The Effect of Thermal Pressure on Collisionless Magnetic Reconnection Rate

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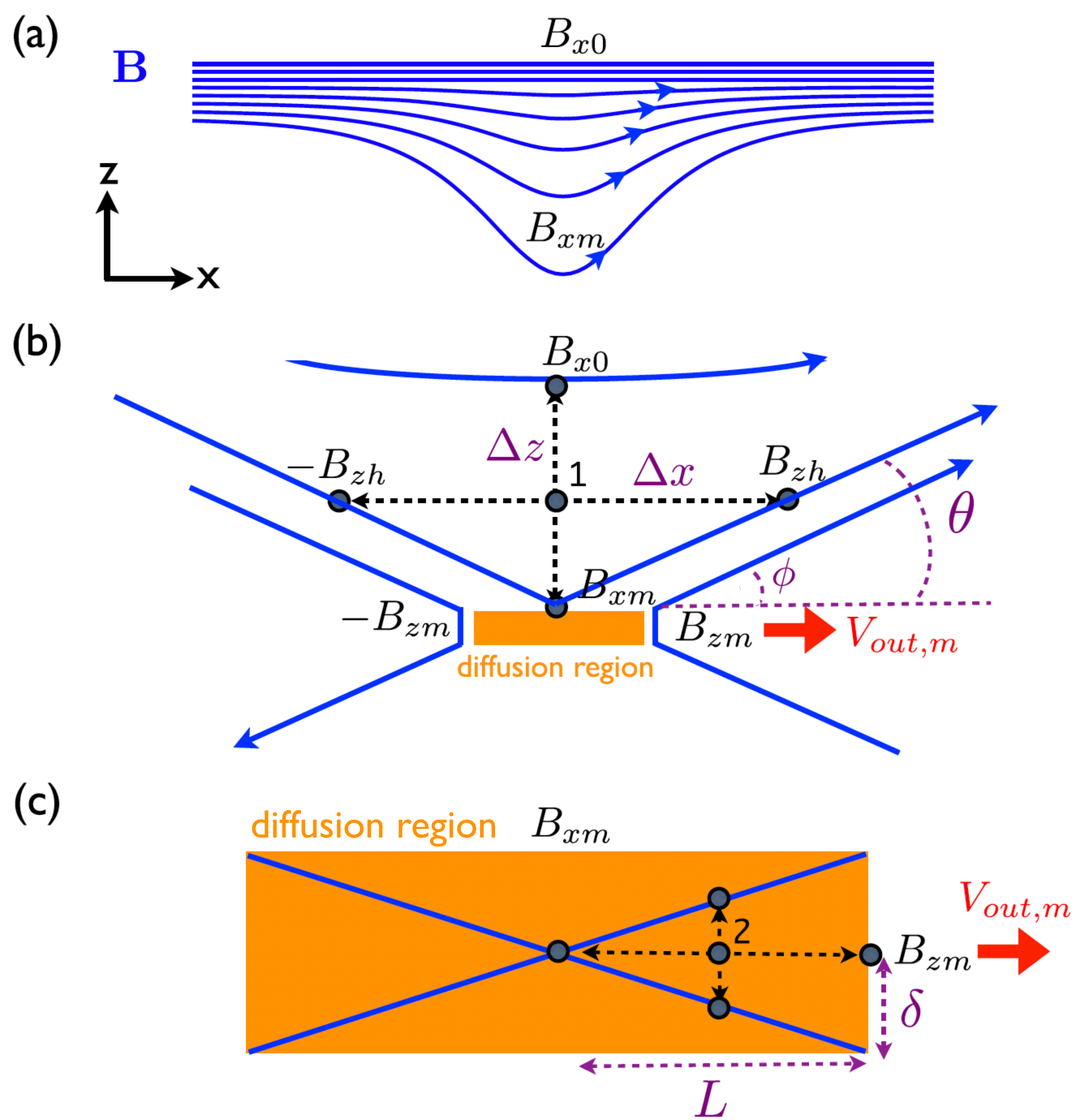
Back-of-the-envelope calculation…

(Liu+ PRL 2017)



step1: Introduce the scale-separation~

→ micro-scale ("m") vs. mesoscale ("0")

step2: analyze the inflow force-balance at point 1

$$\frac{B_{x0}^2 - B_{xm}^2}{8\pi\Delta z} \simeq \left(\frac{B_{x0} + B_{xm}}{2}\right)\frac{2B_{zh}}{4\pi\Delta x}$$

$\rightarrow B_{zm}(S)$ ↖ *Slope* = tanθ

step3: analyze the outflow force-balance at point 2

$\rightarrow V_{out,m}(S)$

step4: connect these two quantities to get the rate~

$$\rightarrow E_y(S) = B_{zm}V_{out,m}/c$$

In the high-β limit,
we need to include the thermal pressure effect…

$$nm_i \frac{\partial \mathbf{V}}{\partial t} + nm_i \mathbf{V} \cdot \mathbf{V} + \nabla \frac{B^2}{8\pi} \simeq \nabla \cdot \left(\frac{\mathbf{BB}}{4\pi} \right)$$

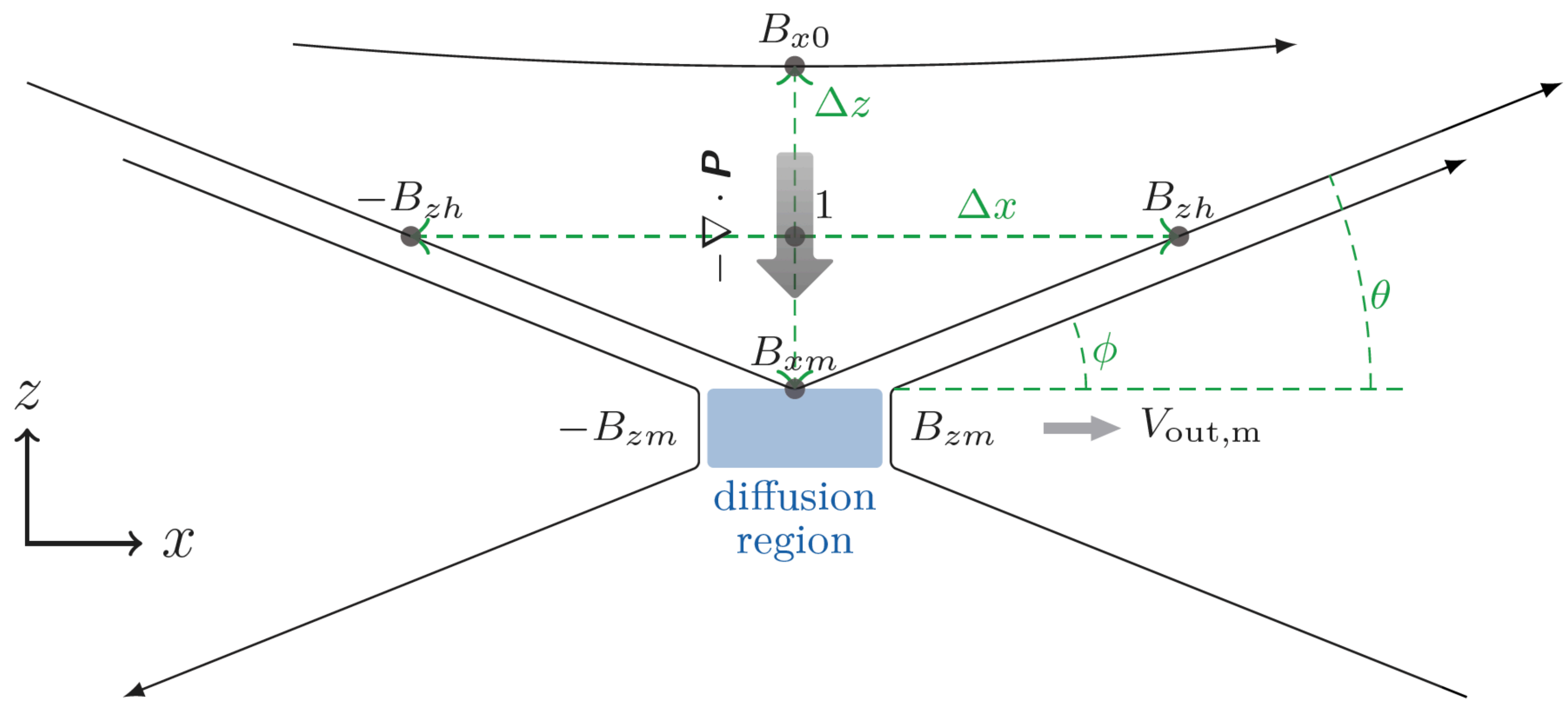
$$\rightarrow nm_i \frac{\partial \mathbf{V}}{\partial t} + nm_i \mathbf{V} \cdot \mathbf{V} + \nabla \frac{B^2}{8\pi} + \nabla P_\perp \simeq \nabla \cdot \left(\varepsilon \frac{\mathbf{BB}}{4\pi} \right)$$

where

$\varepsilon = 1 - 4\pi(P_\parallel - P_\perp)/B^2$ the firehose parameter,
which can weaken the magnetic tension!

Constraint along the inflow (step1&2)

'0' indicates quantities at the mesoscale



'm' indicates quantities at the micro-scale

From the force-balance along the inflow,

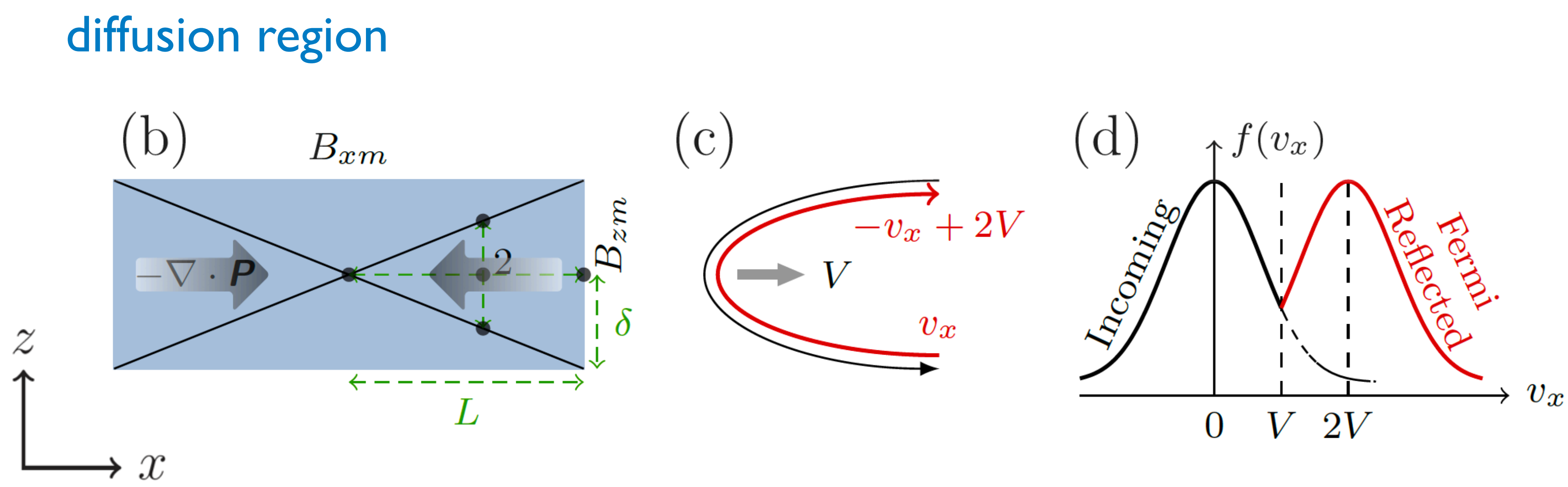
(X. Li & Liu, APJ 2021) arXiv:2104.00173

$$\frac{B_{x0}^2 - B_{xm}^2}{8\pi\Delta z} + \frac{P_0 + P_{i0}(\sqrt{2\beta_{i0}} + B_{xm}/B_{x0})}{\sqrt{2\beta_{i0}} + 1}\frac{B_{x0} - B_{xm}}{B_{x0}\Delta z} = \frac{\varepsilon_1}{4\pi}B_{x1}\frac{2B_{zh}}{\Delta x}$$

- The reduction of B_{xm} is less severe with a higher β.

  —because the pressure gradient helps balance the weaker upstream tension.

Constraint along the outflow (step 3)



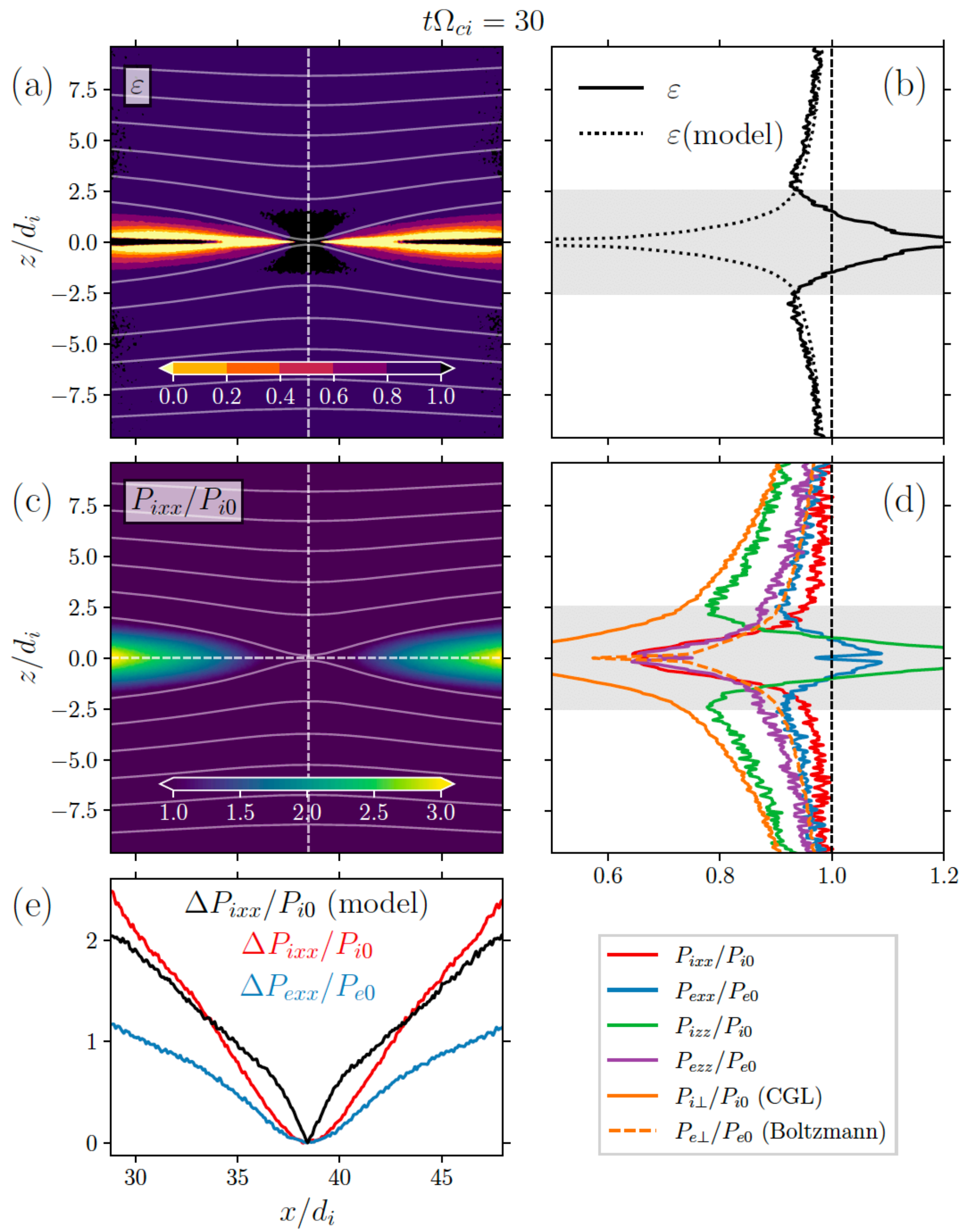
From the momentum equation along the outflow,

$$\frac{n_2 m_i V_{\text{out,m}}^2}{2L} + \frac{B_{zm}^2}{8\pi L} + \frac{\Delta P_{xx,m}}{L} = \frac{1}{4\pi}\frac{B_{zm}}{2}\frac{\varepsilon_m B_{xm}/2}{\delta/2}$$

where $\Delta P_{ixx}(V) = n_0 m_i \left[V^2 + \left(V^2 + \frac{\beta_{i0}}{2}v_{A0}^2\right)\text{erf}\left(\frac{V}{\sqrt{\beta_{i0}}v_{A0}}\right) + V v_{A0}\sqrt{\frac{\beta_{i0}}{\pi}}e^{-V^2/(\beta_{i0}v_{A0}^2)}\right]$

- Outflows can be slowed down by the back-pressure and weaker tension.
- Predicted scaling is consistent with previous 81 PIC simulations and 14 in-situ observations in the solar wind, the magnetosheath, and the magnetotail! (Haggerty+ PoP 2018)

Finding a reasonable closure

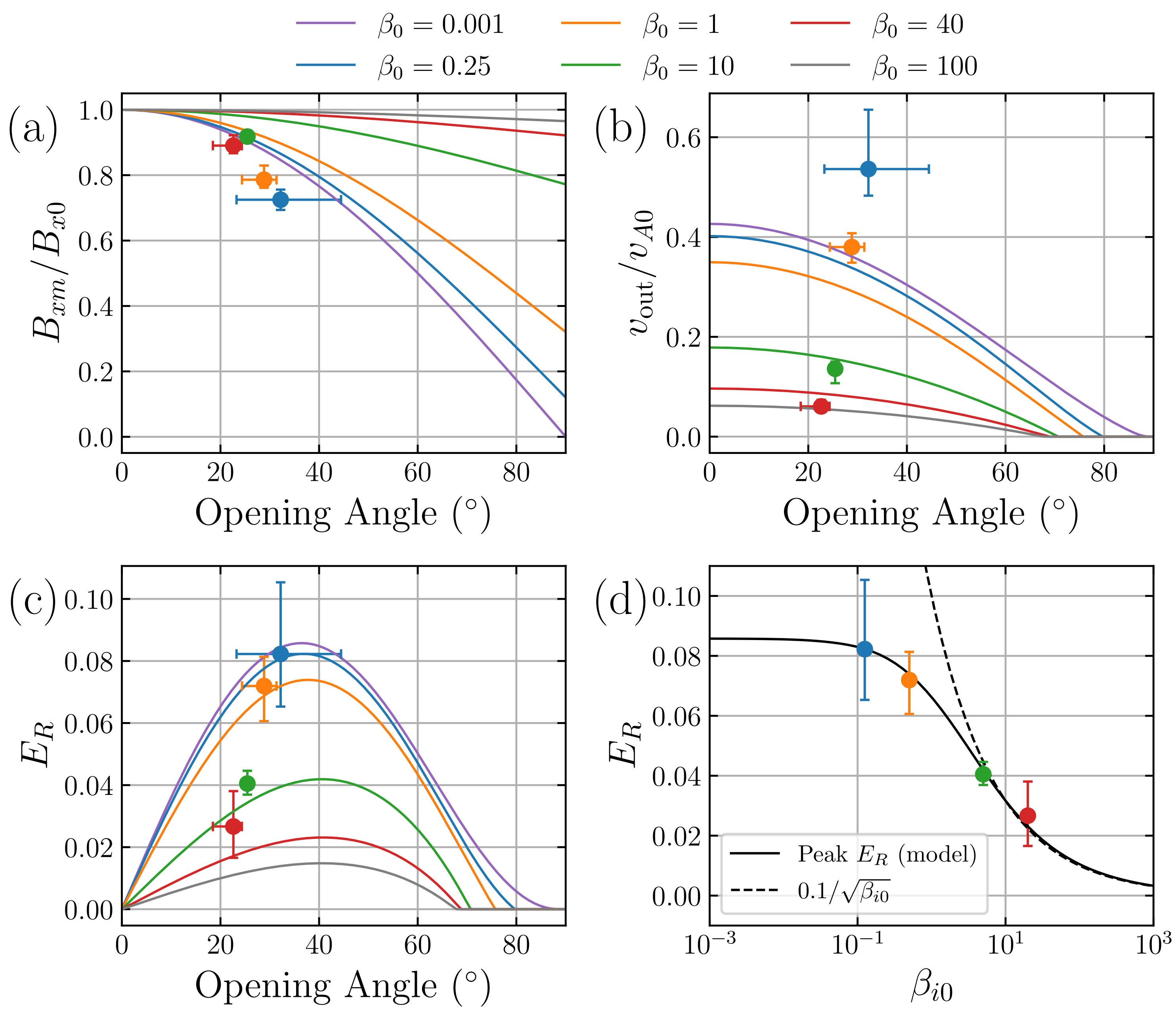


- Fermi-reflection works well to model the back-pressure along the outflow.
- Along the inflow, a combination of CGL, Boltzmann, Le & Egedal closures are considered to model the simulated pressure anisotropy
  — results not very sensitive to the specific choice of closure though~

Predicted reconnection rate in the high-β limit (step 4)

$$E_R = B_{zm} V_{\mathrm{out,m}} / (B_{x0} v_{A0})$$

as a function of the opening angle ($\equiv 2\theta$)



(X. Li & Liu, APJ 2021)
arXiv:2104.00173

- The predicted reconnection rate $R \simeq 0.1/\sqrt{\beta_i}$ in the high-β limit.