Turbulent energy dissipation in thin reconnecting current sheets

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Outline

- Reconnection & turbulence
  - Ion and electron heating
  - Non-thermal particle acceleration
  - Partition of energy

- Thin reconnecting current sheets:
  - quasi-parallel shock
  - Kelvin-Helmoltz vortexes

- Current/future spacecraft data relevant for turbulent reconnection studies

- Summary

Magnetic reconnection

- Violation of the frozen-in condition in thin boundaries (current sheets)

- Consequences:
  - magnetic topology change ($E_{||}$)
  - plasma transport across boundaries
  - plasma acceleration (alfvenic jets)
  - plasma heating
  - supra-thermal particle acceleration

- Importance of scales (collisionless):

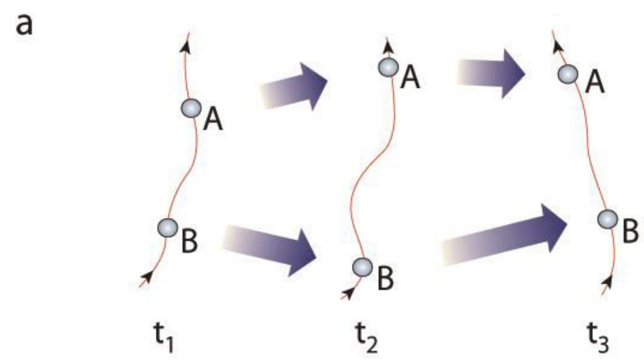
$$\underbrace{\mathbf{E}+\mathbf{u}\times\mathbf{B}}_{\text{MHD}} = \underbrace{\frac{\mathbf{J}}{\sigma_*}}_{\text{anomalous conductivity}} + \underbrace{\frac{\mathbf{J}\times\mathbf{B}}{ne}}_{\text{Hall}} - \underbrace{\frac{\nabla\cdot\mathbf{P_e}}{ne}}_{\text{electron pressure}} + \underbrace{\frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}}_{\text{electron inertia}}$$

MHD | anomalous conductivity | Hall | electron pressure | electron inertia

d_{MHD} (>> ρ_i) ~ 10^3 km

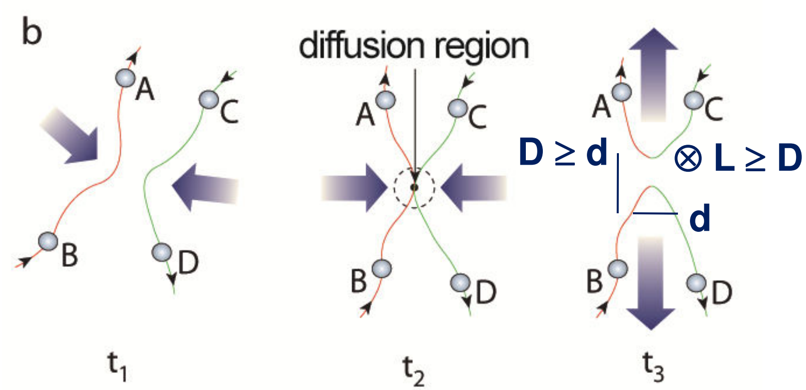
d_{ion} (~ ρ_i) ~ 50 km

$d_{electron}$ (~ ρ_e) ~ 1 km



E' = **E**+**u** x **B** = 0

E||=0



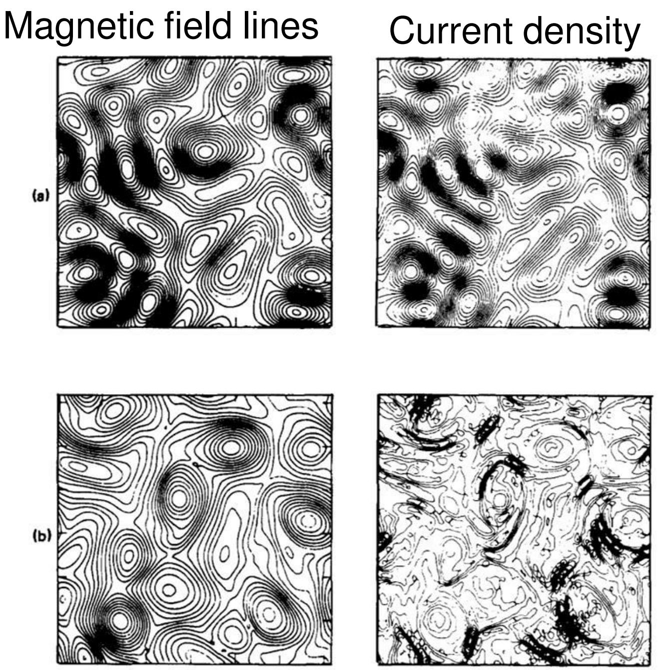
E' = **E**+**u** x **B** ≠ 0

E||≠0

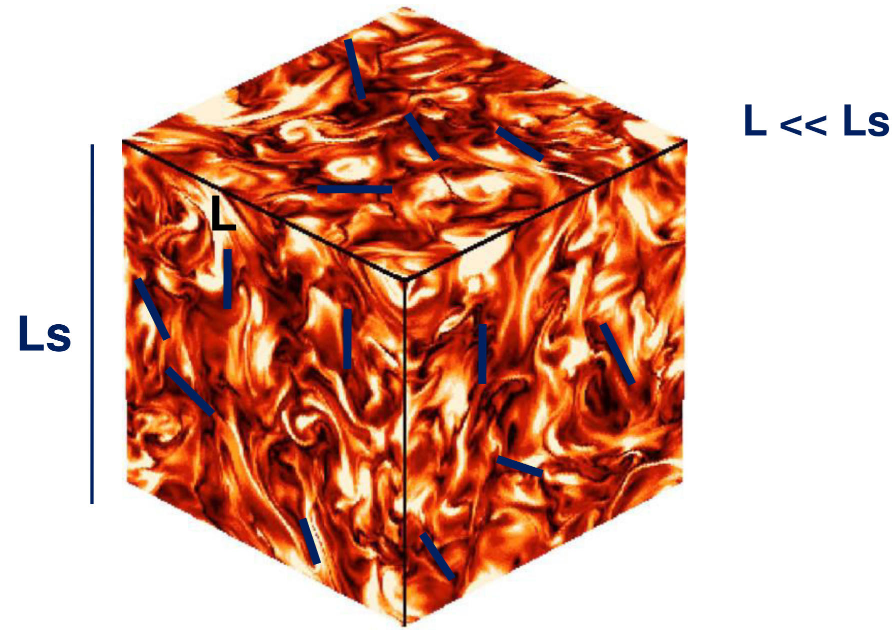
[adopted from Paschmann, Nature, 2006]

Reconnection in turbulent plasma

2D MHD simulation



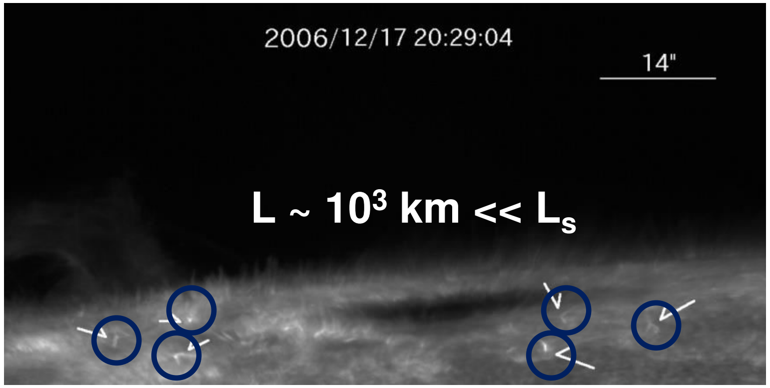
[Matthaeus & Lamkin, Phys. Fluids, 1986]



[Dmitruk & Matthaeus, Phys. Plasmas, 2006]

Many different simulations supports this scenario (MHD, Hall-MHD, PIC, Vlasov): Servidio 2009, Servidio 2011, Camporeale2011, Wan 2012, Karimabadi 2013, Haynes 2014, Valentini2014, Wan 2015

In situ data limited

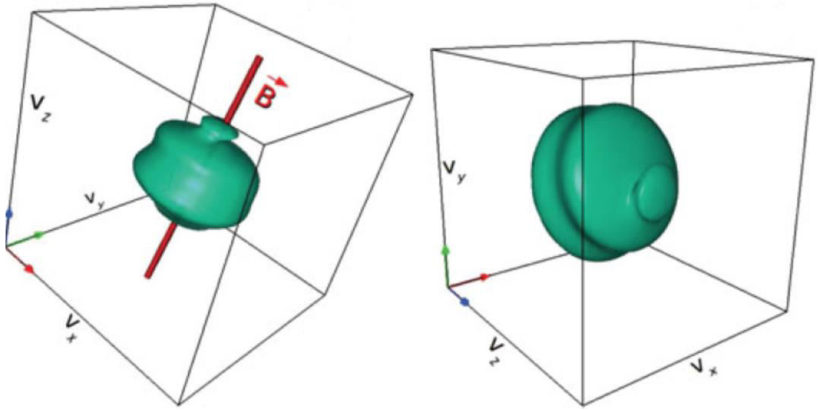


[Shibata +, Science, 2007]

Proton heating

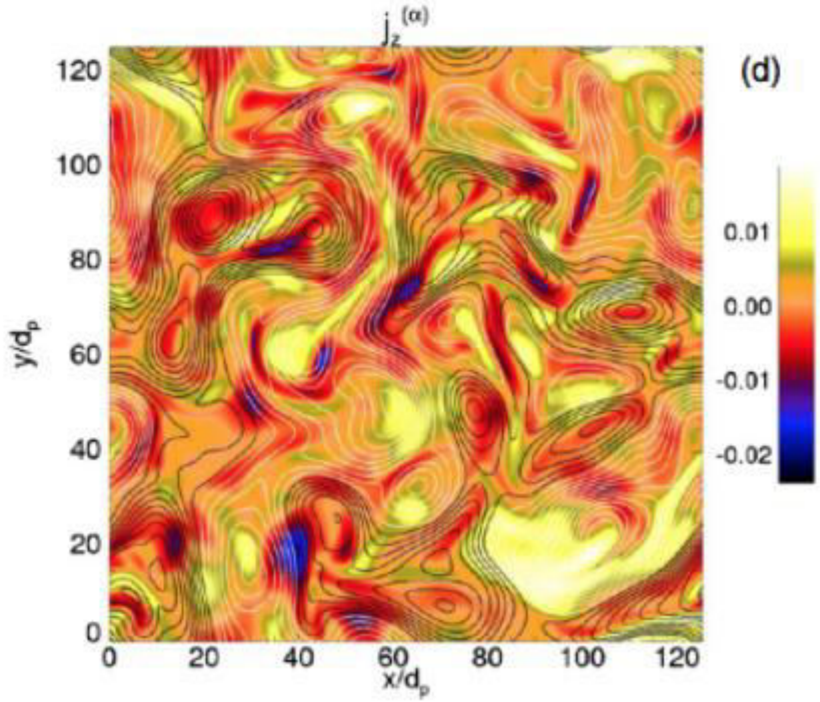
- important proton heating in régions of strong gradients having scale ~ ρ_i e.g. regions of high current (current sheets)

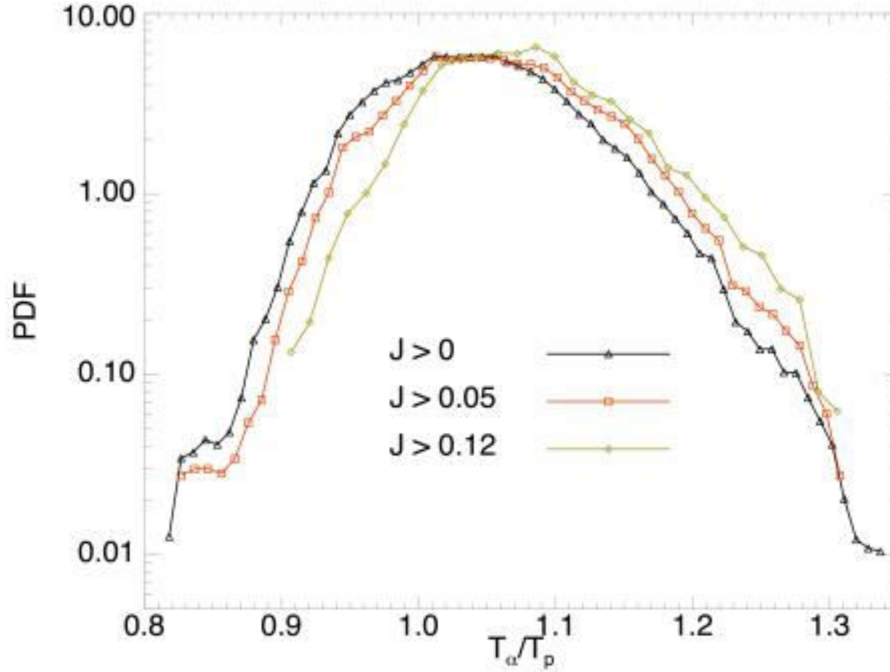
- proton distribution function highly anisotropic



[courtesy F. Valentini]

Ion heating



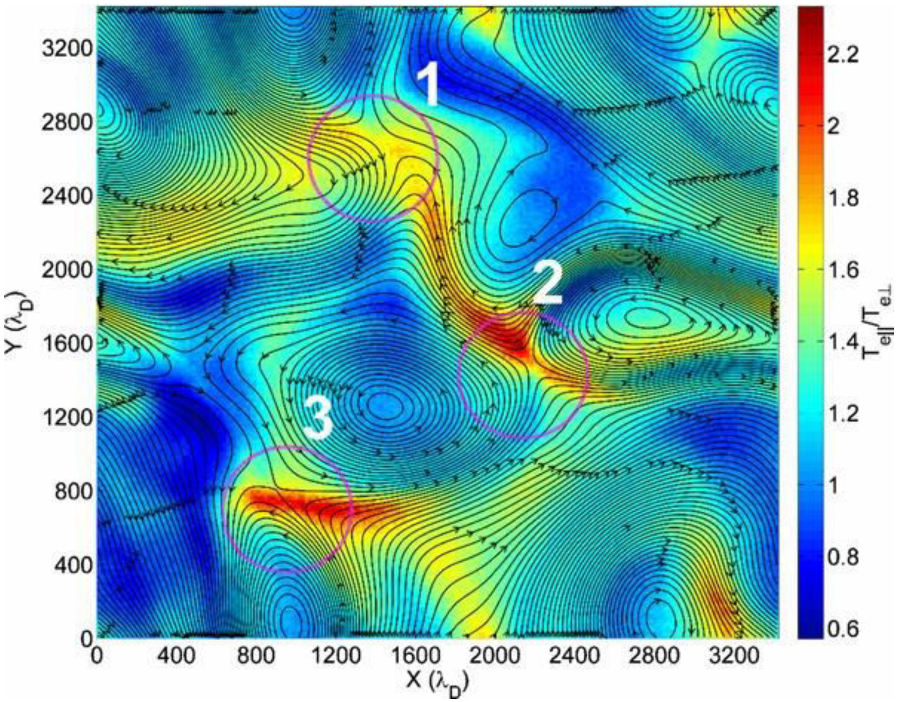


• strong ion heating in current sheets having scale ~ ρ_i

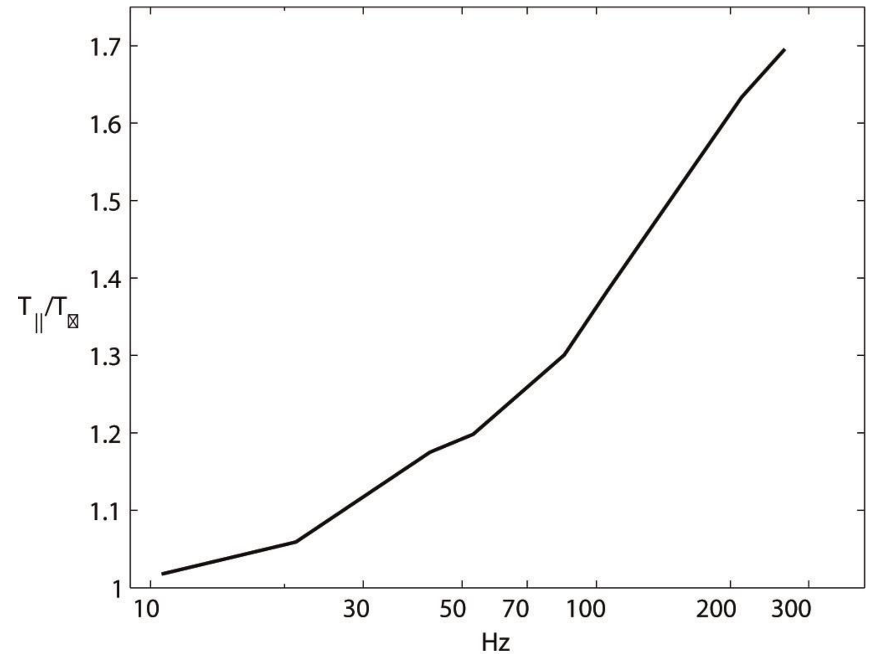
[Perrone+, ApJ., 2013; Perrone+, E. Phys. J. D, 2014]

• increase in temperature is more efficient for alphas than for protons

Electron heating



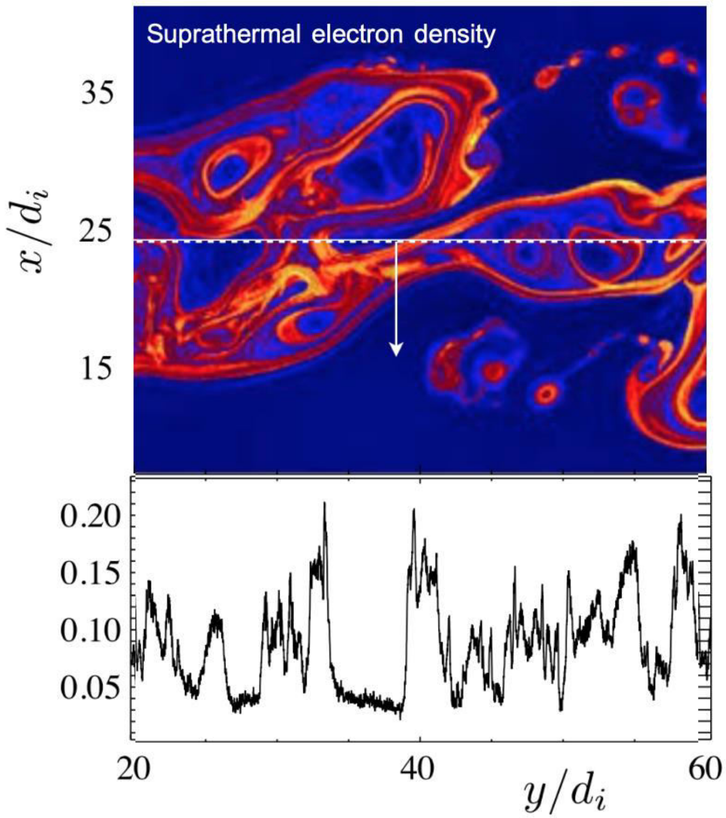
[Haynes+, ApJ,2014]



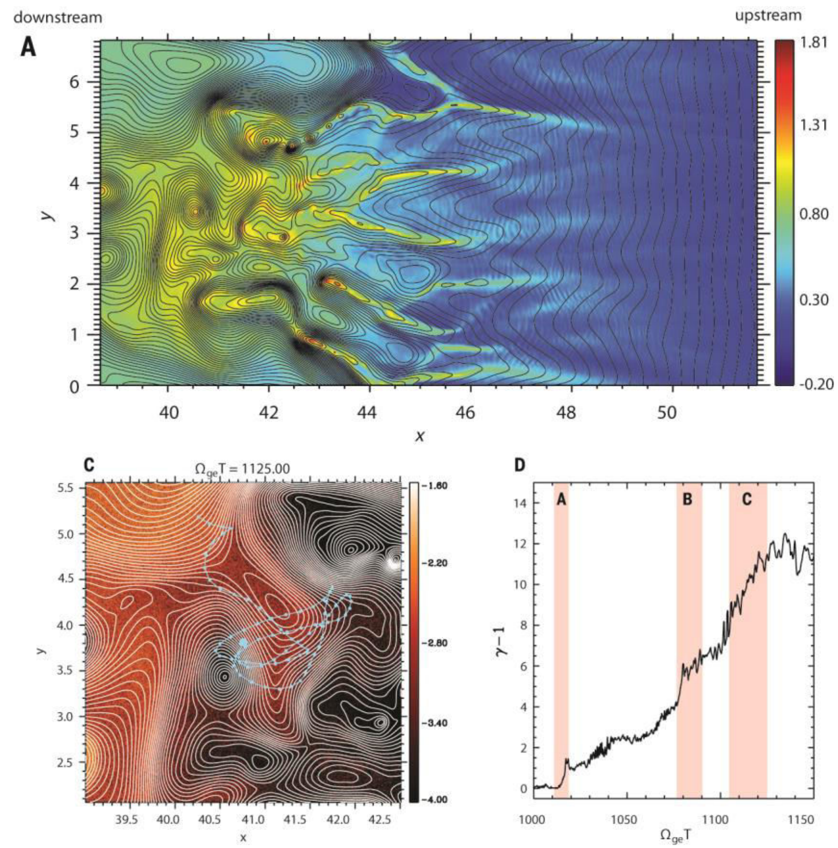
[Camporeale+, ApJ,2011]

- electron heating within thin current sheets
- anisootropy expected around reconnection sites

Non-thermal particle acceleration



[Karimabadi+, Phys. Plasmas, 2013]

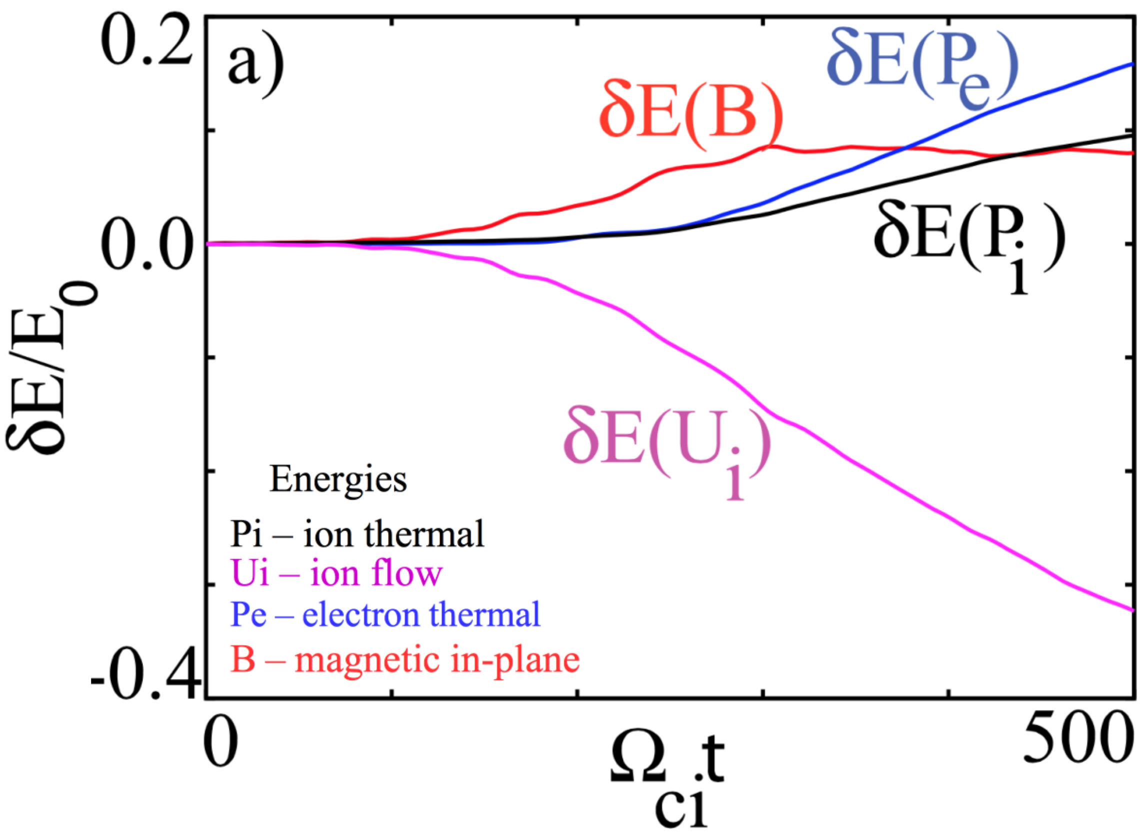


[Matsumoto+, Science, 2015]

strong non-thermal particle acceleration at kinetic scales

see also [Matthaeus+, PRL, 1984; Dmitruk+, JGR, 2006; Drake+, Nature, 2006; Hoshino, PRL, 2012, Zank+, ApJ, 2014]

Partition of dissipated energy

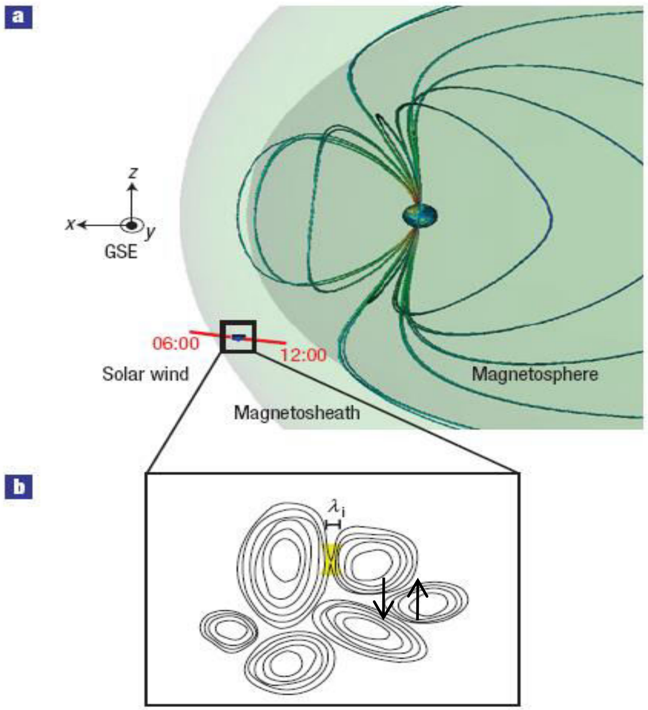


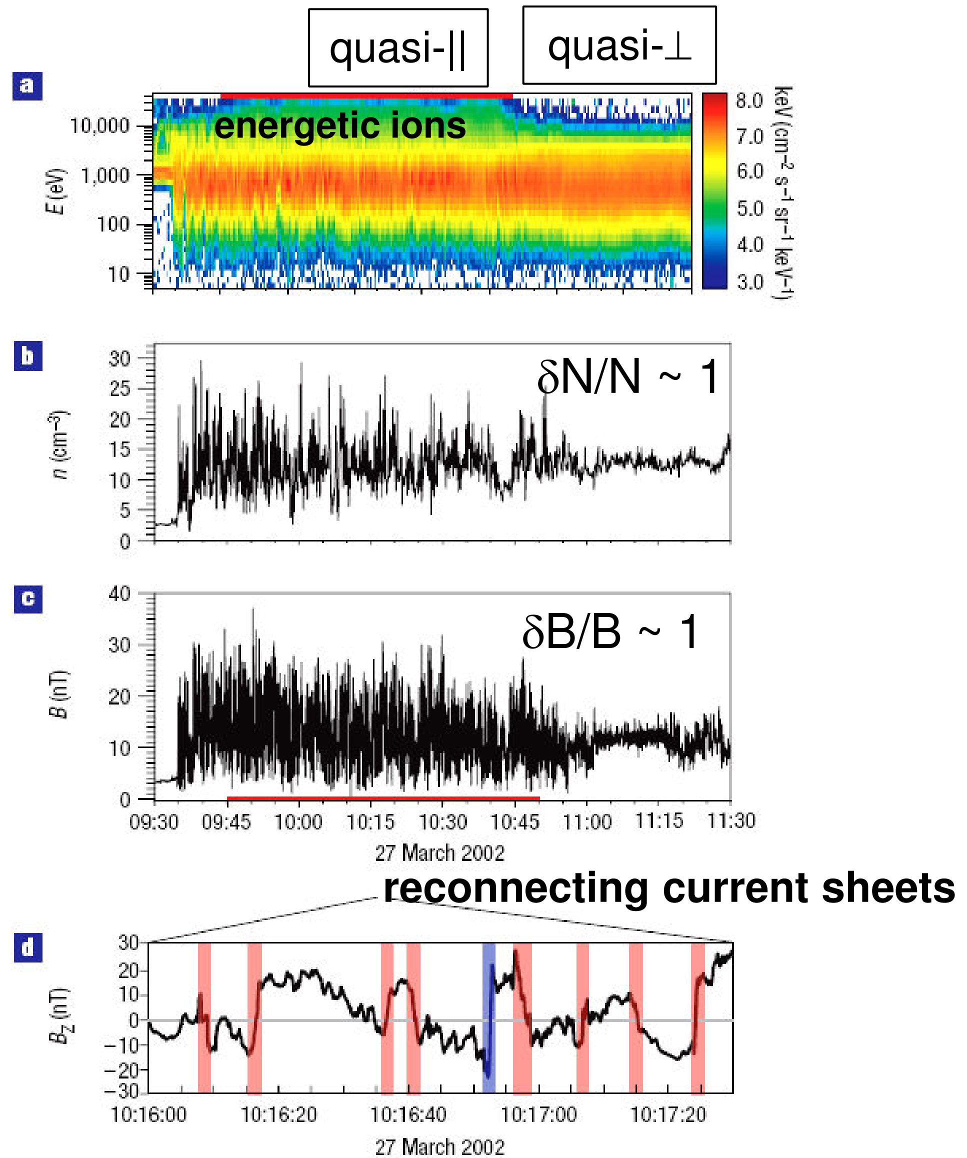
[Karimabadi+, Phys. Plasmas, 2013]

- Partition between species (electrons, protons, heavy ions)
- Partition between energy ranges (thermal, supra-thermal, energetic)

see Eastwood+, PRL, 2012 for magnetotail reconnection case

In situ evidence

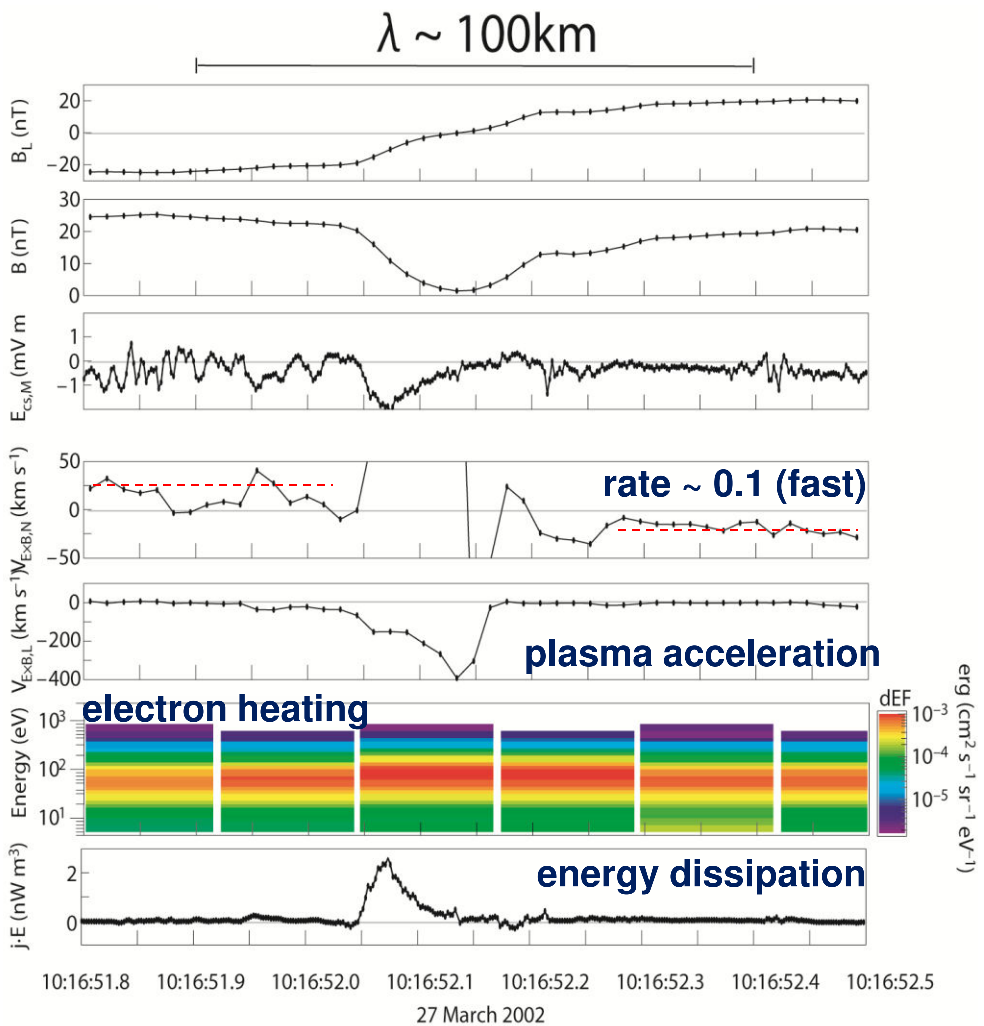




[Retinò+, Nature Physics, 2007]

See also [Gosling+, ApJL, 2007; Chian+, ApJL, 2011; Perri+, PRL, 2012; Osman+, PRL, 2014]

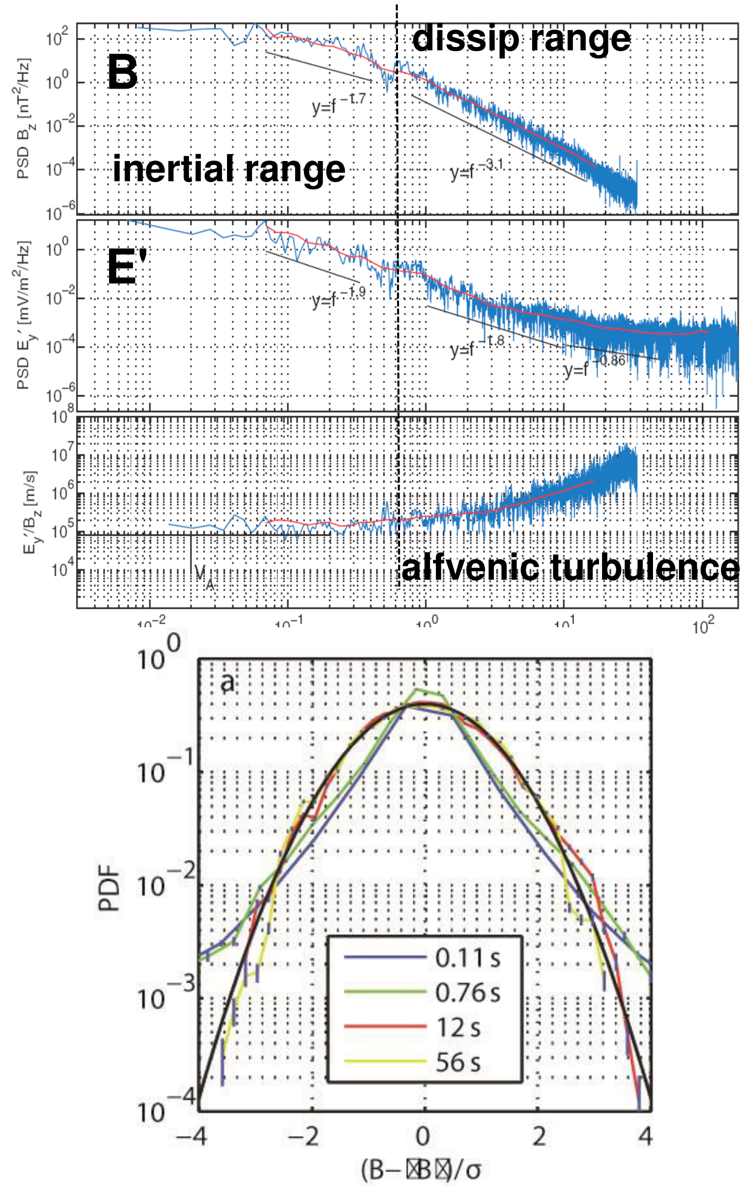
In situ evidence (II)



[Retinò+, Nature Physics, 2007]

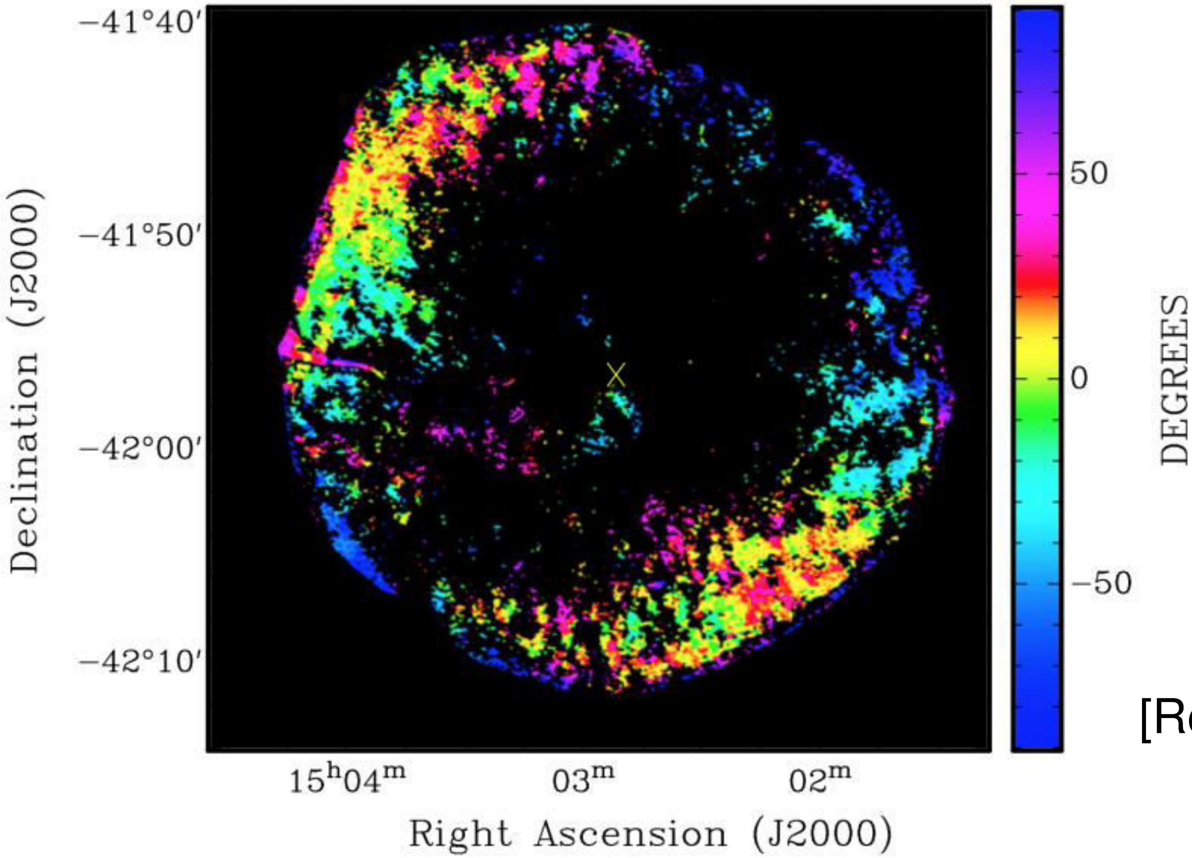
Turbulent energy dissipation in thin current sheets

- alfvenic turbulence with steeper spectrum below proton scales
- intermittency at scales λ_i - ρ_i (close to dissip. range) related to small-scale magnetic islands and current sheets
- dissipation in thin current sheets with d~ λ_i comparable to wave damping around ω_{ci} -> turbulent reconnection competing mechanism for energy dissipation at ion scales



[Sundkvist +, PRL, 2007]

Quasi-parallel shock turbulence

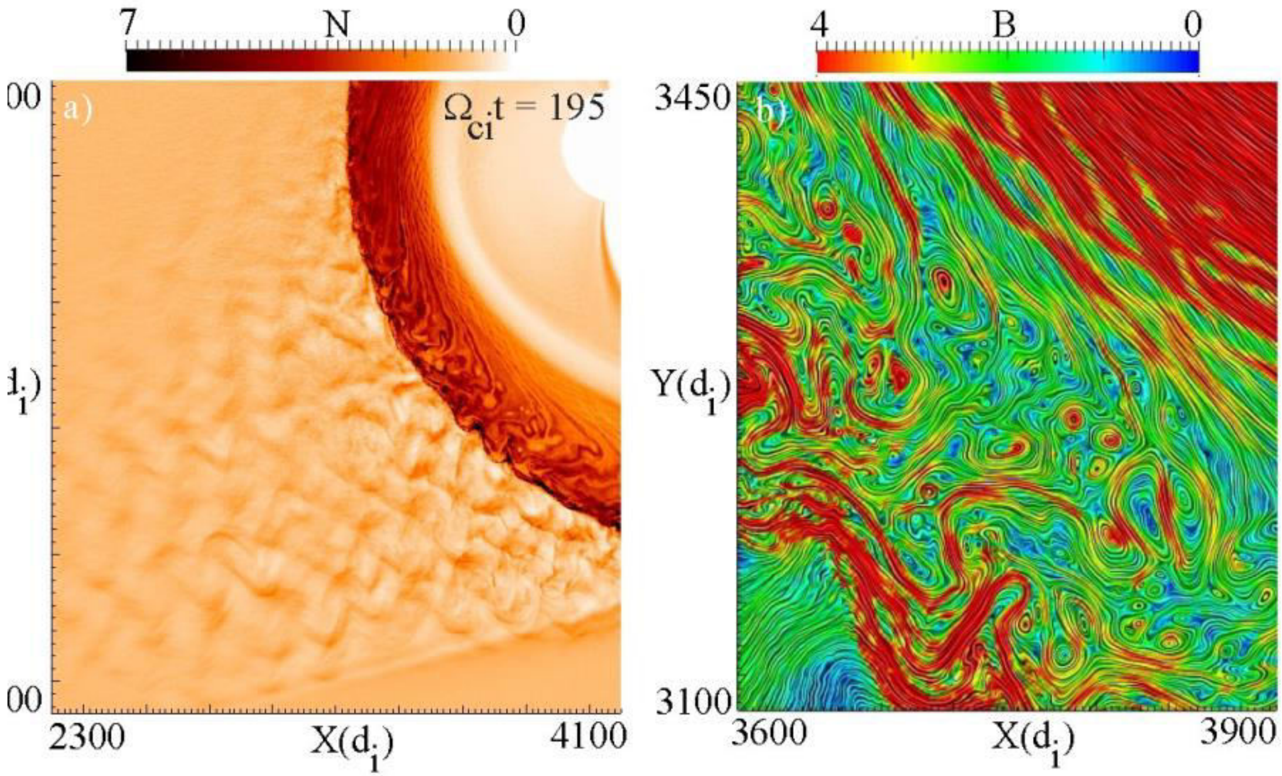


SN 1006

[Reynoso+, AJ, 2013]

most efficient particle acceleration and generation of magnetic turbulence is attained for quasi-par shocks while inefficient acceleration and little to no generation of magnetic turbulence obtains for the quasi perpendicular case.

Numerical simulations



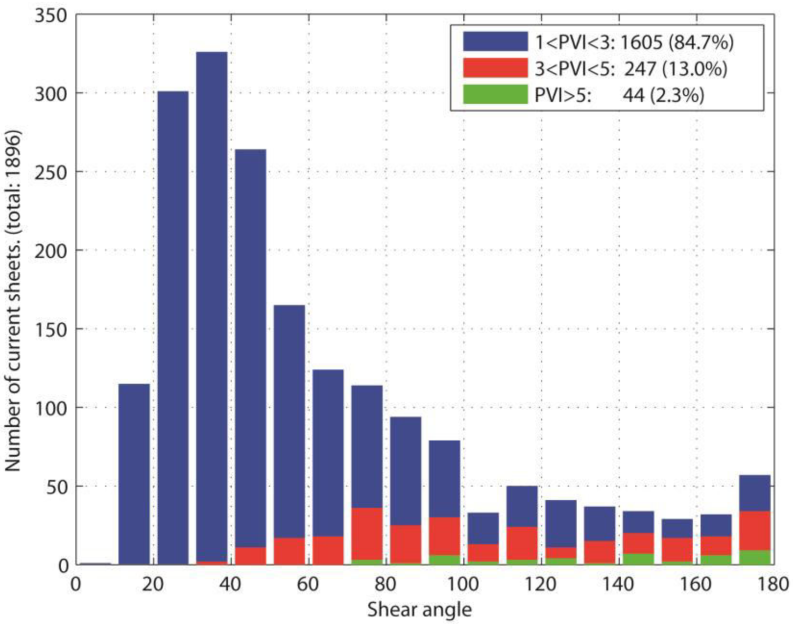
[Karimabadi+, Phys. Plasmas, 2014]

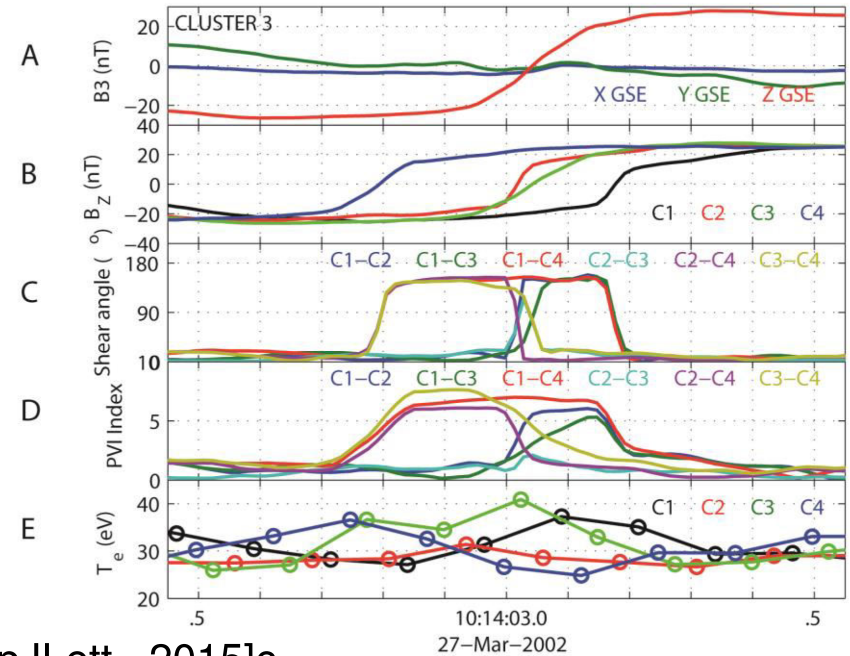
Zoo of structures such as magnetic islands, current sheets, shocklets, vortexes

Reconnecting current sheets play important role for dissipation

Electron heating in thin current sheets (1)

PVI [Greco+, GRL, 2008) $\mathcal{I}(s, \Delta s) = \frac{|\Delta \boldsymbol{b}(s, \Delta s)|}{\sqrt{\langle |\Delta \boldsymbol{b}(s, \Delta s)|^2 \rangle}}.$

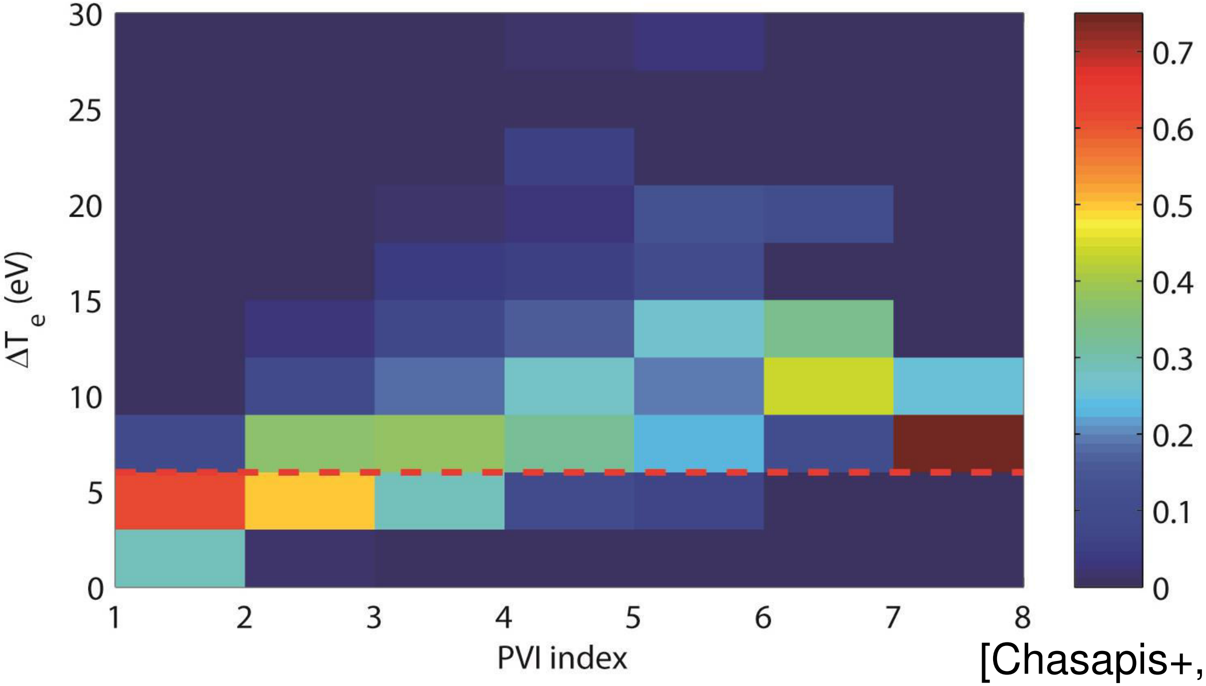




[Chasapis+, ApJLett., 2015]c

- First evidence of local electron heating in thin cureent sheets within turbulence. Current sheets have scales ≤ d_i
- Two distinct populations: (1) 85% with 1<PVI<3 (mostly low shear angle) (2) high PVI >3 with relatively large shear angles. Very high PVI > 5 cases correspond to shear angles larger than 90°.

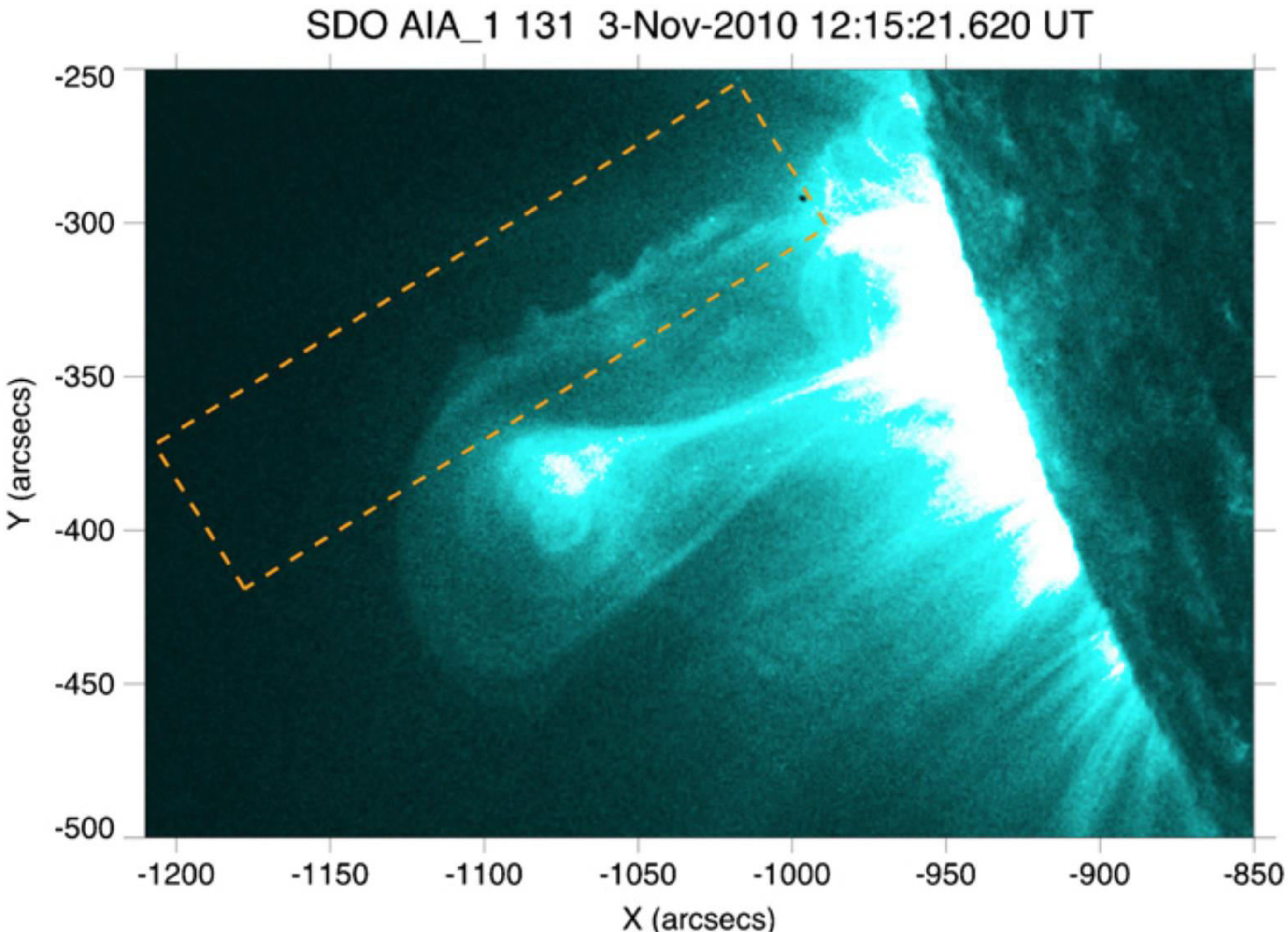
Electron heating in thin current sheets (2)



[Chasapis+, ApJLett., 2015]

- no significant heating occurs in low PVI structures (<3)
- important heating occurs in high PVI >3 structures
- very high PVI >5 current sheets show the strongest heating and most are consistent with reconnection
- results consistent with earlier statistical studies [Osman+,ApJL, 2011]

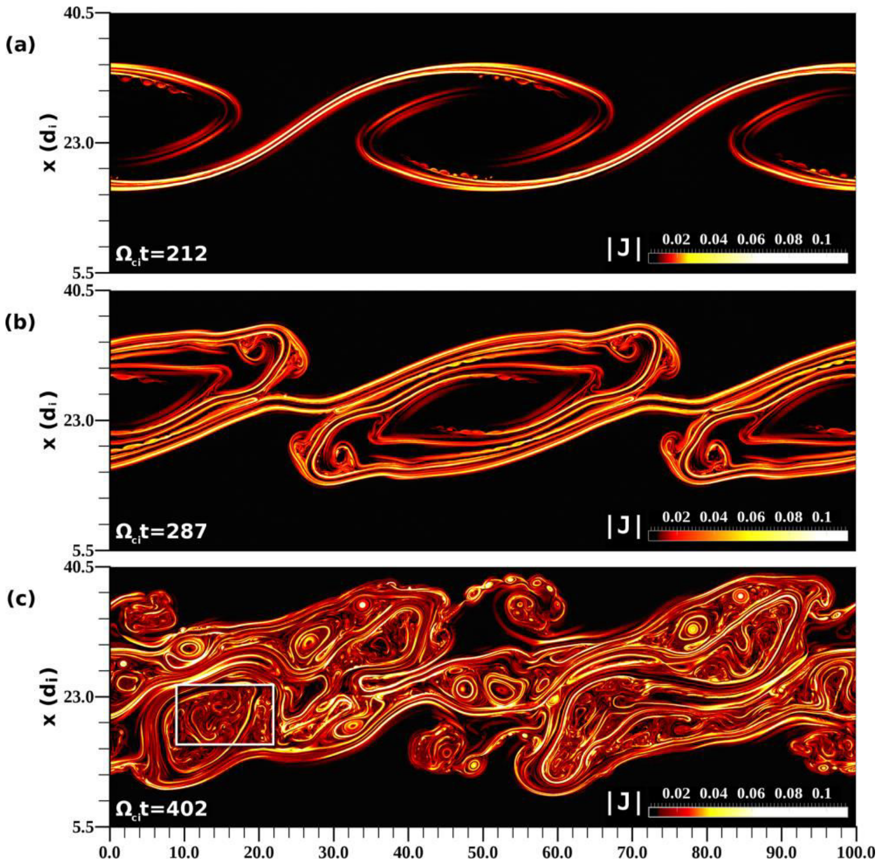
Kelvin-Helmoltz turbulence



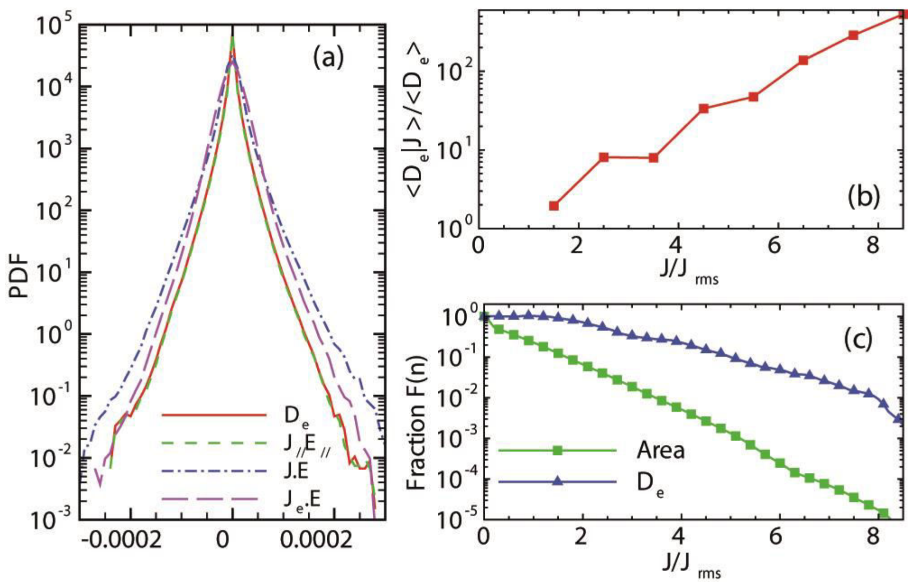
[Foullon+, ApJ, 2011]

Important energy dissipation mechanism in presence of shear flows

Numerical simulations



[Karimabadi+, Phys. Plasmas, 2013]



[Wan+,PRL, 2012]

Heating strongly intermittent heating at kinetic scales

Two-fluid simulations

Continuity equation:

$$\frac{\partial n}{\partial t}+\nabla(n\boldsymbol{U})=0$$

Motion equation of motion (protons, electrons):

$$\frac{\partial n\boldsymbol{U}}{\partial t}=-\nabla\cdot[n(\boldsymbol{U}\boldsymbol{U})+P_{tot}-\boldsymbol{B}\boldsymbol{B}]$$

Adiabatic closures (for both ions ions and electrons:

$$\frac{\partial(nS_{e,i})}{\partial t}=\nabla\cdot(nS_{e,i}\boldsymbol{u}_{\boldsymbol{e},\boldsymbol{i}})=0$$

$$S_{e,i}=P_{e,i}n^{-\gamma} \qquad \gamma=5/3$$

Generalized Ohm's law :

$$\boldsymbol{E}=-\boldsymbol{u}_{\boldsymbol{i}}\wedge\boldsymbol{B}+\frac{\boldsymbol{J}\wedge\boldsymbol{B}}{n}-\frac{1}{n}\nabla P_e=\boldsymbol{u}_{\boldsymbol{e}}\wedge\boldsymbol{B}-\frac{1}{n}\nabla P_e$$

- All quantities are normalized to proton quantities
- Periodic in Y (shear flow), open in X
- Numerical dissipation achieved by using filters [Lele, J. Comp. Phys.,1992]

Initial conditions

$$\boldsymbol{U} = A_{eq} \tanh\left(\frac{x - x_c}{L_{eq}}\right)\hat{\boldsymbol{e}}_y$$

$$A_{eq} = 1 \quad L_{eq} = 6\, d_i$$

$$\boldsymbol{B} = B_0(x)\sin(\theta)\hat{\boldsymbol{e}}_y + B_0(x)\cos(\theta)\hat{\boldsymbol{e}}_z$$

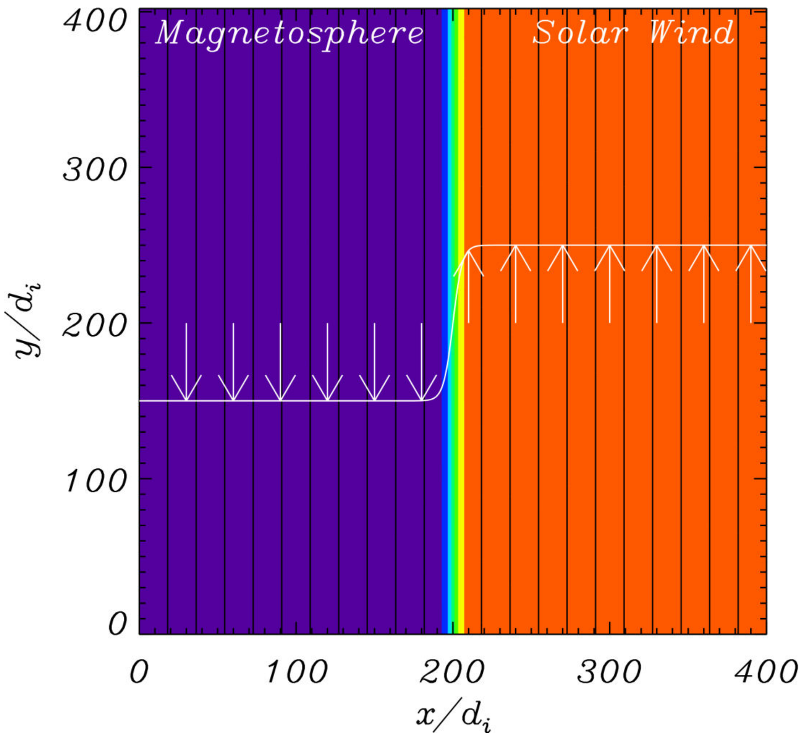
$$\theta = 0.02$$

$$B_0(x) = B_0 = 1.0$$

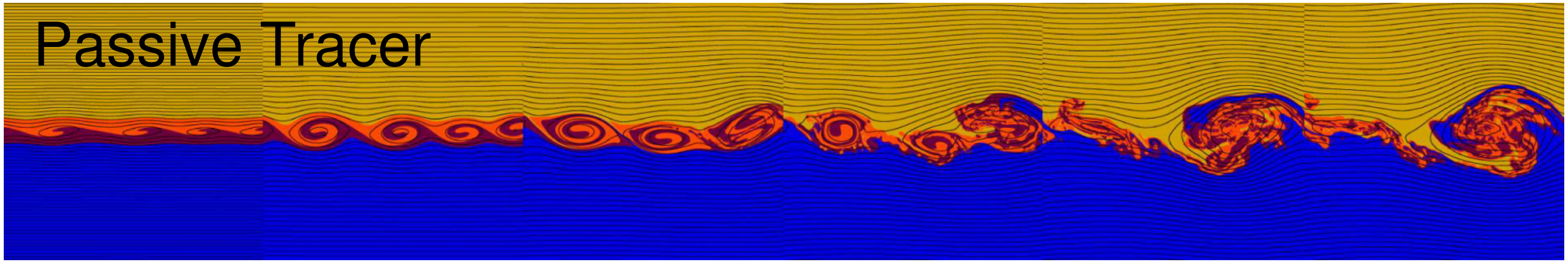
$$n(x) = n_0 = 1.0$$

$$T_i(x) = T_e(x) = 0.5$$

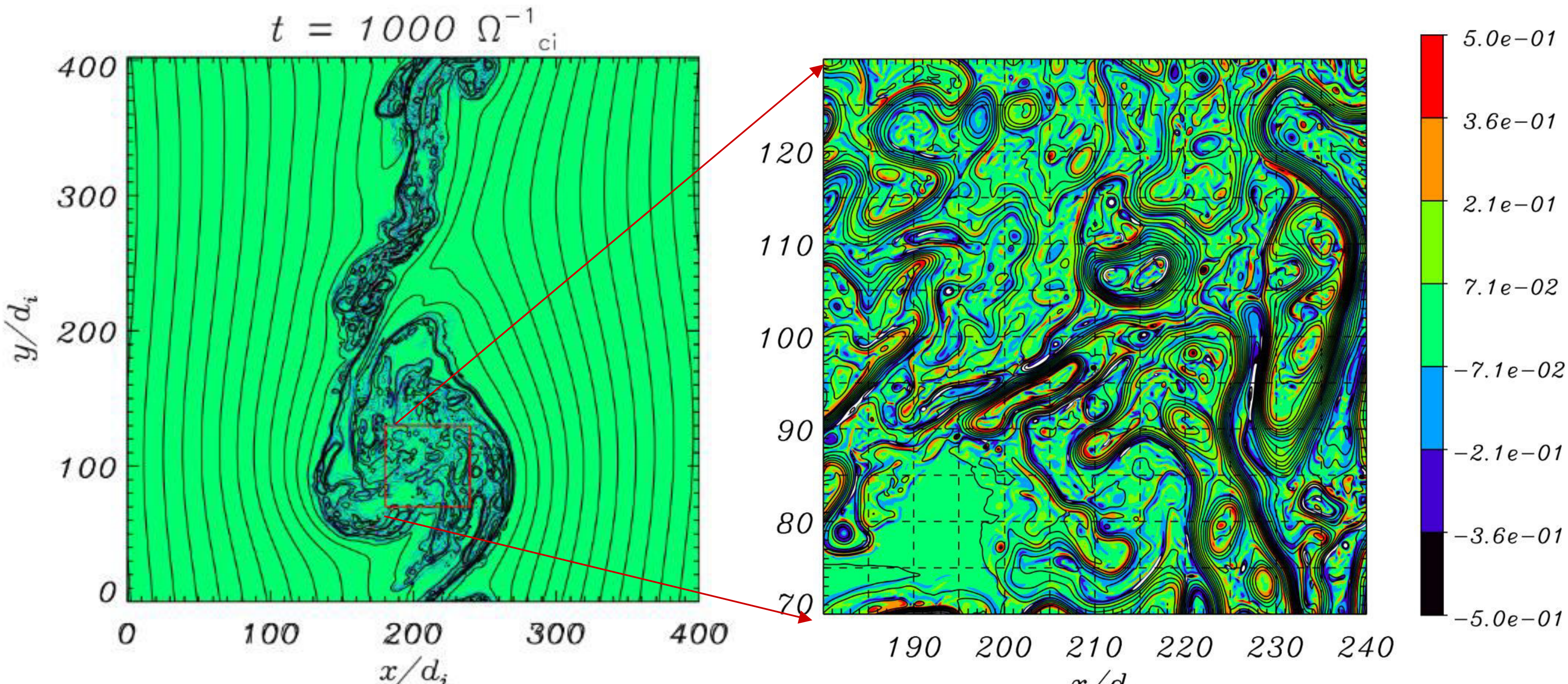
$$N_x \times N_y = 4096 \times 8192$$



Generation of turbulence

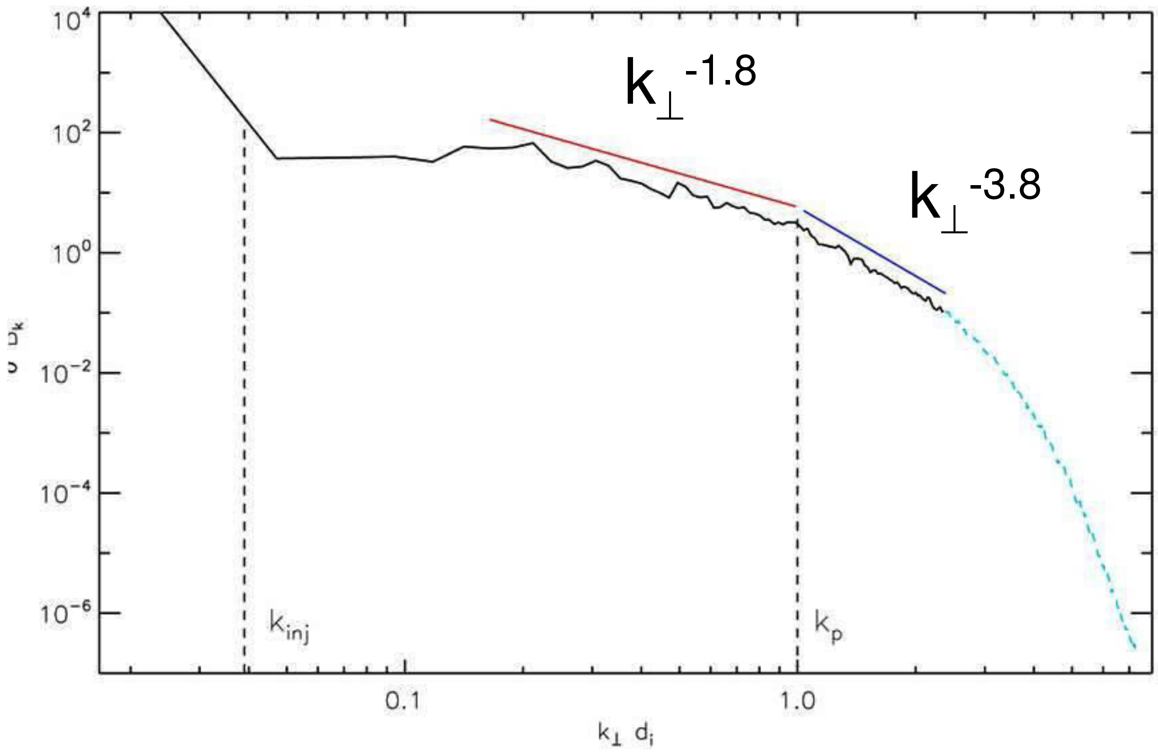


Current Jz:



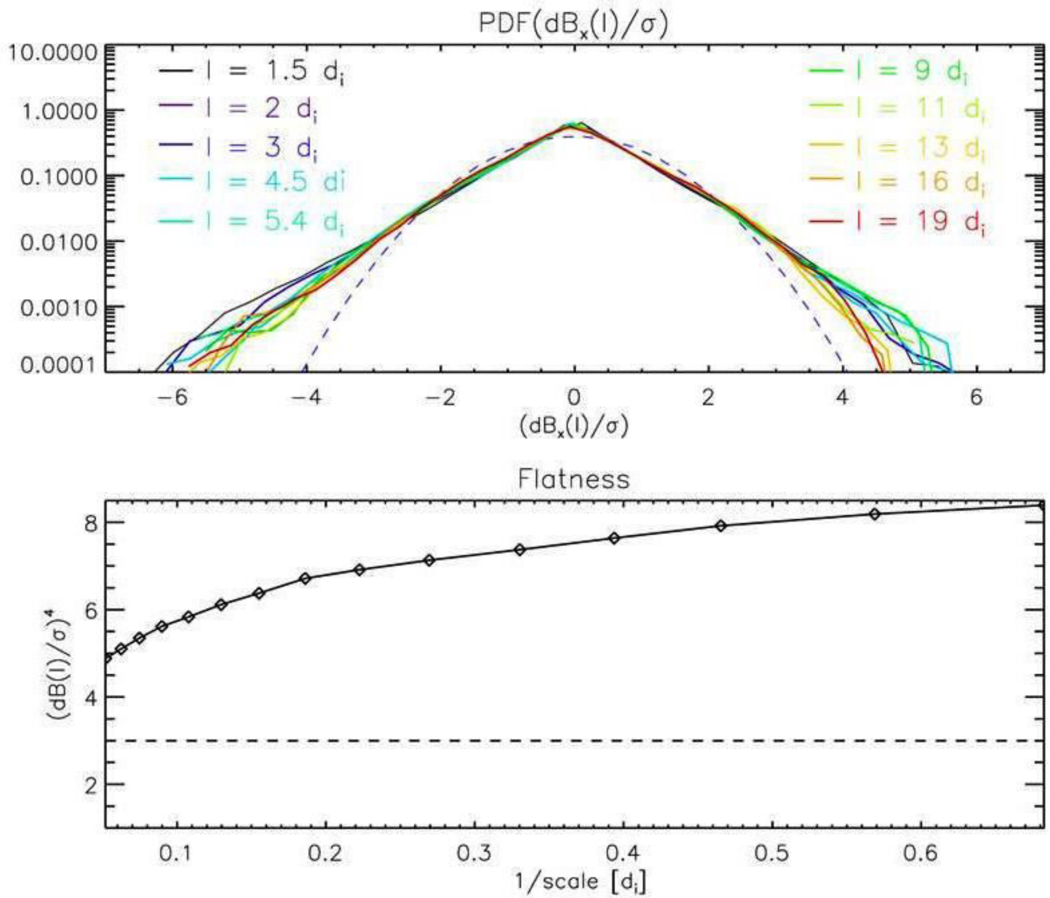
[Rossi+, submitted to Phys. Plasmas, 2015]

Magnetic energy spectrum



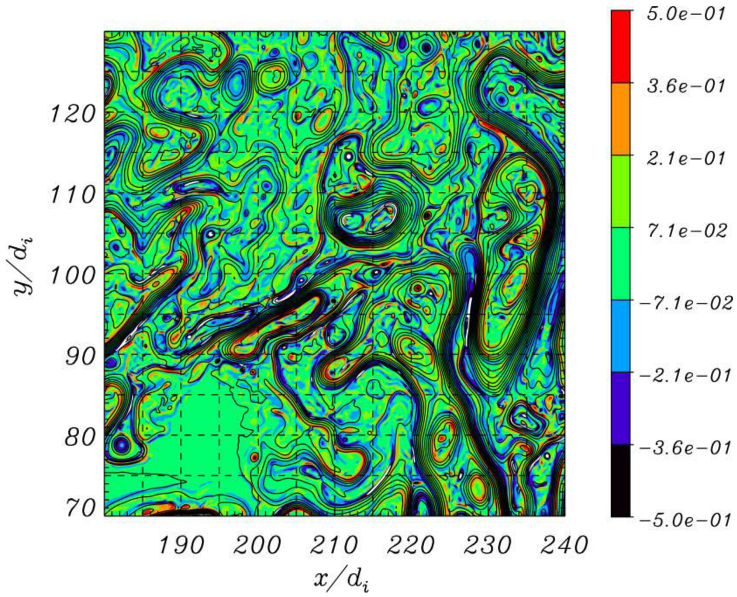
- Isotropic flutuations at suffiently large time $\tan^2(\theta_{shebalin}) \sim 1$
- Injection scale ~ vortex scale
- Spectrum in inertial range compatible with Kolmogorov scaling
- Steeper spectrum below proton scale. Higher slope than found in PIC simulations but compatible with space observations [Alexandrova+, SSR, 2013; Sahraoui+, ApJ, 2013]

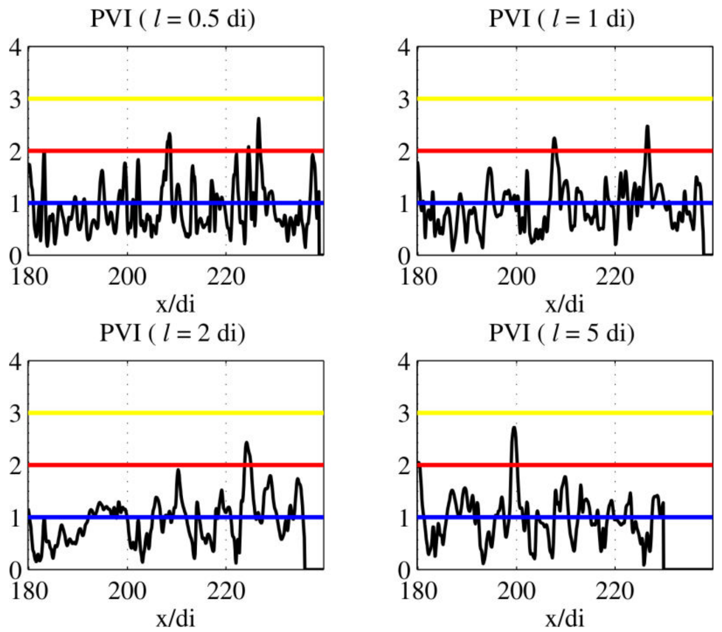
Intermittency

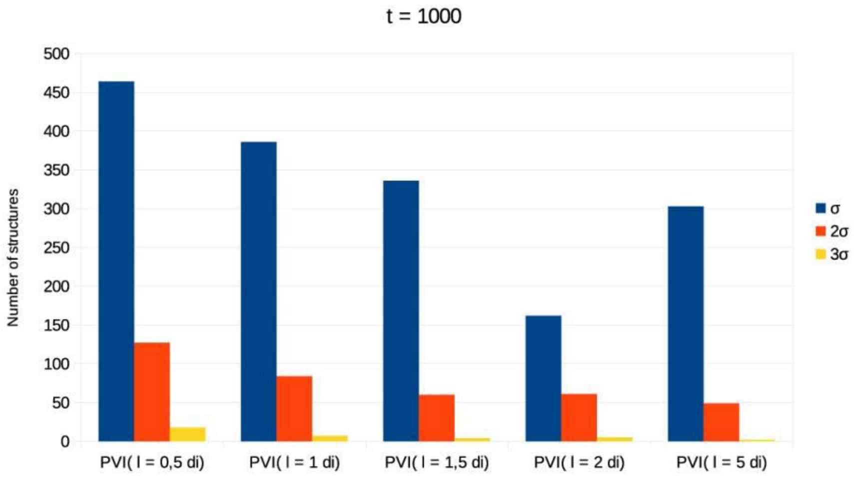


- Scale-dependent deviation from gaussianity (intermittency)
- Tails of PDF associated to small-scale coherent structures

Identification of current sheets

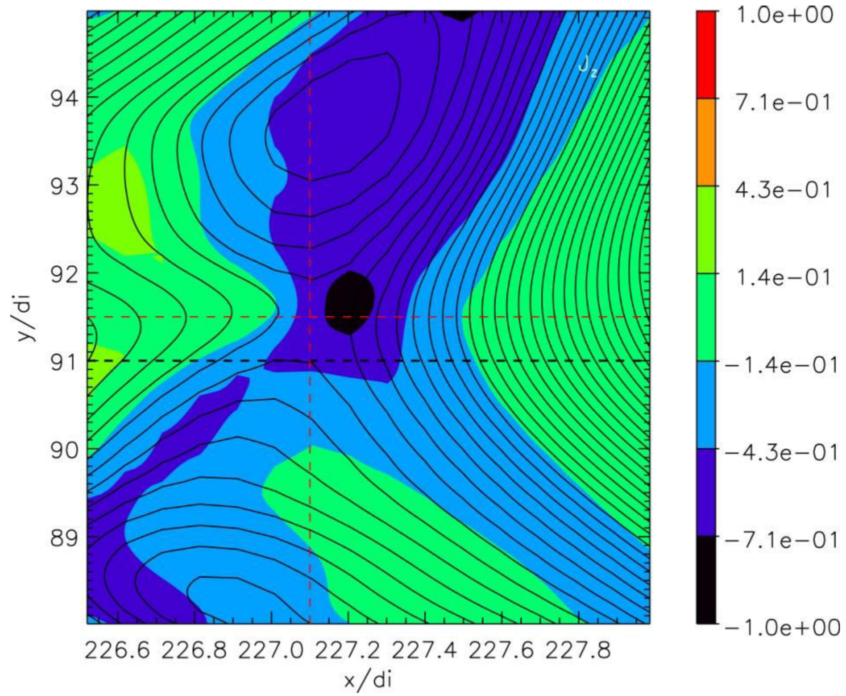


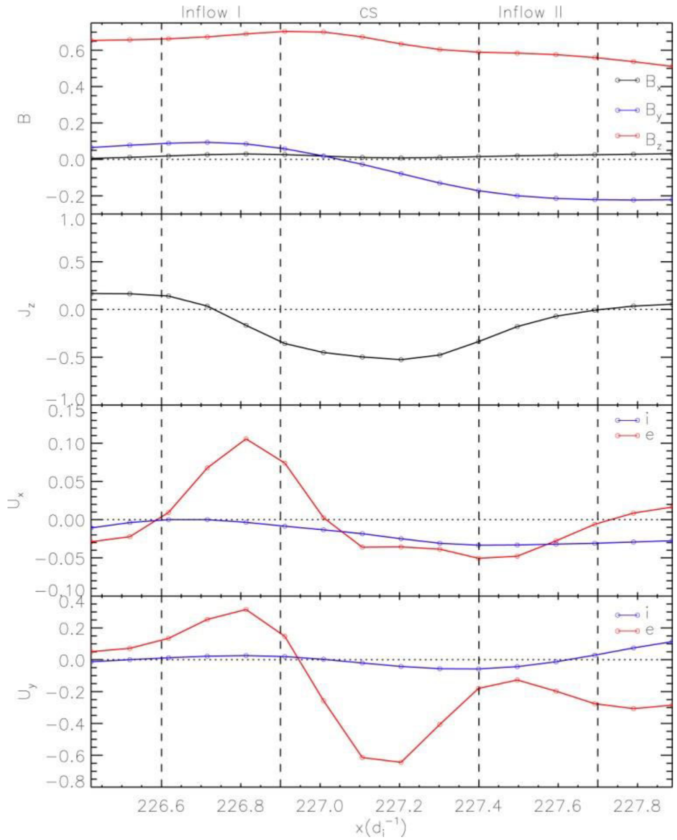




- Current sheets identified trhough PVI [Greco+, JGR, 2008]
- Strongest current sheets have scale ~ 1 di and are expected to be reconnection sites [Servidio+,JGR,2011]

Reconnection signatures





- Magnetic topology and flows consistent with ongoing reconnection with guide ffield Bz/By ~ 5

- Reconnection rate 0.15 – 0.3 consistent with fast reconnection. Rates are higher than expected for Hall reconnection in single sheets [Huba+, 2004; Pritchett+, 2004] but consistent with with rates found in turbulent reconnection [Servidio+, PRL, 2009]. Rates possibly enhanced by turbulence.

Curent/future spacecraft data relevant for reconnection & turbulence

NASA/MMS [http://mms.gsfc.nasa.gov]: **2015**-- near-Earth space
Goal: the physics of reconnection at electron scales (also turbulence, particle acceleration)

ESA/SolarOrbiter [http://sci.esa.int/solarorbiter]: **2018**-- near-Sun corona (62 Rs). **Goals**: solar wind acceleration, coronal heating, production of energetic particles (turbulence, reconnection)

NASA/SolarProbePlus [http://solarprobe.gsfc.nasa.gov]: **2018** -- near-Sun corona (8.5 Rs). Goals: similar to SolarOrbiter

ESA/THOR: mission concept submitted to ESA M4 call fully dedicated to study turbulent energy dissipation at kinetic scales (under evaluation)