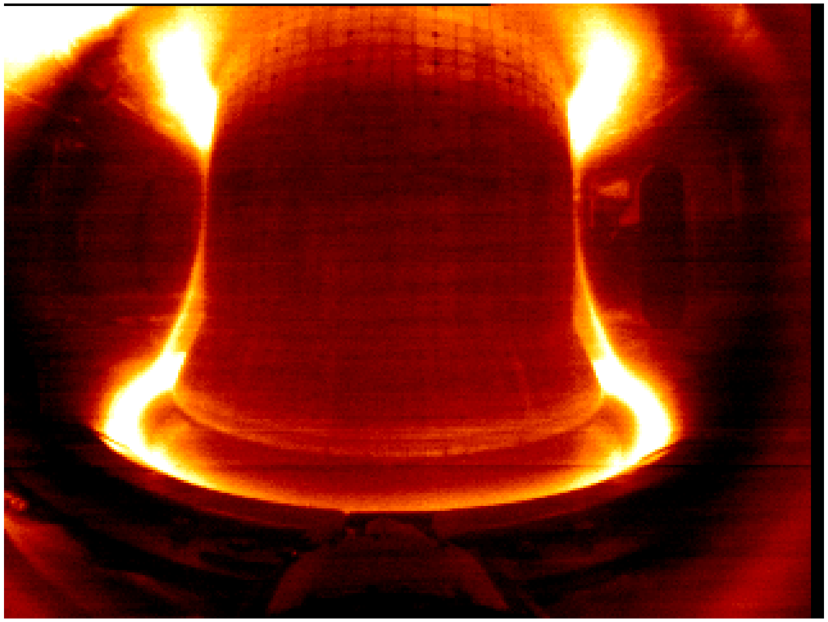
CORE AND EDGE TRANSPORT IN ALCATOR C-MOD

CONNECTIONS ACROSS THE SEPARATRIX



PRESENTED BY M. GREENWALD

COLUMBIA UNIVERSITY – MARCH 4, 2005

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Basic Thesis - Core/Edge/SOL Can't (and Shouldn't) Be Decoupled

- Different regions of plasma are typically disunified
  - Studied by different groups
    - With different diagnostics
    - And different codes
    - Going to different meetings

- But of course as we all know:
  - There is substantial overlap in the physics
  - These regions have unignorable interactions

- **Some of the most interesting physics is at the interfaces between topical areas!**

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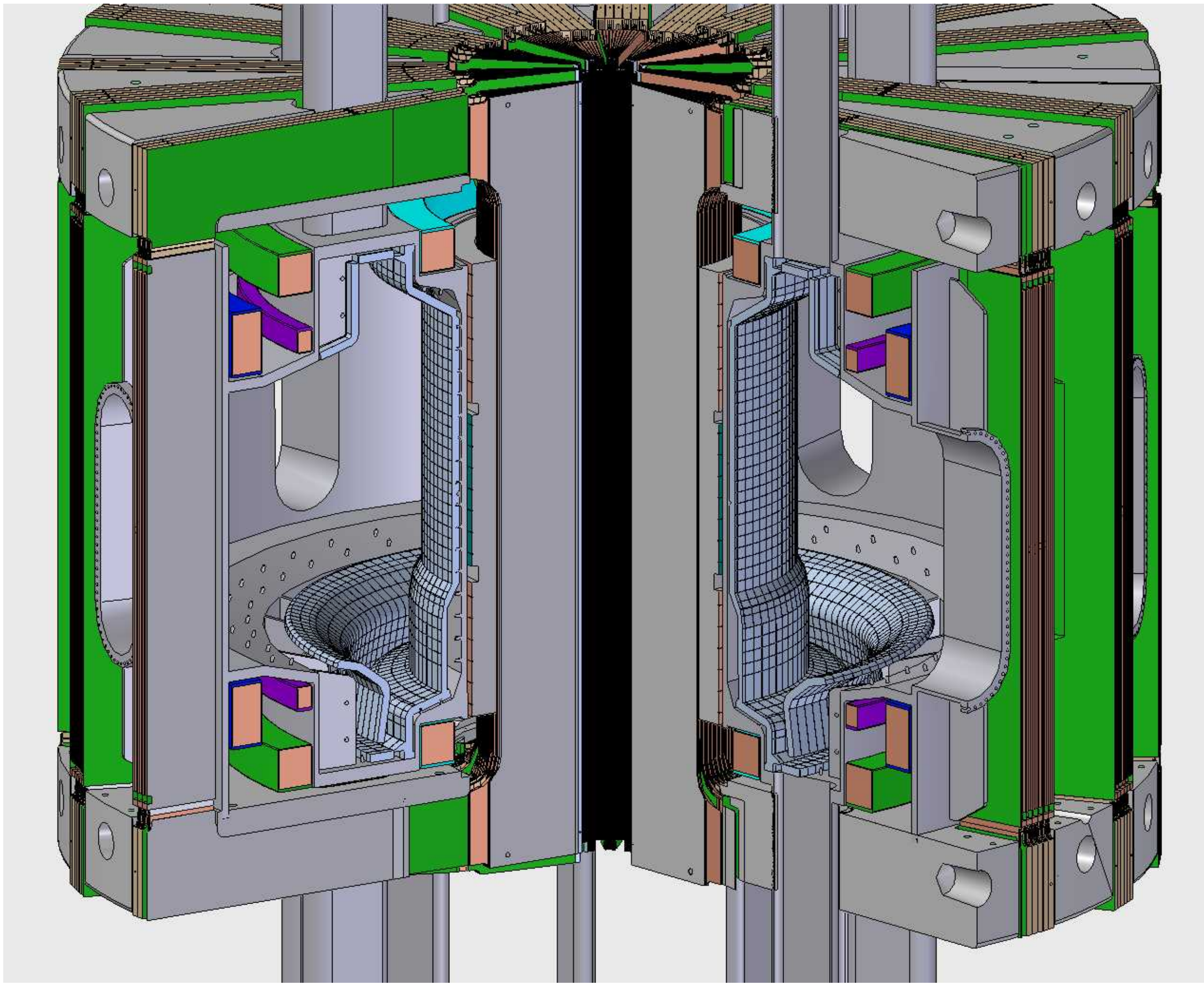
C-MOD BACKGROUND

- C-Mod is a high-field, compact tokamak (R = 0.64 m)
  - $B_T = 2 – 8$ T
  - $I_P = 0.2 – 2$ MA
  - $n_e = 0.2 – 15.0 \times 10^{20}\ m^{-3}$
- We tend to run at higher collisionality and lower β (though much higher pressure) than low-field devices.
  - Te ~ Ti
- Auxiliary heating is with ICRF
  - No core particle source
  - No core momentum source

C-MOD CUTAWAY



OUTLINE – THREE CASE STUDIES

1) If marginal stability sets energy transport, temperature profile couples edge and core physics - profile stiffness

2) SOL flows apparently provide an important boundary condition for core rotation

3) Edge turbulence sets global density limit

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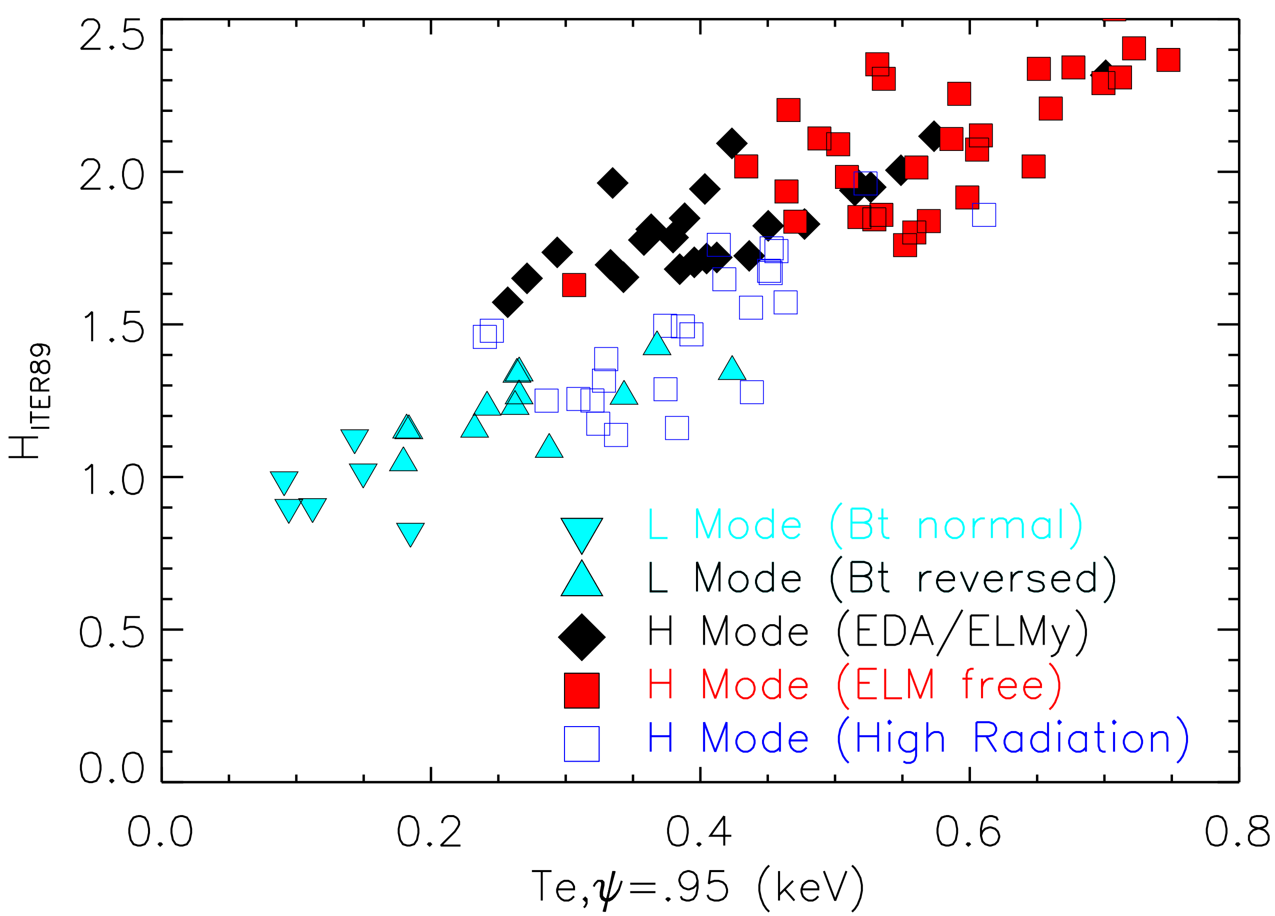
Warm Up

Case 1 – Coupling Through Marginal Stability

Global Transport is Strongly Correlated with Edge Temperature Across Transport Regimes



Greenwald 1996

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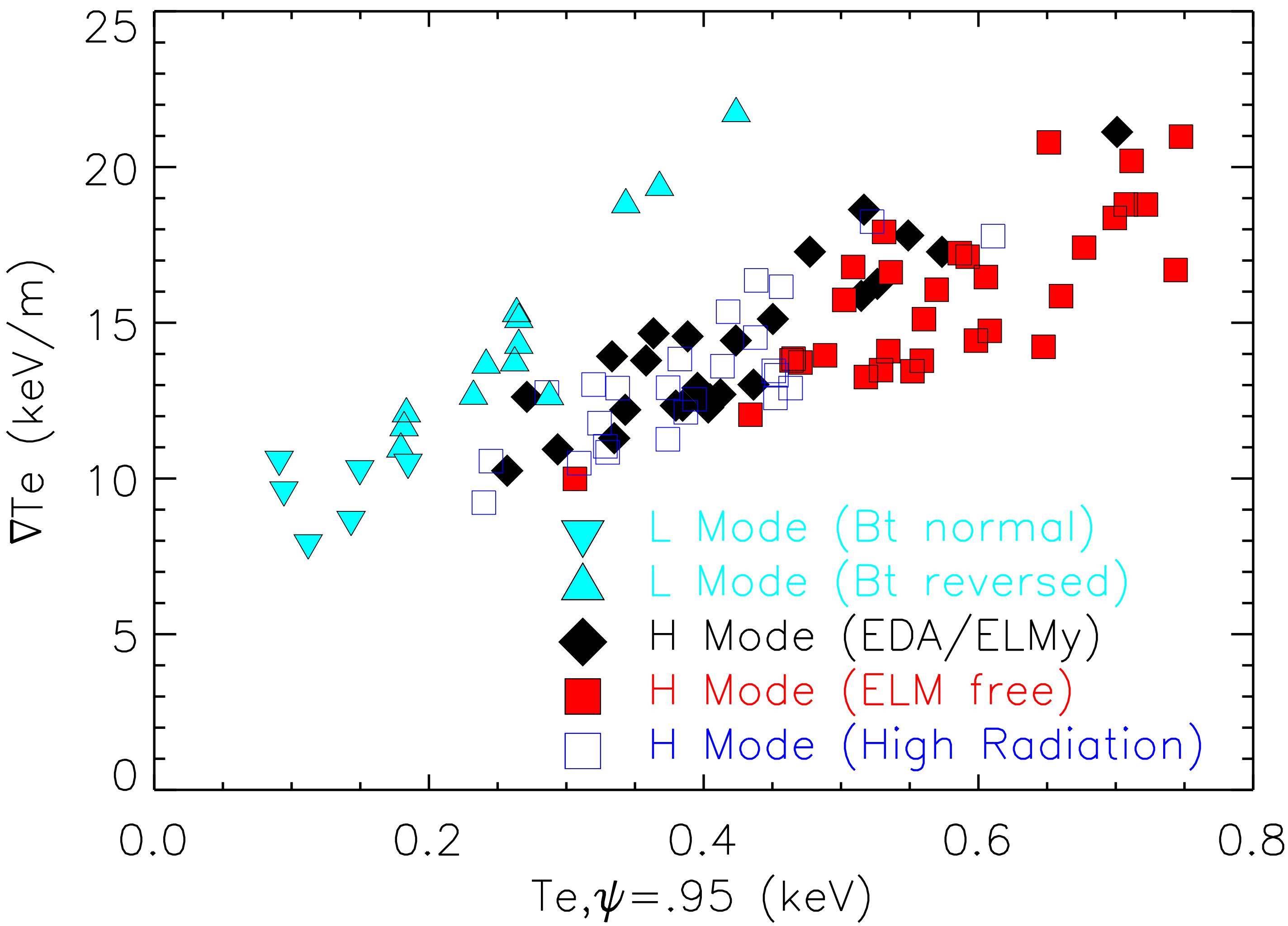
THE CRITICAL PARAMETER IS RELATED TO THE TEMPERATURE GRADIENT



Greenwald 1996

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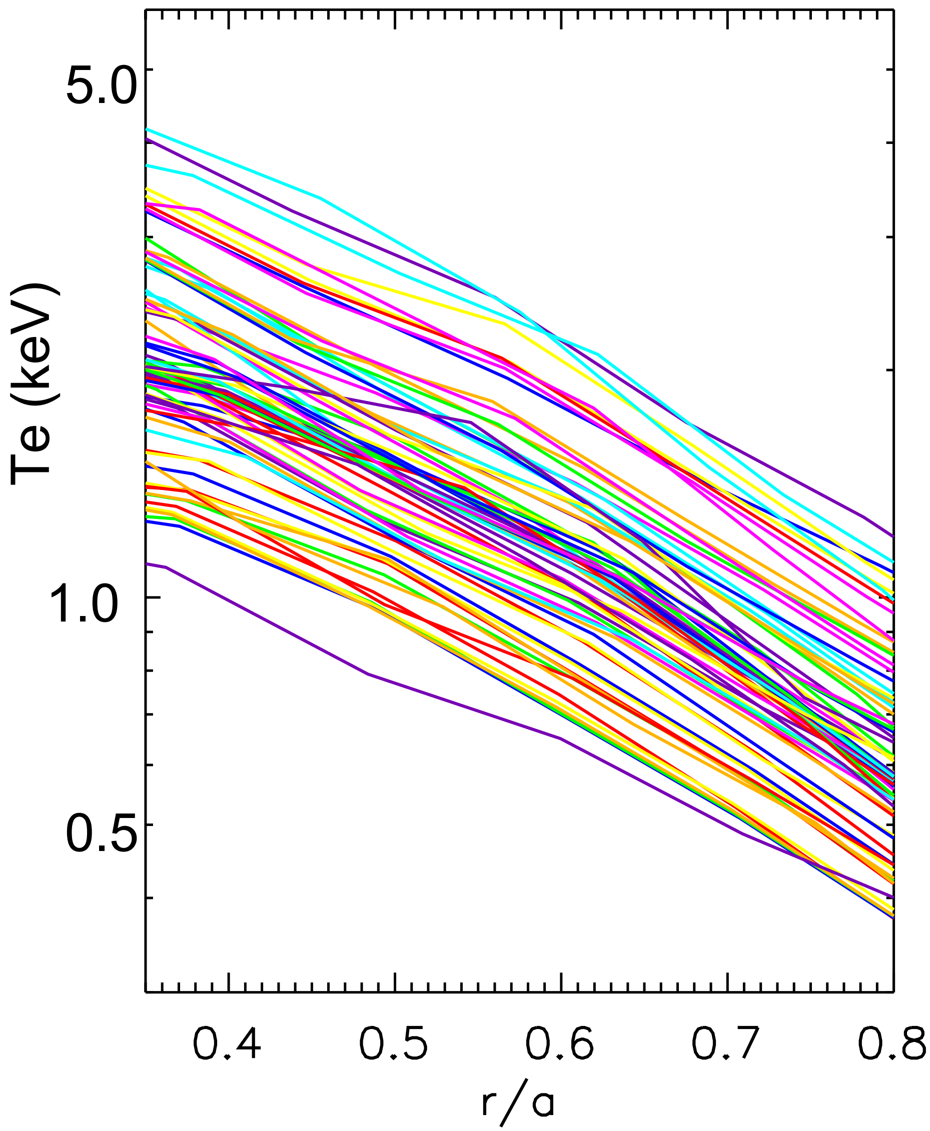
IN FACT, TEMPERATURE PROFILES ARE SELF-SIMILAR UNDER A WIDE VARIETY OF CONDITIONS



- ~100 Random C-Mod shots and times selected from 2003-04
  - 1 MA, 5.3 T
  - Temperature picked at peak of sawtooth
- Otherwise
  - All powers, densities
  - On and Off-axis heating
  - L and H-modes
- Temperature Gradient-Length exists with very narrow range

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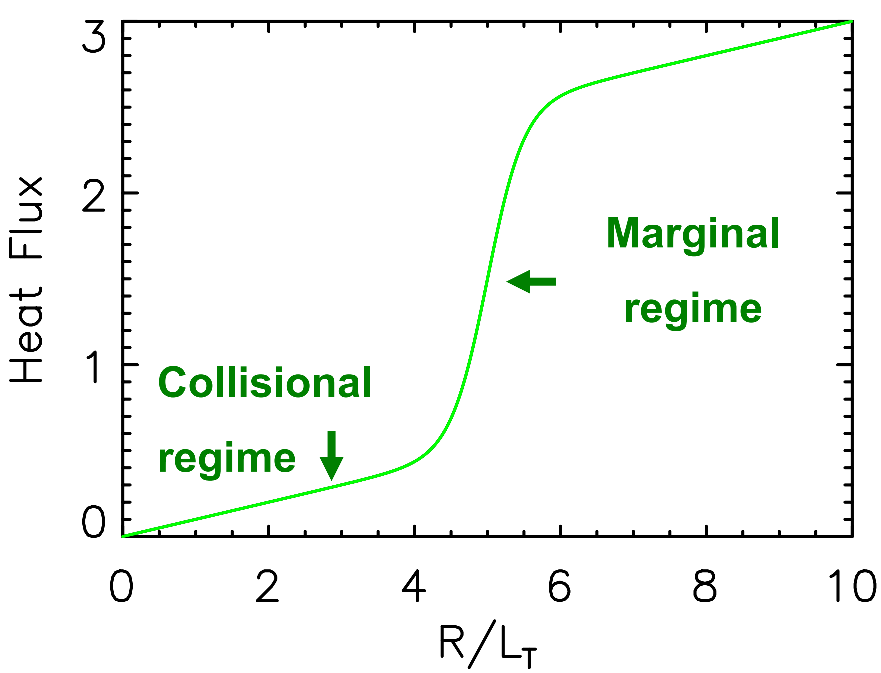
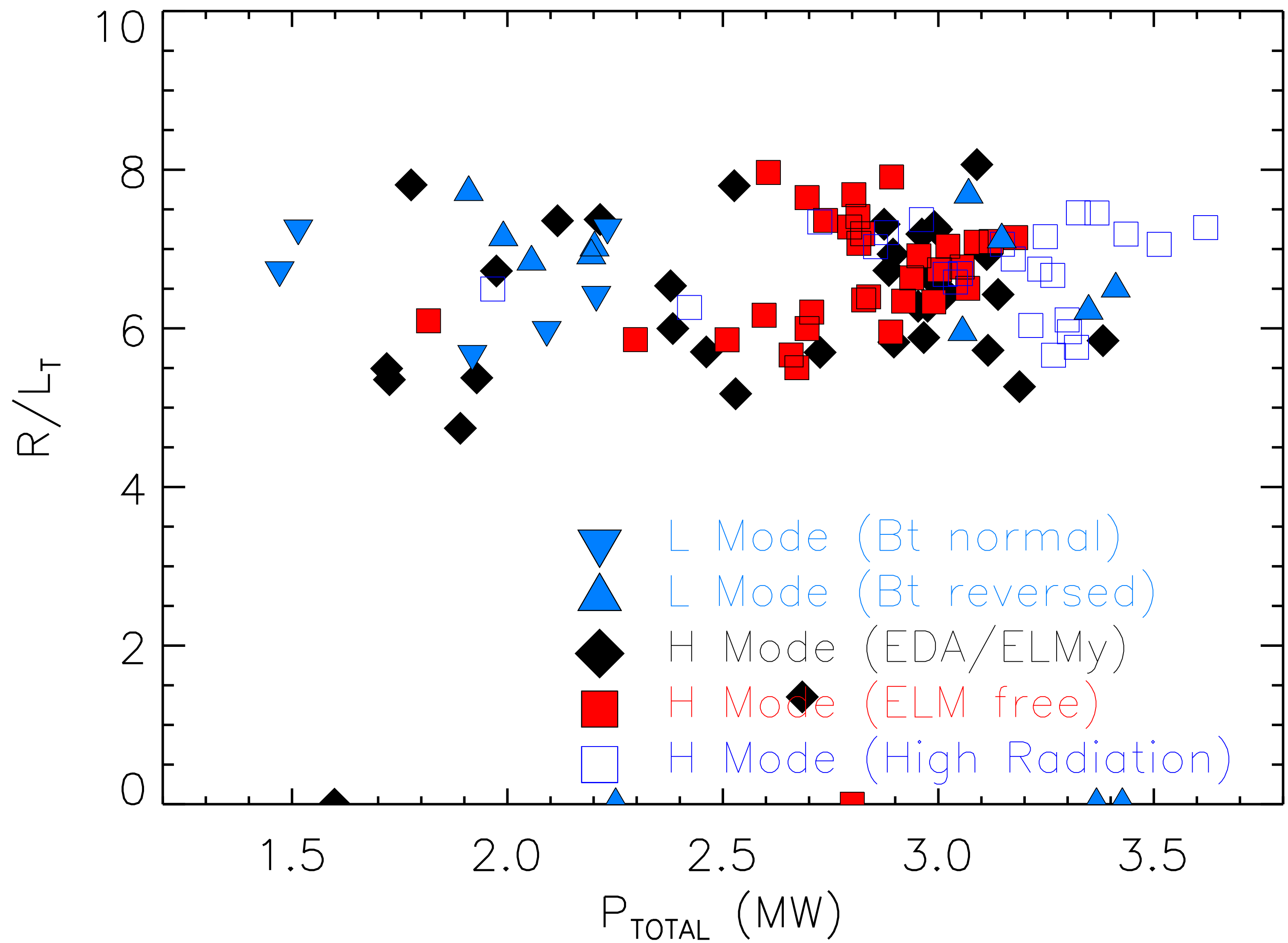
What is Expected Theoretically?

- Free energy in plasma gradients can drive turbulence and transport
- Transport is predicted to be strong if microstability threshold is exceeded
- Theory predicted ITG instability for $\frac{R}{L_{T_i}} \equiv \frac{R \nabla T_i}{T_i} > \frac{R}{L_{T_{CRIT}}}$



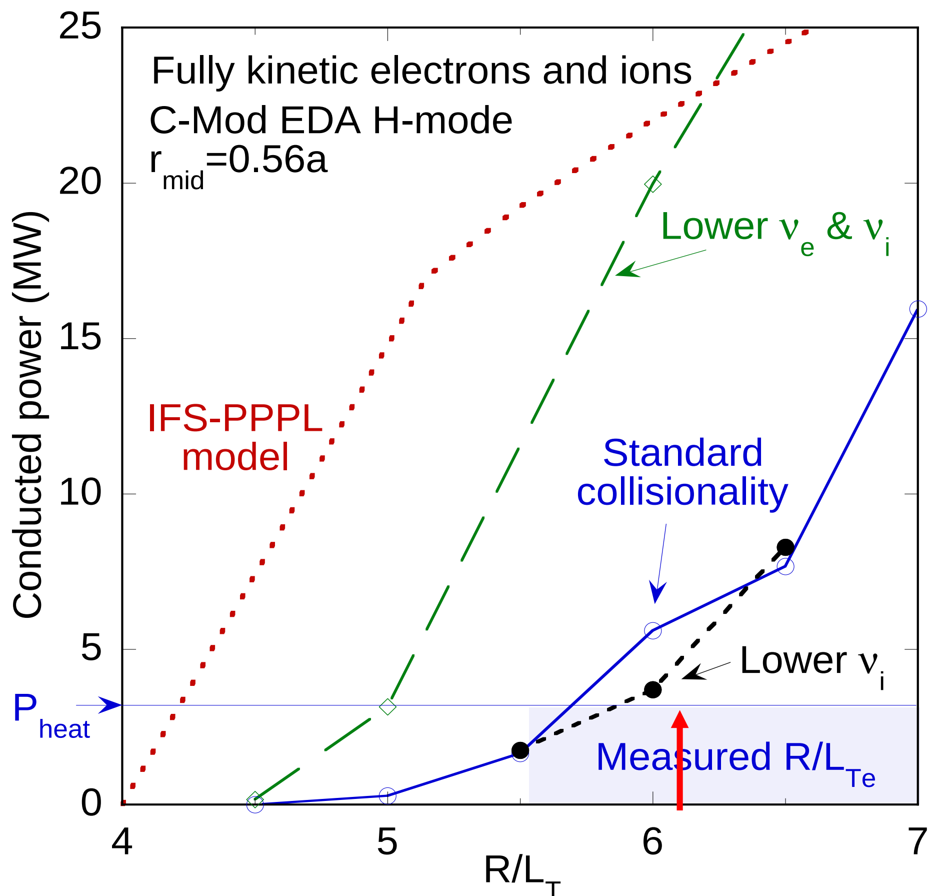
Data From Confinement Database Shows Same (lack of) Trend



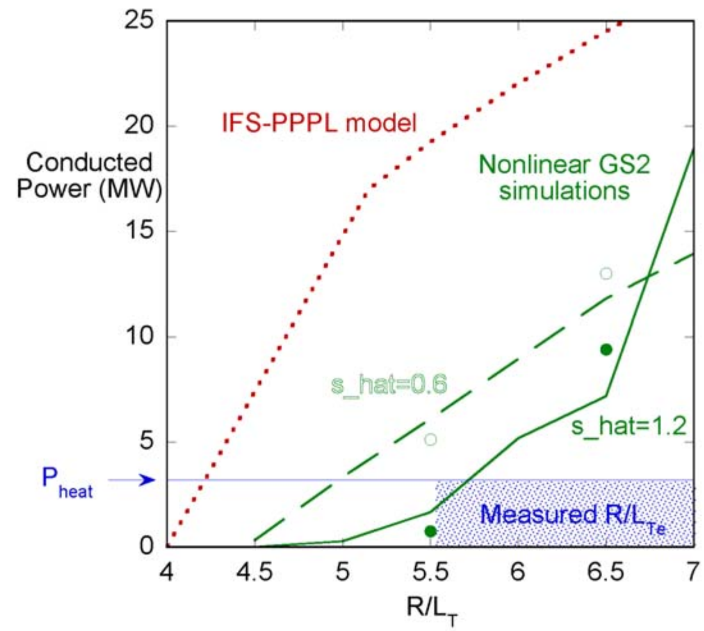
This Effect May be Understood Quantitatively via Non-Linear Gyrokinetic Simulations

Matching experimental profiles requires non-linear calculations and proper treatment of electron dynamics

Nonlinear GS2 simulations



Mikkelsen 2001



Note: There is still a lot of unvalidated physics in these codes.

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CASE 2 – COUPLING BALLOONING TRANSPORT, SOL FLOWS, CORE FLOW AND THE L/H THRESHOLD

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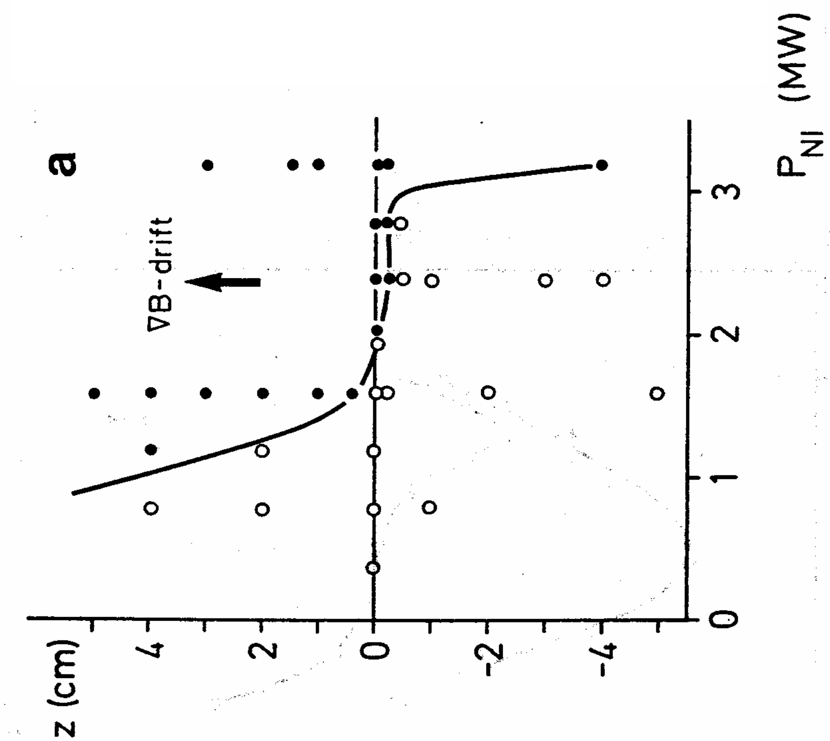
WHAT ARE WE TRYING TO EXPLAIN?

- The L/H Power threshold is typically ~2x higher when ion ∇B drift direction is away from X-point in single null topology when compared to case where ∇B drift direction is toward X-point.
- First reported on ASDEX in 1989
- “Universal” result



Asdex 1989

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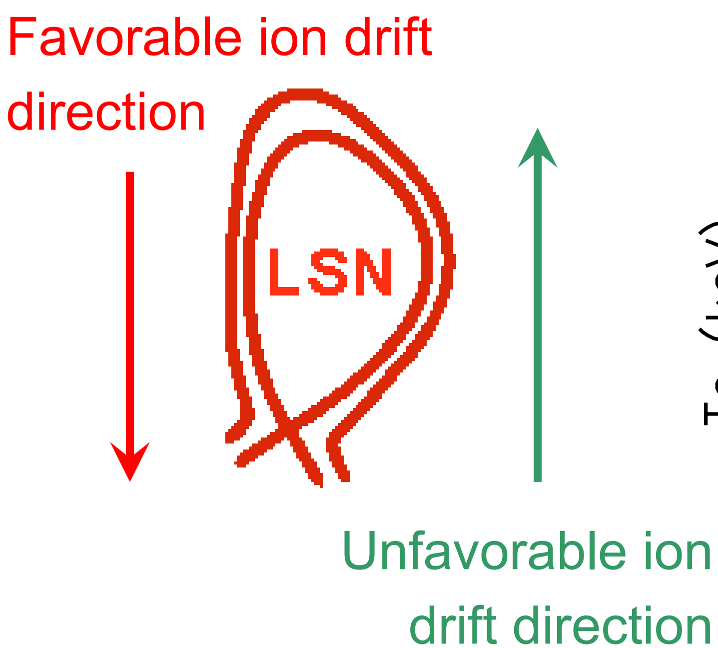
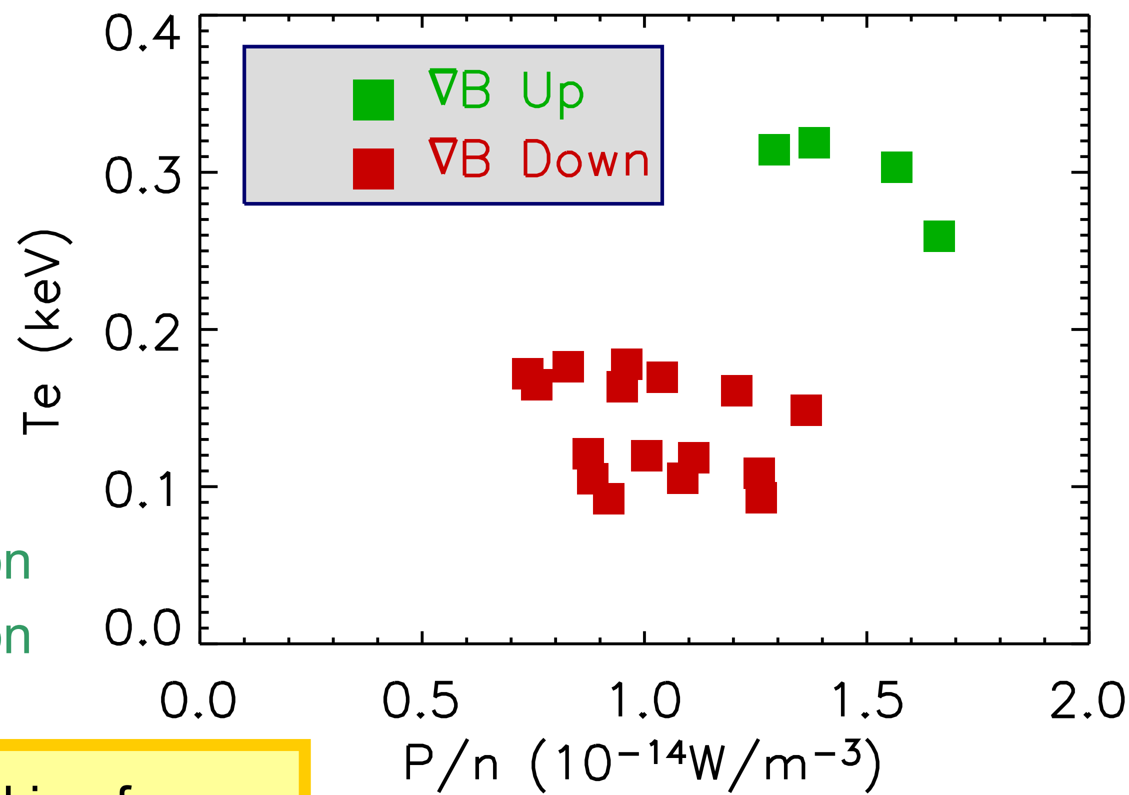
The Effect the ∇B Drift Direction on the H-Mode Threshold is 0^{th} Order and Requires a Robust Explanation





- Size of effect suggests looking for large asymmetries.
- Only occur near separatrix or beyond.

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Proposed Scenario

1. The ballooning character of turbulent transport drives SOL flows

2. The SOL flow responds strongly to changes in magnetic topology.

3. Core flows are coupled strongly to changes in SOL flows
   (SOL flows provide the boundary condition for core flows)

4. This topology dependent boundary conditions for plasma flow may be the explanation for the ∇B drift effect on the H-mode threshold

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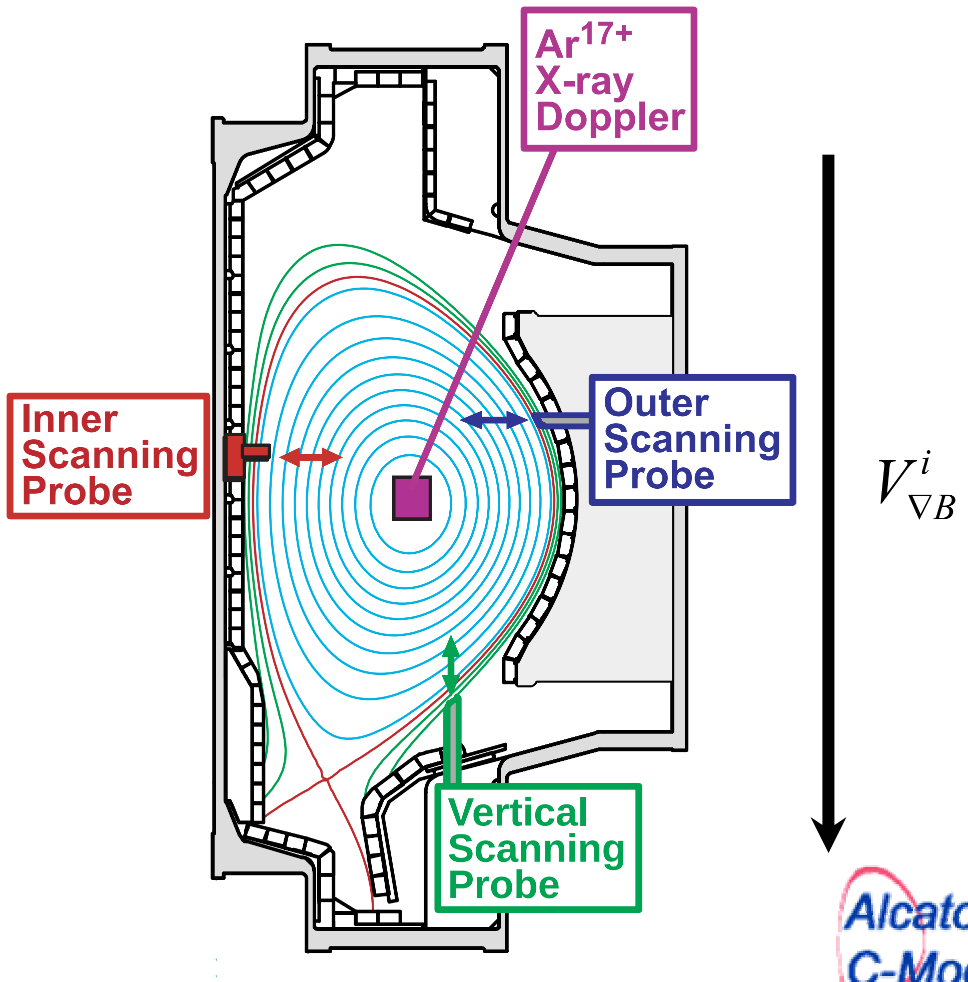
Plasma Heating and Rotation Measurements Without NBI on C-Mod - Provides an Excellent Laboratory to Study These Effects

- Heating is with ICRH + OH
- **Changes in core reflect changes in boundary conditions and momentum transport – not sources**
- SOL flows measured at three locations by fast scanning probes
- Core rotation profiles measured passively with high-resolution x-ray spectrometers



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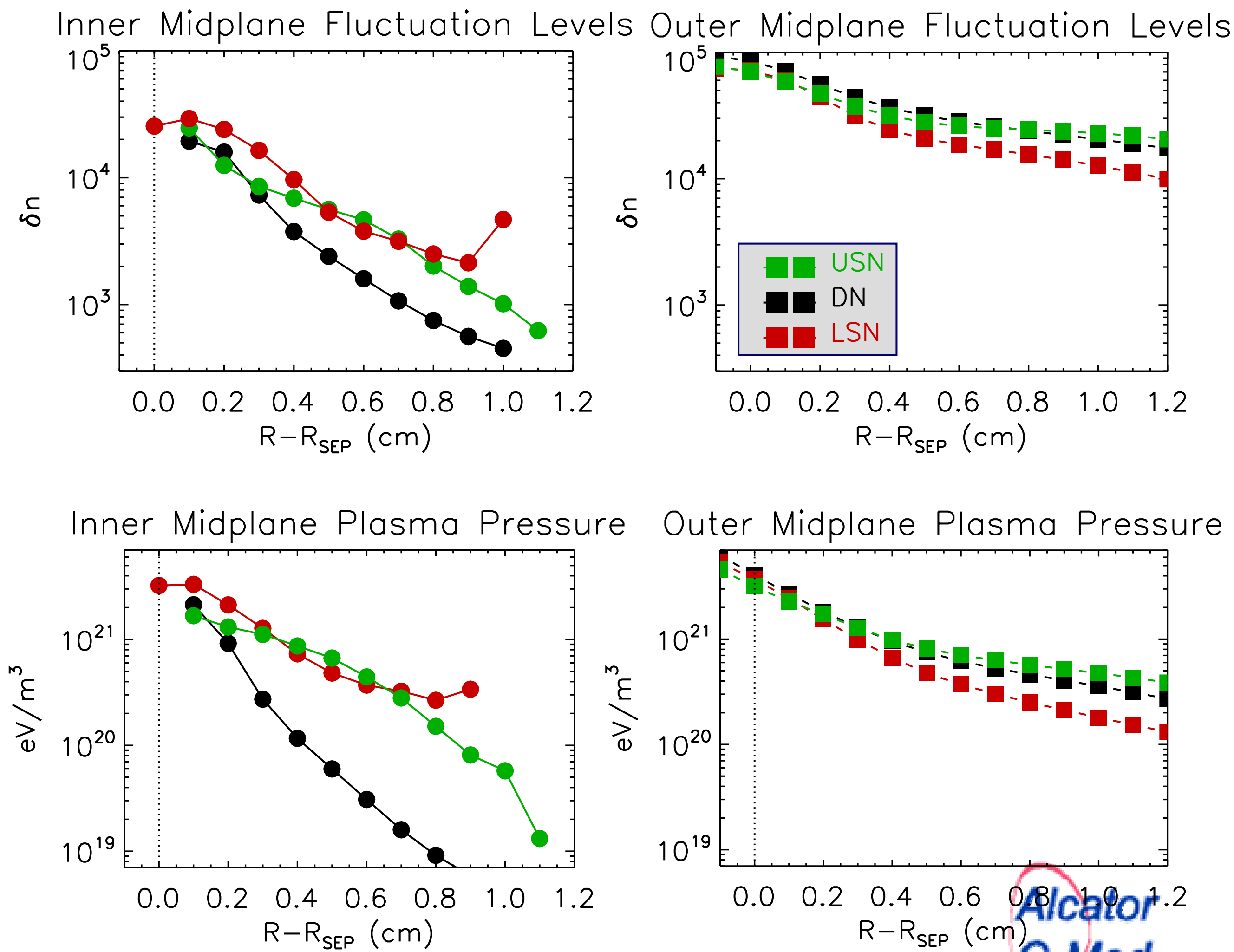
Plasma From Ballooning Transport Flows Along Field Lines to Populate High-Field SOL

- Much higher fluctuation levels (⊥ transport) on low field side – ballooning
- When high-field side is connected (SN), shows similar plasma density
- When not connected (DN), no plasma
- For SN, symmetrizing flows are responsible for high-field plasma



LaBombard 2004

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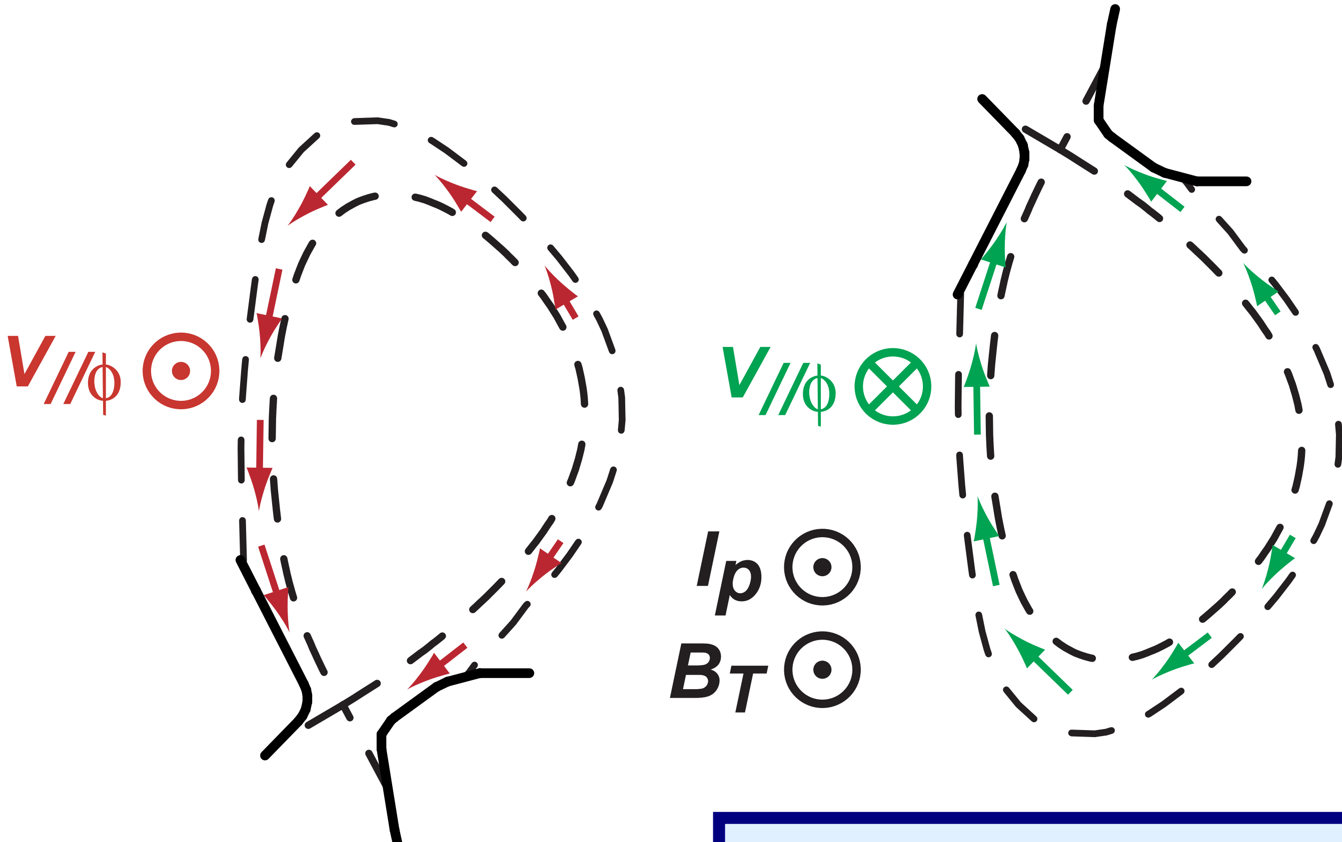
Symmetrizing Flows Driven By Ballooning Transport are Co or Counter Depending on Topology

⊥ transport-driven parallel SOL flows:



These flows are observed with the inner wall probes

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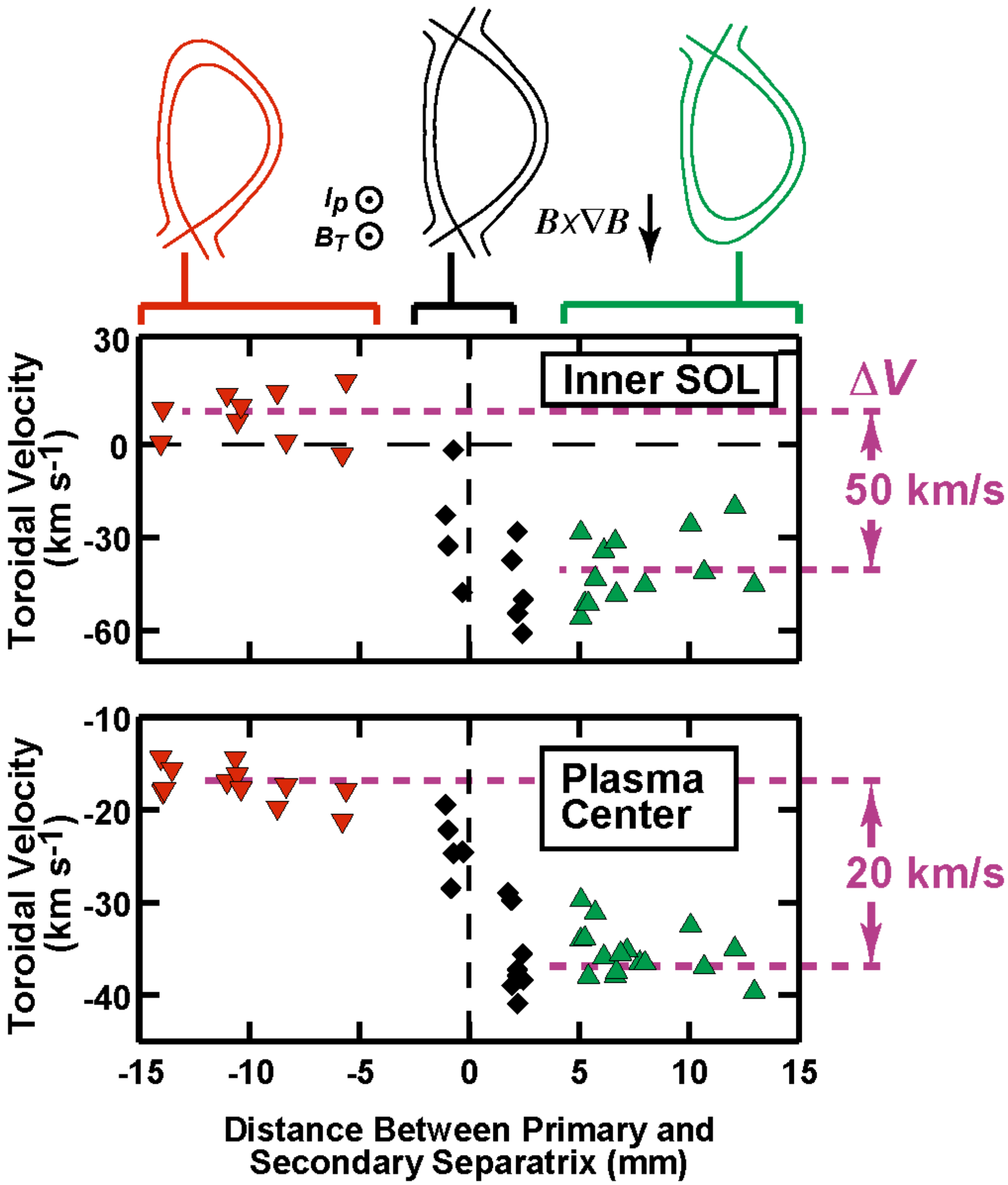
Core Rotation Shows Same Topology Dependence as SOL



- Change in core flows with topology is in same direction and same magnitude as SOL flows
- Core flows exhibit the same extreme sensitivity to edge topology! – each mm counts
- SOL flows are near sonic on high-field side.
- Double null balance is critical

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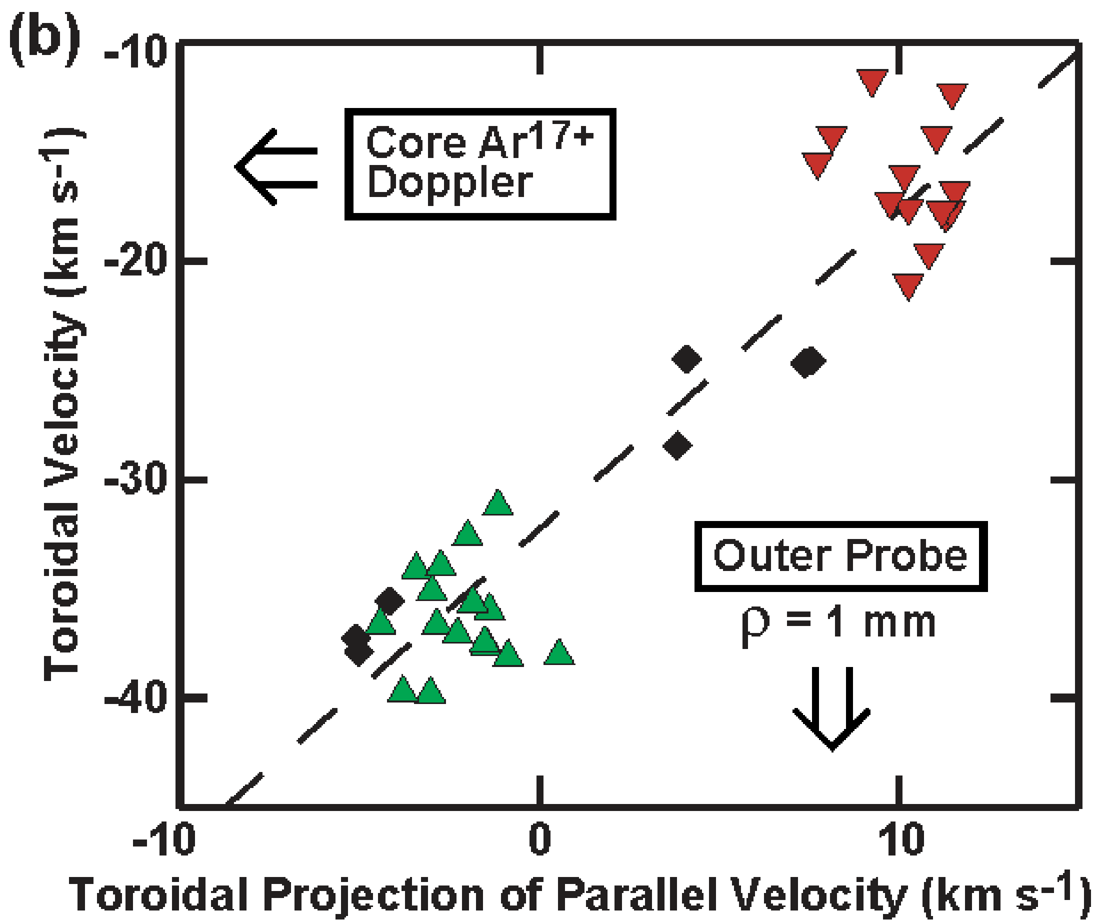
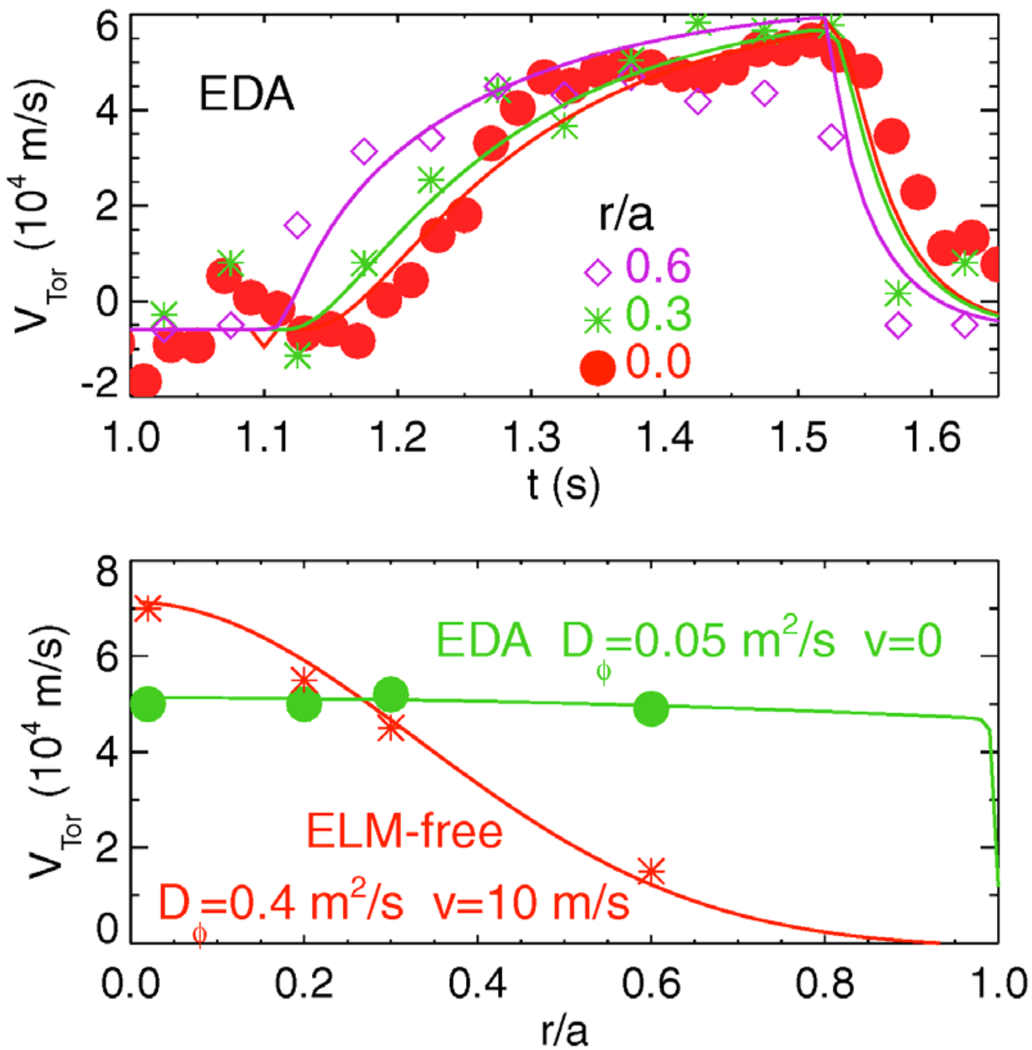
CORE AND SOL FLOWS ARE WELL CORRELATED



- Note: Core and SOL flows track but are **not** identical

Momentum Is Observed to Be Transported From Outside Inward Into Core

- Core rotation responds to change in edge – L/H transition
- Time histories used to obtain transport coefficients.
- Momentum is observed to diffuse and convect inward.



Rice 2003

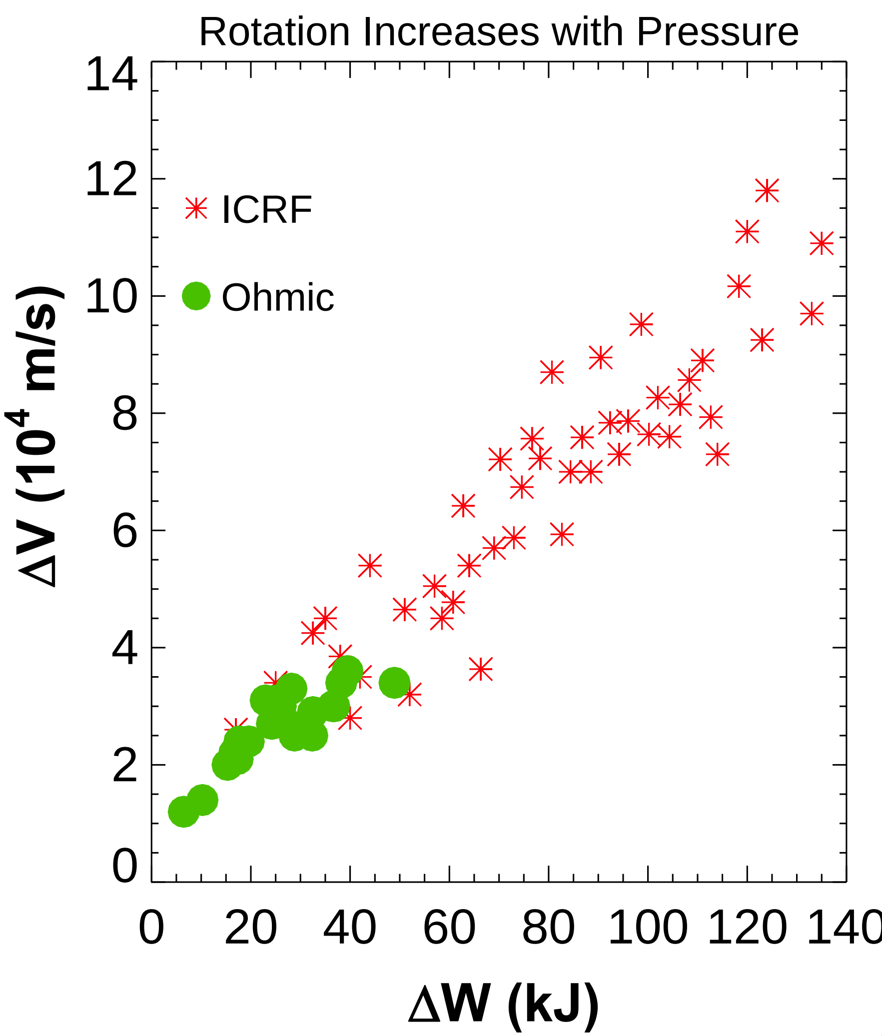
C-Mod

PRESSURE DEPENDENT (TOPOLOGY INDEPENDENT) COMPONENT ALWAYS INCREASES IN CO-DIRECTION WITH PLASMA PRESSURE

Two "contributions" to the flows

1. Topology dependent SOL flows as described above
2. Pressure dependent rotation in both L and H-Mode

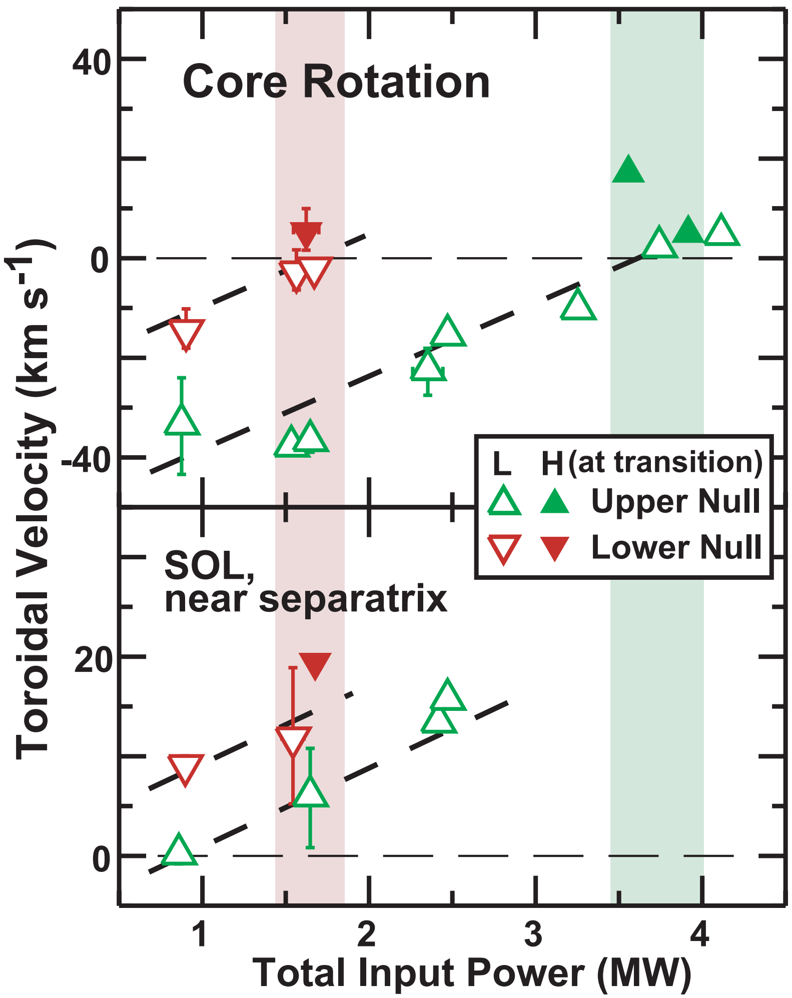
- Net rotation is Sum of Two Effects
- (Observed in core and SOL)



(Plasma Pressure, Power)

To Reach Given Level of Core Flow (Shear) Requires more Pressure (Power) for Unfavorable Drift Direction

- For particular discharge conditions, L/H transition is reached when core rotation reaches some critical value.
- Relevant physics is likely local shear but measurements not available yet…
- For unfavorable drift direction, starting conditions are "farther" from threshold state.



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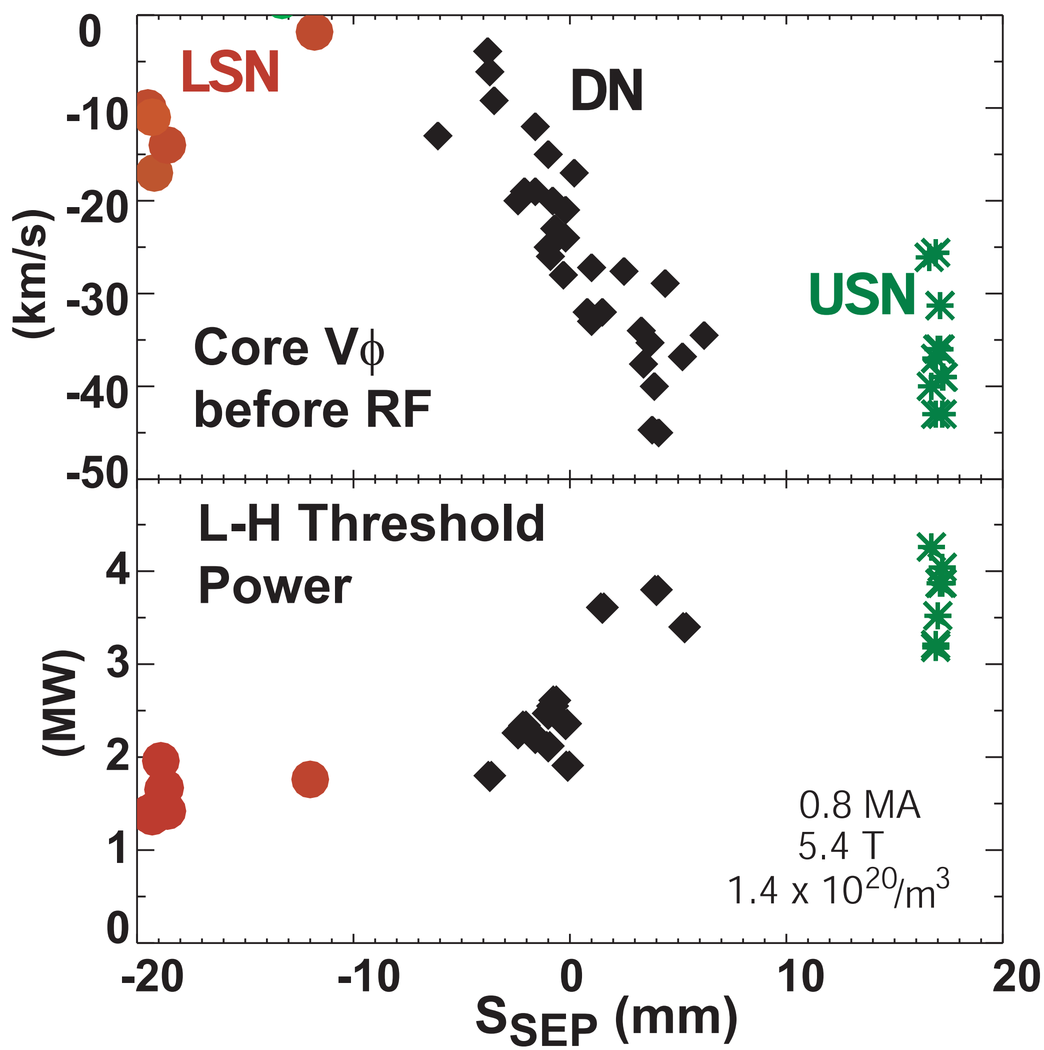
Change in Power Threshold Follows Changes in Flows



- Core flows (and presumably shear) show remarkable sensitivity to topology
- Inconsistent results reported with DN may be the result of this extreme sensitivity

To Summarize H-mode Story

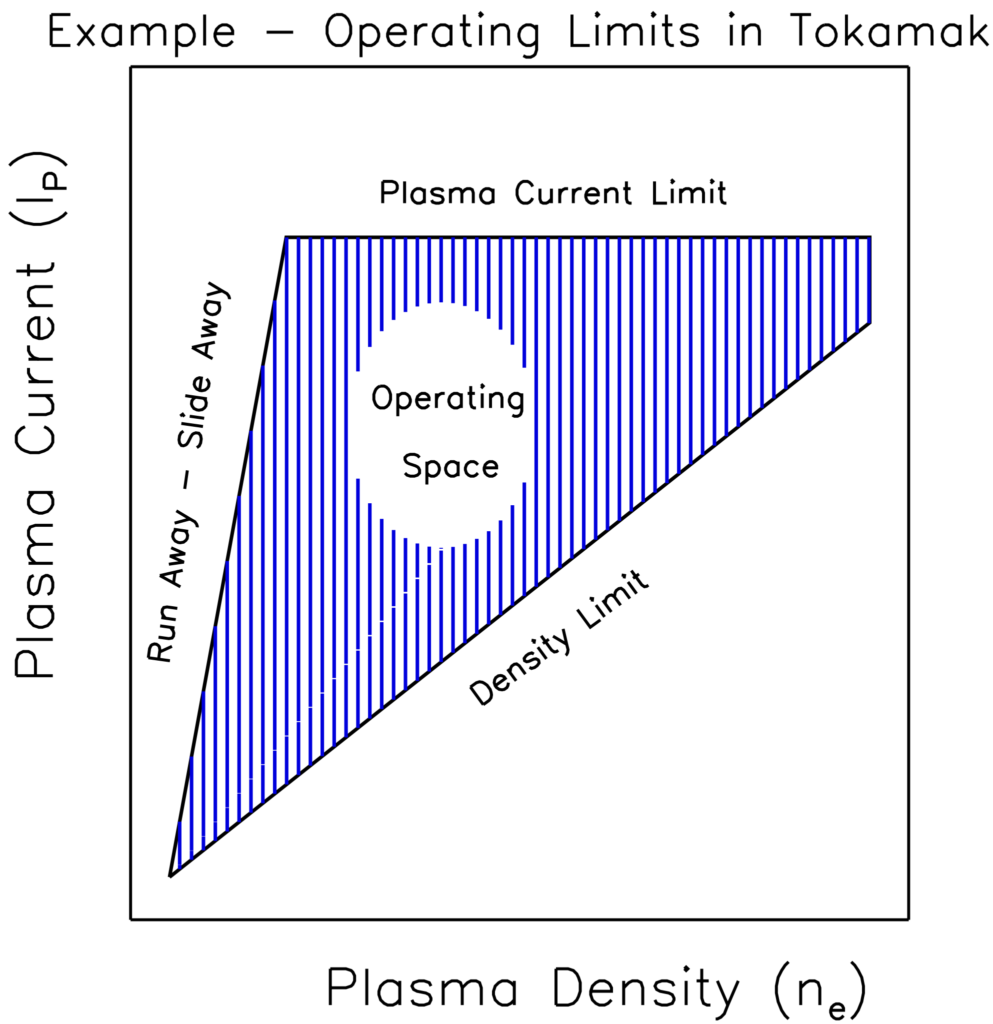
1. Significant parallel flows are driven in the SOL as a result of poloidally asymmetric cross-field transport (ballooning).
2. These flows reverse direction with respect to the plasma current depending on whether the x-point is at the top or bottom of the machine.
3. These flows couple to toroidal rotation in the **confined** plasma
4. There is a separate effect in which both the SOL and core flows increment in the co-current direction when the plasma pressure (input power) is increased.
5. So these two effects add or subtract depending on the topology.
6. Plasmas with the ∇B drift in the unfavorable direction have "farther" to go to get to the same state of rotation.

How this works quantitatively with the details of ExB stabilization and such is still unknown.

CASE 3 – GLOBAL DENSITY LIMIT DETERMINED BY EDGE TURBULENCE

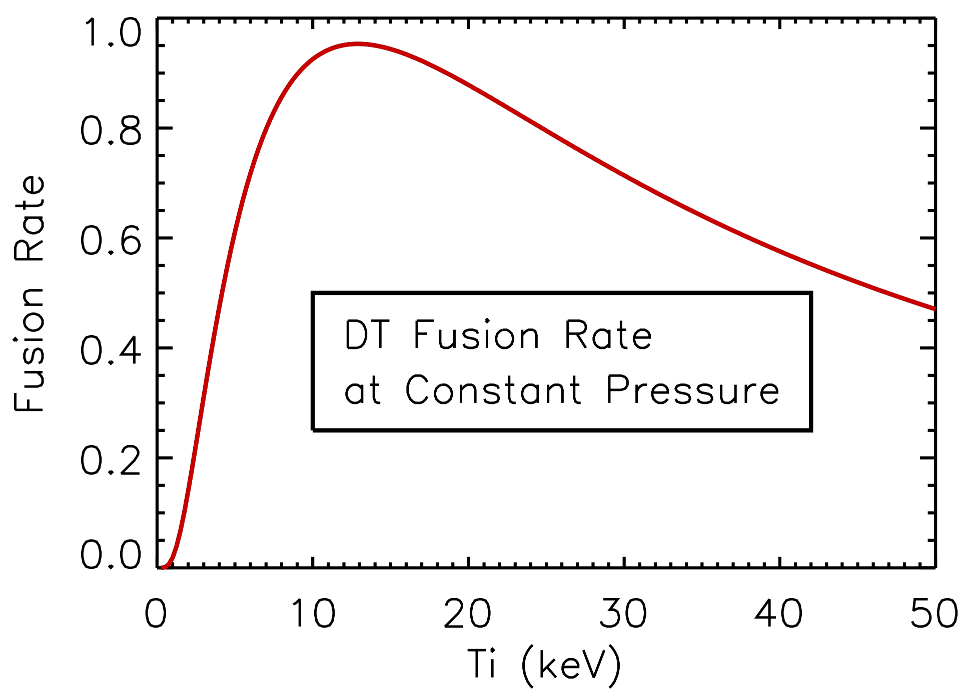
Density Limits - Background

- Magnetic confinement devices don't operate at arbitrary plasma parameters
- There are well established, **distinct** limits on plasma **pressure, current, and density**
- Understanding these limits and their implications has always been an active area of research



DENSITY LIMITS - AN IMPORTANT ISSUE FOR MAGNETIC FUSION

- $R_{DT} \propto n^2 \langle \sigma v \rangle$
- Plasma pressure limited by MHD stability
- At fixed pressure, there is an optimum temperature ⇒ optimum density
- **No guarantee that this density is achievable in any given device**
- Critical issue for conventional tokamak reactor (ITER)

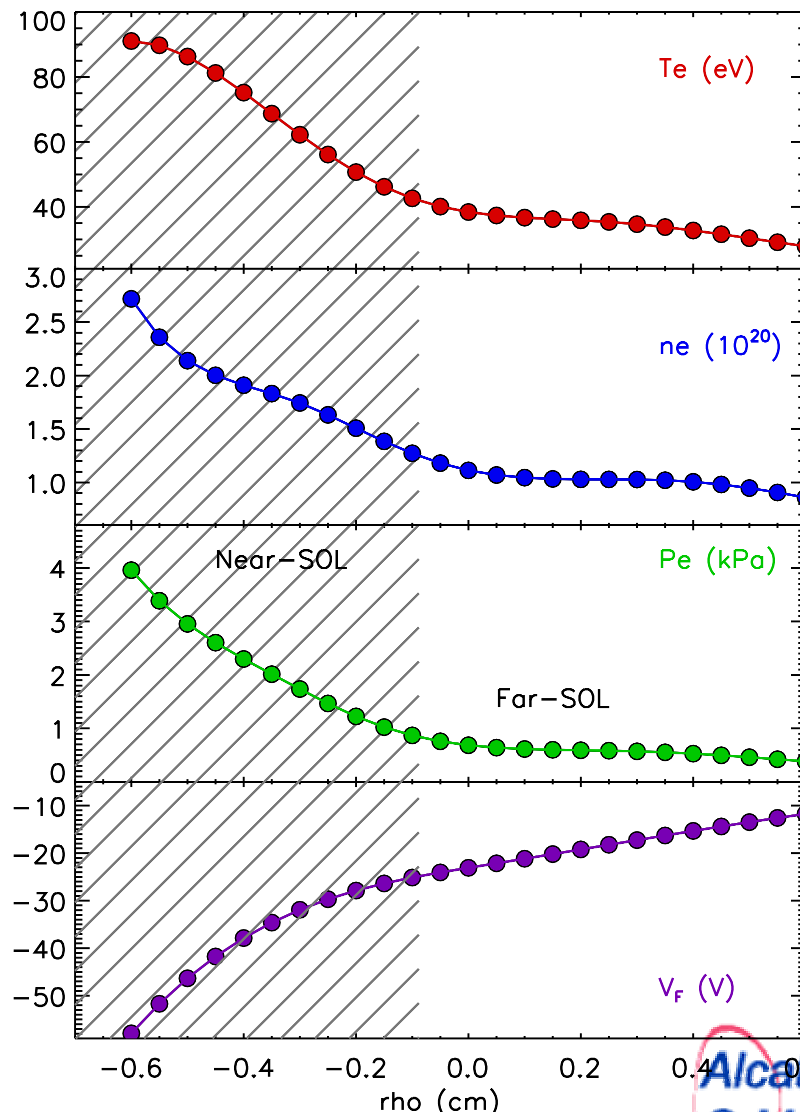


Density Limits - The Physics Problem

- Disruptive limit from edge cooling ⇒ current profile shrinks ⇒ MHD unstable
- **No widely accepted first principles theory available**
- **Not even agreement on critical physics**
- How about the role of radiation cooling? $P_{RAD} \propto n_e^2 f_Z R(T_e)$
  - Power and impurity dependence too strong ⇒ $n_{LIM} \propto \sqrt{P_{IN}/(Z_{EFF}-1)}$
  - Threshold mechanisms (MARFEs, detachment, etc) show up well below density limit
  - Transport assumptions in these models: **ad hoc at best**
- **Hypothesis: Density or collisionality dependent transport ⇒ edge cooling**

TURBULENT TRANSPORT IN EDGE INCREASES WITH COLLISIONALITY

- **Two regimes observed in scrape-off layer (SOL)**
  - Near-SOL: steep gradients, Te high
  - Far-SOL: flat profiles, Te low
- **Particle flux and transport**
  - Near-SOL: cross-field transport low
  - Far-SOL: cross-field transport high
- **Fluctuation changes character**
  - Near-SOL: low amplitude, short correlation times and lengths
  - Far-SOL: large amplitude, bursty, long correlation times



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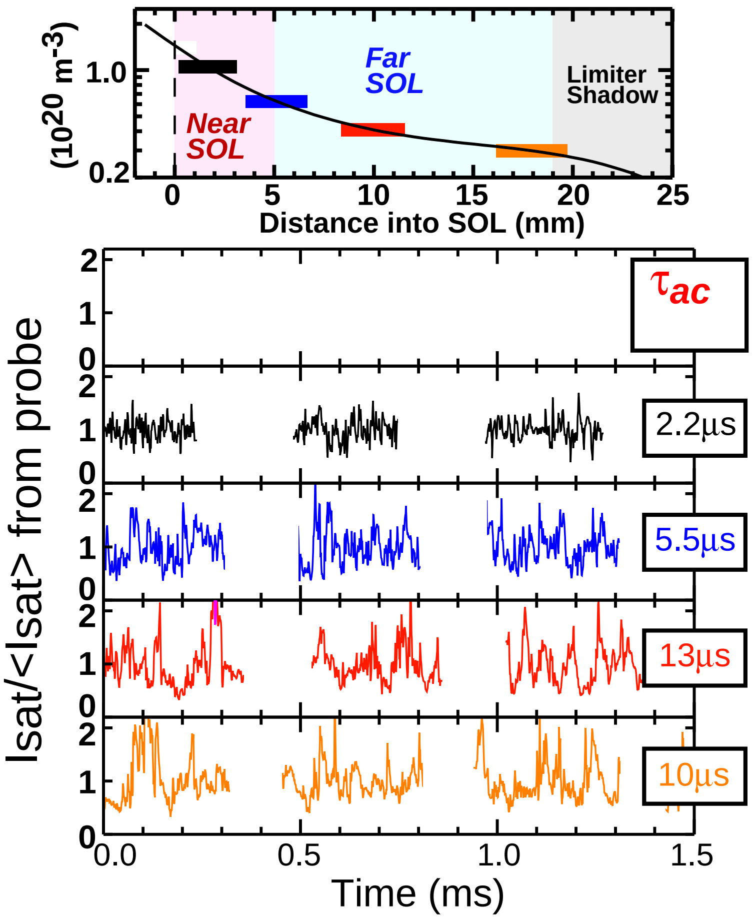
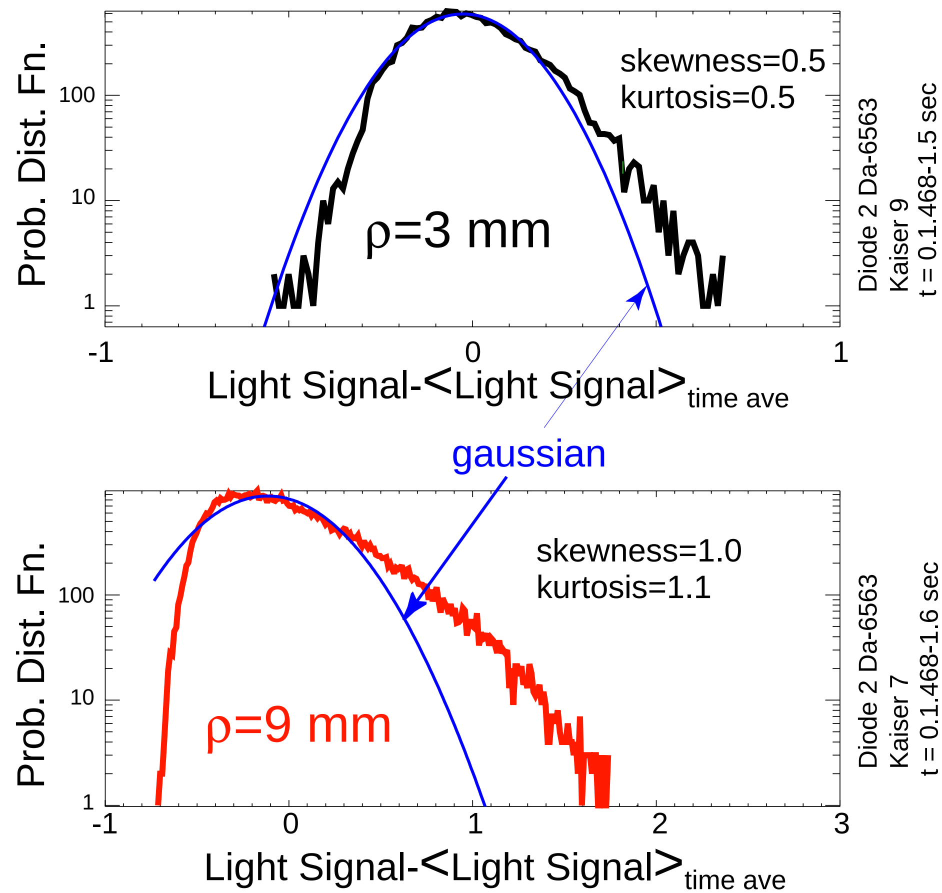
Bursty Transport Dominates SOL



Normalized RMS fluctuation level & auto-correlation time of I_{sat} increase as distance into SOL increases

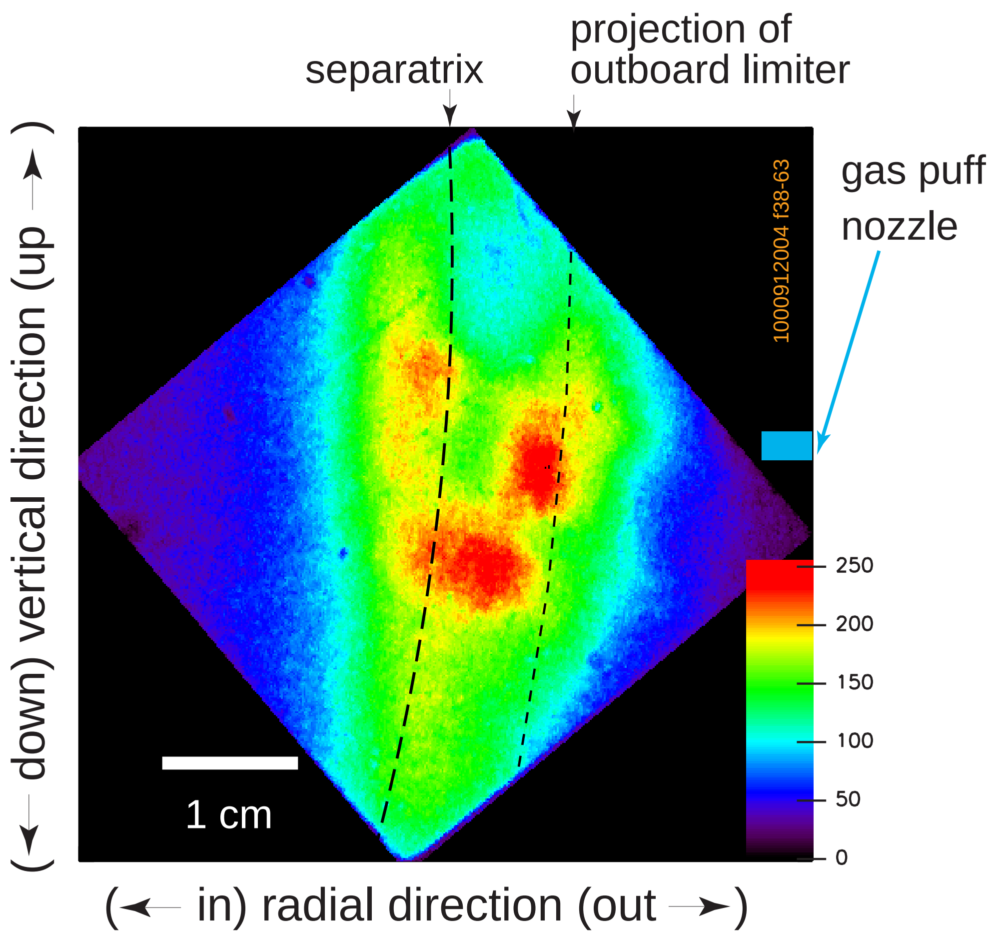


Probability distribution functions of emission get more skewed toward larger events, as distance into SOL increases

Terry 2001

We Can Visualize the Far-SOL Fluctuations - Blobs

- Fast CCD camera images, 4 μsec framing time
- D_2 gas puff ⇒ localization
- Large "blobs" dominate far-SOL
- Blobs move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements



Terry 2002

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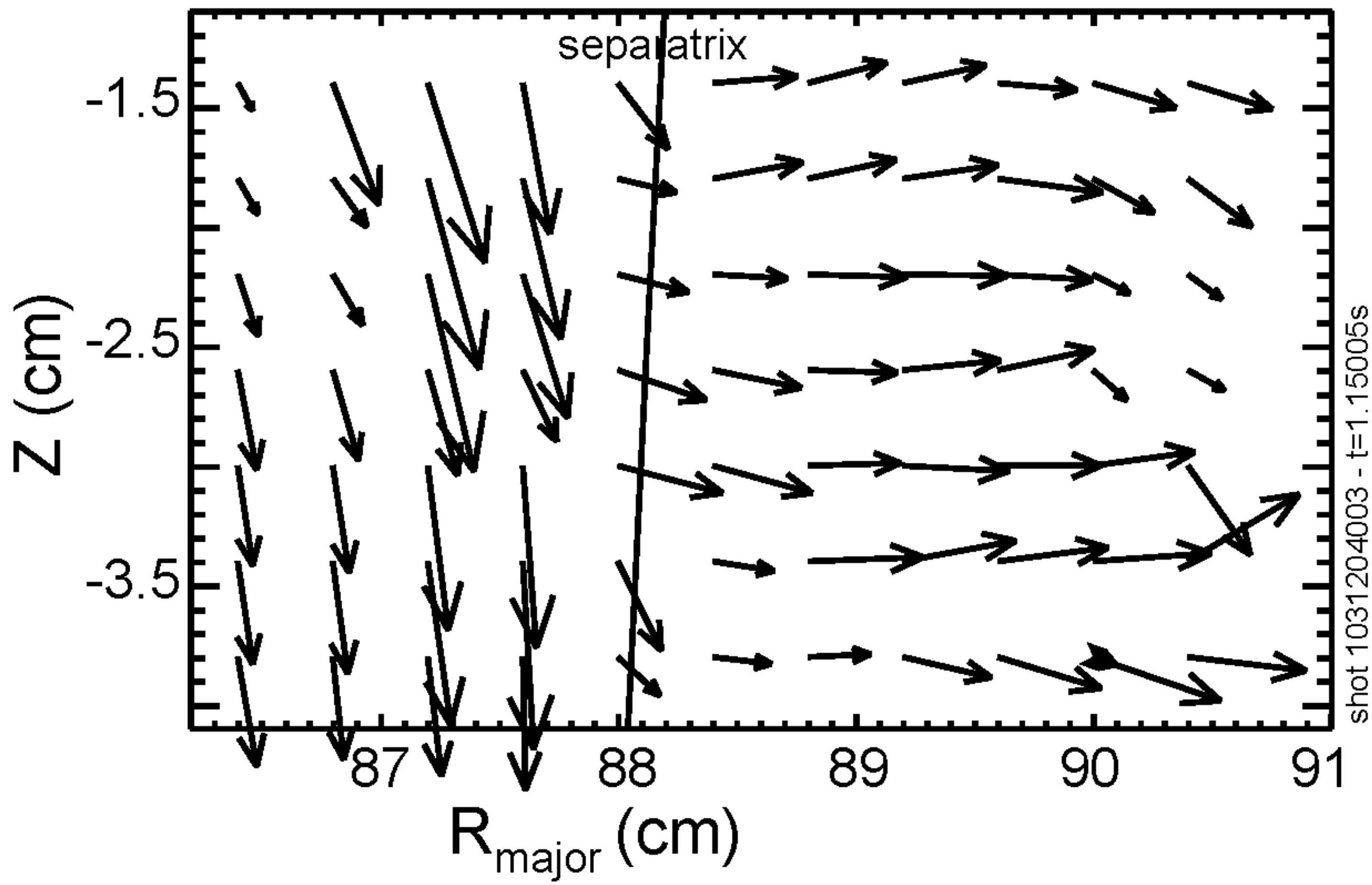
Average Blob Velocity Tends to be Poloidal in the Confined Region and Radial in the SOL



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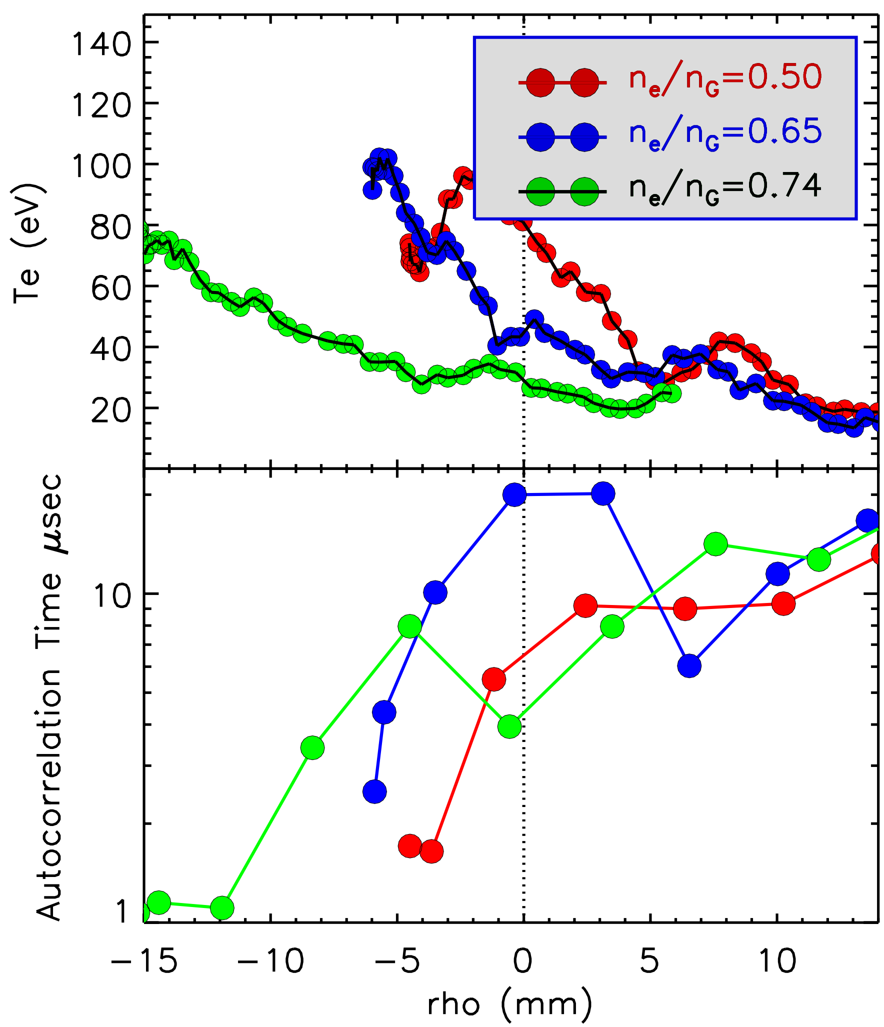
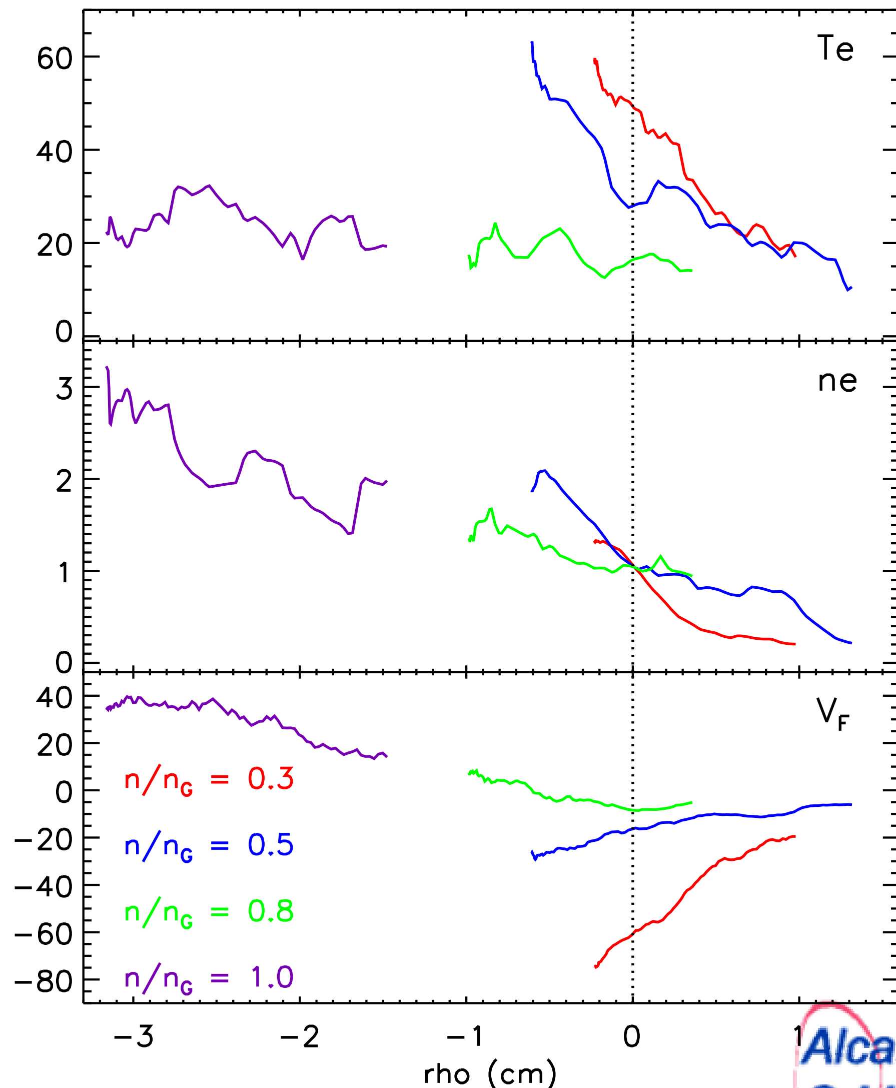
As the Density Limit is Approached, High Transport Regime Crosses Separatrix and Moves Into Main Plasma



- That is: Blobs are formed in "core" regions - closed field lines
- Warm plasma is convecting out; cold neutrals are coming in
- (Neutral physics is part of the story)
- Has the potential to explain range of density limit phenomena
- Fluctuations can cool edge,

As Density is Raised, the Temperature Profile Collapses

- Edge density profiles inside separatrix are not markedly different.
- Temperature collapse begins before $n/n_G \sim 0.8$
- Floating potential well disappears and is replaced by moderate hill
- Note: Cooling will precipitate MARFEs, detachment if they have not already occurred.
- Threshold condition? – need to understand interaction of turbulence, profiles, MHD – feedback loops



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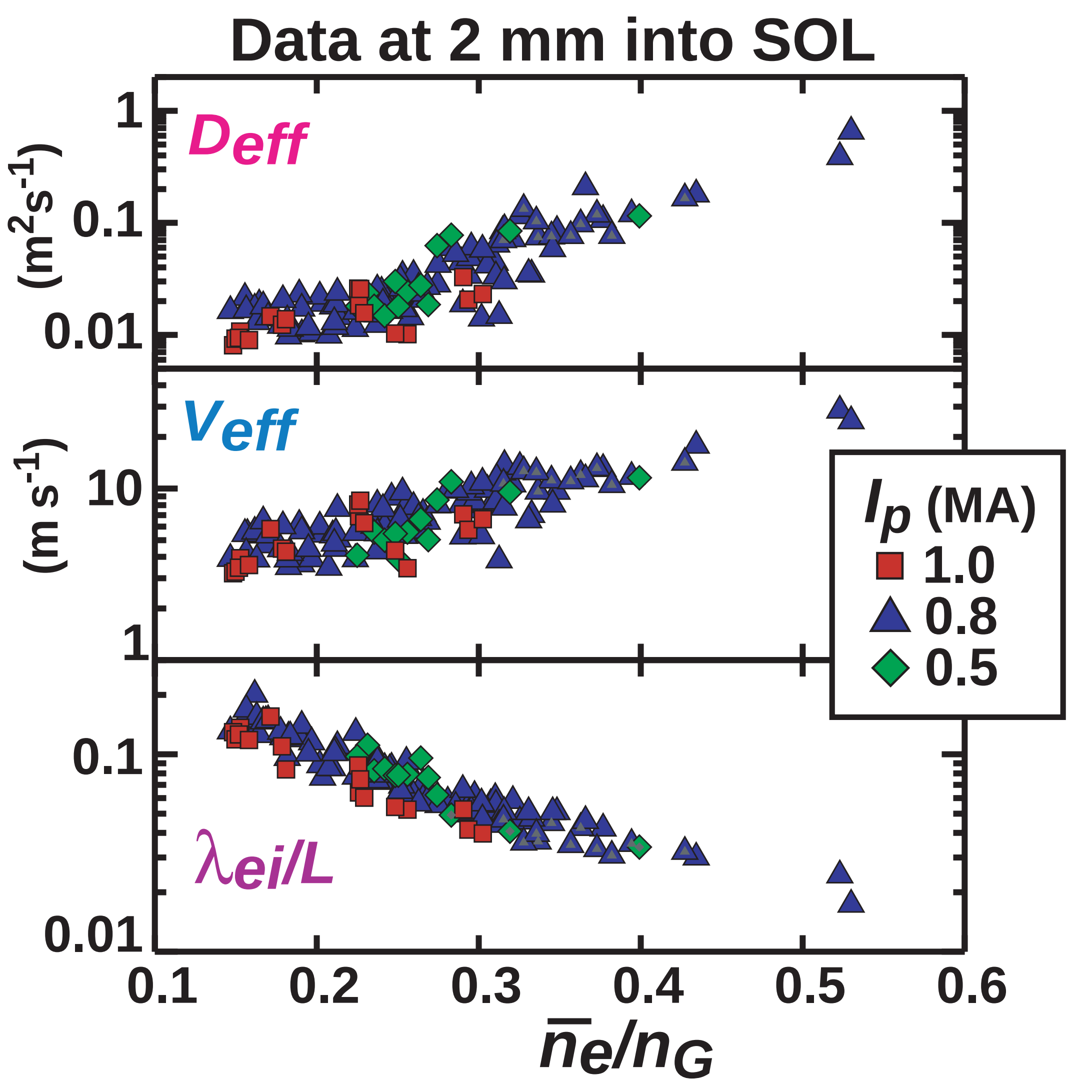
MAGNITUDES OF TRANSPORT PARAMETERS CORRELATE WITH n_e/n_G



- $D_{EFF} = \Gamma/\nabla n$, $V_{EFF} = \Gamma/n$
- n_e/n_G is a proxy for collisionality and other variables critical for the limit
- Turbulence driven convection can compete with parallel transport
- Loss of "stabilizing" influence of parallel transport
- Destruction of shear layer?

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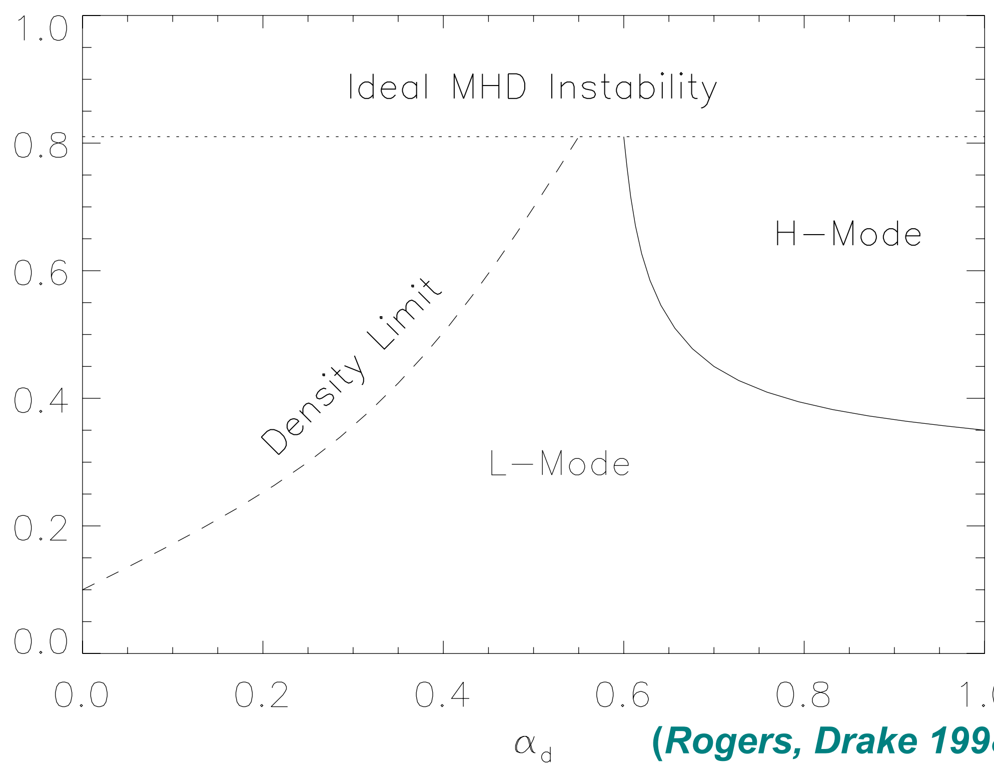
Some Support From Edge Turbulence Simulations

- Non-linear 3D gyro-fluid simulations have found regime of extremely high transport
- $\alpha = -Rq^2 d\beta / dr$ (normalized pressure gradient)
- $\alpha_D = \rho_s c_s t_0 / L_n L_0$

  $$\propto \left(\frac{T^2}{nL_n} \right) \rightarrow \frac{\lambda}{L_n}$$

  (inverse ⊥ collisionality)



(Rogers, Drake 1998)

- Region of ultra-high transport consistent with high density, low temperature
- Similar results from Xu, Hallatschek
- No quantitative predictions yet

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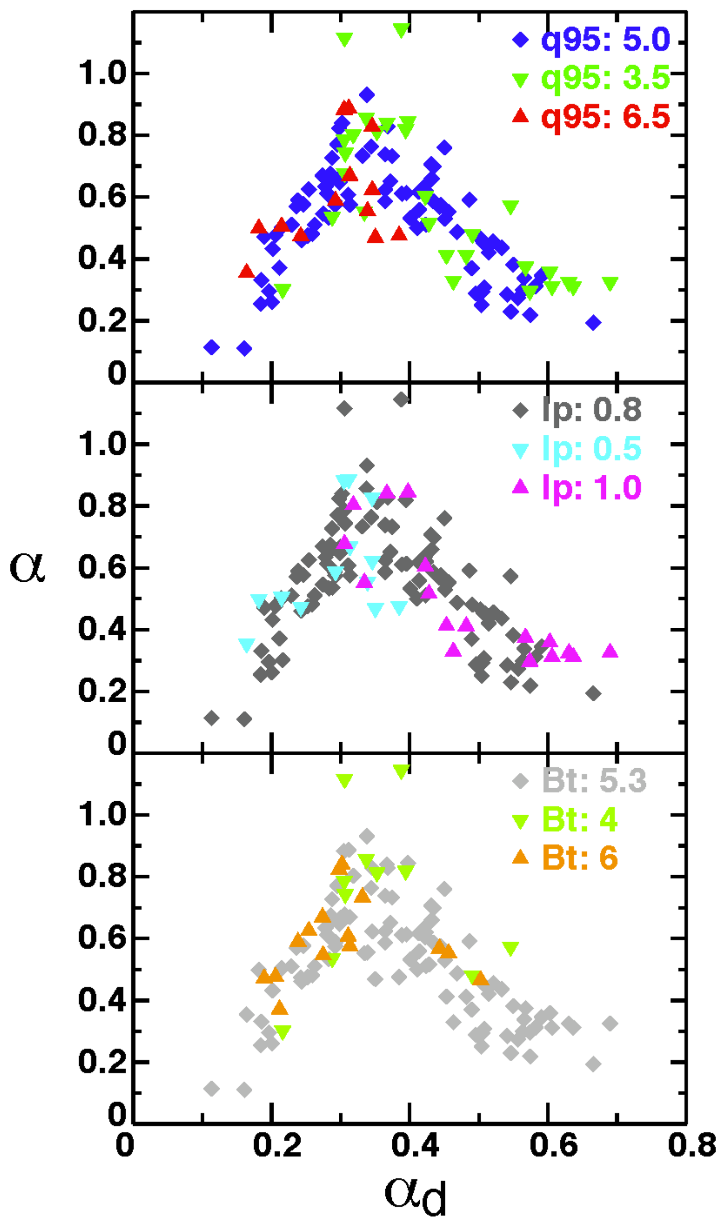
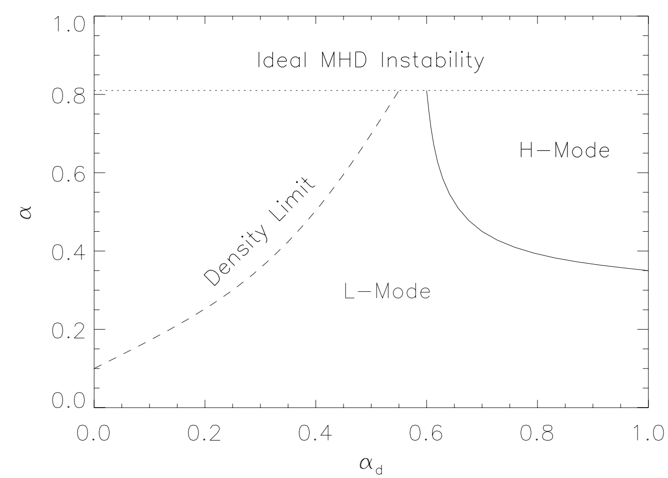
Edge Plasma Pushes Calculated Stability Limits



LaBombard 2003

- α_{MHD} is significant in near SOL
- Unstable region moves inward at higher densities
- Calculations are limited Flux tube, local profiles, no open field lines, separatrix, no profile evolution
- Role of shear layer is uncertain (and not modeled here)



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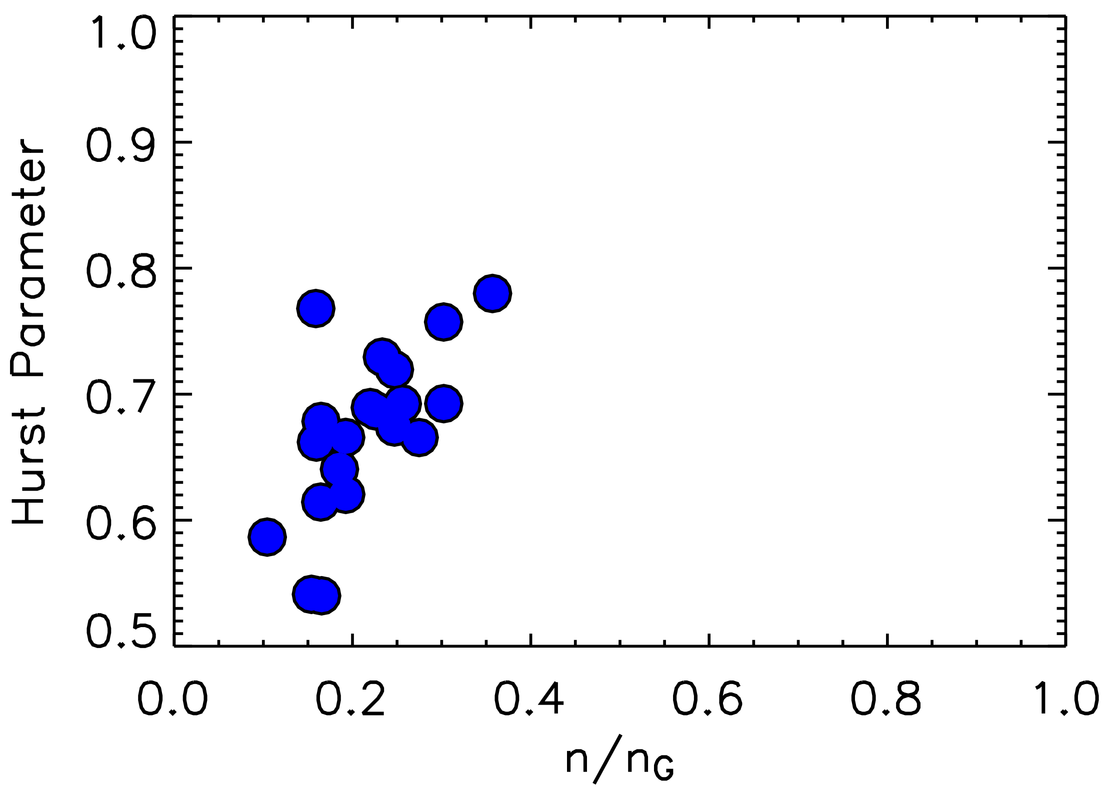
As Density Rises, Edge Fluctuations Show Increasing Long-Time Correlations



Carreras 2004

- Computed with reduced range (R/S) analysis
- H = 0.5 ⇒ Random
- H = 1.0 ⇒ Coherent
- So fluctuations go “global” (large scale) as density limit is approached?

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We Think There is a Plausible Case for Turbulent Transport in the Plasma Edge as THE Critical Physical Mechanism for the Density Limit.

- The dynamics by which enhanced convective transport destabilizes the entire temperature profile has not been worked out quantitatively
- We also need to determine the condition under which the plasma goes MHD unstable
- Is the result sensitive to details of the turbulence?
- How do these results carry over to other devices (RFP) which see a similar limit (or to Stellarators where there are some obvious differences).

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OVERALL SUMMARY

- For the examples given, SOL/Edge/Core coupling is 0^{th} order, not perturbative.
- It may not be possible to understand anything fully without understanding everything.
- Though an awful prospect, we need to deal seriously with the coupling problem