Magnetic Reconnection during Turbulence and the Role it Plays in Dissipation and Heating

Michael Shay

Bartol Research Institute

University of Delaware

C. Haggerty, T. Parashar, W. Matthaeus, R. Bandyopadyay
T. D. Phan, J. F. Drake, Y. Yang, M. Wan, S. Servidio,
P. Wu

M. A. Shay, C. C. Haggerty, W. H. Matthaeus, T. N. Parashar, M. Wan, and P. Wu, **Turbulent heating due to magnetic reconnection**, *Physics of Plasmas,* 25, 012304 (2018);

Haggerty, C. C., T. N. Parashar, W. H. Matthaeus, M. A. Shay, Y. Yang, M. Wan, P. Wu, and S. Servidio, **Exploring the statistics of magnetic reconnection X-points in kinetic particle-in-cell turbulence**, Physics of Plasmas, 24, 102308, 2017, doi:10.1063/1.5001722.

Motivation

- Focus: Turbulence
  - Not reconnection generated turbulence
- Significant advances recently on the nature of plasma heating during magnetic reconnection
  - e.g., Phan et al., 2013, 2104; Yamada et al., 2014, Shay et al., 2014; Haggerty et al., 2015; Wang et al., and many more
- Kinetic simulations of turbulence: some inertial range to electron scales
  - e.g., Howes et al., Tenbarge et al., Karimabadi et al., Parashar et al, Gary et al., and many more.
- Can we apply our understanding of “simple” magnetic reconnection to turbulent heating?
  - Short Answer: Yes …. But …..

Overview

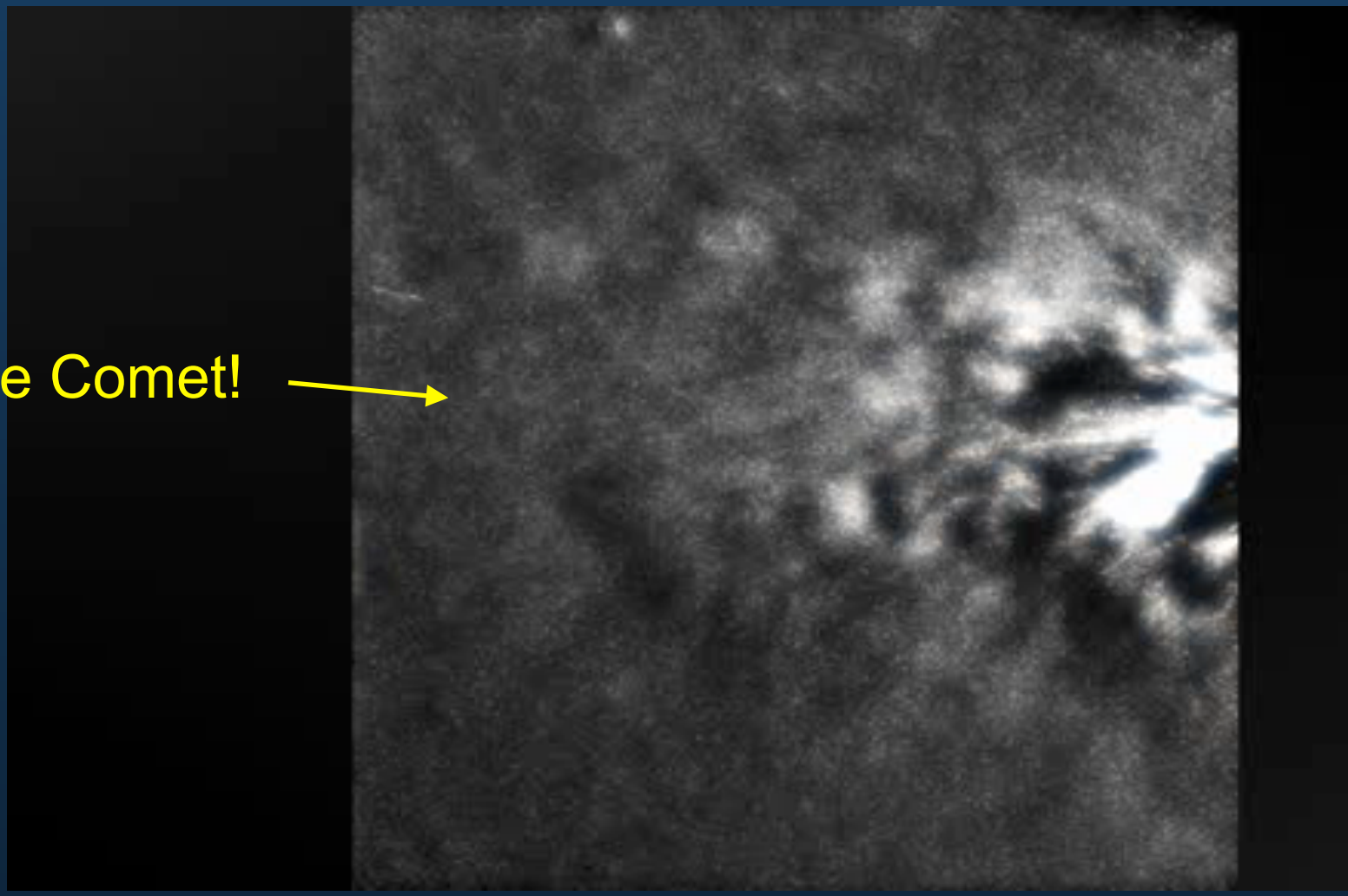
- Background
- Laminar Reconnection Studies
  - Heating in Reconnection Exhausts
- Framework: Apply Heating Predictions to Turbulence
- Kinetic PIC Turbulence Simulations
  - Test Framework
- Statistics of Reconnection: Kinetic PIC Simulations

Overview

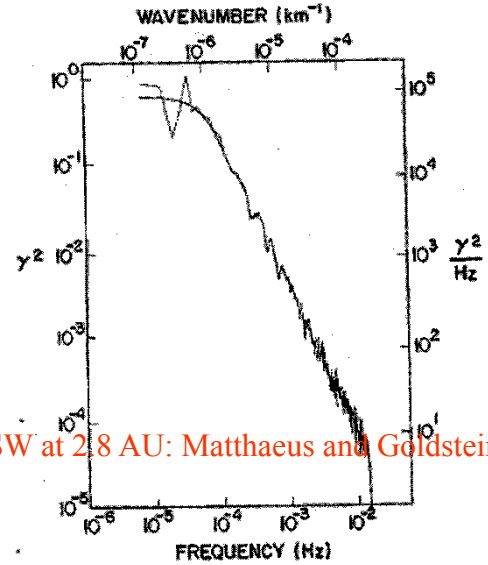
- Background
- Laminar Reconnection Studies
  - Heating in Reconnection Exhausts
- Framework: Apply Heating Predictions to Turbulence
- Kinetic PIC Turbulence Simulations
  - Test Framework
- Statistics of Reconnection: Kinetic PIC Simulations

Solar Wind Turbulence

Notice the Comet!

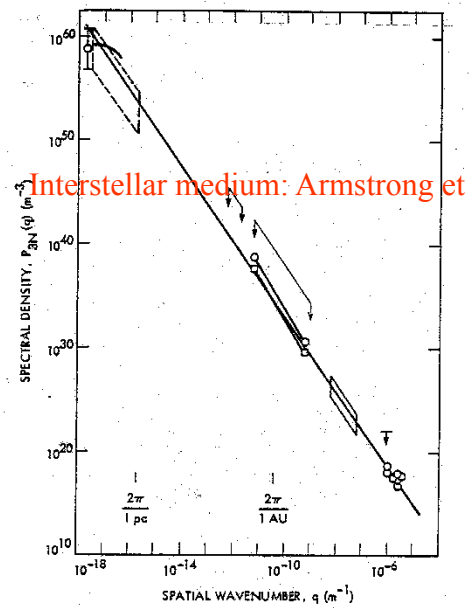


“Powerlaws everywhere”→ Broadband self-similar spectra are a signature of cascade

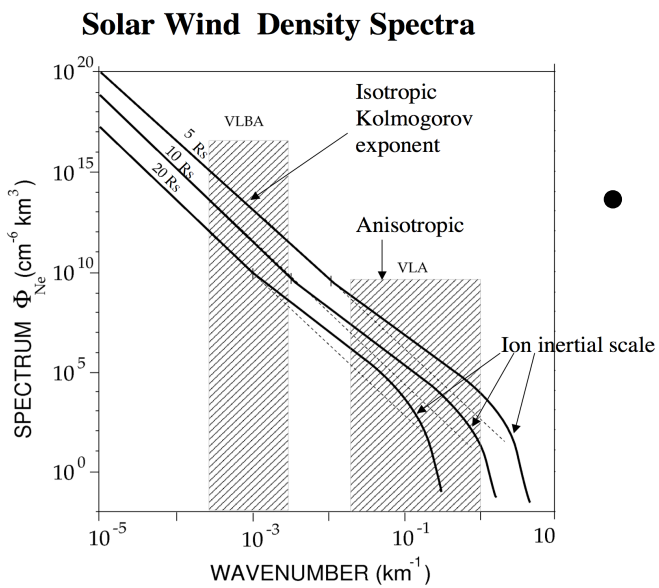


SW at 2.8 AU: Matthaeus and Goldstein

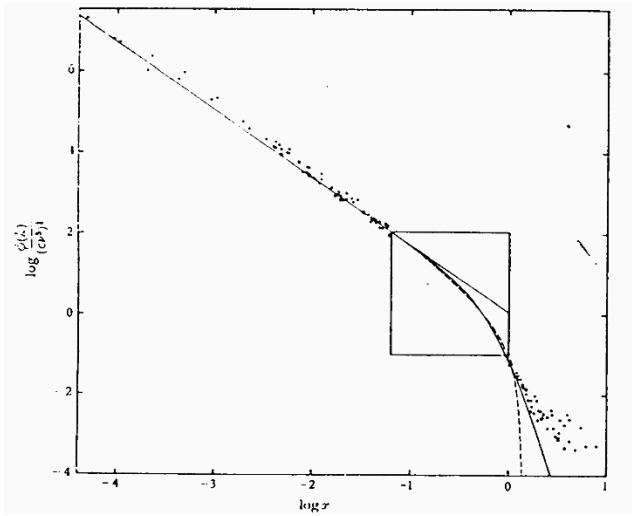
- Solar wind
- Corona
- Diffuse ISM
- Geophysical flows



Interstellar medium: Armstrong et al

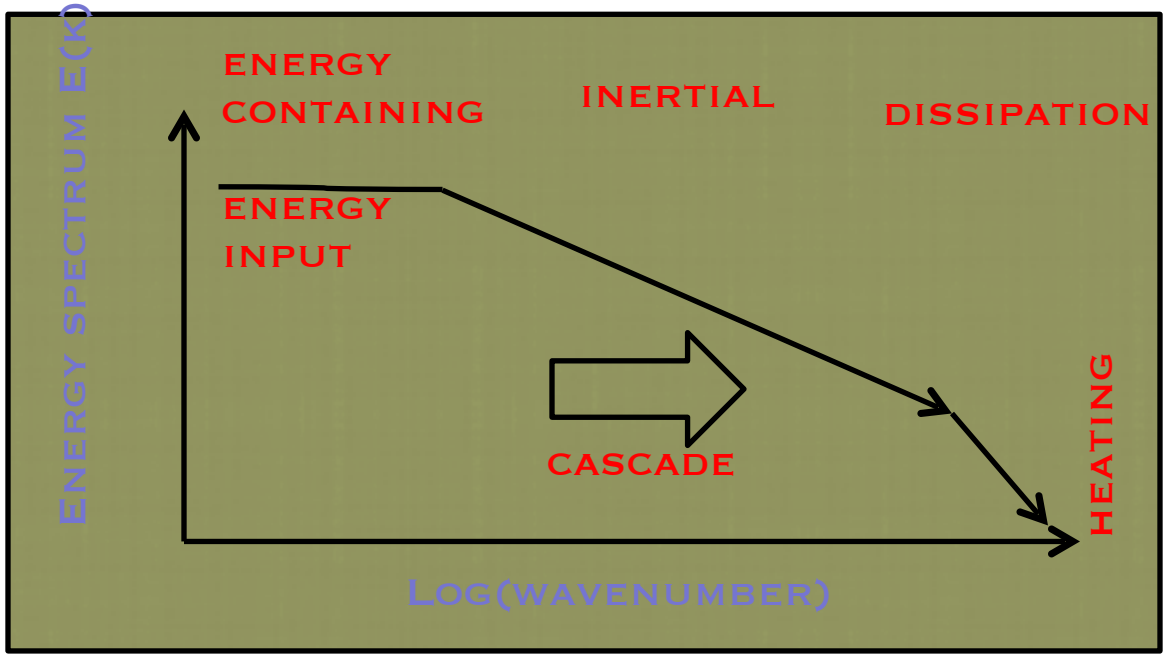


Coronal scintillation results (Harmon and Coles)



Tidal channel: Grant, Stewart and Moilliet

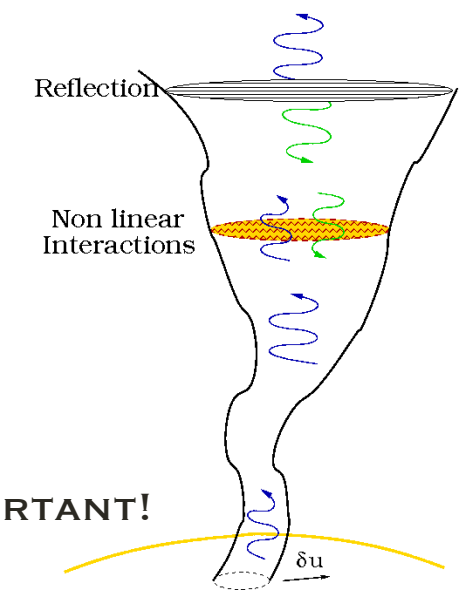
Heating by turbulence cascade



...in corona, turbulence can:

- heat the plasma,
- increasing the pressure gradient
- adding momentum

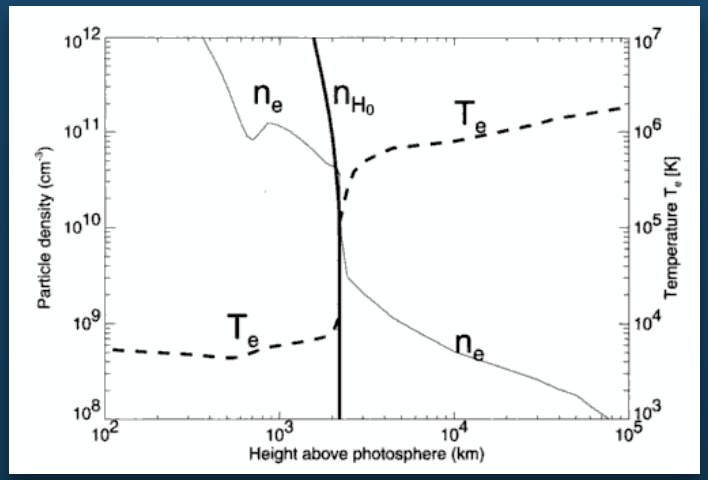
→ producing the solar wind



Where the heating occurs is important!

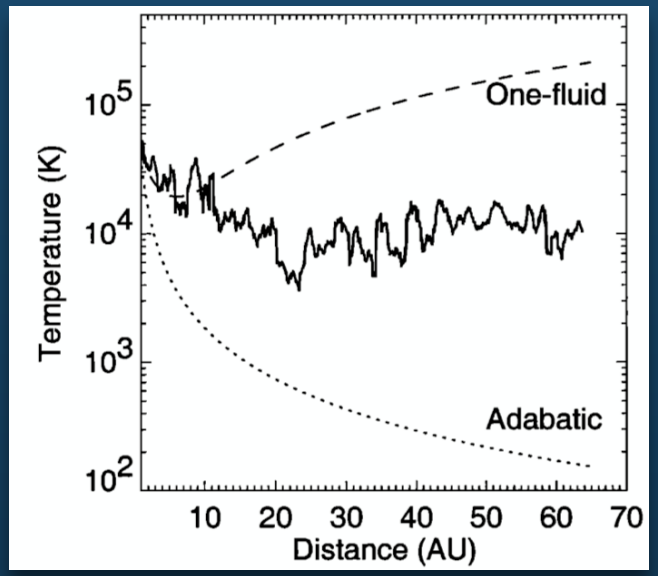
Plasma Heating - Magnetic Dissipation?

- Something is heating the solar corona



Model of Photosphere/Corona Transition
"Physics of the Solar Corona,"
Aschwanden, 2005.

- Something is heating the solar wind



Wang et al., JGR, 106, 29401, 2001

Physical Dissipation Mechanisms for Kinetic Turbulence

The University of Iowa

From SHINE conference, 2014

Howes/Shay Session Description

Three mechanisms have been proposed:

(1) Collisionless Wave-Particle Interactions (Landau damping)

(Leamon *et al*., 1998, 1999, 2000; Quateart & Gruzinov, 1999; Howes *et al*. 2008; Schekochihin *et al*. 2009; TenBarge & Howes 2012)

(2) Stochastic Heating

(Johnson & Cheng, 2001; Chen *et al*. 2001; White *et al*., 2002; Voitenko & Goosens, 2004; Bourouaine *et al*., 2008; Chandran *et al*. 2010; Chandran 2010)

(3) Dissipation in Current Sheets

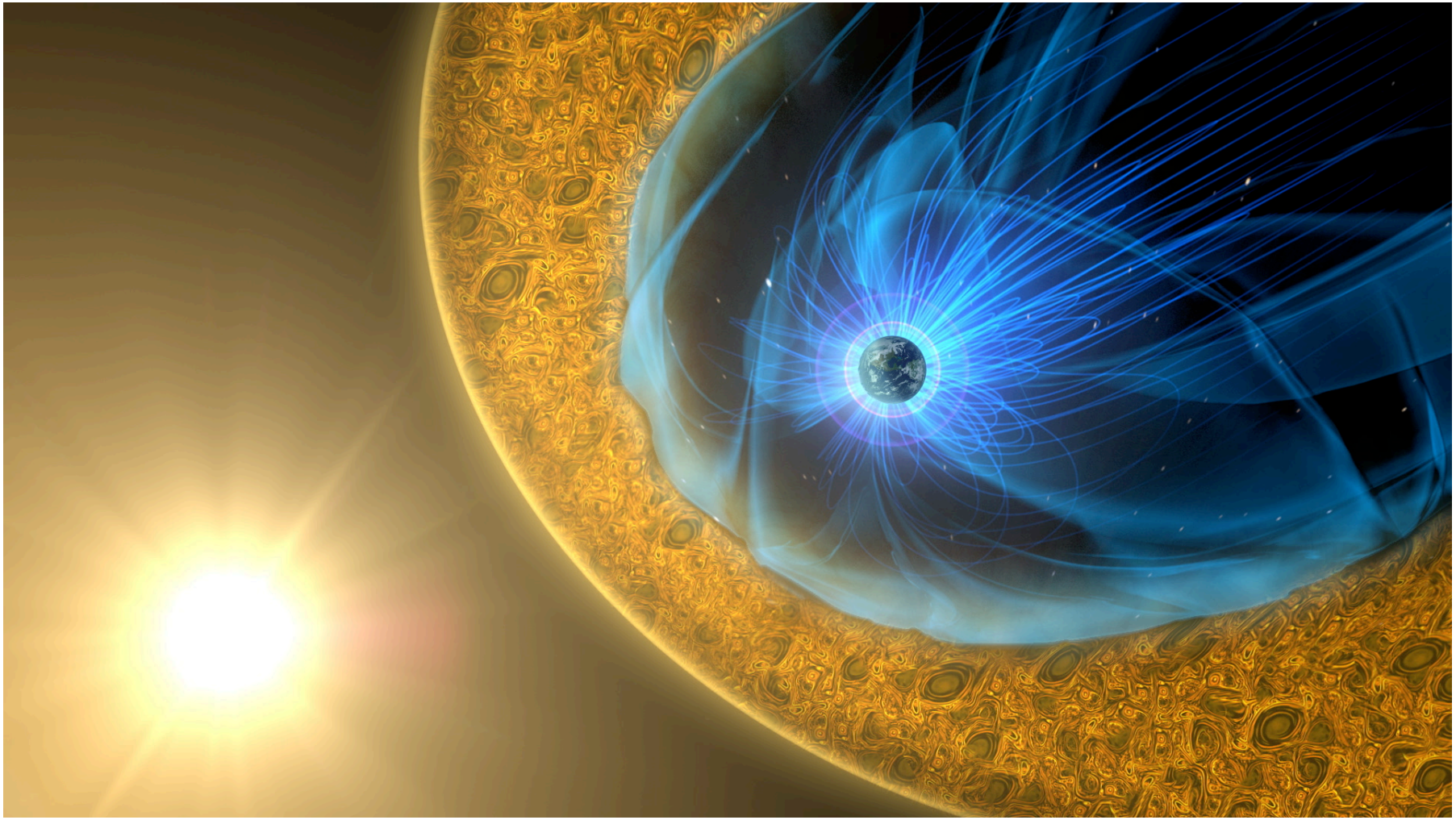
(Dmitruk *et al*. 2004; Markovskii & Vasquez 2011; Matthaeus & Velli 2011; Osman *et al*. 2012; Servidio 2011)

Key Goal:

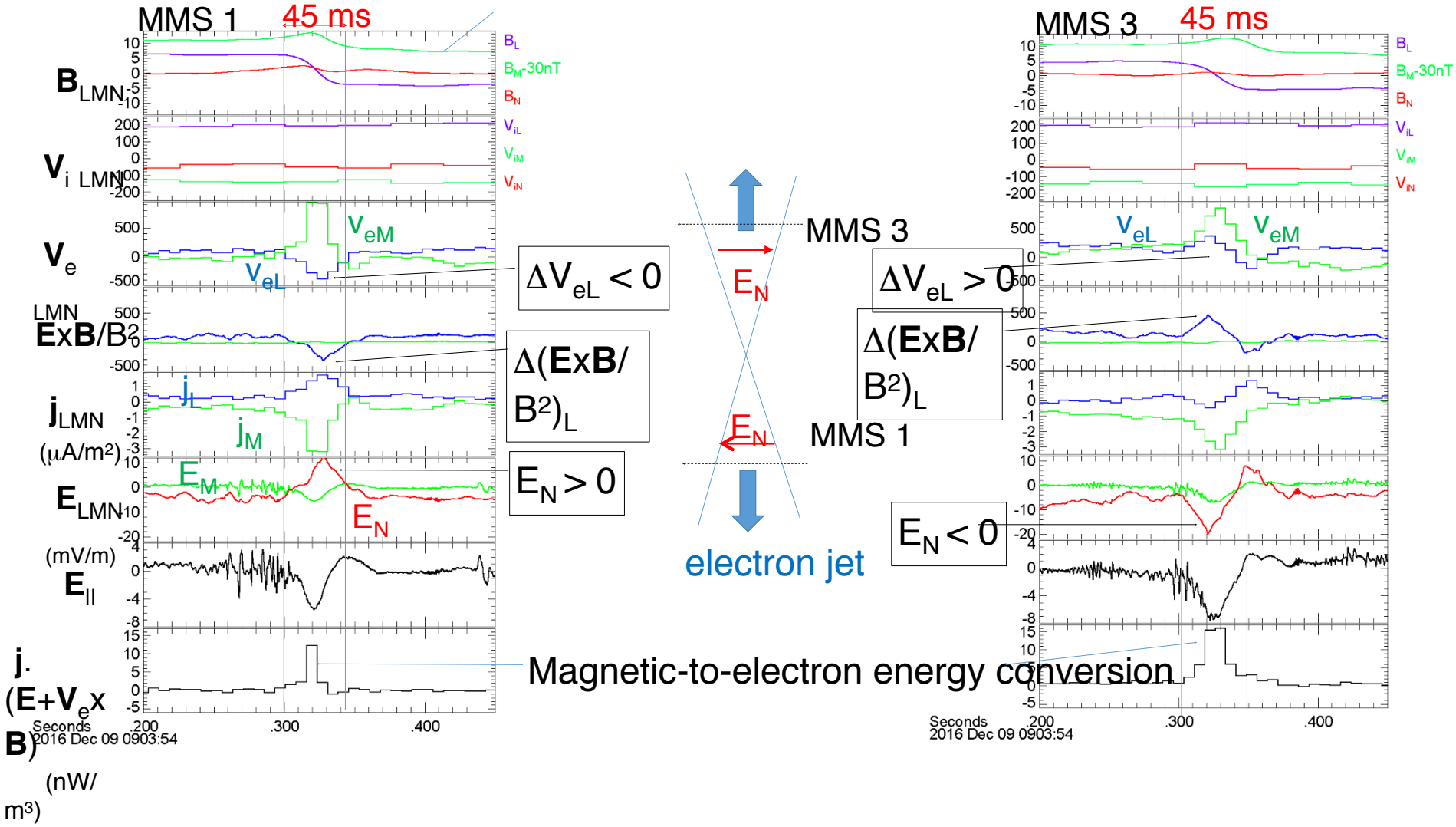
- To compare and contrast the different turbulence theories
- To identify observational and numerical tests to distinguish these distinct models

Phan et al., Nature, 2018

- Reconnection in Turbulent Magnetosheath
  - “Electron-Only” Reconnection



MMS 1 and MMS 3 on opposite sides of the X-line:
smoking gun evidence for reconnection



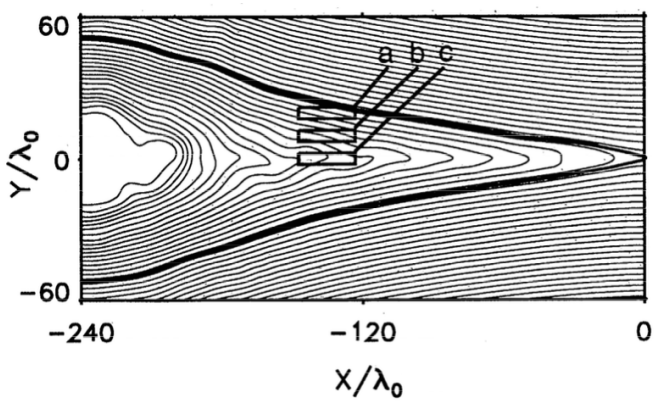
Overview

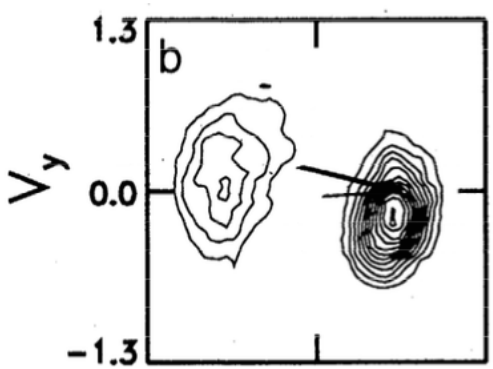
- Background
- Laminar Reconnection Studies
  - Heating in Reconnection Exhausts
- Framework: Apply Heating Predictions to Turbulence
- Kinetic PIC Turbulence Simulations
  - Test Framework
- Statistics of Reconnection: Kinetic PIC Simulations

Character of Reconnection Heating

- Heating Tends to Occur as beams
  - Especially: Ion Heating

Simulations

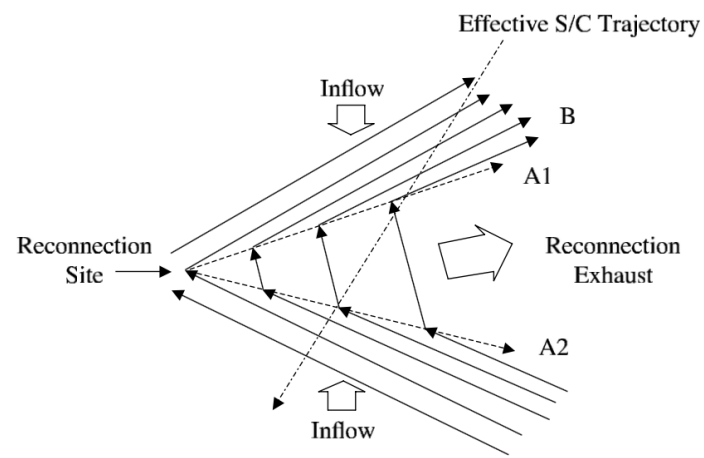




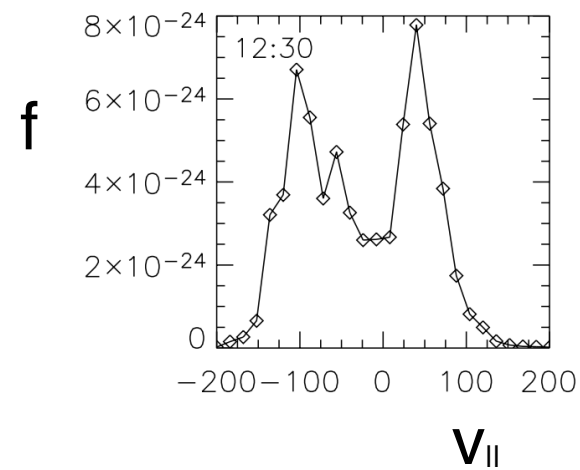
Lottermoser et al., 1998

V_x

Solar Wind Observations



Gosling et al., 2005



“Simple” Problem: Heating in Reconnection Exhausts

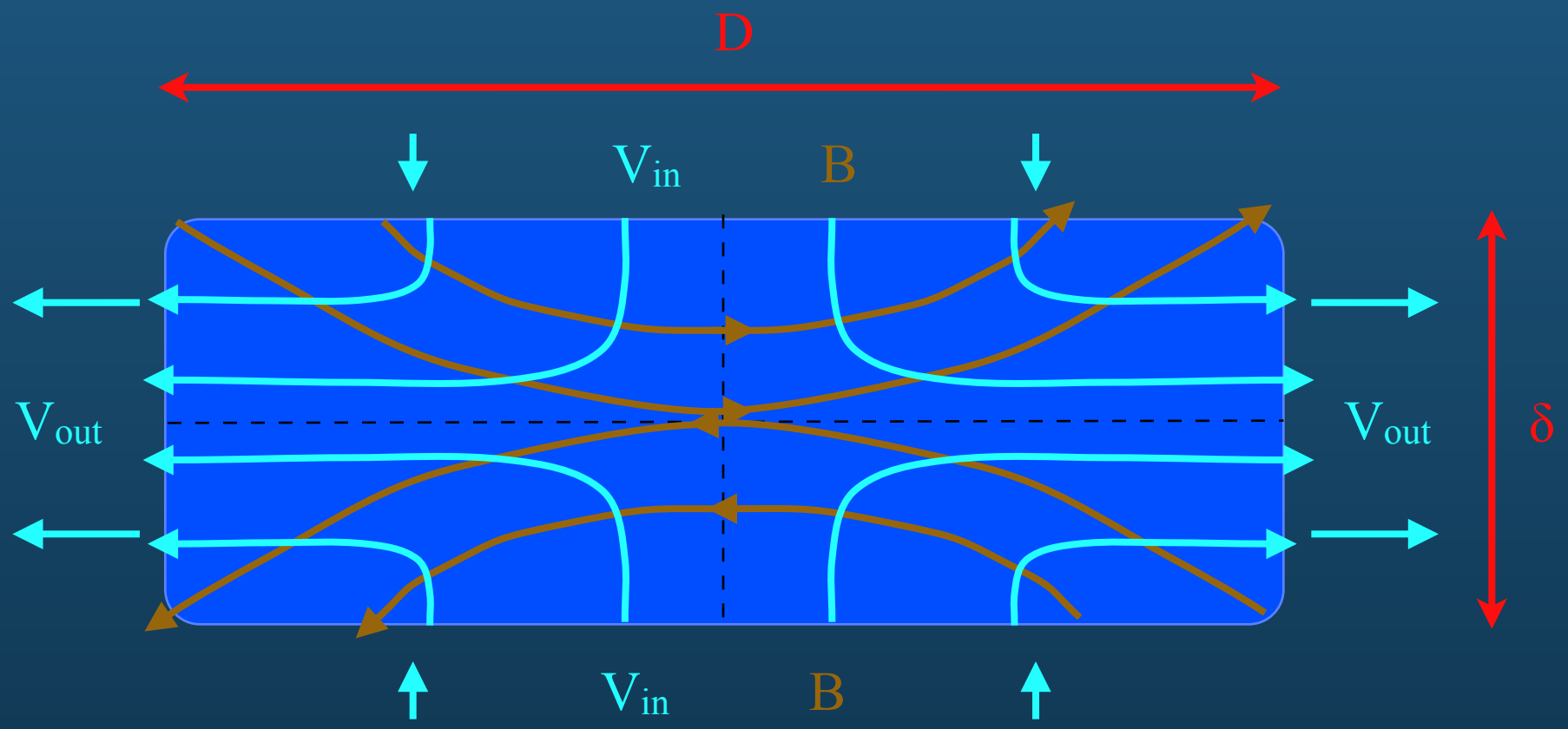
- Focus on Understanding Heating in Reconnection Exhausts
- Heating Definition:

$$\mathbf{T} = \frac{1}{n}\int d^3v f(x,v)(\mathbf{v}-\mathbf{u})(\mathbf{v}-\mathbf{u})$$

$$T = \frac{1}{3}\,\mathrm{Tr}[\mathbf{T}]$$

  – Counter-streaming beams are considered “heating”.
- Systematic Kinetic PIC Simulations

Energy Budget



$$\frac{B^2}{4\pi} V_{\rm in} D = \left[\frac{1}{2} m_i n V_{\rm out}^2 + \frac{\gamma}{\gamma - 1} \Delta T_e n + \frac{\gamma}{\gamma - 1} \Delta T_i n \right] V_{\rm out} \delta + Q_{ix} + Q_{ex}$$

- Magnetic Energy In:
- Flow Energy, Thermal Energy, Heat Flux out

Energy Budget: Heating

- Energy Conservation

$$\frac{B^2}{4\pi} V_{\rm in} D = \left[\frac{1}{2} m_i n_{\rm out} V_{\rm out}^3 + \frac{\gamma}{\gamma - 1} \Delta T_e n_{\rm out} V_{\rm out} + \frac{\gamma}{\gamma - 1} \Delta T_i n_{\rm out} V_{\rm out} \right] \delta + Q_{ix} + Q_{ex}$$

Divide eqn by left hand side

- 1 = α_{flow} + α_{Te} + α_{Ti} + α_{Qi} + α_{Qe}

- α_T = % of released energy that heats a species.
- Important Questions
  - Is α_T a constant? What does it depend on?
  - What is the value of α_T?
  - What is $\gamma/(\gamma\text{-}1)$? (5/2 for adiabatic)

$$\alpha_T \approx \frac{\gamma}{\gamma - 1} \frac{\Delta T}{B^2/(4\pi n)}$$

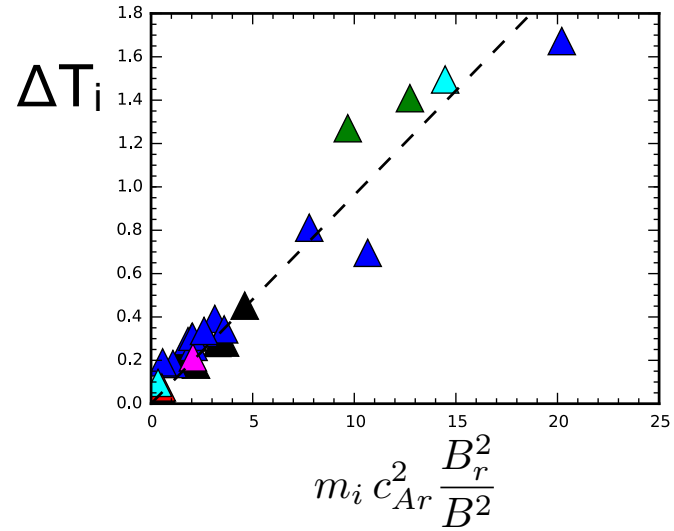
Review in: Shay et al., 2014

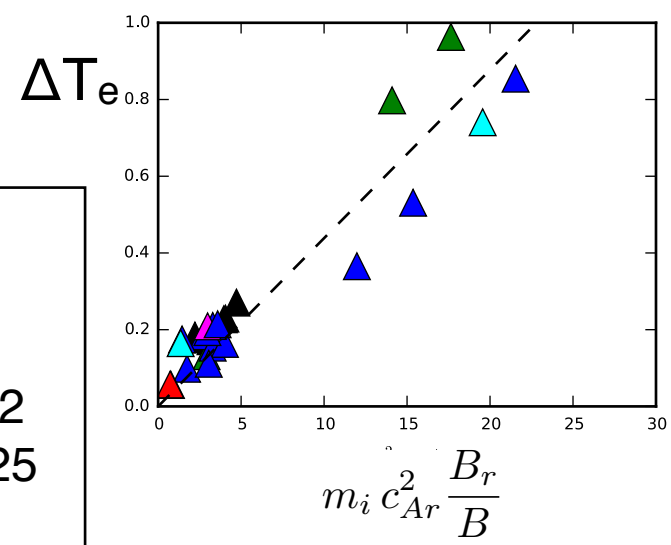
Laminar Reconnection Simulations

- Reconnection heating depends strongly on parameters upstream of x-line.
  - c_{Ar}: Alfven speed based on reconnection field
  - B_r: reconnection field
  - B: Total Field

$$\Delta T_i = M_{Ti}\, c_{Ar}^2\, \frac{B_r^2}{B^2}$$

$$\Delta T_e = M_{Te}\, c_{Ar}^2\, \frac{B_r}{B}$$





- M_{Ti}, M_{Te} are constants
- ΔT_i consistent with Drake et al., 2009
- Relative heating is:

$$\frac{\Delta T_i}{\Delta T_e} \propto \frac{B_r}{B}$$

Dataset limited to:

$B_{guide} > 0.2$
$T_e/T_i < 1.25$
$\beta_i < 2$

Question

- Can we take this knowledge about laminar reconnection and apply it to reconnection during turbulence?

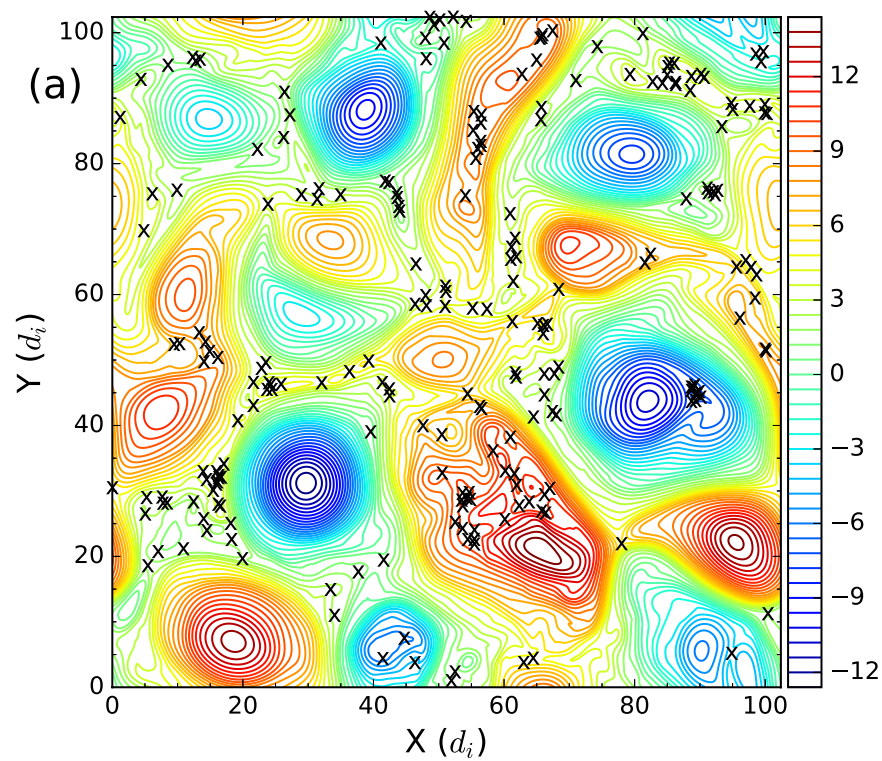
Overview

- Background
- Laminar Reconnection Studies
  - Heating in Reconnection Exhausts
- Framework: Apply Heating Predictions to Turbulence
- Kinetic PIC Turbulence Simulations
  - Test Framework
- Statistics of Reconnection: Kinetic PIC Simulations

Heating in Turbulence Due to Reconnection?

- Multifaceted problem
  - Magnitude and Character of Heating due to Reconnection?
    - What parameters does the heating depend on?
  - Properties of Magnetic Reconnection in Turbulence?
    - How many x-lines? How many reconnecting x-lines?
  - Relative role of heating due to magnetic reconnection versus other sources of heating
- Kinetic PIC Simulation Study
  - Can we apply our understanding of “simple” magnetic reconnection to turbulent heating?
  - What are the statistics of X-lines in kinetic turbulence simulations?

Magnetic Flux Contours with X-llines



Haggerty el al., 2017
Kinetic PIC Turbulence Simulation

Flux Bundles Reconnecting

- Energy released into ions:
  Single Flux Bundle:

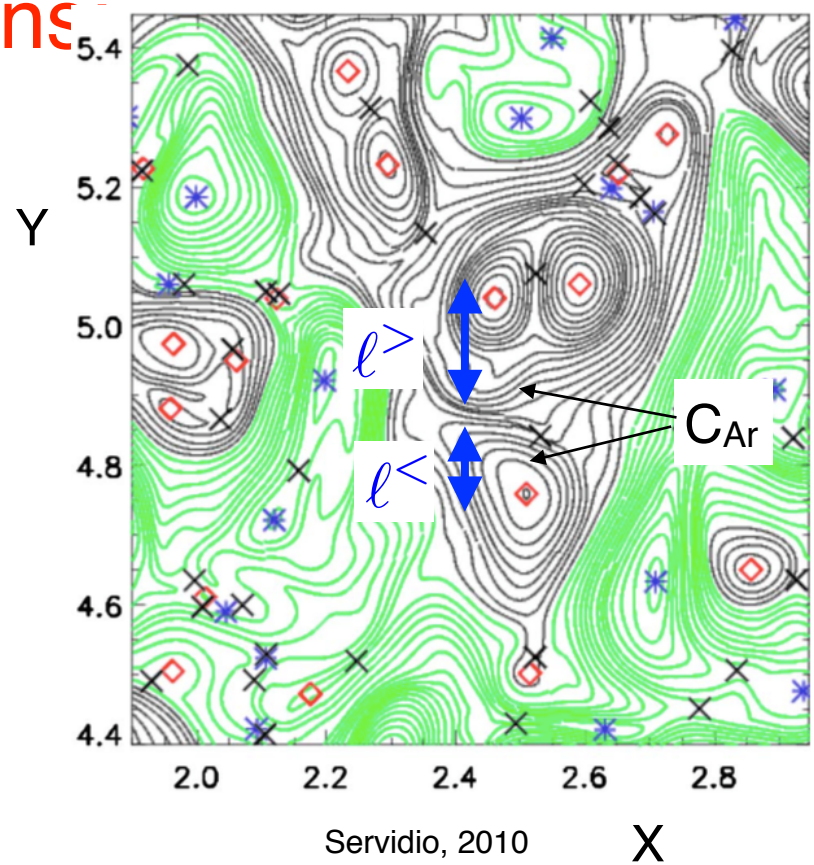
$$\varepsilon_\times = 2\pi\,\Delta T\,\ell^<\,\ell^>\,n_r$$

$$\varepsilon_\times = \frac{M_T}{2}\,\ell^<\,\ell^>\,B_r^2\,\frac{B_r^2}{B^2}$$

- Sum Over All Bundles:

$$\varepsilon = \frac{M_T}{2}\sum_{\text{x-line } i}\ell_i^<\,\ell_i^>\,B_{ir}^2\,\frac{B_{ir}^2}{B^2}$$

Magnetic Flux Contours



Servidio, 2010

$$\varepsilon = \left(\frac{M_T}{2}\sum_{\text{x-line } i}\ell_i^<\,\ell_i^>\right) B_{ir}^2\,\frac{B_{ir}^2}{B^2}$$

Determine B_{ir}?

- Assume mean field is constant and $B_0 >> B_{ir}$
- First estimate: Width of reconnection sites typically ~ d_i
  - What are magnetic fluctuations at scale size d_i?
- Assume δZ at d_i scales like reconnection Alfven speed: $\delta Z_{di} \propto C_{ar}$

$$\frac{c_{Ar}}{c_A} = \frac{B_r}{B} = \frac{\delta Z_{di}}{c_A}\frac{d_i}{d_i} = \frac{\tau_{ci}}{\tau_{nl}(d_i)} \equiv \alpha_{nl}$$

- Where c_A is Alfven speed based on global RMS B
- $\tau_{nl}(d_i)$ is nonlinear time at ion inertial scale
- τ_c is cyclotron time based on global RMS B ≈ B_0

Protons: $$\varepsilon_p = \frac{\delta Z_{di}^4}{c_A^4}\left(\frac{M_T}{2B^2}\sum_{\text{x-line } i} \ell_i^< \ell_i^>\right) = \alpha_{nl}^4 \text{ (Flux Bundle Details)}$$

Electrons: $$\varepsilon_e = \frac{\delta Z_{di}^3}{c_A^3}\left(\frac{M_T}{2B^2}\sum_{\text{x-line } i} \ell_i^< \ell_i^>\right) = \alpha_{nl}^3 \text{ (Flux Bundle Details)}$$

Key Points

- Turbulent heating due to reconnection estimated to be:

$$\varepsilon_p = \alpha_{nl}^4 \, (\text{ Flux Bundle Details })$$

$$\varepsilon_e = \alpha_{nl}^3 \, (\text{ Flux Bundle Details })$$

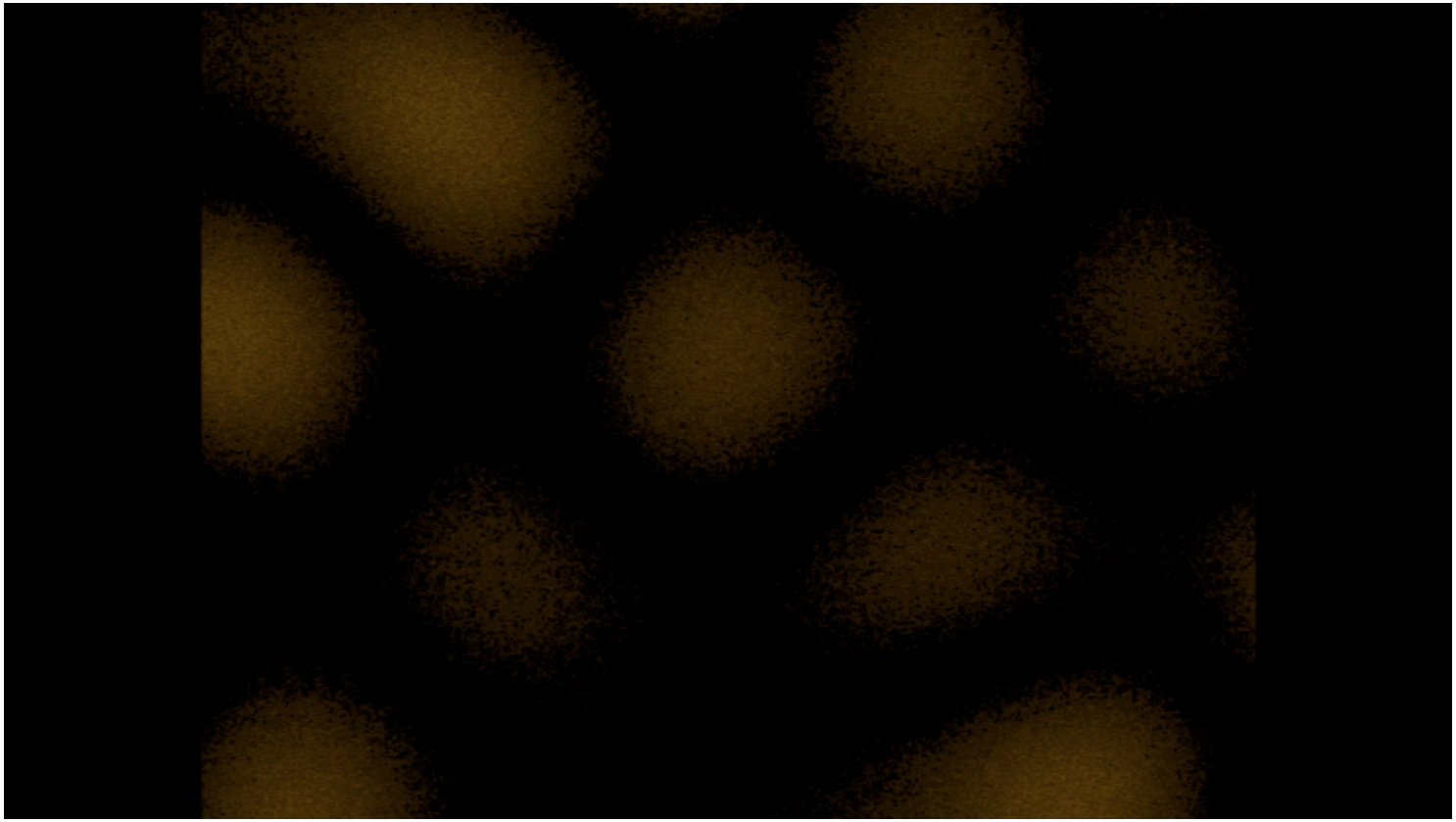
$$\frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl}$$

- Will (Flux Bundle Details) remain invariant as we change turbulence properties?
- Proton to electron heating scaling expected to be more accurate.

Overview

- Background
- Laminar Reconnection Studies
  - Heating in Reconnection Exhausts
- Framework: Apply Heating Predictions to Turbulence
- Kinetic PIC Turbulence Simulations
  - Test Framework
- Statistics of Reconnection: Kinetic PIC Simulations

Kinetic PIC Turbulence Simulations



NASA Phan et al Publicity Movie, 2018

- Wu et al, 2013, Parashar et al., 2016.
- 2 1/2 Dimensions
- Initial uniform Bz = 5
- Initial Perturbation:

$$Z_0^2 \equiv \langle v^2 \rangle + \langle \frac{B^2}{4\pi m_i n} \rangle$$

Turbulence Simulations

- Constant Mean field $B_0 = 5$, $B >> B_r$

run	family	β_i	β_e	Z_0	B_0	λ_c	L	$N_x = N_y$	Q_i/Q_e	τ_c/τ_{nl}	ppg	k
run805.1	PAPJ15	0.08	0.08	1.1	5.0	0.445	1.28	64	0.584	0.534	200	{1,2}
run805.2	PAPJ15	0.08	0.08	0.825	5.0	0.445	2.56	128	0.887	0.340	200	{1,2}
run805.3	PAPJ15	0.08	0.08	0.737	5.0	0.445	5.12	256	0.435	0.260	200	{1,2}
run805.4	PAPJ15	0.08	0.08	0.713	5.0	0.445	10.24	512	0.331	0.209	200	{1,2}
run805.5	PAPJ15	0.08	0.08	0.707	5.0	0.445	20.48	1024	0.343	0.169	200	{1,2}
run809.1	OTVdbB	0.08	0.08	0.718	5.0	3.820	20.48	1024	0.551	0.169	200	{1,2}
run810.1	OTVdbB	0.08	0.08	1.075	5.0	3.928	20.48	1024	0.588	0.251	200	{1,2}
run811.1	OTVdbB	0.08	0.08	1.433	5.0	4.286	20.48	1024	0.754	0.325	200	{1,2}
run812.1	OTVdbB	0.08	0.08	1.790	5.0	4.608	20.48	1024	0.945	0.397	200	{1,2}
Turb808	k13	0.25	0.25	1.0	5.0	0.349	25.6	2048	0.404	0.173	400	{1,3}
Turb812	k13	0.25	0.25	2.5	5.0	0.871	25.6	2048	0.542	0.404	400	{1,3}
Turb813	k13	0.25	0.25	4.0	5.0	1.394	25.6	2048	0.857	0.606	400	{1,3}
Turb814	k24lb	0.25	0.25	2.5	5.0	0.868	25.6	2048	0.697	0.419	400	{2,4}
Turb815	k24lb	0.25	0.25	4.0	5.0	1.389	25.6	2048	1.159	0.646	400	{2,4}
Turb816	k24sb	0.10	0.10	2.5	5.0	0.868	25.6	2048	0.546	0.427	400	{2,4}
Turb817	k24sb	0.10	0.10	4.0	5.0	1.389	25.6	2048	1.010	0.664	400	{2,4}

Determining Nonlinear Time

- Estimate of $\tau_{nl}(d_i)$ based on von Karman-Kolmogorov phenomenology

$$\delta Z_\ell = Z \left(\frac{\ell}{\lambda}\right)^{1/3}$$

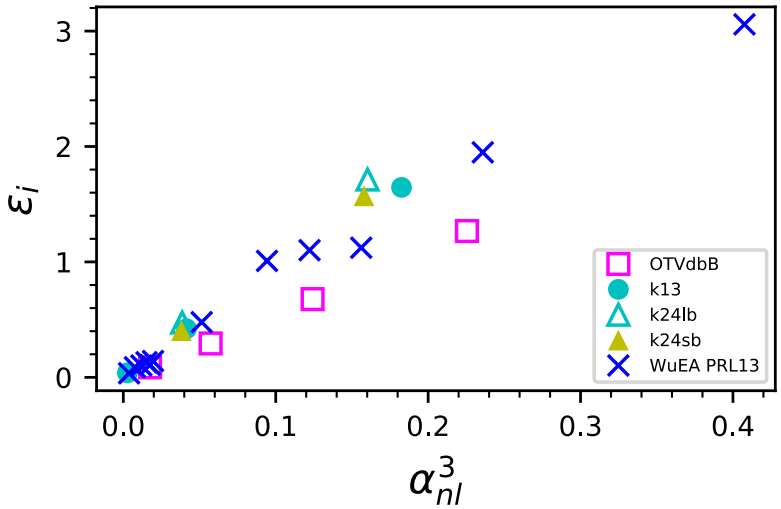
$$\tau_{nl}(\ell) = \frac{\ell}{\delta Z_\ell} = \tau_{nl} \left(\frac{\ell}{\lambda}\right)^{2/3}$$

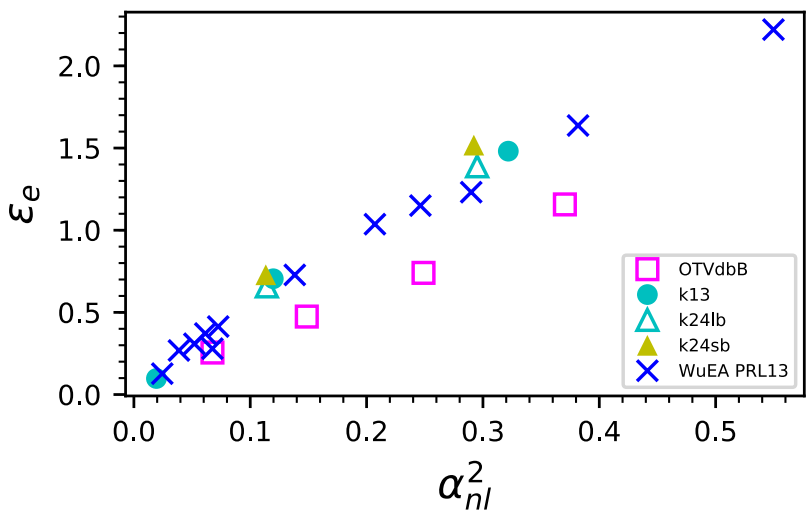
  – λ is correlation or energy containing scale
- Is this estimate applicable to our system?

Turbulence Simulations: Scaling of Heating

Approximate Best Fit Not Consistent

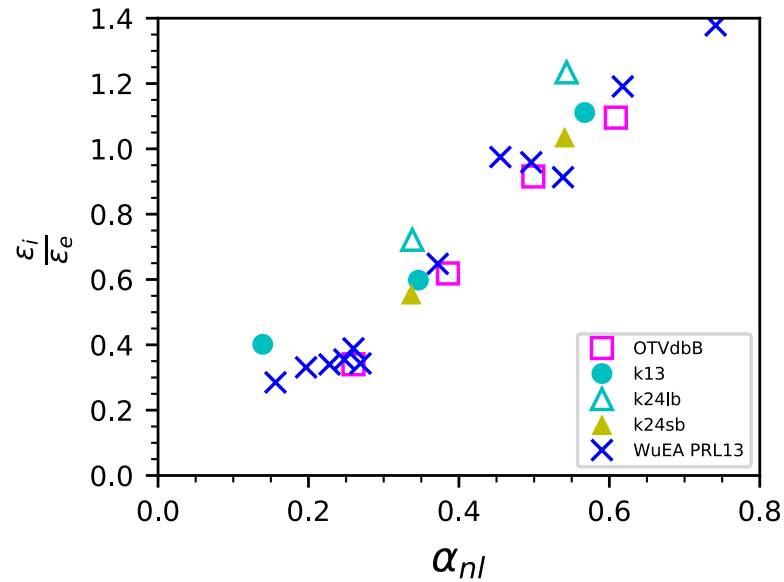
$\varepsilon_p \propto \alpha_{nl}^3$ $\varepsilon_e \propto \alpha_{nl}^2$





Ratio of Heating Matches Well

$$\frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl}$$



Conclusions: Heating

- Turbulence Simulations: $\frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl}$ $\quad \varepsilon_p \propto \alpha_{nl}^{3}$ $\quad \varepsilon_e \propto \alpha_{nl}^{2}$
- Theory Predictions: $\frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl}$ $\quad \varepsilon_p \propto \alpha_{nl}^{4}$ $\quad \varepsilon_e \propto \alpha_{nl}^{3}$
- Why the difference?
  - Is ΔB at d_i scale best measure of magnetic fields upstream of current sheets?
  - $\tau_{nl}(d_i)$ determined ignoring intermittency. Justified?
  - Are the number of x-lines changing with changing parameters?
  - Filling factor of reconnection exhausts?
- $\varepsilon_p/\varepsilon_e$ matches reconnection prediction quite well.
  - Even if some details of scaling of reconnection parameters wrong, taking the ratio removes the discrepancy.