Magnetic Field Lines are a Lie (but Magnetic Reconnection is Very Real)

An introduction to the plasma's preferred topological rearrangement by Jimmy Juno

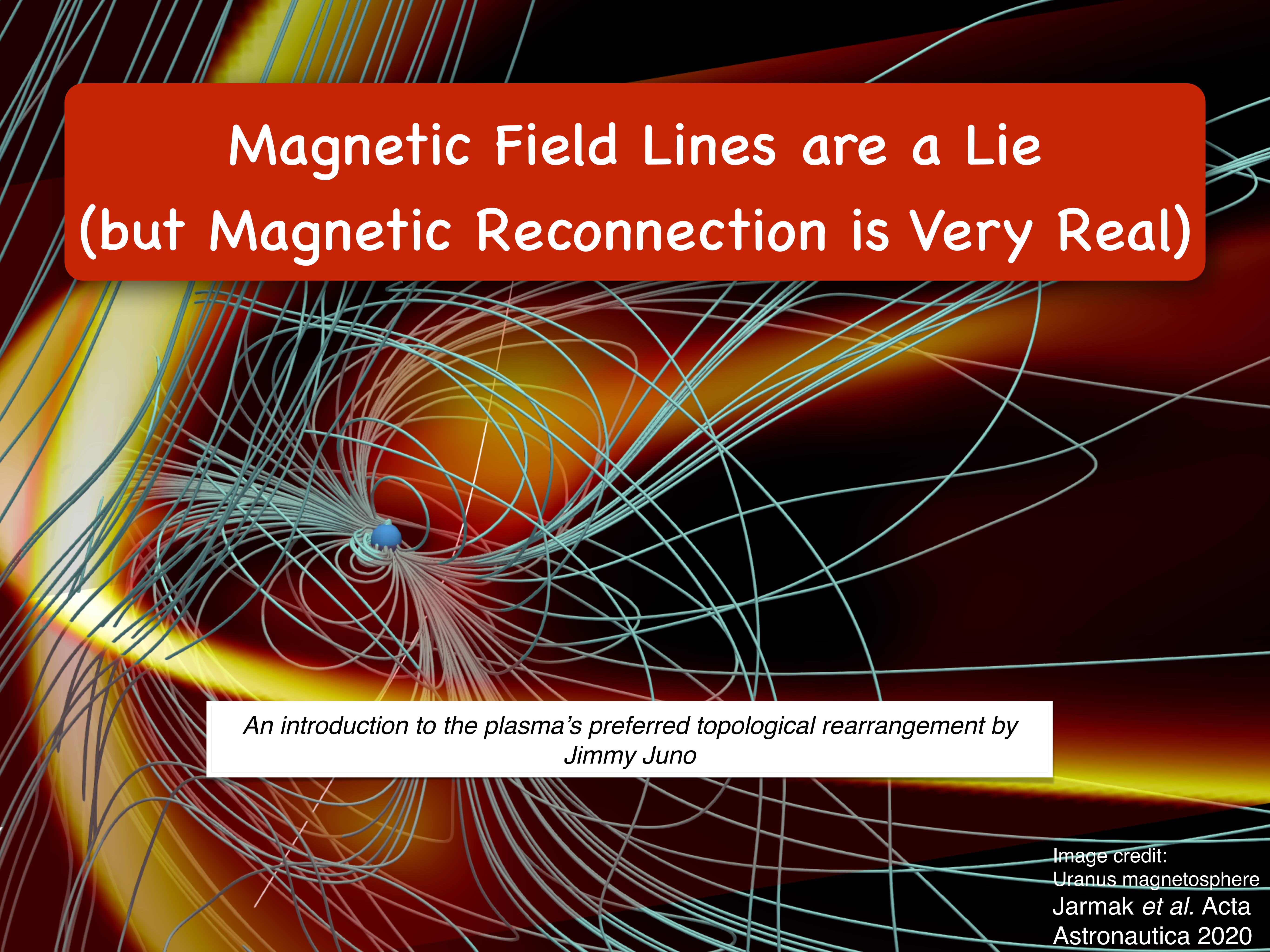


Image credit:
Uranus magnetosphere
Jarmak *et al.* Acta Astronautica 2020

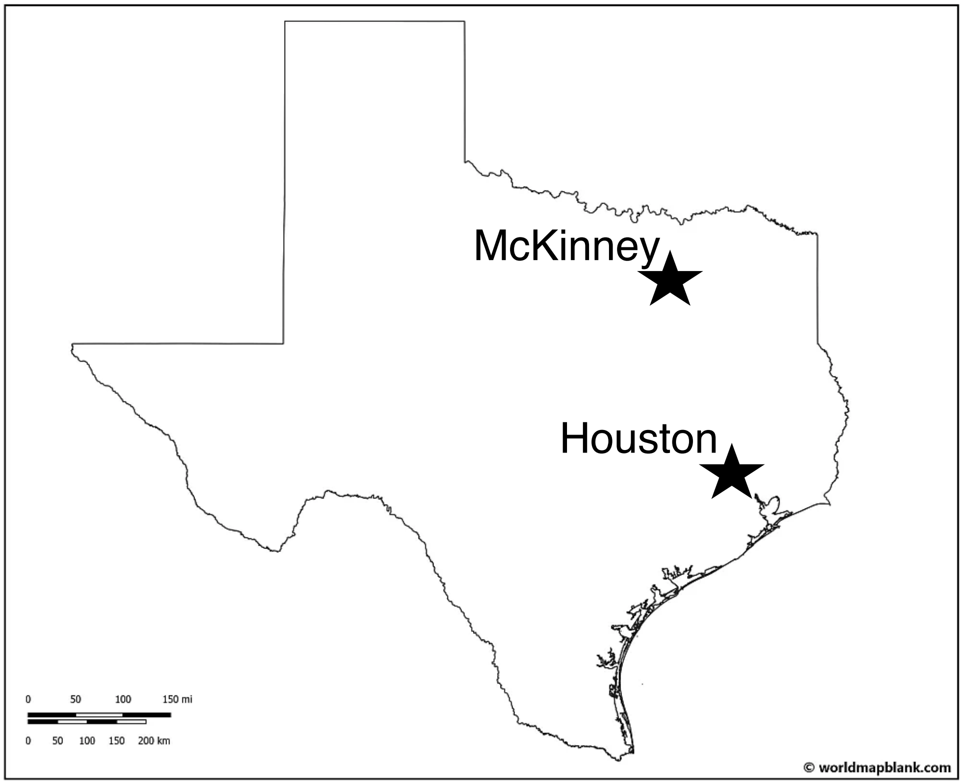
A little bit about me

Staff Scientist

Undergraduate | PhD | Postdoc

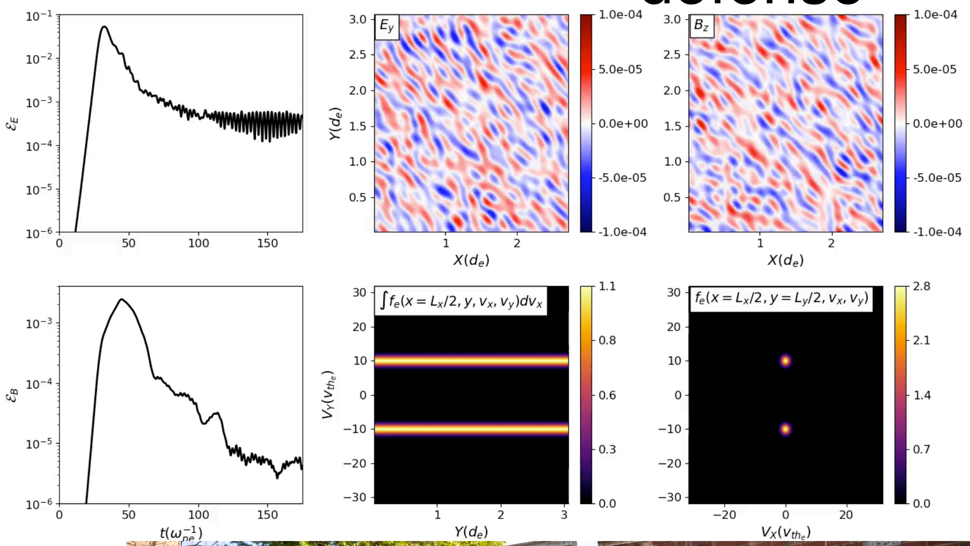
2010 | 2014 | 2020 | 2022-present

RICE UNIVERSITY



UNIVERSITY OF MARYLAND 1856

UMD's first Zoom PhD defense



PPPL

Gkeyll

Life outside work: an ASL book club with the professors of ASL here at Princeton, and refereeing Taekwondo tournaments

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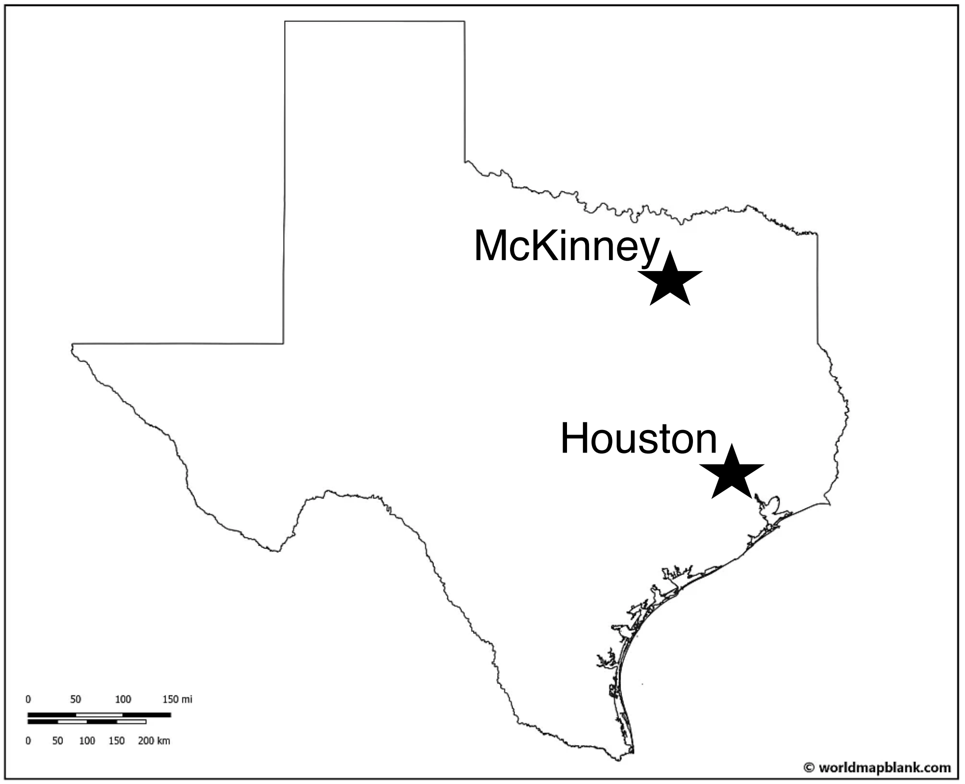

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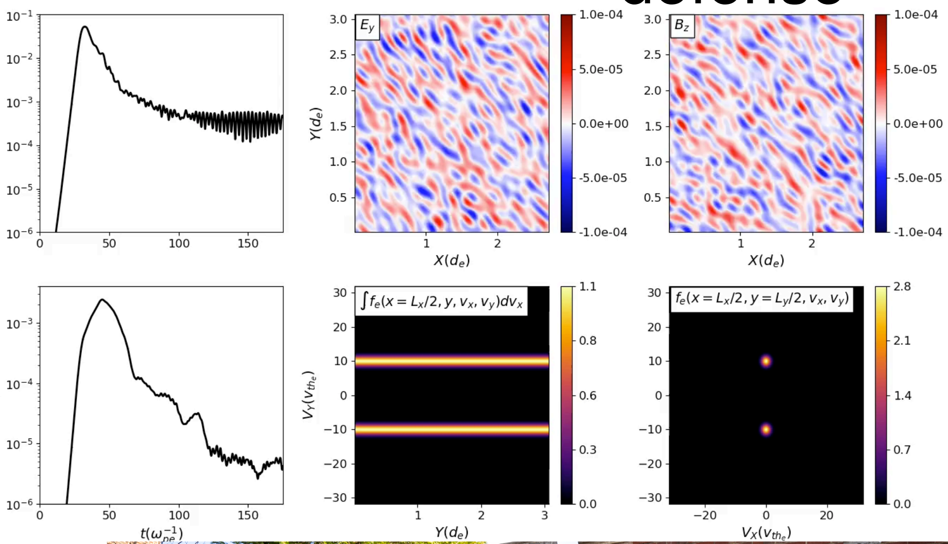

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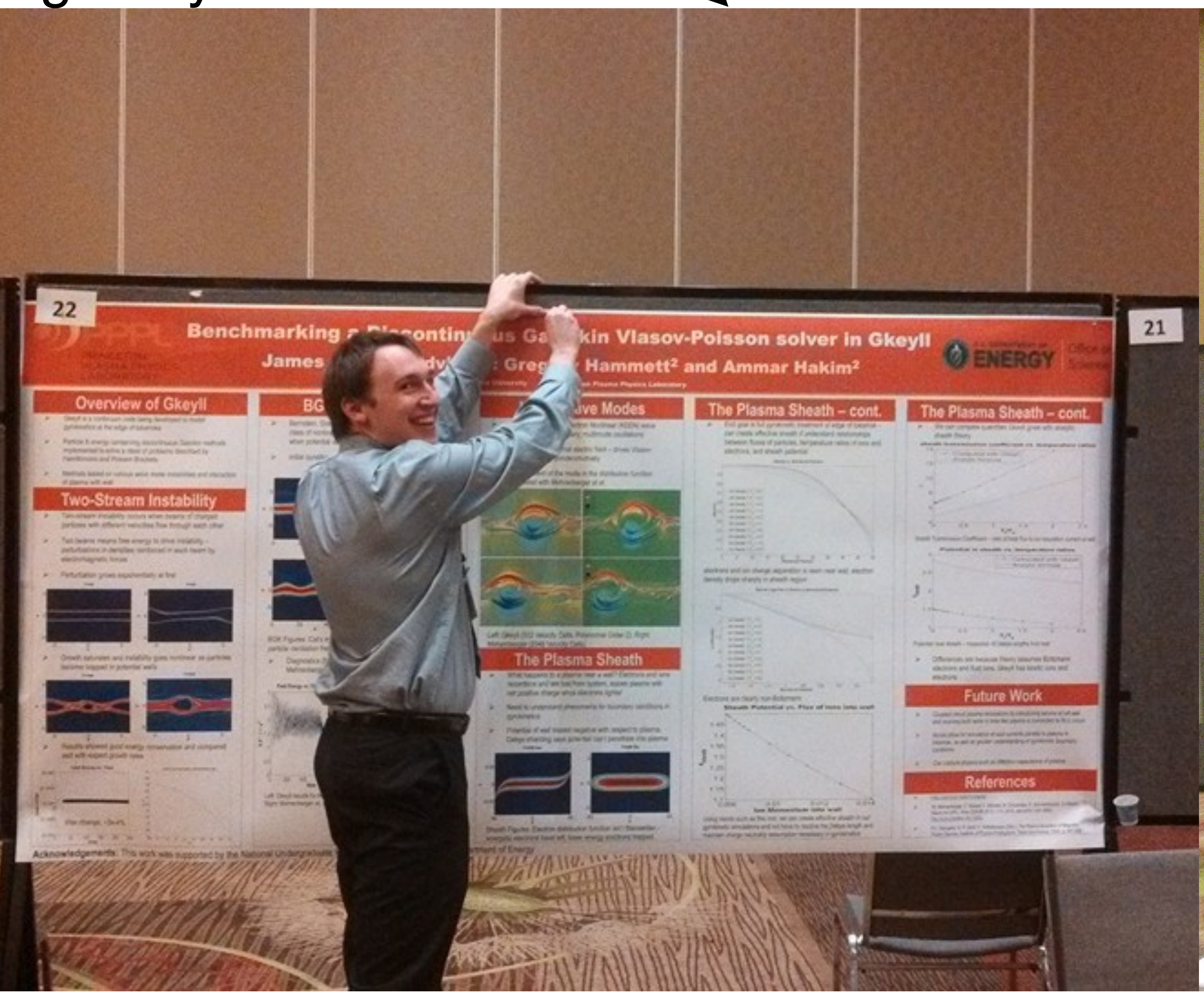
I got my start in SULI too!



No exaggeration to say this program set the course of my career. Once I started working on Gkeyll I never looked back. Pitched my UMD thesis advisor on the idea, got a NASA FINESST fellowship, and now I'm here!

So what is magnetic reconnection?

Video credit: https://svs.gsfc.nasa.gov/11199/

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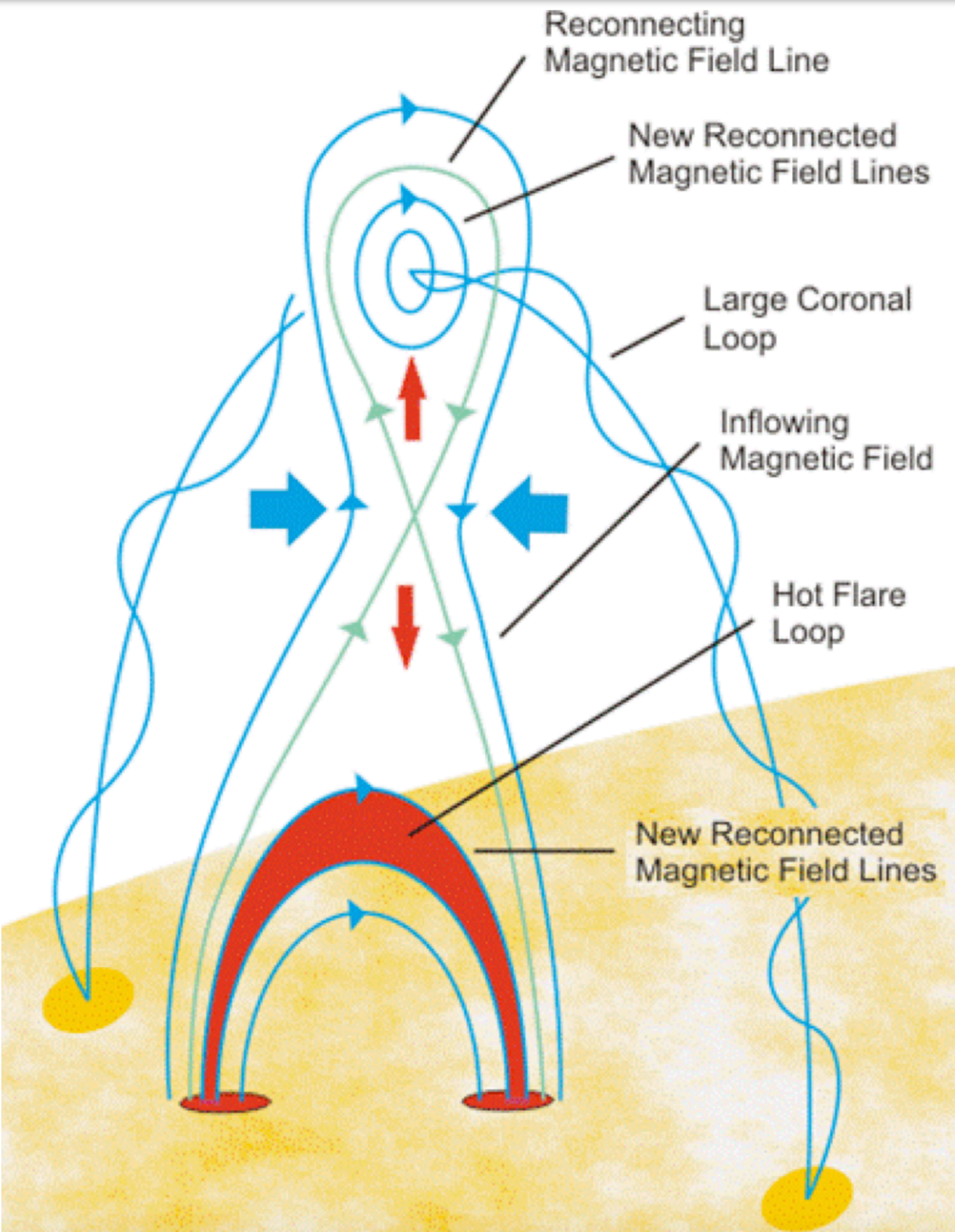
Summarizing our friends at NASA



Schematic of the Carmichael, Sturrock, Hirayama, Kopp and Pneuman, or CSHKP, model of a solar flare (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976)

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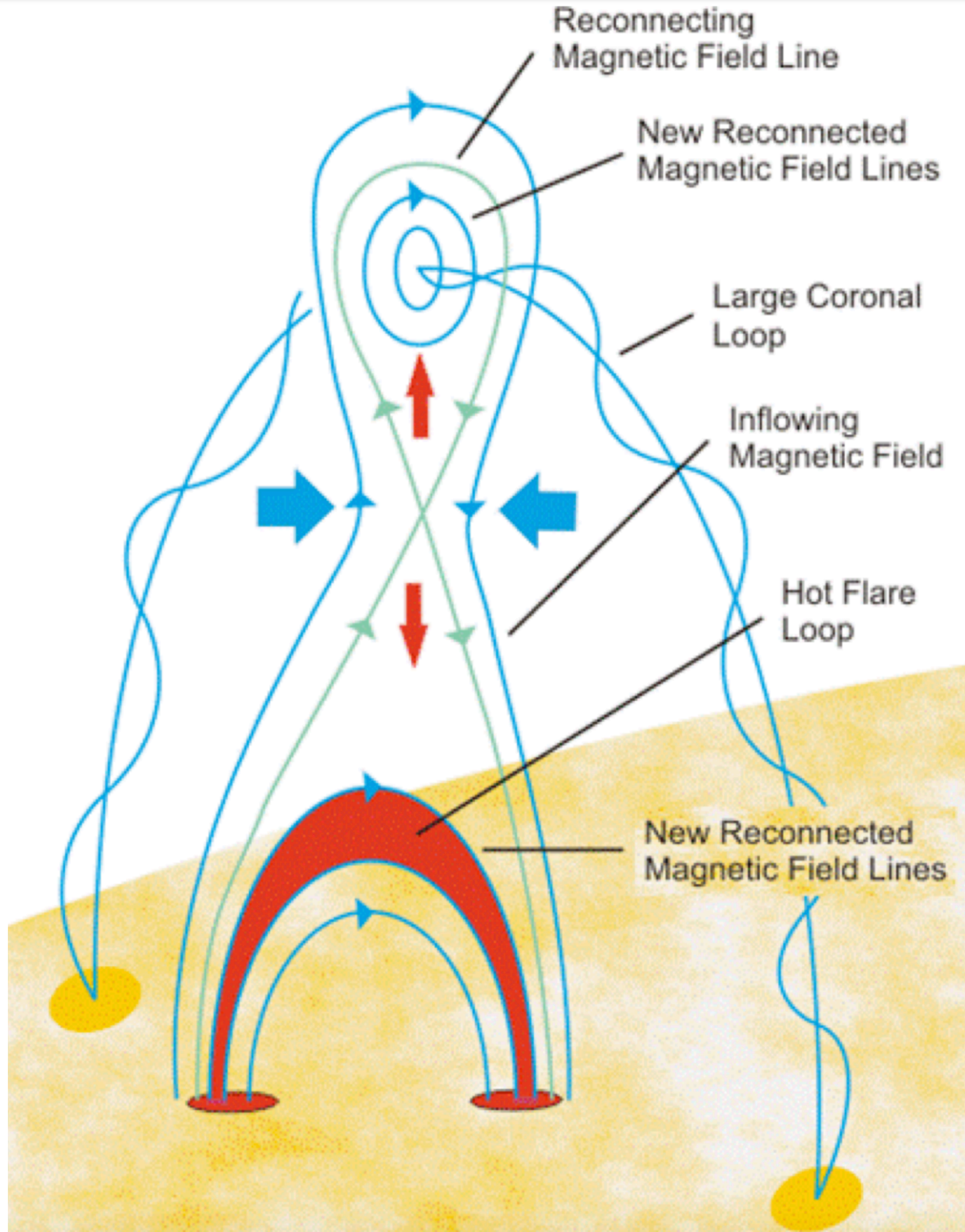

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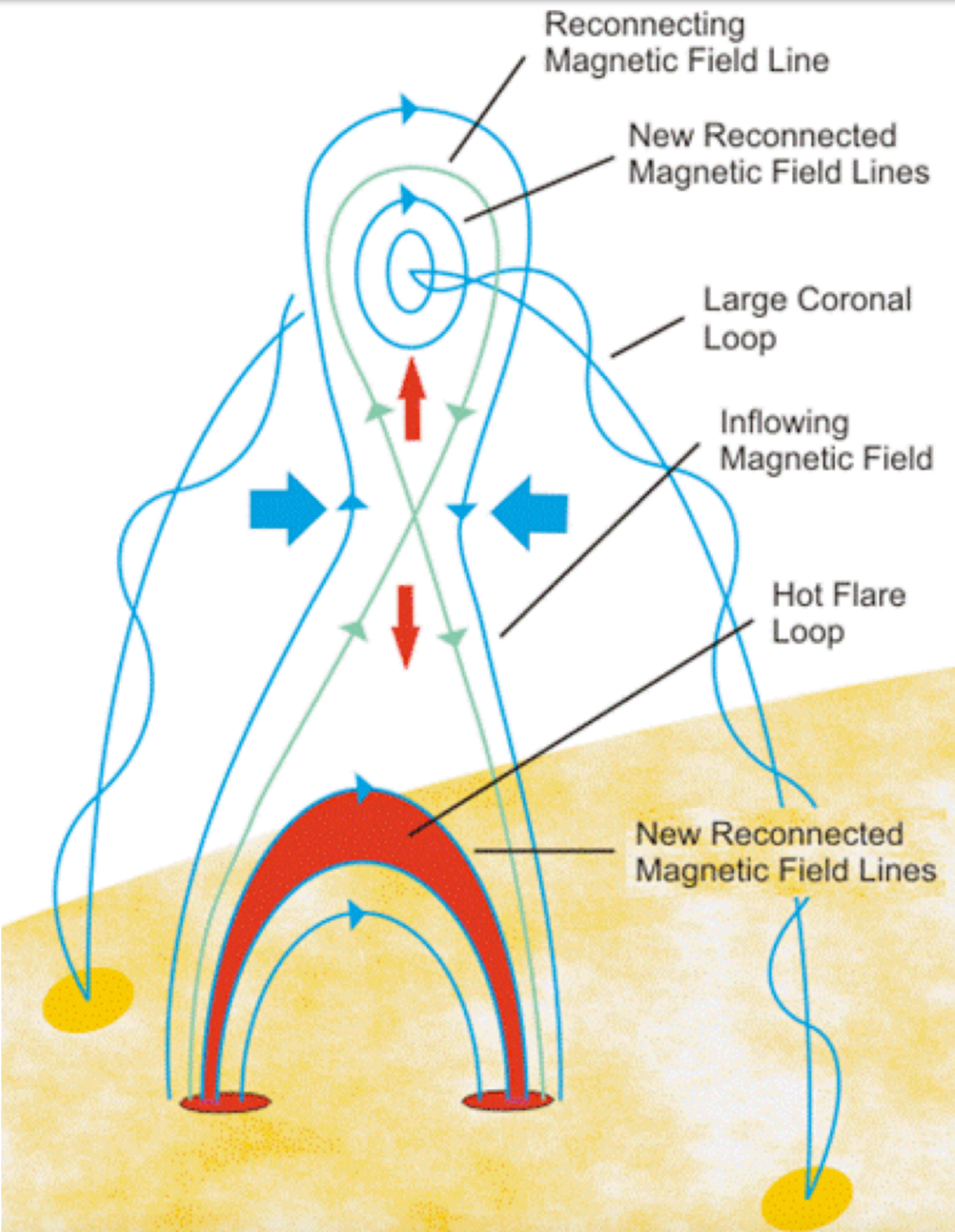

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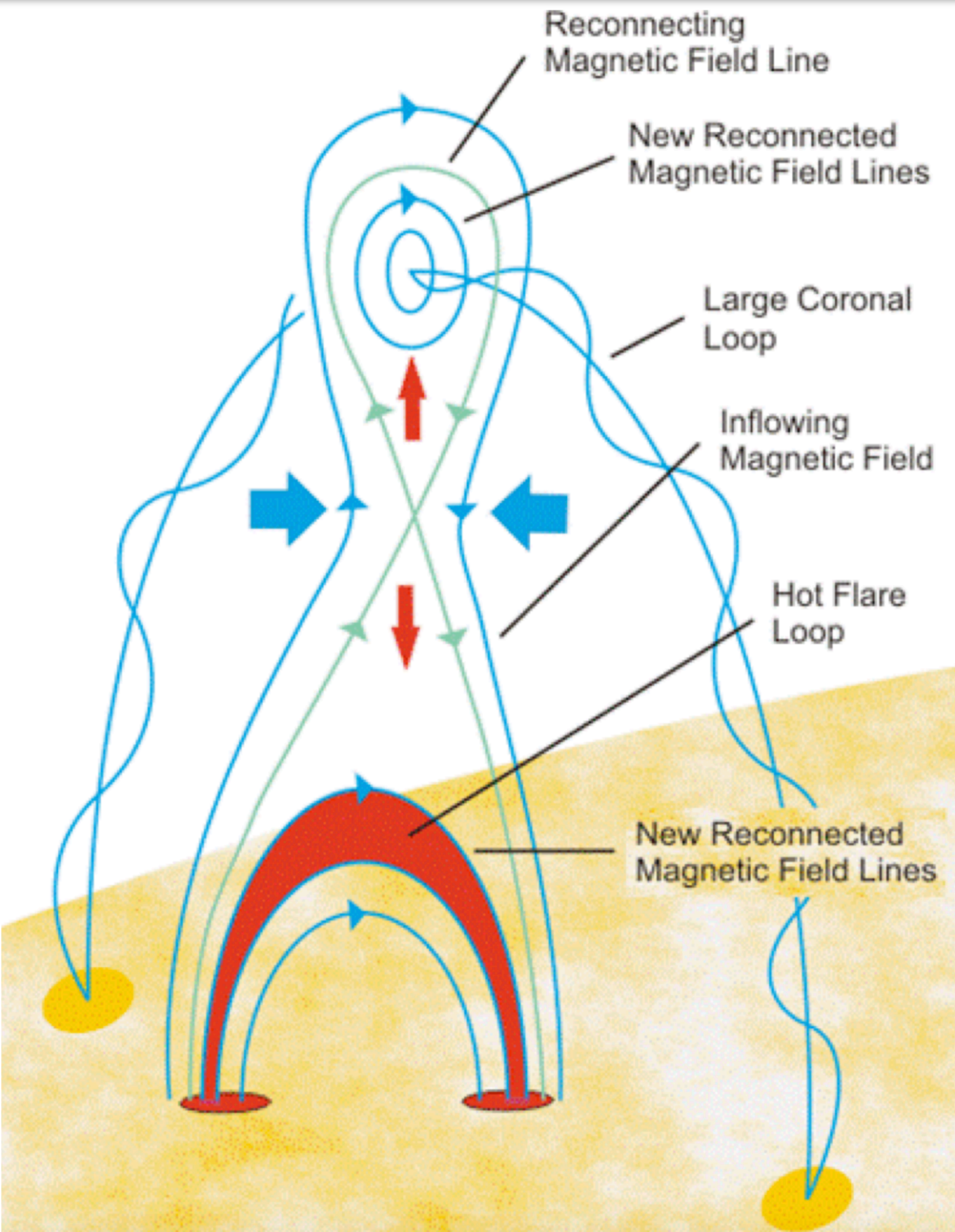

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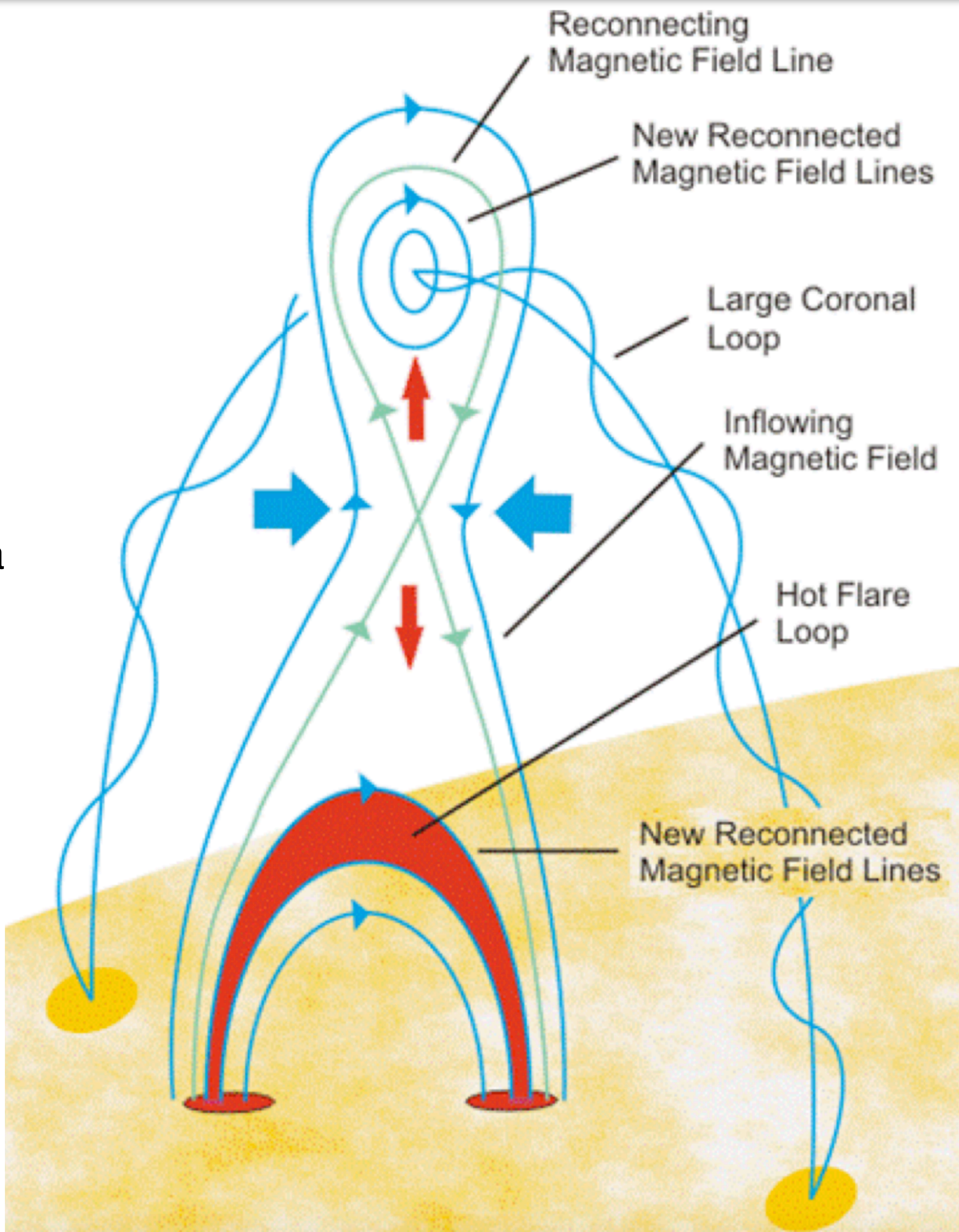
Summarizing our friends at NASA

- Magnetic reconnection involves:
  - A change in the magnetic topology ("field lines connect and disconnect")
  - Which releases energy
  - Leading to a large scale change in the magnetic field structure and significant energization of the plasma



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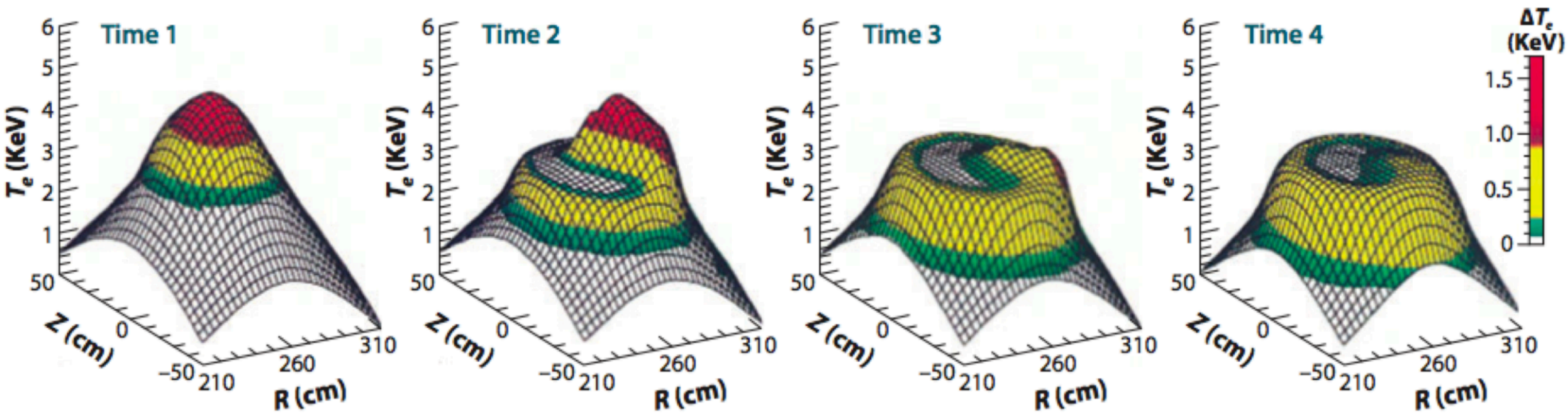
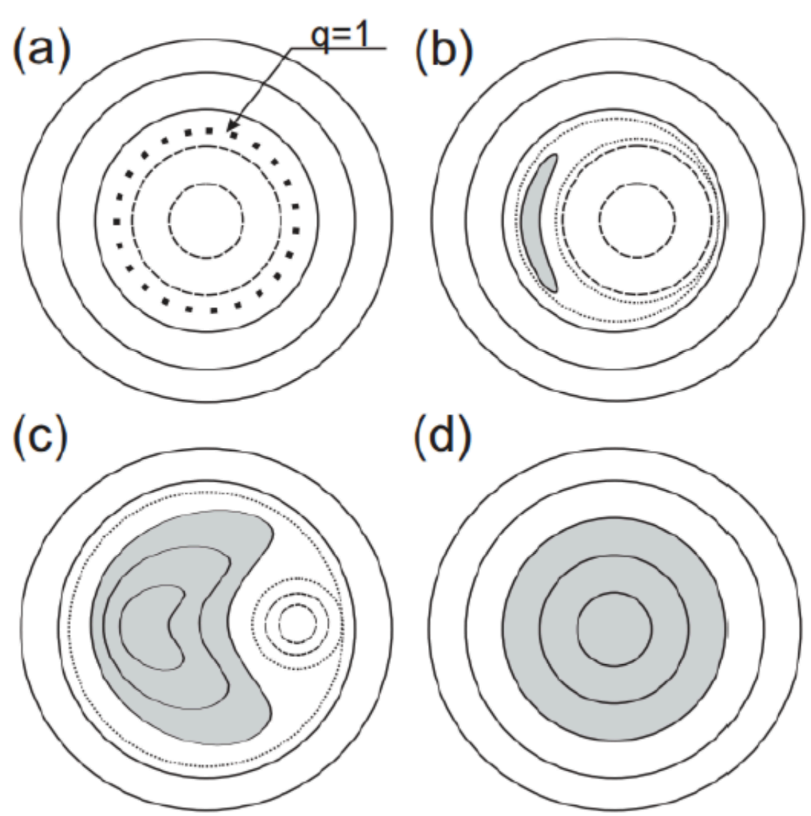
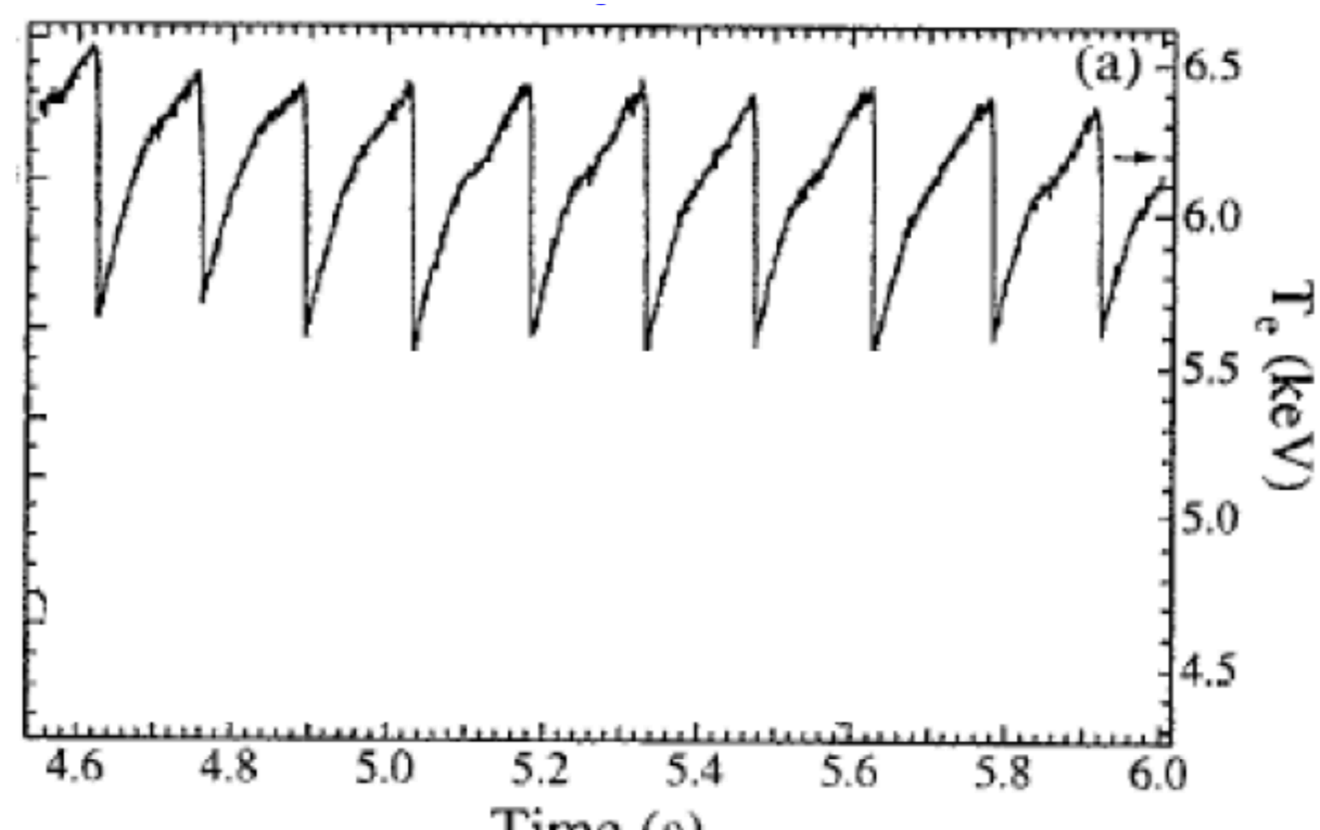
And reconnection happens in many places!

- Collapse of core temperature due to macroscopic reconnection event (sawtooth instability) shown in tomography of electron temperature; Nagayama *et al*. PoP 1996



Schematic of the flux surface rearrangement at the q=1 surface during a sawtooth crash and the cyclic pattern of sawtooth crashes





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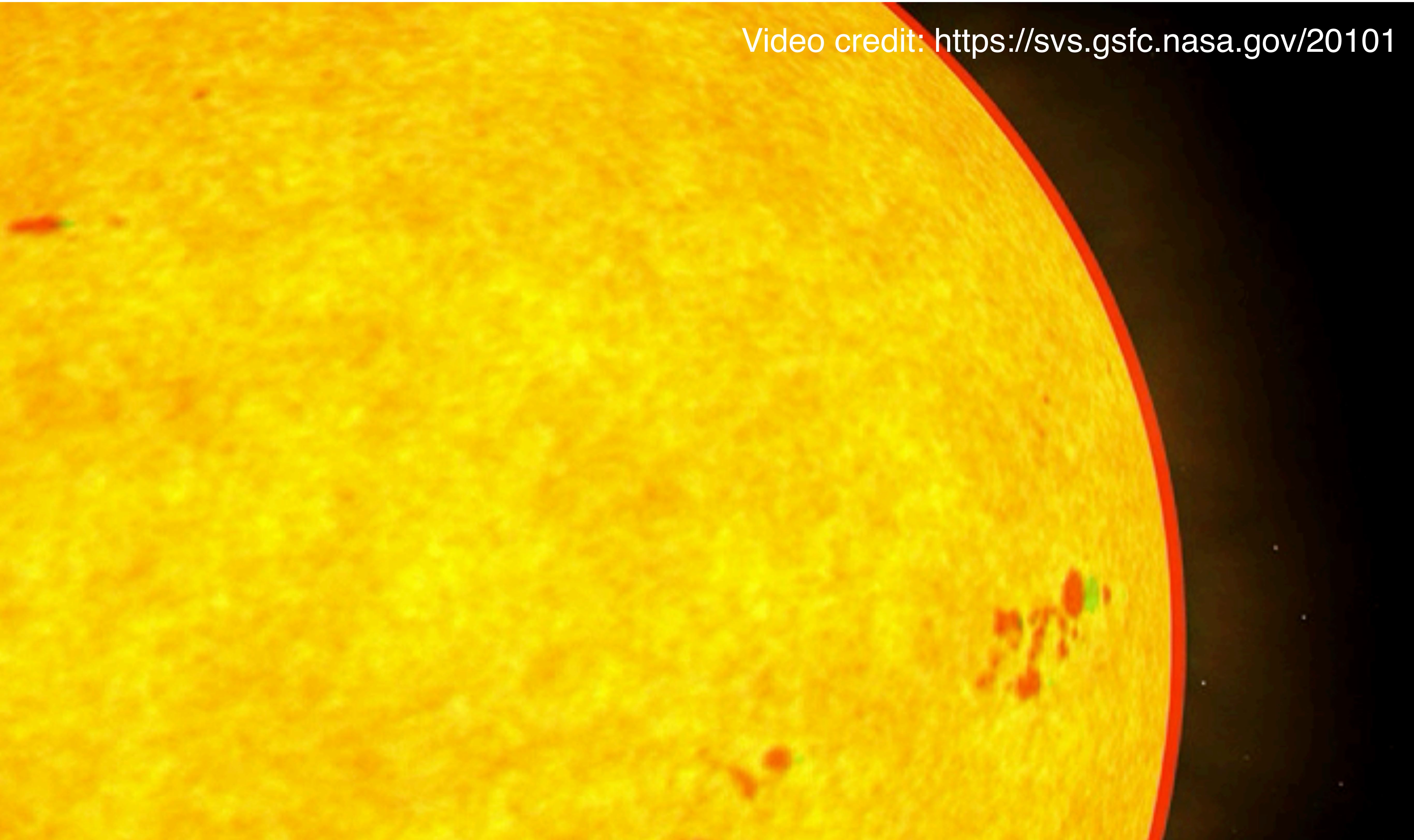

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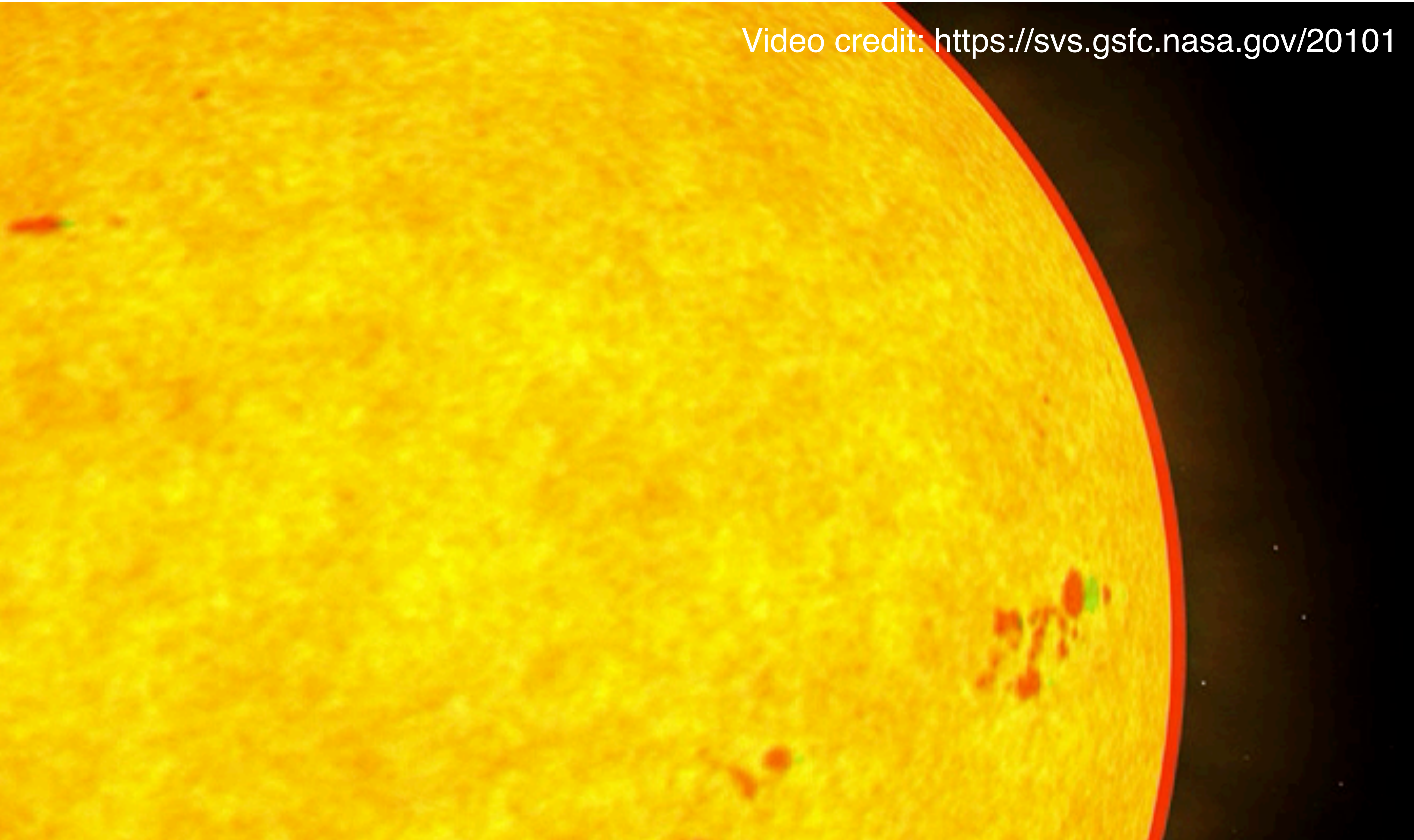

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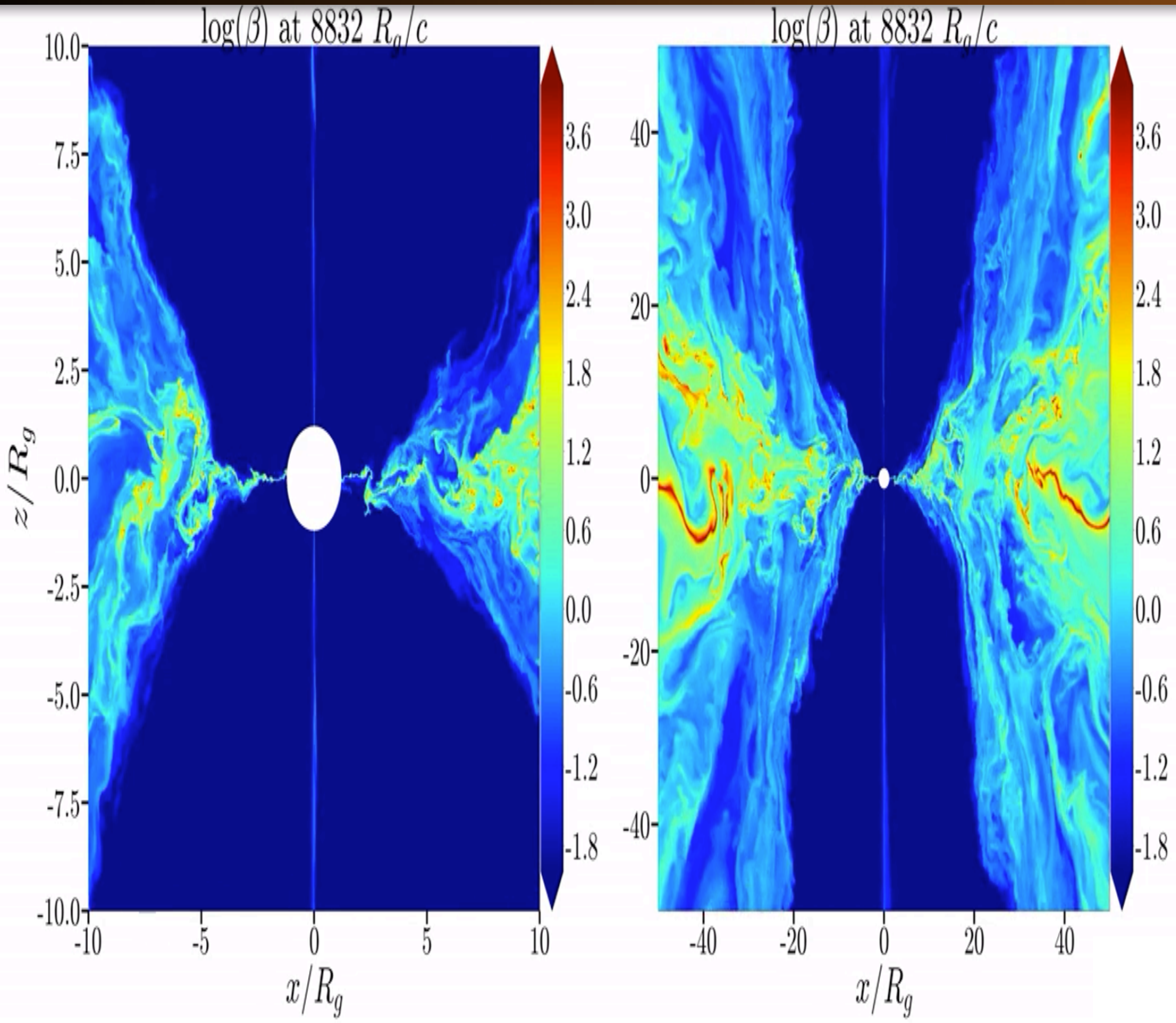
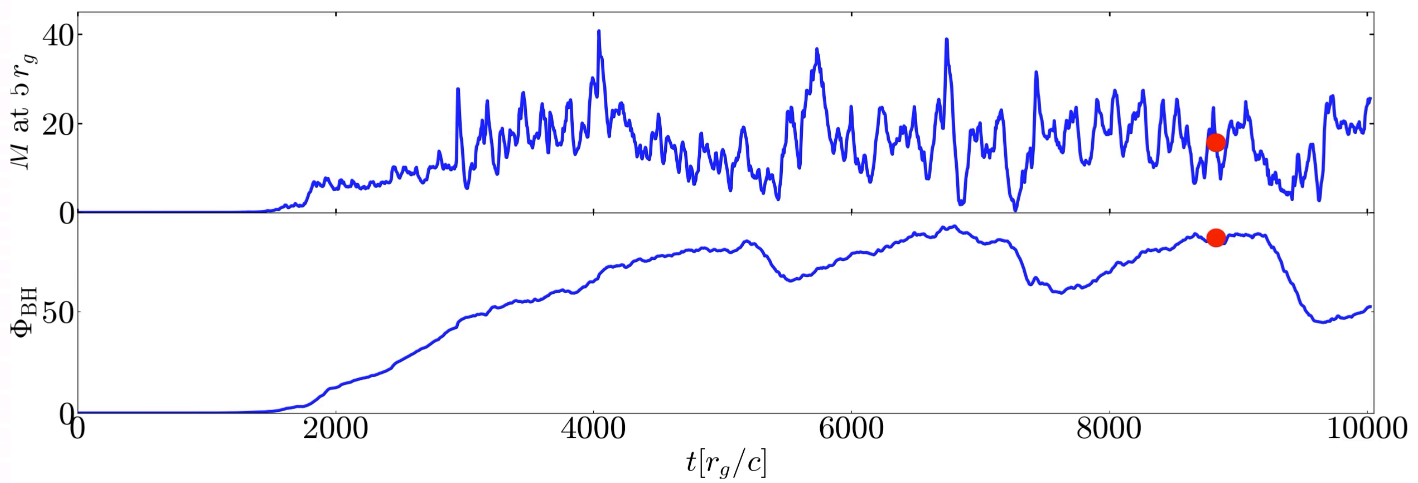
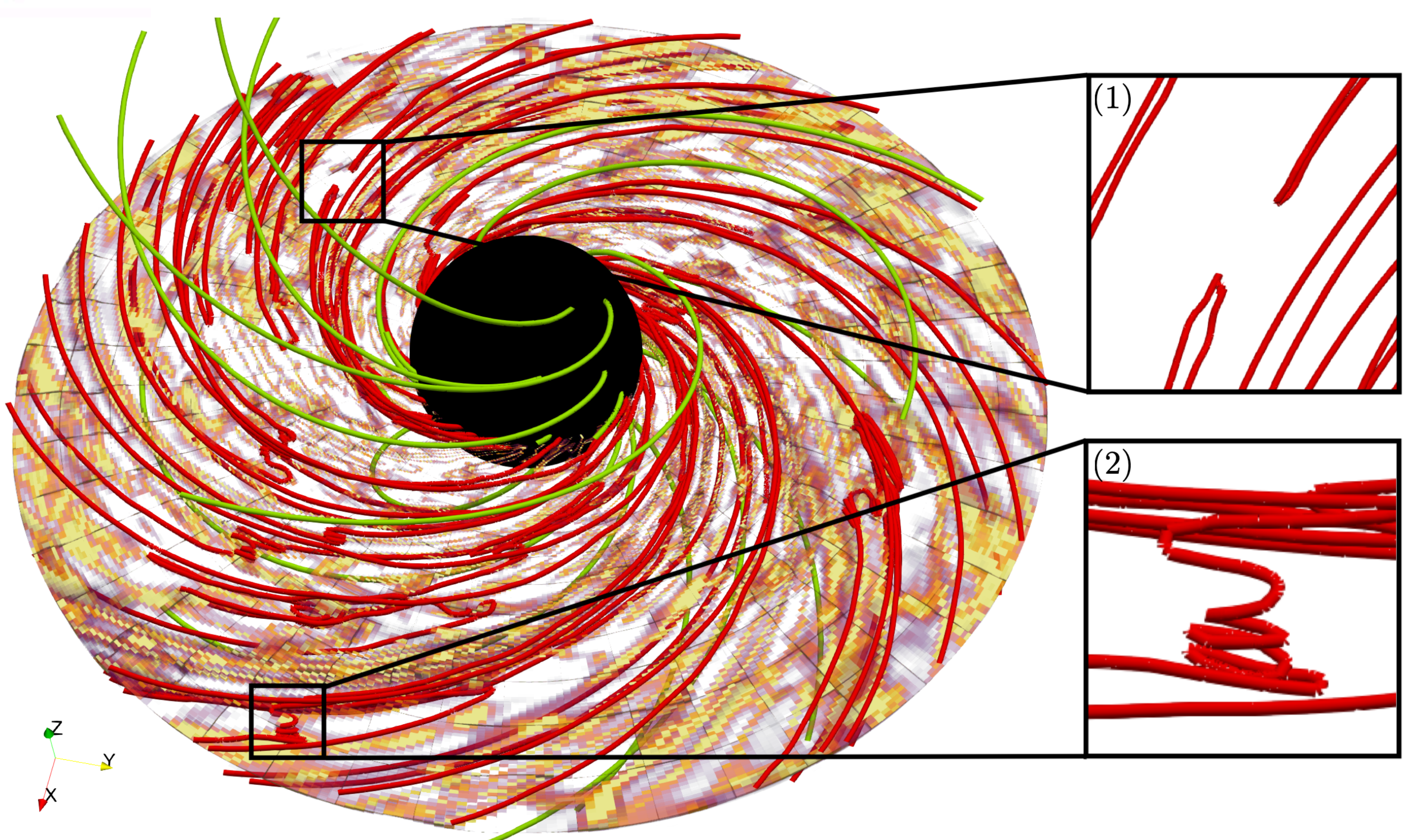




[Ripperda, Liska, Chatterjee, et al, ApJL, 2022]

[Bransgrove, Ripperda, Philippov, PRL, 2021]



Magnetic reconnection shows up around compact objects like black holes too!

Extremely important for resolving the "no-hair" theorem. Reconnection is the process by which black holes shed their magnetic fields, powering powerful flares we routinely observe!

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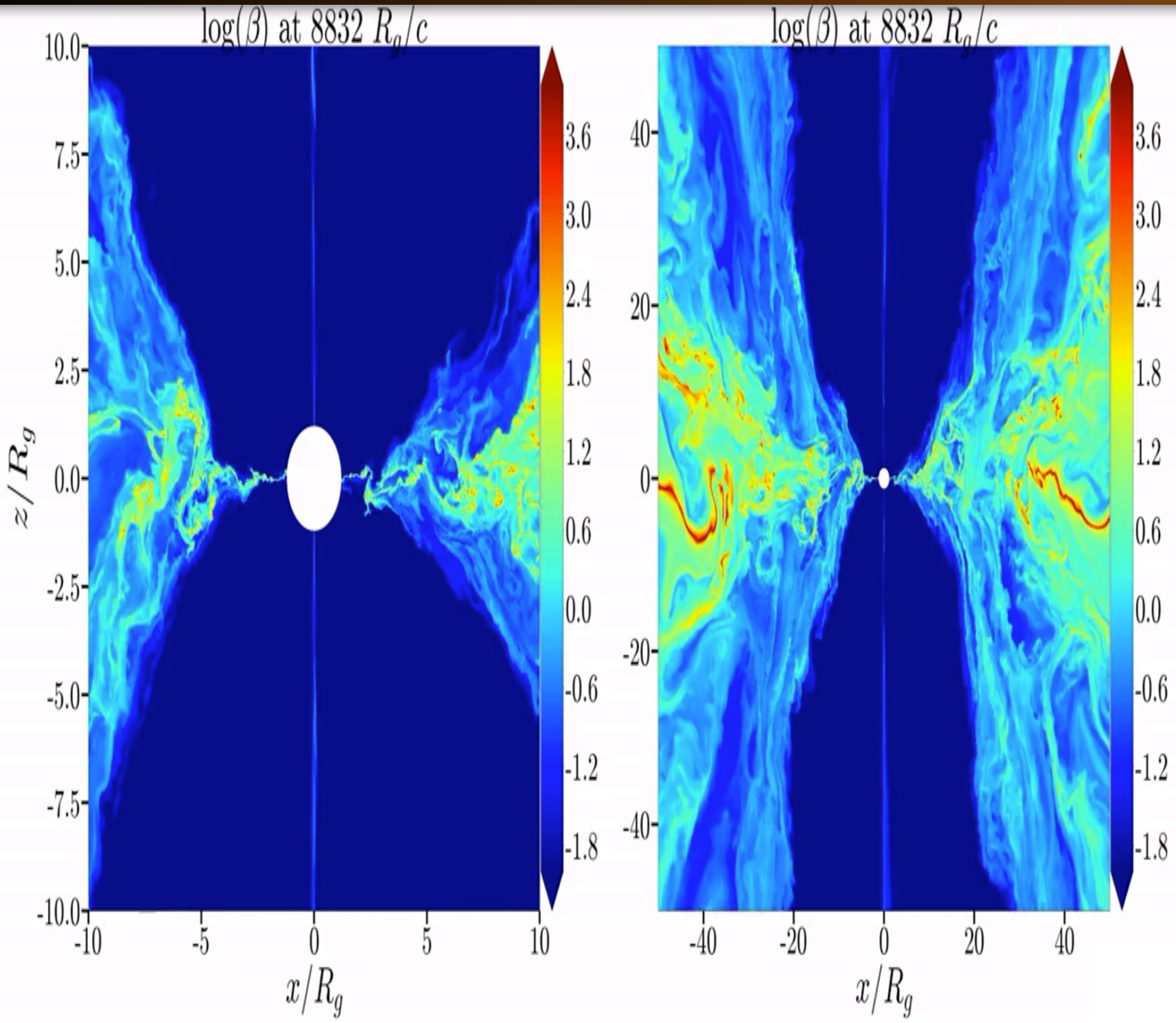

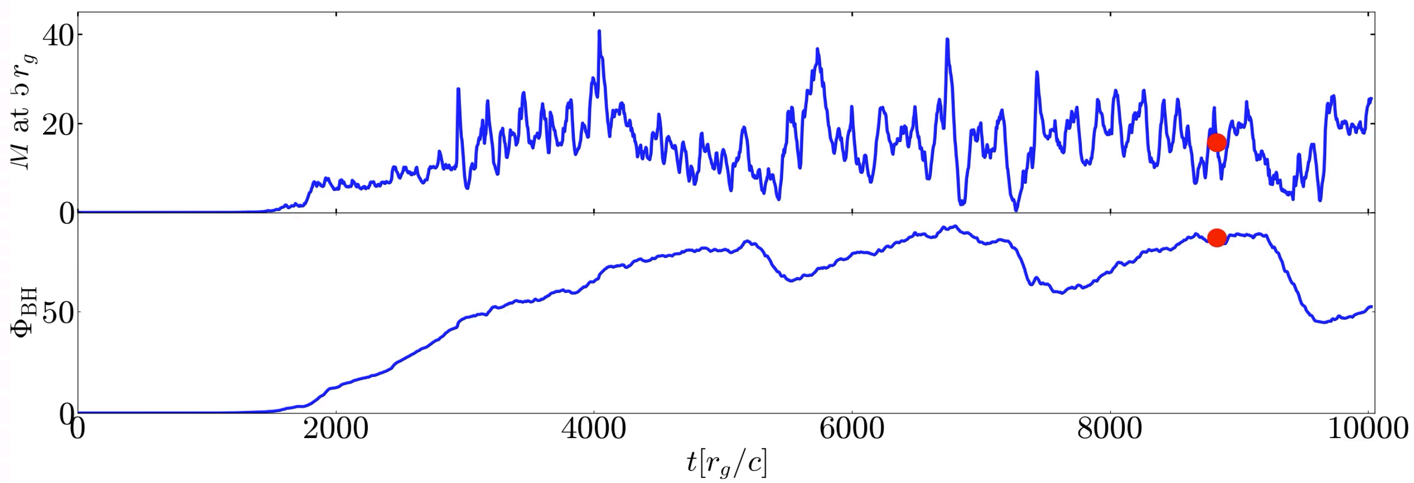

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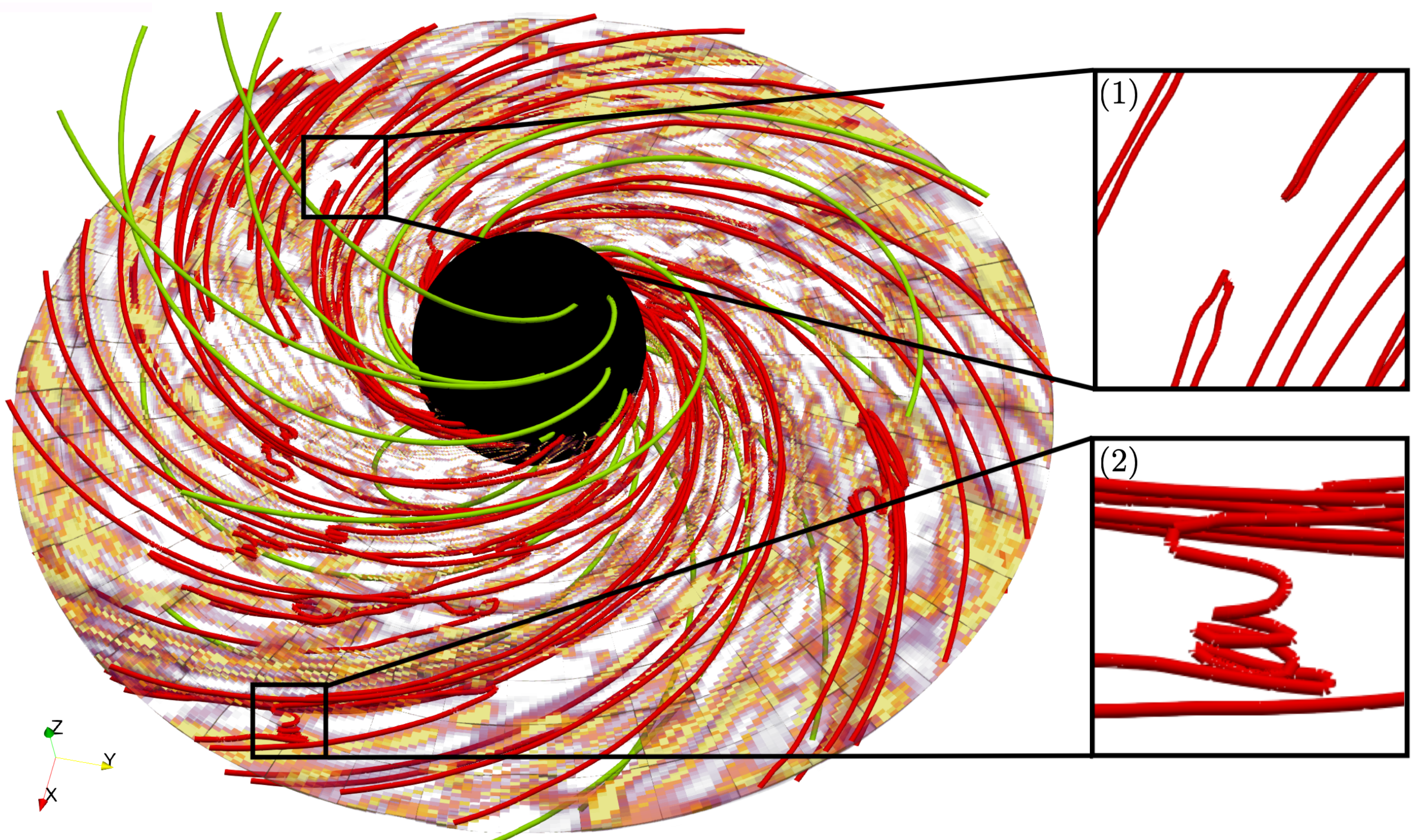

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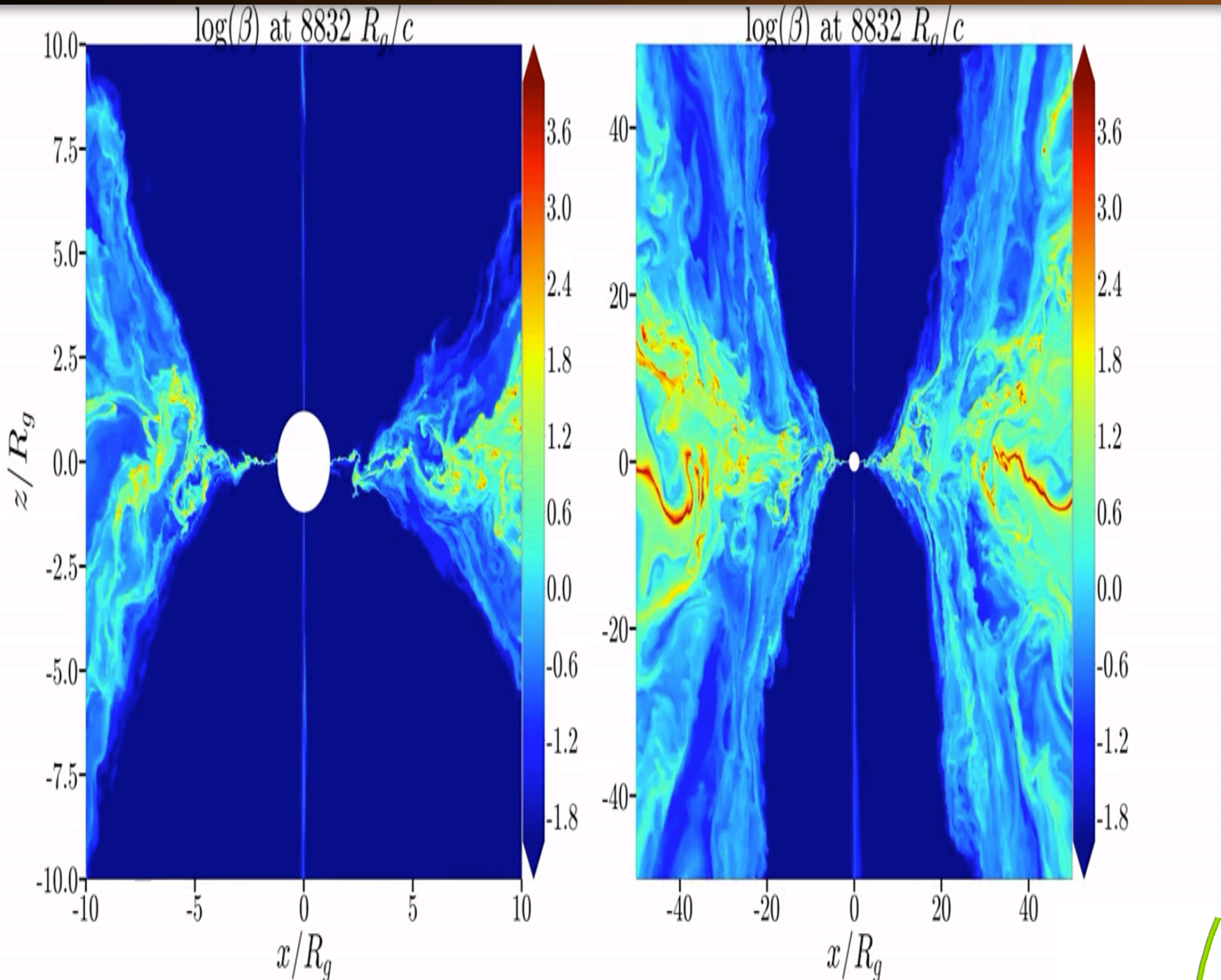

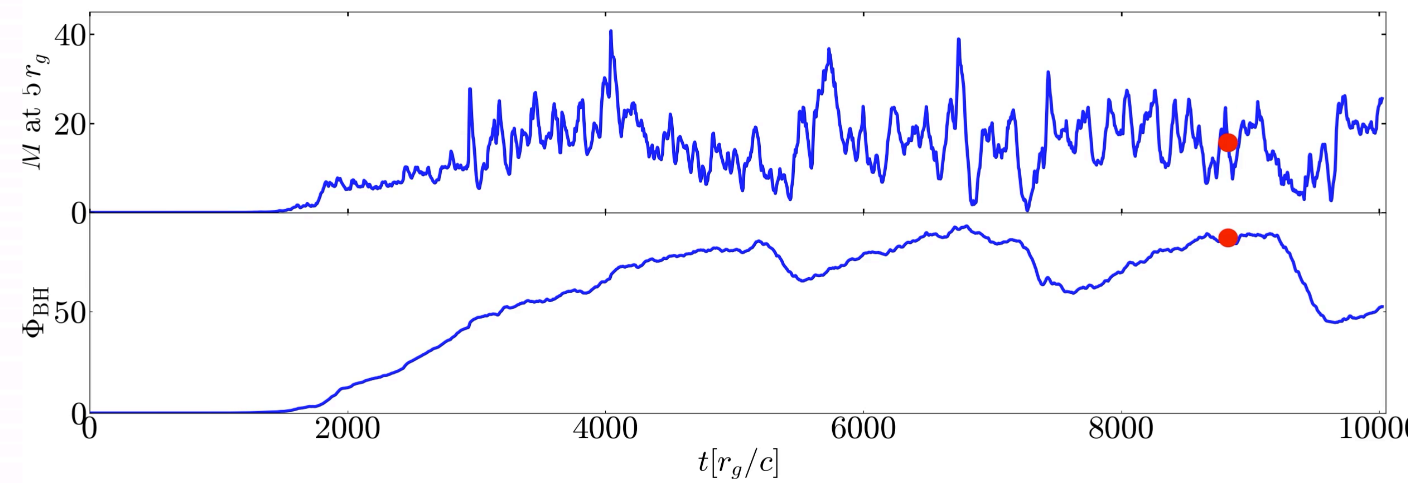

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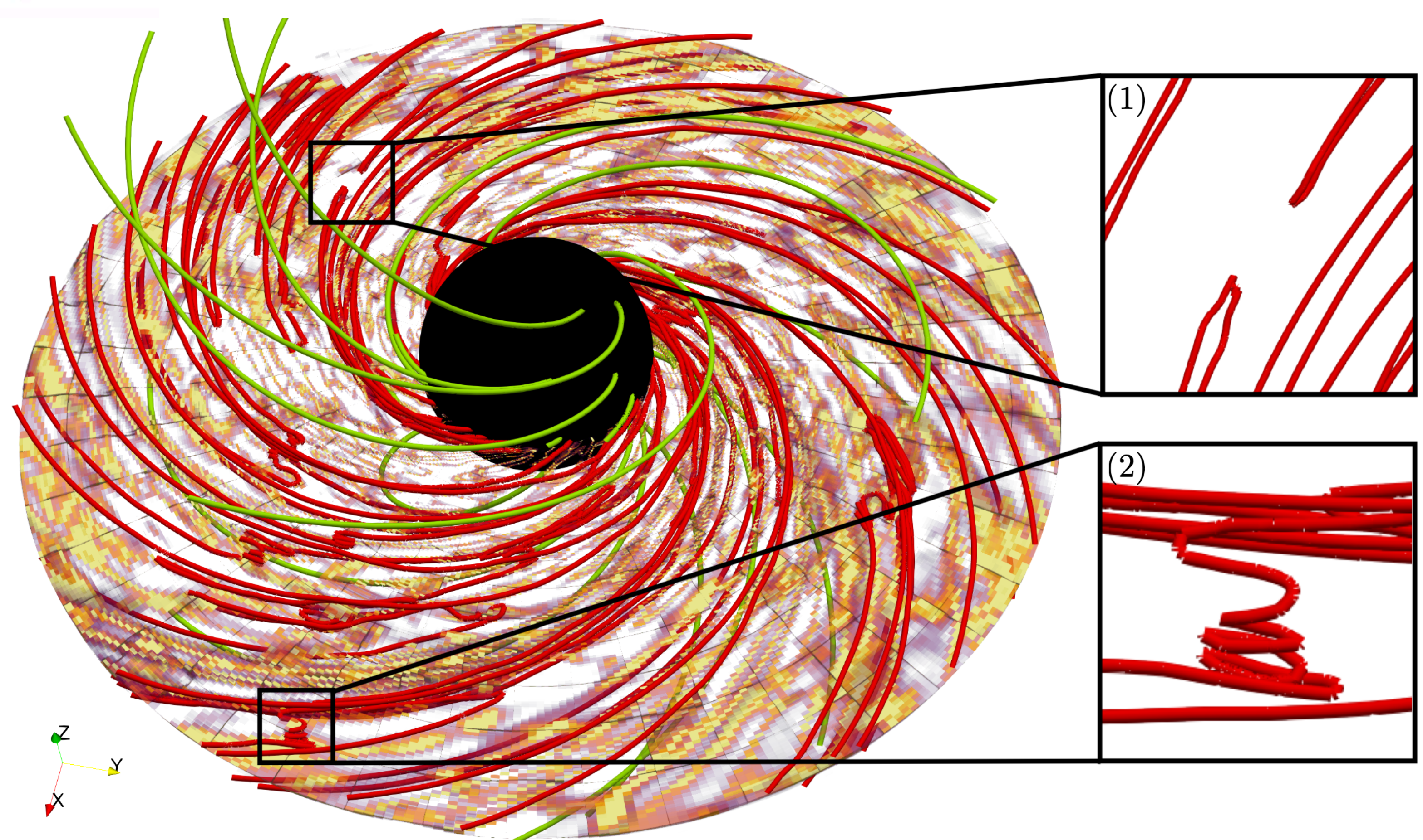

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So this process is everywhere.. but how does it work?

The equations of magnetohydrodynamics (MHD)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$ Mass conservation

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right) = -\nabla p + \mathbf{J} \times \mathbf{B}$$ Momentum conservation

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \nabla \cdot \mathbf{B} = 0$$ Faraday's Law and Gauss' Law

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{\sigma}\mathbf{J}, \quad \mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$ Ohm's Law and Ampere's Law

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{1}{\sigma \mu_0} \nabla \times (\nabla \times \mathbf{B}) = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{\sigma \mu_0} \nabla^2 \mathbf{B}$$

$$\mathcal{E} = \frac{1}{2}\rho u^2 + \frac{p}{\gamma - 1} + \frac{B^2}{2\mu_0}$$

Energy conservation

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \left[\left(\mathcal{E} + p + \frac{B^2}{2\mu_0} \right) \mathbf{u} - \frac{1}{\mu_0} (\mathbf{u} \cdot \mathbf{B})\mathbf{B} \right] = 0$$

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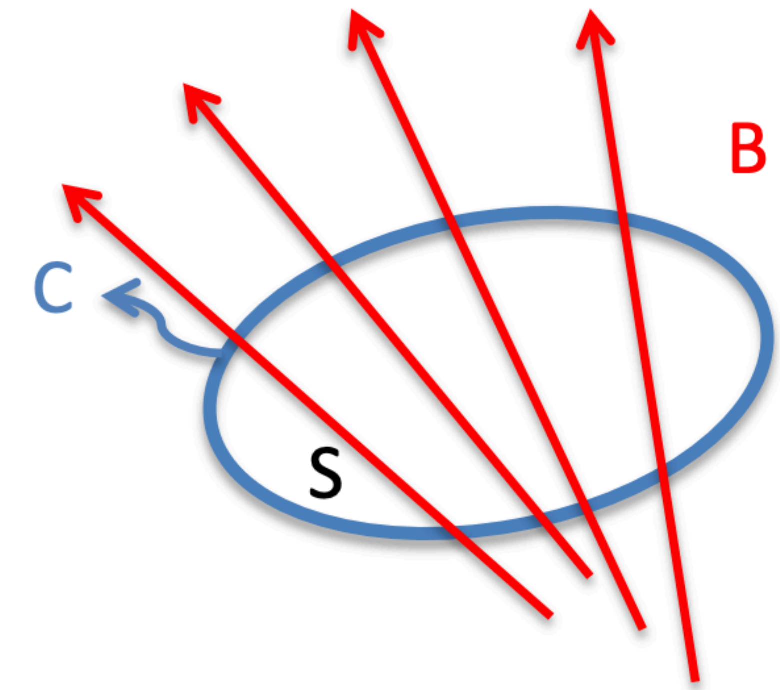
Frozen-in Flux Theorem

Magnetic flux through a surface S, defined by a closed contour C:

$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S}$$



How does Ψ change in time?

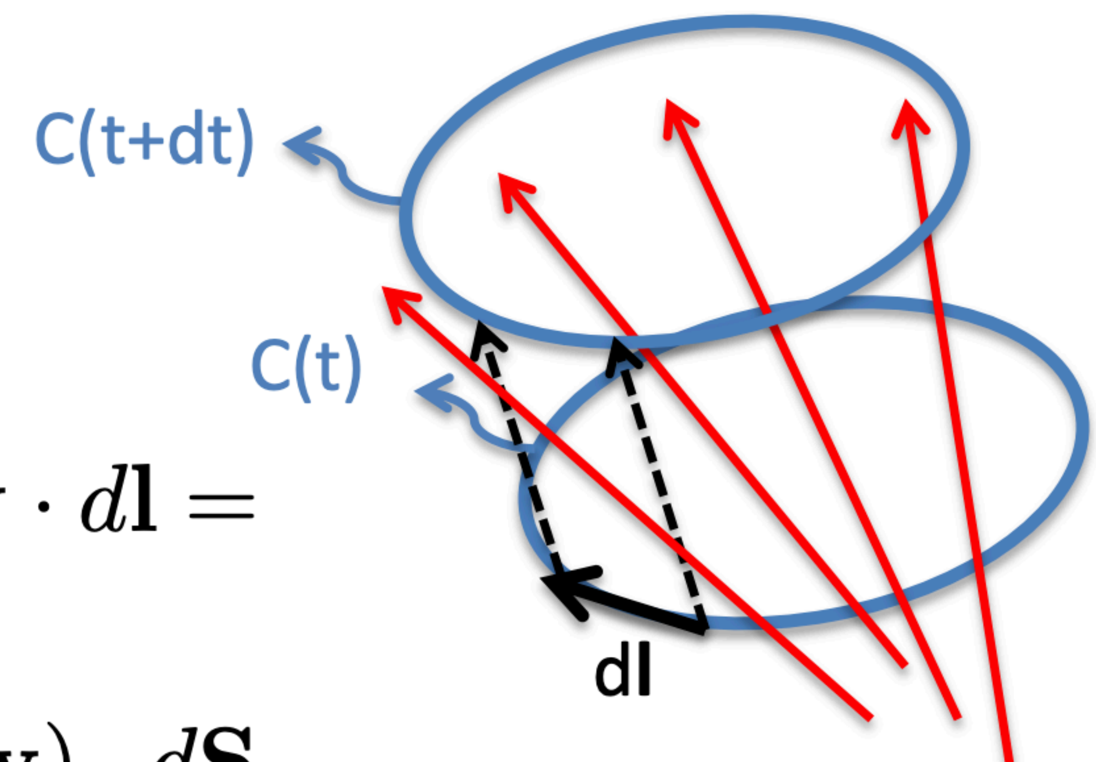
1. the magnetic field itself can change:

$$\left(\frac{\partial \Psi}{\partial t}\right)_1 = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} = - \int_S \nabla \times \mathbf{E} \cdot d\mathbf{S}$$

2. the surface moves with velocity $\mathbf{w}$:

$$\left(\frac{\partial \Psi}{\partial t}\right)_2 = \int_C \mathbf{B} \cdot \mathbf{w} \times d\mathbf{l} = \int_C \mathbf{B} \times \mathbf{w} \cdot d\mathbf{l} =$$

$$\int_S \nabla \times (\mathbf{B} \times \mathbf{w}) \cdot d\mathbf{S}$$



Slide courtesy of Nuno Loureiro, SULI lecture, 2018

Frozen-in Flux Theorem

- We can combine these two equations together to get the total change in the magnetic flux

$$\frac{\partial \Psi}{\partial t} = -\int_S \nabla \times (\mathbf{E} + \mathbf{w} \times \mathbf{B}) \cdot d\mathbf{S}$$

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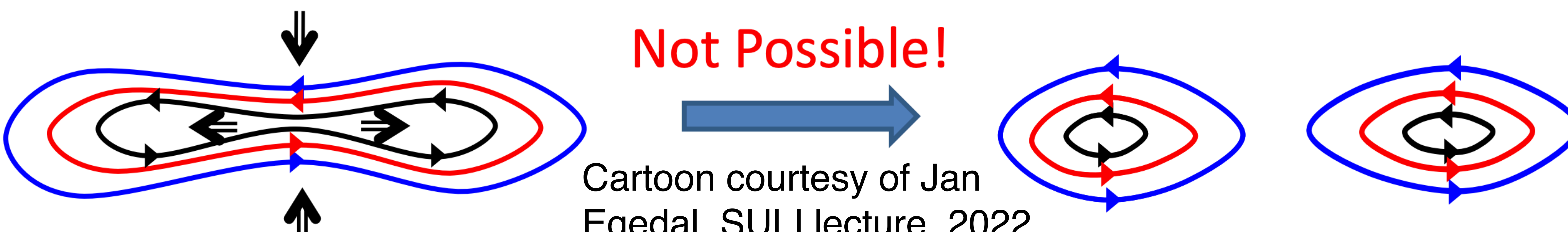
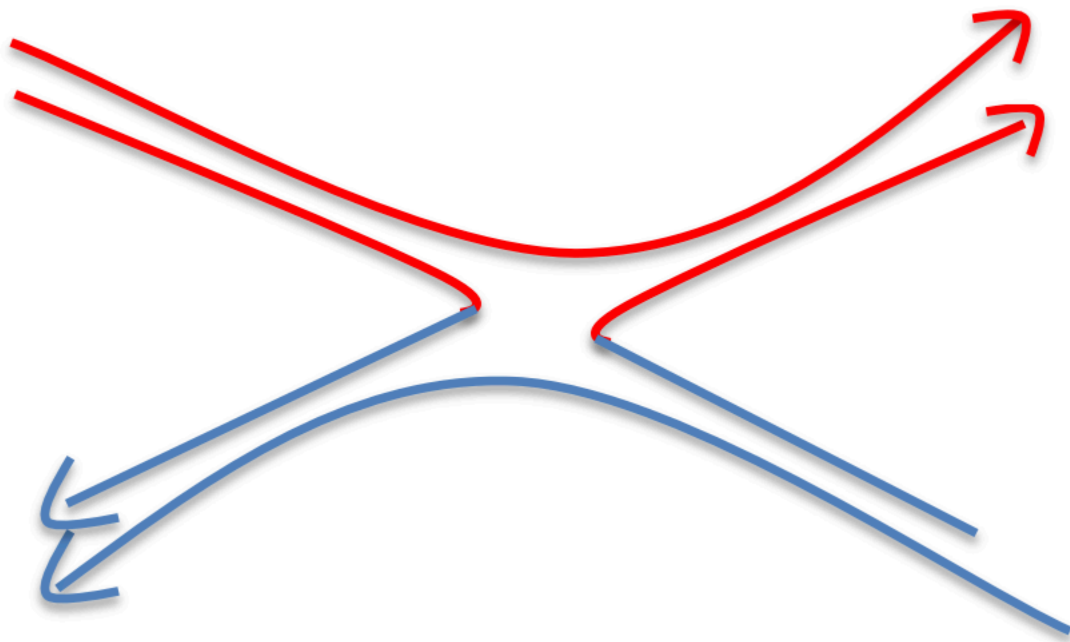


Cartoon courtesy of Jan Egedal, SULI lecture, 2022

How does finite conductivity fit in?



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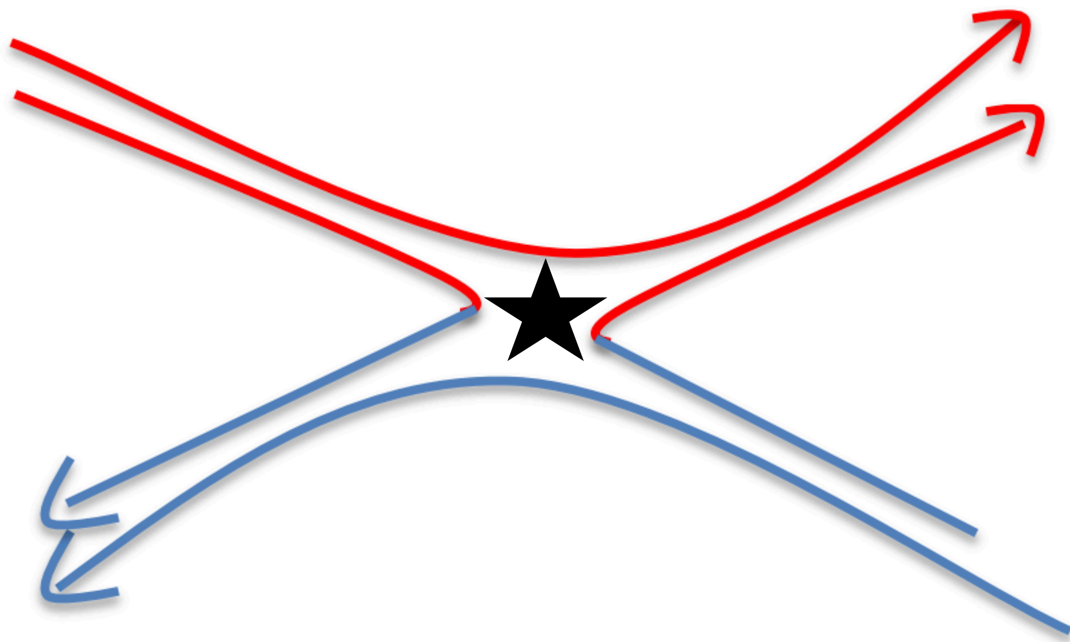
- Something is happening here, right where our field “connects” and “disconnects”



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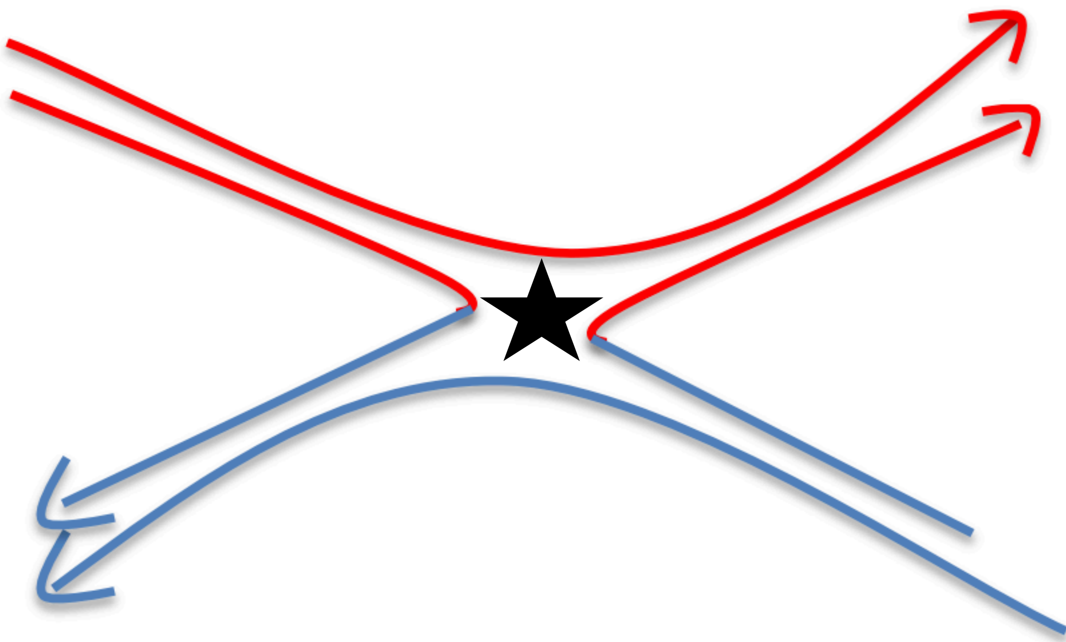

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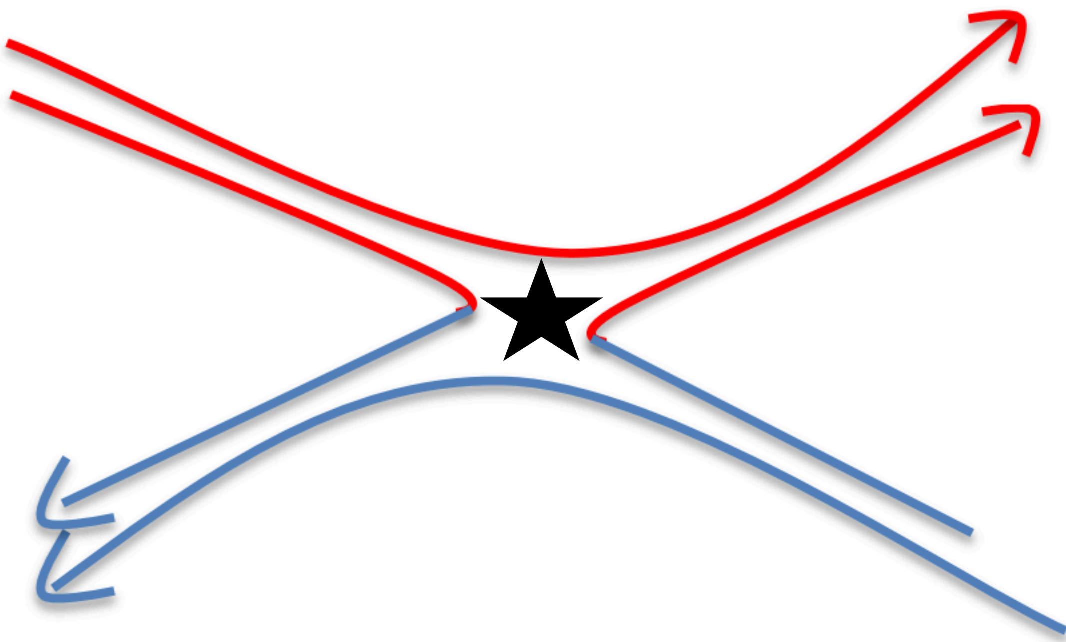

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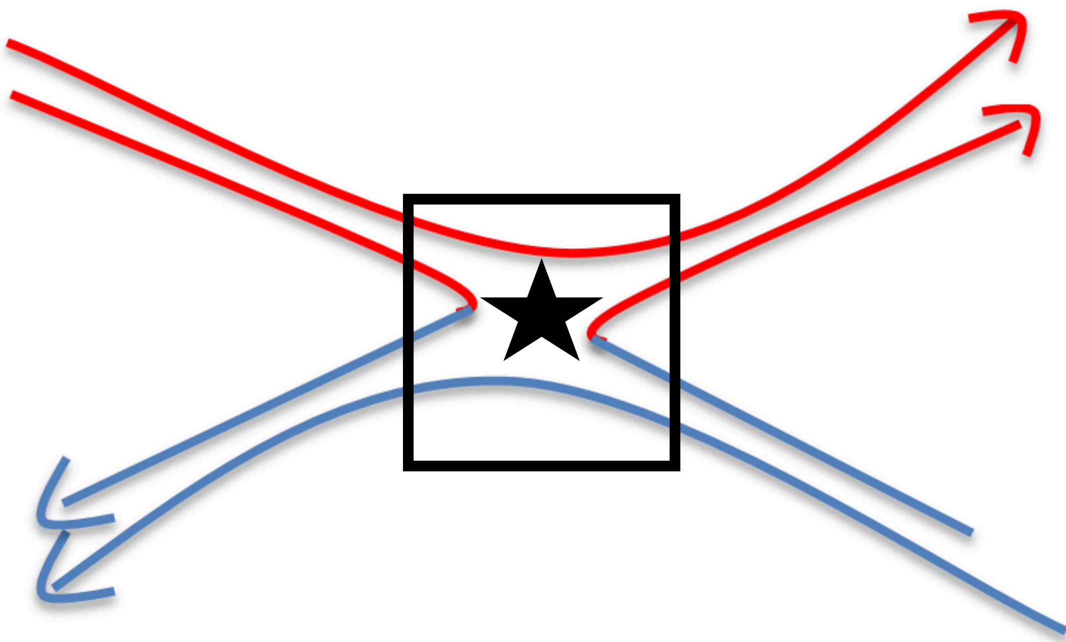

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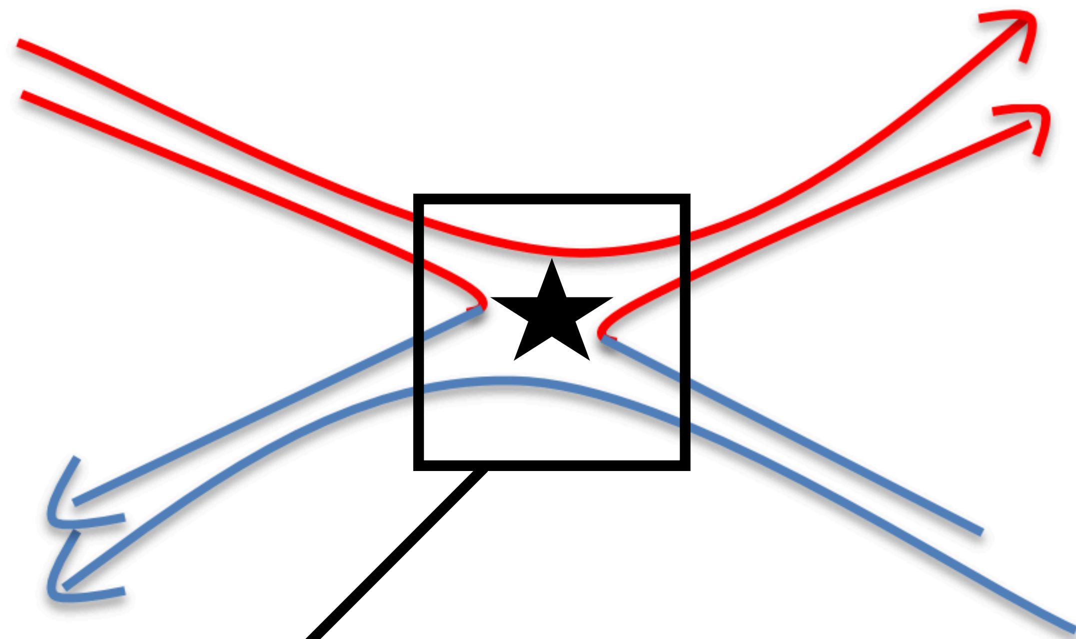

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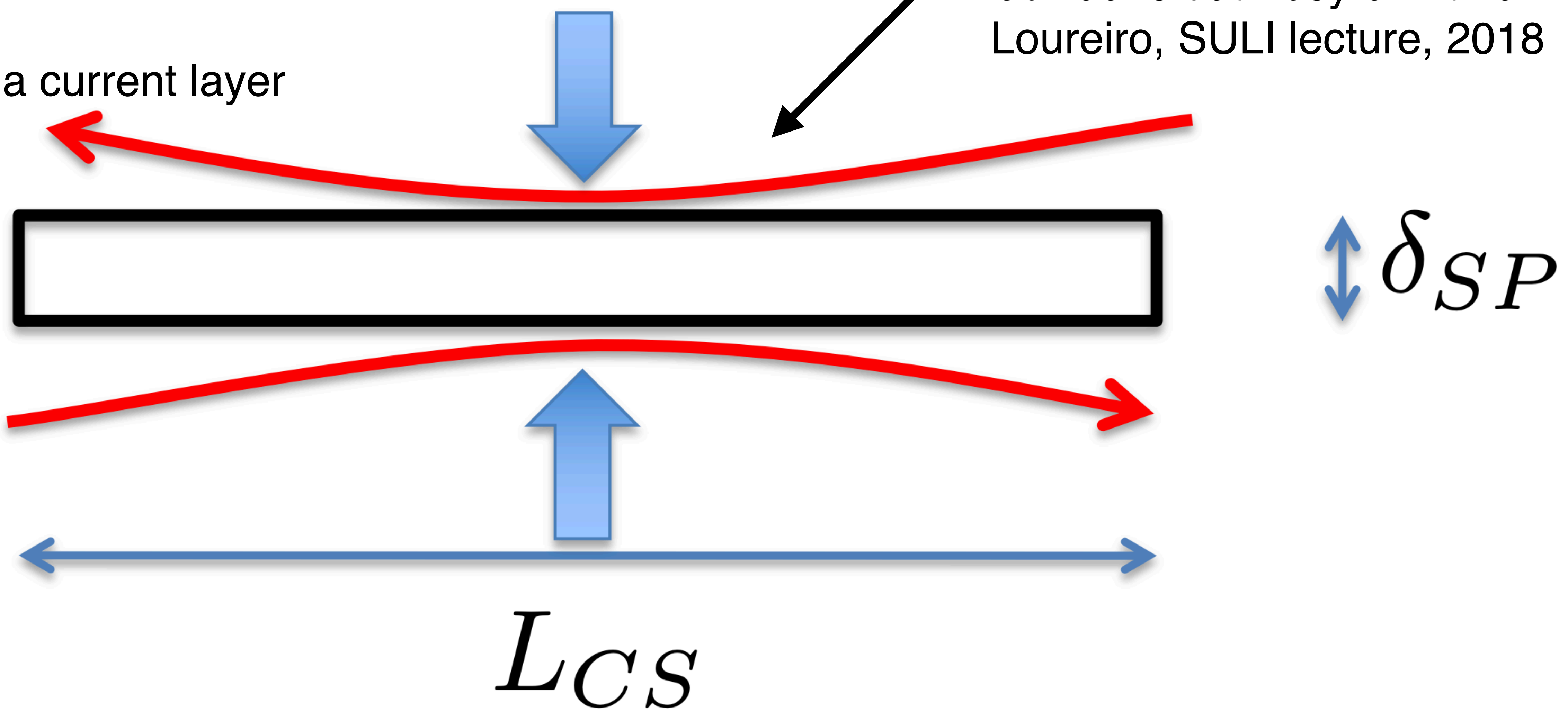

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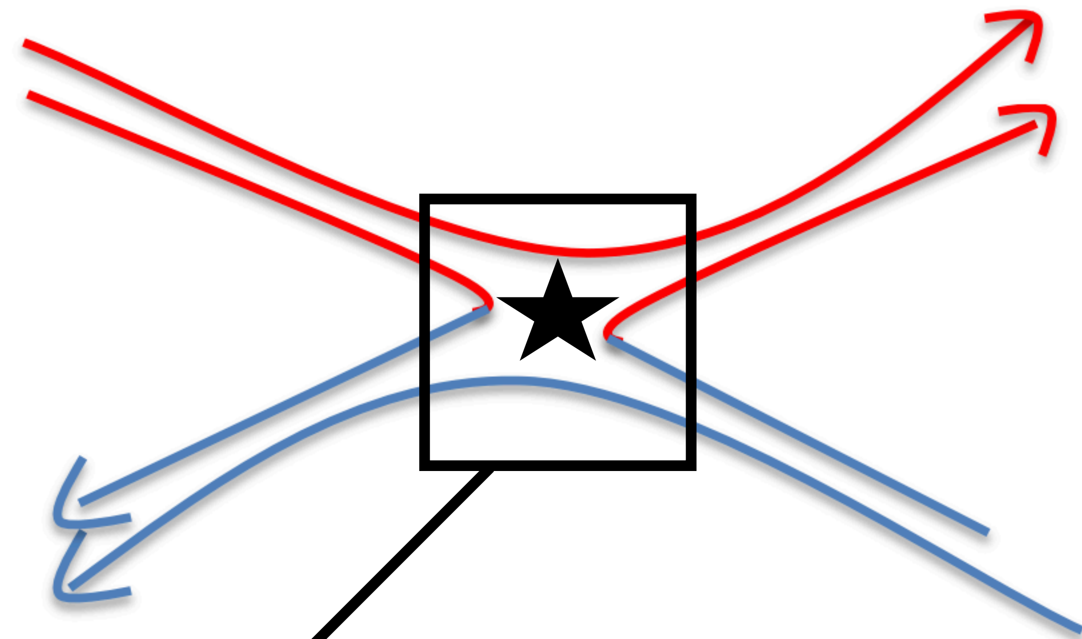

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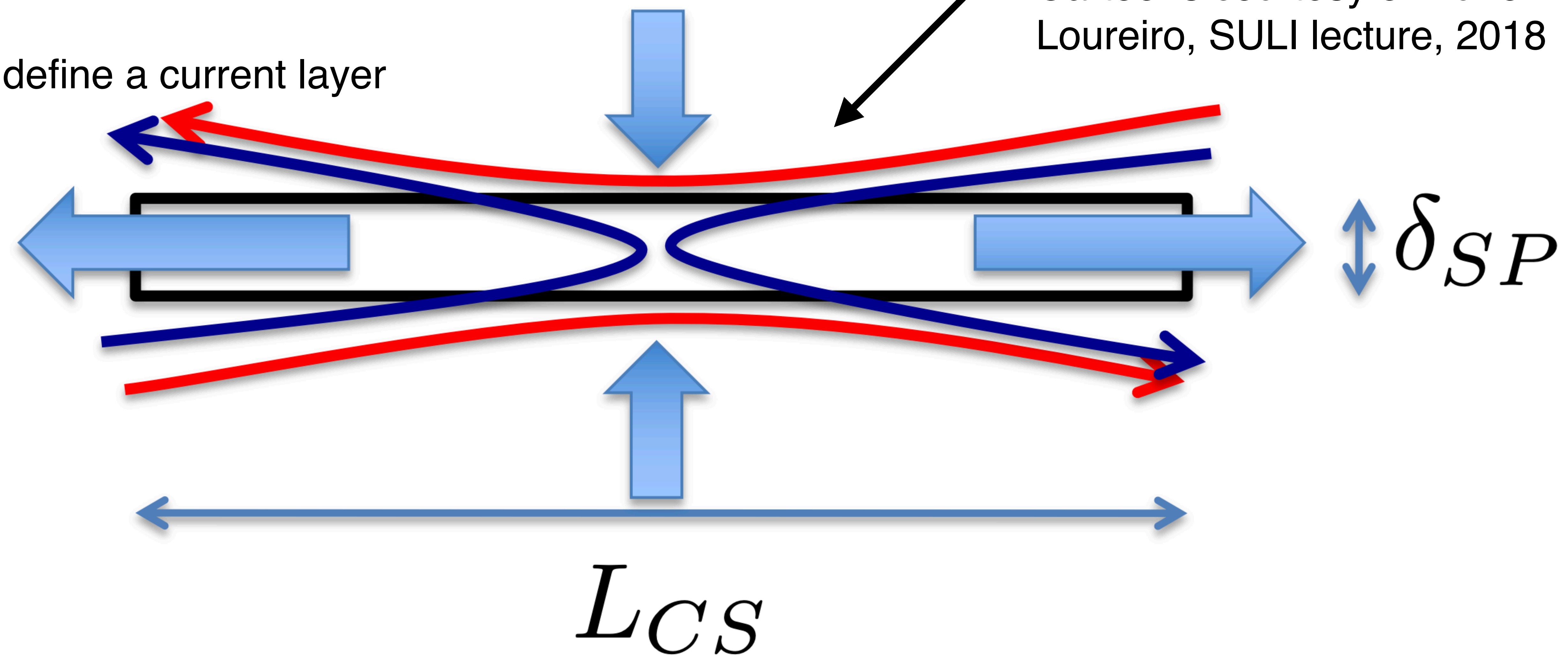
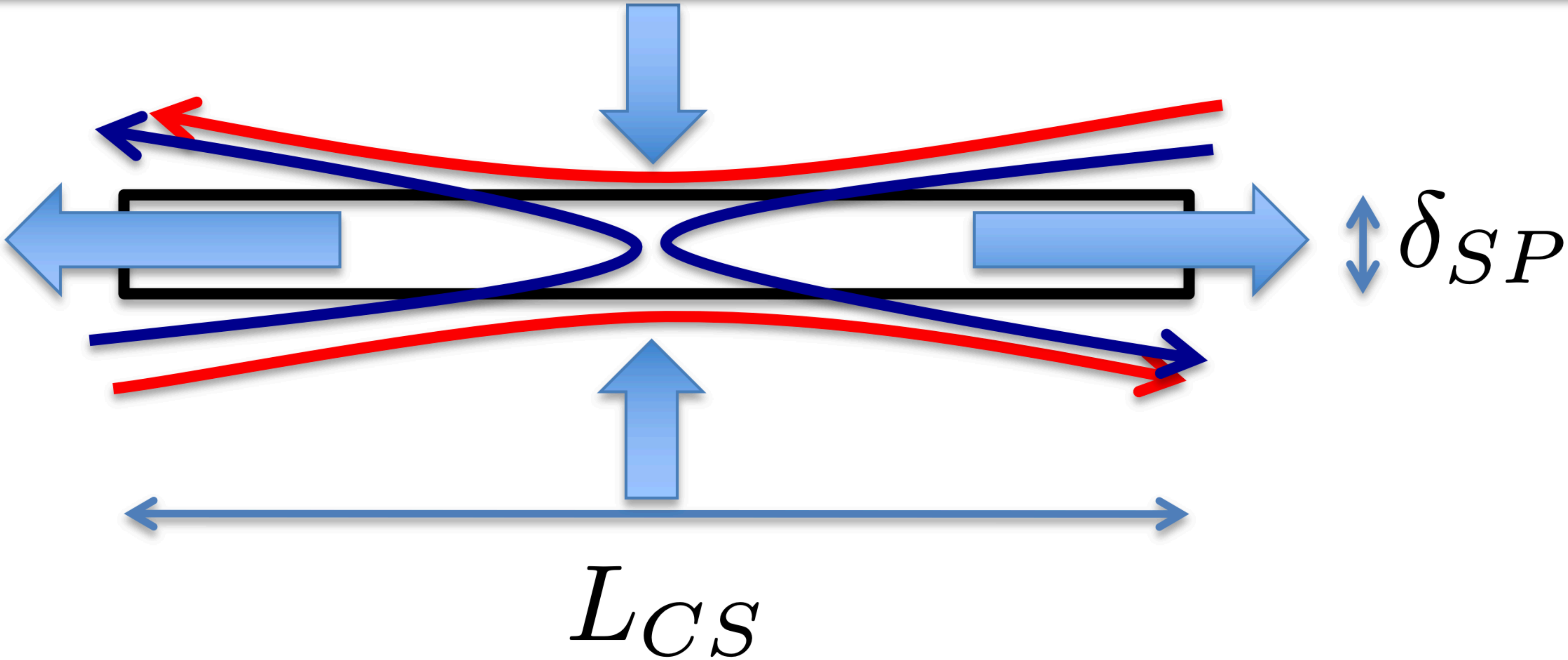


The Sweet-Parker Theory



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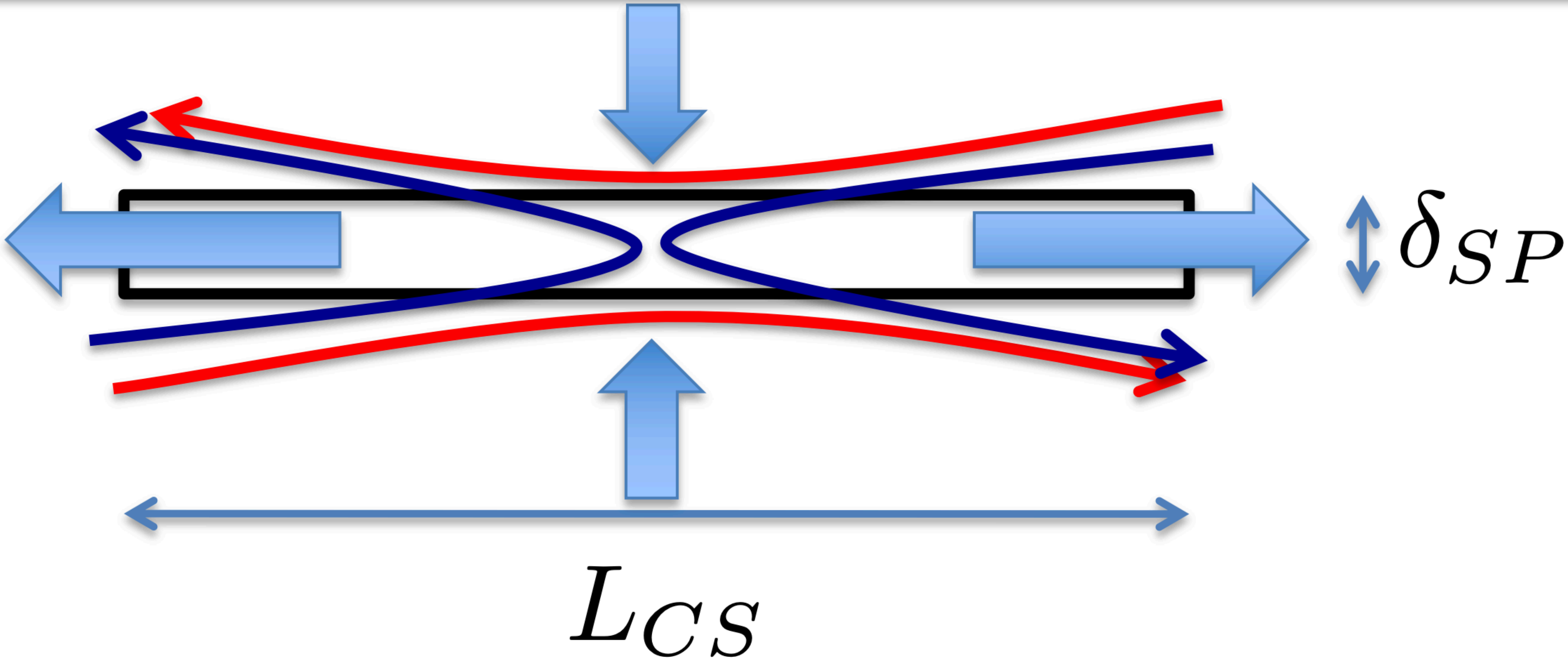

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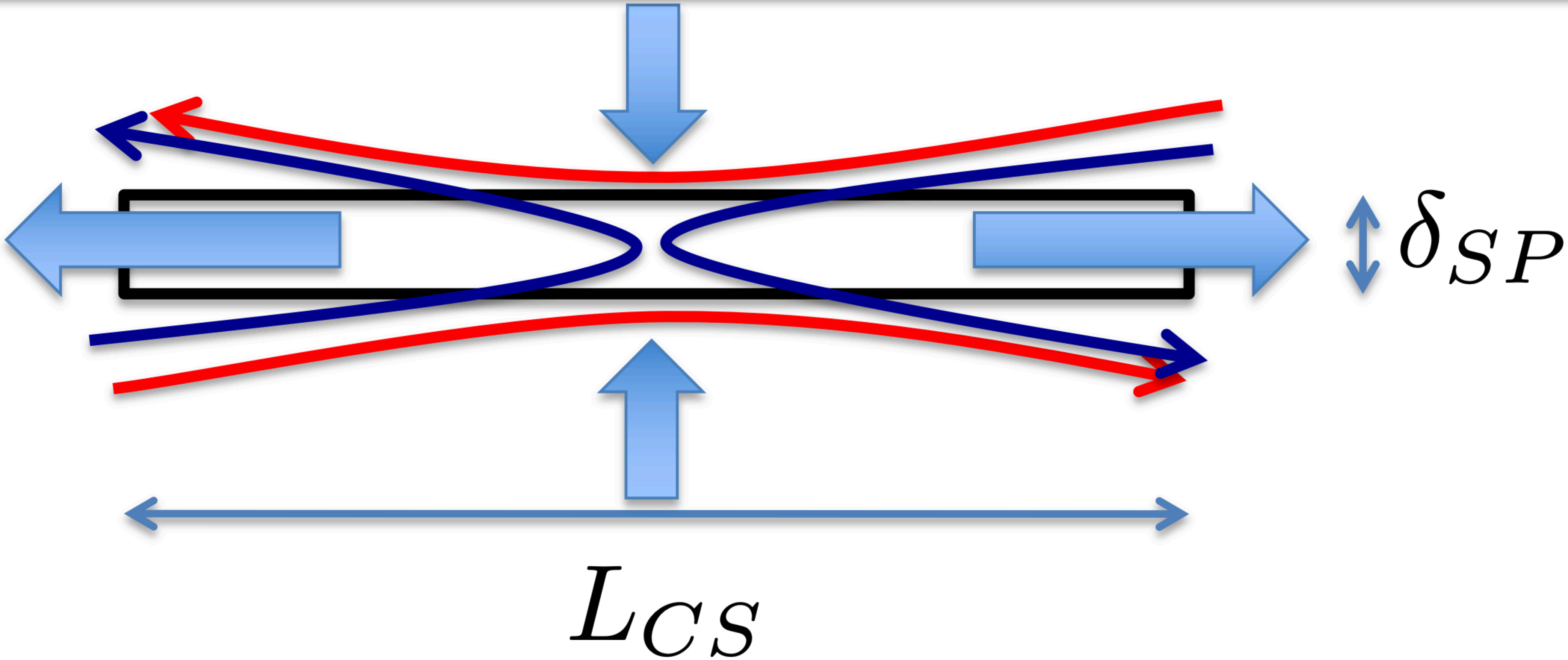
$$\rho v_{\rm in} L = \rho v_{\rm out} \delta \quad \Rightarrow \quad v_{\rm in} = \frac{\delta}{L} v_{\rm out}$$

Mass conservation (assuming incompressibility)

The Sweet-Parker Theory



- Sweet (1958) and Parker (1957) have an elegant argument here: the stuff that goes in, must come out!

$$\rho v_{\rm in} L = \rho v_{\rm out} \delta \quad \Rightarrow \quad v_{\rm in} = \frac{\delta}{L} v_{\rm out}$$

Mass conservation (assuming incompressibility)

$$\left(\frac{B_0^2}{2\mu_0}\right) v_{\rm in} L = \left(\frac{1}{2}\rho v_{\rm out}^2\right) v_{\rm out}\delta$$

$$\frac{B_0^2}{\mu_0}\left(\frac{\delta}{L} v_{\rm out}\right) L = \rho v_{\rm out}^3 \delta$$

Energy conservation (assuming negligible upstream pressure)

$$\frac{B_0^2}{\mu_0} v_{\rm out}\delta = \rho v_{\rm out}^3 \delta \quad \Rightarrow \quad v_{\rm out}^2 = \frac{B_0^2}{\mu_0 \rho} \quad \Rightarrow \quad v_{\rm out} = v_A$$

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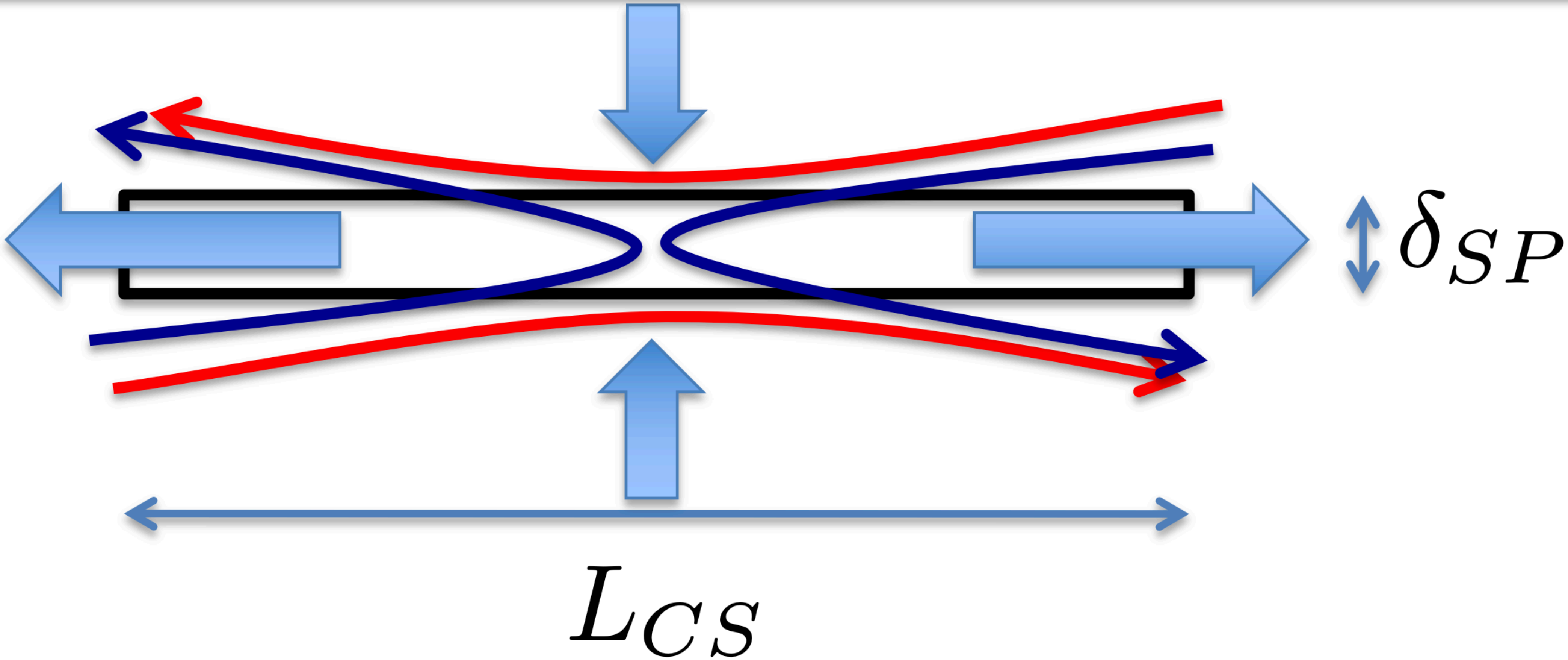

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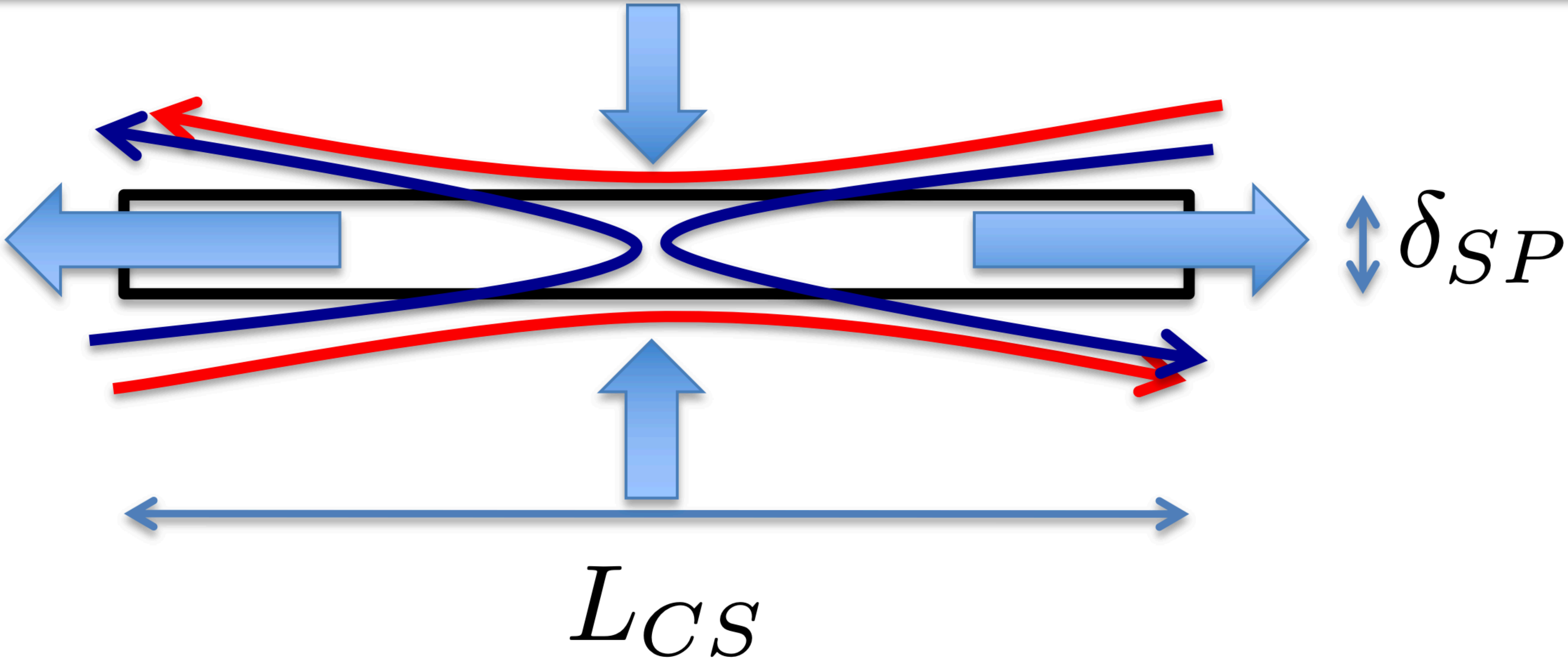

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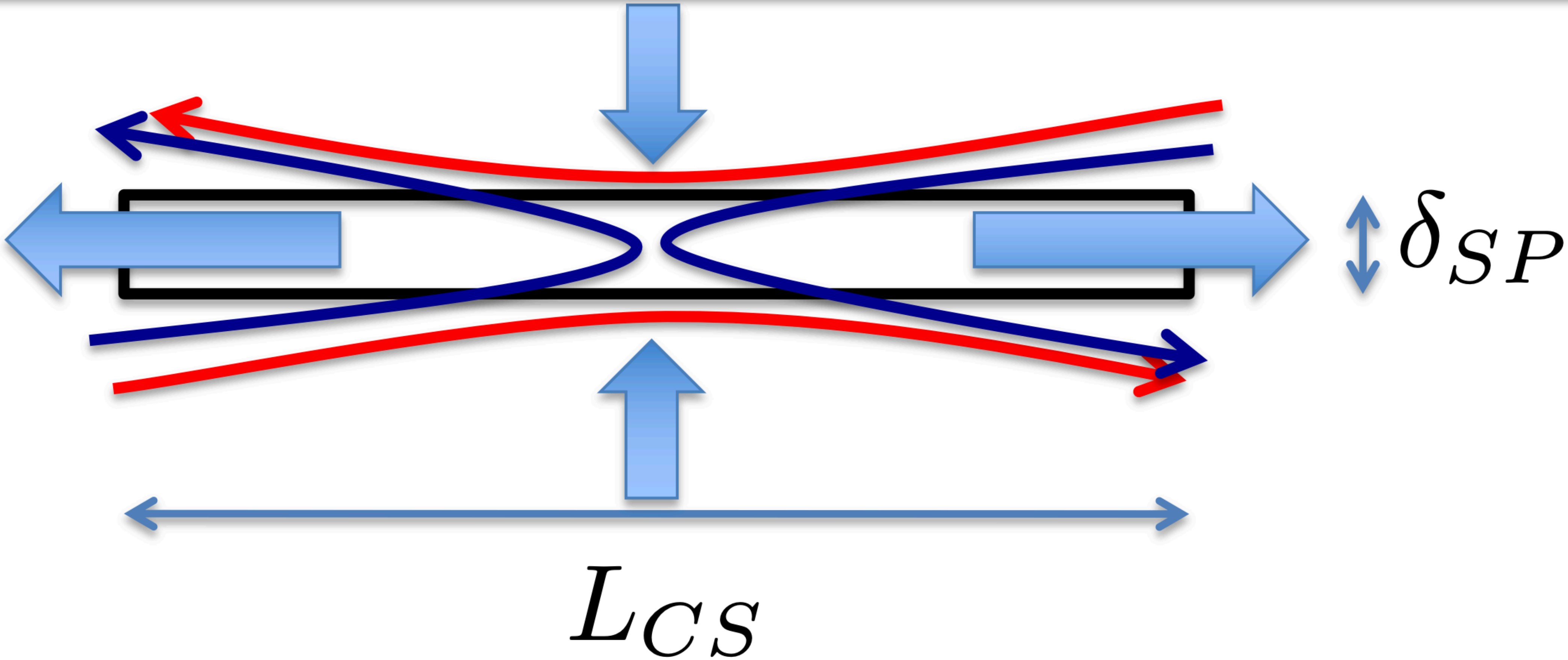
$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{\sigma}\mathbf{J}$$

$$E_z = -v_{\rm in} B_0$$ Outside the layer

$$E_z = \frac{1}{\sigma} J_z = \frac{1}{\sigma\mu_0}\left(\nabla \times \mathbf{B}\right)_z \sim \frac{1}{\sigma\mu_0}\frac{B_0}{\delta}$$ Inside the layer

$$v_{\rm in} \sim \frac{\eta}{\delta}, \quad \eta = \frac{1}{\sigma\mu_0}$$

Putting it all together



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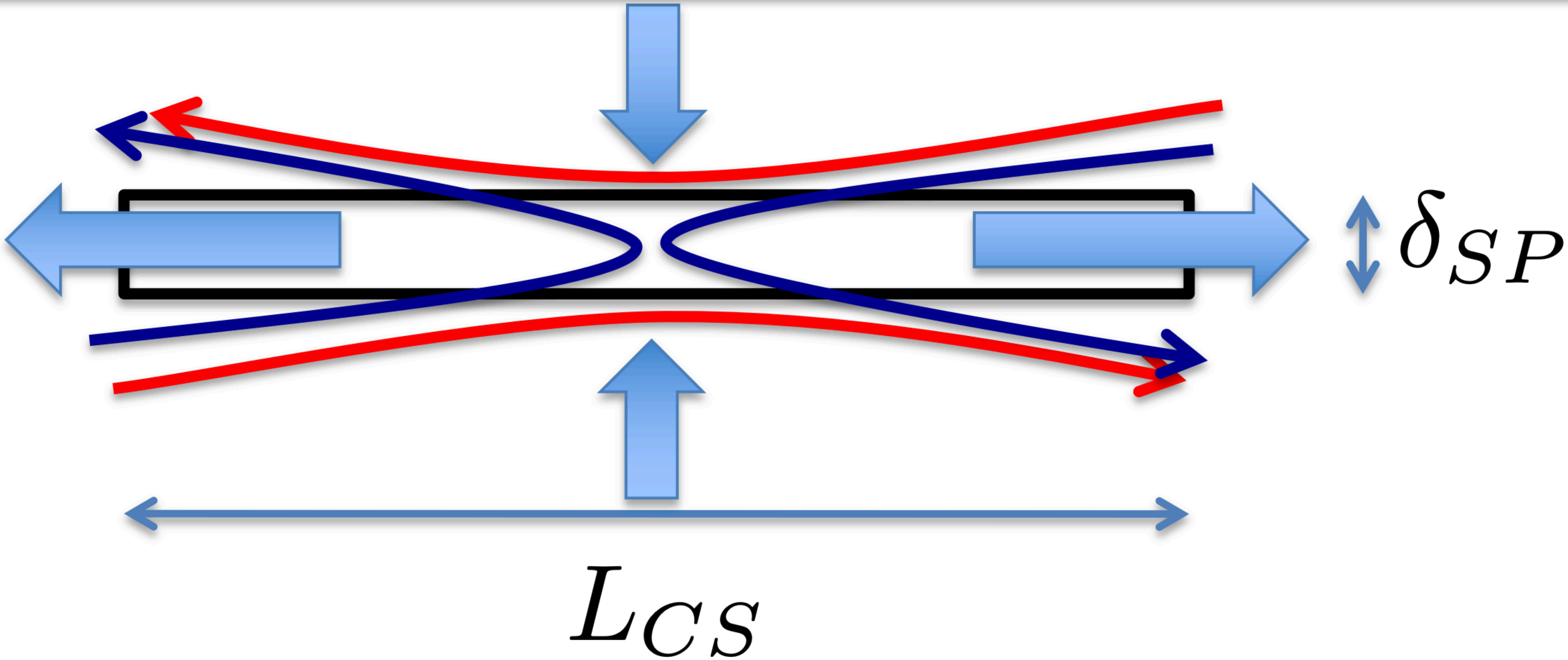

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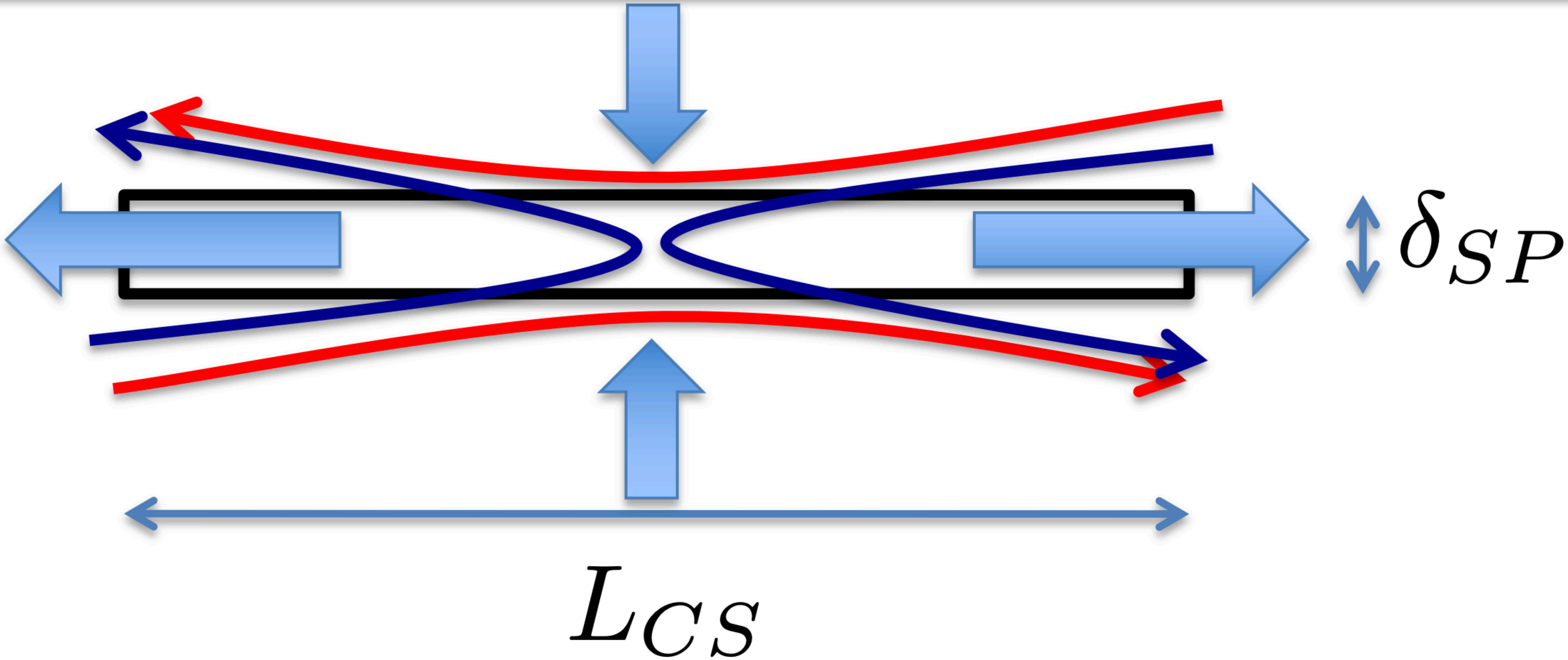

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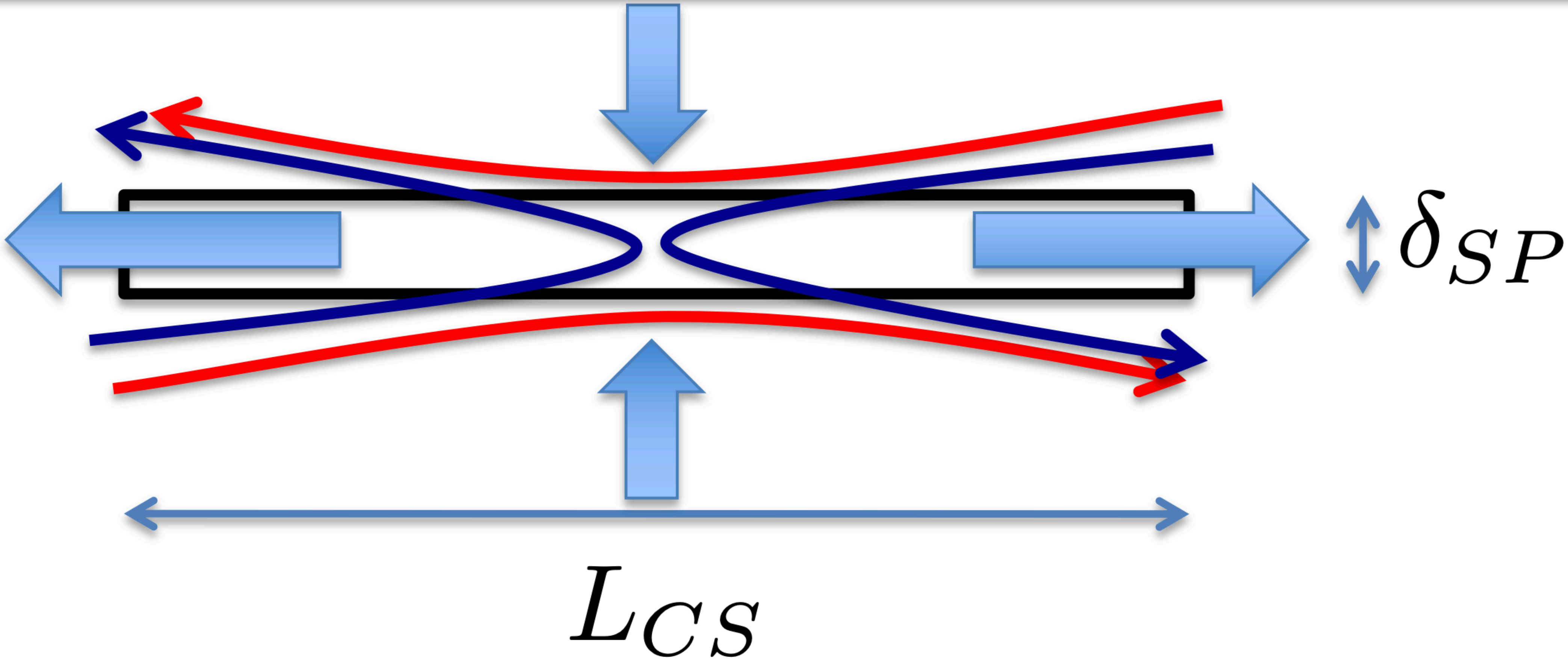

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Typical solar corona parameters yield S~10^14

This theory then predicts that flares should last ~2 months; in fact, flares last 15min – 1h.

So we need faster reconnection, but how?

- We need to add more physics beyond MHD*!

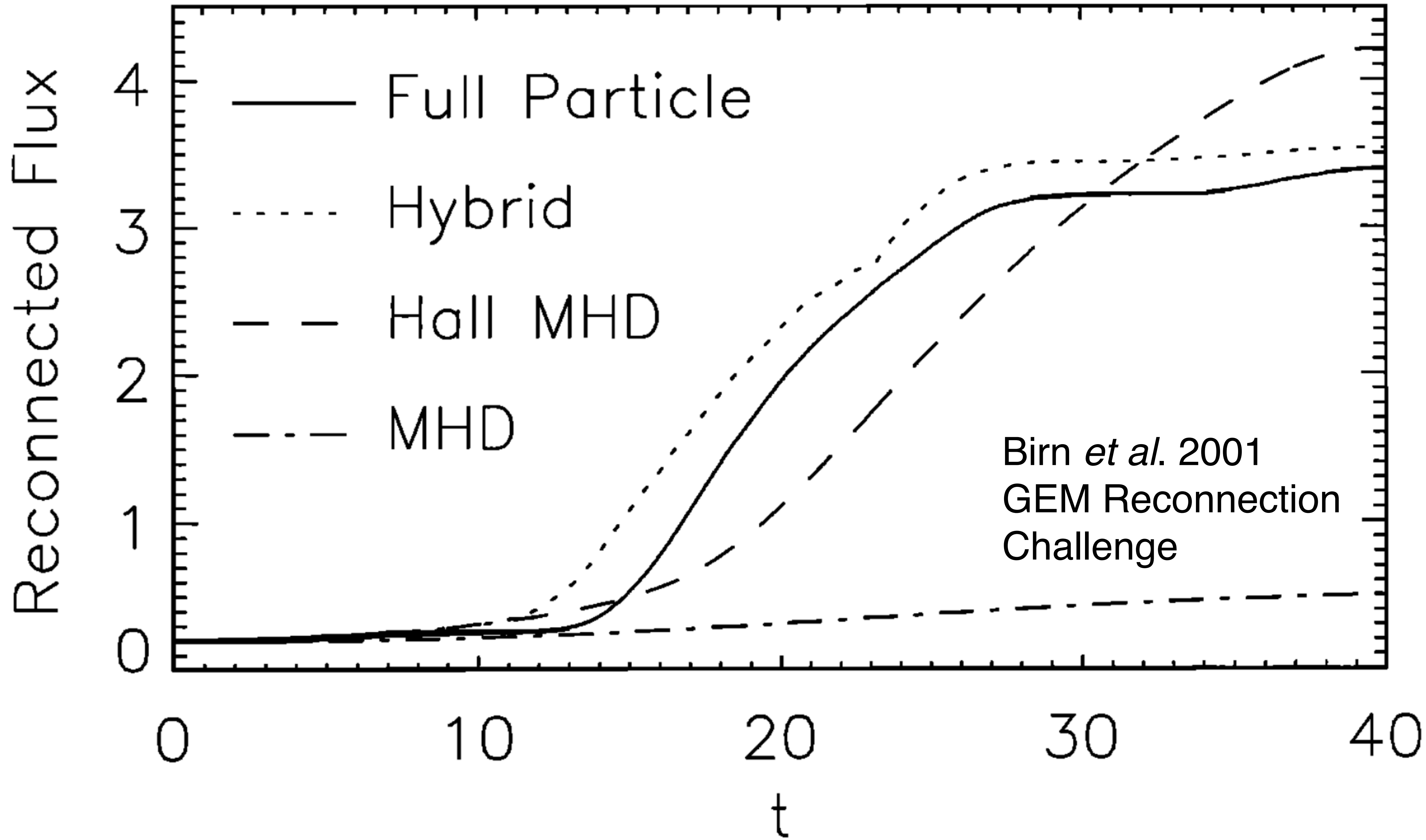

Figure 1. The reconnected magnetic flux versus time from a variety of simulation models: full particle, hybrid, Hall MHD, and MHD (for resistivity $\eta = 0.005$).

*Caveat the MHD can get faster reconnection (but not fast!) via the plasmoid instability

What does “more physics” mean?

- Let’s think back to our Ohm’s Law

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{\sigma}\mathbf{J}$$

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$$\mathbf{E} = \frac{m_e}{q_e \rho_e} \left[\underbrace{\frac{\partial (\rho_e \mathbf{u}_e)}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e \mathbf{u}_e)}_{\rho_e \left(\frac{\partial \mathbf{u}_e}{\partial t} + \mathbf{u}_e \cdot \nabla \mathbf{u}_e \right)} + \nabla \cdot \mathbf{P}_e \right] \underbrace{- \mathbf{u}_e \times \mathbf{B}}_{\sim -\mathbf{u}_i \times \mathbf{B} + \frac{m_e}{q_e \rho_e} \mathbf{J} \times \mathbf{B}} \underbrace{- \frac{m_e \nu_{ei}}{q_e \rho_e} \mathbf{J}}_{\frac{1}{\sigma}\mathbf{J}}$$

How does this work in our specific geometry?

- In a two-dimensional geometry, the important electric field is in z, exactly like with the Sweet-Parker derivation

$$E_z = \frac{m_e}{q_e}\left(\underbrace{\frac{\partial u_{z_e}}{\partial t} + u_{x_e}\frac{\partial u_{z_e}}{\partial x} + u_{y_e}\frac{\partial u_{z_e}}{\partial y}}_{Inertia} + \underbrace{\frac{1}{\rho_e}\left[\frac{\partial P_{xz_e}}{\partial x} + \frac{\partial P_{yz_e}}{\partial y}\right]}_{Pressure/FLR}\right)$$

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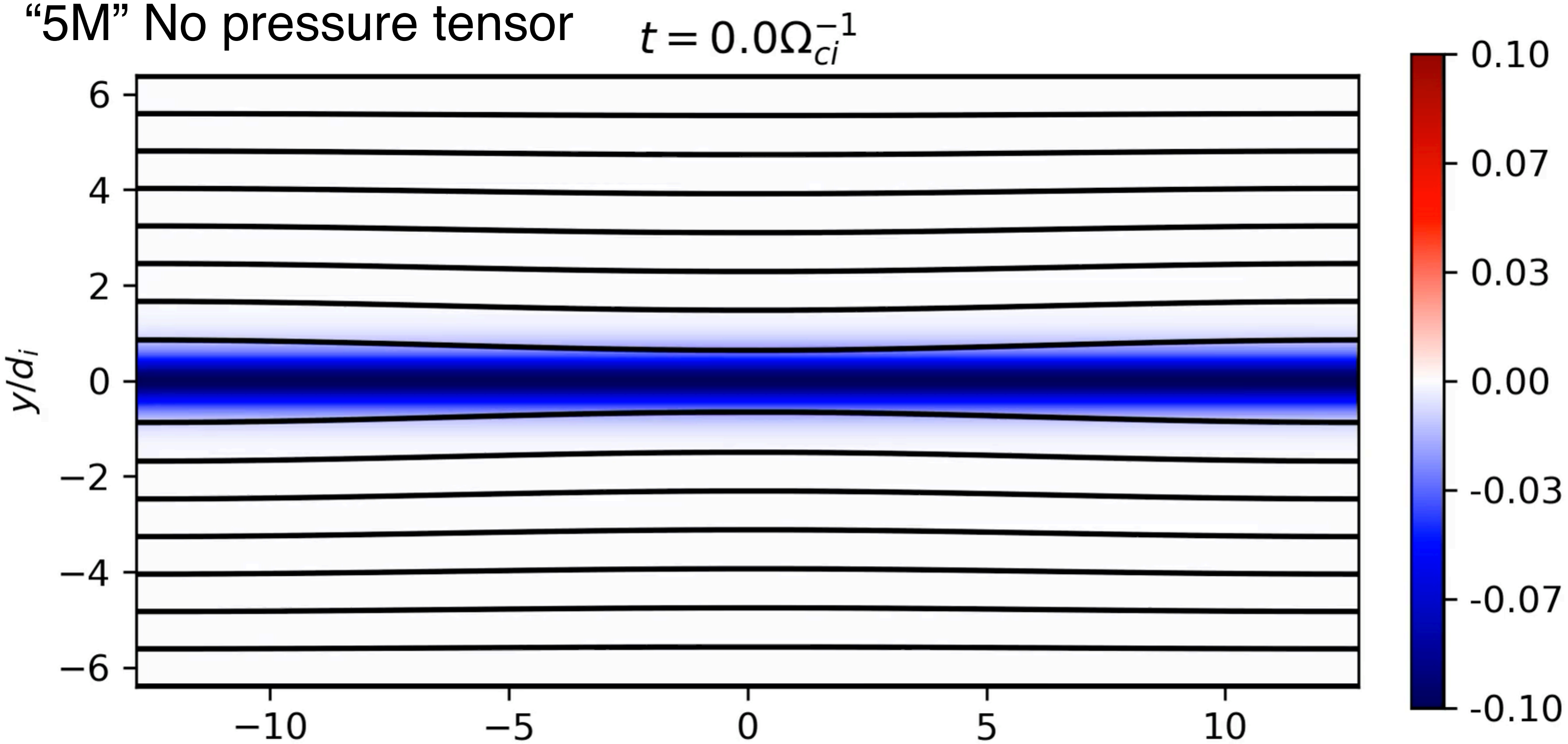
- Note that sometimes, the ideal and Hall terms are grouped together as a single term

Reconnection in multi-fluid models

“5M” No pressure tensor



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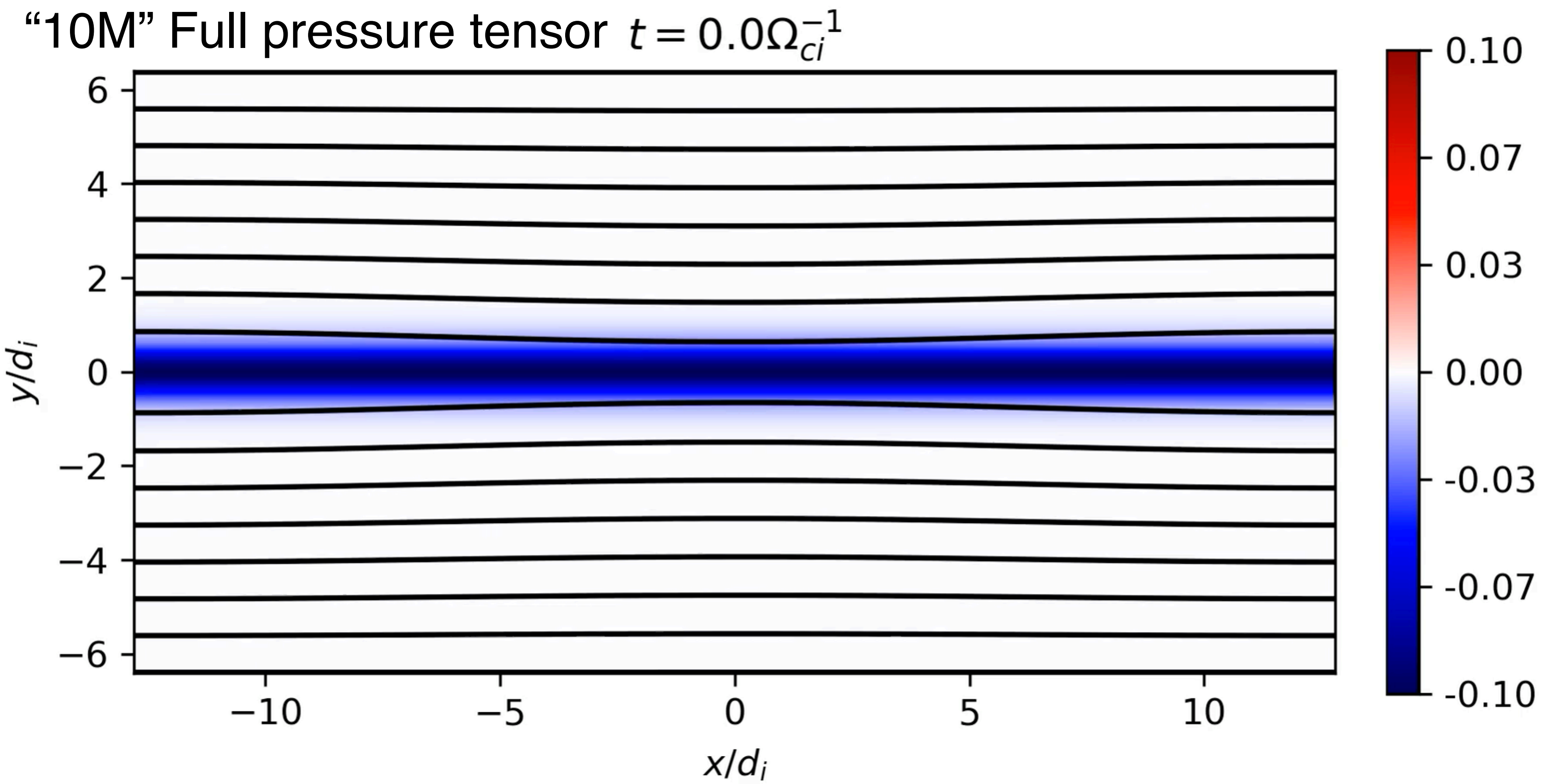

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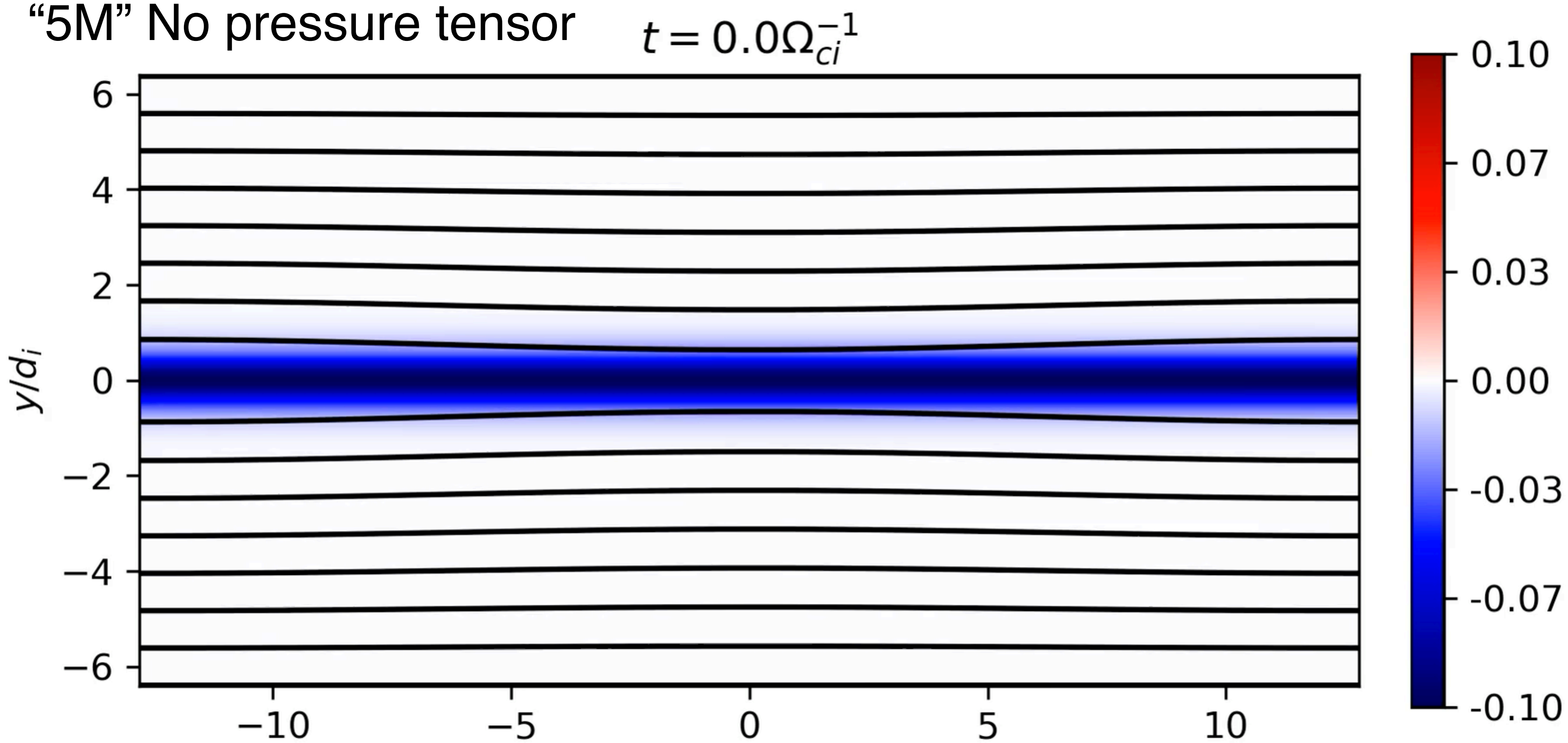

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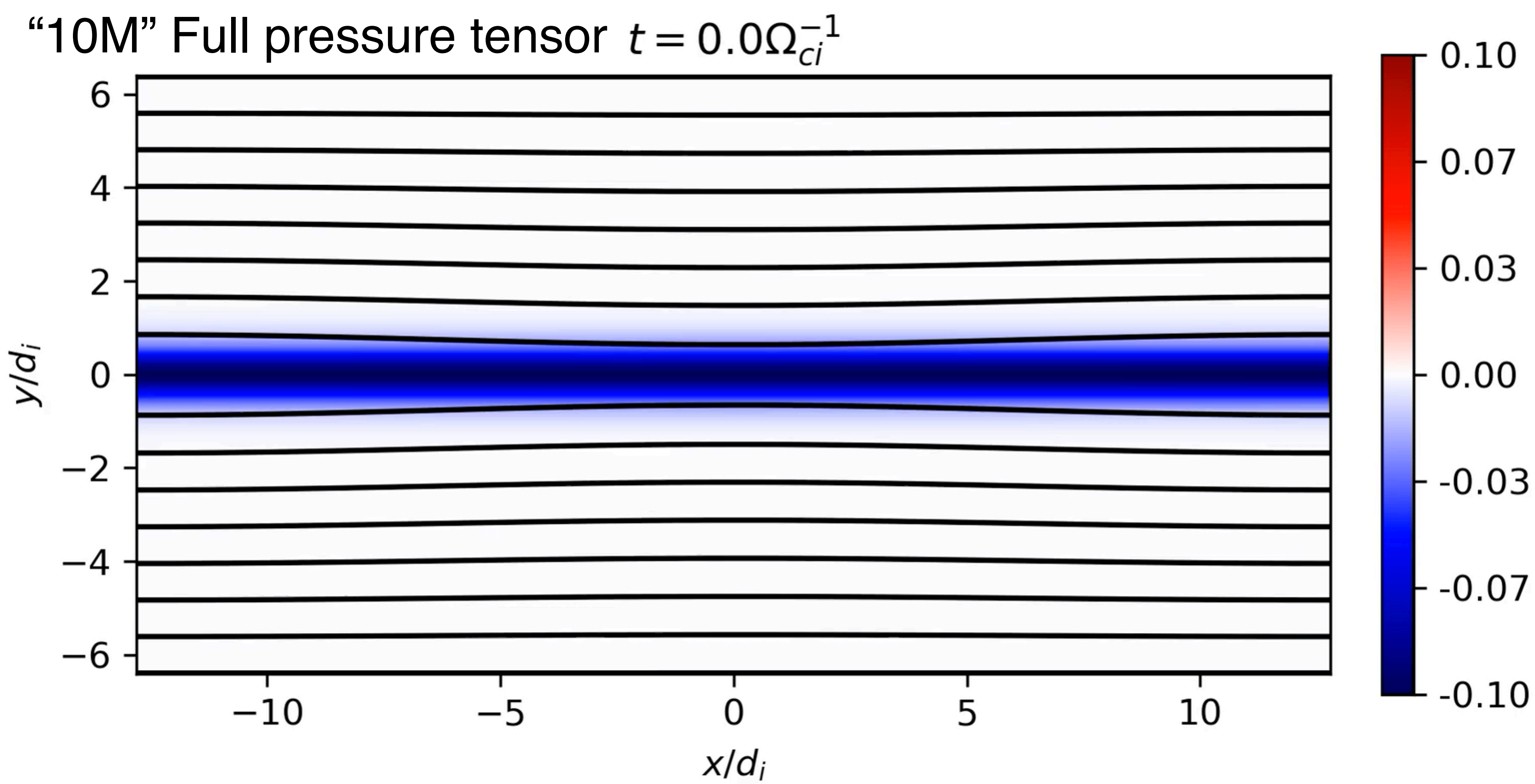

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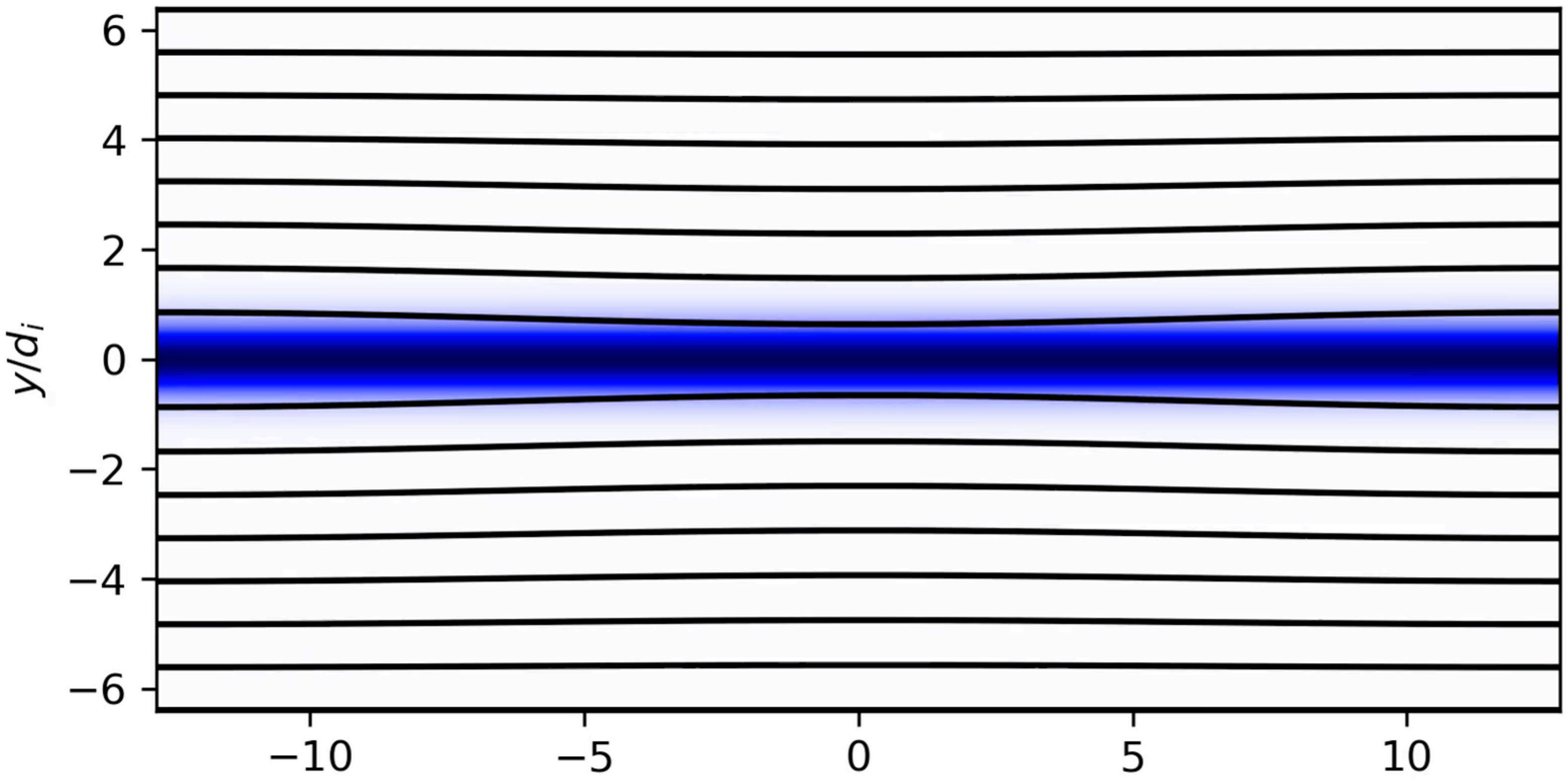

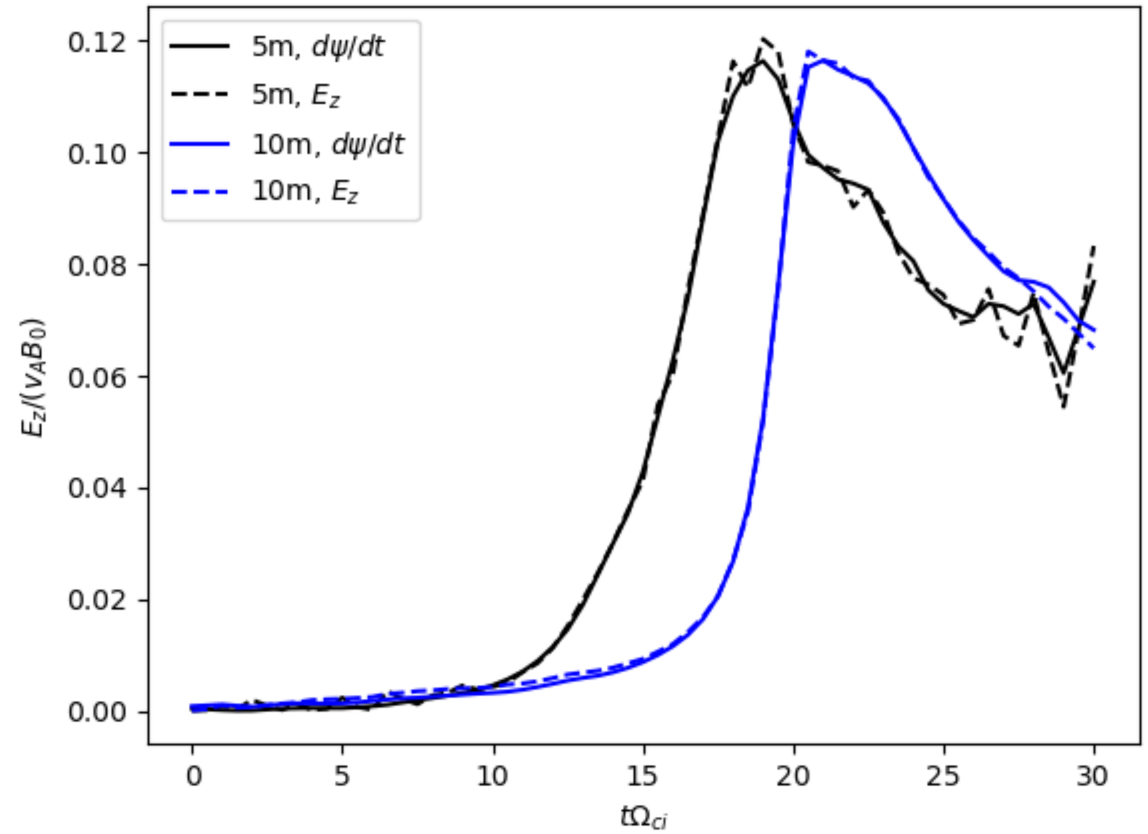

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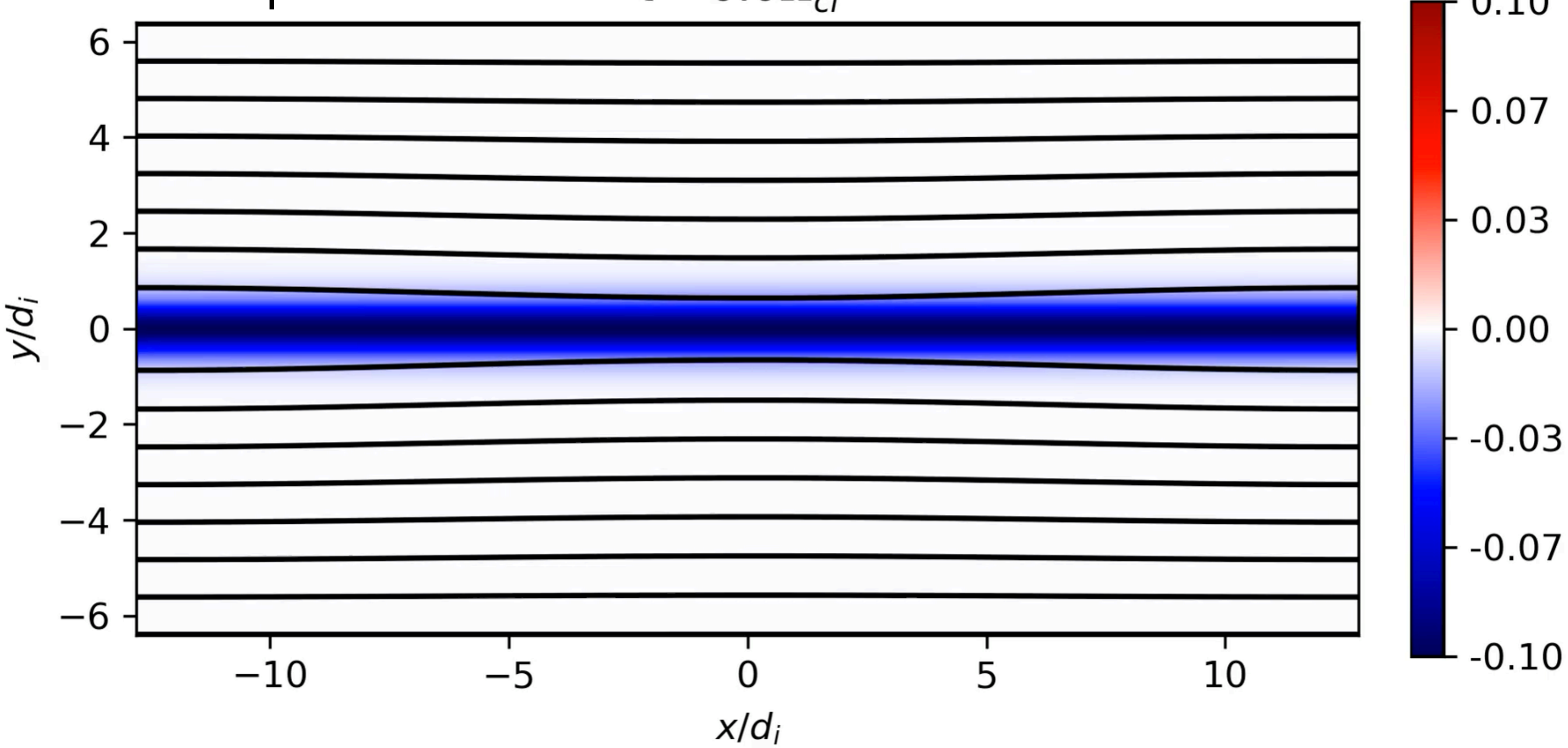

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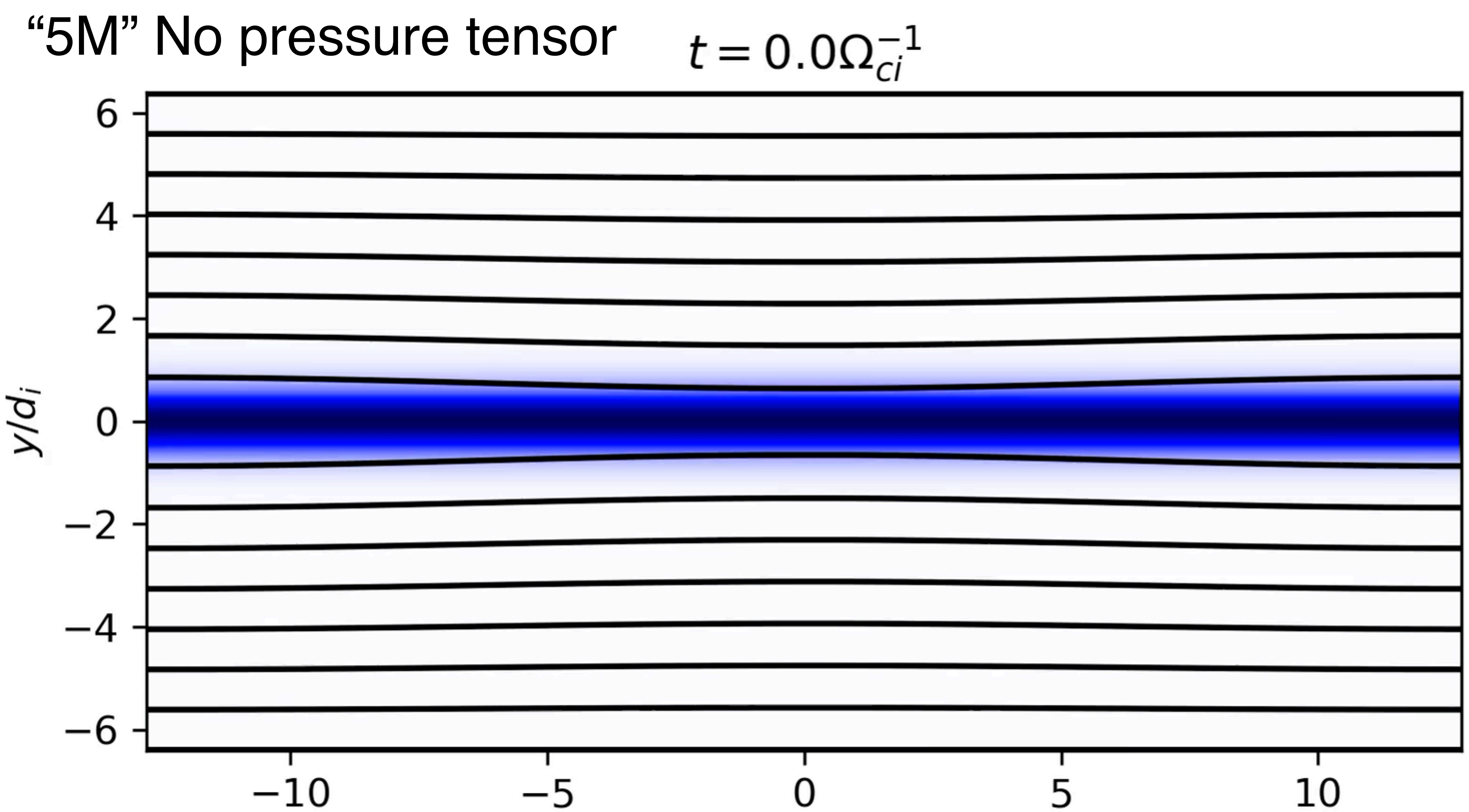

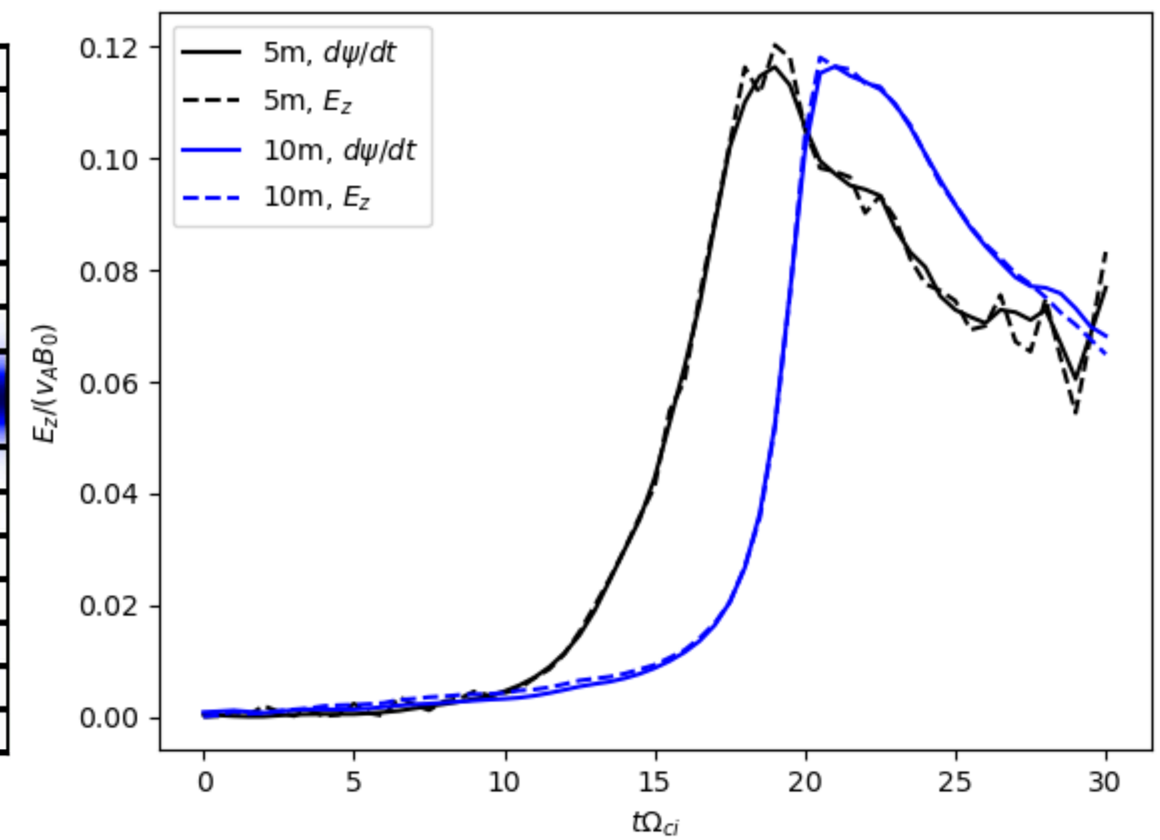

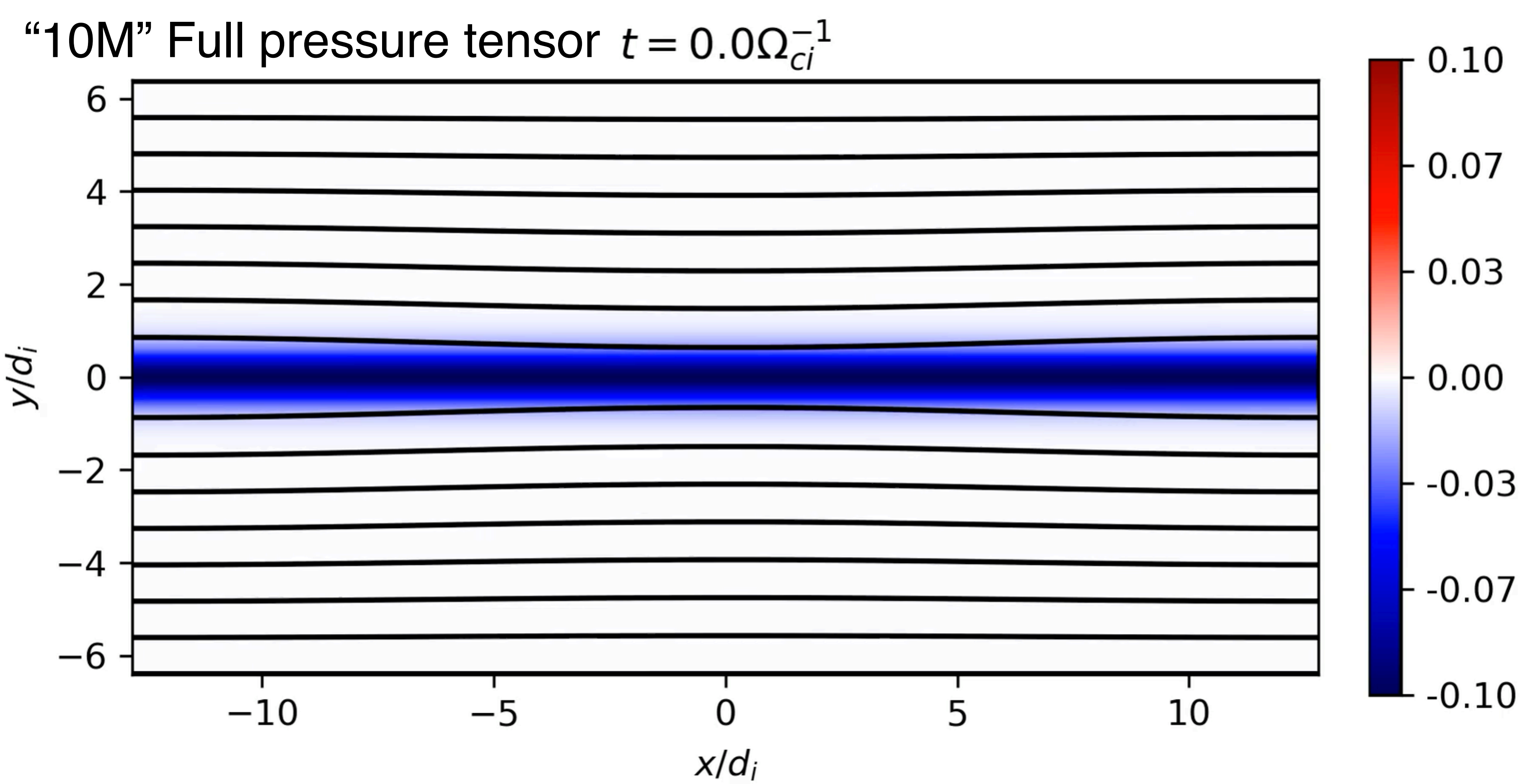

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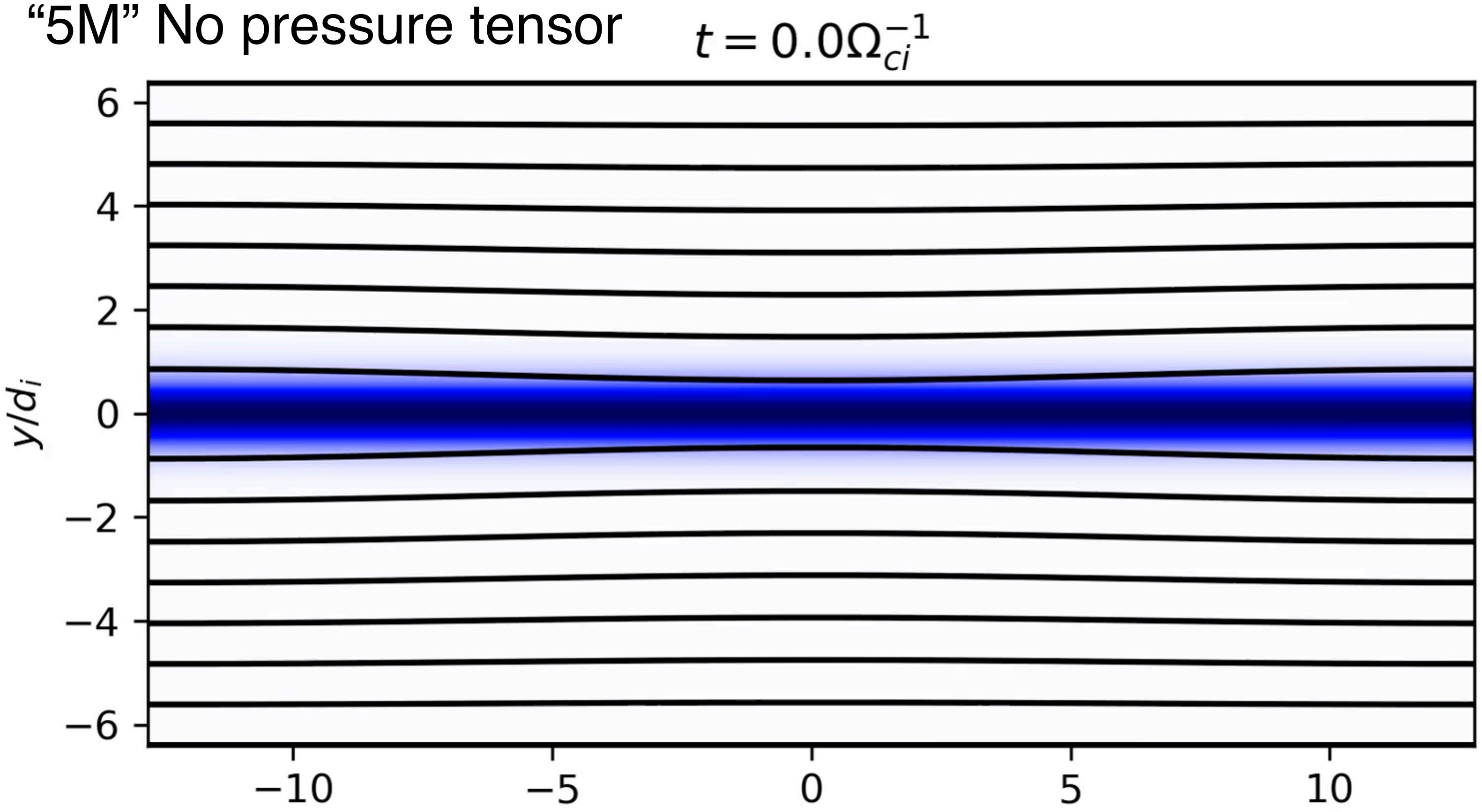

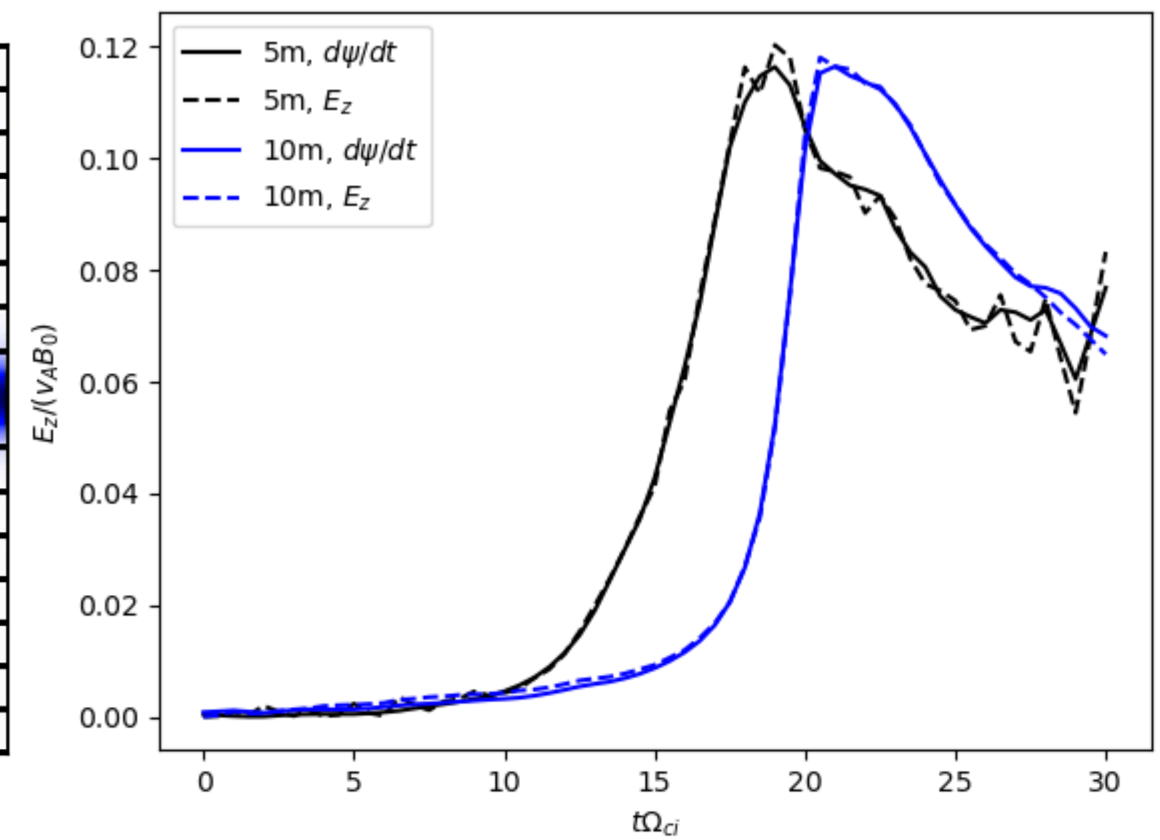

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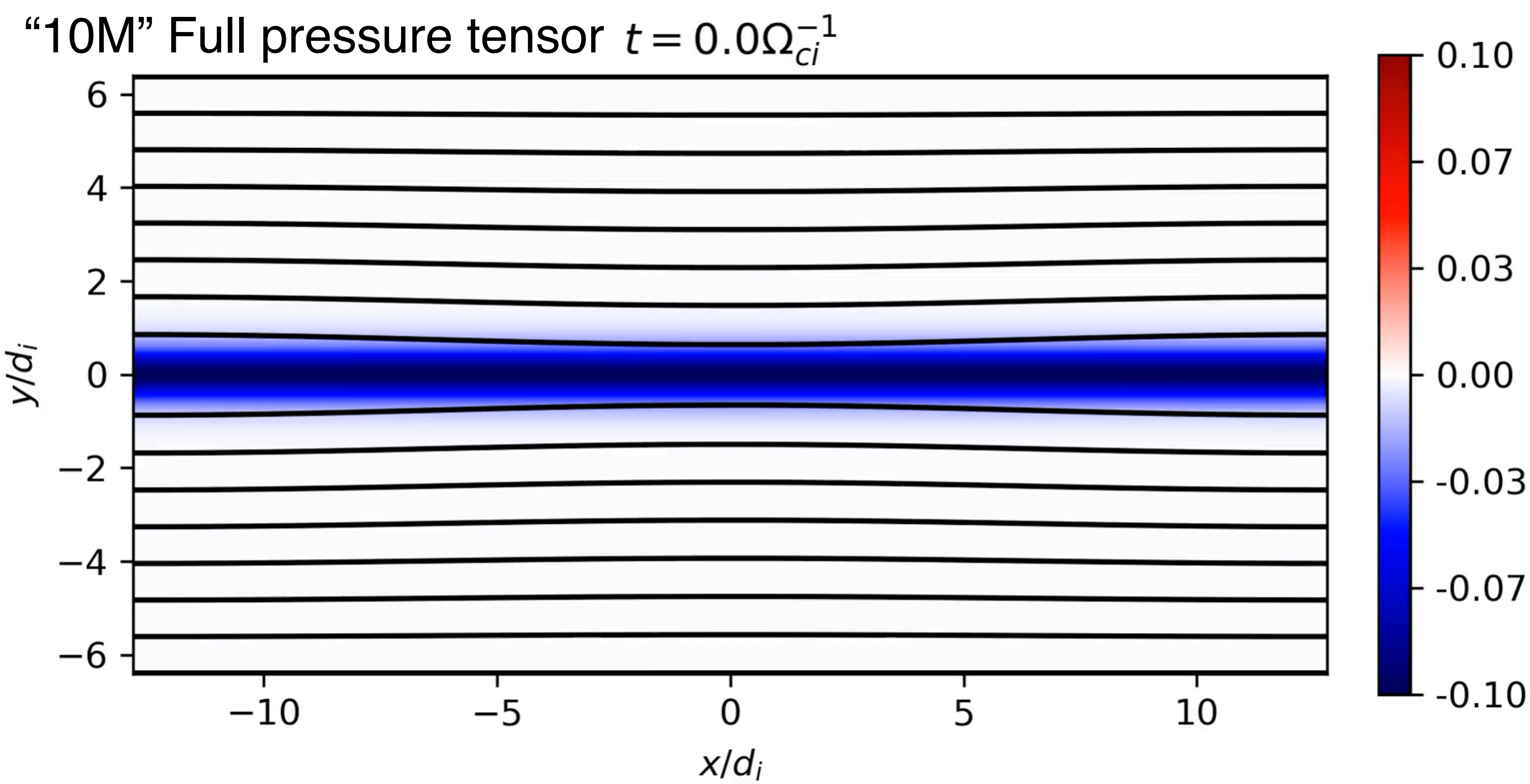

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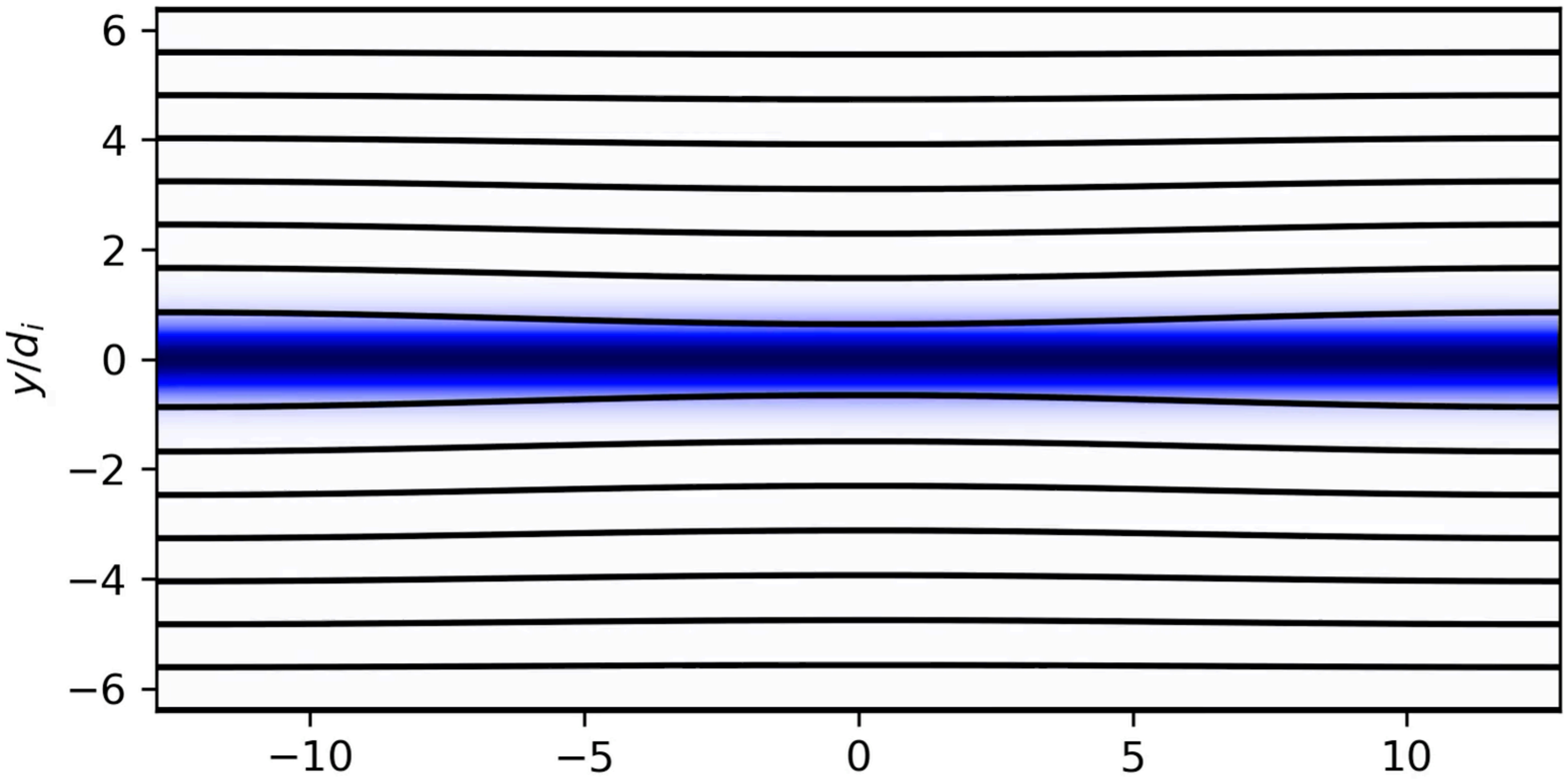

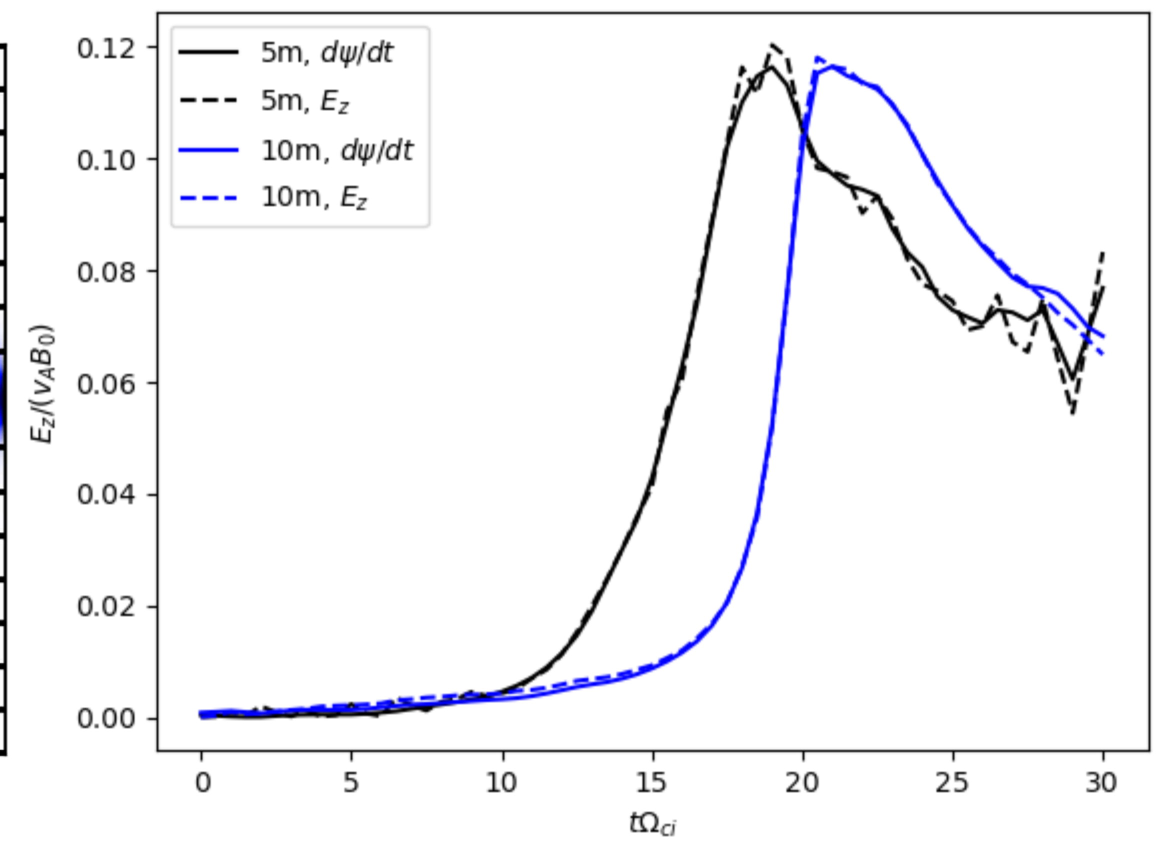

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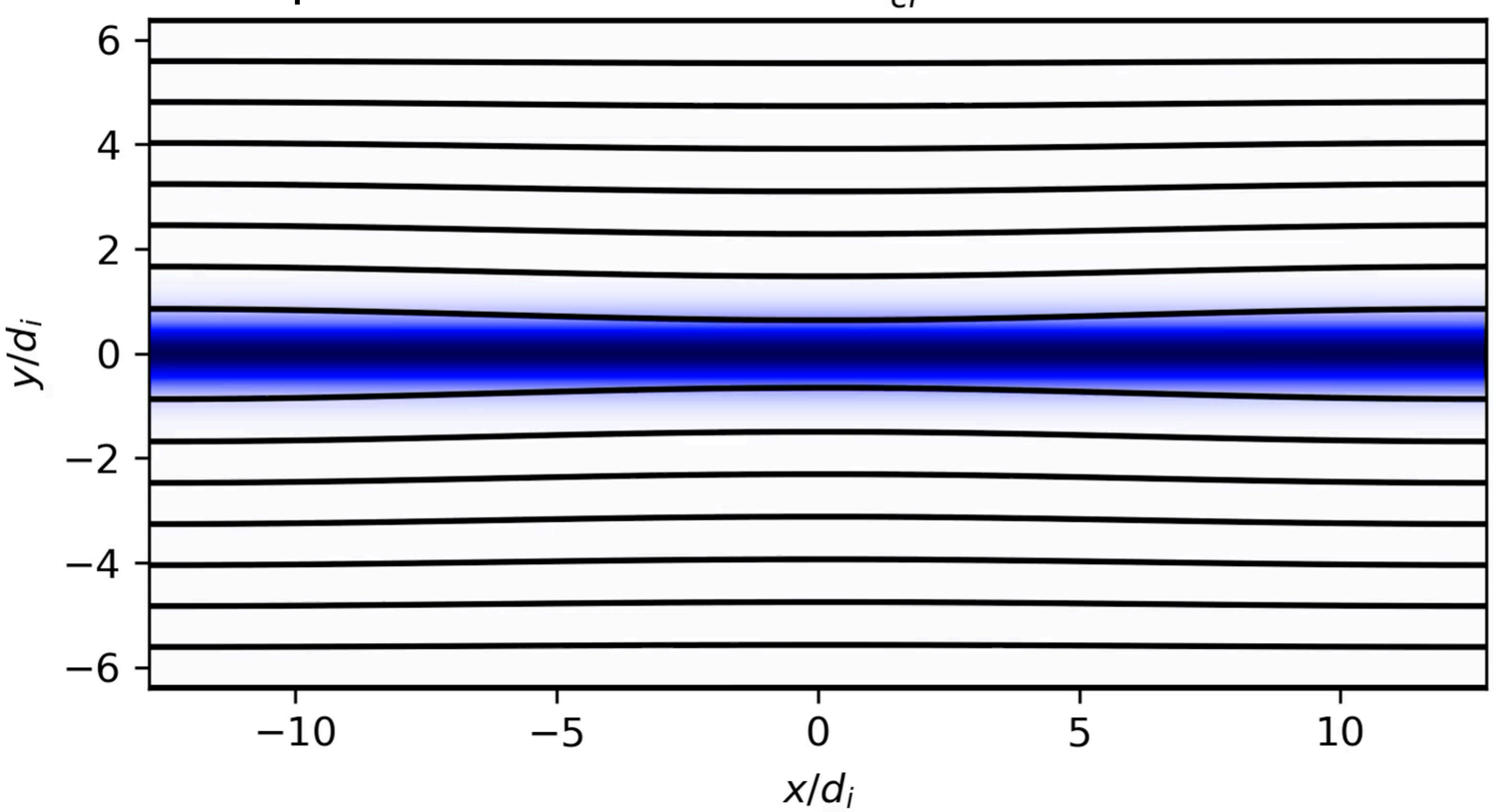

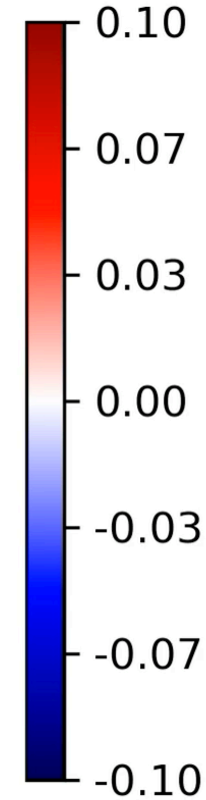

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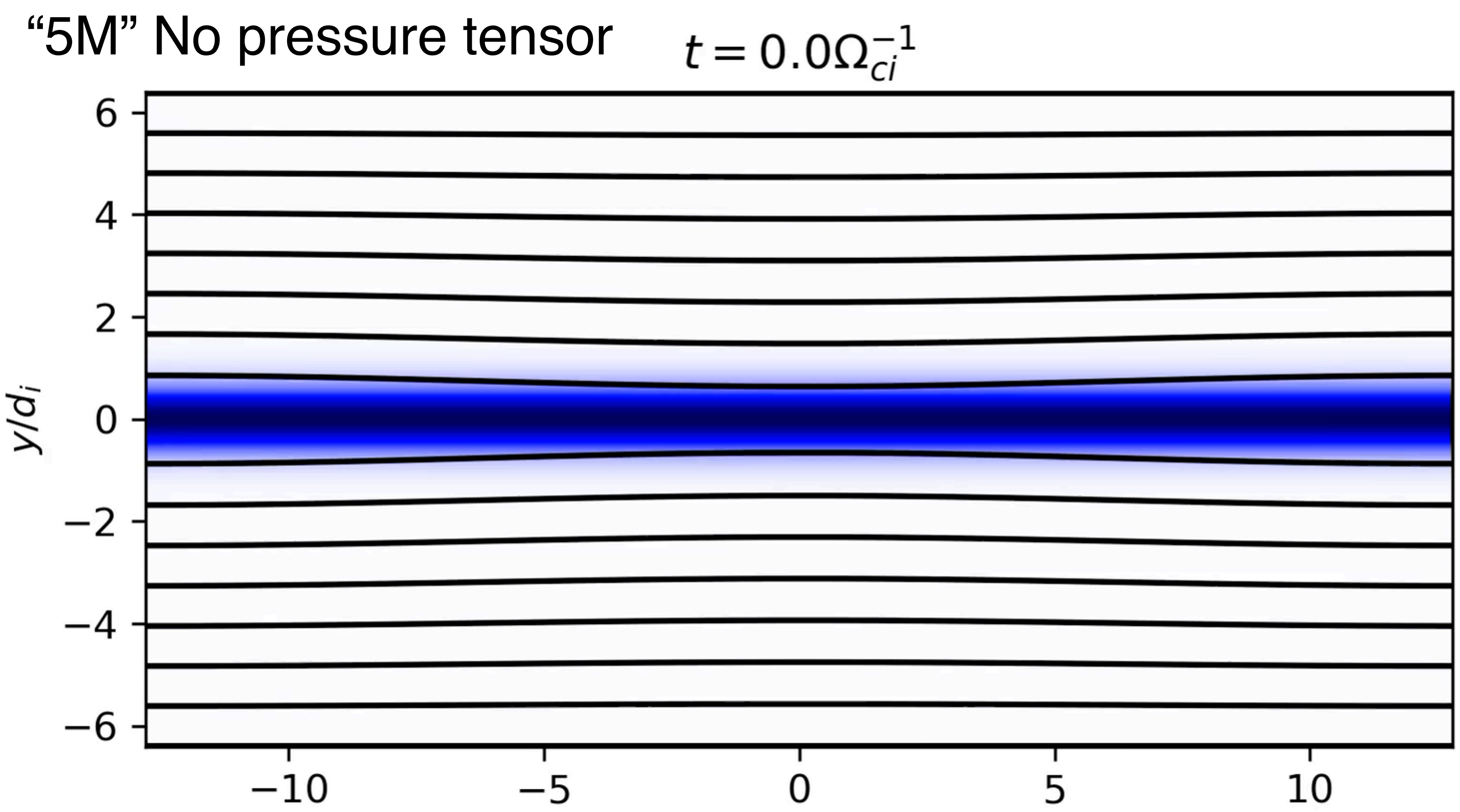

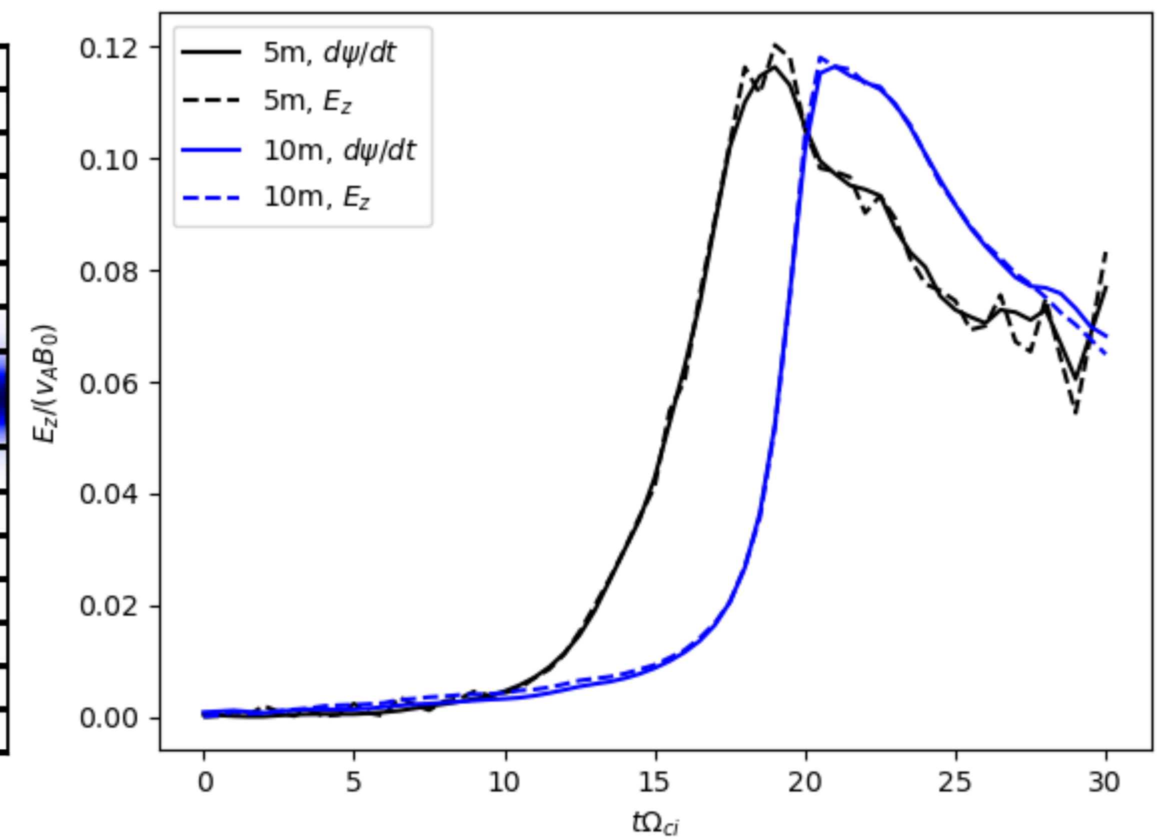

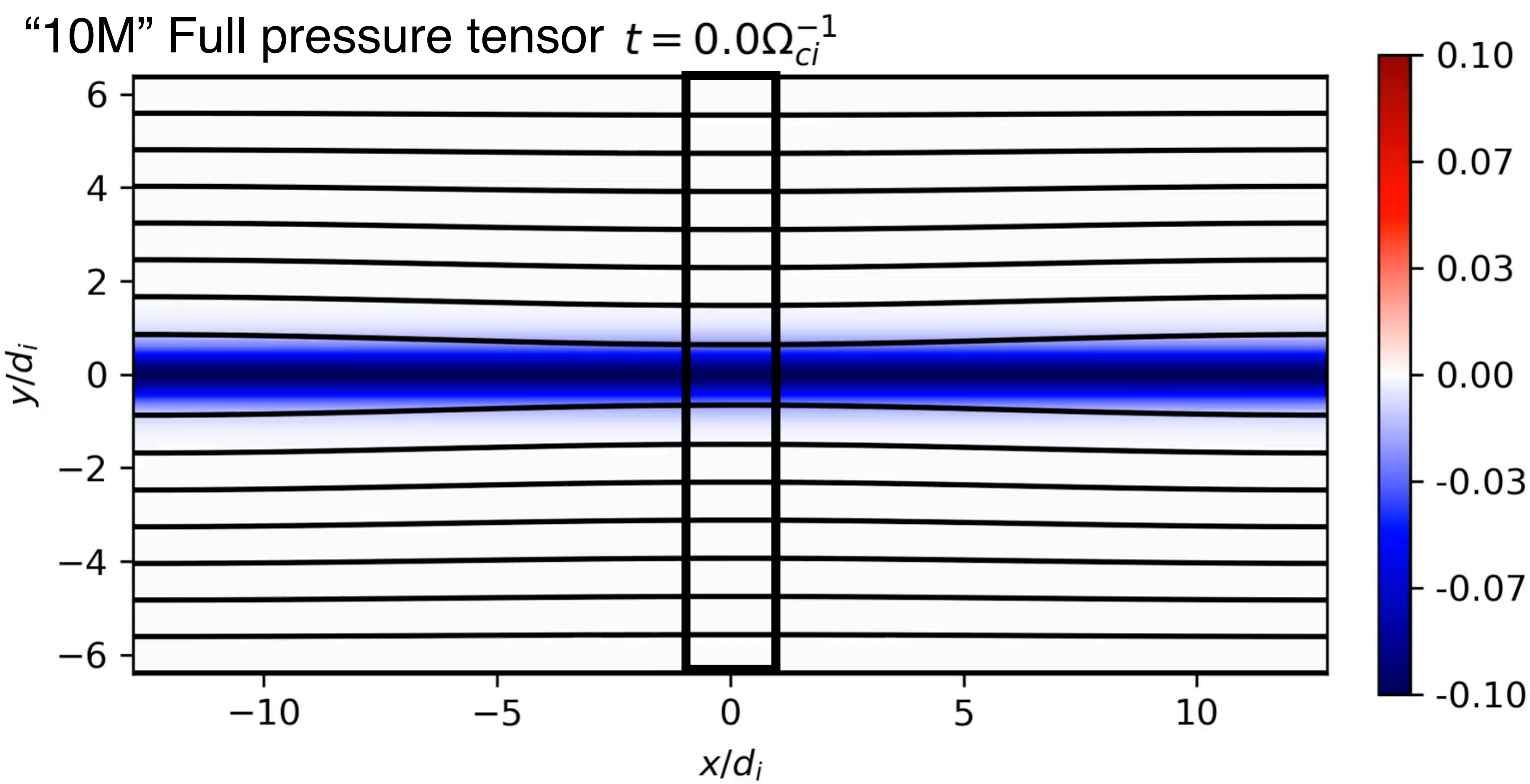

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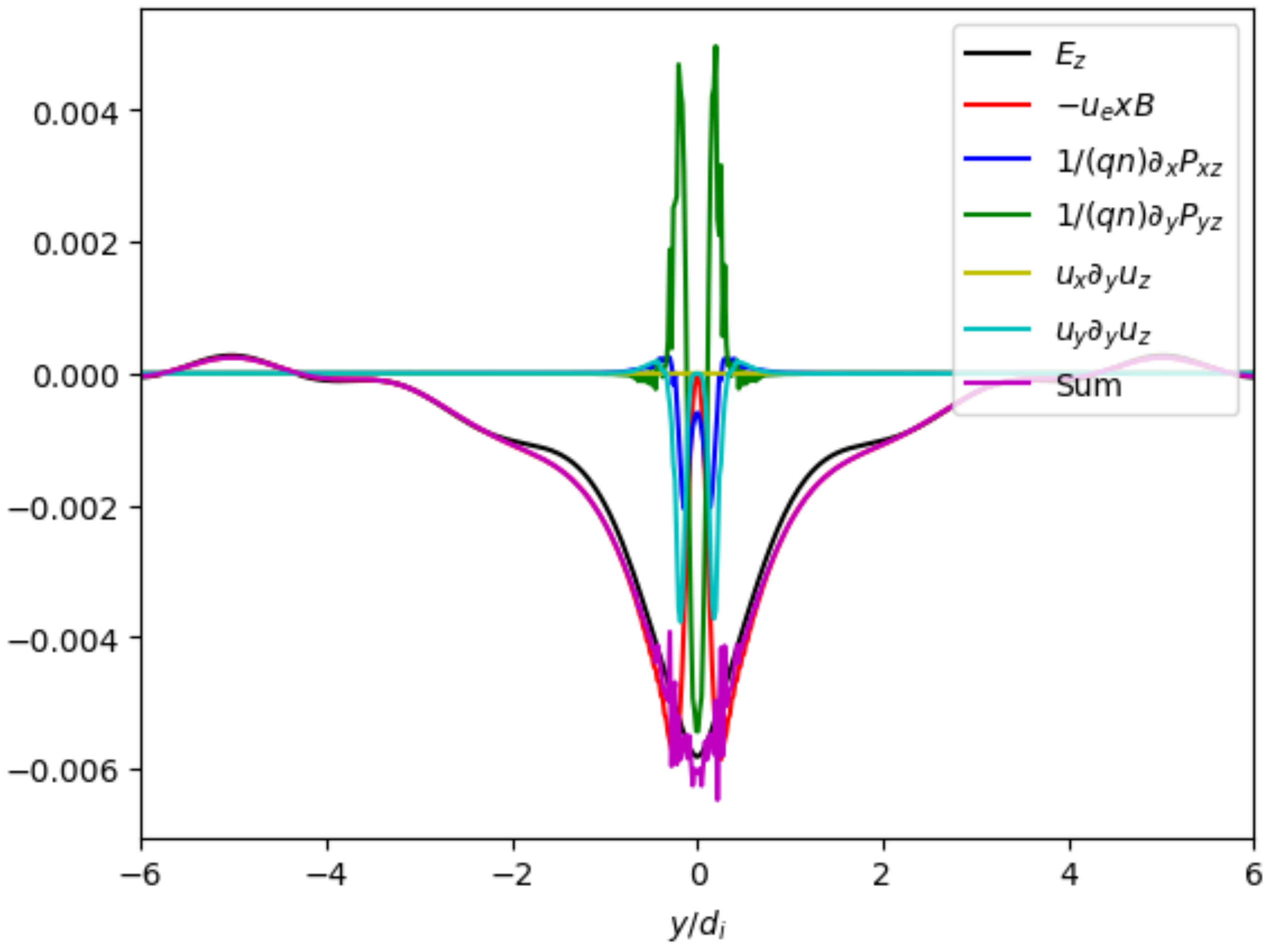

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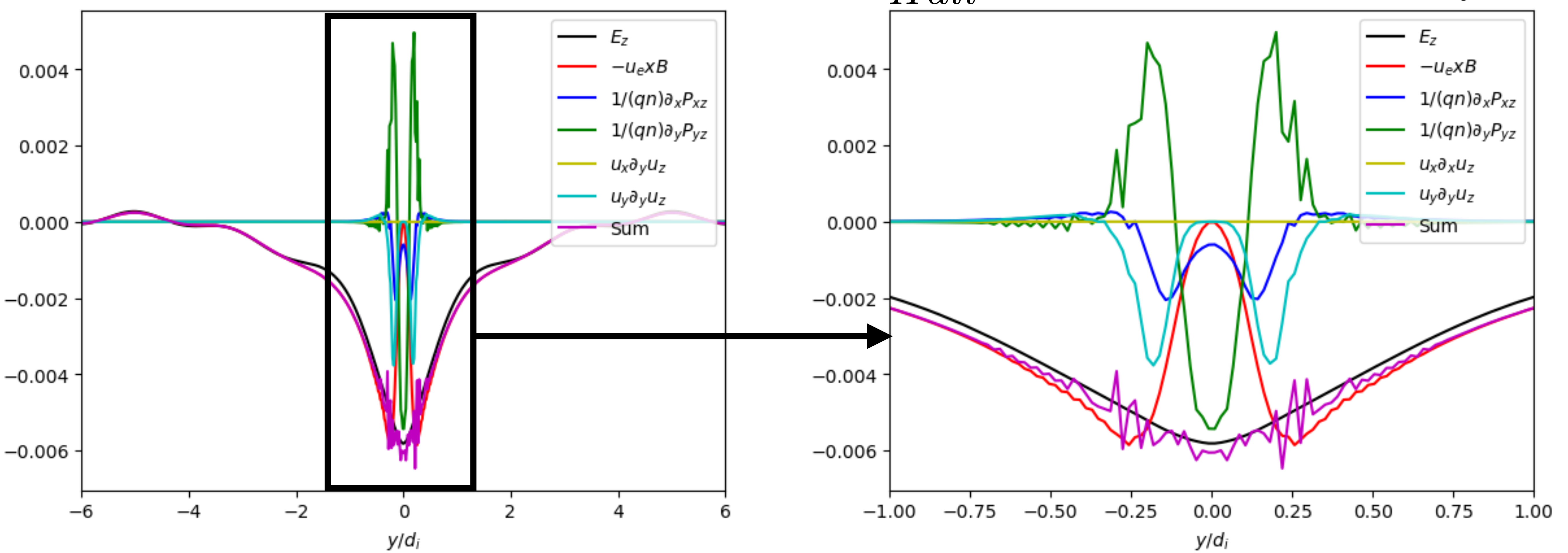

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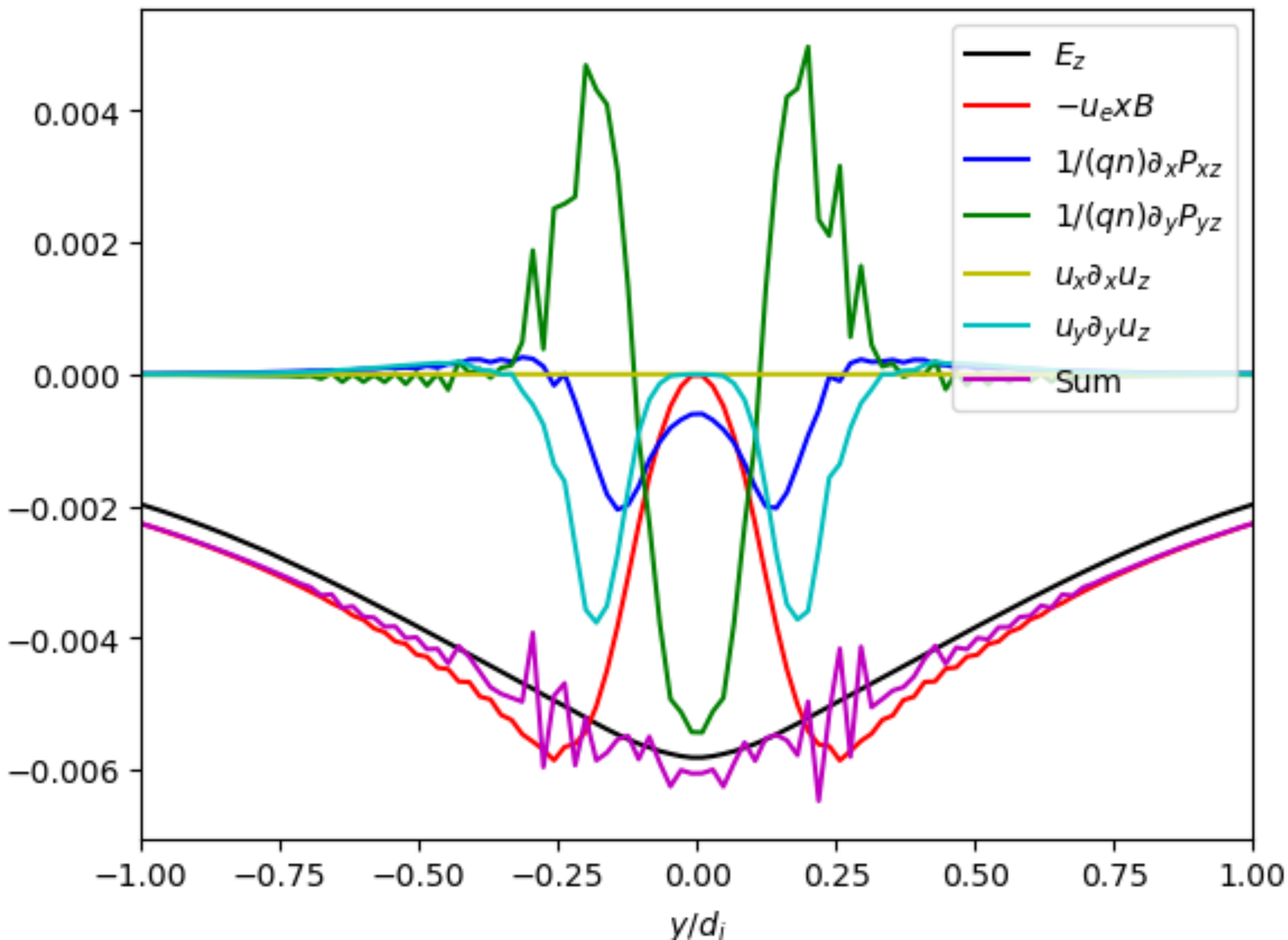

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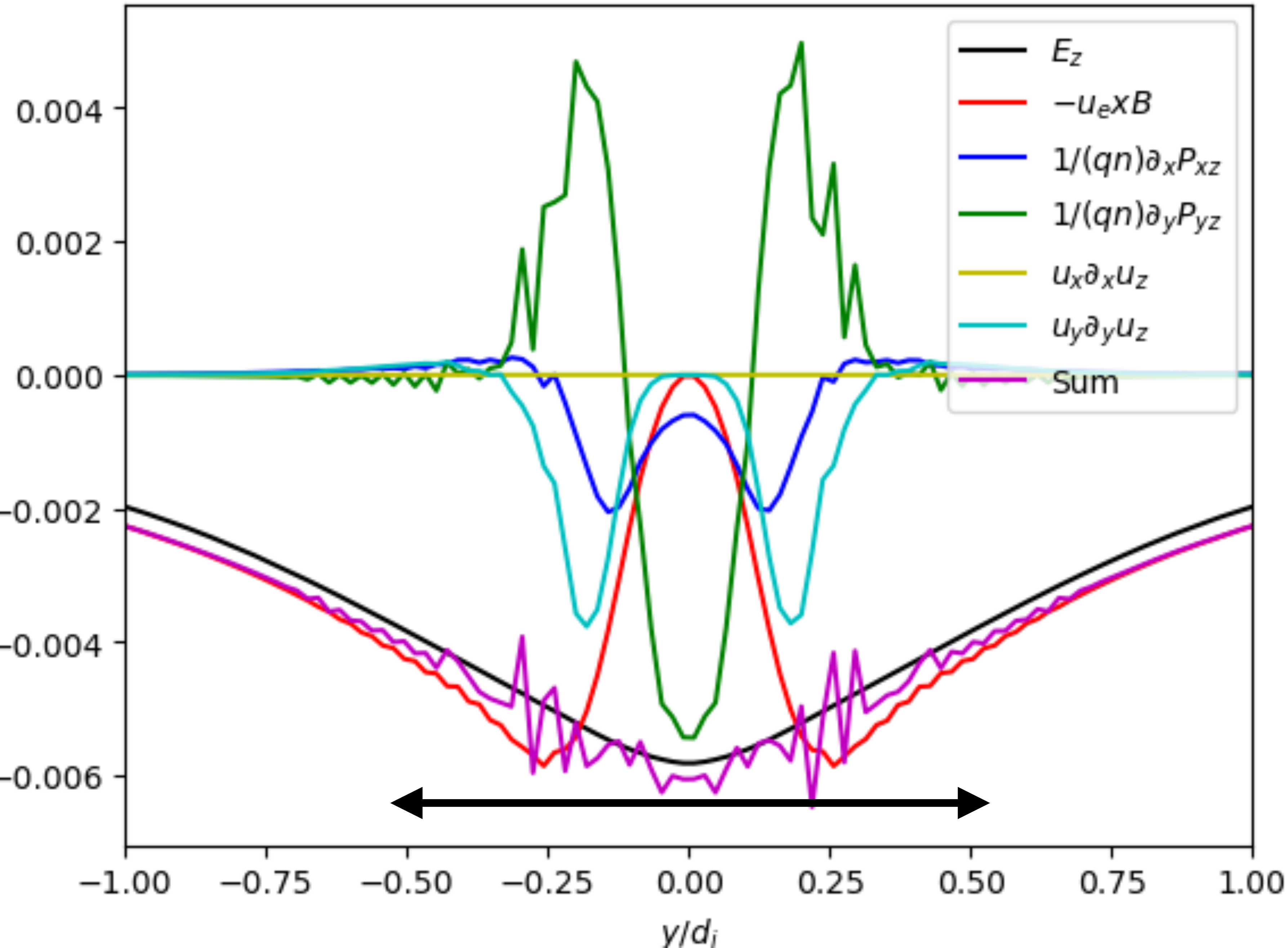

This layer width is much wider -> more flux can be processed and reconnection can proceed faster!

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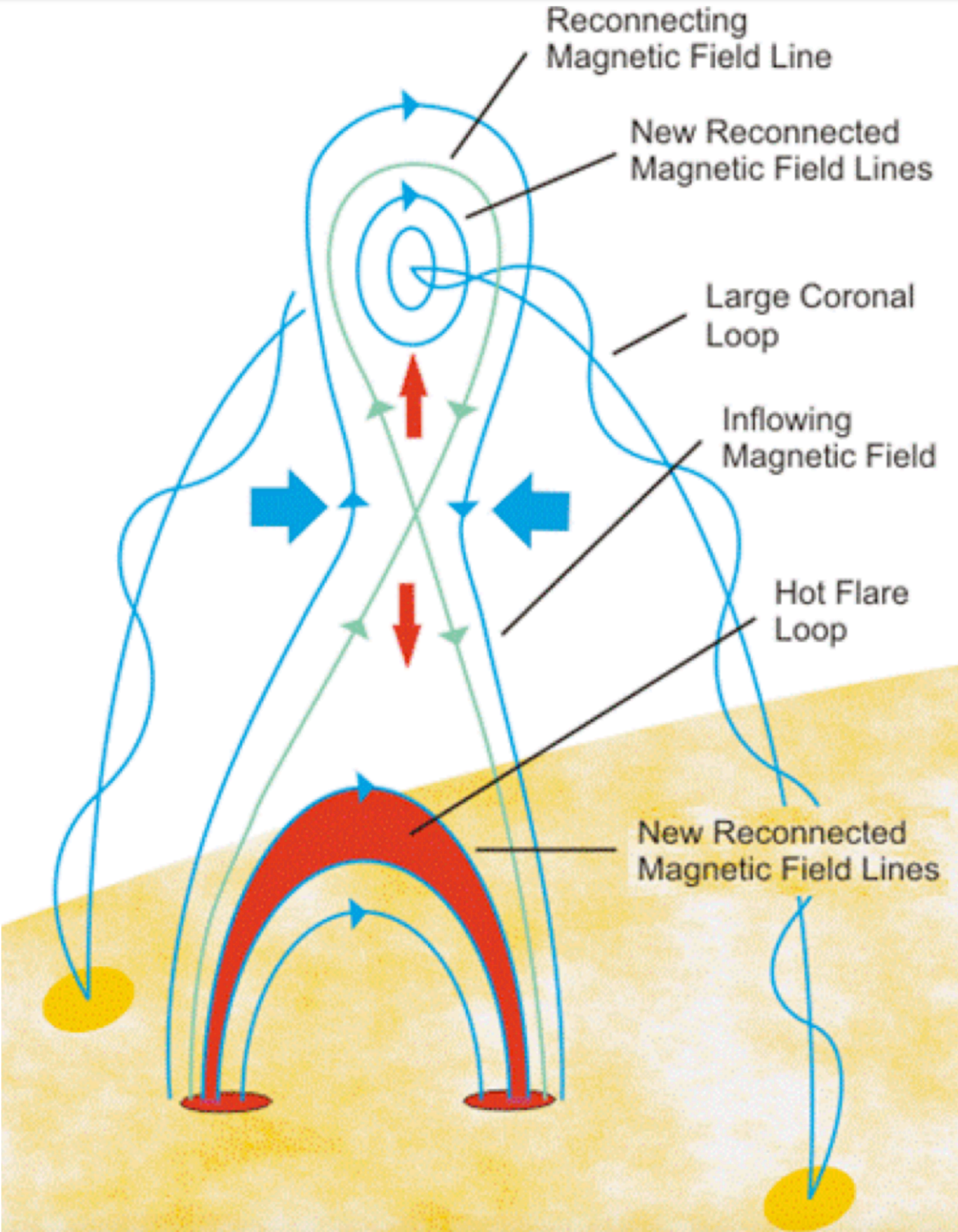
- The real frontier: how does the "micro" affect the "macro"



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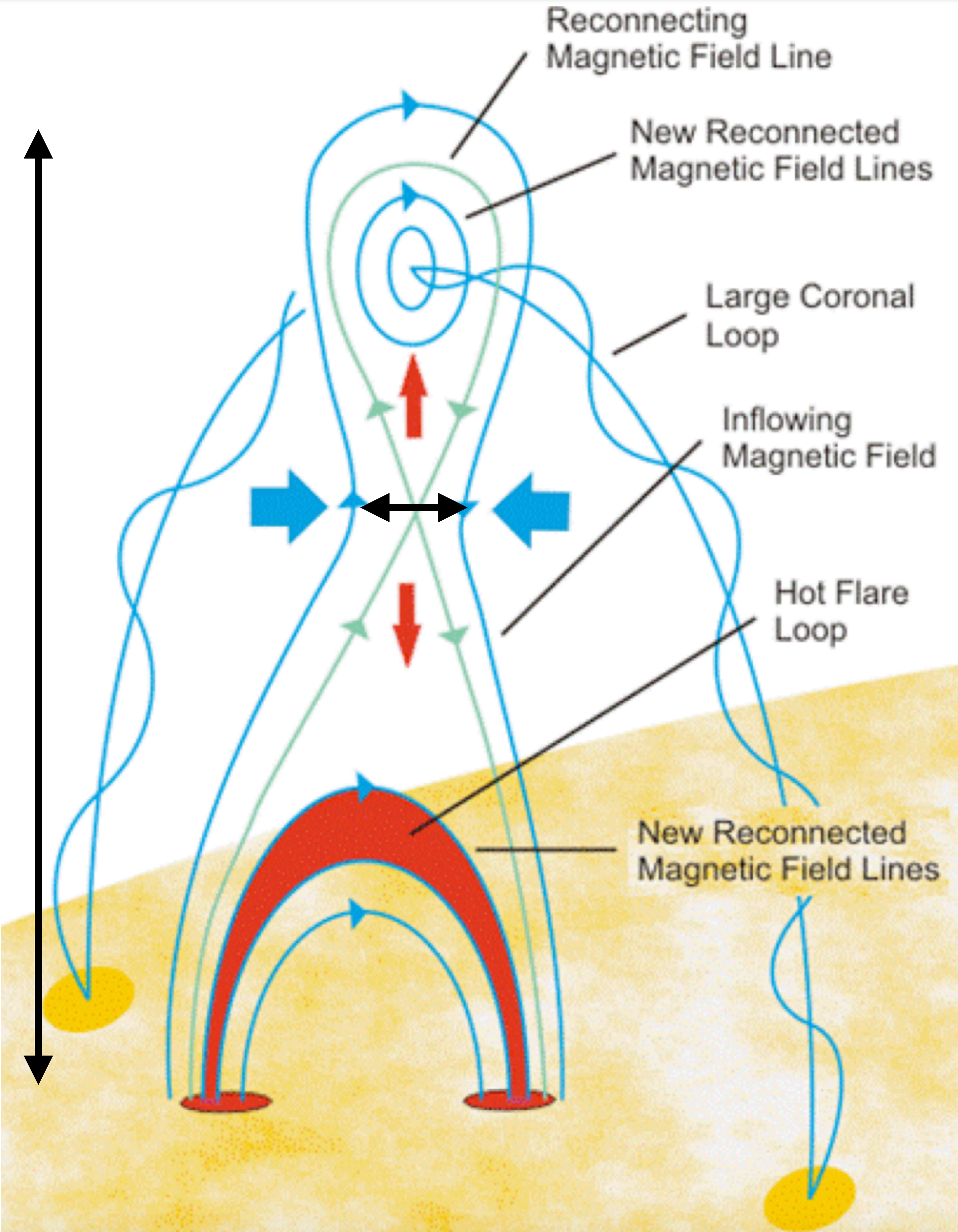

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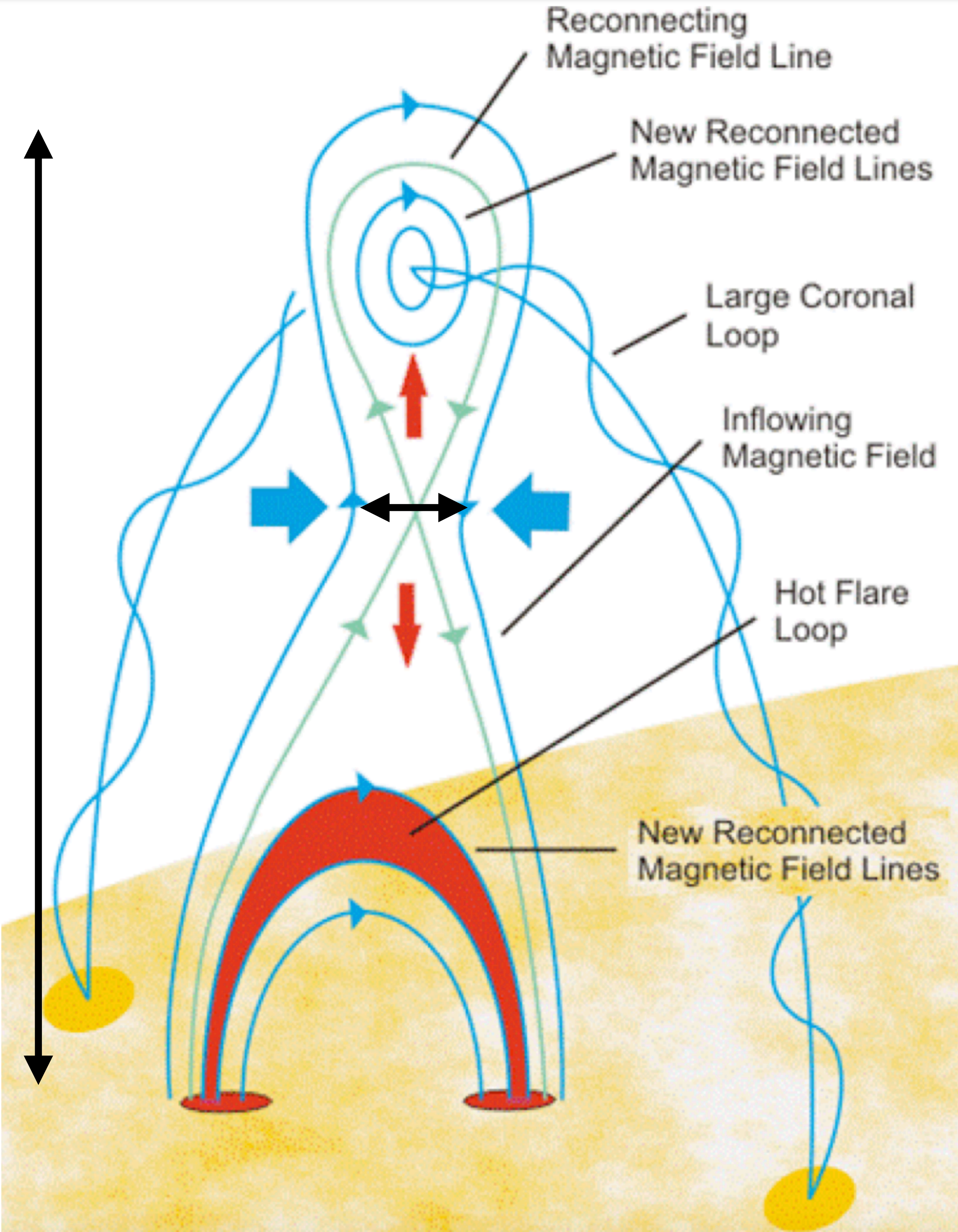

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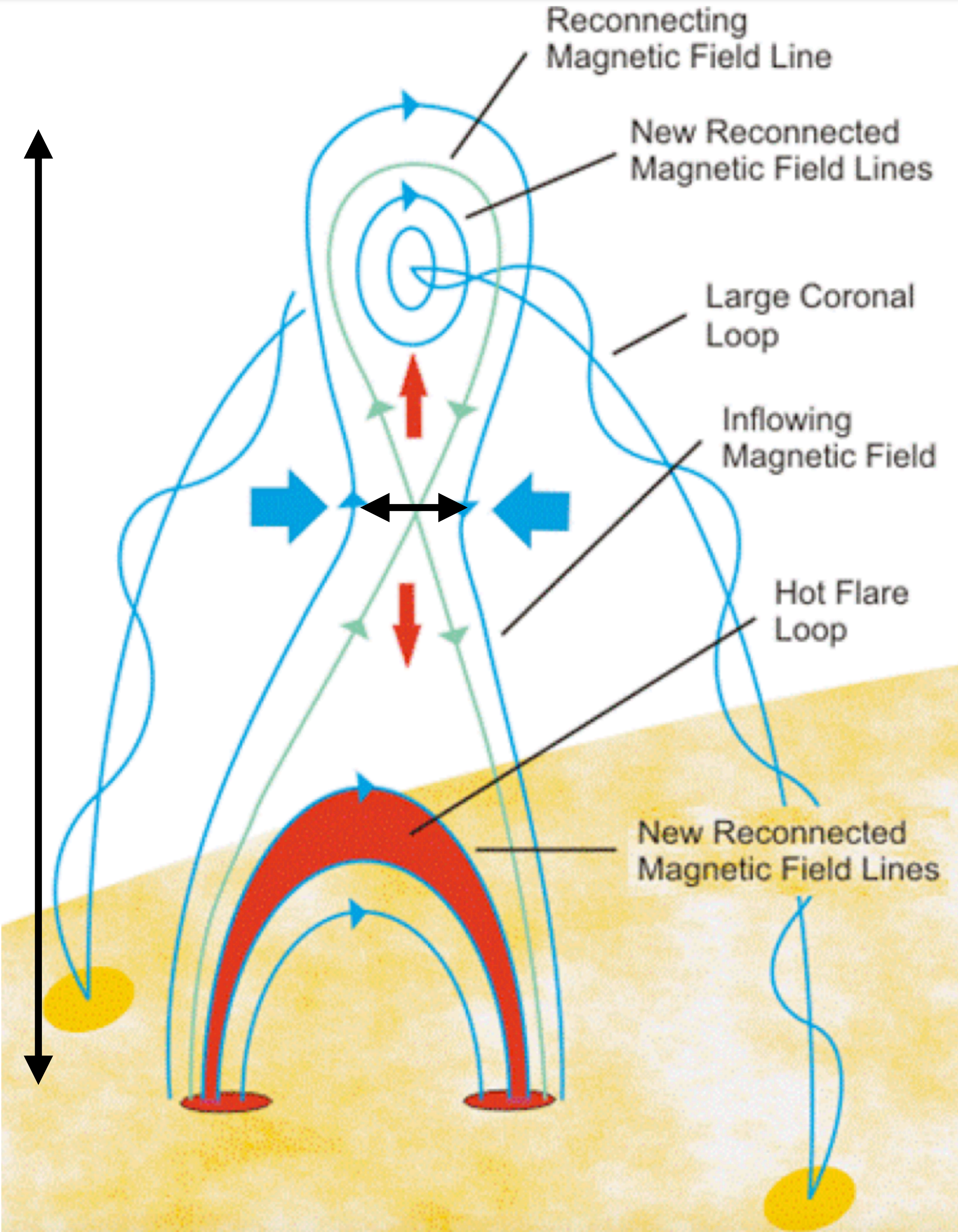

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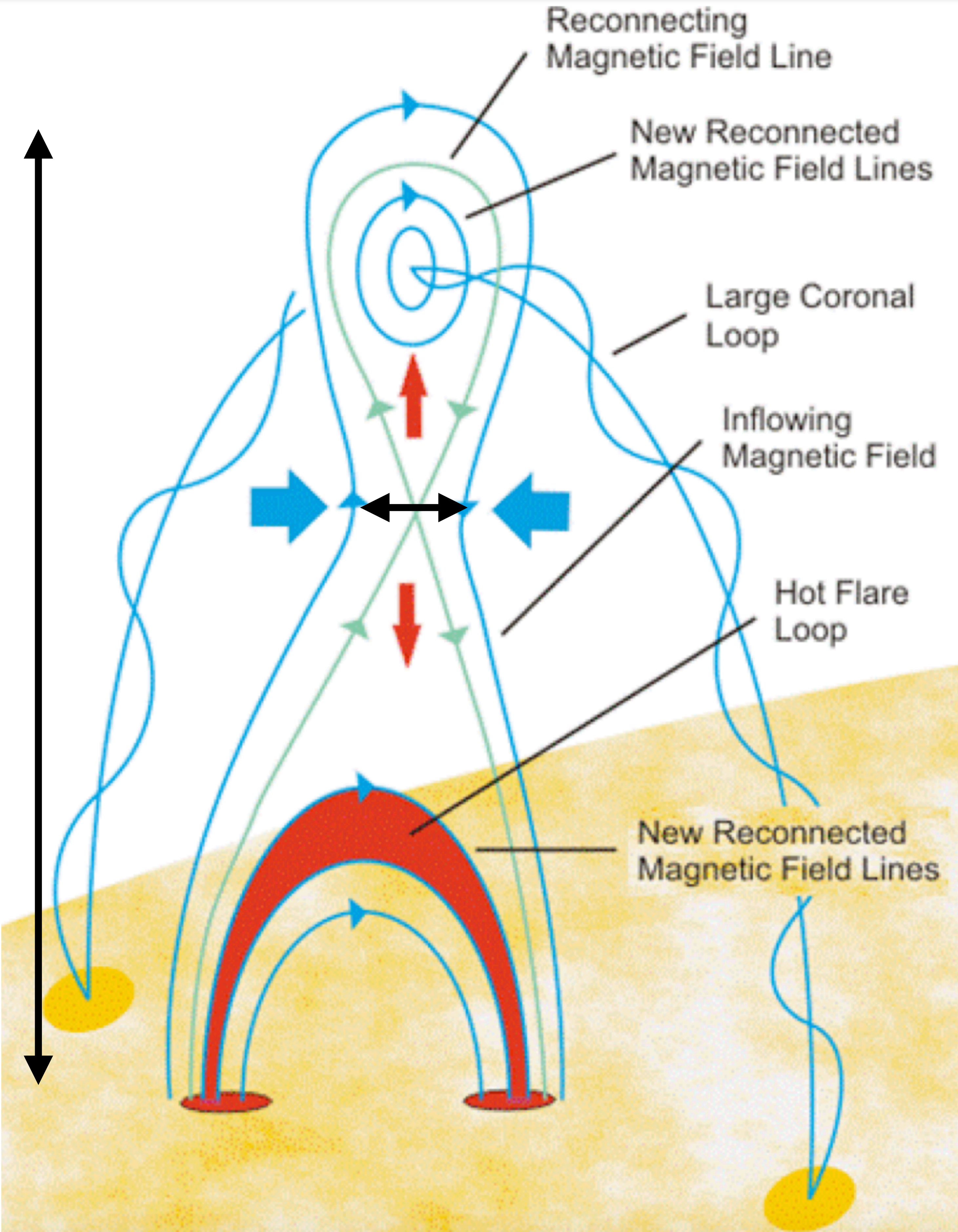
- This scale separation is even worse in astrophysical systems such as black hole accretion…



Concluding thoughts

- Reconnection is occurring everywhere: solar flares, fusion reactors here on Earth, the Earth's magnetosphere, around compact objects like black holes, and more!

- You know now how to make reconnection fast: microphysics in the current layers that form naturally in the complex magnetic structures which develop in plasmas

- This microphysics is essential! Plasmas are such good conductors they want to move the magnetic field with their bulk motions (and vice versa). The "Frozen-in" Flux theorem is a pretty good description at large scales!

- Bridging the micro and the macro brings about a whole host of questions:
  - How much energy does magnetic reconnection deposit in electrons vs. ions?
  - How does reconnection "onset?" How do the current sheets ultimately thin enough for the kinetic physics to become important?
  - How do we explain the **very** energetic (relativistic!) particles we see from reconnection?

- The data I used to produce the movies of magnetic reconnection is accessible via the Plasma Sciences Virtual Laboratory (https://vlab.plasmascience.scigap.org/) and you can follow instructions for the Princeton General Plasma Physics II course to access the data and Jupyter Notebooks yourself if you'd like (https://vlab.plasmascience.scigap.org/documentation/gpp2-march-2025/)
  - You can also download and run Gkeyll directly! https://github.com/ammarhakim/gkylzero

Some further reading (and an experiment here at PPPL!)

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Outstanding Questions and Future Research on Magnetic Reconnection

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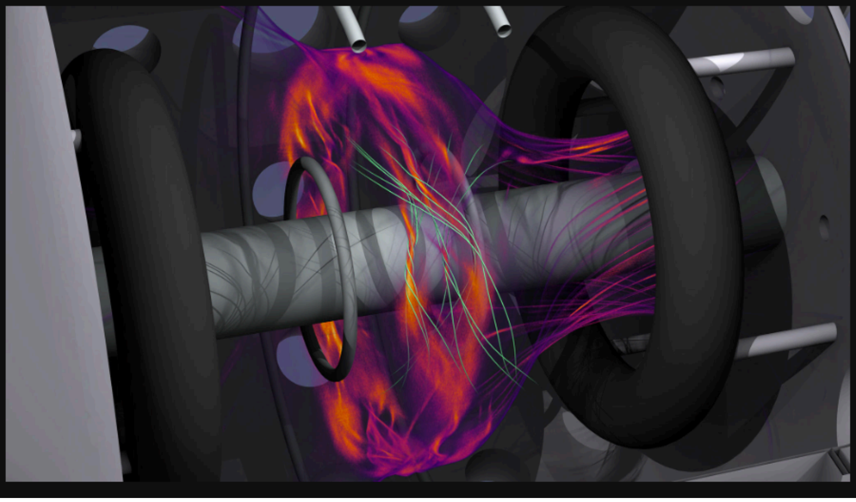

"FLARE is the first device to experimentally explore whether magnetic reconnection can have ***multiple X-points****, potentially widening our basic knowledge about phenomena happening throughout the universe."*

– Jongsoo Yoo, Deputy Head of Discovery Plasma Science

Magnetic Reconnection in the Space Sciences: Past, Present, and Future

Journal of Geophysical Research (JGR)

M. Hesse, P. A. Cassak

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