Electrostatic drift-waves in the FRC: destabilized in the scrape-off layer, robust stabilization in the core

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Outline

1. Simulation code and parameters

2. Core stability

3. Scrape-off layer instability

4. Coupled Core-SOL and Fully Kinetic Ions

Gyrokinetic Toroidal Code (GTC) for FRC simulations

GTC is a first-principles, integrated simulation code which has been extensively used for simulations of kinetic-MHD processes such as microturbulence, energetic particles, magneto-hydrodynamics (MHD), neoclassical effects, and RF heating/current drive

➢ **Upgrades for FRC simulations**

- Realistic C2 equilibrium
- Wedge poisson solver
- Core-SOL coupling

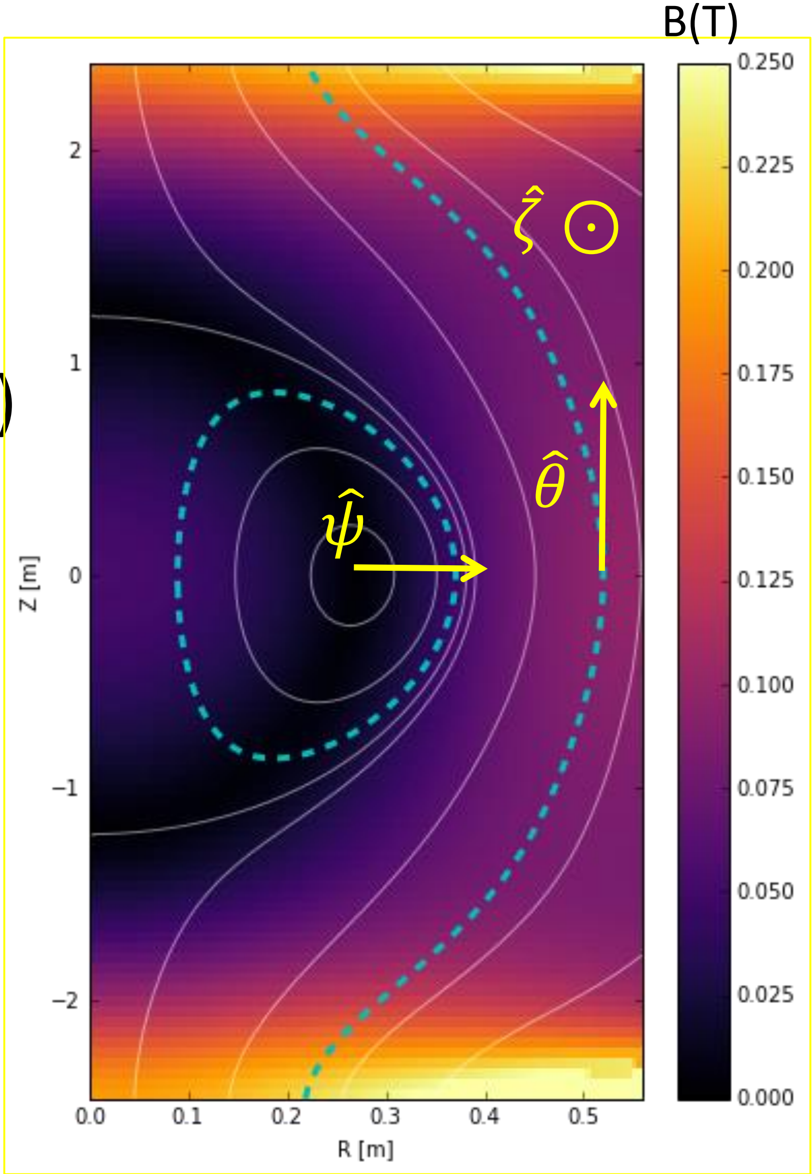
➢ **Capabilities include**

- General 3D geometry & experimental profiles
- Kinetic electrons & electromagnetic fluctuations
- Gyrokinetic or fully kinetic ions
- Equilibrium current
- Neoclassical effects
- Multi-level, hybrid-MPI/OpenMP parallelization up to 10^5 cores
- Ported to GPU (titan) & MIC (tianhe-2)

Realistic C-2 FRC equilibrium

- ➢ Realistic C-2 model equilibrium provided by *S. Dettrick* via modified **'Lamy-Ridge'** equilibrium code translated → into field-aligned mesh in Boozer Coordinates
- ➢ Local simulation geometry (worst case senario)
  - Periodic in θ
  - Local in ψ ($k_\zeta \gg k_r$), dashed cyan lines
  - Periodic in ζ
- ➢ Core and SOL only simulated separately* in work shown in this talk (new capabilities for core-SOL coupling developed and verified)

* D. Fulton et al, "Gyrokinetic particle simulation of a field reversed configuration", Phys. of Plasma 23, 012509 (2016)



Simulation Parameters

- Gyro-kinetic deuterium and electron (with Fokker-Planck collisions)
- $T_i / T_e = 5$, $\kappa = \frac{R_0}{L_n}$, $\eta_e = \eta_i = \eta = \frac{L_T}{L_n} = 1$
- Validity of gyrokinetic model is marginal; fully kinetic ion model being developed

	Core	**SOL**
$n_e (cm^{-3})$	4.0×10^{13}	2.0×10^{13}
$T_i (eV)$	400	200
$\rho_e (cm)$	0.044	0.016
$\rho_i (cm)$	5.98	2.15
$R_0/C_s (\mu s)$	1.78	2.51

Current Progress

1. Simulation code and parameters

2. Core stability

3. Scrape-off layer instability

4. Coupled Core-SOL and Fully Kinetic Ions

No instability found in realistic C-2 core

- No instability found* for $k_\zeta \rho_e \leq 0.3, \eta = 1, \kappa \leq 5$
- Consistent with experimental measurements of low amplitude of core fluctuations
- **Stabilized by**
  - **Ion finite larmour radius effects** (FLR)
  - **Magnetic well** (radially increasing B-field)
  - **Electron parallel dynamics** (shown via artificial elongation of core, or by slowing down electrons via artificial increase of electron mass)

* D. Fulton et al, "Gyrokinetic Simulation of Driftwave Instability in Field Reversed Configuration", Phys. of Plasma 23, 056111 (2016)

What causes the fluctuations?

- No instability found for $k_{\zeta}\rho_e \leq 0.3, \eta = 1, \kappa \leq 5$
- Mentioned stabilization mechanisms are FRC traits

  However, does *not* mean core has no instabilities because…
  - Gyro-kinetic assumption may pre-clude necessary physics of core instability (fully-kinetic ion model + coupled core-SOL)
  - Electrostatic assumption may pre-clude necessary physics of core instability (electromagnetic fluctuations)
  - Specific C-2 magnetic equilibrium model
  - Turbulence spreading from SOL

Current Progress

1. Simulation code and parameters

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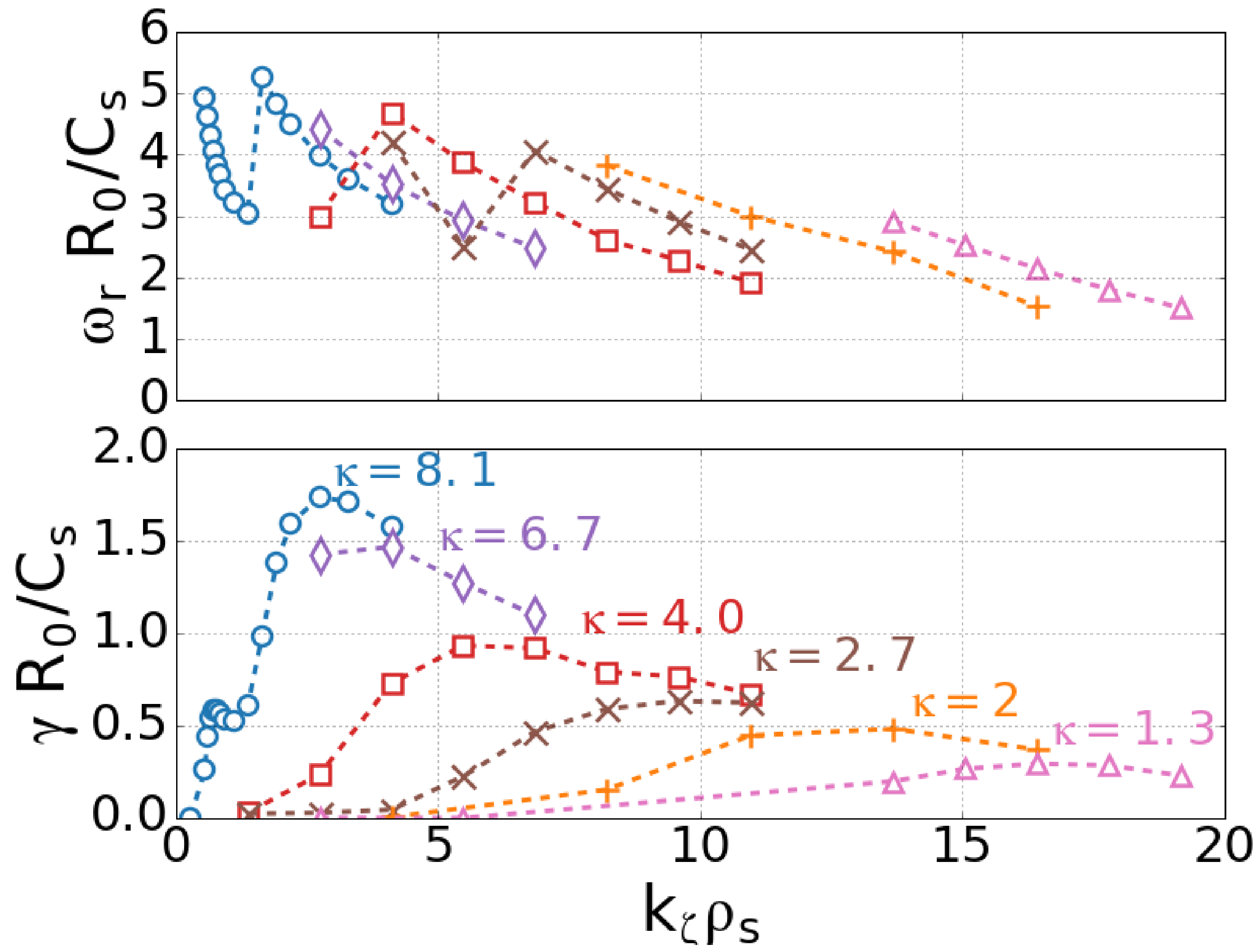
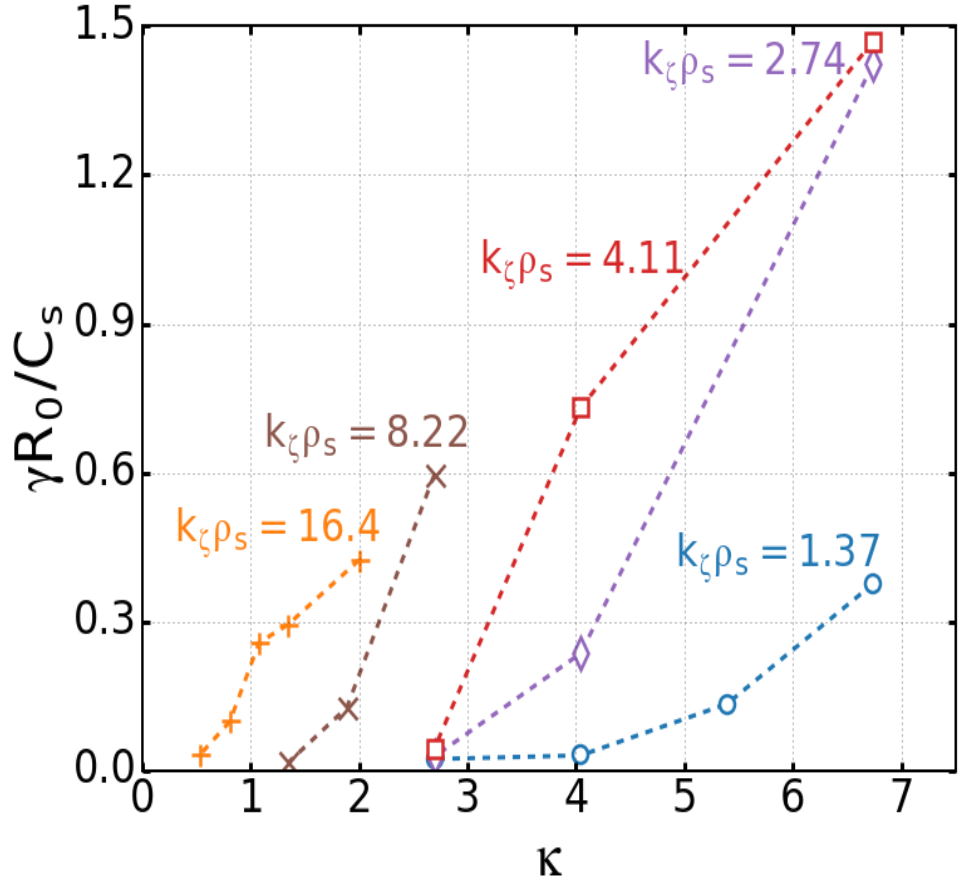
Unstable ion-to-electron-scale modes in C-2 SOL

- Frequency in the electron diamagnetic drift and electron curvature drift direction
- As drive strength decreases, mode shifts toward shorter wavelengths
- Studied effects: particle resonances, Ti/Te, η_e, η_i , FLR, ∇B, collisions*

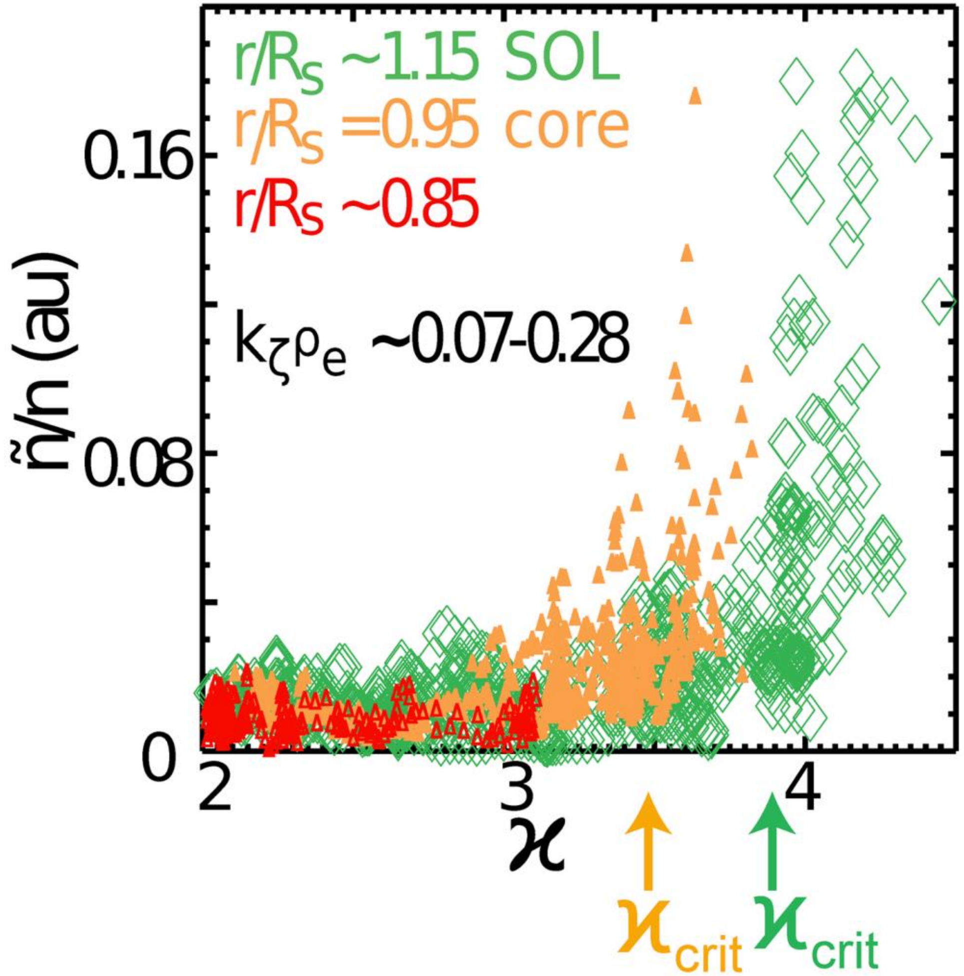


SOL linear thresholds are consistent with experiment

Simulation



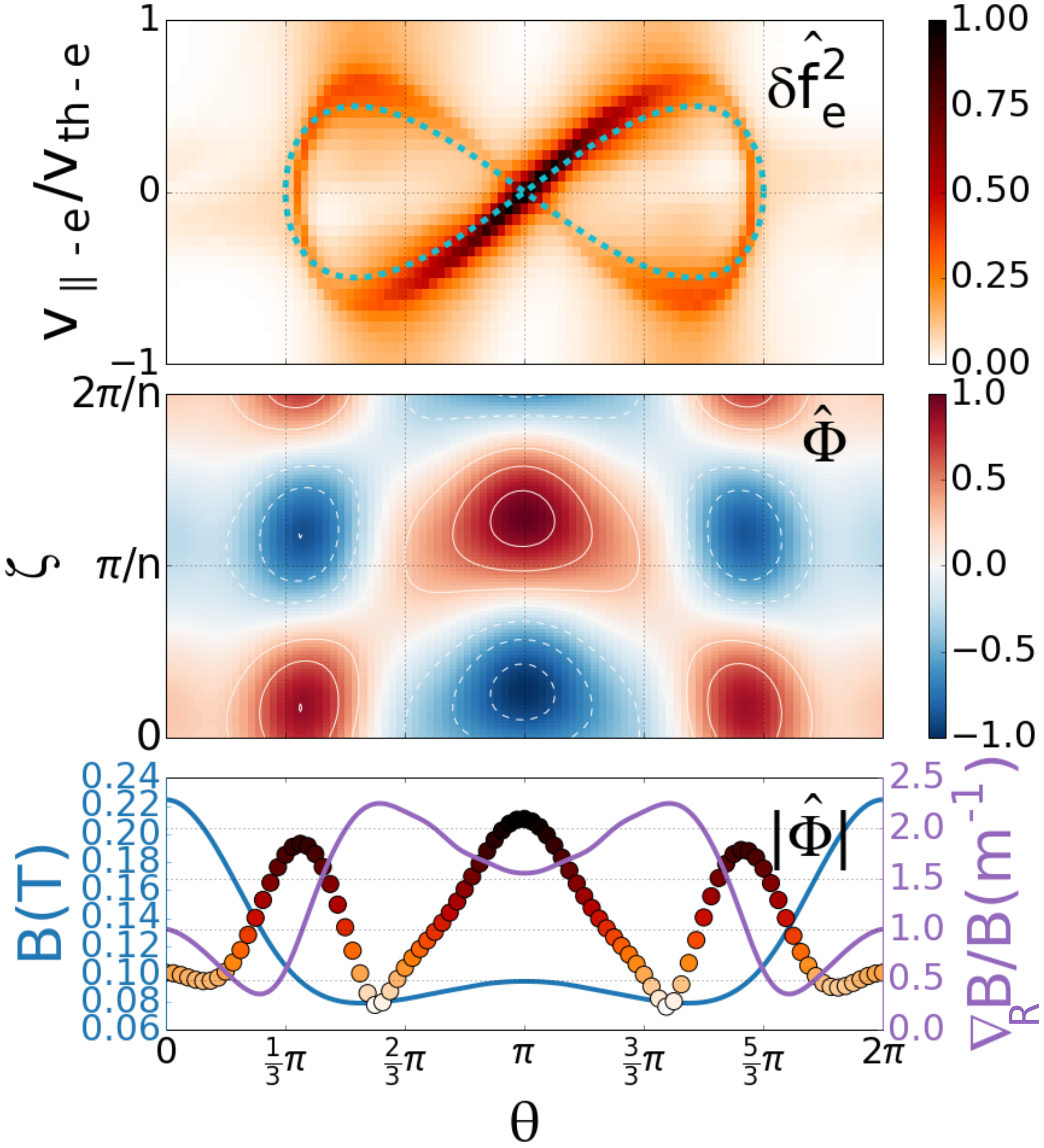
Experiment



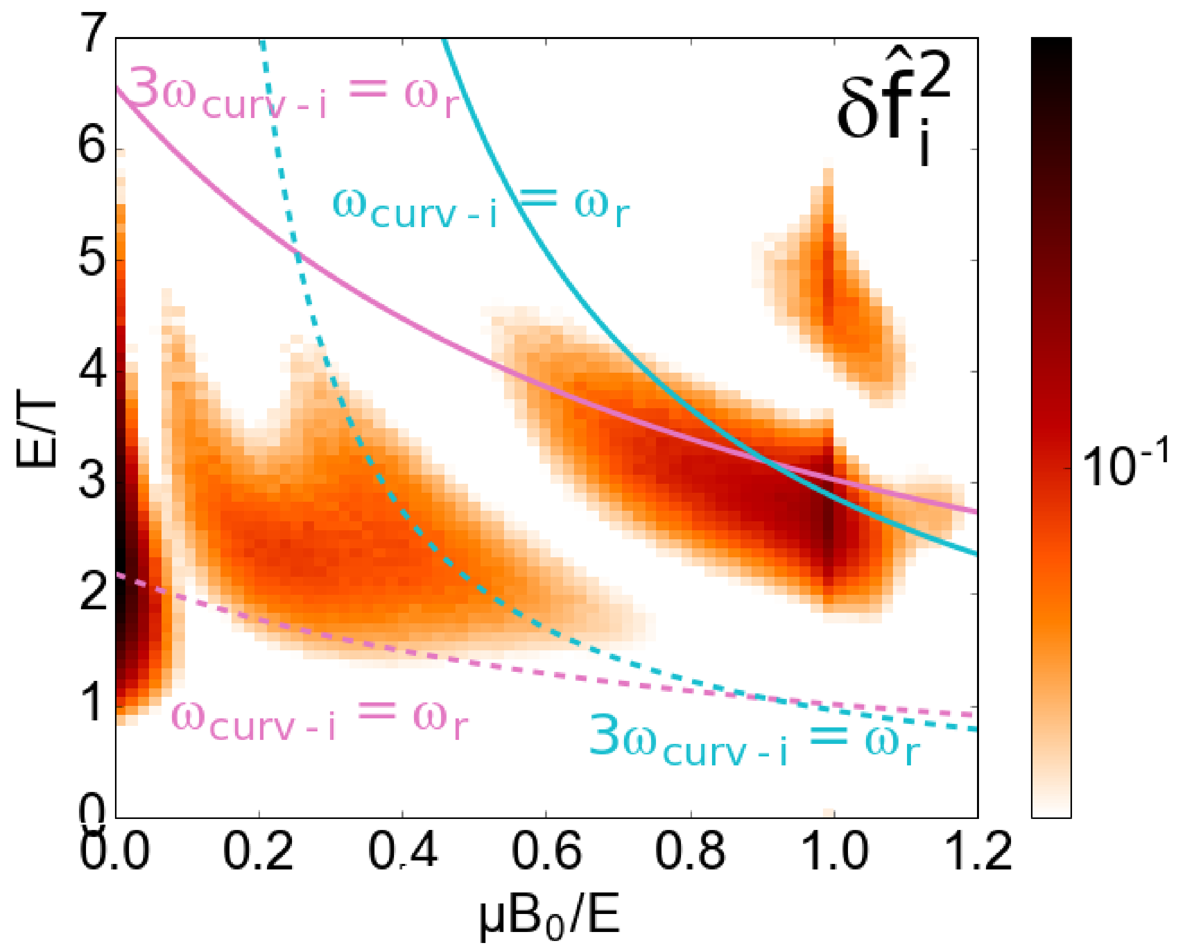
* L. Schmitz et al, "First evidence of suppressed ion-scale turbulence in a hot high-β plasma", in press (2016)

Phase space shows clear electron resonance

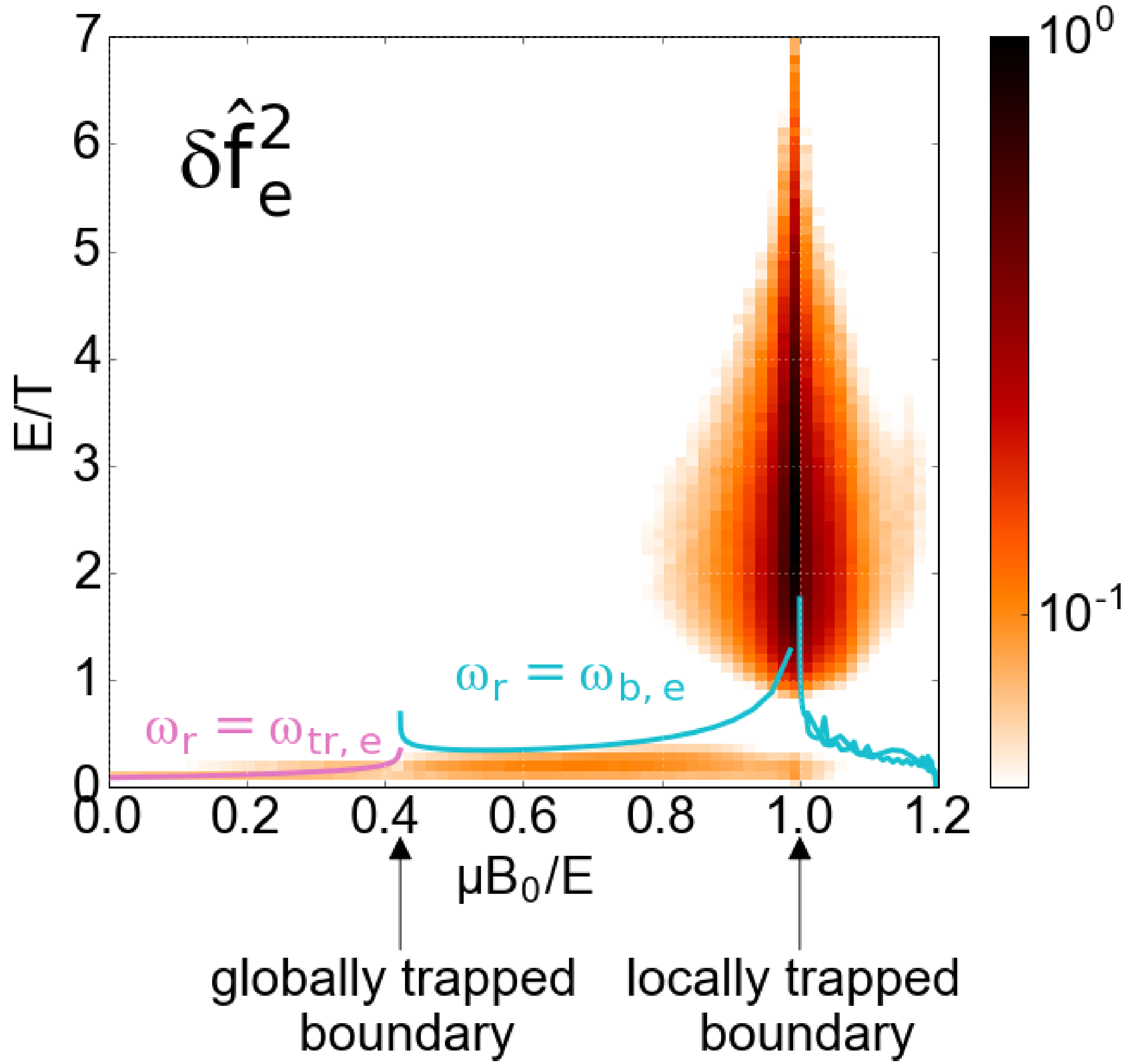
- ➢Resonance due to barely-trapped electrons appear as figure-8 structure shape in $\theta - v_{\|}$ phase space
- ➢Mode structure travels in the electron diamagnetic direction
- ➢Mode structure anti-correlated with magnetic field



Electron bounce motion resonates with mode

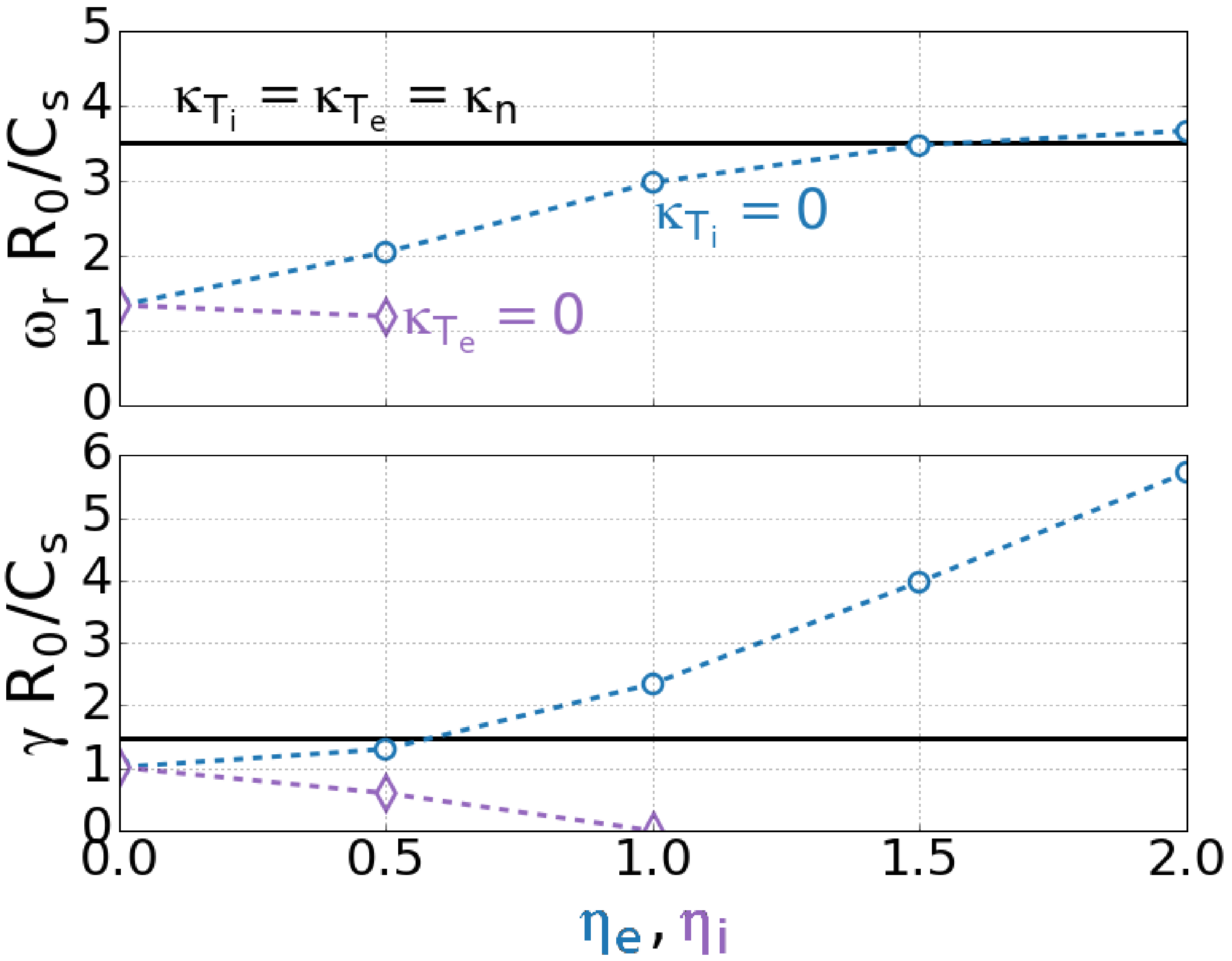


Plotted lines show $\omega_{b,e}\left(\frac{E}{T},\frac{\mu B_0}{E}\right) = \omega_r$



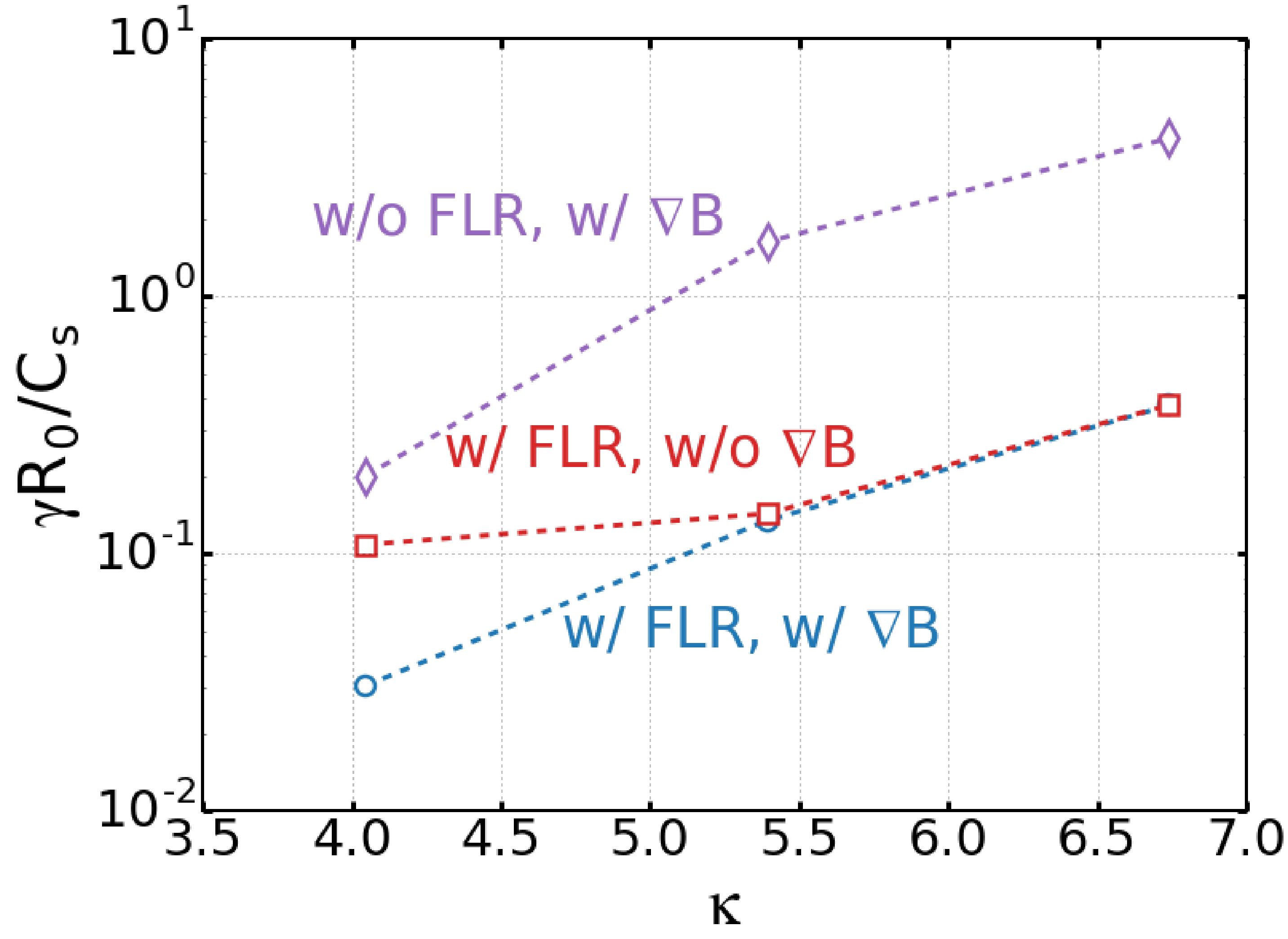
Electron temperature gradient is de-stabilizing

- Scans performed for different values of η *(density gradient drive strength kept constant while temperature gradients are varied)*
- Ion temperature gradient is stabilizing
- Higher T_i/T_e temperature ratio is stabilizing
- Electron temperature gradient is destabilizing
- Can be attributed to the modification of the electron phase space structure



Finite Larmour radius (FLR) and grad-B are stabilizing effects

- $k_\zeta \rho_i = 1.37$ (n=25) scanned with and without FLR and grad-B effects
- FLR is more stabilizing than grad-B
- However, for marginal stability, both will be important

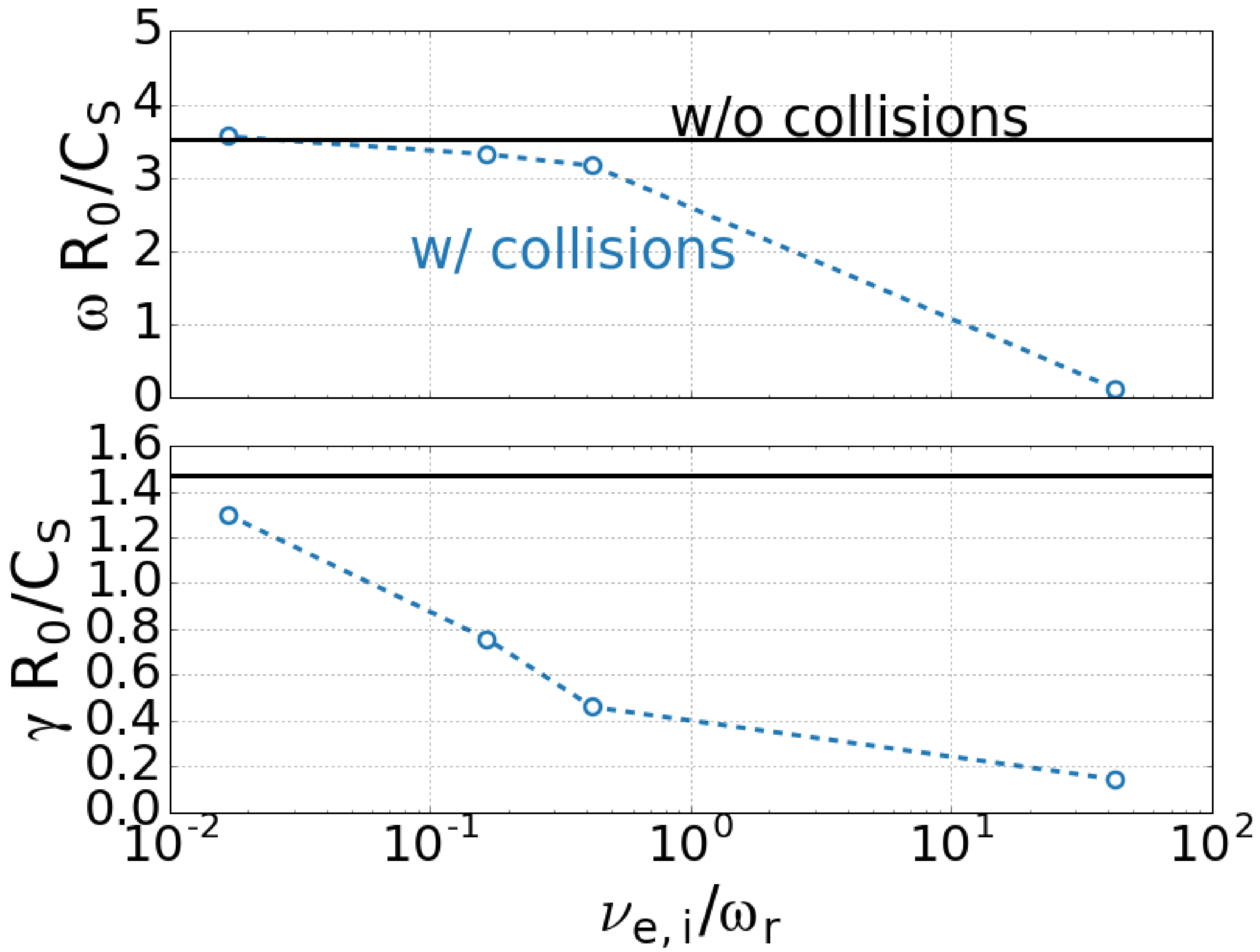


Electron collisions suppress the SOL instability

- Pitch-angle scattering stabilizes the instability

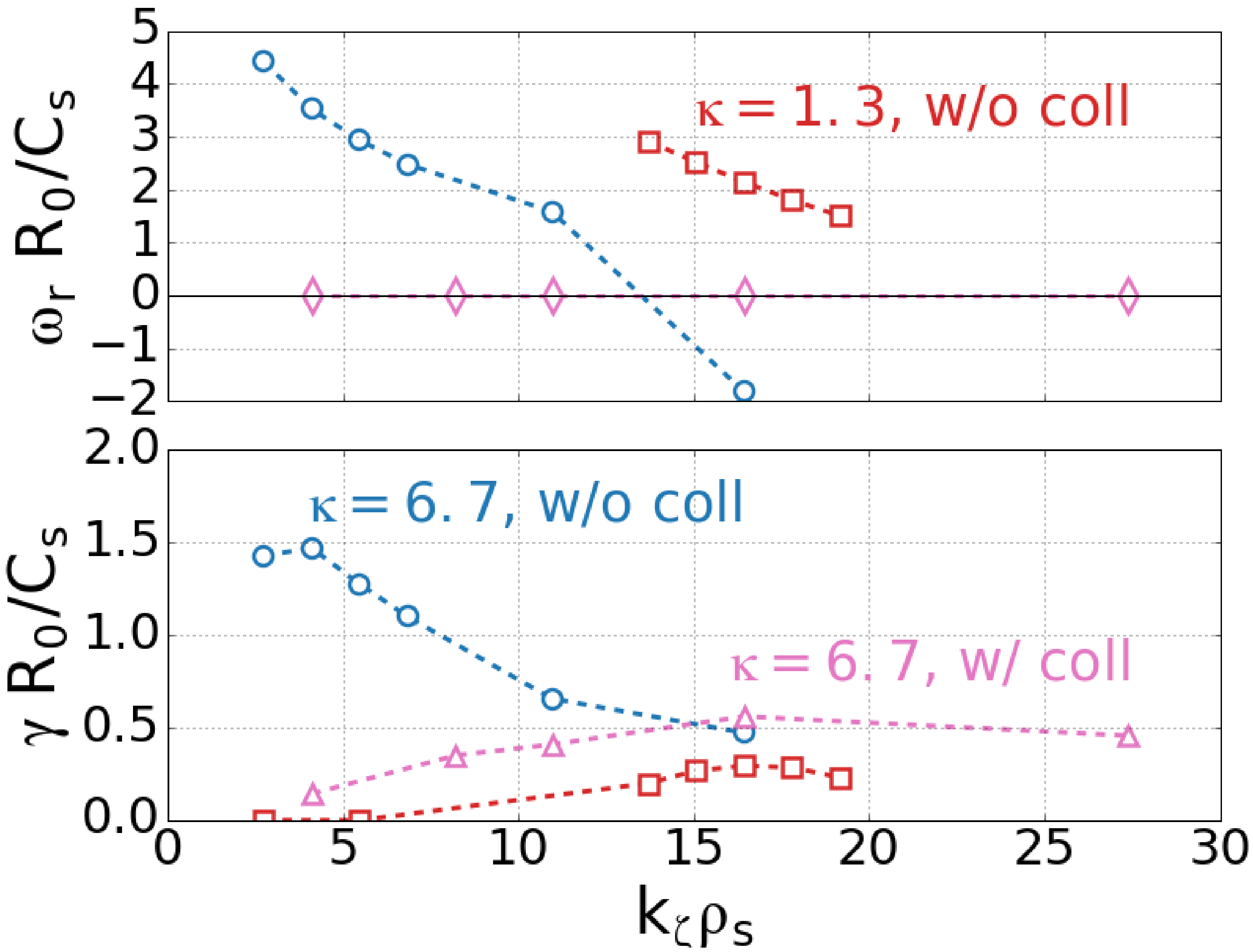
  → electrons scattered from resonant energy-pitch trajectory

- Collisionless case is recovered as collisions are reduced



Collisional instability can still exist

- Barely trapped electron driven branch stabilized by collisions
- Collisional branch can still exist in shorter wavelengths



Summary of current progress*

- Core is **stable**
  - Stabilizing: FLR, magnetic well, electron parallel dynamics
- Collisionless instability in SOL
  - Driven by barely trapped electrons
  - Destabilizing: electron-temperature gradient, density gradient
  - Stabilizing: collisions, higher temperature ratio, FLR, ∇B, ion temperature gradient
  - Collisional instability can also exist
- SOL linear thresholds in simulations consistent with experimentally measured fluctuation thresholds

* C.K. Lau et al, “Drift-wave Stabilities in the Field-Reversed Configuration”, submitted to Nucl. Fusion

Current Progress

1. **Simulation code and parameters**

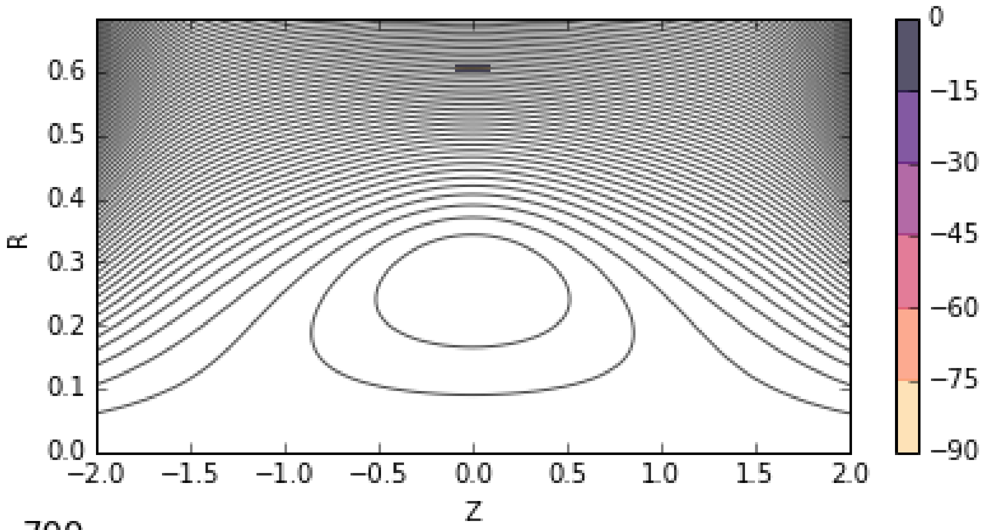
2. **Core stability**

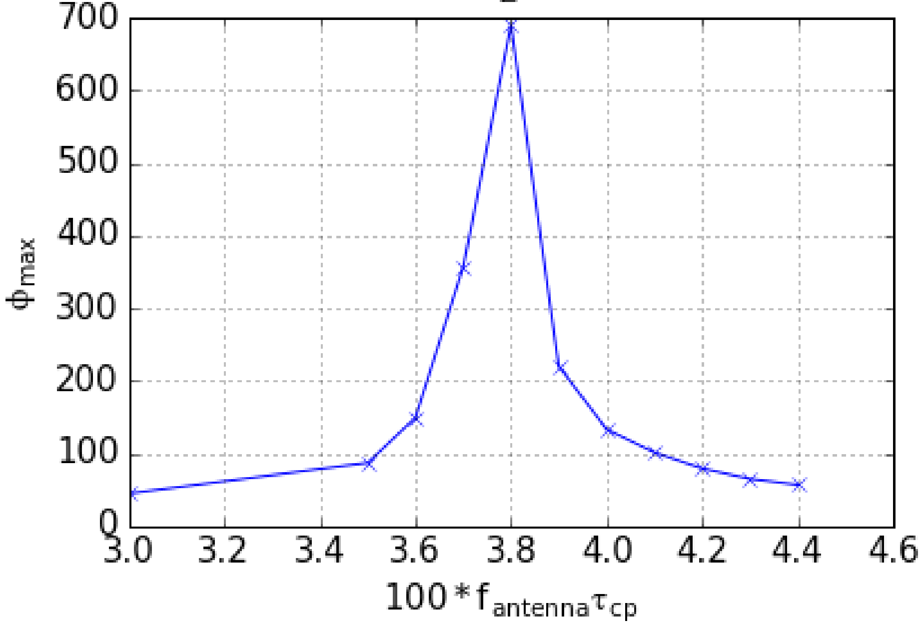
3. **Scrape-off layer (SOL) instability**

4. **Coupled Core-SOL and Fully Kinetic Ions**

Cross-separatrix simulations (ANC)

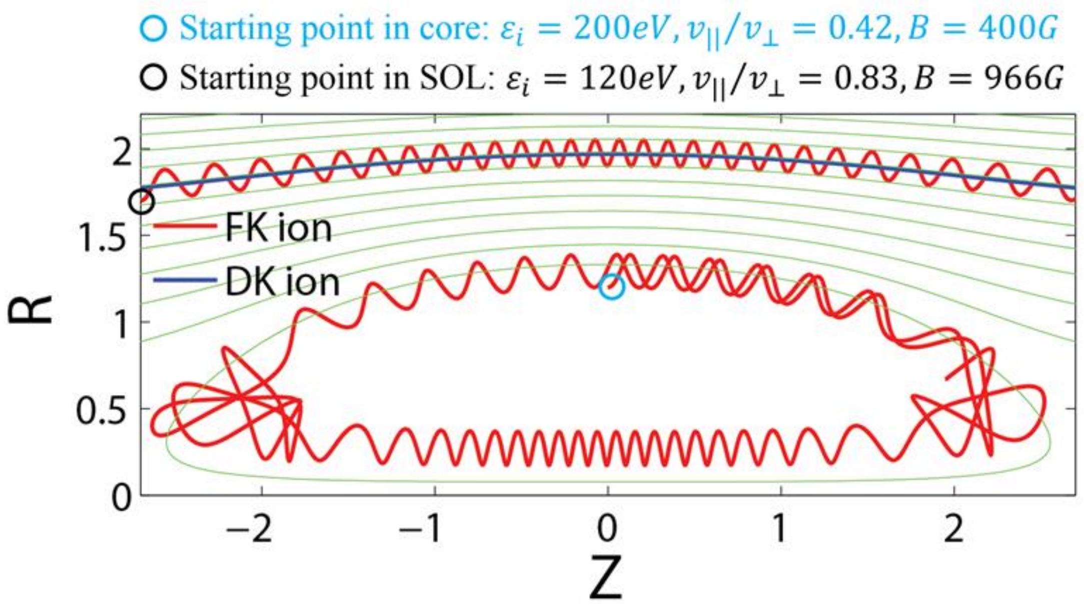
- Inherits algorithms from GTC; modularly designed
- Numerical FRC geometry from LamyRidge
- Drift kinetic particle pusher in (R, Z, ζ) parallelized by MPI
- Parallelized (PETSc/Hypre) field solver, (2D spatial: R,Z; 1D spectral: ζ)
- Verified: (1) ion acoustic wave and (2) driftwave frequencies in simple geometry, (3) driftwave frequency in realistic FRC geometry

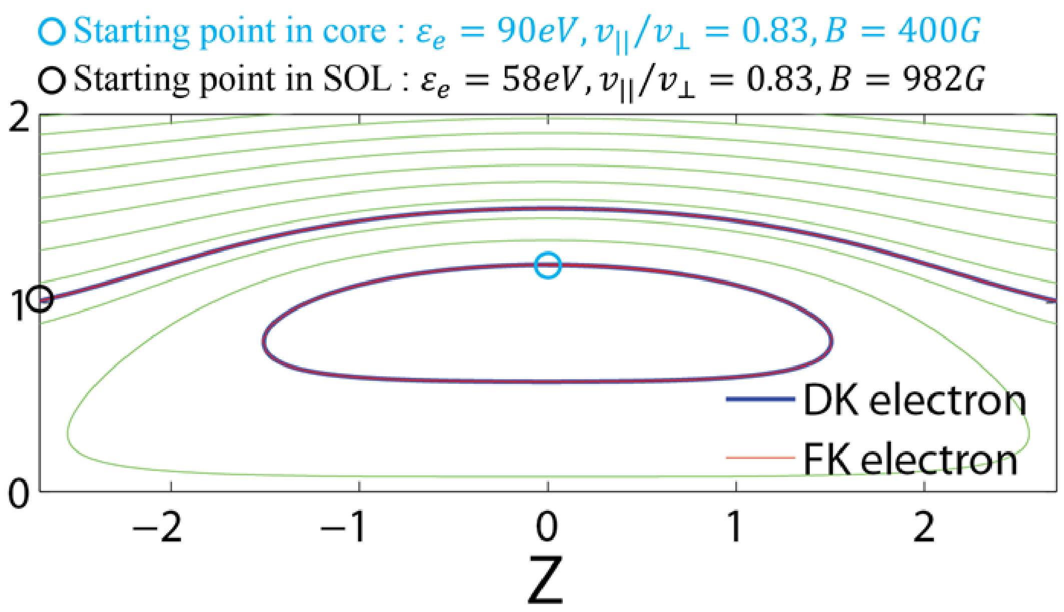




Fully kinetic ions are also underway

- Implemented fully kinetic ion & drift kinetic electron (FKi/DKe) in GTC
- Verified: Boris push & Runge-Kutta for integrating ion cyclotron orbit in realistic FRC geometry using cylindrical coordinates
- Next: self-consistent driftwave simulation with fully kinetic ions





End of talk

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