Defining dissipation/diffusion regions in collisionless magnetic reconnection

and

High-speed fluid dynamics in magnetic reconnection in a low-β plasma

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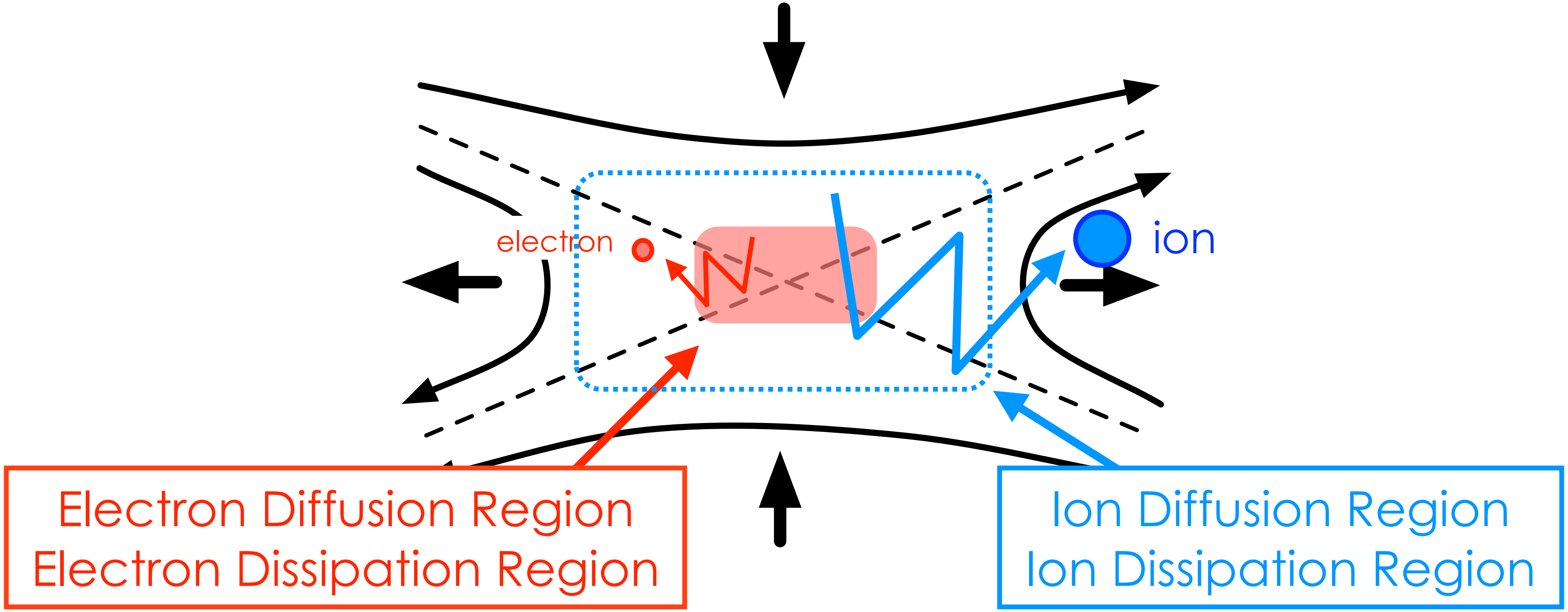
Topic 1:
Defining dissipation/diffusion regions in collisionless magnetic reconnection

[1] Zenitani, Hesse, Klimas, & Kuznetsova, *Phys. Rev. Lett.* **106**, 195003 (2011)
[2] Zenitani & Umeda, *Phys. Plasmas*, **21**, 034503 (2014)

"Diffusion regions" of collisionless reconnection



- How to define "Dissipation" or "Diffusion" regions?

Many proposals ...

[electron]

Dissipation region?

Diffusion region?

- Plasma nonidealness
  $$\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B} \neq 0$$
- Maximum flow speed, $v_{e,max}$
  (Daughton+ 2006, Fujimoto 2006...)
- Electric current, J
- Parallel electric field $E_{||} \neq 0$
- Agyrotropy in velocity distribution function and GCT parameters (Scudder & Daughton 2008)
- Plasma inertial effect (Klimas+ 2010)
  $$E_y^* = -\left[\frac{1}{en_e}\nabla \bullet \mathbf{P}_e + \frac{m_e}{e}\mathbf{v}_e \bullet \nabla \mathbf{v}_e\right]_y > 0$$
- Energy transfer in the electron's moving frame (Zenitani+ 2011, Birn & Hesse 2005)
  $$D_e = J_\mu F^{\mu\nu} u_{e\nu} = \gamma_e[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c(\boldsymbol{v}_e \cdot \boldsymbol{E})]$$
- Diffusion of magnetic flux (Zenitani & Umeda 2014)
- Electron energy gain, J_e . E (Yamada+ Yesterday)

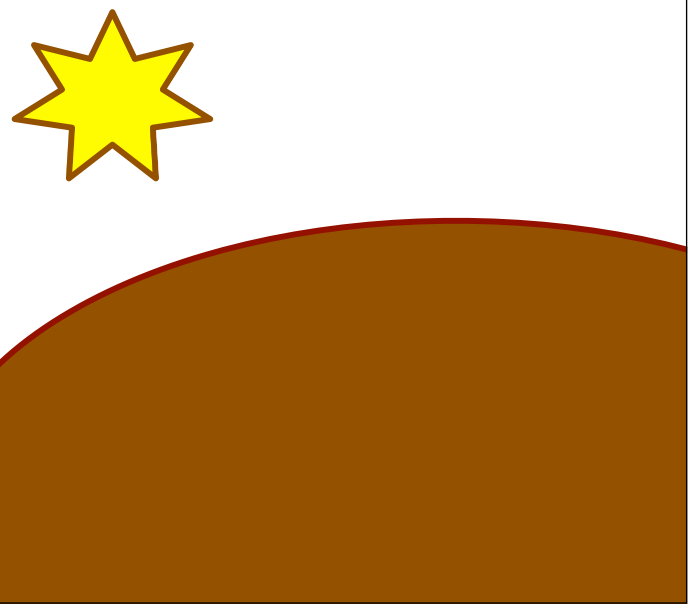
Dissipation region? = A place where magnetic dissipation occurs.

Diffusion region? = A place where magnetic diffusion occurs.

What is magnetic dissipation?

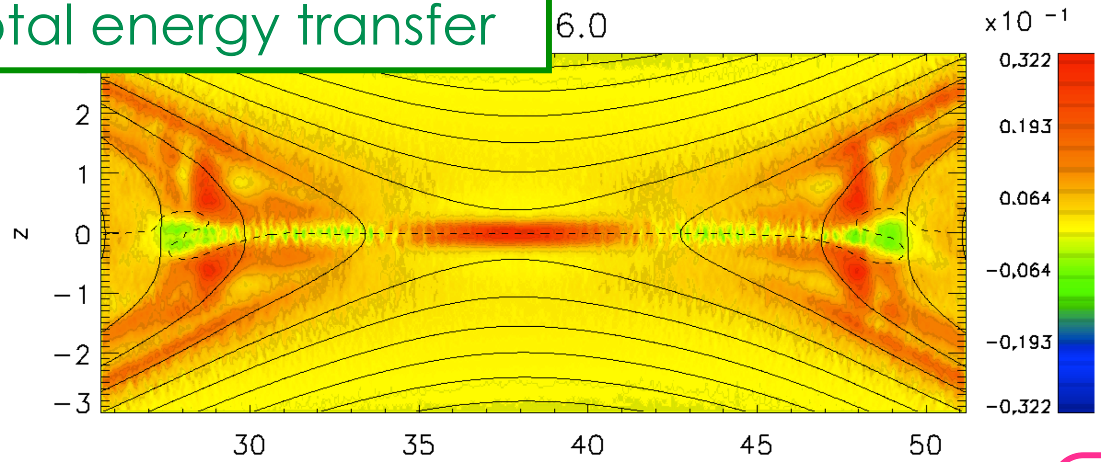
What is Dissipation?

- Irreversible process
- Something that never comes back



Magnetic energy dissipation

Total energy transfer

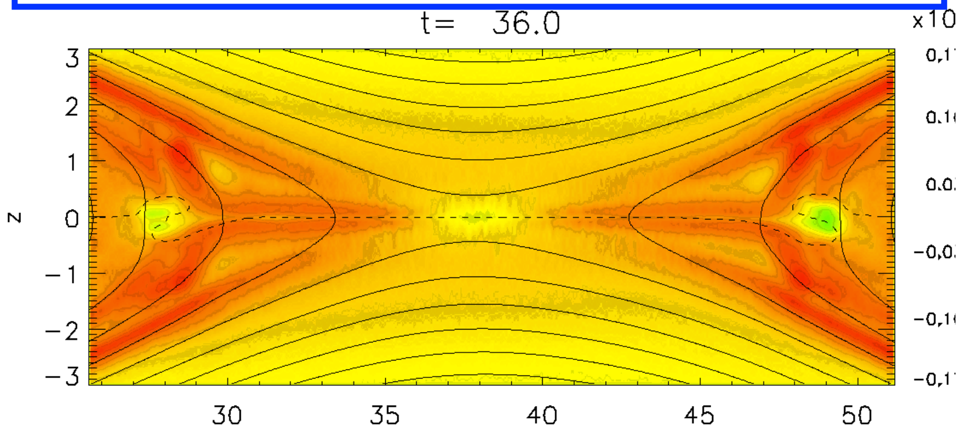


$$\boldsymbol{j}\cdot\boldsymbol{E} = (\boldsymbol{j}\times\boldsymbol{B})\cdot\boldsymbol{v}_{\mathrm{mhd}} + D_e$$

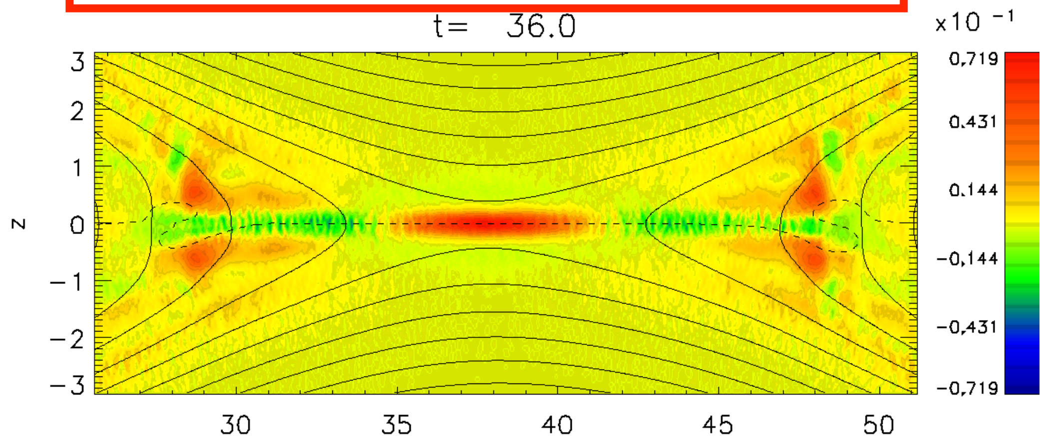
irreversible in MHD

$$\eta \boldsymbol{j}^2 \geq 0$$

Work by Lorentz force (Ideal MHD)



Nonideal energy conversion



Birn & Hesse 2005

2D PIC simulations

Magnetic energy dissipation

Electron-frame dissipation measure

$$D_e = J_\mu F^{\mu\nu} u_{e\nu} = \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right]$$

$$\equiv \boldsymbol{j}' \cdot \boldsymbol{E}'$$

Lorentz factor

Charge density

Electric current in the electron frame

Electric field in the electron frame

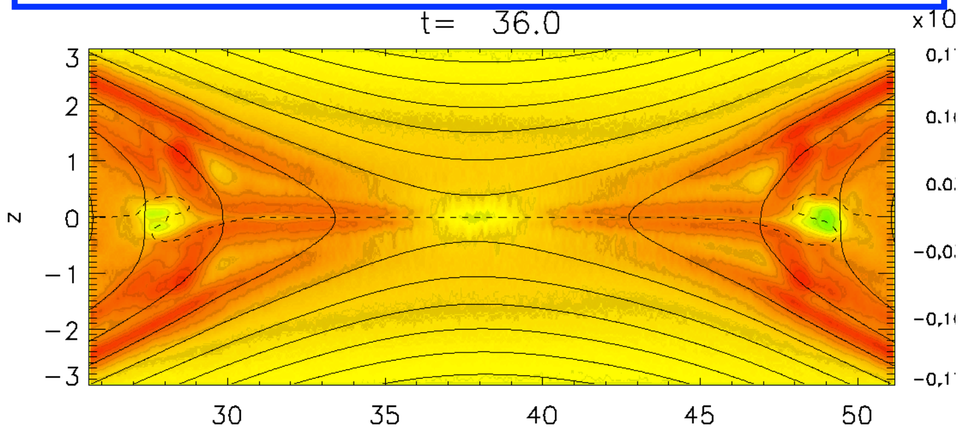
Zenitani+ 2011 PRL

$$\boldsymbol{j} \cdot \boldsymbol{E} = (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\rm mhd} + D_e$$

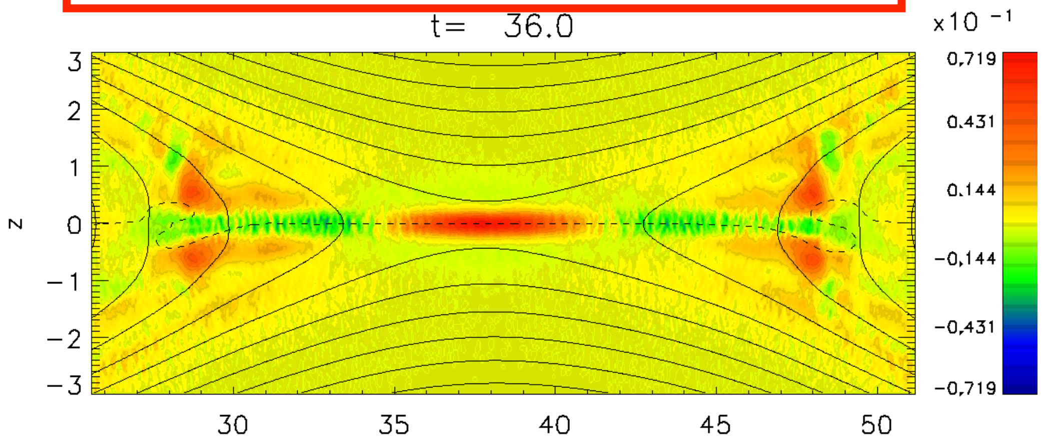
irreversible in MHD

$$\eta \boldsymbol{j}^2 \geq 0$$

Work by Lorentz force (Ideal MHD)

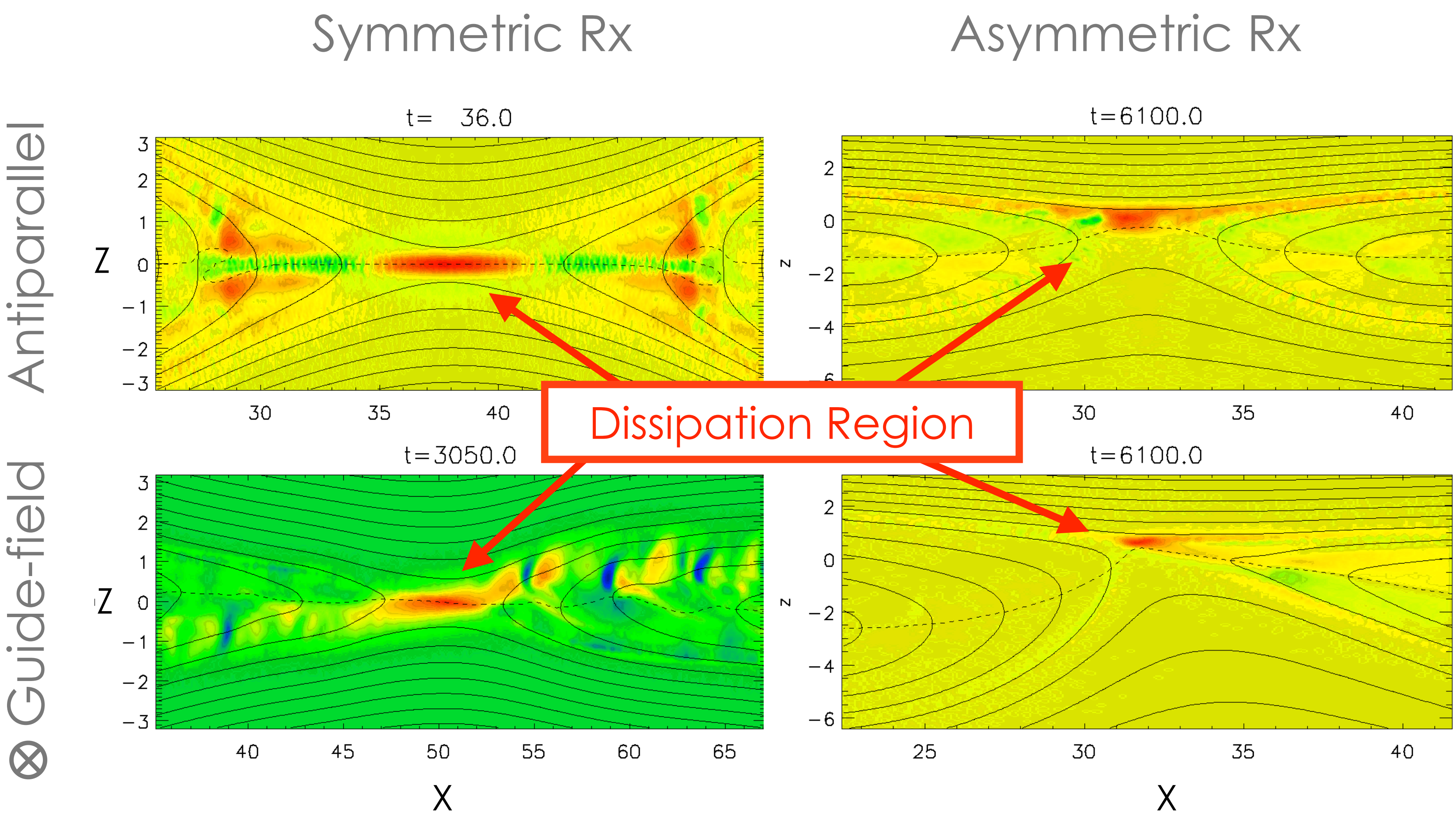


Nonideal energy conversion



Birn & Hesse 2005

D_e in various reconnections



$$D_e = \gamma_e\left[\boldsymbol{j}\cdot(\boldsymbol{E}+\boldsymbol{v}_e\times\boldsymbol{B}) - \rho_c(\boldsymbol{v}_e\cdot\boldsymbol{E})\right]$$

2D PIC simulations

Irreversible?

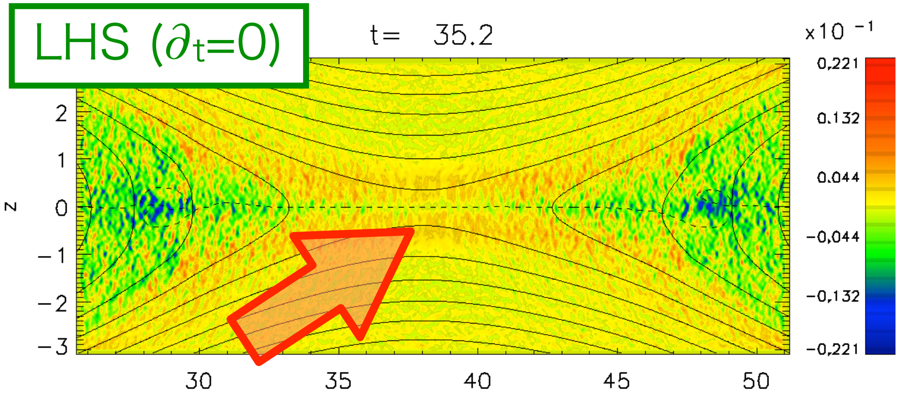
- D_e measure is a driving term to increase MHD entropy

MHD specific entropy

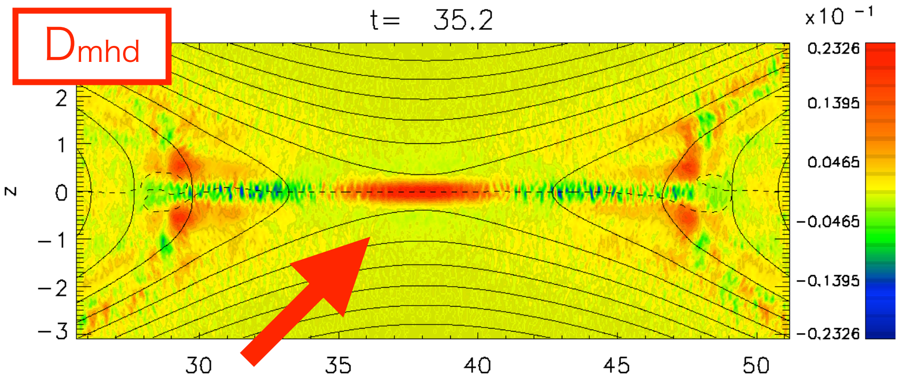
$$\frac{3p}{2}\frac{D}{Dt}\left[\ln\left(\frac{p}{\rho_{\mathrm{mhd}}^{5/3}}\right)\right] = \mathcal{D}_{\mathrm{mhd}} - \nabla\cdot\boldsymbol{q}_{\mathrm{mhd}} - \Pi_{ij}\frac{\partial V_j}{\partial x_i} \gtrsim 0$$

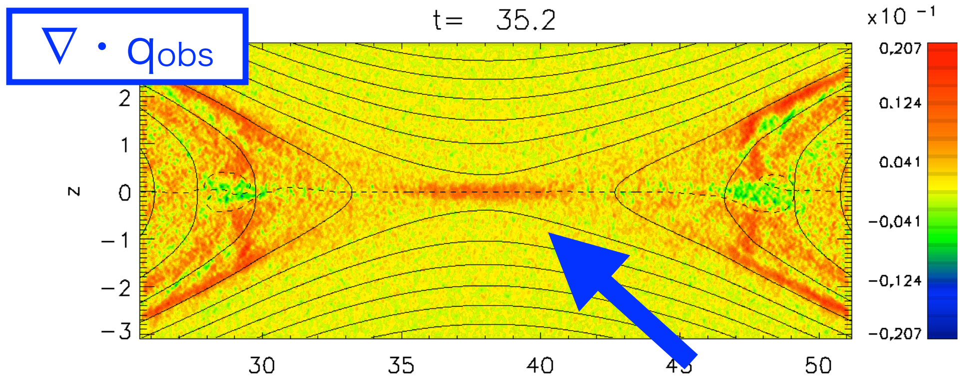
$\approx \mathcal{D}_e$

Rossi & Olbert 1970



- Note: $\frac{D}{Dt} \approx 0$ at the X-line

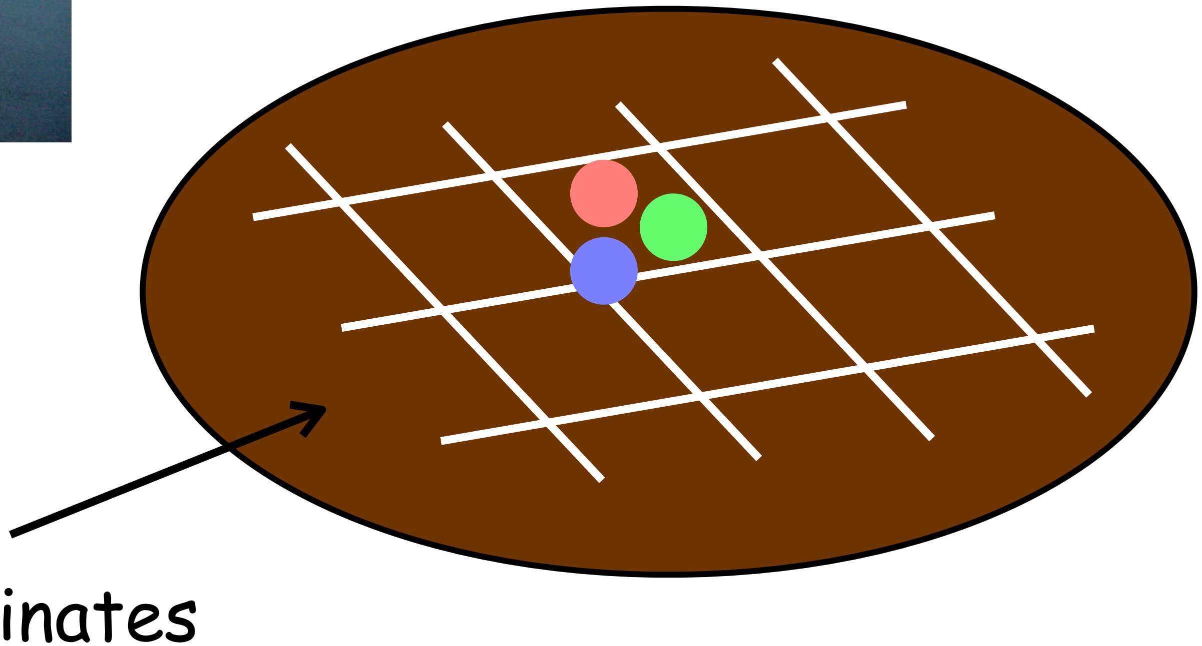




What is magnetic diffusion?

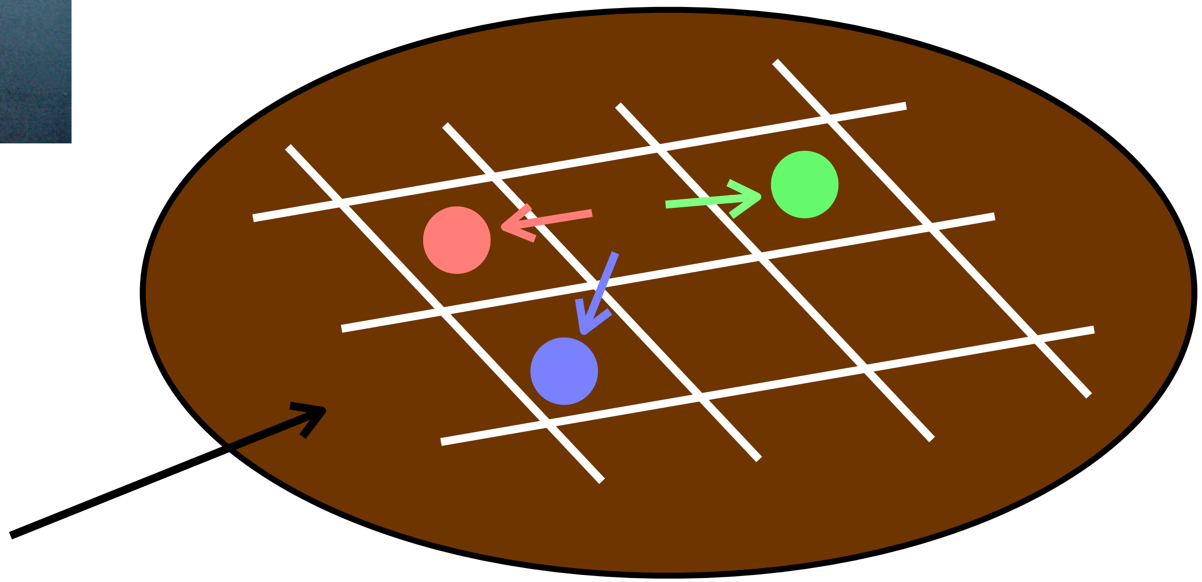
Diffusion in a coffee

- Let's consider colorful sugar elements



Diffusion in a coffee

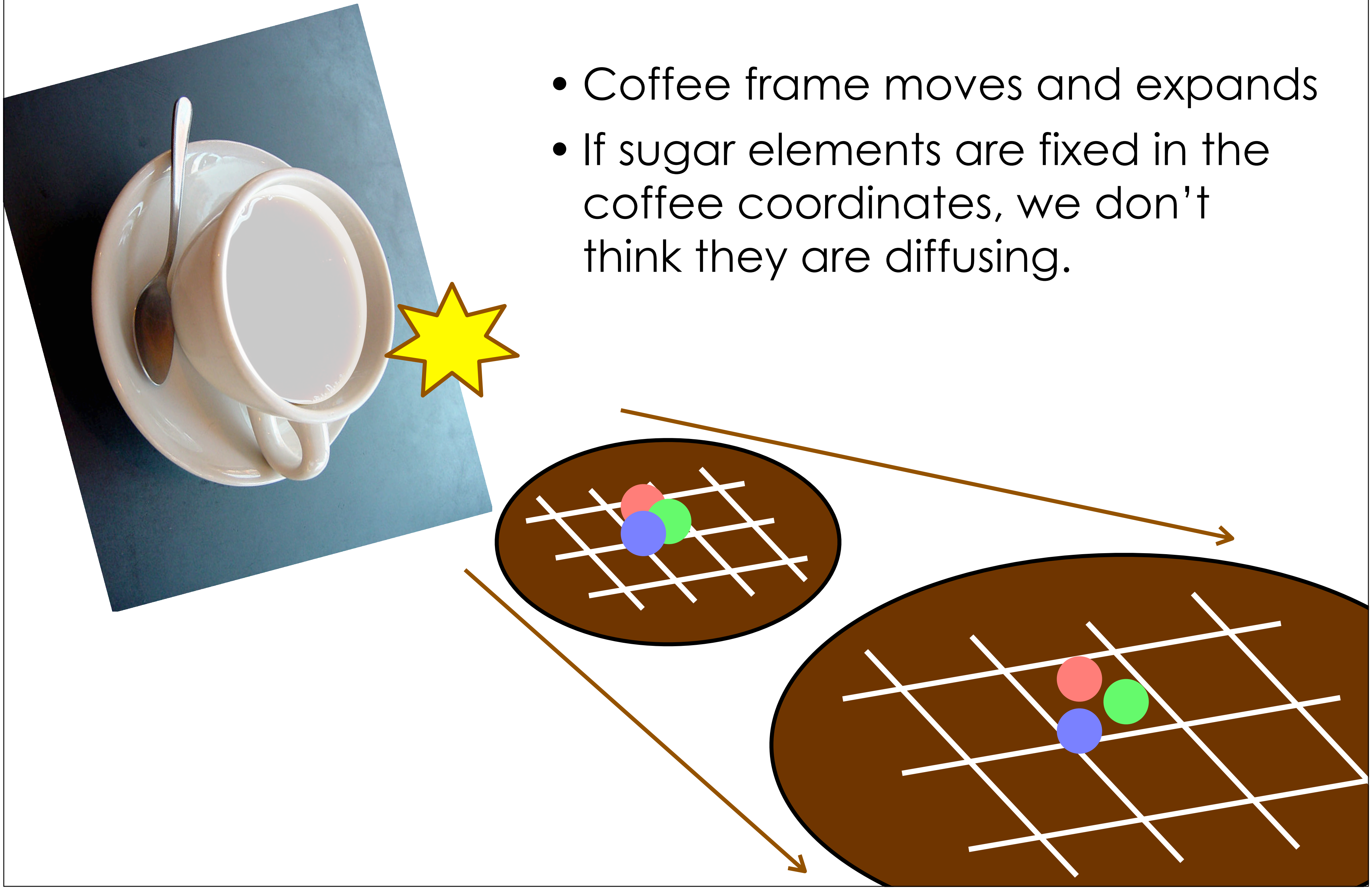
- Let’s consider colorful sugar elements
- Sugar spreads through the diffusion process



Coffee coordinates

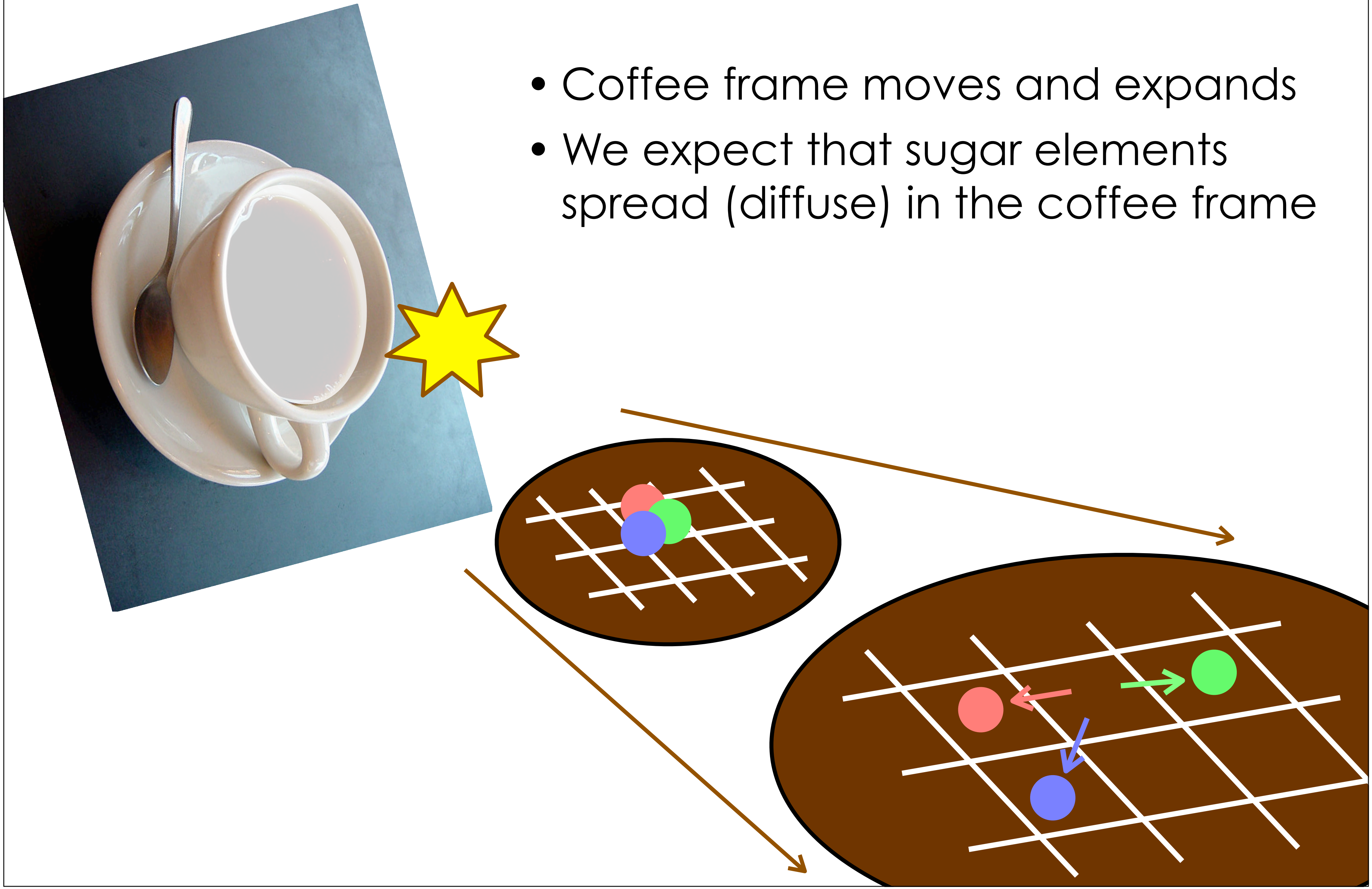
Diffusion in a coffee flow

- Coffee frame moves and expands
- If sugar elements are fixed in the coffee coordinates, we don't think they are diffusing.



Diffusion in a coffee flow

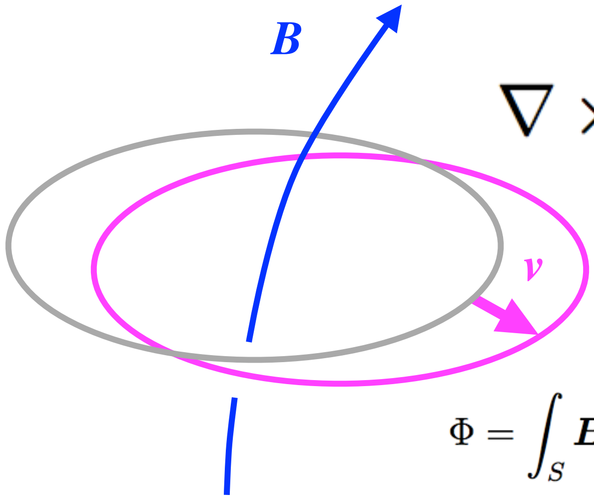
- Coffee frame moves and expands
- We expect that sugar elements spread (diffuse) in the coffee frame



Magnetic flux diffusion

Frozen-in condition
(Flux preservation)

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$$



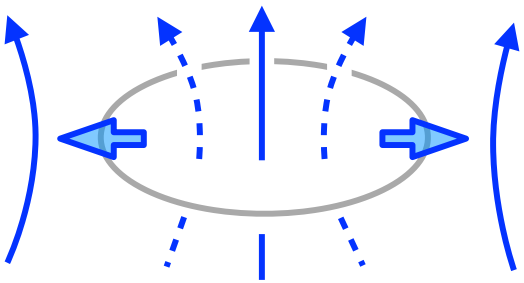
$$\nabla \times \boldsymbol{R} = 0$$

$$\Phi = \int_S \boldsymbol{B} \cdot d\boldsymbol{A}$$

Newcomb 1958
Stern 1966

$$\nabla \times \boldsymbol{R} \neq 0$$

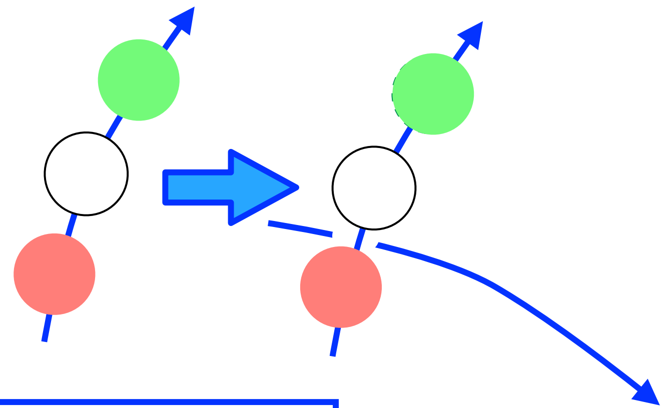
$$\mathfrak{L} = \boldsymbol{b} \cdot (\nabla \times \boldsymbol{R})$$



Magnetic loss

SZ & Umeda 2014

$$\boldsymbol{b} \times (\nabla \times \boldsymbol{R})$$

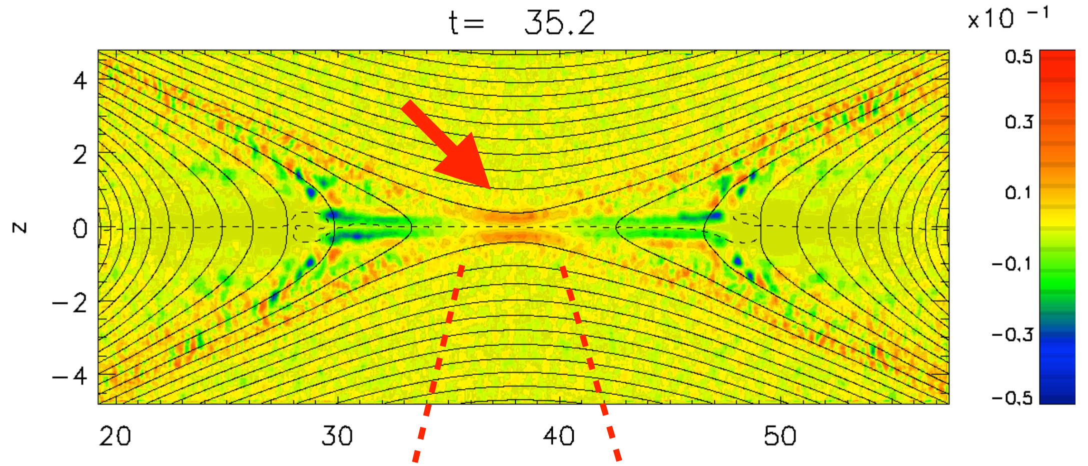


Plasma connectivity
(Line preservation)

Newcomb 1958

Electron diffusion region vs Dissipation region (D_e)

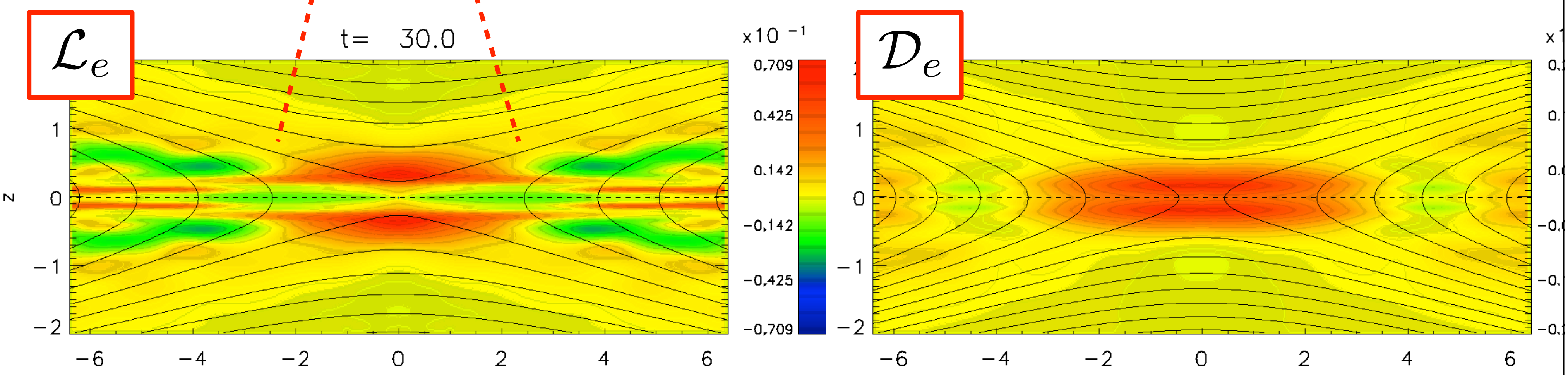
2D PIC simulation (m_i/m_e=100)



- A compact region with [diffusive] magnetic loss

$$\mathfrak{L}_e = \boldsymbol{b} \cdot (\nabla \times \boldsymbol{R}_e)$$

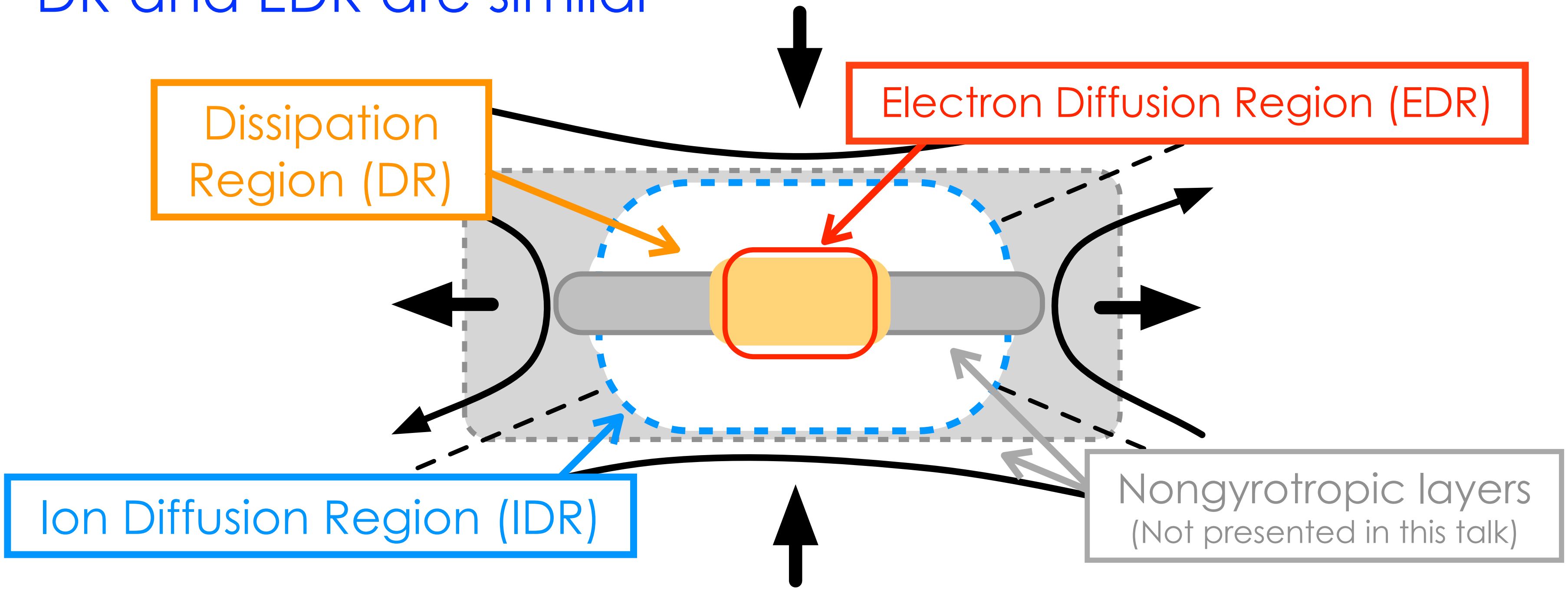
$$\boldsymbol{R}_e \equiv \boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}$$



2D Vlasov simulation (m_i/m_e=25)

Topic 1: Summary

- Dissipation region (DR)
  - Electron-frame dissipation measure
  - Nonideal energy transfer $\mathcal{D}_e \gtrsim 0$
  - Likely irreversible: Driving term in the MHD entropy equation
- Electron diffusion region (EDR)
  - Diffusive evolution of magnetic flux in the electron flow frame $\mathfrak{L}_e \equiv \boldsymbol{b} \cdot (\nabla \times \boldsymbol{R}_e)$
- DR and EDR are similar

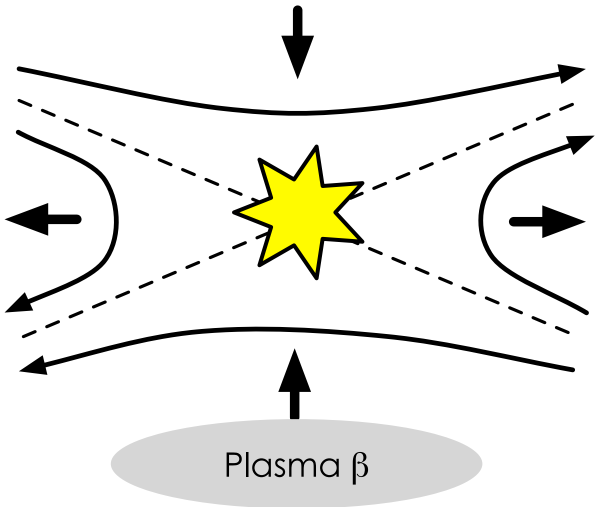


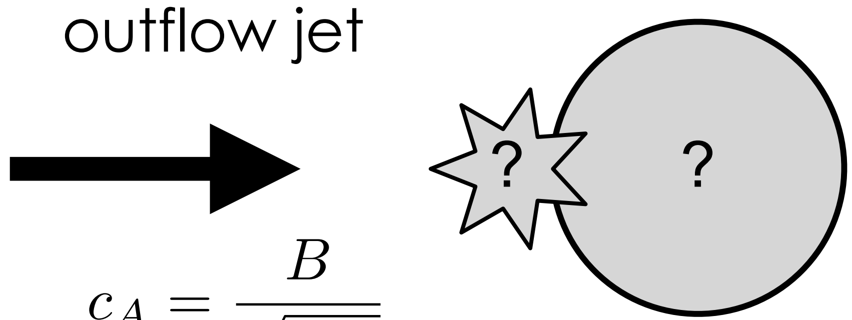
Topic 2:
High-speed fluid dynamics in magnetic reconnection in a low-β plasma

[3] Zenitani & Miyoshi, *Phys. Plasmas* **18**, 022105 (2011)
[4] Zenitani, *Phys. Plasmas* **22**, 032114 (2015)

Motivation

- Magnetic reconnection expels a fast outflow jet at the upstream Alfvén speed
- How does the jet interact with an external medium?





$$c_A = \frac{B}{\sqrt{4\pi\rho}}$$

- Key parameter

$$\beta \equiv \frac{p_{\rm gas}}{p_{\rm mag}} = \frac{8\pi p}{B^2}$$

Alfvén speed

Typical velocity

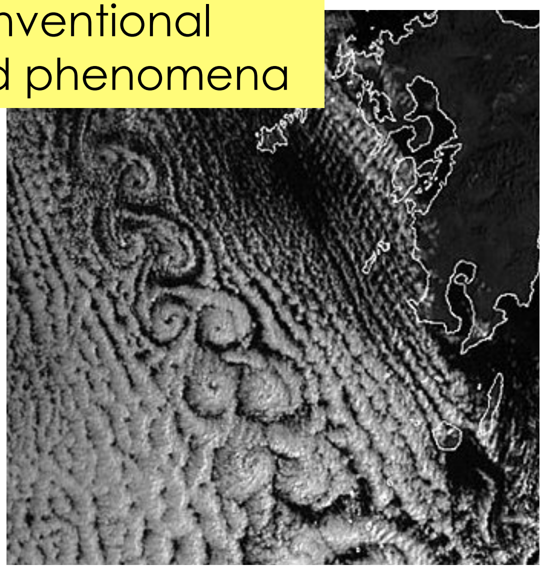
$$\frac{1}{\beta} \sim \left(\frac{c_A}{c_s}\right)^2 \sim \left(\frac{V}{c_s}\right)^2 \sim \mathcal{M}^2$$

Sound speed

Typical Mach number

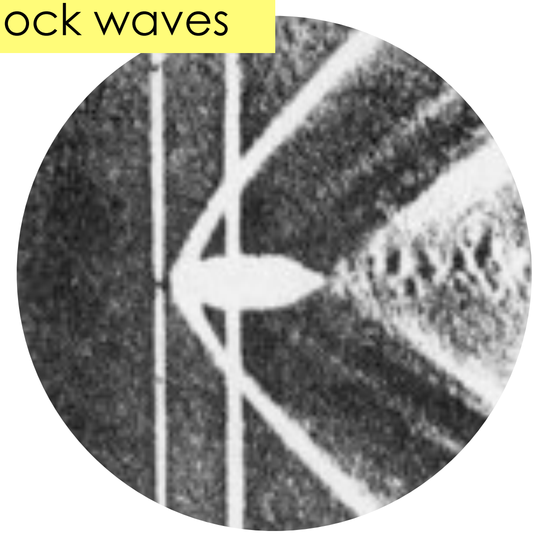
Branches of fluid dynamics

Conventional fluid phenomena



tenki.jp 2015

Shock waves



Mach 1887

1

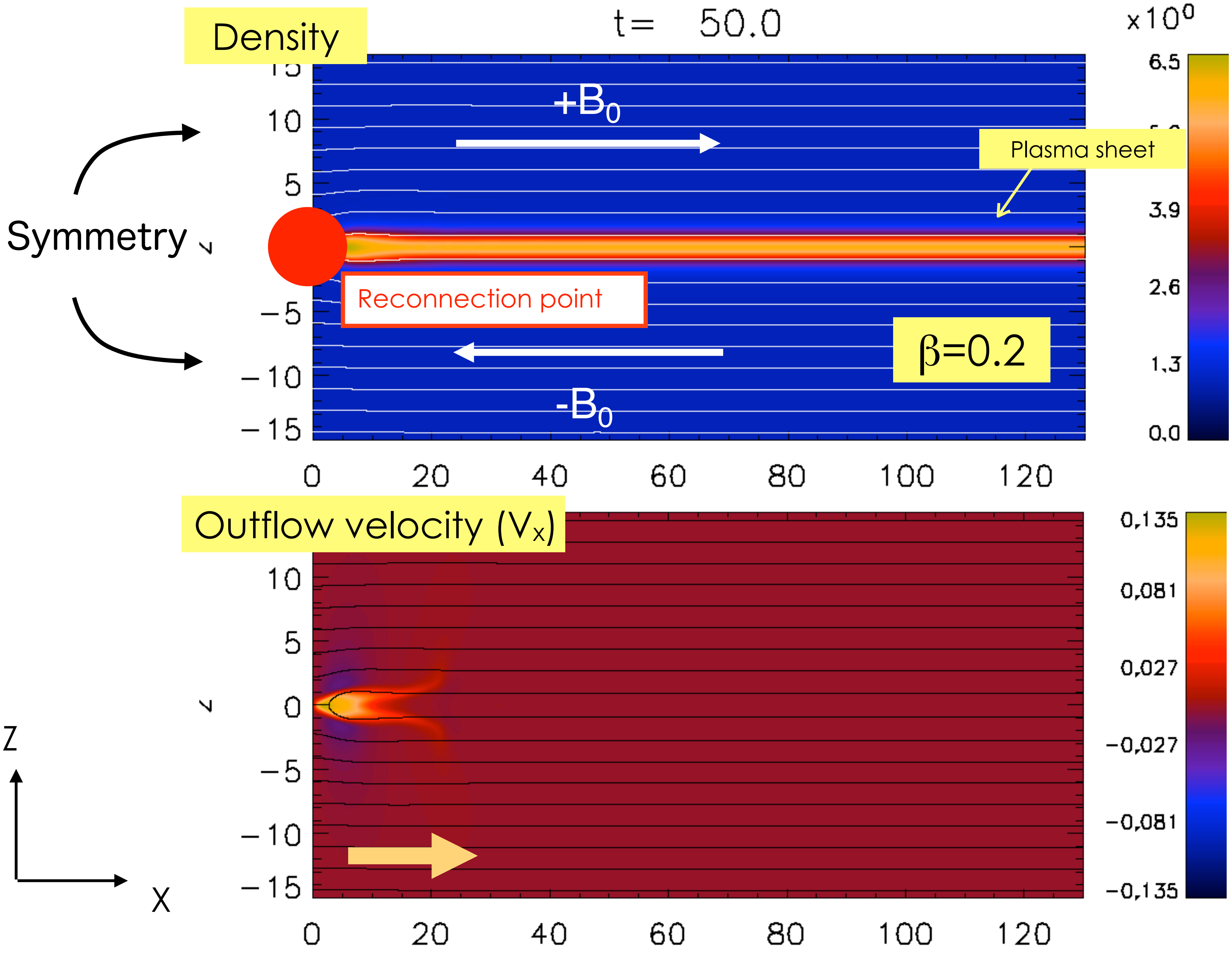
$$\mathcal{M} = \frac{V}{c_s}$$

Subsonic | Transonic | Supersonic

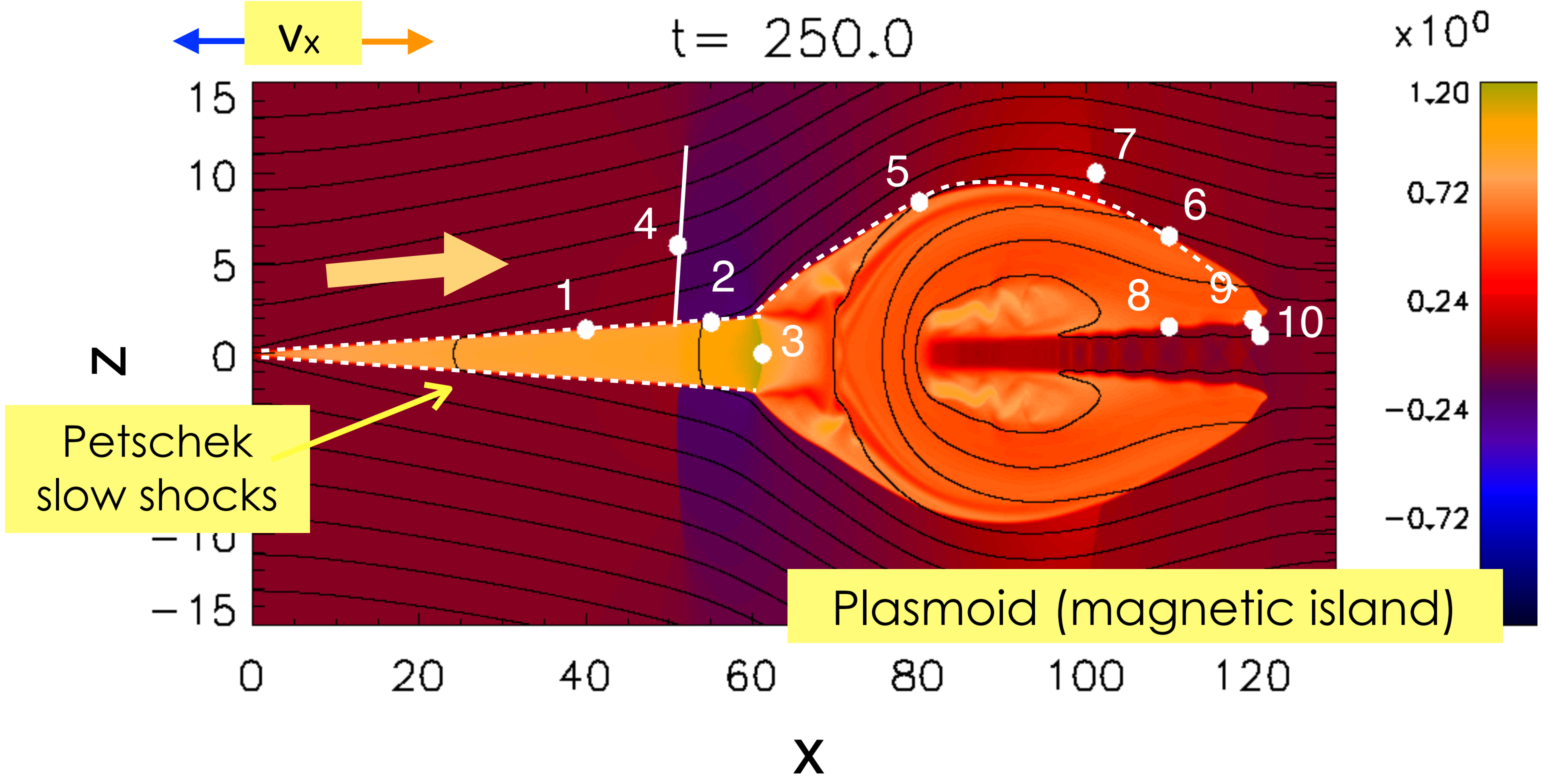
- Incompressible fluids

- Compressible fluid dynamics
- High-speed fluid dynamics
  - Adiabatic effects
  - **Shocks**
  - **Shock-shock interaction**

MHD simulation



Various shocks!



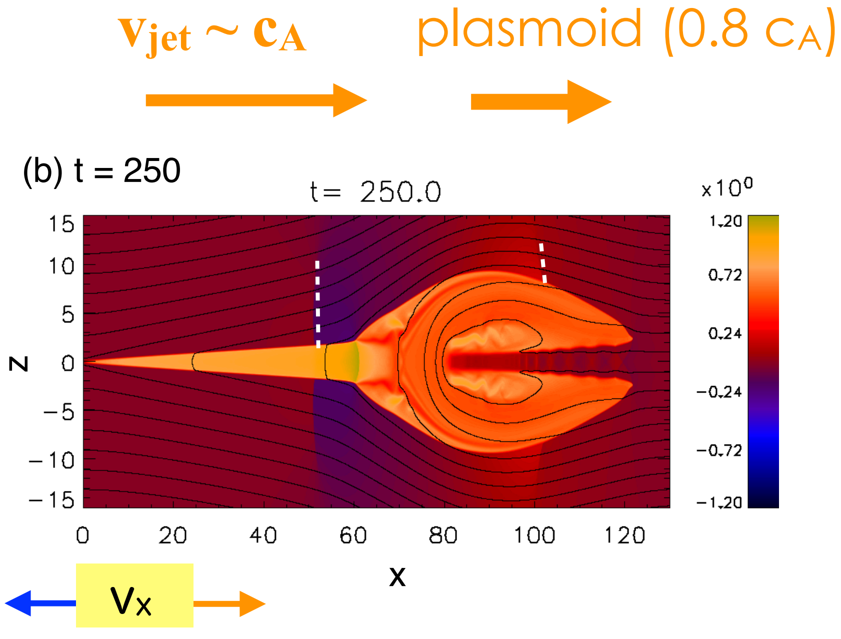
- Extensive analysis on shock conditions (Minimum variance analysis; MVA-B)

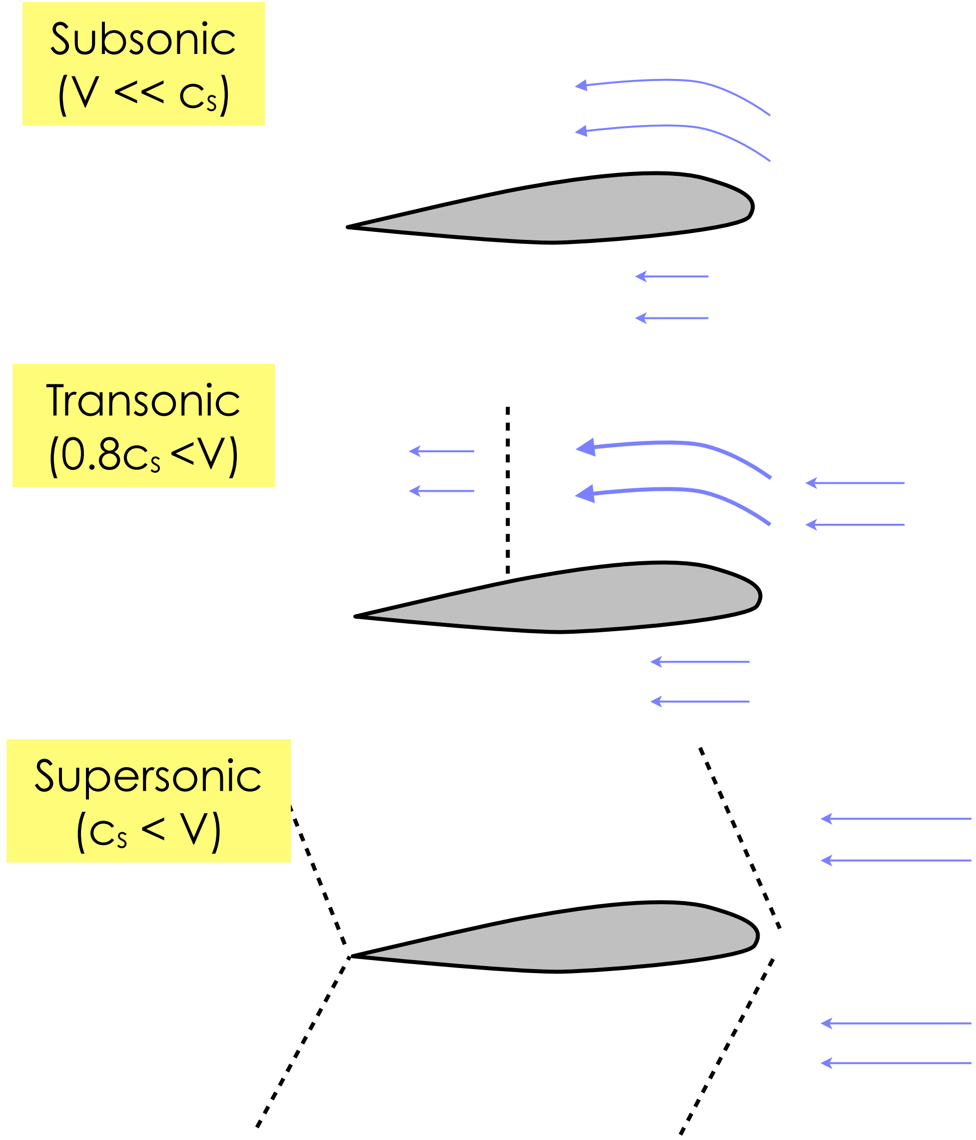
TABLE I. Rankine–Hugoniot analysis. The subscripts 1 and 2 denote the upstream and downstream quantities. The locations (x, z) in the simulation domain [see also Fig. 1(b)], the shock normal vector $\hat{\boldsymbol{n}}$, the shock velocity v_{sh}, the angle between $\hat{\boldsymbol{n}}$ and the upstream magnetic field $\boldsymbol{B}_1$, the upstream plasma beta, flow Mach numbers to fast, intermediate (Alfvén), and slow-mode speeds, and the temperature ratio. The asterisk sign (*) indicates unreliable results (see Sec. III F). The letter (S) indicates a slow shock, (F) is a fast shock, and (U) is unclassified.

No.	Location	(n_x, n_z)	v_{sh}	$\lvert\theta_{BN}\rvert$	β_1	$\mathcal{M}_{f1}$	$\mathcal{M}_{i1}$	$\mathcal{M}_{s1}$	$\mathcal{M}_{f2}$	$\mathcal{M}_{i2}$	$\mathcal{M}_{s2}$	T_2/T_1	
1	(40.0, 1.35)	(−0.03, 1.00)	0.0	86.3	0.22	0.06	0.98	2.49	0.04	0.69	0.69	2.72	(S) Petschek shock
2	(55.0, 1.75)	(−0.04, 1.00)	−0.013	86.3	0.098	0.06	0.88	3.22	0.04	0.58	0.58	4.58	(S) Petschek shock
3	(61.2, 0)	(−1.00, 0.00)	−0.40	90	303	1.41			0.77			1.38	(F) Reverse shock
4	(51.0, 6.0)	(1.00, −0.04)	0.31	9.4	0.12	0.41	0.42	1.34	0.33	0.34	0.78	1.33	(S) Postplasmoid vertical shock
5	(80.0, 8.4)	(−0.18, 0.98)	−0.06	86.5	0.16	0.05	0.85	2.47	0.03	0.56	0.65	2.54	(S) Outer shell
6	(110.0, 6.5)	(0.24, 0.97)	0.19	84.9	0.21	0.06	0.76	1.99	0.05	0.53	0.64	2.06	(S) Outer shell
7	(101.2, 10.0)	(0.94, 0.33)	0.54	25.2	0.23	0.43	0.49	1.15	0.39	0.44	0.87	1.15	(S) Forward vertical shock
8	(110.0, 1.5)	(−0.06, −1.00)	0.10	87.8	1.1	0.12	4.5*	6.5*	0.12	3.9*	4.0*	1.55	(U) Intermediate shock?
9	(120.0, 1.9)	(0.13, −0.99)	0.13	87.1	0.49	0.09	2.0*	3.8*	0.08	1.7*	1.9*	1.86	(U) Slow shock?
10	(120.9, 1.0)	(0.64, −0.77)	0.50	46.8	2.63	1.22	3.00	3.40	0.88	2.66	3.06	1.18	(F) Oblique shock

Normal shock: Analogy to airfoil

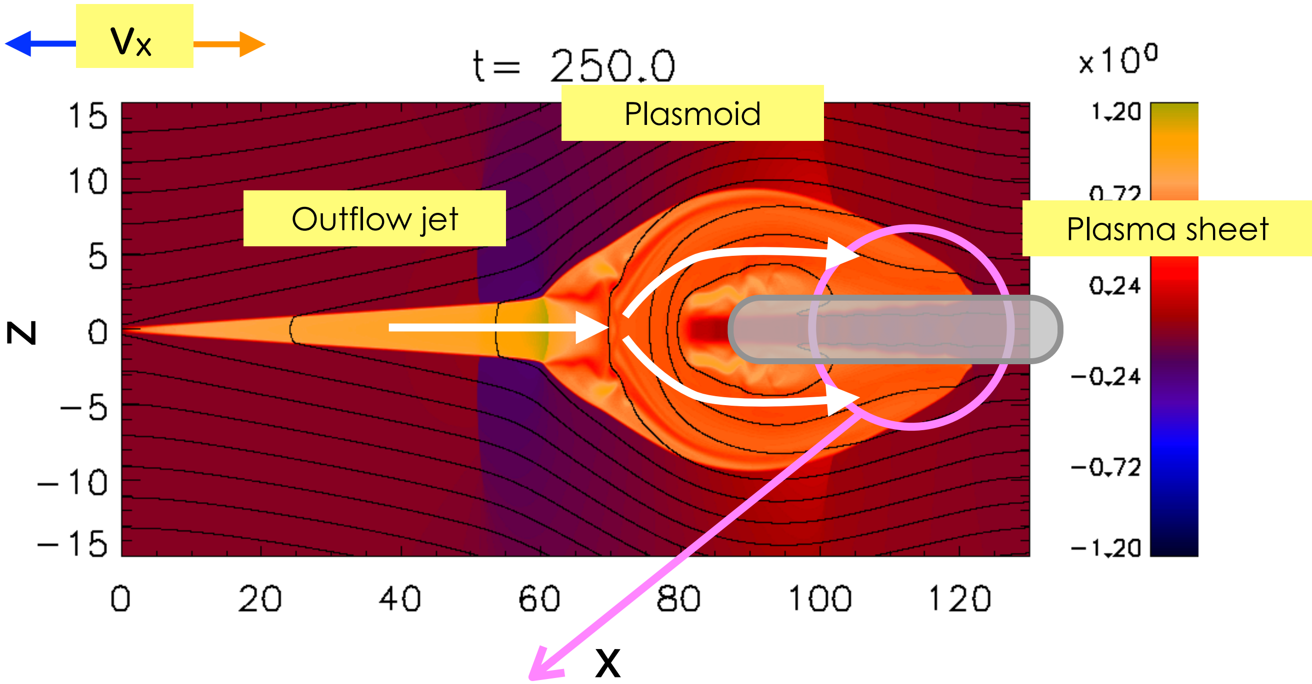
- MHD slow shock
- Recovery shock or recompression shock

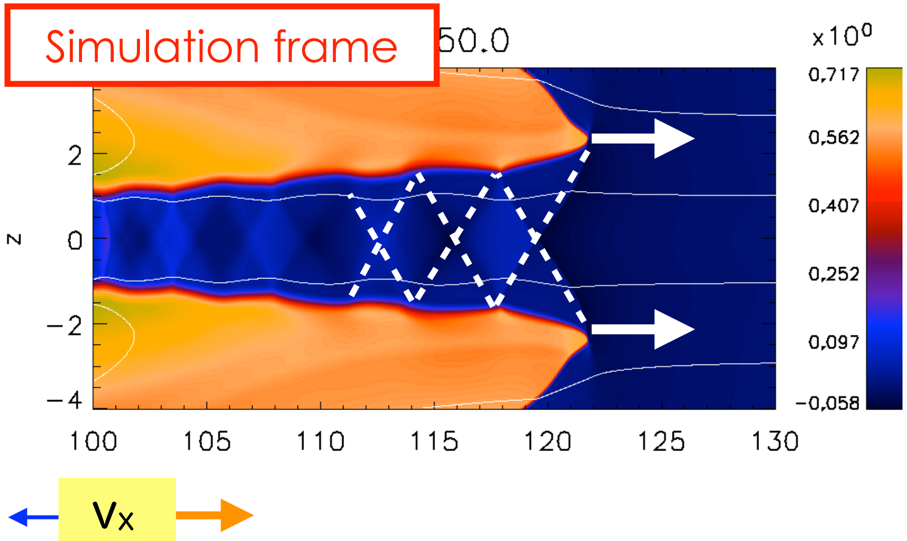




See also https://www.youtube.com/watch?v=8OIqfCTAZQo

Shock diamond



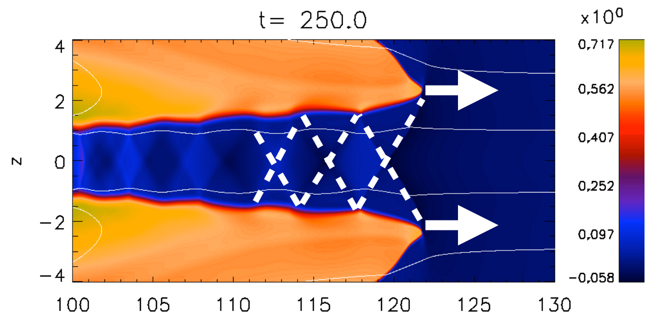


- Bifurcated jets are supersonic

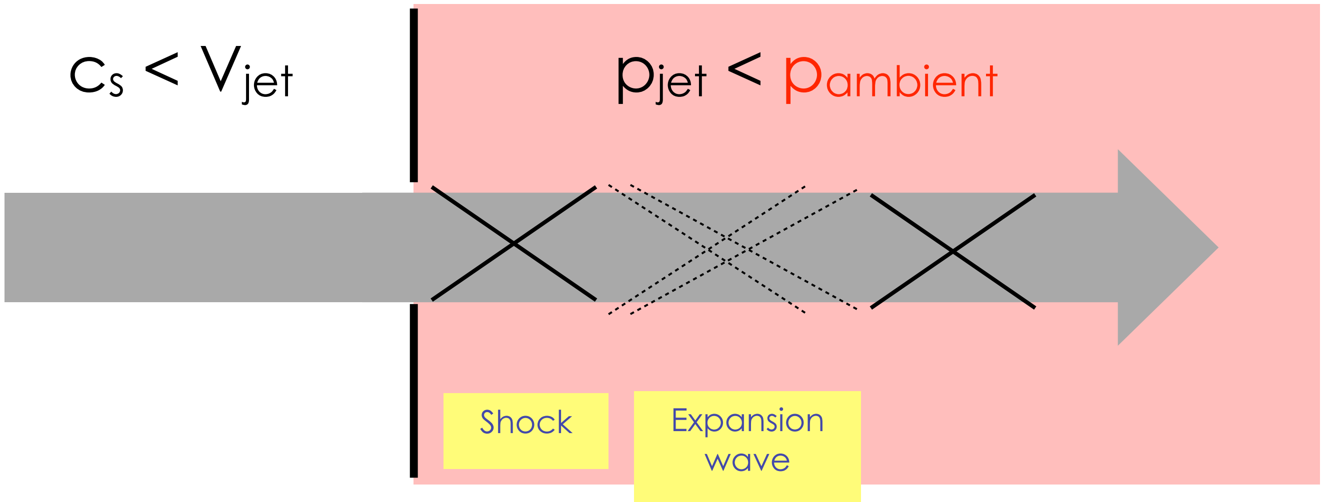
$$v_{jet} \approx c_A > c_s \iff \beta < 1$$

- Diamond pattern inside the plasma sheet, due to multiple reflection of oblique-shocks

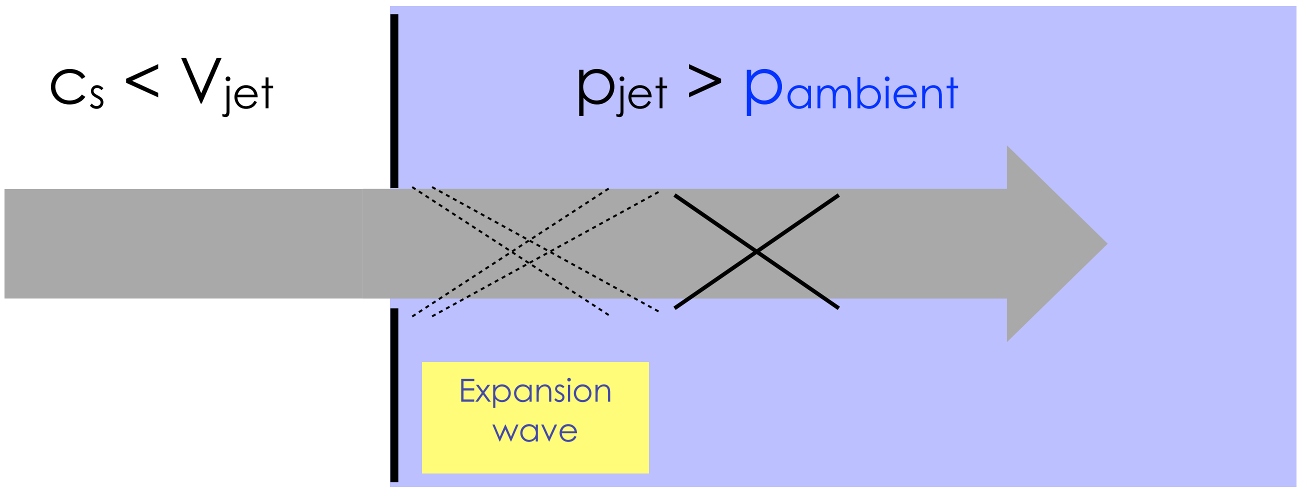
Supersonic nozzle problem



- (a) Over-expanded flow



- (b) Under-expanded flow



Shapiro 1953

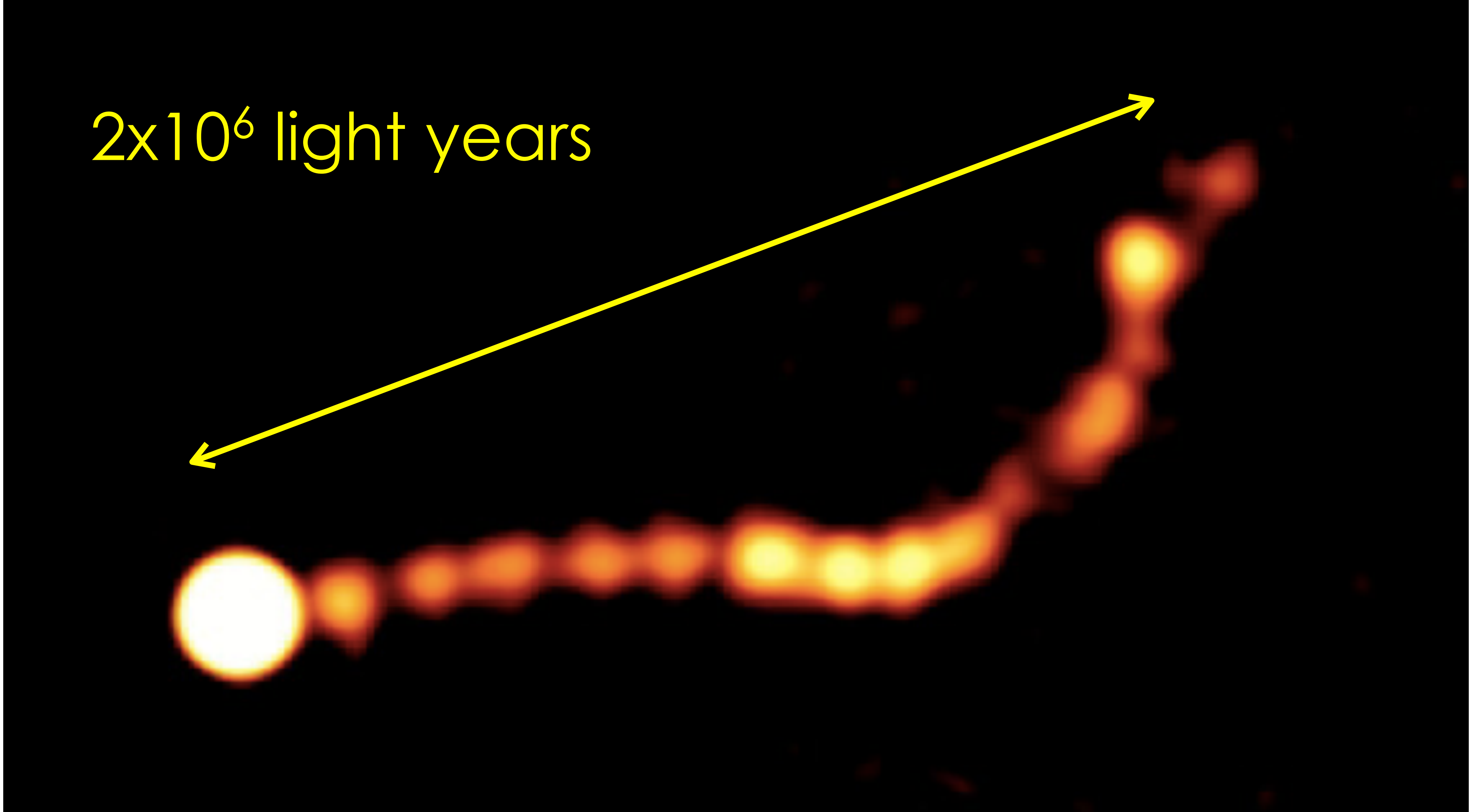
Shock diamonds in aeronautics

BBC online http://www.bbc.com/future/story/20130701-flying-the-worlds-fastest-plane

Shock diamonds in video game

Microsoft Flight Simulator X   https://www.youtube.com/watch?v=S8QGaiE4yWc

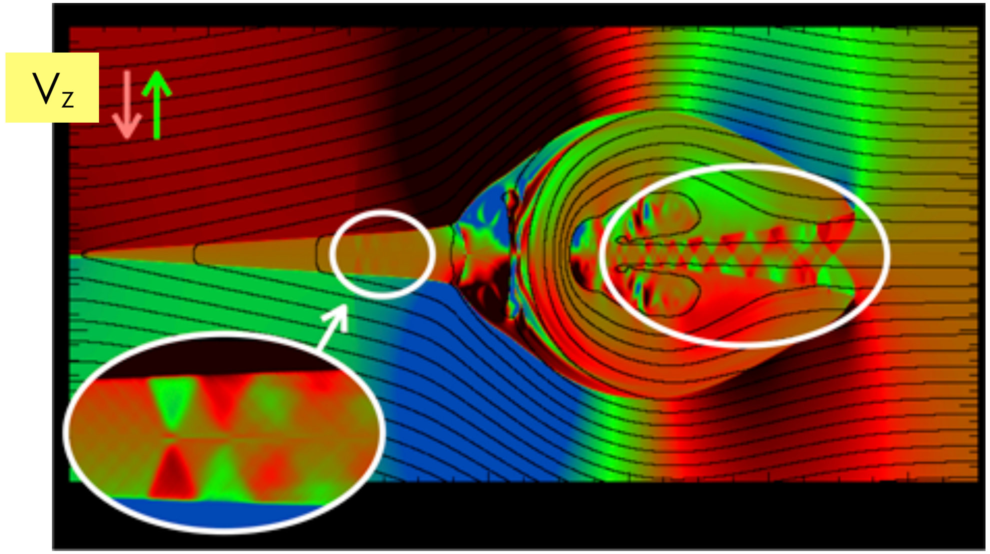
Shock diamonds in astrophysics



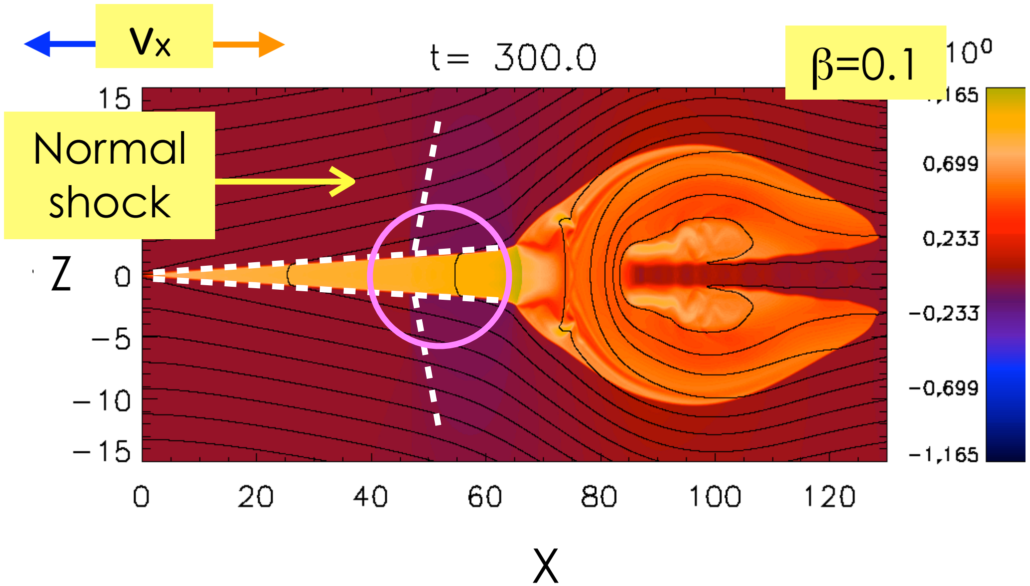
PKS 0637-752   Godfrey+ 2012 ApJ

Hidden shock-diamonds

- Another shock-diamonds are hidden inside the Petschek outflow

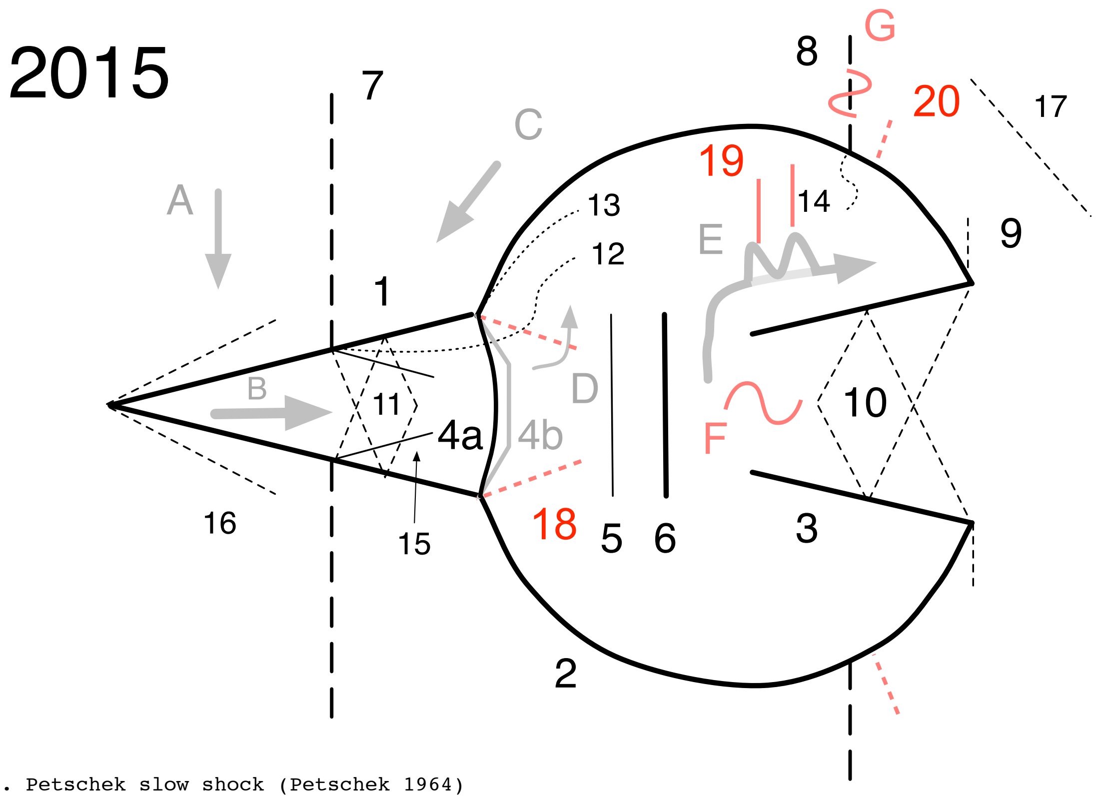


- Shock-crossing point between the normal shock and Petschek slow shock is highly complicated (Zenitani 2015)



Zenitani 2015

The plasmoid diagram



1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995)
3. intermediate shock (Abe & Hoshino 2001) or slow shock (Saito et al. 1995)
4a fast shock (Forbes & Priest 1983)
4b oblique shock & Mach disk (Takasao et al. 2015)
5. looptop front (Ugai 1987)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani et al. 2010)
8. outer vertical slow shock (Zenitani & Miyoshi 2011)
9. fast-mode wave front (Saito et al. 1995)
10. overexpanded shock-diamonds (Zenitani et al. 2010)
11. underexpanded shock-diamonds (Zenitani 2015)
12. contact discontinuity (Zenitani & Miyoshi 2011, 2015)
13. contact discontinuity (Zenitani 2015)
14. contact discontinuity (Zenitani 2015)
15. slow expansion wave front (Zenitani 2015)

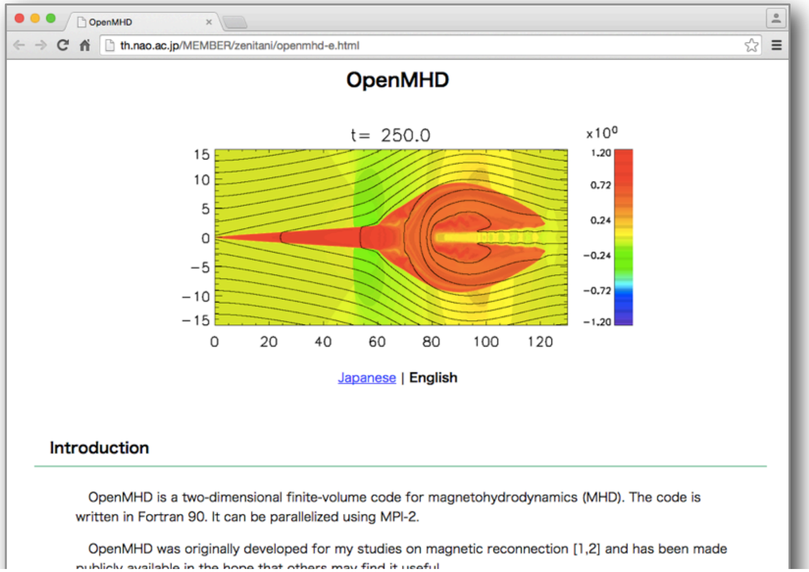
16. conduction front [with heat conduction] (Yokoyama & Shibata 1997)
17. fast forward shock [in asymmetric reconnection] (Nitta et al. 2015)

A. reconnection inflow
B. outflow jet
C. post-plasmoid reverse flow
D. internal flow
E. flapping jet (KH instability)

- A lot more to come
- If you find something new, please send me your references so that I will update the diagram

OpenMHD code

- Simple, Scalable, and Shock-capturing MHD code
  - TVD Runge=Kutta method
  - MUSCL interpolation
  - HLLD flux solver
  - Hyperbolic divergence cleaning
- Reconnection problems are pre-configured



http://th.nao.ac.jp/MEMBER/zenitani/openmhd-e.html

Topic 2: Summary

- MHD evolution of magnetic reconnection in the low-β, high Mach-number regime

$$\frac{1}{\beta} \sim \left(\frac{c_A}{c_s}\right)^2 \sim \left(\frac{V}{c_s}\right)^2 \sim \mathcal{M}^2 \qquad \mathcal{M} > 1$$

- New shock structures = outcomes of high-speed fluid effects
  - Recompression shock
  - Overexpanded shock diamonds at the front
  - Underexpanded shock diamonds inside the outflow exhaust

- The plasmoid diagram - your contributions are welcome
- OpenMHD code - publicly available

Thank you for your attention.
Have a safe return trip!

BBC online http://www.bbc.com/future/story/20130701-flying-the-worlds-fastest-plane