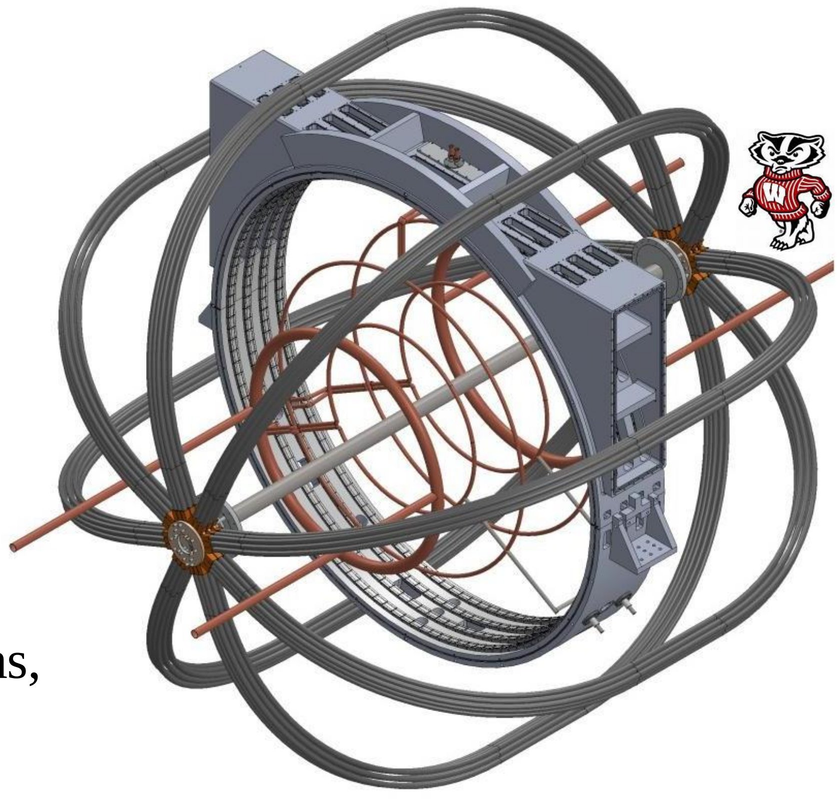
Pressure Anisotropy in Collisionless Reconnection



J Egedal, O Ohia, J Olson, Z Williams,
J Boguski, C Forest, W Daughton,
V. S. Lukin, J Wallace,
and the MPDX-team

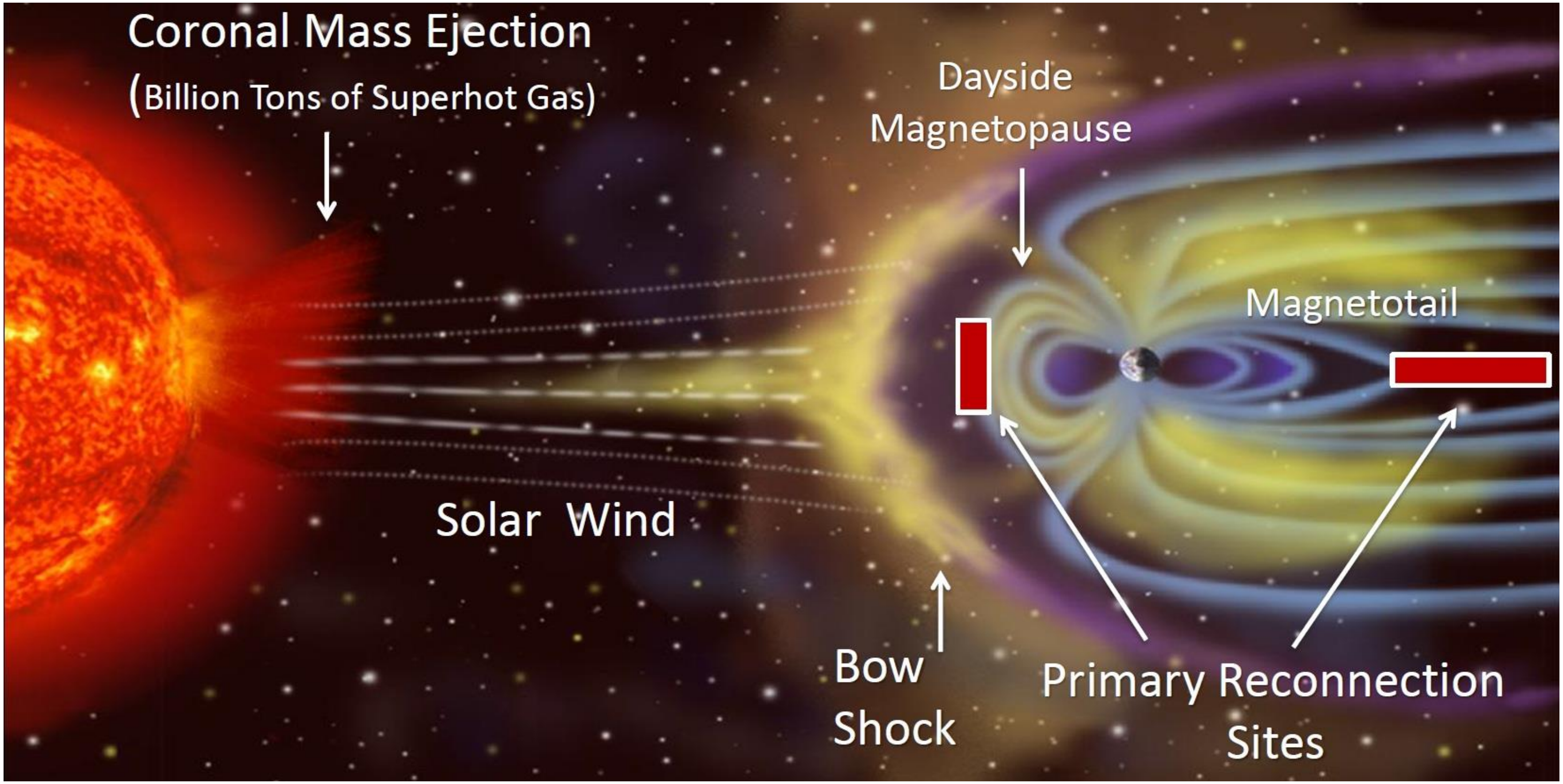
Physics Department, UW-Madison

THE UNIVERSITY of WISCONSIN MADISON

Outline

- Examples of Magnetic Reconnection
- Model for Electron Pressure Anisotropy
- Fixing the Fluid Equations (The Equations of State)
- Regimes of Reconnection
- Opportunities with TREX
- Conclusions

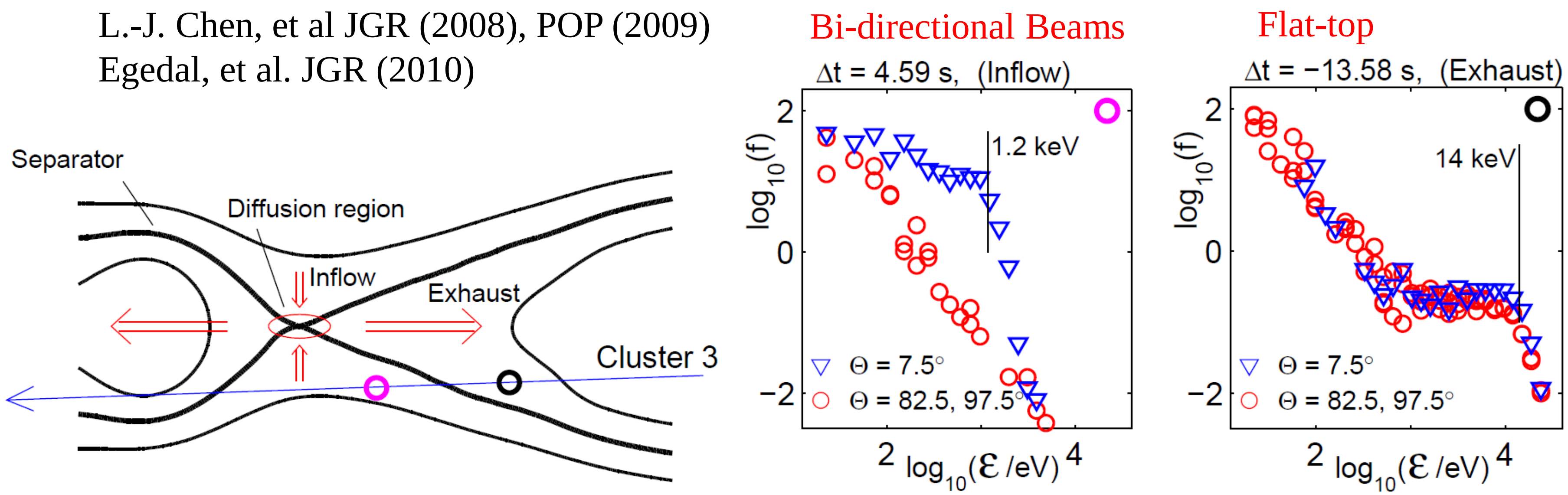
The Earth's Magnetic Shield



Spacecraft Observations of Reconnection

Cluster observations on 2001-10-01.

L.-J. Chen, et al JGR (2008), POP (2009)
Egedal, et al. JGR (2010)



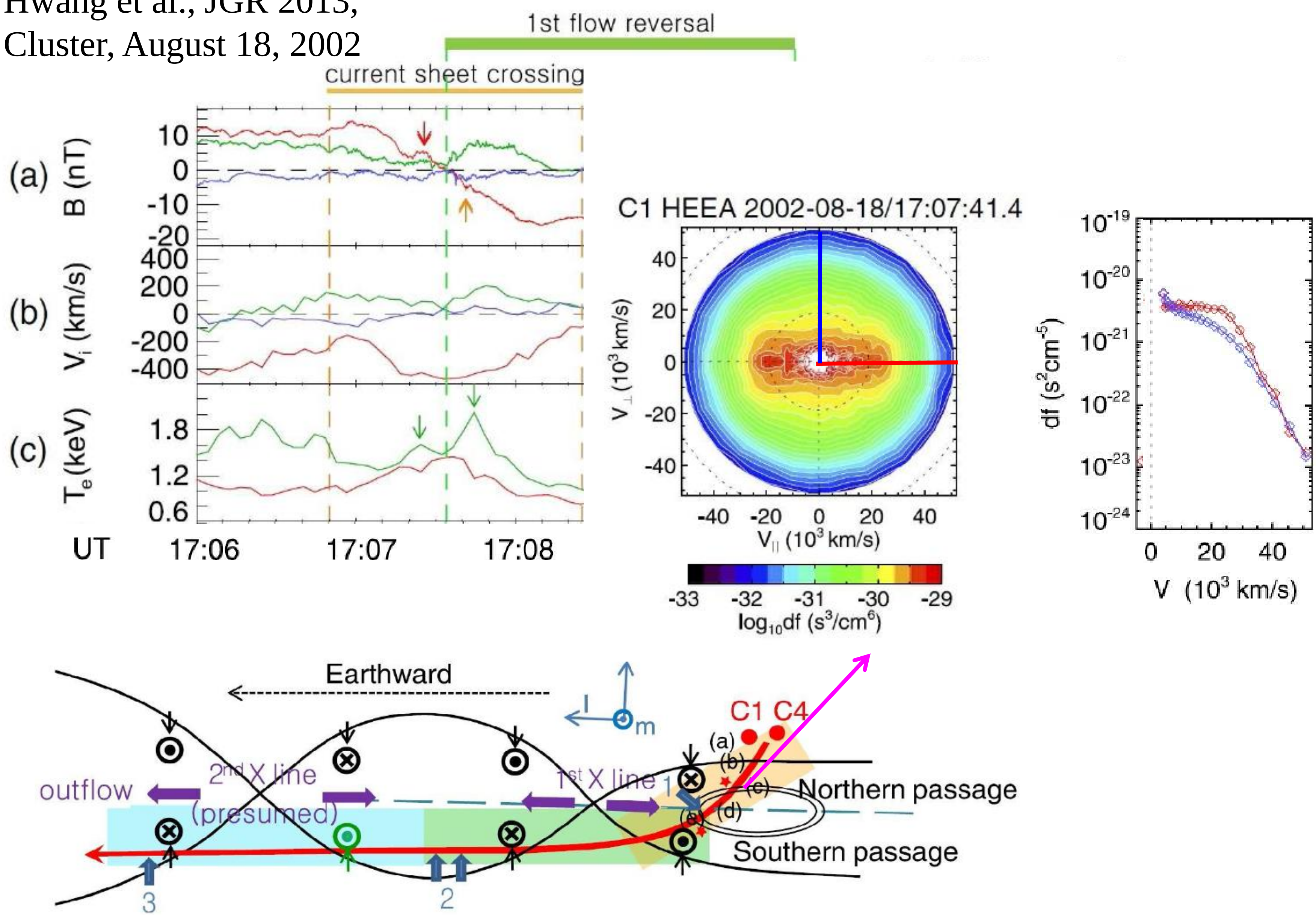
Lobe: $T_{e\infty}$ ~ 0.10 keV

Inflow: $T_{e\perp}$ ~ 0.10 keV, $T_{e\|}$ ~ 1 keV

Exhaust: $T_{e\perp} \sim T_{e\|} \sim$ 10keV = 100 $T_{e\infty}$

Another Cluster Event

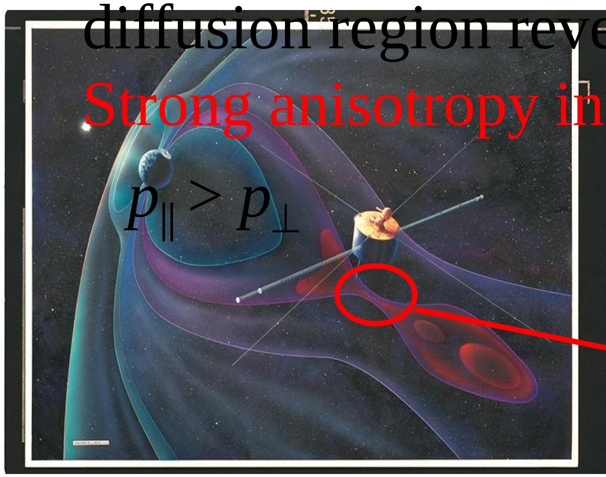
Hwang et al., JGR 2013,
Cluster, August 18, 2002

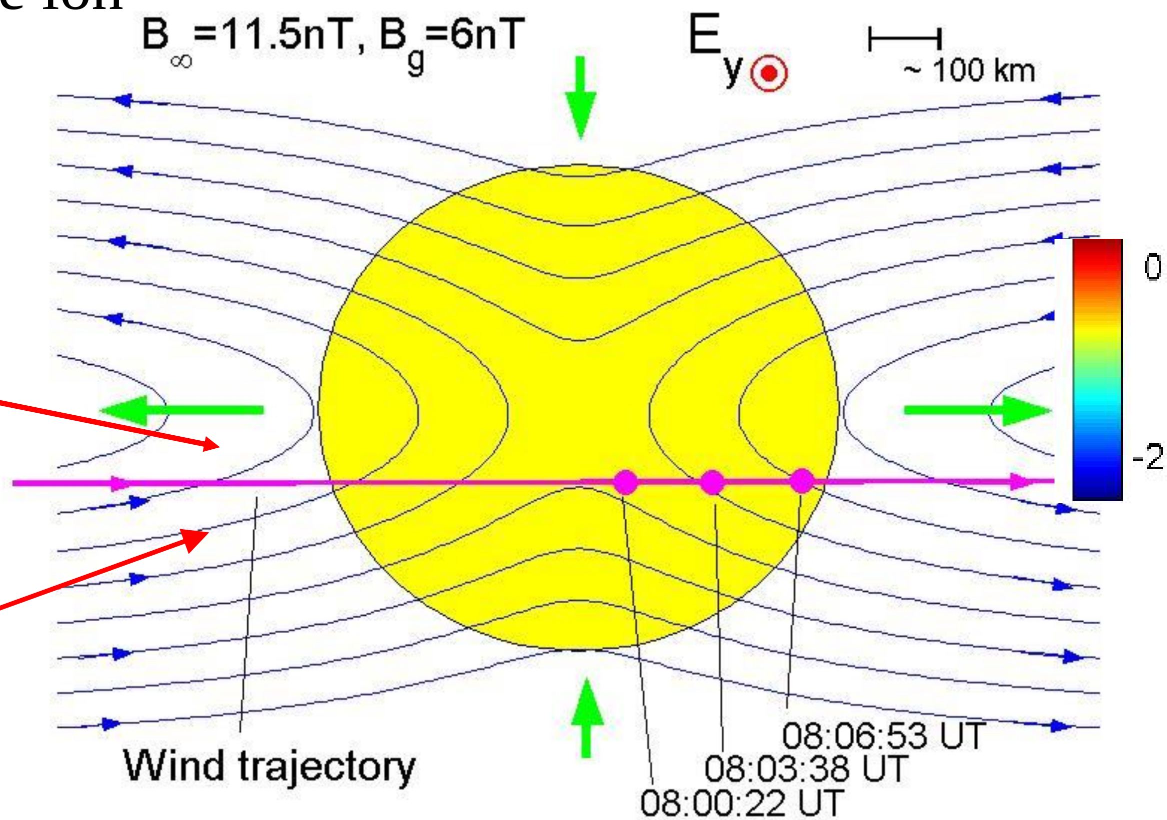


Wind Spacecraft Observations in Distant Magnetotail, 60R_E

- Measurements within the ion diffusion region reveal:
  - Strong anisotropy in f_e

$$p_{\|} > p_{\perp}$$

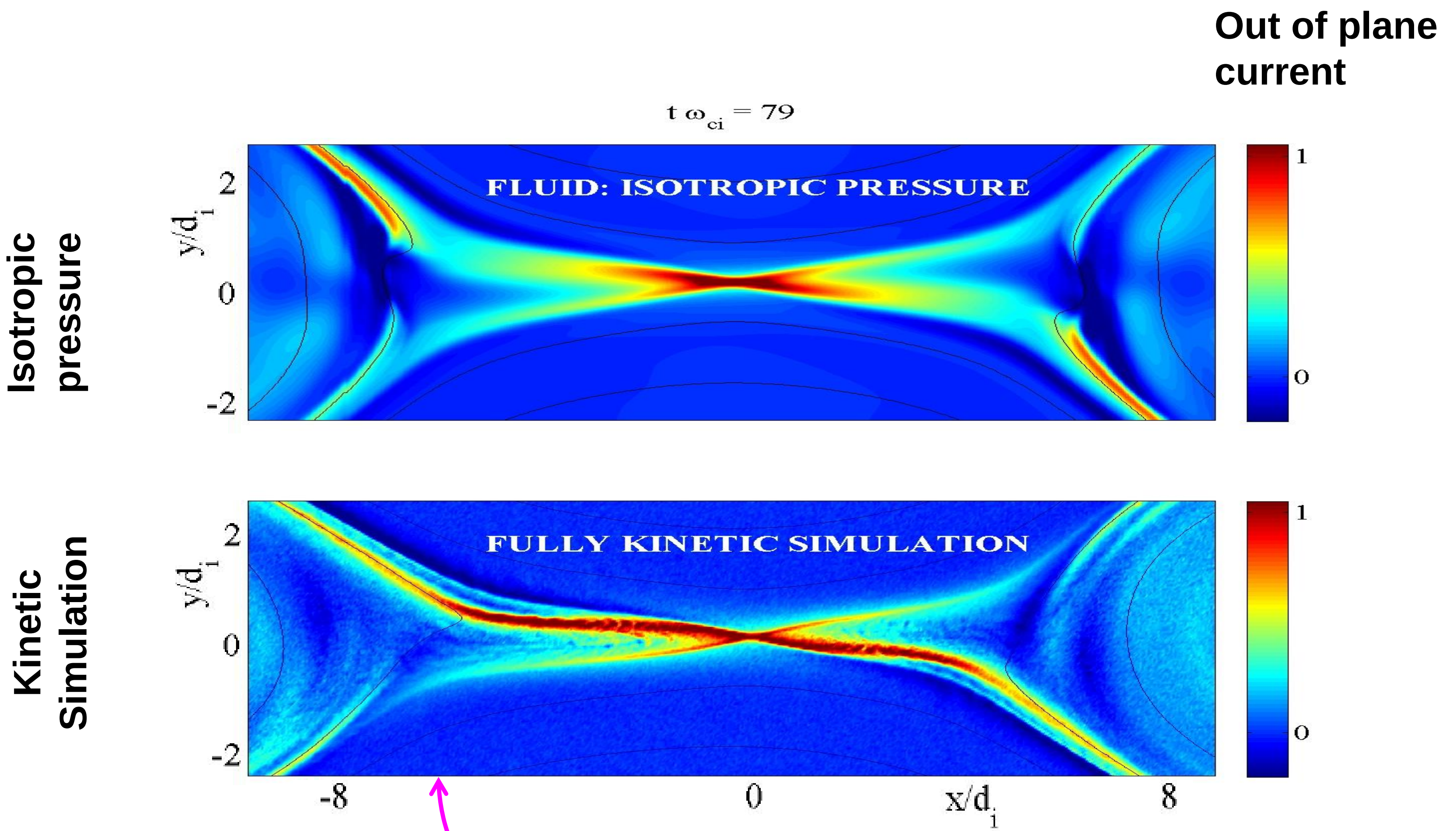




Outline

- Examples of Magnetic Reconnection
- Model for Electron Pressure Anisotropy
- Fixing the Fluid Equations (The Equations of State)
- Regimes of Reconnection
- Opportunities with TREX
- Conclusions

Two-Fluid vs Kinetic Simulations

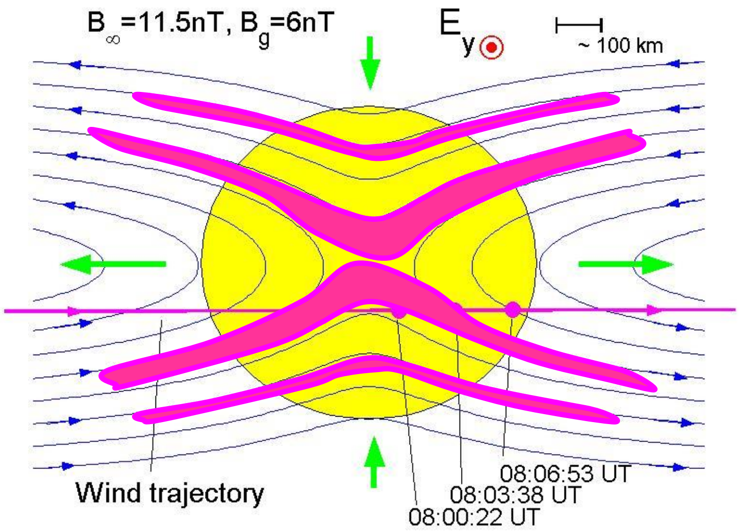


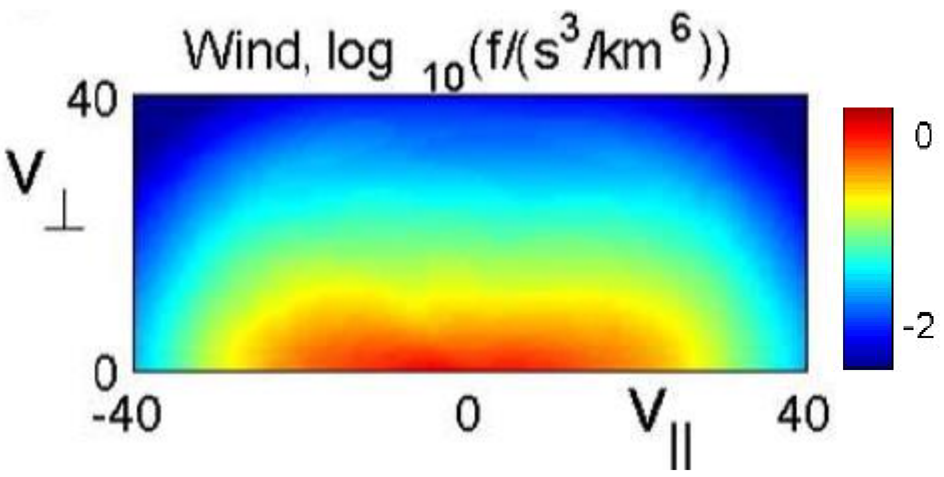
Particle In Cell (PIC) simulation,

Wind Spacecraft Observations in Distant Magnetotail, 60R_E

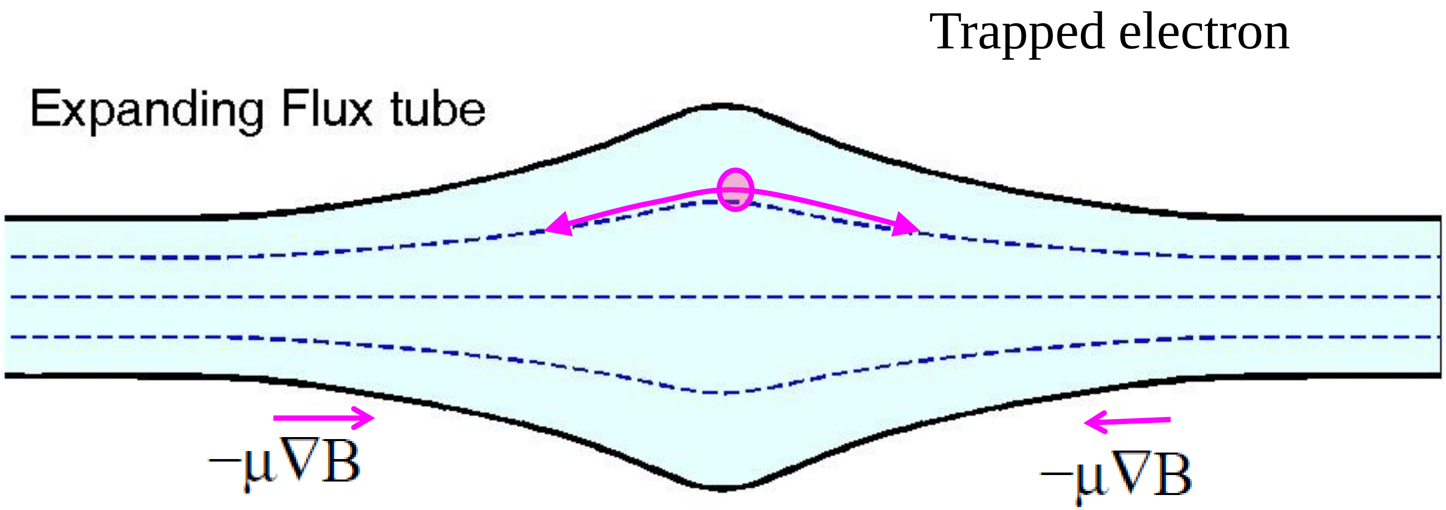
- Measurements within the ion diffusion region reveal:
  Strong anisotropy in f_e

  $p_{\|} > p_{\perp}$





Electrons in an Expanding Flux Tube

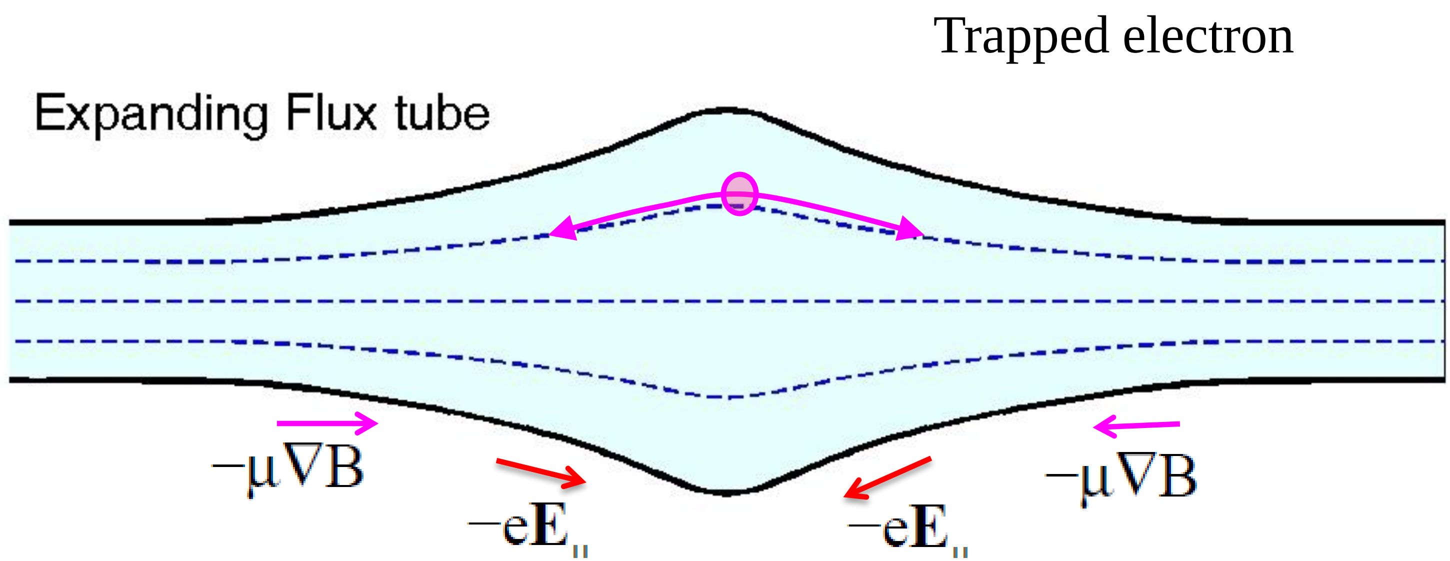


Magnetic moment:

$$\mu = \frac{m\mathrm{v}_{\perp}^{2}}{2B}$$

➔ mirror force:

Electrons in an Expanding Flux Tube

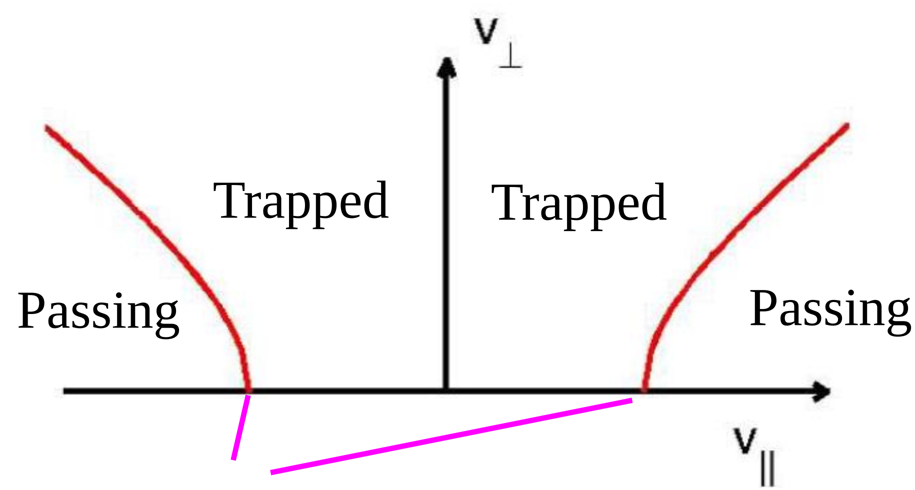


Magnetic moment:

$$\mu = \frac{m v_{\perp}^{2}}{2B}$$

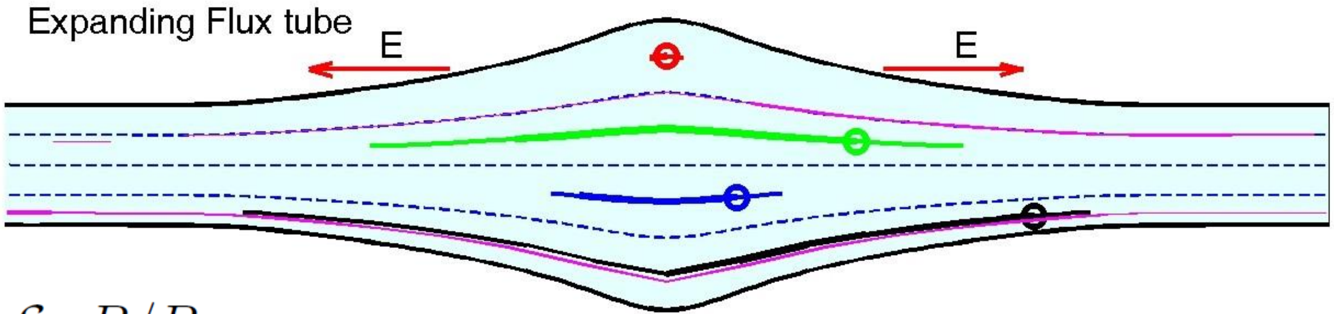
➔ mirror force:

$$\boxed{\Phi_{\parallel}(\mathbf{x}) = \int_{\mathbf{x}}^{\infty} \mathbf{E} \cdot d\mathbf{l}}$$



$$0.5 m v_{\parallel}^{2} = e\Phi_{\parallel}$$

Electrons in an Expanding Flux Tube



Trapped:

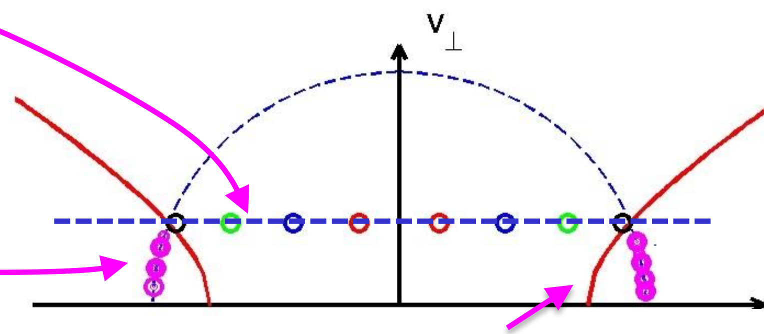
$$\mathcal{E}_\perp = \mu B = \mathcal{E}_\infty B/B_\infty$$

$$\implies \quad \underline{\mathcal{E}_\infty = \mu B_\infty}$$

Passing:

$$\mathcal{E} = \mathcal{E}_\infty + e\Phi_\|$$

$$\implies \quad \underline{\mathcal{E}_\infty = \mathcal{E} - e\Phi_\|}$$



$$\mathcal{E}_{\|\infty} = \mathcal{E} - e\Phi_\| - \mu B_\infty = 0$$

Vlasov:

$$\Phi_\|(\mathbf{x}) = \int_{\mathbf{x}}^{\infty} \mathbf{E} \cdot d\mathbf{l}$$

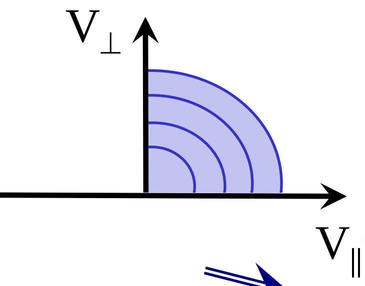
$$\frac{df}{dt} = 0$$

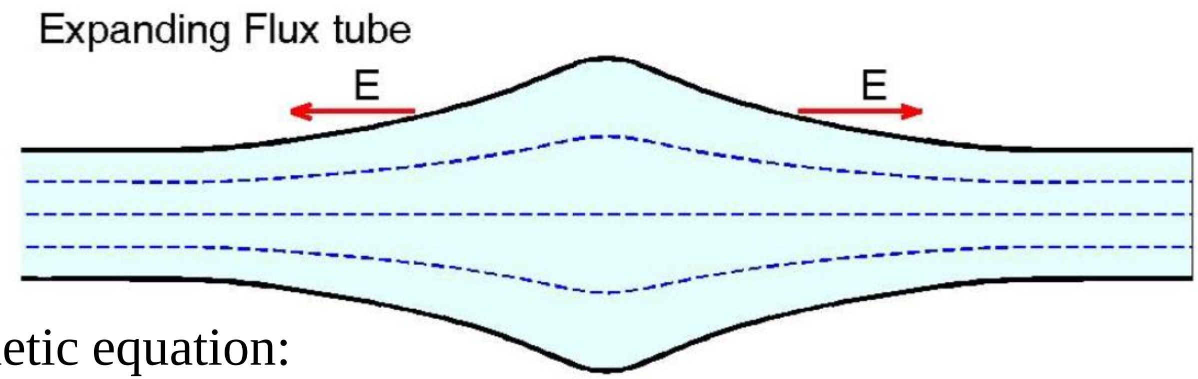
$$f(\mathbf{x}, \mathbf{v}) = f_\infty(\mathcal{E}_\infty)$$

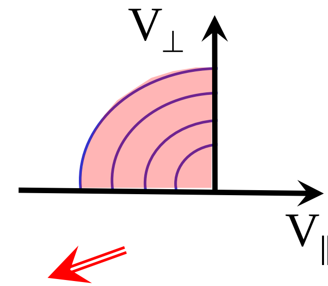
$$\boxed{f(\mathbf{x}, \mathbf{v}) = \begin{cases} f_\infty(\mathcal{E} - e\Phi_\|) & , \text{ passing} \\ f_\infty(\mu B_\infty) & , \text{ trapped} \end{cases}}$$

J. Egedal et al., JGR (2009)

Formal Derivation using an "Ordering"







The drift kinetic equation:

$$\frac{\partial f}{\partial t} + (\mathbf{v}_\parallel + \mathbf{v}_D)\cdot\nabla f + \left[\mu\frac{\partial B}{\partial t} + e(\mathbf{v}_\parallel + \mathbf{v}_D)\cdot\mathbf{E}\right]\frac{\partial f}{\partial \mathcal{E}} = 0$$

Boundary conditions:

$$B = B_\infty$$

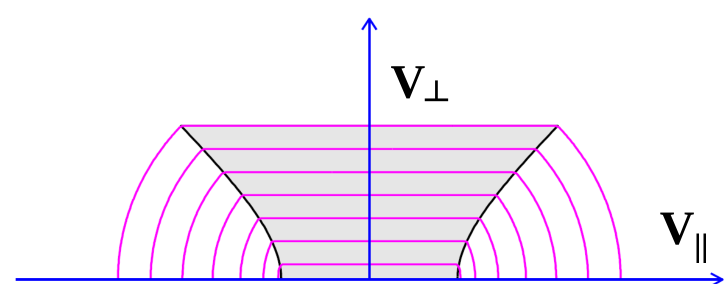
$$f = f_\infty(\mathcal{E}_{\parallel\infty}, \mathcal{E}_{\perp\infty})$$

Ordering:

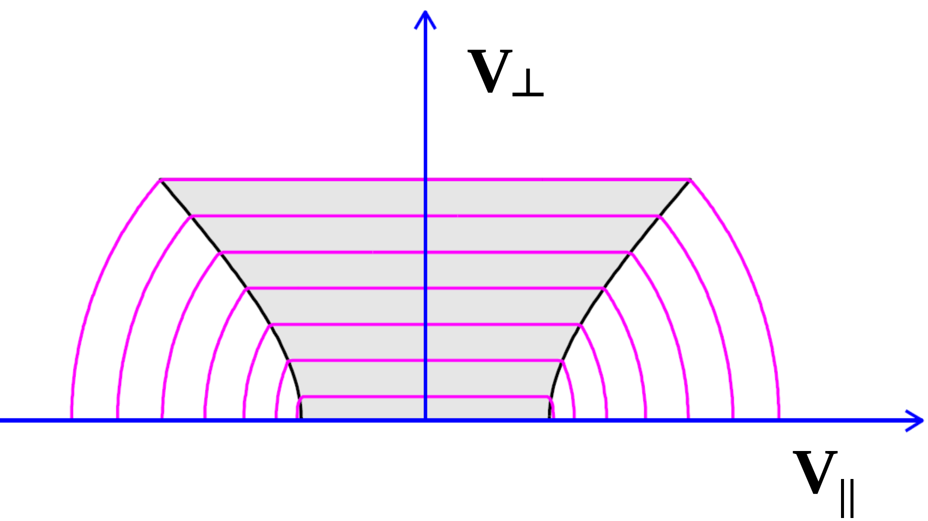
$$\nabla_\parallel \sim \frac{1}{L} \quad , \quad \nabla_\perp \sim \frac{1}{d} \quad , \quad \frac{\partial}{\partial t} \sim \frac{v_D}{d}$$

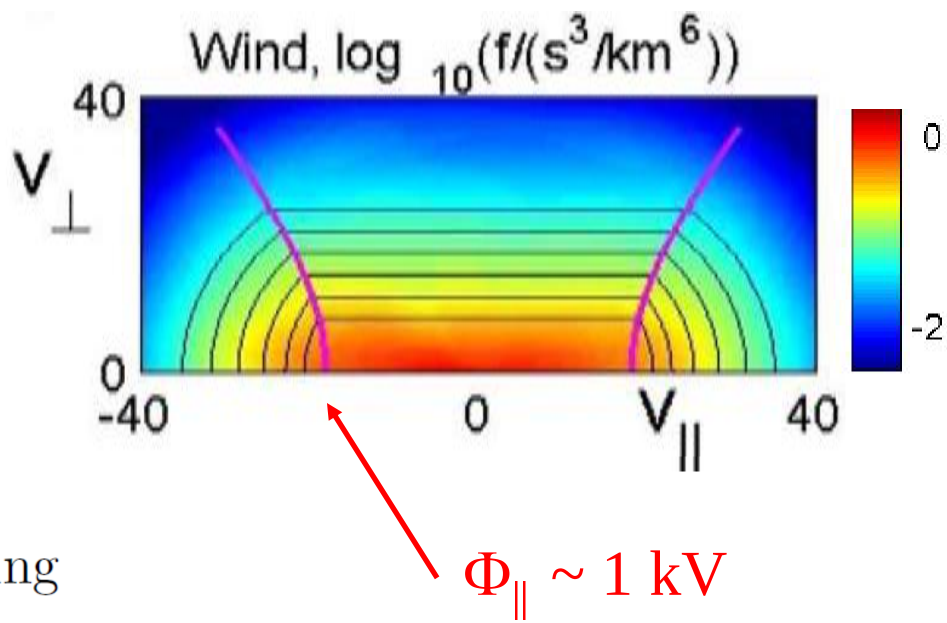
$$\frac{d}{L} \sim \delta \quad , \quad \frac{v_D}{v_t} \sim \delta^2 \qquad f = f_0 + \delta f_1 + \ldots$$

$$\boxed{f_0(\mathbf{x},\mathbf{v}) = \begin{cases} f_\infty(\mathcal{E} - e\Phi_\parallel) & , \ \text{passing} \\ f_\infty(\mu B_\infty) & , \ \text{trapped} \end{cases}}$$



Wind Spacecraft Observations in Distant Magnetotail, 60R_E





$$f(\mathbf{x},\mathbf{v}) = \begin{cases} f_\infty(\mathcal{E} - e\Phi_\parallel) & , \text{ passing} \\ f_\infty(\mu B_\infty) & , \text{ trapped} \end{cases}$$

Field Structure at Full Mass Ratio (P. Pritchett)

Onset of magnetic reconnection in the presence of a normal magnetic field: Realistic ion to electron mass ratio

P. L. Pritchett[1]
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, A10208, doi:10.1029/2010JA015371, 2010

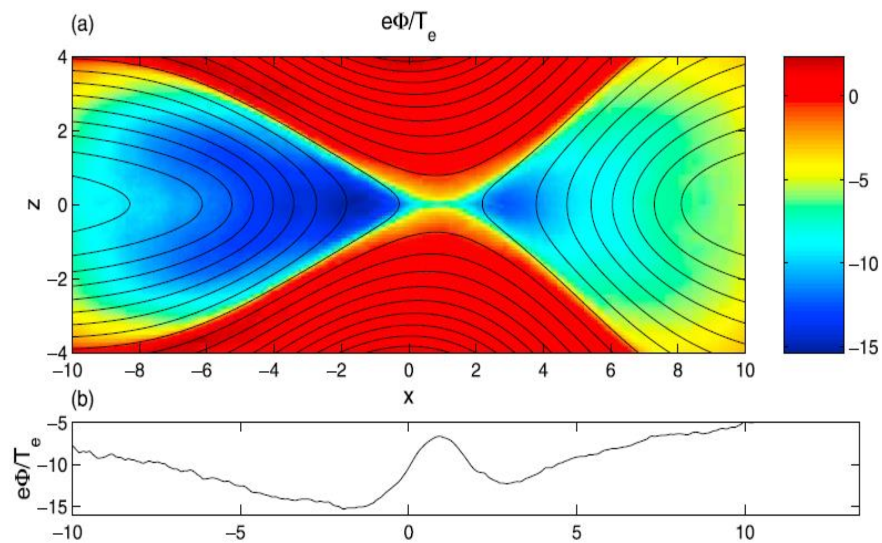


Figure 6. The electrostatic potential $e\Phi/T_e$ at time $\Omega_{i0}t = 40$ for the simulation with $m_i/m_e = 1600$ in (a) the x, z plane and (b) as a profile along x at $z = 0$.

[19] Figure 8a shows the parallel potential $\Phi_{\|}$ computed from the field $E_{\|}$ by the definition [*Egedal et al.*, 2009]

$$\Phi_{\|}(\mathbf{x}) = \int_{\mathbf{x}}^{\infty} \mathbf{E} \cdot d\ell, \tag{3}$$

where the integration is carried out from the point $\mathbf{x}$ along the magnetic field to the boundary of the simulation box. Note that $\Phi_{\|}$ contains contributions from both the electrostatic and inductive electric fields.

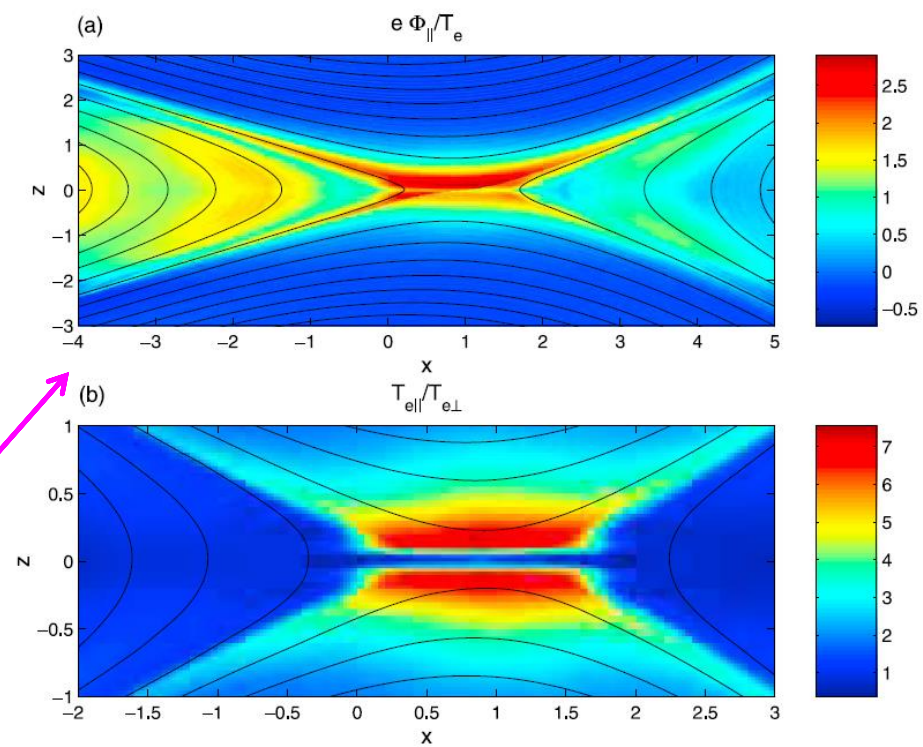


Figure 8. Structure at time $\Omega_{i0}t = 40$ for the simulation with $m_i/m_e = 1600$ for (a) the parallel potential $e\Phi_{\|}/T_e$ and (b) the electron temperature anisotropy $T_{e\|}/T_{e\perp}$.

Outline

- Examples of Magnetic Reconnection
- Model for Electron Pressure Anisotropy
- Fixing the Fluid Equations (The Equations of State)
- Regimes of Reconnection
- Opportunities with TREX
- Conclusions

Upshot: New Fluid Closure (EoS)

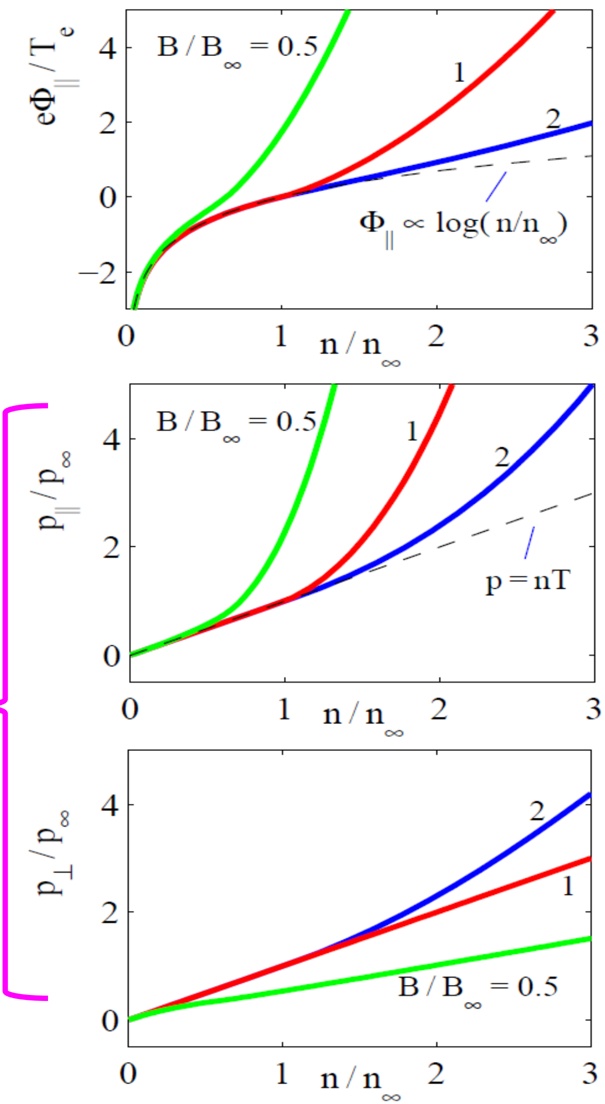
$$f(\mathbf{x},\mathbf{v}) = \begin{cases} f_\infty(\mathcal{E} - e\Phi_{||}) & , \text{ passing} \\ f_\infty(\mu B_\infty) & , \text{ trapped} \end{cases}$$

$\int \ldots d^3v$

$$\begin{cases} n = n(B,\Phi_{||}) \\ p_{||} = p_{||}(B,\Phi_{||}) \\ p_\perp = p_\perp(B,\Phi_{||}) \end{cases}$$

Eliminate $\Phi_{||}$ ➔

$$\begin{cases} p_{||} = p_{||}(n,B) \\ p_\perp = p_\perp(n,B) \end{cases}$$



➔ $\Phi_{||} \gg T_e$

$$p_{||} \propto \frac{n^3}{B^2}$$

$$p_\perp \propto nB$$

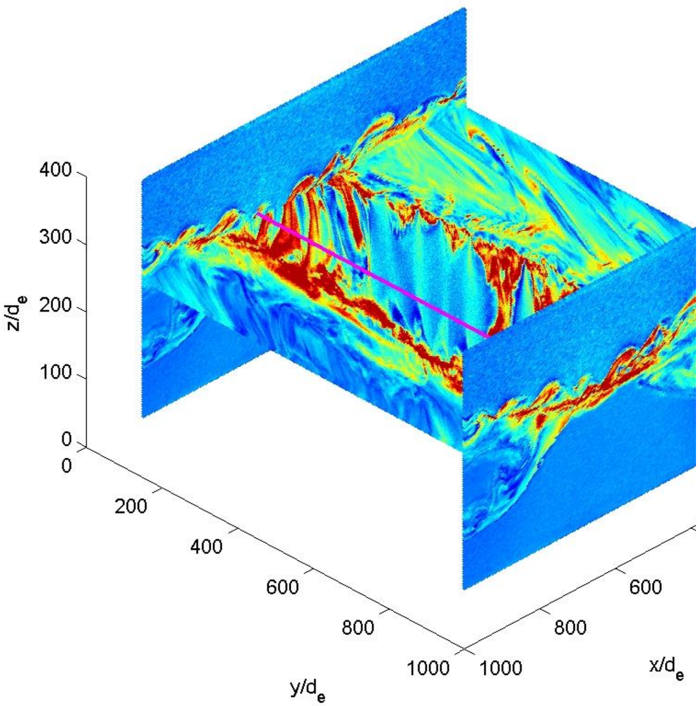
Smooth transition from Boltzmann to double adiabatic (Chew, Goldberger, FE… Low) scaling

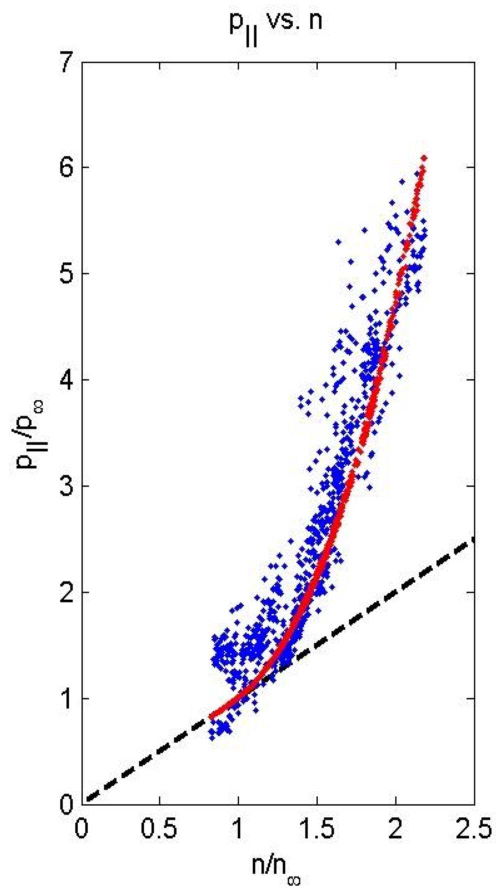
A. Le et al., PRL (2009)

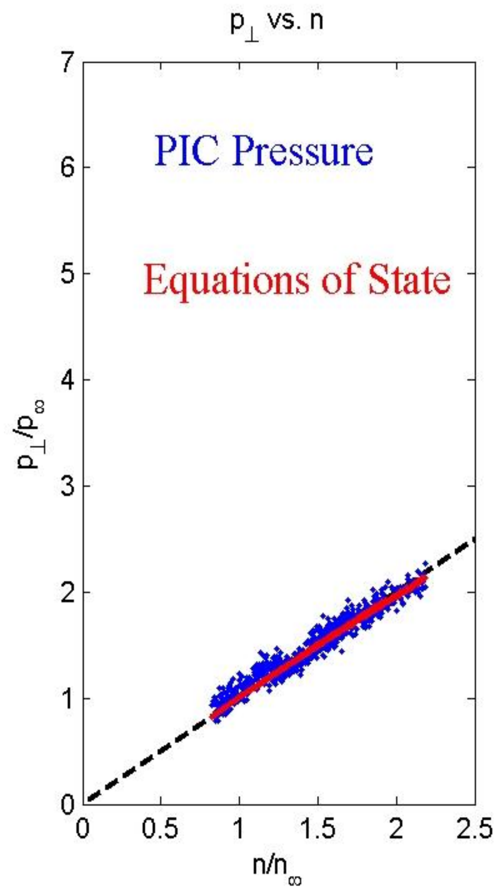
Confirmed in Kinetic Simulations

EoS previously confirmed in 2D simulations,
now also in 3D simulations.

$p_{\|} / p_{\perp}$



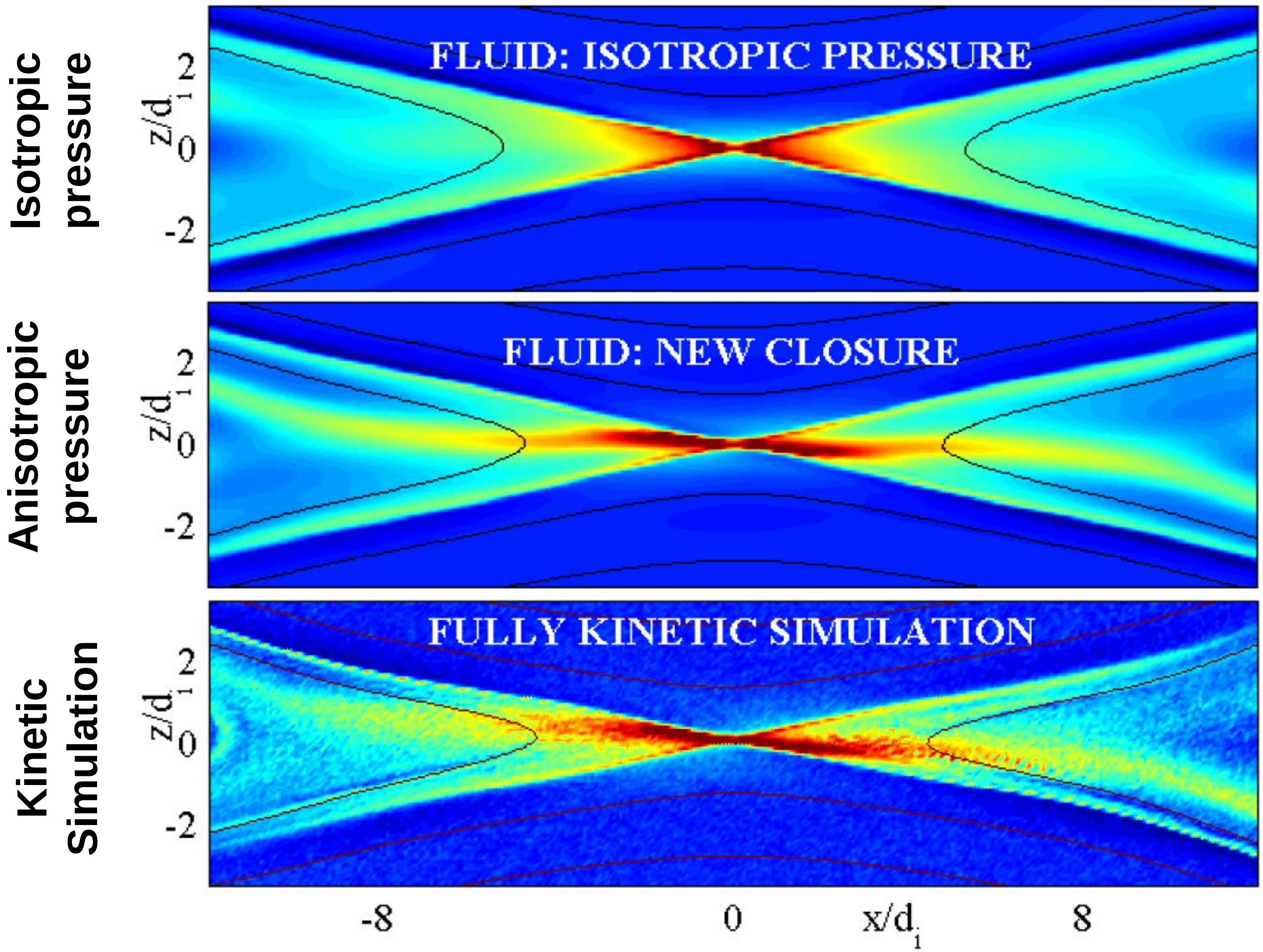




New *EoS* Implemented in Two-Fluid Code

Ohia et al., PRL, 2012

Out of plane current



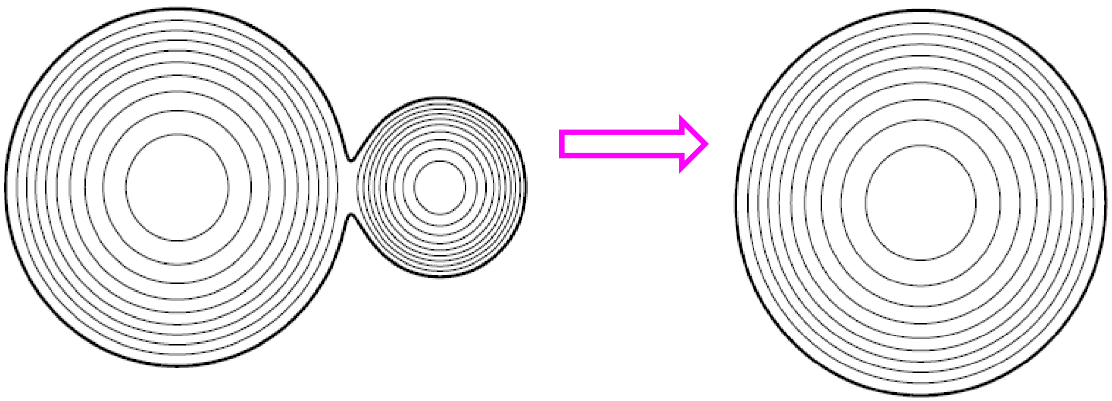
Model for islands?

J. F. Drake[1], M. Swisdak[1], R. Fermo[2]

$$\frac{\partial}{\partial t} f + R\left(\frac{\partial}{\partial v_{\|}} v_{\|} - \frac{\partial}{\partial v_{\perp}^2} v_{\perp}^2\right) f$$

$$= \nu \frac{\partial}{\partial \zeta} \left(1-\zeta^2\right) \frac{\partial}{\partial \zeta} f - \frac{c_{Aup}}{L} f + \dot{A}_T f_{up}$$

$$R = -\dot{B}/B$$

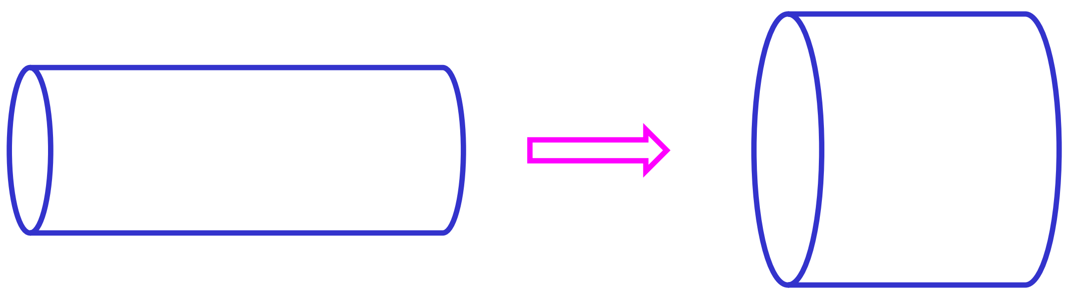


Conserved quantities:

$\mu = m v_{\perp}^2 / B$

$\oint v_{\|} d\ell$

Area, flux, density:



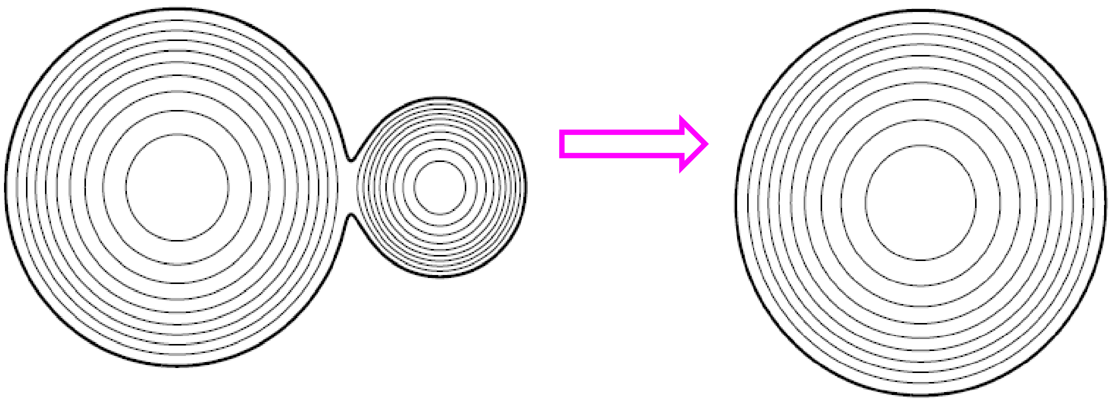
Model for islands?

J. F. Drake[1], M. Swisdak[1], R. Fermo[2]

$$\frac{\partial}{\partial t} f - \left(\frac{\partial}{\partial t}\ln(B)\right)\left(\frac{\partial}{\partial v_\parallel} v_\parallel - \frac{\partial}{\partial v_\perp^2} v_\perp^2\right) f$$

$$- \left(\frac{\partial}{\partial t}\ln(n)\right)\left(1 - \frac{\partial}{\partial v_\parallel} v_\parallel\right) f \ = 0:$$

$$= \nu \frac{\partial}{\partial \zeta}(1-\zeta^2)\frac{\partial}{\partial \zeta} f - \frac{C_{Aup}}{L} f + \dot{A}_T f_{up}$$



In 2D = 0:

Integrates to CGL!

$$p_\parallel \propto \frac{n^3}{B^2}$$

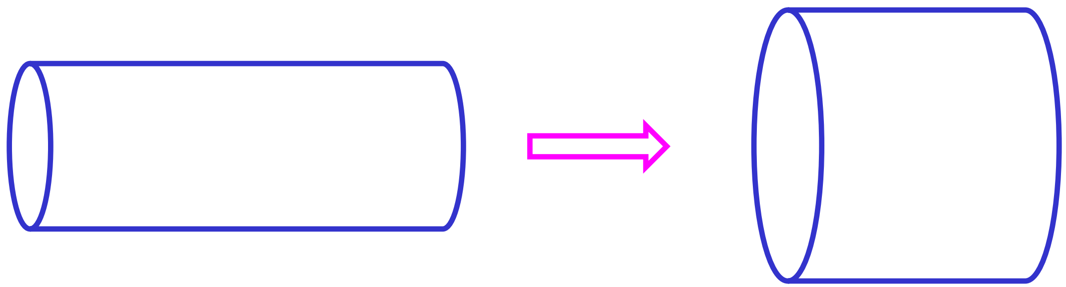
$$p_\perp \propto nB$$

Conserved quantities:

$\mu = m v_\perp^2 / B$

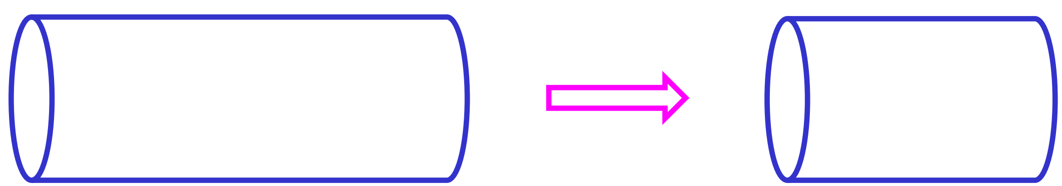
$\oint v_\parallel d\ell$

Area, flux, density:



Generalize:

B-constant, change n:

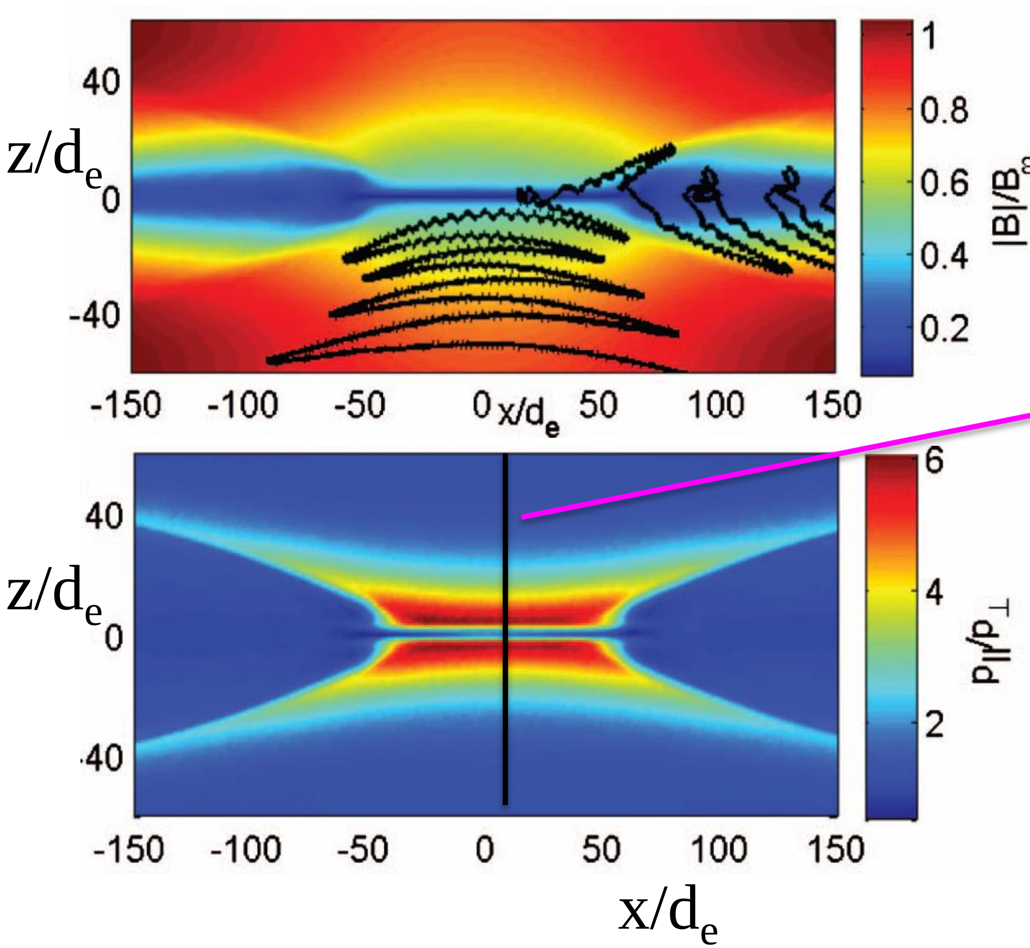


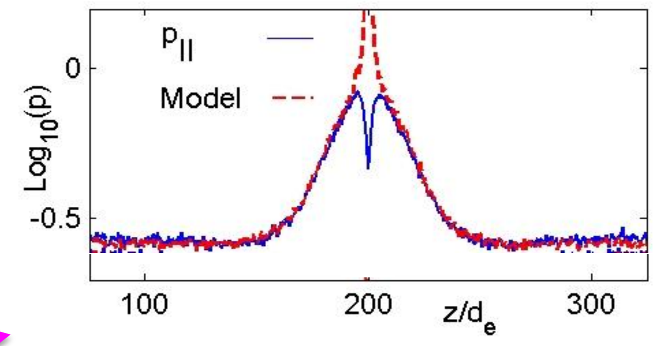
Outline

- Examples of Magnetic Reconnection
- Model for Electron Pressure Anisotropy
- Fixing the Fluid Equations (The Equations of State)
- Regimes of Reconnection
- Opportunities with TREX
- Conclusions

EoS for Anti-Parallel Reconnection?

The electrons are magnetized in the inflow region:





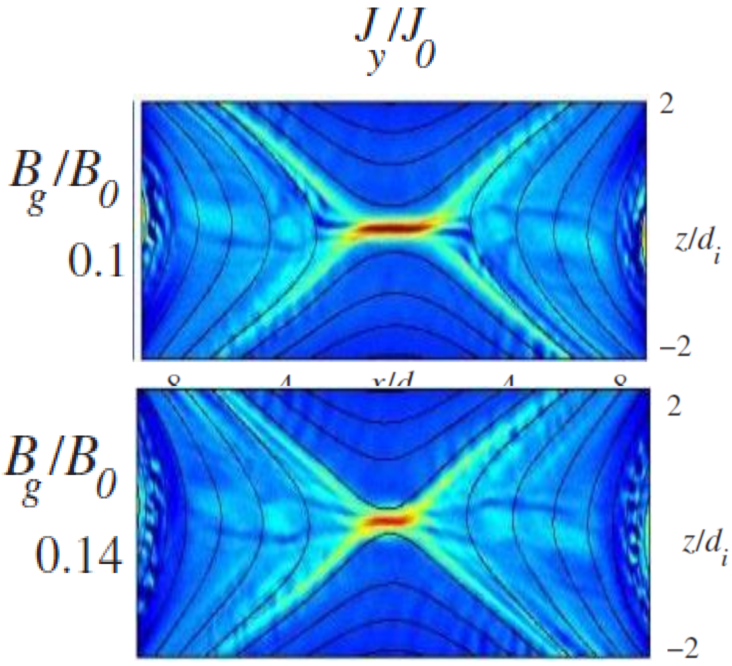
Pitch angle diffusion is controlled by:

$$\kappa = \sqrt{R_B/\rho_e}$$

Depends on B_g and m_i/m_e

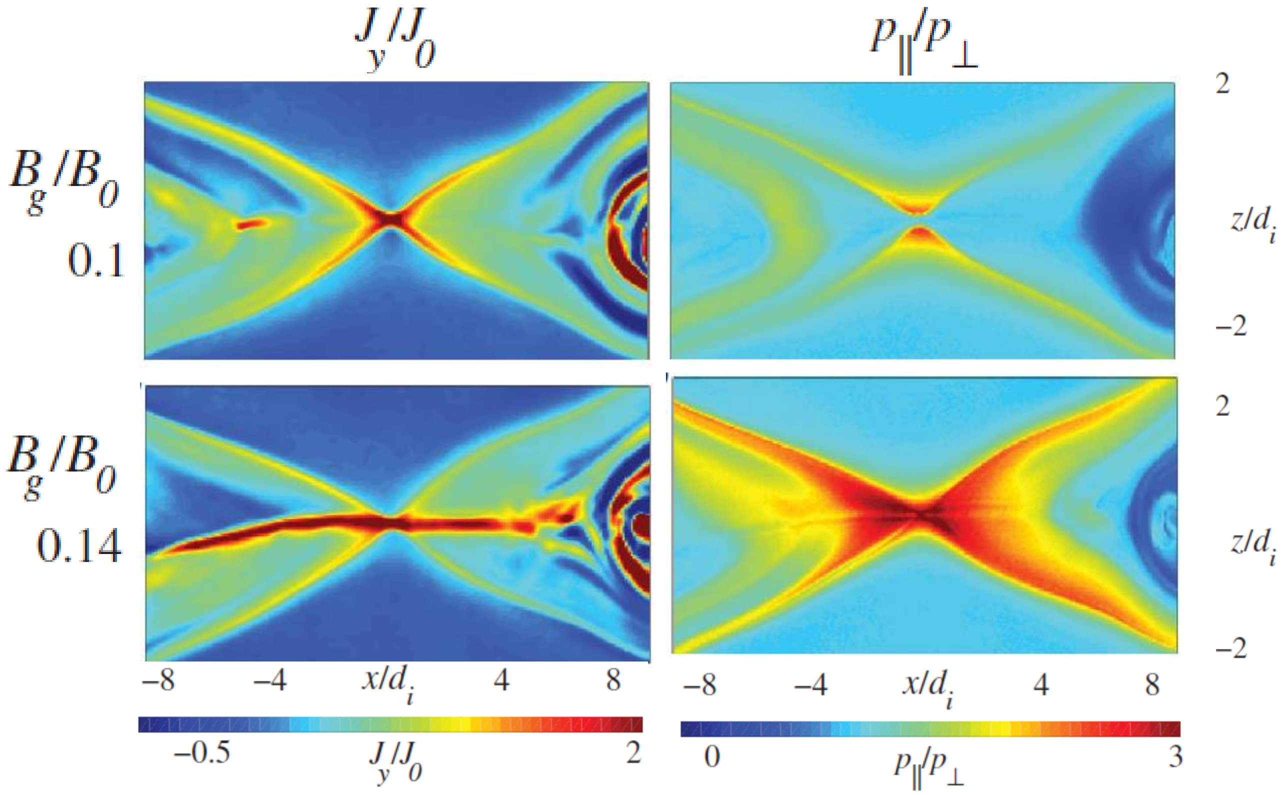
Where does Guide-Field Reconnection Begin?

Kinetic simulation results at $m_i / m_e = 400$, [A Le et al., PRL 2013]



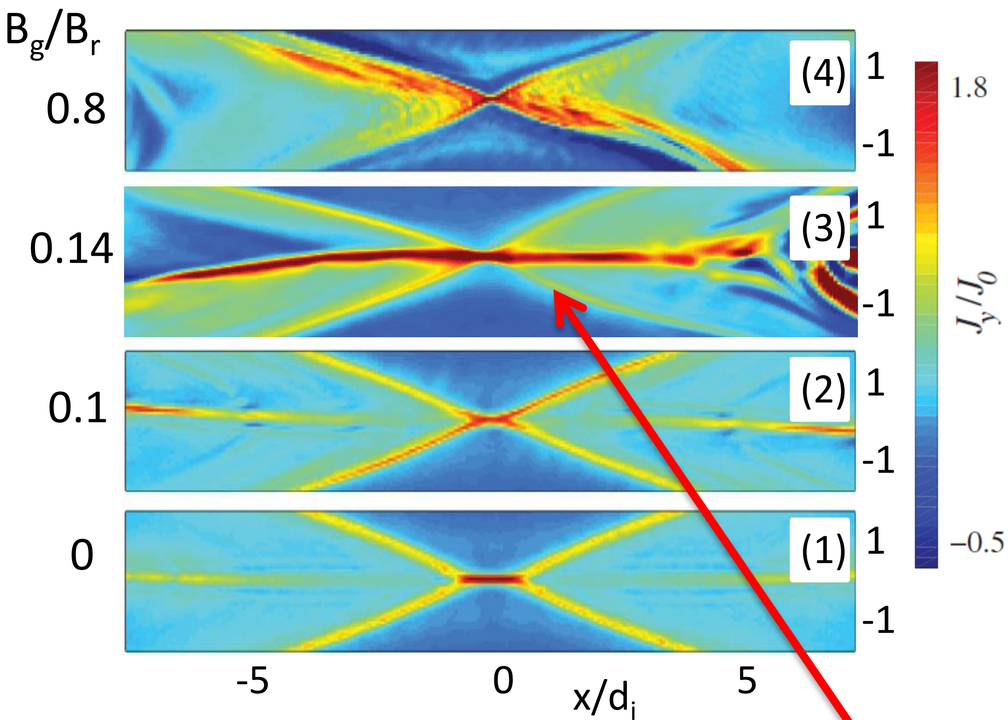
Where does Guide-Field Reconnection Begin?

Kinetic simulation results at $m_i / m_e = 1836$, [A Le et al., PRL 2013]

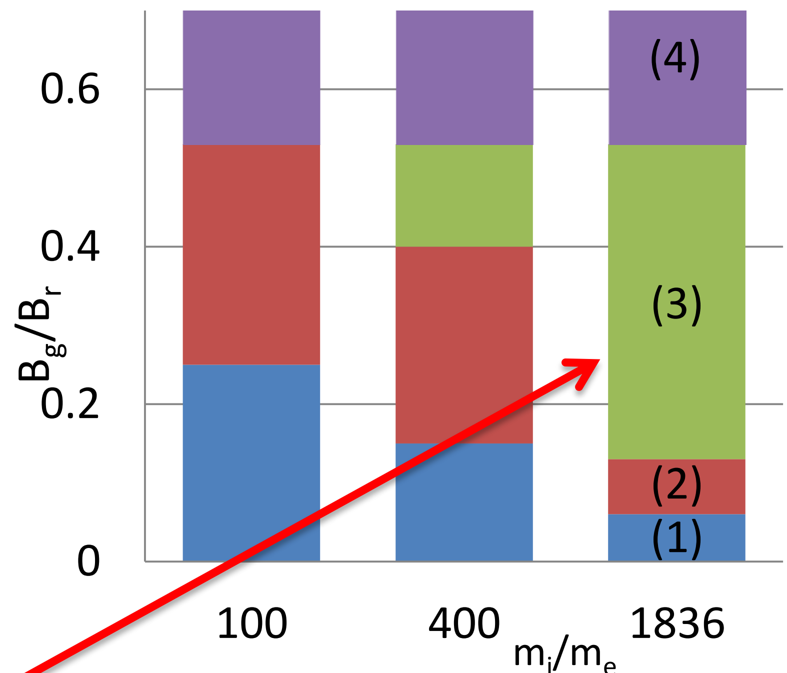


Regimes of the Electron Diffusion Region

J_y in PIC simulations at m_i/m_e = 1836

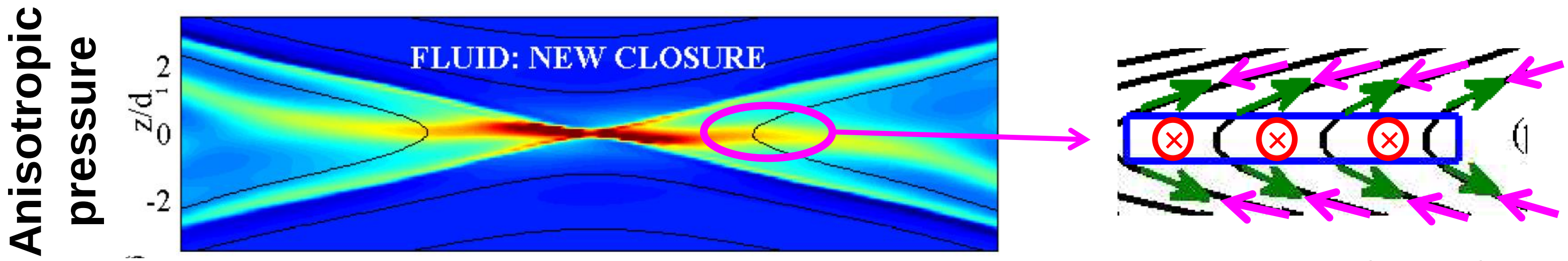


Regimes of reconnection vs. m_i/m_e and B_g



Unexplored regime of reconnection, relevant to the MMS mission

Scaling Law for Electron Heating



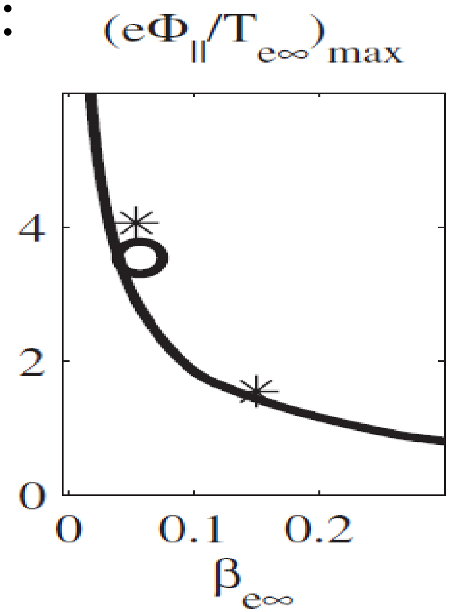
$p_{\|} - p_{\perp}$

Additional current term:

$$J_{\perp \text{extra}} = [(p_{\|} - p_{\perp})/B]\hat{b}\times\hat{b}\cdot\nabla\hat{b}$$

The magnetic tension is balanced by pressure anisotropy:

$$p_{\|}(n,B) - p_{\perp}(n,B) = B^2/\mu_0$$

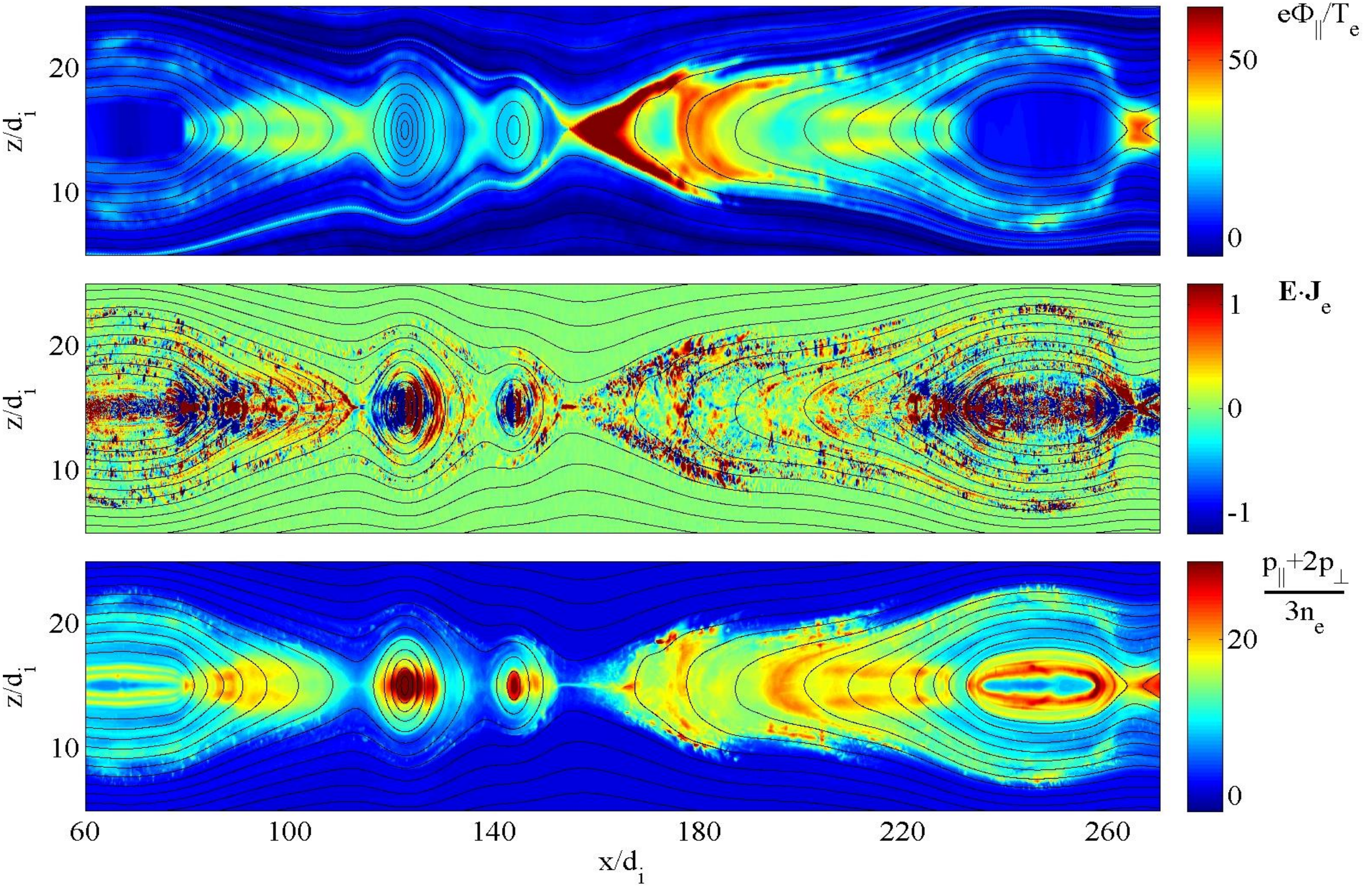


Use *EoS* to get scaling laws:

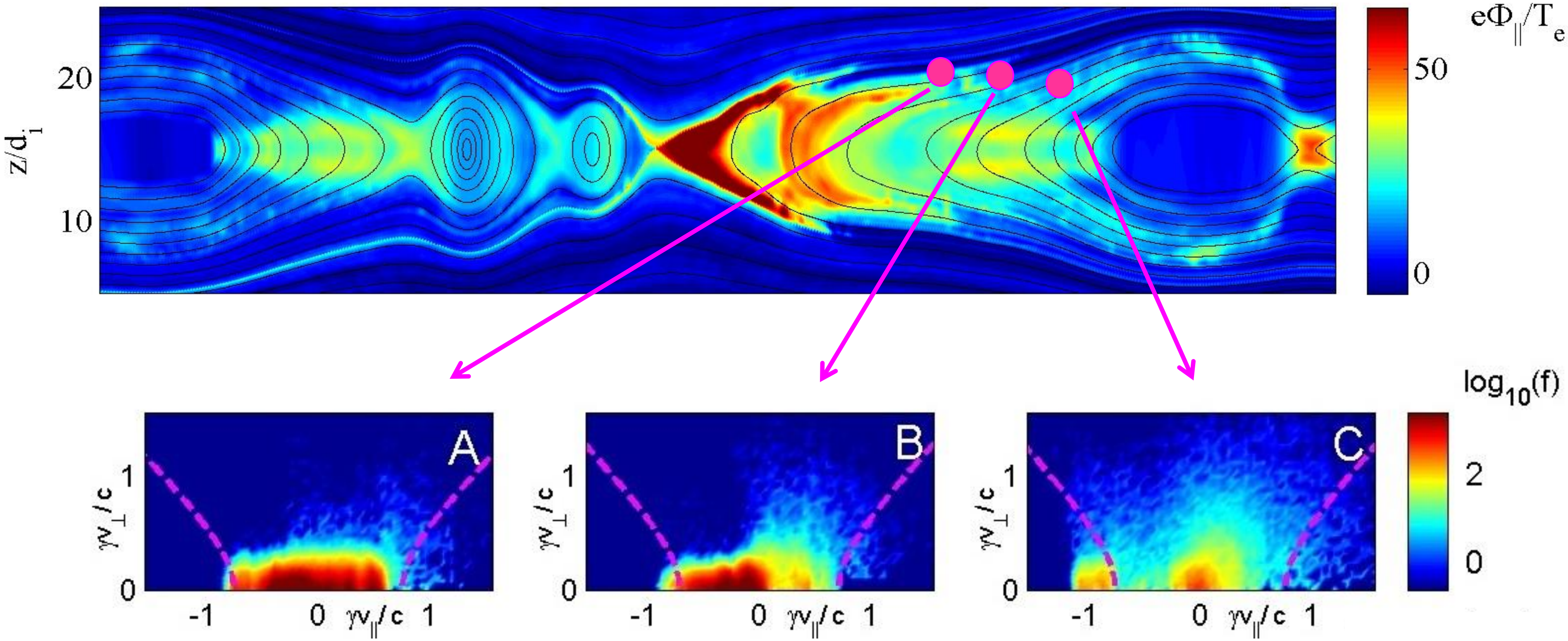
$$\beta_{e\infty} = \frac{\text{plasma pressure}}{\text{magnetic pressure}}$$

Magnetotail: $\beta_{e\infty} = 0.003$

Simulation with $\beta_e \sim 0.003$



Spacecraft Distributions Reproduced



J. Egedal et al., Nature Physics (2012)

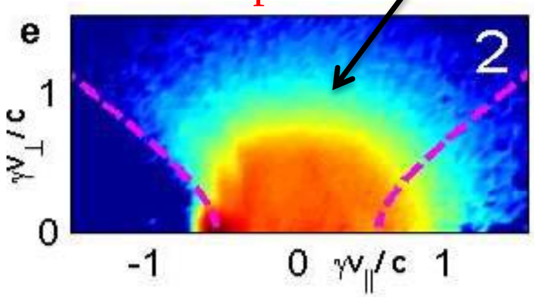
$\Phi_{\|}$ confines electrons, allowing sustained energization by $E_{\perp}$

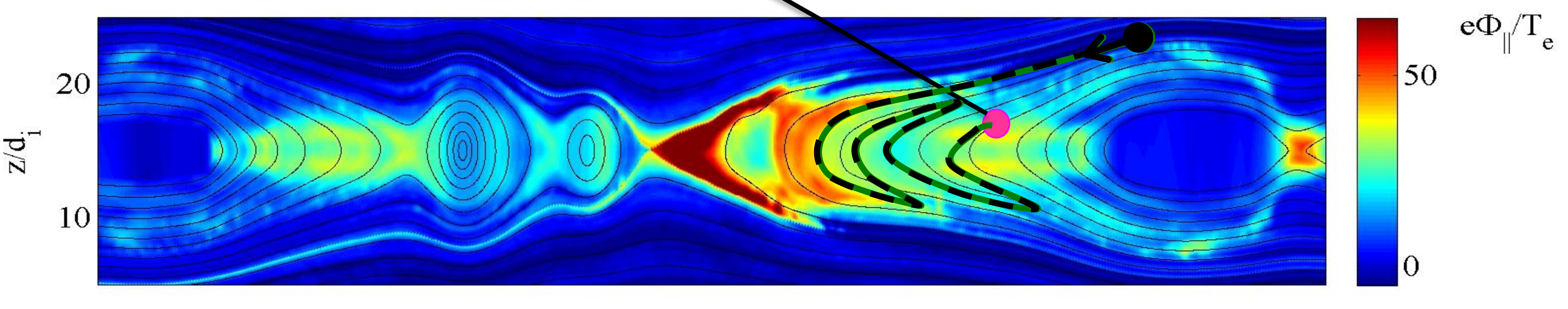
Trapped region with pitch angle scattering

Heated by $\mathbf{v}_d \cdot \mathbf{E}_{\perp}$,

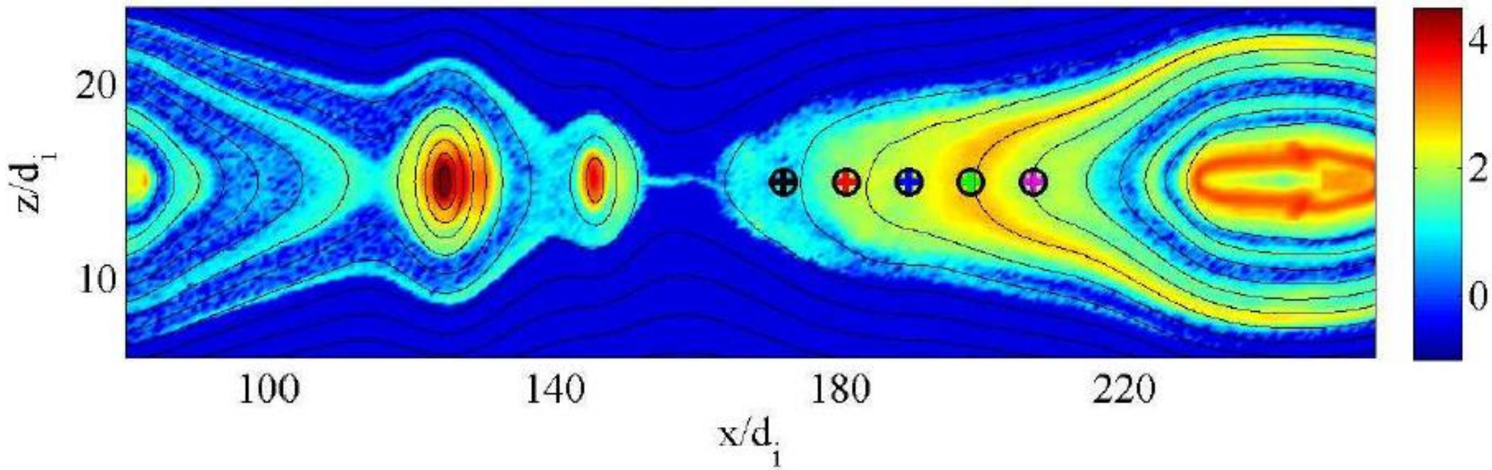
$$\frac{\partial v}{\partial t} \simeq \frac{v_A}{\tau_b}$$

Flat-top

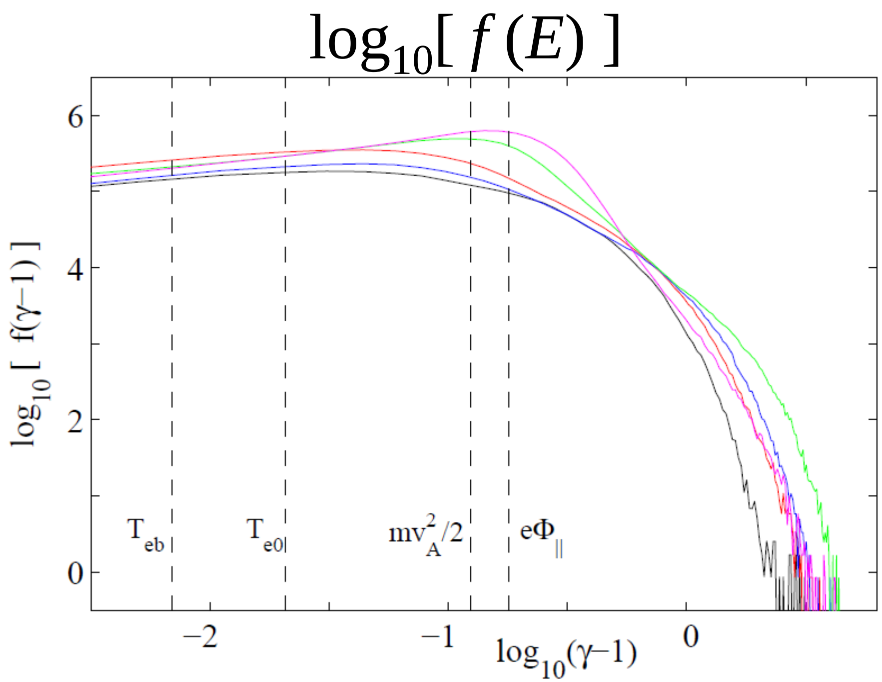


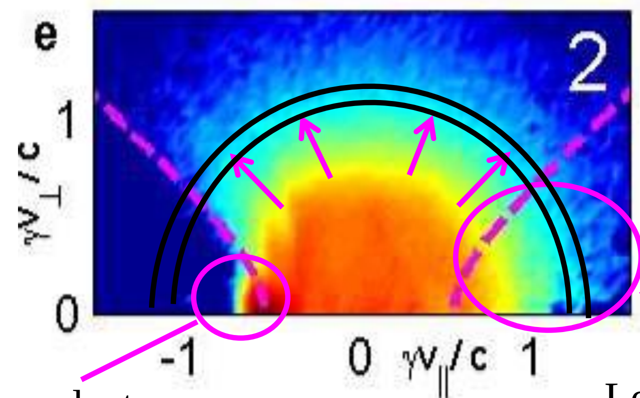


Generation of Super-Thermals



$\log_{10}$ (# of electrons with energies above $1.7mc^2$)





$$\Gamma_v \;=\; f\,4\pi v^2 \frac{\partial v}{\partial t}$$

$$\frac{\partial v}{\partial t} \simeq \frac{v_A}{\tau_b}$$

New electrons

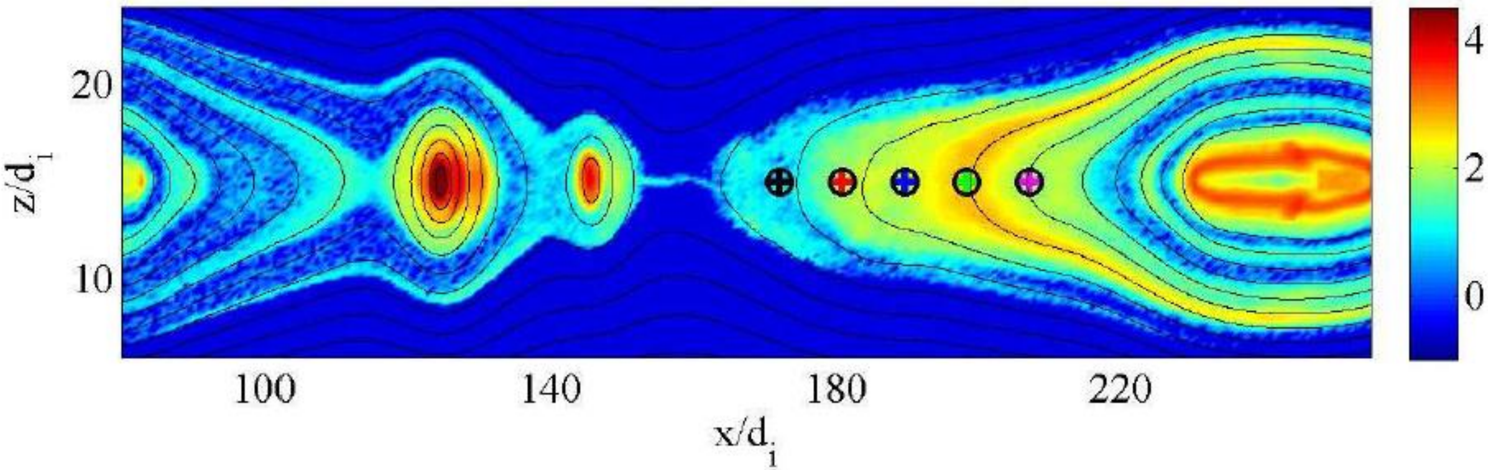
Lost electrons

$$\Gamma_l = dv\, f\, \frac{4\pi v^2}{\tau_b} R_{\text{loss}}$$

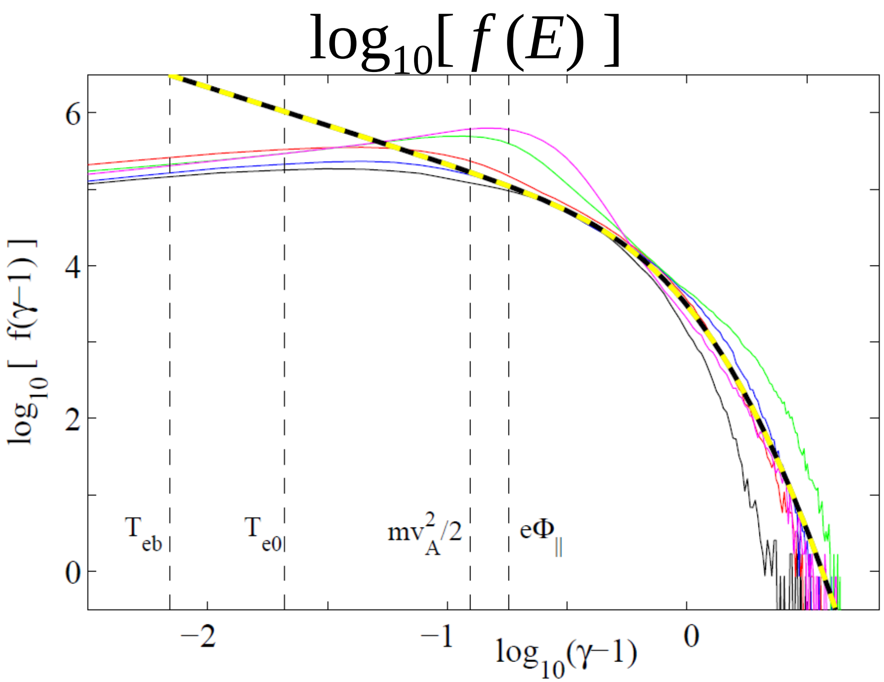
Steady state:

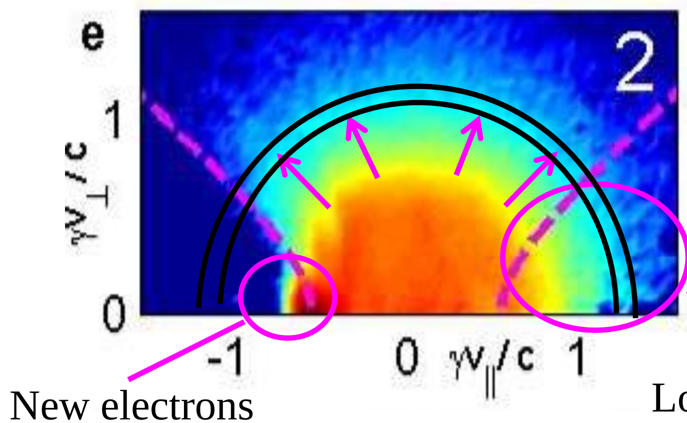
$$dv \frac{d\Gamma_v}{dv} \;=\; \Gamma_l \;\rightarrow\; \boxed{f \;=\; \frac{A}{v^3} \exp\left(-\frac{v\, R_{\text{loss}}}{v_A}\right)}$$

Generation of Super-Thermals



$\log_{10}$ (# of electrons with energies above $1.7mc^2$)





$$\Gamma_v \;=\; f\,4\pi v^2 \frac{\partial v}{\partial t}$$

$$\frac{\partial v}{\partial t} \simeq \frac{v_A}{\tau_b}$$

$$\Gamma_l = dv\, f\, \frac{4\pi v^2}{\tau_b} R_{\rm loss}$$

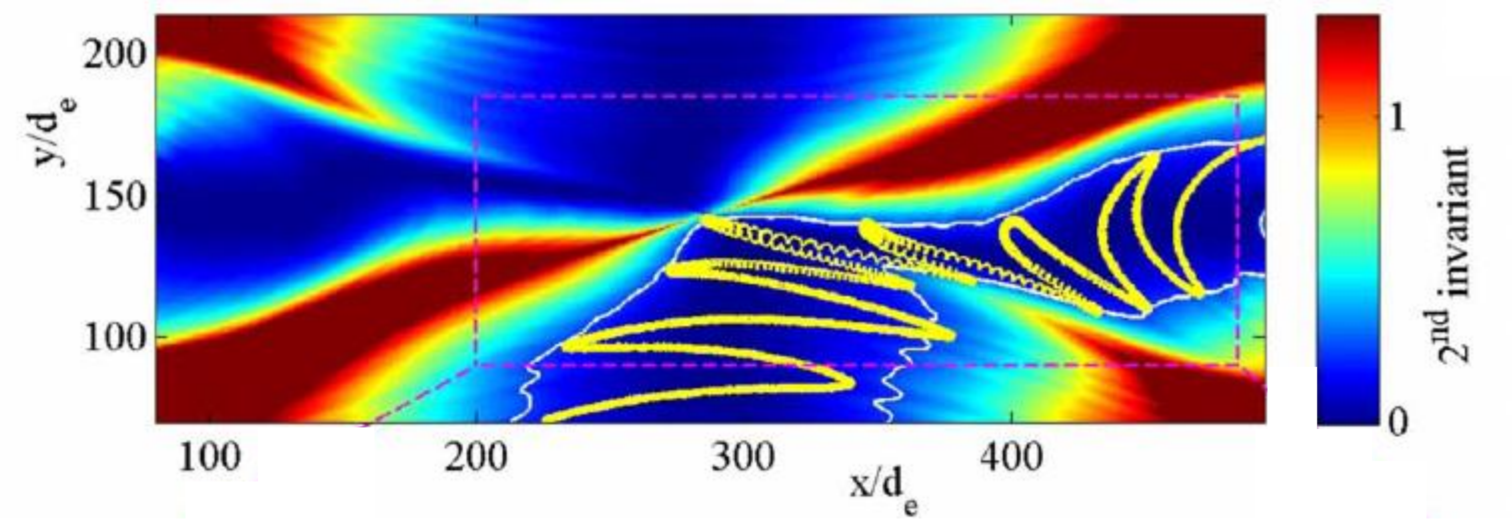
Steady state:

$$dv \frac{d\Gamma_v}{dv} \;=\; \Gamma_l \;\rightarrow\; \boxed{f \;=\; \frac{A}{v^3} \exp\left(-\frac{v\, R_{\rm loss}}{v_A}\right)}$$

Outline

- Examples of Magnetic Reconnection
- Model for Electron Pressure Anisotropy
- Fixing the Fluid Equations (The Equations of State)
- Regimes of Reconnection
- Opportunities with TREX
- Conclusions

Role of Collisions:



Full electron transit must be completed without collisions:

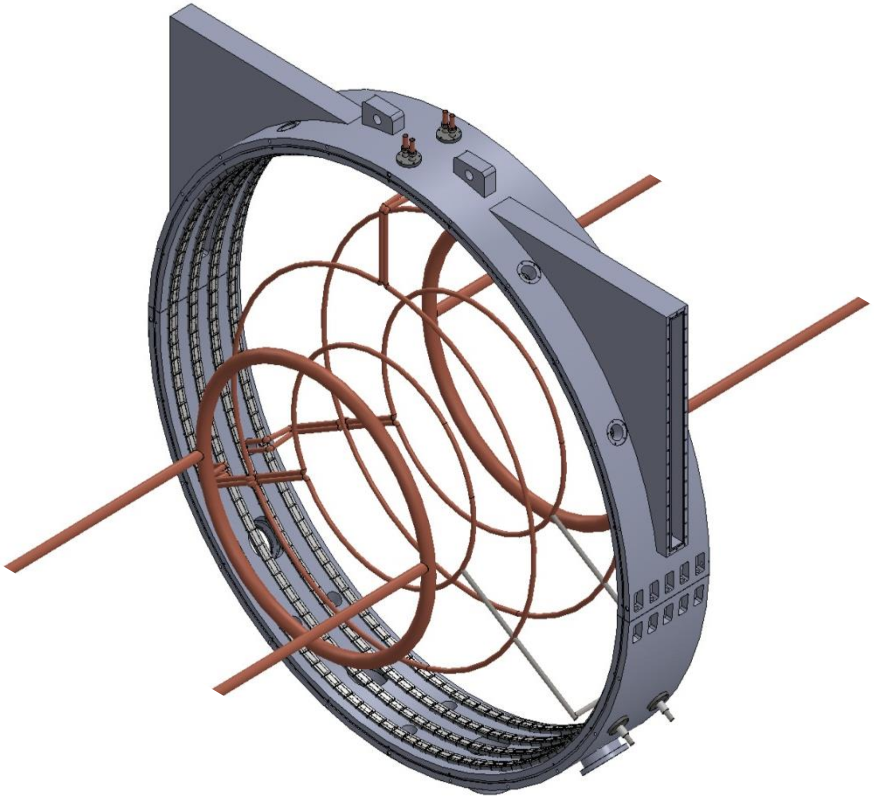
$$\tau_e > \frac{d_i}{0.1 v_A} \quad \Leftrightarrow \quad \nu_e / \omega_{ce} < 0.1 \frac{m_e}{m_i}$$

or

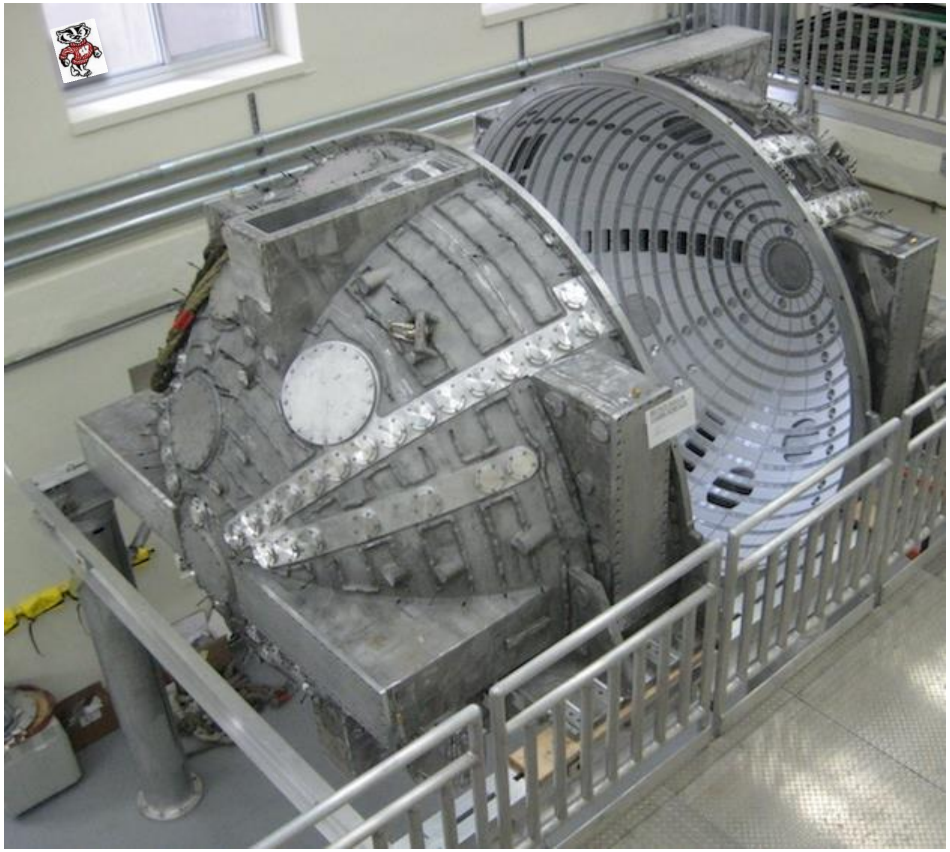
$$\boxed{S > 10^4 \frac{L}{d_i}}$$

Reconnection setup in CRX

Insert holding field coils



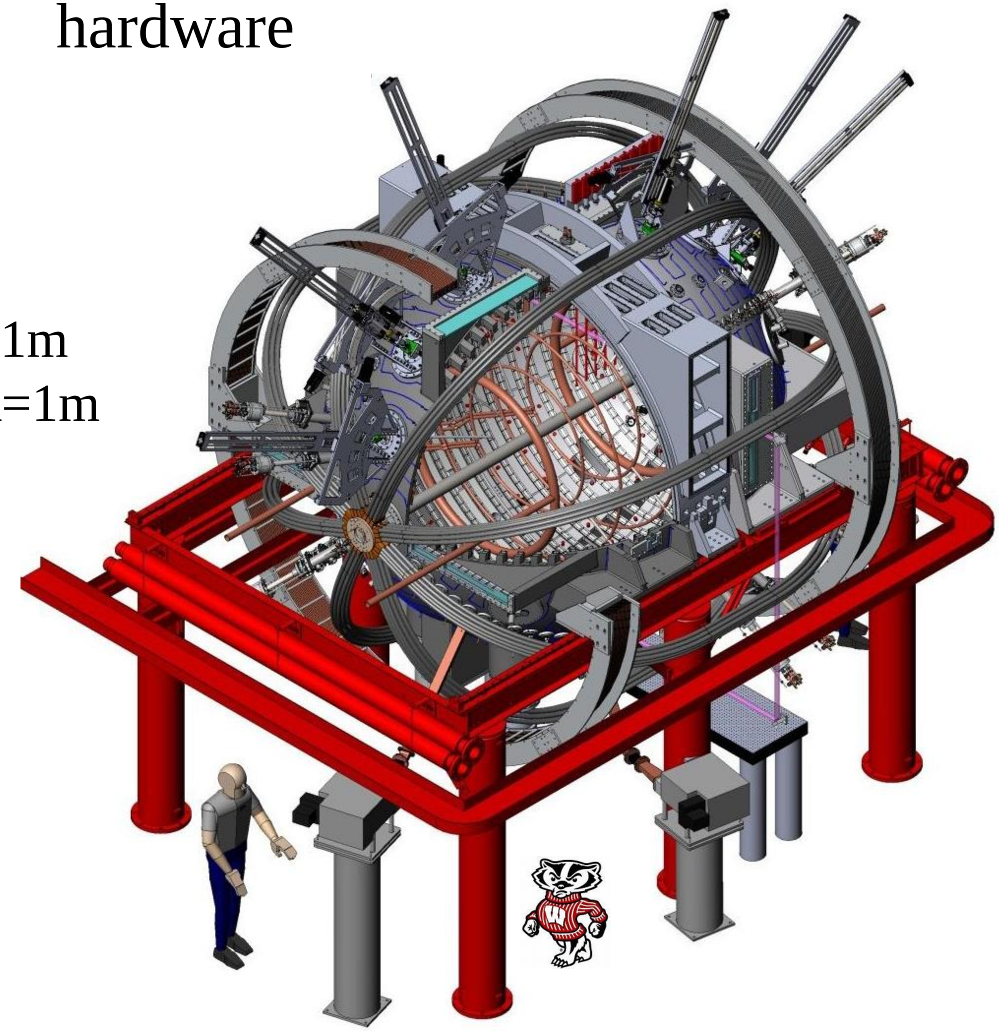
MPDX (just delivered)



Key new hardware

- Helmholtz Coils
  - 2 × 80 turns, CW, 800A
    ➔ B ~ 0.025T
- TF coil
  - 96 turns,
  - CW, 800A, ➔ B= 0.015 T @ R=1m
  - Pulsed, 13kA ➔ B = 0.25 T @ R=1m
- Poloidal field coils
  - 2 × 20 turns, pulsed, 5kA
    ➔ B ~ 0.04T
- Reconnection drive coils
  - 2 × 1 turns, 5kV, 10kA

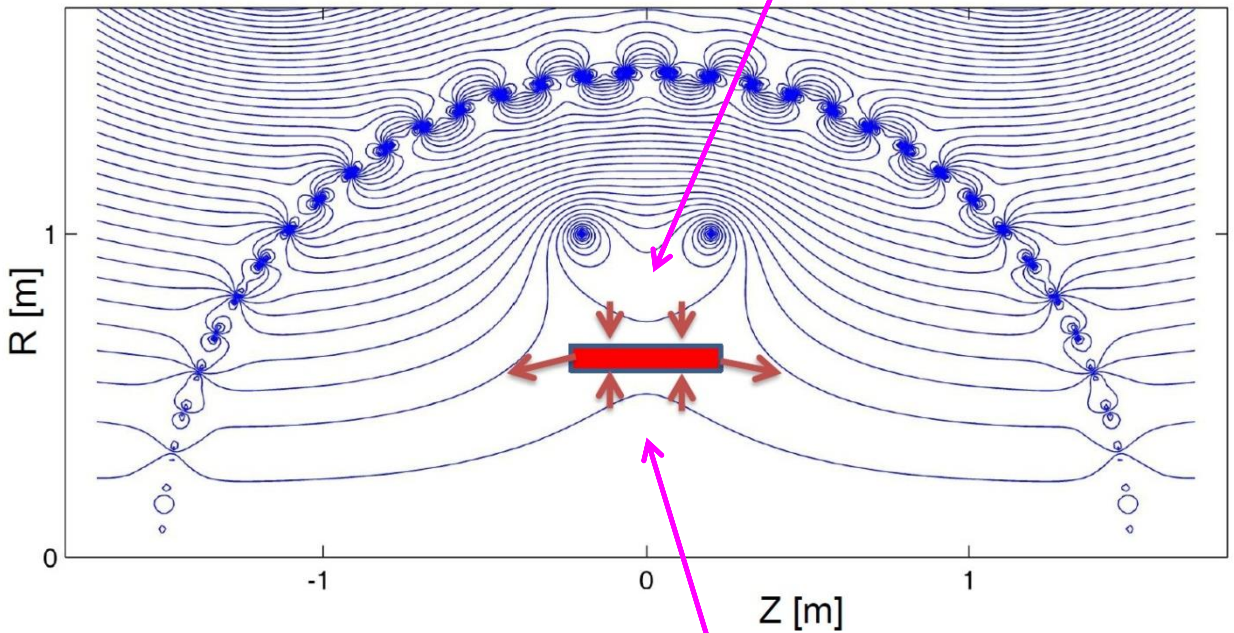
MPDX with TREX hardware



Asymmetric reconnection in TREX

- Simple configuration using the HH-coils plus two internal coils
- This will be the first configuration to be implemented

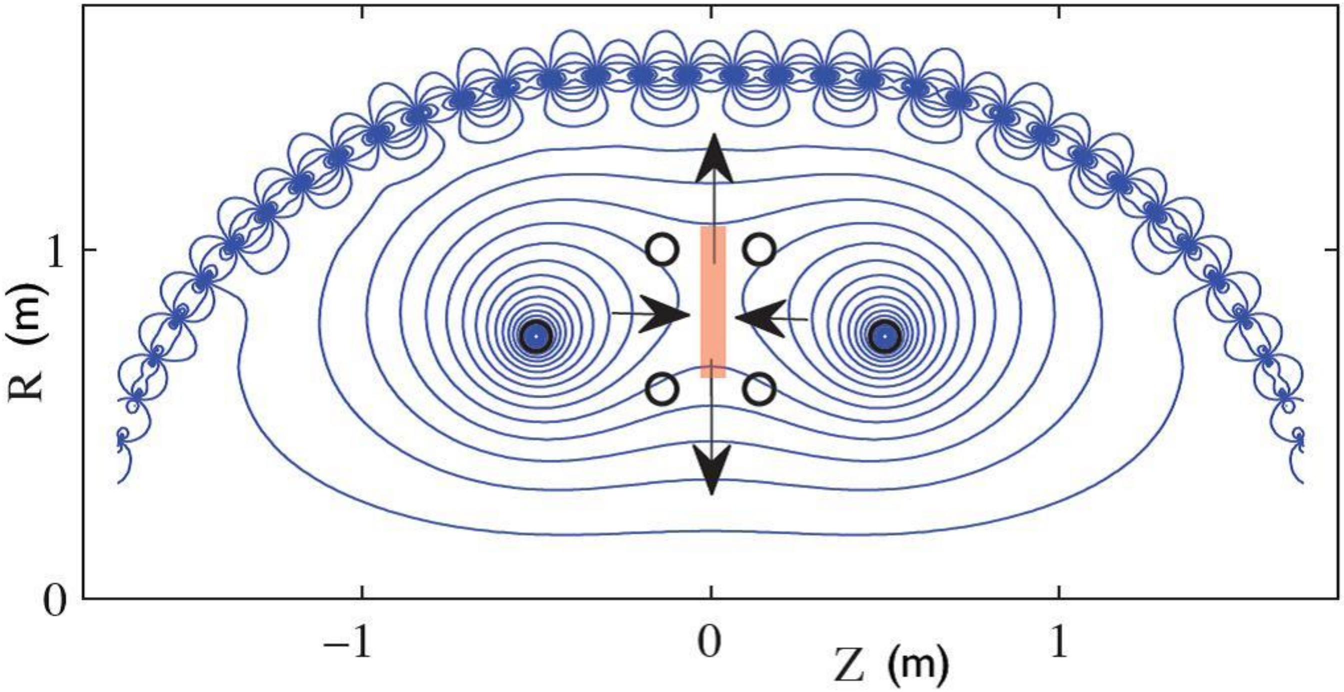
Low β plasma

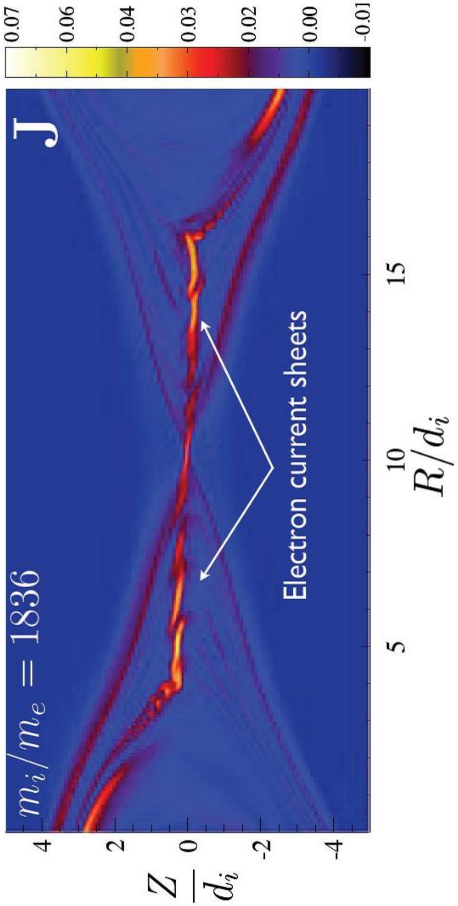


High β plasma

Symmetric Inflow Configuration

TREX, poloidal magnetic fields

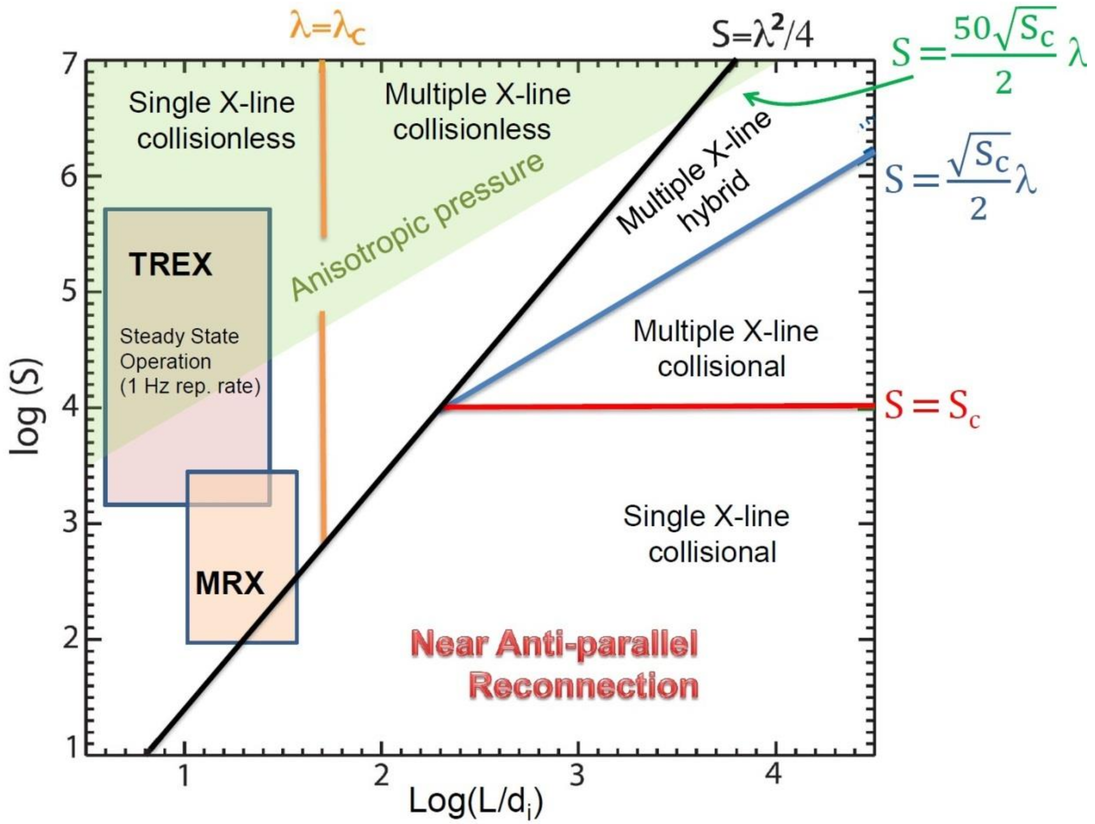




Collisional VPIC simulation

Role of Collisions, Moderate Guide-field Reconnection

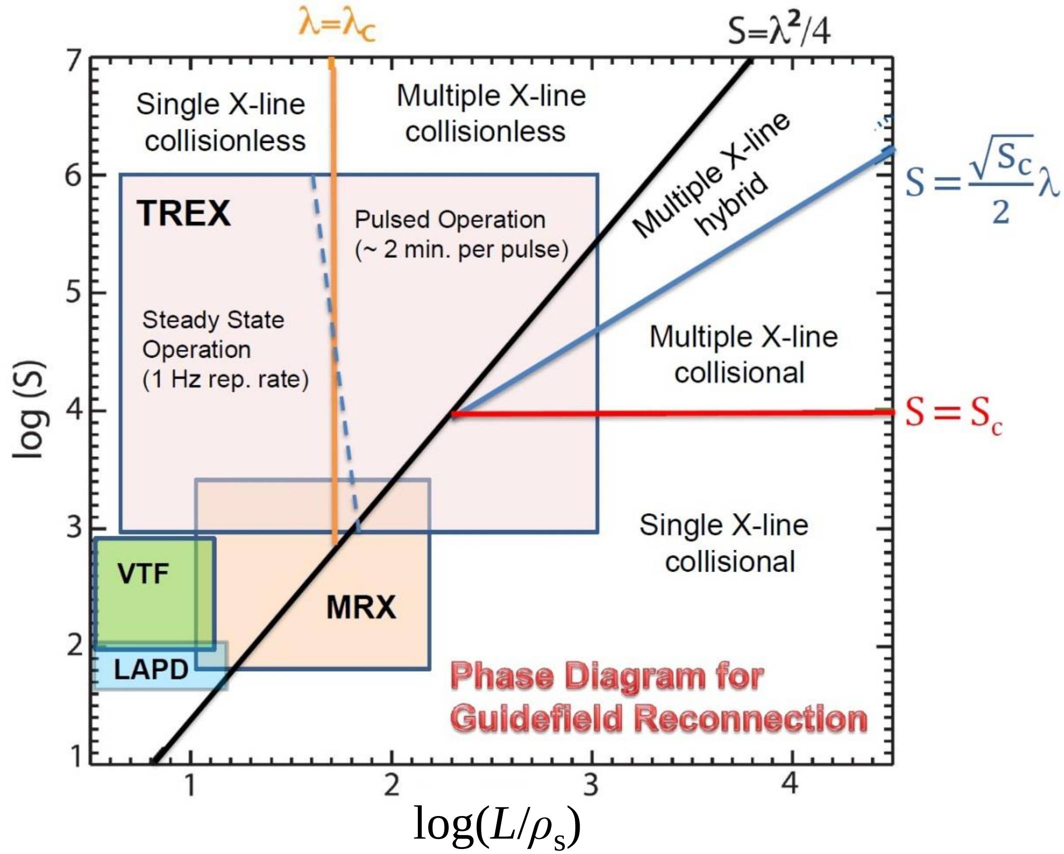
- Continuous operation of magnetic coils
- Plasma pulsed at 1Hz
- B_g = 20 mT at 1m



	$n_e/[10^{18}\ m^{-3}]$	$T_e/[eV]$	$B_r/[T]$	$B_g/[T]$	L/[m]
CRX	0.1-10	8 – 40	0.04	0 – 0.3	0.8 – 1.8
MRX	10 – 100	5 – 10	0.03	0 – 0.1	0.7
VTF	0.1-1	8 – 30	0.01	0.1	0.3

Strong Guide-field Reconnection

- Pulsed operation of magnetic coils
- 3 min between pulses
- $B_g = 0.25\text{T}$ at 1m



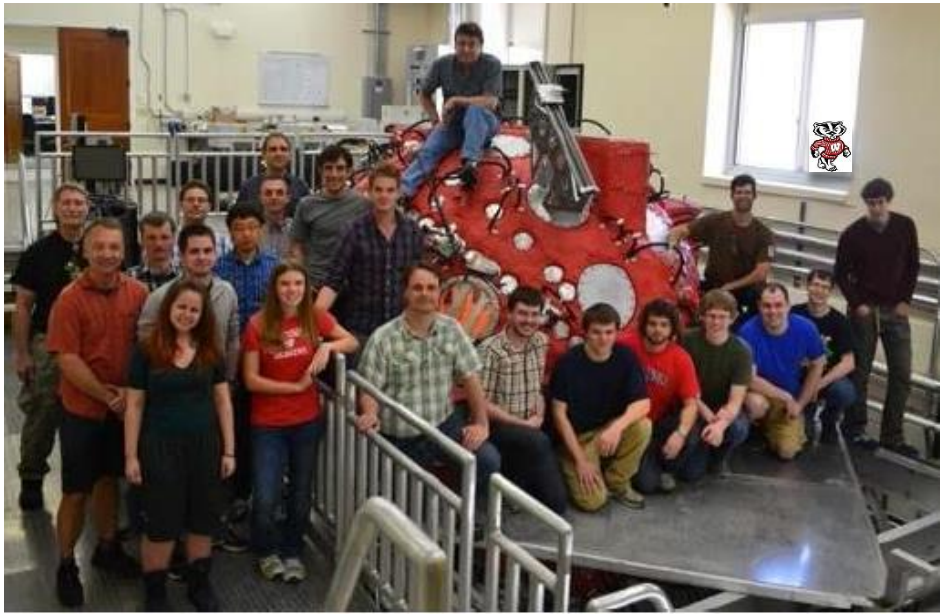
	$n_e/[\mathrm{m}^{-3}]$	$T_e/[\mathrm{eV}]$	$B_r/[\mathrm{T}]$	$B_g/[\mathrm{T}]$	$L/[\mathrm{m}]$
TREX	$10^{17} - 10^{19}$	$8 - 40$	$0 - 0.05$	$0 - 0.3$	$0.8 - 2$
MRX	$10^{19} - 10^{20}$	$5 - 10$	0.03	$0 - 0.1$	0.7
VTF	$10^{17} - 10^{18}$	$8 - 30$	0.01	0.1	0.3

$\rho_s = (2 m_i T_e)^{1/2}/eB$

= "ion sound Larmor Radius"

Conclusion

- The construction of the new Terrestrial Reconnnection EXperiment is well under way
- TREX is highly leveraged against earlier NSF investments through the use of the MPDX-vessel and plasma production
- TREX provides huge flexibility in available configurations, and the insert will allow for fast turn-around.



- Reconnection in an unprecedented range of plasma parameters to be explored
- Thanks to Cary and the MPDX team for a good start on TREX!