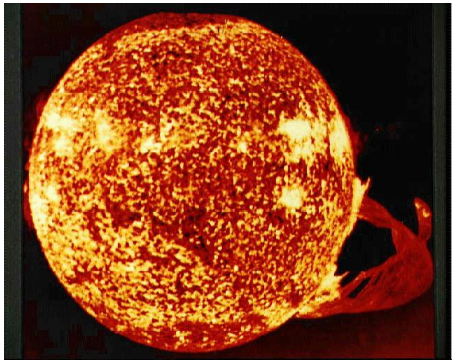
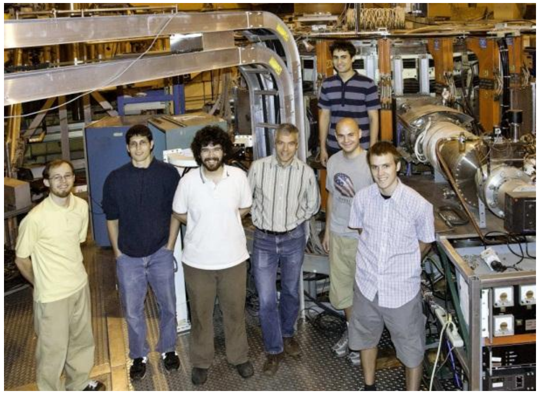
Large-scale electron acceleration by parallel electric fields during magnetic reconnection



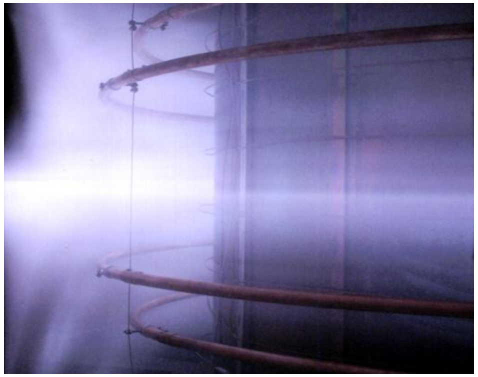


J Egedal, A Le, J Ng,
O Ohia, A Vrublevskis, P Montag
W Daughton & VS Lukin

MIT, PSFC, Cambridge, MA

PIC simulations

Fluid simulations



Massachusetts Institute of Technology

PSFC

Outline

- Description of Magnetic Reconnection
- Spacecraft Observations from the Earth’s Magnetotail
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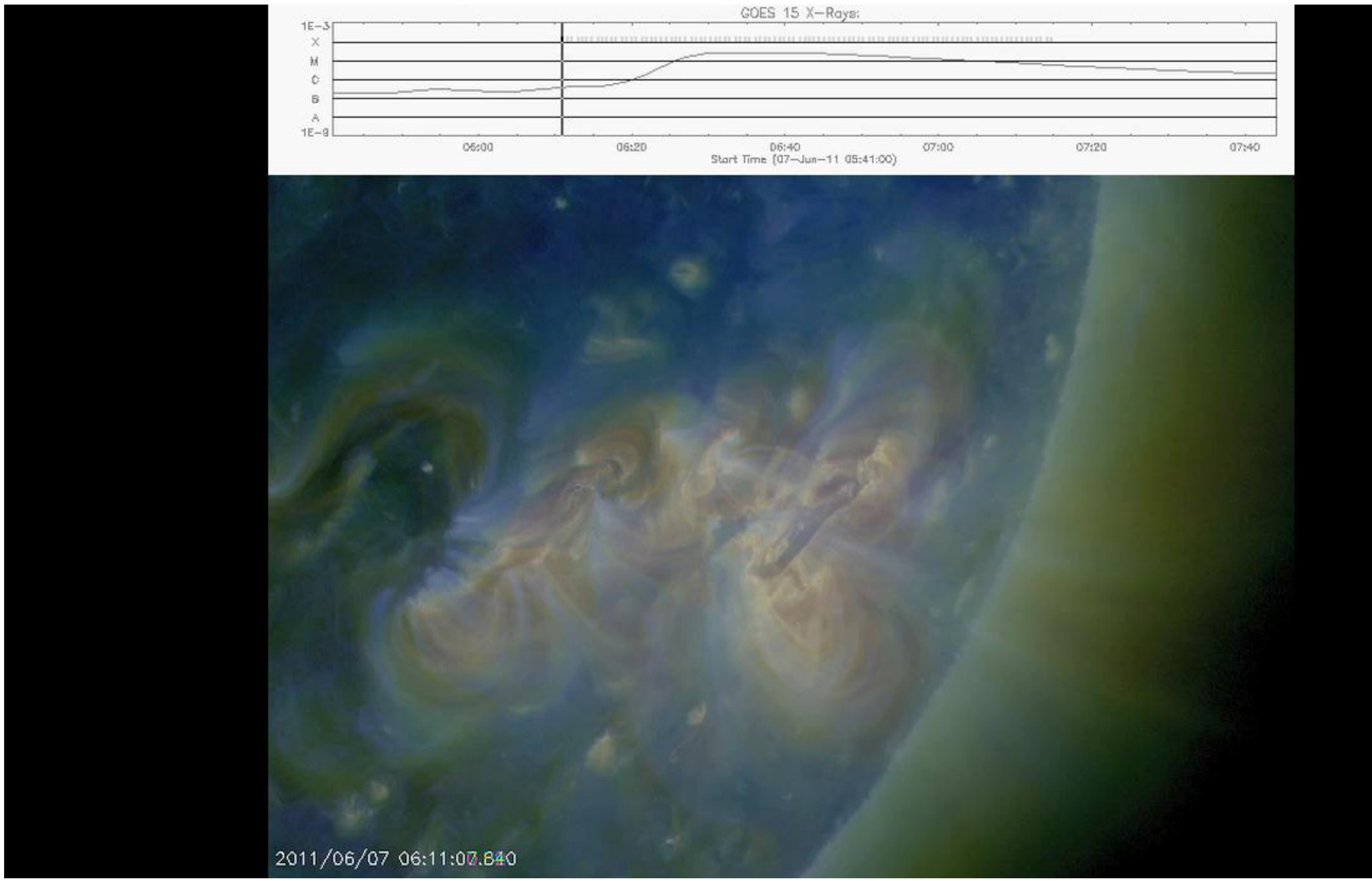
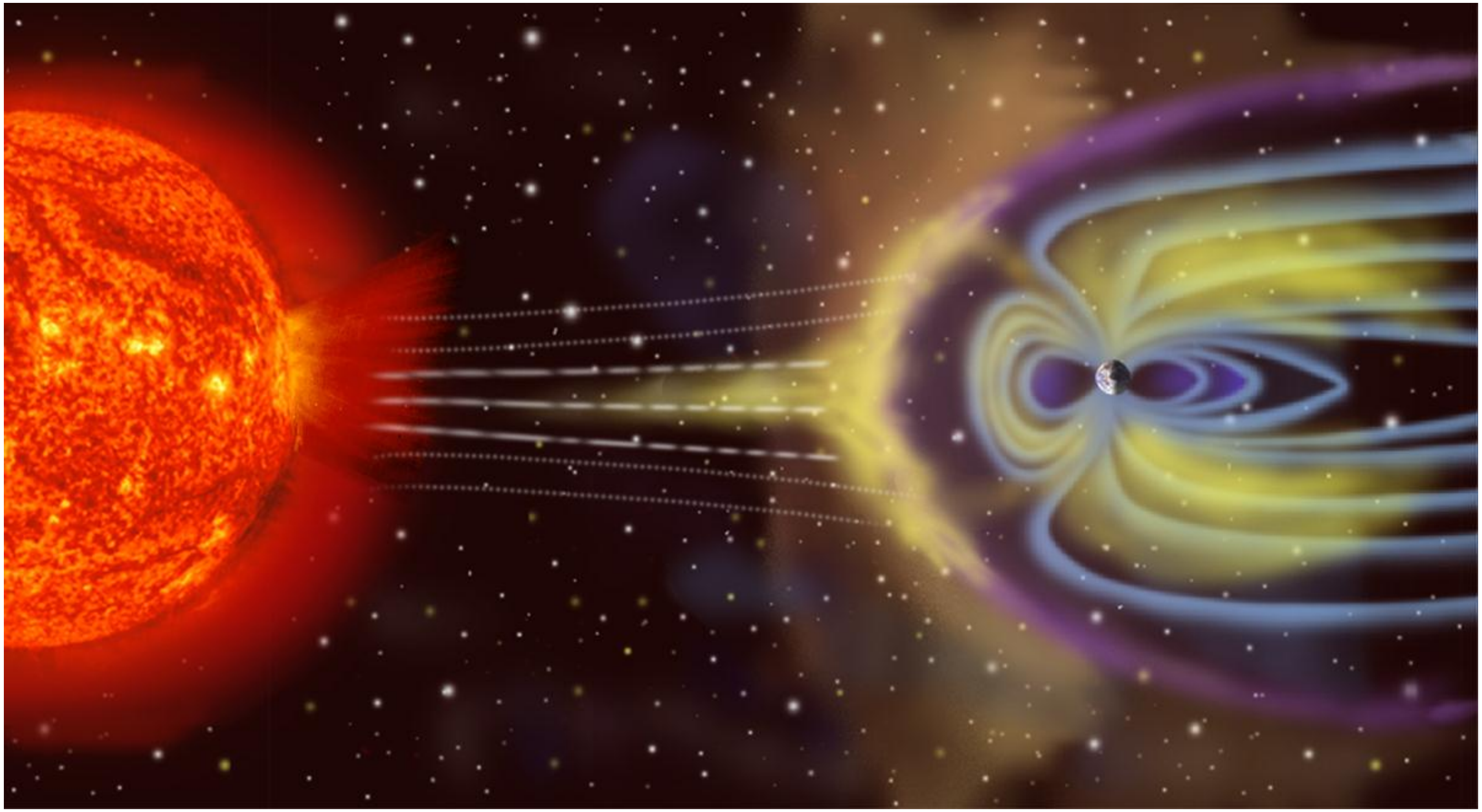
Coronal Mass Ejections

Movie from NASA's Solar Dynamics Observatory (SDO)

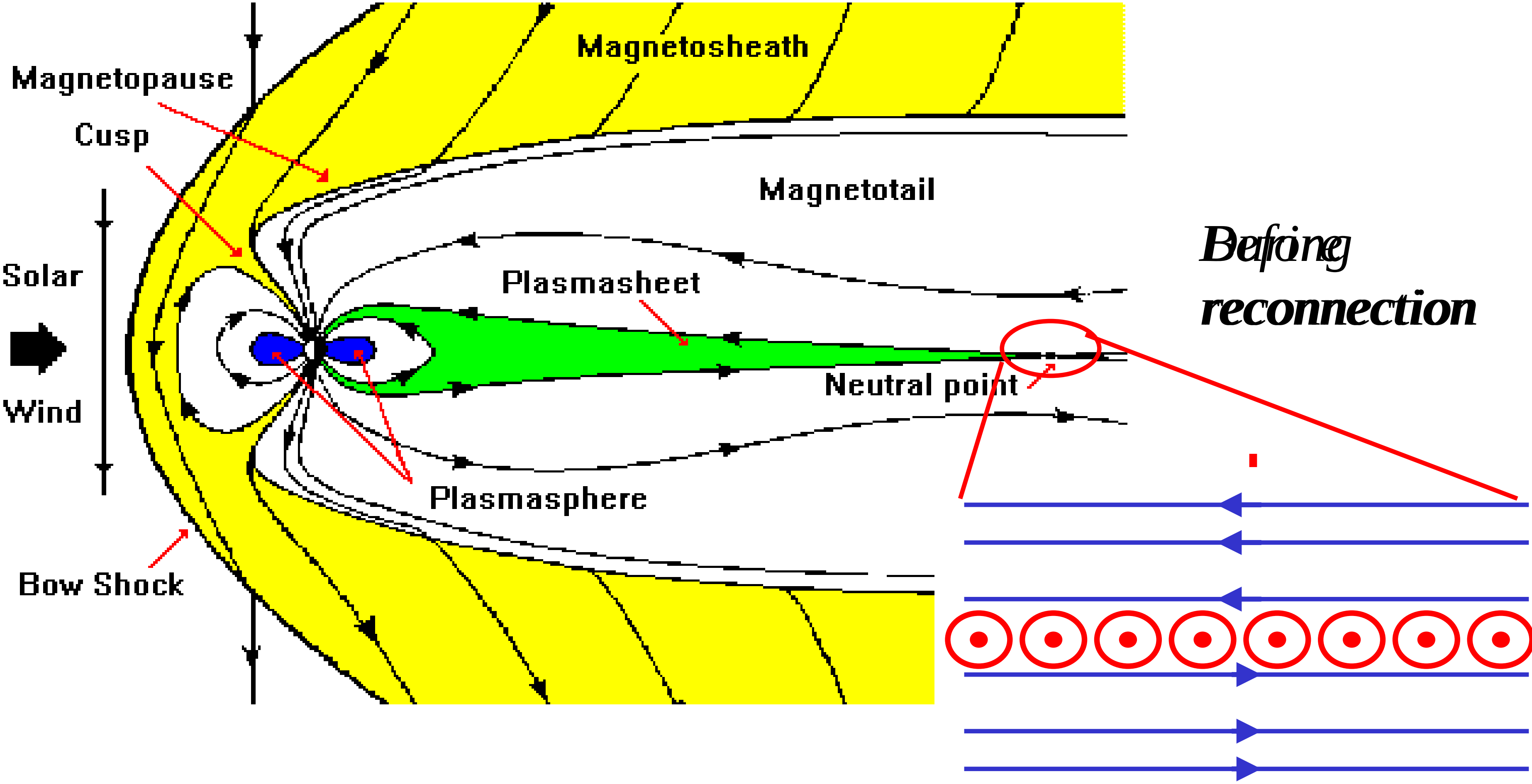


Space Weather

The Solar Wind affects the Earth's environment



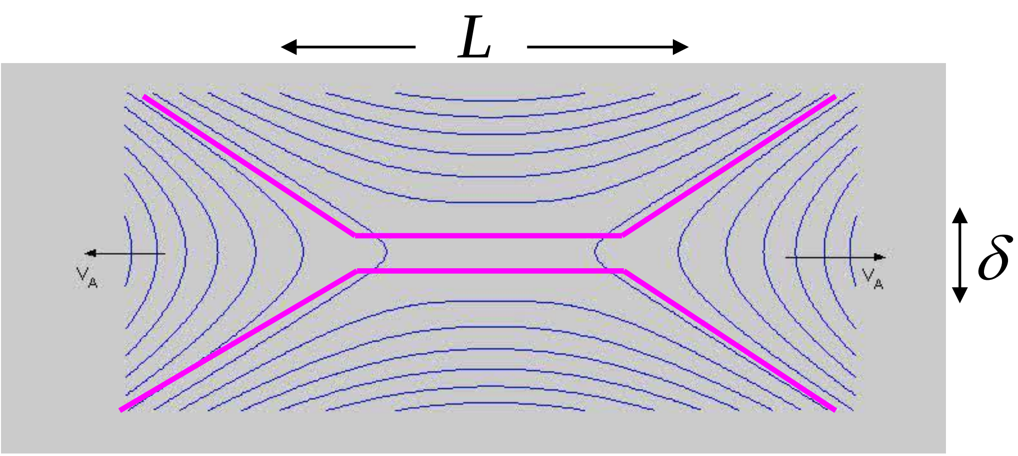
The Earth’s Magnetic Shield



Reconnection: A Long Standing Problem

Simplest model for reconnection:

$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{j}$ [*Sweet-Parker* (1957)]



Outflow speed:

$$v_A = \frac{B}{\sqrt{\mu_0 n m_i}}$$

(Alfven speed)

Sweet-Parker: $L >> \delta$:

$$t_{sp} = \sqrt{t_R t_A} = \sqrt{\frac{\mu_0 L^2}{\eta}} \sqrt{\frac{L}{v_A}}$$

Unfavorable for fast reconnection

Two months for a coronal mass ejections

Plasma Kinetic Description

The collisionless Vlasov equation:

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\ \ \frac{d}{dt} f_j(\mathbf{x}, \mathbf{v}, t) = 0\ ) \cdot \nabla_v\right) f_j = 0$$

$$n_j = \int f_j d^3 v \qquad\qquad \mathbf{J}_j = q_j \int \mathbf{v} f_j d^3 v$$

\+ Maxwell’s eqs.

Vlasov-Maxwell system of equations

Can be solved numerically (PIC-codes)

Fluid Formulation (Conservation Laws)

mass:

$$\frac{\partial n}{\partial t} + \frac{\partial (n u_j)}{\partial x_j} = 0,$$

momentum:

$$mn\left(\frac{\partial u_j}{\partial t} + u_k \frac{\partial u_j}{\partial x_k}\right) + \frac{\partial \mathsf{P}_{jk}}{\partial x_k} \overbrace{- en(E_j + \epsilon_{jkl} u_k B_l) - F_j^{\mathrm{coll}}}^{\textit{Sweet-Parker}} = 0,$$

energy:

$$\frac{\partial \mathsf{P}_{jk}}{\partial t} + \frac{\partial}{\partial x_l}(\mathsf{P}_{jk} u_l + \mathsf{Q}_{jkl}) + \frac{\partial u_{[j}}{\partial x_l}\mathsf{P}_{lk]} - \frac{e}{m}\epsilon_{[jln}B_m \mathsf{P}_{lk]} - \mathsf{G}_{jk}^{\mathrm{coll}} = 0$$

$$\vdots$$

Isotropic (scalar) pressure is the standard closure!

$$p = n\,T$$

Add Maxwell's eqs to complete the fluid model

➔ Fast Reconnection !

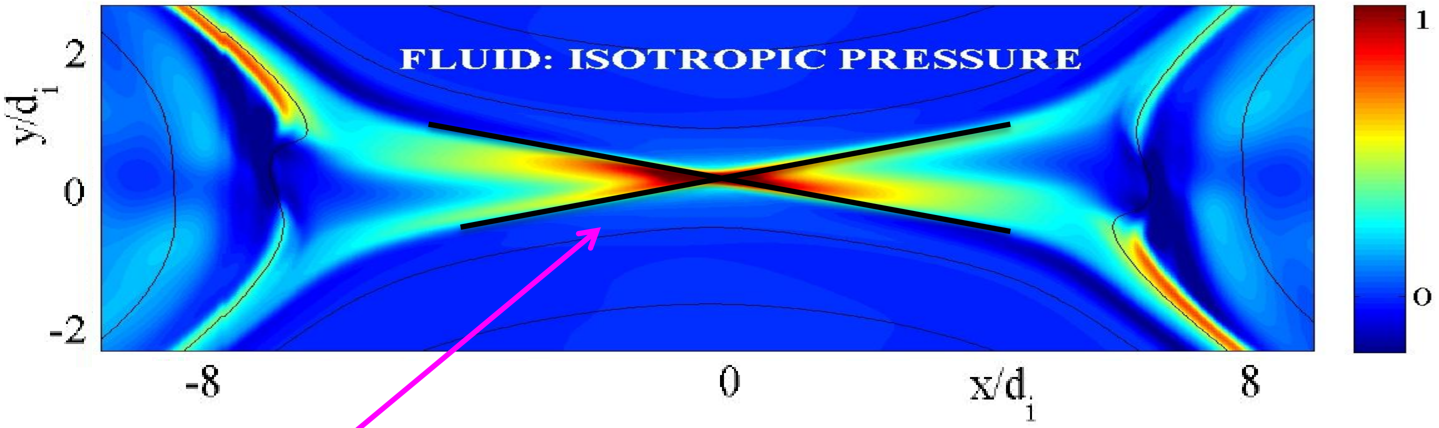
Two-Fluid Simulation

GEM challenge (Hall reconnection)

$\mathbf{E} + \mathbf{v}\times\mathbf{B} = (\mathbf{j} \times \mathbf{B})/ne$ [Birn,…, Drake,… Bhattacharjee, et al. (2001)]

Out of plane current

Isotropic pressure



Aspect ratio: 1 / 10

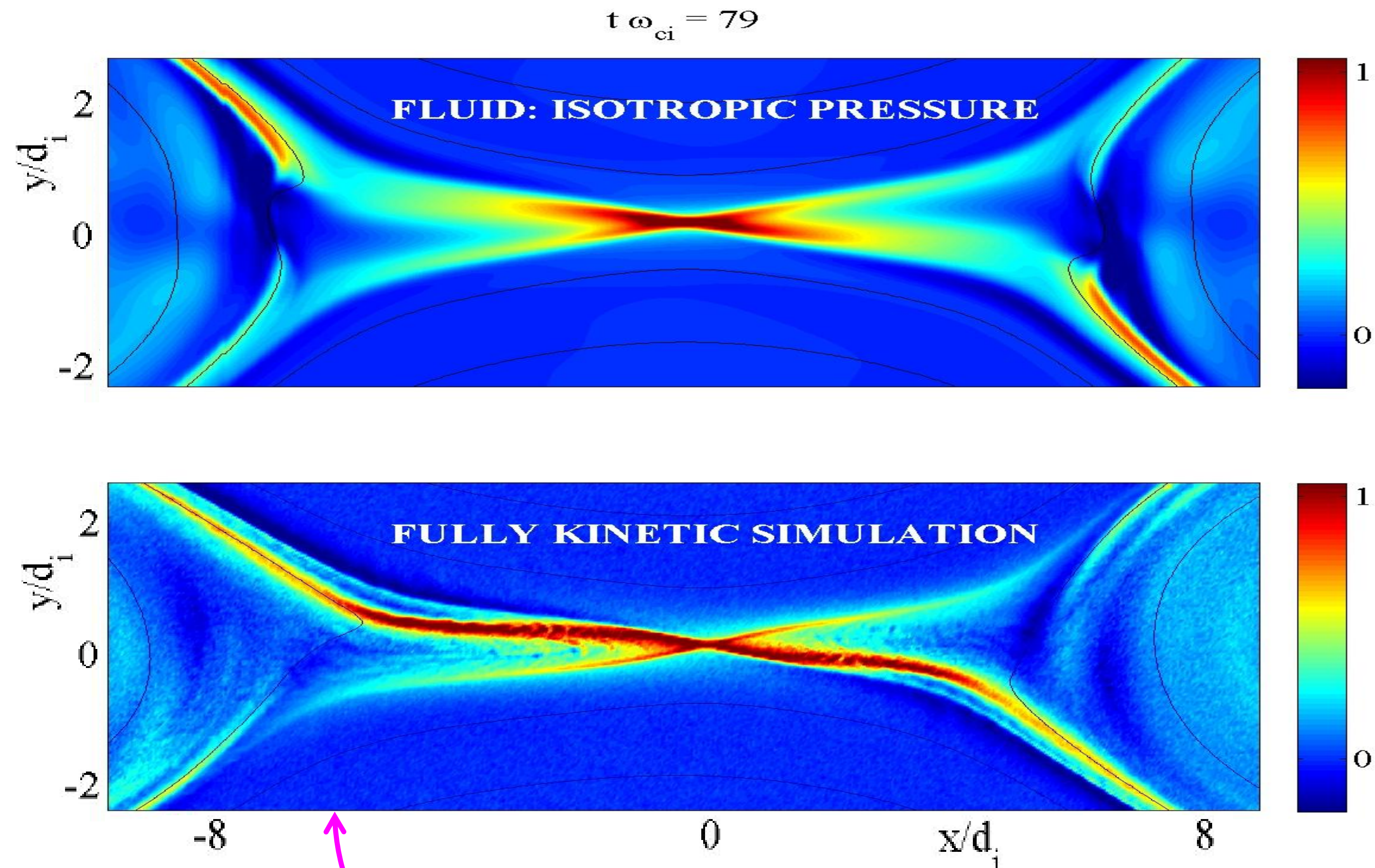
➔ $v_{in} \sim v_A / 10$

Two-Fluid vs Kinetic Simulations

Out of plane current

Isotropic pressure

Kinetic Simulation



Particle In Cell (PIC) simulation,

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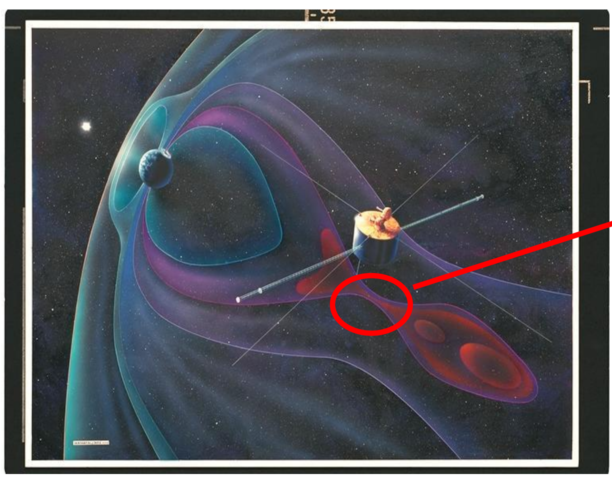
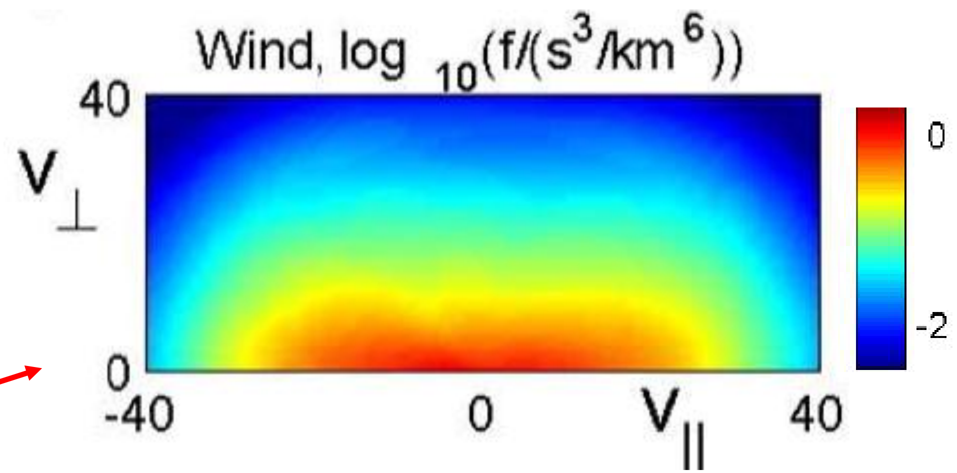
- Measurements within the ion diffusion region reveal:
  Strong anisotropy in f_e

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

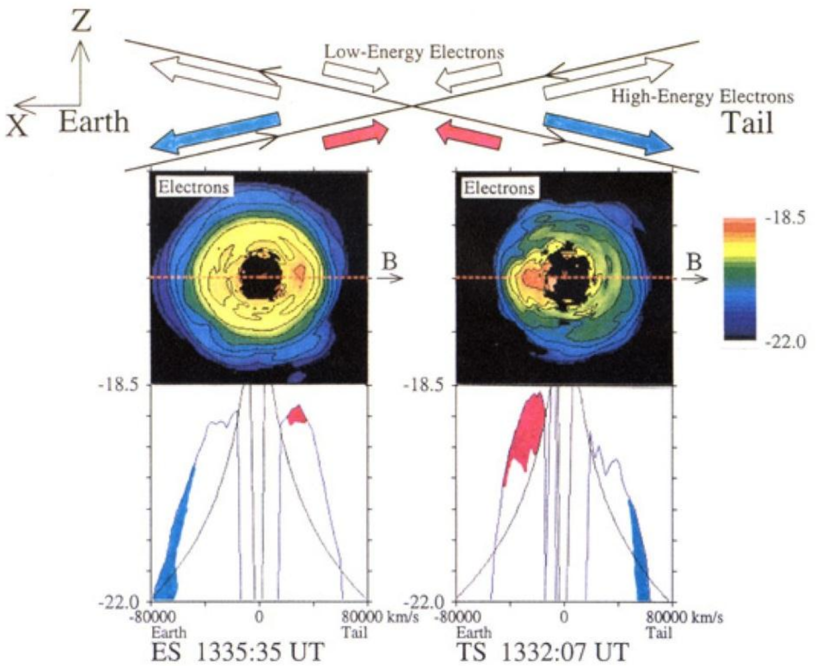




[Øieroset et al., PRL (2001)]

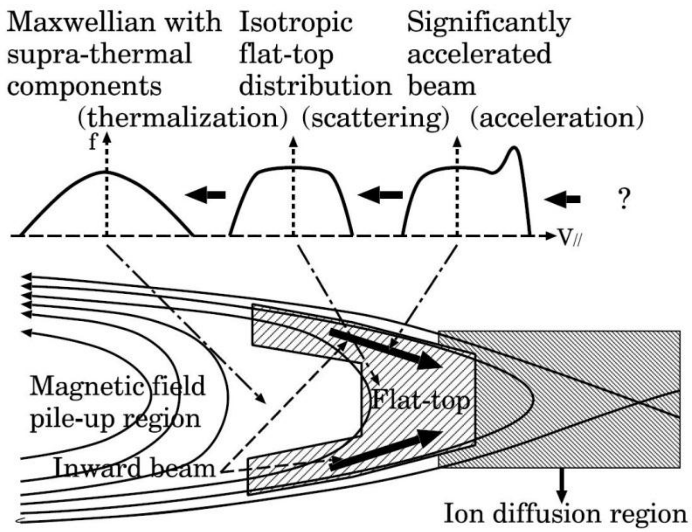
Observed Electron Heating

1-10 keV beam like electron distributions often observed



T. Nagai, et al., *J. Geophys. Res.*, ***106*** , 25.929 (2001).

Flat-top distributions typical in the exhaust; related beams?



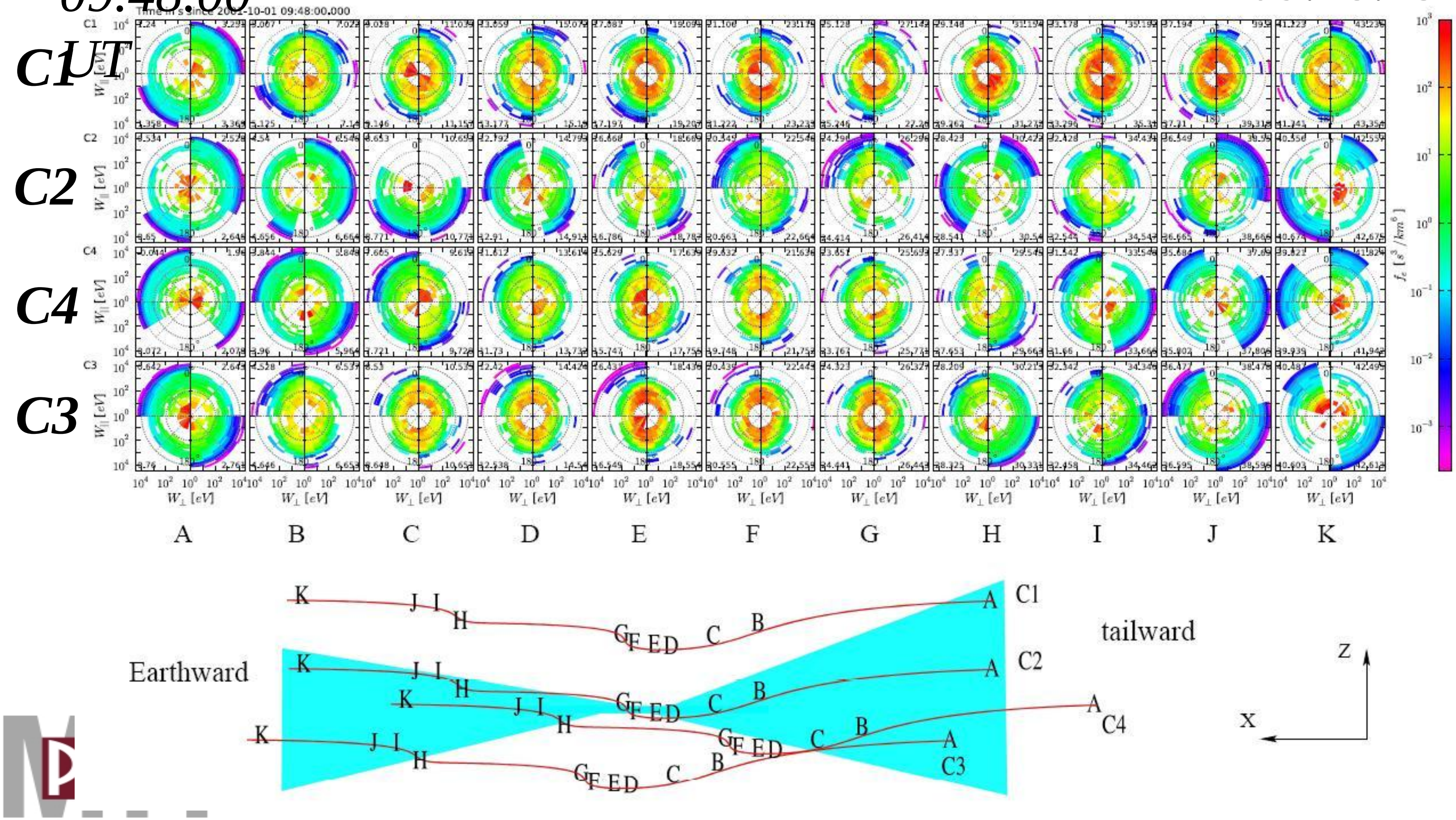
Y. Asano, et al., *J. Geophys. Res.*, ***113***(A1), (2008).

Cluster observations

Cluster observations on 2001-10-01, [L.-J. Chen, JGR (2008)]

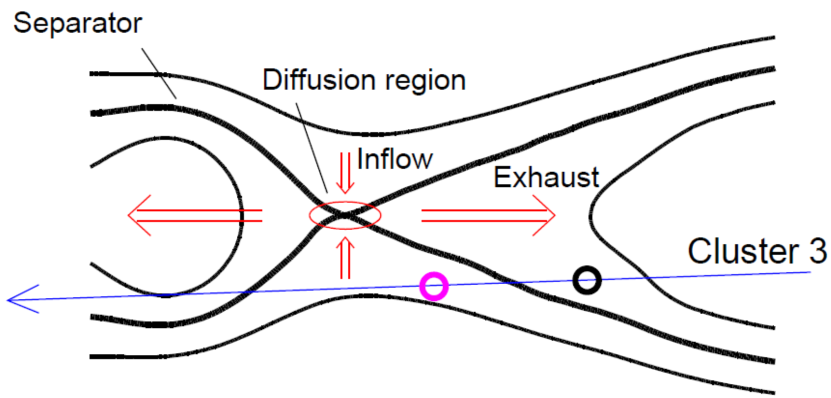
09.48.00 UT

09.48.43UT

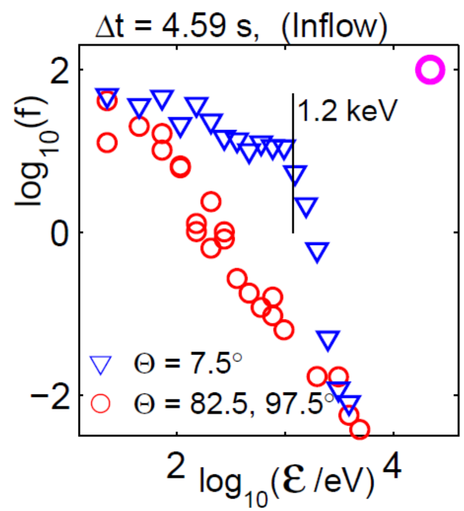


Observed Electron Heating

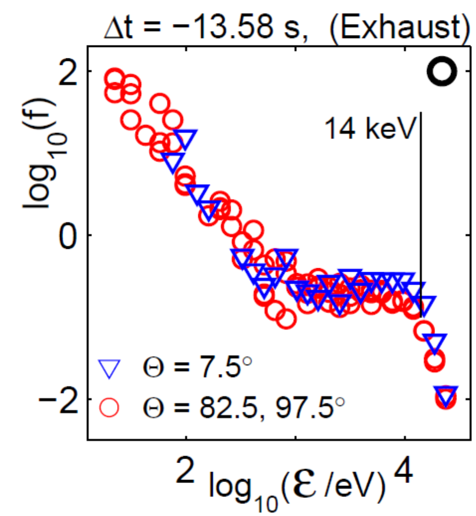
Cluster observations on 2001-10-01.



Bi-directional Beams



Flat-top

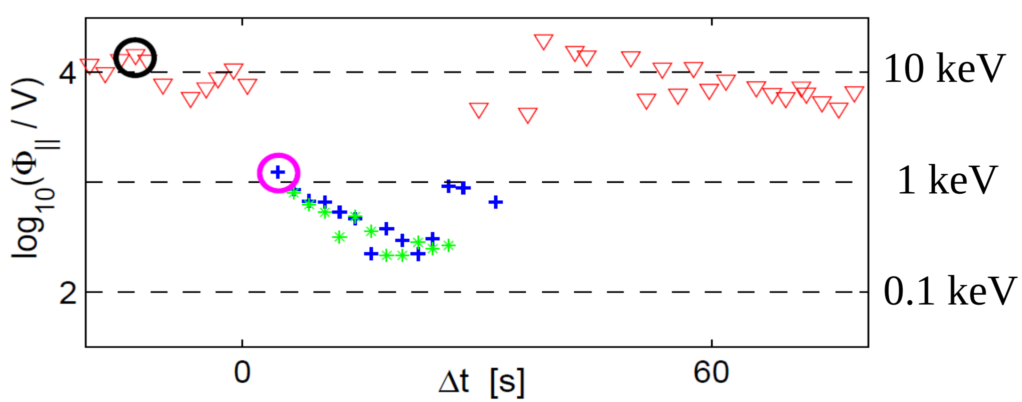


Reproduced from Egedal, …, Chen et al. JGR (2010)
Similar figures given in L.-J. Chen, et al JGR (2008), POP (2009)

Lobe: T_e ~ 0.1 keV

Inflow: $T_{e\perp}$ ~ 0.1 keV, $T_{e\|}$ ~ 1 keV

Exhaust: $T_{e\perp}$ ~ $T_{e\|}$ ~ 10keV



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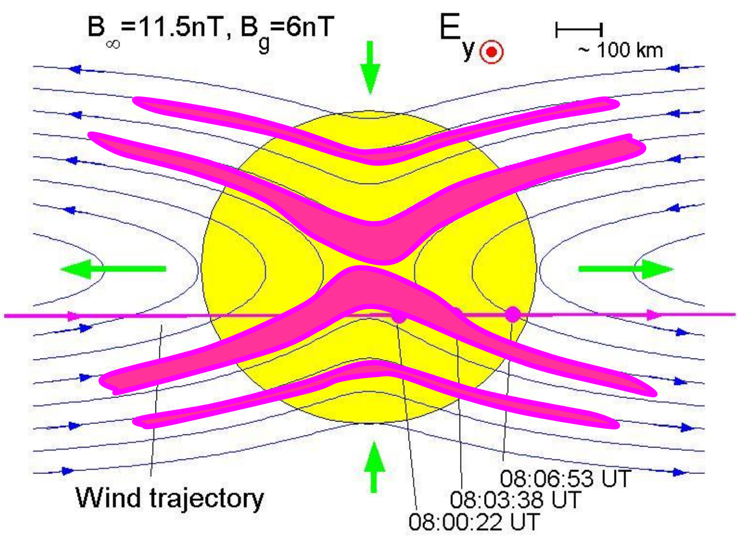
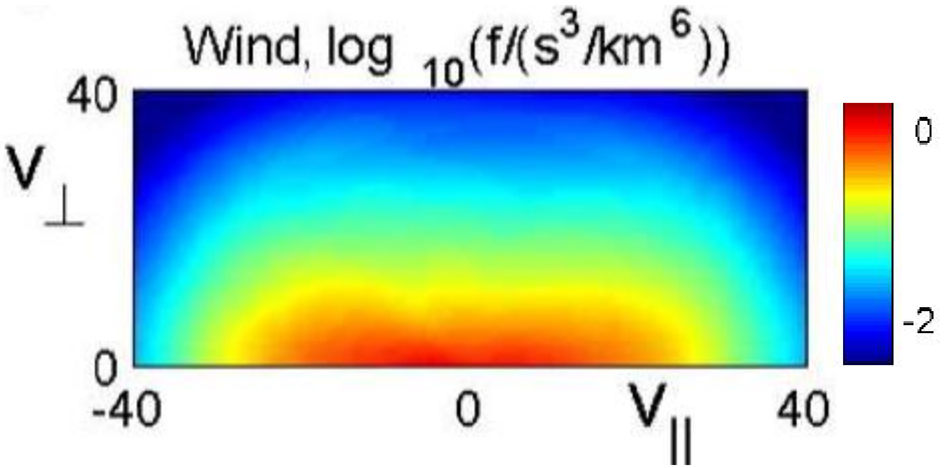
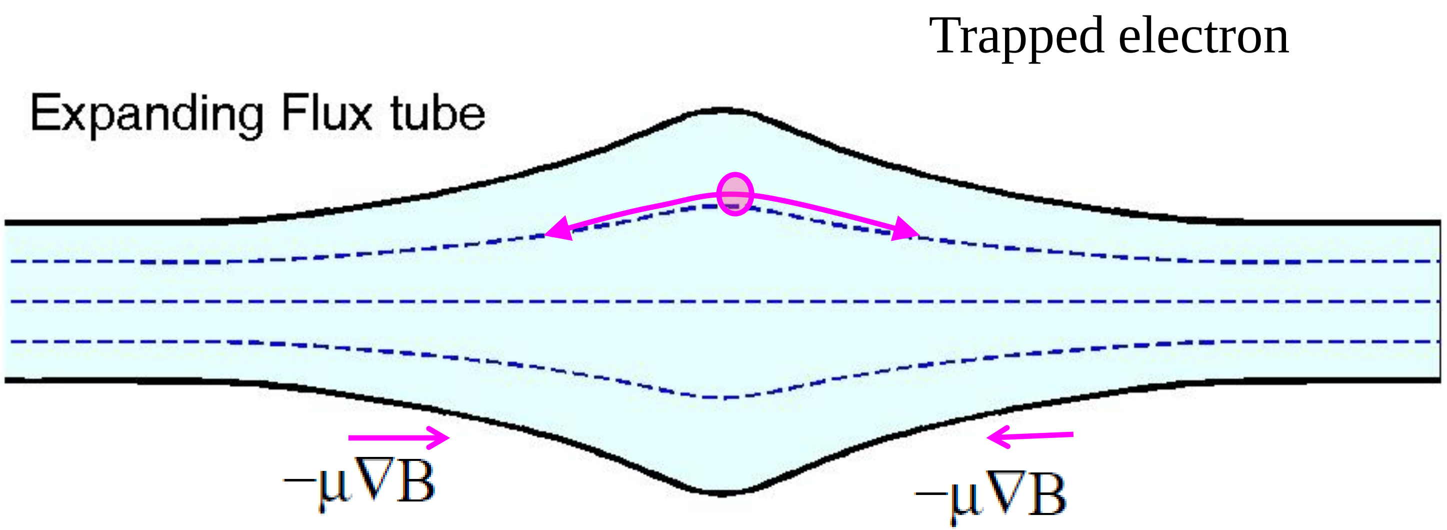




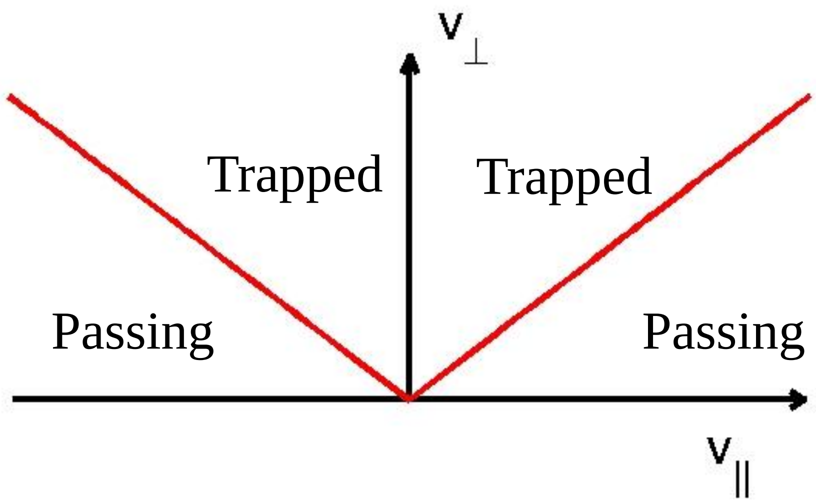
Electrons in an Expanding Flux Tube



Magnetic moment:

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

➔ mirror force:



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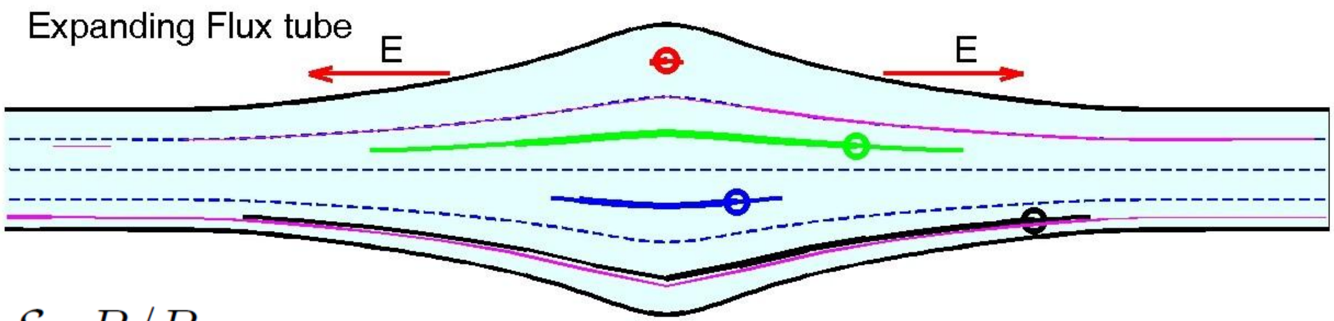
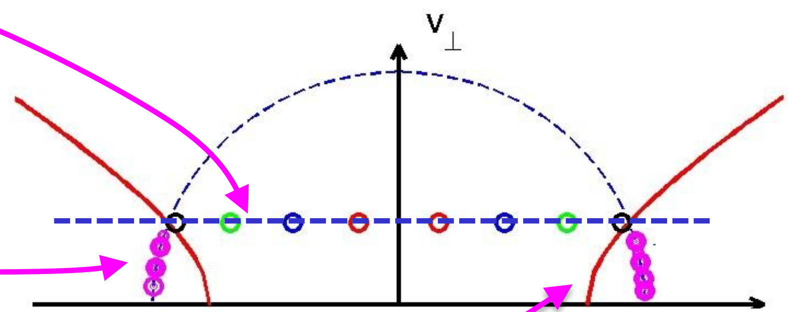


Trapped:

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

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



Passing:

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

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

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

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

Vlasov:

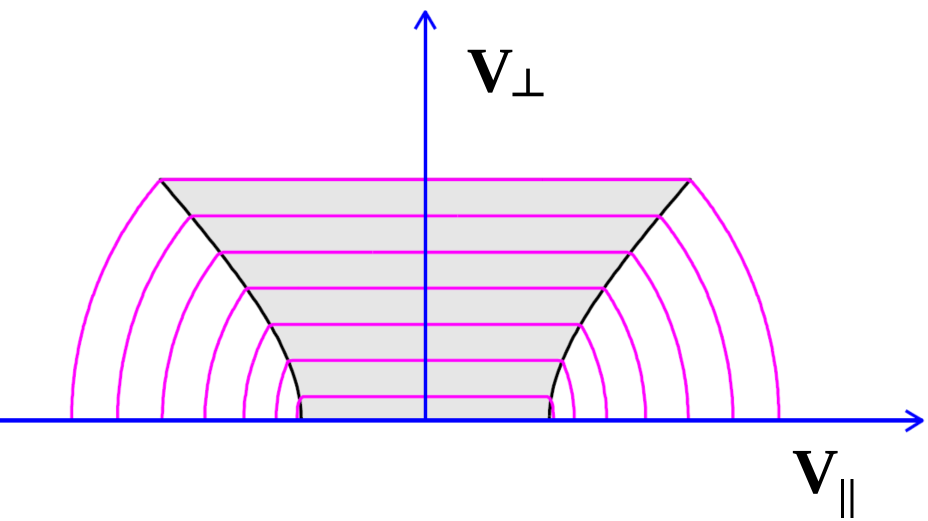
$$\frac{df}{dt} = 0$$

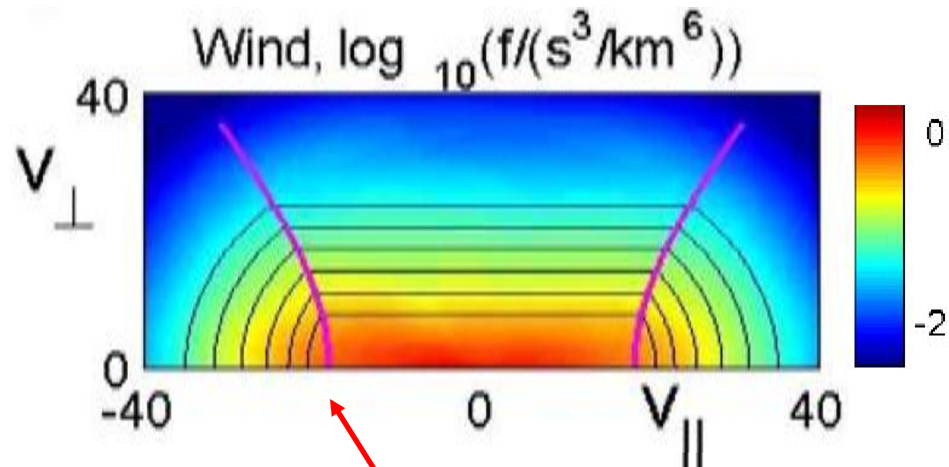
$$f(\mathbf{x}, \mathbf{v}) = f_\infty(\mathcal{E}_\infty)$$

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

J. Egedal et al., JGR (2009)

Wind Spacecraft Observations in Distant Magnetotail, $60R_E$

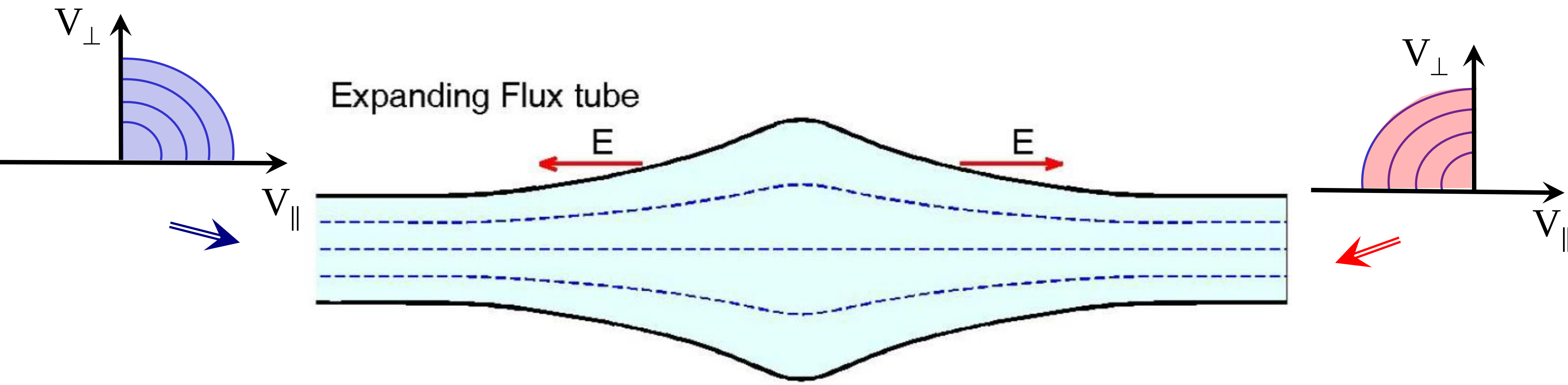




$$f(\mathbf{x},\mathbf{v}) = \begin{cases} f_\infty(\mathcal{E} - e\Phi_{\|}) & , \text{ passing} \\ f_\infty(\mu B_\infty) & , \text{ trapped} \end{cases}$$

$\Phi_{\|} \sim 1$ kV

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:

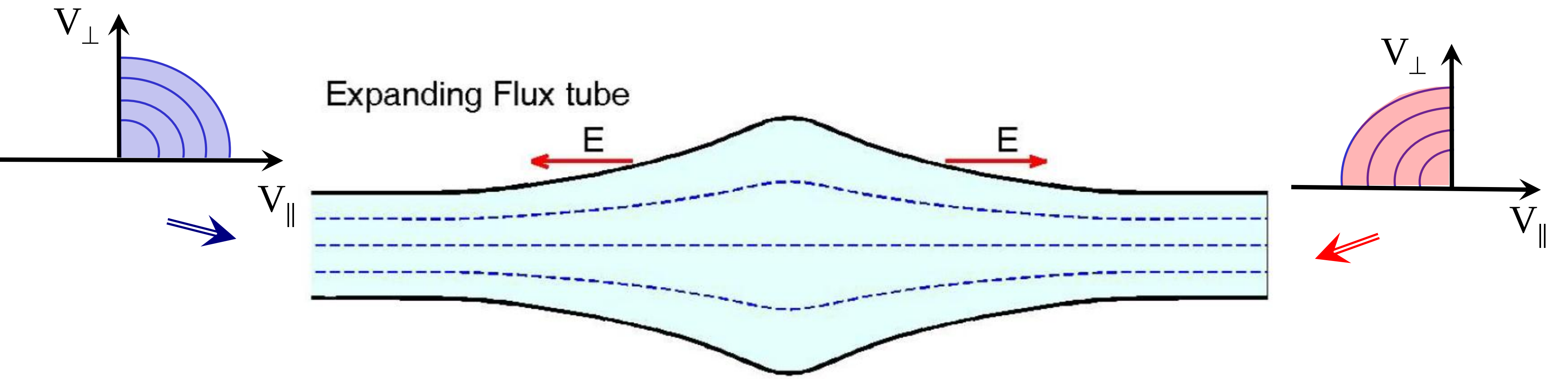
$$B=B_\infty$$
$$f=f_\infty(\mathcal{E}_{\parallel\infty},\mathcal{E}_{\perp\infty})$$

Ordering:

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

$$\frac{d}{L}\sim\delta\quad,\qquad\frac{v_D}{v_t}\sim\delta^2\quad,\qquad\frac{E_\parallel}{E_\perp}\sim\delta$$

Formal derivation, passing electrons



Passing electrons, lowest order equation: $$\mathbf{v}_\parallel \cdot \nabla f + e(\mathbf{v}_\parallel \cdot \mathbf{E})\,\frac{\partial f}{\partial \mathcal{E}} = 0$$

Integrate along characteristics (field lines):

$$f(\mathcal{E}_\parallel, \mathcal{E}_\perp) = f_\infty(\mathcal{E} - e\Phi_\parallel^\pm - \mu B_\infty\,,\, \mu B_\infty)$$

where $\mathcal{E} = \mathcal{E}_\parallel + \mathcal{E}_\perp \quad , \quad \Phi_\parallel^\pm = \int_x^{\pm\infty} \mathbf{E}\cdot d\mathbf{l}_\parallel$

Quasi-neutrality at boundaries: $n = \int f\, d^3v = n_\infty$

(only passing electrons here)

$\rightarrow \int_{-\infty}^{\infty} \mathbf{E}\cdot d\mathbf{l}_\parallel = 0. \quad \rightarrow \quad \Phi_\parallel^+ = \Phi_\parallel^- = \Phi_\parallel$

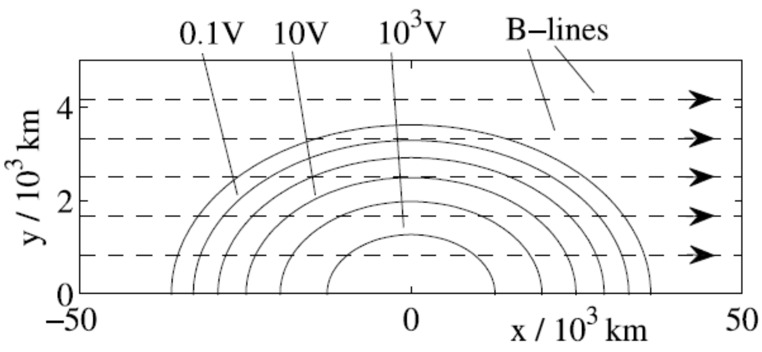
Formal derivation, trapped electrons

Use full equation with solution: $f = g(\mu, J, \phi_J)$

$$= f_\infty\left(\mathcal{E}_{\|\infty}[\mu, J, \phi_j], \mathcal{E}_{\perp\infty}[\mu, J, \phi_j]\right)$$

2nd adiabatic invariant: $J = \oint v_{\|} dl$

t



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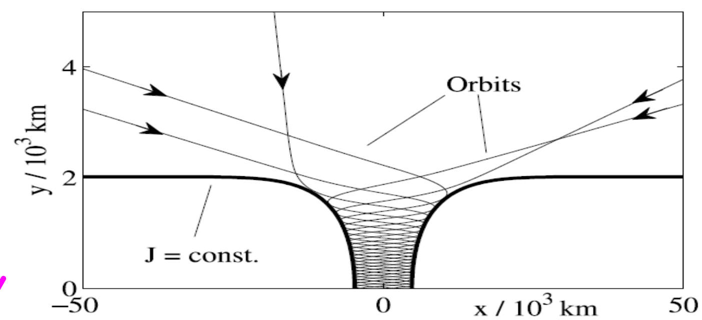


$$\mathcal{E}_{\perp\infty} = h_1(\mu, J, \phi_j) \quad = \mu B_\infty$$

$$\mathcal{E}_{\|\infty} = h_2(\mu, J, \phi_j) \approx 0$$

Only electrons with small parallel energy will be caught in the magnetic and electric well as it develops slowly compared to the electron transit time, τ $(\sim L/v_t)$.

$$\begin{aligned}
\mathcal{E}_{\|\infty} &\leq \mu \frac{\partial B}{\partial t}\tau + e\frac{\partial E_{\|}}{\partial t}\tau L \\
&\simeq \mu B \frac{v_d}{d}\frac{L}{v_t} + eE_{\|}\frac{v_d}{d}\frac{L}{v_t}L \\
&\simeq \delta\left(T_e + e\Phi_{\|}\right) \quad .
\end{aligned}$$

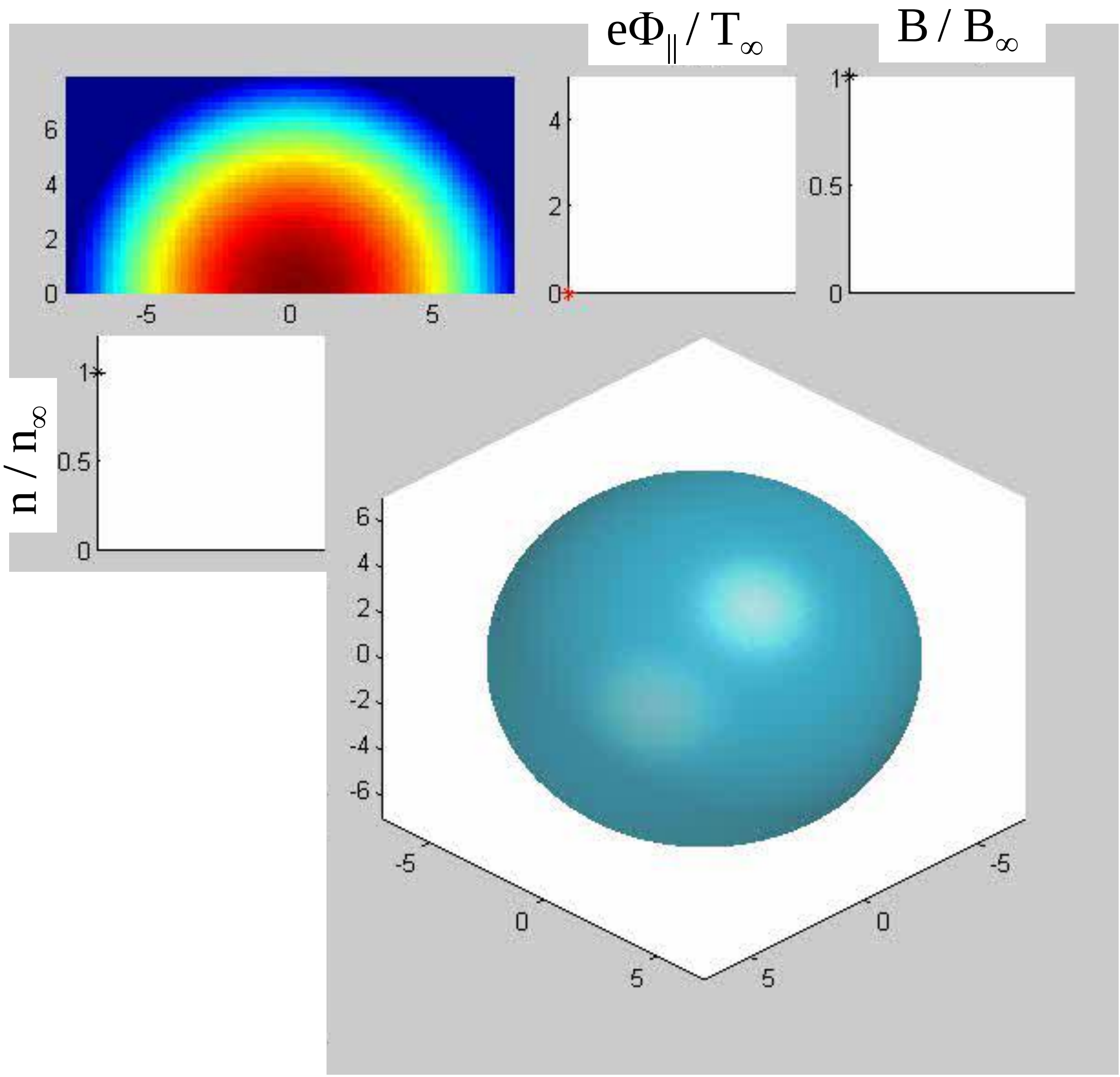
Thus, for Maxwellian f_∞:

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

Kinetic Model → Fluid Closure

Theoretical distribution:

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



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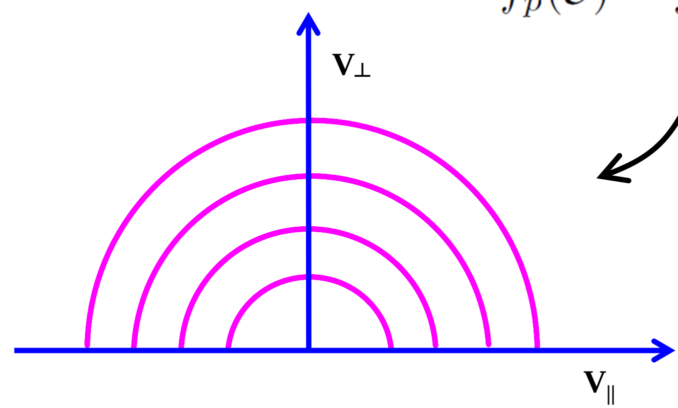
Kinetic Model ➔ Fluid Closure

$$f_p(\mathcal{E}) = f_\infty(\mathcal{E})\, e^{e\Phi_\parallel / T_{e\infty}}$$



$$\Phi_\parallel < 0,\ B > B_\infty \quad \Longrightarrow \quad \text{no trapping}$$

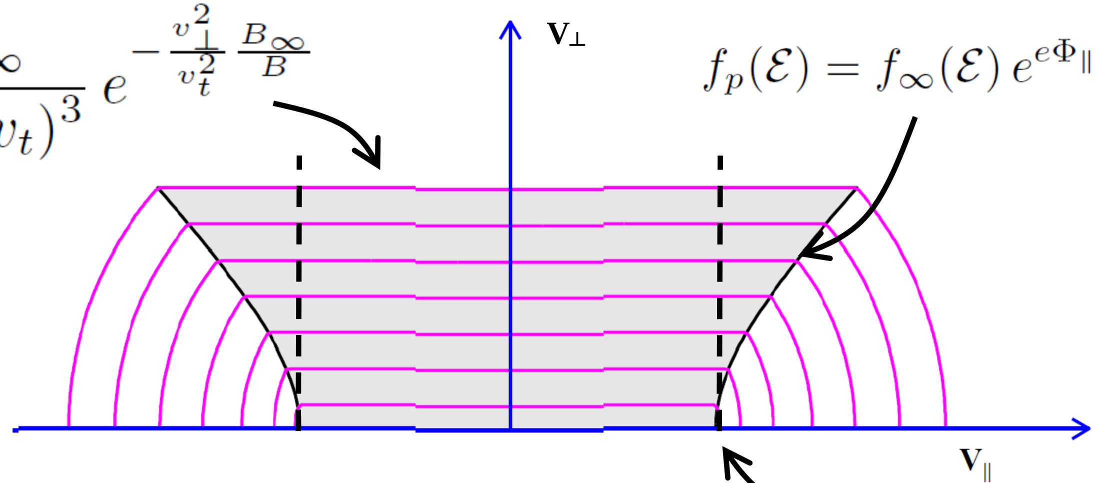
$$n = n_\infty\, e^{e\Phi_\parallel / T_\infty} \quad < \quad n_\infty \qquad , \qquad \frac{e\Phi_\parallel}{T_\infty} = \log\left(\frac{n}{n_\infty}\right)$$

$$p_\parallel = p_\perp = nT_\infty \qquad\qquad \tilde{p}_\parallel = \tilde{p}_\perp = \tilde{n}$$

Kinetic Model ➔ Fluid Closure

$$f_t = \frac{n_\infty}{(\sqrt{\pi} v_t)^3} e^{-\frac{v_\perp^2}{v_t^2}\frac{B_\infty}{B}}$$

$$f_p(\mathcal{E}) = f_\infty(\mathcal{E})\, e^{e\Phi_\| / T_{e\infty}}$$



$$v_\phi = \sqrt{\frac{2e\Phi_\|}{m_e}}$$

$e\Phi_\| \gg T_\infty,\ B < B_\infty$

(ignore contributions from passing electrons)

$$n \simeq \int_{-v_\phi}^{v_\phi} dv_\| \int_0^\infty 2\pi v_\perp dv_\perp f_t = \frac{2}{\sqrt{\pi}} \frac{v_\phi}{v_t} \frac{B}{B_\infty} n_\infty \implies \frac{v_\phi}{v_t} \simeq \frac{\sqrt{\pi}}{2} \frac{\tilde{n}}{\tilde{B}}$$

$$p_\| \simeq m_e \int_{-v_\phi}^{v_\phi} v_\|^2 dv_\| \int_0^\infty 2\pi v_\perp dv_\perp f_t = \frac{1}{3} v_\phi^2 m_e n \implies \tilde{p}_\| \simeq \frac{\pi}{6} \frac{\tilde{n}^3}{\tilde{B}^2}$$

$$\frac{e\Phi_\|}{T_\infty} \simeq \frac{\pi}{4} \frac{\tilde{n}^2}{\tilde{B}^2}$$

$$p_\perp \simeq n T_\infty \frac{B}{B_\infty} \implies \tilde{p}_\perp \simeq \tilde{n}\tilde{B}$$

Kinetic Model ➔ Fluid Closure (EoS)

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

$\int \ldots \, d^3v$

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

$$\Phi_\parallel = \Phi_\parallel(n,B)$$

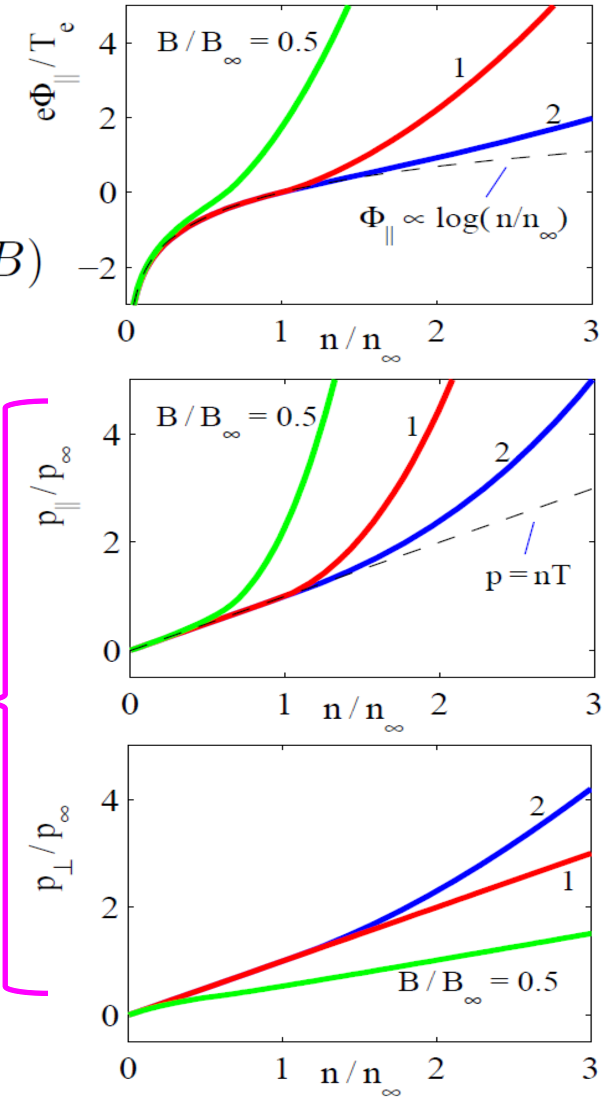
Eliminate $\Phi_\parallel$ ➔

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

$\xrightarrow[\Phi_\parallel \gg T_e]{}$

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

$$p_\perp \propto nB$$

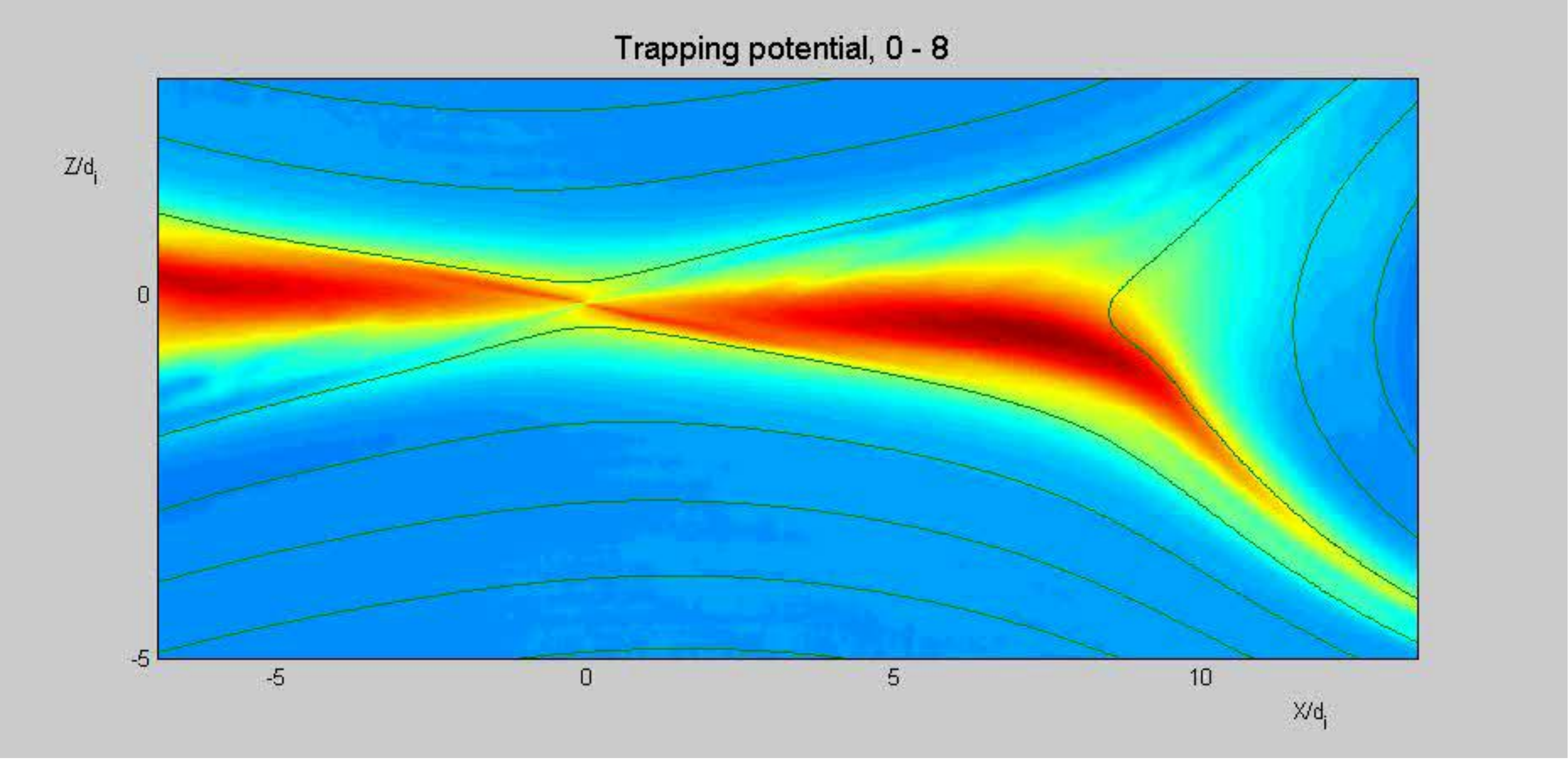


Transition from Boltzmann to double adiabatic CGL-scaling
[G Chew, M Goldberger, F E Low, 1956]

A. Le et al., PRL (2009)

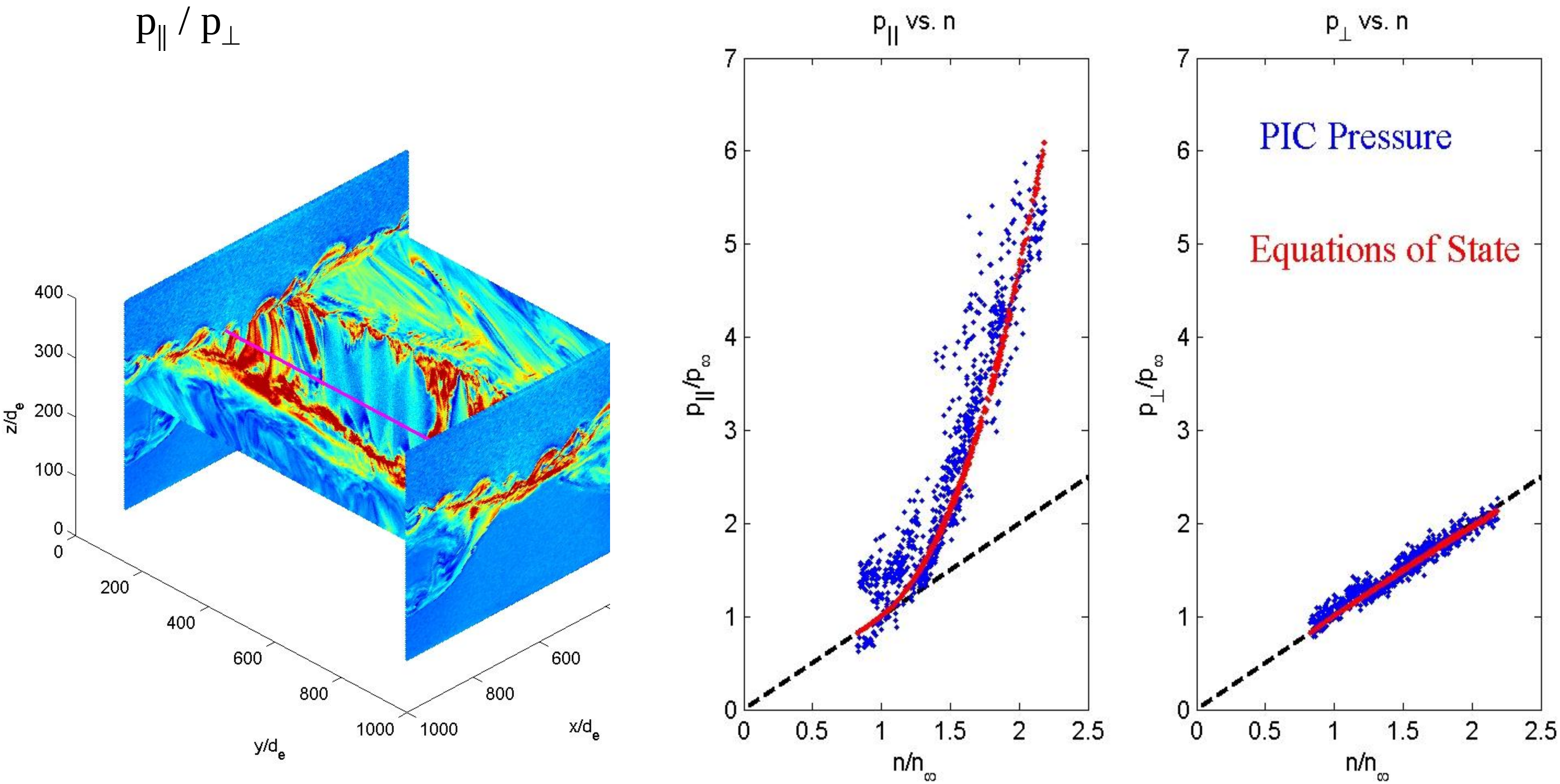
The Acceleration Potential in a Kinetic Simulation

$e\Phi_{||} / T_e$



Confirmed in Kinetic Simulations

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



New EoS Now Implemented in Two-Fluid Code

New code implemented by O Ohia using the HiFi framework developed in part by VS Lukin

Standard two-fluid equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{V}_i) = 0$$

$$m_i n \left(\frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i \right) = \mathbf{J} \times \mathbf{B} - \nabla \cdot \bar{\mathbf{P}} + m_i n \nu_i \nabla^2 \mathbf{V}_i$$

$$\frac{\partial}{\partial t} \left(\frac{p_i}{n^\Gamma} \right) = -\mathbf{V}_i \cdot \nabla \frac{p_i}{n^\Gamma}$$

$$\frac{\partial \mathbf{B}'}{\partial t} = -\nabla \times \mathbf{E}'$$

$$\mathbf{E}' + \mathbf{V}_i \times \mathbf{B} = \frac{1}{ne} \left(\mathbf{J} \times \mathbf{B}' - \nabla \cdot \bar{\mathbf{P}}_e \right) + \eta_R \mathbf{J} - \eta_H \nabla^2 \mathbf{J}$$

$$\mathbf{B}' = \left(1 - d_e^2 \nabla^2\right) \mathbf{B}$$

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

Anisotropic pressure model

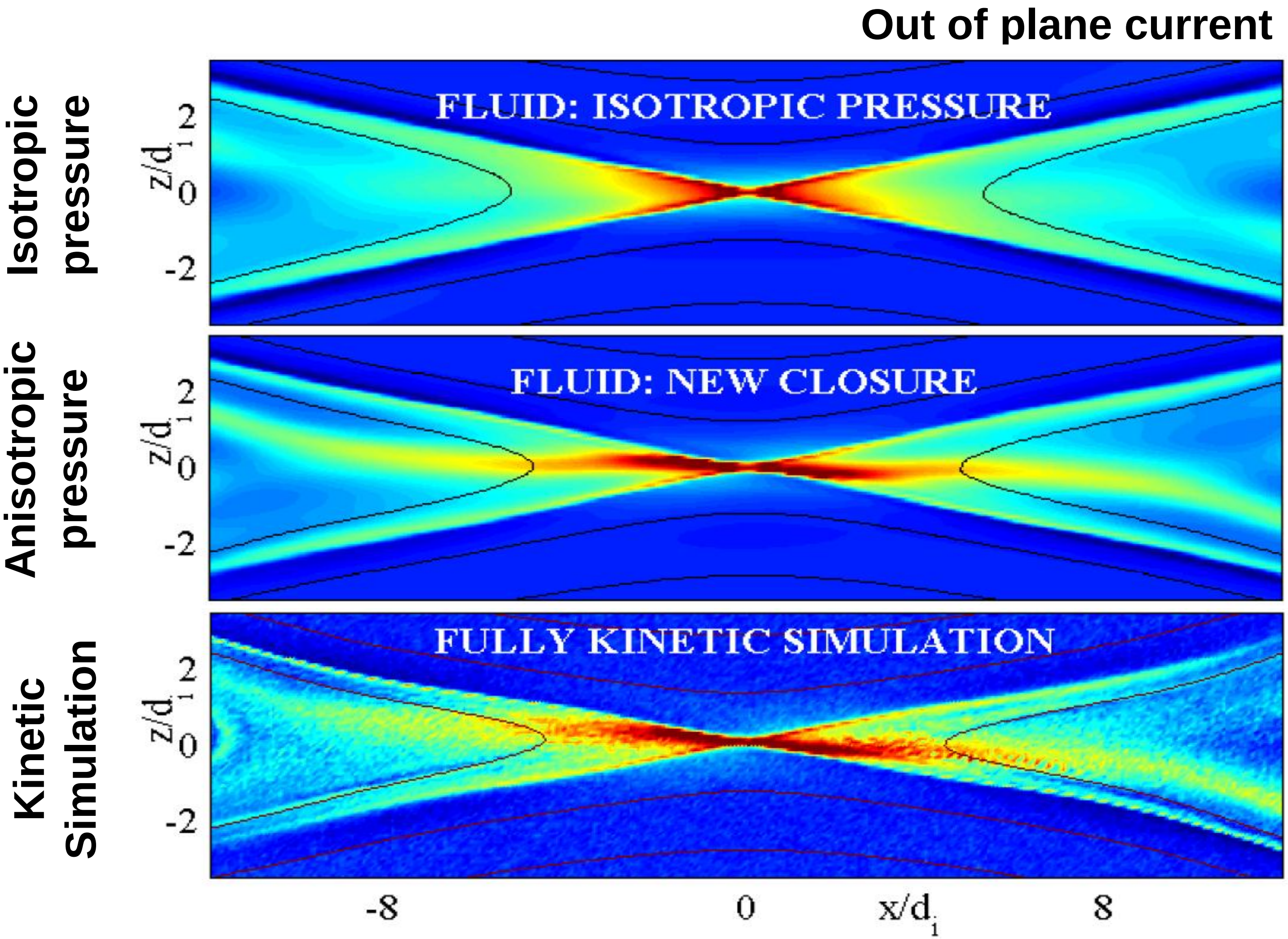
$$\bar{\mathbf{P}} = p_i \bar{\mathbf{I}} + \bar{\mathbf{P}}_e = p_i \bar{\mathbf{I}} + p_\perp \bar{\mathbf{I}} + \left(p_\parallel - p_\perp\right) \frac{\mathbf{B}\mathbf{B}}{B^2}$$

$$p_{*\parallel} = \frac{n_*}{1+\alpha/2} + \frac{\alpha \pi}{6 + 3/\alpha}$$

$$p_{*\perp} = \frac{n_*}{1+\alpha} + \frac{n_* B_*}{1 + 1/\alpha}$$

where $\alpha = n_*^3 / B_*^2$ and for any quantity Q, $Q_* = Q/Q_\infty$

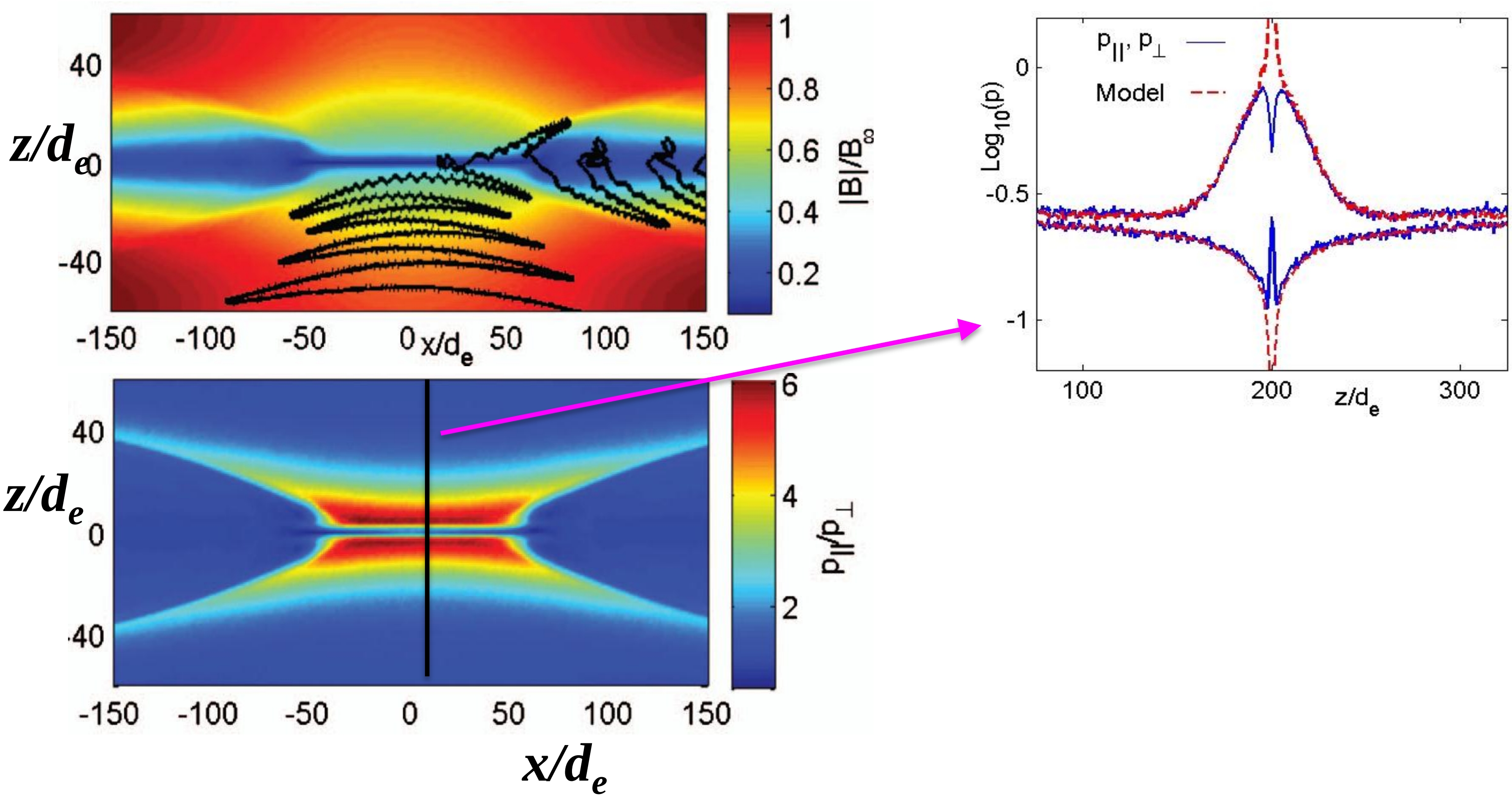
New *EoS* Implemented in Two-Fluid Code



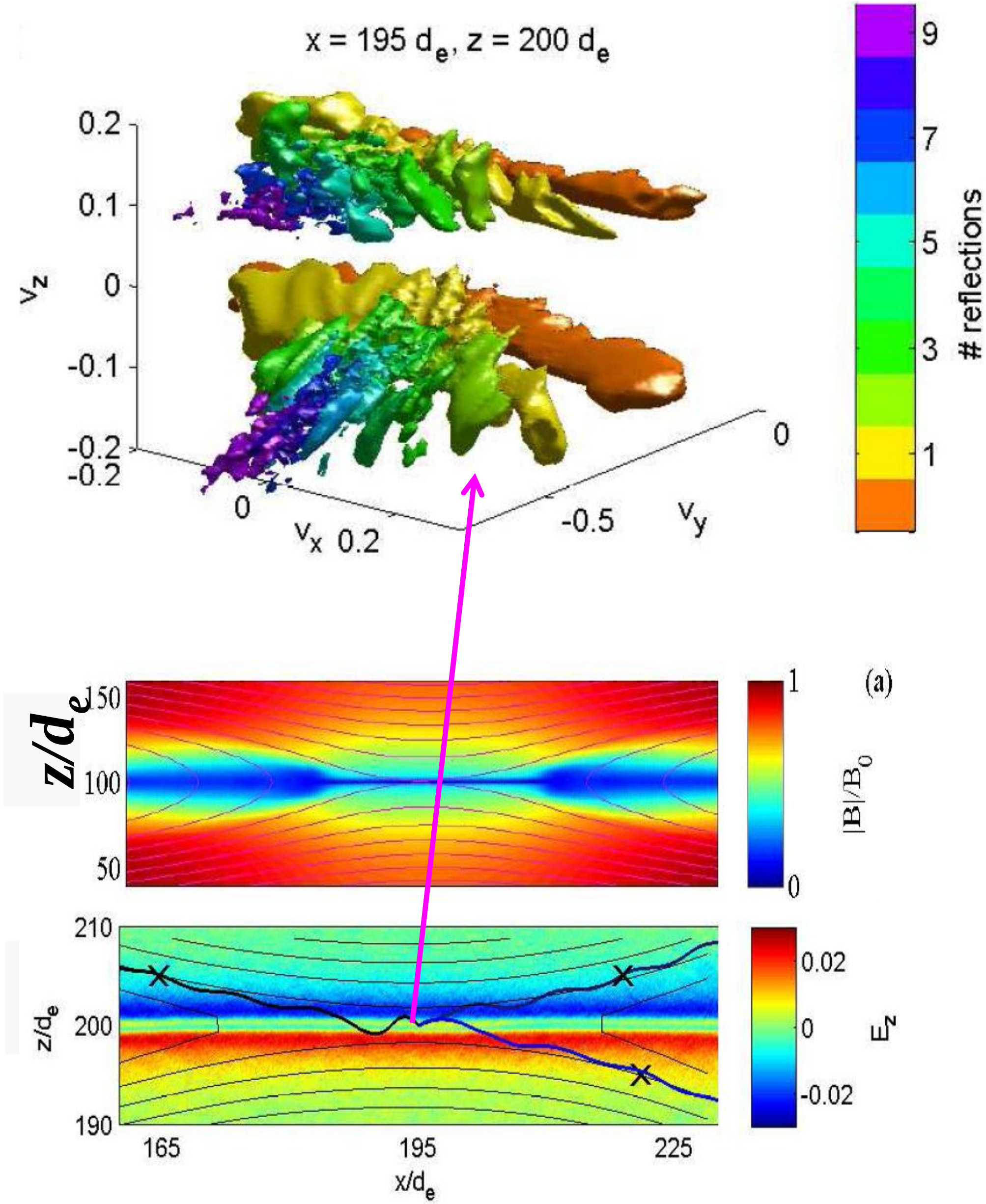
Ohia et al., PRL 2012 (in press)

EoS for anti-parallel reconnection?

The electrons are magnetized in the inflow region:



Electron distributions in the layer [J. Ng et al., PRL2011]



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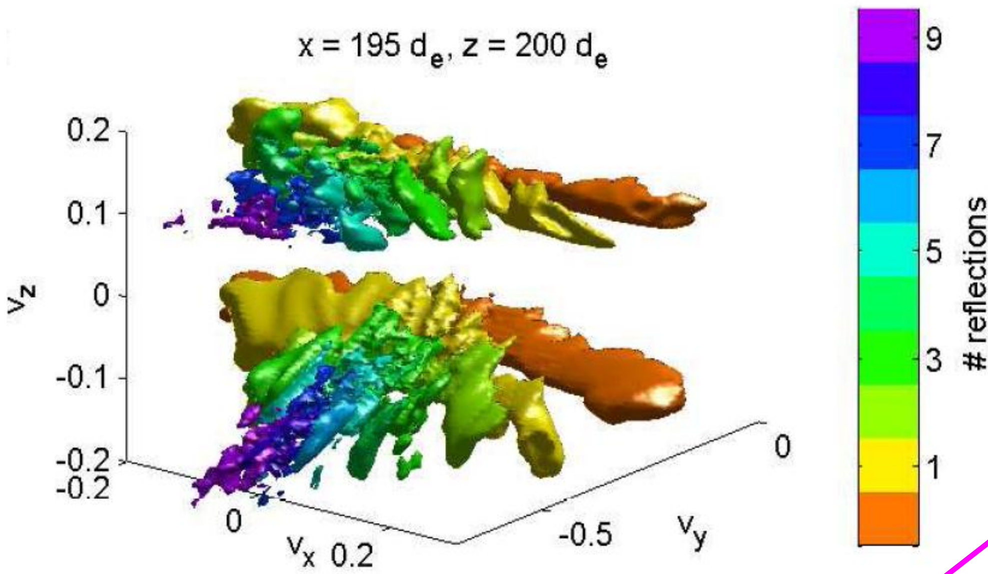

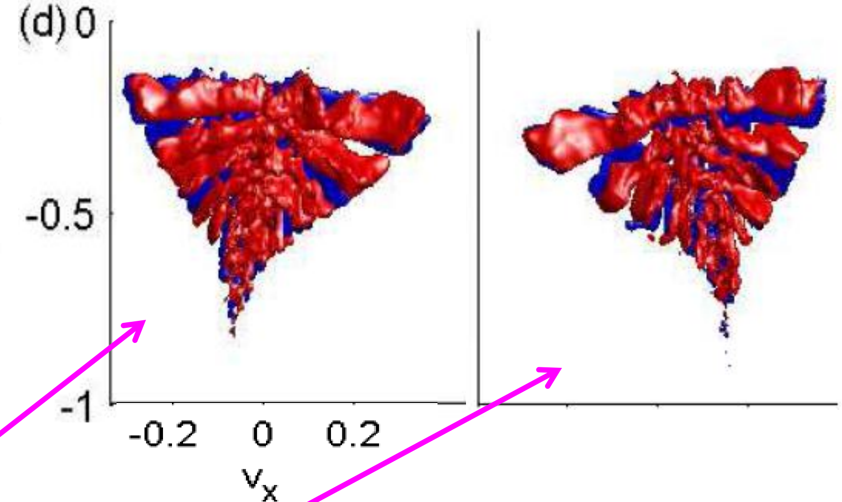

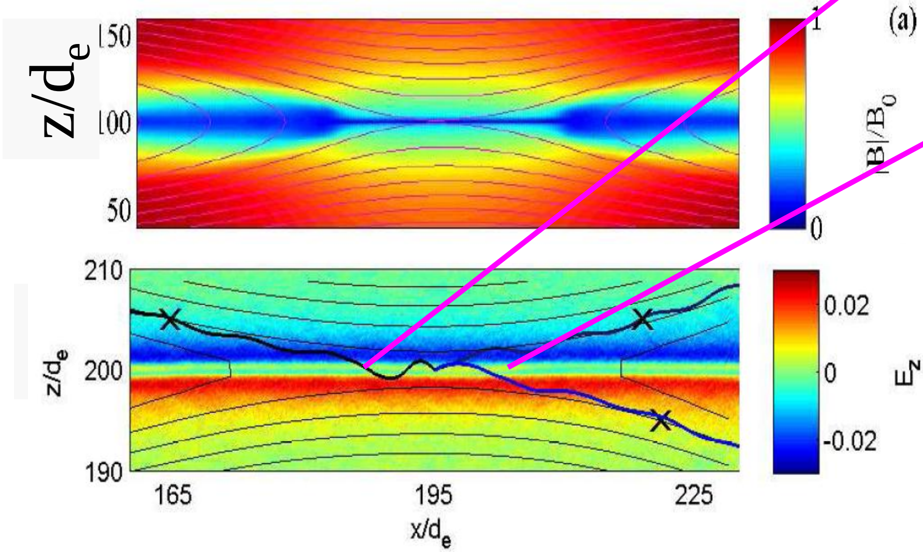

The triangular shape + rotation yield finite $\partial_x P_{xy}$ balancing the reconnection electric field, E_y!

J. Ng et al., PRL (2011)

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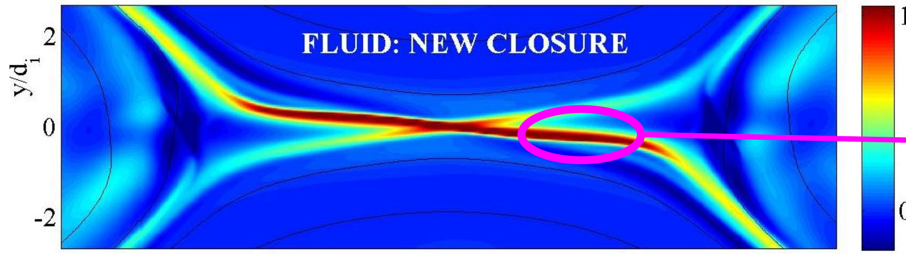
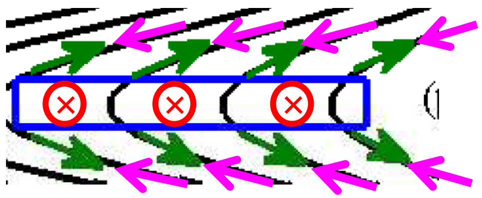
Analytic Model for Electron Jets

Anisotropic pressure





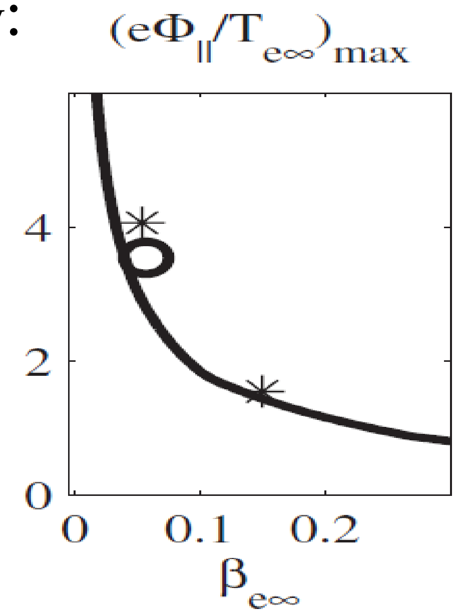
$p_\| - p_\perp$

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:

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

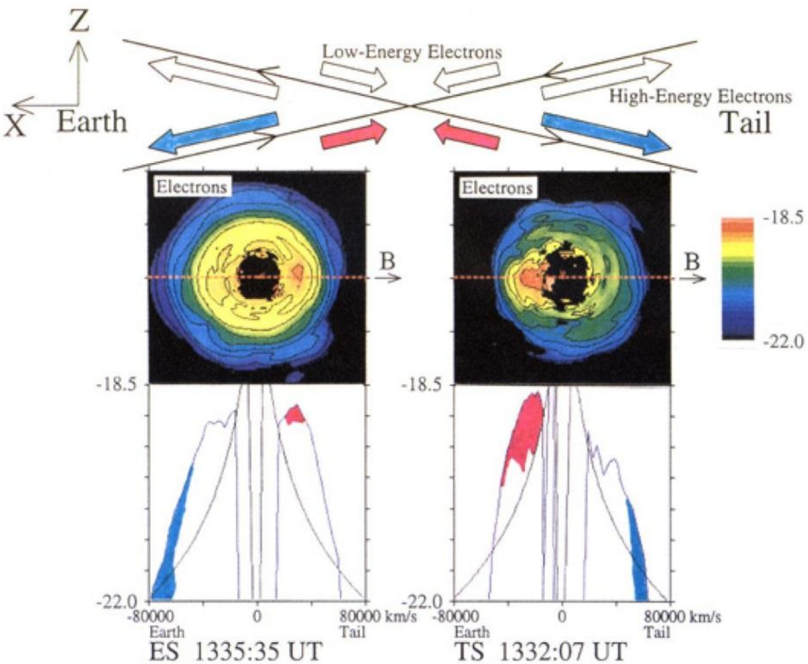


Use *EoS* to get scaling laws:

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

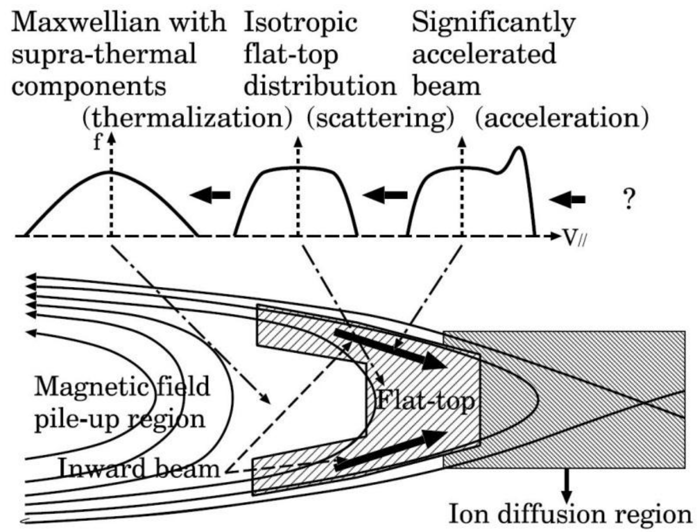
Observed Electron Heating

1-10 keV beam like electron distributions often observed



T. Nagai, et al., *J. Geophys. Res.*, ***106*** , 25.929 (2001).

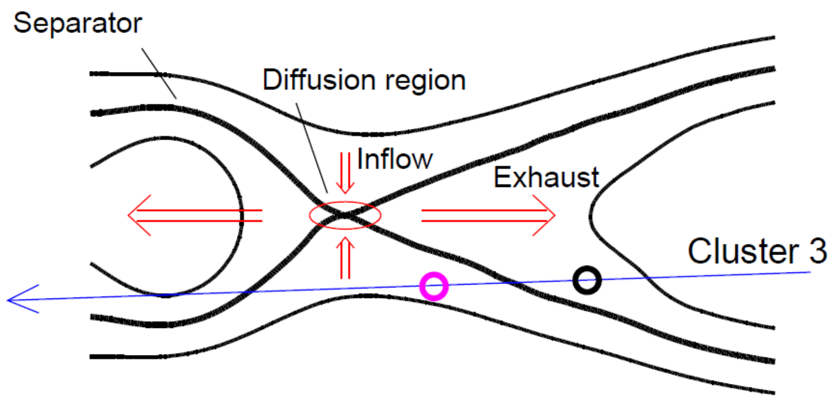
Flat-top distributions typical in the exhaust; related beams?

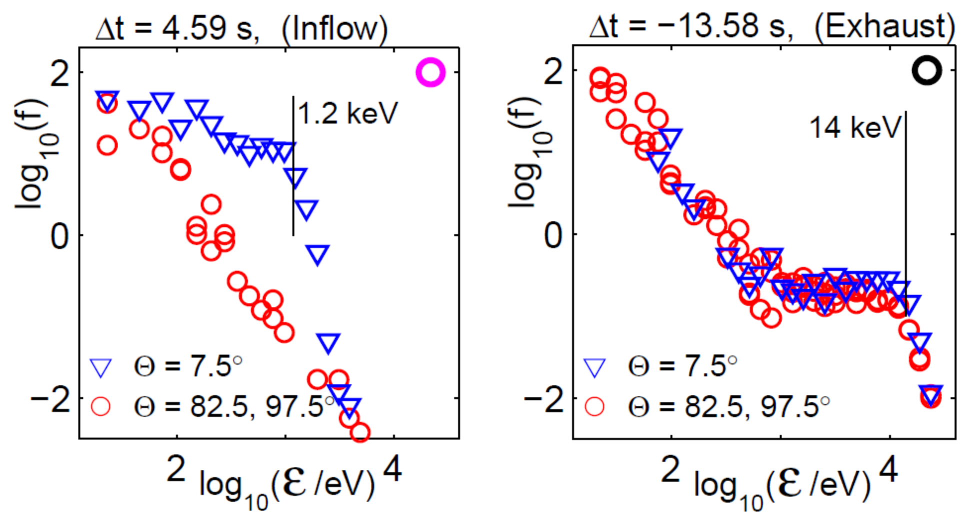


Y. Asano, et al., *J. Geophys. Res.*, ***113***(A1), (2008).

Observed Electron Heating

Cluster observations on 2001-10-01.



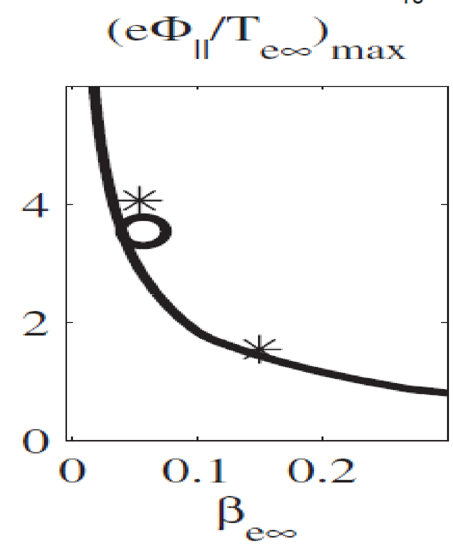


Lobe: T_e ~ 0.1 keV

Inflow: $T_{e\perp}$ ~ 0.1 keV, $T_{e\|}$ ~ 1 keV

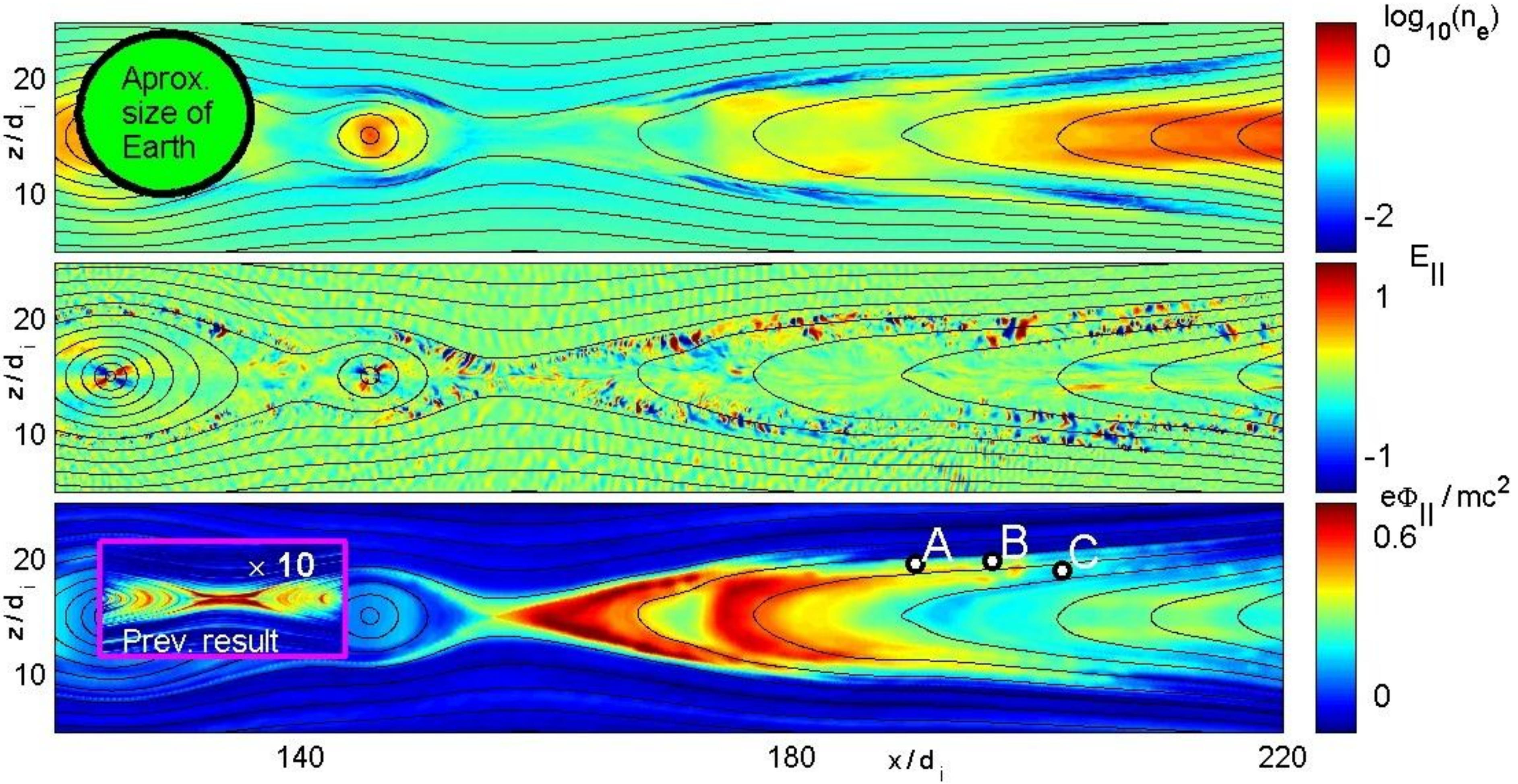
Exhaust: $T_{e\perp}$ ~ $T_{e\|}$ ~ 10keV

For this event $\beta_e \sim 0.003$



New simulation with $\beta_e \sim 0.003$

- 320 d_i long, 180 billion particles!



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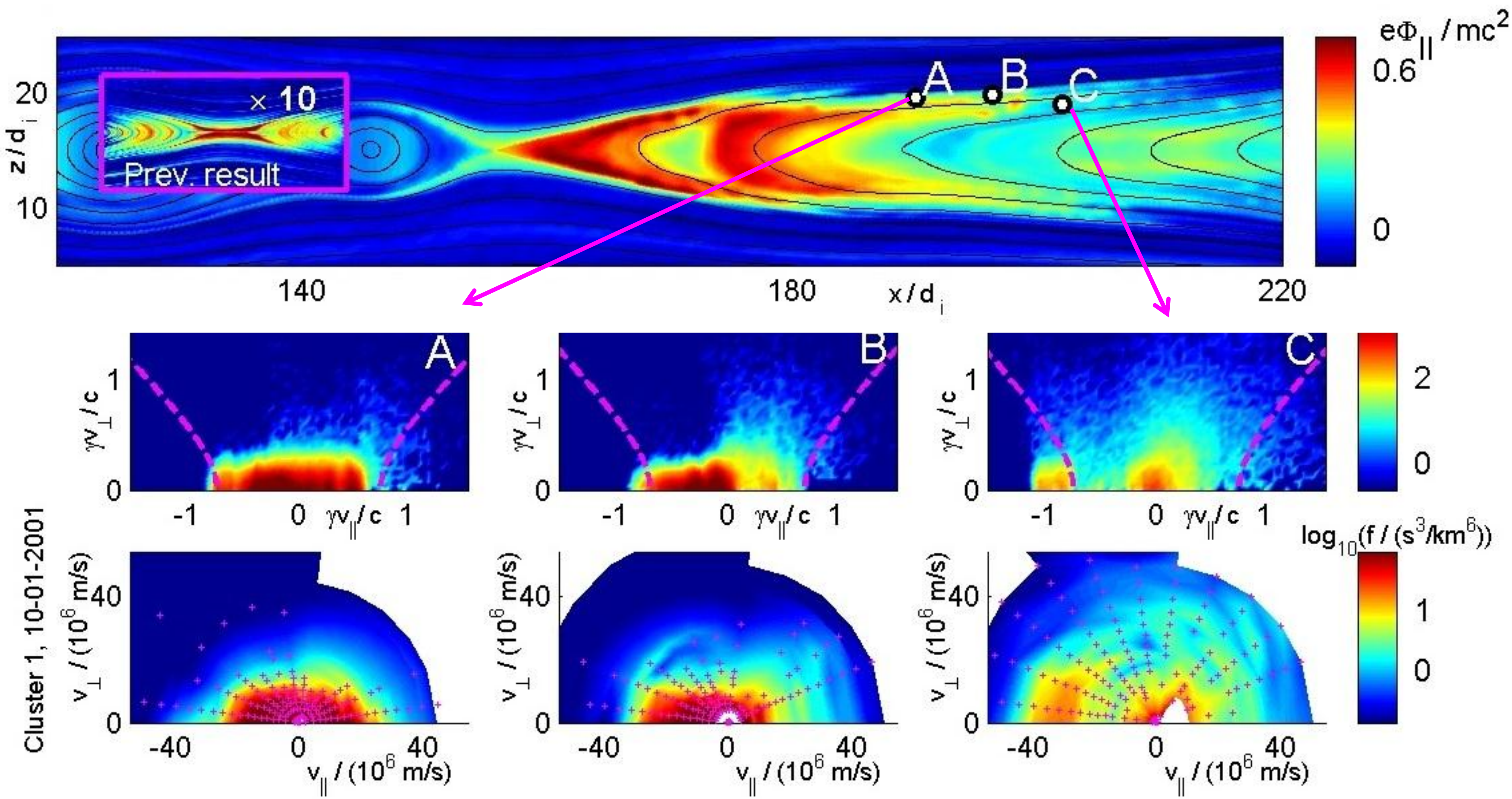
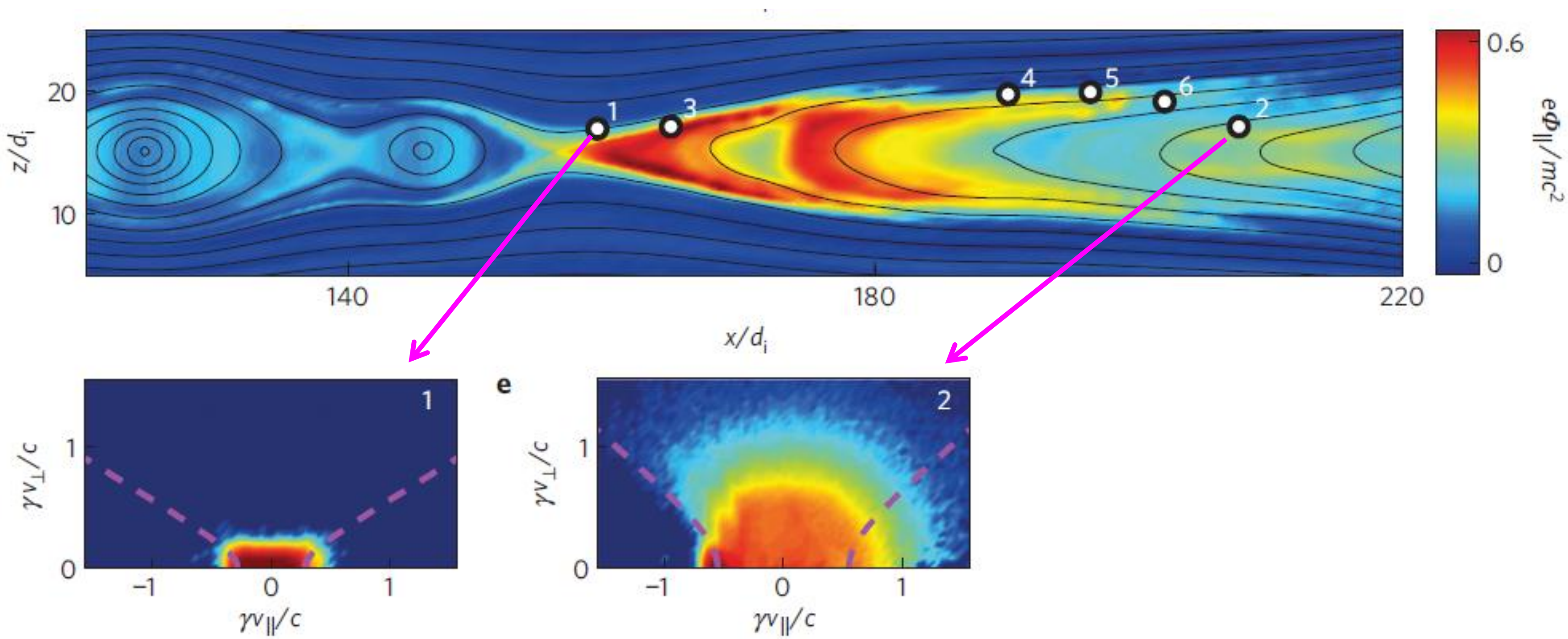
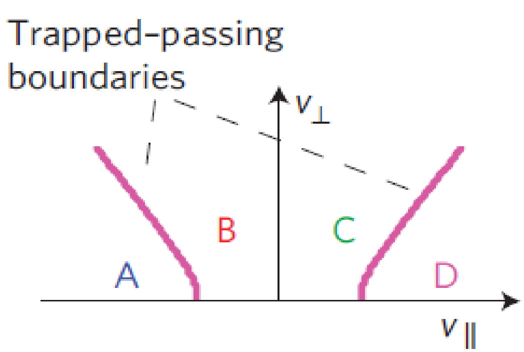


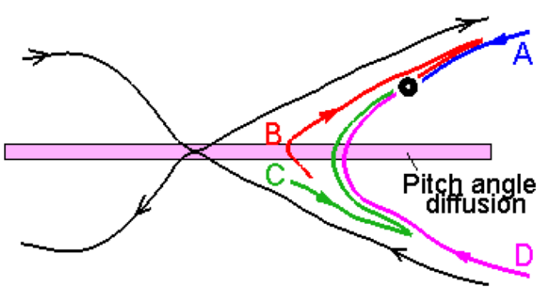
J. Egedal et al., Nature Physics (2012)

Flat-top Distributions

- 320 d_i long, 180 billion particles!







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

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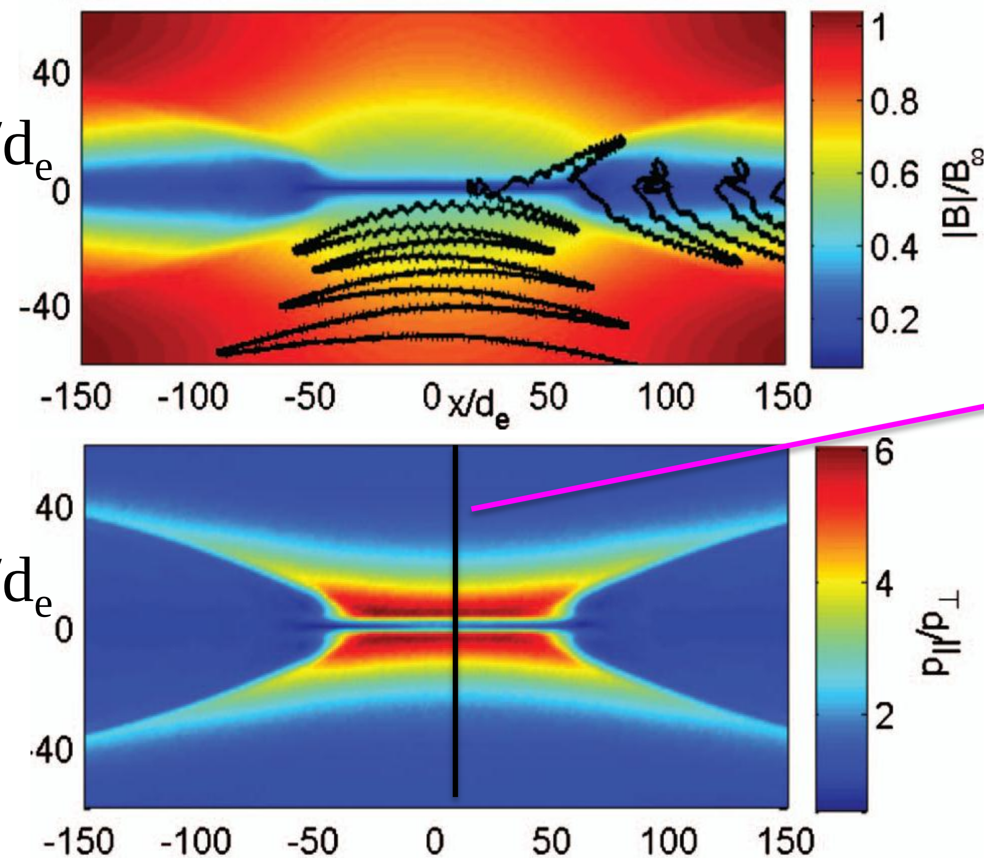
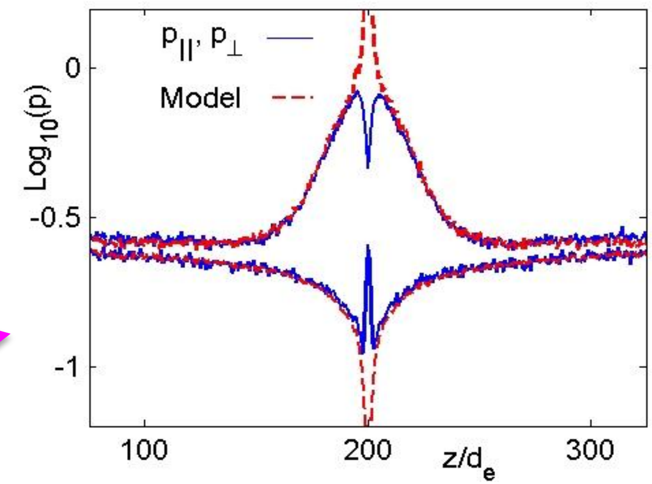
z/d_e



z/d_e

x/d_e



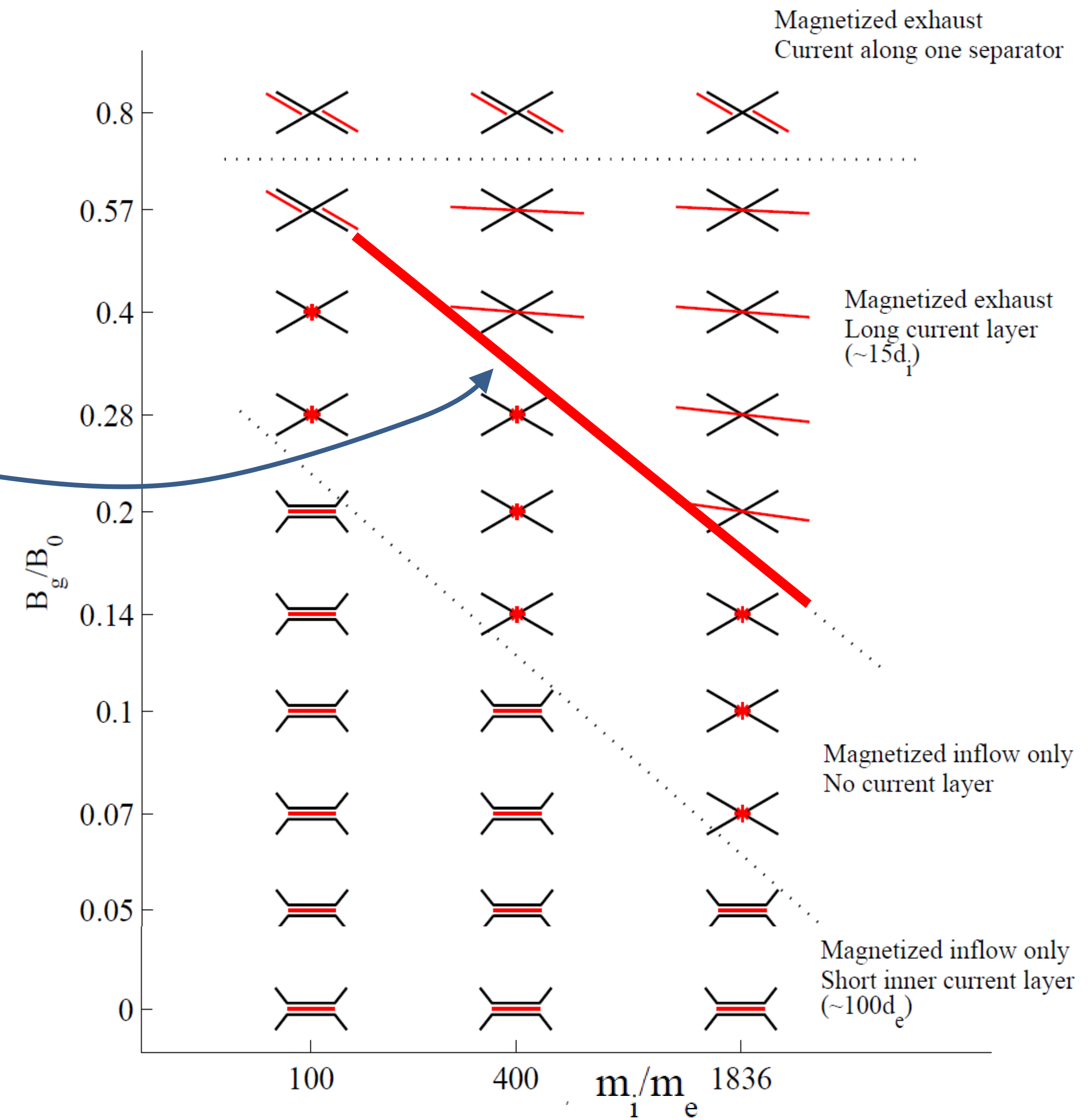
Pitch angle diffusion is controlled by:

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

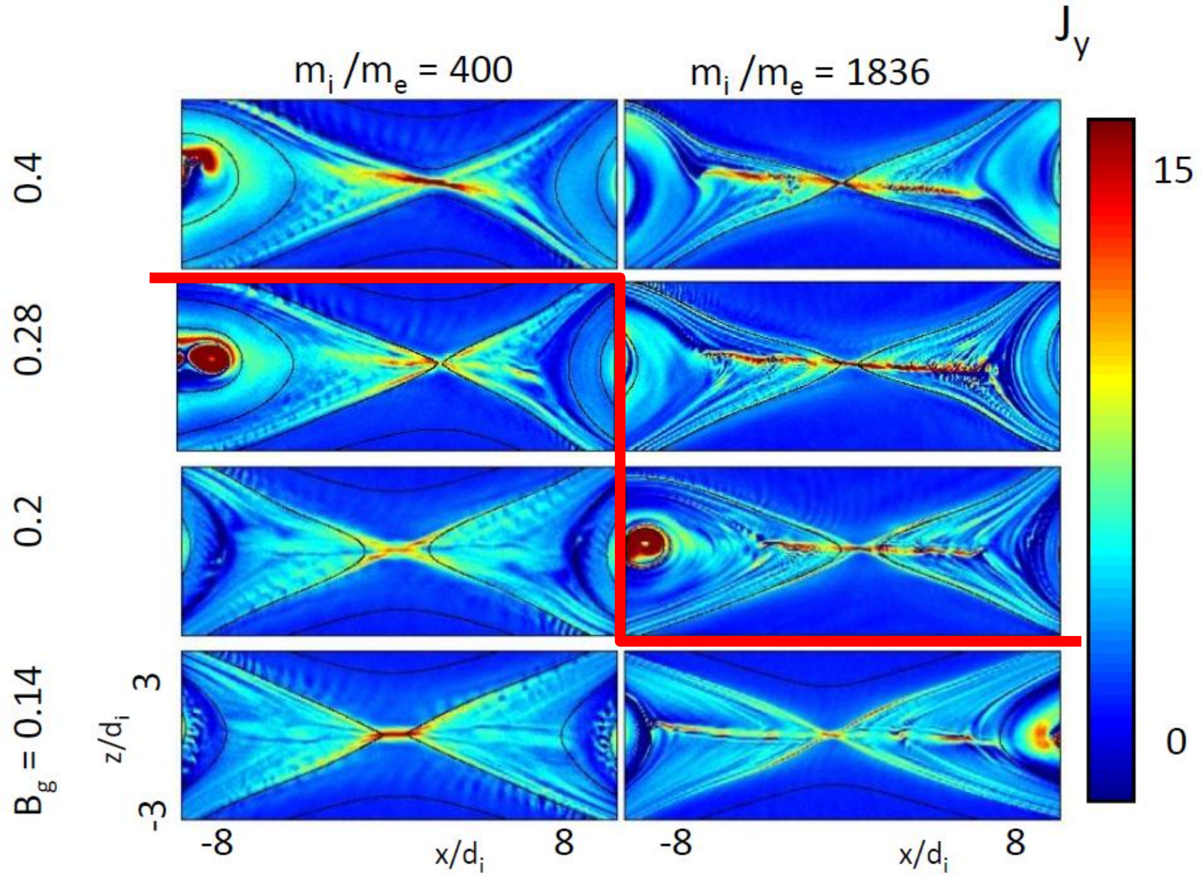
Depends on B_g and m_i/m_e

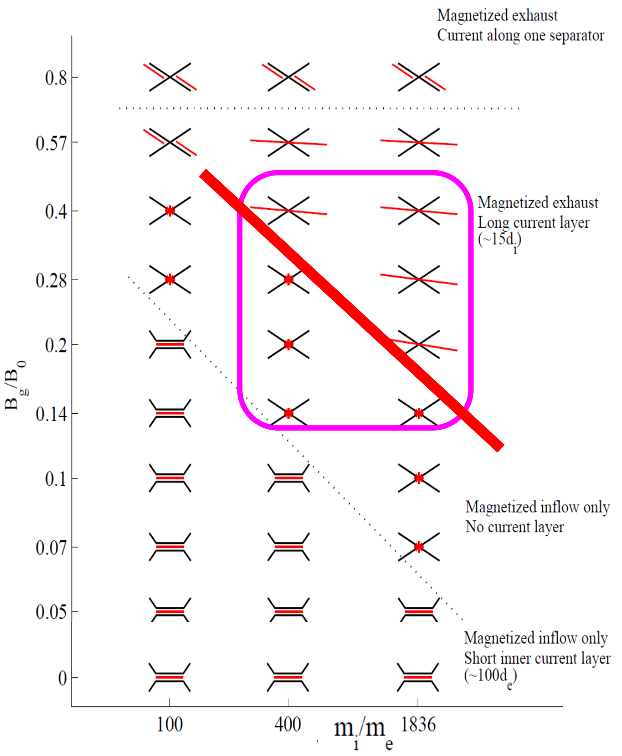
Scan in B_g and m_i/m_e
($\beta_e = 0.03$)

Pitch angle diffusion

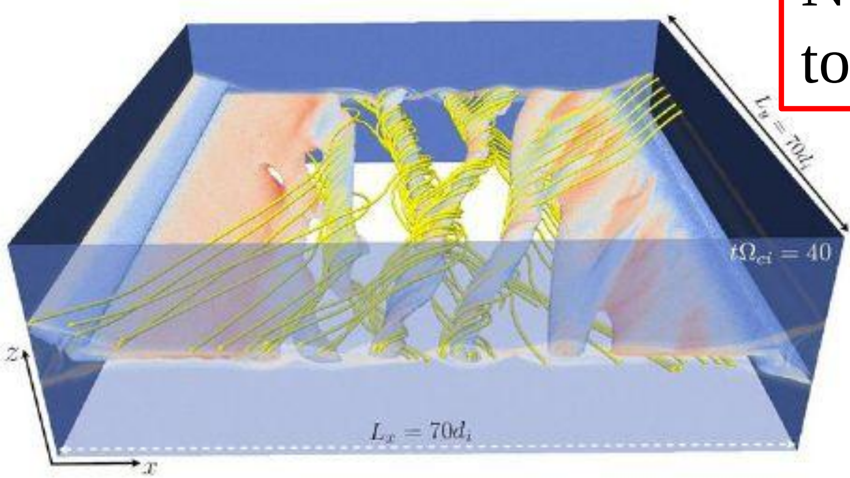


Scan in B_g and m_i/m_e

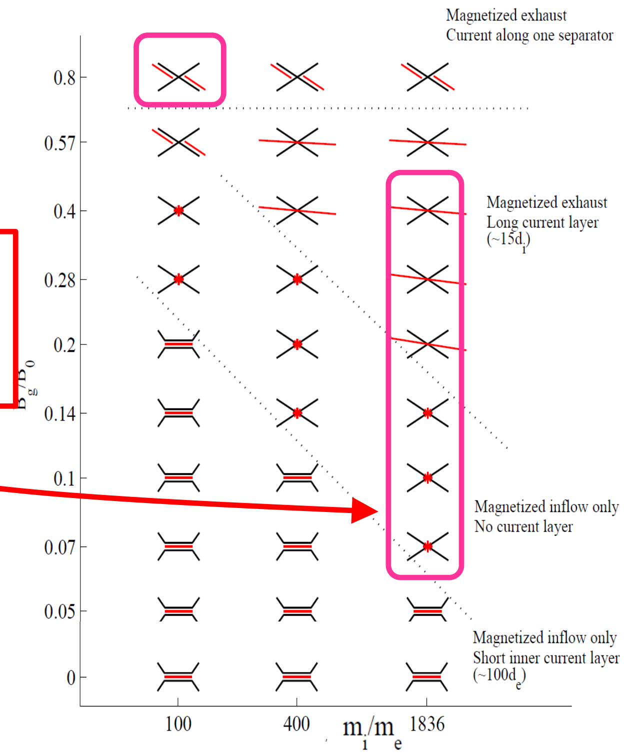


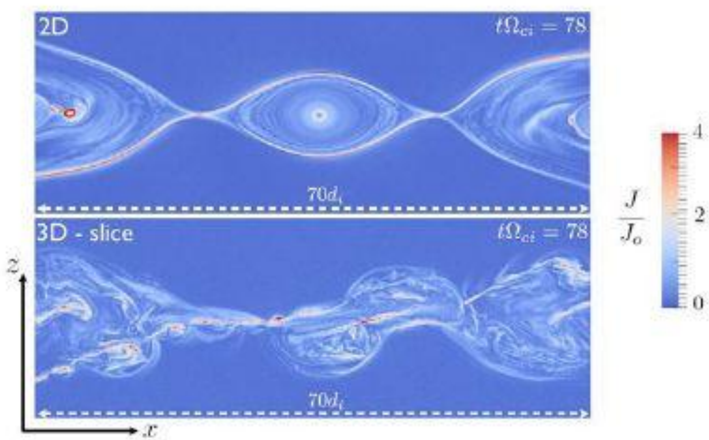


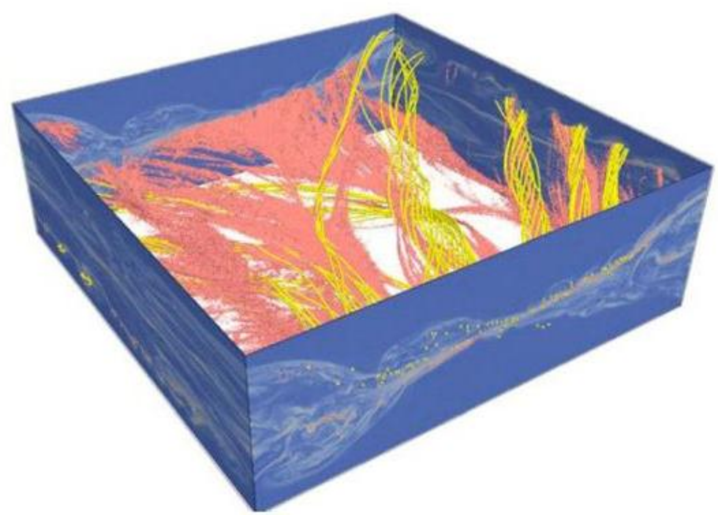
Need Experiment for 3D Reconnection Study



Not accessible to 3D codes!







Daughton et al. [2011].

Requirements on New Experiment

- Large normalized size of experiment: $L/d_i \sim 10$ (high n, large L)
- Low collisionallity to allow $p_{\|} >> p_{\perp}$: $\tau_{ei}\, v_A > d_i$ (low n, high T_e, high B)
- Low electron pressure: $\beta_e < 0.05$ (low n, T_e, high B)
- Manageable loop voltage: $0.1 v_A B_{rec}\, (2\pi R) < 5\mathrm{kV}$ (high n, low B)
- Variable guide field: $B_g = 0 – 4\, B_{rec}$
- Symmetric inflows

Experimental window available in Hydrogen or Helium plasma with

$$n \sim 10^{18}\ \mathrm{m}^{-3},\quad T_e \sim 15\ \mathrm{eV},\quad B_{rec} \sim 15\ \mathrm{mT},\quad L \sim 2\ \mathrm{m}$$

Flare heating by parallel E-fields?

Ohm's law:

$$-enE_{\|} = \hat{\mathbf{b}} \cdot (\nabla \cdot \mathbf{p})$$

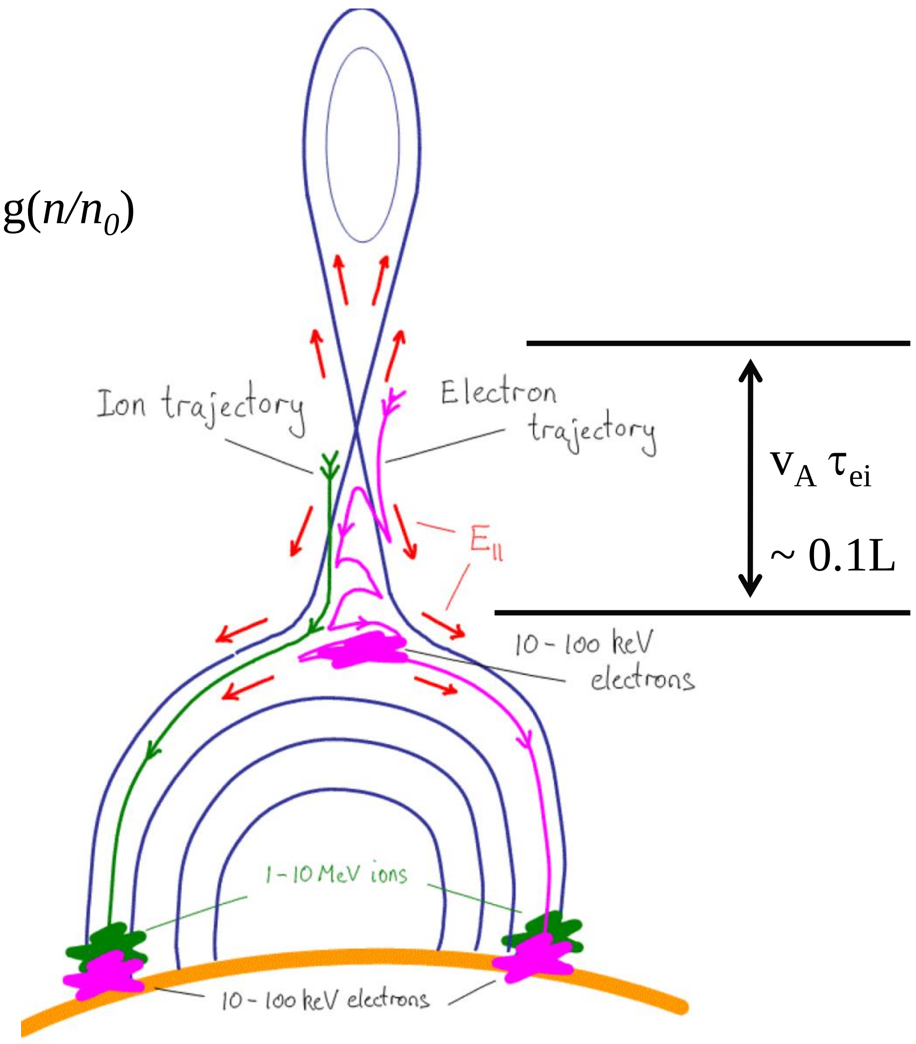
Before reconnection: $p = nT_e \Rightarrow e\Phi_{\|} \sim T_e \log(n/n_0)$

During reconnection: $p_{\|} \propto \dfrac{n^3}{B^2}$

$$\Rightarrow \quad e\Phi_{\|} \approx T_e \frac{(n/n_0)^2}{(B/B_0)^2}$$

$$(n/n_0) \approx 10, \quad (B/B_0) \approx 0.5$$

$$e\Phi_{\|} \approx 400 T_e$$



Conclusions

- A new analytic model for electron the electron distribution function was inspired by the VTF experiment and has been confirmed in kinetic simulations.

- The model has been applied as a closure to the fluid equations and has helped explain electron energization in spacecraft observations.

- Long current layer can be driven by the pressure anisotropy for magnetotail conditions and their investigation requires a new experimental facility.