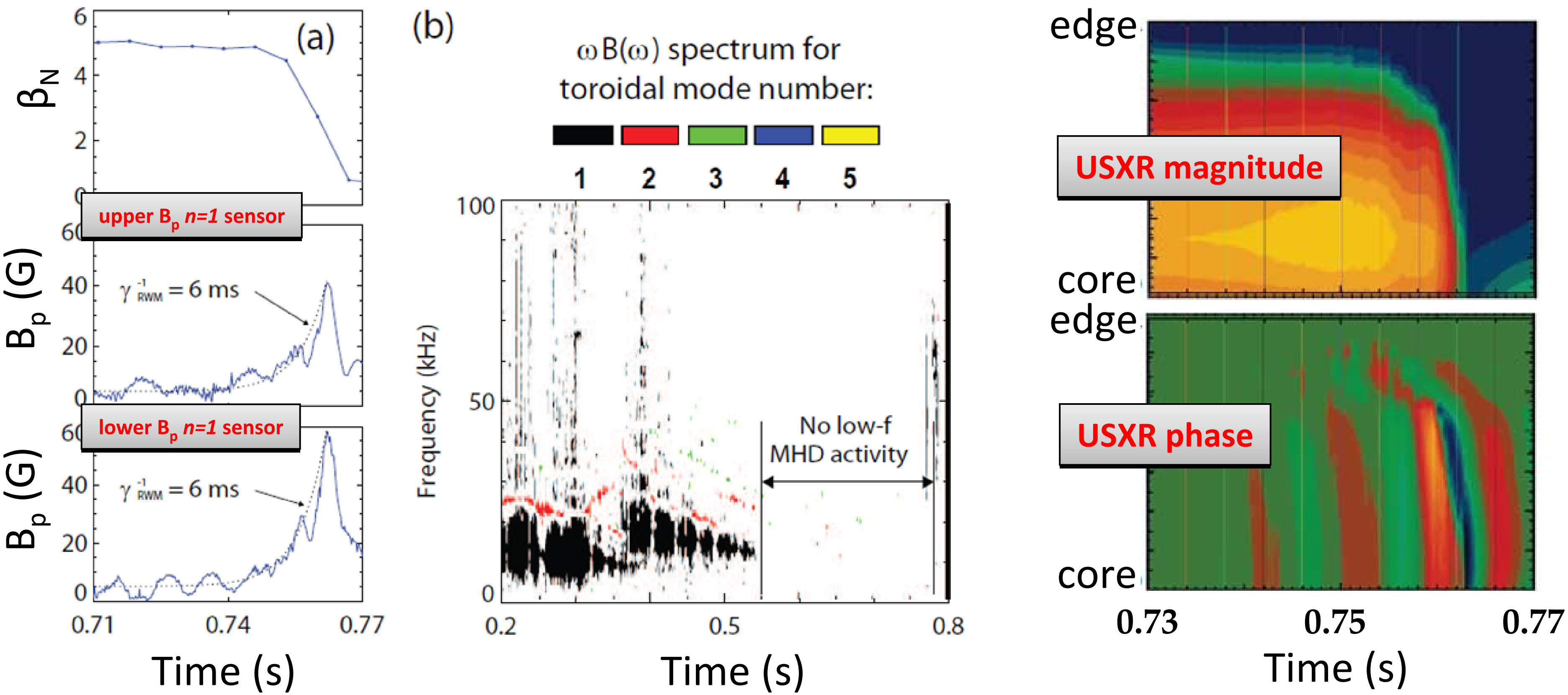
# The resistive wall mode (RWM) is disruptive; it is important to understand the physics of its stabilization

- 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

For more, see [Sabbagh, P4.160]

  - RWMs are observed and diagnosed routinely in NSTX.
  - Kinetic RWM stabilization theory predicts rotational resonances of thermal particles and stabilizing effect of energetic particles.
  - Comparison of theory and NSTX experimental results shows window of intermediate $\omega_\phi$ with weakened stability.
  - Dedicated NSTX experiment examined the role of energetic particles.

# The RWM is identified in NSTX by a variety of observations




– 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

# Kinetic $\delta W_K$ term in the RWM dispersion relation provides dissipation that enables stabilization

A momentum balance: $\rho \frac{d\mathbf{v}}{dt} = \mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbb{P}$ leads to an energy balance:

$$-\frac{1}{2}\int \rho\omega^2 |\xi_\perp|^2 dV = \frac{1}{2}\int \xi_\perp^* \cdot \left[\tilde{\mathbf{j}} \times \mathbf{B}_0 + \mathbf{j}_0 \times \tilde{\mathbf{B}} - \nabla \tilde{p}_F - \nabla \cdot \tilde{\mathbb{P}}_K\right] dV$$

The change in potential energy due to the kinetic pressure is:

$$\delta W_K = -\frac{1}{2}\int \xi_\perp^* \cdot (\nabla \cdot \mathbf{P}_K)\, dV$$

Dissipation from kinetic term enables stabilization of the RWM:

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

[B. Hu *et al.*, Phys. Plasmas **12**, 057301 (2005)]

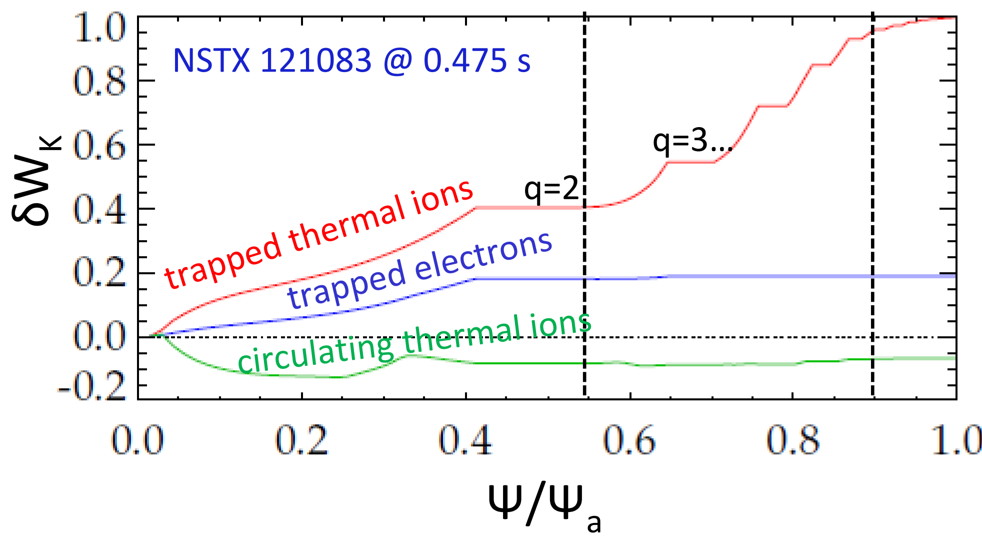
Calculation of $\delta W_K$ with the **MISK** code includes:

- Trapped Thermal Ions and Electrons
- Circulating Thermal Ions
- Alfven Layers (analytic)
- Trapped Energetic Particles

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

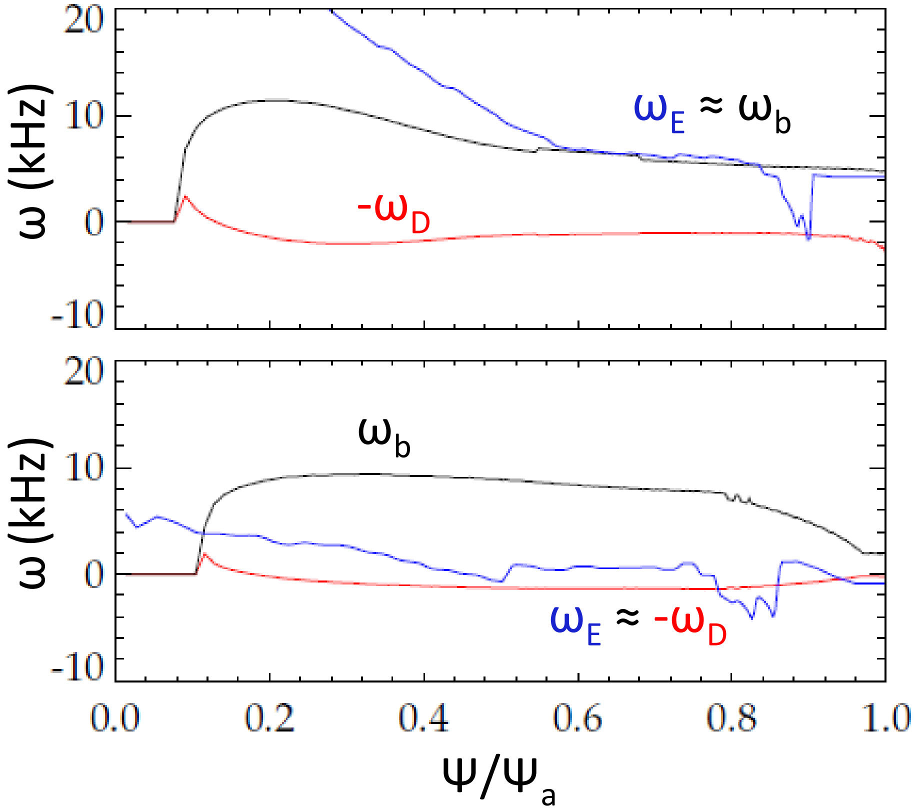
$$\delta W_K = \sum_j \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2 \int_0^{\Psi_a} \frac{d\Psi}{m_j^{\frac{3}{2}} B} \int_{-1}^{1} |\chi| d\chi$$
$$\int_0^{\infty} \left[ \frac{(\omega - n\omega_E)\frac{\partial f_j}{\partial \varepsilon} - \frac{n}{Z_j e}\frac{\partial f_j}{\partial \Psi}}{n\langle\omega_D^j\rangle + l\omega_b^j - i\nu_{\mathrm{eff}}^j + n\omega_E - \omega} \right] \varepsilon^{\frac{5}{2}} d\varepsilon$$
$$\left| \left\langle (3\chi^2 - 1)\, \kappa \cdot \xi_\perp - (\chi^2 - 1)\, \nabla \cdot \xi_\perp \right\rangle \right|^2$$

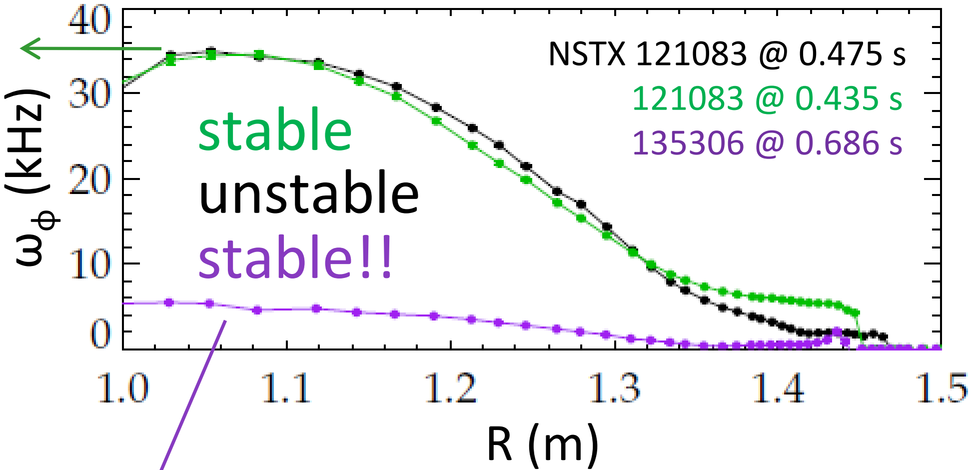
Full $\delta W_K$ eqn. for general $f$




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

# When the rotation is in resonance, the plasma is stable



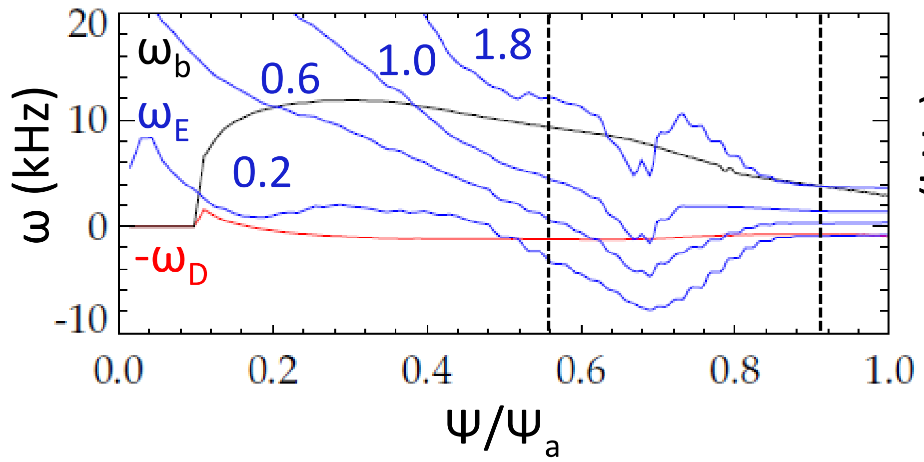



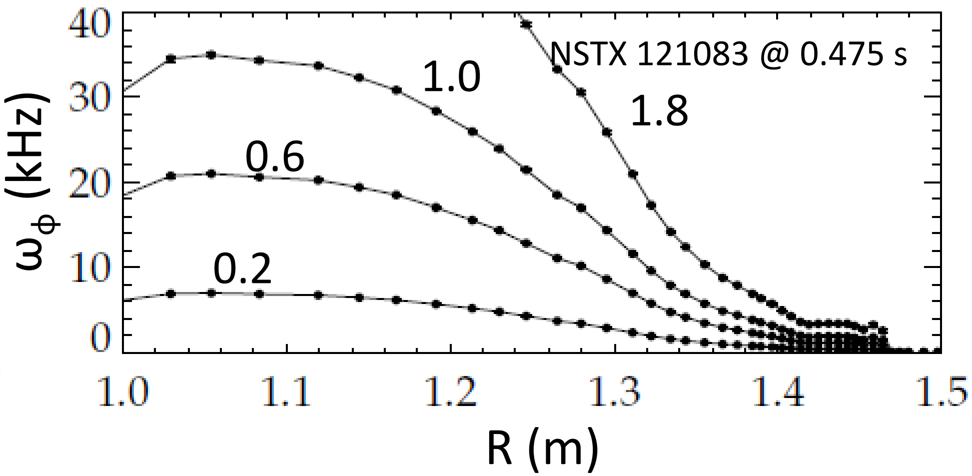

$$\delta W_K \sim \left[ \frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E} \right]$$

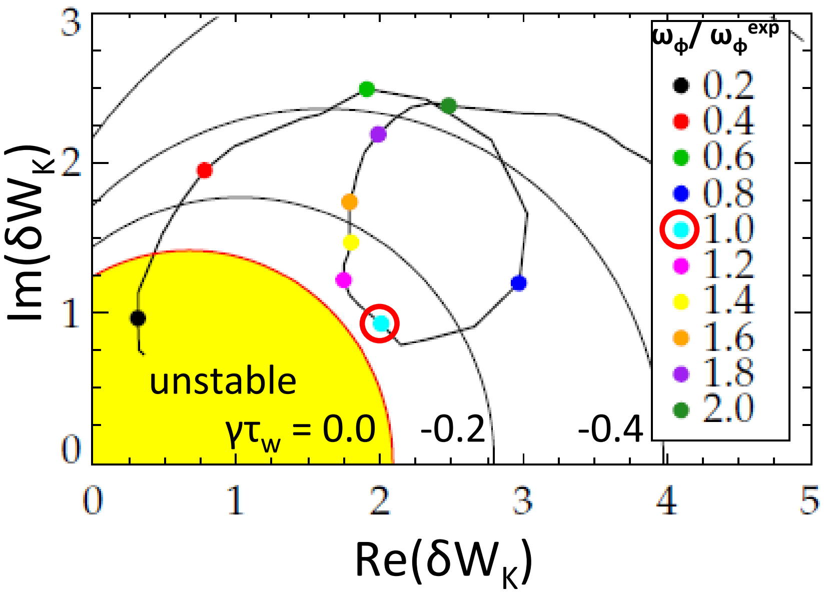
$$\omega_E = \omega_\phi - \omega_{*i}$$

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

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




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

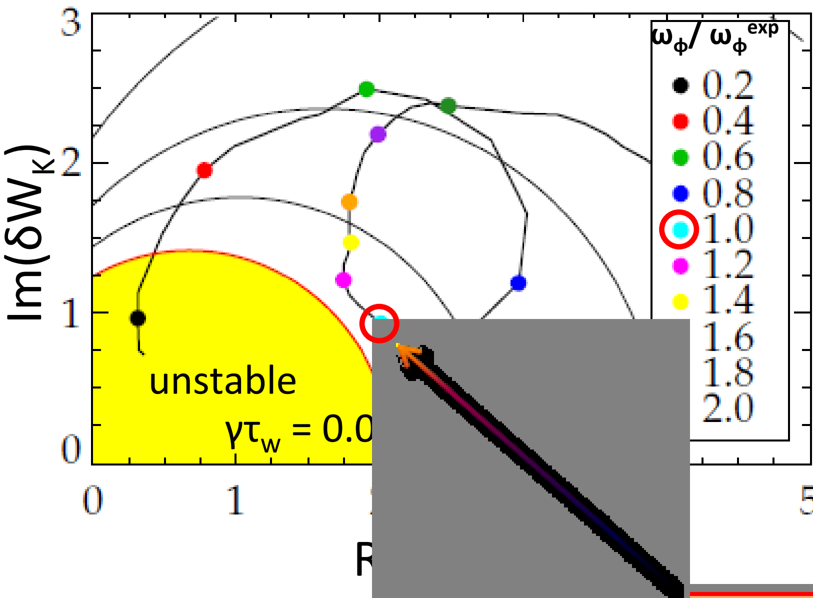
- Rotation profile scan:
  - 0.2: Instability at low rotation.
  - 0.6: Stable: $\omega_D$ resonance.
  - 1.0: Marginal: in-between resonances (actual experimental instability).
  - 1.8: Stable: $\omega_b$ resonance.

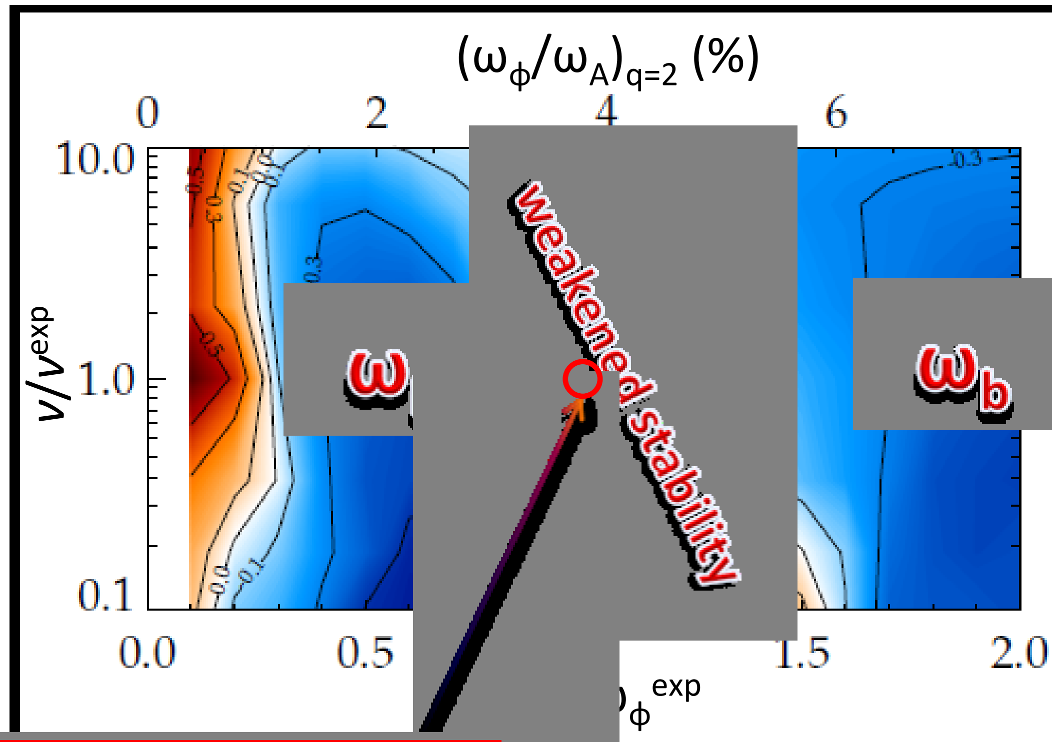
# The weakened stability rotation gap is altered by changing collisionality

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

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

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

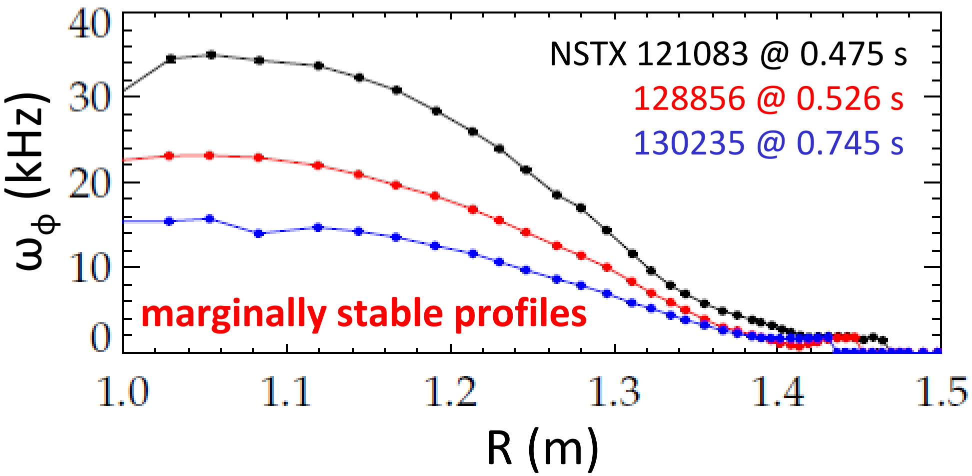


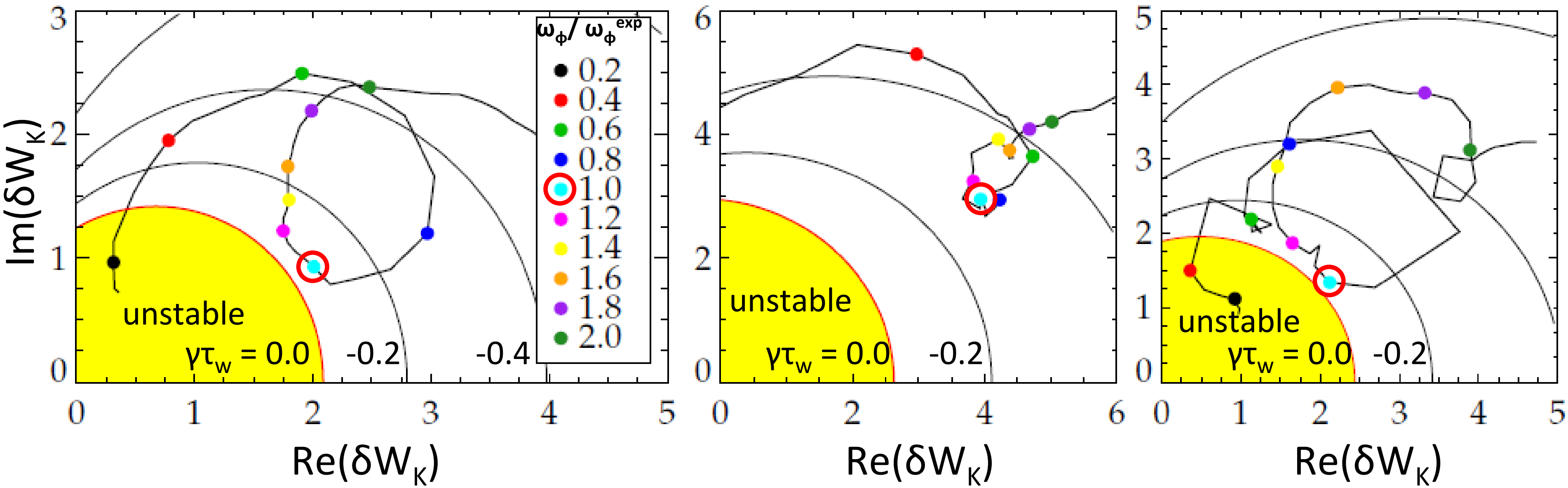




NSTX experimental instability

# 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.



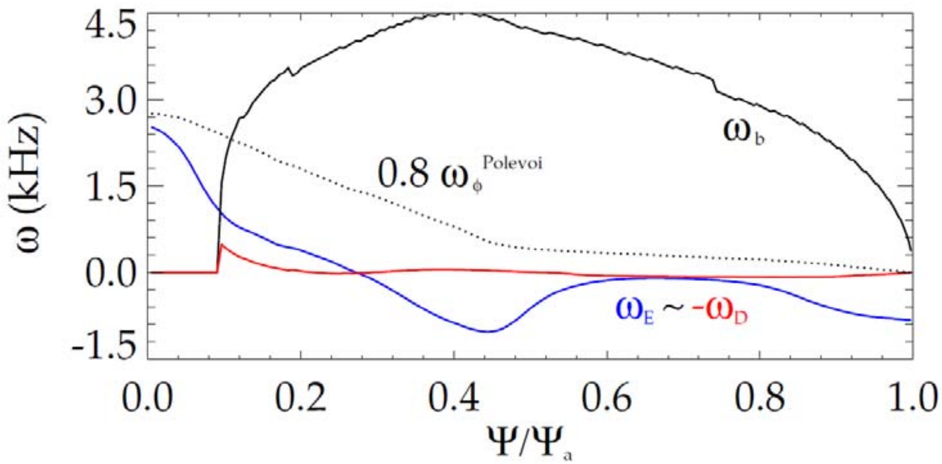

121083 @ 0.475 s

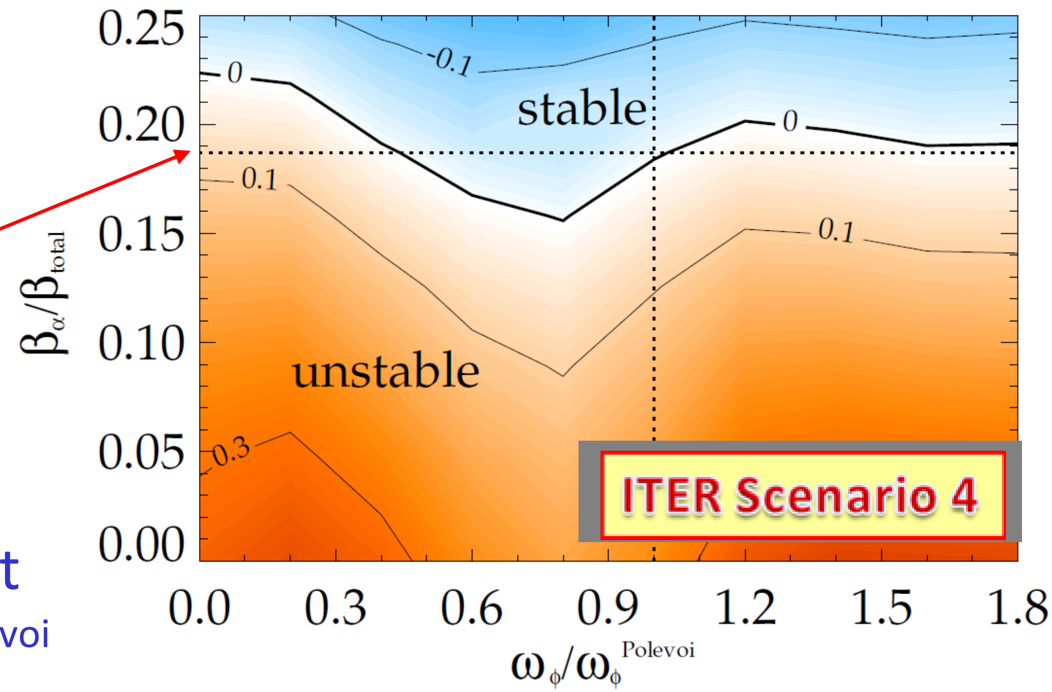
128856 @ 0.526 s

130235 @ 0.745 s

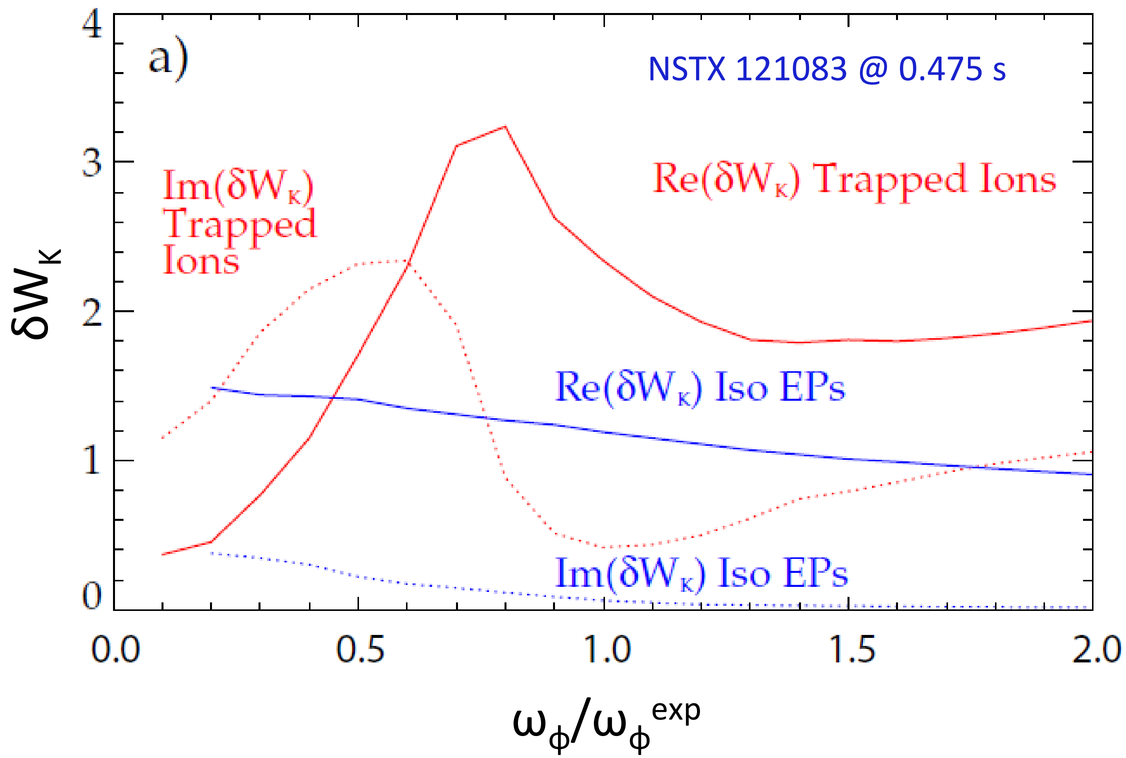
# MISK computed RWM stability of ITER scenario 4 including energetic particles near marginal at $\beta_N = 3$

- ITER advanced scenario 4
  - With $\beta_N = 3$ (20% above n = 1 no-wall limit)
  - Polevoi rotation profile
- Energetic particle effect
  - Isotropic slowing down distribution of alphas
  - Near RWM marginal stability at expected $\beta_a/\beta_{total}$
- Plasma rotation effect
  - Stabilizing precession drift resonance $\omega_\phi = 0.8\ \omega_\phi^{Polevoi}$



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




for energetic particles:

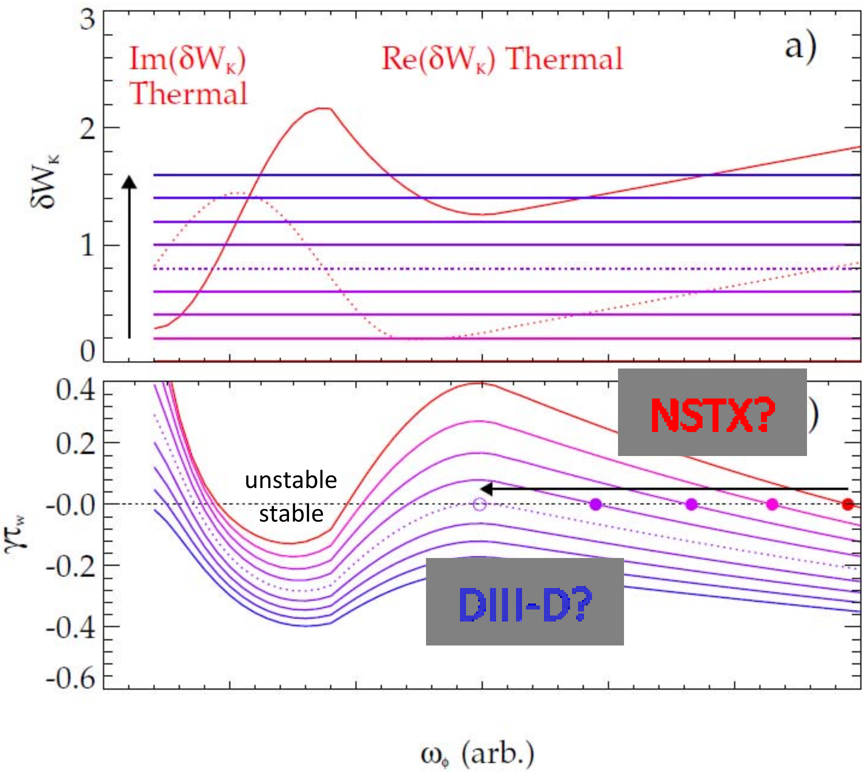
$$\delta W_K \sim \left[ \frac{1}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E} \right]$$

small

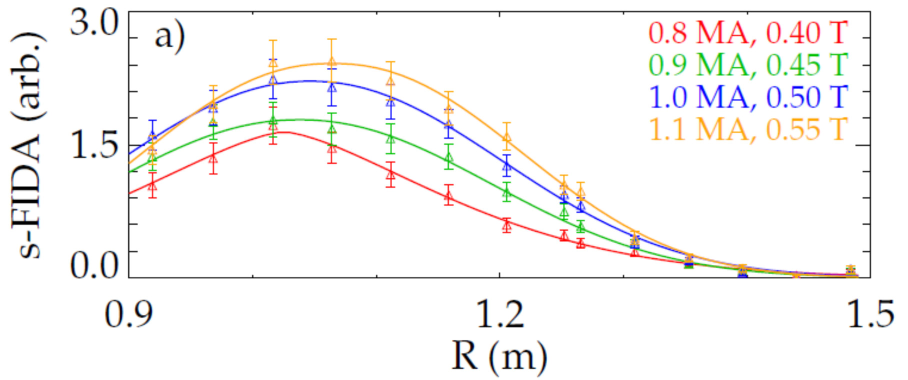
[J. Berkery *et al.*, submitted to Phys. Plasmas (2010)]

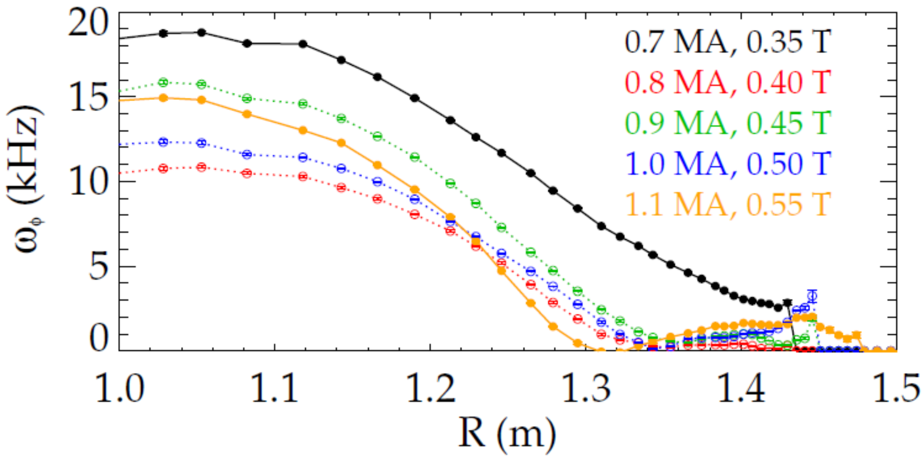
– Significant Re($\delta W_K$), but nearly independent of $\omega_\phi$
– Energetic particles are <u>not</u> in mode resonance
– Effect is not energy dissipation, but rather a restoring force

# An NSTX experiment examined the role of energetic particles in RWM stability



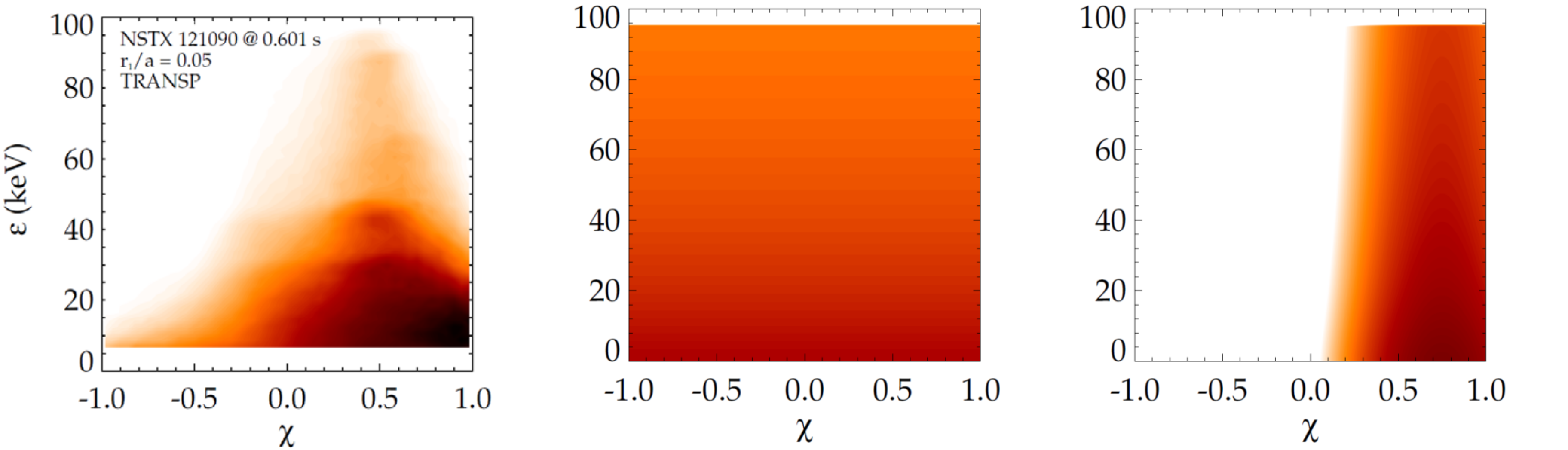

Illustrative example




- Present model, with improvements, can explain exps.
  - NSTX: low EP: unstable more often, rotational resonances seen
  - DIII-D: higher EP: mode stable except when triggered by fishbones

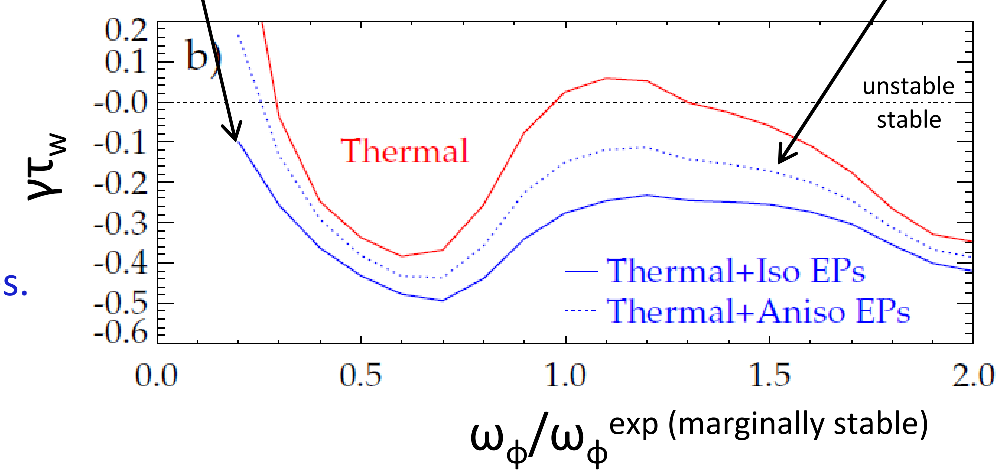
# Anisotropic distribution function of beam ions impacts stability; work continues on improving model




Real (from TRANSP) | Isotropic | Simple anisotropic test case

$\chi_0 = 0.75$, $\delta\chi = 0.25$

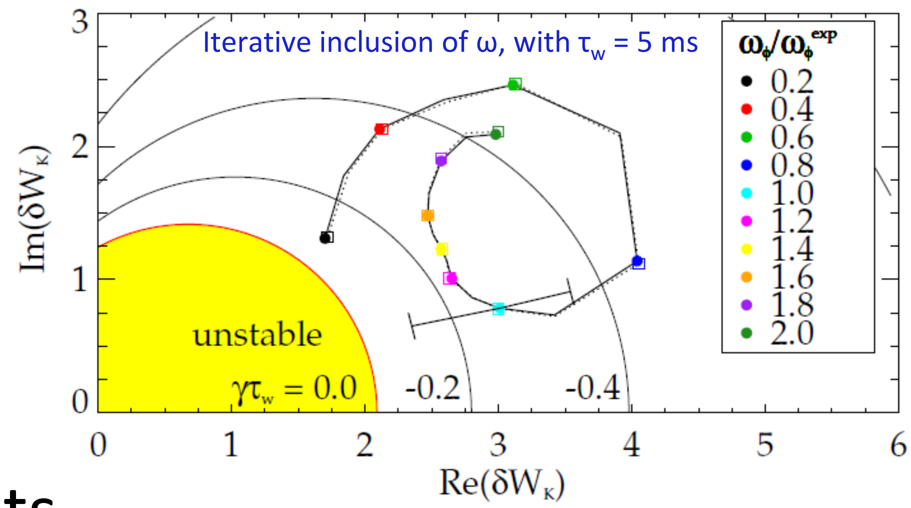
$$f(\varepsilon,\Psi,\chi) = \frac{C(\Psi)}{\varepsilon^{\frac{3}{2}} + \varepsilon_c^{\frac{3}{2}}} \frac{e^{-(\chi-\chi_0)^2/\delta\chi^2}}{\delta\chi}$$




- Work towards analytical model of the TRANSP energetic particle distribution function continues.
- Complicated by multiple sources, energy components and deposition surfaces.

# RWM stabilization model is being carefully assessed for sensitivities

- Perturbative vs. self-consistent approaches
  - Is ξ changed by kinetic effects?
  - Non-linear inclusion of ω




- Sensitivity of code to inputs
  - Calculation is sensitive to profiles. Also, the select of Δq for analytic treatment around rational surfaces (shown above)
- Zero banana width approximation
  - Since RWM is a global mode, this effect may be minimal

These effects are not enough to explain quantitative disagreement.

Improvements to theoretical model are needed…

# Advancements in the theoretical model continue

## Electrostatic effect

The electrostatic component of the perturbed distribution function contributes to δW. This effect is likely to be small, however.

$$\delta W_{\Phi} = -\frac{1}{2}\int e^2 \left|\tilde{\Phi} + \xi_\perp \cdot \nabla\Phi_0\right|^2 \sum_j Z_j^2 \frac{n_j}{T_j} dV$$

[B. Hu *et al.*, Phys. Plasmas **12**, 057301 (2005)]

## Additional anisotropic term

In addition to the effect of anisotropy on $\delta W_K$, when *f* is anisotropic an additional term arises that is proportional $\tilde{\mathbf{B}}_{\|}$ :

$$\delta W_{\tilde{B}} = \sum_j \frac{1}{2}\int\int (HT_j)^* \mu \frac{\tilde{\mathbf{B}}_{\|}}{B}\frac{\partial f_j}{\partial \mu} d^3\mathbf{v}dV.$$

## Centrifugal destabilization

This fluid force term is usually neglected, but it is always destabilizing, and could be important if the plasma rotation Mach number is significant, or for alpha particles rotating at higher frequency ~ $\omega_{*\alpha}$.

$$\delta W_C = -\frac{1}{2}\sum_j \int \xi_\perp^* \cdot [\tilde{\rho}\mathbf{v}_0 \cdot \nabla \mathbf{v}_0]\, dV$$

## Other possibilities:

- Inclusion of plasma inertia term in the dispersion relation.
- Effect of poloidal rotation on $\omega_E$ (small).
- Use of a Lorentz collisionality model instead of current ad-hoc inclusion of collisionality.

$$C\left(\tilde{f}\right) = \frac{1}{2}\nu\Pi_e \frac{\partial}{\partial\chi}\left(1-\chi\right)^2 \frac{\partial \tilde{f}}{\partial \chi}$$

# Kinetic RWM stability model is developed, with comparison to NSTX experiments and application to ITER

- Kinetic effects contribute to stabilization of the RWM, and thermal ion resonances can explain the complex relationship between plasma rotation and stability.
- The **MISK** code is used to calculate the RWM growth rate with kinetic effects for NSTX and ITER.
- Computations indicate that energetic particles have a stabilizing effect, consistent with NSTX experiments.
- Improvements to modeling continue, particularly an improved beam ion anisotropic distribution.

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