ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

February 10, 2022

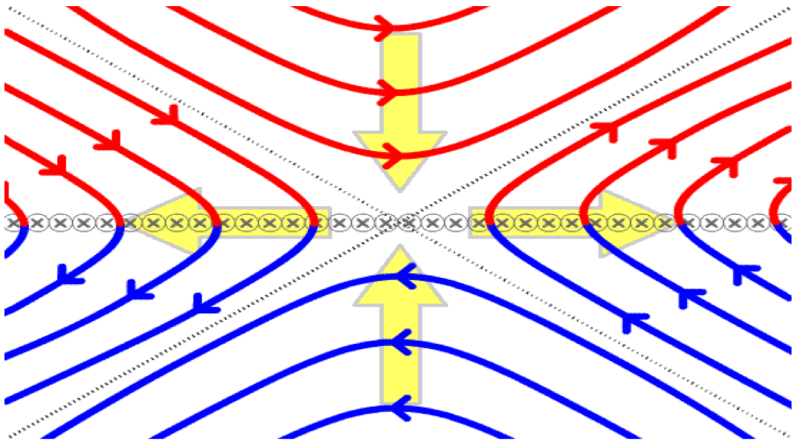
Coronal heating: reconnection & nanoflares (another whirlwind tour)

Dr. Steven R. Cranmer
Dr. Thomas E. Berger

Outline

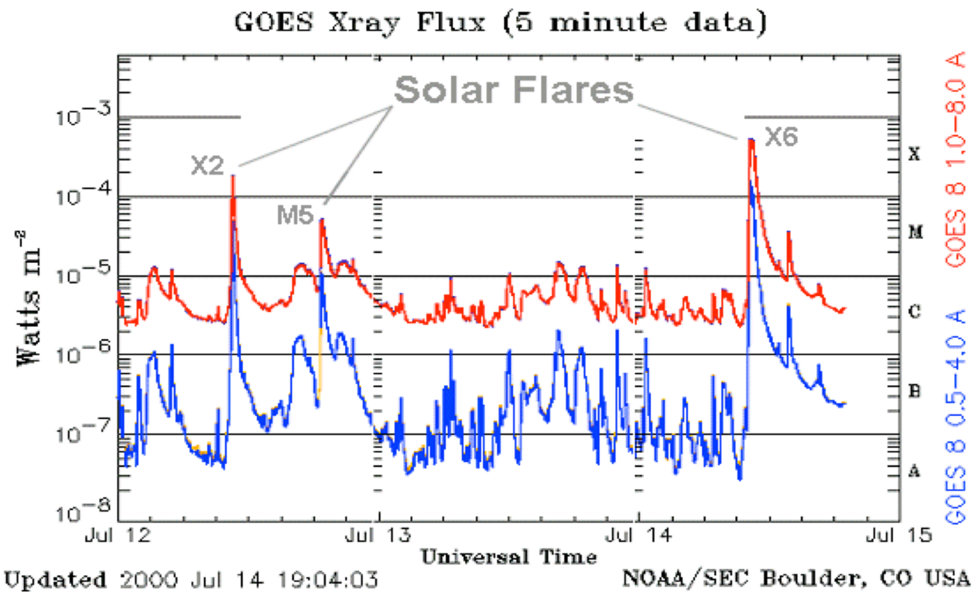
1. Observations (and cartoons!) of reconnection sites on the Sun

2. Overview of magnetic reconnection: how much does it heat?

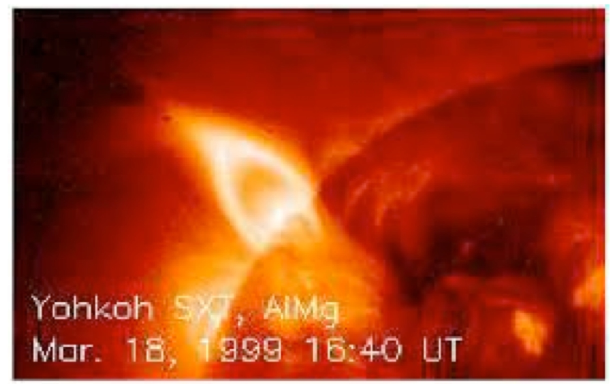


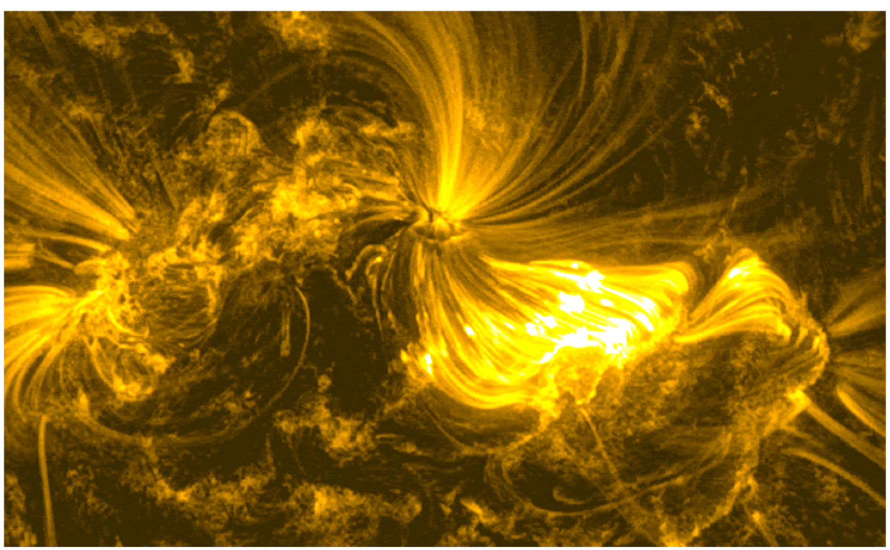
3. How is MHD turbulence relevant to all this…?

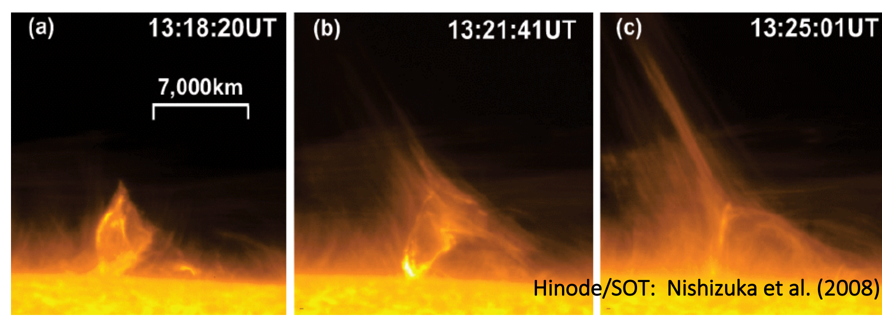
(1) *Solar observations of reconnection sites*



- This isn't a class about **solar flares!**
- However, if the idea is that coronal heating comes from a sum over many discrete/impulsive energy release events, we do need to look in that direction…



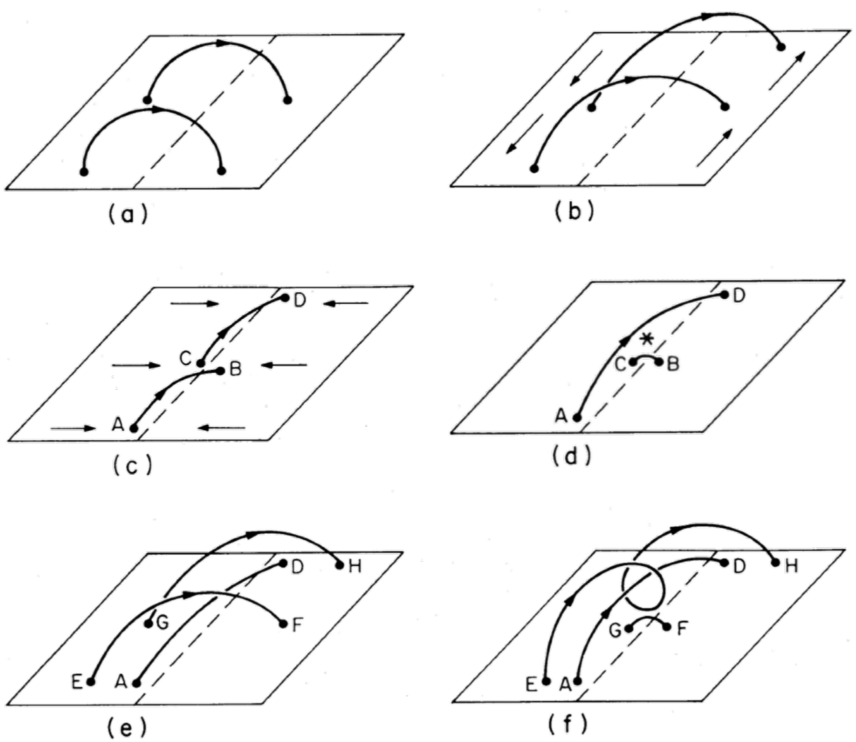




(1) *Solar observations of reconnection sites*

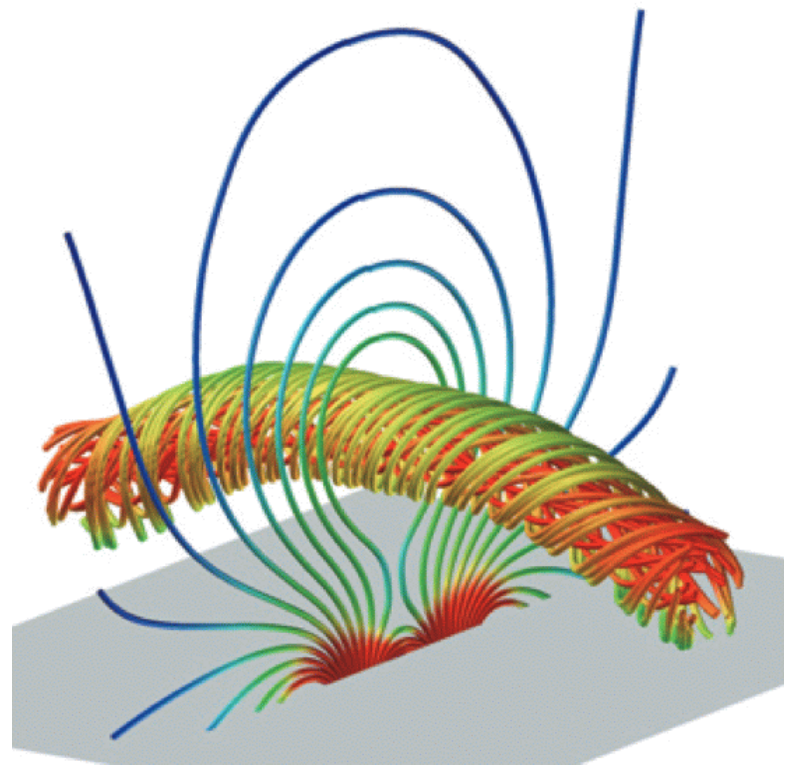
Cartoons! https://www.astro.gla.ac.uk/cartoons/

Twisted fields can build up as a result of shear motions on the surface (van Ballegooijen & Martens 1989)



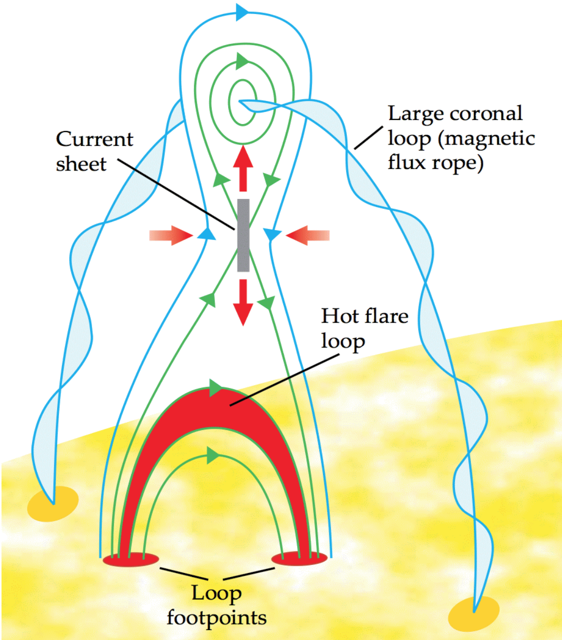
Formation of flux ropes & filaments . . .

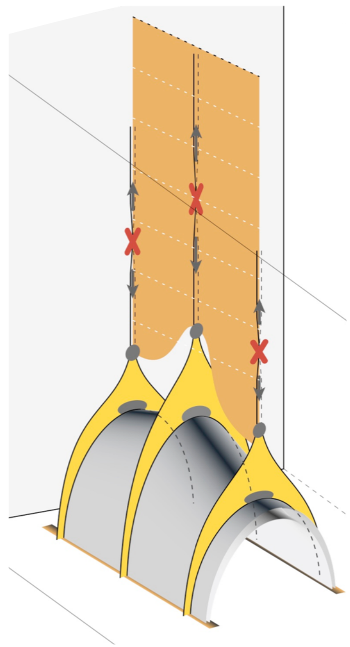
Overlying magnetic field has strong tension… wants to hold everything down.

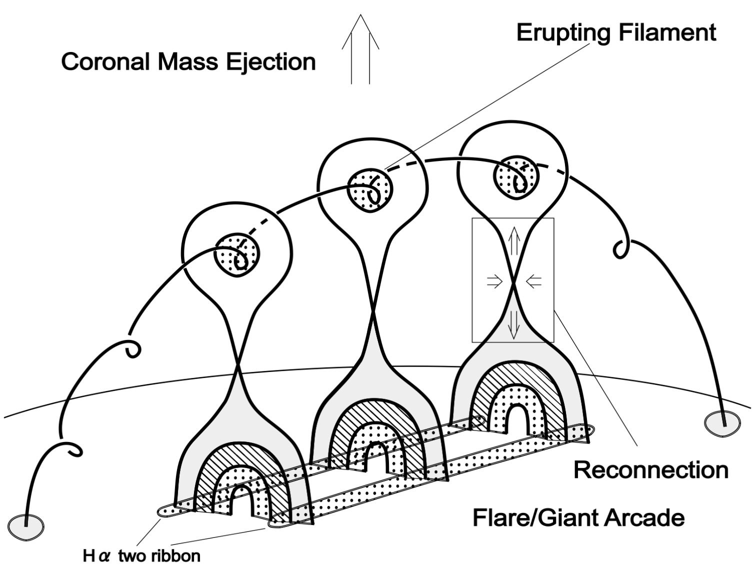


Oppositely pointed magnetic field lines are often pushed together at the coronal base.

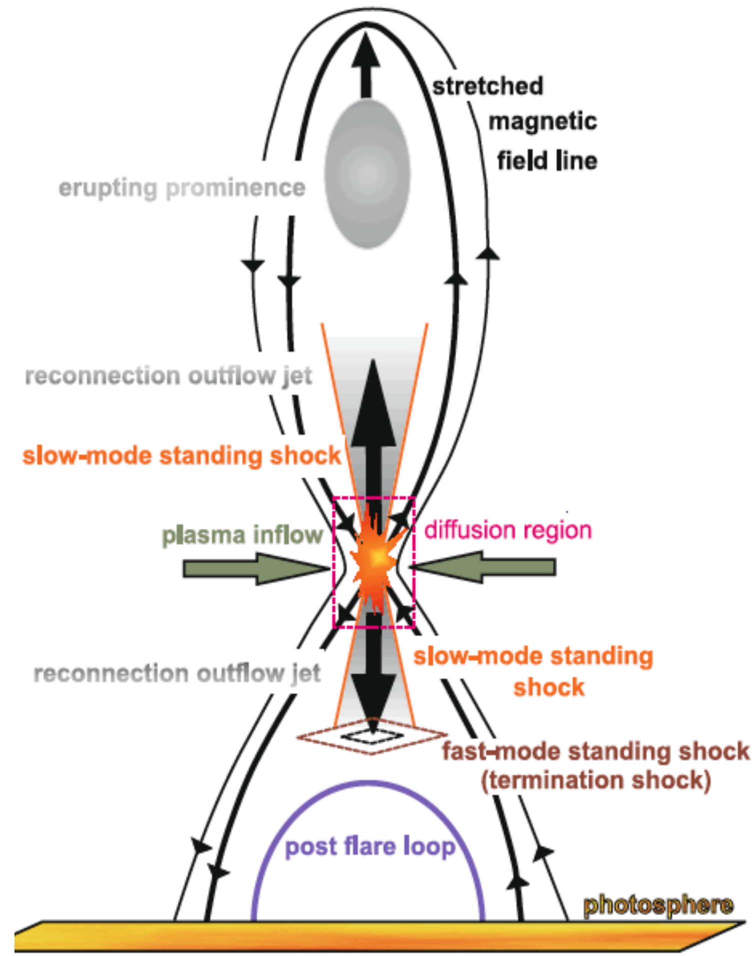
(1) *Solar observations of reconnection sites*







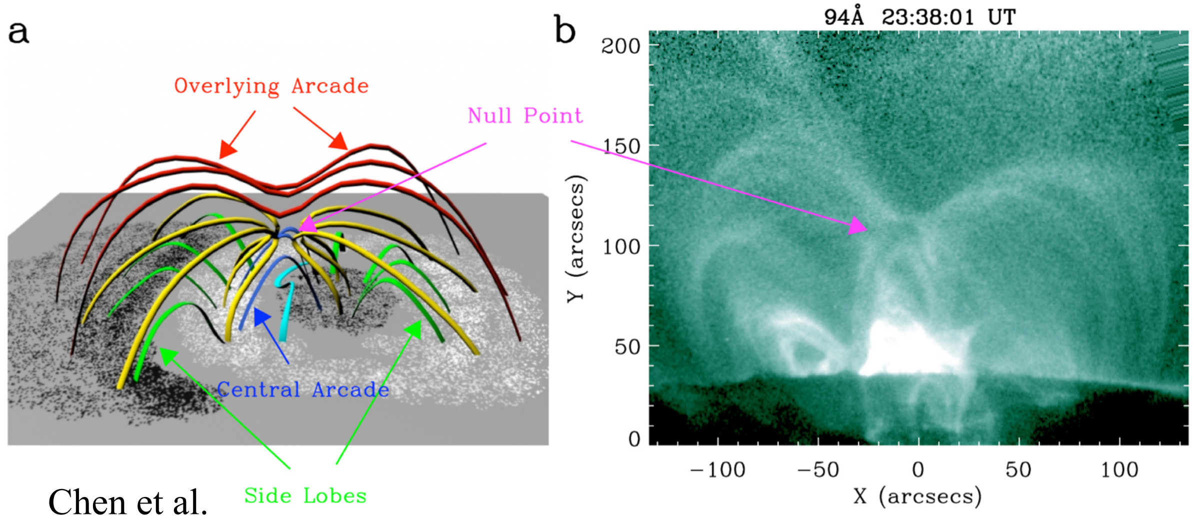
A "standard" picture of solar flares & CMEs has evolved over the years…



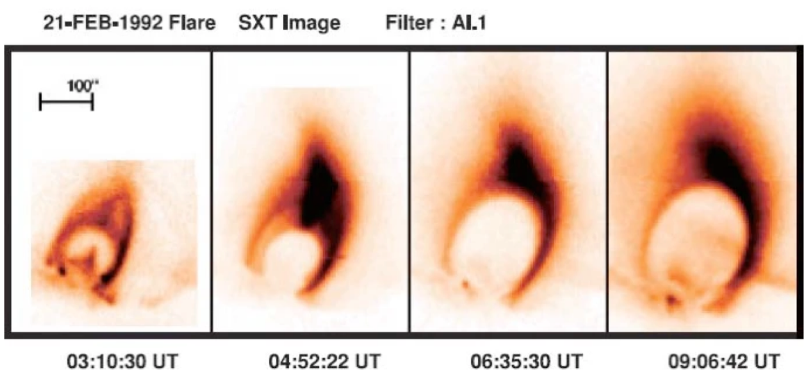
(1) *Solar observations of reconnection sites*

Decades of **observations** tend to support the basic picture of magnetic reconnection at the core of solar eruptive events…

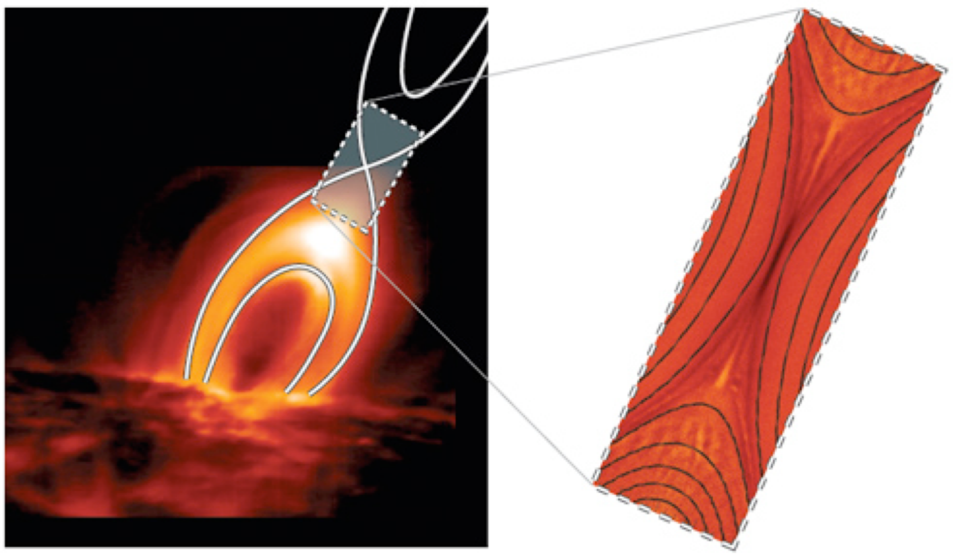
but there's huge variety amongst events…



Chen et al. (2016)



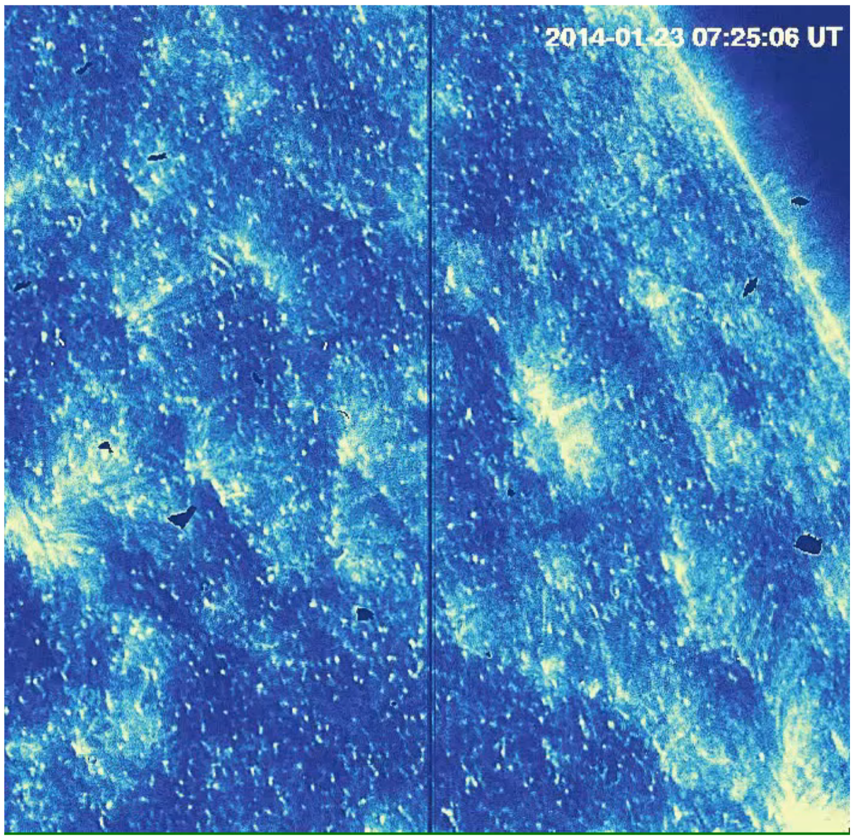
Shibata & Magara (2011)



Burch & Drake (2009)

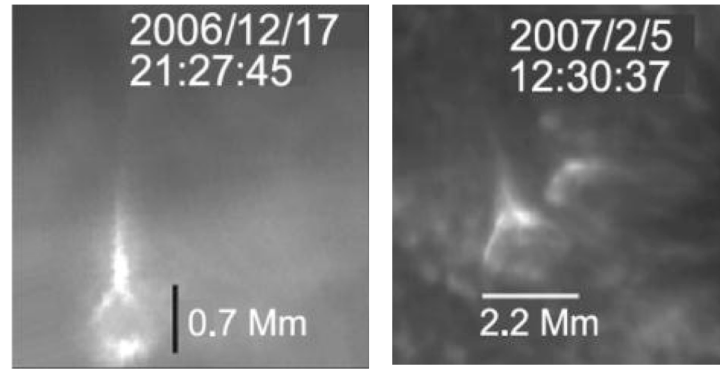
(1) *Solar observations of reconnection sites*

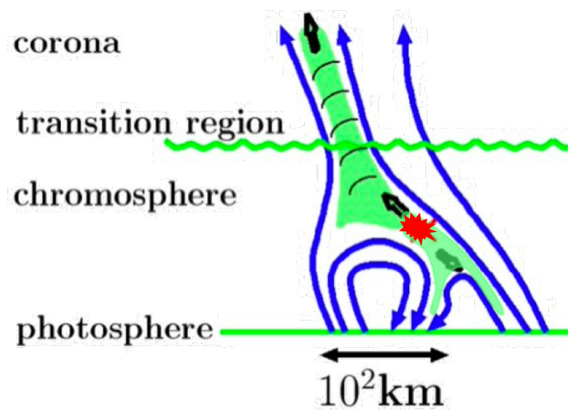
Even down to the **smallest scales** (in the chromosphere), there seems to be some kind of reconnection that drives impulsive events. Spicules, tadpoles, "anemone jets," EUV & X-ray microflares, etc.

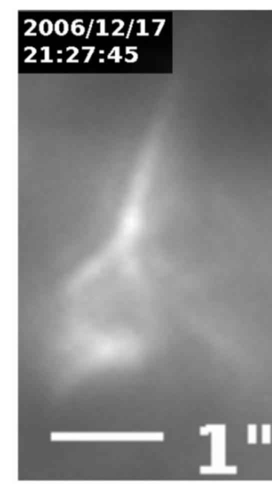


Tian et al. (2014)

Singh et al. (2011)

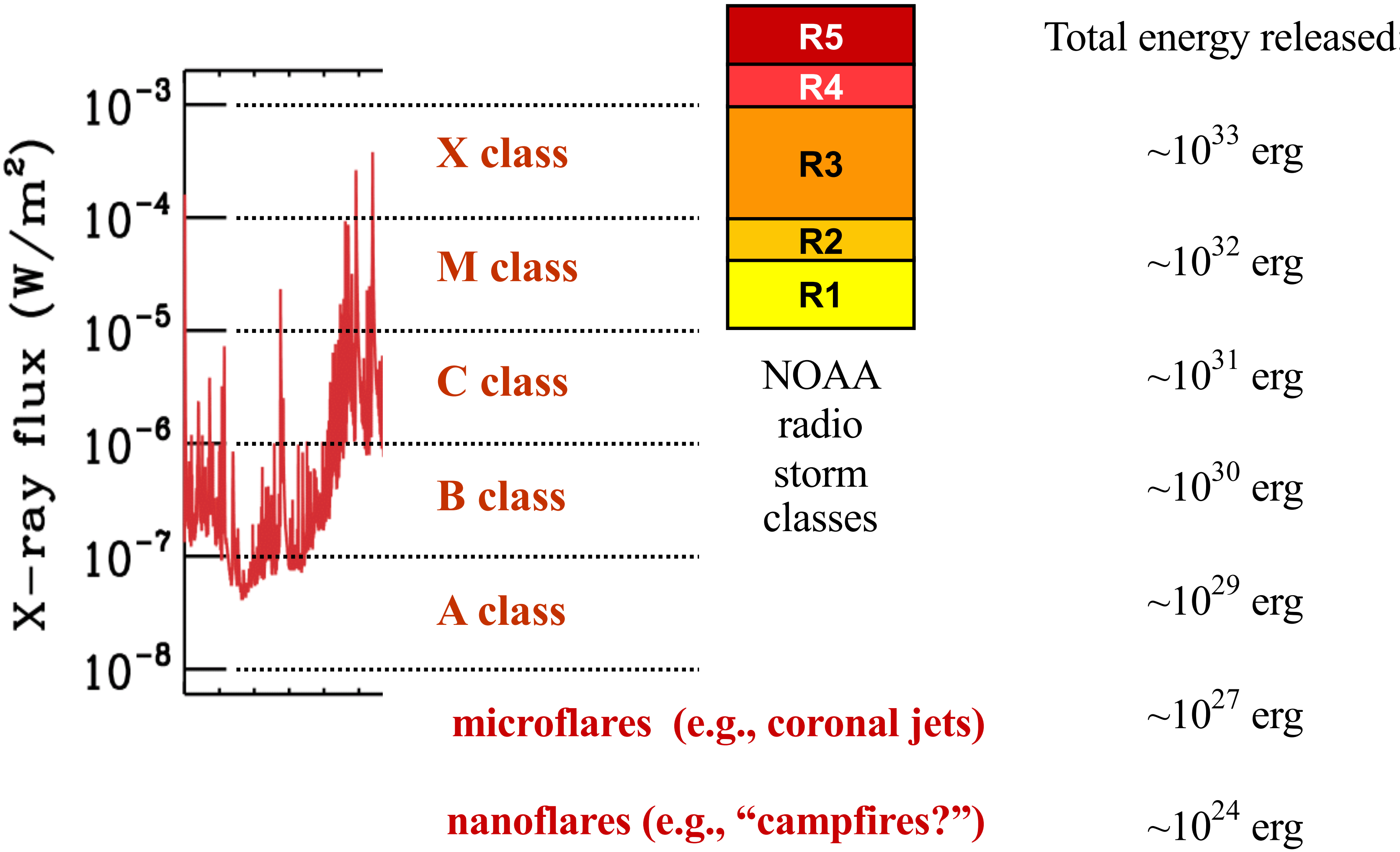






Shibata et al. (2008)

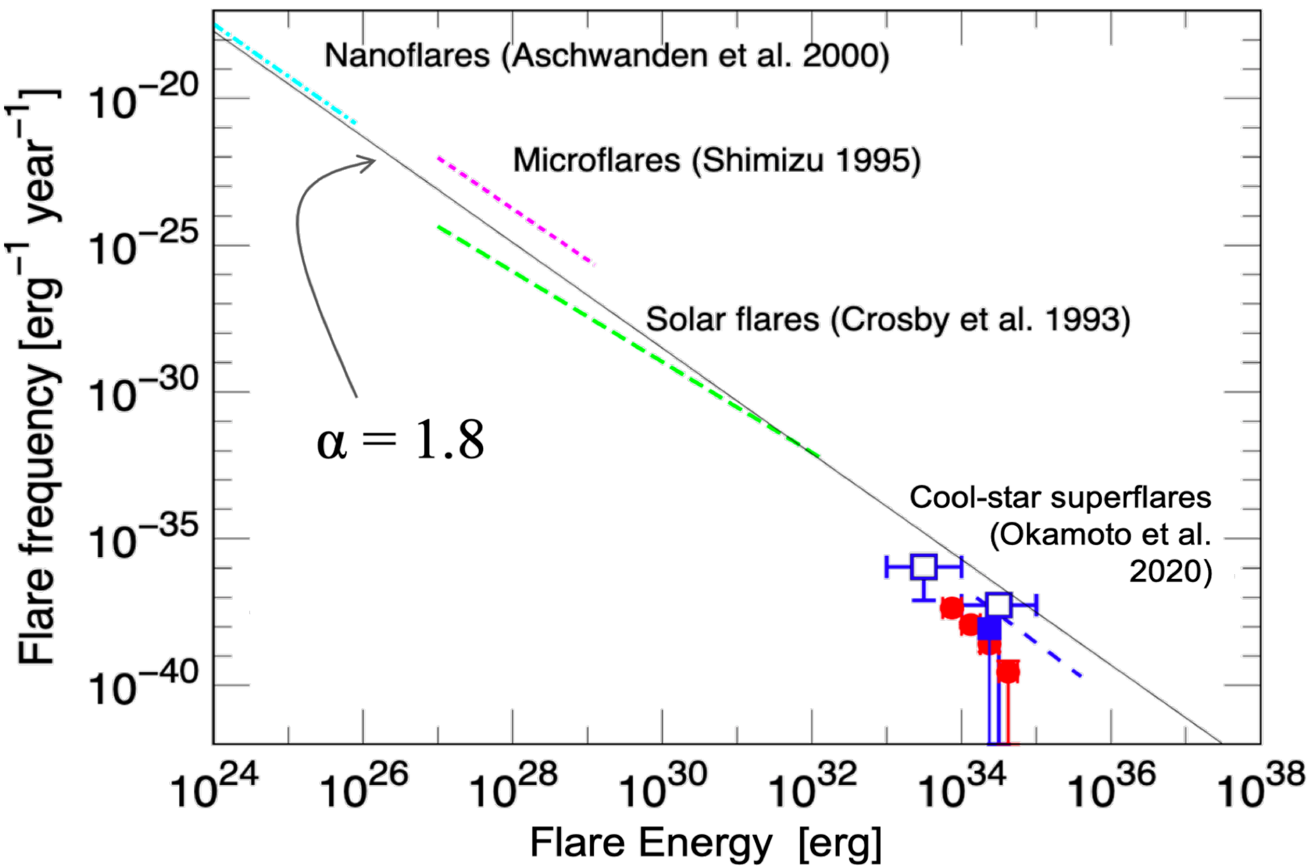
(1) *Solar observations of reconnection sites*



(1) *Solar observations of reconnection sites*

It's been known that {numbers of events} vs. {energy} is a power-law distribution… but Hudson (1991, *Solar Phys,* 133, 357) pointed out the importance of the slope…

$$N(E) \propto E^{-\alpha} \qquad \text{if} \left\{ \begin{array}{c} \alpha > 2 \\ \alpha < 2 \end{array} \right\} \text{the total is dominated by the} \left\{ \begin{array}{c} \text{smallest} \\ \text{largest} \end{array} \right\} \text{events.}$$



but the error bars on the slopes (not shown!) are still large…

and systematic effects may be obscuring the smallest events!

(2) *Overview of magnetic reconnection*

- Let us first introduce a useful dimensionless quantity, the **Lundquist number:**

$$S = \frac{V_{\rm A}\, L}{D_{\rm B}} \sim \frac{V_{\rm A}\, L}{v_{\rm th}\, \ell_{\rm mfp}}$$

typical speeds & length scales of macro-scale MHD flows

typical magnetic diffusion coefficient (i.e., resistive diffusivity) characterizing random-walk speeds & lengths

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- Some use the symbol η for the diffusion coefficient, but I prefer using η for the "actual" **electrical resistivity** (and σ for electrical conductivity):

$$\mathbf{E} = \eta \mathbf{J} \qquad\qquad D_\mathrm{B} = \frac{c^2 \eta}{4\pi} = \frac{c^2}{4\pi\sigma}$$

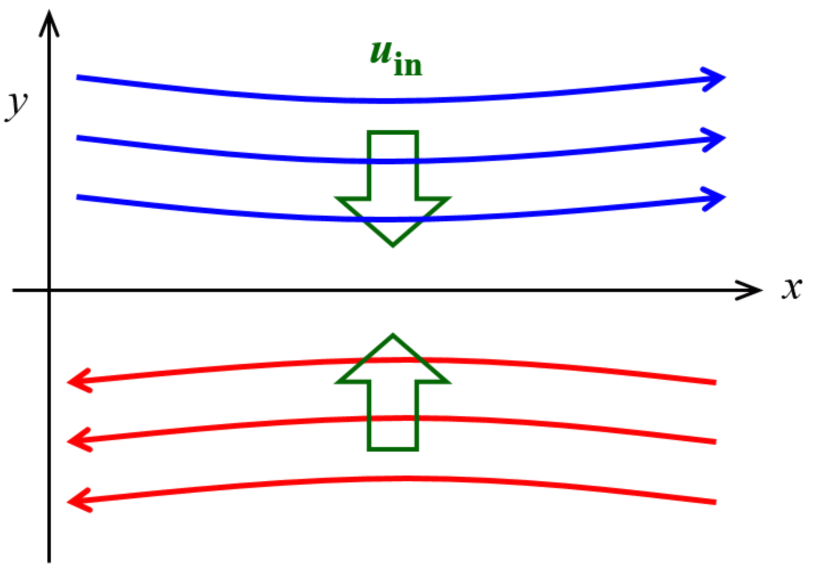
- Most of the coronal volume (along with most astrophysical plasmas) has $S >> 1$ (often exceeding $\sim 10^{12}$), which means resistivity *shouldn't* be important.

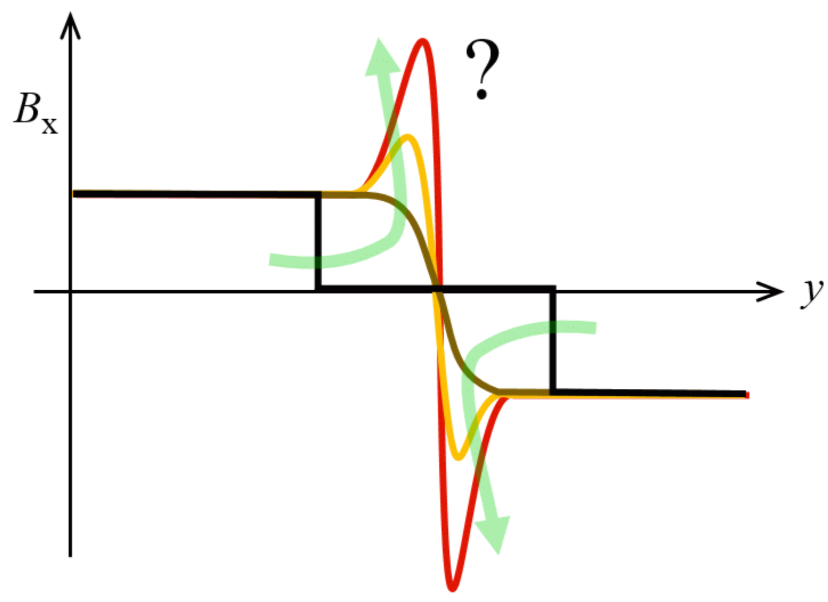
(2) *Overview of magnetic reconnection*

- However, sometimes the field gets twisted up into complex topologies, with small length scales *L*.

$$S = \frac{V_A L}{D_B}$$

- In such regions *S* is no longer >> 1.
- If we want to study what happens when oppositely directed fields are pushed together, we're forced to take resistivity seriously.
- However, what if there was no resistivity? Pushing together perfectly "frozen-in" field lines would lead to a continual build-up… a log-jam…

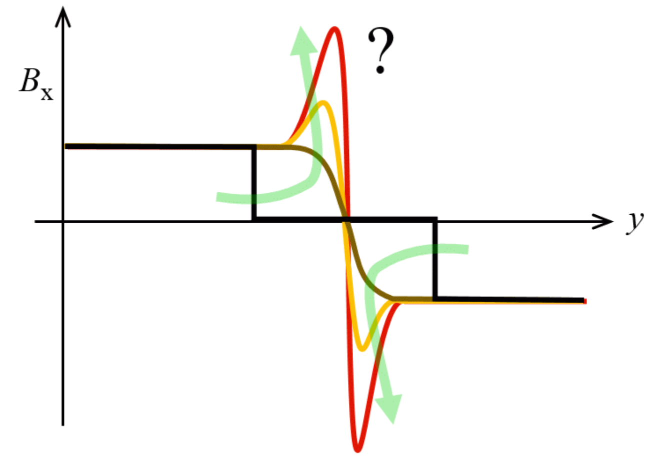




(2) *Overview of magnetic reconnection*

- How to prevent a continuous build-up over time?
- The **resistive term** in the magnetic induction equation causes magnetic energy to diffuse… especially if there are sharp gradients!

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + D_{\mathrm{B}} \nabla^2 \mathbf{B}$$



- Let's look for a **steady-state** between buildup & diffusion.
- Define the thickness of the reconnection region (in *y*) as δ. As fields build up, δ gets smaller. Also, define u_{in} as the speed at which fields are pushed together.
- Eventually, we'll reach a point where they balance…

$$\frac{u_{\mathrm{in}}\,\delta}{D_{\mathrm{B}}} \approx 1 \qquad \Longrightarrow \qquad \delta \approx \frac{D_{\mathrm{B}}}{u_{\mathrm{in}}}$$

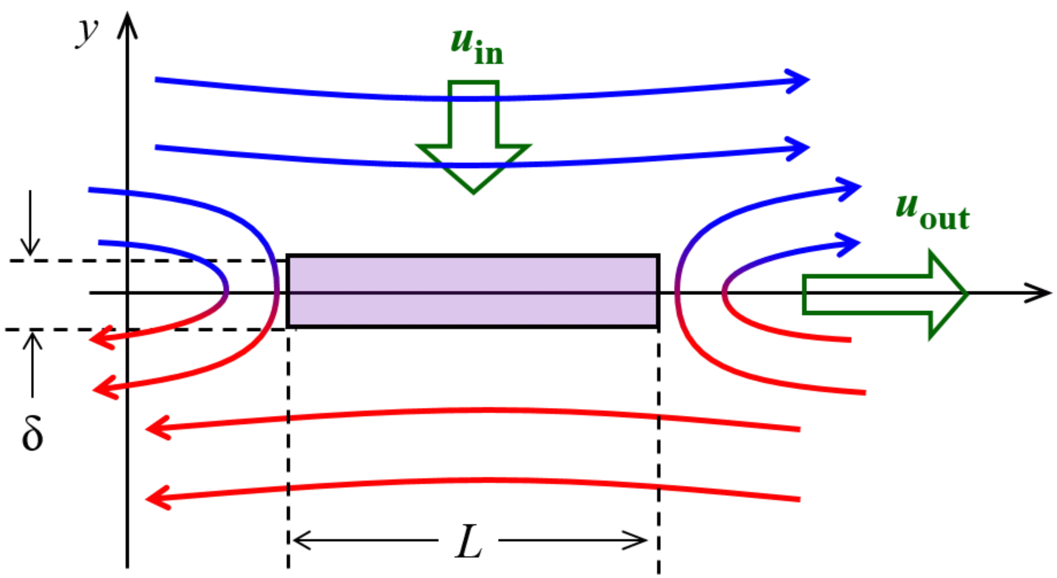
- This is the point at which diffusion balances buildup. Magnetic energy is converted to heat at a continuous rate.

(2) *Overview of magnetic reconnection*

- We still don't know how the corona determines δ or u_{in} .
- The next steps are still not universally agreed upon; it's still a very active field of research.

$$\delta \approx \frac{D_B}{u_{in}}$$

- Let's go over the original (Sweet & Parker 1957) theory, then talk about how more recent research is in the process of improving it.
- Treat the **diffusion region** as 2D and rectangular…



Things we know:

- **B** (strength of inflowing magnetic field)
- L (length scale of the reconnection region parallel to **B**)
- ρ (mass density, assume constant everywhere)

Things we don't know:

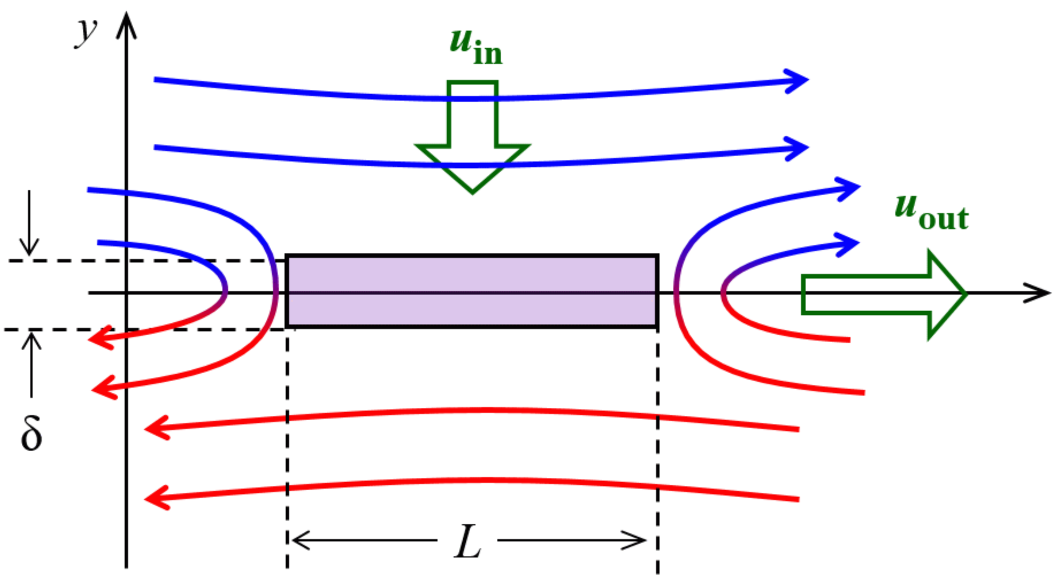
- u_{in} , u_{out} , δ

(2) *Overview of magnetic reconnection*

- To fully specify u_{in} , u_{out} , and δ, we need two more conditions:
- **Mass conservation:** if it's a steady state, then the total mass coming in must balance the total mass going out, in proportion to the dimensions,

$$\rho\, u_{\text{in}}\, L \;\approx\; \rho\, u_{\text{out}}\, \delta$$

Thus, the reconnection region is kind of like a **toothpaste tube** being compressed gently along its long axis, with the toothpaste jetting out forcefully along its short axis:



$$\frac{u_{\text{out}}}{u_{\text{in}}} \approx \frac{L}{\delta} \gg 1$$

(2) *Overview of magnetic reconnection*

- Lastly, there's **energy conservation.**
- Going in: assume motions are so slow that it's dominated by magnetic energy.
- Going out: B-field has been mostly cancelled; the "jets" are mostly kinetic energy.

$\mathcal{E}$ = volume × energy density, so

$$\mathcal{E}_{\text{in}} = \Delta x \, \Delta y \, \Delta z \, U_{\text{B}} = L \, (u_{\text{in}} \Delta t) \Delta z \left(\frac{B^2}{8\pi} \right)$$

$$\mathcal{E}_{\text{out}} = \Delta x \, \Delta y \, \Delta z \, U_{\text{K}} = (u_{\text{out}} \Delta t) \, \delta \, \Delta z \left(\frac{1}{2} \rho u_{\text{out}}^2 \right)$$

$$\text{If } \mathcal{E}_{\text{in}} = \mathcal{E}_{\text{out}} \ , \quad \text{then} \quad u_{\text{out}} = \frac{B}{\sqrt{4\pi\rho}} = V_{\text{A}} \quad \text{(the Alfvén speed)} \ .$$

- In more realistic models, $\mathcal{E}_{\text{in}} \neq \mathcal{E}_{\text{out}}$ since *some* energy must go into heating up the diffusion region, and we can't totally ignore the kinetic (in) & magnetic (out) parts.

(2) *Overview of magnetic reconnection*

- We can now solve 3 equations for 3 unknowns…

$$u_{\rm in} = \frac{u_{\rm out}\,\delta}{L} \qquad \text{(from mass conservation)}$$

$$= \frac{V_{\rm A}\,(D_{\rm B}/u_{\rm in})}{L} \qquad \text{(from energy conservation \& Rm} \approx 1 \text{ in box)}$$

and some additional algebra, in combination with the definition of the Lundquist number, gives

$$u_{\rm in}^2 = \frac{V_{\rm A}^2}{S} \qquad \text{where recall that} \qquad S = \frac{V_{\rm A}\,L}{D_{\rm B}}$$

- Thus, the Sweet-Parker result for the reconnection Alfvénic Mach number (sometimes called the “dimensionless reconnection rate”) is:

$$\mathcal{M}_{\rm A} = \frac{u_{\rm in}}{V_{\rm A}} = \frac{\delta}{L} = \frac{1}{\sqrt{S}} \sim 10^{-6}$$

- In the solar corona: $S \approx 10^{12}$ . . . $V_{\rm A} \approx 1000$ km/s . . . so $u_{\rm in} \approx 0.001$ km/s ?

(2) *Overview of magnetic reconnection*

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- This doesn't make sense. It's too slow.
- A typical flare-producing region, with a size of about 1–10 Mm, "processes" the active-region B-field over a finite time…

$$\Delta t = \frac{\ell}{u_{\rm in}} \approx \frac{1\text{–}10 \text{ Mm}}{0.01 \text{ km/s}} = 10^5 \text{ to } 10^6 \text{ s} \quad \text{(days/weeks)}$$

(2) *Overview of magnetic reconnection*

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- However, observed flares last only 5–10 minutes!

The real u_{in} must be **faster!**

- Observations, simulations, and some lab experiments now show that reconnection in MHD plasmas tends to occur with a narrow allowed range of

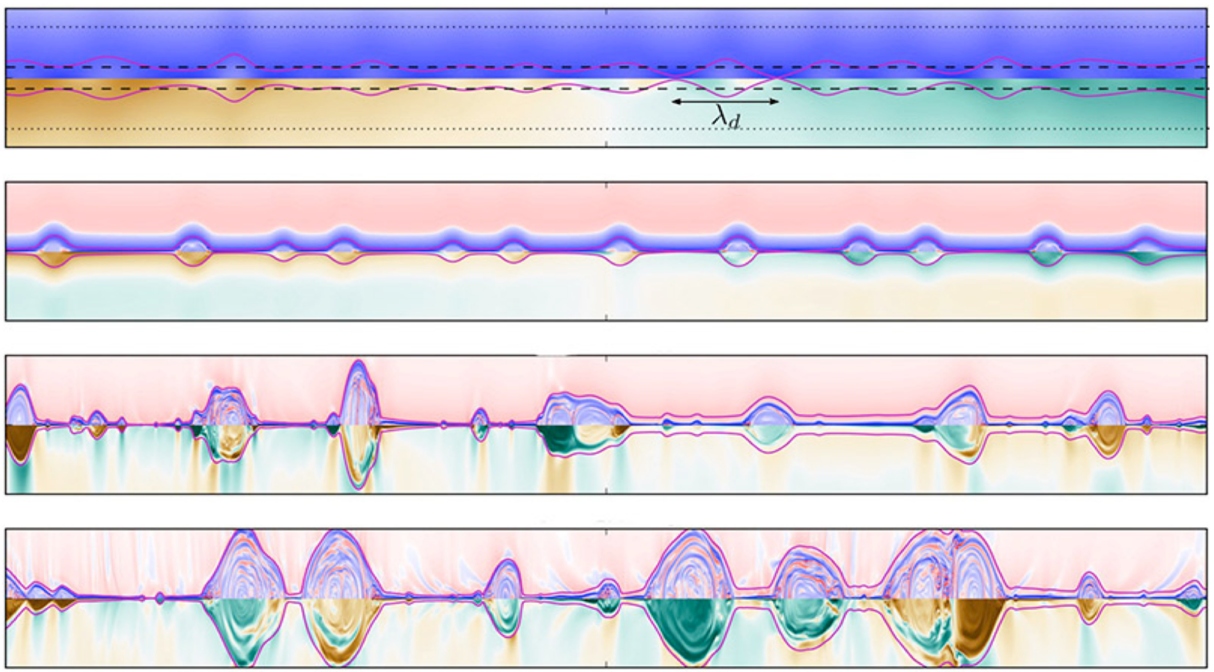
$$\mathcal{M}_A \approx 0.01 \text{ to } 0.1$$

(2) *Overview of magnetic reconnection*

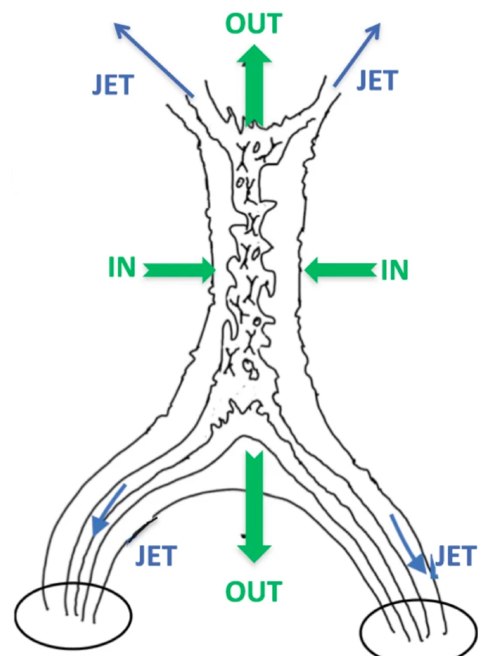
How does the universe get around the constraints of Sweet-Parker theory? It's still a topic of active research, with ~3 main avenues of study…

1. **Plasmoid Instabilities:** The thin diffusion region is unstable to the spontaneous growth of small magnetic "islands." Chaotic (fractal?) eddies produce extra diffusion:

$$\text{larger } D_\text{B} \longrightarrow \text{smaller effective } S \longrightarrow \text{faster } u_\text{in}\ !$$



Huang et al. (2017)

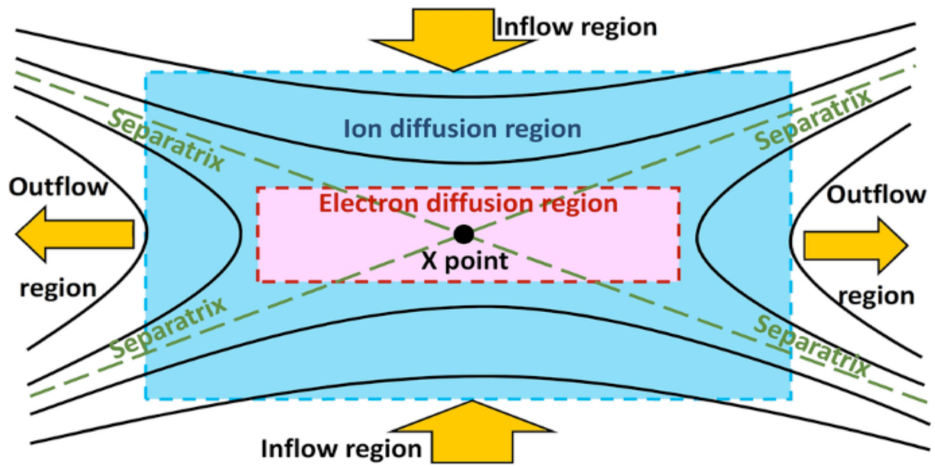


Cairns et al. (2018)

(2) *Overview of magnetic reconnection*

2. **Hall Effect:** If the diffusion region is forced to be smaller than particle Larmor radii, then non-MHD collisionless effects can take over.

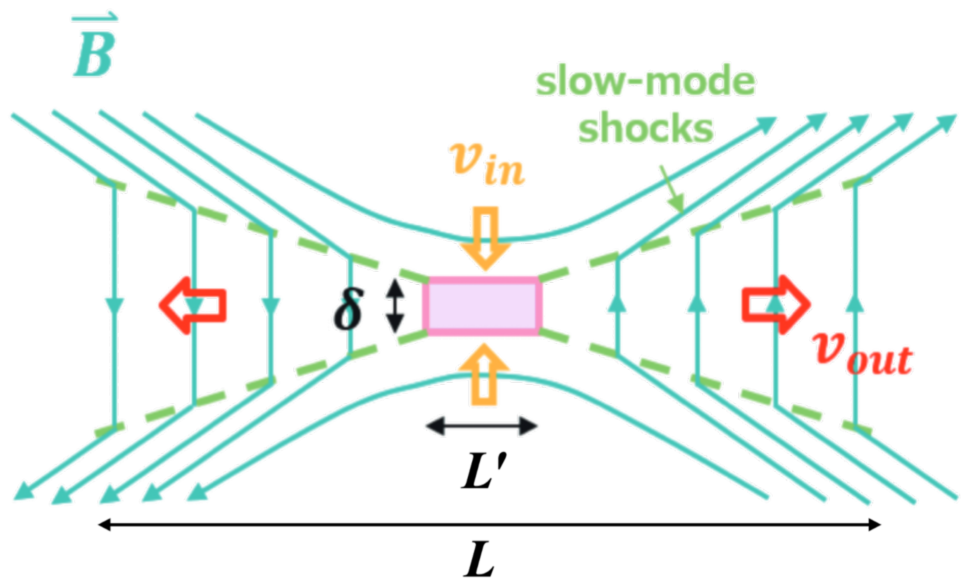
   (electron scales << ion scales)



3. **Petschek reconnection:** Maybe not all flows must pass through the diffusion region. Petschek proposed a model with oblique MHD shocks to help "process" some of the flow.

$$\mathcal{M}_A = \frac{u_{in}}{V_A} \approx \frac{1}{\ln S}$$

   (not as tiny as Sweet-Parker!)

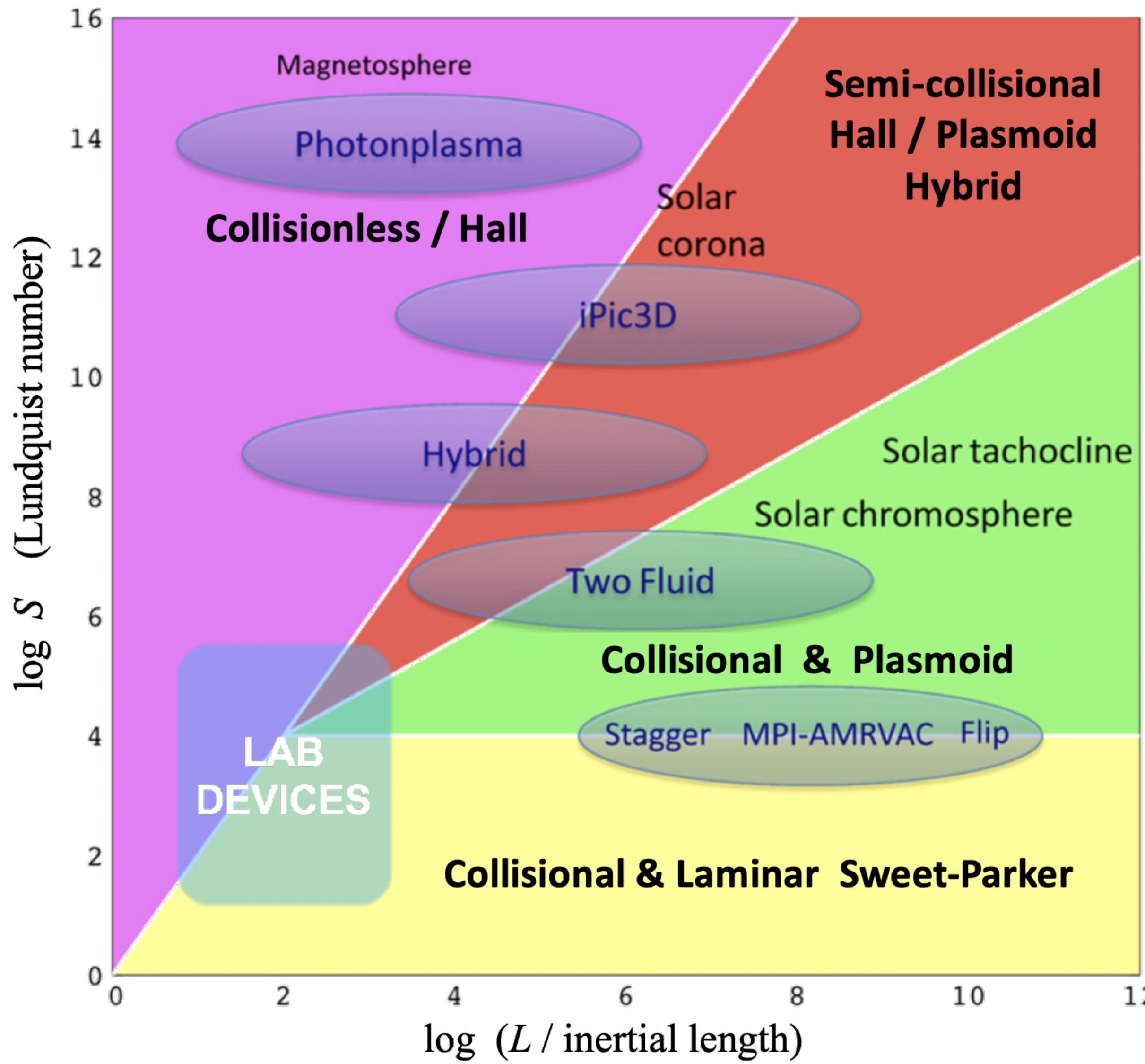


(2) *Overview of magnetic reconnection*

Theorists have fleshed out a kind of "phase diagram" for reconnection modes, illustrating the main regimes and (fuzzy) boundaries →

(Lapenta et al. 2013, *J. Space Weather and Space Climate,* 3, A05)

Observers still find the Petschek model useful… especially for cases where *in situ* instruments fly right through the reconnection regions!



(2) *Overview of magnetic reconnection*

- One more (pretty important) question to ask about reconnection regions:

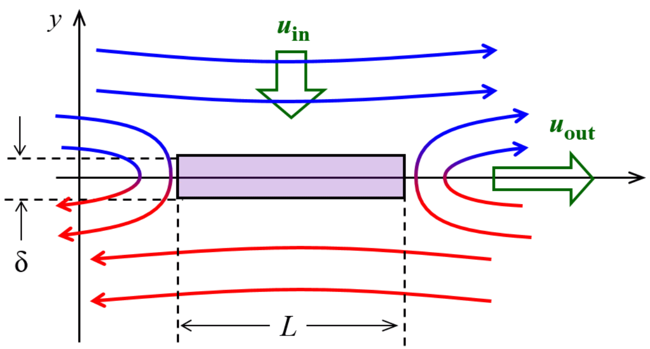
  How much actual **energy (i.e., heating)** can we get out of one?

(2) *Overview of magnetic reconnection*

- One more (pretty important) question to ask about reconnection regions:

  How much actual **energy (i.e., heating)** can we get out of one?

- The diffusion region is often called a **current sheet…** for good reason...



B points mostly along *x*, but varies along *y*. That counts as a nonzero curl!

$$\mathbf{J} = \frac{c}{4\pi}\nabla \times \mathbf{B} \quad \Longrightarrow \quad J_z \sim \frac{c\,B_x}{4\pi\,\delta}$$

- If magnetic energy is dissipated & turned into heat, then

$$Q_{\rm heat} = \mathbf{J}\cdot\mathbf{E} = J_z E_z = \eta\, J_z^2 = \Rightarrow = \frac{u_{\rm in} B^2}{4\pi\,\delta}$$

- Thus, if the event occurs over time Δt, and in a volume $V = L^2\,\delta$, then the energy is:

$$\mathcal{E} = Q_{\rm heat}\, V\, \Delta t = \frac{B^2}{4\pi} L^2\, V_{\rm A} \mathcal{M}_{\rm A}\, \Delta t$$

(2) *Overview of magnetic reconnection*

$$\mathcal{E} = Q_{\rm heat} V \Delta t = \frac{B^2}{4\pi} L^2 V_{\rm A} \mathcal{M}_{\rm A} \Delta t$$

- For typical solar corona regions…

$$\mathcal{E} \approx 10^{30} \text{ erg} \left(\frac{B}{1000 \text{ G}}\right)^2 \left(\frac{L}{1 \text{ Mm}}\right)^2 \left(\frac{V_{\rm A}}{1000 \text{ km/s}}\right) \left(\frac{\mathcal{M}_{\rm A}}{0.1}\right) \left(\frac{\Delta t}{100 \text{ s}}\right)$$

Try a small, barely resolvable "campfire:"

$B \sim 100$ G
$L \sim 0.1'' \sim 70$ km
$\Delta t \sim 10$ s

$\longrightarrow$ $\mathcal{E} \approx 4 \times 10^{24}$ erg ("nanoflare")

Try something pretty massive:

$B \sim 5000$ G
$L \sim 30$ Mm
$\Delta t \sim 100$ s

$\longrightarrow$ $\mathcal{E} \approx 10^{34}$ erg (>X10 superflare!)

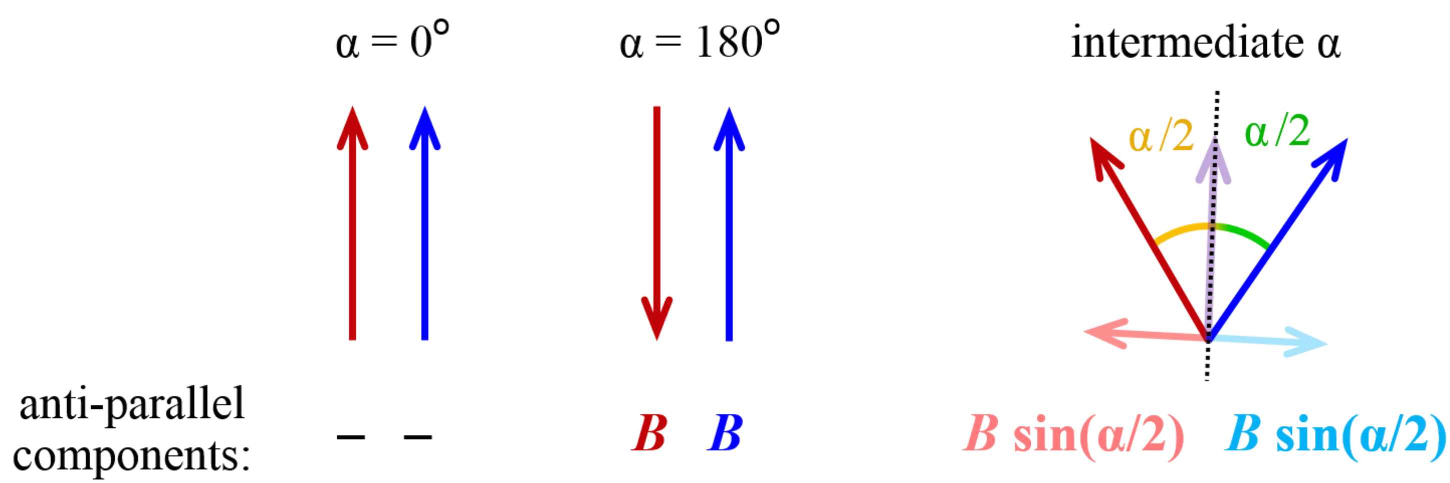
(2) *Overview of magnetic reconnection*

$$\mathcal{E} = Q_{\rm heat}\, V\, \Delta t = \frac{B^2}{4\pi} L^2\, V_{\rm A} \mathcal{M}_{\rm A}\, \Delta t$$

- Two final wrinkles:
- If the fields on either side are **asymmetric,** simulations show that it's fine to

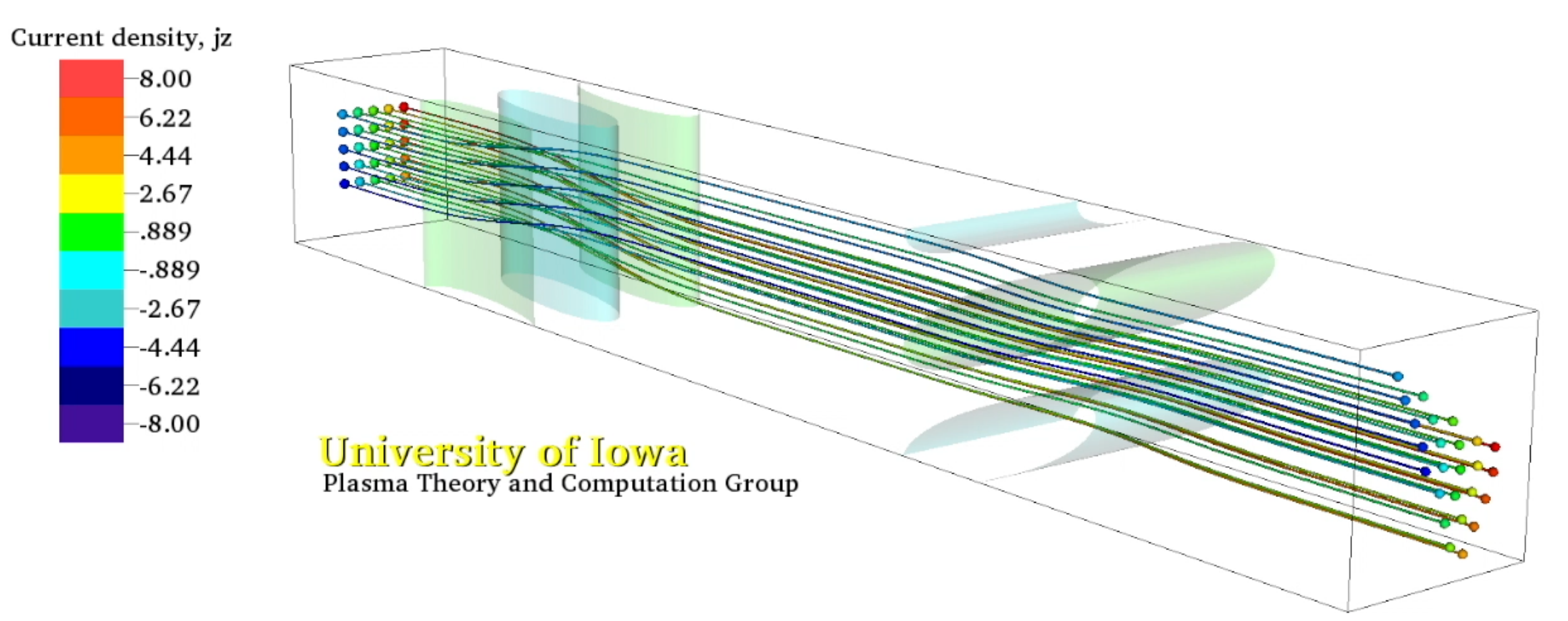
  replace B^2 by $B_1 B_2$

- If the fields on either side aren't exactly anti-parallel (i.e., if there's a common **"guide field"** between them), one can just use the anti-parallel components:



(3) *MHD turbulence and reconnection*

- Unlike hydrodynamic turbulence, when the background **B**-field is strong, the turbulent "eddies" take the form of counter-propagating Alfvén wave packets.
- When packets collide, nonlinear terms in MHD equations generate higher harmonics.
- Kraichnan (1965) found cascade occurs only when there is "power" in both directions…



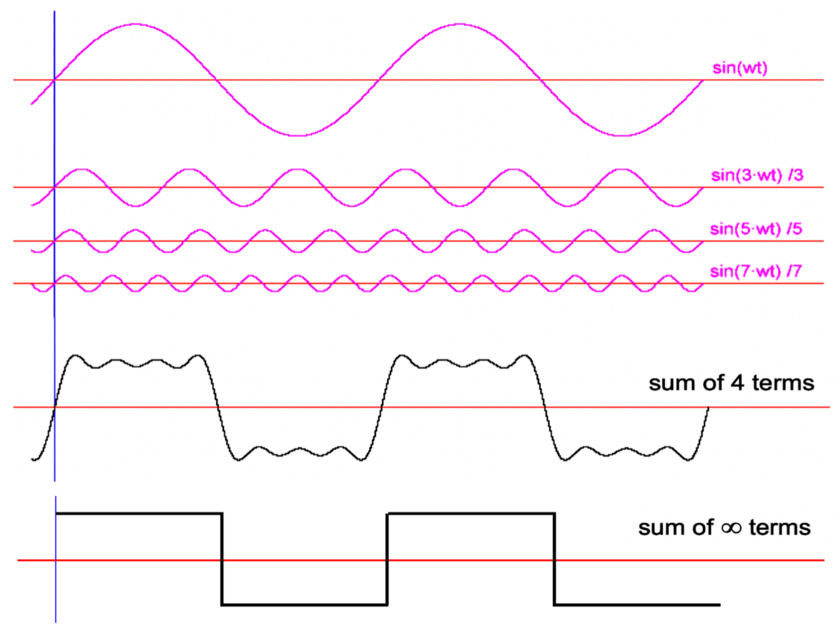
(3) *MHD turbulence and reconnection*

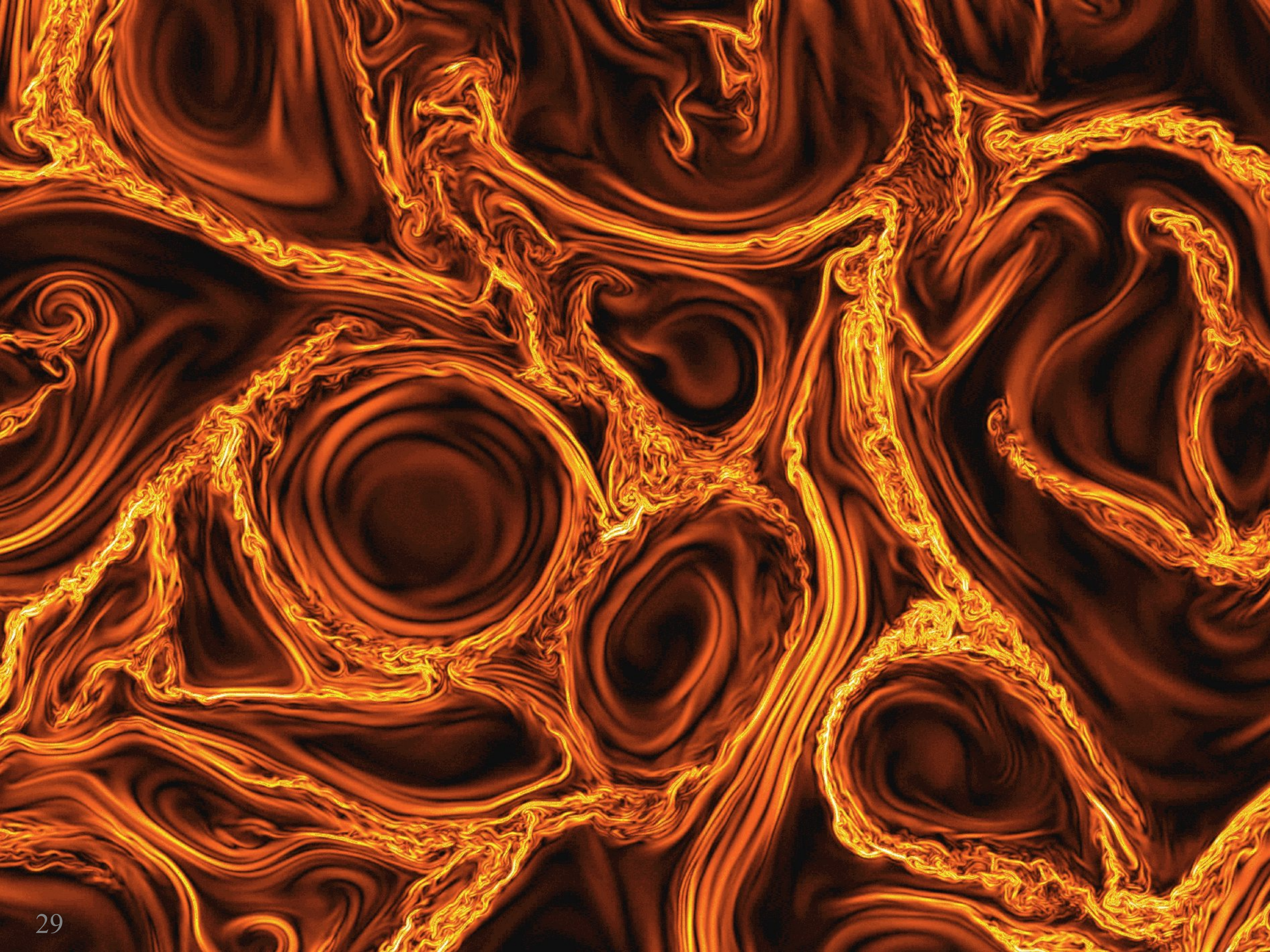
- Because magnetic fields have **tension,** most of the cascade happens perpendicular to the background field. (It's easier to shuffle dried spaghetti than it is to bend it…)

"strong field"

"weak field"

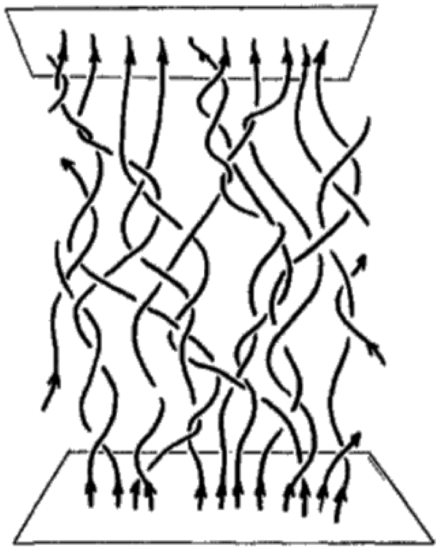
- Wave-packet collisions create higher harmonics (perpendicular to **B**).
- Howes (2016) showed that there's a similar behavior as with the addition of harmonics to make a square wave…
- Thin **current sheets** (at which guide-field reconnection occurs) occur naturally at small (kinetic) dissipation scales.

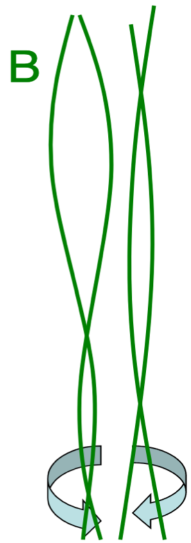




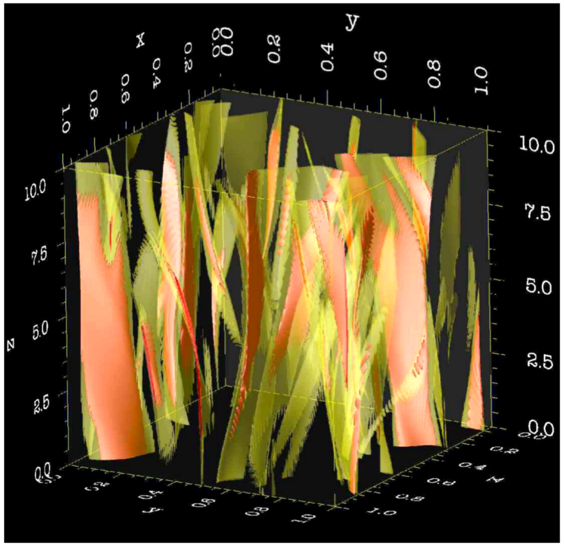
(3) *MHD turbulence and reconnection*

- A snapshot of a current-sheet-filled "box of turbulence" looks pretty much like what Parker (1972, 1983, 1988) had in mind for the tangled/braided DC heating scenario…





van Ballegooijen et al. (2011)



Rappazzo et al. (2007)

- Many models boil down to a cascade rate that's a modification of Kolmogorov's rate:

$$Q_{\text{heat}} \approx \frac{\rho u^3}{\lambda_{\text{ph}}} \left(\frac{\tau_{\text{ph}}}{\tau_{\text{A}}} \right)^q \qquad q = \begin{cases} 0 \ \ \text{(Kolmogorov 1941)} \\ 1\text{–}2 \ \ \text{(Galsgaard \& Nordlund 1996)} \\ 1.5 \ \ \text{(Dmitruk \& Gomez 1999)} \\ 1.5\text{–}2 \ \ \text{(Rappazzo et al. 2008)} \\ 2 \ \ \text{(van Ballegooijen 1986; Parker 1988)} \end{cases}$$

$$m = 2 - q$$
$$n = 1$$

Conclusions

- The **coronal heating problem** is far from being solved, but I hope that we've conveyed some of the relevant physics problems that are involved.

- New observations (higher spatial/time/spectral resolution) are needed!

For next week

- Read paper 3: "Stellar Wind Mechanisms and Instabilities," a review paper by Stan Owocki (2004). PDF is here.

- You only need to read **sections 1, 2, and 3** (numbered pages 163–181; i.e., just the first 19 pages of the PDF)

- Participate in the #paper-3-discussion channel on Slack for next week (February 17, 2022)