NSTX

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The Role of Kinetic Effects, Including Plasma Rotation and Energetic Particles, in Resistive Wall Mode Stability

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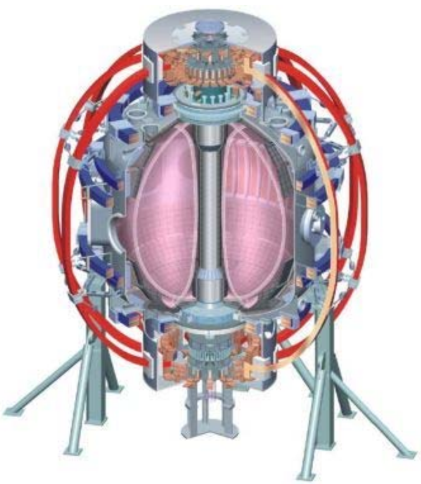

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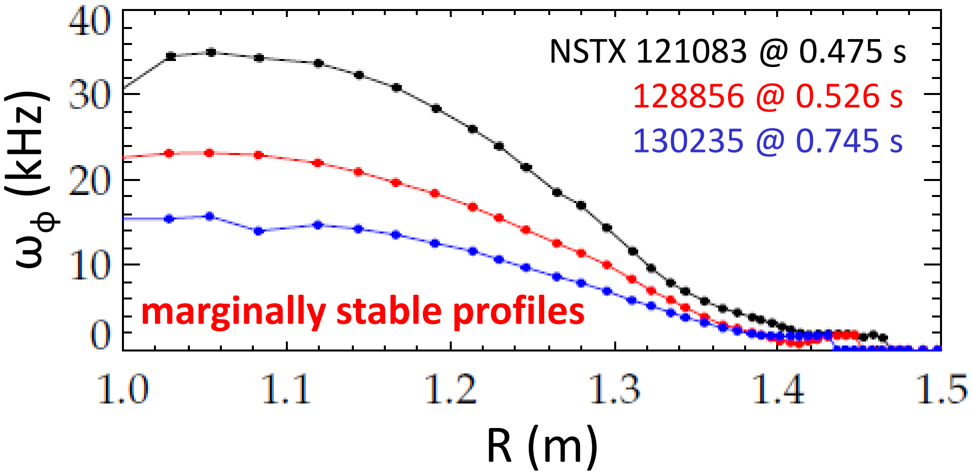
The resistive wall mode (RWM) is disruptive; it is important to understand the physics of its stabilization

- Motivation
  - The RWM limits plasma pressure and leads to disruptions.
  - Physics of RWM stabilization is key for extrapolation to:
    - sustained operation of a future NBI driven, rotating ST-CTF, and
    - disruption-free operation of a low rotation burning plasma (ITER).
- Outline
  - Kinetic RWM stabilization theory: window of ω_ϕ with weakened stability
  - Comparison of theory and NSTX experimental results
  - The role of energetic particles in kinetic theory

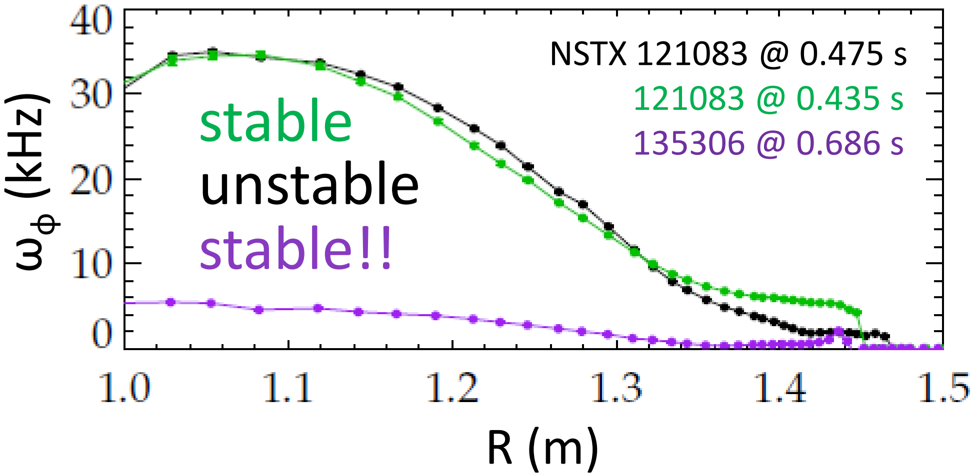
NSTX experimental RWM instability can not be explained by scalar critical rotation theory

In NSTX, the RWM can go unstable with a wide range of toroidal plasma rotation, ω_ϕ.

A.C. Sontag et. al., Nucl. Fus., 47 (2007) 1005



Stable discharges can have very low ω_ϕ.



A theoretical model broad enough in scope to explain these results is needed.

Kinetic δW_K term in the RWM dispersion relation provides dissipation that enables stabilization

1. Ideal theory alone shows instability above the no-wall limit:

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

2. Dissipation enables stabilization:

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

(Hu, Betti, and Manickam, PoP, 2005)

3. Calculation of δW_K with the **MISK** code includes:
   - Trapped Thermal Ions
   - Trapped Electrons
   - Circulating Thermal Ions
   - Alfven Layers (analytic)
   - Trapped Energetic Particles

Typically, trapped thermal ions account for 70-80% of Re(δW_K)

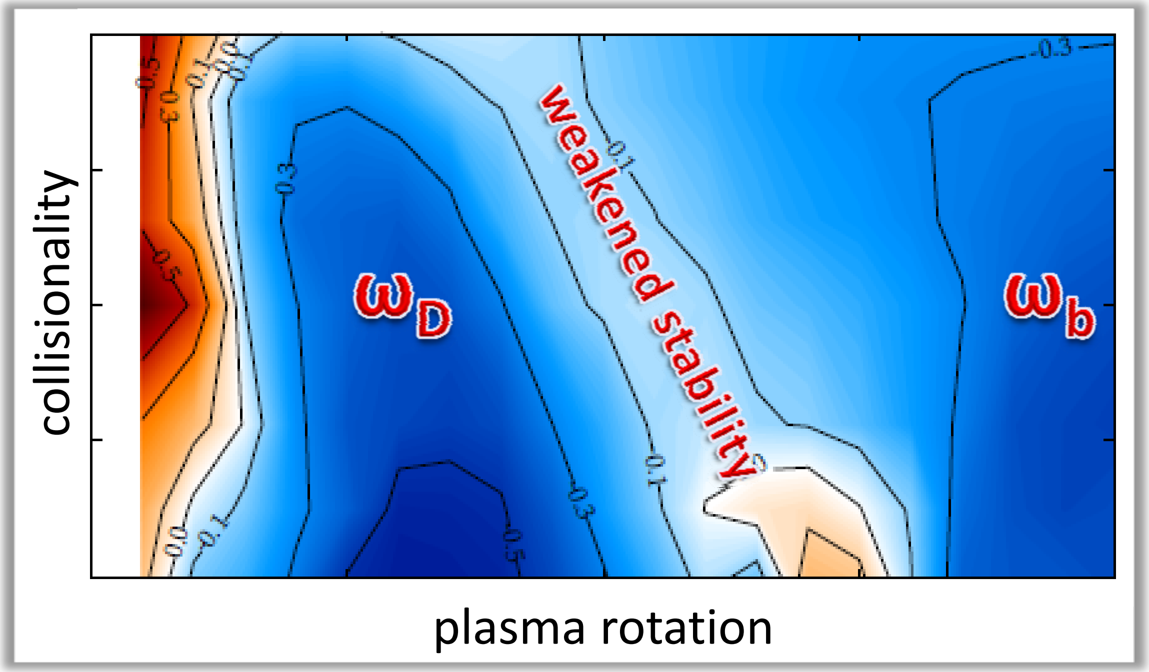
The dependence of stability on plasma rotation is complex

Trapped Ions:

$$\delta W_K \sim \left[\frac{(\omega_r + i\gamma)\frac{\partial f}{\partial \varepsilon} + \frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega_r - i\gamma} \right]$$

precession drift   bounce   collisionality   E×B

$$\omega_E = \omega_\phi - \omega_{*i}$$



Contours of $\gamma\tau_w$

blue stable

red unstable

white marginal

The relation between ω_E, ω_D, and ω_b determines stabilizing wave-particle resonances

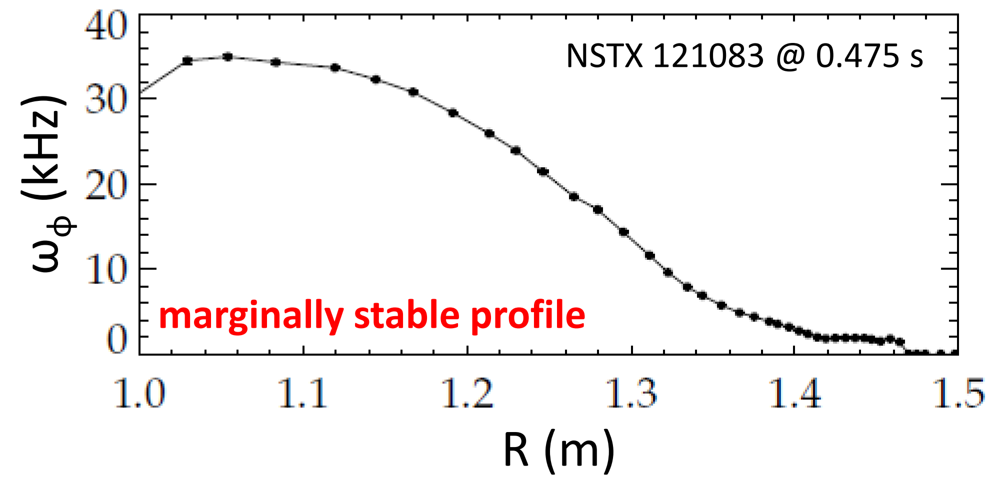
- What causes this rotation profile to be marginally stable to the RWM?
- Examine relation of ω_ϕ to other frequencies:
  - ℓ=0 harmonic: resonance with precession drift frequency:

$$\omega_E + \langle \omega_D \rangle = 0$$

  - ℓ=-1 harmonic: resonance with bounce frequency:

$$\omega_E + \langle \omega_D \rangle - \omega_b = 0$$

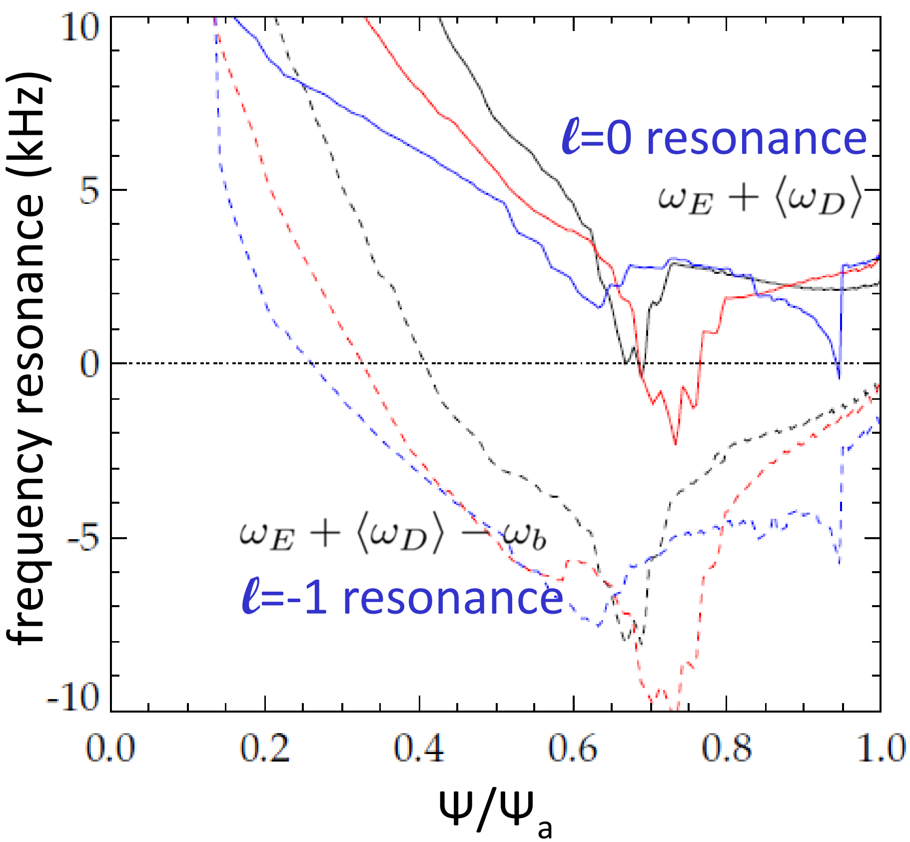
key resonances

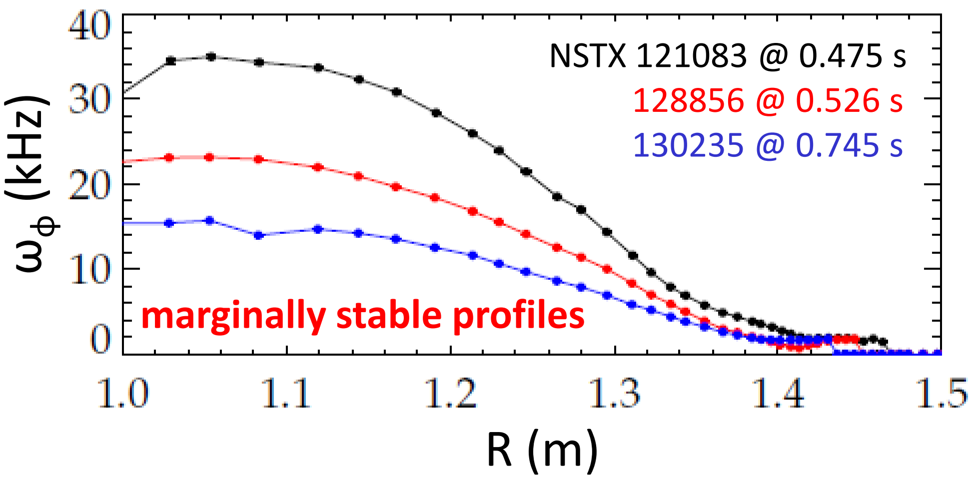


$$\delta W_K \sim \left[\frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\mathrm{eff}} + \omega_E} \right]$$

$$\omega_E = \omega_\phi - \omega_{*i}$$

A window of weakened stability can be found between the bounce and precession drift stabilizing resonances



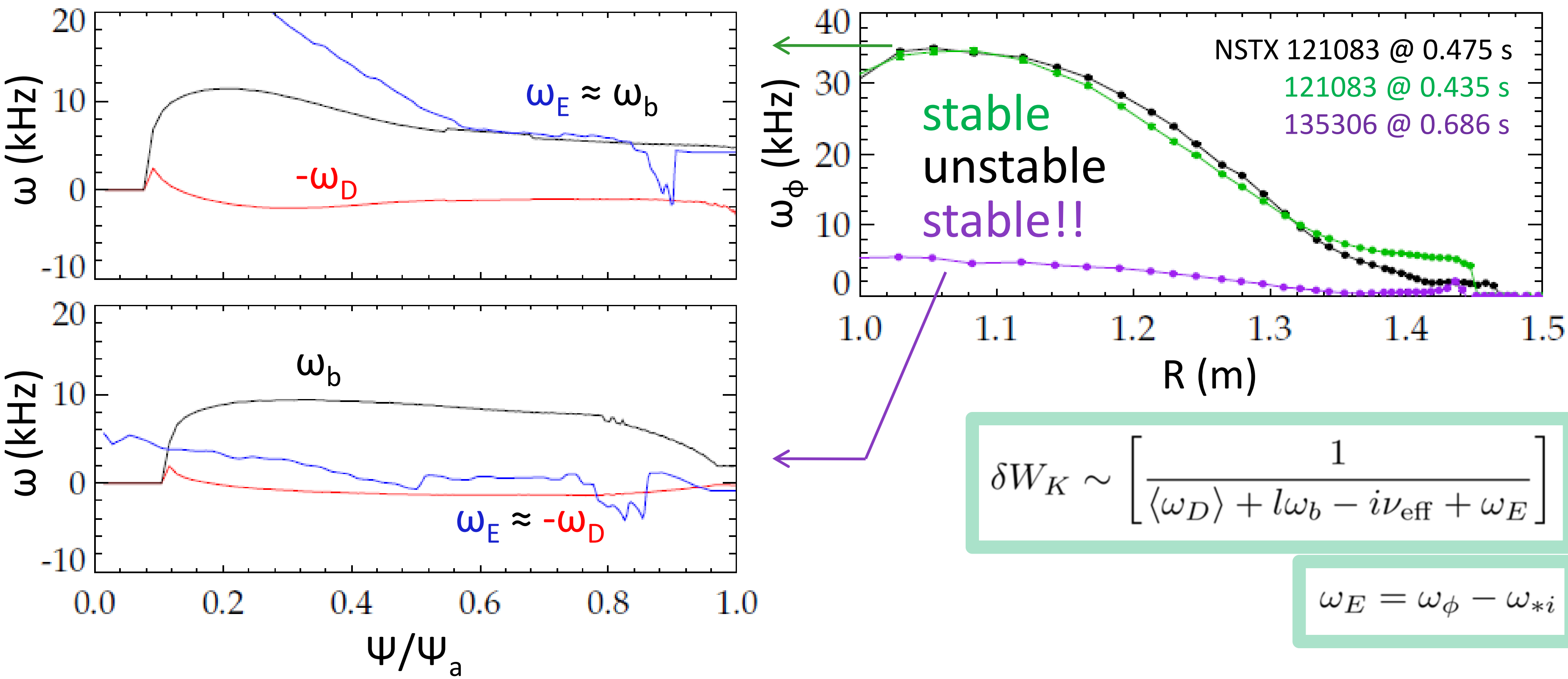


$$\delta W_K \sim \left[\frac{1}{\langle\omega_D\rangle + l\omega_b - i\nu_{\rm eff} + \omega_E}\right]$$

$$\omega_E = \omega_\phi - \omega_{*i}$$

- The experimentally marginally stable ω_ϕ profiles are each <u>off</u> the stabilizing resonances.

When the rotation is in resonance, the plasma is stable



$$\delta W_K \sim \left[\frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E} \right]$$

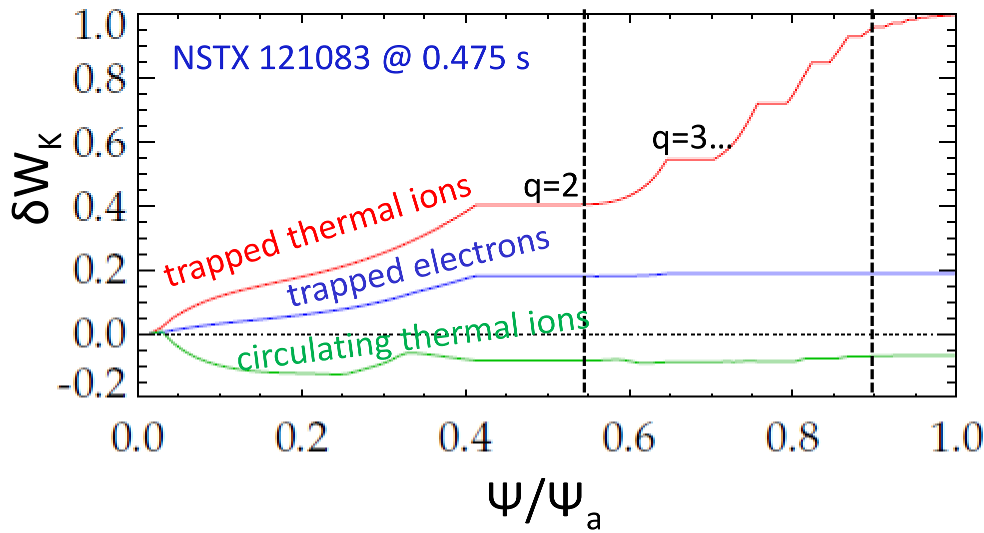
$$\omega_E = \omega_\phi - \omega_{*i}$$

- Stable cases in bounce resonance at high rotation
- Stable cases in precession drift resonance at low rotation

Full MISK calculation shows that trapped thermal ions are the most important contributors to stability

$$\delta W_K = \frac{\sqrt{\pi}}{2} \sum_{\pm\sigma} \int_0^{\Psi_a} \frac{d\Psi}{B_0}(nT) \sum_{l=-\infty}^{\infty} \int_{B_0/B_{max}}^{B_0/B_{min}} d\Lambda\hat{\tau}$$
$$\times \int_0^{\infty} \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{\mathrm{eff}} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{5/2} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$
$$\times \left| \left\langle \left(2 - 3\frac{\Lambda}{B_0/B}\right)(\kappa \cdot \xi_\perp) - \left(\frac{\Lambda}{B_0/B}\right)(\nabla \cdot \xi_\perp) \right\rangle \right|^2$$

Full δW_K eqn. for trapped thermal ions



- Examine δW_K from each particle type vs. Ψ
  - Thermal ions are the most important contributor to stability.
  - Flat areas are rational surface layers (integer q ± 0.2).
- Entire profile is important, but q > 2 contributes ~60%
  - RWM eigenfunction and temperature, density gradients are large in this region.

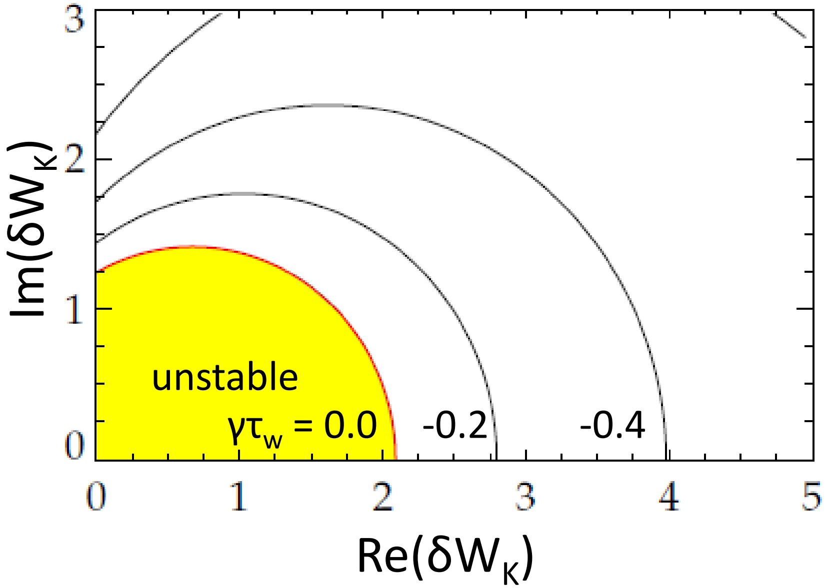
The dispersion relation can be rewritten in a form convenient for making stability diagrams

Contours of γ form circles on a stability diagram of $Im(\delta W_K)$ vs. $Re(\delta W_K)$.

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

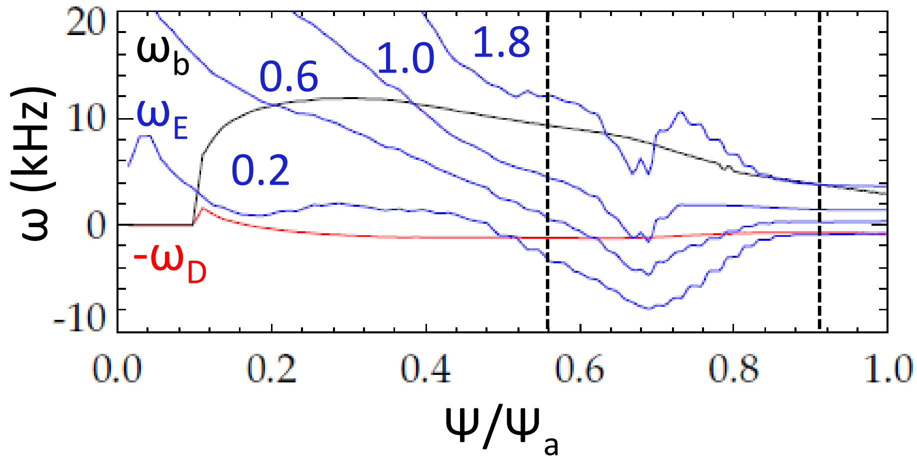
$$\Rightarrow$$

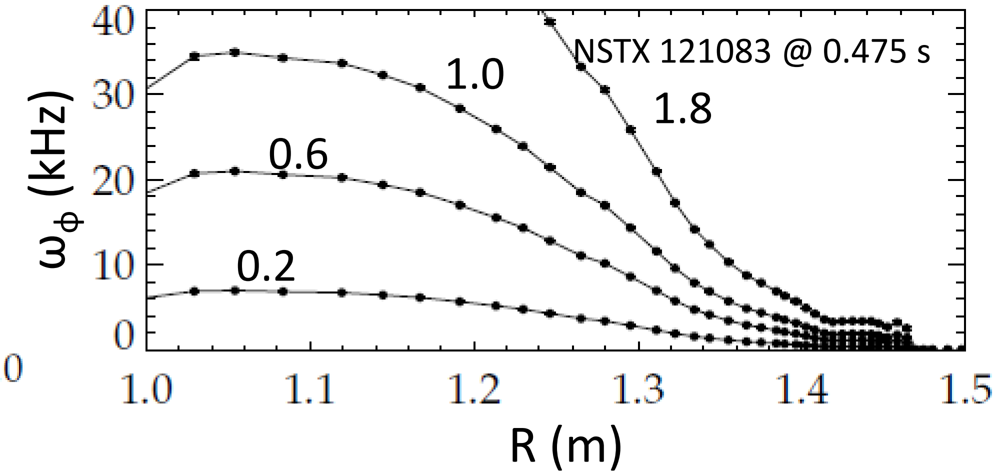
$$\left(Re\left(\delta W_K\right) - a\right)^2 + \left(Im\left(\delta W_K\right)\right)^2 = r^2$$

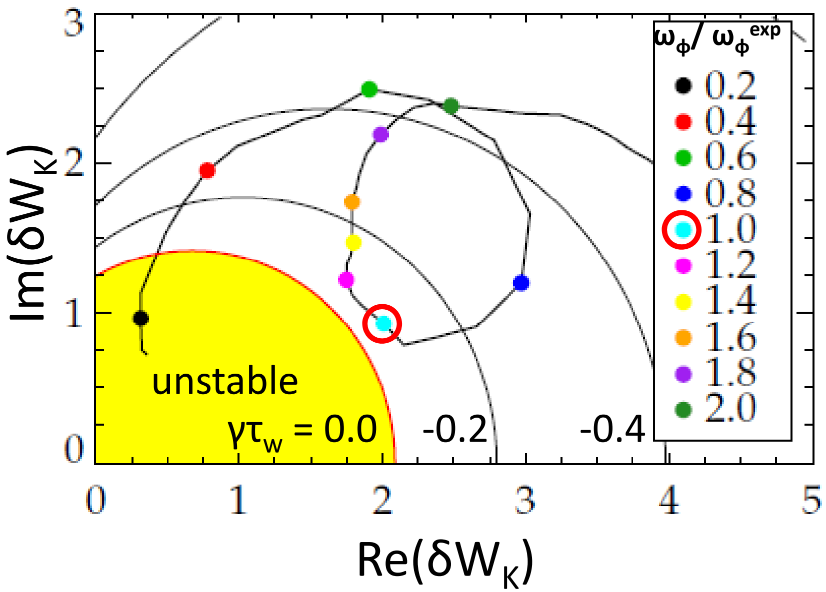


Let us now scale the experimental rotation profile to illuminate the complex relationship between rotation and stability

Scaling the experimental rotation profile illuminates the complex relationship between rotation and stability





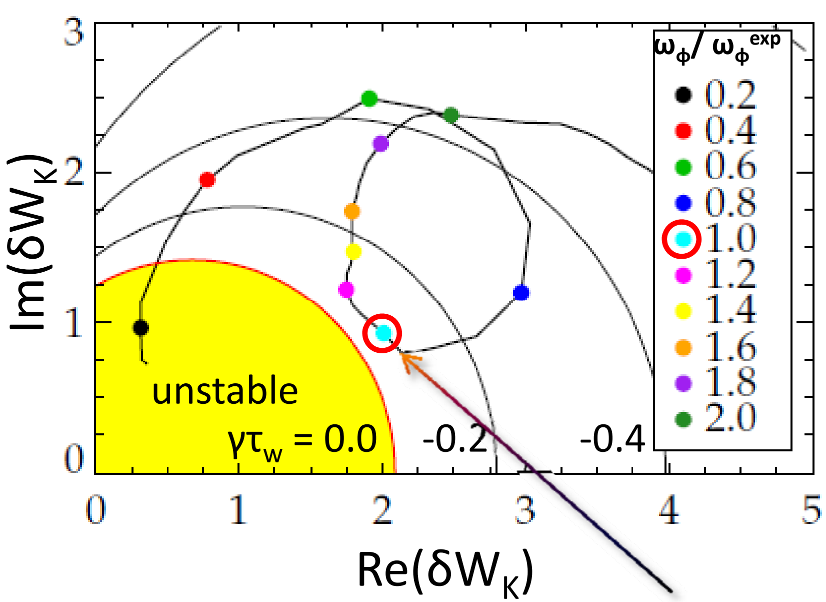


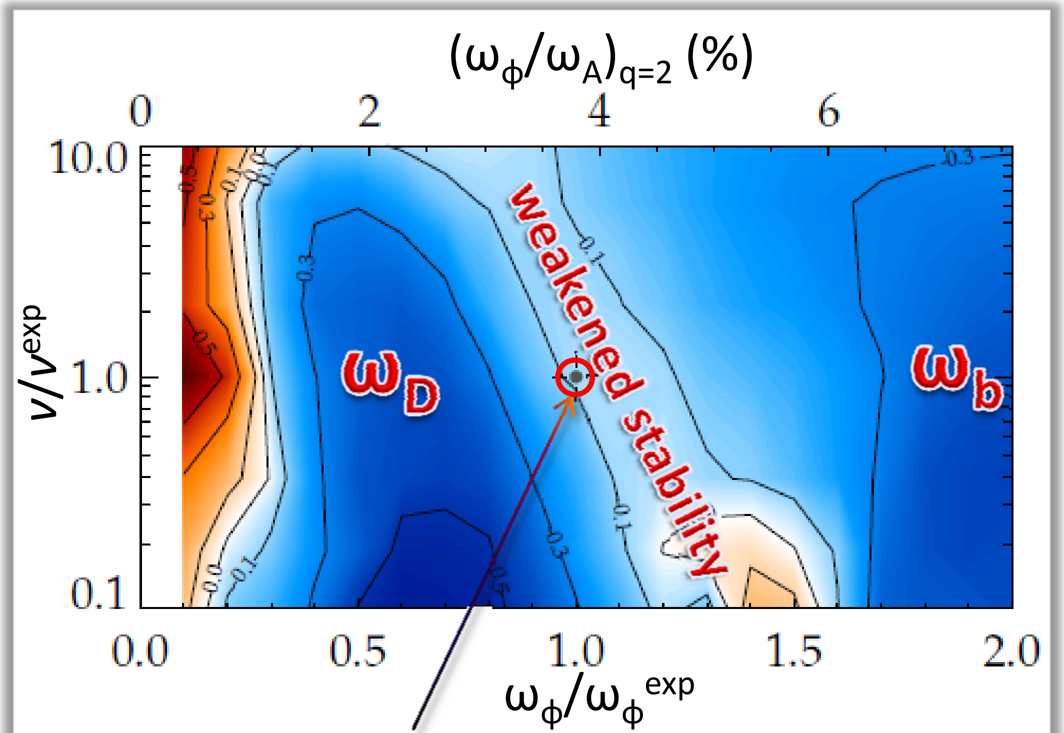
- Rotation profile scan:
  - 0.2: Instability at low rotation.
  - 0.6: Stable: ω_D resonance.
  - 1.0: Marginal: in-between resonances (actual experimental instability).
  - 1.8: Stable: ω_b resonance.

The weakened stability rotation gap is altered by changing collisionality

- Scan of ω_ϕ and collisionality
  - scale *n* & *T* at constant β
  - Changing *ν* shifts the rotation of weakened stability.

$$\delta W_K \sim \left[\frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\mathrm{eff}} + \omega_E} \right]$$

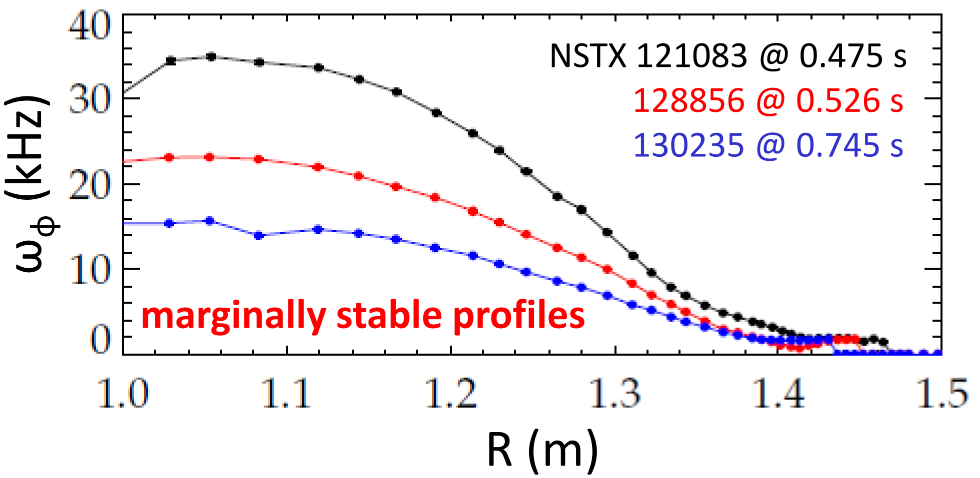


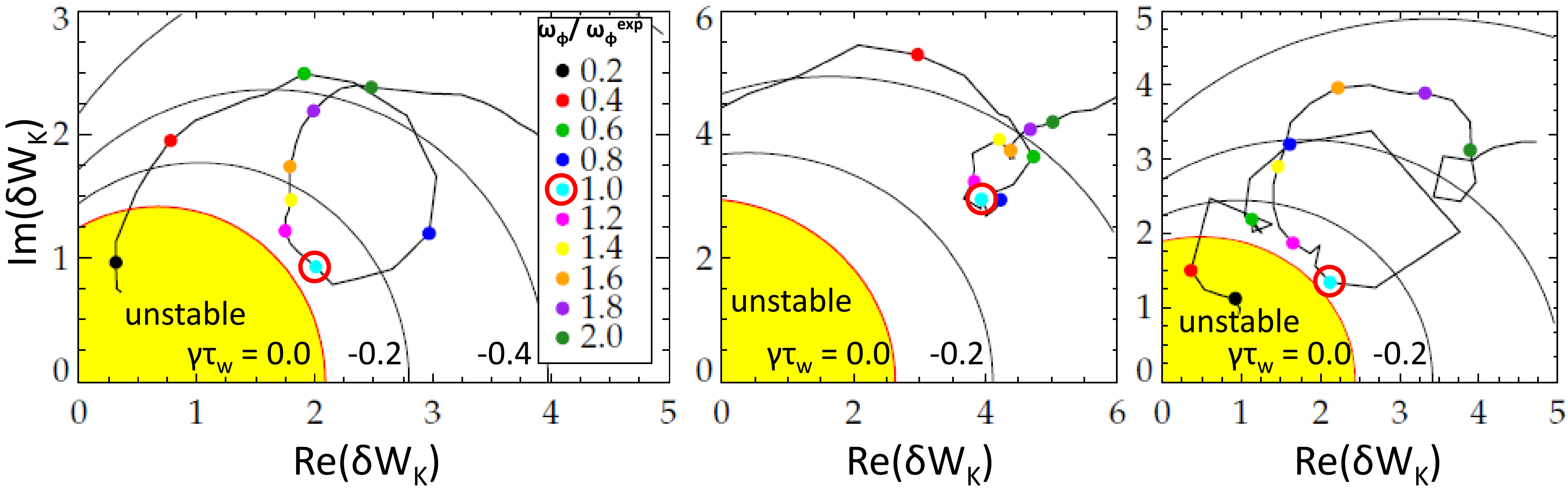


NSTX experimental instability

Widely different experimentally marginally stable rotation profiles each are in the gap between stabilizing resonances

- Sometimes the stability reduction is not enough to quantitatively reach marginal
- Investigating sensitivities to inputs.





121083 @ 0.475 s

128856 @ 0.526 s

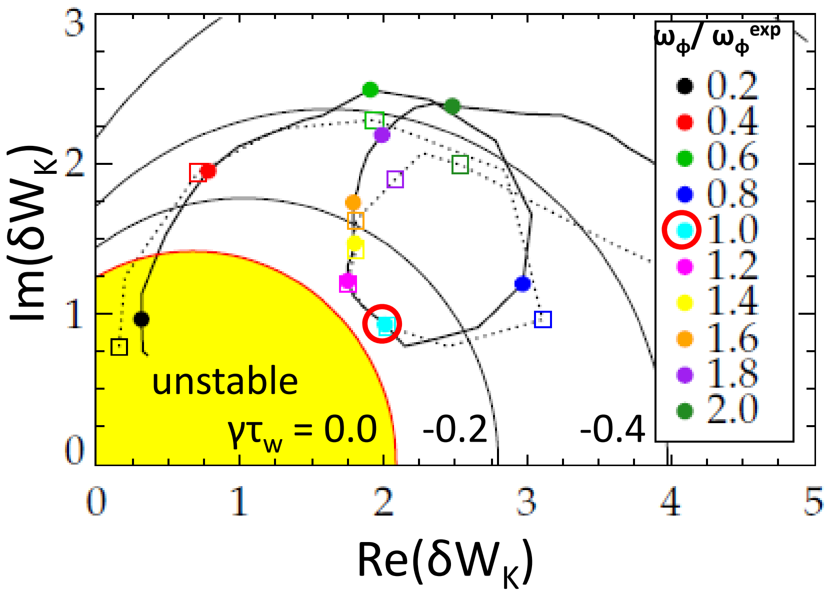
130235 @ 0.745 s

Non-linear inclusion of γ and ω_r in dispersion relation makes very little difference to MISK results

γ and ω_r appear non-linearly on both sides of the dispersion relation.

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

$$\delta W_K \sim \left[\frac{(\omega_r + i\gamma)\frac{\partial f}{\partial \varepsilon} + \frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega_r - i\gamma} \right]$$



- **MARS-K** is self-consistent, **MISK** can use iteration to include the non-linear effect.
- Iteration with τ_w = 1ms (dashed line) makes very little difference to the result, especially when γ is small.

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

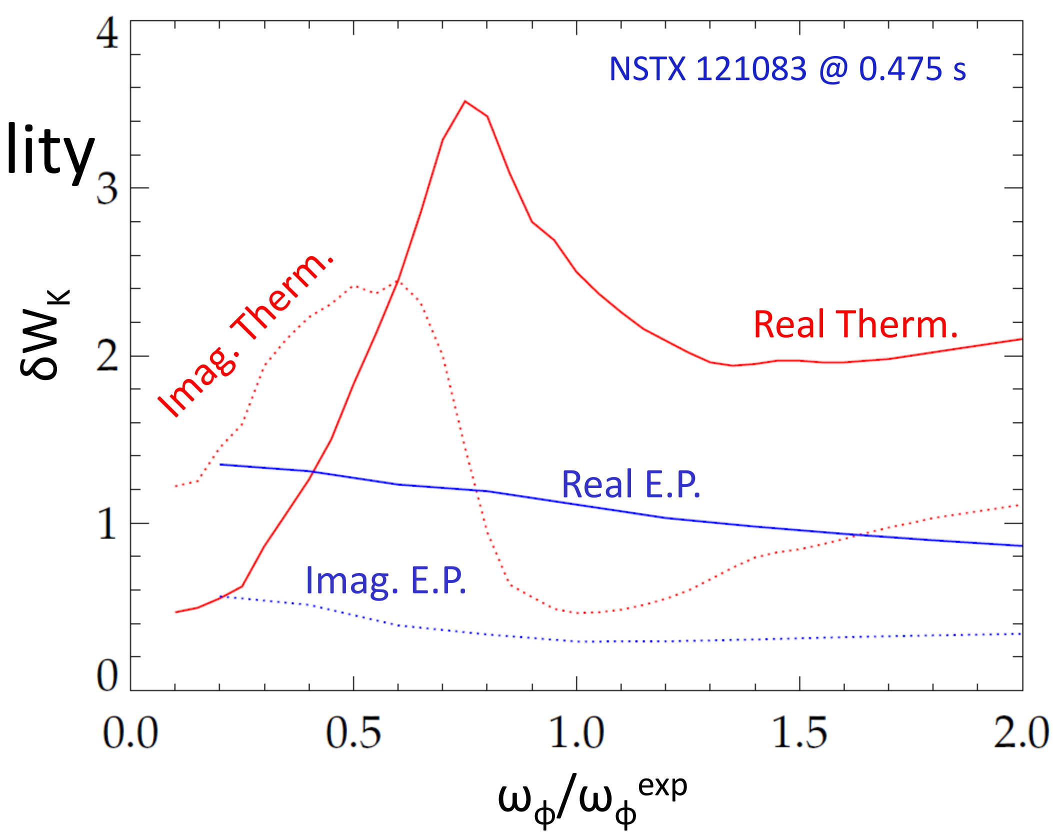
E.P.s: Slowing-down

$$f(\varepsilon, \Psi) = \frac{C(\Psi)}{\varepsilon^{\frac{3}{2}} + \varepsilon_c^{\frac{3}{2}}}$$

$$\delta W_K \sim \left[\frac{(\omega_r + i\gamma)\frac{\partial f}{\partial \varepsilon} + \frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega_r - i\gamma} \right]$$

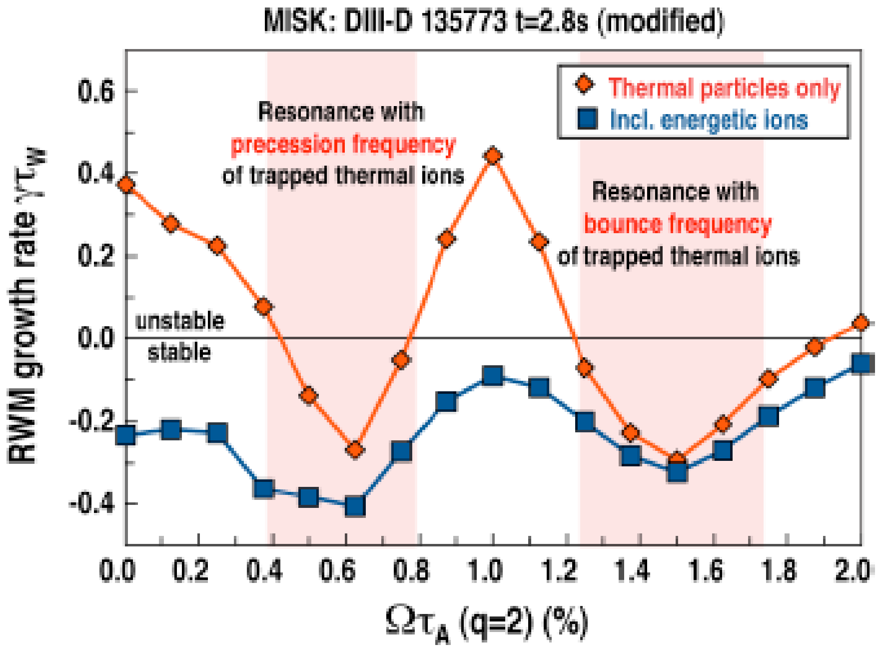
small

- Energetic particles add to δW_K, lead to greater stability
  - Significant Re(δW_K), but nearly independent of ω_ϕ
  - Energetic particles are <u>not</u> in mode resonance
  - Effect is not energy dissipation, but rather a restoring force



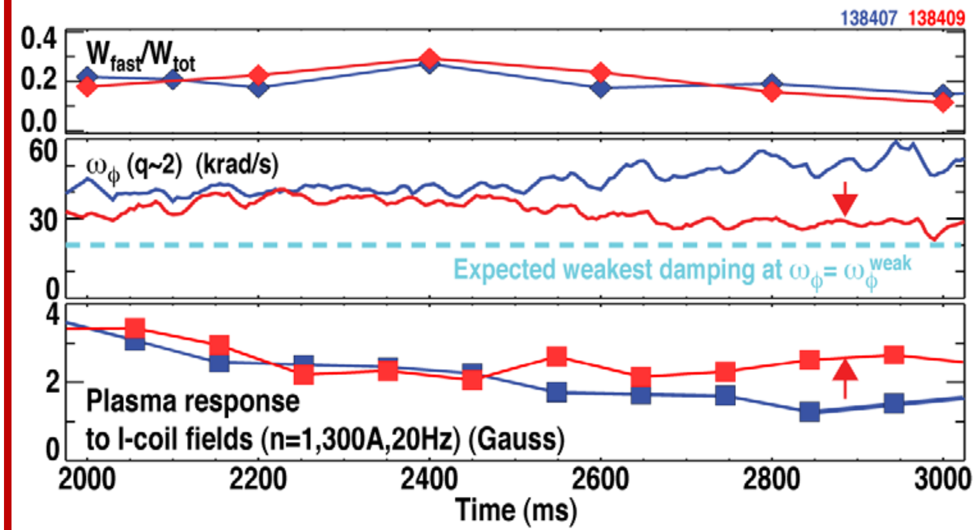
DIII-D experiment motivated by MISK results explored the effect of energetic particles on RWM stability

MISK Analysis



- Predicted instability inconsistent with experiment
- Adding energetic particles makes RWM stable - consistent
- Weakened ω_ϕ profile remains

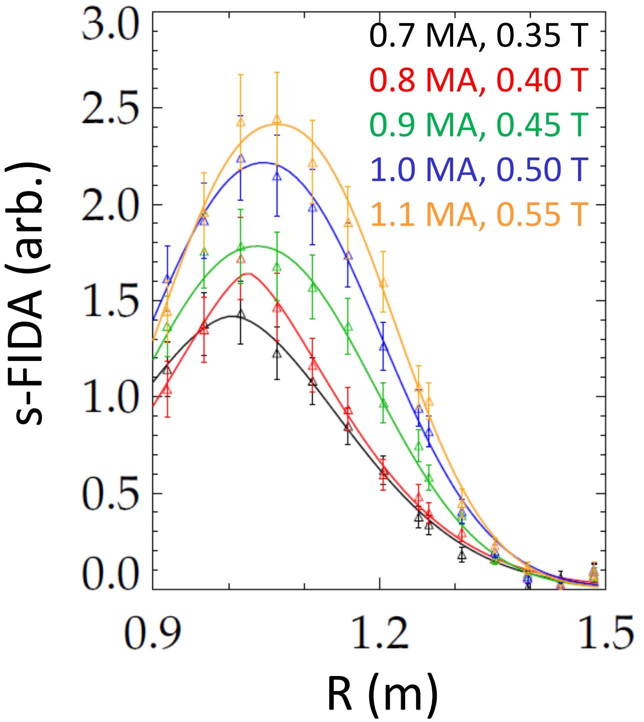
DIII-D Experiment (with Reimerdes)

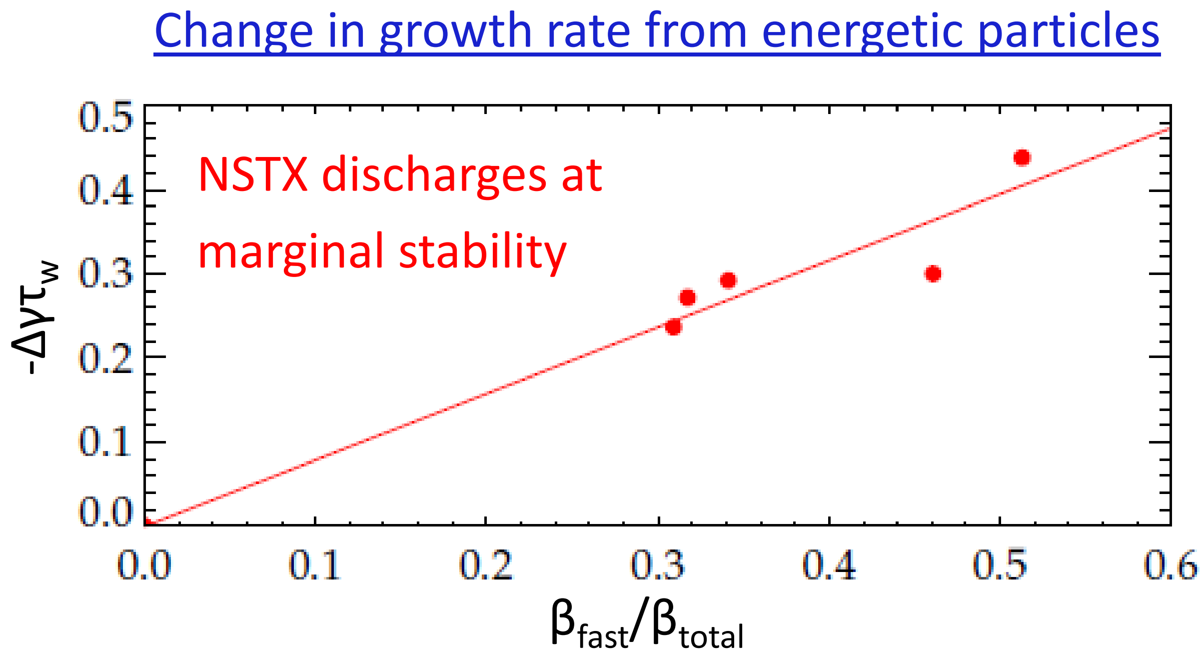


- Higher n_e and I_p reduced W_f/W_t by 40% over previous exp.
- RWM remains stable, but response higher as $\omega_\phi \rightarrow \omega_\phi^{weak}$

DIII-D NATIONAL FUSION FACILITY

NSTX experiment in 2009 found that energetic particles contribute linearly to RWM stability

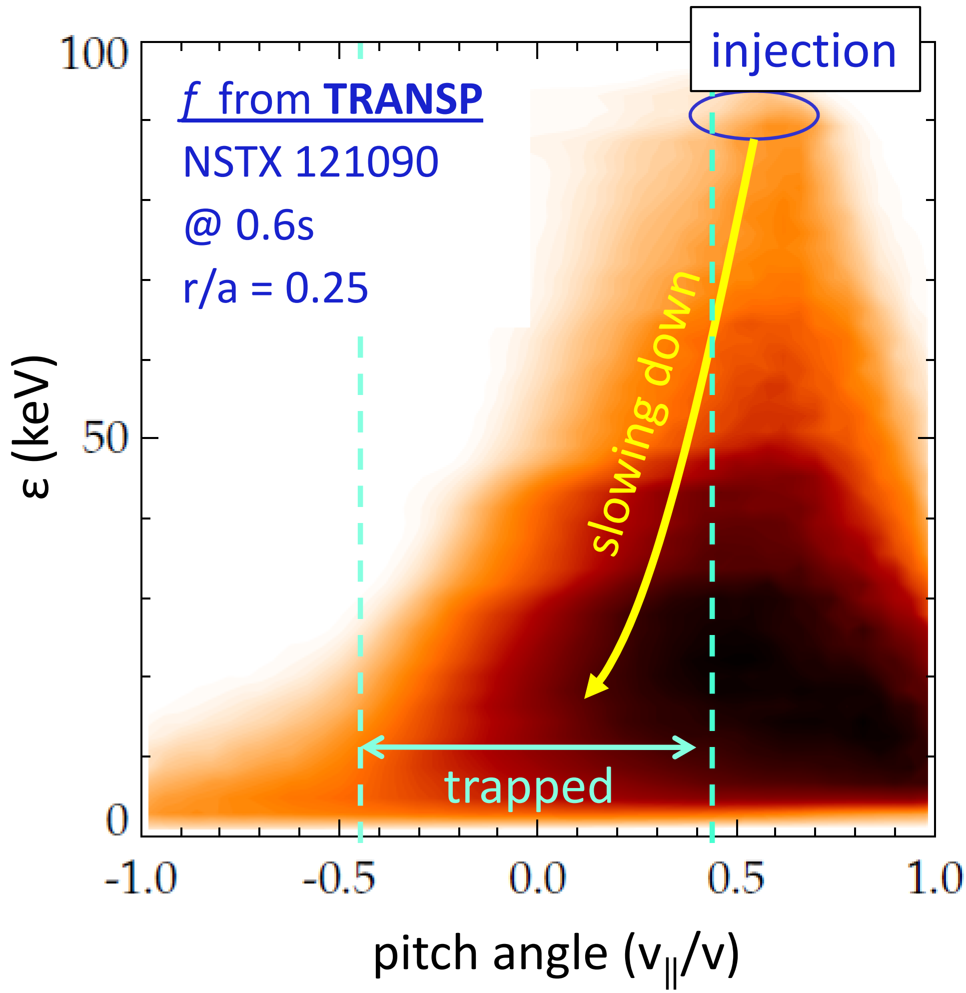




- Despite the additional theoretical stability, these shots experimentally went unstable
  - Investigating whether stabilization from thermal particles is overpredicted by **MISK**.
  - The overprediction of -Δγ from E.P.s is under investigation…

A new, more accurate energetic particle distribution function is being implemented

- Presently *f* is considered independent of pitch angle
  - Not a good approximation for beam ions
  - Overpredicts stabilizing trapped fraction
- Towards better quantitative agreement:
  - Use *f* from **TRANSP** directly

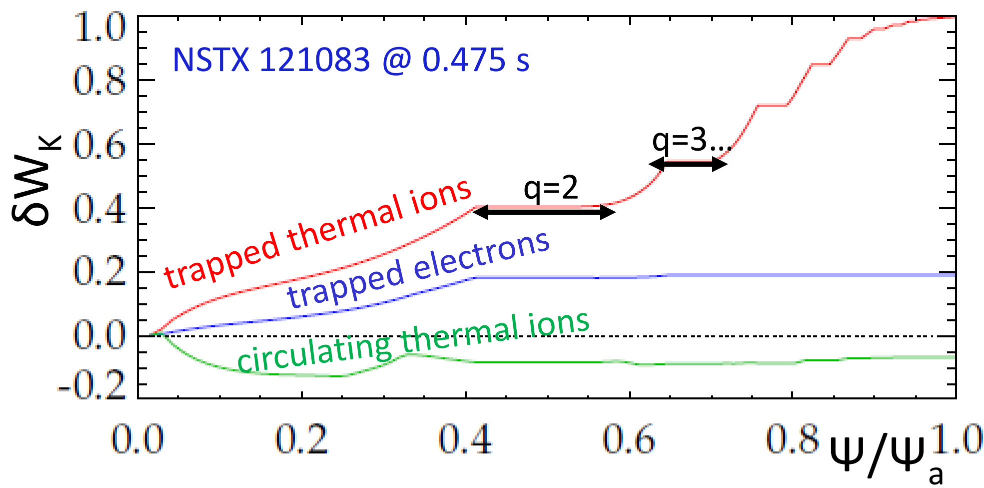


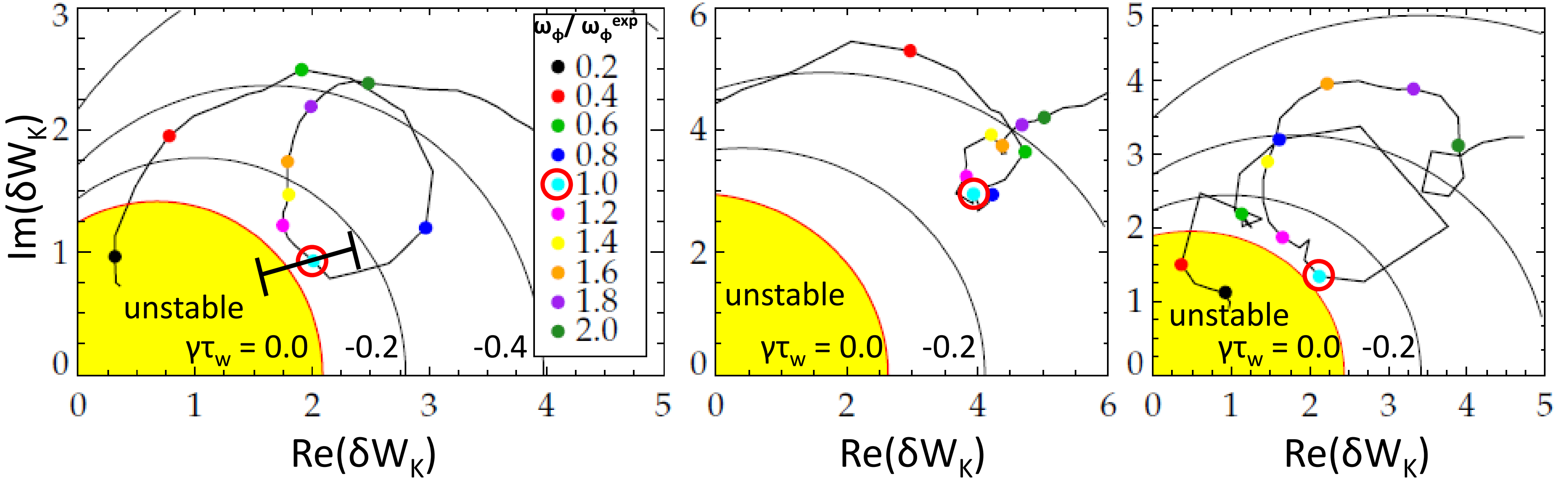
Kinetic RWM stability theory can explain complex relationship of marginal stability with ω_ϕ

- High plasma rotation alone is inadequate to ensure RWM stability in future devices
  - A weakened stability gap in ω_ϕ exists between ω_b and ω_D resonances.
  - Use ω_ϕ control to stay away from, and active control to navigate through gap.
- Favorable comparison between NSTX experimental results and theory
  - Multiple NSTX discharges with widely different marginally stable ω_ϕ profiles fall in this gap.
- Energetic particles provide an important stabilizing effect
  - Works towards quantitative agreement with experiment is ongoing.

Widely different experimentally marginally stable rotation profiles each are in the gap between stabilizing resonances

- Sometimes the stability reduction is not enough to quantitatively reach marginal
- Investigating sensitivities to inputs. ex: Δq = 0.15 – 0.25





121083 @ 0.475 s 128856 @ 0.526 s 130235 @ 0.745 s

Present inclusion of energetic particles in MISK: isotropic slowing down distribution (ex. alphas in ITER)

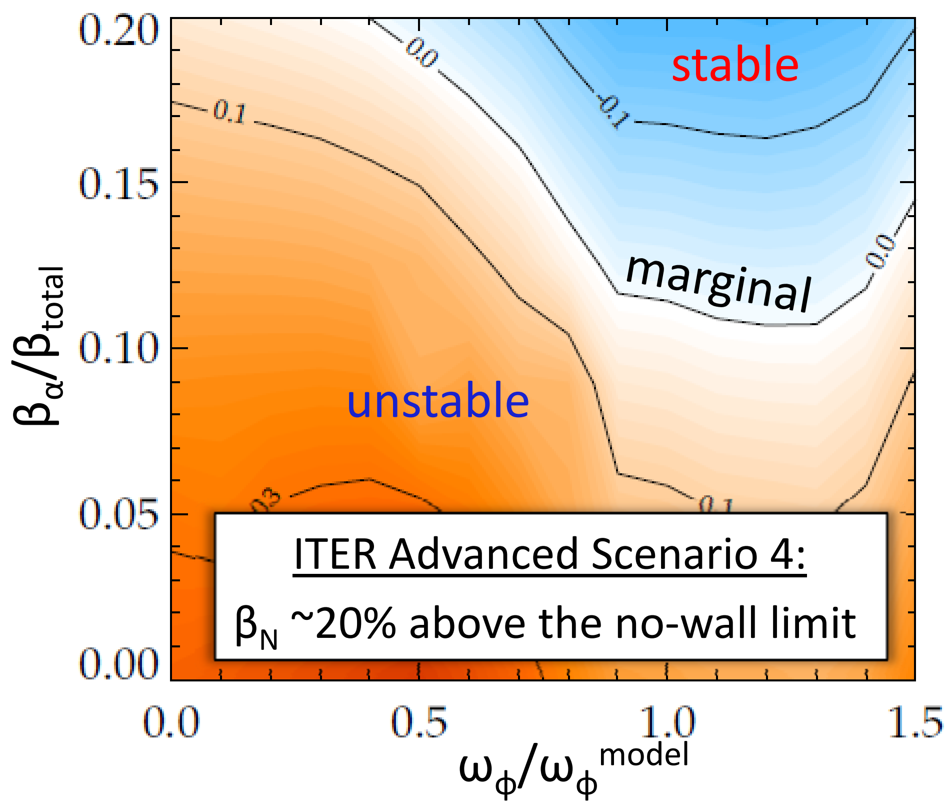
Thermal Particles: Maxwellian

$$\delta W_K \sim \left[\frac{(\omega_r + i\gamma)\frac{\partial f}{\partial \varepsilon} + \frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega_r - i\gamma} \right]$$

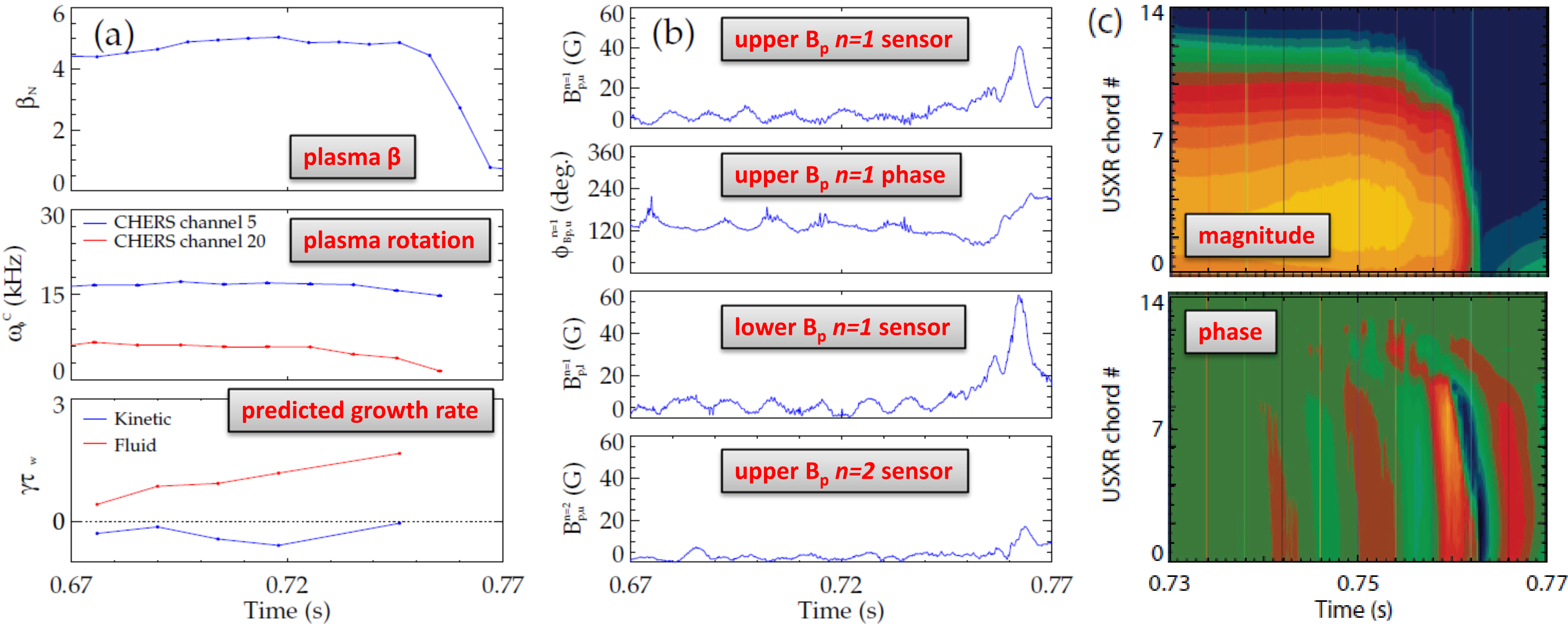
E.P.s: Slowing-down

$$f(\varepsilon, \Psi) = \frac{C(\Psi)}{\varepsilon^{\frac{3}{2}} + \varepsilon_c^{\frac{3}{2}}}$$

- Energetic particles add to δW_K, lead to greater stability
- Example: α particles in ITER
  - Higher β_α leads to greater stability
  - Isotropic f is a good approx.



The RWM is identified in NSTX by a variety of observations



NSTX 130235 @ 0.746 s

- Change in plasma rotation frequency, ω_ϕ
- Growing signal on low frequency poloidal magnetic sensors
- Global collapse in USXR signals, with no clear phase inversion
- Causes a collapse in β and disruption of the plasma