Measurements (and simulations) of plasma turbulence in toroidal magnetic confinement devices

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AST559/APC539
Turbulence and nonlinear processes in fluids and plasmas
April, 2018

This talk is completely biased and in no way comprehensive

- I've used examples I'm familiar with and find useful for illustration
- See the following for broader reviews and thousands of useful references

- Transport & Turbulence reviews:
  - Liewer, Nuclear Fusion (1985)
  - Wootton, Phys. Fluids B (1990)
  - Carreras, IEEE Trans. Plasma Science (1997)
  - Wolf, PPCF (2003)
  - Tynan, PPCF (2009)
  - ITER Physics Basis (IPB), Nuclear Fusion (1999)
  - Progress in ITER Physics Basis (PIPB), Nuclear Fusion (2007)

- Drift wave reviews:
  - Horton, Rev. Modern Physics (1999)
  - Tang, Nuclear Fusion (1978)

- Gyrokinetic simulation review:
  - Garbet, Nuclear Fusion (2010)

- Zonal flow/GAM reviews:
  - Diamond et al., PPCF (2005)
  - Fujisawa, Nuclear Fusion (2009)

- Measurement techniques:
  - Bretz, RSI (1997)

OUTLINE

<u>Lecture #21 (Wednesday, 4/25)</u>

- Fusion, tokamaks, magnetized turbulence & transport, gyrokinetics
- General turbulence characteristics of magnetized 2D drift waves
- Ion gyroradius scale (ITG/TEM) measurements and theory/modeling validation in the tokamak core
- Multiscale turbulence (spanning ion to electron gyroradius scales consistently)
- ExB shear suppression of ion scale turbulence
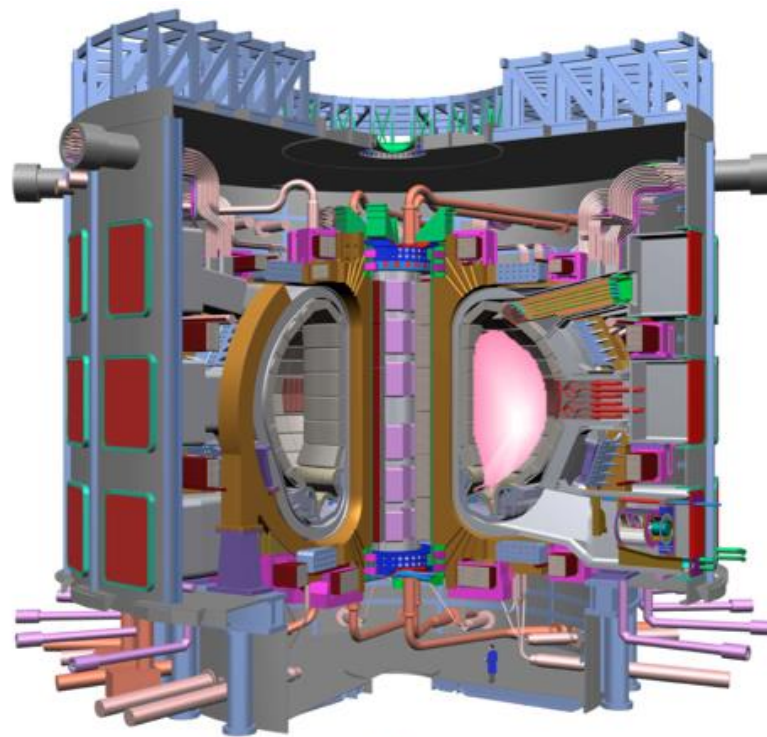- Electron gyroradius scale (ETG) turbulence
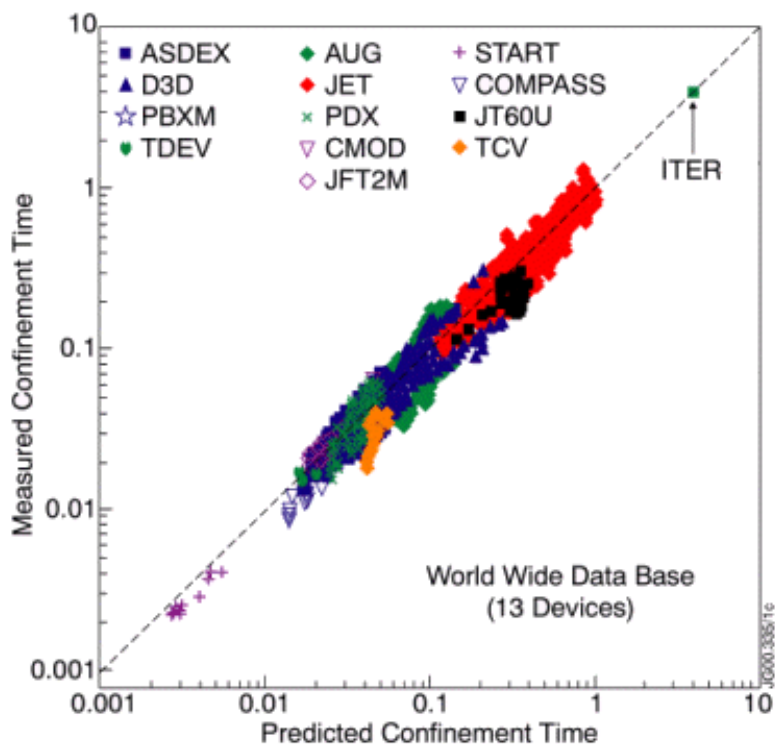
<u>Lecture #22 (Friday, 4/27)</u>

- Finite-beta effects & electromagnetic turbulence (including low aspect ratio influence on ITG stability)
- Zonal flows and geodesic acoustic modes (GAMs)
- L-H transition
- H-mode pedestal turbulence
- Scrape off layer/divertor turbulence
- (Maybe: stellarator turbulence considerations)

Courtesy S. Zweben for some slides and videos
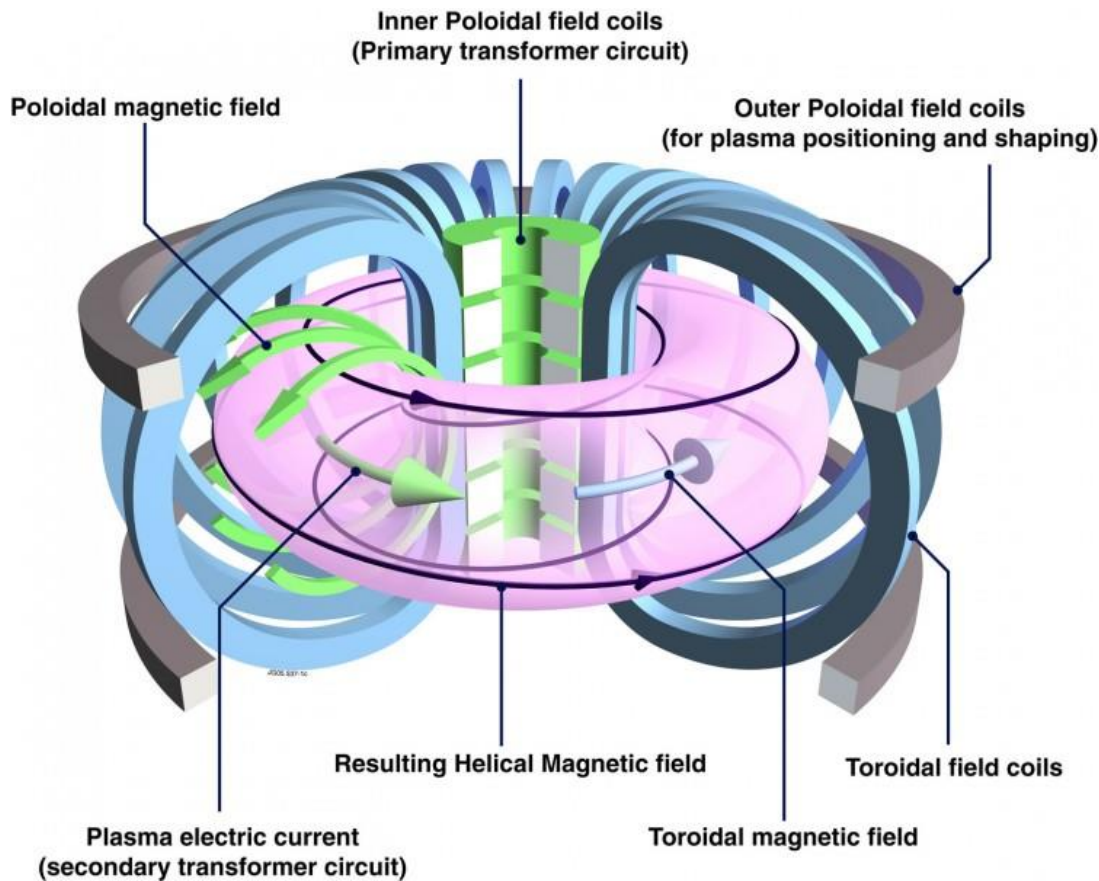
TOKAMAKS AND CONFINEMENT

Magnetic fusion plasmas are a possible solution for large-scale clean energy production

- Need sufficient pressure ($p \sim 2\text{-}4$ atmospheres, at >100 Million $^\circ$C) confined for sufficiently long ($\tau_E \sim 2\text{-}4$ s) for high gain ($P_{fusion} \gg P_{heat}$) burning plasmas

- Confinement time set by turbulence, forces us to pursue huge ($$$) machines, $\tau_E \sim$ pressure $\times$ <u>volume</u> / power

- Can we understand turbulence, and therefore reduce/optimize it for better/cheaper solutions? $\Rightarrow$ **Requires measurement and theory**
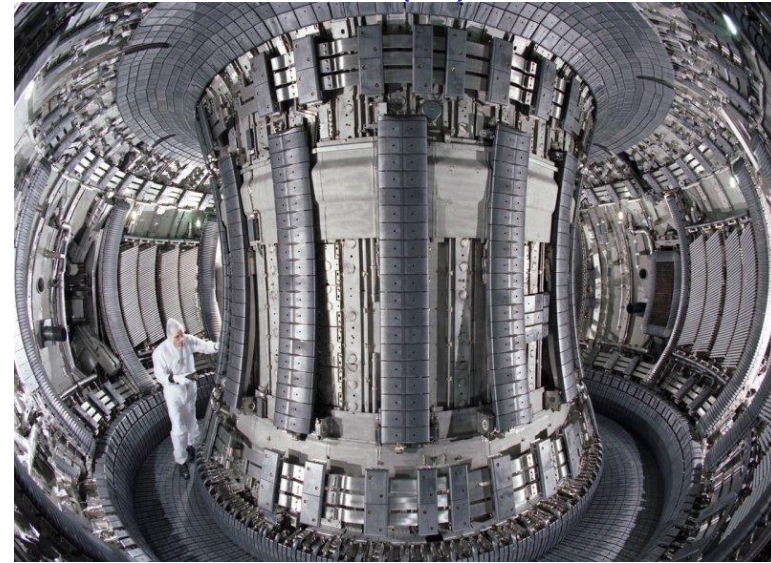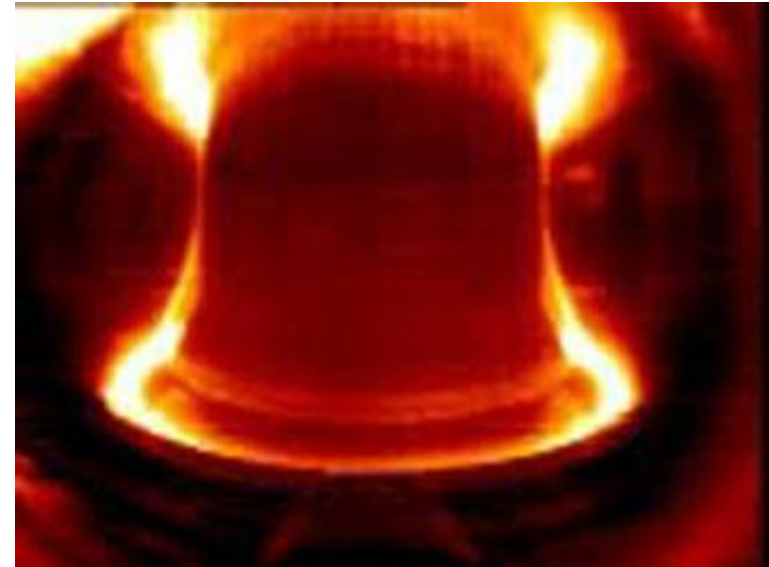
Tokamaks

- Axisymmetric
- Helical field lines confine plasma

JET (UK)

Alcator C-Mod (MIT)

Poloidal magnetic field

Inner Poloidal field coils
(Primary transformer circuit)

Outer Poloidal field coils
(for plasma positioning and shaping)

Resulting Helical Magnetic field

Toroidal field coils

Plasma electric current
(secondary transformer circuit)

Toroidal magnetic field

Inferred experimental transport larger than collisional (neoclassical) theory – extra "anomalous" contribution

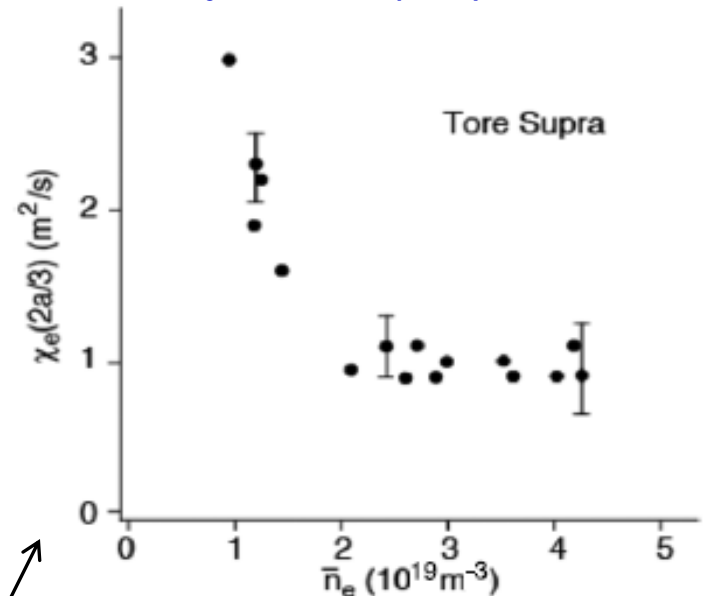**Figure 1.** Results from TFTR showing ion thermal, momentum, diffusivities in an L-mode discharge; reprinted with permission fr American Institute of Physics.

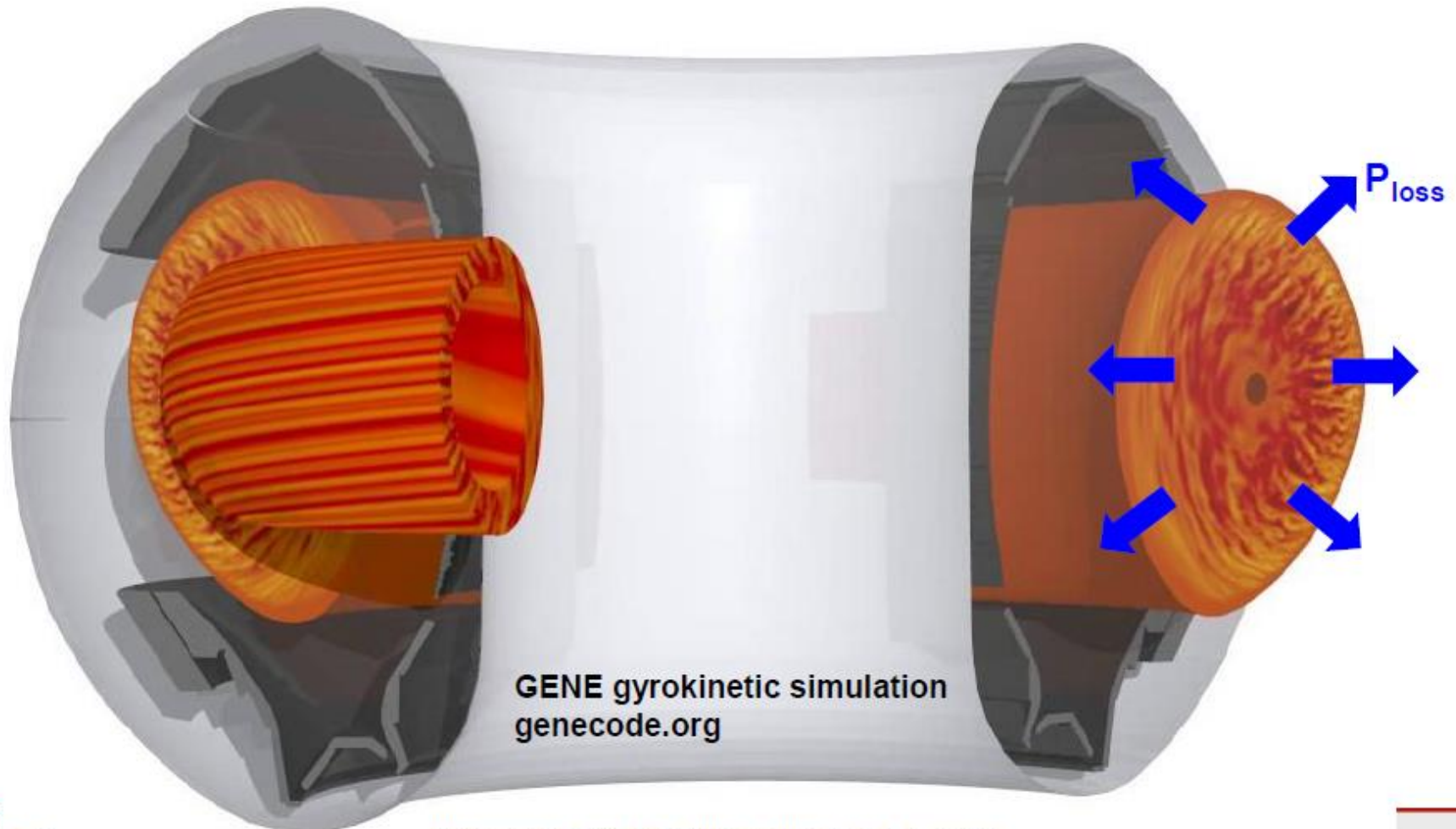- Correlation between local transport and density fluctuations hints at turbulence

Increasing gradients eventually cause small scale micro-instability → turbulence

- Quasi-2D dynamics: small perpendicular scales ($L_\perp \sim \rho_i$), elongated along field lines
- Small amplitude ($\delta n/n < 1\%$), **still effective at transport, limiting** $\tau_E = 3nT/P_{loss}$

P_{loss}

GENE gyrokinetic simulation
genecode.org

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- Quasi-2D dynamics: small perpendicular scales ($L_\perp \sim \rho_i$), elongated along field lines
- Small amplitude ($\delta n/n < 1\%$), **still effective at transport, limiting $\tau_E = 3nT/P_{loss}$**

- Turbulence measurements in ~100 Million C plasma will always be challenging and incomplete

- I'm going to show a lot of results from gyrokinetic turbulence simulations, as they help develop the physics basis to explain and predict

- Such simulations are being used more frequently to predict first and guide experiments

GENE gyrokinetic simulation
genecode.org

Gyrokinetics in brief – evolving 5D gyro-averaged distribution function

$$\frac{\omega}{\Omega} \ll 1$$

$$f(\vec{x}, \vec{v}, t) \xrightarrow{\text{gyroaverage}} f(\vec{R}, v_{\parallel}, v_{\perp}, t)$$

- Average over fast gyro-motion $\rightarrow$ evolve a distribution of gyro-rings

Guiding Center Position
Ring Average
Drift at $u_{\perp}$
$l_{\parallel}$
$l_{\perp}$
Ion Position
B_0
B

Howes et al., Astro. J. (2006)

Gyrokinetics in brief – evolving 5D gyro-averaged distribution function

$$\frac{\omega}{\Omega},\frac{\rho}{L},\frac{\delta f}{f_0},\frac{k_{\parallel}}{k_{\perp}} << 1$$

$$f(\vec{x},\vec{v},t) \xrightarrow{\text{gyroaverage}} f(\vec{R},v_{\parallel},v_{\perp},t)$$

$$f = F_M + \delta f$$

$$\frac{\partial(\delta f)}{\partial t} + v_{\parallel}\hat{b}\cdot\nabla\delta f + \vec{v}_d\cdot\nabla\delta f + \delta\vec{v}\cdot\nabla F_M + \vec{v}_{E0}(r)\cdot\nabla\delta f + \delta\vec{v}\cdot\nabla\delta f = C(\delta f)$$

Fast parallel motion

Slow perpendicular toroidal drifts

Advection across equilibrium gradients (∇T_0, ∇n_0, ∇V_0)

Dopper shift due to sheared equilibrium $E_r(r)$

Perpendicular non-linearity

Collisions

$$\vec{v}_{\kappa} = mv_{\parallel}^2\frac{\hat{b}\times\vec{\kappa}}{qB}$$

$$\vec{v}_{\nabla B} = \frac{mv_{\perp}^2}{2}\frac{\hat{b}\times\nabla B/B}{qB}$$

$$\delta\mathbf{v}_a \doteq \frac{c}{B}\mathbf{b}\times\nabla\Psi_a$$

$$\Psi_a(\mathbf{R}) \doteq \left\langle \delta\phi(\mathbf{R}+\rho) - \frac{1}{c}(\mathbf{V}_0+\mathbf{v})\cdot\delta\mathbf{A}(\mathbf{R}+\rho)\right\rangle_{\mathbf{R}}$$

- Must also solve gyrokinetic Maxwell equations self-consistently to obtain $\delta\varphi$, δB

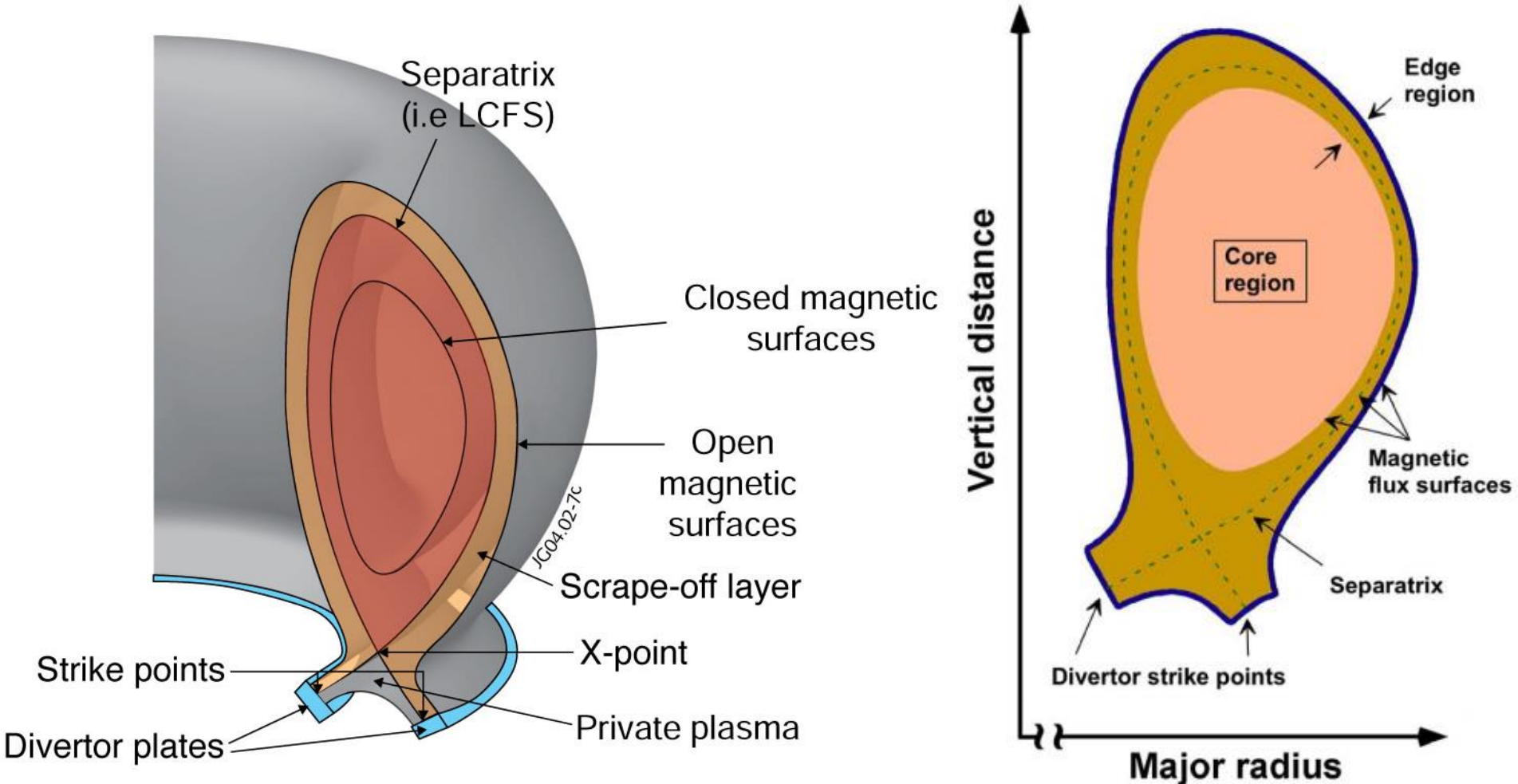# Turbulence advects/mixes/transports energy, particles and momentum

- Turbulence provides a highly nonlinear flux-gradient relationship due to sources of free energy

$$\begin{bmatrix} \Gamma \\ \Pi_\varphi \\ Q_i \\ Q_e \end{bmatrix} = -\begin{bmatrix} \text{flux} - \text{gradient} \\ \text{relationship} \\ \text{matrix} \end{bmatrix} \cdot \begin{bmatrix} \nabla n \\ R\nabla\Omega \\ \nabla T_i \\ \nabla T_e \end{bmatrix}$$

- I realize I'm largely focusing on energy transport, but just as important for a self-consistent reactor solution is:

  – Particle transport → need to fuel D & T in reactors

  – Impurity transport → expelling He ash; avoiding impurity accumulation from e.g. sputtering high-Z (e.g. tungsten) walls

  – Momentum transport → rotation is critical to macrostability (RWM/NTM) and part of self-consistent turbulence solution via E×B sheared flows (*more later*)

Going to refer to different spatial regions in the tokamaks

- Especially **core** (~100% ionized), **edge** (just inside separatrix), and **scrape-off layer** (SOL, just outside separatrix)

Going to refer to different spatial regions in the tokamaks

- Especially **core** (~100% ionized), **edge** (just inside separatrix), and **scrape-off layer** (SOL, just outside separatrix)

GENERAL CORE TURBULENCE CHARACTERISTICS

40+ years of theory predicts turbulence in magnetized plasma should often be drift wave in nature

General predicted drift wave characteristics

- Fluctuations in EM fields (φ, B) and fluid quantities (n,v,T) (although really kinetic at high temperature/low collisionality)

- Finite-frequency drifting waves, $\omega(k_\theta) \sim \omega_* \sim (k_\theta \rho) v_T / L$
  - Can propagate in ion or electron diamagnetic direction, depending on conditions/dominant gradients

- Perpendicular sizes linked to local gyroradius, $L_\perp \sim \rho_{i,e}$ or $k_\perp \rho_{i,e} \sim 1$

- Correlation times linked to acoustic velocity, $\tau_{cor} \sim c_s / R$

- Quasi-2D, elongated along the field lines ($L_{||} >> L_\perp$, $k_{||} << k_\perp$)
  - Particles can rapidly move along field lines to smooth out perturbations

- in a tokamak expected to be "ballooning", i.e. stronger on outboard side
  - Due to "bad curvature"/"effective gravity" pointing outwards from symmetry axis
  - Often only measured at one location (e.g. outboard midplane)

Microwave & far-infrared (FIR) scattering used extensively for density fluctuation measurements

Park, RSI (1985)

Dielectric Waveguide

Plasma

Probe Beam
Local Oscillator
Scattered Radiation

Optical System

Detector

FIR Source

Center Line

MULTI CHANNEL FIR SCATTERING APPARATUS

FIG. 1. Scannable mutichannel FIR scattering apparatus employed on the TEXT tokamak.

- Geometry and frequency determine measureable ω, k

$$\omega_{meas} = \omega_{scat} - \omega_{incident}$$
$$k_{meas} = k_{scat} - k_{incident}$$

- Can be configured for forward scattering, backscattering, reflectometery, …

Broad frequency spectra measured for given scattering wavenumber

Mazzucato, PRL (1982)
Surko & Slusher, Science (1983)

Princeton Large Torus (PLT)

$k\sim7\ cm^{-1}$

- Different scattering angles measure different k, observe spectral decay in wavenumber

Broad drift wave turbulent spectrum verified simultaneously with Langmuir probes and FIR scattering

TEXT, Ritz, Nuclear Fusion (1987)
Wooton, Phys. Fluids B (1990)

FIR

Langmuir probe

FIG. 1. The $S(k_\theta, \omega)$ spectrum at $r = 0.255$ m in TEXT, from Langmuir probes (contours) and FIR scattering (bars indicate FWHM).

- Illustrates drift wave dispersion

- However, real frequency almost always dominated by Doppler shift

$$\omega_{lab} = \omega_{mode}(k_\theta) + k_\theta v_{doppler}$$

- Often challenging to determine mode frequency (in plasma frame) within uncertainties

Small normalized fluctuations in core (≤1%) increasing to the edge

- Combination of diagnostics used to measure fluctuation amplitudes

- Measurements also often show $\delta n/n_0 \sim \delta\varphi/T_0$ (within factor ~2)

ATF stellarator, Hanson, Nuclear Fusion (1992)

TEXT tokamak, Wooton, PoFB (1990)

Fig. 4. Radial profile of density fluctuations (in %) in ATF stellarator obtained by combining results from different diagnostics [177].

FIG. 6. The spatial variation of $\bar{n}/n$ from TEXT ($B_\phi = 2$ T, $I_p = 200$ kA, $\bar{n}_e = 2$ to 3×10^{19} m^{-3}, H$^+$), shown as crosses (HIBP). Also shown are the predictions of two mixing length estimates, $(\bar{n}/n)^{tor}$ and $(\bar{n}/n)^{slab}$. Both electron feature $\bar{n}/n$ and k_θ ($\bar{k}_\theta\rho_s = 0.1$) are interpreted assuming no ion feature is present.

Mixing length estimate for fluctuation amplitude

- In the presence of an equilibrium gradient, ∇n_0, turbulence with radial correlation L_r will mix regions of high and low density

$$\delta n \approx \nabla n_0 \cdot L_r$$

$$\frac{\delta n}{n_0} \approx \frac{\nabla n_0}{n_0} \cdot L_r \approx \frac{L_r}{L_n} \quad \left(1/L_n = \nabla n_0 / n_0\right)$$

$$\frac{\delta n}{n_0} \sim \frac{1}{k_\perp L_n} \sim \frac{\rho_s}{L_n} \quad \left(k_\perp^{-1} \sim L_r ; k_\perp \rho_s \sim \mathrm{cons\,tan\,t}\right)$$

IF turbulence scale length linked to ρ_s, would loosely expect $\delta n/n_0 \sim \rho_s/L_n$

- Another interpretation: local, instantaneous gradient limited to equilibrium gradient

$$\nabla \tilde{n} \approx \nabla n_0$$

$$k_r \tilde{n} \approx \nabla n_0$$

Fluctuation intensity across machines loosely scales with mixing length estimate, reinforces local ρ_s drift nature

Liewer, Nuclear Fusion (1985)

Lechte, New J. of Physics (2002)

2D Langmuir probe array in TJ-K stellarator used to directly measure spatial and temporal structures

tungsten tips

ceramic tubes

- Simultaneously acquiring 64 time signals – can directly calculate 2D correlation, with time
- Caveat – relatively cool (T~10 eV) compared to fusion performance plasmas (T~10 keV)

TJ-K [Ramisch, PoP (2005)]

Radial and poloidal correlation lengths scale with ρ_s reinforcing drift wave nature

TJ-K [Ramisch, PoP (2005)]

- Turbulence close to isotropic

$$L_r \sim L_\theta$$

Temporal scales loosely correlated with acoustic times c_s/a

TJ-K [Ramisch, PoP (2005)]

Collisionally-excited, Doppler-shifted neutral beam fluorescence

$$D^o + e,i \rightarrow \left(D^o\right)^* \rightarrow D^o + \gamma(n = 3 \rightarrow 2, \lambda_o = 656.1 \text{ nm})$$

BES Viewing Geometry on DIII-D

Toroidal Plasma

Neutral Beam

Optical Fibers

Objective Lens

1 m

75 KeV D⁰ Neutral Beam (150 L (R))

$$\frac{\tilde{I}}{I} \mu \frac{\tilde{n}}{n}$$

119525 1100.00

DIII-D
NATIONAL FUSION FACILITY

THE UNIVERSITY of WISCONSIN
MADISON

Spectroscopic imaging provides a 2D picture of turbulence in hot tokamak core: cm spatial scales, μs time scales

- Utilize interaction of neutral atoms with charged particles to measure density

DIII-D tokamak (General Atomics)

142369.01510

1 m

7 cm

9 cm

Movies at: https://fusion.gat.com/global/BESMovies

t=0 μs t=12 μs
t=3 μs t=15 μs
t=6 μs t=18 μs
t=9 μs t=21 μs

27

BES videos

https://fusion.gat.com/global/BESMovies

(University of Wisconsin; General Atomics)

Radial and poloidal correlation lengths scale with ρ_s in core imaging, reinforcing local drift wave nature

DIII-D
Mckee, Nucl. Fusion (2001)

- Correlation length increases with local gyroradius ρ ($\rho_* = \rho/a$)

- Ratio of L_r/ρ relatively constant in radius, for the two different ρ_* discharges

Wavenumber power spectra and autocorrelation time follow local drift wave (gyroBohm) scaling in Tore Supra

- Using CO2 laser scattering
- Two experimental conditions with different ρ_i → normalized spectra overlap
- Wavenumber spectra also shows strong spectral decay (k^{-3}) expected from 2D enstrophy cascade

Hennequin, PPCF (2004)

Example of stronger turbulence measured on outboard side, "ballooning" in nature

- Consistent with bad curvature drive

ISSTOK [Silva, PPCF (2011)]

R

Curvature, "effective gravity"

Evidence for quasi-2D ($L_\parallel \gg L_\perp$)

- Assume an exponential or Gaussian correlation function

$$C(\Delta_\perp, \Delta_\parallel) \approx \exp(-\Delta_\perp / L_\perp)\exp(-\Delta_\parallel / L_\parallel)$$

- Measure correlation between two probes "on the same field line" ($\Delta_\perp \approx 0$) separated a large distance $\Delta_\parallel \gg 0$

  <u>JET edge plasma</u>

  $L_\parallel$ ~ many meters

  $L_\perp$ ~ mm-cm

JET edge [Thomsen, Contrib. Plasma Phys. (2001)]

More direct measurement in TJ-K plasmas

TJ-K [Birkenmeier, PPCF (2012)]

General turbulence characteristics are useful for testing theory predictions, but we mostly care about <u>transport</u>

- Transport a result of finite average correlation between perturbed drift velocity (δv) and perturbed fluid moments (δn, δT, δv)
  - Particle flux, $\Gamma = \langle \delta v \delta n \rangle$
  - Heat flux, $Q = 3/2 n_0 \langle \delta v \delta T \rangle + 3/2 T_0 \langle \delta v \delta n \rangle$
  - Momentum flux, $\Pi \sim \langle \delta v \delta v \rangle$ (Reynolds stress, just like Navier Stokes)

- Electrostatic turbulence often most relevant $\rightarrow$ E$\times$B drift from potential perturbations: $\delta v_E = B \times \nabla(\delta \varphi)/B^2 \sim k_\theta (\delta \varphi)/B$

- Can also have magnetic contributions at high beta, $\delta v_B \sim v_{||}(\delta B_r/B)$ (magnetic "flutter" transport – more later)

Measuring turbulent particle and heat fluxes using Langmuir probes

- Illustrates that turbulent transport can account for inferred anomalous transport (only possible in edge region)
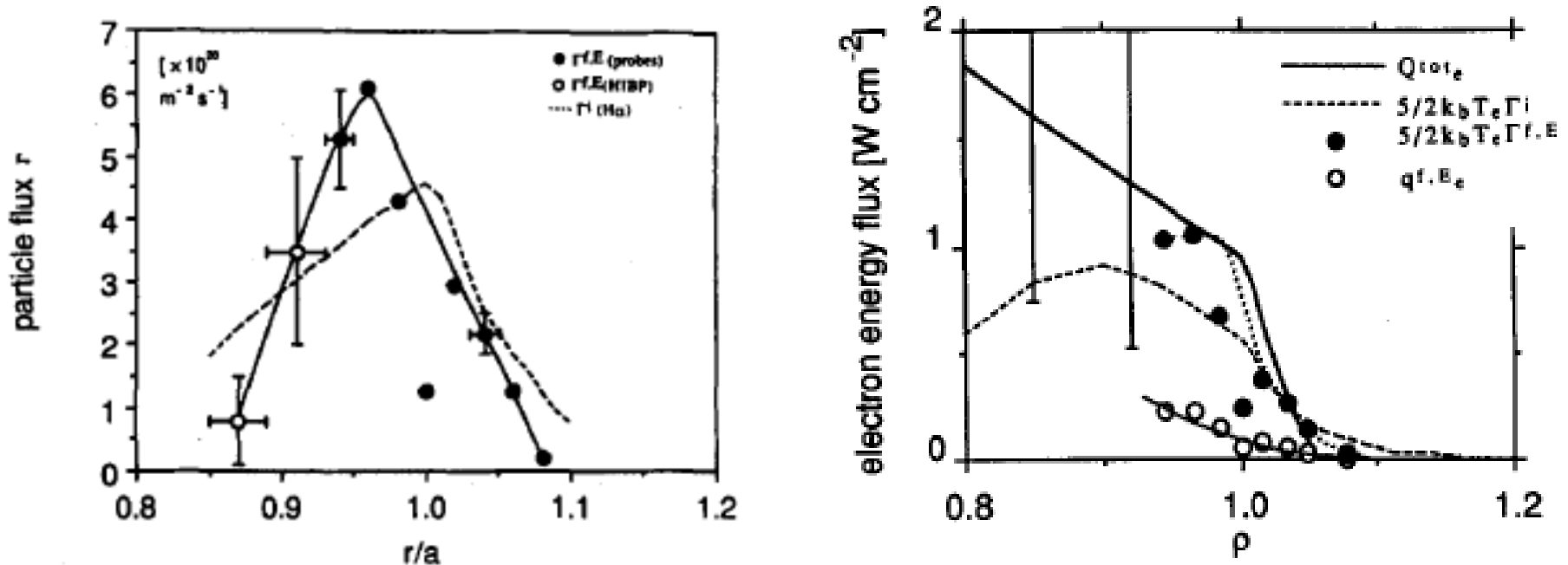
TEXT, Wooton, PoFB (1990)

FIG. 3. A comparison of working particle fluxes in TEXT ($B_\phi = 2$ T, $I_p = 200$ kA, $\bar{n}_e = 3 \times 10^{19}$ m^{-3}, H$^+$), the total Γ^i (from H$_\alpha$), and $\Gamma^{f,E}$ driven by electrostatic turbulence. $\Gamma^{f,E}$ is measured with Langmuir probes (solid line, solid points) and the HIBP (open points).

Useful to Fourier decompose transport contributions, especially for theory comparisons

- E.g. particle flux from electrostatic perturbations:

$$\Gamma(k_\theta) = \frac{nT}{B} \sum_{k_\theta} k_\theta \left| \frac{\delta n(k_\theta)}{n_e} \right| \left| \frac{\delta \varphi(k_\theta)}{T_e} \right| \gamma_{n\varphi}(k_\theta) \sin \alpha_{n\varphi}(k_\theta)$$

Amplitude spectra

coherence

Cross phase

- Everything is a function of wavenumber

Edge Langmuir probe arrays used to decompose turbulent fluxes in k_θ

TJ-K [Birkenmeier, PPCF (2012)]

- Very rare to measure this comprehensively!
- Useful for challenging theory calculations
- Yet to be done this thoroughly for hot tokamak core, where comprehensive gyrokinetic simulations available for comparison

Beyond general characteristics, there are many theoretical "flavors" of drift waves possible in tokamak core & edge

- Usually think of drift waves as gradient driven (∇T_i, ∇T_e, ∇n)
  - Often exhibit threshold in one or more of these parameters
- Different theoretical "flavors" exhibit different parametric dependencies, predicted in various limits, depending on gradients, T_e/T_i, ν, β, geometry, location in plasma…
  - Electrostatic, ion scale ($k_\theta \rho_i \leq 1$)
    - Ion temperature gradient (ITG) – driven by ∇T_i, weakened by ∇n
    - Trapped electron mode (TEM) – driven by ∇T_e & ∇n_e, weakened by ν_e
  - Electrostatic, electron scale ($k_\theta \rho_e \leq 1$)
    - Electron temperature gradient (ETG) - driven by ∇T_e, weakened by ∇n
  - Electromagnetic, ion scale ($k_\theta \rho_i \leq 1$)
    - Kinetic ballooning mode (KBM) - driven by $\nabla \beta_{pol}$
    - Microtearing mode (MTM) – driven by ∇T_e, at sufficient β_e

Challenging to definitively identify a particular theoretical turbulent transport mechanism

- Best we can do:
  - Measure as many turbulence quantities as possible (amplitude spectra, cross-phases, transport
  - Compare with theory (simulation) predictions
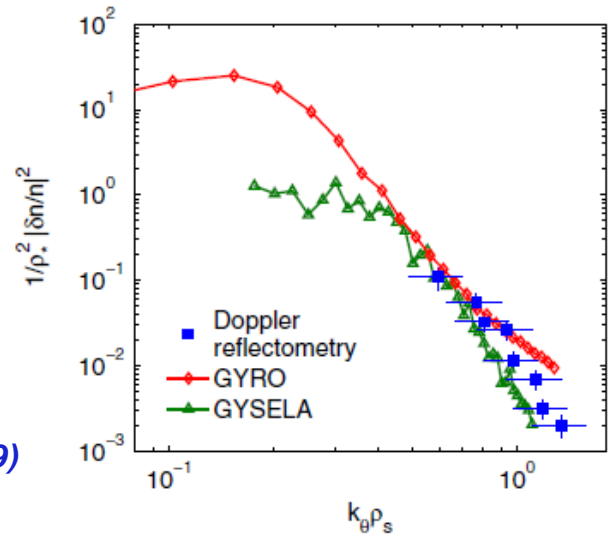 - Scaling equilibrium parameters to investigate trends/sensitivities

CORE ION SCALE TURBULENCE VALIDATION

Transport, density fluctuation amplitude (from reflectometry) and spectral characteristics all consistent with nonlinear ITG simulations in Tore Supra

- Provides confidence in interpretation of transport in conditions when ITG instability/turbulence predicted to be most important

Casati, PRL (2009)

Measurement of both electron density and temperature fluctuations at overlapping locations (DIII-D)

- Using correlation electron cyclotron emission (CECE) to measure δT_e

DIII-D
White, PoP (2008)

Normalized density and temperature fluctuations are very similar in amplitude

DIII-D
White, PoP (2008)

Comparing δn_e, δT_e fluctuation spectra with simulations using synthetic diagnostic
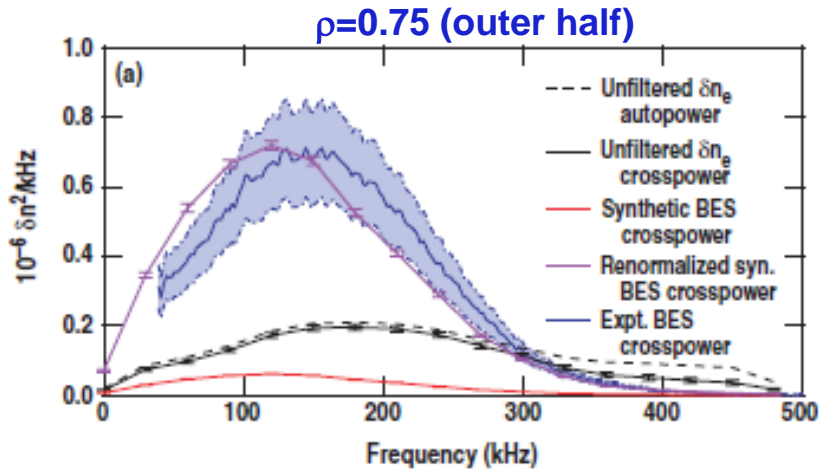
GYRO simulation

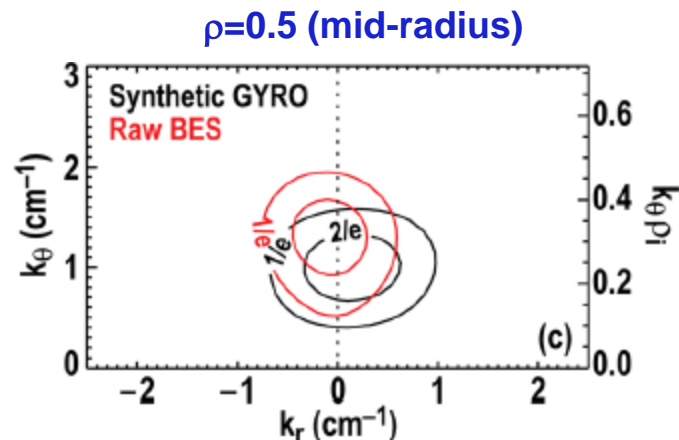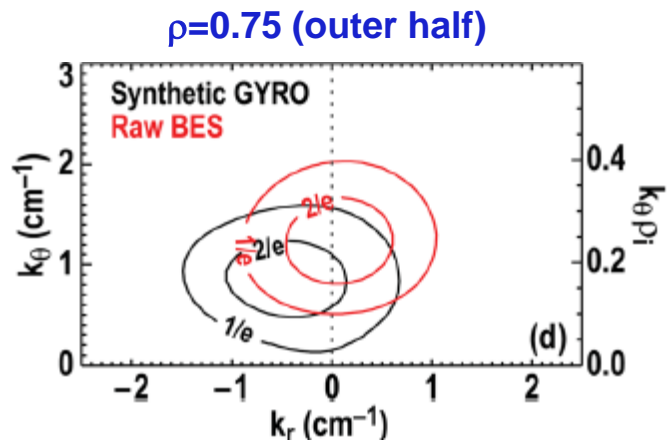- Level of agreement sensitive to accounting for realistic instrument function

ρ=0.5 (mid-radius)

44

Agreement worse further out (ρ=0.75)

- Measured intensity larger than simulations (as is transport), so called **"edge shortfall"** problem challenging gyrokinetic simulations
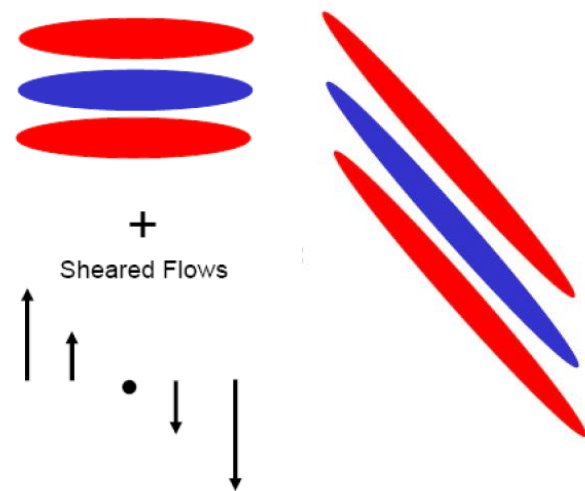

Holland, PoP (2009)

45

Can also compare 2D correlation functions for additional validation, try to understand "shortfall" discrepancy
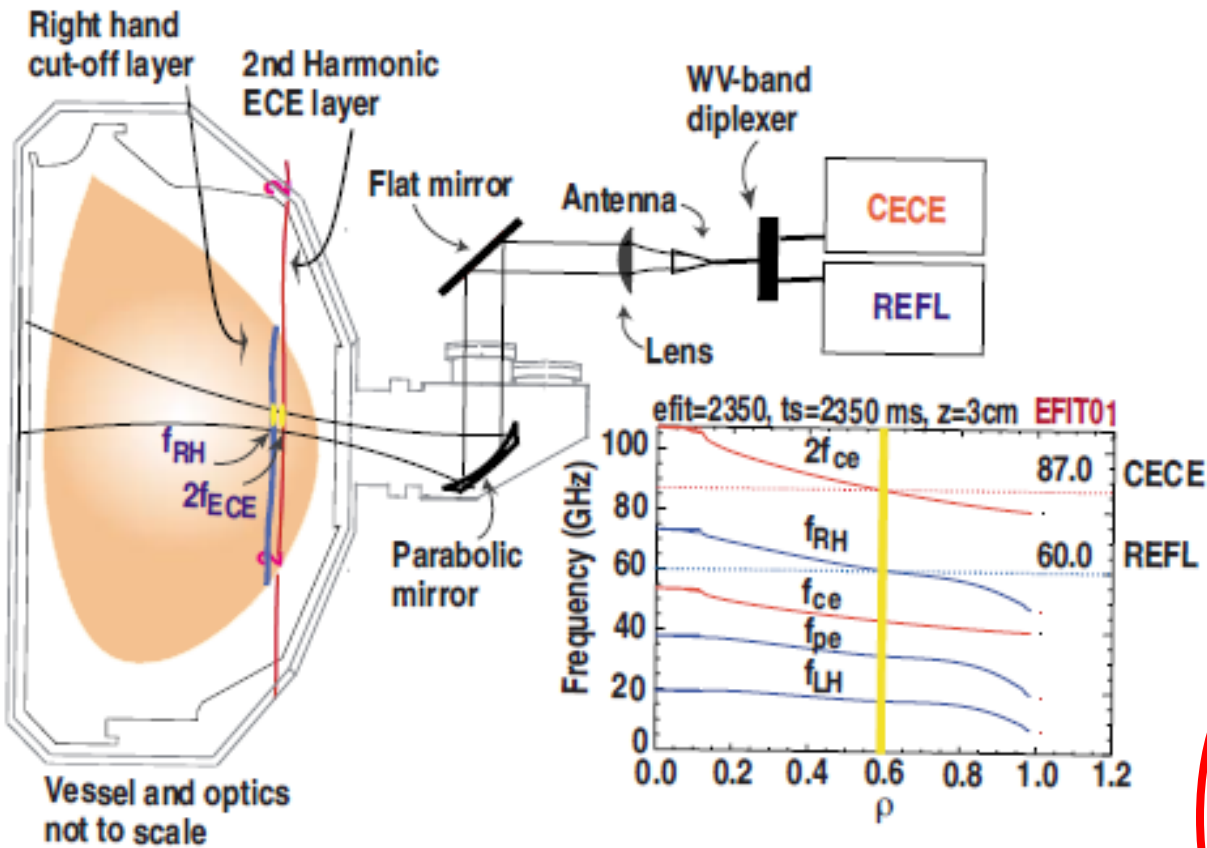
- Comparing 2D correlation/spectra reveals that simulated $\langle k_r \rangle$ is larger than experiment at $\rho = 0.75$

$\rho=0.75$ (outer half)

$\rho=0.5$ (mid-radius)

- Larger $\langle k_r \rangle$ in simulations possibly from tilting due to sheared equilibrium E×B flows being too strongly represented → also consistent with small predicted transport (more later)

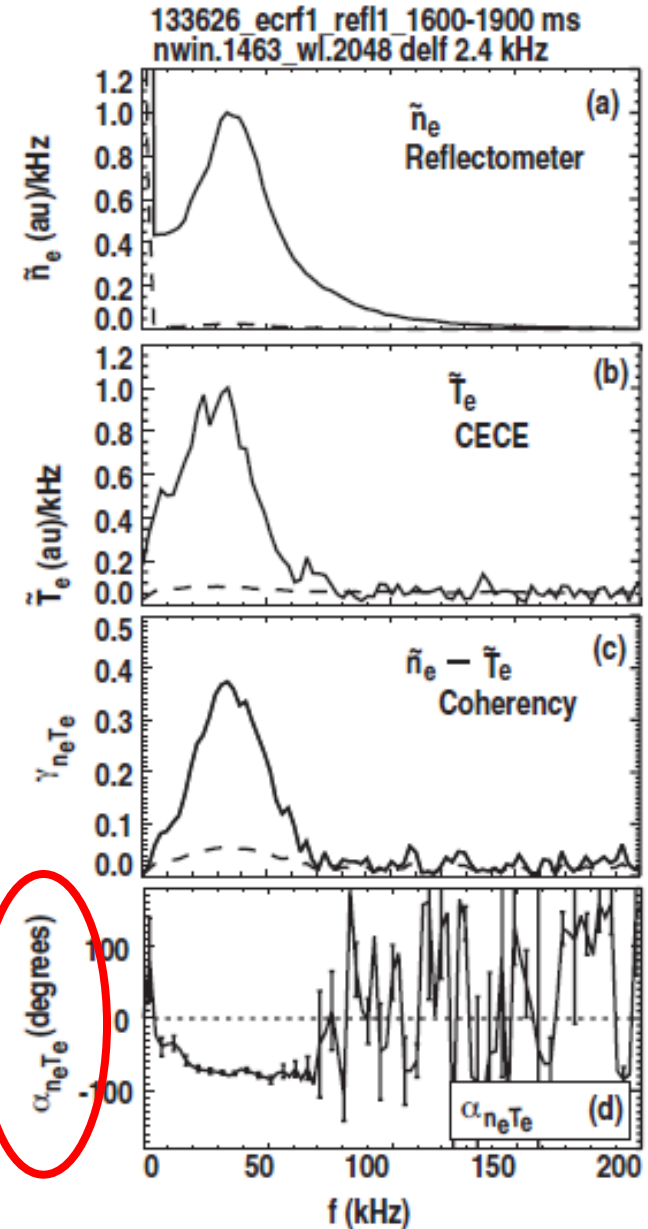- *Has sparked significant international code benchmarking & validation effort*

Simultaneous measurement of n_e and T_e using same beam path allows for cross-phase measurement

Right hand cut-off layer

2nd Harmonic ECE layer

Flat mirror

Antenna

Lens

WV-band diplexer

CECE

REFL

Parabolic mirror

f_{RH}

$2f_{ECE}$

Vessel and optics not to scale

efit=2350, ts=2350 ms, z=3cm   EFIT01

- $2f_{ce}$ — 87.0 CECE
- f_{RH} — 60.0 REFL
- f_{ce}
- f_{pe}
- f_{LH}

Frequency (GHz) vs ρ

$$\gamma_{n_e T_e}(f) = \frac{|\langle S^*_{\tilde{n}_e} S_{\tilde{T}_e}\rangle|}{|\langle S_{\tilde{n}_e}\rangle|^2 |\langle S_{\tilde{T}_e}\rangle|^2}.$$

DIII-D
White, PoP (2010)

133626_ecrf1_refl1_1600-1900 ms
nwin.1463_wl.2048 delf 2.4 kHz

(a) $\tilde{n}_e$ Reflectometer — $\tilde{n}_e$ (au)/kHz

(b) $\tilde{T}_e$ CECE — $\tilde{T}_e$ (au)/kHz

(c) $\tilde{n}_e - \tilde{T}_e$ Coherency — $\gamma_{n_e T_e}$

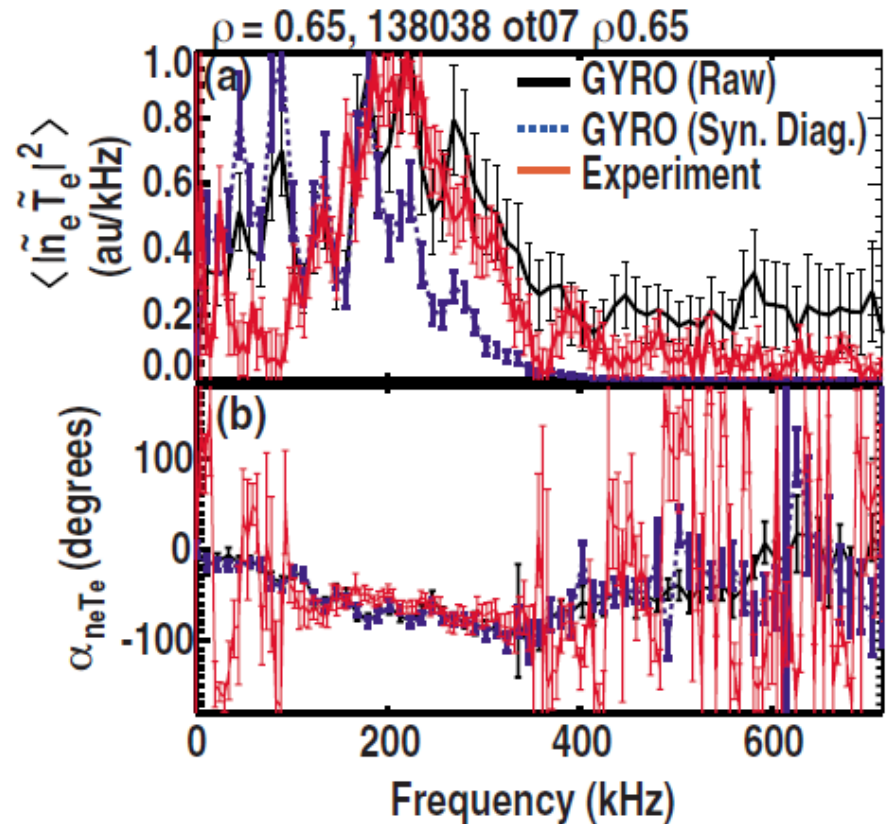(d) $\alpha_{n_e T_e}$ — $\alpha_{n_e T_e}$ (degrees)

f (kHz)

ne-Te cross phases agree well with simulations

- Amplitude spectra and transport fluxes still off by 2-3

TABLE IV. Postexperiment GYRO simulations from 138 038, $\rho=0.65$, $t=1525$ ms. Turbulence amplitudes and cross phase are compared with synthetic diagnostic results.
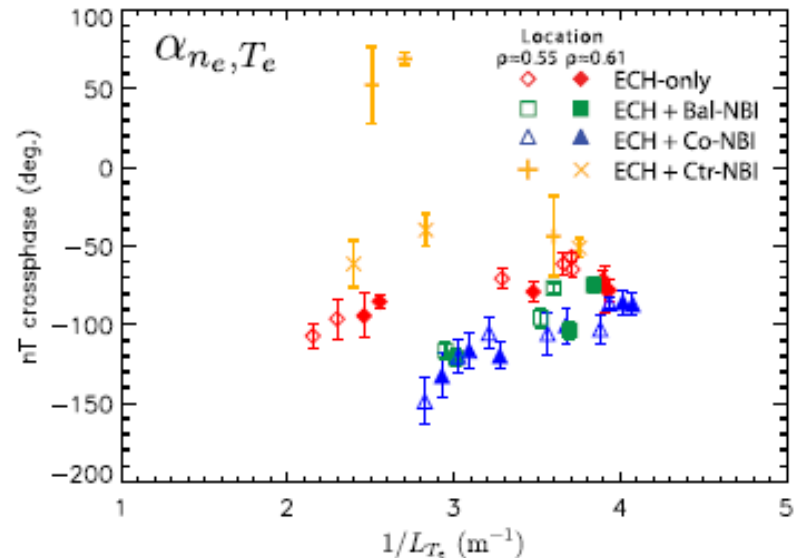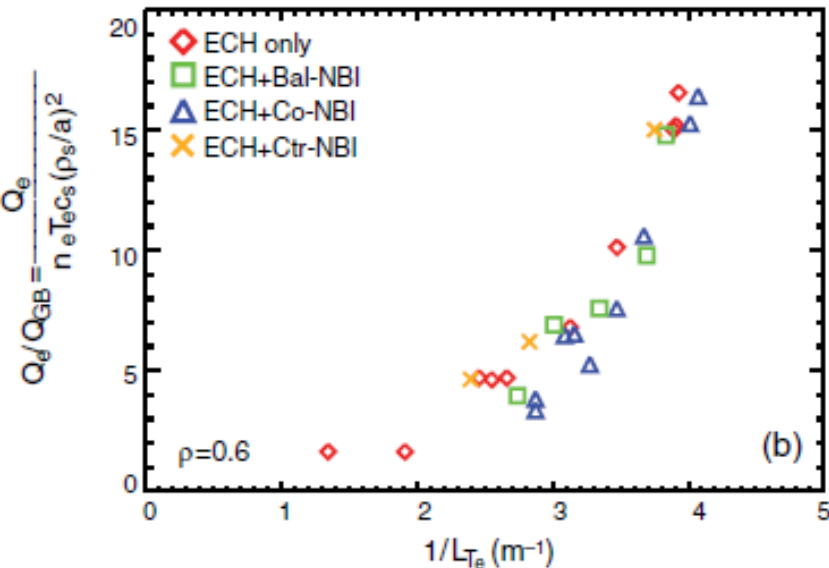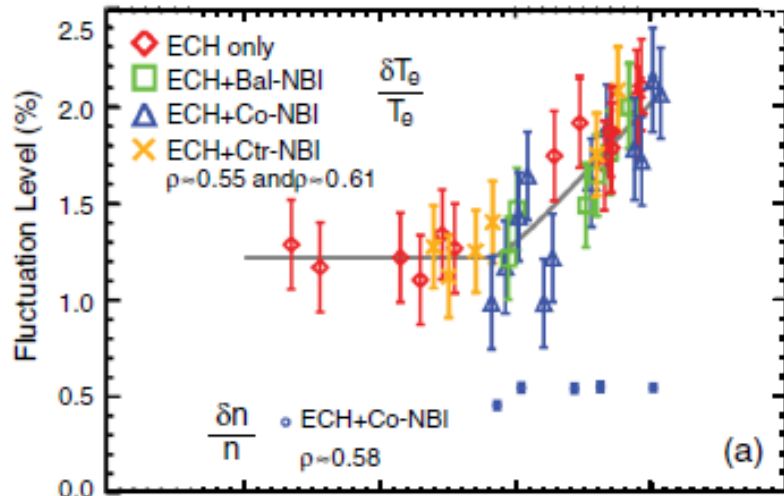
Parameter	GYRO	Experiment
Q_e (MW)	3.77 ± 0.06	2.43 ± 0.02
Q_i (MW)	0.34 ± 0.01	1.32 ± 0.02
$\tilde{T}_e/T_e$ (%)	1.07 ± 0.10	0.95 ± 0.05
$\tilde{n}/n$ (%)	0.25 ± 0.01	0.57 ± 0.06
$\alpha_{n_e T_e}$ (degrees)	71 ± 1	61 ± 12

Measured changes of δT_e, n_e-T_e crossphase and transport with increasing ∇T_e provides constraint for simulations
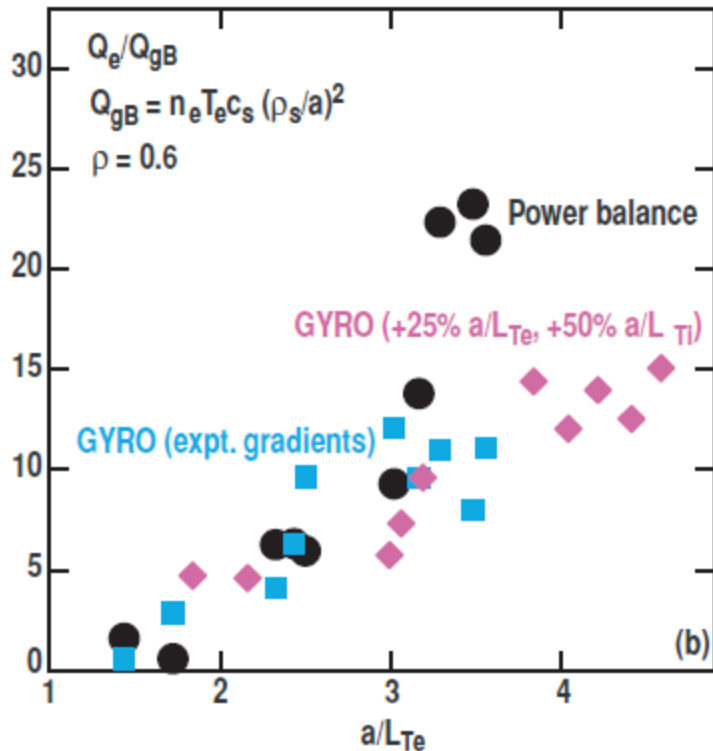

- Increasing fluctuations and transport with a/L_{Te} consistent with enhanced TEM turbulence (∇T_e driven TEM)

DIII-D
Hillesheim, PRL, PoP (2013)

Simulations can reproduce transport for some observations

- Predicted turbulence levels ($\delta T_e/T_e$) always too small, even when accounting for sensitivity to ∇T_e
- Discrepancies point to missing physics in theory/simulation (unresolved?)

Holland, PoP (2013)

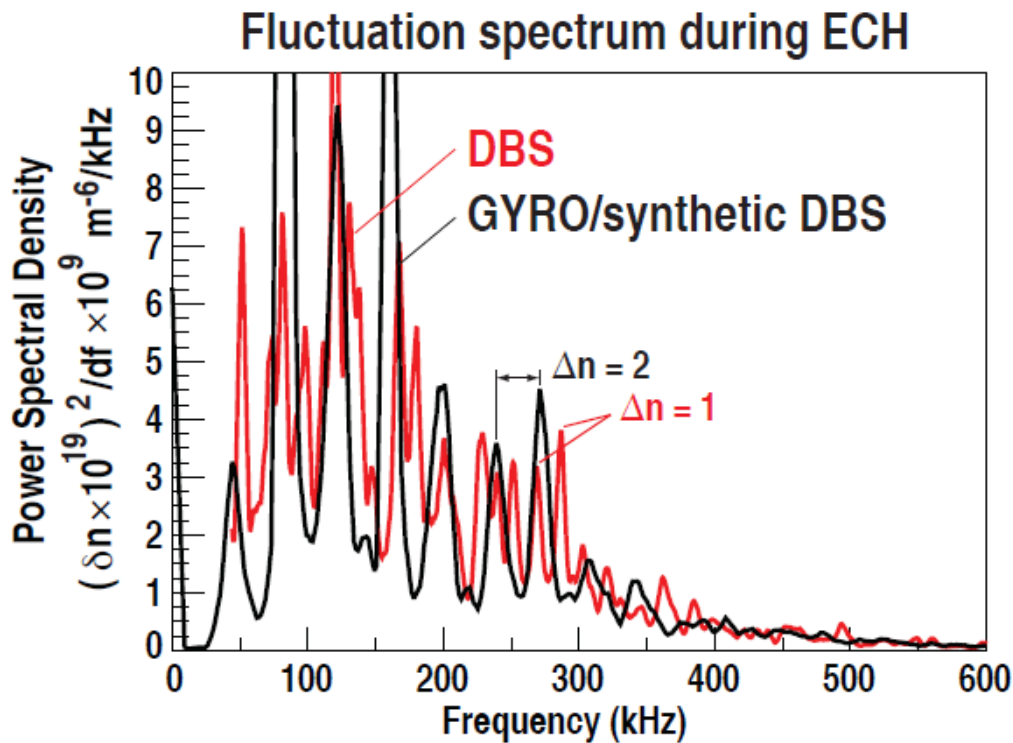# ADDITIONAL EVIDENCE FOR TRAPPED ELECTRON MODE (TEM) TURBULENCE

Quasi-coherent modes observed in the deep core of Tore Supra, TEXTOR and JET tokamaks

- Measured with reflectometers
- Amplitudes large at low collisionality (enhanced TEM growth rates) via low density (below), ECRH heating, …

Arnichand, NF (2015)

Similar coherent modes observed in the core of ECH heated DIII-D QH-modes, reproduced with nonlinear gyrokinetics

Nonlinear GYRO Simulations Reproduce New Coherent Fluctuations Seen on DBS, identifying these as TEMs

Fluctuation spectrum during ECH

DBS
GYRO/synthetic DBS

$\Delta n = 2$
$\Delta n = 1$

Now if we do much less frequency smoothing of same data, drilling down ...

- **Coherent modes in GYRO correspond to resolution used, $\Delta n = 2$**

  - Match every second coherent mode seen on DBS (for which $\Delta n = 1$)

- **High resolution GYRO simulations in progress with $\Delta n = 1$**

- **Similar results for no ECH case**

D. R. Ernst/APS-DPP NI3.00003/10:30-11:00 AM Wednesday, November 18
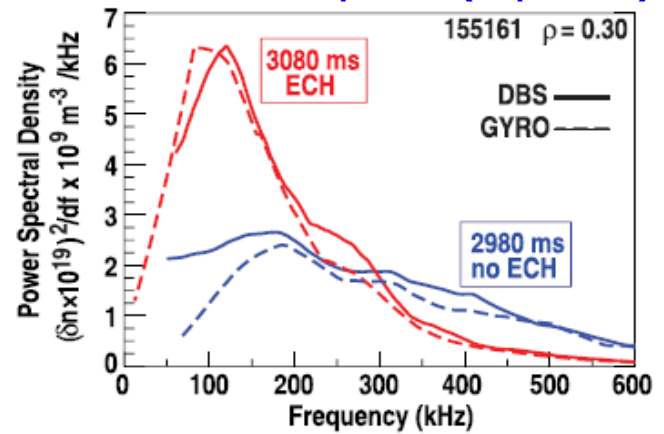
12

Ernst, IAEA (2014), PoP (2016)
Guttenfelder, APS (2015)

53

Nonlinear gyrokinetics of <u>density-gradient</u> driven TEM reproduces change in transport and turbulence with addition of ECH

Measured profiles

Transport fluxes (exp & sim)

- **Nonlinear GYRO simulations illustrate presence of ∇n-driven TEM at $\rho=0.3$**
- **Simulations reproduce magnitude of transport (Q_i, Q_e, Γ_e, Γ_c, Π_φ) and DBS spectra using synthetic diagnostic**
  - Also reproduces changes of transport and DBS with addition of ECH

DBS turbulence spectra (exp & sim)

DND QH-mode 155161 [Ernst, PoP (2016)]
B_T=2.05 T, I_p=1.2 MA
P_{NBI}=5.5 MW (ctr-Ip), P_{ECH}=3.4 MW
β_N=1.5, q_{95}=5.2

Milwaukee (2017)

MULTI-SCALE TURBULENCE (FROM ρ_i TO ρ_e SCALES)

In some instances simulations can account for ion transport, but predicts too small electron transport
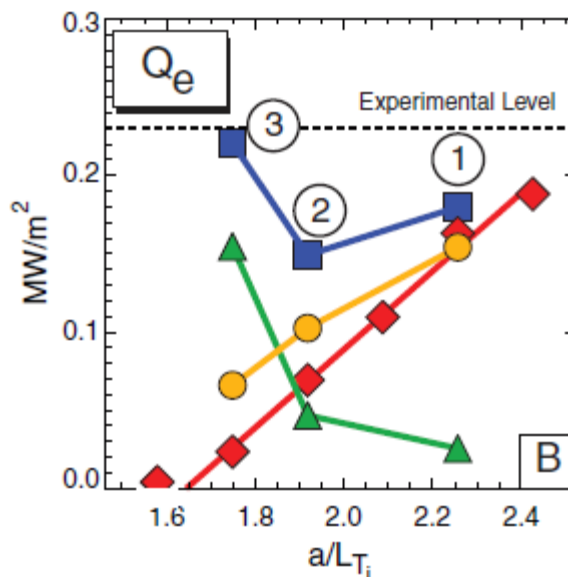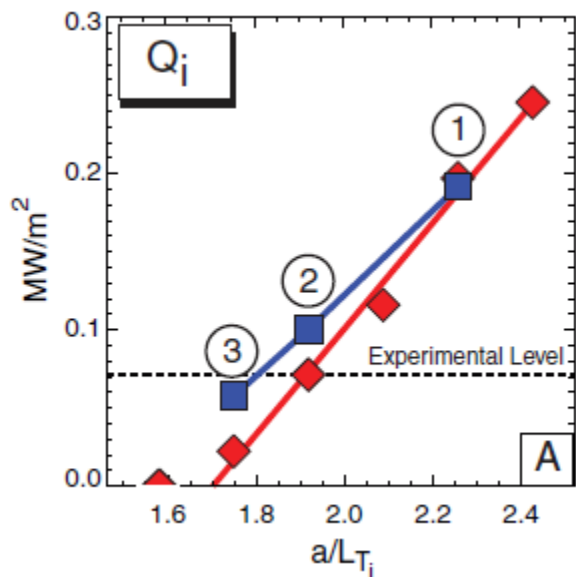

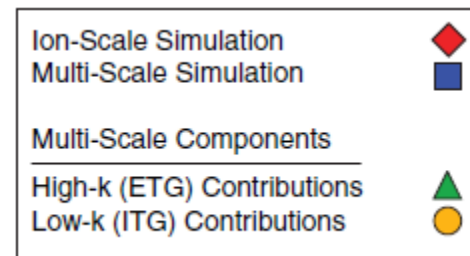*Alcator C-Mod (MIT)*

Howard, PoP (2014)

- Requires self-consistent multi-scale simulations to account for Q_e & Q_i together

- Numerous examples (DIII-D, ITER, C-Mod, NSTX) where this might be important → very expensive computationally ~ 20 M cpu-hrs/sim

Non-intuitive change in predicted transport due to cross-scale coupling between $\sim\rho_i$ and $\sim\rho_e$

- As a/L_{Ti} (=$-R\nabla T_i/T_i$) is reduced towards ITG threshold, Q_i decreases while electron transport increases due to very small scale ($k_\theta\rho_i>1$, $k_\theta\rho_e<1$) turbulence → *can match experiment*
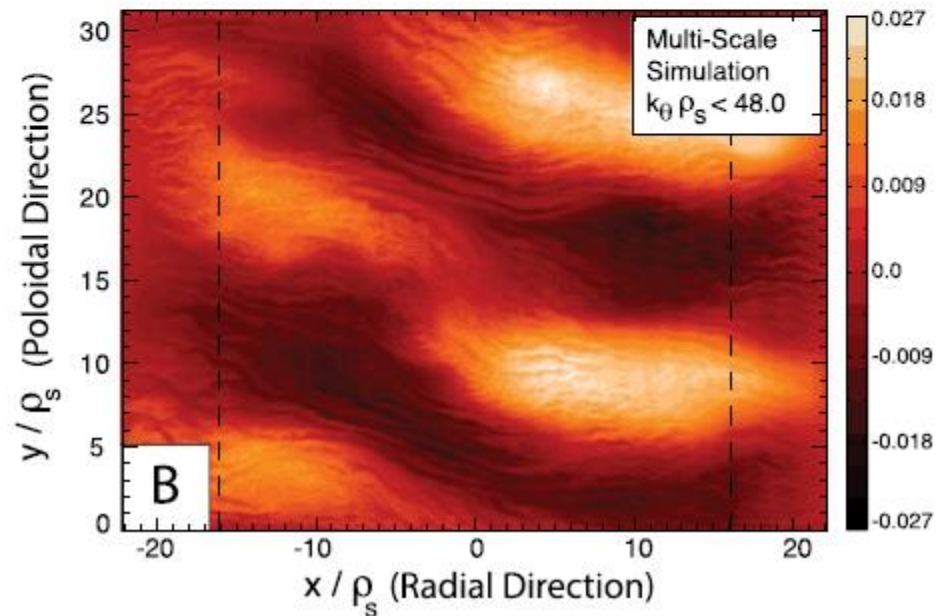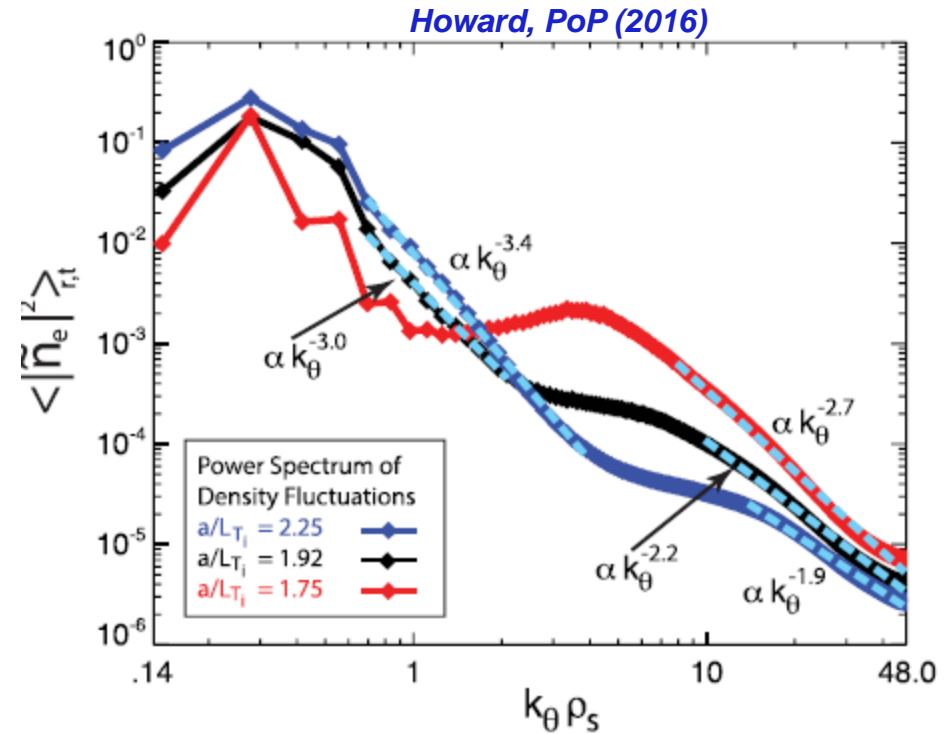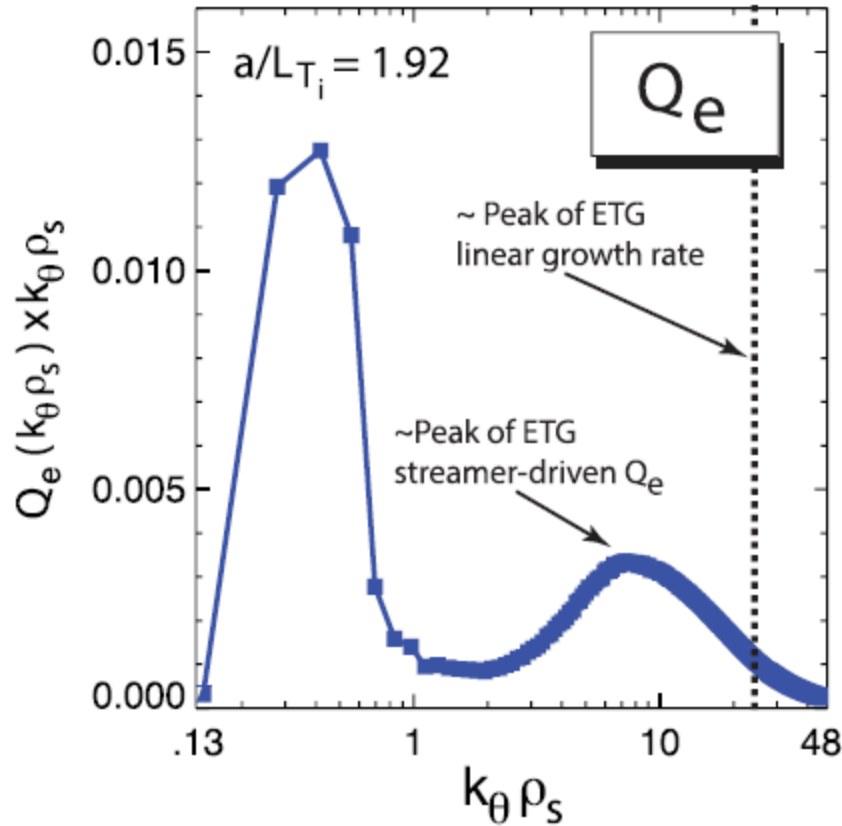

Howard, NF (2016)

ETG-like "streamers predicted to exist on top of ion scale turbulence
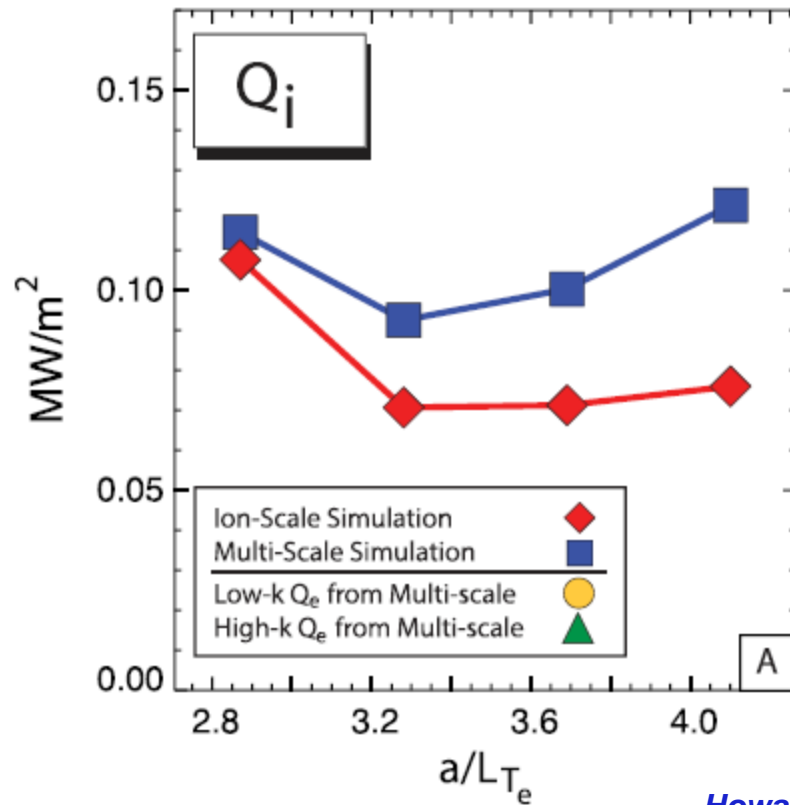

Howard, PoP (2014)

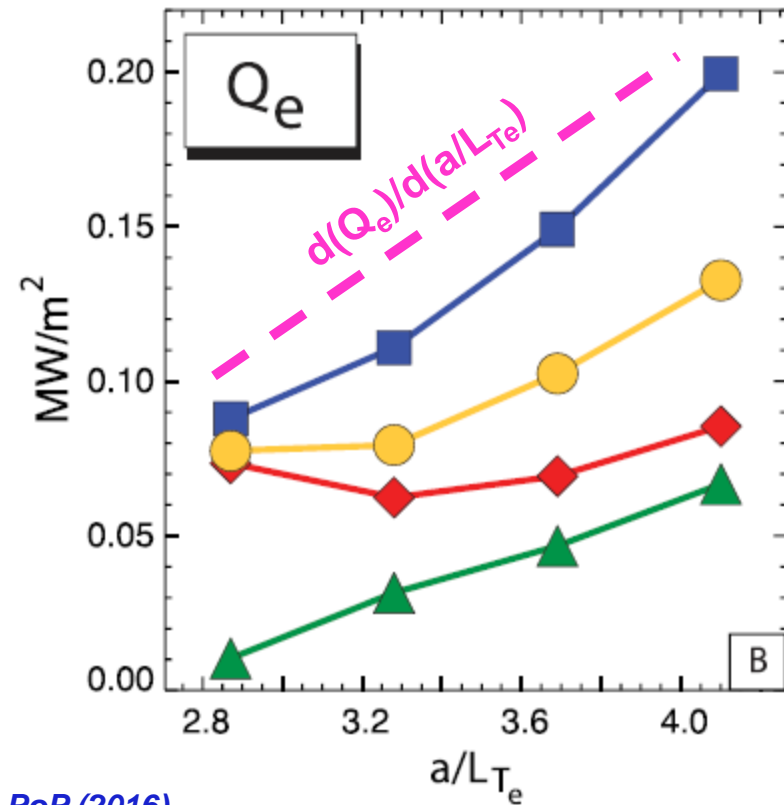# Hot topic: measure change in turbulence spectrum consistent with multi-scale effects

- Proposal to use Phase Contrast Imaging (PCI) on C-Mod (don't think it was done before 2016 end-of-life?)
- Some "multi-scale" turbulence measurements in L. Schmitz, NF (2012)

Stronger electron stiffness, $d(Q_e)/d(\nabla T_e)$, also predicted; consequences observed in perturbative experiments
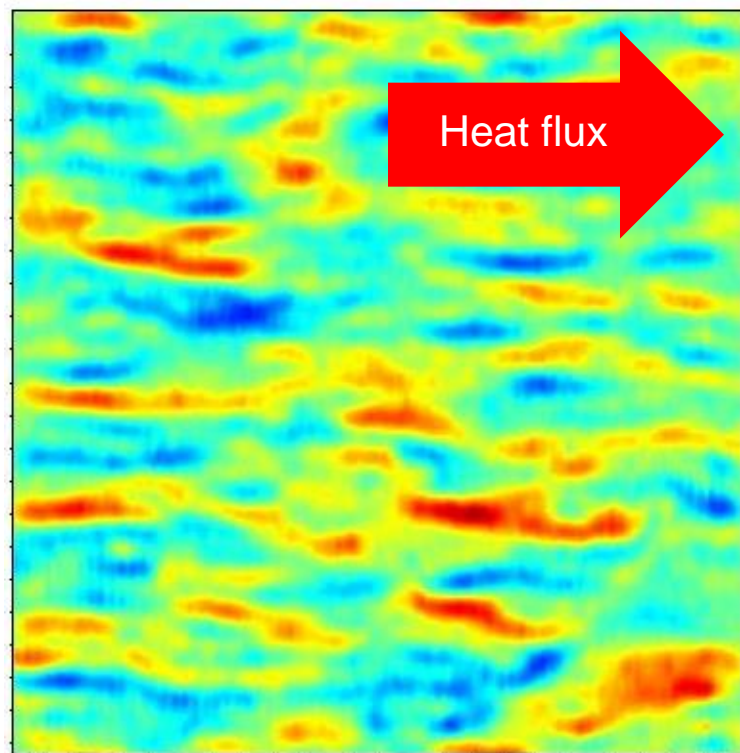

Howard, PoP (2016)

- Transport modeling including above multi-scale effects (Staebler, PoP 2016; Rodriguez-Fernandez, PRL 2018) reproduces observed fast perturbative transport (e.g. introduce a local heat sink/cold puse and watch T_e, ∇T_e propagate)

SUPPRESSION OF ION SCALE TURBULENCE BY SHEARED E×B FLOWS

Large scale sheared flows can tear apart turbulent eddies, reduce turbulence → improve confinement

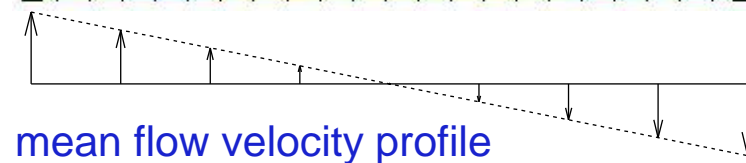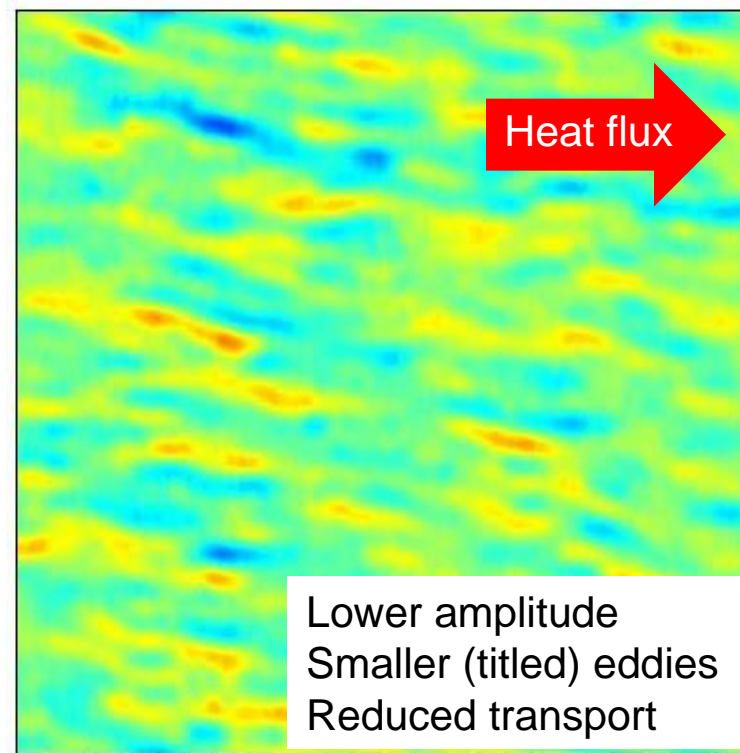Simulations for NSTX (PPPL) – a low aspect ratio tokamak
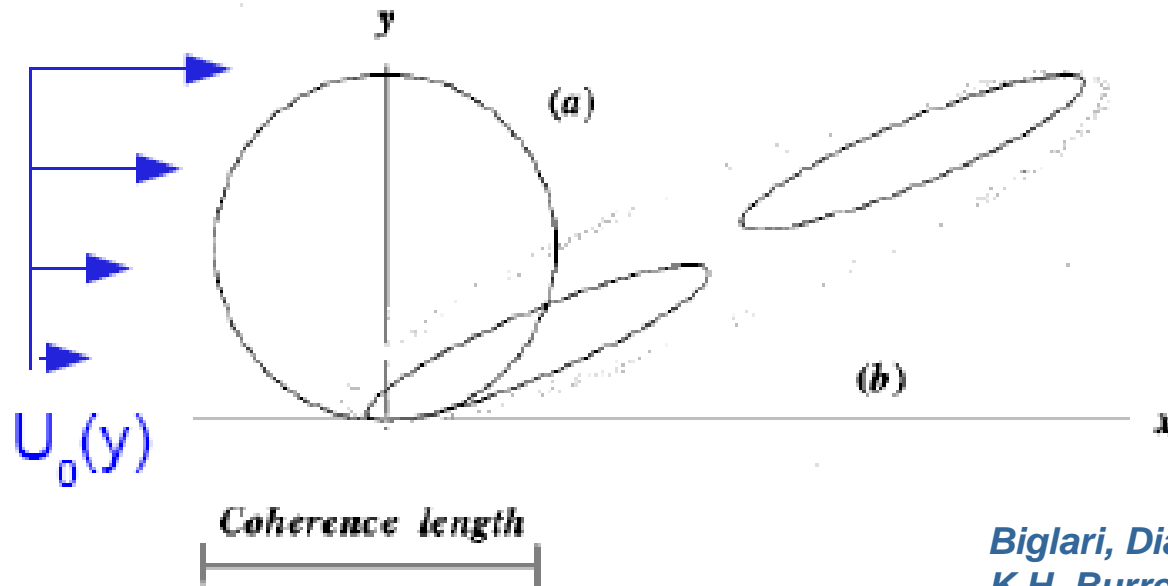
Snapshot of density without flow shear

Snapshot of density with flow shear

Heat flux

Heat flux

Lower amplitude
Smaller (titled) eddies
Reduced transport

100 ion radii
6,000 electron radii
~50 cm

mean flow velocity profile

Equilibrium background (E×B) flows can suppress turbulence

Loosely need:
$$dU/dy > \tau_c^{-1}$$

Biglari, Diamond, Terry, PoFB (1990)
K.H. Burrell, PoP (1997,1999)

- Shear flow in neutral (3D) fluids is a source of free-energy, how does it stabilize turbulence in magnetized plasmas?
- Three conditions for sheared flow suppression of turbulence (Terry, RMP 2000):
  – Shear flow should be stable (→larger Kelvin-Helmholtz threshold in 2D)
  – Turbulence must reside in region of shear flow for longer than an eddy-turnover time/decorrelation time (→tokamak is a periodic system)
  – Dynamics should be 2D (→strong guide magnetic field)

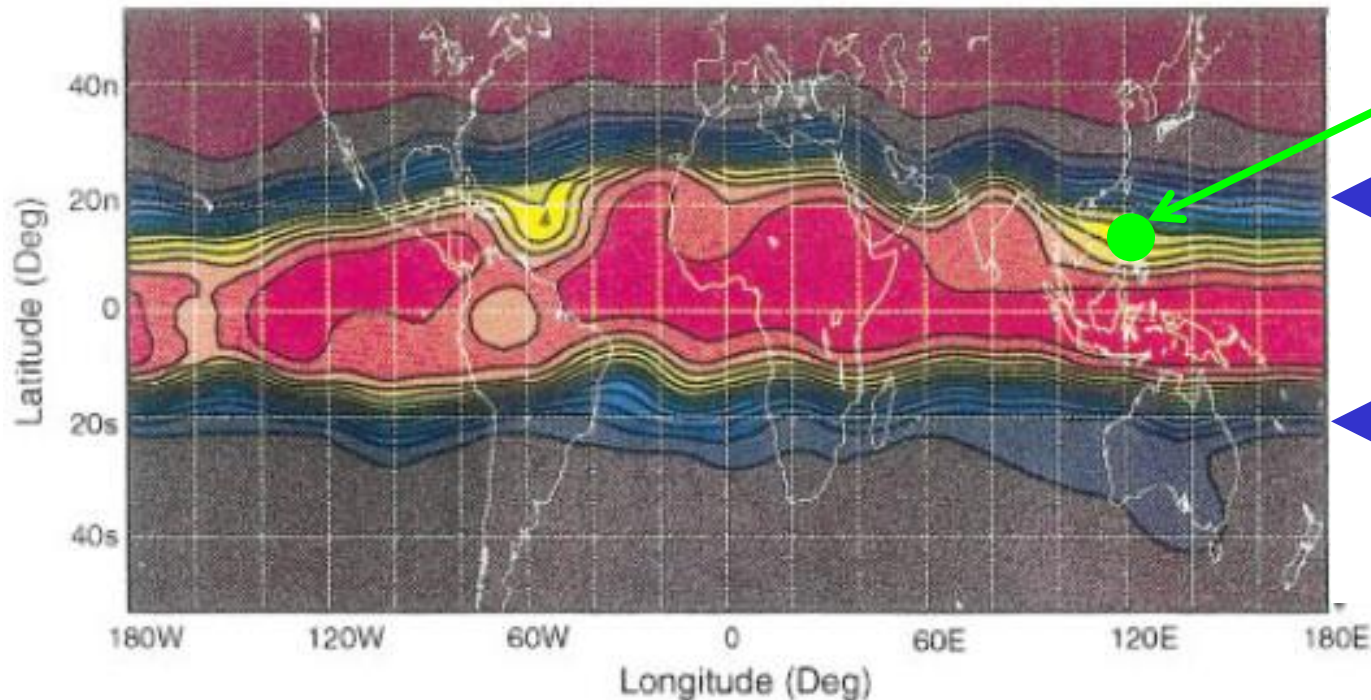# Experimental turbulence and transport measurements of ExB shear suppression

- (I'll show this in section on L-H transition)

There are also examples of turbulence suppression via sheared flows in neutral fluids

- Thin (quasi-2D) atmosphere in axisymmetric geometry of rotating planets similar to tokamak plasma turbulence

- Stratospheric ash from Mt. Pinatubo eruption (1991) spread rapidly around equator, **but confined in latitude by flow shear**
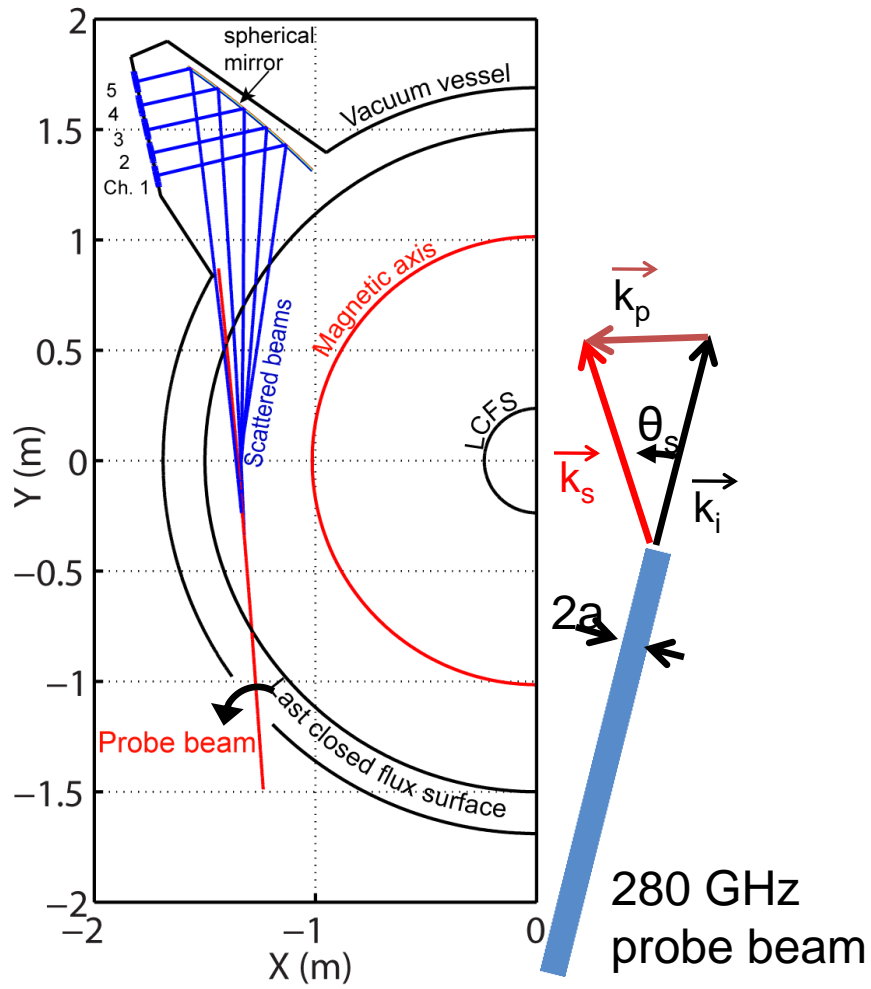
Aerosol concentration

Large shear in stratospheric equatorial jet

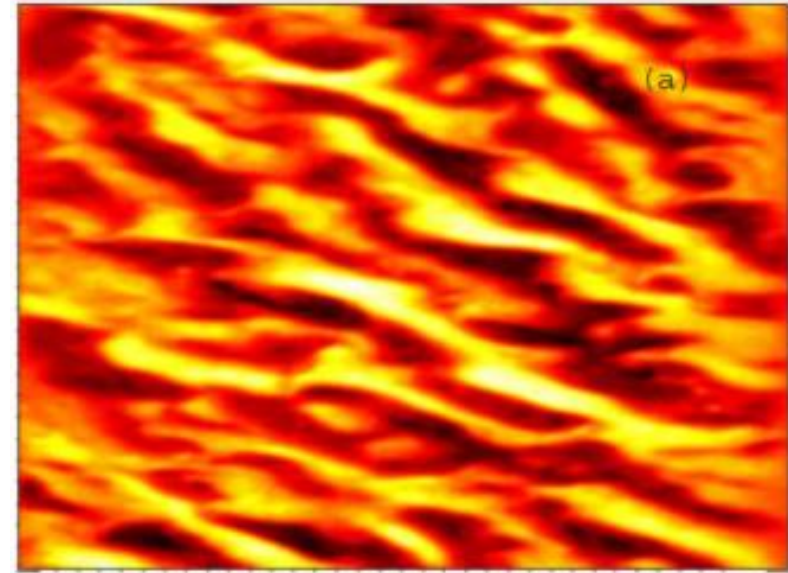(Trepte, 1993)

"PURE" ELECTRON SCALE TURBULENCE (not multiscale)

Can be the only mechanism left if ion scale turbulence suppressed e.g. by E×B shear

Microwave scattering used to detect high-$k_\perp$ (~mm) fluctuations

density fluctuations from ETG simulation

6 ion radii
360 electron radii
~2 cm

Guttenfelder, PoP (2011)

NSTX

280 GHz probe beam

Mazzucato, PRL (2008)
Smith, RSI (2008)

Correlation observed between high-k scattering fluctuations and ∇T_e

- Applying RF heating to increase Te
- Fluctuations increase as expected for ETG turbulence ($R/L_{Te} > R/L_{Te,crit}$)

- Other trends measured that are consistent with ETG expectations, e.g. reduction of high-k scattering fluctuations with:

1. Strongly reversed magnetic shear (Yuh, PRL 2011)
   – Simulations predict comparable suppression (Peterson, PoP 2012)

2. Increasing density gradient (Ren, PRL 2011)
   – Simulations predict comparable trend (Ren, PoP 2012, Guttenfelder NF, 2013, Ruiz PoP 2015)

3. Sufficiently large E×B shear (Smith, PRL 2009)
   – Observed in ETG simulations (Roach, PPCF 2009; Guttenfelder, PoP 2011)
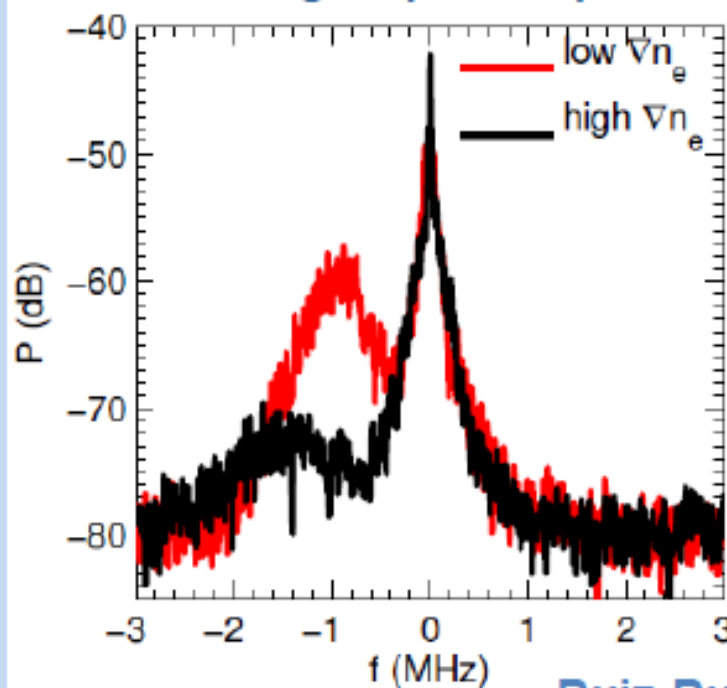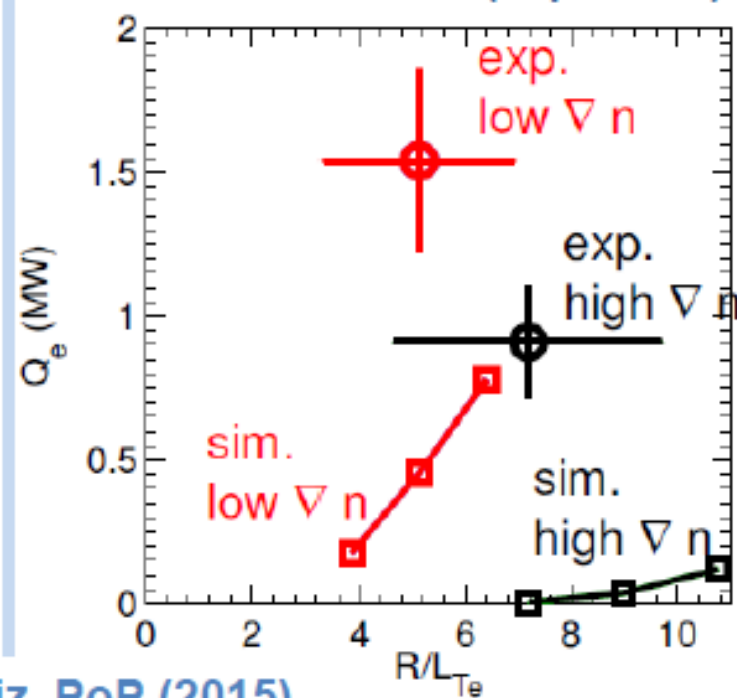
E. Mazzucato et al., NF (2009)

NSTX

Many ETG trends observed in NSTX, challenging to correctly predict transport

- BUT majority of nonlinear gyrokinetic ETG simulations predict Q_e too small to explain experiment

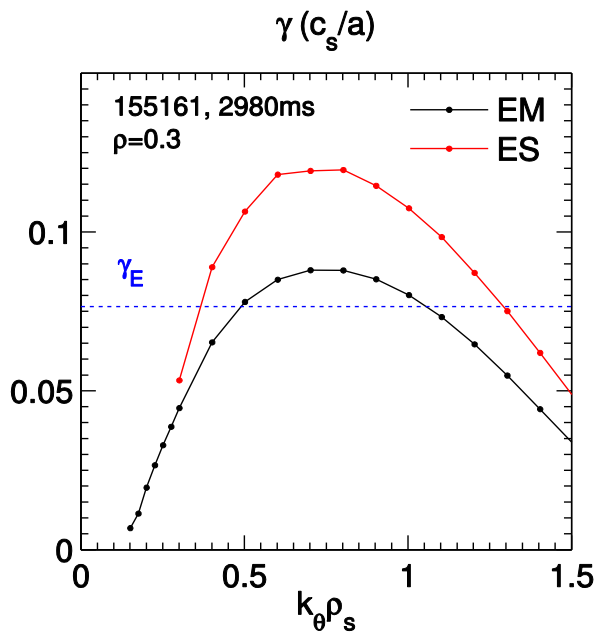**Measured high-k power spectra**

Electron heat flux (exp & sim)

Ruiz-Ruiz, PoP (2015)

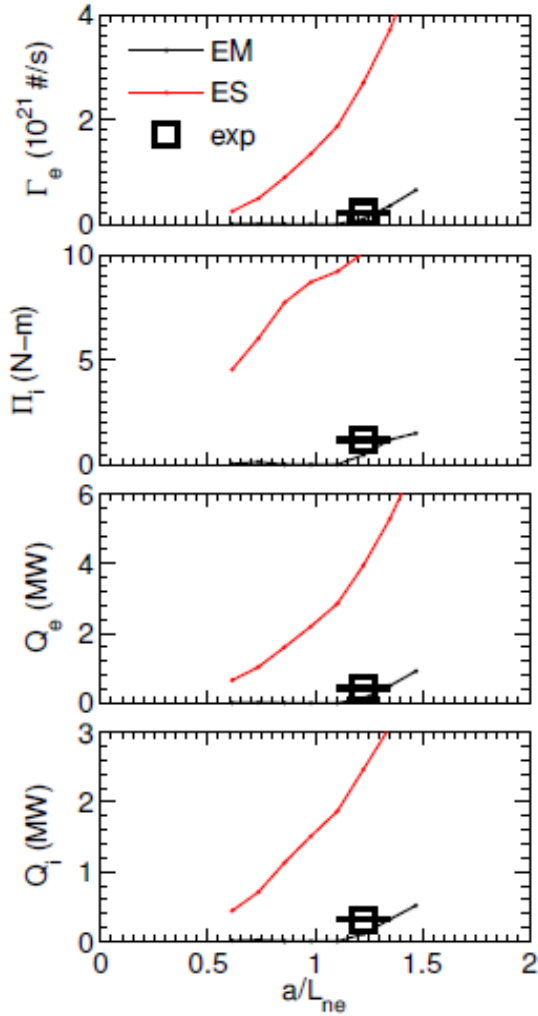*(another potential case for multi-scale simulations)*

ELECTROMAGNETIC EFFECTS ON ITG/TEM TURBULENCE

Electromagnetic stabilization at finite β predicted to be critical for quantitative agreement in NBI-only scenario

- **Good agreement in all transport channels with EM effects (δB)**
  - Near marginal

- **Transport over-predicted in the electrostatic (ES) limit ($\delta B \to 0$)**
  - Downshift of ∇n threshold (for ∇n-TEM instability)

- **Max. growth rates increase ~35% if electromagnetic effects ignored ($\delta B \to 0$)**

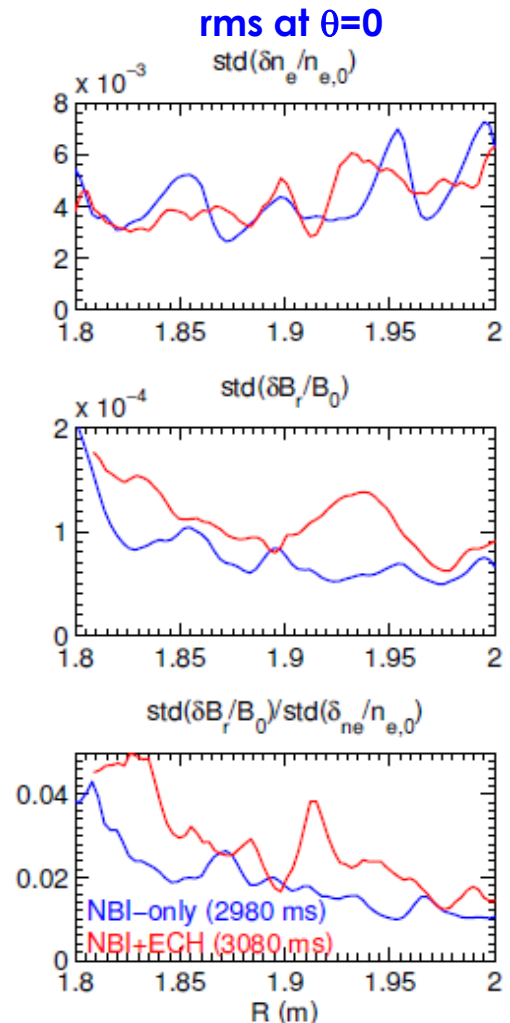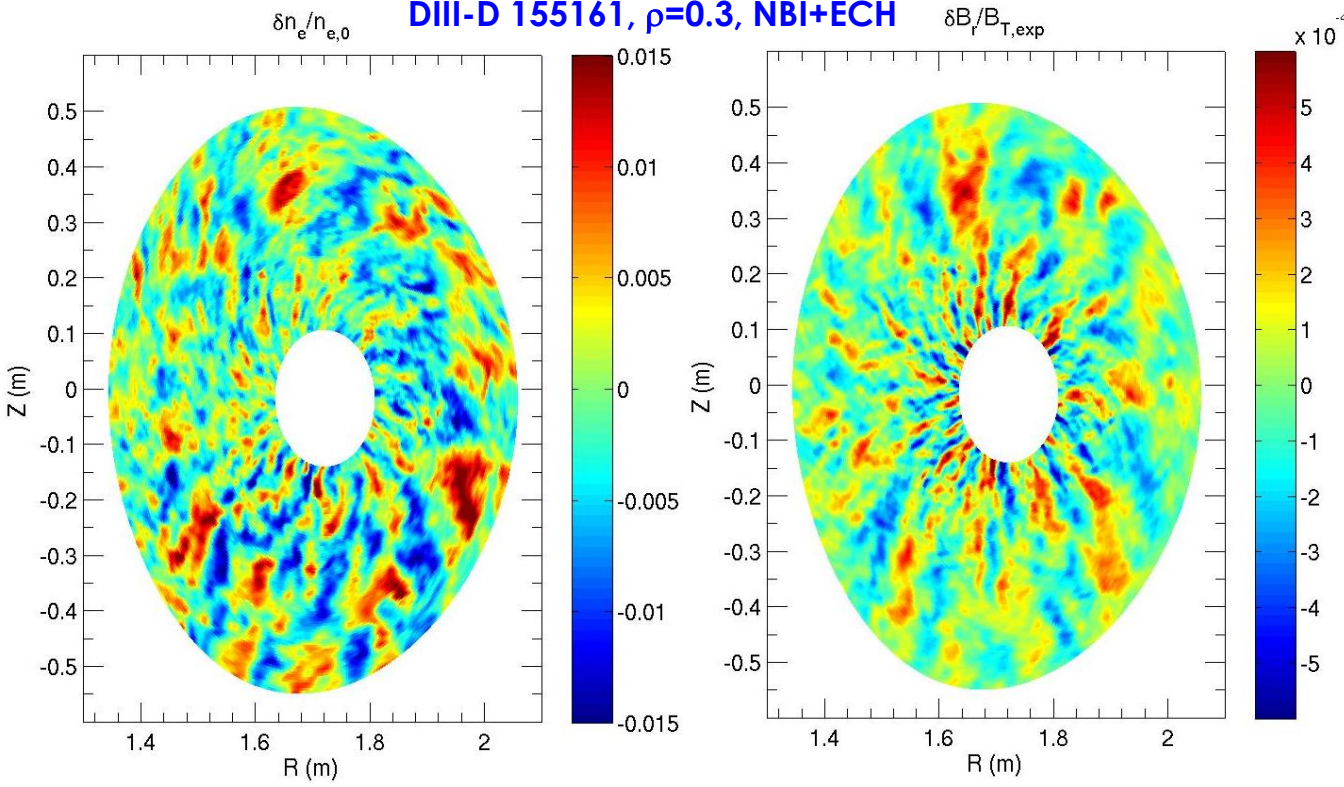**nonlinear GYRO simulations**
DIII-D 155161, $\rho = 0.3$, NBI-only

Guttenfelder, APS-DPP (2015)

Nonlinear gyrokinetic simulations predict $\delta B/B_0 \sim 1\text{-}2 \times 10^{-4}$

- $\delta B \sim 3\text{-}5$ Gauss
- $(\delta B/B_0) / (\delta n/n_0)$ similar to quasilinear ratio $\rightarrow$ useful for scoping (next section)

nonlinear GYRO simulations
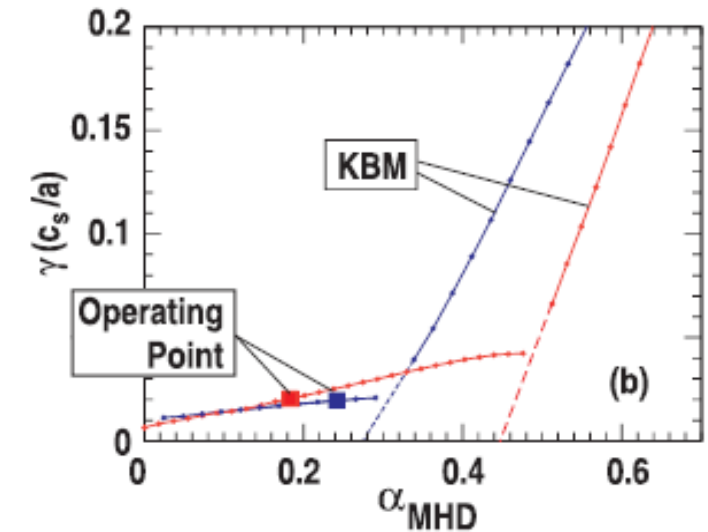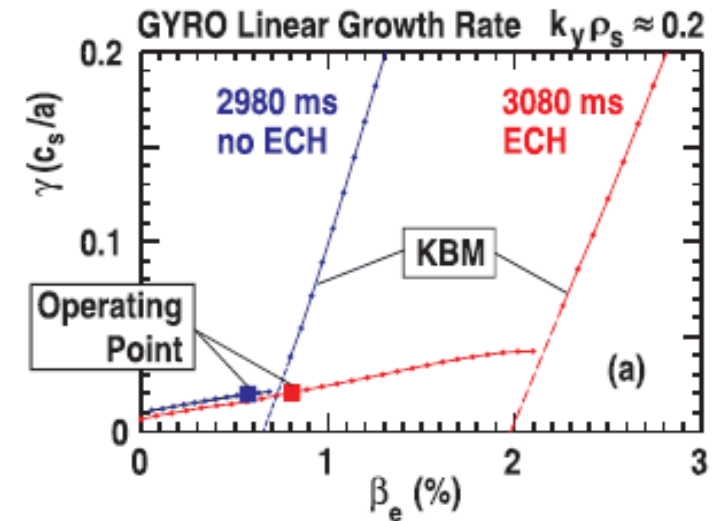**DIII-D 155161, $\rho=0.3$, NBI+ECH**

rms at $\theta=0$

- **Theory [7] predicts EM stabilization strengthens as local pressure gradient ($\alpha = -q^2 \cdot R \nabla P_{tot} \cdot 2\mu_0 / B^2$) approaches the KBM limit (α_{crit})**

- **In GYRO-normalized units:**

$$\alpha_{GYRO} = q^2 \left(\frac{R}{a} \right) \beta_e \sum_s \left[\frac{n_s}{n_e} \frac{T_s}{T_e} \left(\frac{a}{L_{ns}} + \frac{a}{L_{Ts}} \right) \right]$$

- **β_e scan used to identify KBM linear threshold**
  - Does not account for profile changes
- **As a function of α (including profile changes):**
- **NBI-only case, α within ~15% of $\alpha_{crit} \rightarrow$ strong EM stabilization (previous slides)**
- **ECH case has lower α/α_{crit} due to larger $\alpha_{crit} \rightarrow$ weak EM stabilization (not shown)**
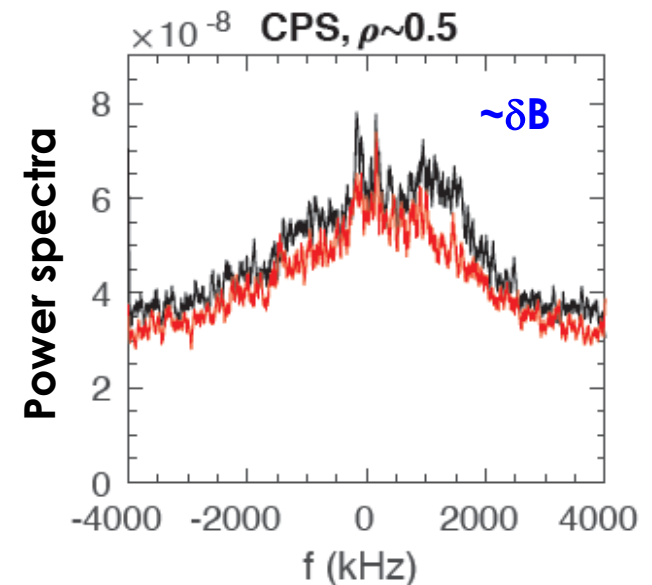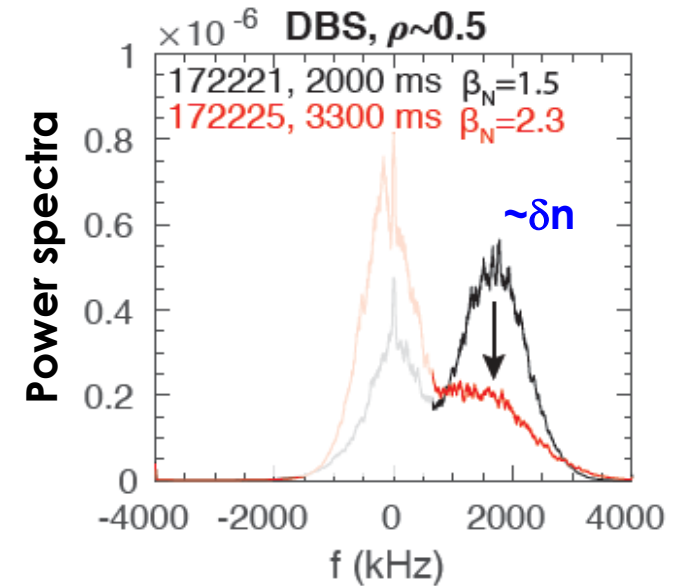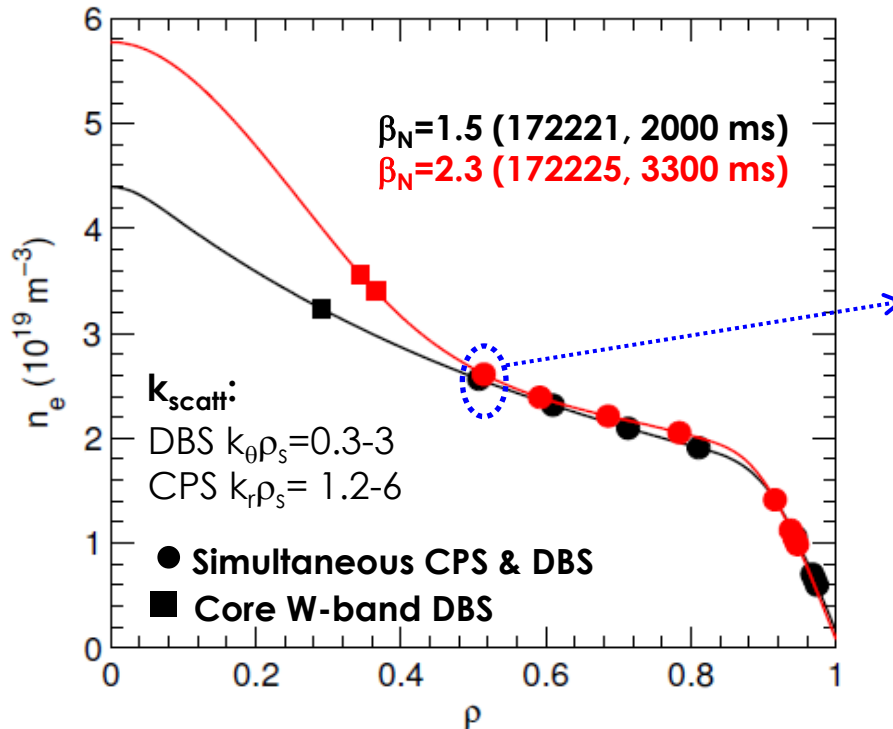

GYRO Linear Growth Rate $k_y \rho_s \approx 0.2$

2980 ms no ECH
3080 ms ECH
KBM
Operating Point
(a)

KBM
Operating Point
(b)

Ernst, PoP (2016)

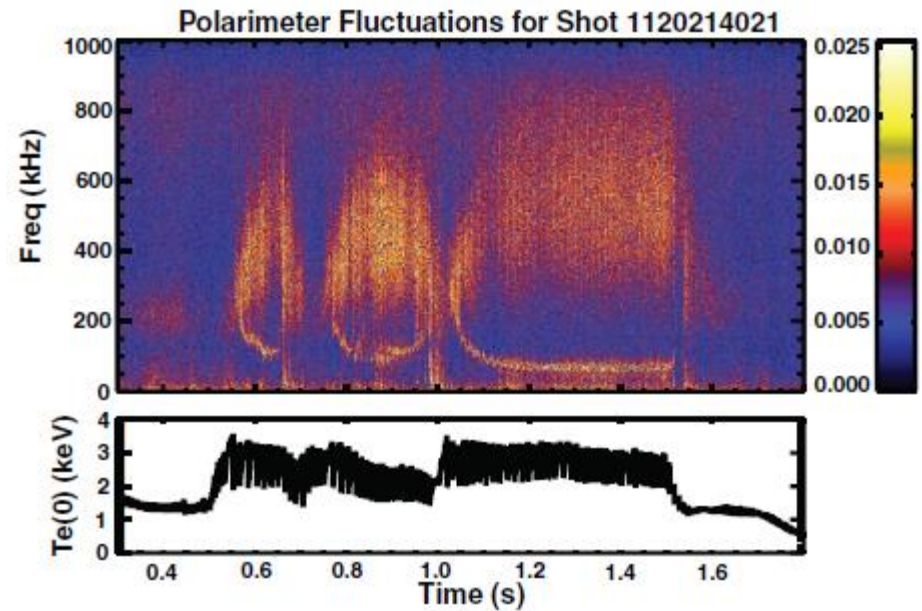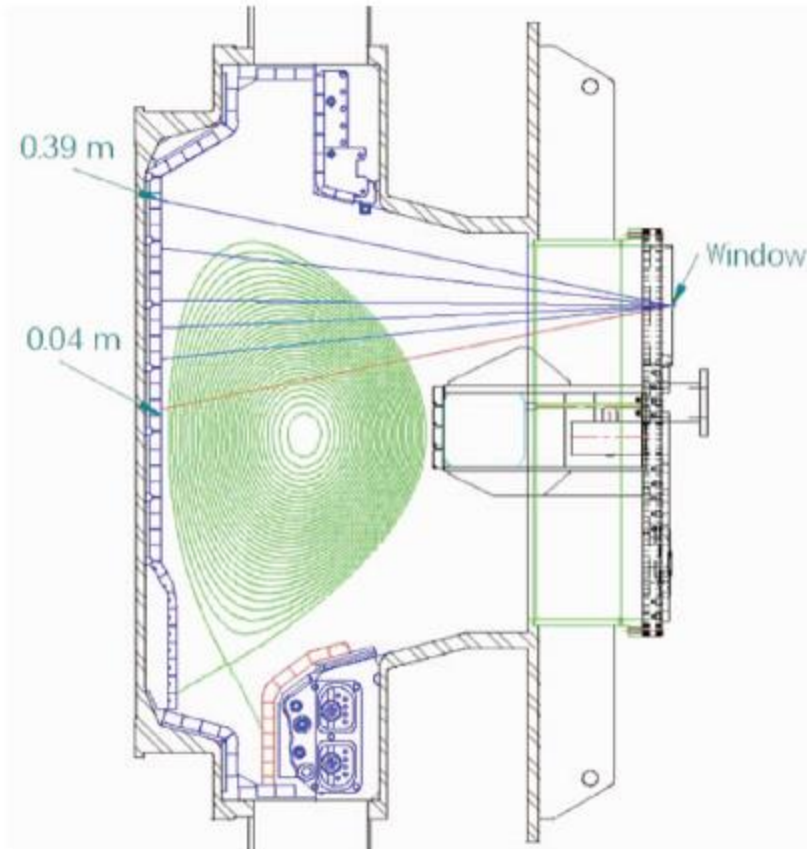# Using Doppler backscattering (DBS ~ δn) and cross polarization scattering (CPS ~ δB) to measure core EM turbulence

- **Increase of CPS/DBS amplitude ratio (~δB/δn) with β consistent with expectations**

⇒ **Requires ray tracing, gyrokinetic simulations + synthetic diagnostics to thoroughly validate**

β_N=1.5 (172221, 2000 ms)
β_N=2.3 (172225, 3300 ms)

k_{scatt}:
DBS $k_\theta \rho_s$=0.3-3
CPS $k_r \rho_s$= 1.2-6

● **Simultaneous CPS & DBS**
■ **Core W-band DBS**

DBS, ρ~0.5
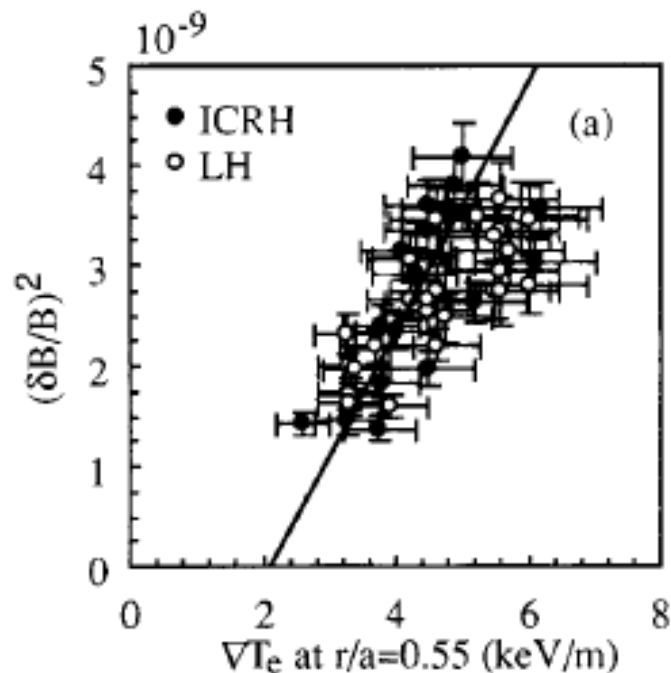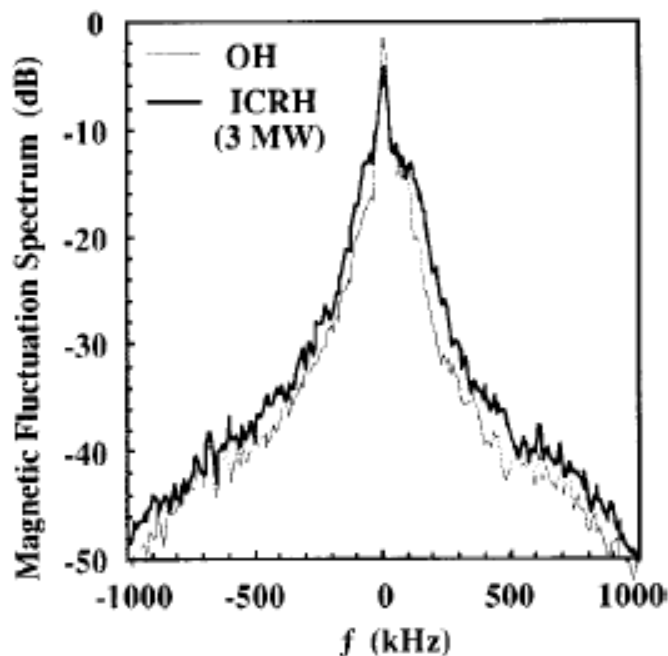172221, 2000 ms β_N=1.5
172225, 3300 ms β_N=2.3
~δn

CPS, ρ~0.5
~δB

Polarimetry on C-Mod has observed broadband high frequency polarization fluctuations

- Requires careful interpretation to separate δn_e and δB influence

Polarimeter Fluctuations for Shot 1120214021
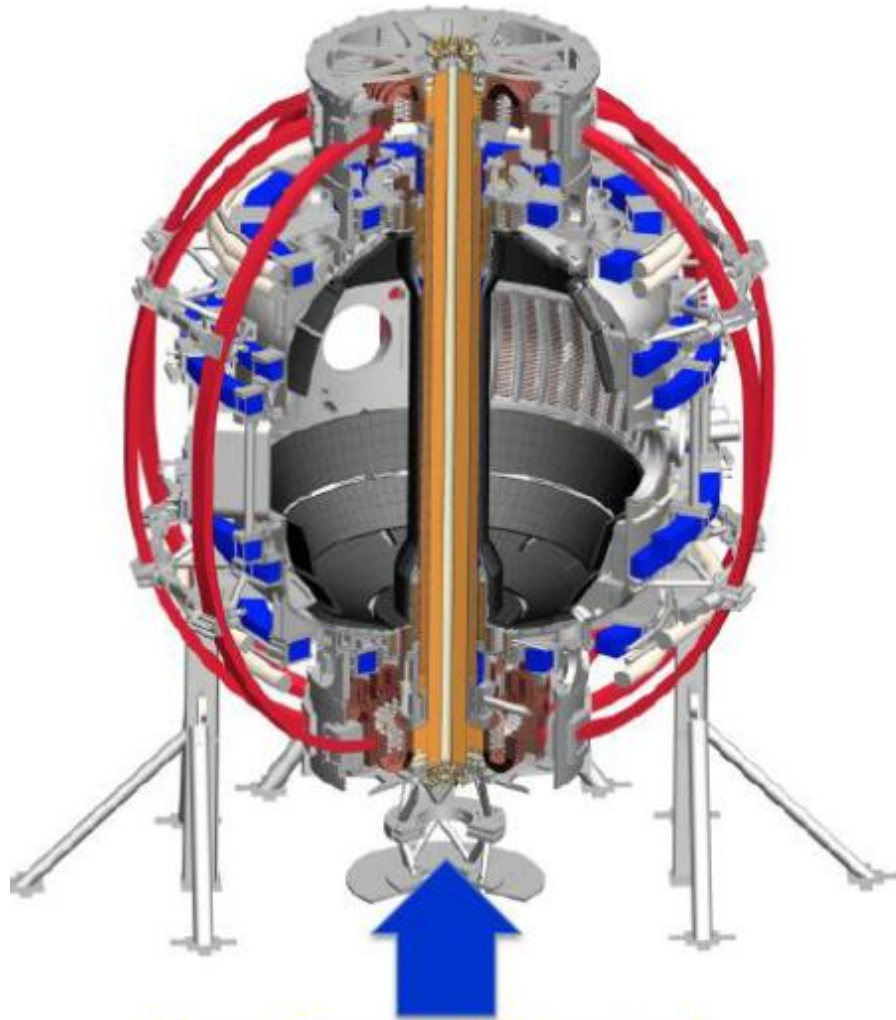
Bergerson, RSI (2012)

Cross polarization scattering used on Tore Supra to measure internal magnetic fluctuations

- Broad δB frequency spectra
- Correlation between $\delta B/B$ increasing with local ∇Te
- However, require additional measurements/simulations to determine weather δB due to
  - $j_{\parallel}$ from predominantly electrostatic turbulence (Callen PRL 1977)
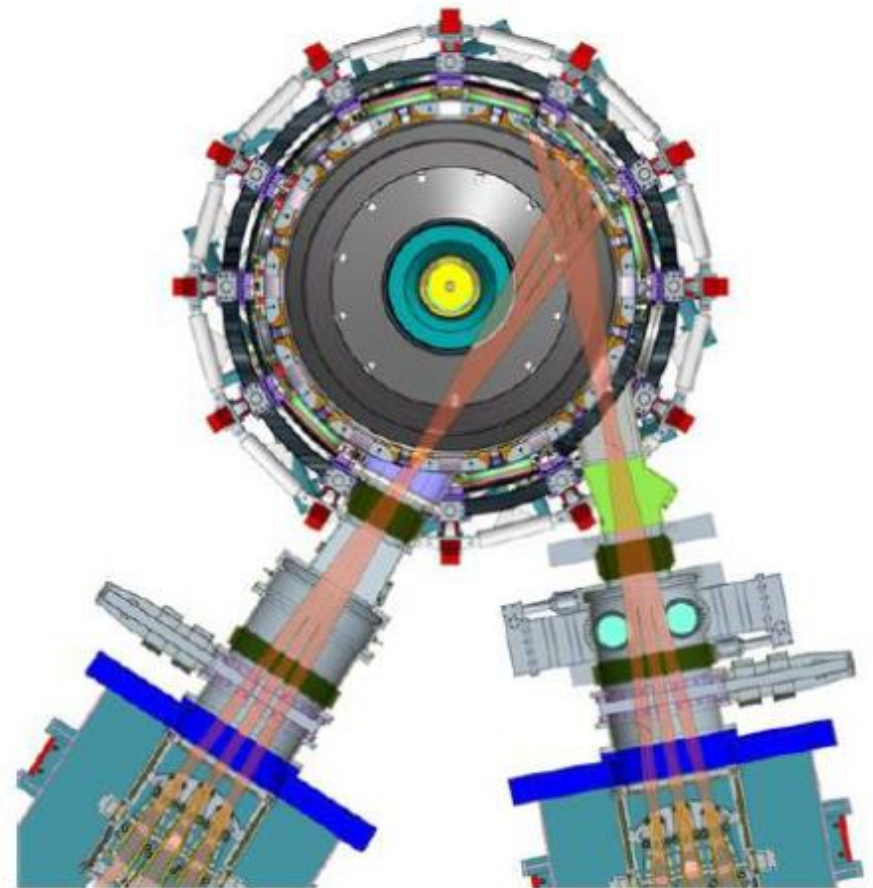 - fundamentally different turbulence (e.g. microtearing)

Colas, Nuclear Fusion (1998)

"PURE" ELECTROMAGNETIC TURBULENCE

But first, an aside on low aspect ratio "spherical" tokamaks, like NSTX-U at PPPL

New Central Magnet
1 Tesla at plasma center, I_p = 2MA, 5s

Original NBI
(R_{TAN} = 50, 60, 70cm)
5MW, 5s, 80keV

New 2nd NBI
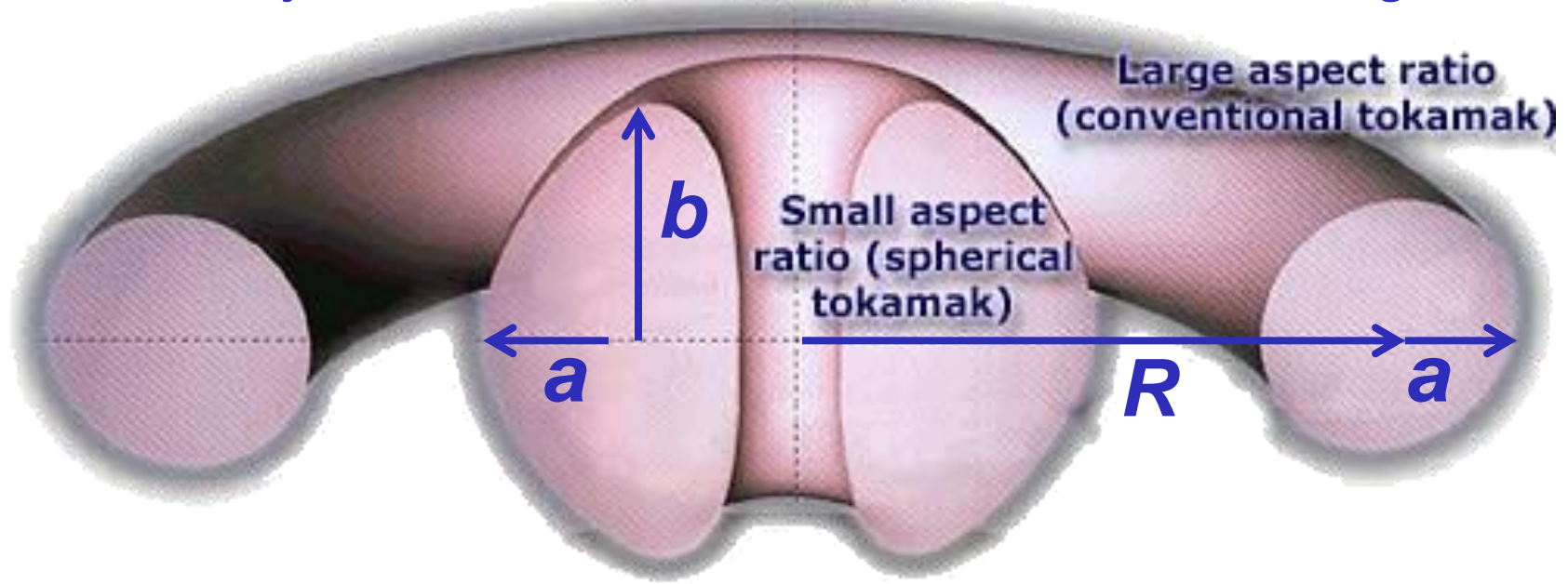(R_{TAN}=110, 120, 130cm)
5MW, 5s, 80keV

Aspect ratio is an important free parameter, can try to make smaller reactors (i.e. cheaper)
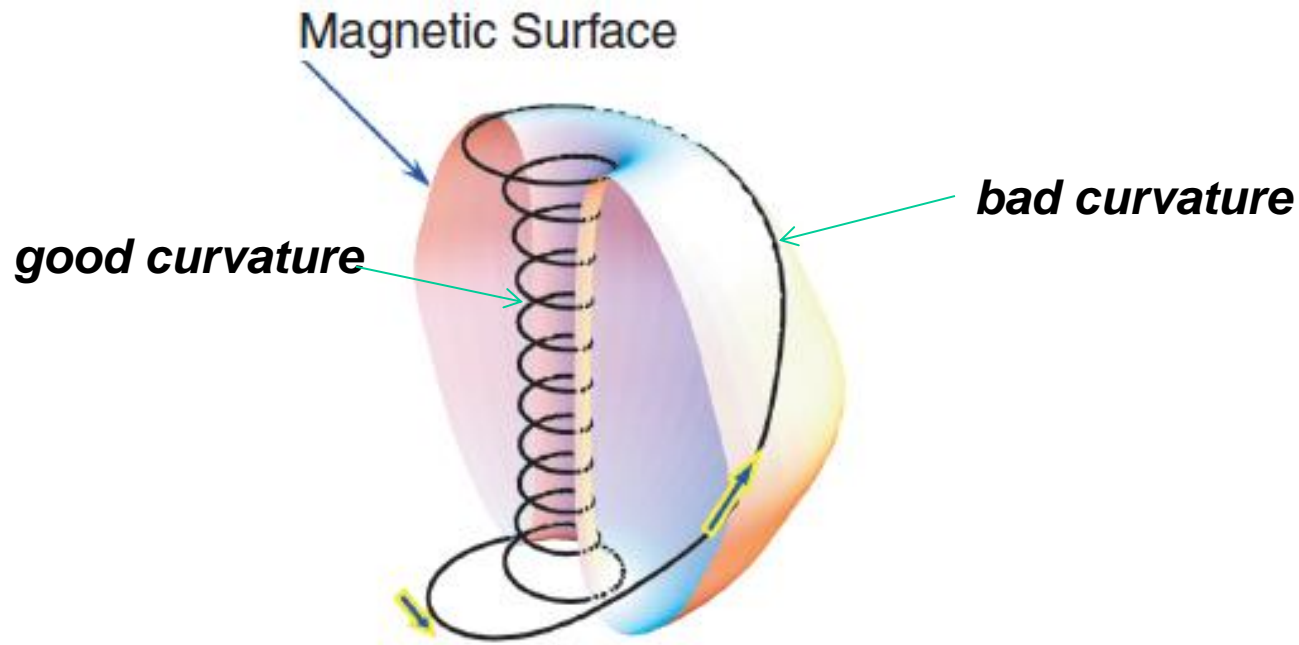
Aspect ratio A = R / a
Elongation κ = b / a

R = major radius, a = minor radius, b = vertical ½ height

Large aspect ratio
(conventional tokamak)

Small aspect
ratio (spherical
tokamak)

But smaller R = larger curvature, ∇B (~1/R) -- isn't this terrible for "bad curvature" driven instabilities?!?!?!
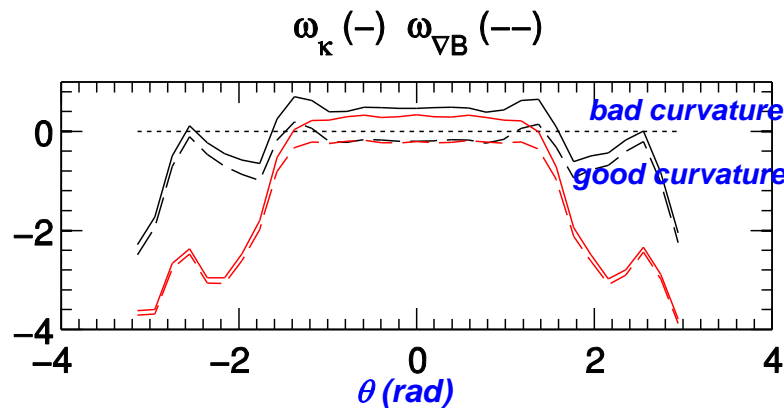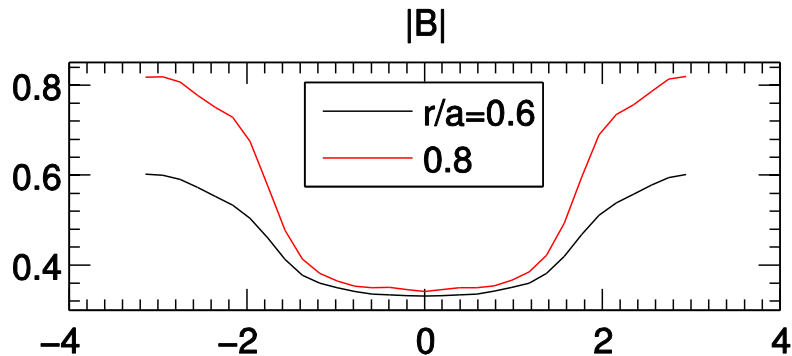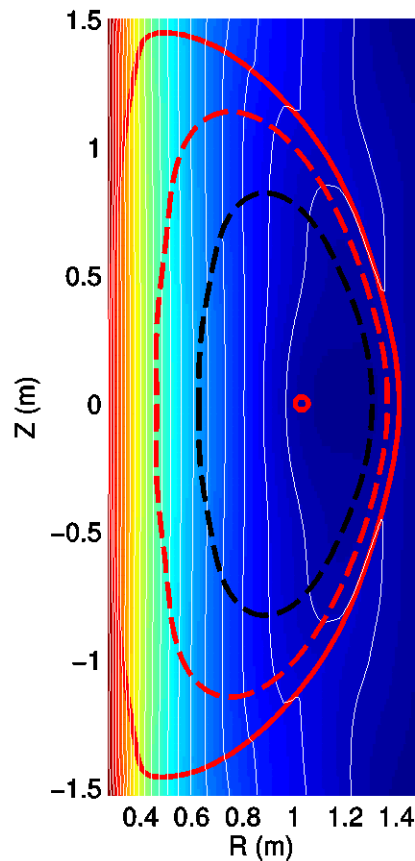
Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**

Magnetic Surface

good curvature

bad curvature

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length $\rightarrow$ **smaller average bad curvature**

- Quasi-isodynamic (~constant B) at high β $\rightarrow$ **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**

$|B|$

r/a=0.6
0.8

ω_κ (–) $\omega_{\nabla B}$ (––)

bad curvature
good curvature

$$\vec{v}_\kappa = mv_\parallel^2 \frac{\hat{b} \times \vec{\kappa}}{qB}$$

$$\vec{v}_{\nabla B} = \frac{mv_\perp^2}{2} \frac{\hat{b} \times \nabla B / B}{qB}$$

θ (rad)

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length $\rightarrow$ **smaller average bad curvature**

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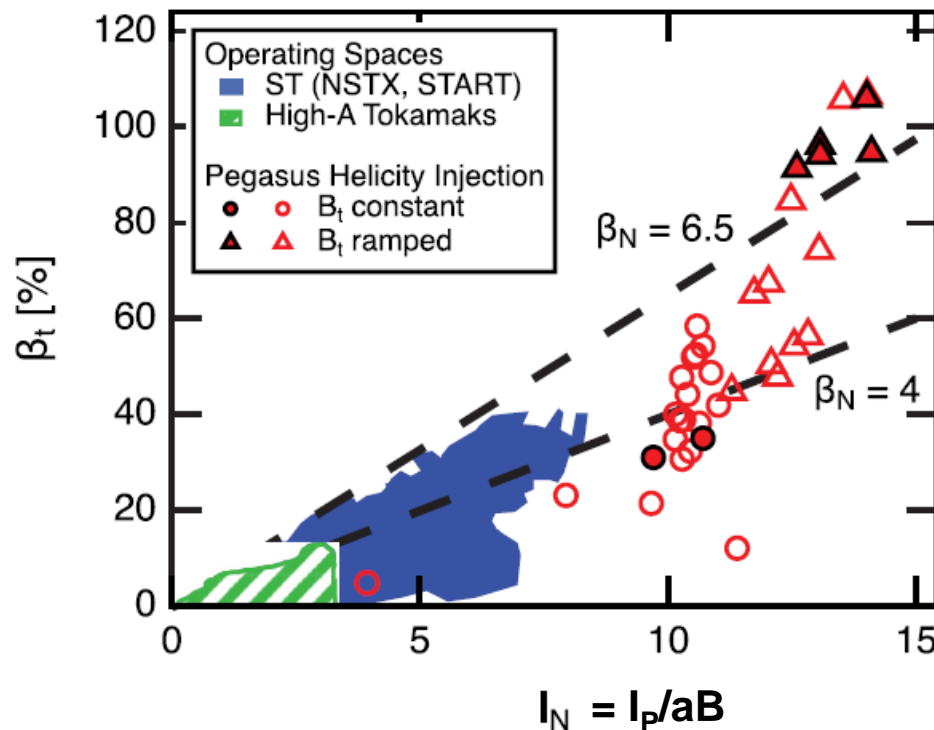
- **These same features stabilize macroinstabilities (MHD), allowing for very high β equilibrium: ~40% on NSTX, ~100% on Pegasus (U-Wisc)**
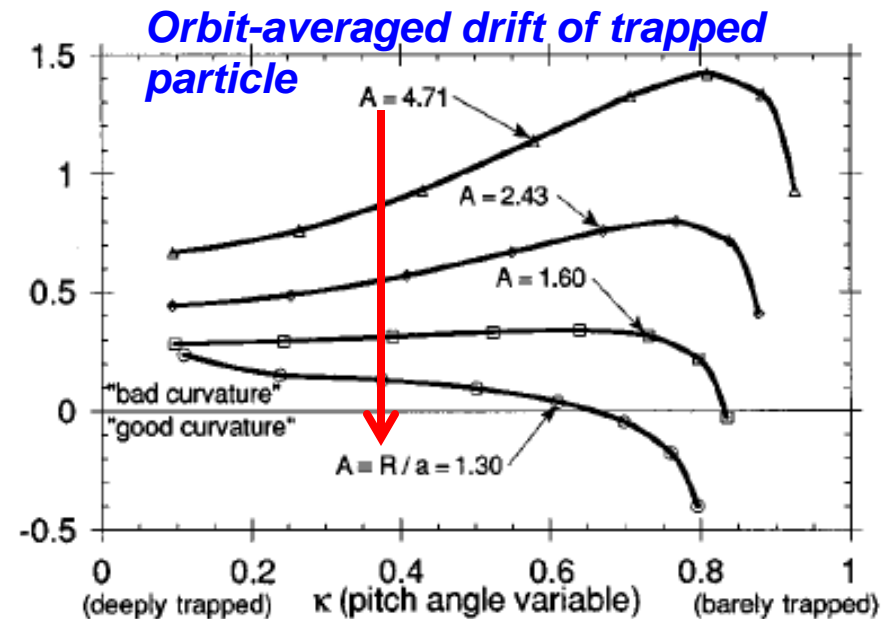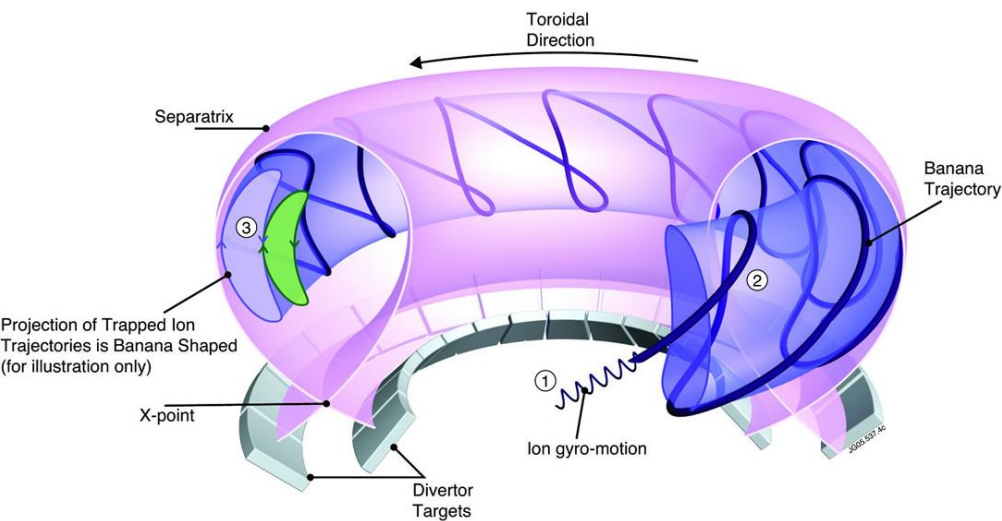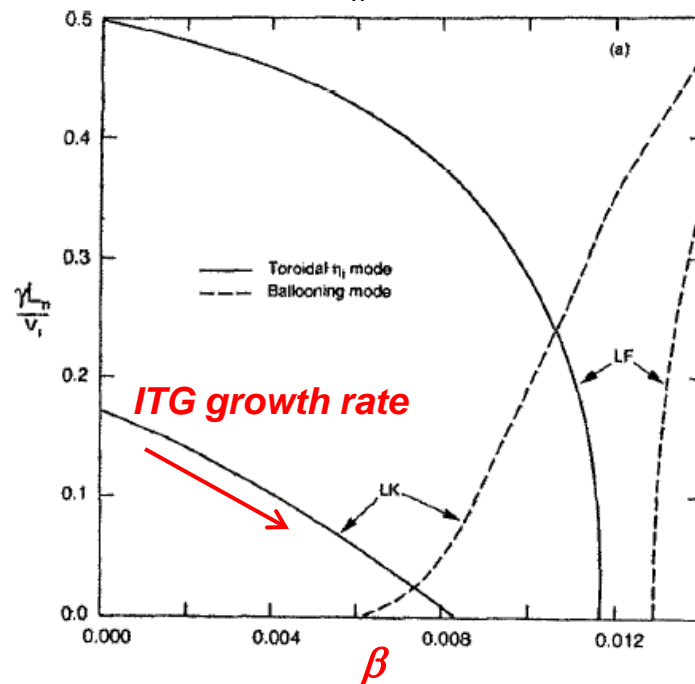
Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves
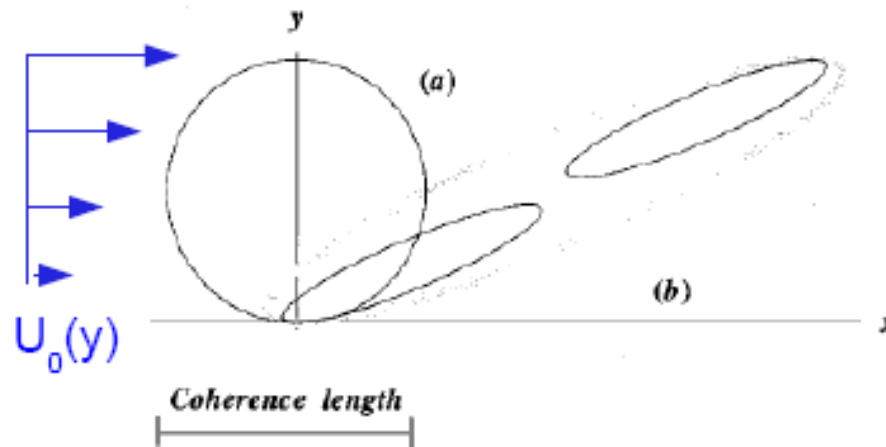
- Short connection length → **smaller average bad curvature**

- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**

- Large fraction of trapped electrons, BUT precession weaker at low A → **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**

Orbit-averaged drift of trapped particle

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

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- Strong coupling to $\delta B_\perp \sim \delta A_\parallel$ at high β $\rightarrow$ **stabilizing to ES-ITG**

ITG growth rate

Kim, Horton, Dong, PoFB (1993)

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

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- Strong coupling to $\delta B_\perp \sim \delta A_\parallel$ at high β $\rightarrow$ **stabilizing to ES-ITG**

- Small inertia ($nm\underline{R}^2$) with uni-directional NBI heating gives strong toroidal flow & flow shear $\rightarrow$ **E$\times$B shear stabilization ($dv_\perp/dr$)**
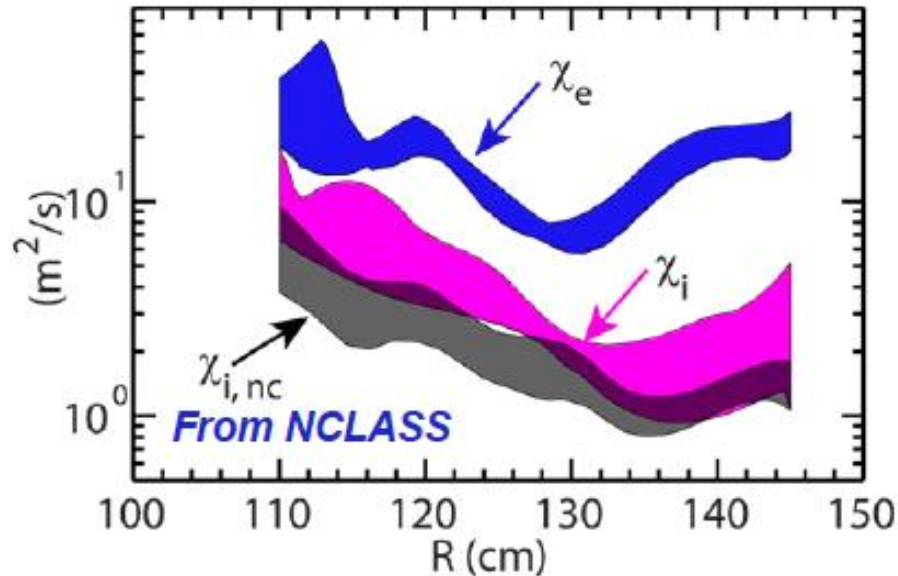

Biglari, Diamond, Terry, PoFB (1990)

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length $\rightarrow$ **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β $\rightarrow$ **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**
- Large fraction of trapped electrons, BUT precession weaker at low A $\rightarrow$ **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**
- Strong coupling to $\delta B_\perp \sim \delta A_\parallel$ at high β $\rightarrow$ **stabilizing to ES-ITG**
- Small inertia (nmR^2) with uni-directional NBI heating gives strong toroidal flow & flow shear $\rightarrow$ **E$\times$B shear stabilization ($dv_\perp/dr$)**
- $\Rightarrow$ **Not expecting strong ES ITG/TEM instability (much higher thresholds)**

- BUT High beta drives EM instabilities:
  - microtearing modes (**MTM**) ~ $\beta_e \cdot \nabla T_e$
  - kinetic ballooning modes/energetic particle modes (**KBM/EPM**) ~ $\alpha_{MHD} \sim q^2 \nabla P/B^2$ & ∇P_{fast}
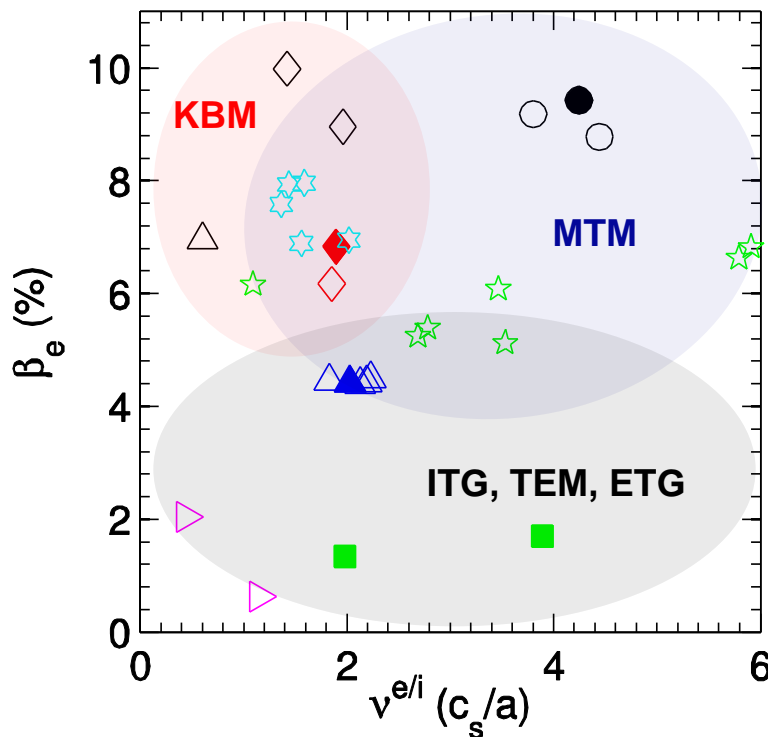- Large shear in parallel velocity can drive Kelvin-Helmholtz-like instability ~$dv_\parallel/dr$

Ion thermal transport in ST H-modes (higher beta) usually very close to collisional (neoclassical) transport theory

Courtesy Y. Ren

- Consistent with ITG/TEM stabilization by equilibrium configuration & strong E×B flow shear

  – Impurity transport (intrinsic carbon, injected Ne, …) also usually well described by neoclassical theory [Delgado-Aparicio, NF 2009 & 2011 ; Scotti, NF 2013]

- **Electron energy transport always anomalous**

  – Toroidal angular momentum transport also anomalous (Kaye, NF 2009)

Predicted dominant core-gradient instability correlated with local beta and collisionality

- For sufficiently small β, ES instabilities can still exist (ITG, TEM, ETG)
- At increasing β, MTM and KBM are predicted $\rightarrow$ depending on ν
  - Various instabilities often predicted in the same discharge – global, nonlinear EM theory & predictions will hopefully simplify interpretation (*under development*)

NSTX

Local gyrokinetic analyses at ~2/3 radius

Low hanging fruit: calculate, characterize & improve analytic treatment of linear MTM threshold scaling (good 1st or 2nd year student project…)

Guttenfelder, NF (2013)

- Collisionality scaling ($\chi_{e,MTM} \sim \nu_e$) consistent with global confinement ($\tau_E \sim 1/\nu$), follows linear stability trends:
  - In the core, driven by ∇T_e with time-dependent thermal force (e.g. Hassam, 1980)
  - *Requires collisionality* → **not explicitly driven by bad-curvature**
- δB leads to flutter transport ($\sim v_{||} \cdot \delta B^2$) consistent with stochastic transport

Predicted transport

Poincare plots of flux-tube surfaces

Guttenfelder, PRL (2011), PoP (2012)   **NSTX**   E. Wang, PoP (2011)

MTM density fluctuations distinct from ballooning modes like ITG (simulations)

NSTX MTM turbulence

DIII-D ITG turbulence

MTM turbulence exhibits large δB amplitude and spatial structure
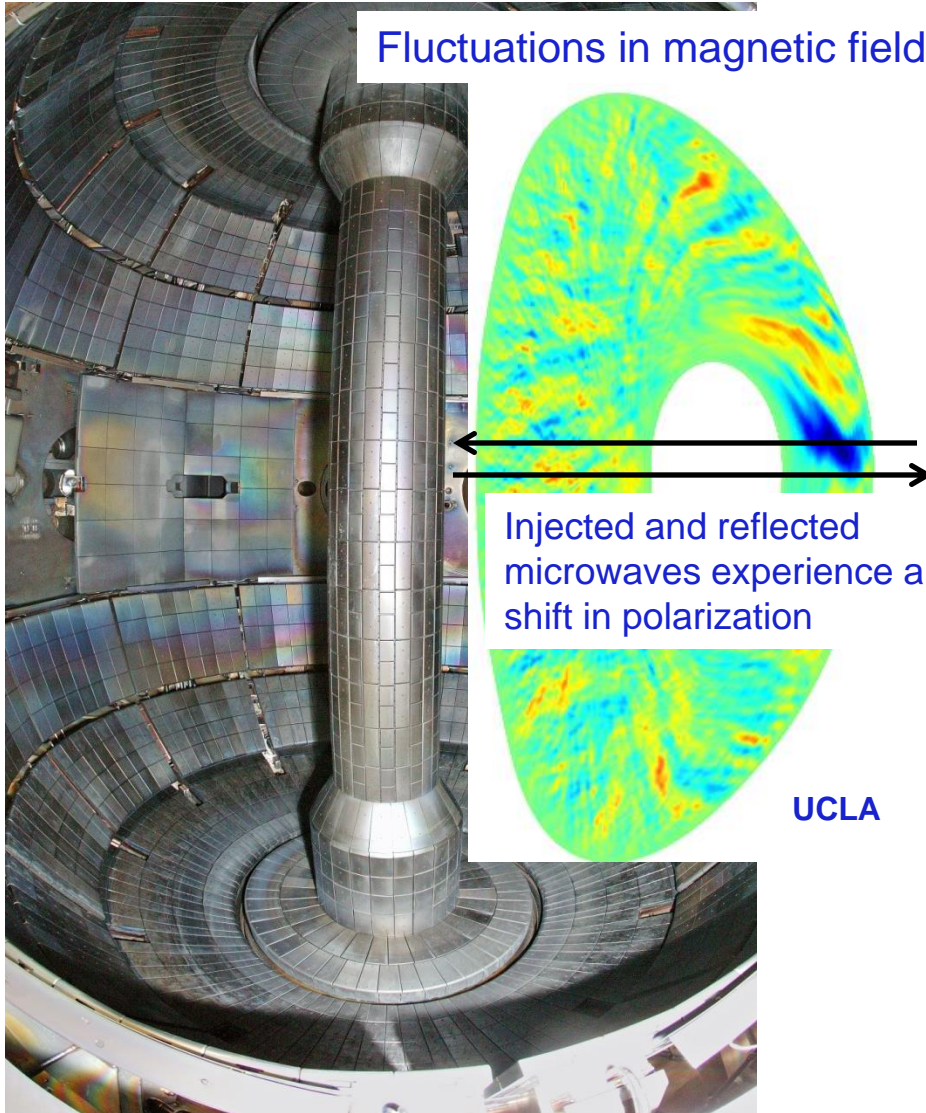
Predictions from MTM simulation

Visualization courtesy F. Scotti (LLNL)

- Narrow density perturbations due to high-m tearing mode around rational surfaces q=m/n
  - Potential to validate with beam emission spectroscopy (BES) imaging [Smith, RSI (2012)]

- Large δB/B~10^{-3}
  - Potential for internal δB measurements via Cross Polarization Scattering, CPS (UCLA collaboration)

Very challenging to measure internal magnetic fluctuations

NSTX (PPPL)

Fluctuations in magnetic field

Injected and reflected microwaves experience a shift in polarization

UCLA

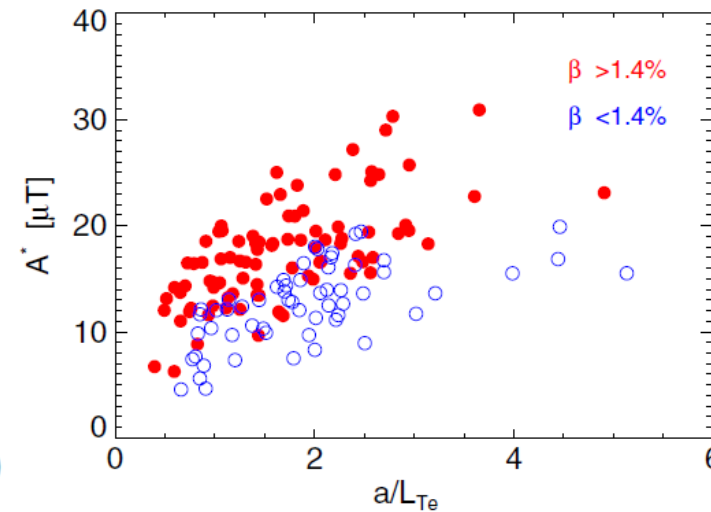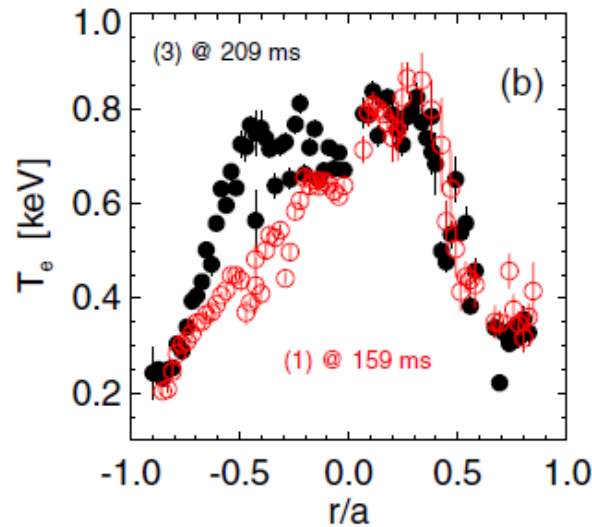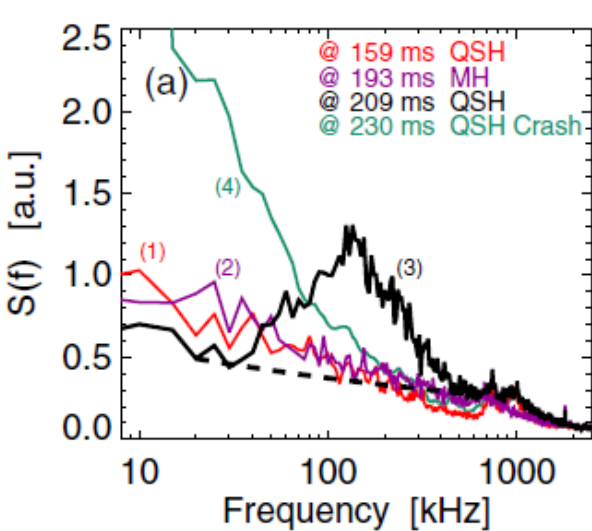- Synthetic diagnostic calculations predict polarimetry could be sensitive

Zhang, PPCF (2013)
Guttenfelder, PRL (2011)

- Will try to validate using CPS (UCLA) on NSTX-U

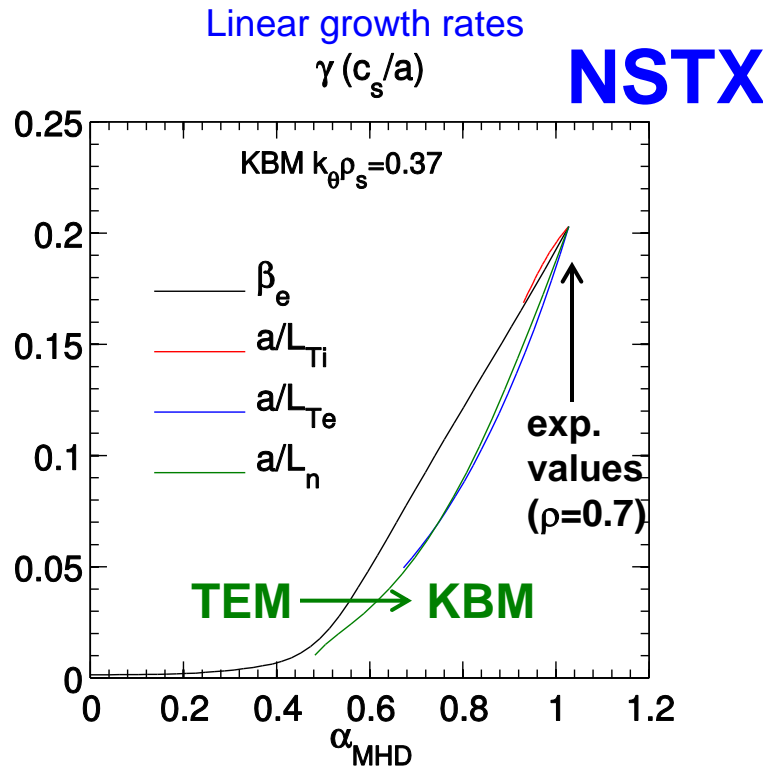# Inference of microtearing turbulence via magnetic probes in RFX reversed field pinch (Zuin, PRL 2013)

- Used internal array of closely spaced (~wavenumber resolved) high frequency Mirnov coils (~dB/dt) mounted near vacuum vessel wall

- Confinement and T_e increase during "quasi-single helicity" (QSH) state → broadband δB measured (3 below left)

- δB amplitude increases with a/L_{Te} & β (expected for MTM)

- Measured frequency and mode numbers (n,m) align with linear gyrokinetic predictions of MTM

- Additional MTM inferences using novel heavy ion beam probe technique (<u>internal, non-perturbative</u>) in JIPPT-IIU tokamak (Hamada, NF 2015)

At high β & <u>lower ν</u>, KBM modes predicted; Sensitive to compressional magnetic ($B_{||}$) perturbations

- Kinetic analogue of MHD high-n ballooning mode, driven by total ∇P (α_{MHD})

- Smooth transition from ITG/TEM at reduced ∇P

- Transport has significant compressional component ($\sim \delta B_{||}$)

Linear growth rates
$\gamma \, (c_s/a)$

NSTX

KBM $k_\theta \rho_s = 0.37$

- β_e
- a/L_{Ti}
- a/L_{Te}
- a/L_n

exp. values ($\rho=0.7$)

TEM ⟶ **KBM**

$$\alpha_{MHD} = -q^2 R \cdot 2\mu_0 \nabla P / B^2$$
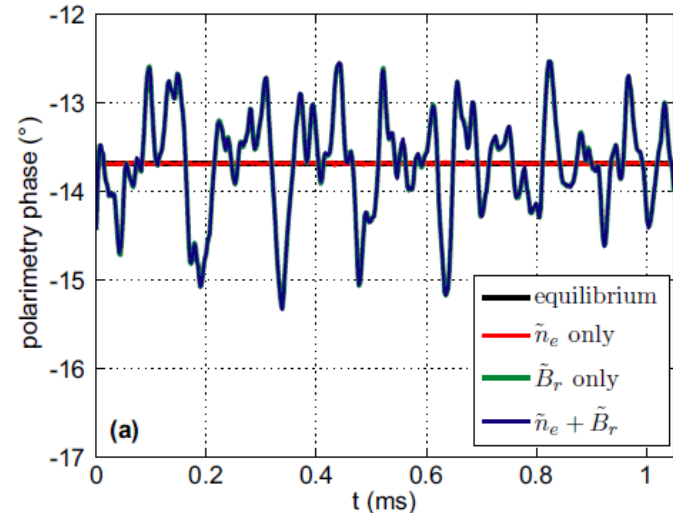
- Modeling suggests KBM important in core of DIII-D β_{pol} (i.e. large bootstrap current) discharges (Staebler, APS 2017)

More low hanging fruit: calculate, characterize linear KBM/EPM threshold scaling in NSTX (good 1st or 2nd year student project…)

Guttenfelder, NF (2013)

ZONAL FLOWS, GAMs

(important elements 2D turbulence nonlinear saturation)

Self-generated "zonal flows" impact saturation of turbulence and overall transport (roughly analogous to jet stream)

- Potential perturbations uniform on flux surfaces, near zero frequency (f~0)
- Predator-prey like behavior: turbulence drives ZF, which regulates/clamps turbulence; if turbulence drops enough, ZF drive drops, allows turbulence to grow again…

Linear instability stage demonstrates structure of fastest growing modes

Large flow shear from instability cause perpendicular "zonal flows"

Zonal flows help moderate the turbulence!!!
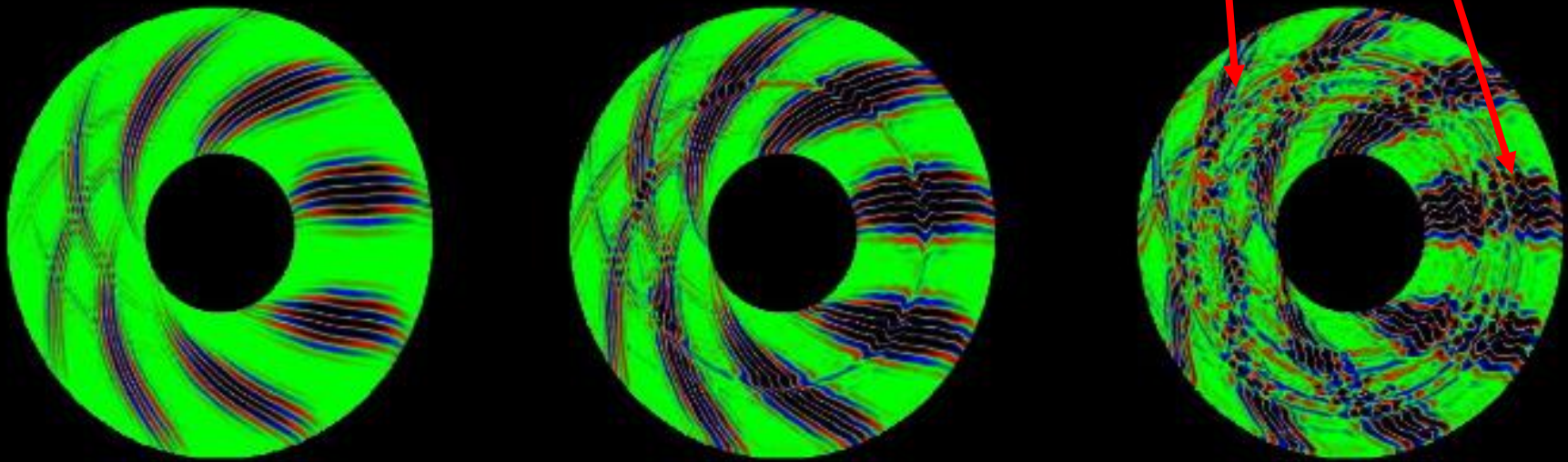
Evidence of zonal flows from measuring potential on same flux surface at two different toroidal locations

- High coherency at very low frequency with zero phase shift suggests uniform zonal perturbation

- Also evidence of a coherent mode around 17 kHZ - geodesic acoustic mode ($\omega_{GAM} \approx c_s/R$) from associated n=0, m=1 pressure perturbation

*CHS, Fujisawa, PRL (2004)*
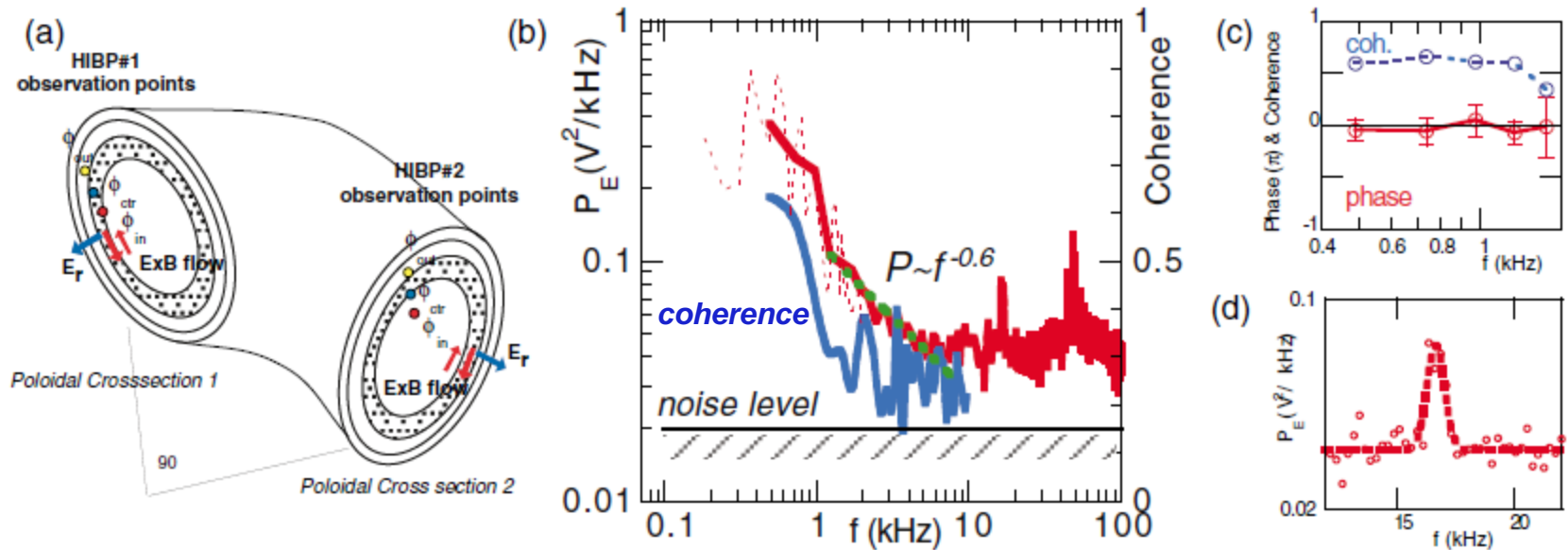
Also found using poloidal flow measurements from BES on DIII-D

- Poloidal flow determined from time delay estimation of poloidally separated BES channels

- High coherency at low frequency, zero phase shift

- Evidence of GAM oscillation

- Relative strength of each varies with radius

DIII-D, Gupta PRL (2003)
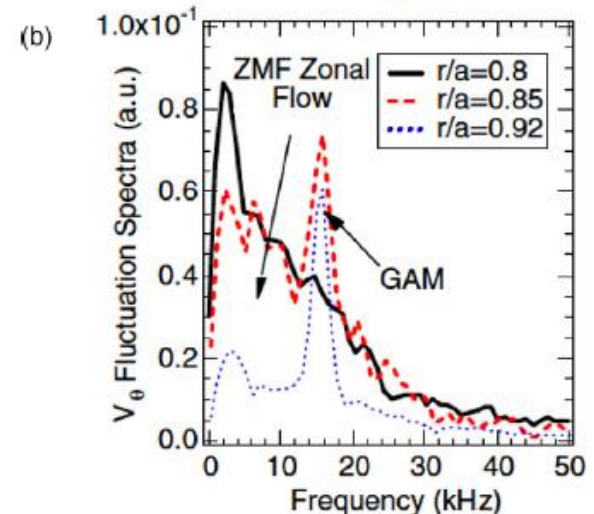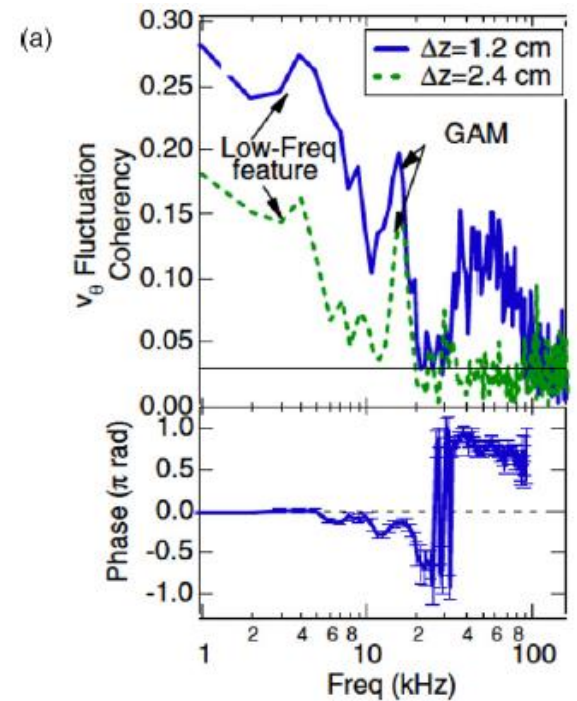
Wide radial envelope of GAM measured in DIII-D using BES

Shafer, PoP (2012)
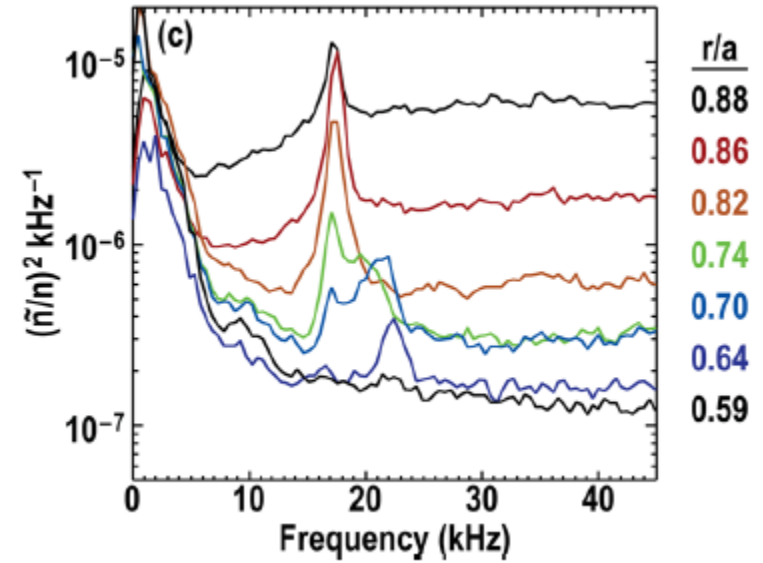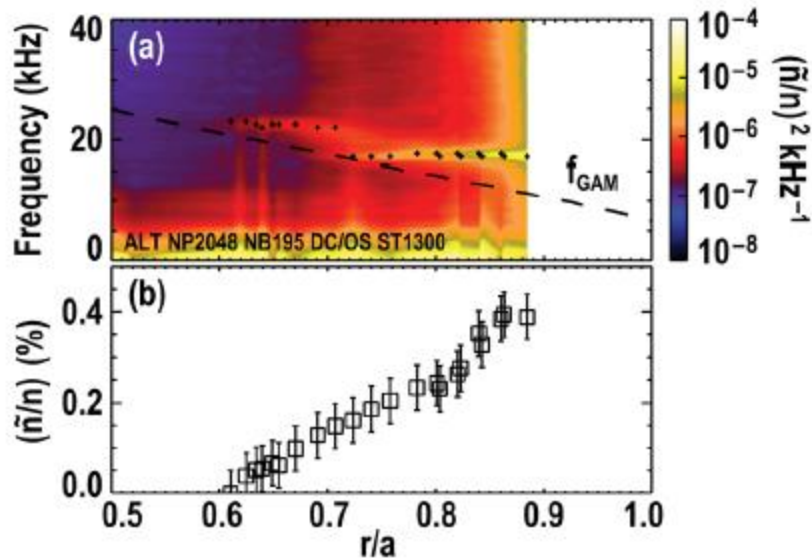
GAM seen on numerous devices using different measurement techniques

- Seems to be in nearly all machines, if looked for

- See Fig. 11 of Fujisawa, Nuclear Fusion (2009) for legend
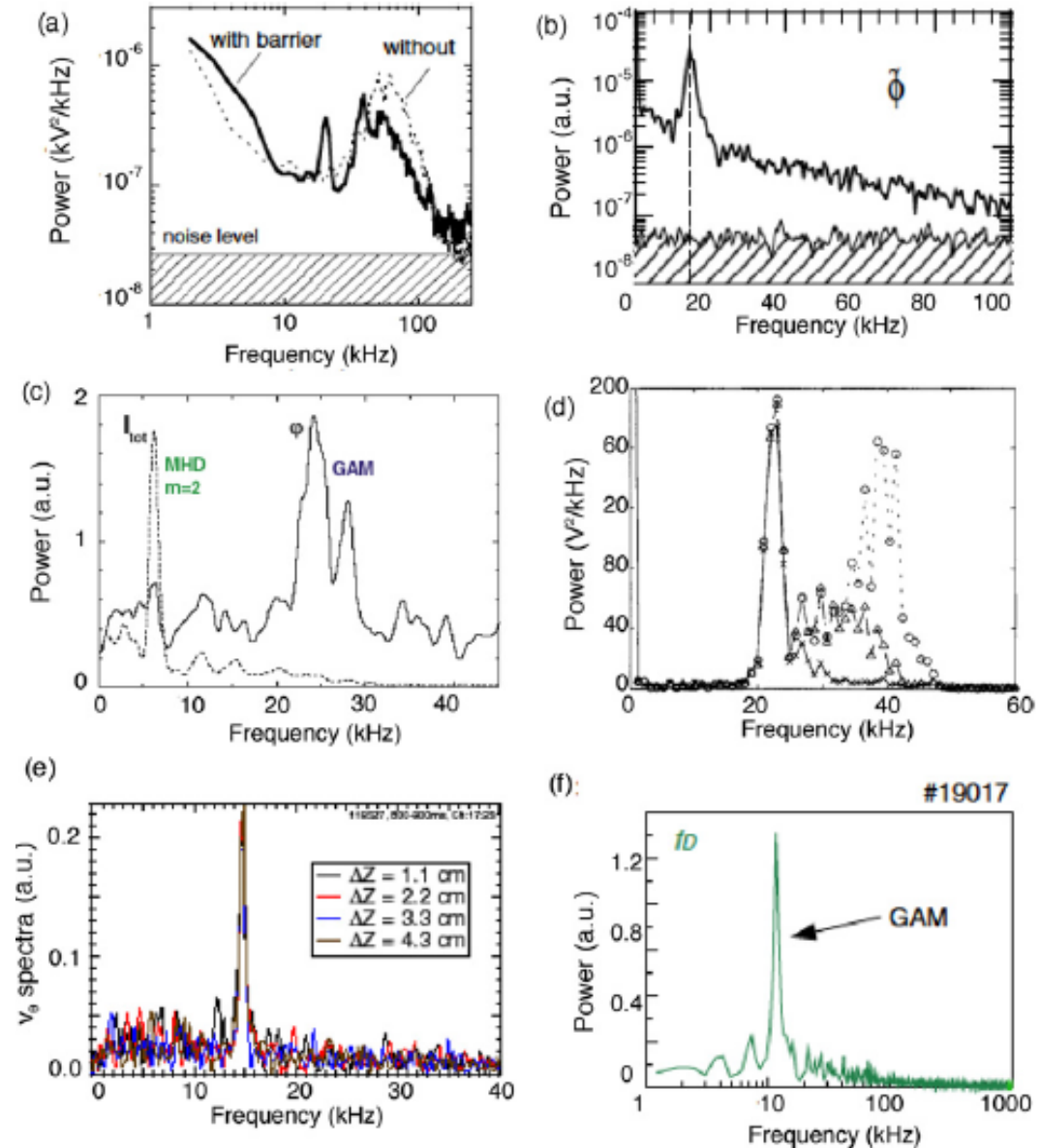
# Broad cross-machine agreement of GAM frequency with theory

- Discrepancies have spurred additional theory developments to refine gam frequency and damping rates (due to geometry, nonlinear effects, …)
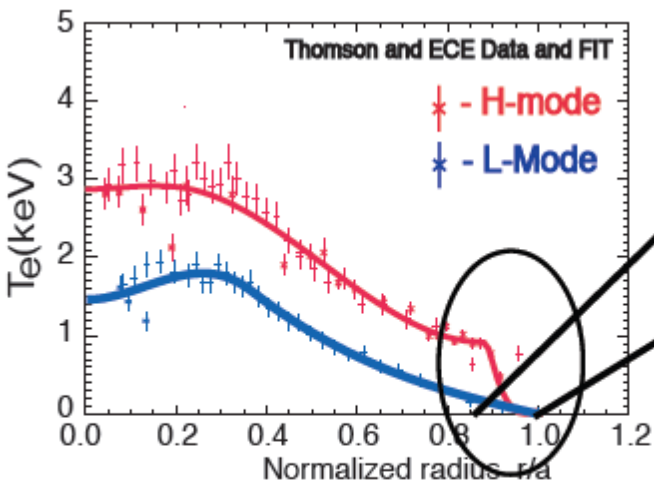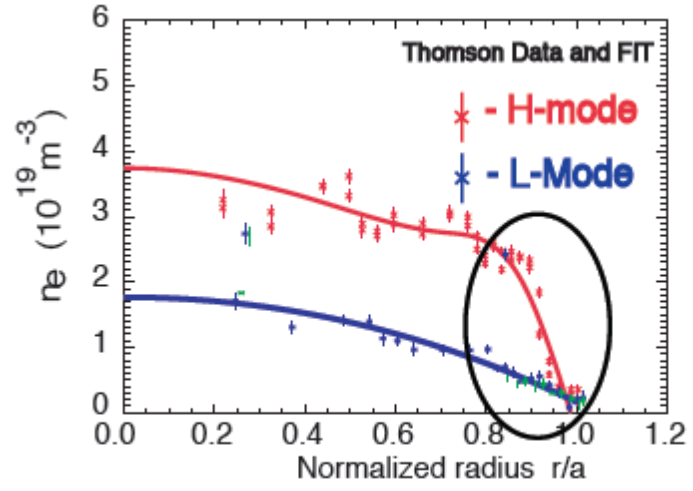

Fujisawa, NF (2009)
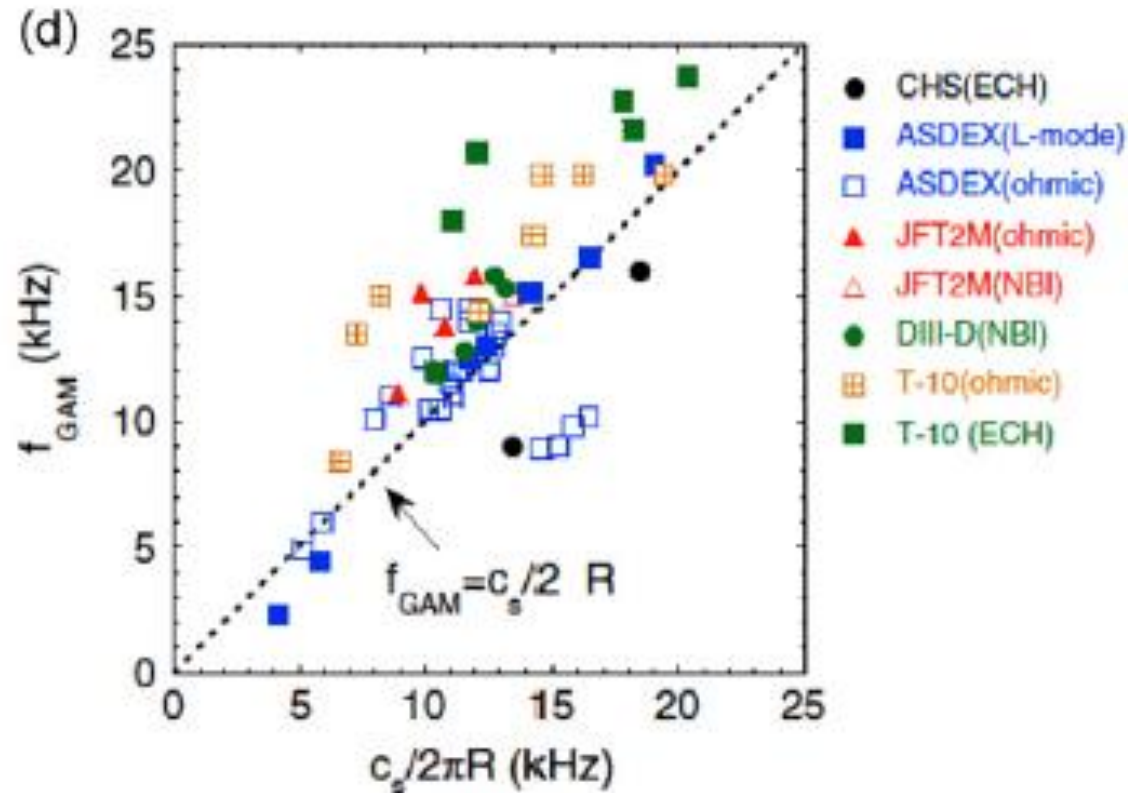
EDGE TURBULENCE
L-H TRANSITION

Going to refer to different spatial regions in the tokamaks

- Especially **core**, **edge** (just inside separatrix), and **scrape-off layer** (SOL, just outside separatrix)
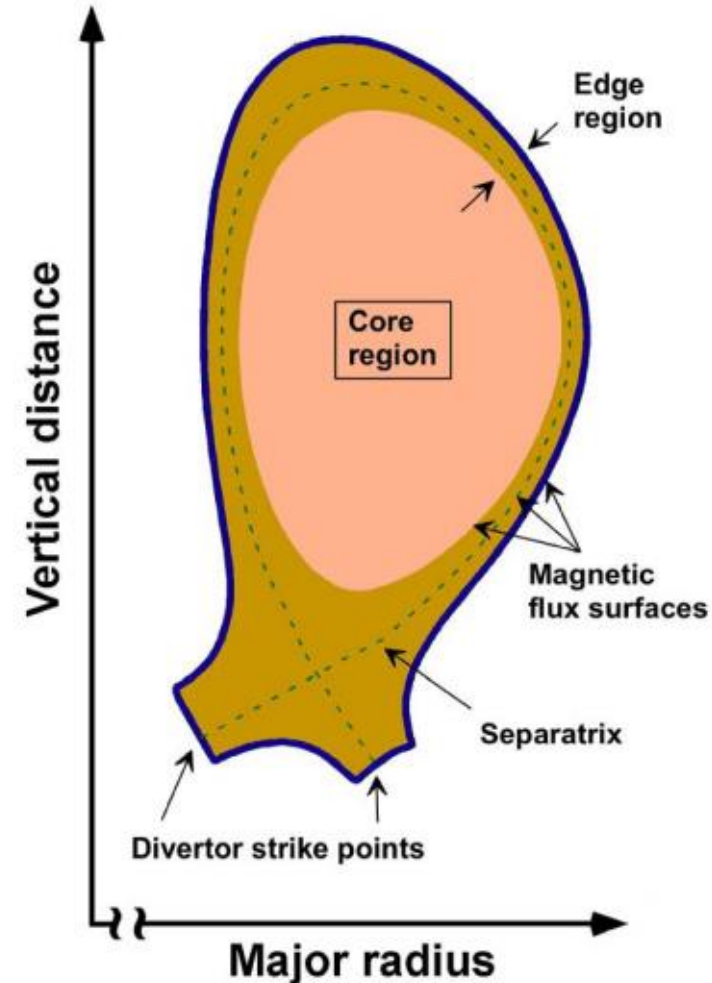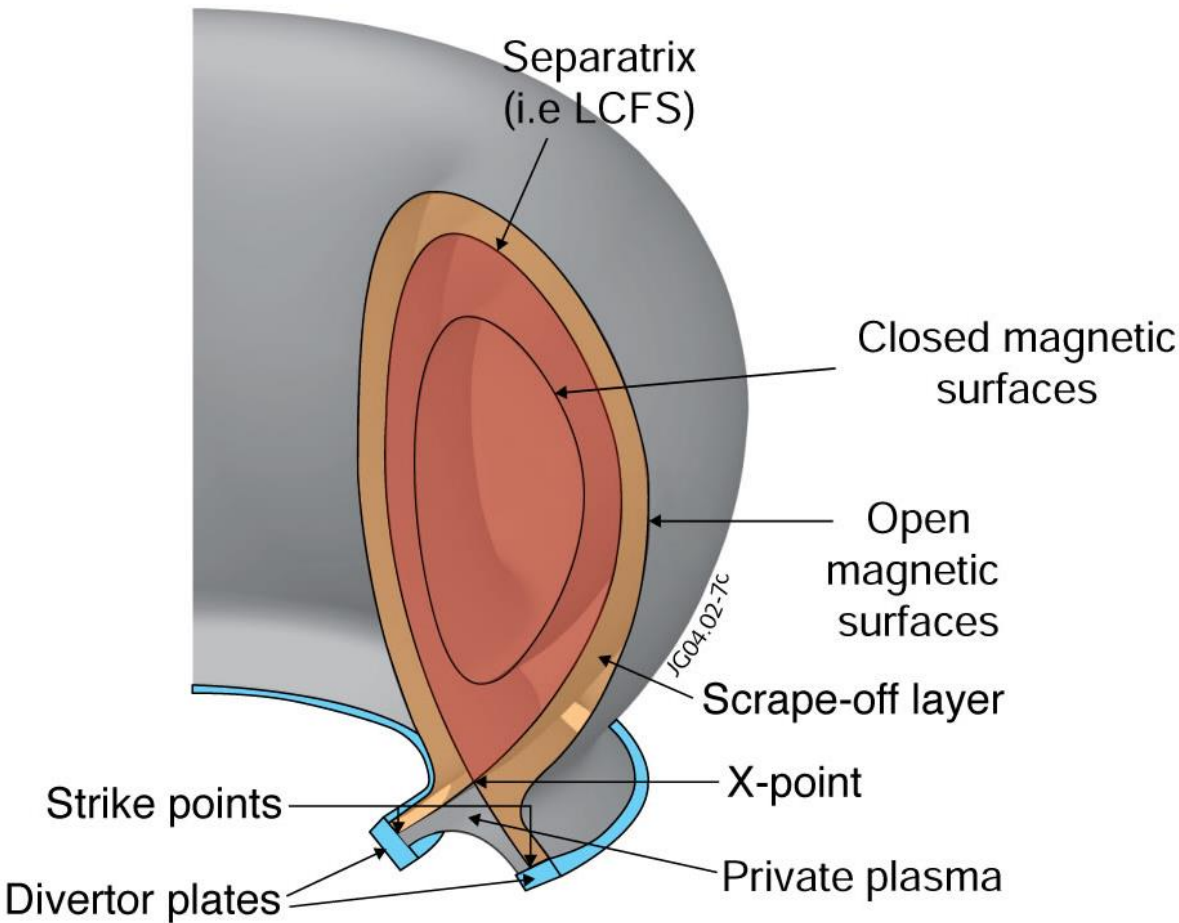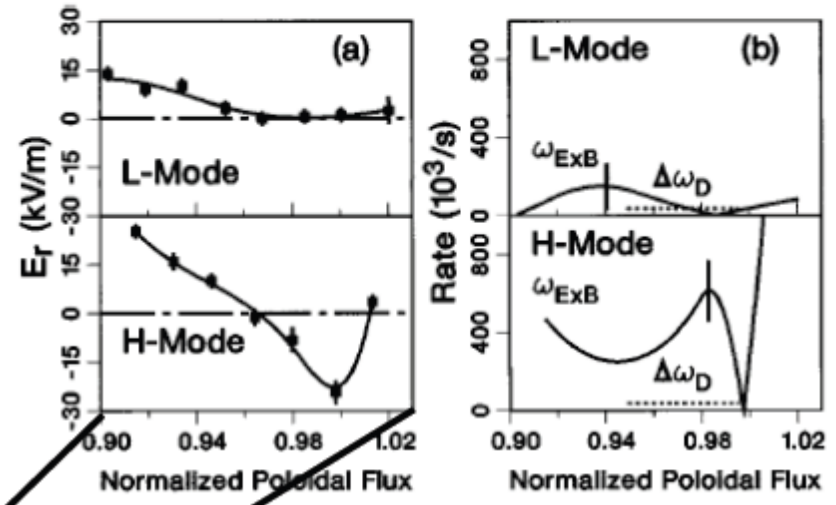
Spontaneous "H-mode" edge transport barrier can form with sufficient heating power → *improved confinement*


Data from DIII-D

(from Carter, 2013)

Burrell 1997

- Correlated with strong shear in equilibrium radial electric field (E_r)
- Suppression of turbulence predicted when equilibrium shearing rate ($\omega_{E \times B}$) > turbulence decorrelation rate ($\Delta\omega_D$) [Biglari, 1990; Hahm, 1994]

Transition from L→H correlated with drop in turbulence amplitude, reduction in radial correlation length

- Consistent with E×B shear suppression

- However, there is still no clear understanding regarding what *initiates* the transition and the dynamics involved

- Practically important for understanding how much power required to reach H-mode (→ *almost all reactor designs assume H-mode*)
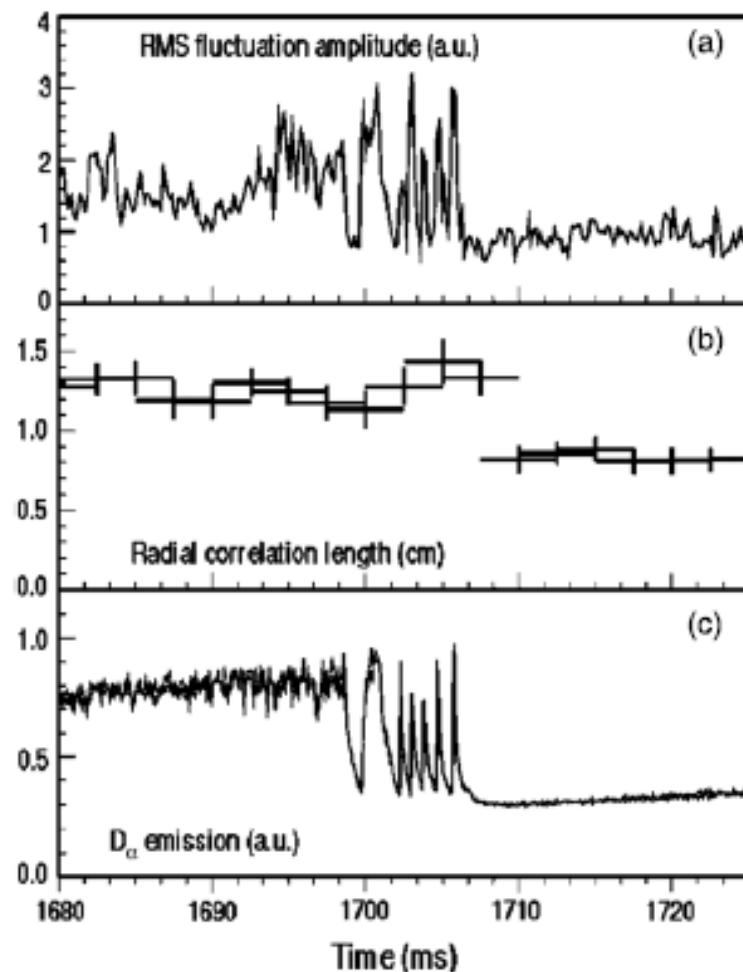

Burrell, PoP (1997)
Coda, Phys. Lett. A (2000)

Multiple doppler backscattering diagnostics provide δn, $\delta v_{E \times B}$ at multiple radii simultaneously

- During dithering L-H phase (identified by D_α signal), $\delta v_{E \times B}$ and δn start to oscillate

- Equilibrium n_e, T_e begin to increase

- Eventually strong equilibrium flow shear locks in, fluctuations drop permanently, and pedestal finishes forming

DIII-D, Schmitz, PRL (2012)
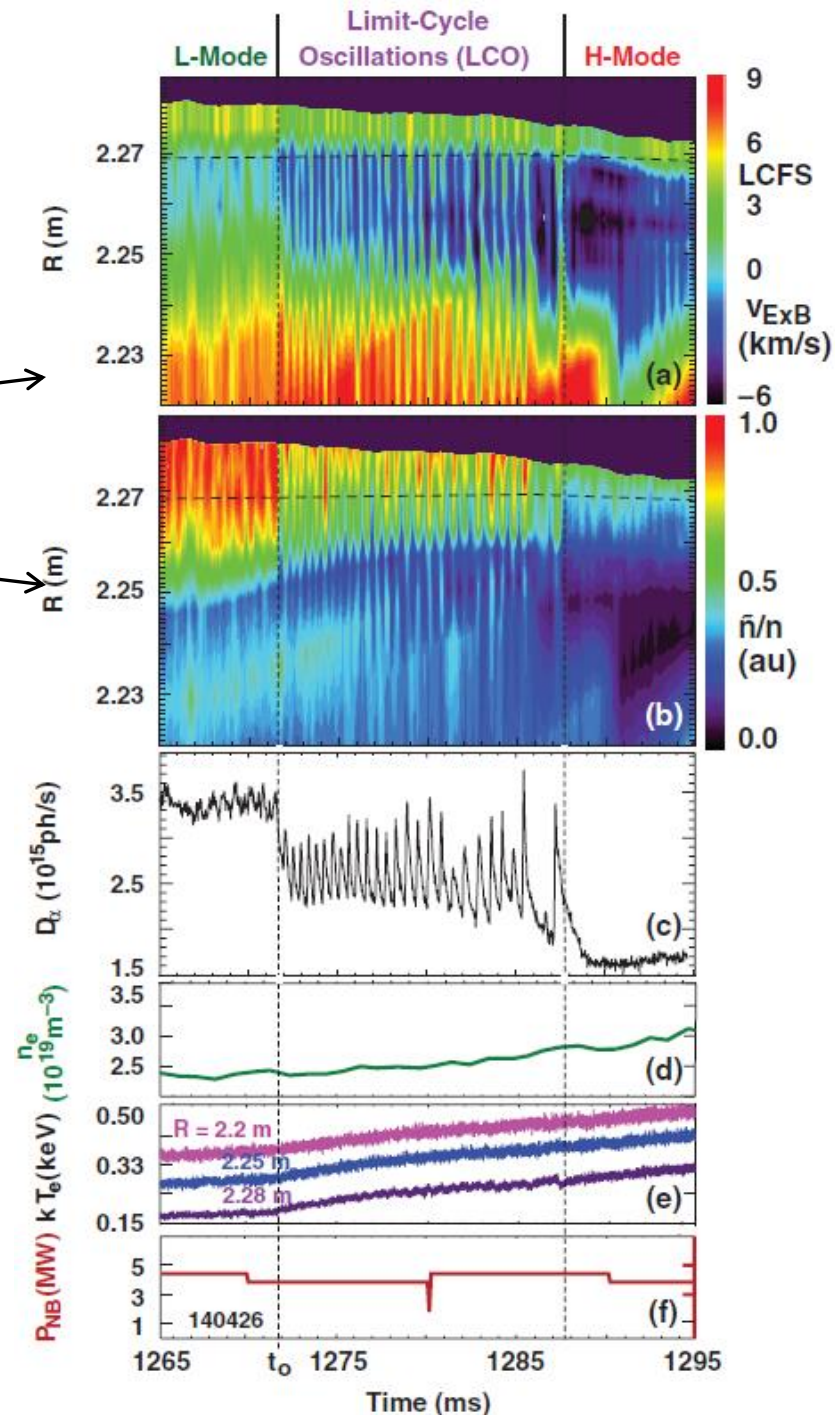
Dynamics consistent with two-predator – prey model (Kim, PRL 2003)

- In L-mode, increasing turbulence drives stronger ZF

- Eventually starts to suppress turbulence, leads to predator-prey limit cycle oscillation between ZF and turbulence

- As confinement (and gradients) increases, equilibrium Er driven by ∇Pi increases, until it is strong enough to maintain suppression
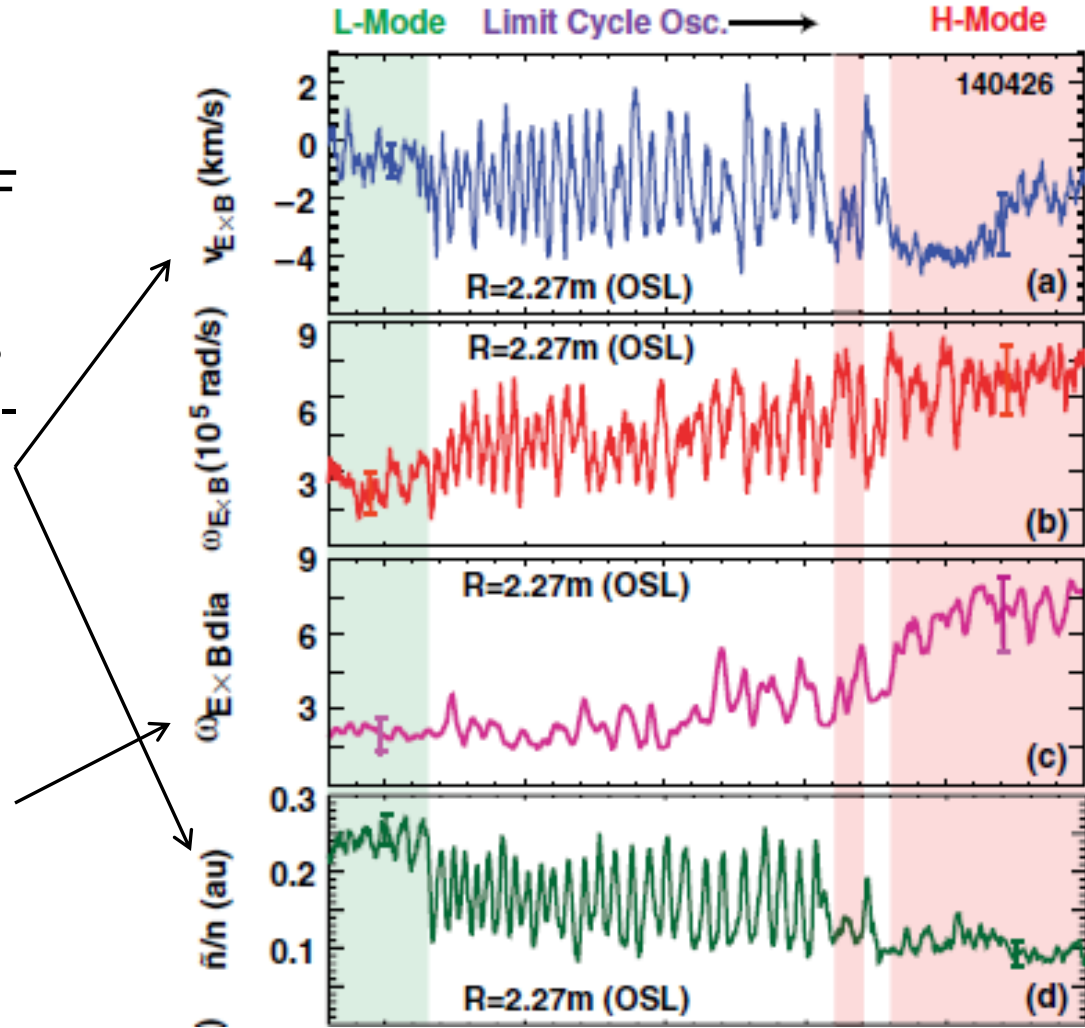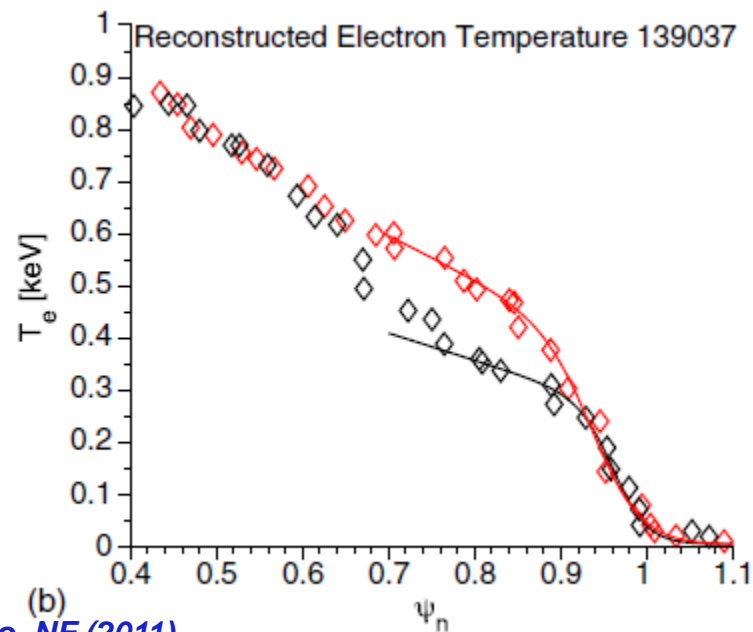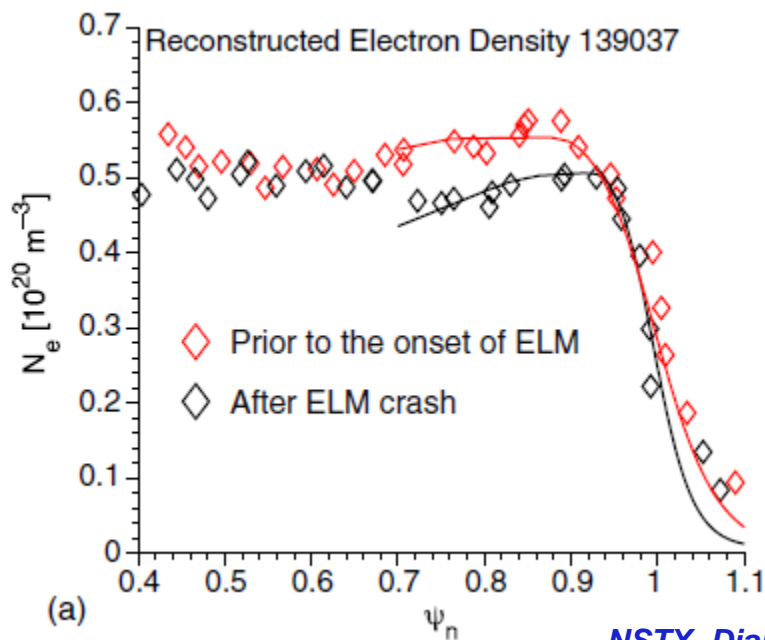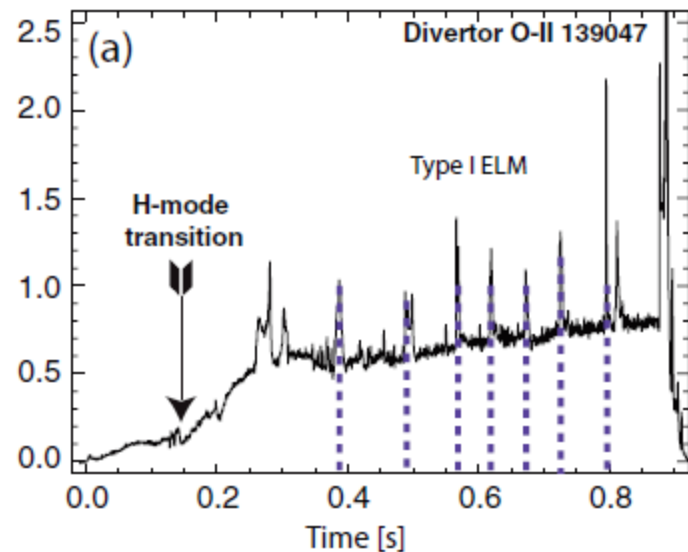
DIII-D, Schmitz, PRL (2012)
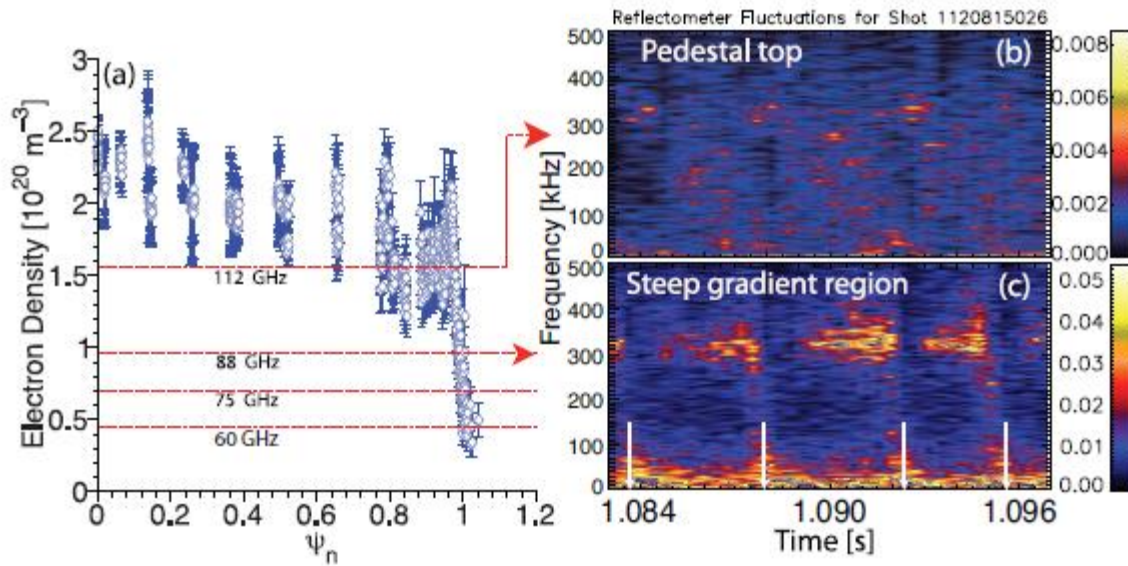
EDGE TURBULENCE
H-mode pedestal

# In established H-modes, periodic MHD instabilities (Edge Localized Modes, ELMs) often occur

- Rapidly expels energy

- Profiles drop after ELM, recover between ELMs

- General question of what transport mechanism limits H-mode pedestal & post-ELM recovery

NSTX, Diallo, NF (2011)

Local density and magnetic fluctuations measured inter-ELM - possible importance of EM turbulence


- Density from reflectometry (& Gas Puff Imaging)
- Magnetic probes inserted 2 cm from separatrix (measures same k_θ as density)
- Evidence for importance of EM turbulence?
- Leading theory posits KBM (EM drift wave) as a key contributor setting H-mode pedestal (Snyder, NF, 2011)

Alcator C-Mod, Diallo, PRL (2014)
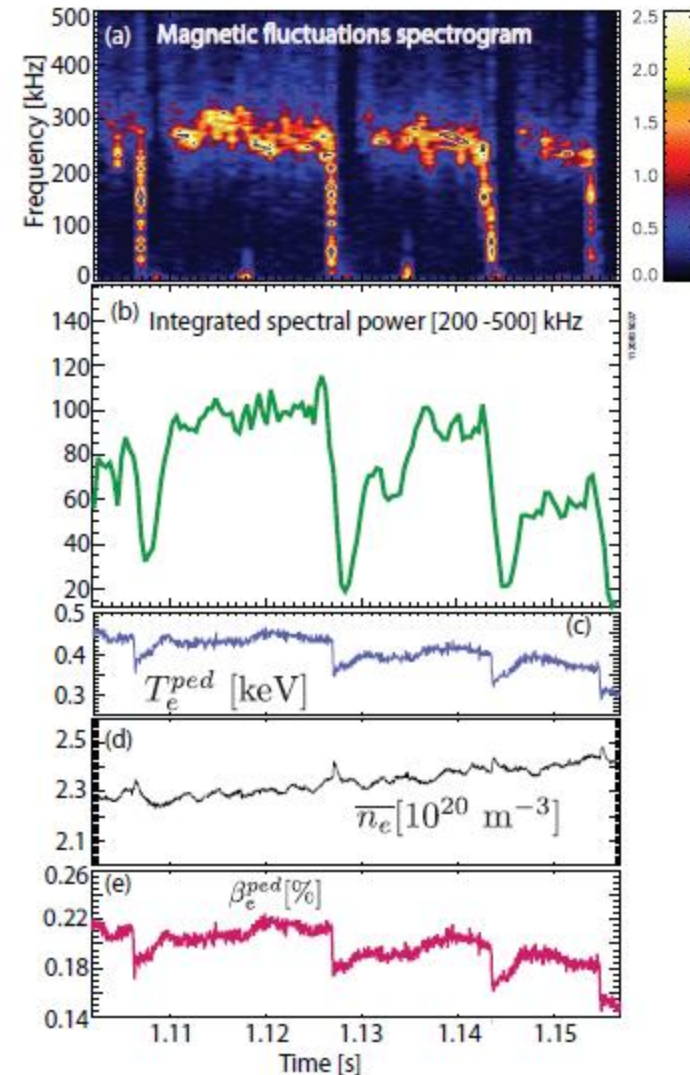
Some preliminary observations in DIII-D H-mode pedestal consistent with KBM (Z. Yan, PRL 2011)

- Large amplitude fluctuations in sharp pedestal gradient region ($\psi_N \sim 0.98$)

- Propagating in ω_{*i} direction

- Mode numbers ~agree with KBM theory
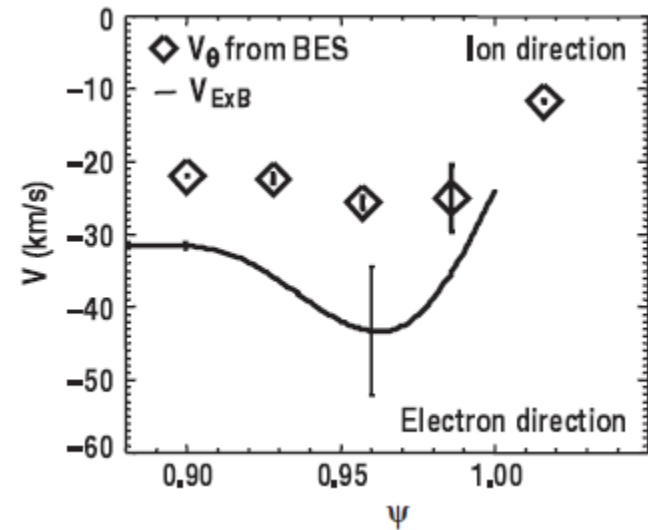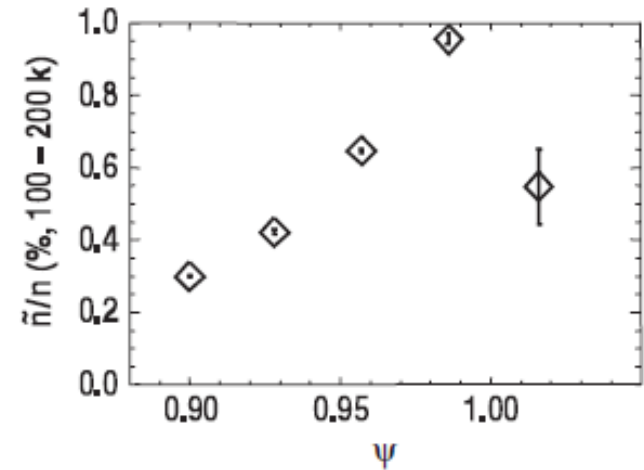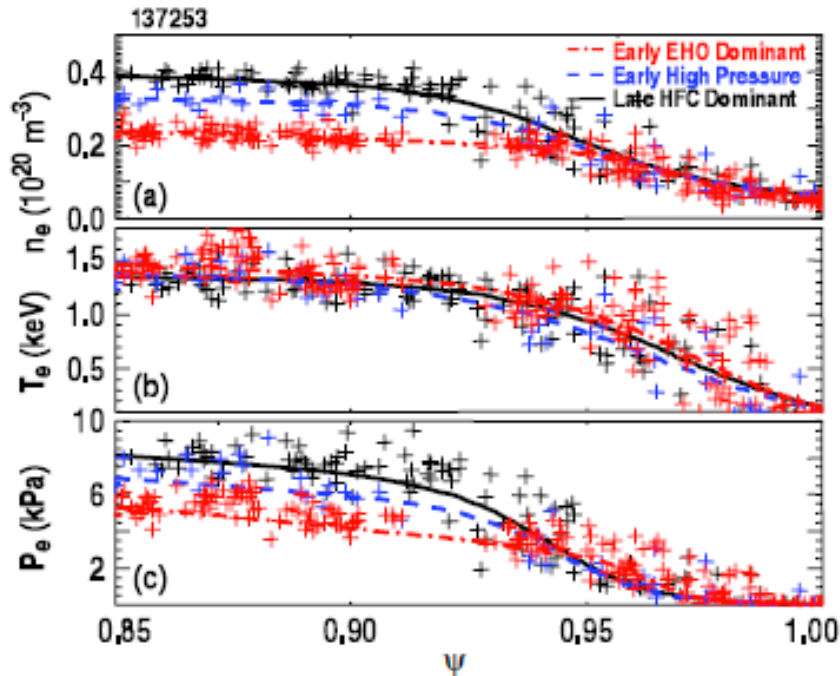
- *A number of newer simulations suggests many mechanisms may be important (Dickinson, 2011; Canik, 2013; Hatch & Kotschenreuther, 2015-2017, ...)*

Various fluctuations observed in ELM free pedestal regions – Weakly Coherent Mode in C-mod I-mode
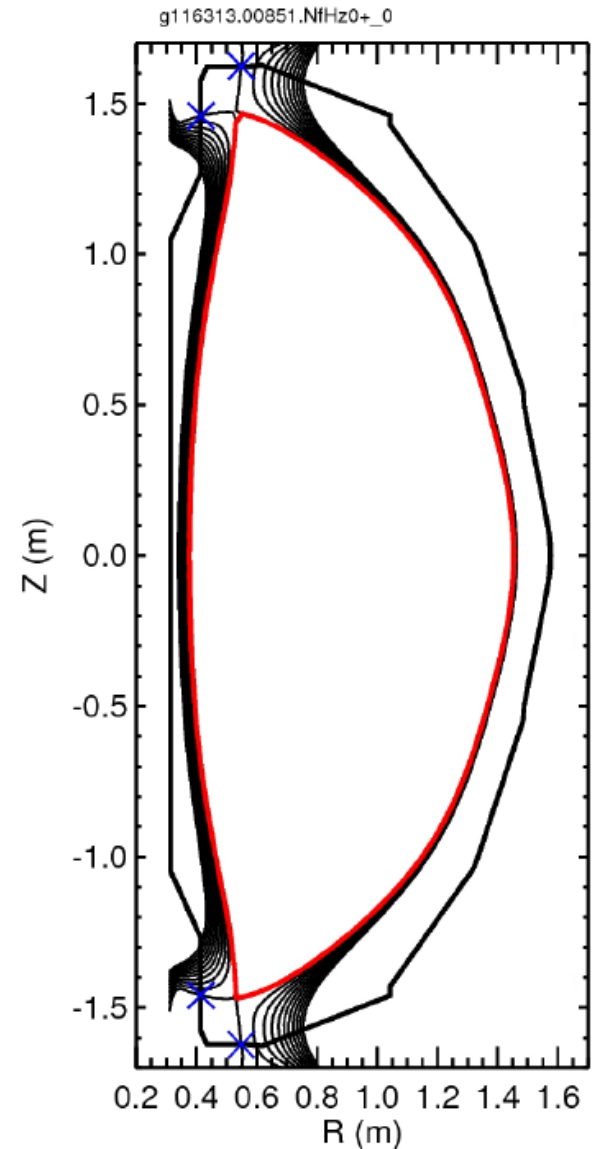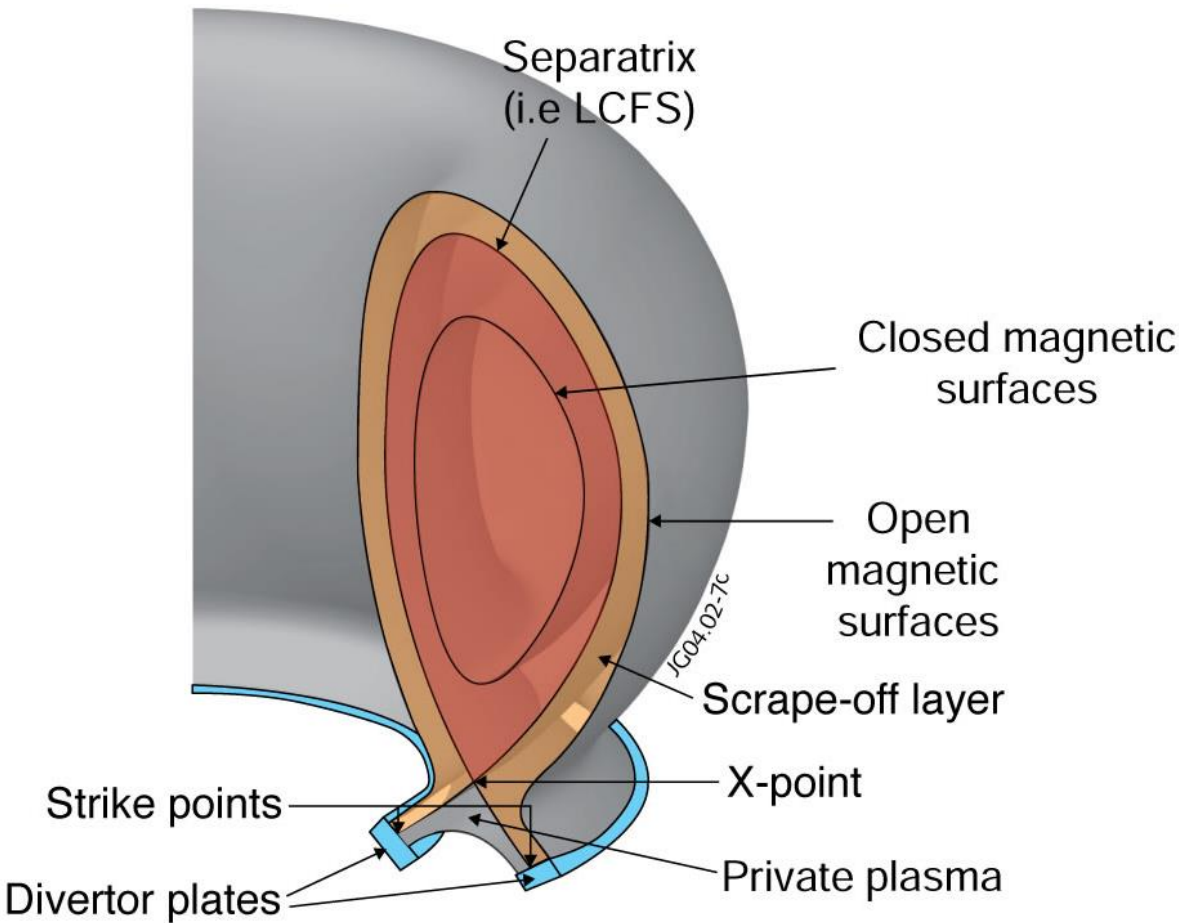
- I-mode in C-mod similar to H-mode except temperature pedestal only

- Evidence for weakly coherent density, temperature & magnetic fluctuations associated with increased particle transport preventing density pedestal

- Other examples exist in ELM-free H-modes (EHO in DIII-D; QCM in C-Mod)

C-mod, White, NF (2011)
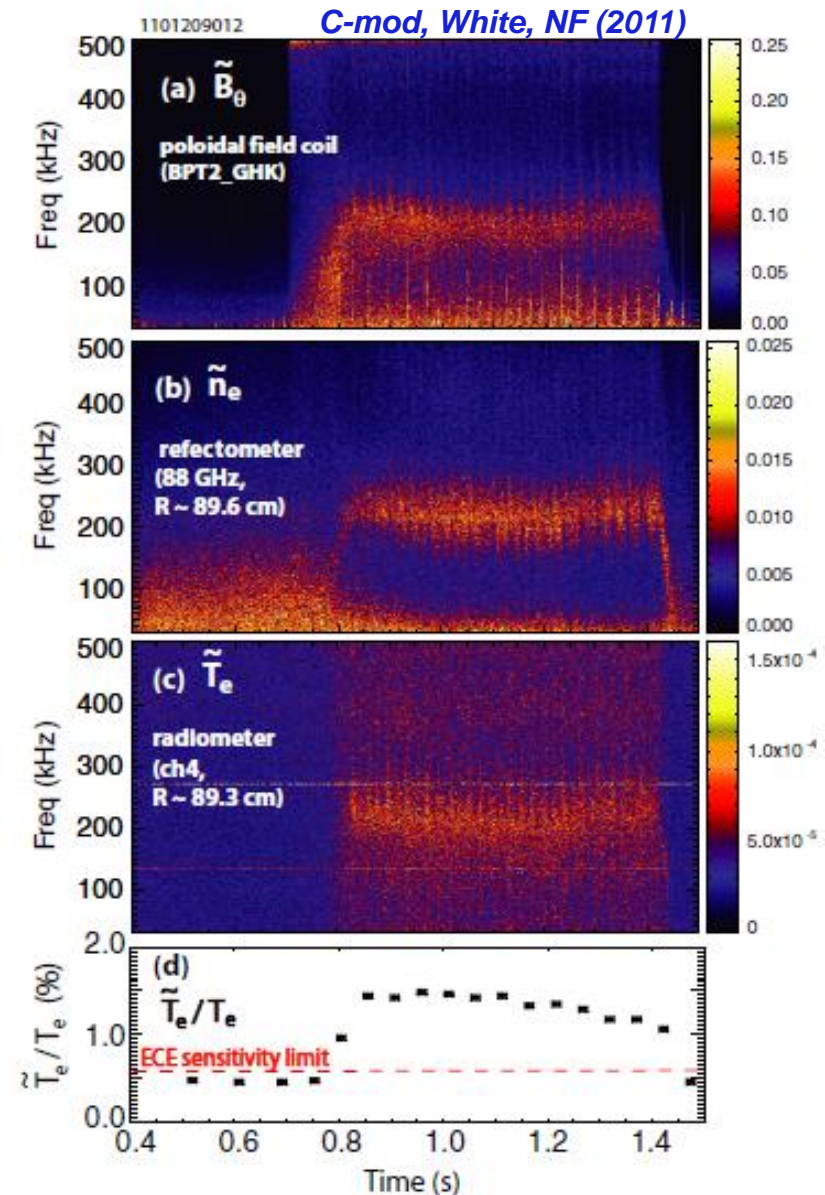
# SCRAPE OFF LAYER TURBULENCE

Going to refer to different spatial regions in the tokamaks

- Especially **core**, **edge** (just inside separatrix), and **scrape-off layer** (SOL, just outside separatrix)

Separatrix
(i.e LCFS)

Closed magnetic
surfaces

Open
magnetic
surfaces

Scrape-off layer

Strike points

X-point

Divertor plates

Private plasma

JG04.02-7c

g116313.00851.NfHz0+_0

Understanding scrape-off-layer (SOL) heat-flux width extremely important under reactor conditions

- Narrow SOL heat flux width λ_q leads to huge (>10 MW/m^2) heat flux density on the divertor plasma facing components (PFCs) → significant concern for sputtering and erosion

- Empirical scaling ($\lambda_q \sim 1/B_{pol,MP}$) very unfavorable for reactors

- **Recent turbulence simulations suggest a possible break from this scaling**

D. Brunner, APS-DPP (2017)
T. Eich, PRL (2011)

XGC-1 turbulence predictions (C.S. Chang)
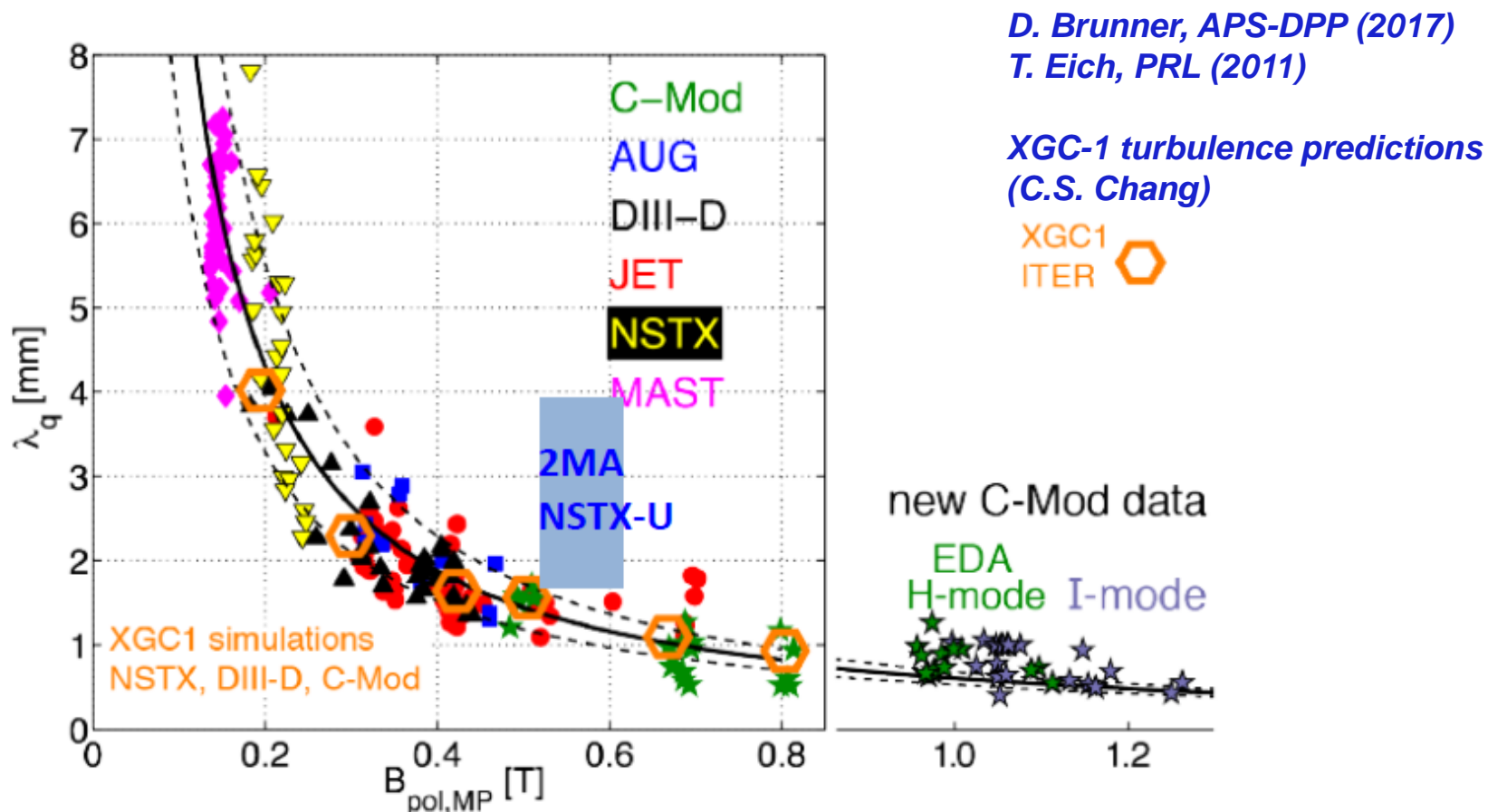
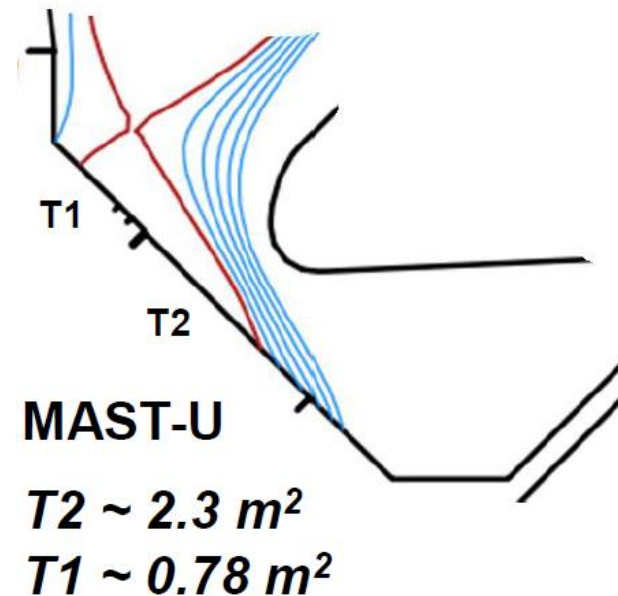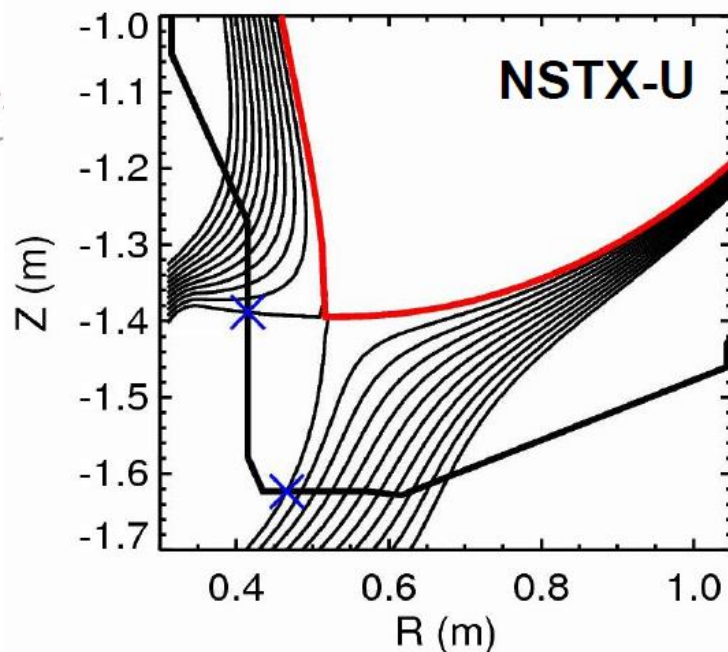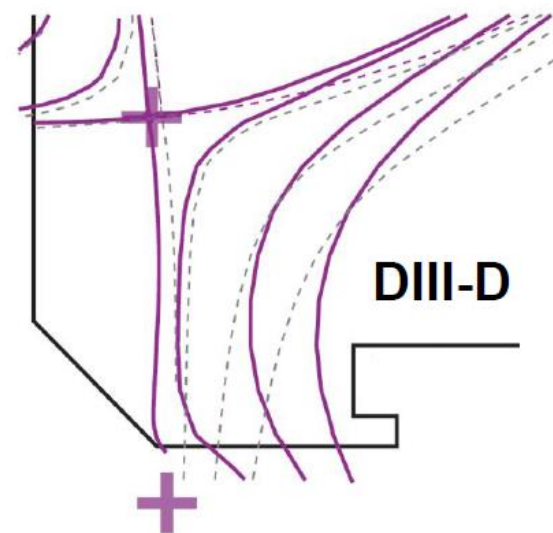# Many options being considered for divertor/SOL magnetic geometry

- Requires additional complexity in poloidal field coils and controllability
- Generally will also required impurity seeding in core/edge plasma to radiate much of the power
- **Spreading (from turbulence) could reduce heat flux density**
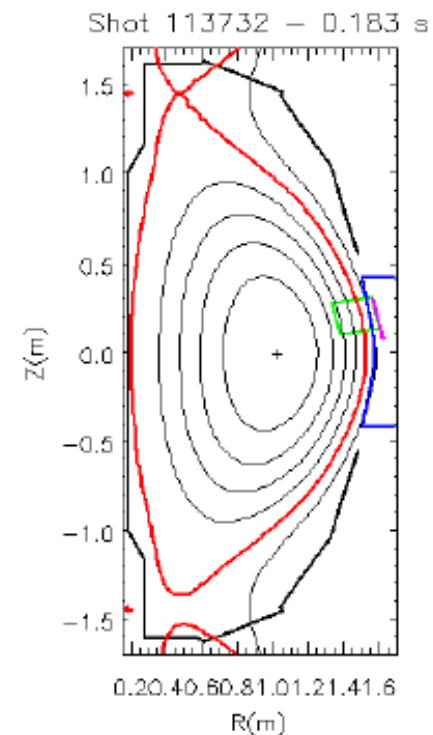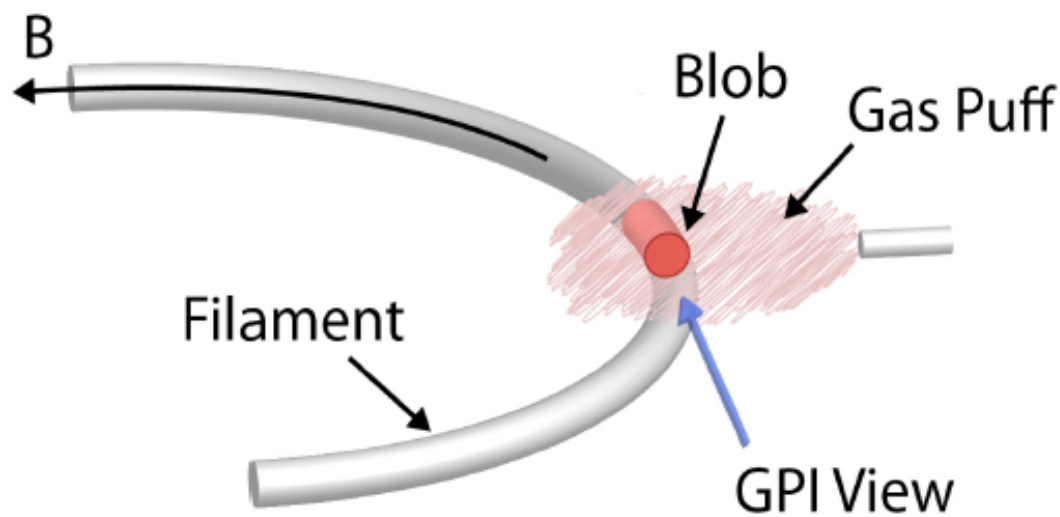
X divertor

Snowflake divertor

Super-X divertor

Edge Turbulence Measurements in NSTX

- High speed cameras make images of edge turbulence

- 3-D 'filaments' localized to 2-D by gas puff imaging (GPI)

Zweben et al, Nuclear Fusion 44 (2004), R. Maqueda et al, Nucl. Fusion 50 (2010)

Lots of videos via Stewart Zweben: http://w3.pppl.gov/~szweben/

- This movie 285,000 frames/sec for ~ 1.4 msec

- Viewing area ~ 25 cm radially x 25 cm poloidally

L-H mode transition t~0.245 s

playback @ 35 µsec/sec
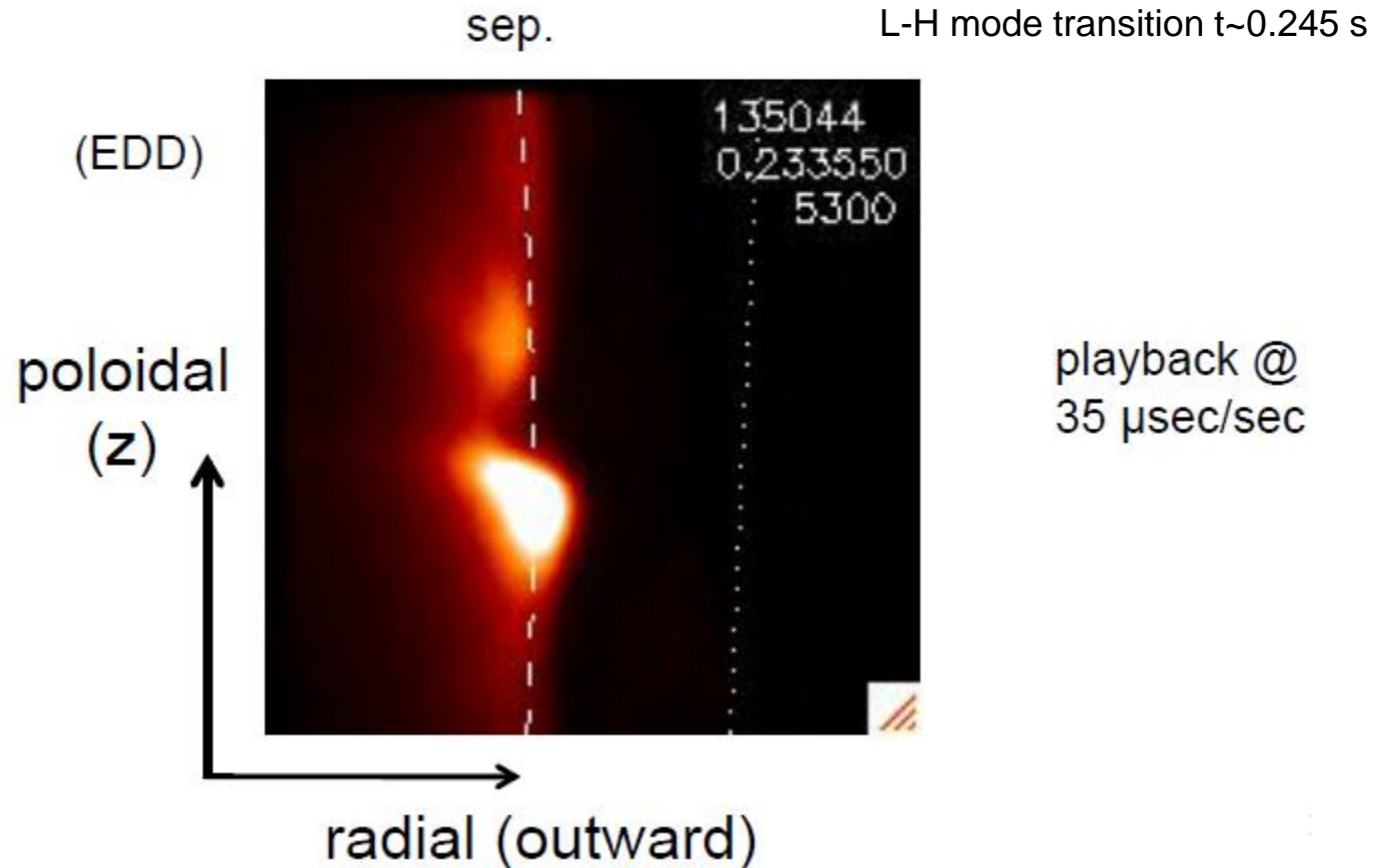
# Outside separatrix, blobs can be ejected and self-propagate to vessel wall

- Plasma is much less dense farther out in scrape-off layer
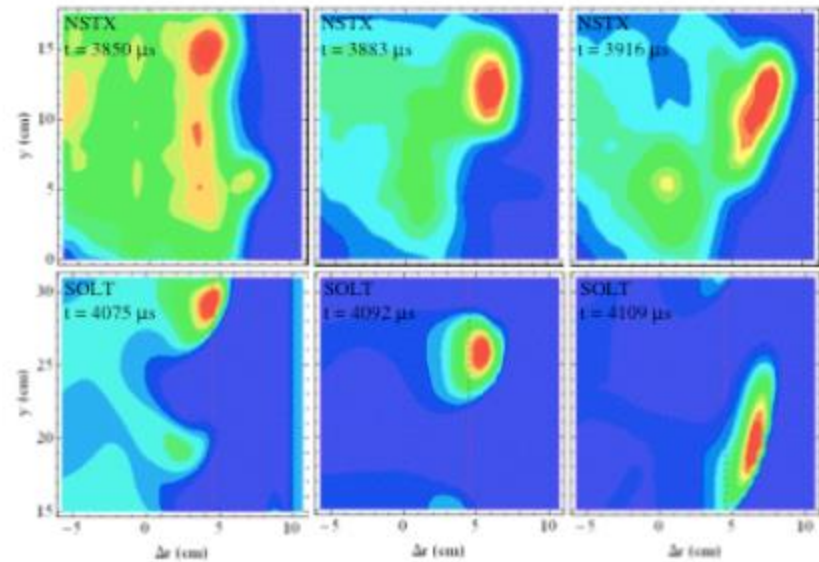- Relative intensity of blob becomes large ($\delta I/I$)
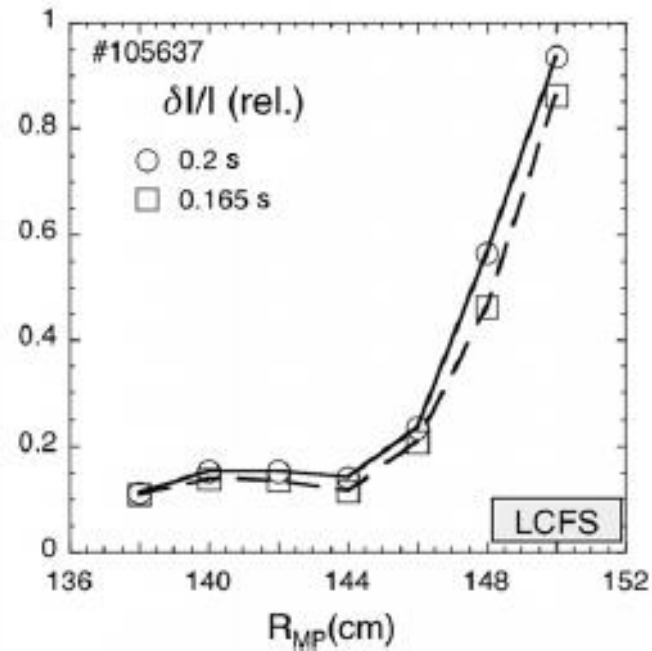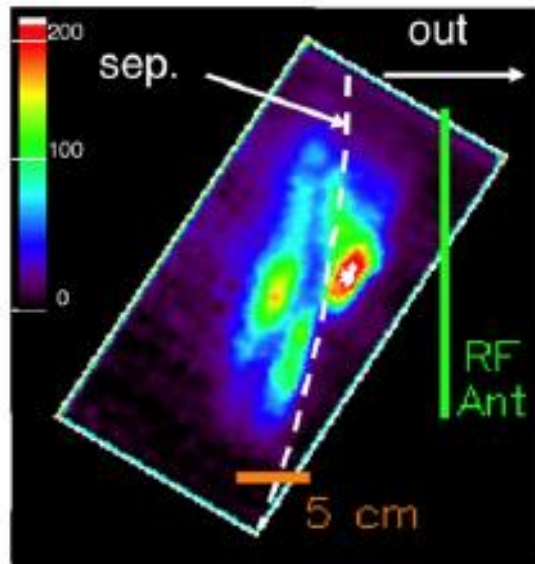
Theories and simulations exist that predict blob characteristics: size, density, velocity

- Simulations further out in edge become progressively more challenging, more effects to deal with (neutrals, open field lines to conducting walls, dust, …)

simple 'blob' model (Krash. 2001)
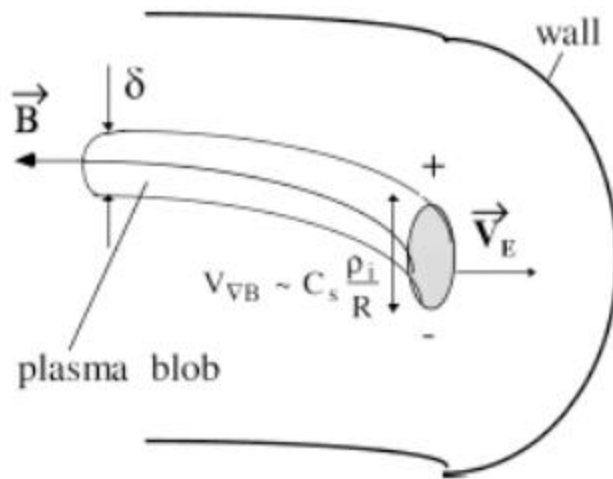
2D turbulence model (D'Ippolito 2008)

SUMMARY

- Many experiments and diagnostics developed to measure fluctuation amplitudes, spectra, cross-phases, transport, etc… in various regions of magnetically confined plasmas

- Many features broadly consistent with toroidal drift wave expectations

- Have seen progress in comparing theory/simulation & measurements, with agreement approving from order-of-magnitude to factor of 2-3 or better in limited cases

- Improves confidence (in some regimes) in our physics understanding, which improves our predictive ability (not really addressed here) → *Plenty more to do*