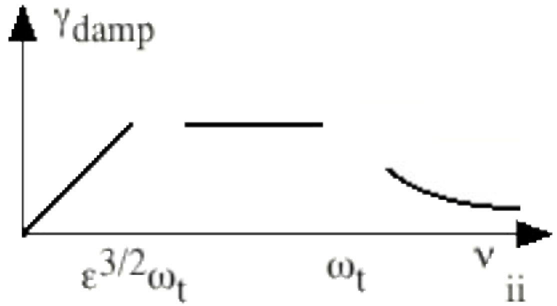
$$\frac{\phi_{\boldsymbol{q}}(t)}{\phi_{\boldsymbol{q}}(0)} = \frac{1}{1 + 1.6\varepsilon^{-1/2} q^2}$$

Role of bananas

Frictional damping



Banana-plateau transition



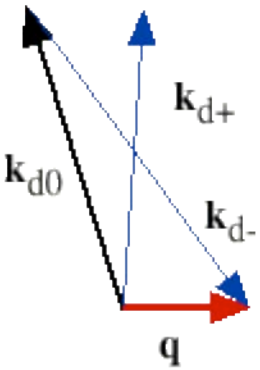
$\gamma_{\text{damp}} \simeq \nu_{ii}/\varepsilon \Rightarrow \chi_i \propto \nu_{ii}$ even in "collisionless" regime

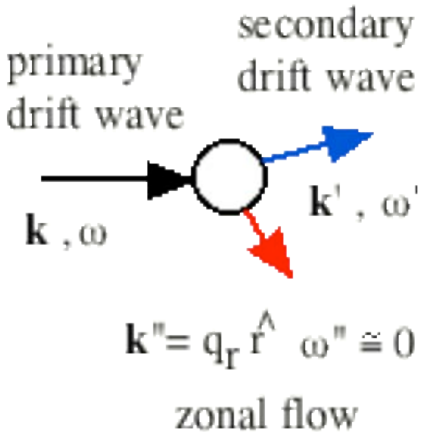
Screening effect if $q_r \rho_p \sim O(1)$

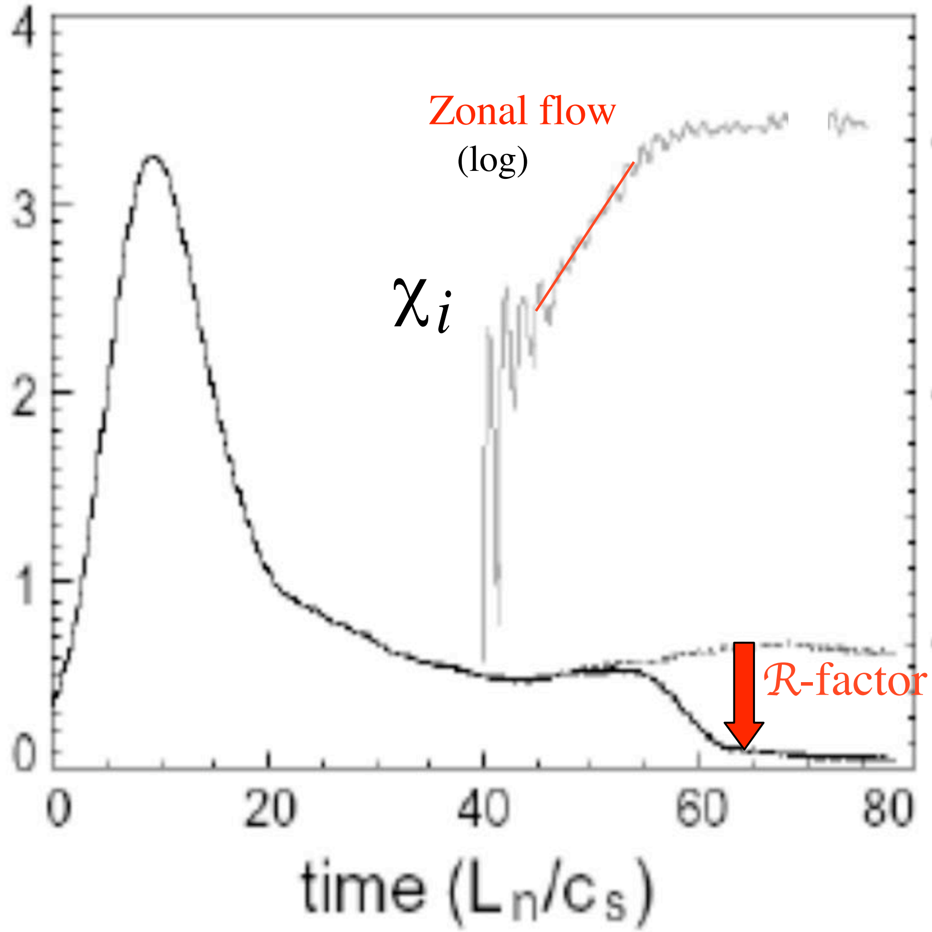
Growth Mechanism

ZFs by

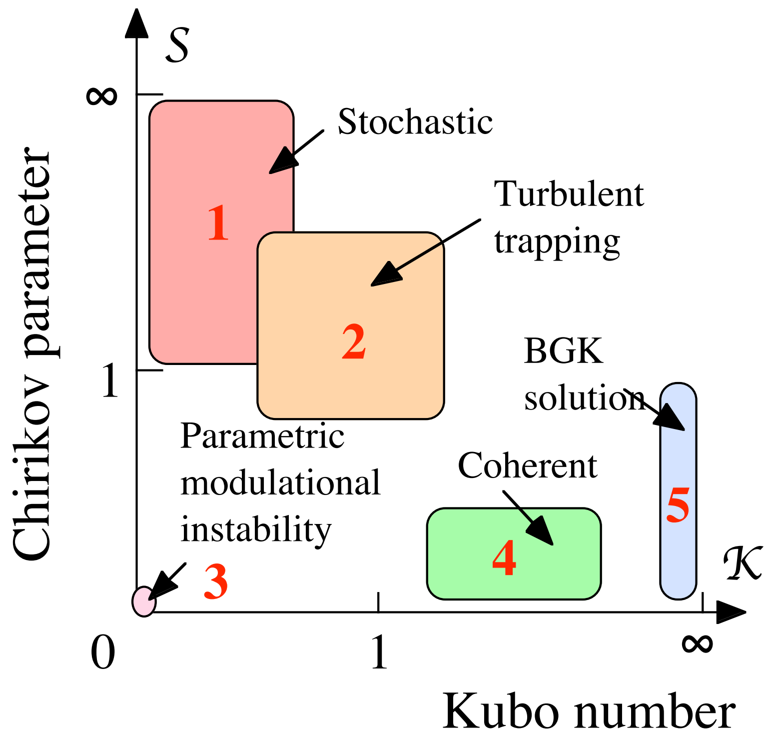
modulational instability

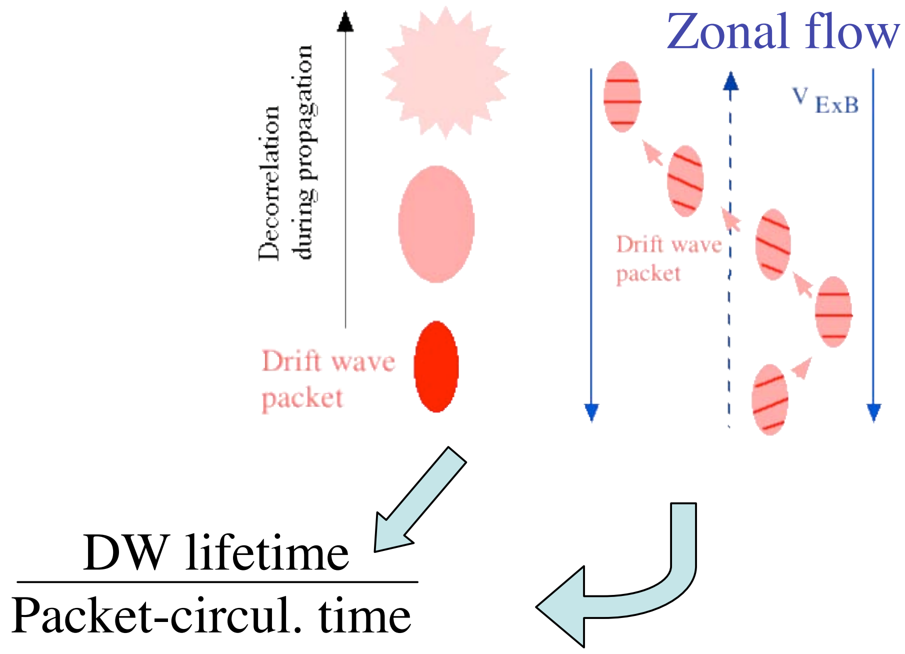






Numerical experiment indicates instability of finite amplitude gas of drift waves to zonal shears





Regime	Keywords	References
1	k_r Diffusion	Zakharov, PHD, Itoh, Kim, Krommes
2	Turbulent trapping	Balescu
3	Single wave modulation	Sagdeev, Hasegawa, Chen, Zonca
4	Reductive perturbation	Taniuti, Weiland, Champeaux
5	DW trapping in ZF	Kaw

Close Relationship: DW + ZF and Vlasov Plasma

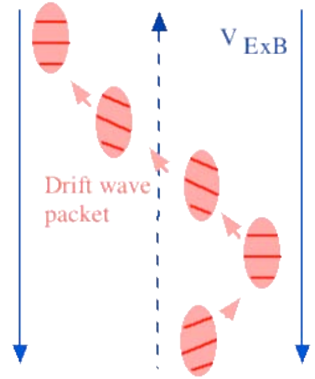
(i) DW + ZF :

$$\frac{dx}{dt} = v_{gx}(\boldsymbol{k}) \qquad \frac{dk_x}{dt} = -\frac{\partial}{\partial x}\left(k_y \tilde{V}_Z\right)$$

$$\frac{dy}{dt} = v_{gy}(\boldsymbol{k}) \qquad \frac{dk_y}{dt} = 0$$

⇒ 'Ray' Trapping

$\Omega = q_x v_{gx}$



$$\frac{\partial}{\partial t}\tilde{V}_Z + \gamma_{\text{damp}}\tilde{V}_Z = -\frac{\partial}{\partial x}\left\langle \tilde{V}_x \tilde{V}_y \right\rangle$$

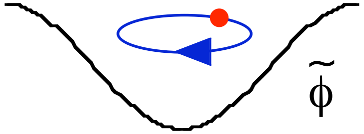
$$\frac{\partial}{\partial t}N + v_{gx}N - \frac{\partial}{\partial x}\left(k_y V_Z\right)\frac{\partial N}{\partial k_x} = \gamma_k N + C_k(N)$$

(ii) 1D Vlasov Plasma :

$$\frac{dx}{dt} = v \qquad \frac{dv}{dt} = \frac{e}{m}\tilde{E}$$

⇒ Particle Trapping

$\omega = k\,v$



$$\frac{\partial \tilde{E}}{\partial x} = 4\pi n_0 e \int dv \; f$$

$$\frac{\partial f}{\partial t} + v\frac{d f}{d x} + \frac{e}{m}\tilde{E}\frac{\partial f}{\partial v} = C(f)$$

Note: Conservation energy between ZF and DW

RPA equations

DW $$\frac{\partial}{\partial t}\left|\tilde{V}_{\mathrm{DW}}\right|^2+\sum_{\boldsymbol{k}}\left(\gamma_{\mathrm{L},\boldsymbol{k}}+C_{\boldsymbol{k}}(N)\right)\left|\tilde{V}_{\mathrm{DW},\boldsymbol{k}}\right|^2=\frac{2}{B^2}\sum_{q_x}\int d^2k\,\frac{q_x^2k_\theta^2k_x\left|V_{\mathrm{ZF},q}\right|^2}{\left(1+k_\perp^2\rho_s^2\right)^2}R(k,q_x)\frac{\partial\langle N\rangle}{\partial k_x}$$

ZF $$\left(\frac{\partial}{\partial t}+\gamma_{\mathrm{damp}}\right)\left|V_{\mathrm{ZF}}\right|^2=-\frac{2}{B^2}\sum_{q_x}\int d^2k\,\frac{q_x^2k_\theta^2k_x\left|V_{\mathrm{ZF},q}\right|^2}{\left(1+k_\perp^2\rho_s^2\right)^2}R(k,q_x)\frac{\partial\langle N\rangle}{\partial k_x}$$

Coherent equations

DW $$\frac{\mathrm{d}P^2}{\mathrm{d}\tau}=P^2-2\,P\,Z\,S\cos(\Psi)$$ (S: beat wave)

ZF $$\frac{\mathrm{d}Z^2}{\mathrm{d}\tau}=-\frac{\gamma_{\mathrm{damp}}}{\gamma_L}Z^2+2\,P\,Z\,S\cos(\Psi)$$

$$\left.\frac{\partial}{\partial t}W_{\mathrm{d}}\right|_{\text{by ZF}}=-\left.\frac{\partial}{\partial t}W_{\mathrm{ZF}}\right|_{\text{by DW}}$$

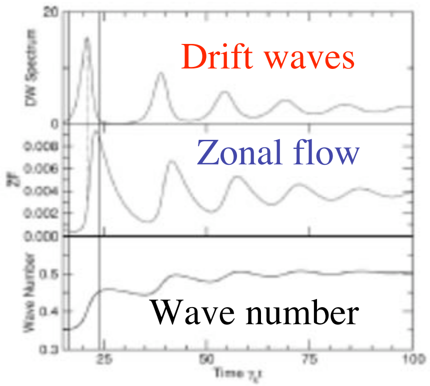
Self-regulating System Dynamics

Simplified Predator-Prey model

DW $$\frac{\partial}{\partial t}\langle N\rangle = \gamma_L \langle N\rangle - \gamma_2 \langle N\rangle^2 - \alpha \langle U^2\rangle\langle N\rangle$$

ZF $$\frac{\partial}{\partial t}\langle U^2\rangle = -\gamma_{damp}\langle U^2\rangle + \alpha\langle U^2\rangle\langle N\rangle$$

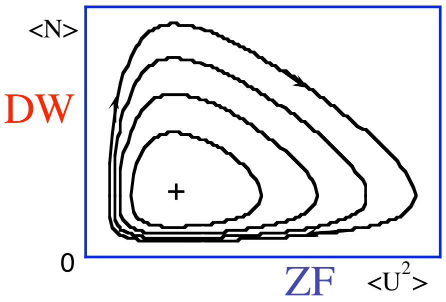
Stable fixed point

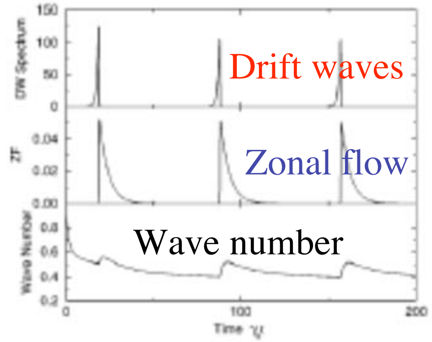


Cyclic bursts

$$\gamma_2 \rightarrow 0$$

(No self damping)



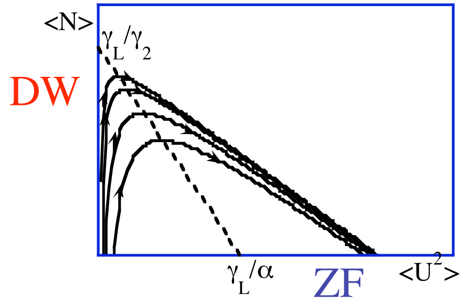


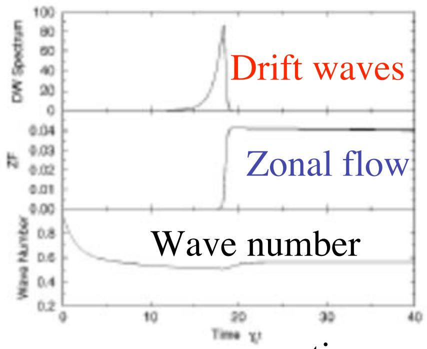
Single burst

(Dimits shift)

$$\gamma_{damp} \rightarrow 0$$

(No ZF friction)



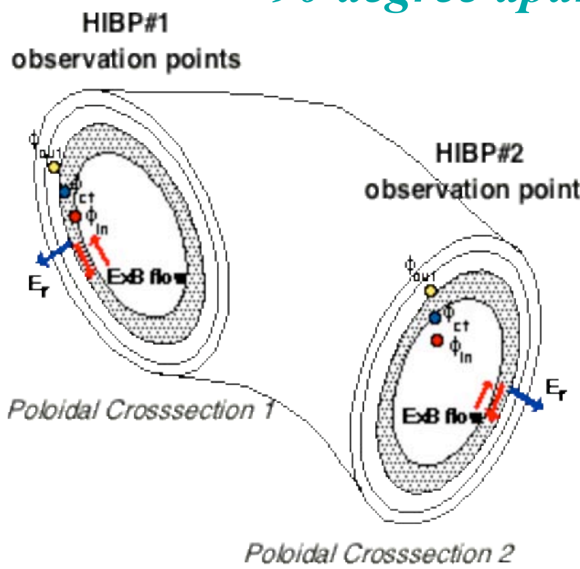


II Current research: "*What we think we understand*"

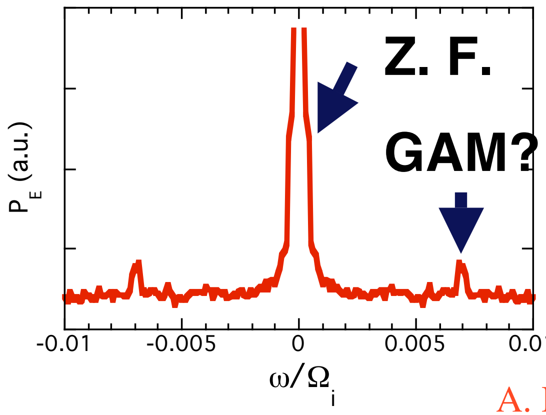
Zonal flows really do exist

CHS Dual HIBP System

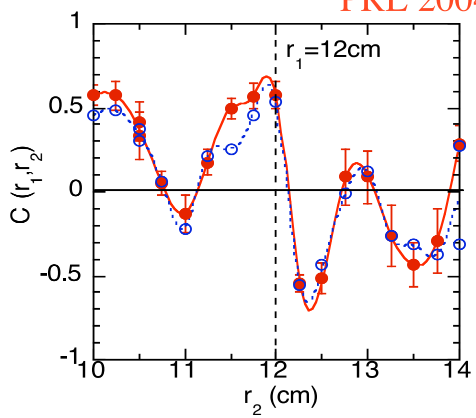
90 degree apart



$E_r(r,t)$



A. Fujisawa et al.,
PRL 2004 in press



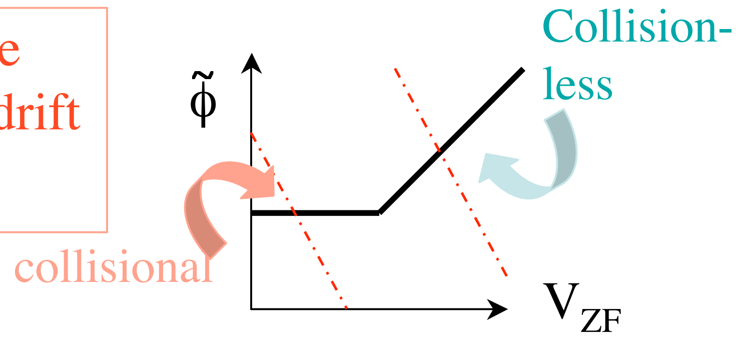
Radial distance

$E_r(r,t)$ { High correlation on magnetic surface,
Slowly evolving in time,
Rapidly changing in radius.

Candidates for Collisionless Saturation

$$\chi = \frac{\gamma_{nl}^{collisionless}}{\omega_{eff}} \chi_{gB}$$

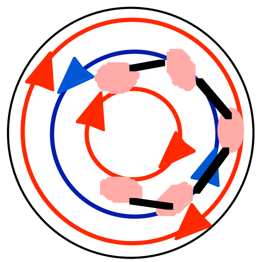
Partial recovery of the dependence of χ_i on drift wave growth rate



Trapping

Plateau in k-space N(k)

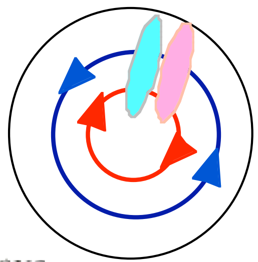
$$\sqrt{V_{ZF}} \propto \omega_{bounce} \simeq \Delta\omega, \gamma_L$$



Tertiary Instability

Returns energy to drift waves

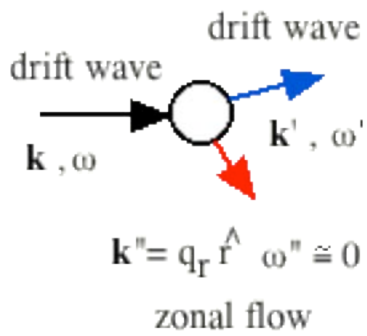
$$V_{ZF} \sim \left| \hat{\phi} + \frac{T_e}{2T_i} \hat{T} \right| q_r$$



Higher Order Kinetics

Analogous to interaction at beat wave resonance

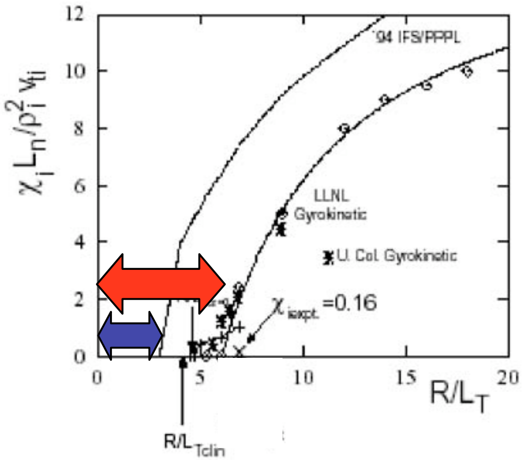
$$V_{ZF} \sim \Delta\omega\, k_\theta^{-1}$$



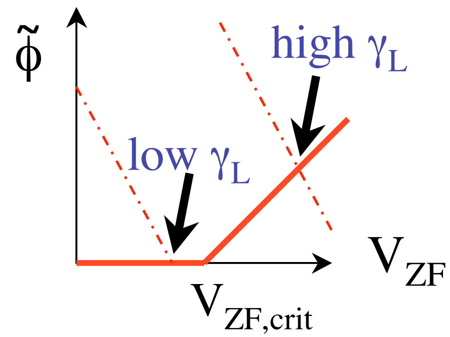
"Near" Marginality

Shift exists

ITER plasma near marginality ⇨
Importance of ZF



Where the energy goes



What limits the "nearly marginal" region:
(Dimits shift)

Mechanisms: Trapping, Tertiary, Higher order nonlinearity,….

An example: $\gamma_{L,\,crit} \sim q_r^2 \bar{k_\theta}^2 \alpha$

(Higher-order nonlinearity model)

Route to the shift is understood, but "the number" is not yet obtained.

Electromagnetic Effect

Subject	Mechanism for ZF growth	Implications for fusion
ZF generation by finite-β drift waves	Modulational instability of a drift Alfven wave	Transport at high-β, L-H transition
Zonal magnetic field generation	Random refraction of Alfven wave turbulence	Possible Z-field induced transition, NTM,…

$$\langle \tilde{v}_r \tilde{v}_\theta \rangle \Rightarrow \langle \tilde{v}_r \tilde{v}_\theta \rangle - \langle \tilde{B}_r \tilde{B}_\theta \rangle$$

Selected structure
Zonal flow ⇨ Zonal field
β ⟶

$$\frac{\partial}{\partial t} B_\theta = -\eta_{ZF} \nabla^2 B_\theta$$

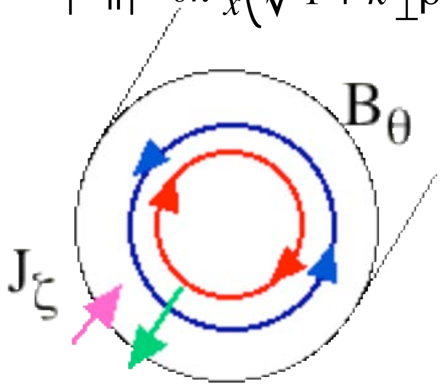
$$\eta_{ZF} = -\frac{4\pi c_s^2 \delta_e^2}{v_{th,e}\left(1 + q_r^2 \delta_e^2\right)} \sum_k \frac{\left(1 + k_\perp^2 \rho_s^2\right)^{5/2}}{2 + k_\perp^2 \rho_s^2} \frac{k_\perp^2 k_y^2}{|k_\parallel|} \frac{\partial^2}{\partial k_x^2} \left(\frac{\langle \omega_k N_k \rangle}{\sqrt{1 + k_\perp^2 \rho_s^2}} \right) f_0$$

⇨ Current layer generation

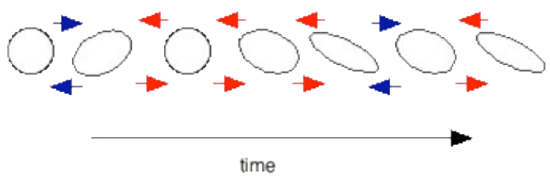
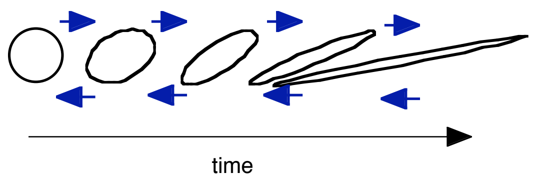
Corrugated magnetic shear,
Tertiary micro tearing mode ?

⇨ **Can seed Neoclassical Tearing Mode**

Localized current at separatrix of tearing mode, ……



Distinction between ZF and mean Field $<E_r>$

	Zonal Flows	Mean Field $<E_r>$
Time	can change on turbulence time scales	changes on transport time scales
Space	oscillating, complex pattern in radius $\sim 20\,\rho_i$	smoothly varying
Stretching Behavior ***k*** of waves	diffusive $\langle \delta k^2 \rangle \propto t$ 	ballistic $\langle \delta k^2 \rangle = t^2 k^2 V_E'^2$ 
Drive	Turbulence	equilibrium ∇p, orbit loss, external torque, turbulence, etc.

Interplay of Zonal Flow and Mean <E$_r$>

Now: Coupling between DW, ZF, mean <E$_r$> and mean profile

Previous: Coupling between DW, mean <E$_r$> and mean profile

Prediction of bifurcation, dither, hysteresis, …

Fluctuations

$$\frac{d\mathcal{E}}{dt} = \mathcal{E}\mathcal{N} - a_1\mathcal{E}^2 - a_2V^2\mathcal{E} - a_3V_{ZF}^2\mathcal{E}$$

Pressure gradient

$$\frac{d\mathcal{N}}{dt} = -c_1\mathcal{E}\mathcal{N} - c_2\mathcal{N} + Q$$

Zonal flow

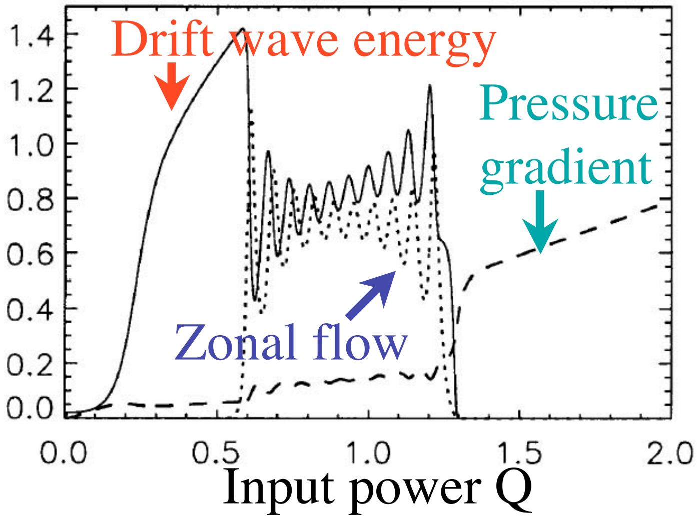
$$\frac{dV_{ZF}}{dt} = b_1\frac{V_{ZF}^2\mathcal{E}}{1+b_2V^2} - b_3V_{ZF}$$

Mean flow

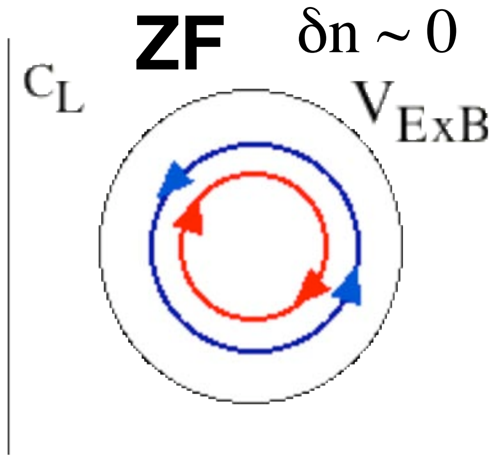
$$\frac{dV}{dt} = \left(V - d\mathcal{N}^2\right) + F_{nonlinear}$$

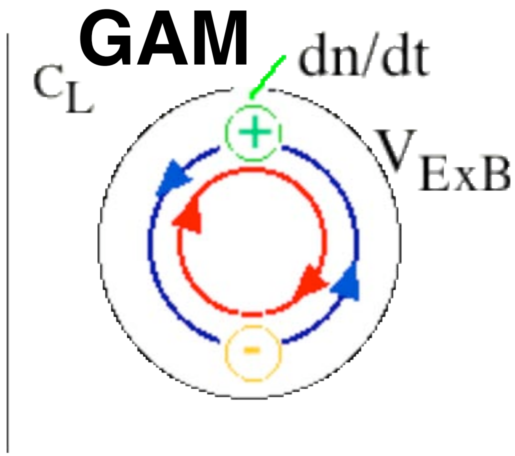
Nonlinearity; orbit loss, etc. in previous model

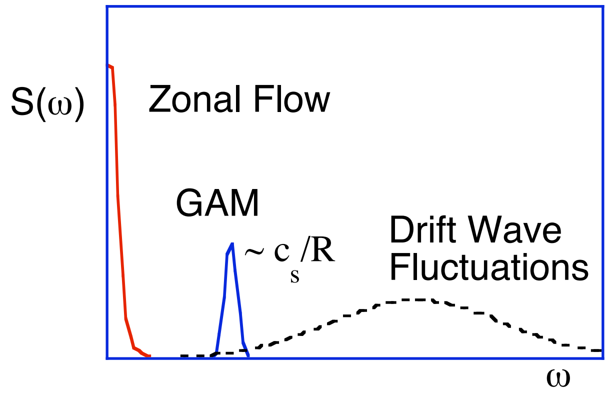
New coupling



Zonal Flow and GAM: two kinds of secondary flow





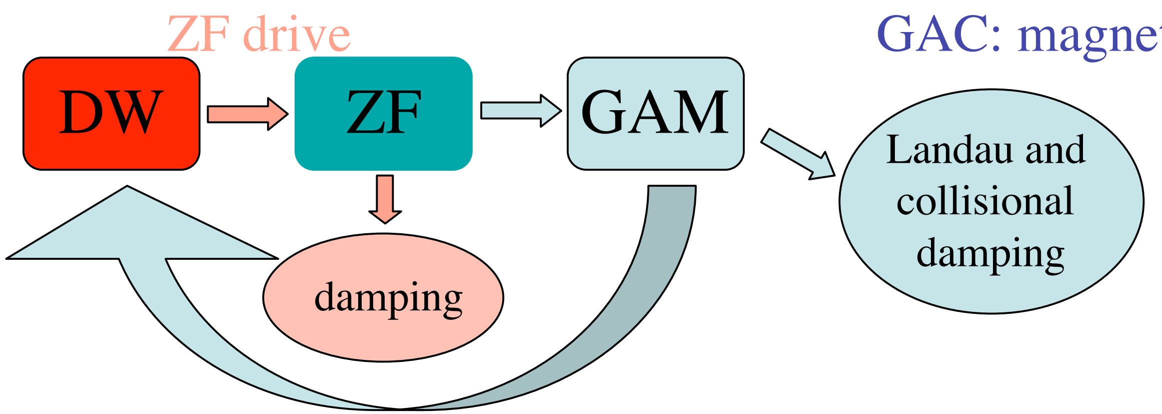


GAMS: important near the edge   Lower temperature: ν_{ii} ↑, and c_s/R ↓

⇨ ZF dynamics and GAM dynamics merge

New feature: geodesic acoustic coupling (GAC)

GAC: magnetic field sensitive



Control Knobs

(i) Zonal Flow Damping ⟸ Collisionality, ε, q, geometry, …
n.b. especially stellarators

(ii) External Drive (e.g., RF) ⟸ Choice of wave, Wave polarity, launching, (e.g., studies of IBW), rational surfaces…

III Future Research: "*What we do not yet understand*"

1. Experimentally convincing link between ZFs and confinement

2. Dominant collisionless saturation mechanism: selection rule ?

3. Quantitative predictability

    (a) $\mathcal{R}$-factor ? - trends ??

    (b) Suppression - γ_E vs γ_{Lin} ?

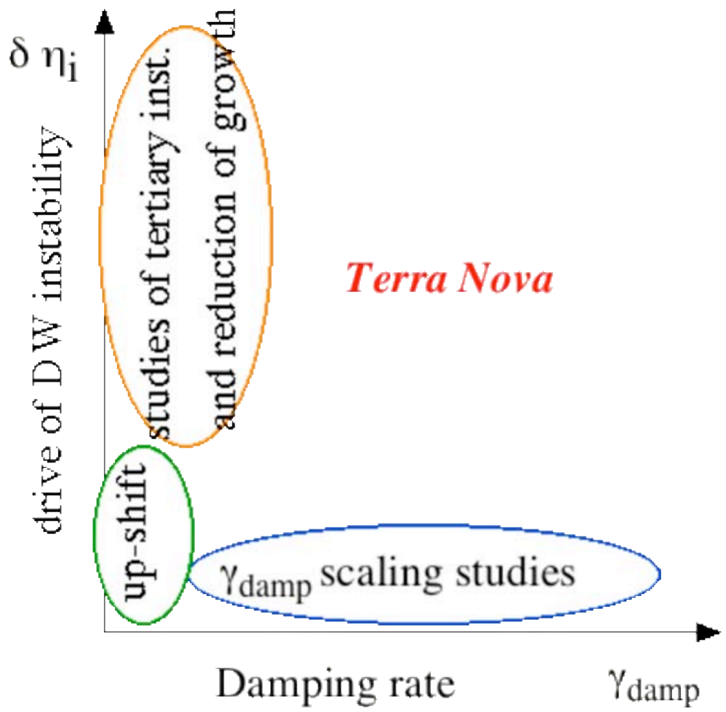
    (c)How near marginality ?

    (d) Effects on transition ?

    (e) Flux PDF ?

4. Pattern formation competition

    ZF vs. Streamers, Avalanches



5. Efficiency of control

6. Mini-max principle for self-consistent DW-ZF system ?

Summary

1. Paradigm Change: DW and turbulent transport → DW-ZF system and turbulent transport

   Linear and quasi-linear theory → Nonlinear theory
   (Simple way does not work.)

2. Critical for Fusion Devices

   e. g., { $\mathcal{R}$-factor ⇒ (Helps along) Route to ITER; Barrier Transitions }

3. Progress and Convergence of Thinking on ZF Physics

4. Speculations: More Importance for Wider Issues

   e.g., TAE, RWM, NTM; peak heat load problem, etc.

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Research on Structural Formation and Selection Rules in Turbulent Plasmas

At Kyushu, NIFS, Kyoto, UCSD, IPP

Plasma Turbulence
- Itoh Project -

Focus

Search for mechanisms of structure formation in turbulent plasmas
Selection rule among realizable states through possible transitions

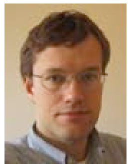
Principal Investigator:
Sanae-I. ITOH

Members and this IAEA Conference

M. Yagi: TH/P5-17 Nonlinear simulation of tearing mode and m=1 kink mode based on kinetic RMHD model

A. Fujisawa: EX/8-5Rb Experimental studies of zonal flows in CHS and JIPPT-IIU

A. Fukuyama: TH/P2-3 Advanced transport modelling of toroidal plasmas with transport barriers



K. Hallatschek: TH/P6-3 Forces on zonal flows in tokamak core turbulence

P. H. Diamond: OV/2-1, This talk

Other member collaborators



Y. Kawai, S. Shinohara, K. Itoh

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