Reconnection Onset and Realizability of Reconnecting Systems

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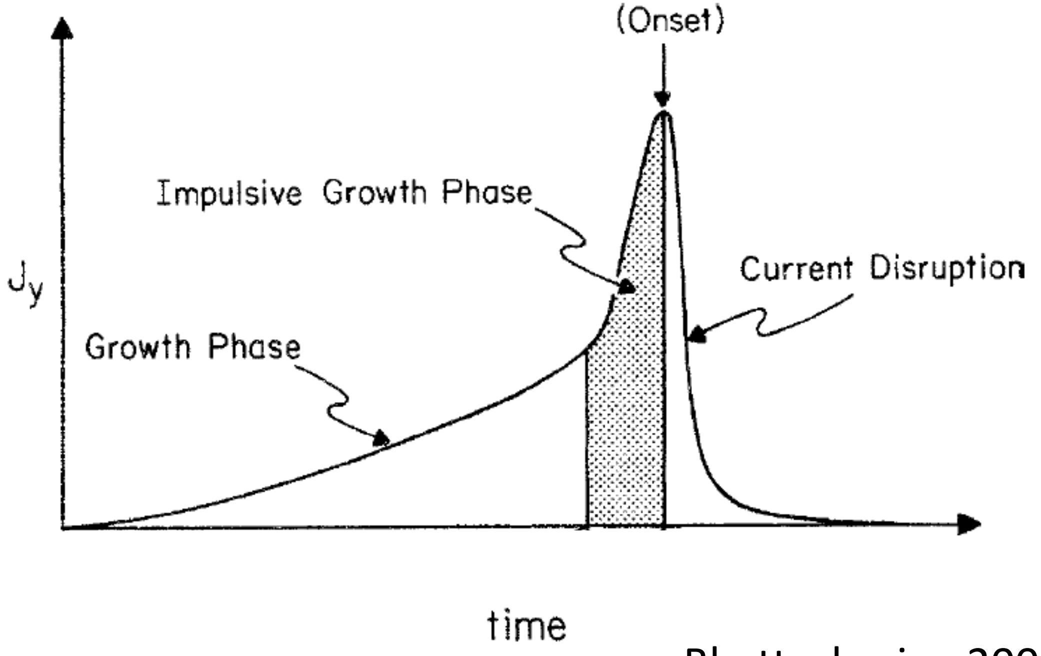
Reconnection Onset

- Magnetic reconnection is a **two-timescale** problem:
  - First, slow energy accumulation (current sheet formation)
  - Then, fast energy release (the reconnection stage proper)



Bhattacharjee 2004

- Transition between these two stages is called the **trigger**, or **onset**, problem: *when does this transition occur, and what causes it?*

- Onset question is arguably much less understood than other aspects of reconnection.

Many studies deliberately bypass the onset stage

- Most simulations and analytical studies begin from an *assumed initial configuration*: a *pre-formed current sheet* which starts reconnecting (fast) right away. *This explicitly precludes the investigation of the onset.*
  - E.g., Sweet-Parker model, or the Petschek model; or electron-scale large aspect-ratio current sheets

- *This assumes that such configurations are realizable*.
  - Realizability could in principle be unrelated to the onset question, but I will argue *that it is not.*

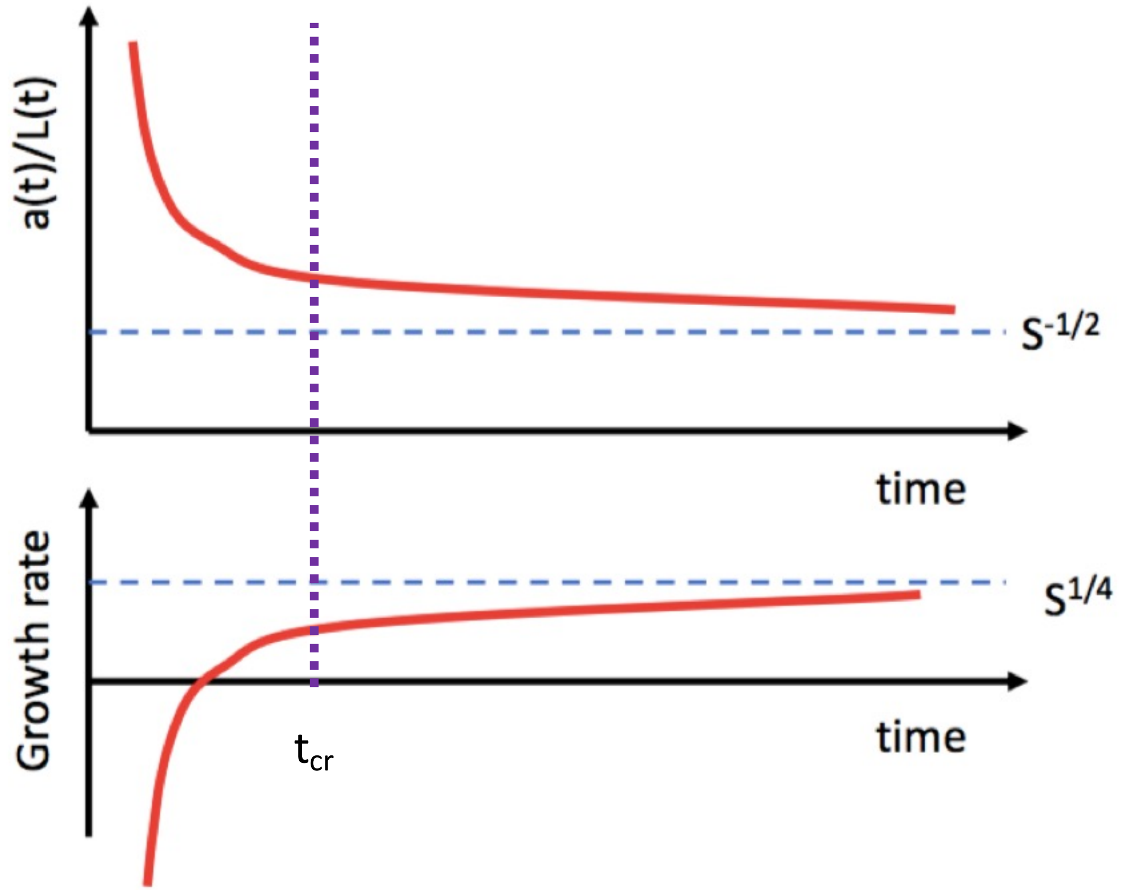
Large aspect-ratio stable current sheets?

Samtaney *et al.*, PRL '09

- Large aspect-ratio SP current sheets are **super-critical** states, i.e., they are violently unstable to the formation of many islands (plasmoids)
(see Loureiro & Uzdensky PPCF 2016 for a review)

Current sheet formation and reconnection onset

- **Implication** is that such CSs *cannot form in the first-place:* a forming CS will **disrupt** before reaching those super-critical aspect ratios.



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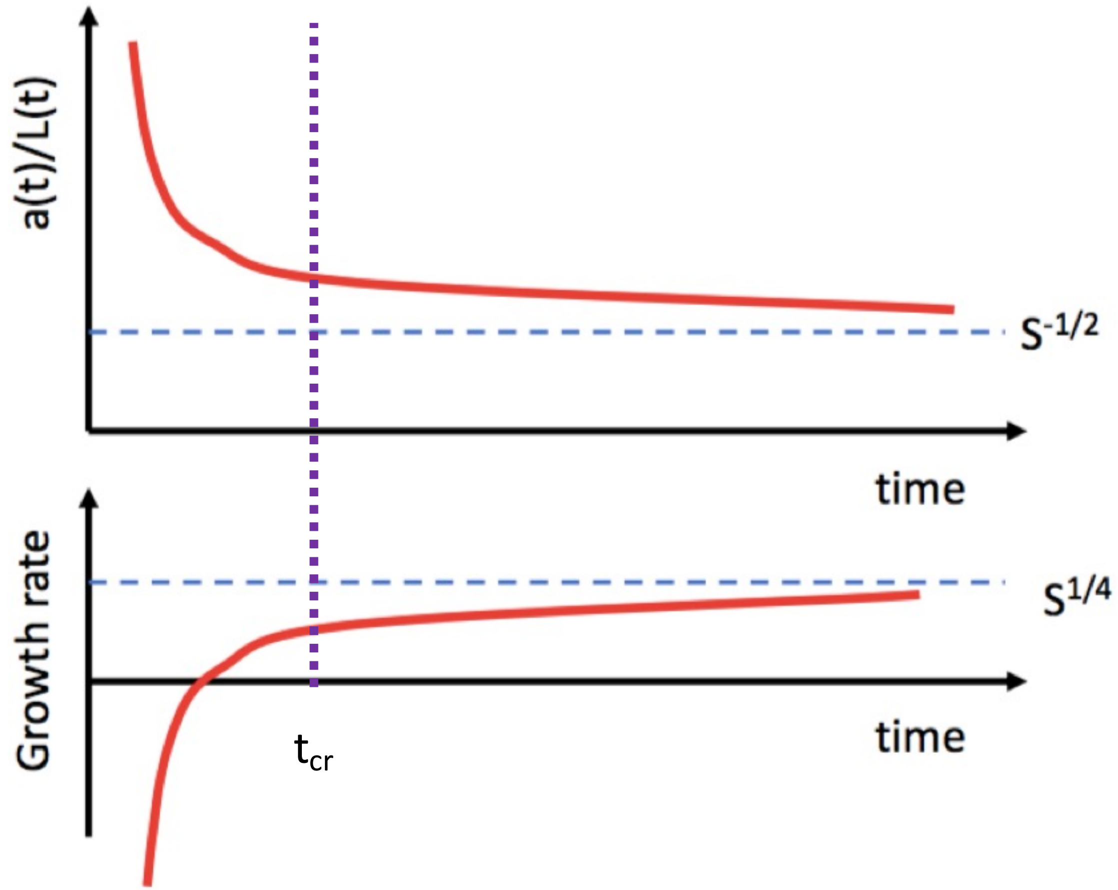

Critical moment of time is when

$$\gamma[a(t), L(t)]\tau_{CS} \sim 1$$

Reconnection onset occurs when this condition is met.

– *What is the maximum CS aspect ratio?*

– *How long until disruption of the CS?*

– *How many islands are generated?*

Pucci & Velli ‘13, Uzdensky & Loureiro ‘16; Comisso *et al.* ‘16, Tolman *et al.* ’18, etc.

Current sheet formation

- **CS formation**: often, ideal-MHD process characterized by:
  - decreasing $a(t)$ – thinning
  - increasing $L(t)$ – stretching/lengthening
  - increasing $B_0(t)$ – strengthening

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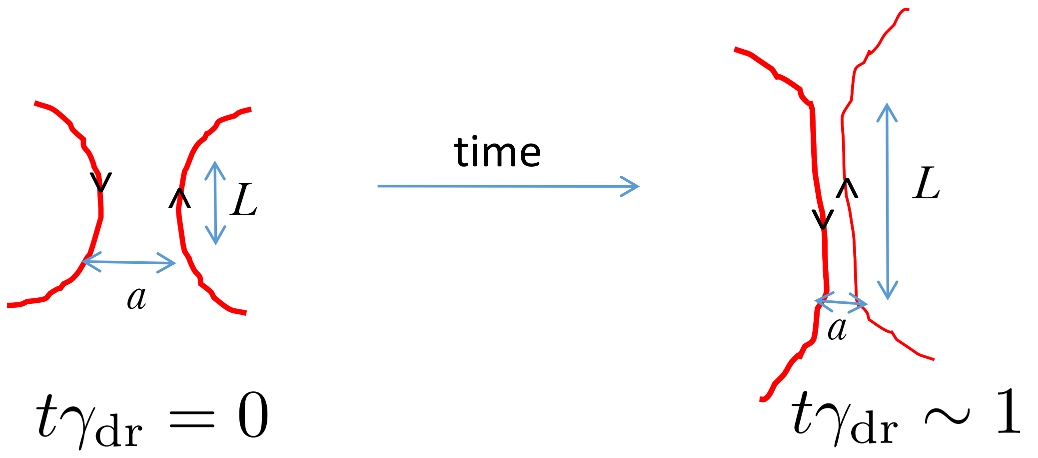
- **CS formation**: often, ideal-MHD process characterized by:
  - decreasing *a(t)* – thinning
  - increasing *L(t)* – stretching/lengthening
  - increasing $B_0(t)$ – strengthening
- The particular CS formation mechanism is not relevant here. For our purposes just need the CS formation driving rate:

$$\gamma_{\rm dr} \equiv \max\left[\dot{a}/a, \dot{L}/L, \dot{B}_0/B_0\right]$$



Aspect ratio $L(t)/a(t)$ increases in time.

Tearing instability of a forming current sheet

- A current sheet is tearing unstable if the instability parameter $\Delta' > 0$.
- For a Harris-type equilibrium, $B_y = B_0 \tanh(x/a)$

$$\Delta' a = 2(1/ka - ka) \approx 2/ka$$

- In a time-evolving sheet, $a = a(t), L = L(t)$, so

$$\Delta'(t)a(t) \approx 2/k(t)a(t) \sim L(t)/(N\, a(t))$$

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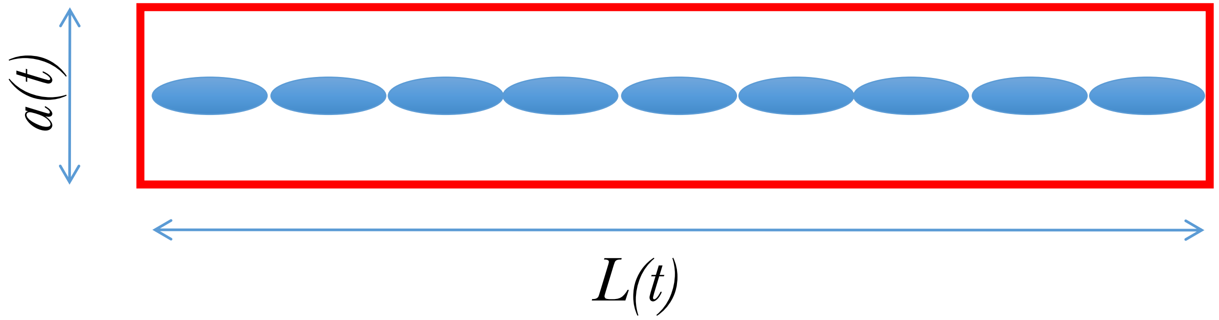
- As soon as $\Delta'(t) > 0$, the **tearing** instability starts to grow:
  - at first, slow, does not affect CS formation process;
  - then, as aspect ratio increases further, $\gamma_{\rm tear}(t)$ increases until

$$\gamma_{\rm tear}(t_{cr}) \sim \gamma_{\rm dr}$$

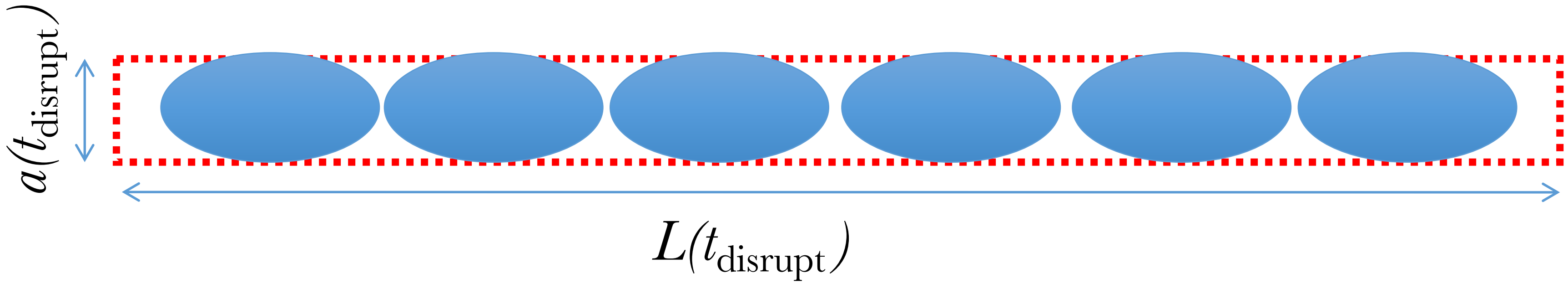
***t_{cr}** is the **critical time** when the tearing growth rate overcomes the CS formation rate. For the rest of the linear regime can think of CS as frozen*

Current sheet disruption

- At early stages (i.e., linear and early nonlinear) the tearing instability does not affect the CS formation process.



- Current sheet is **disrupted by tearing** when ***w(t)=a(t)***



- Understanding this process requires analyzing both the **linear** and **nonlinear** evolution of the islands.

Reconnection onset in resistive MHD

- Once the plasmoid chain develops, its nonlinear evolution quickly leads to plasmoid-mediated reconnection, with a fast (Lundquist-number-independent) reconnection rate.
- **This transition from the slow current sheet build-up to a fast reconnecting stage is the *onset*.**
- Carrying out this analysis in MHD leads to several interesting conclusions:
  - The number of plasmoids (i.e., one or many) depends on the current sheet formation rate: slow drive leads to one plasmoid, fast drive to many
  - Even for Alfvénic drive, the largest aspect ratio before disruption scales as $S_L^{1/3}$ (Pucci & Velli, 2013; Tenerani *et al.* 2016). This is much smaller than the Sweet-Parker aspect ratio ($S_L^{1/2}$).
  - The time to onset is a weak function of Lundquist number
- See Uzdensky & Loureiro, PRL 2016

Application: Reconnection onset in turbulence

- In turbulence, one may ask the exact same question about reconnection onset – except now as a function of *scale*, rather than as a function of *time.*
- That is, one can solve

$$\gamma_t(\lambda)\tau_{nl}(\lambda) \sim 1$$

and determine the scale λ_{cr} at which tearing becomes faster than the eddy-turn-over rate.

- In MHD, this gives $\lambda_{cr}/L \sim S_L^{-4/7}$. Below this scale, spectrum is $k^{-11/5}$. These results can be extended to kinetic regimes.
- See recent papers by Boldyrev & Loureiro; and by Mallet, Schekochihin and Chandran. See C. Dong *et al.* for numerical validation.

Part II:
Onset in collisionless plasmas

General considerations

- Same general logic. But:
  - Many more instabilities to consider now. Tearing (as in the MHD case), but also streaming instabilities (associated with large currents) and pressure-anisotropy-driven instabilities.
  - So, what happens on any particular case depends strongly on plasma parameters (guide-field, beta, etc.)
  - These other instabilities (i.e., other than tearing) may not themselves disrupt the forming sheet; but they may significantly change the reconnection configuration and parameters; e.g., anomalous resistivity.

Onset in a collisionless plasma: tearing

- Consider strongly magnetized plasma (i.e., strong guide-field reconnection). Assume $L \gg \rho_s$.
- Collisionless tearing onset: $\gamma_{tear}\tau_{dr} \sim 1 \rightarrow L/a \sim M_{dr}a^2/(d_e\rho_s)$

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- Is this sheet still on MHD scales, i.e., $a > \rho_s$? Yes, if [Del Sarto 2016, Mallet 2020]

$$\frac{L}{\rho_s} \gg \left(\frac{m_i}{m_e}\beta_e\right)^{1/2} M_{\rm dr}.$$

Easy to satisfy

- So, in this case, a forming current sheet will disrupt due to collisionless tearing *while its thickness is still at MHD scales*.
- *This means that there's no such thing as a system-size stable current sheet with ~ion scale thickness.*

Onset in a collisionless plasma: ion acoustic instability

- Streaming instabilities may also arise as the current builds up.
- Take ion acoustic instability (IAI) as example. Threshold is $v_d \approx c_s$.
- Since $a = \frac{c}{4\pi}\frac{j}{B_{up}}$, this threshold occurs at CS thickness $\frac{a}{d_i} \approx \beta_{e,up}^{-1/2}$
- So, again, we reach the conclusion that sub-ion scale current sheets would not be stable
- [caveat: assuming $\frac{T_i}{T_e} \ll 1$ here (not uncommon); for higher temperature ratios different thresholds apply, leading to thinner current sheets]

Tearing *vs.* ion acoustic instability

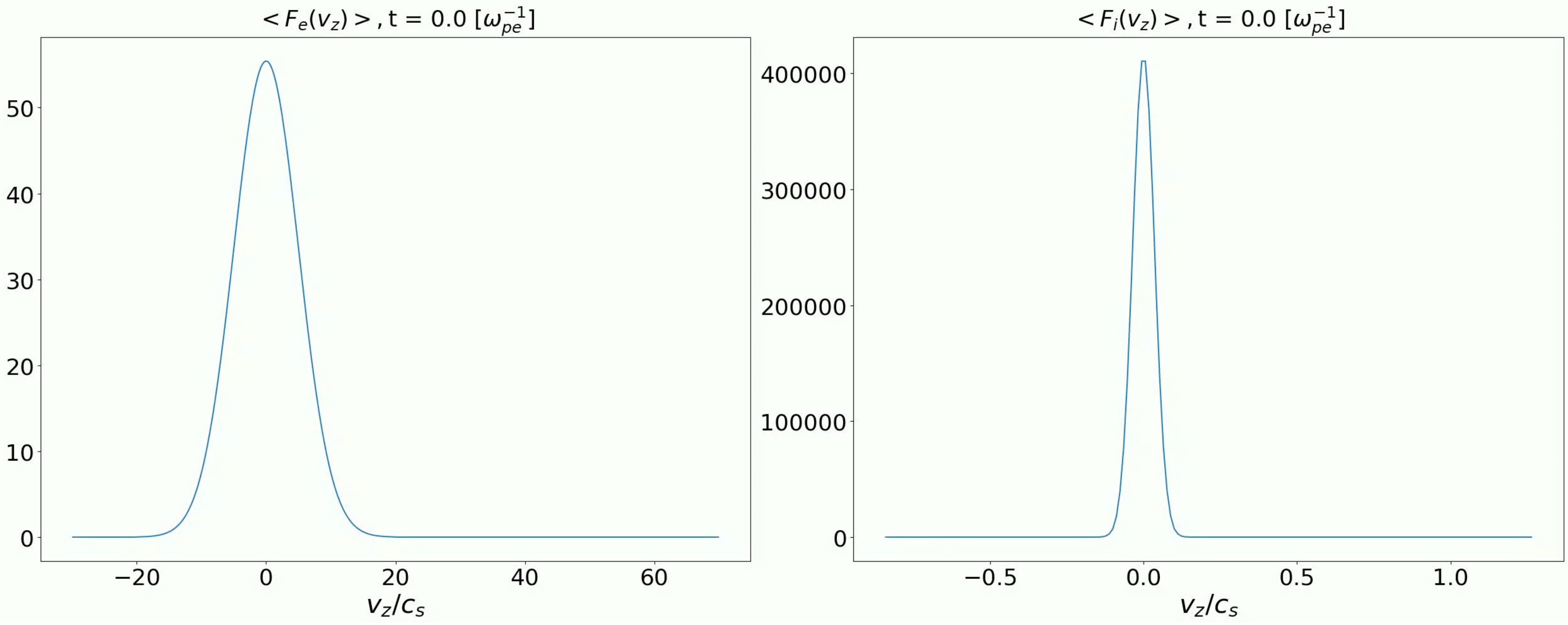
- Which one happens first, tearing or IAI?
- Tearing occurs first if $a_{tear} > a_{IAI}$ requires

$$\frac{L_{tear}}{d_i} > M_{dr}\, \beta_{e,up}^{-3/2} \left(\frac{m_i}{m_e}\right)^{1/2} \beta_e^{-1/2}$$

- I.e., something in the range 10– 10^3. Easy to satisfy in astrophysical environments, and maybe even in the lab.
- This is interesting and complicated: suggests that a forming current sheet would first disrupt to tearing. When plasmoids become nonlinear, current sheets between plasmoids would want to collapse down to d_e scale, and a streaming instability (IAI, Buneman) might be triggered then.

Ion acoustic instability

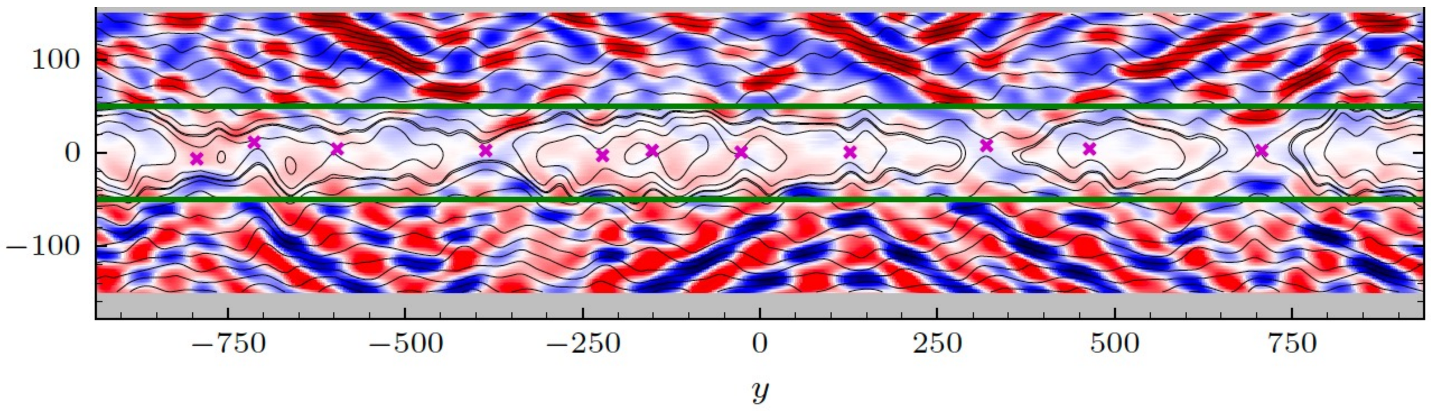
- What may happen when the IAI gets triggered?

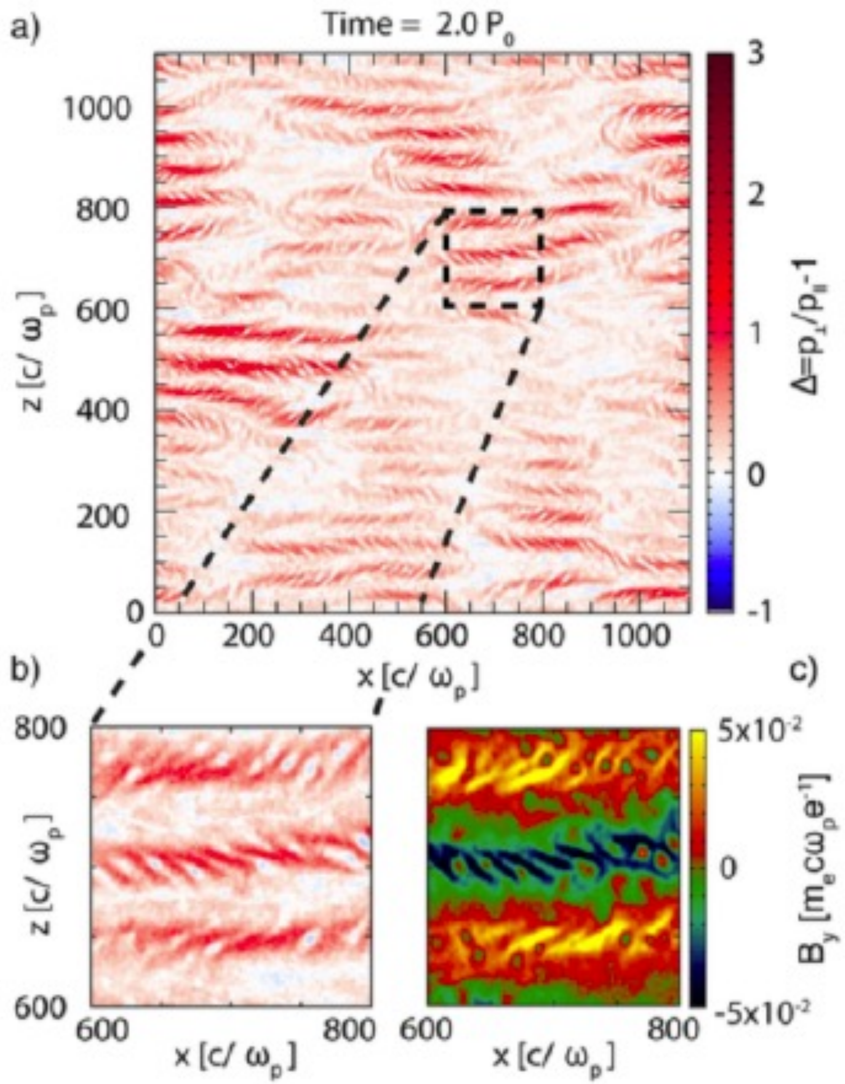


Zhuo Liu, MIT

Example: Reconnection onset with mirror+tearing

- Alt & Kunz and Winarto & Kunz have looked at the triggering of the mirror instability as a current sheet forms in high beta plasmas.





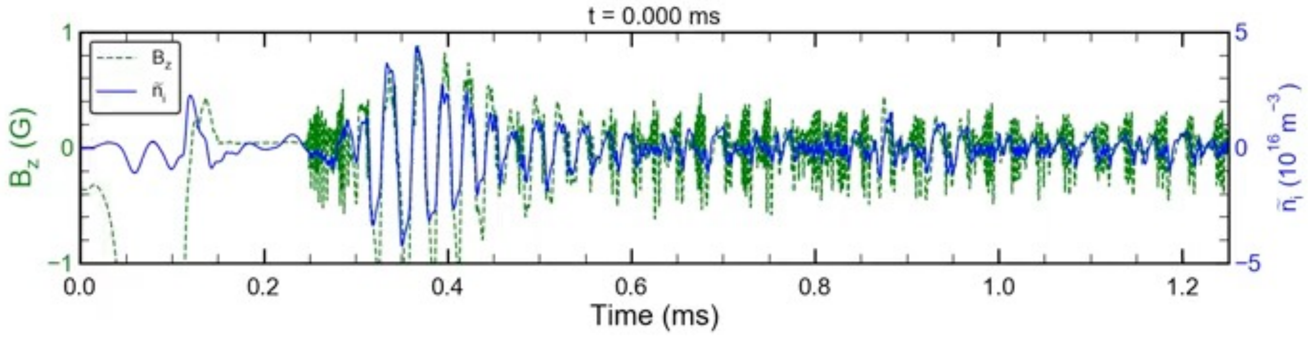
Inchingolo *et al.*, ApJ 2018

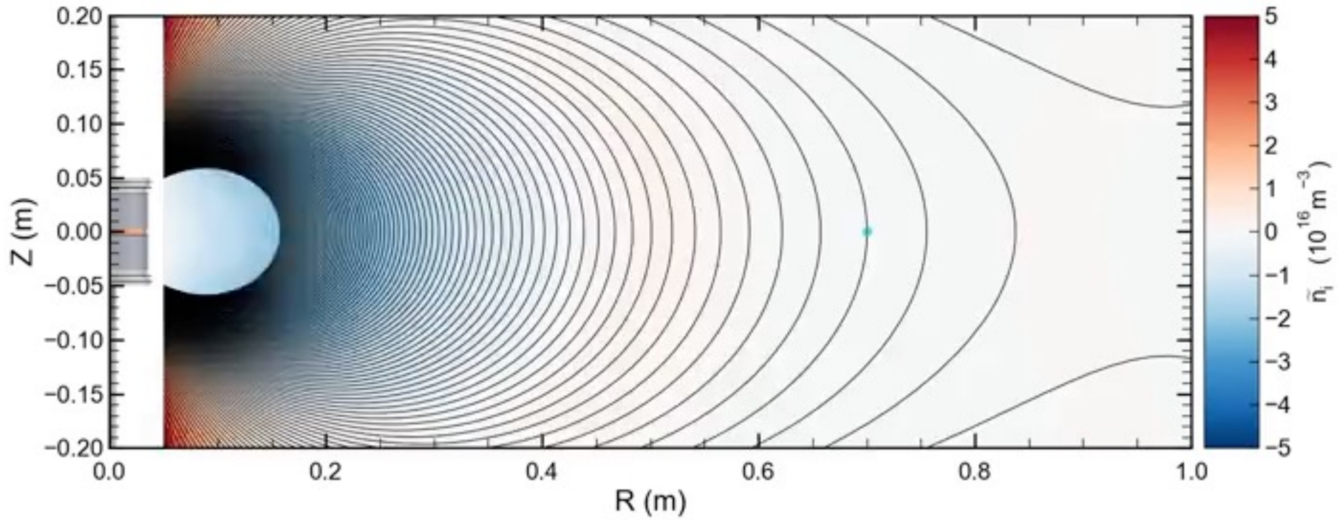
Onset in a laboratory Parker spiral current sheet

- Similar calculation to described earlier, except in the resistive Hall MHD regime.
- Obtain condition for transition from one to many plasmoids:

$$\gamma_{\rm dr} > 4.1\frac{a_0}{L_0}\frac{d_i v_A}{a_0^2}S_H^{-3/14}$$

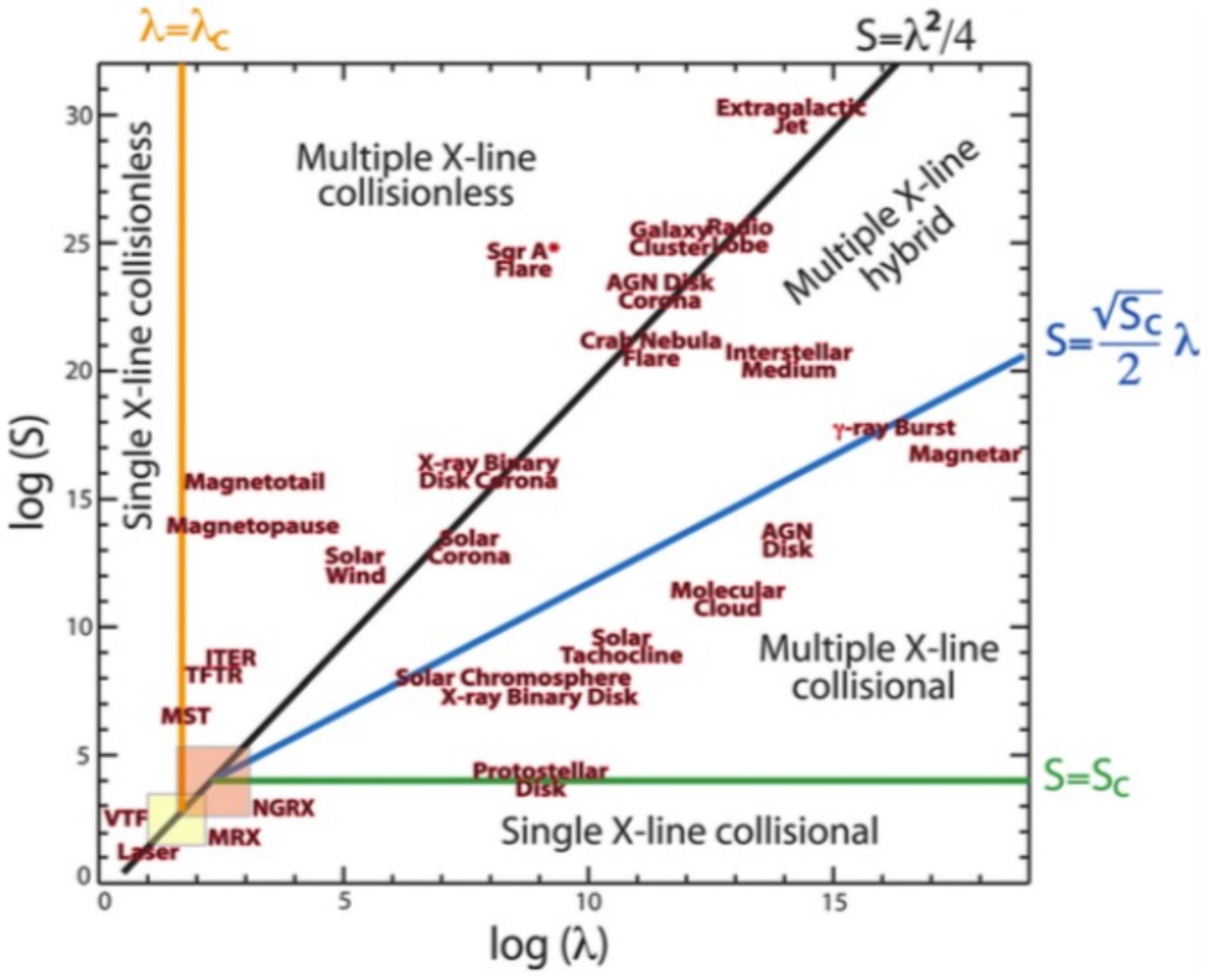
- This gives very good agreement with experiment on the Big Red Ball.





E. E. Peterson *et al.*, JPP 2021

Physically realizable reconnection diagrams



Ji & Daughton, 2011

This diagram hinges on the realizability of a system-size Sweet-Parker sheet, which is impossible (for large systems).

Needs revisiting based on the dynamic onset of reconnection.

Conclusions

- Current sheet instability implies that very large aspect ratio, super-critical, current sheets cannot form in the first place.
    - Current sheet instability must therefore be analyzed in the context of current sheet formation.
    - **Reconnection onset** may be the moment of time when plasmoids disrupt the forming current sheet.
- Same ideas apply to reconnection onset in collisionless plasmas, but range of instabilities to consider is much broader, and requires 3D.
- Realizability implies that one can't bypass the formation process: without it, it's unknown what the parameters and configuration during the actual reconnection stage are.