Metallicity Evolution in the Milky Way through the Collision with the High Velocity Clouds

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Outlines

- Introduction to High Velocity Clouds
  - Observational Features
  - Theory: Origin, Current Status, and Future
- HVCs Colliding with the Galactic Disk
  - Observational Evidence: Smith Cloud, Complex C
  - Implications
- Trace Mixing of Metallicities
  - Numerical Techniques
  - Example (Halo)

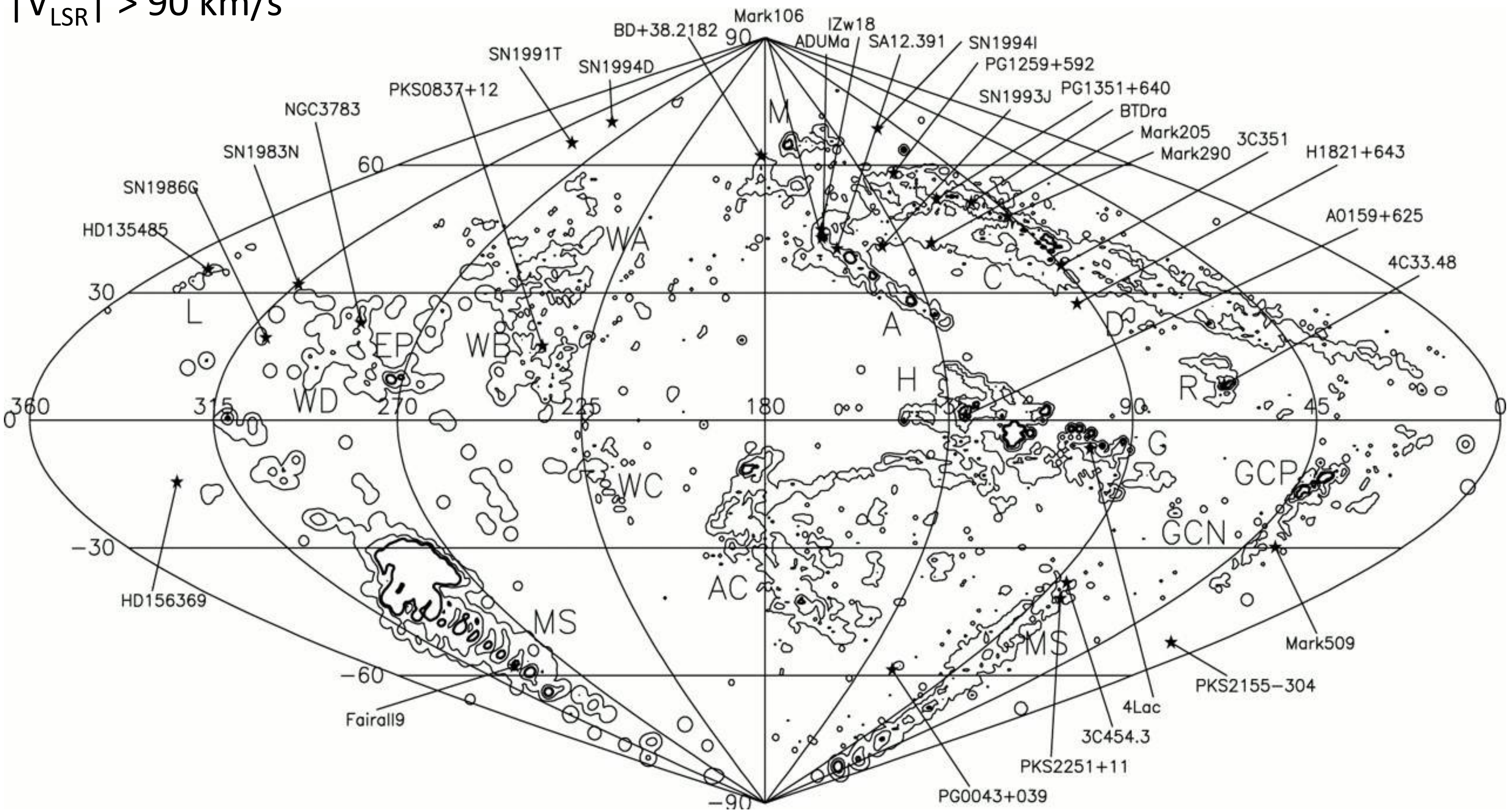
High, Intermediate, and Low Velocity Clouds (HVCs, IVCs, and LVCs)

- Discovered first in 21 cm radio emission by Muller et al. (1963)

- |HVCs| > 90 km/s, |IVCs| < 90 km/s (in LSR)

High Velocity Clouds

|V_{LSR}| > 90 km/s

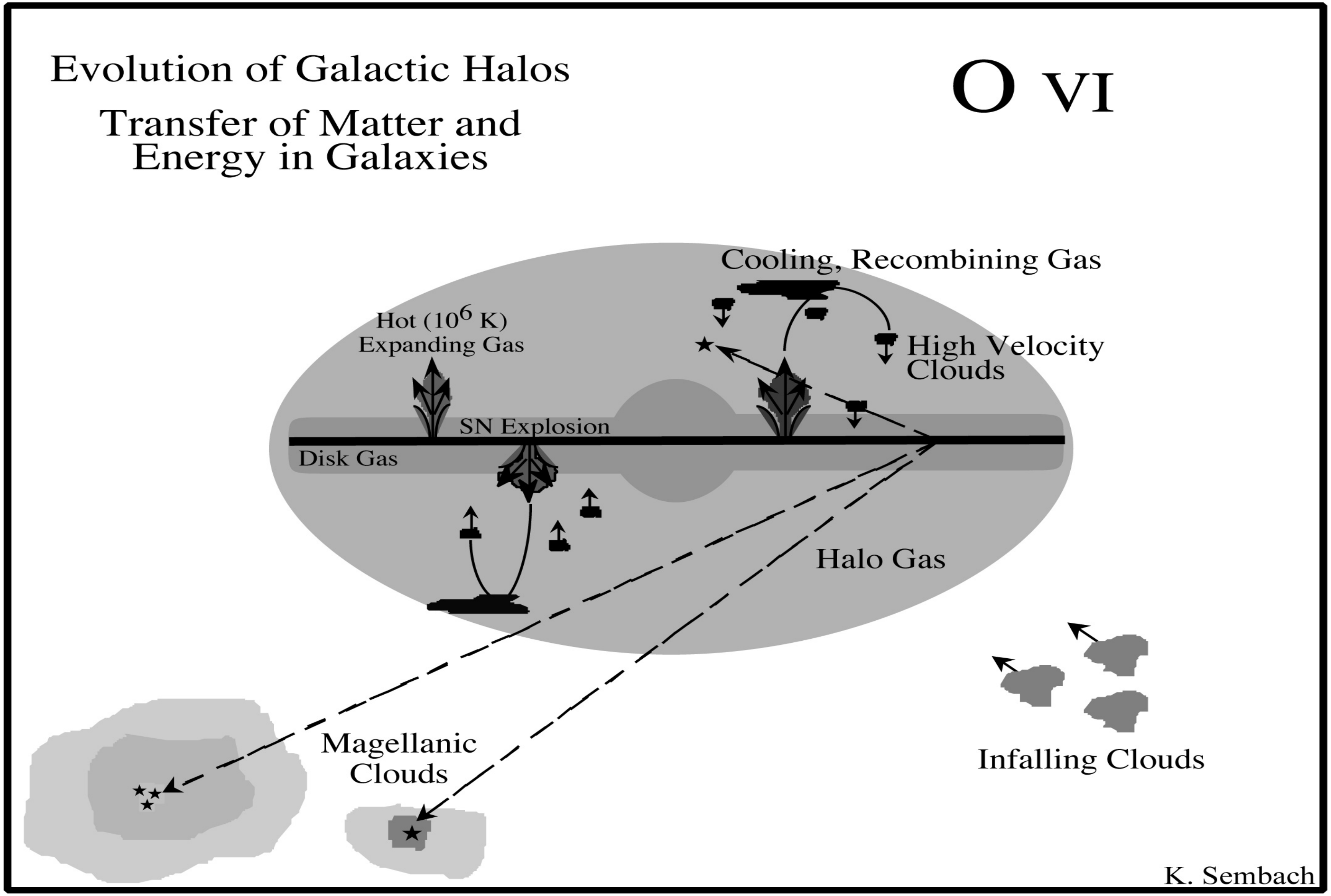


Wakker & van Woerden 1997

Three Possible Origins of HVCs

- Galactic fountain
- Accretion of primordial gas left over from galaxy formation
- Gas stripped off of the nearby dwarf galaxies

The Milky Way



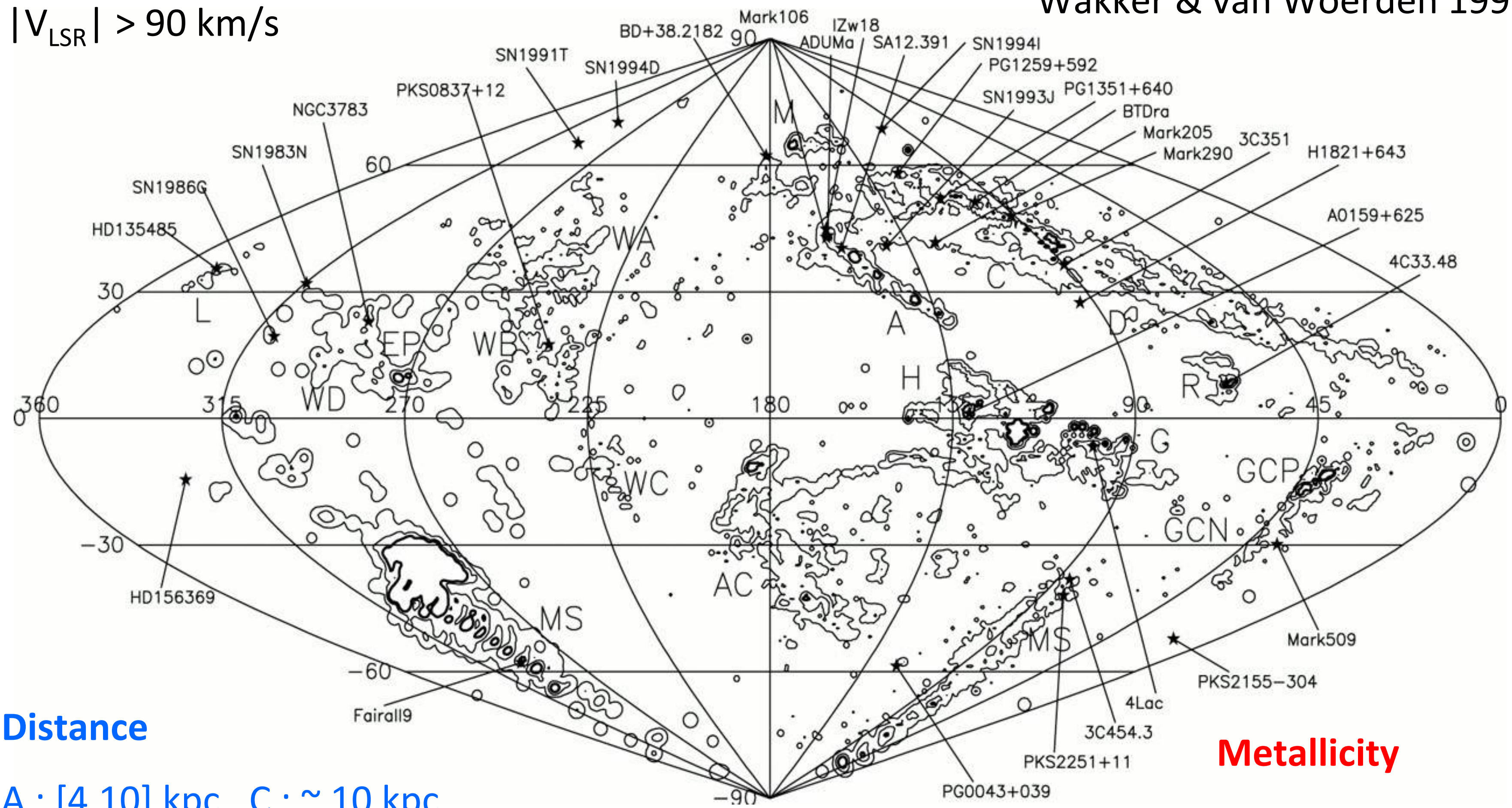
Questions on HVCs

- Where are they from?
  - Distances
  - Metallicities
- How are they interacting with environments?
  - Neutral vs. Ionized (Hα, low ions)
  - High ions (C IV, N V, O VI, and Si IV) in UV
  - X-rays
- What is their ultimate fate?
  - Fuel for the star formation in the Galactic disk

Distances and Metallicities

$|V_{LSR}| > 90$ km/s

Wakker & van Woerden 1997



Distance

A : [4,10] kpc, C : ~ 10 kpc

MII/MIII : < 5 kpc, H : > 5 kpc

EP : > 6.2 kpc, WB : < 8.4 kpc

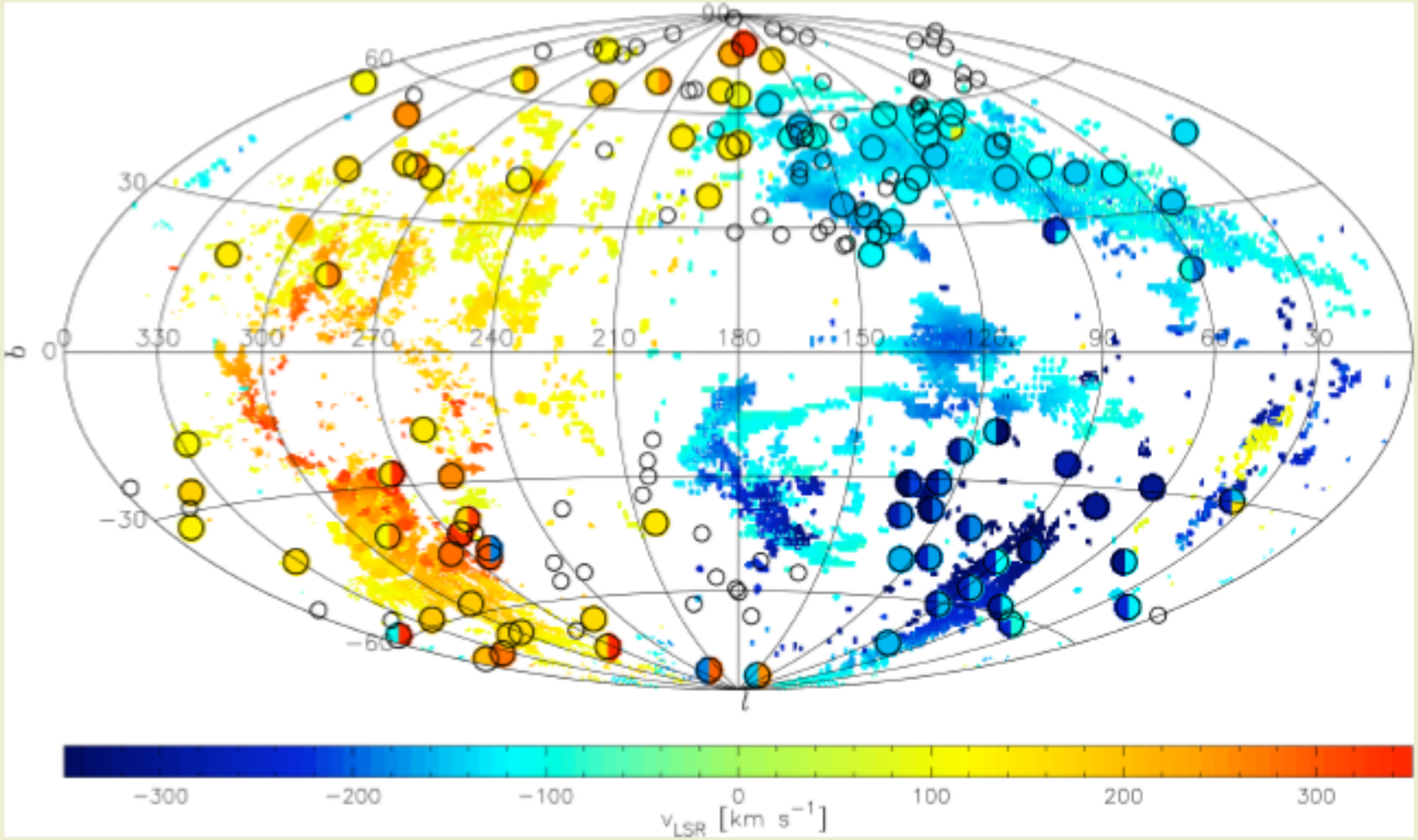
Metallicity

C : ~ 0.1 Solar

MS : ~ 0.3 Solar

M : ~ Solar

OVI HIGH-VELOCITY CLOUDS

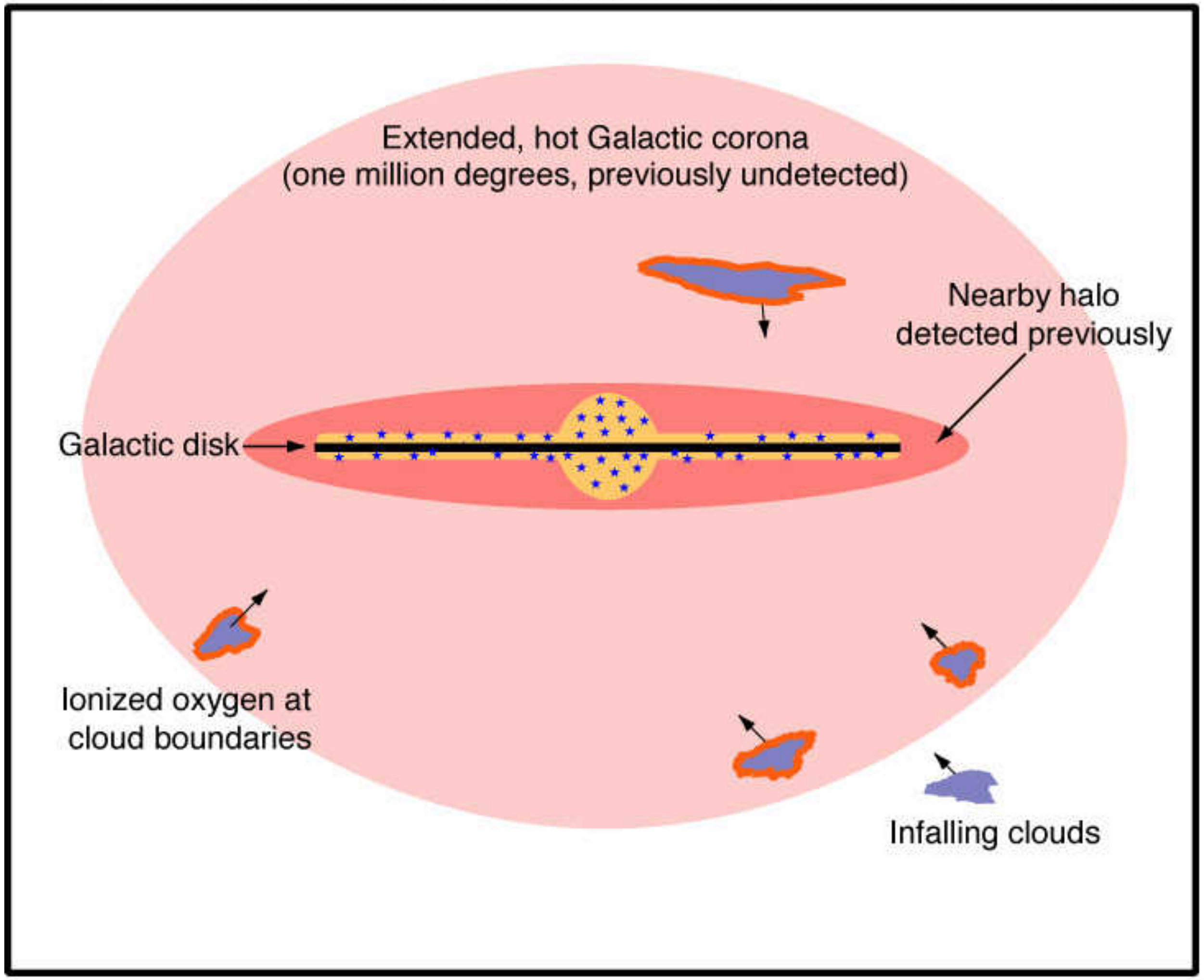


Continues colors: velocities of H I 21 cm emission (| v_{LSR} | >100 km s^{-1})
Circles: velocities of OVI absorption

Sembach et al. 2003

Simulations of HVCs in the Halo

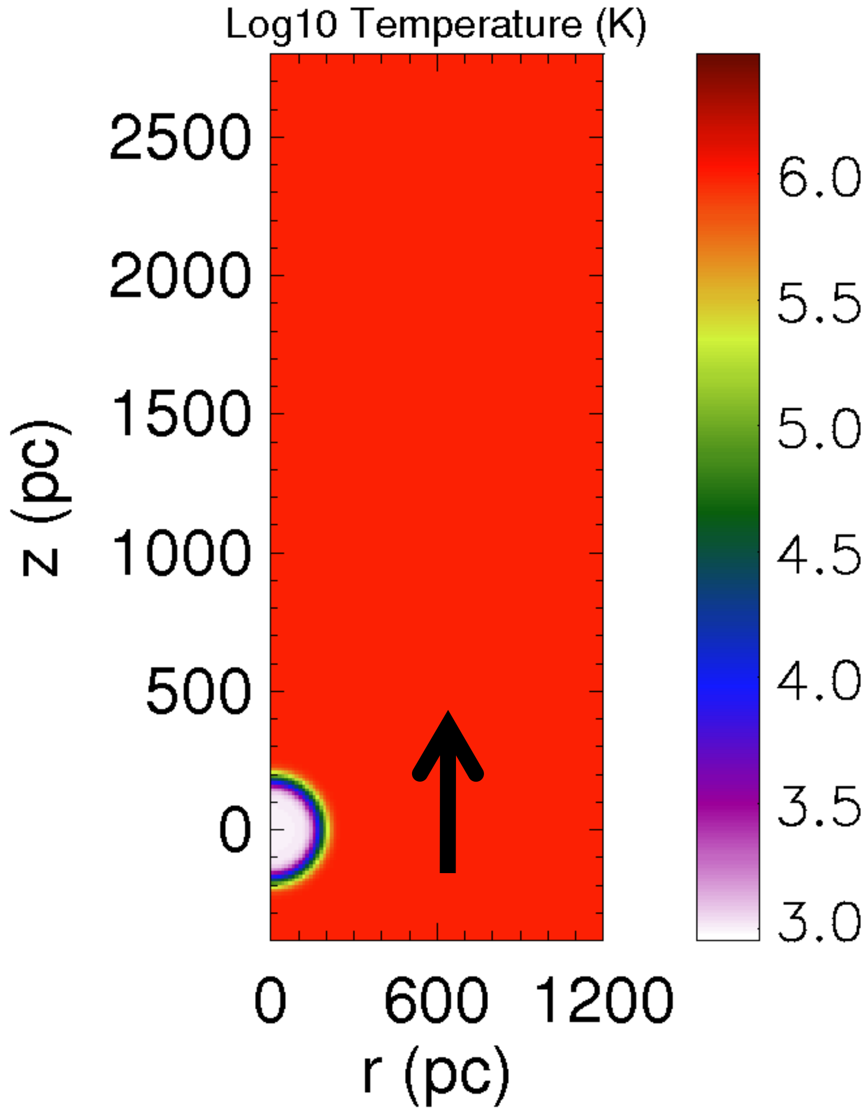
Infalling Clouds Light Up and Reveal Hot Galactic Corona



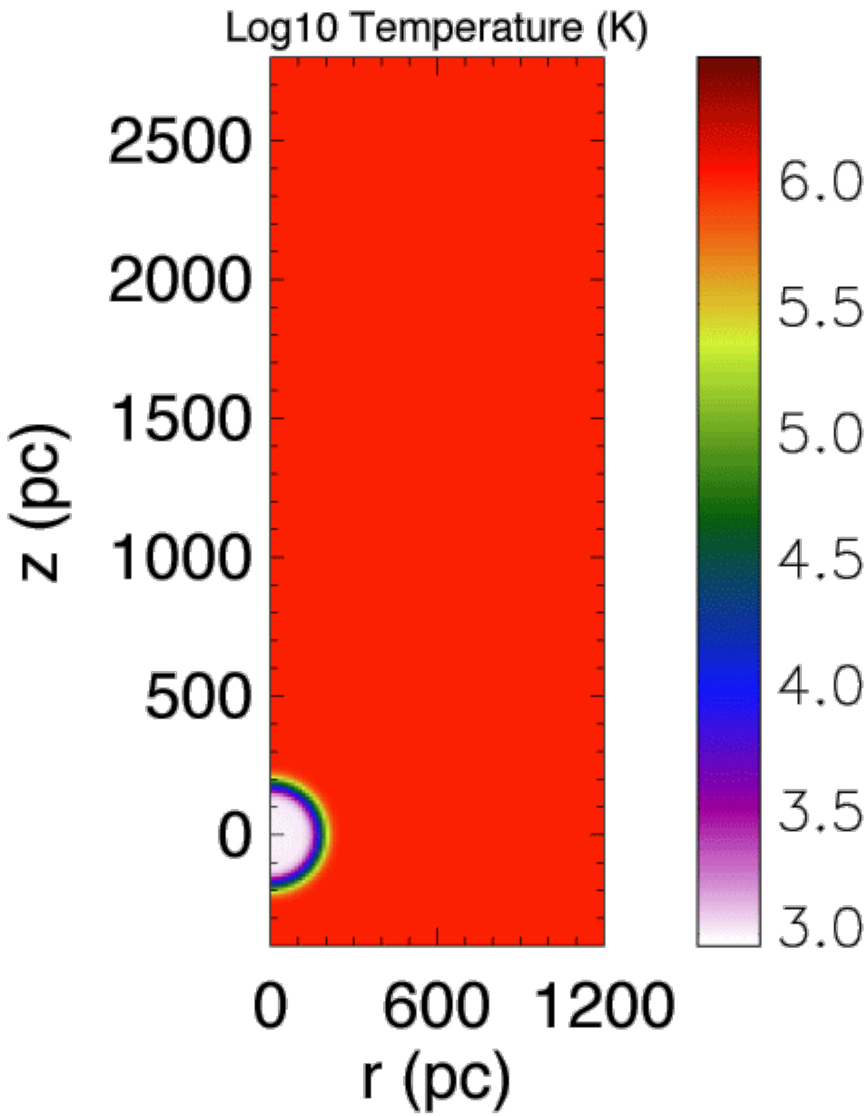
This illustration shows clouds falling onto our galaxy, the Milky Way. These clouds "light up" in ionized oxygen when they encounter the hot, extended corona of gas that surrounds the Milky Way.

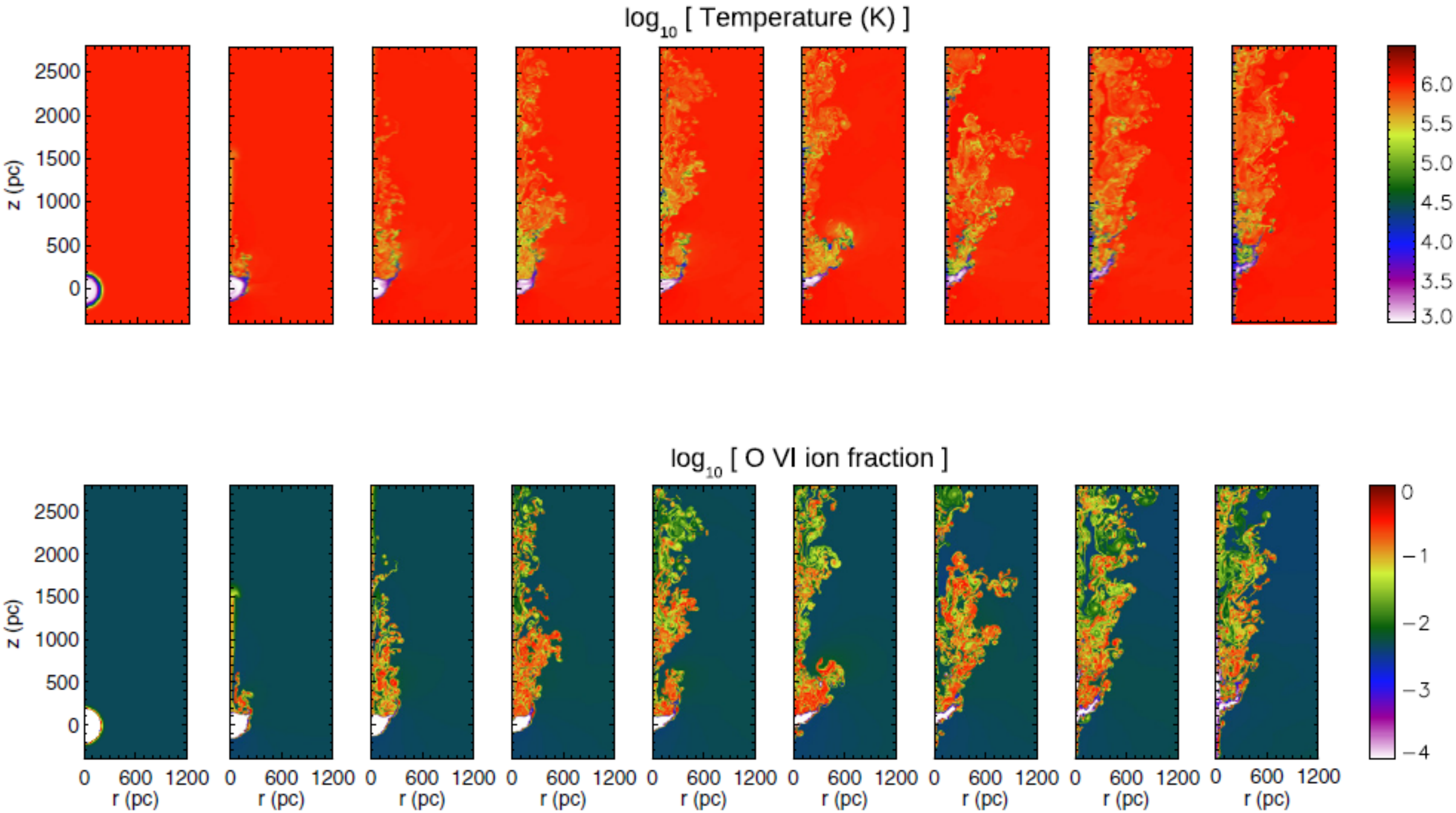
Simulations of HVCs

2D cylindrical coordinates



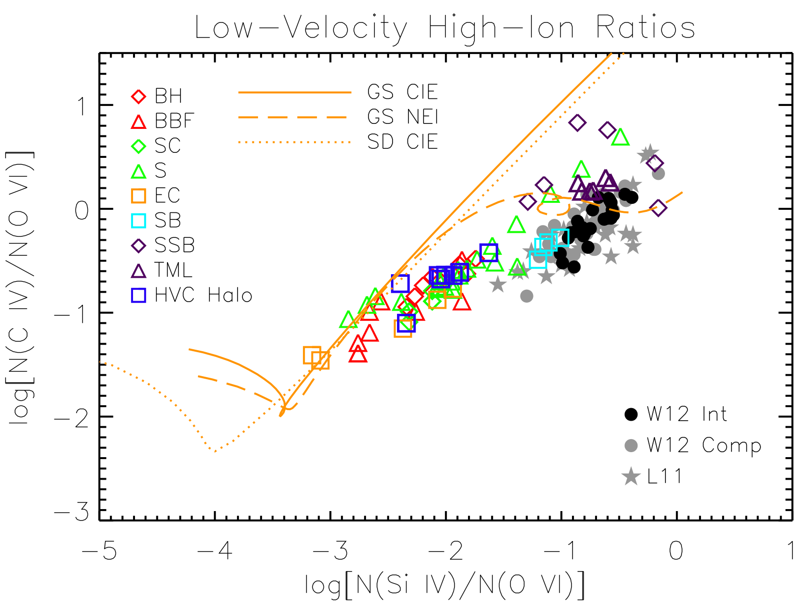
Simulational Study of HVCs

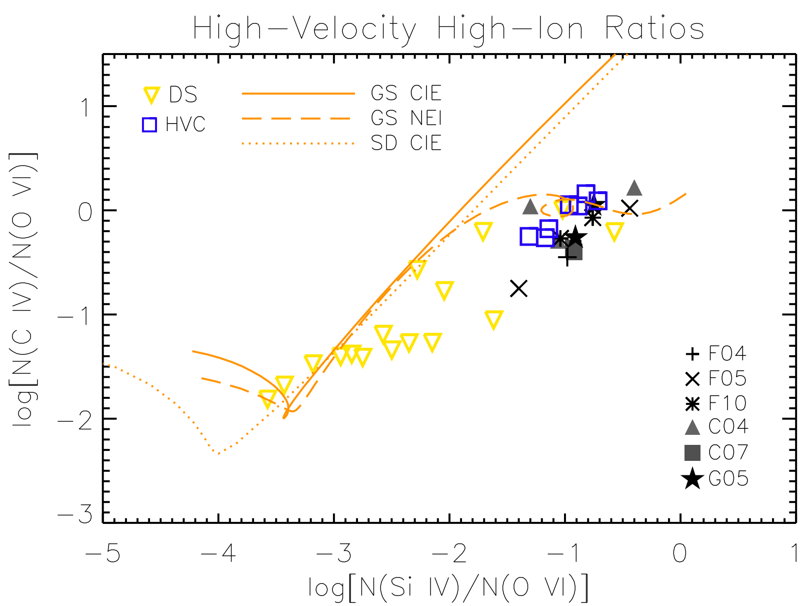




log10 [Temperature (K)]
z (pc)
2500
2000
1500
1000
500
0
6.0
5.5
5.0
4.5
4.0
3.5
3.0
log10 [O VI ion fraction]
0
−1
−2
−3
−4
0 600 1200
r (pc)

Compare with Observations

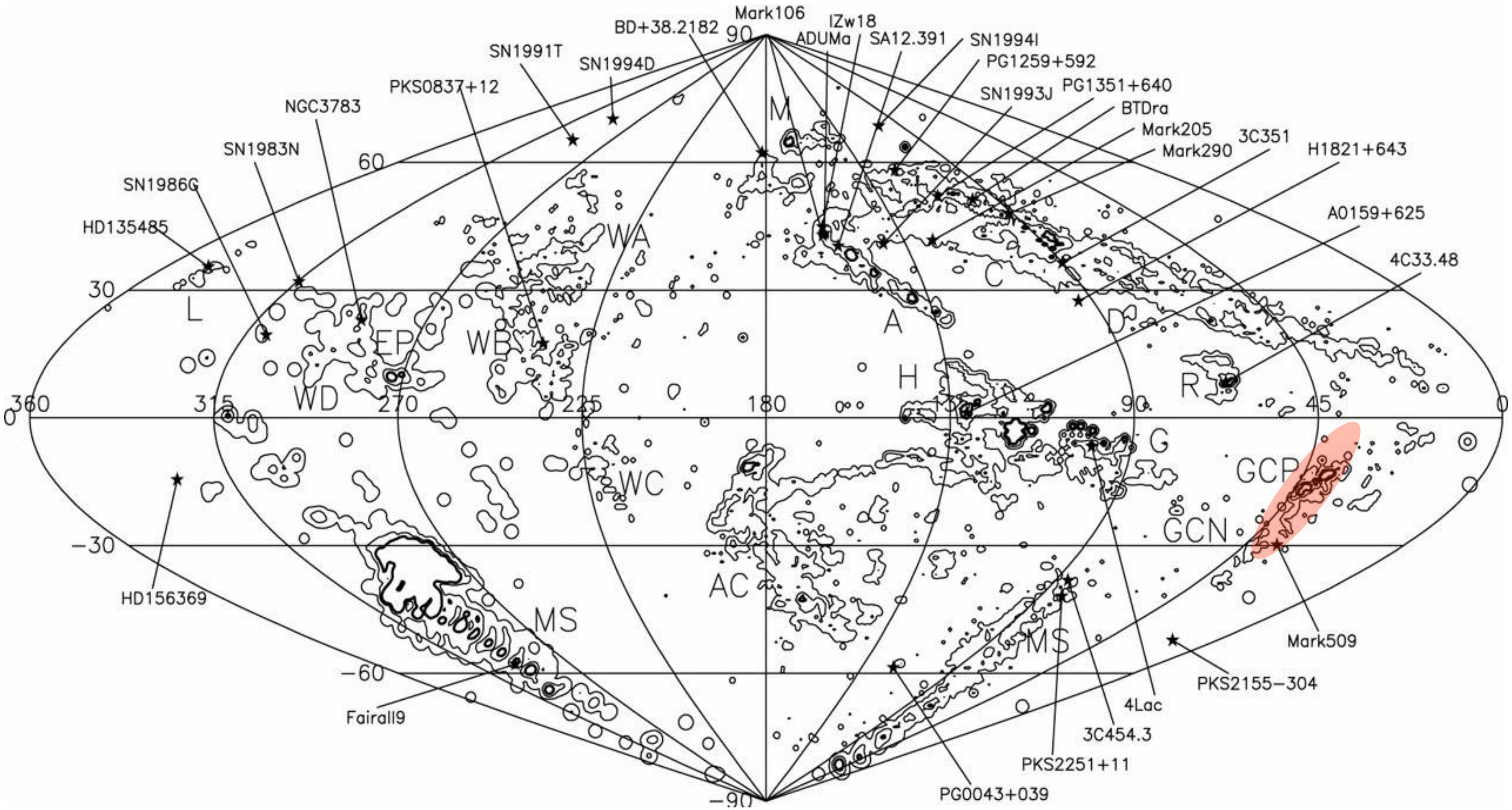




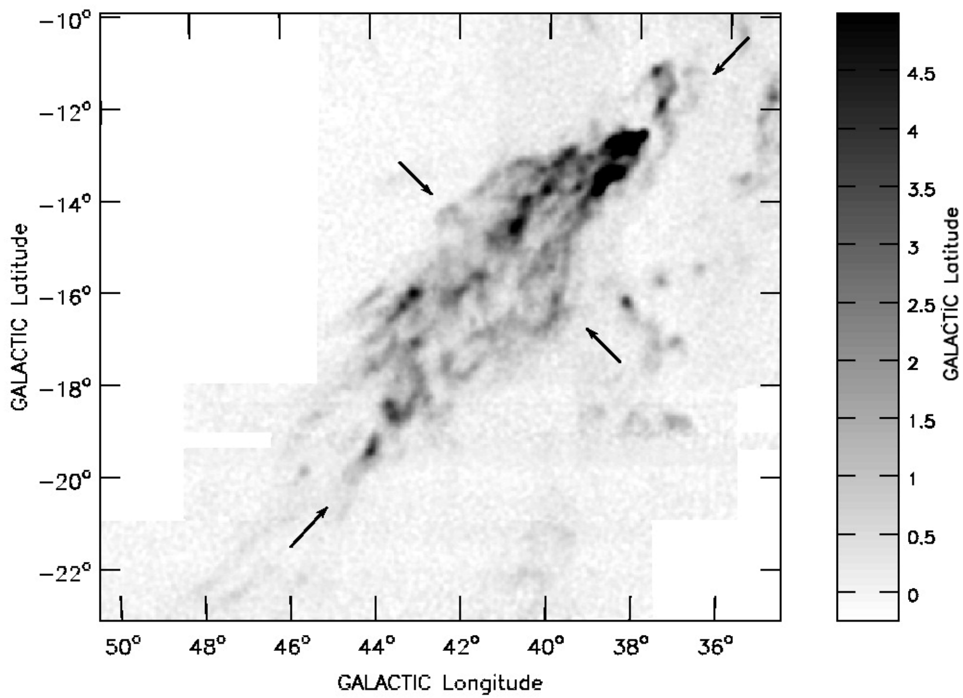
Smith Cloud: an HVC Colliding with the Disk

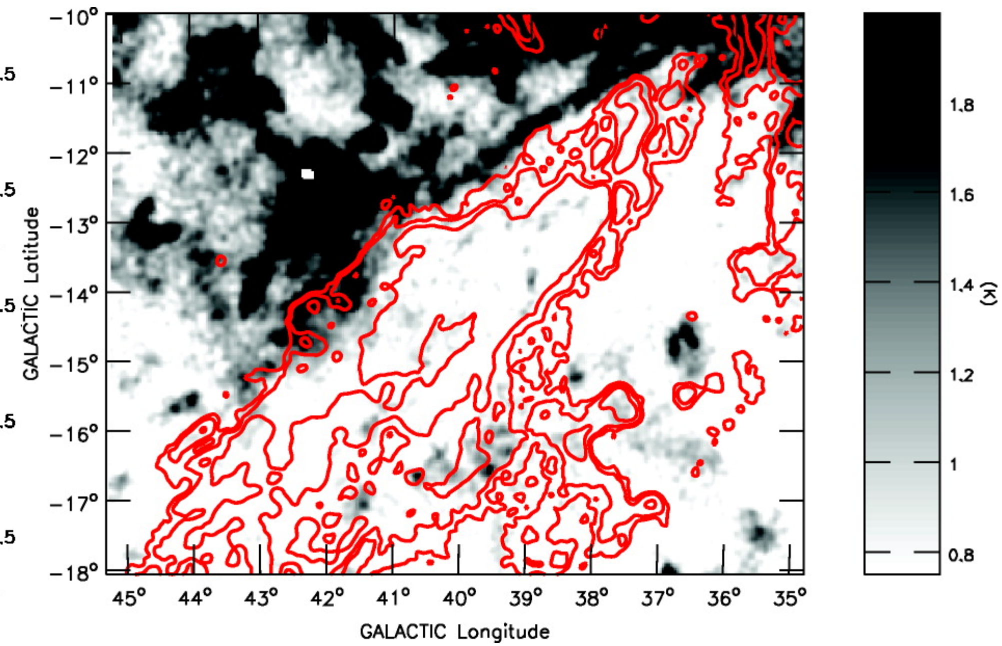
Wakker & van Woerden 1997

$|V_{LSR}| > 90$ km/s



Collision with the Disk: Smith Cloud

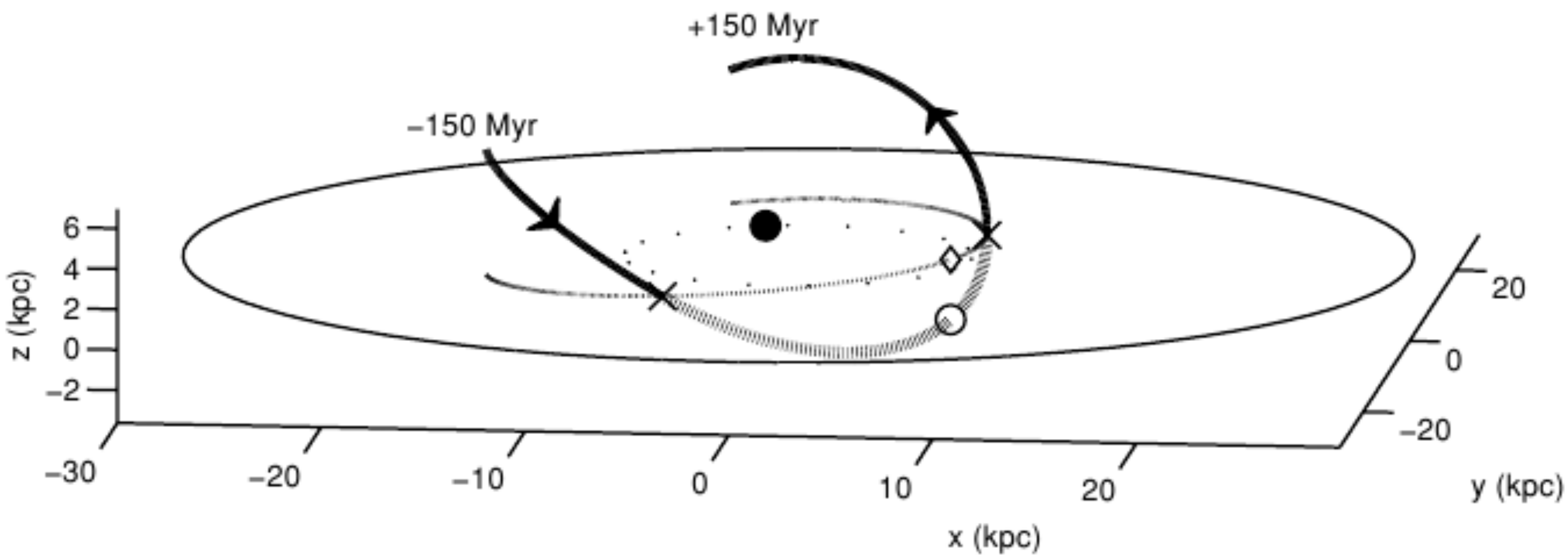




$V_{LSR} = 100$ Km/s

Lockman et al. 2008

Collision with the Disk: Smith Cloud

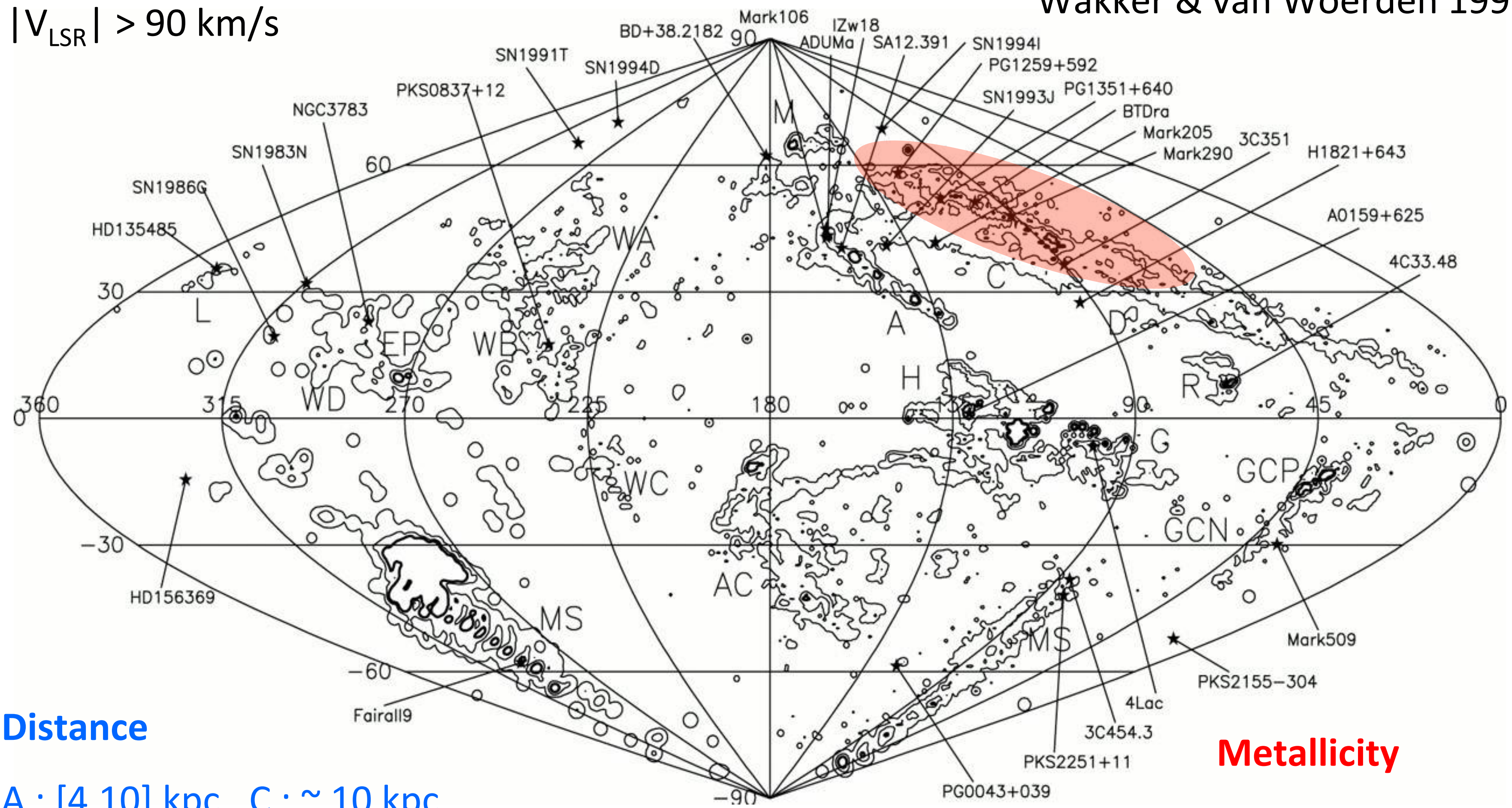


Nichols & Bland-Hawthorn 2009

Complex C

$|V_{LSR}| > 90$ km/s

Wakker & van Woerden 1997



Distance

A : [4,10] kpc, C : ~ 10 kpc

MII/MIII : < 5 kpc, H : > 5 kpc

EP : > 6.2 kpc, WB : < 8.4 kpc

Metallicity

C : ~ 0.1 Solar

MS : ~ 0.3 Solar

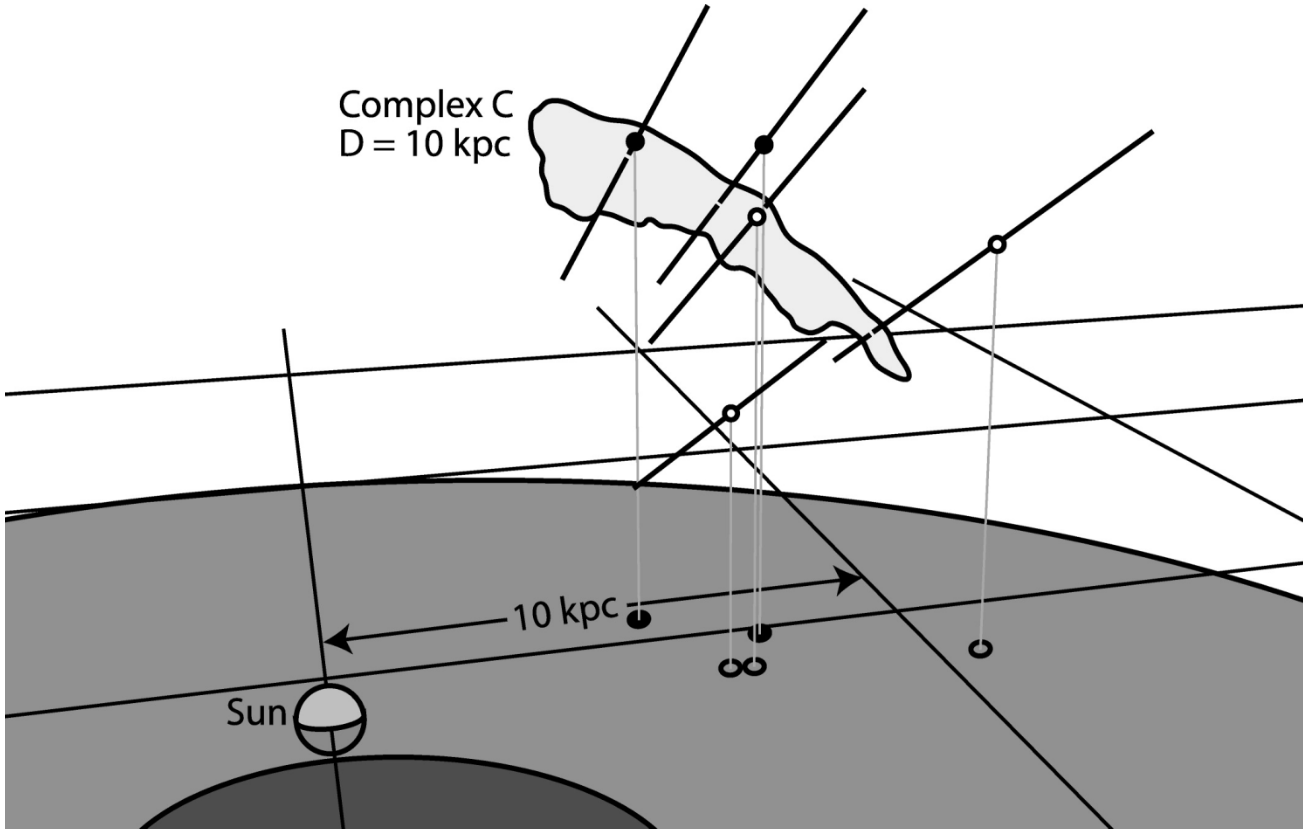
M : ~ Solar

Fate of HVC: Complex C

$M_{HI} = 5 \times 10^6 M_{sun}$

Accretion Rate ~ 0.1 M_{sun} / year

Metallicity ~ 0.1 – 0.5 solar across the cloud



Thom et al. 2008

Questions on Collision Scenario

- Can the cloud survive the collision?
- Can it maintain its cloud shape after the collision?
- (What if the cloud is embedded within the dark matter potential?)

Previous (Simulation) Works

- Tenorio-Tagle et al. 1986
  - h_{disk} = 100 pc (total width = 200 pc)

Table 1. Cloud-galaxy interactions

Case	n_g (cm^{-3})	n_c (cm^{-3})	R_c (pc)	V_r ($km\,s^{-1}$)	Mode	E_K (erg)
1	1	1	10	100	Radiative	$9.44\ 10^{48}$
2	1	1	10	100	Adiabatic	$9.44\ 10^{48}$
3	1	1	10	300	Adiabatic	$8.49\ 10^{49}$
4	1	0.1	10	300	Radiative	$8.49\ 10^{48}$
5	1	100	10	300	Radiative	$8.49\ 10^{51}$
6	1	10	10	300	Radiative	$8.49\ 10^{50}$
7	1	1	10	300	Radiative	$8.49\ 10^{49}$
8	1	1	20	300	Radiative	$6.8\ 10^{50}$

Previous Works (Cont'd)

- Tenorio-Tagle et al. 1987
  - Include Galactic gravity

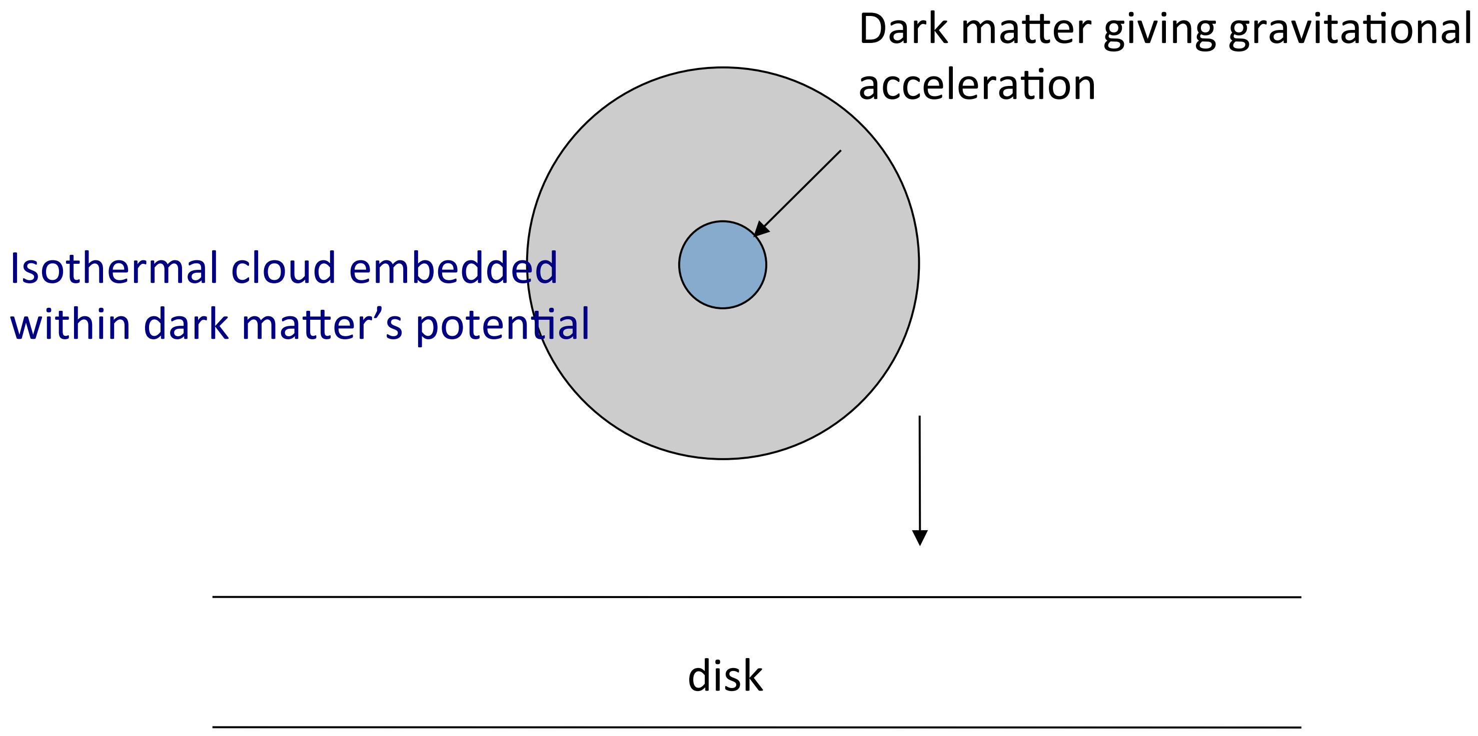
Table 1. Parameters for the disk

Region	$\rho_g(0)$ (10^{-24} g cm^{-3})	h (pc)
GI	15[a]	70[a]
GII	5[b]	100[b]
GIII	0.5[b]	500[c]

[a] From Sanders et al., 1984.
[b] See text.
[c] Kulkarni et al., 1982

Table 2. Models with spherical clouds

Model	Region	n_c (cm^{-3})	R_c (pc)	V_c (km s^{-1})	E_K (erg)	Z_i (pc)
1	GII	1	30	100	$2.5\,10^{50}$	400
2	GI	1	100	100	$9.5\,10^{51}$	650
3	GII	1	100	100	$9.5\,10^{51}$	650
4	GIII	1	100	100	$9.5\,10^{51}$	650
5	GII	0.3	100	50	$7.0\,10^{50}$	650
6	GII	0.3	100	100	$2.8\,10^{51}$	650
7	GII	0.3	100	300	$2.5\,10^{52}$	650
8	GIII	0.3	100	50	$2.4\,10^{51}$	650
9	GIII	1	100	50	$7.0\,10^{50}$	650
10	GIII	1	30	50	$6.4\,10^{49}$	720

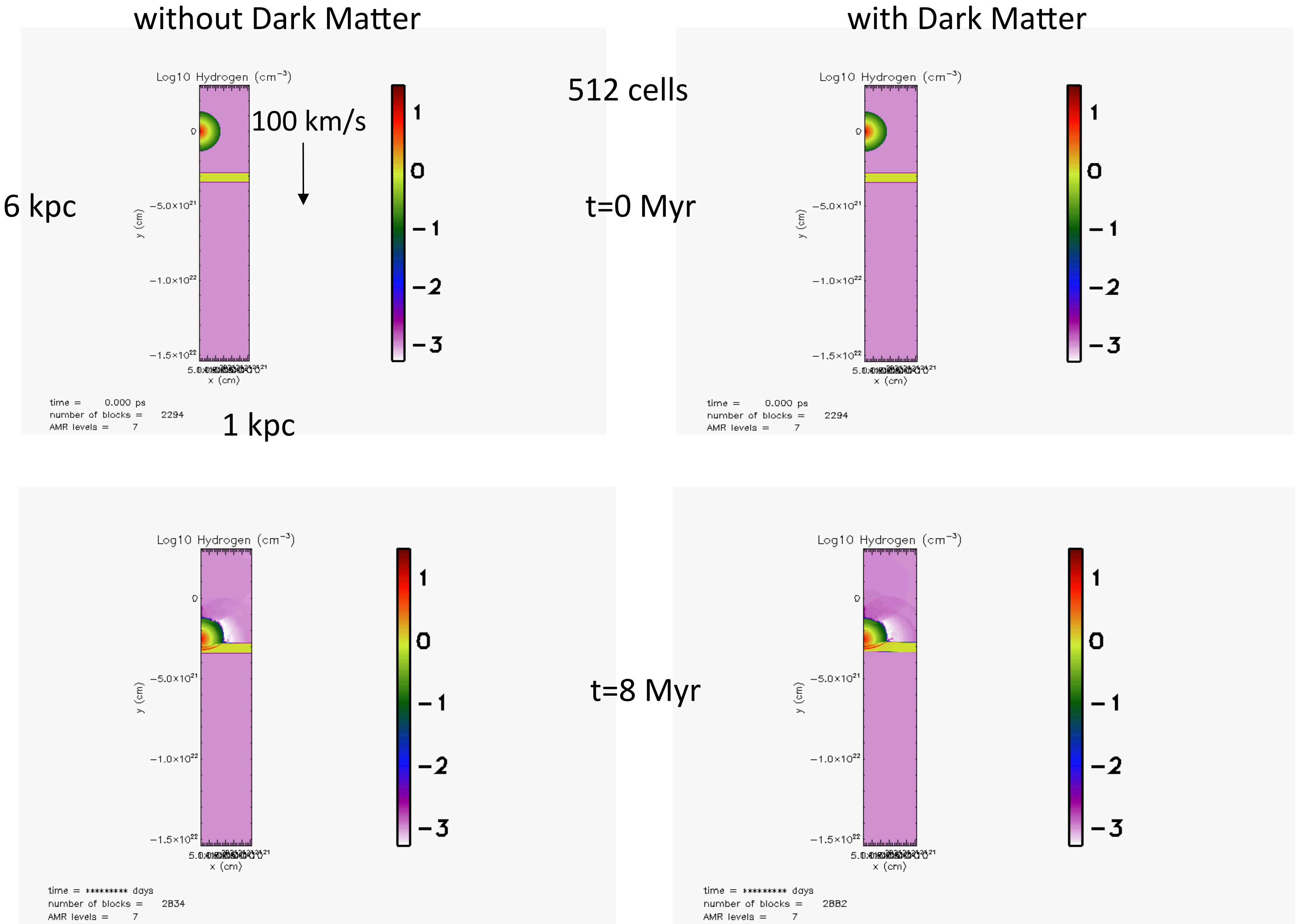

Dark matter giving gravitational acceleration
Isothermal cloud embedded within dark matter's potential
disk

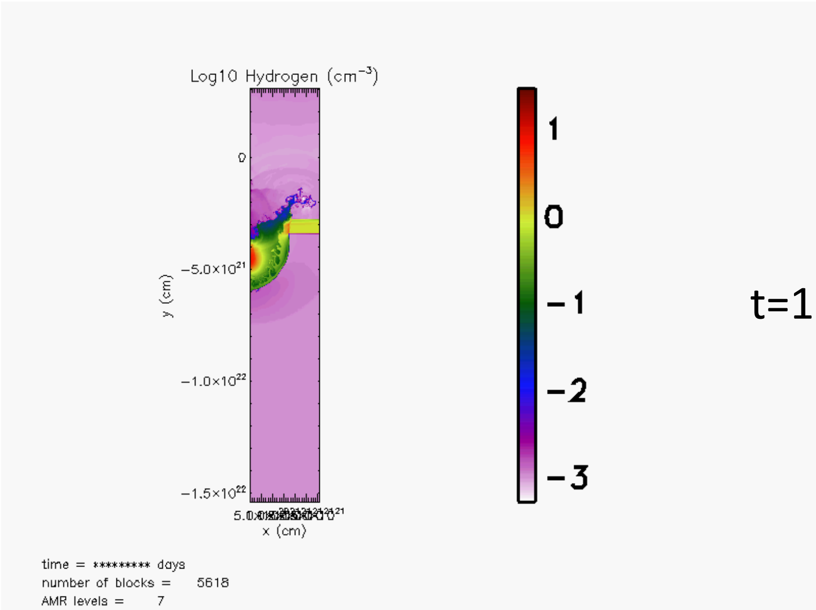
Use the Properties of Dark Matter Halo from Sternberg, McKee, & Wolfire, 2002

- Hot ISM gas
  - $n_{H,ism} = 10^{-3}$ cm^{-3}
  - $T_{ism} = 10^6$ K
- T_{cloud} = 5000 K
- $n_{H,center}$ = 100 cm^{-3}
- X_0 ~ 0.04 (<< 1) i.e., r_{cloud} ~ 110 pc

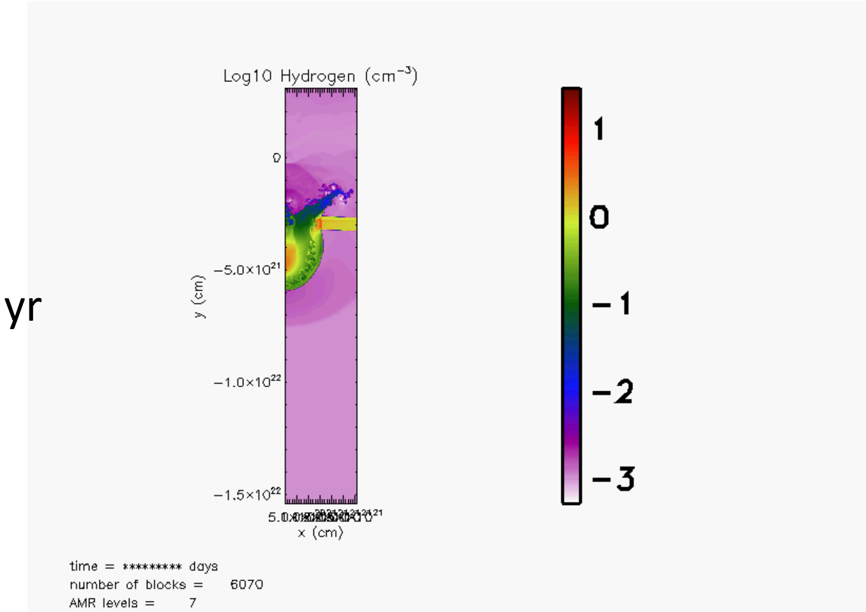
: being consistent with $f_{\rm gas} = \exp\left[-(3/2)\left(v_s^2/c_g^2\right)x\right]$

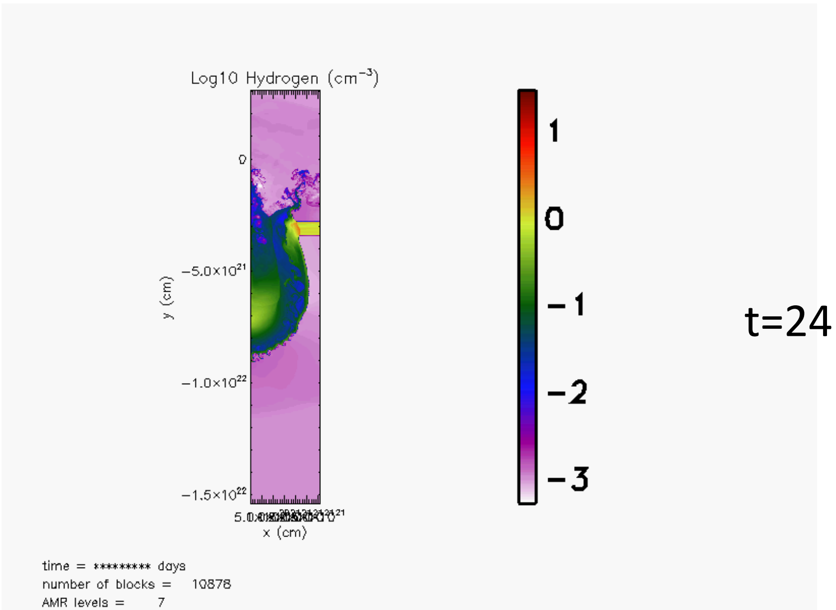
- M_{cloud} ~ 6.5x10^5 M_{sun}


without Dark Matter
with Dark Matter
512 cells
100 km/s
6 kpc
1 kpc
t=0 Myr
t=8 Myr
Log10 Hydrogen (cm^{-3})
y (cm)
x (cm)
time = 0.000 ps
number of blocks = 2294
AMR levels = 7
time = ********* days
number of blocks = 2834
number of blocks = 2882

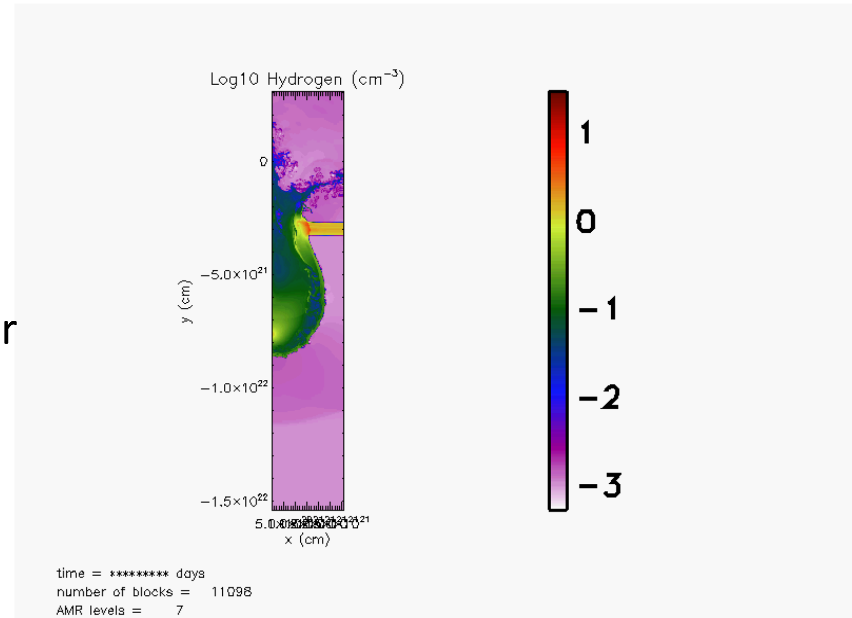


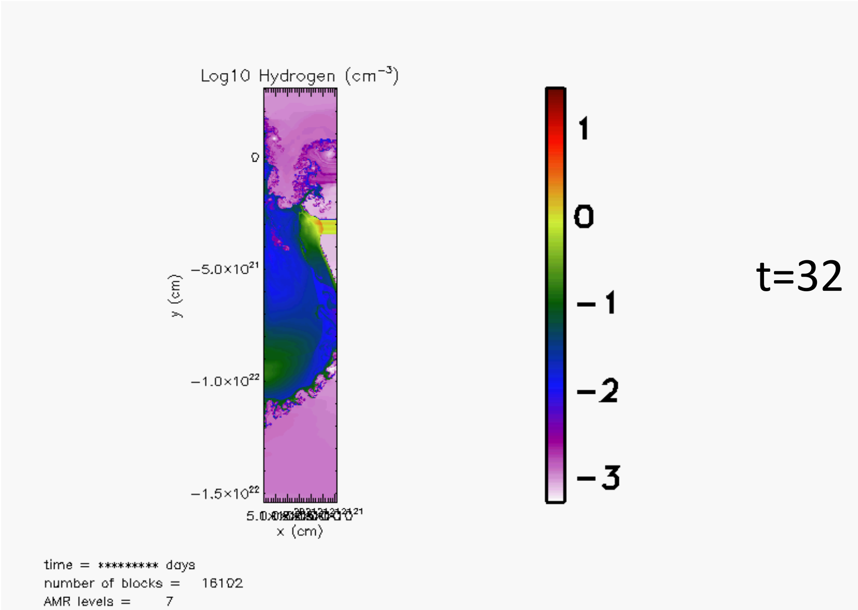
t=16 Myr



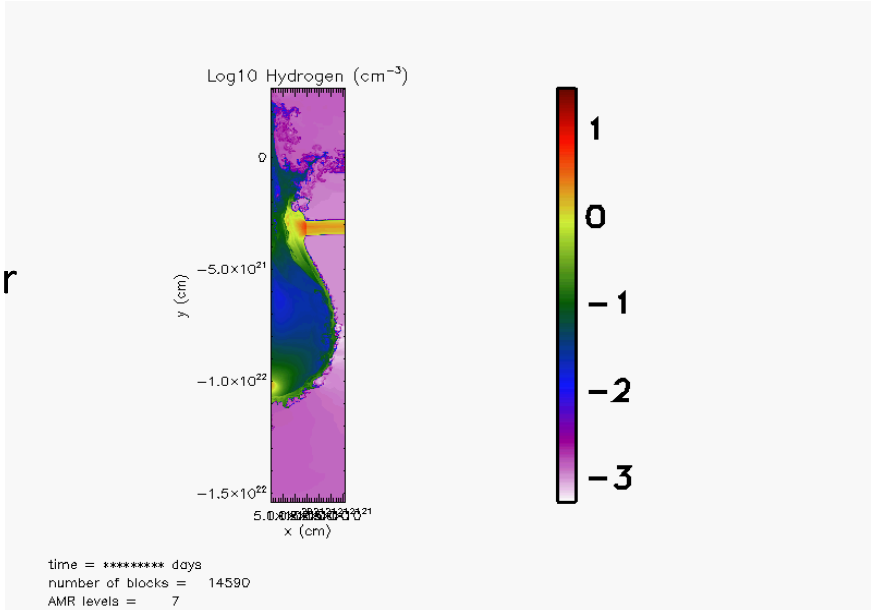


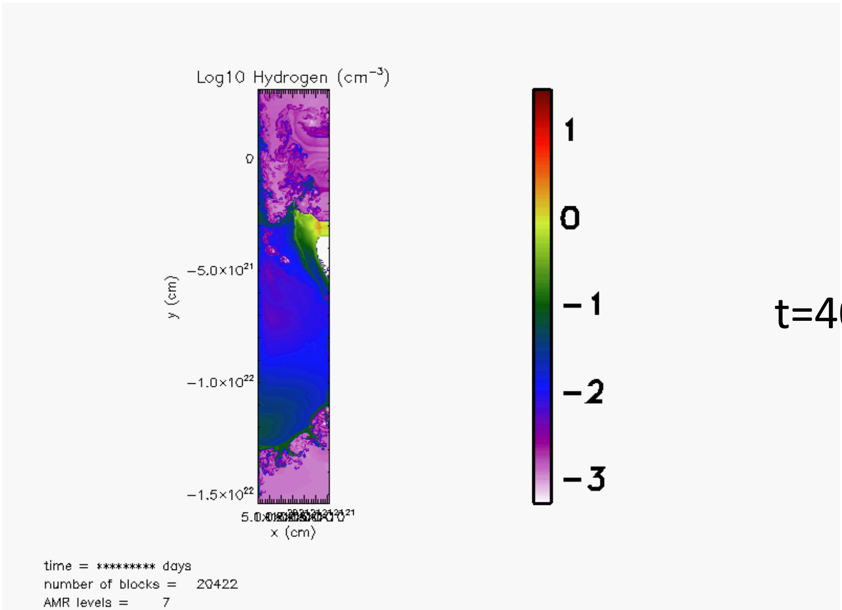
t=24 Myr



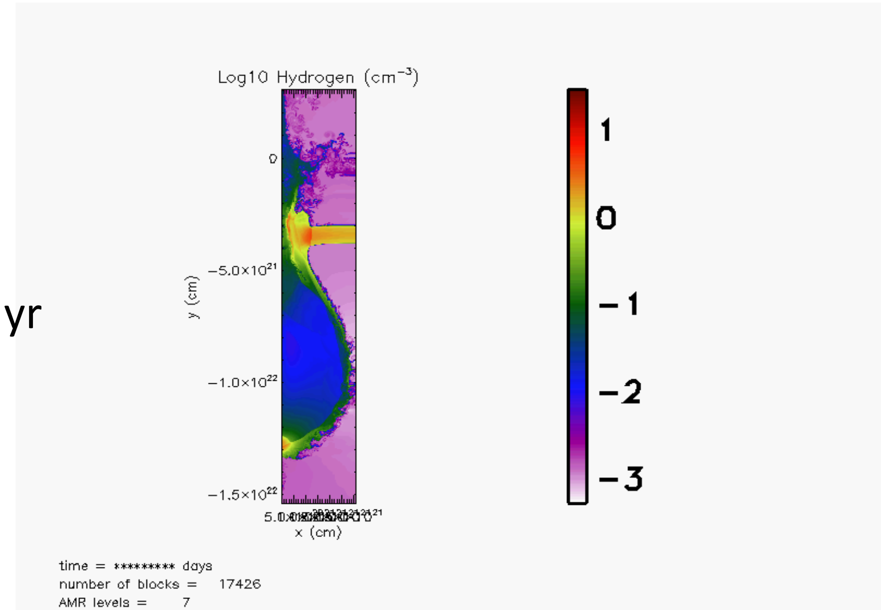


t=32 Myr





t=40 Myr



FLASH

- Developed as open source at Univ. of Chicago (Fryxell et al. 2000, ApJS)
- Modular Package written in Fortran 90
  - Multi-dimension Hydrodynamics including MHD and RHD
  - Parallel Adaptive Mesh Refinement by using PARAMESH
  - Various physical processes: radiative cooling due to line emission, thermal diffusion, gravity, particle tracking, ionization of atoms, nuclear burning with selected chain reactions, etc.

Ionization Module in FLASH

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P &= \rho \mathbf{g} \\
\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\, \mathbf{v}] &= \rho \mathbf{v} \cdot \mathbf{g} \ [+S] \\
\frac{\partial n_i^Z}{\partial t} + \nabla \cdot n_i^Z \mathbf{v} &= R_i^Z \quad (i = 1, \ldots, N_{spec}) ,
\end{aligned}$$

$$R_i^Z = N_e [n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z (\alpha_i^Z + S_i^Z)] ,$$

$$\frac{\partial n_i^Z}{\partial t} = R_i^Z \ (i = 1, \ldots, N_{spec})$$

Non-Equilibrium Cooling in FLASH

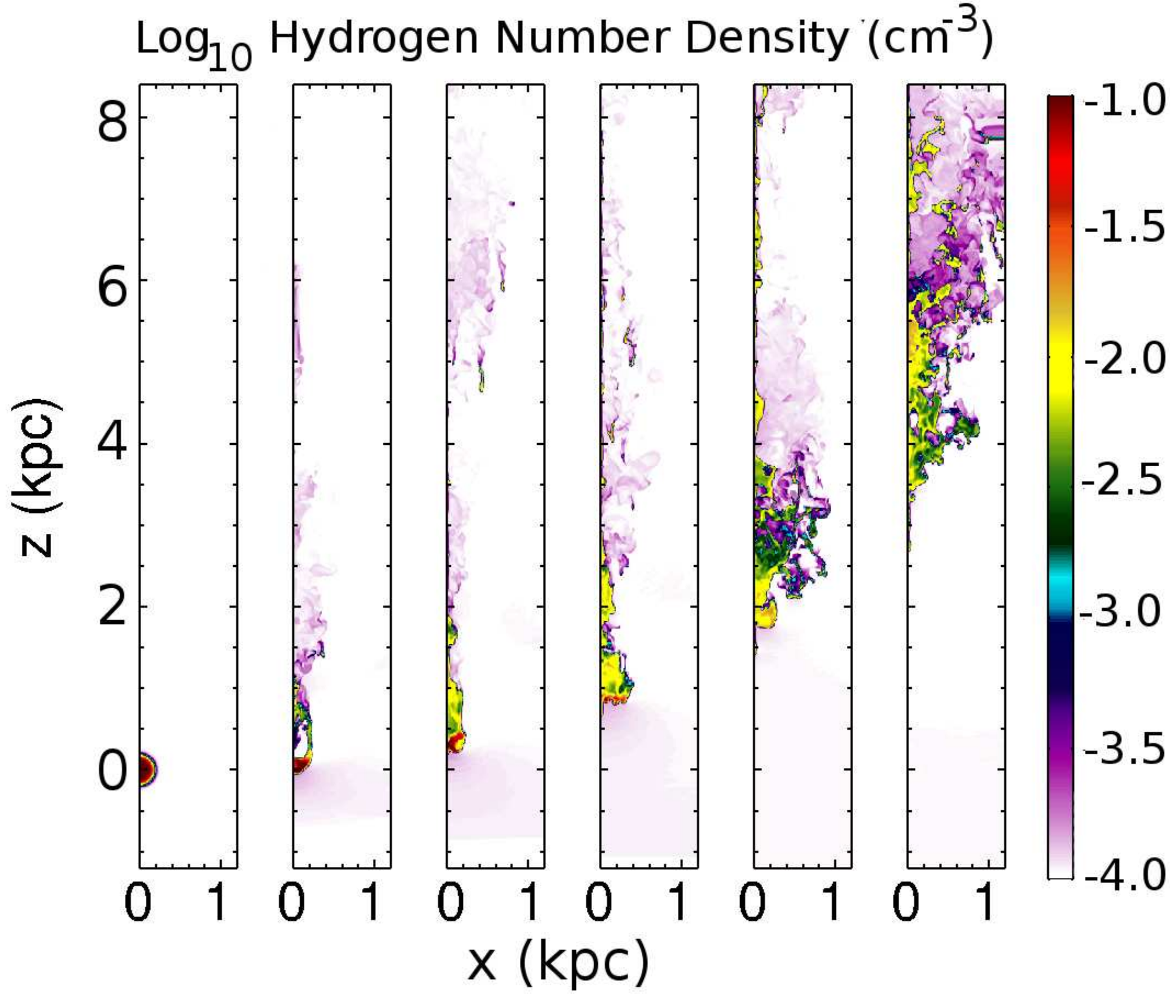
$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P &= \rho \mathbf{g} \\
\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\,\mathbf{v}] &= \rho \mathbf{v} \cdot \mathbf{g} \; [+ S\,] \\
\frac{\partial n_i^Z}{\partial t} + \nabla \cdot n_i^Z \mathbf{v} &= R_i^Z \quad (i = 1, \ldots, N_{spec}) \;,
\end{aligned}$$

$$R_i^Z = N_e [n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z (\alpha_i^Z + S_i^Z)] \;,$$

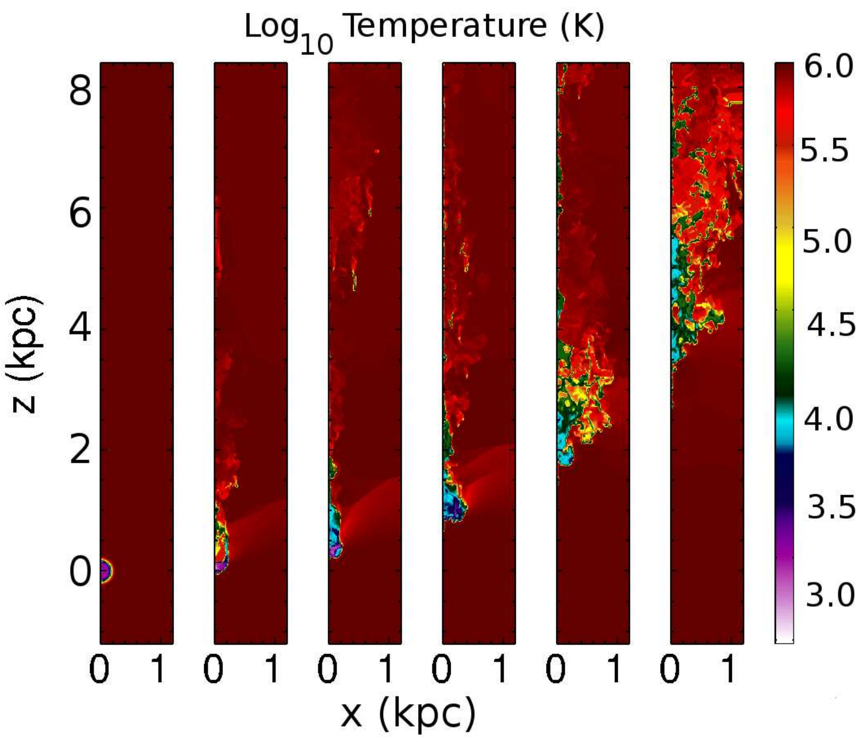
$$\frac{\partial n_i^Z}{\partial t} = R_i^Z \;\; (i = 1, \ldots, N_{spec})$$

Tracing ionization states of abundant elements H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni (~200 ionization states)

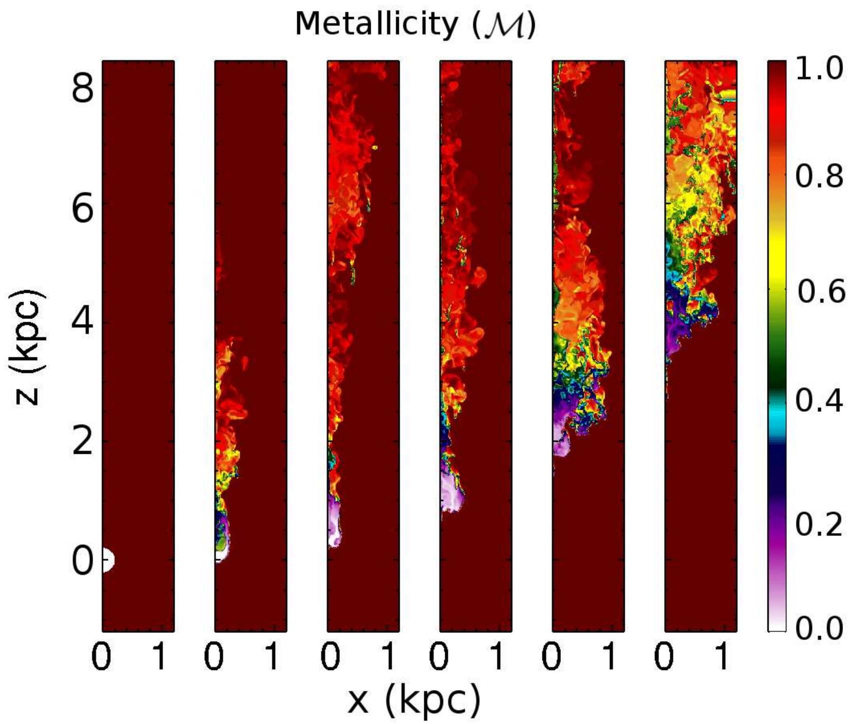
Metallicity Mixing in the Halo



Gritton, Shelton, and Kwak (2014)

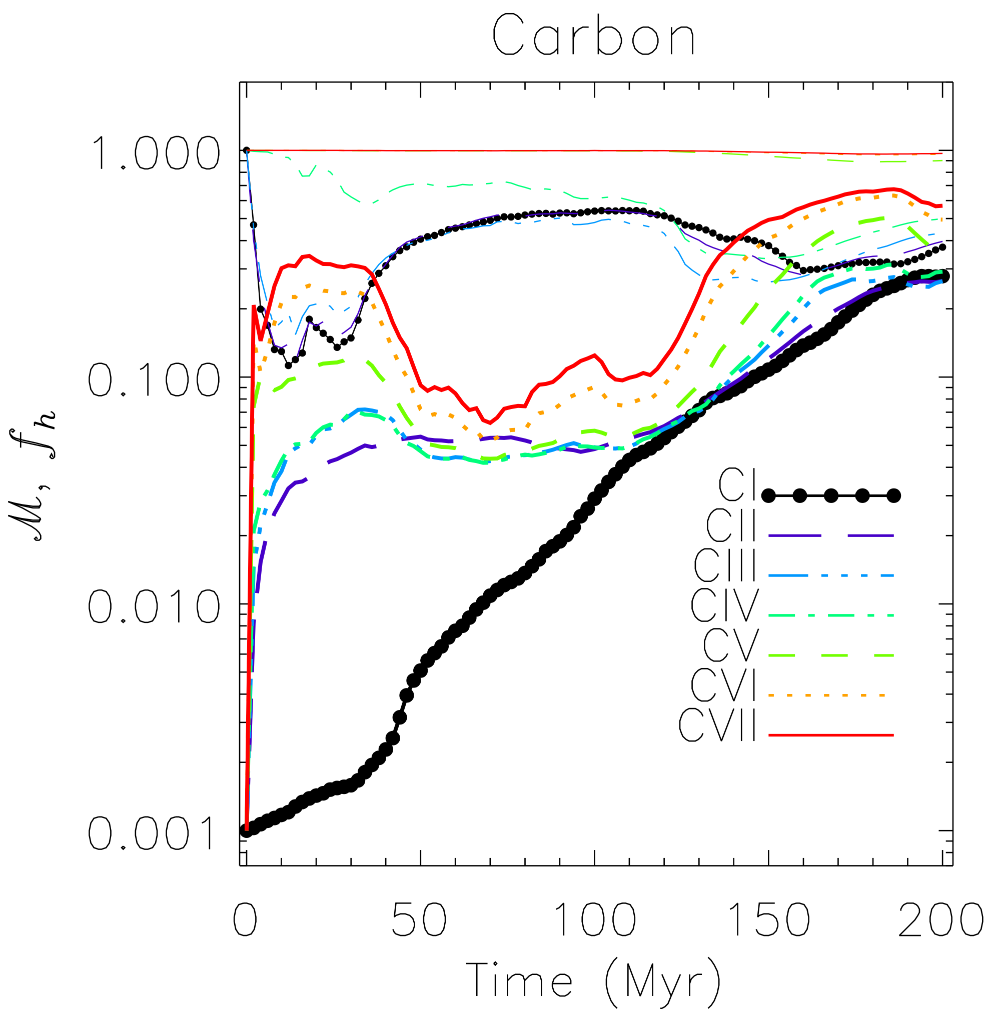


Log$_{10}$ Temperature (K)
z (kpc)
x (kpc)
0 2 4 6 8
0 1
6.0 5.5 5.0 4.5 4.0 3.5 3.0



Metallicity ($\mathcal{M}$)
z (kpc)
x (kpc)
0 2 4 6 8
0 1
1.0 0.8 0.6 0.4 0.2 0.0

Mixing Efficiency with Velocities



Summary

- Metallicity evolution history in the Galactic disk could be affected by the collision of metal-poor HVCs and this process could be traced by numerical simulations that should be capable of tracing the abundance mixing.

Acknowledgements

- Kwang Hyun Sung
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