What sets the minimum thickness of reconnection layer in MRX?

Vadim Roytershteyn

PPPL, October 25th, 2012

Collaborators

Seth Dorfman

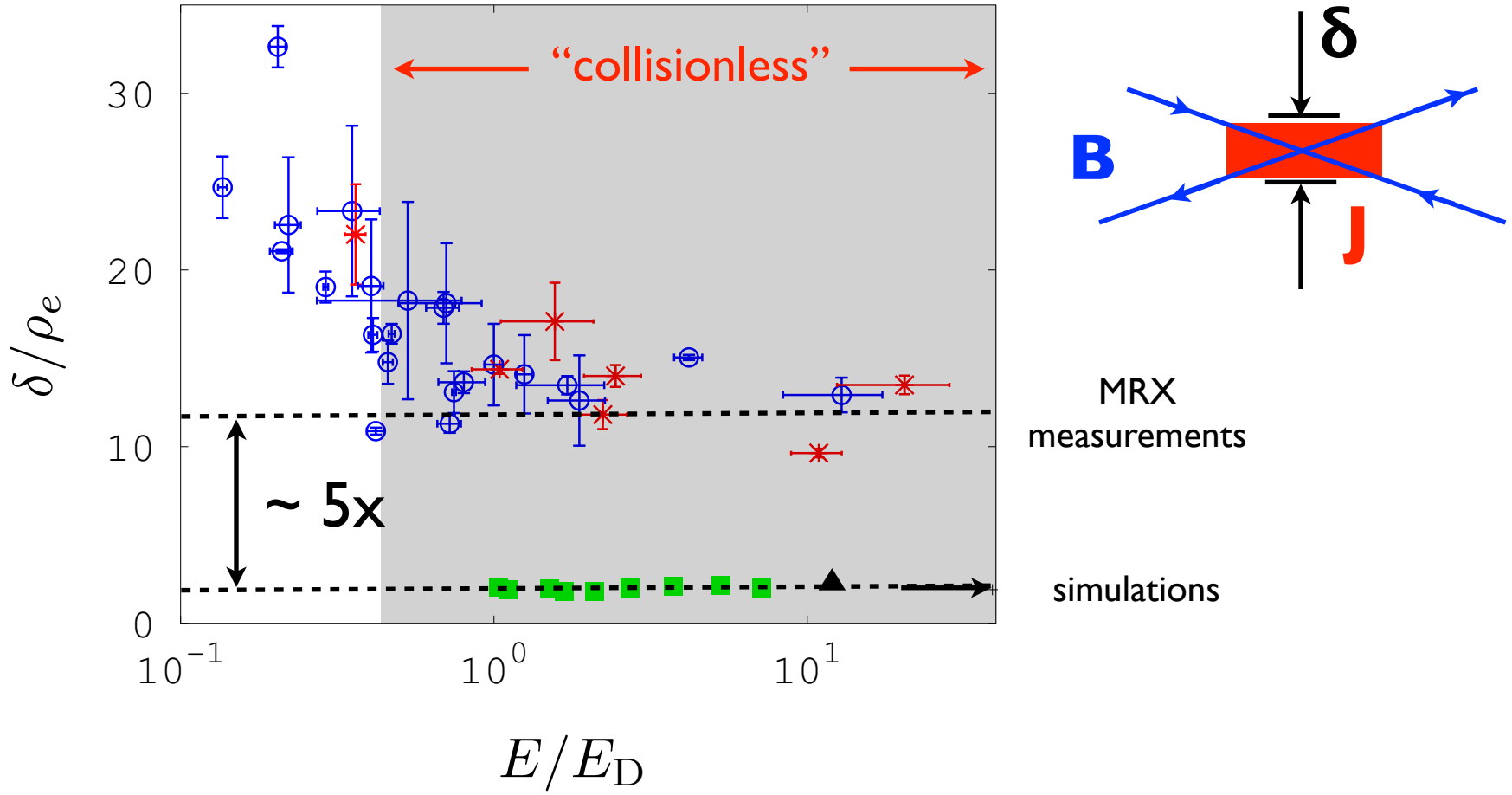
Bill Daughton

Hantao Ji

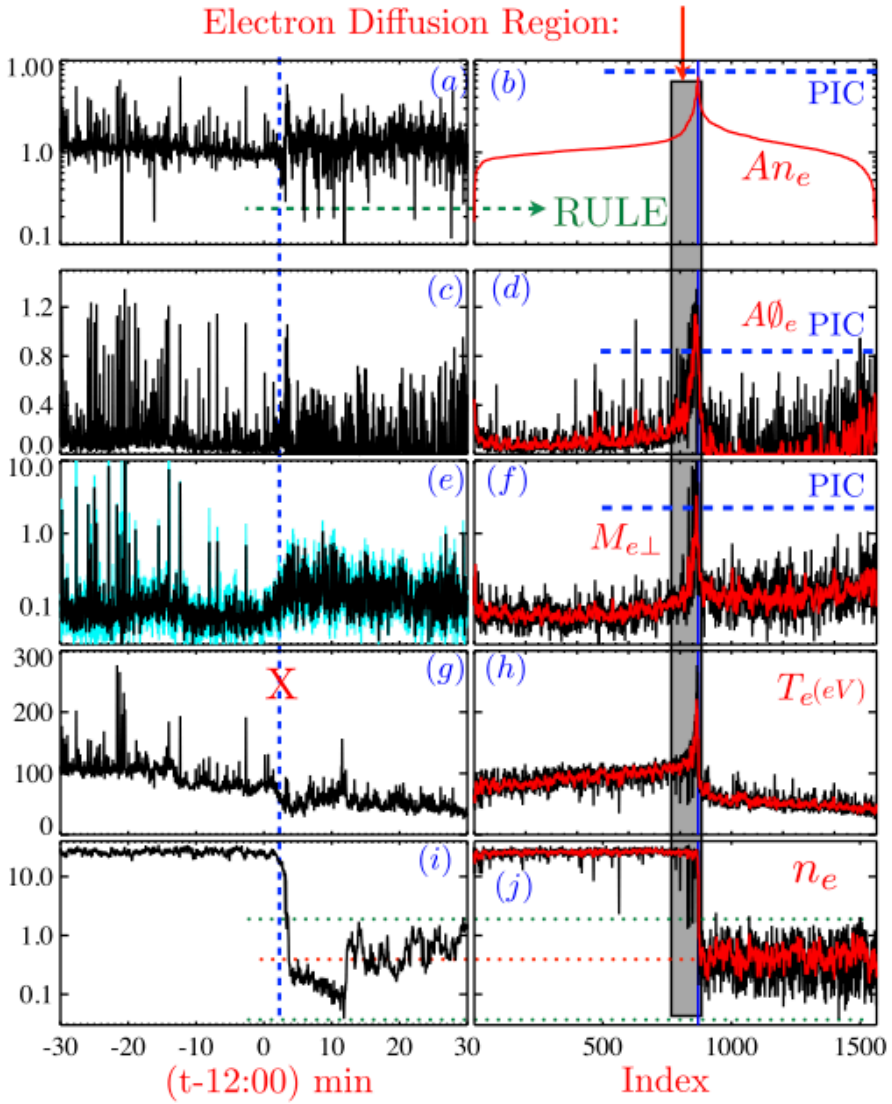
Homa Karimabadi

Masaaki Yamada

Measurements of reconnection layer thickness of in MRX can not be explained by existing theories/simulations



Recent analysis of Polar data support the predictions of simulations (Scudder *et al.*, 2012)



Layer thickness is a "fingerprint" of the reconnection mechanism.

We do not know the mechanism operating in MRX weakly collisional regimes!

Outline

Some details on the simulations and previous results

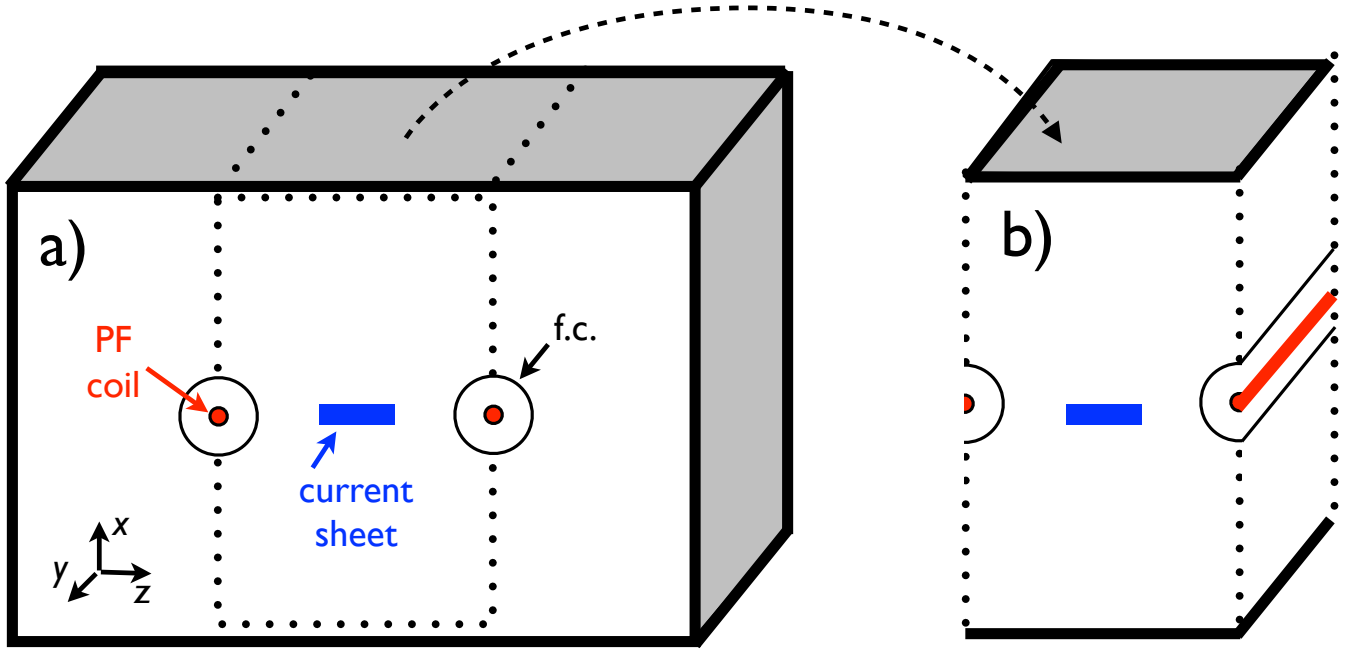
Observed fluctuations of magnetic field are not the answer (overview of a new paper we just submitted)

Questions for the future

Fully kinetic simulations model aspects of geometry and boundary conditions

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v} \cdot \nabla f_s + \frac{q_s}{m_s}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \nabla_{\boldsymbol{v}} f_s = \sum_{s'} \mathcal{C}\{f_s, f_{s'}\}$$

+ Maxwell's equations



Choice of the scaling approach is crucial

Fully kinetic model requires that the problem parameters be scaled. The choice of scaling is crucial since it needs to preserve the physics of interest

Our choice: reference values of

$$\beta \qquad \tau\Omega_{ci} \qquad L/d_i$$

are close to experiment

$$m_i/m_e,\ \omega_{pe}/\omega_{ce}$$

are treated as numerical parameters. Typical values: (100-400) and (2-5) respectively

$d_i = c/\omega_{pi}$ L : system size τ : time scale for the coil current ramp-down

Several choices are possible for the collision frequency scaling

1) Match ν_{ei}/Ω_{ce} (representative range for MRX: 0.01-0.1)

Appropriate for resistive regimes since it ensures matching of

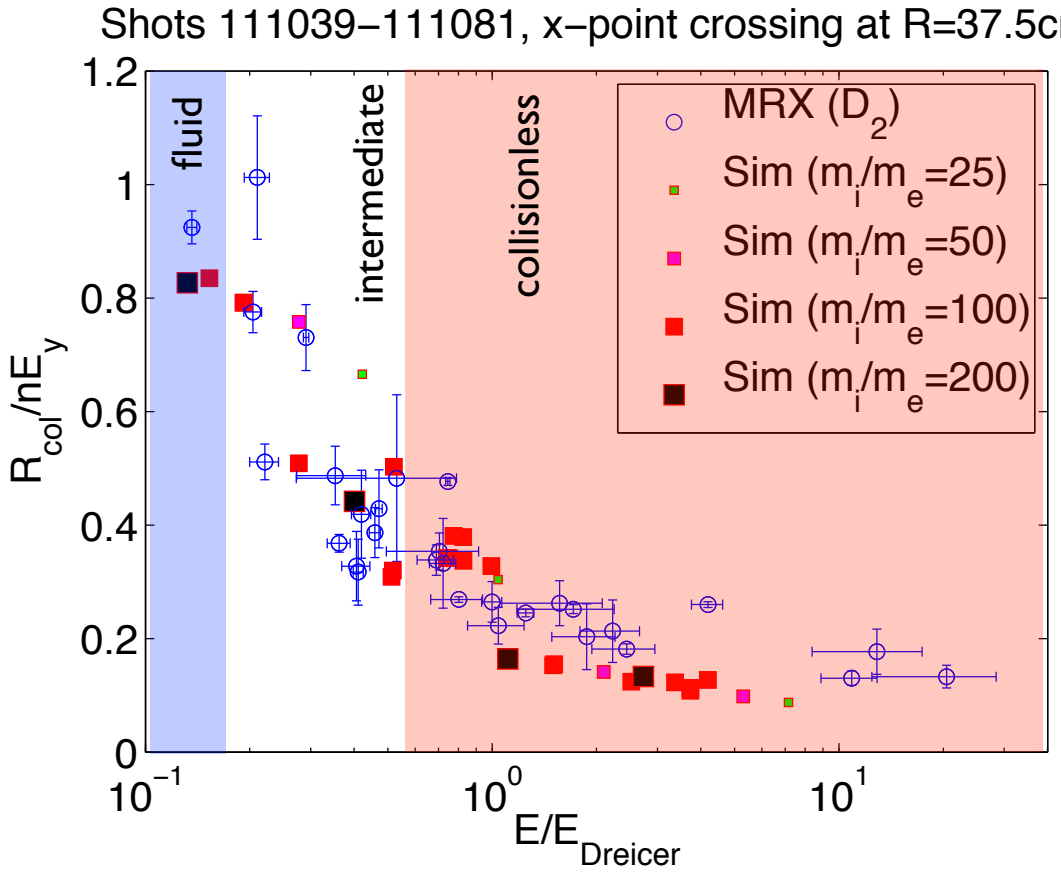
$$S = \frac{LV_A}{D_m} \propto \frac{L}{d_i}\frac{\Omega_{ce}}{\nu_{ei}} \qquad \frac{\delta_{SP}^2}{d_i^2} \propto \frac{L}{d_i}\frac{\nu_{ei}}{\Omega_{ce}}$$

2) Match the ratio between reconnection electric field and the Driecer field (representative range of the experiment: 0.1-0.5). **This is the relevant choice in weakly collisional regimes**

$$\frac{E_R}{E_{\rm crit}} \sim \frac{\mathcal{R}}{\sqrt{\beta_e}}\left(\frac{m_e}{m_i}\right)^{1/2}\left(\frac{\Omega_e}{\nu_{ei}}\right)$$

Several collisionality regimes are accessible in both the experiment and the simulations

$$\underbrace{ne\left(\boldsymbol{E}+\frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right)}_{F_{\mathrm{NI}}}=-\nabla\cdot\boldsymbol{P}+\boldsymbol{R}_{ei}-m_e n\frac{\mathrm{d}\boldsymbol{U}_e}{\mathrm{d}t}$$



$$R_{ei,y}=\int d^3v\, v_y \mathcal{C}_{\mathrm{ei}}\{f_e,f_i\}$$

$$E_{\mathrm{crit}}=\frac{\sqrt{2T_e m_e}}{e}\nu_{ei}$$

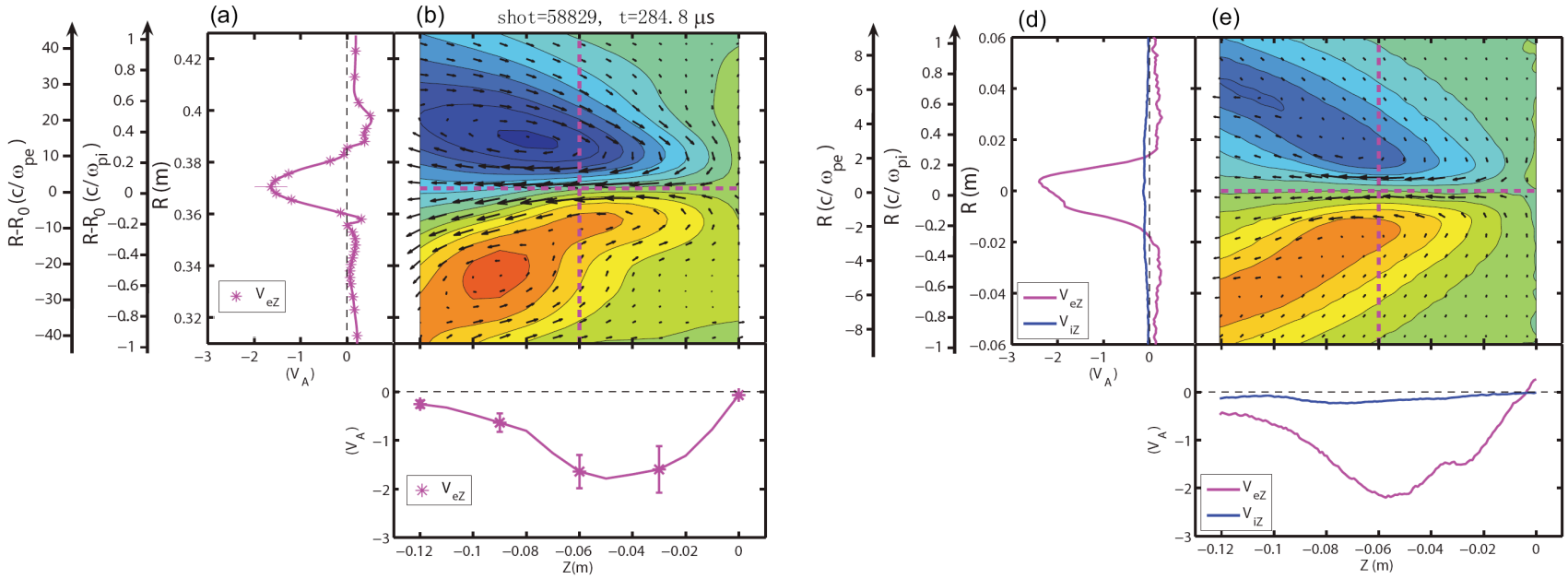
$$\nu_e=\frac{4\sqrt{2\pi}\Lambda n e^4}{3m_e^{1/2}T_e^{3/2}}$$

$$T_e=(\mathrm{tr}\,\boldsymbol{P}_e)/(3n_e)$$

Simulations reproduce the ion-scale current sheet structure

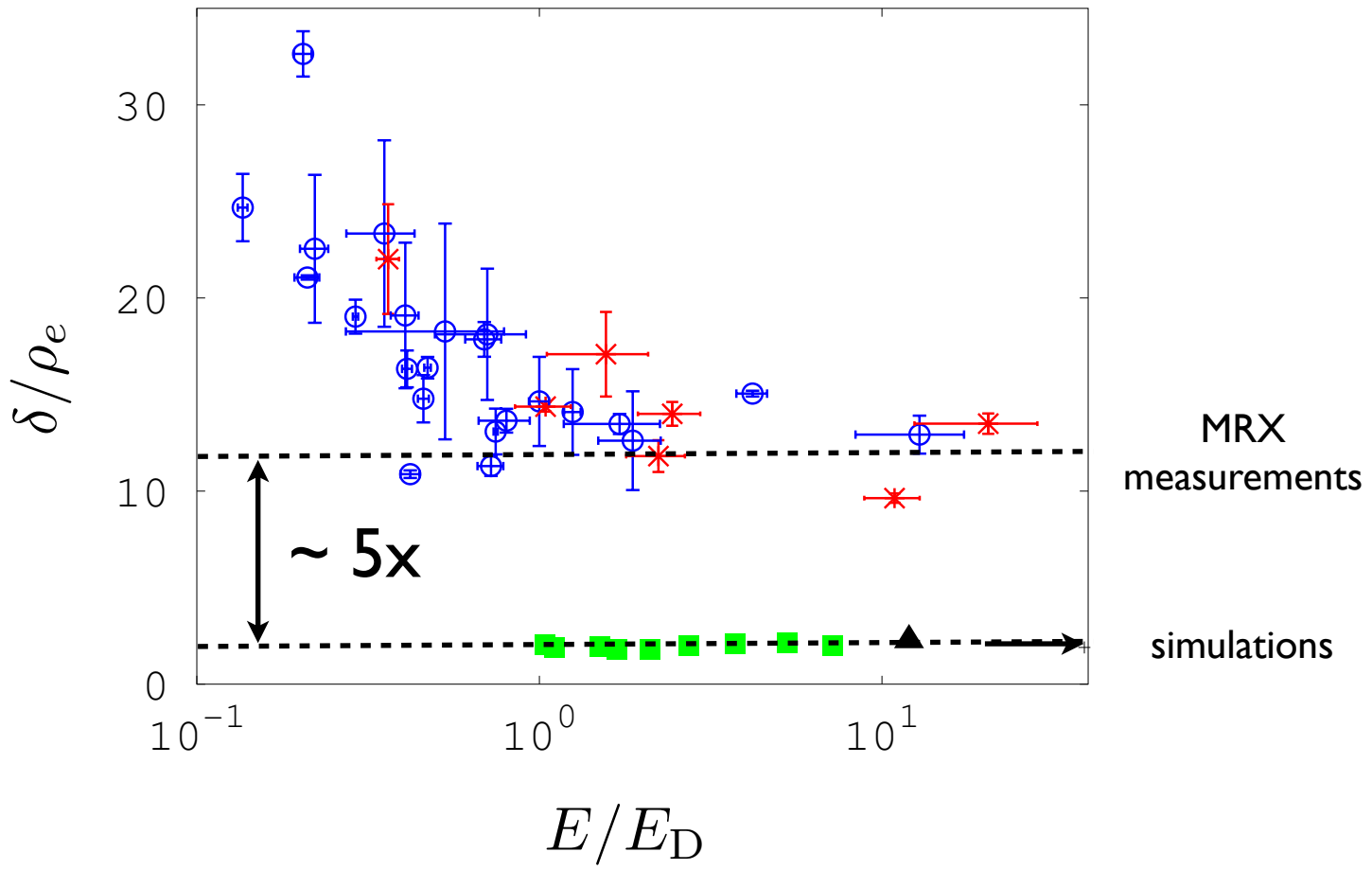
Experiment

2D collisionless



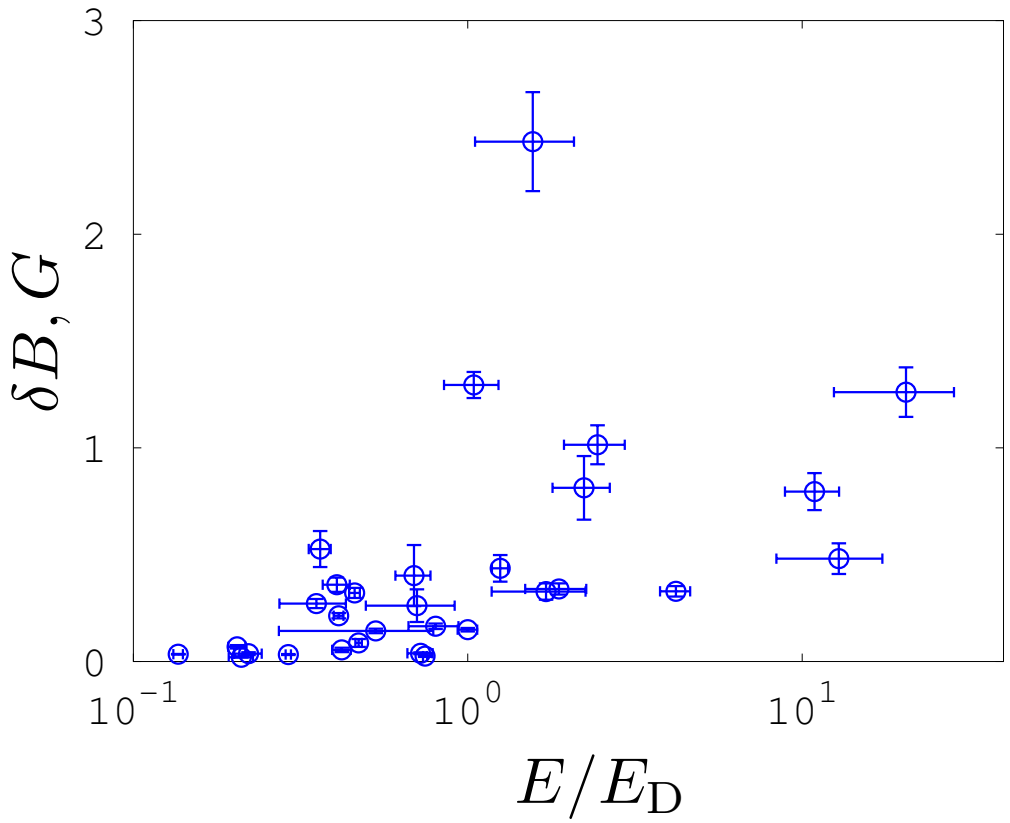
Ji *et al.*, GRL (2008); Dorfman *et al.*, Phys. Plasmas (2008); Ren *et al.*, Phys. Plasmas (2008)

But the observed structure of electron-scale layer can not be reproduced in the simulations

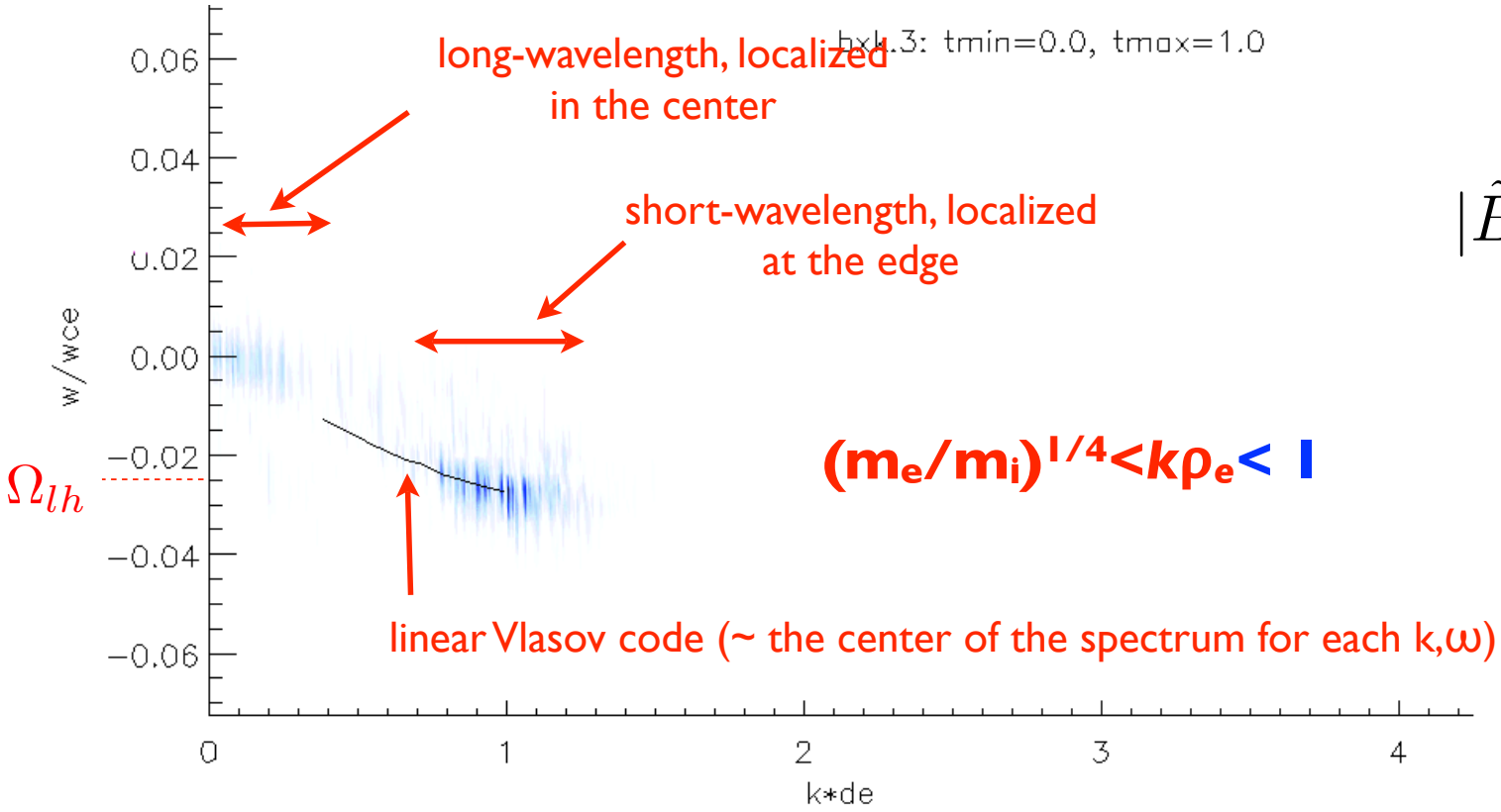


Anomalous transport associated with instabilities has been considered a possible explanation

fluctuations of magnetic field close to the X-line



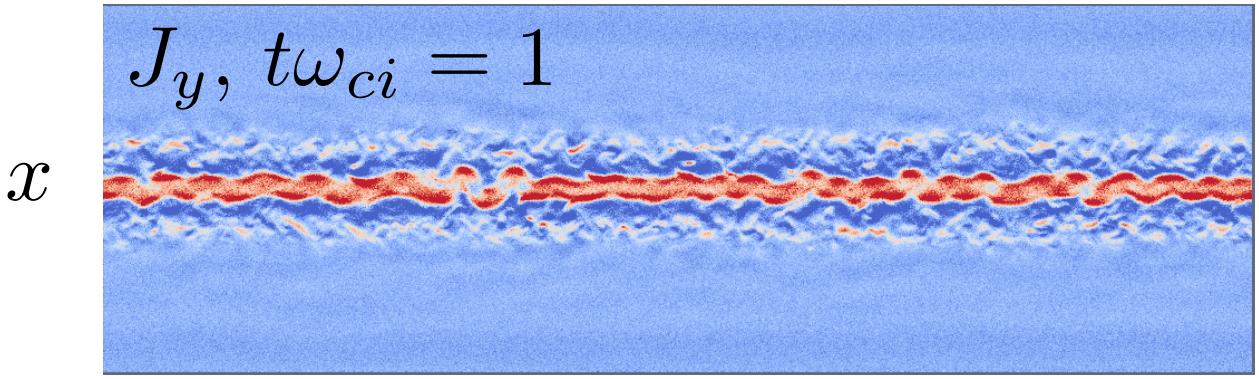
Magnetic fluctuations are of interest, since they are thought to be associated with the most relevant instability

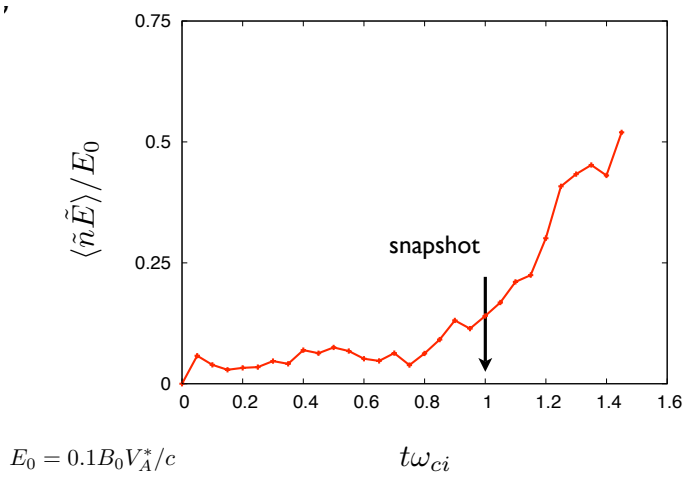


spectrum of magnetic fluctuations in a Harris current sheet with $\delta/\rho_e=10$; $m_i/m_e=1836$; $n_B=0.3$.

In typical current sheet, these are the only current-aligned instabilities with significant growth rate.

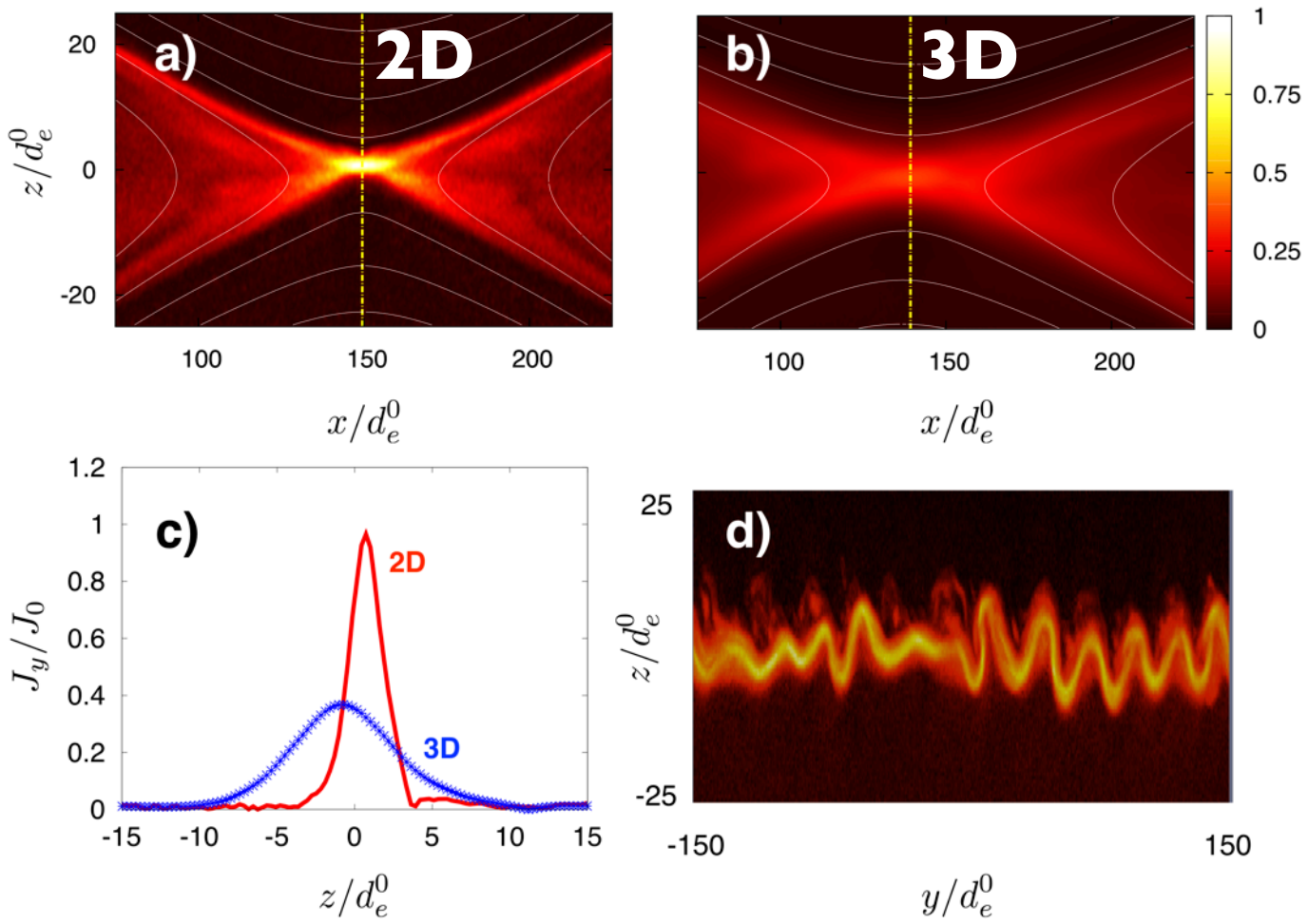
IF these instabilities reach large amplitude, they can induce anomalous transport and broaden the layer





2D simulation, Harris current sheet with δ/ρ_e=10; m_i/m_e=1836; n_B=0.3

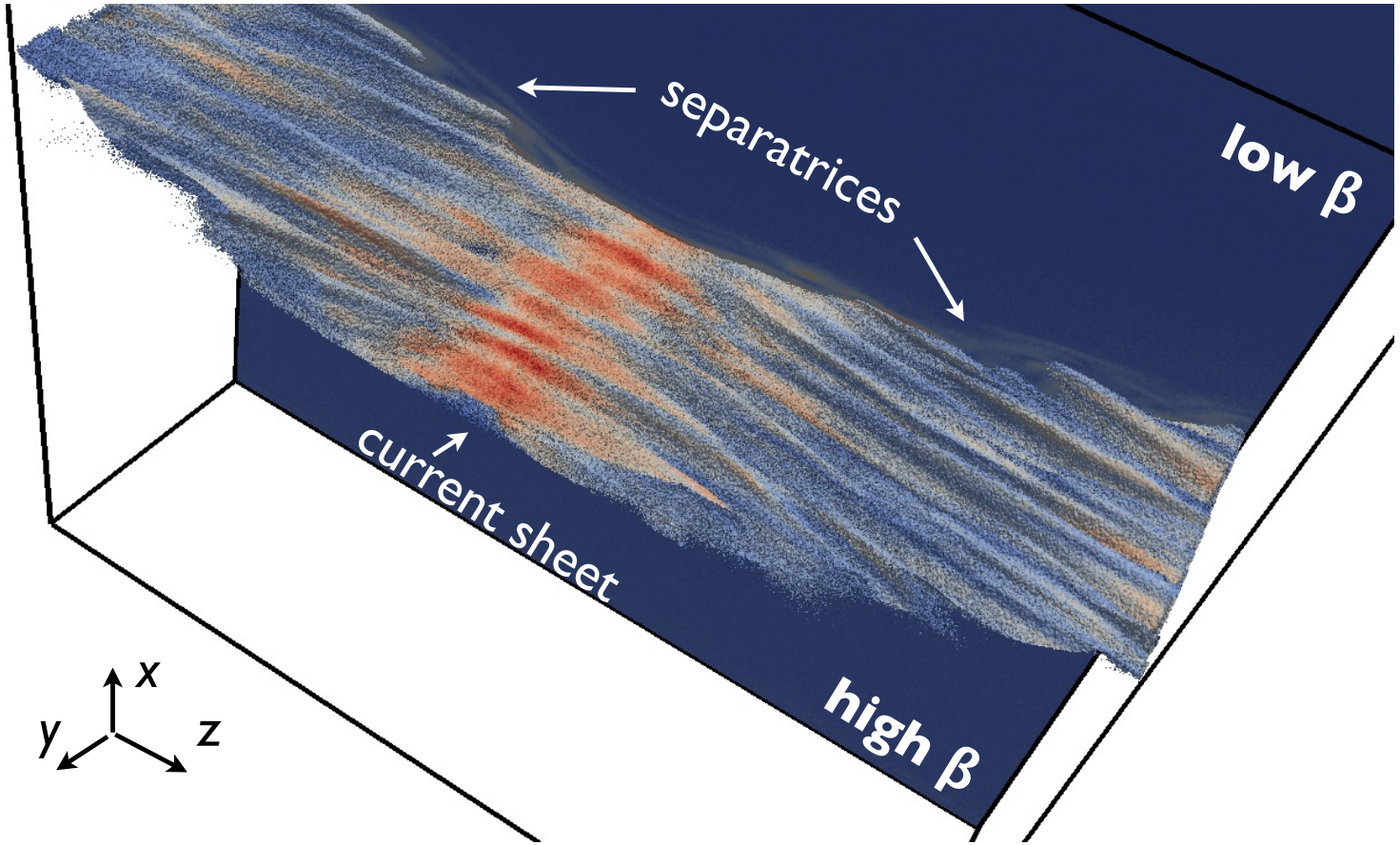
Recent analysis: self-consistent layers are considerably more stable compared to model 1D equilibria; the instability becomes important only at low beta, low Ti/Te, asymmetry



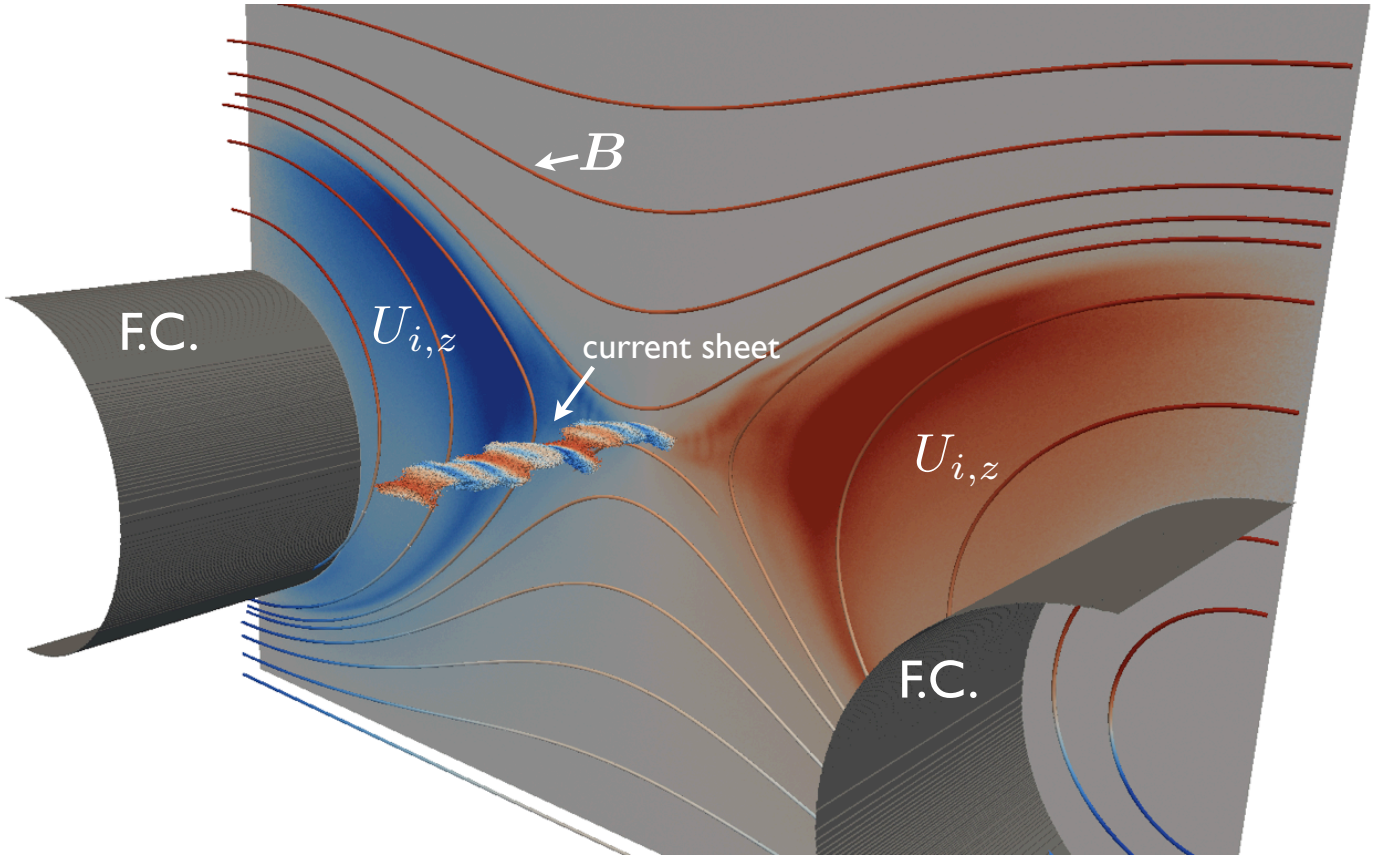
asymmetric, collisionless, open boundary simulation with mi/me=900

Collisionality and aspects of geometry need to be included for MRX analysis. We performed a quantitative comparison of two simulations with the experimental data

Compare experimental data with two simulations : collisionless, high-mass ratio case with open BC (m_e/m_i=900)

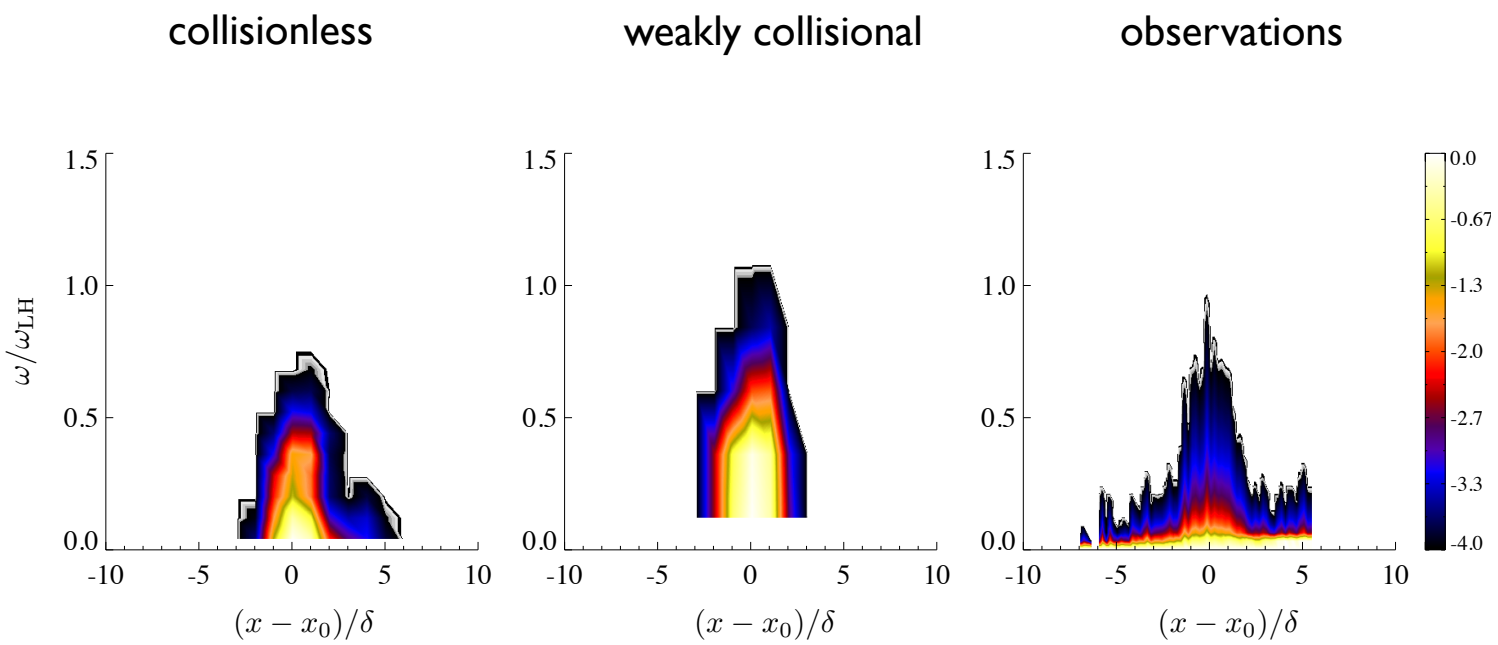


Weakly collisional simulation in MRX geometry with mi/me=300



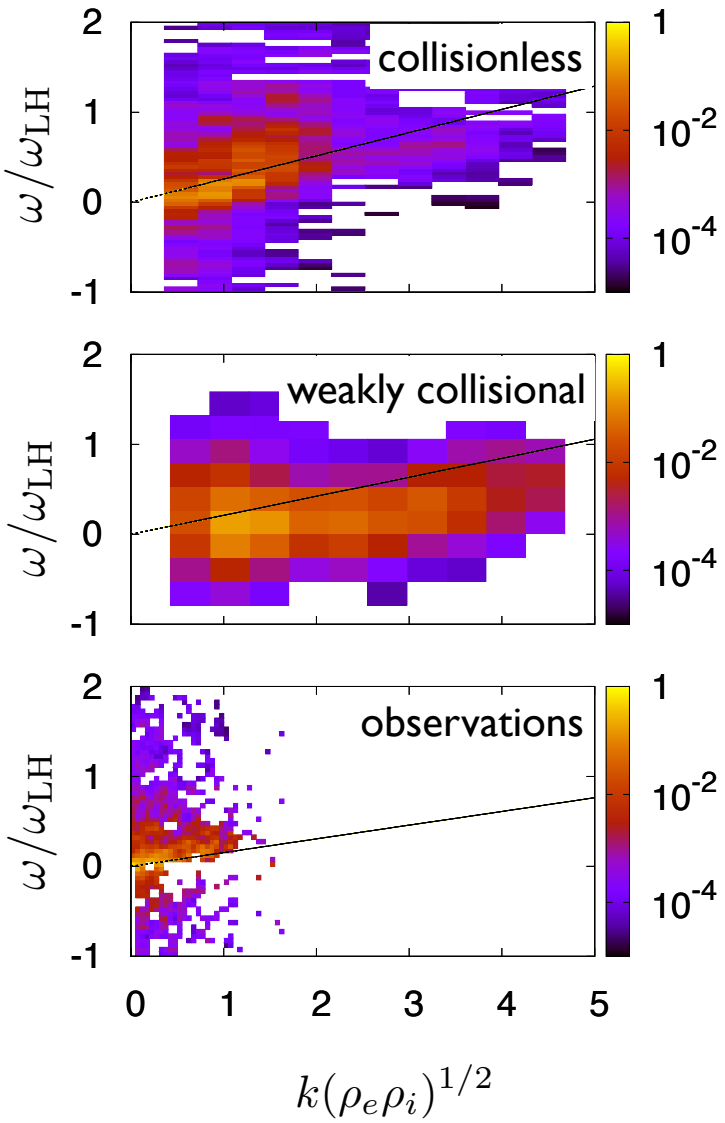
Long-wavelength modes survive in finite collisionality regimes

Comparison with MRX observations reveals considerable similarities:



fluctuations are characterized by lower-hybrid frequencies and are localized near the layer center

Characteristic direction of propagation and frequency and wavenumber ranges are comparable



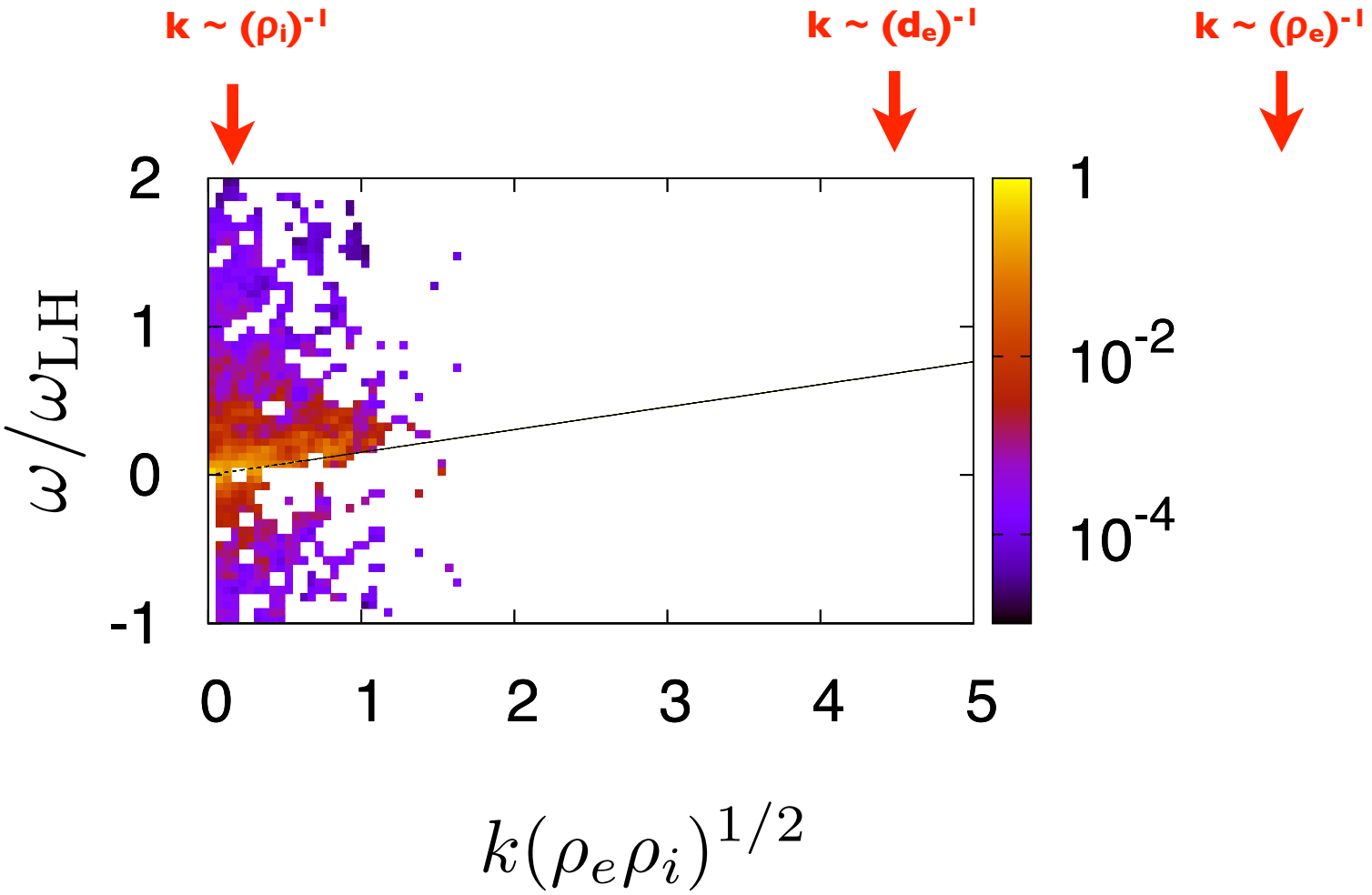
The dominant modes propagate in the direction of electron drift

Frequency range : $\omega < \omega_{LH}$

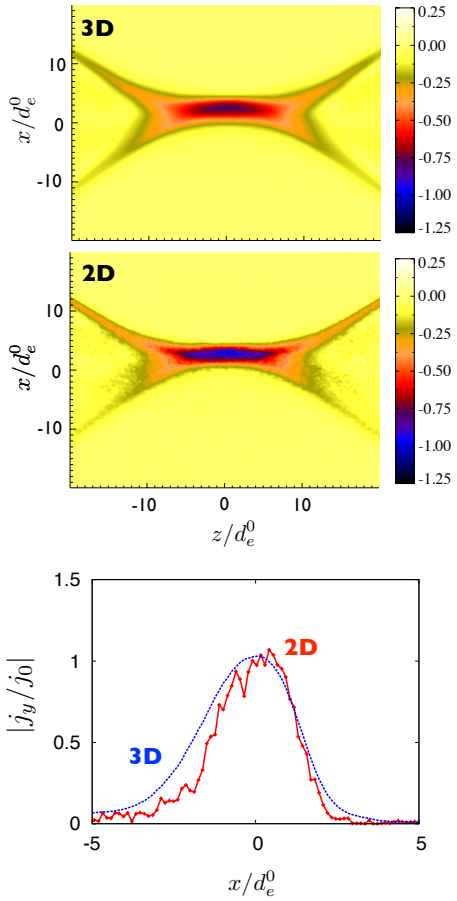
Wavenumber range: $k \sim (\rho_e\ \rho_i)^{-1/2}$

$V_{phase} \sim v_{th,i}$

A closer look at the spectrum

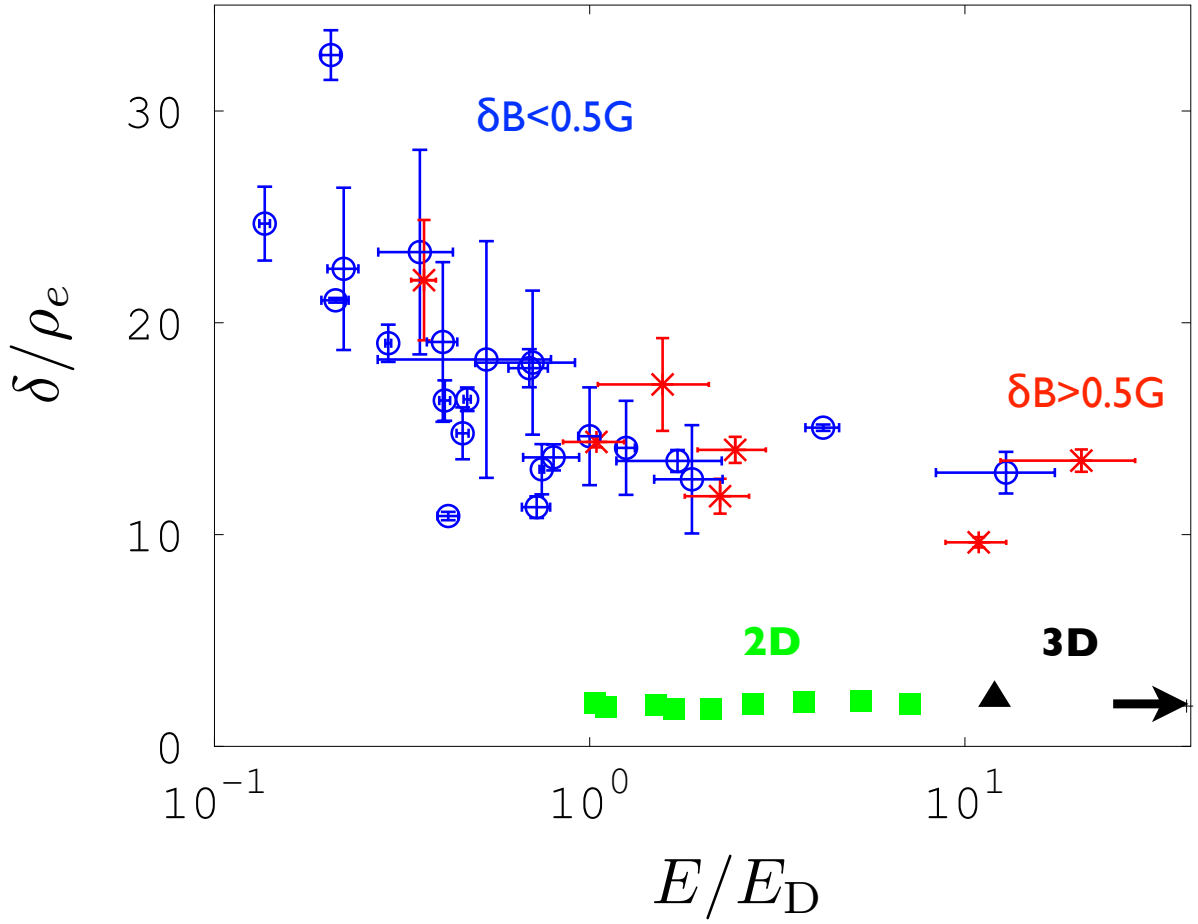


The effect of the fluctuations is rather minimal in the relevant simulations

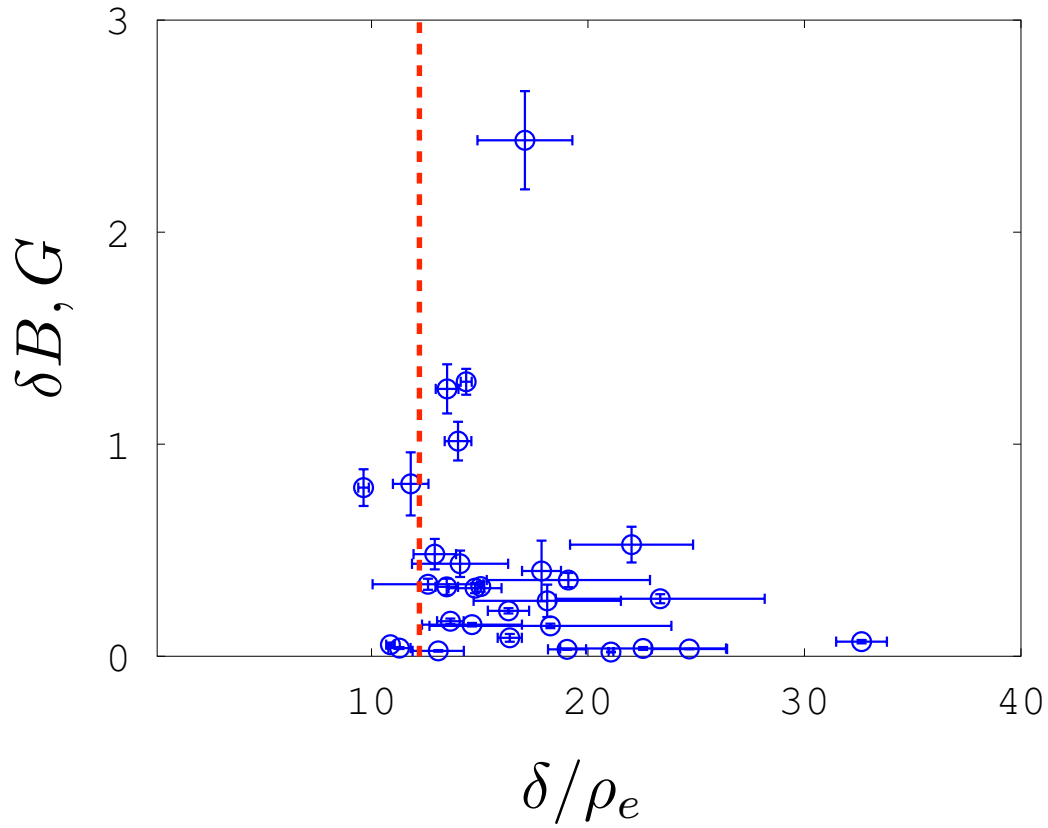


The fluctuations with finite k_y are not allowed in 2D, so such a comparison allows for a direct assessment of the role of instabilities

Observations show that layer thickness in the regimes with $E/E_D>1$ does not depend on the fluctuation amplitude



Crucially, the minimal layer thickness does not depend on fluctuation amplitude



These dependencies are inconsistent with the notion that fluctuations set the minimum width.

Summary

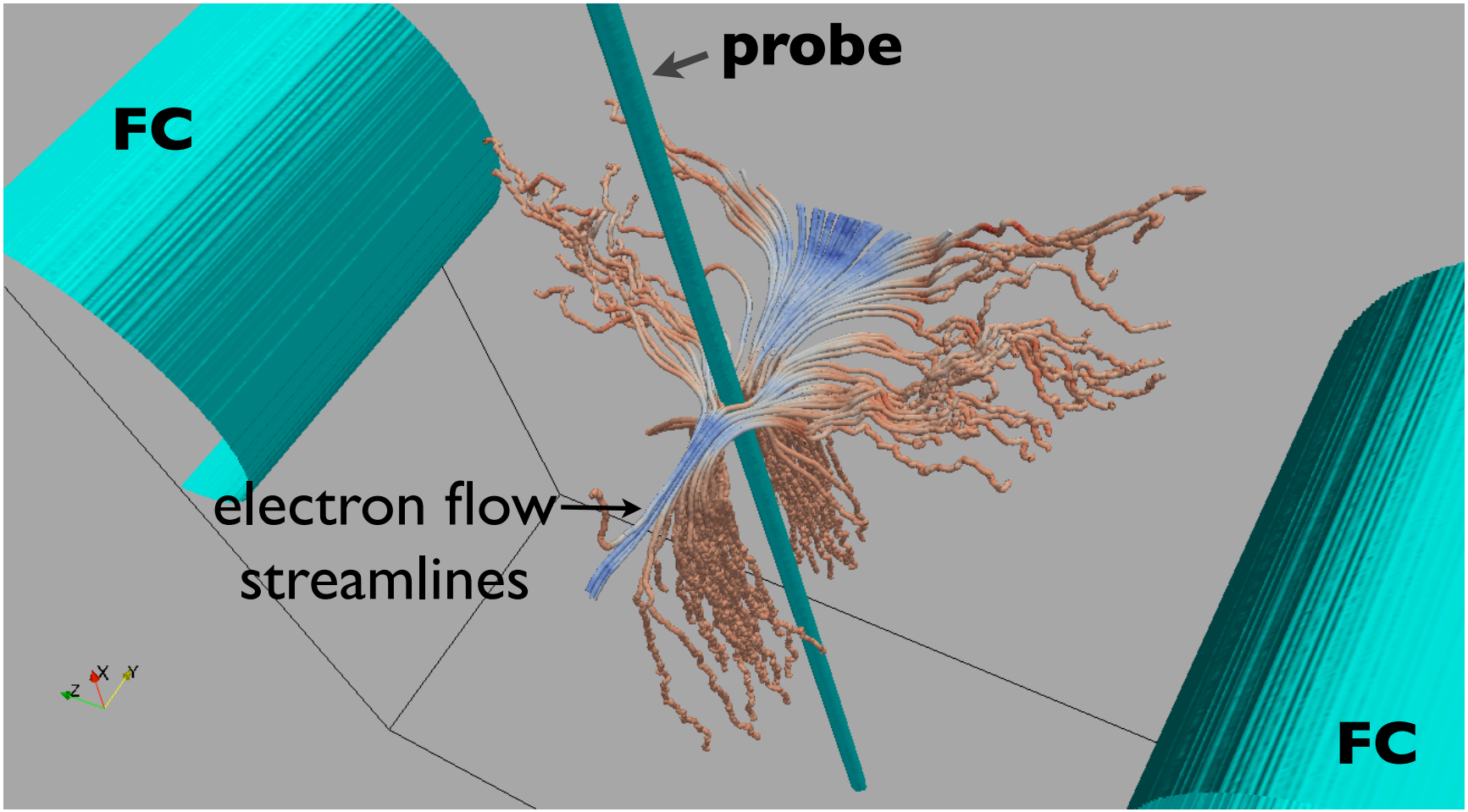
- Truly integrated study, neither simulations not experimental observations are not sufficient by themselves

- Magnetic fluctuations are interesting, but do not do much

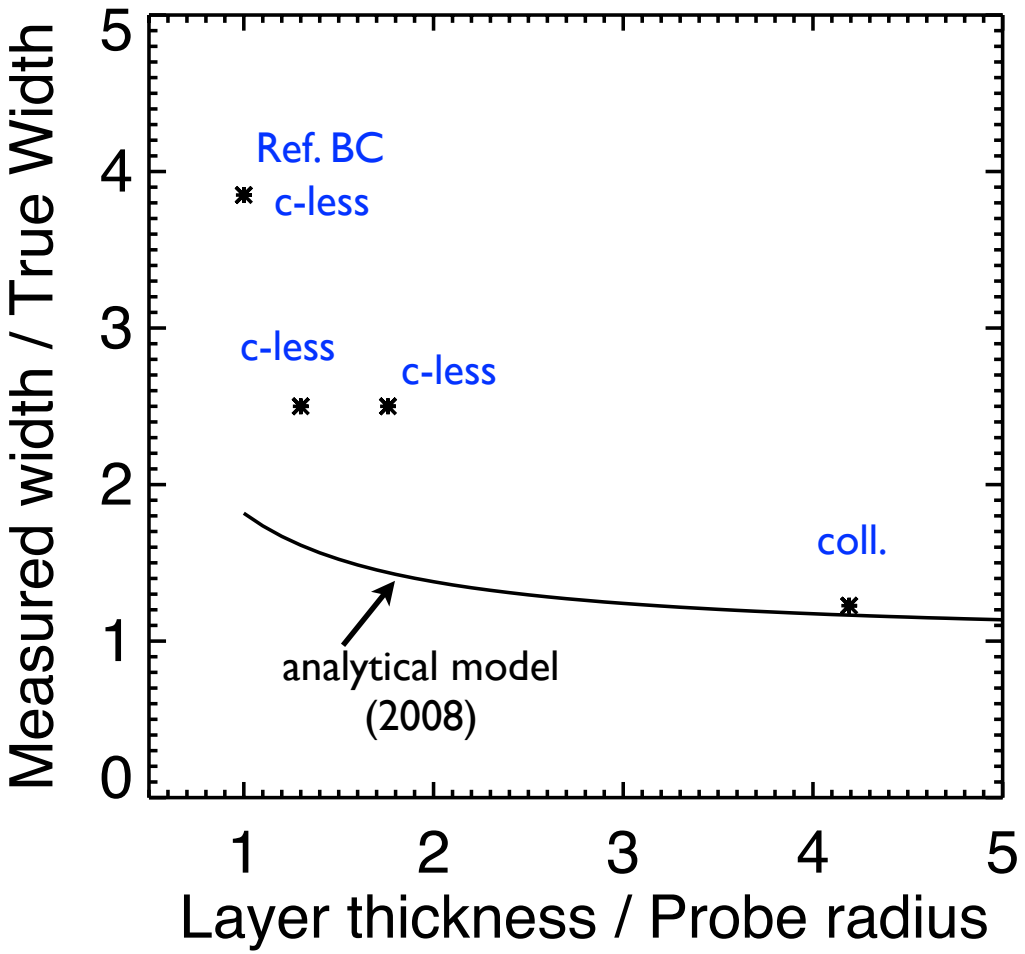
- Layer thickness remains a problem. Factors that have been proposed and considered:

  - neutrals
  - probes
  - collisionality
  - current-driven instabilities

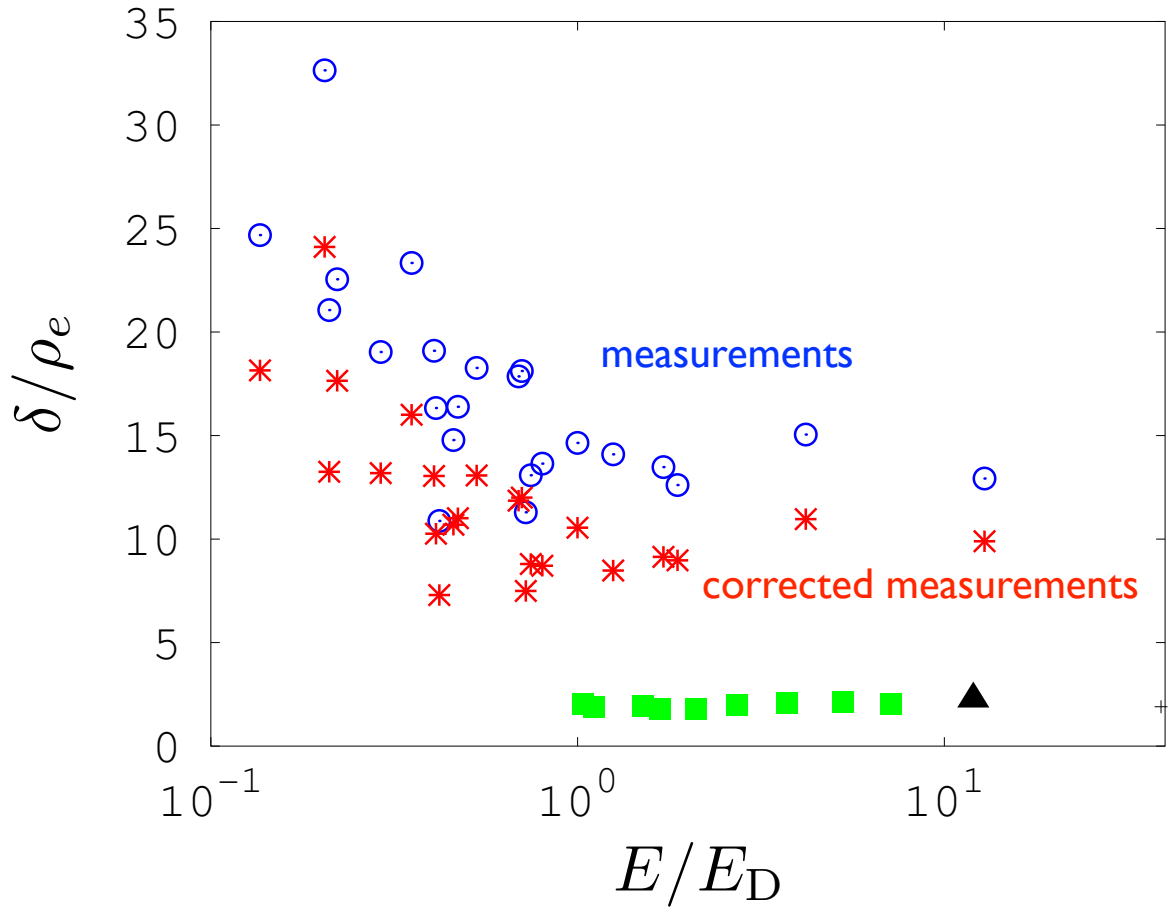
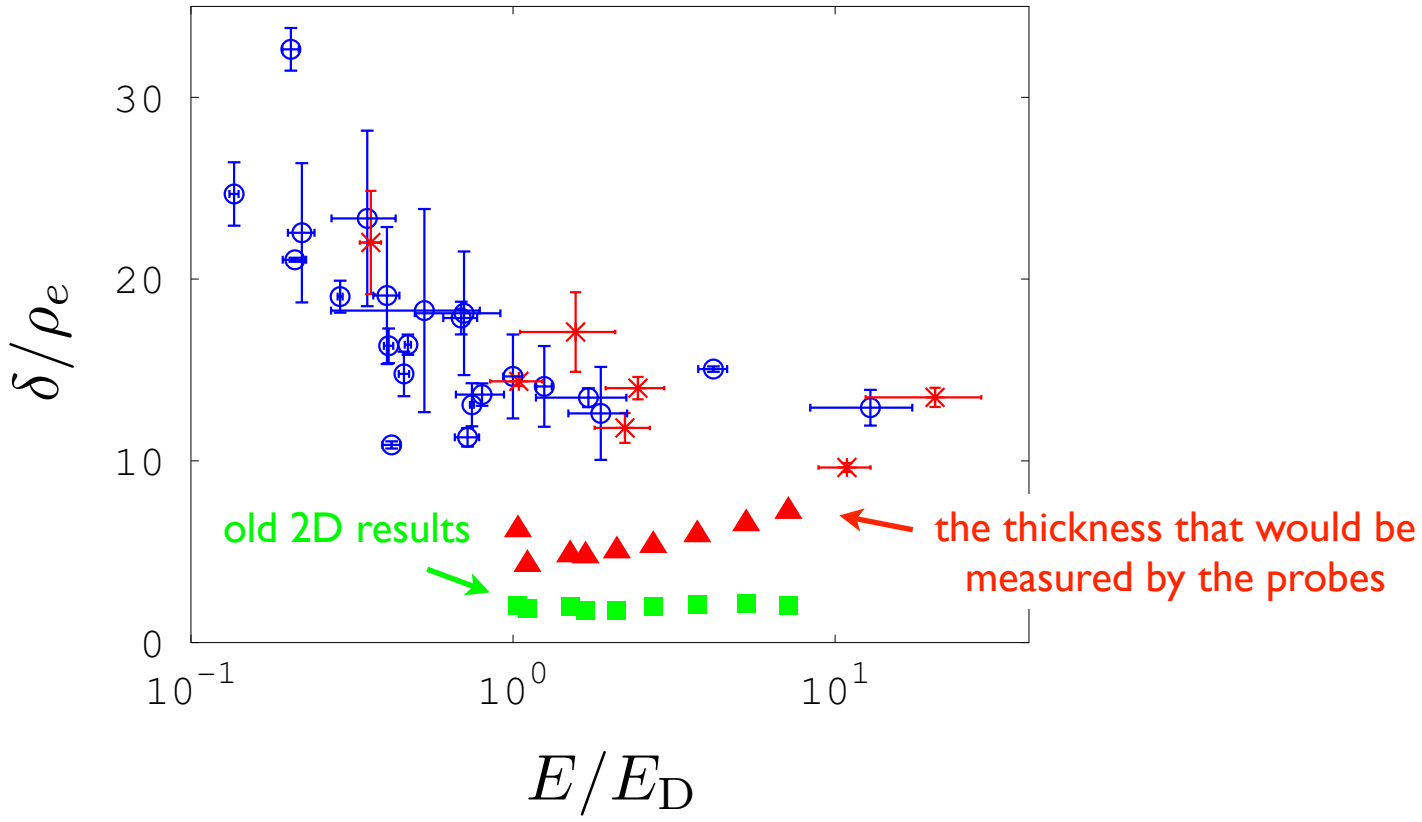
We started putting "probes" in the simulations



Effect of probes depends on the ratio between probe radius and layer thickness and is larger than previously estimated



“Corrected” measurements (preliminary)



Simulation data as would be seen by the probes (preliminary)