Transport and Stability Analysis for STAR Tokamak Using TRANSP, GX, NIMROD, and ELITE Codes

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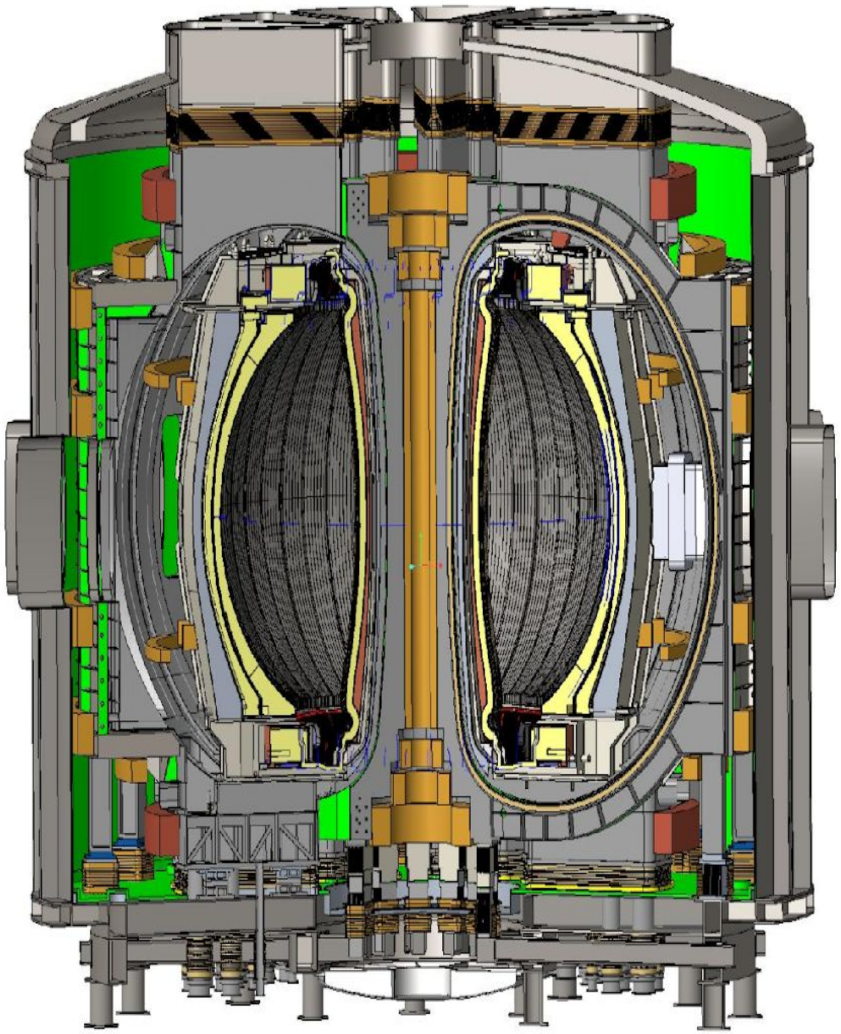
STAR Spherical Tokamak

- $R=4m$, $A=2$, $\kappa=2.3$, $\delta = 0.65$
- 100% non-inductive, 75-80% bootstrap
- $B_T=5.2T$, $f_{Greenwald} = 0.8\text{-}1$, ECCD+NNBI
- $P_{fus} = 0.5\text{-}1.5$ GW, $P_{net} = 100\text{-}500$ MW
- **Evaluating potential to:**
  - Exploit higher pedestal + core confinement to lower TF coil mass, reduce auxiliary heating, and reduce blanket change-out volume
  - Exhaust high projected edge power density and utilizing liquid metals (Li) + gas fueling
  - Longer-term: Assess low recycling wall to control core temperature and density profiles



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Motivation and Outline

STAR will operate at high β and strong shaping, where cross-scale turbulence and MHD stability can strongly constrain performance

For STAR, we do not yet know what sets the relative roles of electron/ion and particle transport, or how different microinstabilities contribute to the transport

Edge stability and ELM avoidance in this regime require consistent treatment of core transport, pedestal structure, and global MHD response

No single code can address all of these questions; we need a multi-code, multi-fidelity framework that connects gyrokinetics, reduced transport models, and resistive/ideal MHD

Goal: build such an integrated workflow (TRANSP–GX/MMM/TGLF–NIMROD) to map STAR's operational space and guide scenario development

Modeling Strategy: Transport and ELM Stability in STAR

- **Goal: use a hierarchy of physics models to understand and predict STAR performance**
- **Core transport questions**
  - **Do reduced models (MMM, TGLF) capture the dominant microinstabilities and heat/particle fluxes in STAR?**
  - **Strategy: validate MMM/TGLF against high-fidelity GX simulations in NSTX and STAR, then use calibrated reduced models for broad TRANSP/T3D scans**
- **Pedestal / ELM stability questions**
  - **What level of MHD fidelity is sufficient to describe STAR pedestal stability (ideal vs resistive, rotation, two-fluid, FLR)?**
  - **Strategy: use NIMROD for extended-MHD studies, with ELITE providing ideal peeling–ballooning reference limits**
- **Common framework**
  - **TRANSP can supply consistent equilibria, sources, and profiles that connect gyrokinetic transport and extended-MHD stability analysis for STAR**

TRANSP is Interpretive and Predictive Code. T3D with GX Brings Embedded Turbulence to TRANSP

TRANSP integrated code has

- **Large selection of sources for H&CD**
  - NUBEAM, TORIC, TORAY, TORBEAM, GENRAY, CQL3D
- **Free- and fixed boundary equilibrium solvers**
  - TEQ, ISOLVER
- **Models for large scale events (sawteeth)**
- **Pedestal models**
- **Synthetic diagnostics**
- **Selection of reduced anomalous and neoclassical models for plasma profile prediction**

PT_SOLVER, the native predictive solver in TRANSP, is modular: alternate solvers and models possible

- **T3D transport solver is implemented in TRANSP**

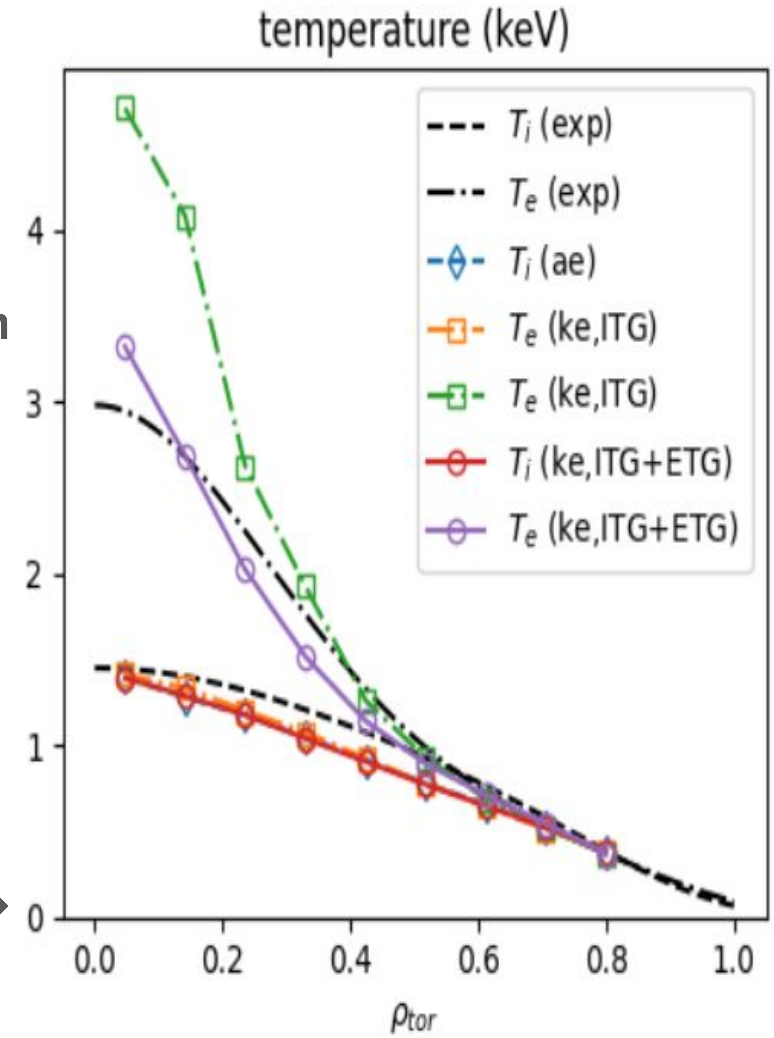
GPU-optimized GX Gyrokinetic Model Makes Predictive Simulation Possible on Transport Time Scales

T3D is transport solver

- Modular solver for dynamic evolution of plasma profiles in tokamaks and stellarators
- Follows algorithms and approaches developed from TRINITY code
- Written in Python

GX model for anomalous transport [https://arxiv.org/abs/2209.06731]

- GX solves the nonlinear gyrokinetic system for low-frequency turbulence in magnetized plasmas
- Use of a Hermite-Laguerre velocity discretization ⇒ allows smooth interpolation between gyrofluid-like resolutions and gyrokinetic resolutions

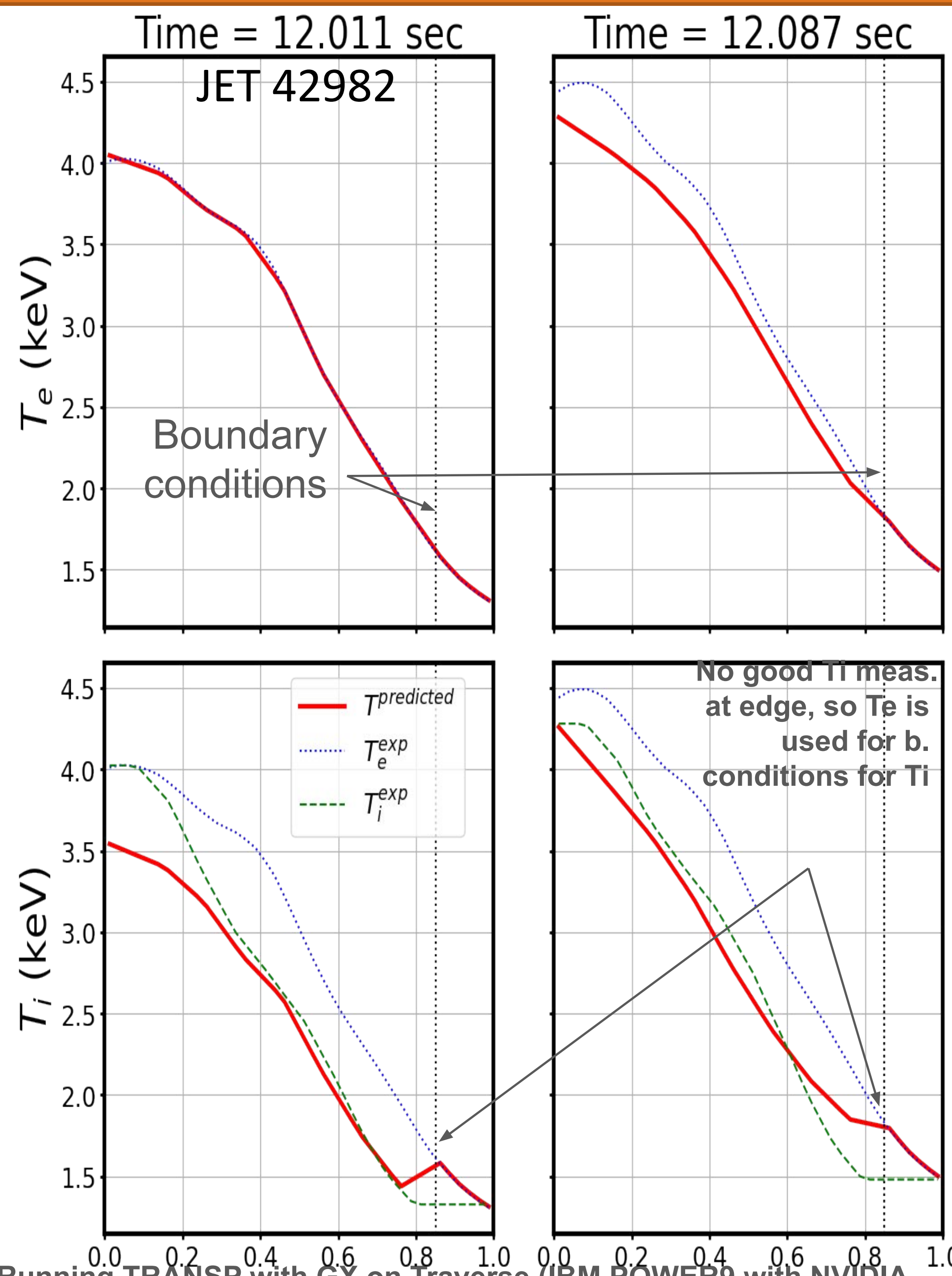


N. Mandell simulation of W7-X plasmas with T3D/GX [APS DPP 2023]

Initial Test with T3D/GX Shows Stability of Coupling Scheme

For the first time, high-fidelity gyro-kinetic GX model for anomalous transport [https://arxiv.org/abs/2209.06731] is Implemented in TRANSP using the T3D/TRINITY transport solver

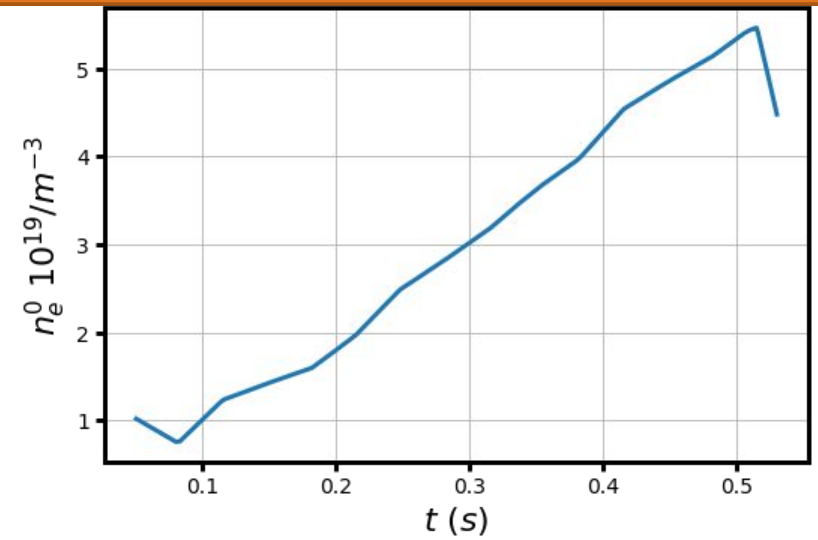
- **Solvers, equilibrium and plasma profiles are evolved self-consistently in coupled simulations**
  - TRANSP Ufiles and PlasmaStates are used for the code coupling
  - TRANSP uses multiple CPUs to compute sources and multiple GPUs for compute fluxes in GX

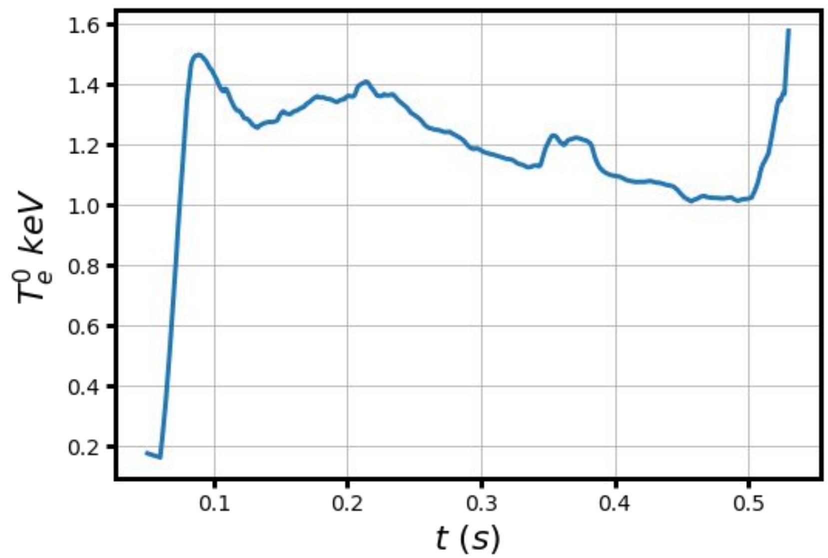


Running TRANSP with GX on Traverse (IBM POWER9 with NVIDIA V100) from 12 to 12.079 sec on 4 nodes (16 GPUs) takes 16 hours

Verifying Reduced Models Predictions with GX Simulation: Starting with Previously Analyzed NSTX Discharge

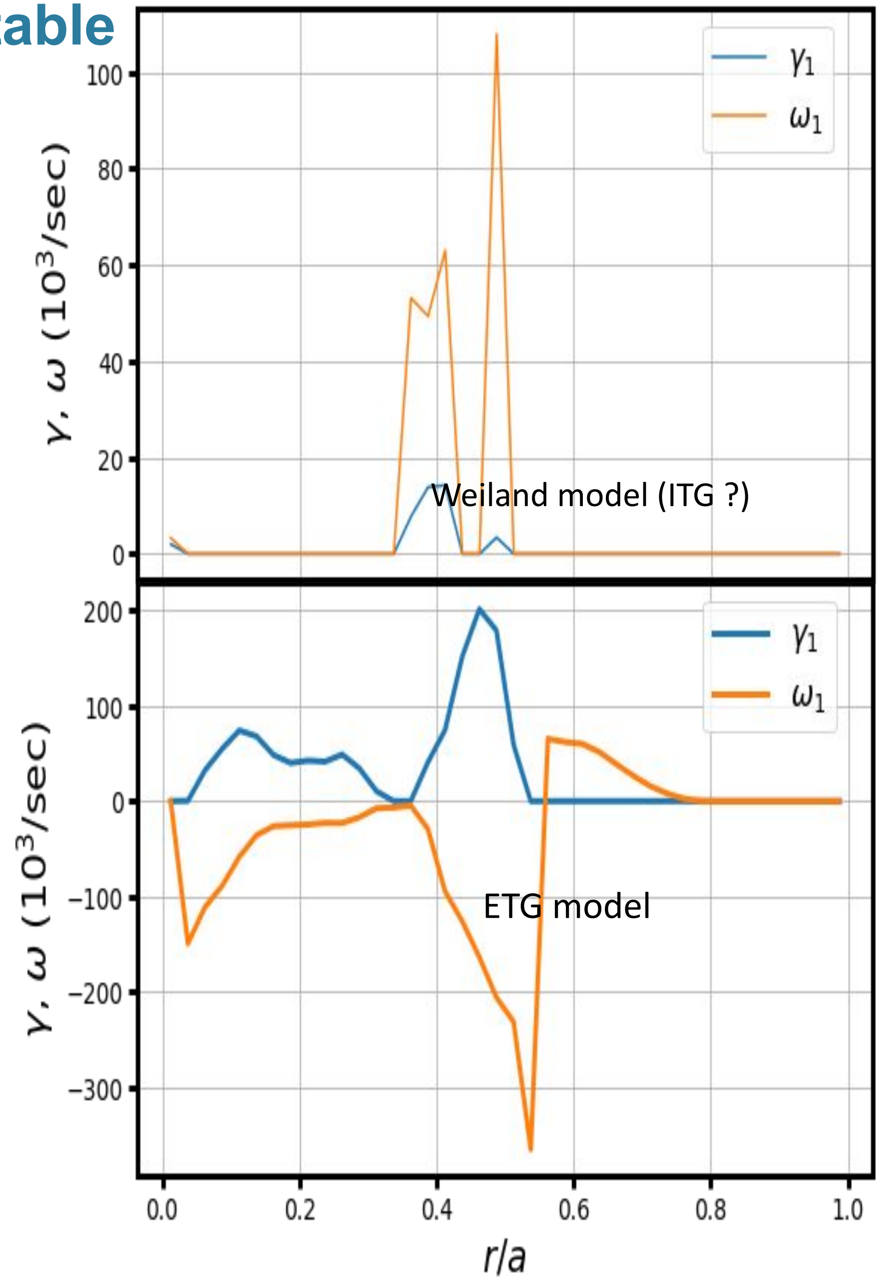
- **Discharge 129041 was an NSTX discharge that was part of the 2008 experimental campaign**
- **Used lithium coatings to achieve an ELM-free H-mode**
- **Lithium coatings were progressively increased**
- **Medium collisionality discharge**
- **It has been investigated using GYRO code by W. Guttenfelder *et al*. Proc. IAEA FEC 2012**
  - **Linear stability analysis and nonlinear fluxes are computed as part of the analysis**
  - **Focus on KBM/TEM and MTMs**

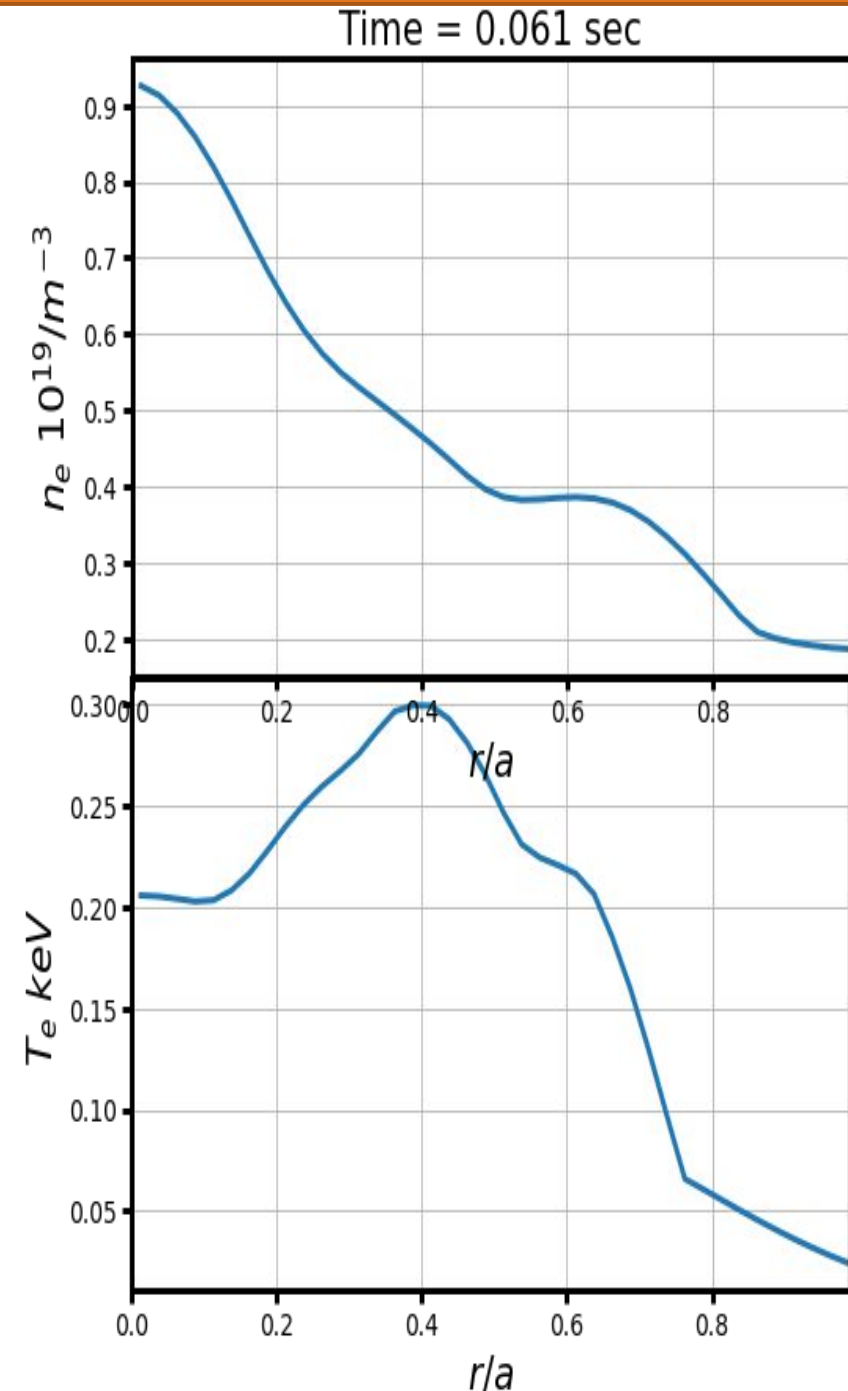




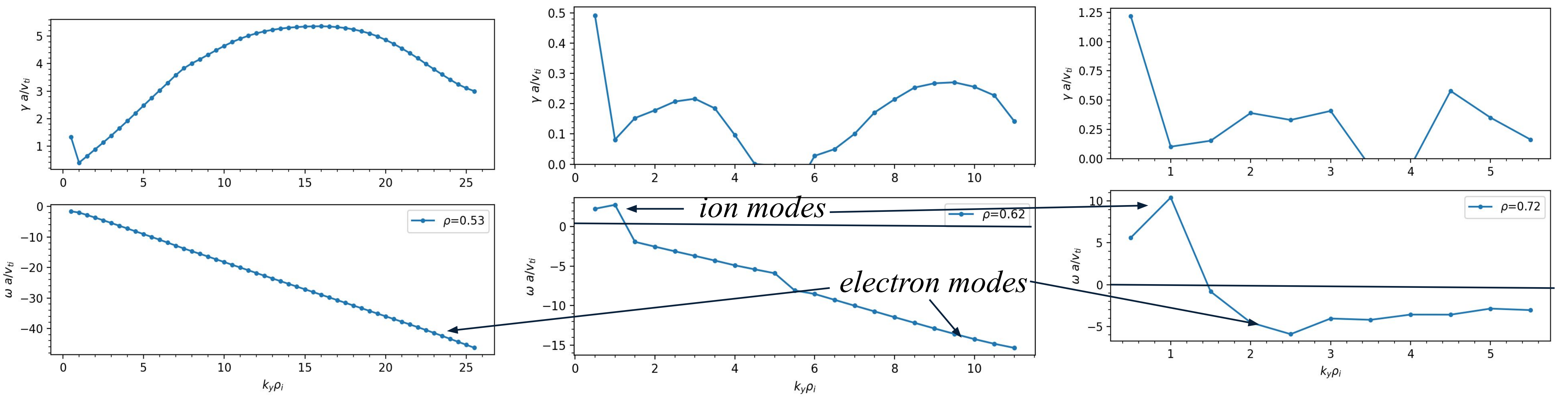
NSTX Discharge 129041: Focus on Early and Late Stages of the Discharge

- **MMM model predicts ITG and ETG to be unstable**

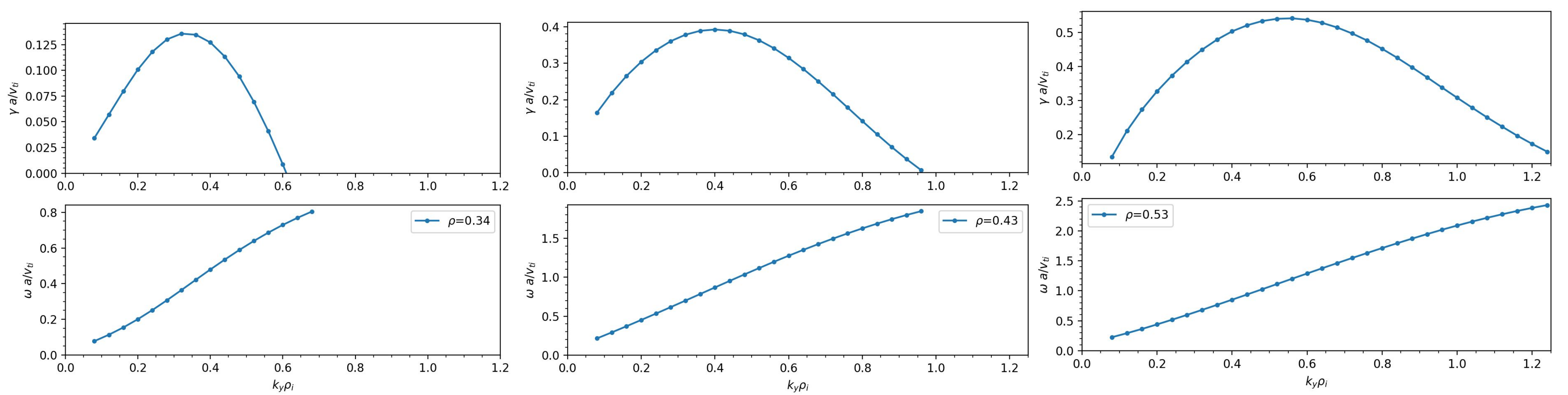




Modes Moving Both in Electron and Ion Diamagnetic Directions are Observed in GX Studies



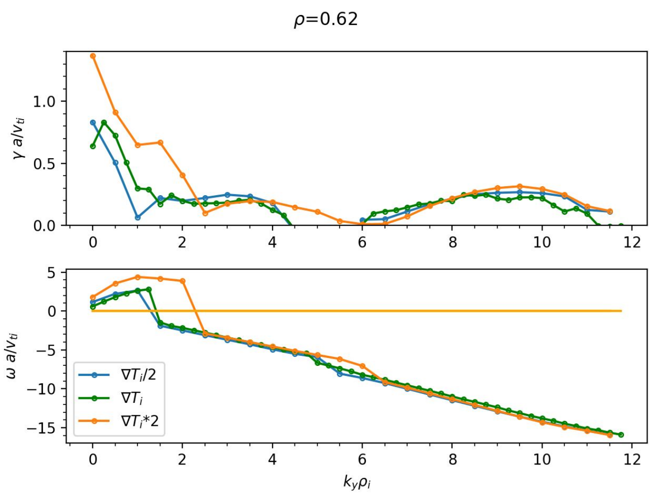
Approximation of adiabatic electrons



Modes Can be Identified Using Various Scans: Gradients, Temperatures, Collisionality, Plasma Beta

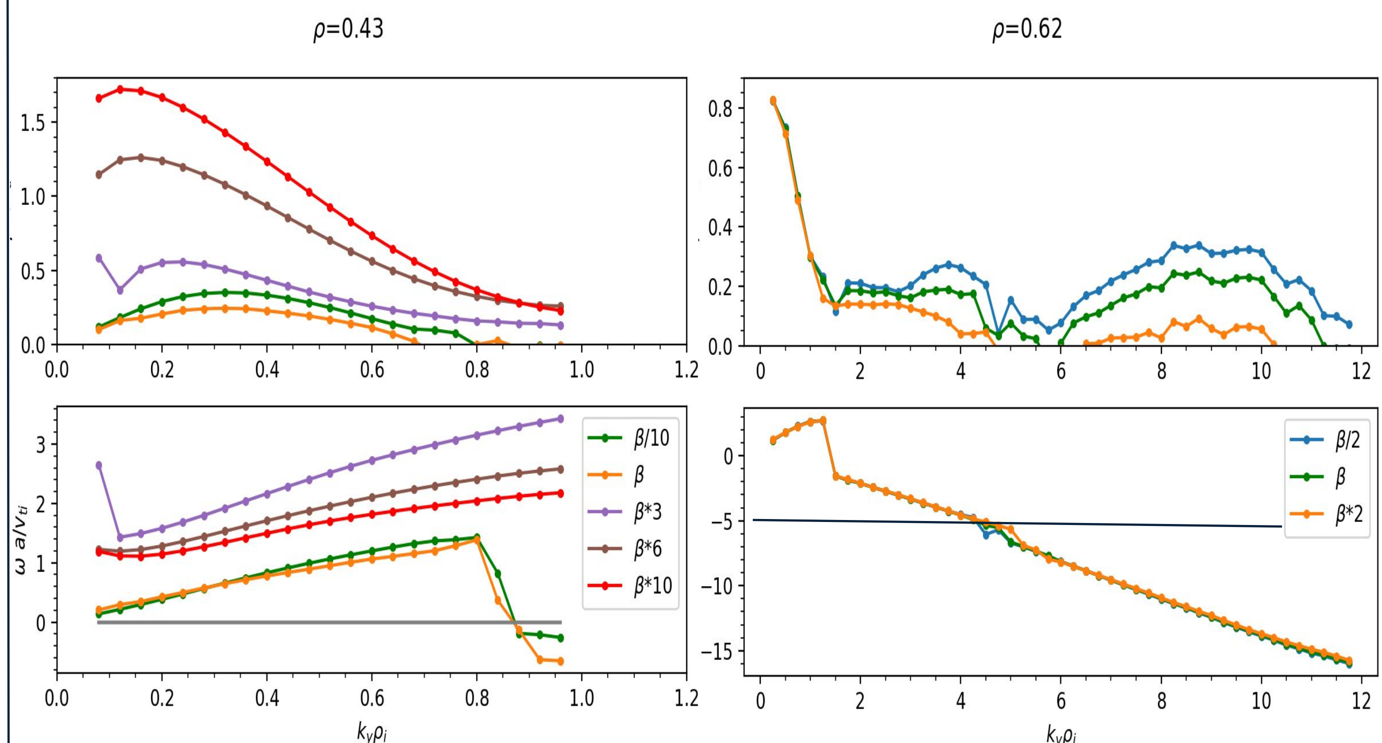
Ion temperature gradient scan:

- Large-scale ion modes strongly destabilized
- Intermediate scale electron modes are affected
- Small-scale electron modes are not affected



Plasma-beta scan:

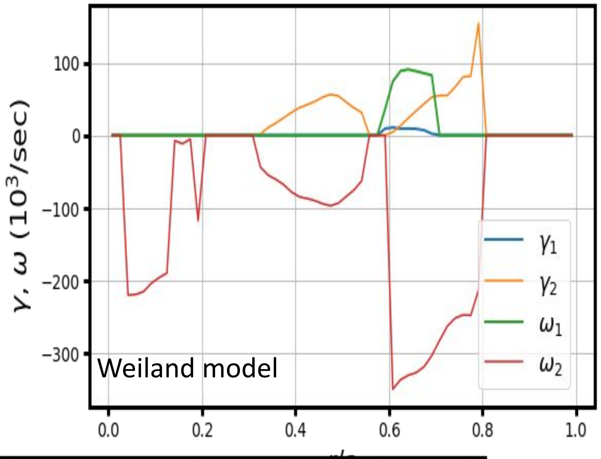
- For outer plasma region, beta has stabilizing effect on electron modes and weak effect on ion modes
- For more inner region, ion modes can be stabilized or destabilized by plasma beta => possible presence of KBM
  - Growth rates, frequencies and scale length are affected

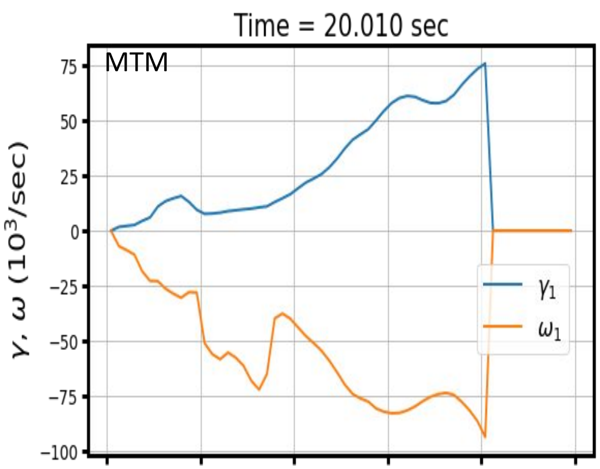


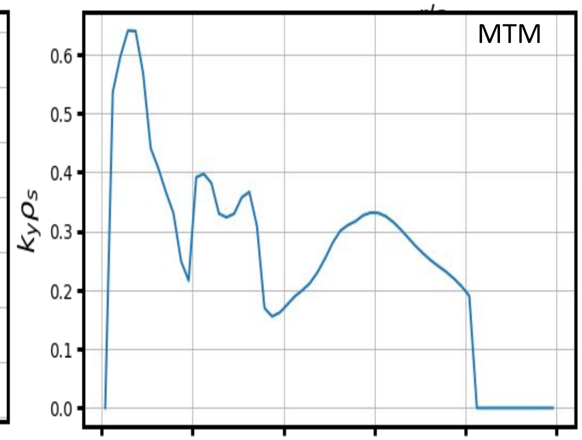
Simulation at later time shows only presence of low-scale electron modes

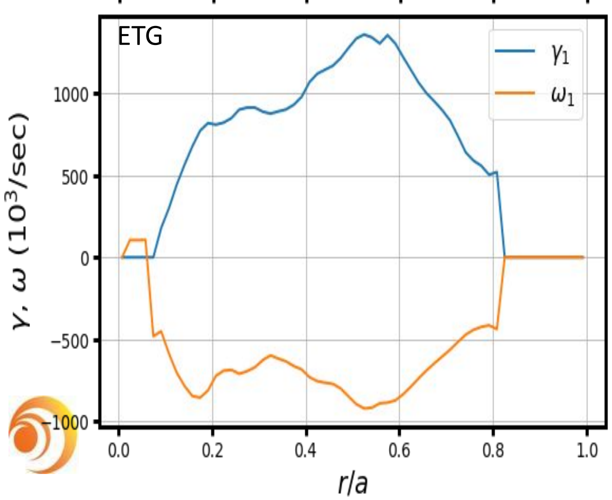
STAR-LM Simulation at 20 s: MMM Analysis Shows a Wide Range of Instabilities Contributing to Transport

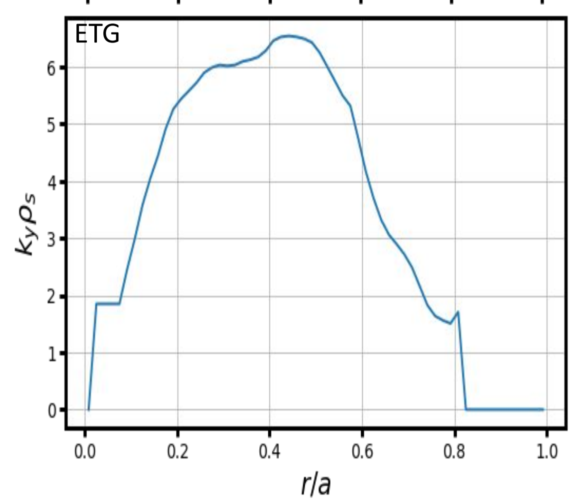
Profiles are constructed for H-mode and consistent with equilibrium used in previous STAR-LM simulation by J. Berkery

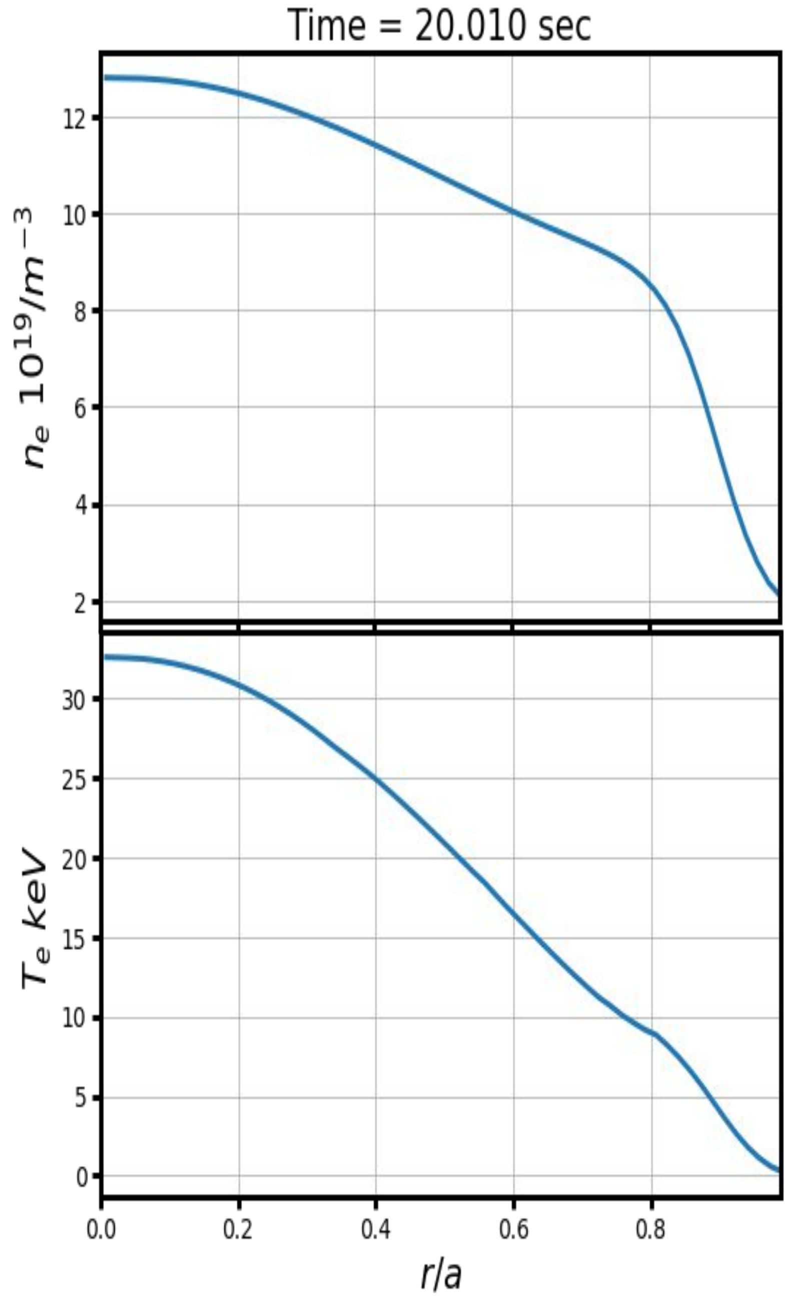






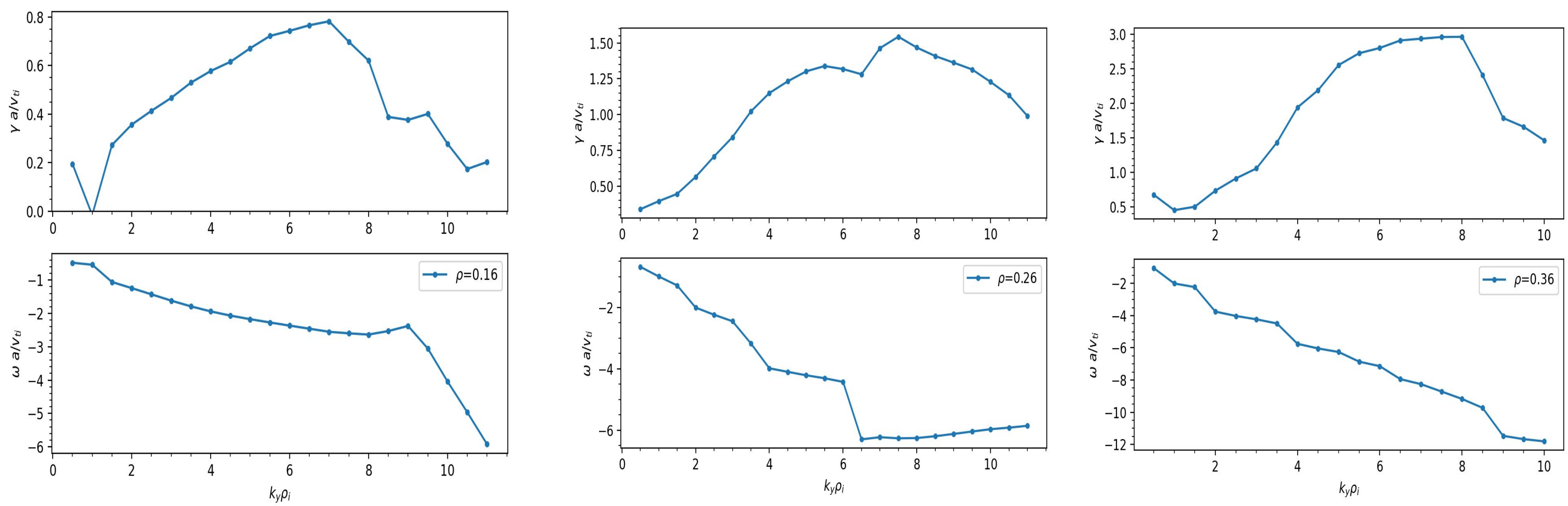


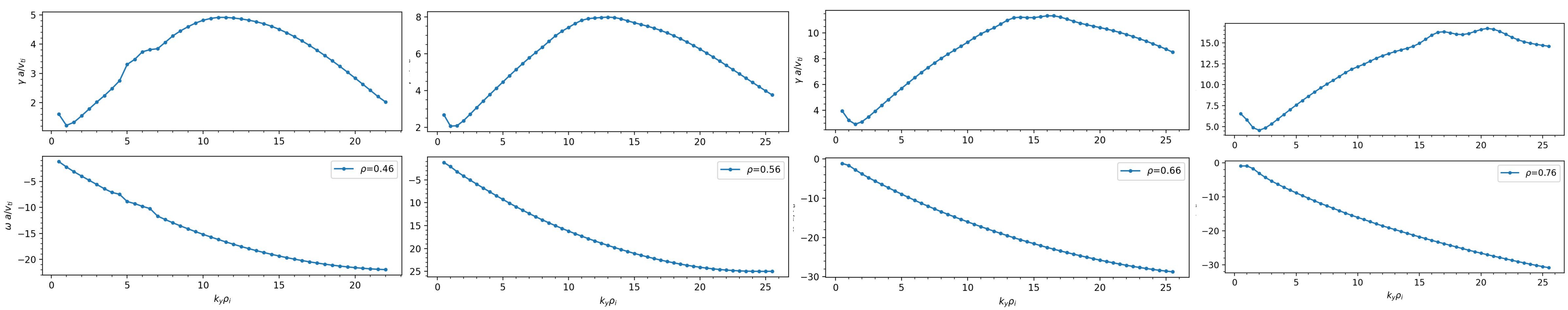




STAR-LM Simulation at 20 sec: No Large-Scale Modes – Scale Length Decreases with Radius

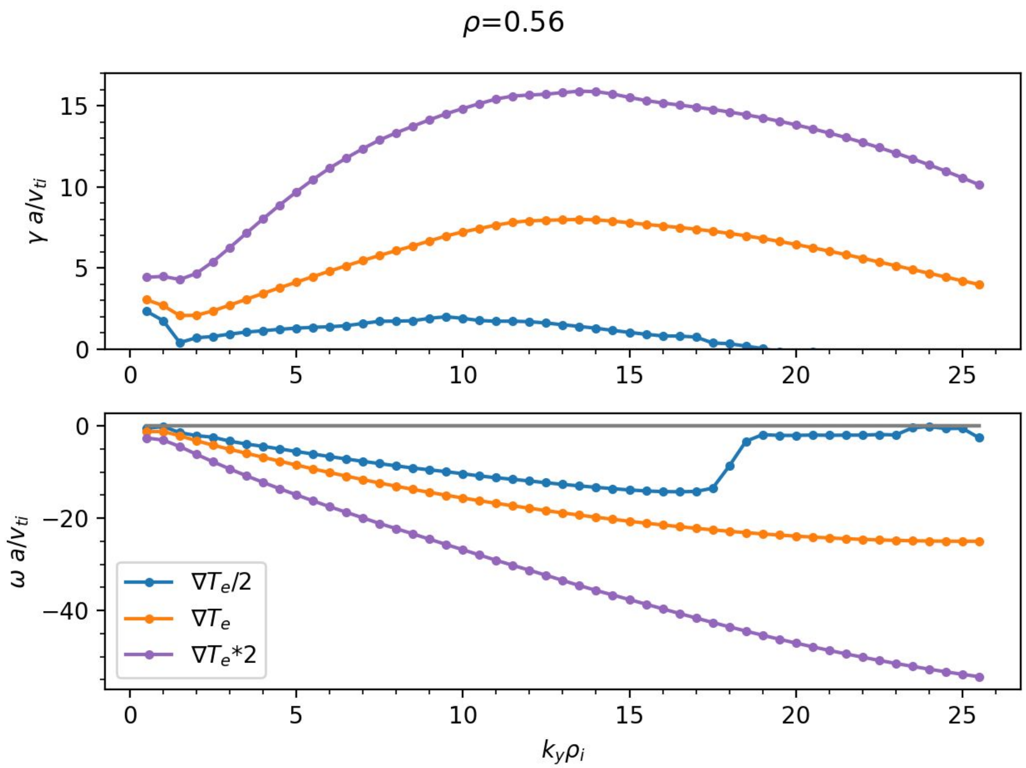
Frequencies and growth rates for different flux tubes

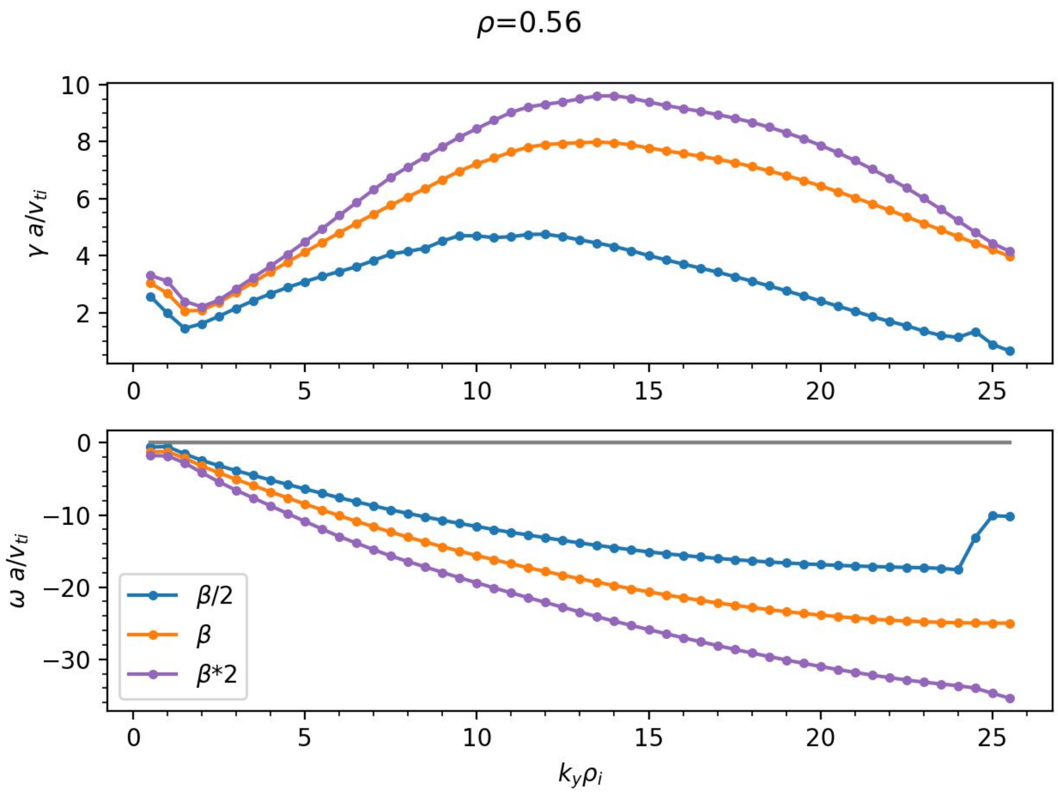




STAR-LM Simulation at 20 sec: Only Modes Moving in Electron Diamagnetic Direction are Observed

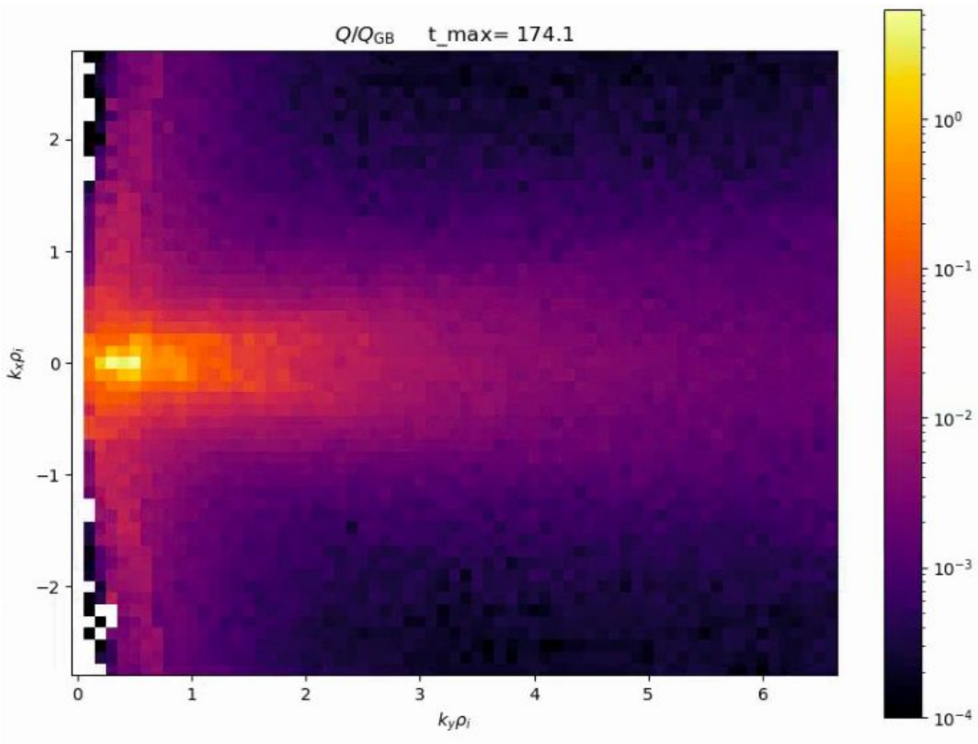
- **Modes are destabilized by electron temperature gradient and plasma beta**
  ⇒ Electromagnetic effects are important

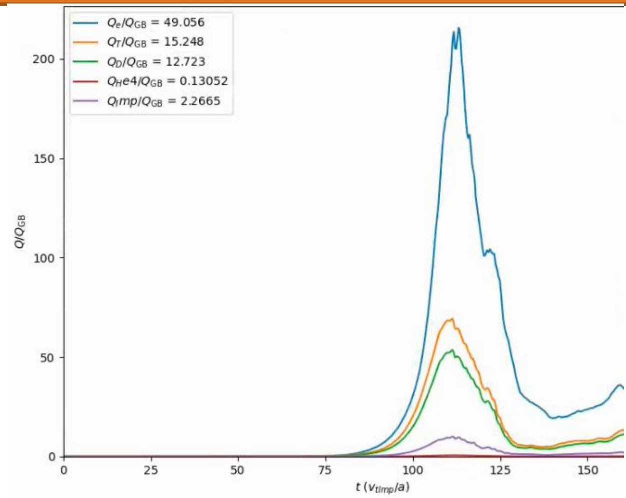


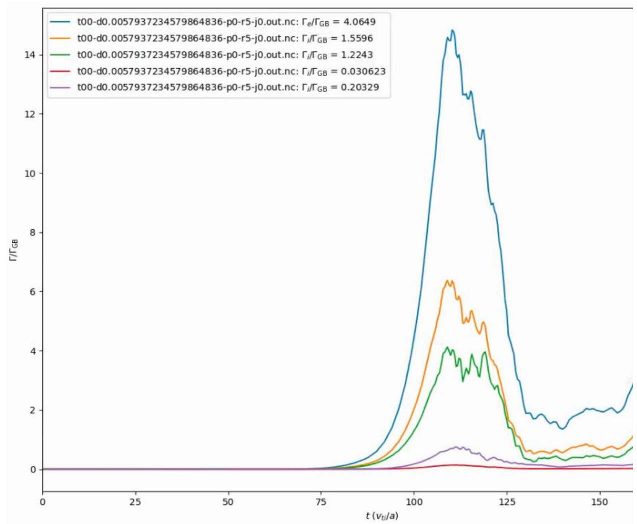


Most Contribution Comes from Large Scale Instabilities Drive the Electron Thermal Transport

- **In nonlinear GX simulations, most transport is driven by MTMs with some contributions from ETG**
- **Non-negligible contributions to the ion thermal transport**





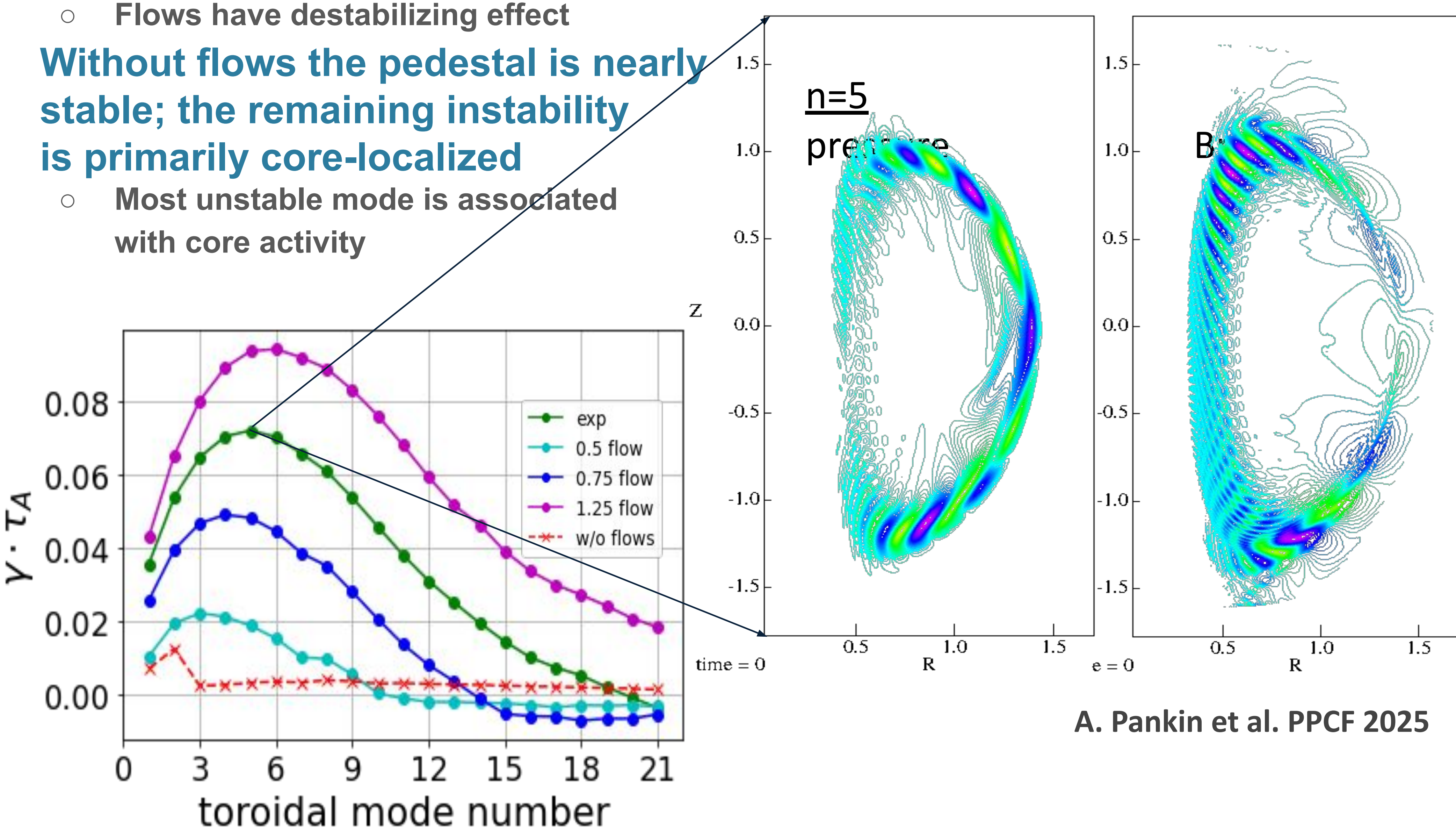


From Gyrokinetic Transport to Pedestal Stability

- **GX in TRANSP gives STAR-relevant information: *q*-profiles, β, gradients, and the relative roles of electron and ion heat transport**
- **These results do not determine the pedestal and edge conditions to must remain ELM-free in STAR scenarios**
- **NIMROD: 3D extended-MHD code used here in single-fluid and two-fluid/FLR variants with rotation for NSTX/STAR-like equilibria**
- **Lessons from NSTX:**
  - **Rotation has a strong impact on mode stability and the ELM spectrum**
  - **Two-fluid and FLR terms can shift growth rates and the distribution of unstable modes**
- **Next step:**
  - **Use NIMROD to test how rotation, resistivity, two-fluid, and FLR physics modify peeling–ballooning stability for STAR-like equilibria**

NSTX 132588: Rotation is Critical

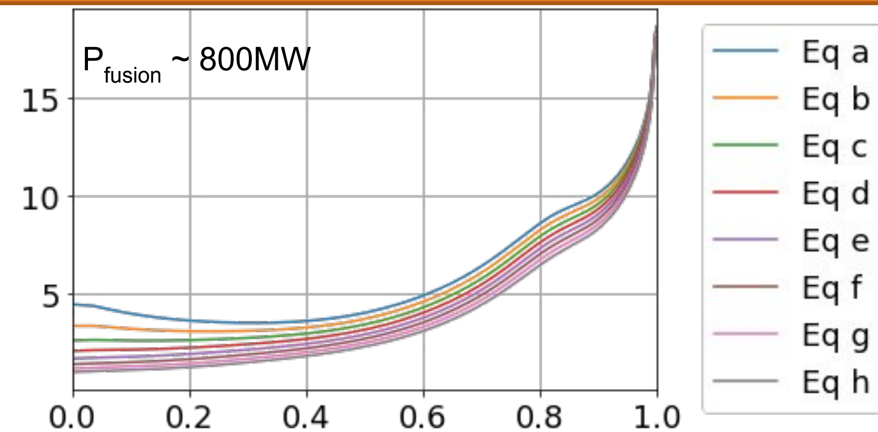
- **Flows has a strong effect on stability**
  - Flows have destabilizing effect
- **Without flows the pedestal is nearly stable; the remaining instability is primarily core-localized**
  - Most unstable mode is associated with core activity



A. Pankin et al. PPCF 2025

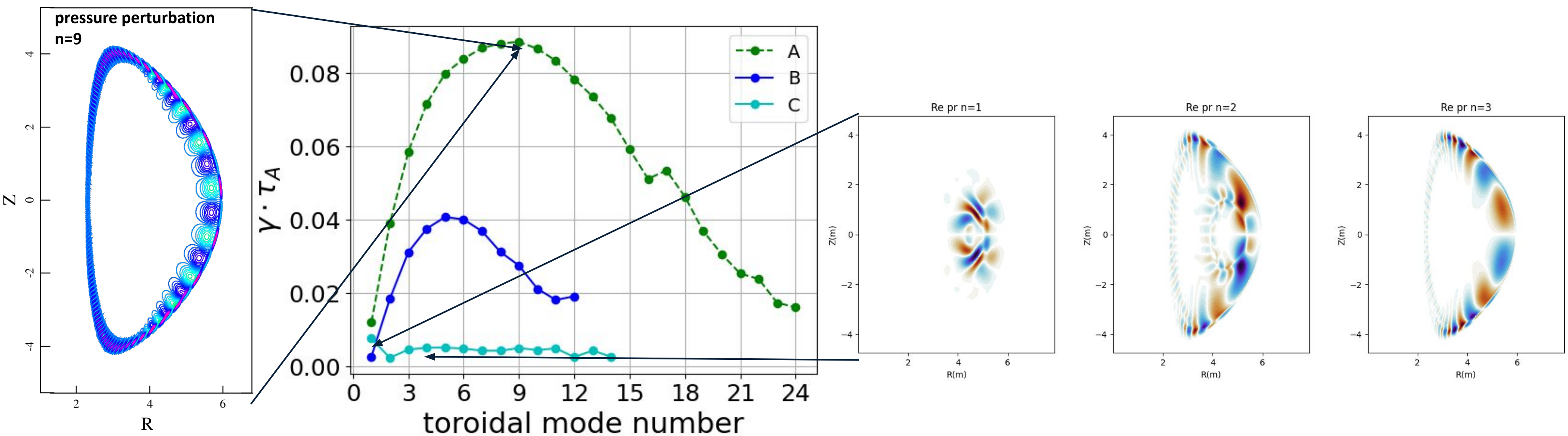
Rotation sensitivity in NSTX suggests that rotation might also be critical for STAR pedestal stability

Single MHD Analysis of *q*-scans of Scenario with P_{fusion}=800MW



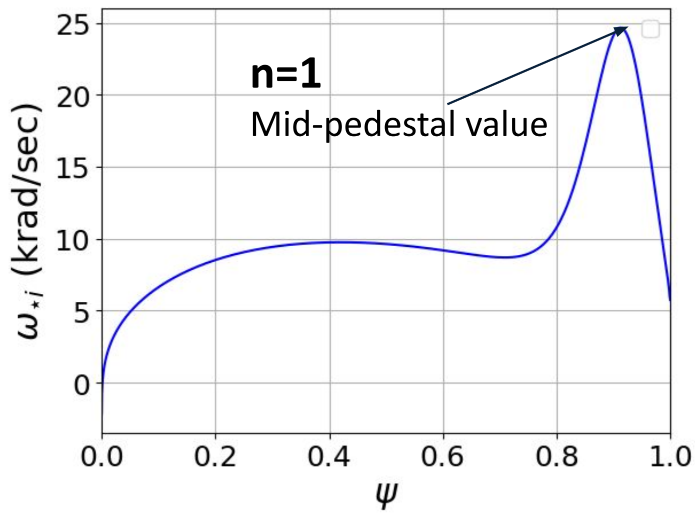
Three equilibria (A, B, and C) are unstable; other equilibria are stable

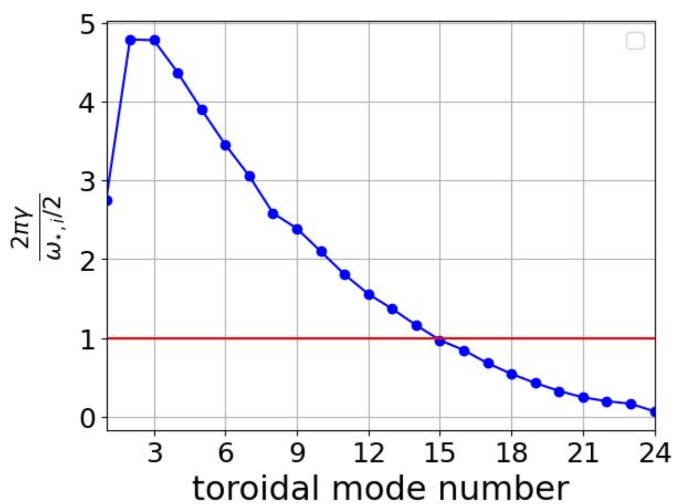
- **Peeling-ballooning modes remains dominant modes in linear simulations for cases A and B**
- **Core mode is dominant for the case C, but PB are still present**



Diamagnetic, Two-fluid, Gyro-viscosity (FLR) Effects

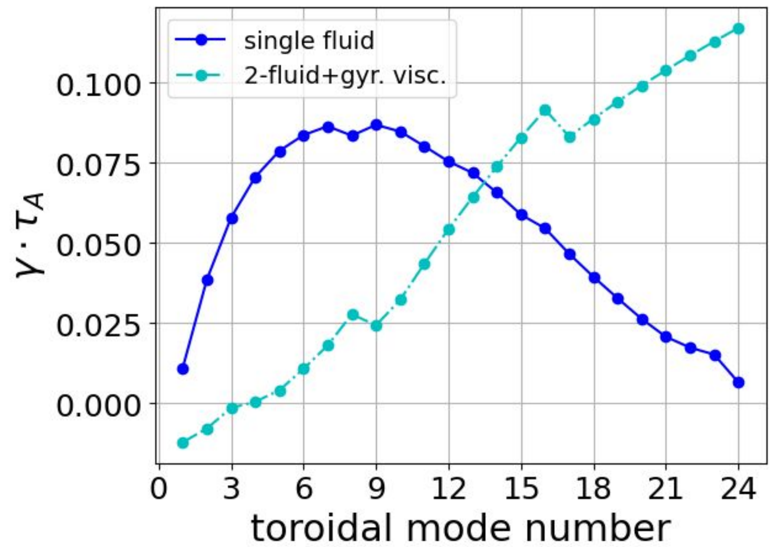
With predicted diamagnetic frequencies, modes n<15 remain unstable

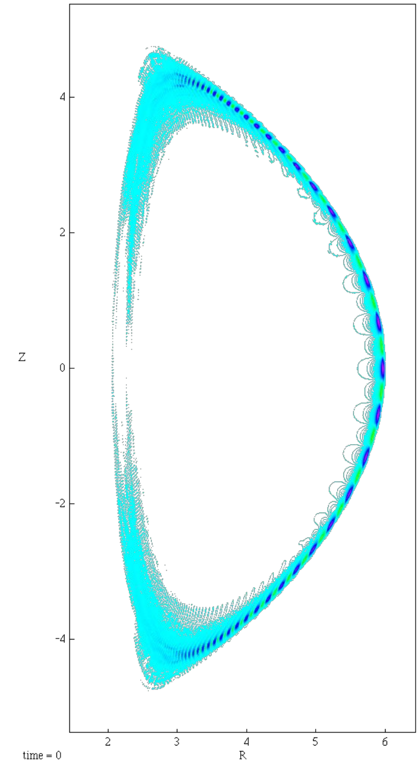




Two-fluid with gyro-viscosity stabilizes low-*n* modes and destabilizes higher-*n* modes (unexpected!)

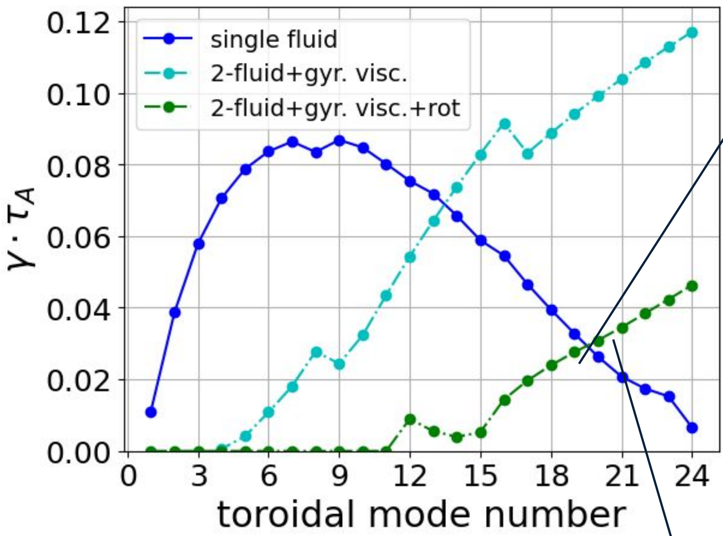
- **No rotation is included**

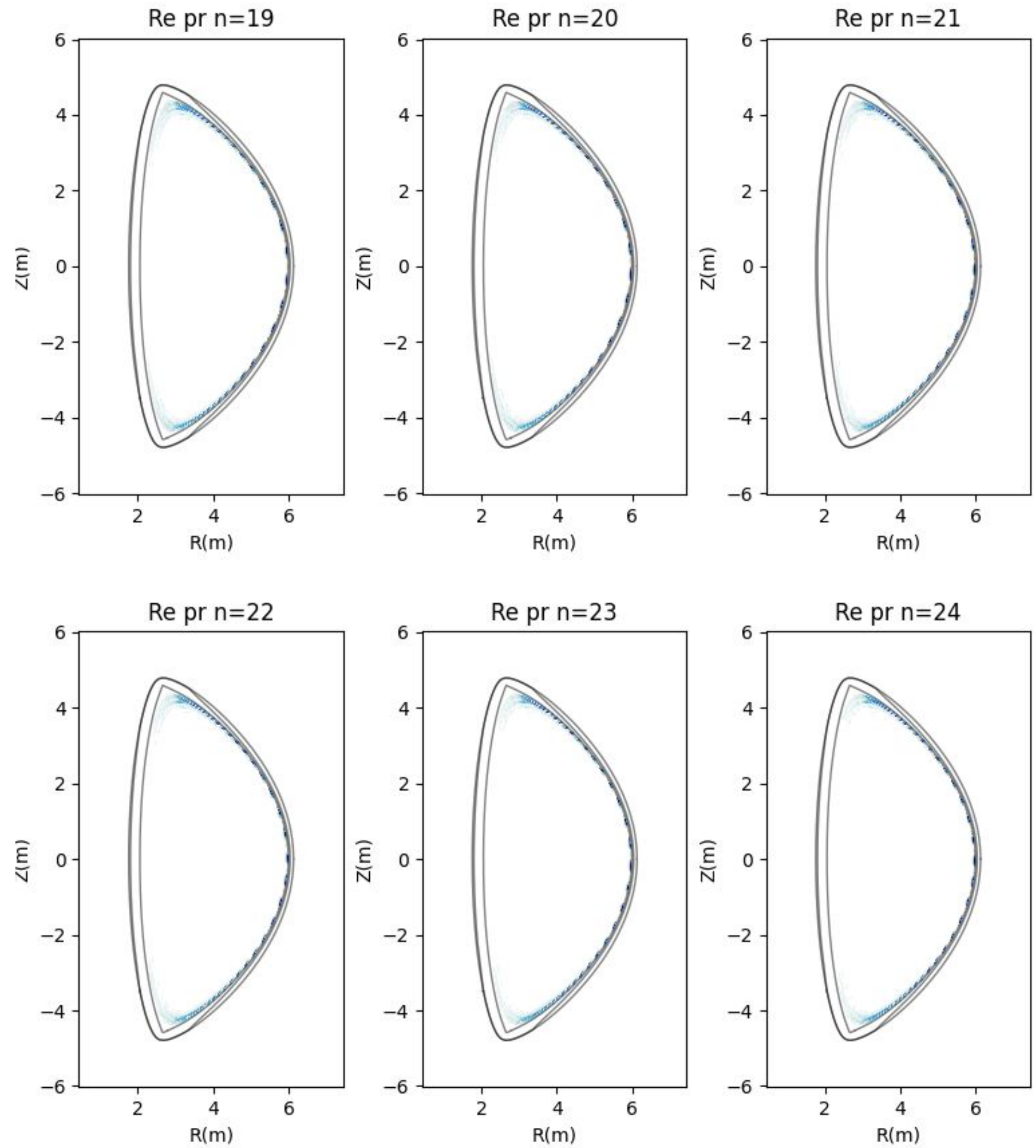




- **Rollover due to diamagnetic effects might required simulations with higher toroidal mode numbers included**
- **Diamagnetic stabilization in single-fluid simulation disagrees with two-fluid simulation that incorporates this effect**

High-n Modes Remain Unstable When All Effects (2fl+FLR+flows) are Included





With rotation, two-fluid, and FLR effects included, high-*n* PB–like modes remain unstable ⟶ extended-MHD physics is essential for STAR pedestal modeling

- **Higher toroidal modes need to be considered**
- **Additional convergence studies are still ongoing**

Summary and Future Work

- **Built a multi-code workflow for STAR based on TRANSP (integration), GX (linear/nonlinear gyrokinetics), reduced transport models (MMM, TGLF), and pedestal/ELM stability tools (NIMROD, ELITE)**
- **Transport: NSTX and STAR studies use GX to identify the dominant microinstabilities and associated fluxes; these results are used to test when MMM/TGLF are accurate enough for predictive STAR scenario scans**
- **Pedestal stability: NIMROD simulations, guided by NSTX experience, show that rotation, two-fluid, and FLR physics significantly affect high-*n* peeling–ballooning stability, and that STAR-like equilibria remain vulnerable to high-*n* modes even when these effects are included, indicating that ideal MHD alone is unlikely to be sufficient for STAR pedestal stability predictions**
- **Overall objective: determine where reduced transport models and ideal MHD tools are sufficient, and where STAR performance predictions require high-fidelity GX and extended-MHD (NIMROD) calculations**
- **Ongoing work: systematic *q*- and β-scans, rotation and collisionality scans, and use of these results to map the STAR operational space and guide scenario development**