Magnetic Reconnection in Flow-Driven Plasmas

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Outline

- Fast reconnection regime for HED plasmas

  Essential ingredients:

  – magnetic flux pile-up due to the very strong supersonic flow drive.

  – reconnection is mediated by collisionless two-fluid effects (Hall and pressure tensor)

- The dynamo effect in accretion disks driven by the magneto-rotational instability: effects of helicity transport, and lessons learned from magnetically confined fusion plasmas

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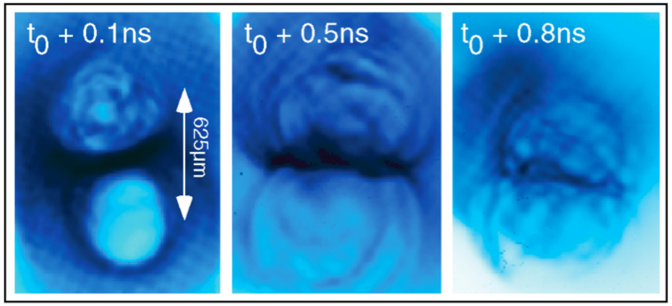
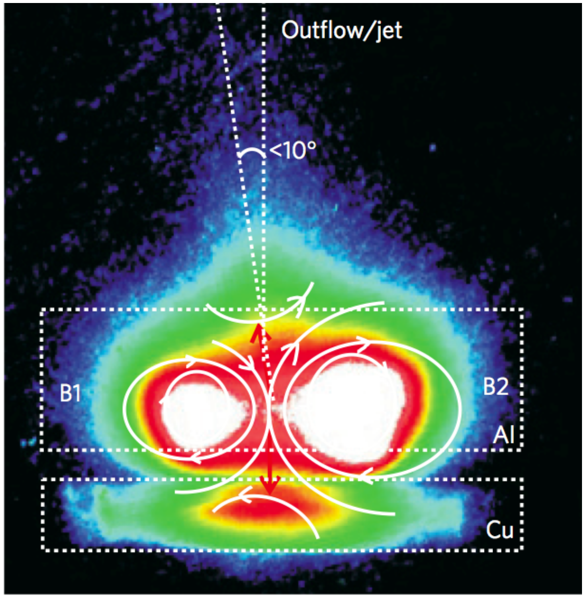
Reconnection observed in plasma bubble experiments

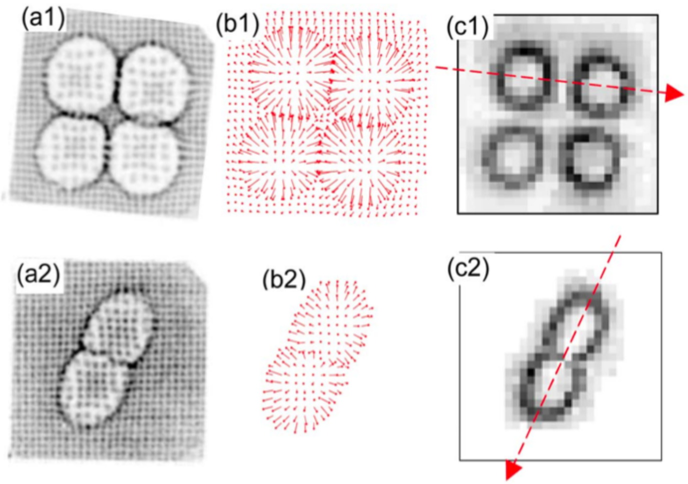
Rutherford [Nilson, et al PRL 2006, PoP 2008]



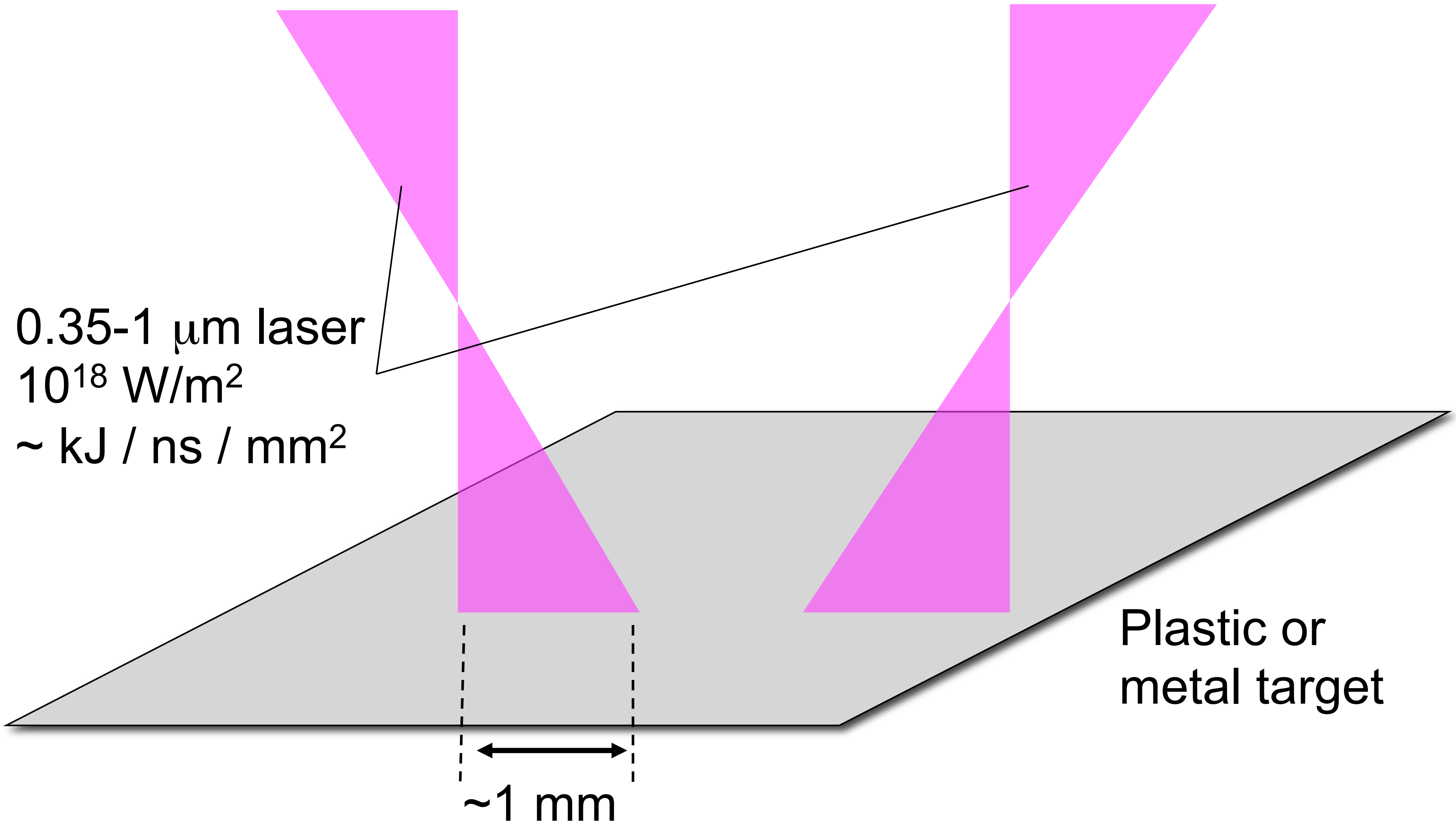
Shenguang [Zhong *et al* Nature Phys 2010]



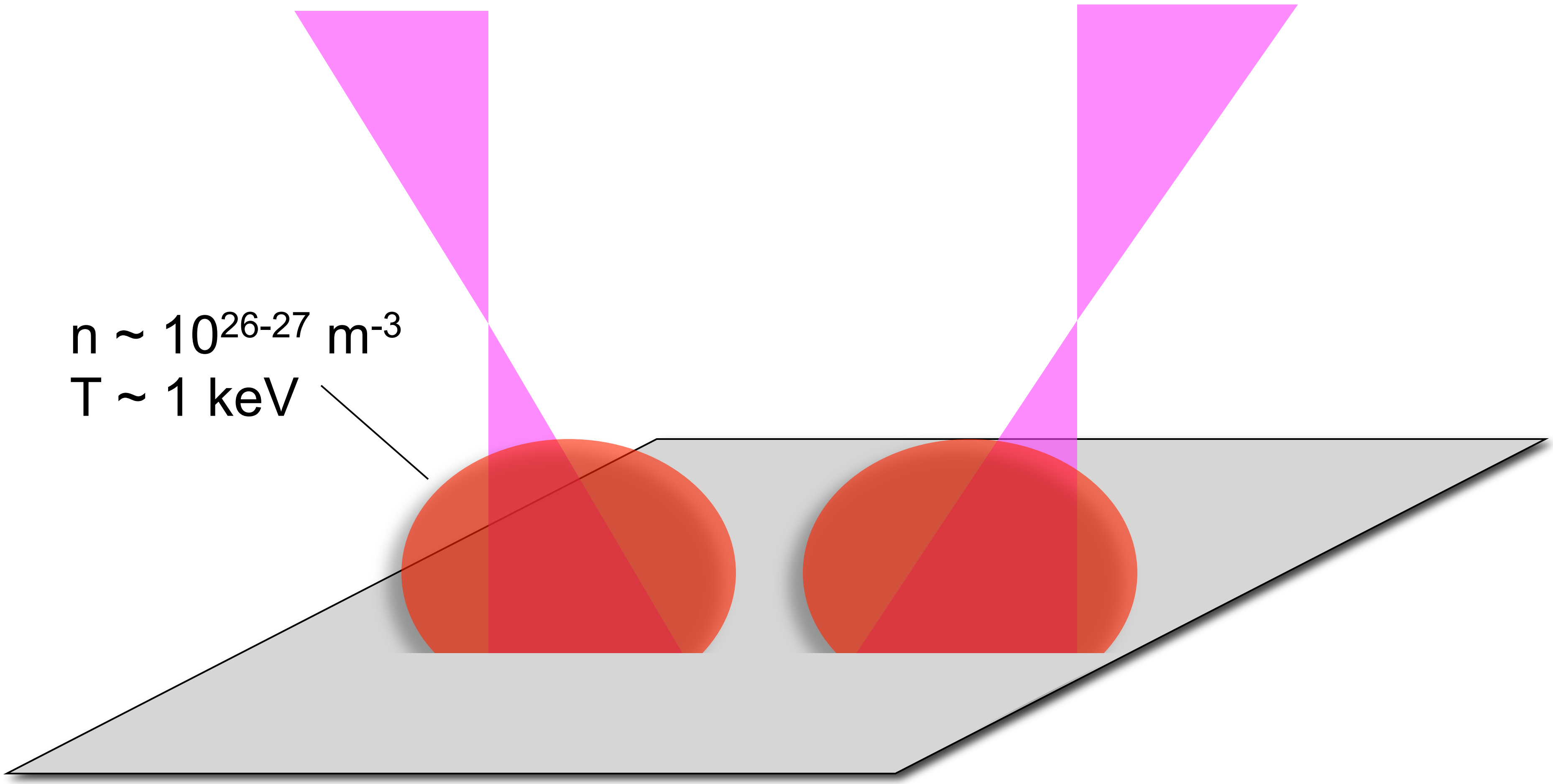
Omega: [C.K. Li, et al PRL 2007]



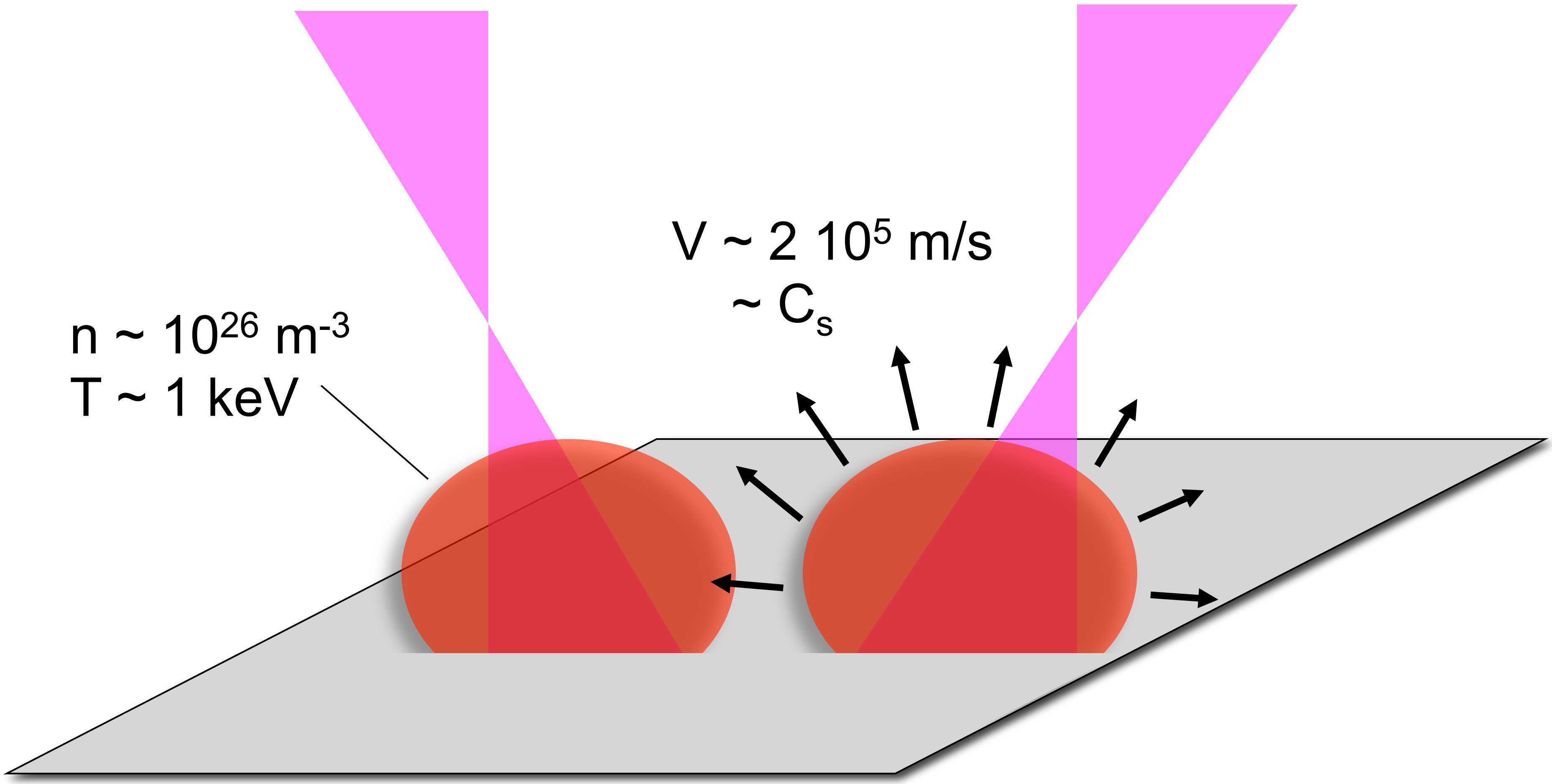
How to make a plasma bubble



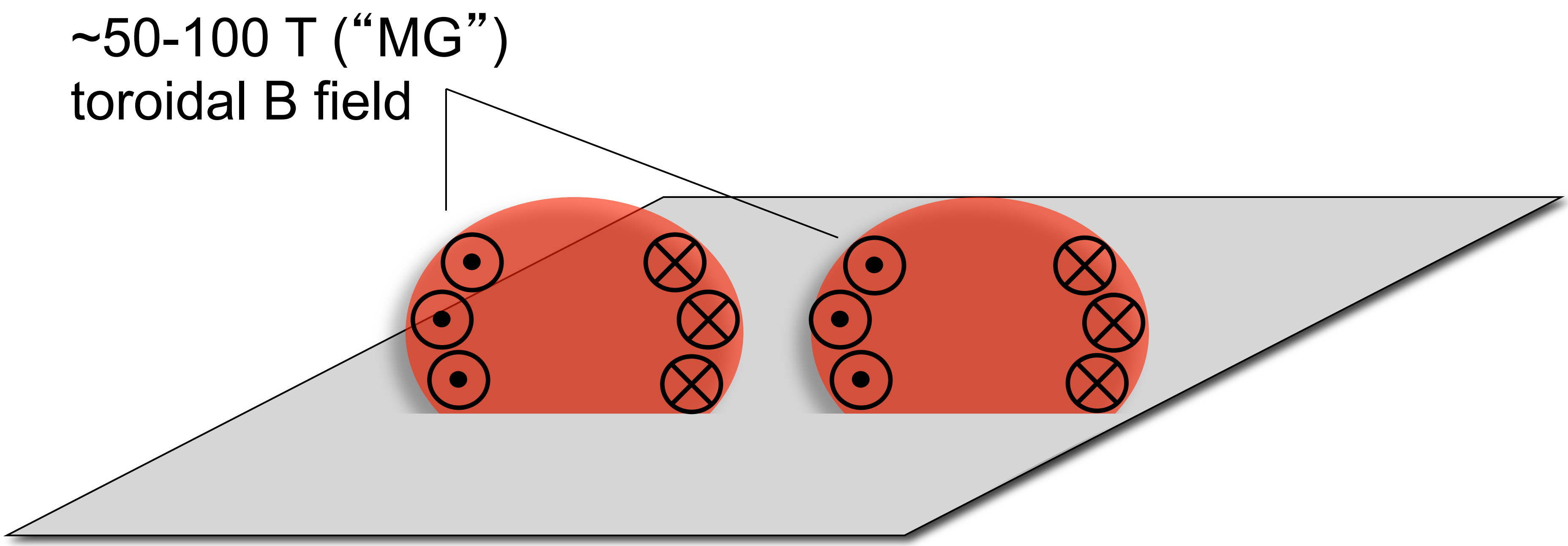
How to make a plasma bubble



How to make a plasma bubble



How to make a plasma bubble



B field generated through a Biermann battery two-fluid effect

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \frac{1}{ne}(\nabla n \times \nabla T)$$

HED bubble reconnection regime

Estimates:

- $L/d_i \sim 20\text{-}100$, $L_B/d_i \sim 3\text{-}5$, $d_i > \delta_{SP}$
- $V_{in} / V_A >= 1$ (strong reconnection drive)

A problem, since fast "two-fluid" reconnection typically gives us only $V_{in} / V_A \sim 0.1\text{-}0.2$

We find this leads to highly dynamic current sheet geometry and *flux pileup*. Compression of B raises *instantaneous* V_A over *nominal* V_{A0}.

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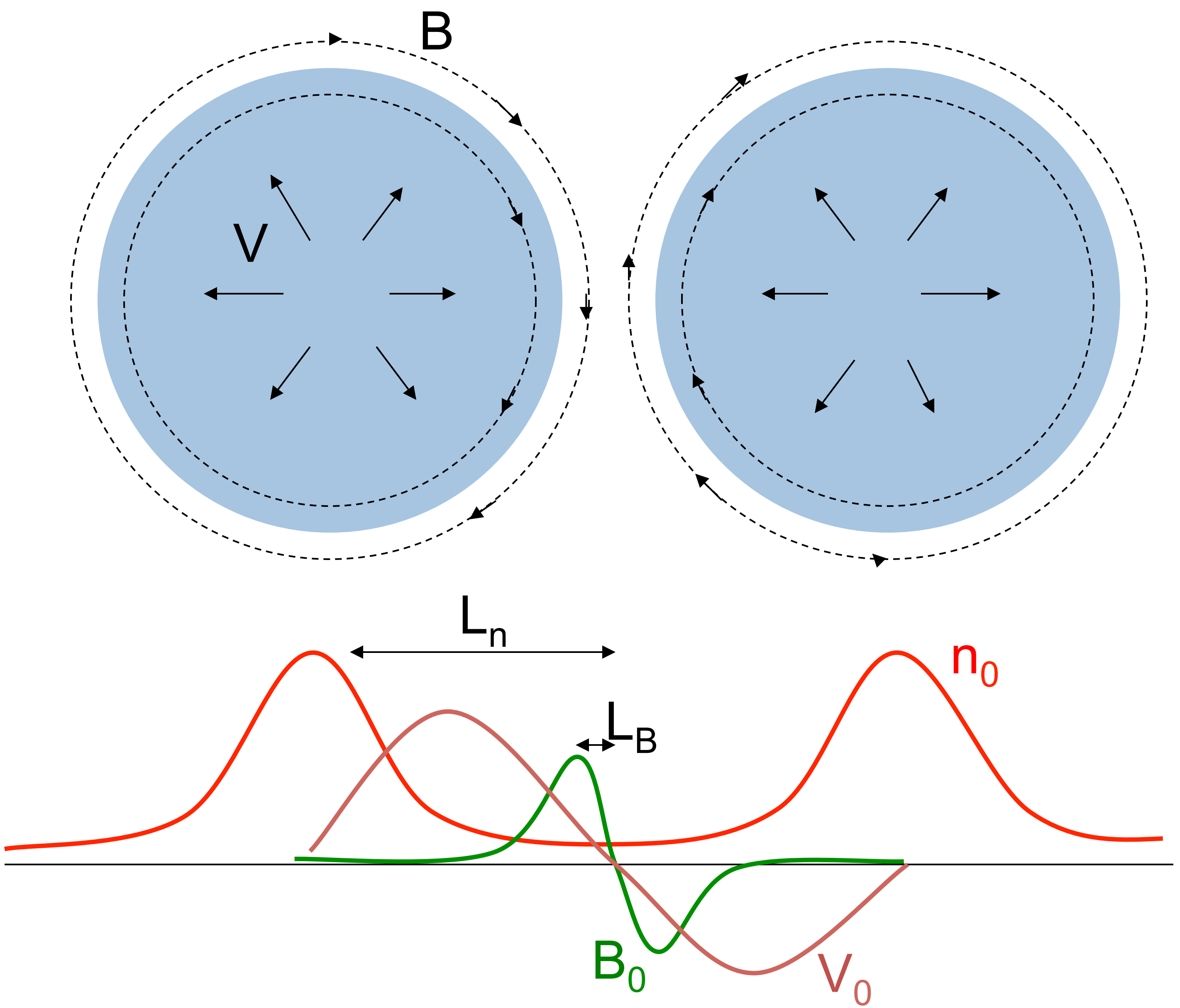
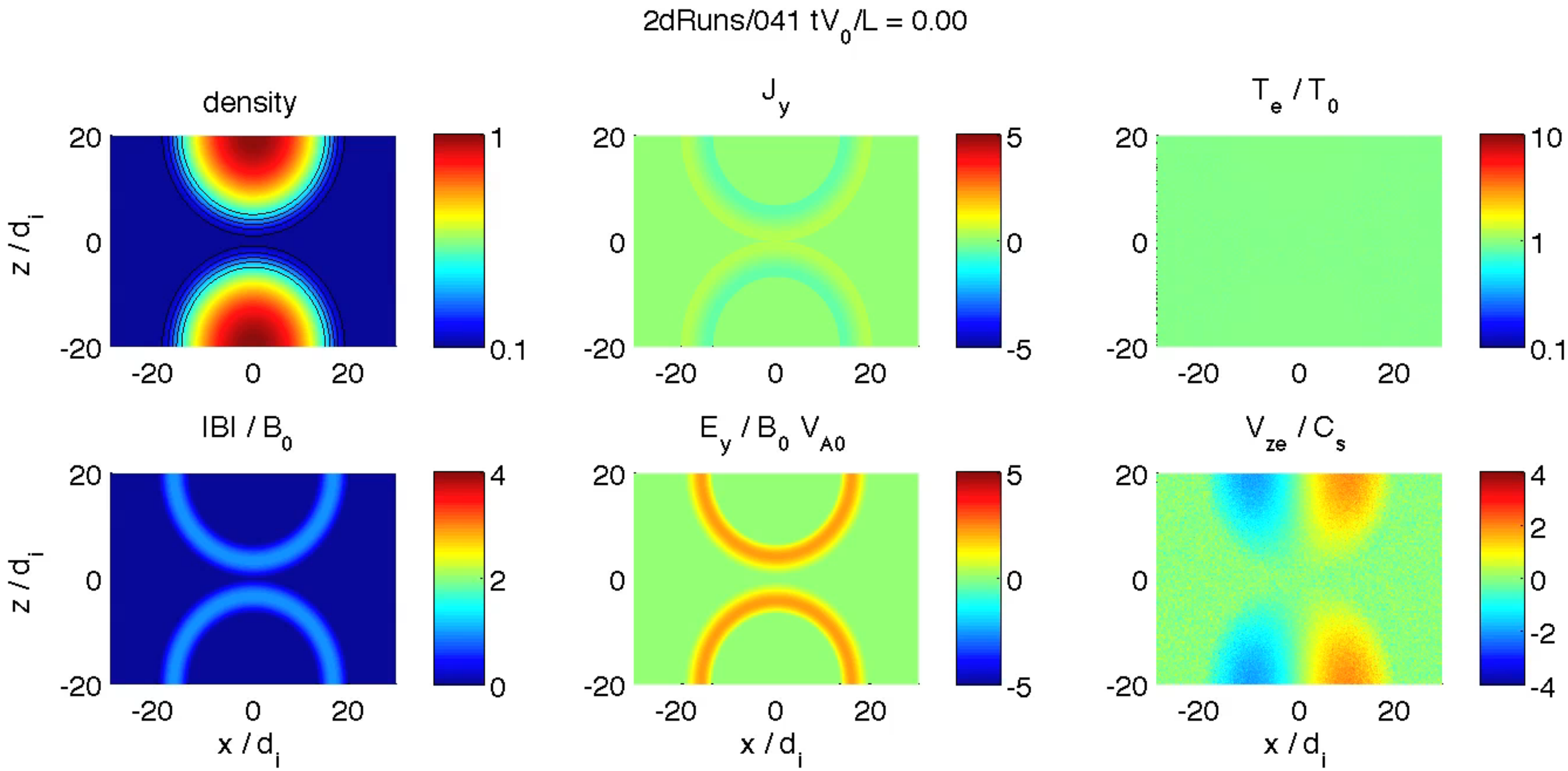
2D PIC simulations for bubble collisions



Bubble reconnection simulation



Parameters (Rutherford-like)

- $L_n/d_i = 20$, $L_B/d_i = 3.3$, $V_0 = 2\ C_s$, $\beta_e = 8$

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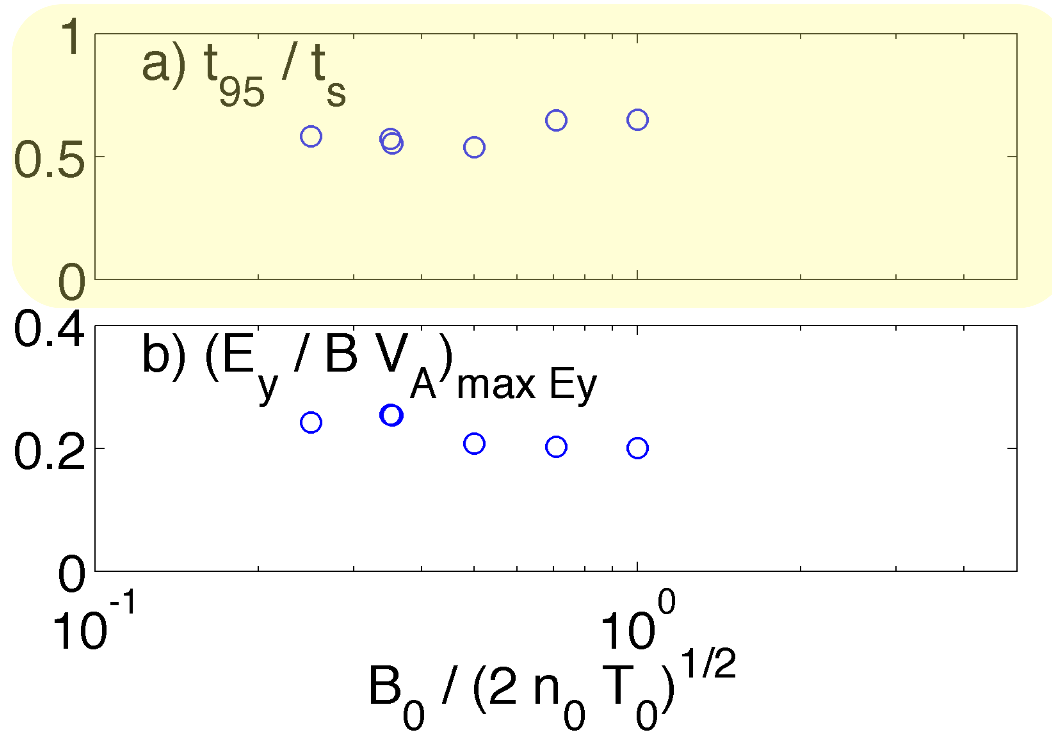
Consequences of flux pileup

Vary initial B_0, but find total reconnection time does not change.

Reconnection independent of nominal V_{A0}



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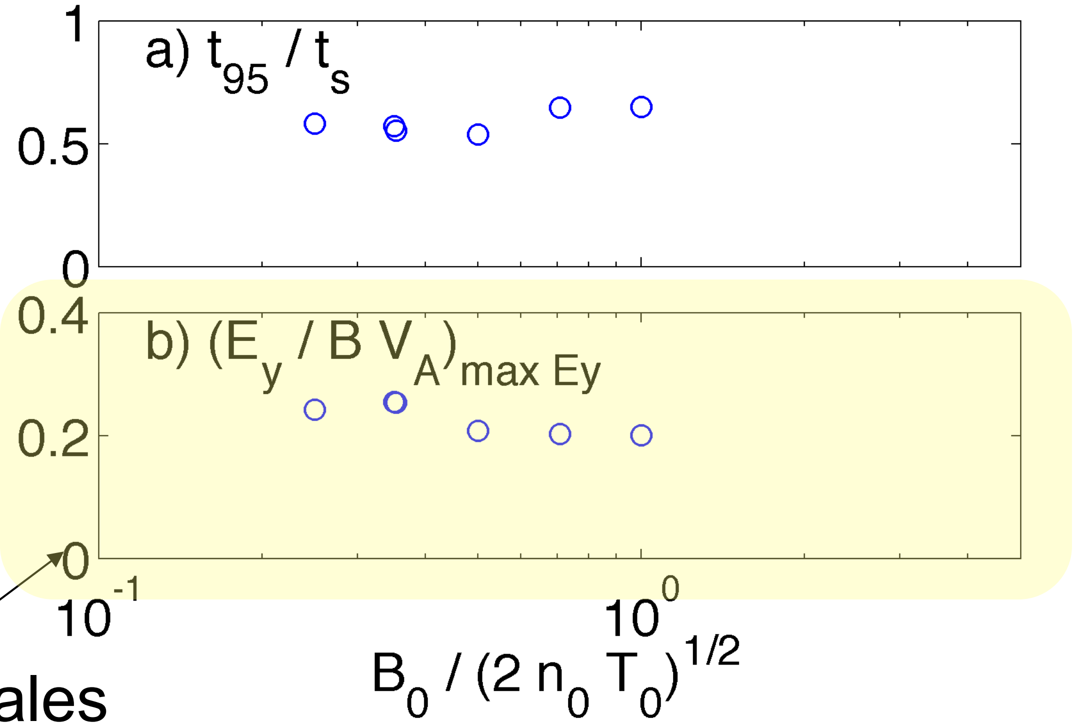

Peak reconnection rate scales with *instantaneous* V_A

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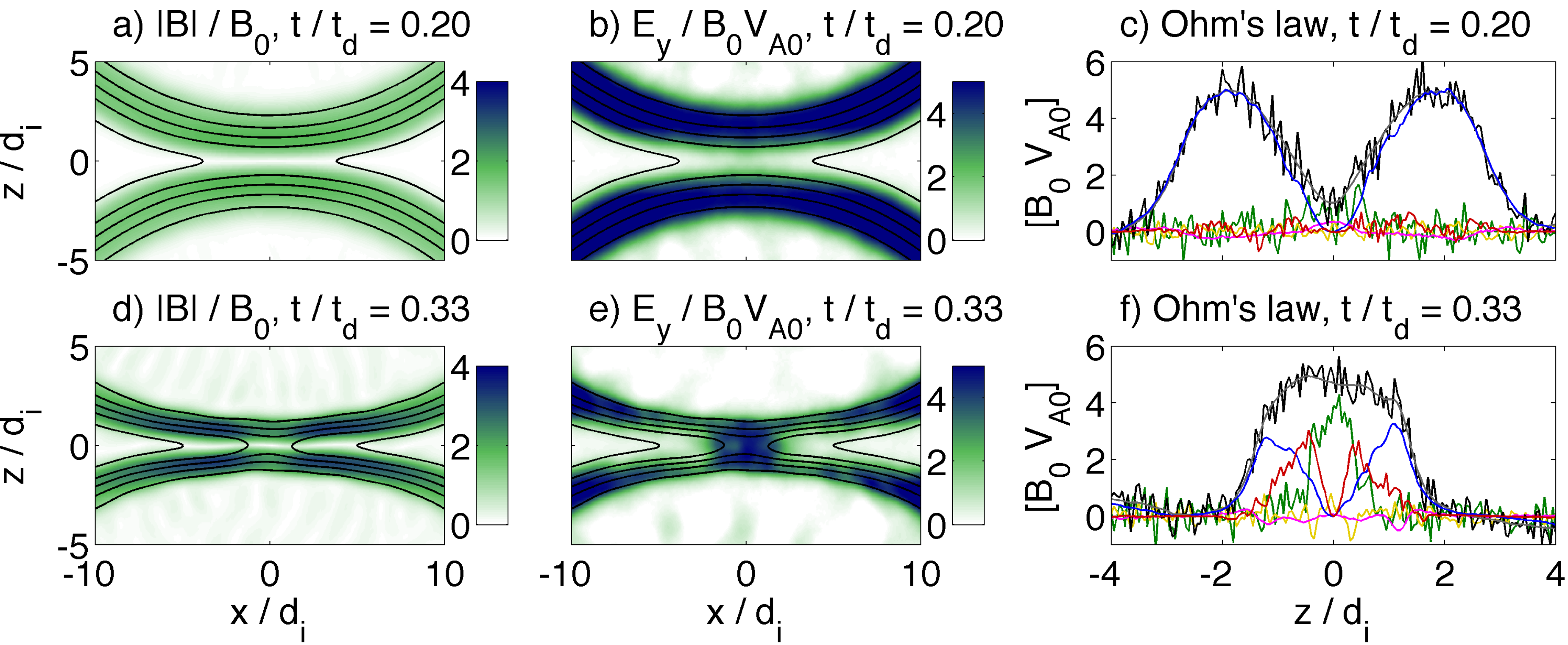
[Fox, Bhattacharjee, Germaschewski, PRL (2011)]

Electron momentum balance



$$E_y + v_i \times B = (1/ne)\, j \times B - (1/ne)\, \nabla_x P_{e,xy} - (1/ne)\, \nabla_z P_{e,zy} - (m_e/e)\, \partial v_e/\partial t$$

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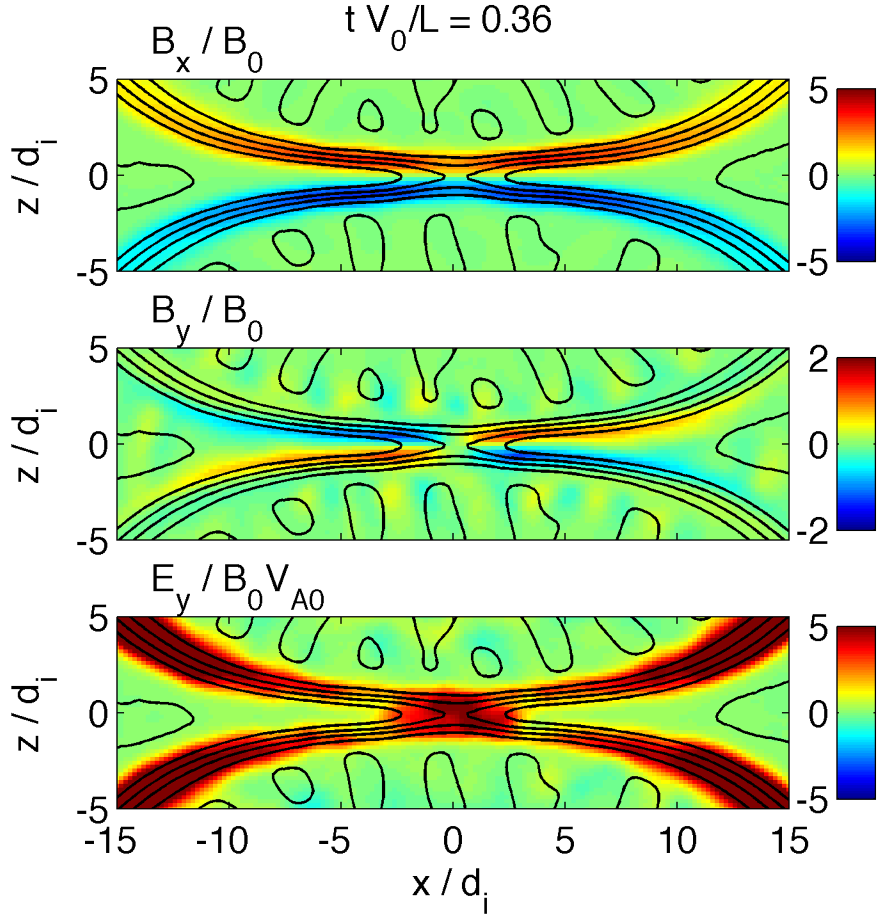
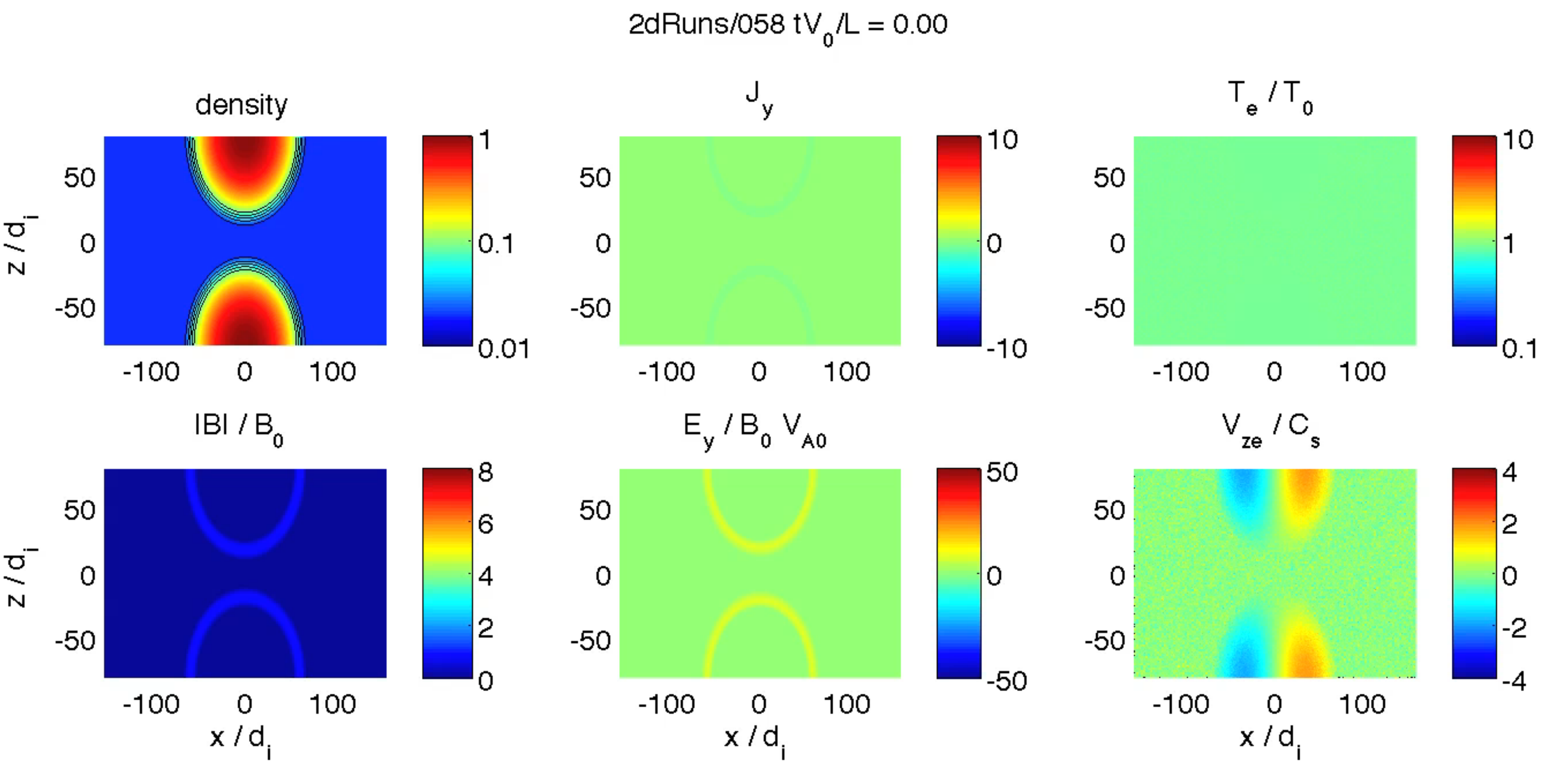
Quadrupole "Hall" magnetic field signature observed

$B_{Hall} / B_{up} \sim 40\%$



$V_0 = 3\ C_{S,}\ L_n = 20\ d_i,\ B_0 = 0.07$

Omega-like Experiment



Baseline results summary

- Recent HED plasma bubble experiments appear to be in a previously inaccessible, strongly-driven reconnection regime with two-fluid effects.
- Collisionless PIC simulations find reconnection with a combination of pile-up and two-fluid effects, and reconnection times in qualitative agreement with experiments

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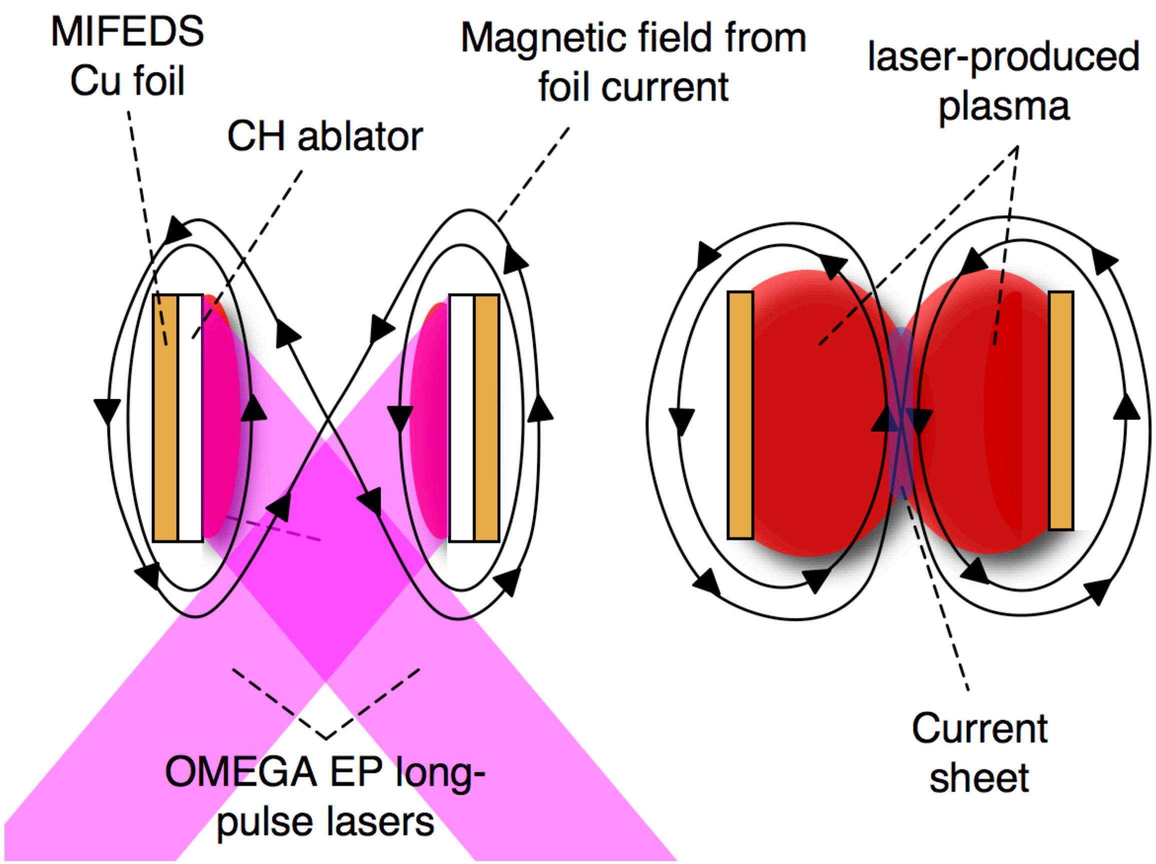
New experiments
(in collaboration with G. Fiksel, P. Nilson, S. Hu, and others at Rochester LLE)



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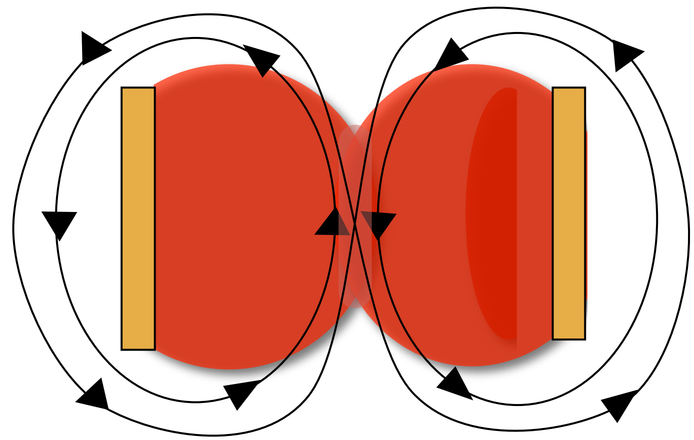
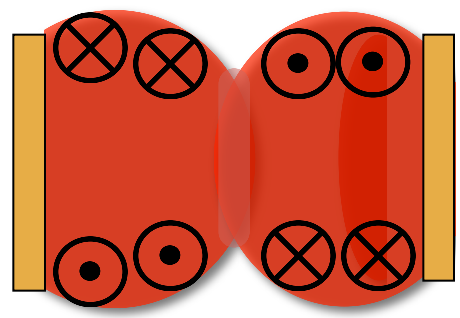
What about self-generated (Biermann) field?

MIFEDS fields

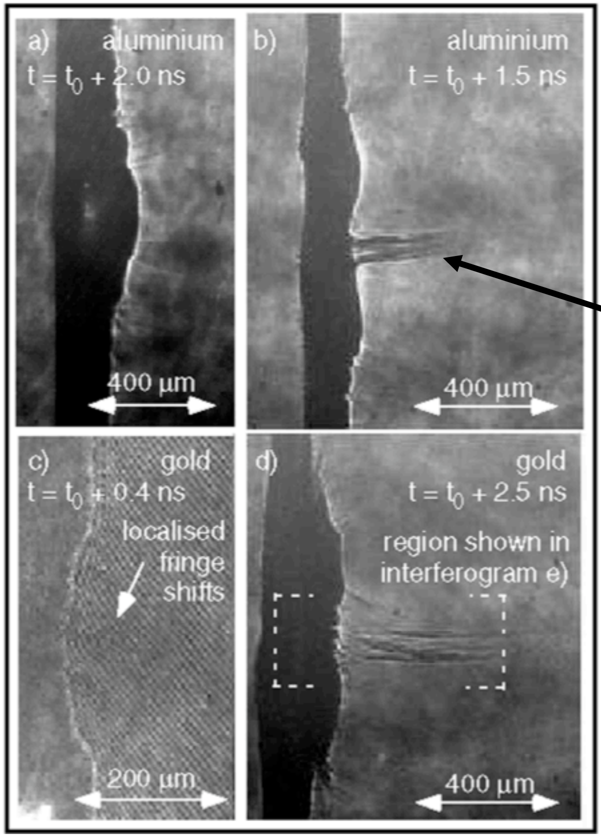


Biermann fields



Biermann *not* explicity in EP simulation models yet

Nilson, *et al* also observe outflow jets



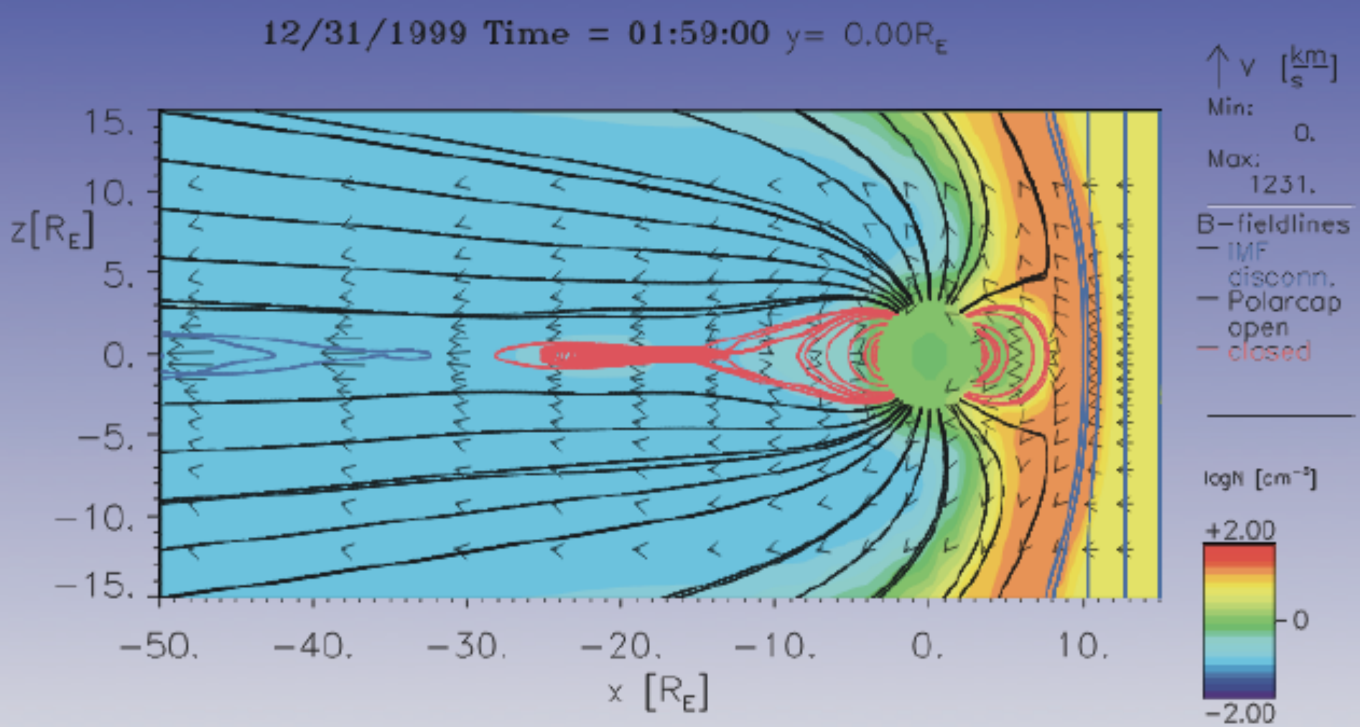
Outflow jet

(with oblique component - 3-d effect and a challenge to theory!)

[Nilson *et al*, PRL 2006, PoP 2008]

Reconnection at the Dayside Magnetopause

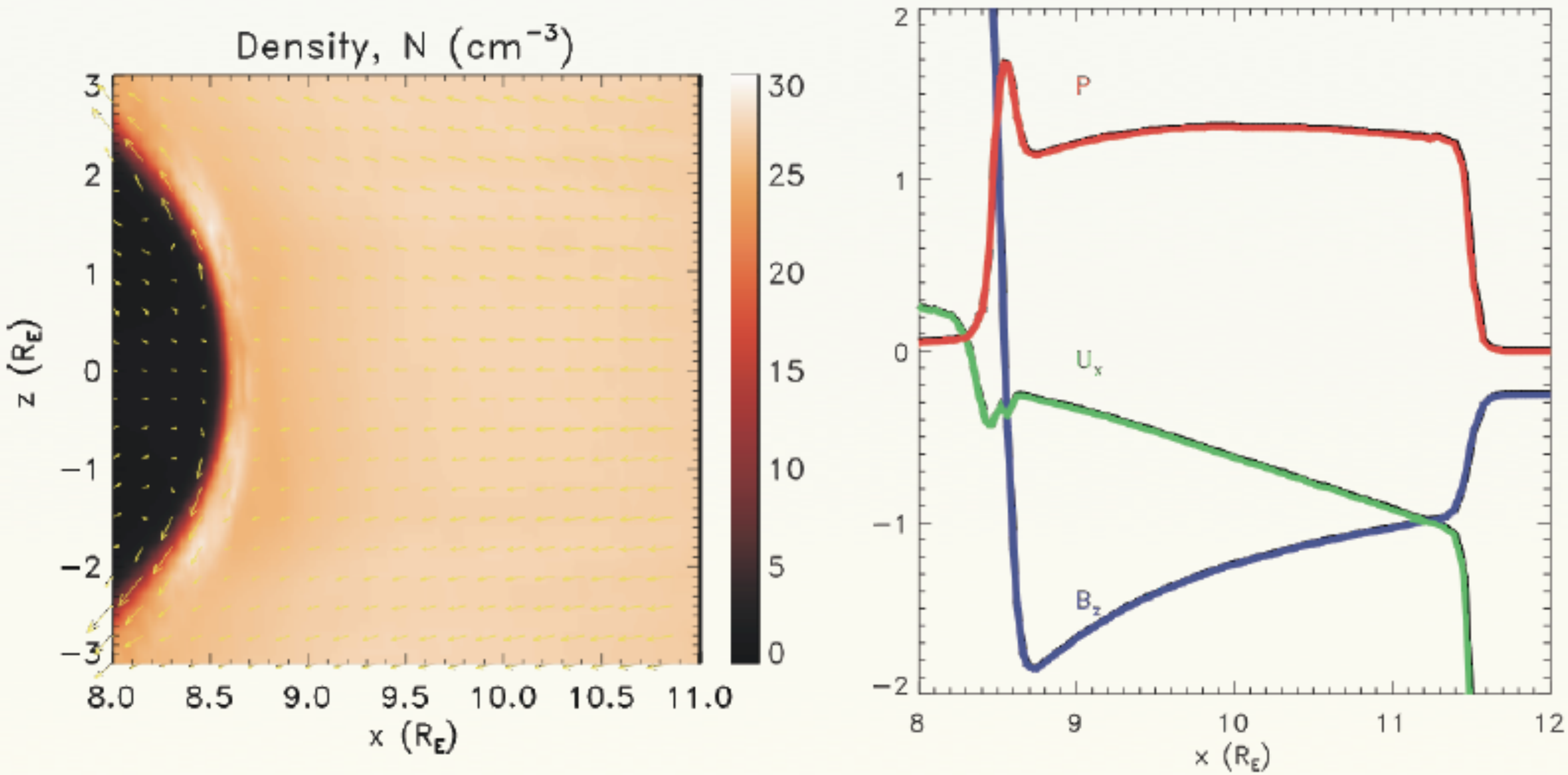
see J. Raeder (JGR, 104, 17357, 1999) for a description of the General Geospace Circulation Model (GGCM)



Steady solar wind conditions, southward IMF, and constant plasma resistivity:

S = {500, 1000, 2000, 5000, 10000}

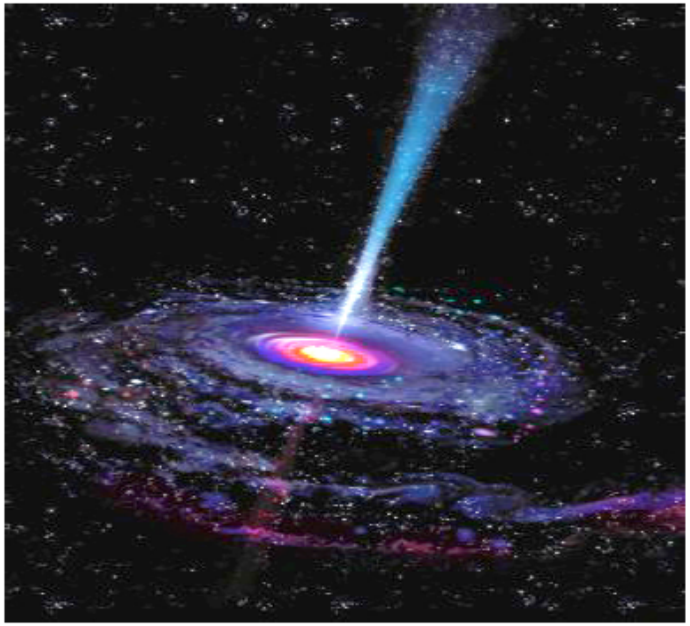
Magnetic Pileup and Associated Plasma Depletion



S = 10000

The magnetorotational Instability (MRI) in accretion disks

- Is it possible for MRI to generate a large scale magnetic field?
- Can MRI produce a turbulent MHD dynamo?



Magnetic field generation through correlated fluctuations

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$< \mathbf{E} > \approx \underbrace{- < \widetilde{V} \times \widetilde{B} >} = \alpha < \mathbf{B} > -\beta < \mathbf{J} >$$

Large-scale dynamo

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The alpha effect can be rigorously written in the form of a total divergence of the helicity flux from fluctuations.

Local magnetic helicity variation is

$$\frac{\partial(\mathbf{A}\cdot\mathbf{B})}{\partial t} + \nabla\cdot\Gamma_k = -2\mathbf{E}\cdot\mathbf{B}.$$

Total helicity flux : $\Gamma_k = -2\mathbf{A}\times\mathbf{E} - \mathbf{A}\times\frac{\partial\mathbf{A}}{\partial t}$

- It can be shown that fluctuation induced dynamo effect is expressed in a divergence form and dissipative terms.

$$<\widetilde{\mathbf{V}}\times\widetilde{\mathbf{B}}> \cdot\mathbf{B} = -\eta<\widetilde{\mathbf{J}}\cdot\widetilde{\mathbf{B}}> - \frac{1}{2}\frac{\partial}{\partial t}<\widetilde{\mathbf{A}}\cdot\widetilde{\mathbf{B}}> \underbrace{-\nabla\cdot<\Gamma_k>/2}_{\text{divergence of helicity flux from fluctuations}}$$

$$<\Gamma_k> = -2<\widetilde{\mathbf{A}}\times\widetilde{\mathbf{E}}> - <\widetilde{\mathbf{A}}\times\frac{\partial}{\partial t}\widetilde{\mathbf{A}}>$$

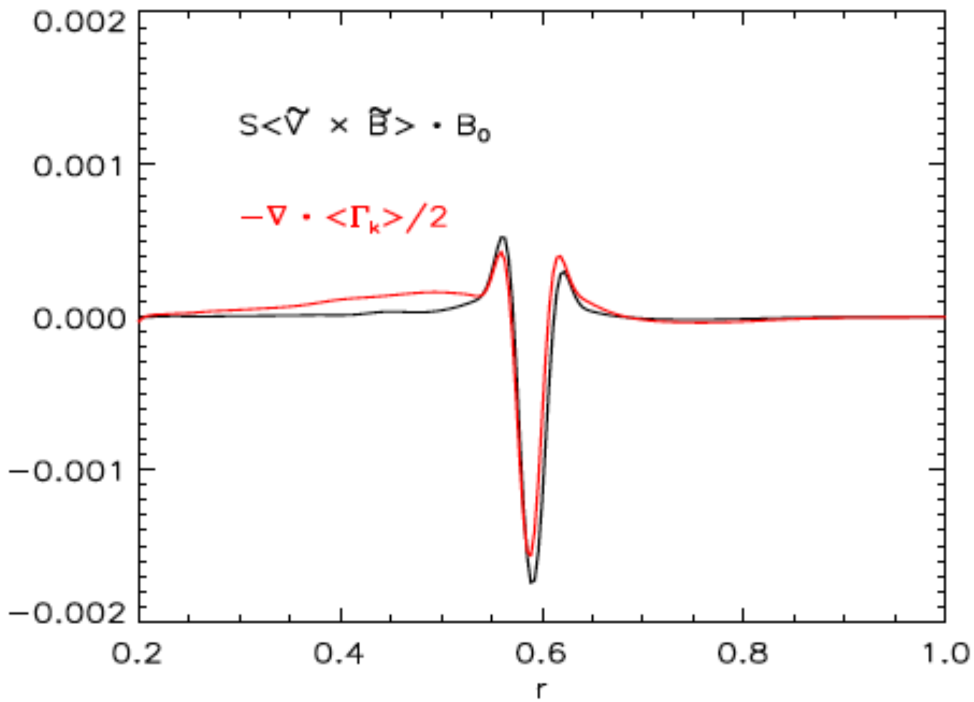
Dynamo term in the form of a total divergence conserves helicity.

- The alpha effect in a total divergence form conserves helicity for flux conserving boundary condition (i.e conducting wall)
- $\int < \widetilde{\mathbf{V}} \times \widetilde{\mathbf{B}} > \cdot \mathbf{B} dv = -\int \nabla \cdot < \Gamma_k > /2 dv = \oint < \Gamma_k > /2 \cdot ds$
- $\int < \widetilde{\mathbf{V}} \times \widetilde{\mathbf{B}} > \cdot \mathbf{J} dv < 0$ dissipates magnetic energy.

For example for tearing mode

- Using *tearing ordering* in the inner layer, Fluctuation induced dynamo effect can be written in a divergence form which is related to the magnetic diffusivity.
- $< \widetilde{\mathbf{V}} \times \widetilde{\mathbf{B}} > \cdot \mathbf{B} \sim -\nabla \cdot (\widetilde{\mathbf{A}} \cdot \mathbf{B}) \widetilde{\mathbf{V}} = \nabla \cdot (\kappa^2 \nabla \frac{\mathbf{J} \cdot \mathbf{B}}{B^2})$

Quasilinear simulations show that the alpha effect can be written in terms of a total divergence for tearing mode with flow.

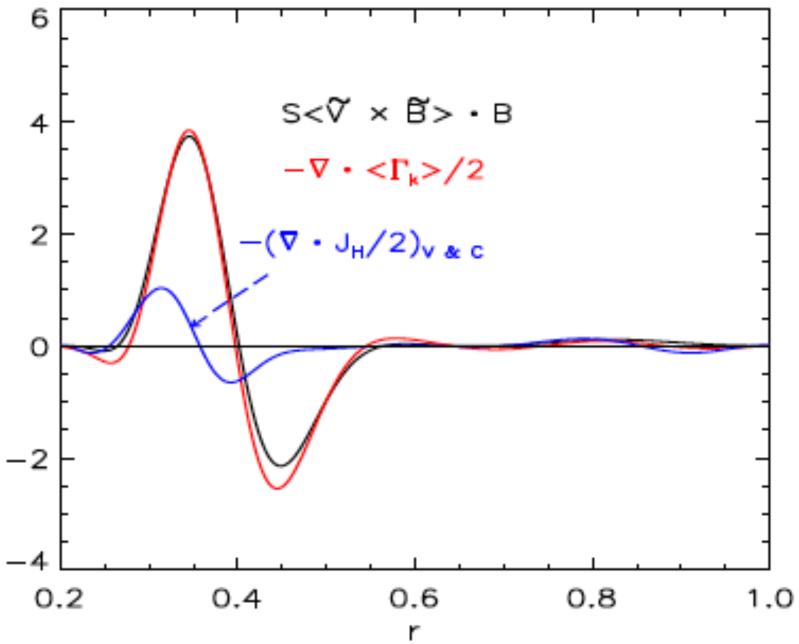


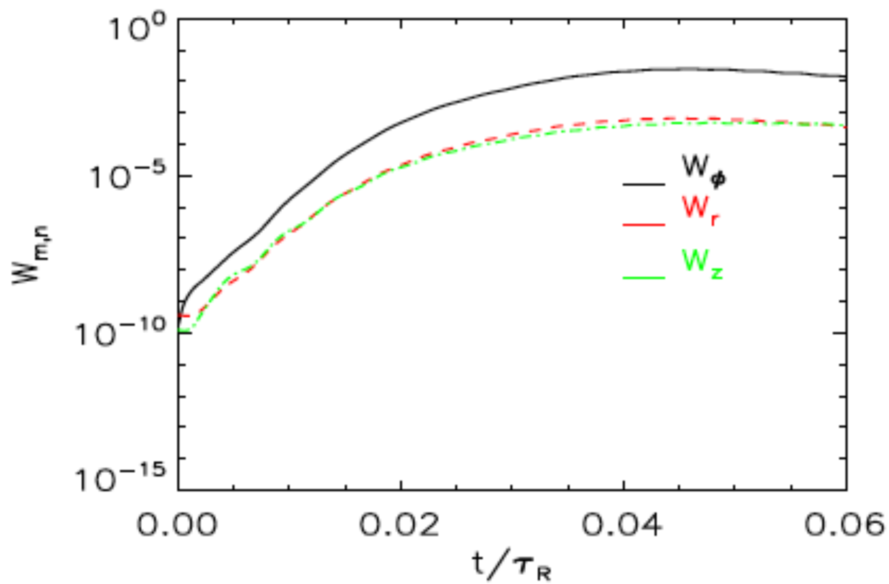
- For m=1 tearing mode with flow, the divergence of the helicity flux from fluctuations has the main contribution to the alpha effect. $<\tilde{\mathbf{V}} \times \tilde{\mathbf{B}}> \cdot \overline{\mathbf{B}} \approx -\nabla \cdot <\Gamma_k>/2$.

Nonlinear simulations show that the alpha effect can be written in terms of a total divergence for an MRI mode.

Divergence forms of m=1 MRI dynamo during nonlinear saturation

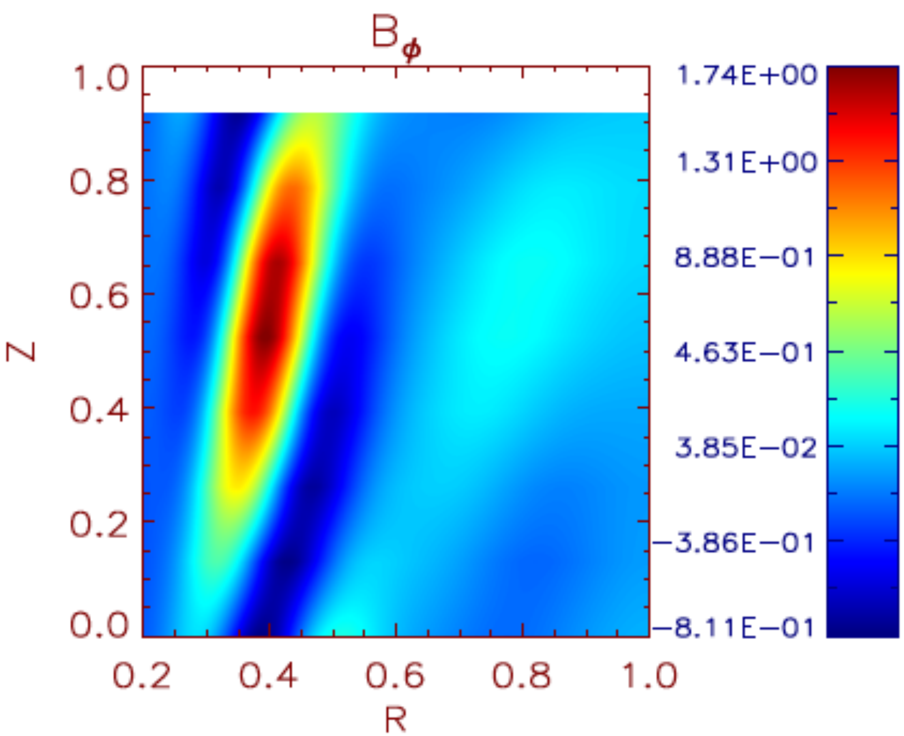
Magnetic energies



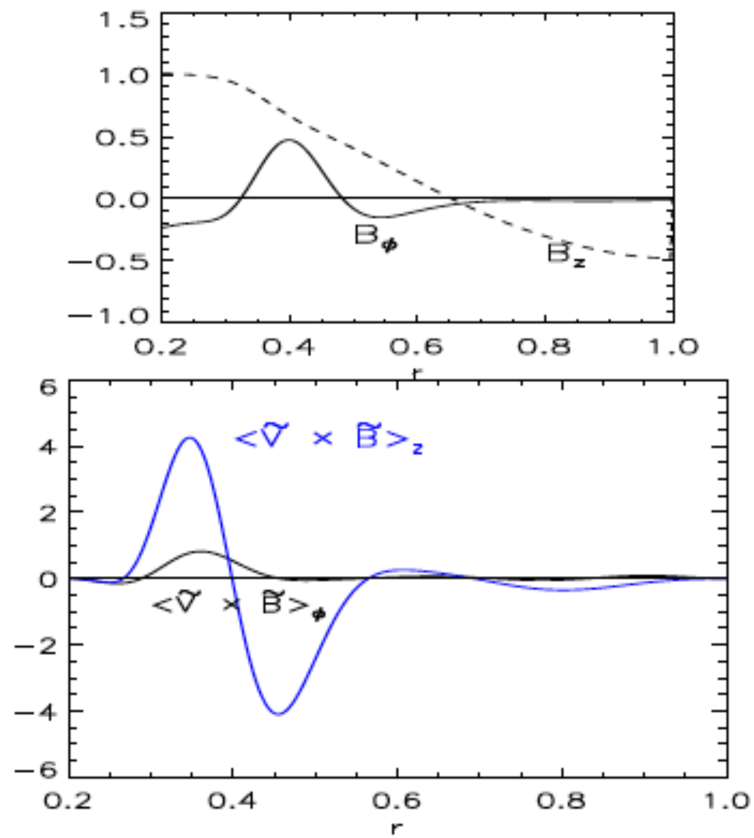


- Nonlinear m=1 MRI mode simulation show , $< \widetilde{\mathbf{V}} \times \widetilde{\mathbf{B}} > \cdot \overline{\mathbf{B}} \approx -\nabla \cdot < \Gamma_k > /2$.
- The helicity flux of Vishniac & Cho produces small dynamo effect.

Large-scale mean toroidal magnetic field (and energy) is generated by the nonaxisymmetric modes.



Total toroidal magnetic field in the RZ plane after saturation



Large-scale surface-averaged toroidal magnetic field

- In the simulation with only vertical B, a large-scale $< B_\phi >$ is generated due to vertical alpha effect.