MHD Simulations of Twisted Magnetic Flux Tube in Galactic Central Region

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「磁気流体プラズマで探る高エネルギー天体現象」研究会

CHIBA UNIVERSITY

Molecular Loops in Galactic Center Region

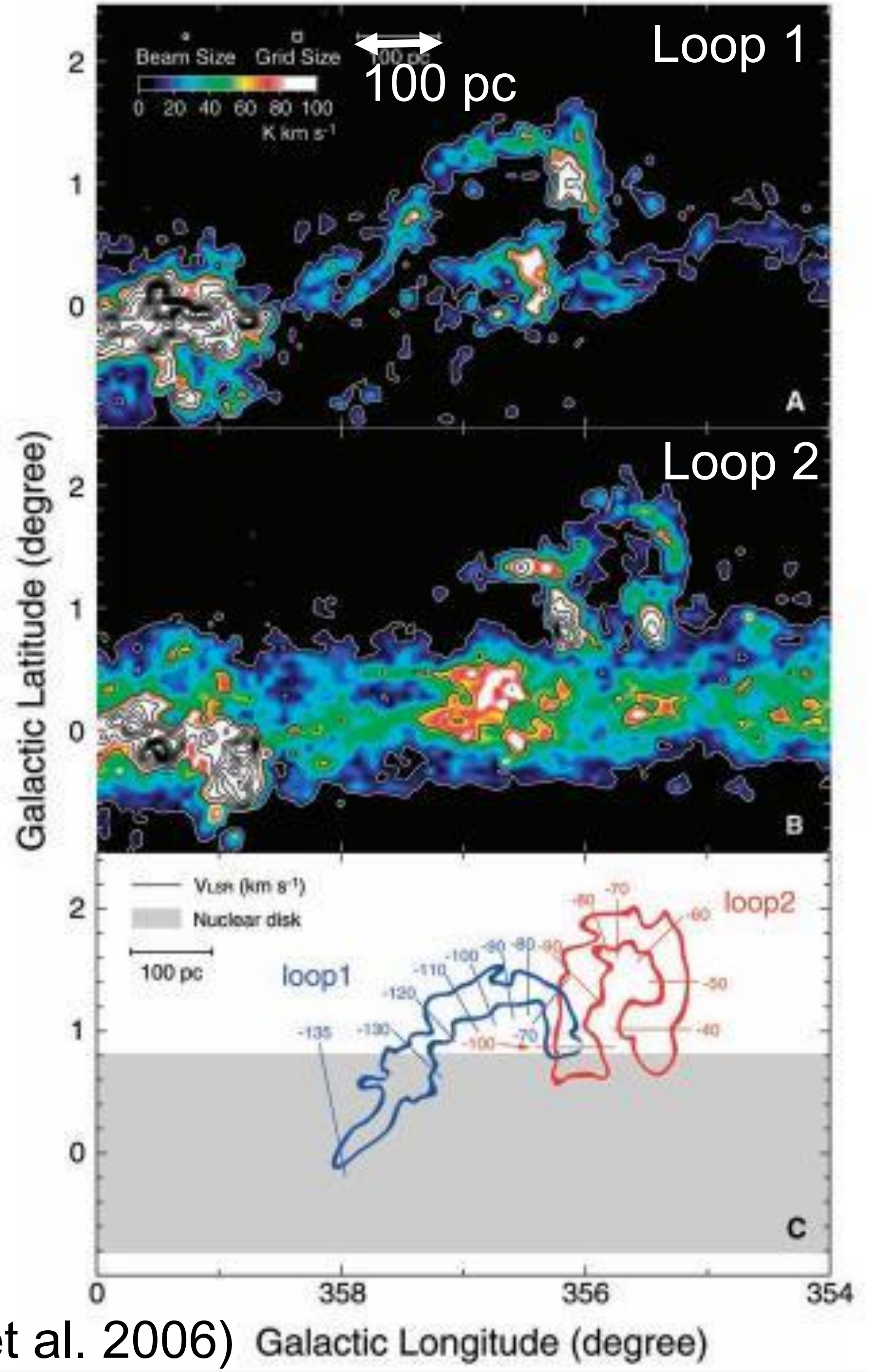
Discovered by CO emission line observation
(Fukui et al. 2006, Fujishita et al. 2009)

Scale of molecular loops
200-600 pc

Strong emission at foot points

Velocity gradient along loops
(~35 km/s per 100 pc)

Strong velocity dispersion at foot points
(40~80 km/s)



(Fukui et al. 2006)

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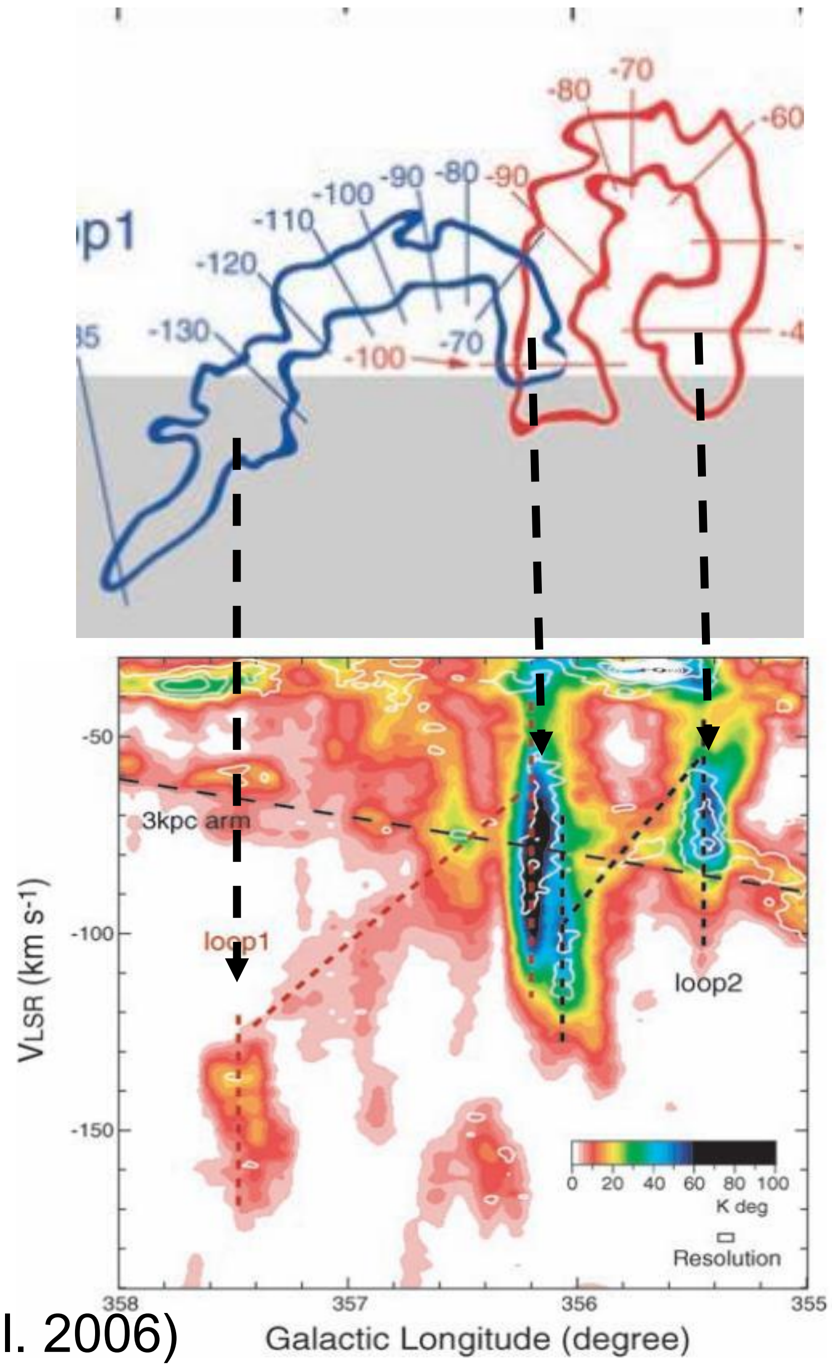
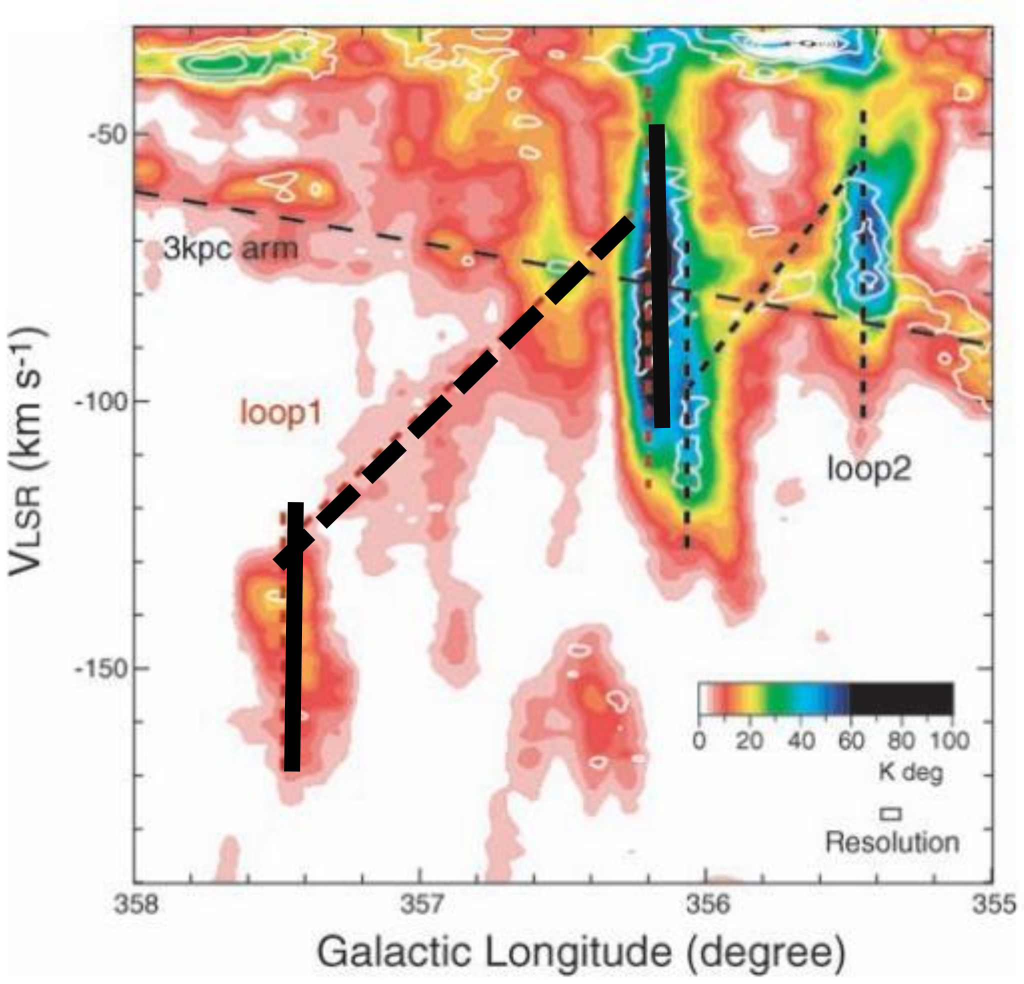
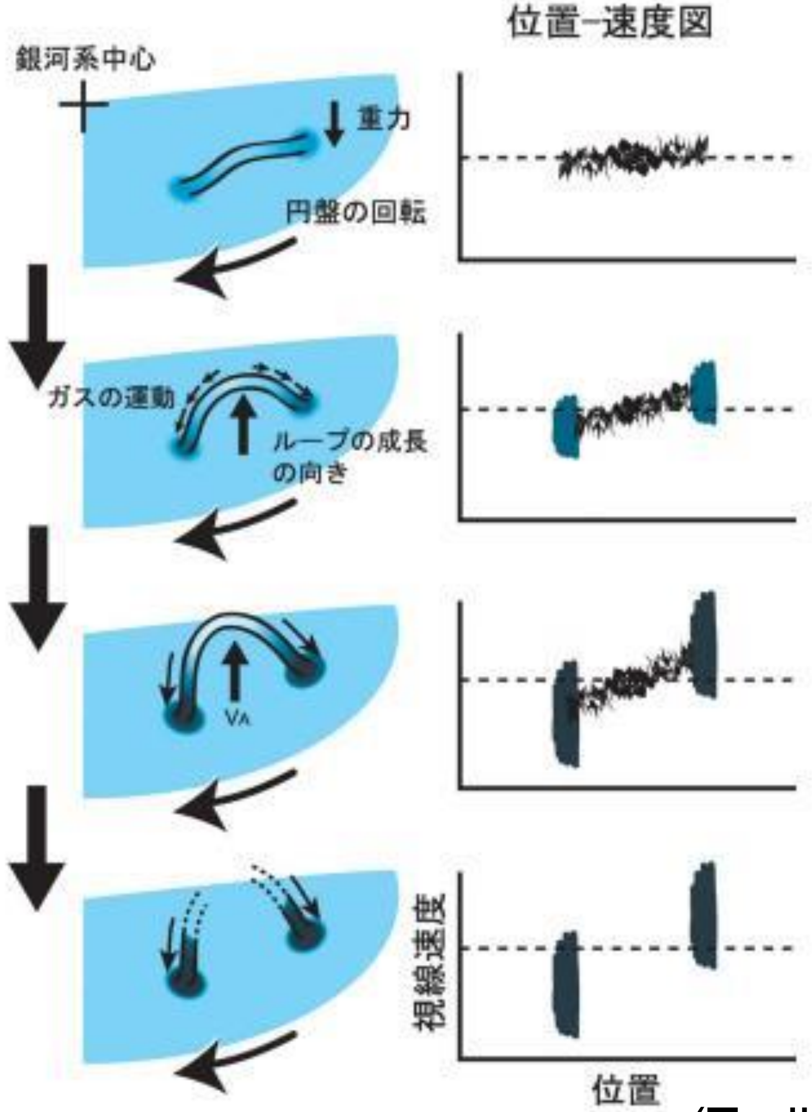


(Fukui et al. 2006)

Parker Instability ?

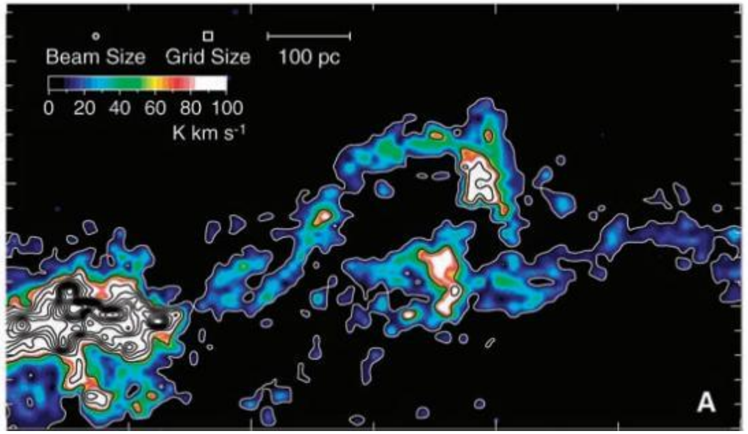


(Fukui et al. 2006)



(Torii et al. 2007)

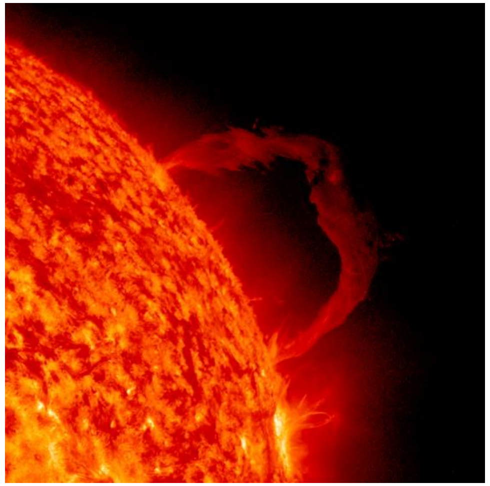
Are Molecular Loops Galactic Prominence ?
(Morris 2006, Torii et al. 2010)



(Fukui et al. 2006)

Molecular loop ~100 K (loop structure)
Interstellar medium ~ 10^4 K (surrounding)

Cold and dense loop structure exists in high temperature and low density environment

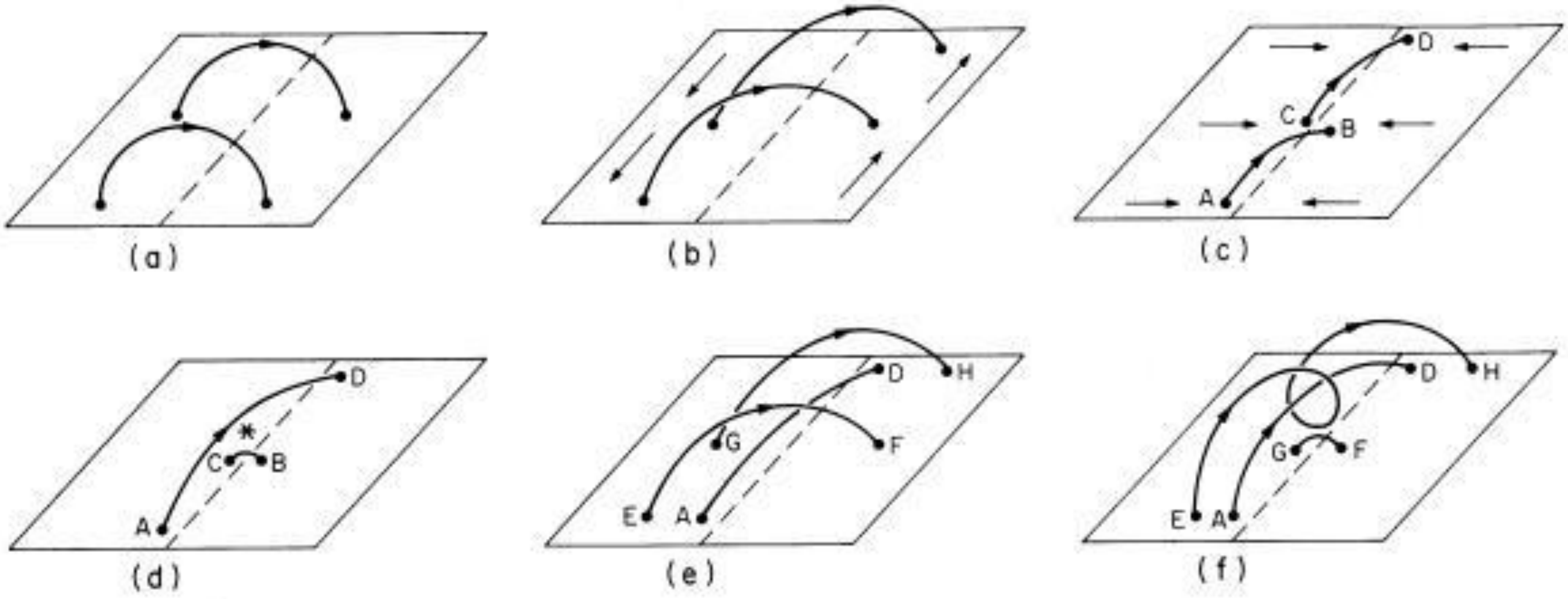


(NASA/SDO 2013)

Solar Prominence ~ 10^4 K (loop structure)
Corona ~ 10^6 K (surrounding)

KR Model

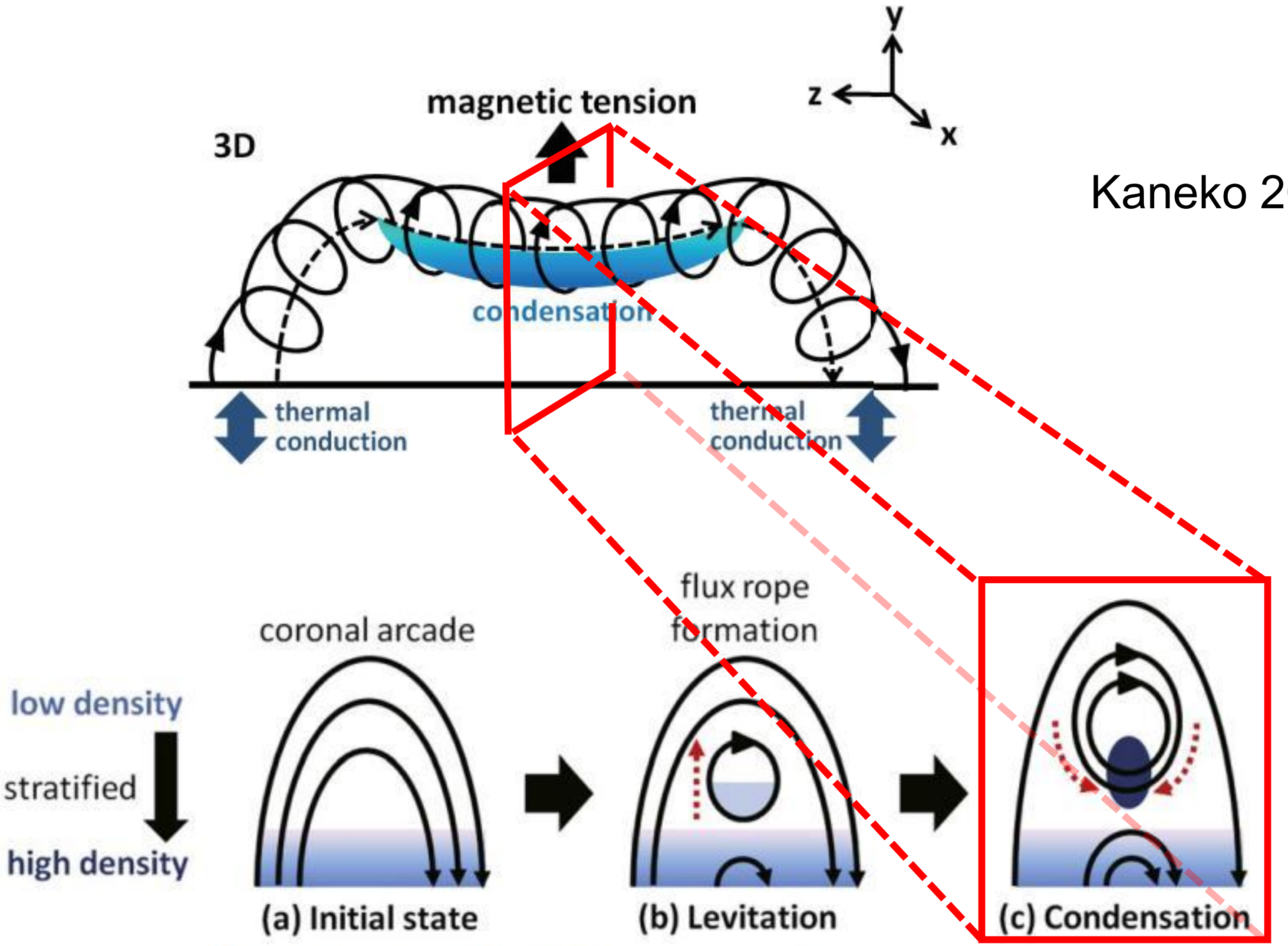
(Kuperus & Raadu 1974)



van Ballegooijen and Martens 1989

Reconnection–Condensation Model

(Kaneko & Yokoyama 2015, 2017)



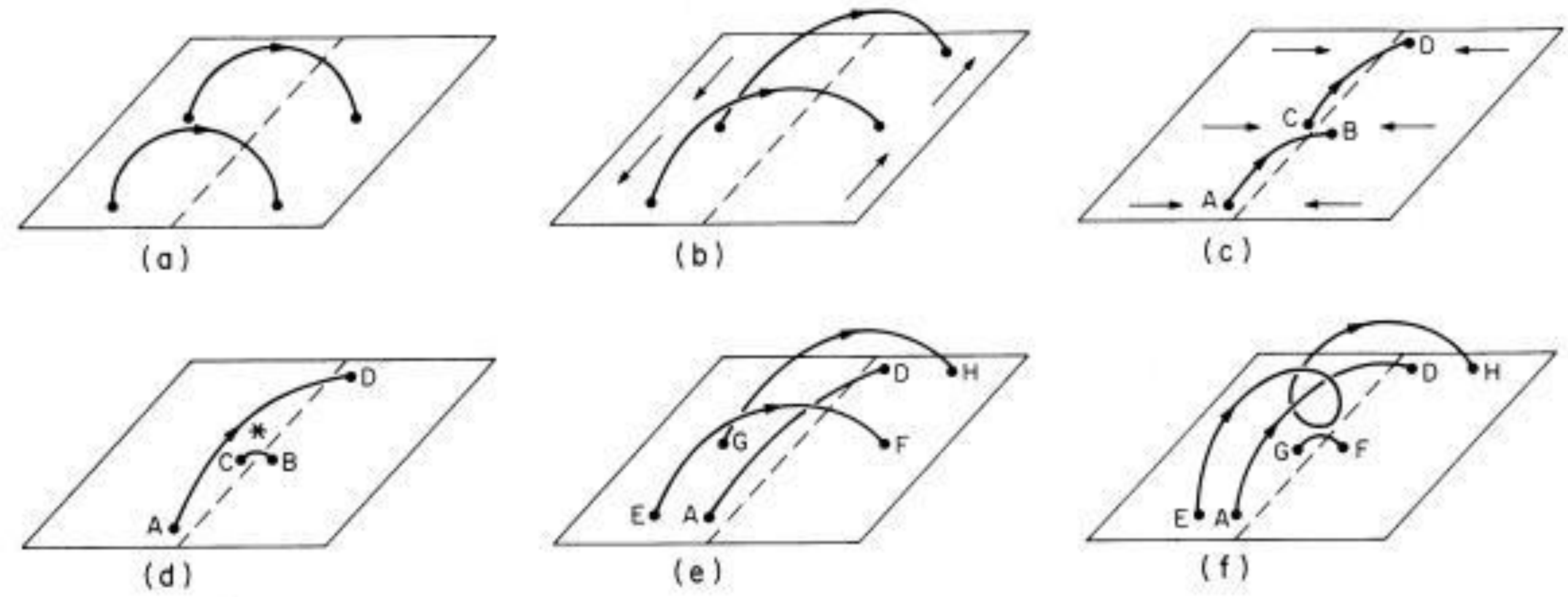
Kaneko 2014

Kaneko & Yokoyama 2015

Figure 1. Schematic of a possible process of in situ radiative condensation.

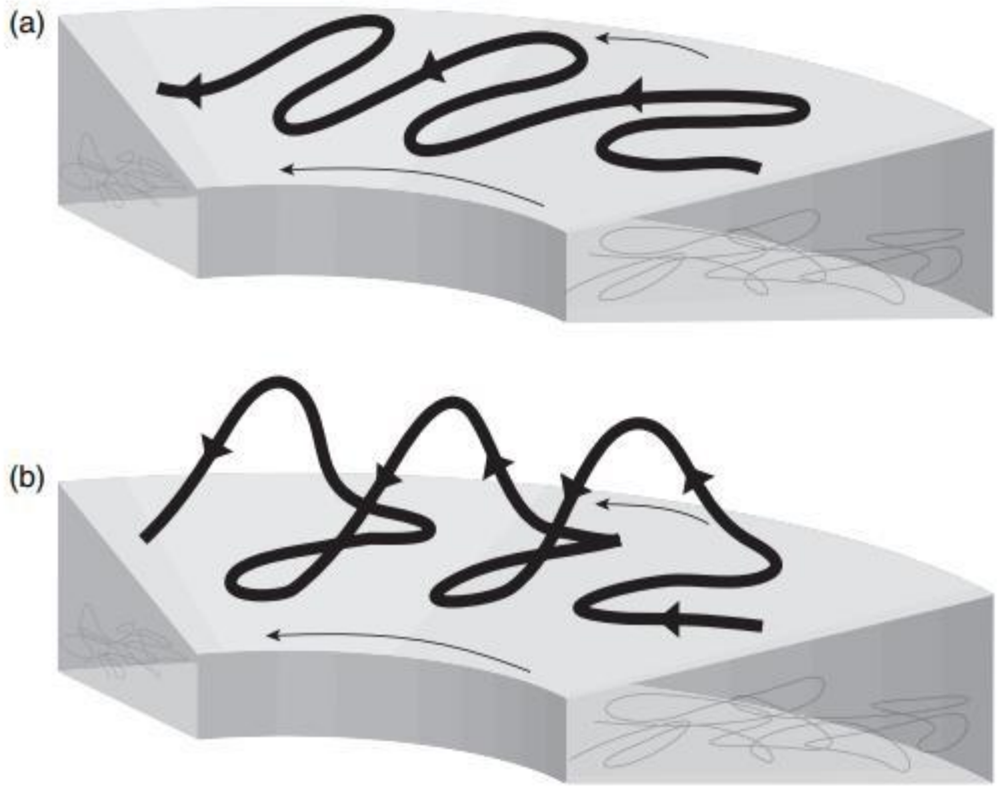
KR Model

(Kuperus & Raadu 1974)

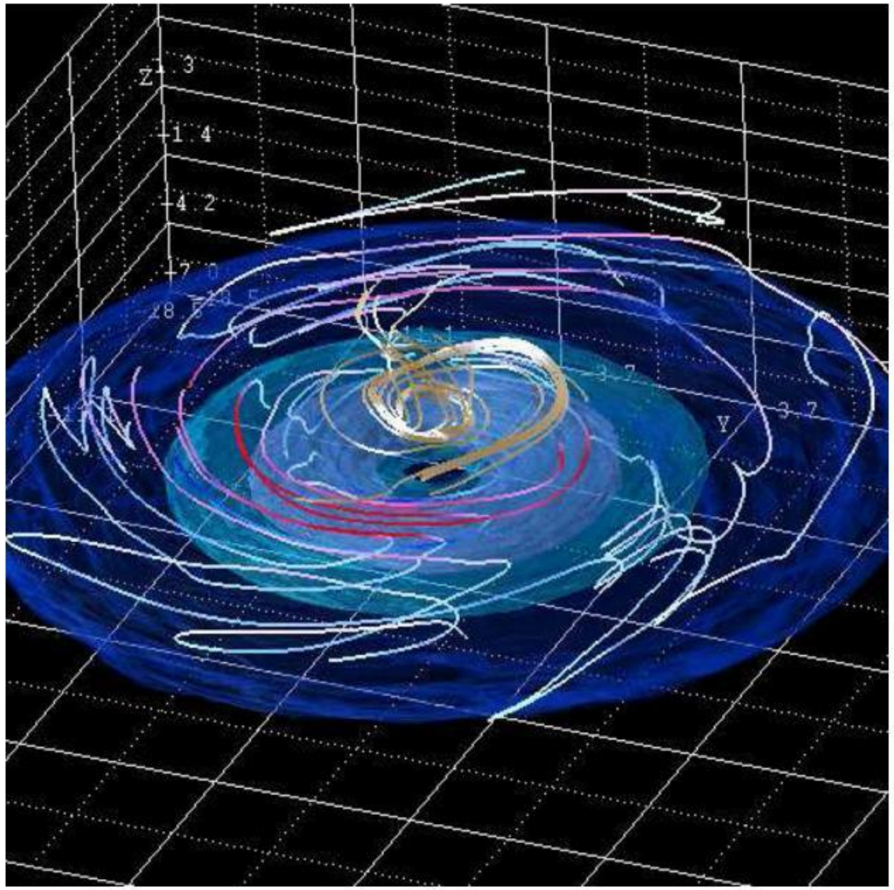


van Ballegooijen and Martens 1989

Magnetic arcade and Foot Point Motion in Galactic Disk



Schematic drawing of the mechanism of the MHD dynamo.

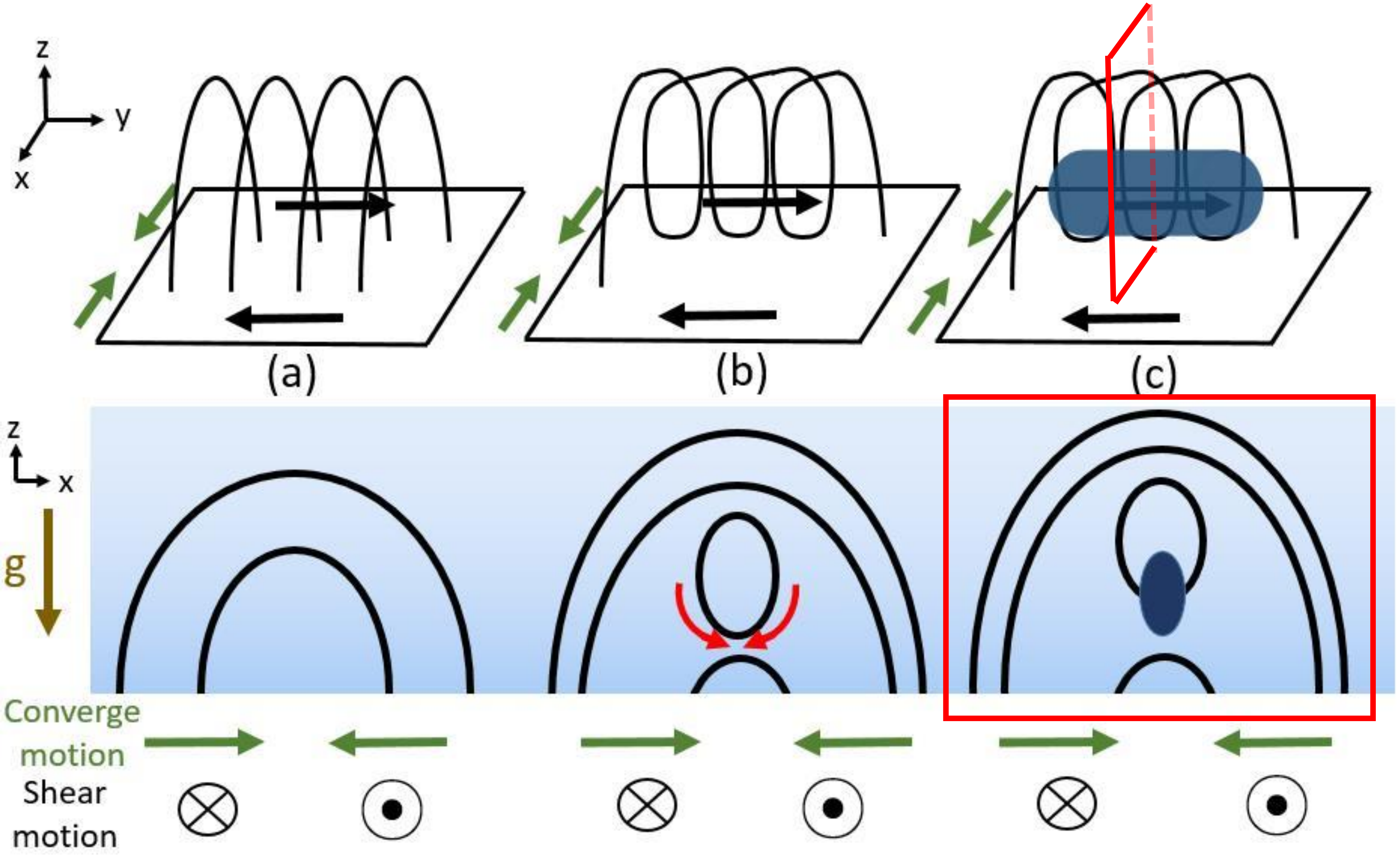


Machida et al. 2013

Aim :

Apply solar prominence model to explain molecular loops in the Galactic central region

2D Simulation Model (Peng & Matsumoto 2017)



2D Simulation Model (Peng & Matsumoto 2017)

z(pc)

$$B_x = -\left(\frac{2L_a}{\pi H_m}\right) B_a \cos\left(\frac{\pi}{2L_a}x\right) \exp\left(-\frac{z}{H_m}\right)$$

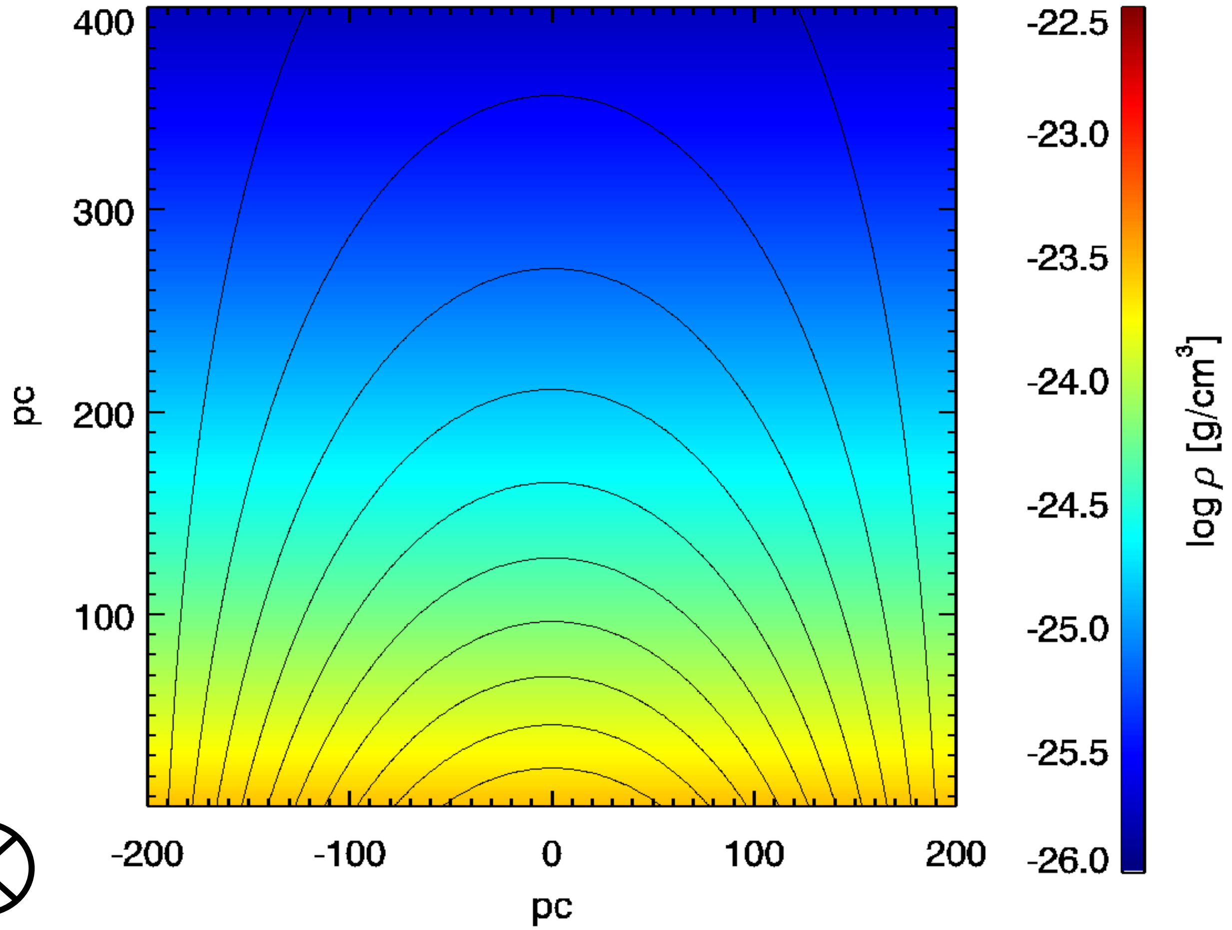
$$B_y = \sqrt{1-\left(\frac{2L_a}{\pi H_m}\right)^2} B_a \cos\left(\frac{\pi}{2L_a}x\right) \exp\left(-\frac{z}{H_m}\right)$$

$$B_z = B_a \sin\left(\frac{\pi}{2L_a}x\right) \exp\left(-\frac{z}{H_m}\right)$$

B_a = 1.54 x 10^{-5} G (β_{bottom} = 0.2)

L_a = 200 pc (half width of magnetic arch)

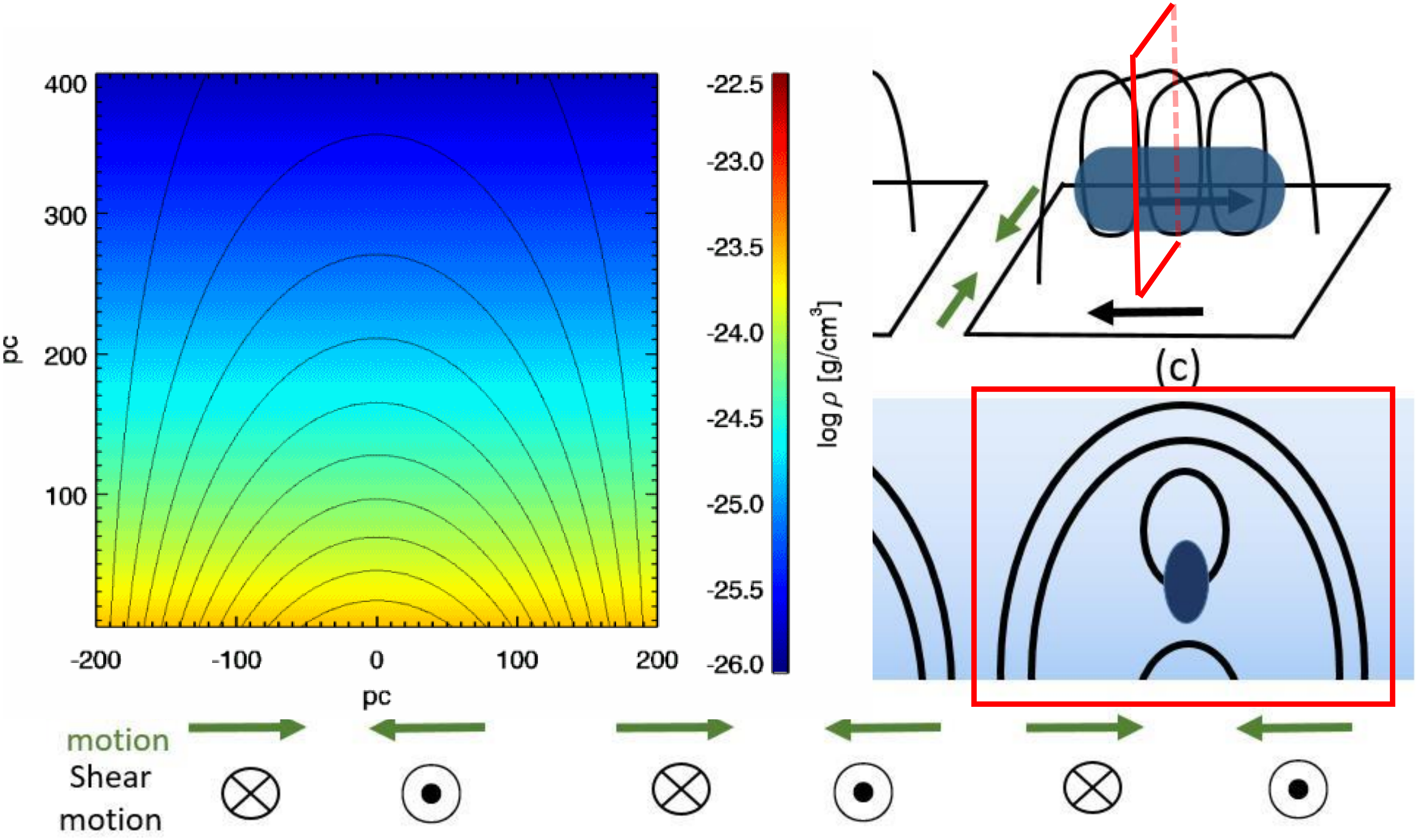
H_m = 200 pc (magnetic scale height)



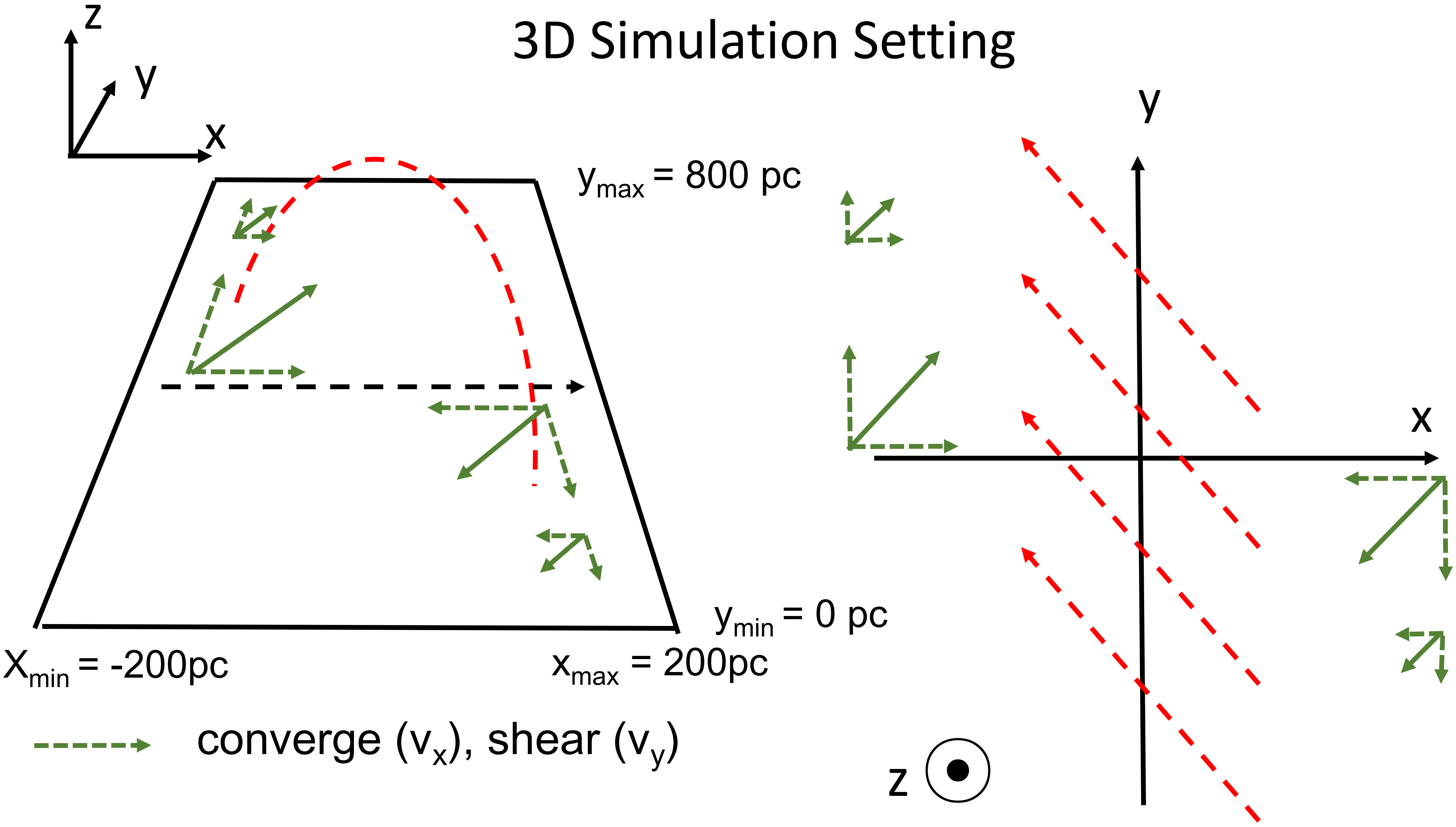
y $\otimes$

x(pc)

2D Simulation Model (Peng & Matsumoto 2017)



3D Simulation Setting



Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla P - \rho \boldsymbol{g} + \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi}$$

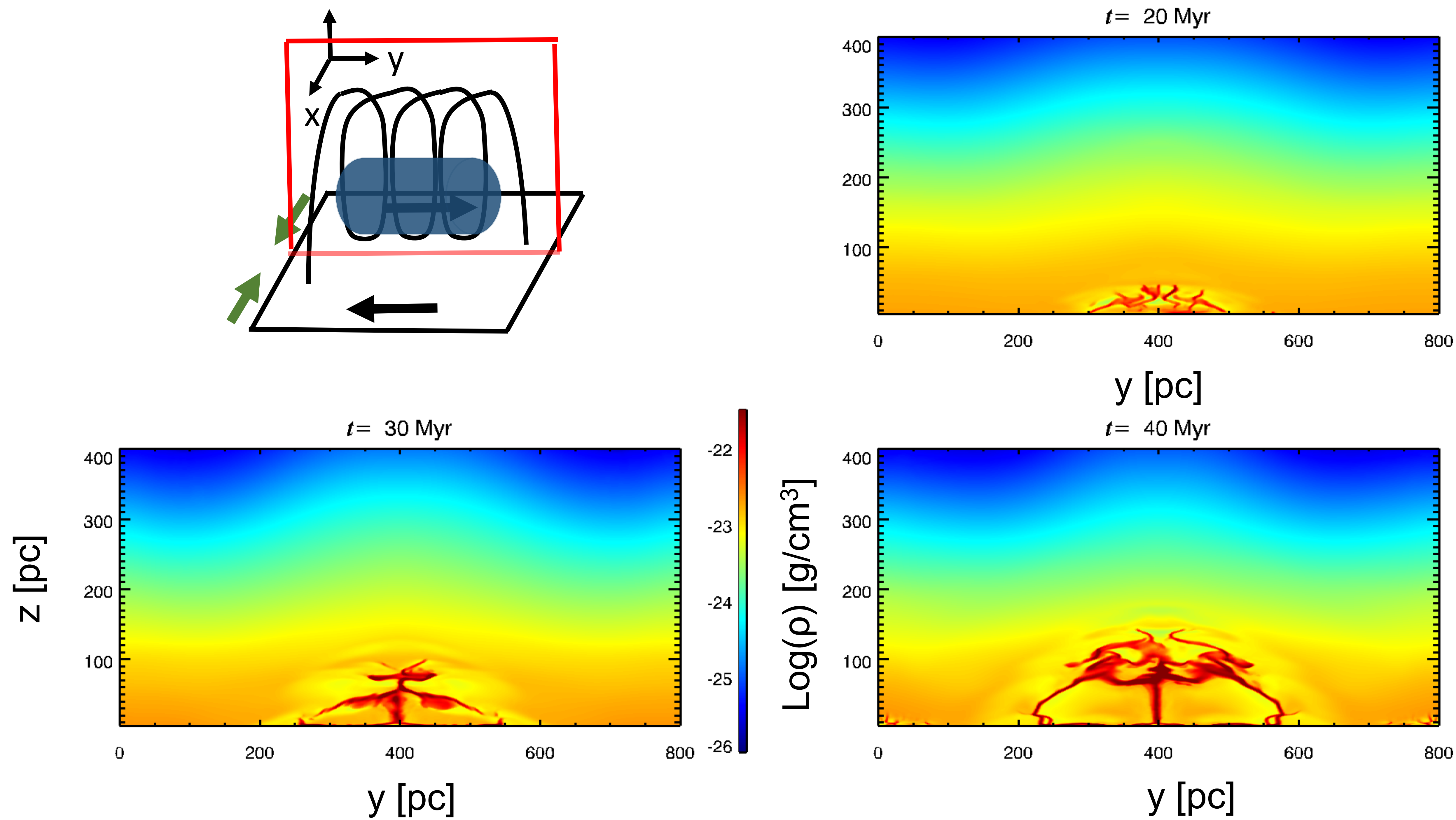
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B} - \eta \nabla \times \boldsymbol{B})$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{B^2}{8\pi} \right) \boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v}) - \eta (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi} \right] = \rho \boldsymbol{v} \cdot \boldsymbol{g} - \rho \mathcal{L}$$

$$E = \frac{P}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{8\pi}$$

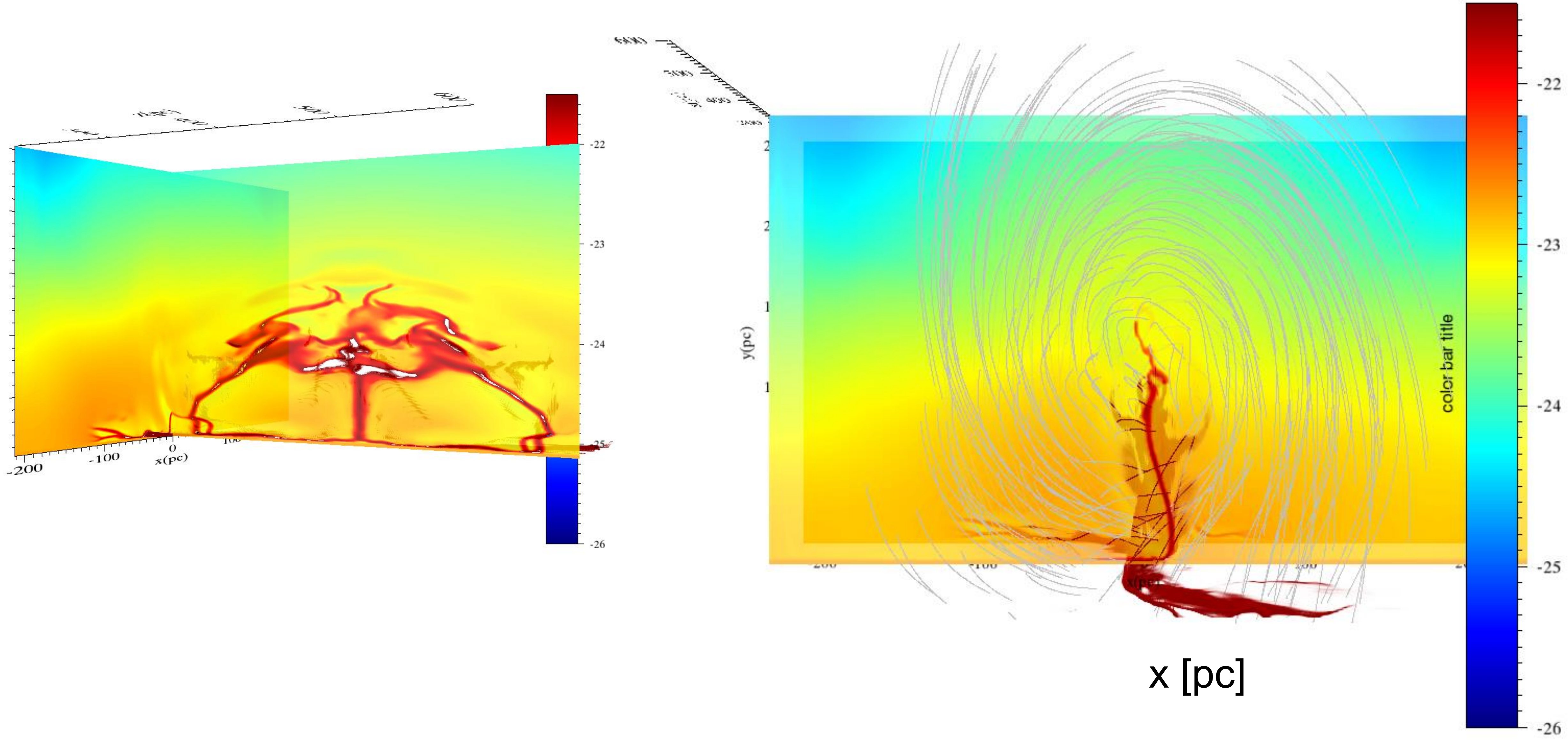
$$\eta = \begin{cases} 0 & J < J_c \\ \eta_0 (J/J_c - 1)^2 & J \geq J_c \end{cases}$$

Anomalous resistivity
(The same form with Kaneko & Yokoyama et al. 2015)
$\eta_0 = 3 \times 10^{23}$ cm^2 s^{-1}
$J_c = 4.0 \times 10^{-17}$ dyn$^{1/2}$ cm s^{-1}

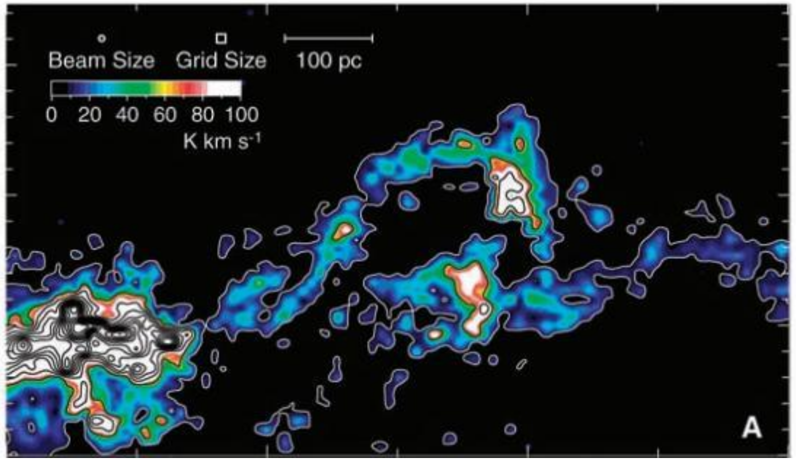


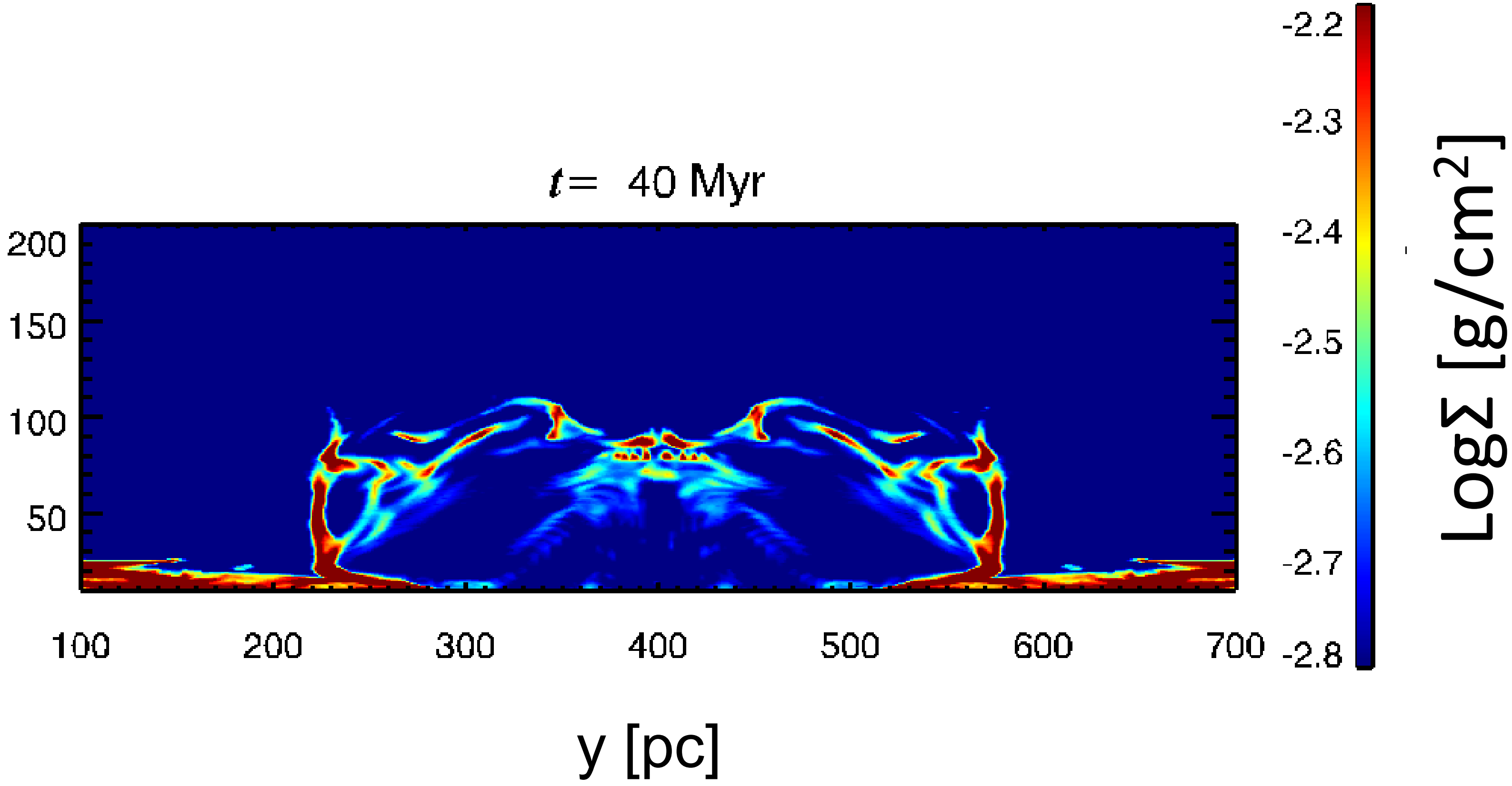
y
x
t= 20 Myr
400
300
200
100
0
200
400
600
800
y [pc]
t= 30 Myr
z [pc]
-22
-23
-24
-25
-26
Log(ρ) [g/cm3]
t= 40 Myr

Flux rope

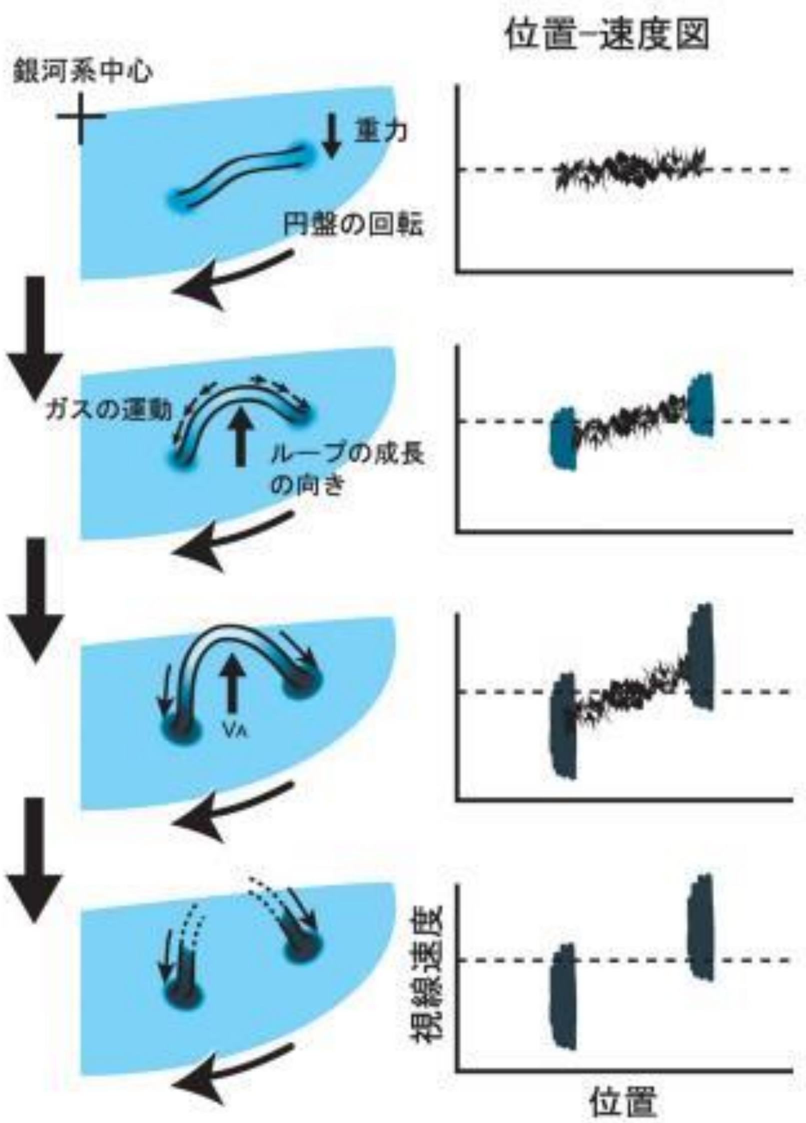


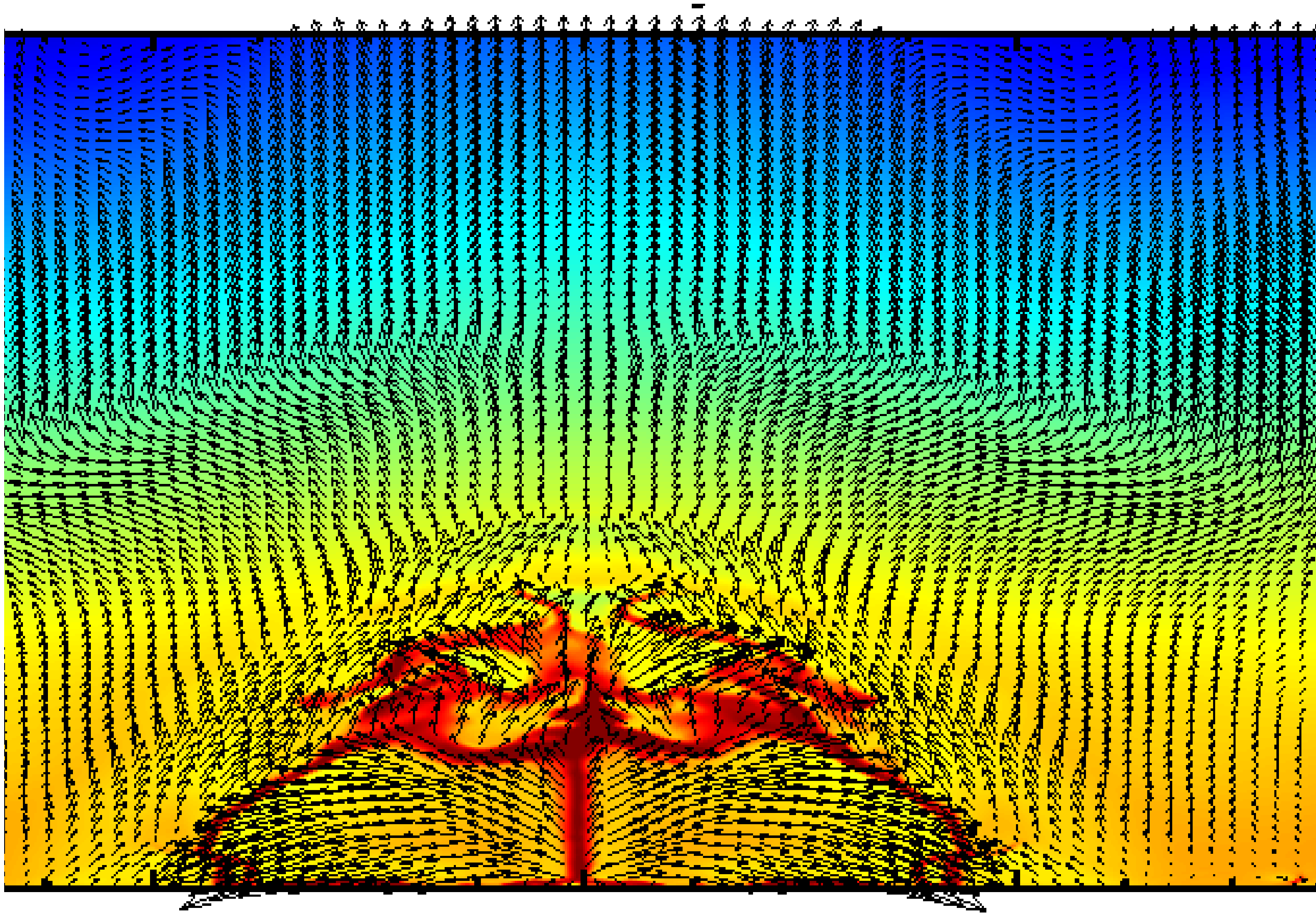
Column Density in x-direction



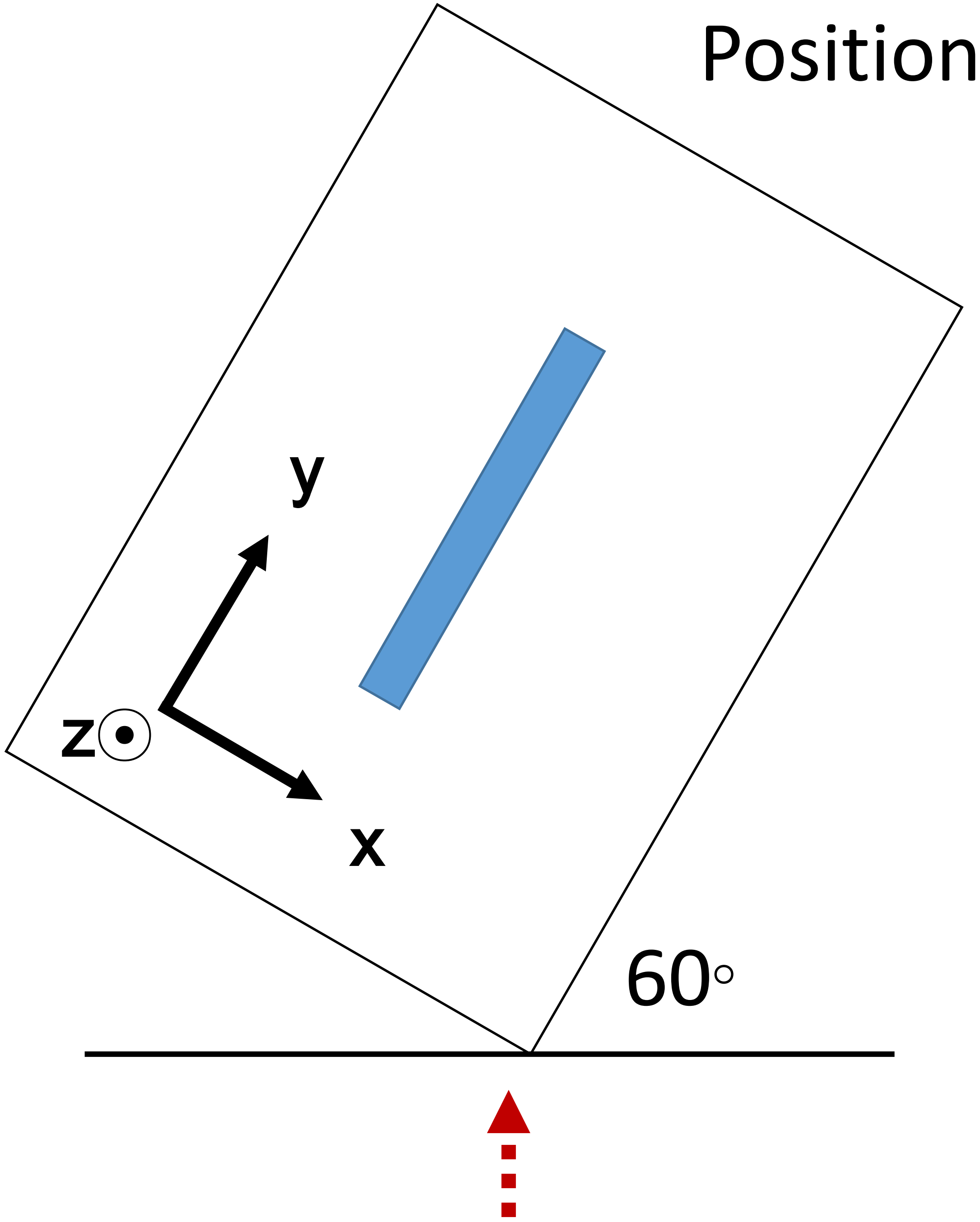


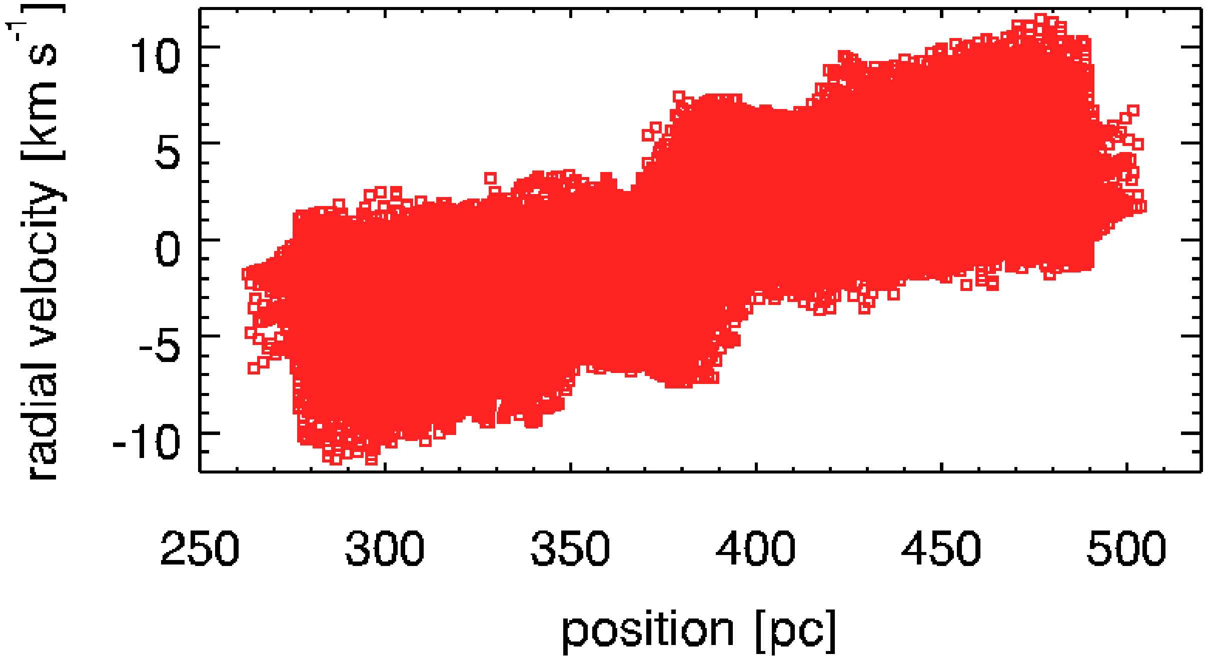
Velocity along the loop





Position-Velocity Diagram





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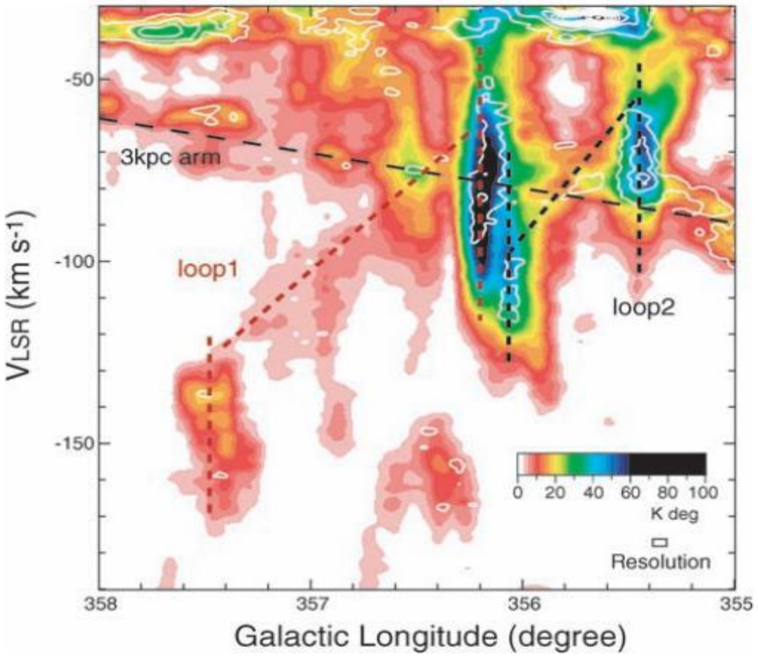

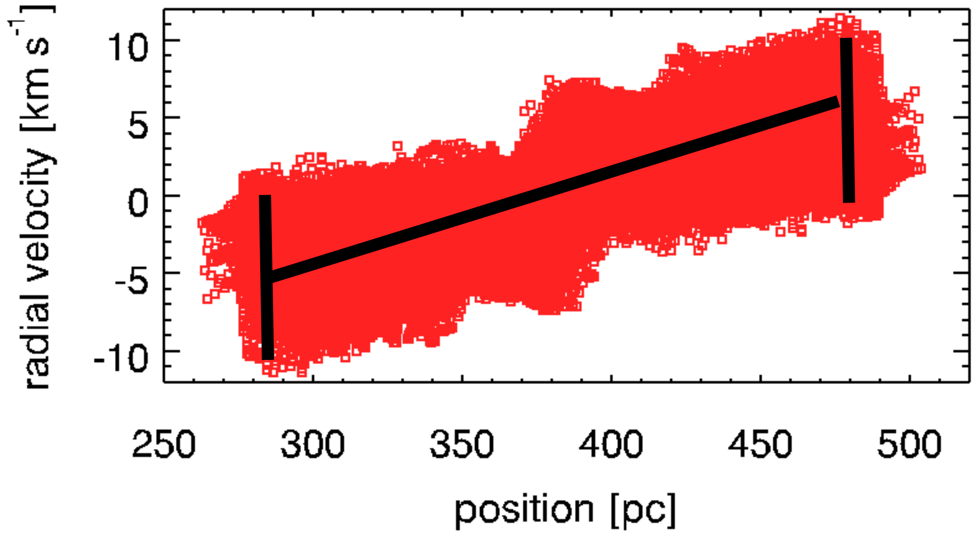

Velocity gradient along loop

Observation : 50~80 km/s

Simulation : ~10 km/s

Velocity dispersion at foot point

Observation : ~50 km/s

Simulation : ~15 km/s

Total mass of molecular loop

Loop1 : 1.6 x 10^6 M_{solar} (Torii et al. 2010)

Loop2 : 1.9 x 10^6 M_{solar} (Torii et al. 2010)

Simulation : 4 x 10^5 M_{solar}

Summary

We present results of 3D MHD simulations based Kaneko & Yokoyama (2015, 2017) in the scale about few hundred pc to study loop-formation in the GC region.

Magnetic arcades was squeezed by foot point motion and gas around x = 0 pc was squeezed. Thermal instability can be triggered at high density region

The relatively high column density loop structure can be formed by adjusted foots points motion

The p-v diagram shows similar trend with observation. We estimated velocity gradient, velocity dispersion of foot point and total mass of the loop.