US-China collaborations on development and application of GTC for fusion simulations

Zhihong Lin
University of California, Irvine

GTC Team

Highlights on recent US-China collaborations on GTC

- Collaborative GTC code development
  - ✓ Stellarator, tokamak with 3D equilibrium, field reversed configuration (FRC)
  - ✓ High frequency modes: ICE, CAE, GAE, LHW, IBW
  - ✓ High performance computing
- GTC physics applications
  - ✓ Microturbulences & neoclassical transport
  - ✓ Energetic particles & Alfven eigenmodes
  - ✓ MHD modes: kink, collisionless, resistive & neoclassical tearing modes
- Productivity since 2017
  - ✓ 28 US-China joint papers
  - ✓ 18 PhD: 3 UCI/PU, 4 PKU (Prof. Yian Lei), 7 USTC/IOP (Prof. Wenlu Zhang), 4 ZJU (Prof. Yong Xiao)

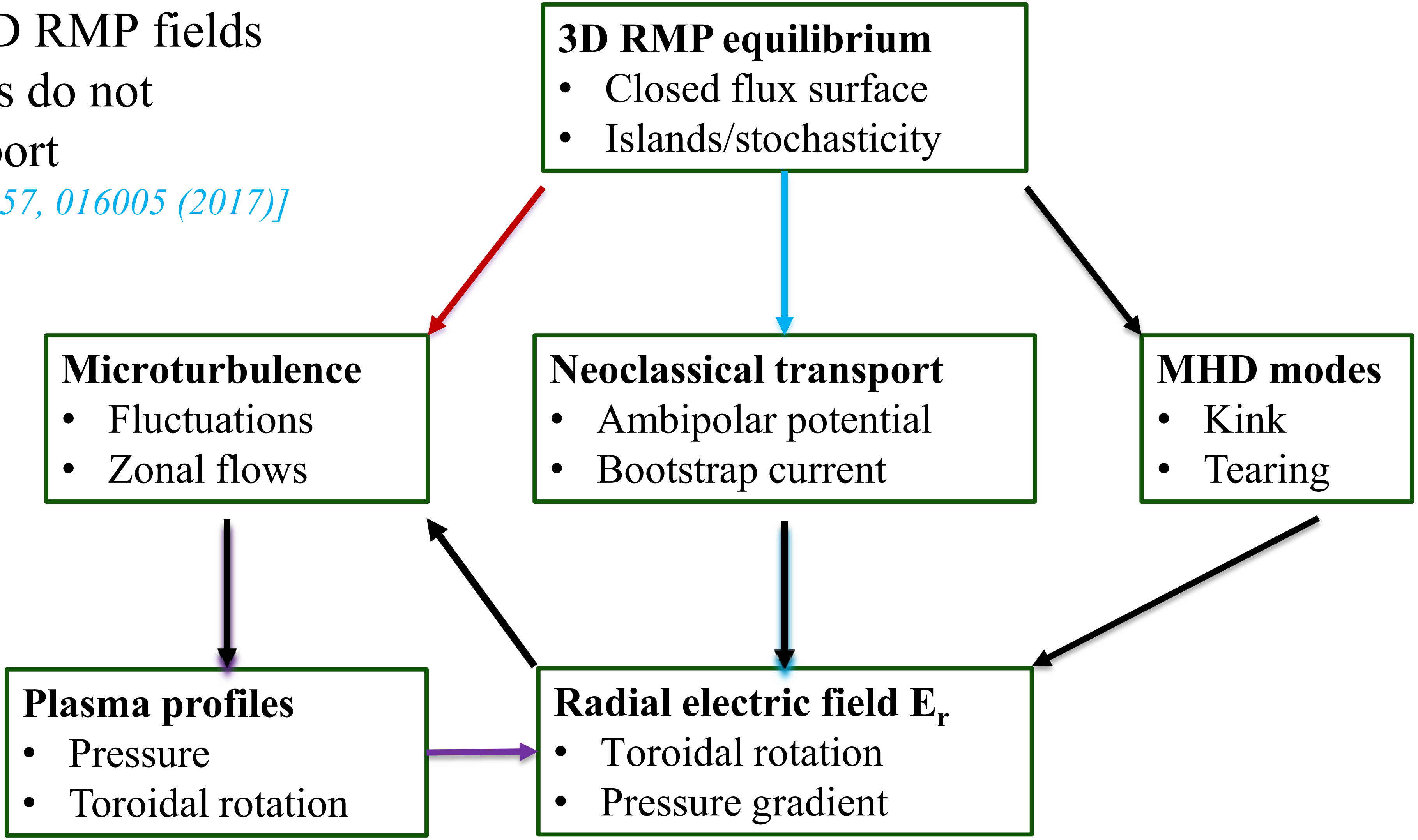
Outlines

- Microturbulences & neoclassical transport in tokamak with RMP and stellarator
- Energetic particles & Alfven eigenmodes
- MHD modes and high frequency modes

How Does 3D RMP Affect Edge Microturbulence?

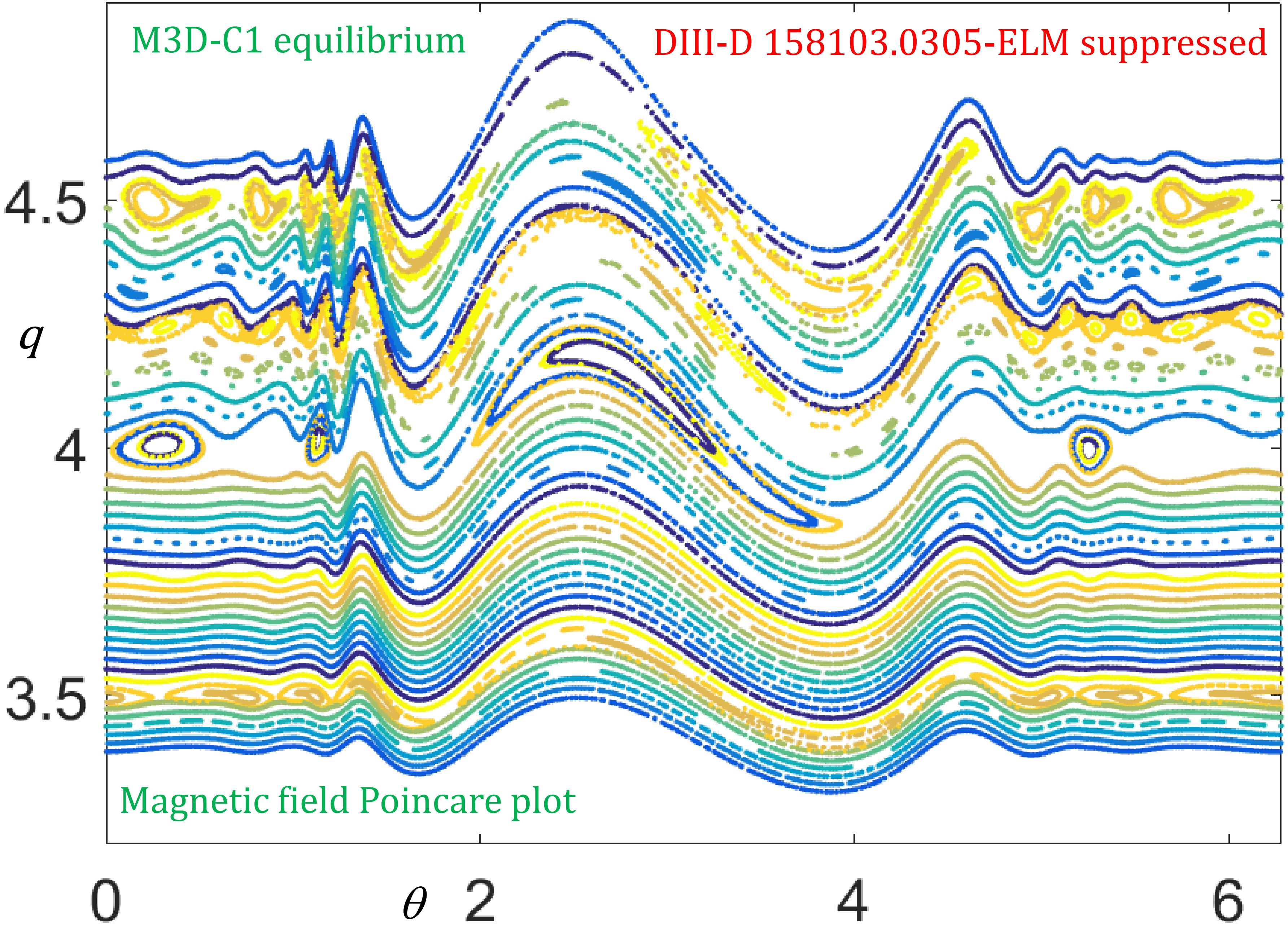
I. Can 3D fields with closed flux-surfaces enhance turbulent transport?
II. Role of magnetic islands and stochastic fields?
III. Indirect effects on microturbulence, e.g., radial electric field shear?

- GTC simulations find 3D RMP fields with closed flux-surfaces do not enhance turbulent transport
  [I. Holod, et al, Nuclear Fusion 57, 016005 (2017)]



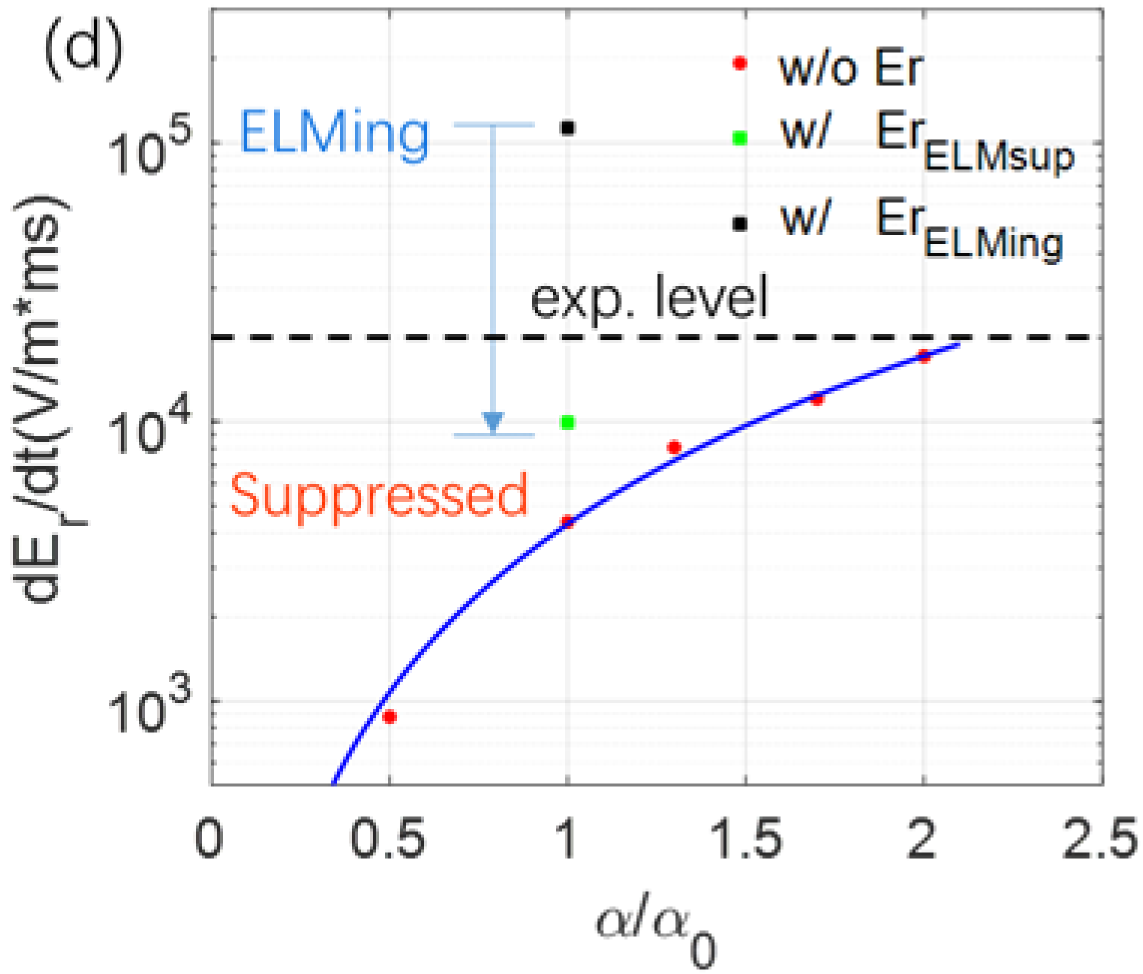
II. Resonant Responses Generate Magnetic Islands & Stochastic Fields

- Poincare plots of RMP magnetic fields
- Magnetic island size smaller than ion gyroradius
  - ✓ No ion responses
  - ✓ Enhanced electron particle flux is non-ambipolar



II. Magnetic Islands and Stochastic Fields Can Modify Radial Electric Field by Neoclassical Transport

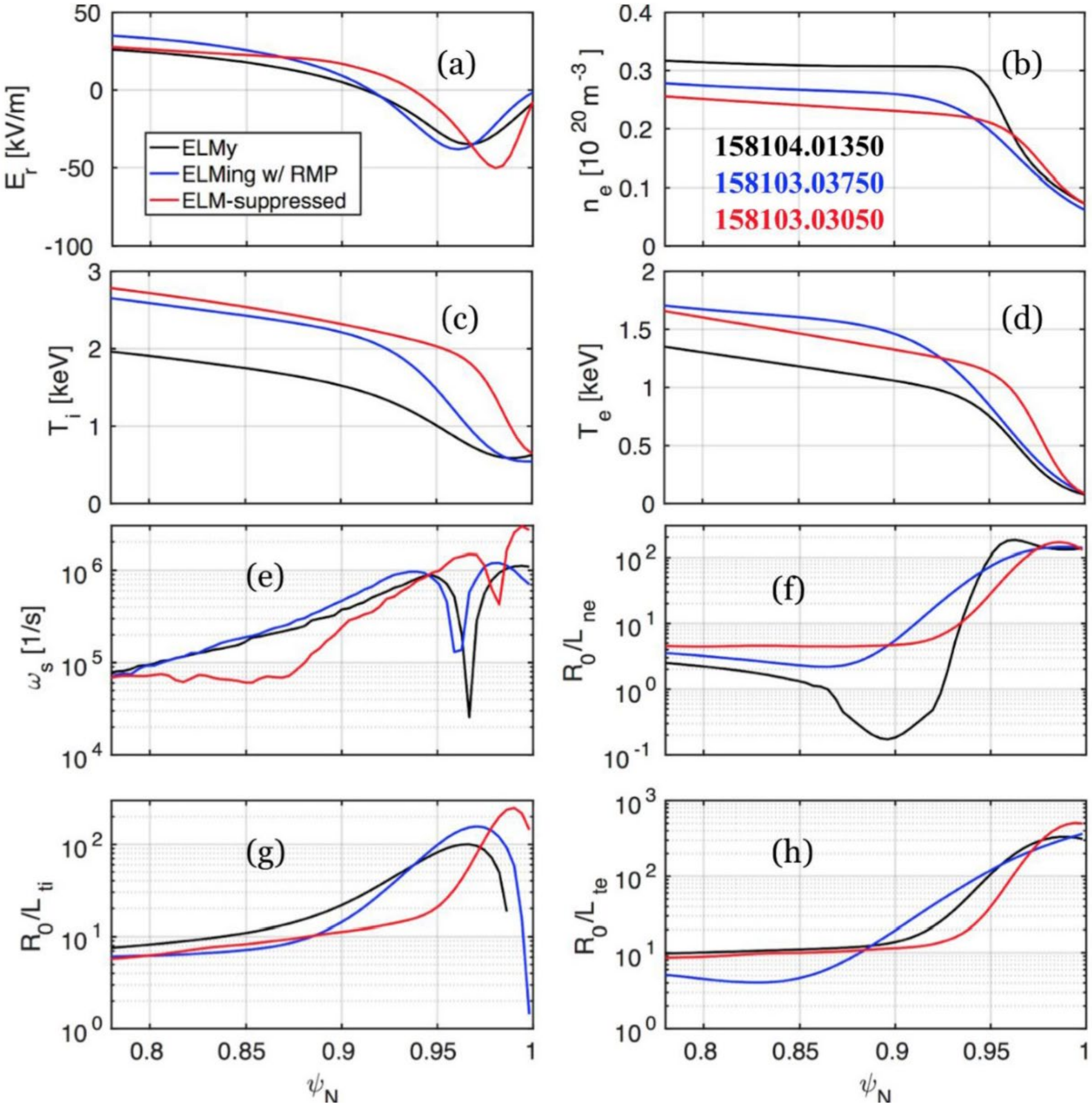
- GTC simulations find that electron particle flux due to RMP flutter transport causes little density pump out
- However, non-ambipolar flutter transport induces rapid changes in radial electric field, which damps toroidal rotation



J. Y. Fu et al, 2021

III.
RMP Induces Changes of Plasma Profiles

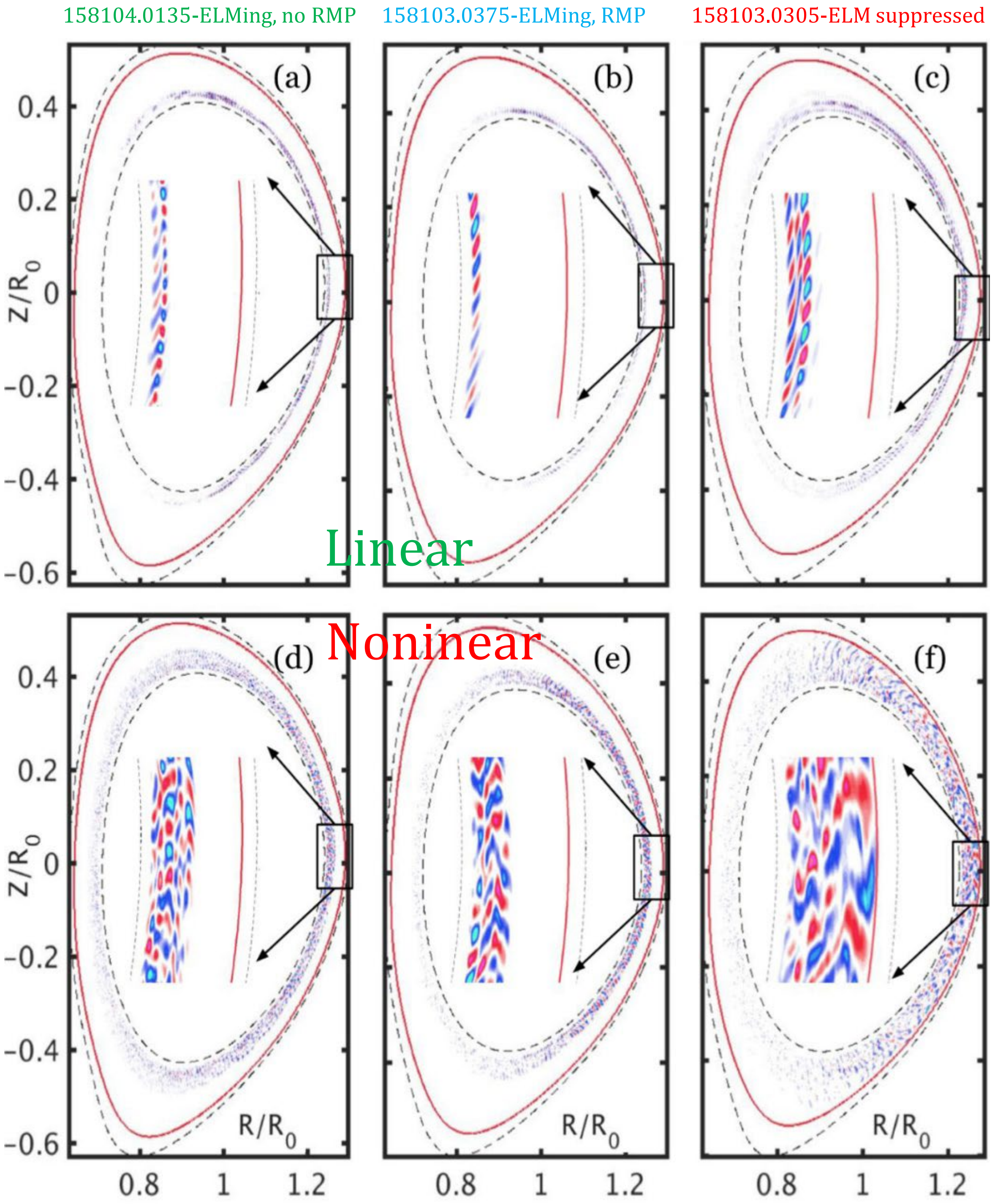
- DIII-D shots with n=2 RMP [*Nazikian et al, PRL2015*]
  - ✓ 158104.1350: ELMing w/o RMP
  - ✓ 158103.3750: ELMing w/ RMP
  - ✓ 158103.3050: ELM suppression



III. GTC Simulations Show That Turbulence Spreads to Pedestal Top

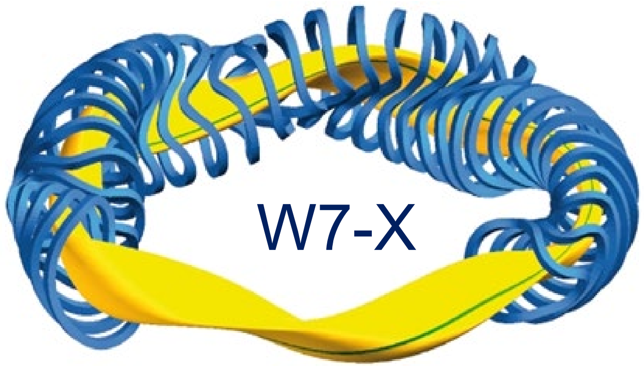
- Linear eigenmodes (*upper panels*) form inside pedestal top
- During ELM suppression, turbulence spreads to q=4 surface (*red circle*) after nonlinear saturation (*lower panels*) due to weaker ExB shear
- Transport in pedestal top increases

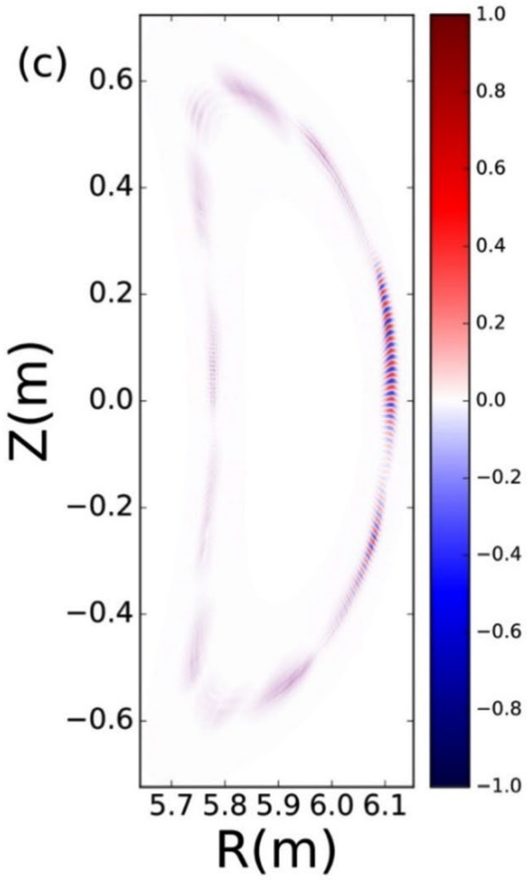
Effects of RMP-Induced Changes of Radial Electric Fields on Microturbulence in DIII-D Pedestal Top,
S. Taimourzadeh, L. Shi, Z. Lin, R. Nazikian, I. Holod, D. Spong,
Nuclear Fusion **59**, 046005 (2019).

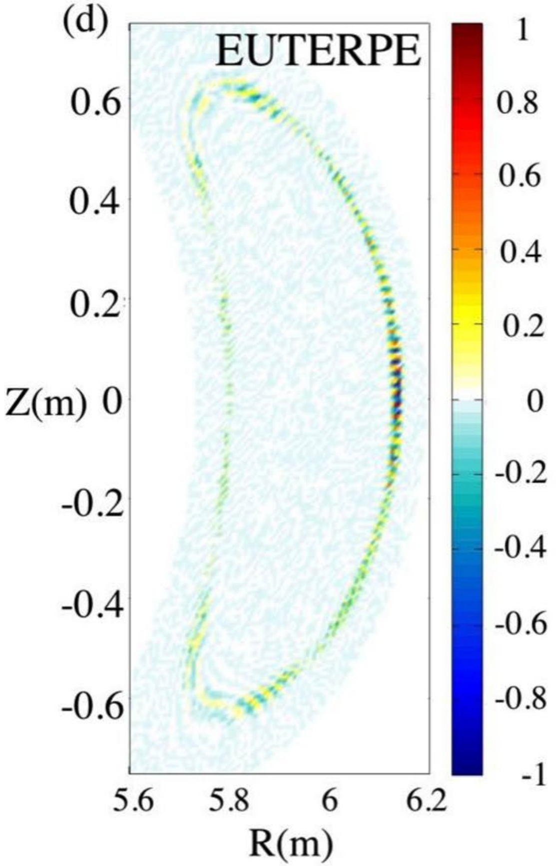


Neoclassical and Turbulent Transport in Stellarators

- Intrinsically 3D stellarator is an attractive fusion reactor concept with steady state operation and reduced risk of disruptions since there is minimal plasma current
- What are properties of turbulent transport and energetic particle confinement in stellarators optimized for neoclassical (collisional) transport?
- GTC simulations of ion temperature gradient (ITG) instability in W7-X agree well with EUTERPE

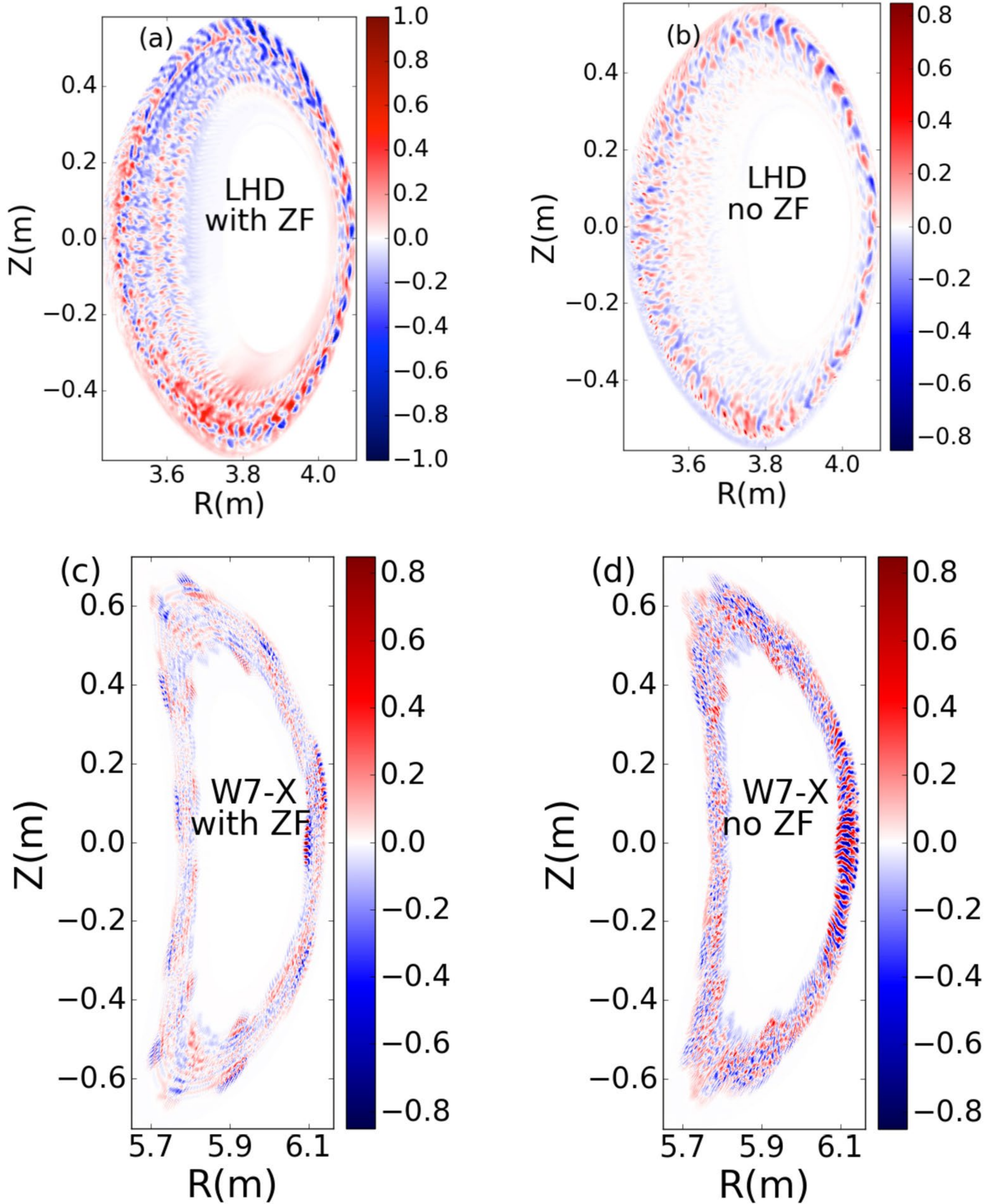






First nonlinear global gyrokinetic simulation of ITG microturbulence in LHD & W7-X

- Neoclassical and turbulent transport intrinsically coupled in 3D equilibrium of stellarators and tokamak with RMP, which requires full flux-surface and radially non-local simulation
- GTC simulations of ITG microturbulence in LHD & W7-X find role of zonal flows and turbulence spreading

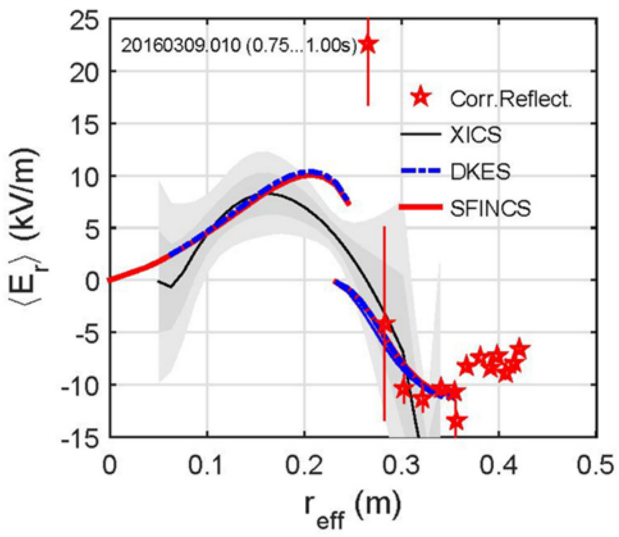


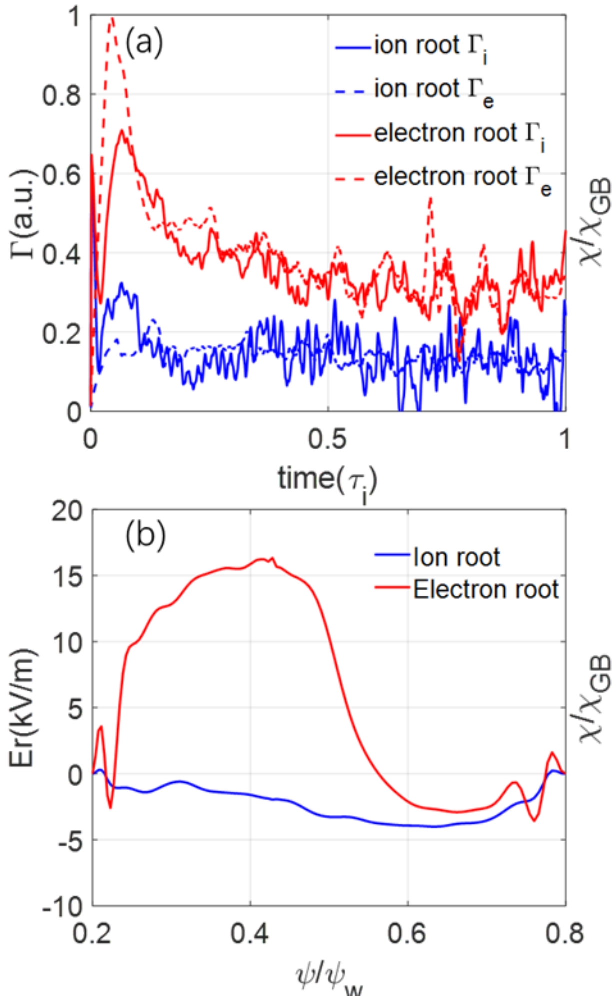
Global Gyrokinetic Particle Simulations of Microturbulence in W7-X and LHD Stellarators, H. Y. Wang, I. Holod, Z. Lin, J. Bao, J. Y. Fu, P. F. Liu, J. H. Nicolau, D. Spong, Y. Xiao, Phys. Plasmas 27, 082305 (2020).

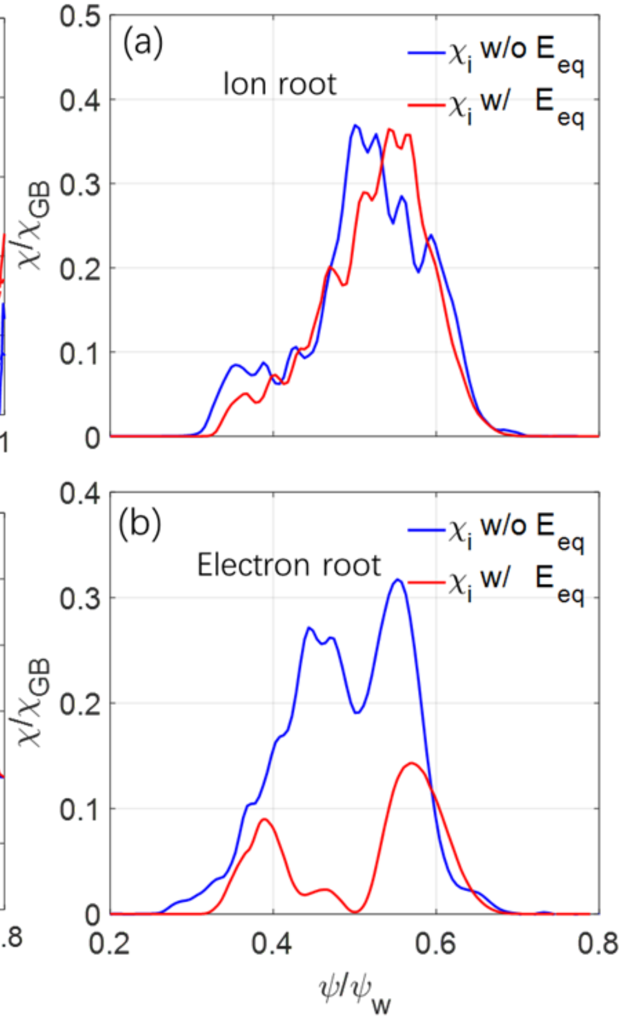
Effects of Ambipolar Electric Field on Microturbulence in W7-X

- GTC neoclassical simulation of ion and electron simultaneously; Radial electric fields calculated self-consistently
- Ambipolarity ($\Gamma_i \sim \Gamma_e$) radial electric fields E_r in W7-X consistent with other codes (e.g. DKES) [*Wolf et al, NF 57, 102020 (2017)*]
- Ambipolar electric fields strongly suppress ITG turbulence in electron root, but modest effects in ion root

[*J. Y. Fu et al, PoP2021*]

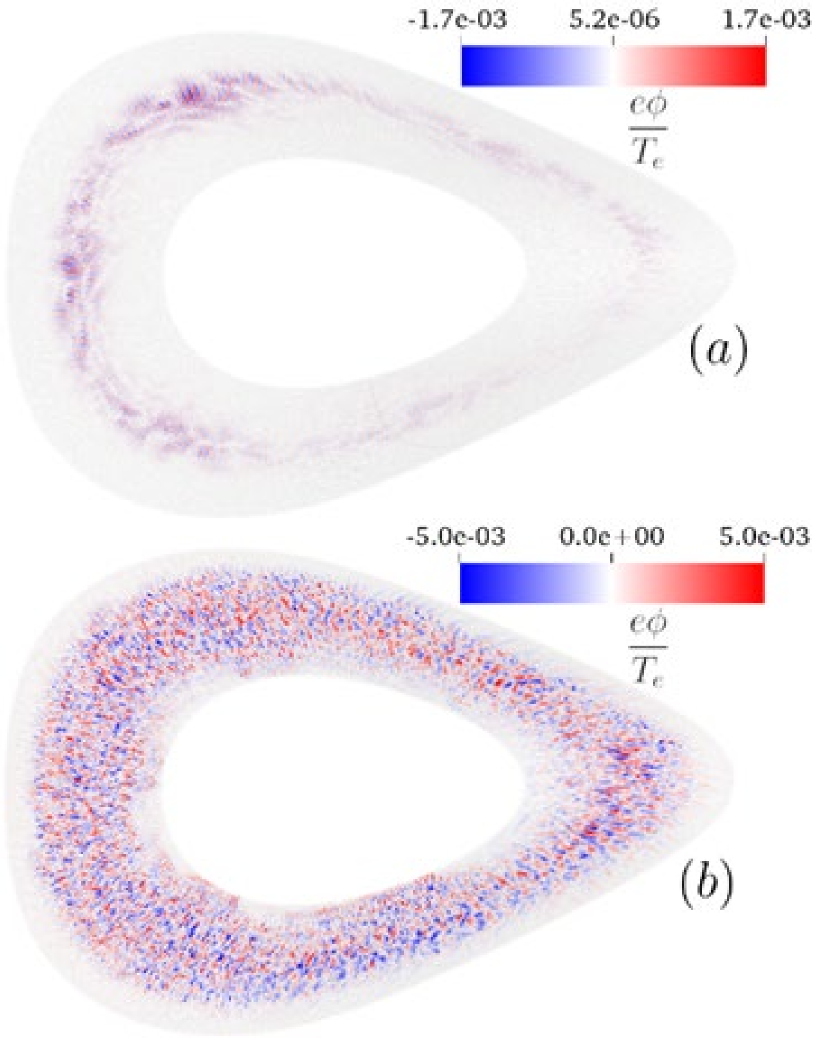




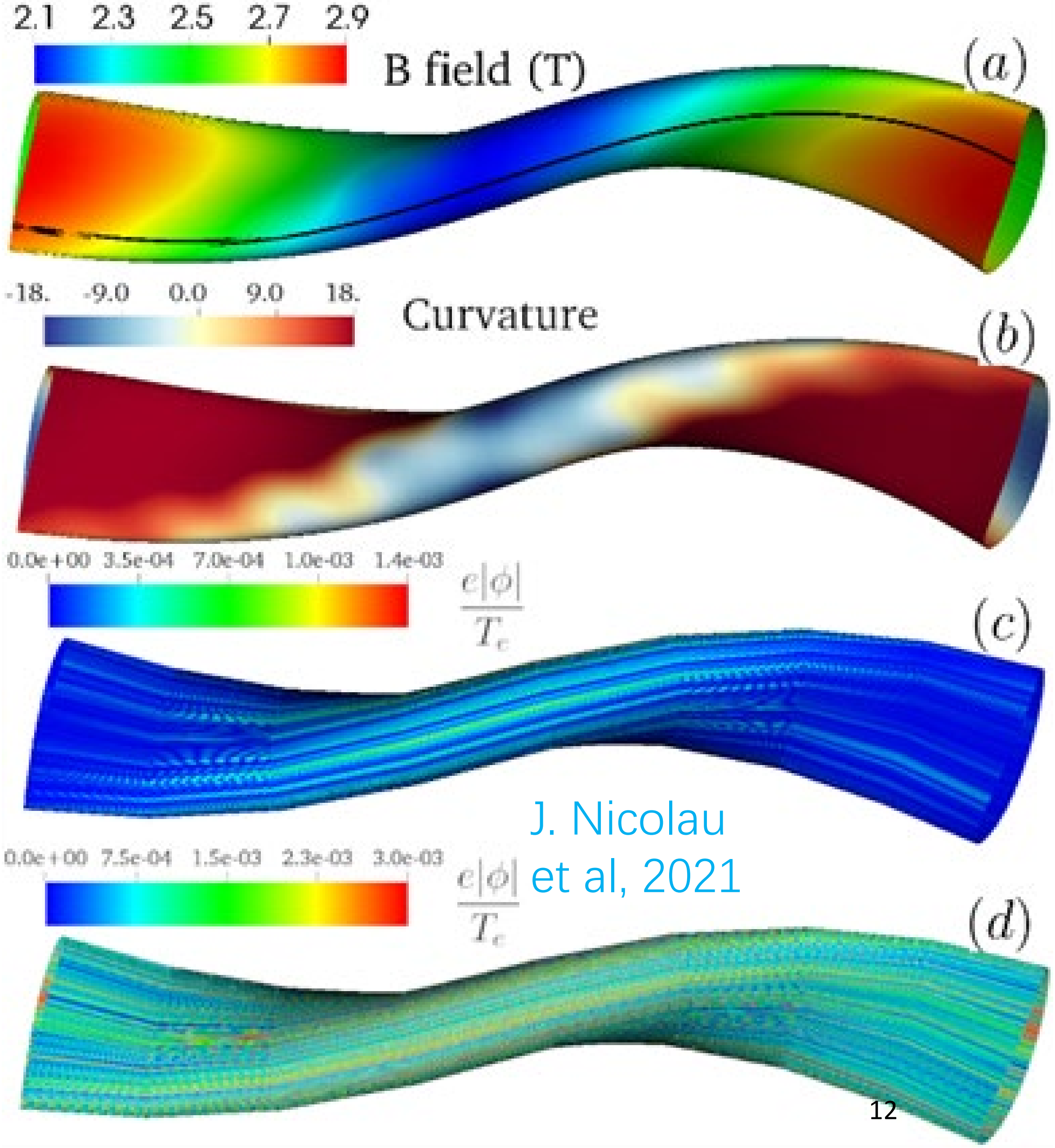


Helically Trapped Electron Mode (HTEM) in W7-X

- GTC global simulations find a new trapped electron modes excited by helically trapped electrons in W7-X stellarator



[*J. Nicolau et al, 2021*]



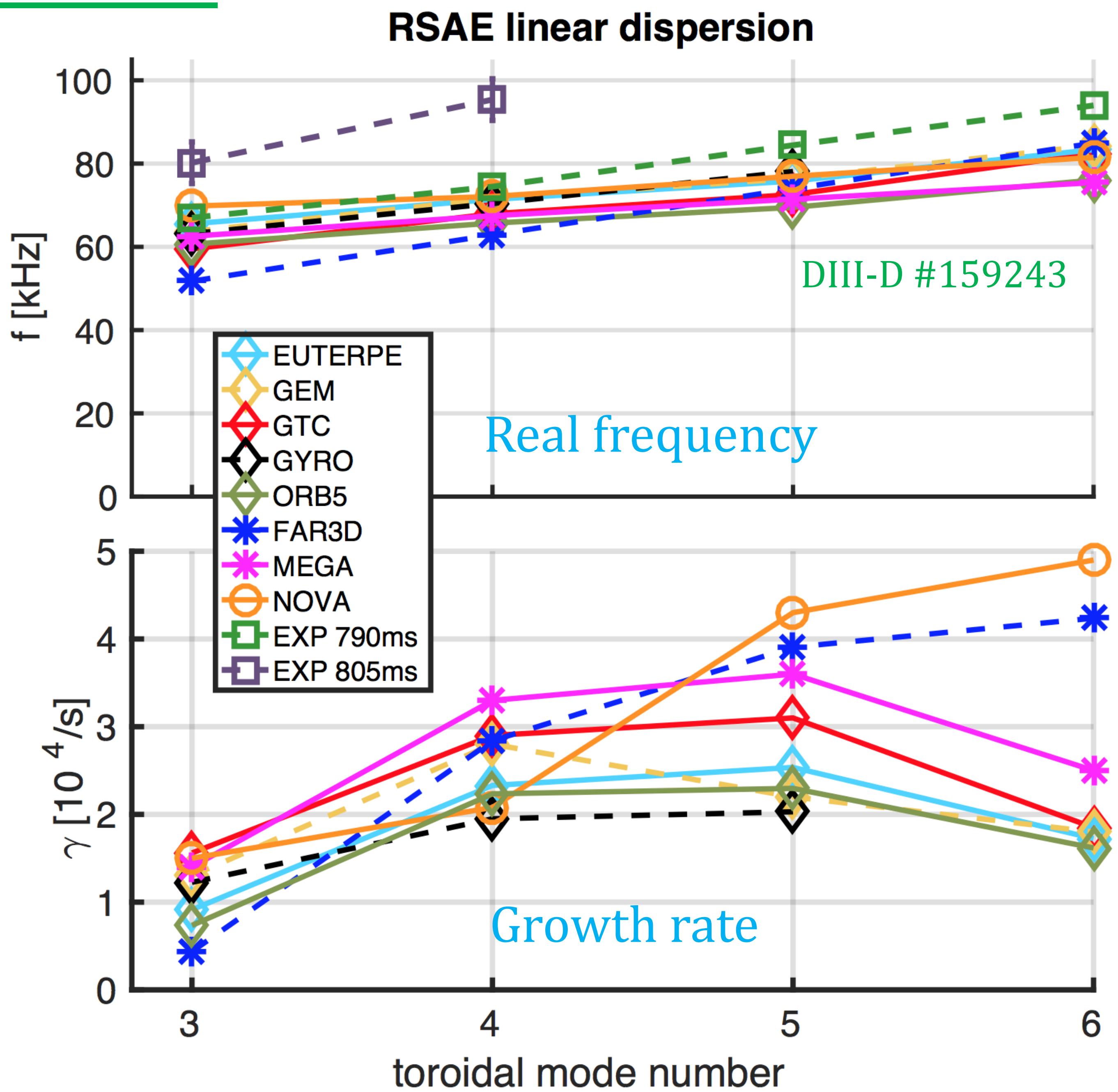
J. Nicolau et al, 2021

Outlines

- Microturbulences & neoclassical transport in tokamak with RMP and stellarator
- Energetic particles & Alfven eigenmodes
- MHD modes and high frequency modes

Integrated Simulations of Energetic Particles

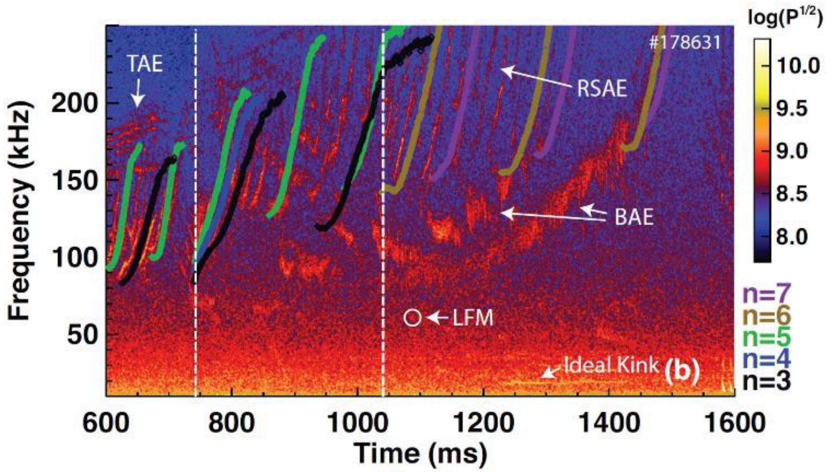
- Integrated simulations of energetic particle needed for burning plasmas
- V&V of SciDAC ISEP Center: UCI, GA, PPPL, ORNL, LBNL, LLNL, PU, UCSD
- Good agreement for reversed shear Alfven eigenmodes (RSAE)
- Frequency agrees better with experiment at 790ms; Simulations use profiles at 805ms; uncertainty in q measurement

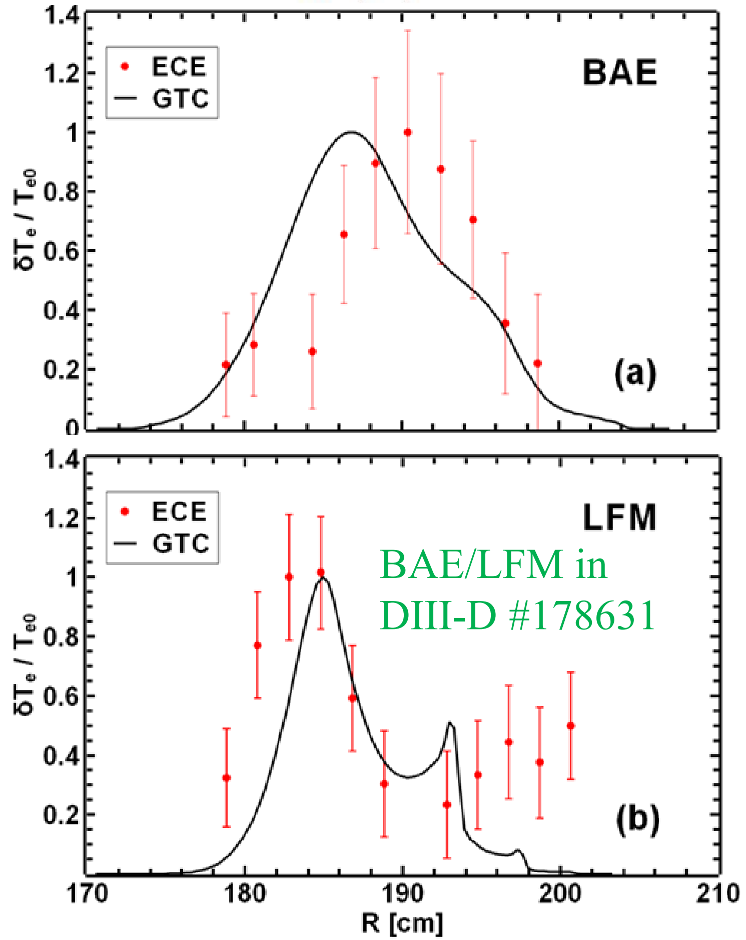


Verification and validation of integrated simulation of energetic particles in fusion plasmas, S. Taimourzadeh, E. M. Bass, Y. Chen, C. Collins, N. N. Gorelenkov, A. Konies, Z. X. Lu, D. A. Spong, Y. Todo, M. E. Austin, J. Bao, A. Biancalani, M. Borchardt, A. Bottino, W. W. Heidbrink, Z. Lin, R. Kleiber, A. Mishchenko, L. Shi, J. Varela, R. E. Waltz, G. Yu, W. L. Zhang, and Y. Zhu, *Nuclear Fusion* **59**, 066006 (2019)

GTC simulation of low-frequency modes in DIII-D

- GTC simulations find beta-induced Alfvén eigenmode (BAE) and a low-frequency mode (LFM) co-exist in DIII-D
- LFM is excited without fast ions and has a frequency inside the gap of beta-induced Alfvén-acoustic eigenmode (BAAE)
- GTC finds that LFM is an interchange-like electromagnetic mode excited by non-resonant drive of pressure gradients
- Compressible magnetic perturbations, which are neglected in most of GK simulations, increases growth rate of LFM & BAE
- Trapped electrons and equilibrium current have modest effects on the BAE and LFM



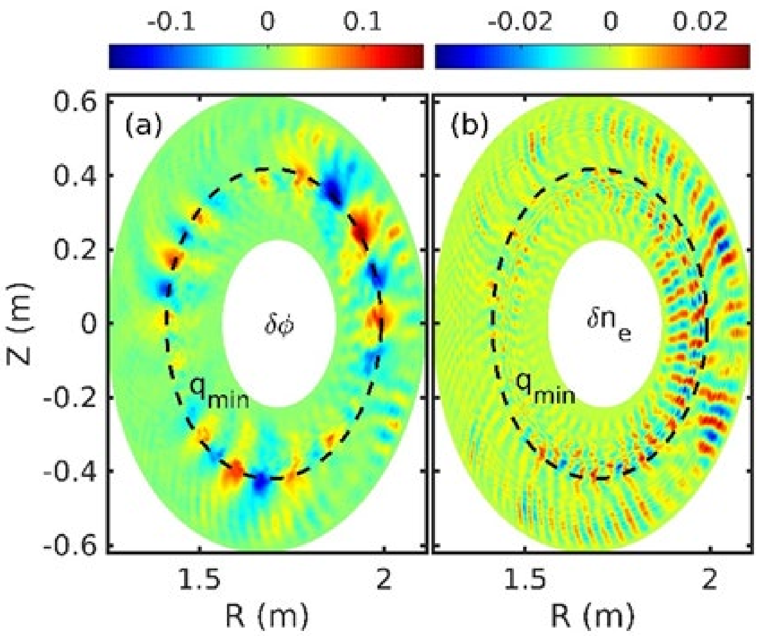


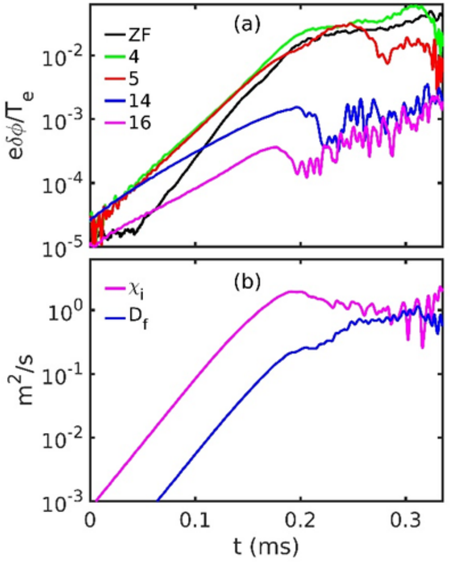
*[Gyrokinetic simulation of low-frequency Alfvénic modes in DIII-D tokamak](), G. J. Choi, P. Liu, X. S. Wei, J. H. Nicolau, G. Dong, W. L. Zhang, Z. Lin, W. W. Heidbrink and T.S. Hahm, Nuclear Fusion **61**, (2021).*

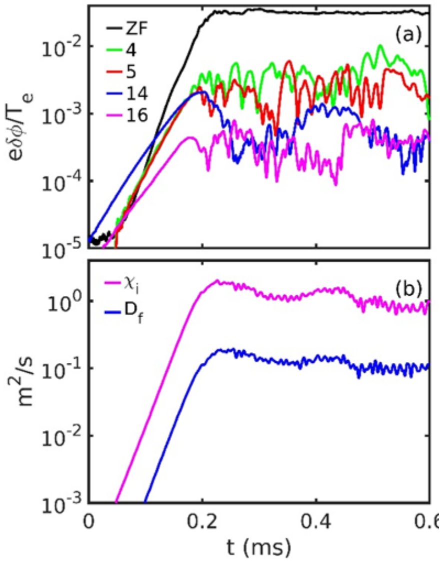
Suppression of Alfven eigenmodes by microturbulence

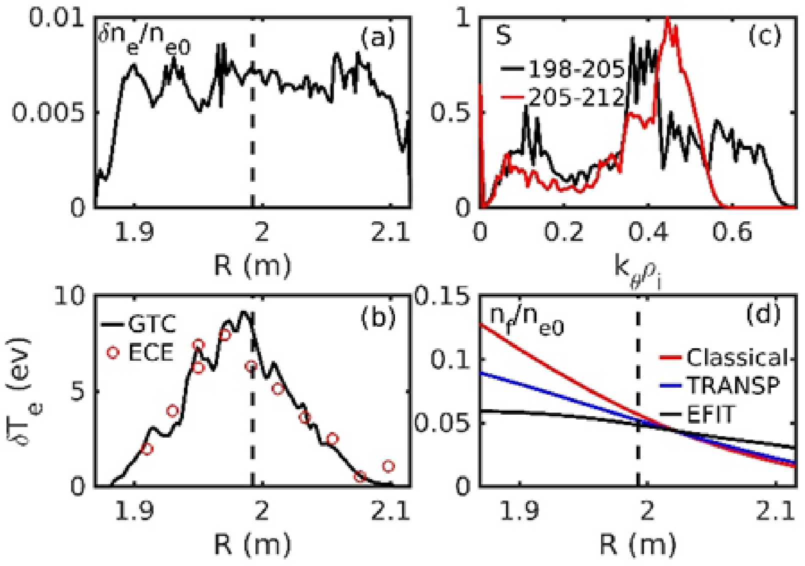
- GTC simulations find that (RSAE) saturated amplitude and EP transport level are an order of magnitude higher than experimental observations
- In simulations coupling micro-meso scales, RSAE amplitude and EP transport are greatly reduced to experimental level due to zonal flow and EP scattering by ITG microturbulence
- Resulting RSAE mode structure and microturbulence intensity agree very well with experimental measurements using ECE) and BES

P. Liu et al, 2021







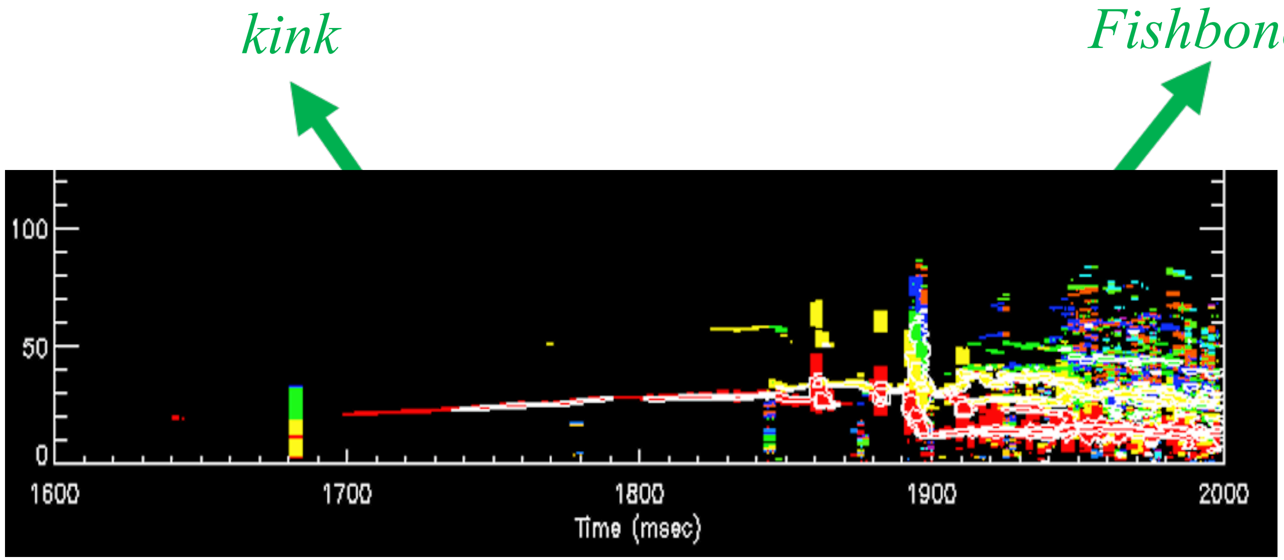


Outlines

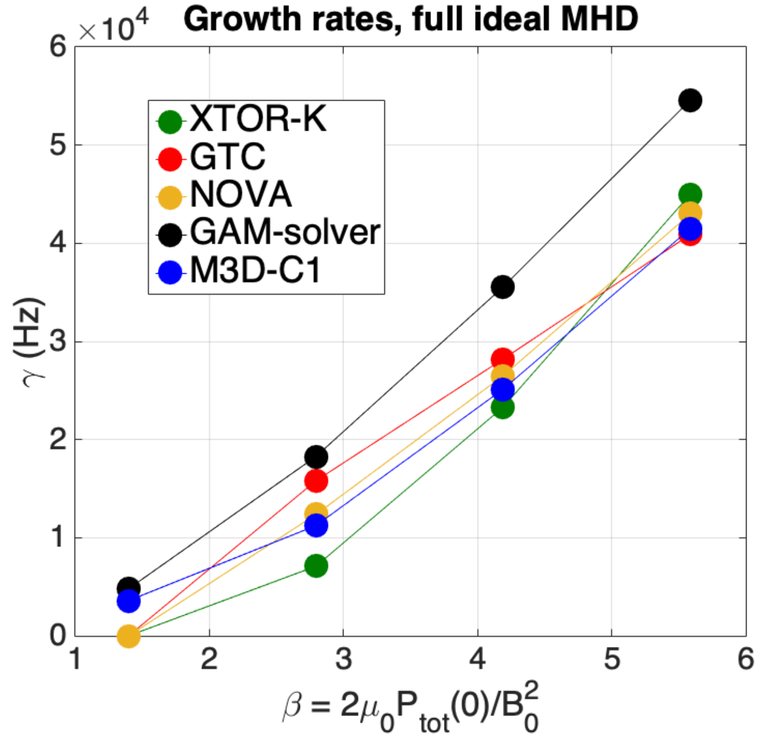
- Microturbulences & neoclassical transport in tokamak with RMP and stellarator
- Energetic particles & Alfven eigenmodes
- MHD modes and high frequency modes

V&V of GTC Simulation of Kink Instability in DIII-D

- Microscopic kinetic effects often play important roles in macroscopic MHD modes
- GTC simulations in MHD limit of internal kink agree well with MHD codes
- GTC gyrokinetic simulations find that kinetic effects significantly reduce growth rate
- GTC simulations of 2000 DIII-D experiments used in deep learning model FRNN for real-time SGTC [*G. Dong, X. Wei, 2021*]
- DOE FES 2022 theory milestone on prediction of α-particle transport in ITER: microturbulence, meso scale AE, MHD modes
- Next step: benchmark for fishbone and NTM simulations



G. Brochard et al, 2021

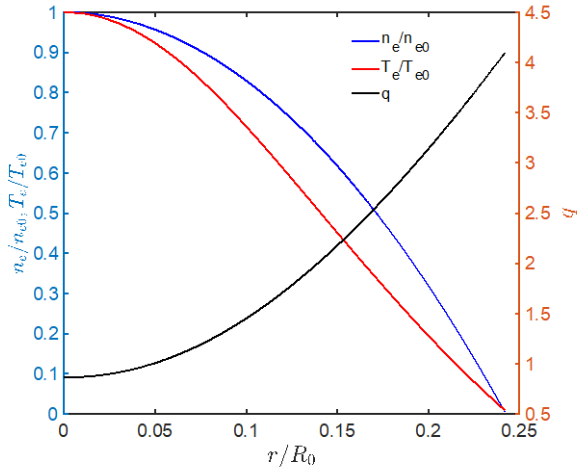


GTC NTM simulations qualitatively agrees with Fitzpatrick's theory

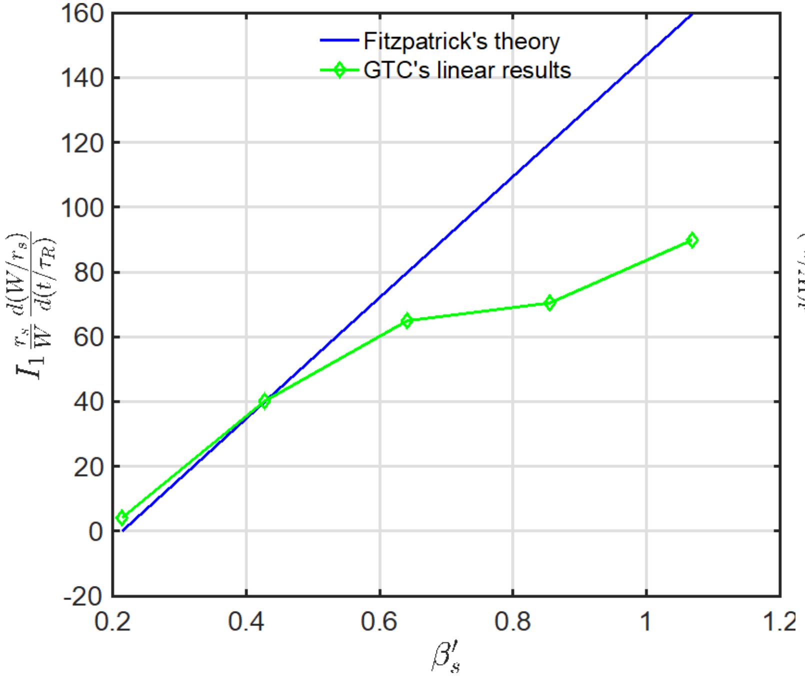
S. Sun et al, 2021

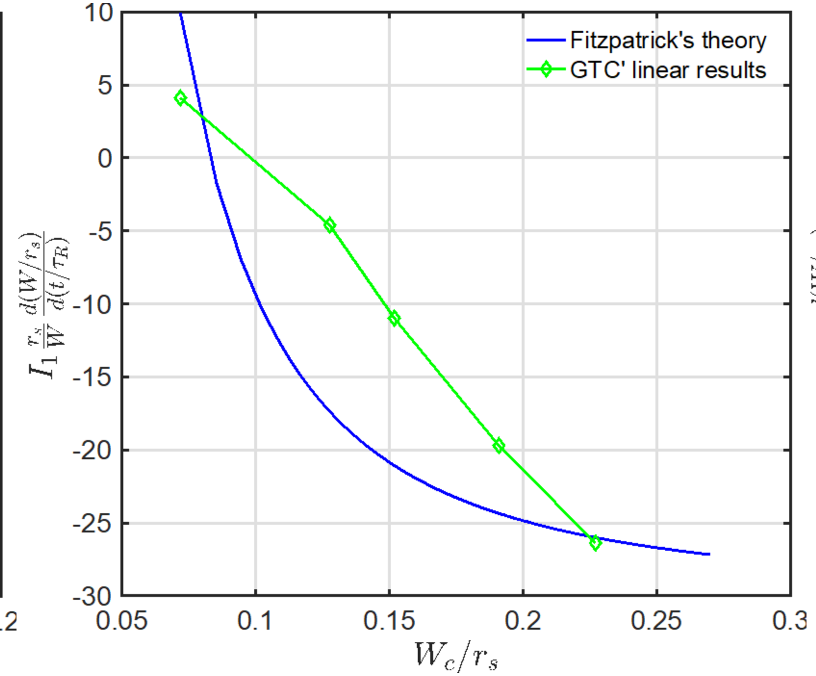
Fitzpatrick PoP 199, NTM growth rate:

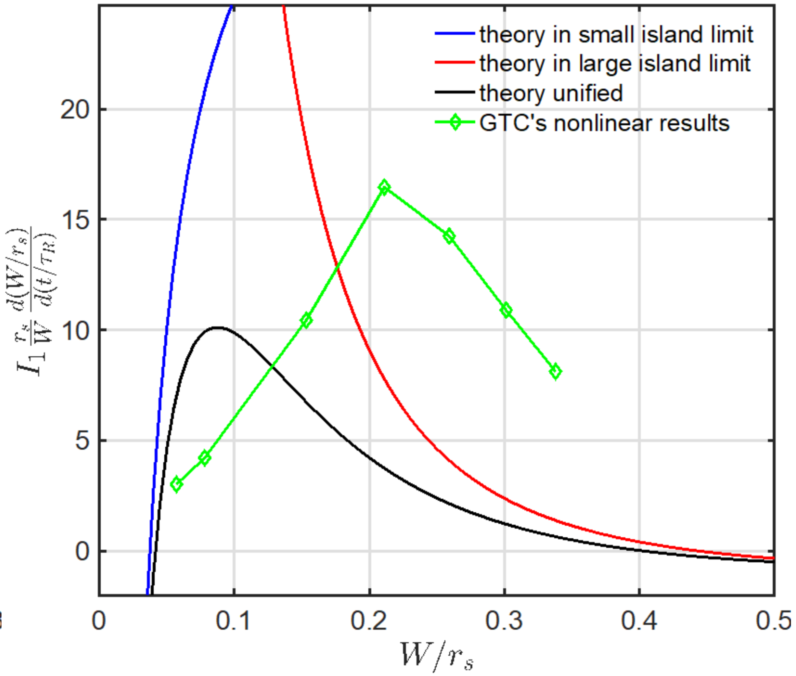
- In small island limit: $I_1\left(\frac{r_s}{W}\right)\frac{d}{d(t/\tau_R)}\left(\frac{W}{r_s}\right) \simeq \Delta' r_s\left(\frac{r_s}{W}\right) + 2.88\sqrt{\epsilon_s}\frac{\beta_s'}{s_s}\left(\frac{r_s}{W_c}\right)^2$
- In large island limit: $I_1\left(\frac{r_s}{W}\right)\frac{d}{d(t/\tau_R)}\left(\frac{W}{r_s}\right) \simeq \Delta' r_s\left(\frac{r_s}{W}\right) + 9.26\sqrt{\epsilon_s}\frac{\beta_s'}{s_s}\left(\frac{r_s}{W}\right)^2$
- Unified: $I_1\left(\frac{r_s}{W}\right)\frac{d}{d(t/\tau_R)}\left(\frac{W}{r_s}\right) \simeq \Delta' r_s\left(\frac{r_s}{W}\right) + 9.26\sqrt{\epsilon_s}\frac{\beta_s'}{s_s}\frac{r_s^2}{W^2+W_d^2}$, here $W_d = 1.8W_c$



GTC's simulation uses HL-2A shot #11727 reconstructed equilibrium.

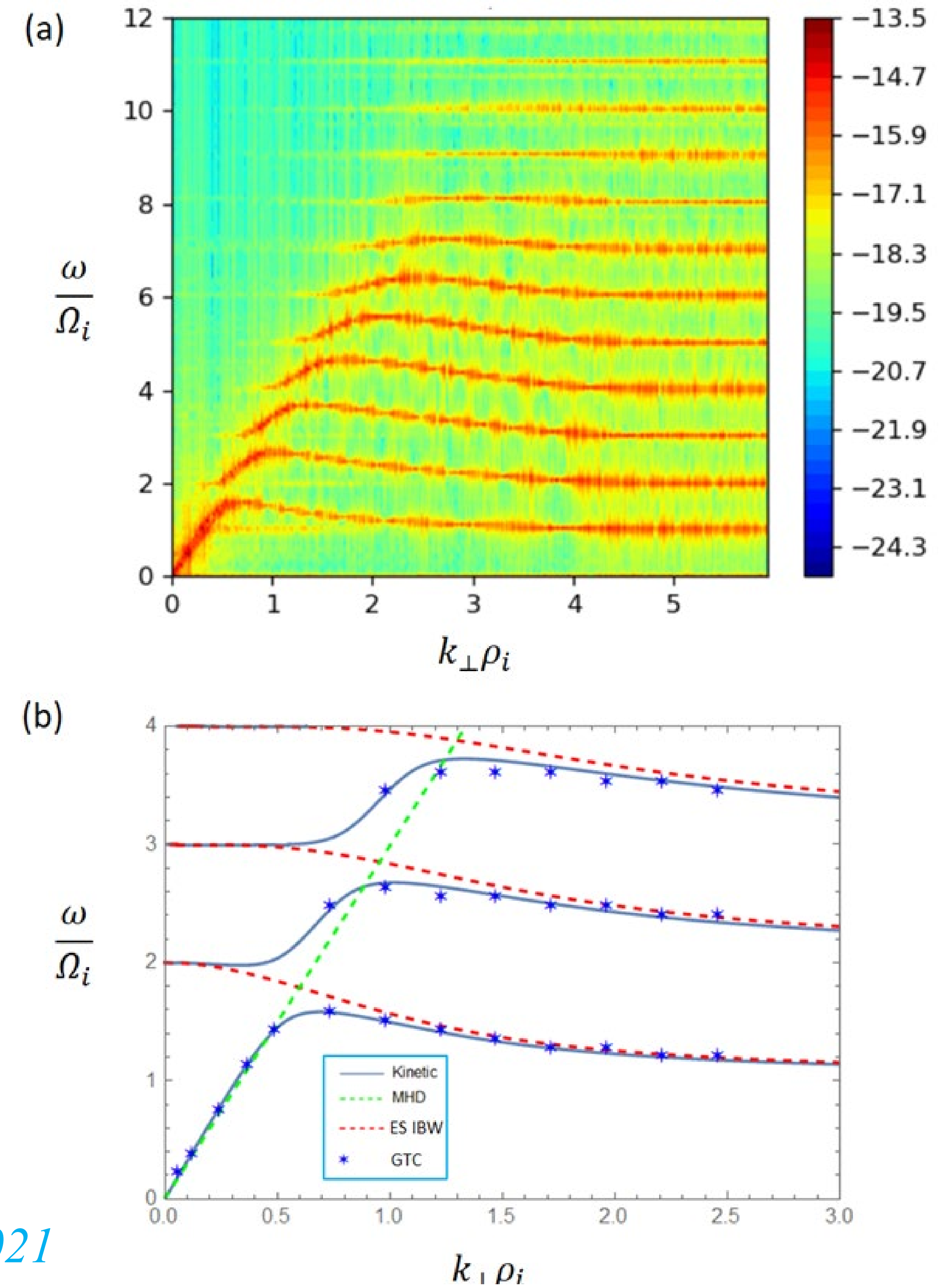






GTC simulation using fully kinetic ion and drift kinetic electron

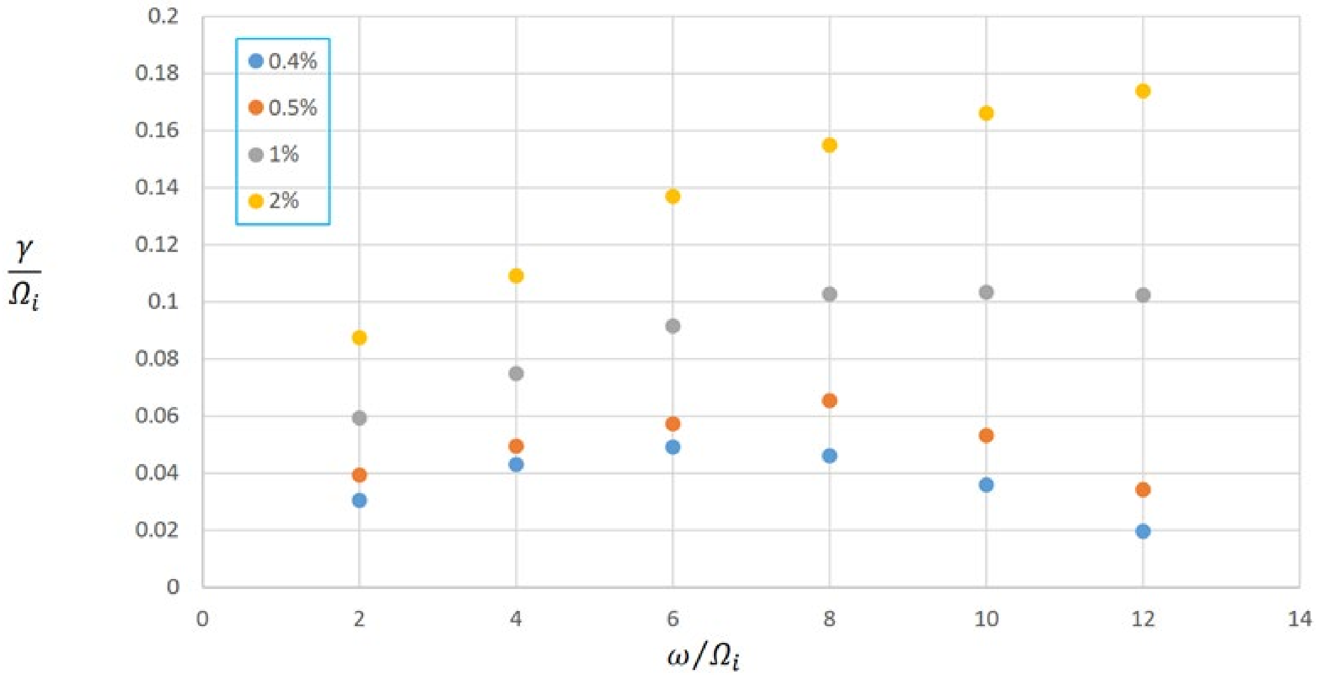
- Simulation model
  - √ Fully kinetic (6D) Vlasov equation for ions (FKi)
  - √ Drift kinetic equation for electrons (DKe)
  - √ Poisson equation for electrostatic potential (□)
  - √ Parallel Ampere's law for parallel vector potential ($\delta A_{\|}$)
  - √ Perpendicular electron force balance for compressible magnetic perturbation ($\delta B_{\|}$)
- Verification of linear simulation of CAE/ICE
  - √ Massless electron, perpendicular propagation ($k_{\|}$=0)
  - √ Simulation with all $k_\perp$ exhibits CAE/ICE (upper panel)
  - √ Simulations with a single $k_\perp$ agree with dispersion relation from kinetic theory (lower panel)

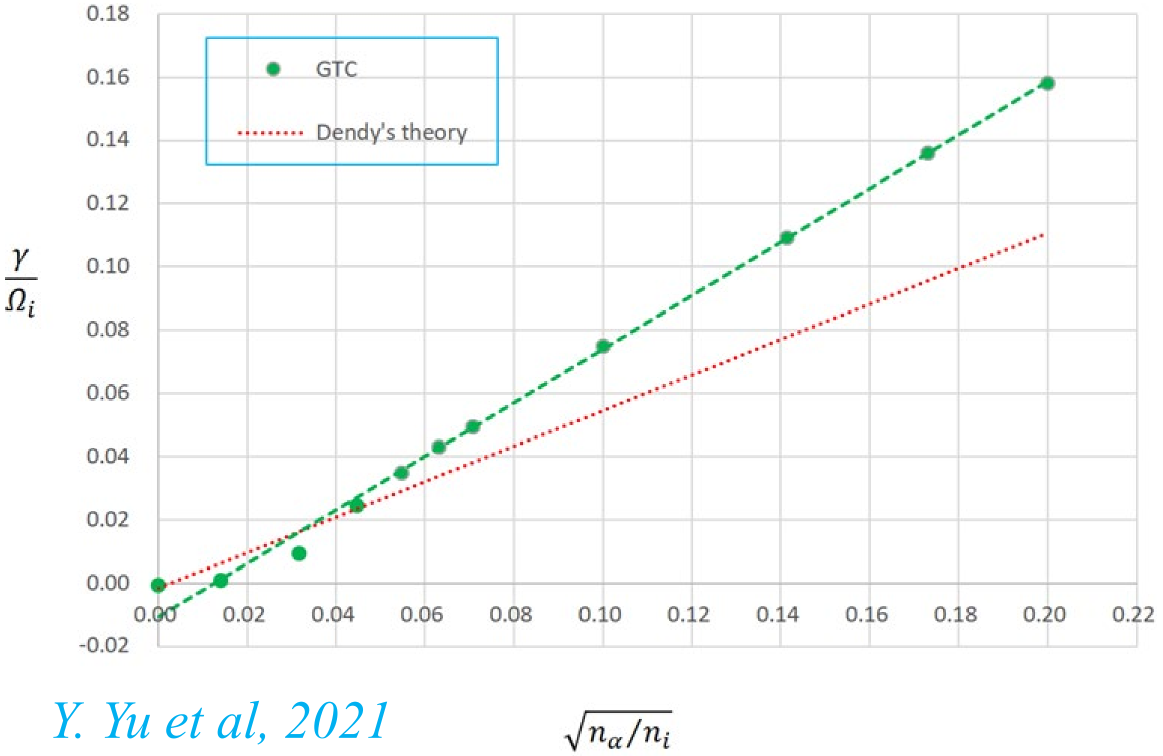


Y. Yu et al, 2021

GTC simulation of ICE excitation by α-particles

- Magnetoacoustic cyclotron instability (MCI) driven by α-particles with population inversion
- Higher harmonics excited by higher α-particle density n_α (left panel)
- Growth rate $\gamma \propto \sqrt{n_\alpha}$ in qualitative agreement with Dendy PF1992 theory (right panel)
- Next step: verification of GAE/CAE with $k_{||} \neq 0$; benchmark with HYM for GAE/CAE





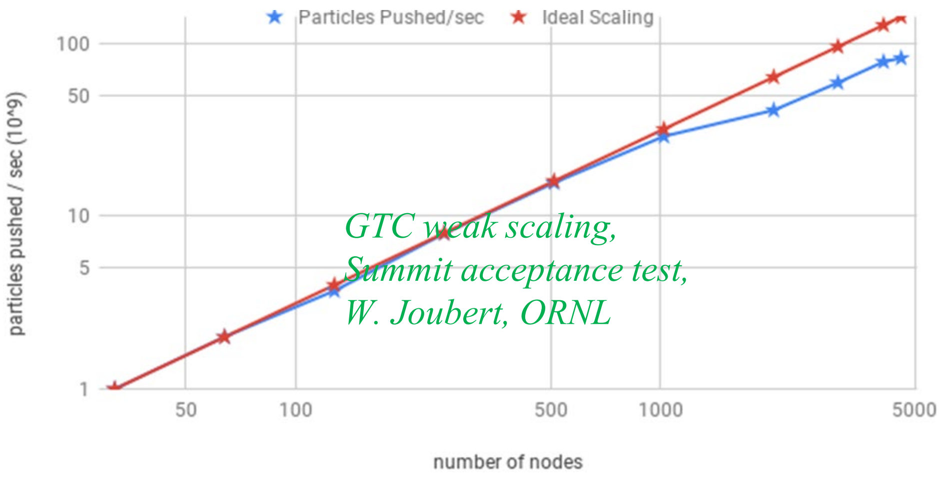
Y. Yu et al, 2021

GTC physics models & applications

- Global integrated simulation of nonlinear interactions of multiple kinetic-MHD processes
- Four kinetic species: thermal ion & electron, fast ion & electron
  - ✓ Gyrokinetic thermal & fast ion, drift kinetic thermal & fast electron
  - ✓ Fluid-kinetic hybrid electron model, conservative scheme for thermal electron
  - ✓ Fully kinetic (6D) ion
  - ✓ Shifted Maxwellian & anisotropic slowing down distribution function
- Three fluid models: reduced resistive MHD, massless & finite-mass electron fluid model
- δf & full-f method, compressible magnetic perturbation, equilibrium current
- Microturbulence: drift-Alfvenic instabilities, collisionless & drift tearing modes
- MHD: Alfven eigenmodes, kink, resistive & neoclassical tearing modes
- Neoclassical transport: pitch-angle scattering, Fokker-Planck collision operators
- High frequency waves: ICE, CAE, LHW, IBW

GTC geometry and computing capability

- Global 3D toroidal geometry for tokamak, stellarator, cylinder
- Magnetic equilibrium geometry from EFIT, VMEC, M3D-C1, s-a model
- Boozer coordinates, global field-aligned mesh
- FD & FEM for gyrokinetic Poisson equation using Pade approximation, integral form solver
- Sparse matrix solver: amgX, *hypre*, PETSc
- Synthetic diagnostics: SDP (ECE & ECEI)
- Three levels of parallelization
  - ✓ MPI toroidal domain decomposition
  - ✓ MPI particle decomposition
  - ✓ Loop level: OpenMP/OpenACC



[W. Zhang et al, SC2018]

1. *New Paradigm for Turbulent Transport Across a Steep Gradient in Toroidal Plasmas*, H. S. Xie, Y. Xiao, and Z. Lin, *Phys. Rev. Lett.* **118**, 095001 (2017).
2. *Excitation of Low Frequency Alfven Eigenmodes in Toroidal Plasmas*, Yaqi Liu, Zhihong Lin, Huasen Zhang, Wenlu Zhang, *Nuclear Fusion* **57**, 114001 (2017).
3. *Effects of electron cyclotron current drive on magnetic islands in tokamak plasmas*, J. C. Li, C. J. Xiao, Z. H. Lin, K. J. Wang, *Phys. Plasmas* **24**, 082508 (2017).
4. *Nonlinear Co-existence of Beta-induced Alfvén Eigenmodes and Beta-induced Alfvén-acoustic Eigenmodes*, Junyi Cheng, Wenlu Zhang, Zhihong Lin, Ding Li, Chao Dong, Jintao Cao, *Phys. Plasmas* **24**, 092516 (2017).
5. *A conservative scheme of drift kinetic electrons for gyrokinetic simulation of kinetic-MHD processes in toroidal plasmas*, J. Bao, D. Liu, Z. Lin, *Phys. Plasmas* **24**, 102516 (2017).
6. *A closed high-frequency Vlasov-Maxwell simulation model in toroidal geometry*, Pengfei Liu, Wenlu Zhang, Chao Dong, Jingbo Lin, Zhihong Lin, and Jintao Cao, *Nuclear Fusion* **57**, 126011 (2017).
7. *Pushforward Transformation of Gyrokinetic Moments under Electromagnetic Fluctuations*, Pengfei Liu, Wenlu Zhang, Chao Dong, Jingbo Lin, Zhihong Lin, Jintao Cao, and Ding Li, *Phys. Plasmas* **24**, 112114 (2017).
8. *Particle simulation of radio frequency waves with fully-kinetic ions and gyrokinetic electrons*, Jingbo Lin, Wenlu Zhang, Pengfei Liu, Zhihong Lin, Chao Dong, Jintao Cao, and Ding Li, *Nuclear Fusion* **58**, 016024 (2018).
9. *A conservative scheme for electromagnetic simulation of magnetized plasmas with kinetic electrons*, J. Bao, Z. Lin, and Z. X. Lu, *Phys. Plasmas* **25**, 022515 (2018).
10. *Development of Finite Element Field Solver in Gyrokinetic Toroidal Code*, Hongying Feng, Wenlu Zhang, Zhihong Lin, Xiaohe Zhufu, Jin Xu, Jintao Cao, and Ding Li, *Commun. Comput. Phys.* **24** 655 (2018).
11. *Simulation of toroidicity-induced Alfven eigenmode excited by energetic ions in HL-2A tokamak plasmas*, Hongda He, Junyi Cheng, J. Q. Dong, Wenlu Zhang, Chenxi Zhang, Jinxia Zhu, Ruirui Ma, T. Xie, G. Z. Hao, A. P. Sun, G. Y. Zheng, W. Chen and Z. Lin, *Nuclear Fusion* **58**, 126023 (2018).
12. *Heterogeneous Programming and Optimization of Gyrokinetic Toroidal Code Using Directives*, Wenlu Zhang, Wayne Joubert, Peng Wang, Matthew Niemerg, Bei Wang, William Tang, Sam Taimourzadeh, Lei Shi, Jian Bao, Zhihong Lin, *Lecture Notes in Computer Science* **11381**, 3–21 (2019). (WACCPD 2018 Workshop, Dallas).
13. *Global simulation of ion temperature gradient instabilities in a field-reversed configuration*, J. Bao, C. K. Lau, Z. Lin, H. Y. Wang, D. P. Fulton, S. Dettrick, and T. Tajima, *Phys. Plasmas* **26**, 042506 (2019).
14. *Global gyrokinetic simulation of microturbulence with kinetic electrons in the presence of magnetic island in tokamak*, K. S. Fang and Z. Lin, *Phys. Plasmas* **26**, 052510 (2019).
15. *Kinetic particle simulations in a global toroidal geometry*, S. De, T. Singh, A. Kuley, J. Bao, Z. Lin, G. Y. Sun, S. Sharma, and A. Sen, *Phys. Plasmas* **26**, 082507 (2019).
16. *Gyrokinetic simulations of nonlinear interactions between magnetic islands and microturbulence*, Kaisheng Fang, Jian Bao, and Zhihong Lin, *Plasma Sci. Technol.* **21**, 115102 (2019).
17. *Verification of gyrokinetic particle simulation of current-driven instability in fusion plasmas. IV. Drift-tearing mode*, Hao Shi, Wenlu Zhang, Hongying Feng, Zhihong Lin, Chao Dong, Jian Bao, and Ding Li, *Phys. Plasmas* **26**, 092512 (2019).
18. *Verification of an energetic-electron-driven b-induced Alfven eigenmode in the HL-2A tokamak*, Yang Chen, Wenlu Zhang, Junyi Cheng, Zhihong Lin, Chao Dong, and Ding Li, *Phys. Plasmas* **26**, 102507 (2019).
19. *Gyrokinetic particle simulations of interactions between energetic particles and magnetic islands induced by neoclassical tearing modes*, X. Tang, Z. Lin, W. W. Heidbrink, J. Bao, C. Xiao, Z. Li and J. Li, submitted to *Phys. Plasmas* **27**, (2020).
20. *Global Gyrokinetic Particle Simulations of Microturbulence in W7-X and LHD Stellarators*, H. Y. Wang, I. Holod, Z. Lin, J. Bao, D. Spong, Y. Xiao, submitted to *Nuclear Fusion* **60**, (2020).
21. *GTC simulation of linear stability of tearing mode and a model magnetic island stabilization by ECCD in toroidal plasma*, Jingchun Li, Chijie Xiao, Zhihong Lin, Dongjian Liu, Xiaoquan Ji, and Xiaogang Wang, *Phys. Plasmas* **27**, 042507 (2020).
22. *Temperature Gradient, Toroidal and Ion FLR Effects on Drift-Tearing Modes*, Hao Shi, Wenlu Zhang, Chao Dong, Jian Bao, Zhihong Lin, Jintao Cao, and Ding Li, *Chin. Phys. Lett.* **37**, 085201 (2020).
23. *Verification of Energetic-Particle-Induced Geodesic Acoustic Mode in Gyrokinetic Particle Simulations*, Yang Chen, Wenlu Zhang, Jian Bao, Zhihong Lin, Chao Dong, Jintao Cao, and Ding Li, *Chin. Phys. Lett.* **37**, 095201 (2020).
24. *Verification of local electrostatic gyrokinetic simulation of driftwave instability in field-reversed configuration*, Shuying Sun, Xishuo Wei, Zhihong Lin, Pengfei Liu, Wenhao Wang, and Huasheng Xie, *Phys. Plasmas* **27**, 112504 (2020).
25. *Electromagnetic modeling of parametric instability for slow waves in lower hybrid frequency range*, J. Bao, Z. Lin, W. L. Zhang, and D. Li, AIP Conference Proceedings **2254**, 080003 (2020).
26. *Linear gyrokinetic simulations of reversed shear Alfvén eigenmodes and ion temperature gradient modes in DIII-D tokamak*, Hongyu Wang, Pengfei Liu, Zhihong Lin, and Wenlu Zhang, *Plasma Sci. Technol.* **23**, 015101 (2021).
27. *Linear simulation of kinetic electromagnetic instabilities in a tokamak plasma with weak magnetic shear*, Yunchuan Zhao, Jiaqi Wang, Dongjian Liu, Wei Chen, Ge Dong, and Zhihong Lin, *Phys. Plasmas* **28**, 012107 (2021).
28. *Effects of Plasma Diamagnetic Drift on Alfven Continua and Discrete Eigenmodes in Tokamaks*, J. Bao, W. L. Zhang, D. Li, and Z. Lin, *Journal of Fusion Energy* **40**, (2021).