Numerical modeling of relativistic magnetic reconnection: Kinetic, two-fluid, and MHD simulations

Seiji ZENITANI

National Astronomical Observatory of Japan

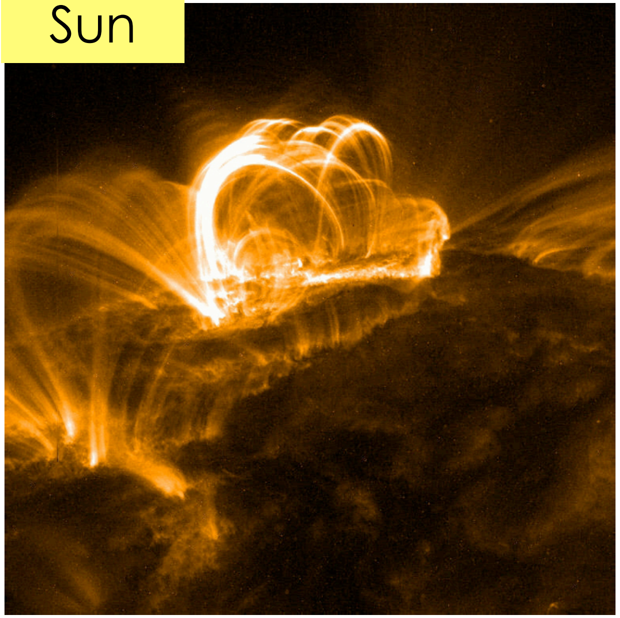
Ackn: M. Hoshino (U. Tokyo), M. Hesse, A. Klimas, M. Kuznetsova (NASA/GSFC), T. Miyoshi (Hiroshima U)

Outline

- 0. Introduction
- 1. Kinetic modeling
  - 2D reconnection
- 2. Fluid modeling
  - RRMHD & two-fluid simulations
  - New insight: high-speed fluid dynamics
- 3. Cross-code comparison
- 4. Summary

Magnetic reconnection

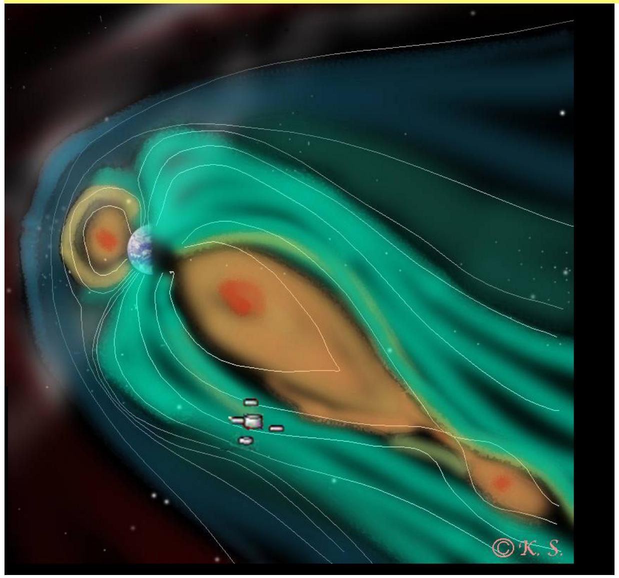
Sun

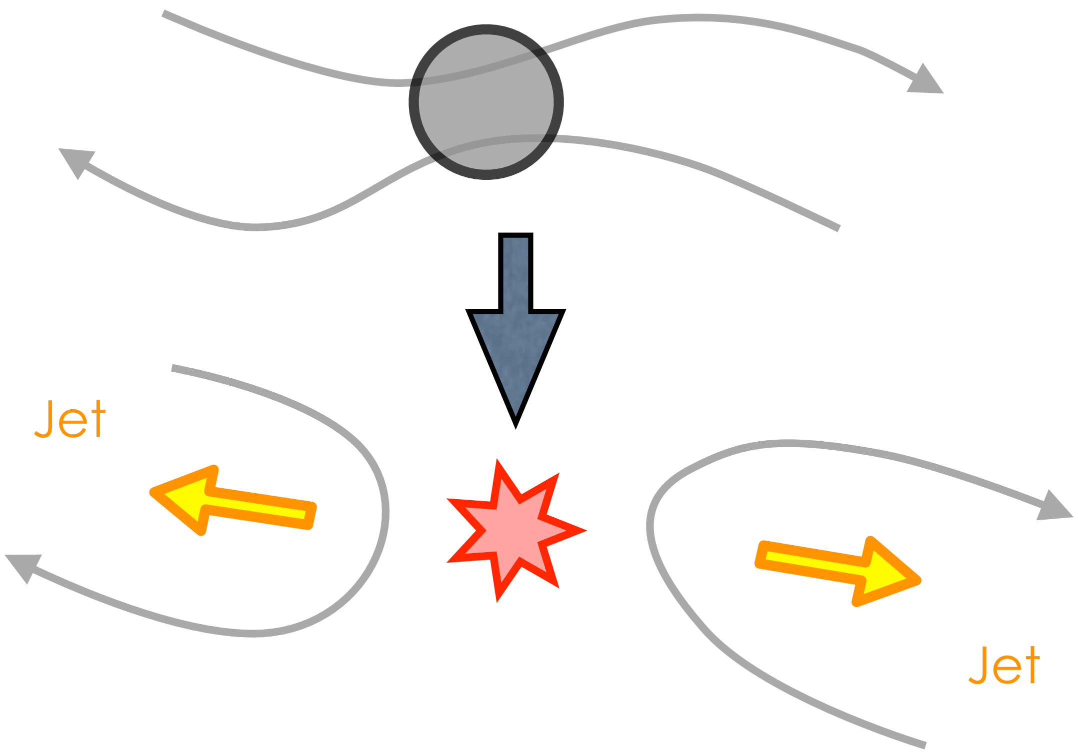


- Re-configuration of magnetic topology
- Release of magnetic energy to plasma energy
- Violation of the ideal condition is necessary

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} \neq 0$$

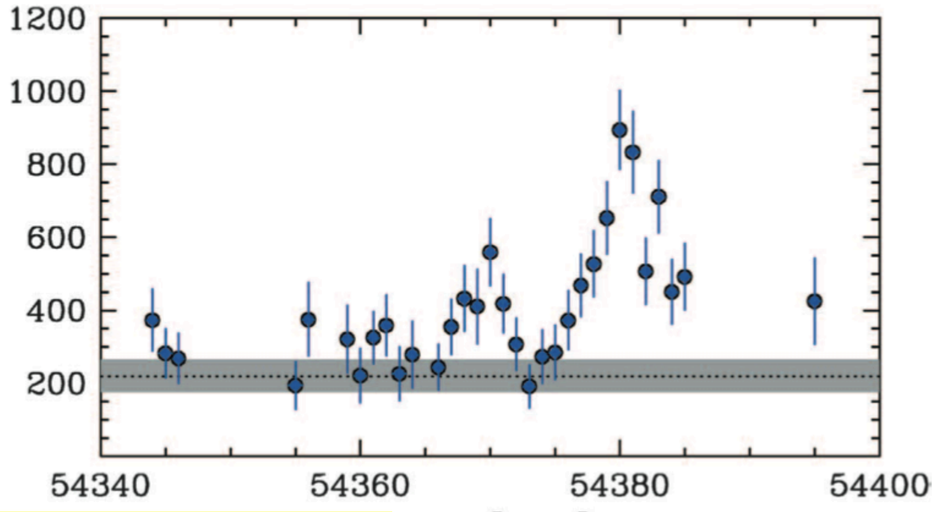
Earth's Magnetosphere





Magnetic reconnection in high-energy settings

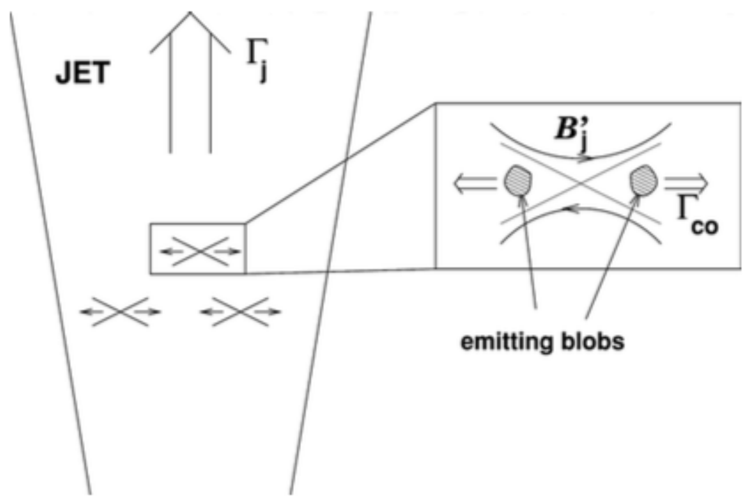
- Magnetically dominated settings
- Special relativity
  - + radiation, pair creation …



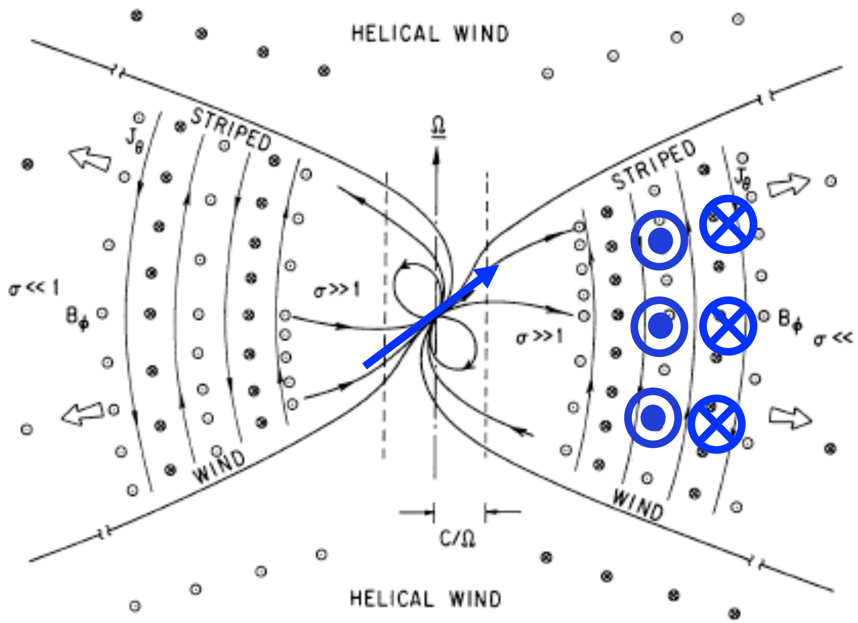
Gamma-ray flares

Tavani 2011

Jet model



Giannios+ 2009



Striped wind

Coroniti 1990

Current status of relativistic reconnection research (2015Q2)

- Theories have been discussed over two decades
- Many works came out after the Crab flare (2011)

MHD theories

Blackman & Field 1994
Lyutikov & Uzdensky 2003
Lyubarsky 2005
Tenbarge+ 2010
Comisso & Asenjo 2014

- Basic properties are under debate

MHD simulations

Watanabe & Yokoyama 2006
Zenitani+ 2010, 11
Zanotti & Dumbser 2011
Takahashi+ 2011
Takamoto 2013
(Zenitani+ 2015)

- Ideal for global modeling

Two-fluid simulations

Zenitani+ 2009

- Meso-scale evolution

Kinetic (PIC) simulations

Zenitani & Hoshino 2001-2008
Jaroschek+ 2004-2009

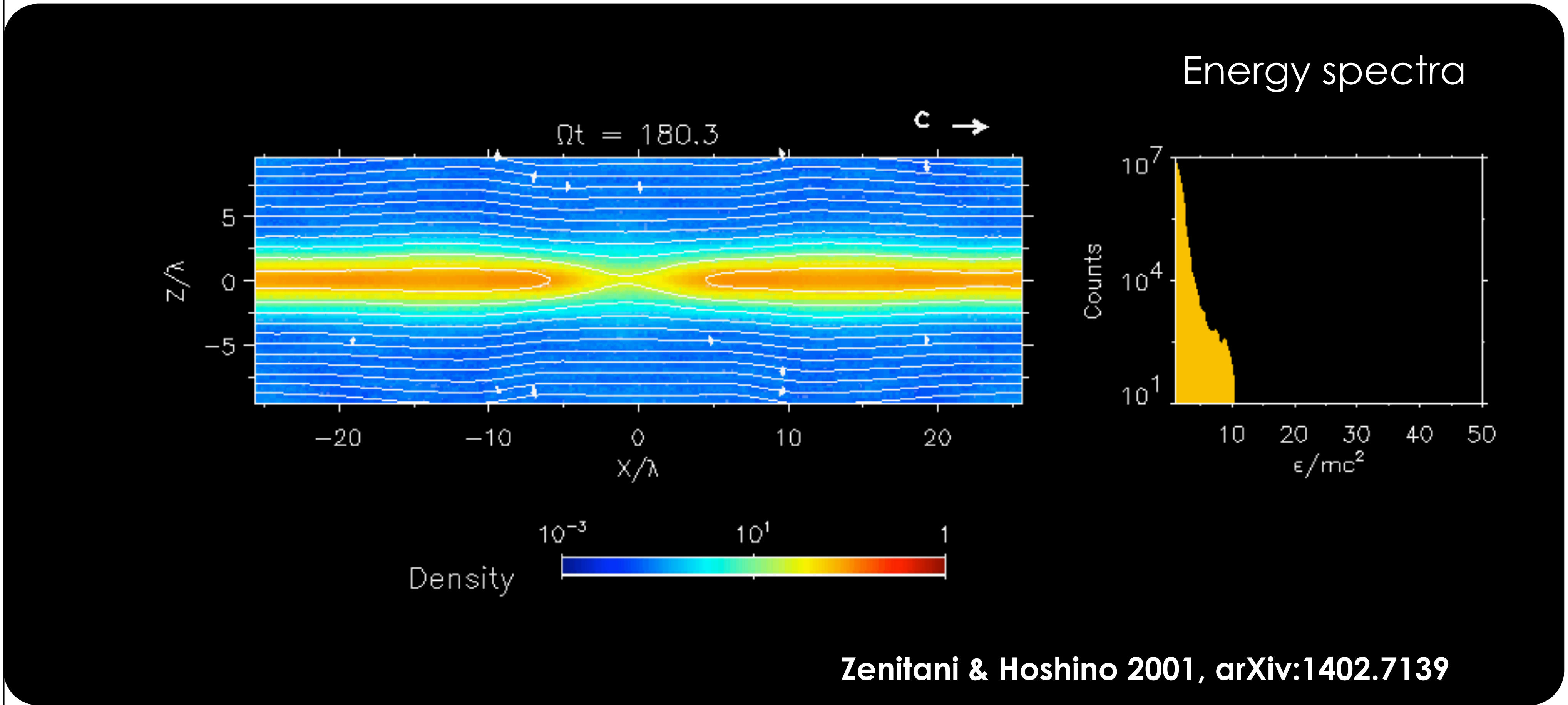
Liu+ 2011
Cerutti+ 2012-2014
Kagan+ 2013
Sironi & Spitkovsky 2014
Melzani+ 2014
Guo+ 2014-2015
Zenitani in prep.

- Fast evolution
- Particle acceleration

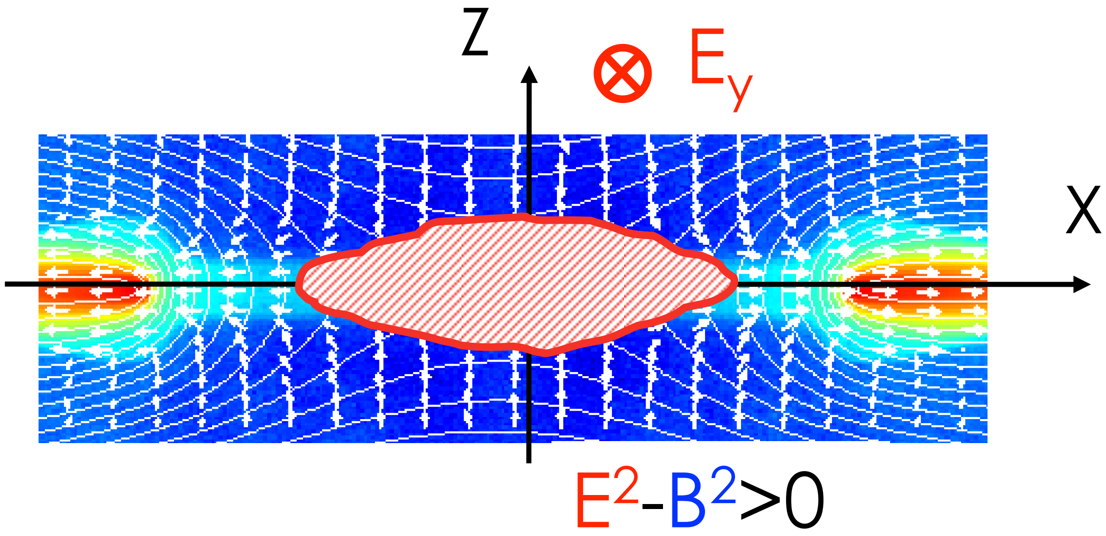
1. Kinetic modeling

2D Particle-In-Cell (PIC) simulation

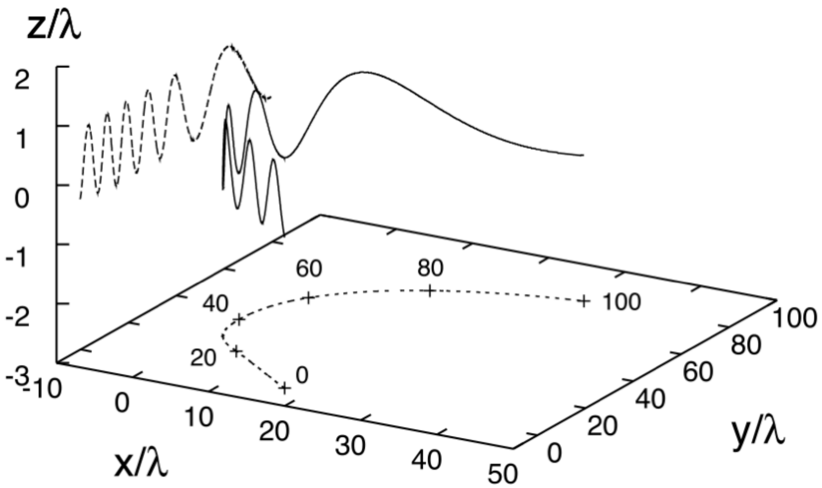
- Fast reconnection and particle acceleration occurs
- Online version: http://th.nao.ac.jp/MEMBER/zenitani/files/reconnection.mov

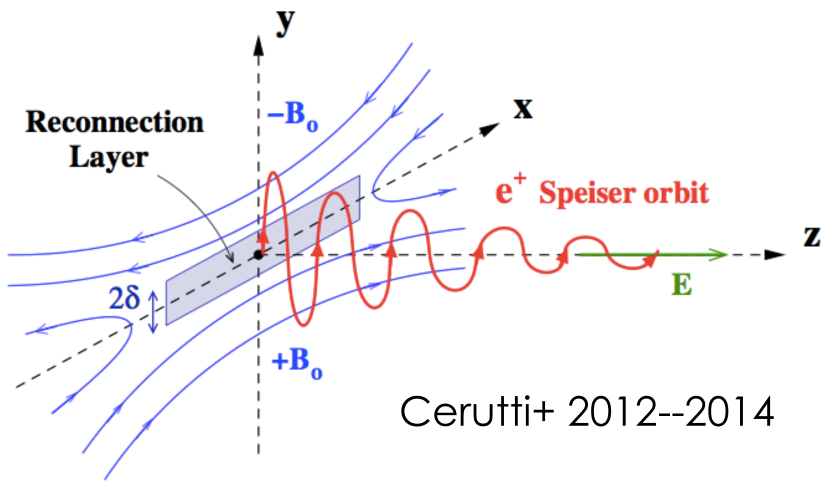


DC particle acceleration



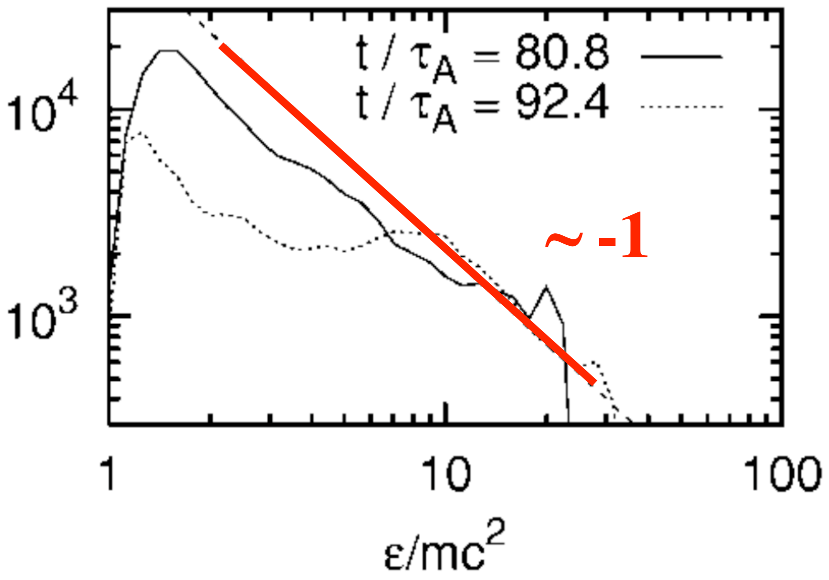
Speiser 1965, Michel 1968,
Zenitani & Hoshino 2001, 2007,
Uzdensky+ 2011, Cerutti+ 2012



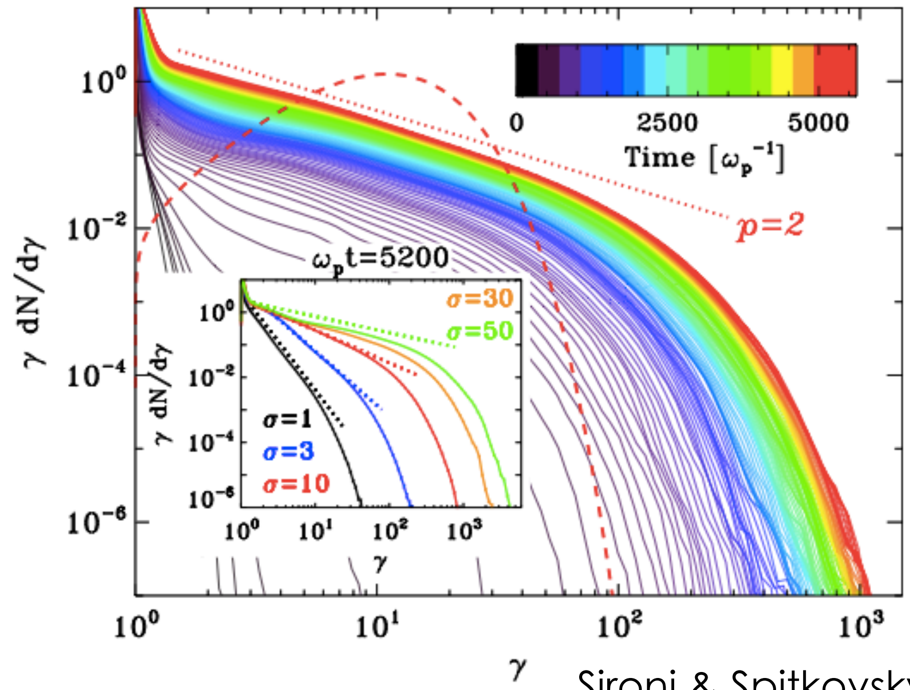


Cerutti+ 2012--2014

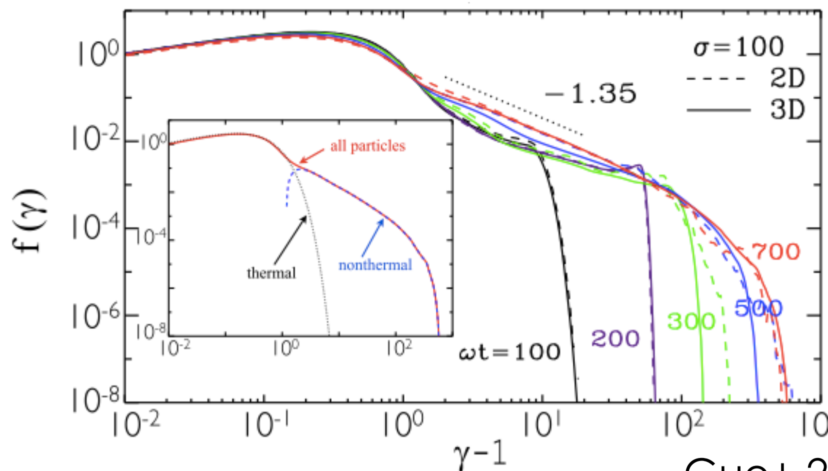
Hard-energy spectra



Zenitani & Hoshino 2001



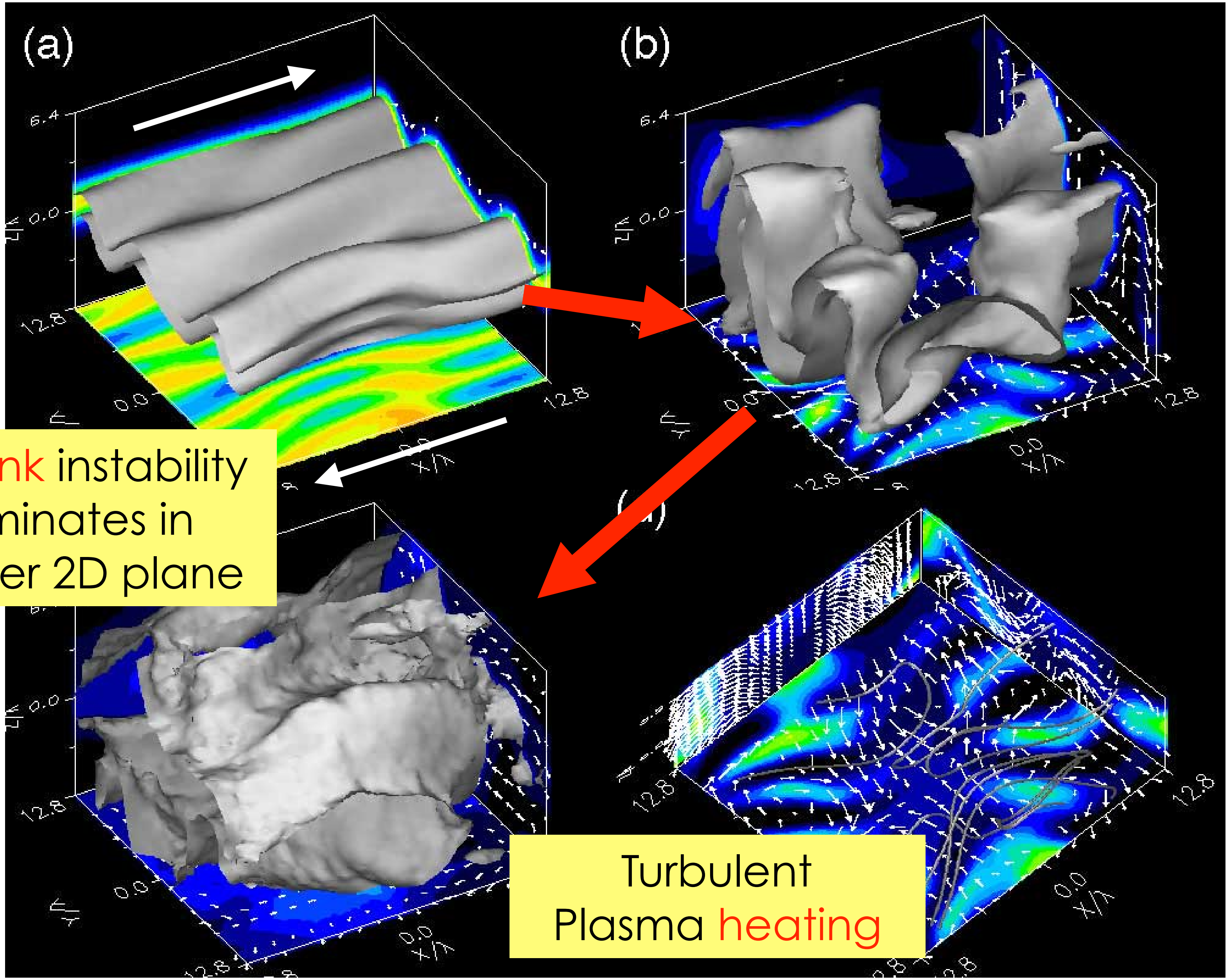
Sironi & Spitkovsky 2014



Guo+ 2014

- Power-law index in earlier works
  s ~ -1 (near acc. region), -2~3 (global)
- Fermi process? Upstream magnetization may control the index (Guo+ 2014)

3D reconnection: Onset problem



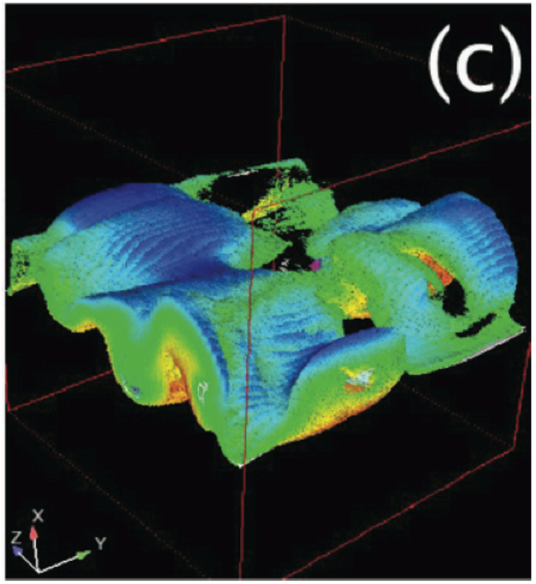
Drift-kink instability dominates in another 2D plane

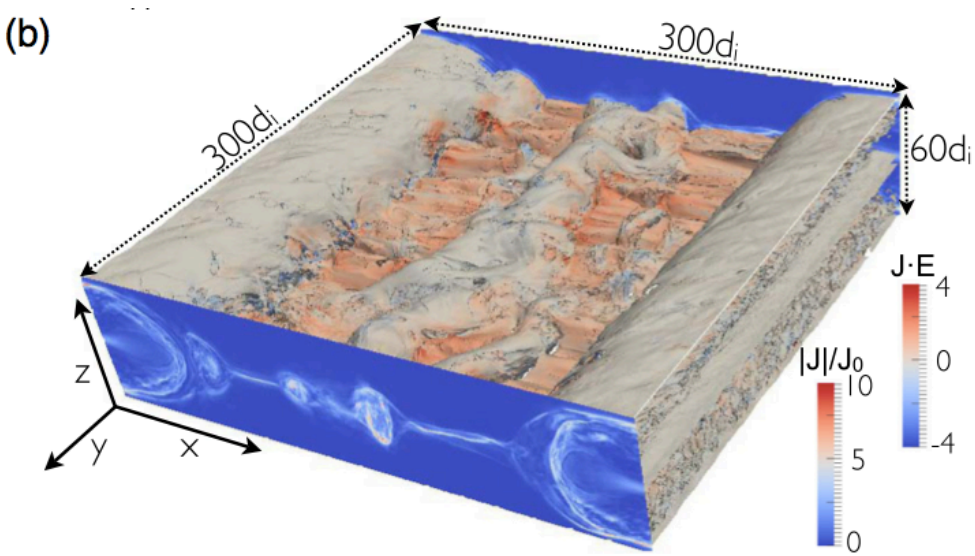
Turbulent Plasma heating

Zenitani & Hoshino 2008

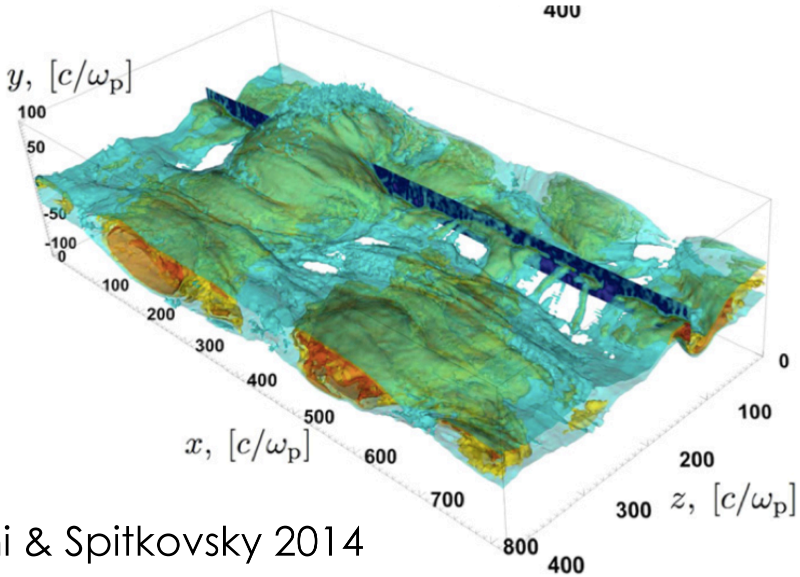
3D large-scale evolution: RX appears to win

Liu+ 2011





Guo+ 2014



Sironi & Spitkovsky 2014

- Kink-mode often saturates
- Reconnection outruns kink, and then particle acceleration turns on
- 3D energy spectra is similar to 2D

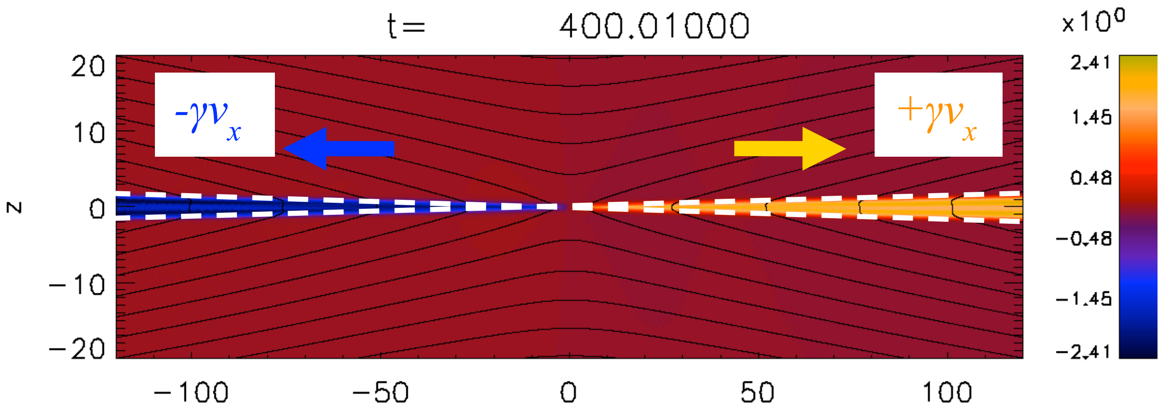
2. Fluid modeling

Relativistic Petschek (PK) reconnection

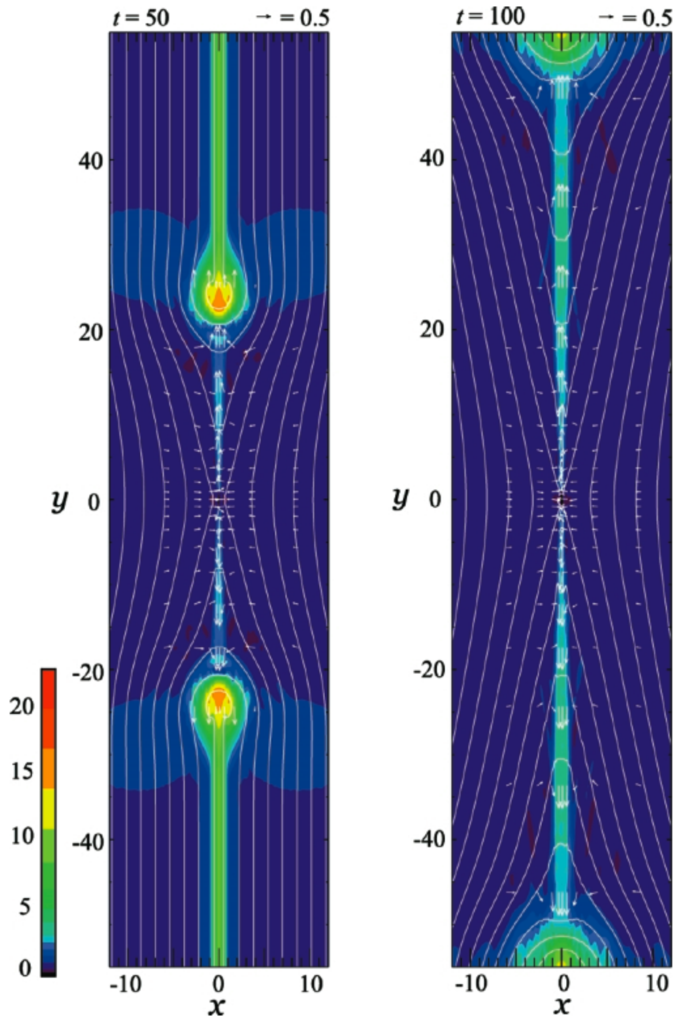
- Relativistic resistive MHD (RRMHD) eqs.
  (Watanabe & Yokoyama 2006, Komissarov 2007)

$$(\rho U^\mu)_{,\mu} = 0, \qquad (T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{\rm em})_{,\mu} = 0$$
$$F^{\mu\nu}_{,\mu} = -J^\nu, \qquad F^{*\mu\nu}_{,\mu} = 0$$
$$F^{\mu\nu} u_\nu = \eta\Big(J^\mu + (J^\nu u_\nu) u^\mu\Big)$$

- Alternative: relativistic two-fluid eqs.
  (Zenitani+ 2009a,b, Barkov+ 2014)



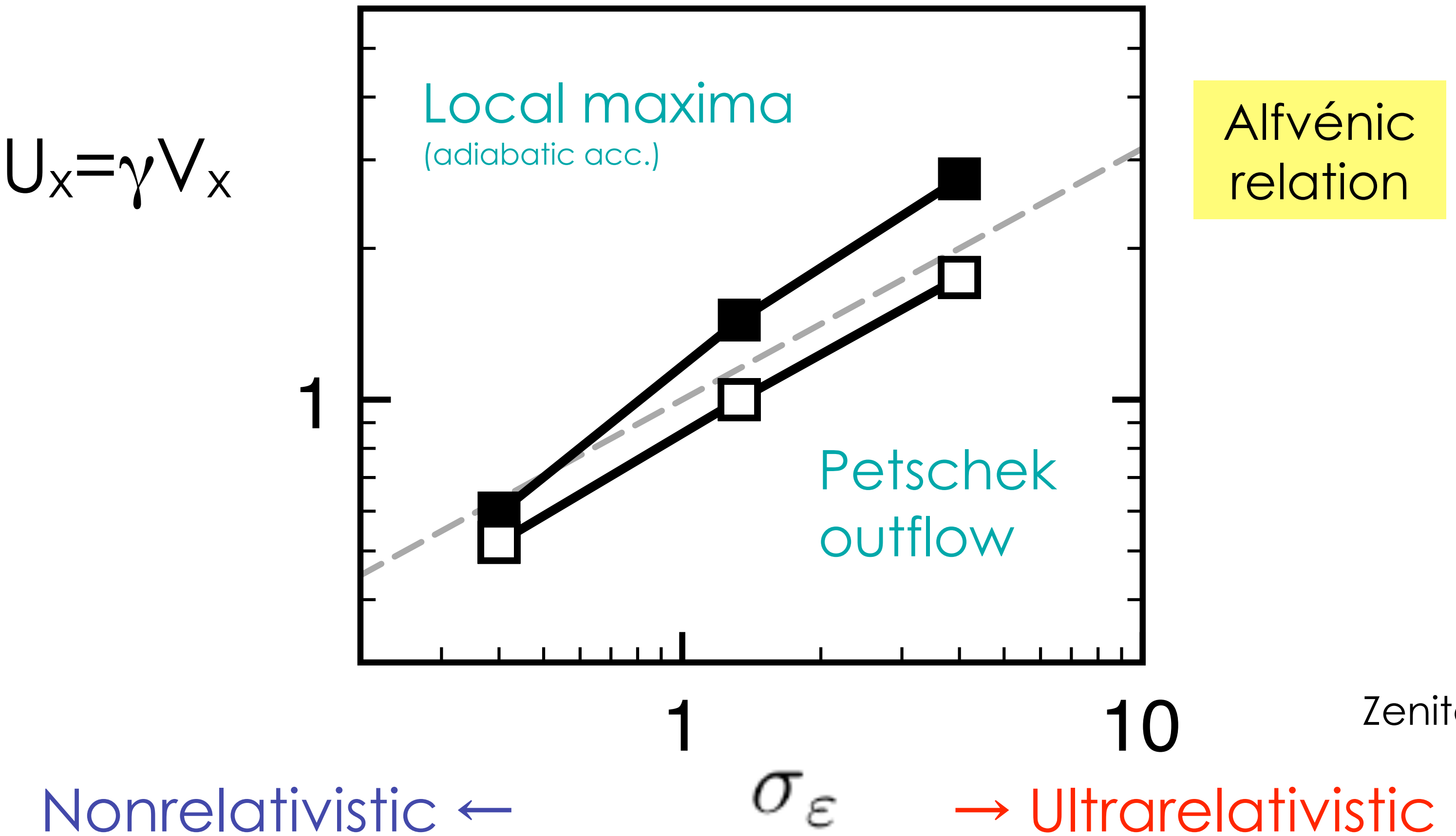
Zenitani+ 2009a



Watanabe & Yokoyama 2006

Relativistic PK reconnection - Alfvénic outflow

- Magnetization parameter $$\sigma_\varepsilon = \frac{B_0^2}{4\pi\gamma^2 w} \left(\approx \frac{8}{5} \frac{\mathcal{E}_{EM}}{\mathcal{E}_{fluid}} \right)$$
- Relativistic Alfvén speed $$\gamma_{jet} v_{jet} \approx \gamma_A c_A = \sqrt{\sigma_\varepsilon}$$

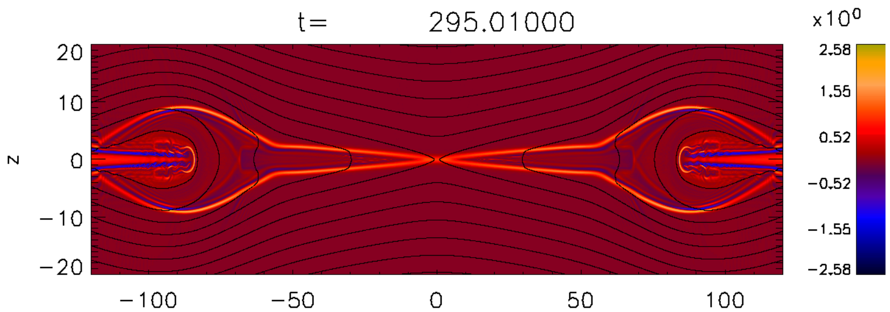


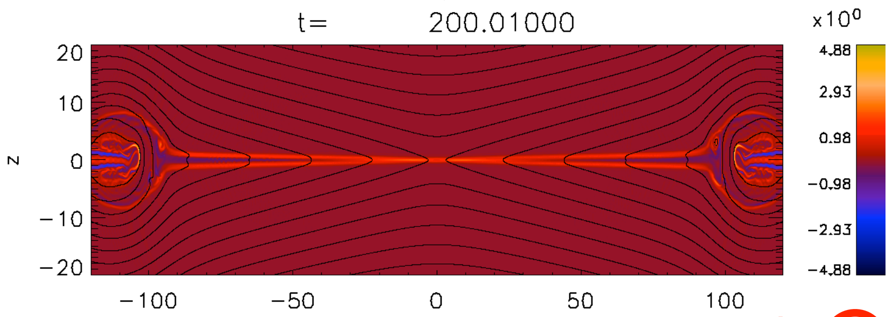
Zenitani+ 2010

Relativistic PK reconnection - a paradox

- Narrower opening angle (Lyubarsky 2005)
- Speed is limited by Alfvén speed

Semi-relativistic (sigma=0.4)

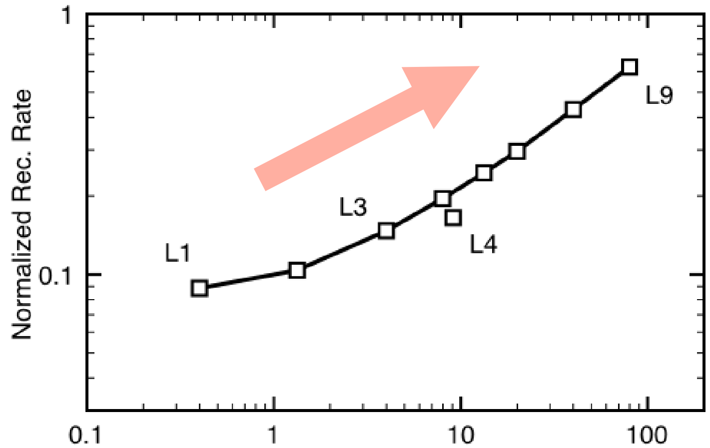




Relativistic (sigma=4)

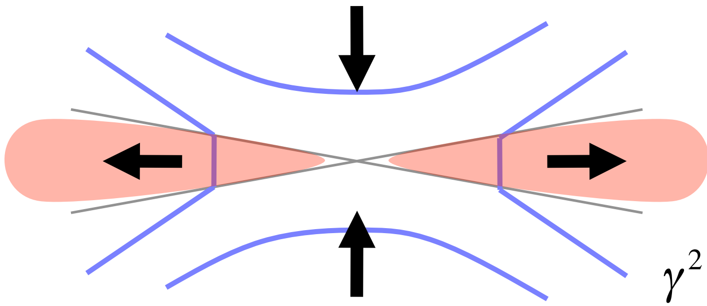
J_y ⊗

- Reconnection rate (flux transfer speed) goes high



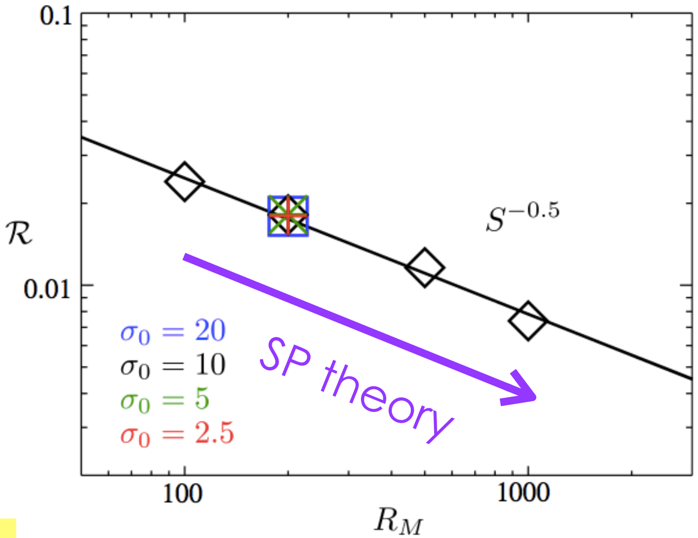
Nonrelativistic ← σ_ε → Ultrarelativistic

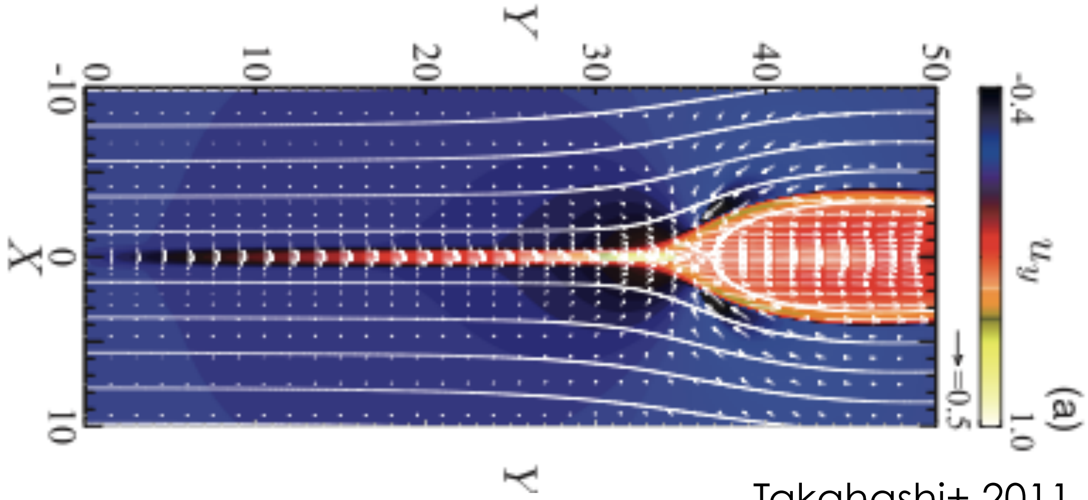
- Heat-dominated flow sustains fast energy throughput



$$\gamma^2 \frac{\Gamma}{\Gamma - 1} p\mathbf{v}$$

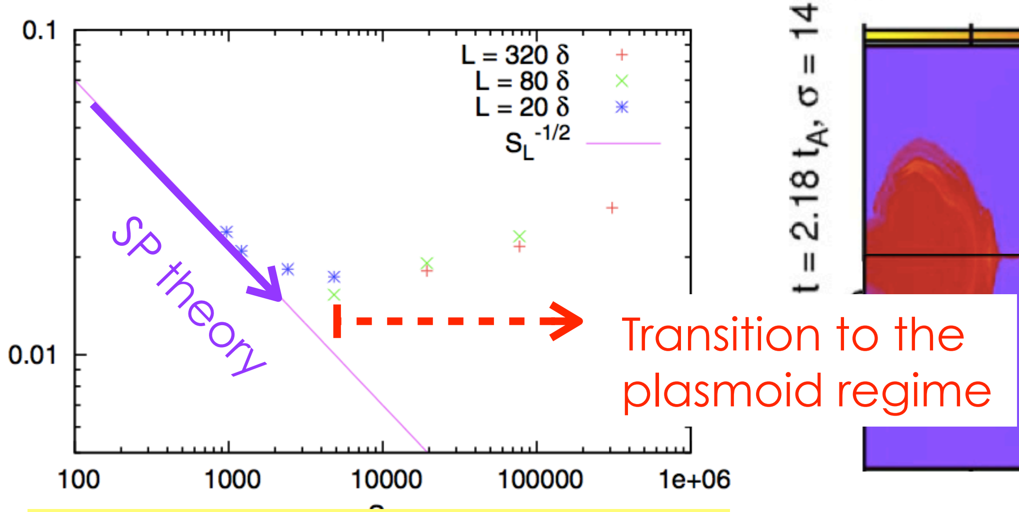
Relativistic Sweet-Parker reconnection

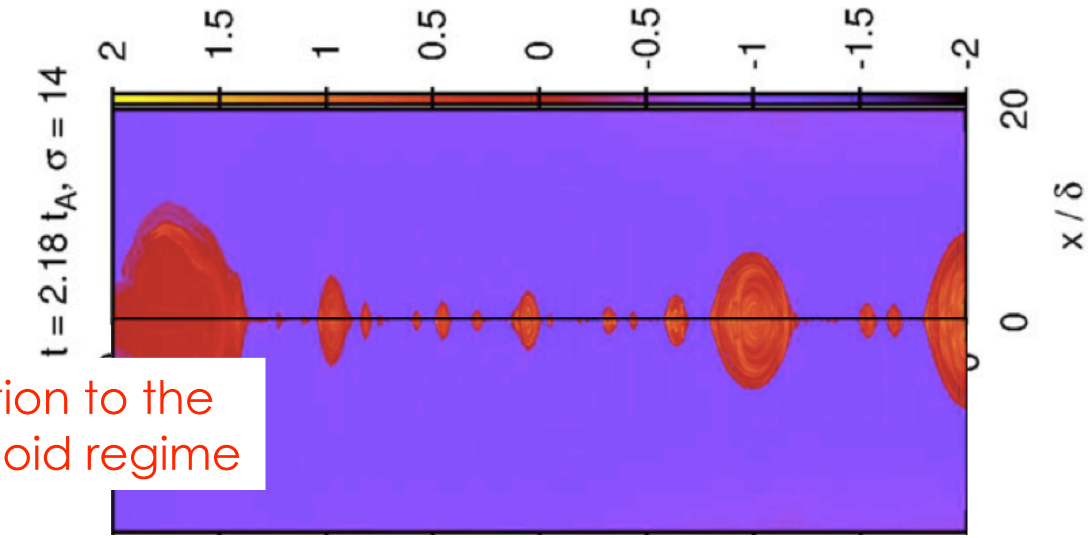




Takahashi+ 2011

Reconnection rate



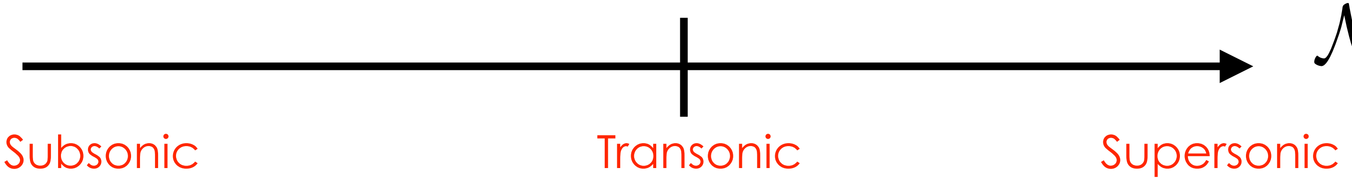


Lundquist number
(Normalized system length)

Takamoto 2013

New insight: High-speed fluid dynamics

- Branches of fluid dynamics



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

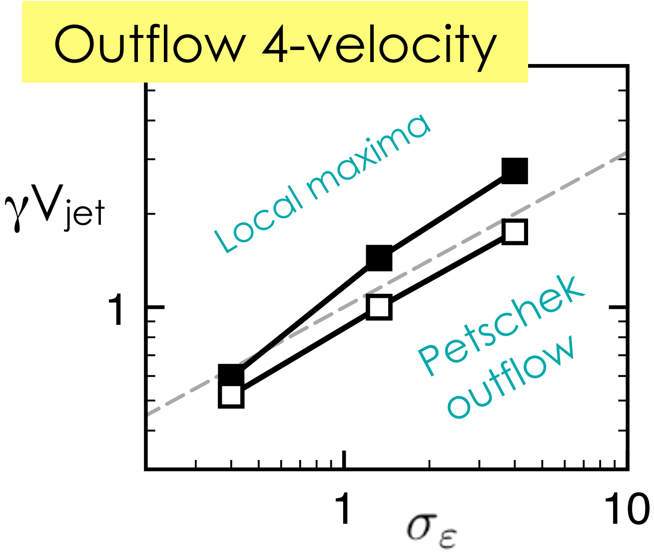
- Incompressible fluids

- High-speed fluid dynamics
- Compressible fluid dynamics
  - Adiabatic effects
  - Shocks
  - Shock=Shock interaction

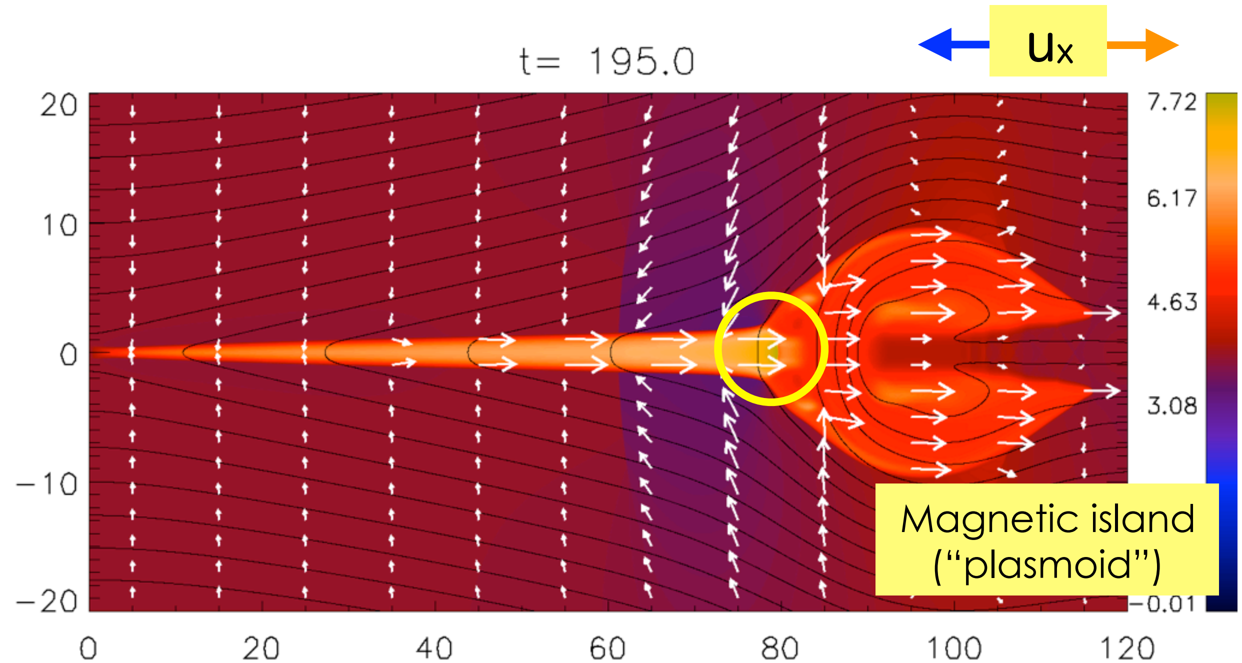
- Relativistic reconnection is usually in the high-speed regime

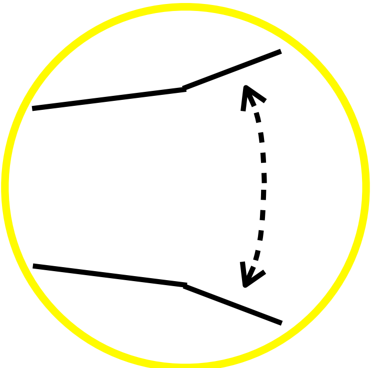
$$c_s \leq \frac{c}{\sqrt{3}} \qquad c_A = c\sqrt{\frac{\sigma_\varepsilon}{1+\sigma_\varepsilon}} \to c \qquad \sigma_\varepsilon > \frac{1}{2}$$

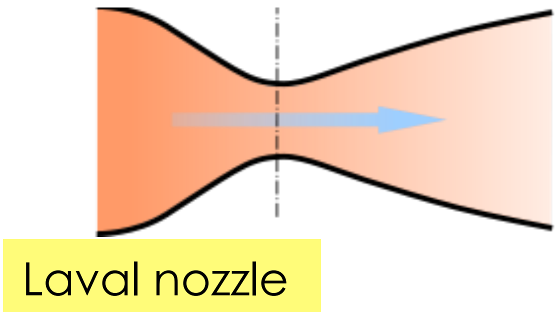
High-speed fluid effects (1/3): Adiabatic acceleration

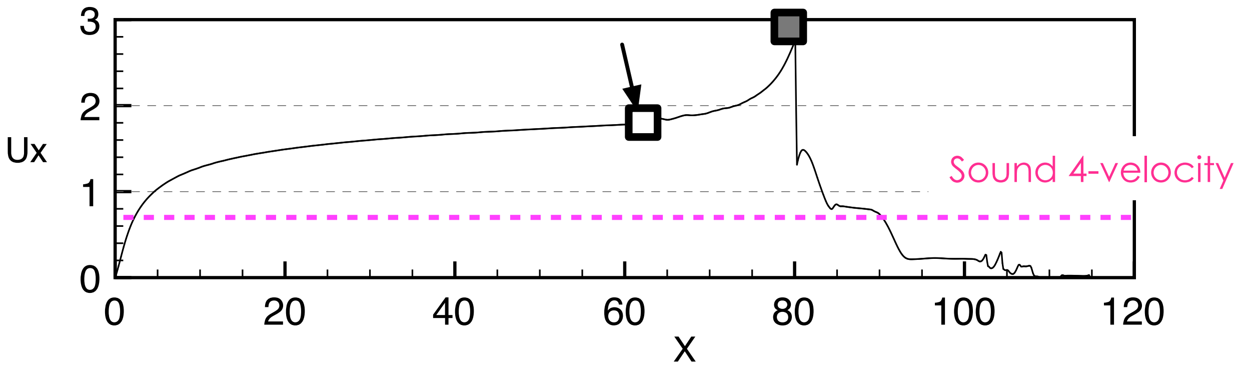


- Proposed by Shimizu & Ugai 2000
- Super-Alfvénic flow was also reported by Zanotti & Dumbser 2011

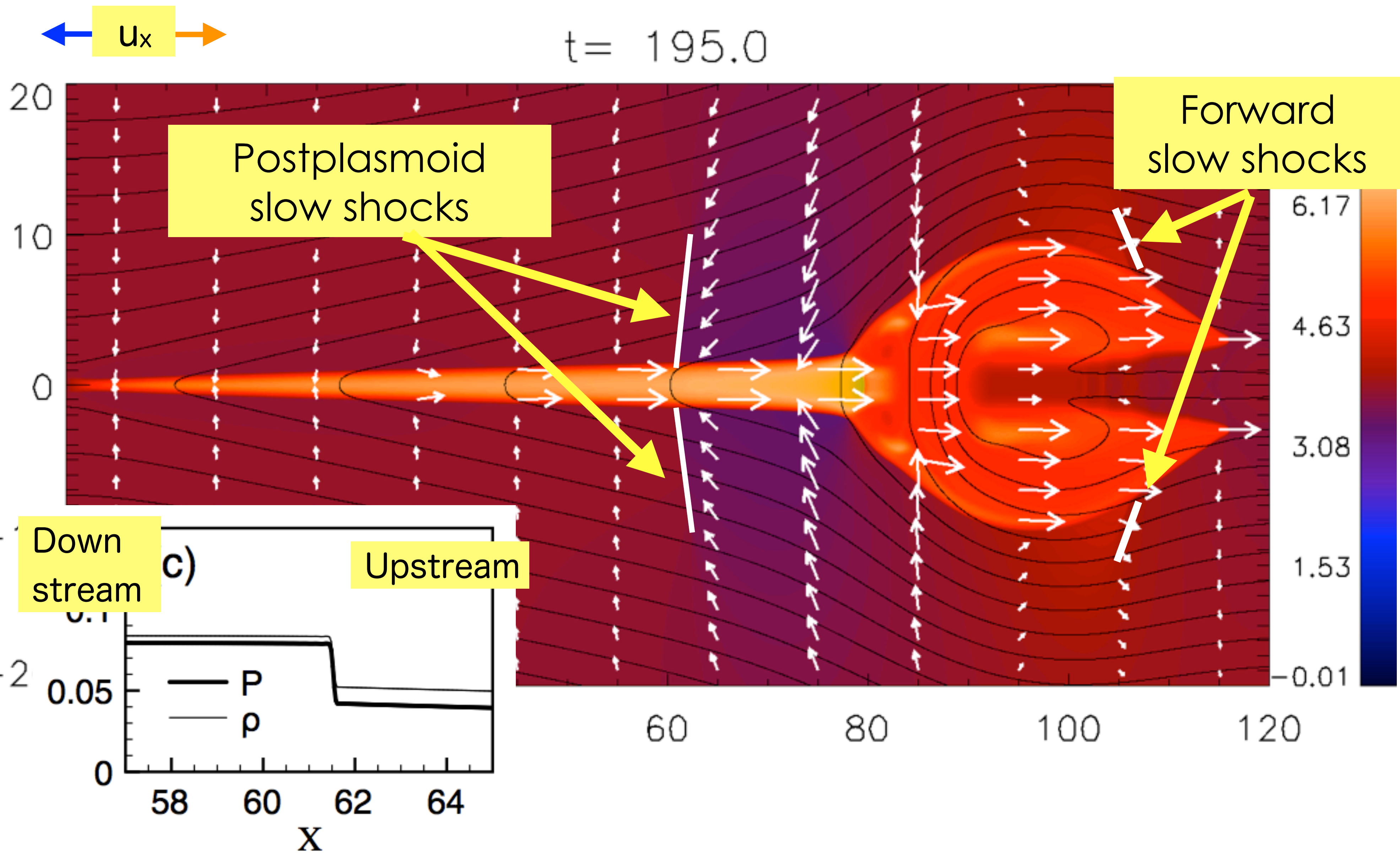








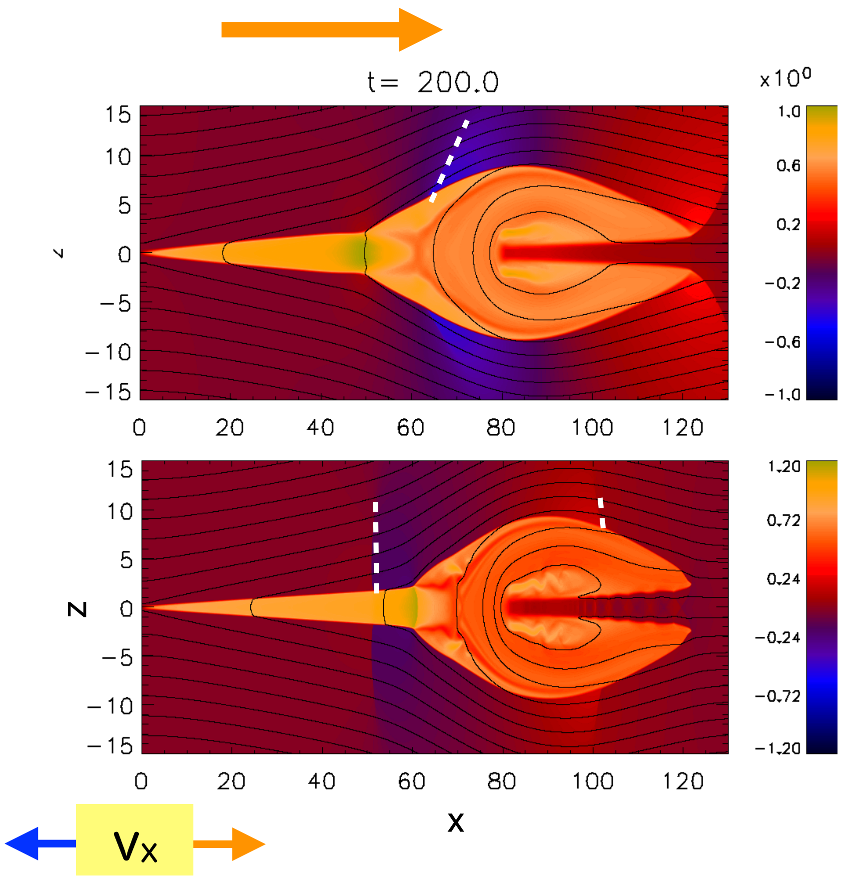
High-speed fluid effects (2/3): normal shocks

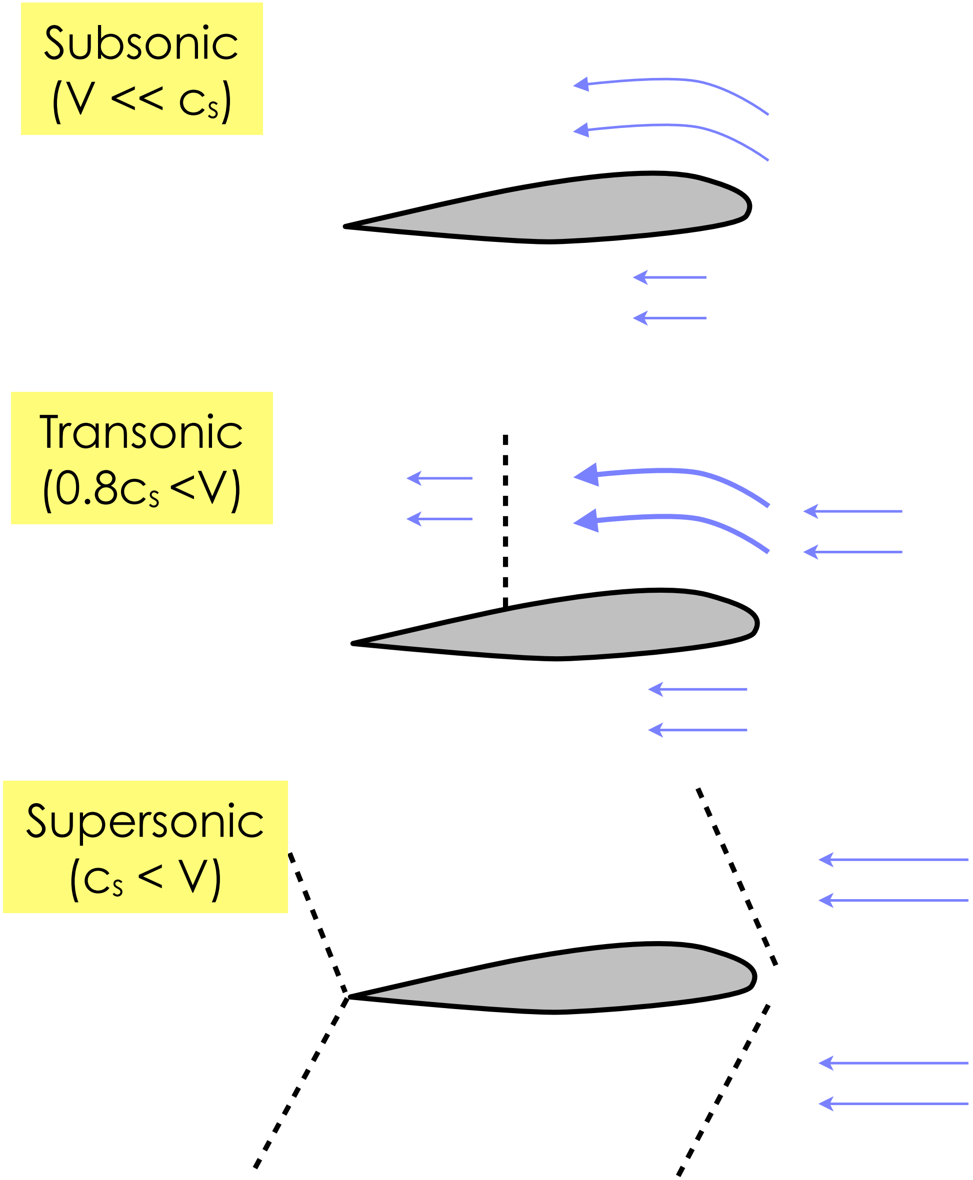


Normal shock (Recompression shock)

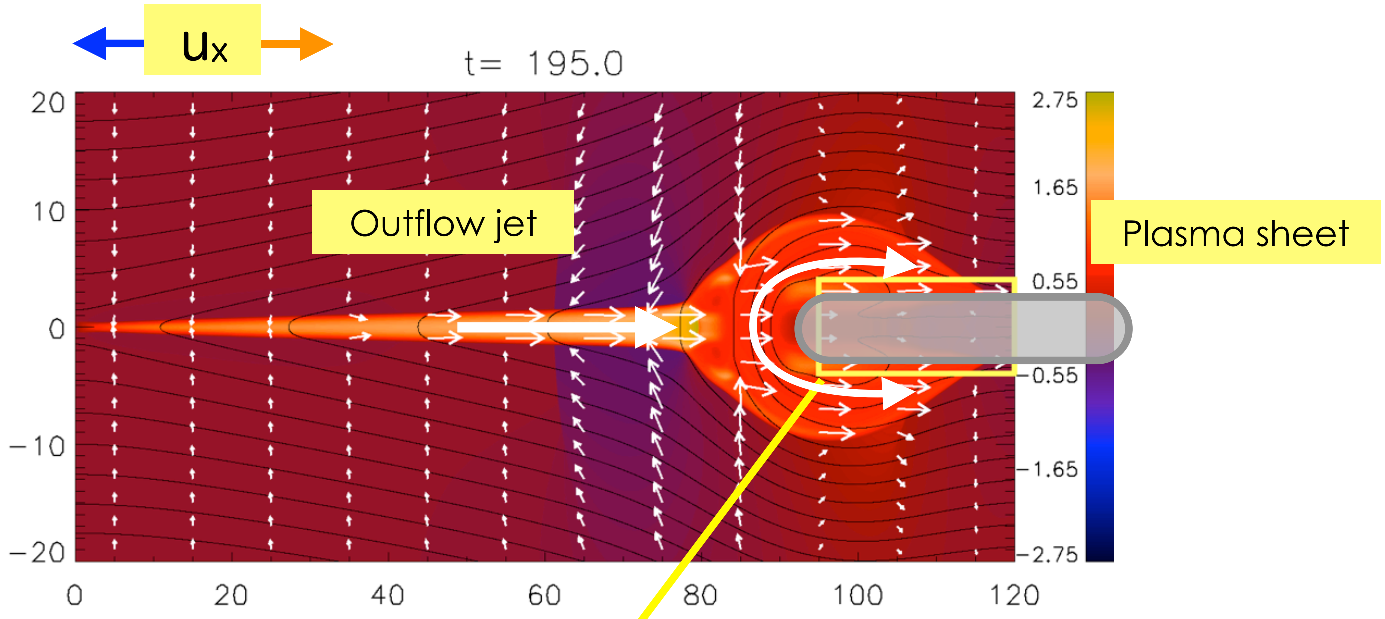
- Magnetic island = Airfoil

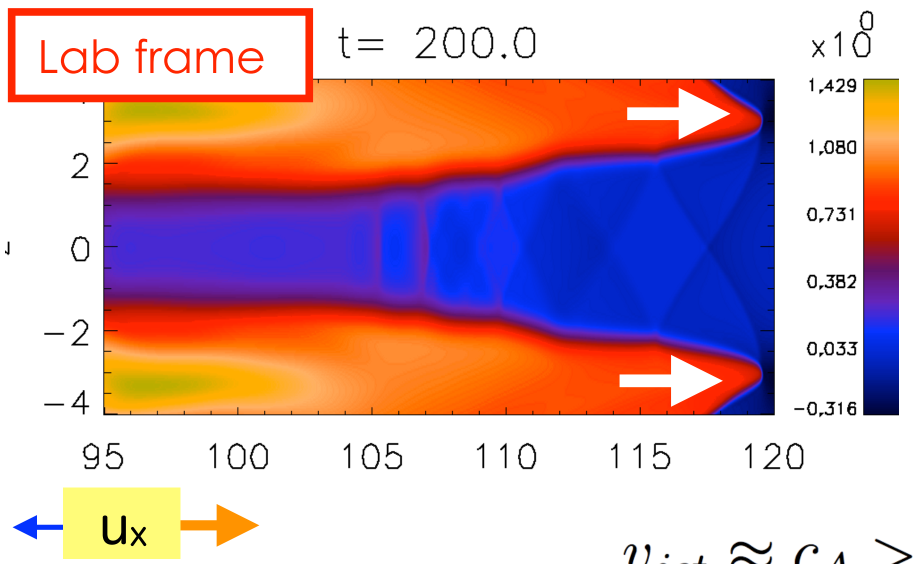
$v_{jet} \approx c_A$

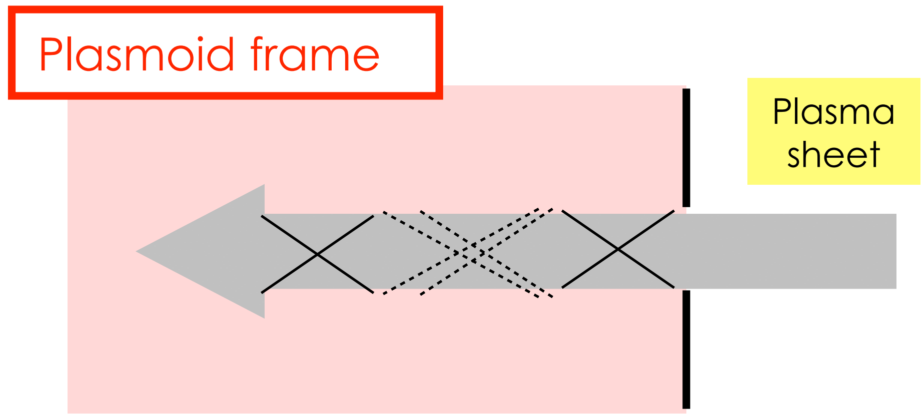




Compressible effects (3/3): Shock diamond

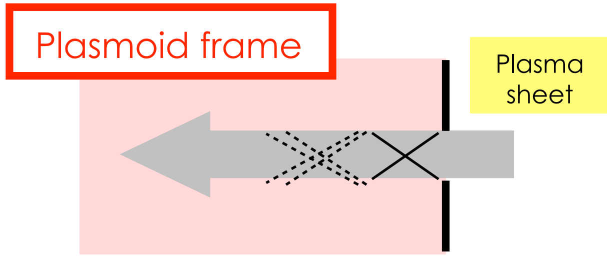




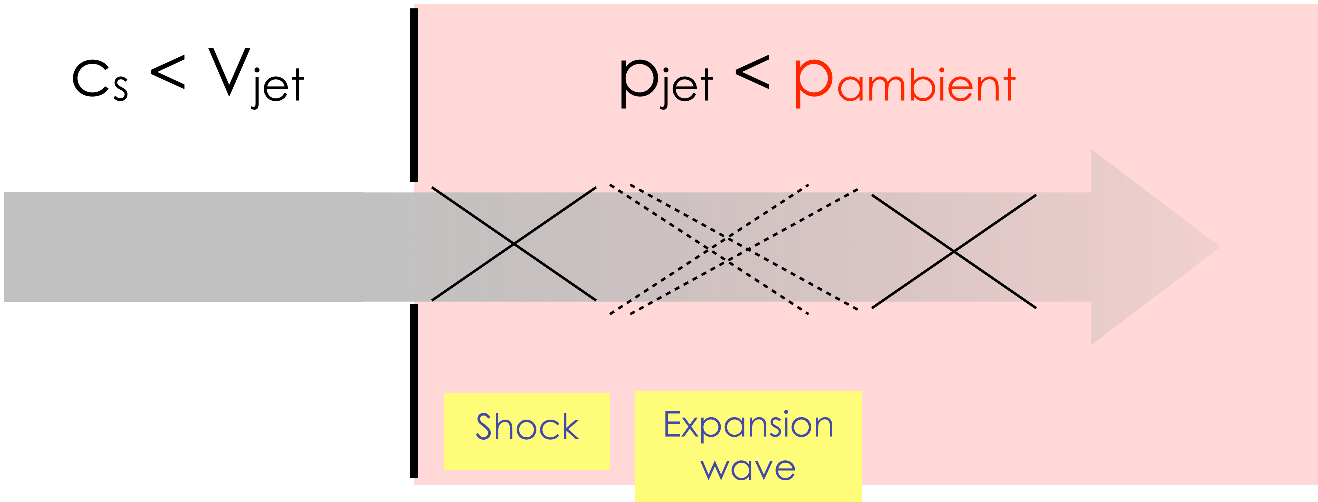


$$v_{jet} \approx c_A > c_s$$

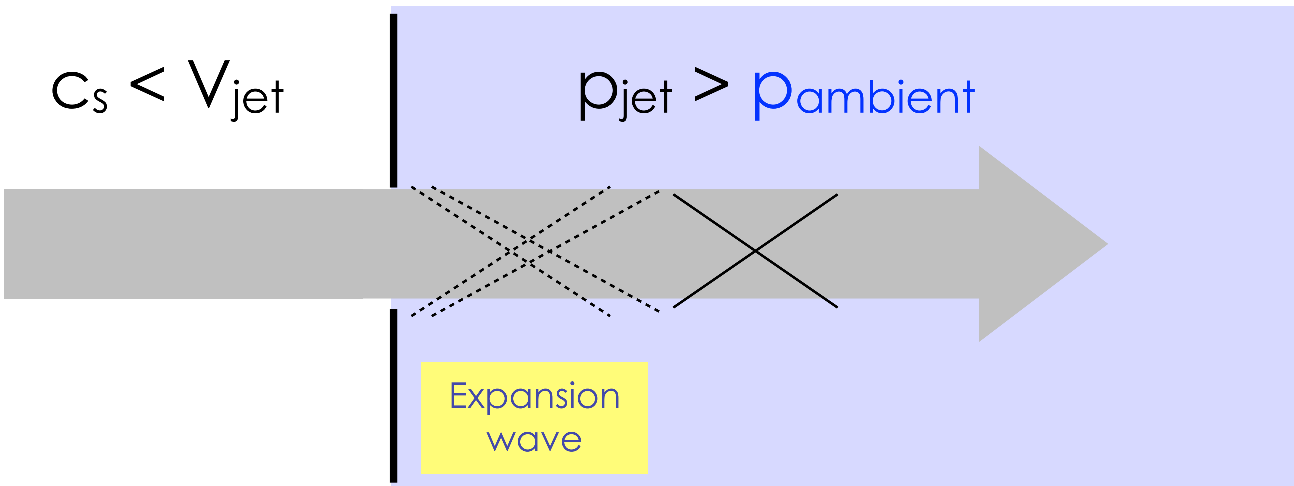
Shock diamond



- (a) Over-expanded flow

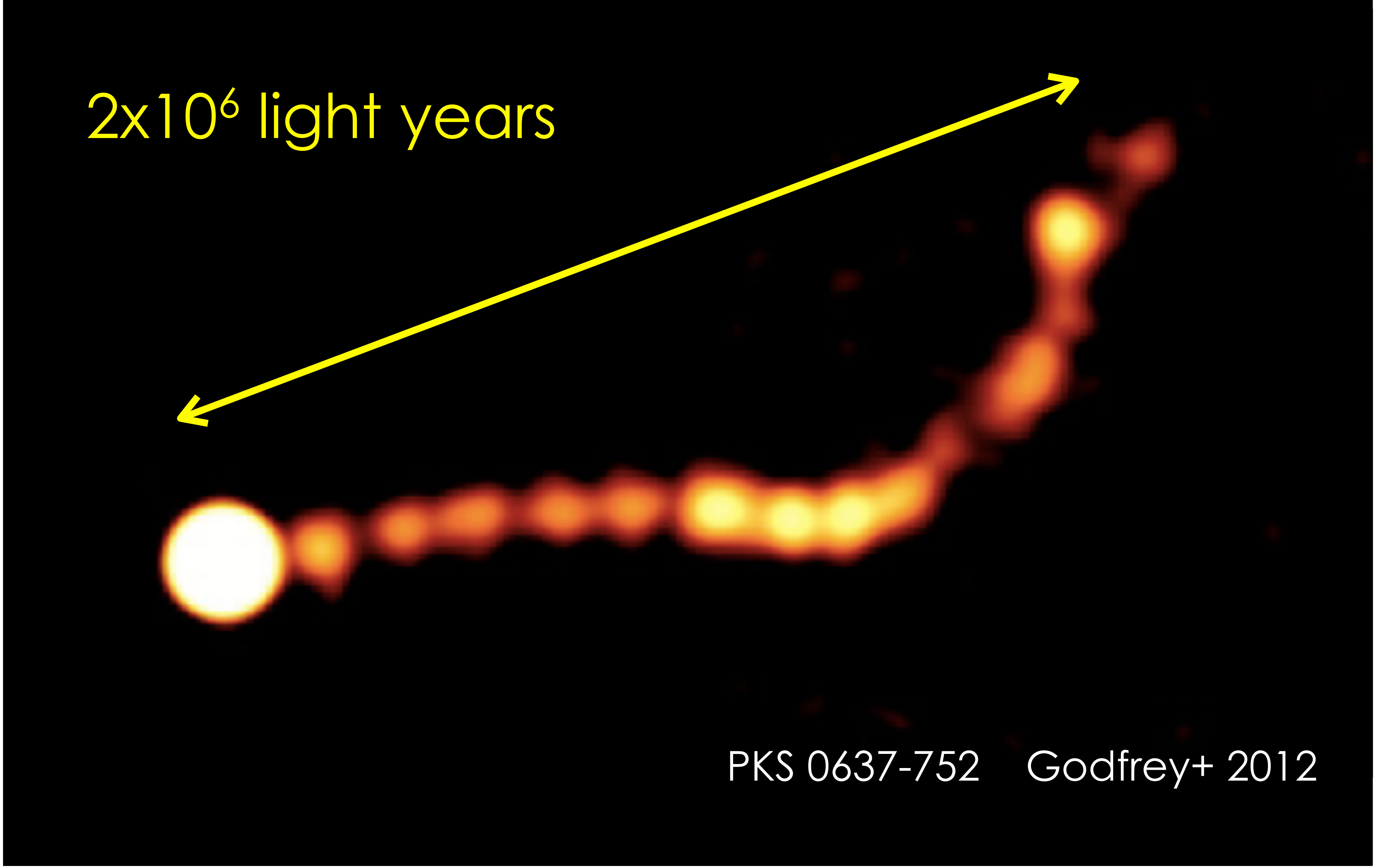


- (b) Under-expanded flow



Shapiro 1953

Shock diamonds in an extragalactic jet



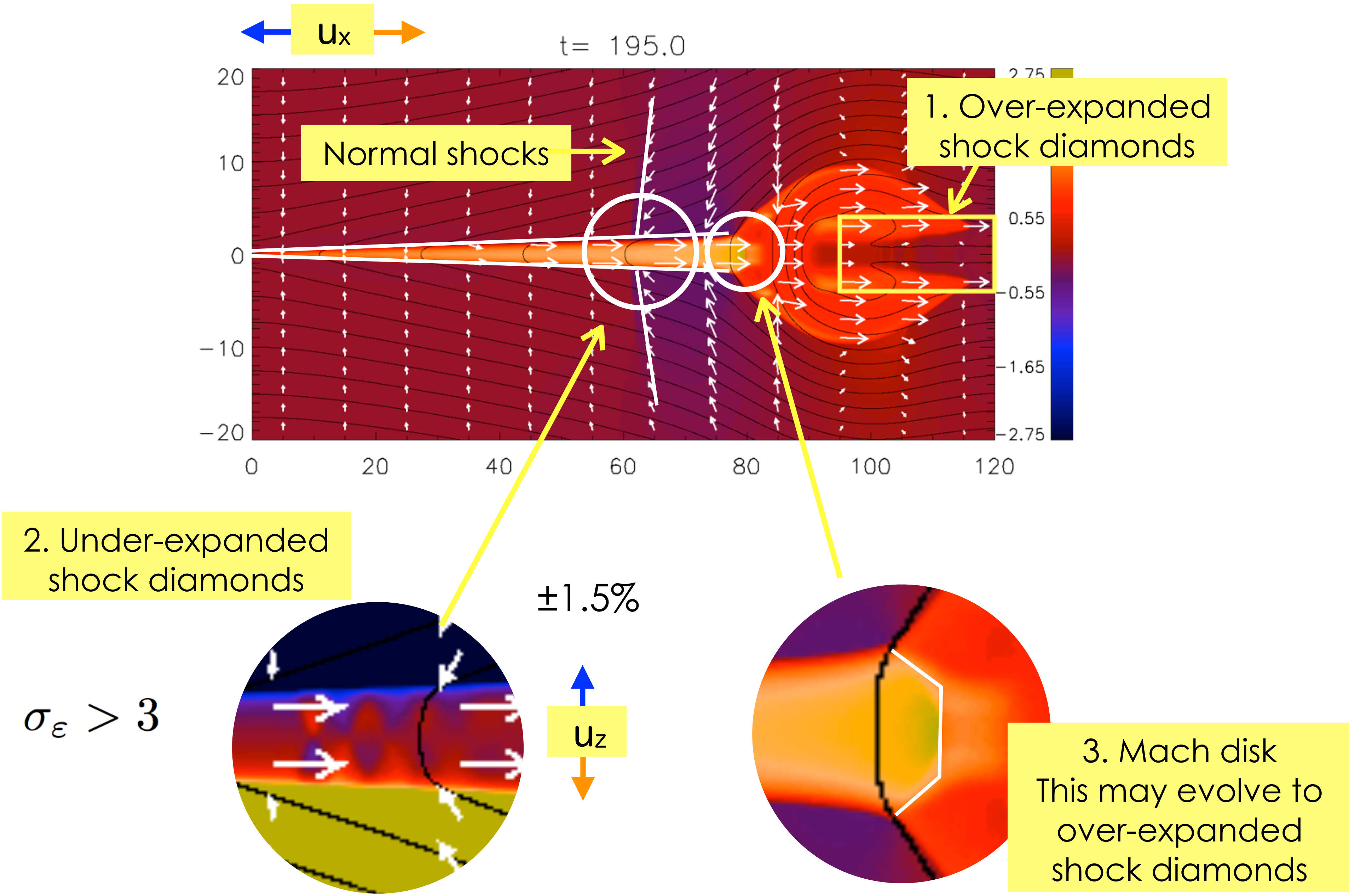
Shock diamonds in aeronautics

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

Shock diamonds in video game

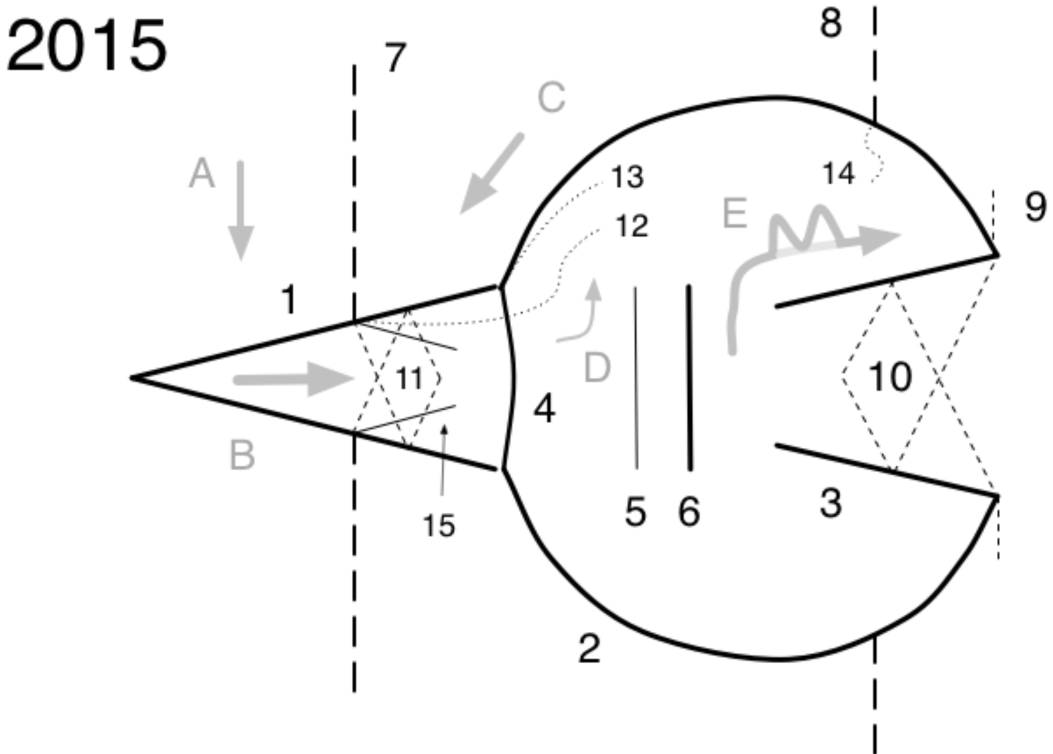
Microsoft Flight Simulator X https://www.youtube.com/watch?v=S8QGaiE4yWc

Some more shock-diamonds



$\sigma_\varepsilon > 3$

Structure of a reconnection-plasmoid system



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)
4. fast shock (Forbes & Priest 1983)
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)

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

- High-speed effects were also missing in nonrelativistic reconnection industry
- They result in complex shock structure in a low-β plasma

$$\beta = \frac{2}{\Gamma}\Big(\frac{c_s}{c_A}\Big)^2 \sim \Big(\frac{c_s}{V}\Big)^2 = \mathcal{M}^{-2}$$

Zenitani & Miyoshi 2011
Zenitani 2015a

3. Cross-code comparison

preliminary

Relativistic kinetic Ohm's law

- MHD simulation relines on pre-defined Ohm's law
- What about self-consistent PIC results?

- Stress-energy tensor

$$W^{\alpha\beta} = \int f(\boldsymbol{u}) u^\alpha u^\beta \frac{d^3u}{\gamma}$$

w^α : heat flow

$$Q^{\alpha\beta} \equiv w^\alpha u^\beta + w^\beta u^\alpha$$

- Standard decomposition

$$W^{\alpha\beta} = w u^\alpha u^\beta + w^\alpha u^\beta + w^\beta u^\alpha + w^{\alpha\beta}$$

- Ohm's law (∂_t=0)

$$\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B} = \frac{1}{\gamma n q} \nabla \cdot \left(w u^i u^j + Q^{ij} + P^{ij} \right)$$

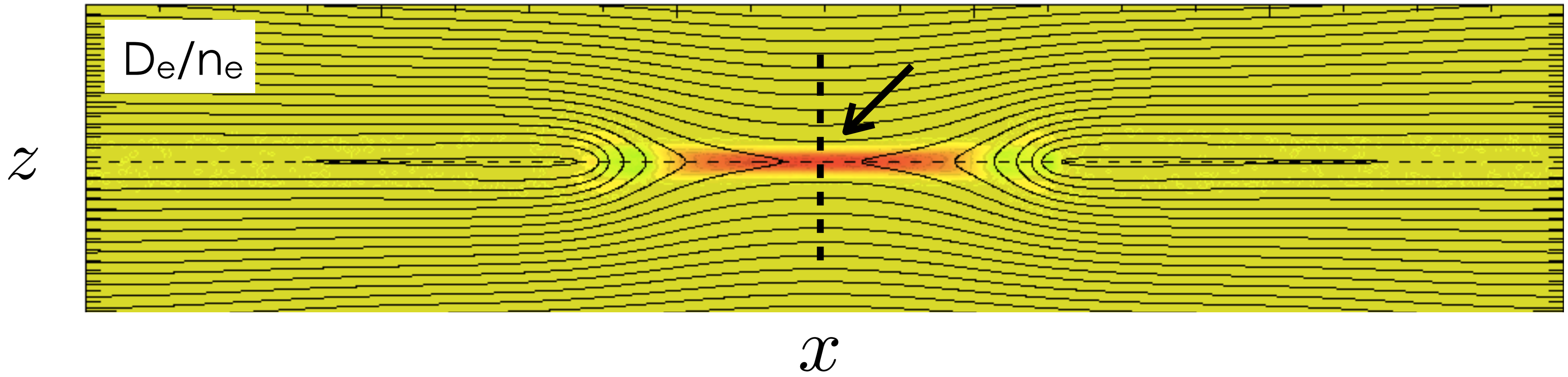
Heat flow term
(Only in relativistic kinetic plasma)

Bulk term
(incl. relativistic pressure)

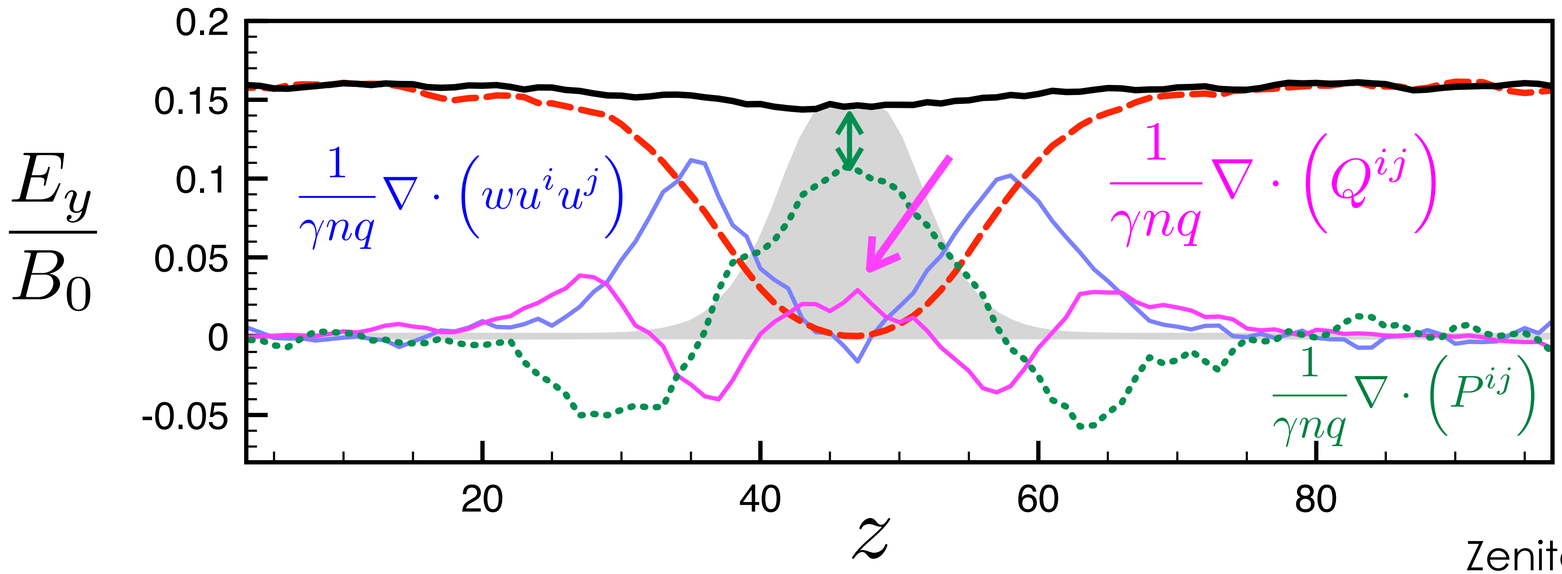
Local momentum transport
(Incl. kinetic div.P term)

Kinetic Ohm's law (cont.)

- Normalized energy dissipation (~ j.E/n ~ $\eta j^2/n$)

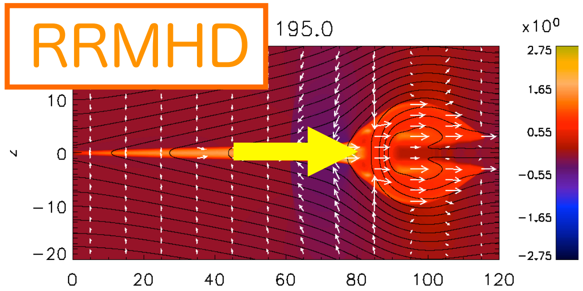


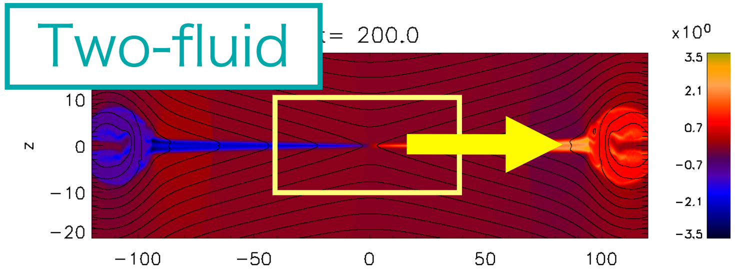
- Ohm's law: relativistic **heat flow term** appears

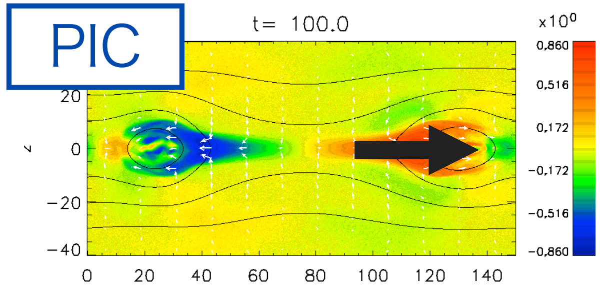


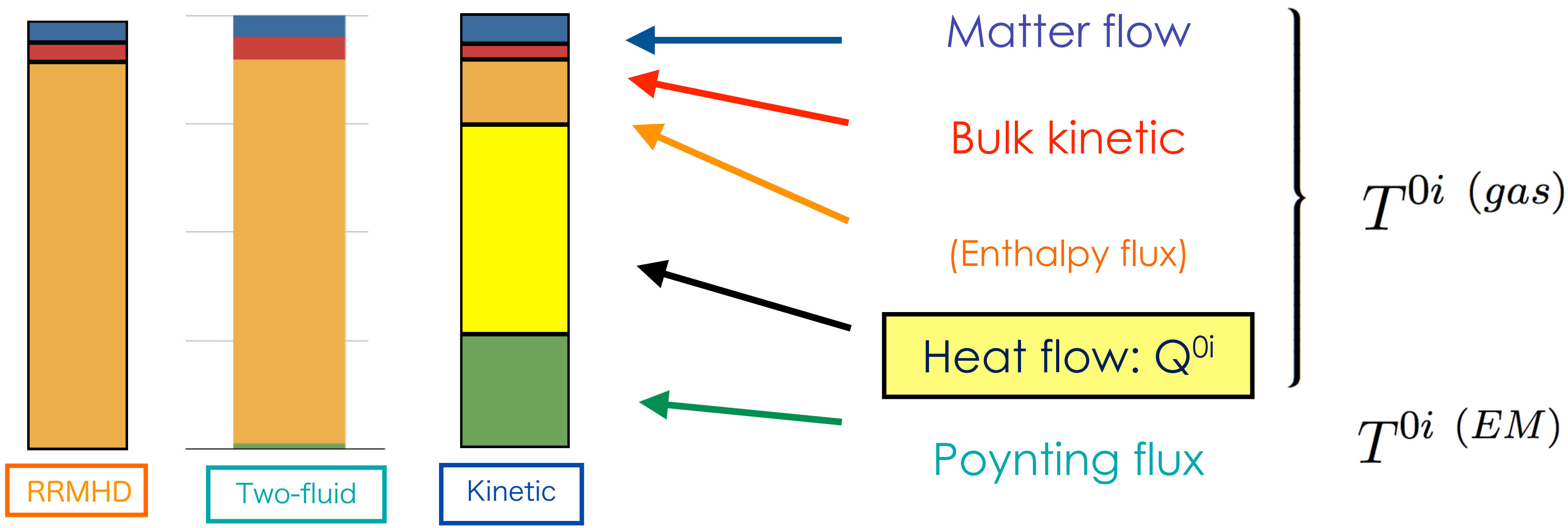
Zenitani in prep.

PIC vs Two-fluid vs RRMHD - energy throughput









- Kinetic term (heat flow) appears to be important

Summary

- Kinetic modeling
  - Reconnection features DC particle acceleration
  - 3D evolution - a kink instability
  - Now it is a field of active research!!

- RRMHD, Two-fluid modeling
  - Straightforward extension of nonrelativistic MHD reconnection
  - Narrower exhaust, faster reconnection rate, heat-dominated flow
  - High-speed fluid effects - adiabatic acc., shocks, shock diamonds

- Cross-code comparison
  - Heat flow appears in the Ohm's law and dominates in the energy budget (due to accelerated particles)