# Saturation of Instability-Driven Turbulence in Confined Plasmas

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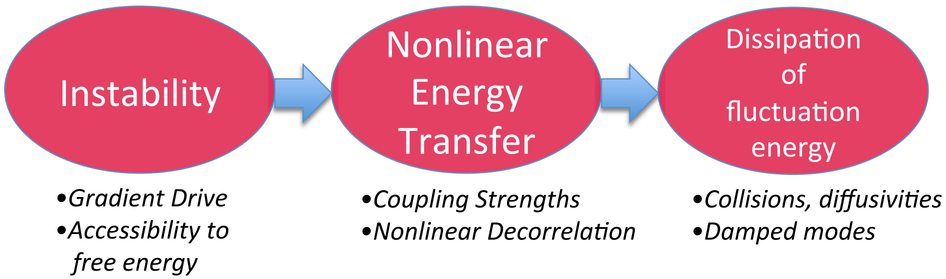
# Saturation of instability-Driven Turbulence in Magnetic Confinement Devices is a Discovery-Science Frontier

Saturation is an extremely important problem




Saturation sets fluctuation levels, spectra, and transport rates

Saturation must be understood for transport reduction strategies

Saturation in kinetic systems (phase space) is a highly complex phenomenon involving interplay among multiple constituents

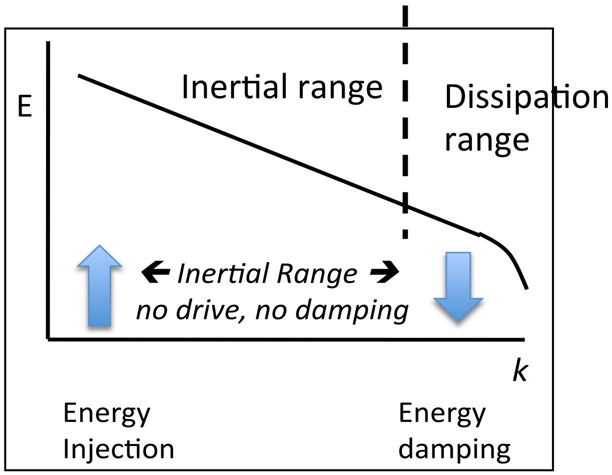
Saturation has received relatively little attention

There are many fundamental open questions

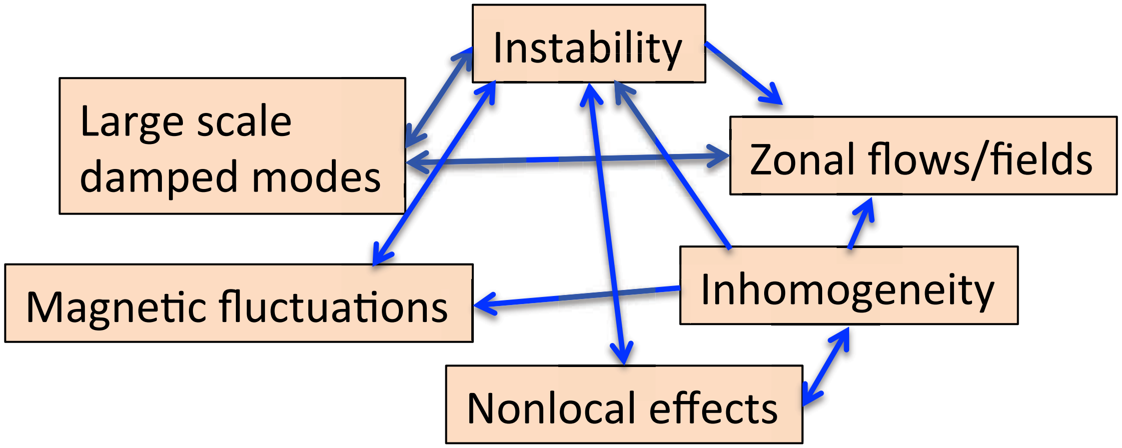
# Saturation is a self-organized process

Self organization is present in simplest saturation problem: Kolmogorov spectrum

- Nonlinearity sets fluctuation level at each scale so that rate of energy transfer from scale to scale is invariant




Magnetically confined plasmas have many additional separate elements




Each can affect fluctuation level, spectrum and transport

Many interaction and feedback loops

- –Not well understood
- –Not all identified

# Saturation is a frontier, despite long history, because historical approaches are too simple

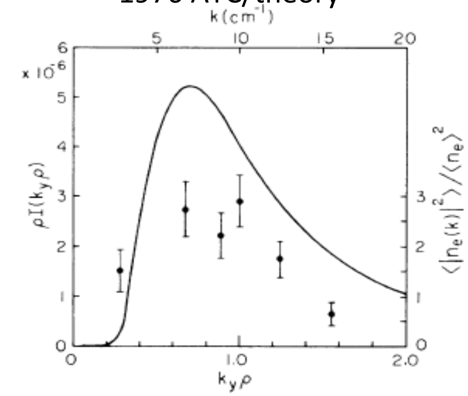
Historical approaches (before comprehensive numerical models)

- Statistical smoothing of nonlinearity (renormalization, closure)
- One-step approaches to balancing of instability energy input with nonlinearity
  - Nonlinear energy transfer to high k
  - Quasilinear flattening of driving gradient
  - Change of eigenmode to modify drive and/or damping

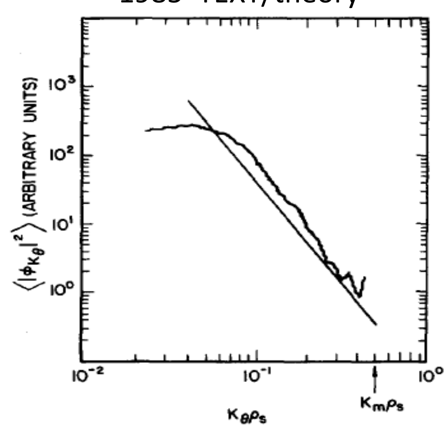
Multiple constituents and complexity of their interactions were not recognized or treated

Agreement with experiment was fortuitous

1976 ATC/theory




1985 TEXT/theory



# Outline

- Description of various feedback loops for interplay of constituents
  - Known interactions
  - Examples
  - Key questions
- Approaches
- Impacts

# Instabilities drive zonal flows/fields, which in turn reduce fluctuation levels and transport

Under study for 15+ years, but *crucial* aspects have been missed (next slides)

Zonal-flow drive by instability described as modulational instability, secondary instability, parametric instability

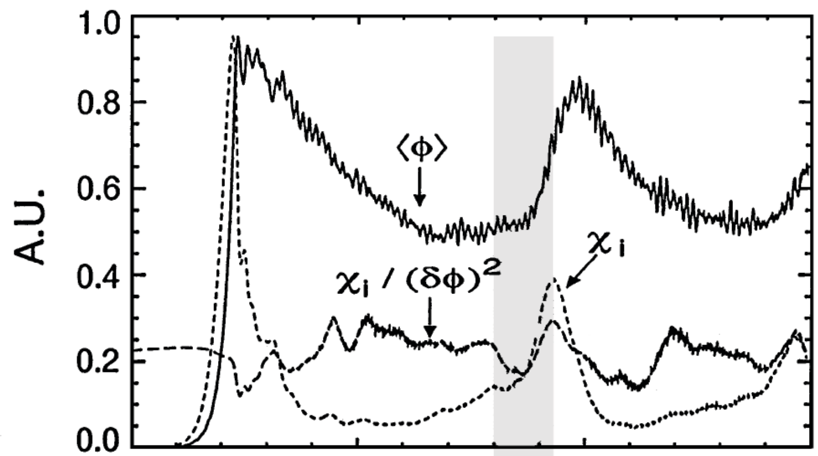
(2 unstable wavenumbers of instability beat to drive zonal flow at $2 \times \gamma$)

Unified picture with GFD: zero frequency mode of wave anisotropy driven by inverse cascade

Zonal flows reduce turbulence levels

Assumed mechanism: E×B shearing

Shearing can be too weak to reduce



Z.H. Lin, 1999

What sets level of zonal flow (collisionless)?

Zonal flows both driven, damped by nonlinearity – what governs ratio?

What is relative importance of shearing versus non shearing mechanisms

# Instabilities drive damped modes at same perpendicular wavenumbers; multiple instabilities may be present at any wavenumber

Gyrokinetic phase space ($x,y,z,v_{||},\mu$)

$x,y$ -> perpendicular wavenumber space

$z,v_{||},\mu$ -> eigenmodes of inhomogeneity – a few grow, many are damped

Damped modes excited by nonlinearity

Dissipate energy in unstable wavenumber range

Huge energy sink for saturation

What is role of subdominant instabilities?

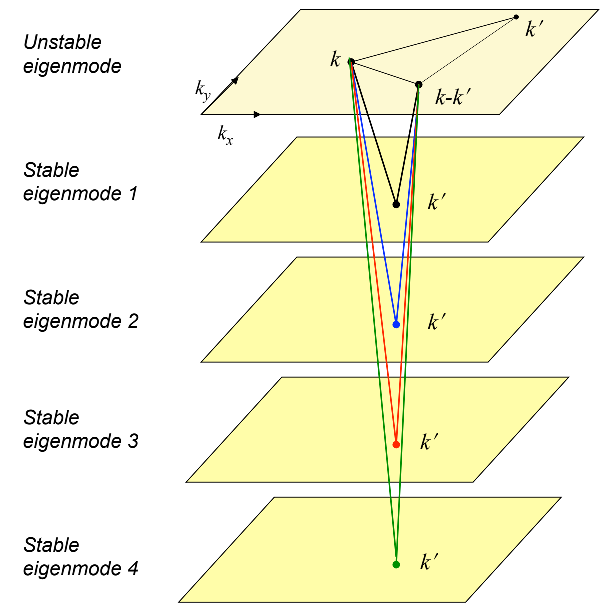
What sets level of damped modes?

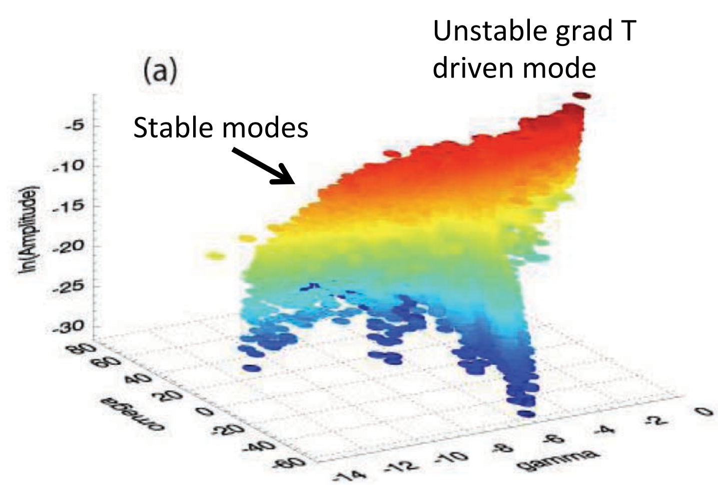
–for different instability drives, collisionality, etc.

How do damped modes affect unstable mode level?

What governs amount of energy going to and dissipated in damped modes vs. transfer to high k?

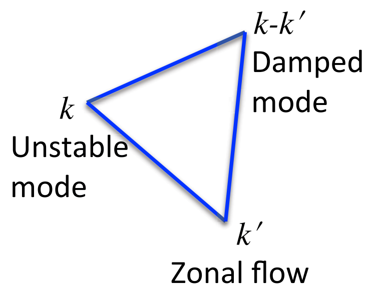
How does it scale with collisionality, driving gradients, beta, shear, etc.



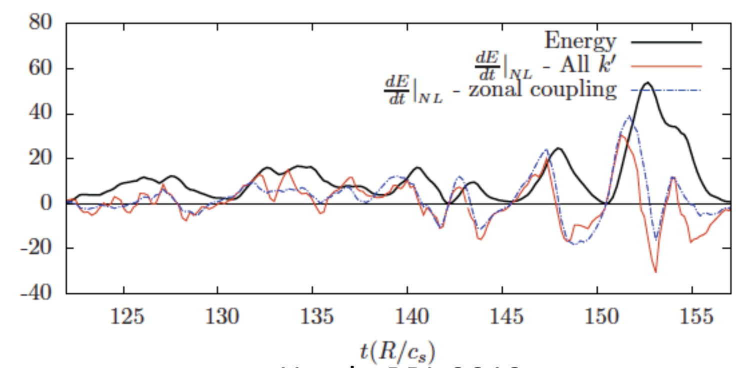
# Zonal flows catalyze nonlinear transfer to damped modes

Nonlinear energy transfer dominated by:




damped mode gets 90%

zonal flow gets 10%



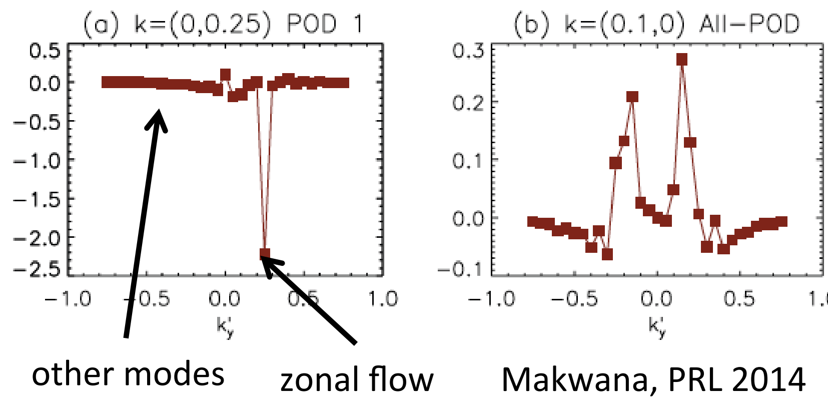

Hatch, PRL 2012

Frequency mismatch (nl interaction time) and zf amplitude make very efficient transfer channel

Reduces fluctuation level (by efficiently accessing sinks) - alternative to shearing mechanism

Transfer from unstable mode

Transfer to zonal flow




Makwana, PRL 2014

What are relative contributions to saturation of catalyzed transfer to damped modes and shearing?

What accounts for dominance of transfer channel to damped modes involving zonal flow?

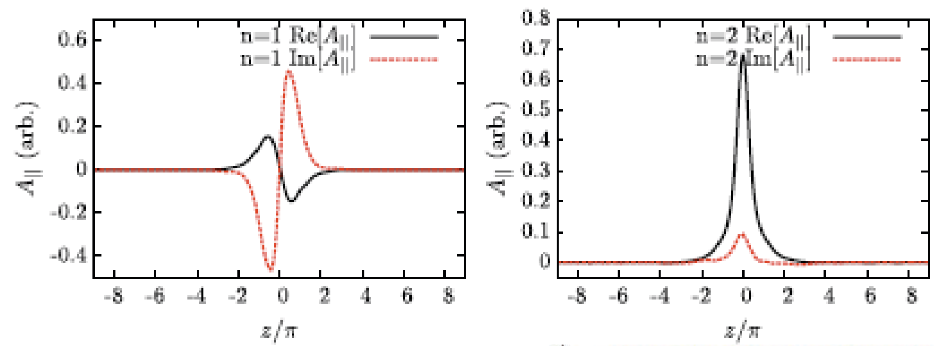
What governs differences in zonal flow drive for different instability regimes and different $\beta$ values?

# Damped modes in finite beta turbulence driven by electrostatic instabilities can tear magnetic surfaces

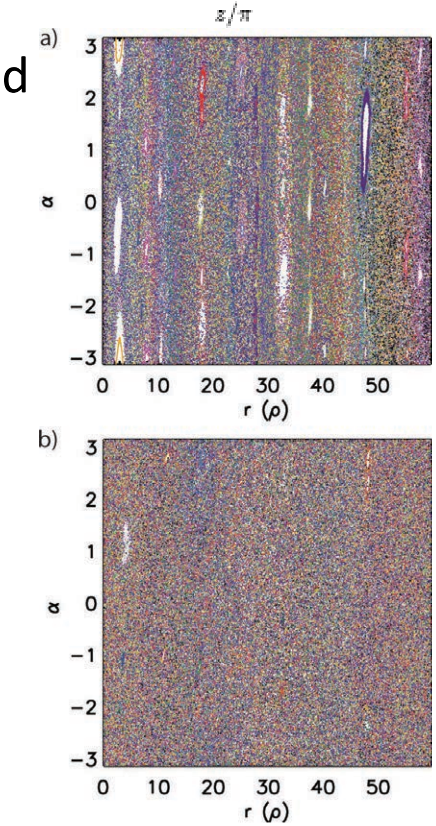
At finite $\beta$ electrostatic instabilities even parity magnetic flux function

=> no tearing

Largest amplitude damped mode has odd parity, tears magnetic surfaces




- Character of turbulence and transport fundamentally changed
- Flutter-induced electron heat transport channel opened
- Zonal flows abet electron thermal transport
- Quasilinear transport approximation fails




Under what conditions do damped modes fundamentally alter nature of saturated state and its transport

When are quasilinear transport approximations valid?

What are breakdown modalities?

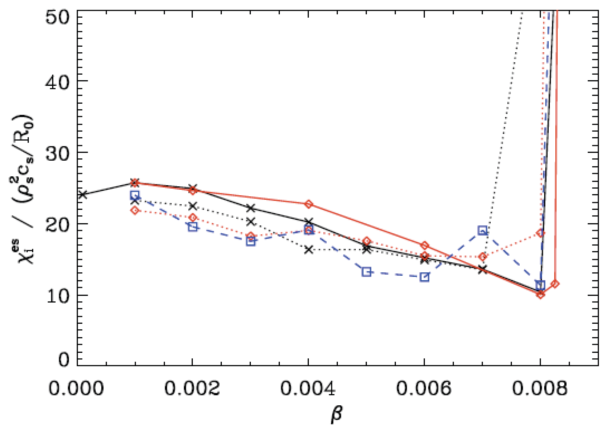
# Magnetic fluctuations can reduce level of zonal flows, raising level of transport

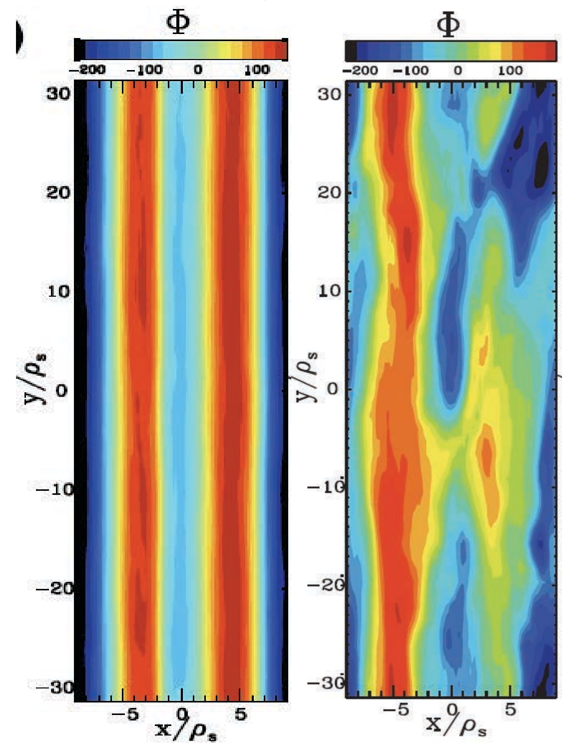
High $\beta$ runaway now known to arise from disabling of zonal flows by magnetic fluctuations

Magnetic fluctuations arise as damped mode

Above critical $\beta$ charge lost irreversibly from rational surface – zonal potential shorted

In RFP, residual tearing fluctuations in plasma with current profile control reduce zonal flows, produce higher transport from trapped electron modes




Which instabilities drive magnetic damped modes?

What is effect on zonal flow levels and transport?

What is effect external magnetic perturbations (RMP) on zonal flows and saturation?

# Turbulent transport feedback on growth rate makes transport intrinsically nonlocal and nondiffusive

Local transport modifications of profiles couple across a driving gradient profile

- Produces nonlocal avalanche-like transport events
- Tends to drive profile to a subcritical value, modifying instability
- Transport becomes fundamentally nonlocal, nondiffusive, and bursty

How do transport modifications of instability affect zonal flow drive, damped mode excitation, and their contributions to saturation?

# Integration of feedback loops in self organized process and other considerations

Feedback loops have been probed in isolation

- How do they fit together?

What happens in different regions of plasma, e.g., core, pedestal, edge?

How is picture modified when there are scale separations?

- –Between zonal flows and instability
- –Between damped modes and zonal flows

Same instabilities occur for tokamak, RFP, stellarator, but saturation can be different - can above processes explain differences?

How do boundaries affect saturation process?

# Approaches I: mode decomposition

Saturation should be studied with interactive approach between experiment, theory, simulation

Fluctuation decomposition techniques should be applied to expt, simulation

(SVD or POD, linear eigenmode)

Decompose fluctuations

Decompose energetics measures

Dissipation rate

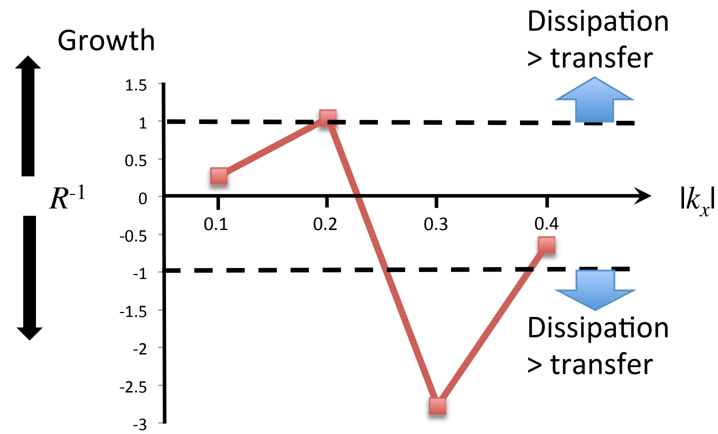
Spectral transfer rate

Mode decomposition represents

new and unique rung on primacy

hierarchy for validation

Ratio of energy dissipated to energy transferred




Fluctuation-decomposed bispectral analysis probes energy transfer to

damped modes and high wavenumber

# Approaches II: study multiple configurations

- Different confinement configurations (tokamak, stellarator, RFP) have same set of microturbulence instabilities (and driving gradients) and zonal flow phenomenology
- Confinement configurations have very different magnetic shear, safety factors, collisionality, $\beta$ values
- Theory and simulation studies across configurations allows separation of drive from nonlinear saturation processes
- Different configurations also have different diagnostic capabilities
- Theory and simulations should be compared for multiple configurations using full validation prescriptions (Terry et al., PoP, 2008)

# Impacts

Saturation governs transport in fusion devices and energization in astrophysics

Thorough understanding will lead to

- improved transport models
- validated modules for integrated modeling
- predictive capability
- transport reduction strategies

Saturation scenario described above is not universal but applies to

- microturbulence in tokamaks, RFPs, and stellarators
- Damped modes occur in many other instabilities

  (Rayleigh-Taylor, Kelvin-Helmholtz, current sheets)

Zonal flows are analogous to large scale symmetry-breaking structures in GFD

  Zonal flows in stratosphere, planetary zonal flows, Taylor-Proudman columns