Particle Energization and the Tearing-Driven Turbulent Cascade

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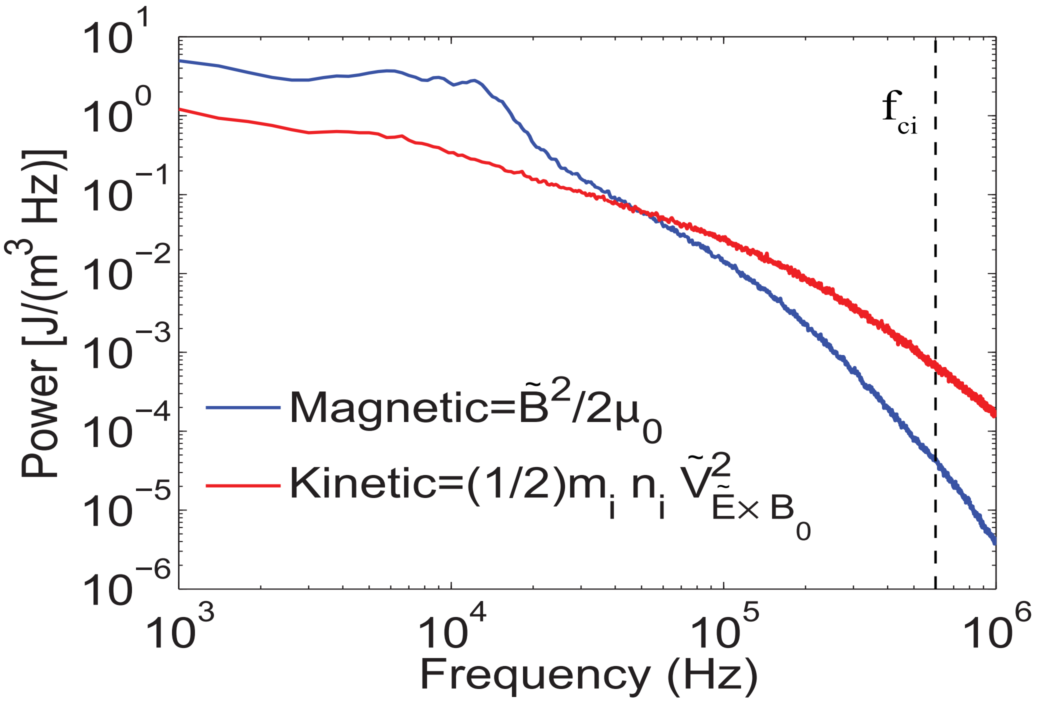
The tearing-driven turbulent cascade and dissipation



- **Connected challenges**:
  - Multi-scale modeling framework that spans global instability to turbulent dissipation
  - Diagnostics and methods that isolate and distinguish particle energization processes

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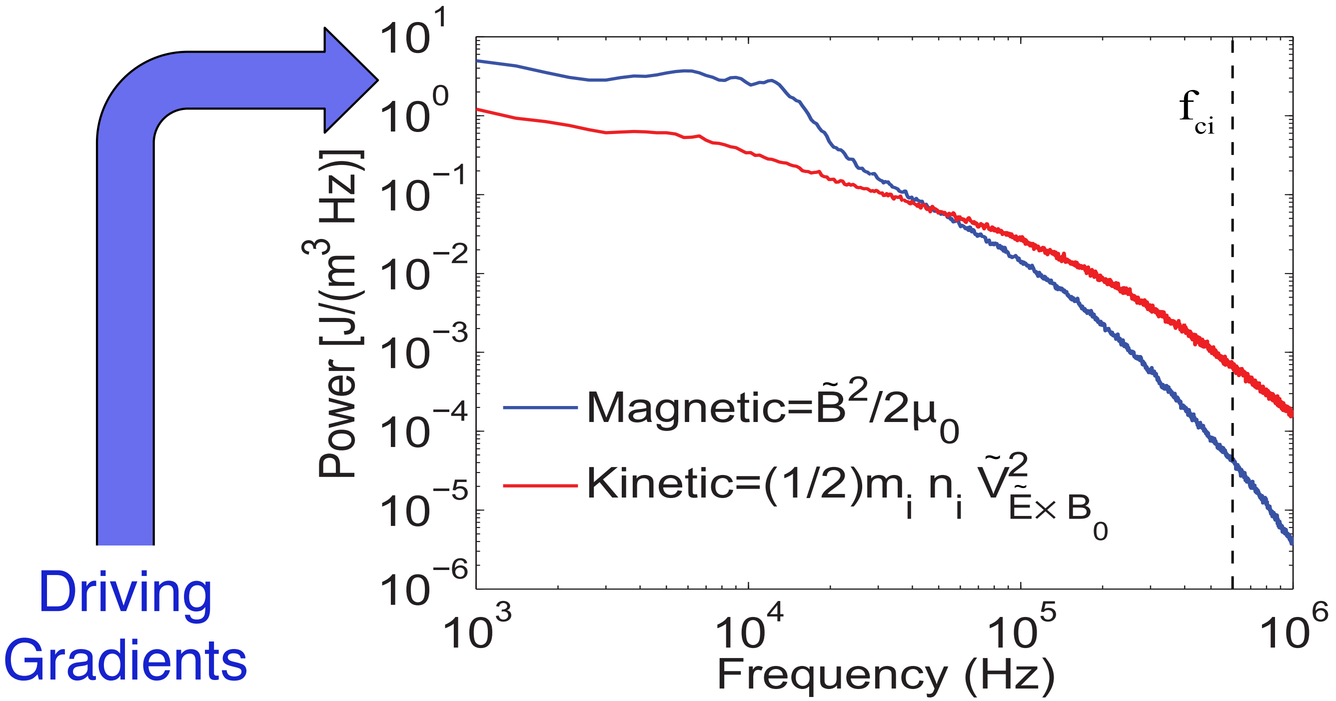

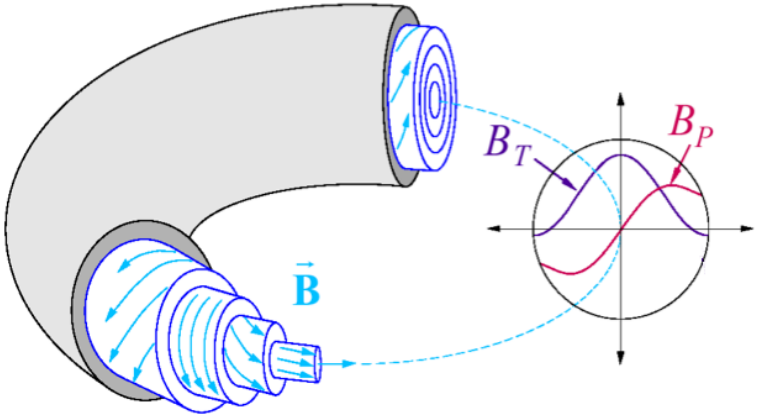

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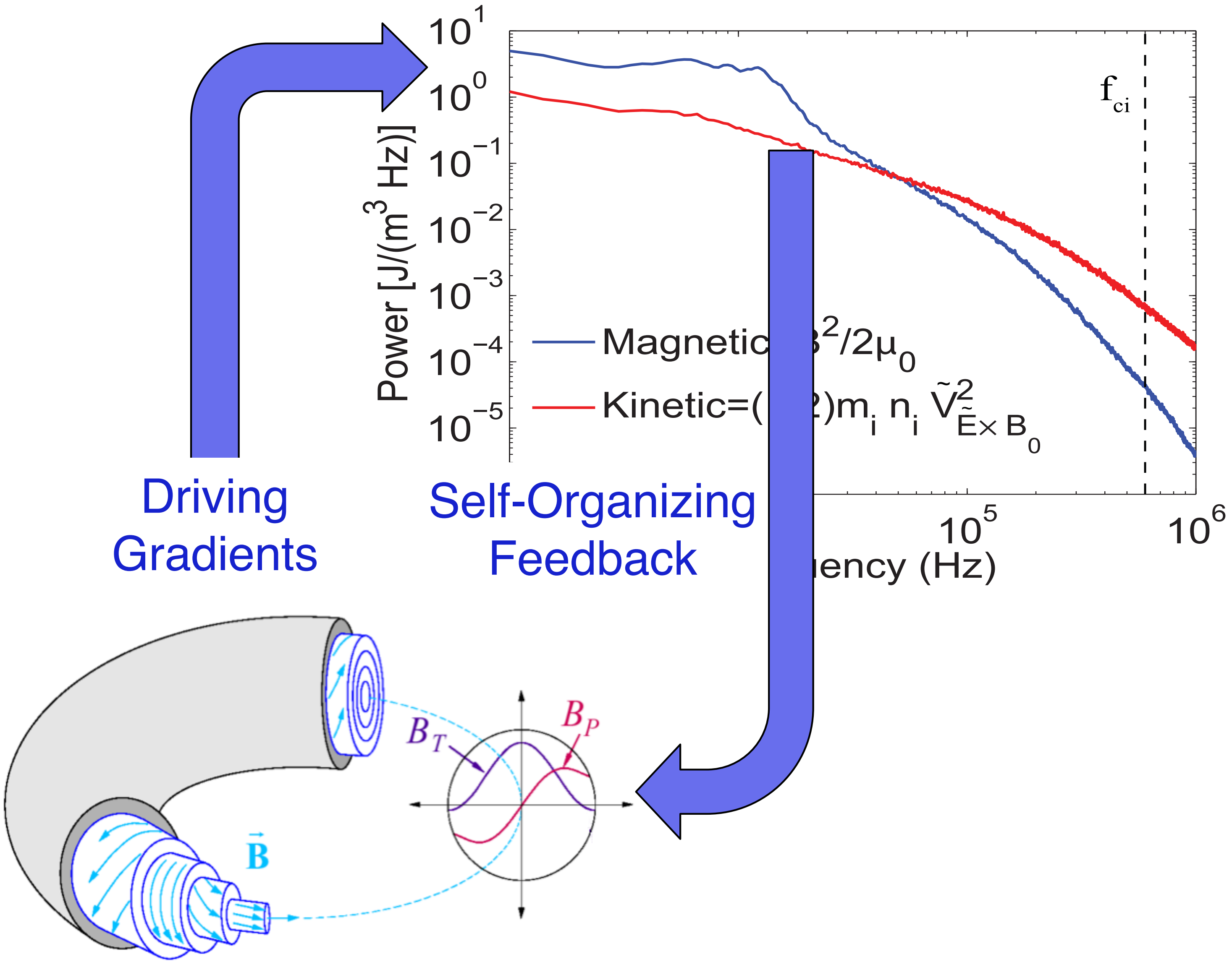
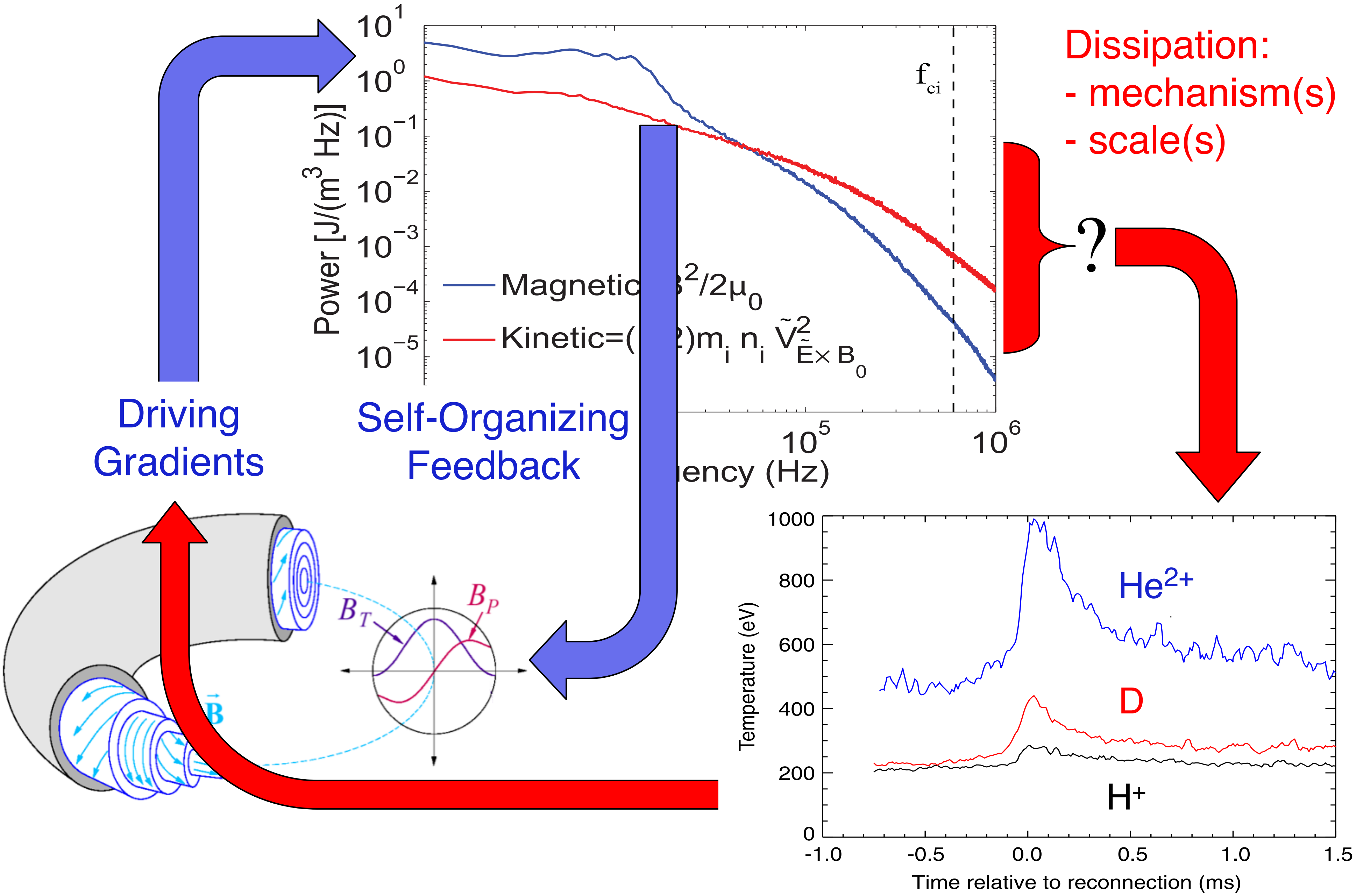


Driving Gradients

Self-Organizing Feedback

The tearing-driven turbulent cascade and dissipation



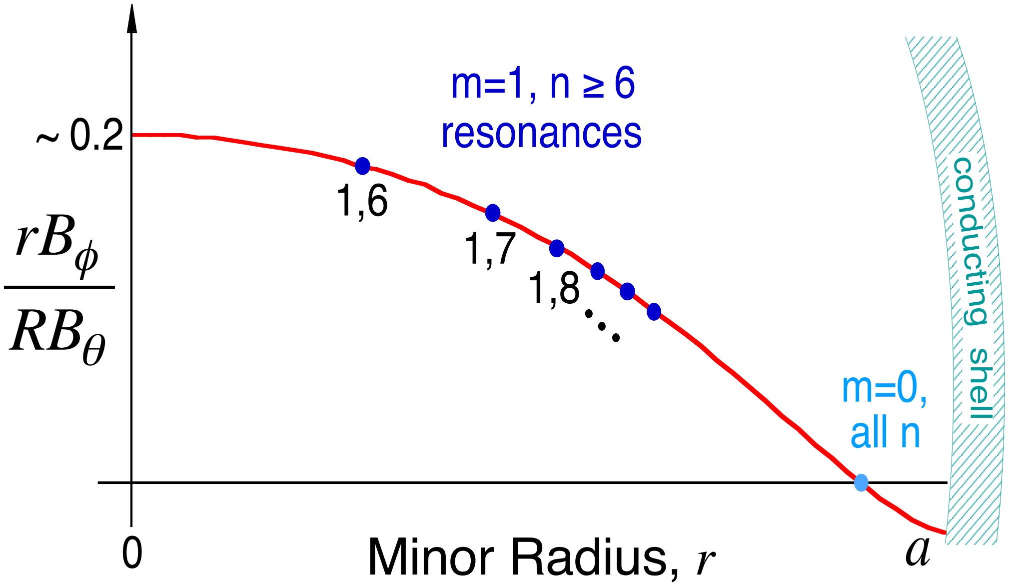
Dissipation:
- mechanism(s)
- scale(s)

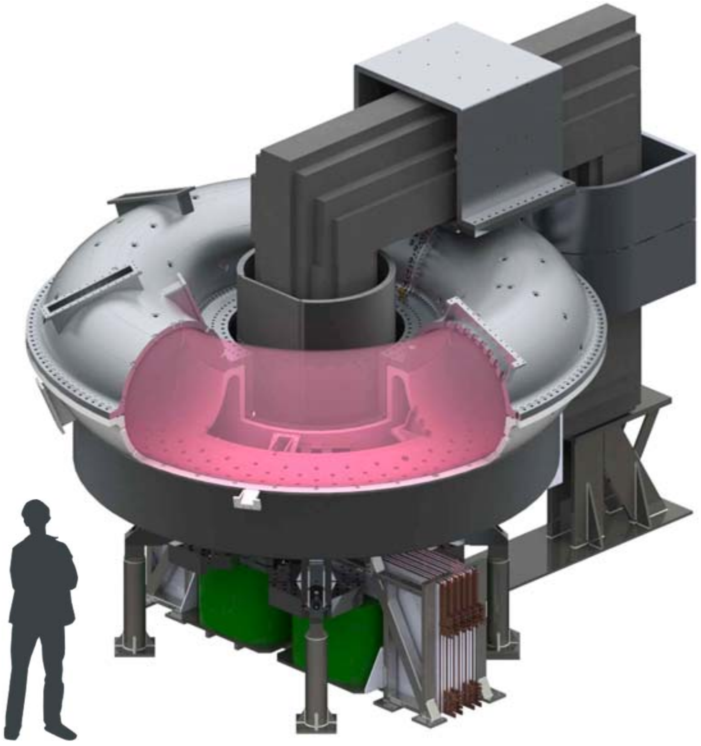
Driving Gradients

Self-Organizing Feedback

MST reversed field pinch plasmas

- Magnetic induction is used to drive a large current in the plasma
  - Plasma current, I_p = 50-600 kA ; $B < 0.5$ T
  - Inductive ohmic heating: 5-10 MW (input to electrons)
  - $T_\mathrm{i} \sim T_\mathrm{e} < 2$ keV, despite weak i-e collisional coupling ($n \sim 10^{19}$ m^{-3})
  - Minor radius, a = 50 cm ; ion gyroradius, $\rho_\mathrm{i} \approx 1$ cm ; $c/\omega_\mathrm{pi} \approx 10$ cm
  - $\beta < 25\%$; Lundquist number $S = 5 \times 10^{4\text{-}6}$





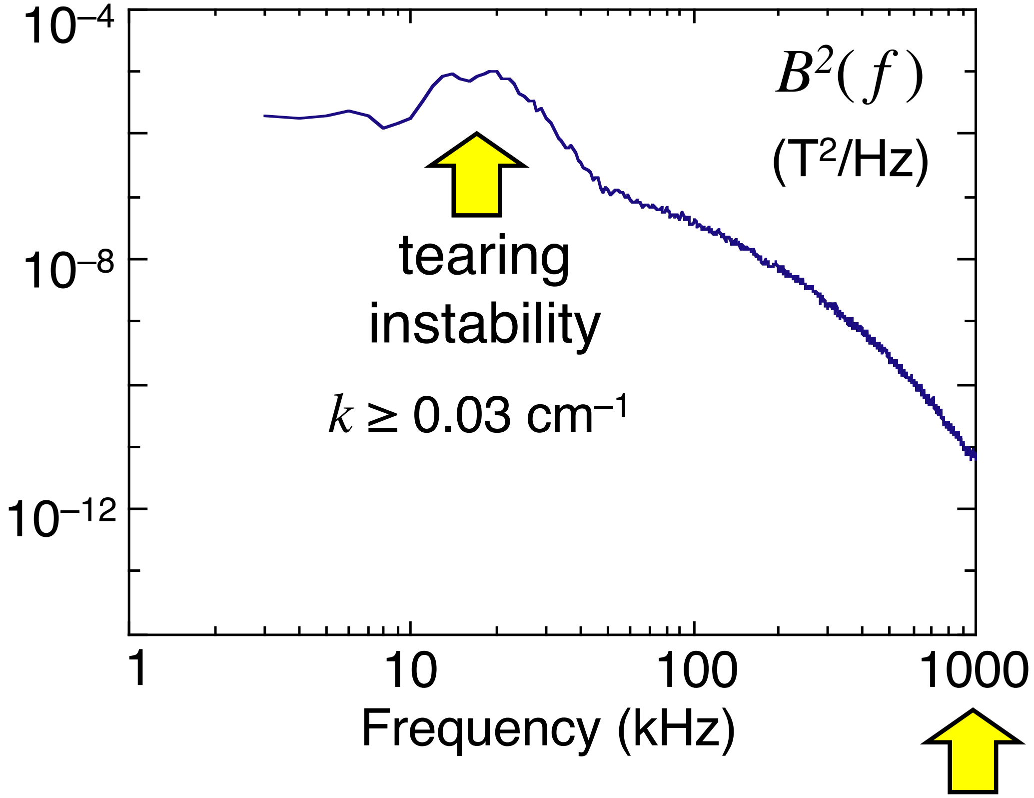
Tearing instability drives a broadband turbulent cascade

Toroidicity allows distinct $k_{||} = 0$ resonant modes at many radii in the plasma:

$$0 = \mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\theta + \frac{n}{R} B_\phi$$

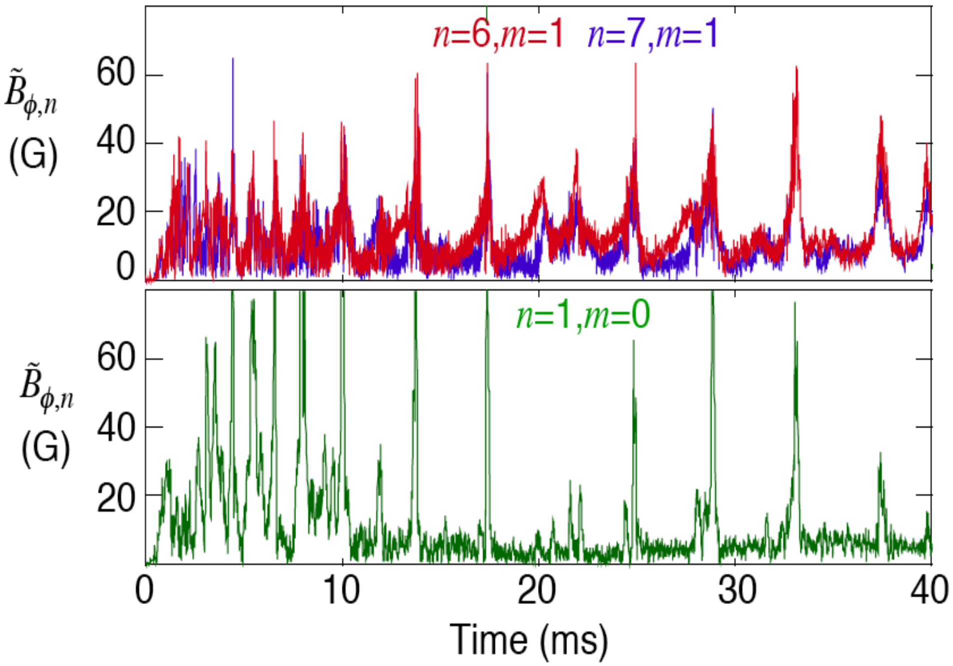
m = poloidal mode number

n = toroidal mode number



$\omega_{ci}/2\pi$

$\rho_i \sim 1$ cm



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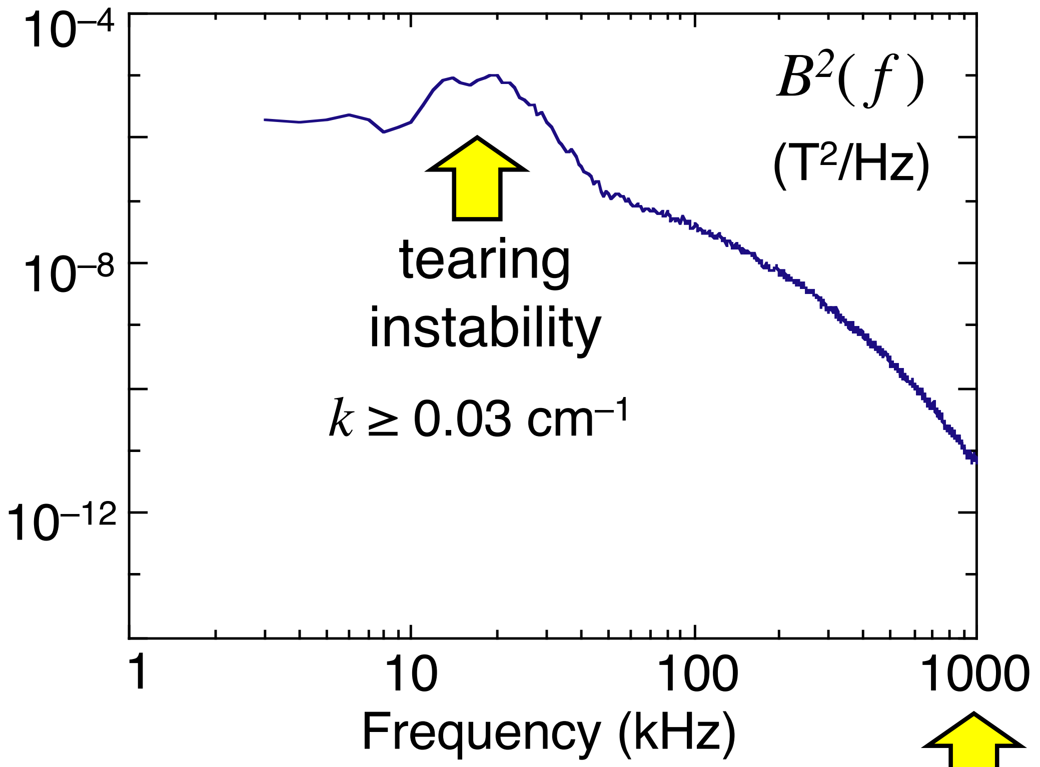

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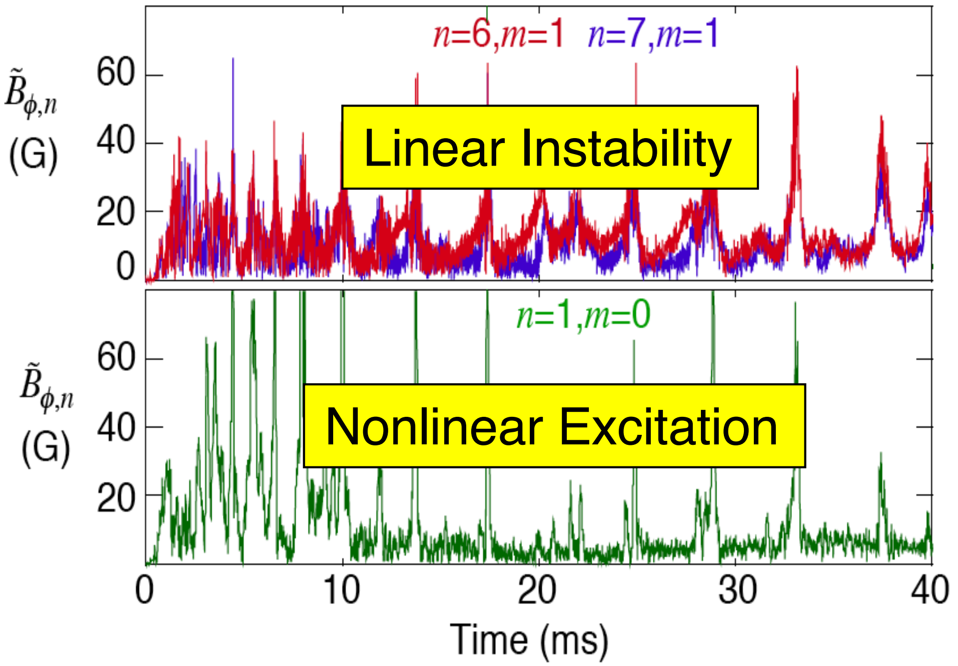
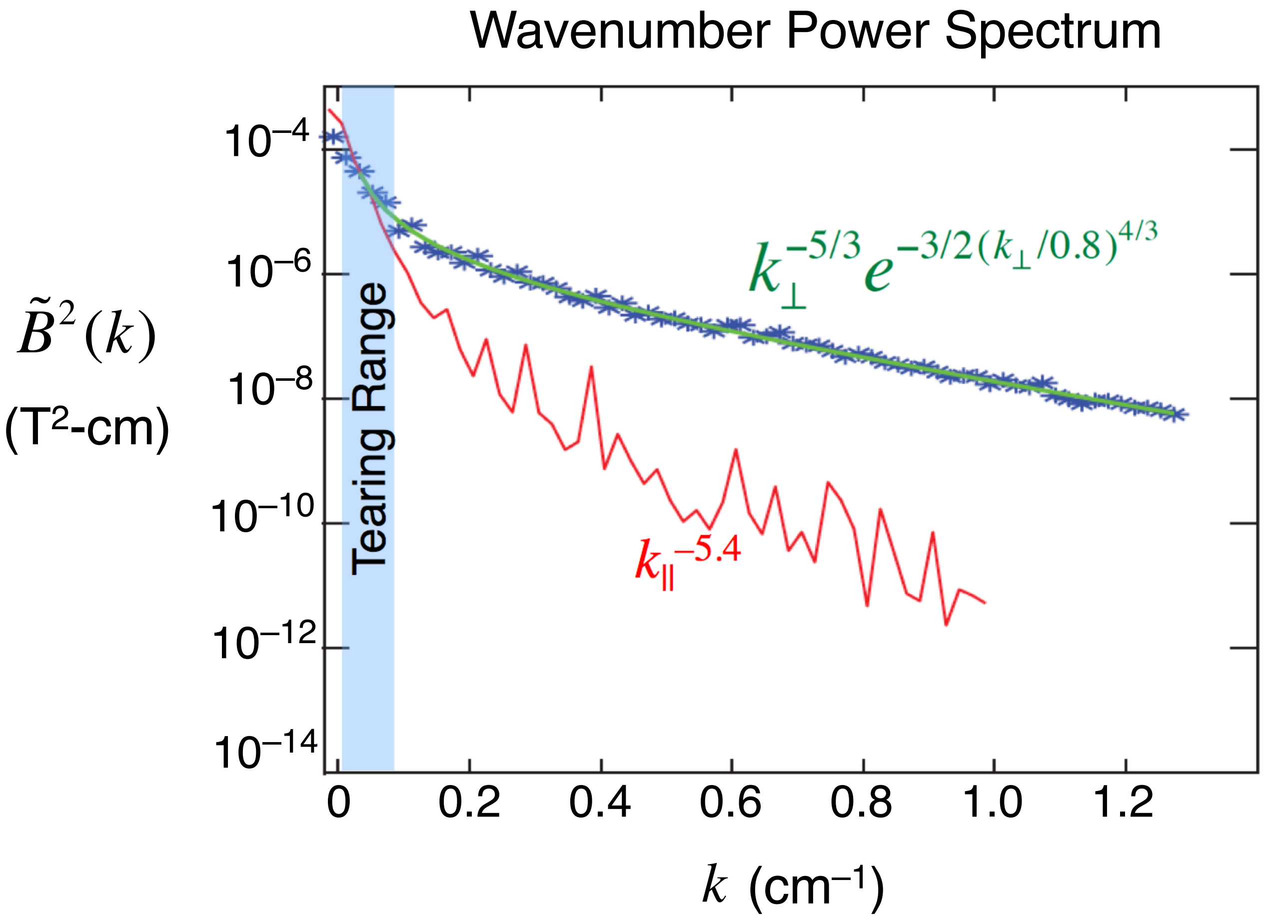


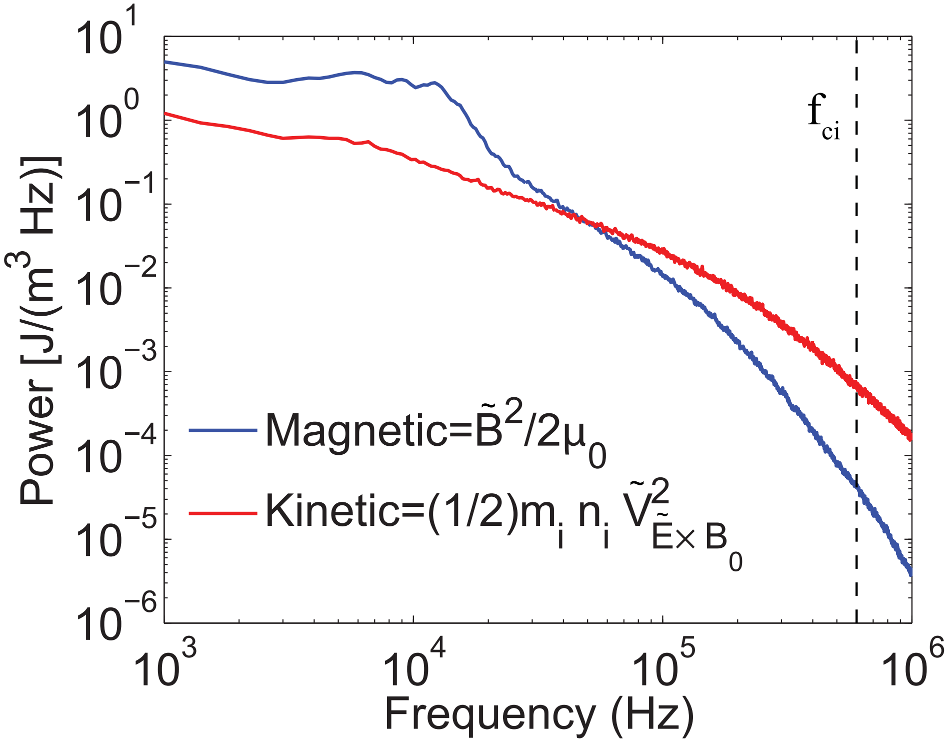
The cascade is anisotropic and hints at a non-classical dissipation mechanism

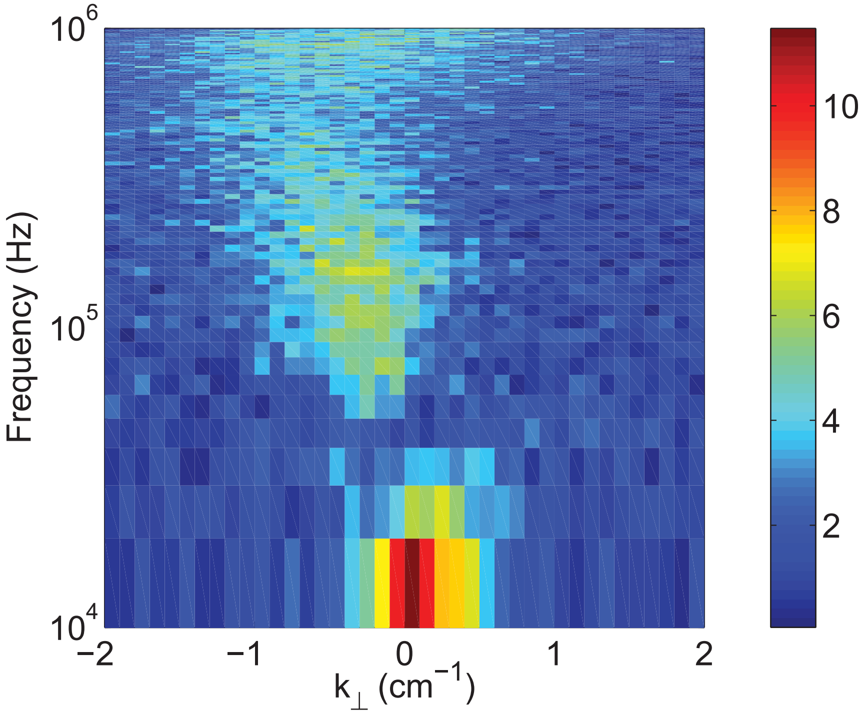
- The $k_\perp$ spectrum fits a dissipative cascade model (Y. Ren, PRL 2011; P. Terry, PoP 2009)
- Onset of exponential decay (dissipation) occurs at a smaller $k_\perp$ than expected for classical dissipation



New evidence for the onset of drift waves at intermediate scales

- Turbulence becomes kinetic energy dominant at $k_\perp \rho_s \approx 0.2$
- Signatures consistent with drift waves (Thuecks et al, PoP 2017)

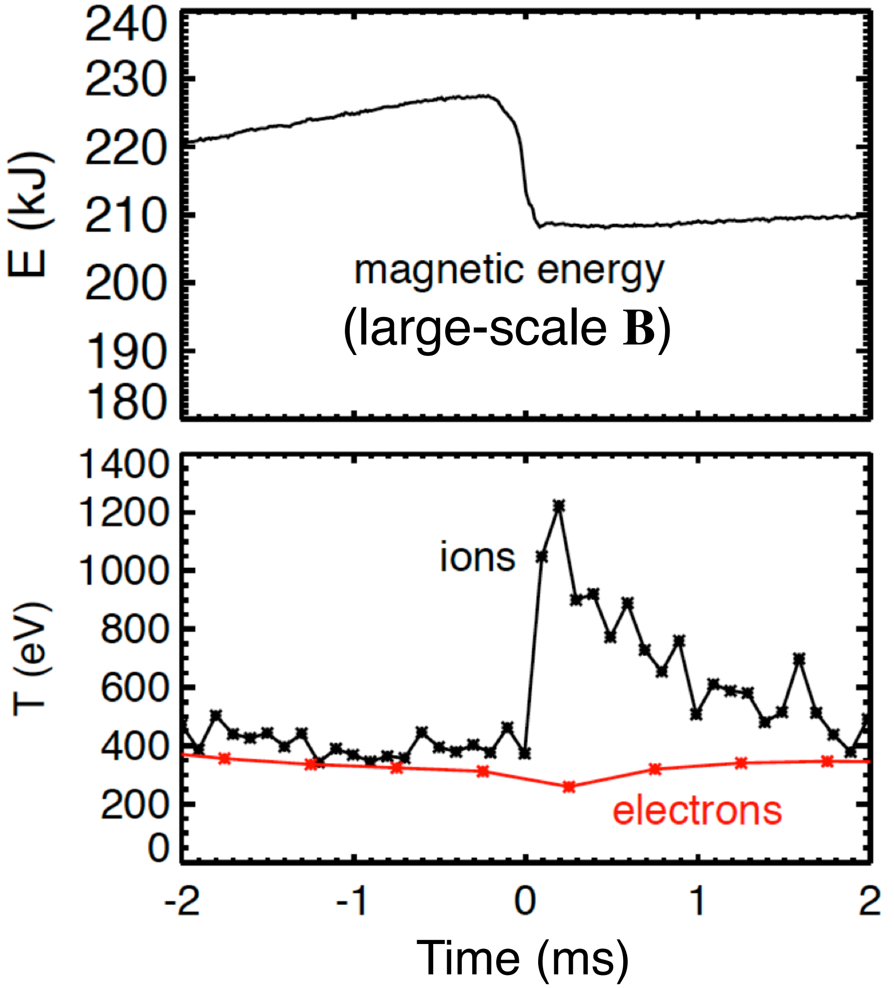




Non-collisional Ion Energization

Powerful ion energization is associated with impulsive magnetic reconnection events

- Instantaneous heating rate up to 10 MeV/s (50 MW)



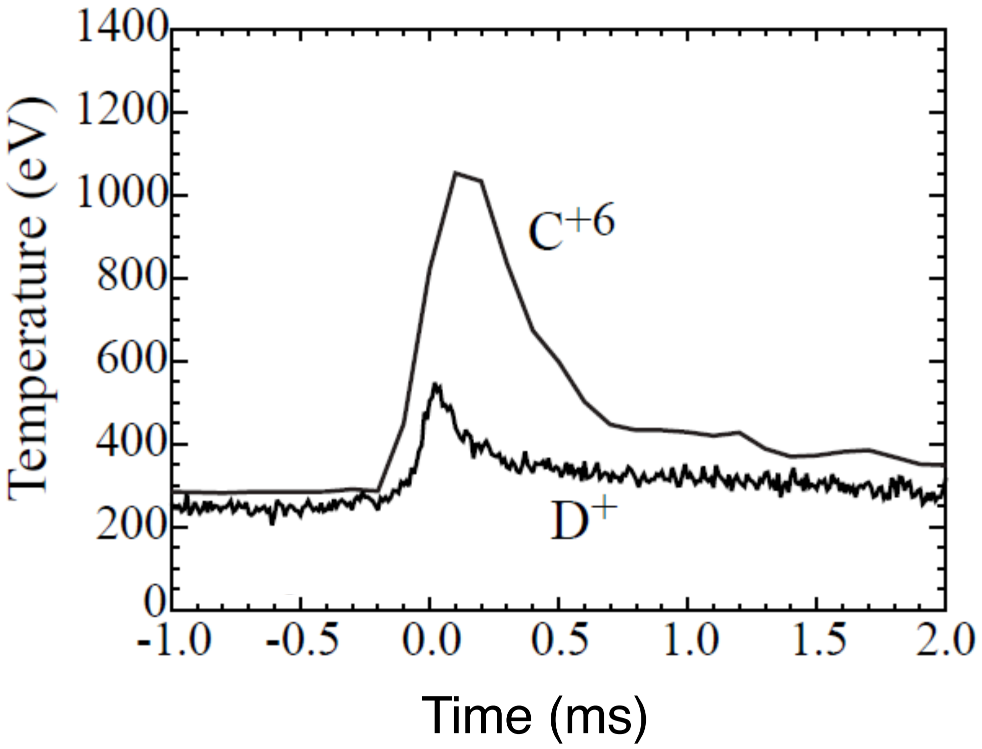
Relative to Reconnection Event

$T_i > T_e$

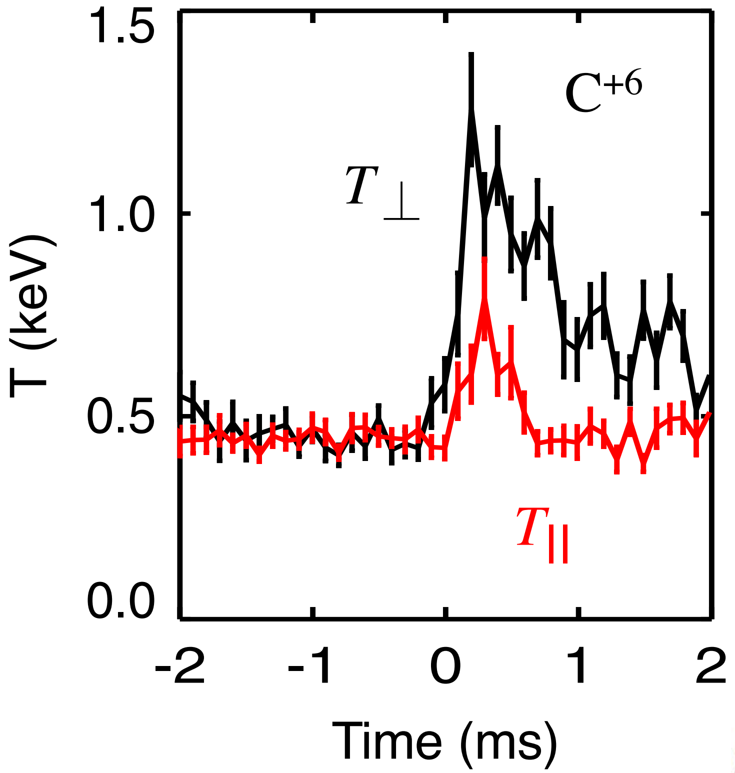
Heating is anisotropic and species dependent

- Ion distribution diagnostics on MST:
  - Rutherford scattering for majority ion temperature
  - Charge-exchange recombination spectroscopy (CHERS) for minority ions
  - Neutral particle energy analyzers

Minority Ions Hotter than Majority Ions

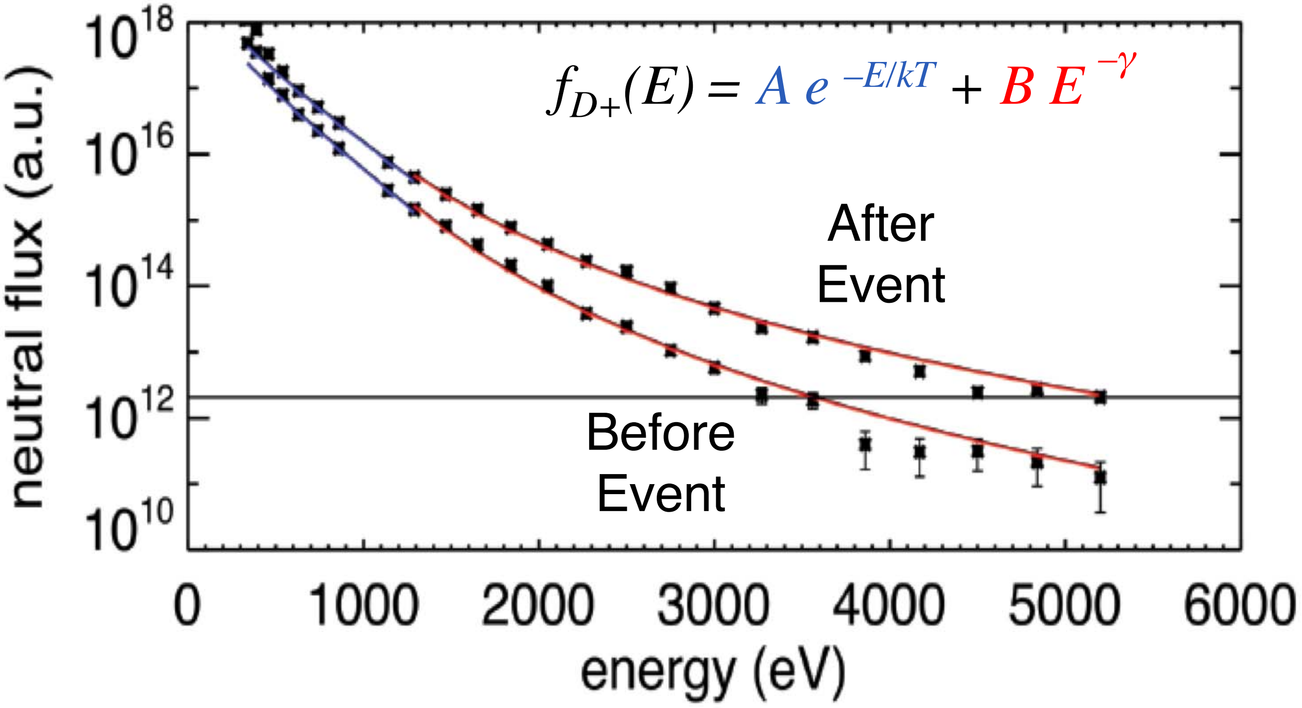


Heating is Anisotropic



An energetic ion tail is generated and reinforced at each reconnection event

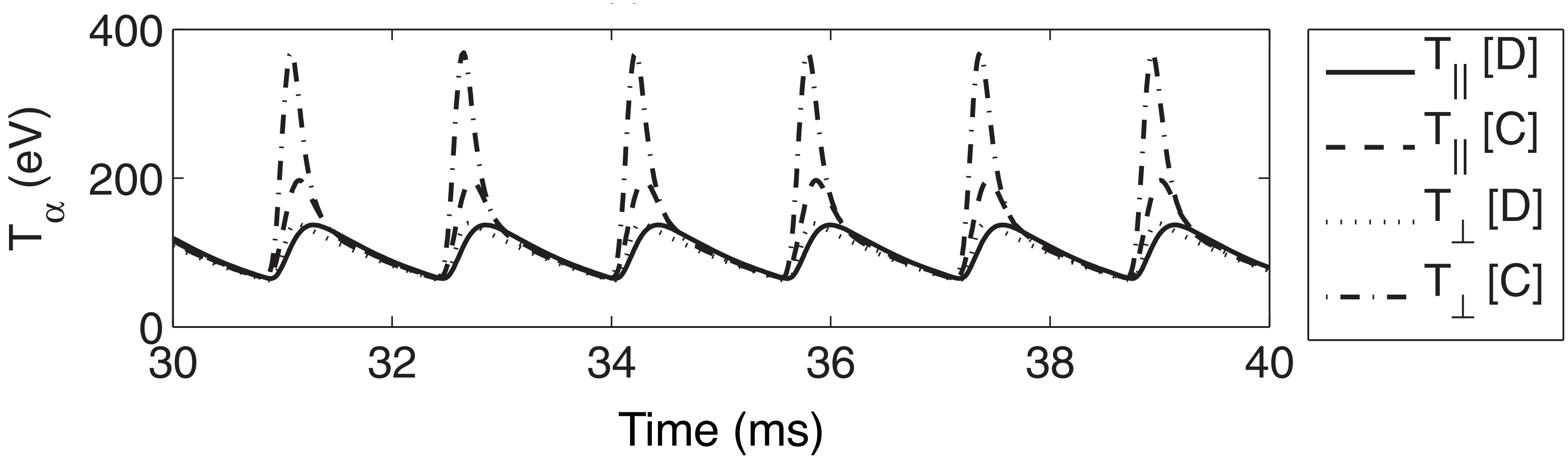
- Distribution is well-fit by a Maxwellian plus a power-law tail



Proposed Ion Heating Mechanisms

The models proposed for ion heating in the RFP are similar to those for the solar corona and wind

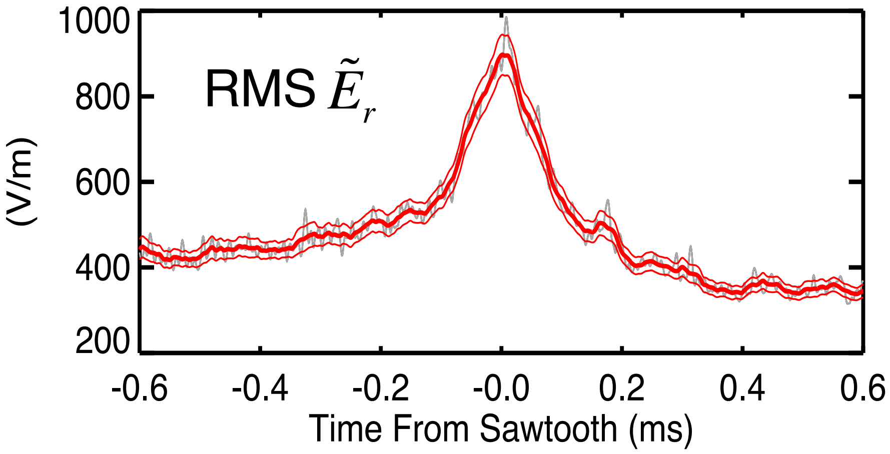
- **Cyclotron-resonant heating**:
  - Feeds off the turbulent cascade to gyro-scale
  - Preferential perpendicular heating, but with collisional relaxation
  - Preferential minority ion heating, since $\tilde{B}^2(\omega_{ci})$ is larger where ω_{ci} is smaller
  - Mass scaling is predicted with dominant minority heating and collisional relaxation

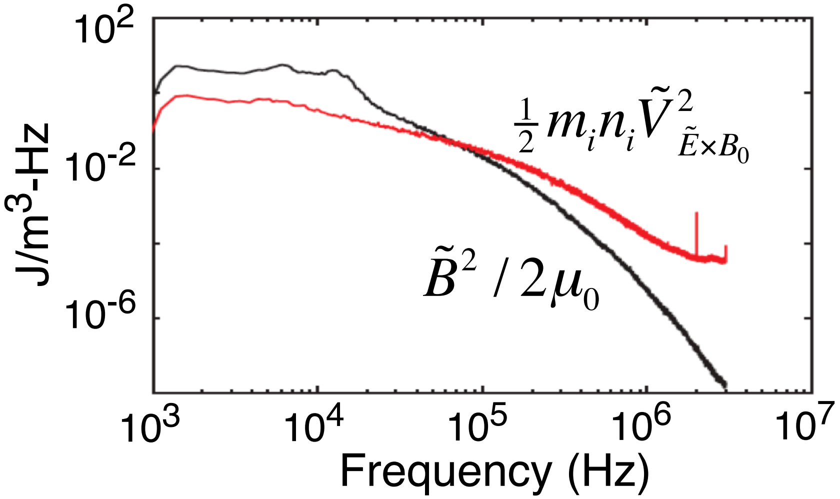


Tangri et al., PoP **15** (2008)
(similar to Cranmer et al)

The models proposed for ion heating in the RFP are similar to those for the solar corona and wind

- **Stochastic heating**:
  - Feeds off large electric field fluctuations and a distinct chaotic diffusion process
  - Monte Carlo modeling yields MST-like heating rates (Fiksel et al, PRL 2009)
  - Predicts mass scaling close to that observed





Does non-Alfvenic cascade help make heating more powerful?

Viscous heating is not sufficient

- No experimental evidence for the required large sheared flow
- Perpendicular flow is dominant for tearing modes for which the classical viscosity is small
- Difficult to achieve the large impulsive heating rates seen in MST plasmas
- See, e.g., Svidzinski et al, PoP **15** (2009)

The need for multi-scale modeling

- Fluid treatment of tearing instability and the self-organizing feedback is mature but does not encompass small scales
  - Nonlinear MHD and two-fluid models (NIMROD, DEBS)
  - Typical spatial resolution $k\rho_i \lesssim 0.3$
  - Braginskii dissipation, sometimes artificially enhanced for numerical purposes

- A large-scale electric field (dynamo flux) is created in the self-organizing feedback
  - Energization on the largest scale, e.g., energetic ions
  - Two-fluid nature allows ions and electrons to respond differently

- Boundary conditions are important
  - Unavoidable consequence of being a confined plasma
  - Coupling to other modes like drift waves, even if they are stable
  - Boundary interfaces are generic, e.g., corona or magnetosphere

(Some) next step RFP experimental opportunities

- Diagnostics and methods that discriminate heating mechanisms
  - Limited measurements suggest ion heating is preferentially perpendicular
  - Test bed for wave-particle correlation study
  - Diagnostic challenge is significant, so understanding probably hinges on modeling predictions for turbulence characteristics

- Plasma control improvements, e.g., current magnitude and duration
  - *Lower* the Lundquist number to isolate MHD regime (versus two-fluid)
  - Increase access for both intrusive and nonintrusive diagnostics

- Inject plasmoids
  - Mix with tearing-driven turbulence
  - Increase beta
  - Form shocks

Computational model for tearing-relaxation recently extended to include two-fluid effects

- Nonlinear multi-mode evolution solved using NIMROD
- Motivated by measurements that suggest coupled electron and ion relaxation

Ohm’s law:

$$\mathbf{E} = -\mathbf{V}\times\mathbf{B} + \frac{1}{ne}\mathbf{J}\times\mathbf{B} - \frac{1}{ne}\nabla p_e + \eta\mathbf{J} + \frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}$$

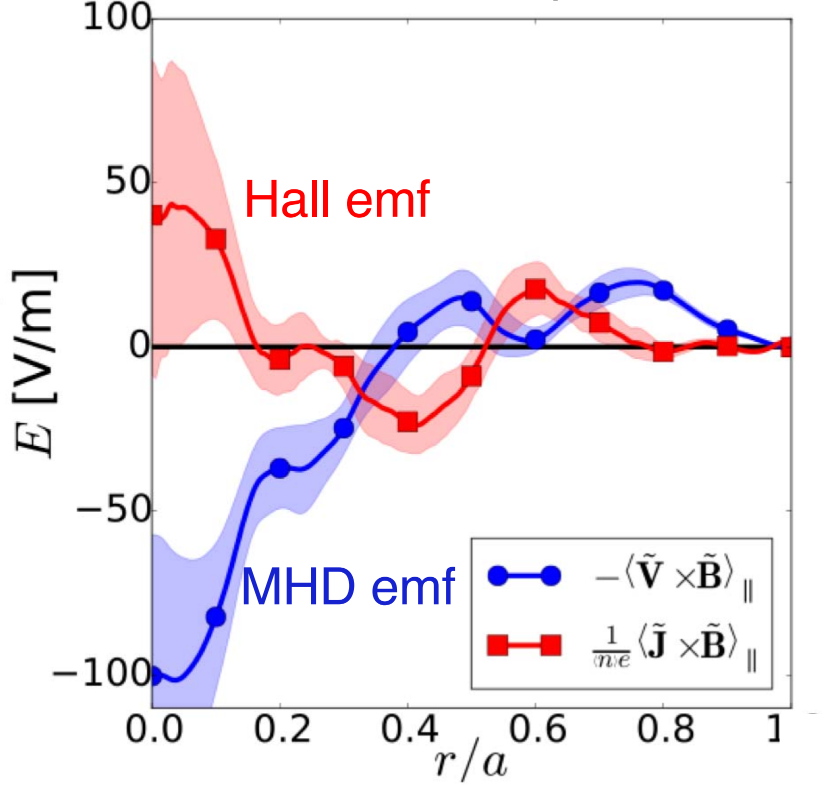
Momentum:

$$nm_i\frac{d\mathbf{V}}{dt} = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi_{gyro} - \nabla\cdot\nu n m_i\mathbf{W}$$

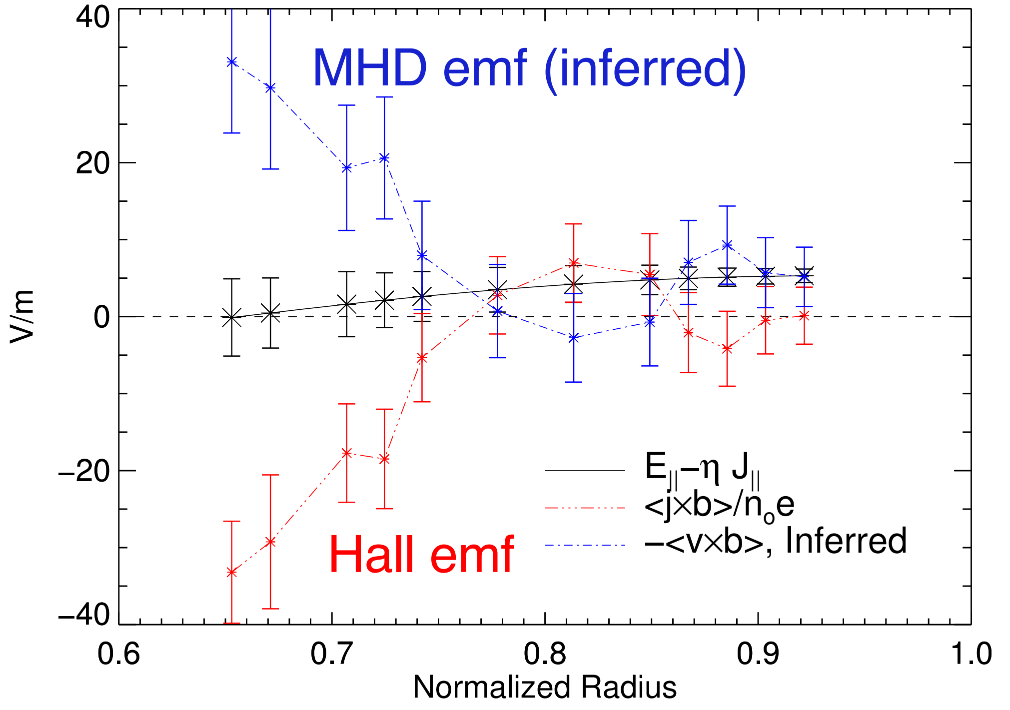
Relaxation process couples electron and ion momentum balance

Two-fluid relaxation signatures are measured, e.g., Hall emf

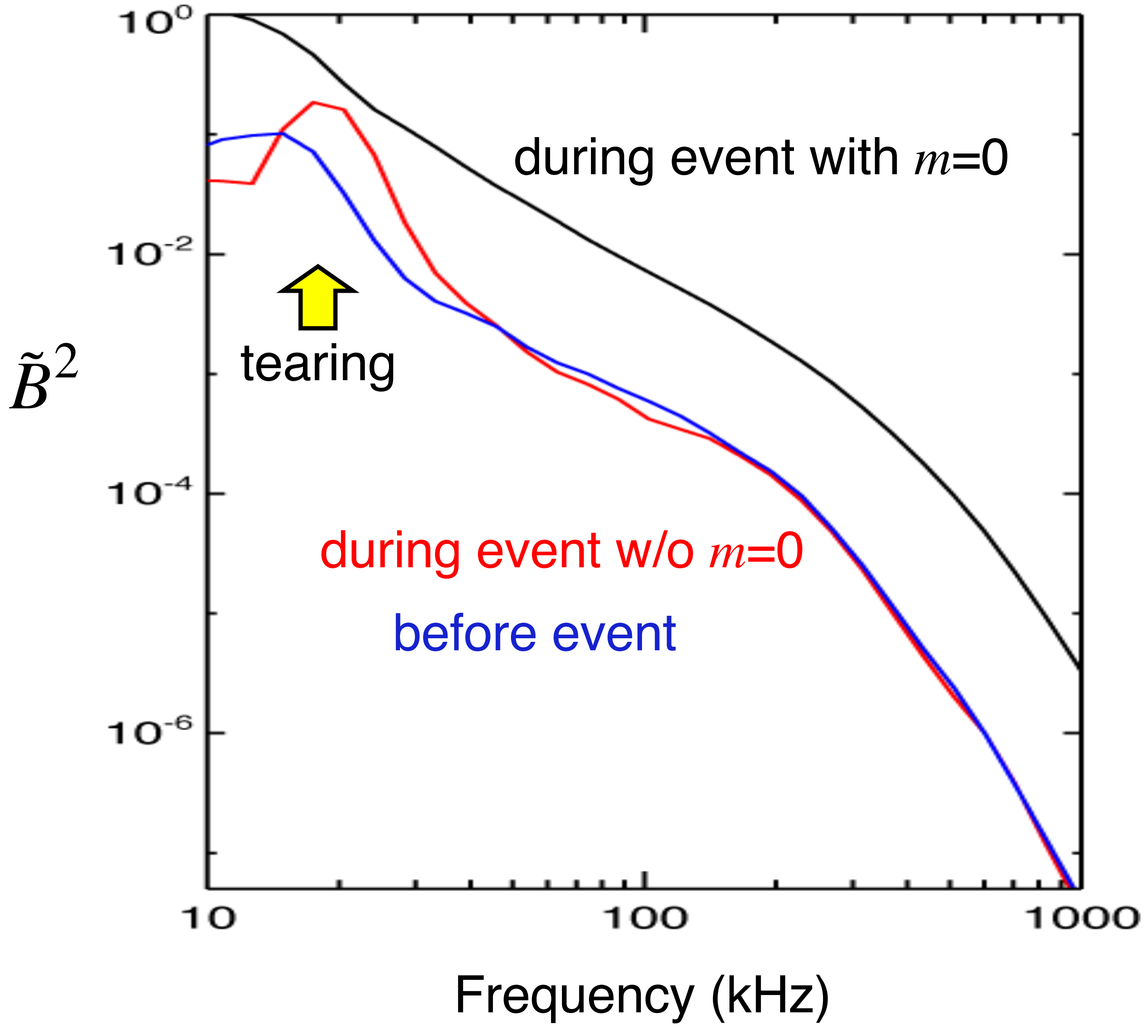
NIMROD Computation



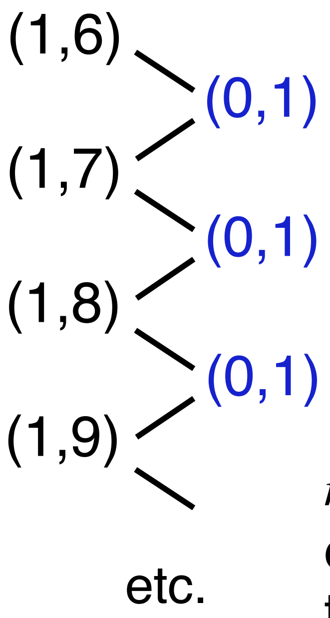
Deep-Insertion Magnetic Probe in MST



The turbulent cascade is not as strong when nonlinear coupling at the driving scale is disabled

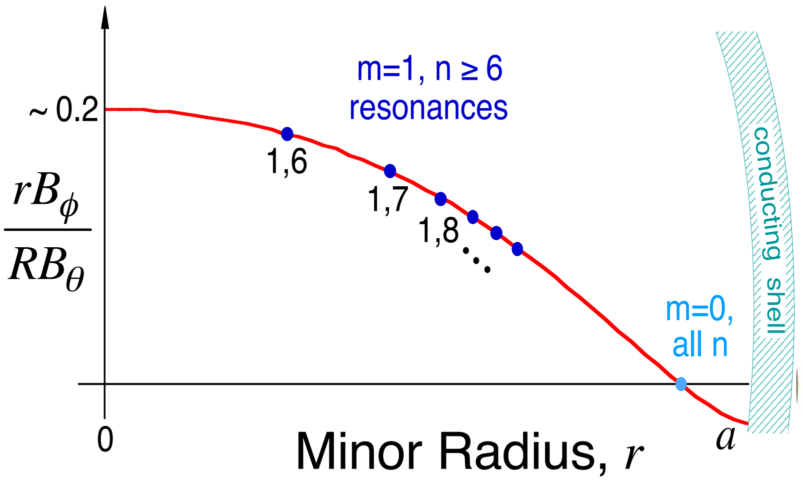


Schematic of 3-wave cascade:

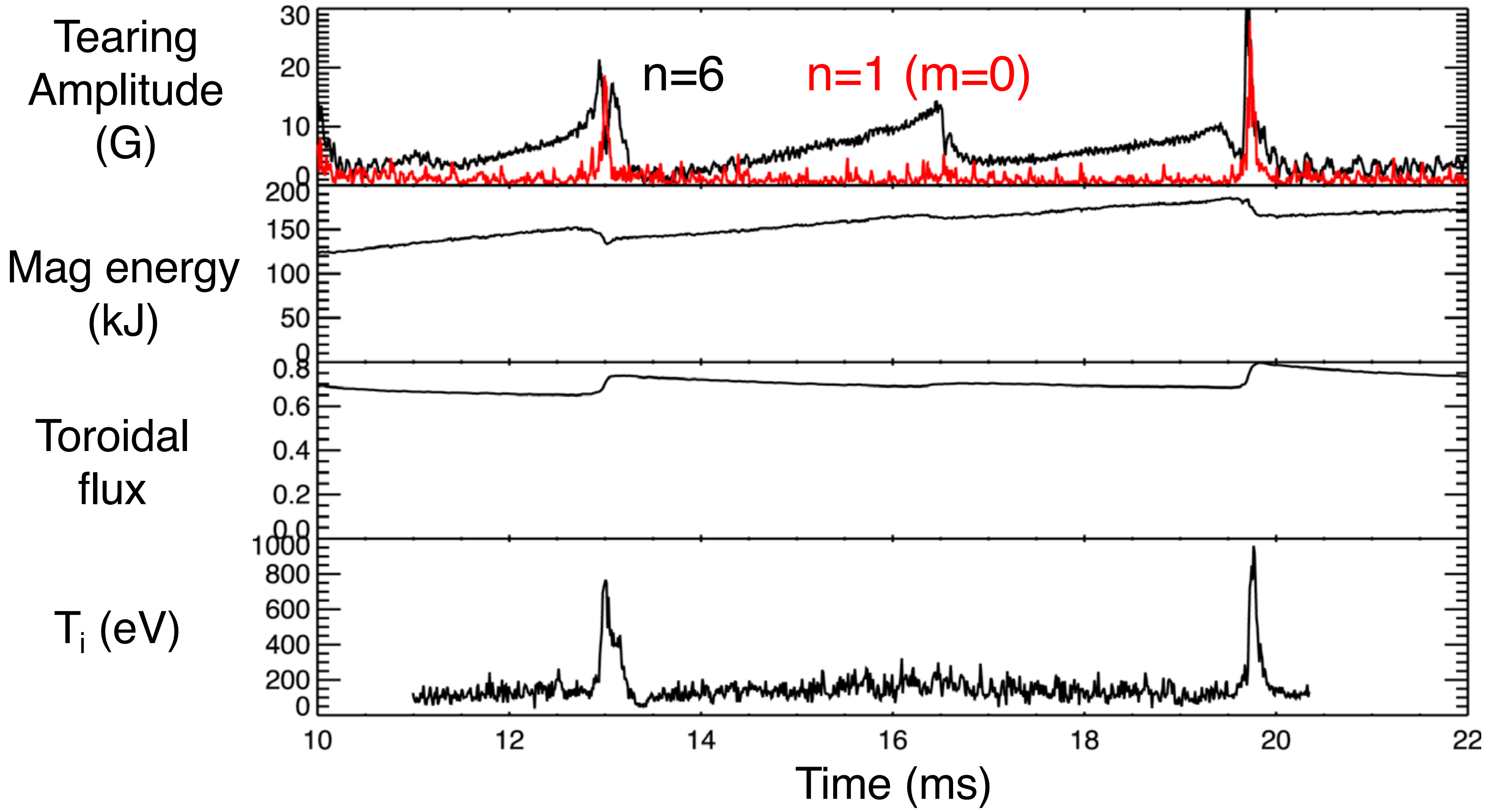

(1,6)
(0,1)
(1,7)
(0,1)
(1,8)
(0,1)
(1,9)
etc.

Same $m = 0$ couples to many $m = 1$

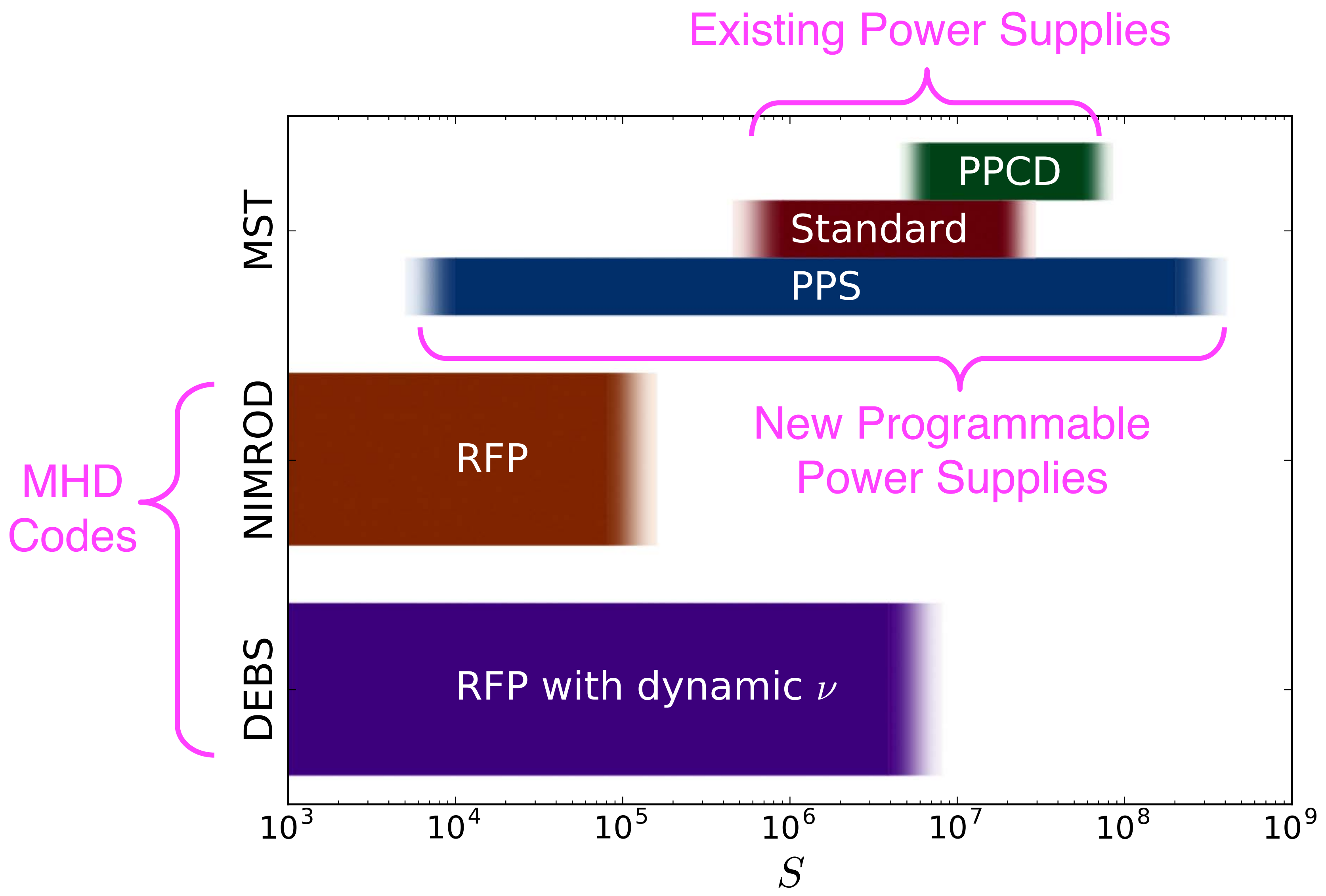
$m \geq 2$ branch drives the cascade to smallest scales



Particle energization correlates with power flow into the cascade

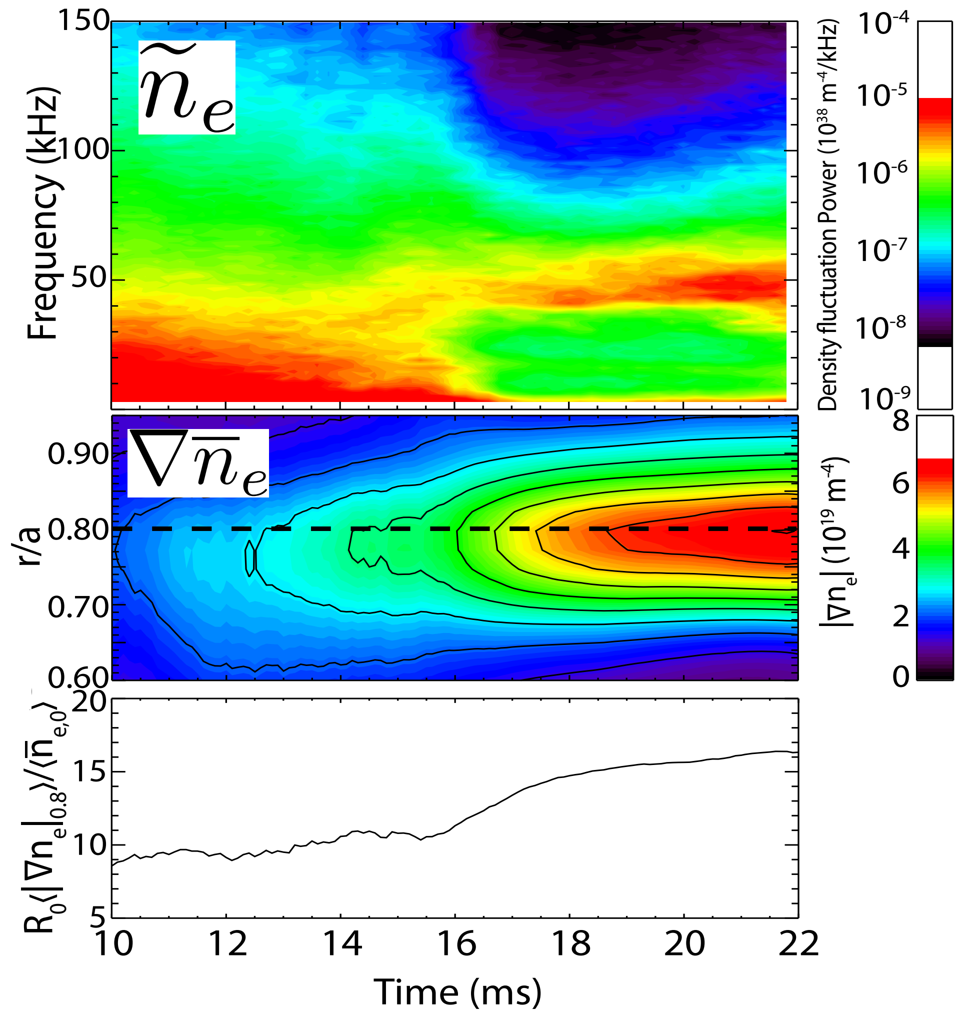


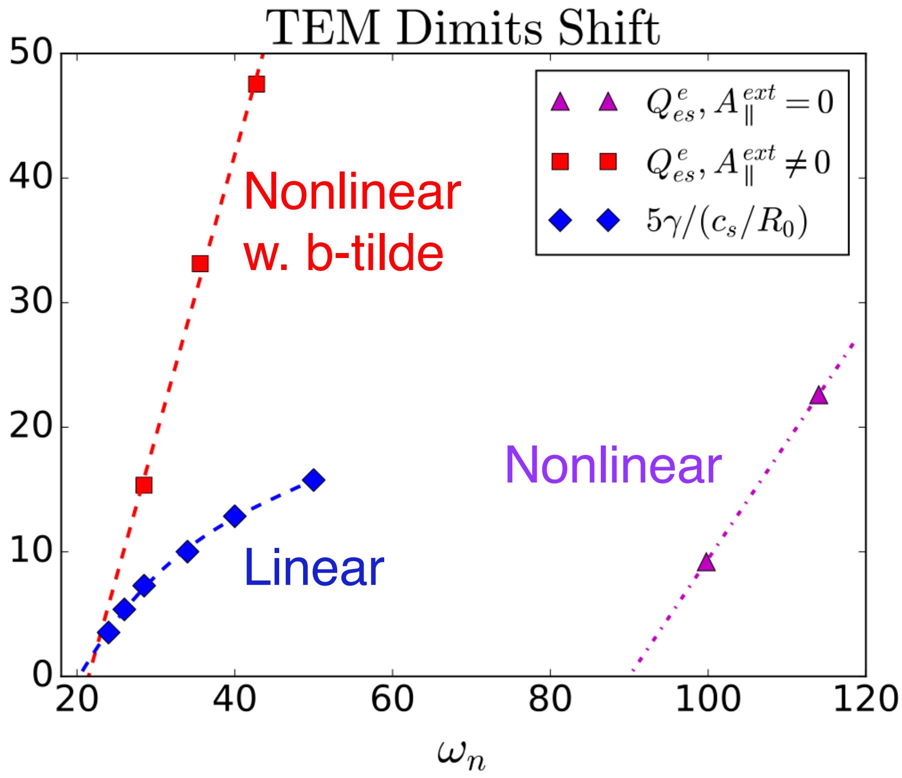
New power supplies enable four orders of magnitude in Lundquist number, $S \approx 3 \times 10^{4\text{-}8}$



Gyrokinetic modeling for the tearing cascade is a next challenge

- GENE modeling identifies standard drift mode branches in RFP equilibria
- Initially motivated by improved-confinement regime, but gradients in standard conditions are close to marginal stability (if not unstable)





Summary

- Ion heating and acceleration associated with magnetic reconnection from tearing instability is a powerful process in the RFP laboratory plasma
  - Gyro-resonant and stochastic processes are likely candidates to support the observed rapid heating and other features
  - Energetic tail formation for ions and electrons

- Global self-organization strongly coupled to turbulence and dissipation
  - Correlations in electric and magnetic field fluctuations are a hallmark of dynamo feedback
  - Inhomogeneity on the system scale, e.g., strong edge gradients
  - Global magnetic flux change drives produces ion runaway energization
  - Impact of transport processes, which can be quite different for ions and electrons