Zonal flows: insights from tokamak to stellarator

Zhihong Lin

University of California, Irvine

GTC Team

IWLS 2026

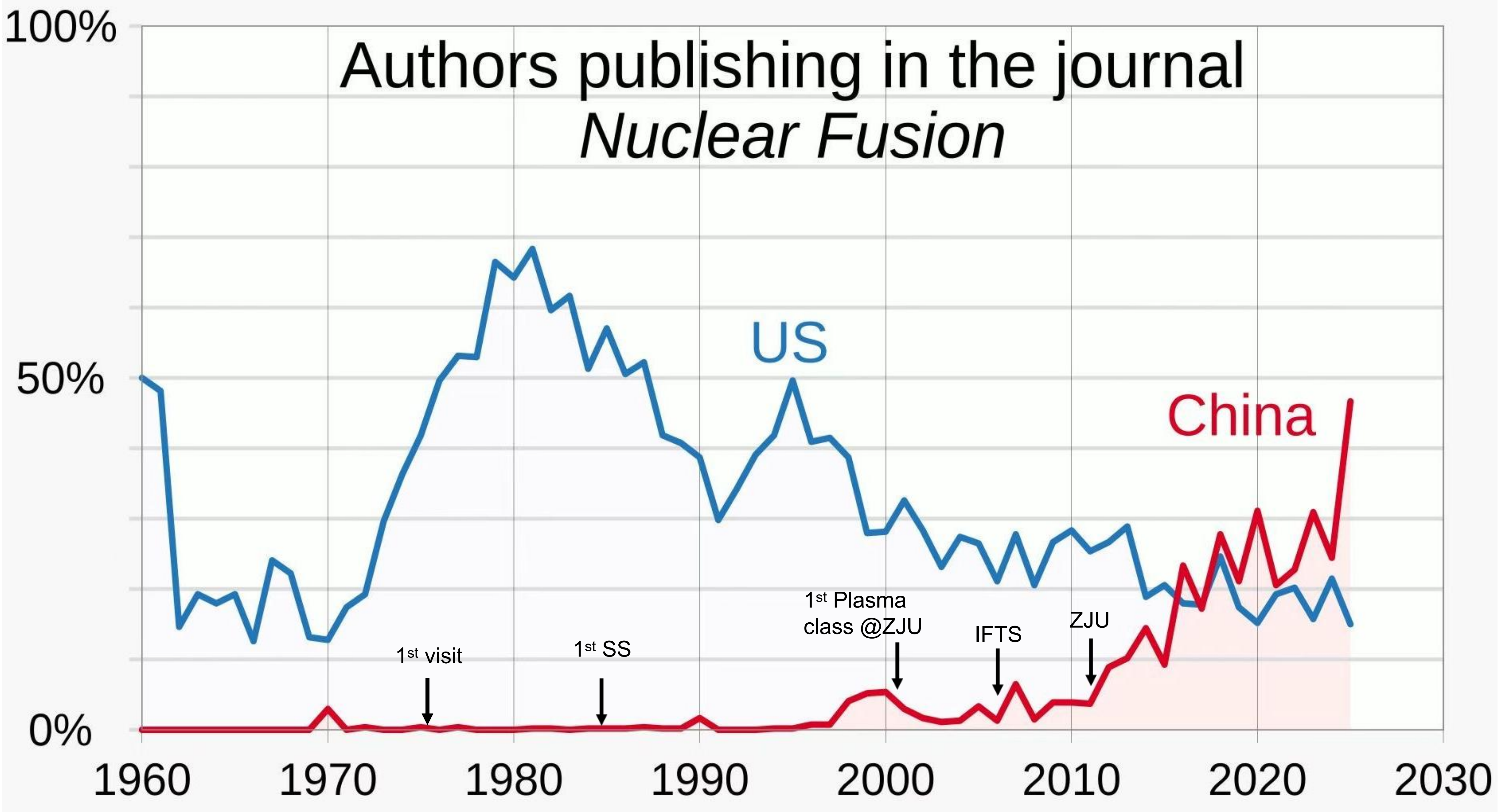
James Clerk Maxwell Prize for Plasma Physics (2012)

Liu Chen

University of California, Irvine

Citation: *"For seminal contributions to plasma theory, including geomagnetic pulsation, kinetic Alfvén wave, toroidal Alfvén eigenmode, fishbone oscillation and energetic particle mode, nonlinear dynamics of drift wave, and nonlinear gyrokinetic equation."*

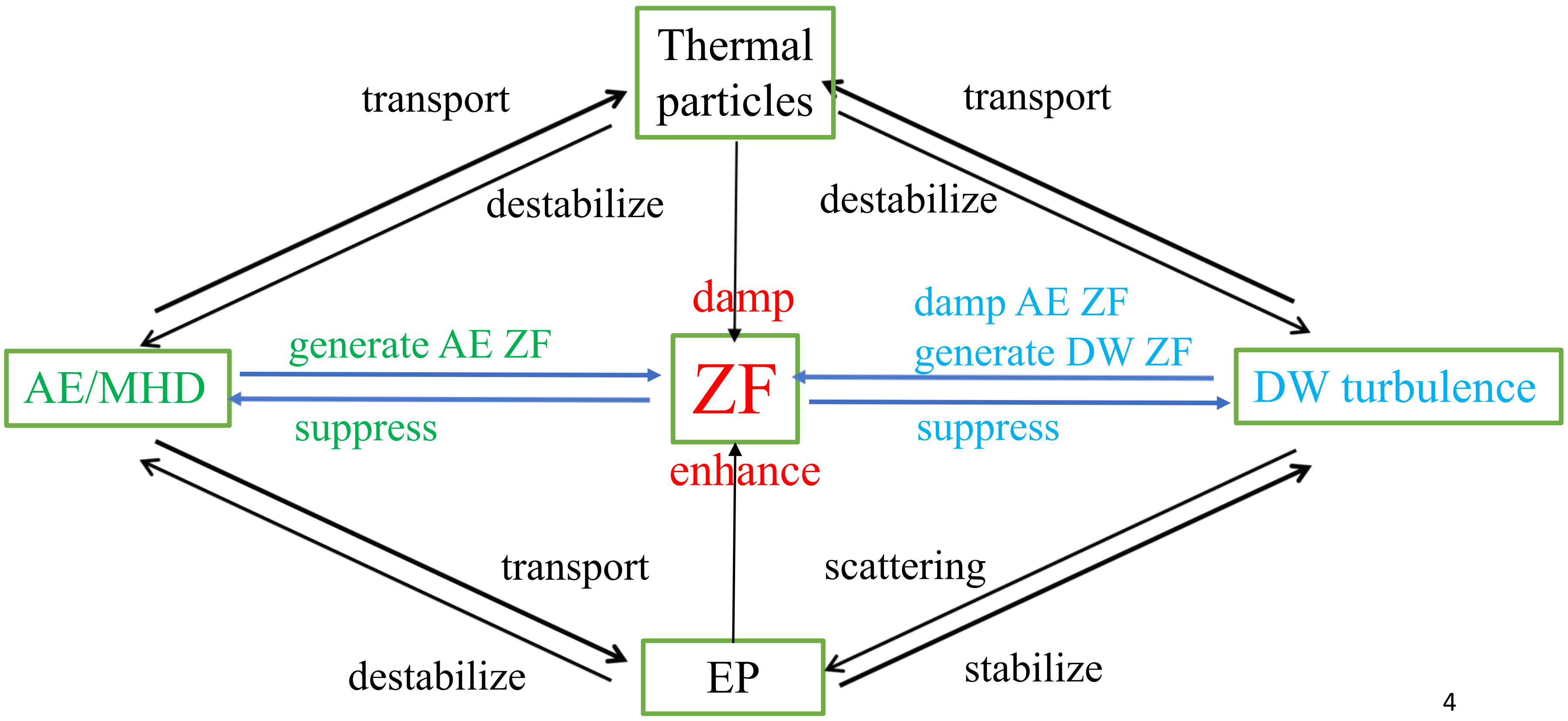
Liu Chen received his Bachelor's degree from National Taiwan University in 1966, and his PhD from University of California at Berkeley in 1972. From 1972 to 1974, he was a postdoctoral staff member at Bell Laboratories. In 1974, he joined Princeton Plasma Physics Laboratory as a research scientist, and, later, also became a faculty member in the Department of Astrophysical Sciences. In 1993, he was appointed a Full Professor in the Department of Physics and Astronomy of University of California at Irvine, and, in March 2012, became an Above-Scale Professor Emeritus. Currently, he is a Professor of Physics and the Director of Institute for Fusion Theory and Simulation of Zhejiang University, Hangzhou, China. His current research is focused



Authors publishing in the journal
Nuclear Fusion
100%
50%
0%
US
China
1st Plasma
class @ZJU
IFTS
ZJU
1st visit
1st SS
1960
1970
1980
1990
2000
2010
2020
2030

Outline

- Turbulence self-regulation by zonal flows: foundation of plasma turbulence theory
- Cross-scale interaction facilitated by zonal flows
- Zonal flows optimization of stellarator



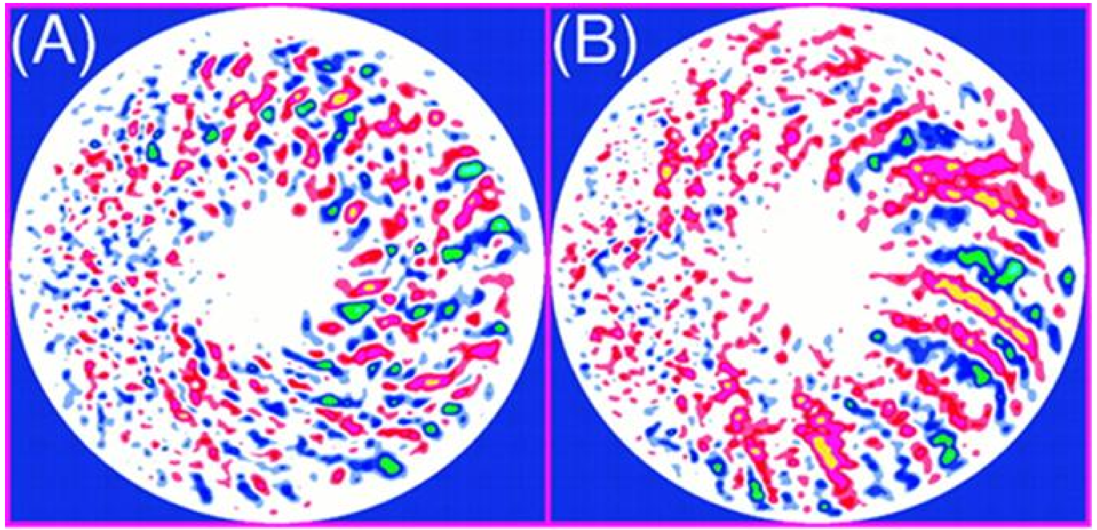
Turbulence self-regulation by ZF in magnetic fusion plasmas

- GTC gyrokinetic simulation of ion temperature gradient (ITG) instability in tokamak

  ⟶ ITG nonlinearly generates ZF

  ⟶ ZF shear saturates ITG instability and reduces transport level

[*Lin et al, Science* ***281****, 1835 (1998)*]



with zonal flow no zonal flow

- Relevance to transition from low to high confinement regime in tokamak inspired intense simulations and theoretical studies, and experimental search of ZF
- First massively parallel fusion simulation heralded the era of high-performance computing (HPC) for fusion simulation

Foundation for modern theory of plasma turbulence

- Turbulence self-regulation by ZF is universal

  ⟶ Trapped electron mode (TEM) turbulence *[Y. Xiao, PRL2009]*

  ⟶ Kinetic ballooning mode (KBM) turbulence *[G. Dong, NF2019]*

- Stellarator *[H. Wang, PoP2020]*
- Field-reversed configuration (FRC) *[X. Wei, PoP2021]*
- Hasegawa-Mima Equation predicts inverse cascade of turbulent spectral energy toward minimal wavenumbers nonlinearly generates zonal flows *[A. Hasegawa et al, PF1979]*
- Foundation for modern theory of plasma turbulence

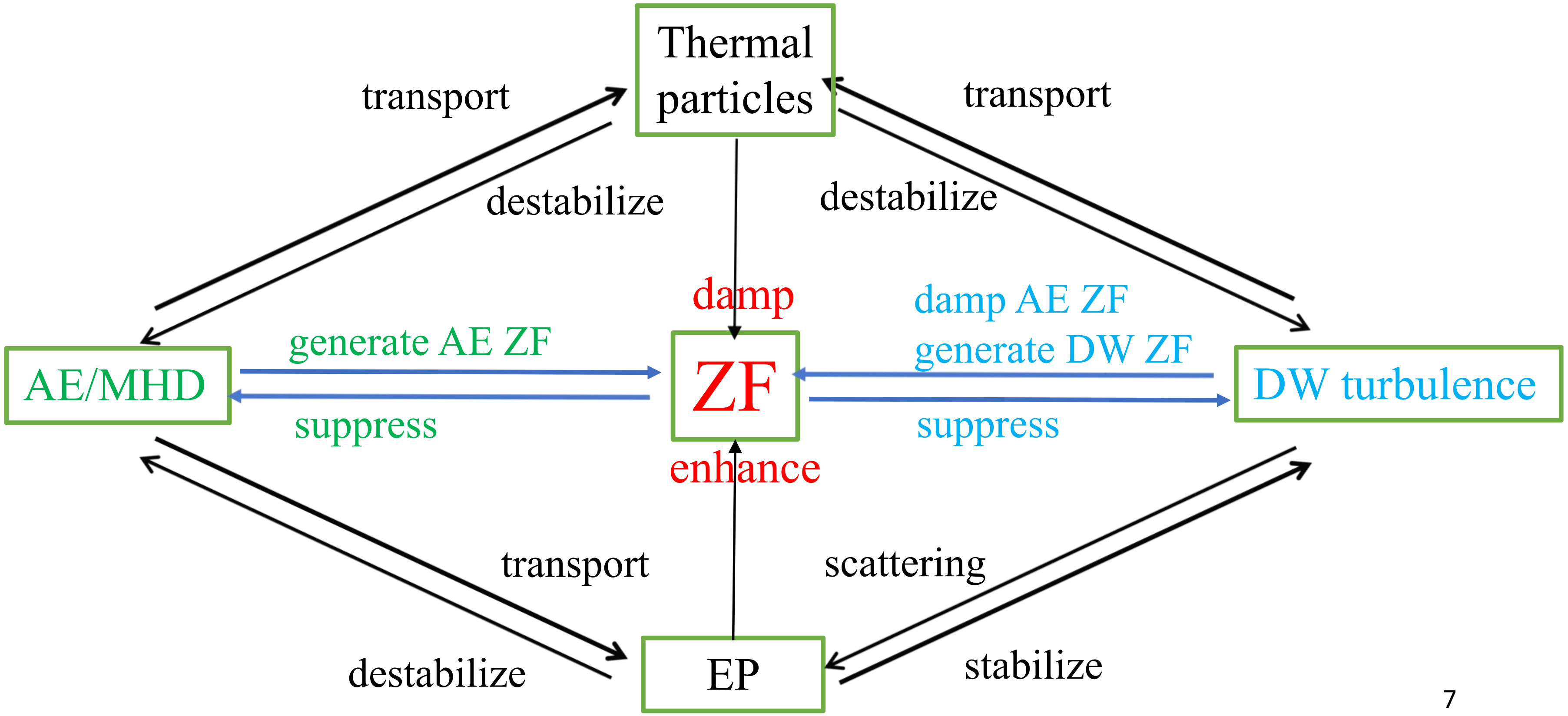
  [M. N. Rosenbluth & F. L. Hinton, PRL1998;

  L. Chen et al, PoP2000;

  P.H. Diamond et al, PPCF2005]

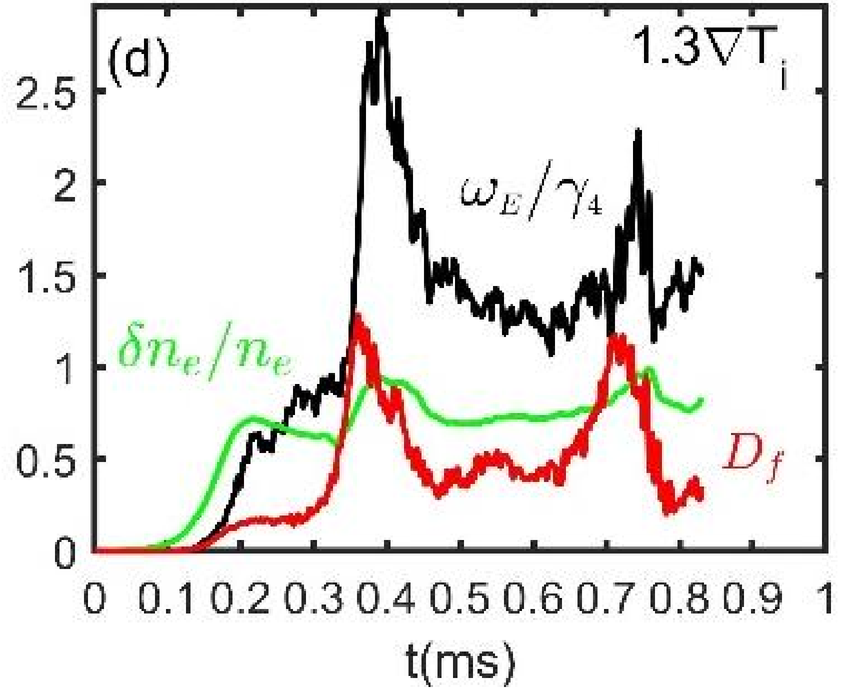
Outline

- Turbulence self-regulation by zonal flows
- Cross-scale interaction facilitated by zonal flows: rise of exascale computing
- Zonal flows optimization of stellarator

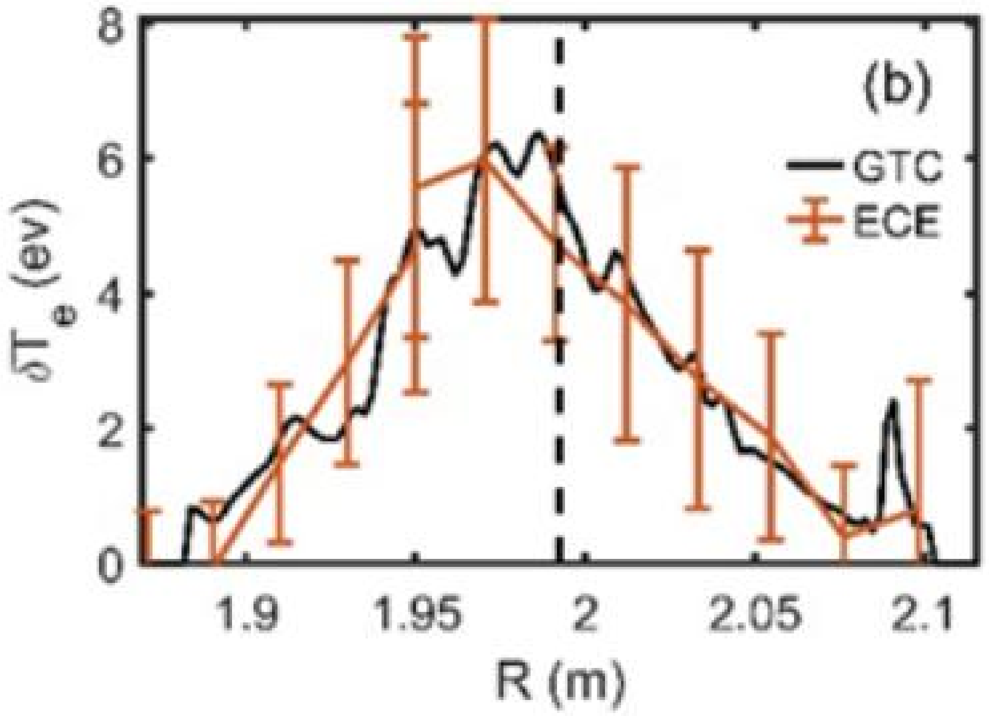


ZF saturate meso-scale Alfven eigenmode (AE) in tokamak

- GTC simulation find AE generates ZF, which saturate AE instability excited by EP
- AE structures and amplitudes from simulation with ZF agree, **for the first time**, with measurement of electron temperature fluctuations in DIII-D
- Microturbulence damps AE ZF: microturbulence increases AE amplitude & EP transport
- AE ZF suppress microturbulence thermal plasma transport

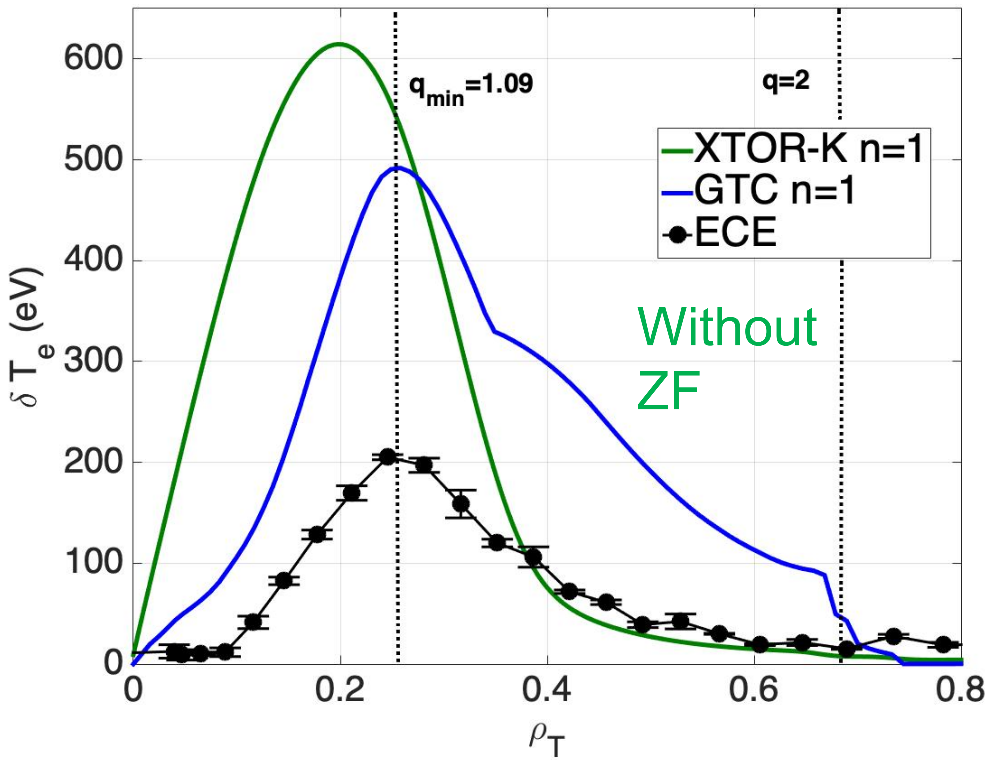


P. Liu et al, PRL 128, 185001 (2022)

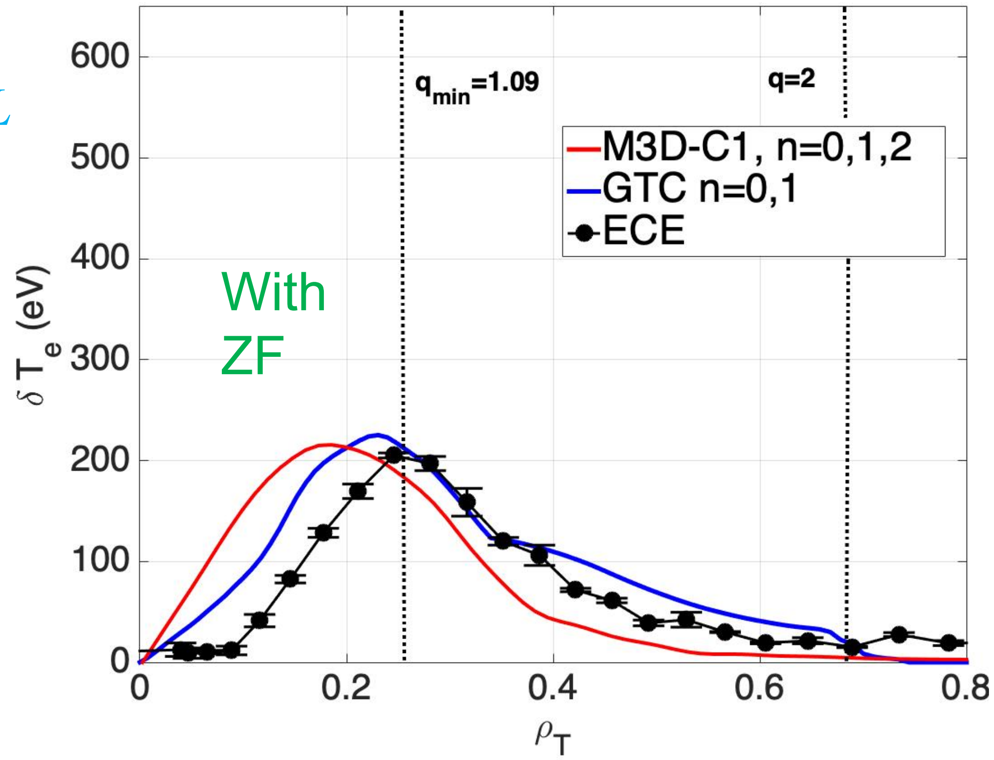


ZF saturate macroscopic MHD mode fishbone in tokamak

- GTC gyrokinetic simulation of fishbone mode excited by EP in DIII-D
  - ⟶ Incorporating compressible magnetic perturbation & equilibrium current for MHD modes
- Fishbone saturation is dominated by self-generated ZF
  - ⟶ Wave-wave nonlinearity vs. wave-particle nonlinearity
- Fishbone amplitude from simulation with ZF agrees with DIII-D measurement



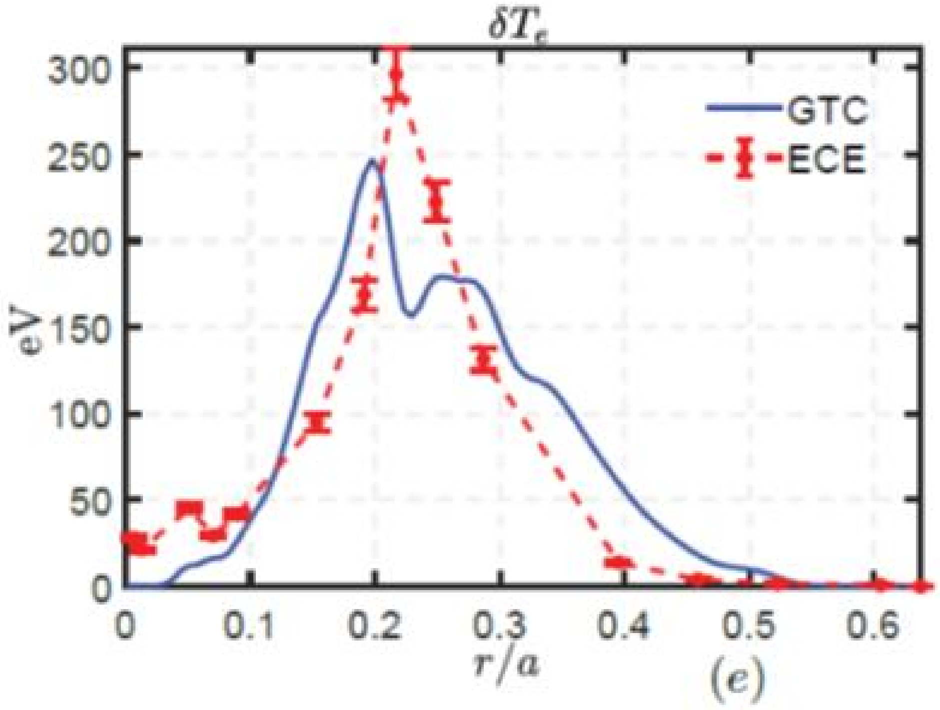
G. Brochard et al, *PRL* 132, 075101 (2024)

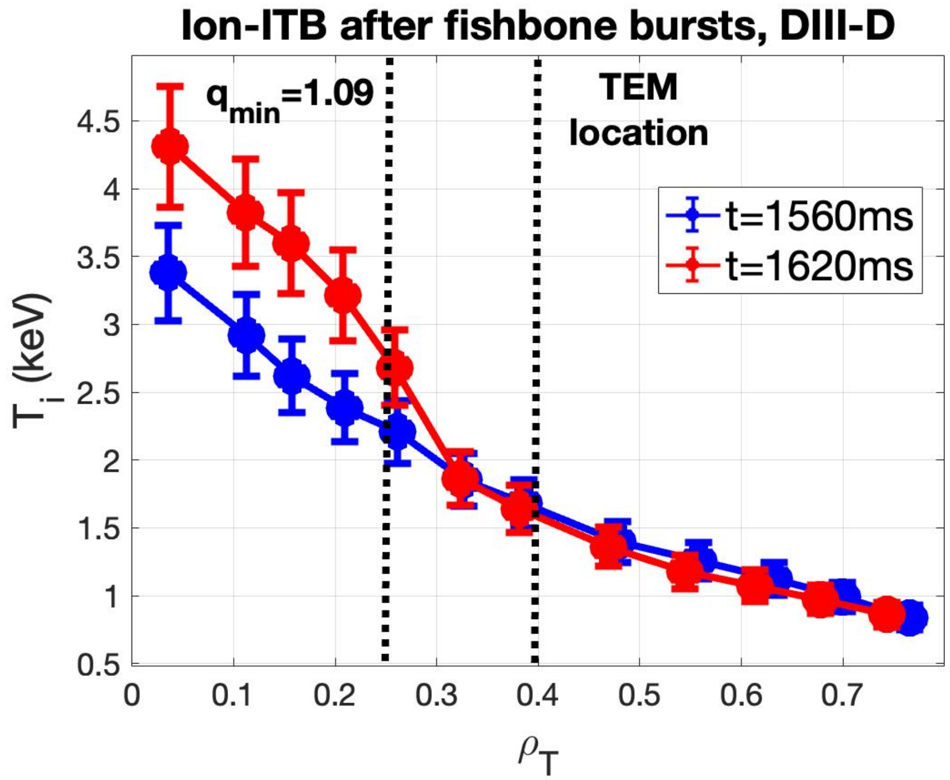


Fishbone ZF possibly leads to internal transport barrier (ITB) in DIII-D

- Fishbone ZF shearing rate much larger than TEM growth rate in GTC simulation
- Ion-ITB observed in DIII-D after fishbone bursts occurring at t ∈ [1580,1620] ms
- GTC cross-scale simulation finds that ZF is generated by fishbone & significantly reduces ITG intensity and ion heat conductivity to experimental level in EAST tokamak

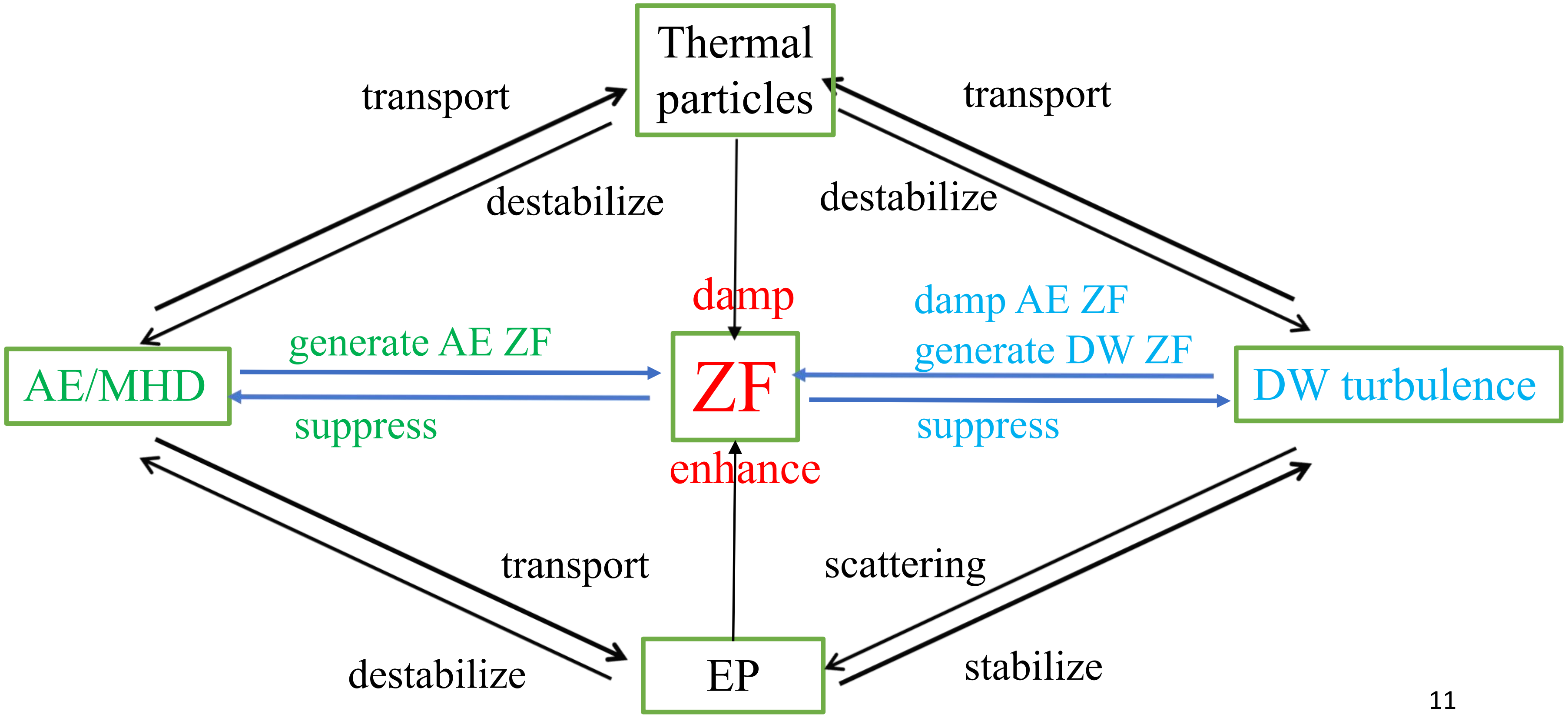
[Y. Ma et al, submitted, 2025]

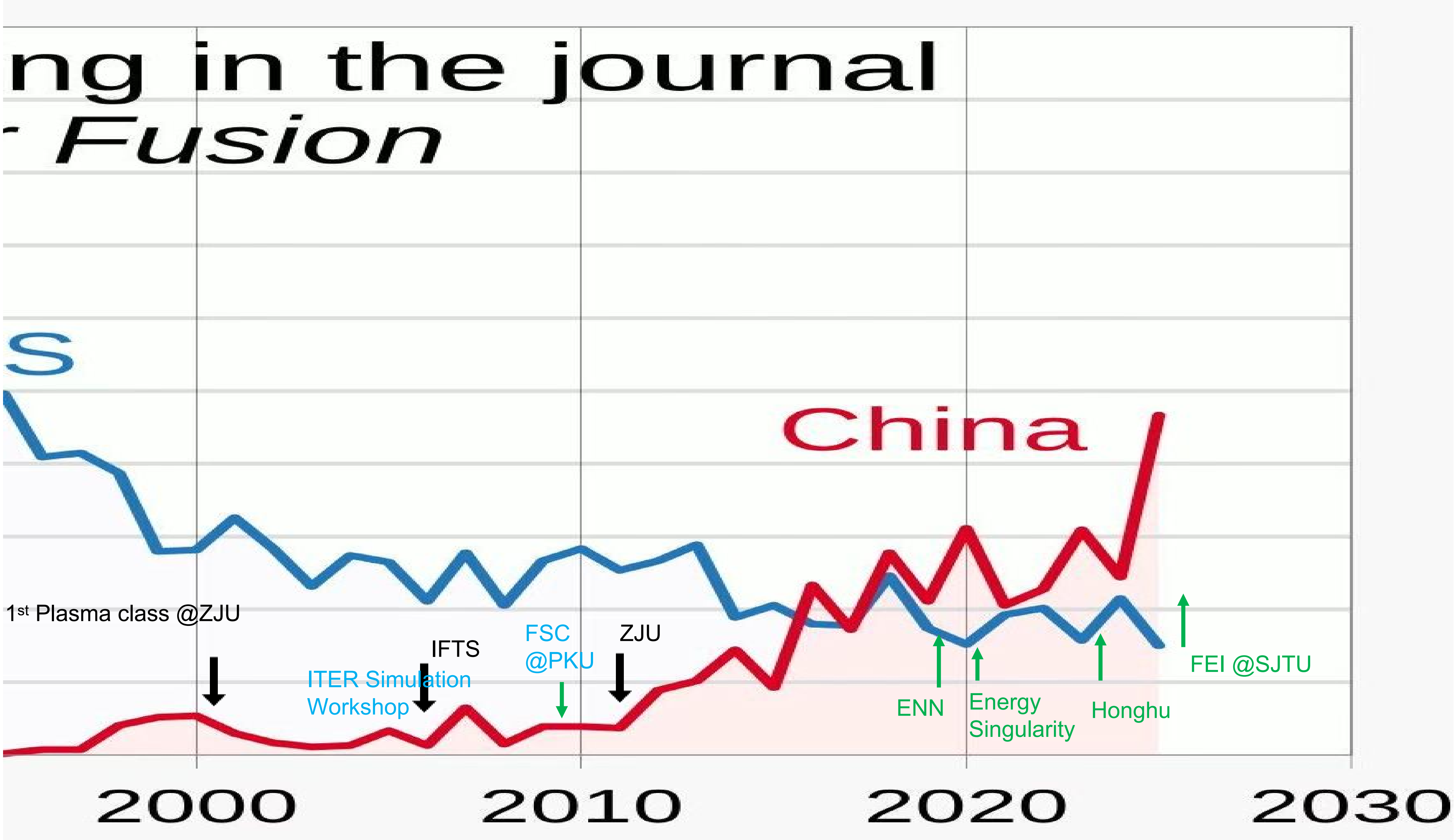




Outline

- Turbulence self-regulation by zonal flows
- Cross-scale interaction facilitated by zonal flows
- Zonal flows optimization of stellarator: genesis of AI

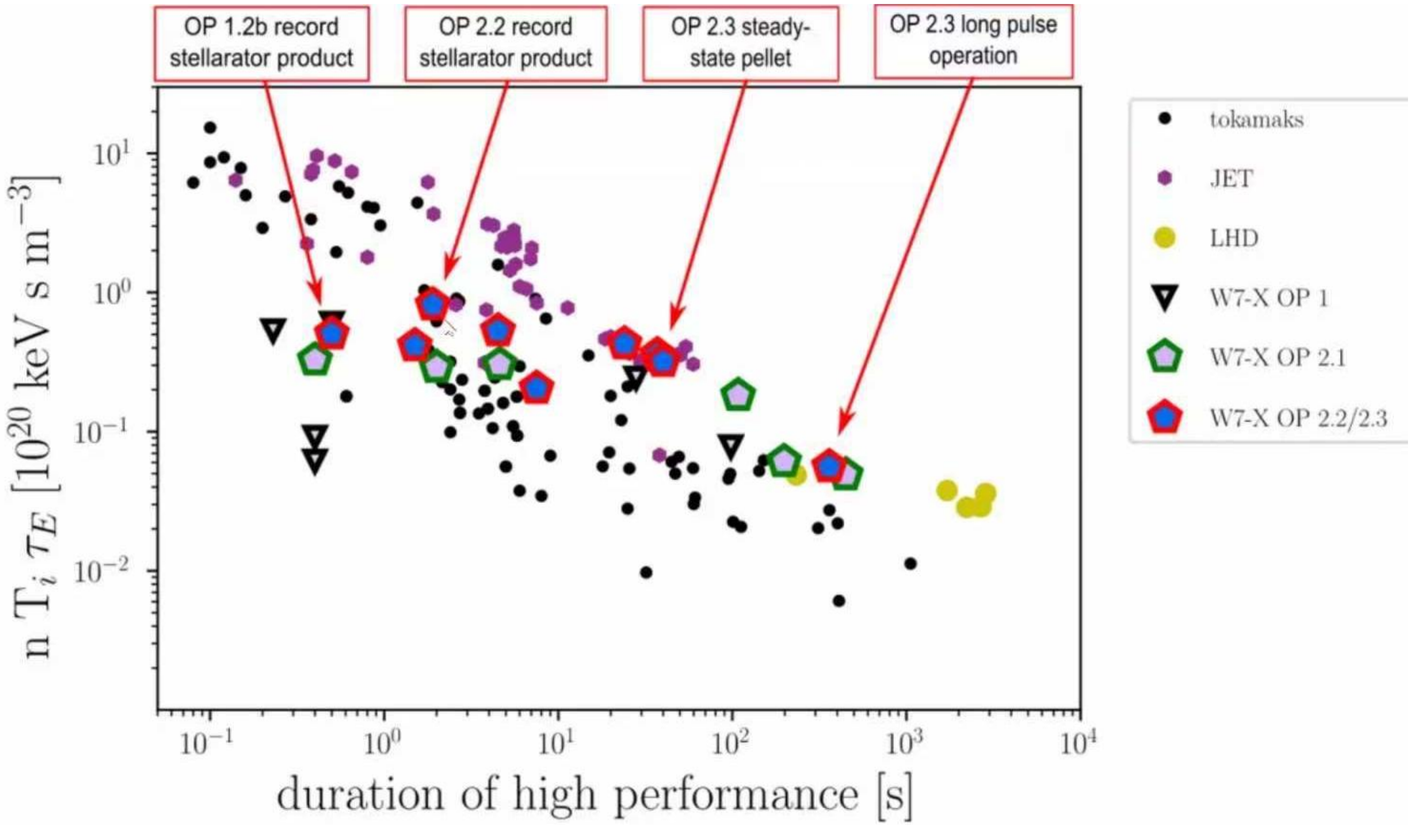


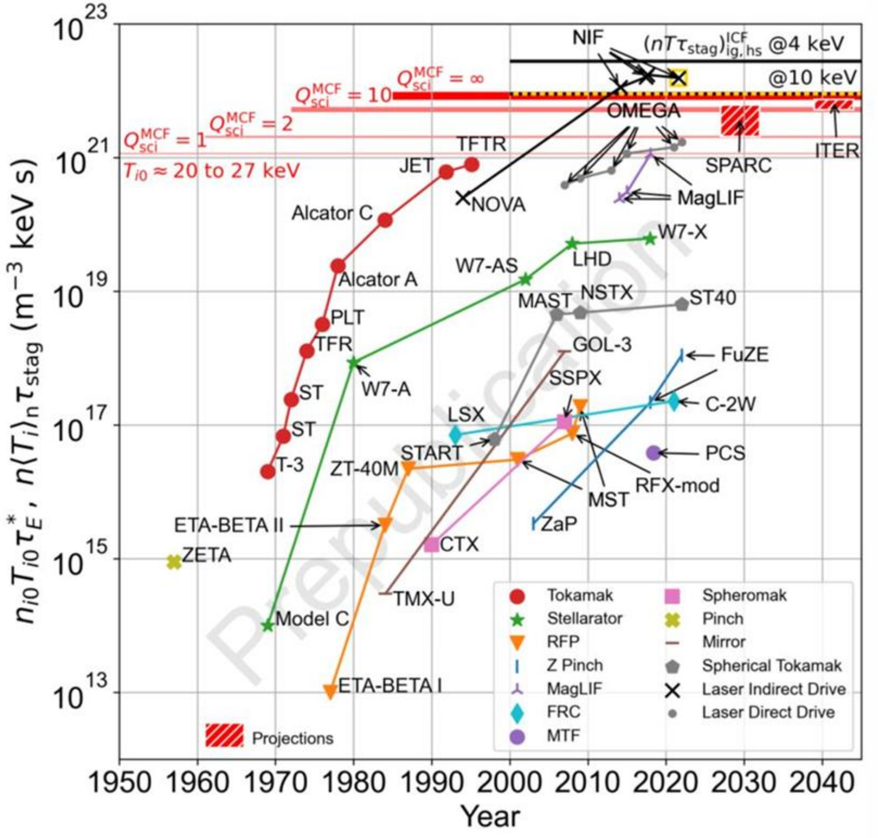


ng in the journal
r Fusion
S
China
1st Plasma class @ZJU
IFTS
ITER Simulation Workshop
FSC @PKU
ZJU
ENN
Energy Singularity
Honghu
FEI @SJTU
2000
2010
2020
2030

Optimized stellarator can be an attractive fusion reactor

- Steady state operation: no current drive & disruption
- Single particle loss of energetic paticles (e.g., α-particles) minimized in optimized stellarator
- Long pulse W7-X triple-product higher than any tokamak
- 3D geometry: infinite opportunities to manipulate ambipolar electric field and ZF
- New frontier: HPC/AI optimization of turbulent transport in stellarator





Geometry effects on ZF can be explored to optimize turbulence transport

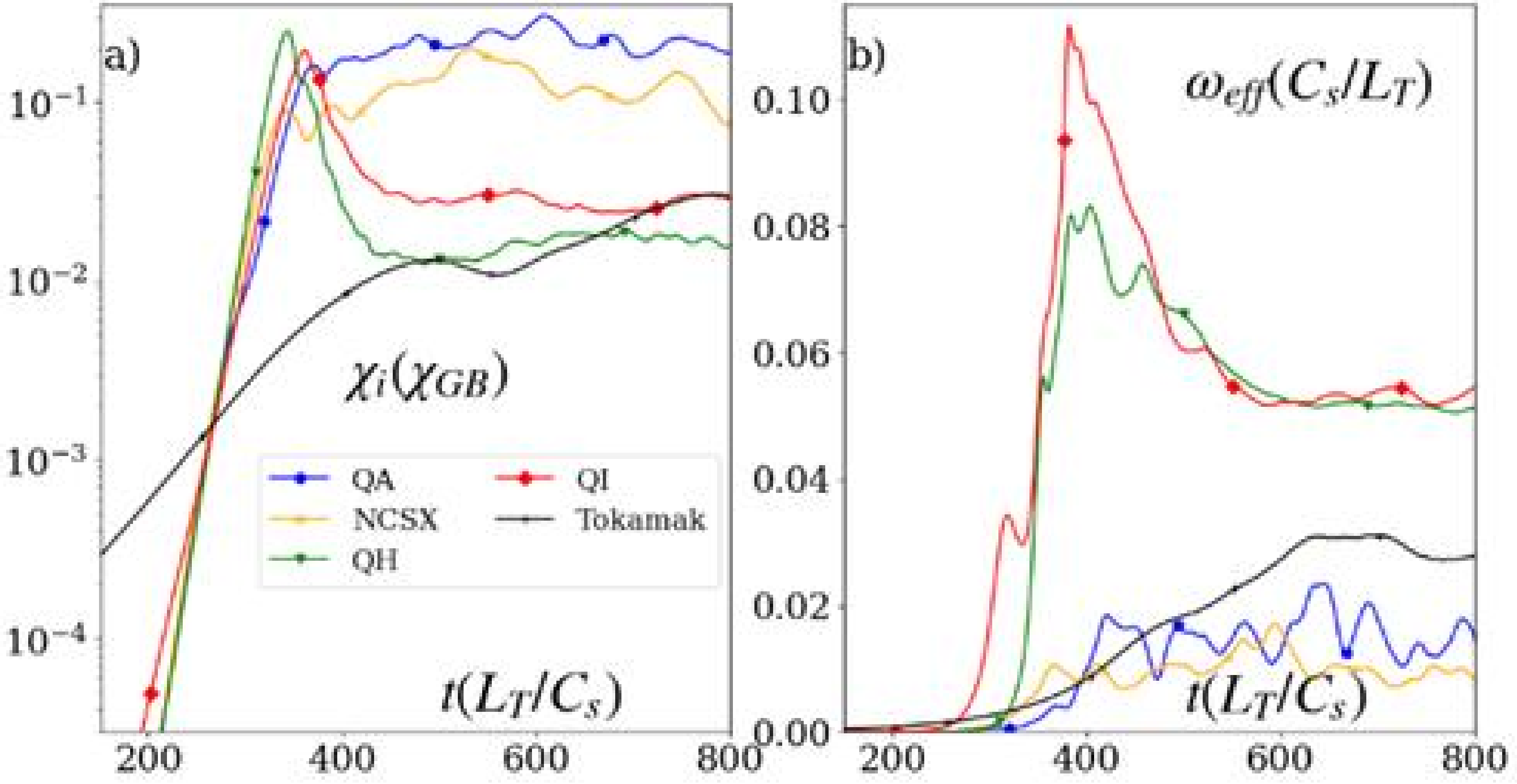
- ITG transport in QH & QI similar to ITER despite much higher linear growth rates; QA transport much higher
- Both QH & QI have higher ZF linear residual and lower ZF nonlinear frequency: mode effective suppressing turbulence
- QI has very small bootstrap current

→ Island divertor

→ Excellent QI quality at high-β

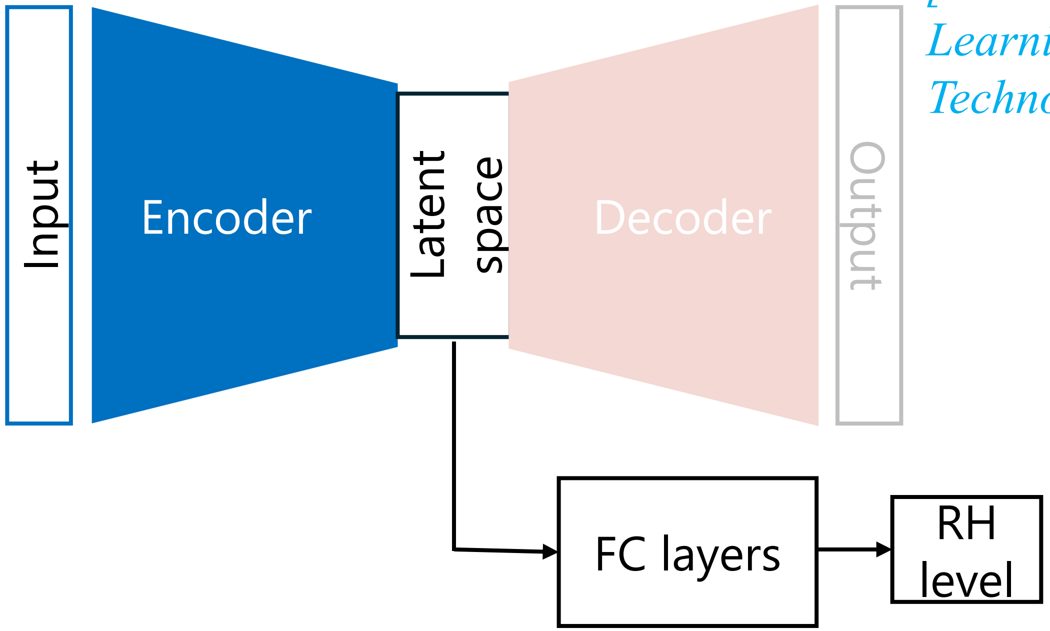
[H. Chen et al, NF 2025]

[H. Zhu et al, JPP 2025]

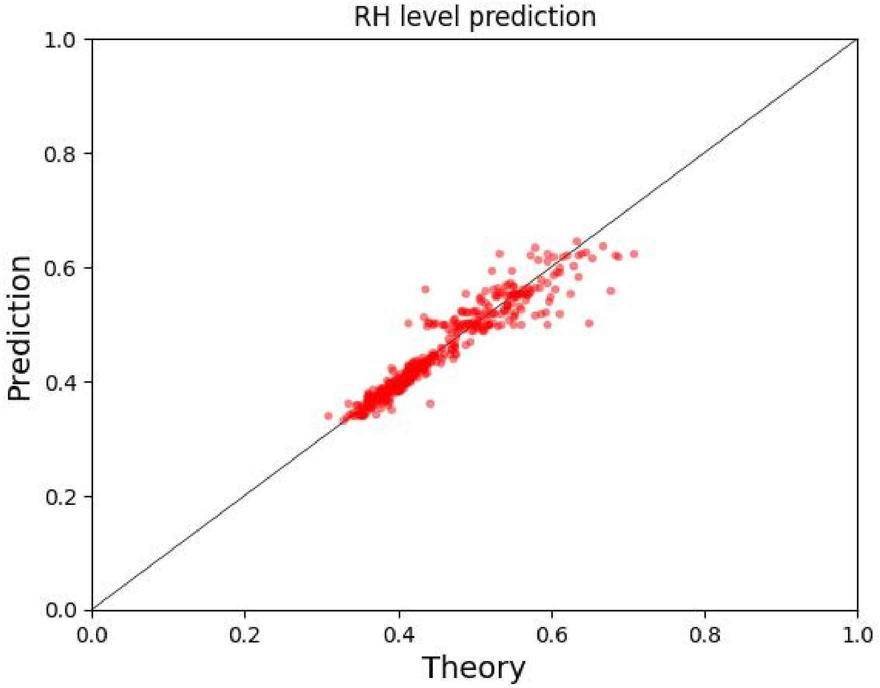


AI dimensionality reduction to optimize turbulent transport in stellarator

- Optimization of turbulent transport needs surrogate model SGTC trained by many GTC global simulations to sample high dimensional parameter space
- Use AI to reduce from high dimensional parameter space to low dimensional latent space to reduce sampling points
- Use latent space to sample parameter space with desired properties
- Used latent space representation to directly predict RH level, which agrees well with theory



[Z. Bai et al, Machine Learning: Science and Technology 2025]



Latent space patten of RH level can be used to sample parameter space

- 15,000 GTC global nonlinear simulations have been performed; data are used to train SGTC surrogate model to be incorporated in turbulence optimization
- Distribution of RH levels in 3D latent space exhibits organized structures, which can be used to sample regimes of low transport levels
- Used latent space representation to predict transport level, which agrees reasonanly with simulations

[X. Wei et al, 2026]