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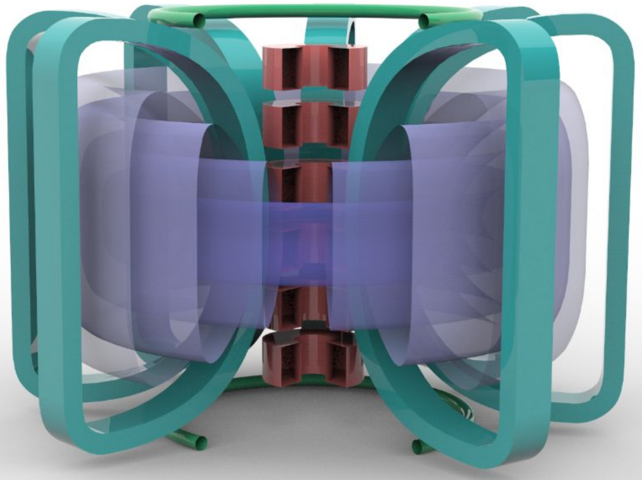
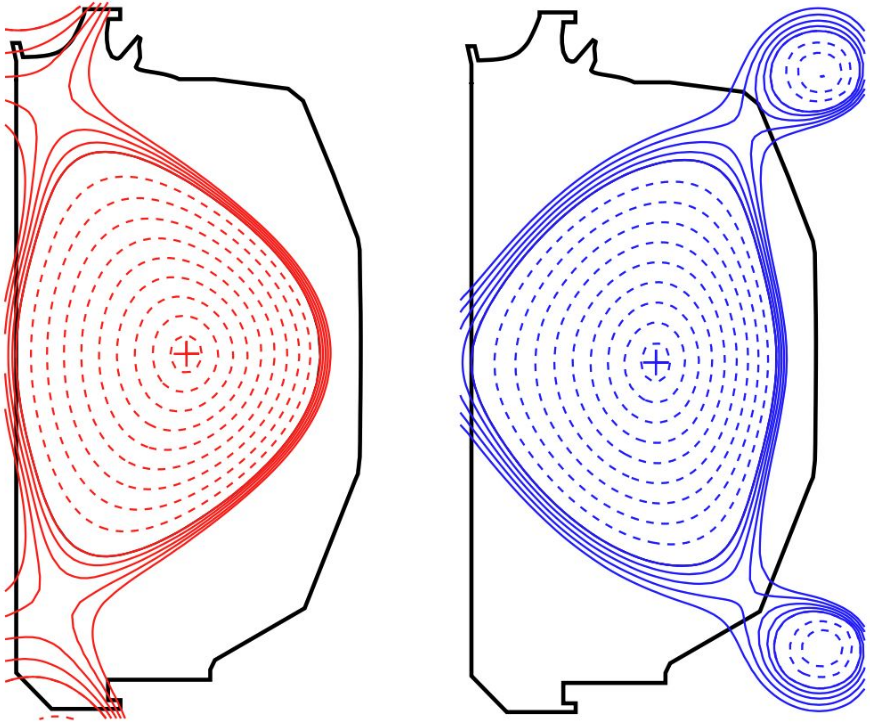


Second Stability Access in Neg-D Reactors

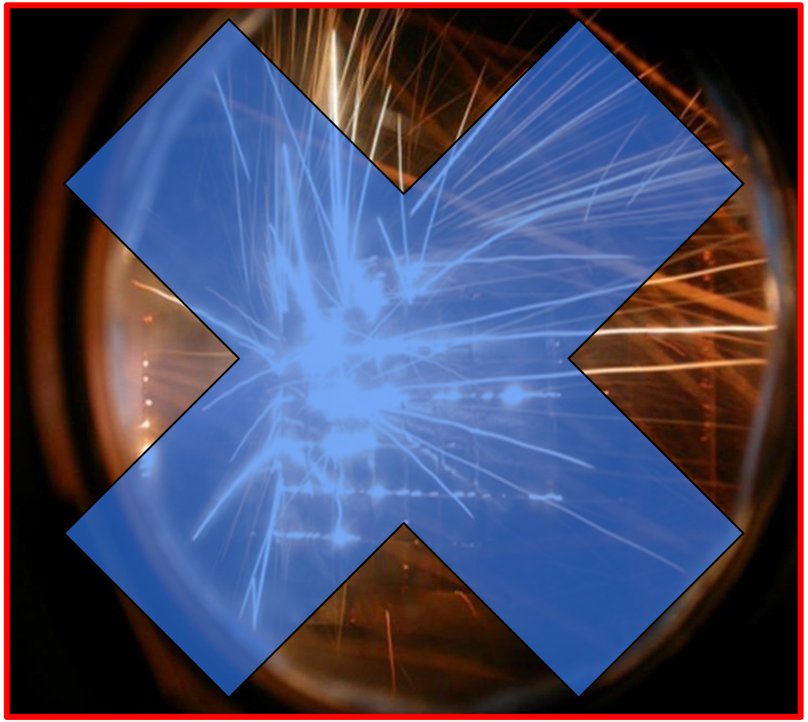
A. O. Nelson
with C. Paz-Soldan and S. Saarelma

April 11th, 2022
NSTX-U / Magnetic Fusion Science Meeting

Neg-D: L-modes with H-mode like confinement



Austin, et. al. PRL (2019)



https://www.iter.org/newsline/166/628

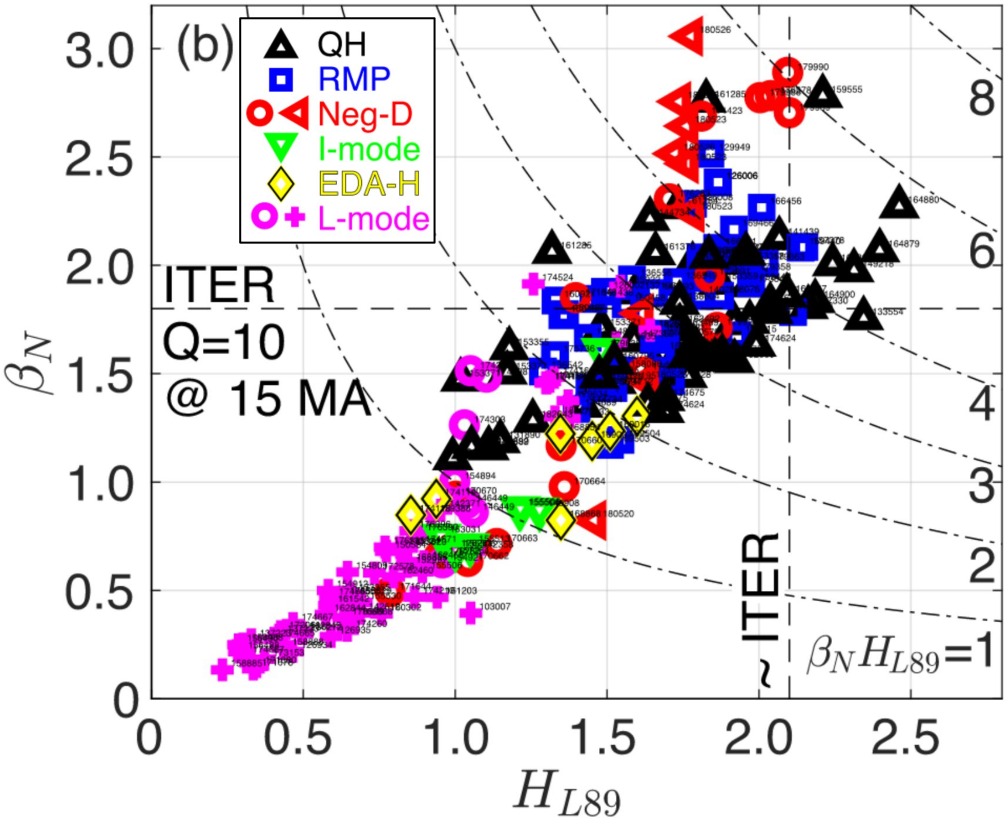
Neg-D compares well with other no-ELM scenarios

Core:

- High pressure and confinement due to turbulence reduction
- Stability is generally worse

Edge:

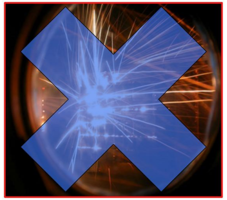
- Exhaust integration could be alleviated
- H-mode and ELMs avoided through MHD?



Paz-Soldan, PPCF (2021)

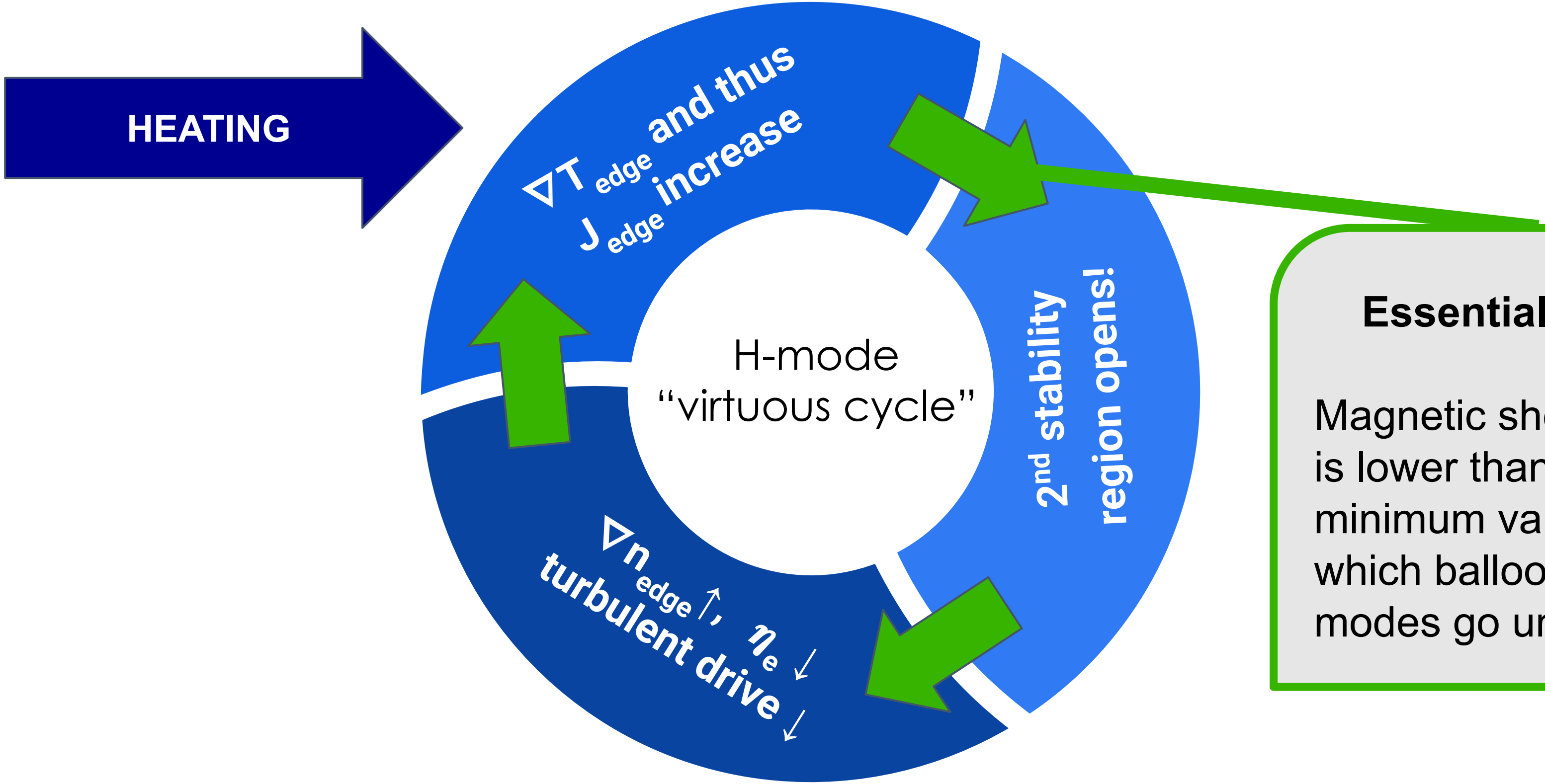
Outline

- Introduction to Negative Triangularity



- **H-mode suppression in Neg-D: a case of ballooning instability?**
- **How does shape impact second stability access?**
- **Extrapolation of ballooning physics to reactors**

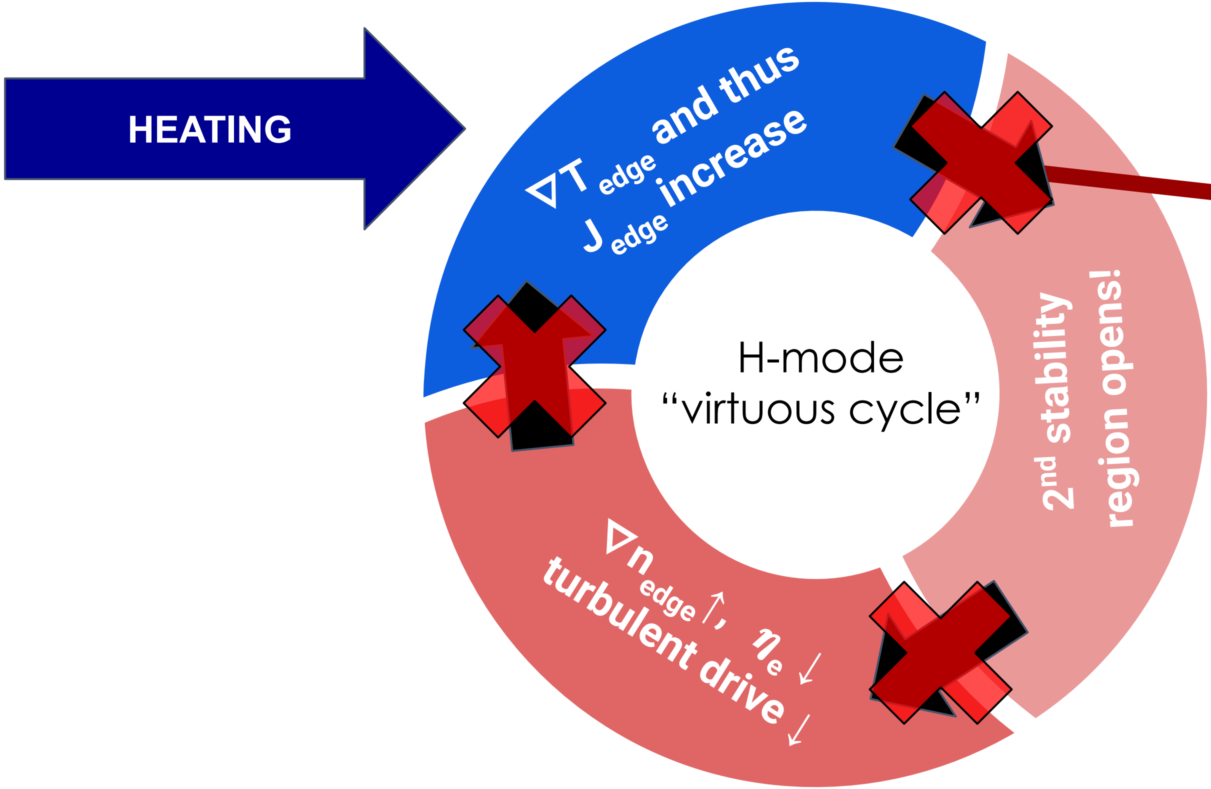
H-mode access follows “virtuous cycle”



Essential criteria:

Magnetic shear in edge is lower than the minimum value at which ballooning modes go unstable

Neg-D: ballooning modes clamp ∇n_{edge} - stuck in L-mode!



Essential criteria:

Magnetic shear in edge is lower than the minimum value at which ballooning modes go unstable

Ballooning mode instability is a function of *s* and *α*

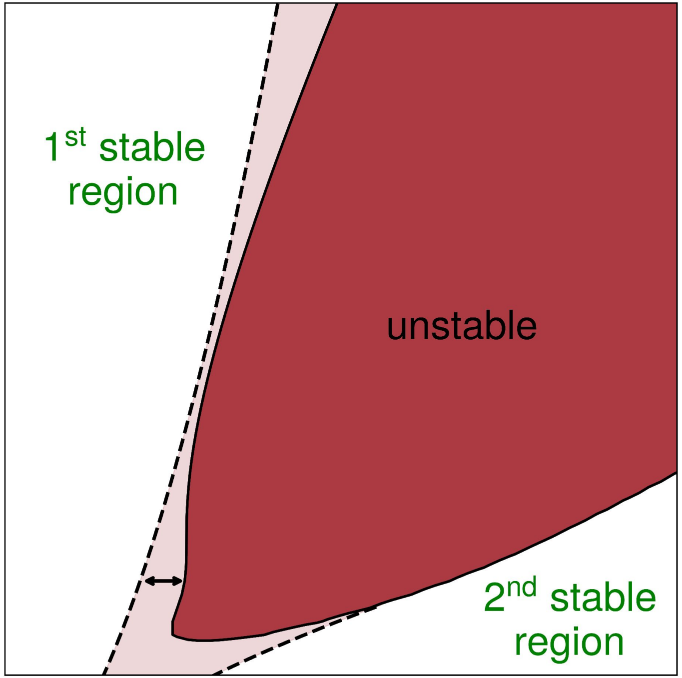
- Local shear:

$$\hat{s}(r,\theta) \sim s(r) - \alpha(r)\cos\theta$$

  - Shear stabilization prop. to $\hat{s}^2$

- 1st stability region:
  - As s increases, max(α) increases

- 2nd stability region:
  - Requires $\alpha > s$ to achieve $\hat{s} \ll 0$

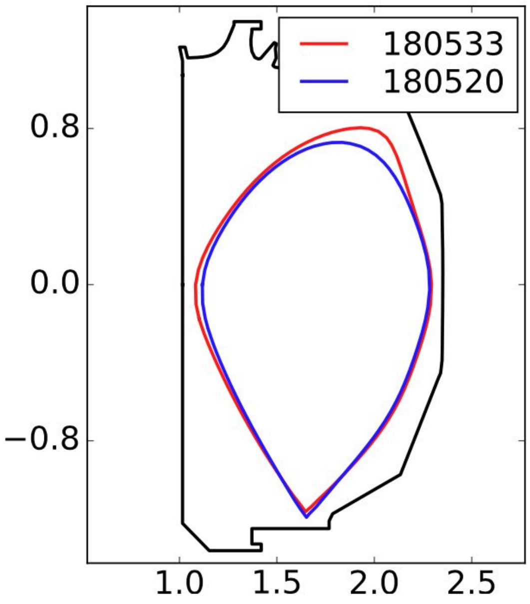


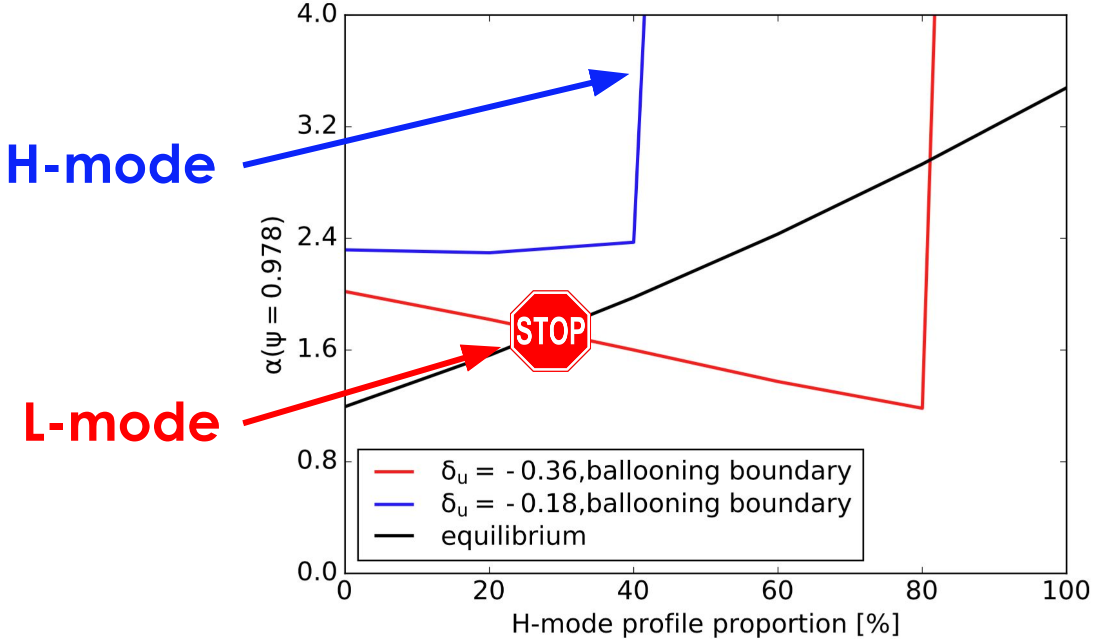
$$s = \frac{r}{q}\frac{dq}{dr}$$

$$\alpha = -\frac{2\mu_0 R_0}{B_T^2} q^2 \frac{dp}{dr}$$

DIII-D H-modes limited by $n = \infty$ ballooning modes (1/2)

- A slight change in δ_u responsible for loss of H-mode on DIII-D
  - correlated with loss of access to the second stability region!

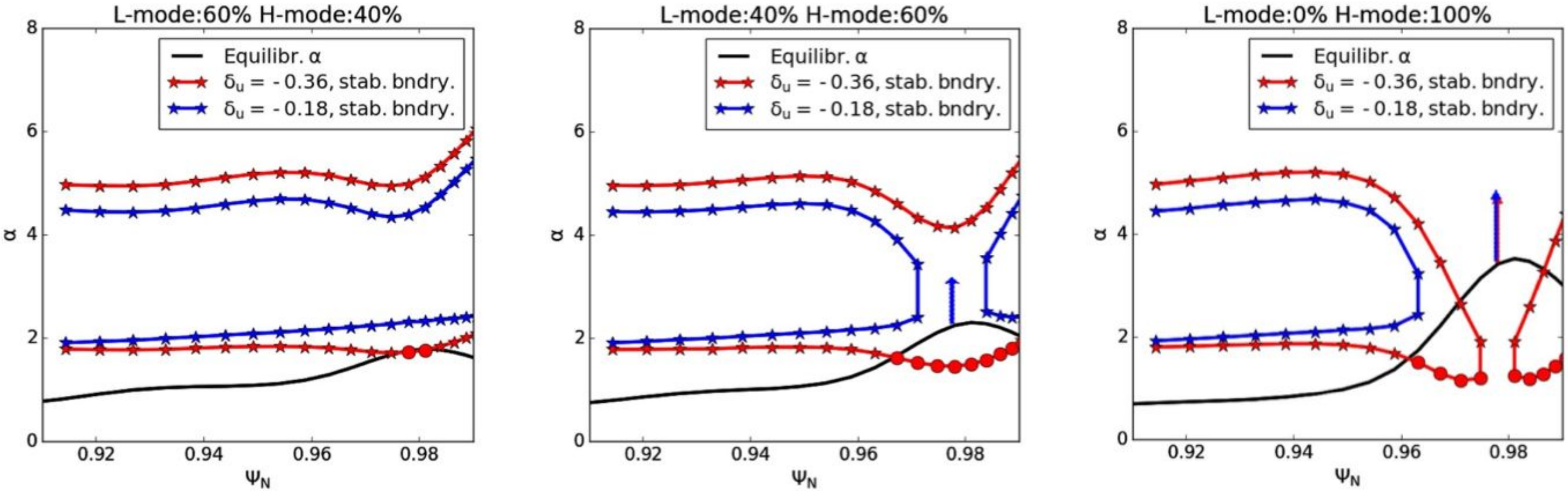




Saarelma, et. al. PPCF (2021)

DIII-D H-modes limited by n = ∞ ballooning modes (2/2)

- Ballooning stability boundaries can be calculated in 1D
  - a function of both the **plasma profiles** and the **equilibrium shape**



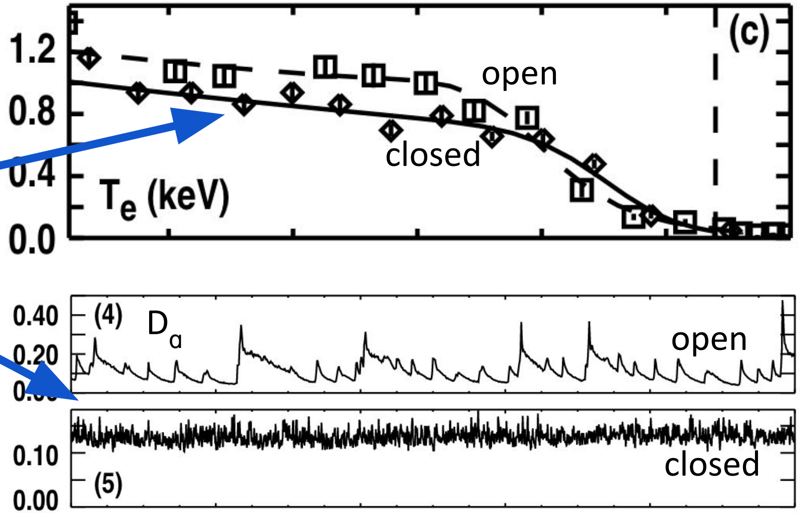
Saarelma, et. al. PPCF (2021)

- At strong shaping, ballooning modes clamp pedestal gradients

Caveats: 1st-stable operation not strictly L-mode

- On DIII-D, C-Mod, ASDEX, JT-60U (and others?), H-mode operation in the 1st stability regime has been reported

- Generally associated with:
  - High shear / collisionality
  - Reduced pedestal pressures
  - Increased ELM frequency
  - Decreased ELM amplitude

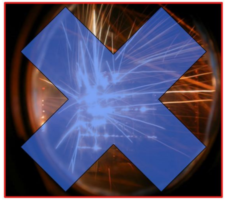


Ferron, et. al. NF (2000)

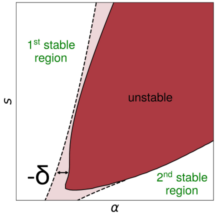
- Neg-D on DIII-D: ELMs suppressed with increased NBI heating (Guanying Yu)

Outline

- Introduction to Negative Triangularity



- H-mode suppression in Neg-D: a case of ballooning instability?



- How does shape impact second stability access?

- Extrapolation of ballooning physics to reactors

Goals and methods

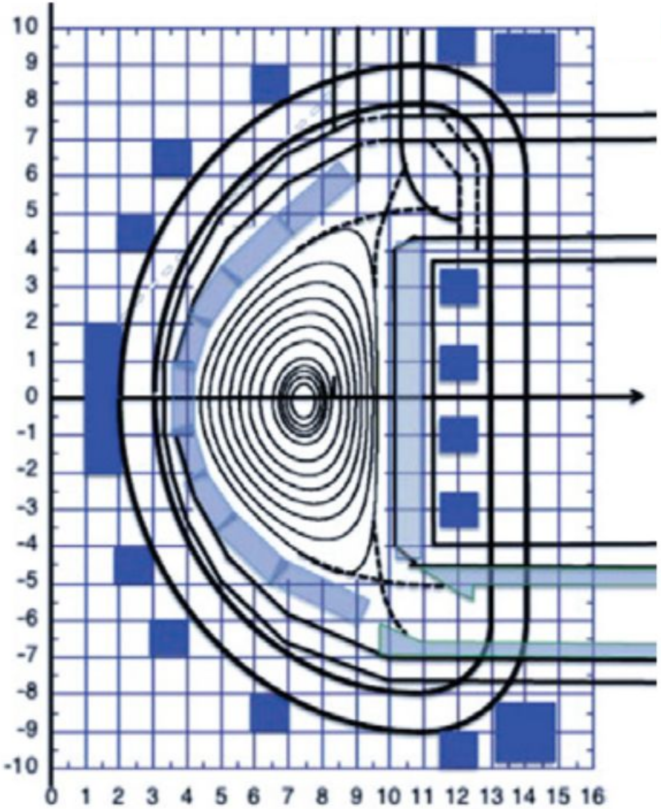
- Understand broadly how shape impacts second stability access
  - Will Neg-D reactors still be in L-mode?
  - Are there other alternatives for shape-based H-mode suppression?
- CHEASE used for equilibria generation
- BALOO used for infinite-*n* ballooning calculation
- Profiles from EPED parameterization
- Bootstrap current self-consistently calculated from Sauter definitions

Base equilibria from neg-D reactor study

- Base target:
  - R_0 = 7 m
  - κ = 2
  - B_0 = 6 T
  - β_N = 2.5
  - a_{minor} = 2.6 m
  - ζ = 0.1
  - I_p = 15 MA

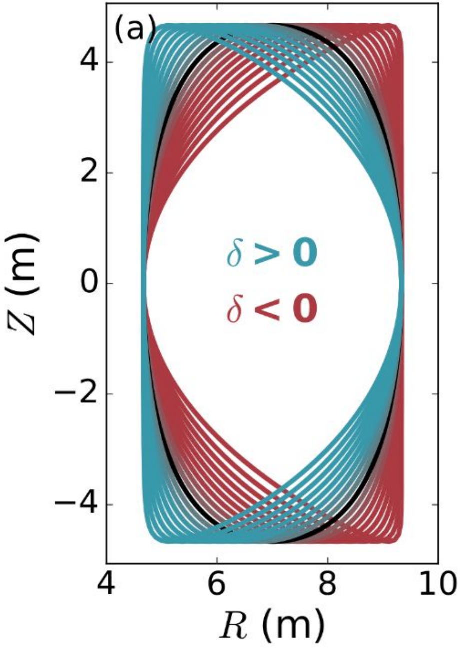
- Everything will be scanned….

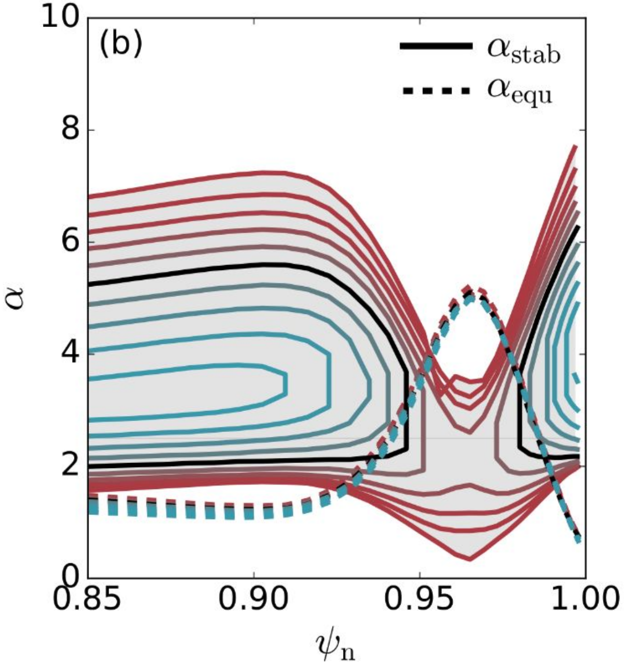
- Configuration with δ = -0.8 already analyzed with KINX
  - Pedestals in the 1st stable region



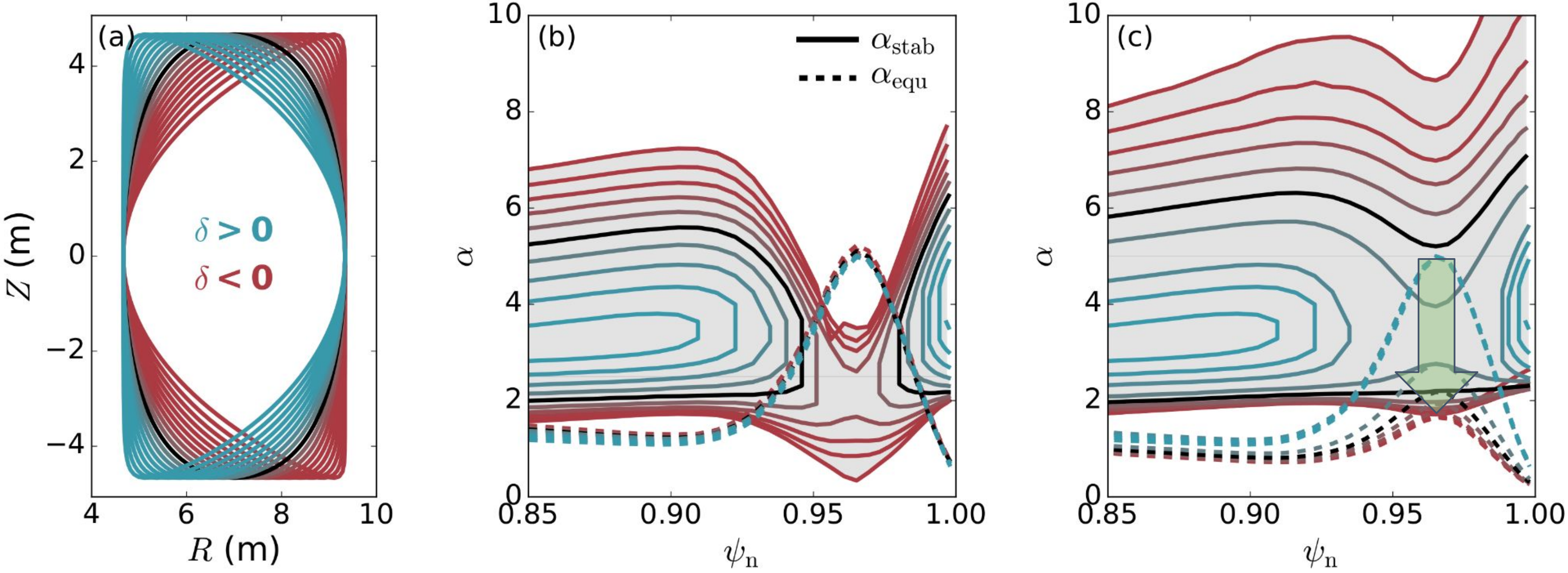
Medvedev, et. al. NF (2015)

Reduced triangularity closes second stability region



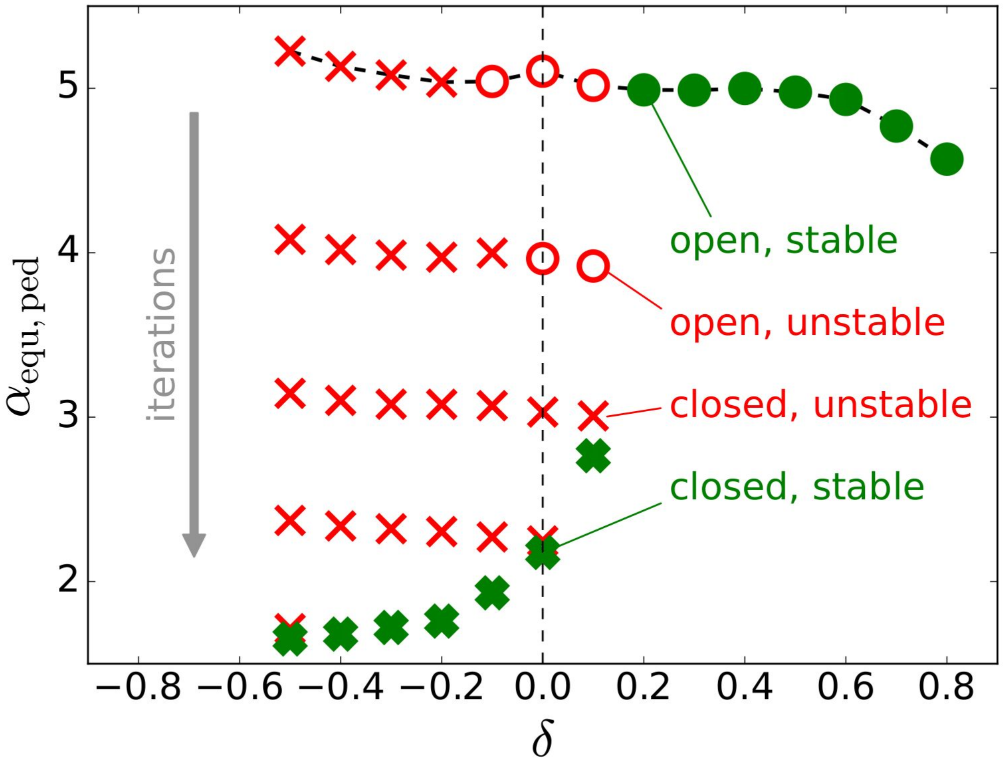


Pedestal height reduced to maintain MHD stability



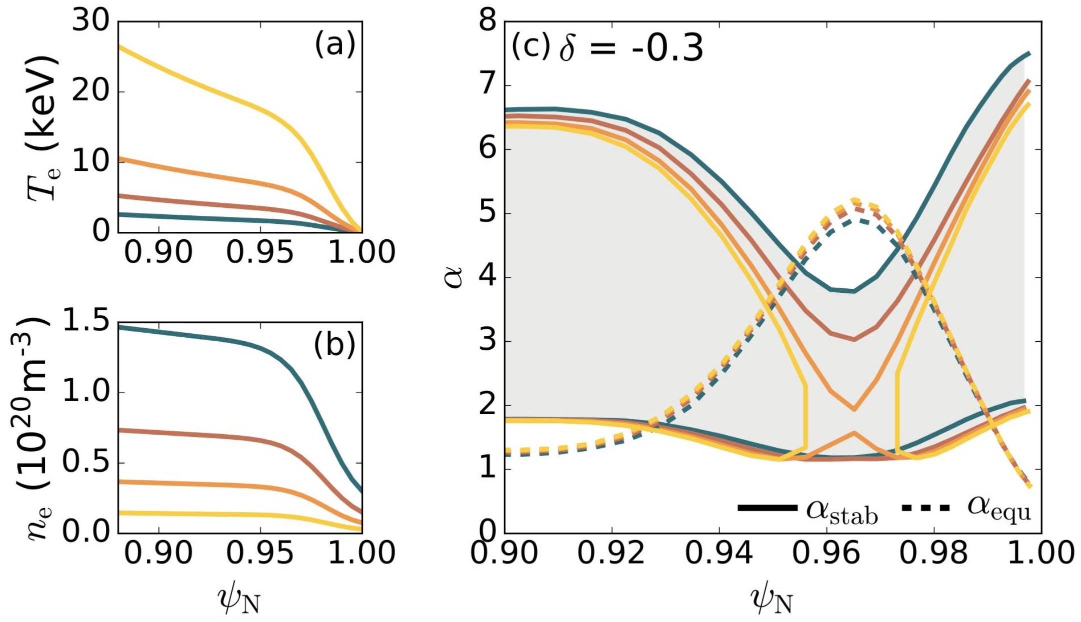
Reduced δ < 0 leads to reduced edge pressure

- Pedestal height is iteratively decreased until maximum stable profile is found
- Critical δ exists for which 2nd stability can be accessed
- Ballooning-limited pedestal height decreases with $\delta < 0$

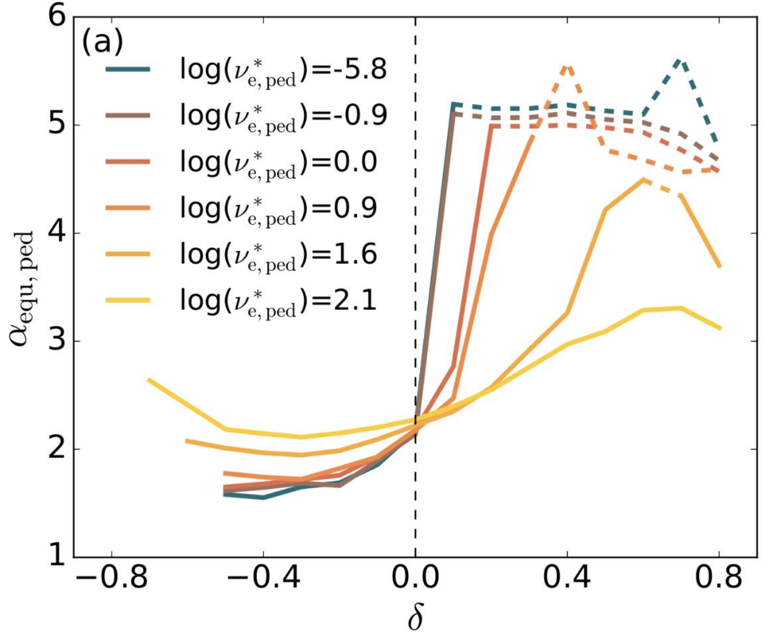


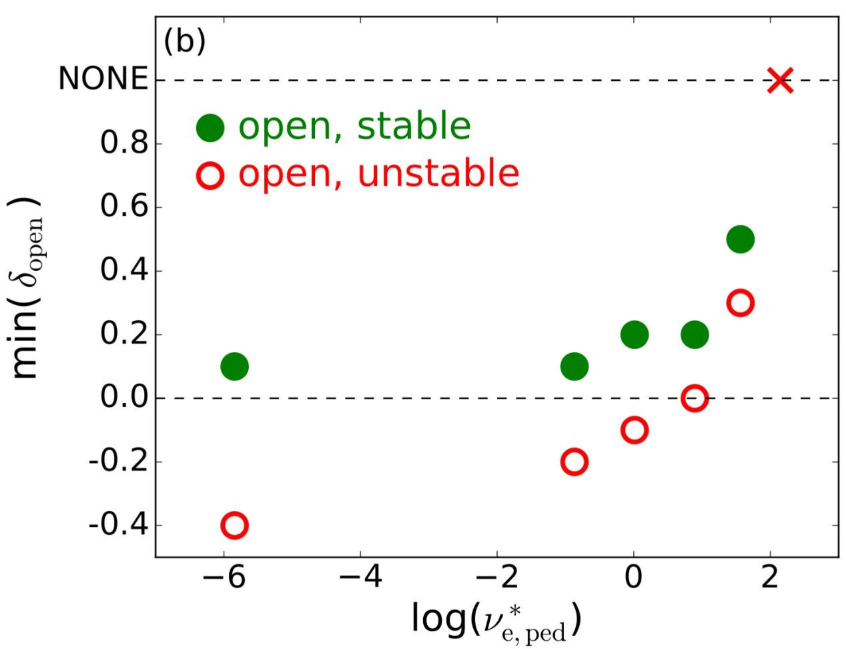
Details of the kinetic profiles also impact stability

- We can play with: **T/n** ↑ → **v** ↓ → **Jboot** ↑ → **s** ↓
- With enough bootstrap current, access to the second stability region can be achieved even at $\boldsymbol{\delta} \ll 0$!



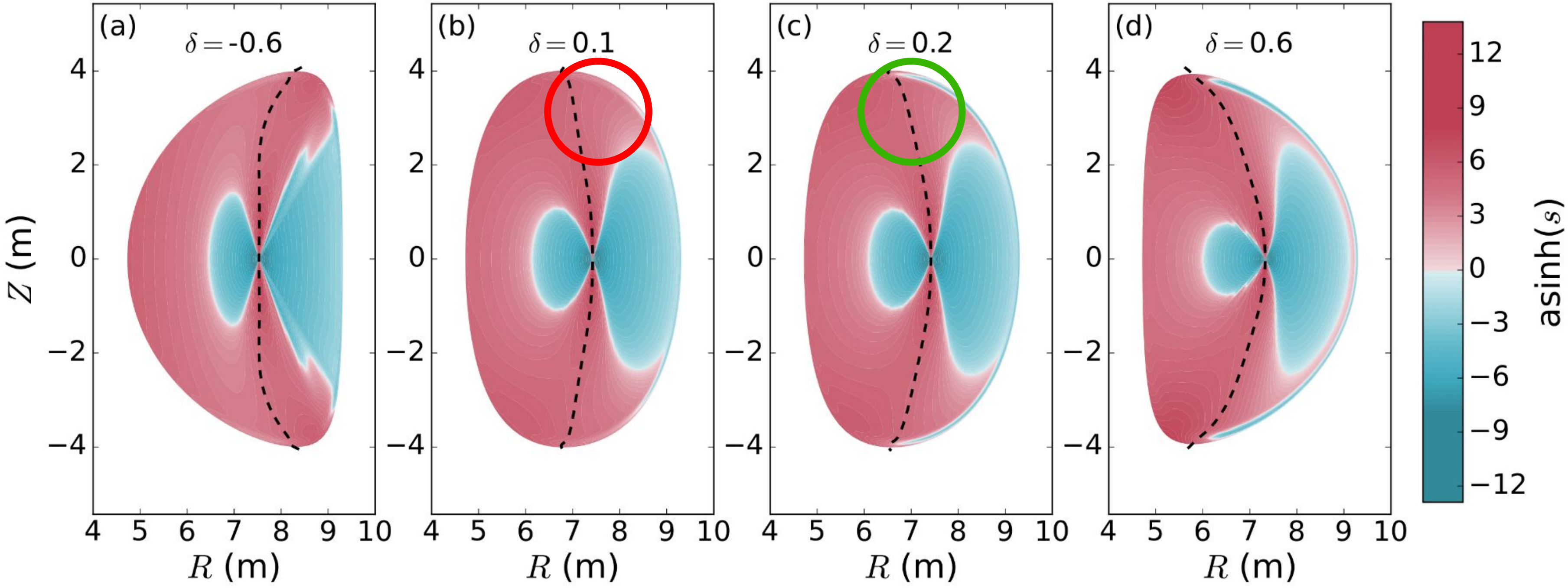
Large changes in ν* needed to change access





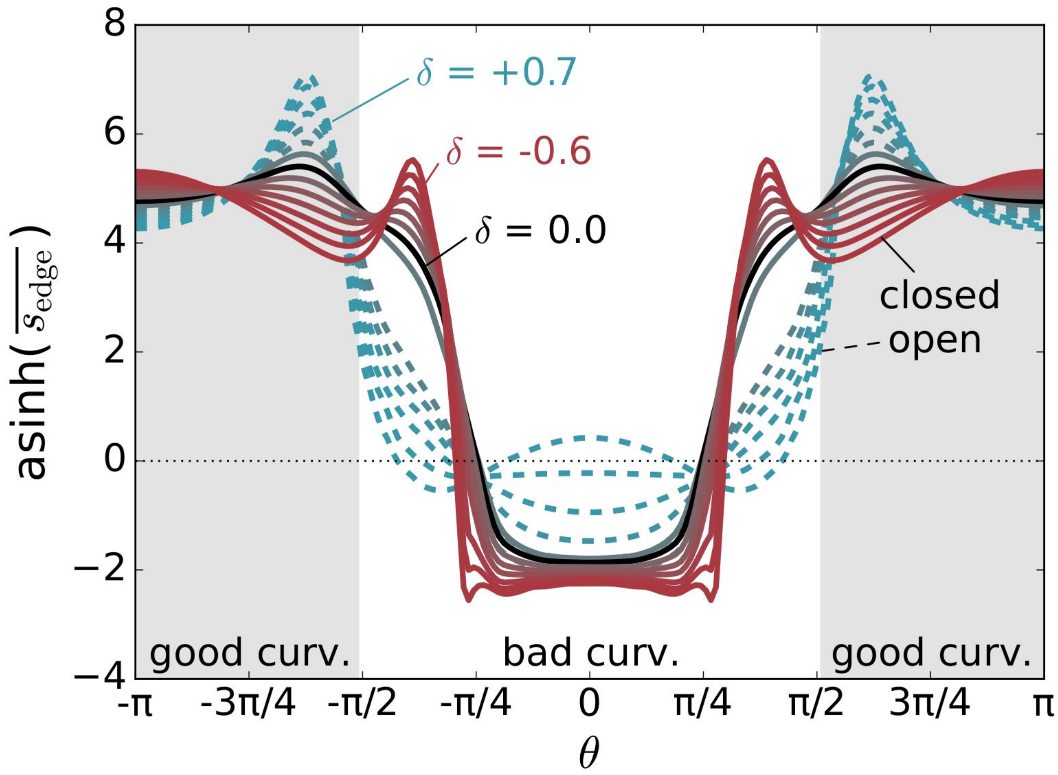
Why this effect? Triangularity modifies local shear!

- Local shear defined as: $s \equiv -\frac{\vec{B} \times \nabla\psi}{|\nabla\psi|^2} \cdot \nabla \times \left(\frac{\vec{B} \times \nabla\psi}{|\nabla\psi|^2} \right)$

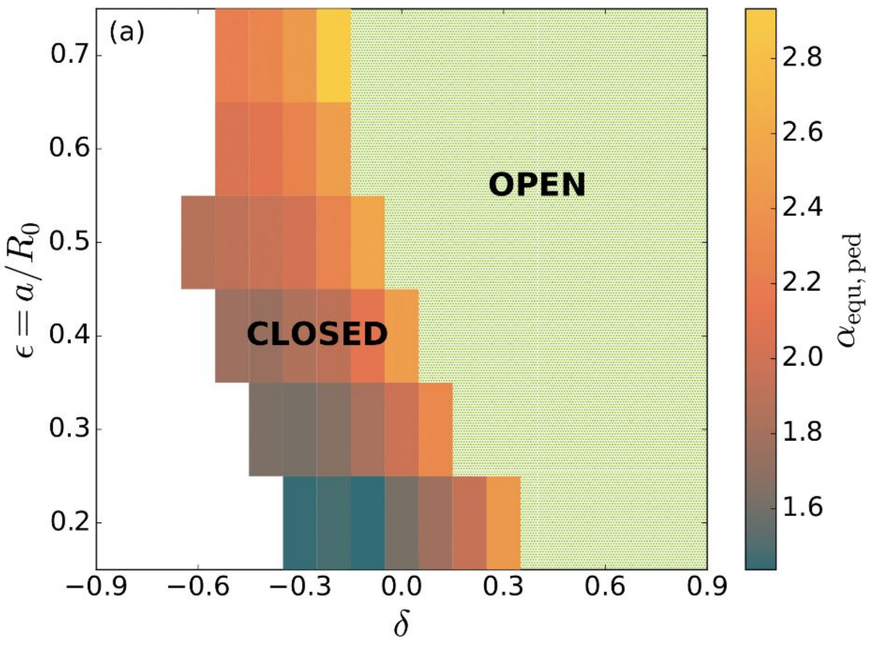


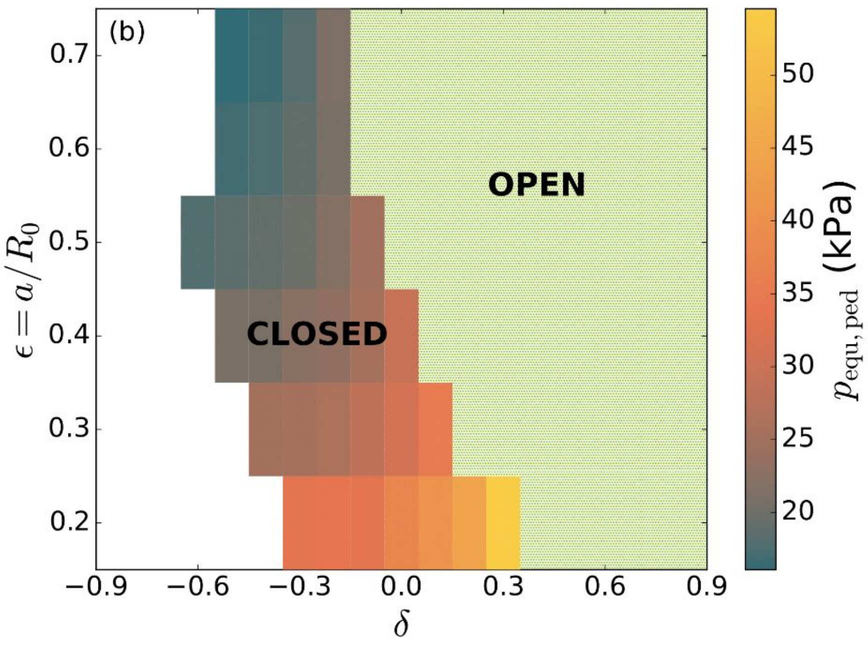
Increased local shear in bad curv. prevents 2nd stability

- Local shear strong function of geometry
- When peak of shear profile ventures into the bad curv. region, access to 2nd stability is lost!
- This forces a LFS zero-crossing
  -> destabilizing



Decreased aspect ratio enables H-mode at lower δ





Three effects important for stability in δ - ϵ space

1. Strengthening of B_p on bad curv. side
   - High-β gives rise to large Shafranov shift
   - Shortens “bad curv. connection length”

2. At low aspect ratio, local shear in bad curv. region is diminished
   - As β increases, LFS local shear decreases
   - Facilitates shear reversal at high enough β

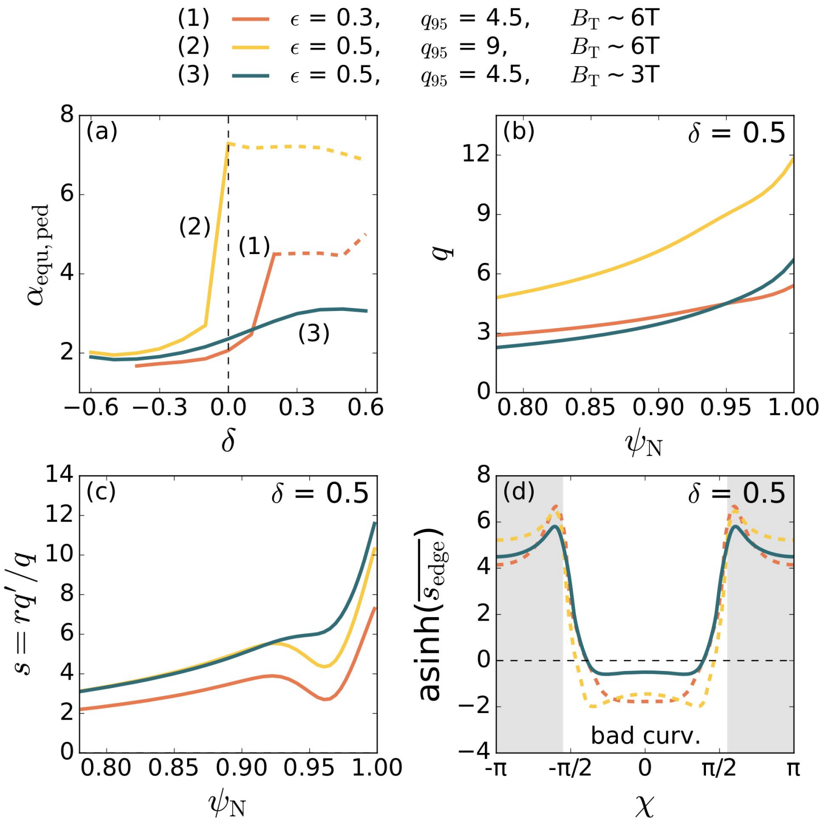
3. At low aspect ratio and high *q*, favorable curvature is enhanced
   - Suppresses unfavorable contribution of B_p to κ_n

Local shear must be ***sufficiently*** negative for stability

- Increase ϵ at constant B_p, I_p:
  - q_{95} increases
  - δ_{crit} decreases
  - max(α) increases

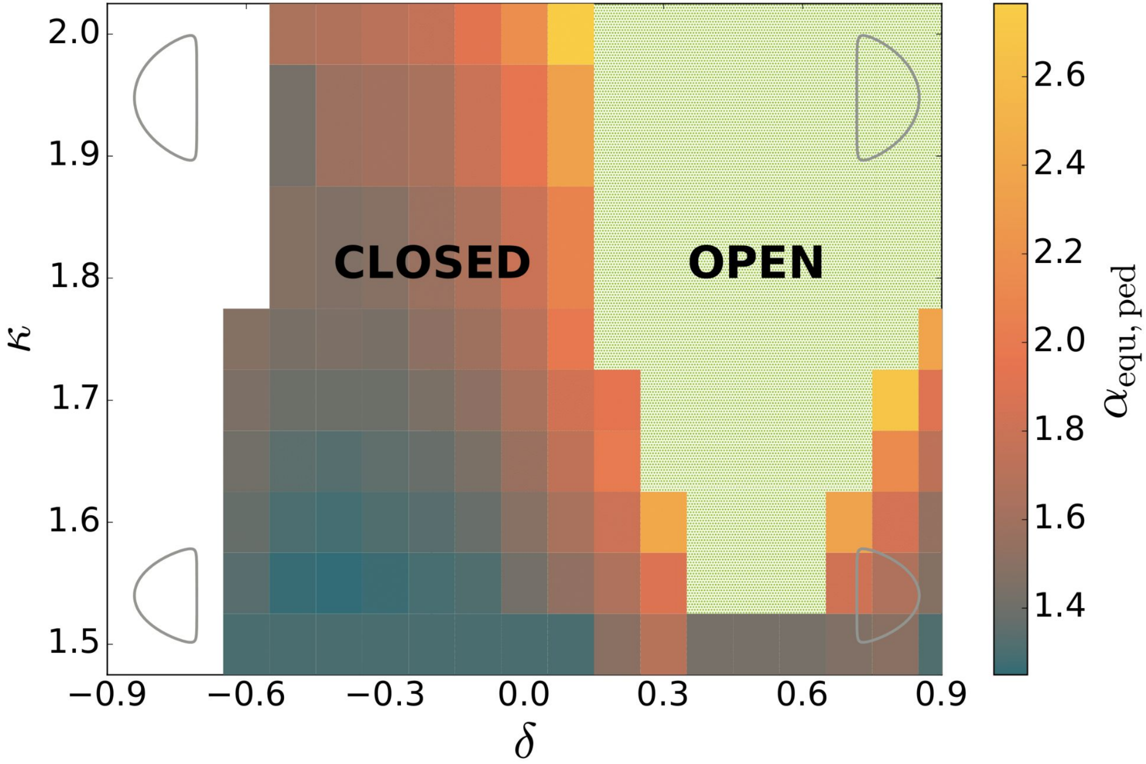
- Increase ϵ at constant q_{95}, I_p:
  - B_T drops
  - δ_{crit} increases
  - max(α) increases

- At low q_{95}, high ϵ, local shear is not low enough!



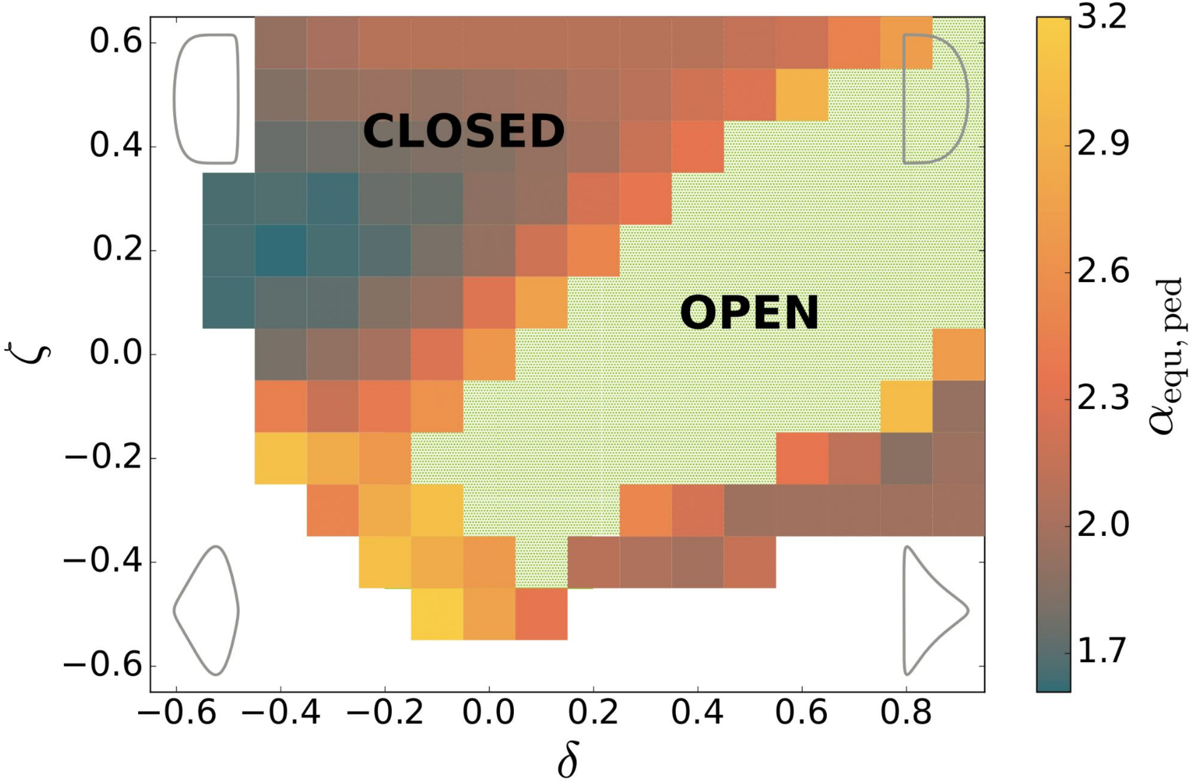
At low elongation, 2nd stability access fully closes

- At large κ, stability is relatively unaffected
- At small κ, 2nd stability is closed for all δ
- Lower ballooning-limited pedestals at high κ

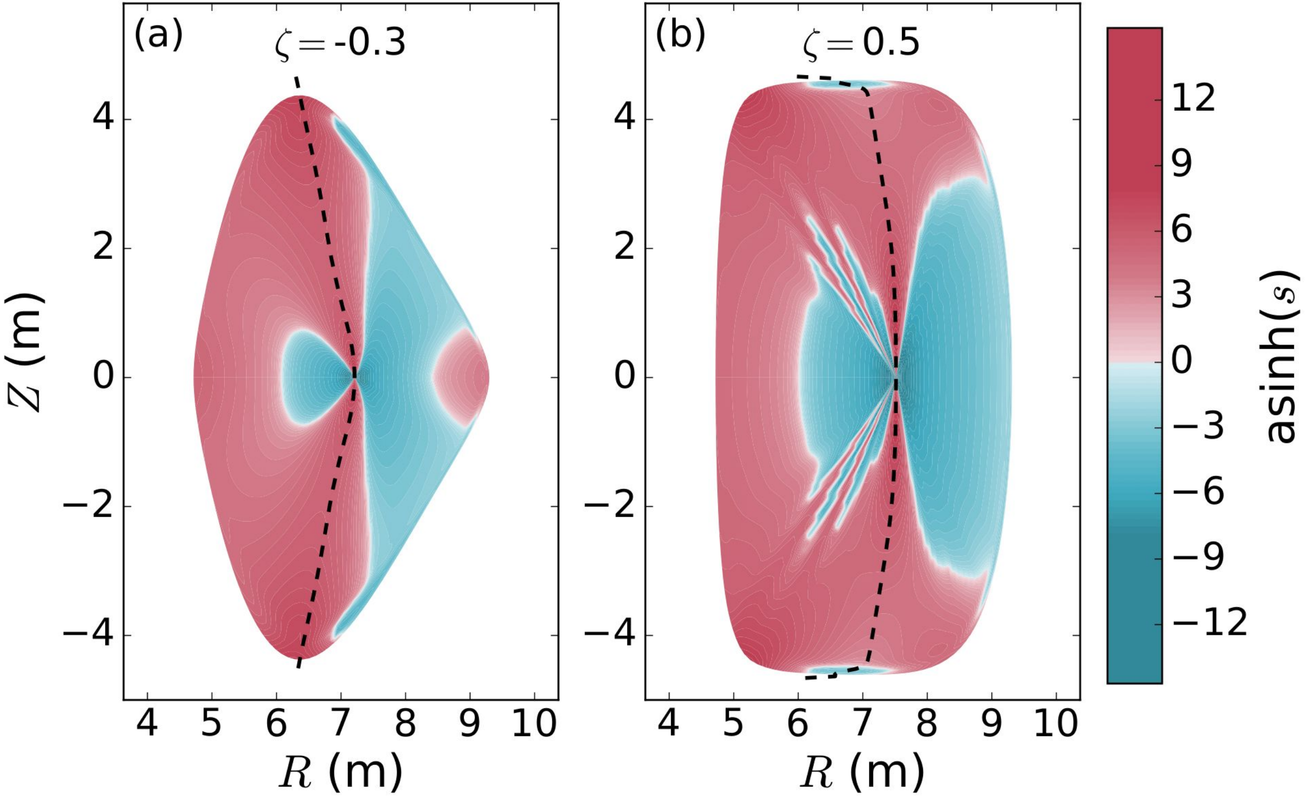


For stability, squareness cannot be too high or too low

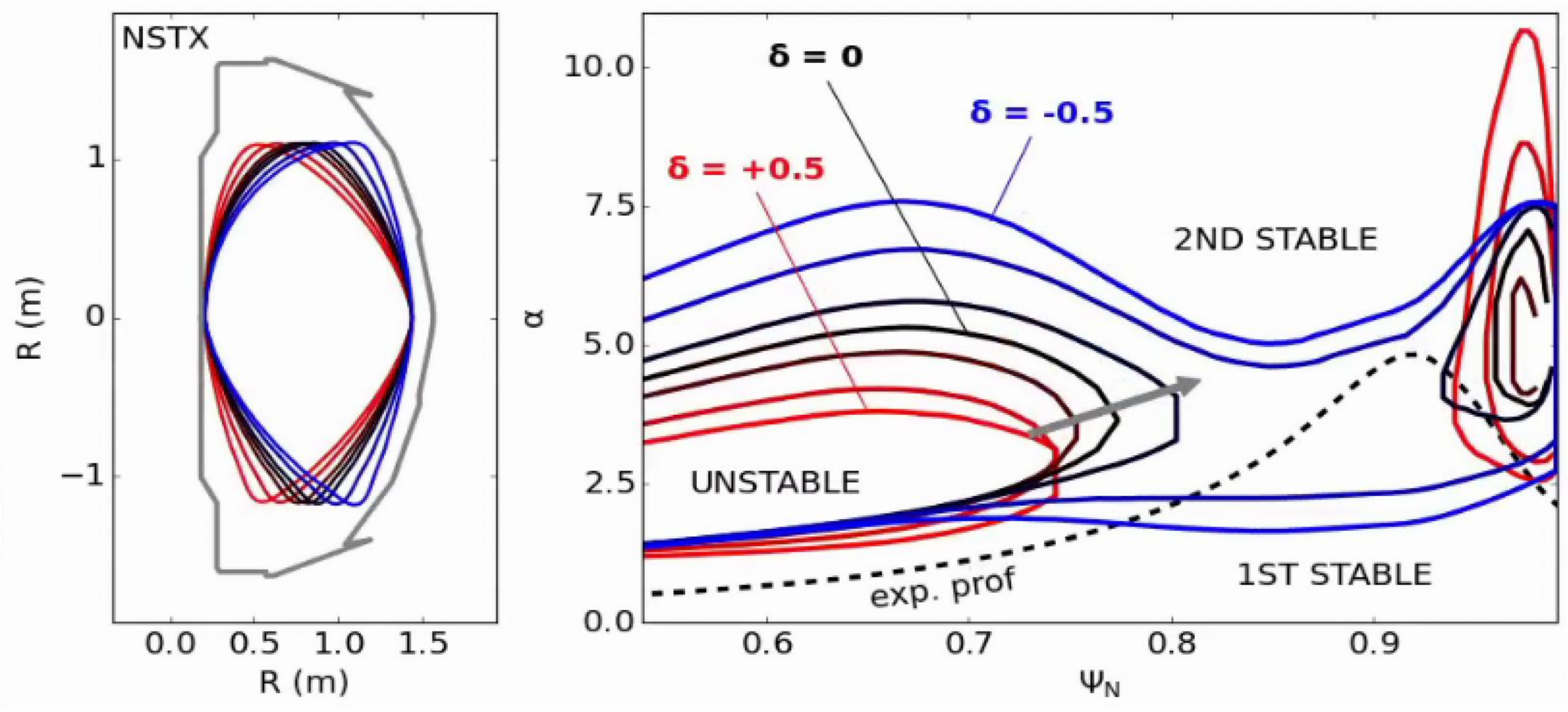
- Medium squareness needed for 2nd stability access
- Still a strong function of δ!
- Similar to old DIII-D experiments



Extreme squareness also modifies bad curv. local shear!



Bonus: NSTX H-mode suppression through Neg-D



Outline

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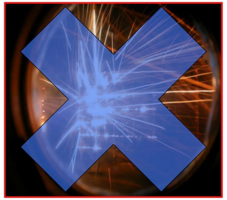

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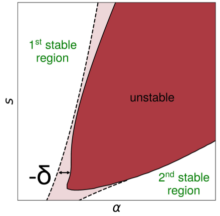
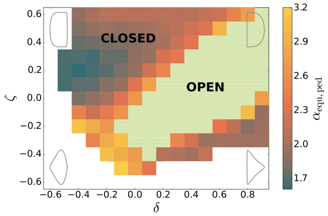


- How does shape impact second stability access?

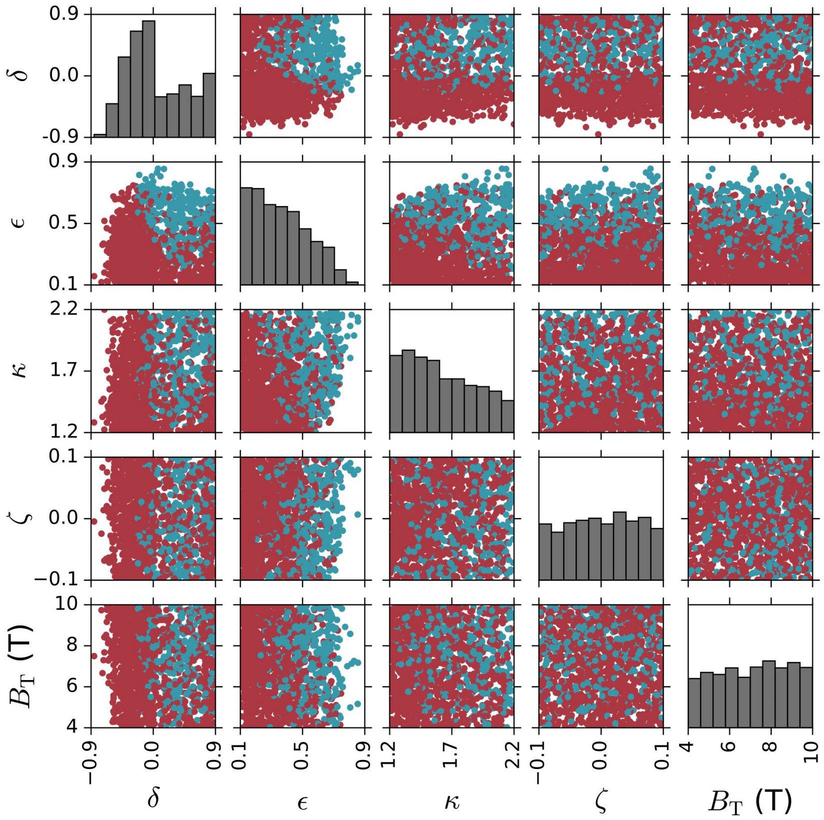


- **Extrapolation of ballooning physics to reactors**

Database of >1500 random equilibria generated

- Parameters selected from:

-0.9	>	δ	>	0.9
0.1	>	ϵ	>	0.9
1.2	>	κ	>	2.2
-0.1	>	ζ	>	0.1
2 m	>	a_{minor}	>	4.5 m
4 T	>	B_T	>	10 T
8 MA	>	I_p	>	20 MA
0.5e20 m^{-3}	>	$n_{e,ped}$	>	2e20 m^{-3}
1e20 m^{-3}	>	$n_{e,core}$	>	3e20 m^{-3}
1 keV	>	$T_{e,ped}$	>	2.5 keV
15 keV	>	$T_{e,ped}$	>	3 keV
0.03	>	Δ_{ped}	>	0.07

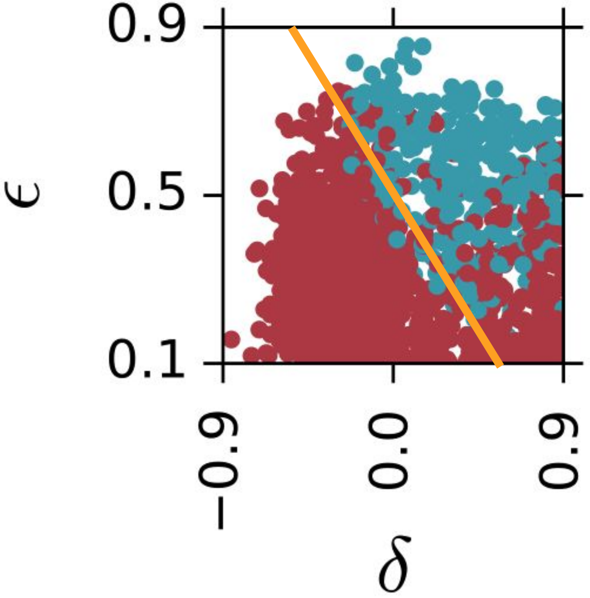


Simple linear classification can ~predict stability access

- Best LDA predictor (89% accuracy score):

$$x = 15.629 - 0.419 B_{\mathrm{T}} - 13.140\epsilon - 3.096\kappa - 3.361\delta + 3.450\zeta$$

  - Predicted stable if: $\frac{1}{1+\exp(x)} > 0.5$



- Using only δ and ϵ, already accuracy of 84%

- Adding collisionally has no strong effect
  - Shape is most important!

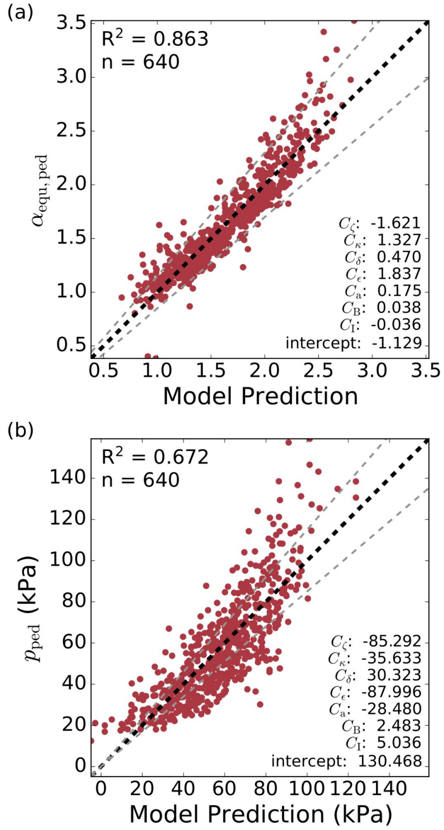
Scalings to maximum pedestal height available

- For cases where the maximum edge pressure is limited by ballooning modes, pedestal limit fit by:

$$\alpha_{\mathrm{equ,ped}} = C_0 + C_\kappa \kappa + C_\epsilon \epsilon + C_\delta \delta + C_\zeta \zeta + C_{\mathrm{a}} a_{\mathrm{minor}}[\mathrm{m}] + C_{\mathrm{B}} B_{\mathrm{T}}[\mathrm{T}] + C_{\mathrm{I}} I_{\mathrm{p}}[\mathrm{MA}]$$

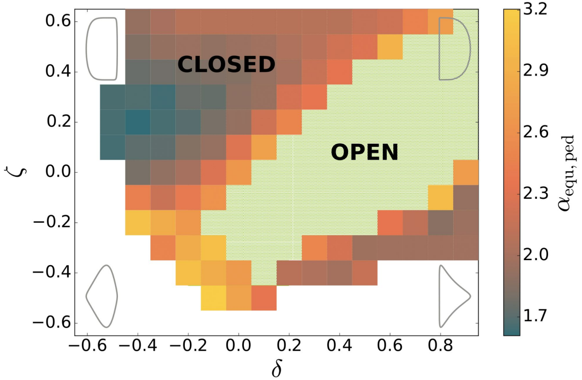
- Critical stabilizing factors associated with the pressure gradient, rather than pressure itself

- Scaling available for incorporation in to systems codes, but recommend to run BALOO directly
  - BALOO module added to STEP code

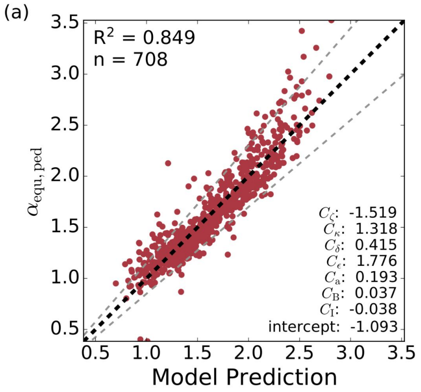


Conclusions: Neg-D reactors robustly suppress H-mode

- Neg-D presents an interesting ELM-free scenario
- H-mode suppression in Neg-D likely set by $n = \infty$ ballooning modes, which are destabilized by increased bad curvature local shear

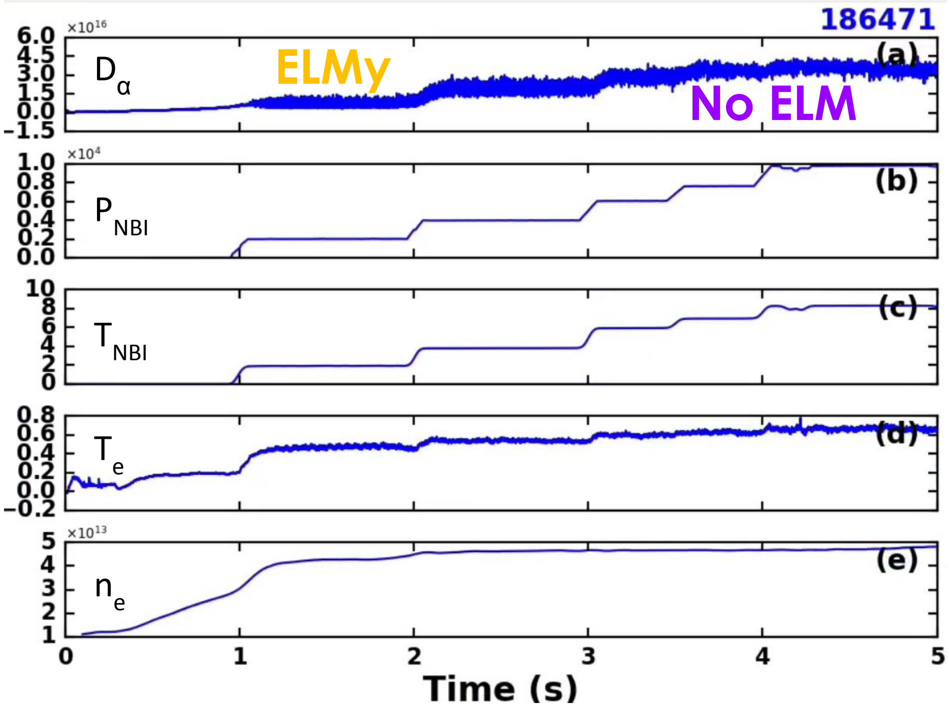


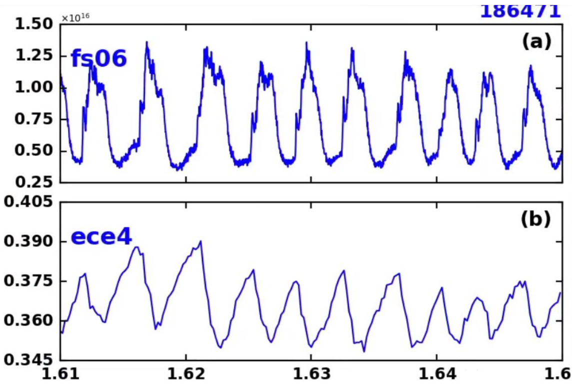
- Stability is a complicated function of shape!
  - Easier access at low aspect ratio
  - Restricted at low elongation
  - Restricted at large and small squareness
- Preliminary scaling laws developed for systems codes



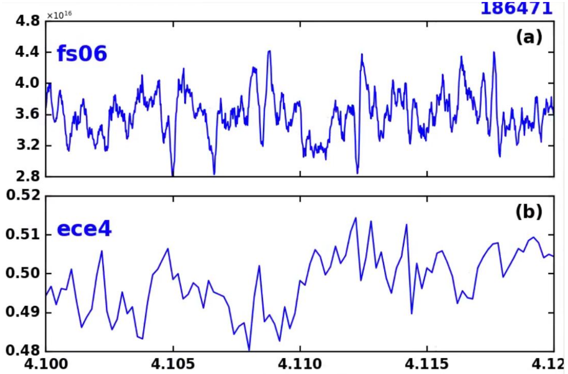
Backup Slides

ELMs suppressed at high power in DIII-D neg-D (δ = -0.4)





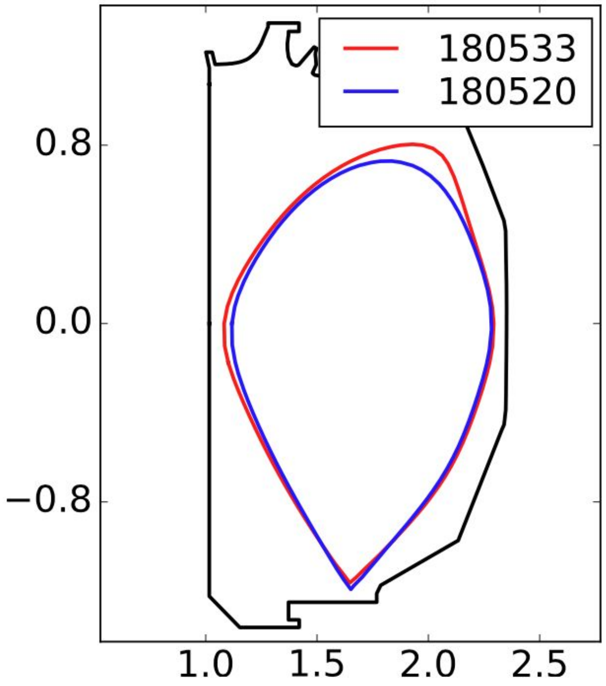
ELMy

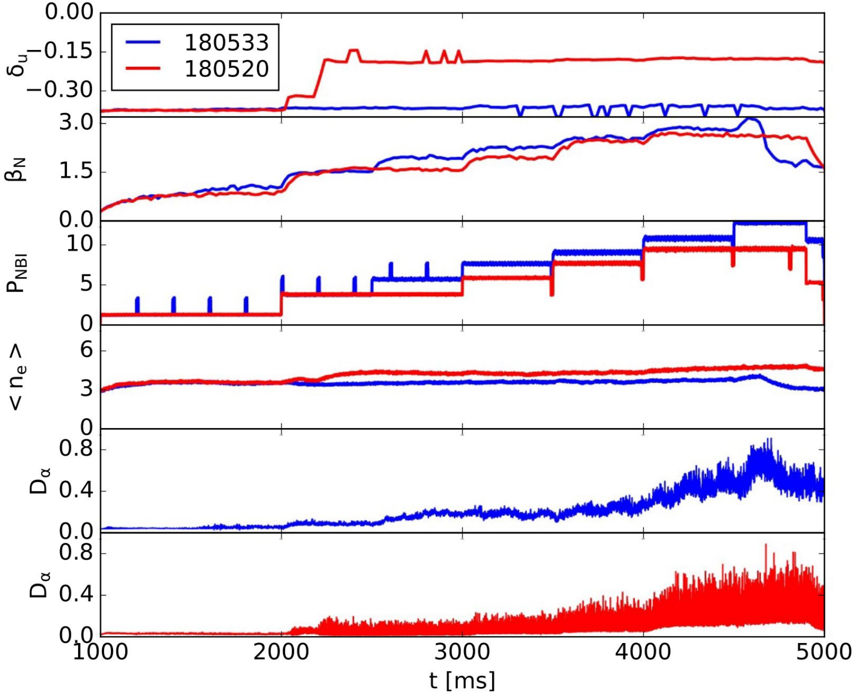


No ELM

Courtesy of Guanying Yu

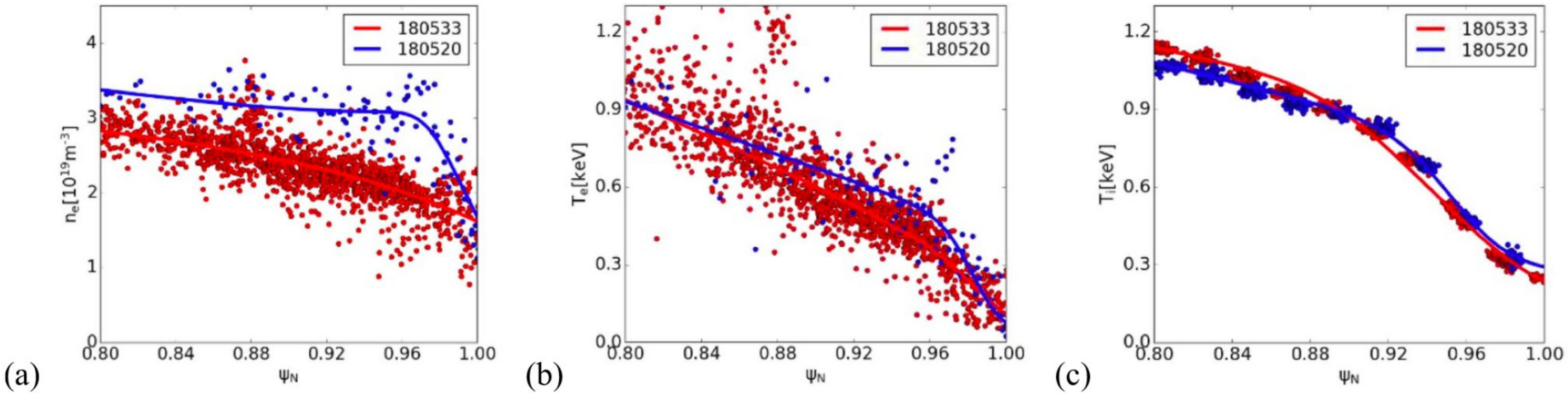
DIII-D NT discharges in L- and H-mode

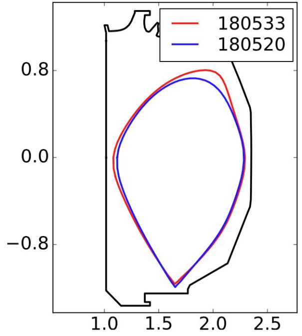




Saarelma, et. al. PPCF (2021)

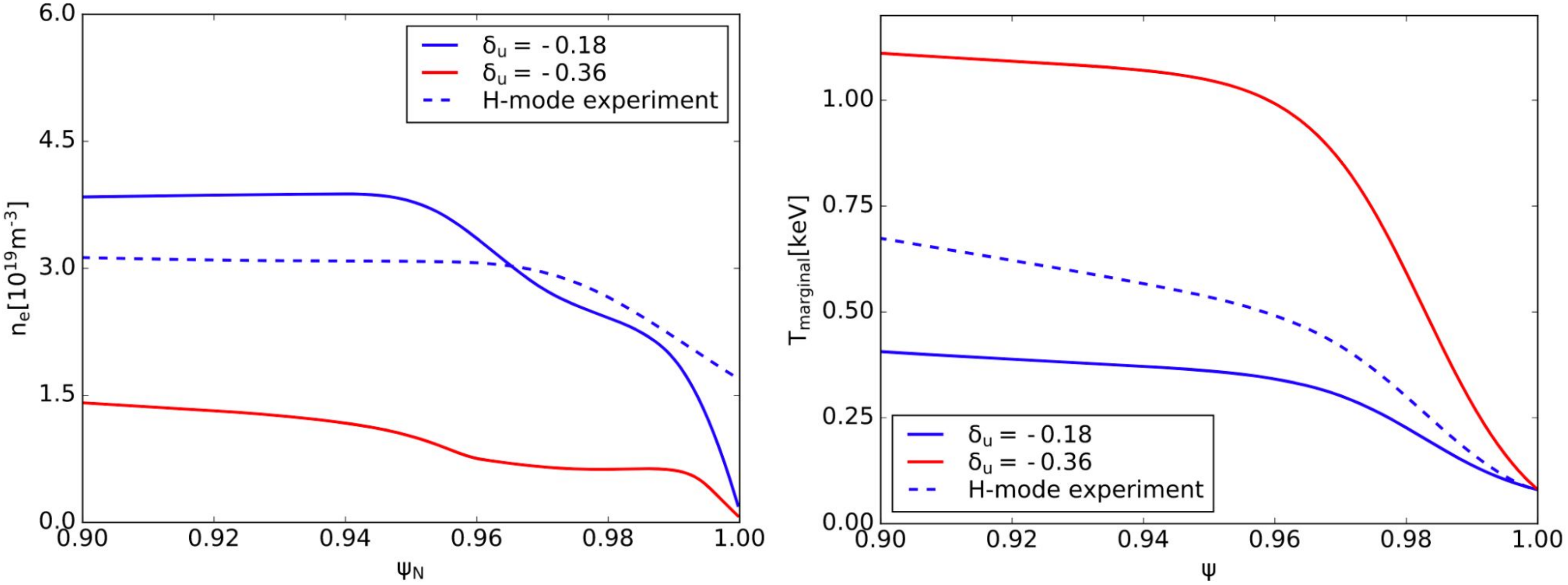
DIII-D NT profiles in L- and H-mode





Saarelma, et. al. PPCF (2021)

Arbitrary adjustment of density profile

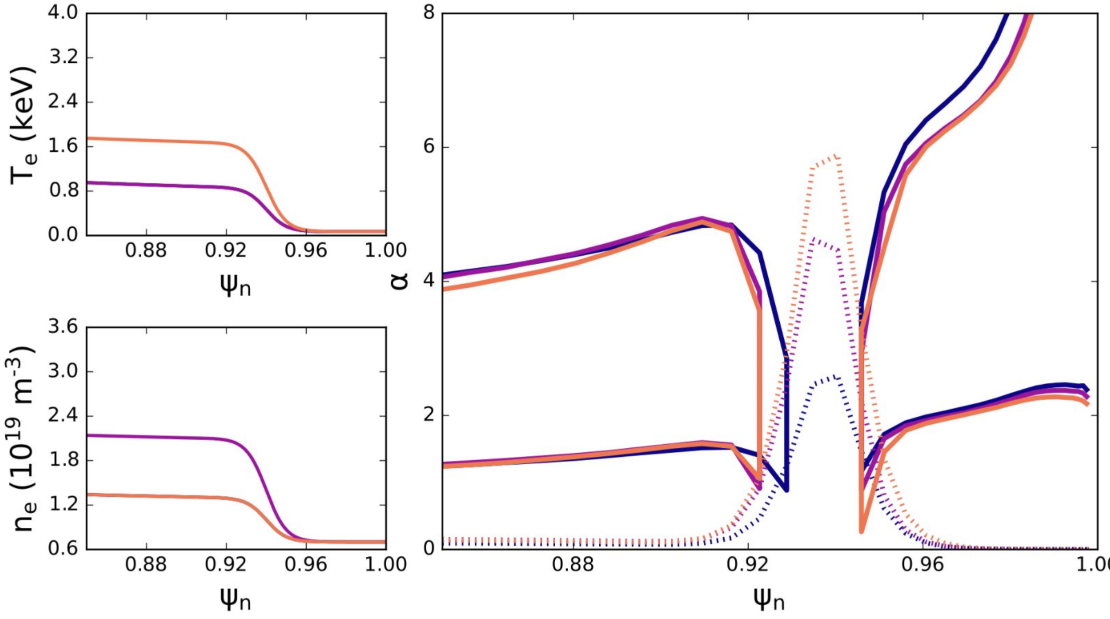


Saarelma, et. al. PPCF (2021)

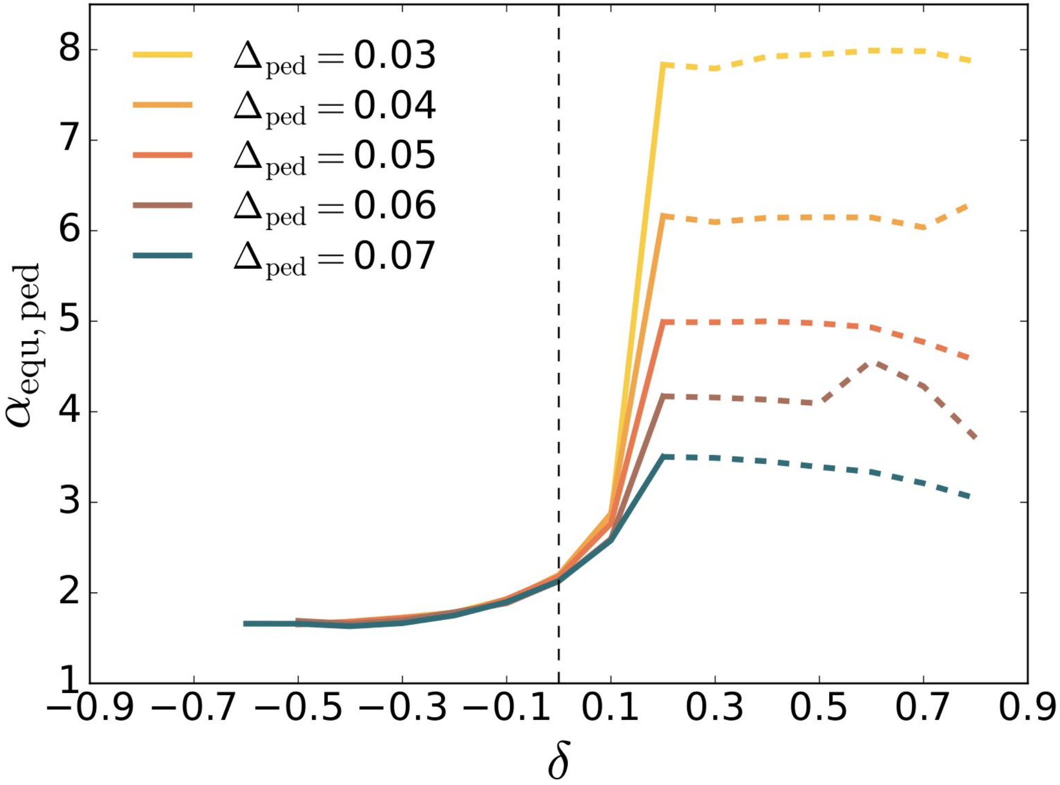
Armor H-mode access possible with arbitrary profiles

- At strong -δ, H-mode access blocked by ballooning instability
- With arbitrary profile control, we can reopen 2nd stability access

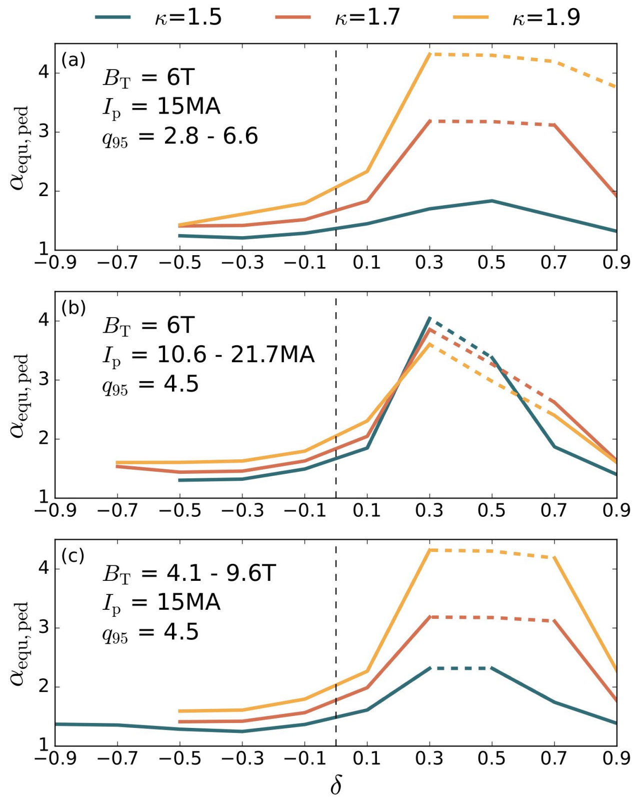
- Profile adjustments:
  - **Steep gradient region limited to ψ_n = 0.93-0.95**
  - Pedestal flattened outside of ψ_n=0.96 to avoid instability
- Is this possible?



Profile gradient dependence on pedestal width



Elongation scans at fixed q_{95}



Tests of breaking axisymmetry