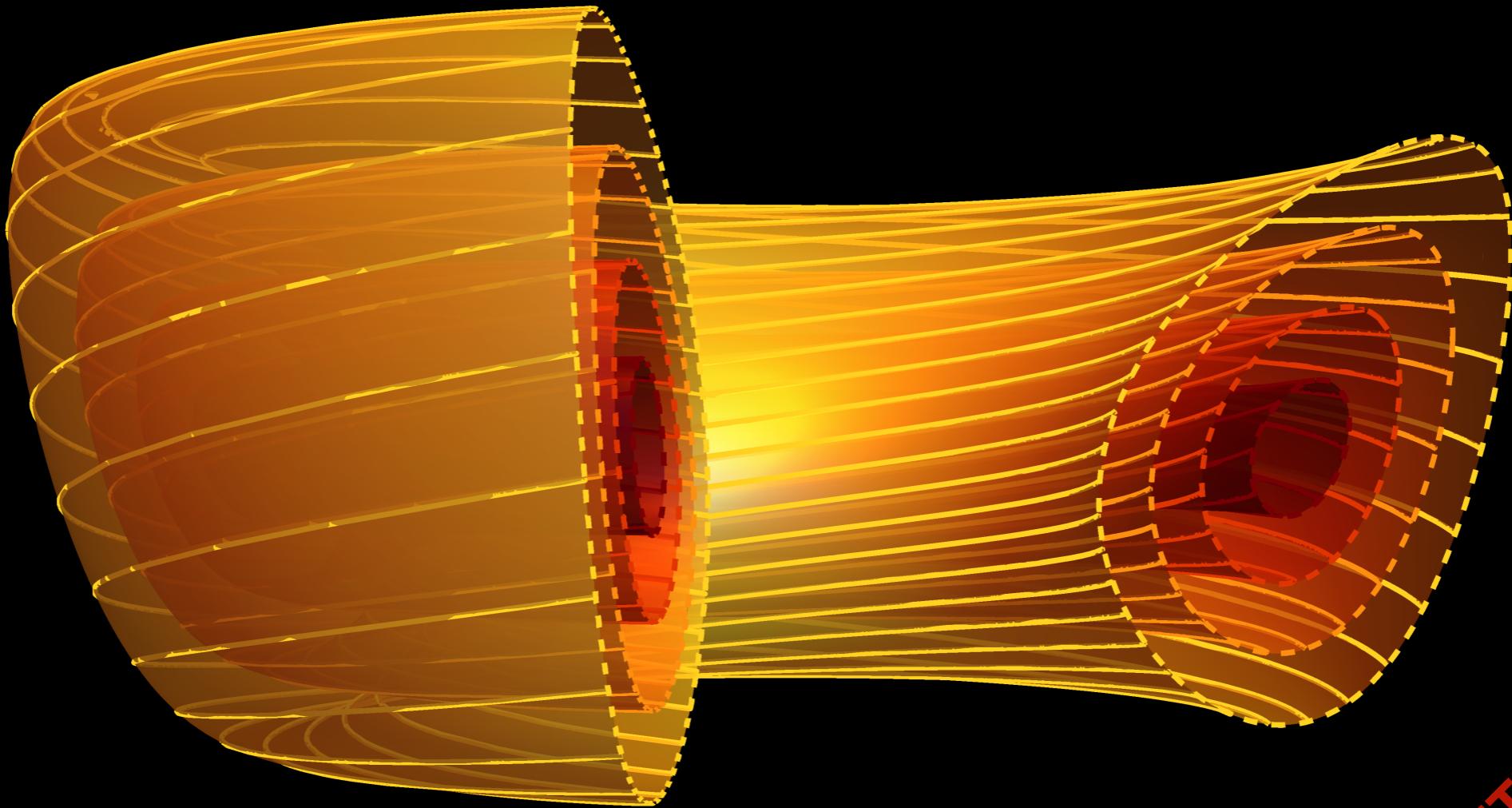


# Up-down asymmetry: progress and plans



Justin Ball<sup>1</sup>  
F.I. Parra<sup>2,3</sup>, S. Brunner<sup>1</sup>, O. Sauter<sup>1</sup>,  
M. Barnes<sup>2,3</sup>, and M. Landreman<sup>4</sup>

**CAUTION:**  
experimental  
results enclosed

<sup>1</sup>EPFL, <sup>2</sup>Oxford University, <sup>3</sup>CCFE, and <sup>4</sup>University of Maryland

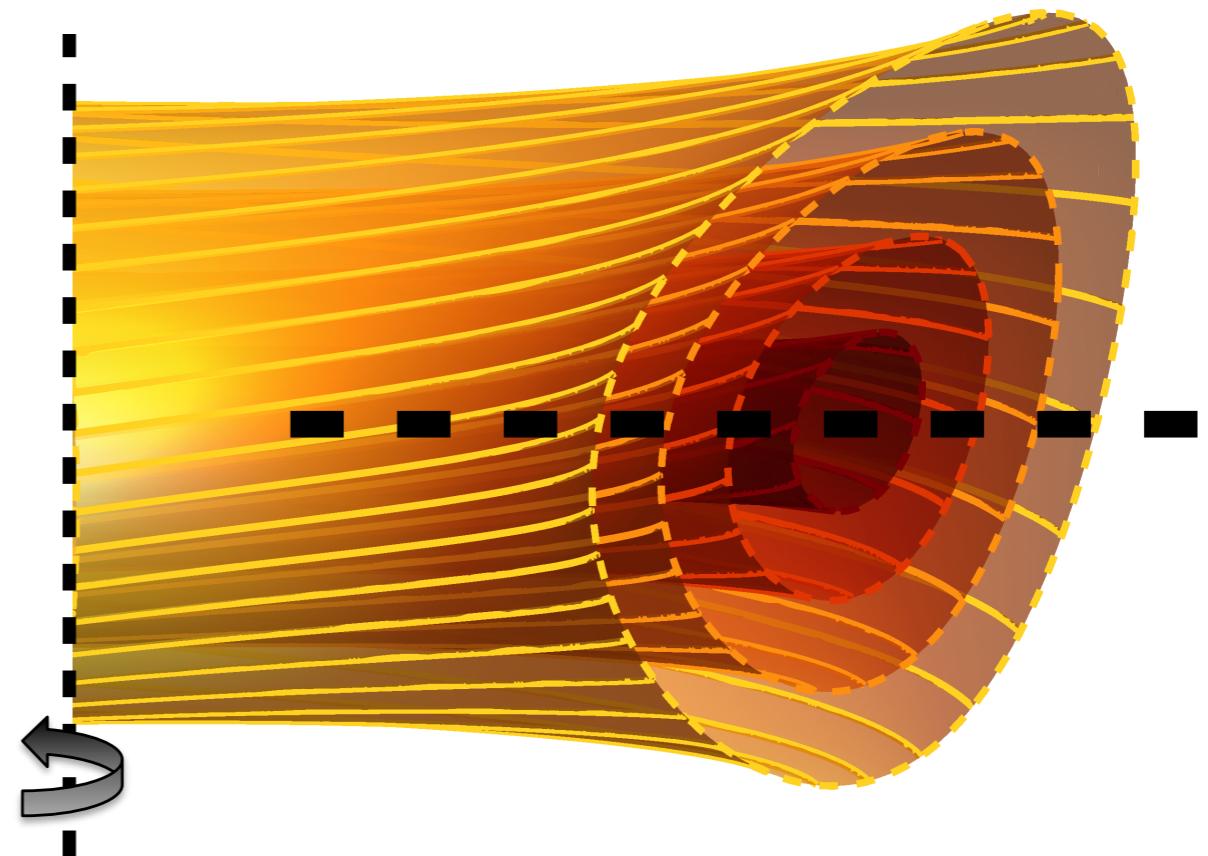
10th Vienna Plasma Kinetics Working Meeting  
19 July 2017

# Motivation

Peeters et al. *PoP* (2005). & Parra et al. *PoP* (2011).

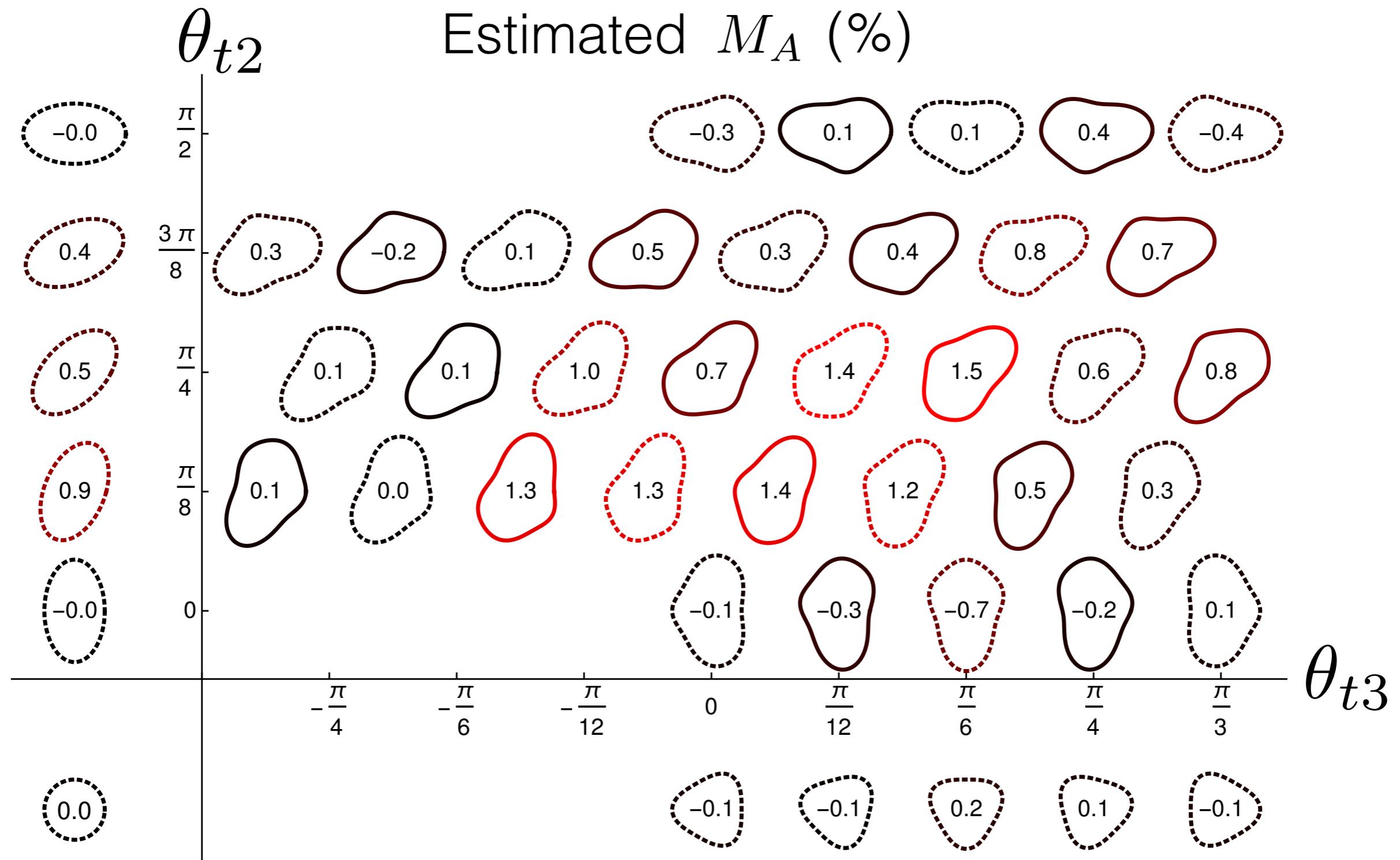
Sugama et al. *PPCF* (2011).

- Toroidal plasma rotation is important in existing experiments as it can stabilize MHD modes and reduce turbulence
- Maximize “intrinsic” rotation in a stationary plasma
- For ITER and beyond, we need rotation that scales with size
- A theoretically-promising option is:
  - Up-down asymmetry in the magnetic equilibrium
- Other effects are small in  $\rho_* \ll 1$



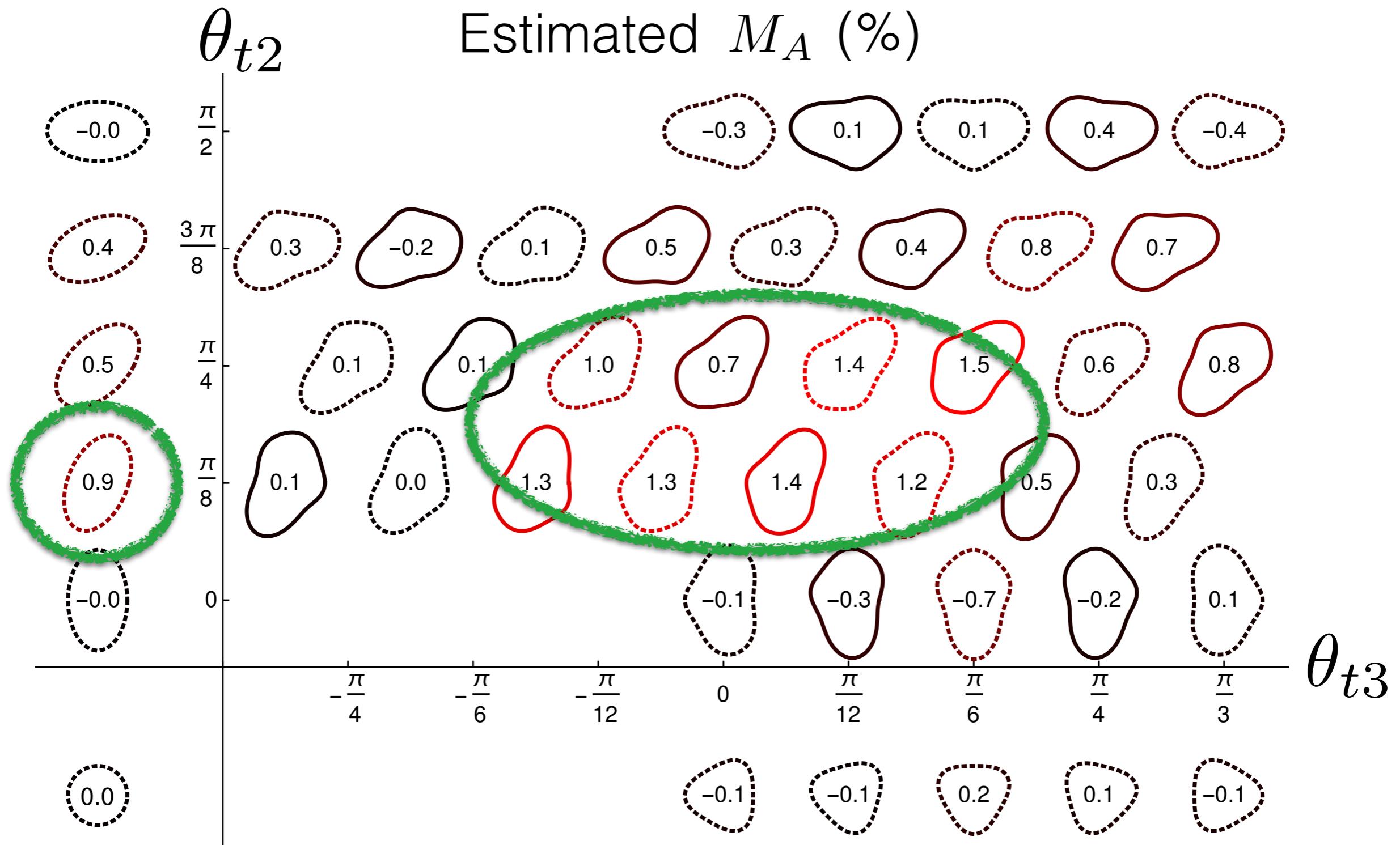
# Estimate rotation with nonlinear local gyrokinetics

J. Ball. PhD thesis, Oxford (2016).



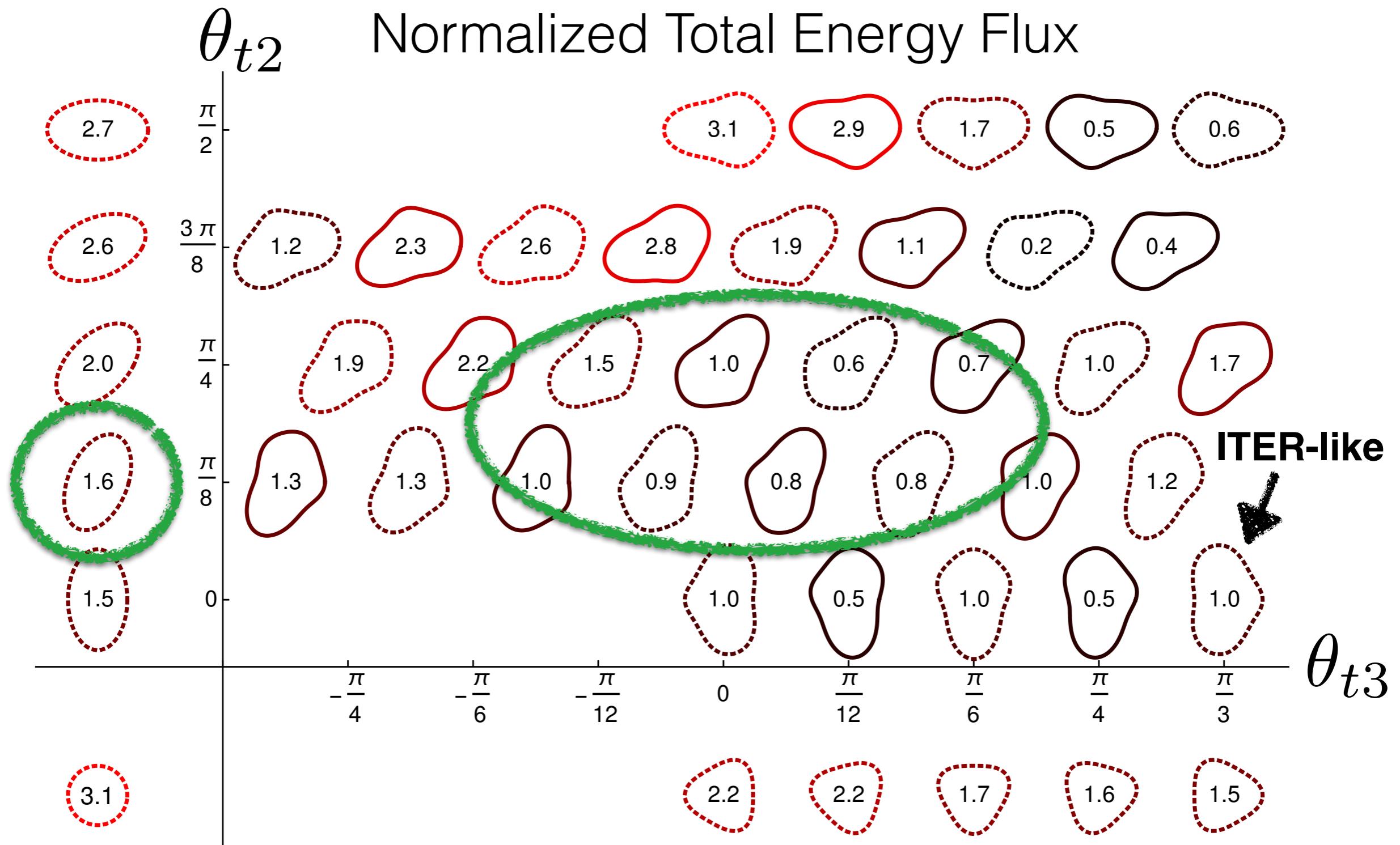
# Estimate rotation with nonlinear local gyrokinetics

J. Ball. PhD thesis, Oxford (2016).



# Improved energy confinement

J. Ball, PhD thesis, Oxford (2016).



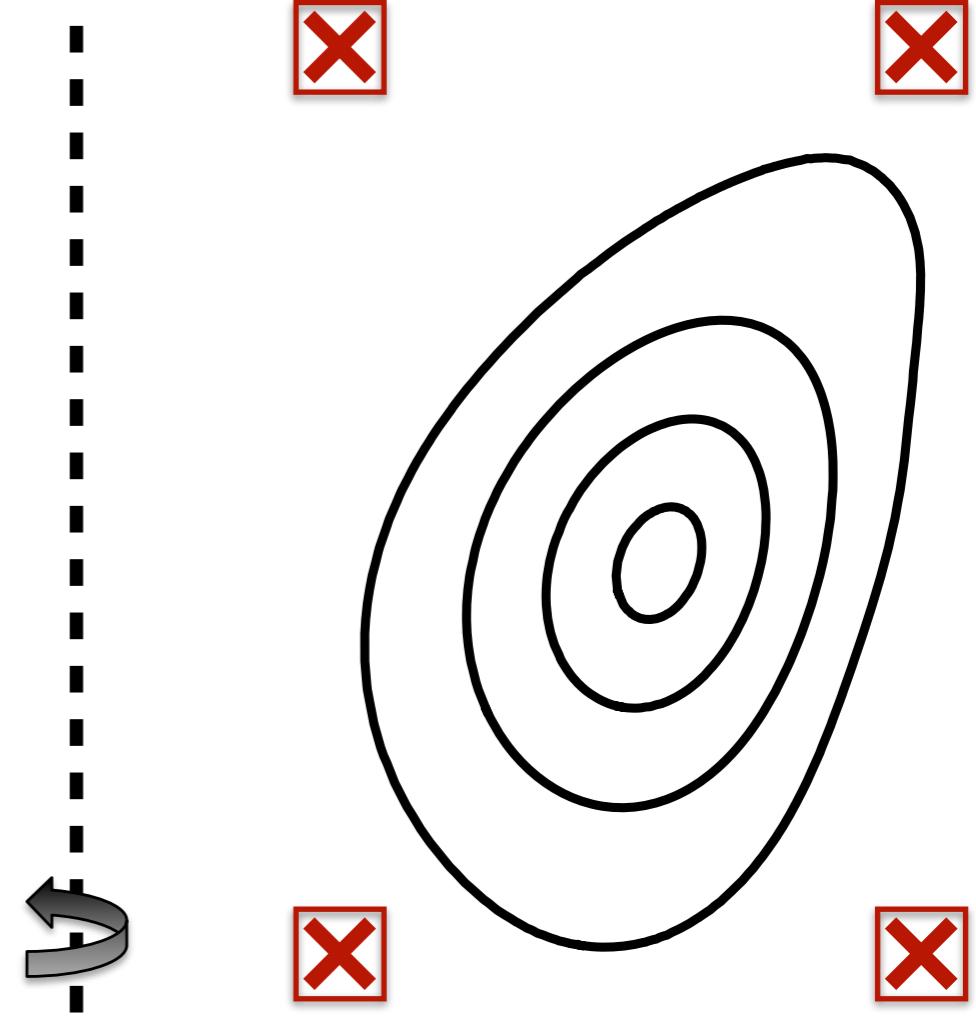
# Find practical shapes

- Grad-Shafranov eq. with simple current profile:  $R^2 \vec{\nabla} \cdot \left( \frac{\vec{\nabla} \psi}{R^2} \right) = \mu_0 j_\zeta R = \text{const}$
- To lowest order in aspect ratio, solutions are cylindrical harmonics:

$$\psi(r, \theta) = \frac{\mu_0 j_\zeta R}{4} r^2 + \sum_{m=2}^{\cancel{3}} C_m r^m \cos(m(\theta + \theta_{tm}))$$

**vacuum solution**

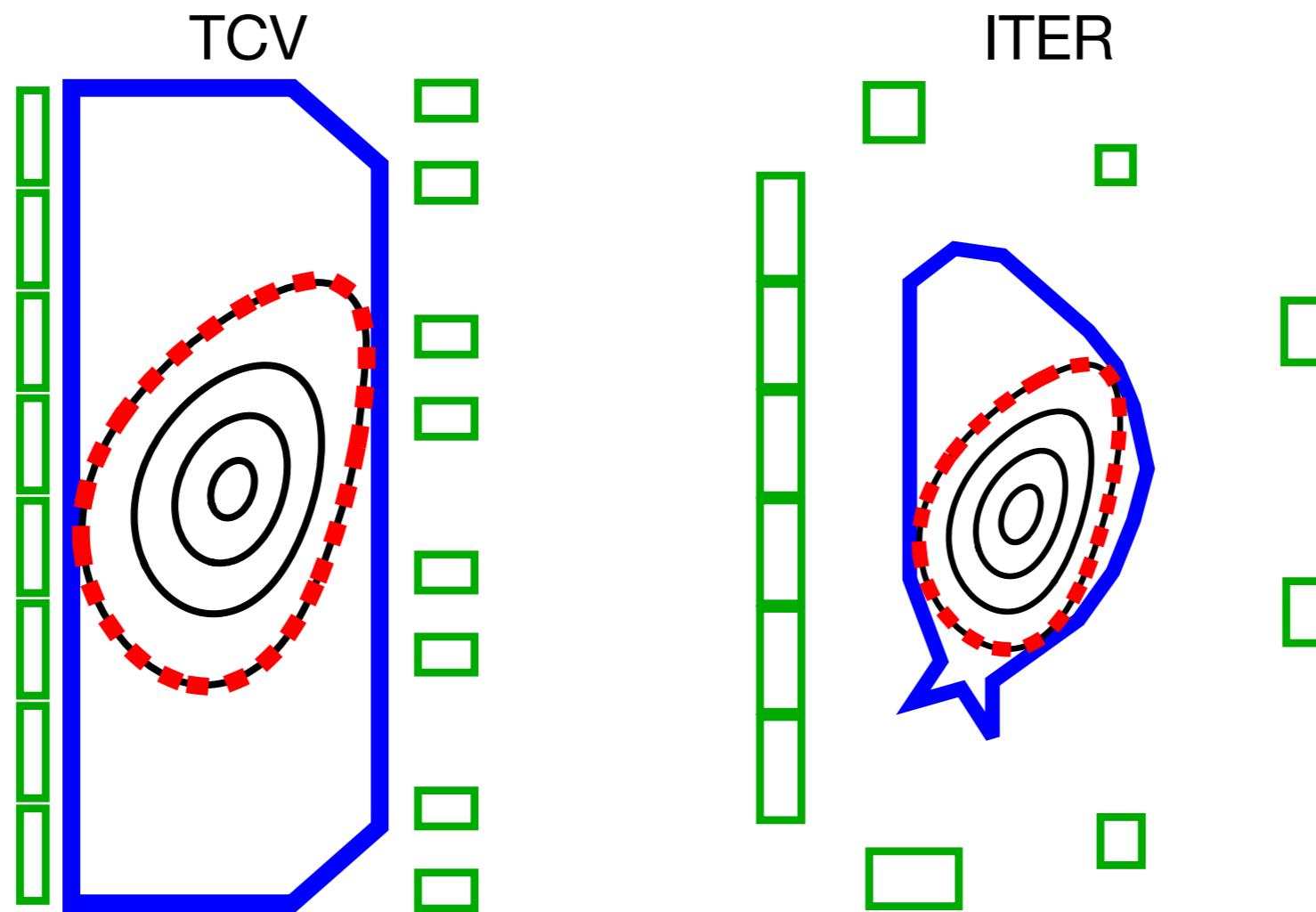
- Low harmonics will propagate most effectively across vacuum and plasma regions
- Invert cubic to find  $r(\psi, \theta)$ , the shape of each surface in the equilibrium



# Are these shapes practical?

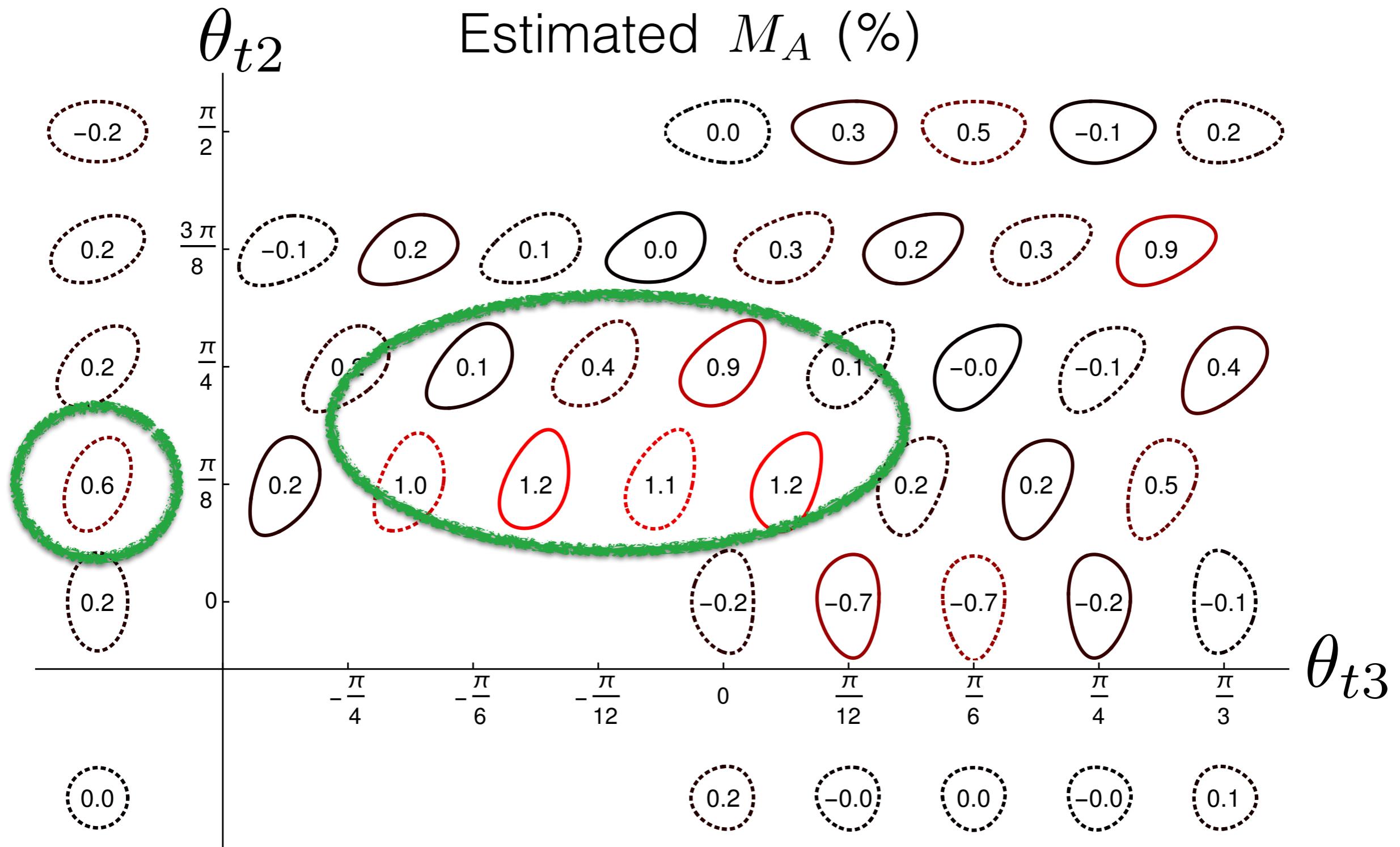
Landreman et al. *Phys. Plasmas* (2016).  
Hofmann et al. *Comput. Phys. Commun.* (1988).

- Use FBT or VMEC (with least-square solver) to find the coils currents needed to create our target shape
- Indicates that the TCV and ITER coil sets can create this shape:



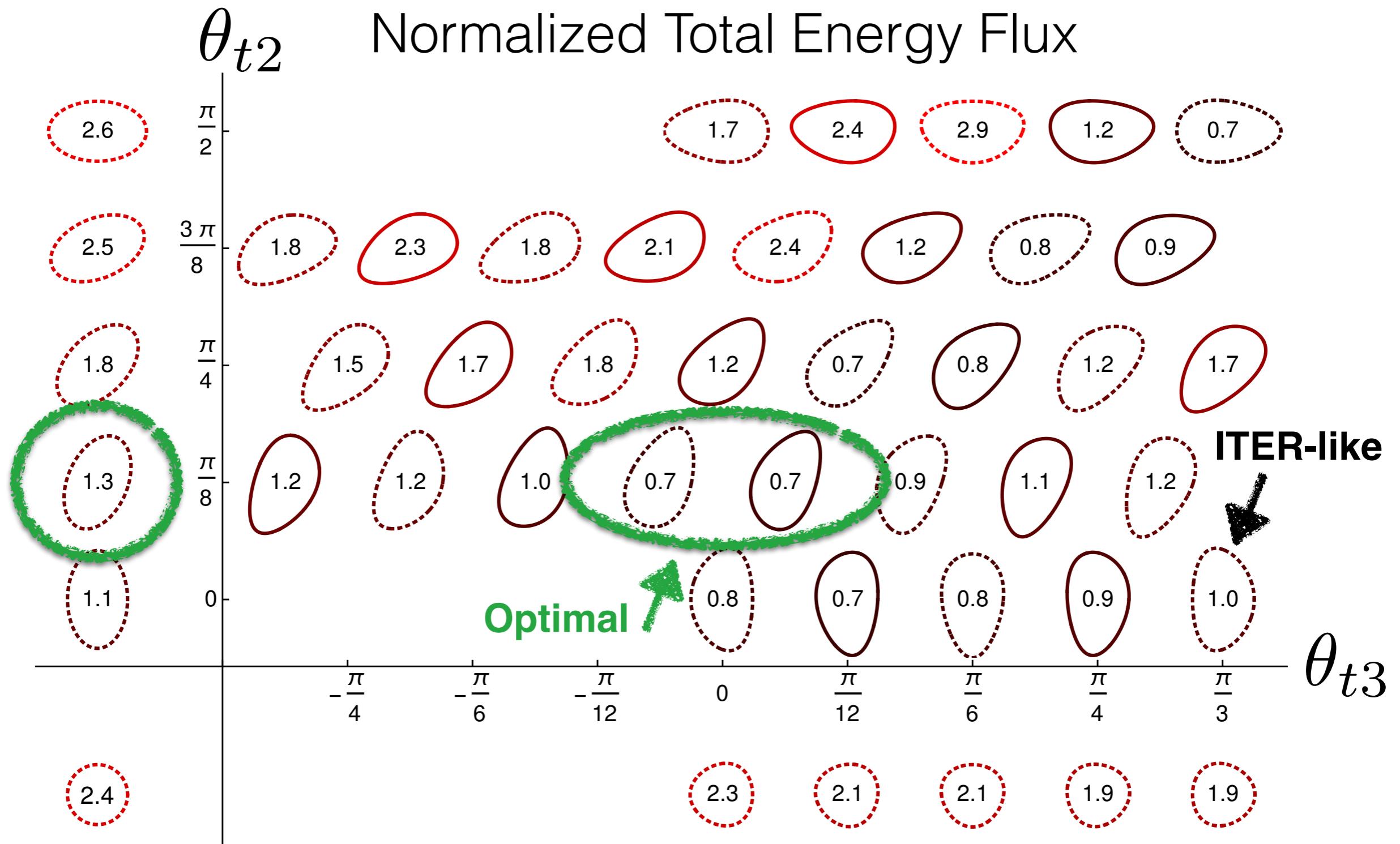
# Rotation in the more realistic shapes

J. Ball et. al. arXiv:1703.03375



# Energy confinement in the more realistic shapes

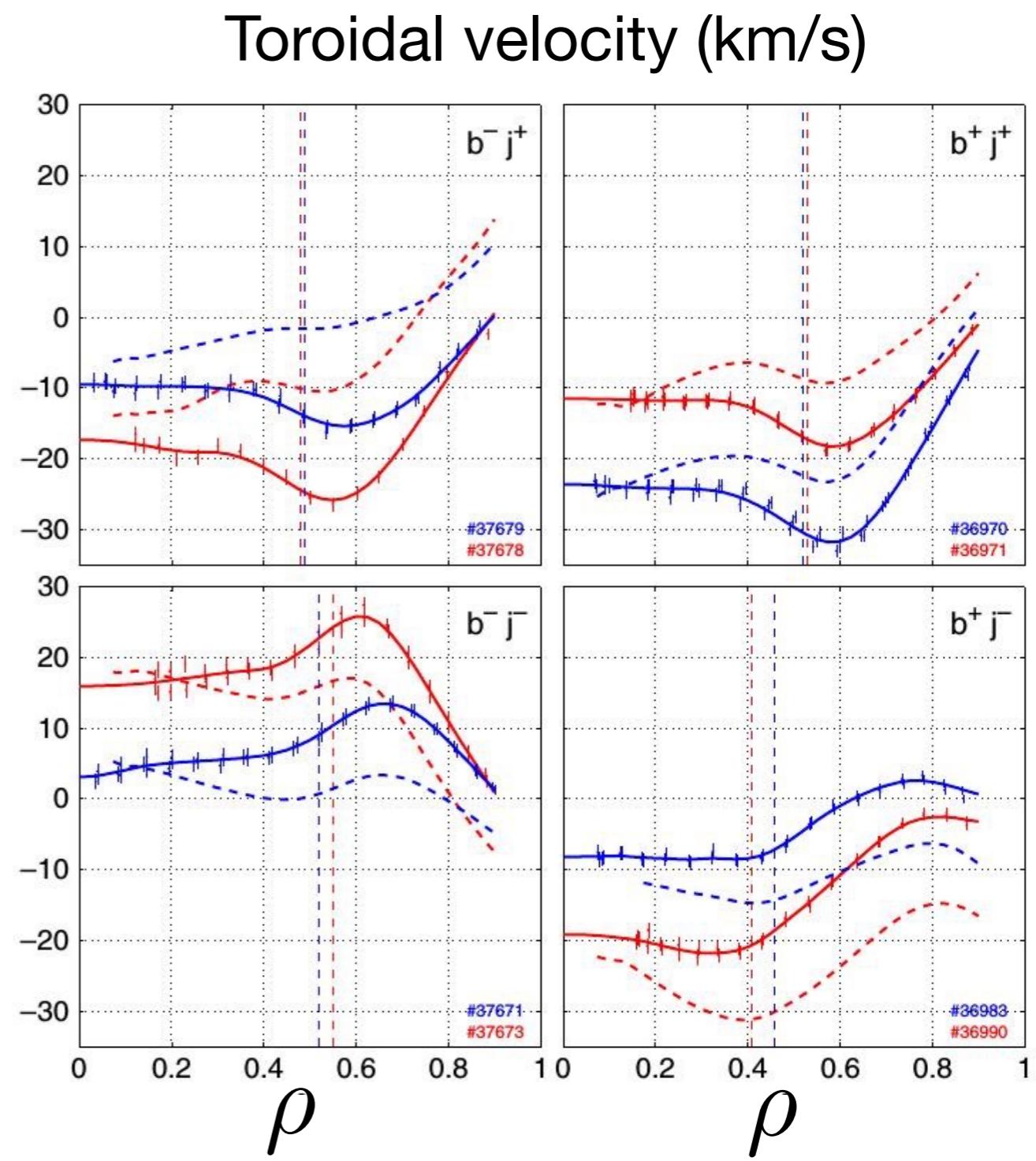
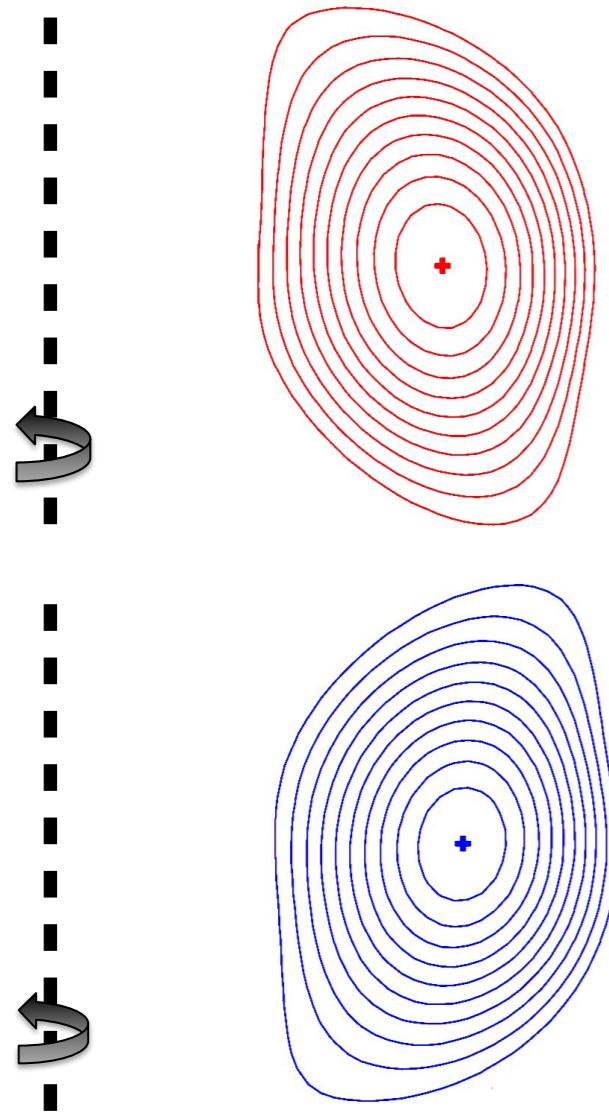
J. Ball et. al. arXiv:1703.03375



# Experimental confirmation

Camenen et al. *PRL* (2010).

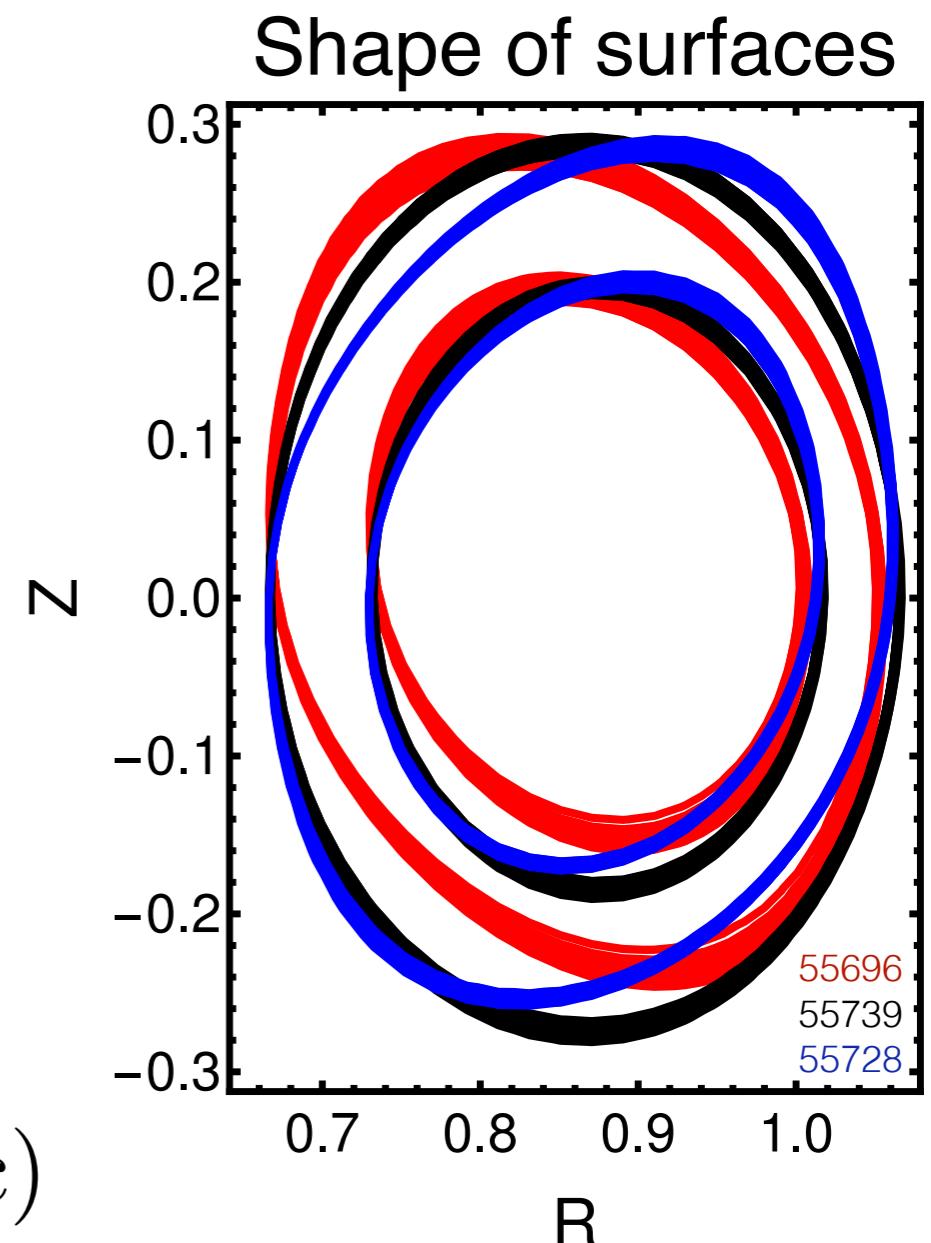
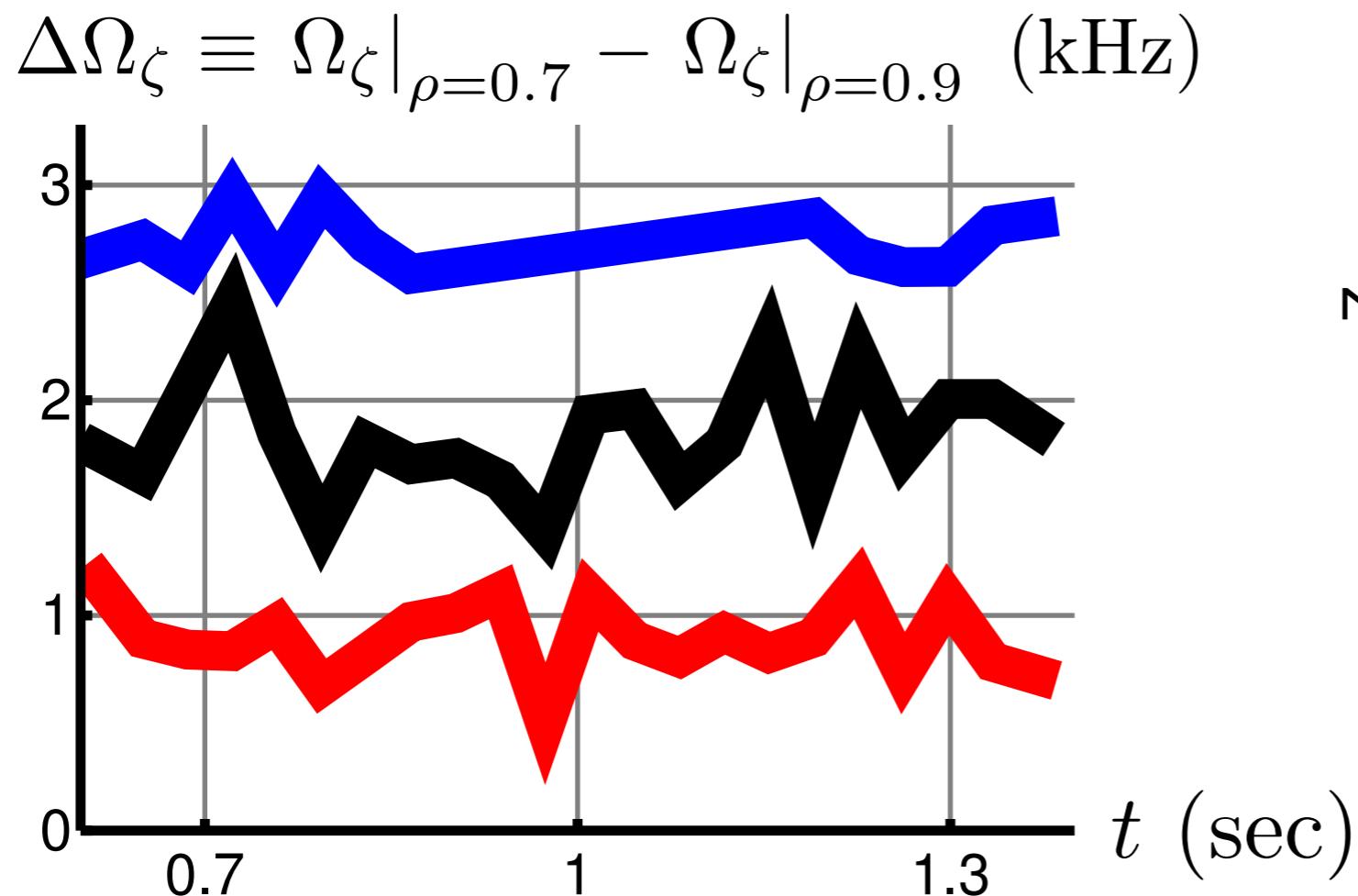
- TCV experiments by Camenen et al. observed intrinsic rotation from up-down asymmetry



# TCV exp. - shot-by-shot tilt scan

Camenen et al. *PRL* (2010).

- Change geometry between shots, while keeping experimental parameters fixed (e.g. current, density, temperature, etc.)
- Modest elongation magnitude of  $\kappa = 1.4$



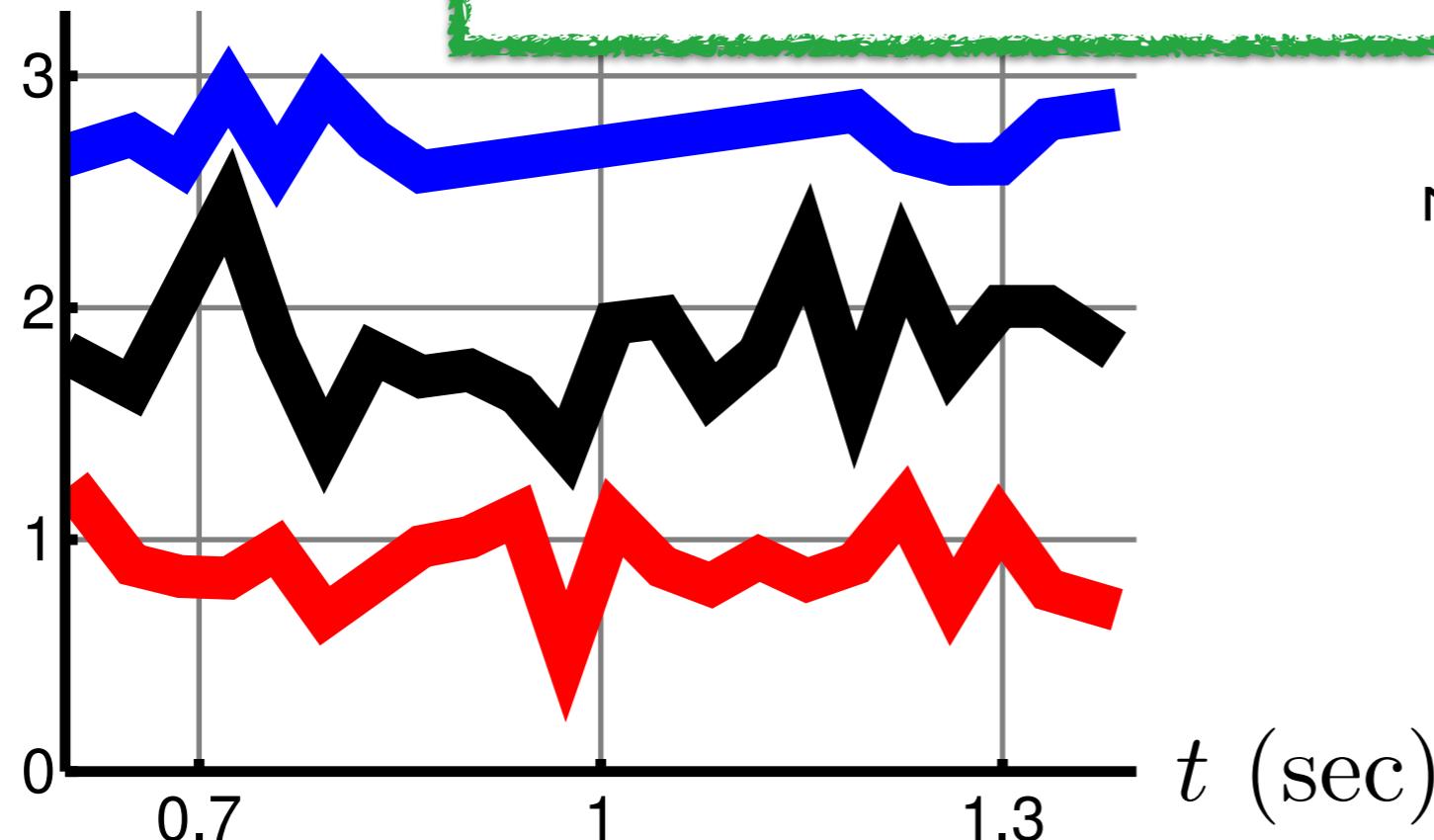
# TCV exp. - shot-by-shot tilt scan

Camenen et al. *PRL* (2010).

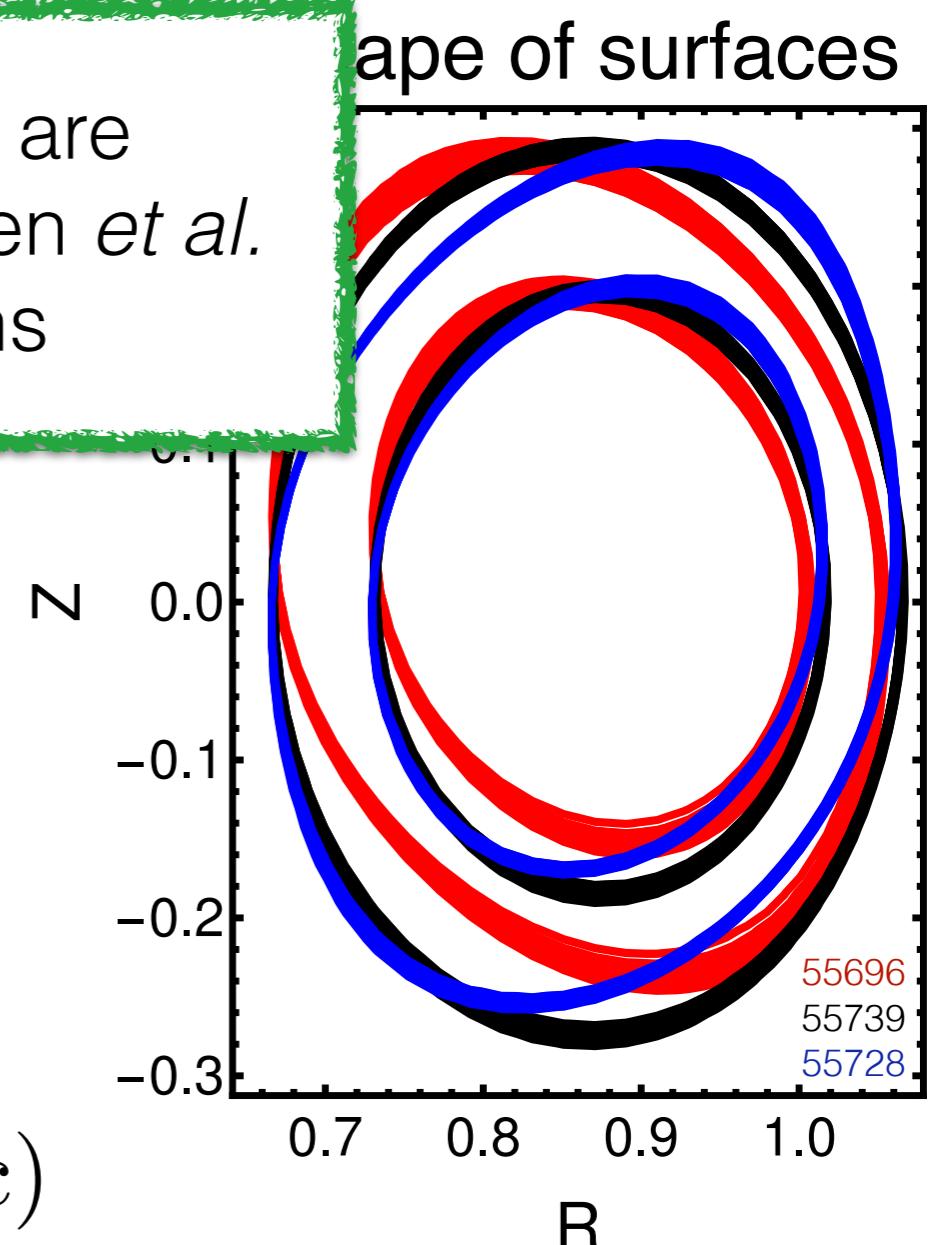
- Change geometry between shots, while keeping experimental parameters fixed (e.g. current, density, temperature, etc.)

- Modest elongation

$$\Delta\Omega_\zeta \equiv \Omega_\zeta|_\rho$$



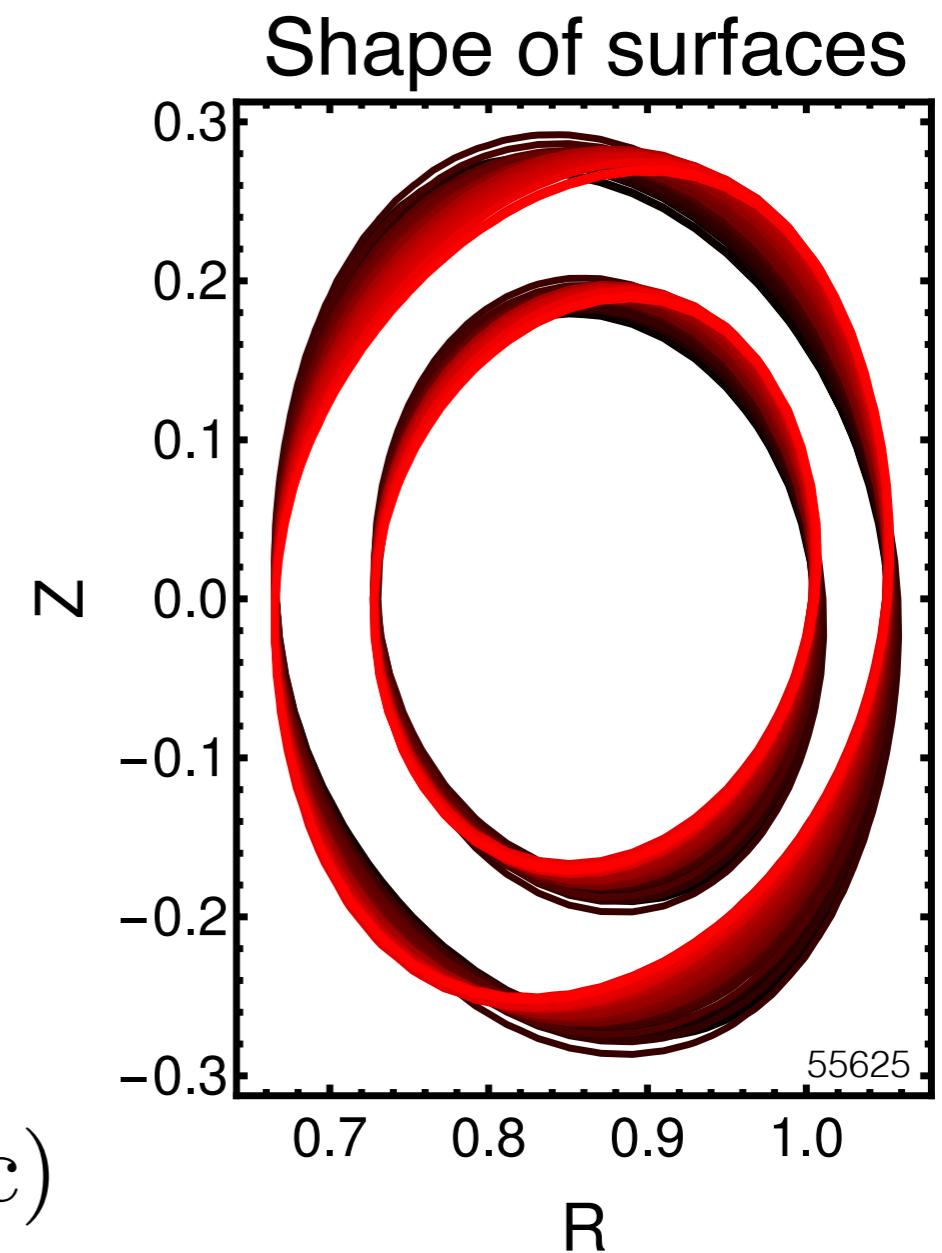
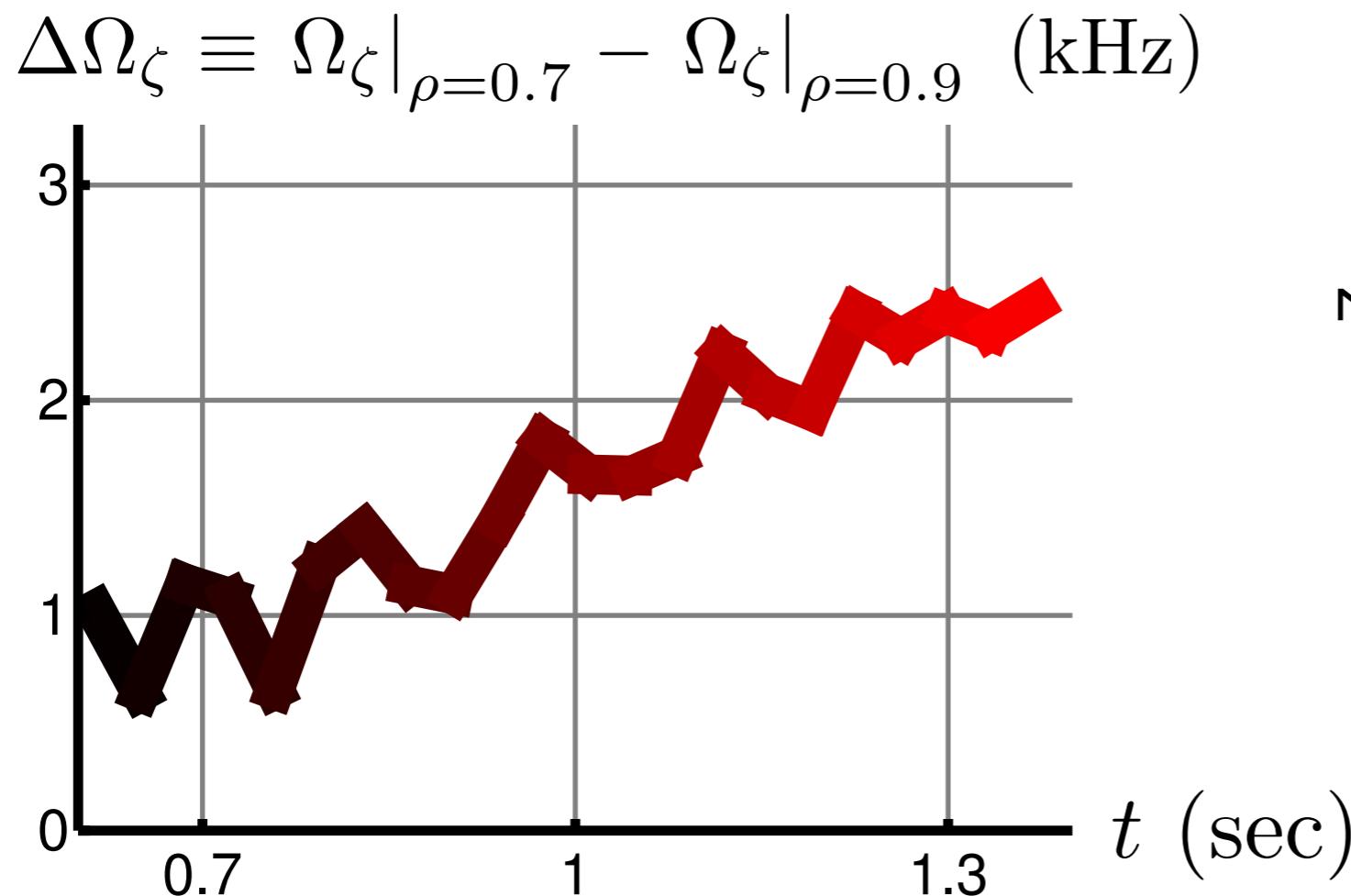
Sign and magnitude are  
**consistent** with Camenen *et al.*  
and our simulations



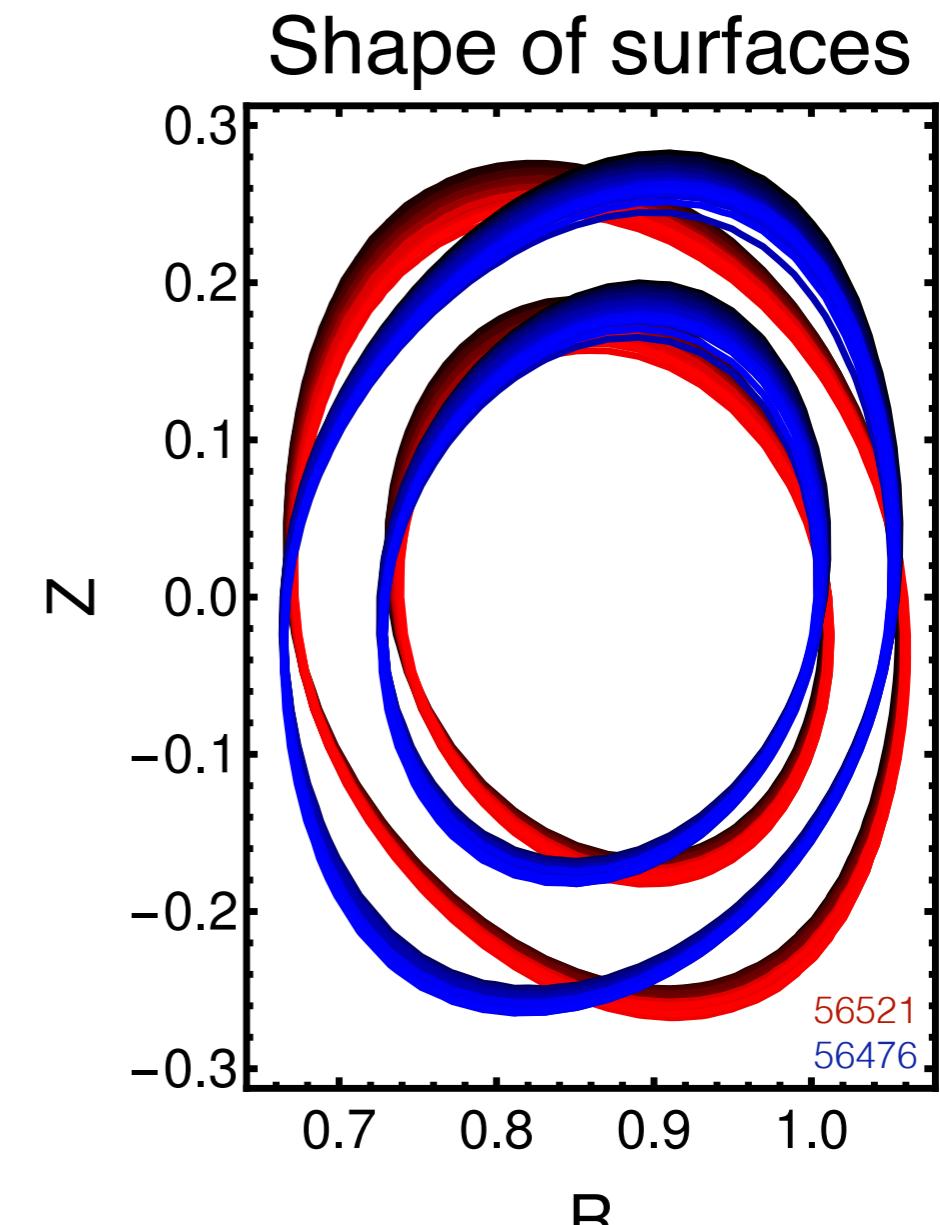
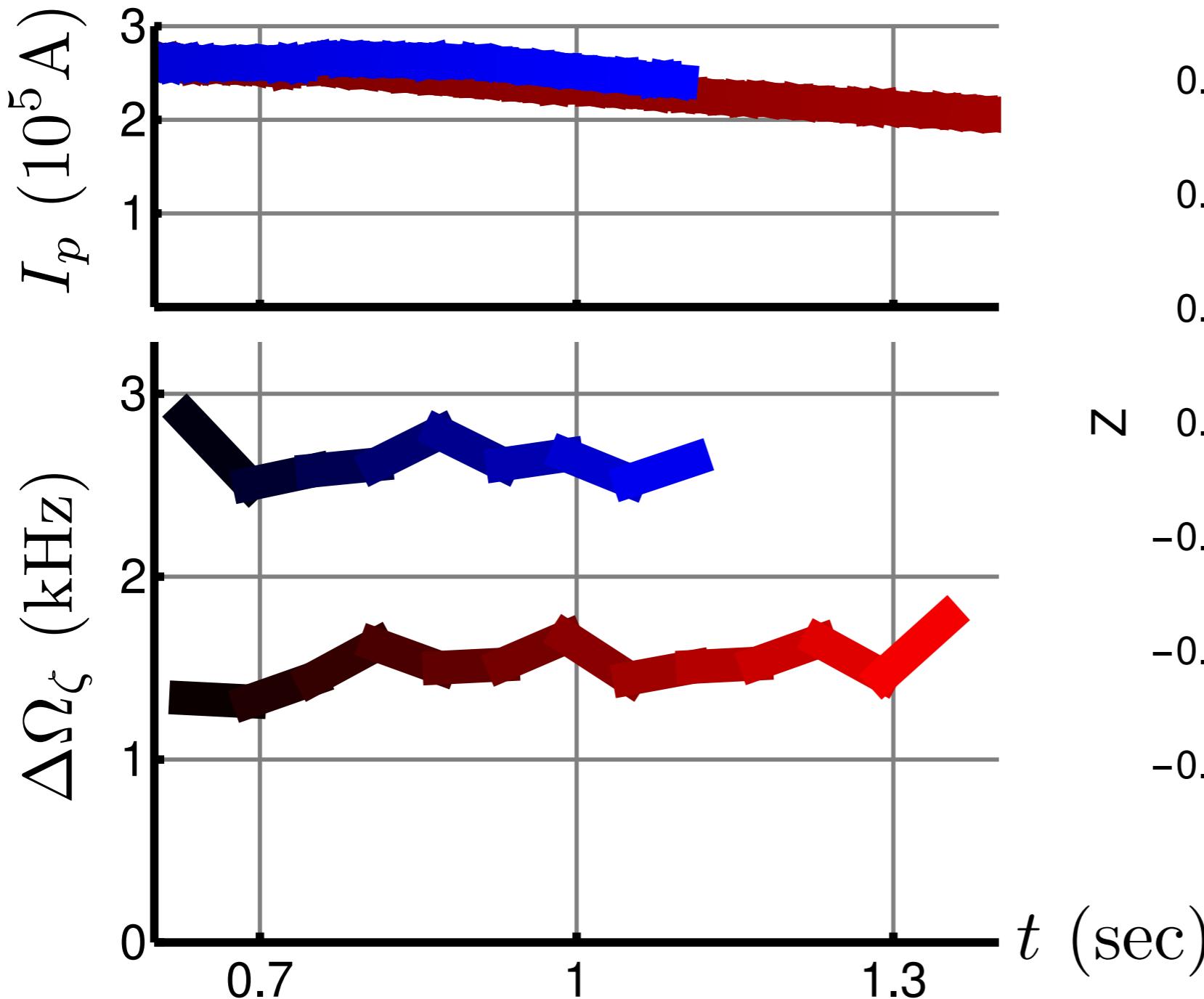
# TCV exp. - shot-by-shot tilt scan

Camenen et al. *PRL* (2010).

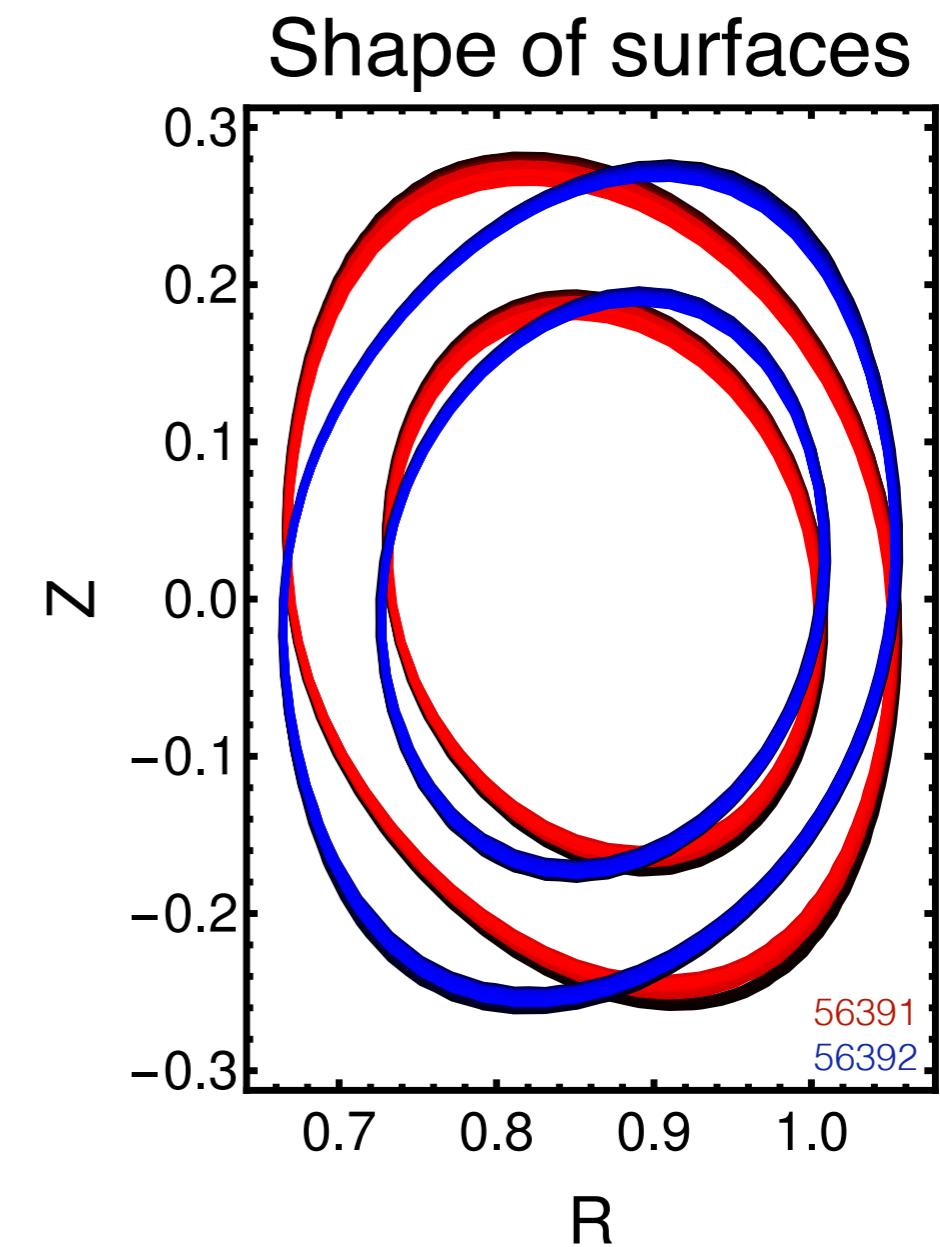
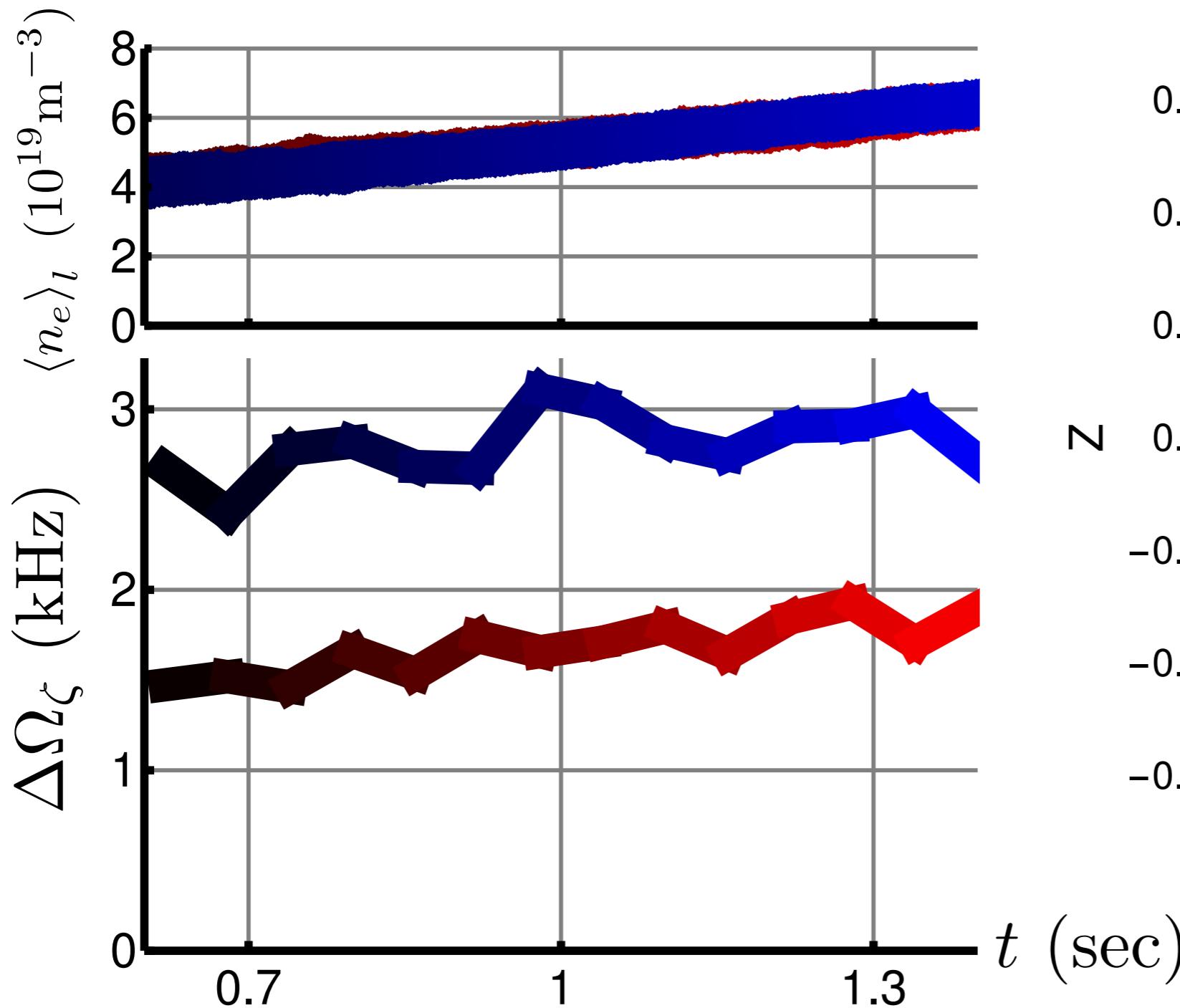
- Change geometry within shot, while keeping experimental parameters fixed (e.g. current, density, temperature, etc.)
- Modest elongation magnitude of  $\kappa = 1.4$



# TCV exp. - current scan within shot



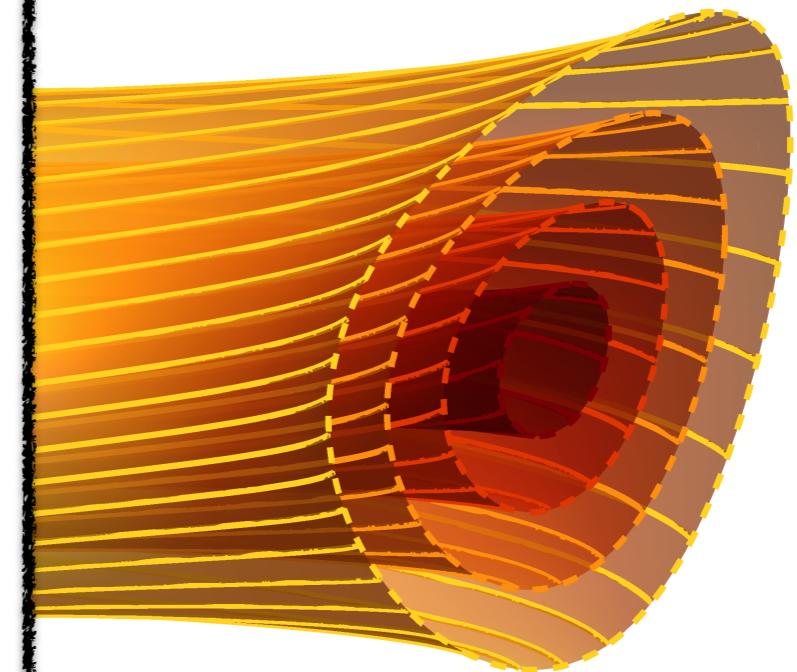
# TCV exp. - density scan within shot



# On-going work

- Experimentally create complex, optimized shapes
  - 4 shots, all failed for reasons unrelated to shaping
- Modified GENE to investigate momentum transport in up-down asymmetric geometries
  - Circular geometry gives similar results to GS2
  - Currently running tilted ellipse

The “optimal” geometry



$$\kappa = 1.63 \quad \theta_{t2} = \pi/8$$

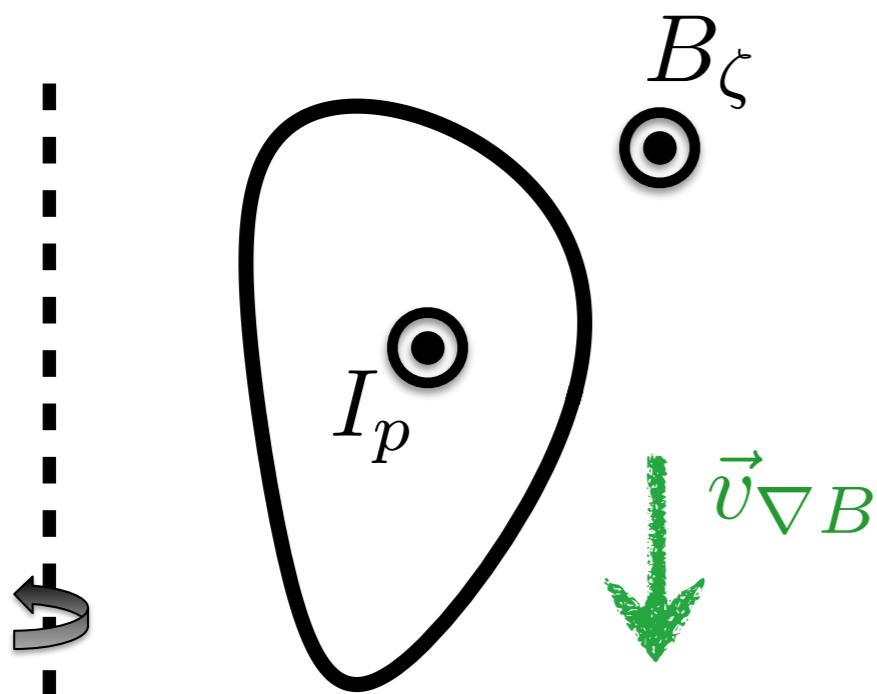
$$\delta = 0.3 \quad \theta_{t3} = 0$$

$M_A > 1\%$  in ITER

# Future work - transport bifurcations

Wagner et al. PPCF (2007).

- Role of rotation from up-down asymmetry in transport bifurcations
- H-mode power threshold is 3x lower when the ion  $\vec{\nabla}B$  drift is towards the X-point (i.e. **favorable**), not away (i.e. **unfavorable**)

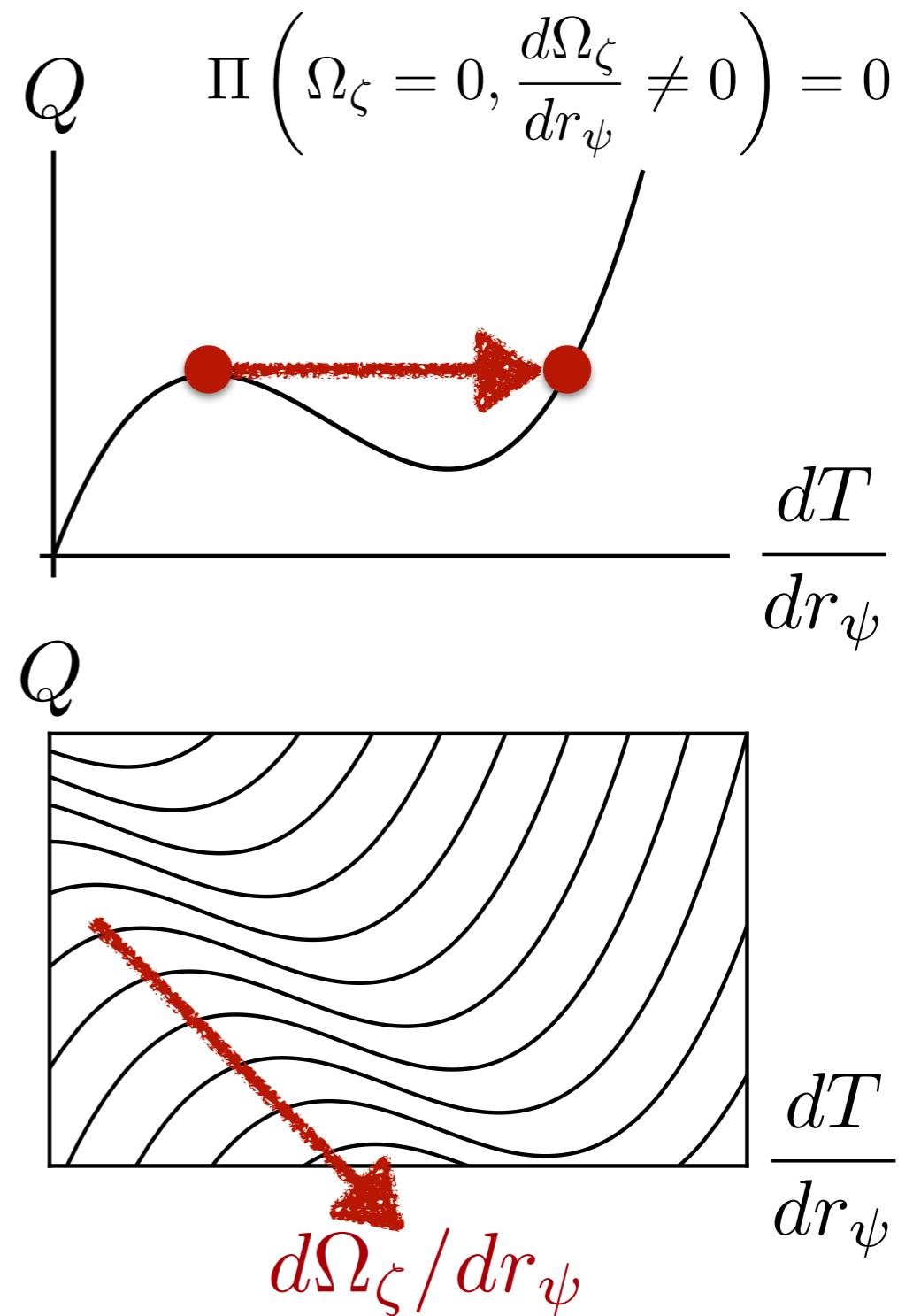


Sym. breaking mech.	$B_\zeta$	$I_p$	u-d refl.
Ion $\vec{\nabla}B$ favorability	-	+	-
Up-down asym.	-	-	-
Radial profile var.	+	-	+
Neoclassical			
Turb. acceleration			
Finite orbit widths			
Neutrals			???

# Future work - transport bifurcations

E. Highcock. PhD thesis, Oxford (2012).

- Investigate in “optimal” geometry using:
  - Scan temperature gradient, setting the flow shear to cancel the momentum flow
- OR
- Perform full two-dimensional scan in temperature gradient and flow shear (à la Highcock)
- How close to the X-point?



Thank you!