Introduction to H-mode plasmas: L-H transition, pedestal, ELMs

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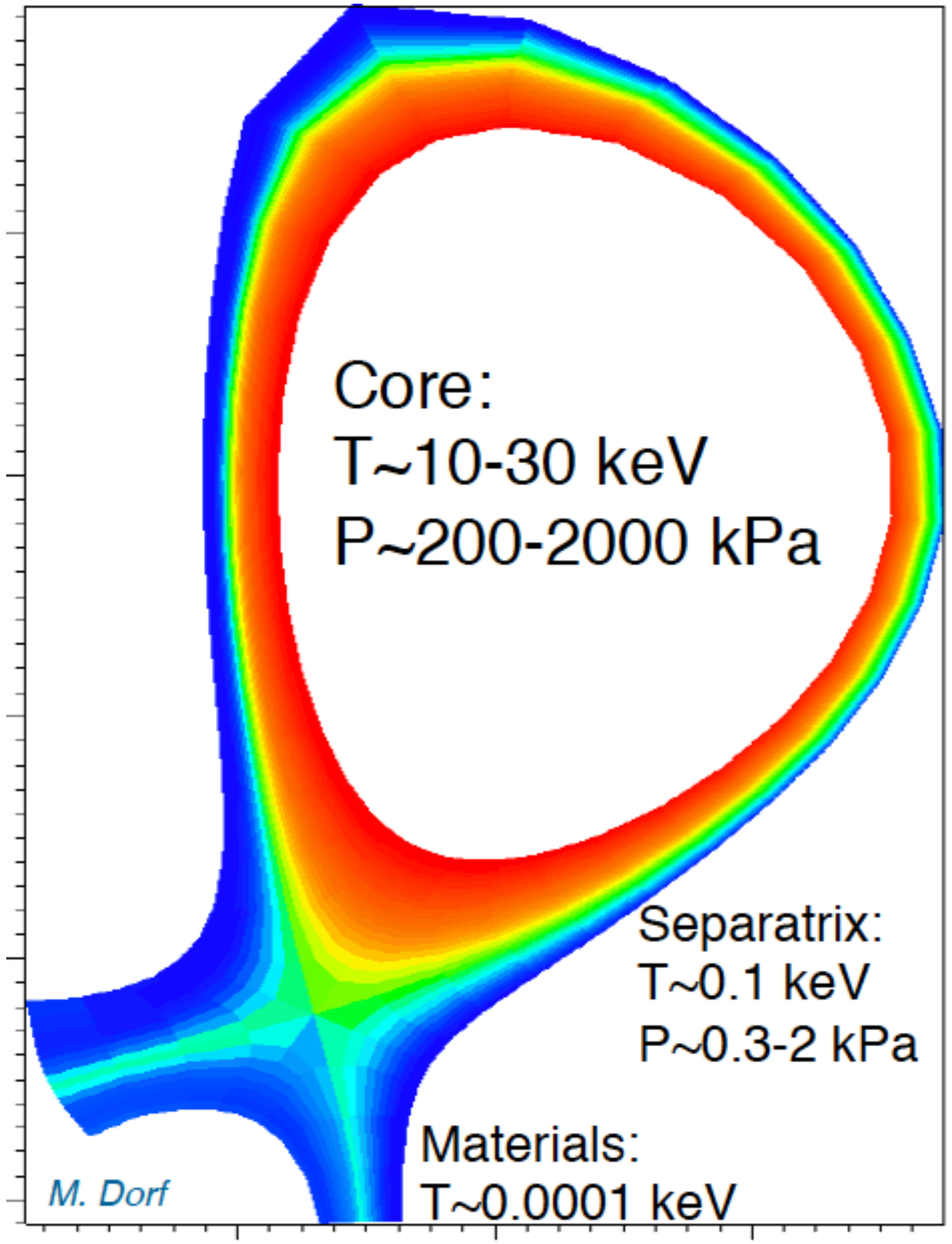
Acknowledgements: R. Maingi, P. Snyder, F. Laggner, and Max Fenstermacher

Material extracted from:

W. Suttrop Advanced PhD course 2010
H. Wilson Lectures on Transport and stability of pedestals in tokamaks 2014
E. Wolfrum Introduction to the physics of the pedestal in between ELMs ='inter-ELM' 2017
P. Snyder APS-DPP Review talk 2018

Fundamental Challenge: Fusion Conditions in Core Compatible with Edge/Materials



Background: What is H-Mode?

As plasma is increasingly heated past a threshold, there is bifurcation to an improved confinement state.

H-mode = high confinement mode

Plasma state with increased ratio of stored kinetic energy vs heating power

H-mode pedestal = Edge transport barrier

Region of reduced radial transport at the plasma boundary

The critical region of interaction (also known as the H-mode pedestal) mediates the tension between core and edge, and plays a defining role in the performance of both.

Outline

- **L-H transition phenomenology**
  - *Turbulence suppression*
  - *Access condition dependencies*
  - *Radial electric field shear*
- **Formation of the Pedestal**
  - *Brief overview*
  - *Importance of pedestal*
  - *Challenge in diagnosing pedestals*
- **Edge localized modes**
  - *How do we arrive at theses ELMs?*
  - *ELM types survey*
- **The type I ELM cycle**
  - *Stability: Description*
  - *Pedestal evolution during ELM cycle*
  - *What control the pedestal?*
- **EPED model a predictive model for the pedestal pressure**
  - *Mechanics*
  - *Other dependencies*
- **Small ELM regimes as a viable option for ITER**

- **Summary**

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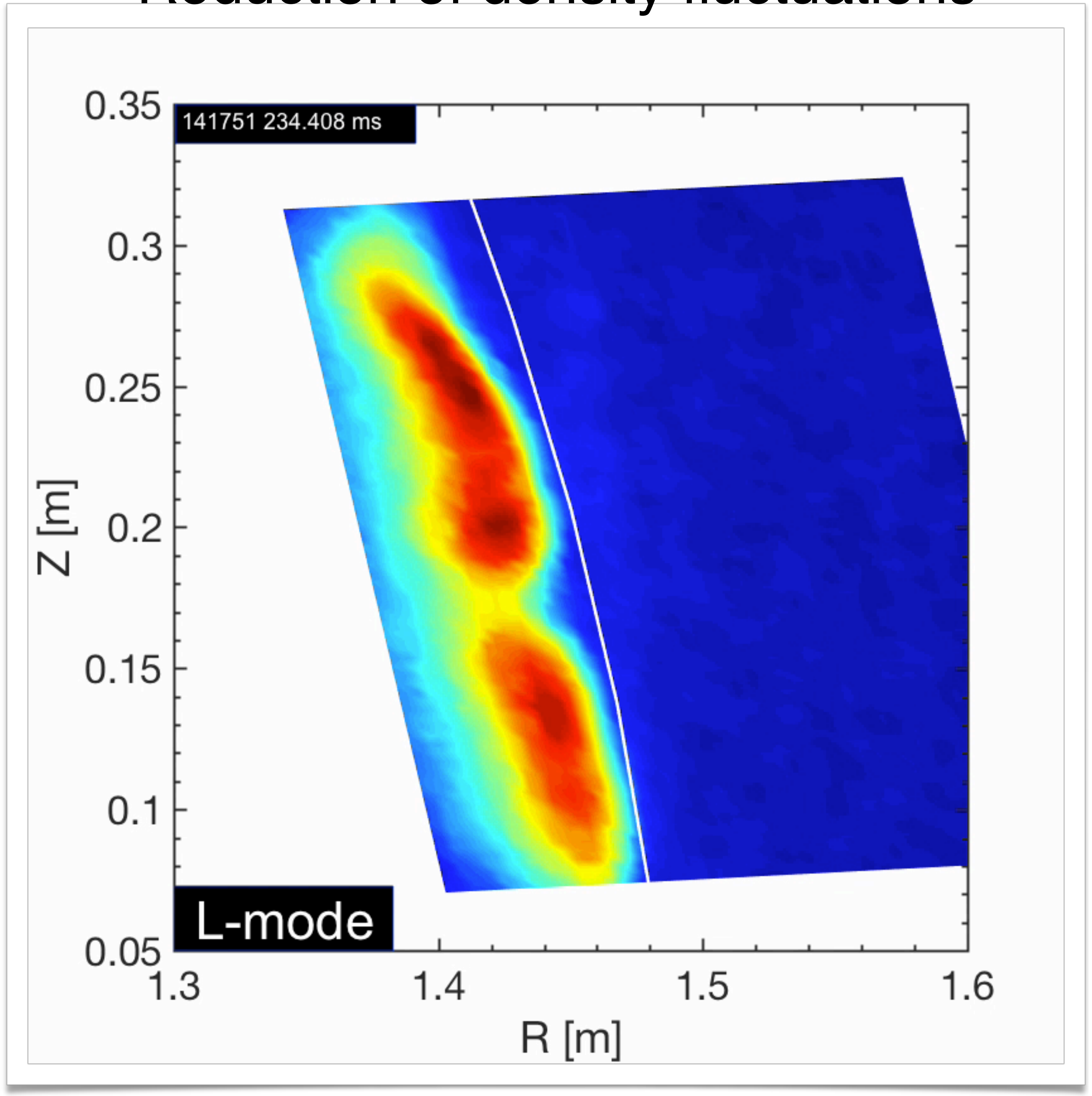
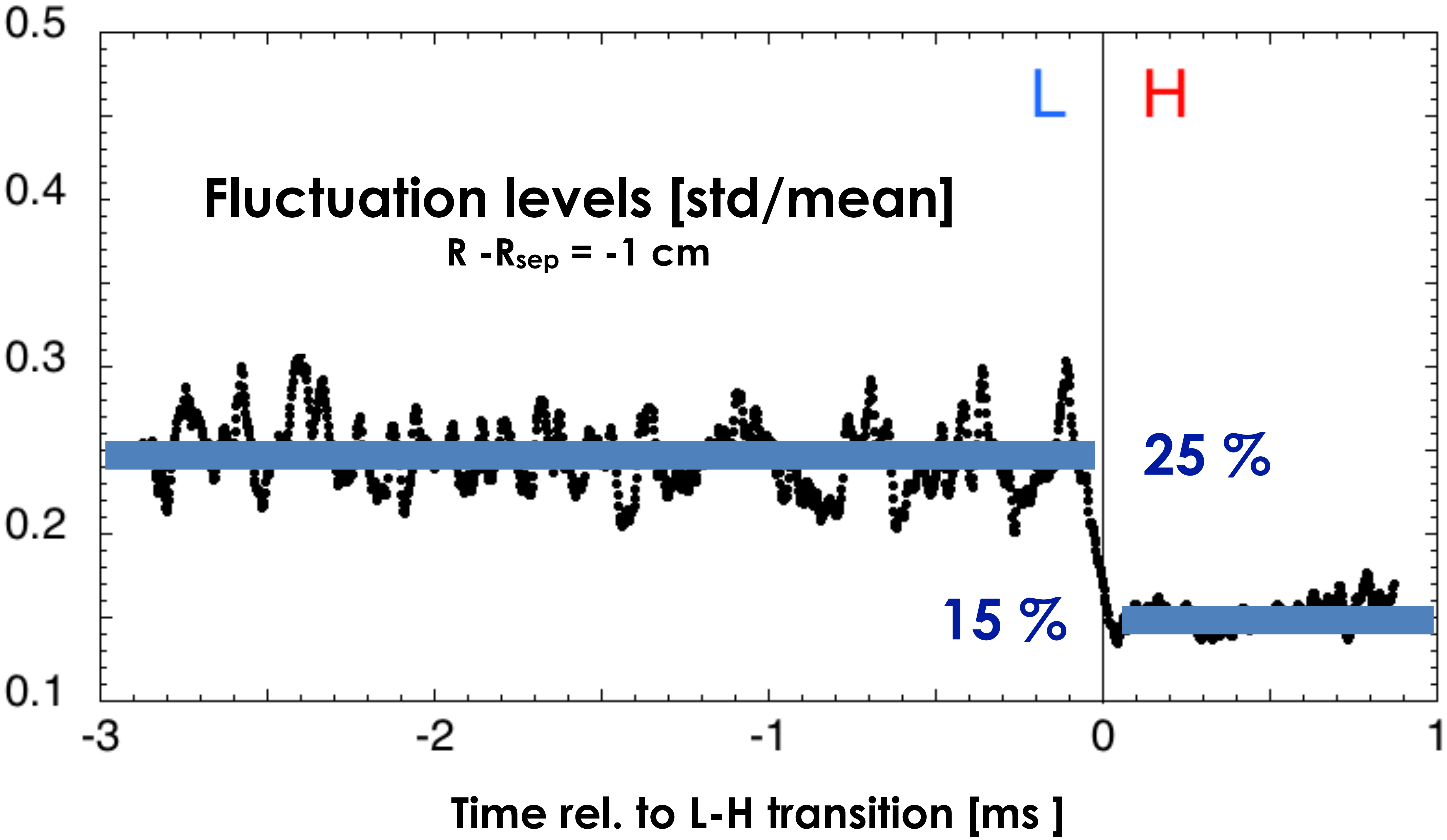
Suppression of Turbulence: characteristic of the H-mode transition

GPI provides edge turbulence images

Views neutral Da light emission

Reduction of density fluctuations





Phenomenology is akin to a phase transition!

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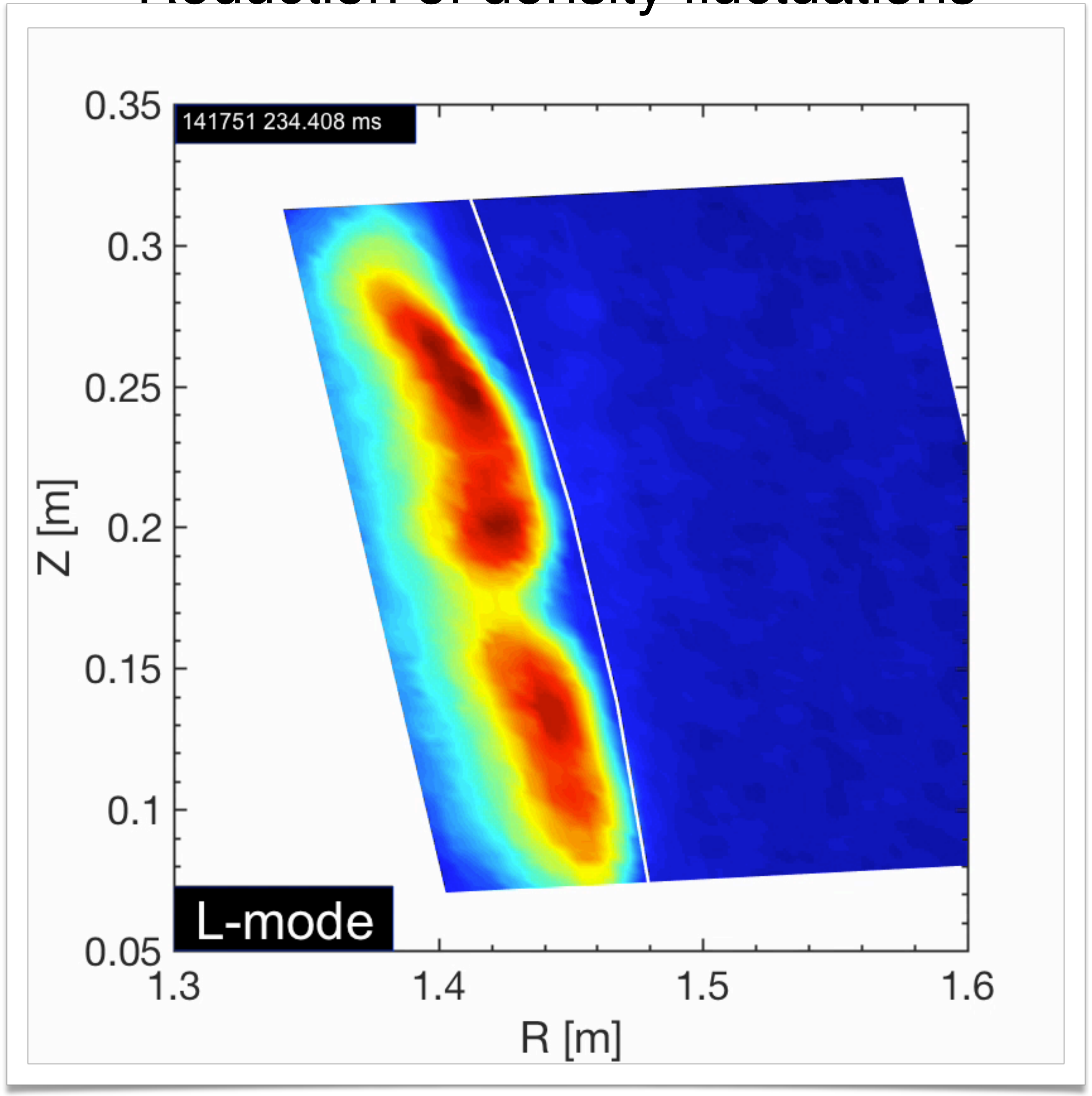

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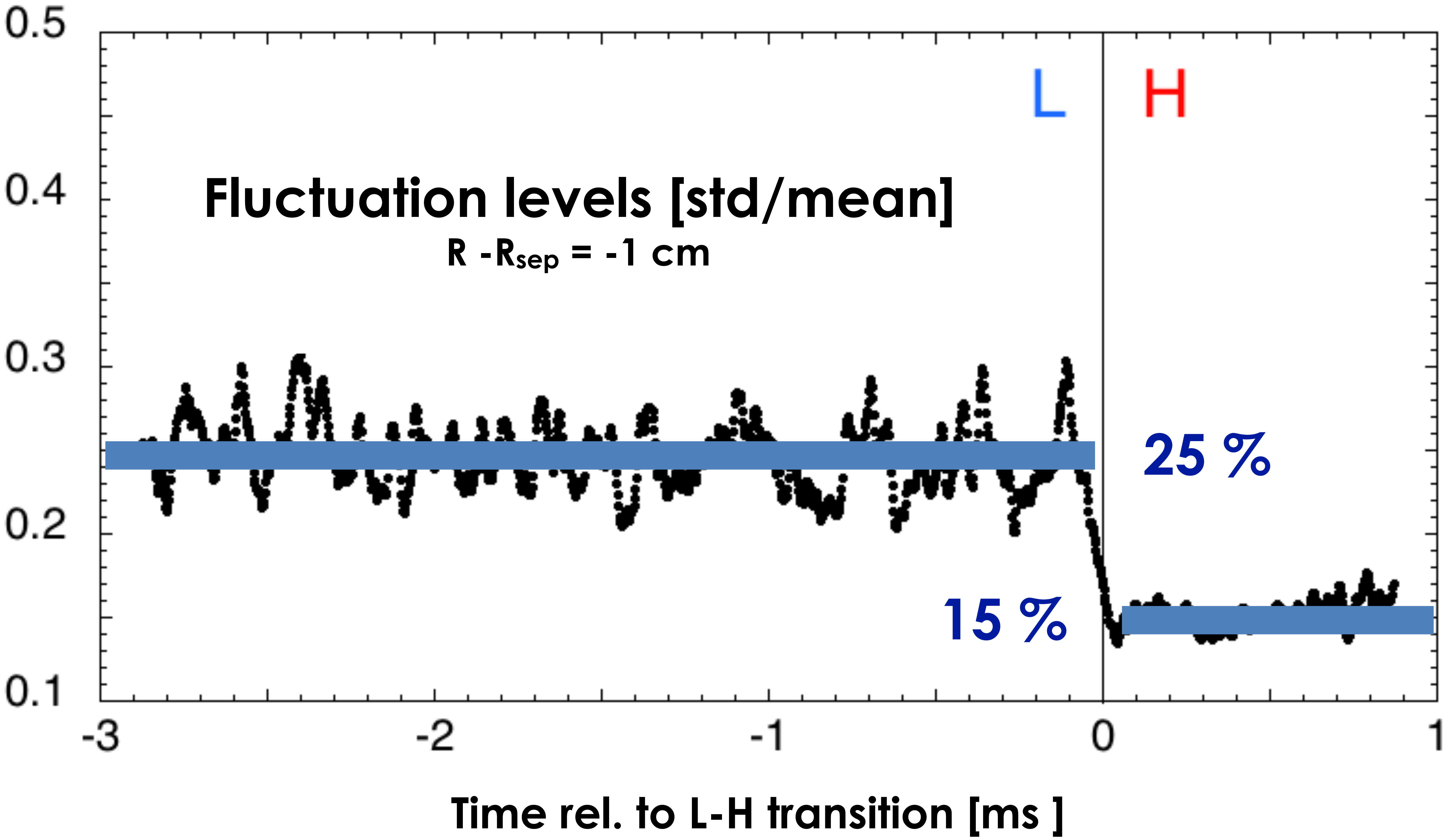

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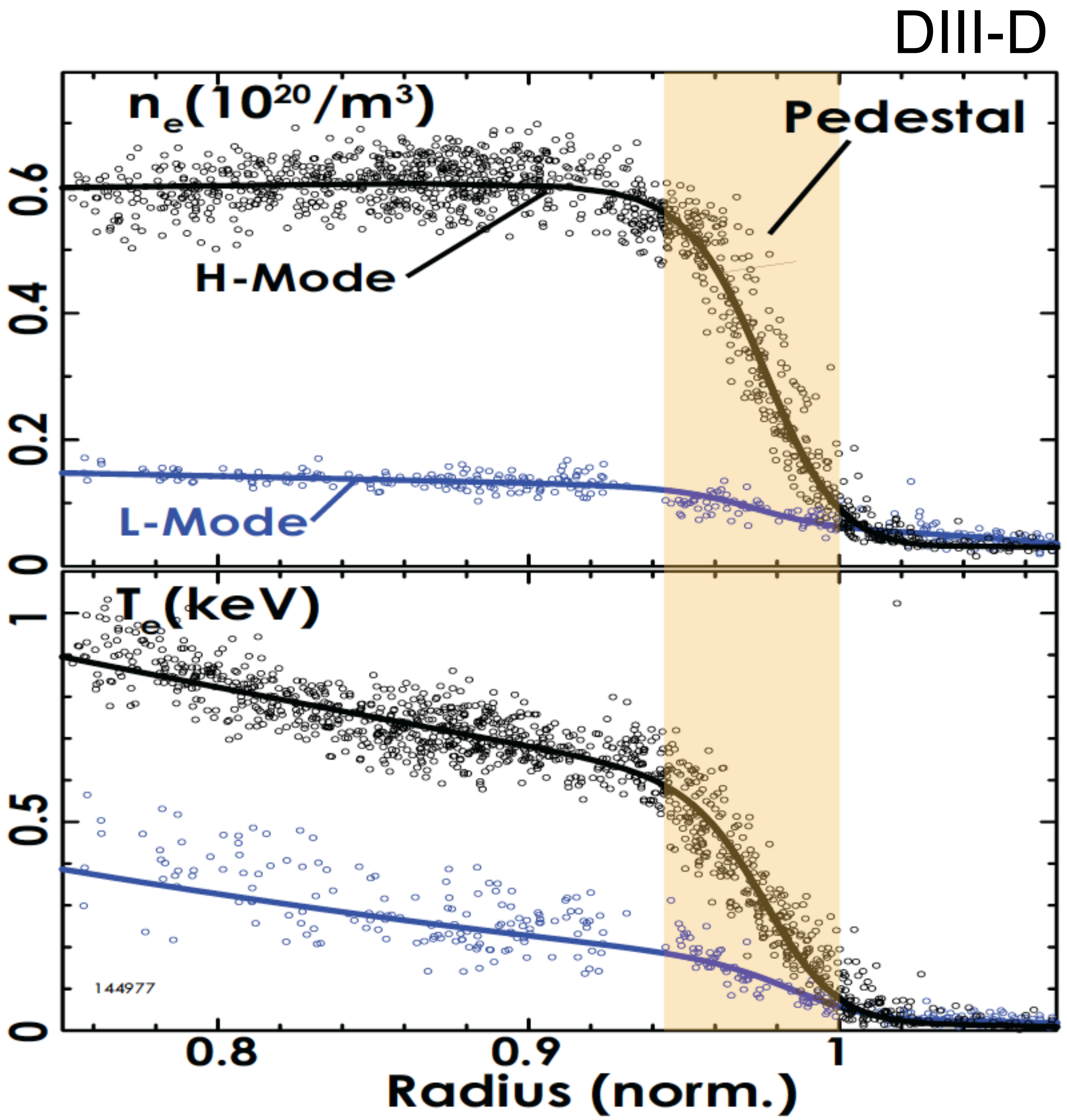
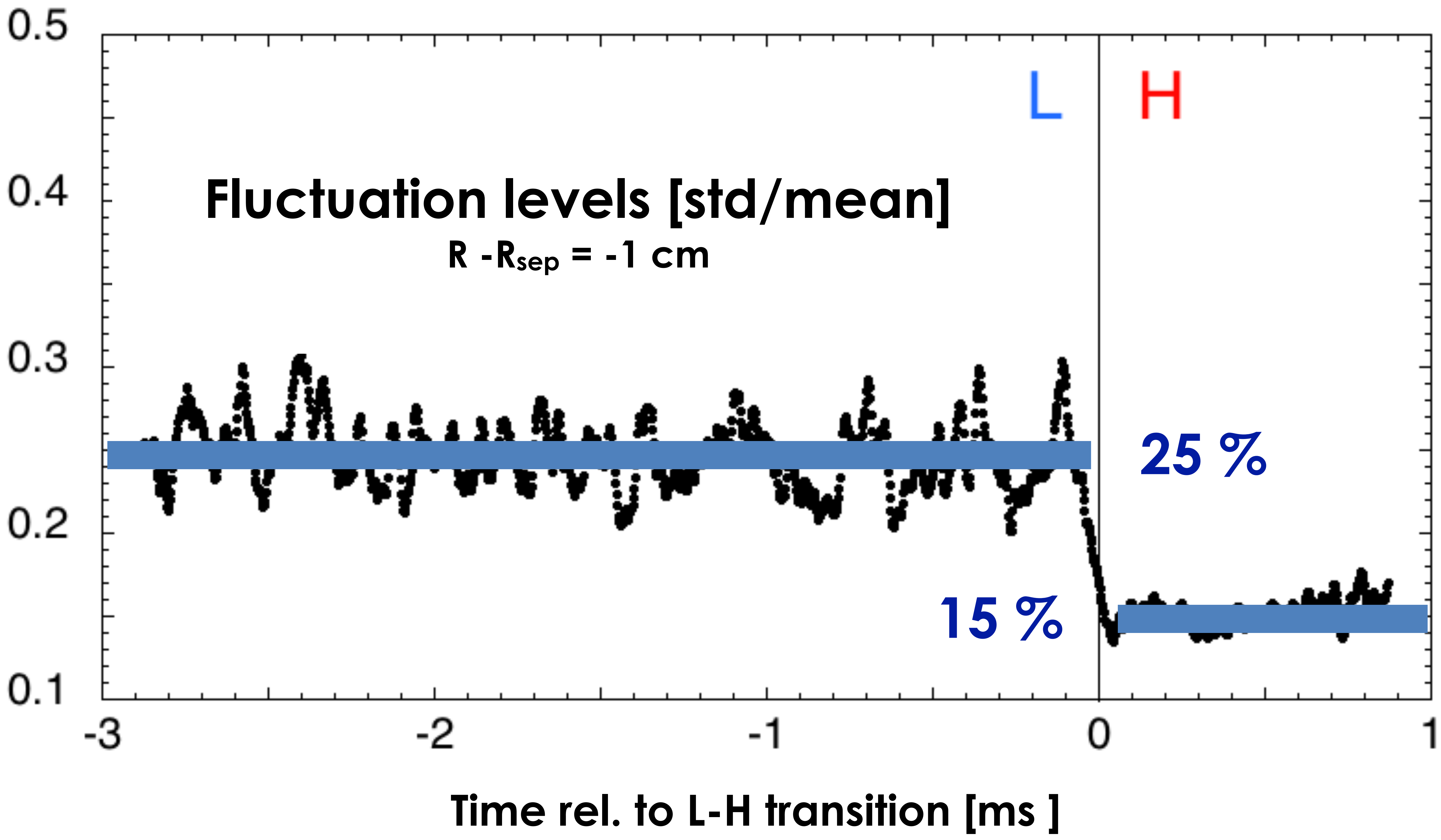
Suppression of turbulence - emergence of a transport barrier

Increased pressure gradient



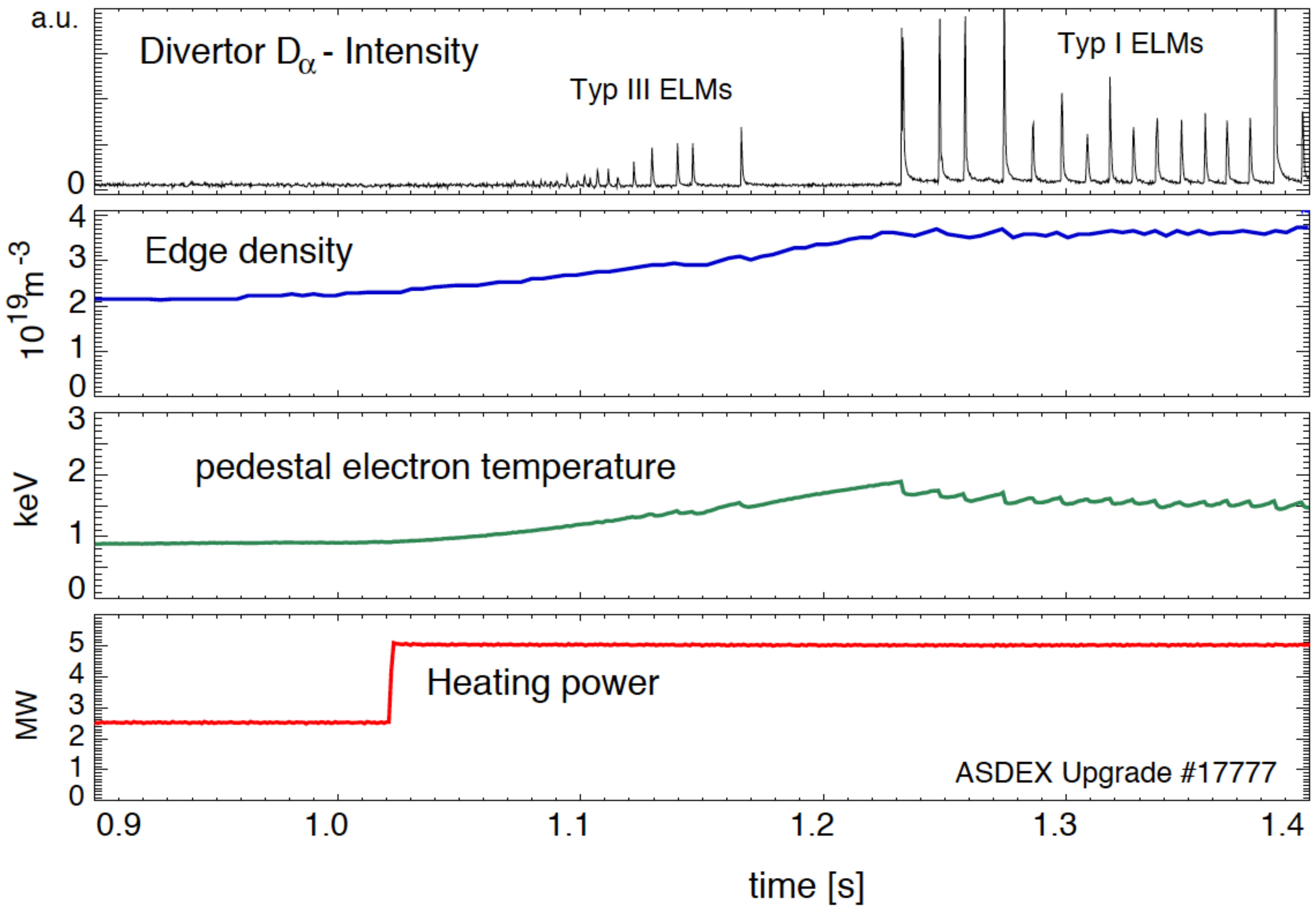
[Courtesy T.H. Osborne]



What limits the rise of the edge pressure gradient?

Steep gradient drives instability (Edge localized Modes)

Cycle consists of: ELM - Loss of density and temperature - reheat - new ELM

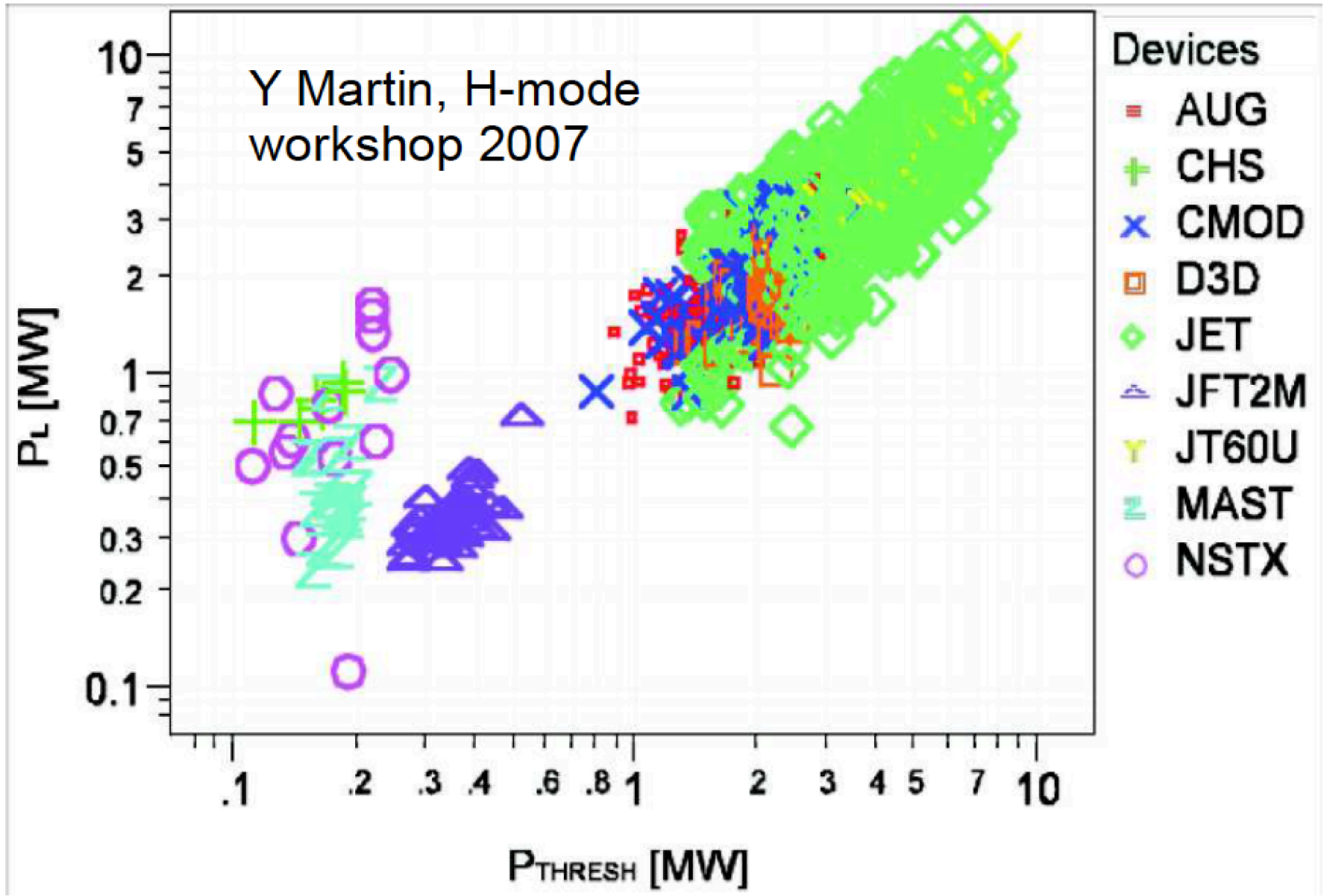


Minimum heating power access condition?

- H-mode transition occurs if loss power P_L across plasma surface is above a threshold power (P_{thresh})
- P_{thresh} is proportional to surface
- P_{thresh} depends on plasma density and toroidal field
- Hysteresis: $P_{L\text{-}H} > P_{H\text{-}L}$

Stored energy

$$P_L = P_{heat} - dW/dt - P_{rad,core}$$



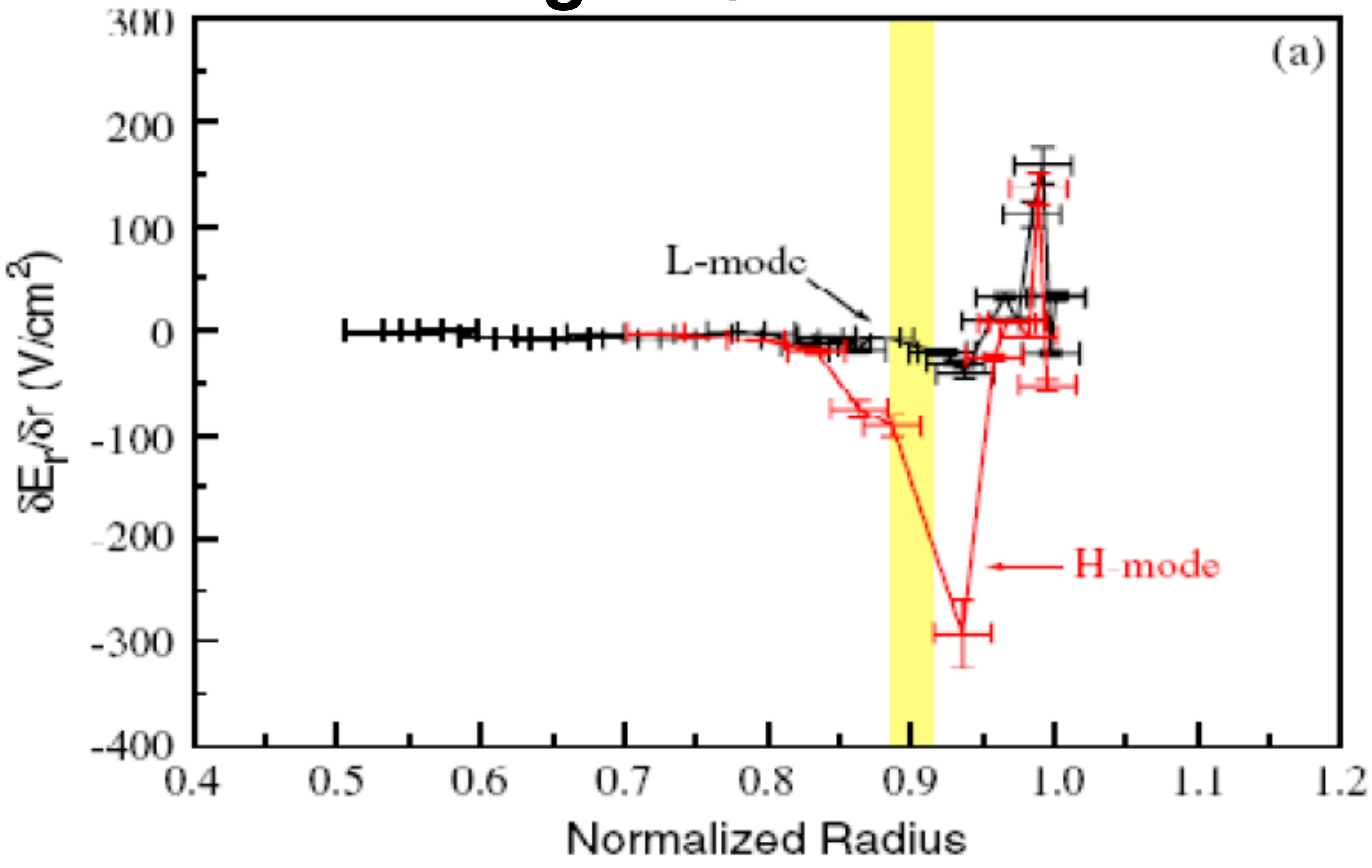
$$, \quad P_{\mathrm{Thresh}} = 0.0488\, \mathrm{e}^{\pm 0.057}\, n_{\mathrm{e20}}^{\;0.717\pm0.035}\, B_{\mathrm{T}}^{\;0.803\pm0.032}\, S^{0.941\pm0.019}$$

W. Suttrop Advanced PhD course 2010

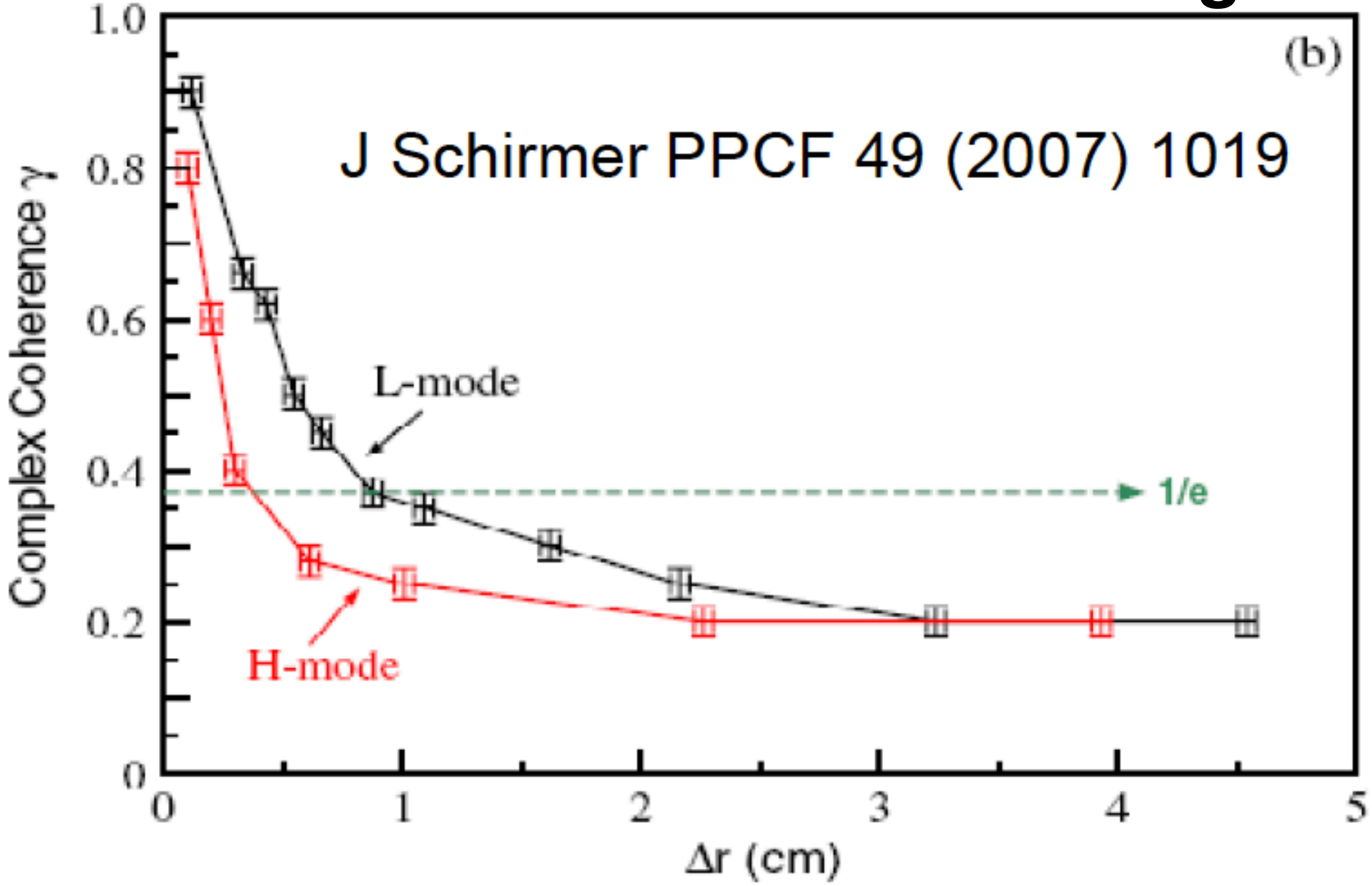
E_r shear and radial correlation lengths

H-mode exhibits:

Much larger E_r' than L-mode

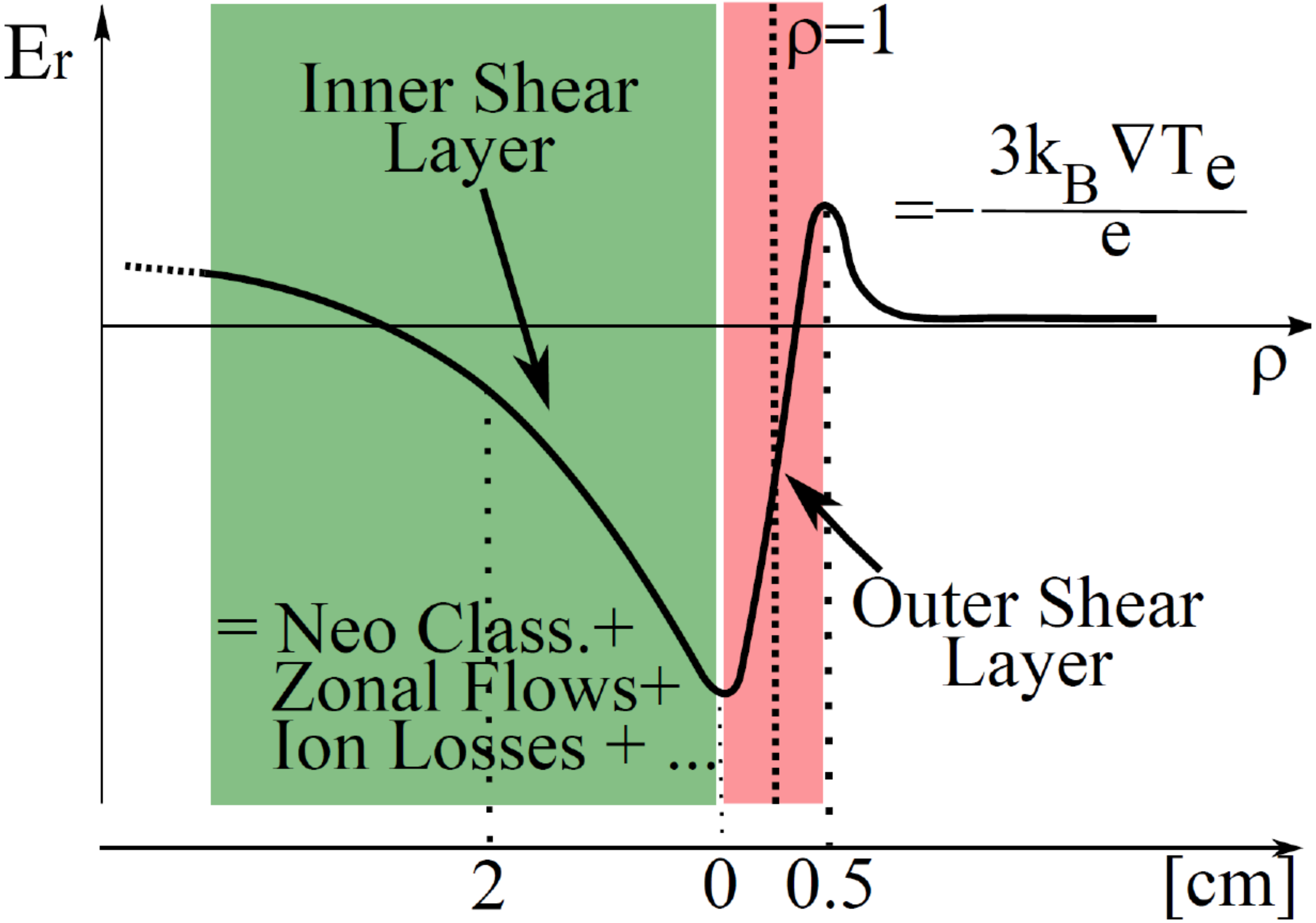


Smaller radial correlation length



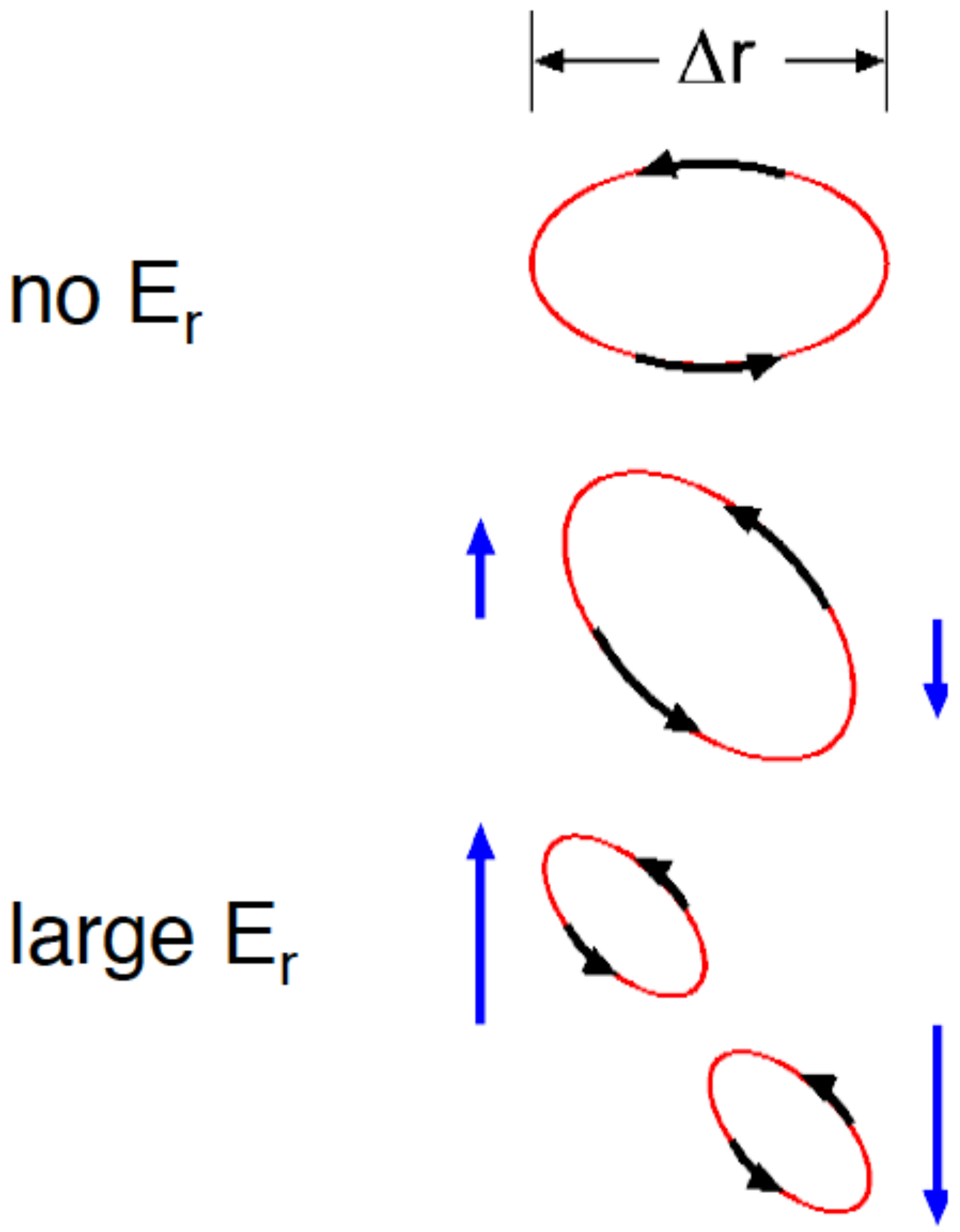
W. Suttrop Advanced PhD course 2010

Final E_r profile has two shear layers



Cavedon, AUG Ringberg 2016

How do we get to the transport barrier?



Radial electric filed produces ExB drift: $\mathbf{V} = \dfrac{\mathbf{E}\times\mathbf{B}}{B^2}$

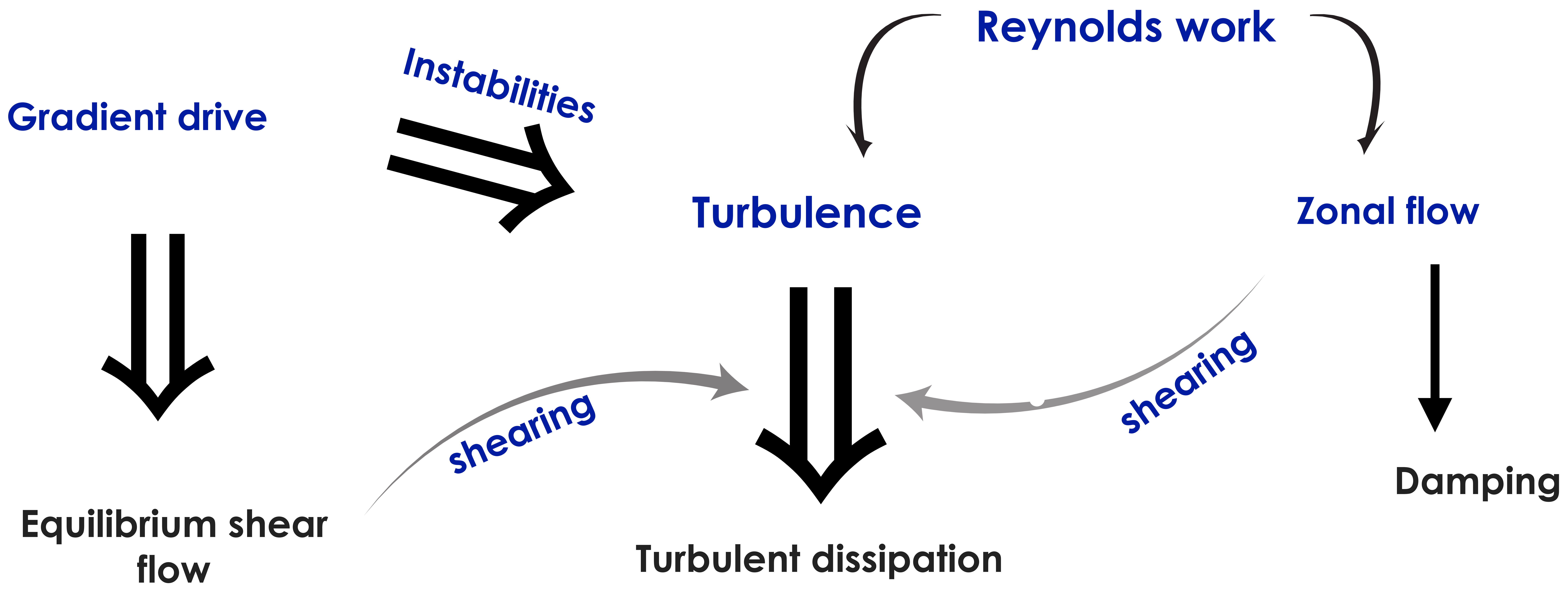
Radial force balance: $\boxed{E_r = \dfrac{\nabla p_i}{Z_i e n_i} - v_{\theta i} B_\varphi + v_{\varphi i} B_\theta}$

Sheared E_r x B velocity decorrelates the turbulent eddies which leads to reduced transport

Hypothesis condition: Shear rate > instability growth rate

$$\boxed{\gamma_{E\times B} = v'_{E\times B} > \gamma}$$

Summary of L-H transition



Reynolds work

Gradient drive

Instabilities

Turbulence

Zonal flow

shearing

shearing

Damping

Equilibrium shear flow

Turbulent dissipation

Diallo, APS Invited 2017
Diallo, IAEA Oral 2016

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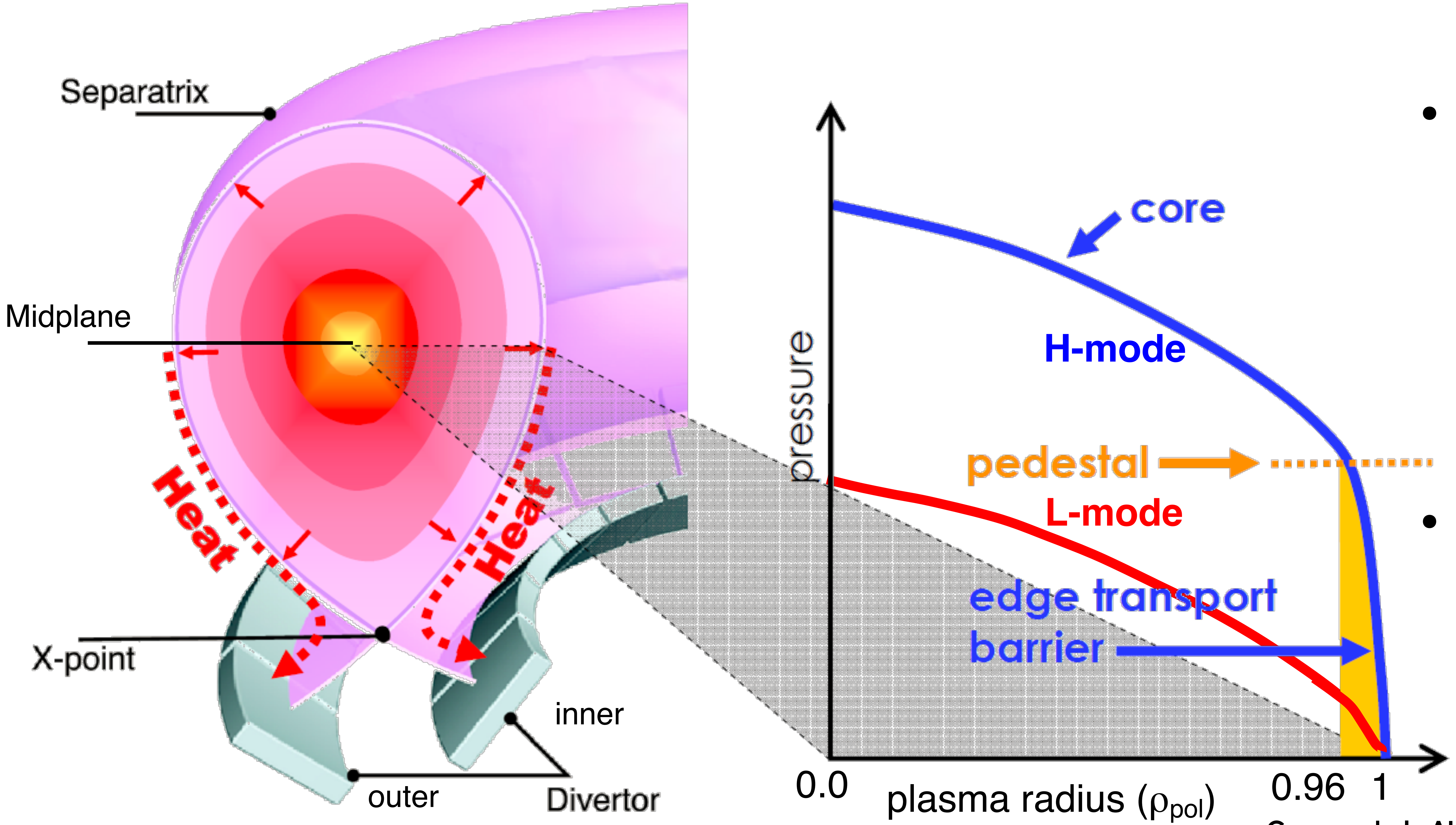
The Pedestal

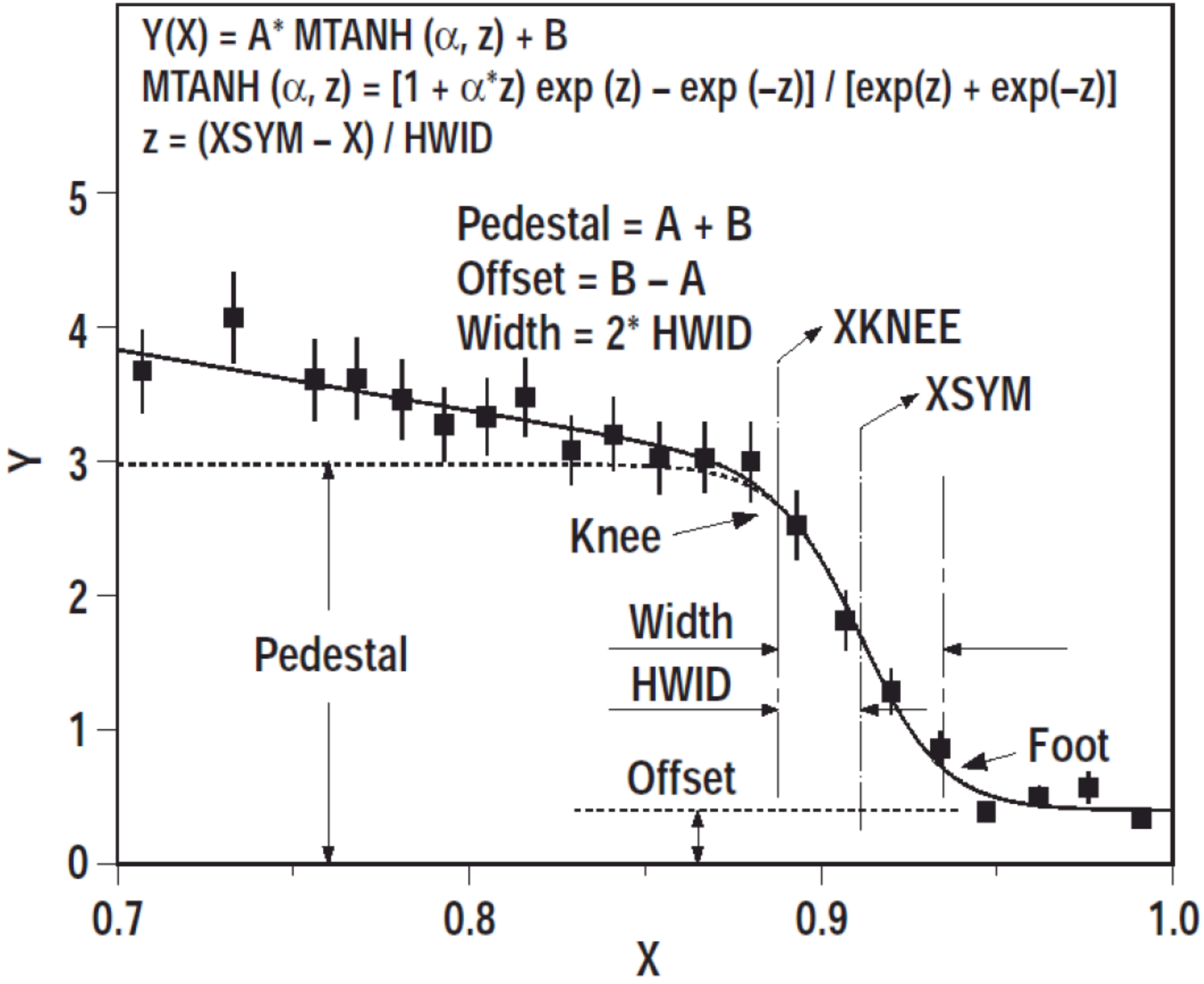
The improvement in confinement is due to a region of steep pressure gradient at the plasma edge: At the plasma edge, this is referred to as the pedestal region



Connor et al., AIP Conf. Proc. 2008

- **The pressure in the plasma core is proportional to the pedestal pressure**
- **Pedestal physics is very important for tokamaks**

Basic pedestal structure: the modified tanh profile

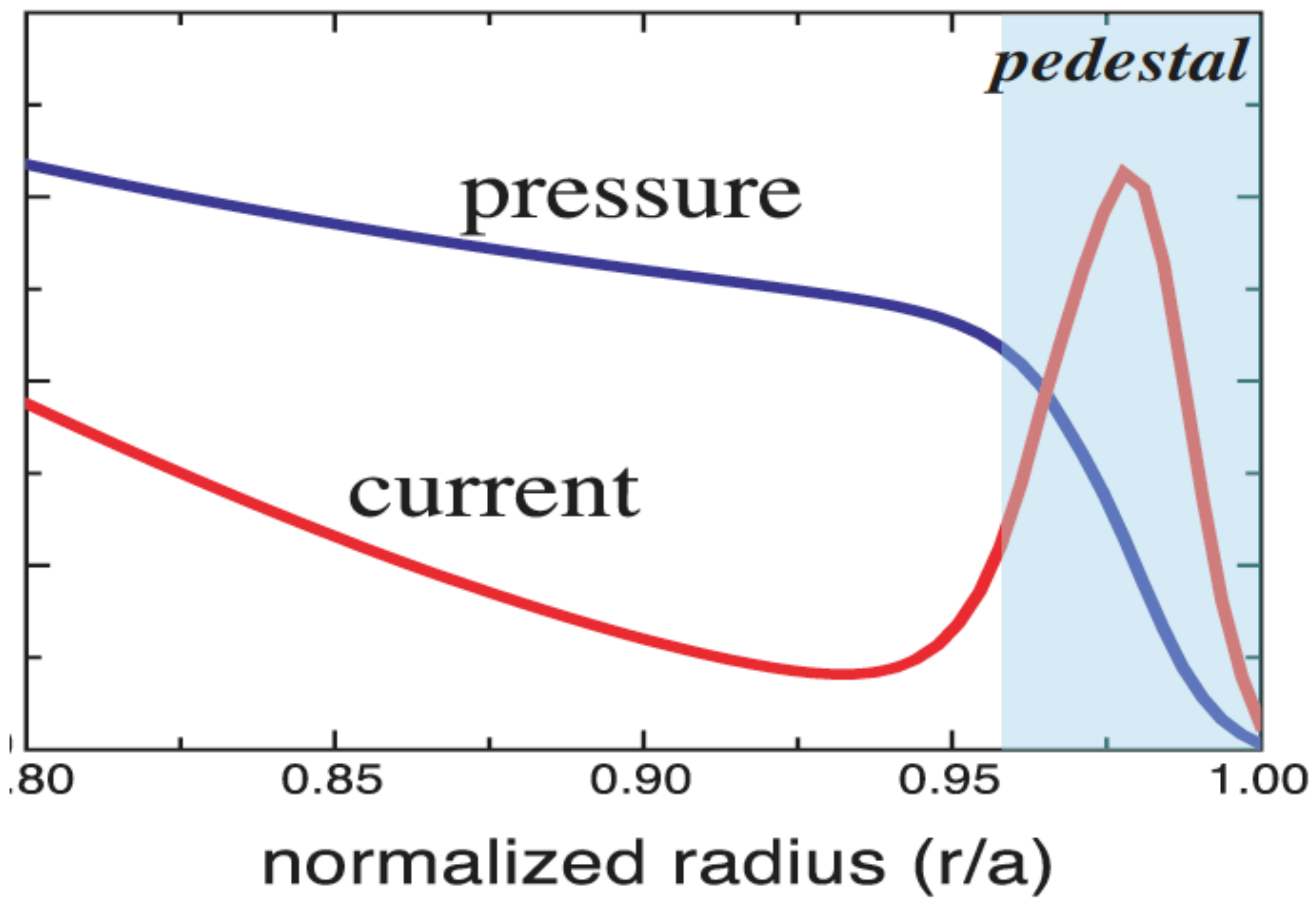


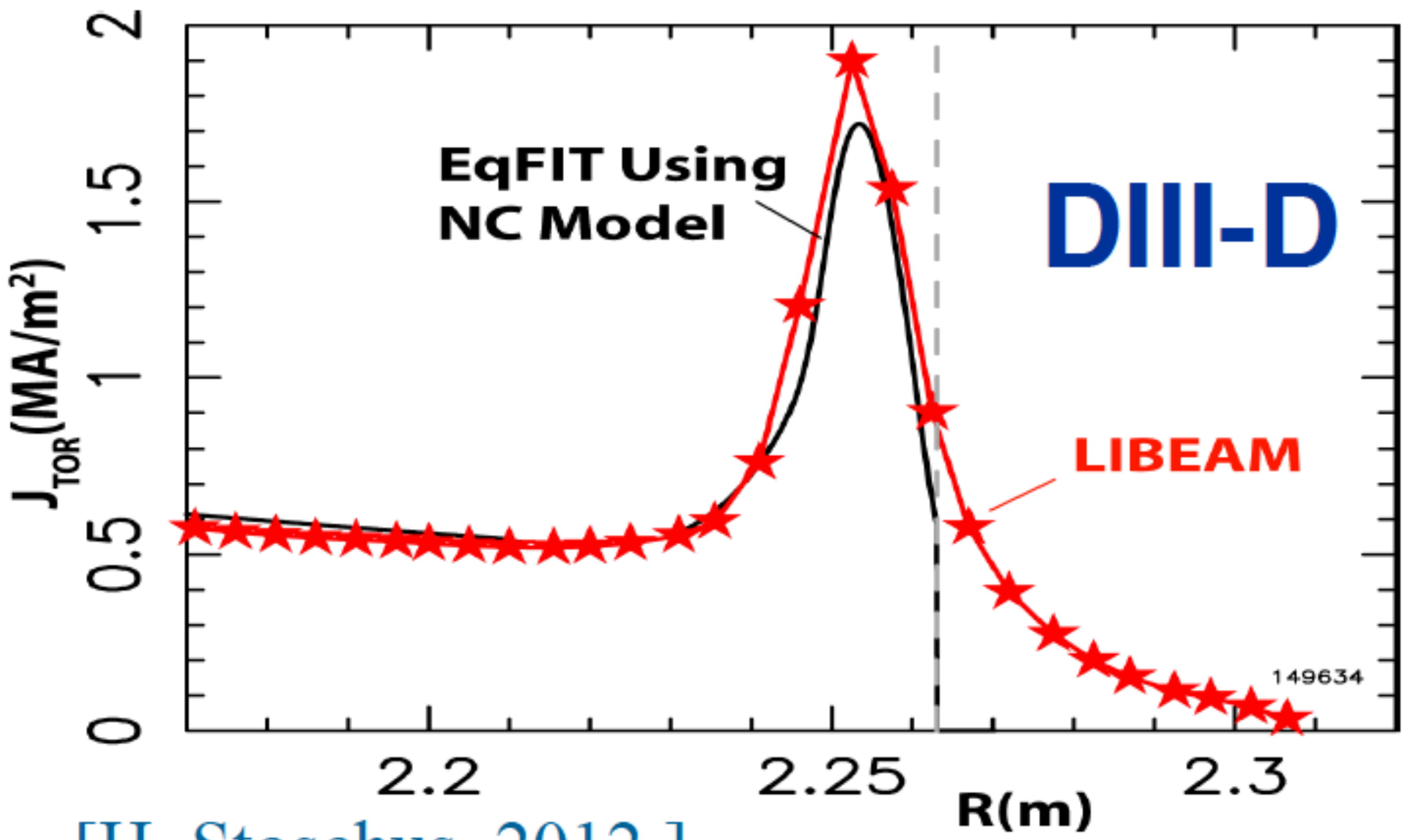
R J Groebner,
NF 41 (2001) 1789

Resulting edge Bootstrap current

- **Pressure gradient gives rise to toroidal bootstrap current**

$$j_b \propto \frac{dp/dr}{B_\theta\left(1+0.9\sqrt{\nu_e^*}\right)}$$



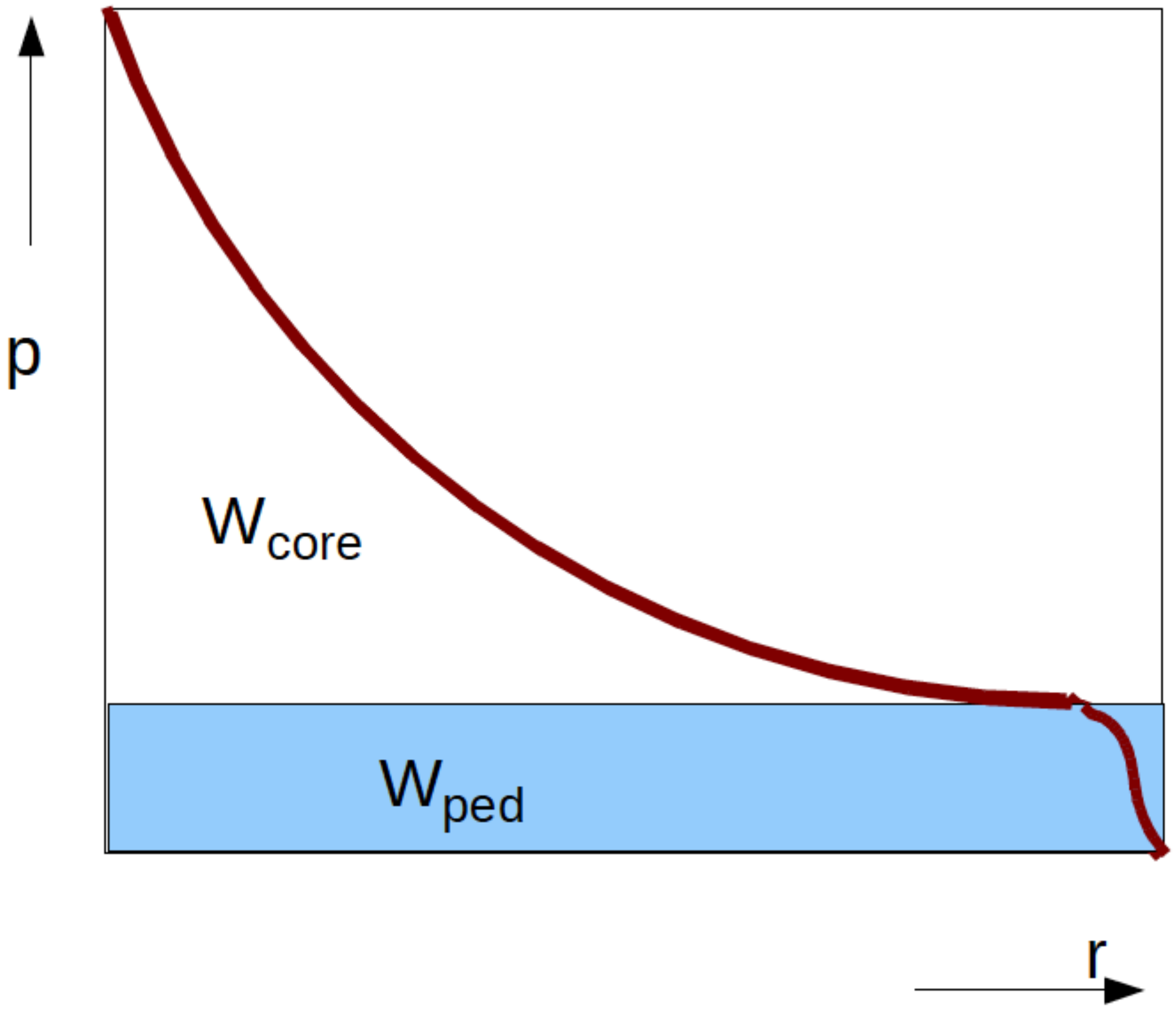


[H. Stoschus, 2012]

The pedestal: so narrow but impactful

- **H-mode pedestal stores additional kinetic energy**
- **High pressure core rests on the edge pedestal**
- **Can have >10x increase in T, and >40x increased P across this layer**
  - Typically larger relative increase than core
- **Overall, it is paramount to understand how the pedestal forms and what sets its width.**

$$W_{tot} = W_{core} + W_{ped}$$

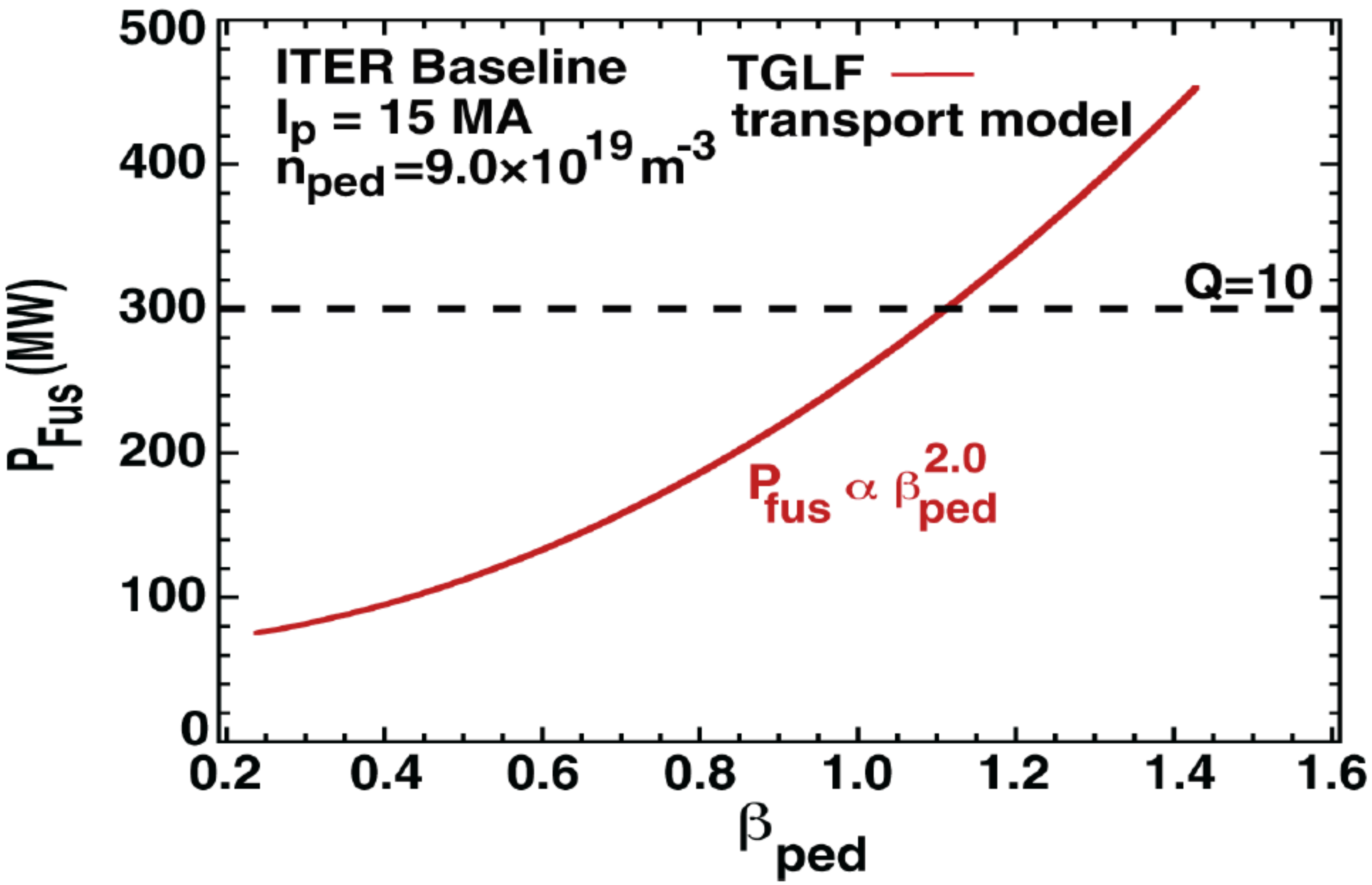


W. Suttrop Advanced PhD course 2010

Fusion performance rests upon the pedestal

- **Future burning plasmas rely on maintaining high pedestal pressure**

ITER Fusion Power



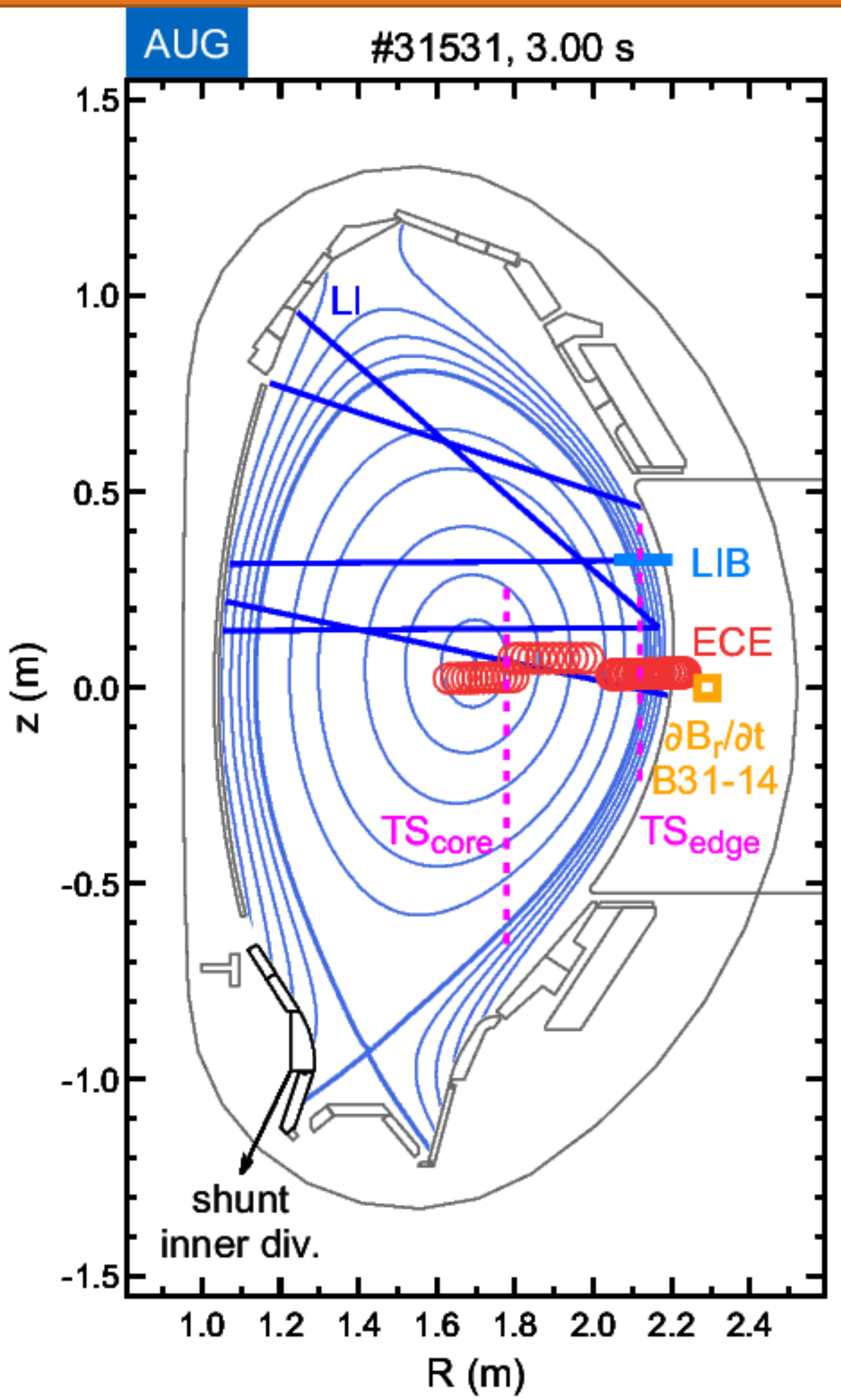
[J. Kinsey, *Nucl. Fusion* **51** 083001 (2011)]

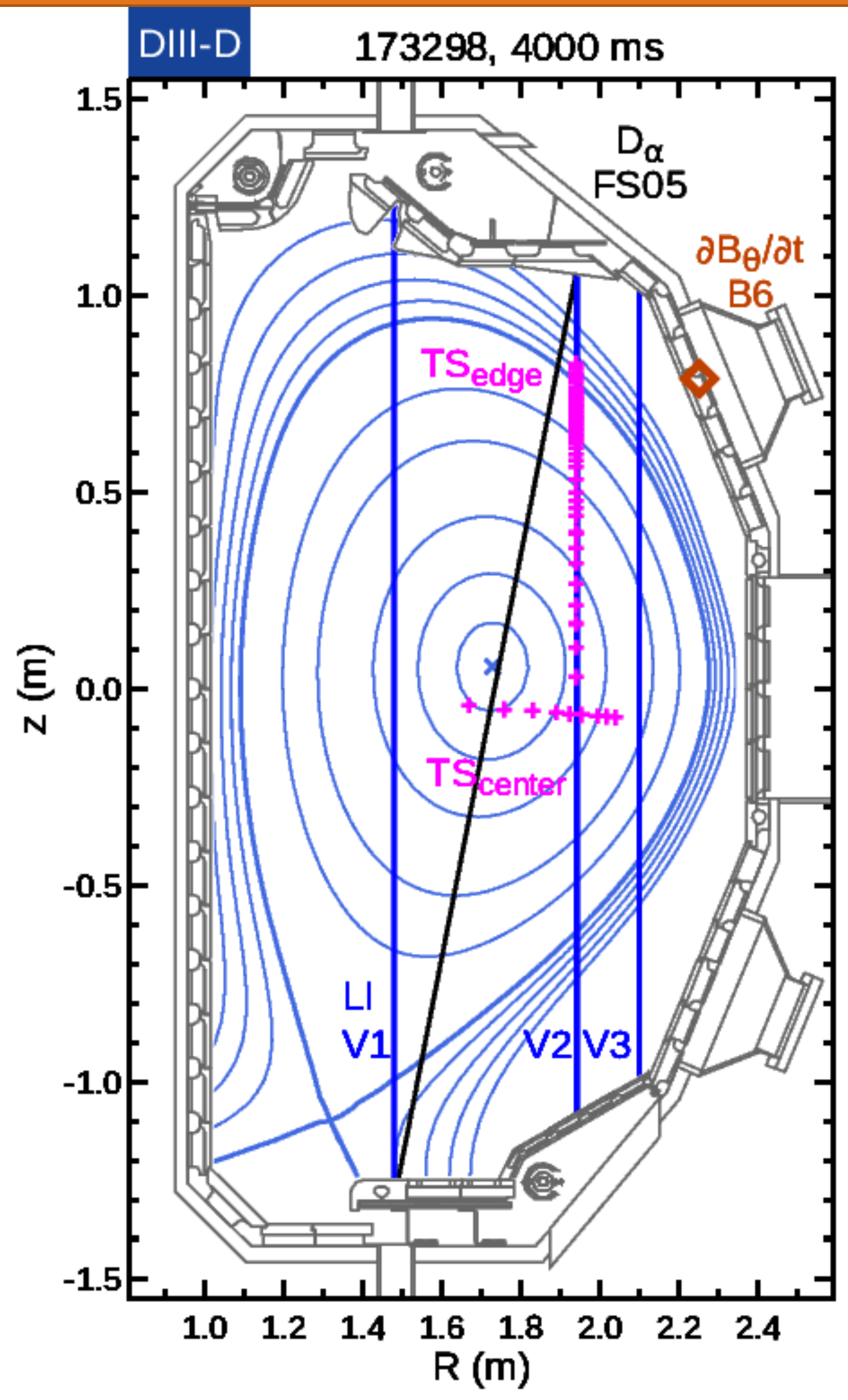
Challenges in diagnosing the pedestal

- **Profiles & fluctuations required for good interpretation**

- **Uncertainties are associated with every measurement**
- **Awareness necessary when interpreting**

- **Understand and to consider the fundamental limitations of the utilized diagnostics**
- **Some examples:**
  - **ECE: shine through**
  - **BES: radial widening of emission profile**
  - **CER: assumption of equilibrium temperature**





Lagnner 2018

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Large pressure and current gradients in pedestal drive MHD instabilities

- **Potential Energy with stabilizing and destabilizing terms**
  - Negative energy implies MHD instability
  - $\boldsymbol{\xi}$ = displacement of plasma fluid, $\mathbf{B}_1$ = magnetic field perturbation

Compression of the magnetic field,
(Fast, magneto-acoustic waves)

magnetic field line bending
(Alfven waves)

compression
(Slow, magneto-acoustic waves)

$$\delta W = \tfrac{1}{2}\int dV\left(\left|B_{1,\perp}\right|^2 + B_0^2\left|\nabla\cdot\xi_\perp + 2\xi_\perp\cdot\kappa\right|^2 + \lambda p_0\left|\nabla\cdot\xi\right|^2\right)$$

$$-\int dV\left(2(\xi_\perp\cdot\nabla p_0)(\kappa\cdot\xi_\perp) + J_{0,\parallel}(\xi_\perp\times B_0 / B_0)\cdot B_{1,\perp}\right)$$

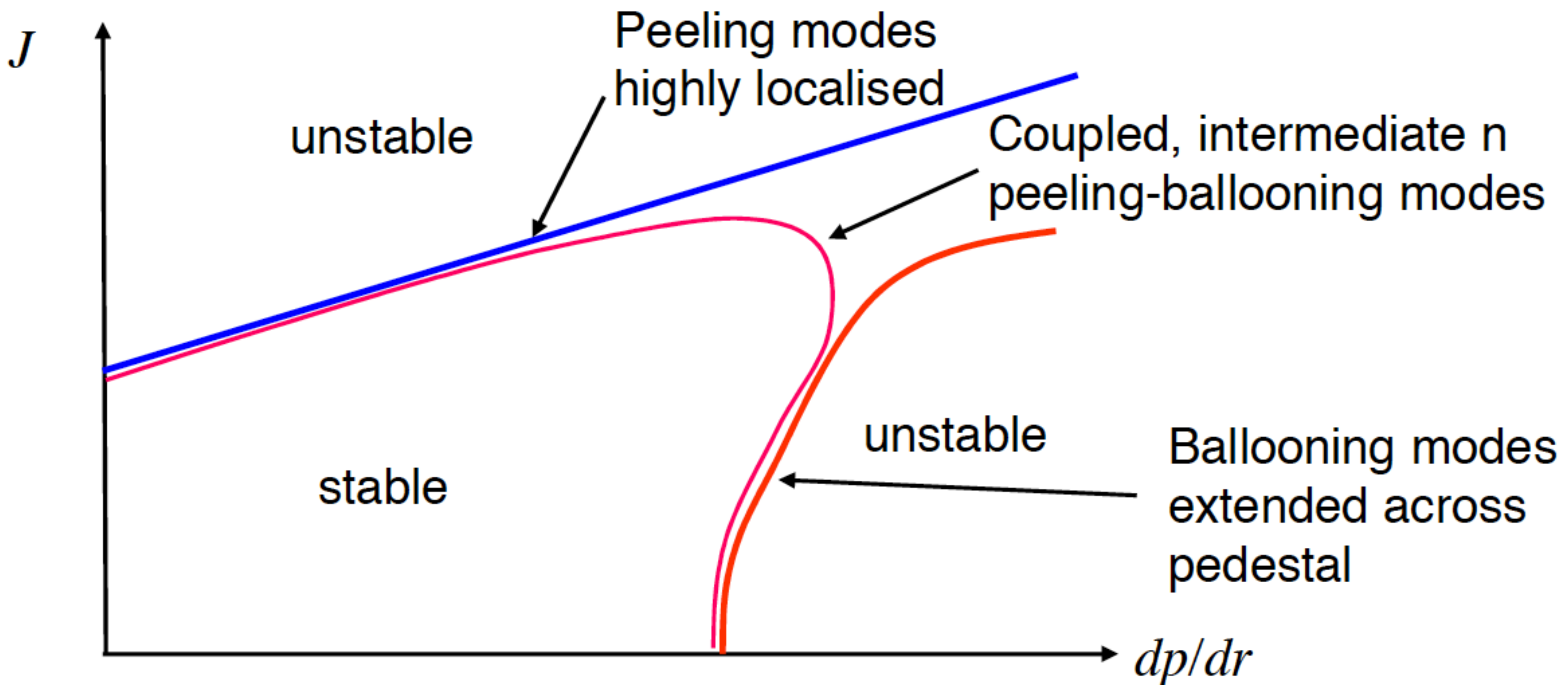
pressure gradient destabilizing
(κ=field curvature) **ballooning** drive

parallel current destabilizing
kink/peeling drive

Snyder Review Talk APS DPP 2018

Edge-Localized-Modes: the Peeling ballooning model

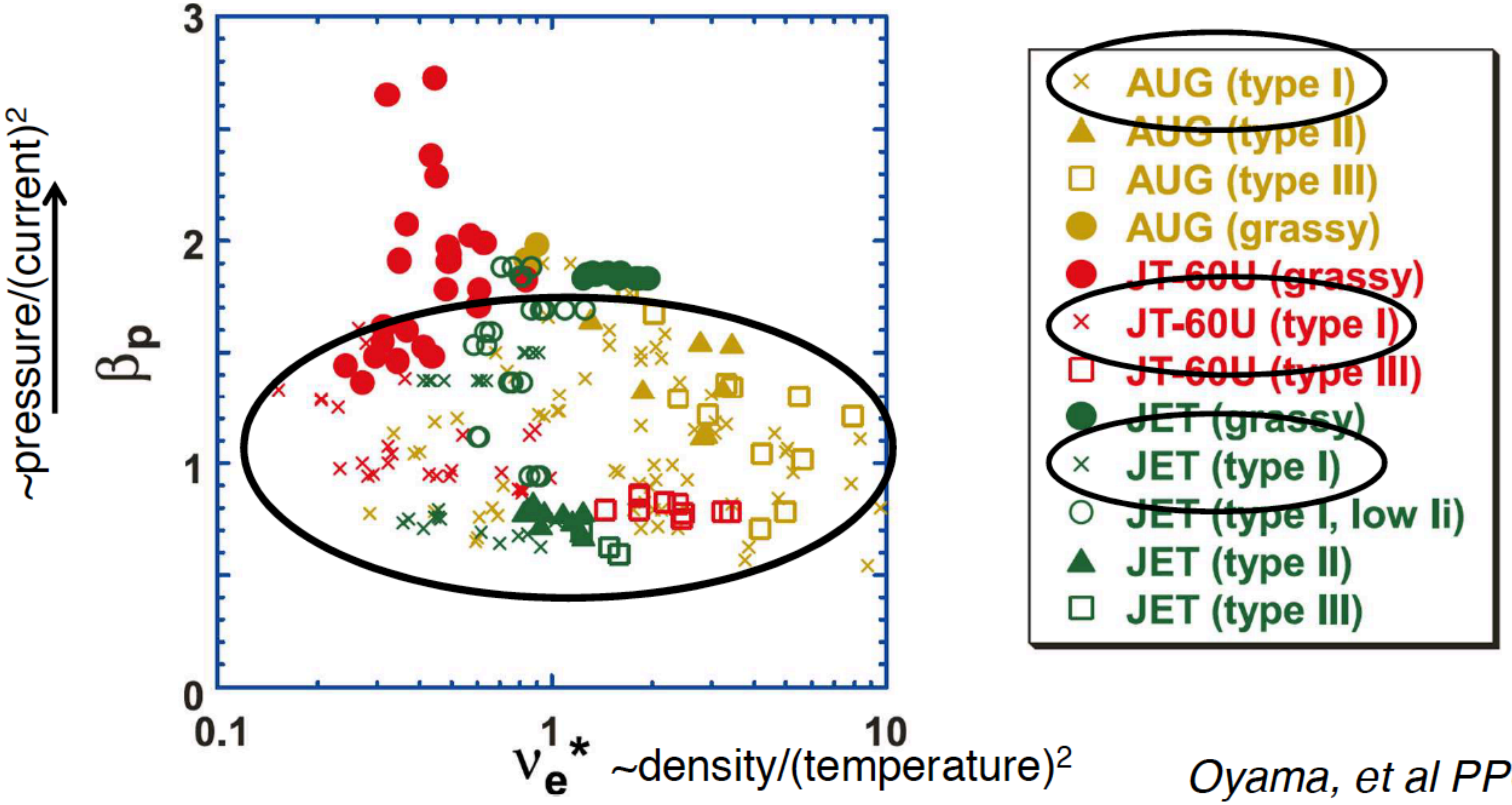
- **Large "Type I" ELMs are thought to be triggered by coupled peeling-ballooning modes:**
  - **Ballooning mode is destabilized by pressure gradient, but stabilized by current density**
  - **Peeling mode is destabilized by current density, but stabilized by pressure gradient**
  - **The modes can couple, leading to a somewhat complicated stability boundary**



H. Wilson Lectures on Transport and stability of pedestals in tokamaks 2014

Range of Edge-localized modes: Type I ELMs

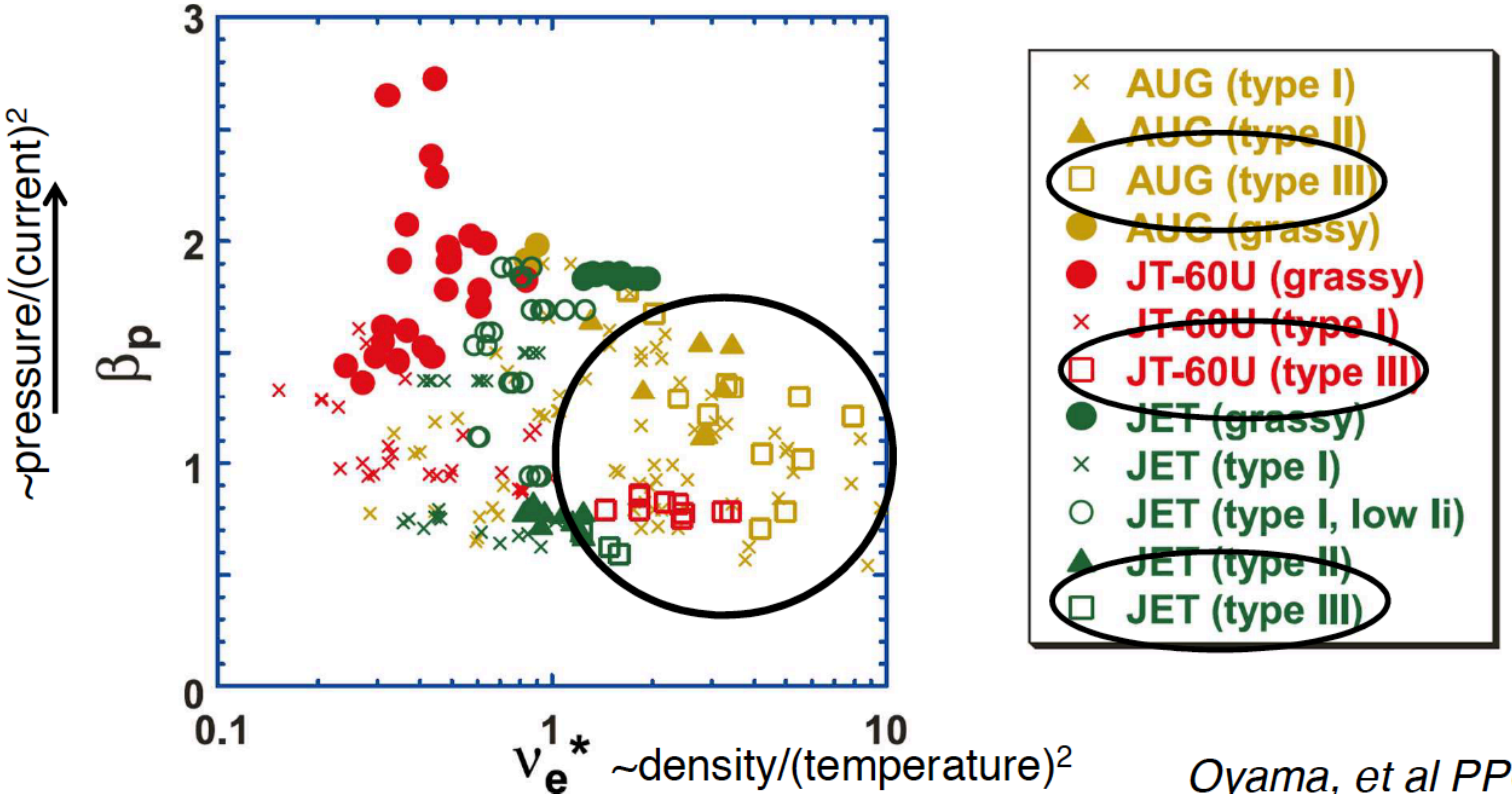
- **Type I ELMs** are the most prevalent, over a wide range of parameters
  - Good confinement, but large ELMs
  - Cannot be tolerated on ITER
  - Well-explained by the peeling-ballooning modes



Oyama, et al PPCF (2006)

Type III ELMs: More benign, but degrade confinement

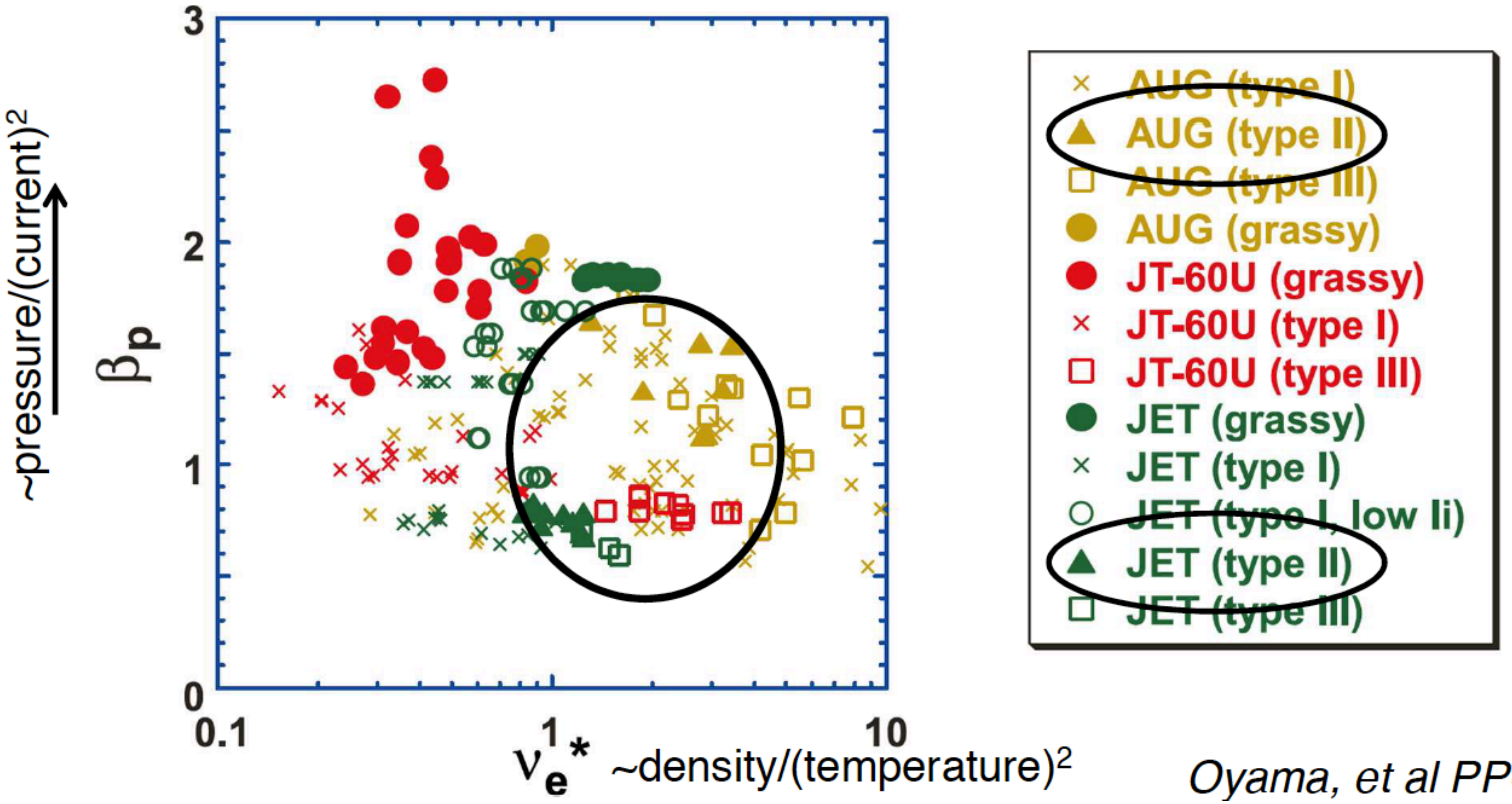
- **Type III ELMs** typically occur close to the L-H transition
  - Small ELMs, but reduced confinement
  - Confinement degradation not desirable for ITER
  - A high collisionality and low collisionality branch



Ovama, et al PPCF (2006)

Type II ELMs: Small ELMs with good confinement

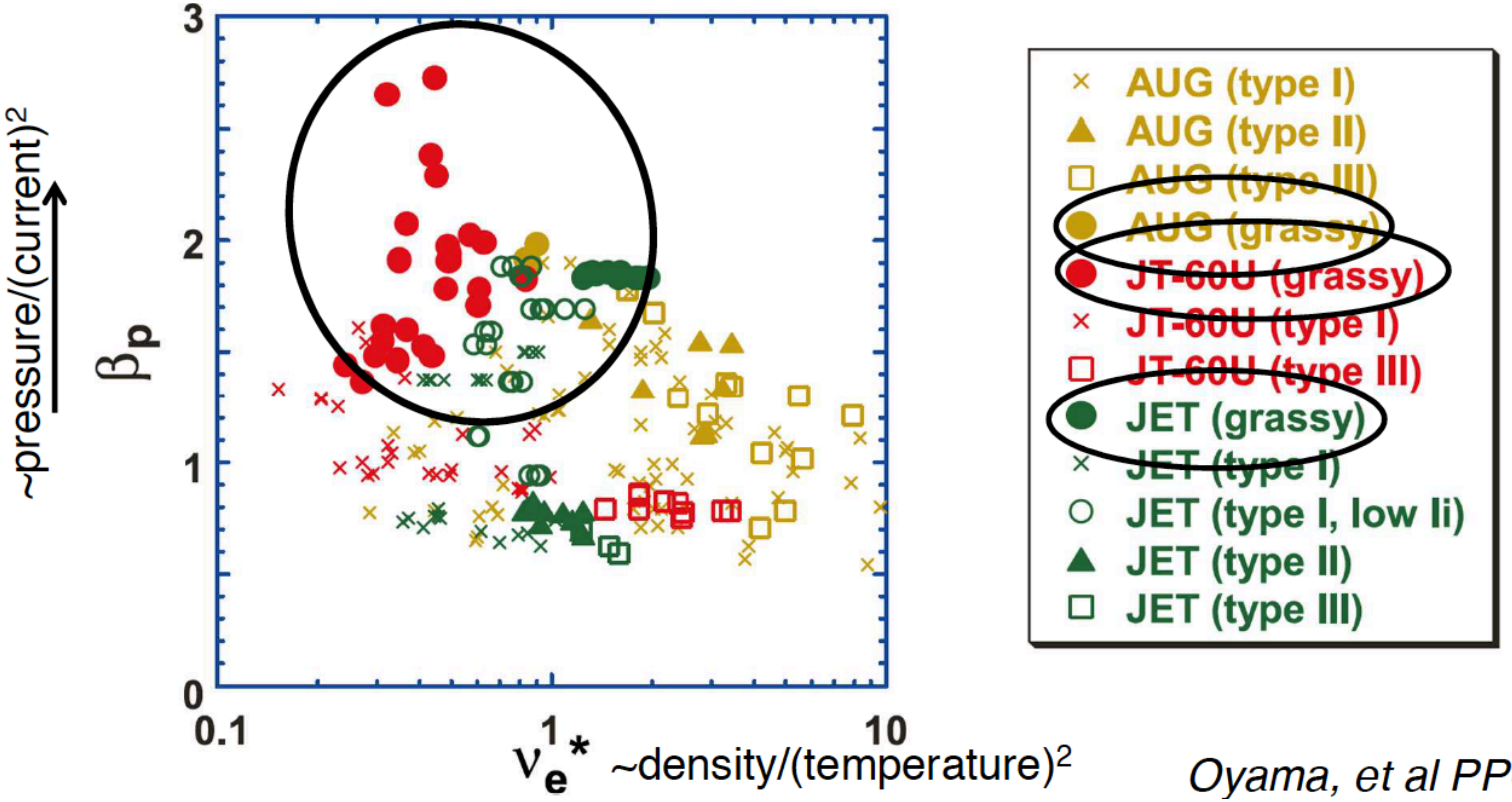
- **Type II ELMs** occur at high collisionality in plasmas with **strong shaping**
  - Small ELMs, and good confinement
  - They can co-exist with Type I ELMs
  - Is high collisionality inconsistent with ITER?



Oyama, et al PPCF (2006)

Grassy ELMs: Small ELMs with good confinement

- **Grassy ELMs** occur at low collisionality, strong shaping
  - High β_p and q_{95} required (low current?)
  - Small ELMs, and good confinement
  - Could be a viable regime for ITER (if accessible to ITER)



Oyama, et al PPCF (2006)

Summary

ELM Type	Access criteria	Confinement	Size	ITER implication
Type I	High power; wide parameter regime	Good	Large	Excessive erosion
Type II	Strong shaping; high collisionality; high q95	Good	Small	Collisionality too high for ITER?
Type III	Lower power; high and low collisionality branches	Poor	Small	Confinement unacceptable; inaccessible at high power?
Grassy	Strong shaping; high β_p; low collisionality	Good	Small	Possible tolerable ELM regime

H. Wilson Lectures on Transport and stability of pedestals in tokamaks 2014

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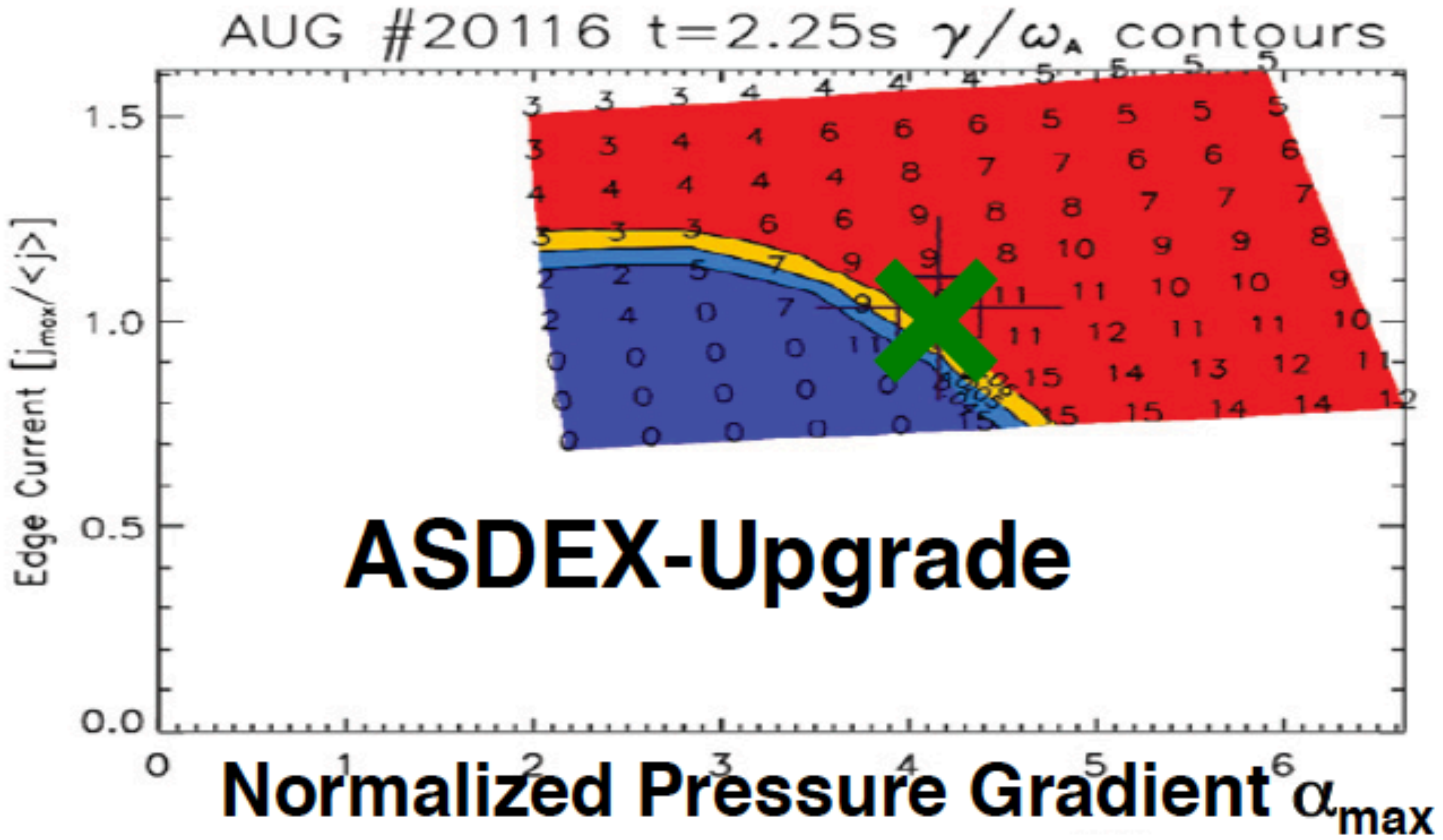
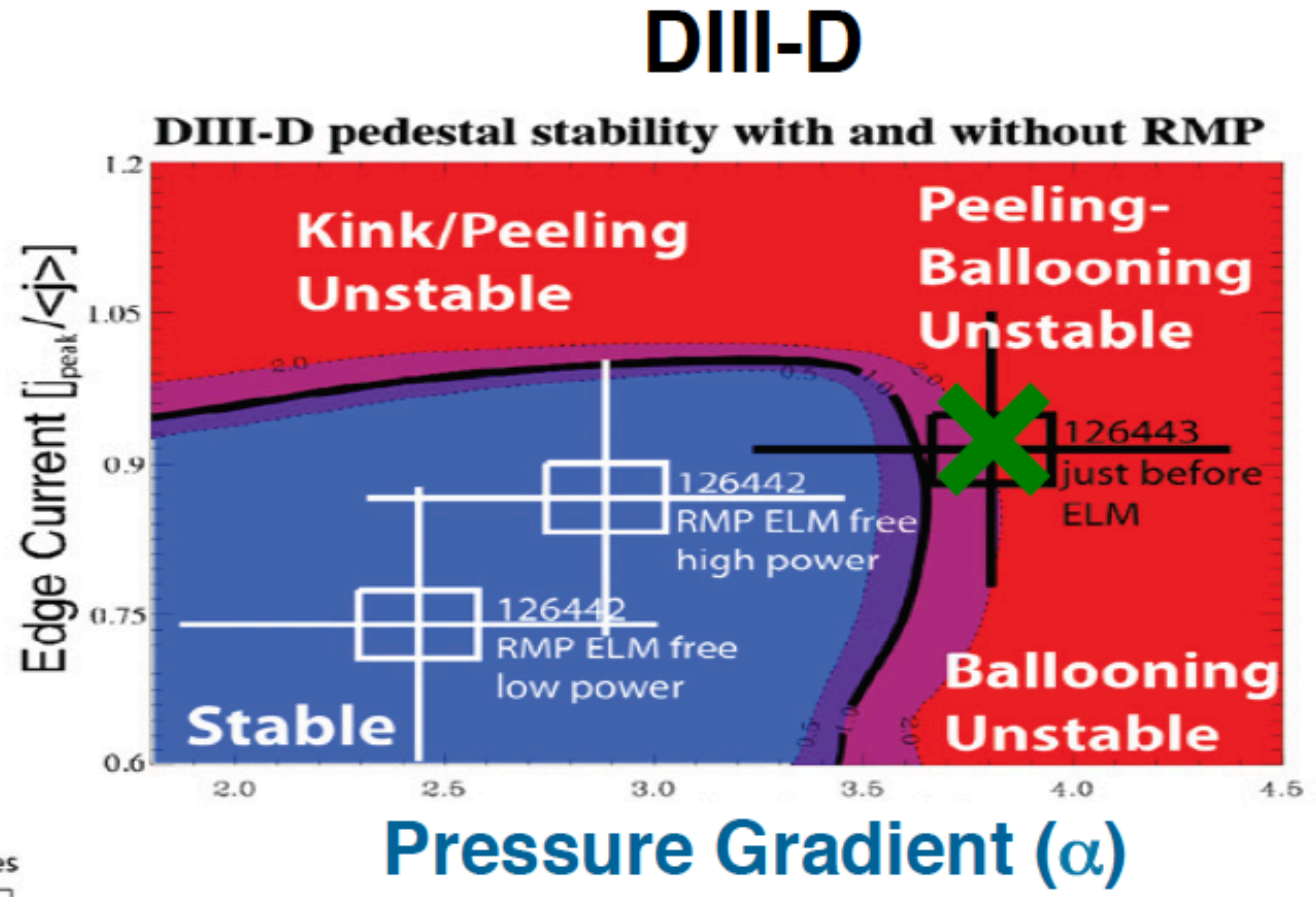
Let's revert to the type I ELM cycle

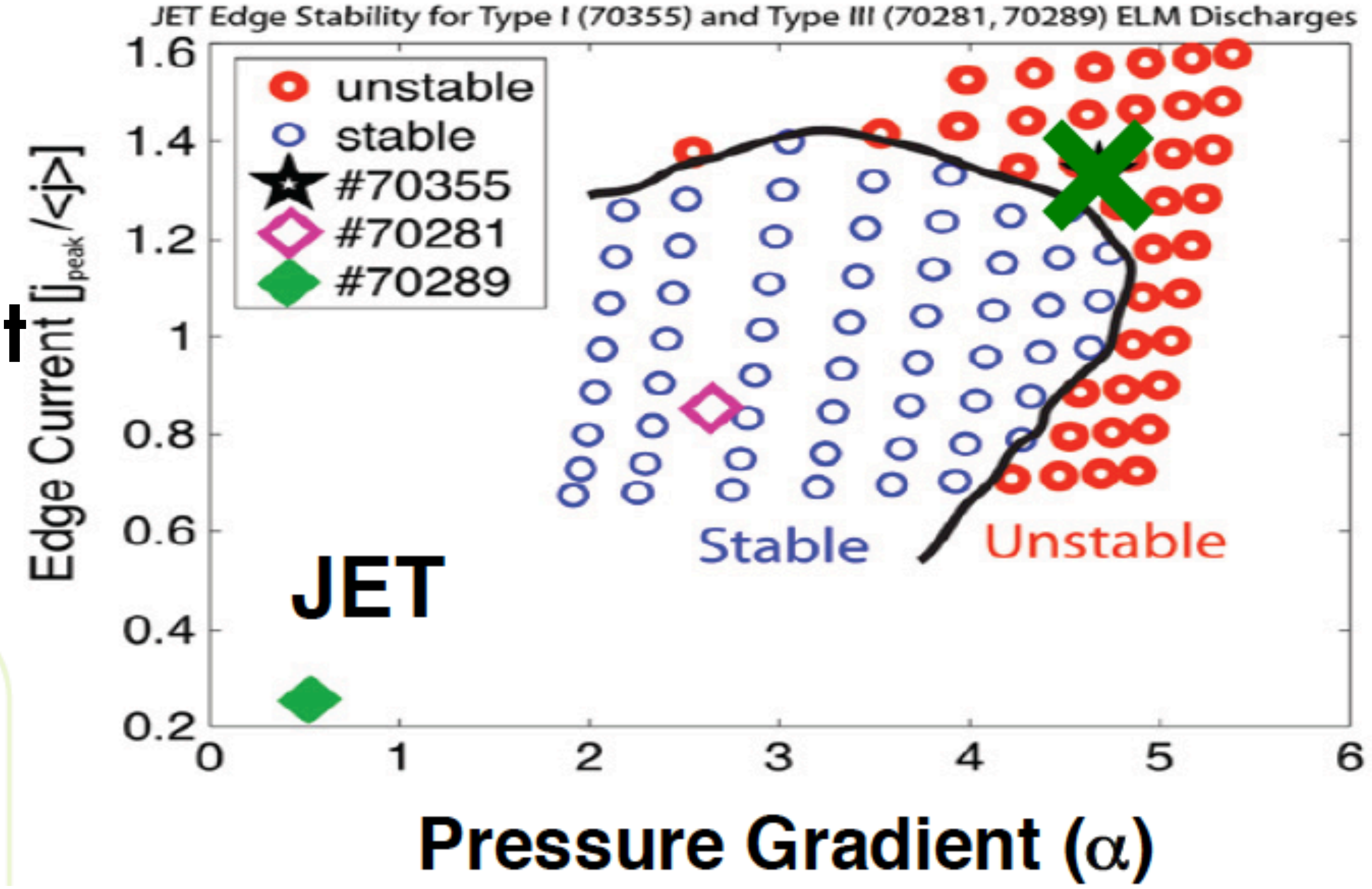
- **The coupled peeling-ballooning mode stability diagram provides a model for Type I ELM cycle**

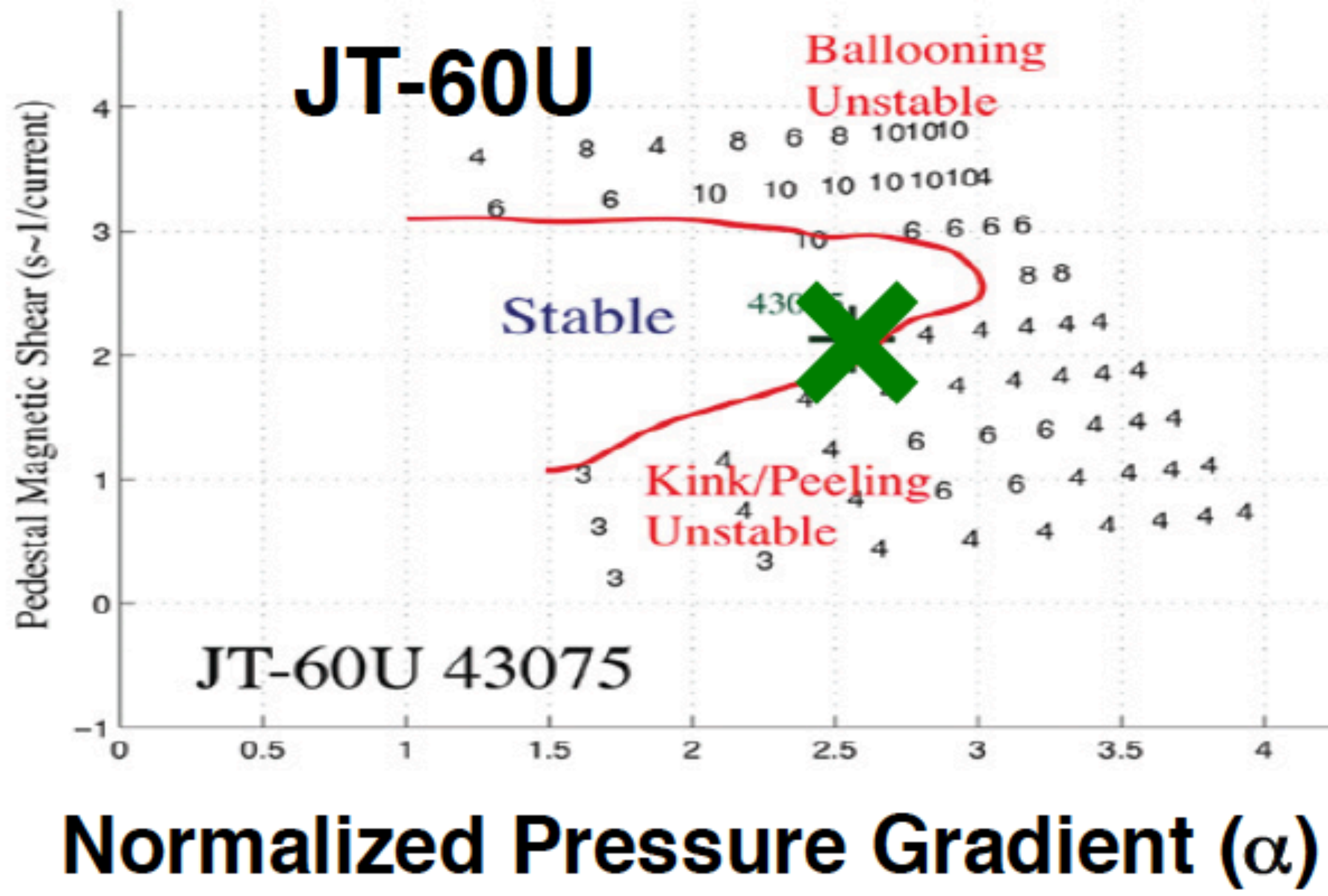
Experiments on all tokamaks consistent with peeling-ballooning trigger

- **Validated on all major international tokamaks**
- **ELM crash within 20% of calculated pedestal stability limit**









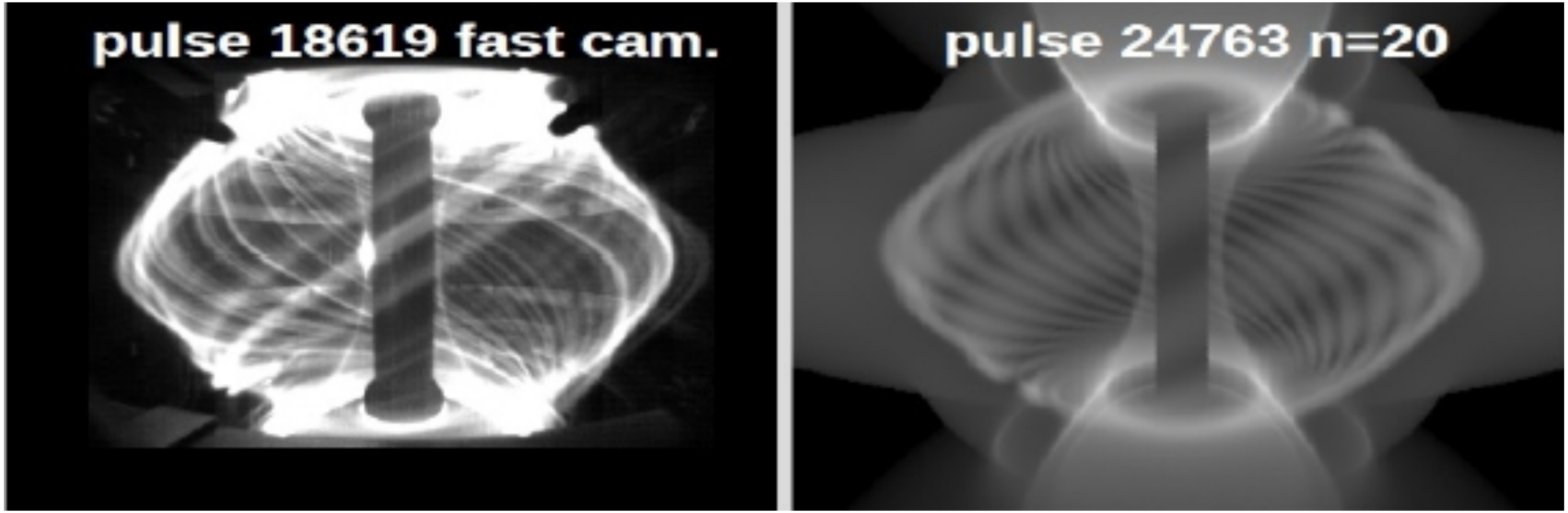
[S. Saarelma 2007, C. Konz 2008, N. Oyama 2005, N. Aiba 2009, P. Snyder, Nucl. Fusion 49 085035 (2009)]

Observed ELM Spatial Structure Similar to Calculated Peeling-Ballooning Modes

- **Complicated structure but mode number similar to that calculated from linear stability**

MAST

Visible Image **Calculated Mode (JOREK)**



Simulating a full ELM cycle with multi-scale physics is a grand computational challenge.

[S. Pamela, Plasma Phys. Control. Fusion 55 095001 (2013)]

P. Snyder APS-DPP Review talk 2018

Pedestal gradient recoveries during the ELM cycle

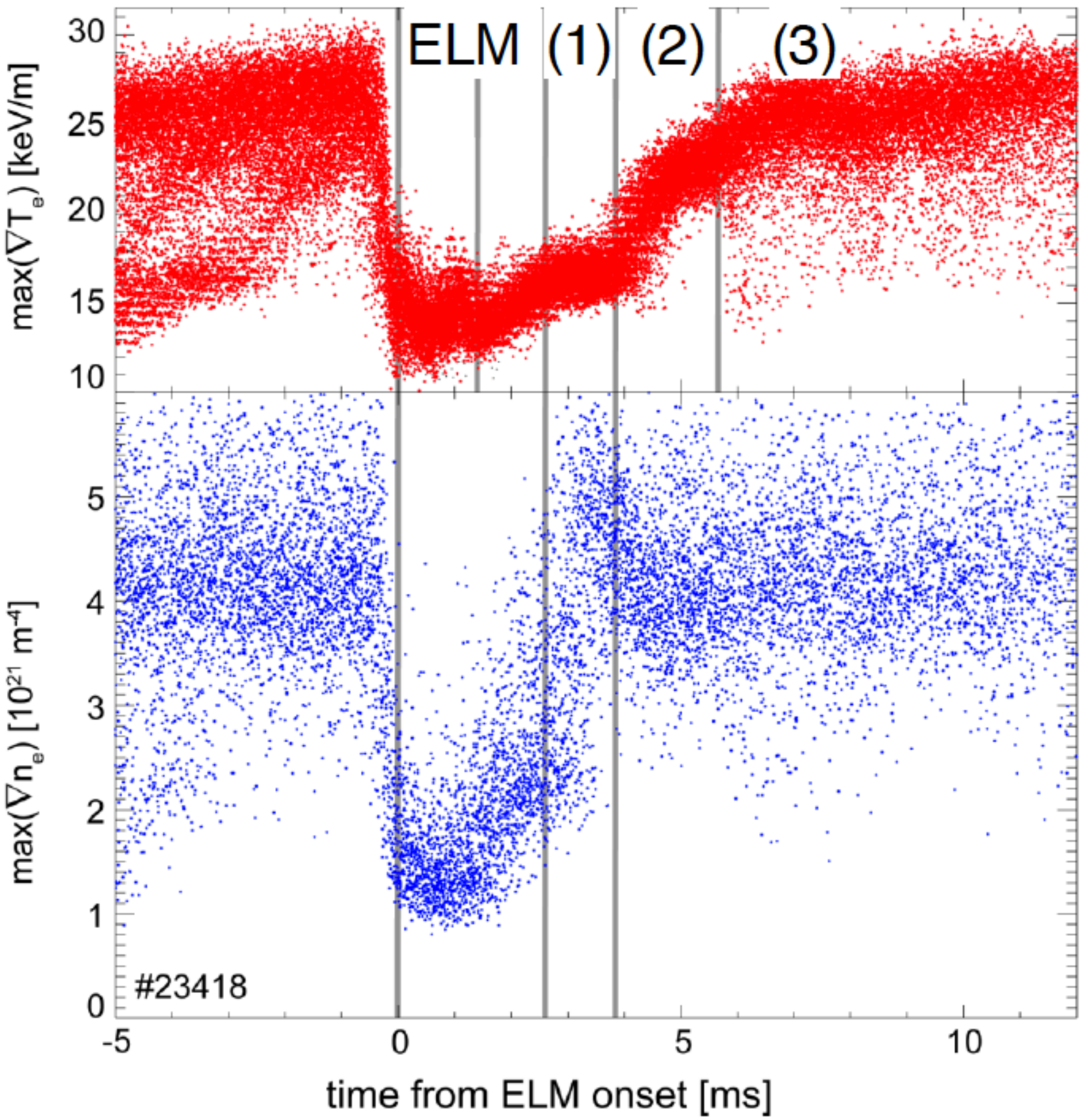
- **ELM cycle studies reveal different recovery timescales of Te and ne**

- **∇Te recovery show three phases**

(1) **∇T_e recovery is delayed and ∇n_e snaps back quickly**

(2) **∇T_e continues to recover while ∇n_e is saturated**

(3) **∇T_e slowly evolves to saturation**

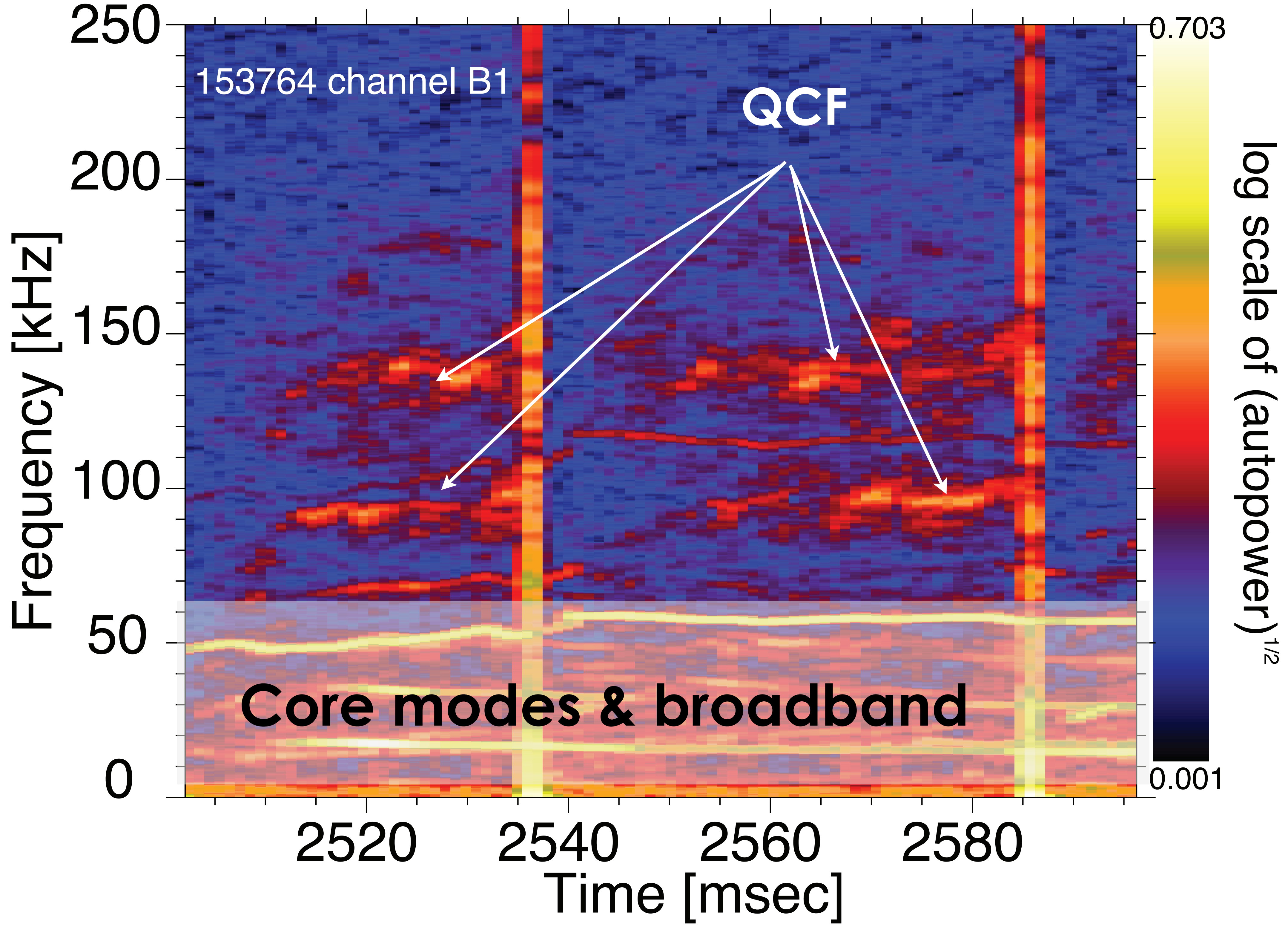


A. Burckhart et al, PPCF 2010; Diallo PoP 2015; F. Laggner et al, PPCF 2016

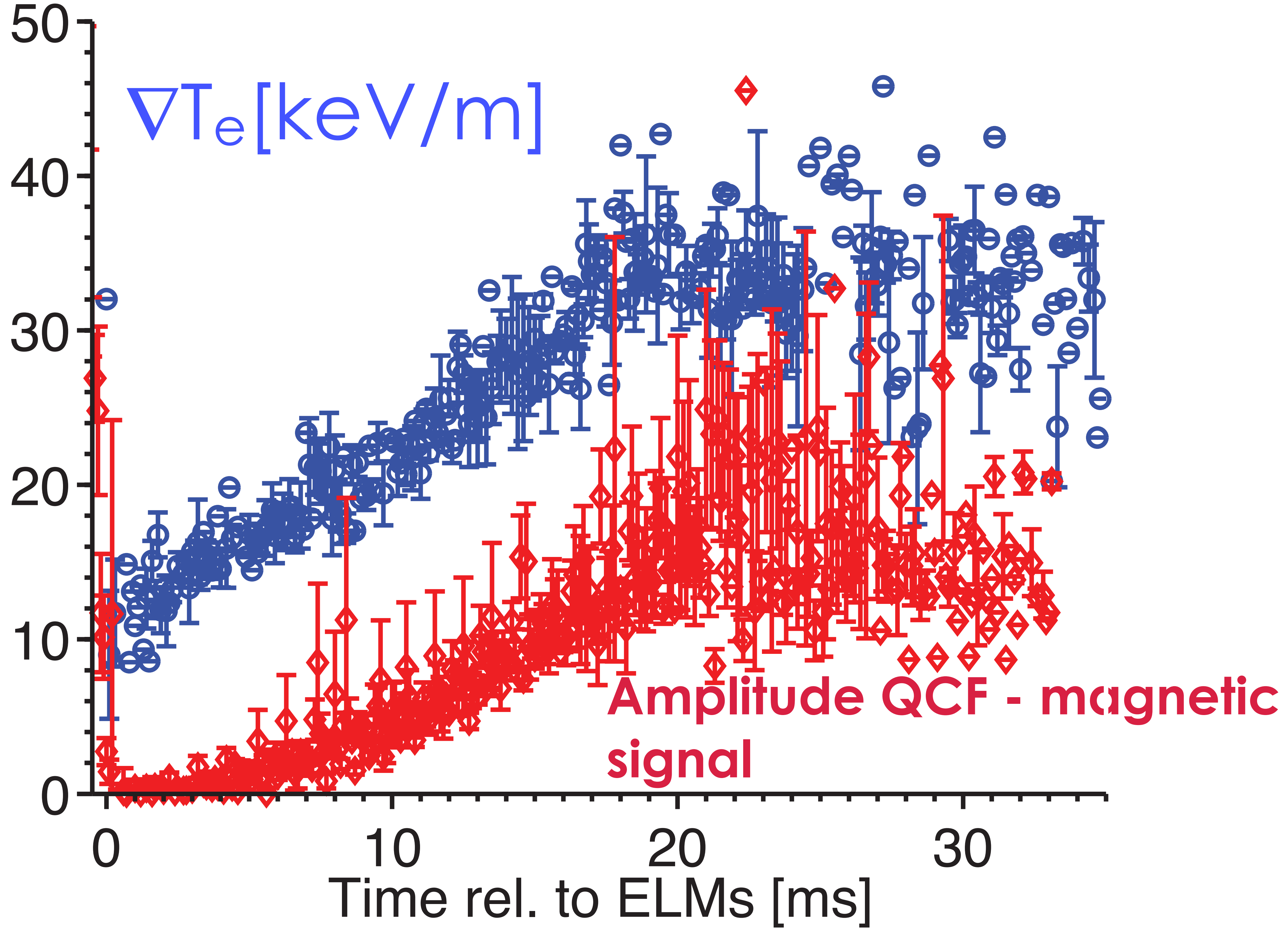
Measurements on DIII-D reveal the existence of pedestal localized mode during the ELM cycle: Quasi-Coherent Frequency (QCF)

- **QCF Onsets at Given Temperature Gradient and its Evolution Tracks the Gradient Evolution**

Magnetic fluctuations spectrogram



Evolution of QCF amplitude and Temperature gradient



Diallo, Physics of Plasma 2015

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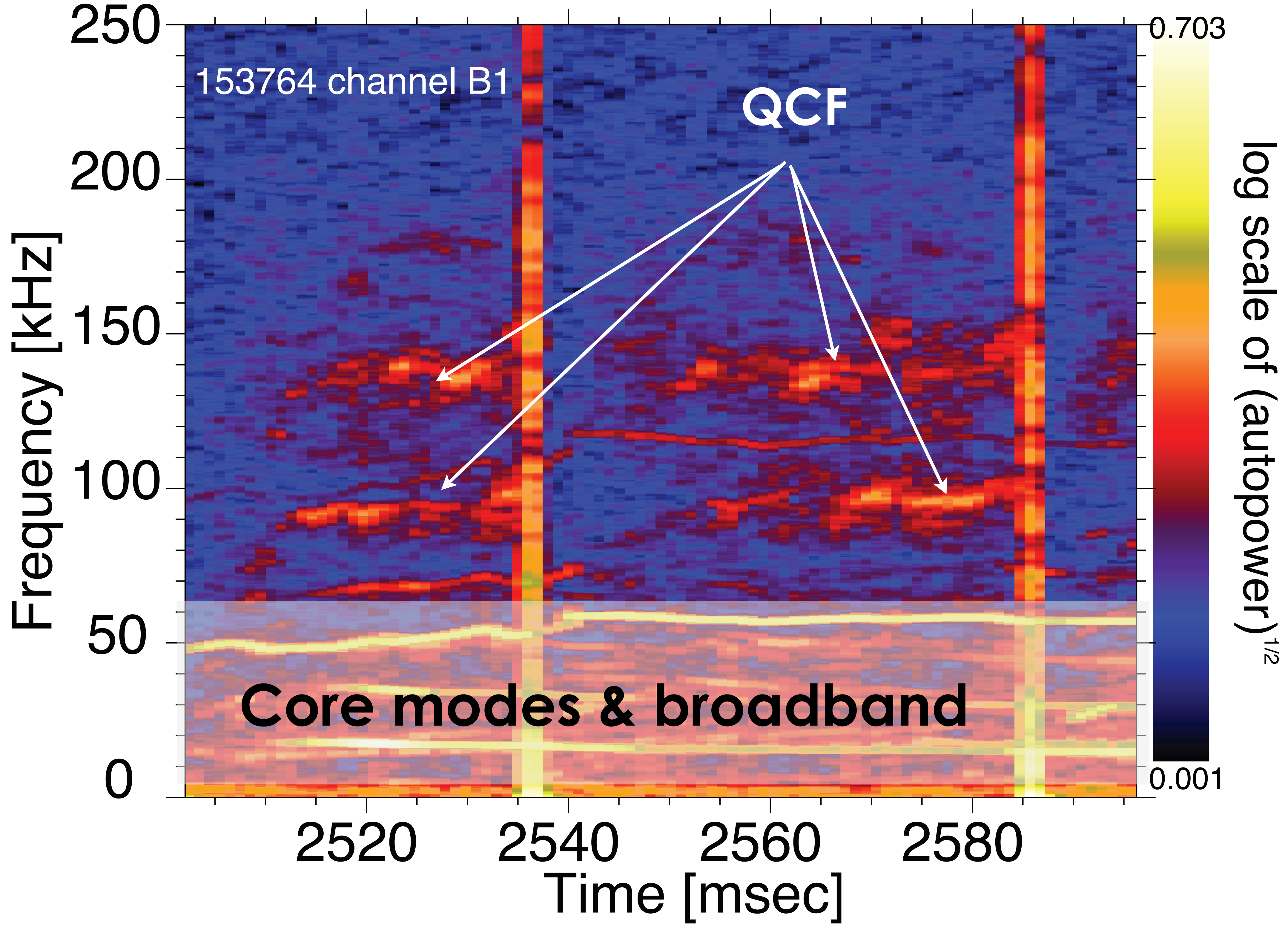

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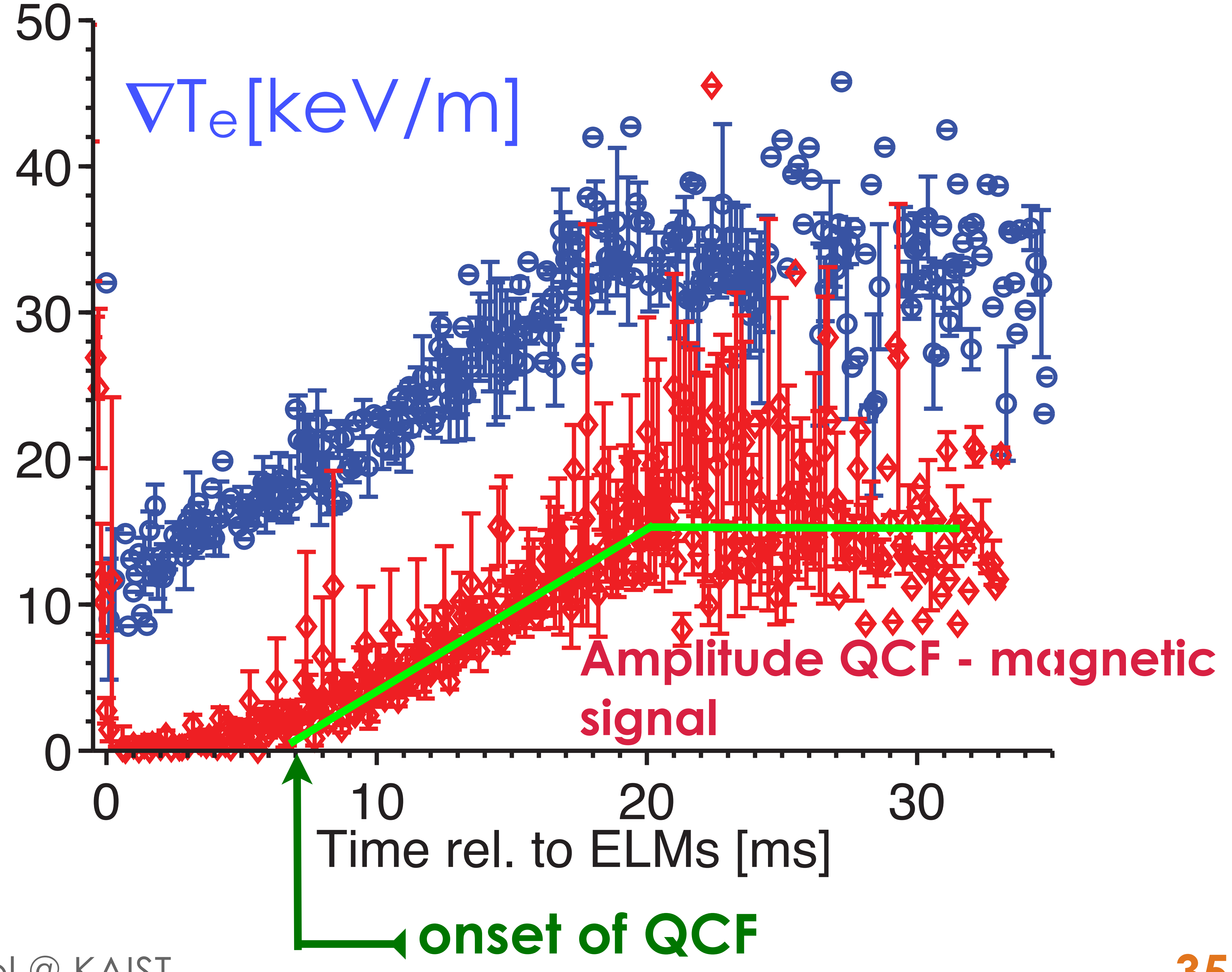


Diallo, Physics of Plasma 2015

Summary of possible inter-ELM transport mechanisms

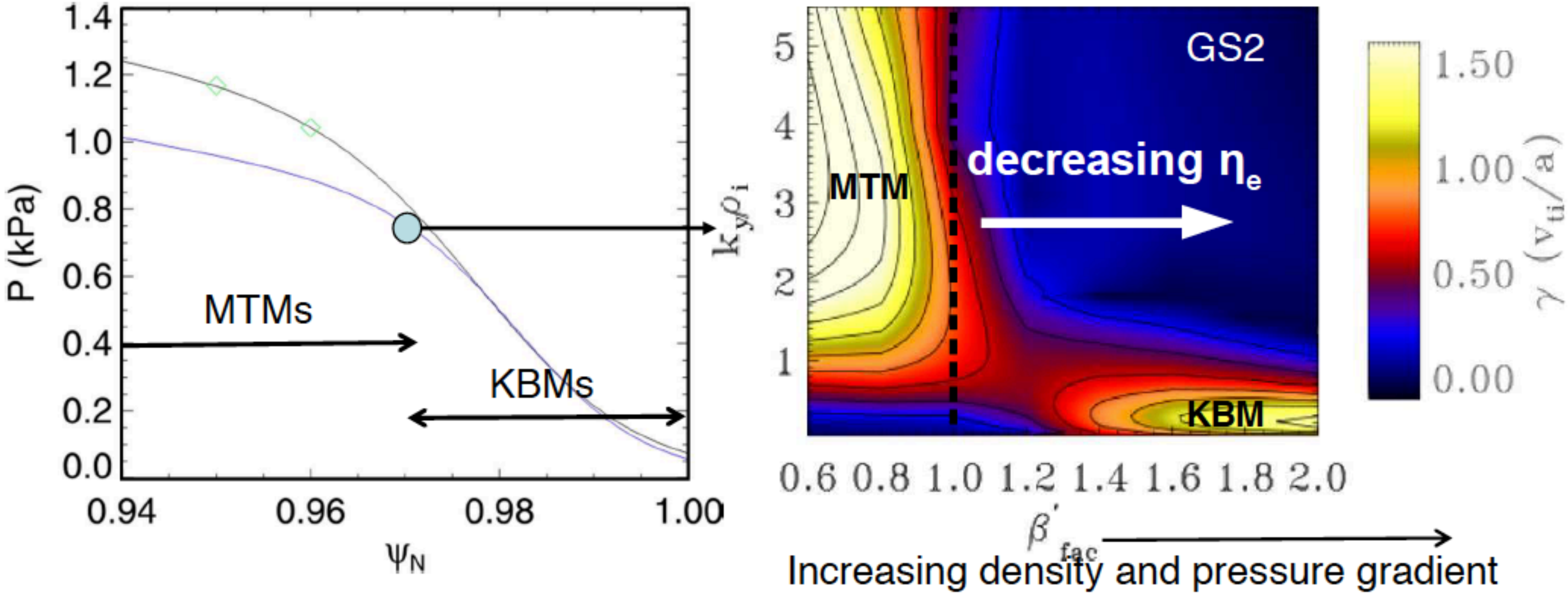
- **Transport processes in the pedestal can be explored by considering the pedestal evolution between ELMs**

P. Manz, PPCF 2014

Instability	Drive	Prop.	Scale	$\alpha_{\phi,\tilde{p}}$	$\alpha_{\phi,\tilde{T}_e}$	$\omega(L_\perp/c_s)$	Parity
IPM	$J_\parallel$	n.p.	$k_\theta \rho_s \ll 0.1$				Global
(I–R)BM	∇p	n.p.	$k_\theta \rho_s < 0.1$	$\pi/2$			Ball.
KBM	$\nabla T_{e,i}$	i dia.	$k_\theta \rho_s \sim 0.1$	$\pi/2$			Ball.
KPBM	$\nabla p_{e,i}$	e dia.	$k_\theta \rho_s \ll 0.1$				Ball.
MTM	∇T_e	e dia.	$k_\theta \rho_s \sim 0.1$	0		0.1–1	Tear.
ITG	∇T_i	i dia.	$0.1 < k_\theta \rho_s \leqslant 1$	$\pi/2$	π	0.1–1	Ball.
TEM	$\nabla T_e, \nabla n$	e dia.	$0.1 < k_\theta \rho_s$	0	$\pi/2$		Ball.
ETG	∇T_e	e dia.	$k_\theta \rho_s > 1$	$\pi/2$	$0 - \pi/2$	0.5–100	Ball.

Micro-instabilities in the pedestal appears to set its structure

- **Gyrokinetic simulations of the MAST pedestal show:**
  - **At low density gradient, the micro-tearing mode is unstable**
  - **At higher density gradient this mode is stabilized, but the kinetic ballooning mode is instead destabilized as the pressure gradient rises**



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A model for pedestal formation

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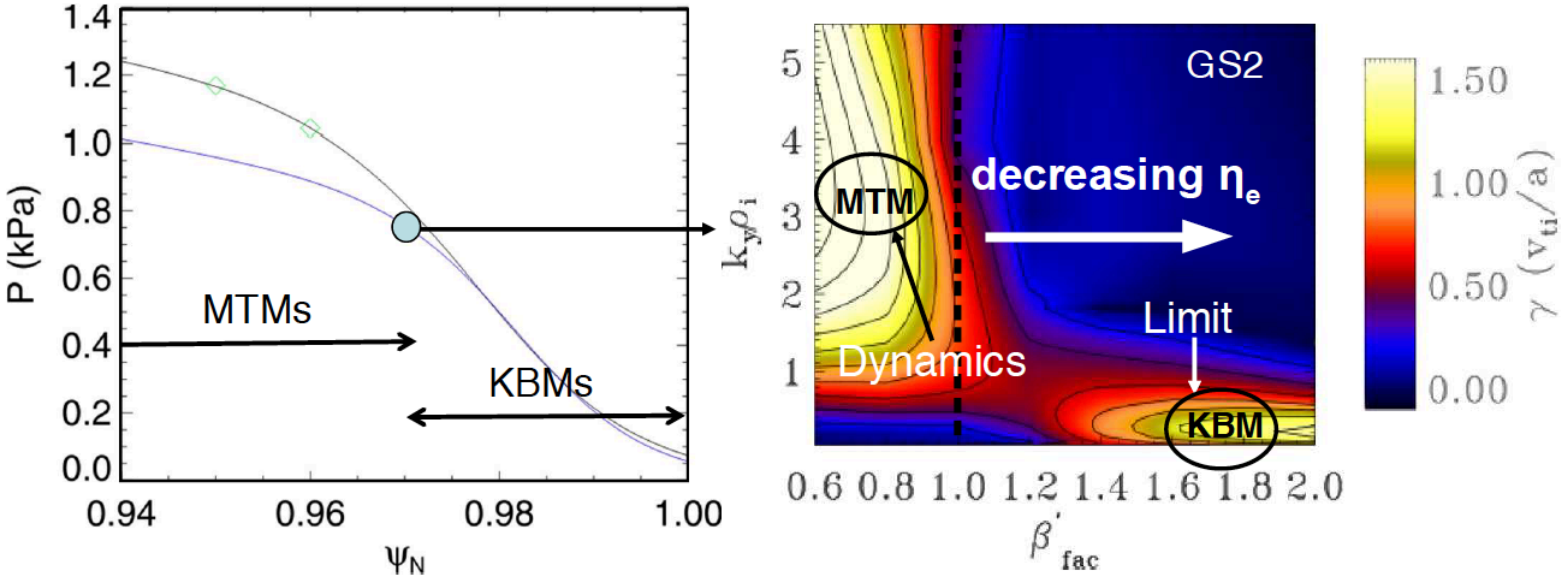
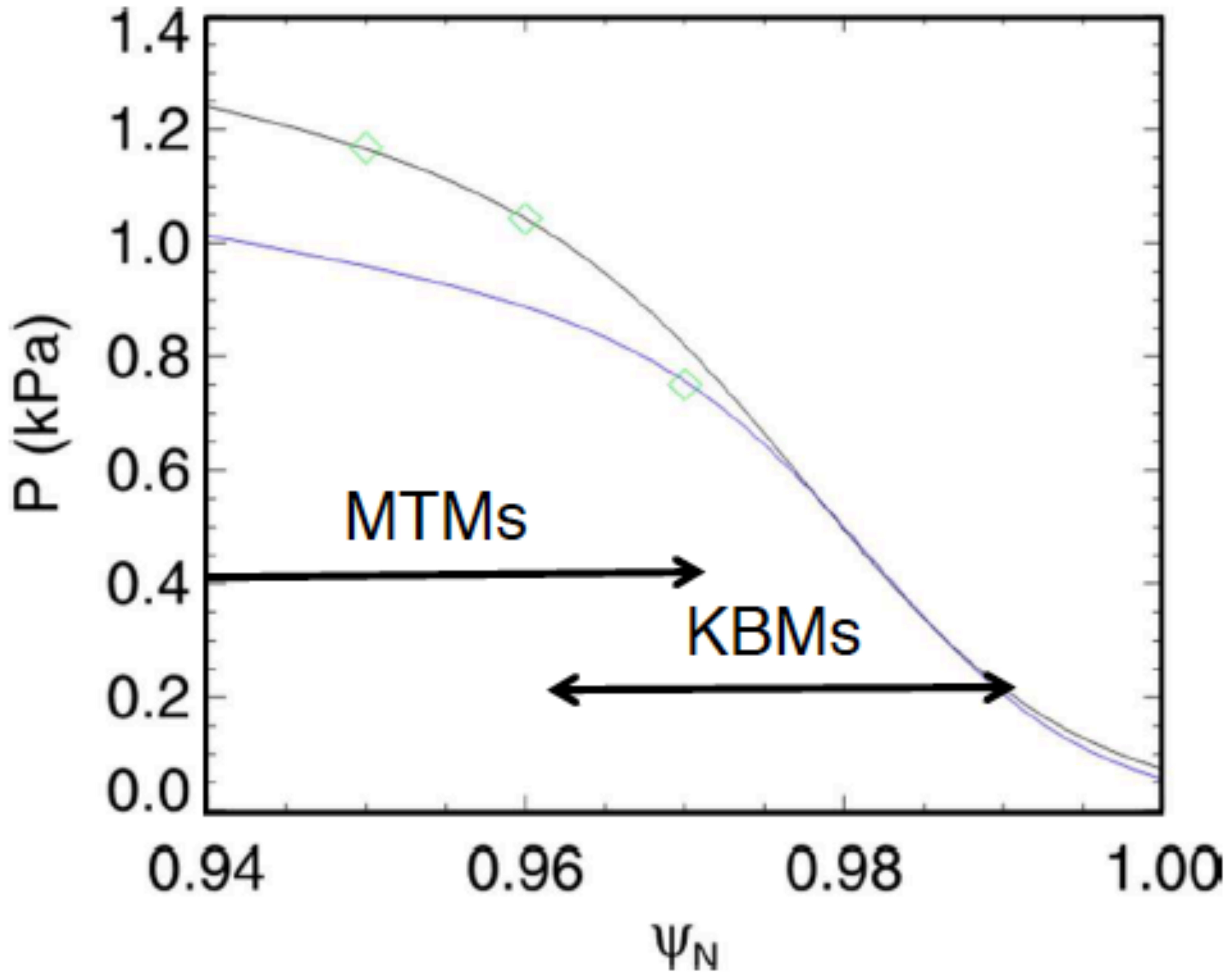
- **Simulations suggest the following model:**
  - **The pedestal gradients are initially held low by the micro-tearing mode**
  - **This mode is initially stabilized close to the plasma edge, allowing the pressure gradient to build until the KBM is destabilized**
  - **As the MTM is progressively stabilized, the pedestal widens into the core**

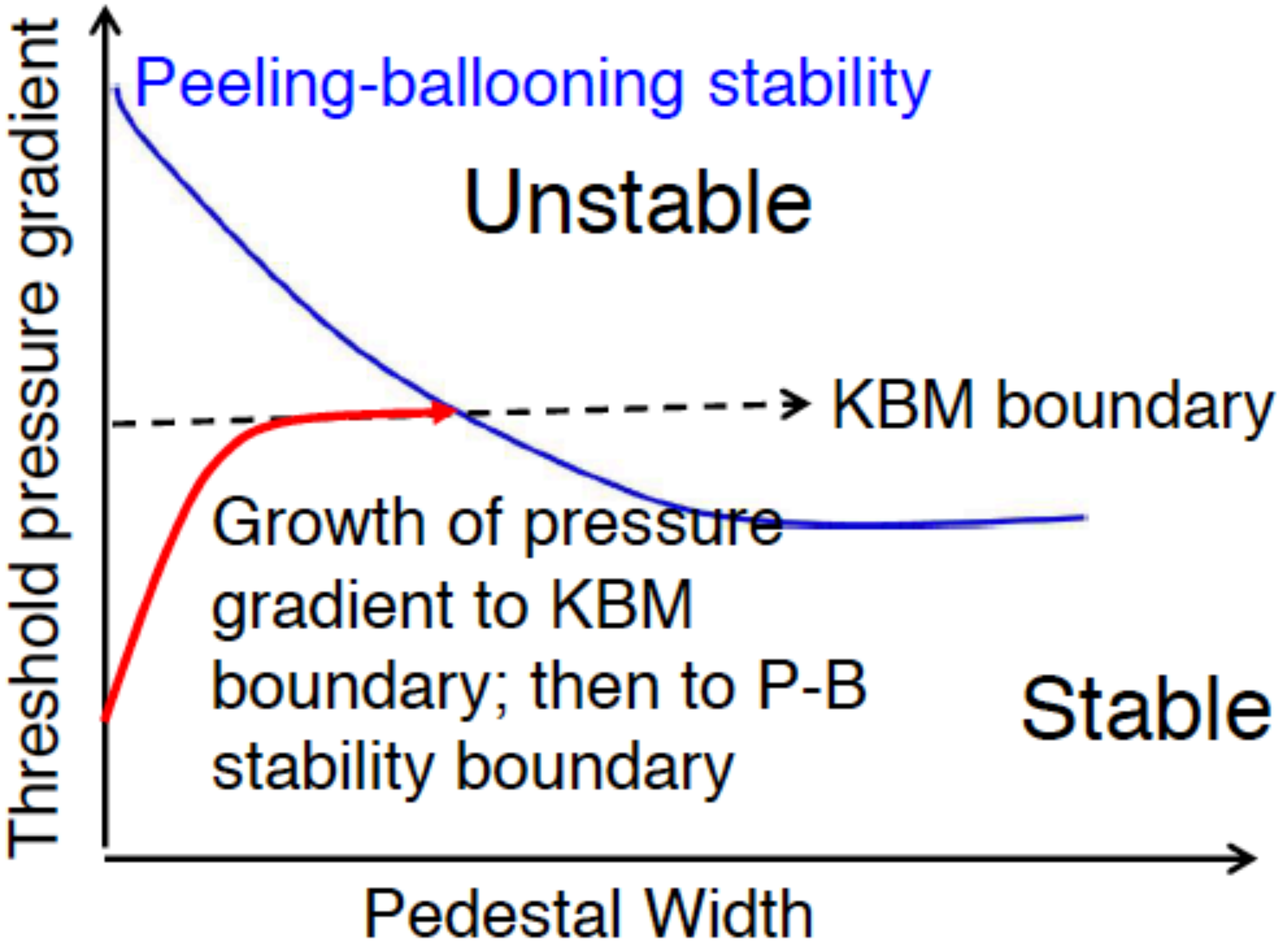


D. Dickinson, et al, PPCF 2011 D. Dickinson, et al, PRL 2012

What limits the extent of the pedestal penetration ?

- **The more the pedestal penetrates, the greater the pedestal width and the higher the core pressure**
  - **So what limits the pedestal width?**
- **It is actually the peeling-ballooning stability limit**
  - **A wider pedestal has a lower threshold for instability**





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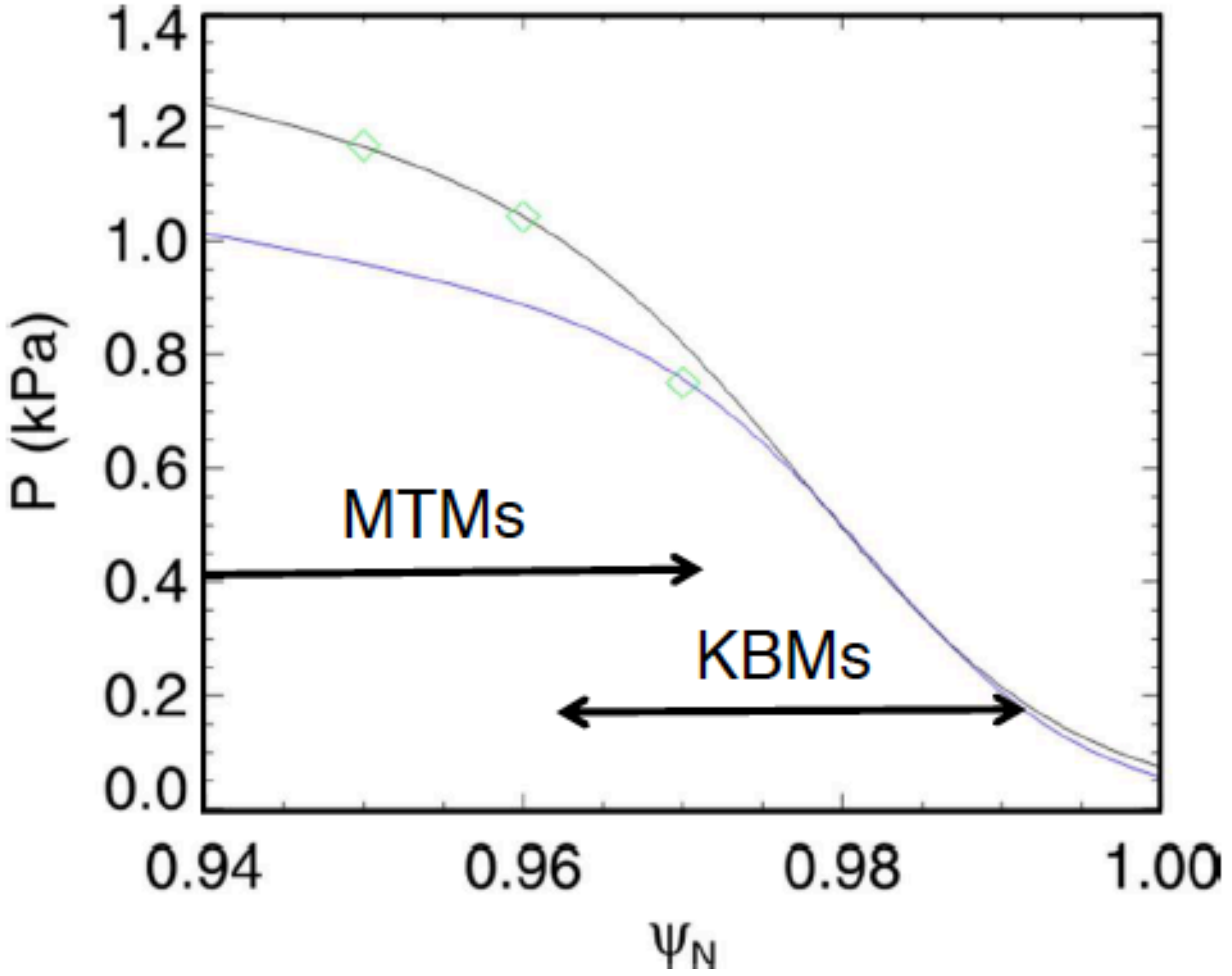

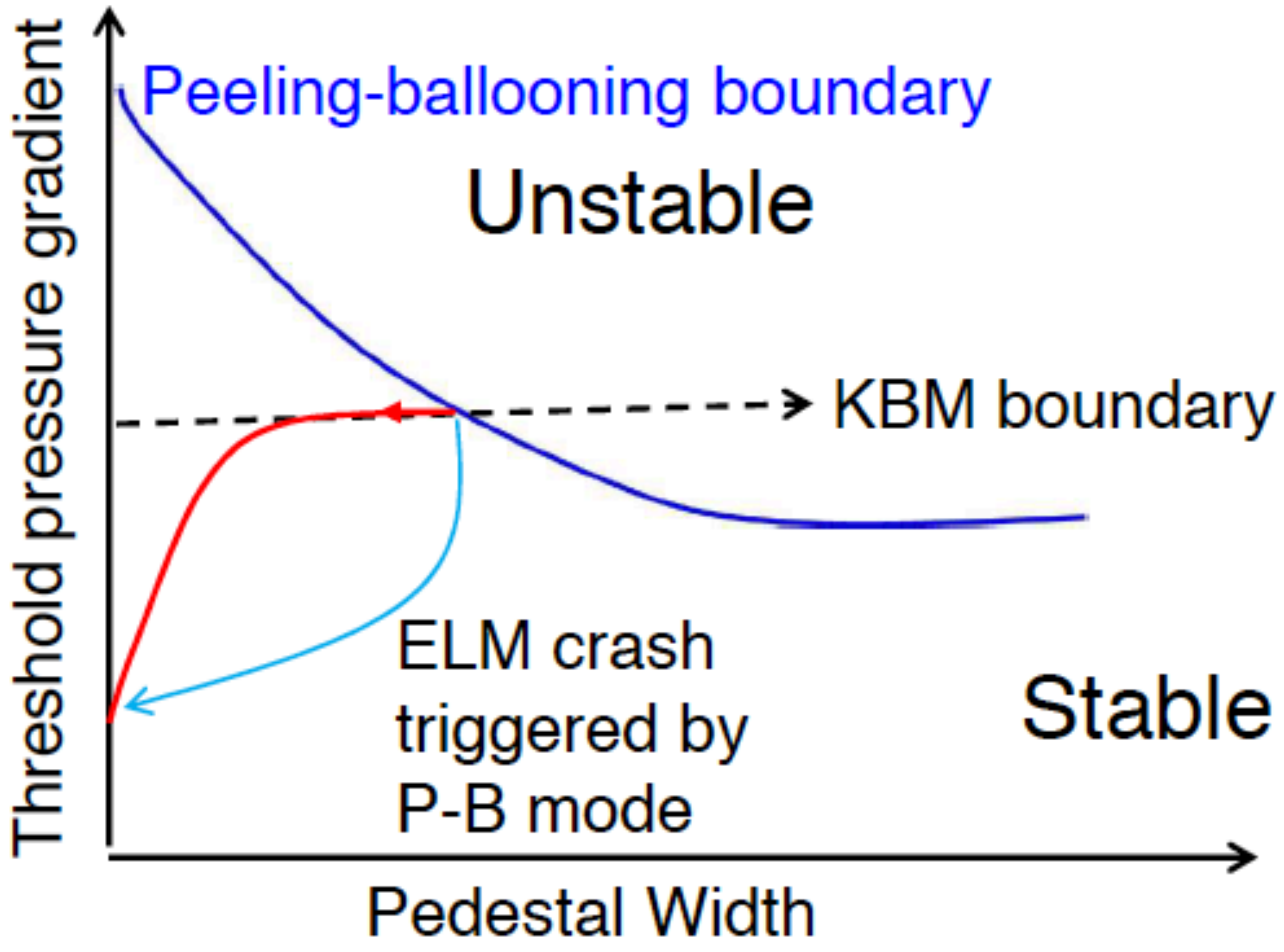

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Outline

- L-H transition phenomenology
  - *Turbulence suppression*
  - *Access condition dependencies*
  - *Radial electric field shear*
- Formation of the Pedestal
  - *Brief overview*
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  - *How do we arrive at theses ELMs?*
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- The type I ELM cycle
  - *Stability: Description*
  - *Pedestal evolution during ELM cycle*
  - *What control the pedestal?*
- **EPED model a predictive model for the pedestal pressure**
  - ***Mechanics***
  - ***Other dependencies***
- Small ELM regimes as a viable option for ITER

- Summary

EPED model:a predictive model for the pedestal pressure

- **EPED divides the instabilities that impact transport & stability in the pedestal into 2 categories:**
  - **“Global” modes: extend across edge barrier including significant impact at top**
  - **“Nearly-local” modes within the edge barrier**

Conjecture: while neoclassical and electron microinstabilities drive transport, KBM commonly provides the final constraint on the pressure gradient.

- **Key elements: neoclassical bootstrap current, nearly local KBM, global peeling ballooning**
- **Density is taken as key input**

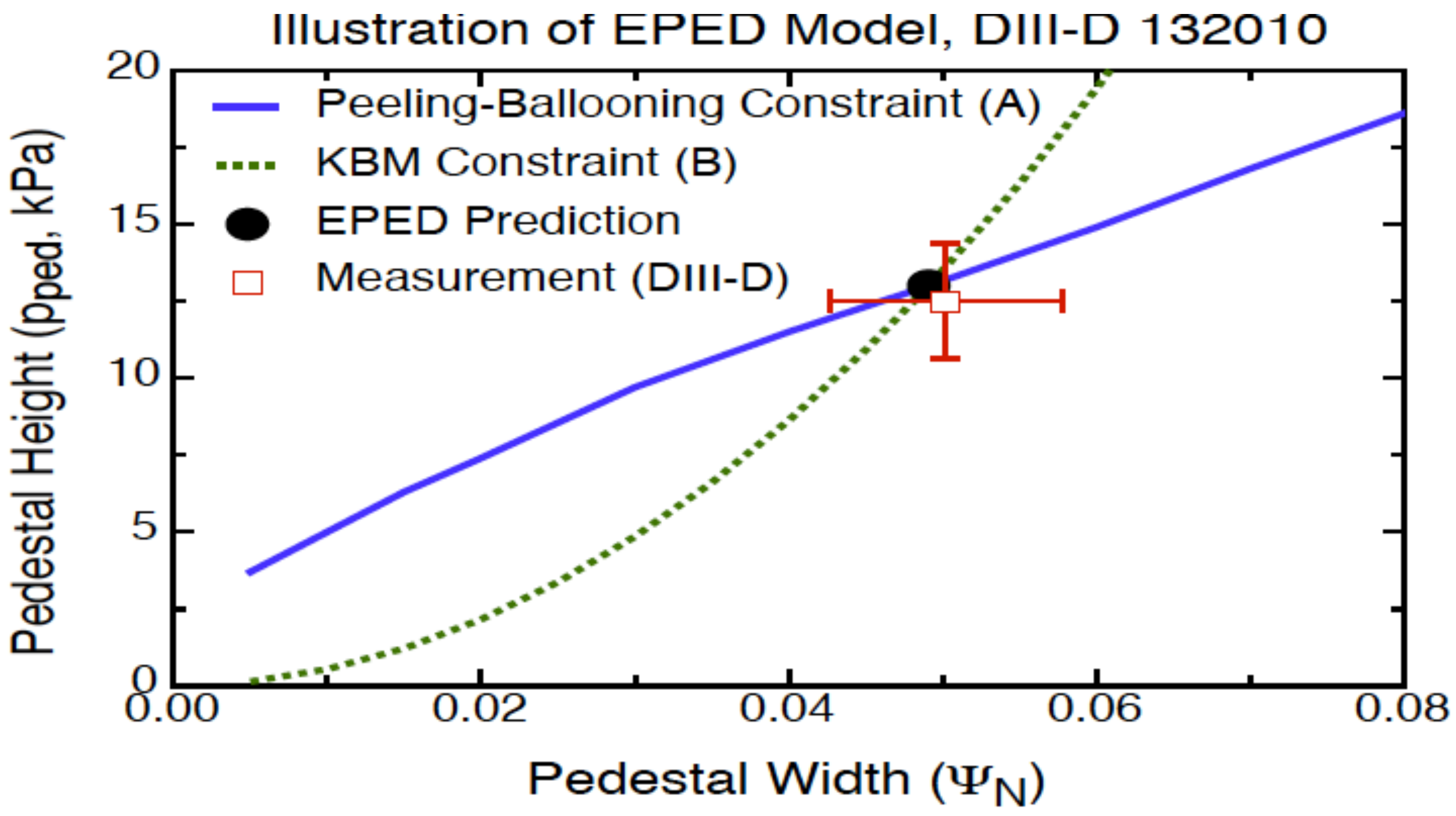
Mechanics of the EPED Predictive Model

- **Input**: B_t, I_p, R, a, κ, δ, n_{ped}, m_i, [β_{global}, Z_{eff}]
- **Output**: Pedestal height and width (no free of fit parameters)

A. P-B stability calculated via a series of model equilibria with increasing pedestal height

ELITE, n=5-30 nonlocal diamagnetic model from BOUT++ calcs

B. KBM onset: $\Delta \sim \beta_p^{1/2}$



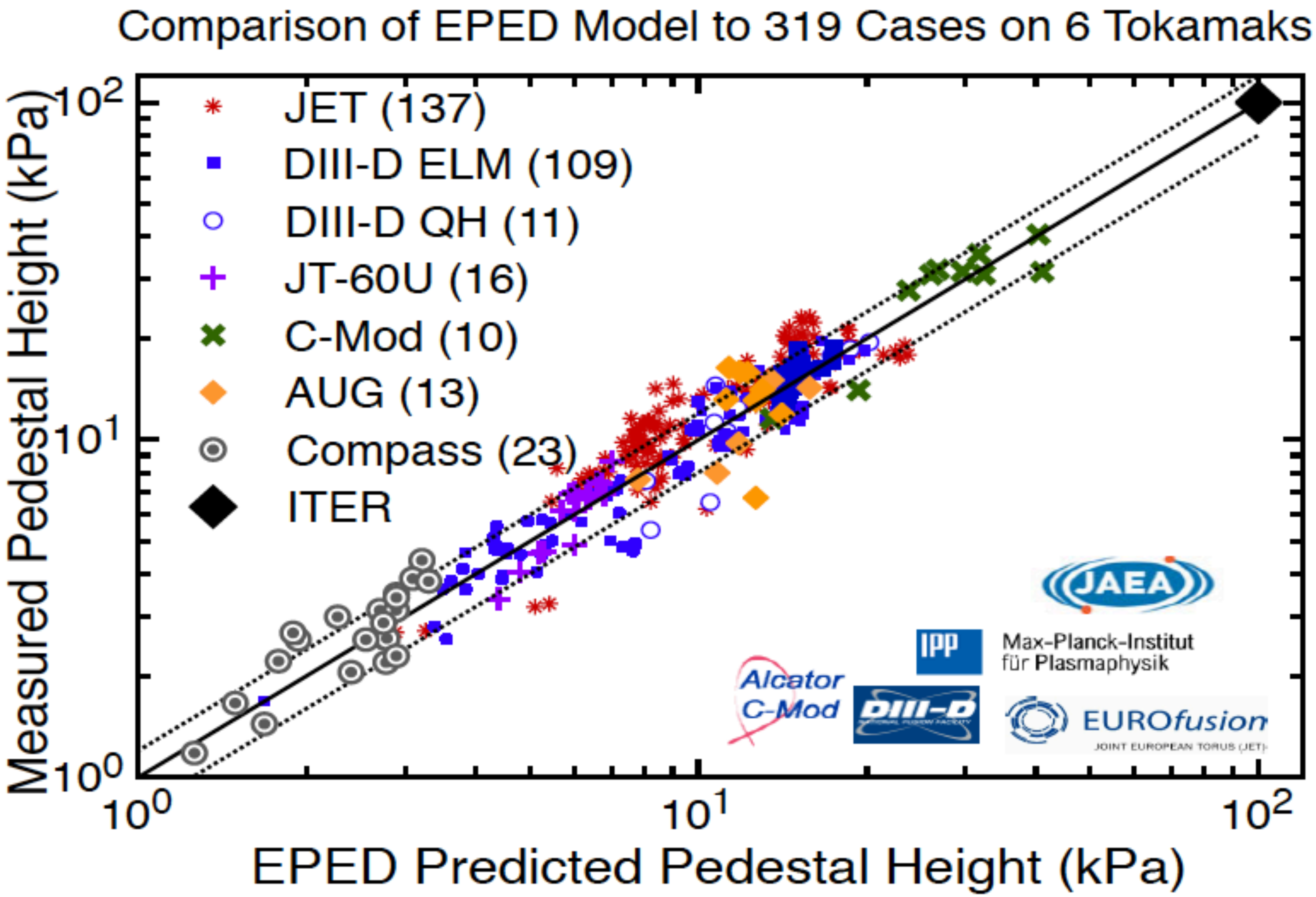
*P.B. Snyder et al Phys Plas **16** 056118 (2009), NF **51** 103016 (2011)*

P-B stability and KBM constraints are tightly coupled: If either physics model (A or B) is incorrect, predictions for both height and width will be systematically incorrect

Effect of KBM constraint is counter-intuitive: Making KBM stability worse increases pedestal height and width

P. Snyder APS-DPP Review talk 2018

Numerous Experimental Tests of EPED Conducted

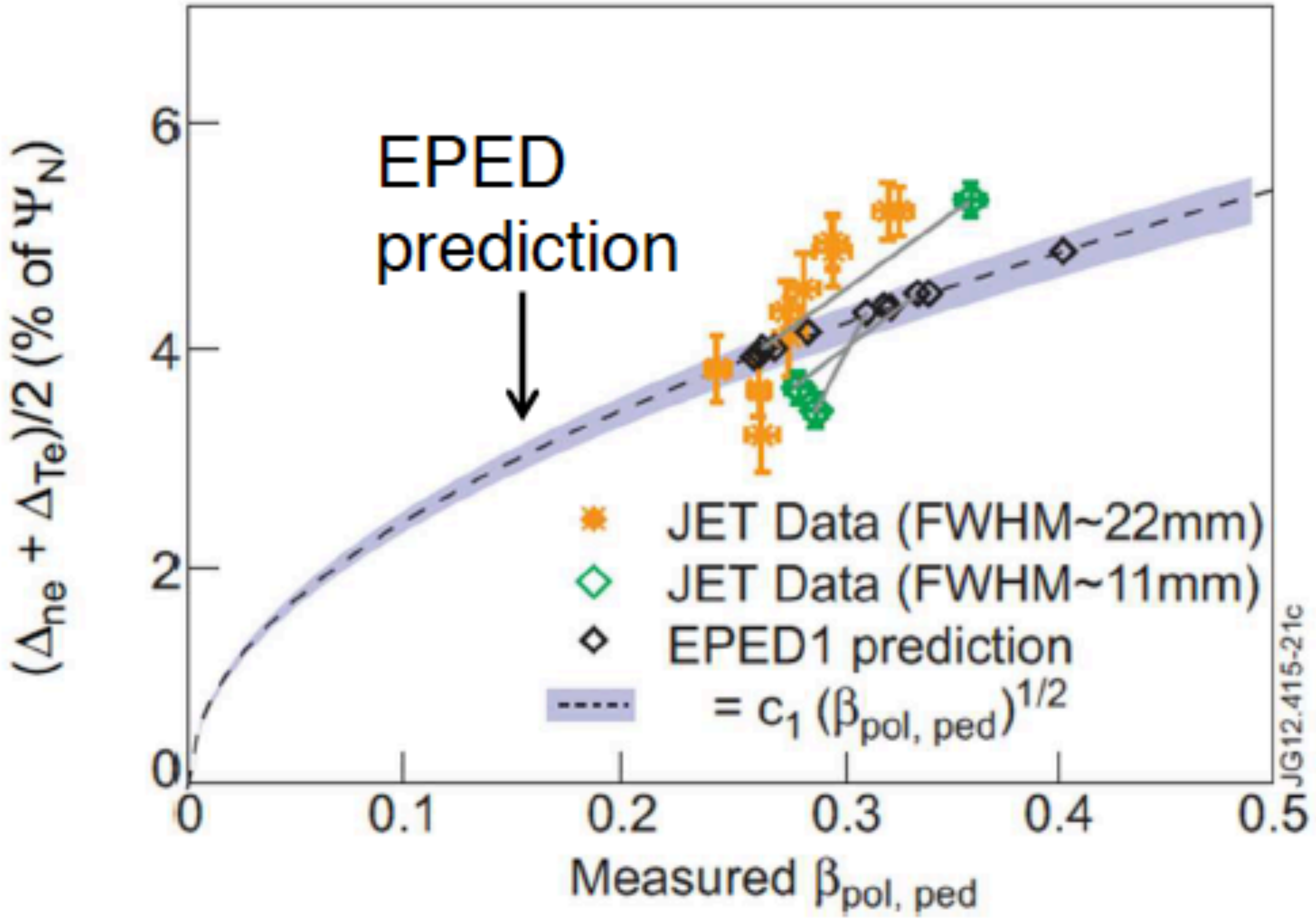


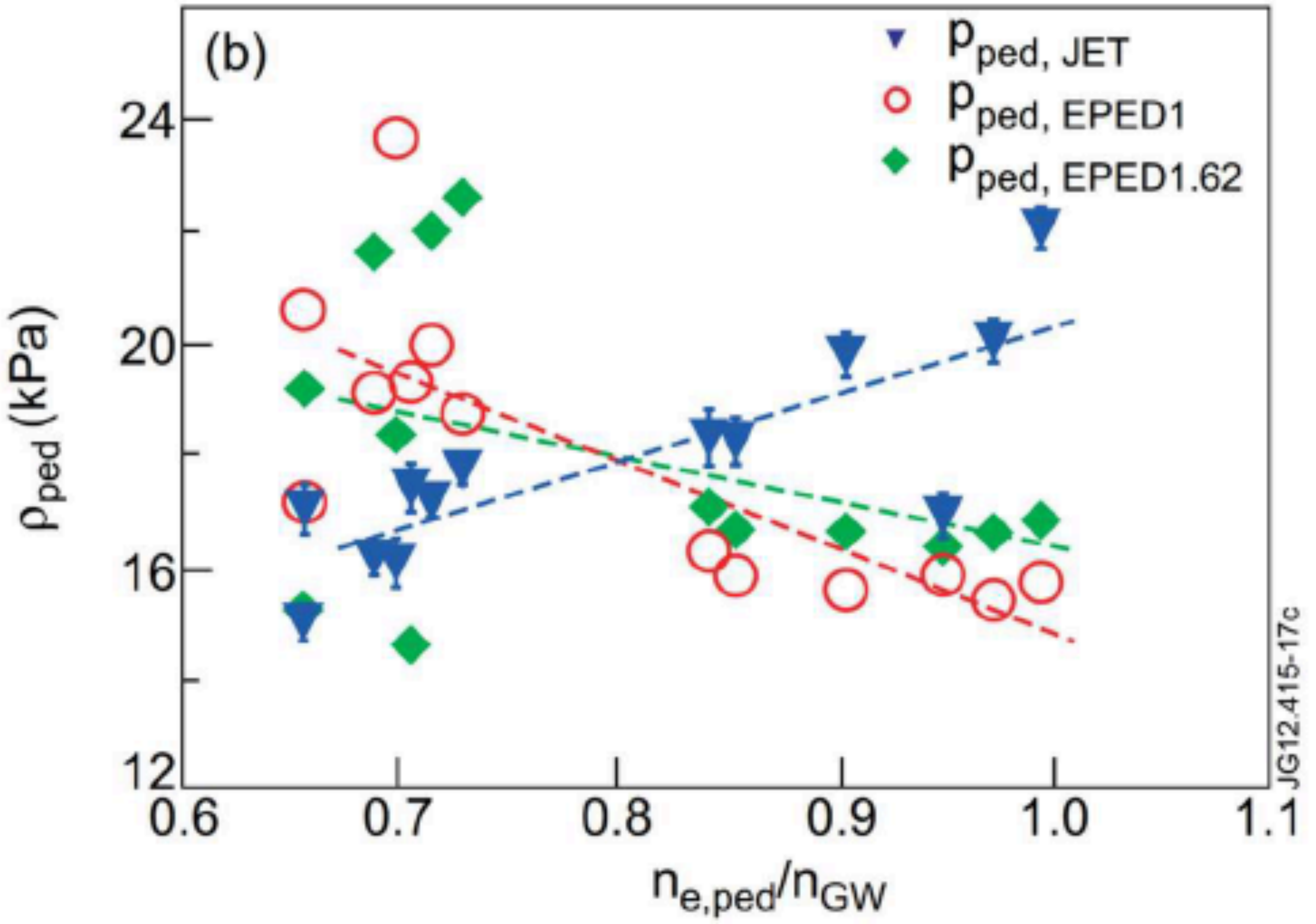
- >800 Cases on 6 tokamaks
- Broad range of density (~1-24 10^{19}m-3), collisionality (~0.01-4), $f_{GW,ped}$ (~0.1-1.0), shape (δ~0.05-0.65), q~2.8-15, pressure (1.7 - 35 kPa), βN~0.6-4, Bt=0.7-8T
- Typical σ~20-25%

P. Snyder APS-DPP Review talk 2018

EPED model: A major advance, but not the full picture

- **While EPED broadly predicts pedestal width, there are differences in trends**
- **Recent analysis from JET, for example:**





M Leyland, et al, Nucl Fusion 2013

Also on JET, the pedestal appears to narrow into the ELM cycle, rather than broaden – a challenge for the model (but there are ideas)

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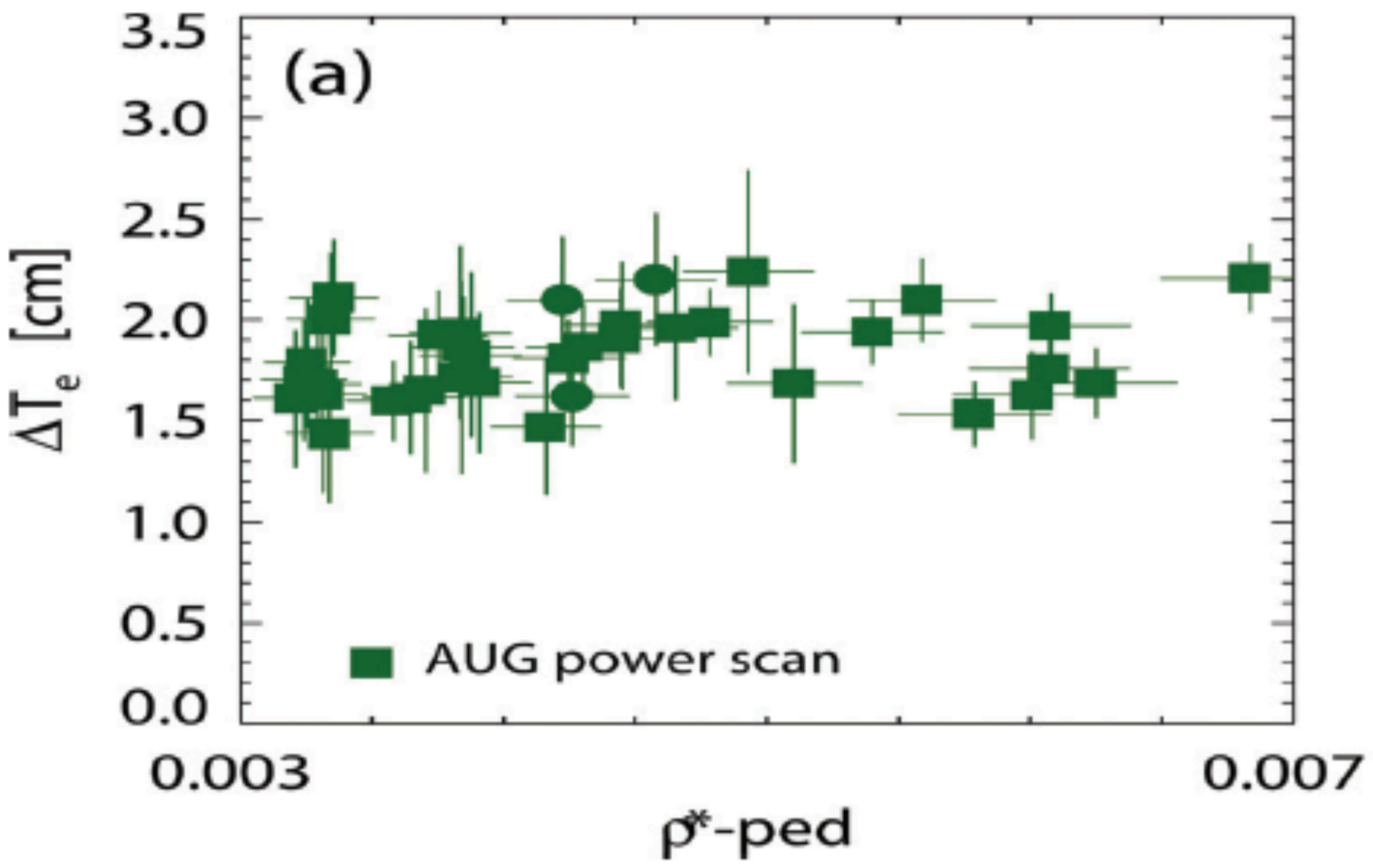
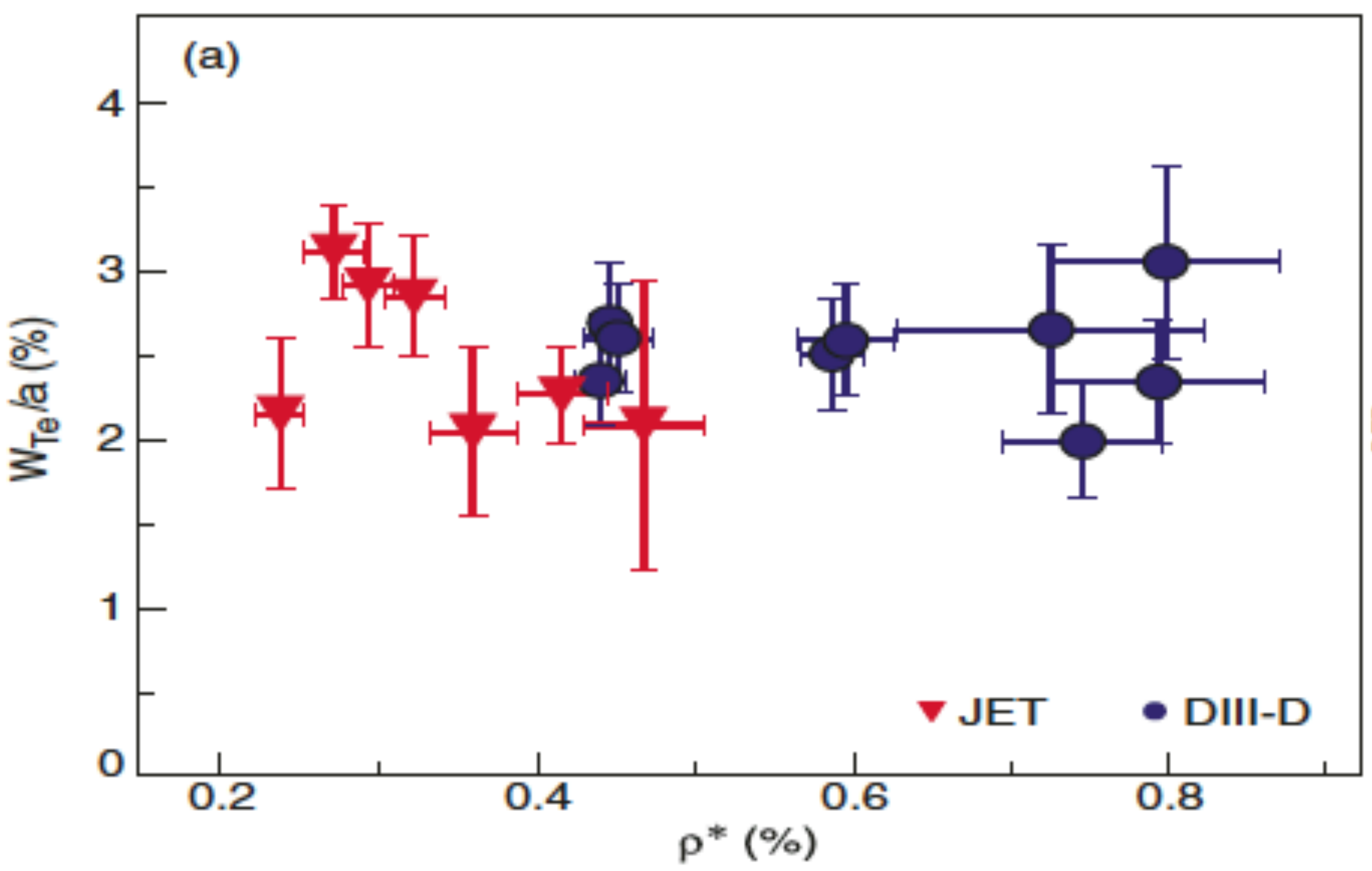
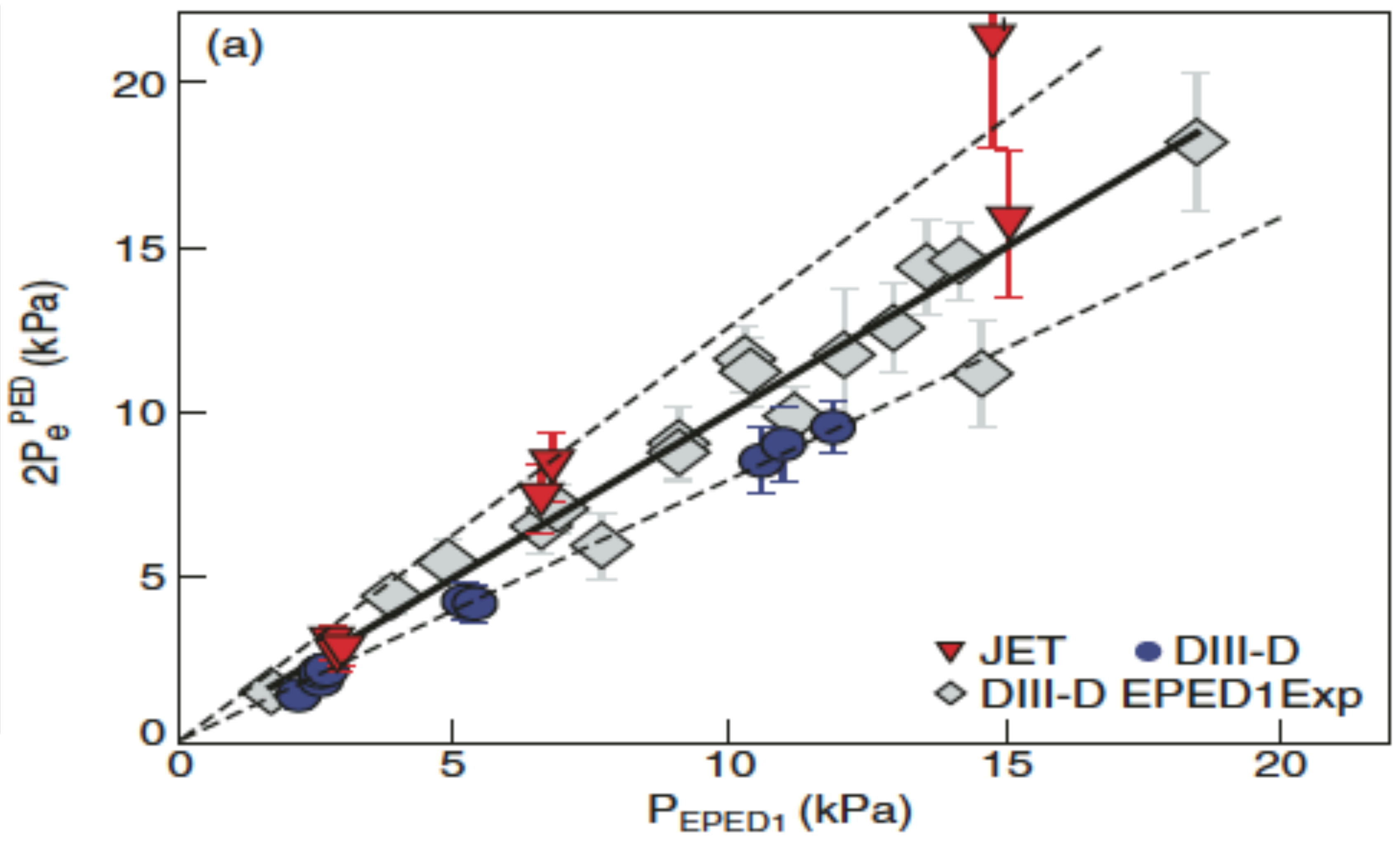
Dependence on ρ* Important for Predictions of ITER

- Key dimensionless parameters for ITER or DEMO reactor matched on existing machines (ν^*,β,q, ε) **except ρ***







Important to continue testing and developing understanding at very small ρ*

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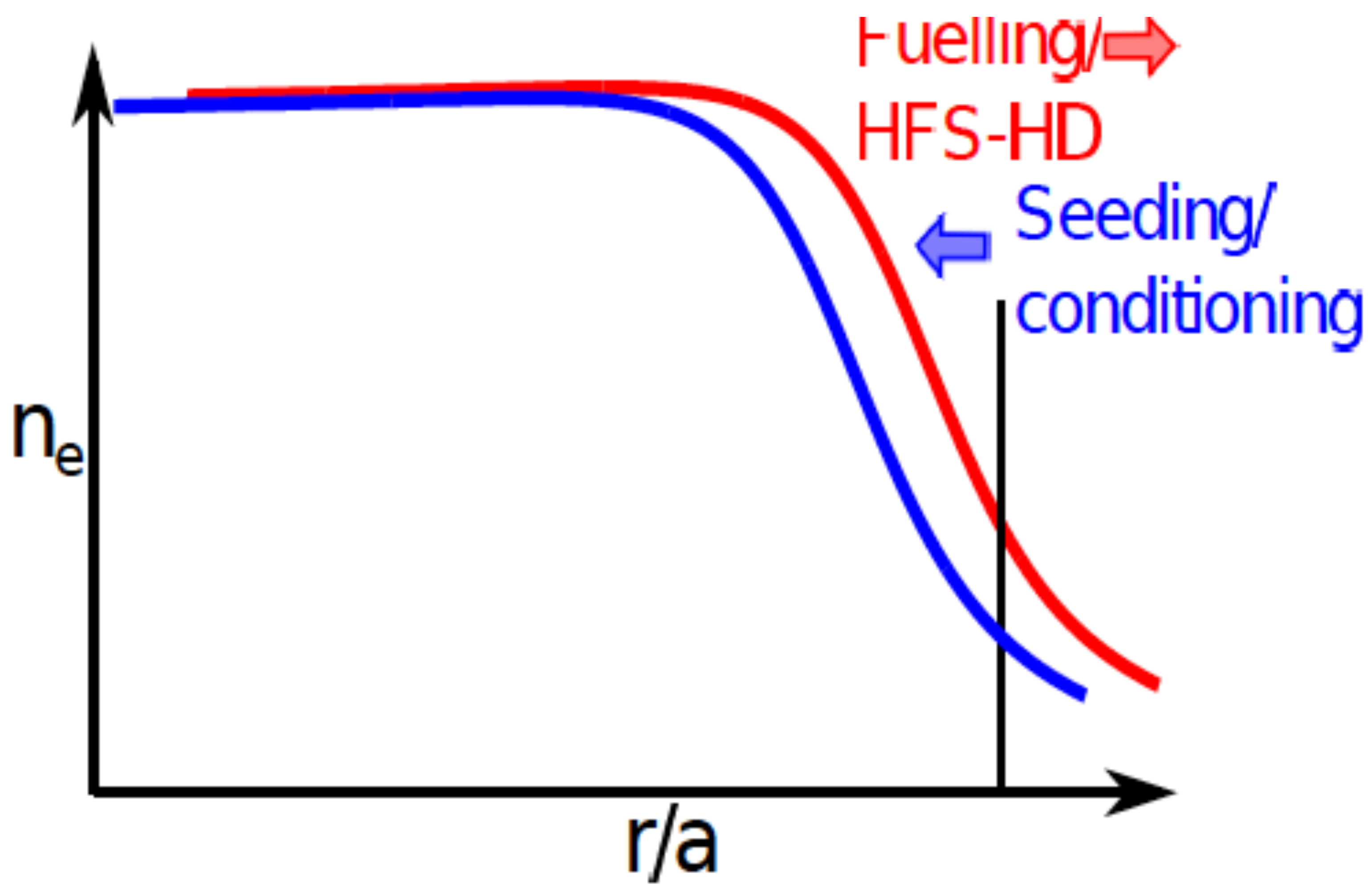
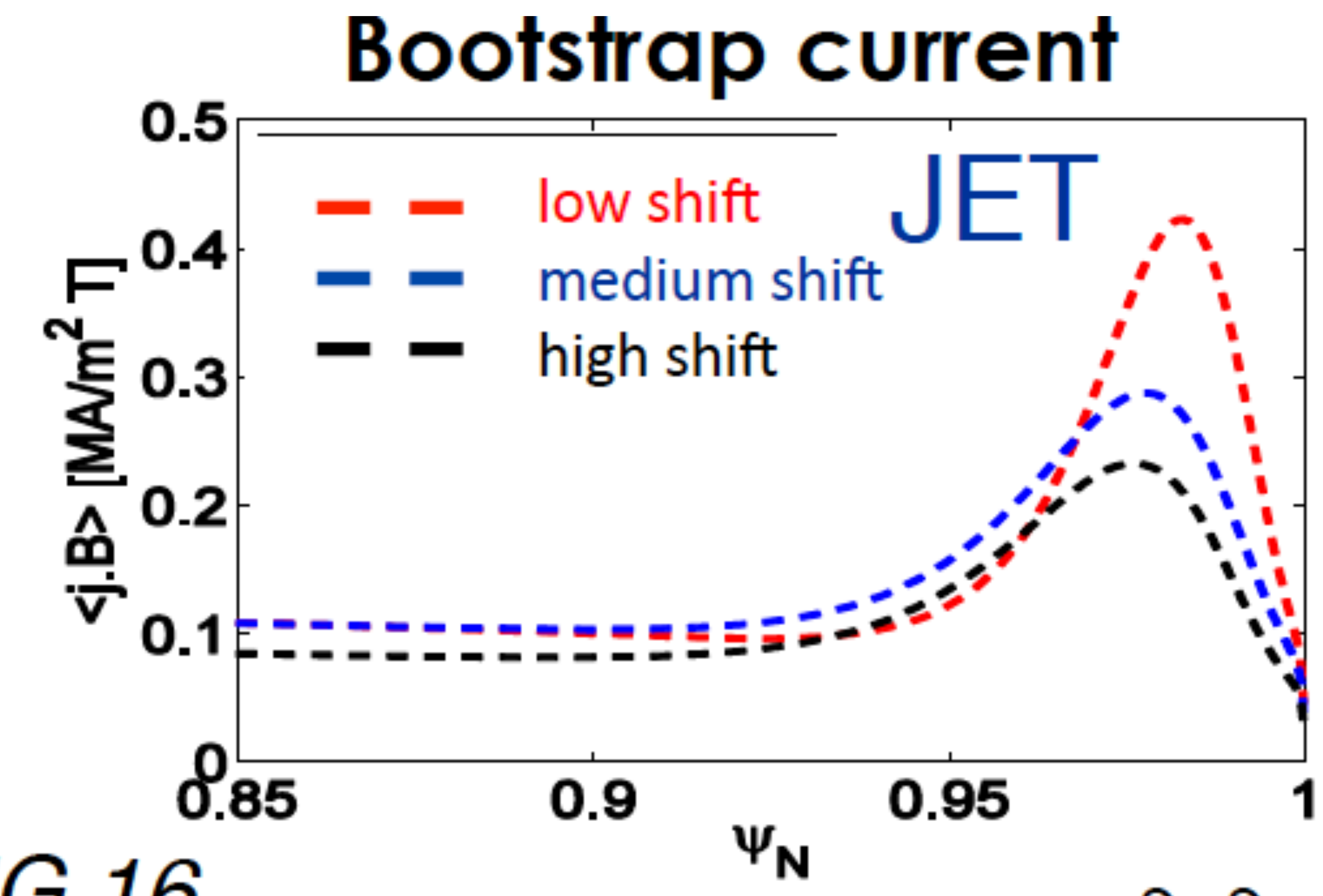
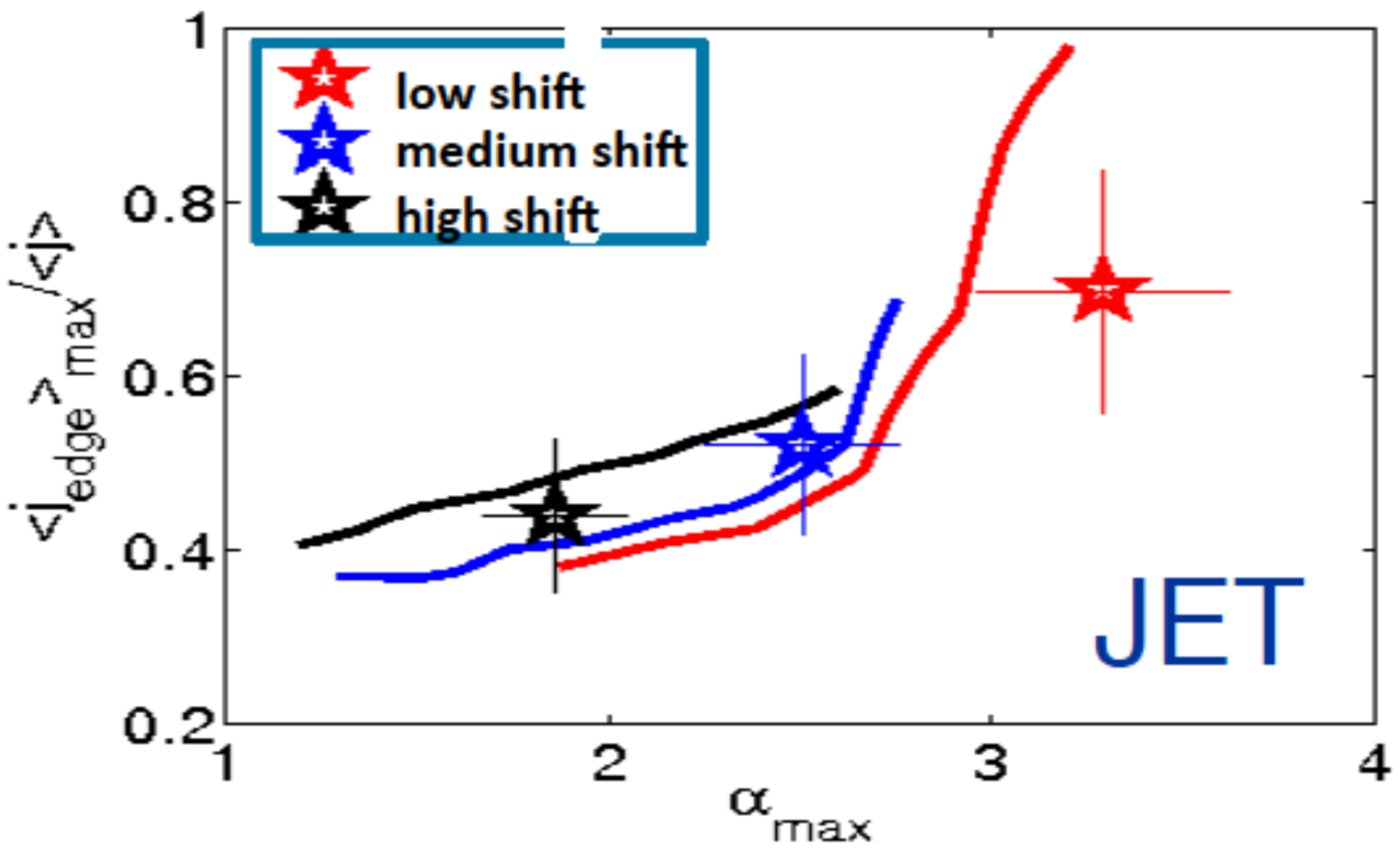
Fuelling and Impurity seeding can alter density profiles, and can deacrease or increase the pedestal height



M. Dunne, AUG 16





S. Saarelma 17, C. Maggi NF17

- **Density profile can be altered by fueling and seeding, changing collisionality and bootstrap current profile**
- **At high collisionality (p-limited pedestal), high gas puff unfavorable for pedestal height**

Predictive capability for effects of fueling and seeding on density and impurity profiles

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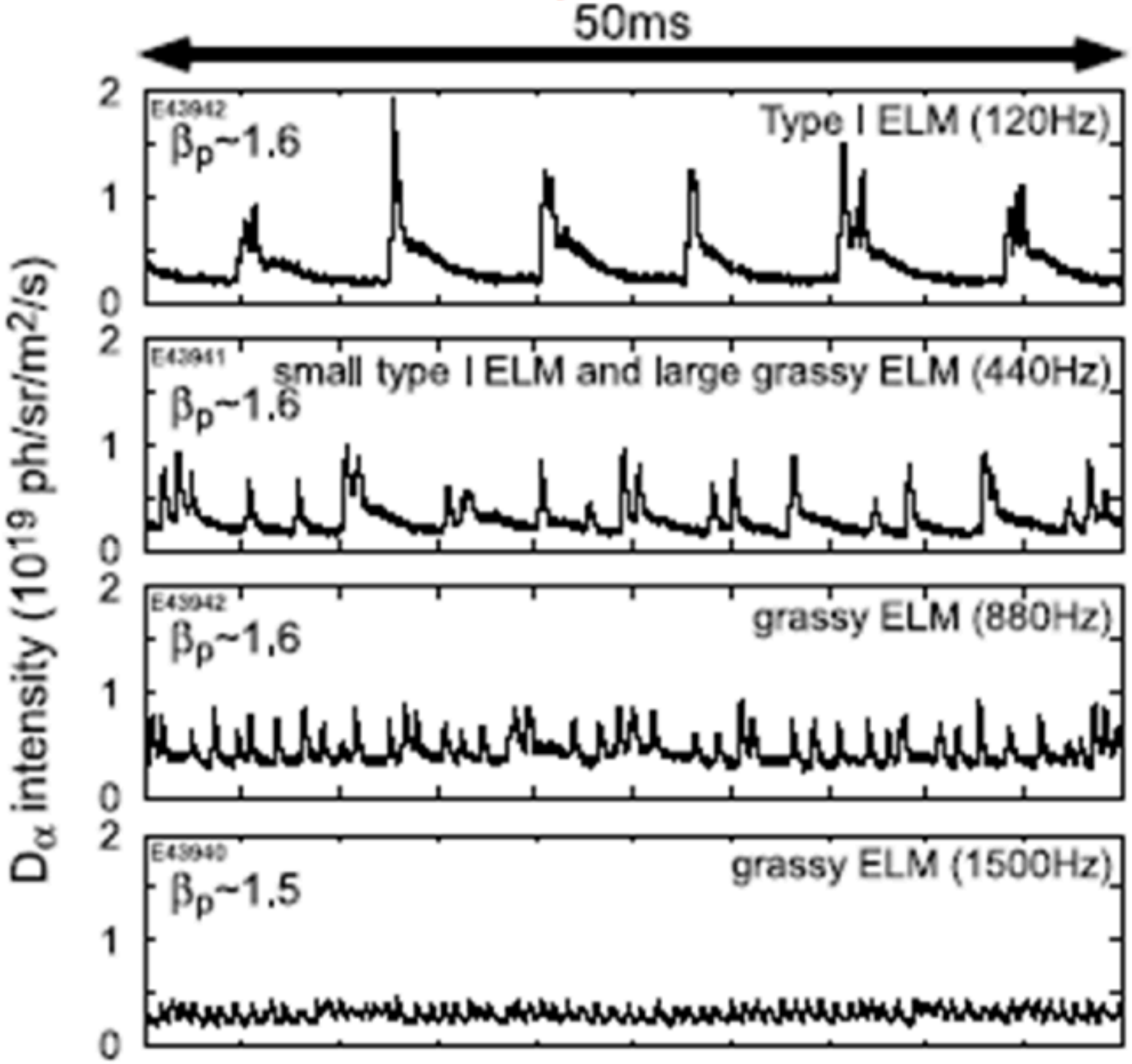
- Summary

Could this be an ingredient tom achieve small ELM regimes?

JT-60U *Oyama 2005*

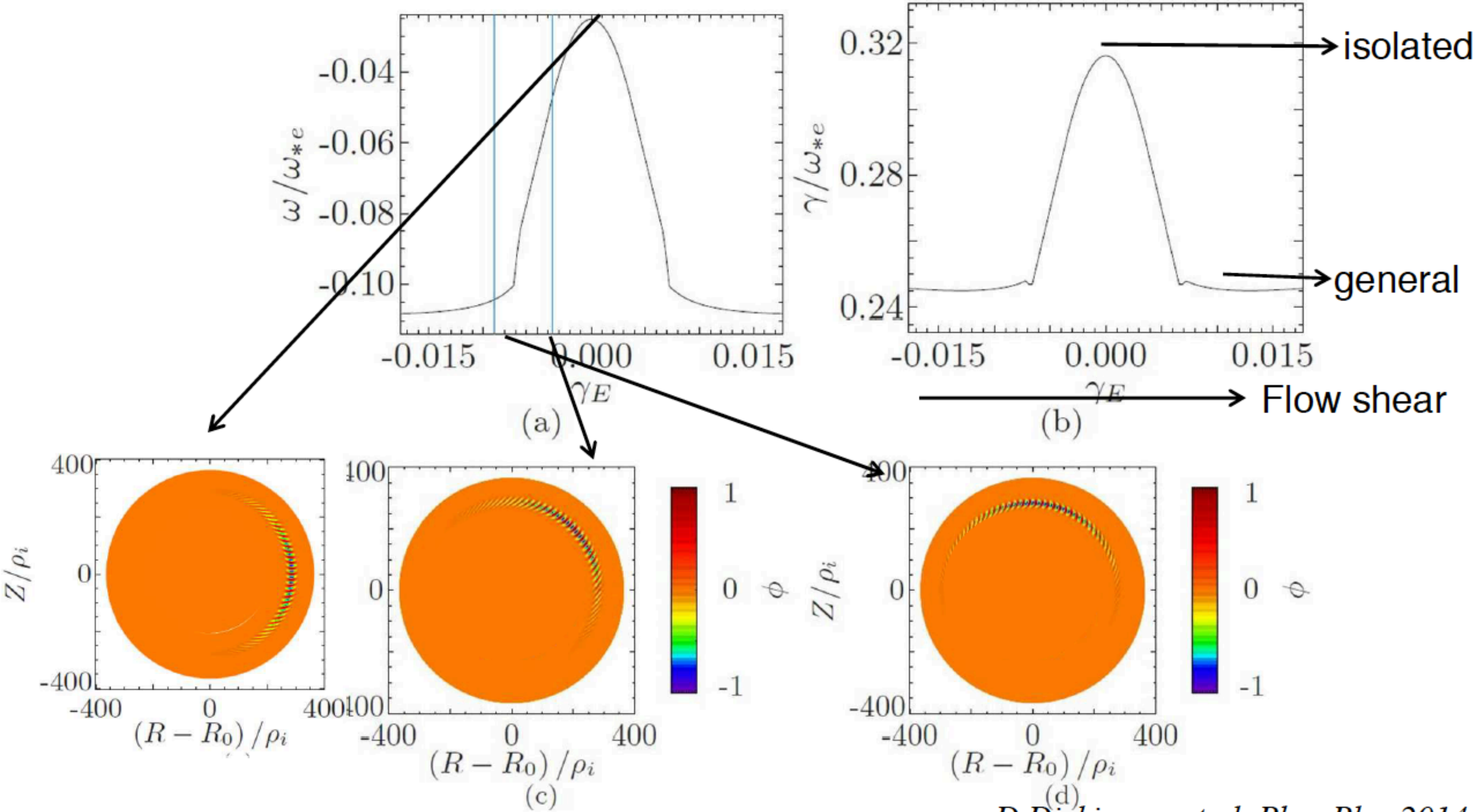


Large ELMs

Increase flow shear

Small ELMs

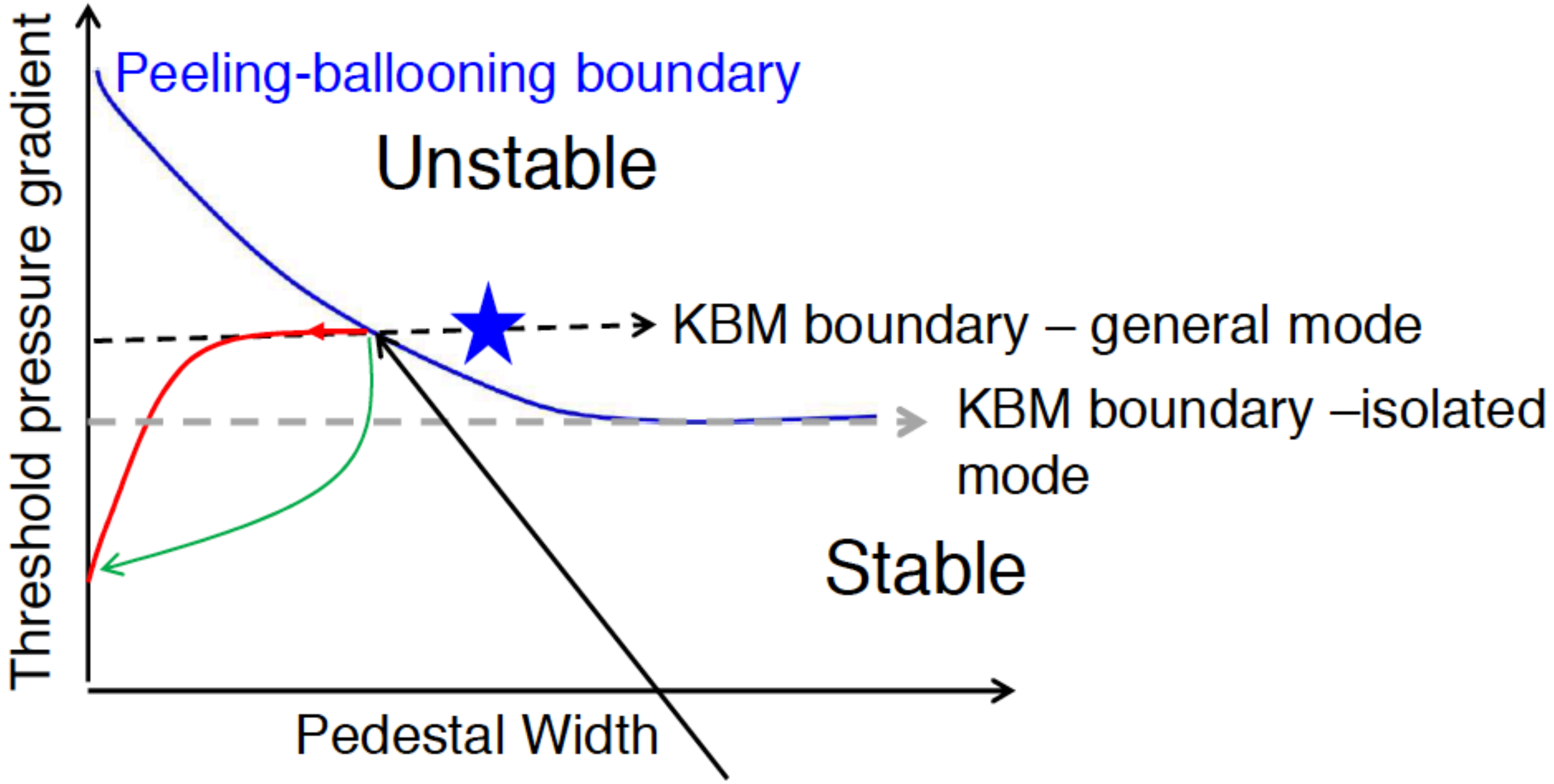
Flow shear provides a control knob: Transition between isolated and general modes



D Dickinson, et al, Phys Plas 2014

Towards a model for small (Grassy?) ELMs

- Return to our pedestal evolution model
- Assume at some point ✪ the conditions are right for the isolated mode
- Large ELM situation ✪ beyond ideal MHD boundary



PB mode leads to large ELM and plasma never accesses isolated mode

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Towards a model for small (Grassy?) ELMs

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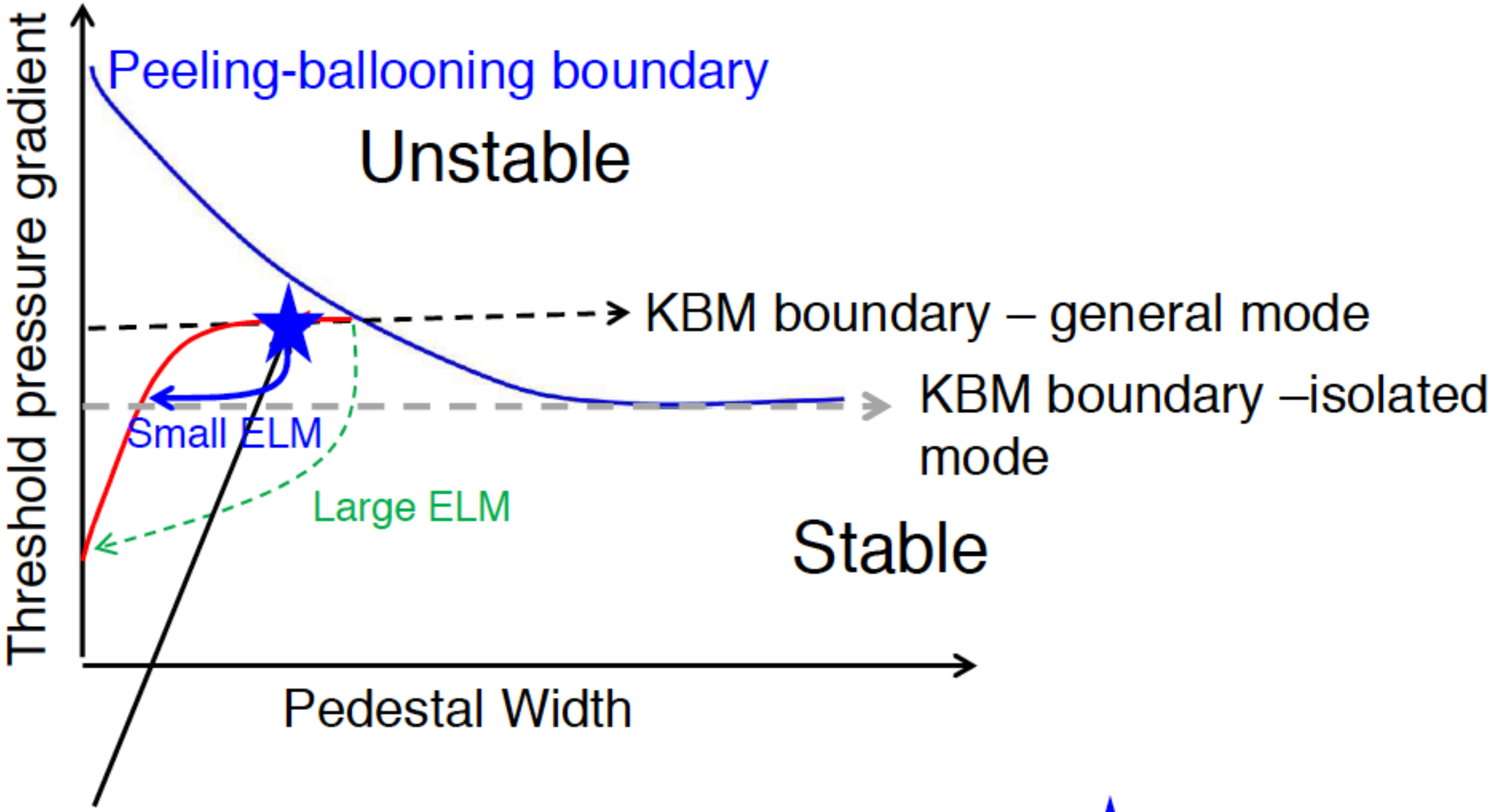
- **Return to our pedestal evolution model**
- **Assume at some point ✪ the conditions are right for the isolated mode**
- **Small ELM situation ✪ is encountered before large scale MHD event**



If conditions for isolated mode are satisfied at ★ (as flow evolves), plasma suddenly unstable ⇒ small ELM crash

Summary

- The pedestal region is key for confinement in ITER and the requirements of the plasma exhaust system
- The pedestal properties are a consequence of an interaction between turbulence and stability
- Plasma eruptions called ELMs are potentially very damaging for ITER
  - The largest "Type I" ELMs are well-understood in terms of peeling-ballooning modes, and cannot be tolerated on ITER
  - A range of possible ELM control techniques will be available on ITER
  - Ideal MHD stability properties indicate that the no-ELM QH Mode may be accessible for ITER (edge flow shear may be key) [See Max's Lecture]
  - Small ELM regimes are more of a challenge – we have some ideas, but still great uncertainty whether they can be accessed on ITER
- Despite being a very small region, the pedestal is key to ITER performance and operation

Take-home message

The critical region of interaction is the edge transport barrier (also known as the H-mode pedestal), which mediates the <u>tension</u> between core and edge, and plays a defining role in the performance of both.

Exciting New Discoveries in Pedestal Physics will lead to Improvements in Fusion Performance!