Verification and Validation of Particle Simulation of Turbulent Transport in FRC

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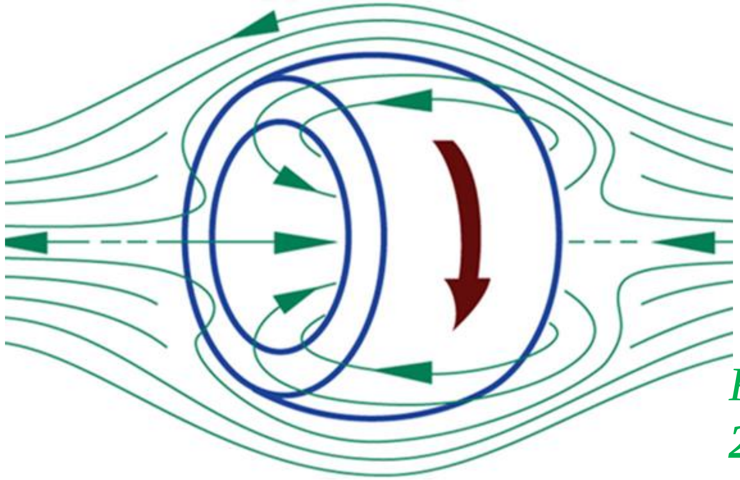
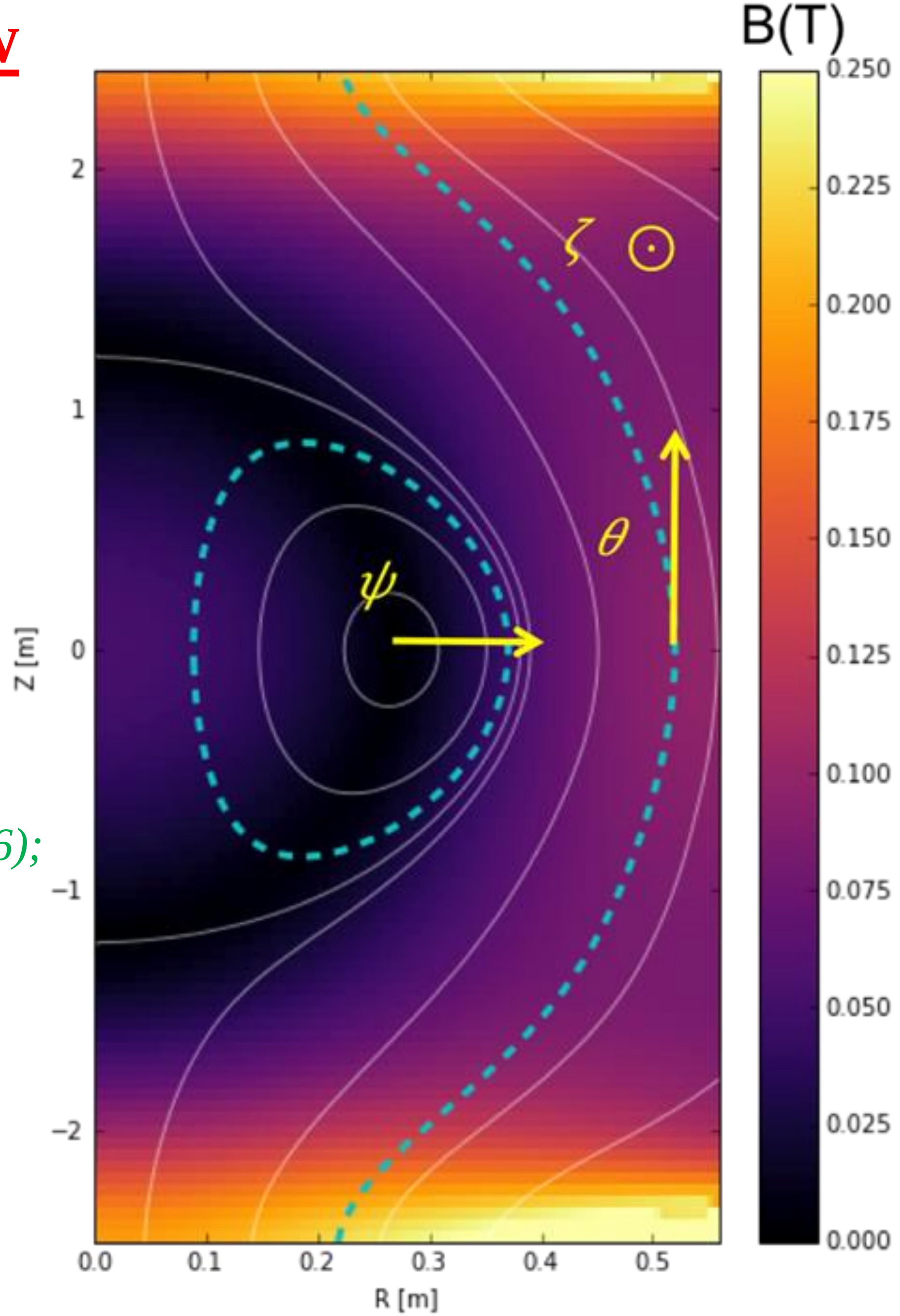
What cause turbulent transport in FRC and how does confinement extrapolate to a reactor?

- Low frequency (< ion cyclotron frequency) fluctuations observe by Doppler Backscattering (DBS) in C-2 FRC
- Gyrokinetic model valid in SOL and in outer part of FRC core: $<\rho_i/L_B>\approx 0.2$ (core), $<\rho_i/L_B>\approx 0.006$ (SOL)
- Gyrokinetic toroidal code (GTC) [*Lin et al, Science, 1998*] upgraded to simulate microturbulence in FRC



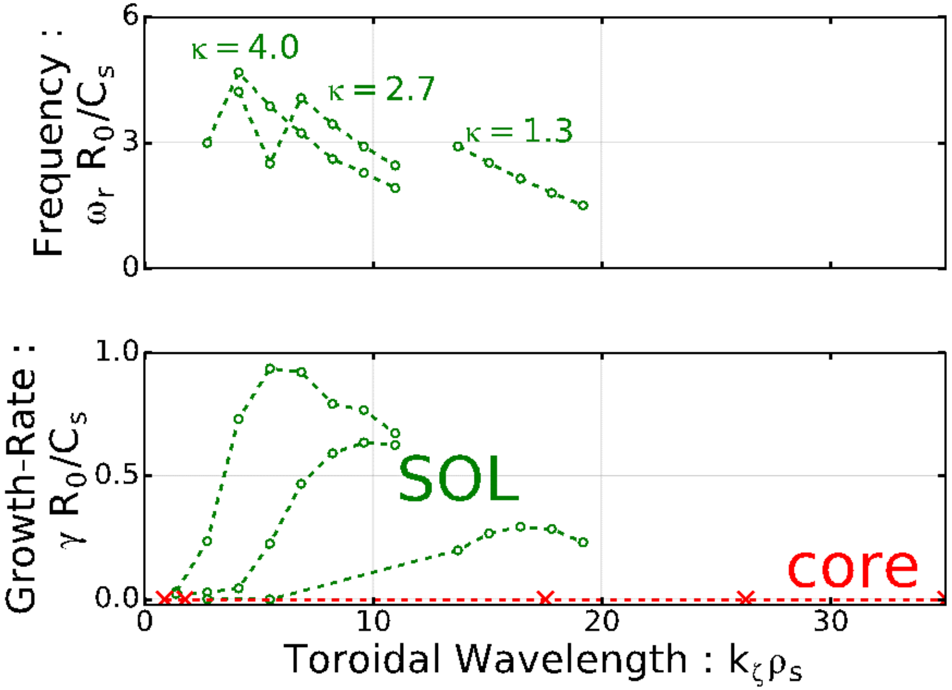
Rostoker, et al, Science ***278****, 1419 (1997)*

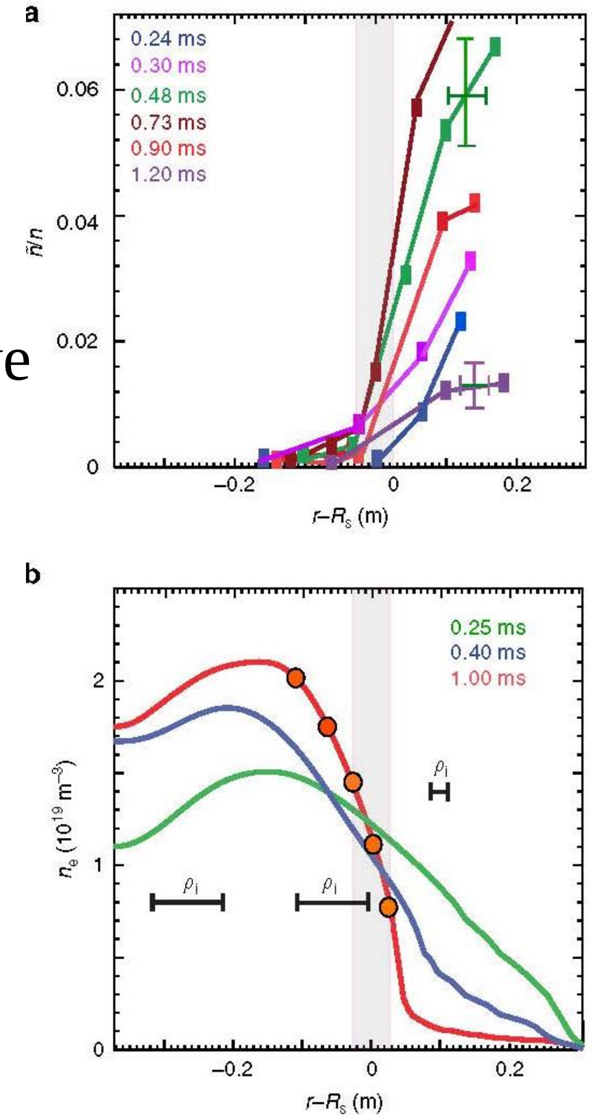
Fulton et al, PoP ***23****, 012509 (2016); PoP* ***23****, 056111 (2016)*

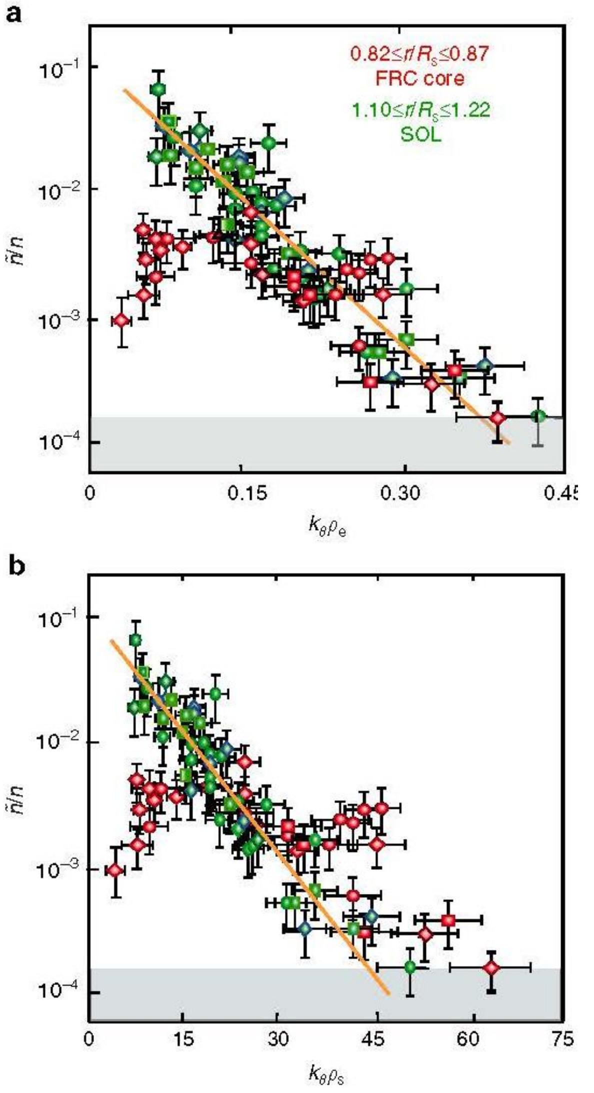


Ion-scale driftwave stable in FRC core

- DBS finds ion-scale fluctuations (most detrimental to confinement) strongly suppressed in the core, resulting in a nearly classical ion thermal confinement
- GTC local simulations find core driftwave stabilized by magnetic pressure gradient, large Larmor radius, short field lines





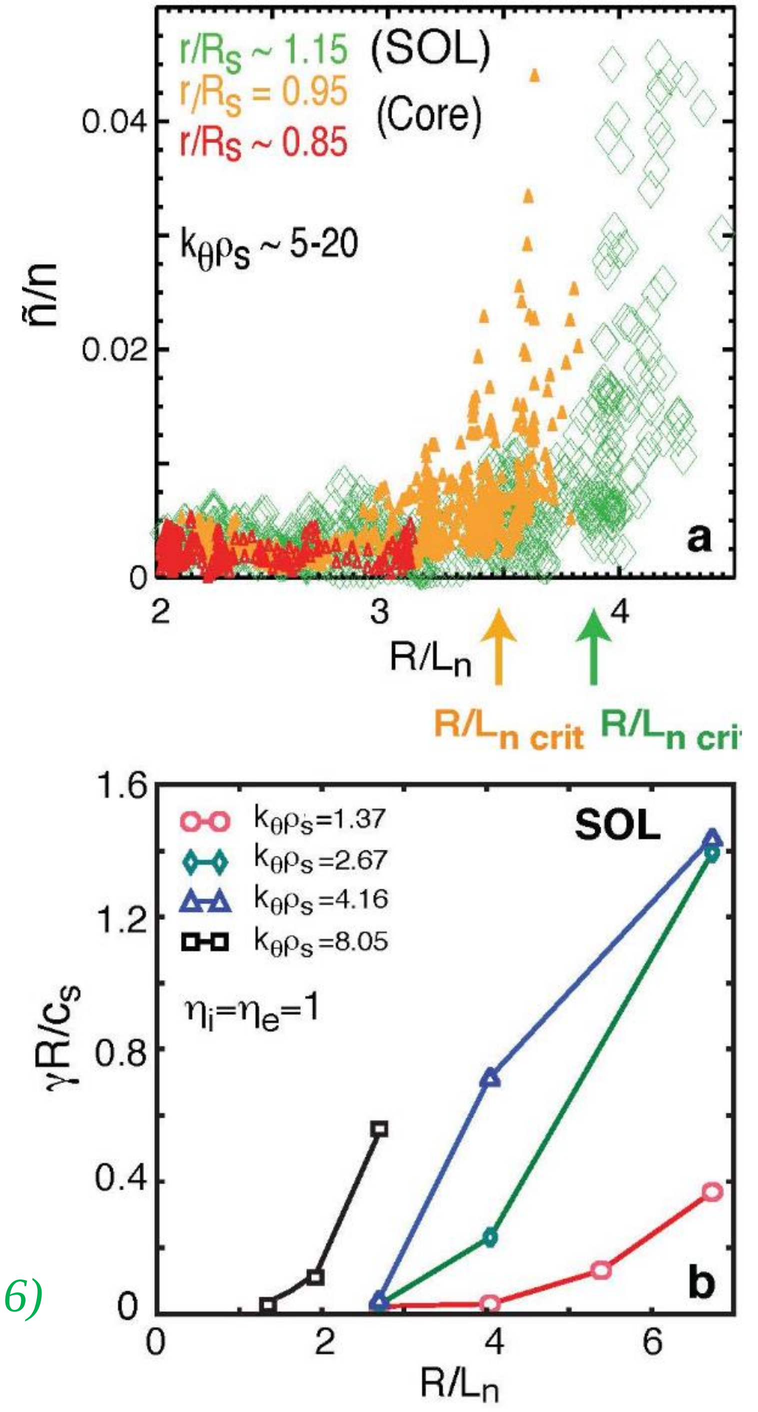


*Lau et al, PoP **24**, 082512 (2017)*

Ion-to-electron scale drift-interchange modes unstable in SOL

- In C2 FRC SOL, ion- and electron-scale turbulence is observed once a critical pressure gradient is exceeded
- Critical gradient increases in the presence of sheared plasma flow induced via electrostatic biasing (ExB shearing)
- DBS radial cross-correlation of SOL density fluctuations confirm that the observed SOL turbulence is indeed responsible for radial plasma transport
- GTC local simulations find SOL drift-interchange modes unstable with critical pressure gradient, agree qualitatively with C-2 FRC data. Collisions are stabilizing

*Schmitz et al, Nature Communications **7**, 13860 (2016)*

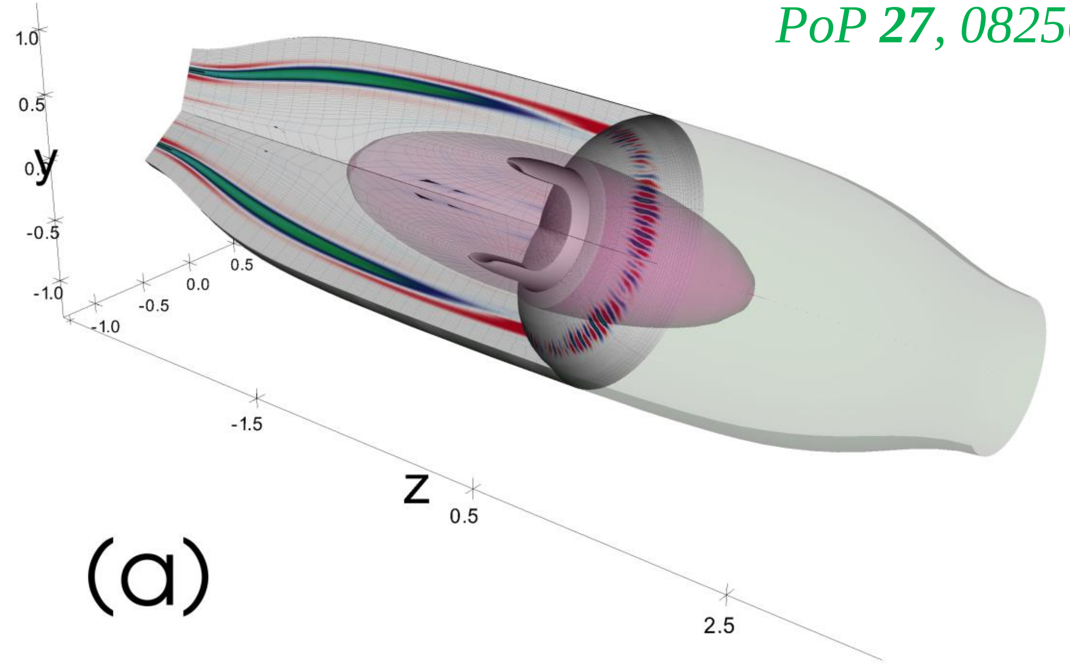


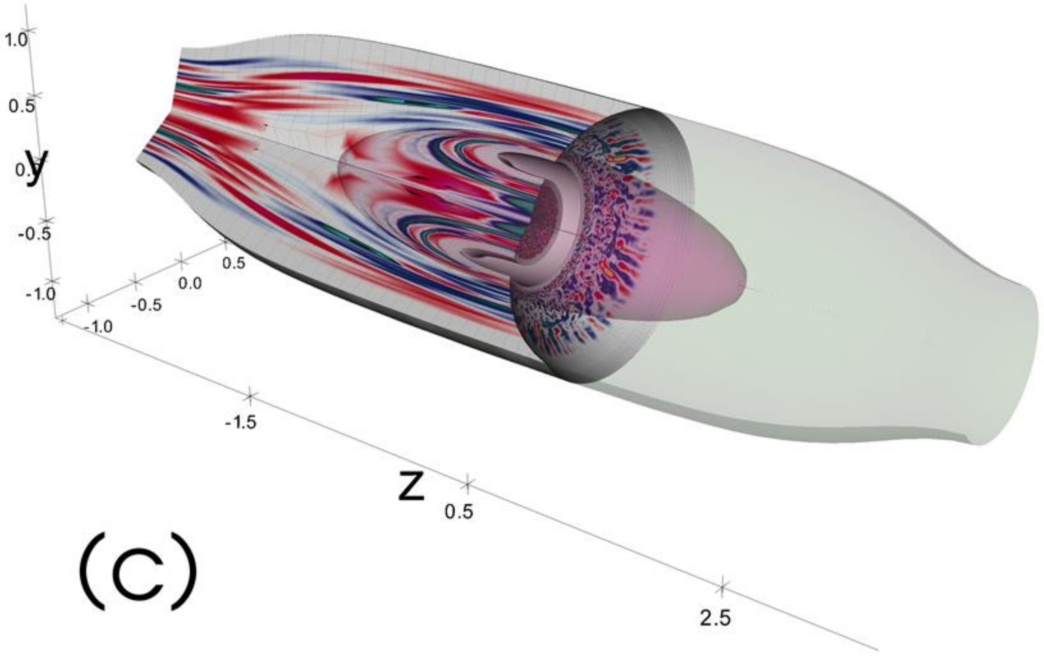
Global ANC gyrokinetic simulations find turbulence spreading from SOL to core in C-2U FRC

Linear instability grows in SOL while core stays stable

After SOL instability saturates, turbulence spreads to core

*Lau et al., NF **59**, 066018 (2019); PoP **27**, 082504 (2020).*





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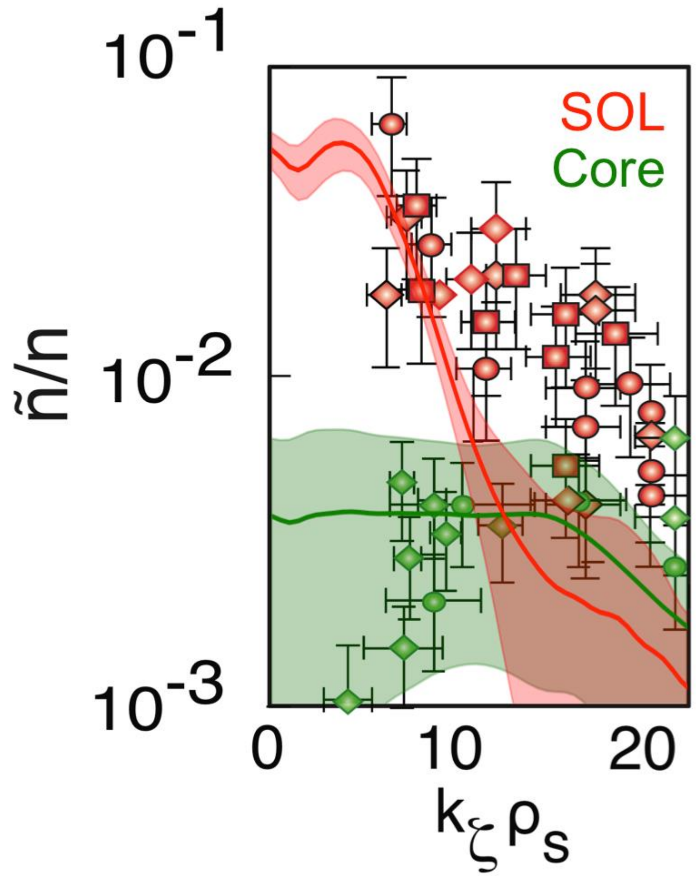
ANC simulation[1] compared to C-2U experiment[2]

- **Instability in SOL**
  - Source of turbulence
  - Inverse cascade from high to low wavenumbers
- **Core is stable**
  - Turbulence spreads from SOL to core
  - Lower amplitude in core from balance of damping mechanisms and spread rate from SOL

[1] C. Lau et al, Nuclear Fusion (2019)
[2] L. Schmitz et al, Nature Communications (2016)



Lines (-): simulation results
Shapes (■): exp. measurements[2]

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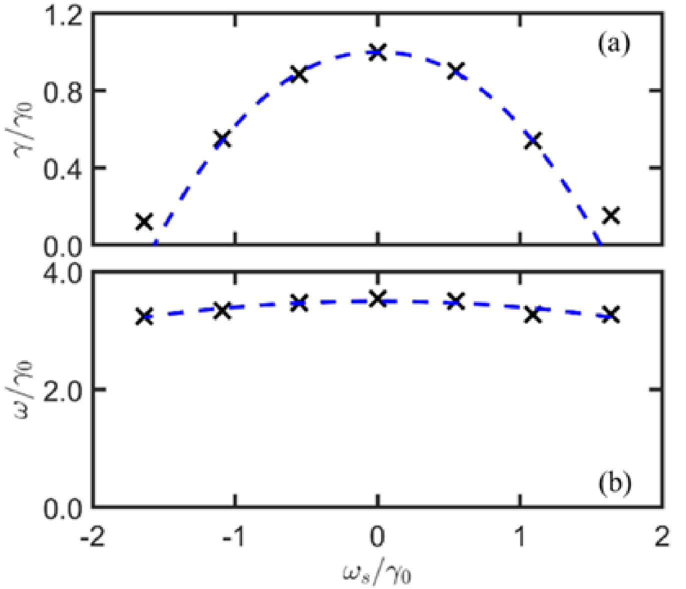
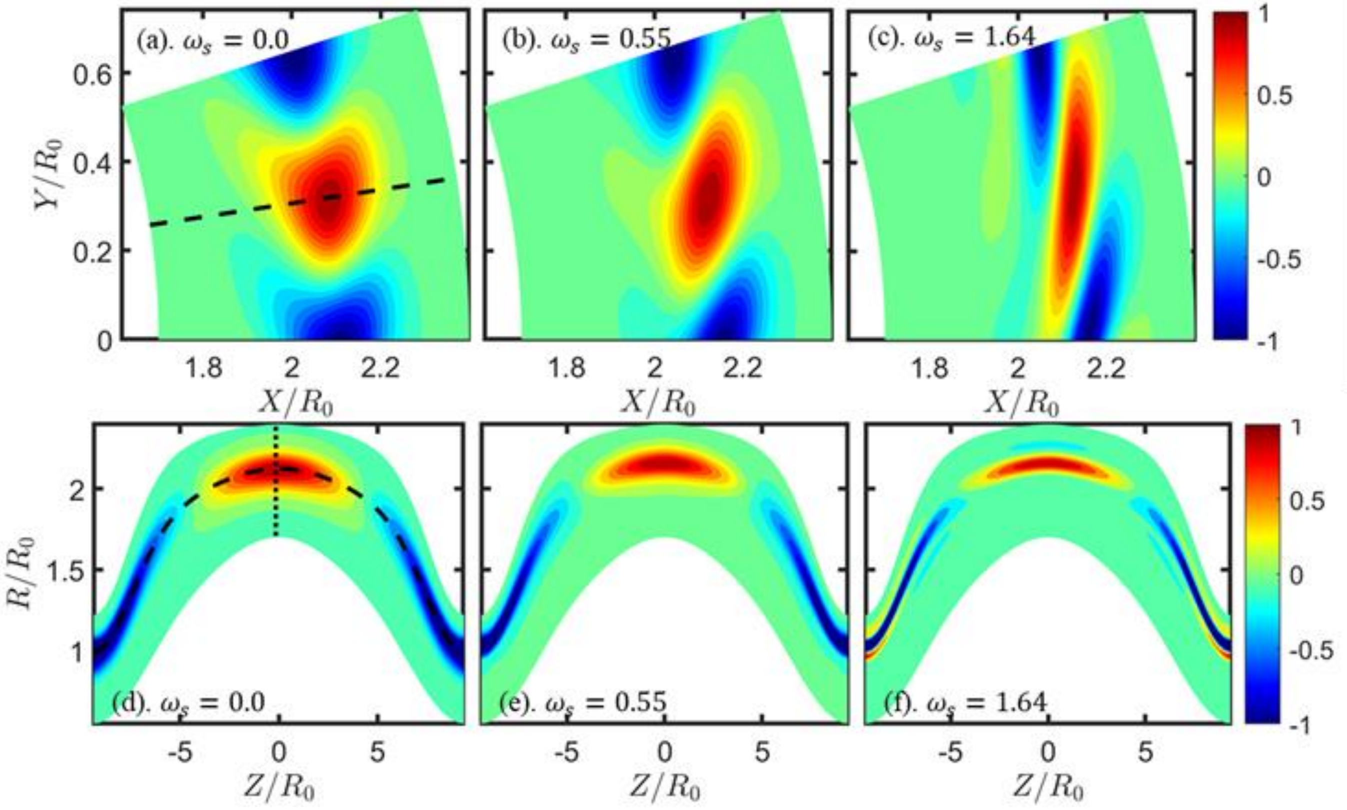
GTC-X gyrokinetic simulations find equilibrium electric field shear stabilizes ITG in FRC SOL

- GTC-X [*Bao et al, PoP* ***26***, *042506 (2019)*] gyrokinetic simulations of ITG in FRC SOL
- Equilibrium E×B flow shear reduces ITG growth rate γ
- Stabilization by tilting mode structure on toroidal plane and reducing radial mode width on poloidal plane
- Maximal growth rate with an un-tilted mode structure occurs when radial shear of Doppler-shifted local mode frequency is zero



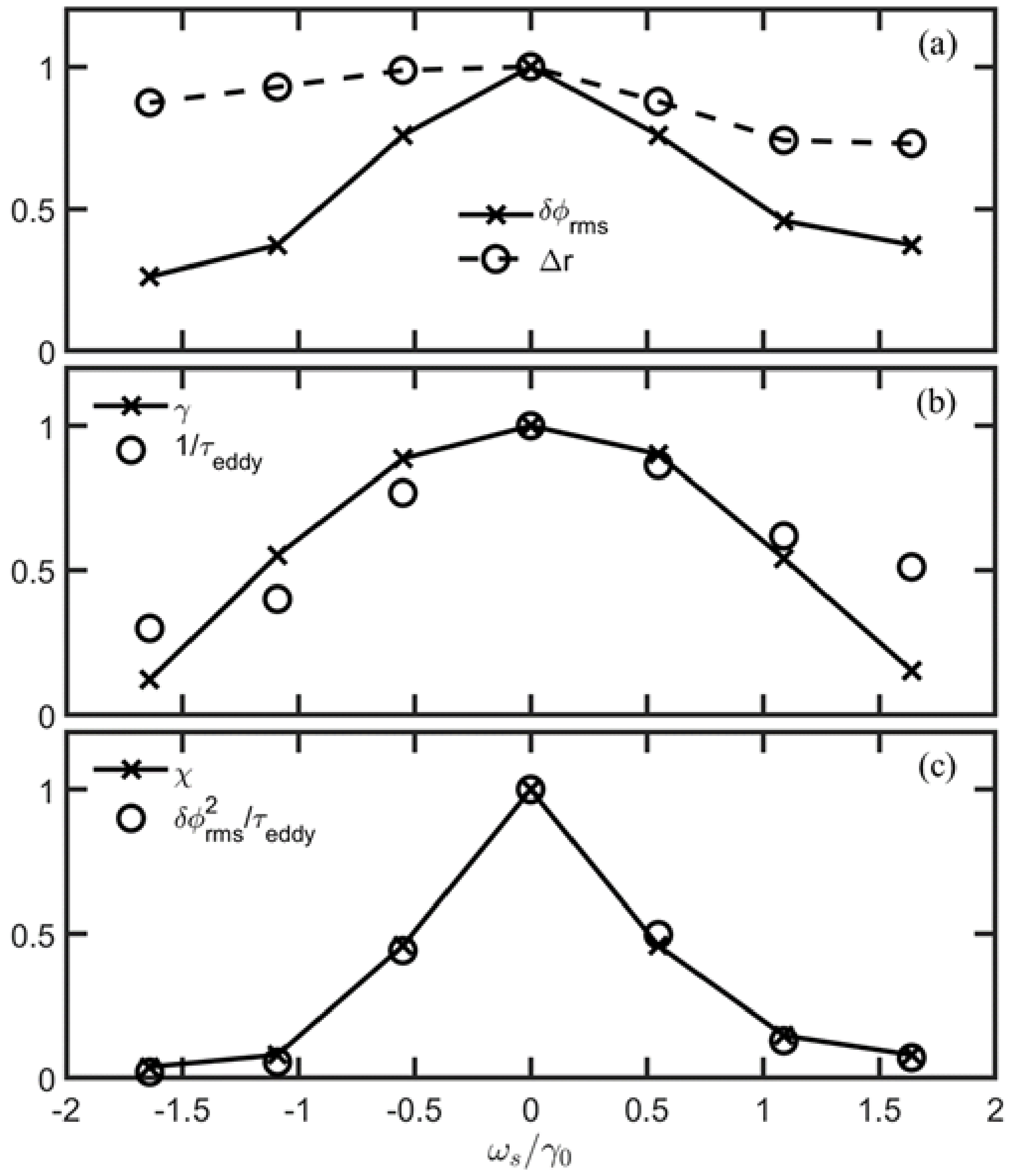
[*Wang et al, PPCF* ***63***, *065001 (2021)*]



E×B flow shear reduces ion heat transport by reducing both turbulence intensity and eddy size

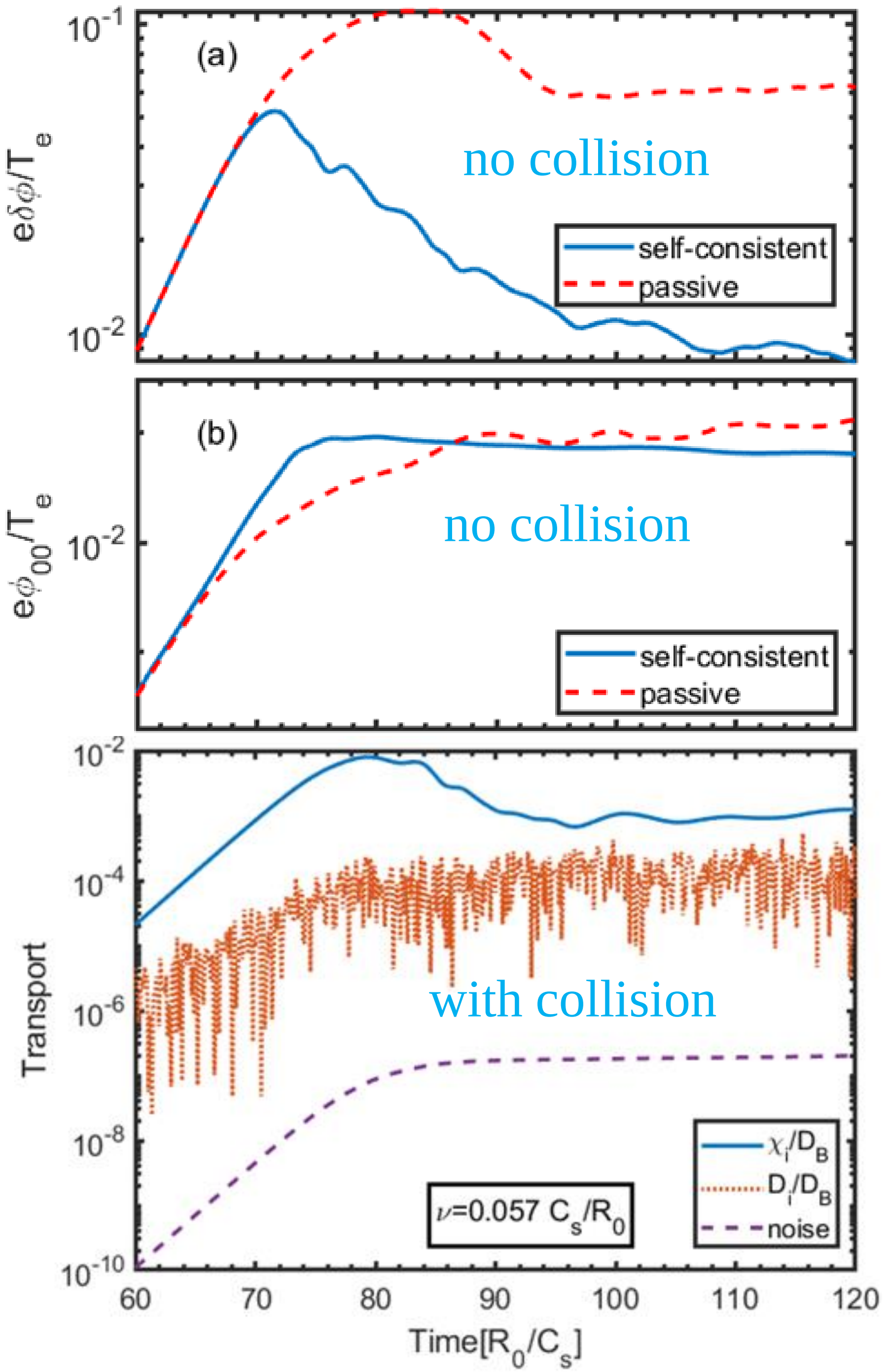
- Fluid eddy rotation is dominant saturation mechanism for ITG instability in the absence of zonal flows
- Parallel wave-particle decorrelation is dominant mechanism for ITG turbulent transport
- Random walk model using guiding center radial excursion as characteristic length scale and eddy turnover time as characteristic time scale
- Simulations suggest maximizing radial shear of Doppler-shifted local mode frequency can effectively suppress ITG instability and associated transport in the FRC SOL

[Wang et al, PPCF ***63****, 065001 (2021)]*



Zonal flows are dominant mechanism for nonlinear saturation of ITG instability

- GTC-X gyrokinetic simulations of ITG in FRC SOL find zonal flows are nonlinearly generated
- Zonal flows remain undamped and gradually suppress turbulent transport to a very low level
- Collisional damping gradually reduces zonal flow amplitude to a lower level, which allows finite ITG turbulence intensity and ion heat transport in SOL
- Differences of zonal flow dynamics in FRC and tokamak:
  - ZF in FRC has no collisionless damping due to lack of toroidal magnetic field, while in tokamak is quickly damped due to magnetic pumping effects
  - Collisional damping of ZF in FRC is due to viscosity (weaker classical diffusion), while in tokamak due to fiction between trapped and passing ions (stronger neoclassical effects)



Energy confinement time increase with plasma temperature

- GTC-X simulations find steady state turbulence intensity and ion heat transport proportional to collision frequency
- Similarly favorable transport scaling has been experimentally observed in the FRC experiments and NSTX spherical tokamak
- To improve plasma confinement in FRC, collisions should be minimized (e.g., higher temperature, lower impurity content etc) and breaking of toroidal symmetry (e.g., ripple fields, macroscopic MHD activities etc) should be avoided

[Wei et al, submitted to NF (2021)]