Gyrokinetic Simulations of Energetic Particle-Driven TAE/ EPM Transport Embedded in ITG/TEM Microturbulence

by
E.M. Bass

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GENERAL ATOMICS

Outline: A Fully-gyrokinetic Treatment of Energetic Particle Instabilities and Transport

The gyrokinetic code GYRO gives energetic particle (EP) transport by low-*n* Alfvén eigenmodes (AEs) and high-*n* microturbulence, made possible by a gyrokinetic treatment of all particle species

Local, linear simulations show multiple AEs — driven unstable by hot alpha particles — alongside core ion temperature gradient (ITG) and trapped electron mode (TEM) microturbulence

Nonlinear simulations reveal that destabilized AEs can cause weak or strong EP transport. Microturbulence can push the onset of strong EP transport to higher EP driving gradients

Whether causing strong our weak EP transport, the present low-*k* AEs do not appear to hurt thermal species confinement

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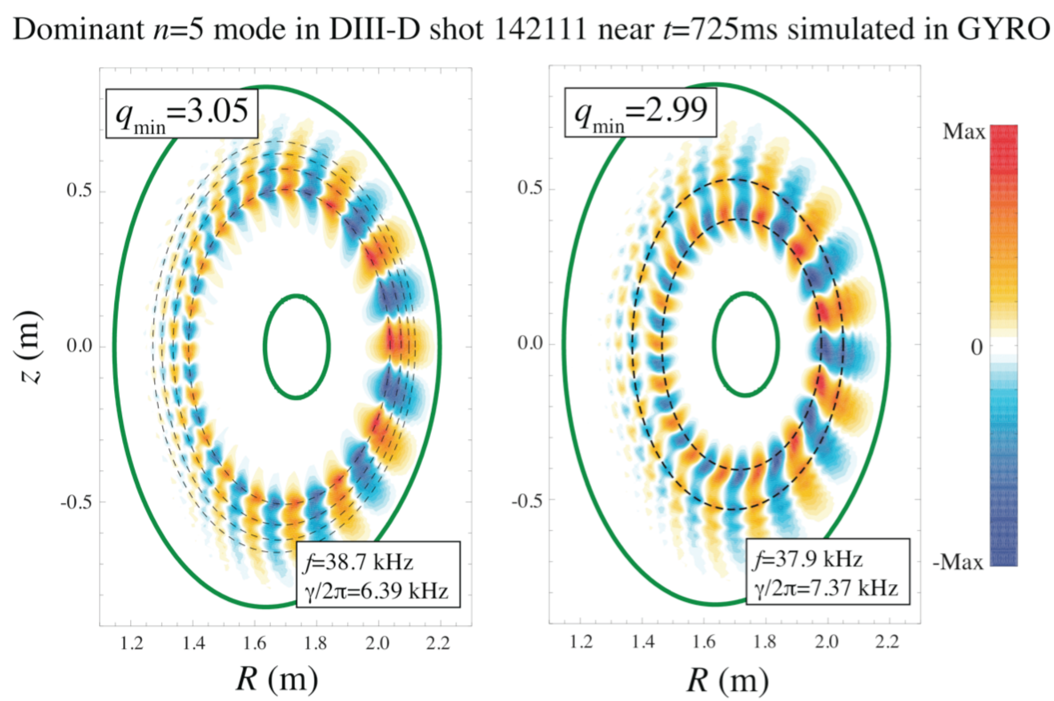
Instabilities Excited by Energetic Particles (EPs) May Limit Heat Confinement in ITER and Beyond

Energetic particles (EPs), particularly fusion-produced alpha particles, can excite a variety of Alfvén eigenmodes that may cause heat loss in the EP channel and thwart a burning plasma scenario

- **The toroidal Alfvén eigenmode (TAE) exists in ideal MHD, but is driven unstable by EPs**
- **The energetic particle mode (EPM) is predicted when gyrokinetic EPs are treated non-perturbatively**
- **A full gyrokinetic treatment shows these modes (and others) lie on a continuum**



We treat EP transport by local Alfvén eigenmodes (small ρ_* limit) with the gyrokinetic code GYRO

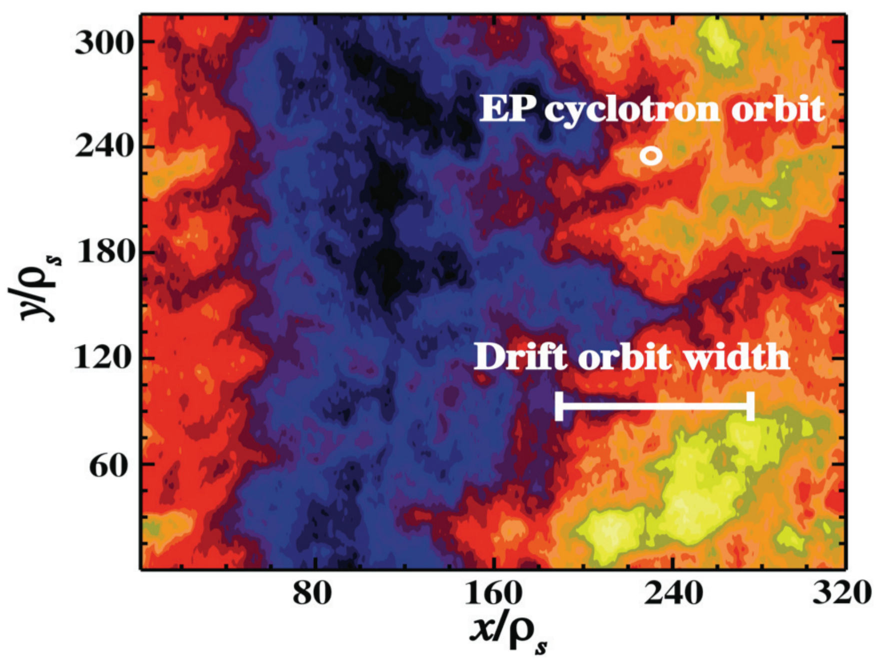
L. Chen and F. Zonca, Nucl. Fusion **47**, S727 (2007). (and references therein)

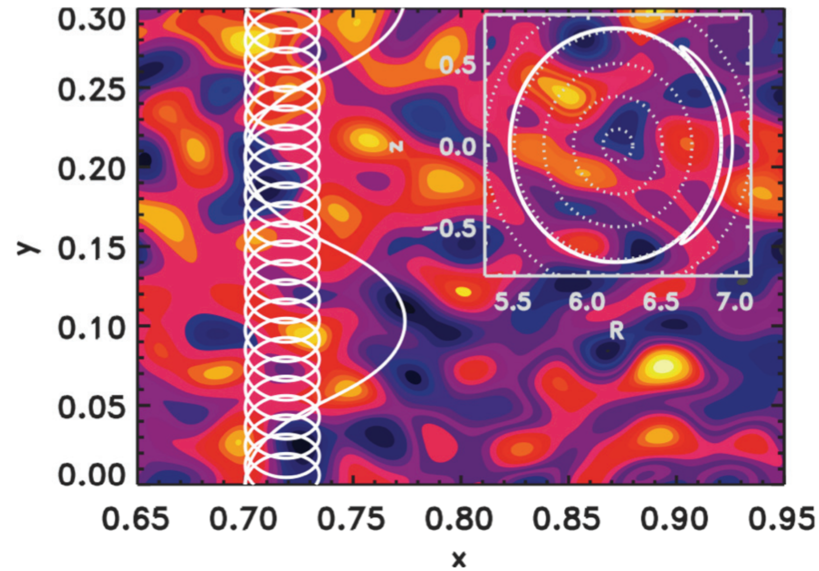
Long-wavelength TAE/EPM Modes Can Couple to EPs with Large Orbits

Large EP orbits partially average over short-wavelength ITG/TEM fluctuations. Induced flux is finite but small

$$D_{\text{EP}} \propto \left(\frac{T_i}{E_{\text{EP}}}\right)^{\alpha} \chi_i \quad ; \quad \alpha \geq 1$$

ϕ - <ϕ> in a nonlinear GYRO run with driven TAE/EPM turbulence. n_{EP}/n_e=0.007, a/L_{EP}=4, all other parameters GA standard case





Drift orbits for two 100keV EPs (trapped and passing). Adapted from Hauff and Jenko (2008)

However, TAE/EPM instabilities have longer wavelength. Orbit averaging does not reduce these long-wavelength fluctuations

But we can still treat TAE/EPM fluctuations as local microturbulence at sufficiently small ρ_*

W. Zhang, Z. Lin, and L. Chen, PRL **101**,095001 (2008)
T. Hauff and F. Jenko, PoP **15**, 112307 (2008)

Alfven eigenmodes as Local, High-*n* Microturbulence

We treat the TAE and EPM in the local microturbulence paradigm, qualitatively different from global MHD-background, kinetic-EP studies

Global
- ✓ Low-*n*
- ✓ Saturation usually via particle trapping and distribution function flattening

Local
- ✓ Higher-*n*, steady-state fluctuation intensities and fluxes with fixed driving gradients
- ✓ Saturation via radial flow shear non-linearly driven at *n*=0 (zonal flows)
- ✓ Largely analogous to ITG/TEM turbulent transport

Strongest kinetic drive seen at $k_\theta \rho_{\mathrm{EP}} = \frac{nq}{r}\rho_s\sqrt{\frac{m_i T_{\mathrm{EP}}}{m_{\mathrm{EP}} T_i}} \approx 0.3$, equivalent to $k_\theta \rho_s \approx 0.04$

DIII-D
$n \approx 4$

ITER
$n > 12$

Decreasing $\rho_* = \rho_s / a$

$\rho_* \approx 0.0025$ → $\rho_* \approx 0.0008$

As device size (and/or magnetic field) increases, Alfvén eigenmodes look more and more like microturbulence

Microturbulence Interacting with Alfven Eigenmodes Creates a "Soft" Transport Regime

Without microturbulence:

The *critical gradient* of strong, intermittent transport onset is very near the linear stability threshold of Alfvén eigenmodes (Aes)

With microturbulence:

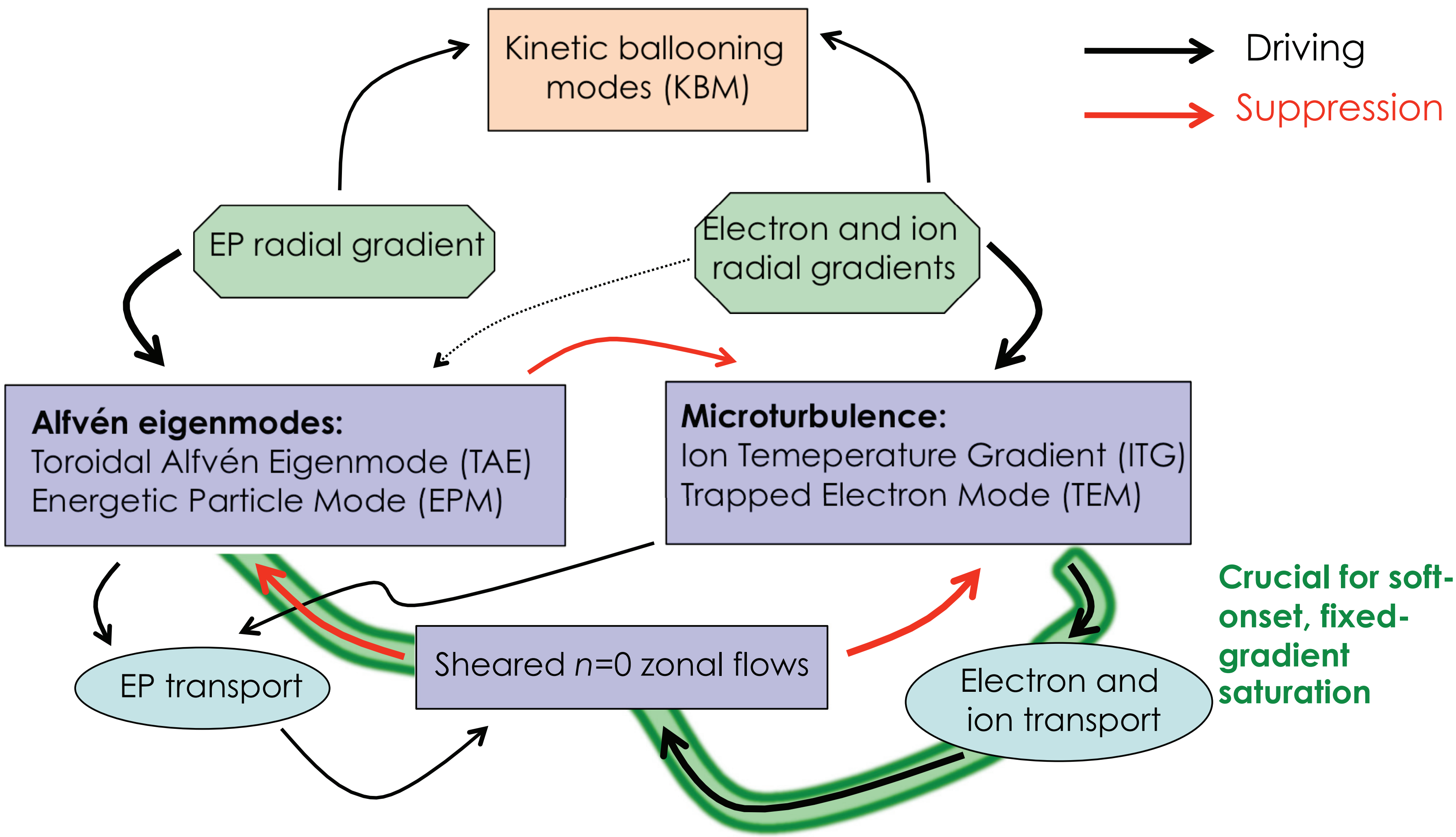
The *critical gradient* is pushed above TAE/EPM linear threshold by microturbulence-driven zonal flows. Three transport regimes exist

Microturbulent transport	"Soft Onset" TAE/EPM transport	Strong TAE/EPM transport
Below (and just above) the TAE/EPM stability threshold, microturbulence drives EP transport	Above the TAE/EPM linear stability threshold, but below a *critical gradient* (up to twice the threshold drive level), EP transport is enhanced with a "soft onset."	Above the *critical gradient*, strong (and intermittent transport) appears.

By moving the *critical gradient* to higher EP drive, microturbulence may allow steeper EP profiles in fusion devices.

F. Zonca et. al. in *Theory of Fusion Plasmas*, ed. J. W. Connor et. al. (Editrice Compositori, Bologna, 2000), pp. 17–30.

Complex Interdependencies Govern Microturbulent Interaction with AEs



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Hot Alpha Particles Added to the GA-standard Flux Tube Scenario

Electromagnetic, flux-tube simulations to study destabilized Alfvén turbulence

Simulation requirements:

- **Include a Maxwellian EP species with a sufficiently large density gradient to drive TAE/EPM turbulence. Maxwellian distribution means no beam-driven (velocity space) modes (e.g. EGAM). Alright for spatially driven turbulence***
- **Background species gradients to drive the usual ITG/TEM turbulence, generating larger zonal flows to help EP driven modes saturate**
- **Physically relevant parameters that can be easily compared to previous simulations**

Choose a deuterium plasma (GA standard case) with sparse, hot α particles:

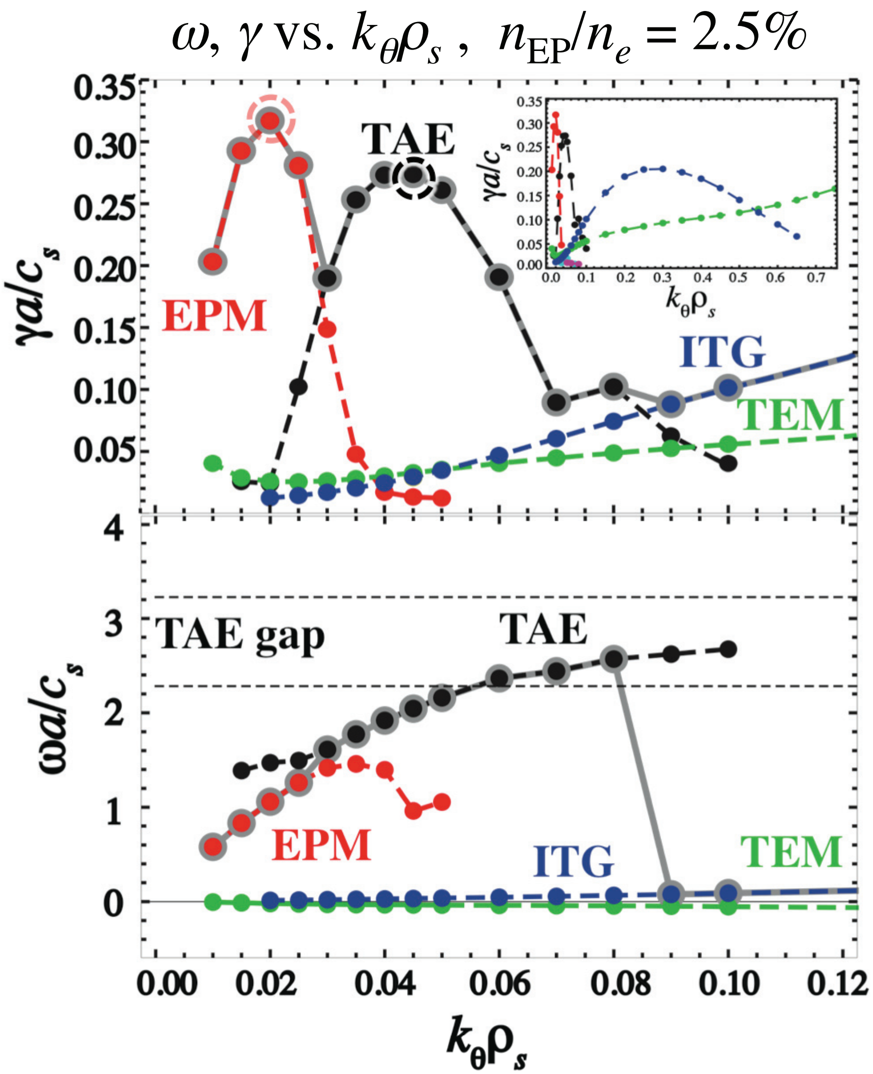
$q = 2$	$b_e = 0.002$	$T_{EP}=100T_e$	Energetic particle parameters
$s = 1$	$T_i = T_e$	$a/L_{nEP} = 4$	
$R = 3a$	$a/L_{ne} = a/L_{ni} = 1$	$a/L_{TEP} = 0$	
$r = 0.5a$	$a/L_{Te} = a/L_{Ti} = 3$	$0.5\% \leq n_{EP}/n_e \leq 3.5\%$	

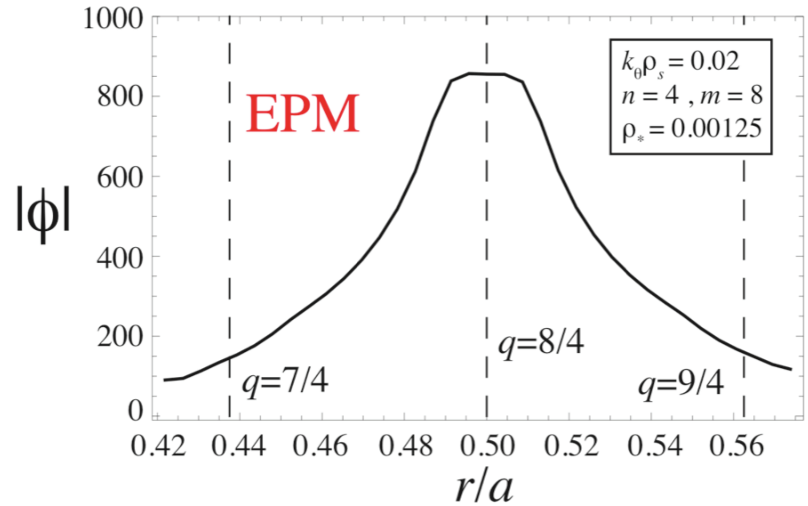
Note: $\frac{v_{\mathrm{th\,EP}}}{c_s} = 10 << \frac{v_A}{c_s} = 31.6$

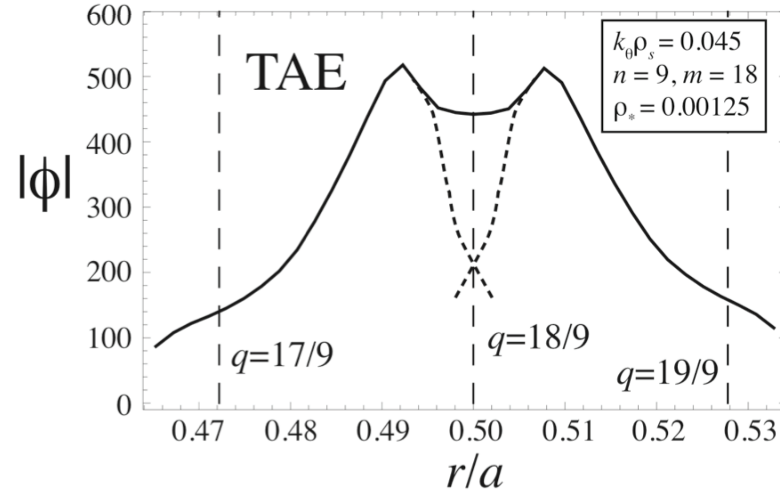
Only n_{EP} varies. With all gradient lengths fixed, this is equivalent to varying the EP kinetic drive $dP_{EP}/dr = T_{EP} n_{EP}/L_{n_{EP}}$

* C. Angioni, A.G. Peeters, PoP **15**, 052307 (2008)
C. Estrada-Mila, J. Candy, R.E. Waltz, PoP **13**, 112303 (2006)

New GYRO Eigensolver Reveals TAE and EPM Existing Side-by-side



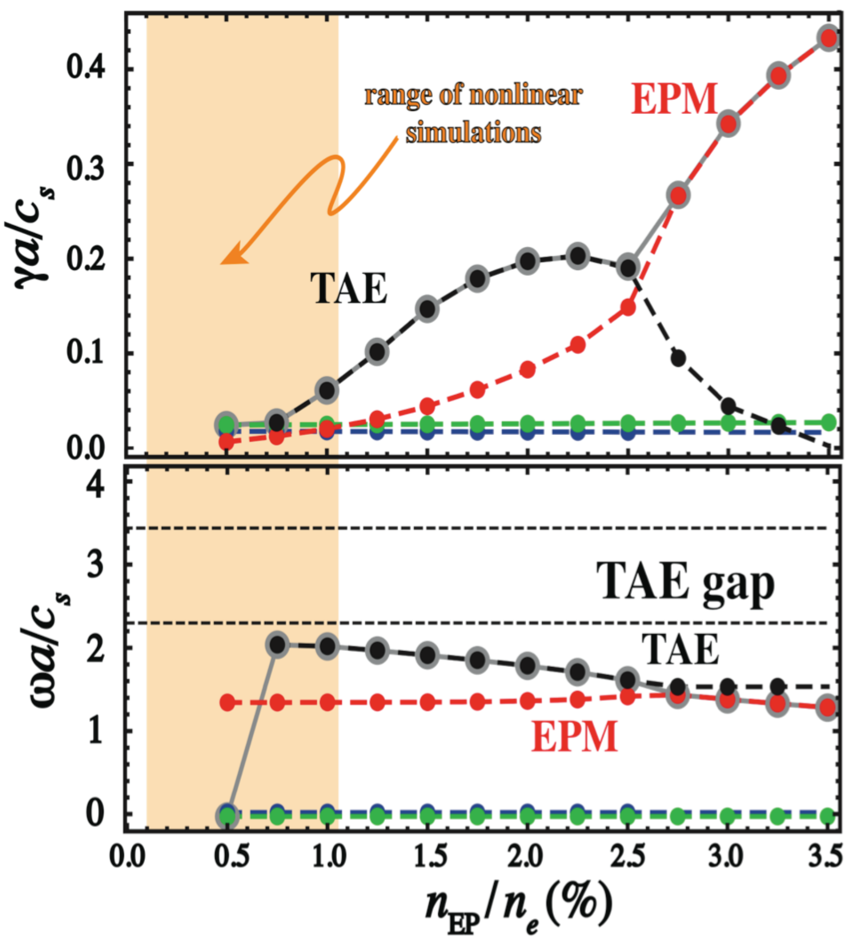




Frequency and growth rate for unstable modes found by the GYRO eigensolver.

At ITER-relevant EP Density, TAE/EPM Linear Growth Rate is Small

$\omega,\ \gamma$ vs. n_{EP} , $k_\theta \rho_s = 0.03$



The density of energetic alpha particles in ITER is likely to remain below n_{EP}/n_e=1.0%.
C. Estrada-Mila, J. Candy, R.E. Waltz,
PoP **13**, 112303 (2006)

In this range, the largest Alfvén growth rates are less than half the peak ITG growth rate. However, weak $\vec{k}_1 \times \vec{k}_2$ coupling to zonal flows (due to low toroidal *n*) makes them potentially more dangerous to EP confinement

For our parameters, the most unstable low-*n* modes lie on the "EPM-like" end of the continuum between the TAE and EPM

Frequency and growth rate for unstable modes found by the GYRO eigensolver

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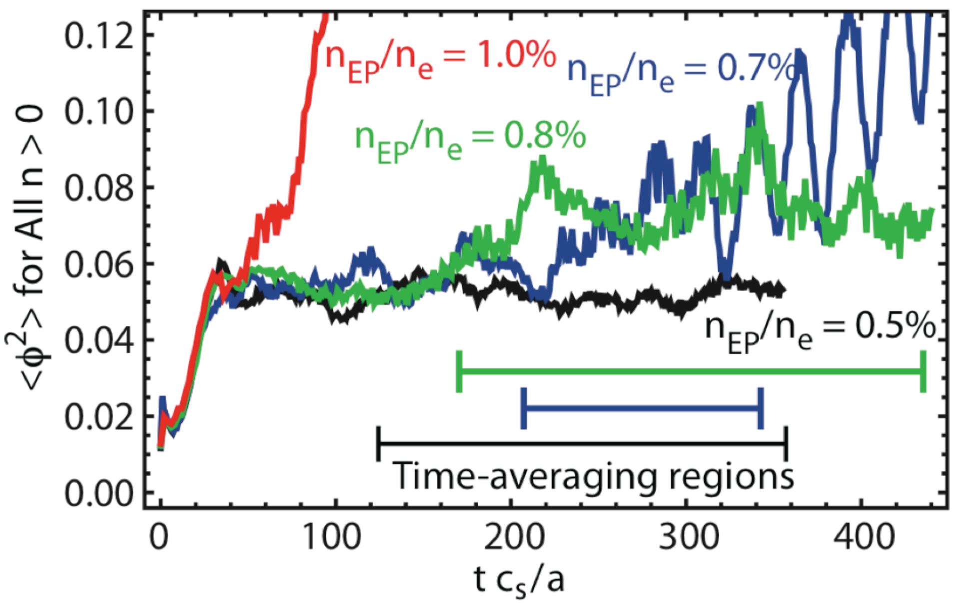
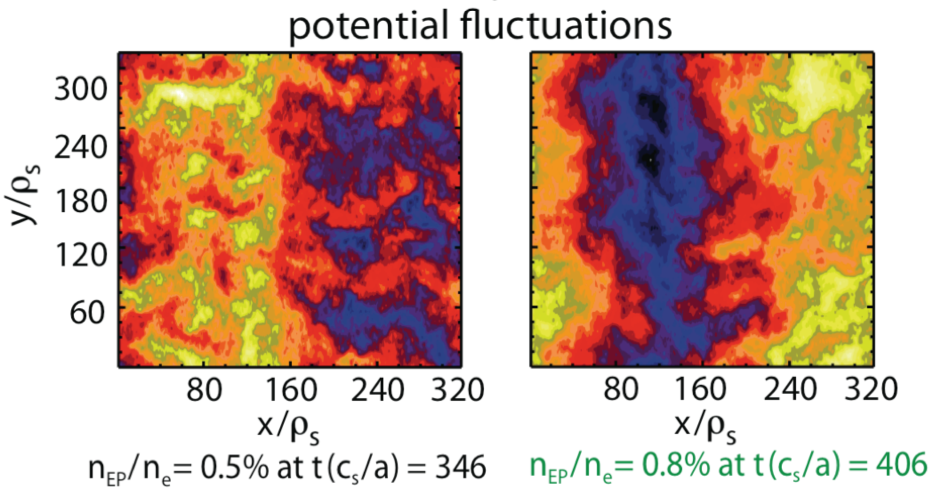
40-mode Nonlinear Simulations Show Onset of TAE/EPM Above EP Drive Threshold





With TAE/EPM drive below threshold, EPs are passive tracers and turbulent spectrum consists of ITG/TEM fluctuations

Above threshold, low-*k* TAE/EPM fluctuations are strong, leading to much larger turbulent vortices

Some finite-drive states do not saturate at long times (reason unknown). We use the quasi-saturated region preceding runaway where it seems reasonable

Above n_{EP}/n_e=0.8%, all simulations show rapid runaway, indicating strong transport that must ultimately saturate by relaxation of the driving EP gradient

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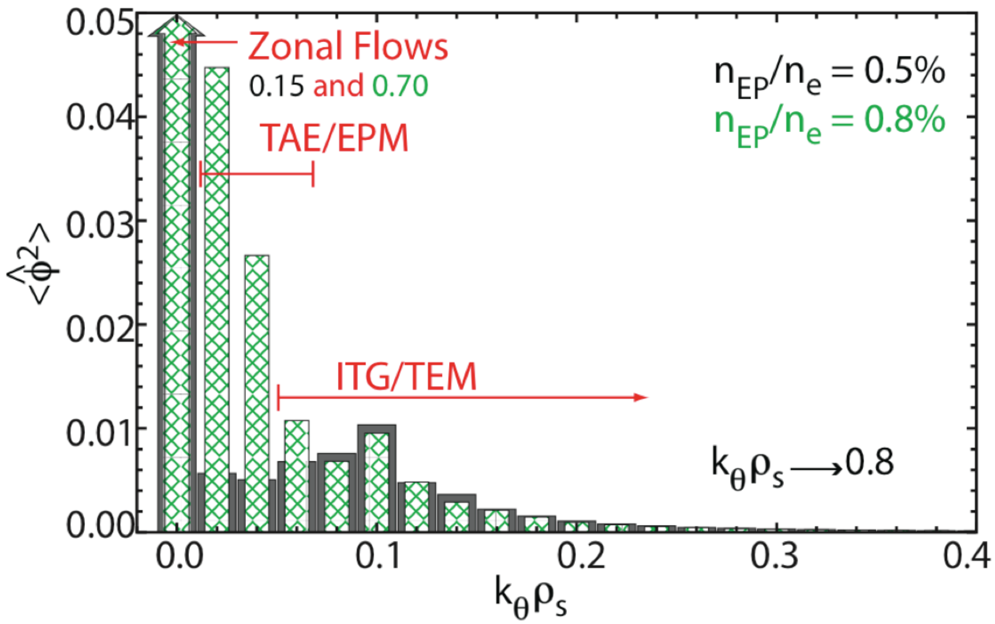
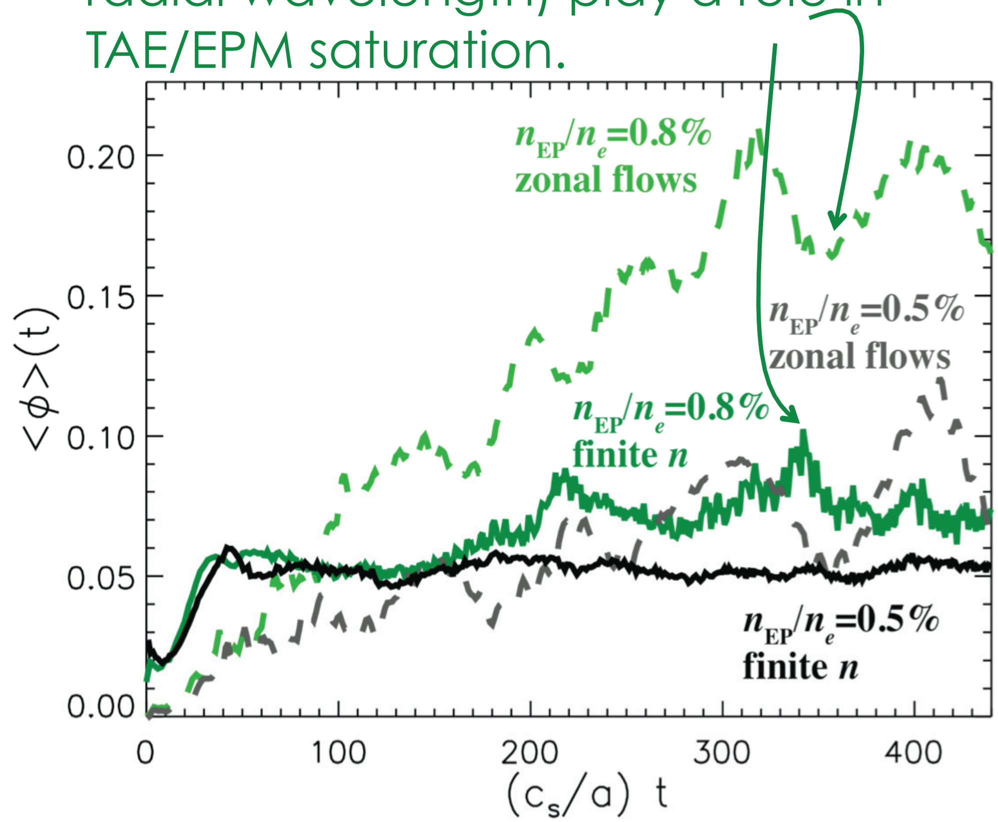
Low-*k* Intensity Increases with TAE/EPM Onset



Low-*k*, TAE/EPM spectral increases in the soft-onset regime.

A slight reduction in ITG/TEM intensity accompanies TAE/EPM onset.

Increased zonal flows in the EP-driven case (primarily at long radial wavelength) play a role in TAE/EPM saturation.



Zonal flow shear ($\Sigma(\phi_k k_r)^2$) comes from short radial wavelength ITG/TEM driven zonal flows and is about the same in EP-driven and un-driven cases.

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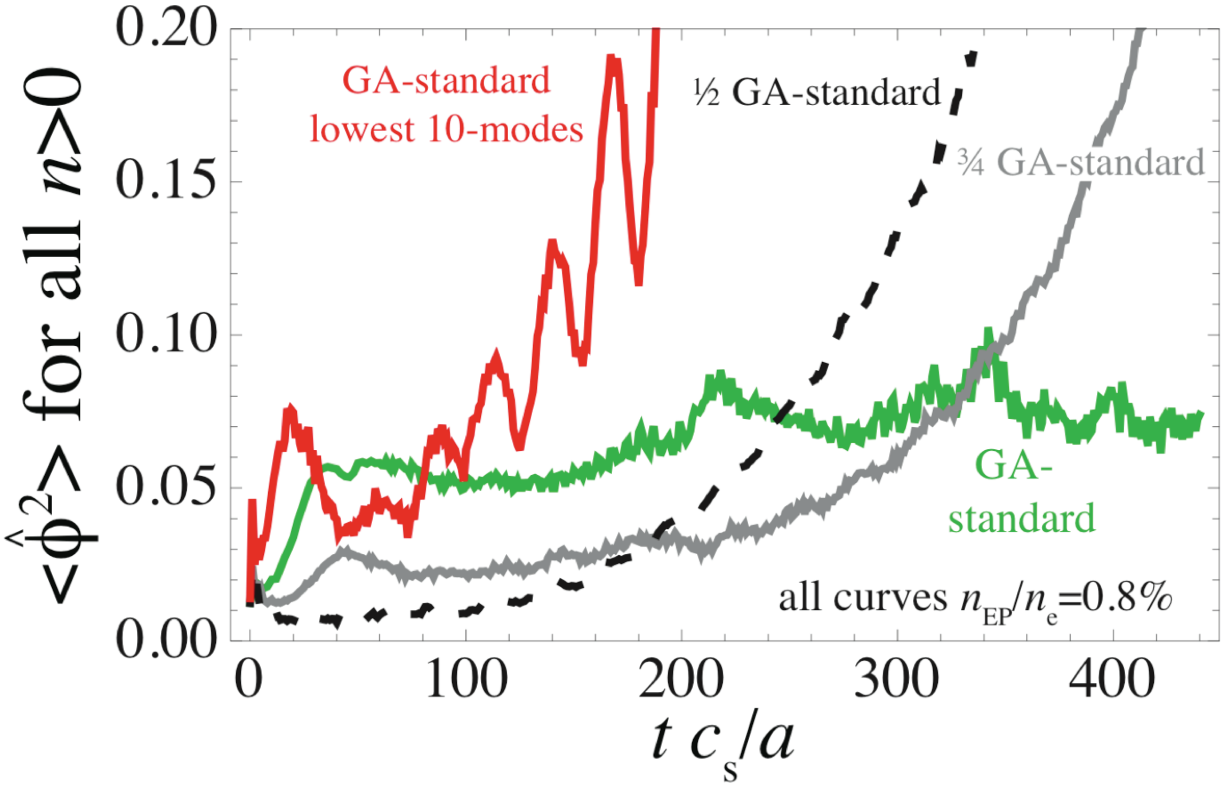
Without ITG/TEM Turbulence, Strong EP Transport Results



ITG/TEM turbulence generates sheared zonal flows that keep TAE/EPM fluctuations in check.

Reducing background gradients (and thus ITG/TEM drive) below the GA-standard values destroys the saturated state.

Removing the ITG/TEM spectral components of the turbulence while keeping background driving gradients at GA-standard values also destroys saturation.

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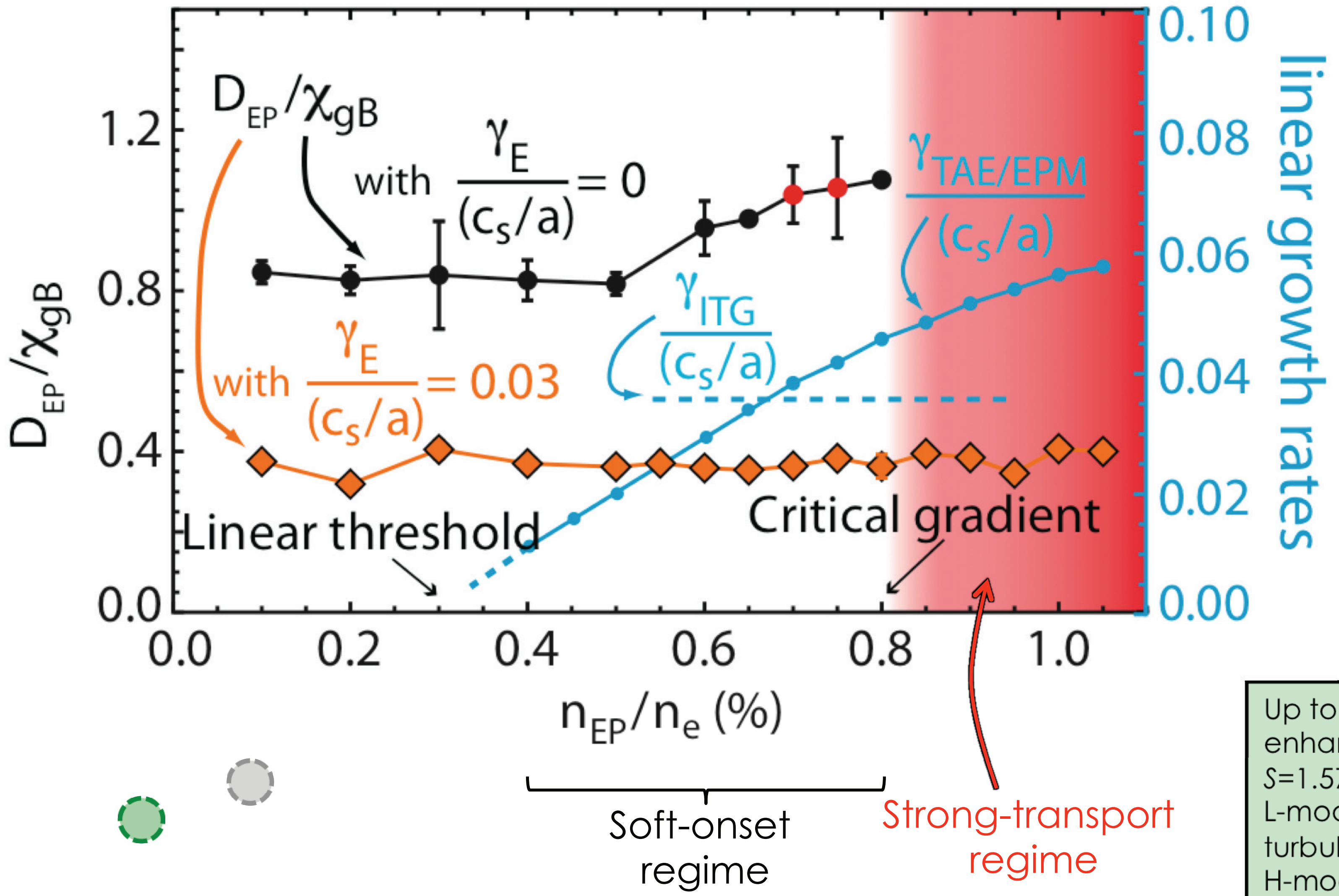
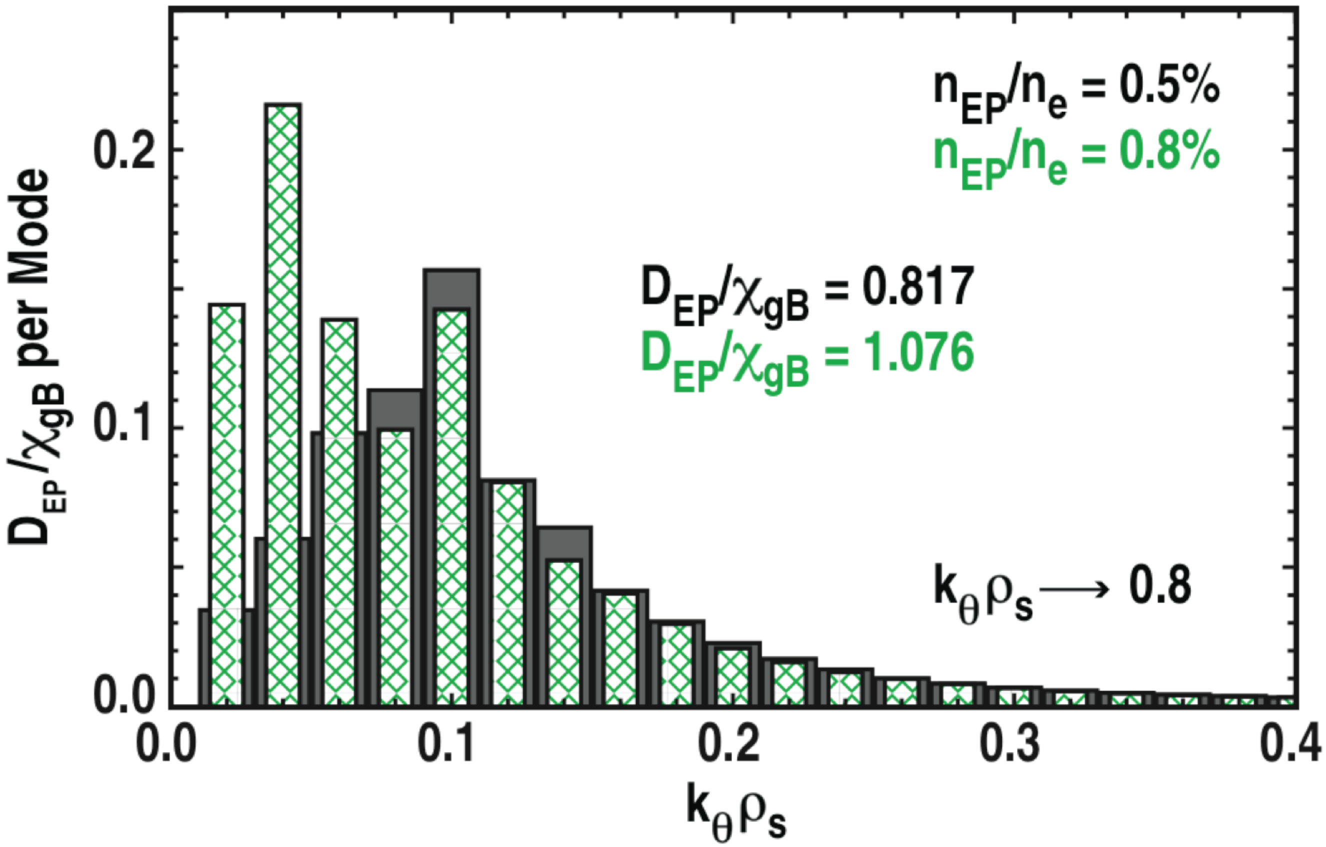
TAE/EPM Causes a Soft Transport Enhancement Until the Critical Gradient is Reached



Up to 66% above transport-enhancement threshold, S=1.57 is well below DIII-D L-mode core ITG/TEM turbulence values (S=2-3). H-mode can be even higher.

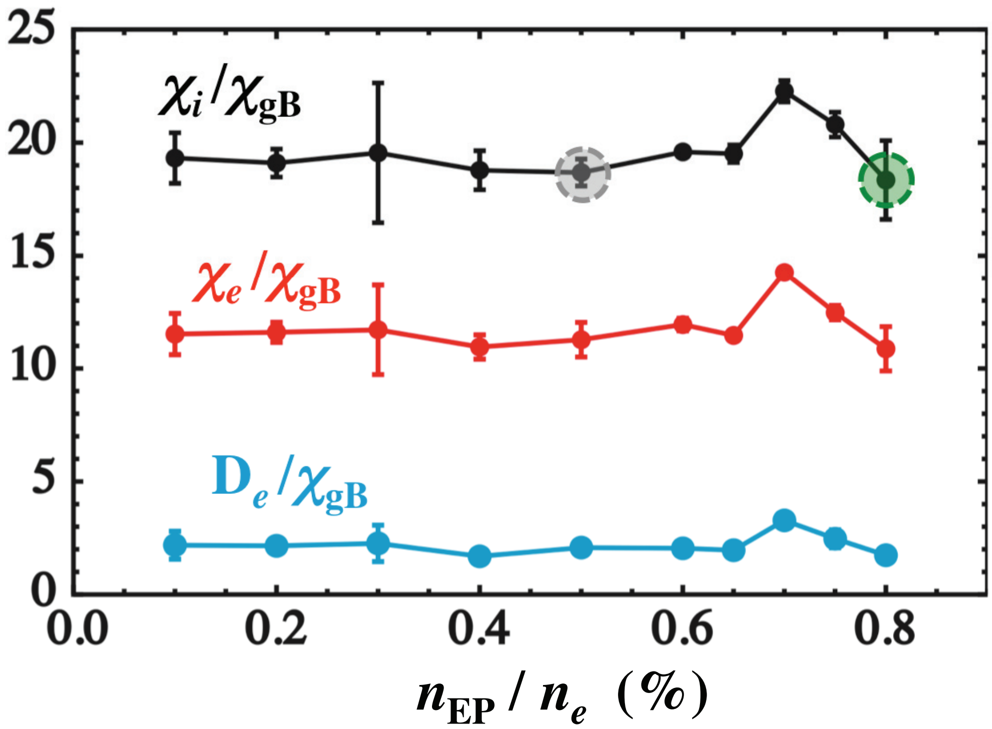
EP Diffusion Spectral Contributions Show Enhancement at Low *k*



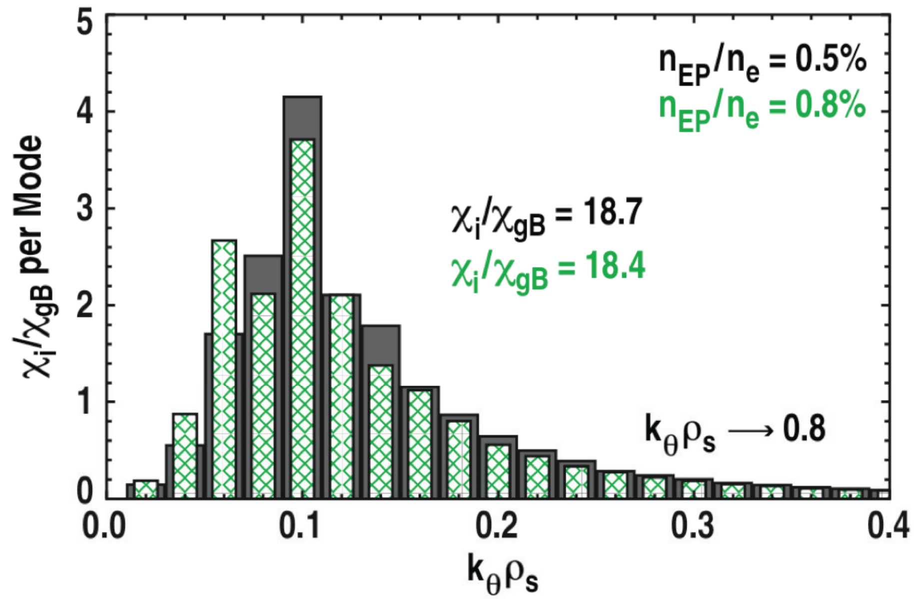
Below threshold, D_{EP}/χ_{GB} is consistent with ITG/TEM tracer transport

TAE/EPM kinetic drive increases EP transport and shifts spectrum to lower k_θ (n)

TAE/EPM Has Nominal Effect on Background Transport



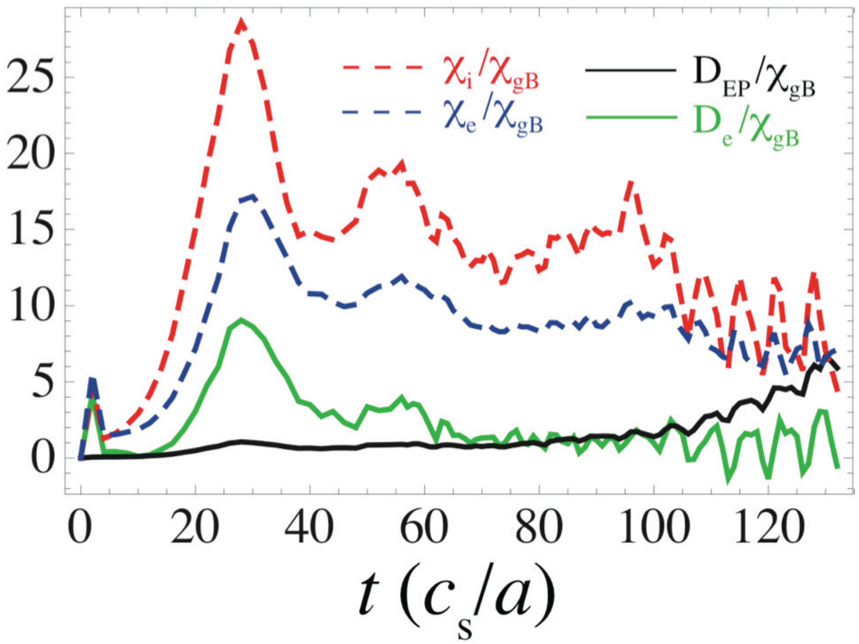
For background species, additional transport from low-k_θ fluctuations is approximately counterbalanced by a shear-induced reduction of higher-k_θ ITG/TEM fluctuations



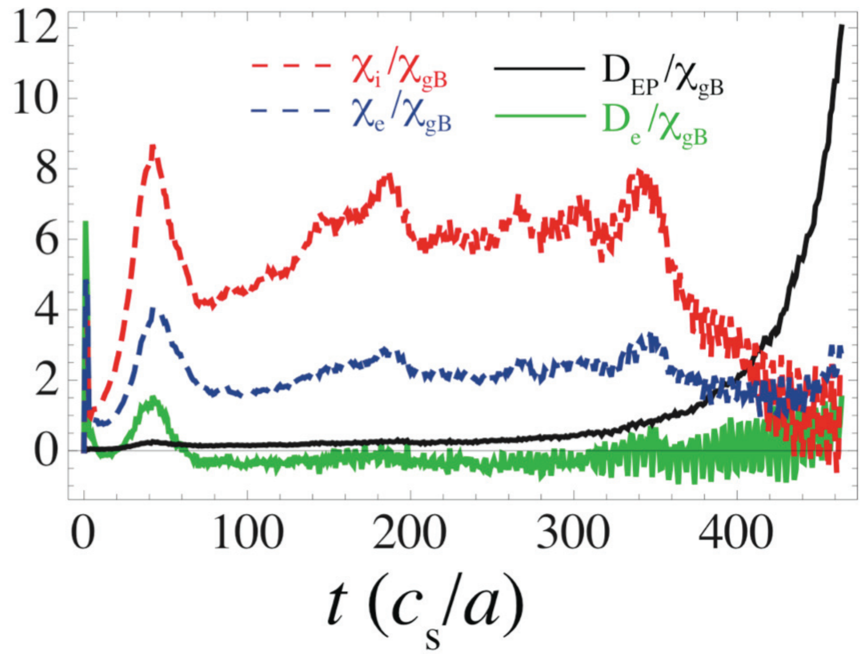
Ion heat diffusivity χ_i shows minimal shift to lower-$k_\theta\rho_s$. Magnitude is nearly unchanged as n_{EP} kinetic drive increases

n_{EP}/n_e	D_{EP}/χ_{gB}	D_e/χ_{gB}	χ_i/χ_{gB}	χ_e/χ_{gB}
0.5%	0.82 ± 0.03	2.08 ± 0.27	18.7 ± 0.6	11.3 ± 0.8
0.8%	1.08 ± 0.01	1.74 ± 0.29	18.4 ± 1.7	10.9 ± 1.0

Runaway States Show Reduction in Background Transport!



n_{EP}/n_e=0.1%, full GA-standard background species gradients



n_{EP}/n_e=0.5%, ¾ GA-standard background species gradients

A rise in low-*n* TAE/EPM suppresses ITG/TEM length scales. Background species transport does not run away.

GYRO Has Successfully Studied Alfvén Eigenmode Transport

- **Energetic particles (and heat) are transported by microturbulence and low-$k_\theta\rho_s$ Alfvén eigenmodes (Aes)**

- **For sufficiently small EP drive, even linearly unstable AEs cause a relatively weak transport enhancement**

- **Above a *critical gradient*, EP transport becomes strong. An intermittentant process of strong transport and EP profile flattening likely takes over**

- **ITG/TEM microturbulence may help EP confinement by pushing the *critical gradient* to higher EP drive. A steeper EP profile is possible with microturbulence.**

- **In all transport regimes, AEs cause very little thermal-species transport. Runaway, low-*k* AEs appear to suppress ion and electron transport.**

The GYRO Code

GYRO is a versatile, parallelized initial-value solver of the gyrokinetic equations (electrostatic or electromagnetic) in toroidal geometry

- ✓ Tracks up to four kinetic species (electrons and three ions), each with a Maxwellian velocity distribution and independent temperature
- ✓ Local (flux tube) or global simulations
- ✓ Treats one toroidal number mode number *n* at a time (linear) or a spectrum of interacting *n* numbers (non-linear)

Linear operation	Non-linear operation
Growth rate, frequency, and eigenfunction of the leading mode	Saturated intensity of linearly driven turbulence Total non-linear diffusion and *n*-dependence

Well benchmarked against several linear, nonlinear, and electromagnetic flux tube gyrokinetic codes (e.g. GS2, GENE, GEM)

http://fusion.gat.com/THEORY/gyro/

J. Candy, R.E. Waltz, JCP **186** 545 (2003)