Magnetohydrodynamic structure of a plasmoid in low beta plasmas

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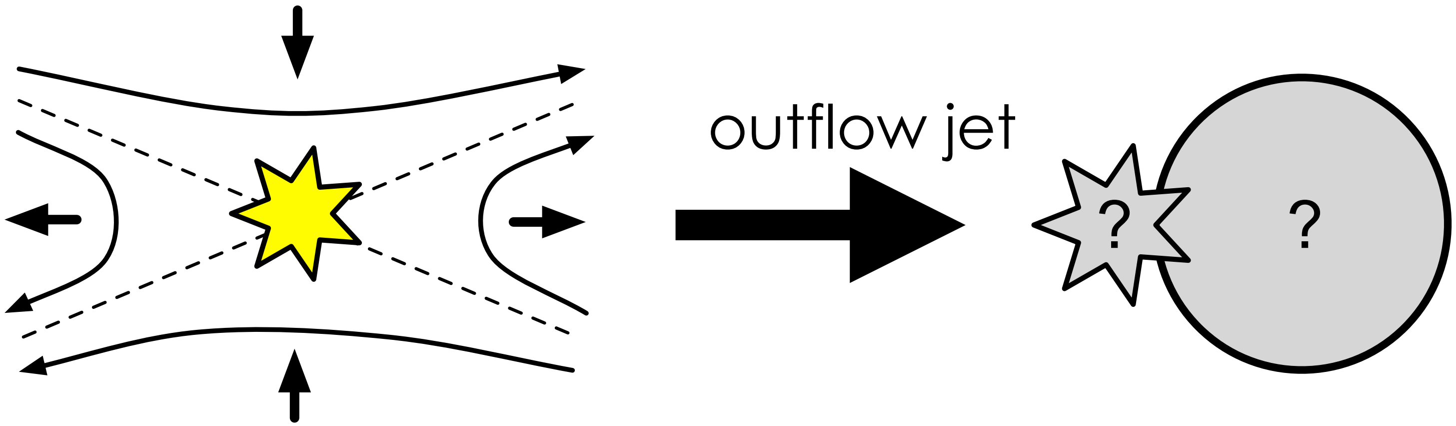
Motivation (1/2)

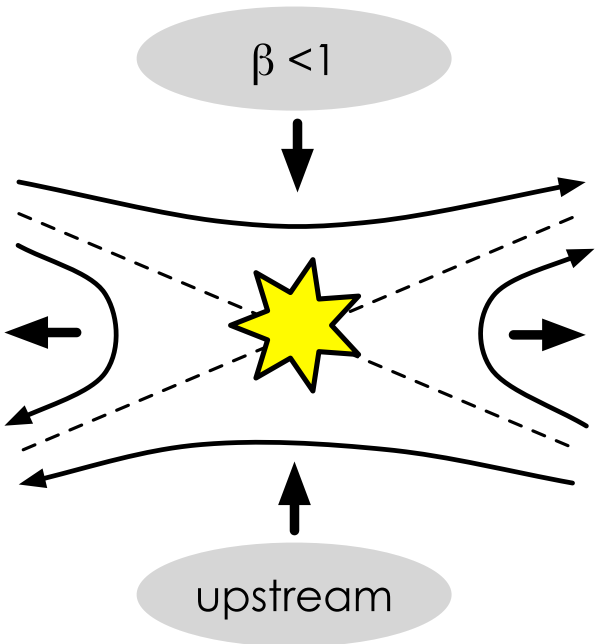
- Reconnection expels fast outflow jet
- How does the jet interacts with the outer environments in a large-scale system?

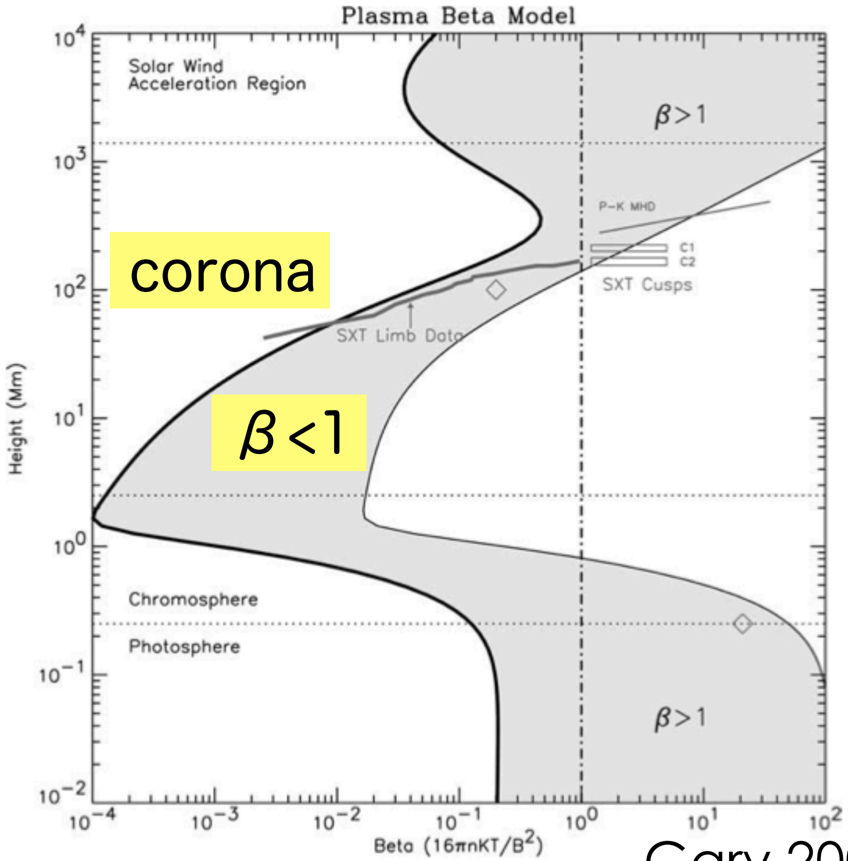


- MHD approximation is useful to explore large-scale evolution of plasma systems

Motivation (2/2): low-beta plasmas

- Magnetotail lobe: β < 1
- Lower corona: β < 1





Gary 2001

- Upstream plasmas control the reconnection
- The plasma beta $\beta=2p/B^2$ is usually low in the upstream region in reconnection environments, but the influence of low-beta plasmas is unclear.

MHD equations

- Resistive MHD equations in a conservative form
- We develop a new HLL-type MHD code to solve the equations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + p_T \boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}) = 0,$$
$$\frac{\partial e}{\partial t} + \nabla \cdot \Big((e + p_T)\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B} + \eta \boldsymbol{j} \times \boldsymbol{B} \Big) = 0,$$
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) + \nabla \times (\eta \boldsymbol{j}) = 0,$$

- Ohm's law is incorporated in the eqs.

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

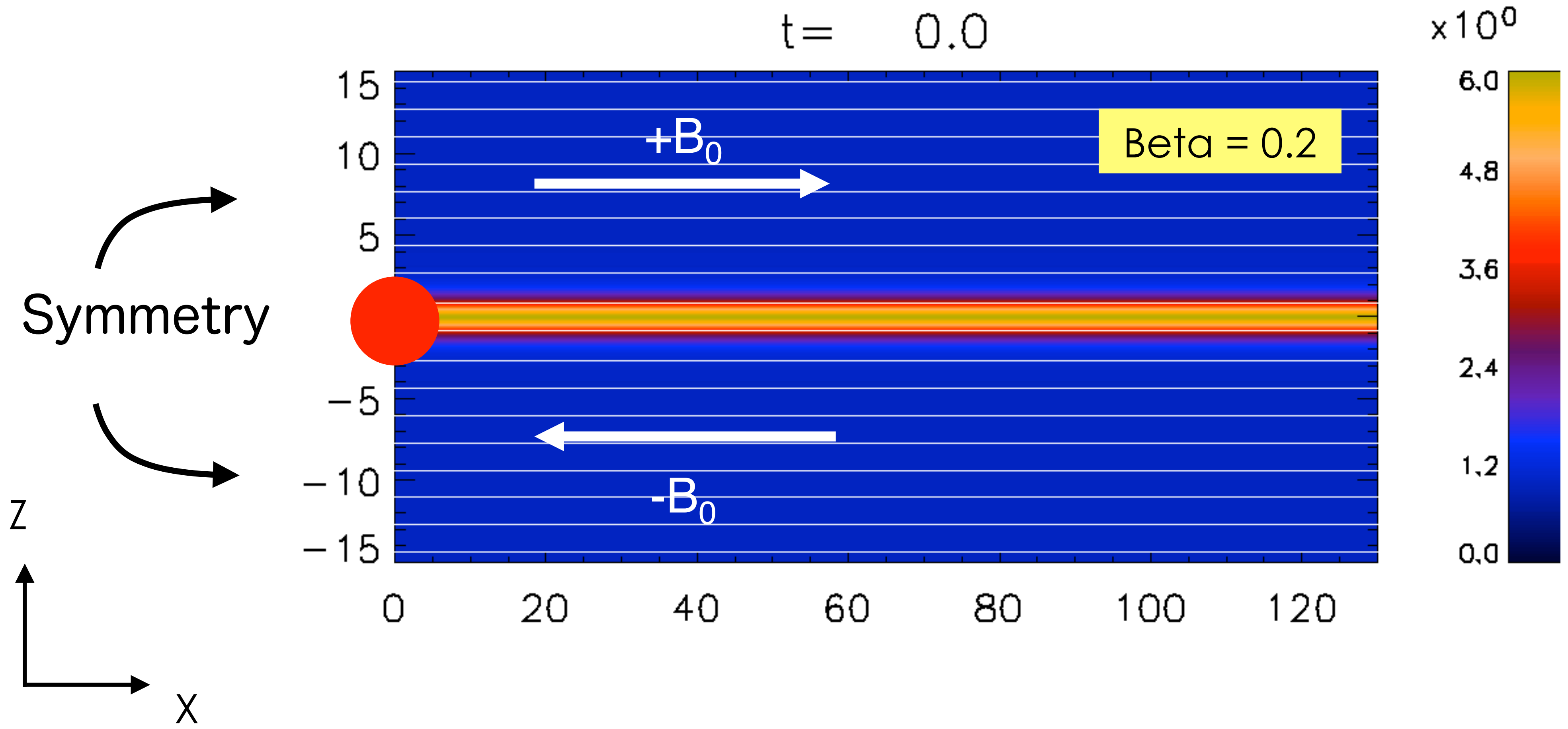
Modern MHD code

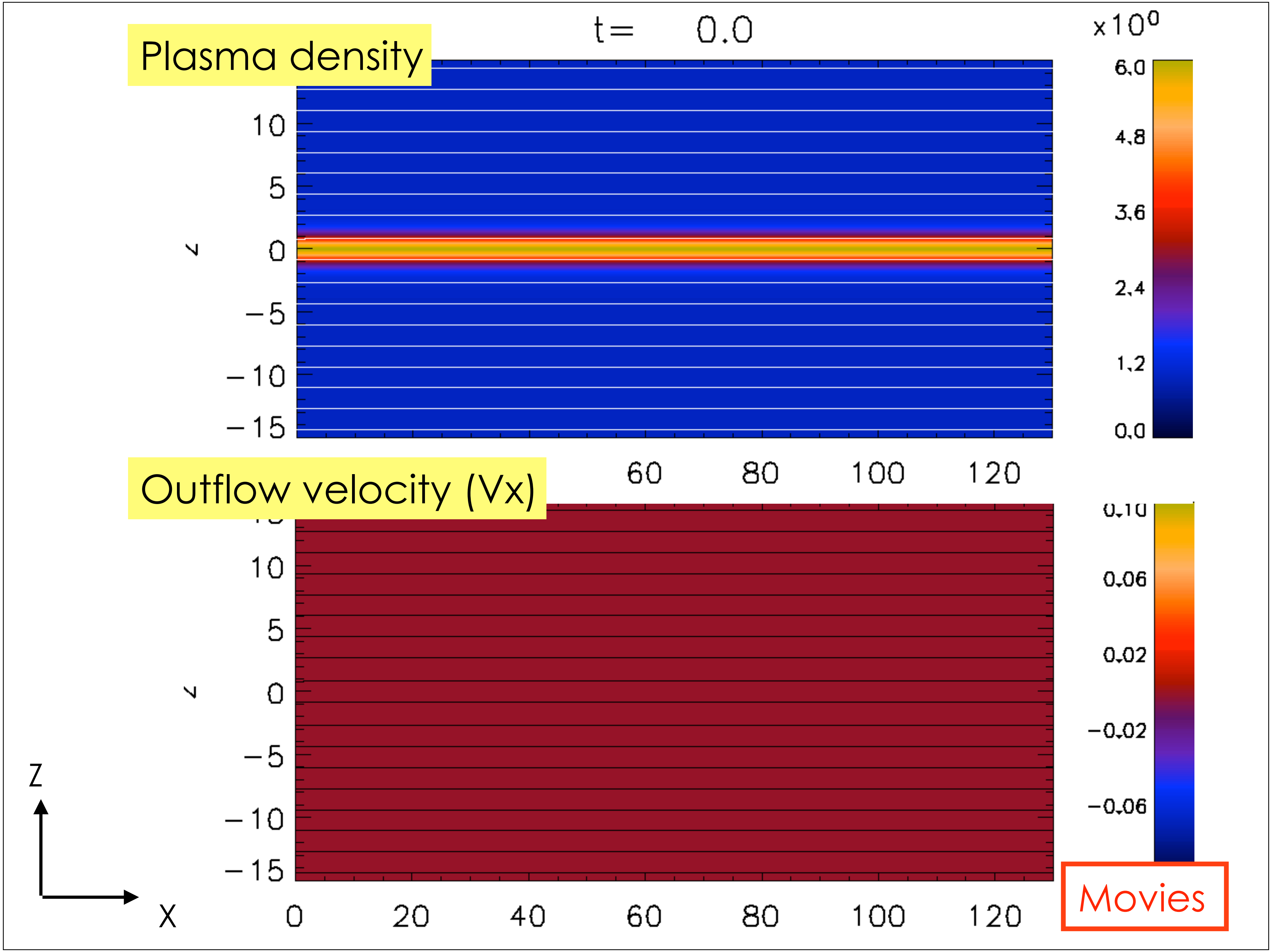
- Finite volume, High Resolution Shock Capturing (HRSC) code

- Numerical flux
  - HLL method (Harten, Lax, van Leer, 1983)
- Spacial discretization
  - 2nd order MC limiter (van Leer, 1977)
  - 2nd order discretization of the current (Tóth 2008)
- Time marching
  - 2nd order TVD Runge-Kutta method (Shu & Osher 1988)
- Solenoidal condition (div B=0)
  - Hyperbolic divergence cleaning (Dedner et al. 2002)

System configuration

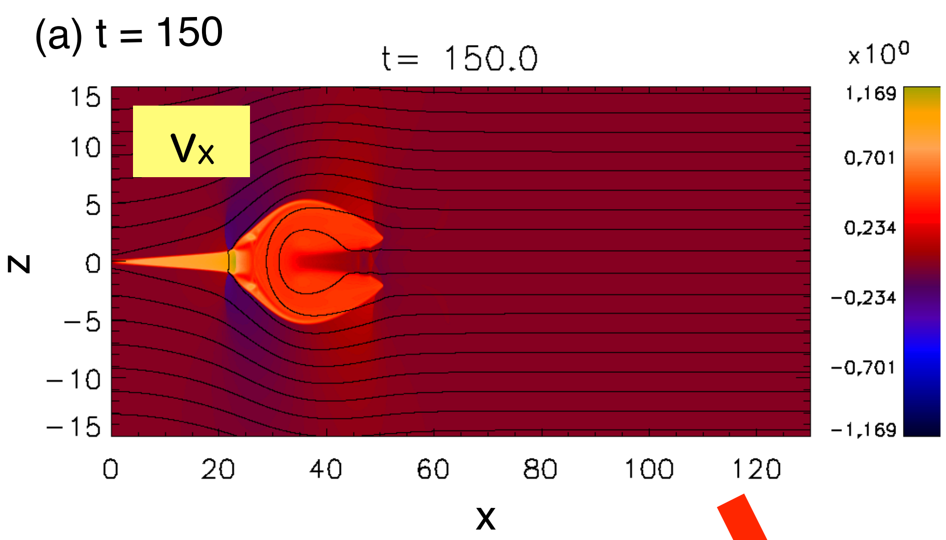
- A Harris-sheet with anti-parallel fields
- Domain: [0, 200] x [0, 150] (6000 x 4500 cells)
- Low beta in the upstream: $\beta = 2p/B^2 = 0.2$
- Localized resistivity

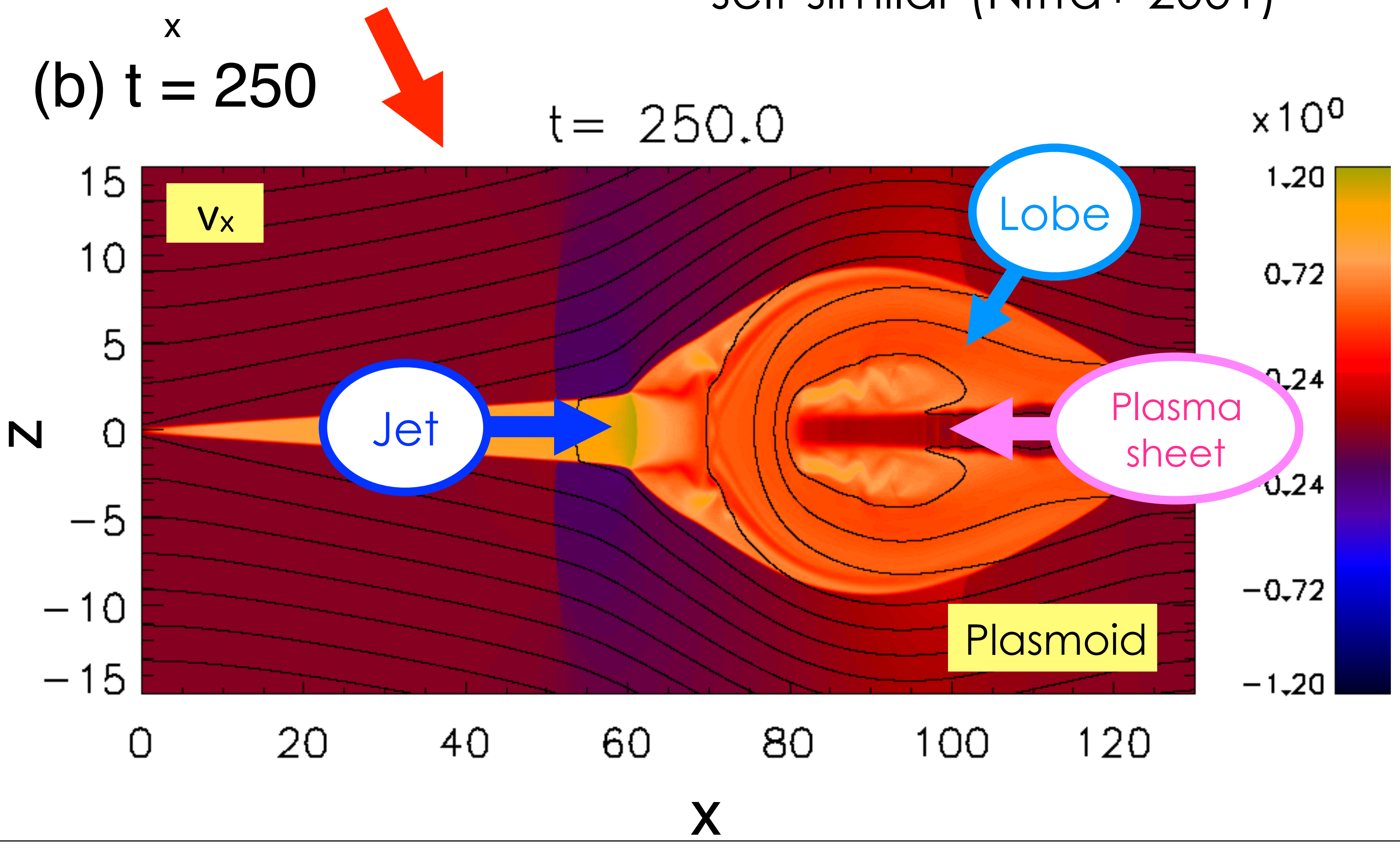



Plasma density
t= 0.0
x10^0
6.0
4.8
3.6
2.4
1.2
0.0
10
5
0
−5
−10
−15
z
60
80
100
120
Outflow velocity (Vx)
0.10
0.06
0.02
−0.02
−0.06
Z
X
0
20
40
Movies

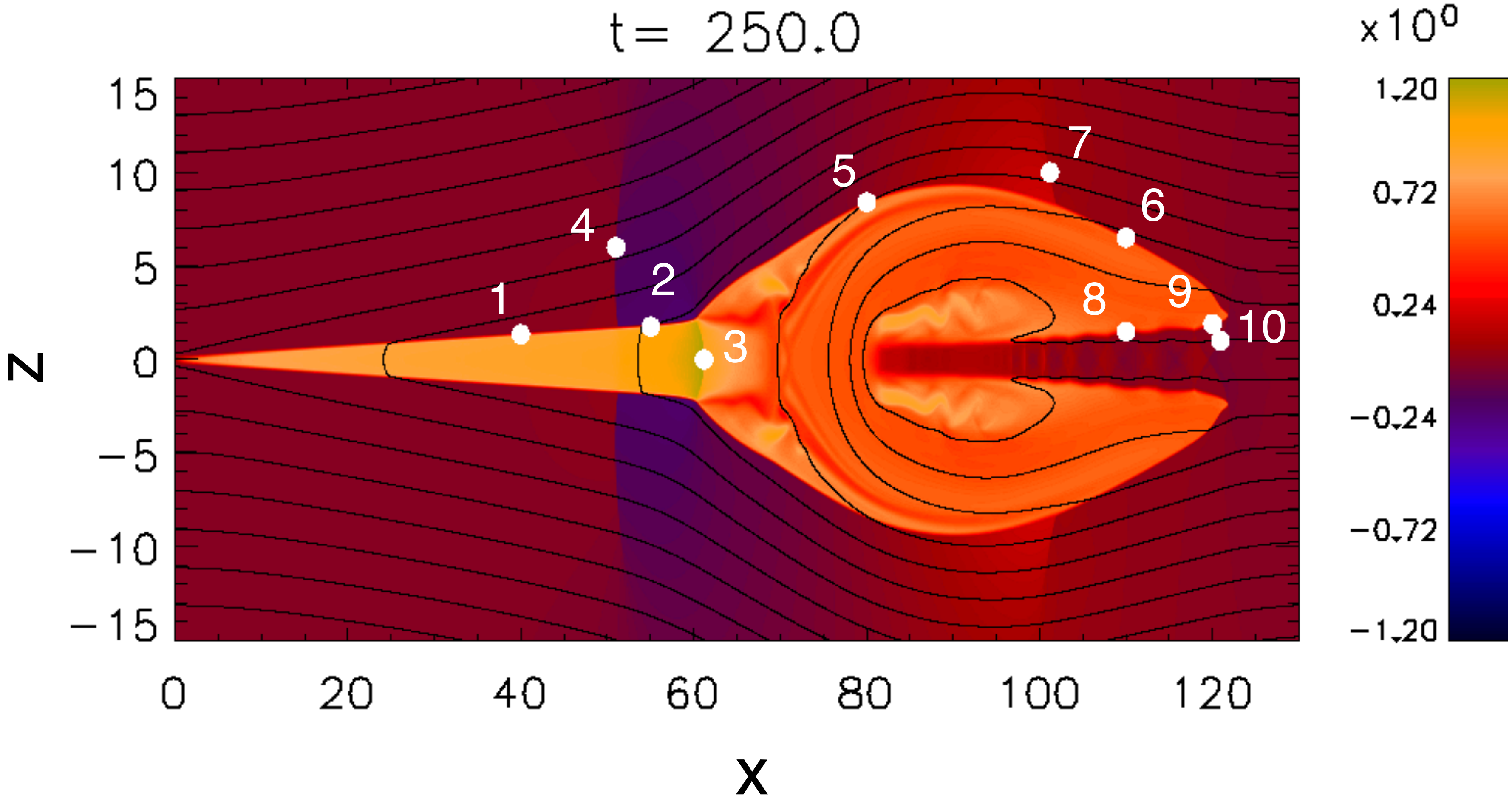
"Plasmoid"

- A big "island" grows
- Various plasma sources
- Late-time evolution: self-similar (Nitta+ 2001)





Various shocks!



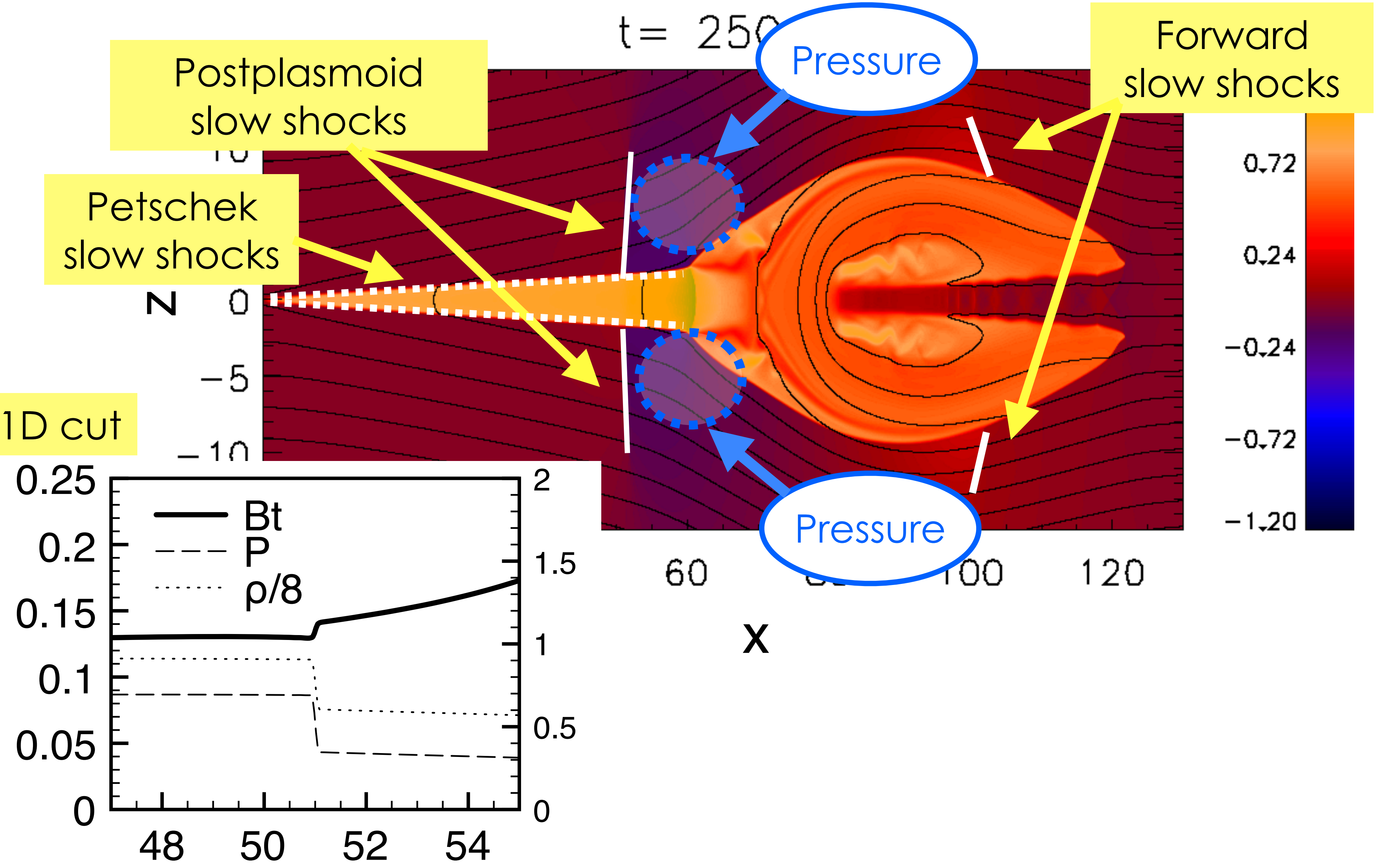
Rankine-Hugoniot Analysis

- The shock normal (**n**) is computed by a minimum variance method
- Shock velocity vs MHD velocities in the normal direction (**n**)
- Unclassified cases could be improved by Roe/HLLD schemes

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 $v_{\rm sh}$, 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.

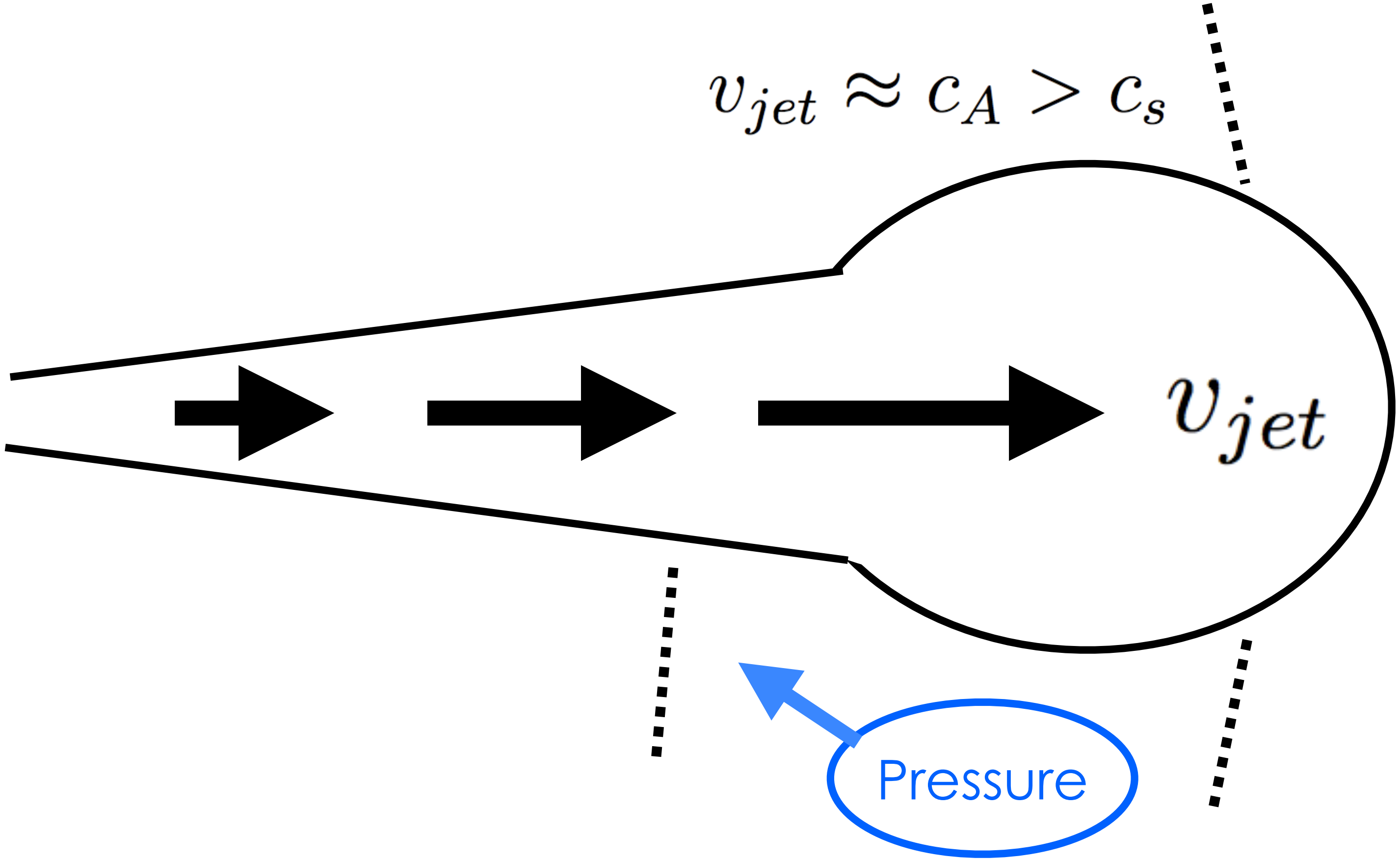
No.	Location	(n_x,n_z)	$v_{\rm sh}$	$\lvert\theta_{BN}\rvert$	β_1	$\mathcal{M}_{f1}$	$\mathcal{M}_{i1}$	$\mathcal{M}_{s1}$	$\mathcal{M}_{f2}$	$\mathcal{M}_{i2}$	$\mathcal{M}_{s2}$	T_2/T_1	
1	(40.0, 1.35)	(−0.03, 1.00)	0.0	86.3	0.22	0.06	0.98	2.49	0.04	0.69	0.69	2.72	(S) Petschek shock
2	(55.0, 1.75)	(−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

Vertical slow shocks



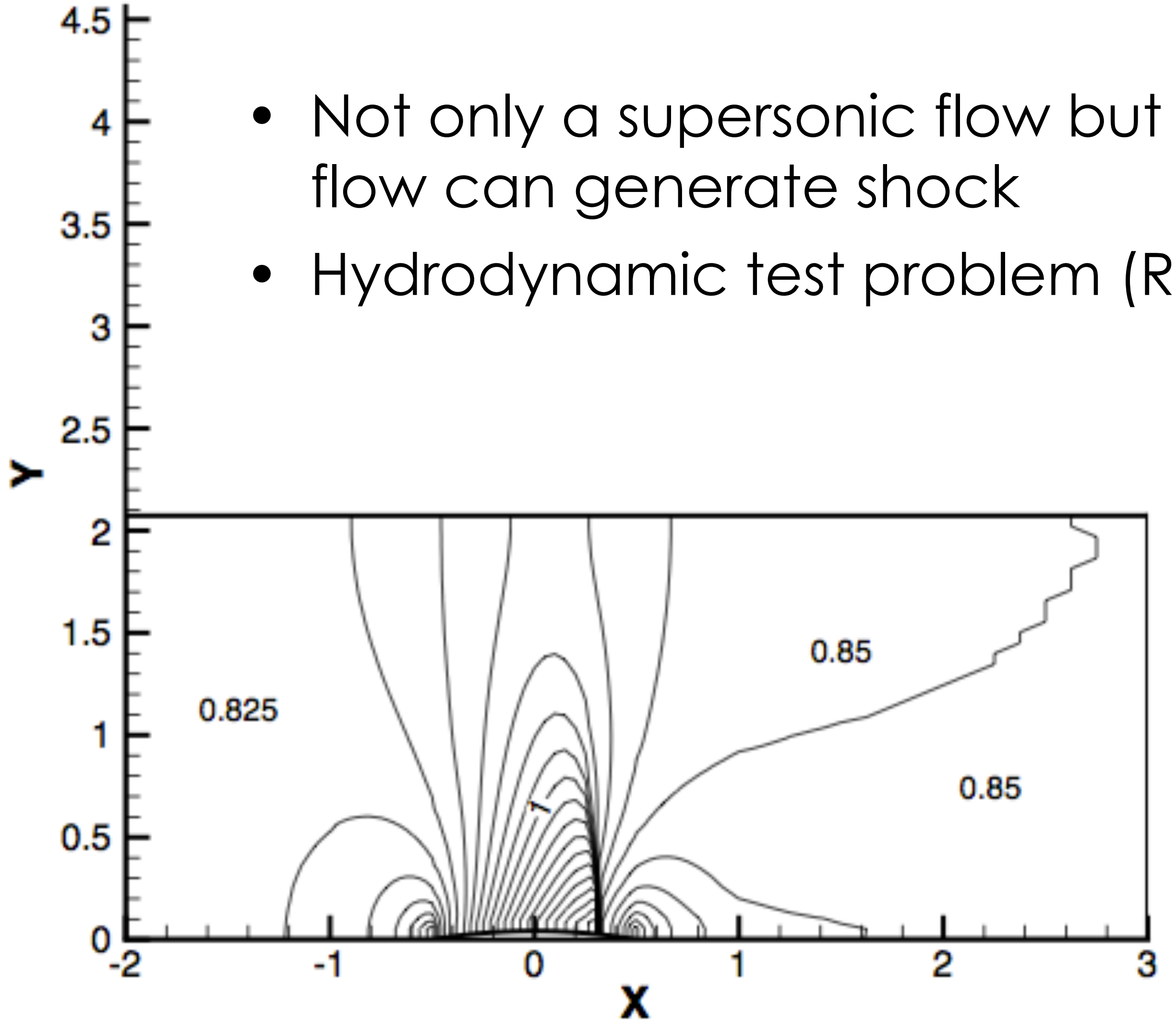
Why do we see vertical slow-shocks?

- From a simple algebra, $c_A > c_s \iff \beta < 1$
- Reconnection system travels faster than the local slow-mode in the stationary upstream plasmas: slow shock stands there
- We'll see one or two pairs of slow-shocks in low-beta plasmas



Analogy: transsonic bump problem

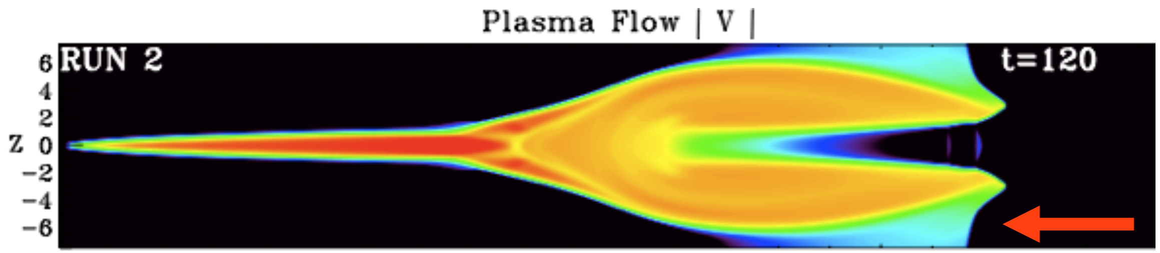
- Not only a supersonic flow but also a transsonic flow can generate shock
- Hydrodynamic test problem (Rizzi & Viviand 1981)



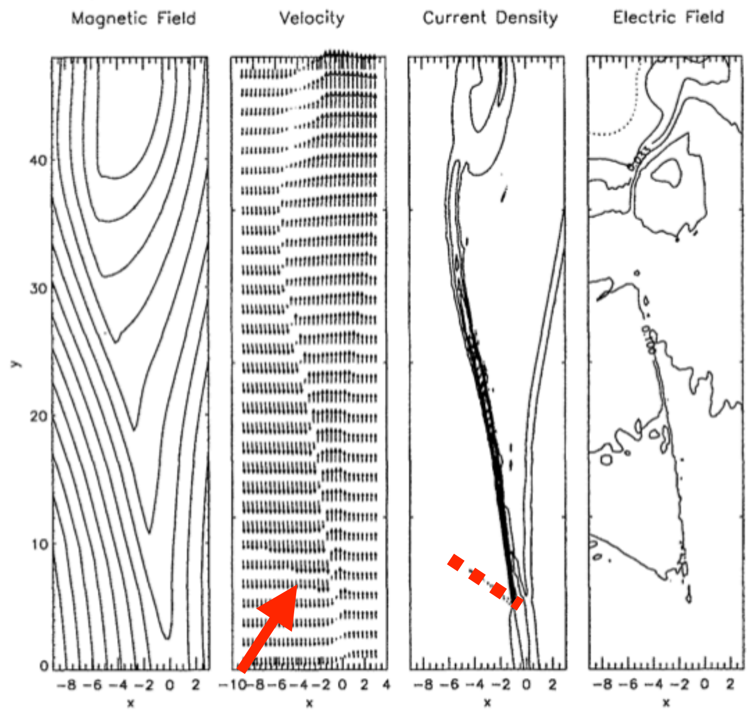
Kermani & Plett 2001

Vertical shocks in previous research

- We finally understand that they were vertical slow-shocks (+ offset by a shear-flow).

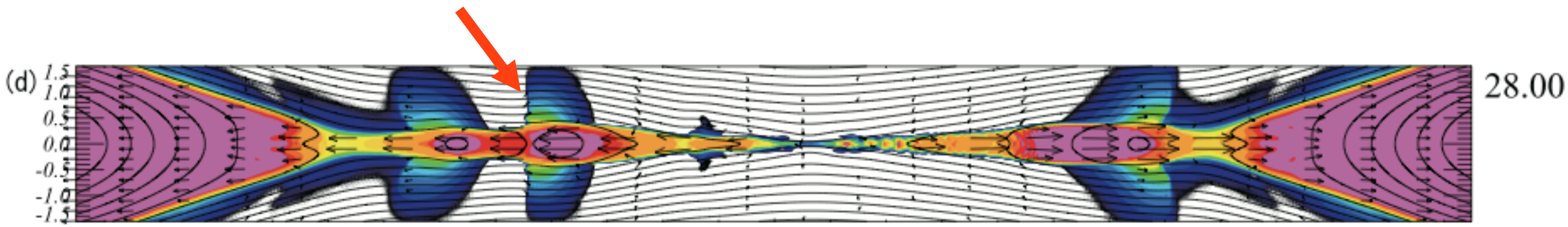


Abe & Hoshino 2001



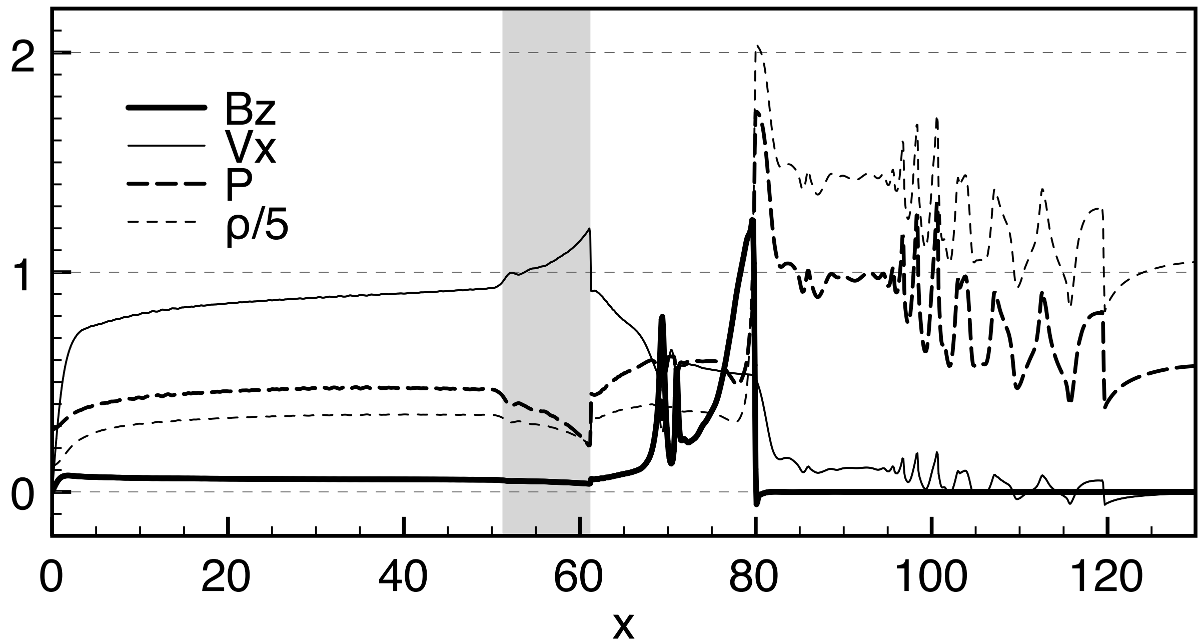
La Belle-Hamer et al. 1994

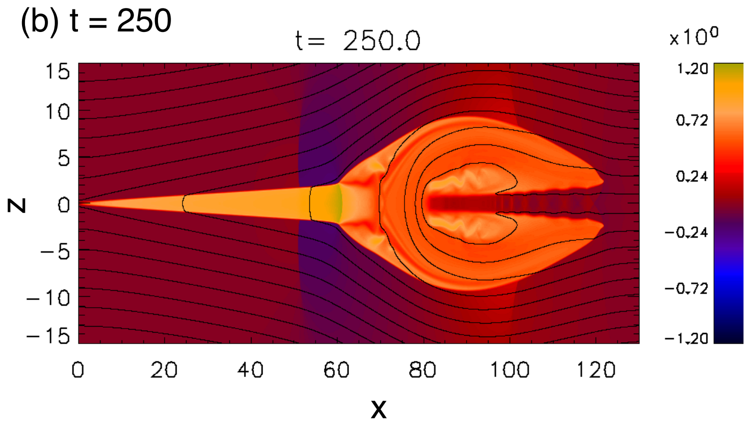
"Bow shock?"



Tanuma & Shibata 2007

1D profile : Super-Alfvénic outflow

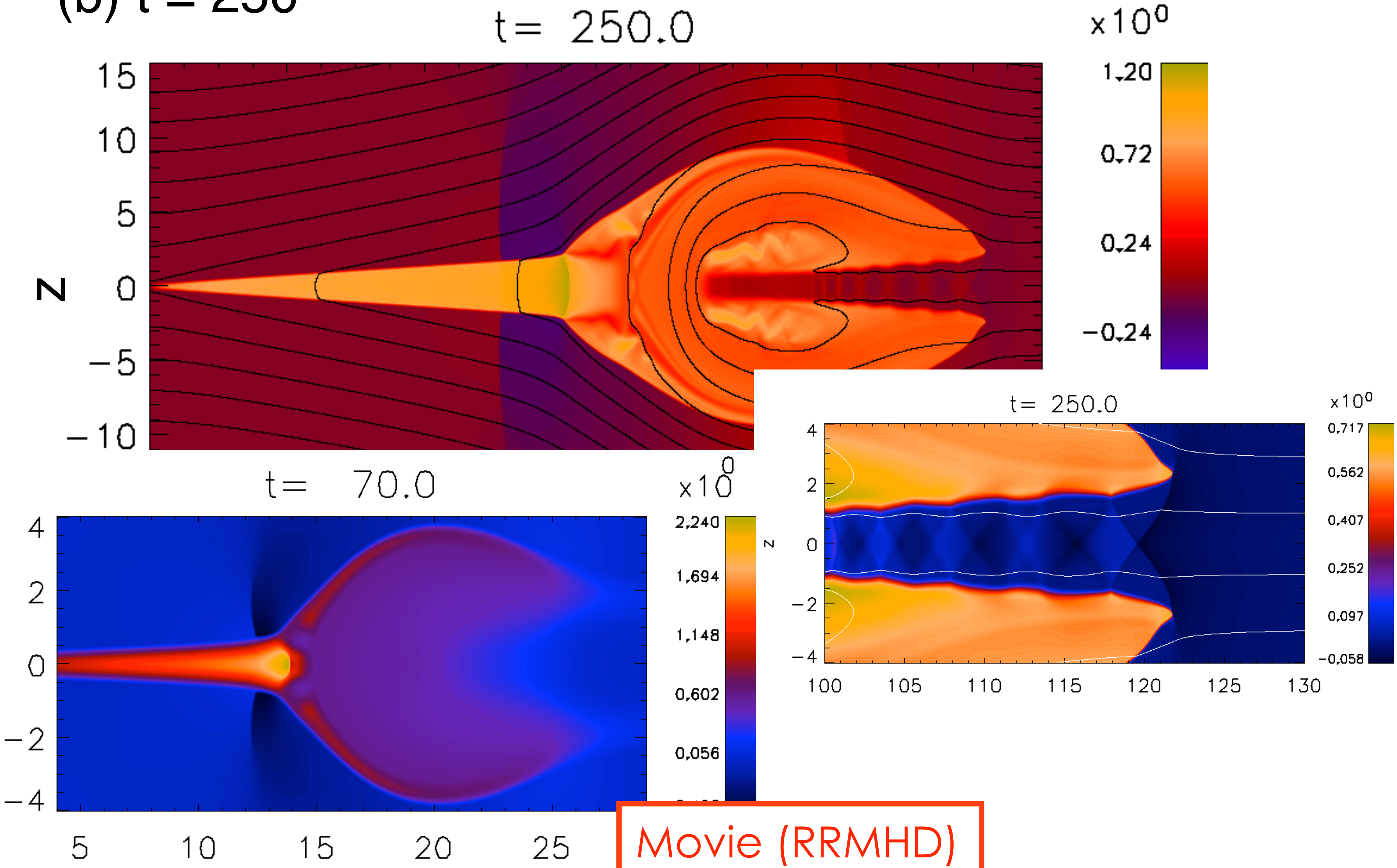




- Combined effect
  - 1. New Rankine-Hugoniot condition across the SS
  - 2. Adiabatic acceleration of the supersonic flow (Shimizu & Ugai 2000, 2003)

Diamond-chain: oblique shock-reflection

(b) t = 250

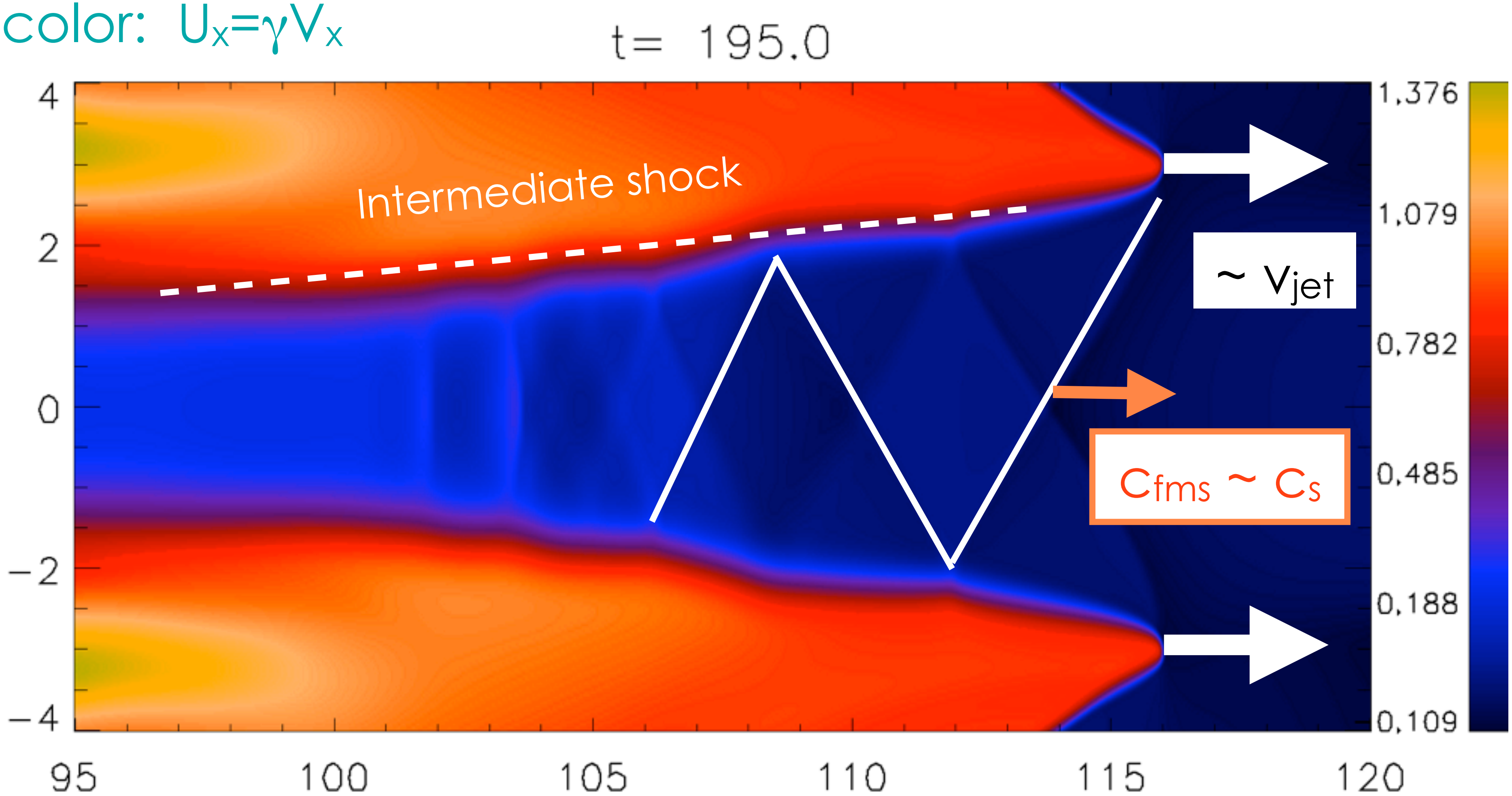


Movie (RRMHD)

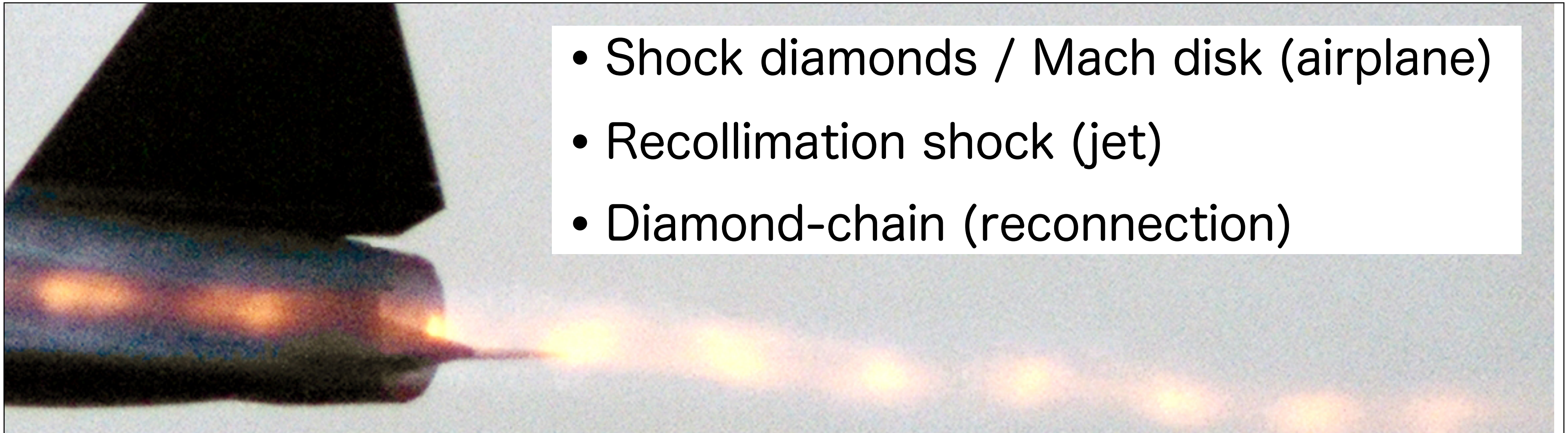
Again, shock condition

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

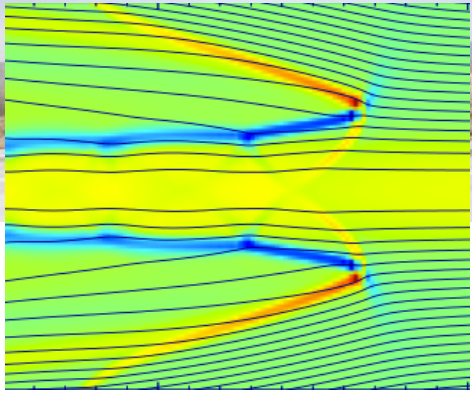
color: $U_x = \gamma V_x$



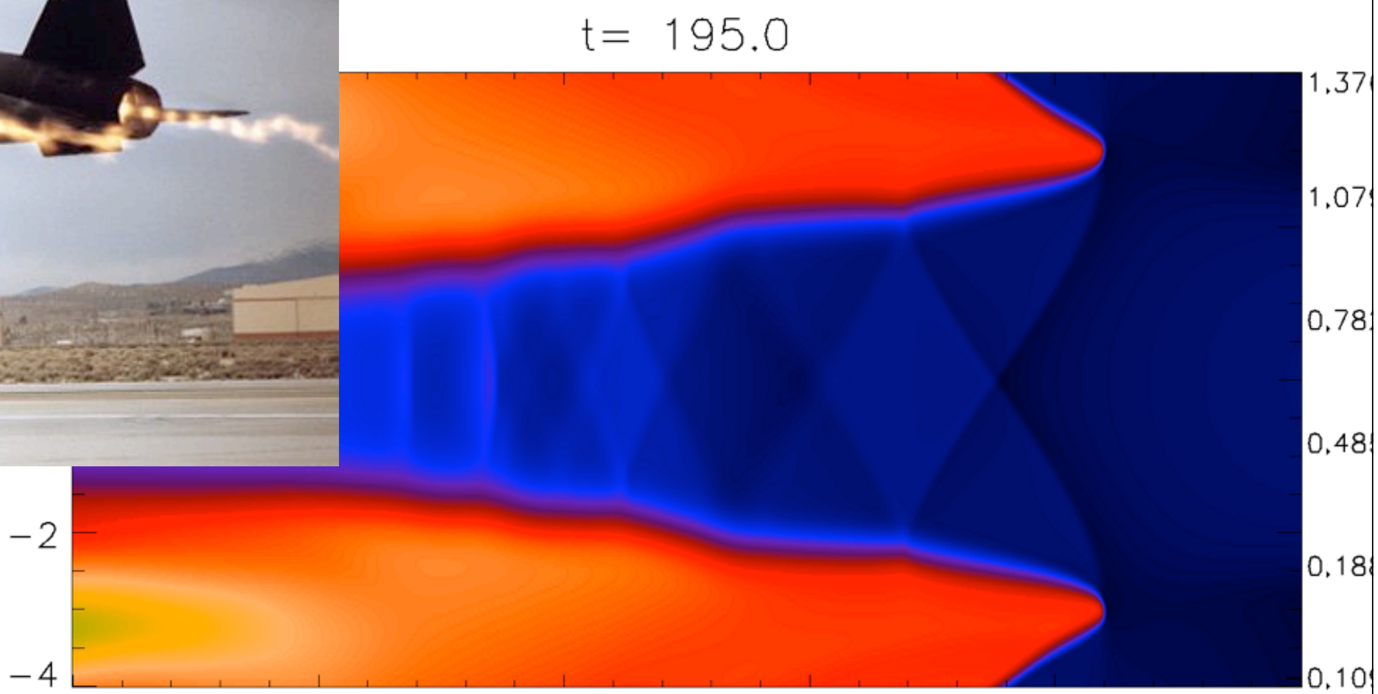
- Shock diamonds / Mach disk (airplane)
- Recollimation shock (jet)
- Diamond-chain (reconnection)



http://www.aerospaceweb.org/question/propulsion/q0224.shtml
http://en.wikipedia.org/wiki/Shock_diamond



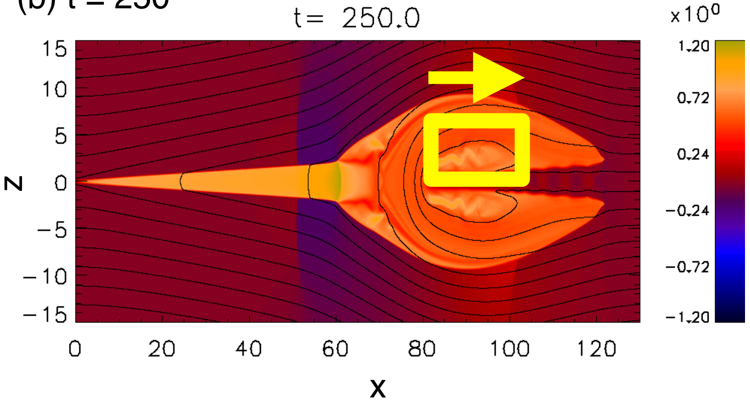
S. Abe 1999 (M. Thesis)

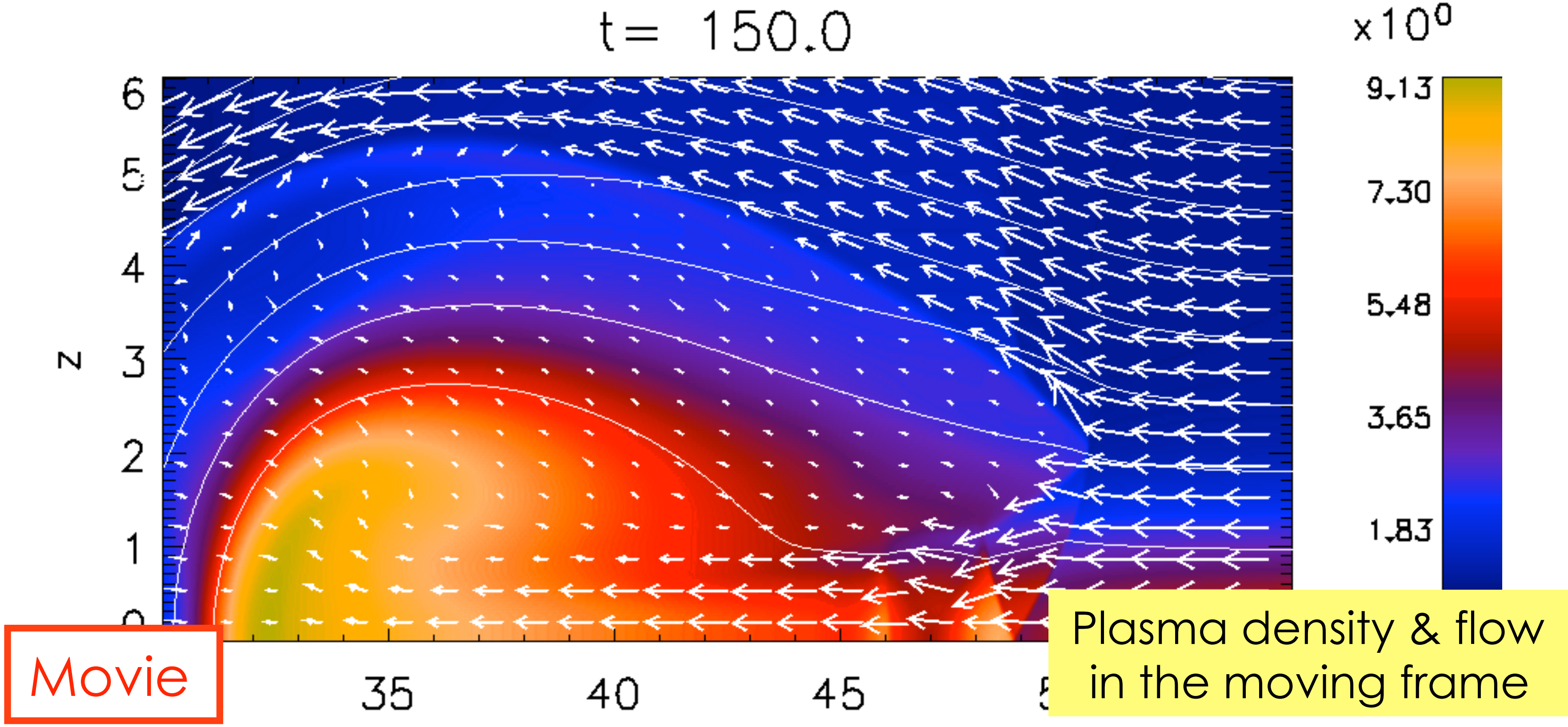


Kelvin-Helmholtz instability inside the plasmoid

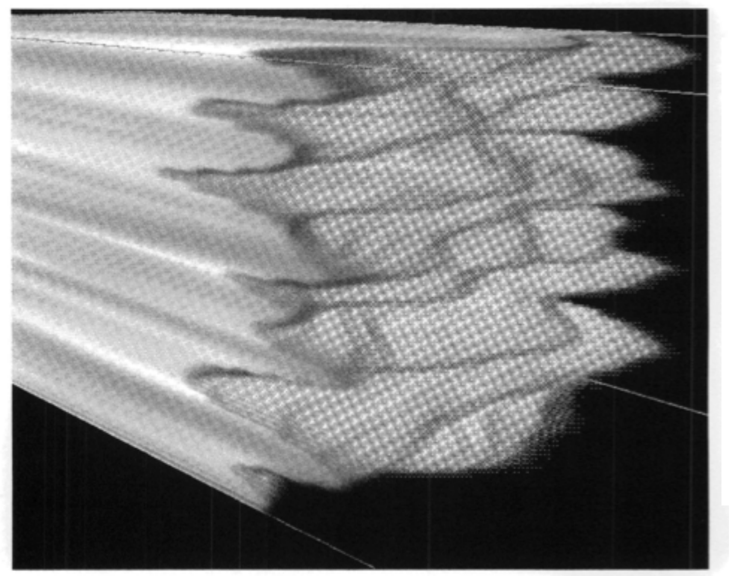
- Plasmas are hit and reflected by the reconnection jet front
- The reflected flow is KH-unstable

(b) t = 250



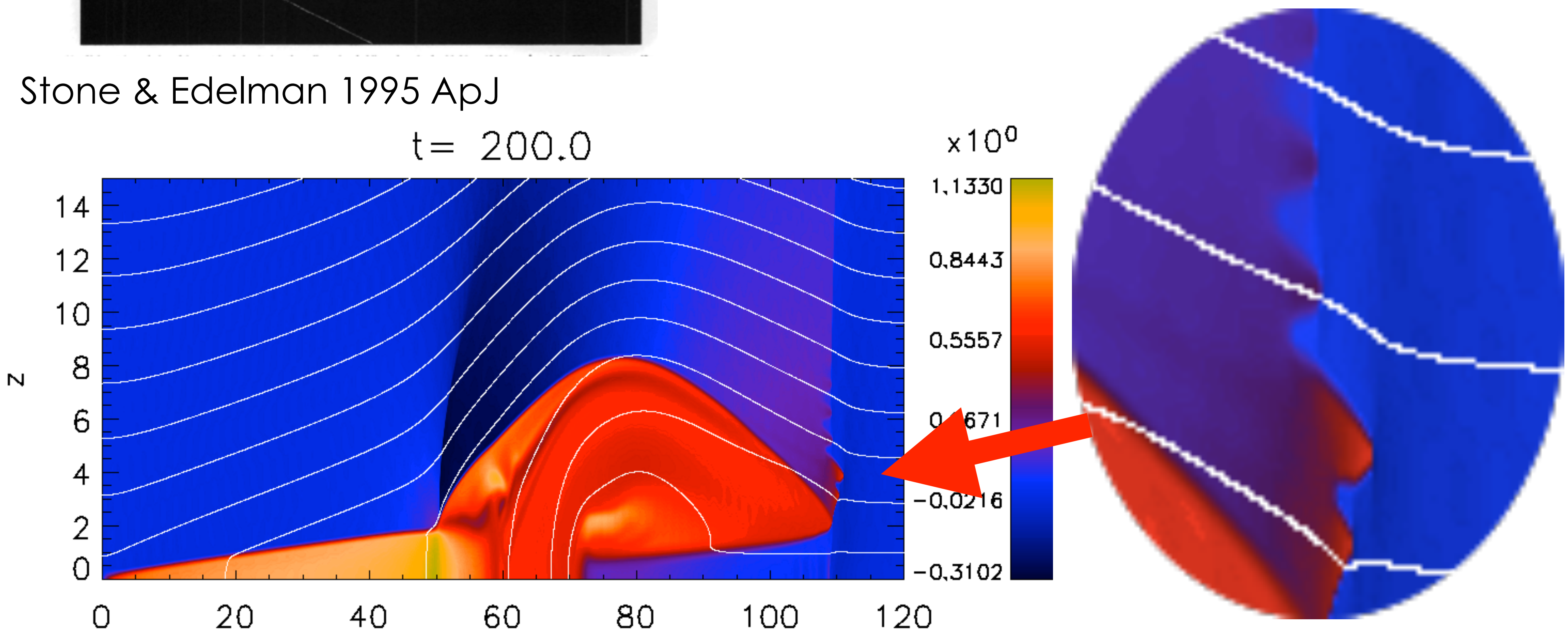


Corrugation instability?



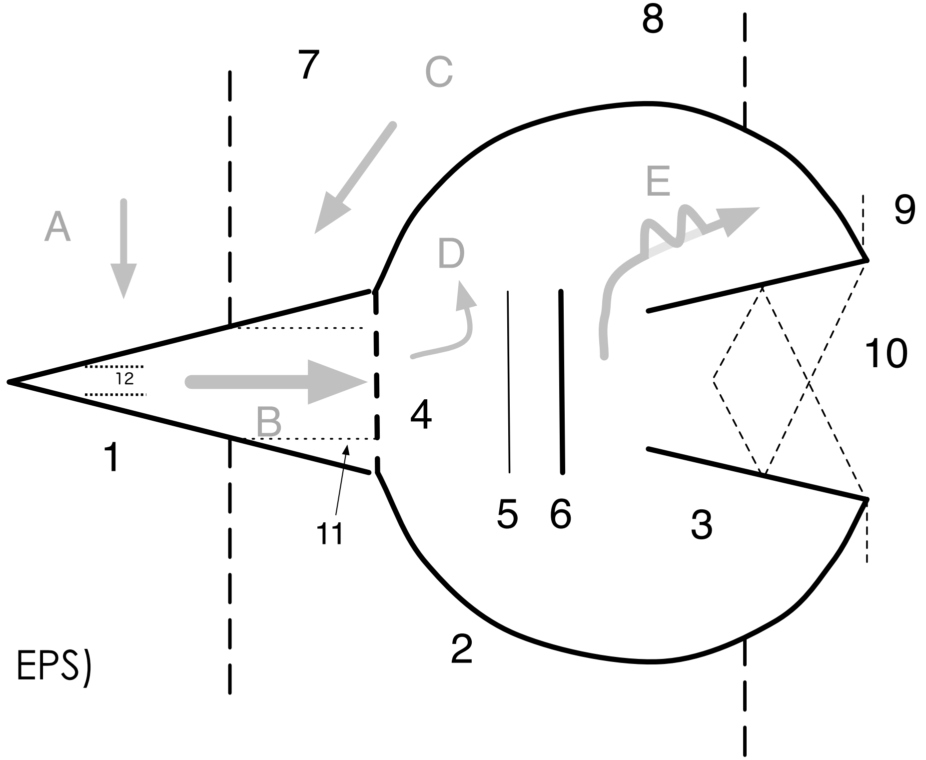
Stone & Edelman 1995 ApJ

- In the actual world, the vertical slow-shocks can be affected by
  - Non-MHD mixing
  - Anisotropy
  - The 2D/3D corrugation instability



A complete catalog of plasmoid structures

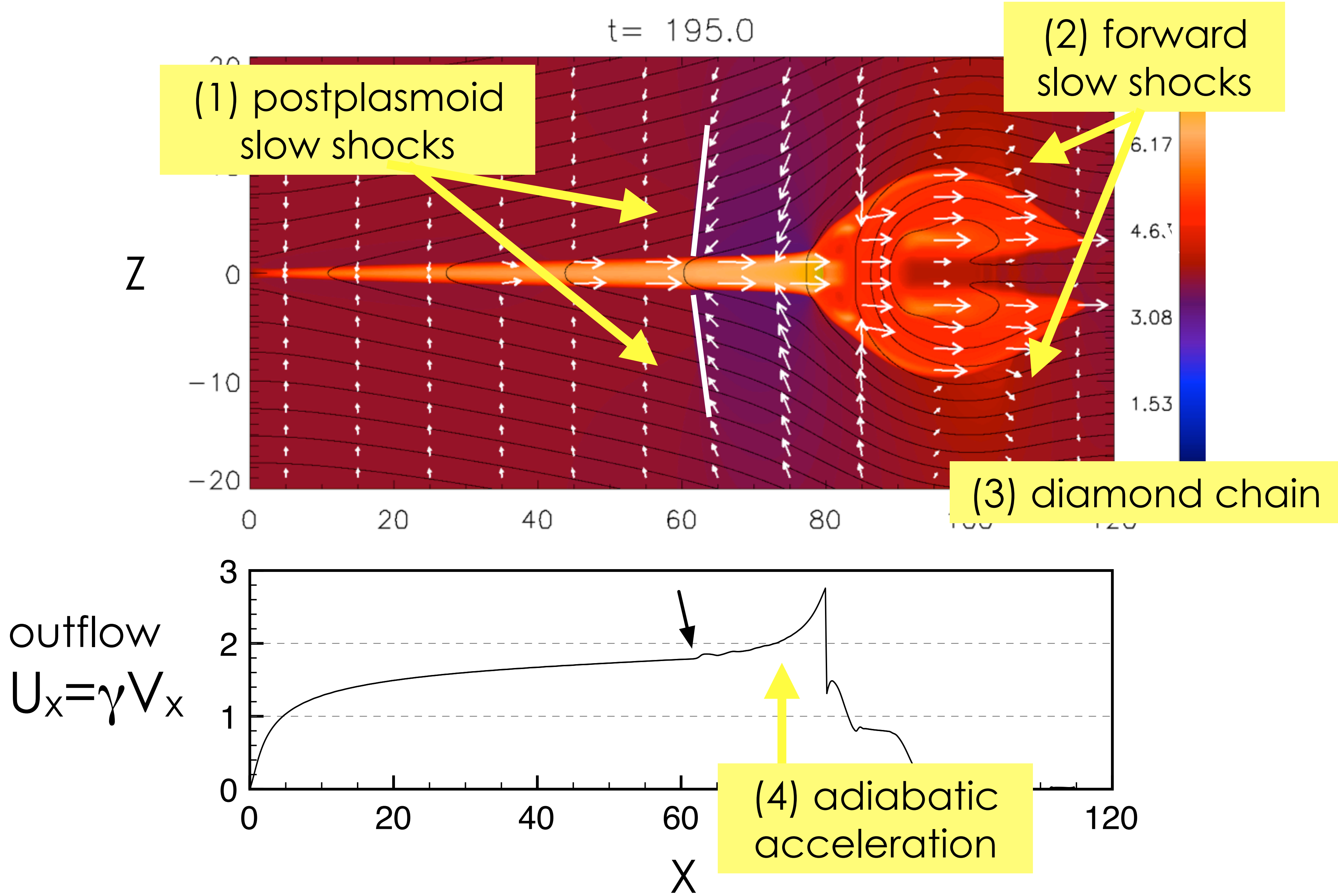
A. reconnection inflow
B. outflow jet
C. post-plasmoid backward flow
D. internal flow
E. flapping jet (KH instability)



1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995 PoP)
3. intermediate shock (Abe & Hoshino 2001 EPS)
4. fast shock (Forbes & Priest 1983 SoP)
5. loop-top front (Ugai 1987 GRL)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (SZ et al. 2010 ApJ)
8. outer vertical slow shock (SZ & Miyoshi 2011 PoP)
9. fast-mode wave front (Saito et al. 1995 JGR)
10. shock-reflection (diamond-chain) (SZ et al. 2010 ApJ)
11. contact discontinuity (SZ & Miyoshi 2011 PoP)
12. contact discontinuity (Hoshino et al. 2000 JGR)

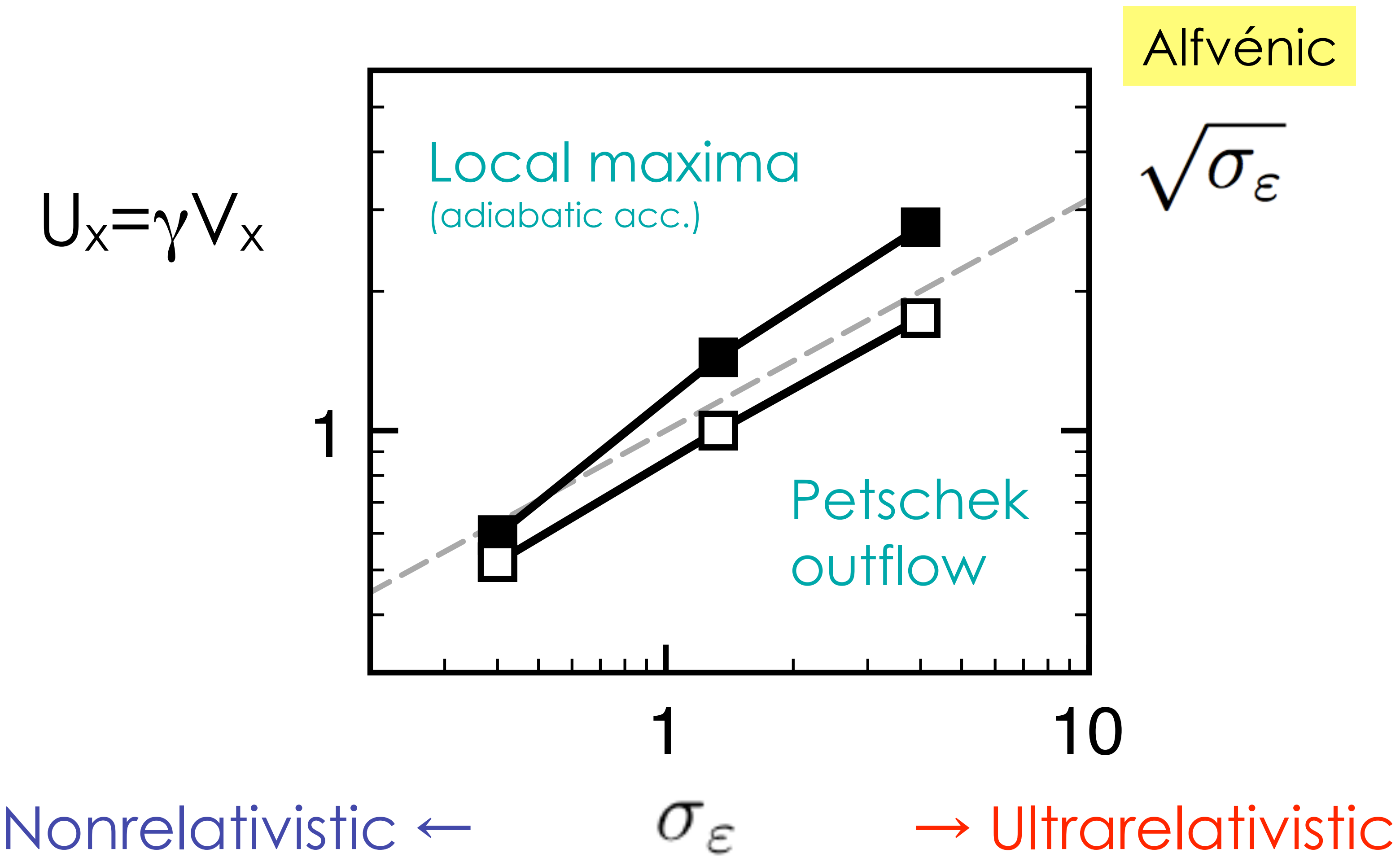
Zenitani & Miyoshi 2011 PoP

Relativistic Reconnection (RRMHD code)



Maximum outflow

- Petschek outflow : $\gamma_{jet} v_{jet} \approx \gamma_A c_A = \sqrt{\sigma_\varepsilon}$



Zenitani et al. 2010 ApJL

Relativistic shock condition

- The same shock condition

$$v_{jet} \approx c_A > c_s$$

- In the magnetically dominated regimes, Alfvénic outflow jet is always supersonic.

$$\sigma_\varepsilon > \frac{1}{2} \qquad c_A > \frac{c}{\sqrt{3}} > c_s$$

- Shock-capturing code is essential for high-sigma regime of our interest

Summary

- Large-scale MHD evolution of an extreme plasmoid in reconnection in low beta [and relativistic] plasmas
- Complex structures
  - Vertical slow shocks
  - Diamond chain
  - Super-Alfvénic adiabatic acceleration
  - KH instability in the plasmoid and many more
- Modern HRSC code is essential to explore shock-dominated MHD phenomena
- References:

  - [1] S. Zenitani, T. Miyoshi, Phys. Plasmas, **18**, 022105 (2011)
  - [2] S. Zenitani, M. Hesse, and A. Klimas, Astrophys. J., **716**, L215 (2010)