NSTX-U is sponsored by the
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Fusion Energy Sciences

Pedestal Structure and Control

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for the NSTX-U Team

NSTX-U PAC-39
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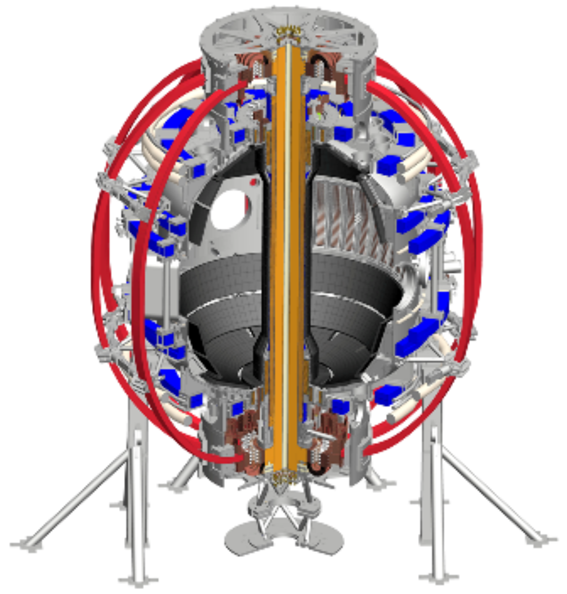

Supported by U.S. DoE under contract DE-AC02-09CH11466

NSTX-U will address important questions for H-mode pedestal in fusion science

- **High B_t and I_p, and access to strong shaping will extend pedestal structure studies to low ν, and high pressures**

Charge #3

- **Develop predictive pedestal model (EPED-like) for ST, and address open EPED questions for all R/a**

Charge #2

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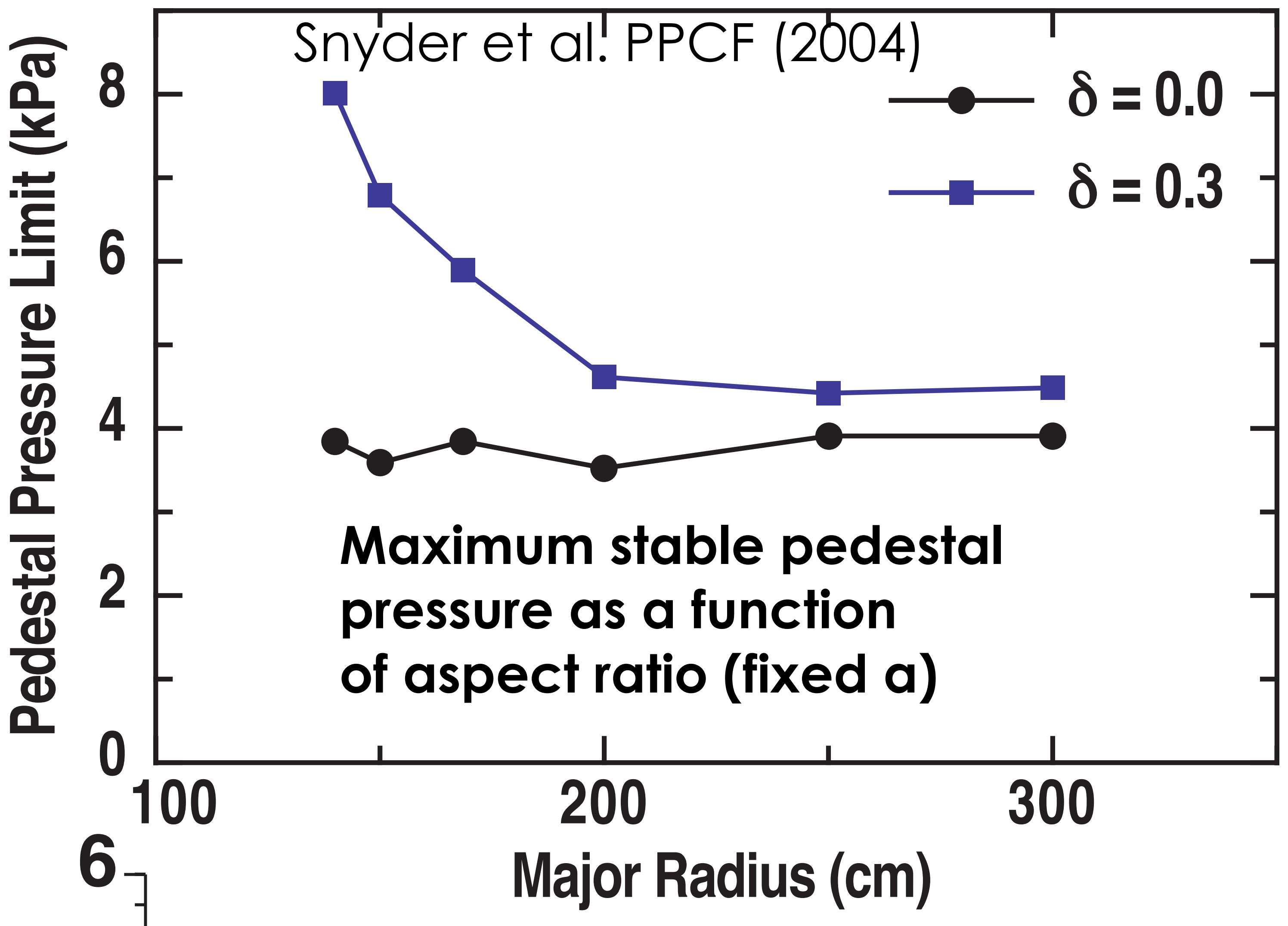
Strong shaping capability in NSTX-U will allow unique tests of ideal MHD stability limits

Charge #3

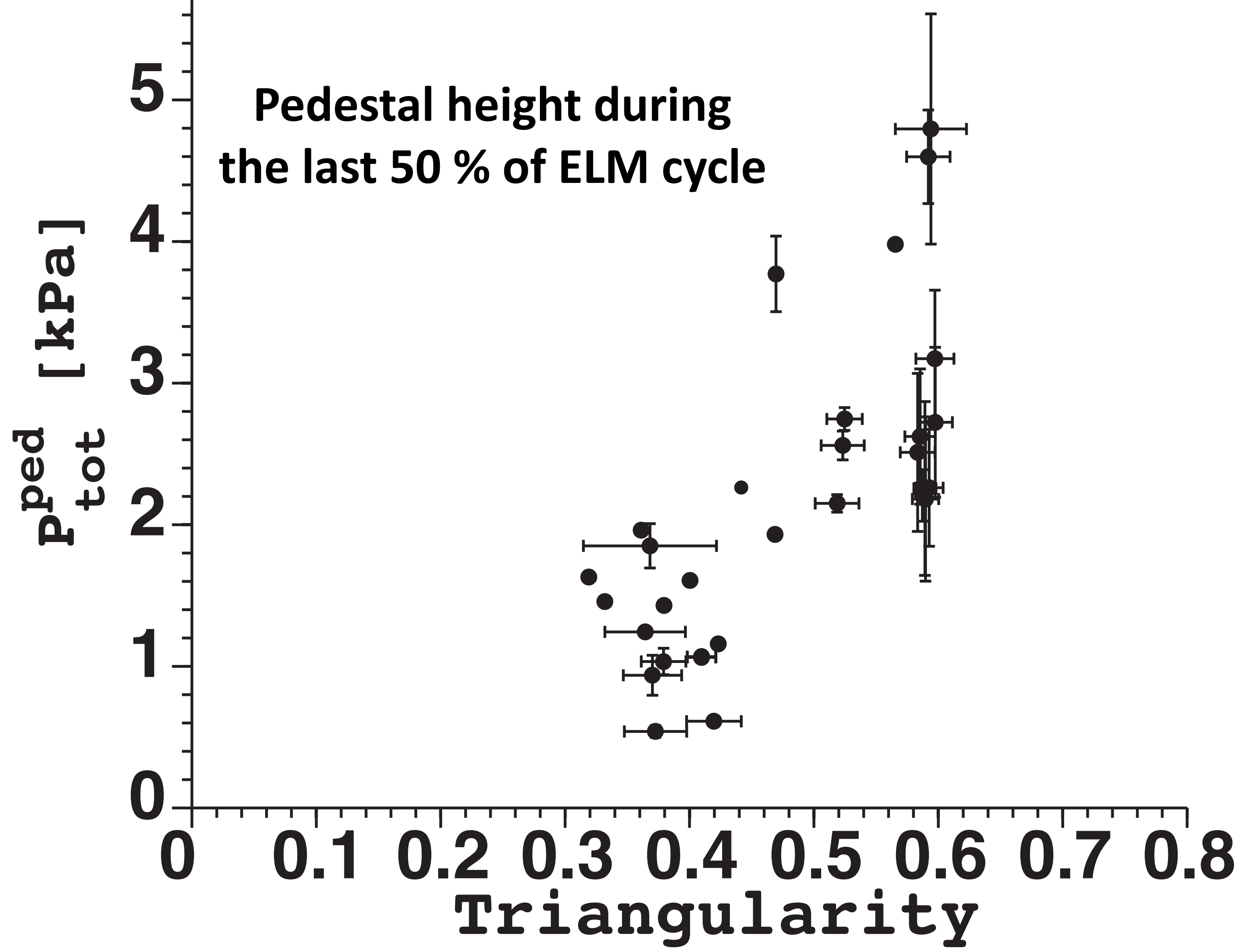
- **Ideal MHD has predicted improved edge stability at low R/a**
  - Magnitude of improvement depends on triangularity, elongation, squareness

- **NSTX showed strong increase in pedestal pressure with triangularity**

- **NSTX-U will have the widest range of δ (0.3-0.8), κ (1.8-2.7), and squareness (0-0.5) to determine the optimum pedestal stability limits**
  - Flexible shaping at high power.



Maximum stable pedestal pressure as a function of aspect ratio (fixed a)



Pedestal height during the last 50 % of ELM cycle

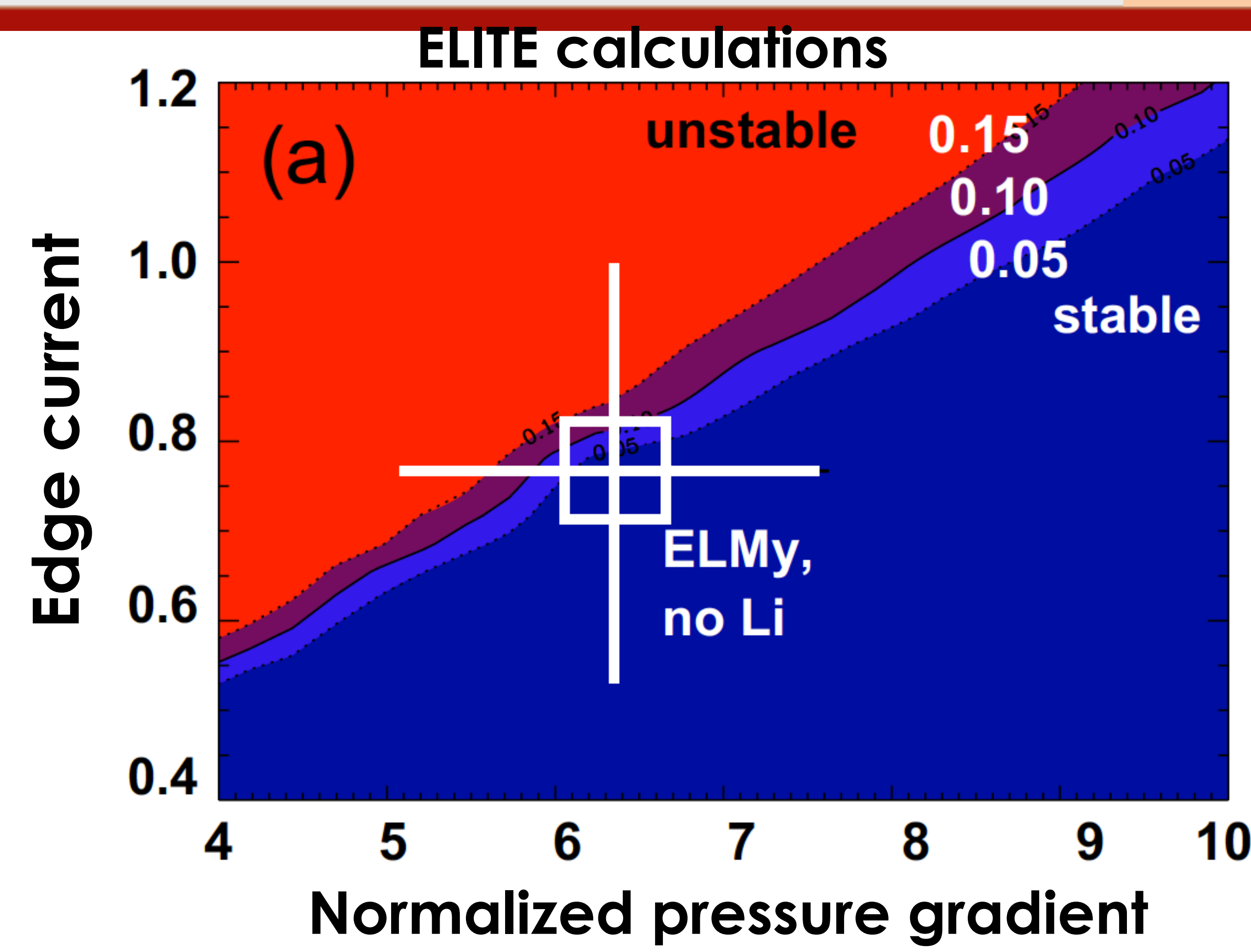
Low collisionality achievable in NSTX-U will access pedestals with ideal and resistive MHD

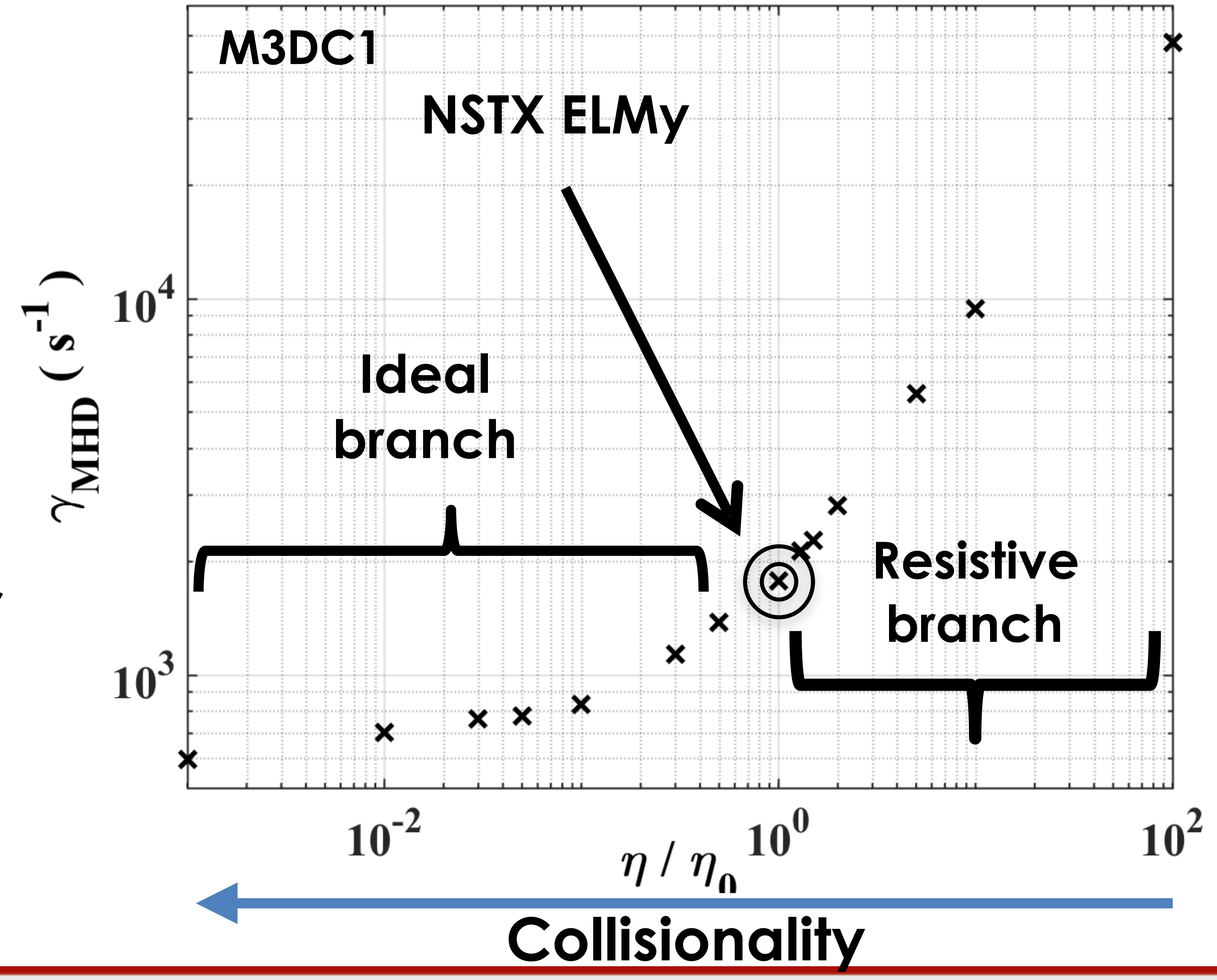
Charge #3

- **In NSTX, stability analysis of ELMy H-modes identified slowly growing peeling-ballooning modes**
  - $0.05 < \gamma/\omega^*/2 < 0.1$ just before ELM onset

- **Resistive MHD calculations with M3D-C1 suggest resistive modes have larger growth rate ➟ unstable (G. Canal, to be published)**
  - NSTX had pedestal top $\nu > 0.5$, so resistive MHD cannot be neglected

- **NSTX-U pedestal top collisionality is projected to go down to 0.1, so ideal and resistive MHD effects can be separated**
  - Better chance of achieving edge ideal MHD stability limits





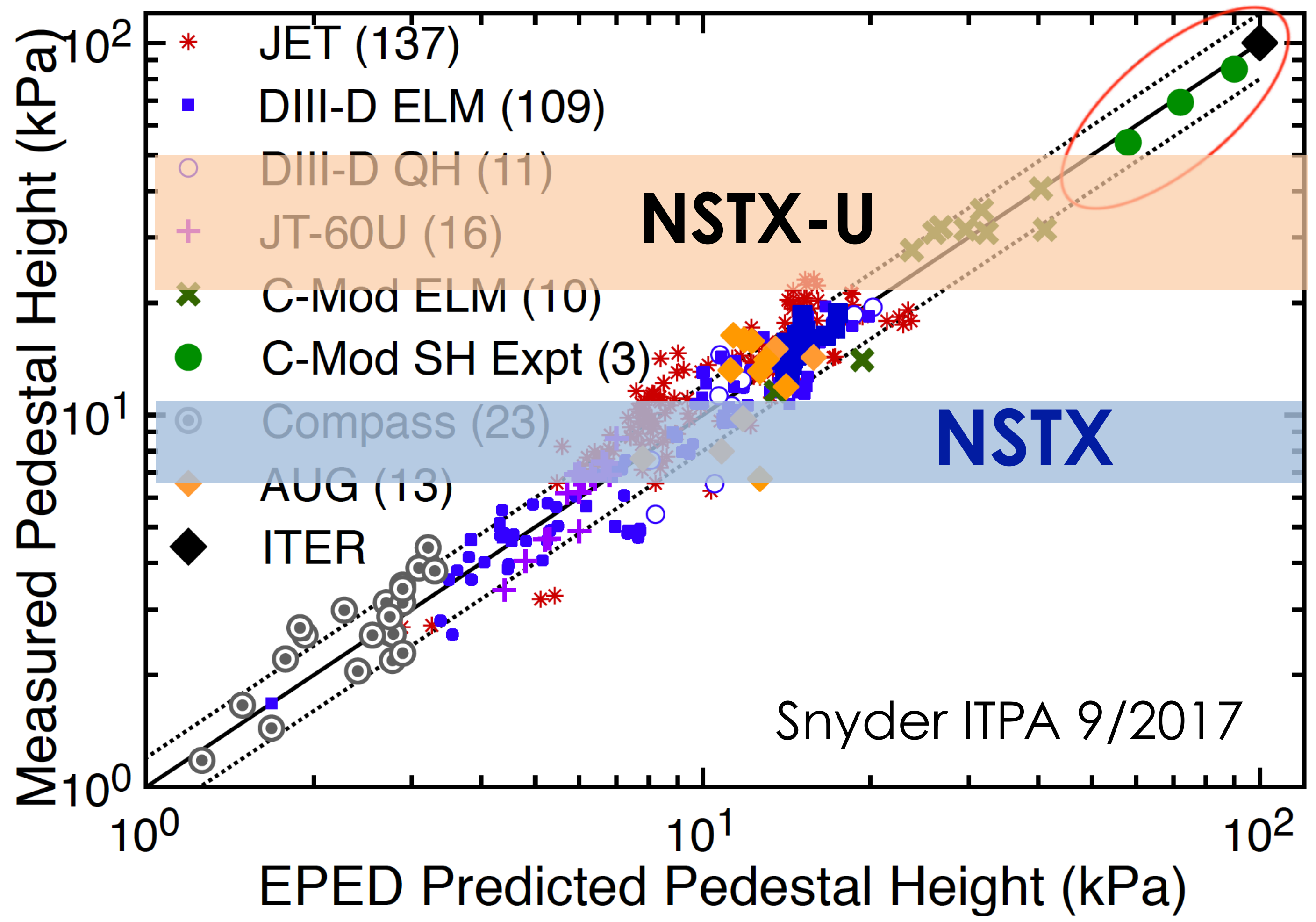
Higher I_p, B_t and heating power in NSTX-U will increase pedestal pressure by 3-5x from NSTX

Charge #3

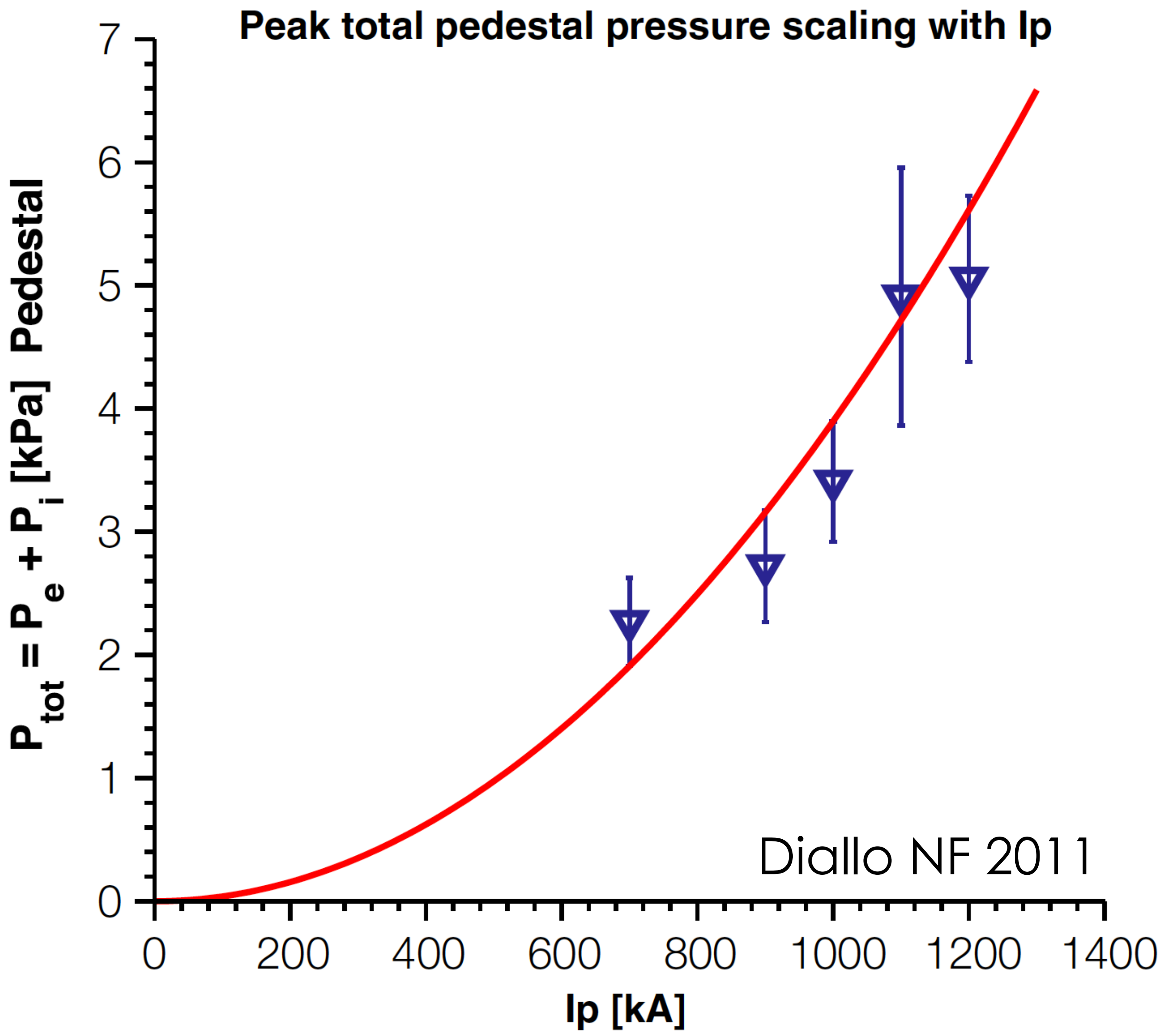
- $\beta_n \propto \langle P\rangle/(B_t \times I_p) \Longrightarrow \langle P\rangle \sim \beta_n \times I_p \times B_t$

- Assume constant β_n then $P_{ped} \sim \langle P\rangle \Longrightarrow P_{ped}$ ➠ **3x higher in NSTX-U than NSTX**
  - 15 - 20 kPa ELMy H-mode & 20 - 30 kPa for enhanced confinement regimes

- In NSTX, some evidence that $P_{ped} \sim I_p^2 \Longrightarrow$ 27 - 36 kPa ELMy and 36 -54 kPa for enhanced confinement regimes
  - **Highest projected pedestal pressure for an ST**



Snyder ITPA 9/2017



Diallo NF 2011

NSTX-U will address important questions for H-mode pedestal in fusion science

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Charge #3

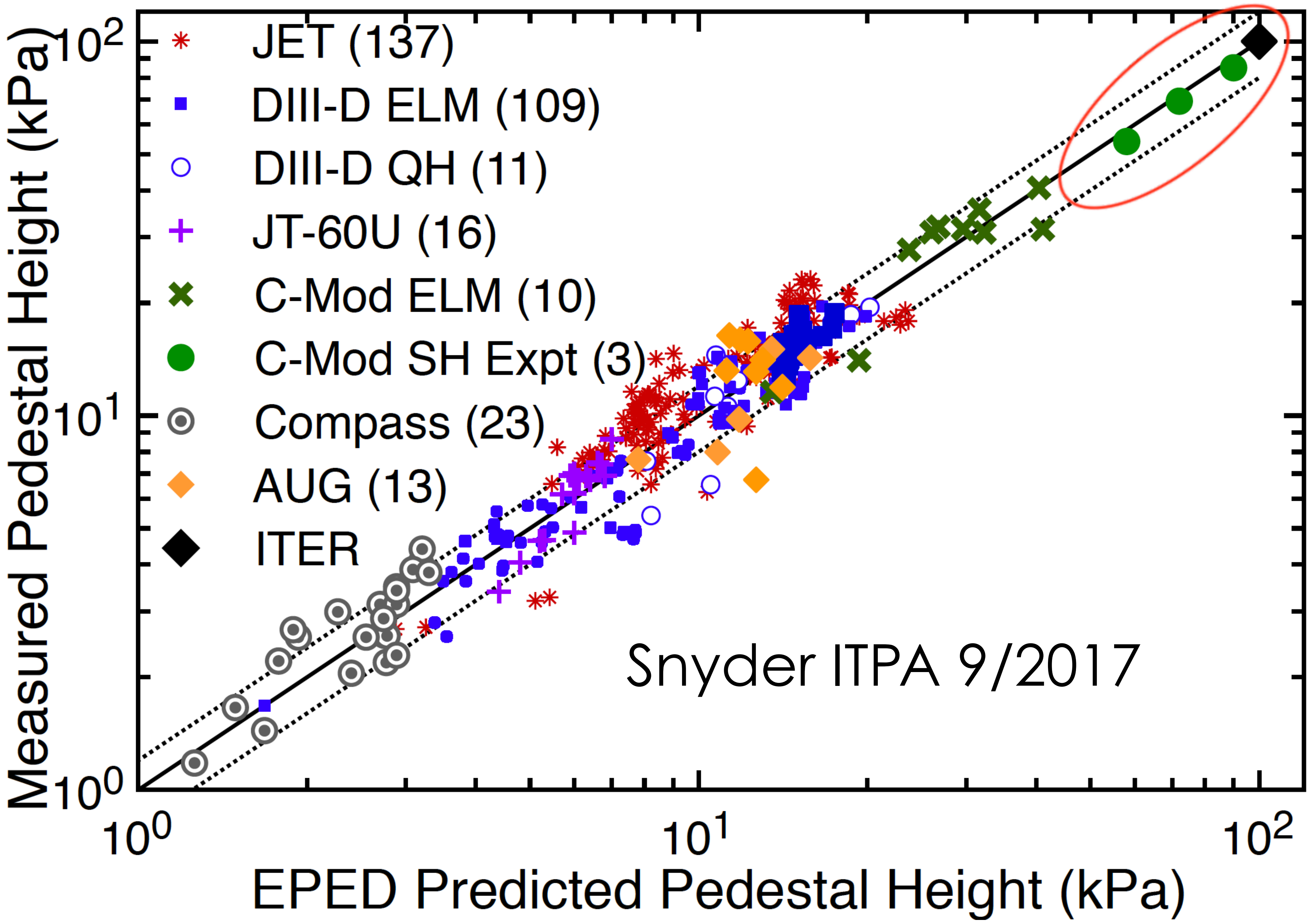
- Develop predictive pedestal model (EPED-like) for ST, and address open EPED questions for all R/a

Charge #2

There is a need to develop pedestal predictive EPED-like model for ST

Charge #2

- **EPED is a pedestal model with predicts pedestal pressure height and width**
  - based on two key limiting instabilities
    - nearly local kinetic ballooning modes (KBMs) → regulate transport between ELMs
    - non-local peeling–ballooning (P–B)mode → trigger for edge-localized mode (ELM)



Snyder ITPA 9/2017

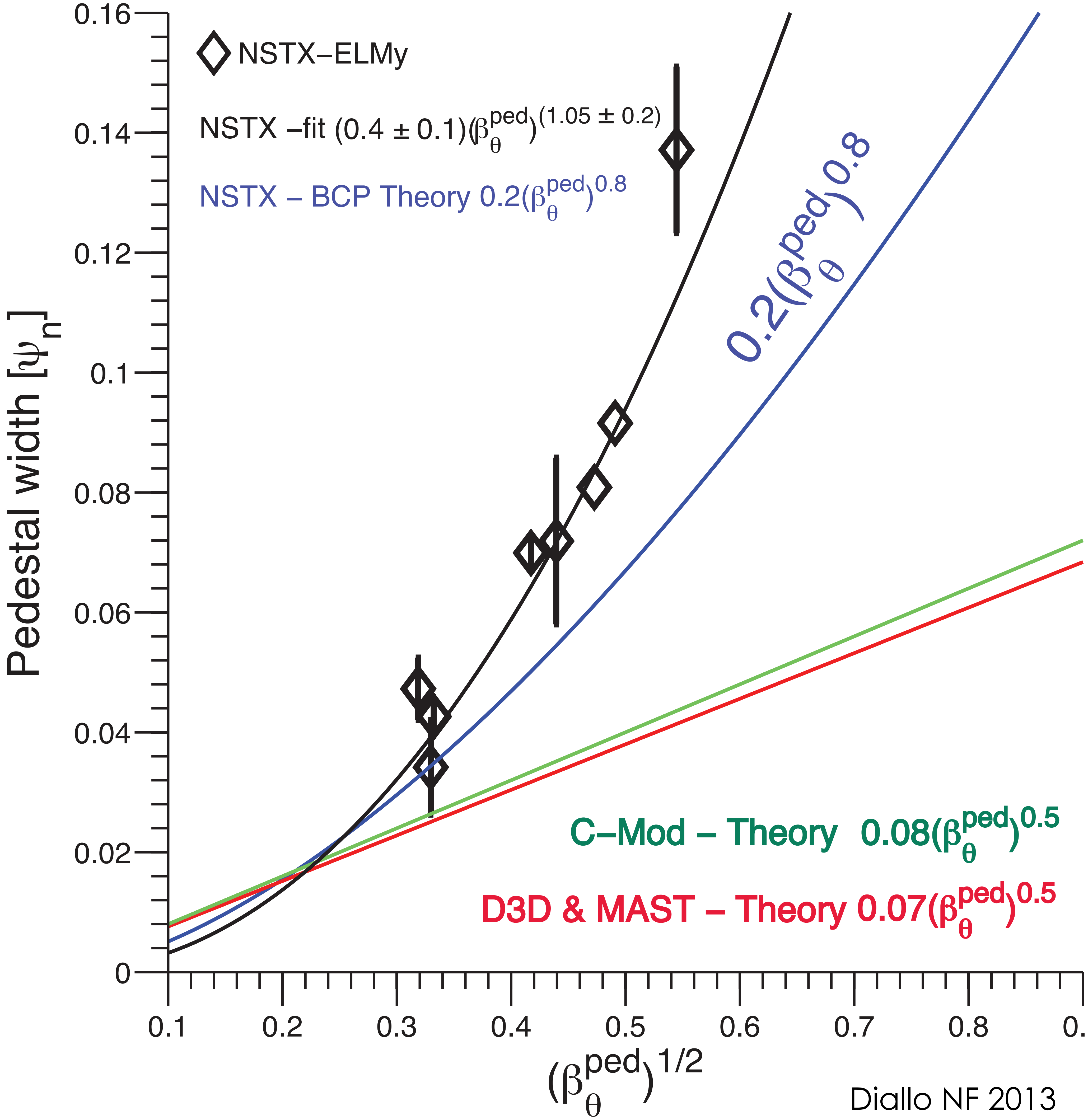
- **EPED 1.6 is in good agreement with large multi-machine datasets**

- **However, EPED fails to predict STs**

NSTX showed a larger pedestal width with different scaling than EPED predictions for higher R/a

Charge #2

- **EPED KBM constrain results in width ~ $0.076\times\sqrt{\beta_{pol}^{ped}}$**
  - In NSTX, both the leading constant and exponent were larger and qualitatively consistent with preliminary calculations: $0.4\times(\beta_{pol}^{ped})^{1.05}$ Groebner NF 2013
- **NSTX and MAST typically operated at different points within the stability boundary**
  - NSTX was typically kink peeling limited (low-n)
  - MAST was shown to be limited by high-n ballooning modes or at the nose of the peeling-ballooning limit
- **Large range of pedestal pressure (from $1.7\mathrm{x}I_p$ and $1.8\mathrm{x}B_t$), and excellent pedestal diagnostics are necessary ingredients for development of EPED-like model for ST**

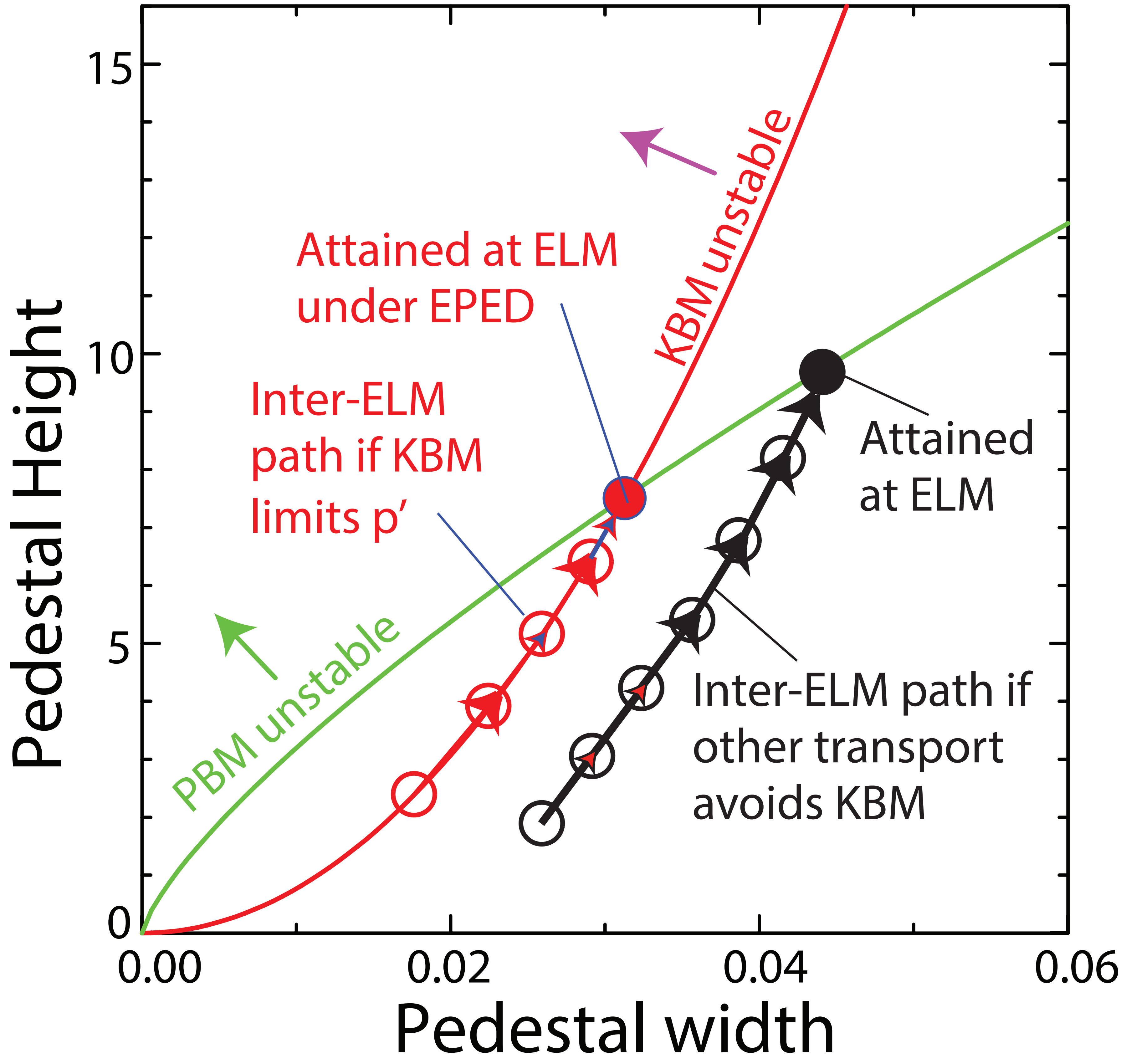


Diallo NF 2013

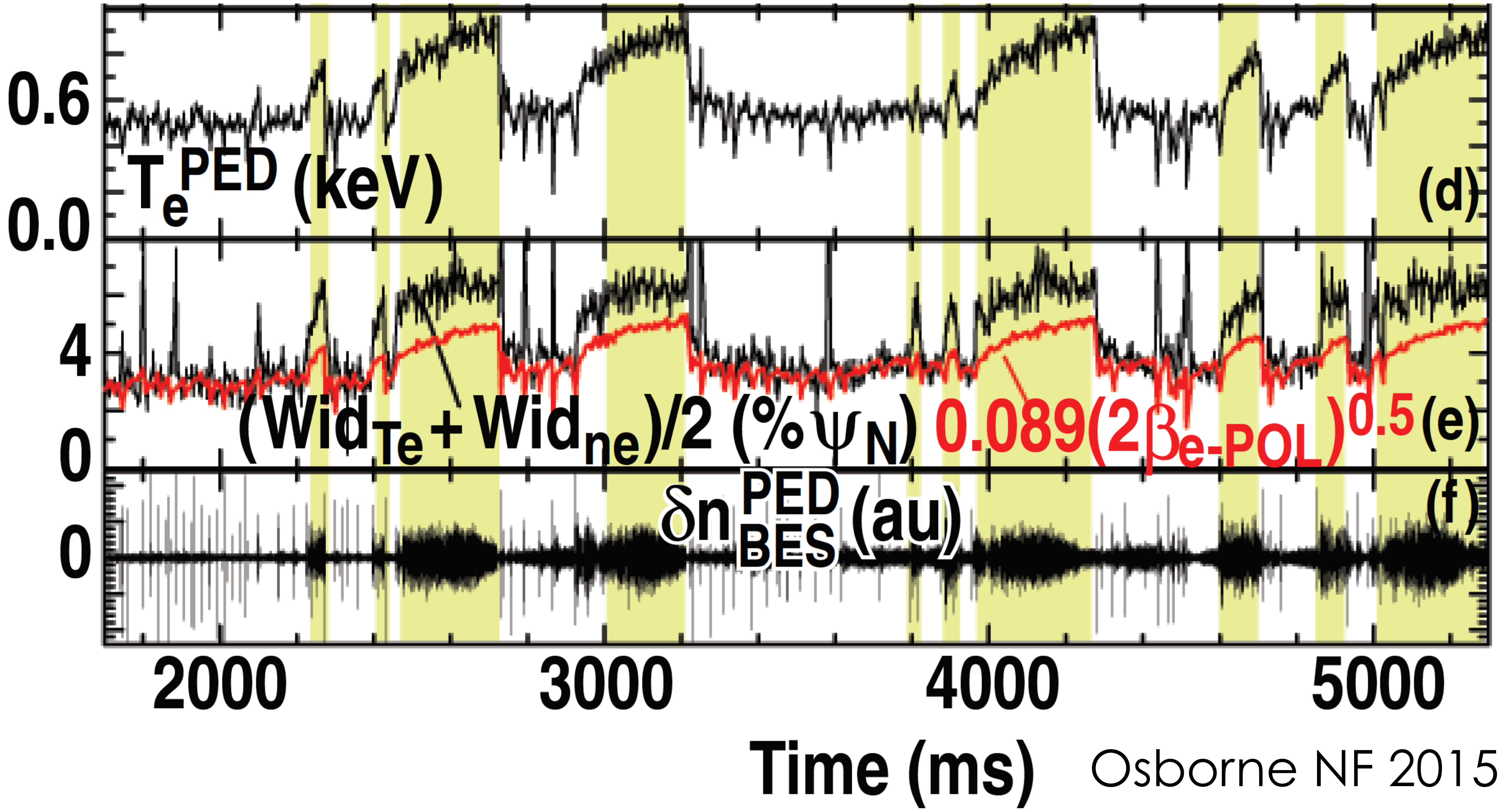
EPED width scaling fails in presence of pedestal localized instabilities that are not KBM

Charge #2

- If transport can reduce gradients below KBM onset limit, pedestal can grow wider and higher before ELM onset due to peeling-ballooning mode



- Presence of bursty chirping mode BCM (stimulated by Li injection) allowed pedestal width and height to grow well above EPED predictions

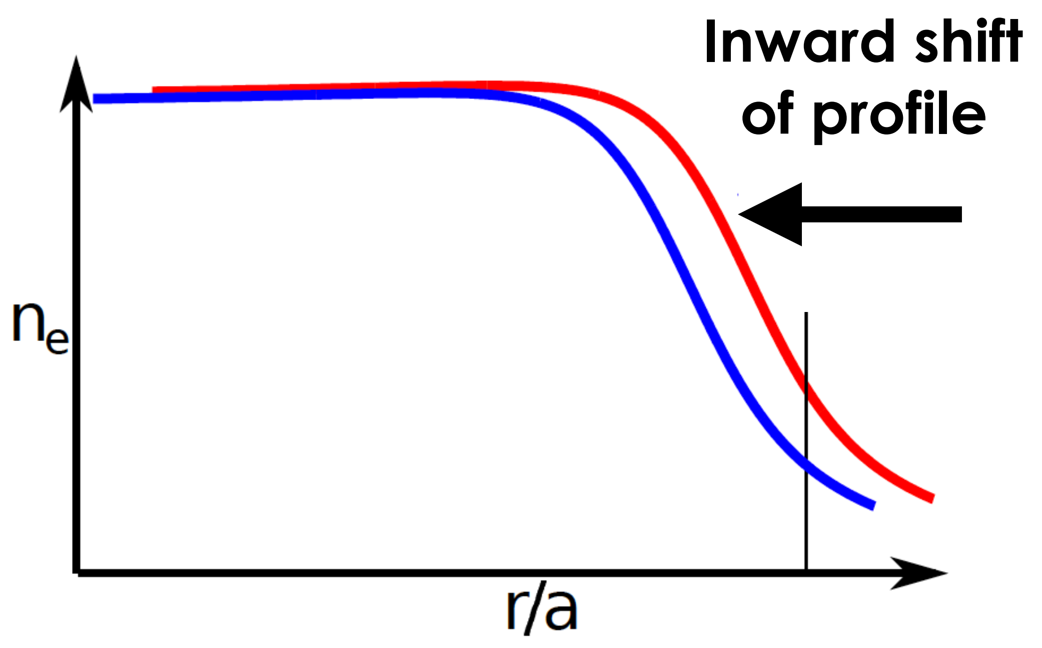


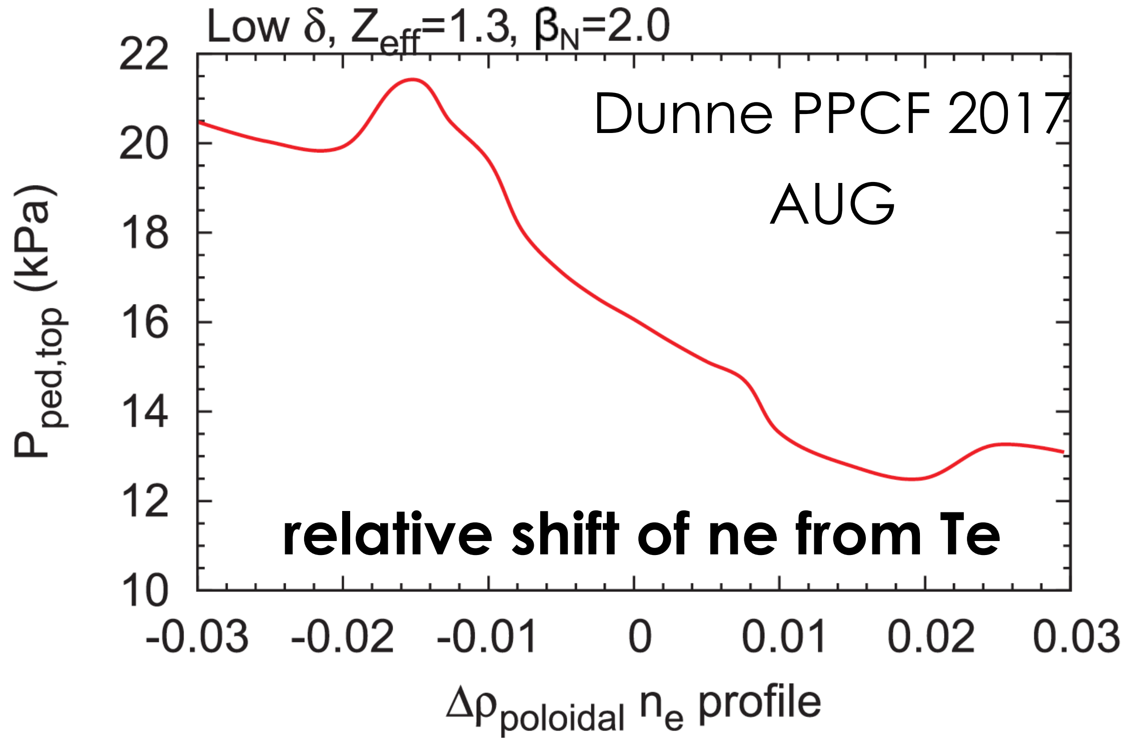
Osborne NF 2015

Variations of the density profile relative to the temperature profile can improve understanding of pedestal structure towards optimization

Charge #2 & #3

- **Shift in n_e profile relative to T_e profile allows higher P_{ped} with N_2 seeding, e.g. from AUG**
  - Allows ~ 2x higher pedestal pressure experimentally and theoretically

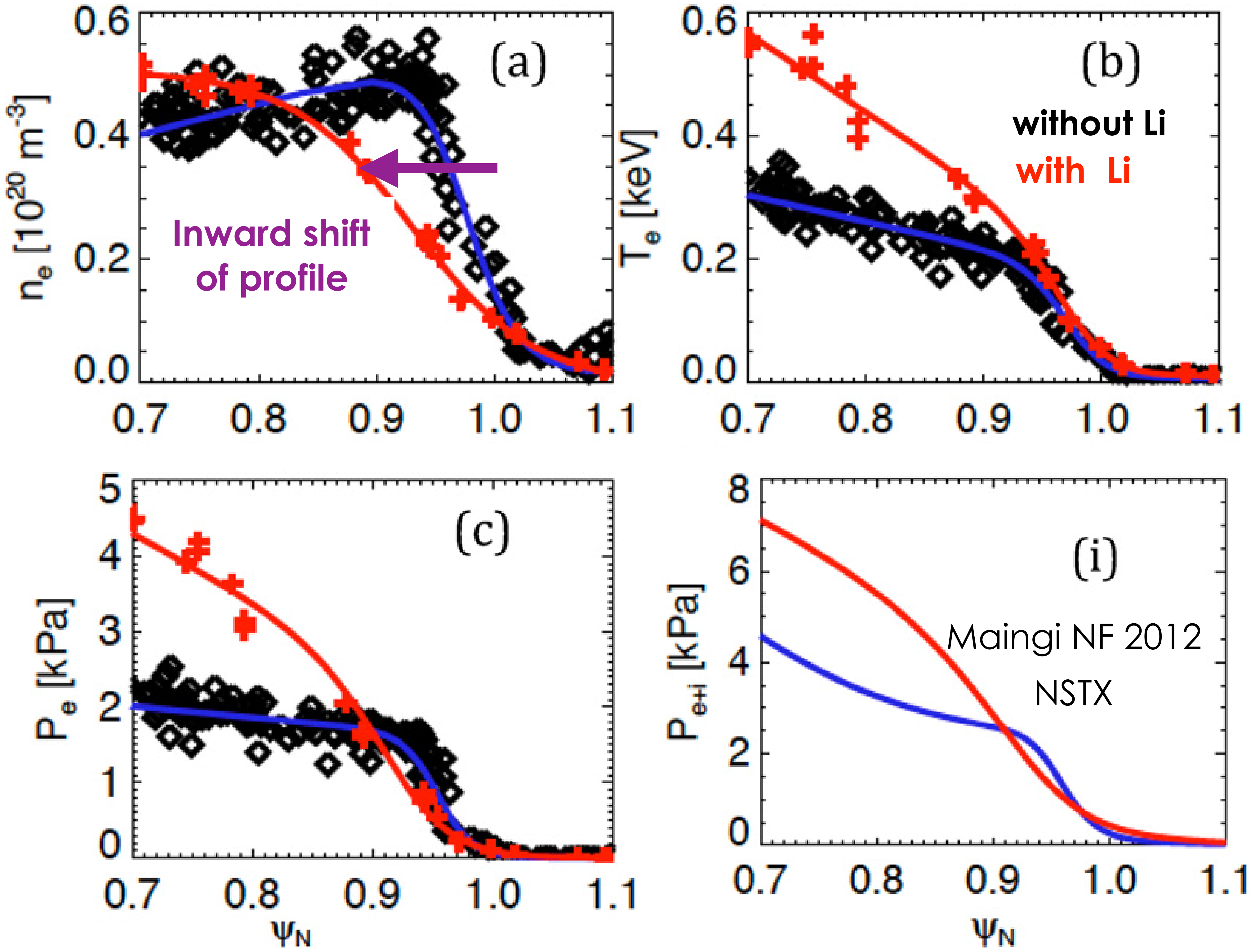




- **Relative shift in density profile relative to temperature profile was up to 10% in ψ_n in NSTX with Li conditioning, compared with e.g. 5% in DIII-D and 2-3% in AUG**
  - Widest range of profile control demonstrated in NSTX
  - 2x higher total P_{ped}

JRT 2019: NSTX will be used to test how fueling, reduced recycling, and transport affect the density pedestal structure.

- **NSTX & NSTX-U can control the amount of the profile shift by varying the amount of Li conditioning**
  - Help to understand the relative roles of the n_e and T_e profiles in achievable pedestal stability at all R/a



NSTX-U with its comprehensive diagnostic suite coupled with first principle codes will provide world class SOL turbulence research

Charge #2,#3,#4

- **SOL turbulence plays an important role in confinement, plasma-material interaction, and L-H transition physics**
  - Edge turbulence contributes to transport across the separatrix, and affects the edge temperature profile and density profile
  - **However, for SOL turbulence there is incomplete validation of first-principle modeling**

Zweben NF 2015 and PPCF 2016
for summary of NSTX GPI SOL results

- **NSTX provided excellent edge turbulence (via 2D GPI & BES) coverage in large range of physics parameters that motivated modeling with SOLT, GBS, and XGC1**
  - See Zweben NF 2015, PPCF 2016 for a summary

- **High B_t and I_p as well as low collisionality will enable NSTX-U to advance SOL turbulence research**

Maqueda NF 2010, Scotti RSI 2012

  - Complete coverage for the divertor imaging as well as mirror Langmuir probes will enable the study of the 3D turbulence structure
  - Provide direct connection with first principle simulation (e.g., XGC1)

NSTX-U will have excellent pedestal turbulence diagnostics coverage as well as state-of-art simulation codes

Charge #3

- **Pedestal turbulence has been shown (see backup slide 17) to exhibit robust observation suggesting robust physics at play in standard R/a ➠ that could be extended in ST**
  - University of Wisconsin will have BES channels aimed at the pedestal to resolve low-k density fluctuations
  - The UCLA Team will be providing intermediate-k density (DBS) and magnetic(CPS) fluctuations, as well as fixed frequency reflectometers
  - UC-Davis in collaboration PPPL will provide high-k and 2D imaging low-k density fluctuations
  - Collaboration with PSFC plan to install the Mirror Langmuir probes

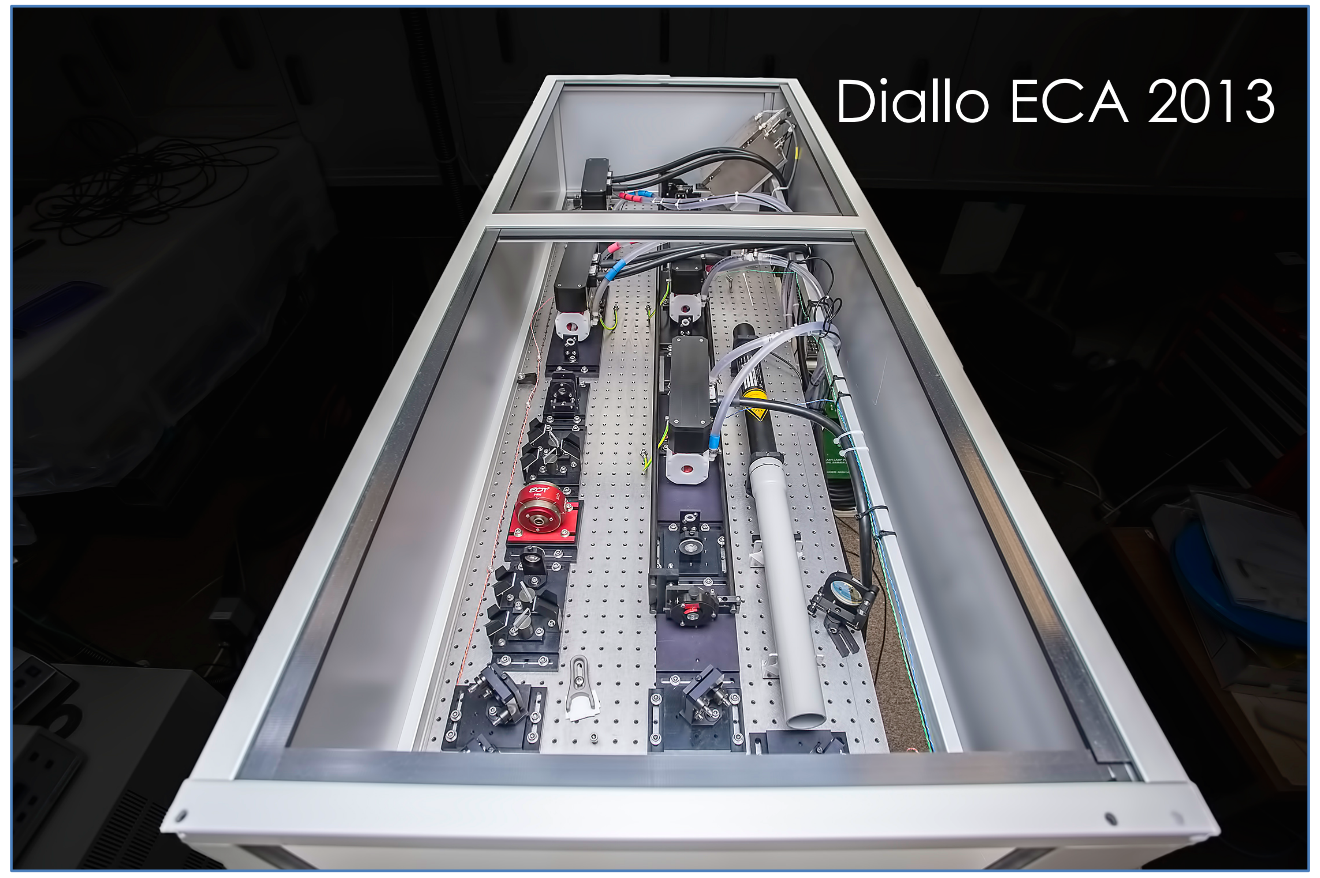
- **Pedestal simulations will support the turbulence measurements by identifying the fluctuations and associated transport**
  - CGYRO; GENE & XGC1

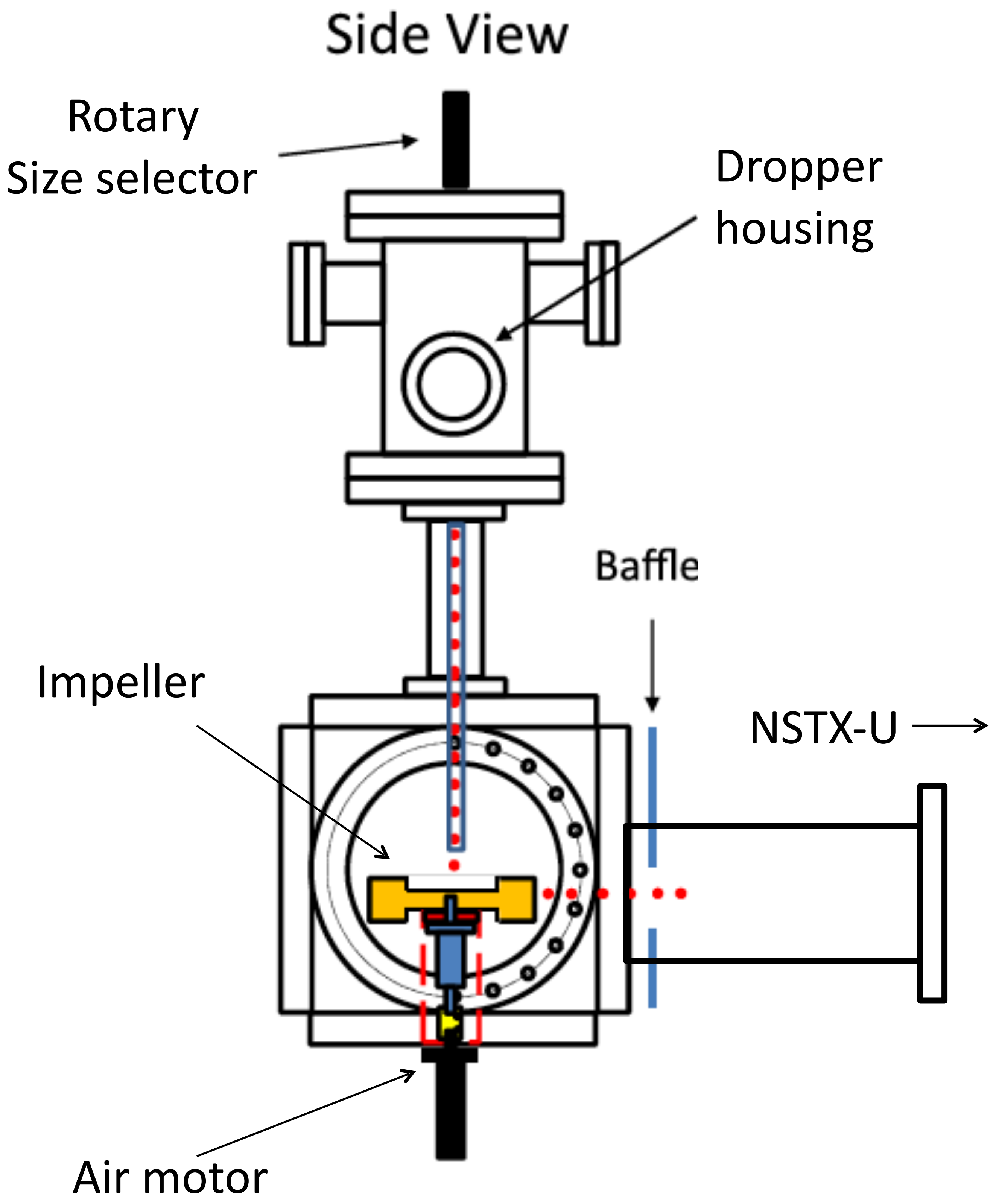
NSTX-U will provide world class pedestal evolution diagnosis and control

Charge #2 & #3

- **World leading pedestal diagnosis of inter-ELM cycle with the Pulsed Burst Laser System (PBLS) (up 20 kHz rep rate)**
- **ELM mitigation via ELM pace-making with a number of actuators**
  - Impurity granule injector (B, Li, C, …)
  - Magnetic perturbations
  - Vertical jogs
- **ELM elimination via low-Z injection**
- **Prospects for advanced control of pedestal with PBLS and actuators**

Pulsed Burst Laser System (PBLS)


Diallo ECA 2013



NSTX-U will address important questions for H-mode pedestal in fusion science

- **High B_t and I_p, and access to strong shaping will extend pedestal structure studies to low collisionality, and high pressures**

  Charge #3
  - Access to low ν will enable to disentangle the roles of ideal MHD and resistive MHD in ELM stability, an unresolved puzzle from NSTX
  - Wide range of shaping (δ = 0.3-0.8, κ= 1.8 to 2.7, squareness 0 to 0.5, double-null vs single-null) will enable unique tests of edge stability at low R/a
  - Higher I_p, B_t in NSTX-U will increase previous pedestal pressure by 3-5x

- **Develop predictive pedestal model (EPED-like) for ST, and answer open EPED questions independent of R/a**

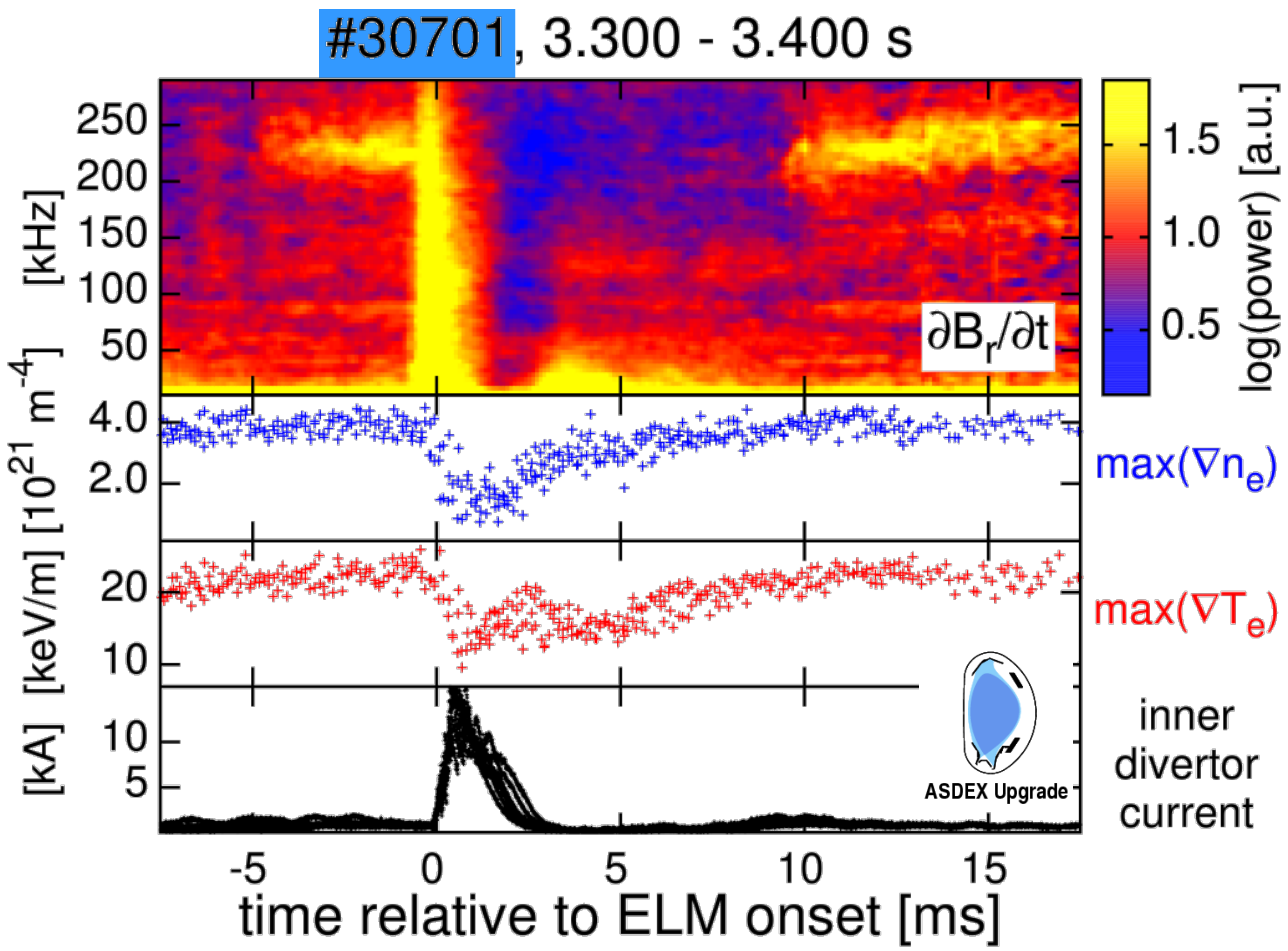
  Charge #2
  - NSTX-U will explore the pedestal width scaling different from conventional aspect ratio
  - Lithium coating will be used to manipulate recycling and density profile to understand pedestal stability and performance

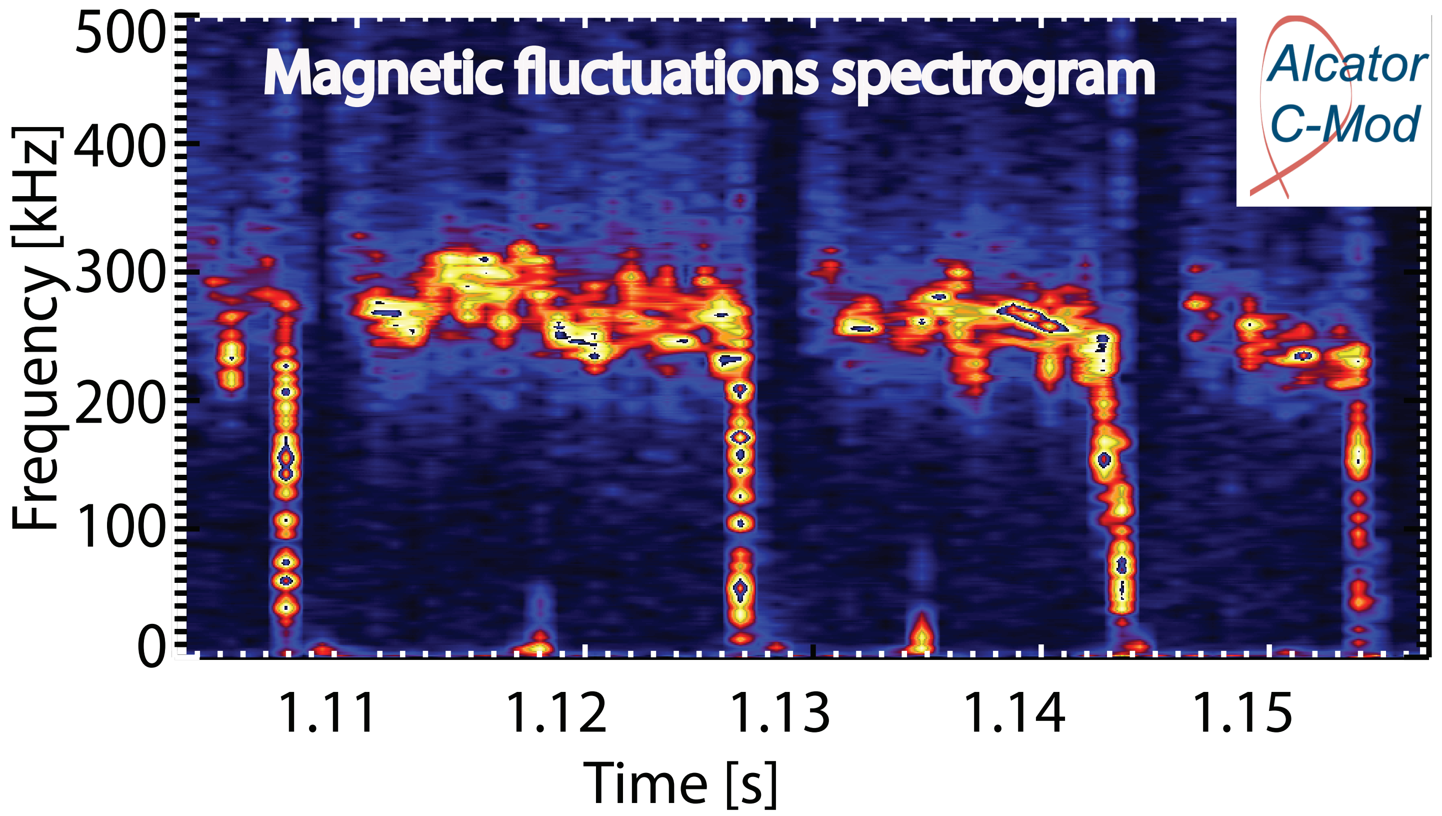
Backup

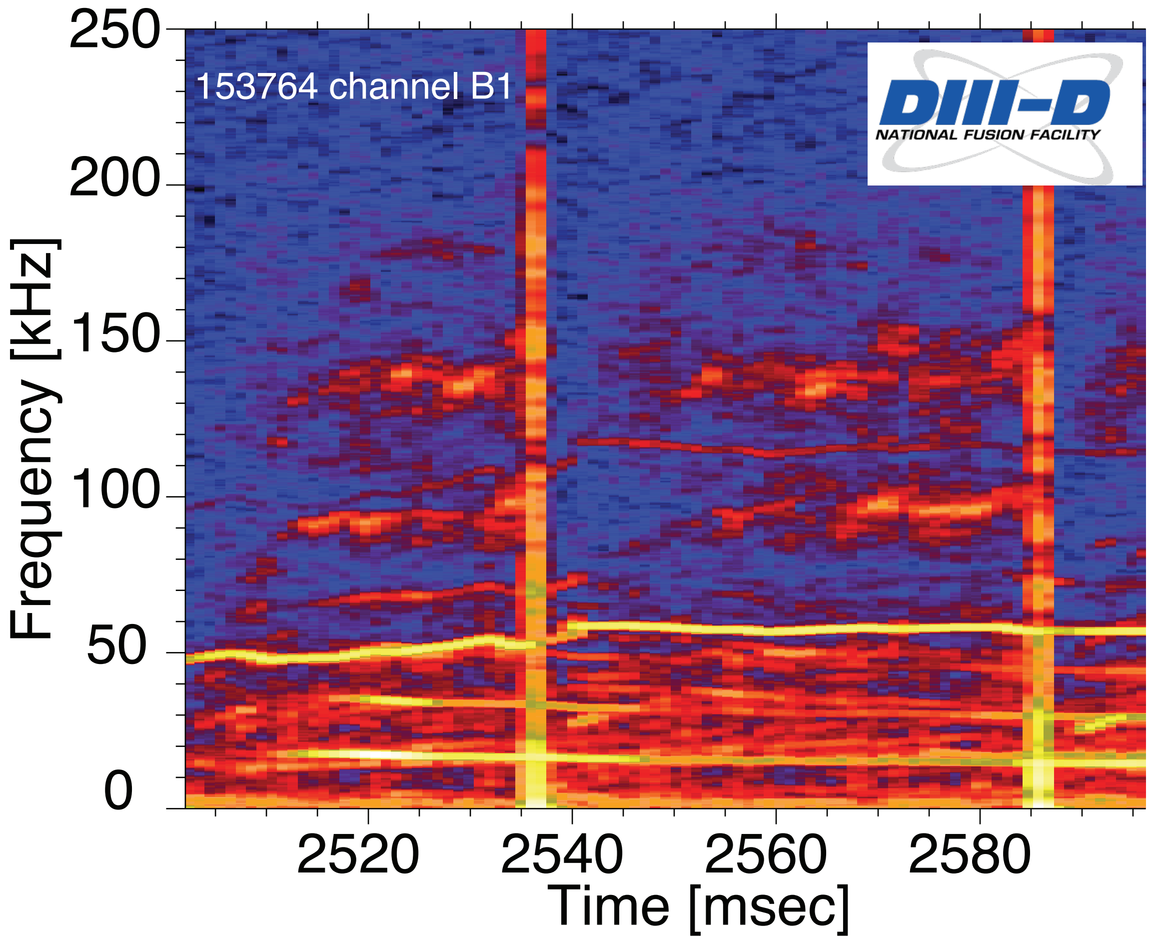
Pedestal fluctuations are observed to clamp the temperature pedestal gradient: robust physics at play that can be extended to strongly shaped ST

Charge #4

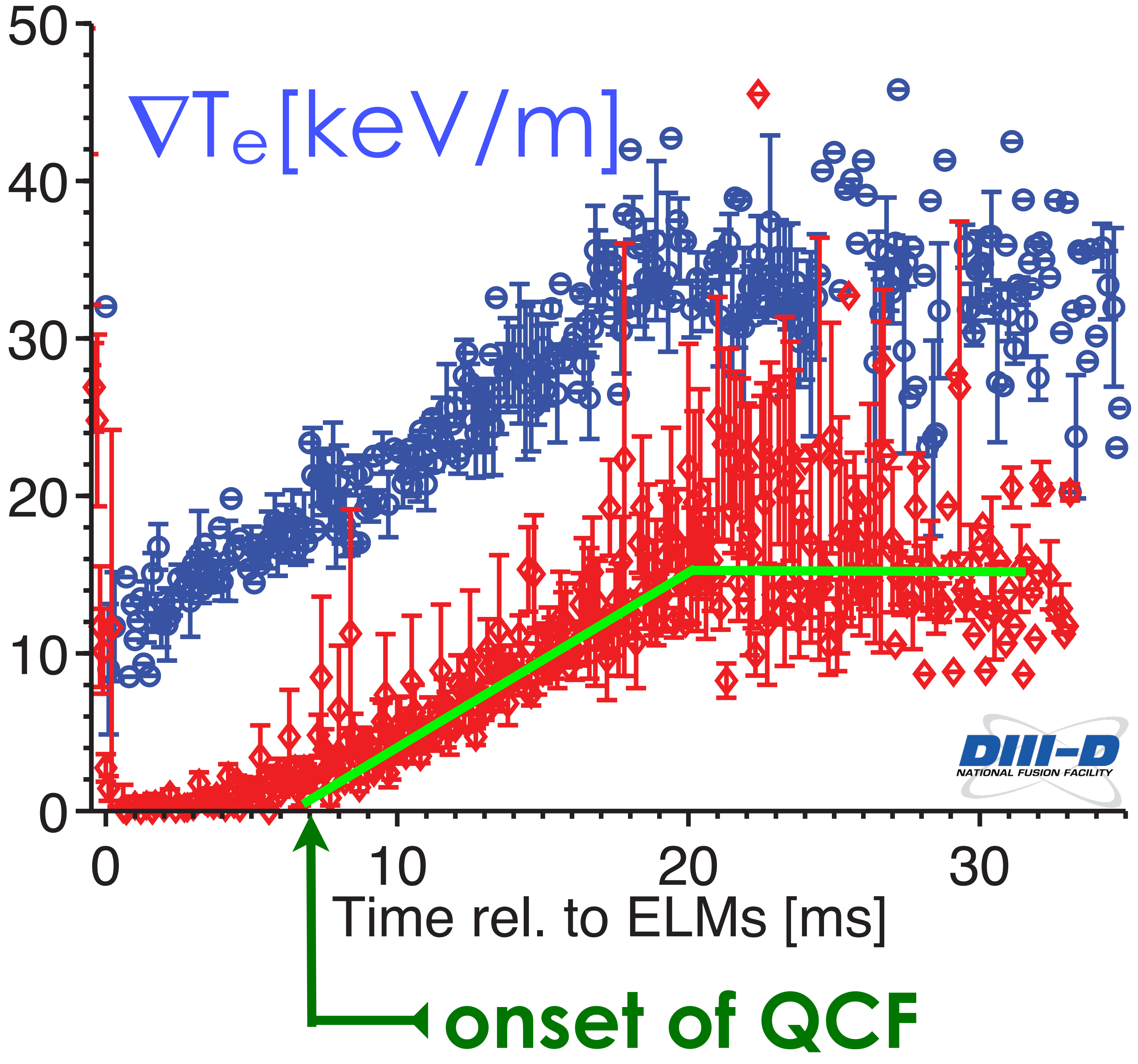
- **C-Mod, DIII-D, AUG, EAST, HL2A clearly showed the existence of quasi-coherent fluctuations correlating with pedestal evolution**
  - Density pedestal recovers faster than temperature that is clamped by edge-localized electromagnetic quasi-coherent fluctuations







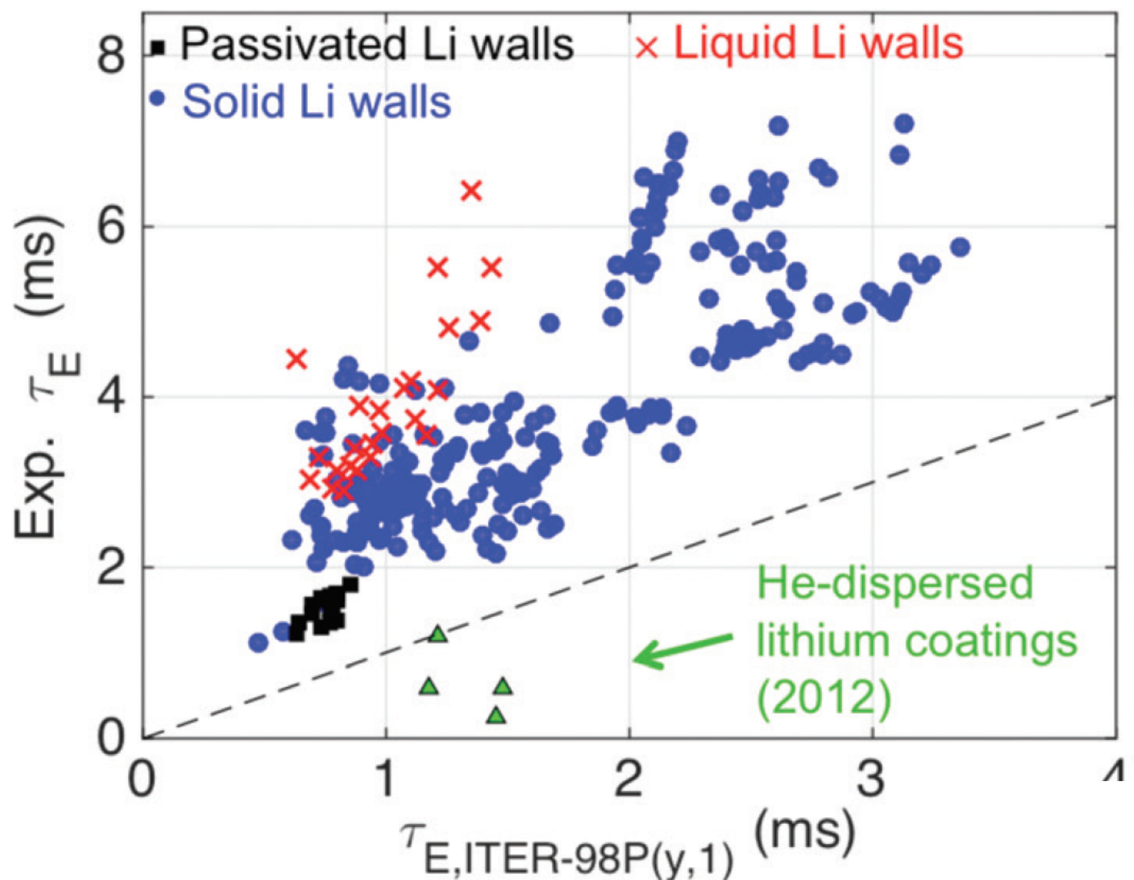
Evolution of QCF amplitude and Temperature gradient



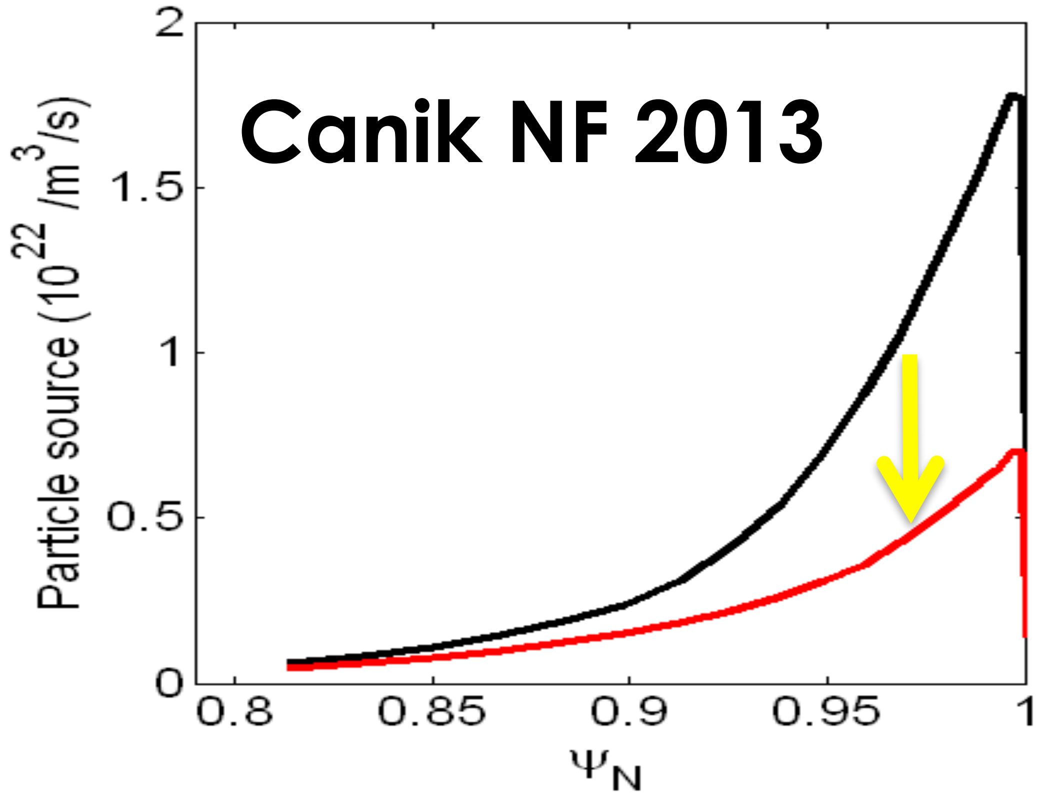
Pedestal structure physics: high confinement with low recycling

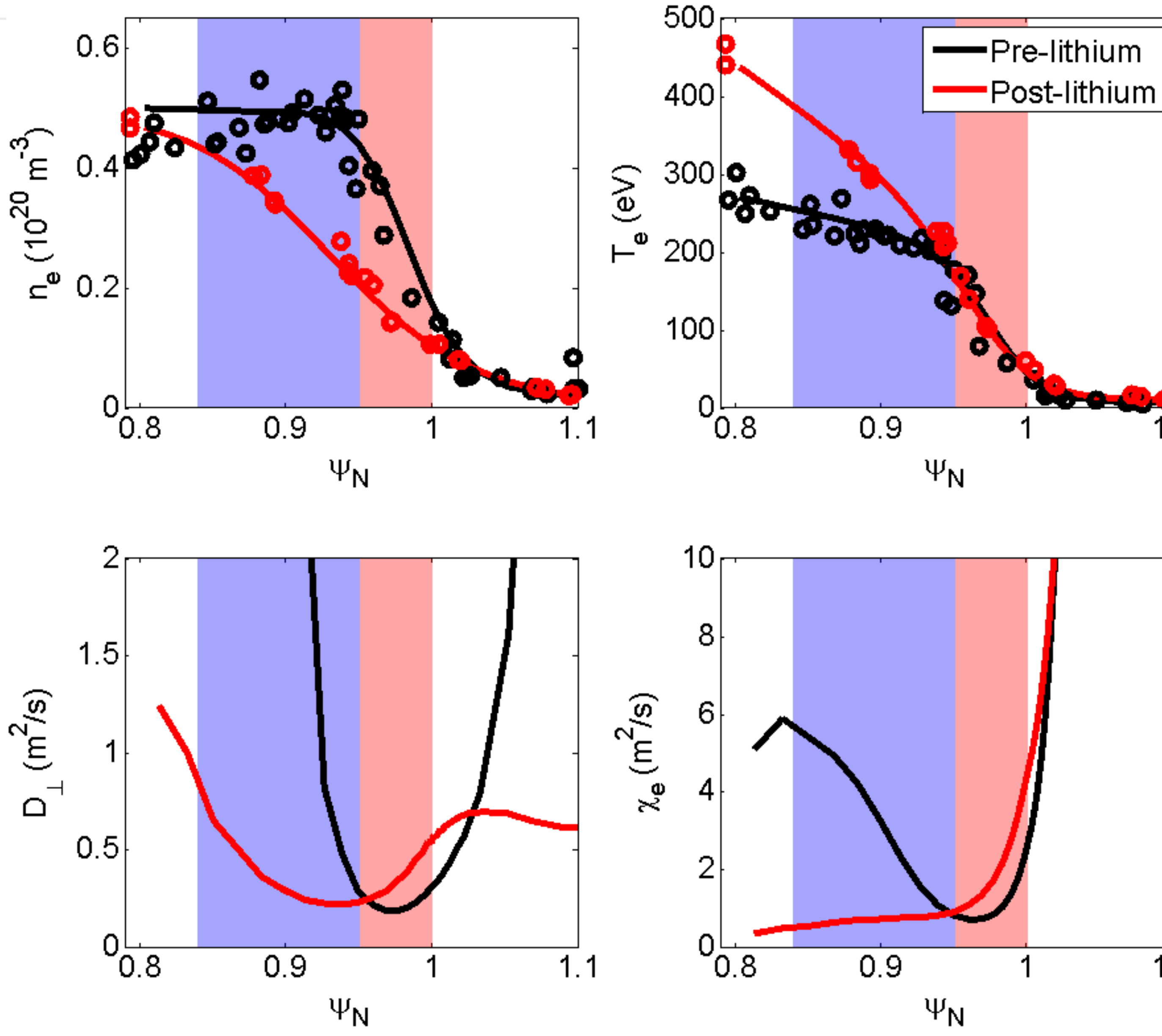
- **High confinement associated with low recycling via e.g. Li walls in LTX**
  - -Reduced edge fueling allows temperature to rise

- **H-factor increased by 50-100% in NSTX with Li coatings on graphite PFCs**
  - -Target recycling coefficient reduced from 0.98 to 0.90
  - -Core fueling source dropped 50%
  - -Edge ne profile reduced
  - -Linear GS2 calcs showed:
    - -ETG destabilized in pedestal - T_e gradient clamped, so that P_e and P_{tot} followed n_e -> stabilized ELMs
    - -Micro tearing stabilized near pedestal top which allowed T and confinement to increase



Schmitt PoP 2015

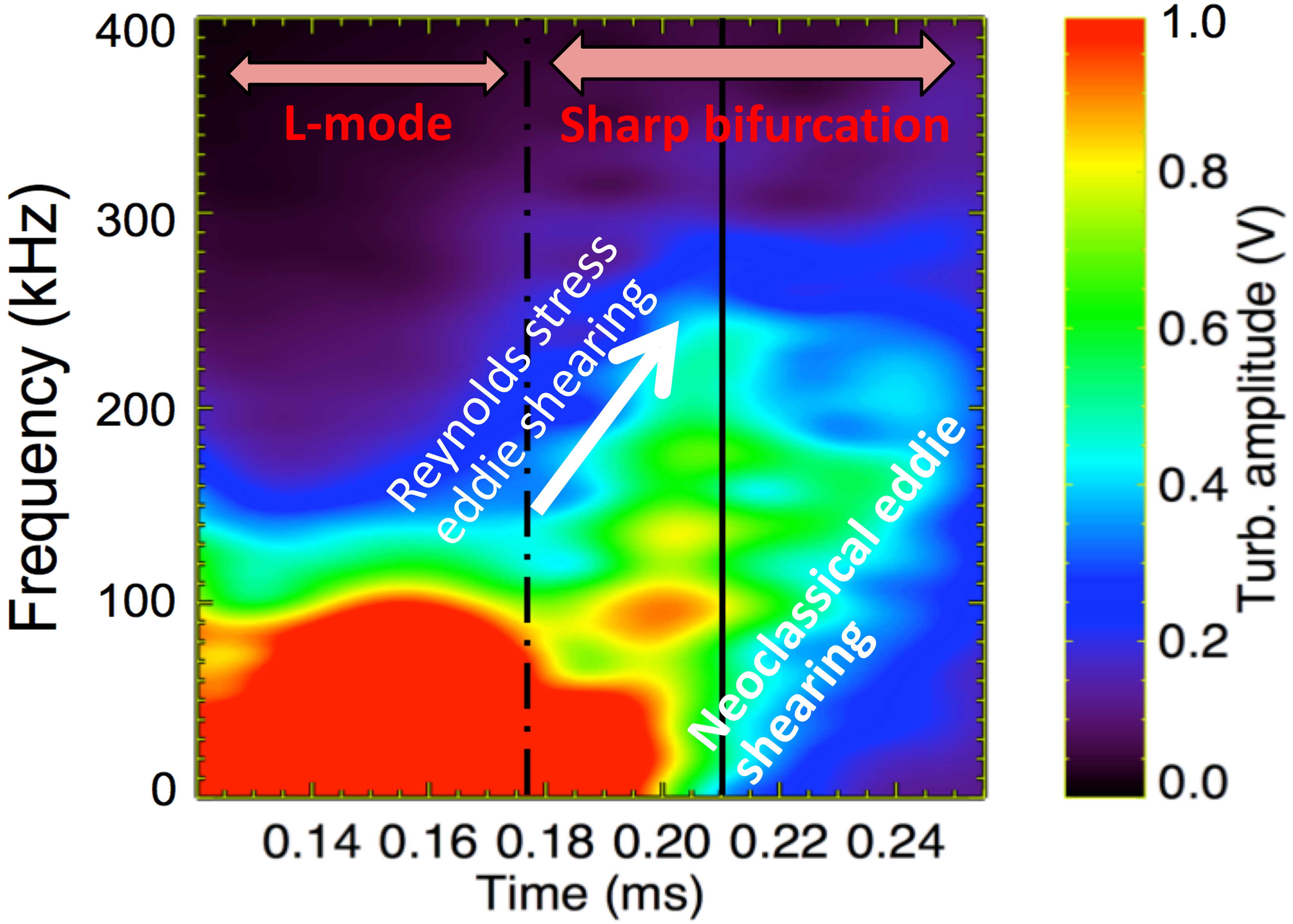




Experimental confirmation is needed to support these calcs

NSTX-U provides a test bed for neoclassical physics: crucial for understanding L-H physics and pedestal formation

[Chang et al., PRL 2017, using a C-Mod plasma]



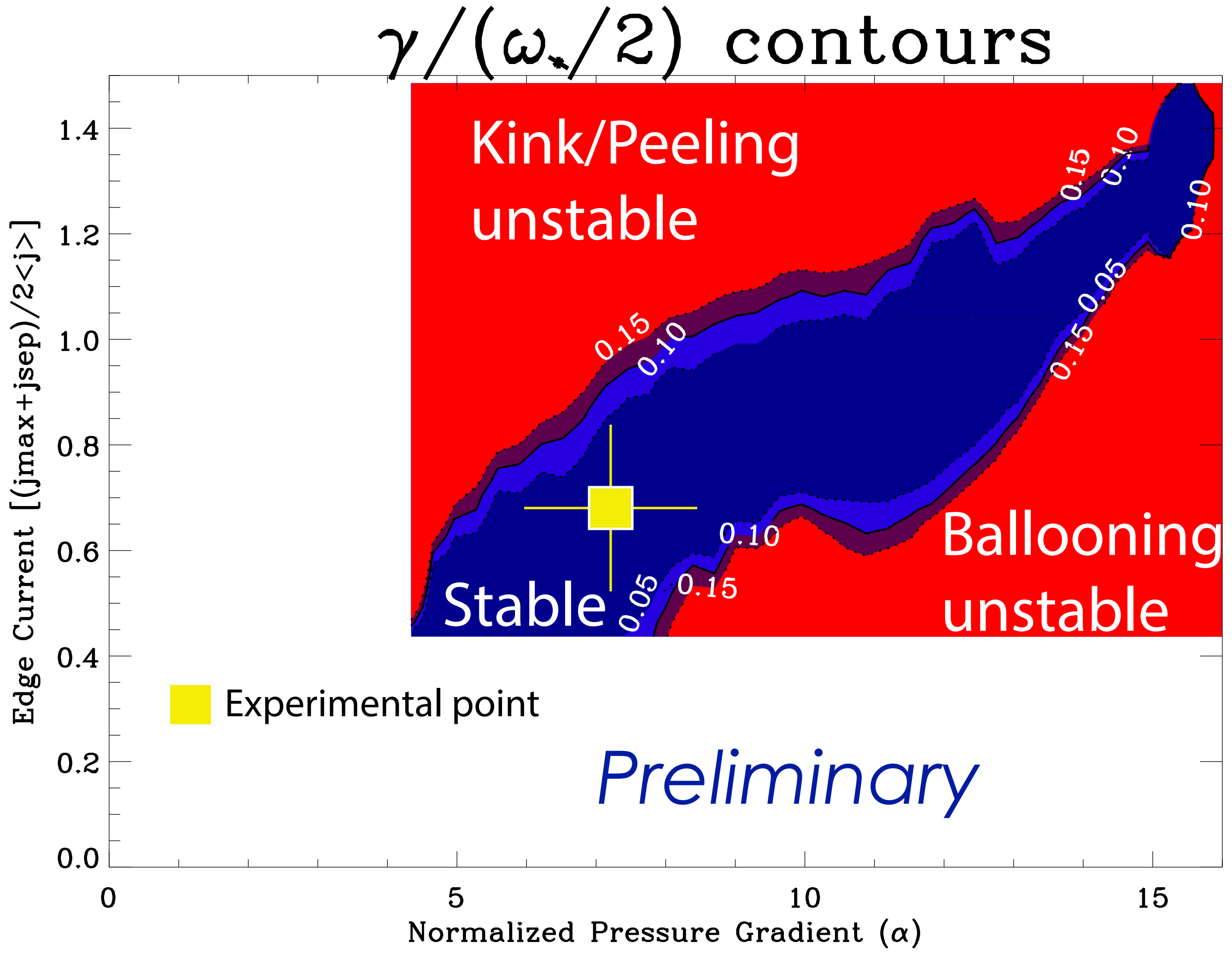
- **XGC finds that L-H bifurcation is from combination of turbulent Reynolds and neoclassical (X-point orbit-loss, here) forces**
- **How will this combination affect ITER when the small ρ_* destroys the Grad-p driven ExB?**
  - Survival of the X-point orbit-loss effect by high T_i expected
- **NSTX-U will be highest-T_i & most strongly shaped large-ST: excellent machine for neoclassical edge physics study**
  - Manipulate recycling by Li wall coating
  - Neoclassical effect on pedestal width? EPED does not work.

Can enhanced pedestal stability be achieved and understood in NSTX-U?

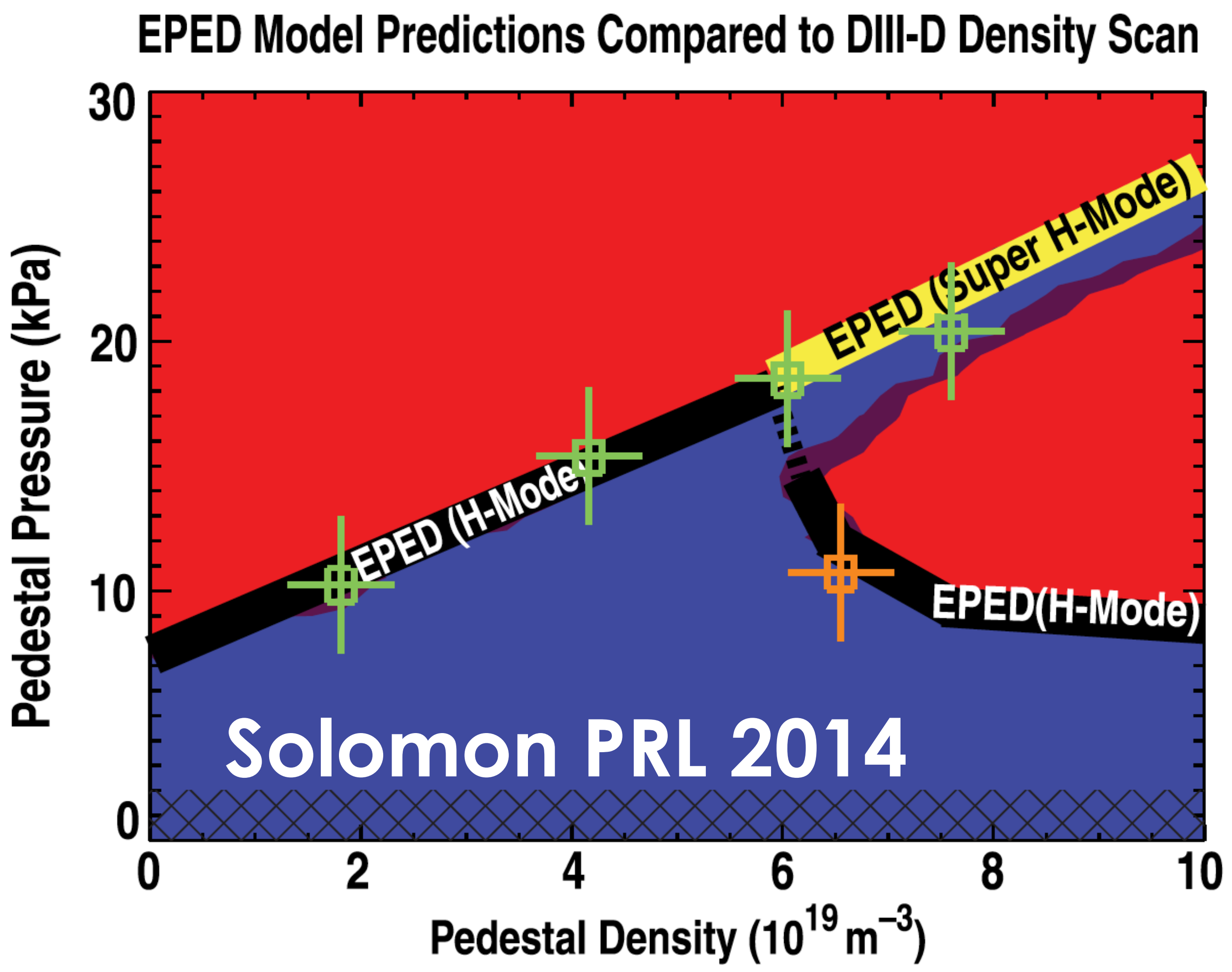
Charge #3

- **How robust is the super H-mode channel measured in DIII-D and is there an access path at low R/a, which has stronger shaping naturally?**
  - Previous ELITE calculations have shown a super H-mode like channel in NSTX;

can a such channel be found for low R/a in general and NSTX-U in particular?

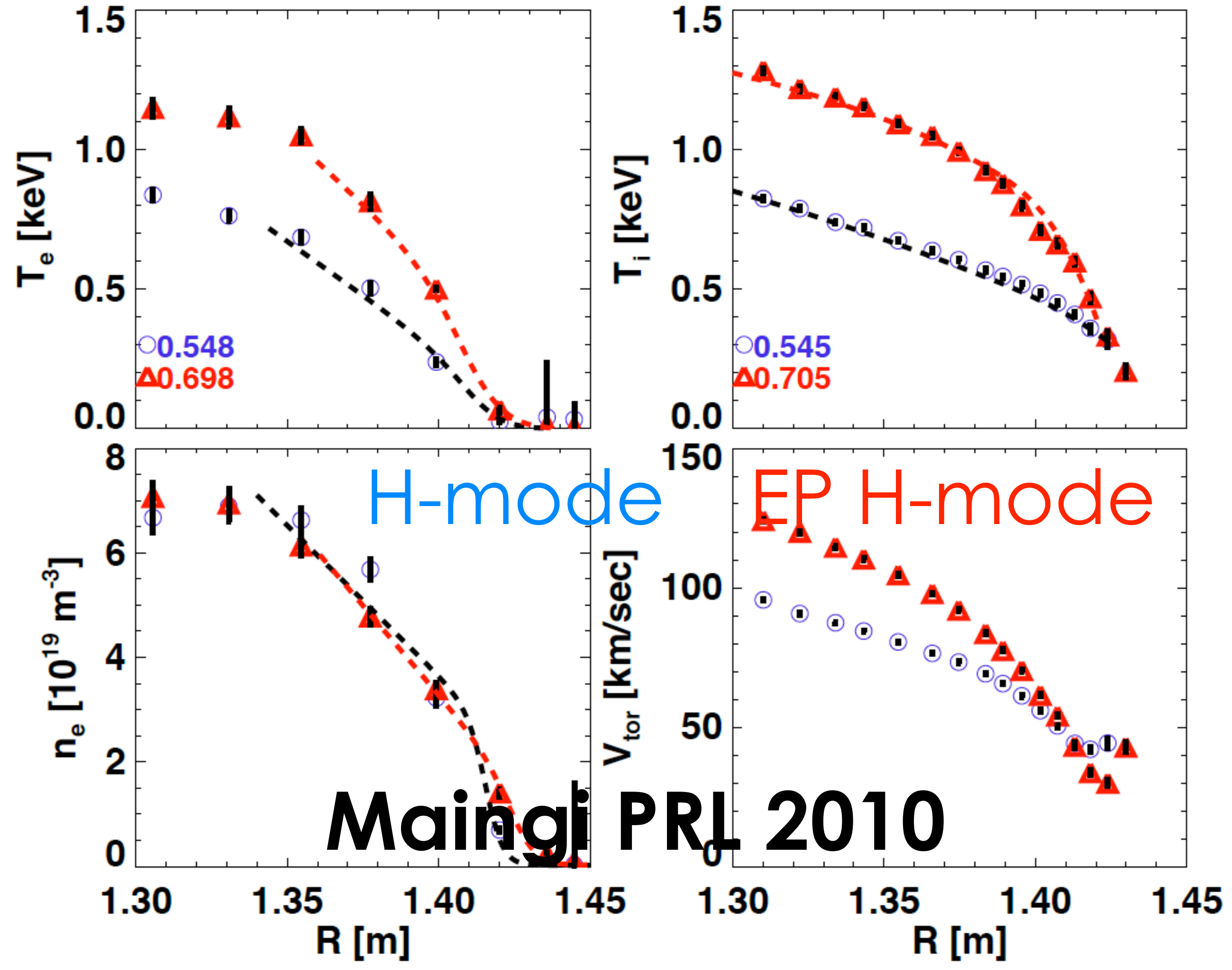


Preliminary



Solomon PRL 2014

- **Can Enhanced Pedestal H-mode, which was observed in NSTX, be obtained for long pulse in NSTX-U?**
  - High pedestal Ti, Te, stable beta-N; H98 ≤ 1.8

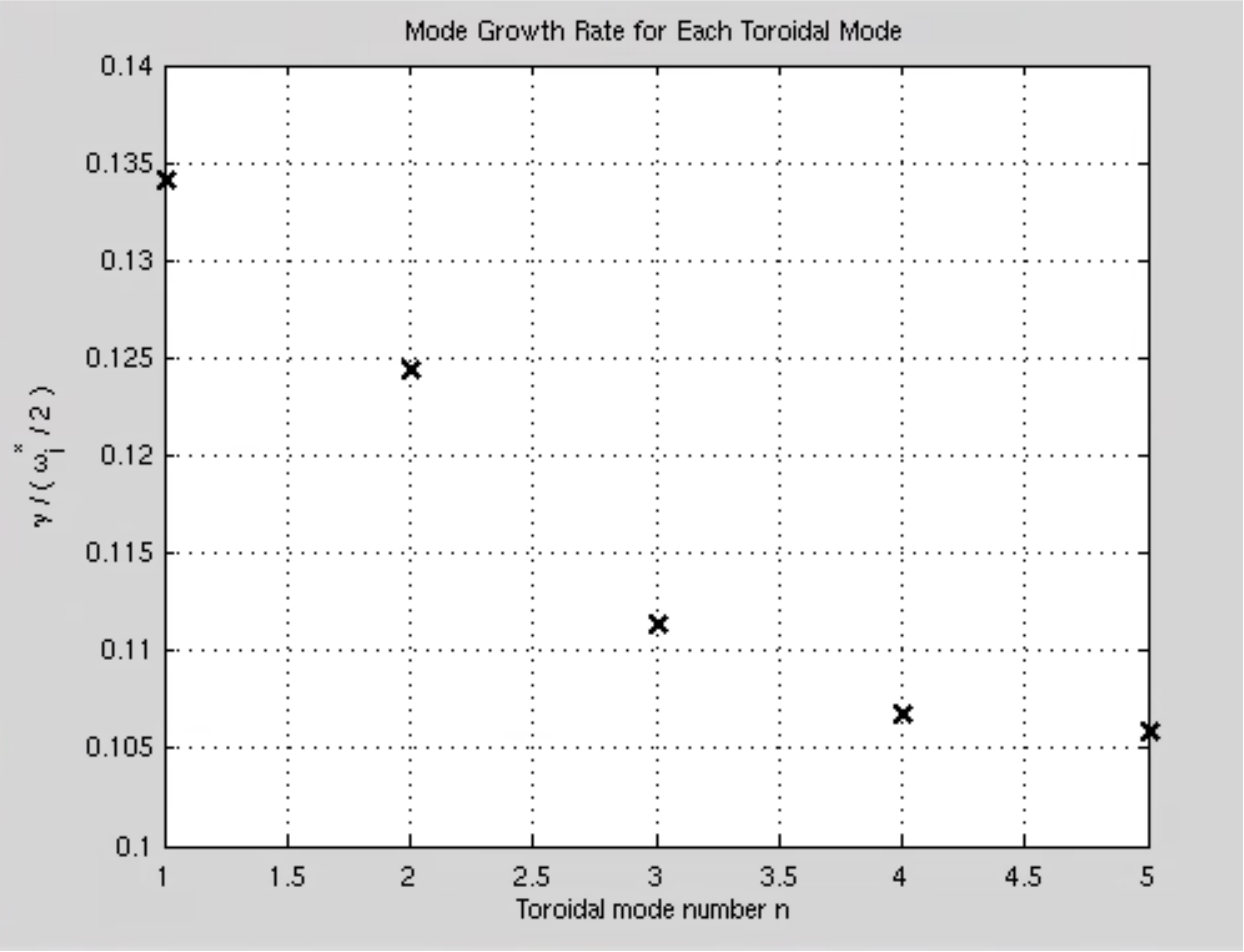


Maingi PRL 2010

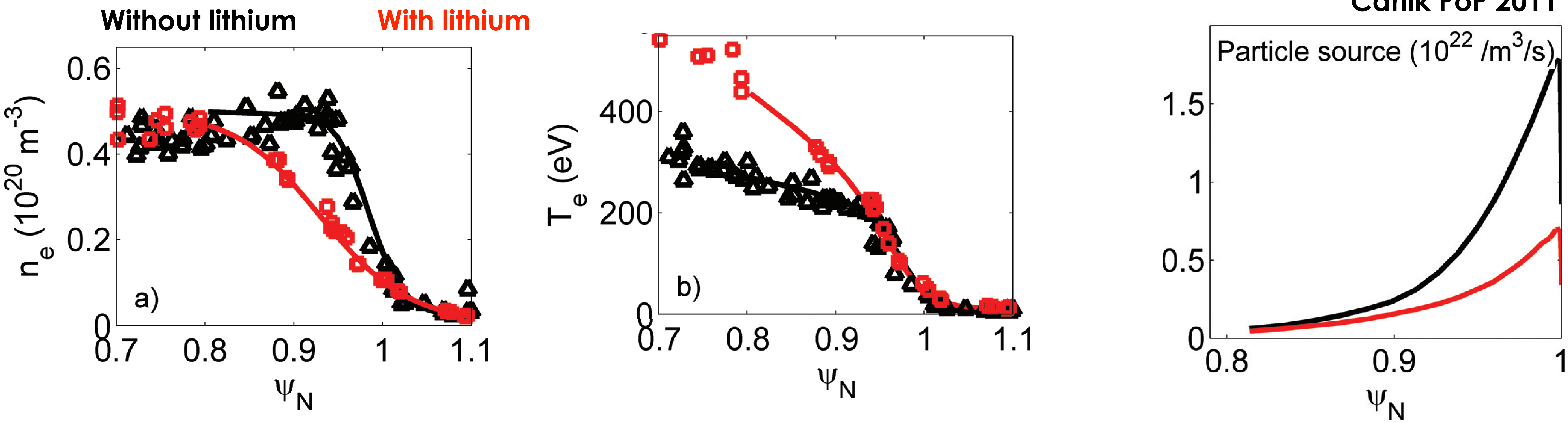
ELITE and M3D-C1 results agree with respect to ideal modes

- **M3D-C1 results are in agreement with ELITE results for NSTX, which show ideal modes with ~ 10x lower normalized growth rates**
  - Resistive modes have larger growth rates but are not captured by ELITE

- **The criterion γ / (ω_i^* / 2) = 1, which works well for DIII-D plasmas, is derived from ideal MHD**
  - A more general dispersion relation that accounts for resistive modes must be used for NSTX and possibly NSTX-U



Lithium coatings provide an unique control knob to the particle source

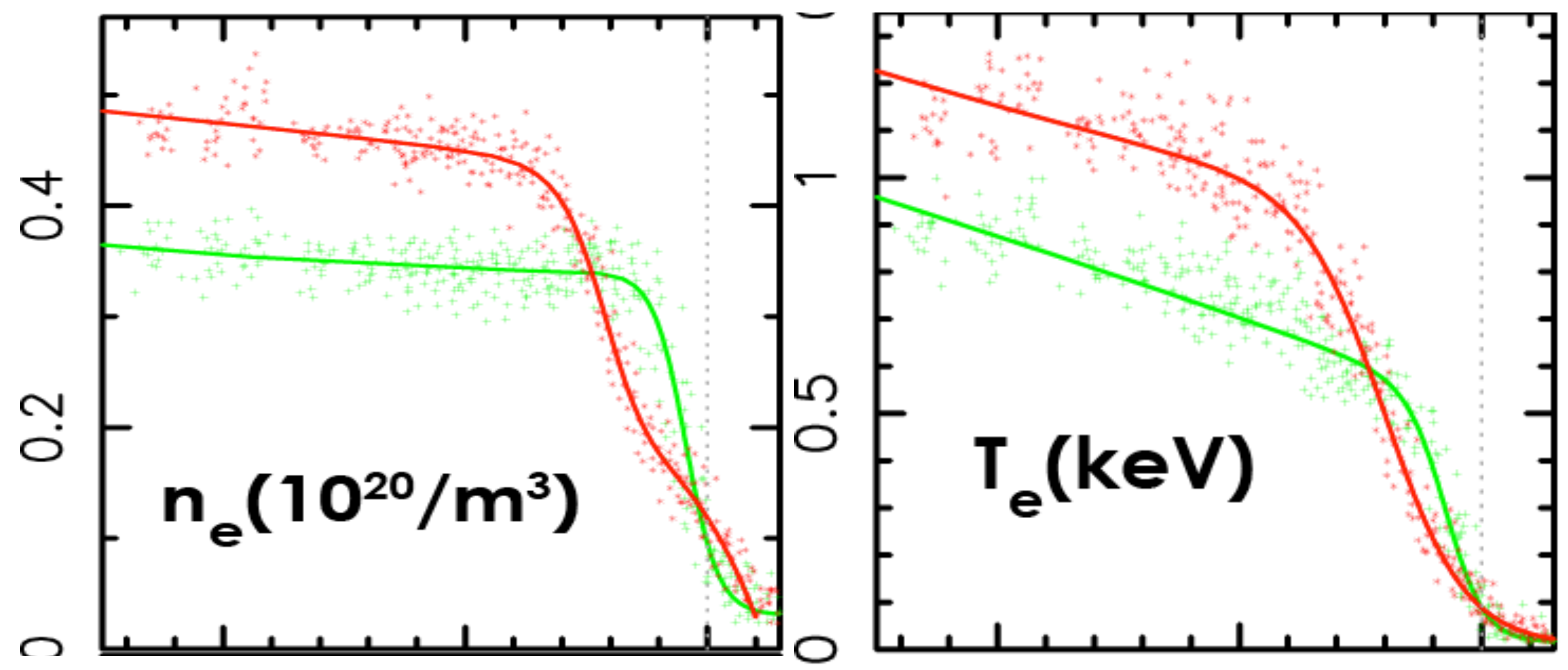


Canik PoP 2011

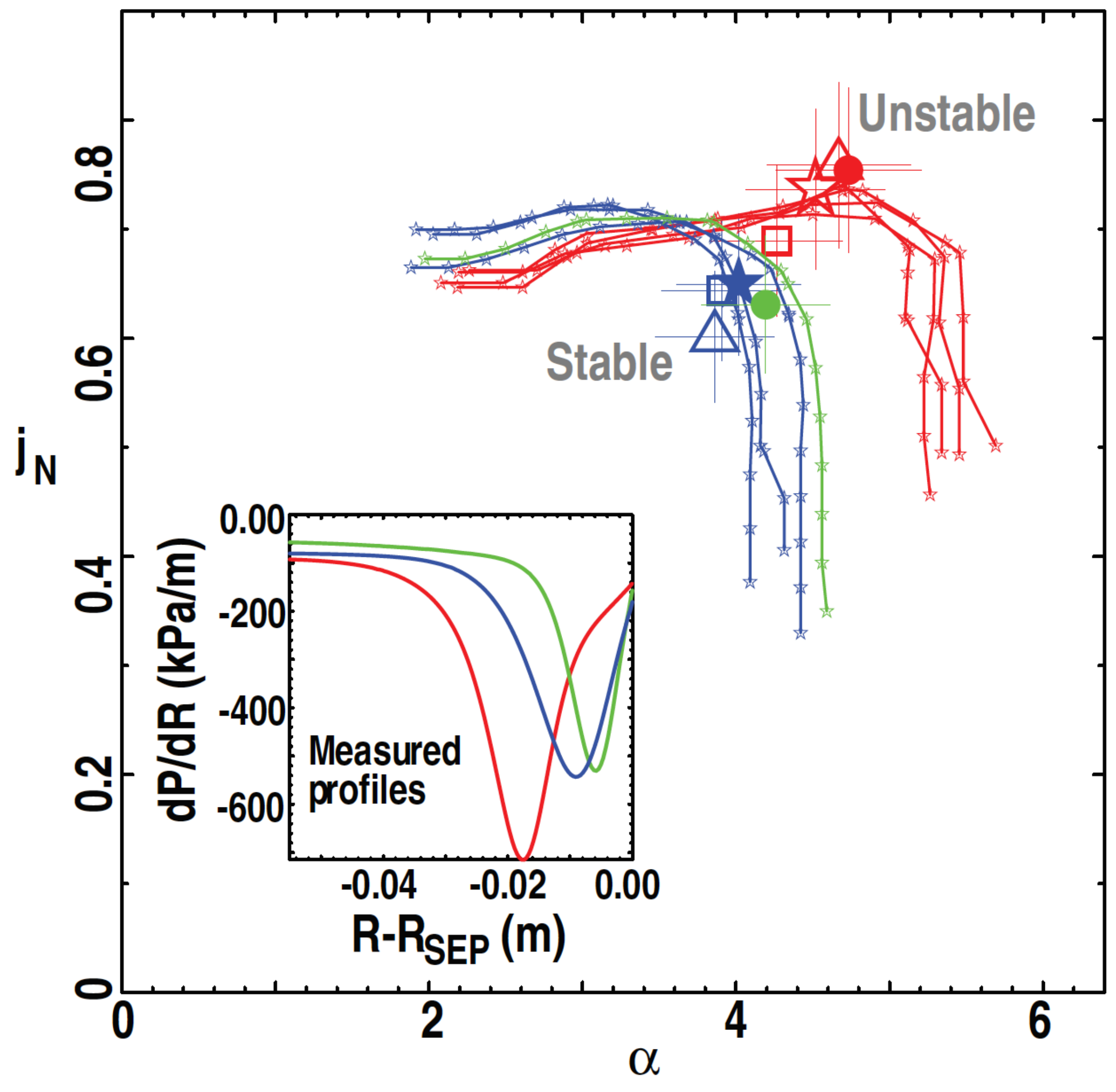
- Lithium wall conditioning suppresses ELMs and provides better confinement
- NSTX demonstrated that lithium widens the pedestal temperature while relaxing the density gradient
- Existence of a particle pinch vs. diffusion in setting the pedestal density structure can be directly tackled on NTSX-U
  - Tools: novel fast measurements (PBLS) density & temperature dynamics, in conjunction with SGI and lithium;
  - NSTX-U can demonstrate the key role of pinch vs. diffusion

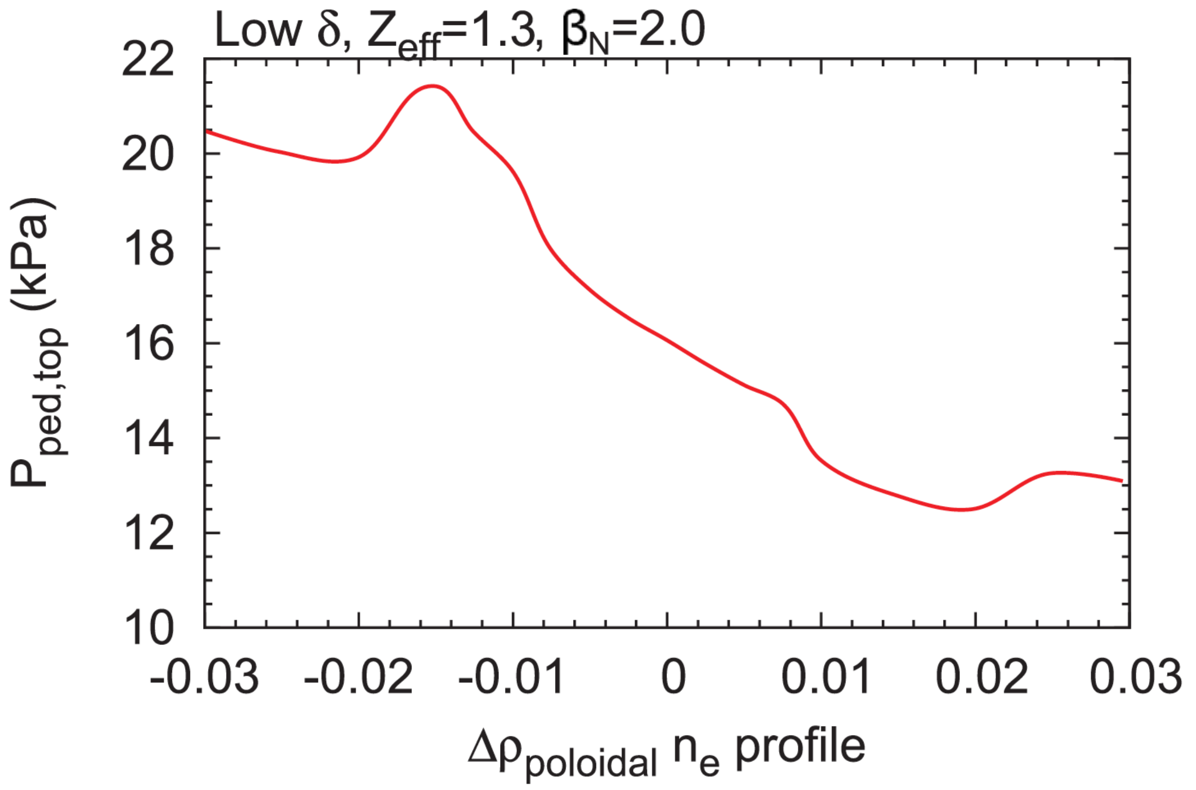
ELITE calculations agree with experimental profiles that are altered by pedestal localized instabilities, fueling…

Charge #2



- ELITE analysis of kinetic equilibria are consistent with high achieved pedestal pressure when density and temperature profiles shift relative to each other and/or the separatrix
  - Relative shift can occur due to enhanced fluctuations or reduced fueling
  - EPED underestimates the pedestal width and height in these cases, but ELITE calculation can still be used to extend EPED





Dunne PPCF 2017