

# Progress on Disruption Event Characterization and Forecasting (**DECAF**) in Tokamaks

**S.A. Sabbagh<sup>1</sup>**, J.W. Berkery<sup>1</sup>, Y.S. Park<sup>1</sup>, J.H. Ahn<sup>1</sup>, Y. Jiang<sup>1</sup>, J.D. Riquezes<sup>1</sup>, R.E. Bell<sup>2</sup>, M.D. Boyer<sup>2</sup>, A.H. Glasser<sup>3</sup>, J. Hollocombe<sup>4</sup>, J. Kim<sup>5</sup>, A. Kirk<sup>4</sup>, J. Ko<sup>5</sup>, W. Ko<sup>5</sup>, L. Kogan<sup>4</sup>, B. LeBlanc<sup>2</sup>, J.H. Lee<sup>5</sup>, Y.K. Oh<sup>5</sup>, F. Poli<sup>2</sup>, S.D. Scott<sup>2</sup>, A. Thornton<sup>4</sup>, L. Terzolo<sup>5</sup>, S.W. Yoon<sup>5</sup>, S.J. Wang<sup>5</sup>, Z.R. Wang<sup>2</sup>

<sup>1</sup>*Department of Applied Physics, Columbia University, New York, NY*

<sup>2</sup>*Princeton Plasma Physics Laboratory, Princeton, NJ*

<sup>3</sup>*Fusion Theory and Computation, Inc., Kingston, WA*

<sup>4</sup>*Culham Centre for Fusion Energy, UKAEA, Abingdon, UK*

<sup>5</sup>*National Fusion Research Institute, Daejeon, Republic of Korea*



NSTX-U / Magnetic Fusion  
Science meeting

**MAST-U**



**24 Sep 2018**

**KSTAR**

**PPPL**

**NSTX-U**



**Princeton, NJ USA**

# A broadened disruption prediction and avoidance analysis is progressing for ITER and future tokamaks

- ❑ Motivation: Disruption prediction/avoidance is a critical need
  - ❑ A highest priority DOE FES (Tier 1) initiative - present “grand challenge” in tokamak stability research:
    - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption allowance: < 1 - 2% (energy + E&M loads); << 1% (runaways)
- ❑ Talk Outline
  - ❑ Disruption Event Characterization and Forecasting (**DECAF**) review
  - ❑ Present DECAF development and initial multi-device examination (now including MAST)
  - ❑ Key related analysis (e.g. long pulse, high beta KSTAR kinetic equilibrium reconstruction, stability analysis, high non-inductive plasmas)
  - ❑ “Predict-first” TRANSP analysis: 2018/2019 KSTAR operation with 2<sup>nd</sup> NBI system
  - ❑ Summary / next steps

# International collaborative research on disruption prediction/avoidance expands effort to MAST-U, KSTAR

## ❑ US DOE supports our efforts

- ❑ Multi-institutional collaborative grant on KSTAR, new grant on MAST-U
- ❑ Multi-faceted physics research includes equilibrium, stability, transport, control, diagnostic hardware elements
  - Research originated on the NSTX spherical torus

## ❑ Personnel

### ❑ Columbia U.:

- S.A. Sabbagh\* (Lead PI), Y.S. Park, J.H. Ahn\*, Y. Jiang\* (post-doctoral)
- J.W. Berkery\*, J. Bialek (part time); J.D. Riquezes\* (Columbia student)

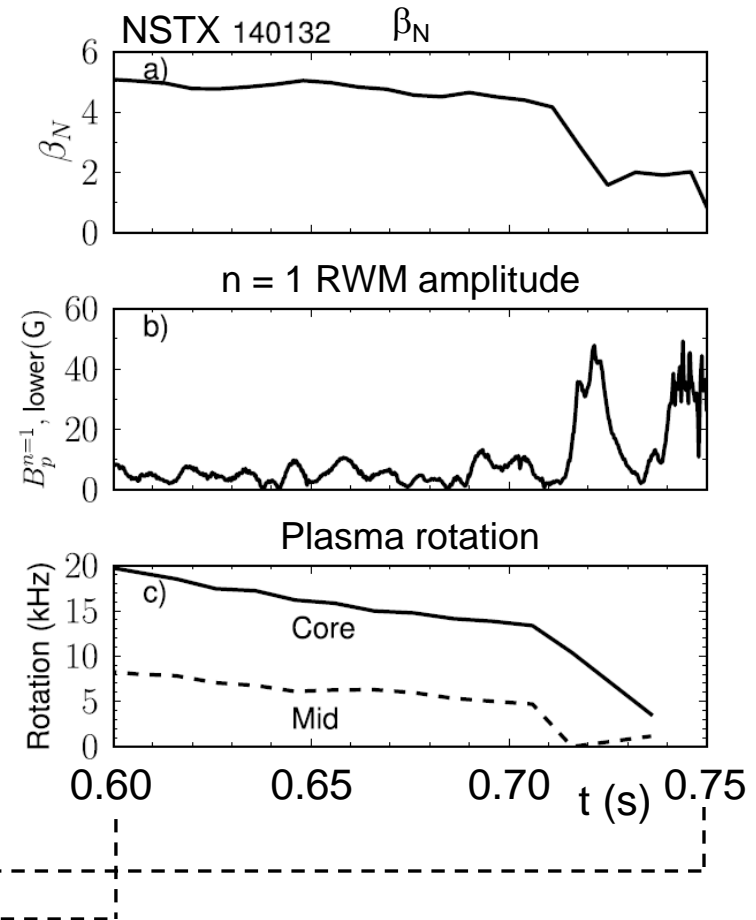
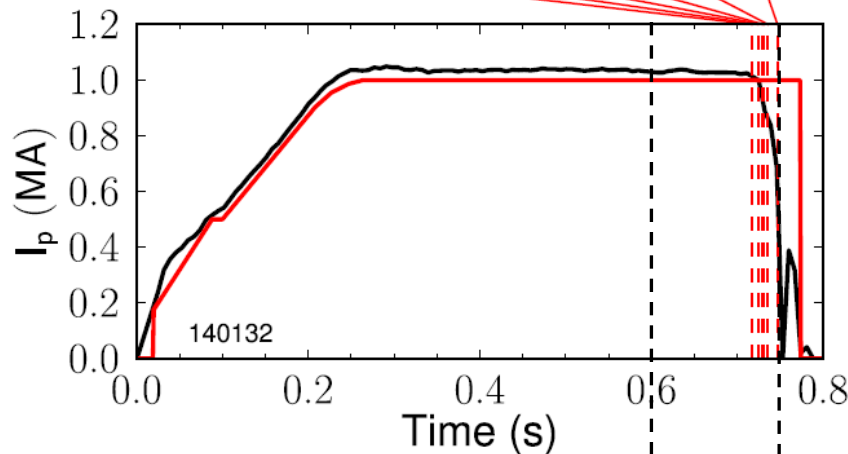
❑ PPPL: S. Scott (~full time, inst. PI), M. Boyer, B. LeBlanc (part time)

❑ MIT/ORISE: E.S. Marmor (inst. PI), B. Mumgaard

\*PPPL TSDW meeting speakers

# Brief review: the DECAF code automatically computes **events + disruption event chains** leading to disruption

## Disruption event chain

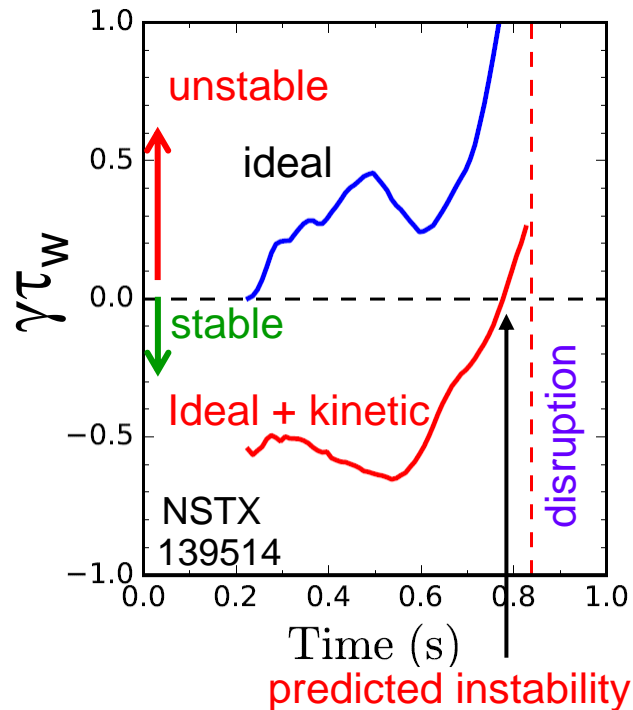


### Events (in this chain)

- RWM: resistive wall mode
- VDE: vertical instability
- WPC: wall proximity control
- LON: low density warning
- IPR: not meeting  $I_p$  request
- LOQ: low  $q$  warning
- DIS: disruption

# DECAF reduced kinetic MHD model computations forecast the instability boundary to unstable global MHD modes

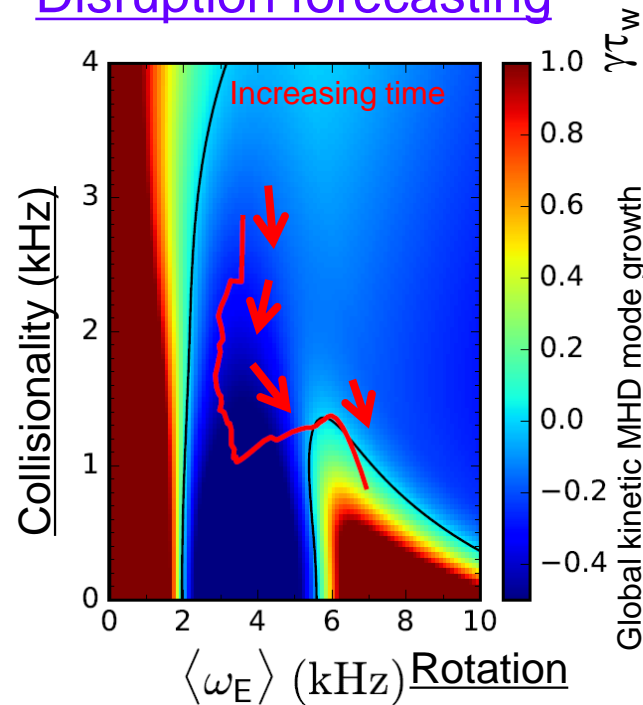
## Norm. growth rate vs. time



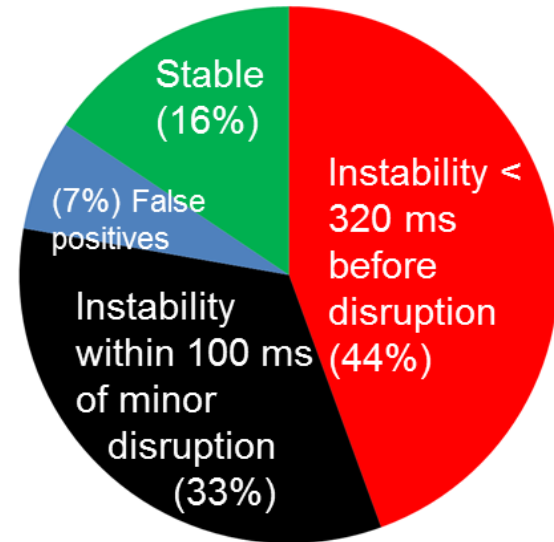
## □ Favorable characteristics

- Stability contours CHANGE for each time point
- Possible to compute growth rate prediction in real time

## Disruption forecasting



## Predicted instability statistics




- 84% of shots are predicted unstable (**stringent evaluation**)
- 44% predicted unstable < 320 ms (approx.  $60\tau_w$ ) before current quench
- 33% predicted unstable within 100ms of a minor disruption

J.W. Berkery, S.A. Sabbagh, R. Bell, *et al.*, Phys. Plasmas **24** (2017) 056103

# DECAF code and initial successful research/results is now advancing to a new level

## ❑ DECAF brief highlights of prior results

- ❑ First automated event chain analysis (followed deVries' manual work)
- ❑ Excellent performance on smaller, targeted databases (NSTX)
  - **DIS** event always found (100%), **VDE** event appeared in 90% of cases
  - Computed events accurately represented experiment (~ 10 events)
  - Physics model forecasted global MHD disruptions with ~ 85% reliability
- ❑ Disruption chains often repeated, e.g.: 

## ❑ Recent progress

- ❑ New DECAF MHD events allow analysis of general databases
- ❑ Coupling of new physics analysis tools and DECAF events
- ❑ Multi-machine databases (analysis now starting)
- ❑ Large database processing with small number of verified events

**Very rapid progress on DECAF in these directions occurring day-to-day at the moment**

# Progress on DECAF now moving to processing of multi-machine databases

## Analysis

- Kinetic equilibrium / stability analysis on KSTAR; planned for MAST

## DECAF database started

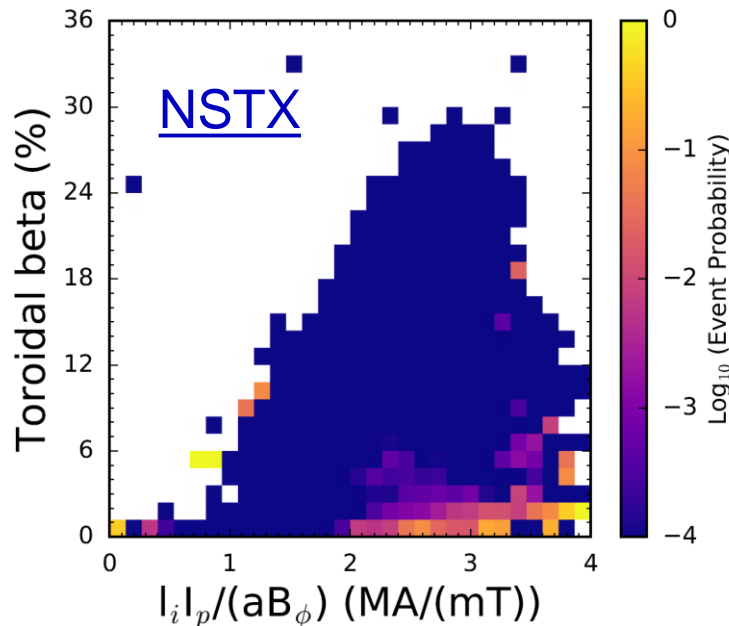
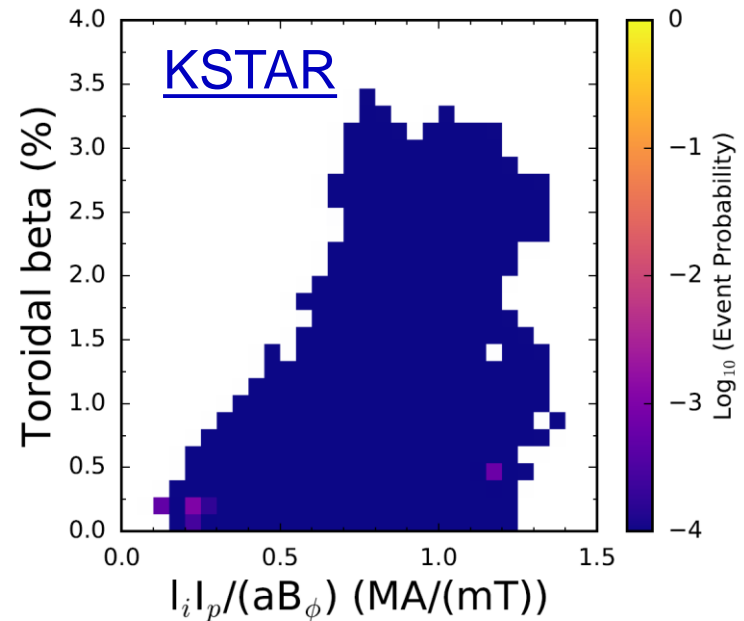
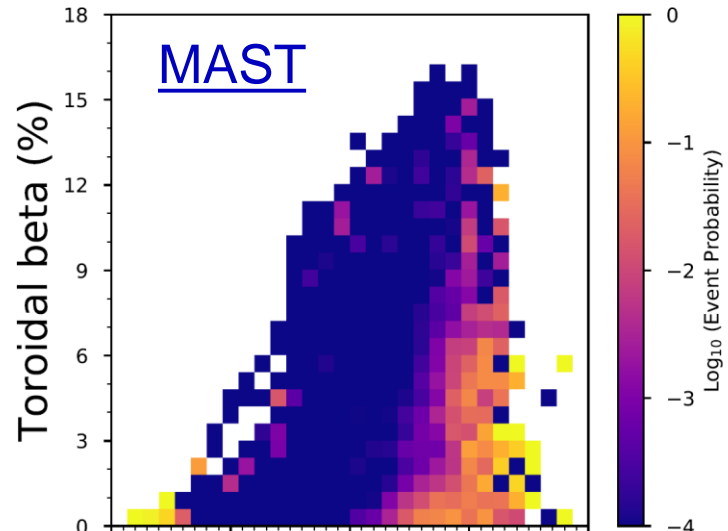
- Requires storage of DECAF analysis

Device / Capability	KSTAR	MAST	NSTX	DIII-D	TCV
Full database access (type)	Yes (MDSplus)	Yes (UDA)	Yes (MDSplus)	Yes (MDSplus)	Yes (MDSplus)
Database analysis	started	started	started		started
Equilibrium analysis	Kinetic + MSE	scheduled	Kinetic + MSE	available	
Stability	Ideal, Resistive Kinetic MHD	scheduled	Ideal, kinetic MHD (resistive)	Ideal, kinetic MHD	
shot*seconds (for kinetic analysis)	1,886 (2016+2017)	2,667 (est) (M7,M8, M9 runs)	2,000 / year (est)		

- Aim to bring in ASDEX-Upgrade, JET, and C-Mod databases



# Initial analysis of large databases further supports published result that **disruptivity doesn't increase with plasma $\beta$**

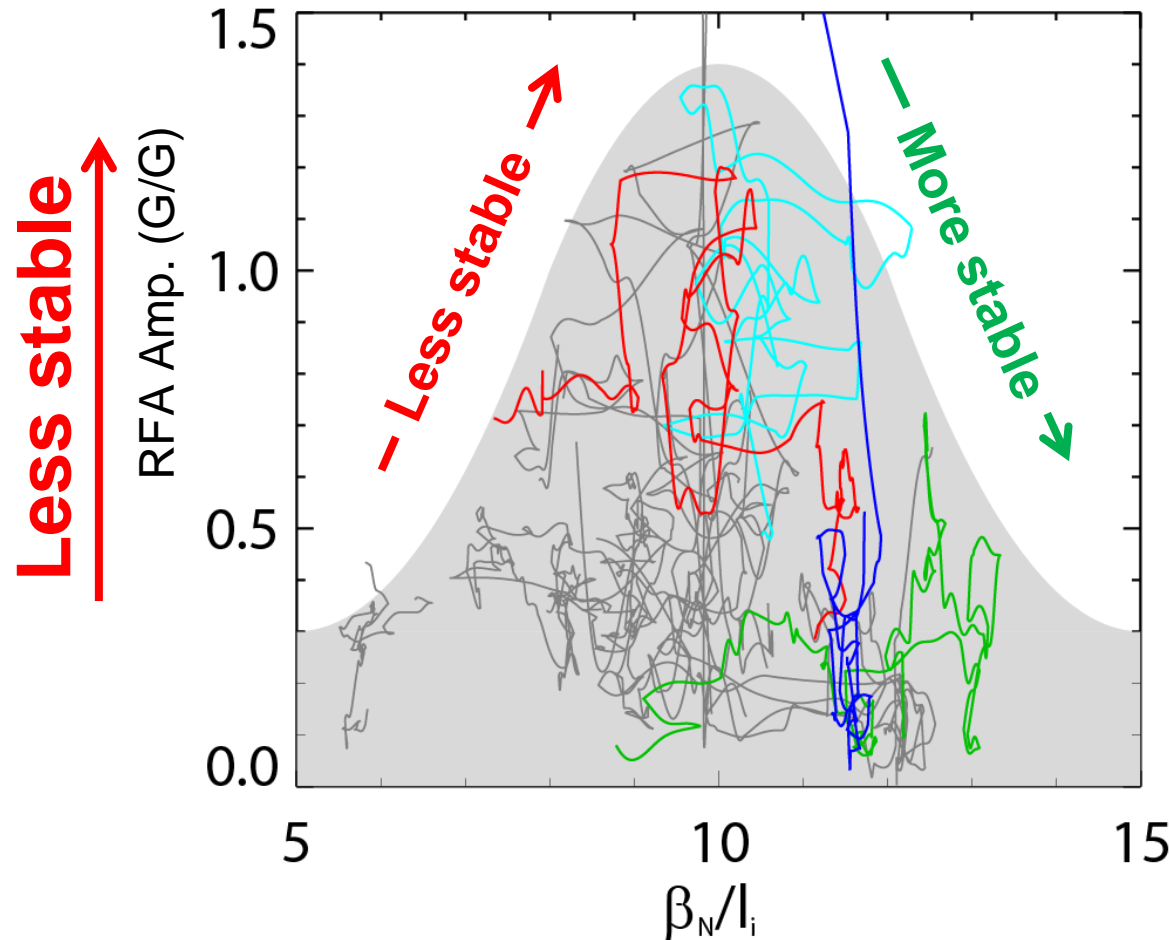


- ❑ DECAF analysis of **DIS** event
  - ❑ Similar to a “standard” disruptivity analysis
  - ❑ Shots analyzed at 10 ms intervals
- ❑ Analysis during  $I_p$  flat-top
  - ❑ MAST: 8902 plasmas analyzed
  - ❑ NSTX: 4706 plasmas analyzed
  - ❑ KSTAR: 750 plasmas analyzed (so far)



# Experiments directly measuring global MHD stability verify that highest $\beta_N/I_i$ is **not** the least stable scenario (NSTX)

## Resonant Field Amplification (RFA) measurement of stability

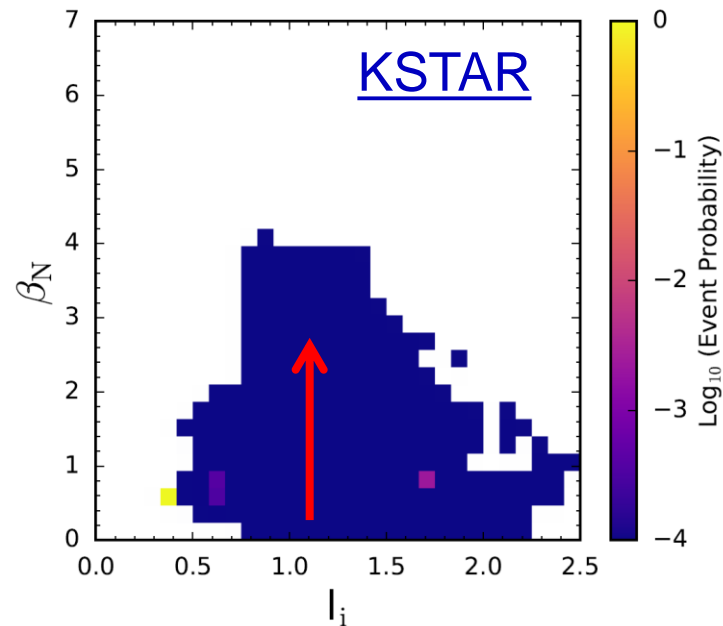
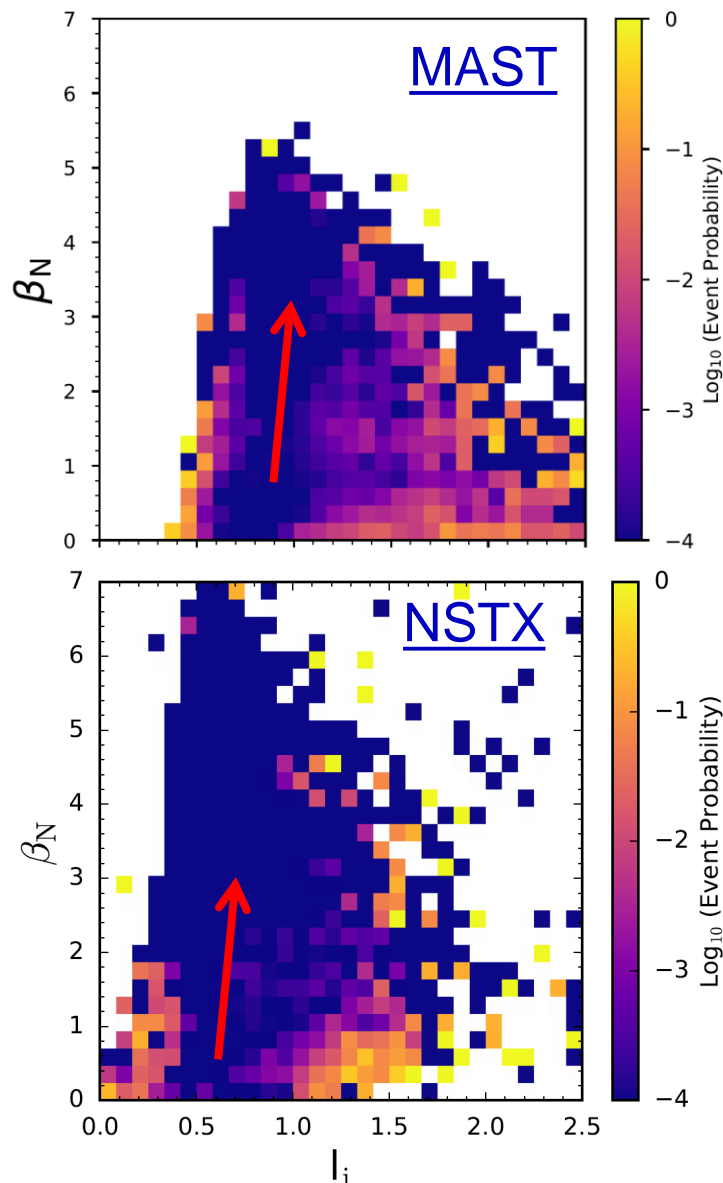


□ Non-intuitive stability increase at high  $\beta_N/I_i$

□ decreases up to  $\beta_N/I_i = 10$ ,  
increases at higher  $\beta_N/I_i$

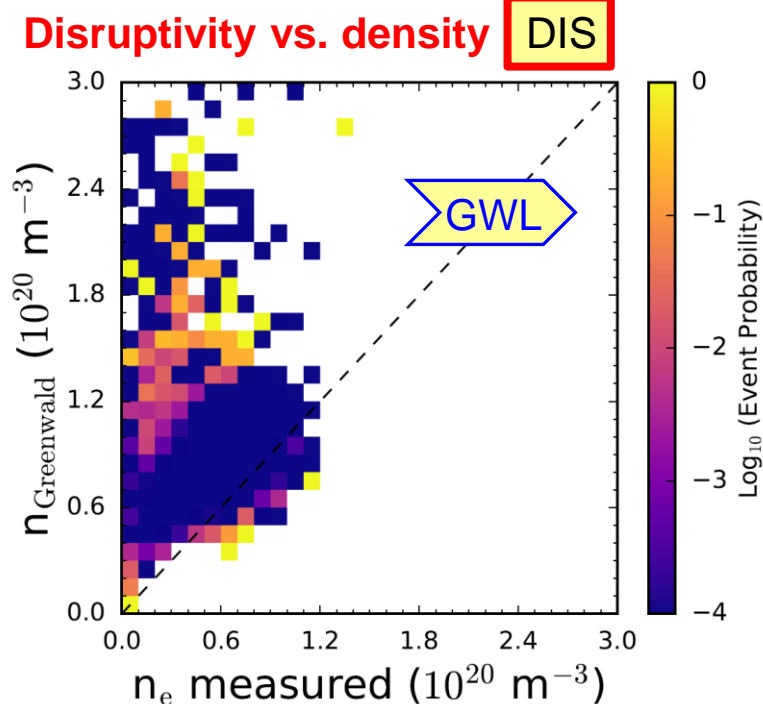
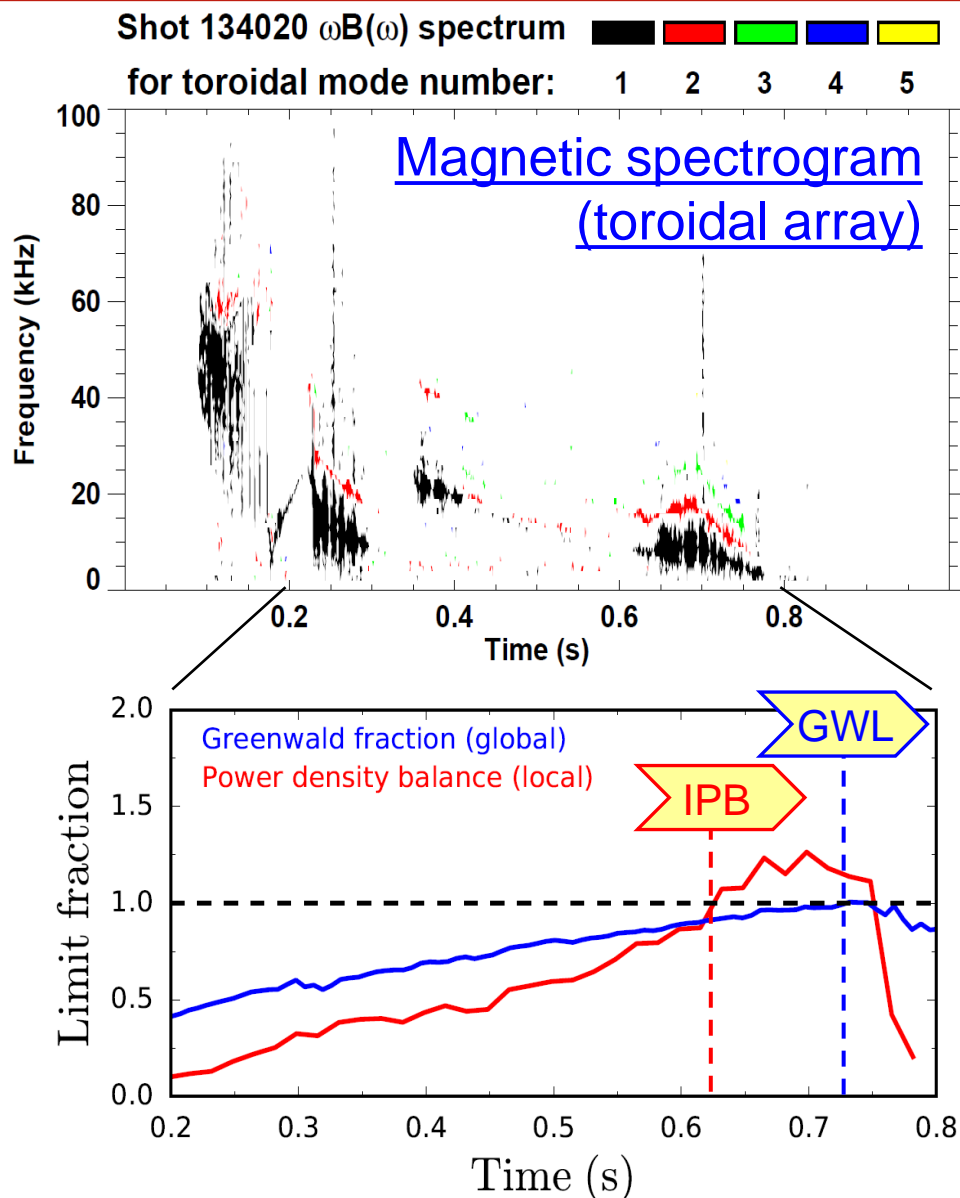
□ Understanding:  
Results consistent with kinetic stabilization theory invoking physical resonances

# Initial analysis of large databases further supports published result that disruptivity doesn't increase with $\beta_N$



- ❑ DECAF analysis of **DIS** event
  - ❑ Shots analyzed at 10 ms intervals
  - ❑ NEXT STEP: DECAF event chain analysis
- ❑ Analysis during  $I_p$  flat-top
  - ❑ MAST: 8902 plasmas analyzed
  - ❑ NSTX: 4706 plasmas analyzed
  - ❑ KSTAR: 750 plasmas analyzed (so far)

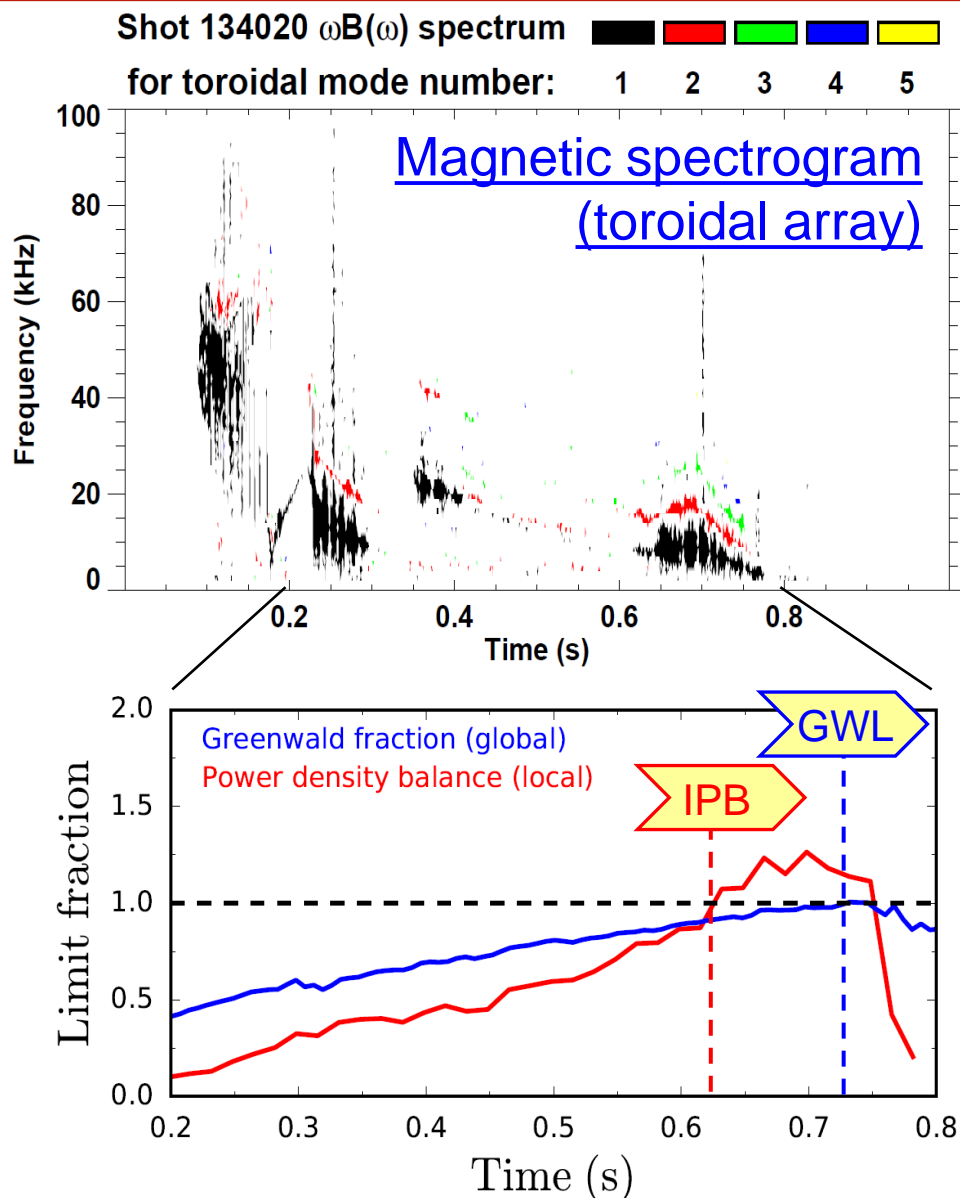
# DECAF density limit analysis started: global, local density limits examined, correlation of MHD onset near limits



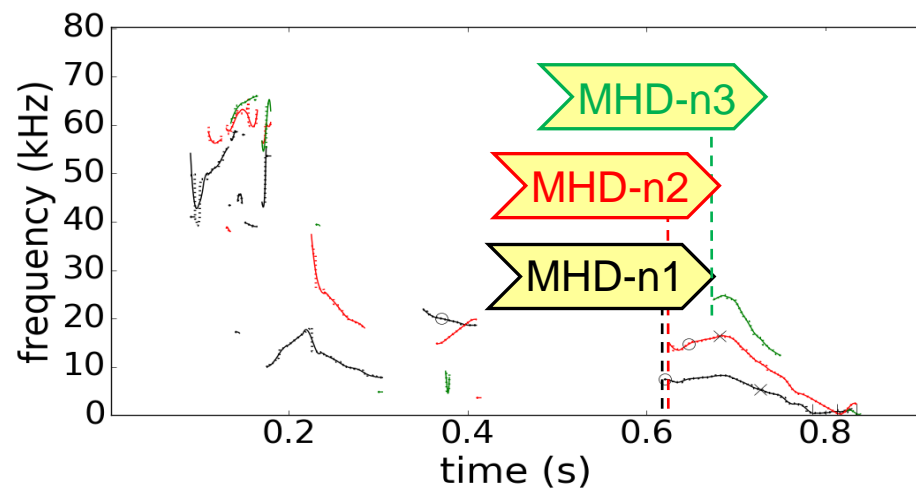
- ❑ Greenwald limit
  - ❑ Approaches 1 near mode lock
- ❑ Rad. island power balance
  - ❑ Examining utility of this physics model for disruption warning

See talk by J. Berkery, Wednesday

# More powerful automated MHD event objects have been developed for DECAF



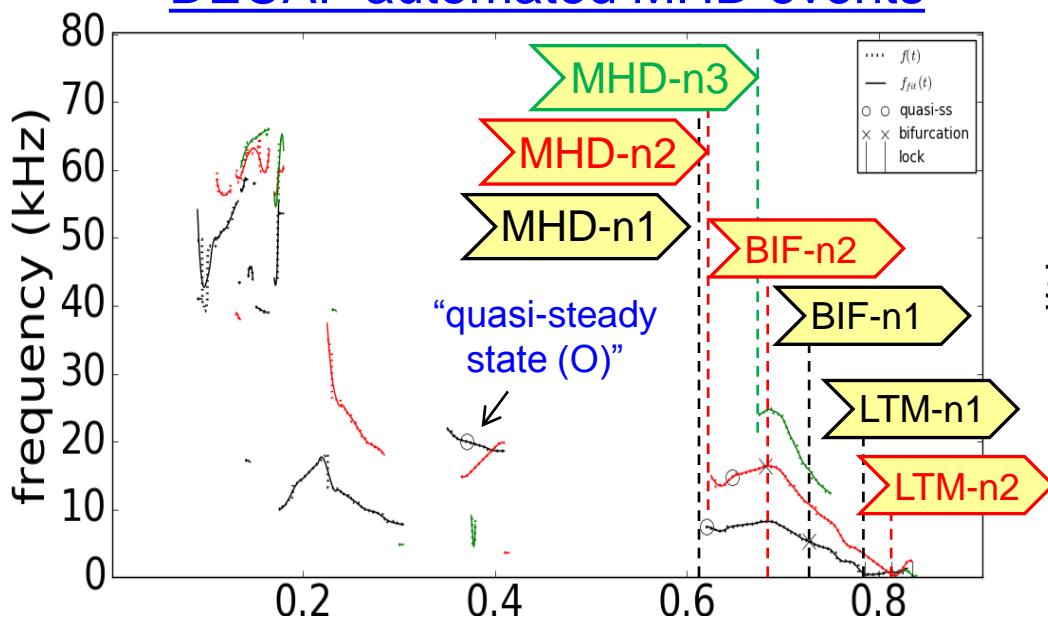
## DECAF automated MHD events



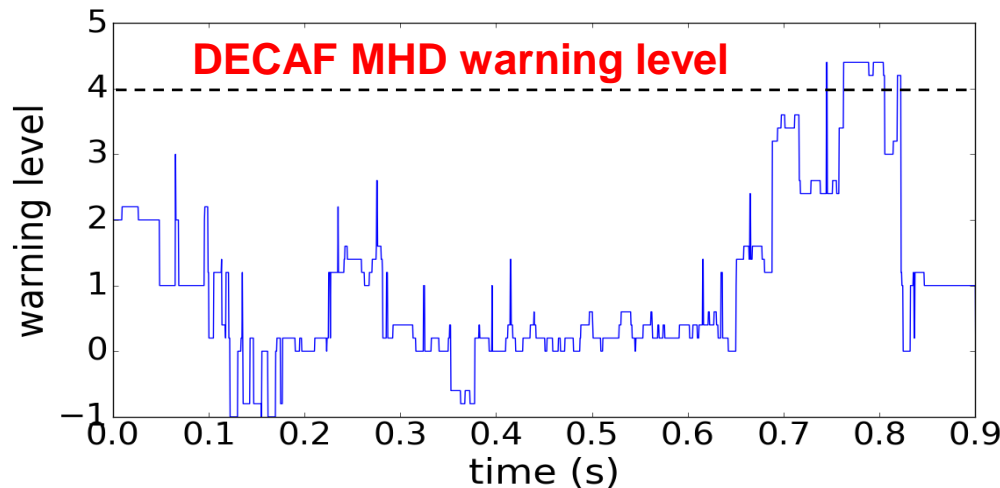
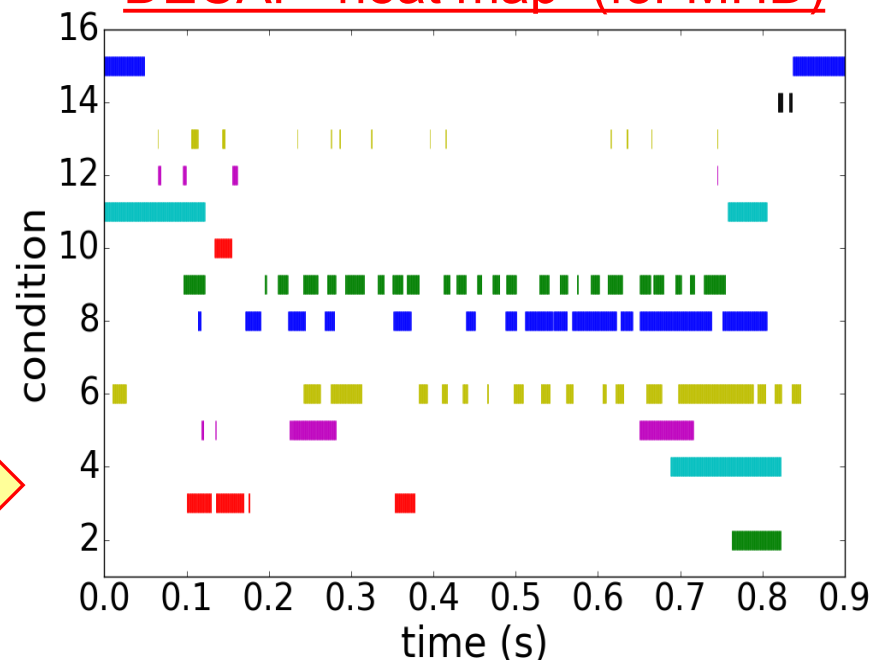
- More capable MHD event objects required for analysis of wider tokamak databases
- DECAF MHD events now include
  - Mode number (n) discrimination
  - Full history of mode evolution, including bifurcation and locking
  - Many disruption warning criteria

# New DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level

## DECAF automated MHD events



## DECAF "heat map" (for MHD)

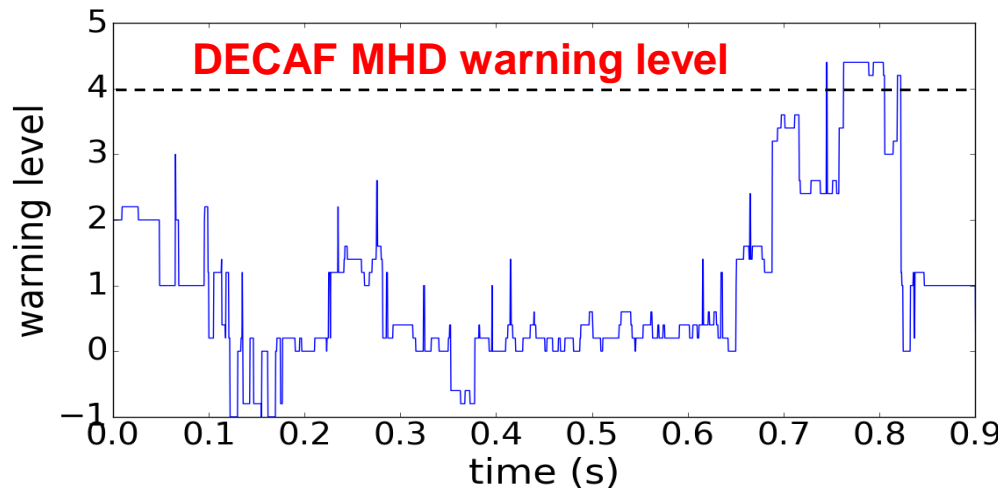
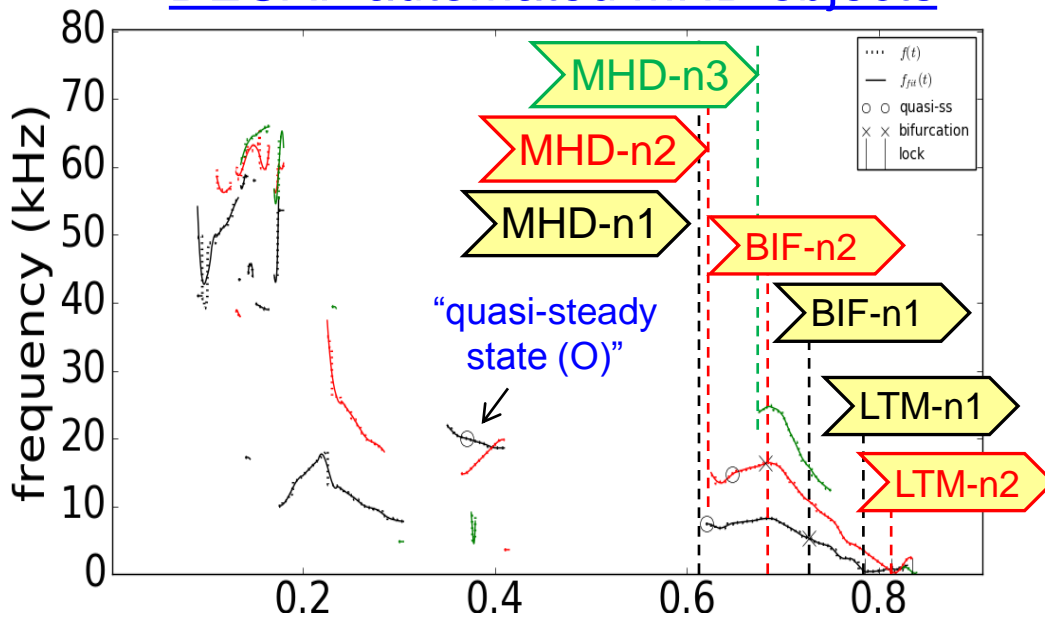


### Initial findings

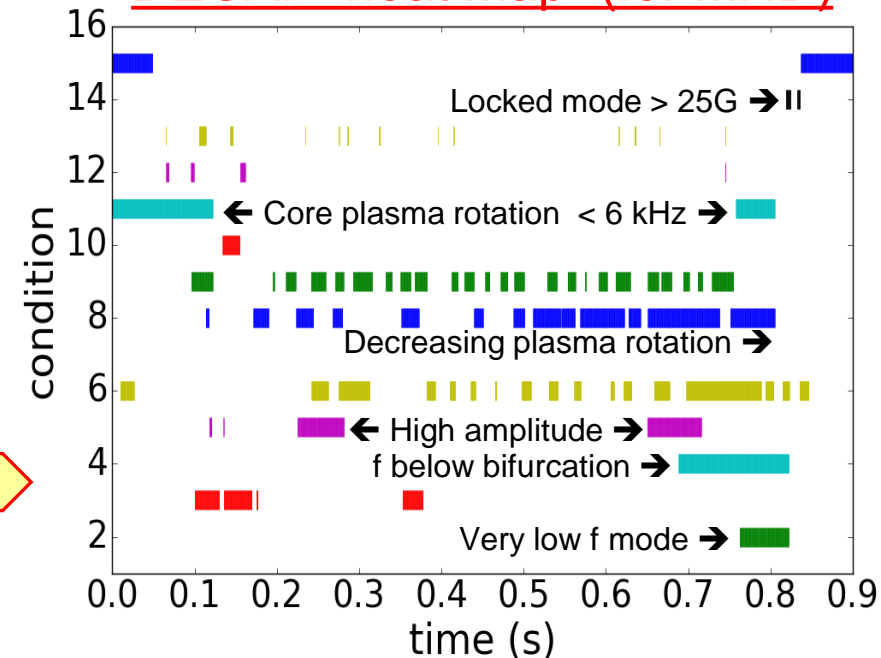
- Clear "safe" and "unsafe" periods of MHD appear in warning level
- Criterion history of wider range of plasma parameters improved the disruption warning reliability → illustrated by "Heat Map"

# MHD heat map illustration summarizes understanding of disruption warning level

## DECAF automated MHD objects



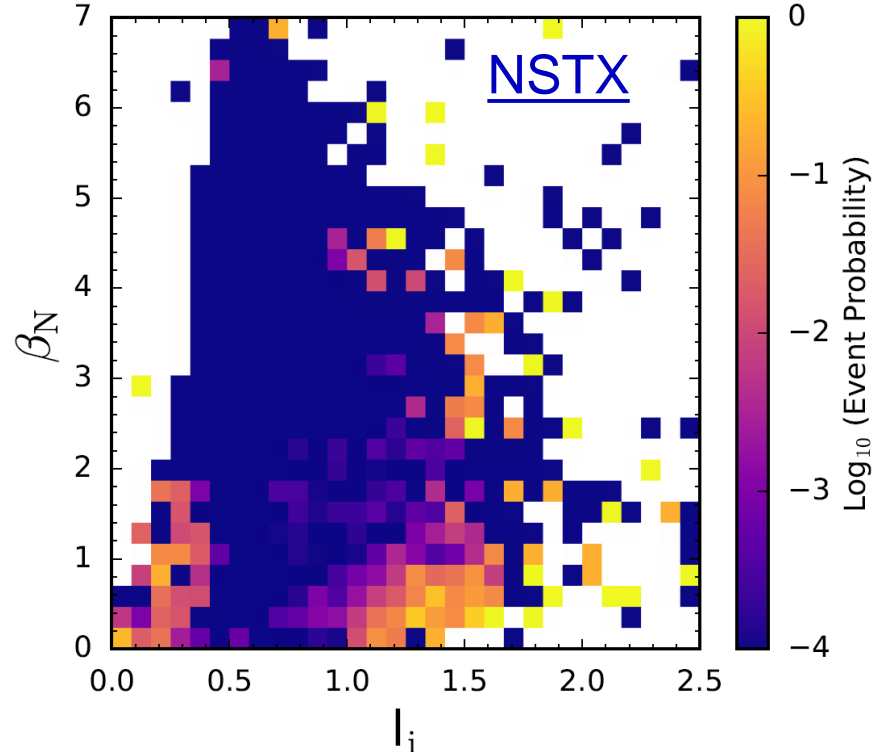
## DECAF "heat map" (for MHD)



- Some notables for this heat map
  - Mode frequency below bifurcation, decreasing plasma rotation key
  - Early, slow warning level evolution
  - Locked mode amplitude important, but warning comes in late

See TSDW talk by J. Riquezes

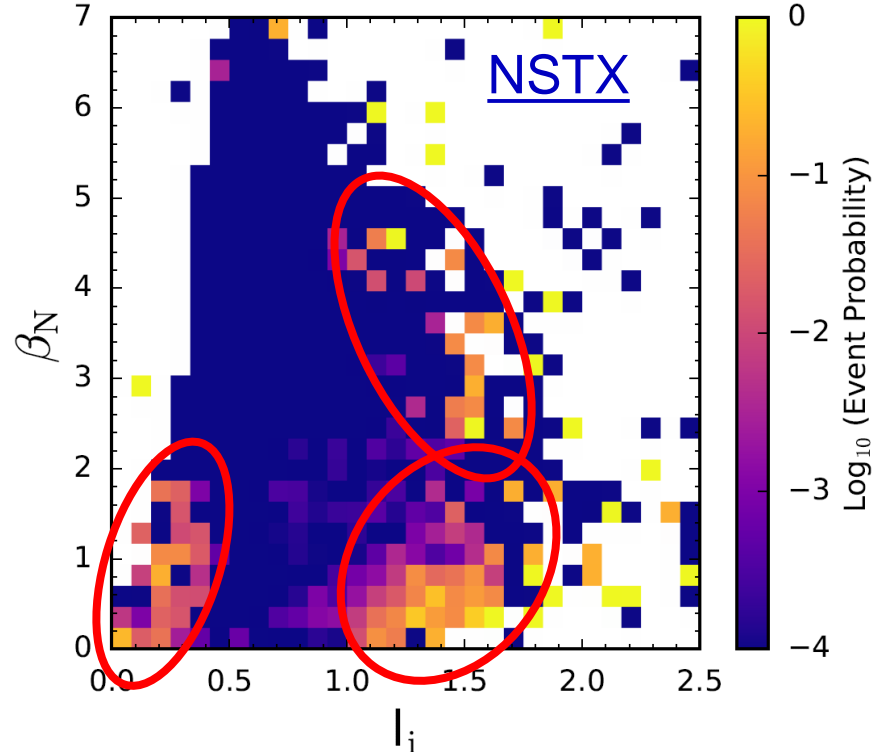
# While disruptivity plots provide important information, they can be misleading when used incorrectly



□ Example: What are the most important regions to study on this plot?



# While disruptivity plots provide important information, they can be misleading when used incorrectly

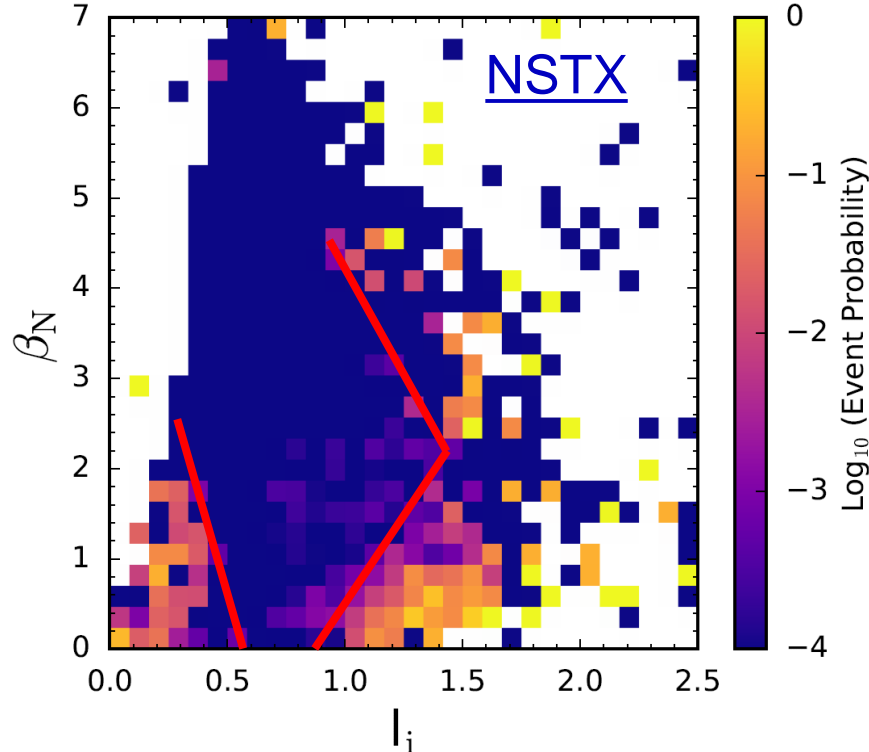


□ Example: What are the most important regions to study on this plot?

□ A human might focus on the high disruption probability regions

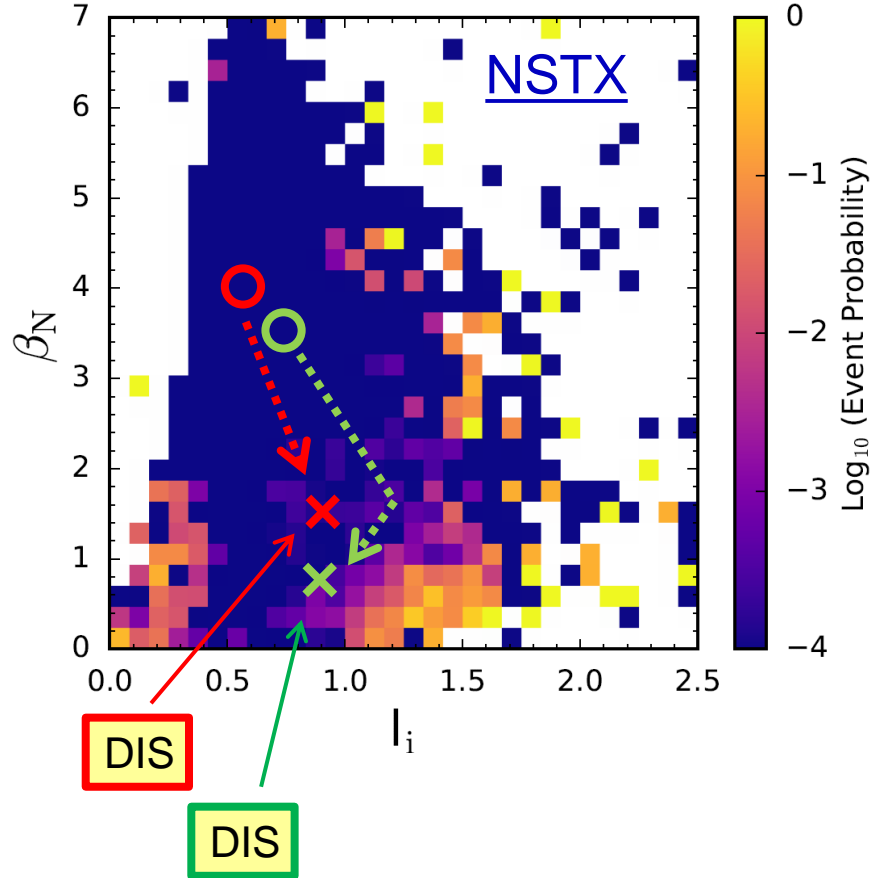
→ What causes the disruptions? (low  $\beta_N$ , mid- $I_i$  ???)

# While disruptivity plots provide important information, they can be misleading when used incorrectly



- ❑ Example: What are the most important regions to study on this plot?
- ❑ A human might focus on the high disruption probability regions
- ❑ Black-box machine learning might segregate disruptive from non-disruptive regions of the plot and learn from that division

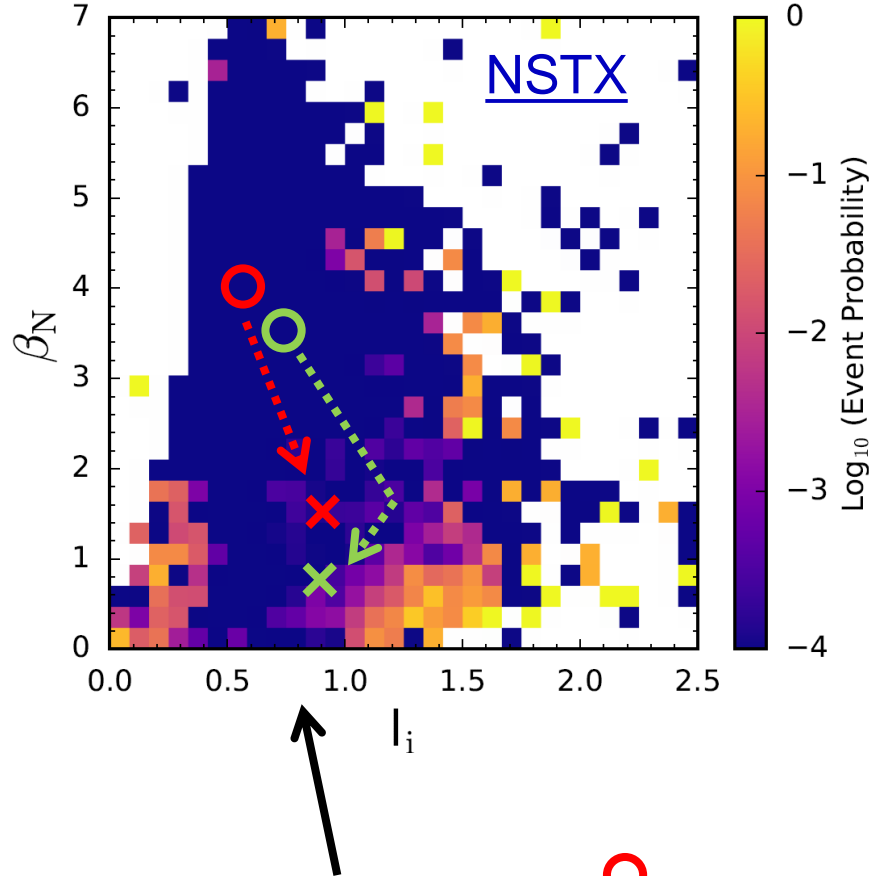
# While disruptivity plots provide important information, they can be misleading when used incorrectly



□ Example: What are the most important regions to study on this plot?

- A human might focus on the high event probability regions
- A machine learning algorithm might segregate disruptive from non-disruptive regions of the plot and learn from that division
- Problem → plasma conditions can change significantly between first problem detected and when disruption happens

# While disruptivity plots provide important information, they can be misleading when used incorrectly



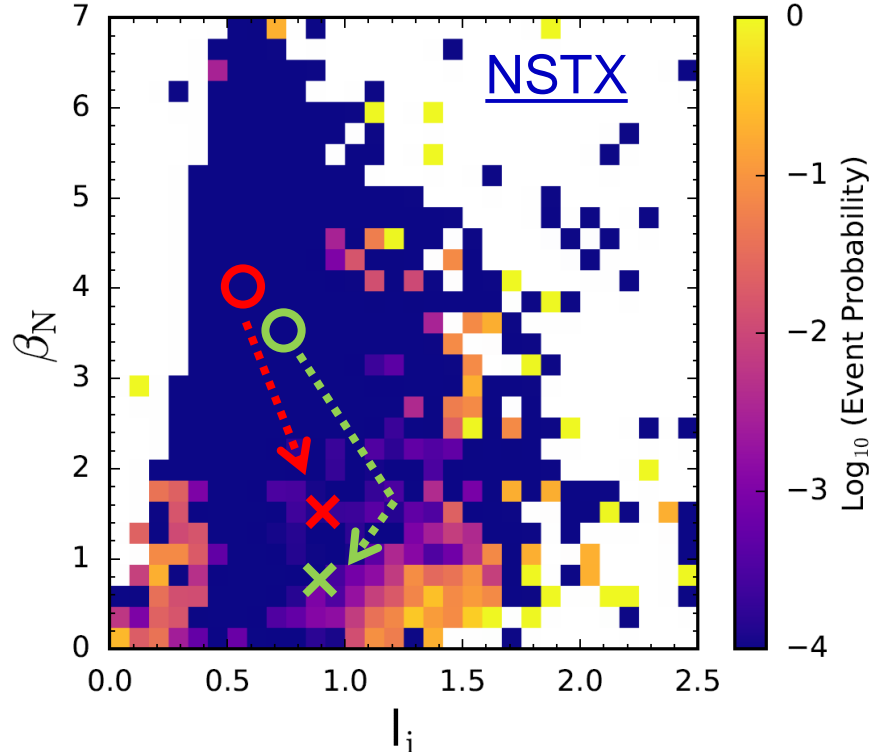
□ Example: What are the most important regions to study on this plot?

- A human might focus on the high event probability regions
- A machine learning algorithm might segregate disruptive from non-disruptive regions of the plot and learn from that division
- Problem → plasma conditions can change significantly by the time the disruption happens

□ **Answer: the circles ○ ○ mark the key region to study!**

- The shots suffer different “events” that are started in this region, and end up far from that region when they disrupt (at the crosses ✗ ✗)

# While disruptivity plots can provide information, they can be highly misleading when used incorrectly



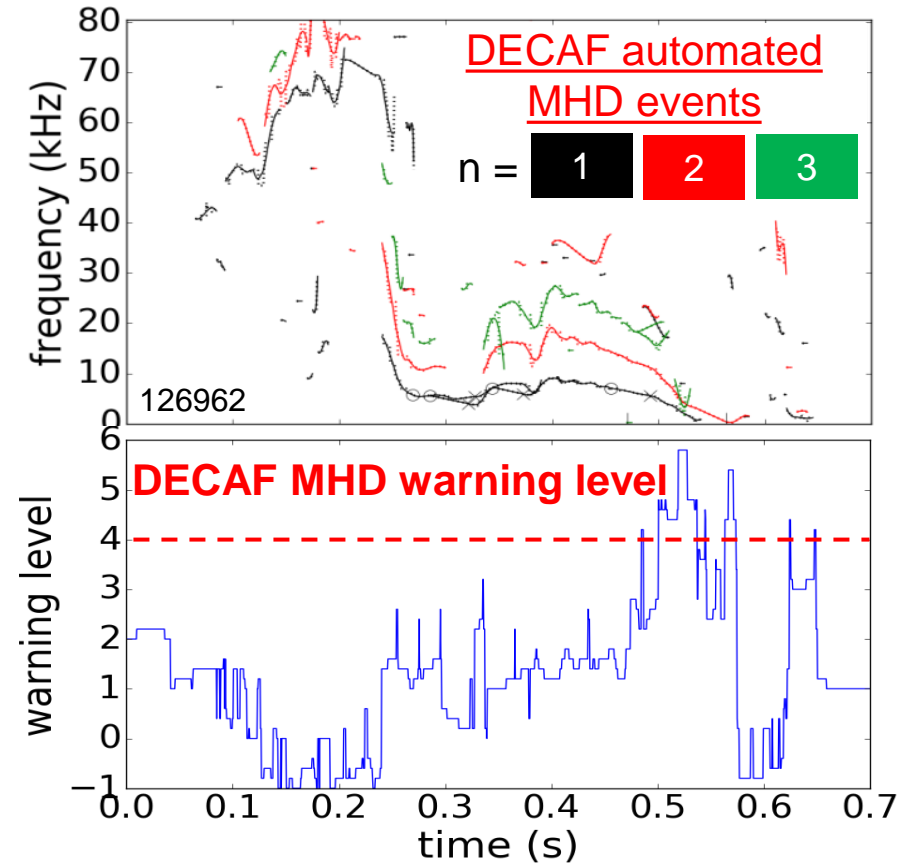
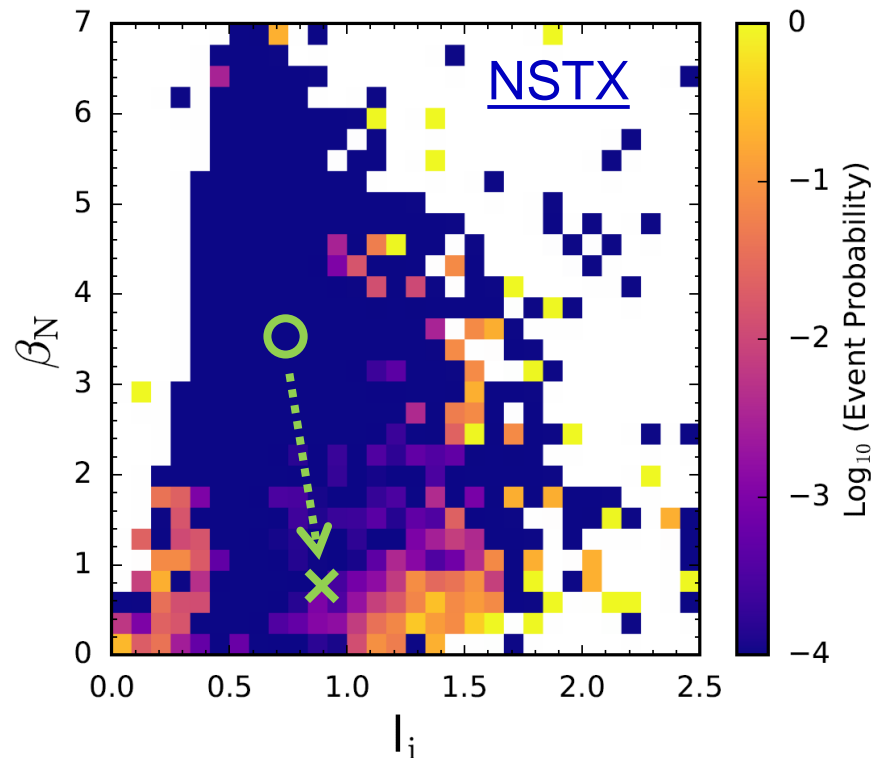
□ Example: What are the most important regions to study on this plot?

- A human might focus on the high event probability regions
- A machine learning algorithm might segregate disruptive from non-disruptive regions of the plot and learn from that division
- Problem → plasma conditions can change significantly by the time the disruption happens

## □ Key Lessons:

- 1) Using a “disruption database” that only contains data near the disruption time is misleading for disruption forecasting
- 2) Only analyzing plasma conditions near the disruption time is not useful in many cases, even if one can figure out a way to forecast 100% accurately

# Standard disruptivity plots give no insight into physics; DECAF reveals the physics to provide improved forecasting

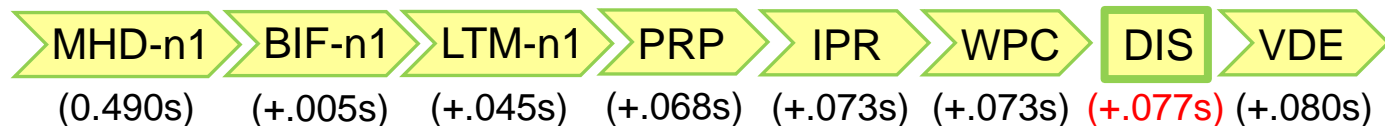


❑ Long interval leading up to disruption

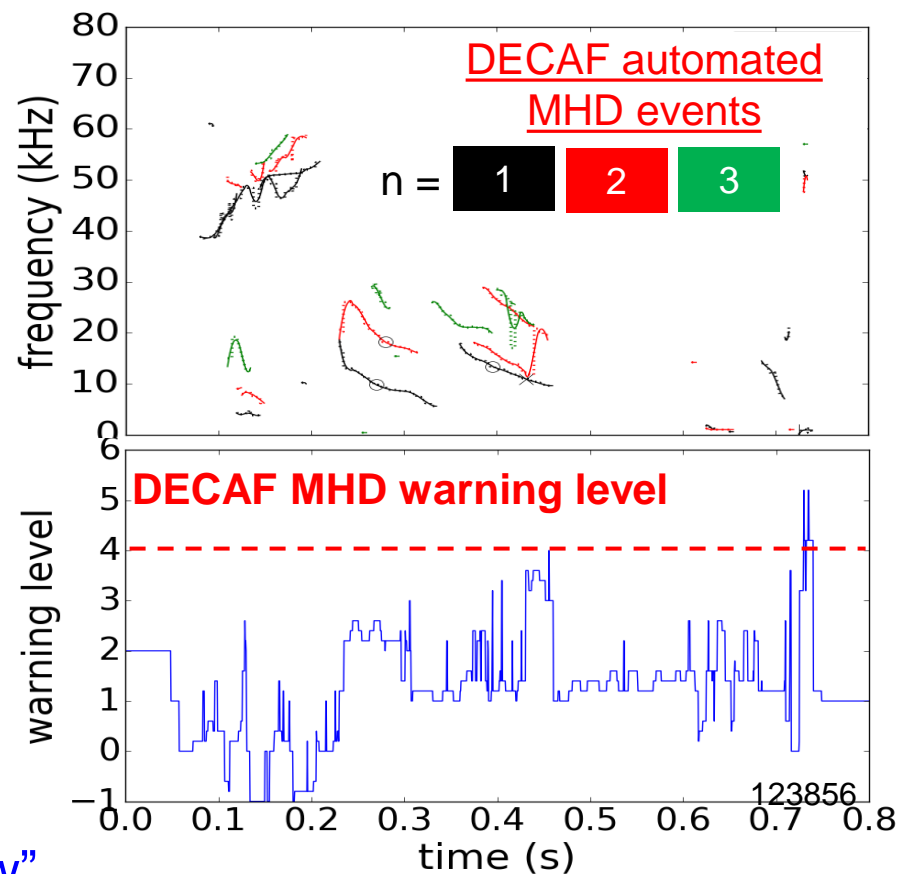
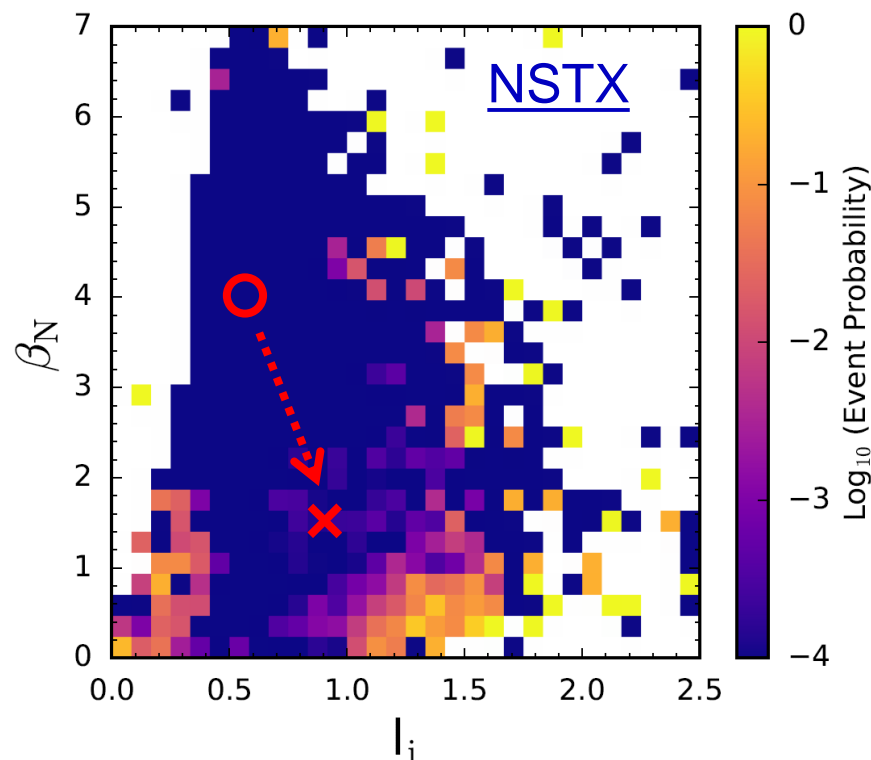
❑ Rotating MHD slows, bifurcates, and locks

❑ Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS

DECAF  
event chain



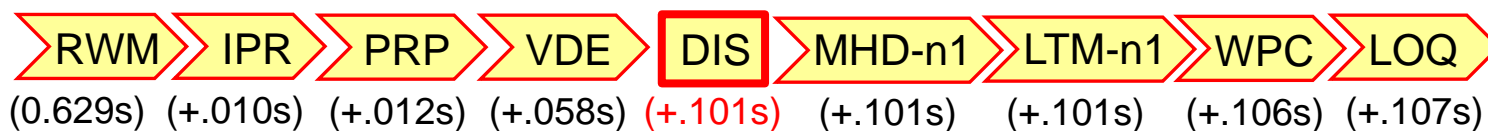
# Standard disruptivity plots give no insight into physics; DECAF reveals the physics to provide improved forecasting



## Global MHD (RWM) can also be “slow”

- Rotating MHD warning level decreases after 0.46s → **DANGEROUS** for RWM onset
- H – L back transition (PRP) drags out time to disruption (> 100 ms)

DECAF  
event chain





# DECAF is fueled by coordinated research that continues to validate/develop physics models

## ❑ Global MHD

- ❑ Detection: available magnetic diagnostics, plasma rotation, equilibrium
- ❑ Forecasting: Kinetic MHD model has high success in NSTX, DIII-D

## ❑ Resistive MHD

See TSDW 2018 talk by J. Riquezes

- ❑ Detection / forecasting: available magnetic diagnostics, plasma rotation
- ❑ Forecasting: starting examination of MRE → start with  $\Delta'$  evaluation

See TSDW 2018 poster by Y. Jiang

## ❑ Density limits

- ❑ Detection: rad. power, global empirical limit
- ❑ Forecasting: starting examination of rad. island power balance model

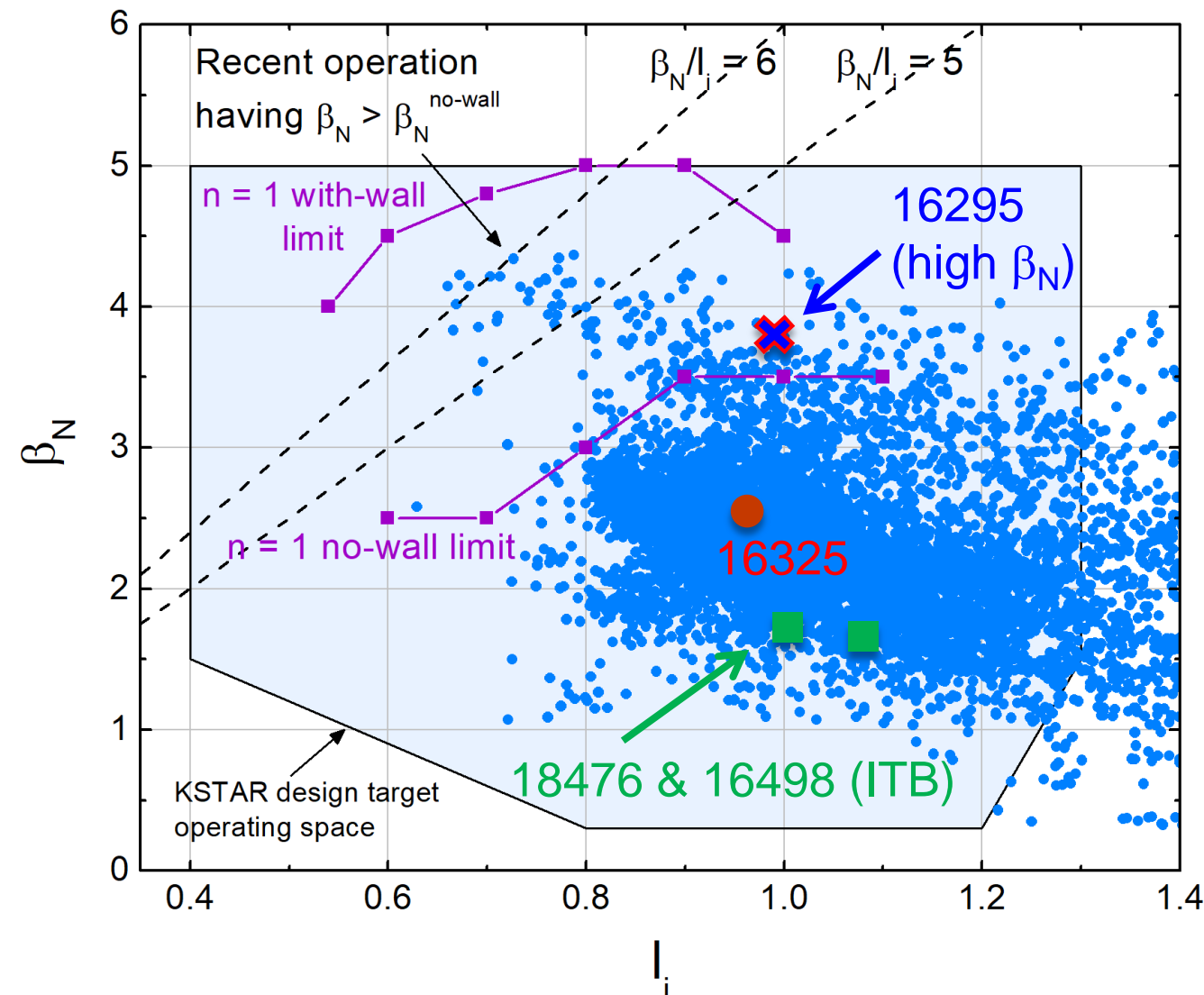
See talk by J. Berkery in 2 weeks

## ❑ Physics analysis / experiments to build DECAF models

- ❑ Interpretive and “predict-first” analysis of KSTAR long-pulse, high beta plasmas with high non-inductive fraction

See TSDW 2018 poster by J.H. Ahn

# KSTAR kinetic equilibria w/ MSE are examined in the context of past published database



## Examples in talk

✕ 16295

□ High  $\beta_N$  plasma

● 16325

□ Higher  $B_T$  ( $q_{95}$ )

□ Higher edge bootstrap current

■ 18476 & 16498

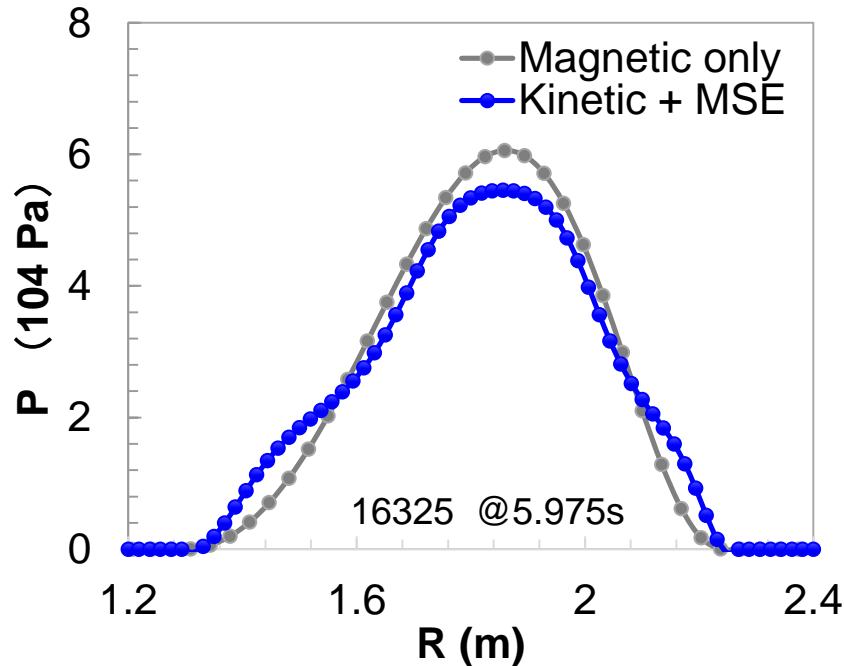
□ Internal Transport Barrier (ITB)

□ Many thousands of kinetic equilibria run during testing

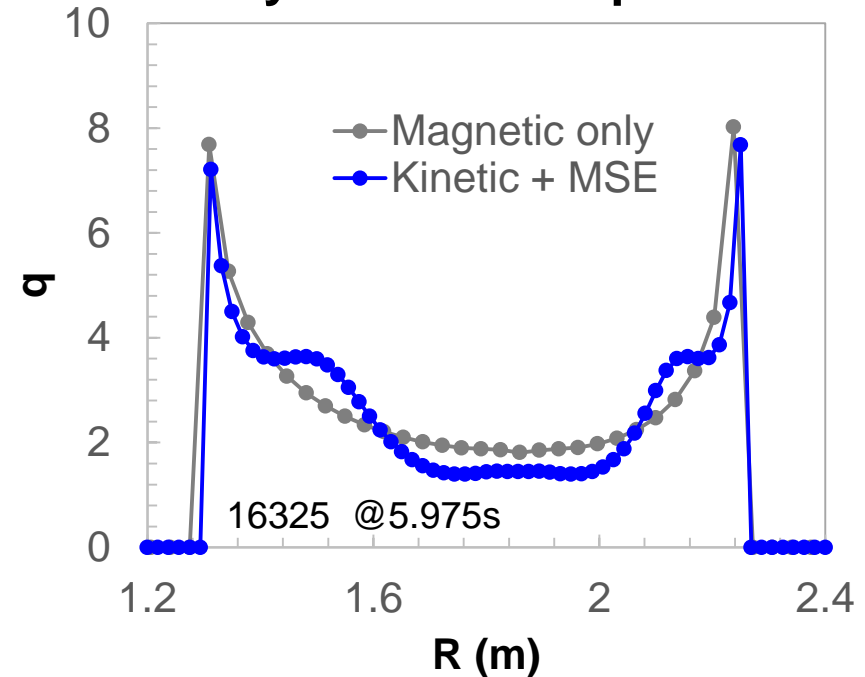
Y.S. Park, S.A. Sabbagh, *et al.*, Nucl. Fusion **53** (2013) 083029 (magnetics-only)

# Kinetic equilibria with MSE produces greater detail in P and q profiles than magnetics-only

## Pressure Profile



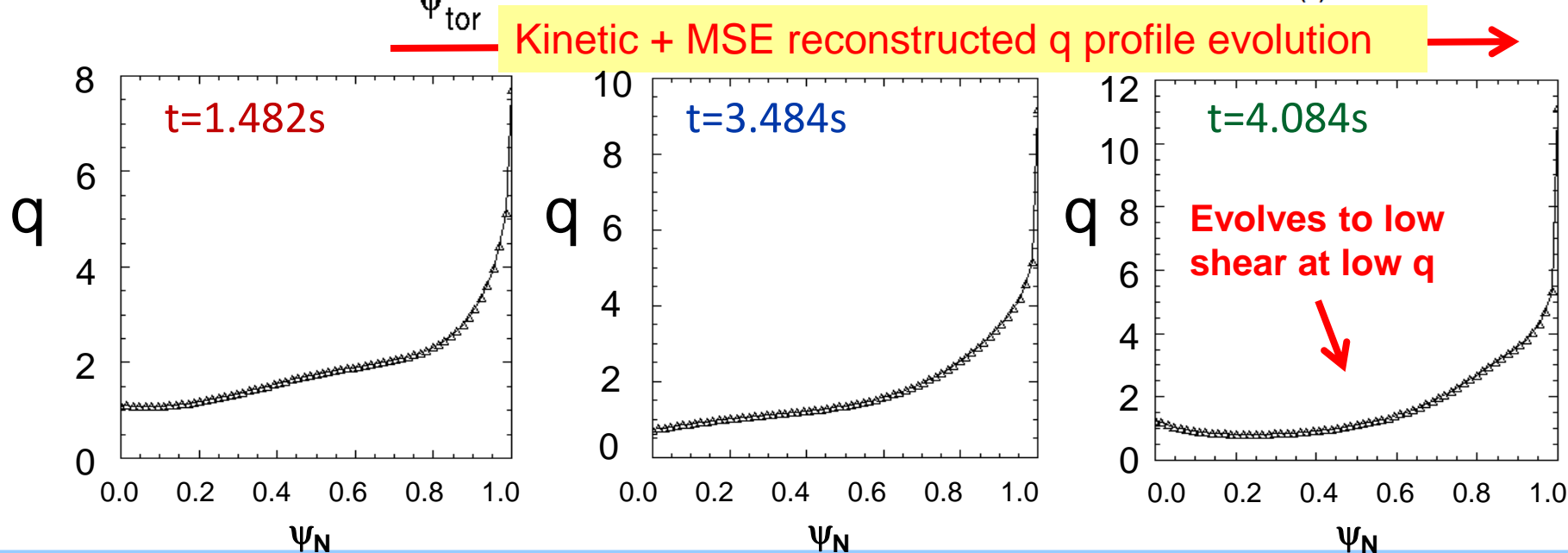
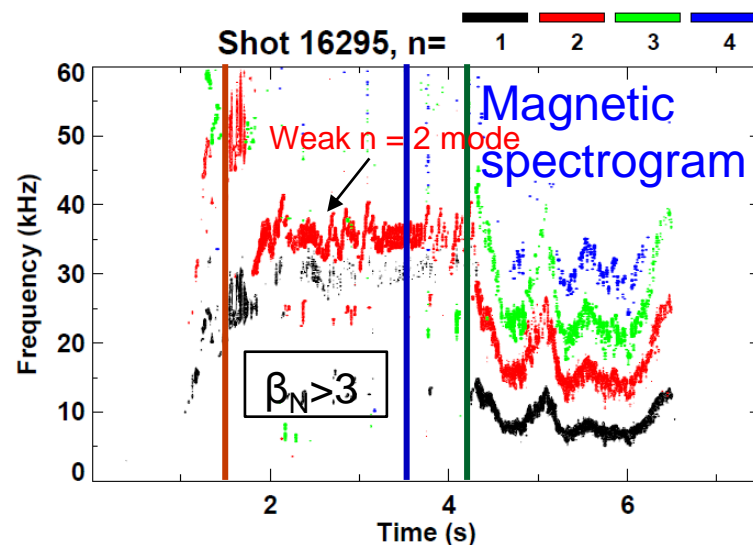
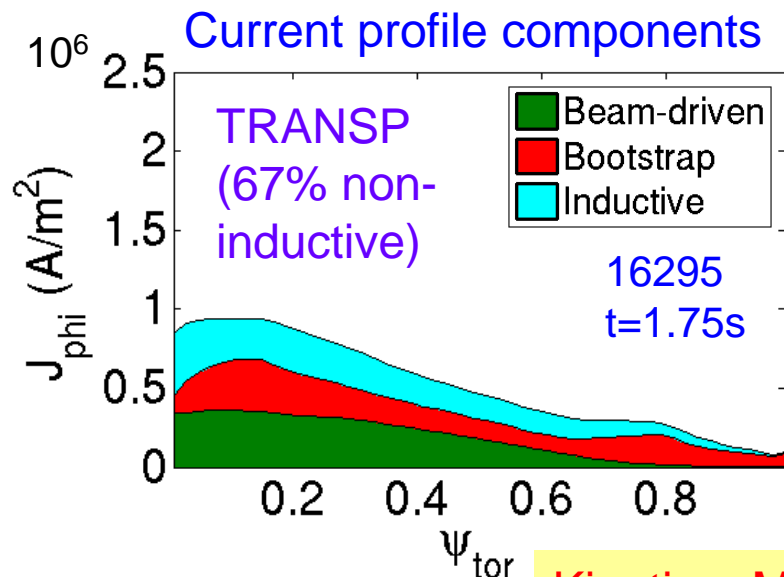
## Safety factor at Midplane



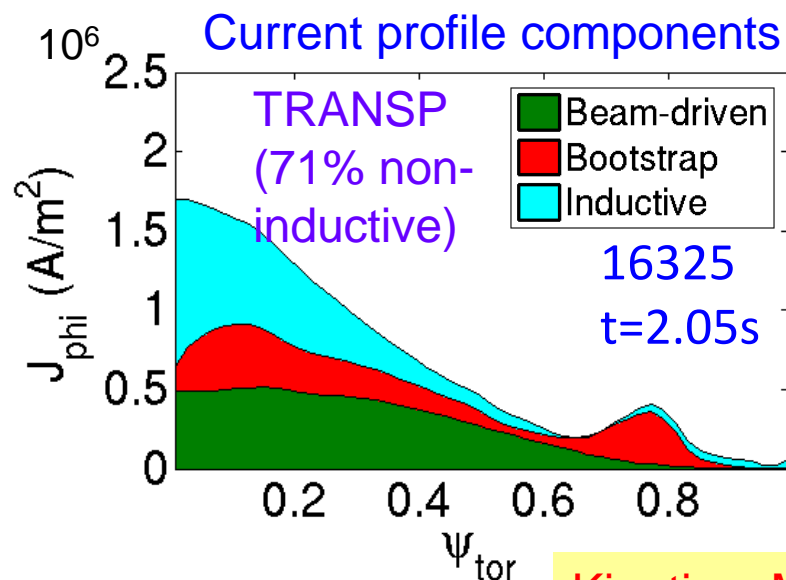
Global parameter	$\chi^2$	Error	R <sub>axis</sub> (cm)	Z <sub>axis</sub> (cm)	$\kappa$	$\delta_{TOP}$	$\delta_{BOT}$	$\beta_T$	$\beta_p$	$\beta_n$	$I_i$	$q_{95}$
Magnetic only	202	1.60E-07	186.1	-0.7	1.68	0.54	0.80	0.95	1.86	1.89	1.05	6.39
Kinetic	231	9.70E-05	185.6	-2.4	1.68	0.50	0.80	1.09	1.95	2.10	0.97	5.91

See TSDW 2018 poster by Y. Jiang

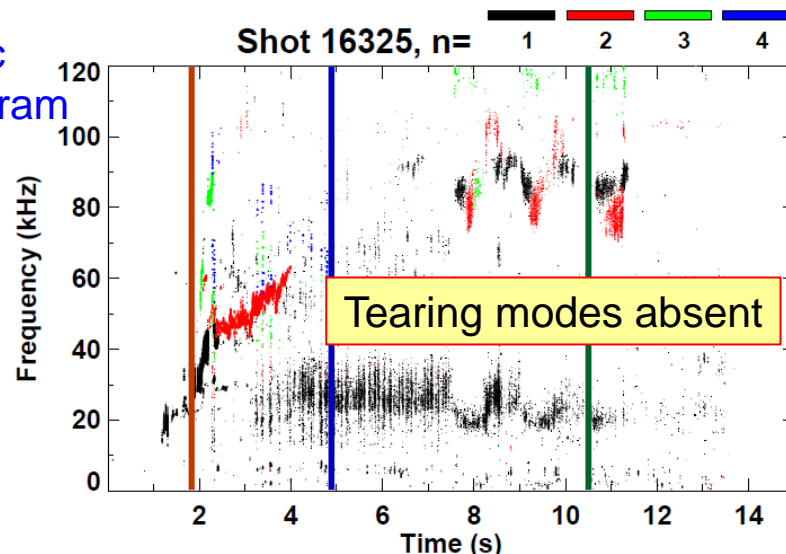
# A broad non-inductive current fraction profile leads to low shear at low $q$ in high $\beta_N$ plasma



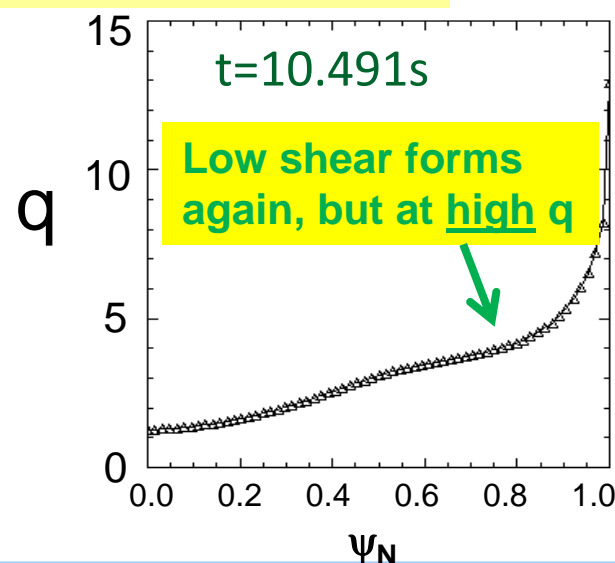
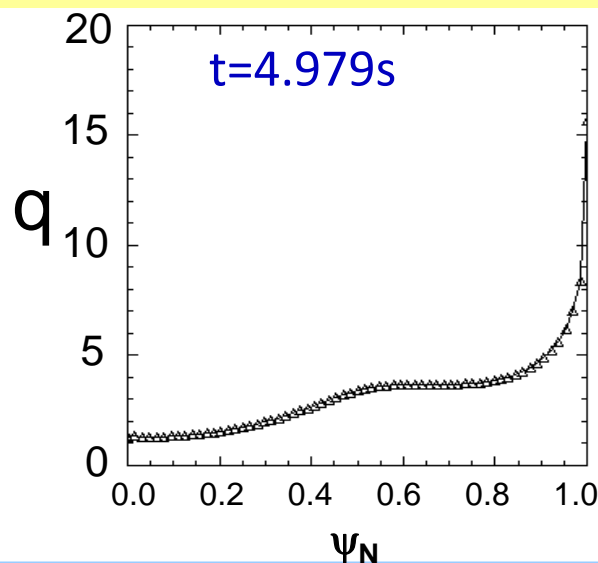
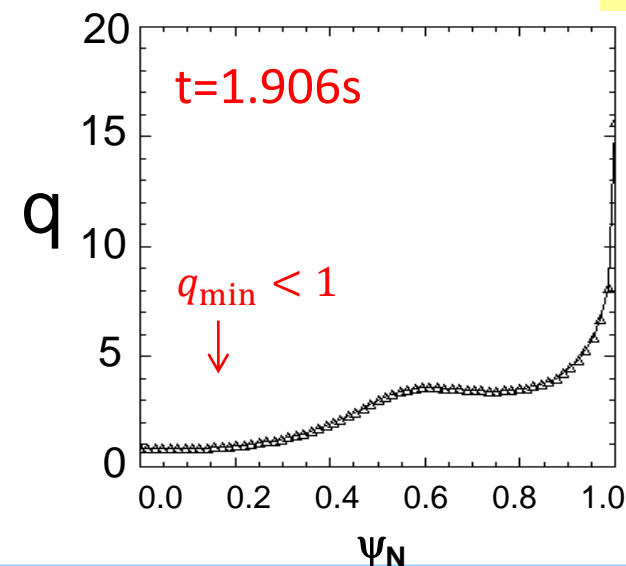
# Kinetic EFIT reconstructed again shows evolution to low-sheared q-profiles but now at high q



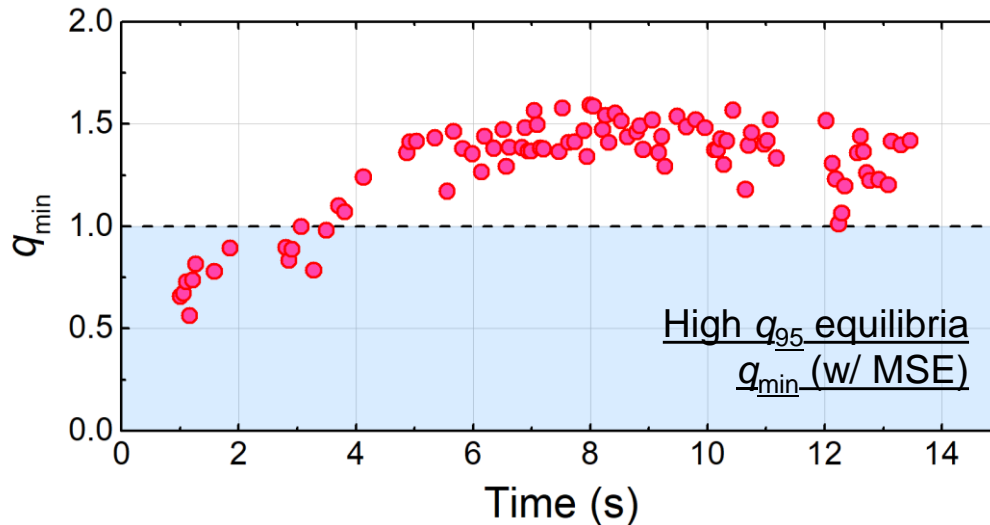
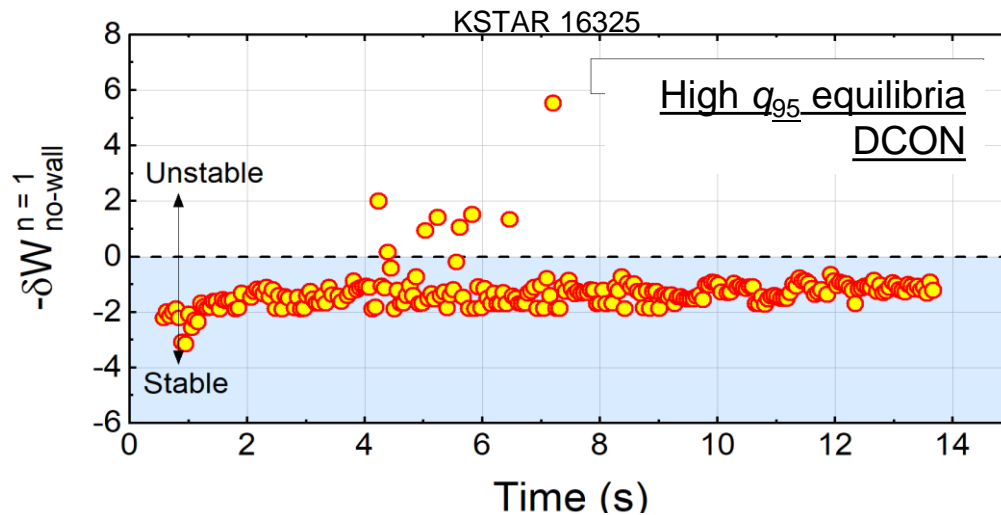
Magnetic spectrogram



Kinetic + MSE reconstructed q profile evolution



# Higher $q_{95}$ plasma has greater ideal $n = 1$ no-wall stability in DCON, closer to marginal stability



□ Unlike higher  $\beta_N$  plasma, equilibria is mostly stable to  $n = 1$  ideal modes in DCON

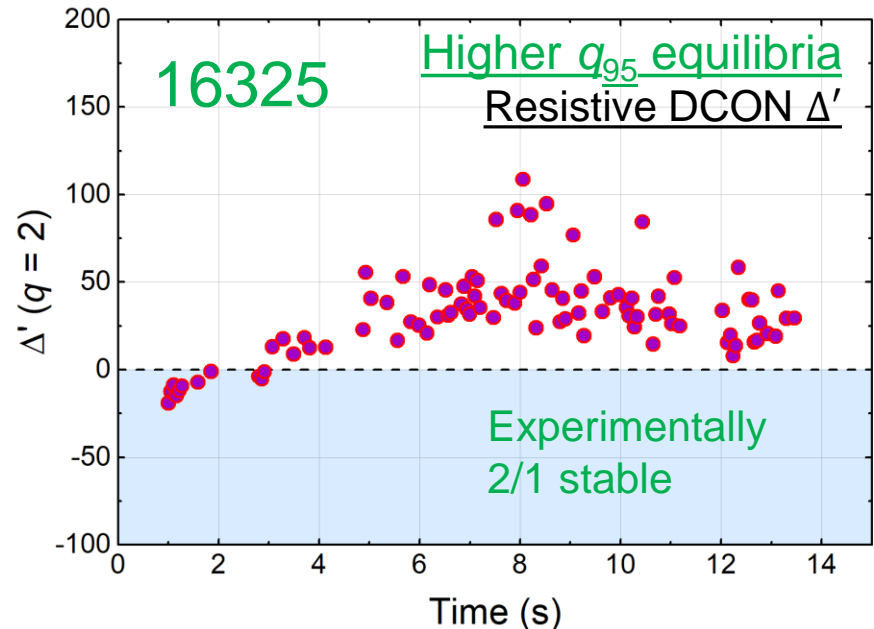
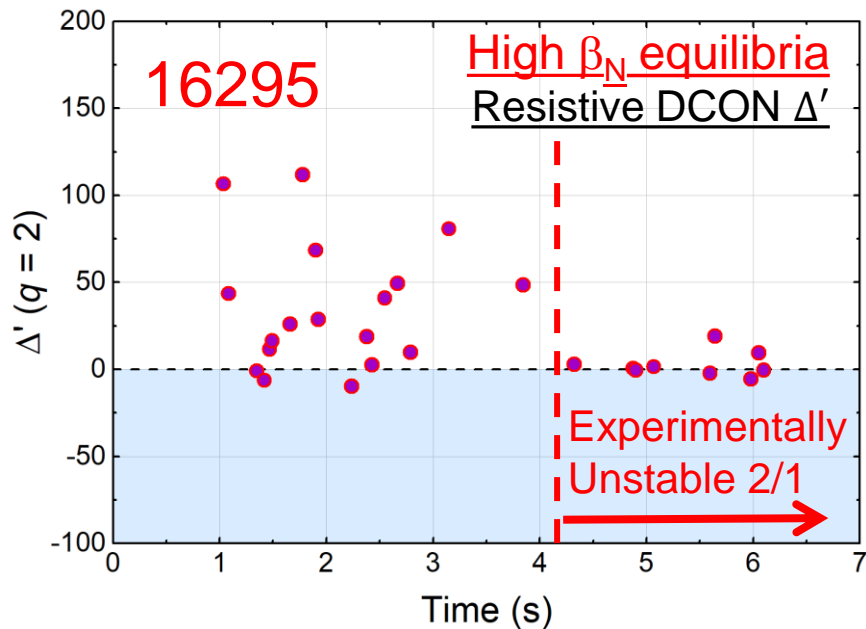
□ Note generally smooth evolution of stability criterion – reached with improved kinetic equilibria

□ The  $q$ -profile at higher  $B_T$  evolves higher  $q_{\min}$  above 1

□ Sawteeth disappear

□ Reconstructed lower  $q$  shear at higher values of  $q$  does not lead to  $n = 1$  instability in DCON

# Classical tearing stability examined using **resistive DCON** code for high $\beta_N$ and higher $q_{95}$ plasmas



- ❑ Classical tearing stability index,  $\Delta'$ , computed at the  $q = 2$  surface using outer layer solutions
- ❑ At higher  $q_{95}$ ,  $\Delta'$  is mostly positive predicting unstable classical tearing mode
  - Indicates that neoclassical effects or wall effects need to be invoked to produce stability

A.H. Glasser, *et al.*, Phys. Plasmas **23** (2016) 112506



# Kinetic reconstructions focused first on KSTAR plasmas with high-non-inductive fraction

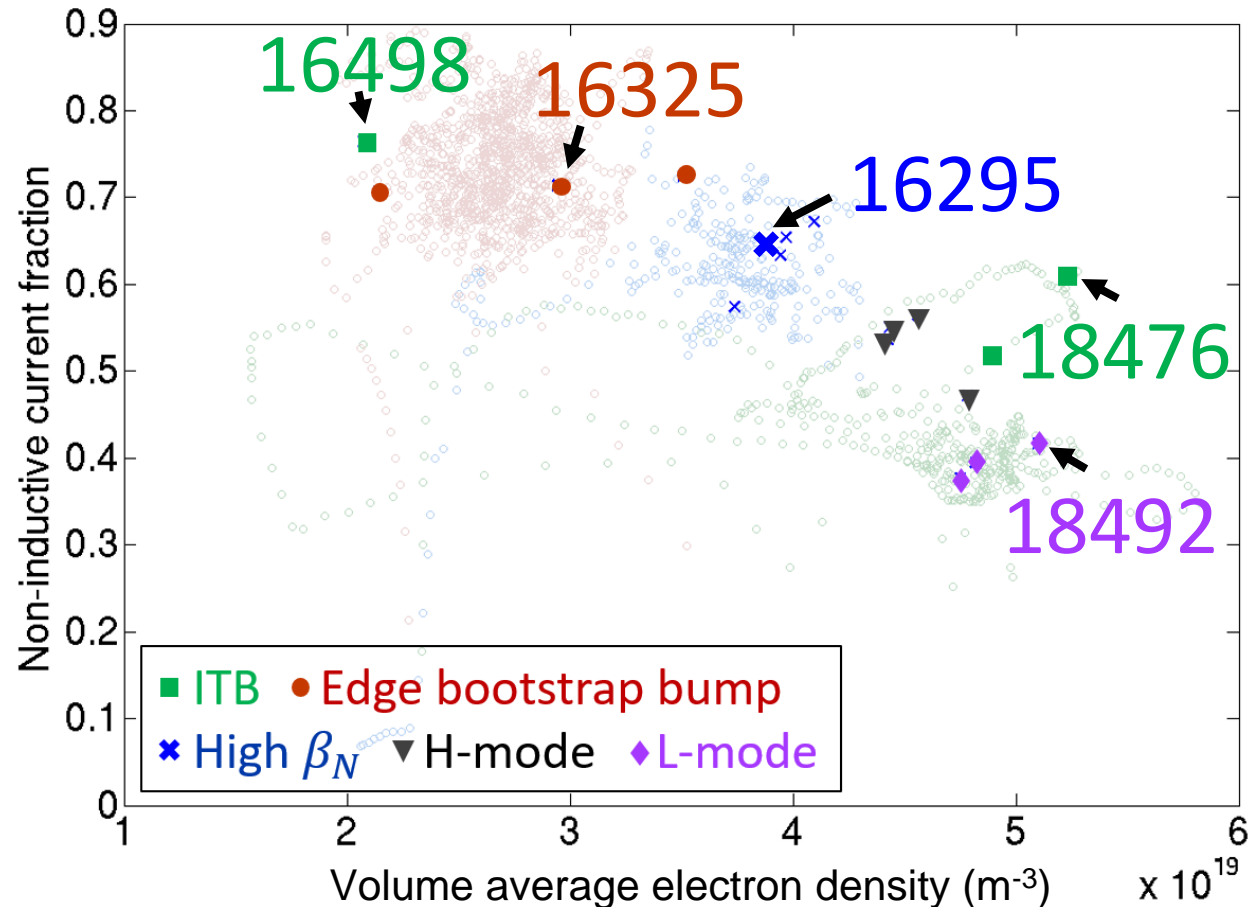
TRANSP analysis

Non-inductive fraction

Beam-driven

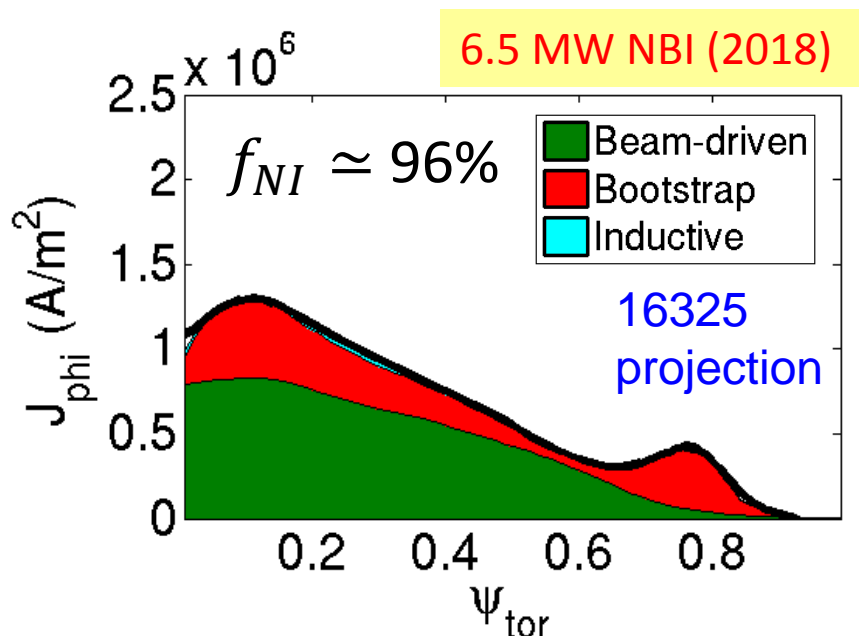
Bootstrap

Non-inductive fraction is key for stable high beta steady state operation



→ See TSDW 2018 poster by J.H. Ahn (Columbia U.)

# Predictive transport capability (TRANSP) allows “predict-first” projections for upcoming runs



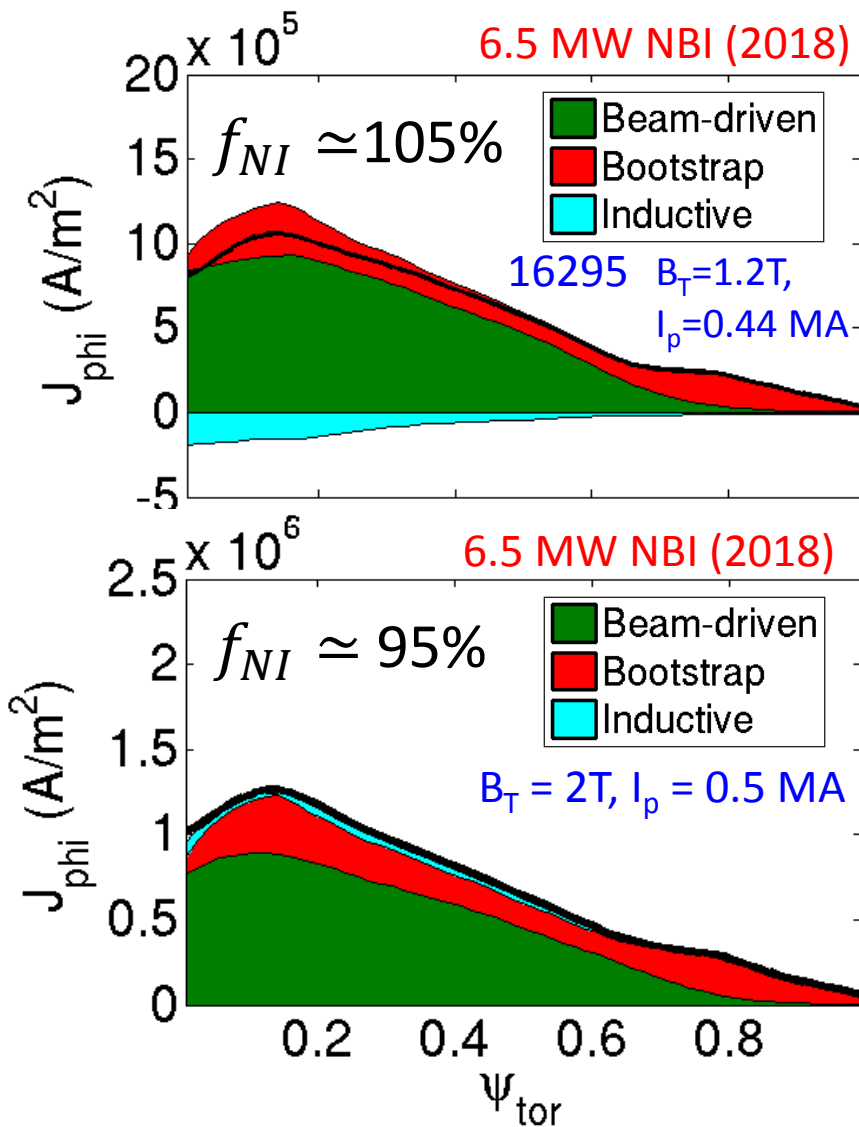
## Project from existing KSTAR plasmas

- Set fraction of Greenwald density and confinement factor ITER  $H_{98y2}$
- Neoclassical ion transport, electron transport set to match  $H_{98y2}$
- KSTAR 1<sup>st</sup> and 2<sup>nd</sup> NBI systems are modeled (incl. aiming angles); power levels set realistically based on MSE needs, etc.

TRANSP 16325	2016 actual	2018 NBI	2019 NBI
NIC fract. (%)	71%	96%	130%
$\beta_N$	2.7	3.4	4.4
$I_i$	0.9	0.91	0.95
$T_i(0)$ (keV)	4.5	5.5	7.2
$T_e(0)$ (keV)	4.6	3.3	3.3
$n_e(0)$ ( $10^{20}\text{m}^{-3}$ )	5.2	5.6	5.5
$f_{\text{Greenwald}}$	0.5	0.5	0.5
$H_{98y2}$	1.25	1.25	1.25

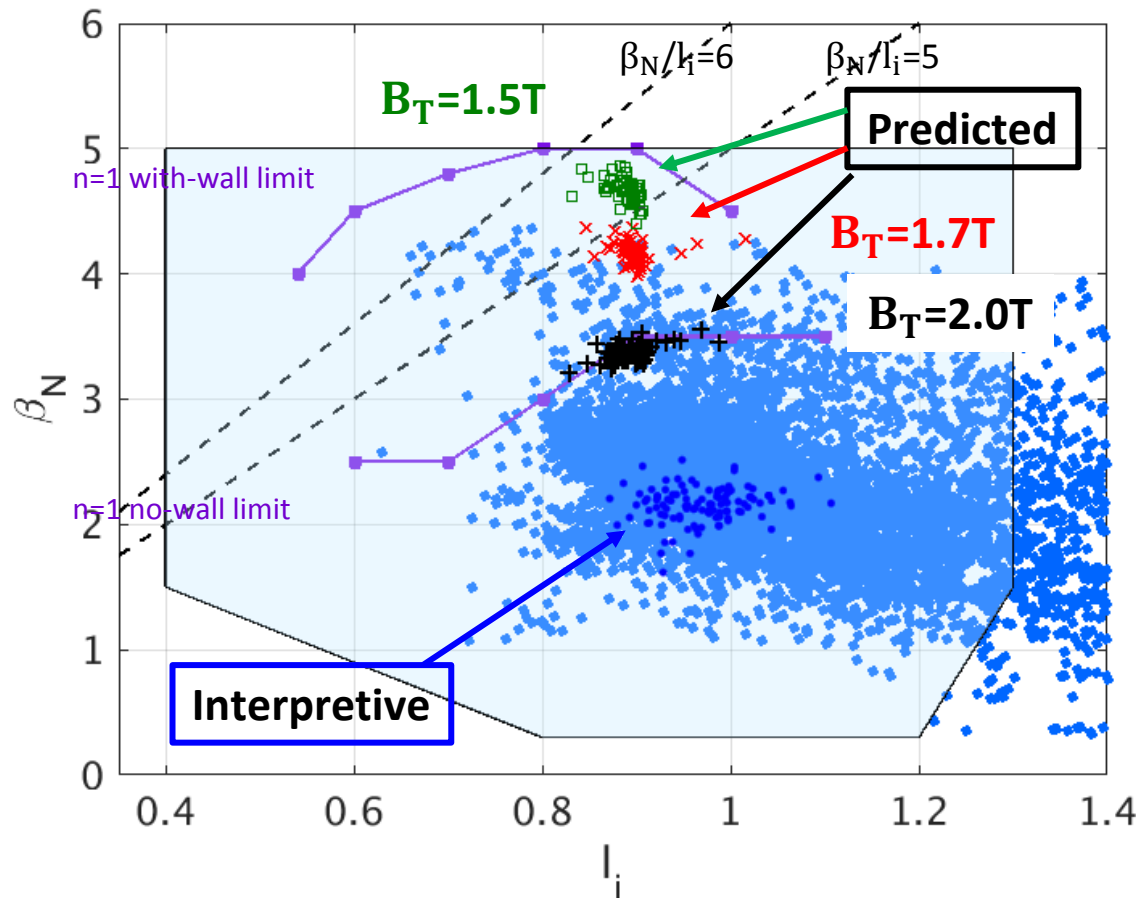
→ See TSDW 2018 poster by J.H. Ahn (Columbia U.)

# Transport analysis projections allow for variations of plasma parameters to meet targets



TRANSP 16295 ( $B_T$ ; $I_p$ )	2016 actual (1.2T)	2018 NBI (1.2T)	2018 NBI (2T, 0.5 MA)	2019 NBI
NIC fract. (%)	67%	105%	95%	126%
$\beta_N$	3.5	5.4	3.5	4.4
$I_i$	0.9	0.83	0.95	0.84
$T_i(0)$ (keV)	3.6	4.8	5.4	7.3
$T_e(0)$ (keV)	2.3	2.8	3.2	3.3
$n_e(0)$ ( $10^{19}m^{-3}$ )	6.0	4.8	5.6	5.6
$f_{Greenwald}$	0.6	0.5	0.5	0.5
$H_{98y2}$	1.25	1.25	1.25	1.25

# Predictive TRANSP analysis shows KSTAR design target $\beta_N \sim 5$ can be approached with $f_{NI} \sim 100\%$



- NBI increased
  - existing shot: 4.5 MW
  - 2018 NBI taken as 6.5 MW
- By altering  $I_P$  and  $B_T$  values,  $\beta_N > 4$ , up to KSTAR design target 5 can be achieved with 100% non-inductive current fraction

# Rapidly-expanding DECAF approach provides a new paradigm for disruption prediction research

- ❑ Multi-faceted, integrated approach to disruption prediction and avoidance with several key characteristics
  - ❑ Physics-based approach yields understanding that is needed for confident extrapolation of disruption forecasting
  - ❑ Physics-based DECAF events can guide how to avoid disruption
  - ❑ Full multi-machine databases used (full databases needed!)
  - ❑ Open to all methods of data analysis (physics, machine learning, etc.)
- ❑ Automated determination of disruption event chains teach us the important regions of operating space to study
  - ❑ Disruption DB “boundaries” are often NOT the important regions
- ❑ Next steps
  - ❑ Couple new MHD events to other events to reduce false positives
  - ❑ Expand number of DECAF events evaluated in large database analysis
  - ❑ **Begin evaluation of simple quantitative figures of merit on large databases → aim for APS DPP 2018 meeting for these results**

# **Announcement: Research Activity RA(19-1): “Expand disruption prediction and avoidance capability for tokamaks”**

## **❑ NSTX-U Research Activity milestone for FY19**

- ❑ Research activity will allow for communication of continuing DECAF analysis on multiple devices, interaction with interested researchers
  - follows from prior NSTX disruption prediction/avoidance Working Group effort)
- ❑ Expand disruption event characterization, prediction, avoidance to more tokamaks (KSTAR, MAST expansion, continue NSTX, DIII-D, etc.)

## **❑ Some subjects**

- ❑ Continued improvement of the accuracy of disruption event warnings, disruption event chains vs. experiment, while reducing false positives
- ❑ Discussion/development of new physics, empirical, AI/ML models to improve disruption prediction performance
- ❑ Assessment of technical causes for disruptions, relation to physics

## **❑ Format**

- ❑ Monthly meetings planned discussing DECAF research progress
- ❑ Open to NSTX-U Team + all interested (contact: [sabbagh@pppl.gov](mailto:sabbagh@pppl.gov))

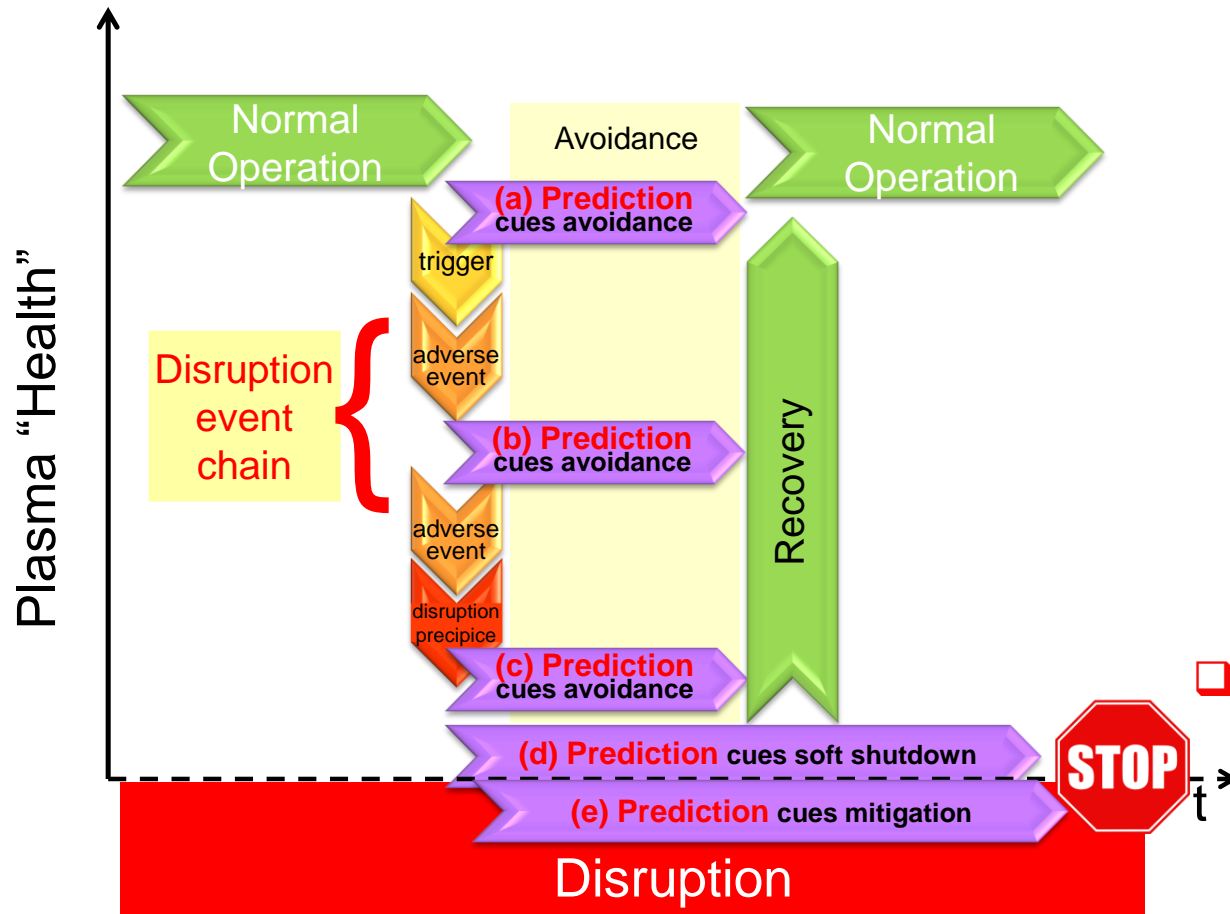
# Supporting slides follow

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# Disruption event characterization is a critical and logical step in a disruption avoidance plan

Disruption prediction/avoidance framework  
(from DOE “Transient Events” report (2015))



## □ Approach to disruption prevention

- Identify disruption event chains
- Predict events in disruption chains
- Cue disruption avoidance systems to break event chains
  - Attack events at several places with active control

## □ Expand analysis to more tokamak data

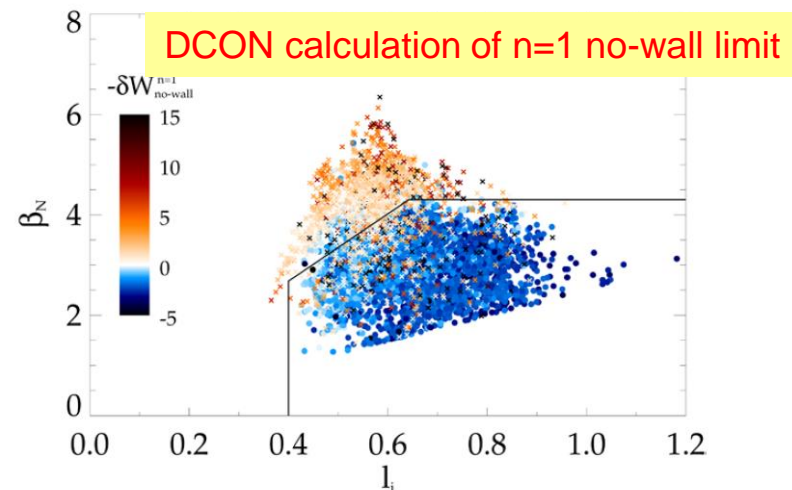
- Requires expansion of code analysis tools

# A reduced kinetic RWM model was created for DECAF code analysis

## Elements: mode growth rate calculation

### ❑ Ideal component $\delta W$

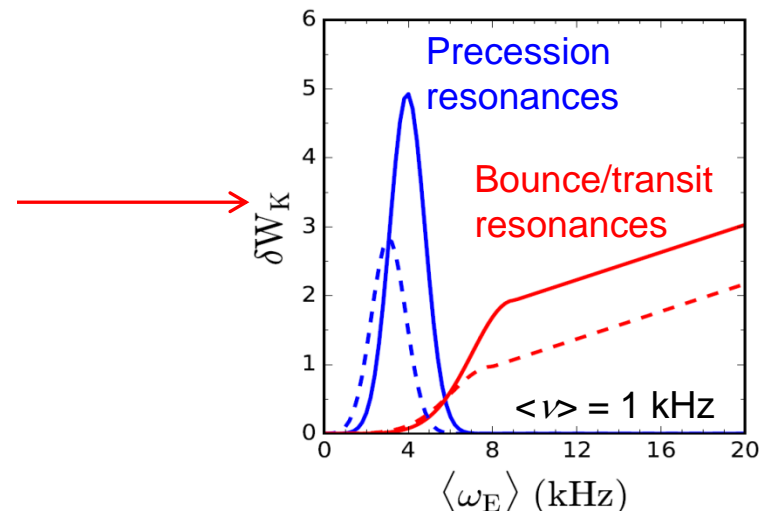
- ❑ Equilibrium quantities including  $I_i$ ,  $p_0/\langle p \rangle$ ,  $A$ , used in beta limit models for  $\delta W_b$ ,  $\delta W_{inf}$



J.W. Berkery, S.A. Sabbagh, R.E. Bell, *et al.*, NF 55 (2015) 123007

### ❑ Kinetic component $\delta W_k$

- ❑ Functional forms (mainly Gaussian) used to reproduce **precession** and **bounce/transit** resonances
- ❑ Height, width, position of peak depend on **collisionality**

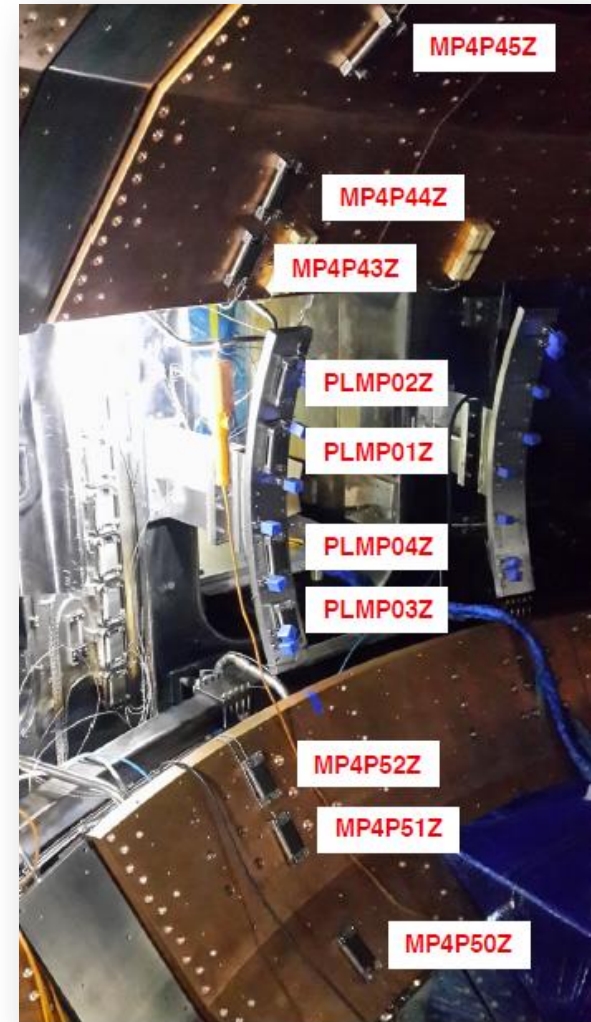


# KSTAR magnetic diagnostics provide the basis for “magnetics-only” equilibrium reconstruction

- ❑ KSTAR equilibrium magnetics
  - ❑ Flux loops (45)
  - ❑ Magnetic probes (105)
  - ❑ Plasma currents (1)
  - ❑ Coil currents (18)
  - ❑ Loop voltage monitors (5)
  - ❑ Vessel wall current groups (12)
- ❑ Stabilizing plates / divertor plates included in model
- ❑ PF, IVC, IVCC currents in model

S.A. Sabbagh, et al., Nucl. Fus. **41** (2001) 1601

Y.S. Park, et al., Nucl. Fus. **51** (2011) 053001



- Magnetic probes on the passive plates and outboard limiter  
(Photo courtesy of J.G. Bak and S.H. Hahn)

# Kinetic data supplements magnetics input for KSTAR kinetic equilibrium reconstructions

## ❑ Motional Stark Effect (MSE)

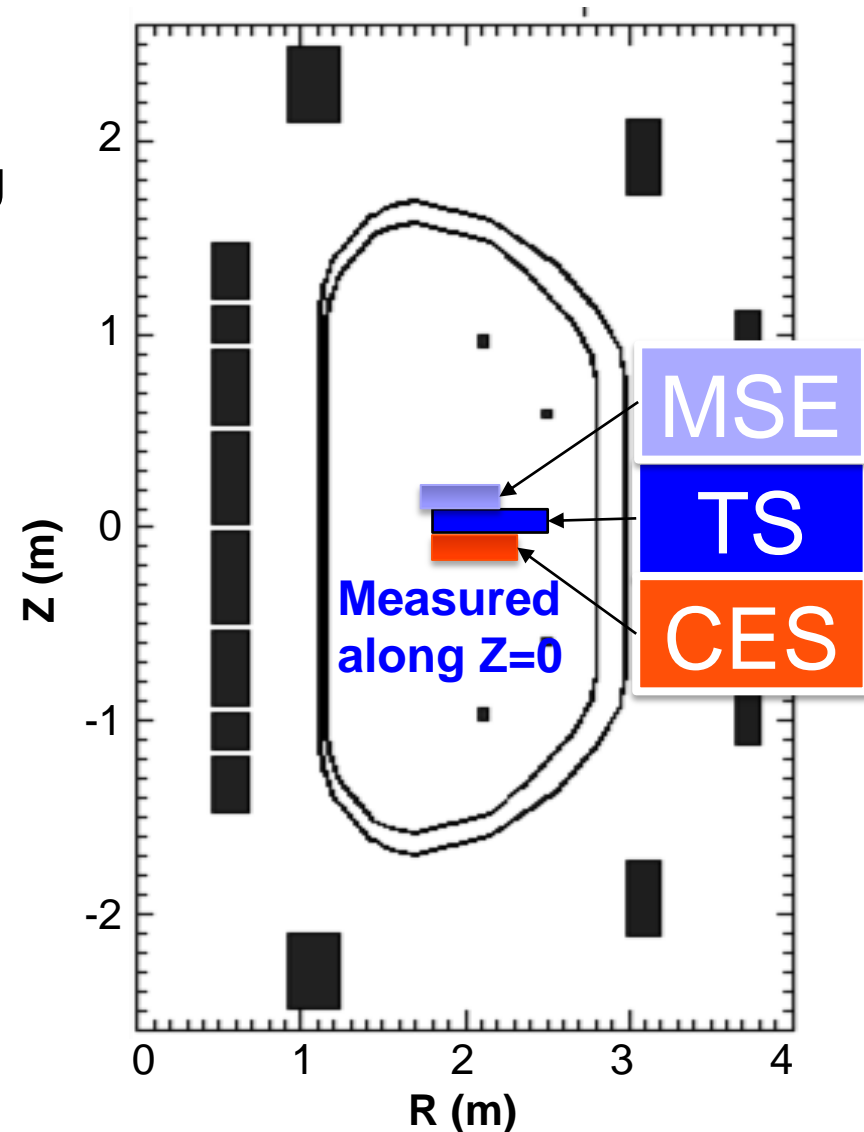
- ❑ MSE (up to 25 channels) measuring plasma magnetic field pitch angle

## ❑ Thomson scattering (TS)

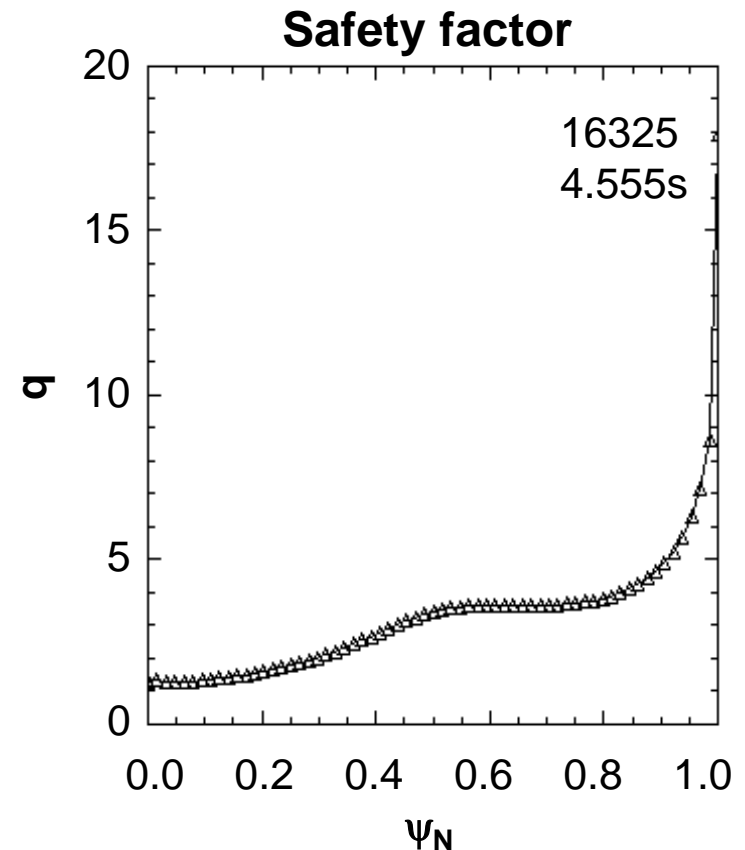
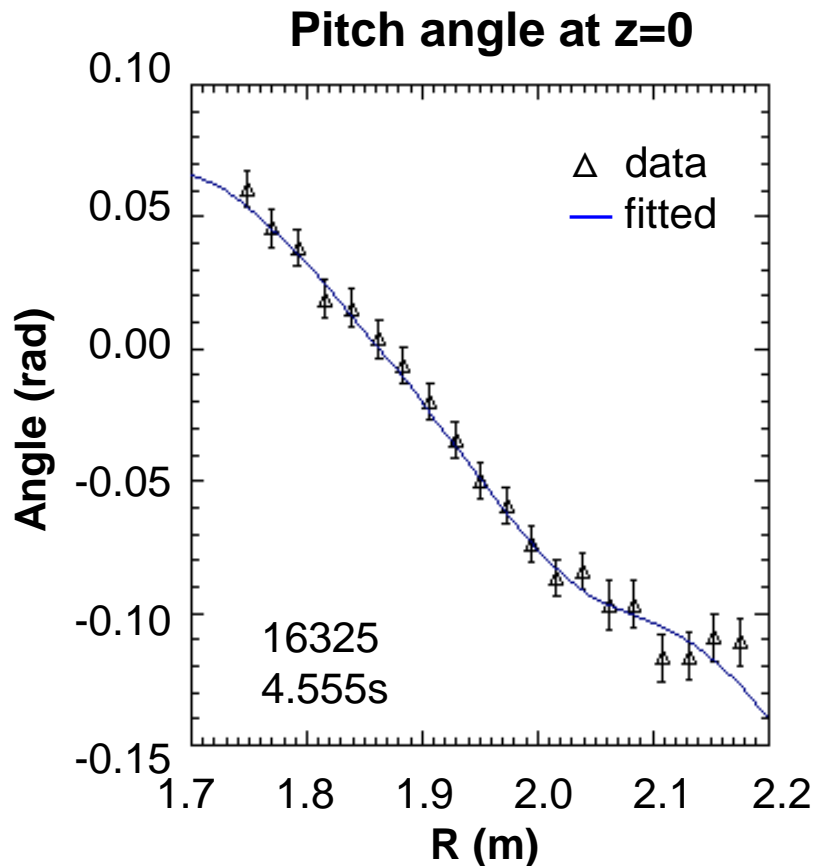
- ❑ TS 27 channels
- ❑ Electron density & temperature ( $N_e$ ,  $T_e$ )

## ❑ Charge exchange spectroscopy (CES)

- ❑ CES 32 channels
- ❑ Ion Temperature ( $T_i$ )



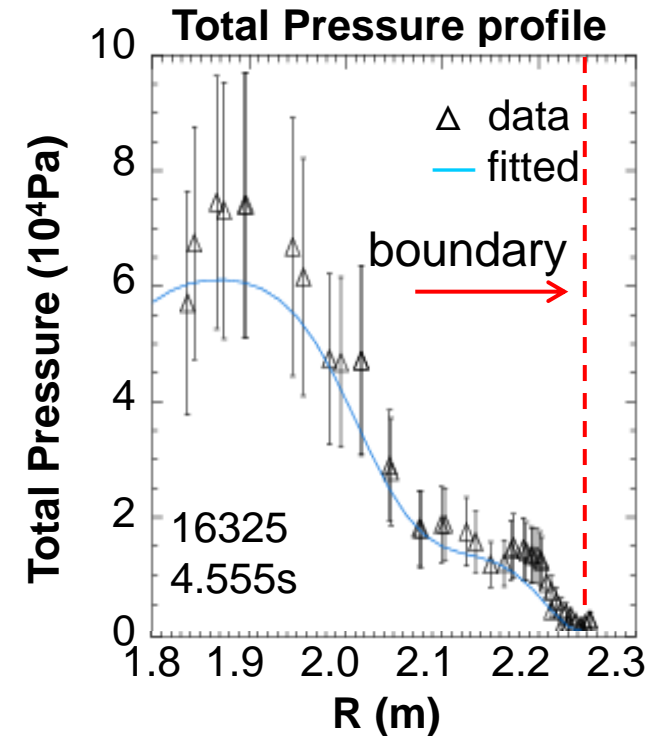
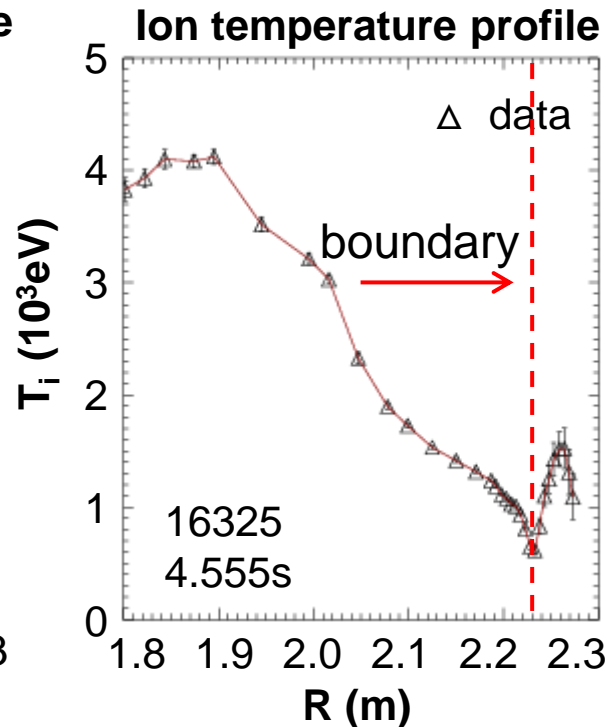
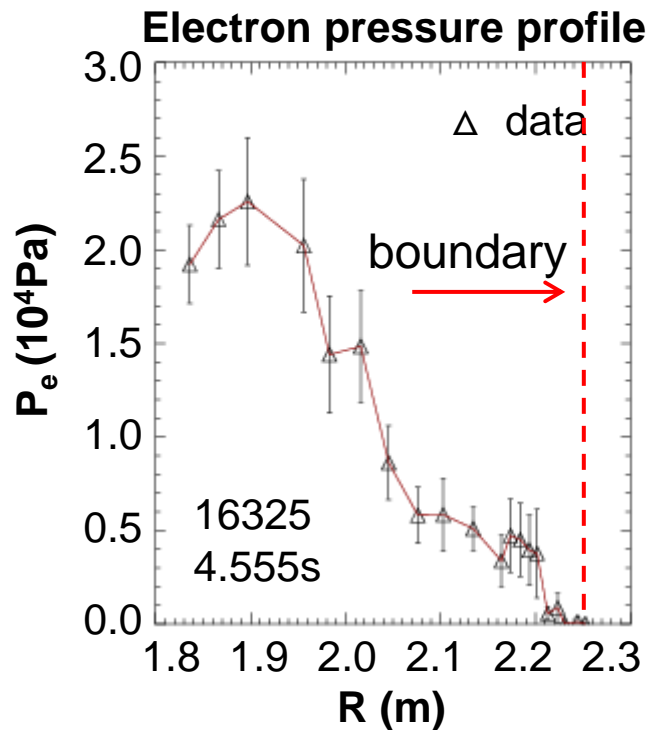
# Motional stark effect data provides magnetic pitch angle, q-profile constraint



- Systematic and statistical error estimates included in error bars
- E.g. background light subtraction (w/ Jinseok Ko, S. Scott)

# “Partial kinetic” approach for total pressure allows greater flexibility in profile shape

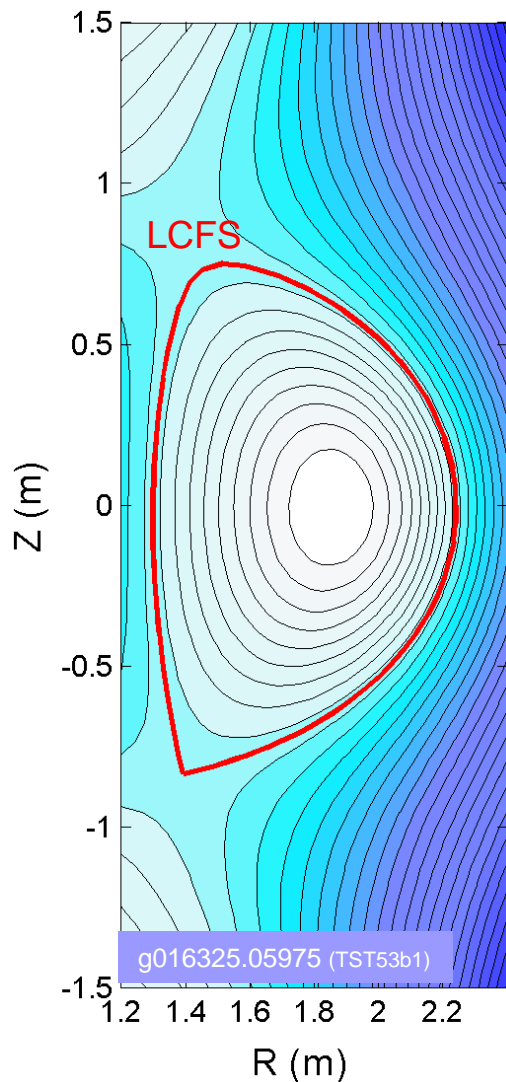
- Electron Pressure  $P_e \leftarrow 27$  Thomson scattering ( $T_e$  &  $N_e$ ), systematic error
- Ion Pressure  $P_i \leftarrow 32$  CES ( $T_i$  &  $N_i$  estimated from  $N_e$ )
- Fast particle pressure  $P_{\text{fast}}$  “based” on  $P_e$  with 100% error bar
- Total pressure  $P_{\text{tot}} = P_e + “P_i” + “P_{\text{fast}}”$  with large total error





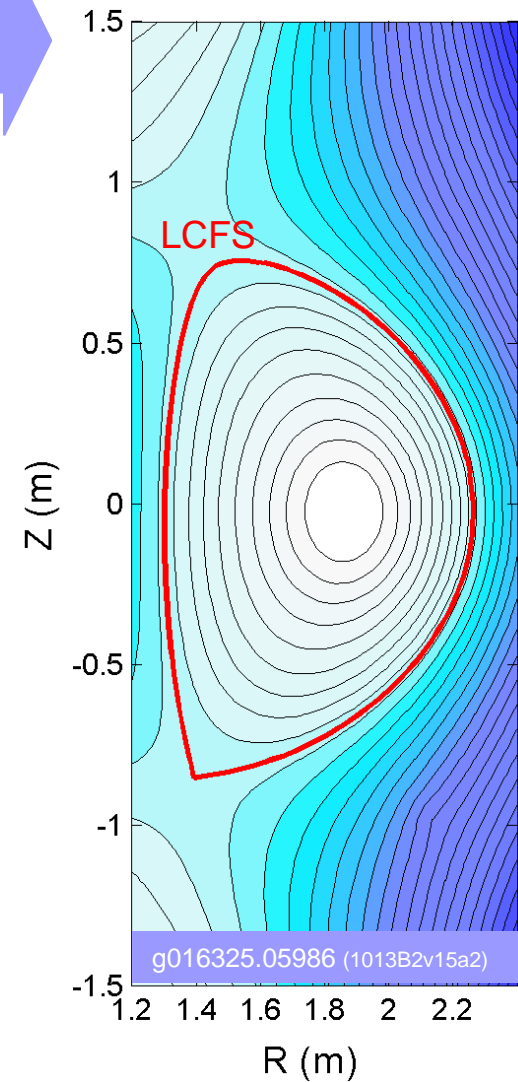
# Kinetic equilibrium with MSE has similar global parameters to magnetic-only equilibrium, some differences do occur

Poloidal flux contours



Magnetic only	Global parameter	Kinetic
202.4	$\chi^2$	222.6
1.86	$R_{\text{axis}}(\text{m})$	1.86
-0.01	$Z_{\text{axis}}(\text{m})$	-0.02
1.68	$\kappa$	1.68
0.54	$\delta_{\text{TOP}}$	0.51
0.80	$\delta_{\text{BOT}}$	0.81
0.95	$\beta_{\text{T}}$	1.04
1.86	$\beta_{\text{p}}$	1.86
1.89	$\beta_{\text{n}}$	1.99
1.05	$I_{\text{i}}$	0.96
6.39	$q_{95}$	5.96

Poloidal flux contours

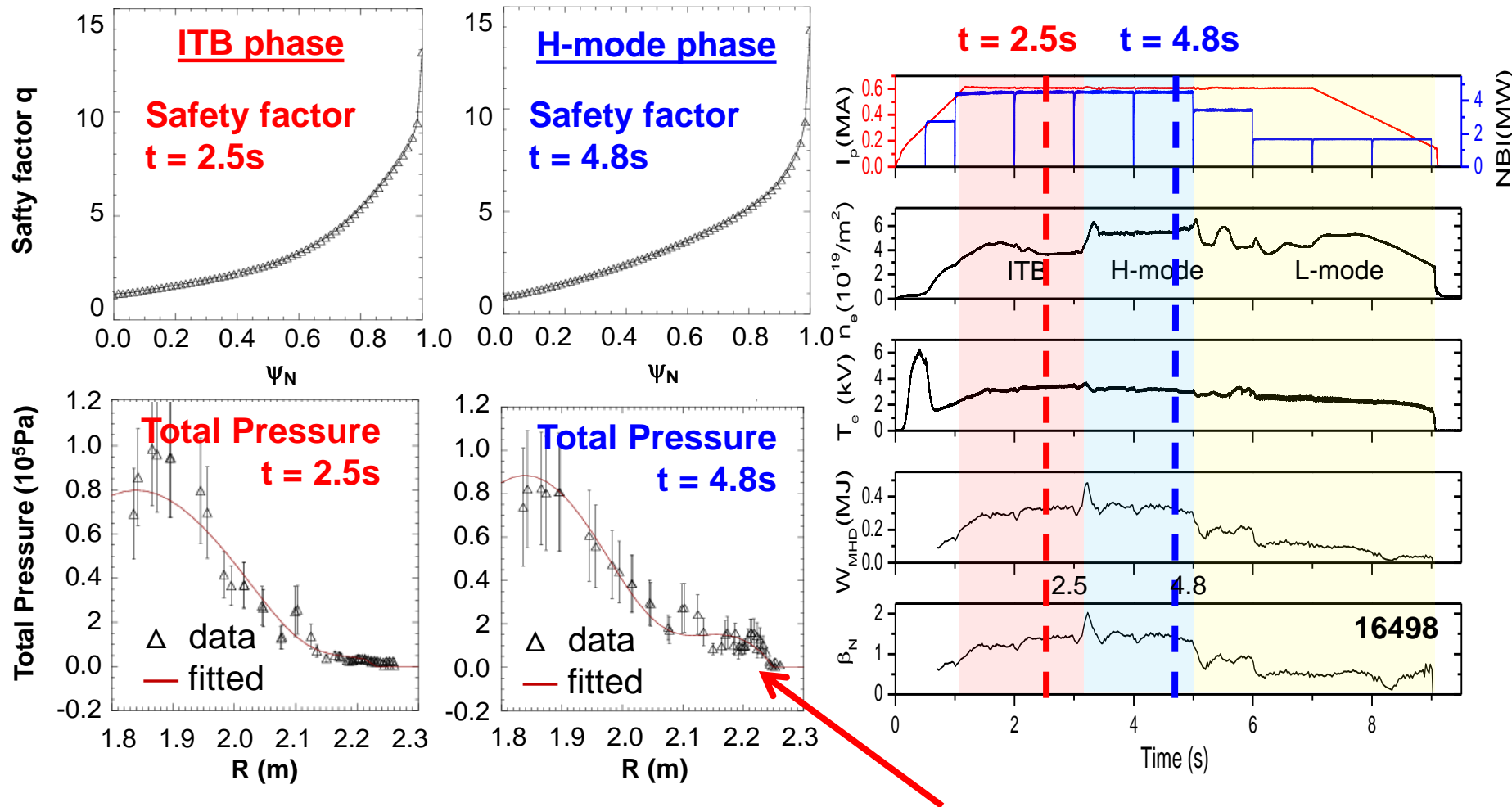


16325 5.975s

16325 5.986s



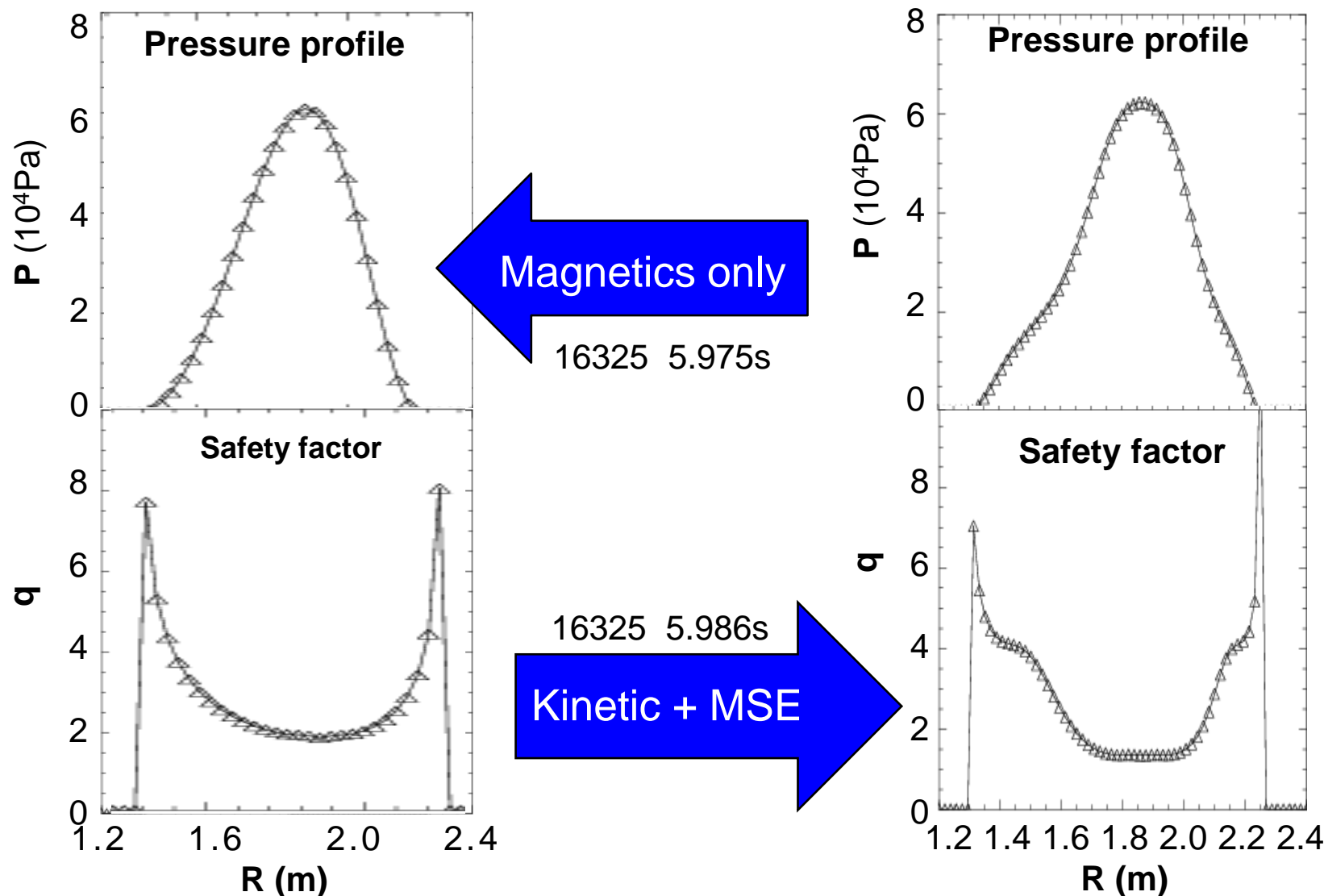
# Clear pressure profile distinction between Internal Transport Barrier and H-mode phases



- ❑ Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase → see poster by Y. Jiang (CU) Tuesday

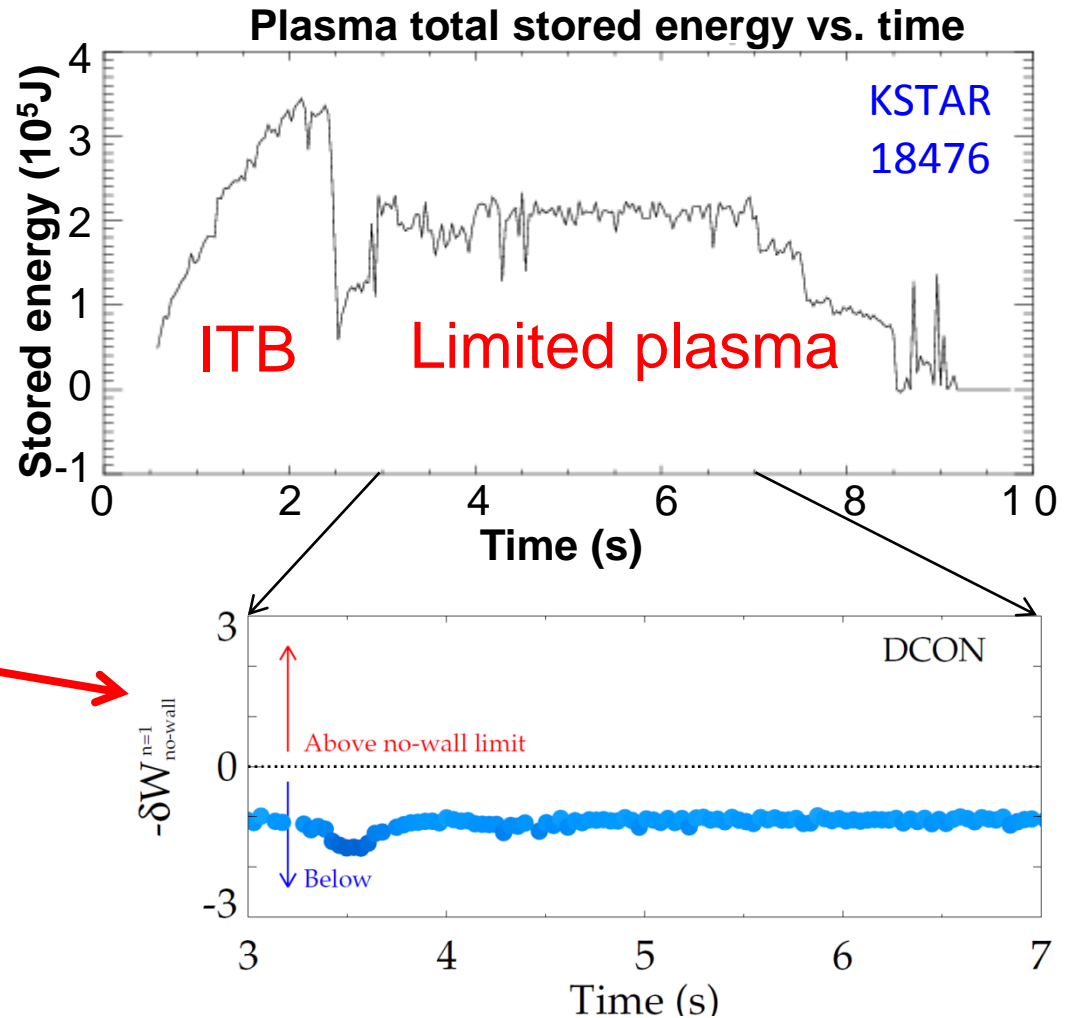
Xp by Jinil Chung

# In contrast, kinetic equilibrium reconstruction with MSE produces substantial detail in P and q profiles



# DCON ideal stability of kinetic equilibria with good convergence yield steady analysis evolution

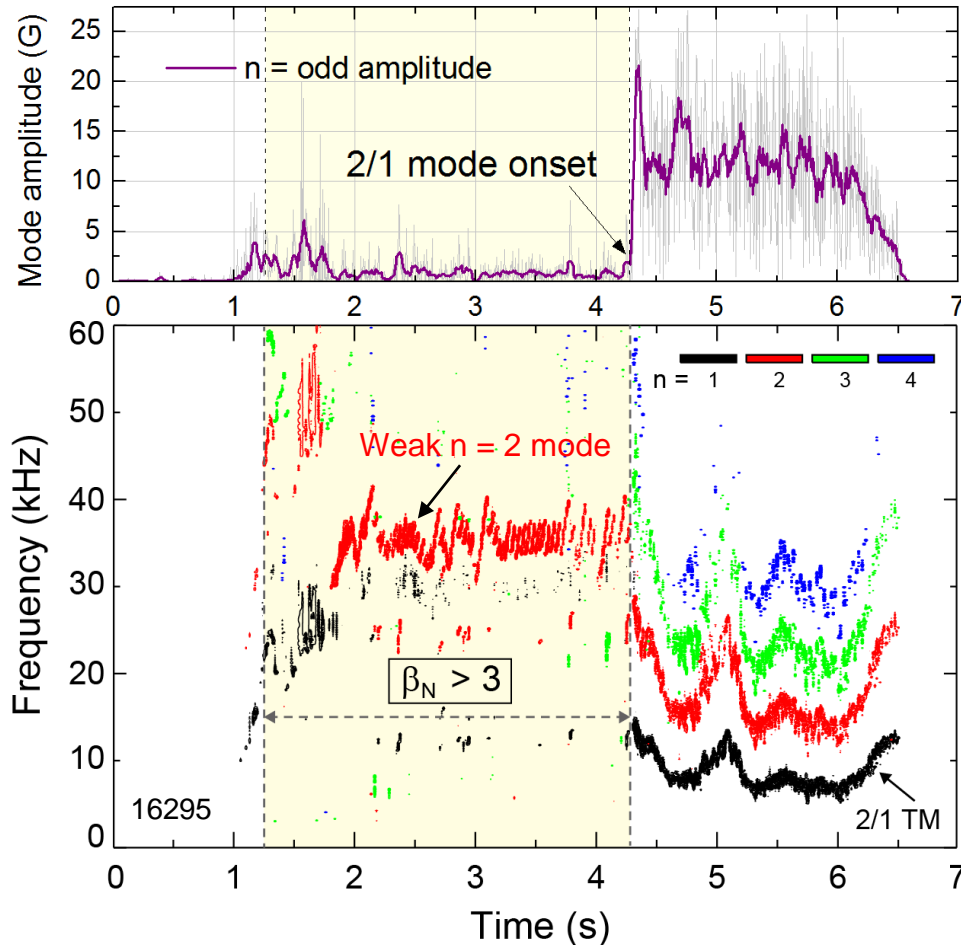
- ❑ DCON stability calculations of  $\delta W$  indicate if plasma exceeds the ideal no-wall beta limit
- ❑ Analysis of new KSTAR kinetic equilibria indicates ideal stability (below no-wall limit) during period shown (as expected)



DCON: (A. H. Glasser, Physics of Plasmas **23** (2016) 072505

# Strong 2/1 tearing mode onset terminated high $\beta_N$

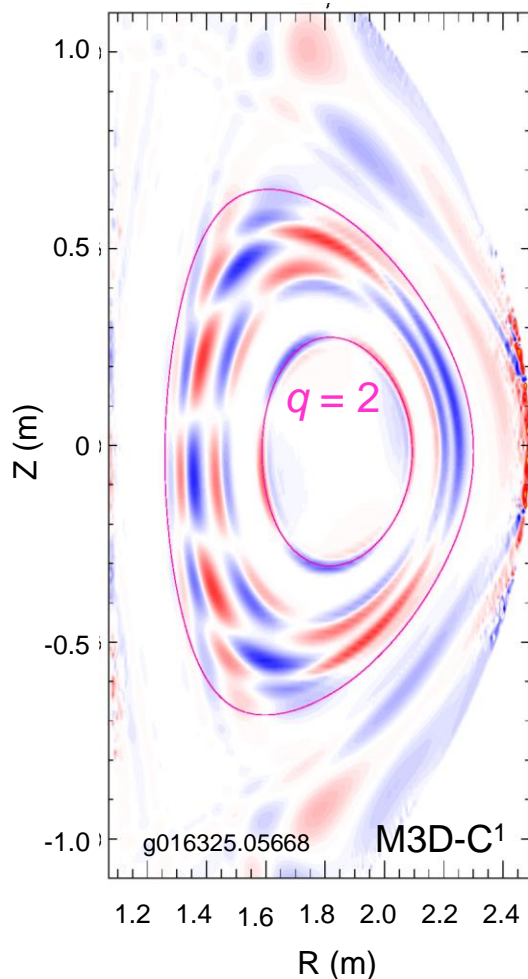
## Mode amplitude and toroidal magnetic probe spectrum in high $\beta_N$ discharge



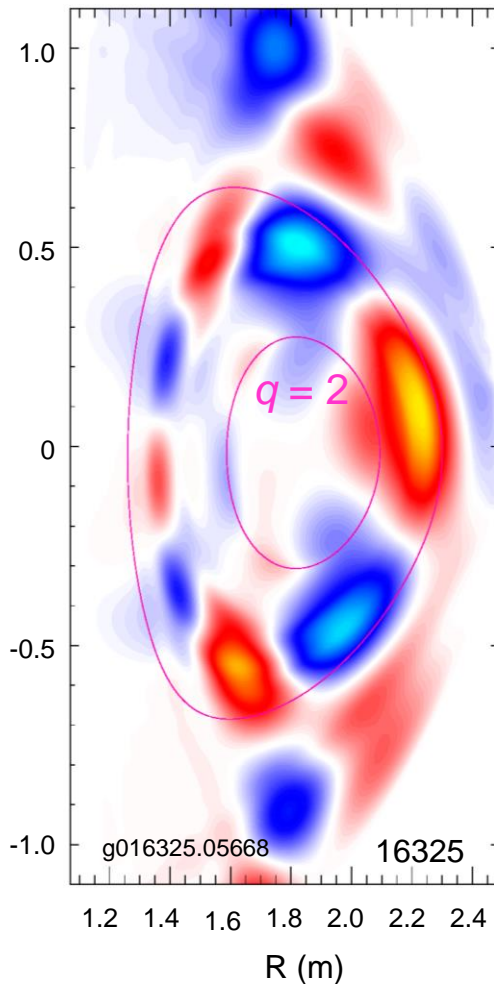
- ❑ Weak  $n = 2$  activity during high  $\beta_N$  phase
  - ❑  $|\delta B_p| \sim 2$  G
- ❑ High  $\beta_N$  operation was limited by strong 2/1 tearing mode onset
  - ❑ Measured mode amplitude  $> 20$  G
  - ❑ Both  $W_{\text{tot}}$  and  $\beta_N$  were reduced by  $\sim 35\%$  but maintained H-mode
- ❑ Plasma rotation profile significantly reduced by  $> 20\%$  due to the 2/1 mode onset

# Resistive tearing mode stability of higher $q_{95}$ plasma examined using M3D-C<sup>1</sup>

Perturbed toroidal  
current



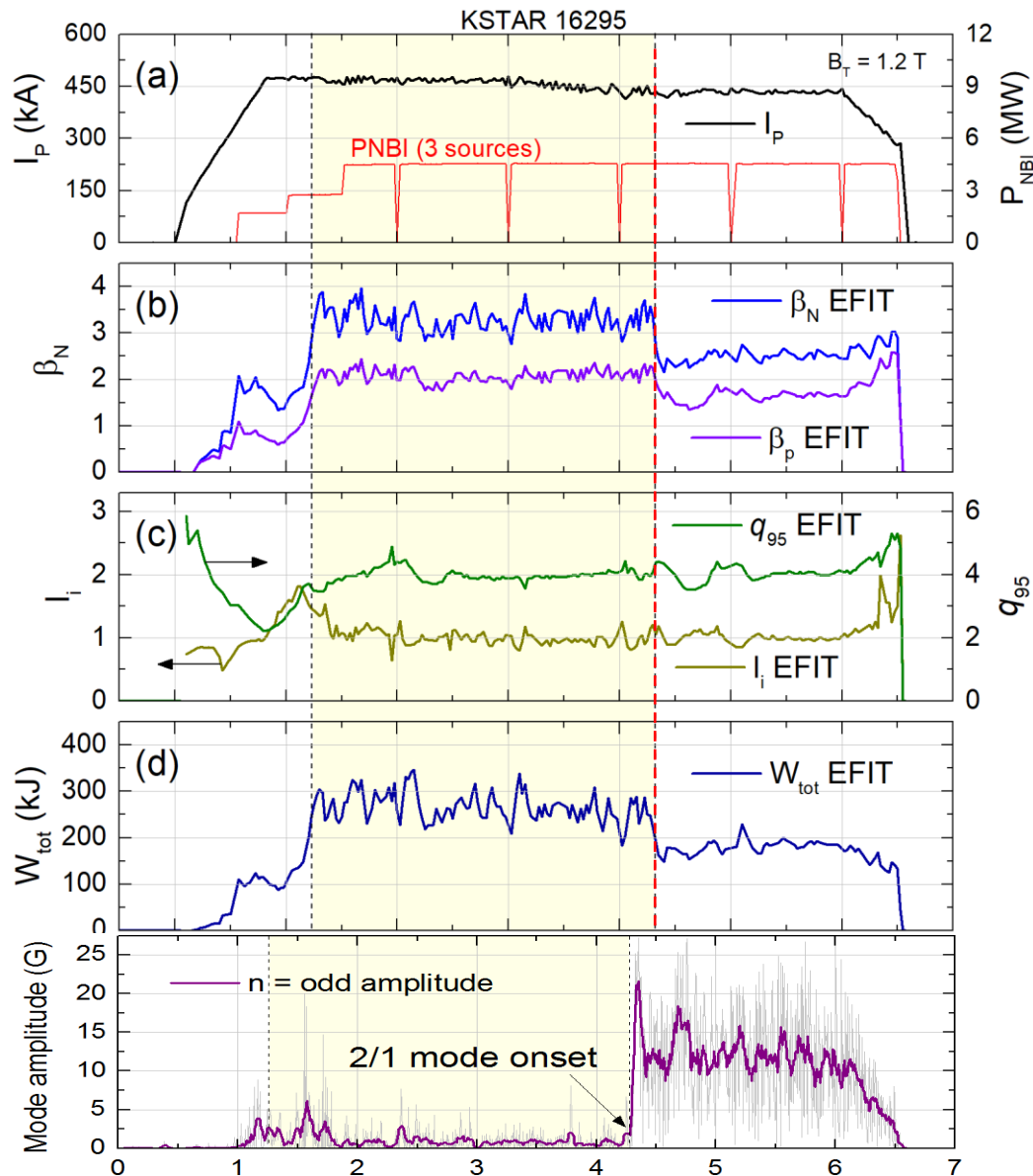
Perturbed poloidal  
flux



- Kinetic equilibrium 16325 at  $t = 5.668s$ 
  - $\beta_N = 2.0, \beta_p = 1.9, q_{min} = 1.4$
  - DCON  $\rightarrow$  ideal stable)
- Resistive MHD computed to be stable by M3D-C<sup>1</sup>
  - Consistent with experiment
  - Initial analysis showing capability – will be continued

(M3D-C<sup>1</sup>: S.C. Jardin, *et al.*, J. Comput. Phys. **226** (2007) 2146)

# High $\beta_N > 3$ equilibria limited by rotating MHD



High  $\beta_N$  plasmas were significantly extended to longer pulse by utilizing improved plasma control

Sustained high  $\beta_N^{avg} = 3.3$  achieved for 3 s

$I_p \sim 450$  kA,  $B_T = 1.2$  T,  
 $q_{95} = 4.0-4.5$ ,  $W_{tot} = 270$  kJ

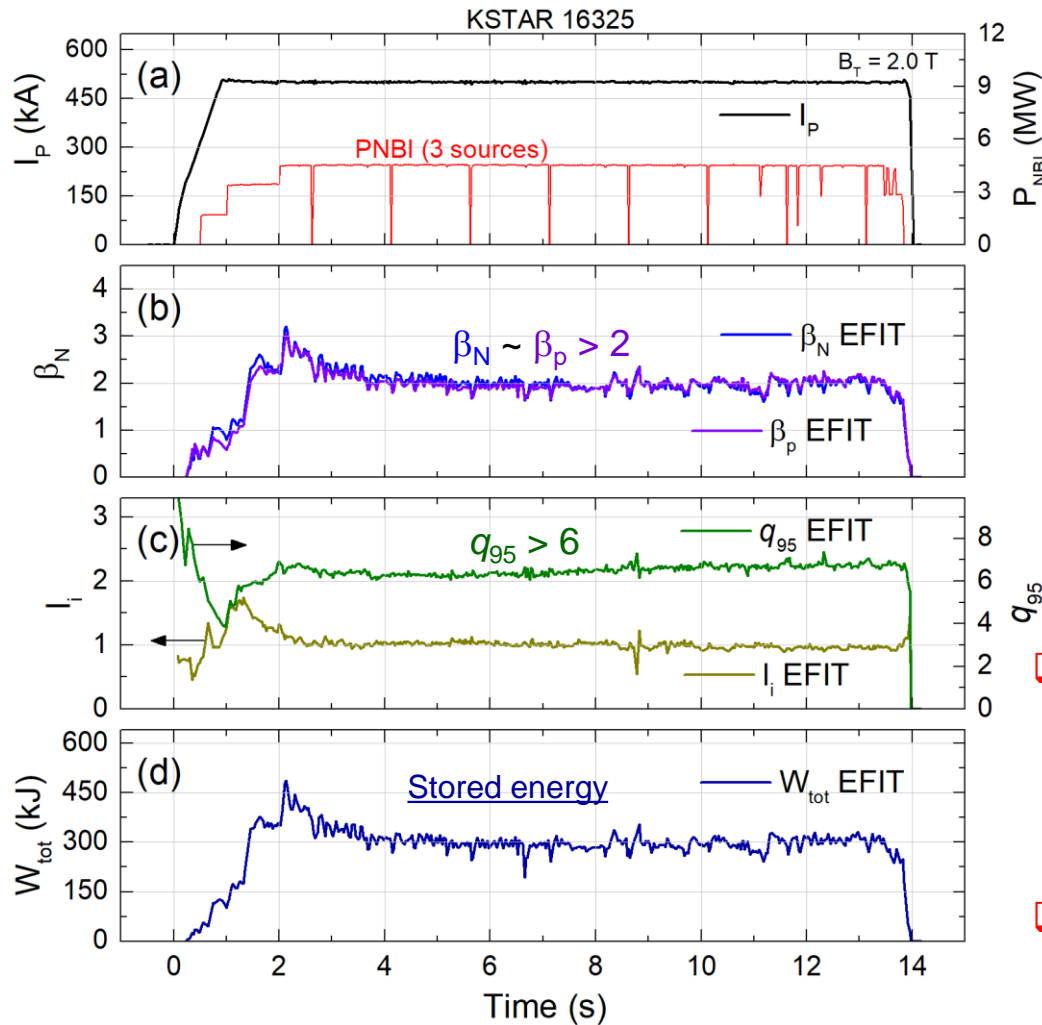
2/1 tearing mode onset at high  $\beta_N$  phase

Consequently reduces  $\beta_N$  and  $W_{tot}$  by ~35%

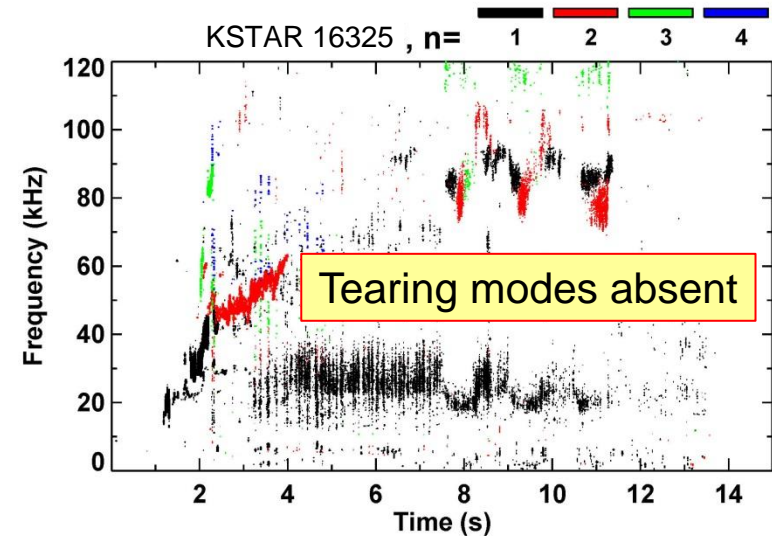
Measured mode amplitude >20 G (2G at weak activity)



# Comparative equilibria having higher $q_{95}$ shows significantly different MHD stability (shot 16325)



## Magnetic probe spectrogram



- ❑ Plasma operation at elevated  $B_T$  produced equilibria having higher  $q_{95}$  and  $\beta_p$
- ❑ Unlike shot 16295, discharge doesn't experience major beta-limiting MHD activity



# Several stability codes are being used to analyze KSTAR kinetic equilibrium reconstructions

## ❑ Ideal MHD analysis (kink/ballooning, resistive wall modes)

❑ Ideal DCON (A. H. Glasser, Phys. Plasmas **23** (2016) 072505)

❑ PEST (R.C. Grimm, J.M. Greene, and J.L. Johnson, Methods in Comp. Phys. **16** (1976) 253)

## ❑ Kinetic MHD analysis (kinetic kink, resistive wall modes)

❑ MISK (B. Hu, R. Betti, and J. Manickam, Phys. Plasmas **12** (2005) 057301)  
(J.W. Berkery, S.A. Sabbagh, et al., Phys. Rev. Lett. **104** (2010) 035003)

## ❑ Tearing modes

❑ Resistive DCON (A.H. Glasser, et al., Phys. Plasmas **23** (2016) 112506)

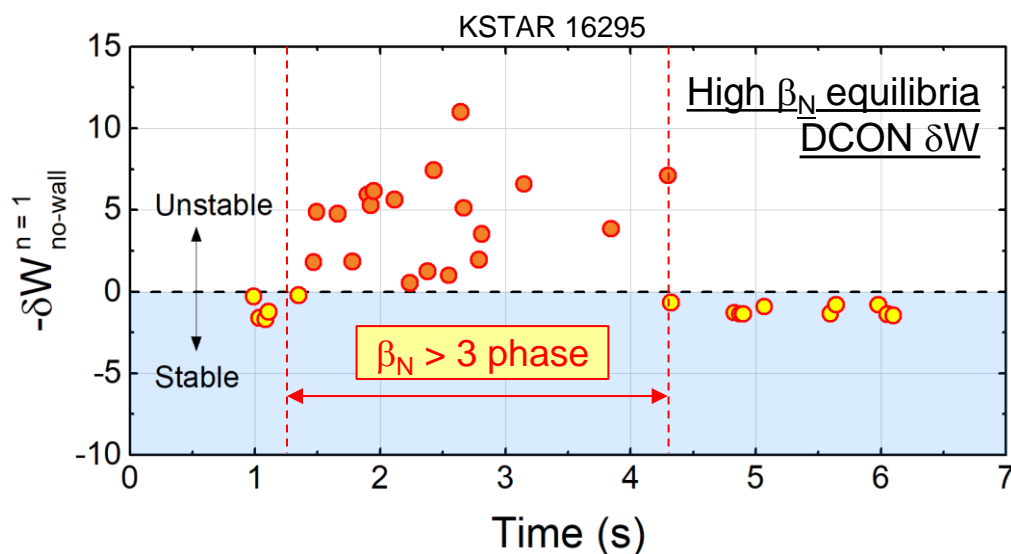
❑ M3D-C<sup>1</sup> (S.C. Jardin, et al., J. Comput. Phys. **226** (2007) 2146)

**INITIAL EMPHASIS** on determining the quality of equilibrium convergence needed for reliable stability analysis

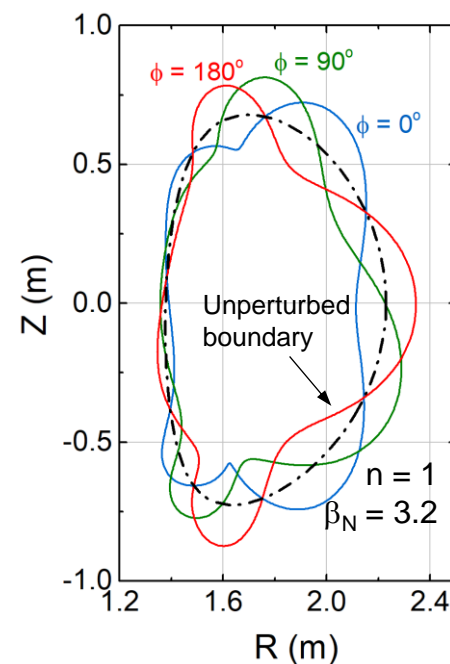
➔ see poster by Y. Jiang (CU) Tuesday

# DCON stability calculation shows high $\beta_N$ equilibria are subject to $n = 1$ ideal instability

DCON analysis, ideal  $n = 1$  mode, no-wall boundary condition



DCON computed  $\delta B_n$  of unstable  $n = 1$  mode at  $t = 2.356$  s



- At observed high  $\beta_N$  phase, DCON calculates unstable  $n = 1$  mode with no-wall ( $\beta_N > \beta_N^{\text{no-wall}}$ )
- Hypothesis: global kink / resistive wall modes stabilized by kinetic effects

DCON: A.H. Glasser, Phys. Plasmas **23** (2016) 072505

# Calculations of kinetic modifications to ideal stability examined with the MISK code

## □ Kinetic modification to ideal MHD

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

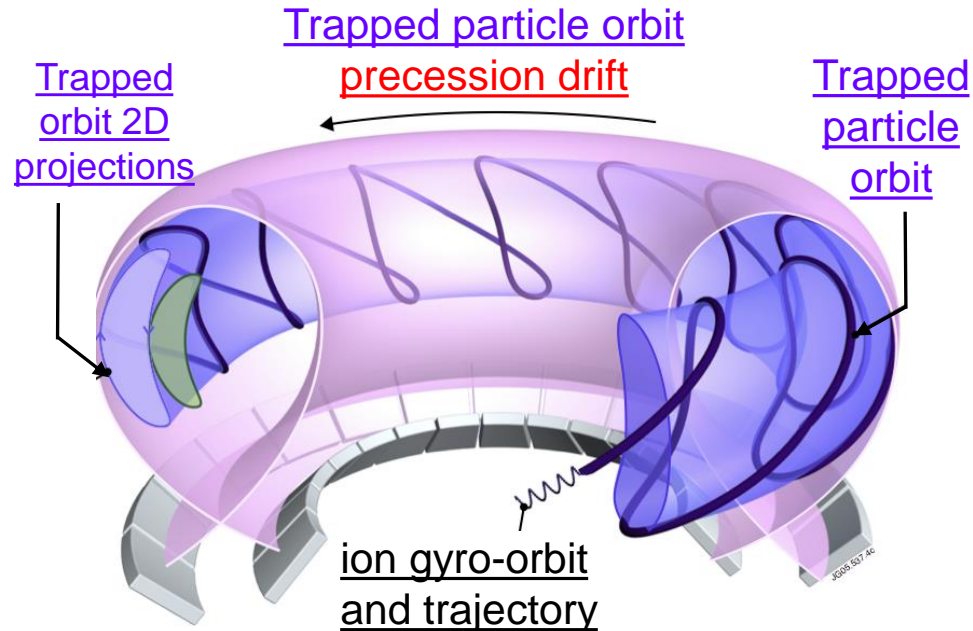
## □ Stability depends on

- Trapped / circulating ions, trapped electrons
- Particle collisionality
- Energetic particle (EP) population
- Integrated  $\omega_\phi$  profile matters: broad rotation resonances in  $\delta W_K$

plasma integral over particle energy

$$\delta W_K \propto \int \left[ \frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle \omega_D \rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

precession drift
bounce
collisionality
 $\omega_\phi$  profile (enters in  $\omega_E$ )

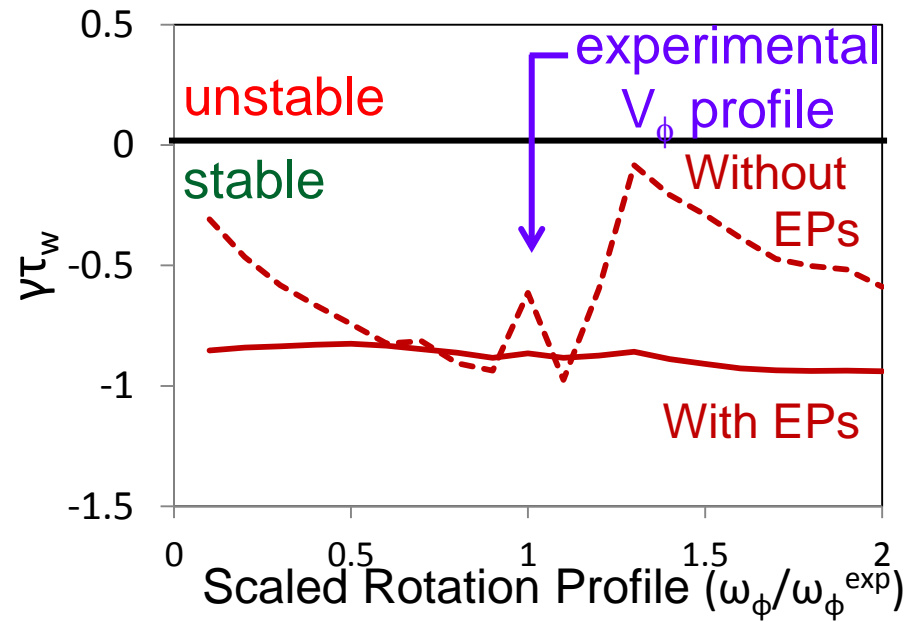
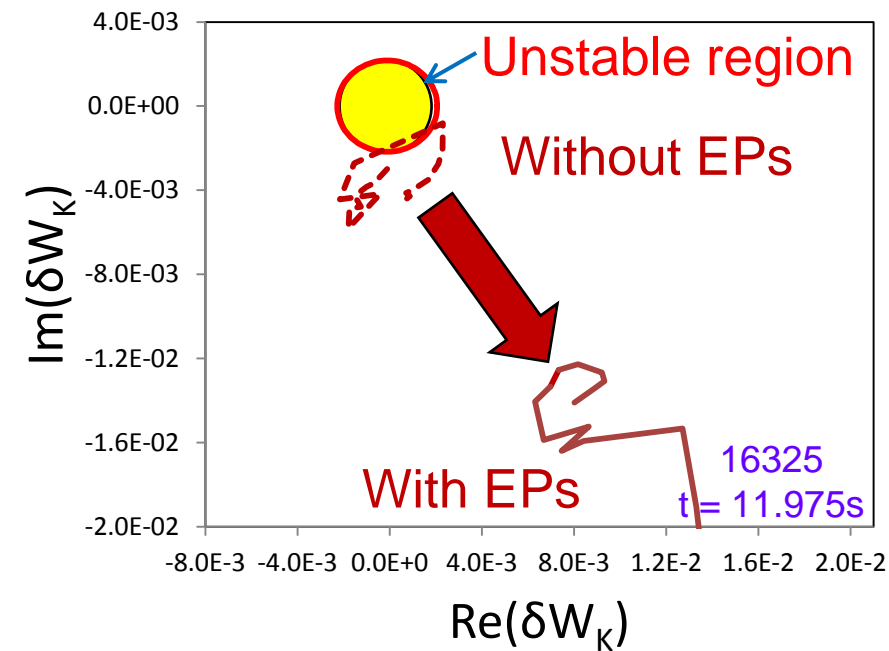


(Fig. adapted from R. Pitts et al., Physics World (Mar 2006))

NSTX CALCULATIONS: Some references:

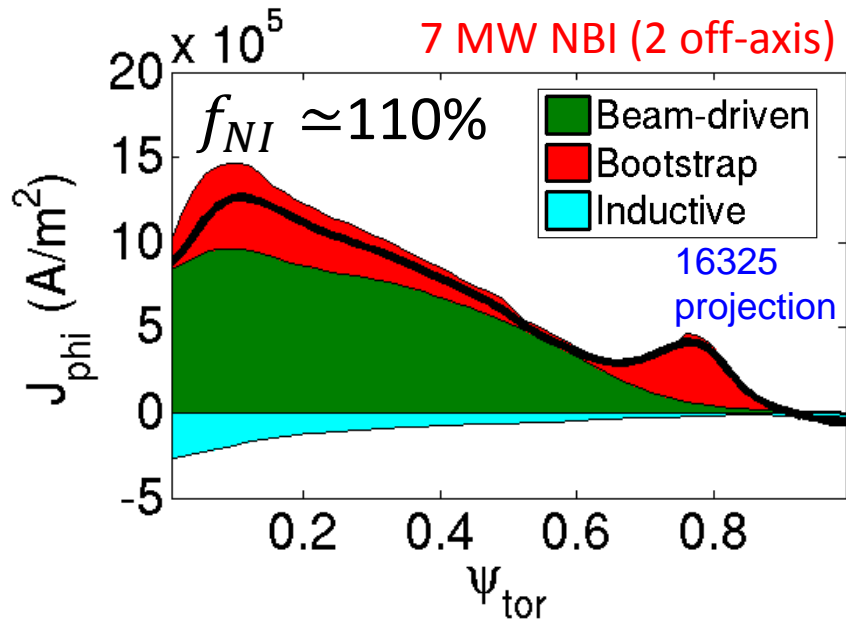
- J. Berkery et al., PRL **104** (2010) 035003
- S. Sabbagh, et al., NF **50** (2010) 025020
- J. Berkery et al., PRL **106** (2011) 075004
- S. Sabbagh et al., NF **53** (2013) 104007
- J. Berkery et al., PoP **21** (2014) 056112
- J. Berkery et al., NF **55** (2015) 123007
- J. Berkery, et al., NF **24** (2017) 056103

# MISK kinetic RWM stability analysis shows stability, significant stabilizing effect of energetic particles



- ❑ Resistive wall modes (RWM) computed to be stable (consistent with experiment)
- ❑ Close to marginal stability when examining variation of experimental rotation profile and without considering energetic particles
- ❑ Additionally, energetic particles contribute large stabilizing effect

# TRANSP analysis shows new off-axis NBI sources can broaden current profile somewhat



TRANSP 16325	2016 actual	4 NBI (mid- plane)	4 NBI (2 off axis)
NIC fract. (%)	71%	103%	110%
$\beta_N$	2.7	3.65	3.65
$I_i$	0.9	0.96	0.92
$T_i(0)$ (keV)	4.5	6.3	5.6
$T_e(0)$ (keV)	3.6	3.3	3.3
$n_e(0)$ ( $10^{19}\text{m}^{-3}$ )	3.2	5.5	5.5
$f_{\text{Greenwald}}$	0.5	0.5	0.5
$H_{98y2}$	1.25	1.25	1.25

→ see poster by J.H. Ahn (Columbia U.) on Tuesday for further KSTAR TRANSP analysis

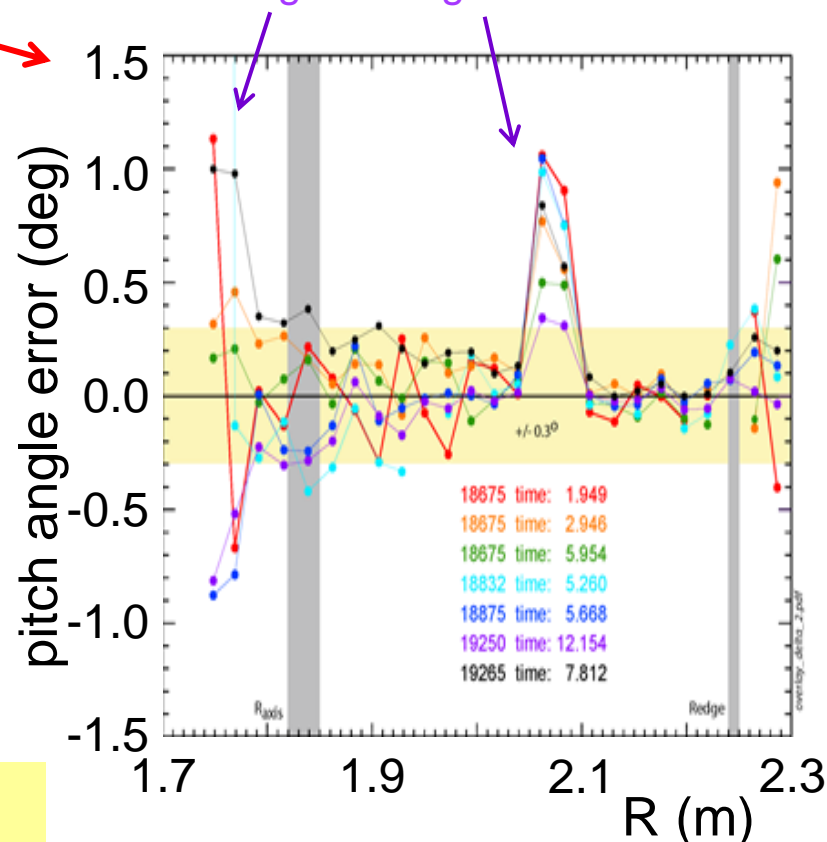
# Kinetic equilibrium / stability analysis will continue to improve thru Columbia / PPPL / MIT Collaboration

- ❑ Transferred 10 channel MSE background light polychrometer from C-Mod to KSTAR (4/2017)
  - ❑ Investigating improvement of MSE measurement by background light subtraction
  - ❑ DOE has funded 15 additional BL polychrometer channels (for 2018)
- ❑ Collaborative interaction to further improve Thomson scattering data
- ❑ Continued improvement of kinetic equilibrium reconstruction / stability analysis
  - ❑ E.g. Improved modeling / planned neural net delivery of fast particle pressure  $P_{\text{fast}}$

➔ All supporting the main disruption prediction and avoidance research goals

(S.D. Scott (PPPL), et al.,)

Pitch angle can be troublesome on some channels due to neglect of background light subtraction





# Broadened disruption prediction and avoidance research centered around DECAF is progressing for future tokamaks

## ❑ DECAF code is rapidly developing

- ❑ Initial published results showed strong promise of new, automated “event chain-based” research paradigm
- ❑ DECAF event objects expanded in capability now include event criteria histories; innovation continues (e.g. direct coupling of events)
- ❑ Models defining events are highly flexible (e.g. can include diagnostic comparisons, physics models, machine learning tools/techniques)

## ❑ Physics-based approach on multiple devices key to success

- ❑ Understanding is key to disruption forecasting extrapolability, reliability
- ❑ New DOE funding for disruption prediction/avoidance on MAST; KSTAR research including kinetic equilibria, stability, TRANSP analysis
- ❑ Research includes active mode detection/control, directed experiments

## ❑ “DECAF database” has begun

- ❑ Storage of intermediate results, est. growth to 100's of TB (“big data”!)