Perturbed Equilibria and ELM Suppression in DIII-D, and Implications for ITER

by

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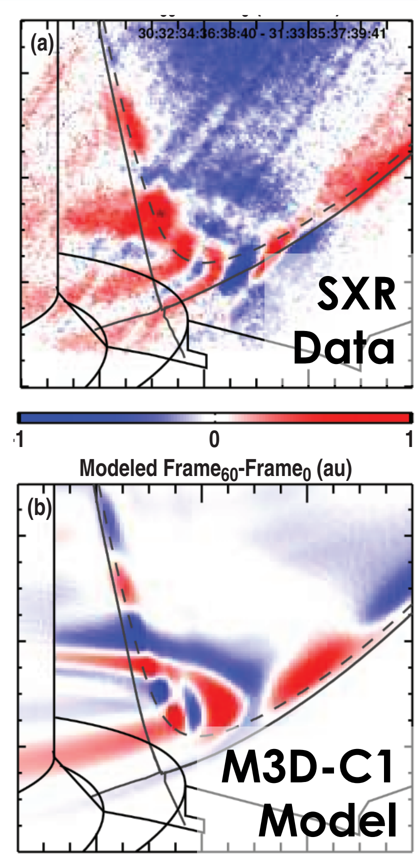
Improved 3D Modeling and Pedestal Dynamics Models Allow Better Predictions of ELM Suppression

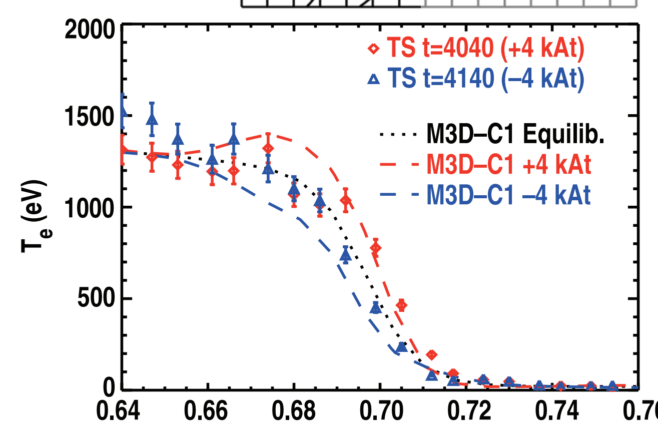
- **Despite successfully mitigating ELMS with Resonant Magnetic Perturbations (RMPs) on many tokamaks, we still lack a good predictive model**
- **In a set of DIII-D discharges, it was found that the Vacuum Island Overlap Width (VIOW) correlates with ELM suppression***
- **Actual mechanism of ELM suppression is more complicated than VIOW**
  - VIOW ignores plasma response (kinking, screening)
  - Pedestal is probably not stochastic, so "IOW" may not be physical
- **We apply advances in *modeling capabilities* and *understanding of pedestal dynamics* to develop new correlation criteria for ELM suppression; apply to ITER**

*Fenstermacher *Phys. Plasmas* **15**, 056122 (2008)

Plasma Response to RMP Significantly Alters the Magnetic Fields in H-Mode Edge

- **Plasma tries to exclude magnetic islands**
  - "Screening"; where ω_e is large (steep gradient region and core)
- **RMPs drive (stable) modes to finite amplitude**
  - "Kink response"
  - Driven reconnection; where ω_e is small (pedestal top)
- **Including plasma response is necessary to accurately model edge measurements**
  - T_e, n_e profiles in edge strongly affected by "kink response" (Shafer NI2.00006, this morning)
  - Linear two-fluid modeling (M3D-C1) is successful in reproducing measured profiles





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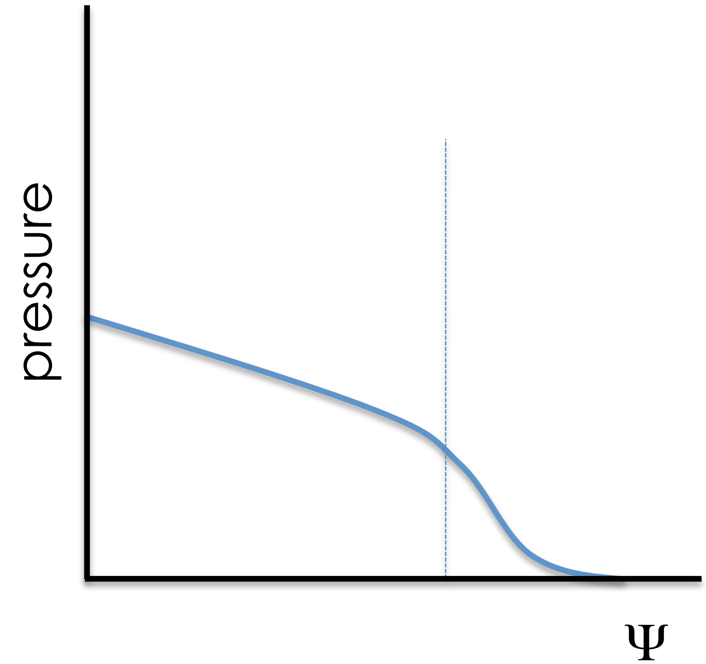
EPED Model Suggests ELM Suppression Requires Enhanced Transport Localized at Pedestal Top

- **EPED Model of pedestal structure:**
  - Gradient determined by local KBM stability
  - Width grows until global PB stability threshold is reached (ELM)

*P. Snyder UP8.00050, Thurs. afternoon



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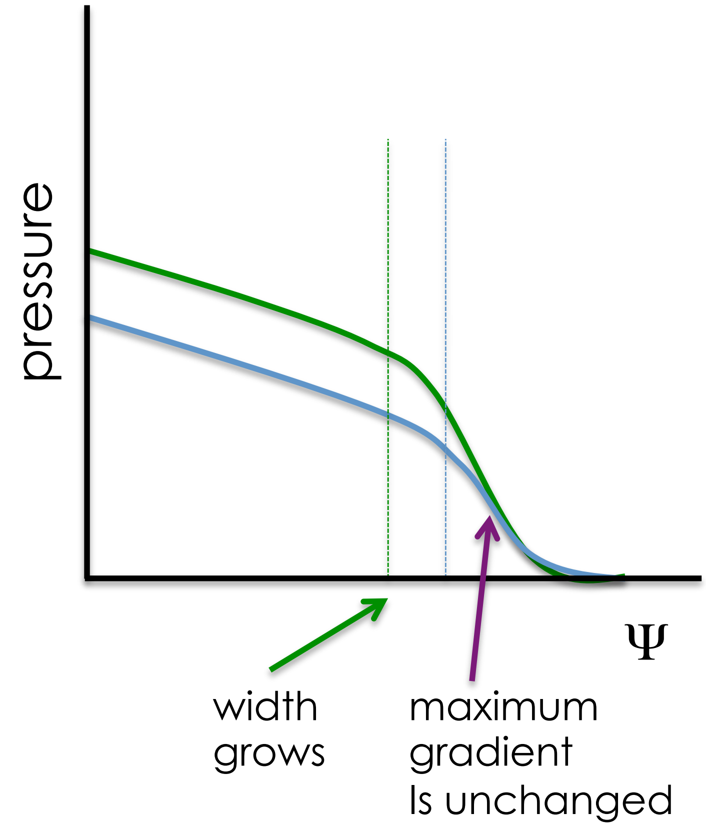

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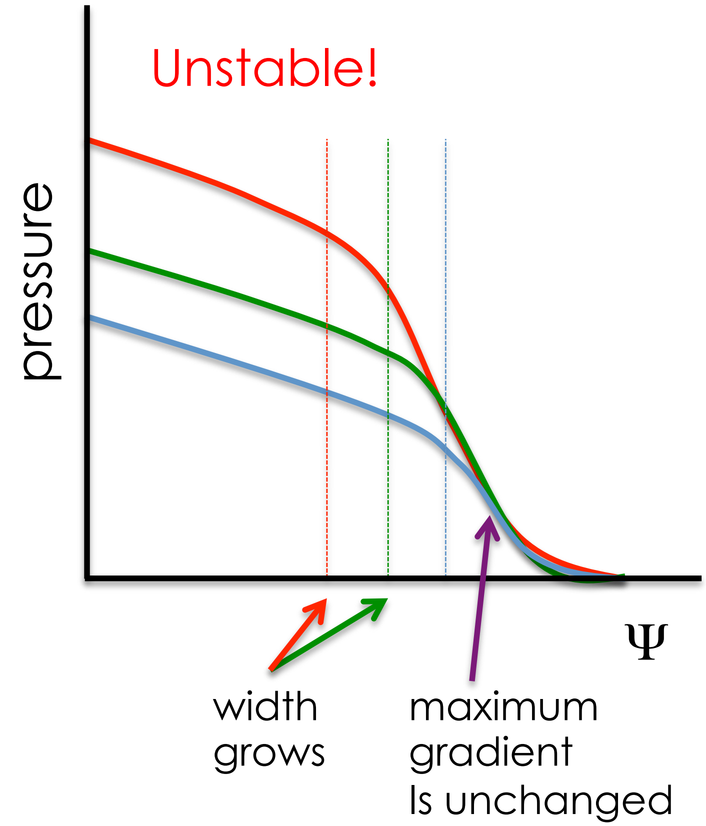

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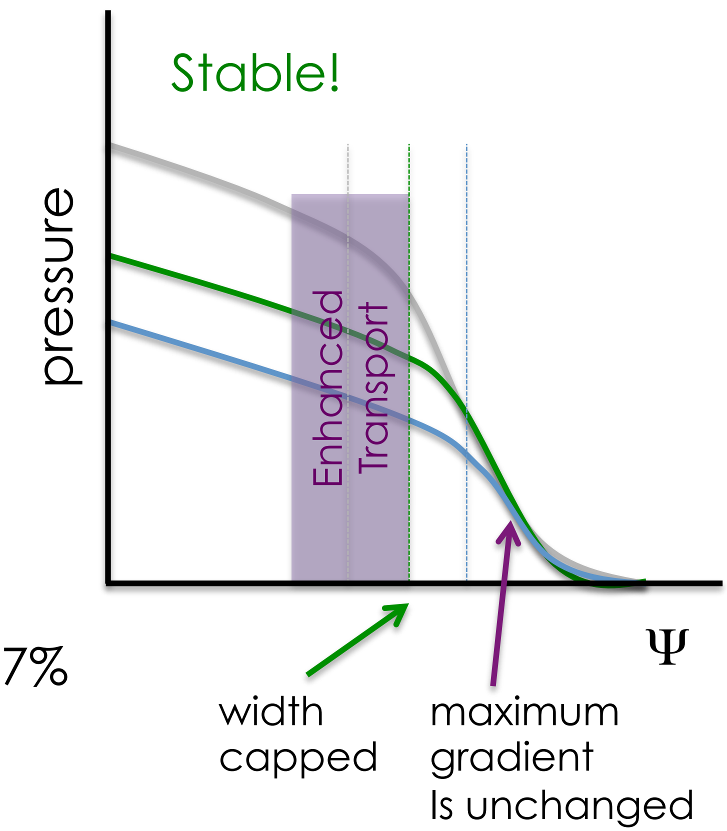
- **Implies model of ELM suppression:**
  - Something stops widening of pedestal before threshold
  - Requires enhanced transport at Ψ≈96–97%



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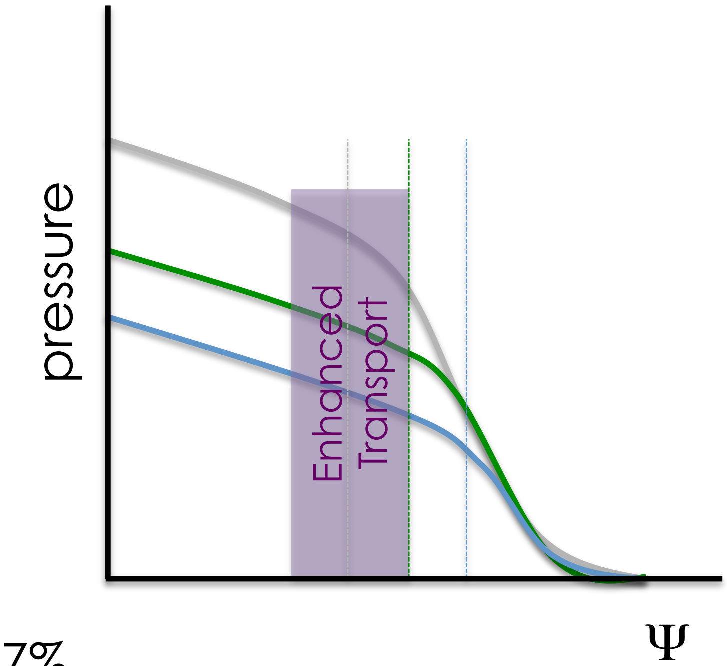

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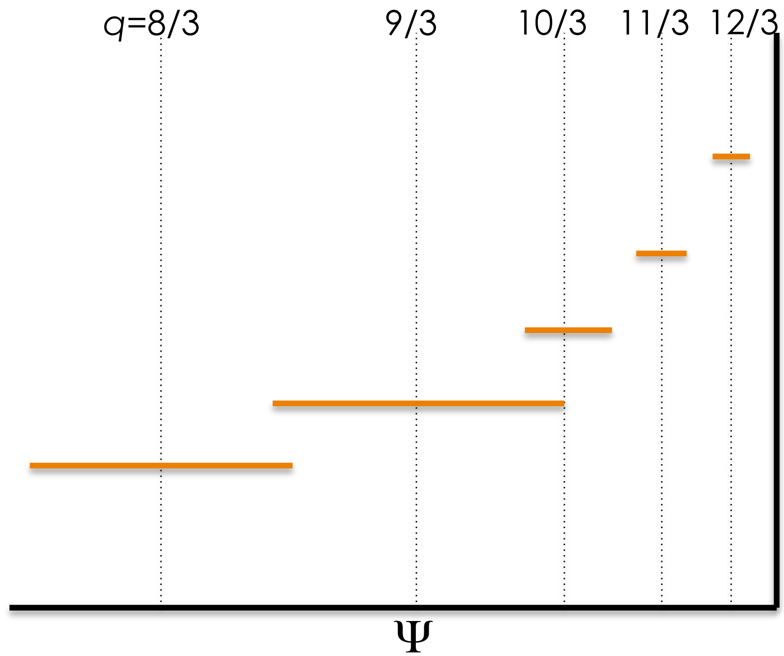
  - Something stops widening of pedestal before threshold
  - Requires enhanced transport at $\Psi \approx 96\text{–}97\%$

- **Predictive modeling needs model of RMP effect on transport**
  - Enhanced classical transport? (S. Smith, NI2.00005, earlier today)
  - Change to KBM stability? (C. Hegna, PP8.00058, right now)
  - Stochasticity? (D. Orlov, YI3.00006, Friday morning)

"Local Chirikov" Value Gives Indication of Localized Stochasticity

- **Island width is estimated using pitch-resonant field at each mode-rational surface**

$$w(\Psi_m) = \frac{2}{\pi}\sqrt{\frac{\psi_{mn} q}{\psi' q'}}$$



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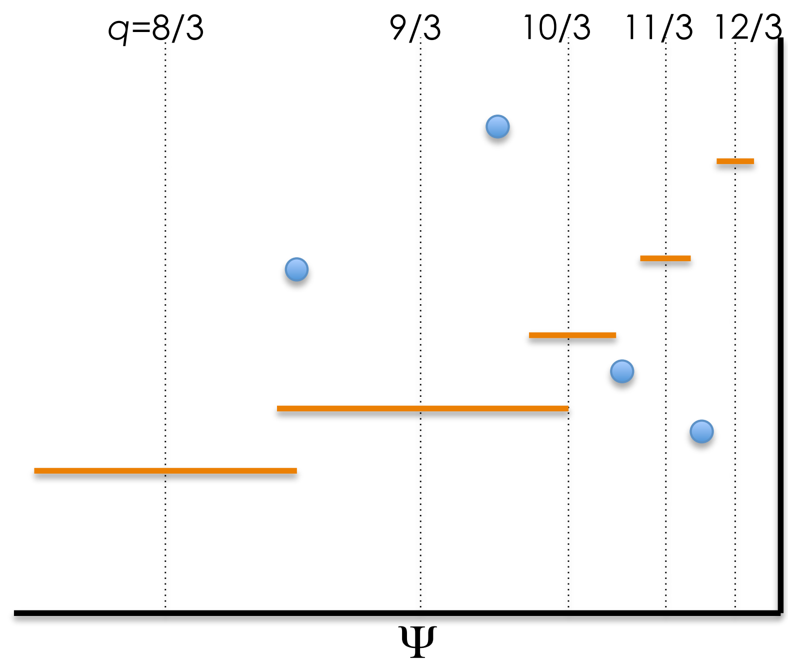
$$\sigma\left(\frac{\Psi_{m+1}+\Psi_m}{2}\right) = \frac{1}{2}\frac{w(\Psi_{m+1})+w(\Psi_m)}{\Psi_{m+1}-\Psi_m}$$



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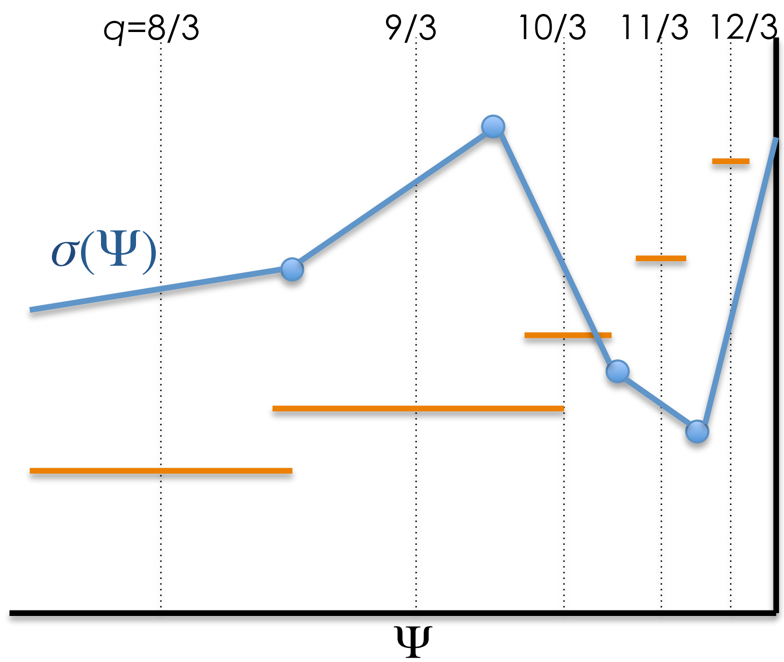
- **"Local Chirikov" value is defined by linear interpolation of these values**



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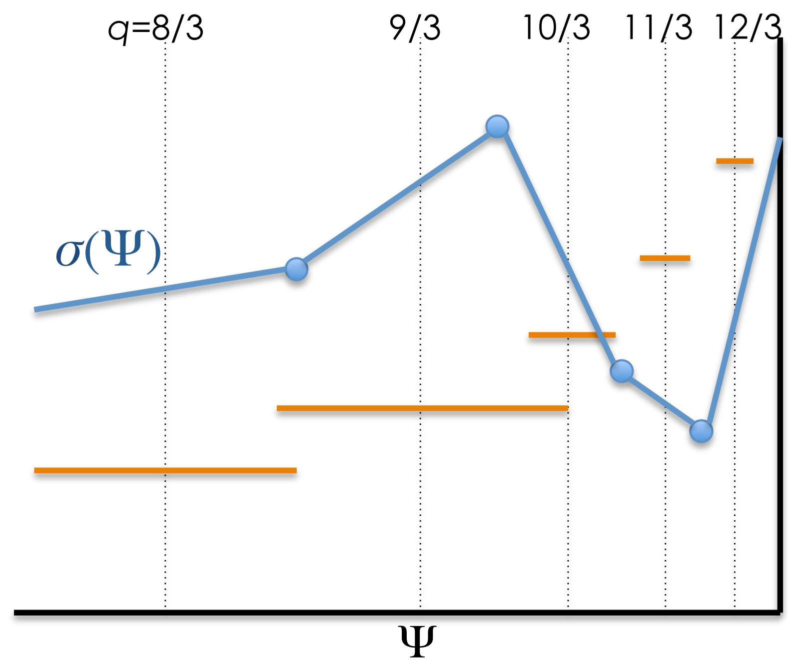
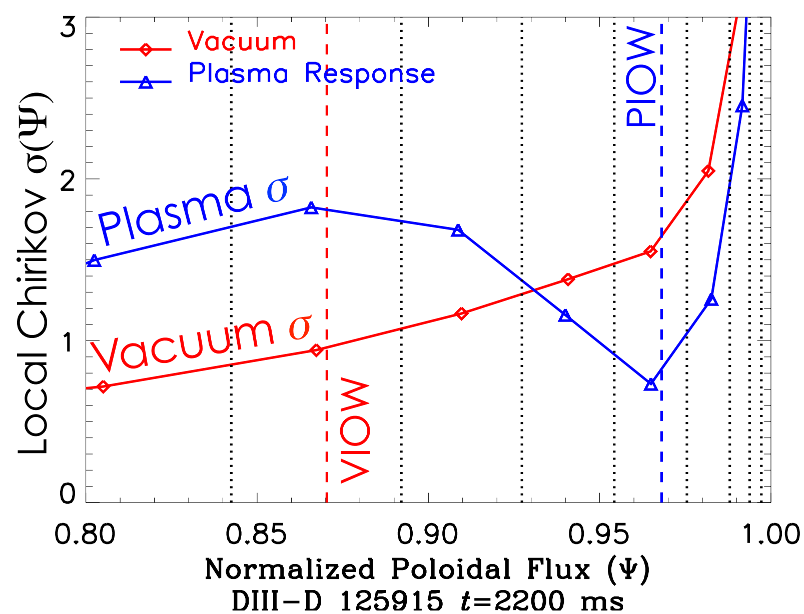
- **Plasma response reduces σ in the pedestal**





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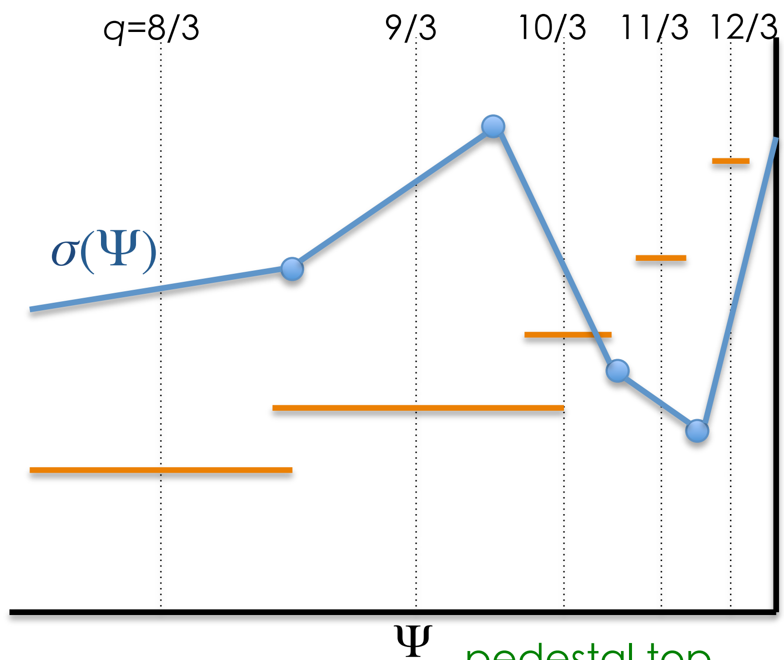
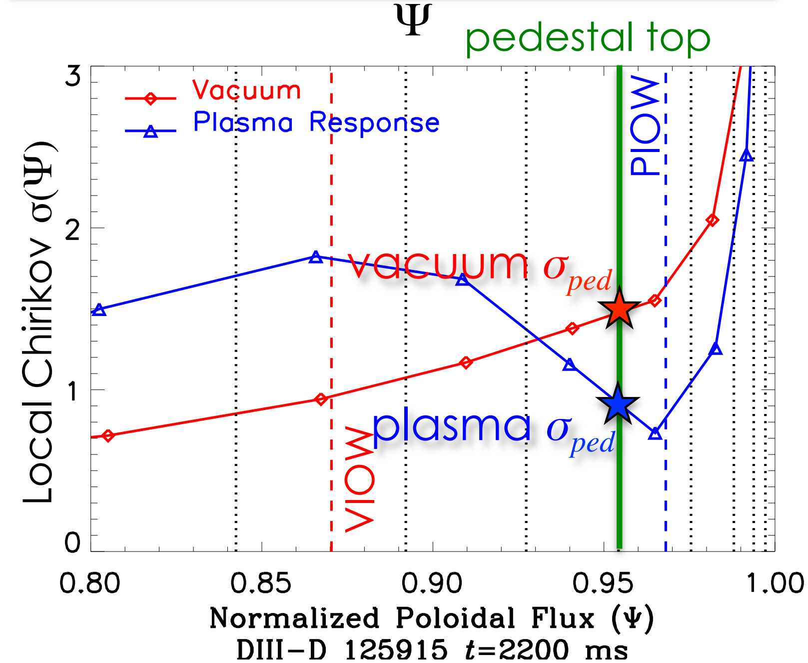
- $\sigma_{ped} = \sigma(\Psi_{ped})$





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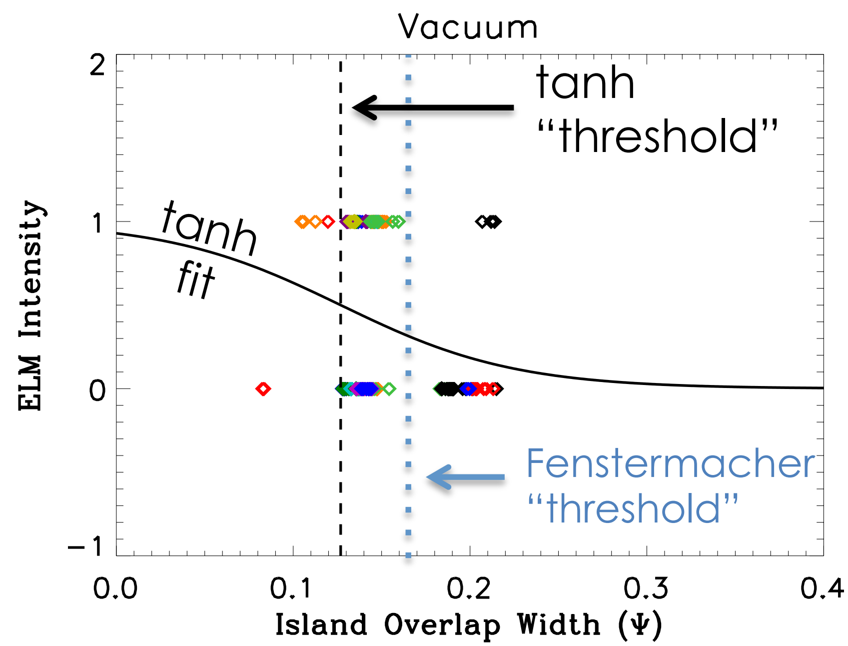
IOW and σ_{ped} Metrics Are Tested on a Set of DIII-D Discharges

- **Considered set of 13 discharges at 162 times with *n*=3 RMP applied**

- **IOW and σ_{ped} evaluated for each time, with and without plasma response**
  - Plasma response is calculated with M3D-C1, using a linear two-fluid model (Spitzer resistivity, includes rotation)
  - Calculations include *n*=3 response, not *n*=0 transport changes

- **Correlation with ELM Suppression is quantified by fitting tanh to "ELM Intensity" as a function of the metric**
  - *ELMing*: ELM Intensity = 1
  - *Suppressed*: ELM Intensity = 0



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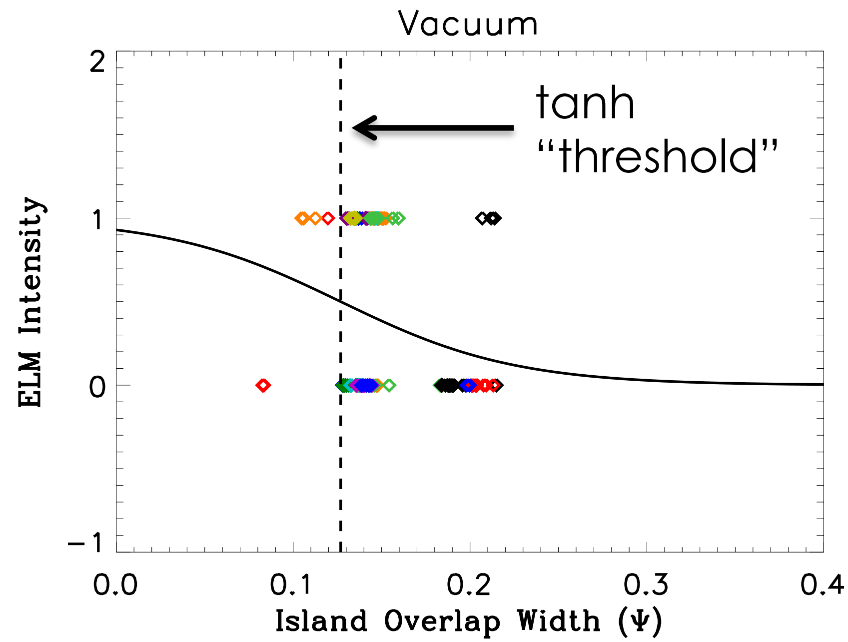
σ_{ped} Correlates Better Than IOW; Plasma Response Doesn't Always Improve Correlation

- **"Accuracy": fraction of times correctly classified by the threshold from tanh fit**

Metric	Threshold	Accuracy
Vacuum IOW	12.7%	63%
Plasma IOW	6.4%	70%
Vacuum σ_{ped}	1.55	89%
Plasma σ_{ped}	0.90	73%



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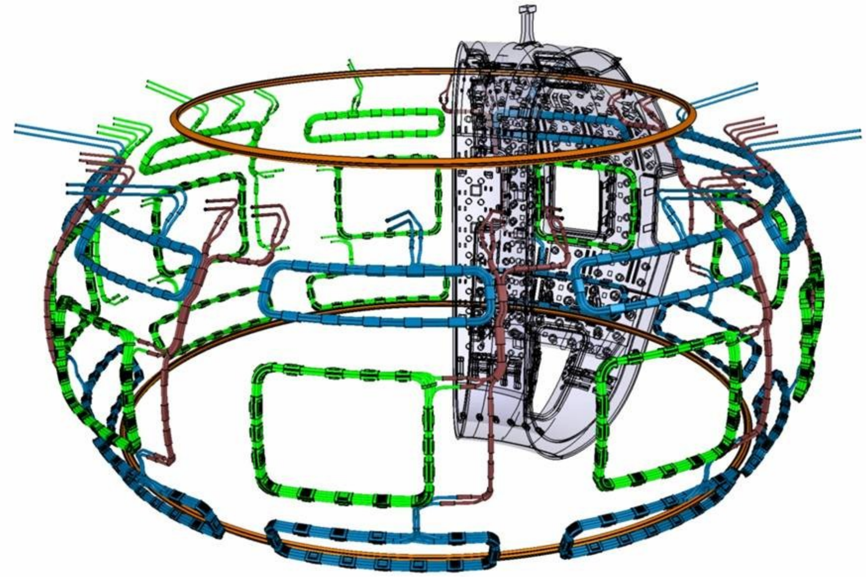
New Metrics are Better, But Still Imperfect

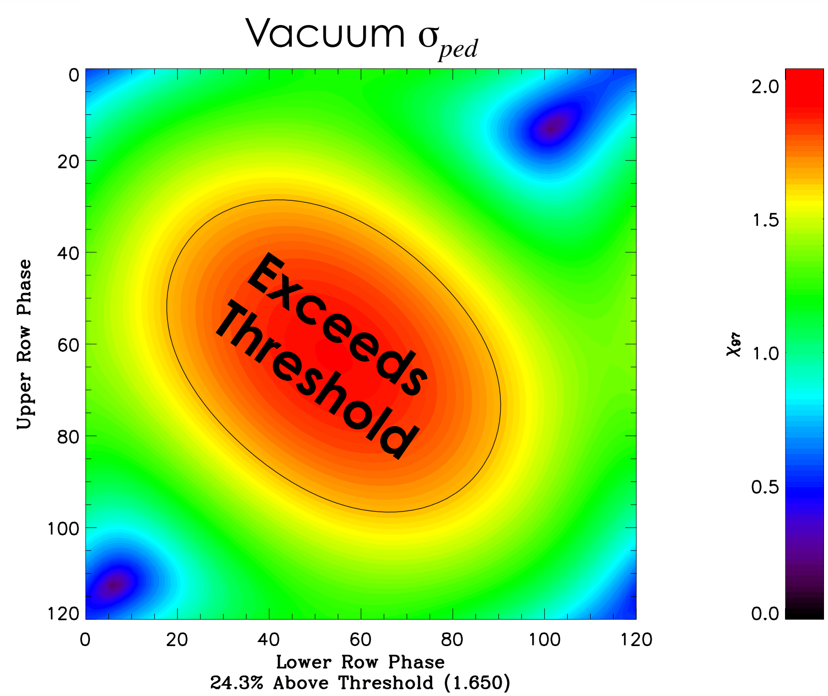
- **Plasma response is sensitive to the equilibrium**
- **Plasma response conflates cause / effect of suppression**
- **Only the *n*=3 component is considered here**
  - Strong evidence that sidebands can be important (Orlov)
  - Fenstermacher (2008) VIOW definition includes sidebands
- **Linear response misses some important physics**
  - Amplification of islands implies nonlinear effects important
  - IOW and σ_{ped} are imperfect indicators of enhanced transport

Suppression Correlation Metrics Have Been Applied To Several ITER Scenarios

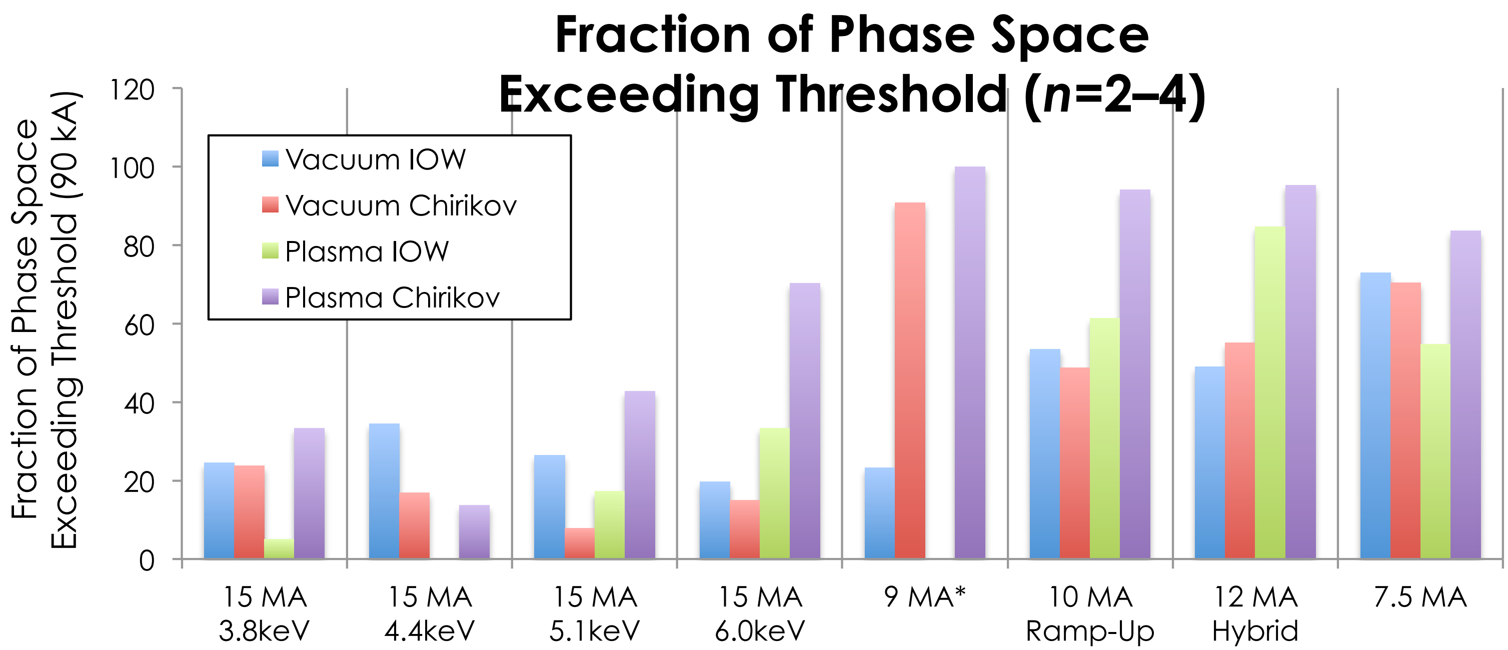
- **Metrics have been calculated for 8 ITER scenarios, *n*=1–4**
  - 15 MA Q_{DT}=10 T_{ped}=3.8, 4.4, 5.0, and 6.3 keV
  - 12 MA Hybrid
  - 10 MA Ramp-Up
  - 9 MA
  - 7.5 MA

- **IOW and σ_{ped} calculated as a function of the phase of the upper and lower coil rows (relative to center row)**





Suppression Threshold of Three of Four Metrics Can Be Achieved for All ITER Scenarios



*only n=4 considered for 9 MA scenario

- **Thresholds for three of four metrics can be satisfied for all scenarios**
  - Plasma IOW cannot be satisfied for 2/8 scenarios
- **Metrics tend to agree on optimal coil phases; generally find easier suppression at higher *n***

Summary

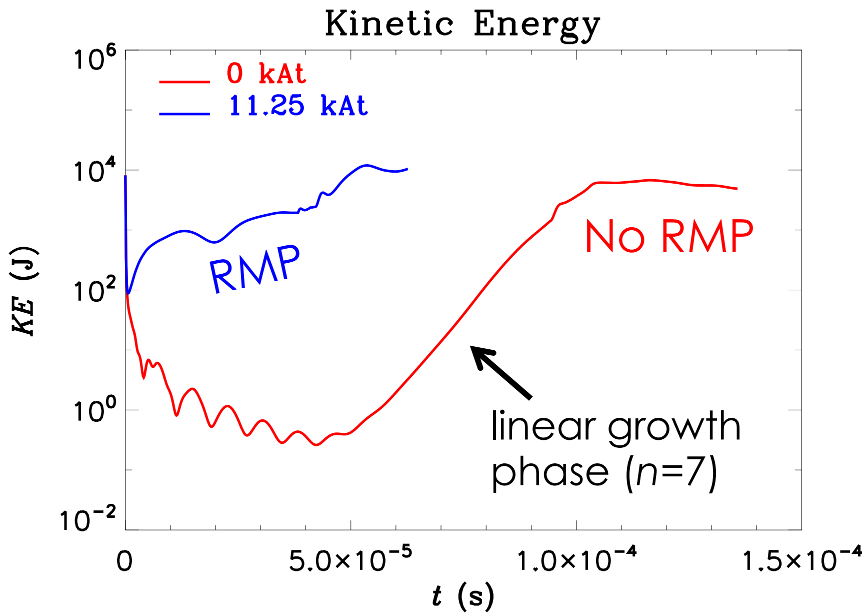
- **Applying new understanding of pedestal evolution and perturbed 3D equilibria yields improved ELM suppression metrics**
  - Local measure of stochasticity at pedestal top (σ_{ped}) appears to correlate better than vacuum island overlap width
  - Still imperfect (don't recover q_{95} window)
- **Three of four metrics can be satisfied for all ITER scenarios**
  - Encouraging, but not definitive
- **For truly predictive models, better understanding of transport in 3D geometry is needed**

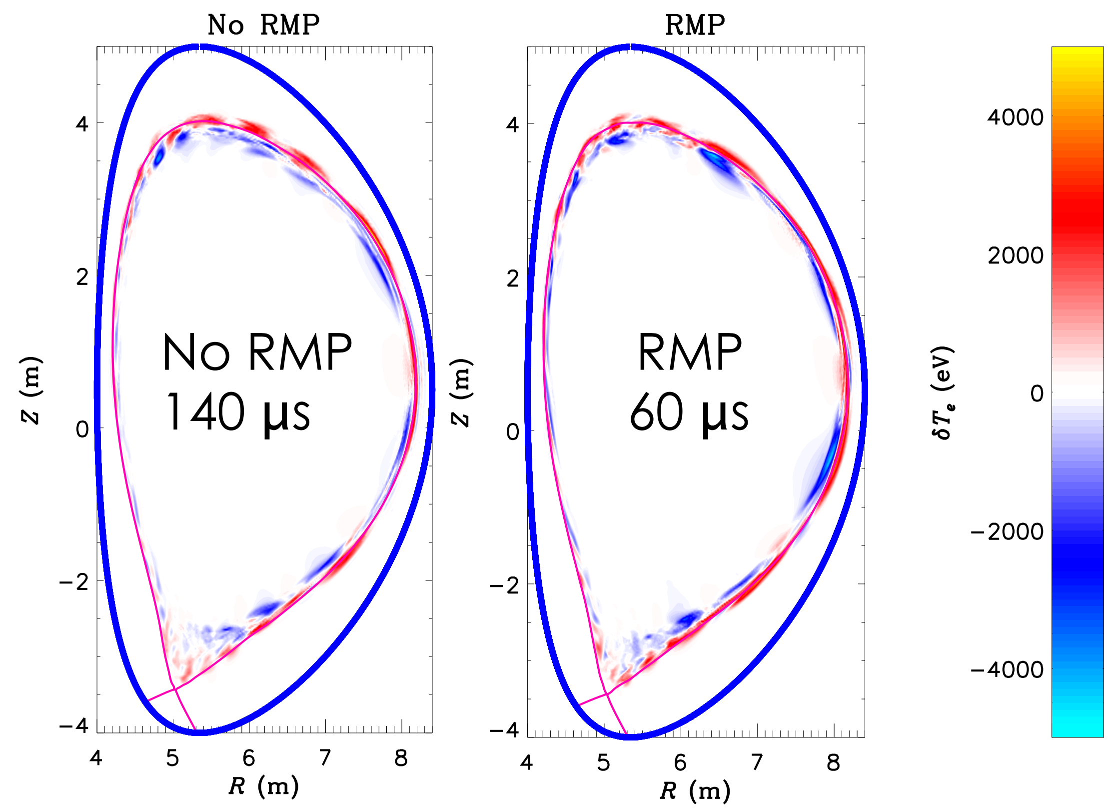
ELM Suppression is a Top DIII-D Priority

- **R. Nazikian, GO4.00004:** Pedestal Response to Resonant Magnetic Perturbations in DIII-D H-mode Plasmas
- **A. Wingen, GO4.00005:** A Possible Connection of Plasma Response to RMP ELM Suppression in DIII-D
- **S. Smith, NI2.00005:** Magnetic Flutter Plasma Transport Induced by 3D Fields in DIII-D
- **M. Shafer, NI2.00006:** Plasma Response Measurements of Non-Axisymmetric Magnetic Perturbations on DIII-D
- **C. Hegna, PP8.00058:** The effects of weakly 3-D equilibrium on MHD stability of tokamak pedestals
- **T. Evans, UP8.00025:** 3D Magnetic Perturbation Effects on Transport in Tokamaks
- **P. Snyder, UP8.00050:** Optimizing Pedestal Performance with the EPED Model
- **A. Leonard, XR1.00001:** Edge Localized Modes (ELMs) in Tokamaks
- **D. Orlov, YI3.00006:** Suppression of Type-I ELMs with a Reduced I-coil Set in DIII-D

Extra Slides

Nonlinear Response Calculations Show Effect on ELM Stability





- **Reduced two-fluid nonlinear calculations show significant effect on pedestal from RMPs with just 11.25 kA in control coils**
- **RMP causes PB to mode to rapidly achieve "nonlinear" amplitude**

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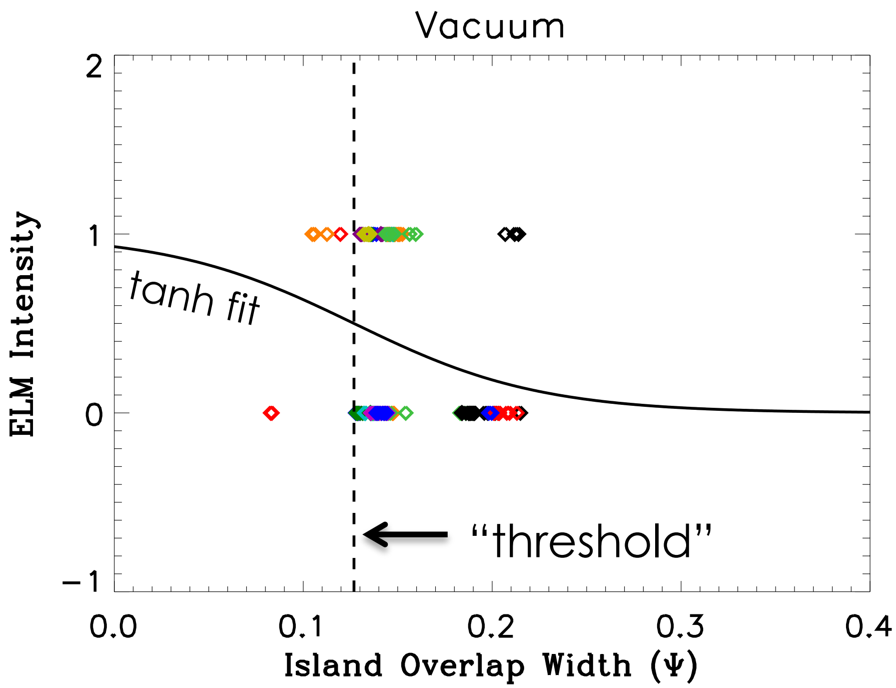
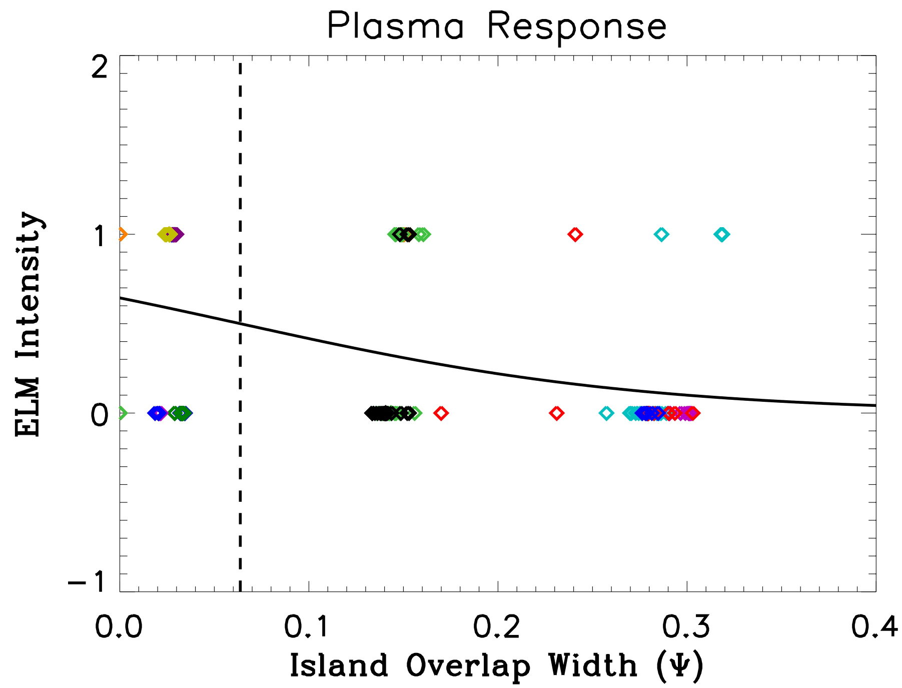
Including Plasma Response Improves IOW Correlation



accuracy = 63%



accuracy = 70%

- **"Accuracy" defined as fraction of cases that are correctly classified using the best-fit "threshold"**

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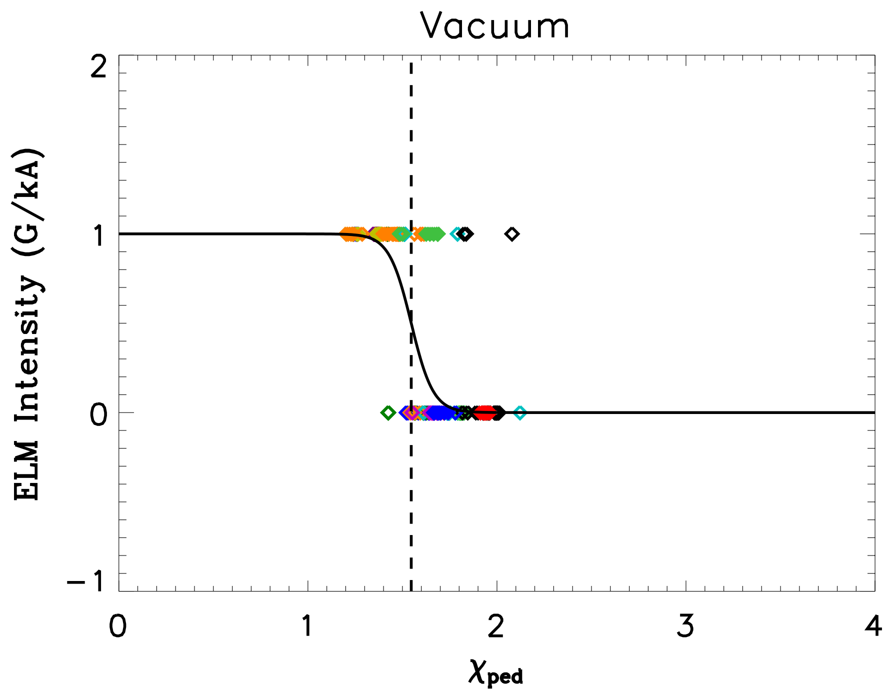
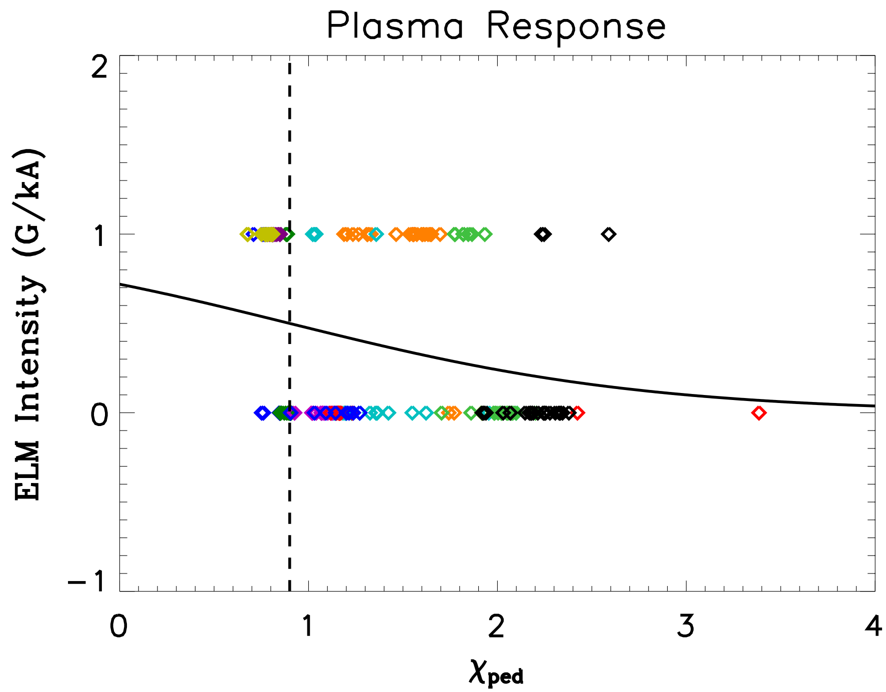
Local Chirikov Parameter Correlates With Suppression Better than IOW



accuracy = 89%



accuracy = 73%

- **Best correlation is found when $\sigma(\Psi)$ is evaluated at the pedestal top (σ_{ped}, usually $\Psi \approx$ 96–97%)**
- **Including plasma response *reduces* correlation!**