Simulating Plasma Turbulence at NESRC: *Towards a Predictive Model for Heat Loss in Fusion Reactors*

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Alcator C-Mod

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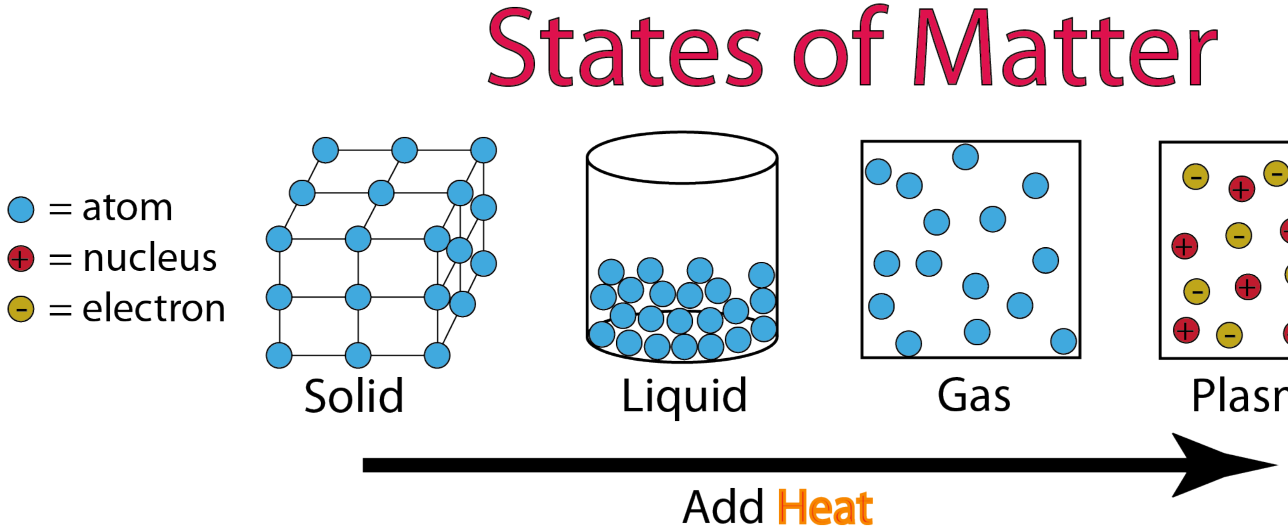
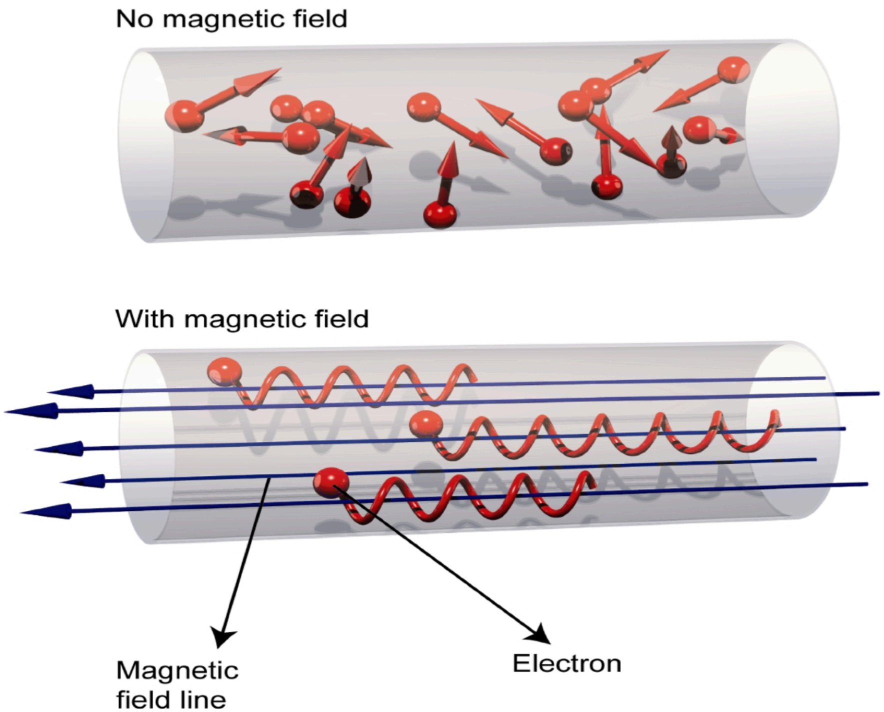
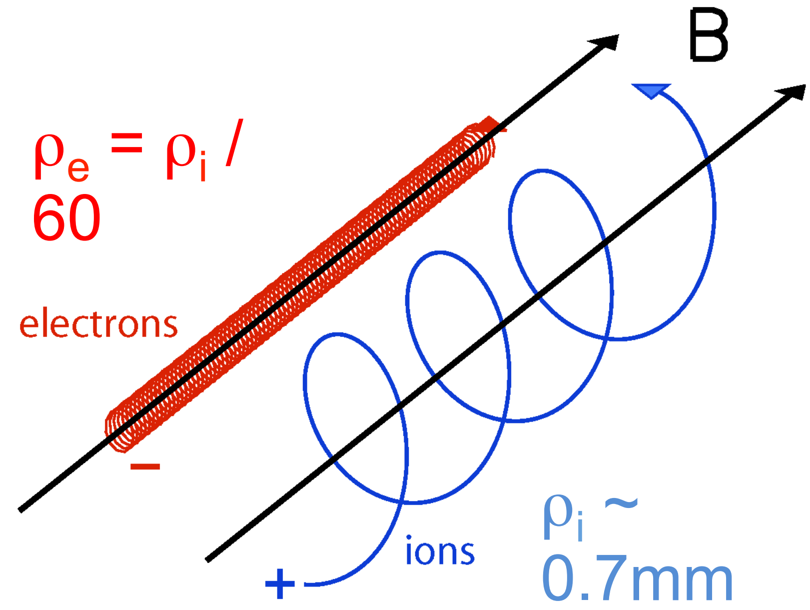
Plasma is an Ionized Gas that Exhibits Collective Behavior



- Plasma exist when the electrons have enough energy to “detach” from their nuclei (ions) resulting in a collection of free ions (+) and electrons (-)
- In plasma physics we measure temperature in electron-volts (eV)
  - 1 electron volt = 11,600K
  - Ionization occurs ~ 13.6 eV ~158,000 K
- Most importantly for this talk, due to their electro-magnetic nature, plasmas can support a rich variety of waves, motions, and structures

Plasmas Can be Confined With Magnetic Fields, Resulting in a Set of Characteristic Scales





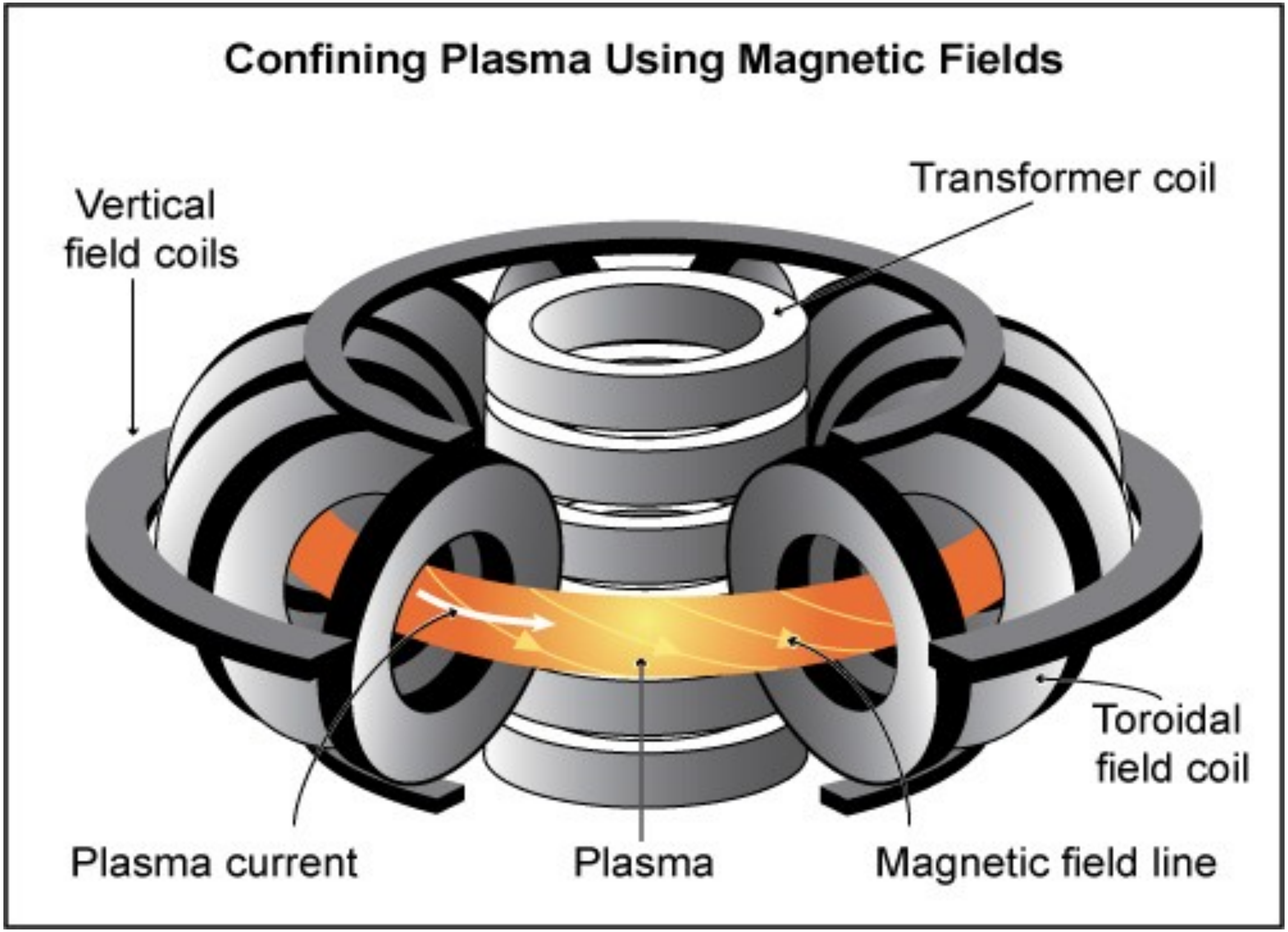
Charged particles are held “confined” perpendicular to B field lines

….BUT…. No confinement parallel to B

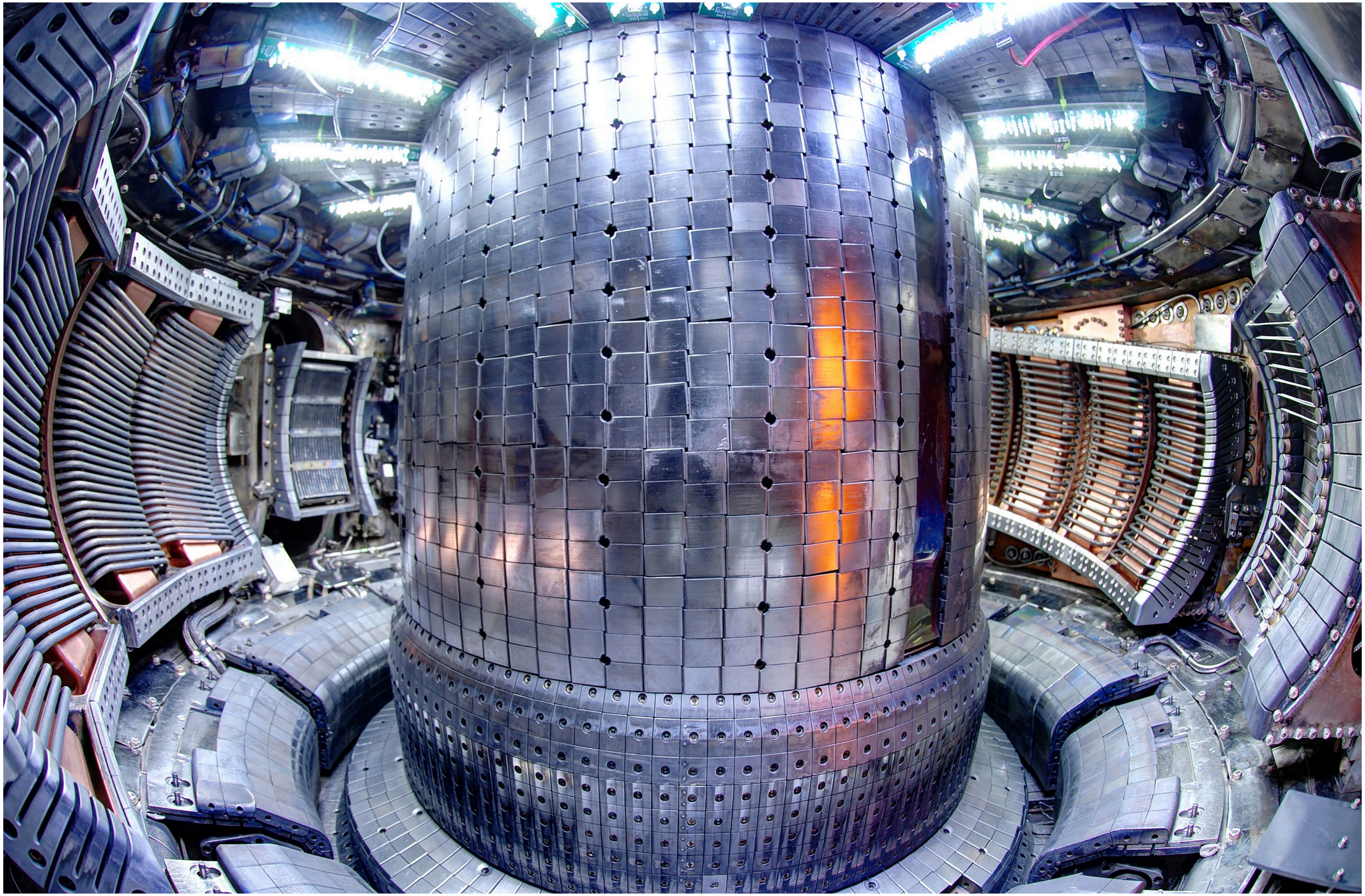
Gyro-radius or Larmor radius $\rho = \dfrac{mV_\perp}{qB} \propto \dfrac{\sqrt{mT}}{B}$

Gyro-frequency $\omega_c = \dfrac{qB}{m}$

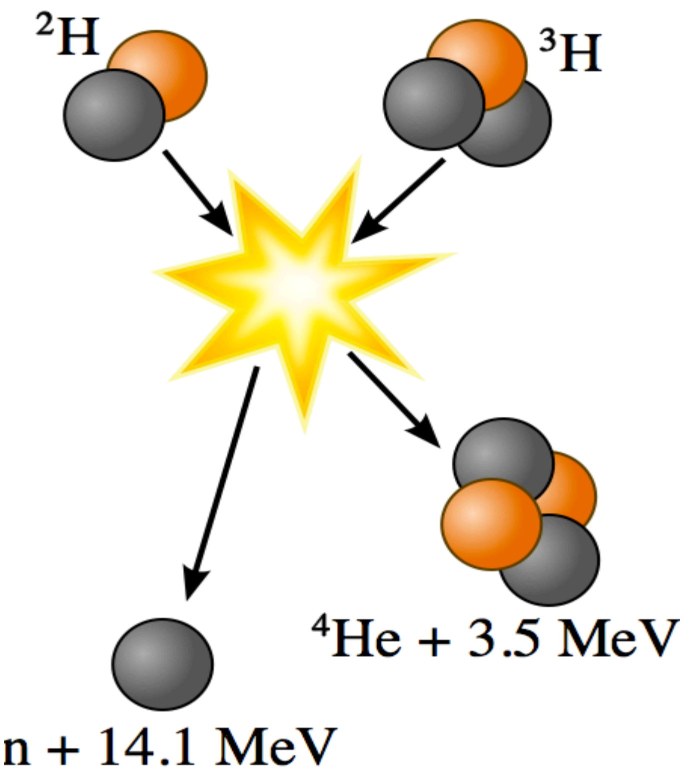
The Leading Candidate for Confining Plasma for Development of Fusion Energy is the Tokamak



An Inside View of the Alcator C-Mod Tokamak at MIT



Fusion Requires High Pressure and Confinement – Measured Heat Losses Have Exceeded Theory

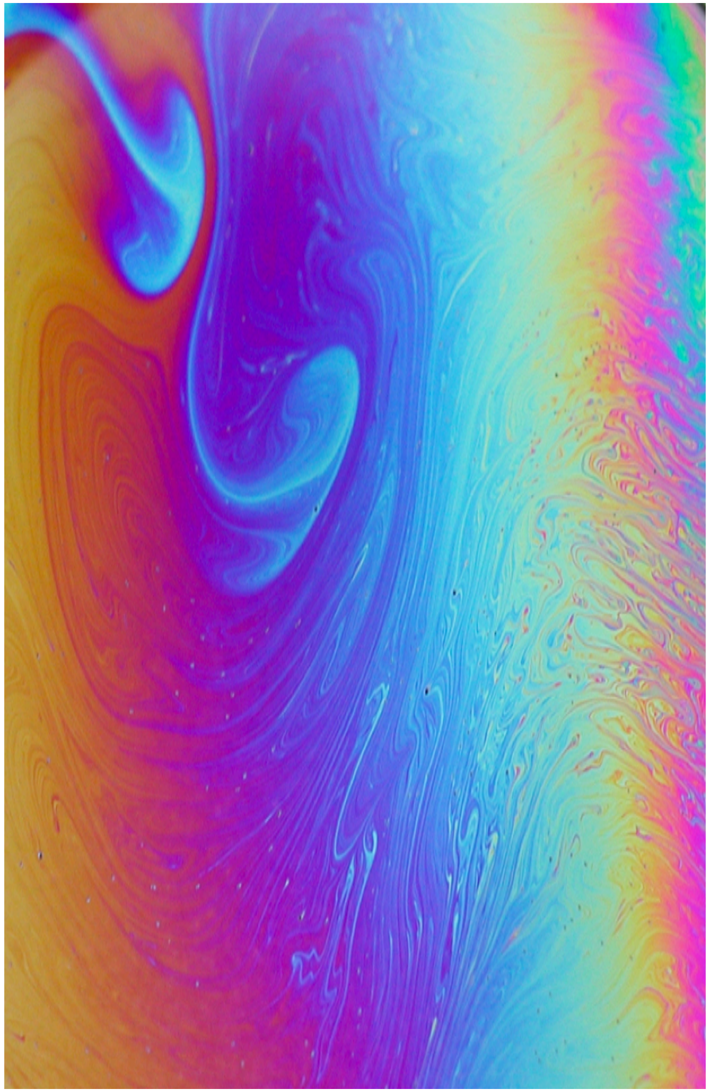


- Fusion requires ~$n = 10^{20}$ m^{-3} (1 Million times less dense than air – Achieved in experiment)
- A temperature of ~ T = 15 keV (~175 Million degrees K– Achieved in experiment)
- Need to keep plasma this hot (confined) for τ = 1 – 10 sec (energy confinement time)
- The conditions needed for fusion energy are represented by the "Lawson Criterion"

$$n\,T\,\tau = 8 \text{ atm x sec}$$

- Experimental heat losses can exceed collisional theory by up to 10,000x
- Turbulence is now generally assumed to be responsible for high levels of transport in fusion devices

Turbulence is a Complex, Nonlinear, Multi-Scale Phenomena That Plays a Crucial Role in Plasmas

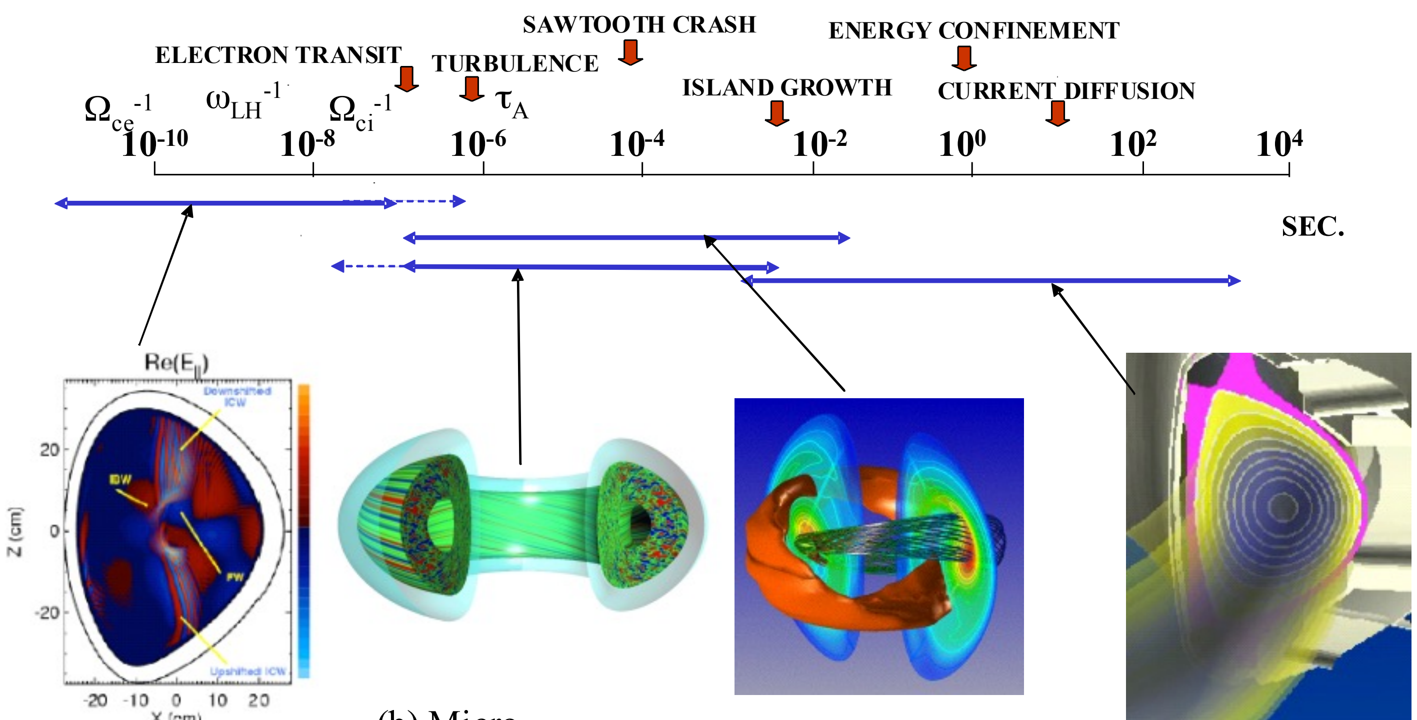


- Apparently random fluctuations about a mean value - leading to enhanced mixing and transport
- Confined plasma turbulence has…
  - Weak collisions
  - Electro-magnetic fluctuations are present
  - Energy injected at multiple scales
  - Quasi-2D turbulence (extended along field)
  - Driven by the inherent temperature and density gradients in confinement plasma

Turbulence fundamentally limits the performance of fusion reactors – representing a major roadblock to the development of fusion energy

Plasmas Exhibit Phenomena Which Occur on a Wide Range of Temporal and Spatial Scales

Relevant timescales for a burning plasma experiment



(a) RF codes

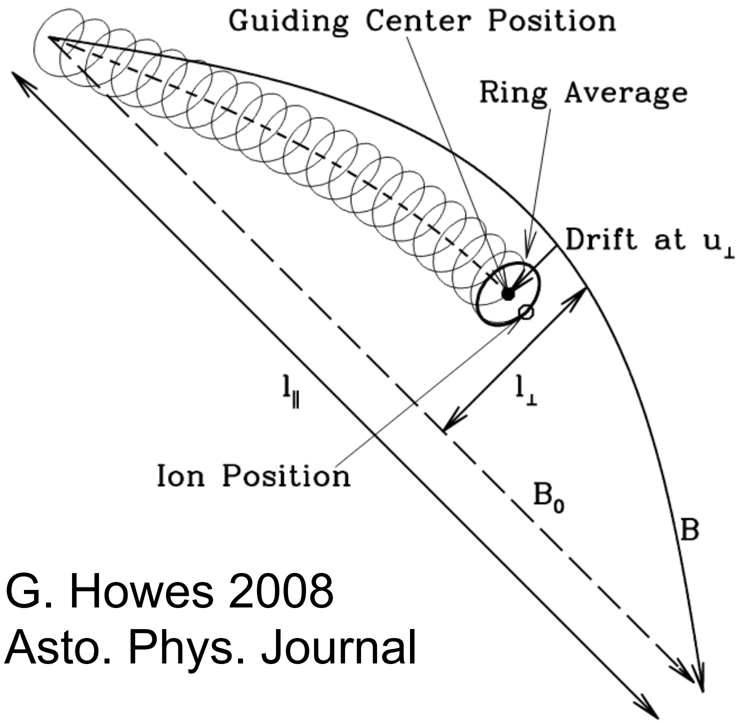
(b) Micro-turbulence codes

(c) Extended-MHD codes

(d) Transport Codes

- Relevant spatial scales span 4-5 orders of magnitude
- Relevant temporal scales can span 12-14 orders of magnitude!

Plasma Turbulence is Modeled Using the Gyrokinetic – Maxwell System of Equations



G. Howes 2008
Asto. Phys. Journal

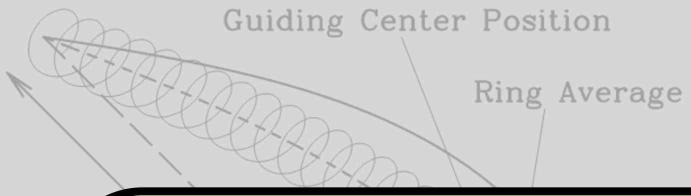
- A fusion plasma may have ~ 10^{20} particles, so a statistical approach is taken
- Boltzman equation coupled with Maxwell's equations describes the evolution of the plasma distribution function: "kinetic"

$$\frac{\partial f}{\partial t} + \mathrm{v} \cdot \nabla f + \frac{q}{m}\left[E + \mathrm{v} \times B\right] \cdot \nabla_{\mathrm{v}} f = C(f)$$

- 6 phase space dimensions (spatial coordinates (x,y,z) ; velocity coordinates (v_x,v_y,v_z)) and time; a huge range of scales.

- Averaging over the fast gyro-motion can reduce spatial dimensions to 5-D and eliminates turbulent timescales faster than gyromotion → "gyrokinetic"
- Major gyrokinetic codes are run at NERSC: GYRO, GENE, GS2, GTS, XGC, GEM, etc.

Plasma Turbulence is Modeled Using the Gyrokinetic – Maxwell System of Equations



- A fusion plasma may have ~ 10^{20} particles, so a statistical approach is taken

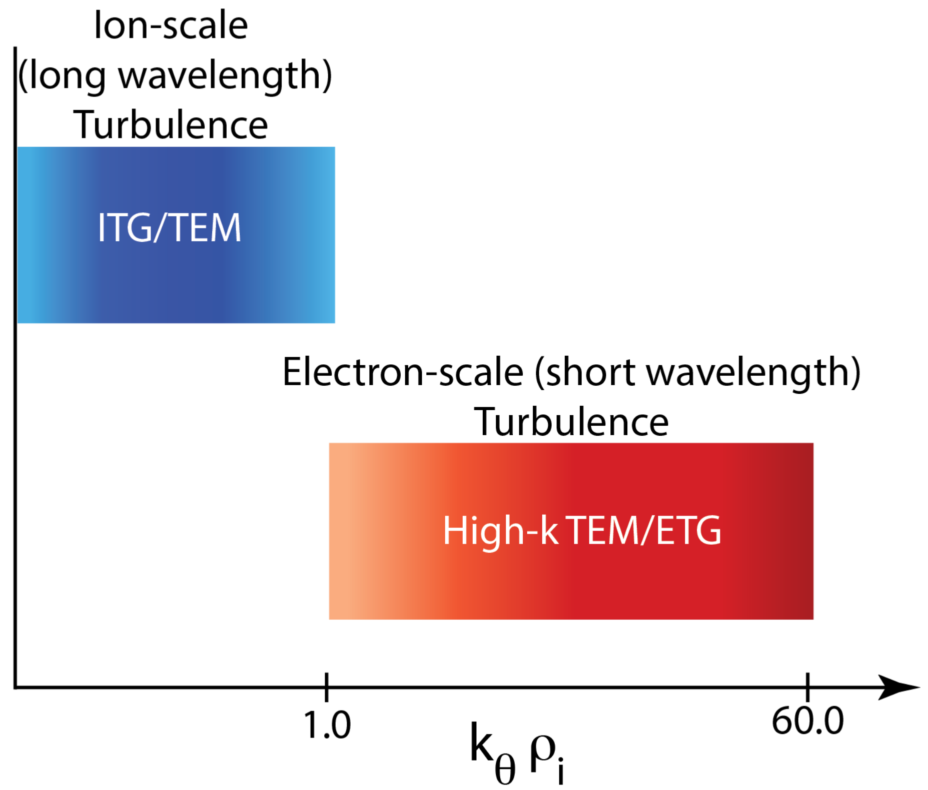
Over the past decade, much of the research in plasma turbulence and transport has attempted to validate the gyrokinetic model.

With the ultimate goal of producing a predictive transport model to inform design and operation of future fusion devices…

- Averaging over the fast gyro-motion can reduce spatial dimensions to 5-D and eliminates turbulent timescales faster than gyromotion → "gyrokinetic"
- Major gyrokinetic codes are run at NERSC: GYRO, GENE, GS2, etc.

The Instabilities Responsible for Turbulence Exist at Both Long (ion-scale) and Short (electron-scale) Wavelengths

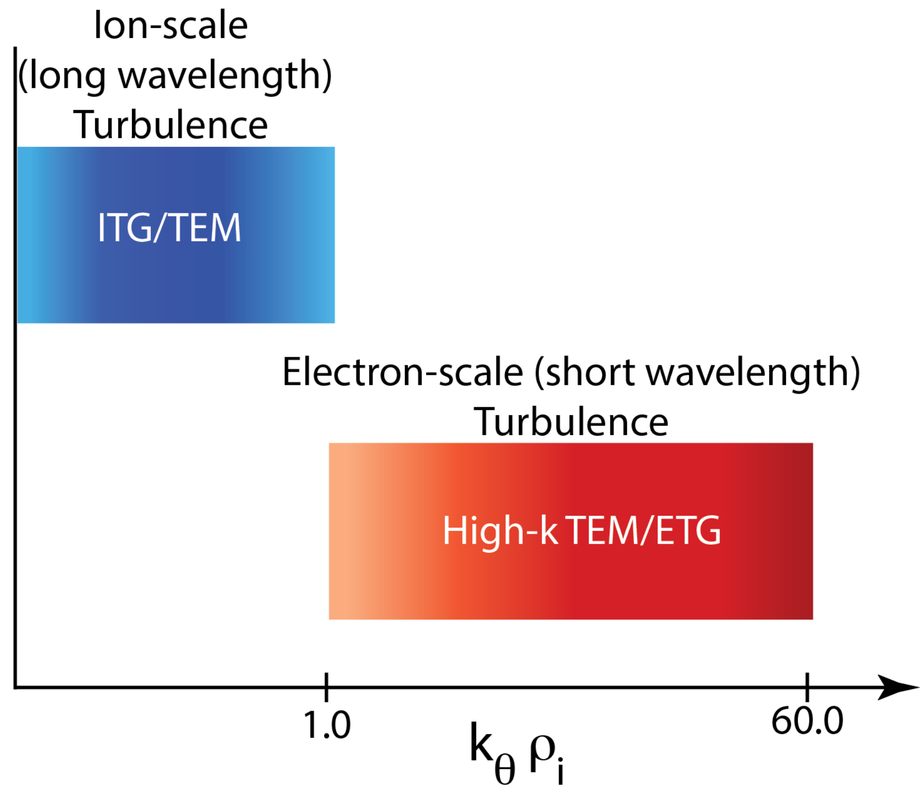
- Ion-Scale, Long Wavelength turbulence
  - Exists at $k_\theta \rho_i < 1.0$
  - Ion Temperature Gradient (ITG) mode : Driven by gradients in ion temperature
  - Trapped Electron Mode (TEM) : Driven primarily by gradient of electron density, electron temperature.
- Large eddies sizes associated with this turbulence (~5-8ρ_i correlation lengths)



- Ion-scale turbulence generally accounts for all of experimental ion heat loss but electron heat losses are frequently unaccounted for with this model alone

The Instabilities Responsible for Turbulence Exist at Both Long (ion-scale) and Short (electron-scale) Wavelengths

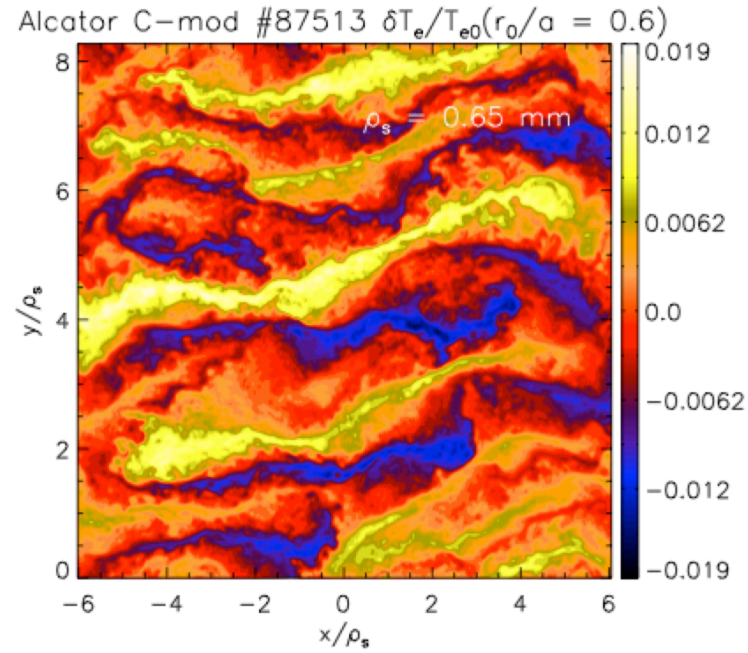
- Electron-scale, short wavelength turbulence
  - Exists with $k_\theta \rho_i > 1.0$
  - Electron Temperature Gradient (ETG) mode : Driven by gradients in electron temperature
  - Analog of ITG in the electron temperature
  - Exists at a scale ~60x smaller ; ~60x faster time scales
  - Drives exclusively electron heat transport



- Early estimates suggested transport scales like ~ $1/k^2$, implying negligible role

Theory, Simulation, and Experiment Suggest Short Wavelength Turbulence Can Cause Electron Heat Transport

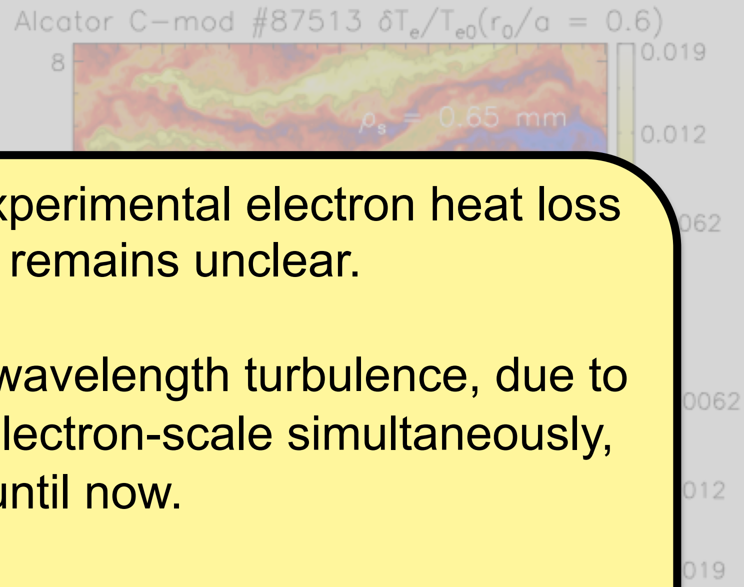
- Dorland, *et al.* – PRL 2000 & Jenko, *et al.* - PRL 2002
  - ETG turbulence can form radially elongated “streamers” (Example on right)
  - May be capable of driving experimental levels of heat flux
- Theory suggests that when long-wavelength turbulence is unstable, ETG streamers will be torn apart [Holland and Diamond PoP 2004]



- The difficulty of measuring high-k fluctuations has resulted in limited experimental evidence [*Mazzucato PRL ‘08 ; Smith PRL ’09]*, [Rhodes *PoP ’07*]
  - New efforts are in progress to measure electron-scale turbulence in fusion plasmas

Theory, Simulation, and Experiment Suggest Short Wavelength Turbulence May Play an Important Role in Electron Heat Transport

- Dorland, *et al.* – PRL 2000 & Jenko, *et al.* - PRL 2002



After decades of research into the origin of experimental electron heat loss in fusion reactors its exact cause remains unclear.

Despite evidence for the importance of short wavelength turbulence, due to the difficulty of simulating the ion-scale and electron-scale simultaneously, it had never been done until now.

The first multi-scale gyrokinetic simulations have shown that the coupled turbulence behavior is needed to explain experiments.

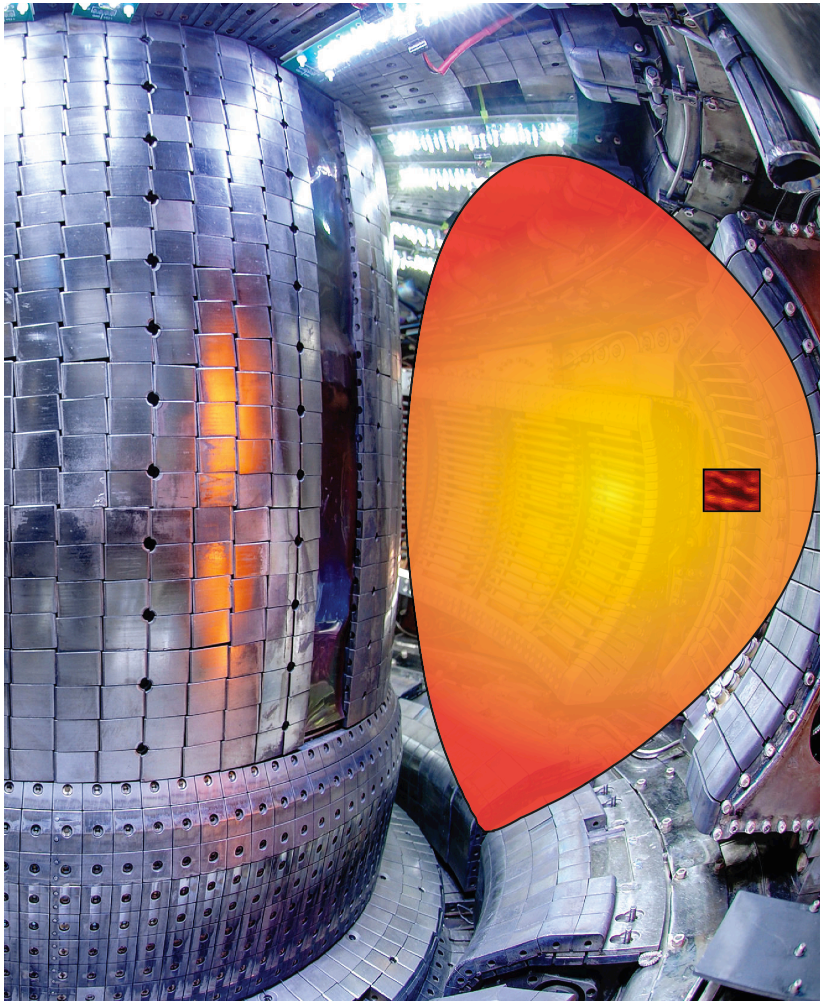
- The difficulty of measuring high-k fluctuations has resulted in limited experimental evidence [*Mazzucato PRL '08 ; Smith PRL '09]*, [Rhodes *PoP '07*]
  - New efforts are in progress to measure electron-scale turbulence in fusion plasmas

We Performed the First Realistic Simulations Capable of Capturing Coupled Ion and Electron-Scale Turbulence

- Experiments compared to gyrokinetic model
  - Ion-scale simulation unable to account for electron heat loss
  - Motivated multi-scale simulations
- Large range of spatial ($k_\theta \rho_i \sim 0.1$ to 60.0) and temporal scales (60x) required

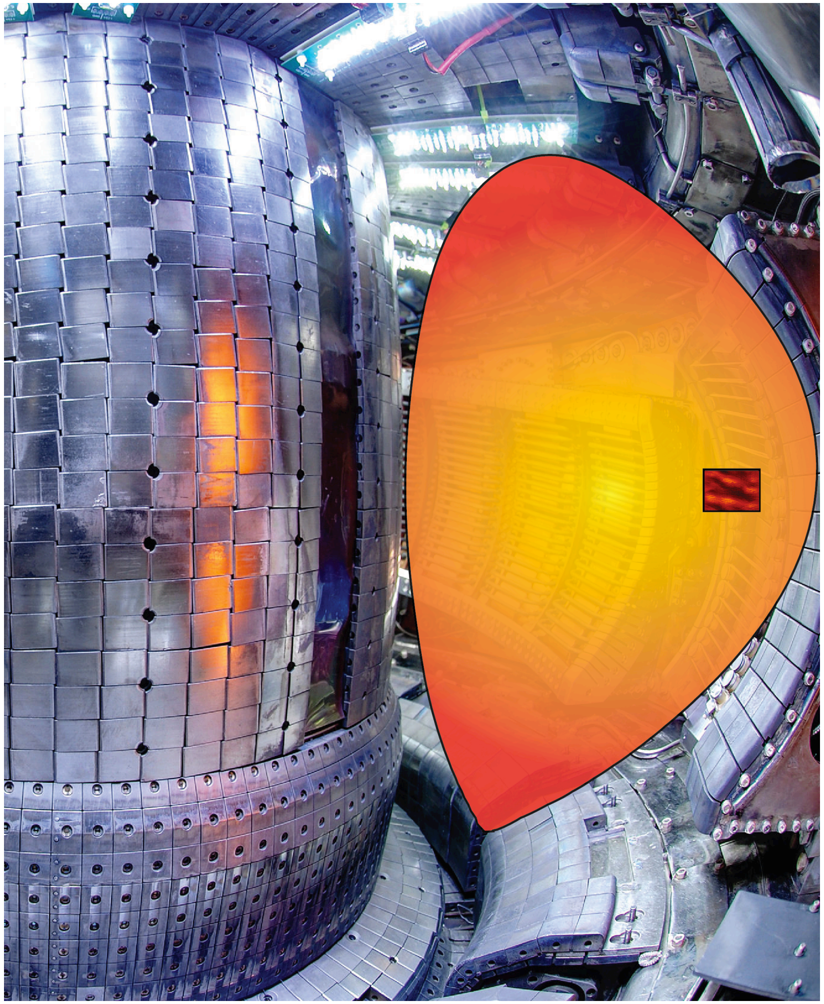
→ extremely computationally expensive!

- A handful of previous attempts (~6) reduced scale separation artificially, which can lead to incorrect results [N.T. Howard et al. PPCF 2015]
- These new simulations have the real scale separation, designated by mass ratio $\mu = (m_D/m_e)^{.5} = 60.0$



We Performed the First Realistic Simulations Capable of Capturing Coupled Ion and Electron-Scale Turbulence

- All simulations were local (representing a single radial location in the plasma)
- Arguably the highest physics fidelity turbulence simulations ever performed
    - Experimental inputs were used
    - 3 gyrokinetic species (deuterium, electrons, impurities)
    - Electrostatic turbulence
    - Rotation effects (ExB shear, etc.)
    - Collisions
    - Realistic electron mass: $\mu = (m_i/m_e)^{.5} = 60.0$



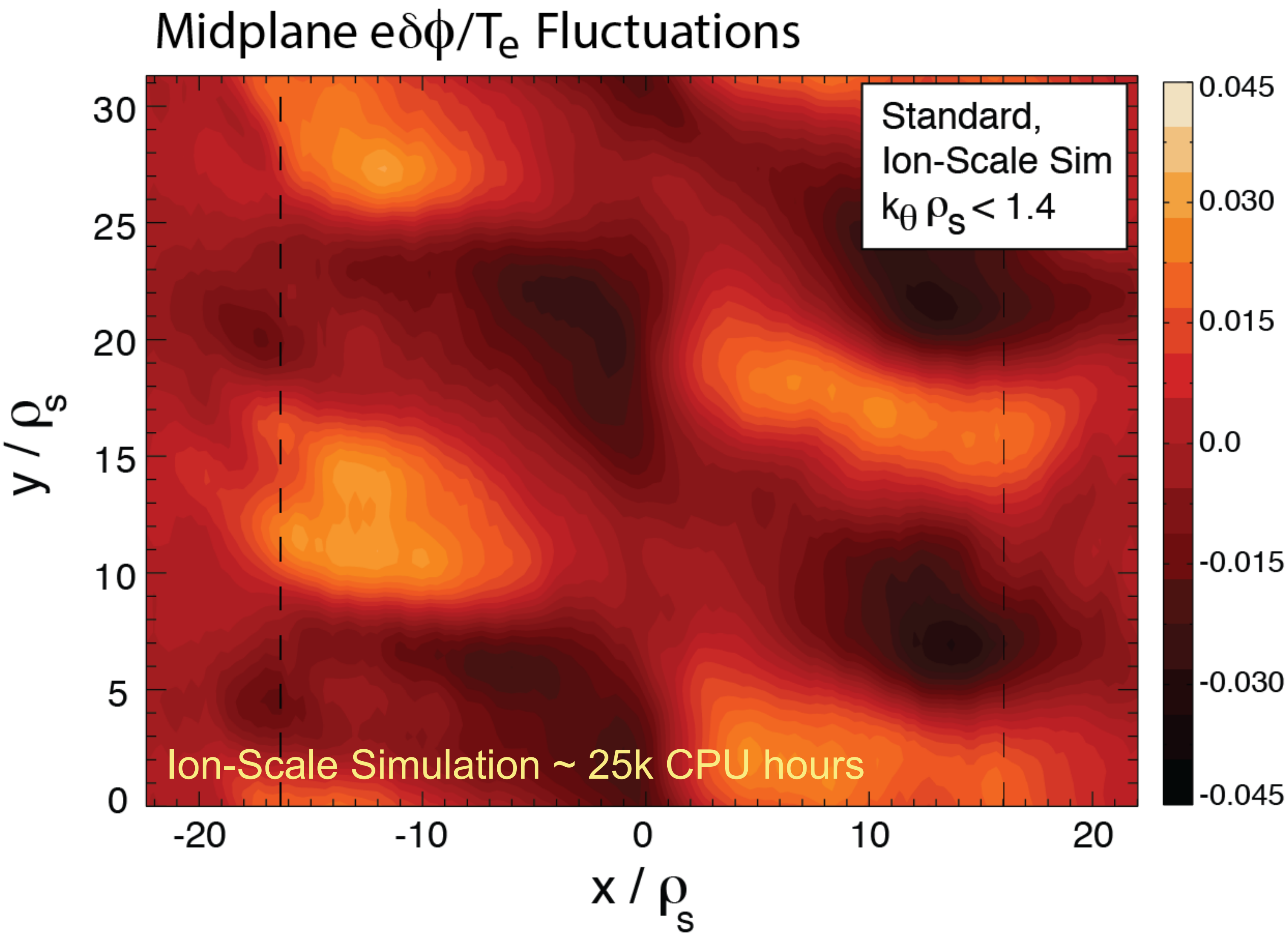
Using the GYRO Code on the NERSC Hopper and Edison Systems, a Set of 9 Multi-Scale Simulations were Performed

Simulations were performed using the GYRO code developed by Jeff Candy and Ron Waltz at General Atomics

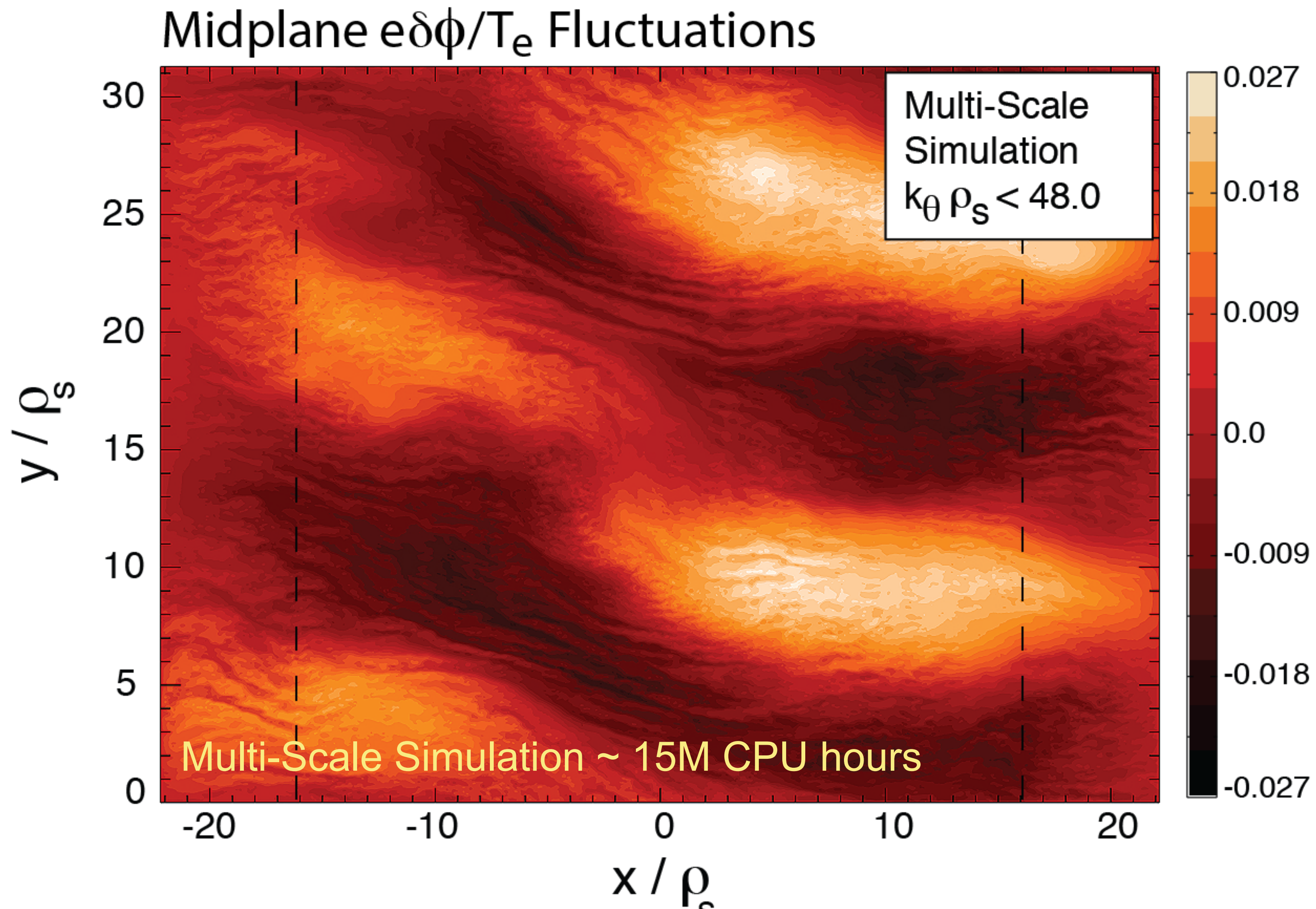
GYRO is an initial value, Eurlerian gyrokinetic-Maxwell solver
- Finite-difference in x, spectral in y
- 4^{th} order Explicit Runge-Kutta (implicit-explicit is possible option)
- MPI/OpenMP implementation
- Demonstrated linear scaling up to ~60k cores

Simulation details
- Simulation box size of (L_x x L_y) ~ 60 x 44ρ_i (perpendicular to field)
- 1800 radial grid points ; $\Delta x/\rho_i = 0.0333$
- 342 complex modes in y
- Captures long and short wavelengths simultaneously
- ITG/TEM/ETG turbulence up to $k_\theta\, \rho_i$ up to ~48.0
- Fluctuation outputs of ~500GB per simulation
- These nine multi-scale simulations were performed totaling ~ 150M CPU hours using 17-35k processors and up to ~37 days per simulation

Standard, Ion-Scale Simulation Display Large Eddies in the Potential Fluctuations



Using Multi-Scale Simulation, ETG-Streamers Were Shown to Coexist with Ion-Scale Eddies in the Core of Alcator C-Mod



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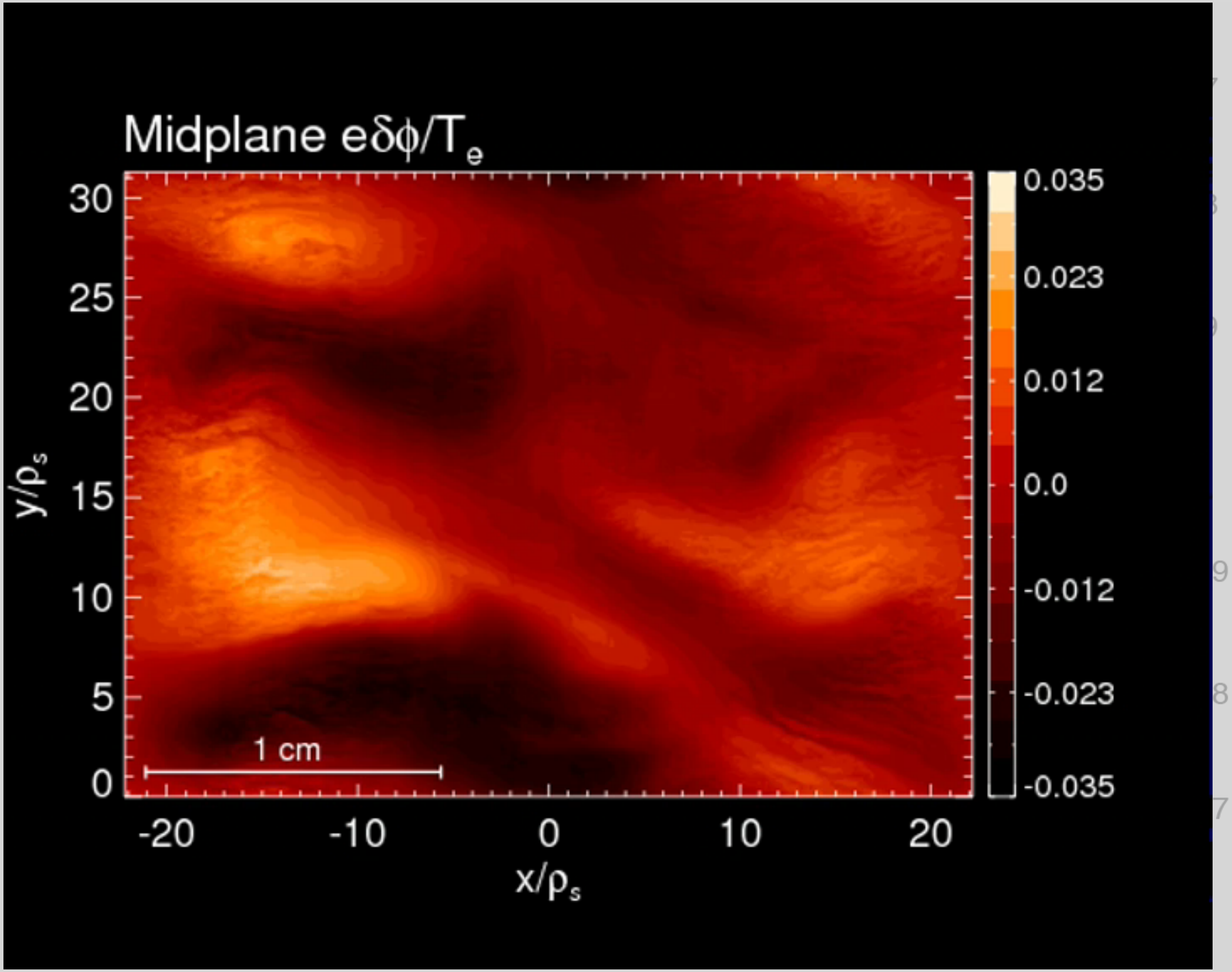
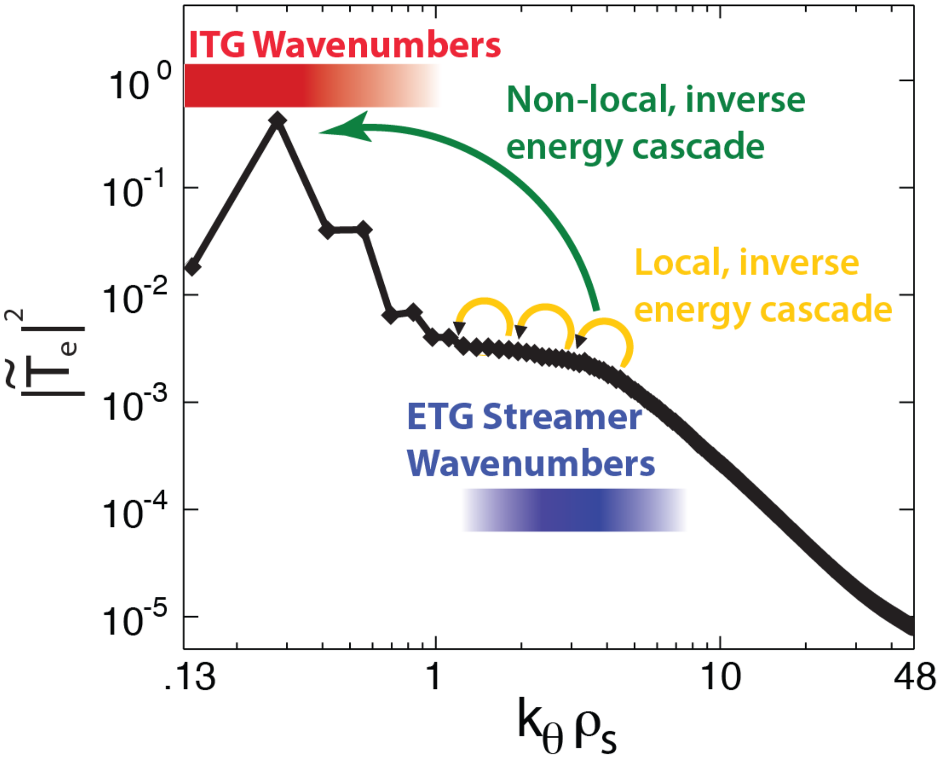


Multi-Scale Simulation Revealed New Interactions Between Ion-Scale and Electron-Scale Turbulence

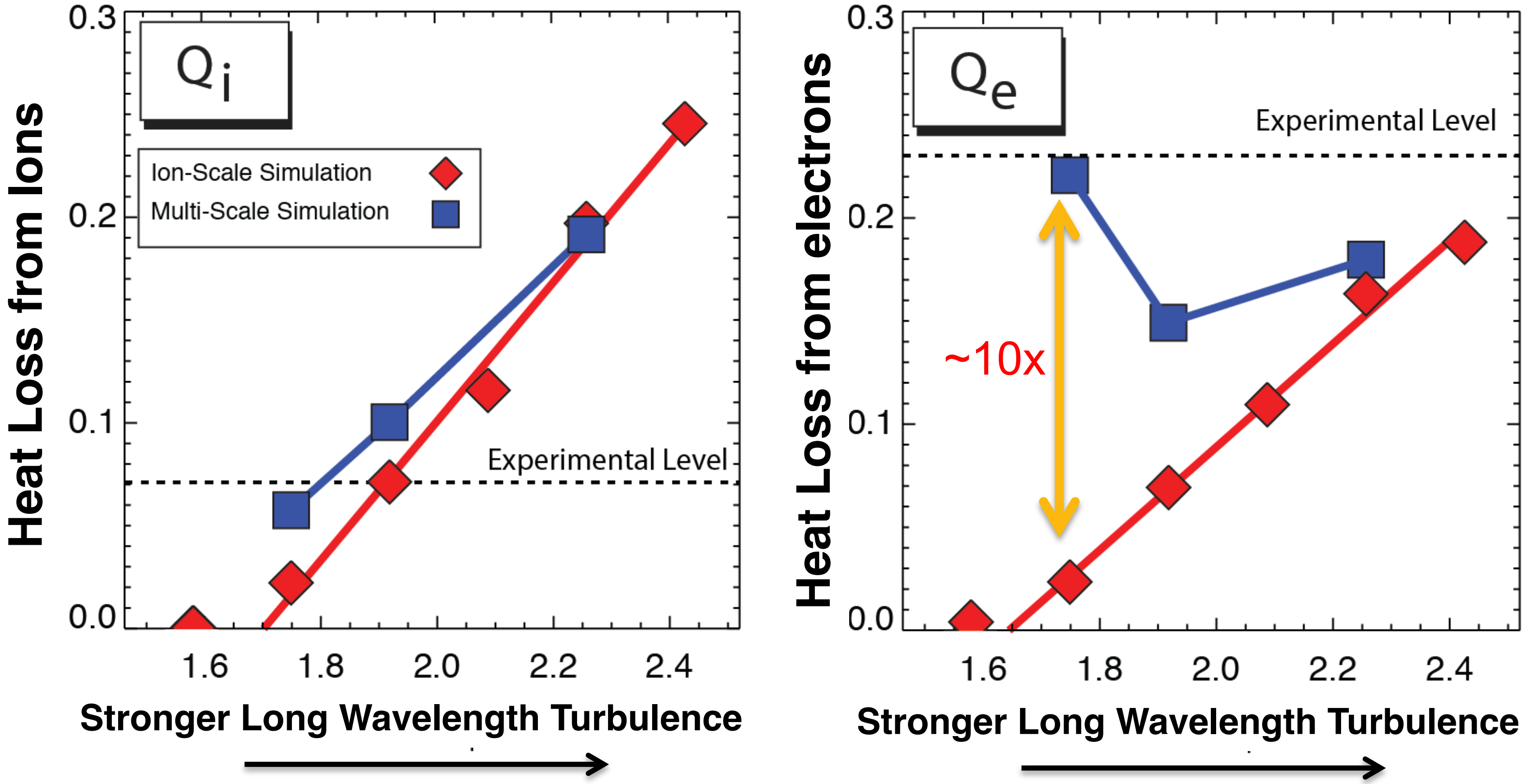


- Ion and electron-scale turbulence were found to strongly interact:
  - Modification of turbulence damping mechanisms (zonal flows)
  - Suppression of electron-scale turbulence by ion-scale turbulence
  - Cross-scale energy transfer
- Energy transfer analysis was performed on simulated fluctuation outputs
  - The presence of local and non-local (in k) inverse energy cascades was demonstrated

- The cartoon above demonstrates the transfer of energy from local and nonlocal inverse cascades.

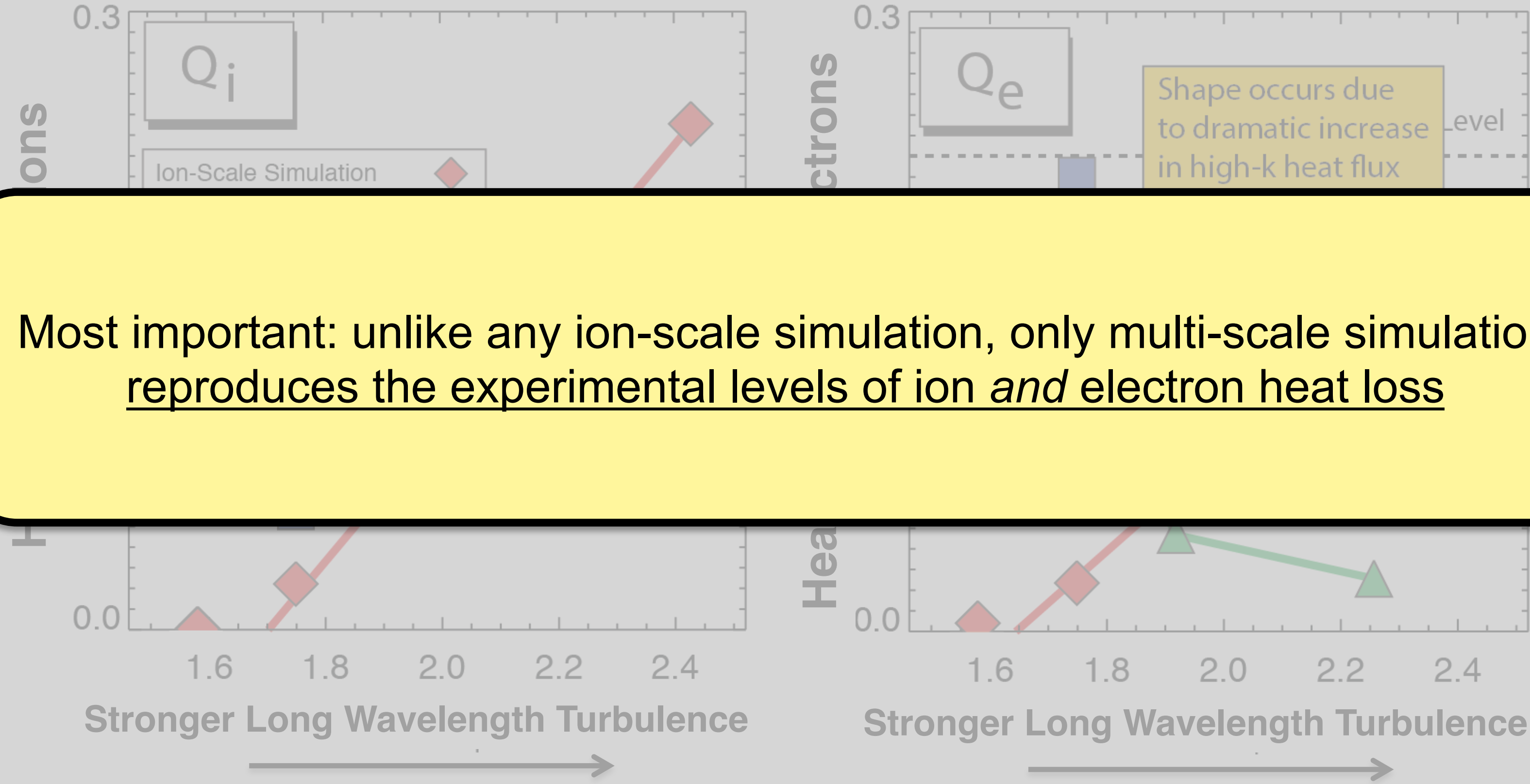
- These coupling mechanisms result in dramatic changes in the simulated heat losses

Multi-Scale Simulation Electron Heat Losses are 10x Ion-Scale Simulation and Dramatically Alters Response to Drives



- No variation of ion-scale simulation can simultaneously reproduce Q_e and Q_i
- Multi-scale simulation displays dramatically different response of the heat losses to change in the long wavelength turbulence drive
- Up to a factor of 10 increase the in the electron heat loss is observed

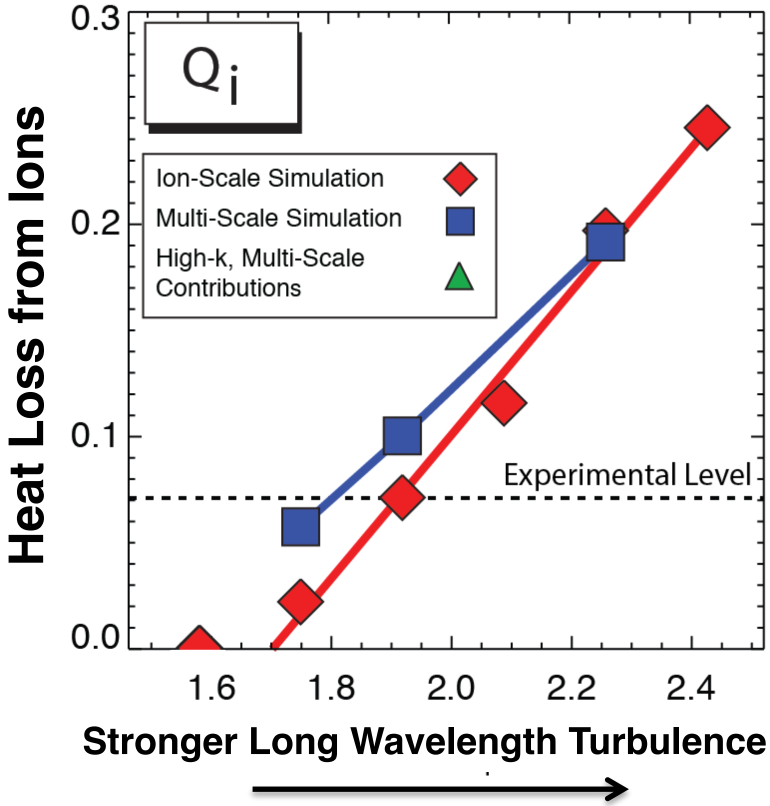
Multi-Scale Simulation Electron Heat Losses are 10x Ion-Scale Simulation and Dramatically Alters Response to Drives

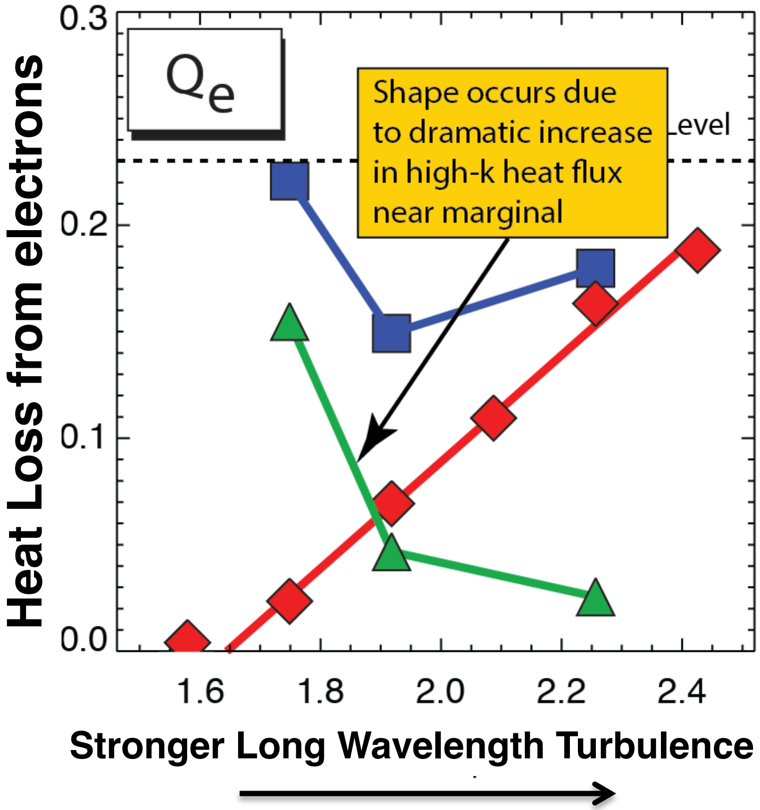


Most important: unlike any ion-scale simulation, only multi-scale simulation reproduces the experimental levels of ion *and* electron heat loss

- In conditions with weakly driven long wavelength turbulence, short wavelength turbulence drives large levels of heat loss
- The competition between the short and long wavelength turbulence results in the "U" shaped response of the electron heat loss

As the Drive for the Long Wavelength Turbulence is Reduced, Heat Losses From Short Wavelengths Increase





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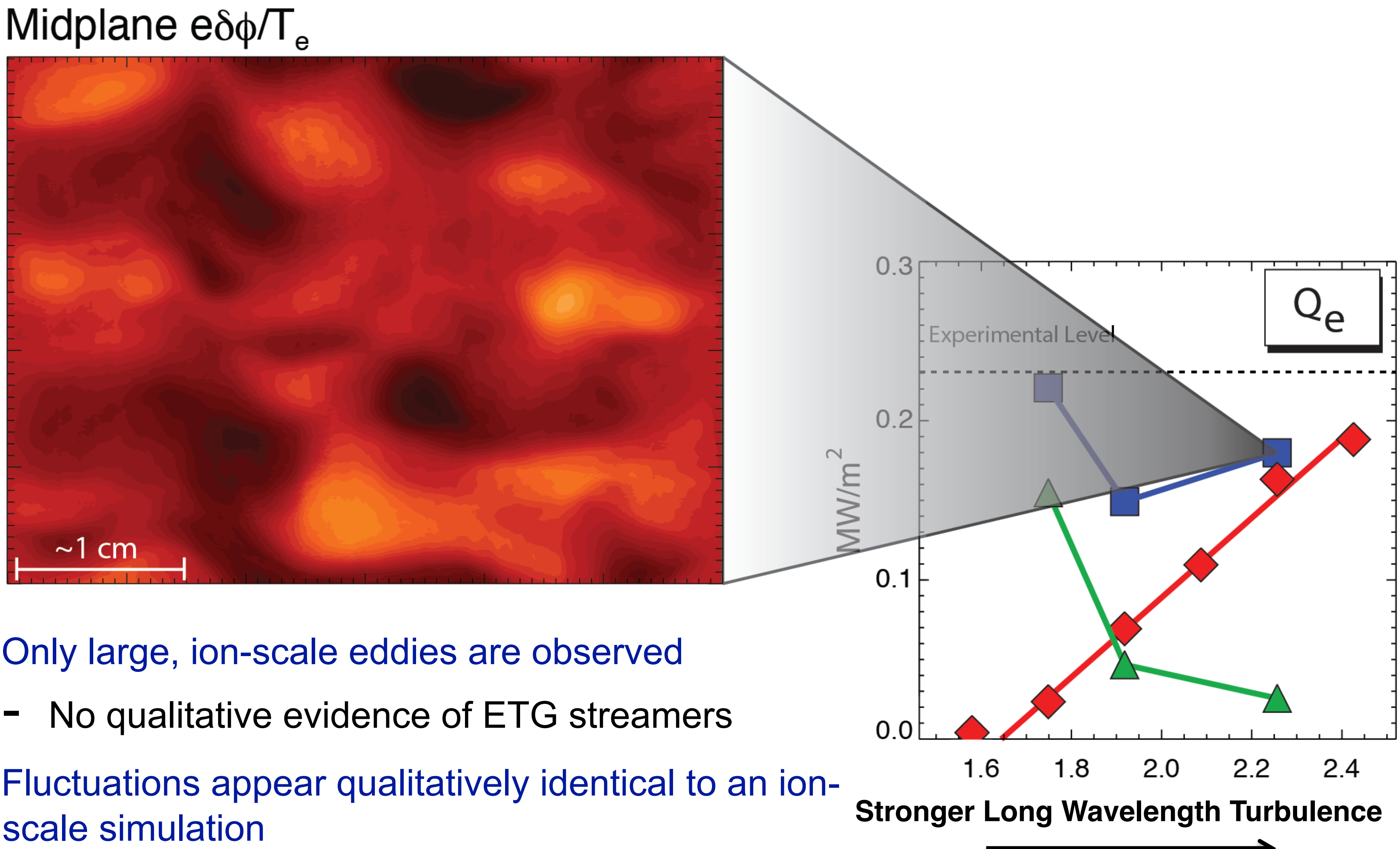
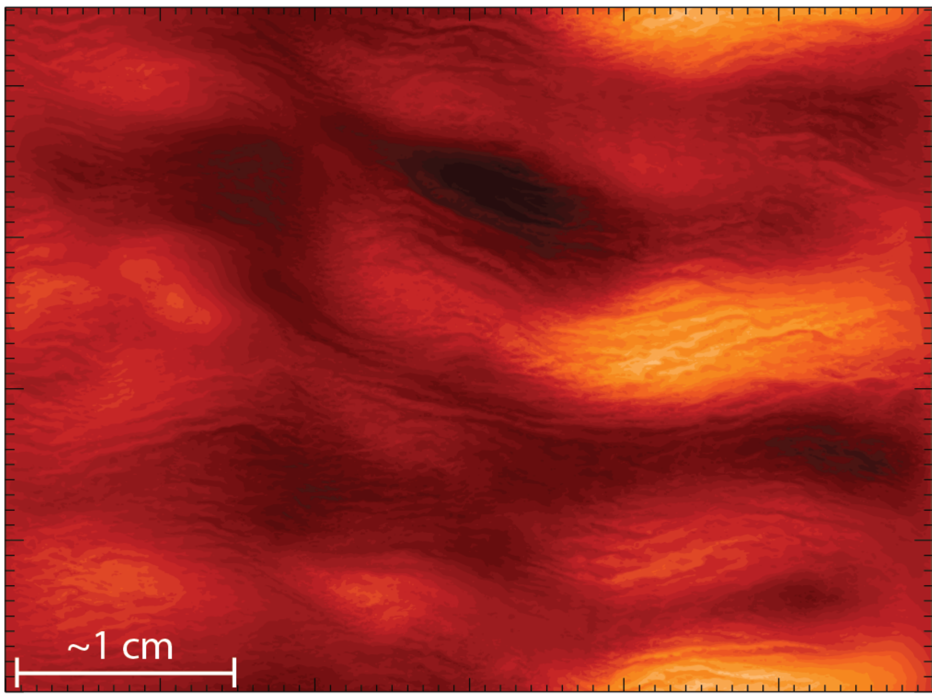
When Long Wavelength Turbulence is Strongly Driven Ion-Scale Eddies Dominate

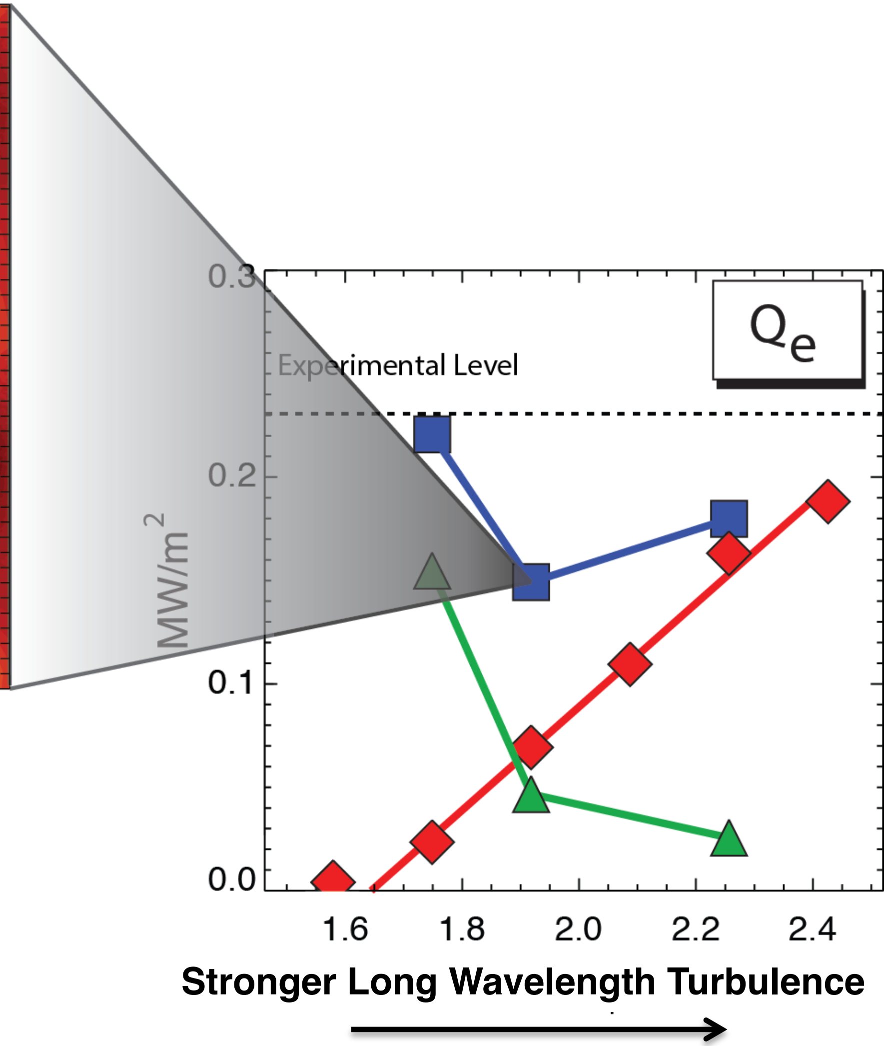


- Only large, ion-scale eddies are observed
  - No qualitative evidence of ETG streamers
- Fluctuations appear qualitatively identical to an ion-scale simulation

When the Long Wavelength Drive is Reduced, Ion-Scale Eddies Coexist and Interact with ETG Turbulence

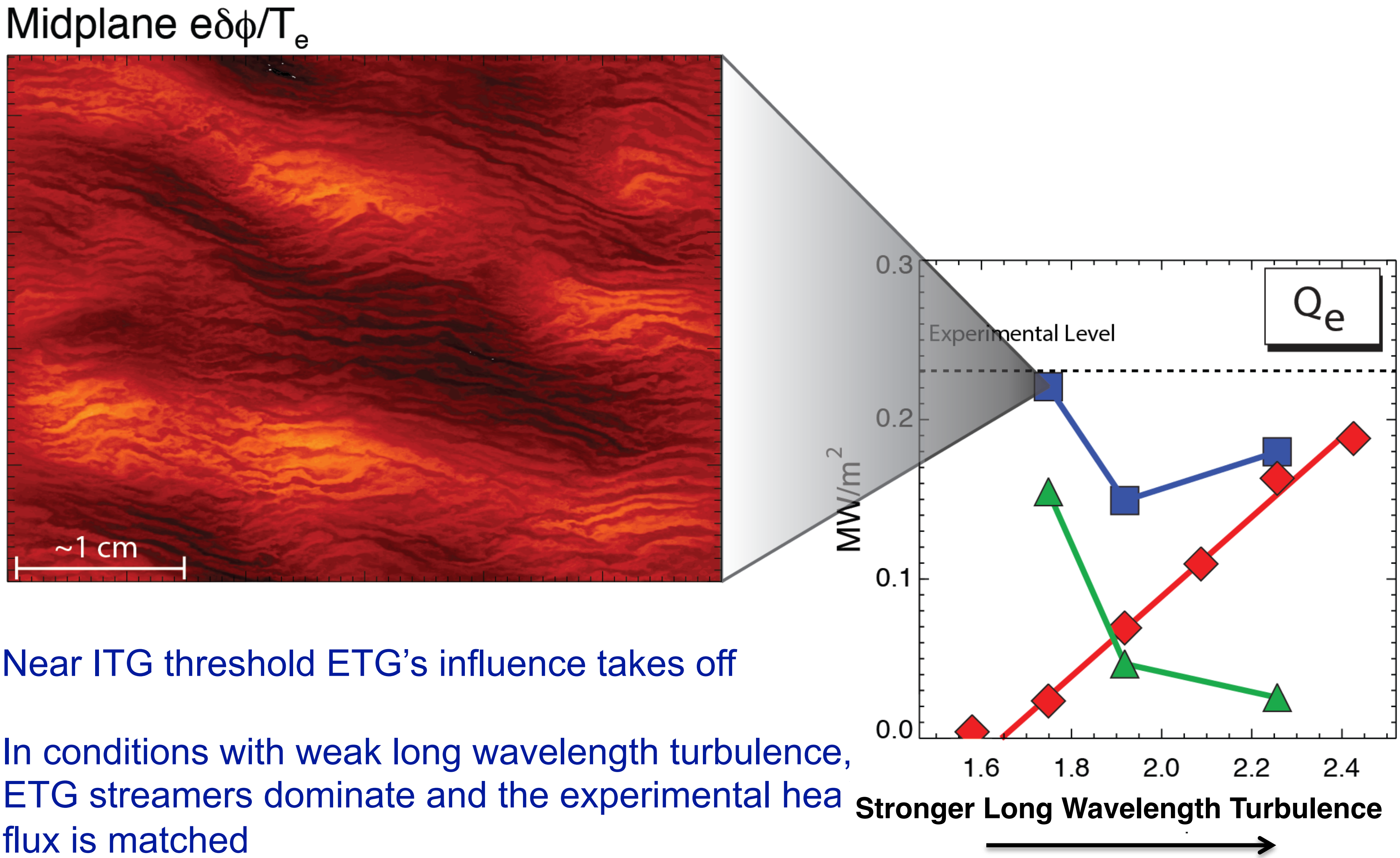
Midplane $e\delta\phi/T_e$





- Marginally driven ITG turbulence exists
- Large, ion-scale eddies coexist with ETG streamers

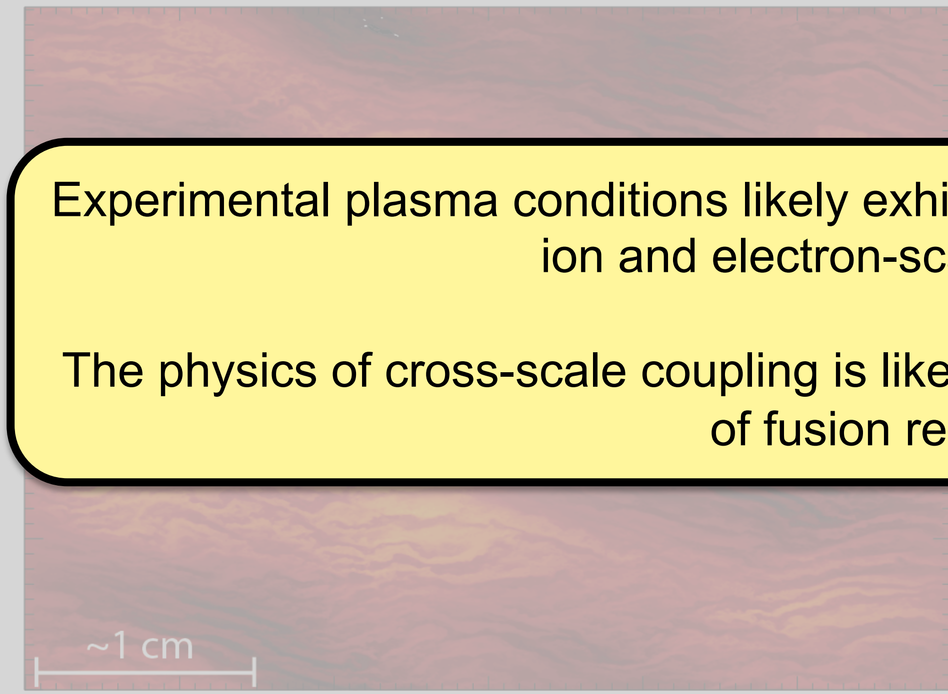
Near Threshold for Long Wavelength Turbulence, Streamers Dominate and the Experimental Heat Loss is Recovered



- Near ITG threshold ETG's influence takes off
- In conditions with weak long wavelength turbulence, ETG streamers dominate and the experimental hea flux is matched

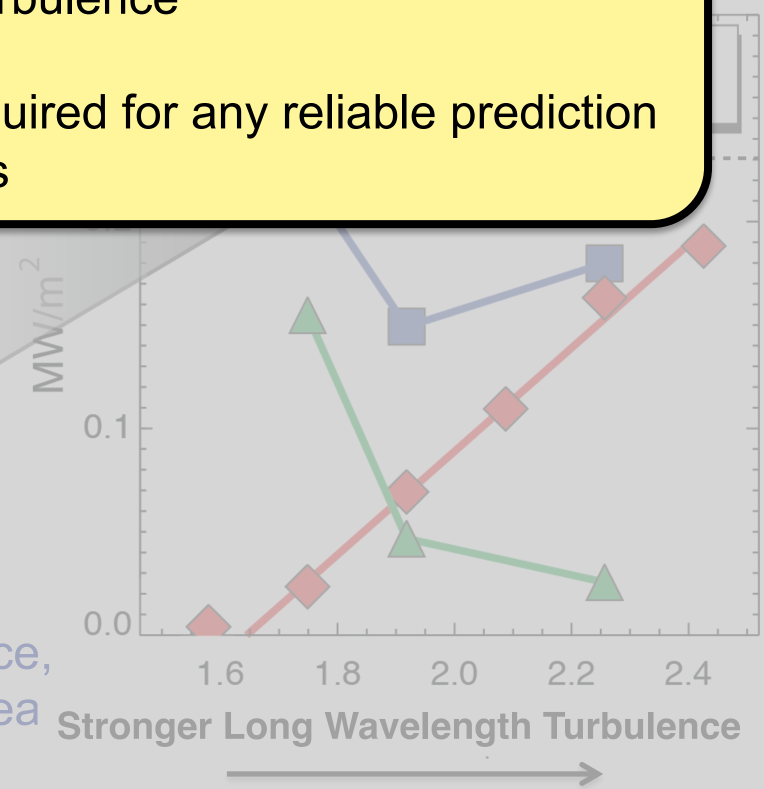
Near Threshold for Long Wavelength Turbulence, Streamers Dominate and the Experimental Heat Loss is Recovered

Midplane $e\delta\phi/T_e$



Experimental plasma conditions likely exhibit coexisting and strongly interacting ion and electron-scale turbulence

The physics of cross-scale coupling is likely required for any reliable prediction of fusion reactors



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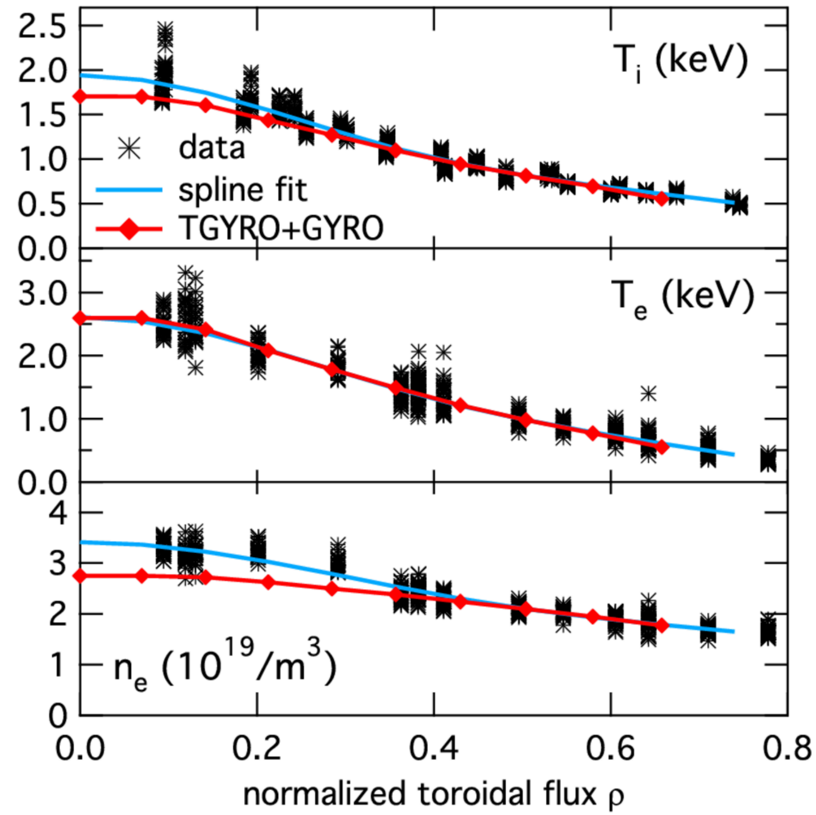
Advances in Algorithms and Upcoming Platforms Will Make Multi-Scale Simulation Routine

- Due to their requirements, these simulations are not yet routinely used to analyze/predict experiments
- Multi-scale simulations / new physics needed to guide predictions for fusion reactors
- A simple scaling from these results indicates ~1 Billion CPU hours could be required for a profile prediction (like in the figure, which was done with ion-scale only)



From J. Candy et al. PoP 2009

- Exascale computers and beyond may make such calculations not only possible, but routine, allowing for the reliable prediction of fusion performance and advancing the development of fusion energy

Multi-Scale Simulation Revealed the Origin of "Missing" Electron Heat Loss in Fusion Reactors

- Using dedicated experiments and NERSC computing facilities we were able to perform the first set of realistic, multi-scale gyrokinetic simulations

- Unlike ion-scale simulation, only multi-scale simulation was able to reproduce experiment
  - Comparisons were made Q_e, Q_i, and χ_{inc} (not shown) and were able to match all measurements within uncertainties

- Electron-scale turbulence coexists with ion-scale turbulence in fusion plasmas

- Strong interactions between ion and electron-scale turbulence were observed
  - Turbulence was enhanced at all scales, and electron heat losses up to 10x larger than standard ion-scale simulation were found
  - New coupling mechanisms, including cross-scale energy transfer were explored

- *Advances in algorithms and computing will enable routine multi-scale simulation of plasma turbulence – providing a clear path to a predictive model to inform the design and operation of fusion devices*

Fundamental Challenges to Fusion Simulation

- Extreme range of time scales – wall equilibration/electron cyclotron $O(10^{14})$
- Extreme range of spatial scales – machine radius/electron gyroradius $O(10^{4})$
- Extreme anisotropy – mean free path parallel to magnetic field / perpendicular $O(10^{10})$
- Non-linearity – turbulence and MHD
- Sensitivity to geometric details
- High dimensionality – basic object of plasma is 7D $\rightarrow f(\mathbf{x}, \mathbf{v}, t)$, described by non-linear Boltzmann equation

$$\frac{\partial f}{\partial t} + \underbrace{\mathrm{v} \cdot \nabla f}_{\text{convection}} + \underbrace{\tfrac{q}{m}\left[E + \mathrm{v} \times B\right] \cdot \nabla_{\mathrm{v}} f}_{\text{convection in velocity space}} = \underbrace{C(f)}_{\text{Collisional relaxation toward Maxwellian in velocity space}}$$

Details of the Numerical Implementation in GYRO

- in radius its "arbitrary" order finite-difference. Typically its 4th or 6th order, with a 4th or 6th derivative upwind dissipation. That means 3rd or 5th order upwind in radius.

- Fully spectral in toroidal angle (y).

- it has a semi-implicit option in time, but the multiscale runs are 4th-order explicit RK.

- Gyroaverages are "truncated pseudospectal”

- the poloidal discretization is complicated. The kinetic equation is 3rd order upwind, whereas the field solve is quadratic or cubic finite element.

- velocity space (2 dimensions) is Gaussian quadrature so its spectrally accurate. It works to our disadvantage because low-accuracy, inefficient, brute-force, velocity space is what provides a huge amount of scalable work for PIC codes.

- Velocity space and the spectral dimension (y) are distributed by MPI - Use of OpenMP allows for distribution of radial grid