Demonstrating the Multiscale Nature of Electron Transport Through Experimentally Validated Simulations

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New simulations show turbulent transport is robustly multiscale for reactor-relevant plasma parameters

- New gyrokinetic (GK) simulations show short-wavelength electron temperature gradient (ETG) modes contribute significantly to transport at mid-radius in well-coupled, electron-transport dominated plasmas with small particle and momentum sources

- Only multiscale GK simulations that simultaneously resolve ion- and electron-scale turbulence are able to simultaneously reproduce ion and electron energy fluxes in Alcator C-Mod and DIII-D L- and H-mode plasmas within experimental uncertainties
  - Conventional ion-scale simulations systematically underpredict electron energy flux Q_e for these cases

- These simulations show there are significant nonlinear cross-scale couplings between ion and electron scales
  - **Multiscale turbulence cannot be modeled as simple sum of ion and electron scale turbulence**

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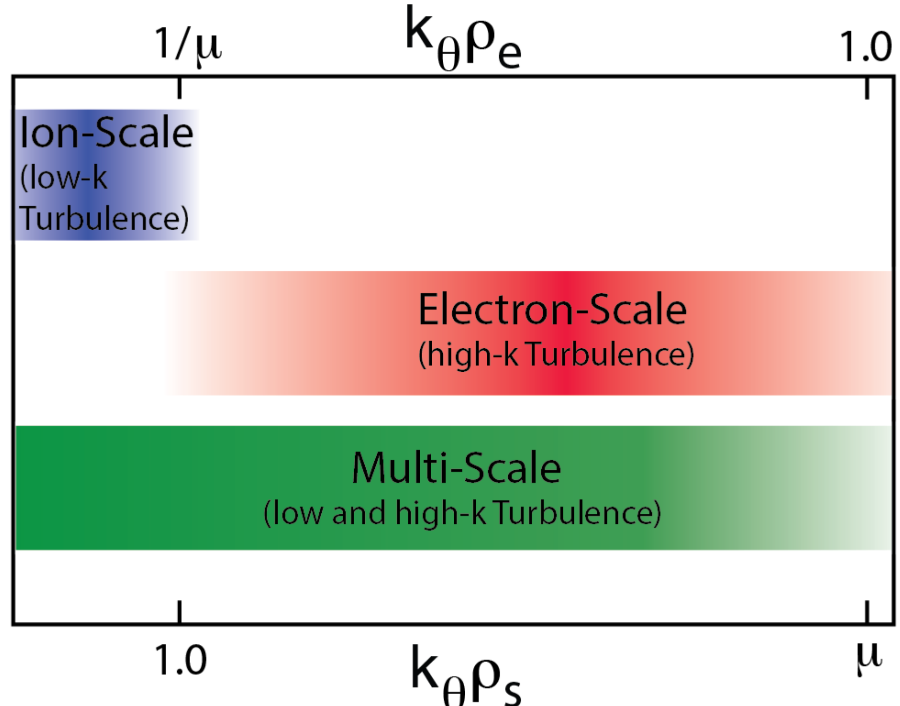
Need to understand when electron-scale transport matters to accurately predict ITER and beyond

- Typically GK simulation focus on ion scales because it is only range that carries ion thermal & momentum transport- sets T_i and V_{tor} profiles
  - Also very expensive to resolve beyond these scales

- However, essential to predict electron as well as ion transport for reactors- e- carry most power, α's heat e-, current evolution, etc.

- Fluctuations on both ion- and electron-scales can drive Q_e
  - **When do electron-scale fluctuations matter?**

Scales Simulated in Different Simulation Types



(μ = 60.0 : Realistic Mass)
(μ < 60.0 : Reduced Mass)

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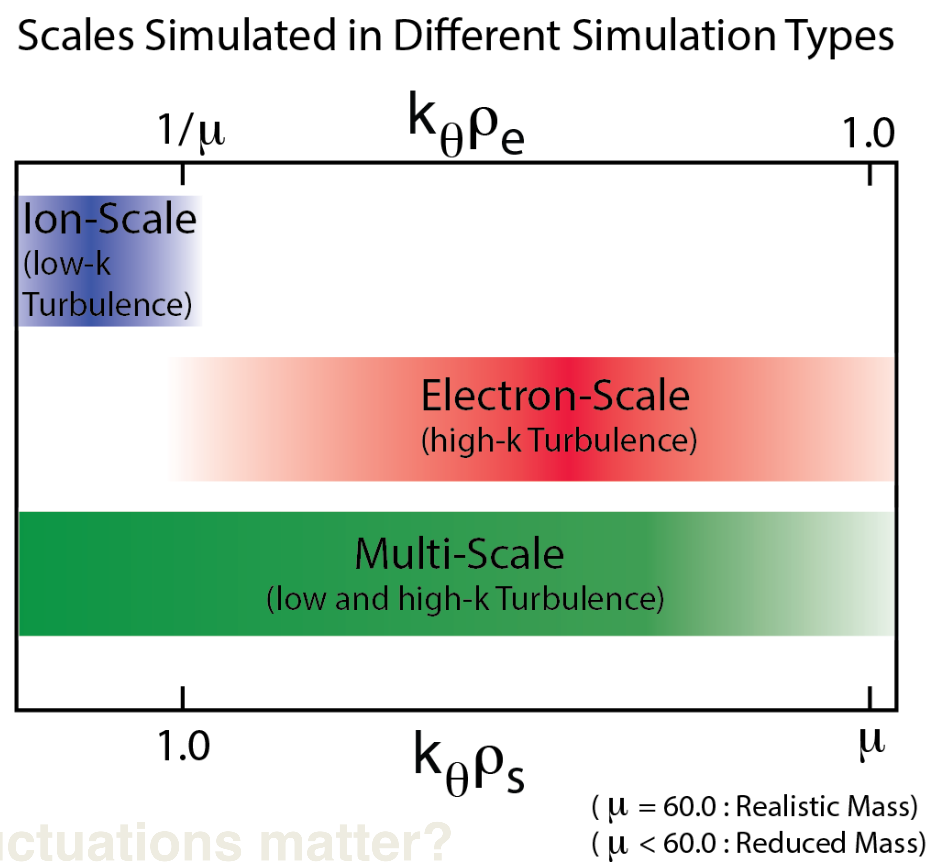

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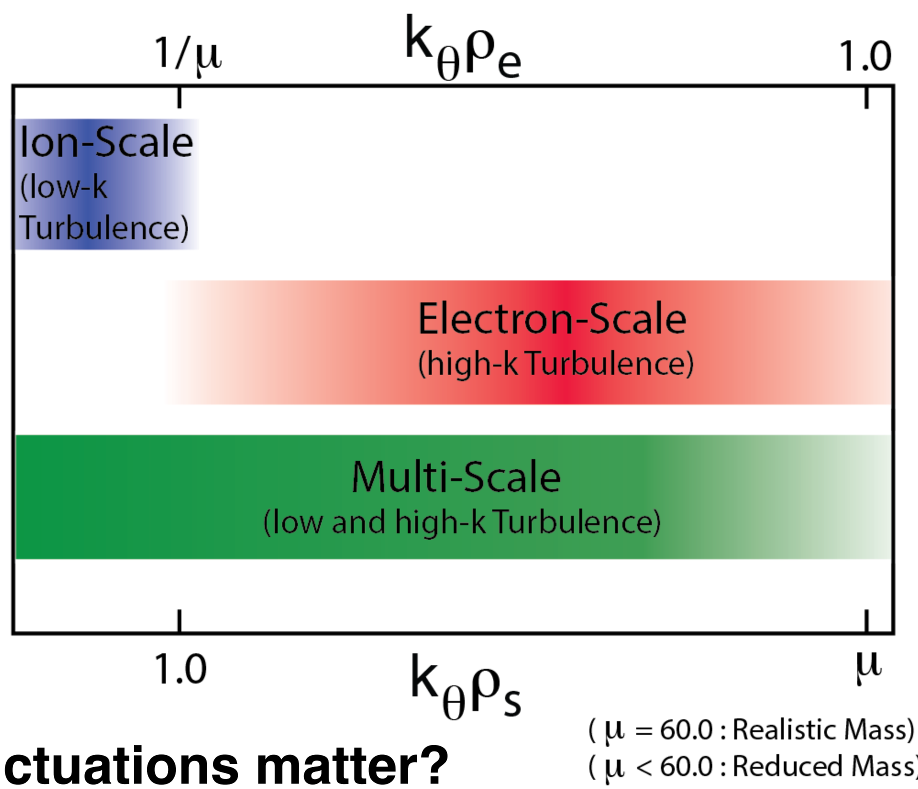

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Previous work has shown electron-scale turbulence can matter for idealized conditions

- Previous multiscale GK simulations [Jenko:2006, Candy:2007, Waltz:2007, Görler:2008, Schmitz:2012, Maeyama:2015] demonstrated possibility of significant electron-scale contributions to transport for idealized parameters and reduced mass-ratio
  - Common finding that strong ion-scale turbulence can suppress electron-scale fluctuations, consistent with theoretical expectations [Holland:2003]
  - Shown in work by Howard *et al* (2015 PPCF) that use of reduced mass ratio impacts results qualitatively and quantitatively

- To date, no self-consistent simulations of experimentally realized parameters, at correct mass ratio, have demonstrated significant simultaneous contributions from ion and electron scales

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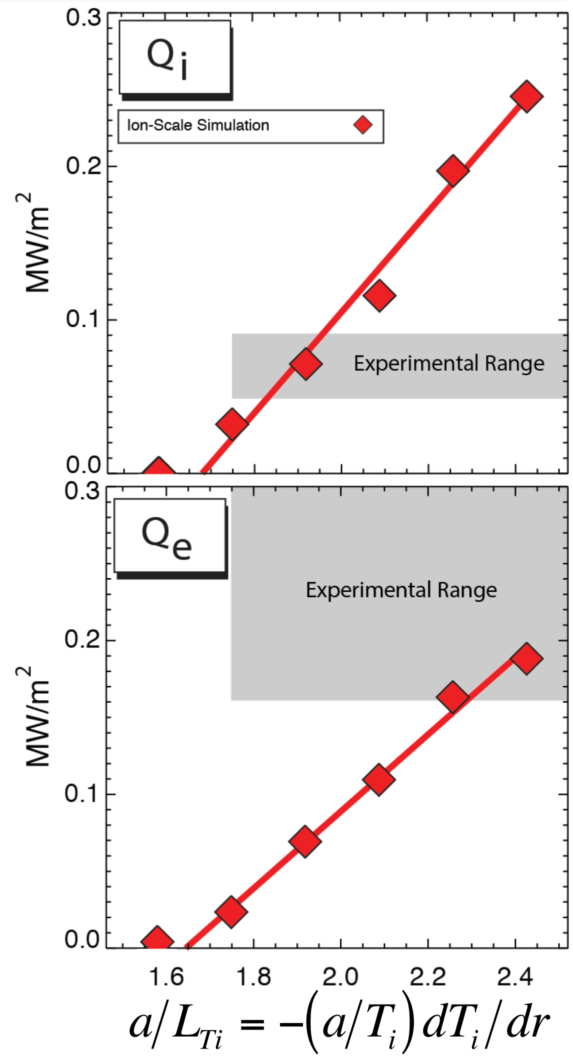
Ion-scale gyrokinetic simulations of a typical Alcator C-Mod L-mode discharge underpredict Q_e

- Ion-scale (long wavelength) simulations underpredict electron energy flux Q_e when matching Q_i at multiple radii [Howard PoP 2013]
  - Focus on $\rho_{tor} = 0.55$ here
- From extensive ion-scale gyrokinetic simulation (32 nonlinear runs), find under-prediction of Q_e is robust within uncertainties [Howard Nucl. Fusion 2013]



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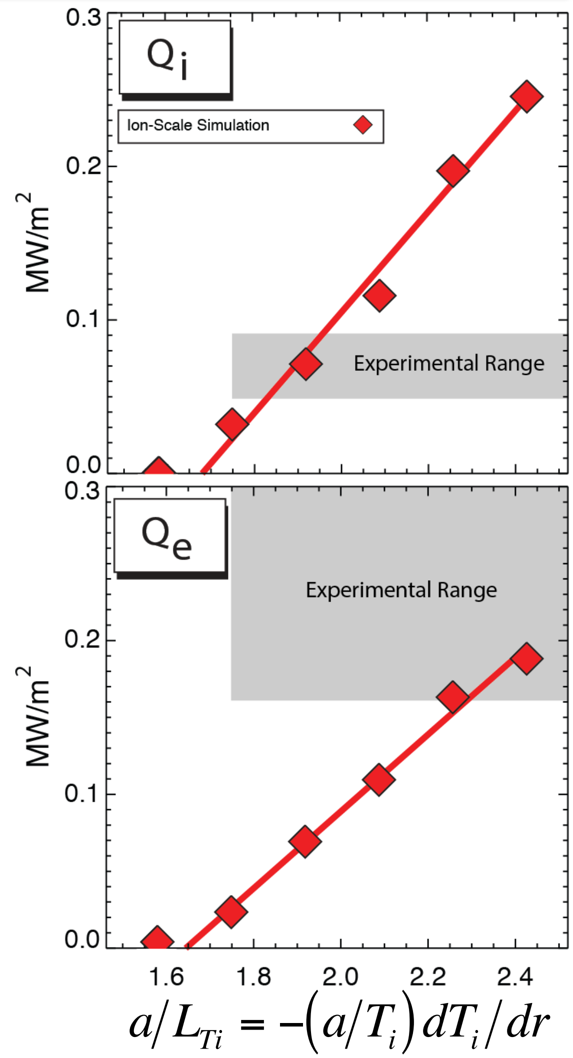

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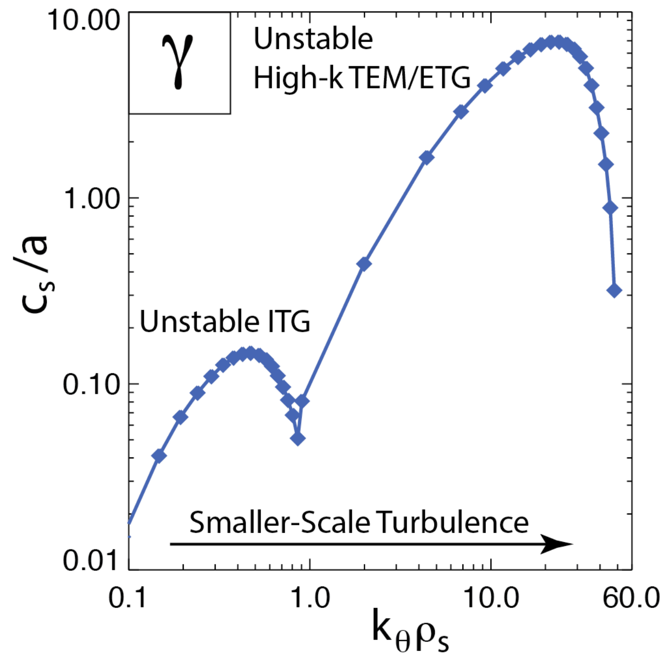

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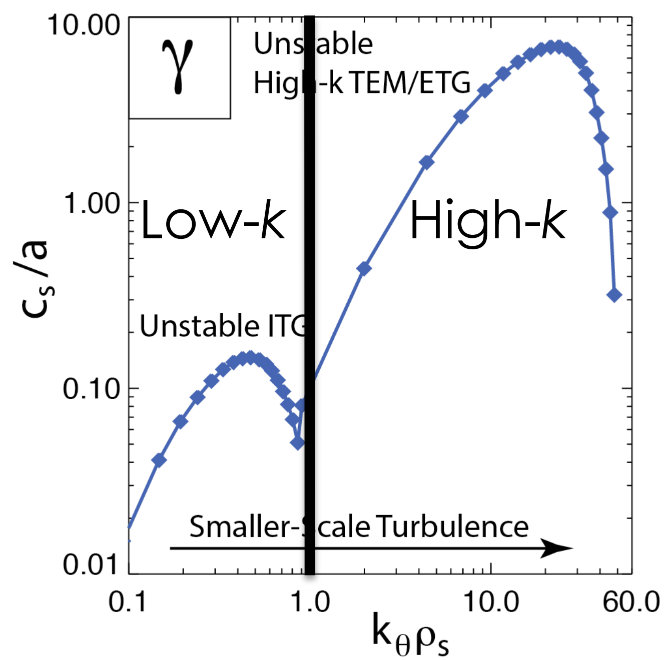

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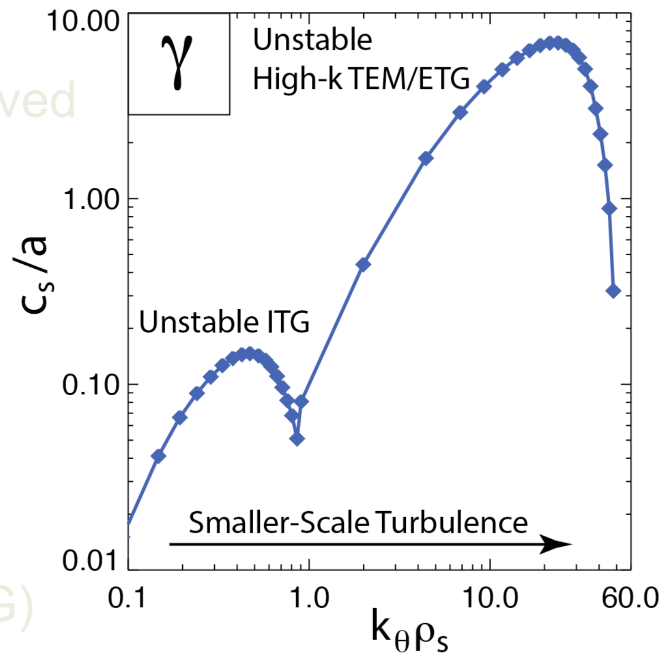
To resolve discrepancy, perform multi-scale gyrokinetic simulations with GYRO code

- Performed scans of a/L_{Ti} and a/L_{Te} around their experimental values
- Realistic electron mass: $\mu = (m_D/m_e)^{1/2} = 60.0$
  - High physics fidelity:
    - All input parameters experimentally-derived
    - 3 gyrokinetic species (electrons, deuterium, boron)
    - Electrostatic turbulence
    - Rotation effects (ExB shear, etc.)
    - Collisions
  - Simulation box size of 44 x 44ρ_s
  - 342 toroidal modes ; Captures both long and short-wavelengths (ITG/TEM/ETG) up to $k_\theta \rho_s$ up to ~48.0 = $k_\theta \rho_e$ ~ 0.8
  - 7 total simulations were performed, totaling ~ 120M CPU hours using 17-35k processors and ~37 days per simulation



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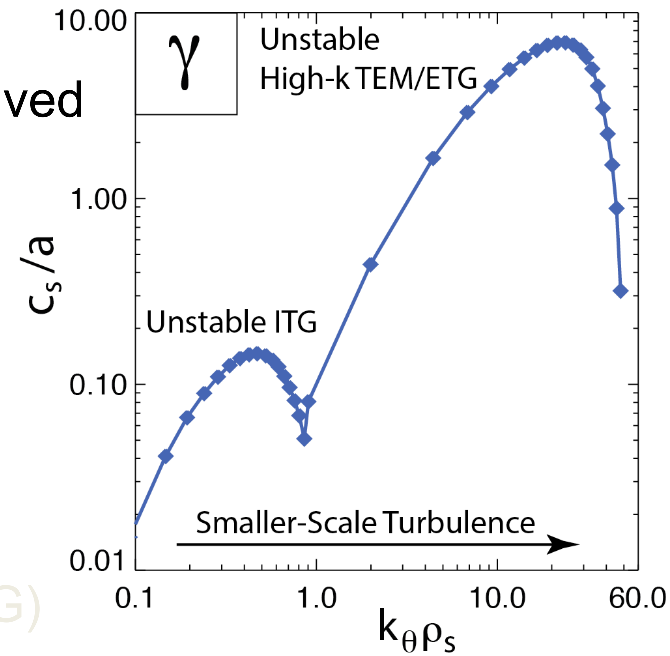

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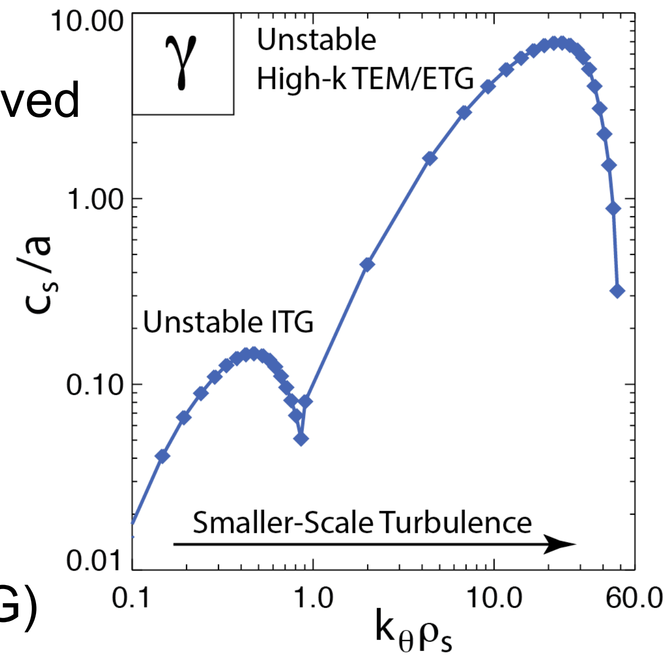

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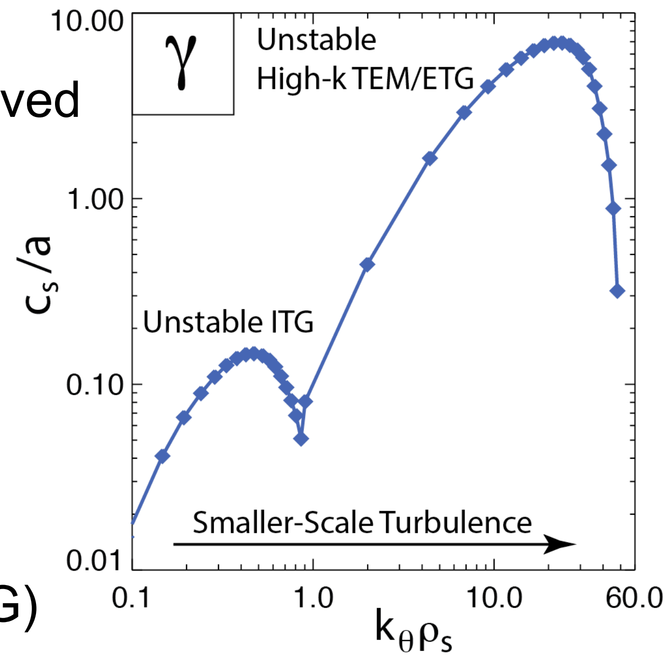

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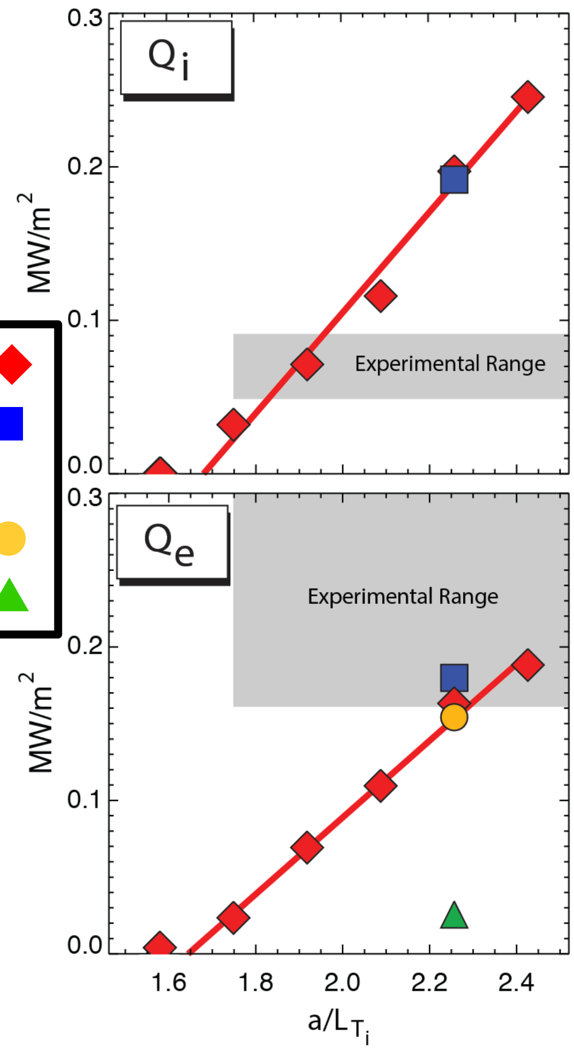
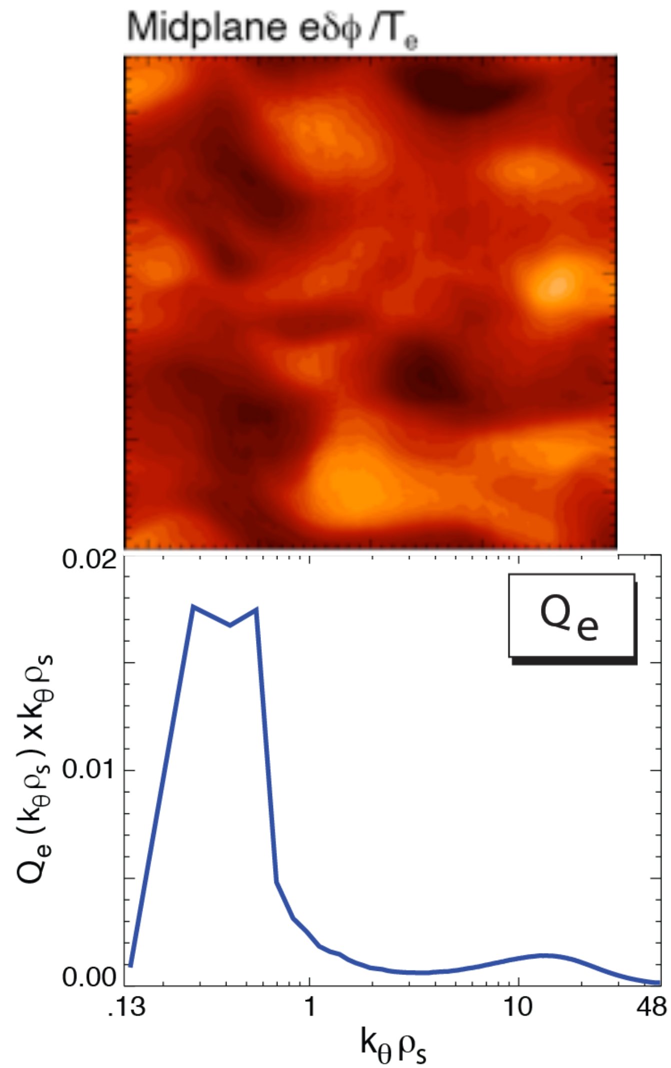
For strong ITG (low-*k*) drive, multiscale simulation predicts similar fluxes as ion-scale simulation

Ion-scale ◆
Multi-scale ■
Multi-scale Components
Low-*k* (ITG) contributions ●
High-*k* (ETG) contributions ▲





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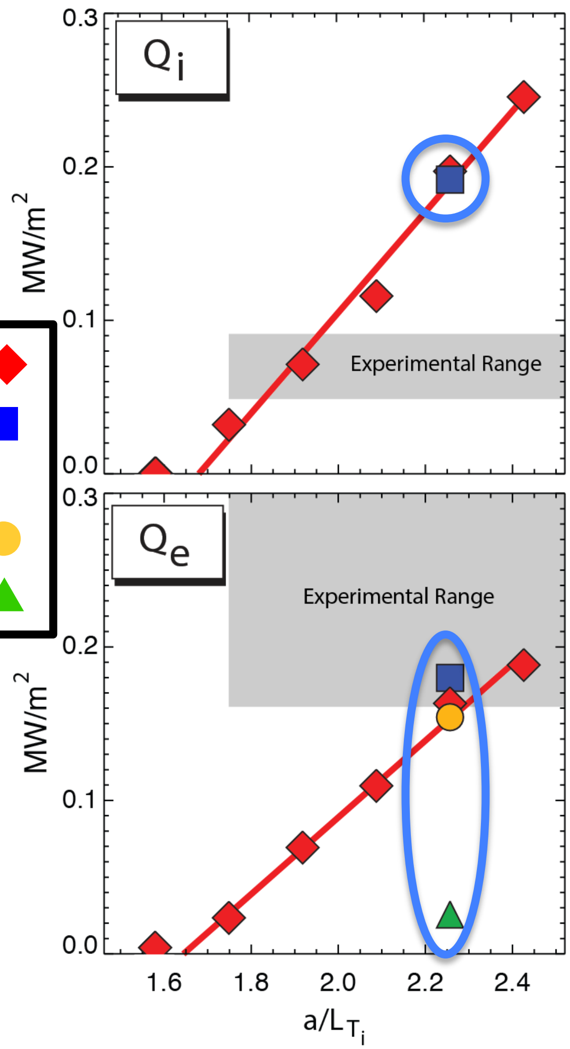
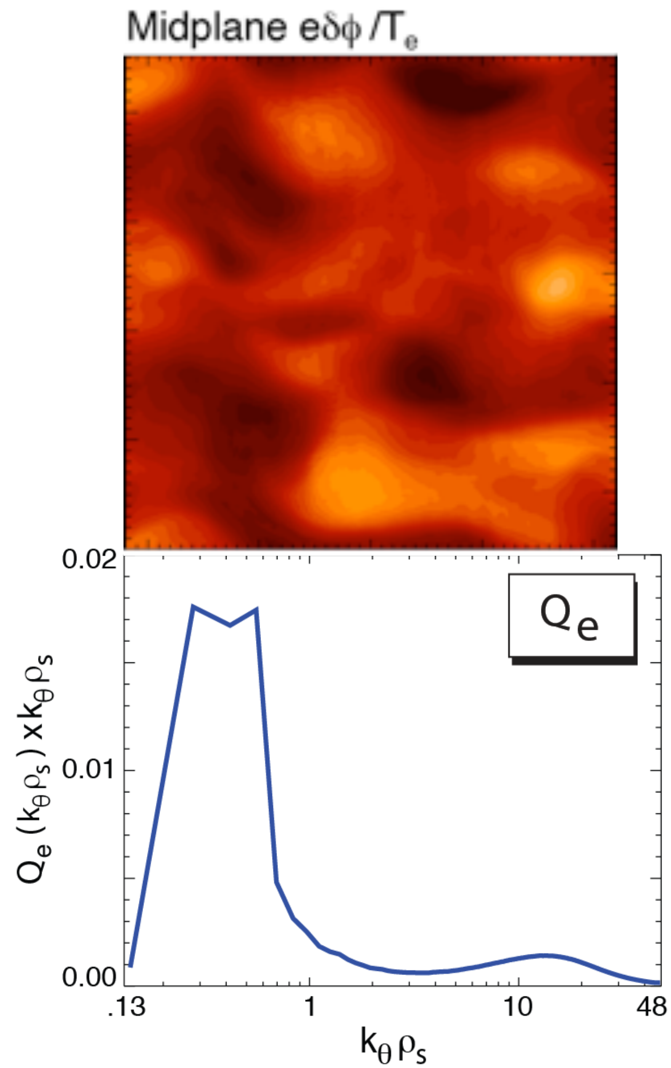
For strong ITG (low-*k*) drive, multiscale simulation predicts similar fluxes as ion-scale simulation

Shows regime where ion-scale GK simulations ok: strong ITG drive, $Q_i \approx Q_e$

- **Ion-scale** ◆
- **Multi-scale** ■
- **<u>Multi-scale Components</u>**
- **Low-*k* (ITG) contributions** ●
- **High-*k* (ETG) contributions** ▲





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At weaker ITG drive, inclusion of high-k fluctuations significantly increases predicted Q_e *and* Q_i

Cross-scale couplings in multiscale simulation lead to increased low-k turbulence
➔ increased Q_i, low-k Q_e

Ion-scale ◆
Multi-scale ■
<u>Multi-scale Components</u>
Low-*k* (ITG) contributions ●
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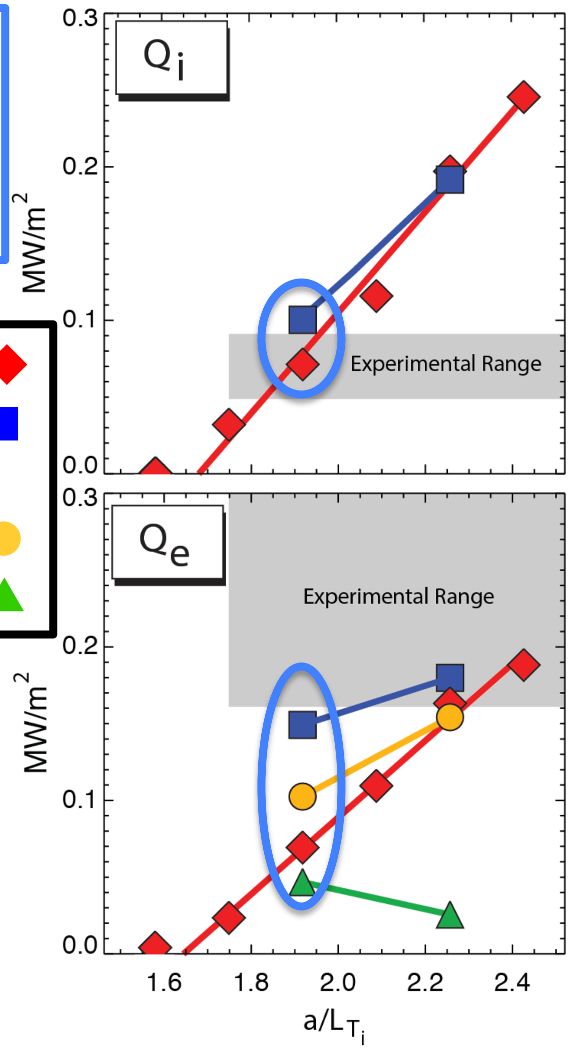

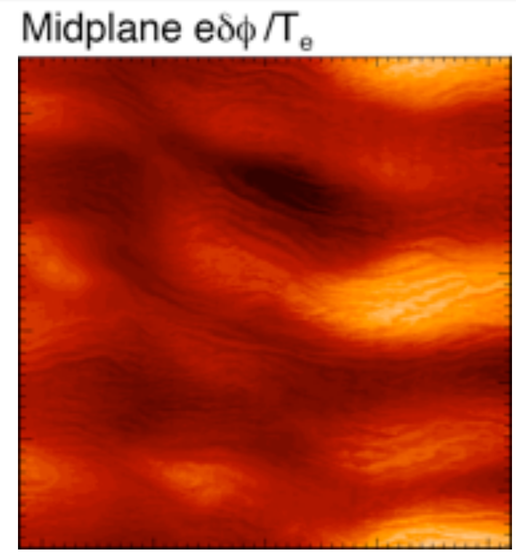

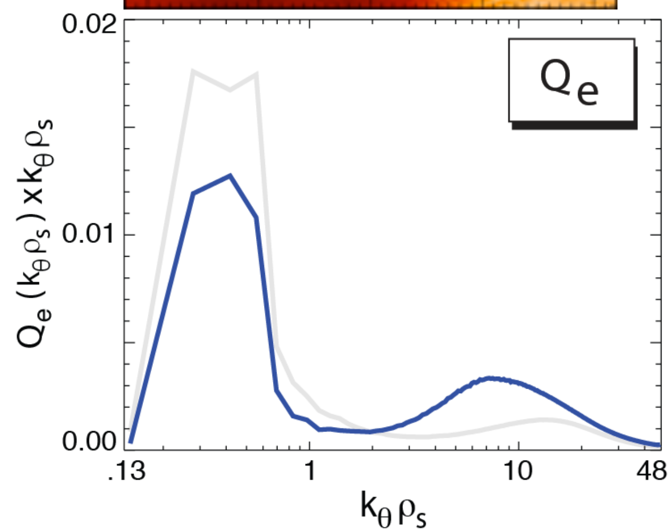

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Only the multiscale results are able to **simultaneously** match Q_e and Q_i

Cross-scale couplings in multiscale simulation lead to increased low-*k* turbulence
➔ increased Q_i, low-*k* Q_e

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Multi-scale ■
Multi-scale Components
Low-*k* (ITG) contributions ●
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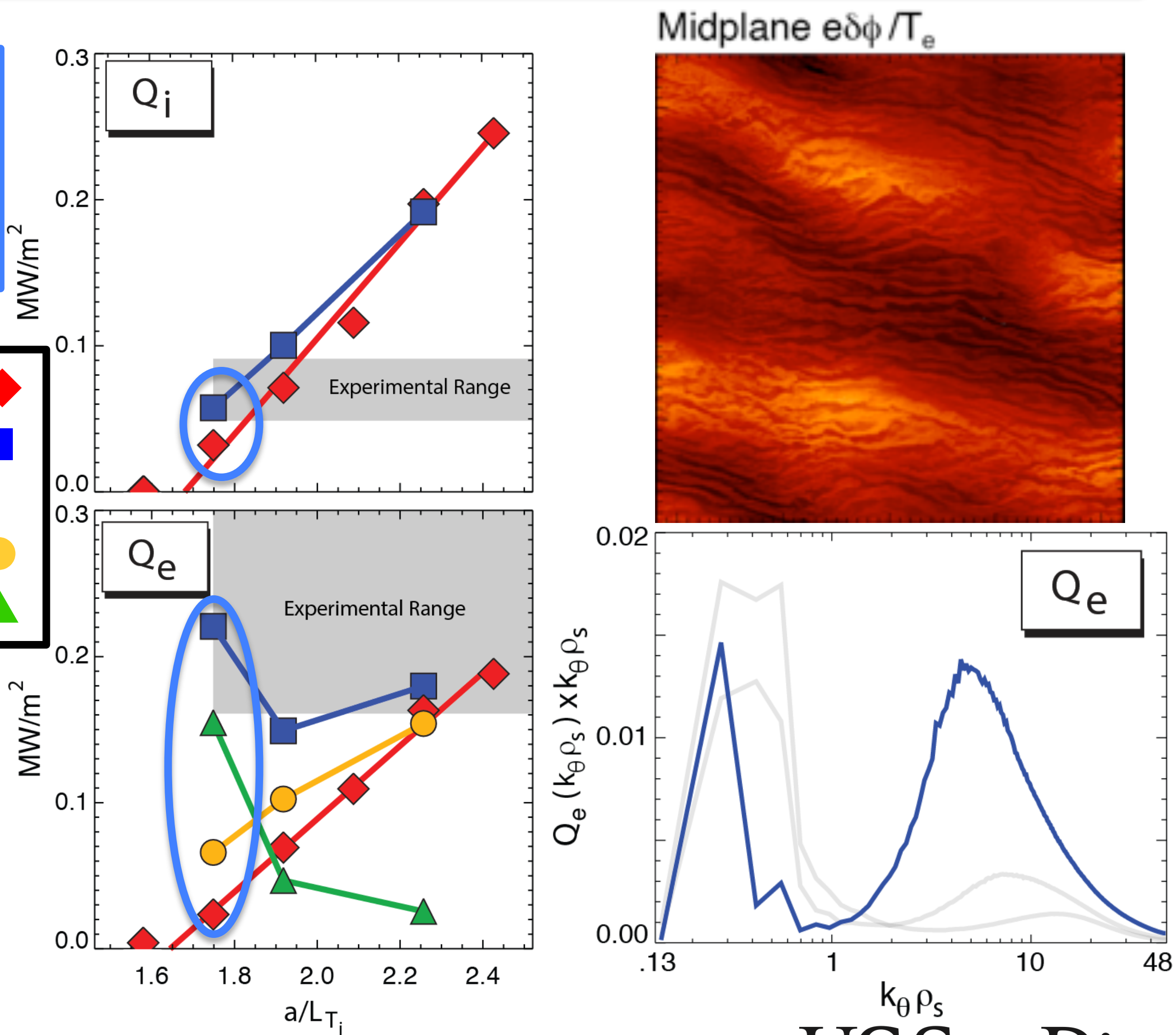

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When ITG is stable, electron turbulence collapses into a low-flux zonal-flow dominated state

Saturation via slow build-up of low-*k* ZF driven by ETG streamers, consistent with Colyer *et al* (2016)

Ion-scale ◆
Multi-scale ■
Multi-scale Components
Low-*k* (ITG) contributions ●
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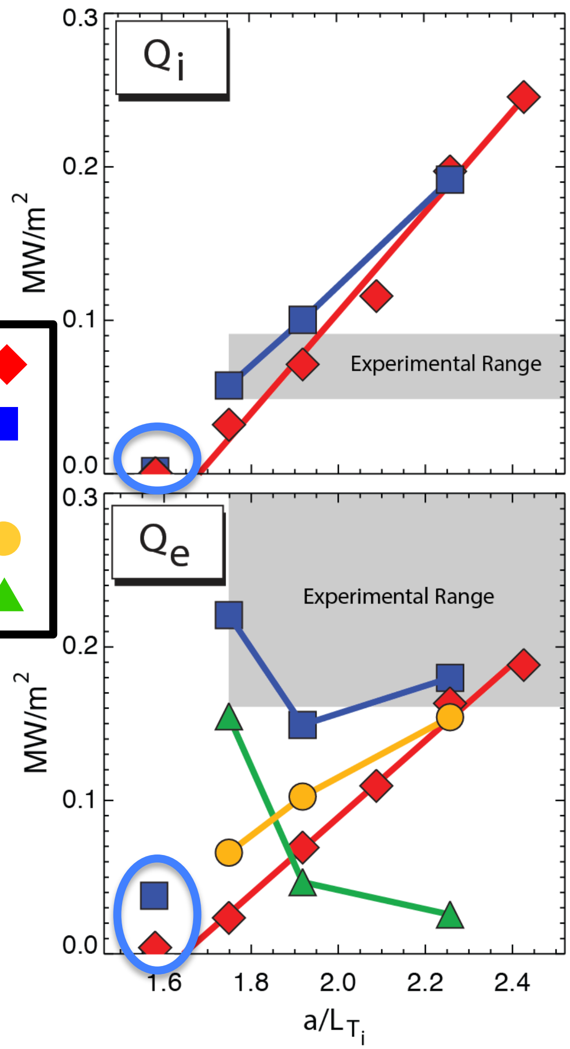

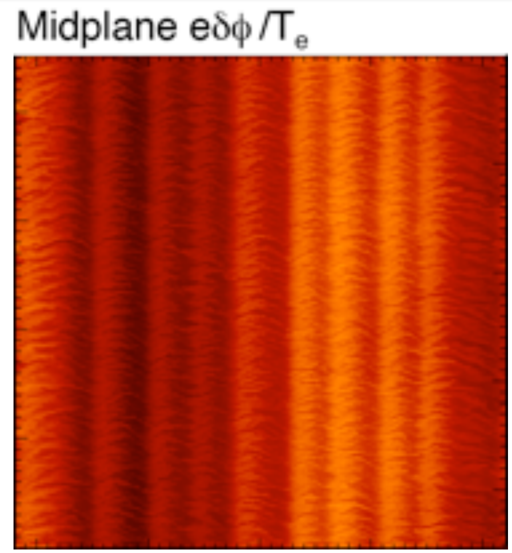

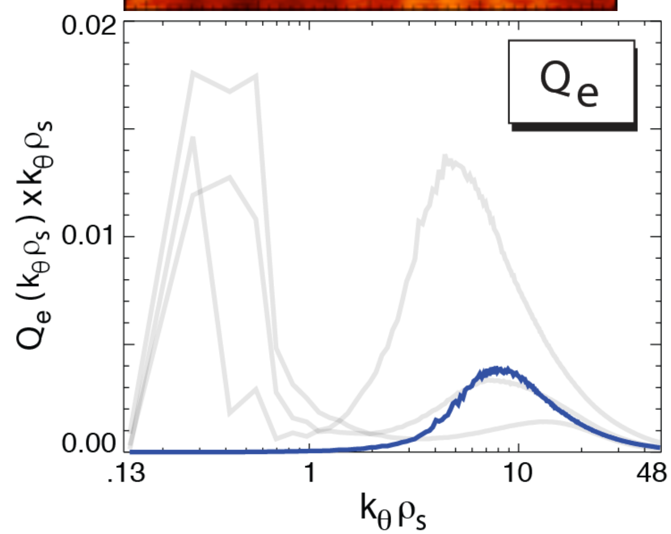

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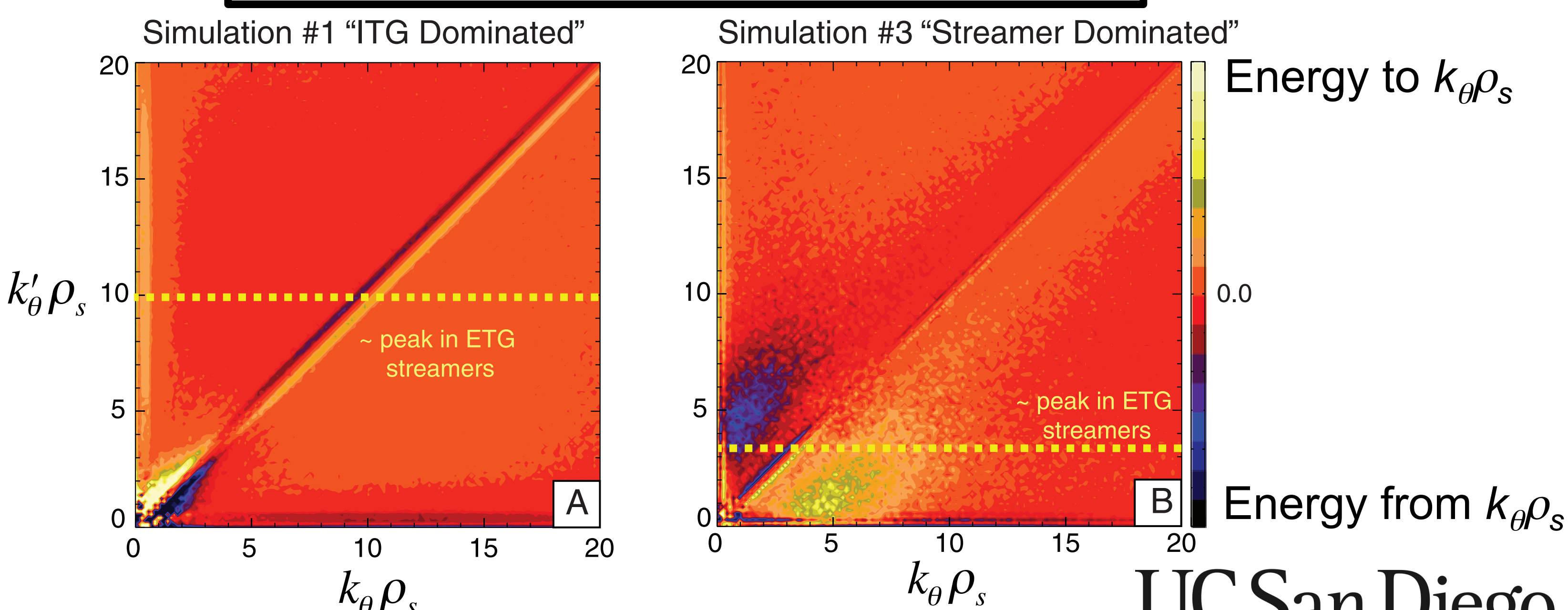
Both local and non-local nonlinear energy transfer processes contribute to cross-scale couplings

- To better understand nature of couplings between low-*k* and high-*k* observed in multiscale results, examine cross-bispectrum ***T*(*k*,*k′*)**
  - Quantifies rate of fluctuation energy transfer <u>from</u> fluctuations at ***k′*** <u>to</u> fluctuations at ***k*** via 3-wave interaction
  - Observe parameter-dependant mix of forward and inverse, local and nonlocal transfers- **no simple story of couplings**

$$T(k,k') = -\mathrm{Re}\left\langle \tilde{T}_e^*(k)\tilde{v}_{ExB}(k-k')\cdot\vec{\nabla}\tilde{T}_e(k')\right\rangle$$



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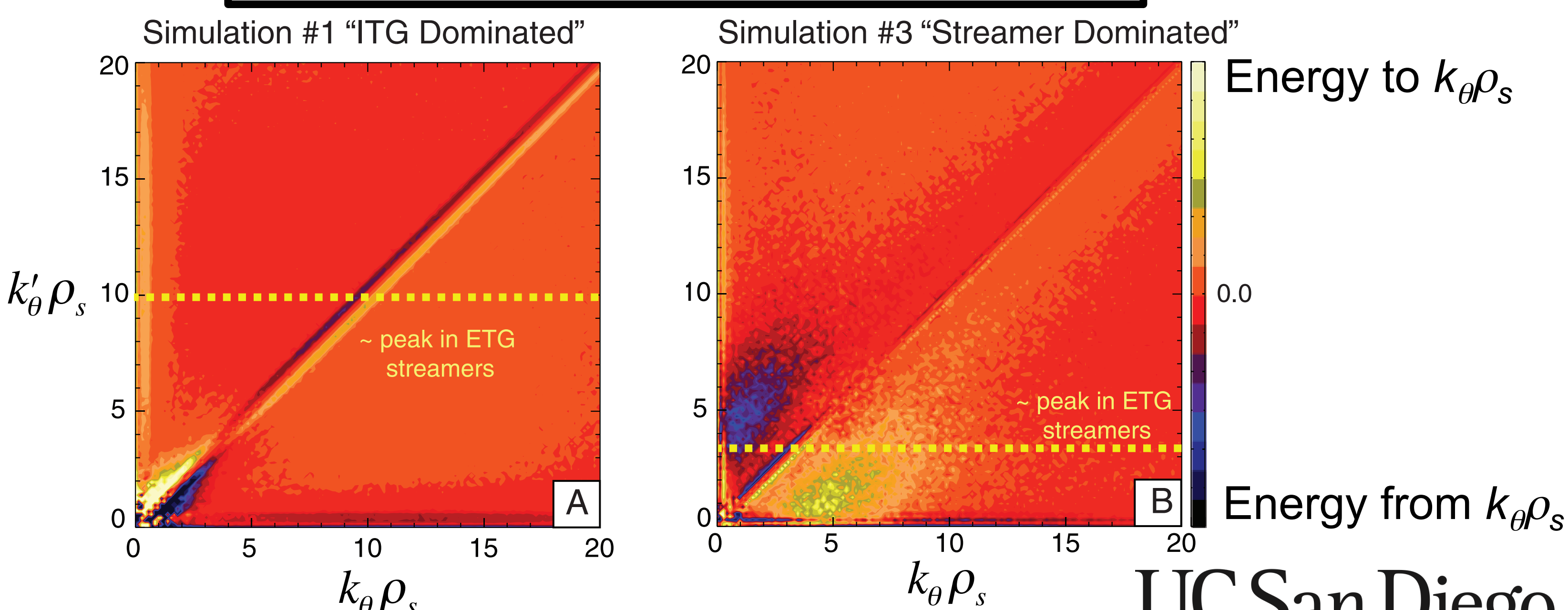

Alcator C-Mod

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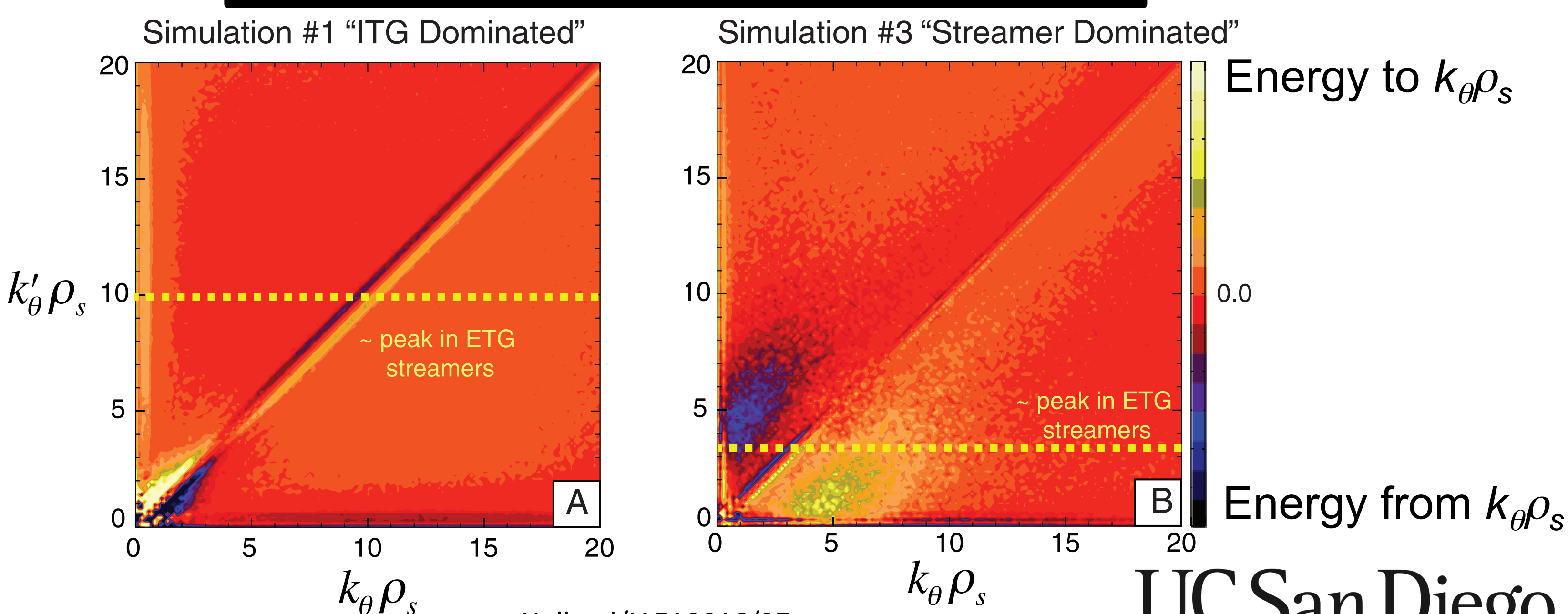

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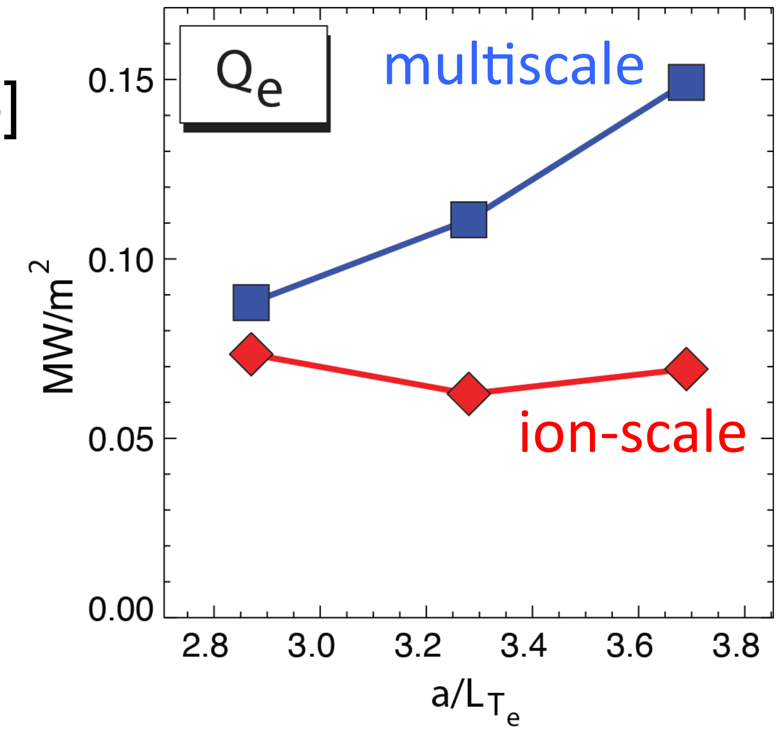
Additional validation measure: only multiscale simulations match measured $\chi_{e,inc} = d(Q_e)/d(n_e \nabla T_e)$

- Analysis of partial sawtooth crashes in discharge yields **$\chi_{e,inc}$ = 1.6 ± 0.4 m²/s** [Creely *et al*, Nucl. Fusion 2016]



- Increasing a/L_{Te} in ion-scale simulations gives no response in Q_e ($\chi_{e,inc}$ ≈ **0 m²/s**), inconsistent with observations

- Increasing a/L_{Te} in multiscale simulations increases Q_e, and predicted **$\chi_{e,inc}$ = 1.4 m²/s** is consistent with experimental analysis

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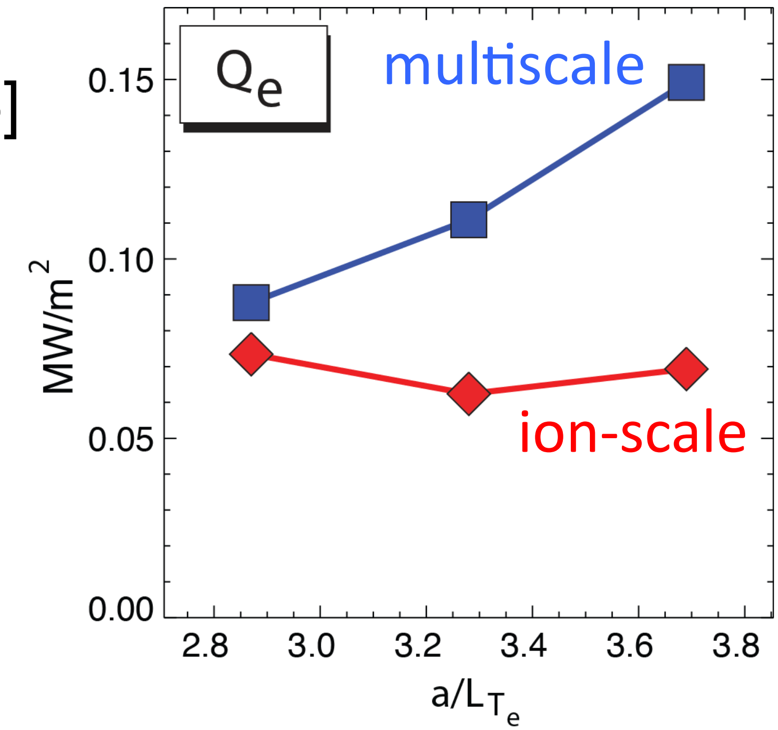

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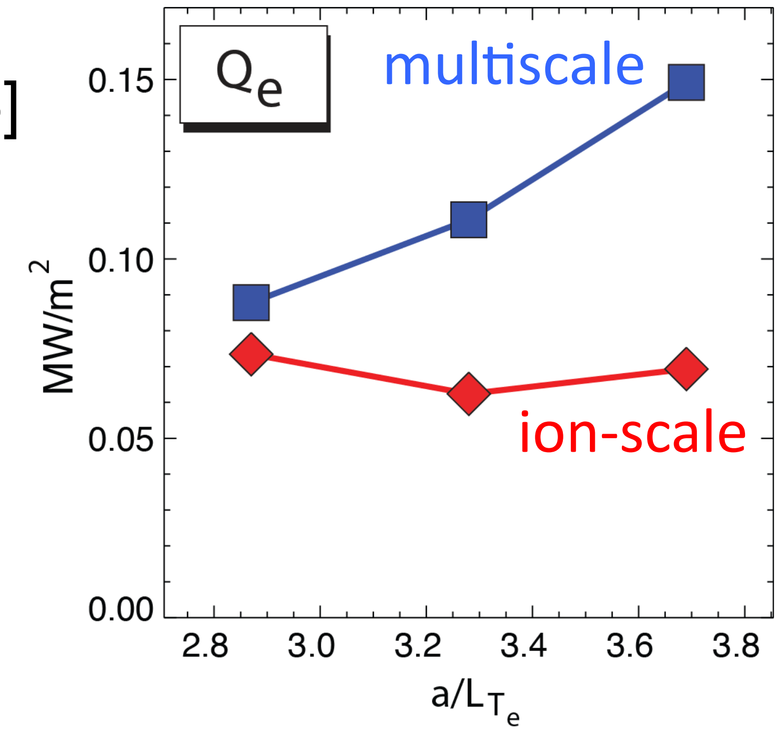

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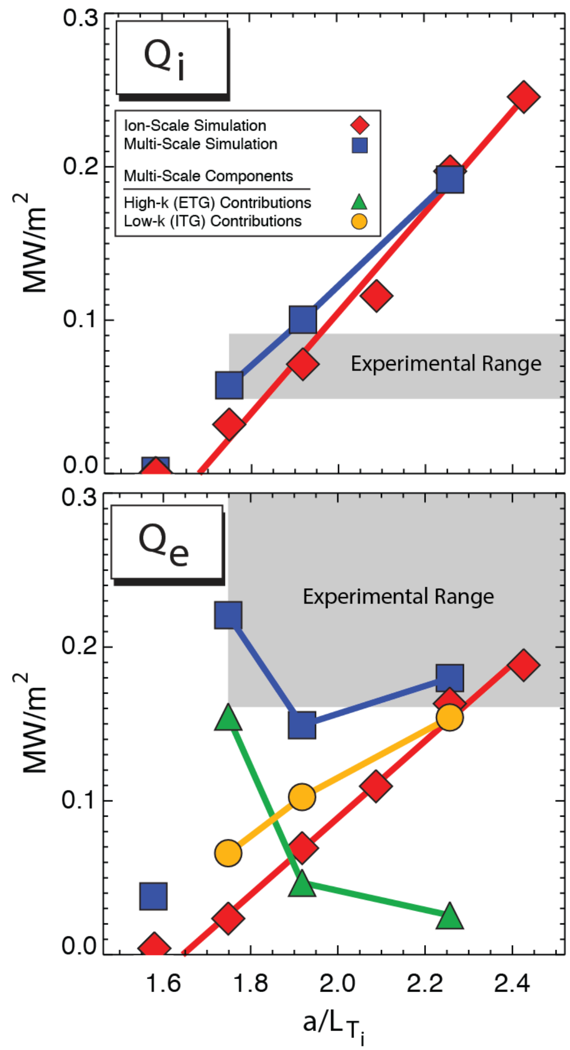
Alcator C-Mod simulations demonstrate importance of multiscale physics for accurate transport predictions

- Only first-of-kind multiscale GK simulations are able to simultaneously match Q_i and Q_e within experimental uncertainties
  - Multiscale simulations also reproduce measured $\chi_{e,inc}$ while ion-scale simulations cannot

- Observe significant cross-scale coupling in multiscale simulations- low-*k* and high-*k* dynamics are not independent

- Results raise obvious question- **will multiscale physics matter in reactor-relevant H-modes?**



Alcator C-Mod

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Alcator C-Mod simulations demonstrate importance of multiscale physics for accurate transport predictions

- Only first-of-kind multiscale GK simulations are able to simultaneously match Q_i and Q_e within experimental uncertainties
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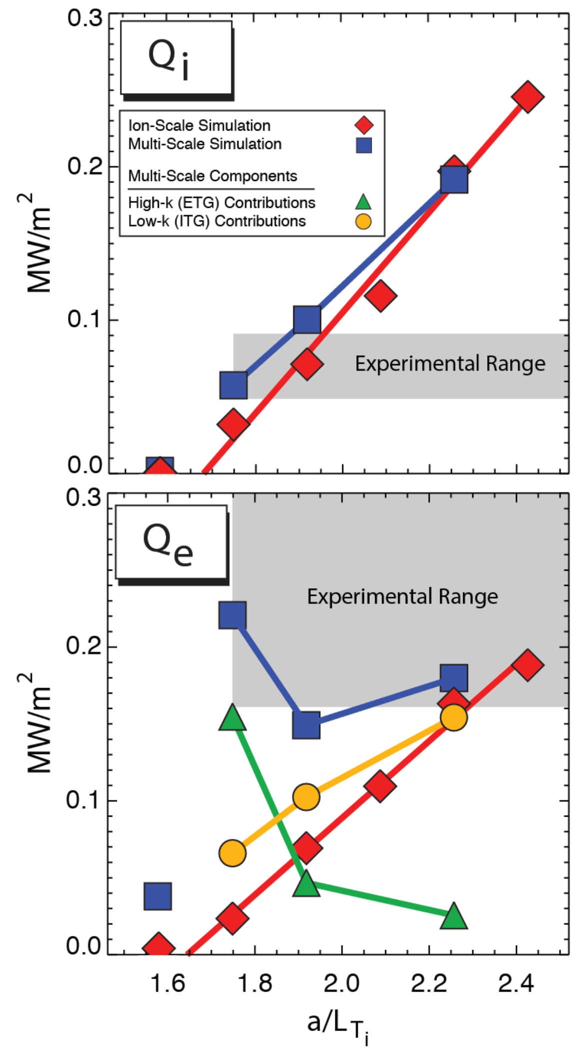

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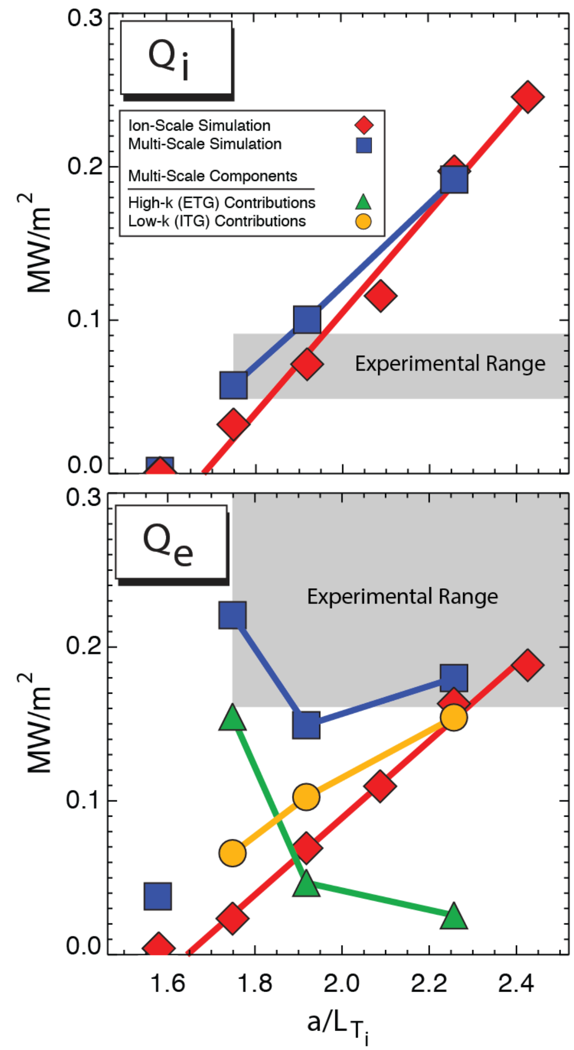

Alcator C-Mod

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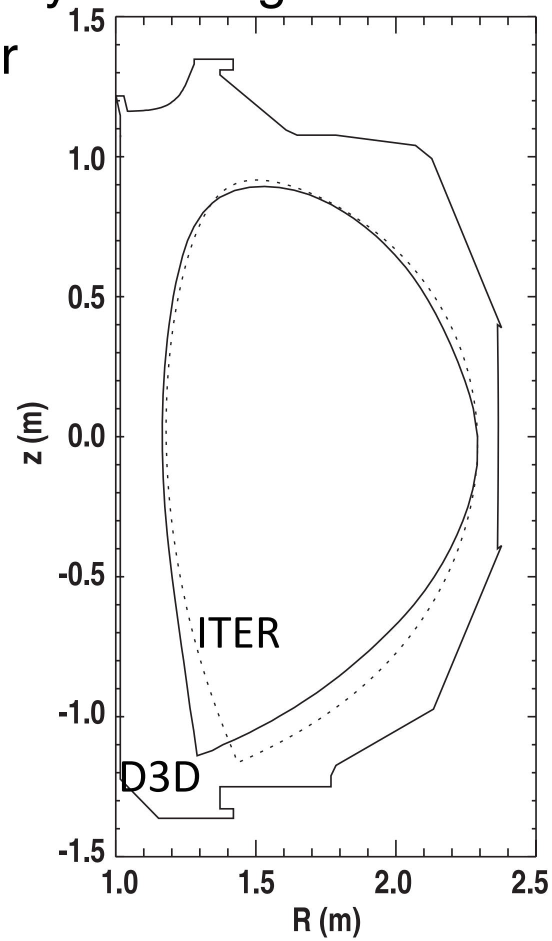
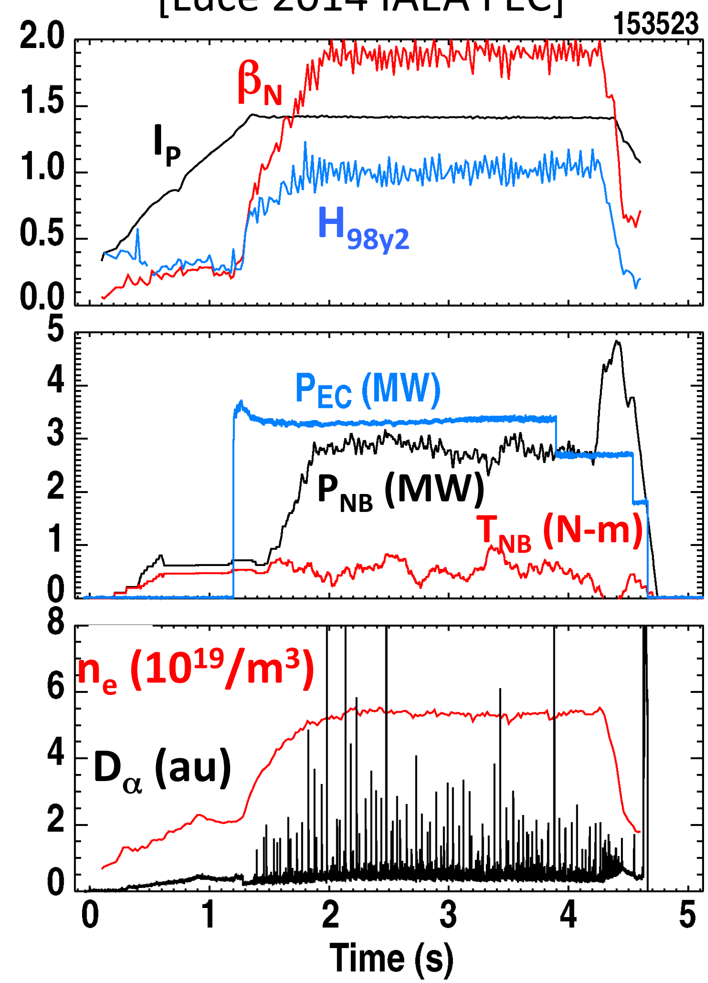
Begin by investigating importance of multiscale physics in a DIII-D ITER baseline discharge

- Consider a steady discharge with:
  - ITER-similar shape
  - dominant electron heating
  - low fueling and torque
  - $q_{95} = 3.3$
  - $H_{98y2} = 1$
  - $\beta_N = 1.8$



[Luce 2014 IAEA FEC]



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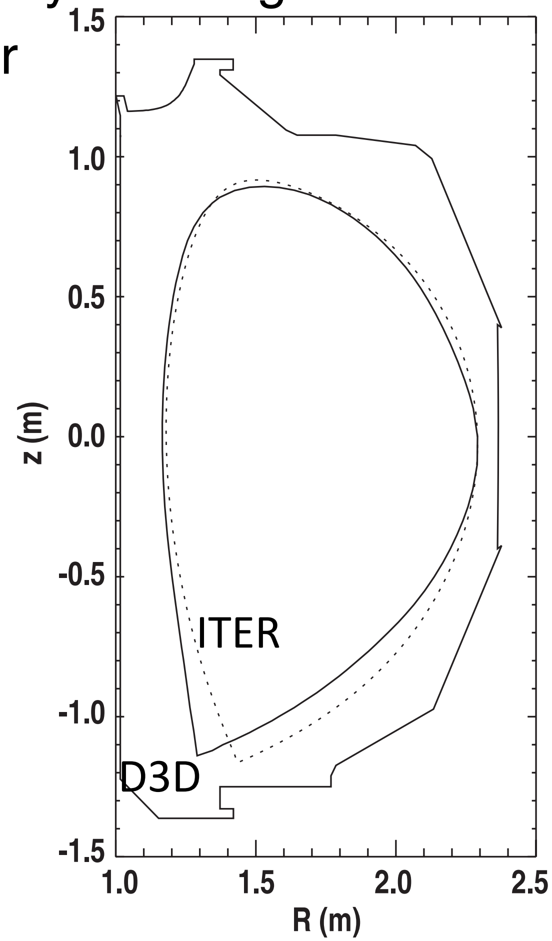

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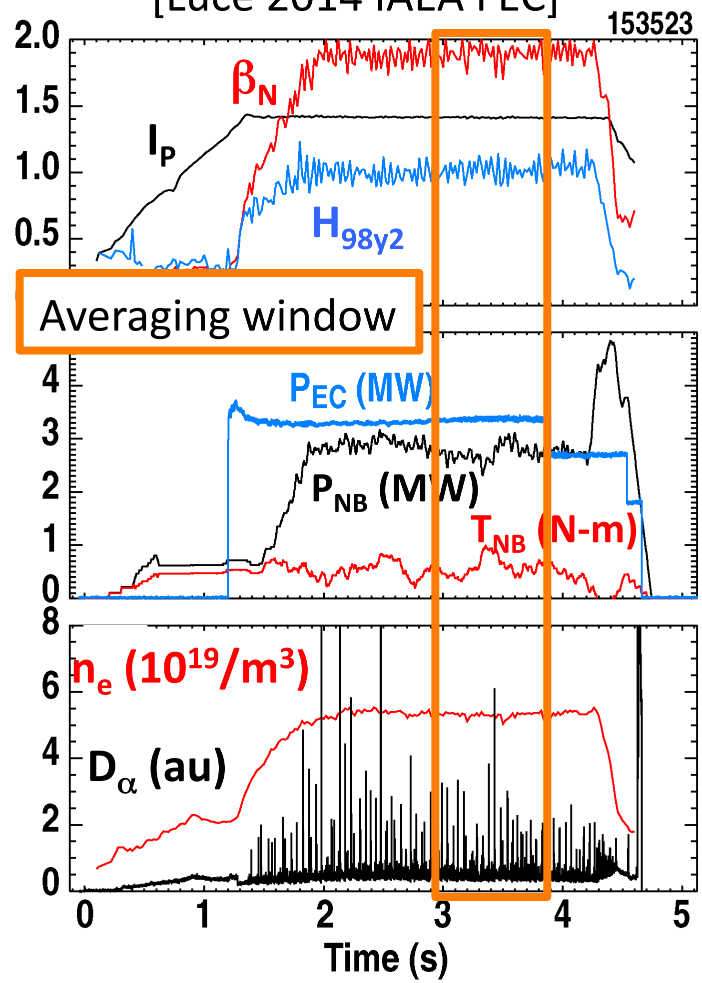
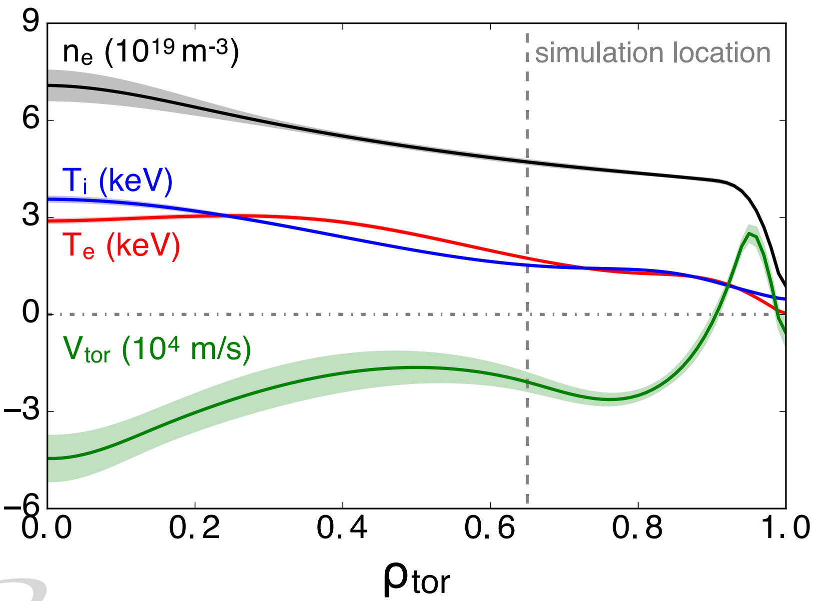
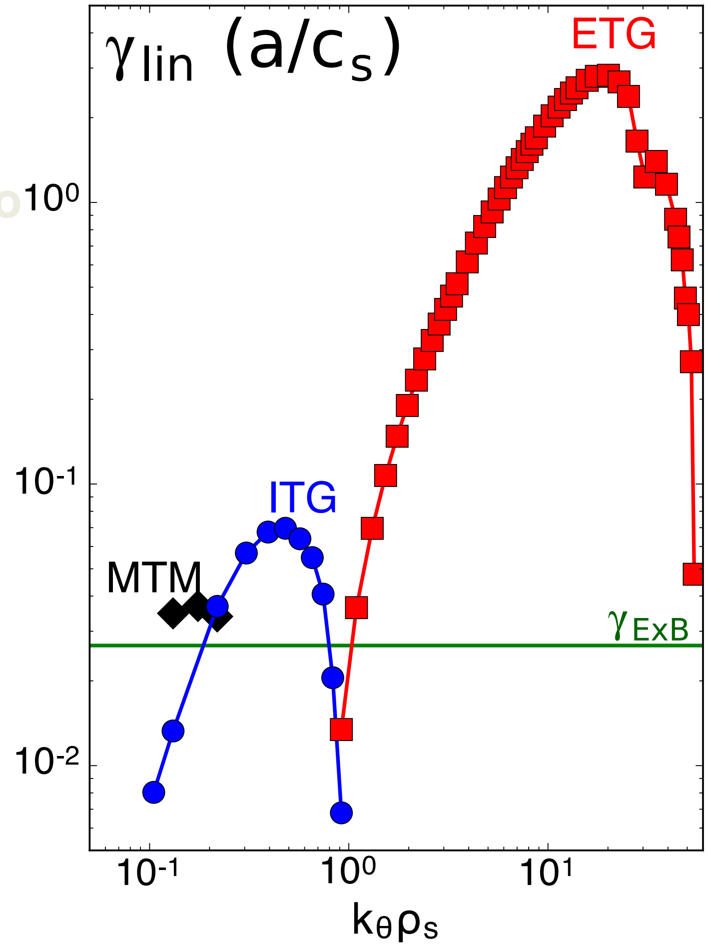


DIII-D ITER baseline H-mode plasma exhibits similar linear stability character as Alcator C-mod L-mode

- At ρ_{tor} = 0.65, **ITG** is weakly unstable, **ETG** strongly unstable
  - Simulation setup similar to C-Mod but includes magnetic fluctuations and carbon instead of boron impurity
  - Low-*k* **microtearing modes (MTM) also** linearly unstable, but do not appear to contribute in nonlinear simulations





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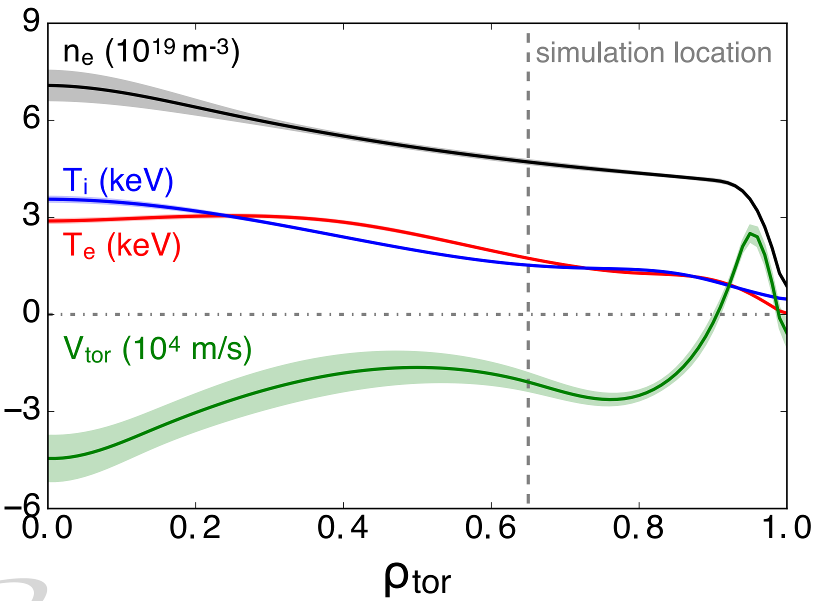

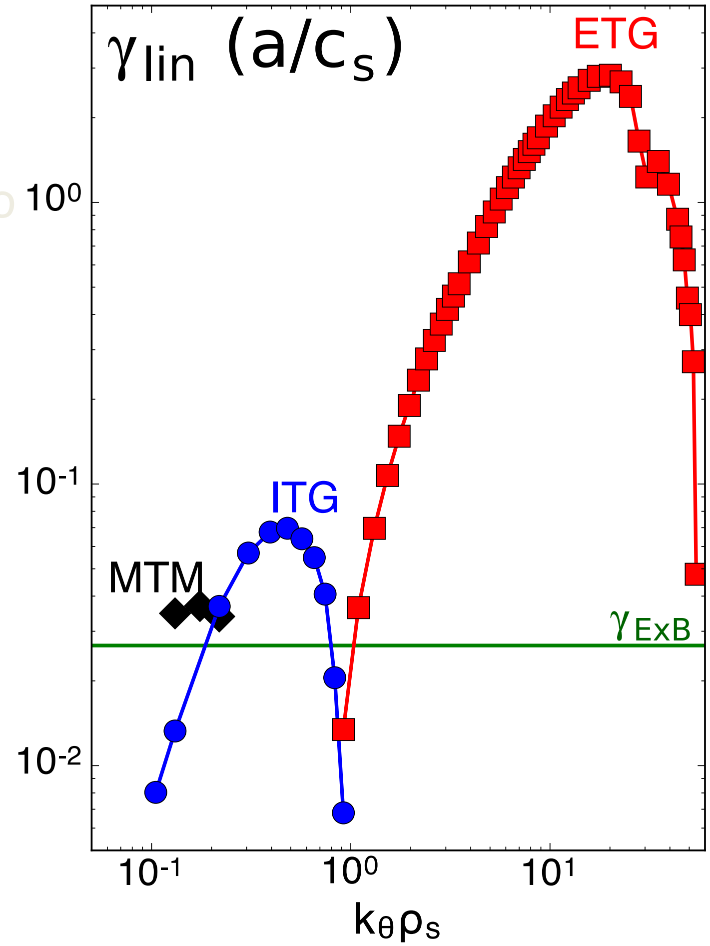

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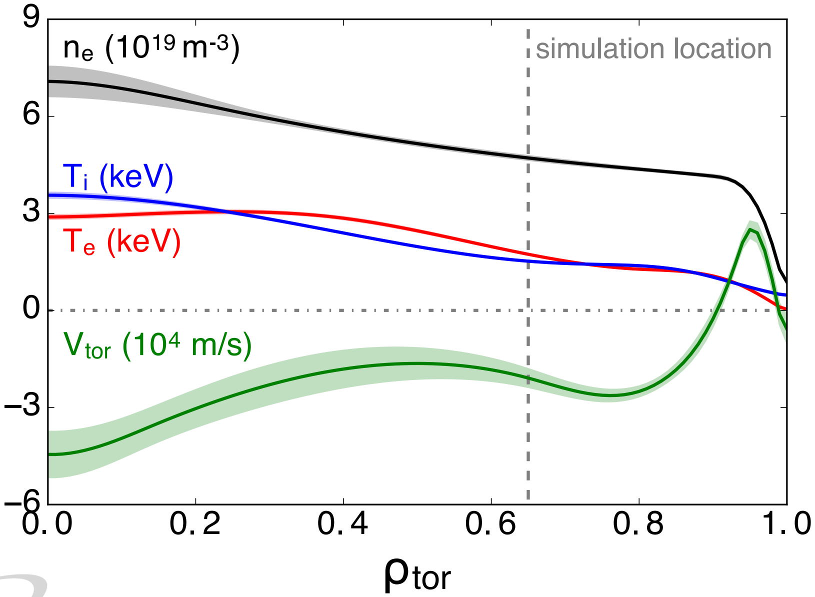

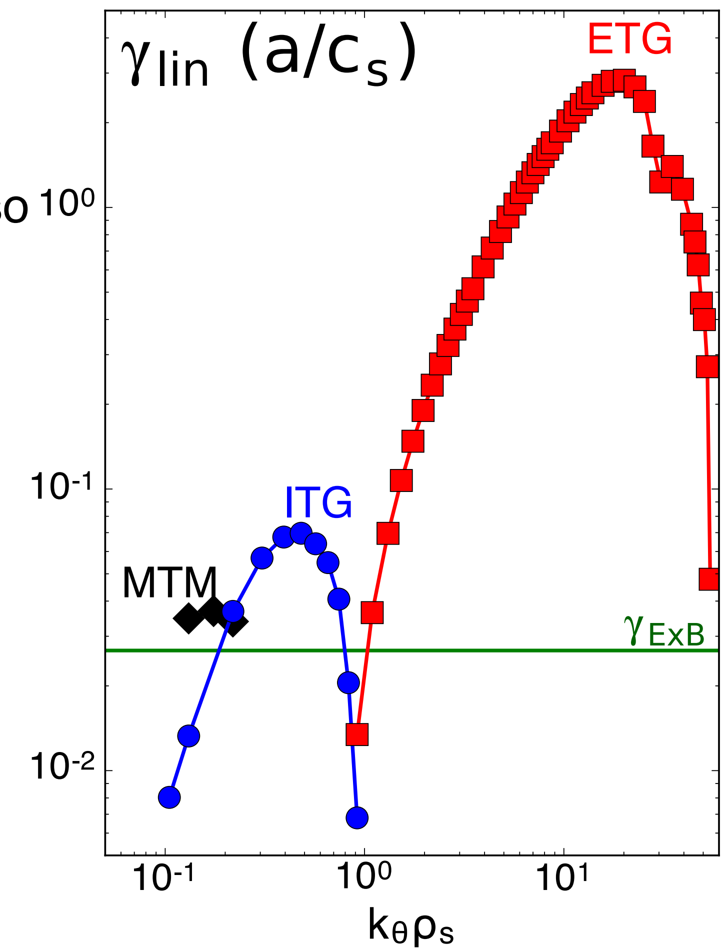

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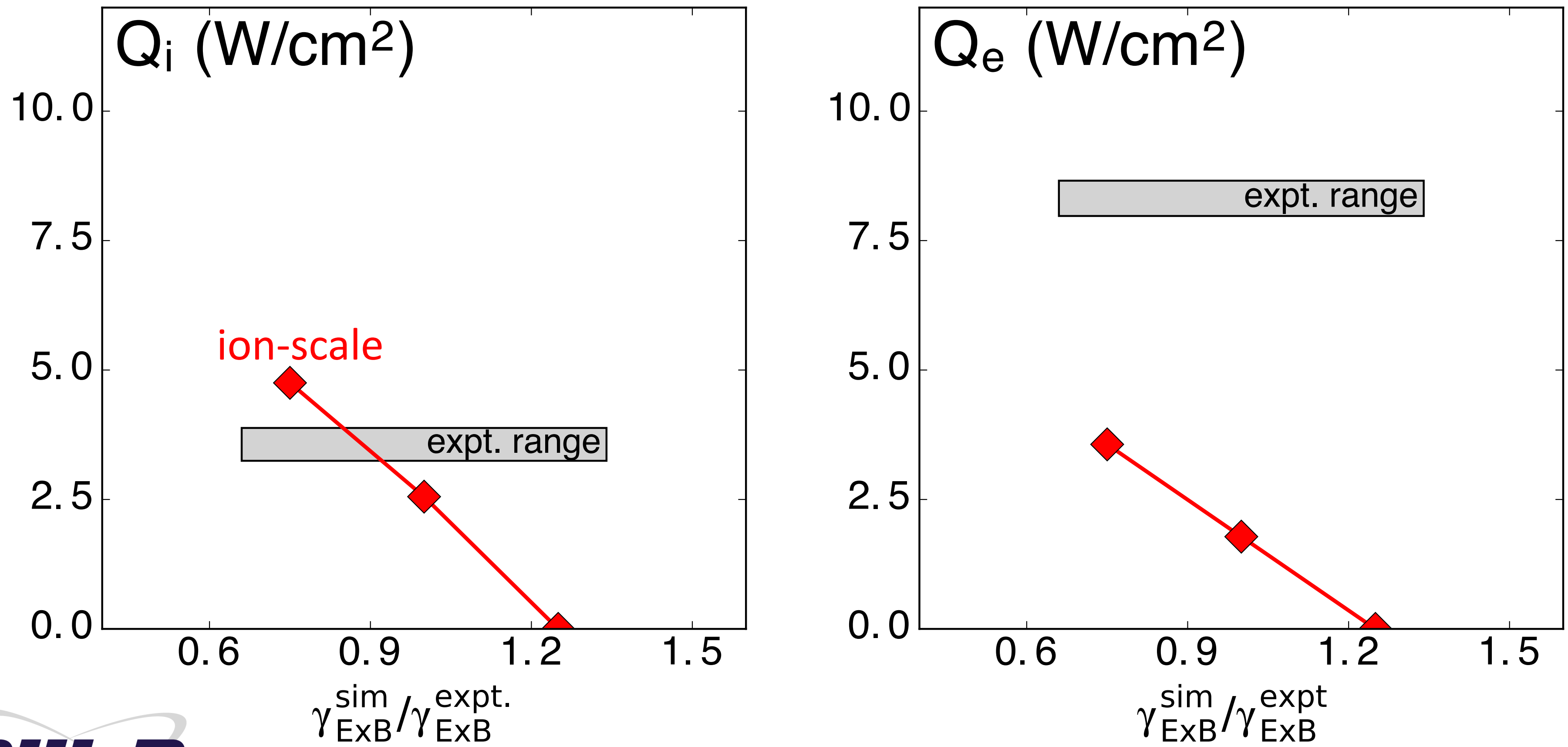
Ion-scale simulations underpredict Q_e when matching Q_i for DIII-D ITER baseline discharge

- Vary equilibrium E x B shear rate γ_{ExB} instead of $a/L_{Ti,e}$ because it provides largest model sensitivity within experimental uncertainties



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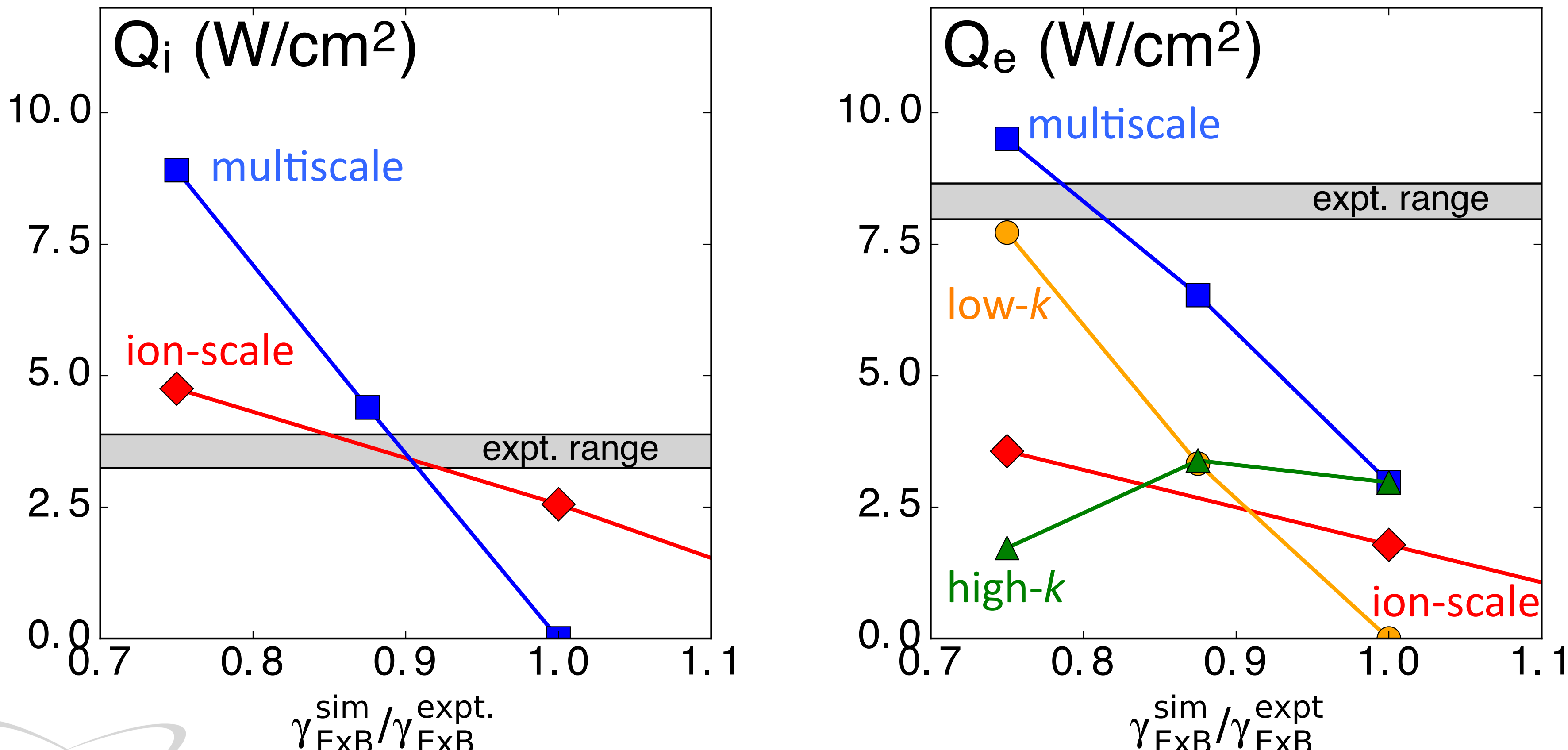
Initial multiscale simulations of DIII-D ITER baseline scenario come much closer to *simultaneously* matching Q_i and Q_e

- **Caveat**: simulations very bursty, can easily transition between ion-scale over-prediction and near-zero flux zonal flow dominated states



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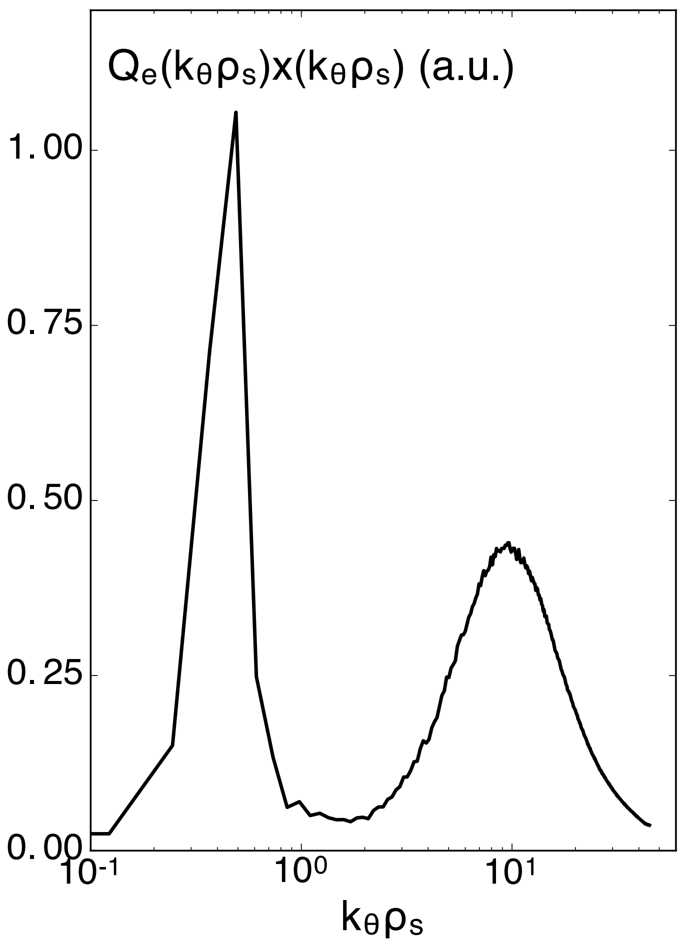
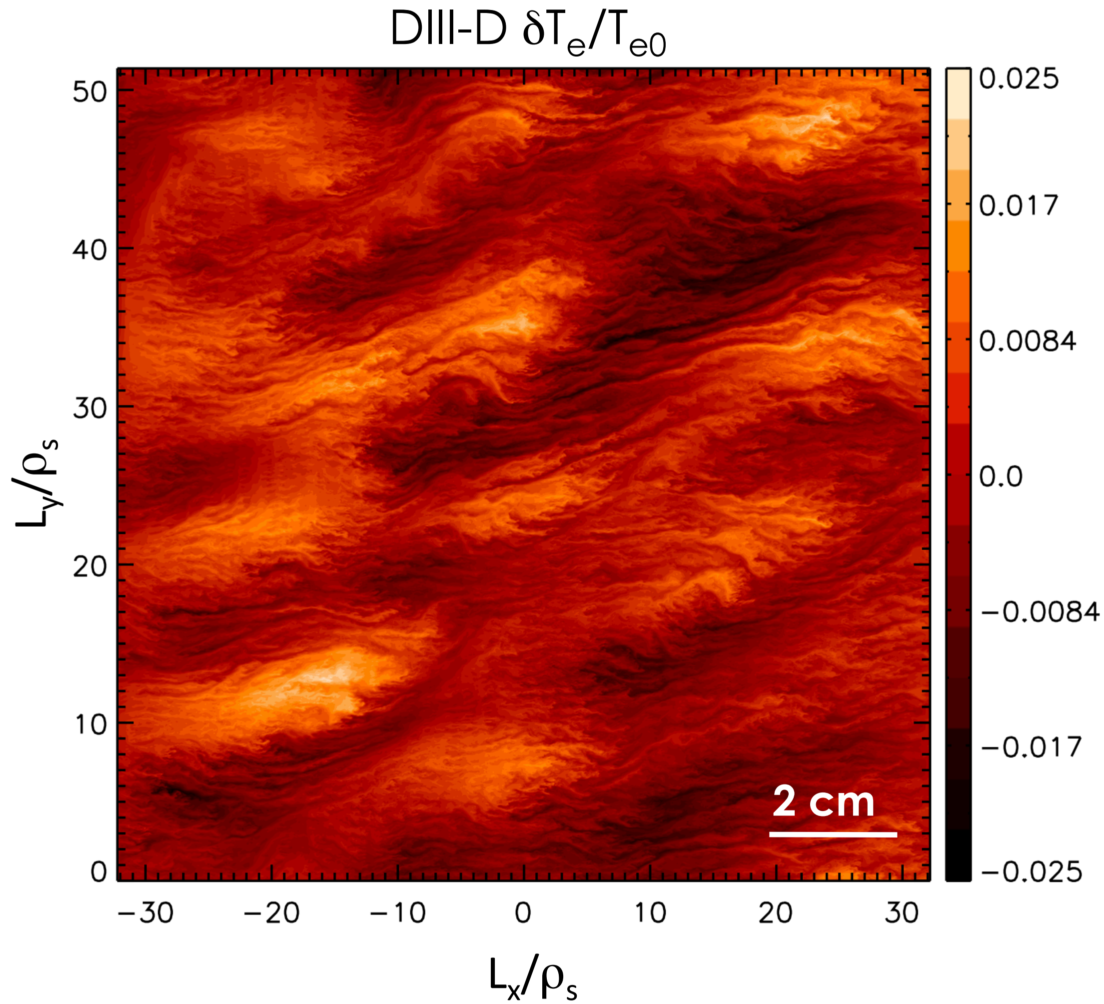
High-*k* fluctuations can provide 50% or more of total Q_e at ρ_{tor} = 0.65 in DIII-D ITER baseline plasma





New simulations show turbulent electron transport is robustly multiscale for reactor-relevant plasma parameters

- Multiscale turbulence dynamics operative at mid-radius in reactor-relevant Alcator C-Mod L-mode and DIII-D ITER baseline H-mode

- Need multiscale simulations to match Q_i and Q_e in these plasmas
  - Ion-scale underpredicts Q_e when matching Q_i
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- Multiscale results are not simple sum of ion and electron scale dynamics-**cannot model as such**
  - Low-*k* can suppress high-*k* and high-*k* can enhance low-*k*
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