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Magnetohydrodynamic Simulations of the Formation of Molecular Clouds in Our Galactic Center

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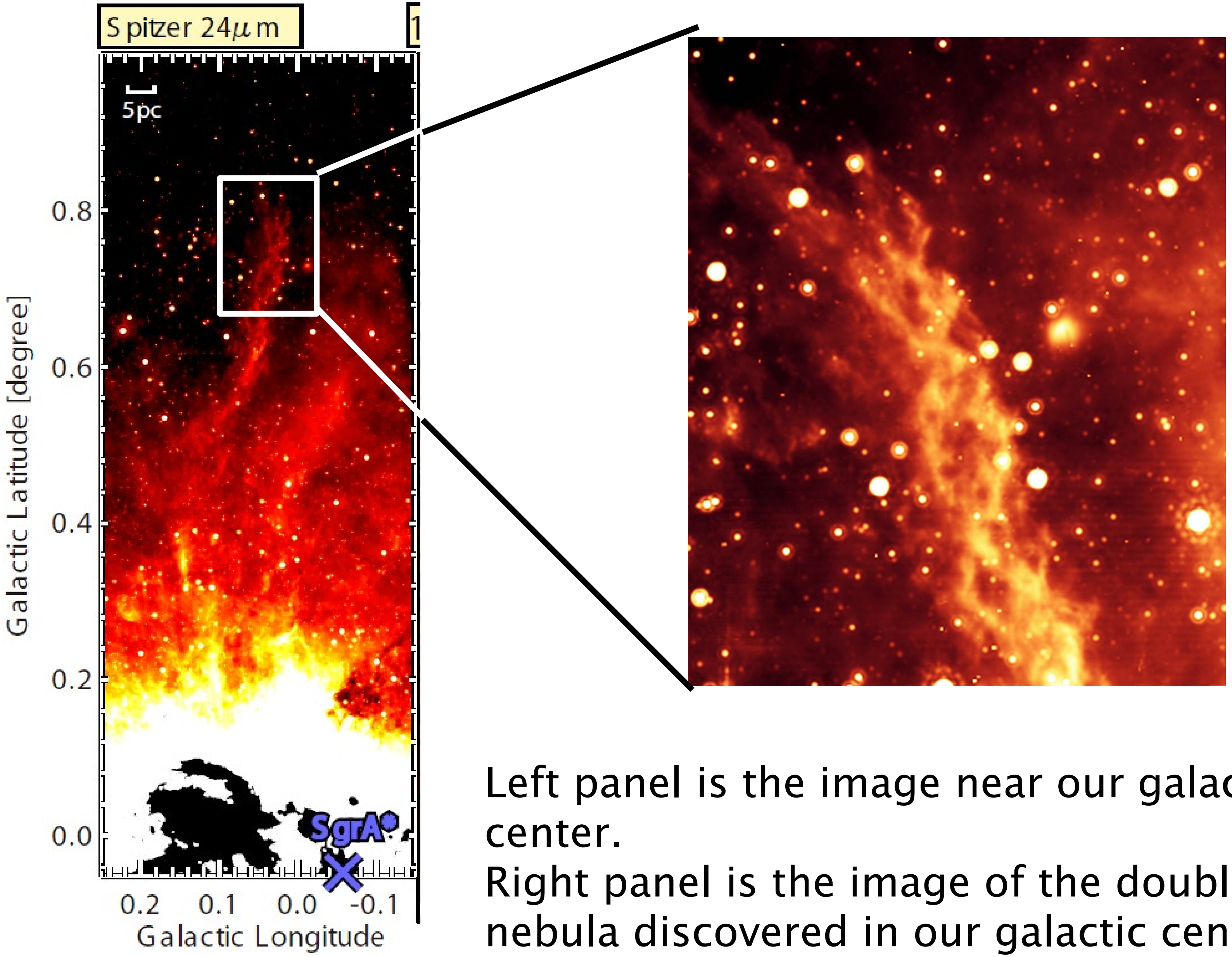
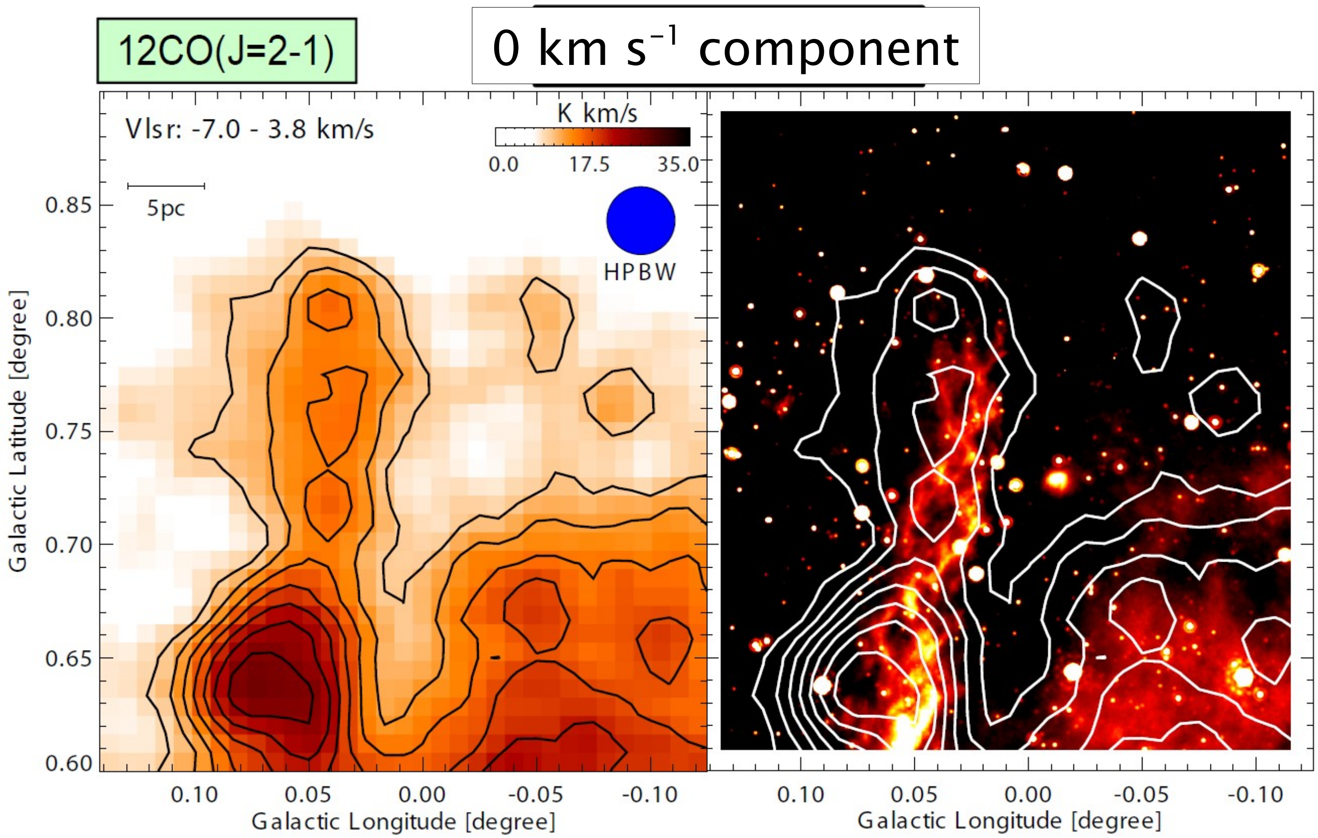
The Double Helix Nebula in Our Galactic Center



Left panel is the image near our galactic center.
Right panel is the image of the double helix nebula discovered in our galactic center.

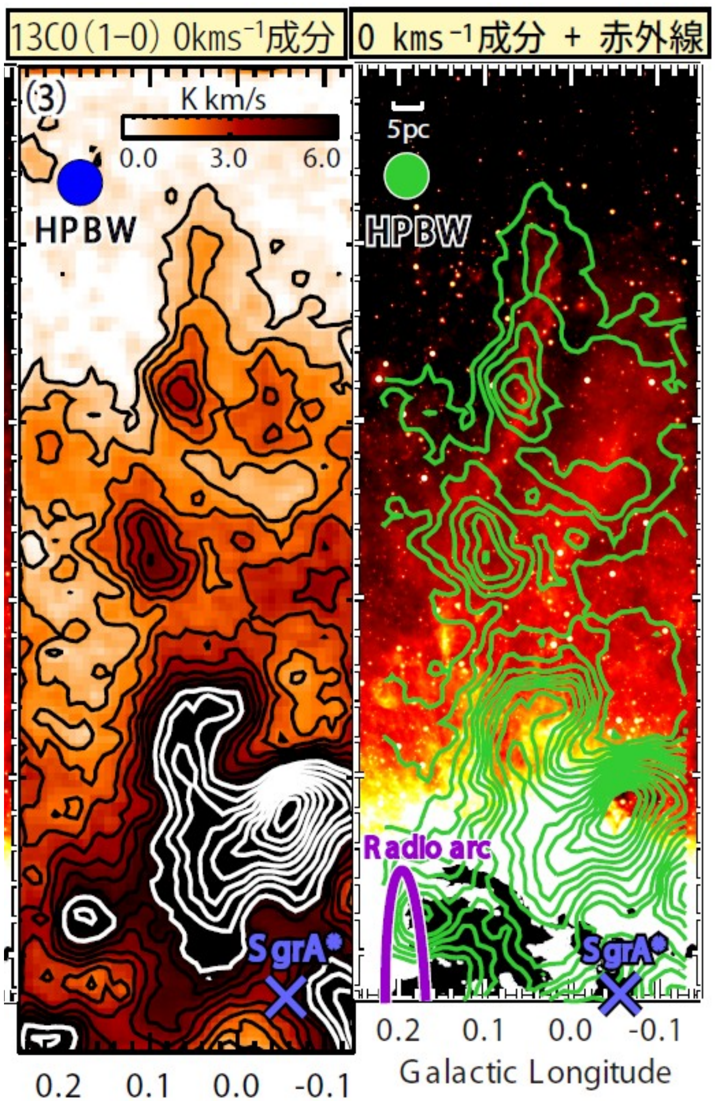
Molecular Clouds Surrounding the Double Helix Nebula (DHN)

NANTEN2 CO observations revealed that two component molecular clouds (line of sight velocity=0km/s, −35km/s) are surrounding the DHN in our galactic center.



Color in left panel and contours in right panel contours show the distribution of CO(J=2−1) integrated intensity. (Enokiya et al. 2012)

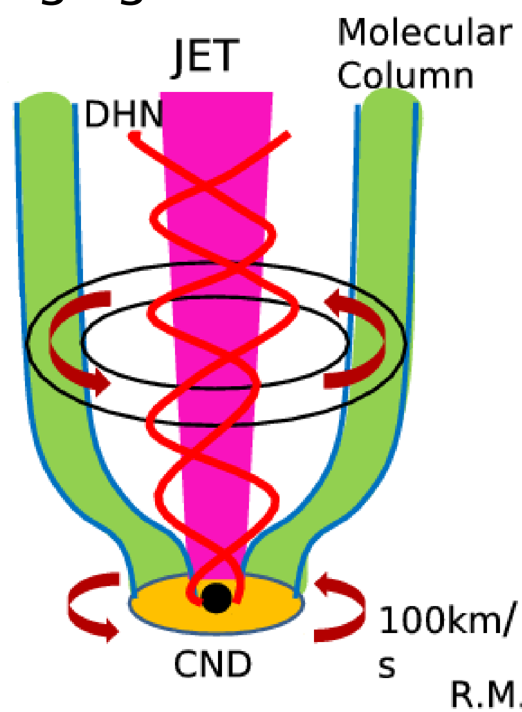
Molecular Column ConnectingDHN and Sgr A*



Enokiya et al. 2012

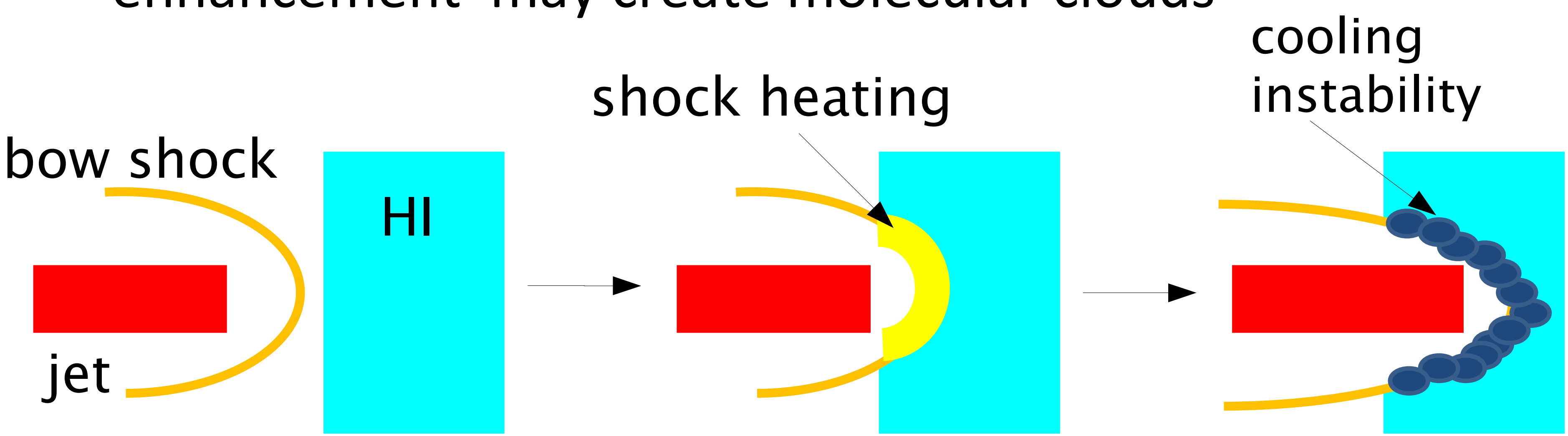
Peaks of the molecular density connect DHN and Sgr A*

Molecular column can be formed either by outflows from circumnulear disk (CND), or by the interaction of the jet ejected from the accretion disk surrounding Sgr A* and ISM



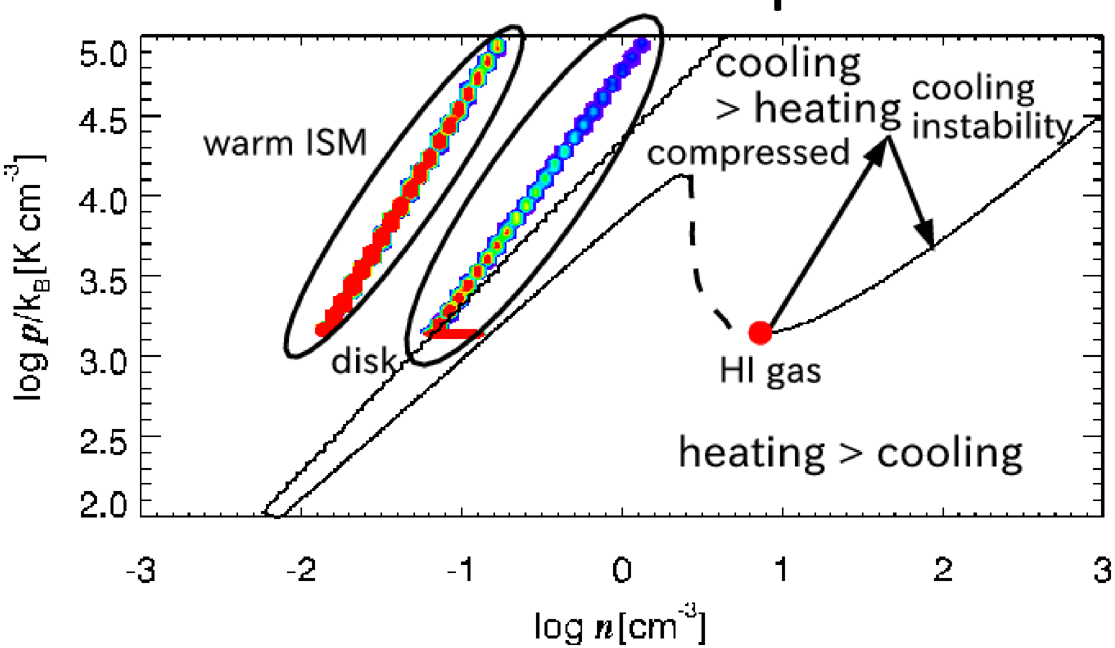
How Can Jet Create Molecular Clouds?

- The neutral hydrogen (HI) cloud is compressed by the bow shock
- The cloud is heated up but since its density increases, cooling rate increases
- Temperature decreases and density further increases
- Cooling instability triggered by the density enhancement may create molecular clouds



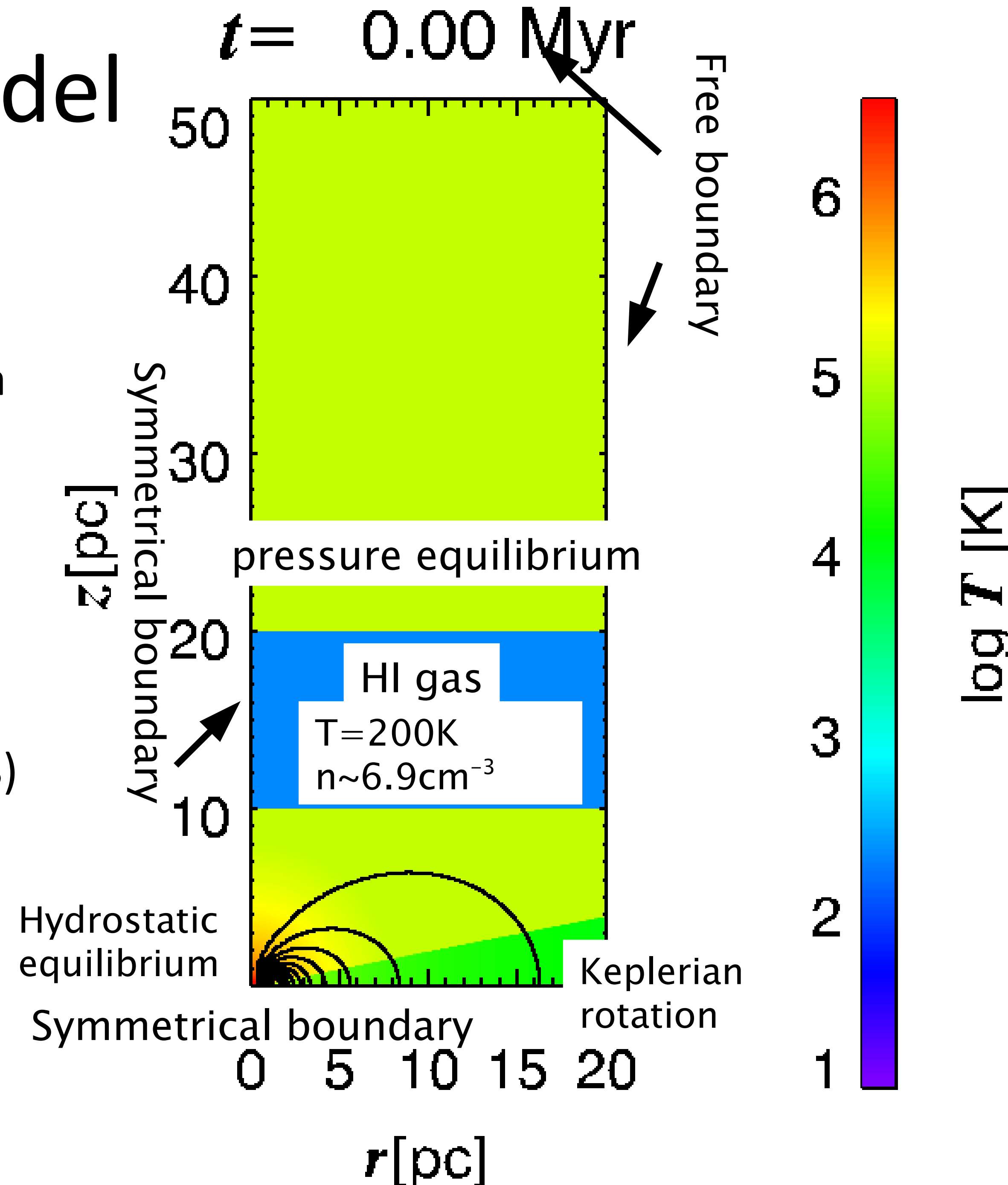
Cooling Function of the ISM

- Use the cooling function considering cosmic ray heating and radiative cooling (Inoue et al. 2006)
- Cooling function $L = -n\Gamma + n^2\Lambda(T)$
- We assumed L=0 when $T>10^4$K
- Black curve shows thermal equilibrium curve

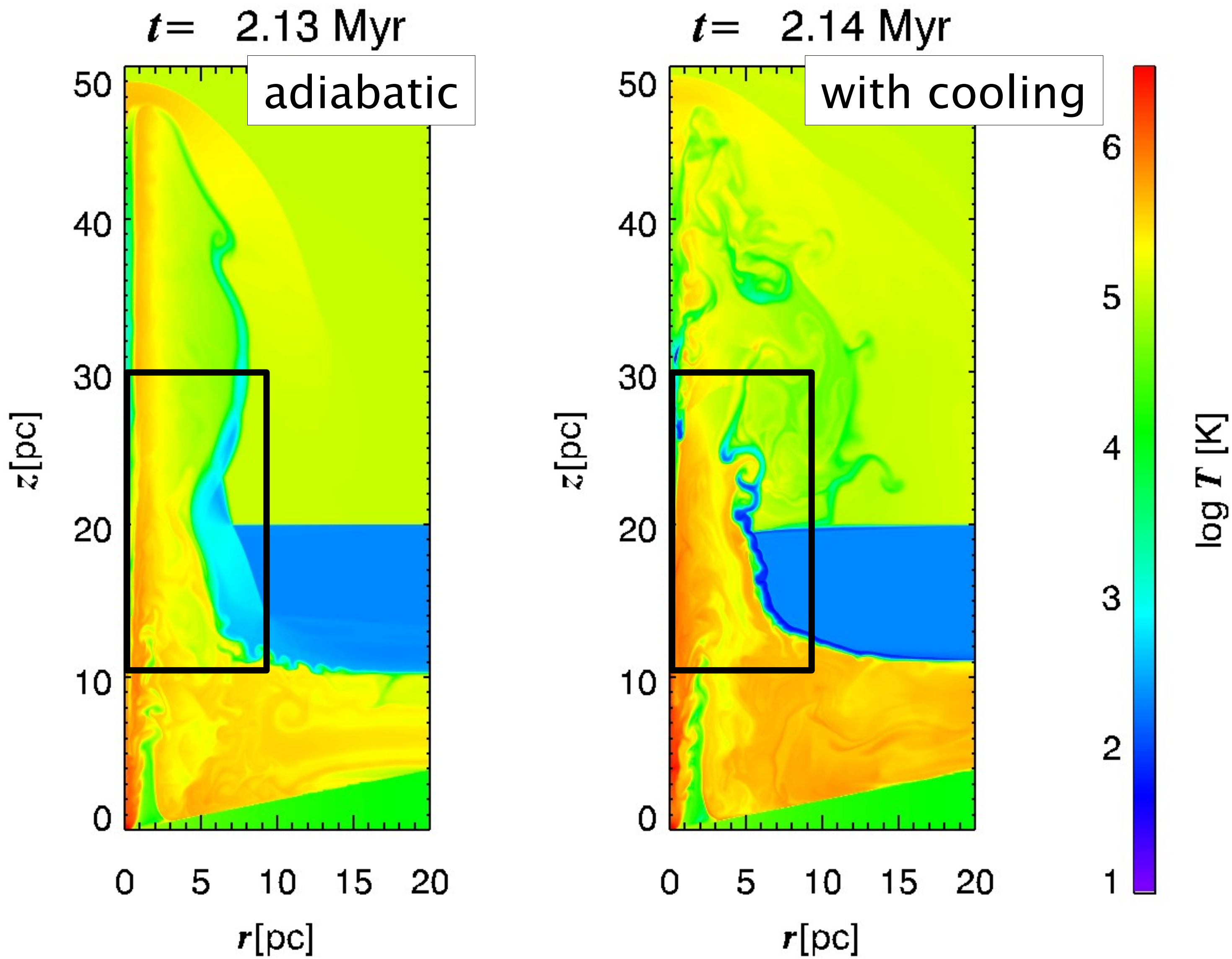


Simulation Model

- Disk inner radius is 0.3pc
- We assumed polytropic relationa $p \propto \rho^{\Gamma}$ in the corona
- Gravitational potential
  $\Phi = -4.4\times10^{6} GM_{s}/R$
  (R<8pc), Φ=const (R>8pc)
- We assumed dipole magnetic loops threading the disk (Mikami et al. 2008)
- 2D cylindrical coordinate (r,z) ,HLLD scheme (Miyoshi & Kusano 2005)
- Mesh (N_r,N_z)=(400,920)

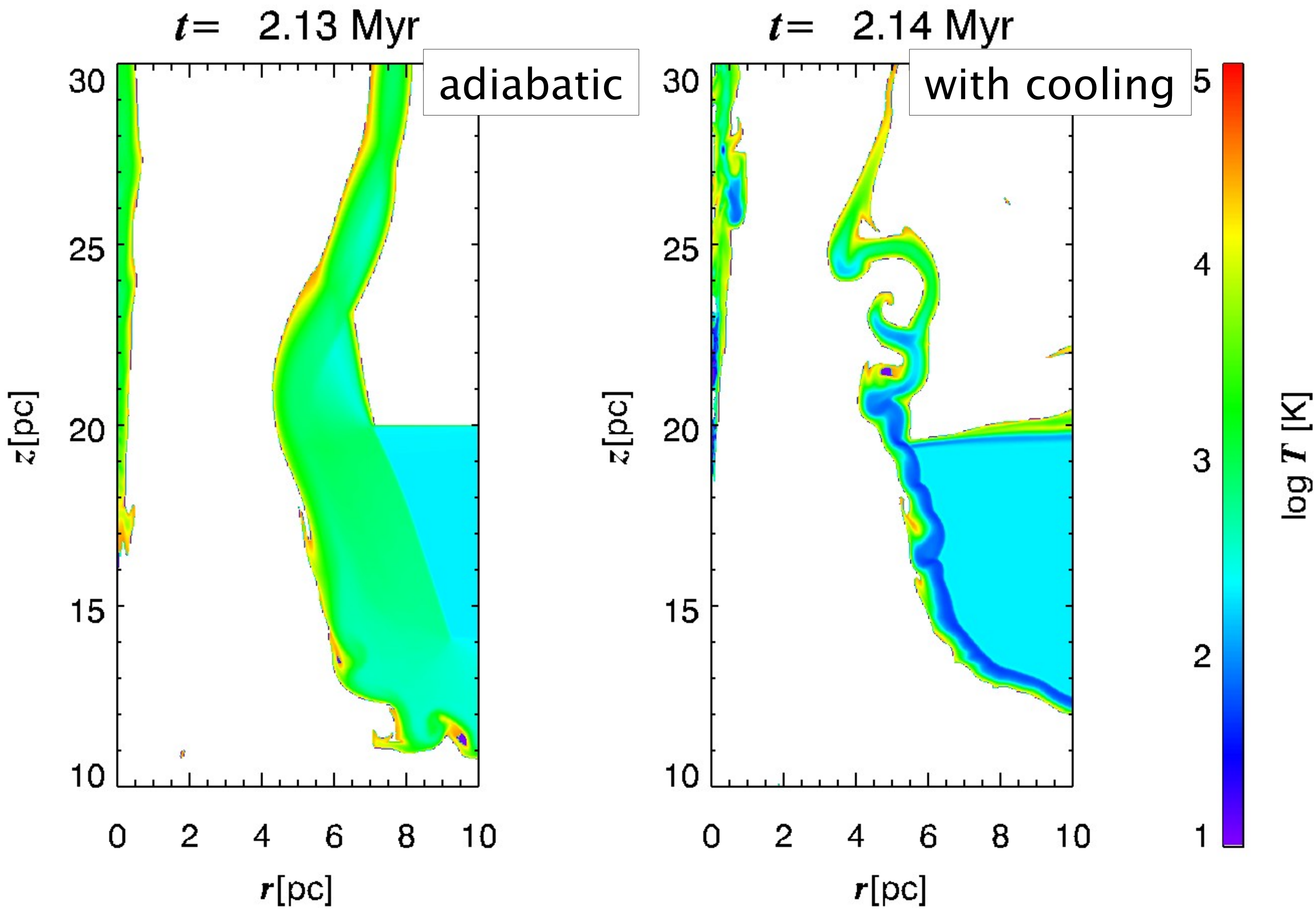


Formation of Magnetic Tower



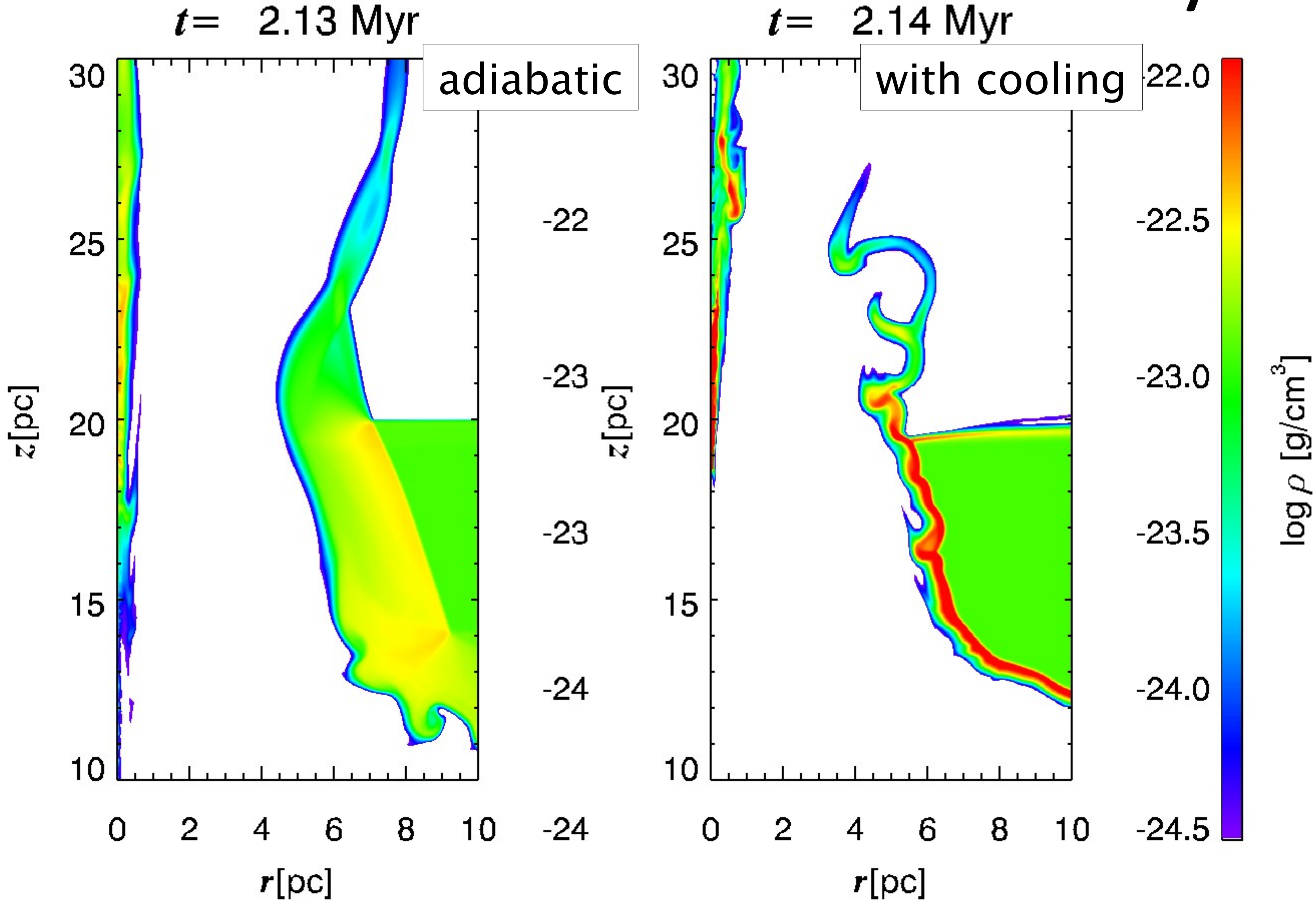
A hot jet formed by twisting the magnetic loops.
Its speed is comparable to the rotation speed at the footpoints of the jet

HI gas cooled down by cooling



HI gas is heated up but subsequently cooled down to T~50K

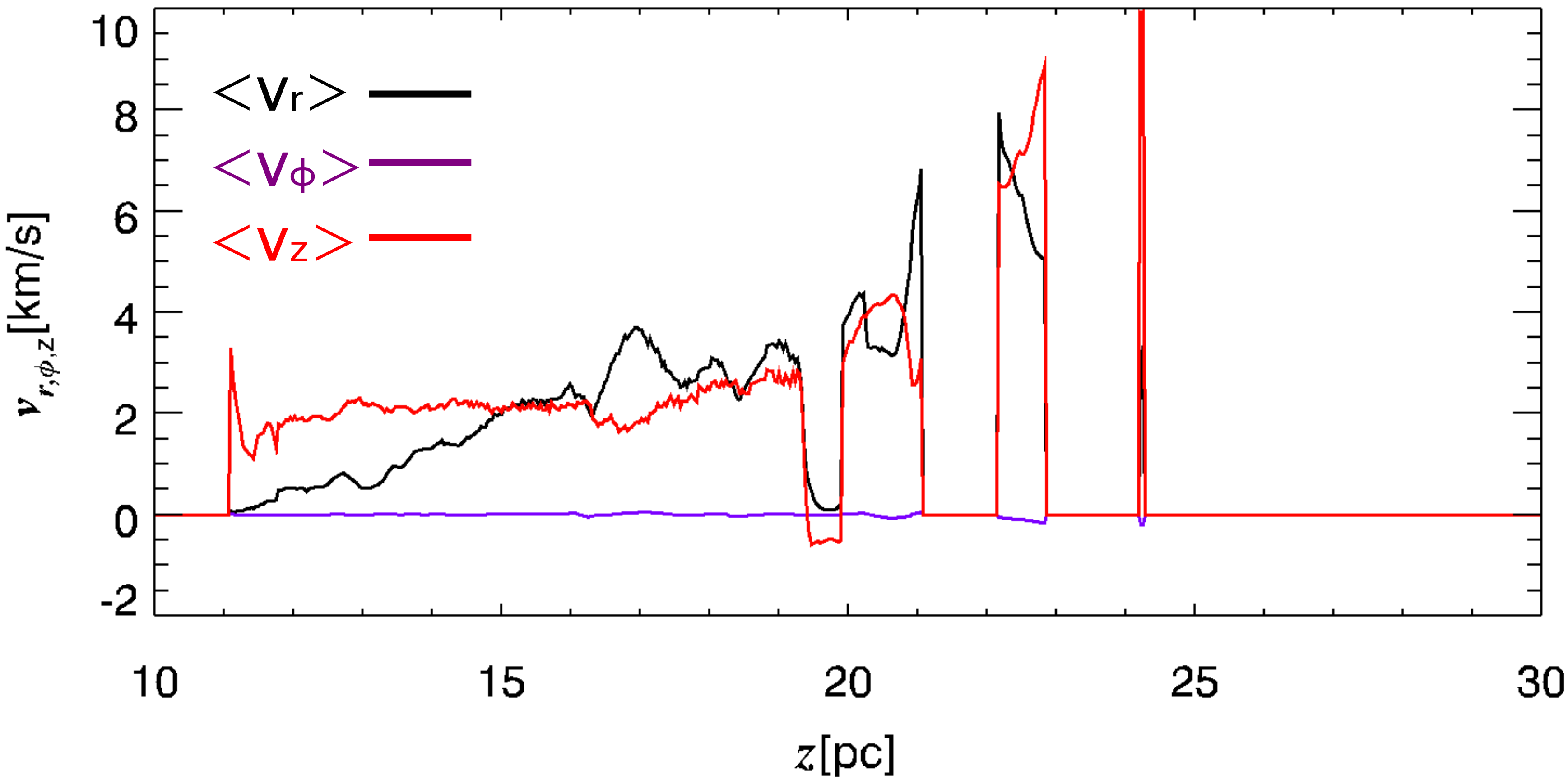
Enhancement of the Density



In adiabatic simulations, the number density increases up to 10.
On the other hand, in simulations with cooling,
the number density increases up to n~100.

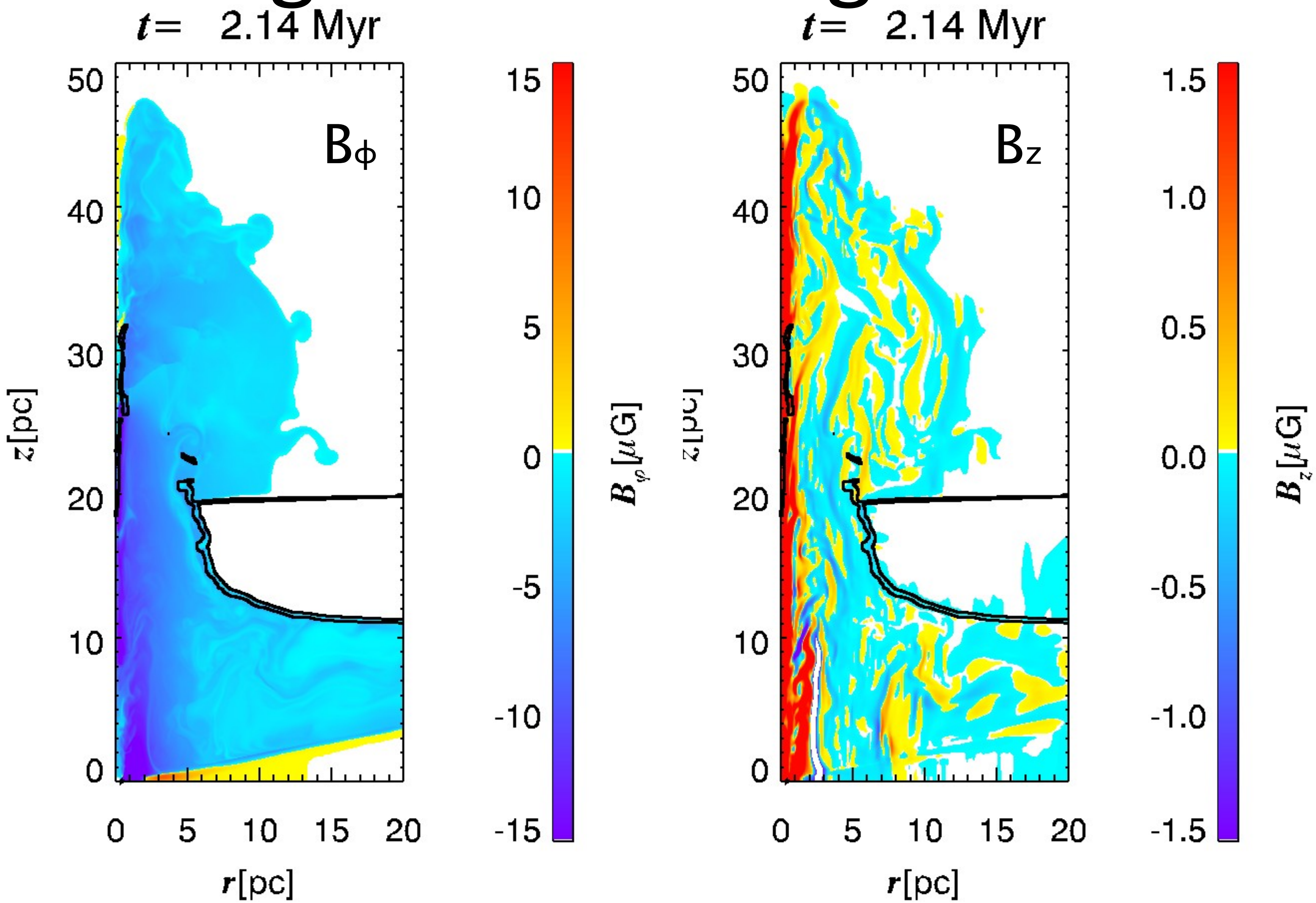
Velocity Distribution in the Cold Dense Region

The mean velocity of the region where $n > 10\mathrm{cm}^{-3}$



The rotation speed of the dense gas is much smaller than the radial and vertical velocity.
The velocity along the rotation axis is comparable to the radial velocity.

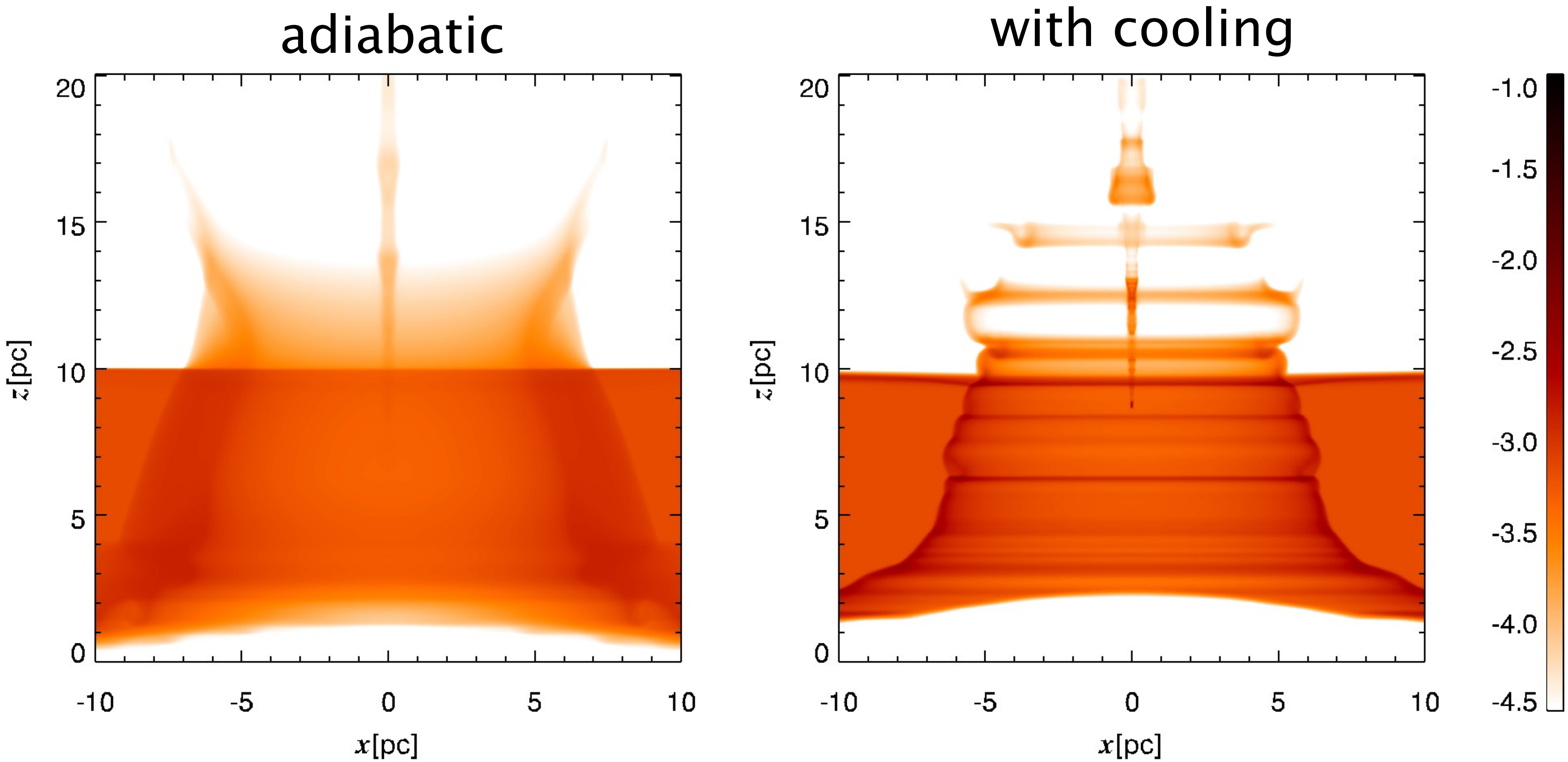
Strong Toroidal Magnetic Field



The toroidal magnetic field generated by twisting the magnetic loops is ten times stronger than B_z.

The region where B_z is positive grows along the z direction.

Comparison of the Column Density



The column density is high off the jet axis
adiabatic → smooth and faint distribution
cooling → sharp distribution and
higher than the column density in adiabatic simulations

Summary

- We carried out 2D axisymmetric MHD simulations with cooling of the interaction of the magnetic tower jet with the interstellar gas
- The cold dense column is formed around the magnetic tower jet
- The rotation speed of the dense gas is much smaller than that of the jet and its velocity along the rotation axis is comparable to its speed with the radial direction