Cooling effects of an optically-thin synchrotron radiation during the Petsheck-type magnetic reconnection process

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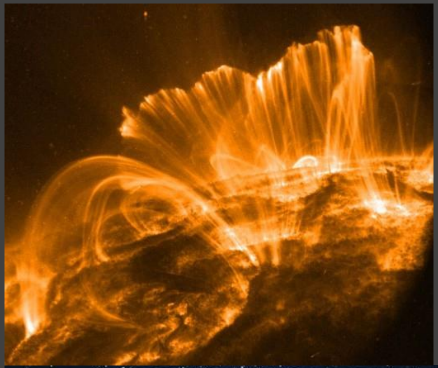
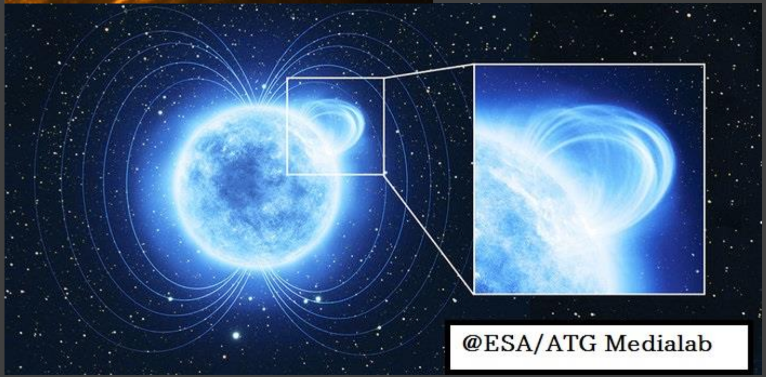
High energy astrophysical phenomena driven by the magnetic reconnection

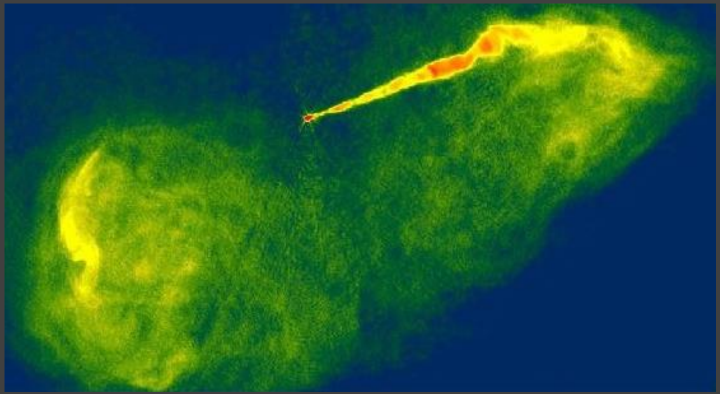
- Magnetic reconnection can be the physical mechanism which can quickly convert the magnetic energy to the plasma kinetic and thermal energy.



(above) Solar flares
(below) Magnetars



(above) Black hole accretion discs
(below) Relativistic jets



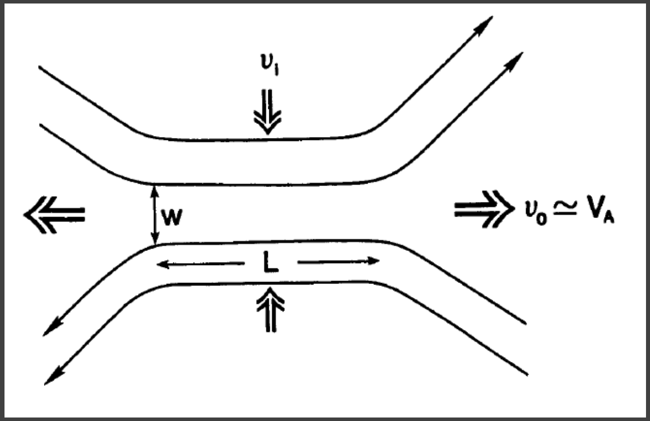
Classical magnetic reconnection models

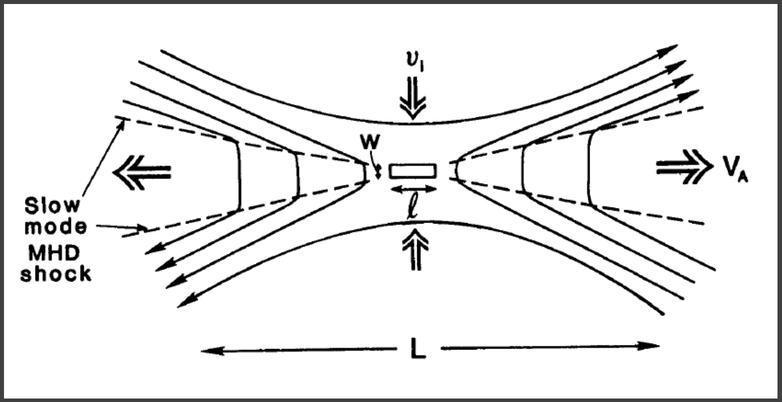
- Magnetic reconnection is the physical mechanism which can quickly convert the magnetic energy to the plasma kinetic and thermal energy.

Reconnection rate:

$$R = \frac{v_{in}}{V_A} \propto R_m^{-\frac{1}{2}}, R_m \equiv \frac{\tau_D}{\tau_A}$$

$$R \propto (\log R_m)^{-1}$$





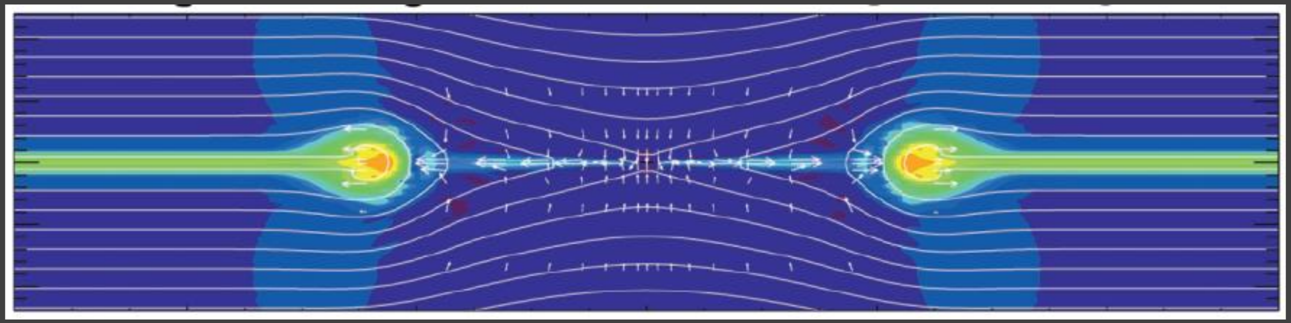
(left) Sweet-Parker type reconnection model.
(right) Petschek type reconnection model.

Recent numerical simulations of radiative-relativistic magnetic reconnection

In high energy plasmas, $V_A \sim c$, relativistic magnetic reconnection is important physical mechanism.

Relativistic magnetic reconnection processes have been numerically investigated.

(Watanabe+2006, Zenitani+2010, Takahashi+2011)



Watanabe & Yokoyama 2006

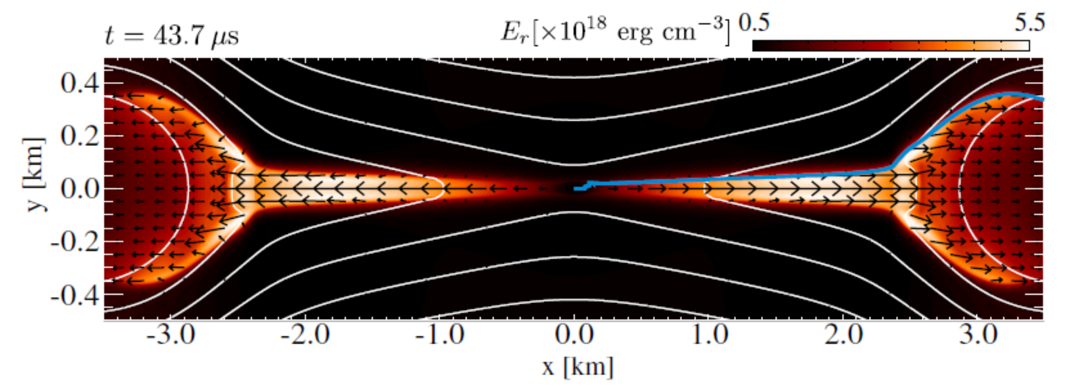
Recent numerical simulations of radiative-relativistic magnetic reconnection

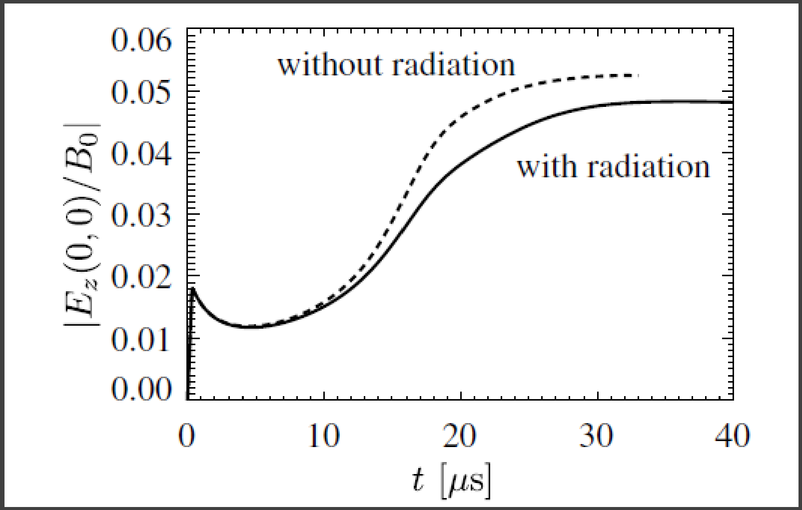
The radiation force can be dominant, and may affect the reconnection dynamics.

(Jaroschek&Hoshino 2009, Takahashi+ 2013)

The reconnection rate is reduced by the electron scattering.

Takahashi+2013
The radiation energy density distribution

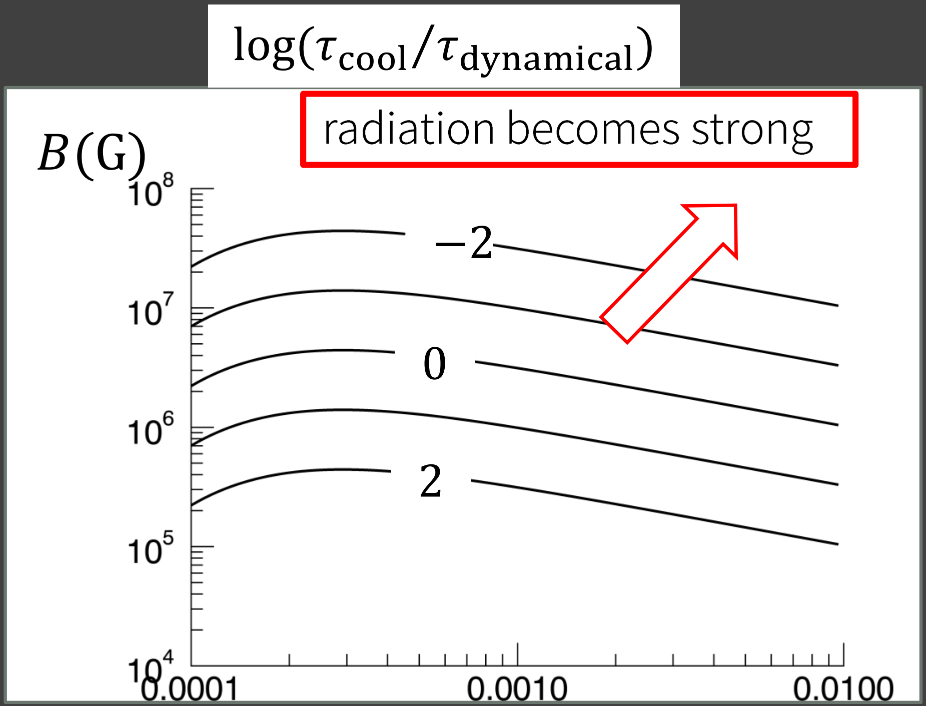




Numerical setting: synchrotron emission from thermal electrons

For magnetically dominated plasmas, the synchrotron radiation can play important roles.

(Jaroschek&Hoshino 2009, Uzdensky 2015).



$\theta_i \equiv k_B T / m_i c^2$

However, the synchrotron radiation has never been considered for MHD simulation.

We performed MHD simulations considering the effects of the synchrotron cooling.

Relativistic-Resistive MHD equations with synchrotron cooling and initial condition

Basic equations

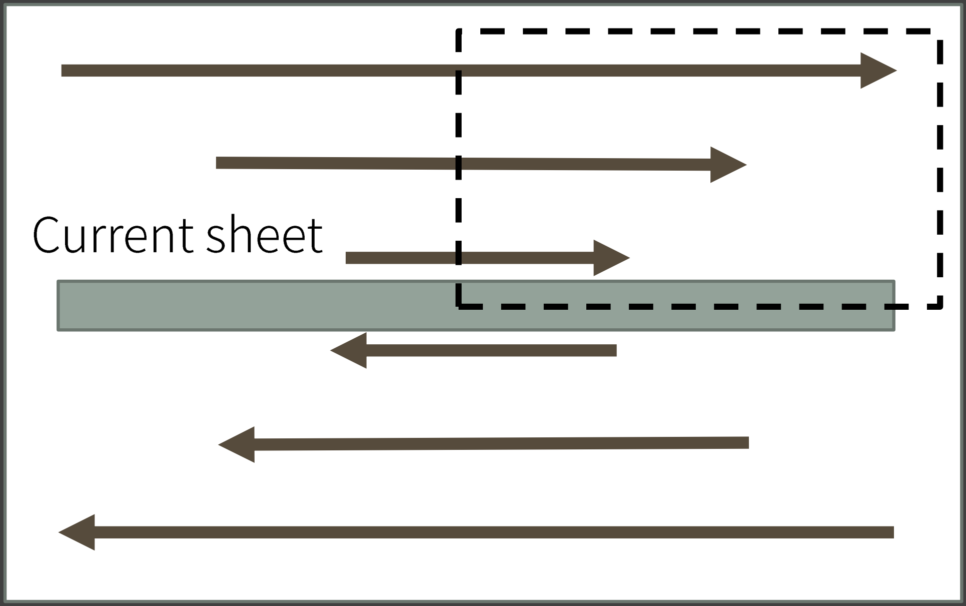
$$\partial_t(\Gamma\rho) + \nabla\cdot(\Gamma\rho\boldsymbol{v}) = 0,$$
$$\partial_t e + \nabla\cdot\boldsymbol{m} = -q(\rho, T, B),$$
$$\partial_t m_i + \nabla_j\cdot\Pi_{ij} = 0.$$
$$\partial_t\boldsymbol{B} + \nabla\times\boldsymbol{E} = 0,$$
$$\partial_t\boldsymbol{E} - \nabla\times\boldsymbol{B} = \boldsymbol{j}.$$

The radiation emissivity, $q \propto \rho B^2 T^2$ (Esin+ 1996).

For simplicity, we assume the optically-thin radiation and single fluid approximation.

Initial conditions

- $[x, y] = [0{:}\,180, 0{:}\,45]$.
- Isothermal current sheet.
- MHD equilibrium.
- Spatially localized resistivity.

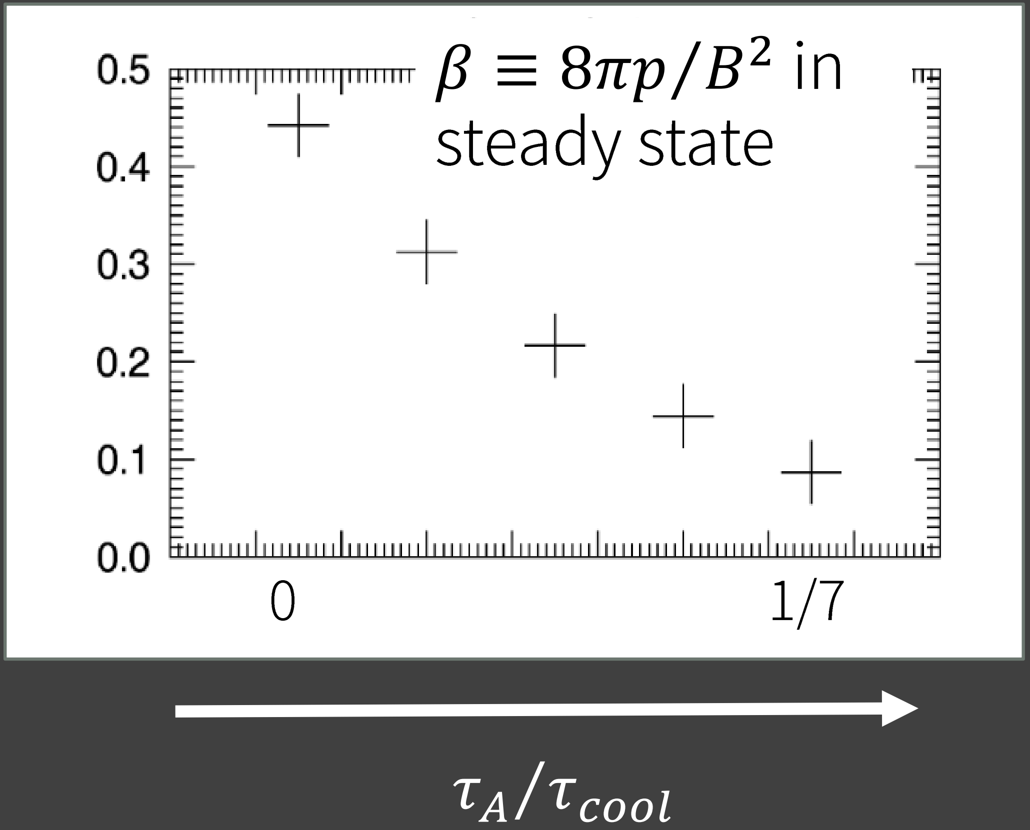


Relativistic reconnection process considering the radiation cooling

We have performed relativistic reconnection simulations with

- $\sigma \equiv B^2/4\pi\rho c^2 = 3,$
- $\beta \equiv 8\pi p/B^2 = 1/3,$
- $V_A/c \sim 0.71, \Gamma_A = 2.$

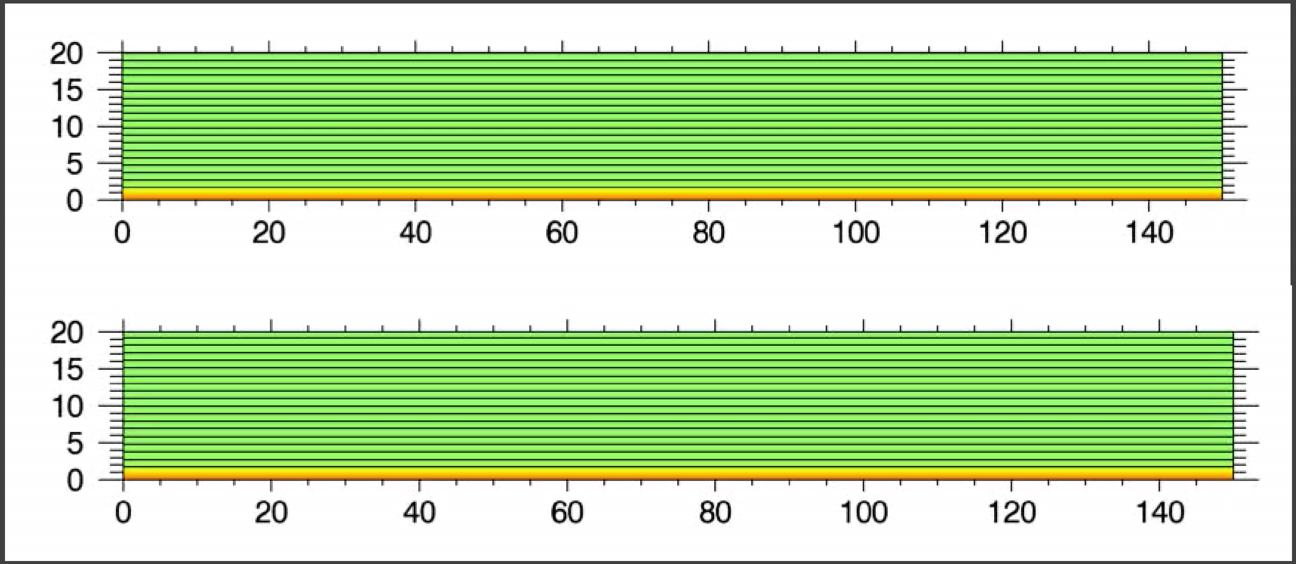
In steady state, the inflow gas pressure depends on the cooling timescale, since plasmas outside the current sheet are cooled by the radiation,.



Petschek reconnection with/without cooling: time evolution of density profiles

without radiation

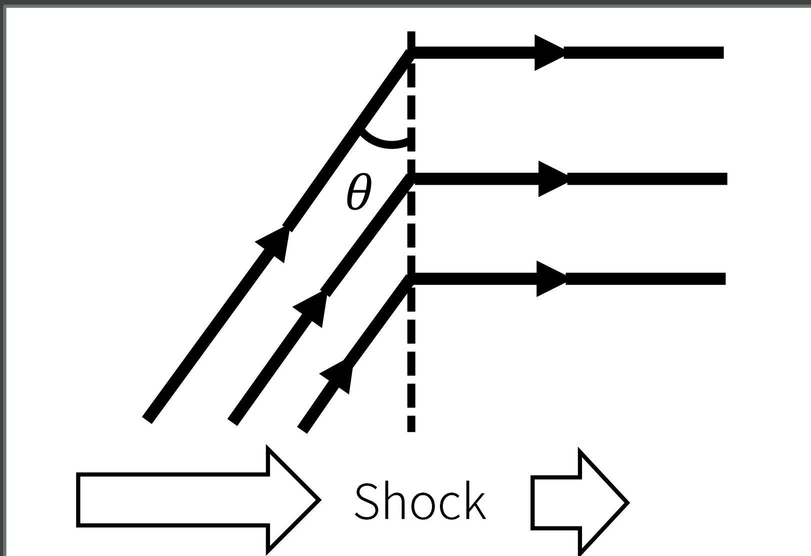
The cooling timescale
： τ_A/τ_{cool}=1/7

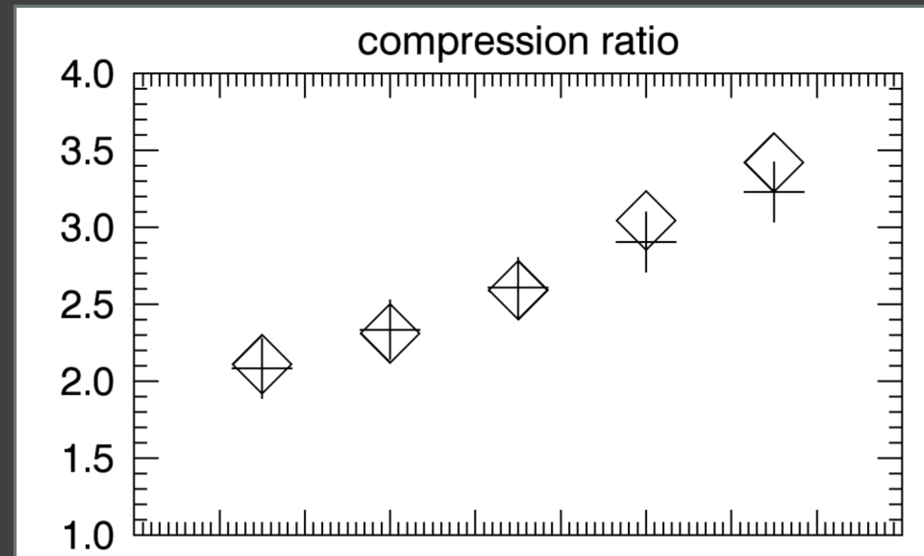


With radiative cooling,

- The outflow plasmas are more compressed.
- The outflow opening angle becomes smaller.

The plasma compression ratio: the switch-off shock





τ_A/τ_{cool}

Considering the switch-off shock condition, the plasma compression ratio closes to

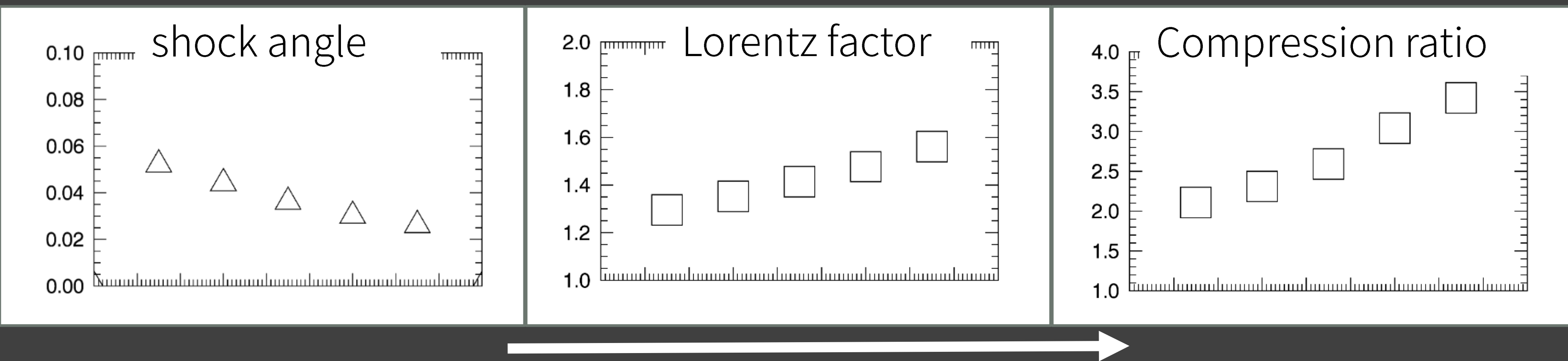
$$\rho_2/\rho_1 \to 1 + (\Gamma\beta_1 + \Gamma - 1)^{-1},$$

as $\theta \to 0$.

Diamonds: ρ_2/ρ_1,

Cross: $1 + (2\gamma\beta_1 + \gamma - 1)^{-1}$

The reconnection rate of the relativistic reconnection process with optically-thin cooling

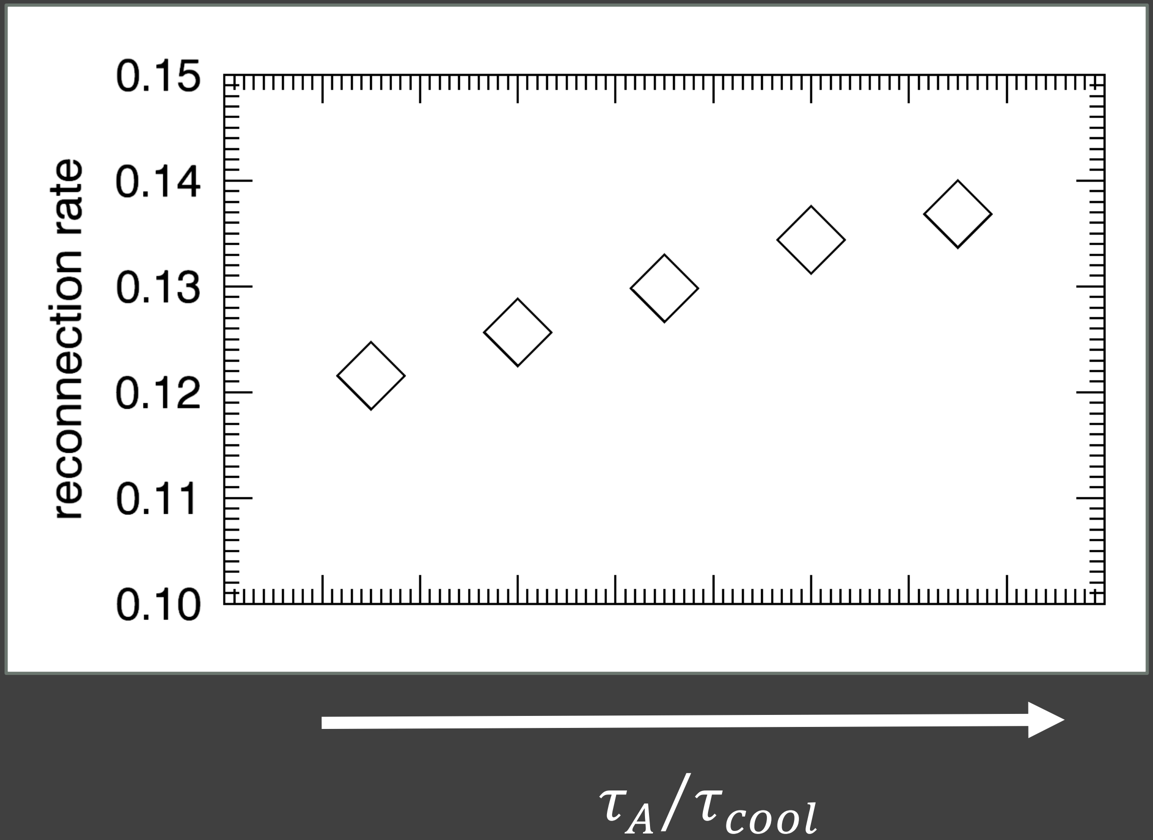


τ_A/τ_{cool}

- Increasing of the compression effect, the reconnection rate is enhanced.
- The outflow Lorentz factor increases.

$$R = \frac{v_{\rm in}}{v_{\rm out}} \sim \frac{\delta}{d} \times \frac{\gamma_{\rm out}}{\gamma_{\rm in}} \times \frac{\rho_{\rm out}}{\rho_{\rm in}}$$

The reconnection rate of the relativistic reconnection process with optically-thin cooling



In the relativistic simulation results, we found that reconnection rate is enhanced with the radiative cooling.

$$\frac{v_{\rm in}}{v_{\rm out}} \sim \frac{\delta}{d} \times \frac{\rho_{\rm out}}{\rho_{\rm in}} \times \frac{\gamma_{\rm out}}{\gamma_{\rm in}}$$

Summary

- We performed 2D Relativistic MHD simulations with considering the synchrotron radiation cooling.
- When τ_{cool} is smaller than $\tau_{\mathrm{rec}} = 10 - 100\tau_A$, the plasma beta outside the current sheet goes down by the radiation cooling.
- The reconnection rate is enhanced by the plasma compression effect due to the radiation cooling.