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Electromagnetic Effects—Recent GENE Results

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Electromagnetic effects on Turbulent Transport

- Electromagnetic effects enter equations proportional to:

  plasma beta: $\beta = \frac{n_{0e} T_{0e}}{B_0^2 / 2\mu_0}$

- As β increases, plasma has enough energy to produce significant **magnetic fluctuations**

  ➔ Fluctuating $\delta\vec{B}$

➔High beta is very desirable for a fusion plasma.

$$\underbrace{nT}\underbrace{\tau_E} \geq 3 \times 10^{21} m^{-3} keVs$$

$$\beta = \frac{\boxed{n_{0e} T_{0e}}}{B_0^2 / 2\mu_0}$$

What is the effect on turbulent transport?

Electromagnetic Effects - Motivation

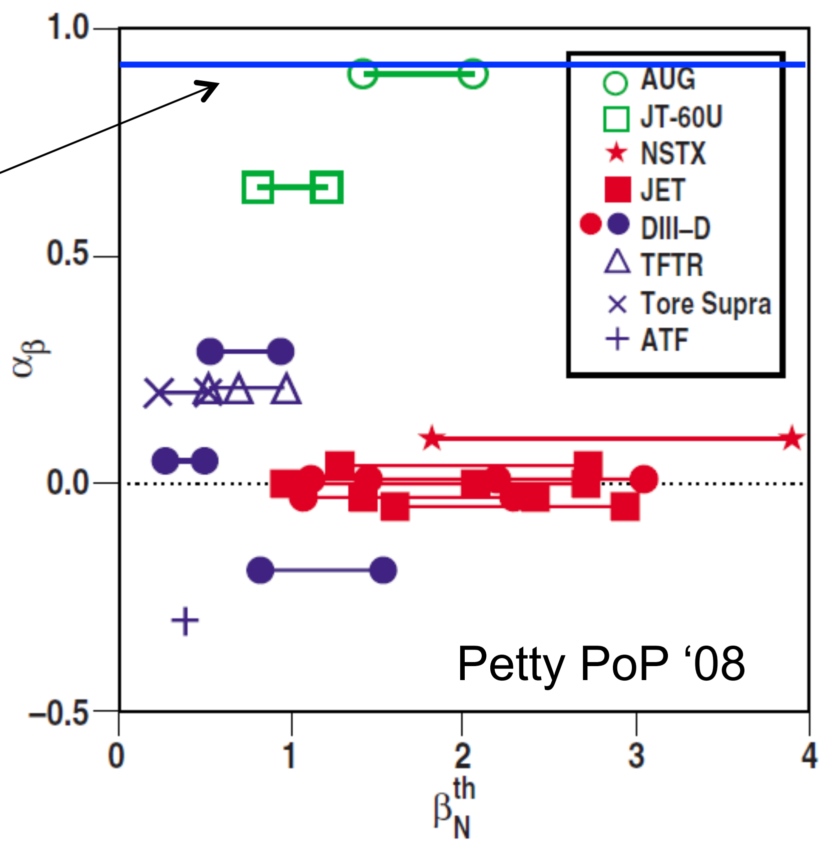
Confinement time:

Wide variation in beta scaling

$$\tau_E \propto \beta^{-\alpha}$$

Multi-machine database

How can we account for discrepancy?
How can we extrapolate to ITER?

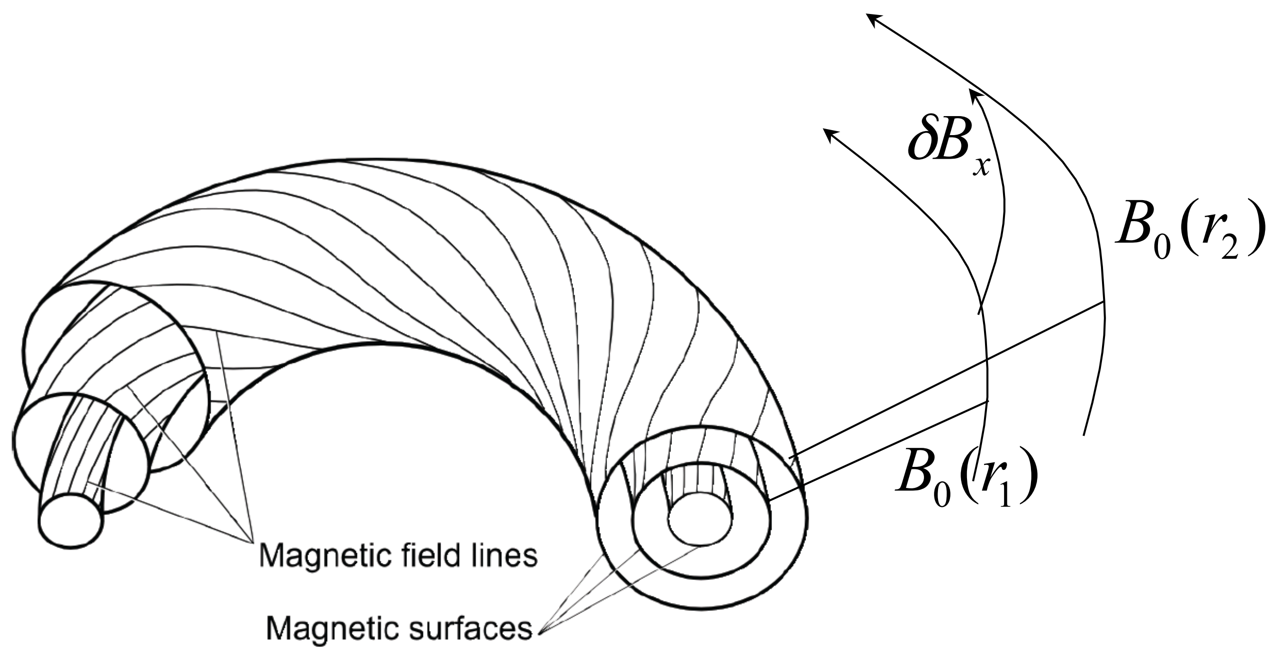


Stochastic Magnetic Transport

Electrostatic transport: **ExB advection of heat**: $Q = \langle v_{Er} \delta T \rangle \propto \langle \phi \delta T \rangle$

Electromagnetic effects: self-consistently evolving δB

Additional transport channel: electrons streaming along perturbed magnetic field lines. $Q = \langle q_{e\|} \delta B_x / B_0 \rangle$



Outline

1. Microtearing Turbulence
2. Subdominant microtearing modes in electromagnetic ITG/TEM turbulence
3. New β limit - non-zonal transition
4. Conclusions

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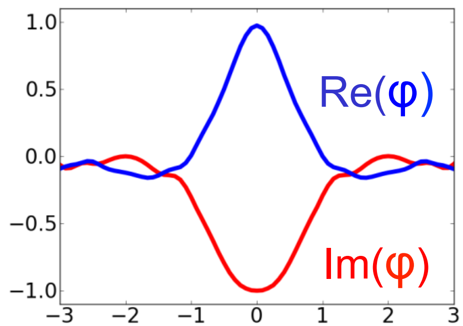
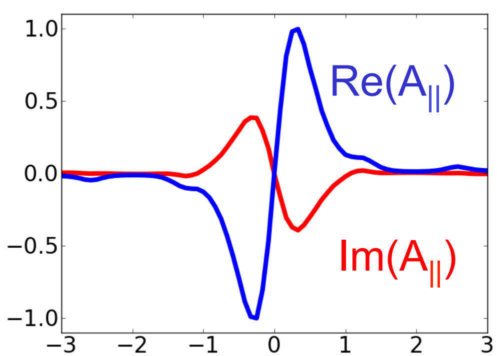
Microtearing--Very Extended Mode Structures

ITG modes

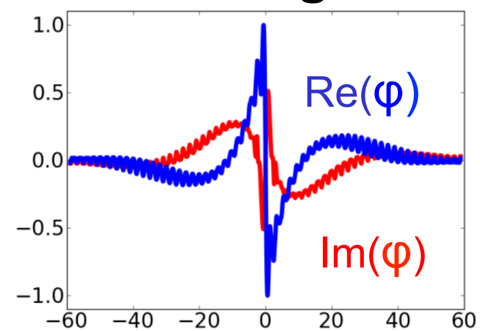


Ballooning parity

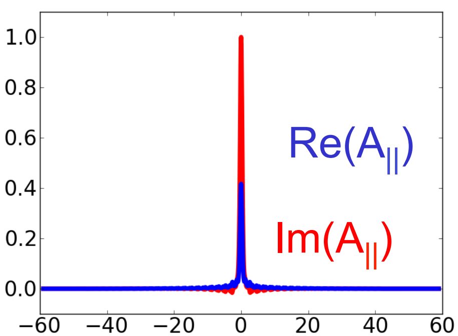


z/π

Microtearing modes



Tearing parity

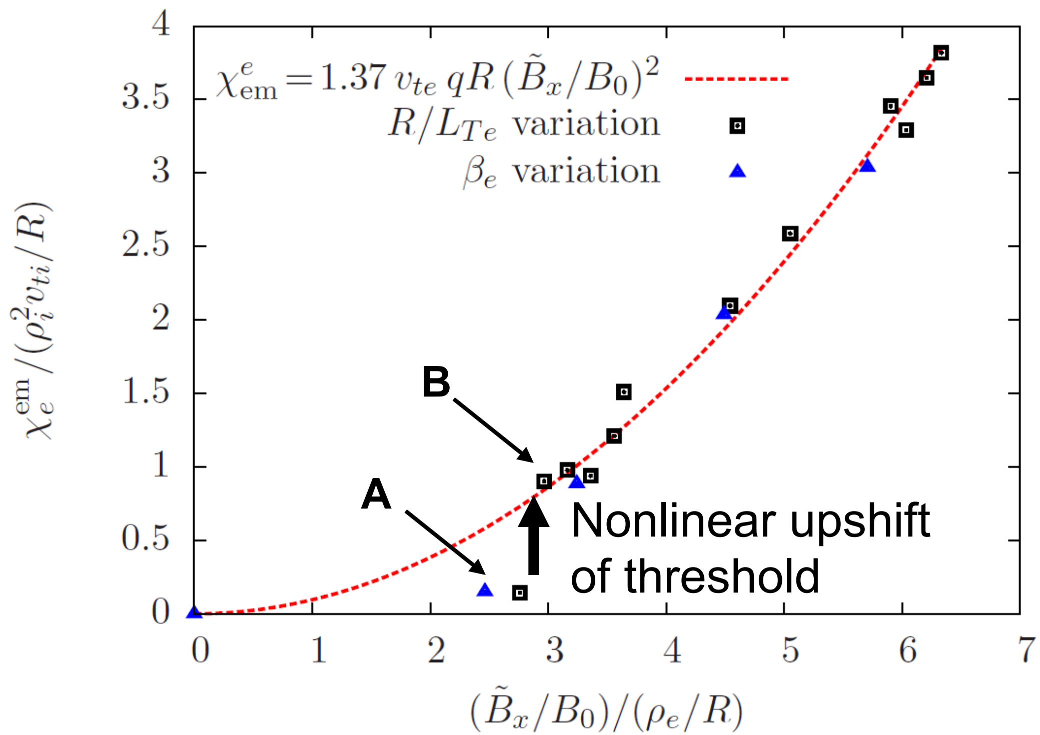


z/π

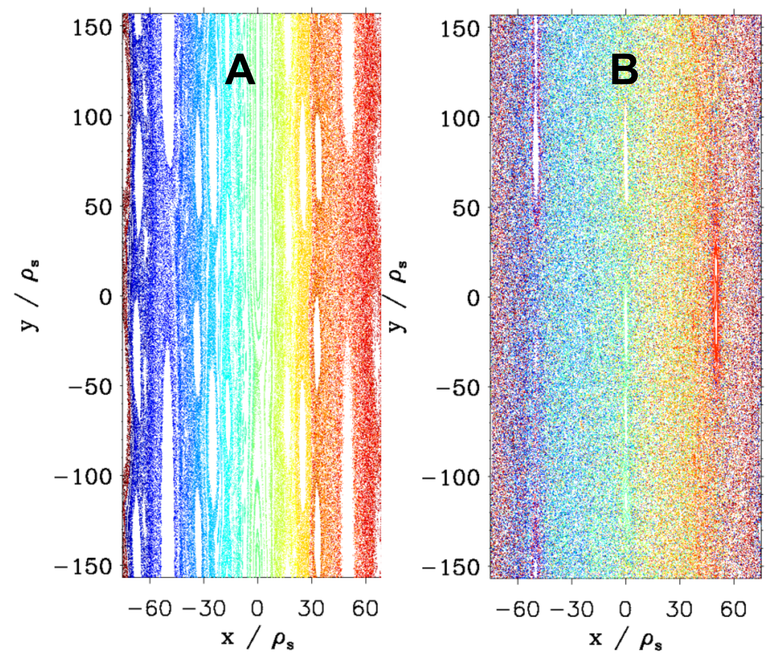
Resonant component extracted by integral along field line.
➔ITG has no resonant component (at kx=0), microtearing is resonant.

$$A_{||}^{res} = \int A_{||}(x = x_{res}(k_y), k_y, z)dz$$

First Successful Nonlinear Microtearing Simulations



Poincare plot of magnetic field lines



Diffusivity model:

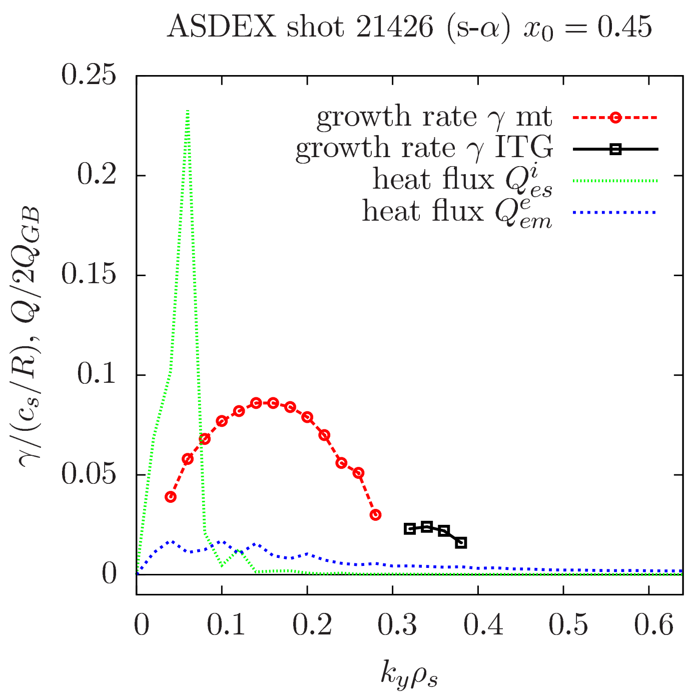
$$\boxed{\chi_e = 1.37 qRv_{Te}\left(\frac{\delta B_x}{B_0}\right)^2}$$

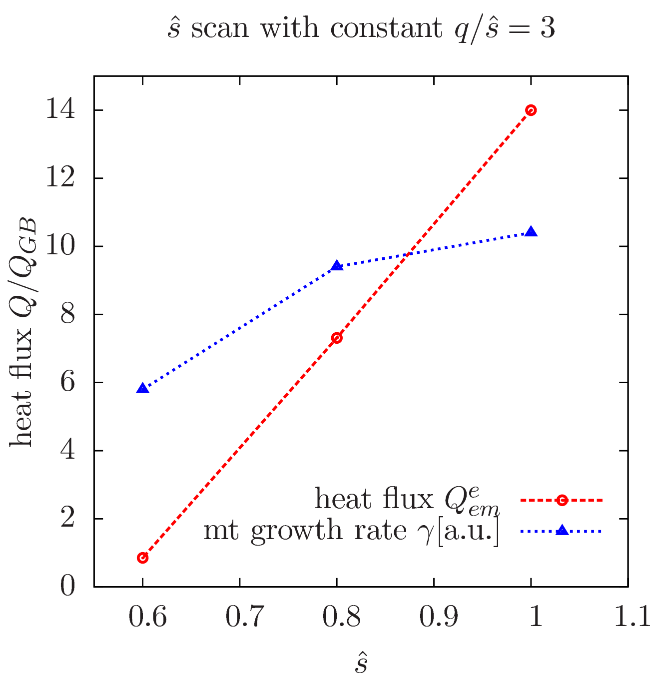
H. Doerk et al., PRL '11.

- **Experimentally relevant levels of electron heat transport**
- **Effective threshold** for onset of strong transport (**A** to **B**)
- In stochastic cases **(B)**, GENE results confirm diffusivity model.

First Successful Nonlinear Microtearing Simulations

Preliminary results (pending convergence tests, etc.)





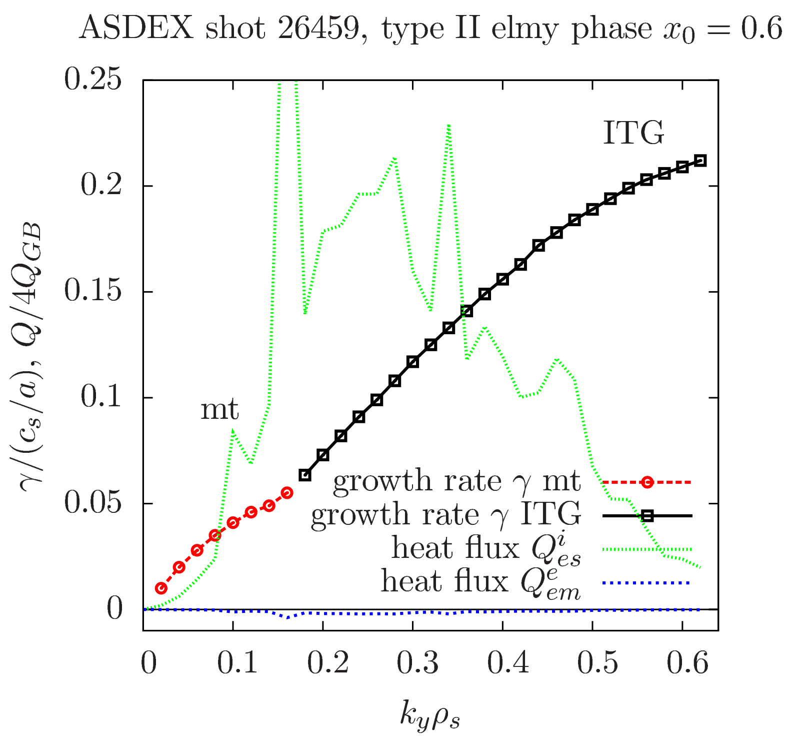
Why is EM transport so low?

Higher magnetic shear → higher EM transport (presumably due to closer rational surfaces).

Suggests microtearing likely to be important in outer core.

Mixed ITG, Microtearing Turbulence

Preliminary results (pending convergence tests, etc.)



r/a=0.6 and a shear of s=1.3
(still need s scan in this case)

No contribution from microtearing.
➔microtearing can be robustly unstable without producing transport.

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ITG Turbulence with Electromagnetic Effects

Before nonlinear GK microtearing was tackled . . .

➔basic question

What are electromagnetic effects on ITG/ TEM turbulence?

Several interesting and puzzling results over past decade:

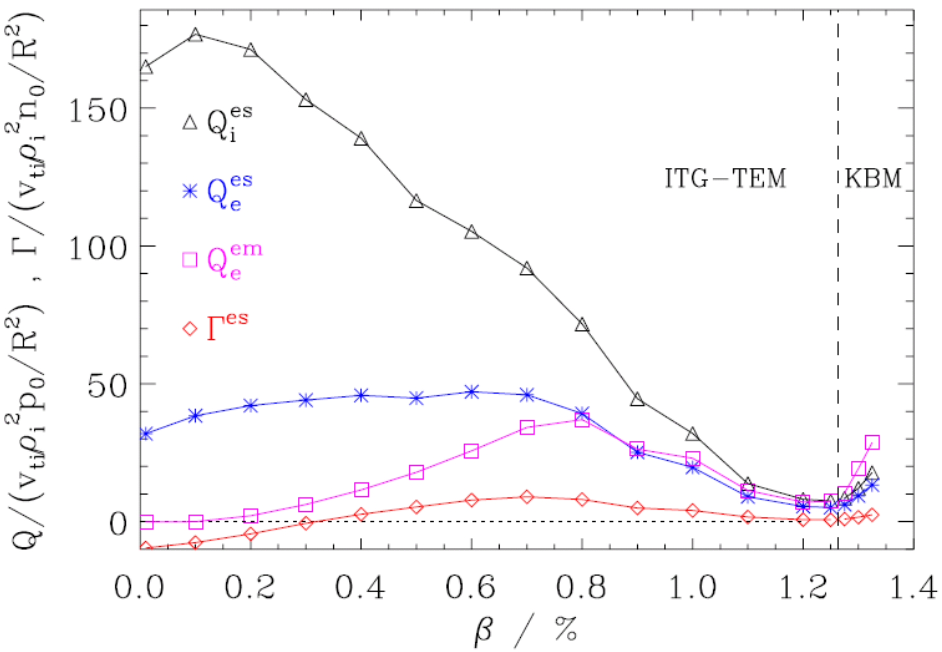
Specifically ITG (CBC):
Parker PoP ‘04, Candy PoP ‘05, Pueschel PoP ‘08,
Waltz PoP ‘10, Nevins PRL ‘11, Wang PoP ‘11

Significant Electromagnetic Transport

ITG driven turbulence [Candy PoP ‘05, Pueschel PoP ’08]:

Suppression of ES transport greater than expected from decreasing growth rates.

Levels of electron electromagnetic heat transport that approach electrostatic transport as beta increases.

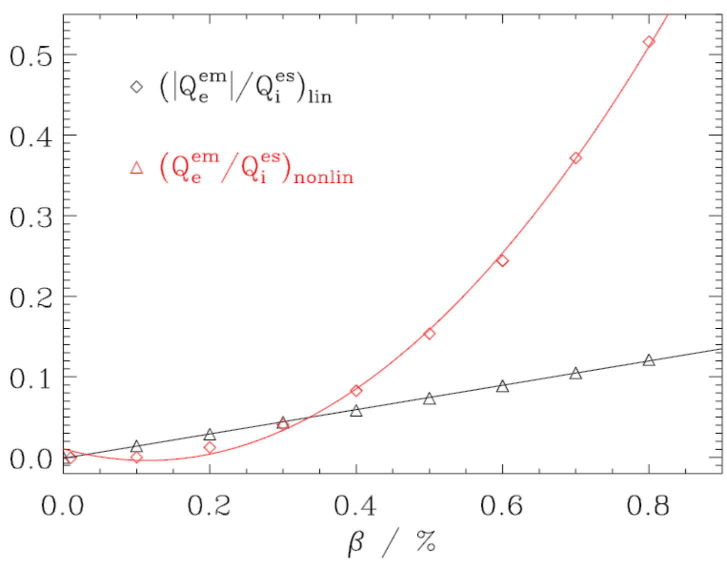


Pueschel, PoP, ‘08

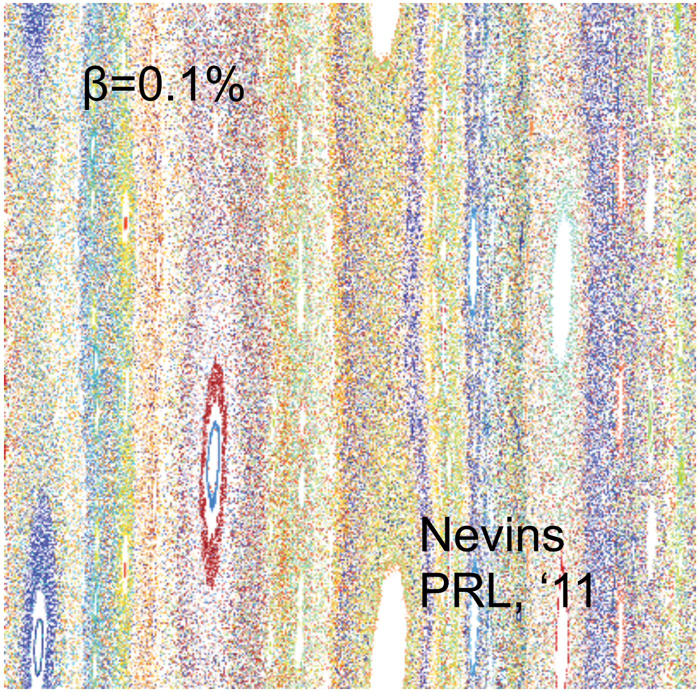
Introduction – Recent Results

ITG driven turbulence:

Near-ubiquitous magnetic stochasticity – even at low values of beta [Nevins PRL11, Wang PoP '11]



Beta scaling inconsistent with ITG expectation [Pueschel '08]



ITG mode (at kx=0) has ballooning, not tearing parity.

What is the cause?

Observations of electromagnetic effects inconsistent with properties of the driving ITG modes.

What is the explanation for the observed stochasticity and transport

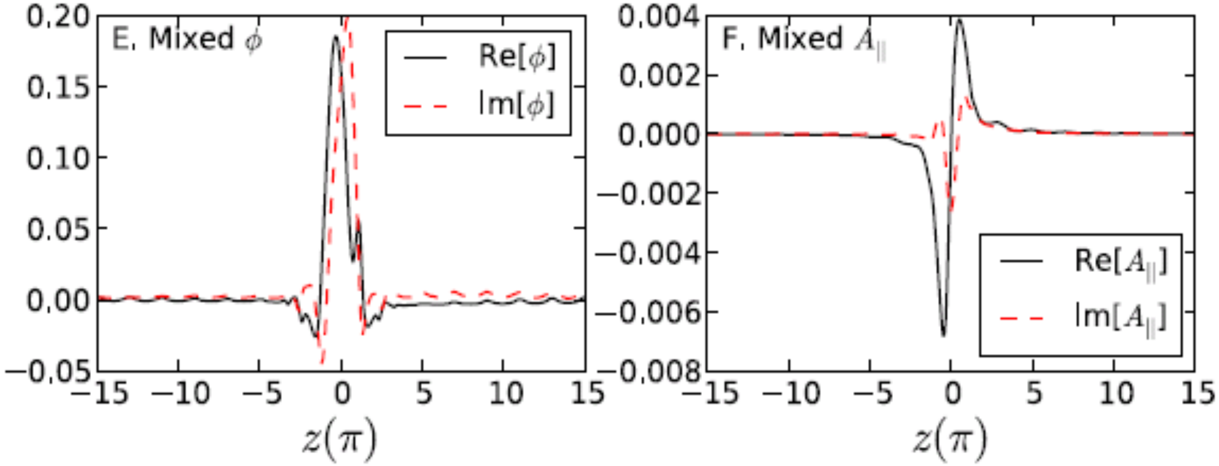
(Hatch et al. PRL ’12, Hatch et al. PoP ’13)

Candidates:

--|kx|>0 ITG modes

--Some other mode with tearing parity

Perfect ballooning parity no longer enforced at |kx|>0

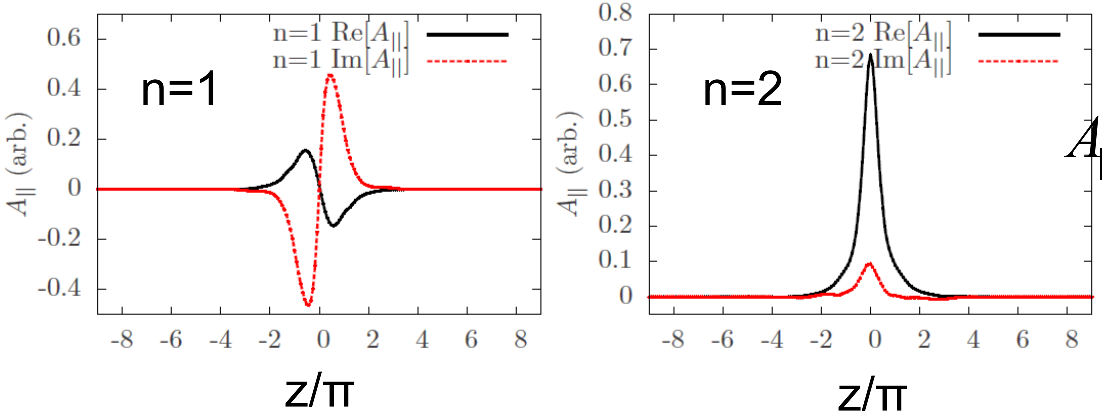


Even / Odd symmetry is no longer enforced at $k_x \neq 0$. But modes are still "predominantly even" or "predominantly odd".

➔Distinguish with Parity Factor

$$\boxed{P = \frac{\left|\int dz A_{\|k_x,k_y}(z,t)\right|}{\int dz \left|A_{\|k_x,k_y}(z,t)\right|}}$$

Perfect ballooning parity no longer enforced at |kx|>0



POD

$$A_{\|k}(z,t) = \sum_n A_{\|k}^{(n)}(z) h_k^{(n)}(t)$$

➔Distinguish with Parity Factor

$$P = \frac{\left| \int dz A_{\|k_x,k_y}(z,t) \right|}{\int dz \left| A_{\|k_x,k_y}(z,t) \right|}$$

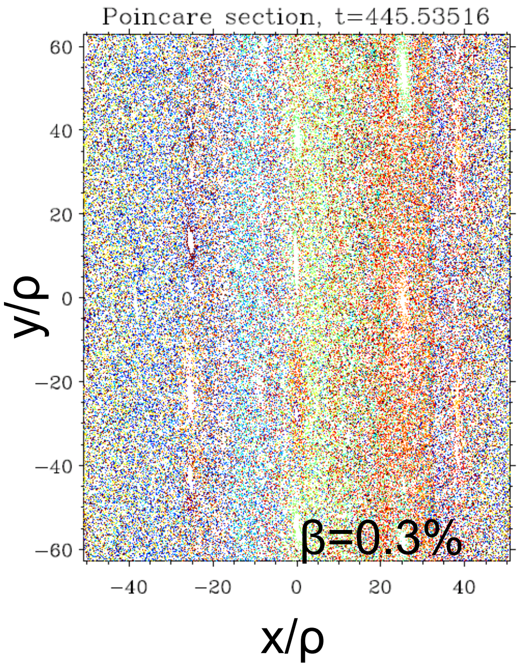
Construct a “tearing-ballooning” decomposition:

$$\boxed{A_{\|k_x,k_y}(z,t) = A_{\|k_x,k_y}^{(ball)}(z,t) + A_{\|k_x,k_y}^{(tear)}(z,t) + A_{\|k_x,k_y}^{(res)}(z,t)}$$

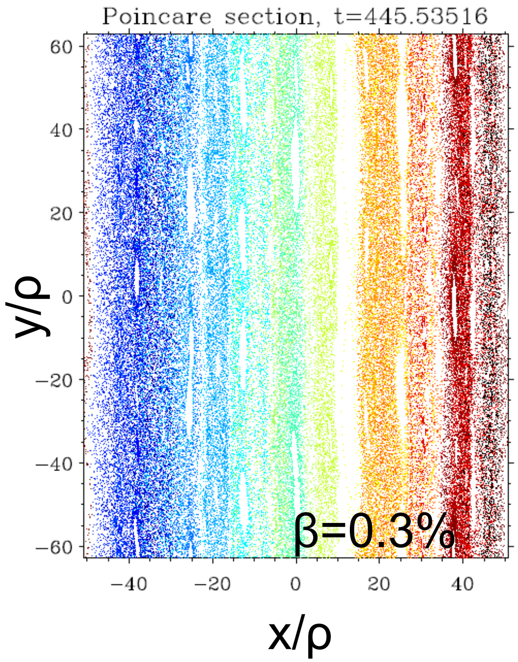
Stochasticity caused by tearing component

$$A_{\|k_x,k_y}(z,t) = A^{(ball)}_{\|k_x,k_y}(z,t) + A^{(tear)}_{\|k_x,k_y}(z,t) + A^{(res)}_{\|k_x,k_y}(z,t)$$

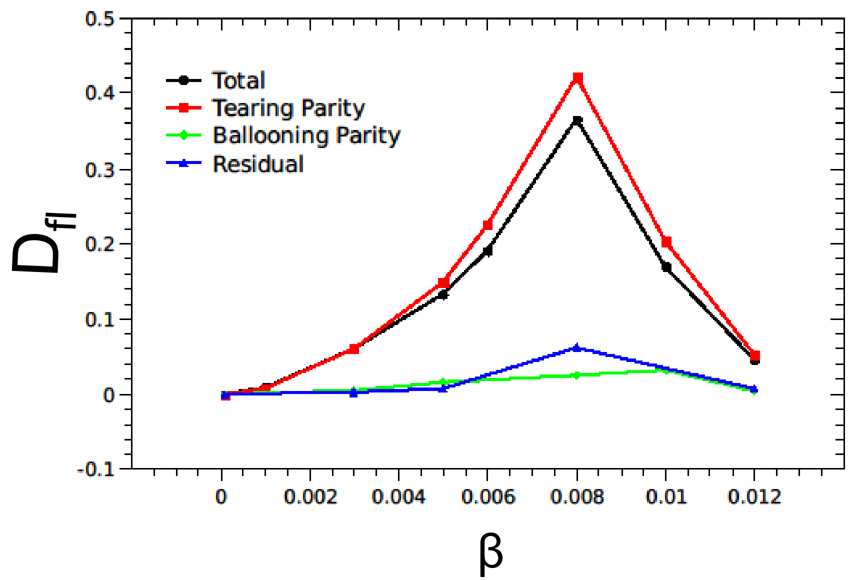
$$A^{(tear)}_{\|k_x,k_y}(z,t)$$



$$A^{(ball)}_{\|k_x,k_y}(z,t)$$



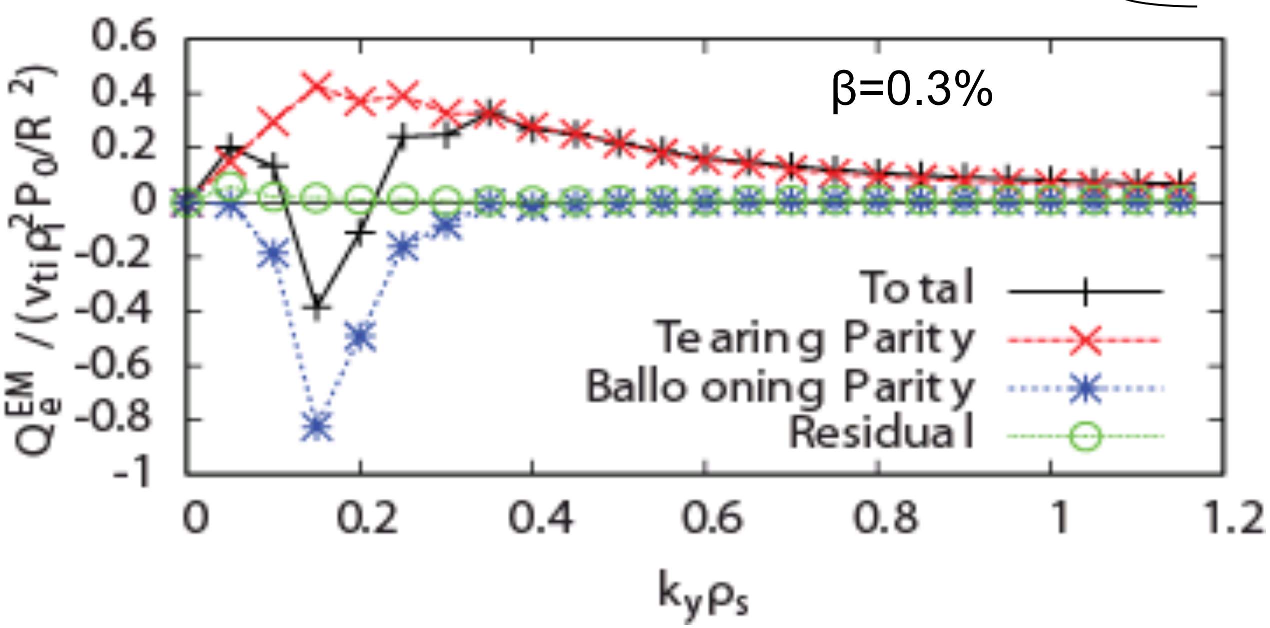
$$D_{fl} = \lim_{l\to\infty}\frac{1}{l}\left\langle \left| r_i(l) - r_i(0)\right|^2 \right\rangle$$

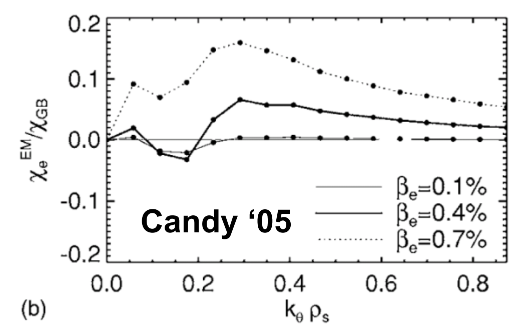


Magnetic transport – superposition of ITG and tearing

$$A_{\parallel k_x,k_y}(z,t) = A^{(ball)}_{\parallel k_x,k_y}(z,t) + A^{(tear)}_{\parallel k_x,k_y}(z,t) + A^{(res)}_{\parallel k_x,k_y}(z,t)$$

$$\begin{cases} Q_e^{EM(tot)} = q_{e\parallel} B_x / B_0 \\ Q_e^{EM(tear)} = q_{e\parallel} B_x^{(tear)} / B_0 \\ Q_e^{EM(ball)} = q_{e\parallel} B_x^{(ball)} / B_0 \\ Q_e^{EM(res)} = q_{e\parallel} B_x^{(res)} / B_0 \end{cases}$$





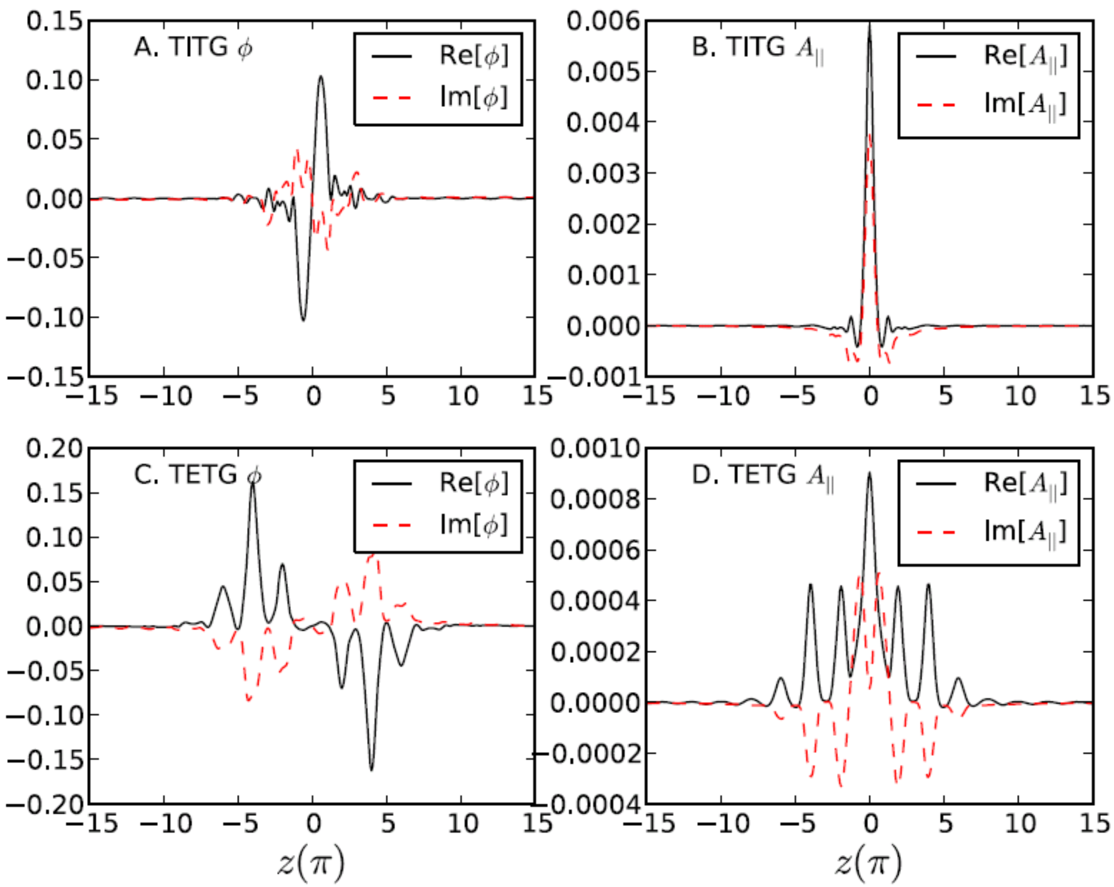
What Kind of Tearing Mode?

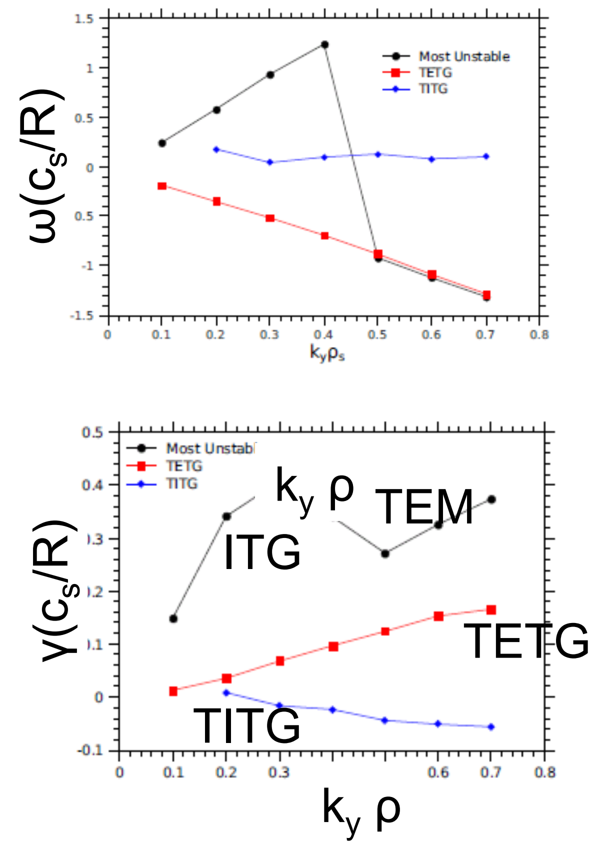
Stochasticity and transport due to *some* kind of tearing mode

What are the candidates?

Tearing ITG (TITG)
Tearing ETG (TETG)
Microtearing

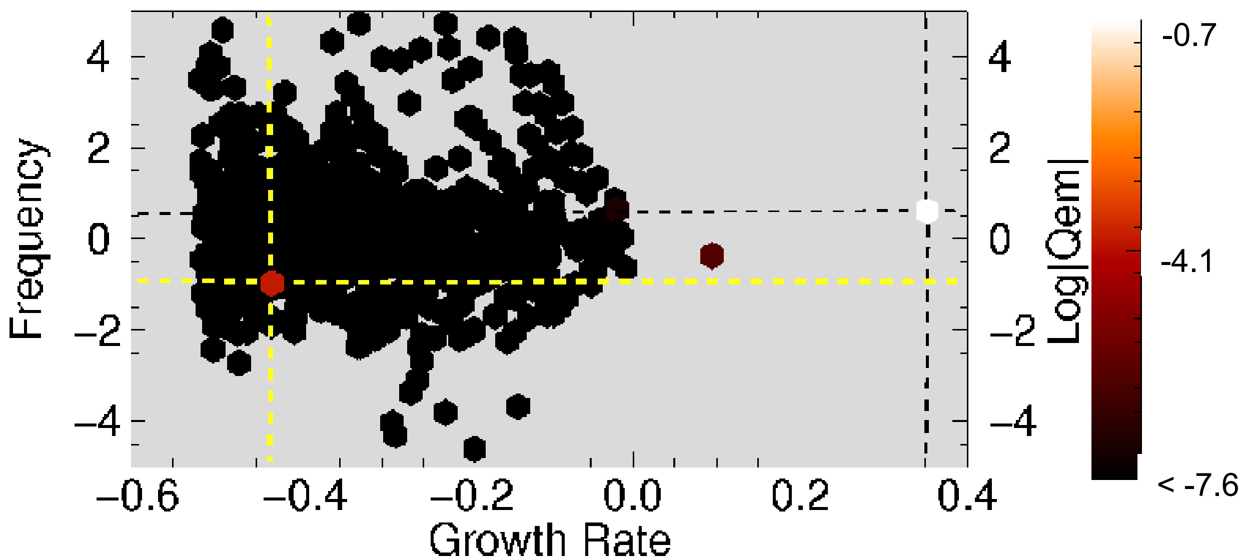
Linear spectrum – many modes with tearing parity





Note: similar mode identified just inside pedestal top in DIIID (Wang, 2012)

Subdominant Microtearing Mode Deep in the Spectrum



Microtearing mode deep in the spectrum (need full eigenvalue solver)

Microtearing—Intrinsically Electromagnetic

Using GENE eigenmode solver.

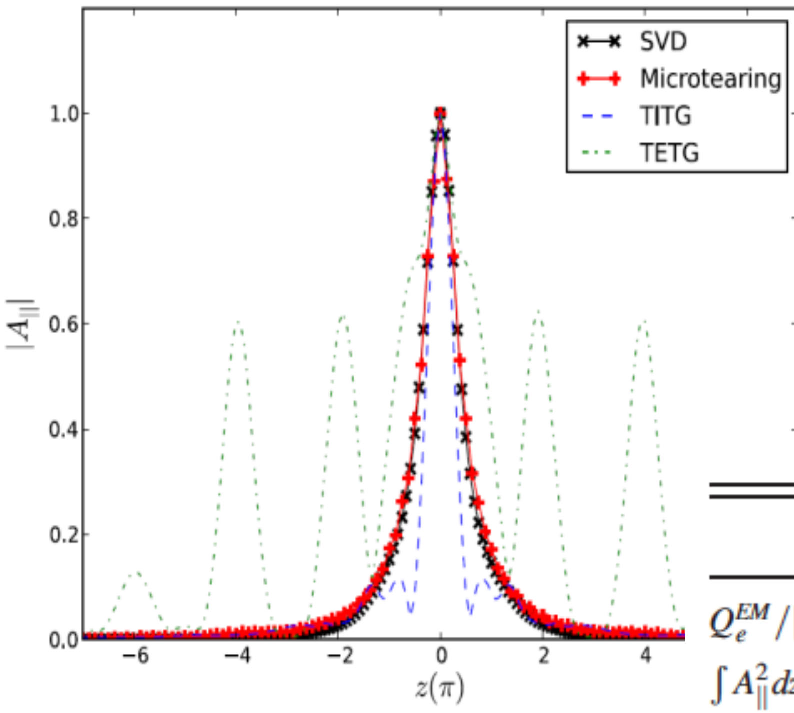
	ITG	TITG	ETG	TETG	Micro Tearing[1]
Tearing Parity		X		X	X
Frequency	+	+	-	-	-
R/Lti Threshold	X	X			
R/Lte Threshold			X	X	X
Low-β Threshold					X
$\lvert A_{\parallel}\rvert^2 / \lvert\phi\rvert^2$	<<1	<<1	<<1	<<1	~1
$\lvert$QeEM/ QeES$\rvert$	<<1	<<1	<<1	<<1	>1

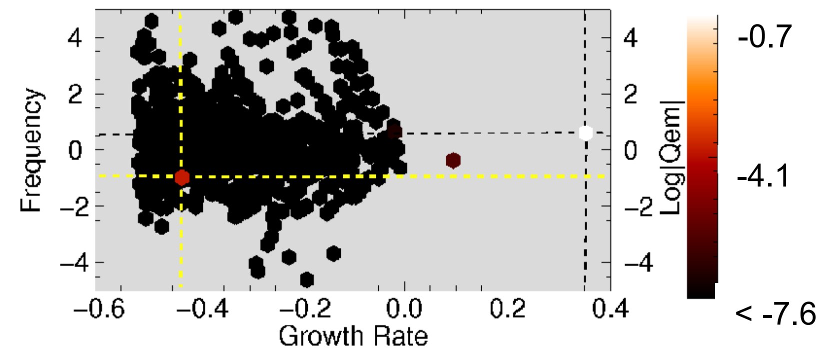
TITG, TETG: Note electromagnetic

Microtearing—intrinsically electromagnetic

(1) Doerk, PRL, '11,

Stochasticity and Transport Due to Actual Microtearing Mode

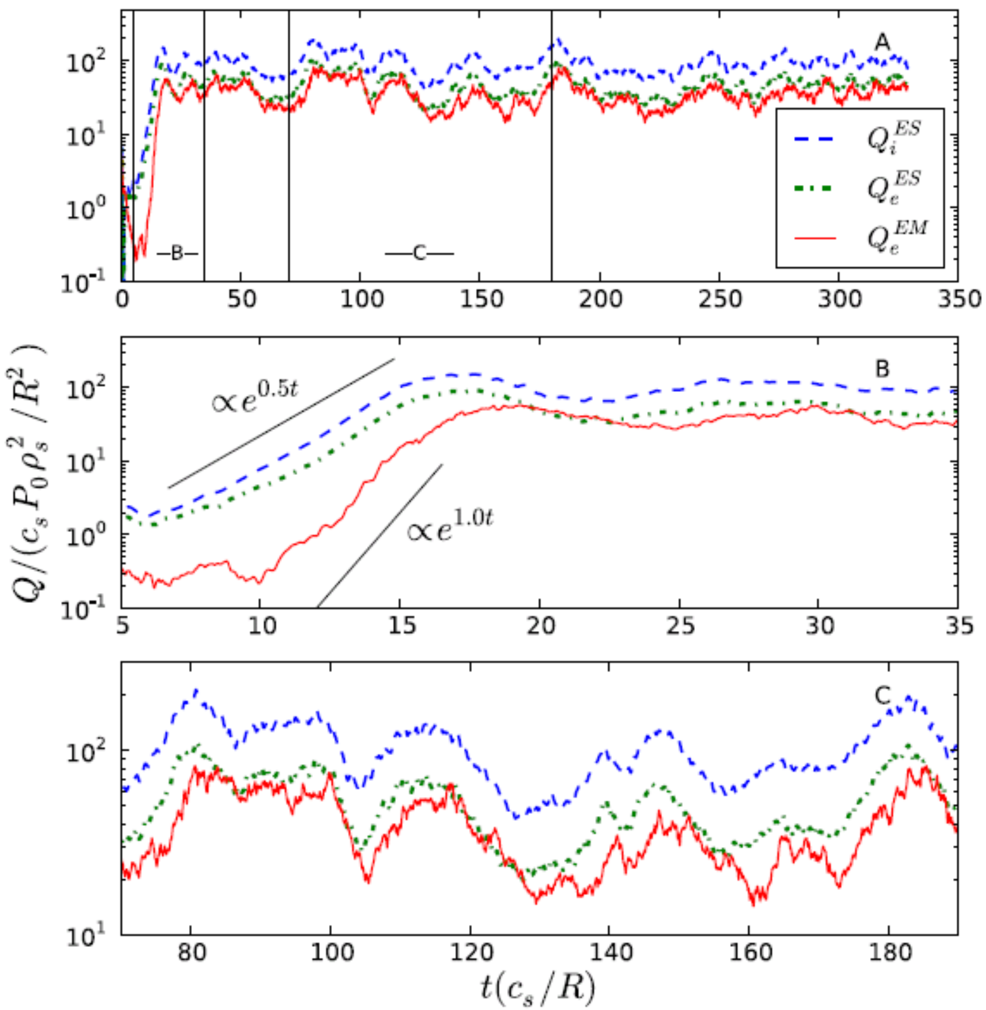




	TITG	TETG	MTM	SVD
$Q_e^{EM}/\lvert Q_i^{ES}\rvert$	4.8×10^{-3}	-0.13	730	330
$\int A_{\parallel}^2 dz / \int \Phi^2 dz$	1.3×10^{-3}	2.8×10^{-5}	0.10	0.16

Summary, stochasticity and transport:
--not due to finite kx ITG
--due to tearing parity fluctuations
--not associated with TITG/TETG modes
--definitively linked to **microtearing**

Stable Mode➔Nonlinear Excitation



Time trace of electromagnetic component:
Nonlinear time scales.

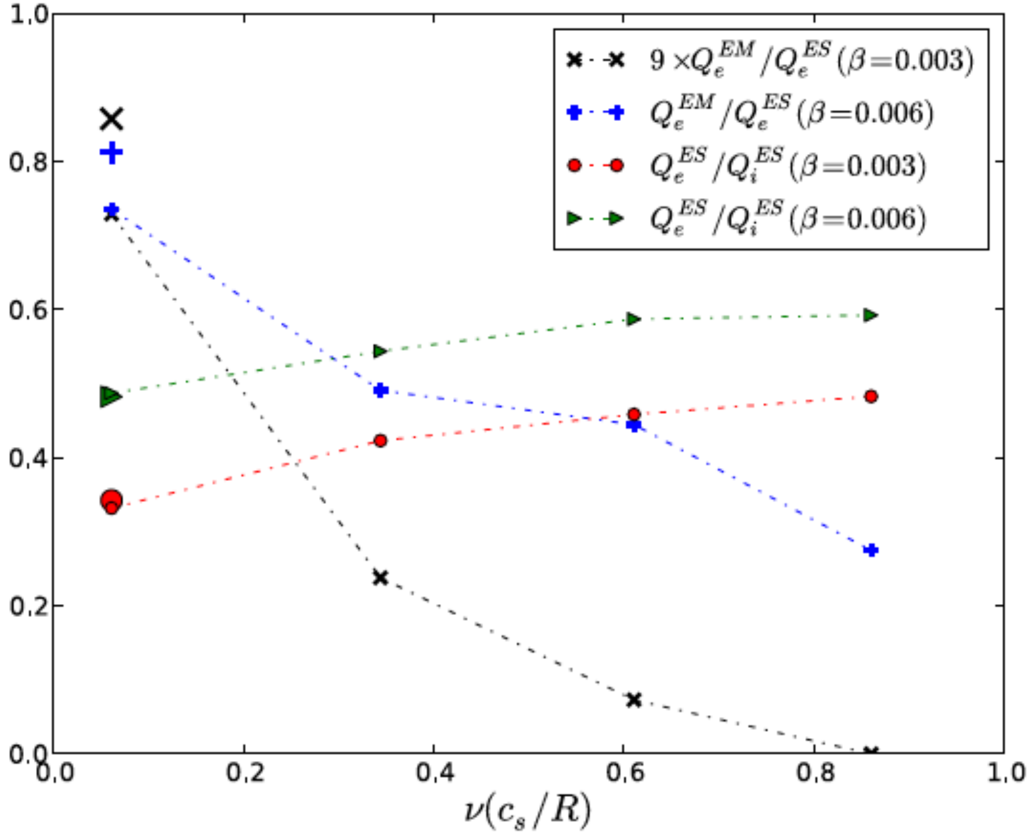
What is the excitation mechanism?

Free energy evolution equation
for tearing mode

$$\frac{\partial E_k^{(tear)}}{\partial t} = L[g_k^{(tear)}, g_k] + \sum_{k_\perp} N[g_k^{(tear)}, g_{k'}, g_{k-k'}] + c.c.$$

➔zonal modes excite microtearing

Microtearing Considerations



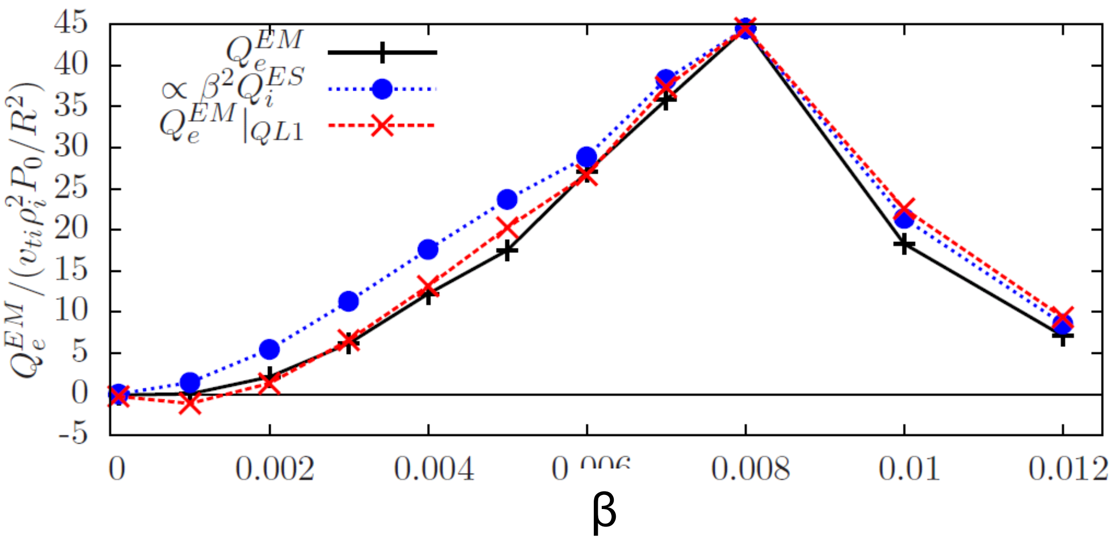
EM transport suppressed at high collisionality.

Simple model captures β-dependence

$$Q_e^{EM(tear)}(\beta) = \sigma_0 (\beta / \beta_{crit})^2 Q_i^{ES}$$ Stochastic tearing transport

$$Q_e^{EM} = Q_i^{ES} \left(\sigma_0 (\beta / \beta_{crit})^2 + \left\{ \frac{Q_e^{EM}}{Q_i^{ES}} \right\}_{ITG-lin} \right)$$

ITG/TEM – quasilinear contribution



Database of ~30 EM simulations covering typical core parameters:
σ_0=1 appears to be an upper bound (rarely exceeded, excluding microtearing).
➔Large EM transport not expected from ITG/TEM drive.

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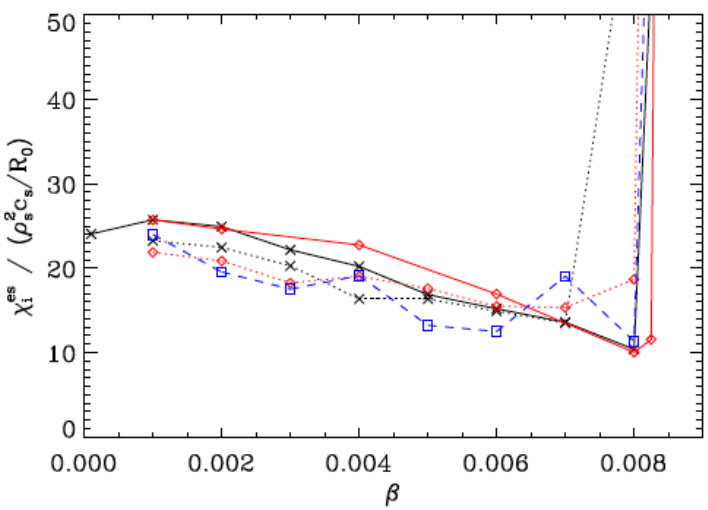
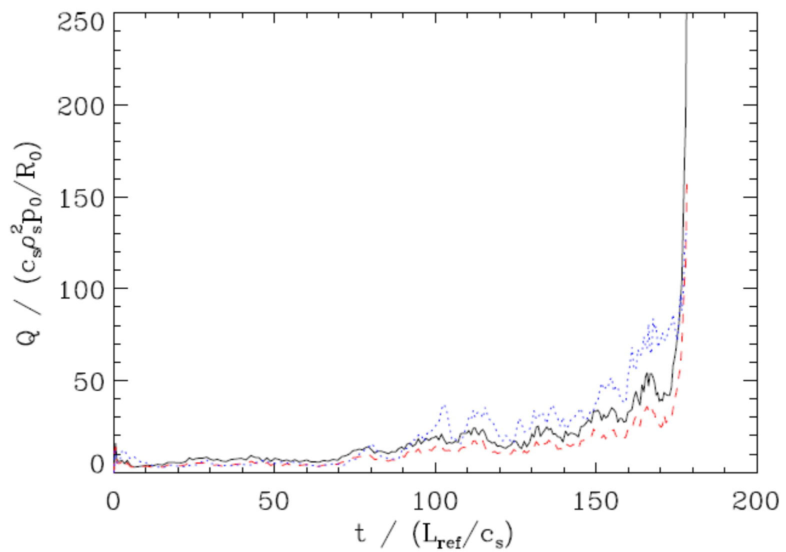
High Beta 'Runaway'➔Non-Zonal Transition



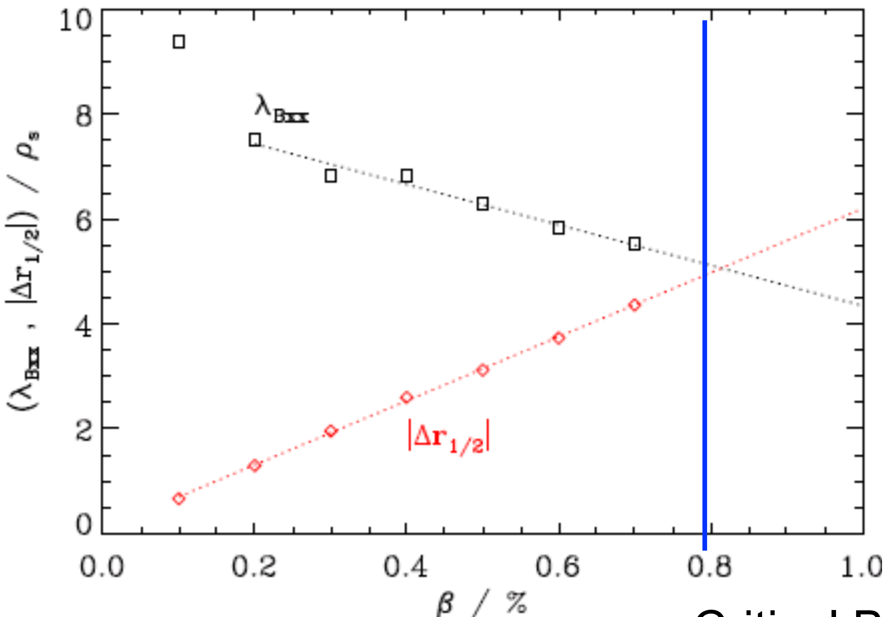
High beta runaway above β~0.8%
Reproducible by many codes.



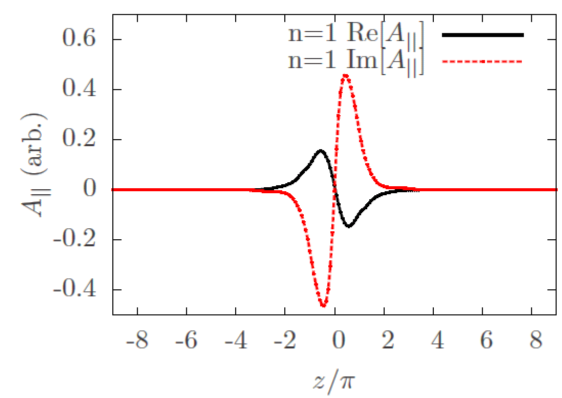
Runaway after long 'semi-saturated' phase.

High Beta 'Runaway'→Non-Zonal Transition

Work by M.J. Pueschel



Critical Beta

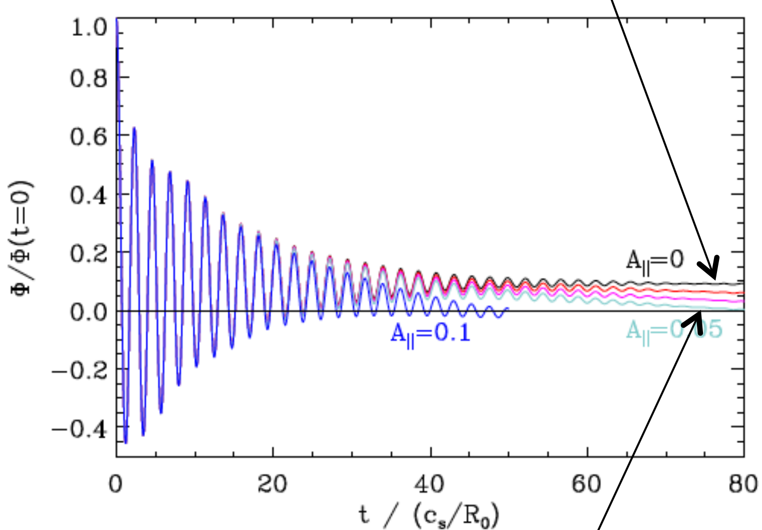


If half-turn displacement exceeds correlation length→non-resonant perturbations can contribute to stochasticity.

Effect of Magnetic Fluctuations on Zonal Flows

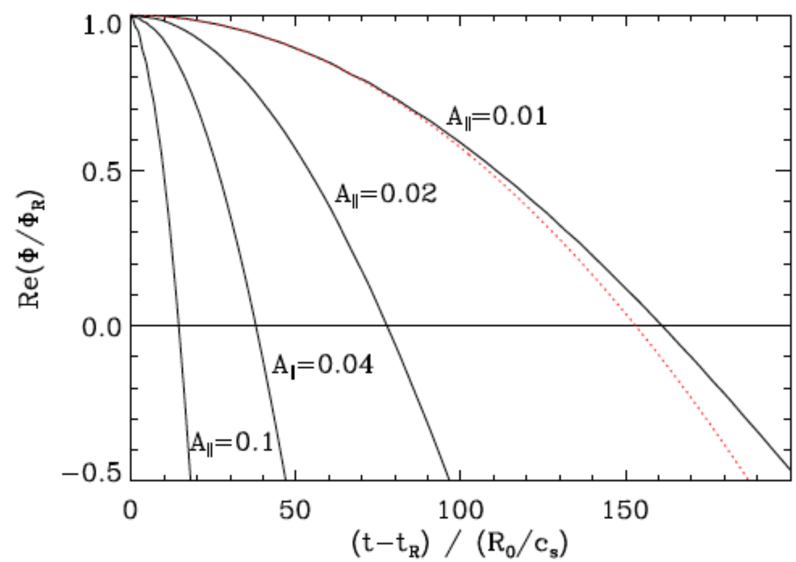
$$\Phi_{\mathrm{R}} = \frac{\Phi(t=0)}{1 + 1.6 q_0^2/\epsilon_{\mathrm{t}}^{1/2}}$$

Rosenbluth-Hinton residual



With A$_{||}$ ➔ decay

A$_{||}$ included after GAM decay
➔ decay proportional to t^2



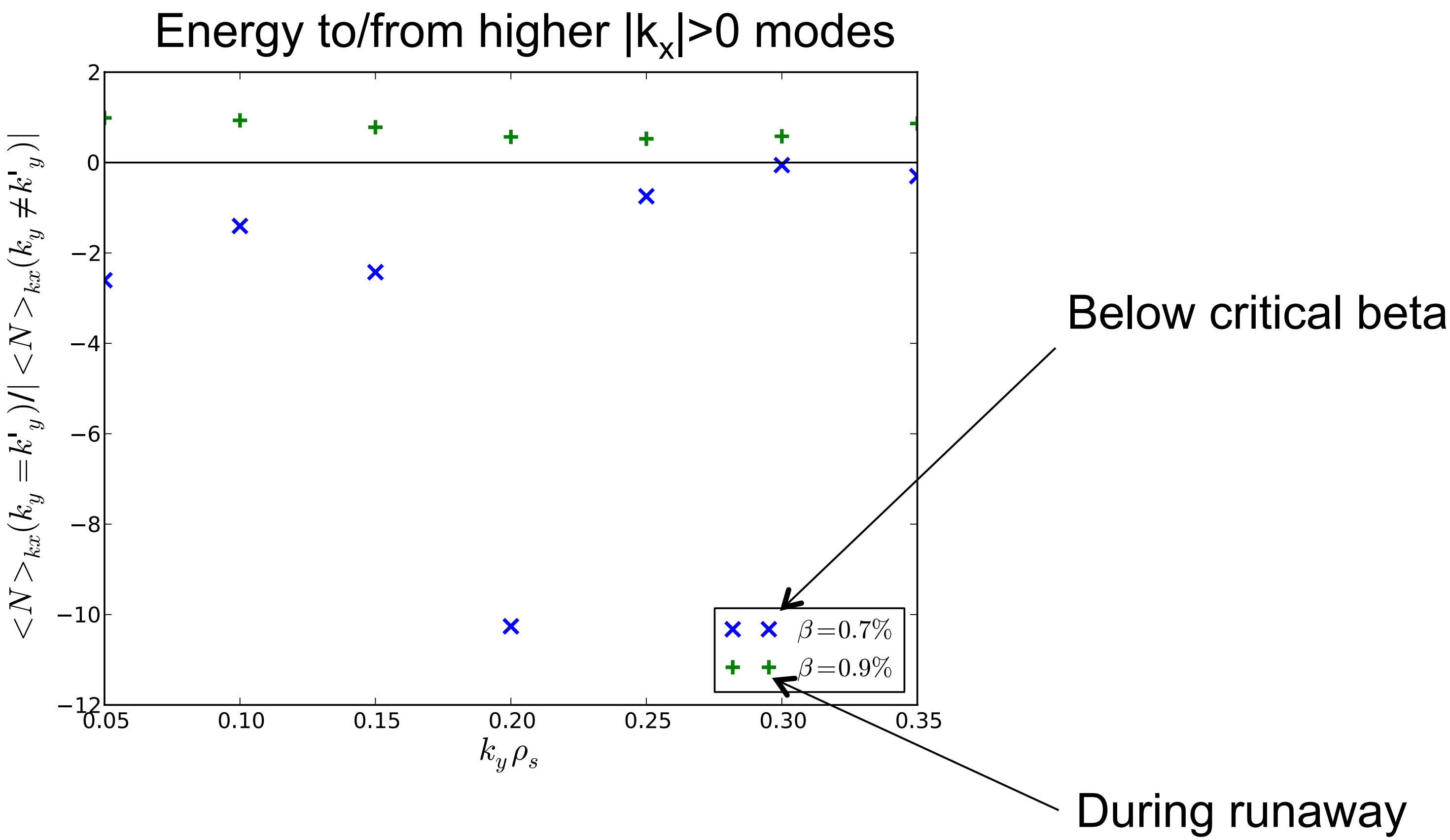
Agrees with analytic calculation (P. Terry)

$$\Phi(t) = \Phi_{\mathrm{R}} - \left(\mathcal{S}_{\alpha^2} - \frac{T_{\mathrm{i0}}}{T_{\mathrm{e0}}} \frac{2\alpha^2(\Phi_{\mathrm{R}} - 3\mathcal{S}_{\alpha^2}/\alpha^2)}{k_x^2 \rho_{\mathrm{s}}^2 (1 + 1.6 q_0^2/\epsilon_{\mathrm{t}}^{1/2})} \right) t^2 + \mathcal{O}(\alpha^4 t^4)$$

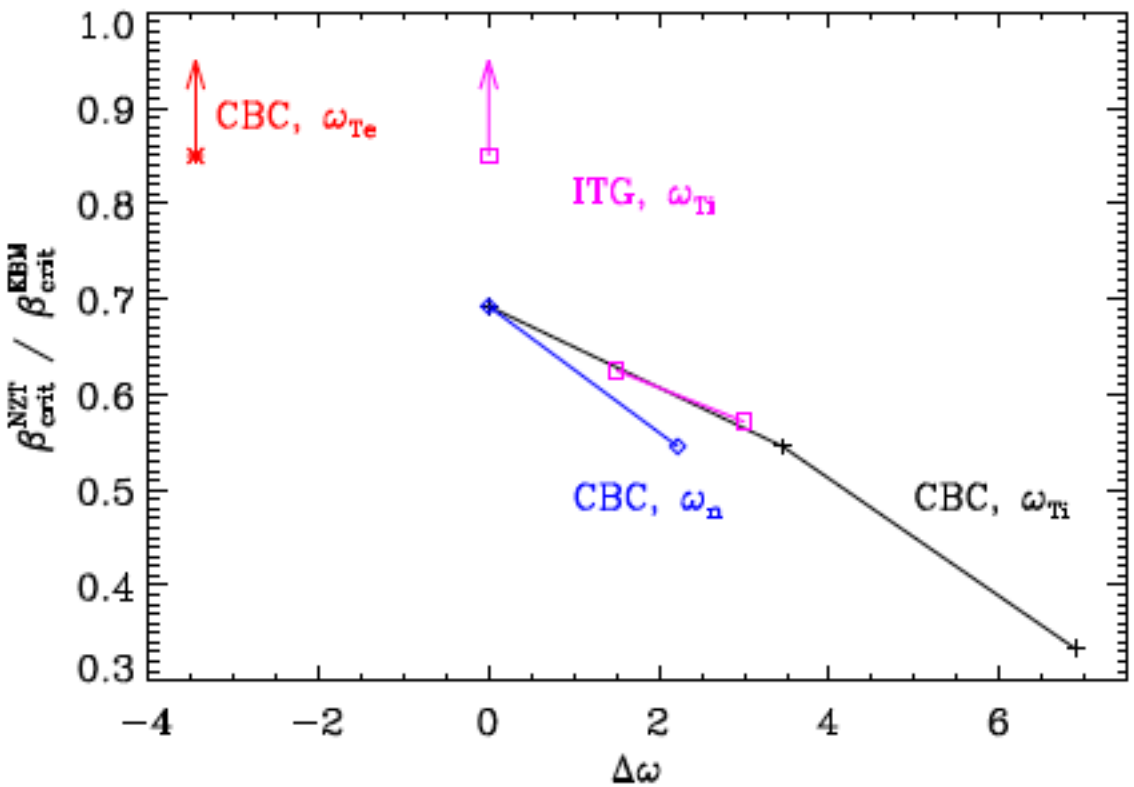
Fundamental Change in ZF Dynamics

During runaway➔zonal coupling *drives* kx=0 modes.

Pre-runaway➔standard picture: ZF transfers energy to higher k_x.



Critical NZT beta usually expected to exceed KBM critical beta



Lower gradients➔critical KBM beta probably reached before critical NZT beta.

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Summary / Conclusions

- Microtearing modes can be unstable and **produce significant levels of transport** in standard tokamaks
  - Most likely active at **higher shear.**
- **However,** there are cases where EM transport is very low despite microtearing linearly unstable.
- ITG driven turbulence excites linearly stable microtearing modes
  - Magnetic transport is superposition of **outward stochastic contribution** from nonlinearly excited microtearing modes and **inward contribution from ITG**.
  - Database of EM simulations: Q_{EM} rarely exceeds $(\beta / \beta_{crit})^2 Q_i^{ES}$
- High β runaway ➔ non-zonal transition
  - Zonal flows suppressed when non-resonant fluctuations become important
- Microtearing is **challenging** and often **unintuitive**
  - Difficult to resolve numerically
  - Can be insignificant even when linearly unstable
  - Can be active even when linearly stable

Backup slides

Contributions to EM Transport

$$Q_e^{EM} = \langle \tilde{q}_{e||} \tilde{B}_x \rangle / B_0$$

$$\tilde{q}_{e||} = -n_{0e} \chi_{e||} \left(\boxed{\frac{d\tilde{T}_{e||}}{dz}} + \frac{\tilde{B}_x}{B_0} \frac{d\tilde{T}_{e||}}{dx} + \boxed{\frac{\tilde{B}_x}{B_0} \frac{dT_{e0}}{dx}} \right)$$

ITG mechanism

Stochastic transport (tearing) mechanism

Nonlinear transfer functions - identify excitation mechanism.

Gyrokinetic free energy:

$$E_k = \sum_j \pi B_0 n_{0j} T_{0j} \int dz dv_{\|} d\mu J(z) \frac{f_j^2}{F_{0j}} + D(k_\perp)\phi^2 + \frac{k_\perp^2}{\beta} A_\|^2$$

Energy evolution equation:

$$\frac{\partial E_k}{\partial t} = L[g_k, g_k] + \sum_{k_\perp} N[g_k, g_{k'}, g_{k-k'}] + c.c.$$

Nonlinear Transfer function:

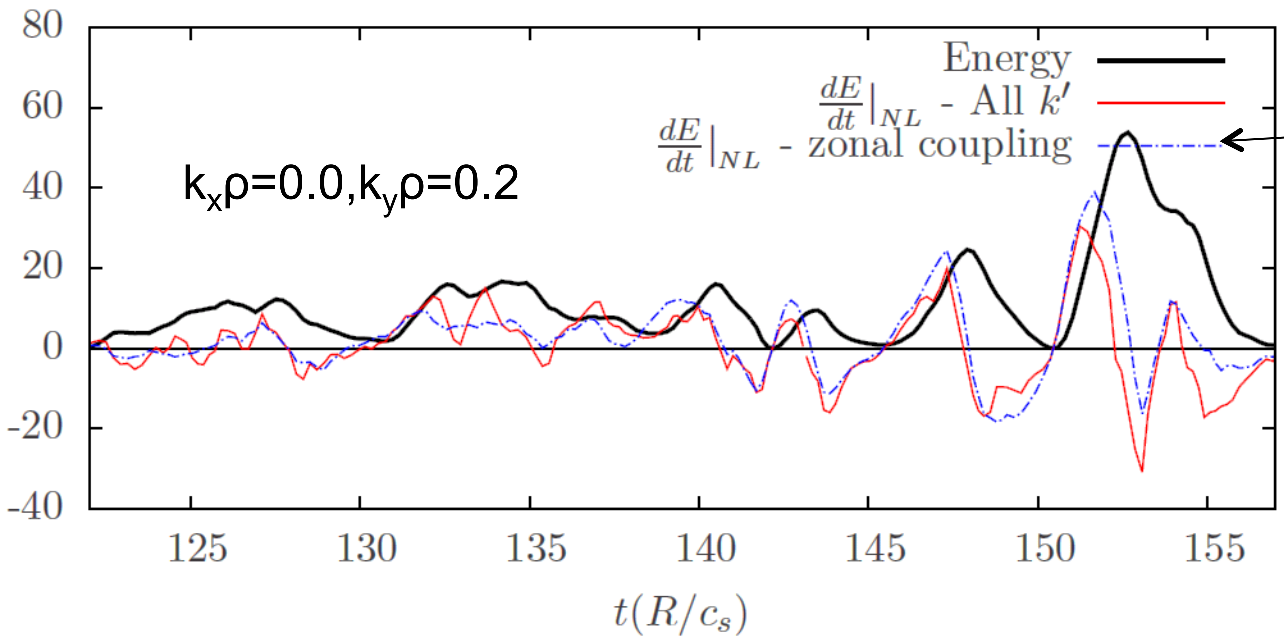
$$N_{k,k'} = \int dz dv_\| d\mu (k_x' k_y - k_x k_y') \left[\frac{q_j F_{oj}}{T_{0j}} \chi_j^*(k) \chi(k') g(k-k') - g_j^*(k) \chi(k-k') g(k') \right]$$

Energy transferred between k and k’ $\quad N_{k,k'} = -N_{k',k}$

Excitation mechanism: coupling with k_y=0

$$\frac{\partial E_k^{(tear)}}{\partial t} = L[g_k^{(tear)}, g_k] + \sum_{k_\perp} \boxed{N[g_k^{(tear)}, g_{k'}, g_{k-k'}]} + c.c.$$

Free energy evolution equation
for tearing mode



Energy transfer involving coupling with zonal wavenumbers (k_y=0):

$k_y'\rho = 0.0, k_y''\rho = 0.2$

$k_y'\rho = 0.2, k_y''\rho = 0.0$

Nonlinear mechanism which stabilizes ITG in turn drives microtearing and produces additional transport channel.

POD of distribution function: Self consistent $A_{||}$, ϕ

Construct POD of distribution function:

$$g_{kx,ky}(z,v_{||},\mu,t)=\sum_n f^{(n)}_{kx,ky}(z,v_{||},\mu)h^{(n)}_{kx,ky}(t)$$

➔Tearing parity mode with large EM heat flux (POD n~2-5)