U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Kinetic Resistive Wall Mode Stabilization Physics in Tokamaks

Jack Berkery

Columbia University

S.A. Sabbagh[1], R. Betti[2], H. Reimerdes[3], J. Hanson[1],
A. Balbaky[1], R.E. Bell[4], A. Diallo[4], S.P. Gerhardt[4], B.P. Le Blanc[4], J.E. Menard[4], M. Podesta[4], Z.R. Wang[4]

[1]Columbia University, [2]University of Rochester, [3]Ecole Polytechnique Fédérale de Lausanne, [4]PPPL

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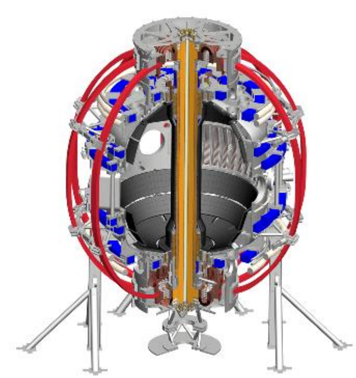
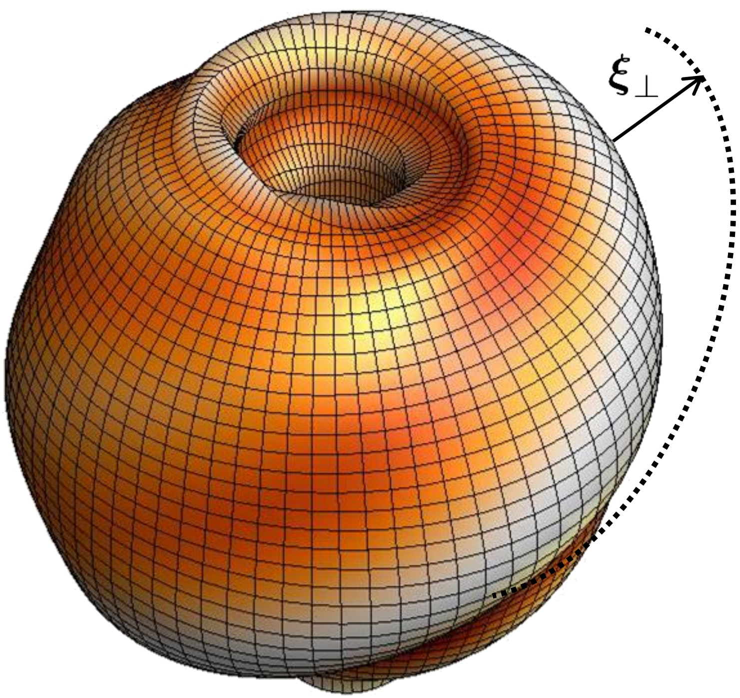


Outline

- **RWM Definition and Motivation**
- **Kinetic Stability Theory**
  - **Rotation**
  - **Collisionality**
  - **Energetic Particles**
- **Comparison of Calculations and Experimental Results**
- **Stability Estimation and Rotation Profile Control**
- **Summary**

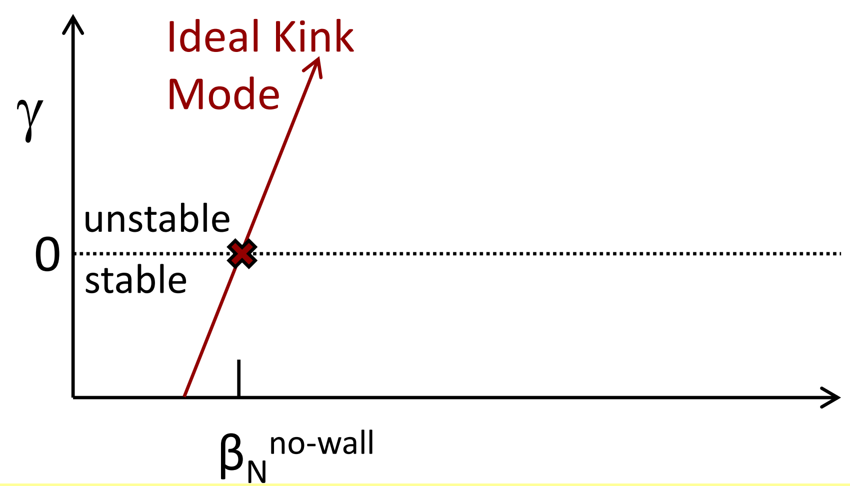
An unstable RWM is an exponential growth of magnetic field line kinking that can cause disruptions

- The resistive wall mode (RWM) is a kinking of magnetic field lines slowed by penetration through vessel structures



[S. Sabbagh et al., Nucl. Fusion 46, 635 (2006)]

$$\xi_\perp \sim e^{\gamma t}$$



RWMs can cause a collapse in β, disruption, and termination of the plasma

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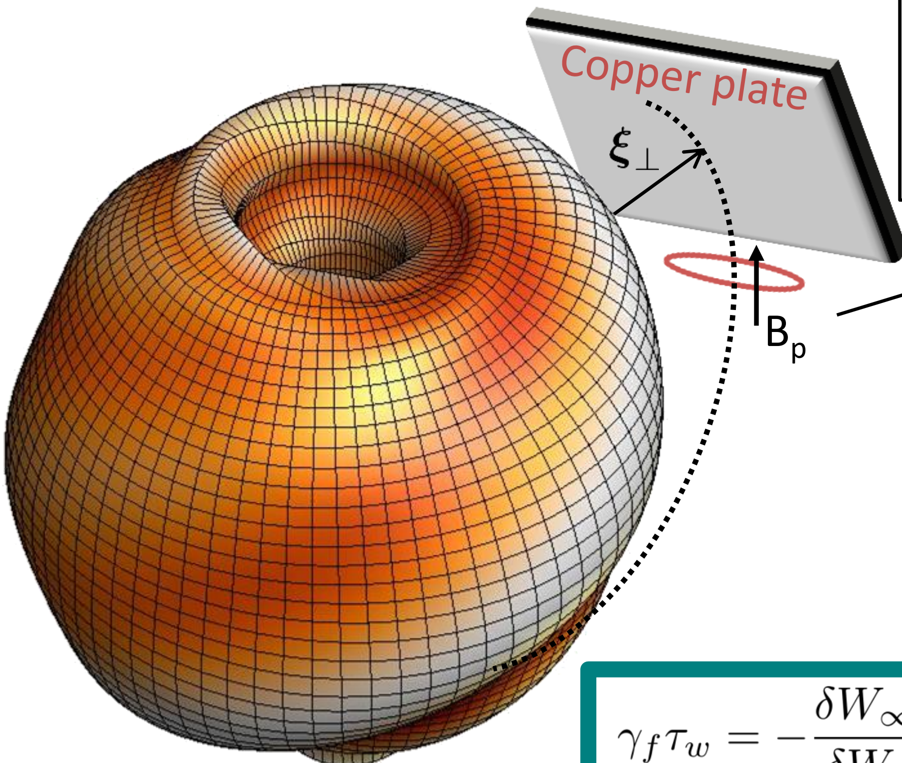

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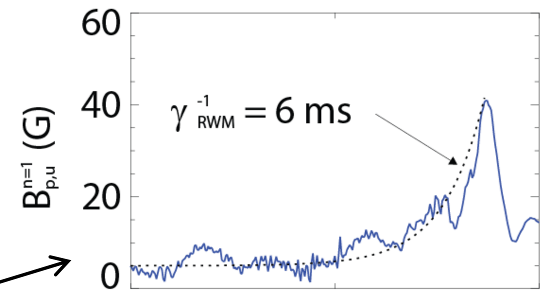
where

$\gamma \sim \tau_w^{-1}$



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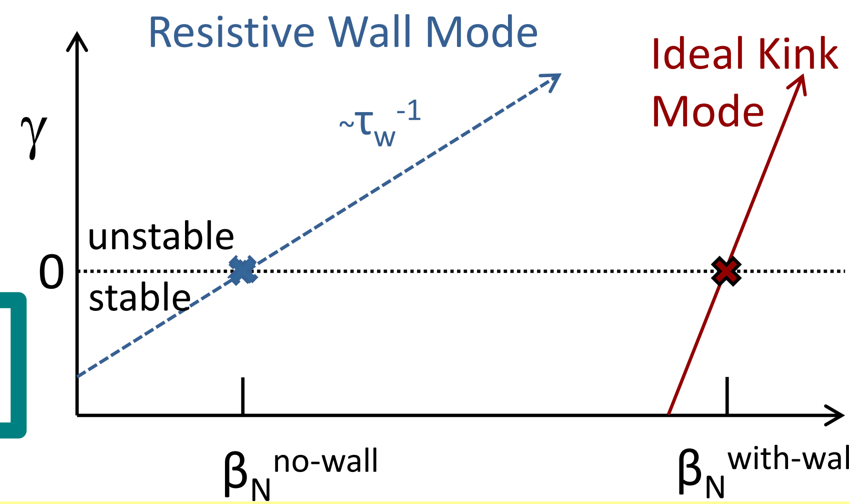
$$\gamma_f \tau_w = -\frac{\delta W_\infty}{\delta W_b}$$



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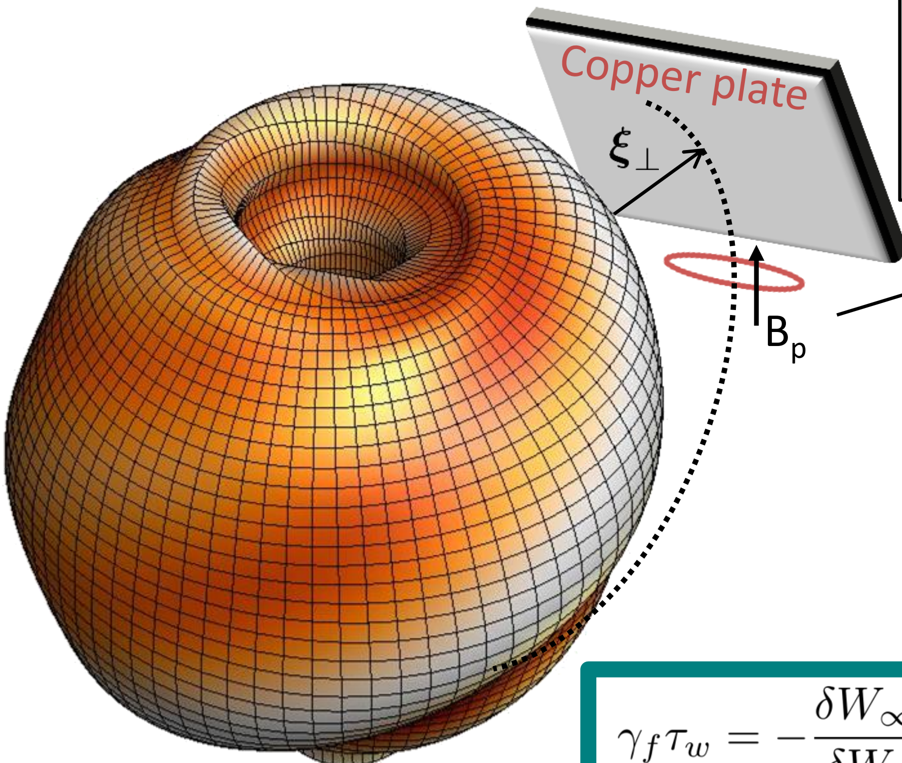

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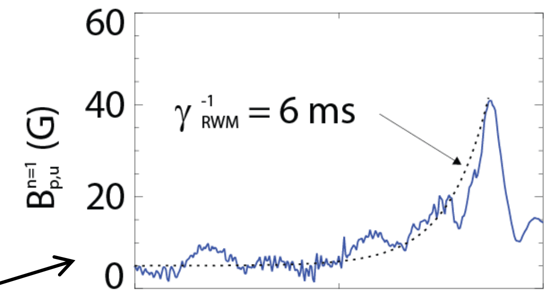

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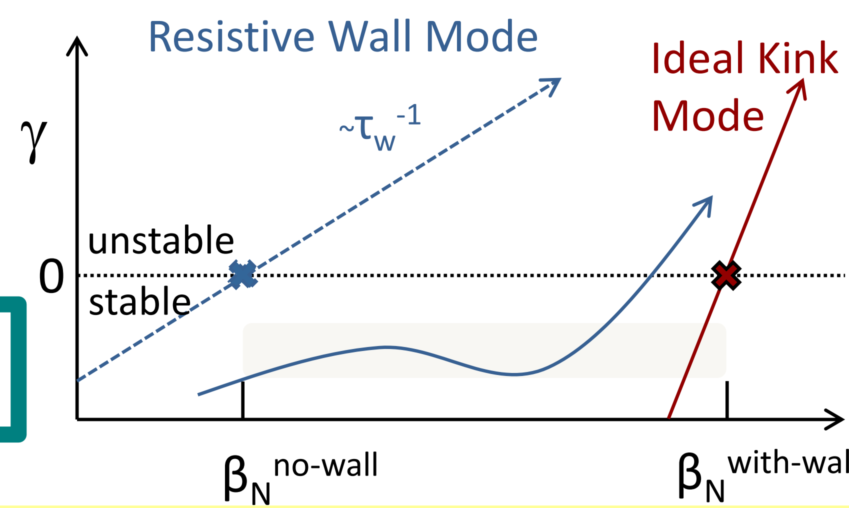

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RWMs can cause a collapse in β, disruption, and termination of the plasma

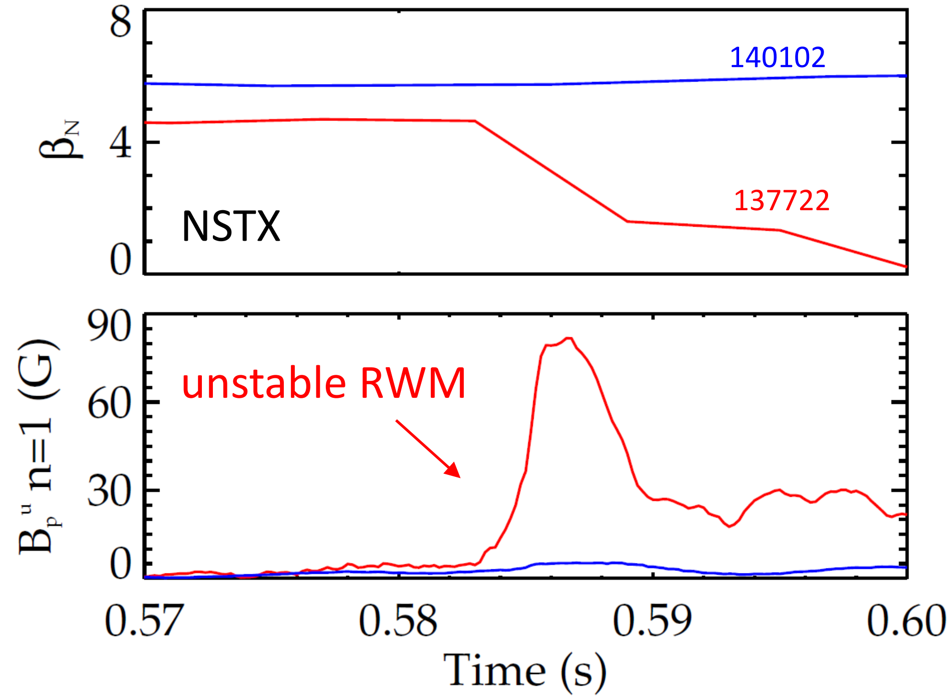
A scalar critical plasma rotation model can not explain RWM stability; it depends on the ω_ϕ *profile*

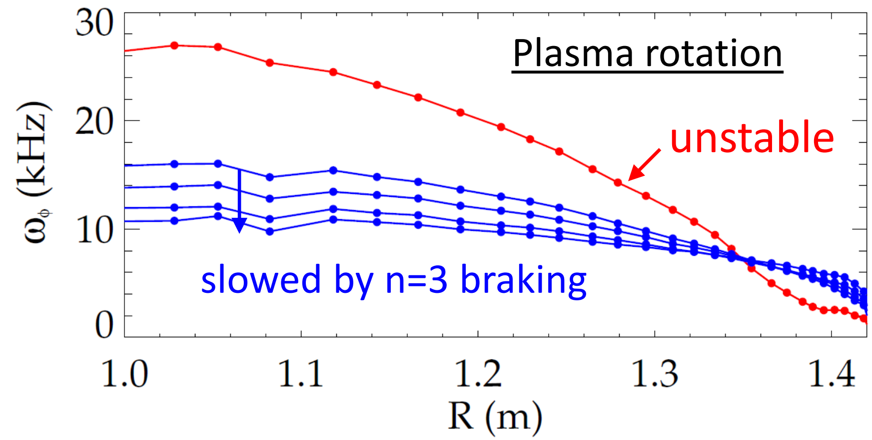
- Early stability theories:
  - Collisional dissipation of mode energy
  - Rotational damping

    But models with scalar “critical rotation” for stability could not explain experiments
- Unexplained experiments
- New theory: consider kinetic effects

Ideal Stability | Kinetic Effects

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$





[B. Hu et al., Phys. Rev. Lett. 93, 105002 (2004)]

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  - Collisionality
  - Energetic Particles
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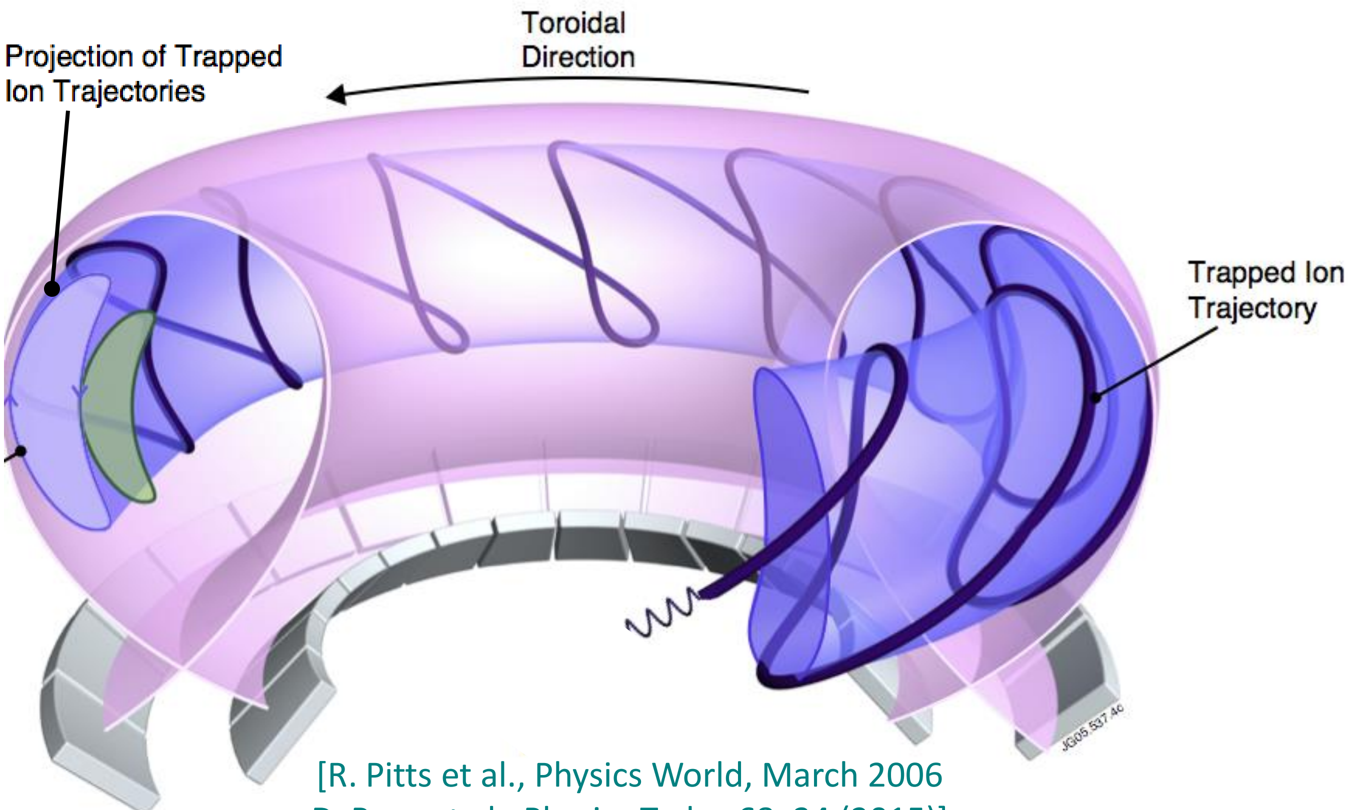
"Kinetic effects" means taking into account complicated particle motion rather than treating the plasma as a fluid



[R. Pitts et al., Physics World, March 2006
D. Pace et al., Physics Today 68, 34 (2015)]

MISK code

- Solves for RWM growth rate
- δW_K is solved by using $\tilde{f}$ from the drift kinetic equation

Precession Drift ~ Plasma Rotation

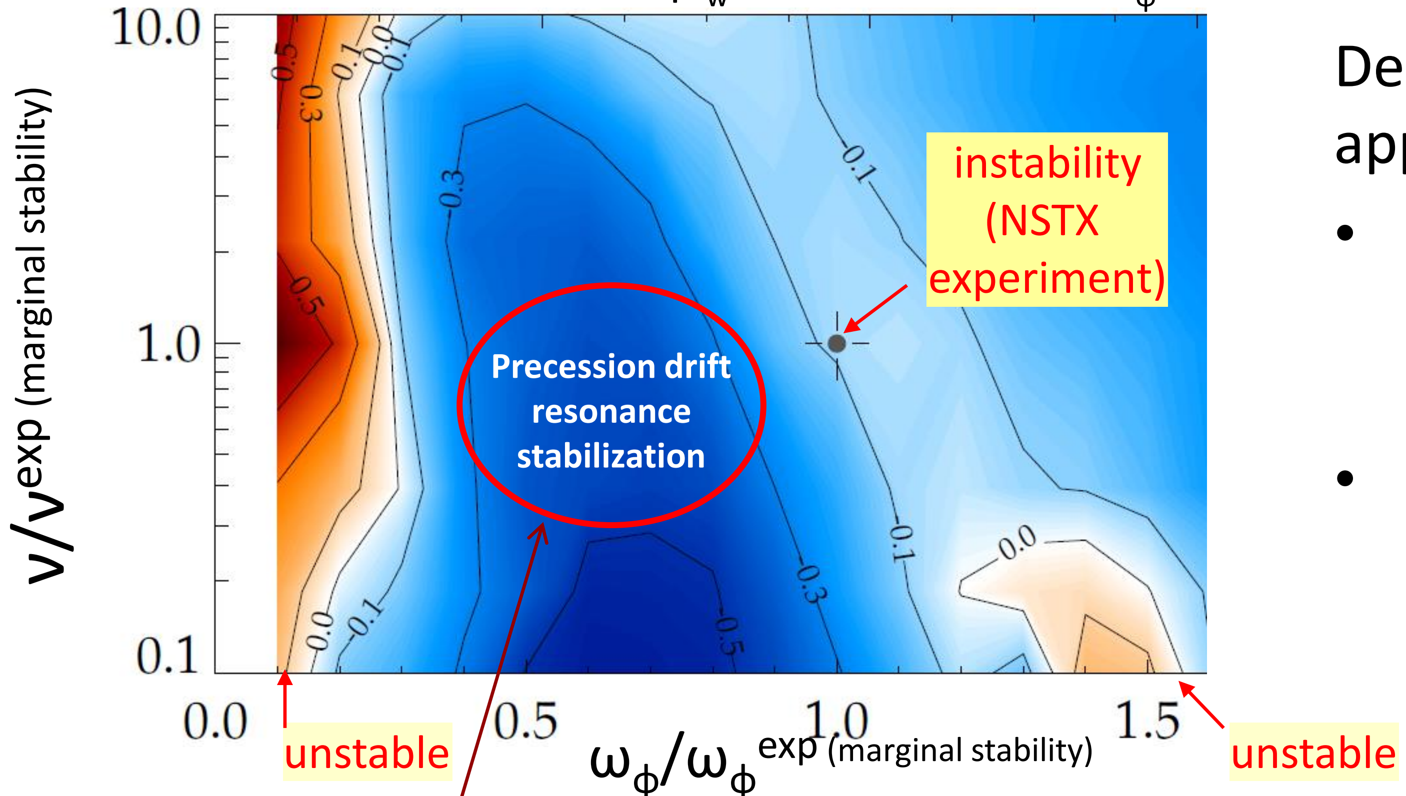
Rotational resonance effect

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

[J. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)]

Kinetic theory consistent with RWM destabilization at intermediate plasma rotation

MISK calculations of $\gamma\tau_w$ contours vs. ν and ω_ϕ



Destabilization appears between:

- precession resonance at low ω_ϕ
- bounce resonance at high ω_ϕ

Precession Drift ~ Plasma Rotation

Rotational resonance effect

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

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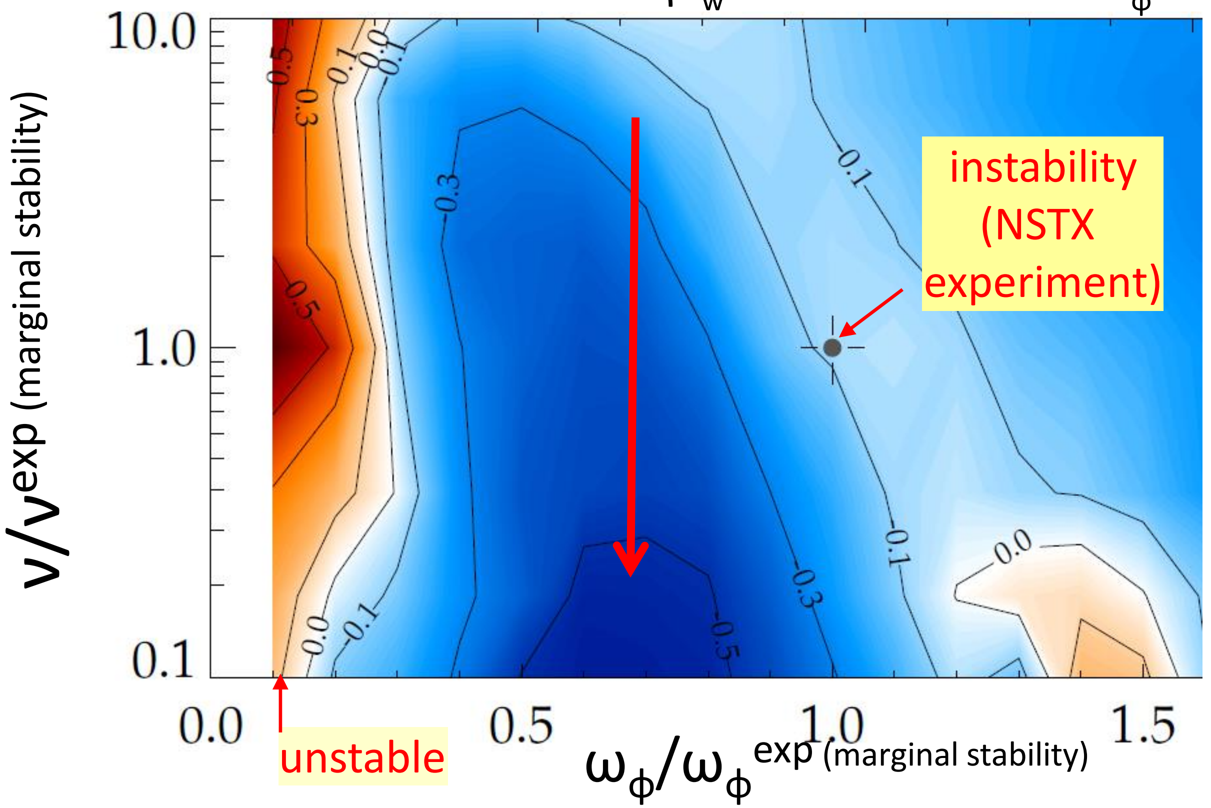
Collisionality affects the strength of kinetic resonances

MISK calculations of $\gamma\tau_w$ contours vs. ν and ω_ϕ



- Early theory predicted RWM stability should decrease at low *ν*
- Kinetic RWM stability theory:
  - Stabilizing resonant kinetic effects enhanced at low ν
- Important for ITER

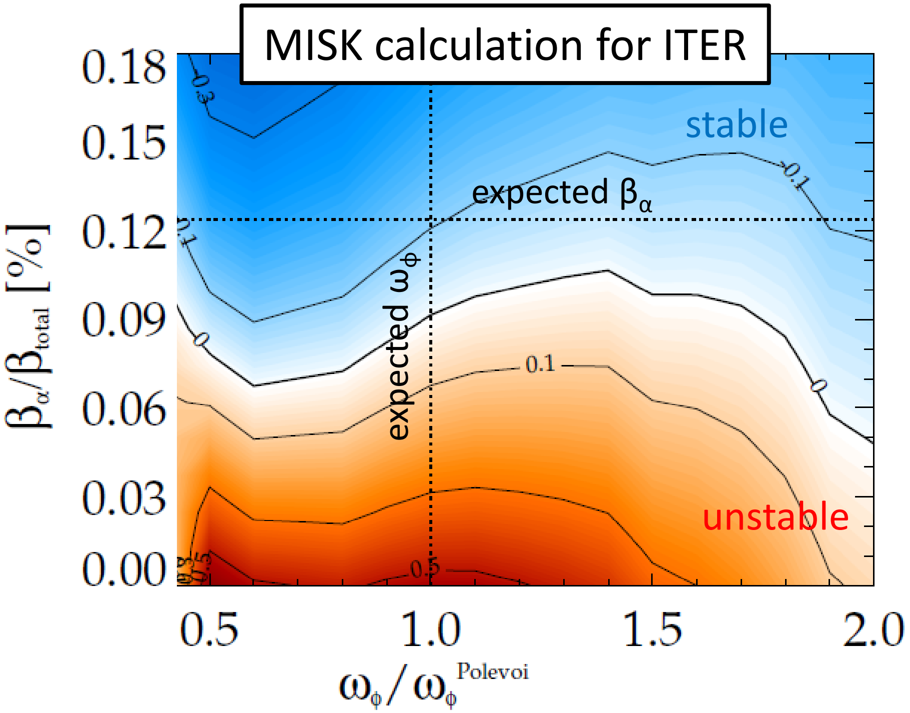
Collisionality effect

Collisionality

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

[J. Berkery et al., Phys. Rev. Lett. 106, 075004 (2011)]

Energetic particles provide a stabilizing force that is nearly independent of rotation and collisionality



- Energetic partilces provide stabilizing effect
- Energetic particles are not in mode resonance
  - Effect is nearly independent of ω_ϕ
  - Effect is not energy dissipation, but rather a restoring force

Large for EPs — Precession Drift

Small for EPs — ~ Plasma Rotation, Collisionality

Energetic particle effect

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

[J. Berkery et al., Phys. Plasmas 17, 082504 (2010)]

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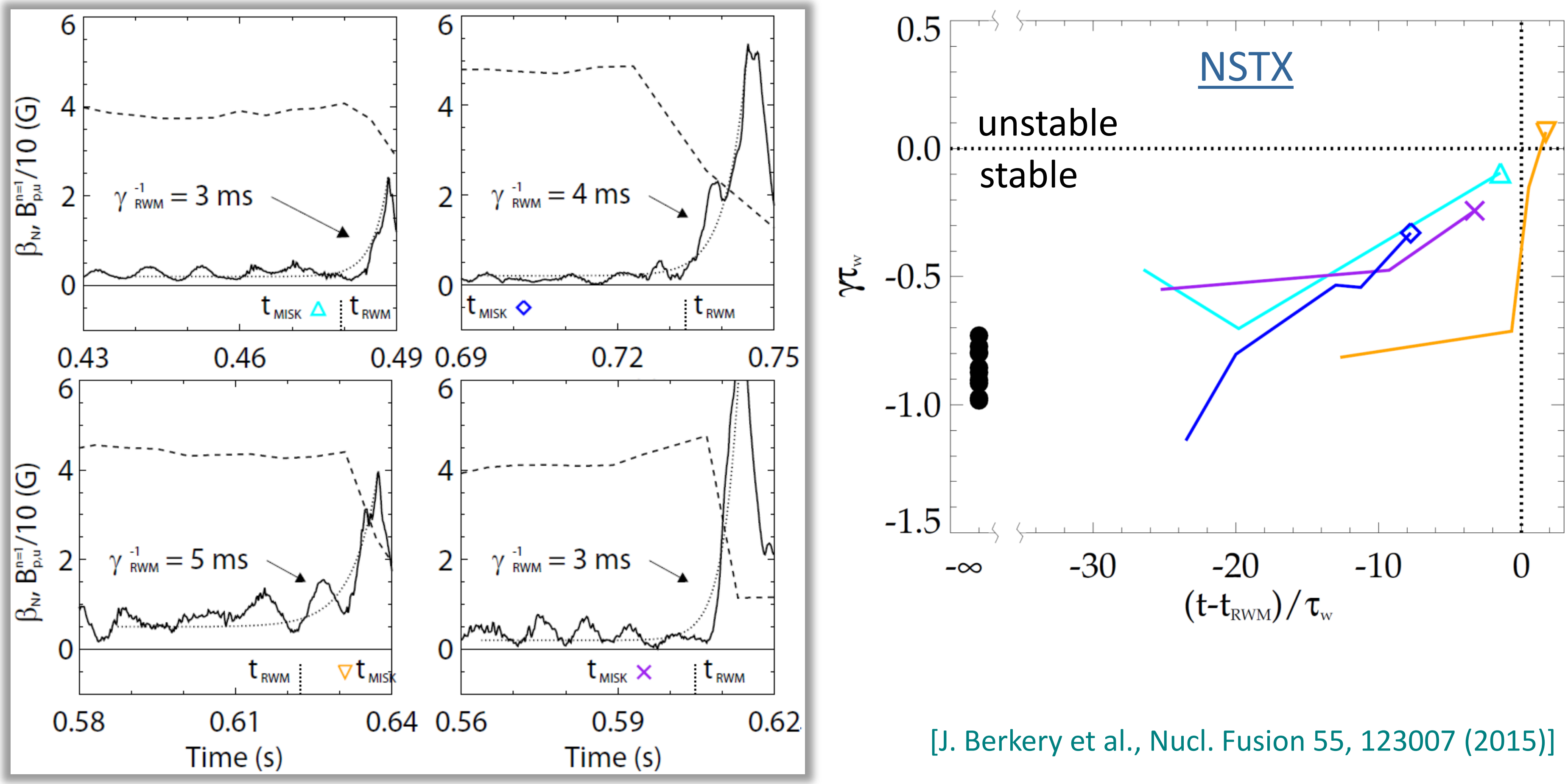
MISK calculations validated against unstable experimental plasmas; reproduce approach towards marginal stability



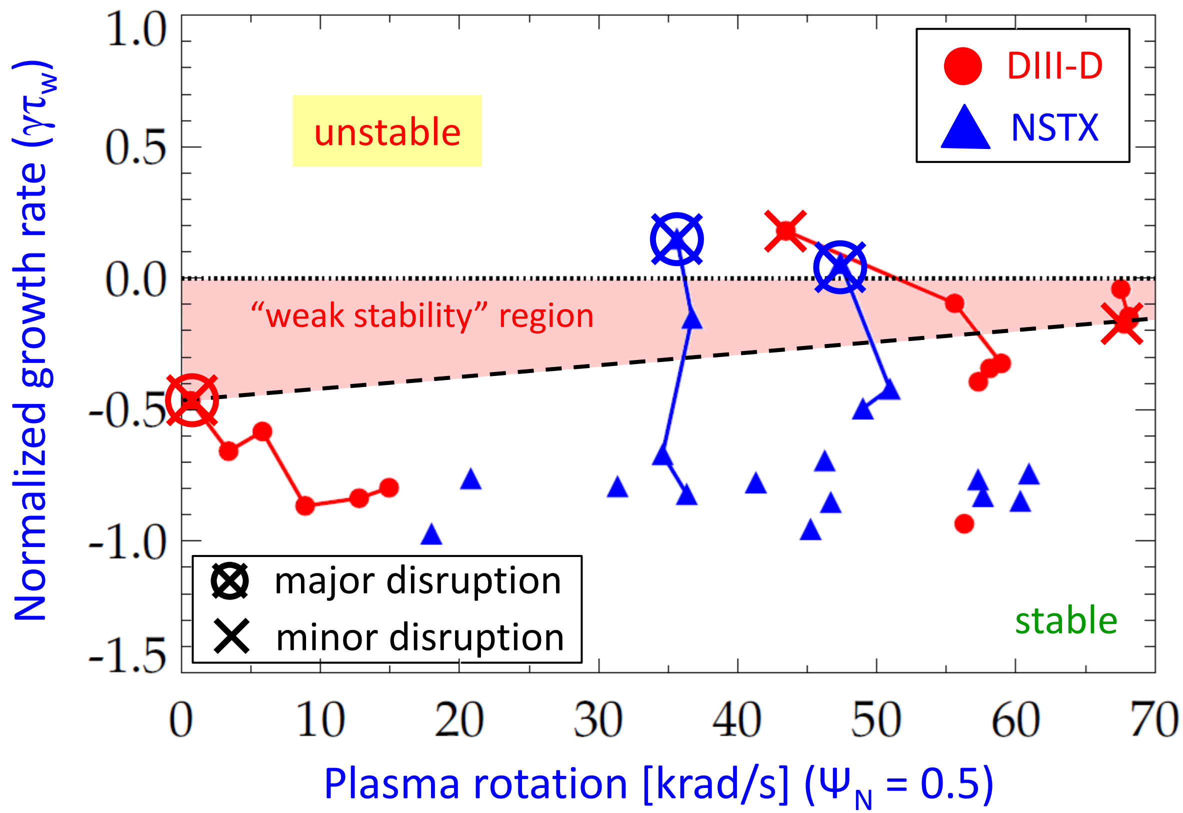
[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

- MISK calculations including kinetic effects have been tested against many marginally stable NSTX experimental cases

Kinetic RWM stability physics unites results from DIII-D and NSTX plasmas

- Addition of kinetic effects yields agreement with marginal point in NSTX
- Further testing against DIII-D experiments shows good agreement
- Strong bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

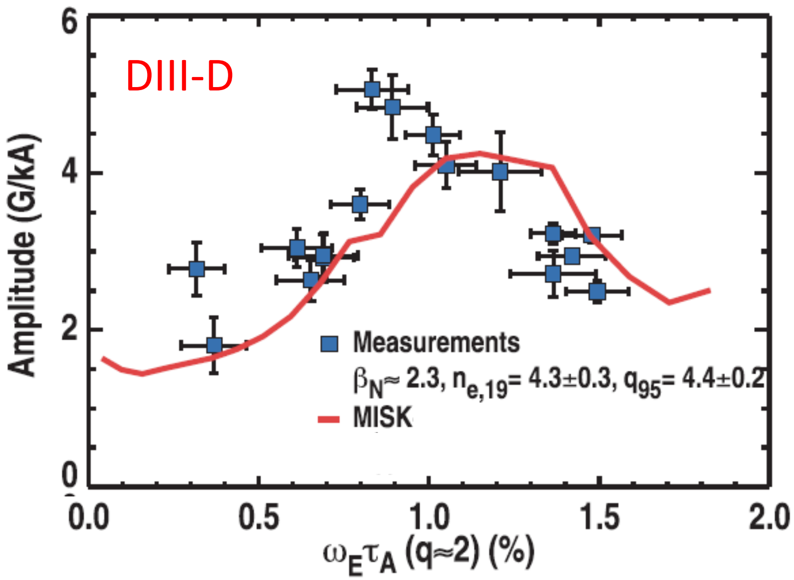
Kinetic RWM stability analysis for experiments (MISK)



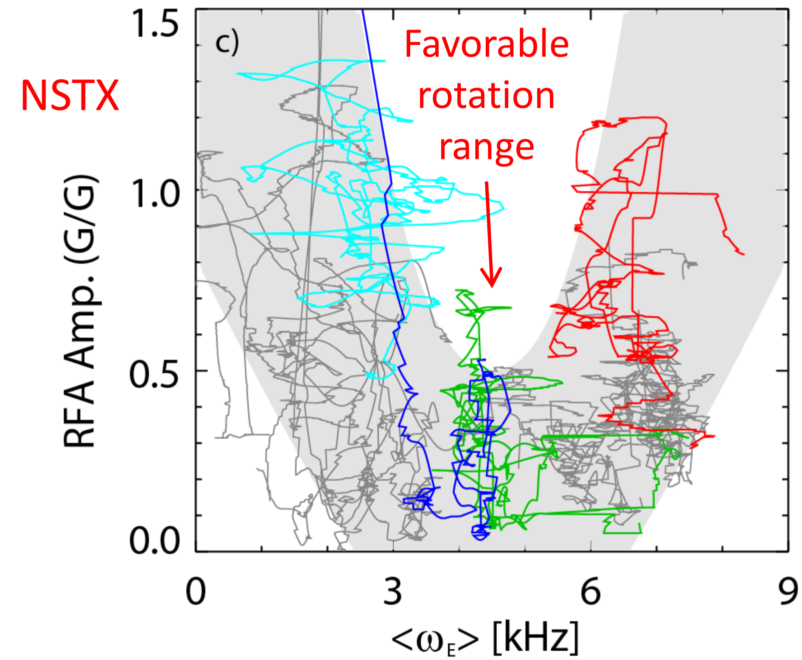
DIII-D NATIONAL FUSION FACILITY

[S. Sabbagh, J. Berkery, J. Hanson, et al., APS invited 2014]

Active MHD spectroscopy experiments show the importance of kinetic effects in stable plasmas as well



[H. Reimerdes et al., Phys. Rev. Lett. 106, 215002 (2011)]



[J. Berkery et al., Phys. Plasmas 21, 056112 (2014)]

- Resonant field amplification indicates weakening stability
  - Plasma response is enhanced where kinetic effects and RWM stability are weak

- Discharge trajectories for 20 NSTX plasmas shows favorable ω range
  - Matches theoretical expectation for precession drift resonance

MISK calculations match experiments

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Physics understanding from previous research used to construct a reduced kinetic model

- Goal is to forecast γ in real-time using parameterized reduced models for δW terms
- Need δW_K as a function of the most important, real-time measurable quantities

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

MISK[2] Calculations

Compared to experiments

Fluid terms

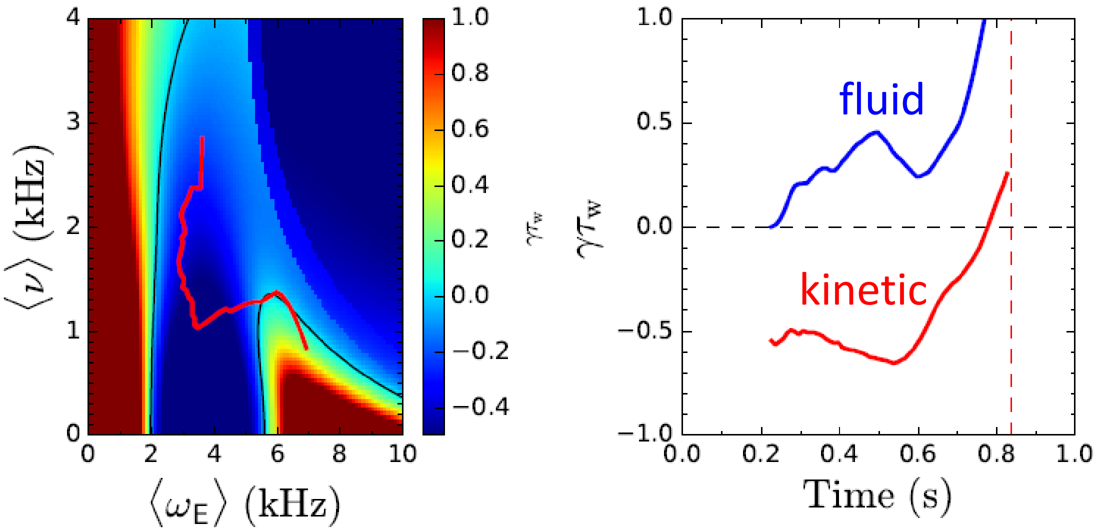
Kinetic effects:

Rotation

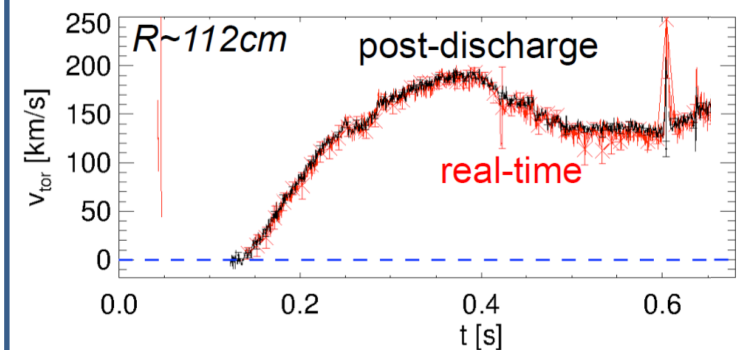
Collisionality

+ Energetic Particles

Reduced Kinetic Model



Real-time velocity data now available on NSTX-U



Rotation controller designed using NBI, NTV

Summary

- RWM stability must be understood for future devices
- Kinetic theory modifies ideal stability, includes rotation, collisionality, and energetic particle effects
- ITER stability projections show all kinetic effects important
- MISK code calculations can explain experimental stability
- Reduced models needed for real-time disruption avoidance

Fluid terms

Kinetic effects

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

~ Rotation Collisionality

$$\delta W_K \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu}$$

Rotation resonance

Collisionality

Energetic Particles