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Magnetohydrodynamic Simulations of the Formation of Molecular Clouds toward the Star Cluster Westerlund2

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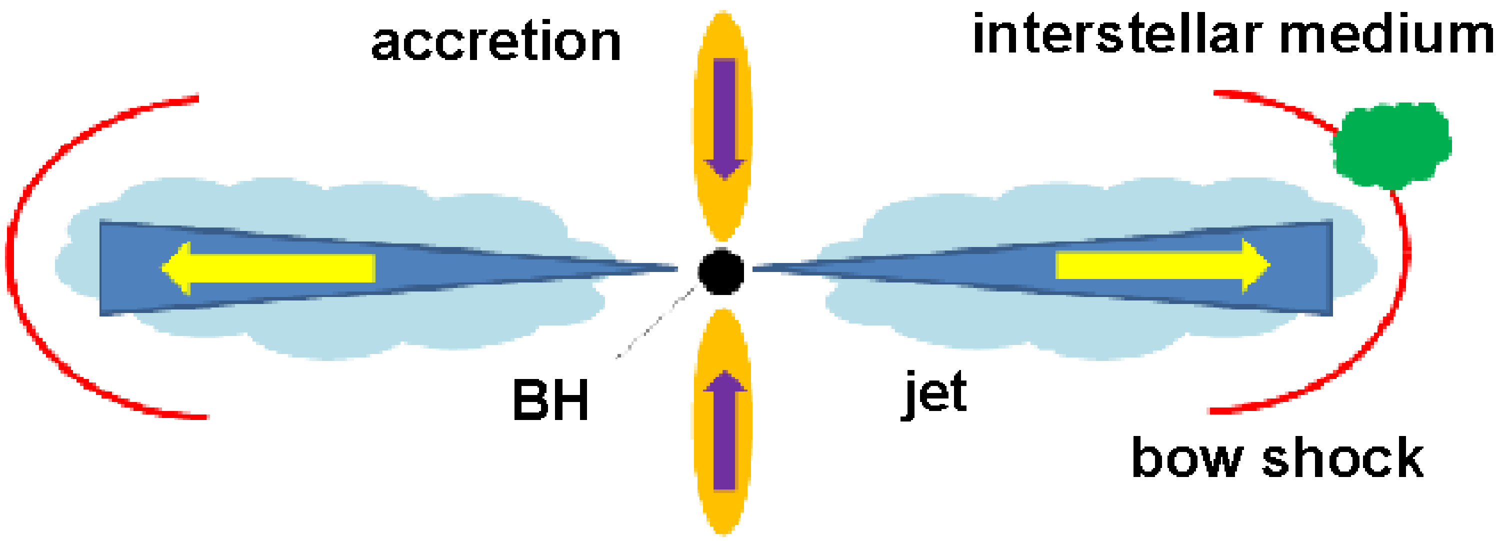
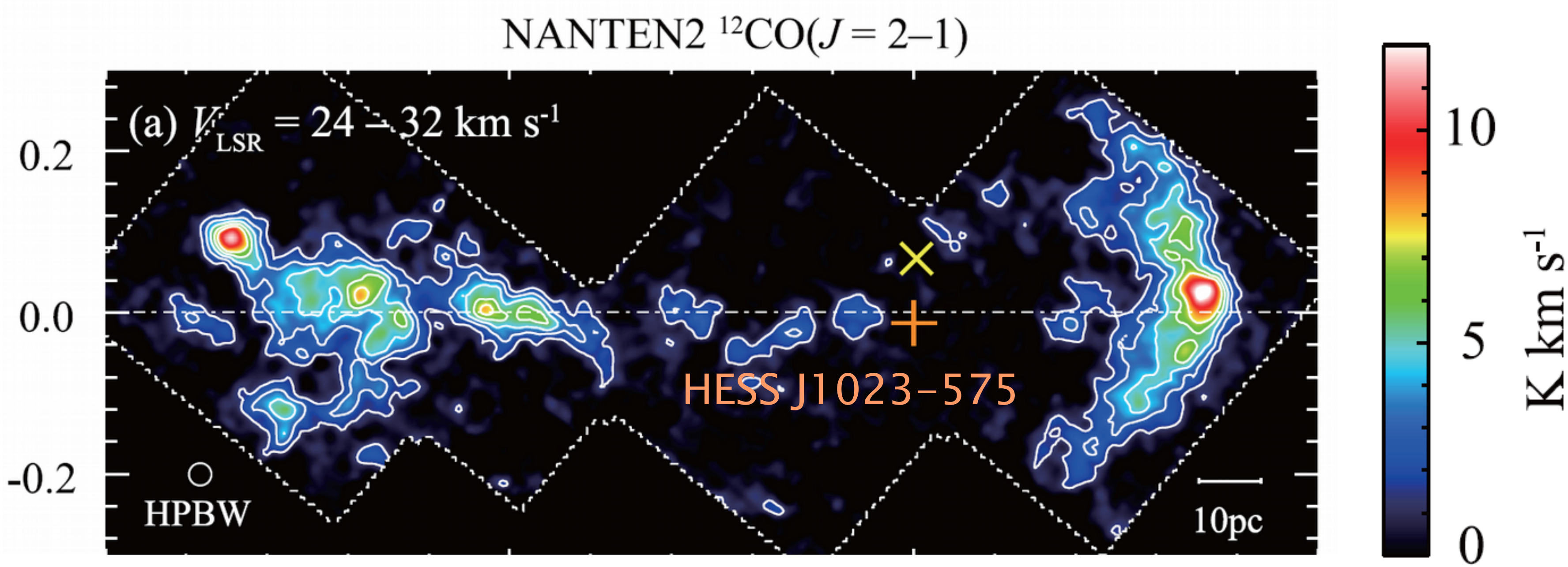
Interaction of a Micro-quasar Jet with Interstellar Medium



- Jet transport the energy released near the black hole to the distant region
- Interstellar medium is affected by the propagation of the jet

Observations of Molecular Clouds

Molecular clouds toward the stellar cluster Westerlund 2 and the TeV γ-ray source HESS J1023−575 are observed by the NANTEN2 and Mopra telescopes (Furukawa et al. 2014).

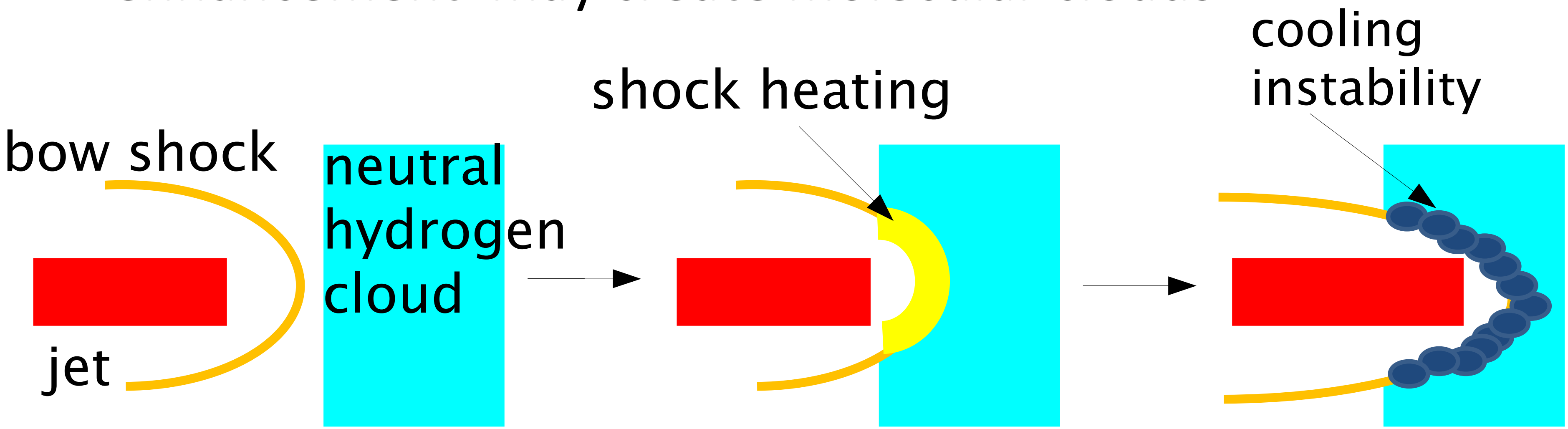


NANTEN2 observations of molecular clouds toward Westerlund 2

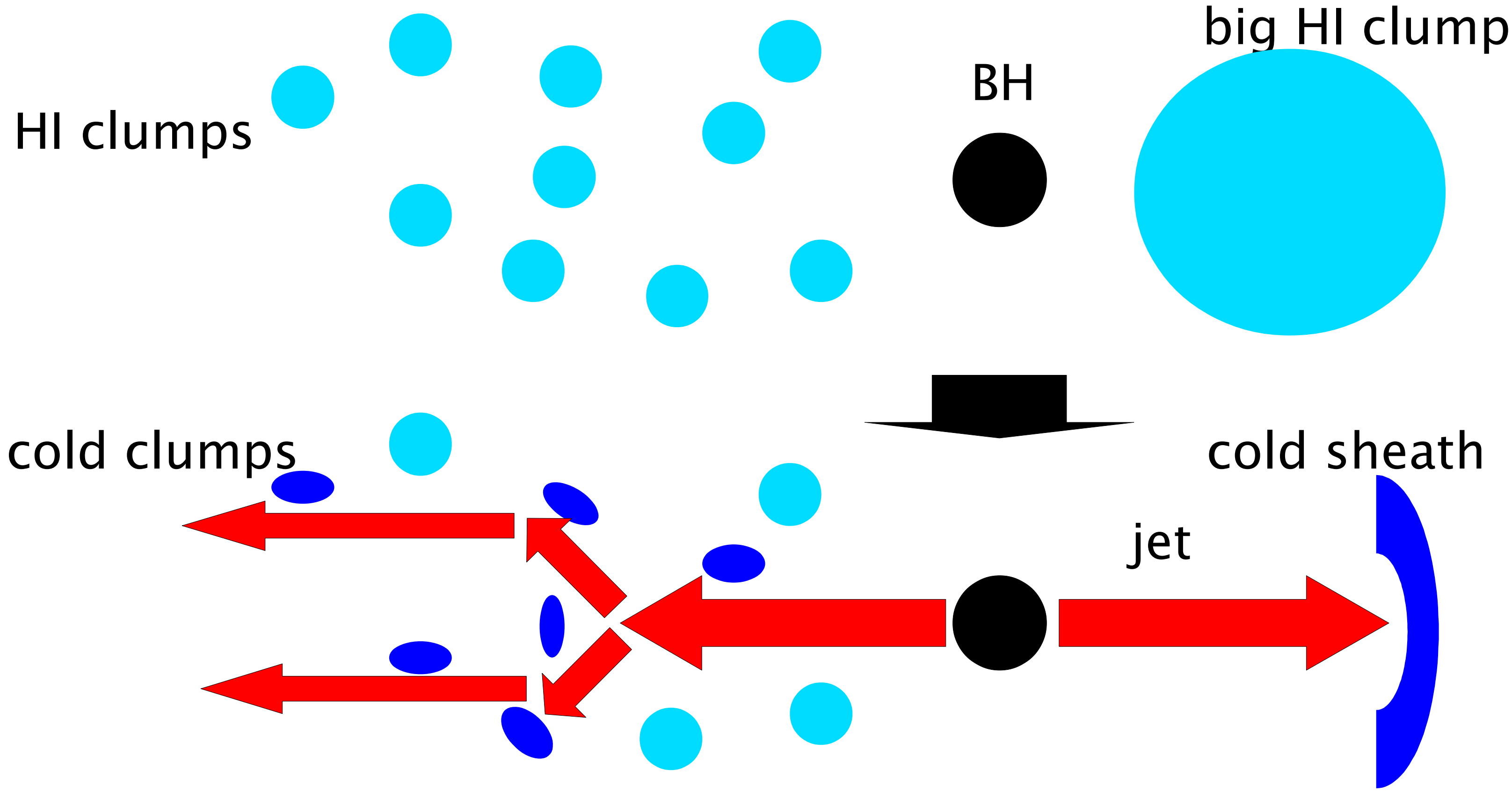
These molecular clouds can be formed by the interaction of the jet with the interstellar neutral hydrogen (HI) gas.

How Can Jet Create Molecular Clouds?

- The neutral hydrogen 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



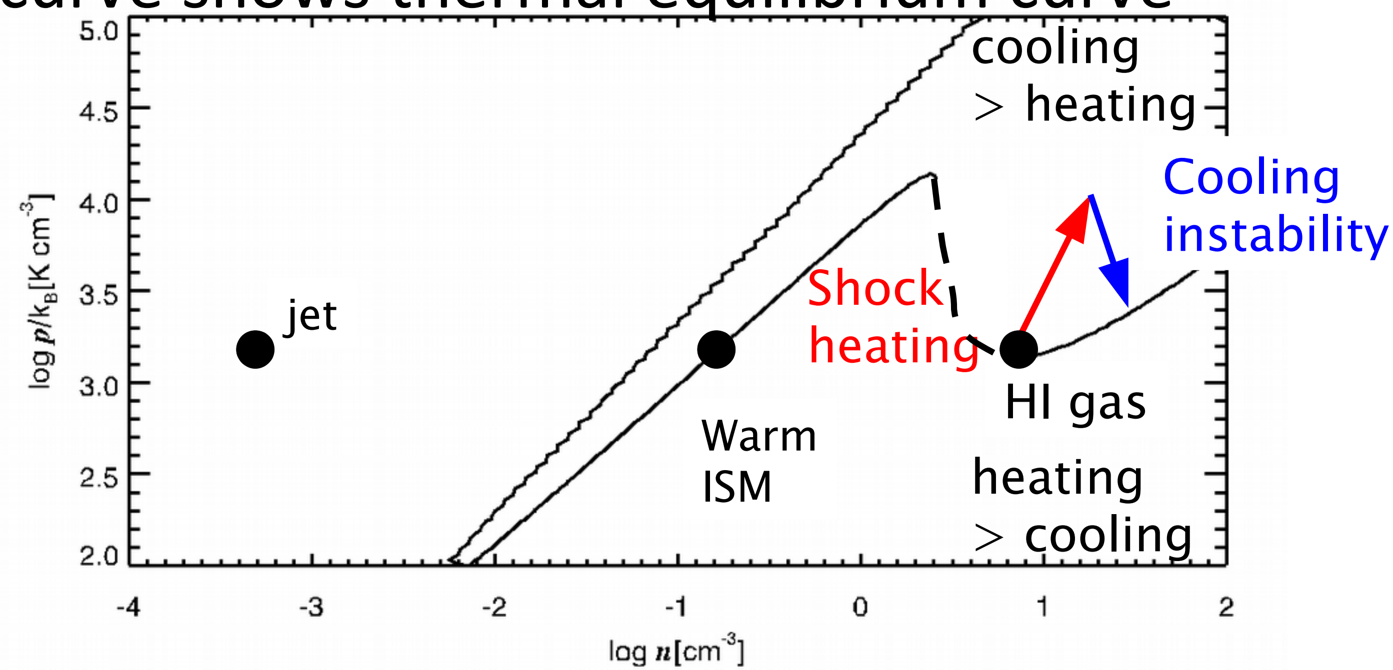
A Schematic Picture of Our Model



- When the jet interacts with a big HI cloud, the jet sweeps a big HI cloud and forms the arc cloud
- When the HI gas is clumpy, the jet propagates along the channels between HI clouds
- The shock compression of the HI clouds by the jet may induce the cooling instability in HI clouds

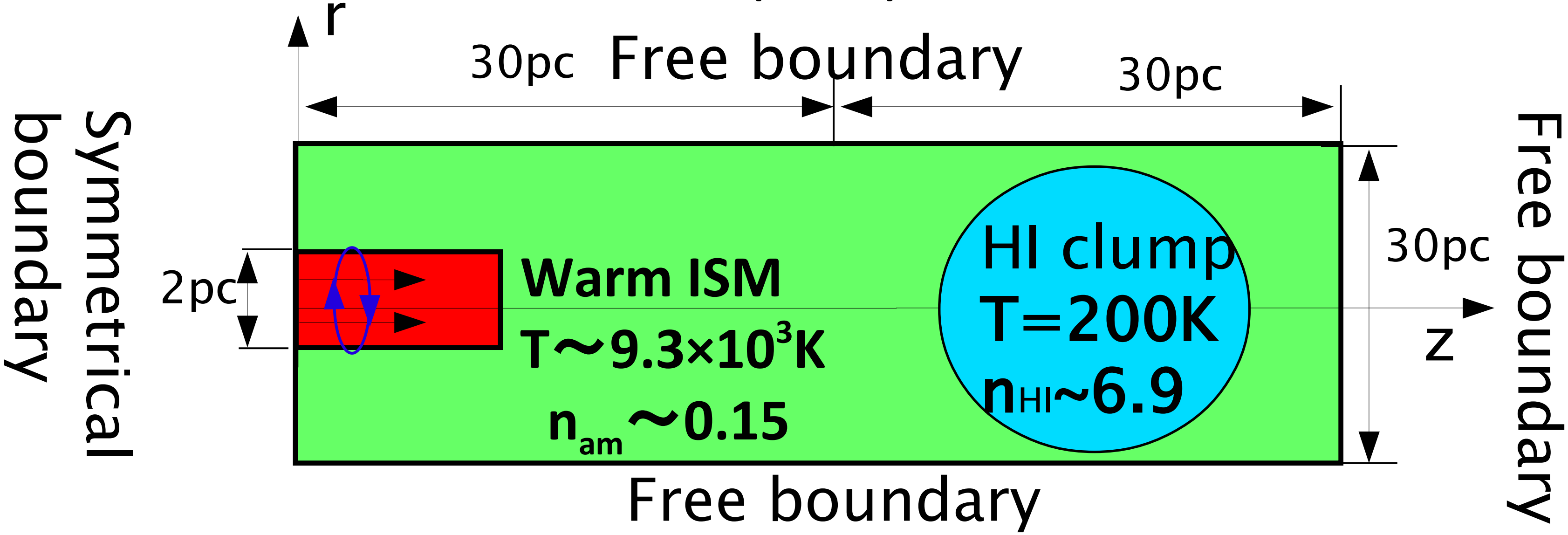
Cooling Function of the Interstellar Medium

- Use the cooling function taking into account 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 for Big HI Clump

- Pressure equilibrium between the warm interstellar medium (ISM) and the HI clouds

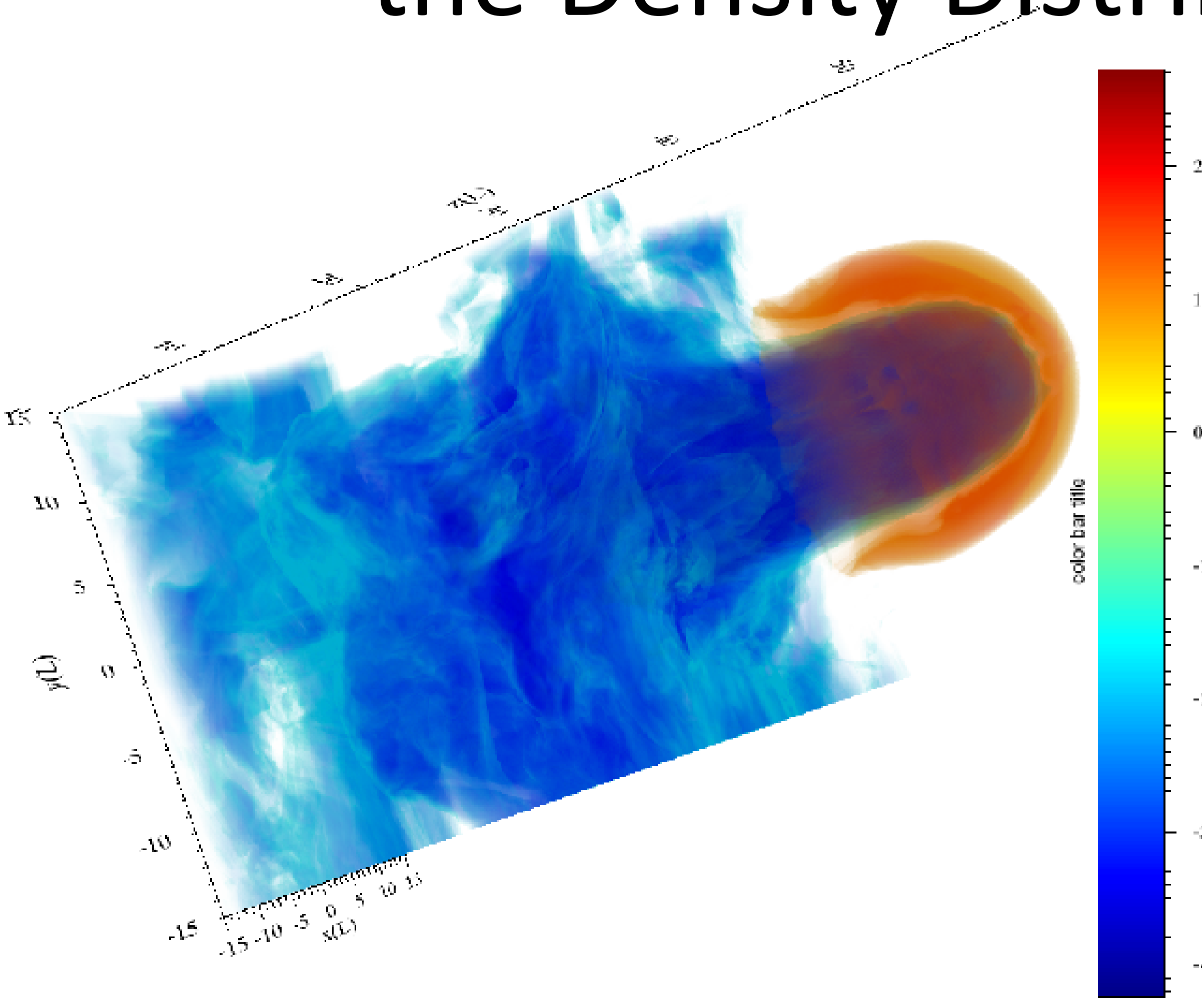


v_j~580km/s (Mach 3), T_j~2×10^6K

toroidal magnetic field B_ϕ, $\beta = P/(B^2/2) = 100$

- 3D simulations(x, y, z) ,HLLD scheme (Miyoshi & Kusano 2005)
- Mesh (N_x, N_y, N_z)=(300,300,600)

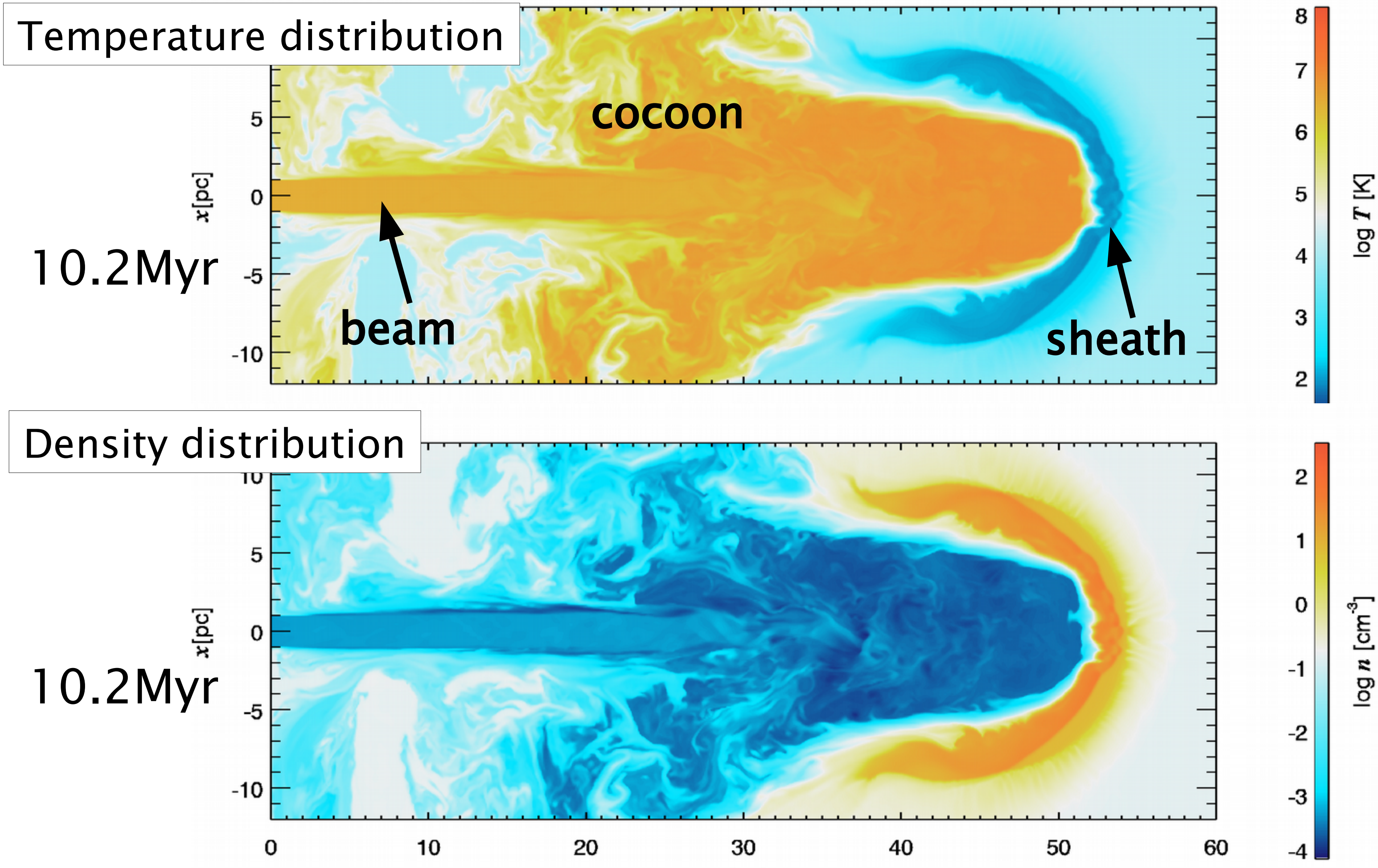
Volume Rendered Image of the Density Distribution



- Blue – Low density region (jet gas)
- Orange – High density region formed by interaction of the jet with a big HI cloud

- The jet sweeps the HI cloud after the jet collides with the HI cloud

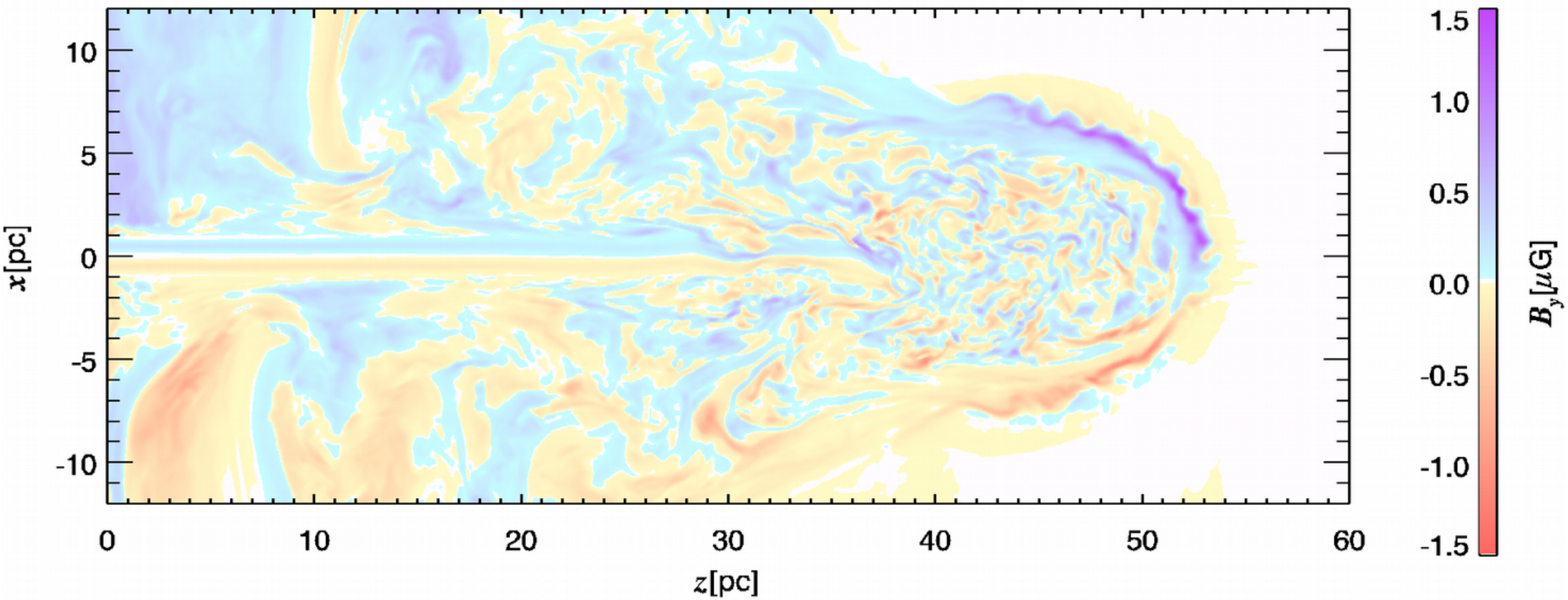
Numerical Results



- The shocked gas is cooled down to about 50K by the cooling effect
- The dense gas compressed by the bow shock forms a dense sheath

Amplification of the Toroidal Magnetic Field

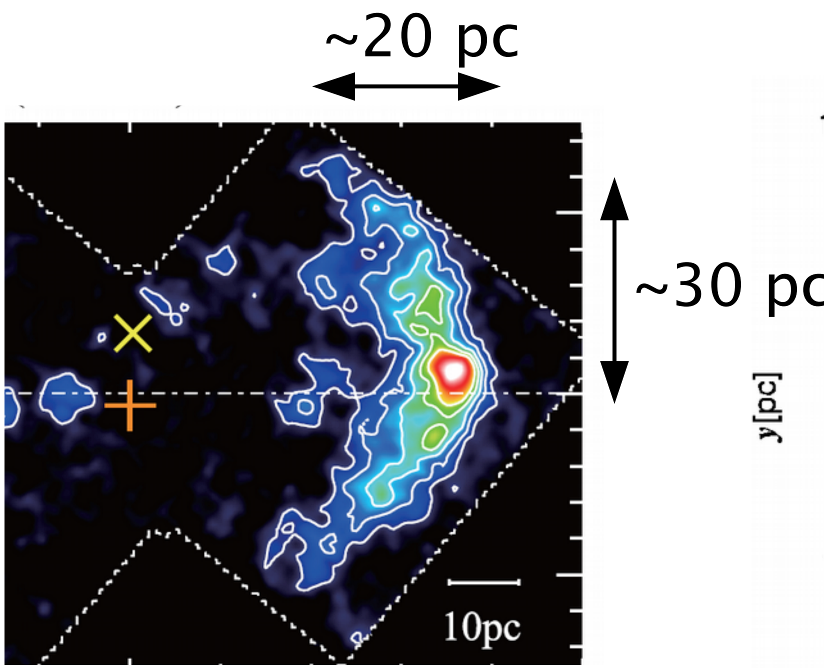
B_y distribution



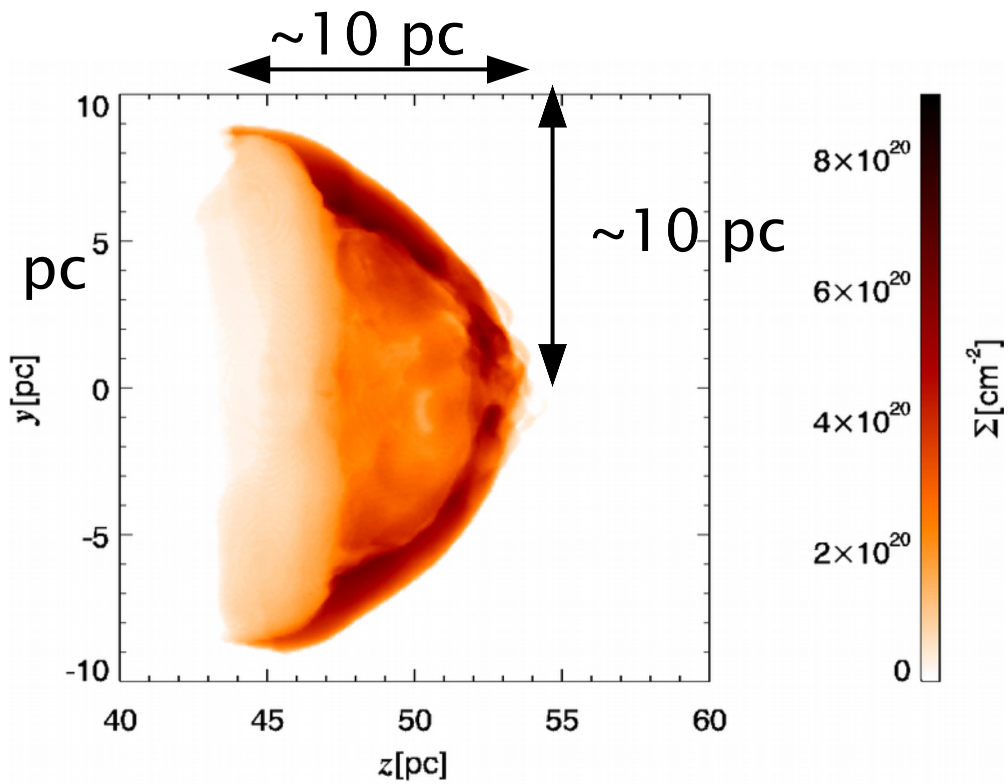
- The turbulent magnetic field appears behind the jet head
- The toroidal magnetic field is amplified between the cocoon and the cold, dense sheath

Column Density of the Cold, Dense Gas

Column density of the cold, dense region where T<100K

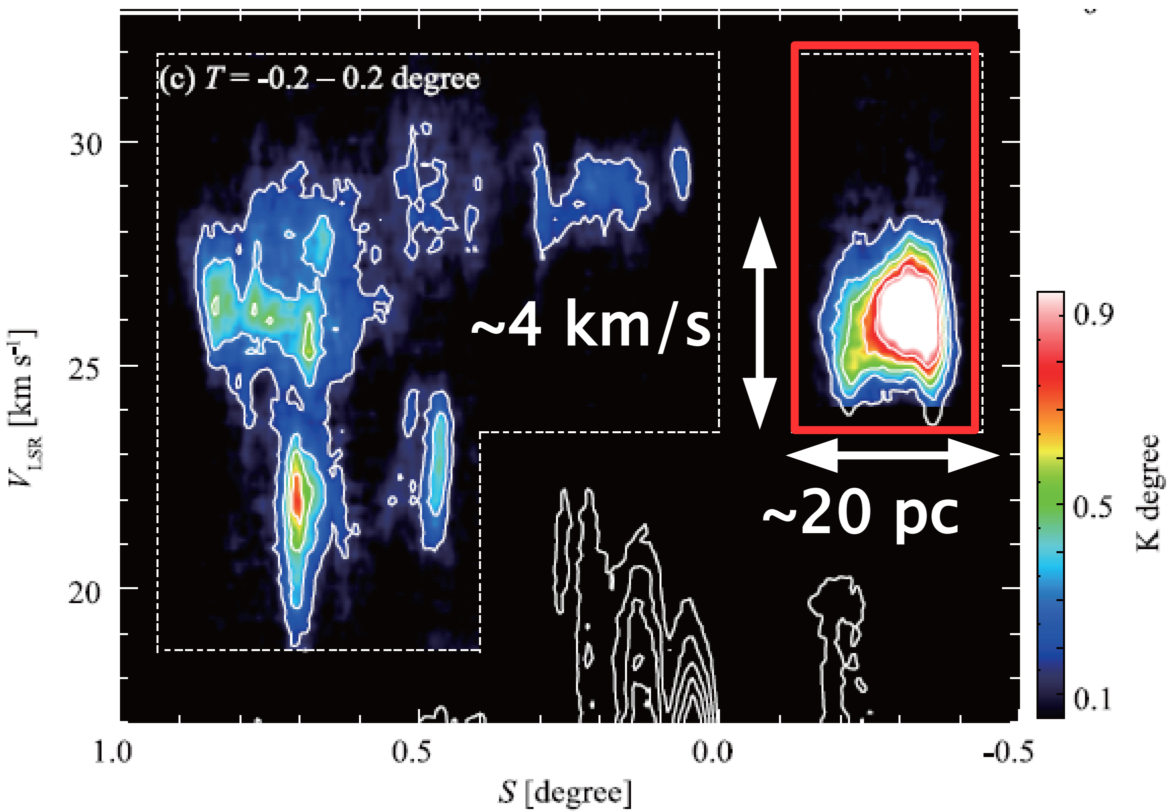


NANTEN2 observations
(Furukawa et al. 2014)



- The column density is high in the sheath
- It is low on the jet axis because the jet swept the HI cloud
- The shape of the high column density region looks like an arc

Position Velocity Diagram



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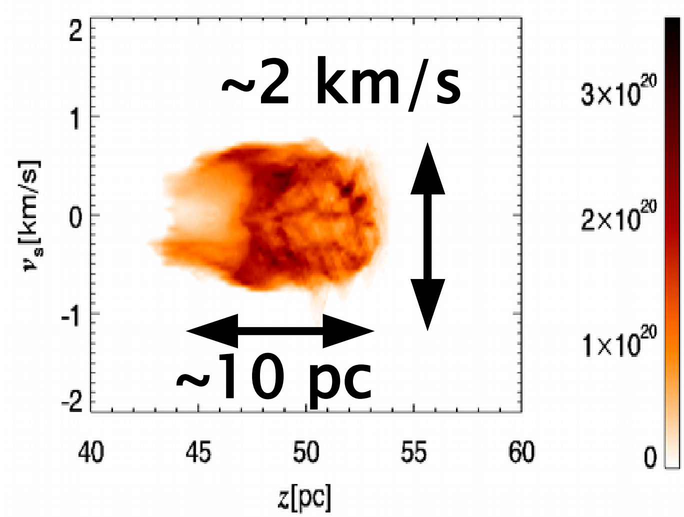
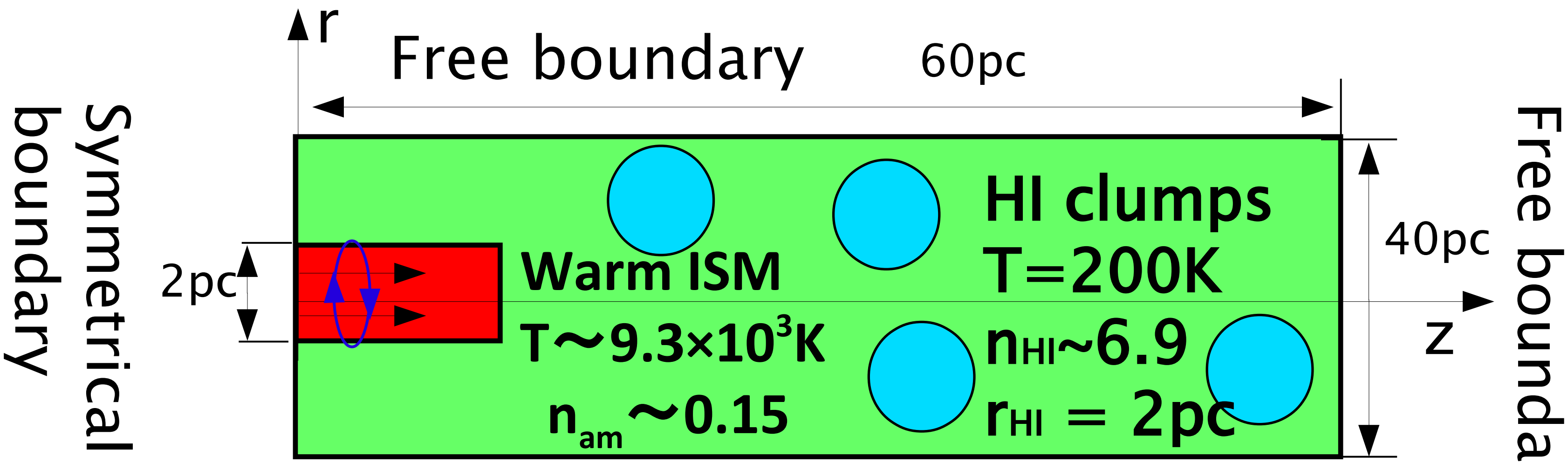


- The shape is similar to that of observation (left panel)
- The velocity dispersion is 2km/s in simulation which is about half of that in observation

Simulation Model for Clumpy HI Clouds

- Pressure equilibrium between the warm interstellar medium (ISM) and HI clumps
- We put HI clumps ramdomly in the region z > 10pc
- Filling factor of HI clumps V_{HI}/V_{total} is assumed to be 0.8

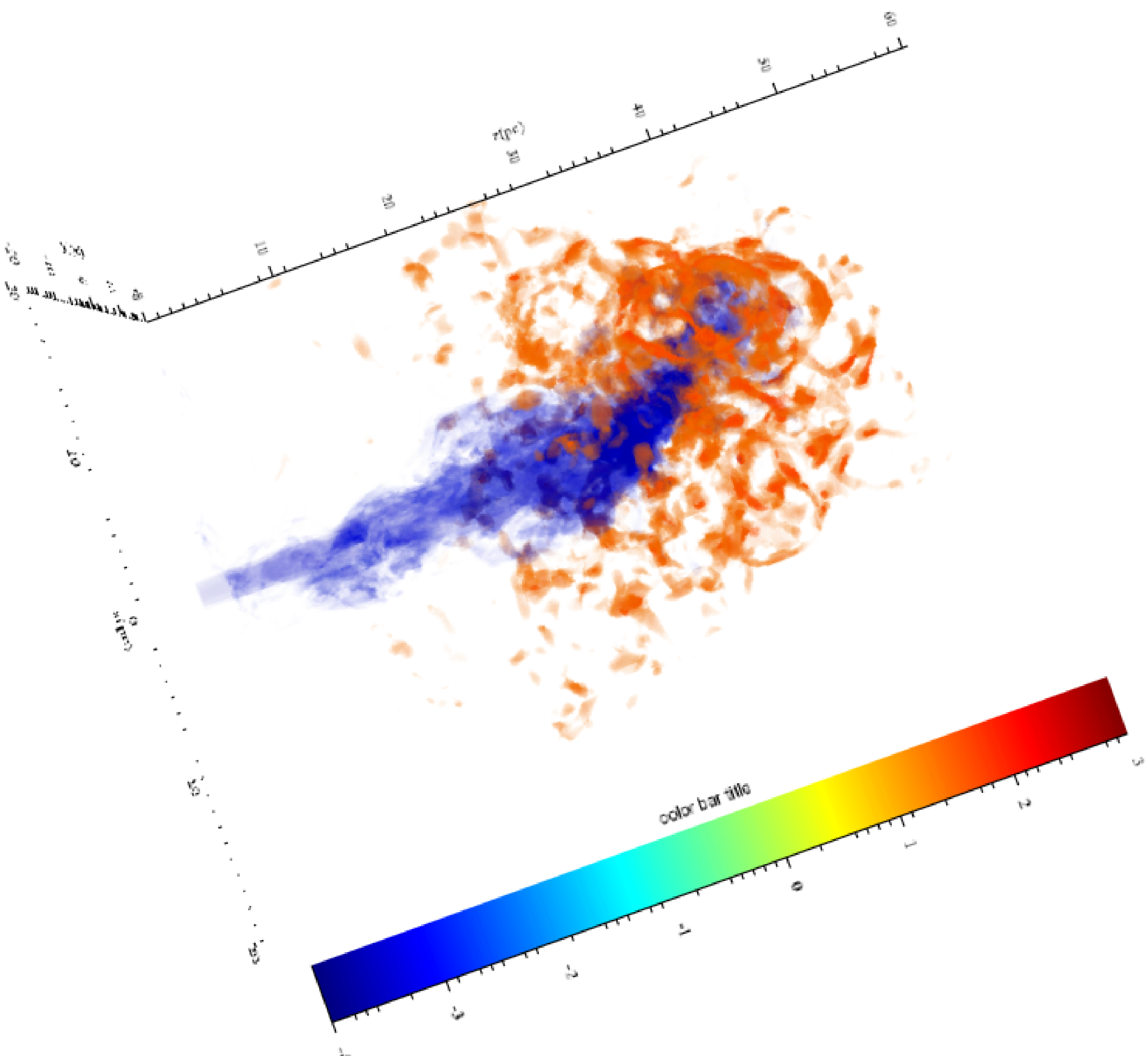


v_j~580km/s (Mach 3), T_j~2×10^6K

toroidal magnetic field B_ϕ, $\beta = P/(B^2/2) = 100$

- 3D simulations(x, y, z) ,HLLD scheme (Miyoshi & Kusano 2005)
- Mesh (N_x, N_y, N_z)=(400,400,600)

Volume Rendered Image of the Density Distribution

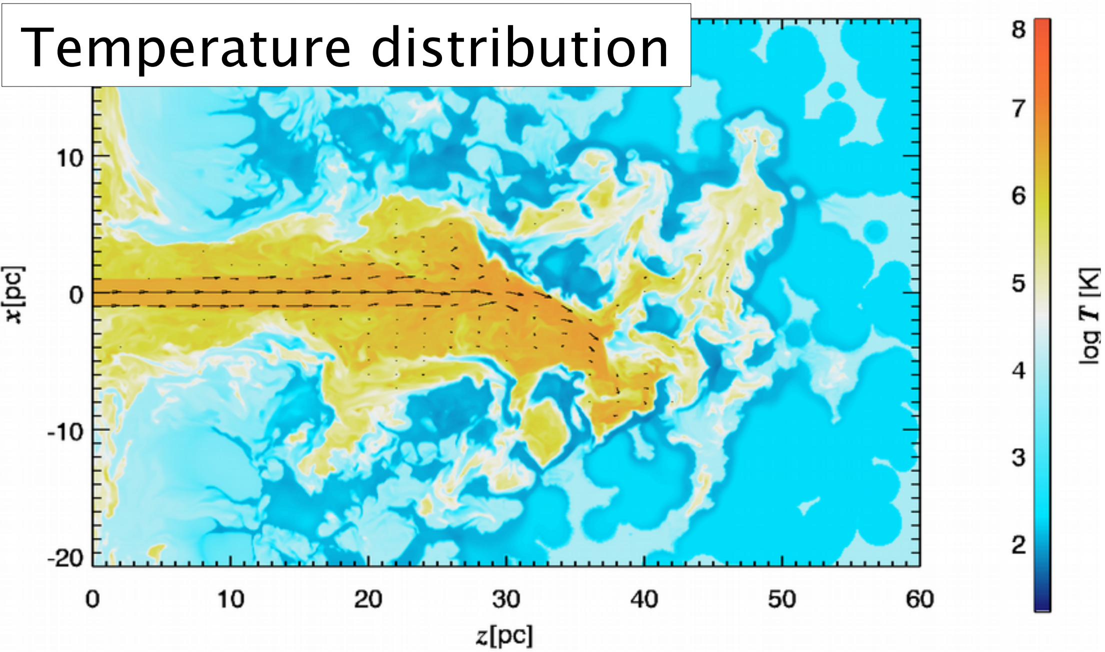


- Blue – Low density jet gas
- Orange – Cold, dense gas

- Shocked HI clumps form clumpy cold, dense clouds

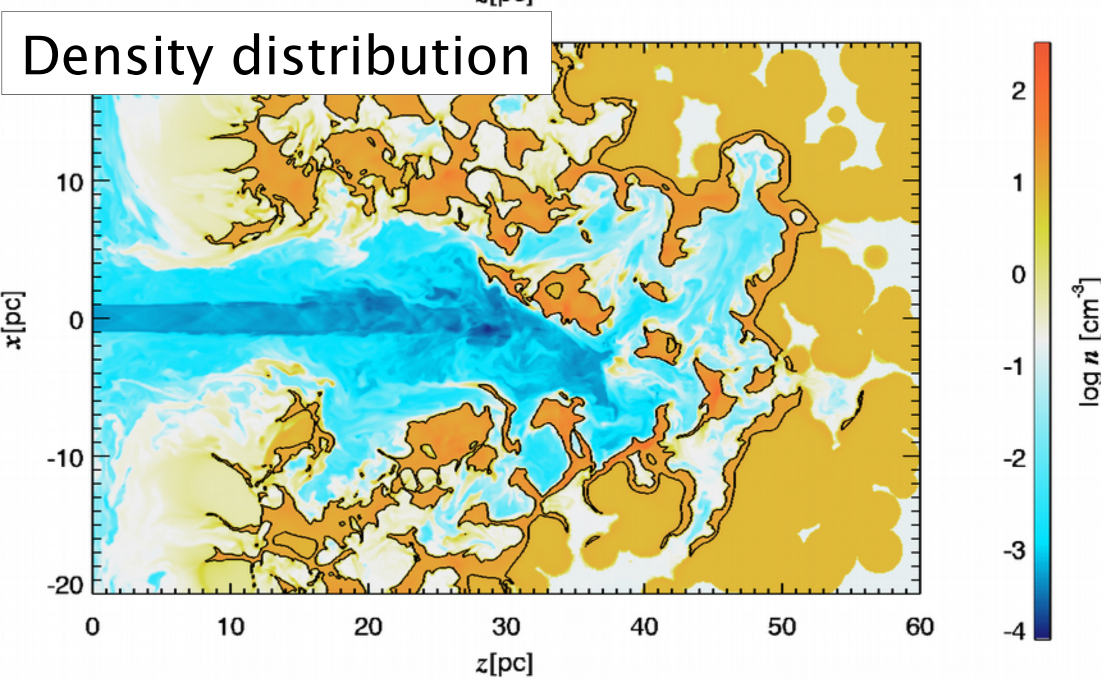
Numerical Results at 7.2Myr

Temperature distribution



- The shocked gas is cooled down to about 60K by the cooling
- The maximum density is about $80cm^{-3}$ (black contours show $n > 10cm^{-3}$)

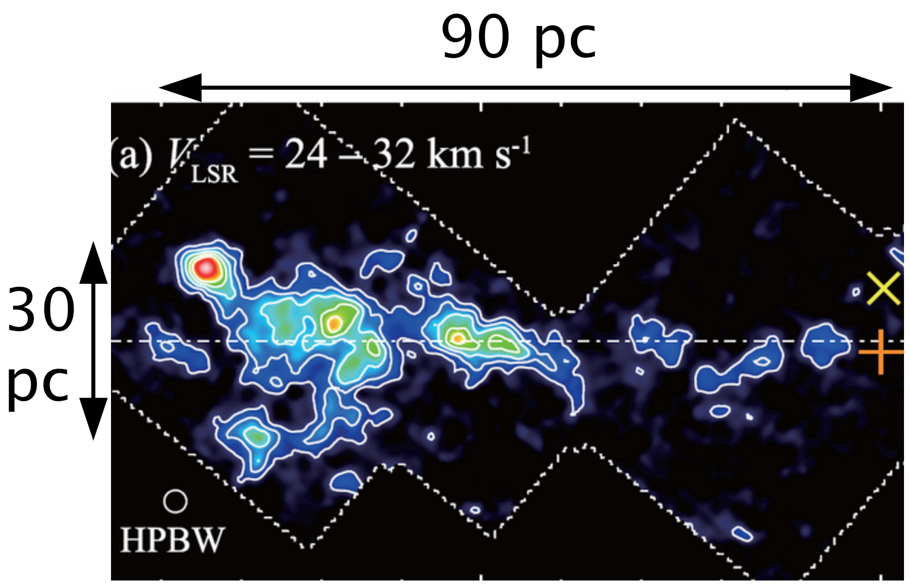
Density distribution



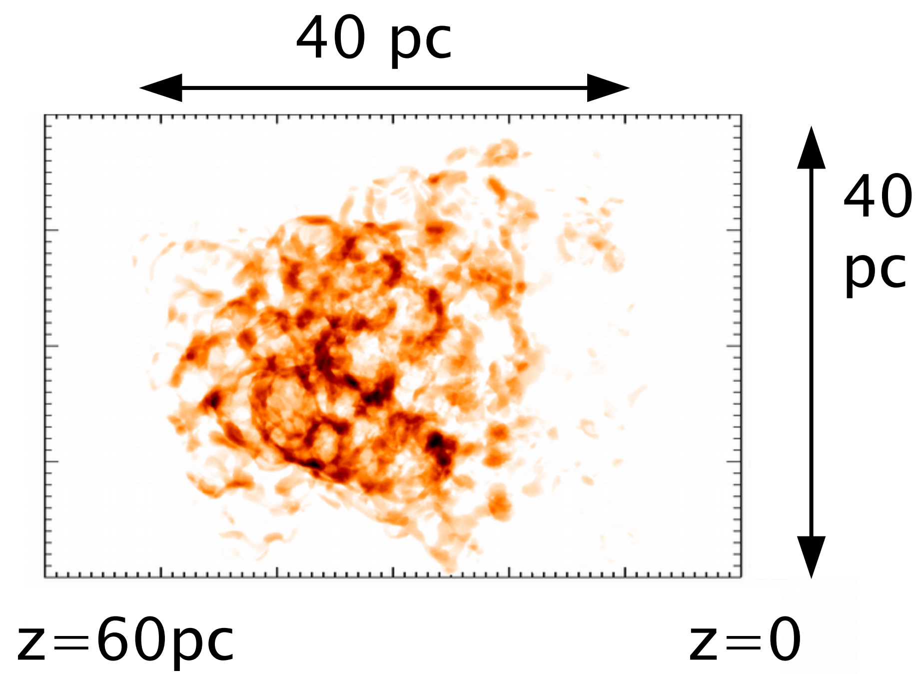
- HI clumps compressed by the bow shock form cold dense clumps
- The jet breaks up into branches since the jet can propagate in channels between HI clumps

Column Density of the Cold, Dense Gas

Column density of the cold, dense region where T<100K

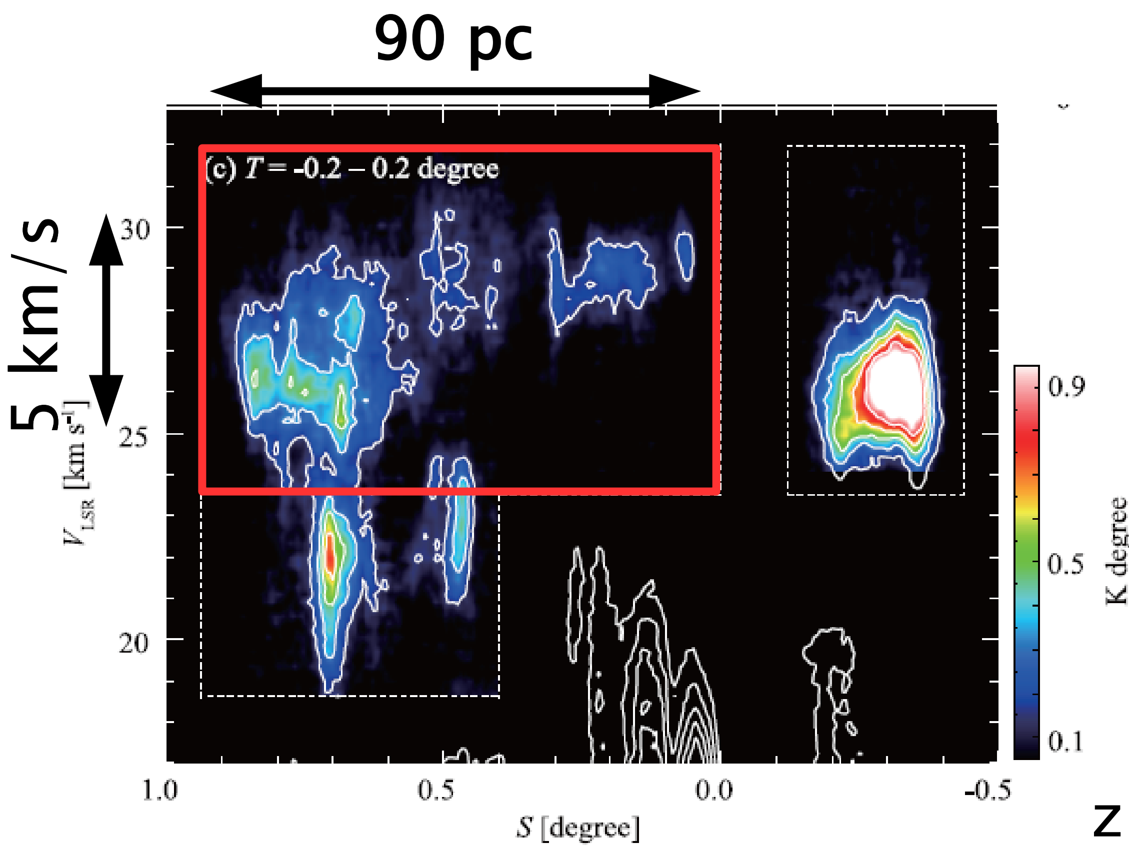


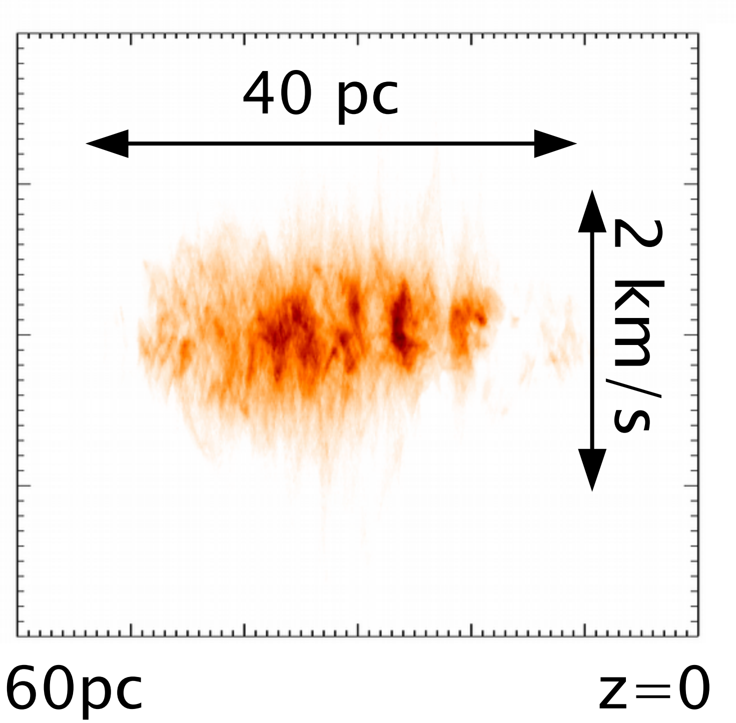
NANTEN2 observations
(Furukawa et al. 2014)



- High column density region are clumpy
- The width of the high column density region becomes as broad as 40pc

Position Velocity Diagram





NANTEN2 observations
(Furukawa et al. 2014)

- Distribution is extended to the jet axis
- The dispersion of the line of sight velocity is about half of that in observation (left panel)

Summary

- We carried out 3D MHD simulations of the formation of molecular clouds by supersonic jet interacting with either a big HI gas cloud or HI clumps
- When the jet interacts with the multiphase interstellar medium, the cold, dense sheath is formed by shock compression and subseqent cooling
- When the volume filling factor is moderate, the distribution of the cold, dense region is similar to the jet cloud
- When the volume filling factor is large, the distribution of cold, dense clumps approaches to the arc-shape
- The arc-shaped and jet like molecular cloud observation in Westerlund 2 can be explained by jet propagation into a big HI cloud and clumpy HI clumps, respectively