Neoclassical toroidal viscosity at low electric field in DIII-D

A.J. Cole, C.C. Hegna, J.D. Callen
University of Wisconsin, Madison, WI

W. Solomon (PPPL),
A.M. Garofalo,
H. Reimerdes (Columbia),
DIII-D Team
General Atomics, San Diego, CA

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Breaking toroidal symmetry induces nonambipolar particle fluxes and neoclassical toroidal flow damping

- General form of banana-drift branch of solutions

$$Z_i e \Gamma_i^{na} = -M_i n_i \langle R^2 \rangle \nu_{\|} \delta B_{3D}^2 T_i \left(\frac{p_i'}{Z_i e p_i} + \frac{\phi'}{T_i} + \frac{c_t}{Z_i e} \frac{T'}{T_i} \right)$$

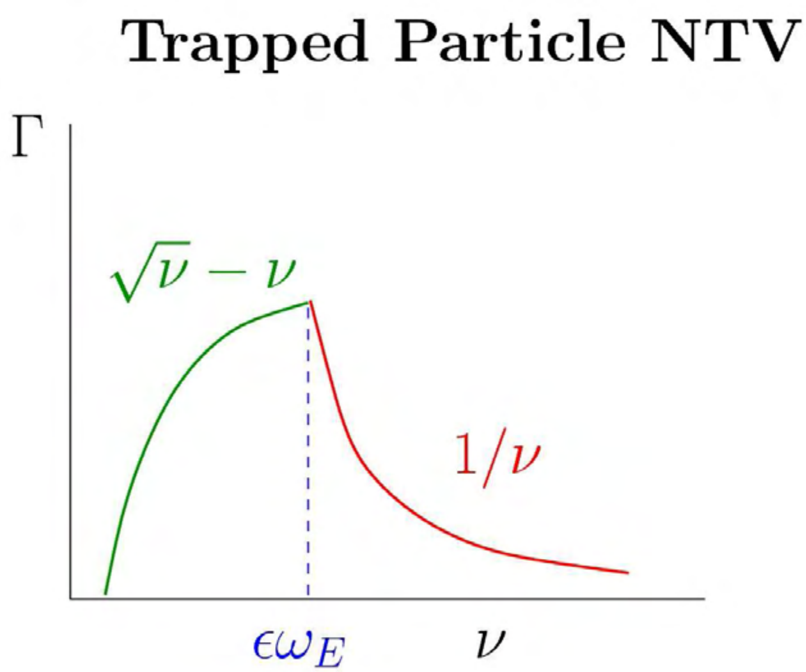
where $' = d/d\chi$ (poloidal flux)

- Flux-friction relation gives the equivalent toroidal viscosity

$$Z_i e \Gamma_i^{na} = \langle \vec{e}_\zeta \cdot \vec{\nabla} \cdot \Pi_{\|} \rangle$$

- Infinitesimal **neoclassical toroidal viscosity [NTV]** torque element is

$$dT_{NTV} = -dV \langle \vec{e}_\zeta \cdot \vec{\nabla} \cdot \Pi_{\|} \rangle$$



Radial force balance allows thermodynamic forces to be replaced by plasma flow in flux surface

$$dT_{NTV} = -Z_i e \Gamma_i^{na} dV = dM_i \langle R^2 \rangle \nu_{||} \delta B_{3D}^2 T_i \left(\frac{p_i'}{Z_i e p_i} + \frac{\phi'}{T_i} + \frac{c_t}{Z_i e} \frac{T'}{T_i} \right)$$

where $' = d / d\chi$ (poloidal flux)

Radial force balance: $\frac{p_i'}{Z_i e p_i} + \frac{\phi'}{T_i} = \frac{q \vec{V}_i \cdot \vec{\nabla} \theta - \vec{V}_i \cdot \vec{\nabla} \zeta}{T_i}$

$$dT_{NTV} = -dM_i \nu_{||} \delta B_{3D}^2 \left(\langle R^2 \Omega \rangle - \langle R^2 \Omega_{NTV} \rangle \right)$$

$\Omega = \vec{V}_i \cdot \vec{\nabla} \zeta$ — toroidal rotation rate

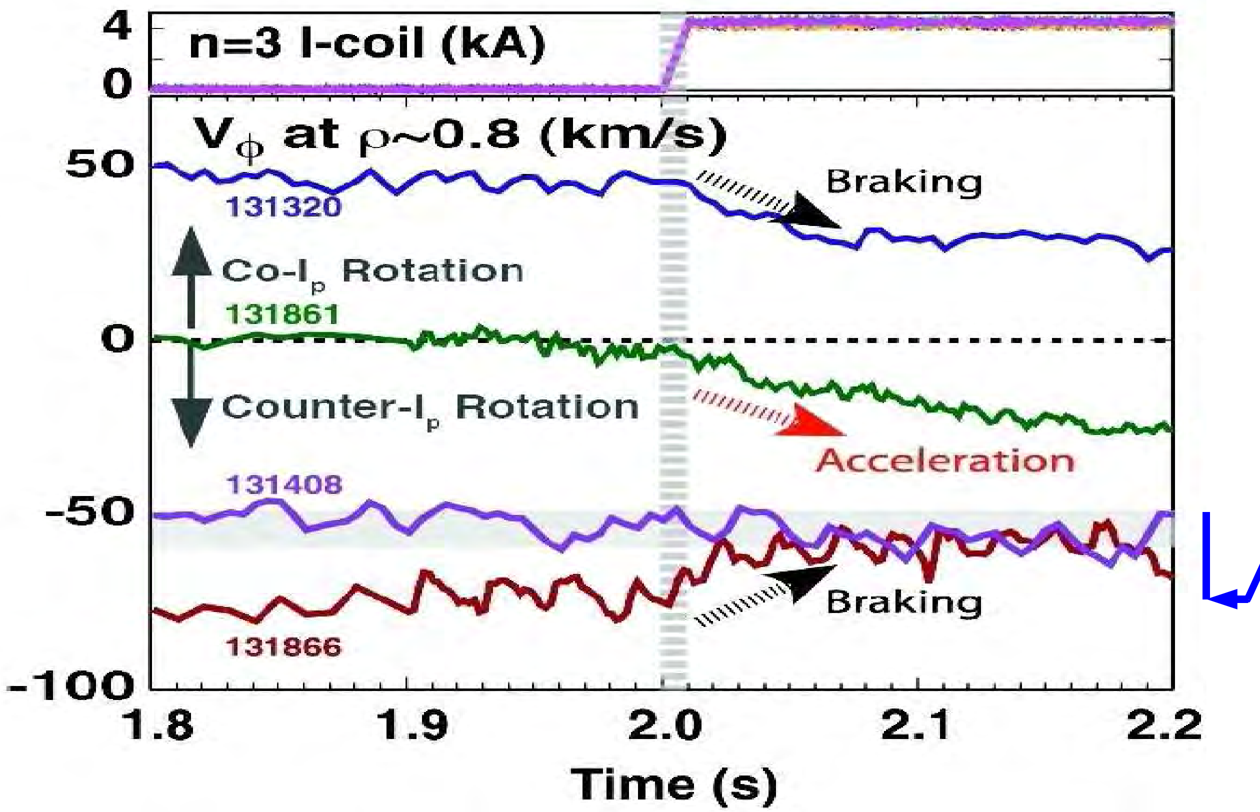
$q \vec{V}_i \cdot \vec{\nabla} \theta = \frac{c_p}{Z_i e} \frac{d T_i}{d\chi}$ — poloidal rotation rate

$\Omega_{NTV} = \frac{c_p + c_t}{Z_i e} \frac{d T_i}{d\chi}$ — NTV offset rotation rate

Recall when $\delta B_{3D} \ll \epsilon$ flowing damping in fast (poloidal) and slow (toroidal) directions are solved successively

Applying large external n=3 fields damps toroidal flow to offset value

$$dT_{NTV} = -dM_i \nu_{\|} \delta B_{3D}^2 \left(\langle R^2 \Omega \rangle - \langle R^2 \Omega_{NTV} \rangle \right)$$



A.M. Garofalo, et al: PRL **101**, 195005 (2008); PoP **16**, 056119 (2009)

NTV variation at low radial electric field $\omega_E \to 0$

•Previous work compared data against different asymptotic NTV regimes: 1/nu, nu

•Recall that NTV torque is a function of both collisionality and radial electric field

$$dT_{NTV} = -dM_i \nu_{||} \delta B_{3D}^2 \left(\langle R^2 \Omega \rangle - \langle R^2 \Omega_{NTV} \rangle \right)$$

$$\nu_{||} = \nu_{||}(E_r, \nu_i)$$

•Present focus: investigate large variation in damping rate at low electric field
--where superbanana drift orbits have largest radial excursions

Low collisionality trapped-particle NTV regimes in collisionality---radial electric field space (cartoon)

Relevant banana-drift regimes:

$1/\nu$

K.C. Shaing PoP **10**, 1443 (2003)

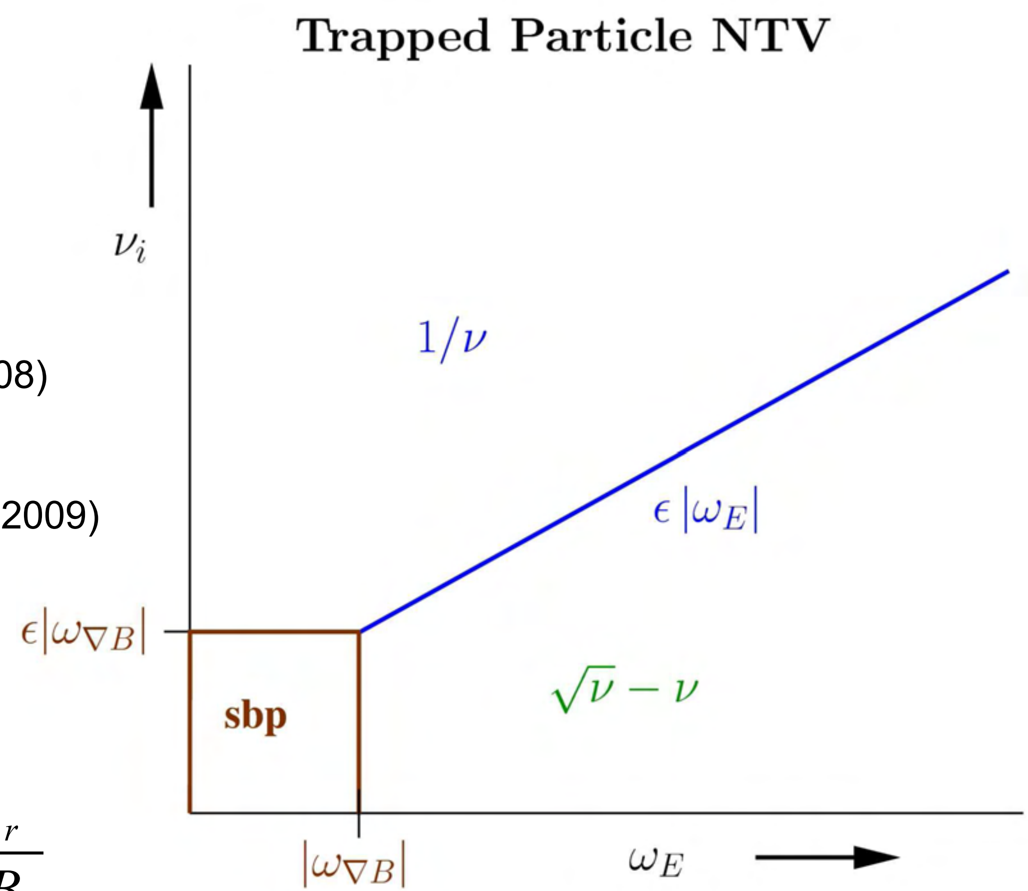
$\sqrt{\nu}-\nu$

K.C. Shaing et al, PoP **15**, 082506 (2008)

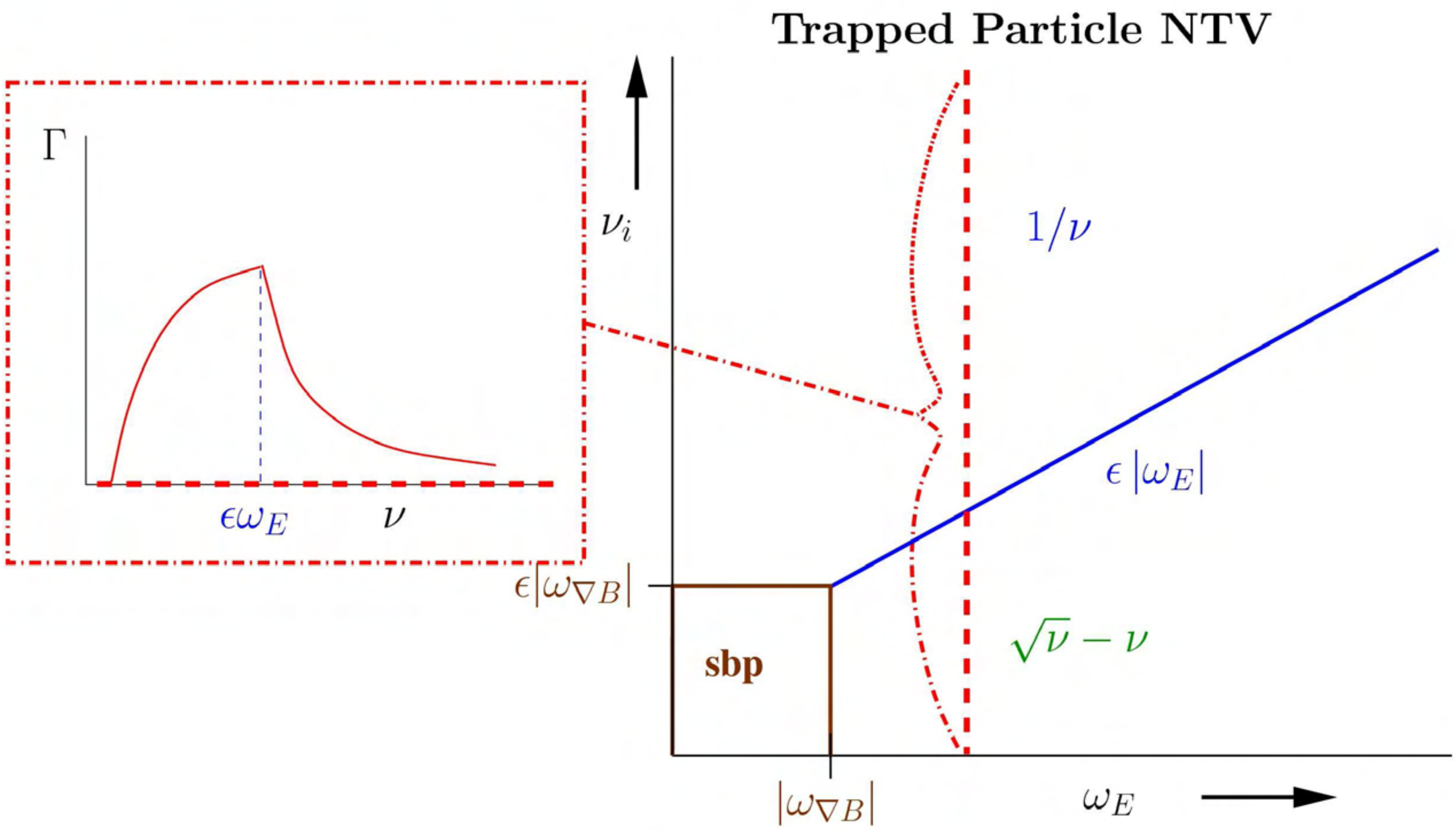
Superbanana plateau

K.C. Shaing, et al., PPCF **51**, 035009 (2009)

$$\omega_{\nabla B} \simeq \frac{T_i}{Z_j e R B_\theta} \frac{d\epsilon}{dr} \qquad \omega_E = \frac{E_r}{R B_\theta}$$



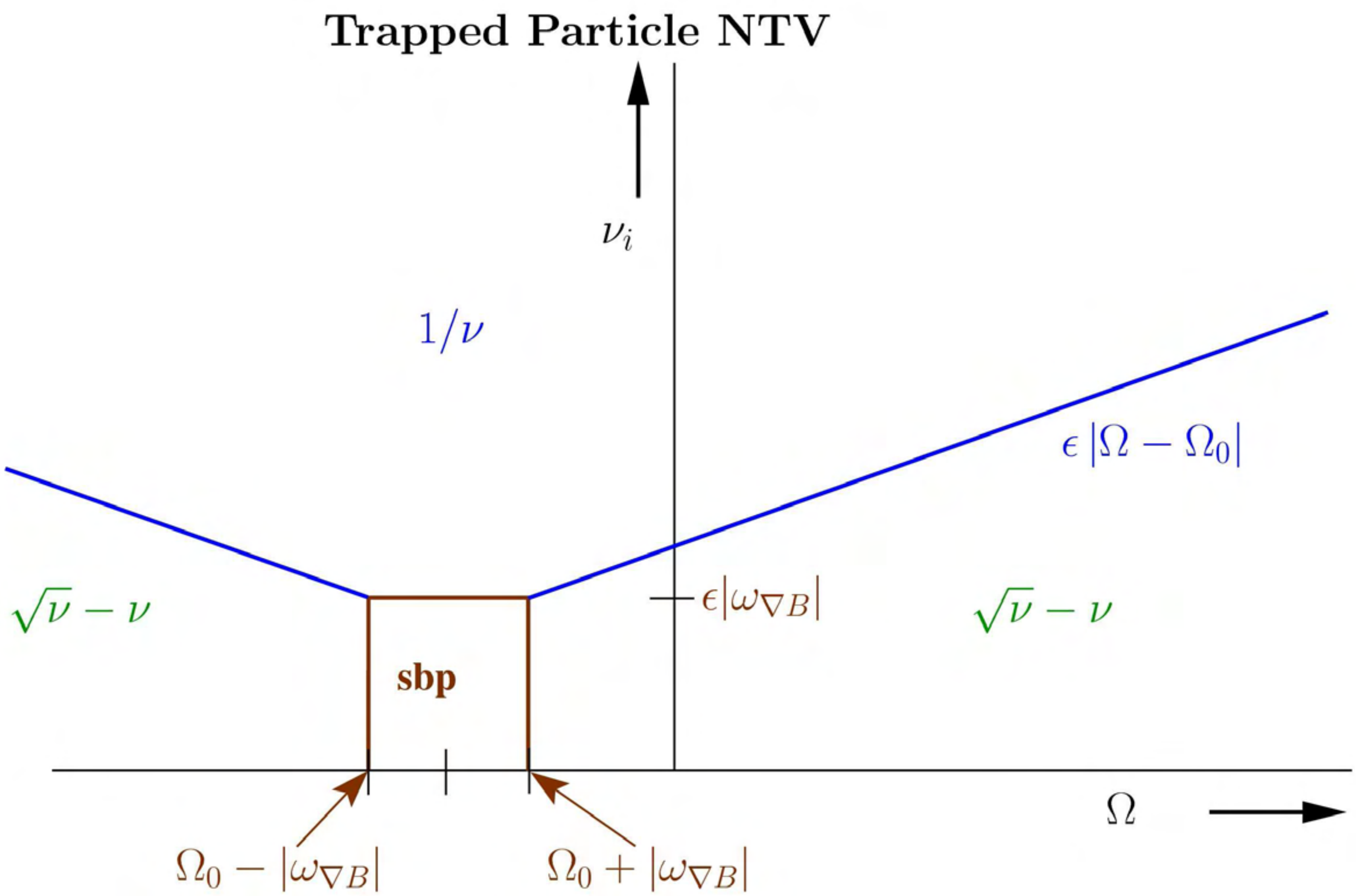
Familiar nonambipolar flux picture is plotted along collisionality axis at finite, fixed radial electric field



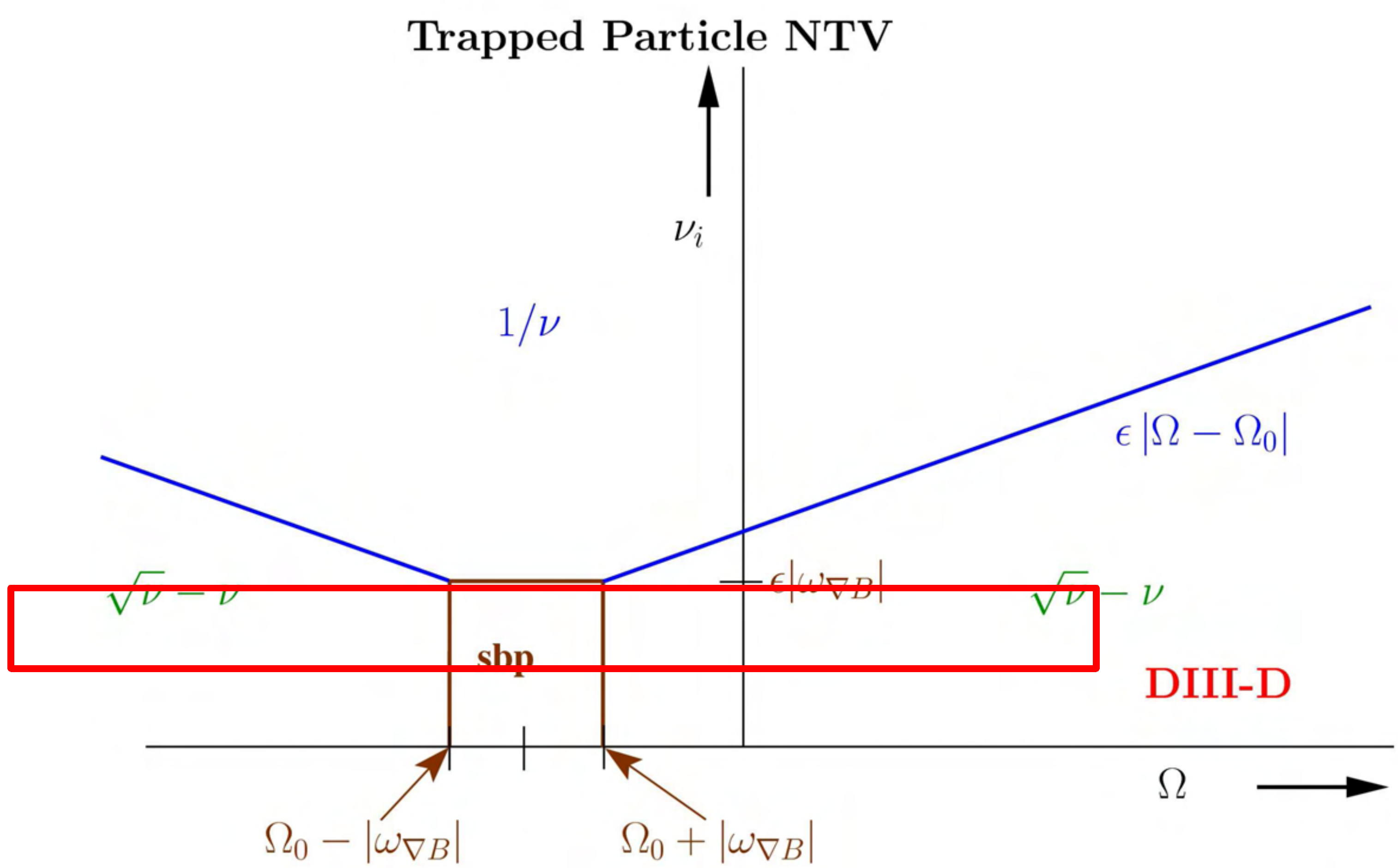
Radial force balance maps electric field to toroidal rotation rate

- Radial force balance: $$\frac{p_i'}{Z_i e p_i} + \frac{\phi'}{T_i} = \frac{q\vec{V}_i \cdot \vec{\nabla}\theta - \vec{V}_i \cdot \vec{\nabla}\zeta}{T_i}$$
- This can be rewritten as $$\boxed{\omega_E = \Omega_0 - \Omega}$$
- The electric precessional drift is $$\omega_E = \frac{d\phi}{d\chi}$$
- Radial electric field goes to zero as $$\Omega \rightarrow \Omega_0 = \frac{c_p - 1}{Z_i e}\frac{dT_i}{d\chi} - \frac{T_i}{Z_i e n}\frac{dn}{d\chi}$$
- Recall c_p comes from $$q\vec{V}_i \cdot \vec{\nabla}\theta = \frac{c_p}{Z_i e}\frac{dT_i}{d\chi}$$

Low collisionality trapped-particle NTV regimes in collisionality---toroidal rotation rate space (cartoon)



Varying toroidal rotation at fixed collisionality will cause a transition in NTV regimes



Construct ion-root cylindrical model using Padè approximation for experimental validation in DIII-D

$$dT_{NTV}[Nm] = -2\, n_i\, e\, T_i[eV]\, dV\, \delta B^2 K(\Omega - \Omega_{NTV})$$

$$K \equiv \frac{0.21\sqrt{n \nu_i}}{\left(|\Omega - \Omega_0|\right)^{3/2} + .30\sqrt{\nu_i/|n\epsilon|}\,|\omega_{\nabla B}| + .04\left(\nu_i/|n\epsilon|\right)^{3/2}}$$

- Approximate $d/d\chi \simeq d/(R B_\theta dr)$

$$\omega_E \simeq \frac{E_r}{R B_\theta} \qquad \Omega_0 \simeq \frac{T_i}{Z_i e R B_\theta}\left(\frac{1 - c_p}{L_T} + \frac{1}{L_n}\right)$$

- Magnetic drift for thermal super-bananas and **averaged** NTV offset are

$$\omega_{\nabla B} \simeq \frac{T_i}{Z_j e R B_\theta}\frac{d\epsilon}{dr} \qquad \Omega_{NTV} \simeq \frac{c_p + .91}{Z_j e R B_\theta}\frac{dT_i}{dr}$$

Recovering the $\sqrt{\nu}$ regime

$$dT_{NTV}[Nm] = -2 n_i e T_i [eV] dV\, \delta B^2 K(\Omega - \Omega_{NTV})$$

$$K \equiv \frac{0.21\sqrt{n\nu_i}}{\left(|\Omega - \Omega_0|\right)^{3/2} + .30\sqrt{\nu_i/|n\epsilon|}\,|\omega_{\nabla B}| + .04\left(\nu_i/|n\epsilon|\right)^{3/2}}$$

•Magnetic drift for thermal super-bananas and averaged NTV offset are

$$\omega_{\nabla B} \simeq \frac{T_i}{Z_j e R B_\theta}\frac{d\epsilon}{dr} \qquad \Omega_{NTV} \simeq \frac{c_p + .91}{Z_j e R B_\theta}\frac{dT_i}{dr}$$

Recovering the $1/\nu$ regime

$$dT_{NTV}[Nm] = -2 n_i e T_i [eV] dV\, \delta B^2 K(\Omega - \Omega_{NTV})$$

$$K \equiv \frac{0.21\sqrt{n\nu_i}}{\left(|\Omega-\Omega_0|\right)^{3/2} + .30\sqrt{\nu_i/|n\epsilon|}\,|\omega_{\nabla B}| + .04\left(\nu_i/|n\epsilon|\right)^{3/2}}$$

•Magnetic drift for thermal super-bananas and averaged NTV offset are

$$\omega_{\nabla B} \simeq \frac{T_i}{Z_j e R B_\theta}\frac{d\epsilon}{dr} \qquad \Omega_{NTV} \simeq \frac{c_p + .91}{Z_j e R B_\theta}\frac{dT_i}{dr}$$

Recovering the superbanana plateau regime

$$dT_{NTV}[Nm] = -2 n_i e T_i [eV] dV\, \delta B^2 K(\Omega - \Omega_{NTV})$$

$$K \equiv \frac{0.21\sqrt{n\nu_i}}{\left(\left|\Omega - \Omega_0\right|\right)^{3/2} + .30\sqrt{\nu_i/|n\epsilon|}\left|\omega_{\nabla B}\right| + .04\left(\nu_i/|n\epsilon|\right)^{3/2}}$$

•Magnetic drift for thermal super-bananas and averaged NTV offset are

$$\omega_{\nabla B} \simeq \frac{T_i}{Z_j e R B_\theta} \frac{d\epsilon}{dr} \qquad \Omega_{NTV} \simeq \frac{c_p + .91}{Z_j e R B_\theta} \frac{d T_i}{d r}$$

Varying toroidal rotation at fixed collisionality, torque model exhibits "peak" near $E_r=0$

•Patched kernel exhibits "Lorentzian-like" behavior

$$K \equiv \frac{0.211\sqrt{n\,\nu_i}}{\left(\left|\Omega-\Omega_0\right|\right)^{3/2}+\left(W/2\right)^{3/2}}$$

$$\left(\frac{W}{2}\right)^{3/2} = .30\sqrt{\nu_i/|n\epsilon|}\,|\omega_{\nabla B}| + .04\left(\nu_i/|n\epsilon|\right)^{3/2}$$

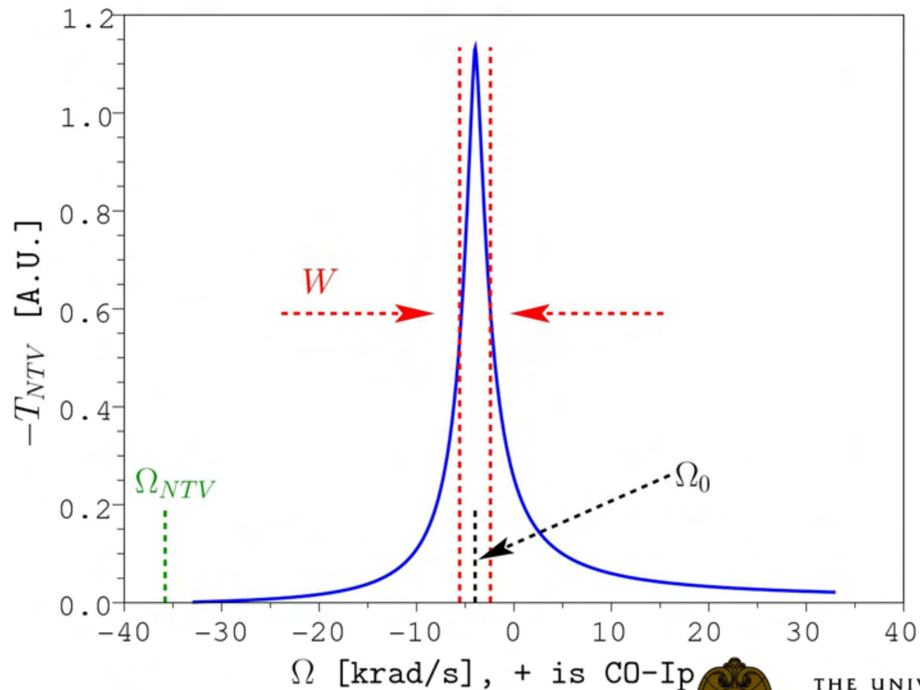
•Zero radial electric field occurs when toroidal rotation rate is near

$$\Omega_0 = \frac{T_i}{Z_i e R B_\theta}\left(\frac{1-c_p}{L_T}+\frac{1}{L_n}\right)$$

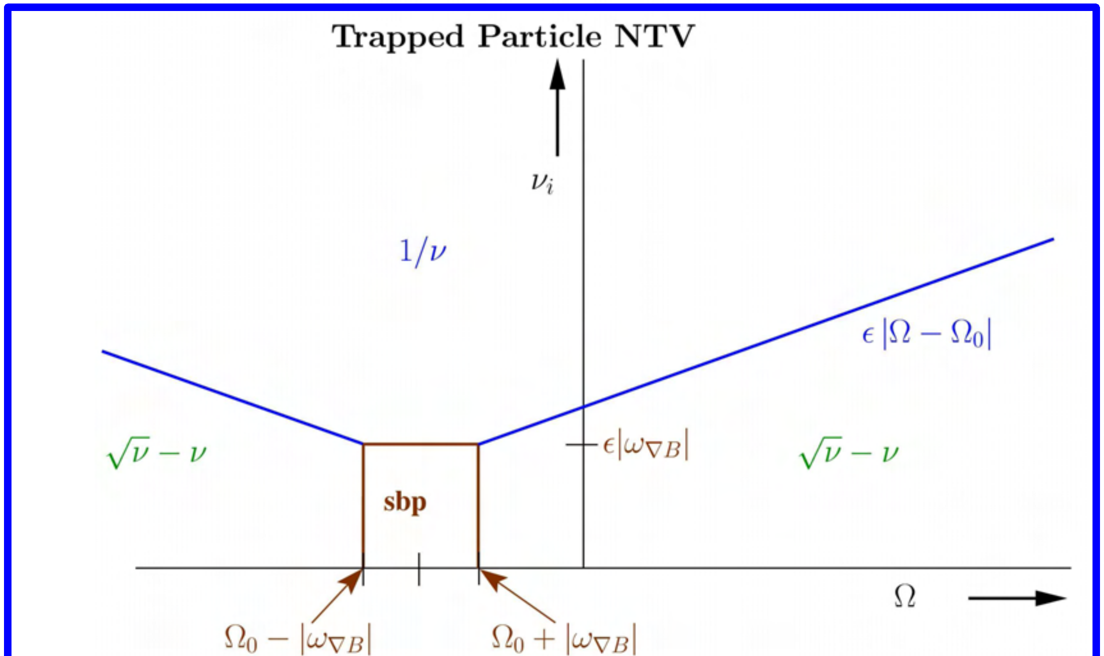
•Recall c_p comes from

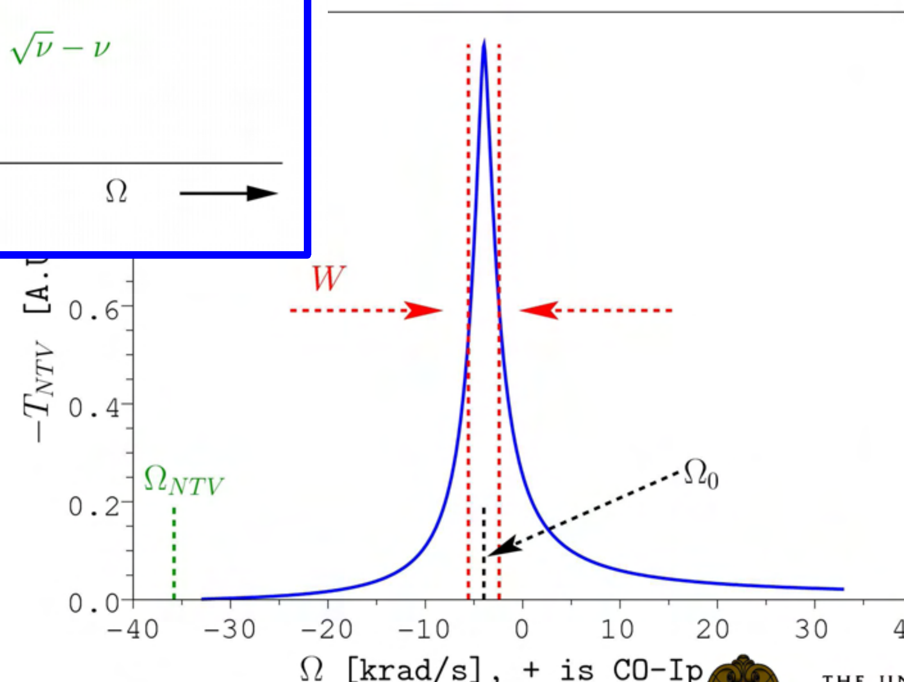
$$q\vec{V}_i\cdot\vec{\nabla}\theta = \frac{c_p}{Z_i e}\frac{dT_i}{d\chi}$$

NTV torque on single surface



Varying toroidal rotation at fixed collisionality, torque model exhibits "peak" near $E_r = 0$





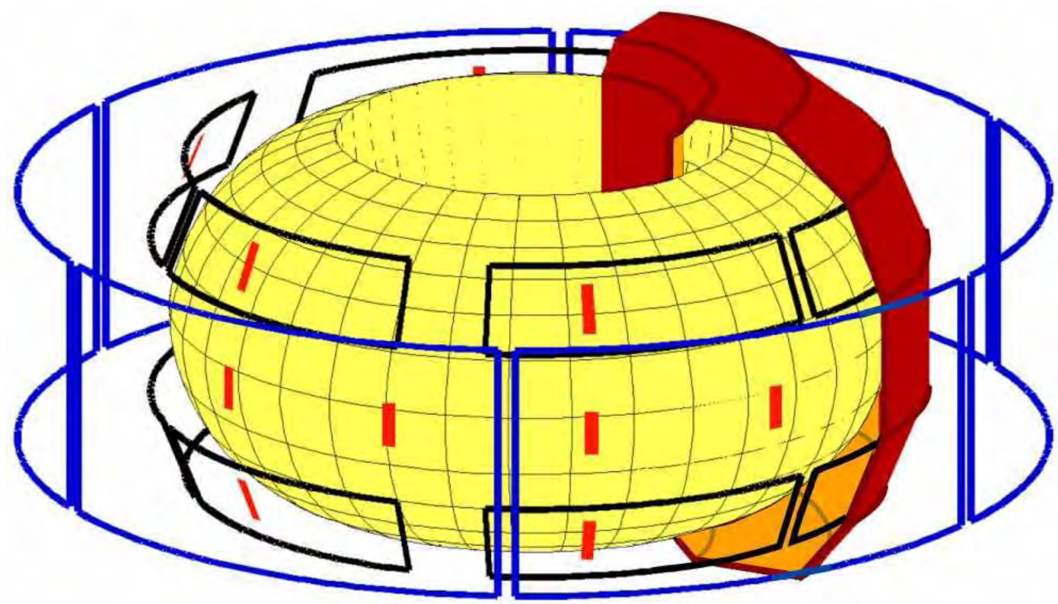
$$\Omega_0 = \frac{T_i}{Z_i e R B_\theta}\left(\frac{1 - c_p}{L_T} + \frac{1}{L_n}\right)$$

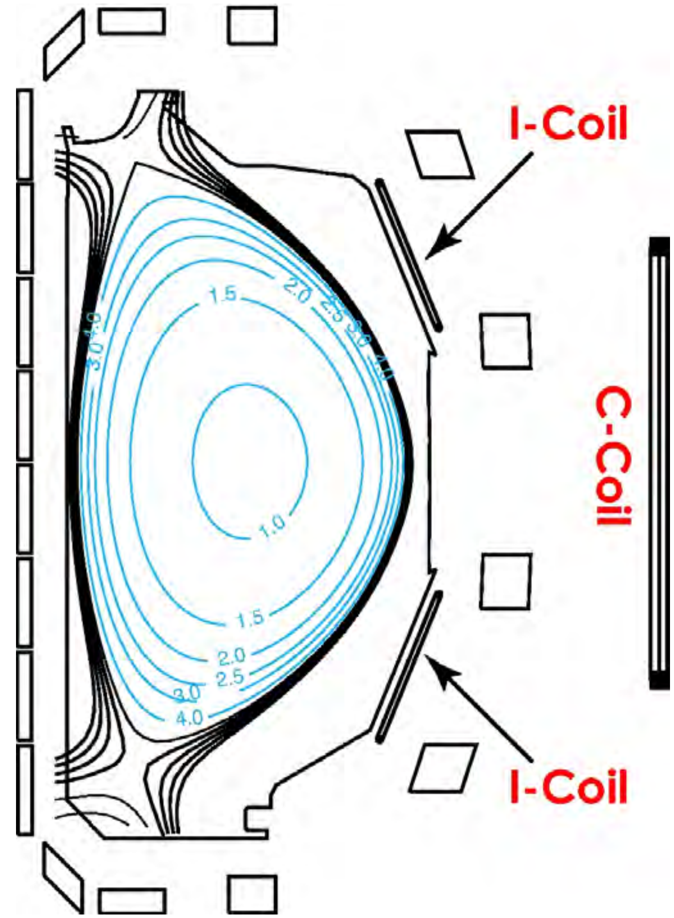
• Recall c_p comes from

$$q\,\vec{V}_i \cdot \vec{\nabla}\theta = \frac{c_p}{Z_i e}\frac{d\,T_i}{d\,\chi}$$

Near balanced beam injection gives DIII-D ability to scan toroidal rotation value and observe peak

- Use NBI feedback to measure required beam torque with and without n=3 fields applied by I-coils.
- Repeat for several rotation values





Experimental traces show clear indication of n=3 applied neoclassical toroidal viscosity

- Establish desired initial rotation rate

$$T_{NBI} + S = 0$$

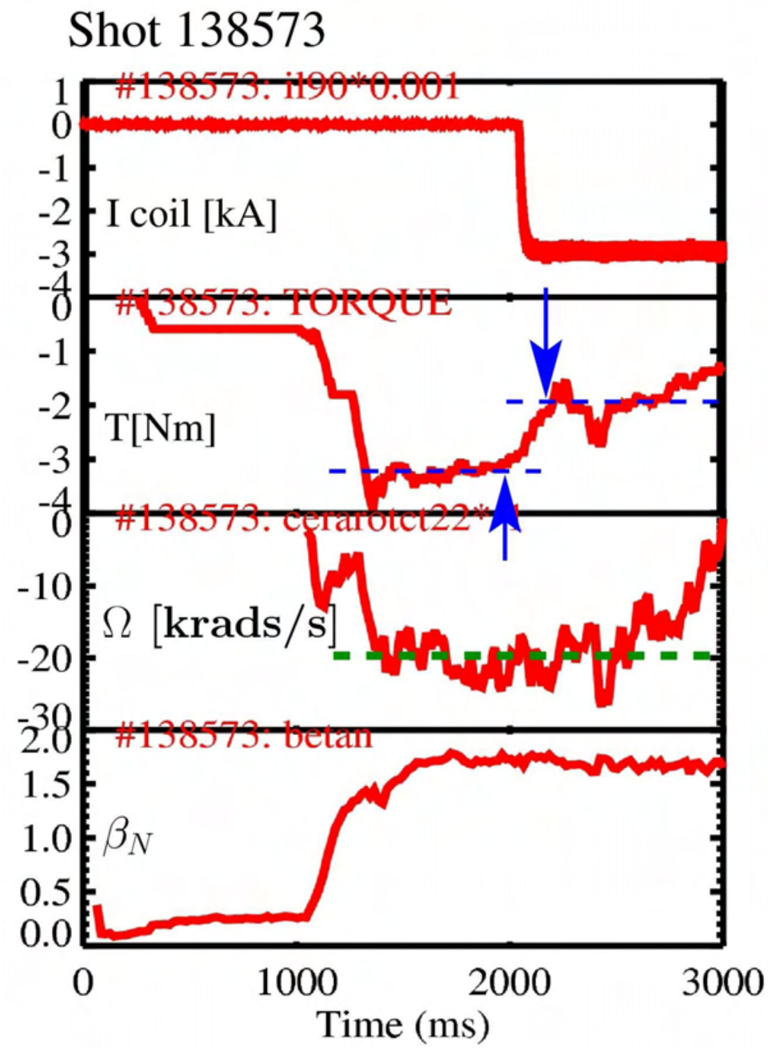
- Maintain rotation with feedback on T22 ChERS channel very near $\rho \sim 0.8$

- Rapidly switch-on I-Coils to apply n=3 fields

- Measure change in NBI torque before and after I-coil switch-on to determine total torque applied by I-coils

$$\Delta T_{NBI} = -T_{NTV}$$

- Repeat for different values of toroidal rotation rate



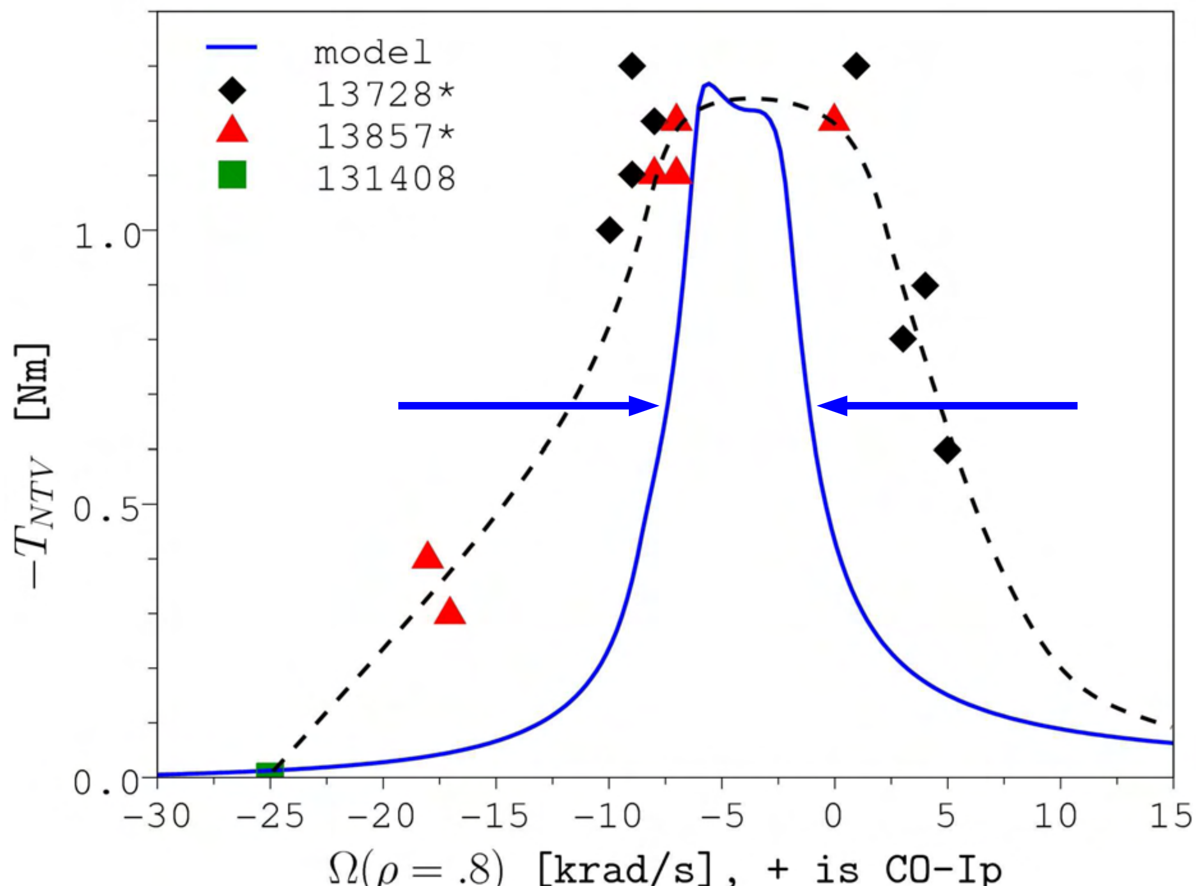
Radial integration of cylindrical torque model broadens peak, for a decent fit to data

$$-T_{NTV}[Nm]=\int dV\,2\,n_i e\,T_i[eV]\,\delta B^2\,K(\Omega-\Omega_{NTV})$$

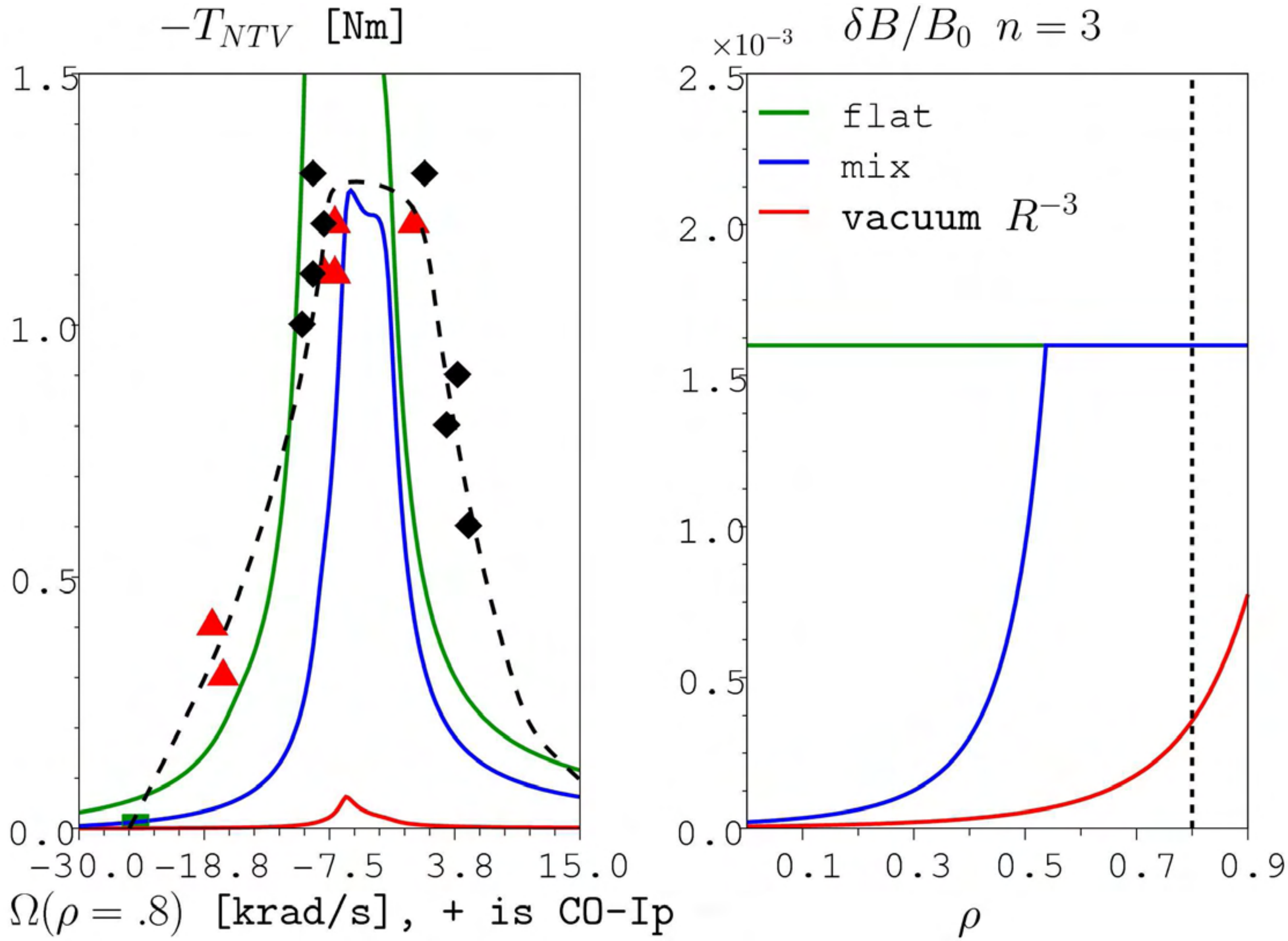
Only two fitting parameters

- $\delta B/B_0$ in plasma
- axisymmetric poloidal rotation value c_p

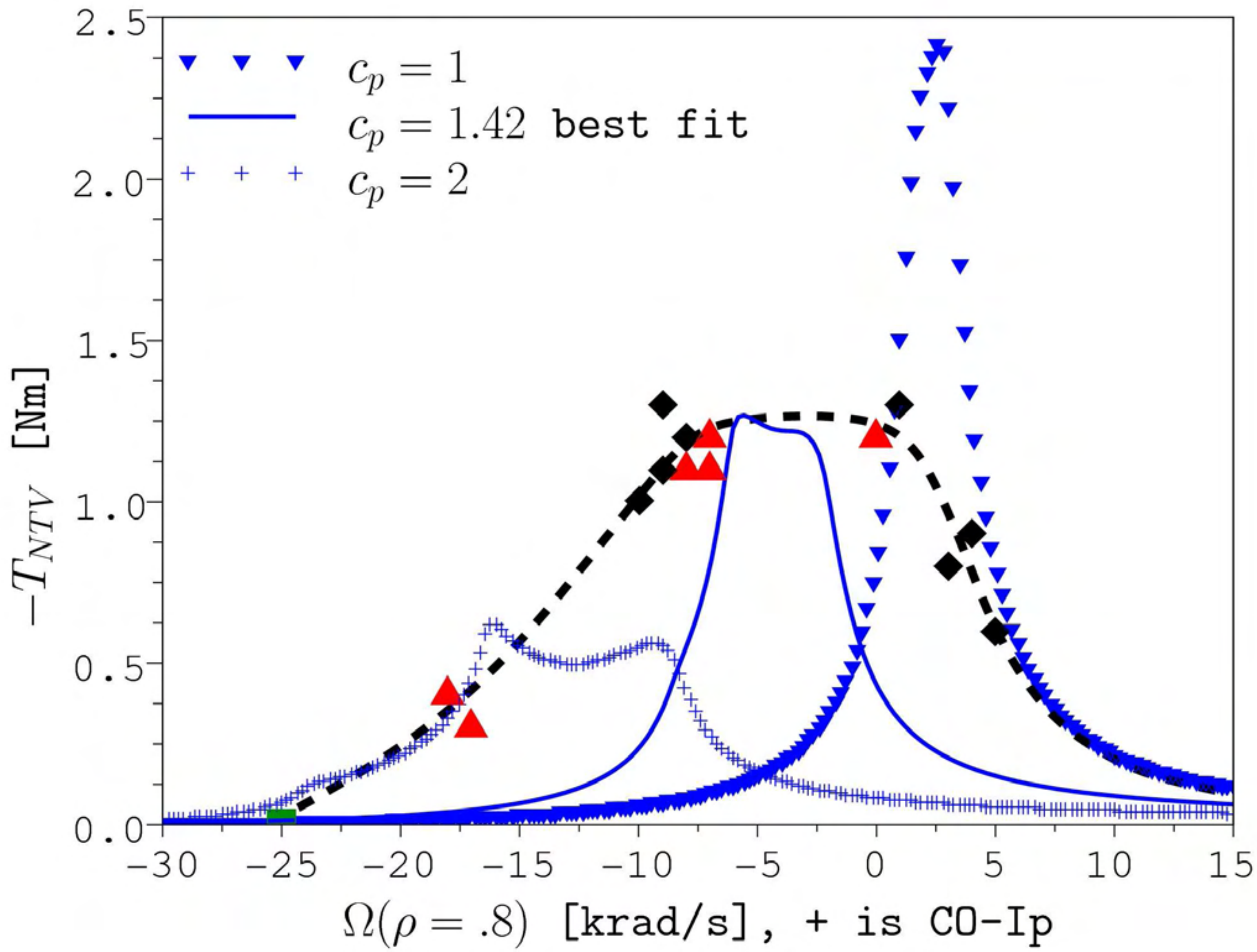
$$q\vec{V}_i\cdot\vec{\nabla}\theta=\frac{c_p}{Z_i e}\frac{dT_i}{dX}$$



Overall torque height and shape sensitive to radial $\delta B/B_0$ profile chosen



Location of NTV torque peak highly sensitive to axisymmetric poloidal rotation value cp



Summary and conclusions

- Balanced NBI and I-coil fields allow DIII-D to access 3-D physics of low radial electric field neoclassical toroidal viscous damping
- DIII-D observed peak in the neoclassical toroidal viscous force as a function of toroidal rotation, predicted by theory
- Peak is highly sensitive to neoclassical poloidal rotation value find best "fit" value of $c_p \simeq 1.42$, which is in the ballpark
- This is tokamak version of stellarator observation that with with no radial electric field, non-axisymmetry-induced superbanana transport becomes very large