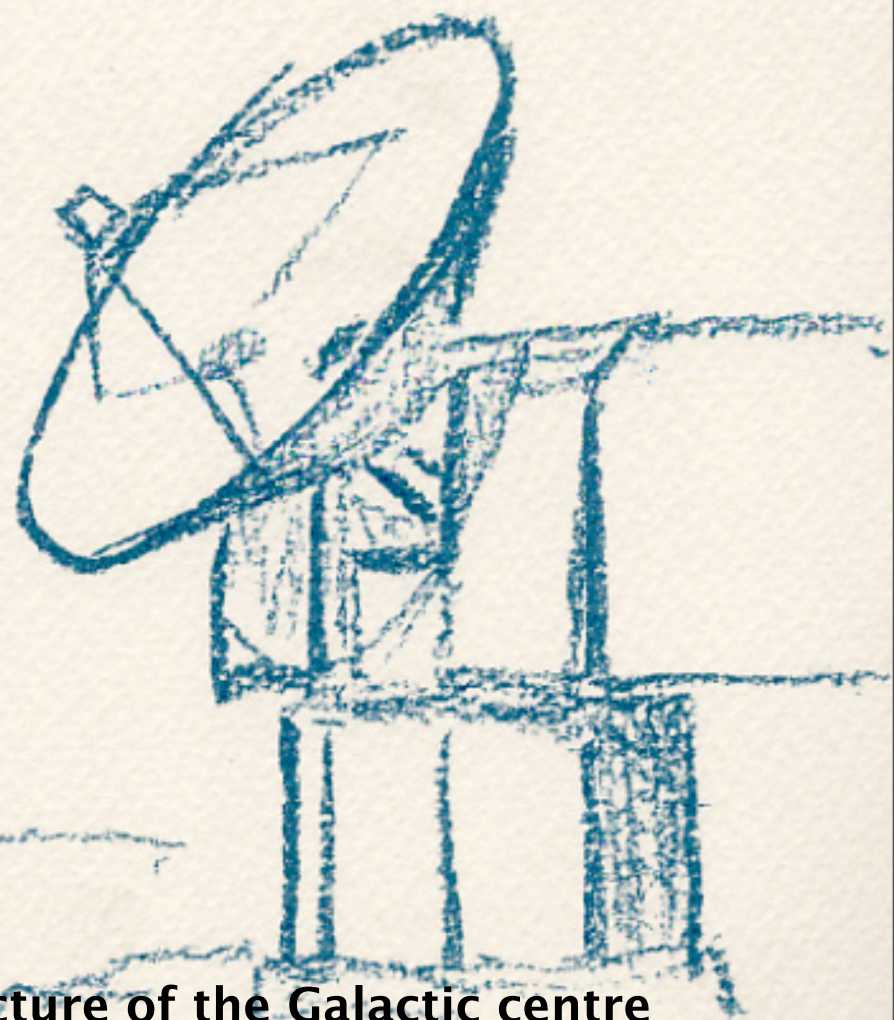
Association of molecular clouds with high energy features in the Galactic centre



Yasuo Fukui

Nagoya University

The emerging, multi-wavelength picture of the Galactic centre
October 17-20, 2011 Heidelberg

Molecular clouds vs. high energy radiation

1) CO-TeV gamma rays correspondence, hadronic process

   [HESS1745, Hayakawa et al. 2012 PASJ in press]

2) CO-X rays correspondence, good

   -- Cosmic ray acceleration in CMZ,

   [SNRs or 2nd order Fermi, Amano+ 2011 PASJ in press]

3) CO-radio lobe correlation, possible

4) Origin of vertical high-b features, star formation or Parker instability

   [Fukui et al. 2006, Science 314,106]

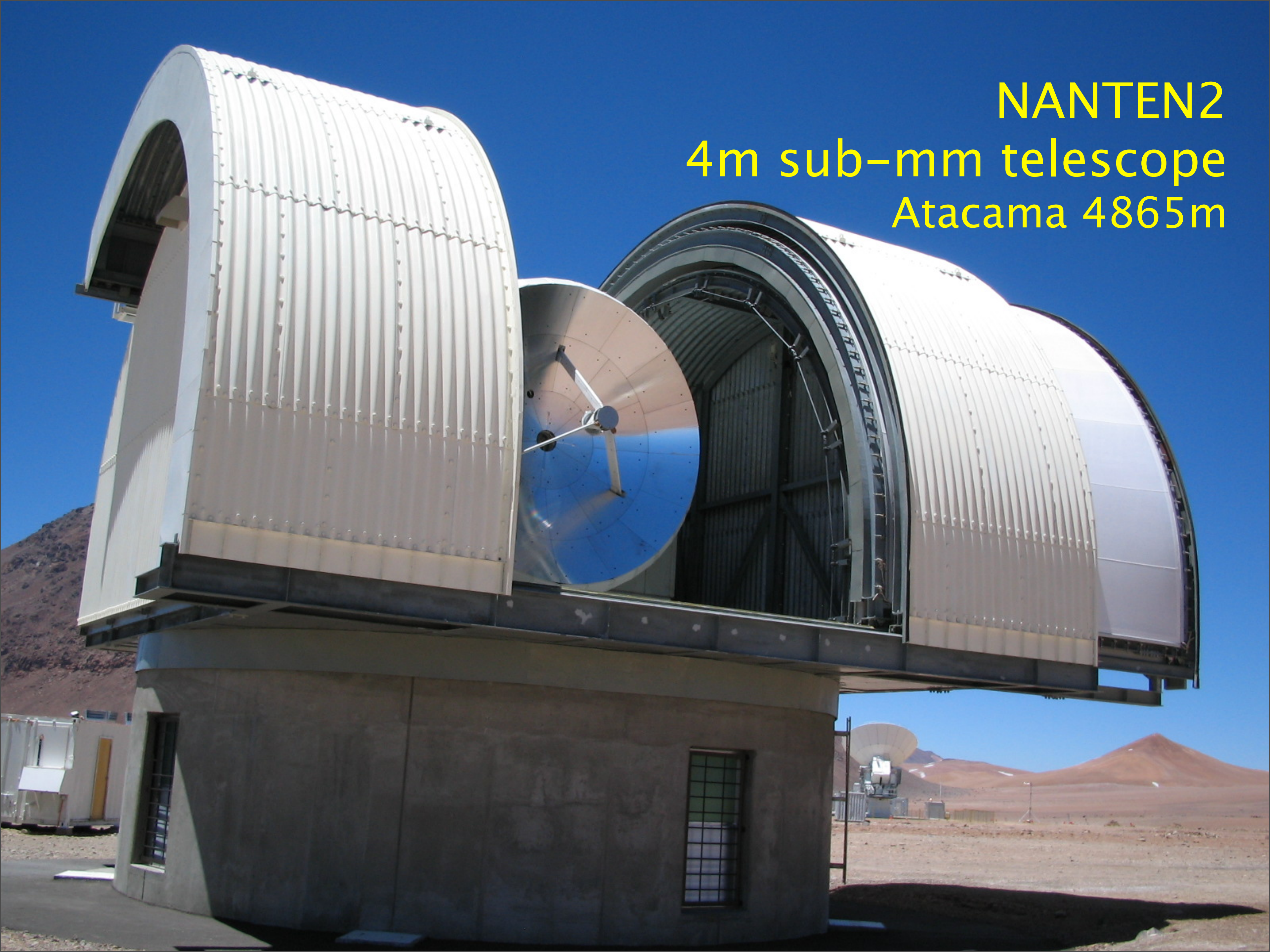
5) High mass stars: Cluster formation and isolated high mass star in the dense foot points, triggered by cloud-cloud collision;

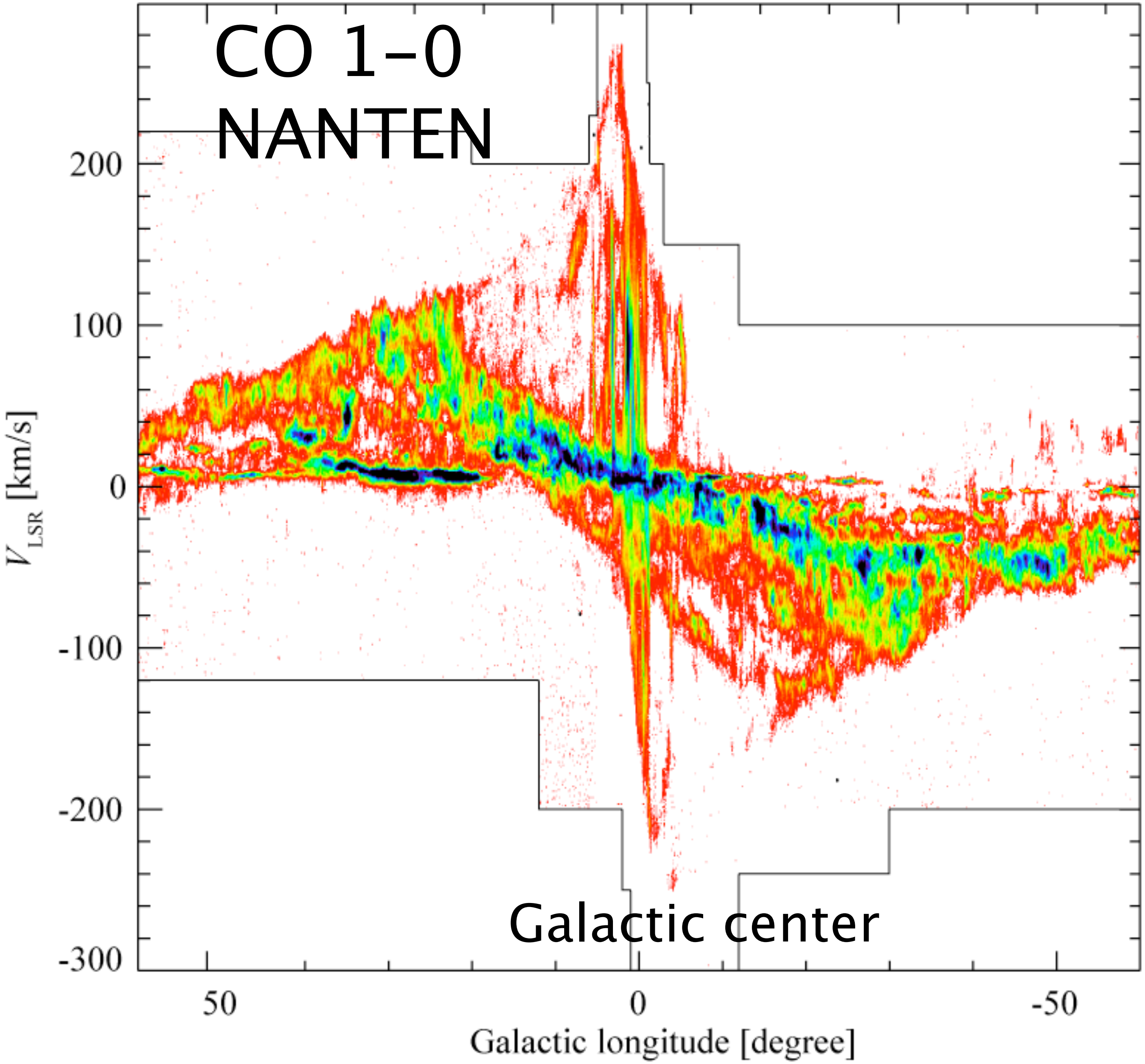
   Sgr C and Sgr B2 and ~ 30 high mass stars

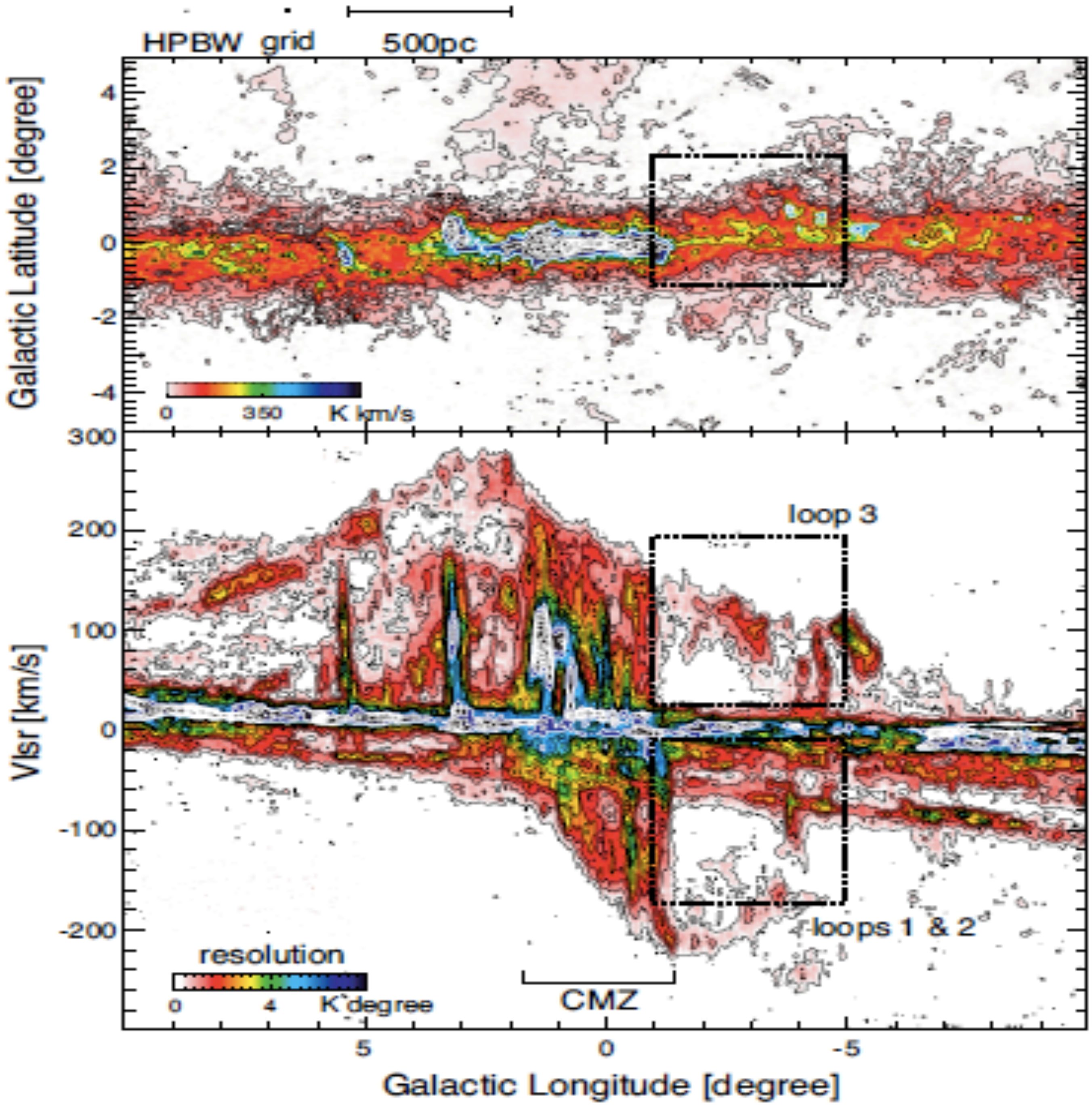
   [e.g., cloud-cloud collision in M20, Torii et al. 2011 ApJ 738, 46]

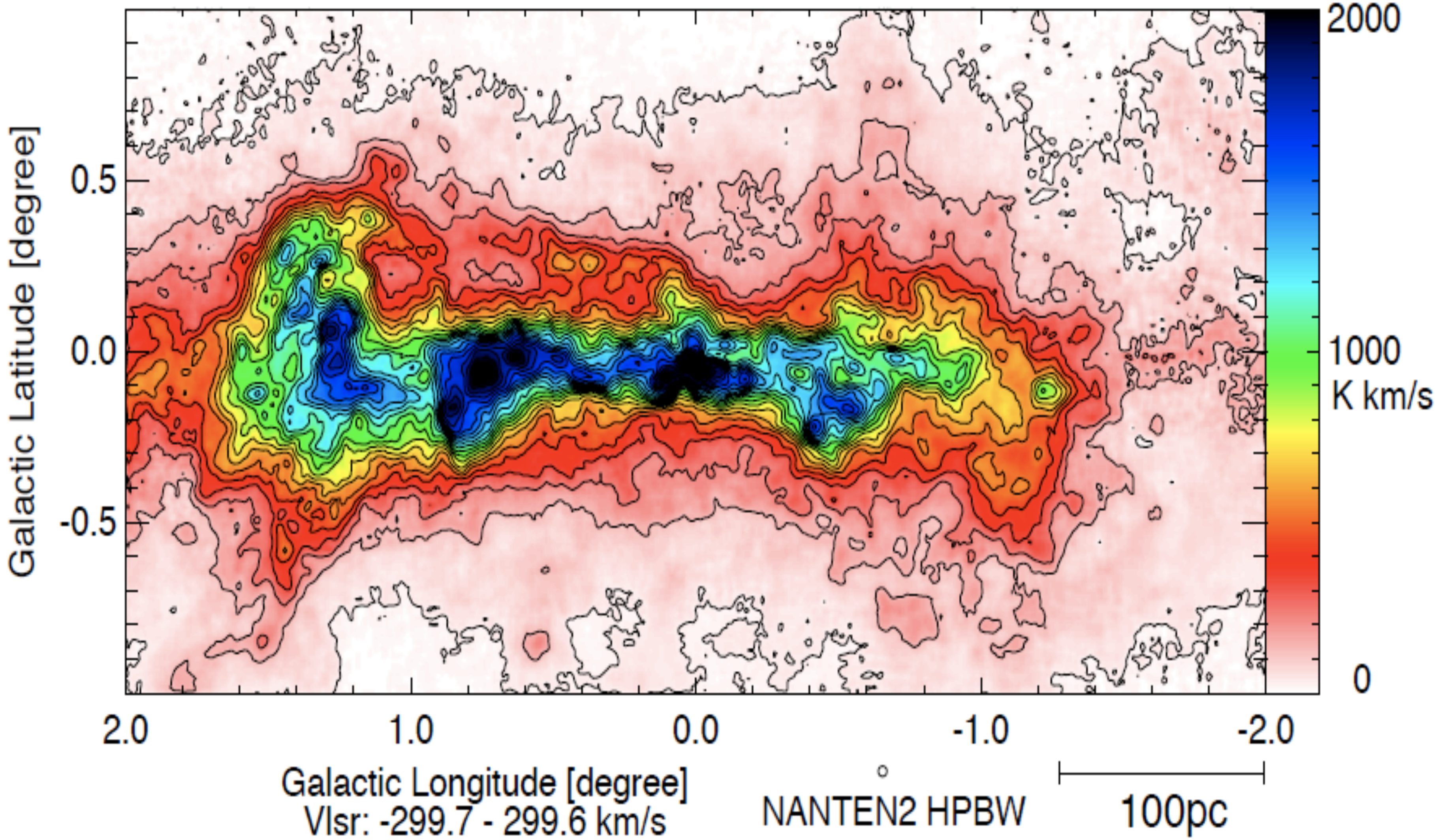
Molecular halo of the CMZ

- CO is the best tool to probe dense gas, small A_{10} coeff.
  CO only is sensitive to low density molecular gas (several x 100 cm^{-3})
- CMZ halo of 10^6 Mo over the CMZ
  [talk Kazufumi Torii]
- Molecular clouds toward DHN above Sgr A*
  [talk Rei Enokiya]
- High z of 200pc requires "wind" from the CMZ. Possible connection with the wind by magnetic or stellar activity

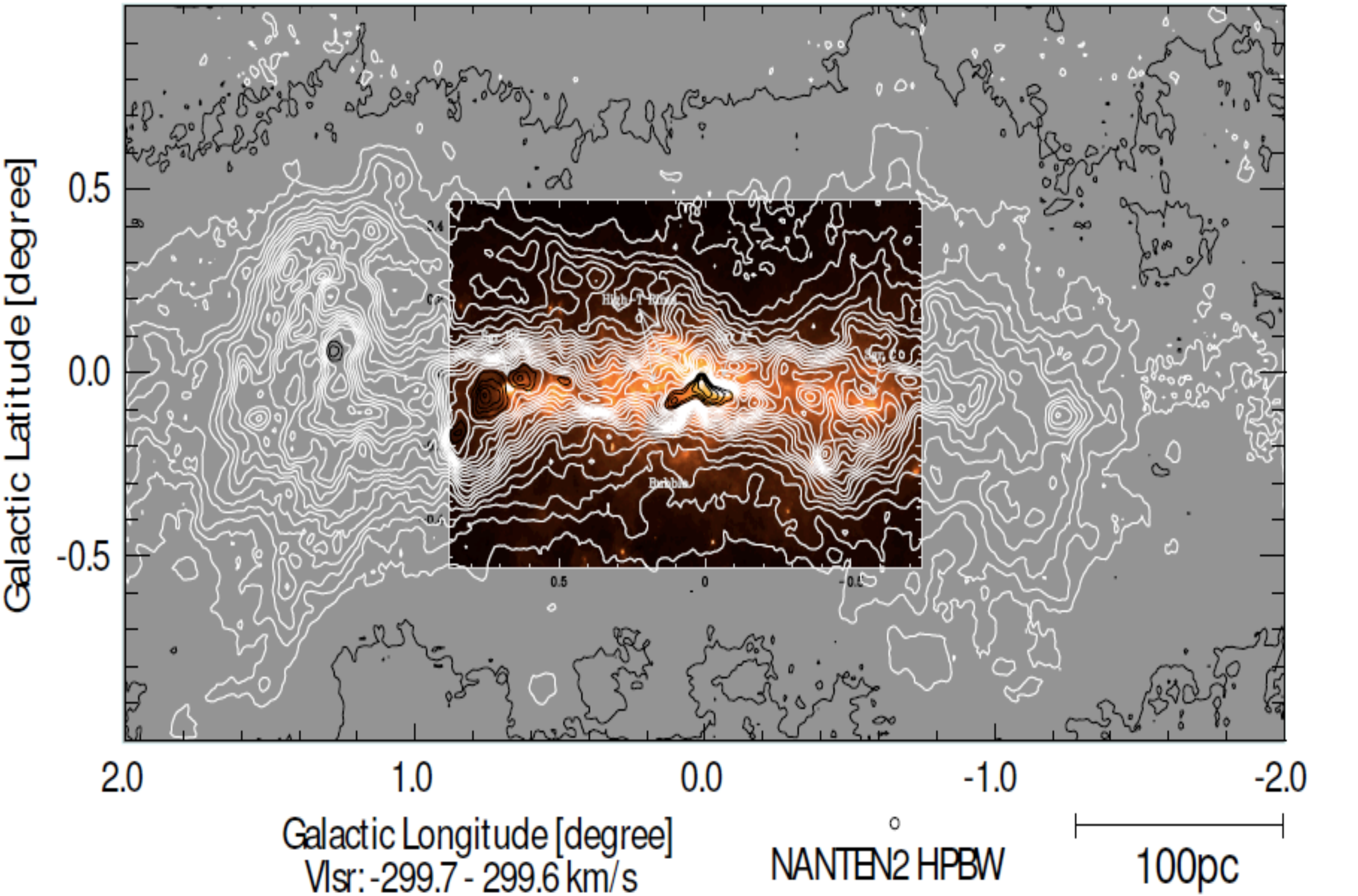

NANTEN2
4m sub-mm telescope
Atacama 4865m


CO 1–0
NANTEN
Galactic center
200
100
0
-100
-200
-300
V_{LSR} [km/s]
50
0
-50
Galactic longitude [degree]


HPBW grid
500pc
Galactic Latitude [degree]
0
350
K km/s
loop 3
loops 1 & 2
Vlsr [km/s]
resolution
0
4
K degree
CMZ
Galactic Longitude [degree]

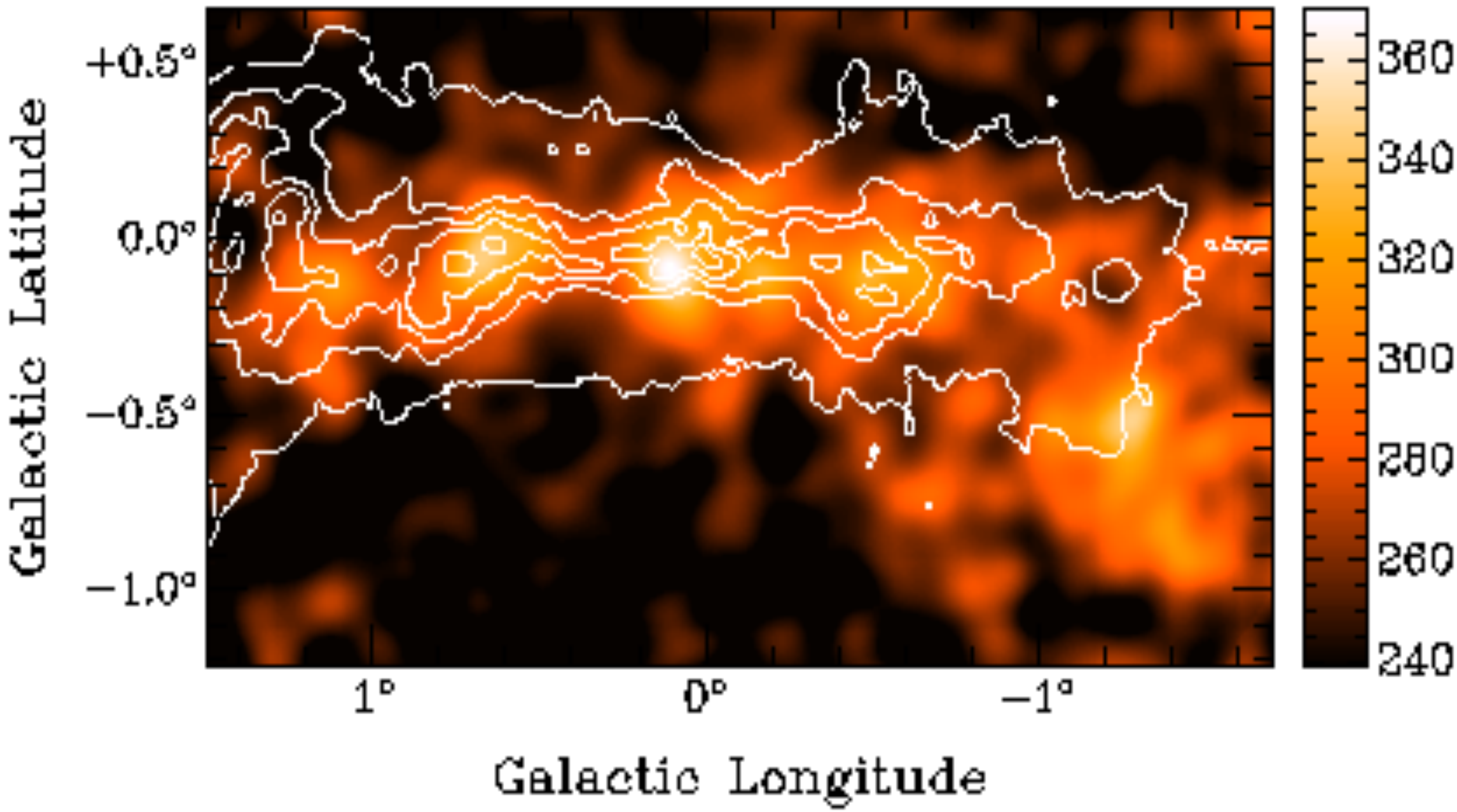


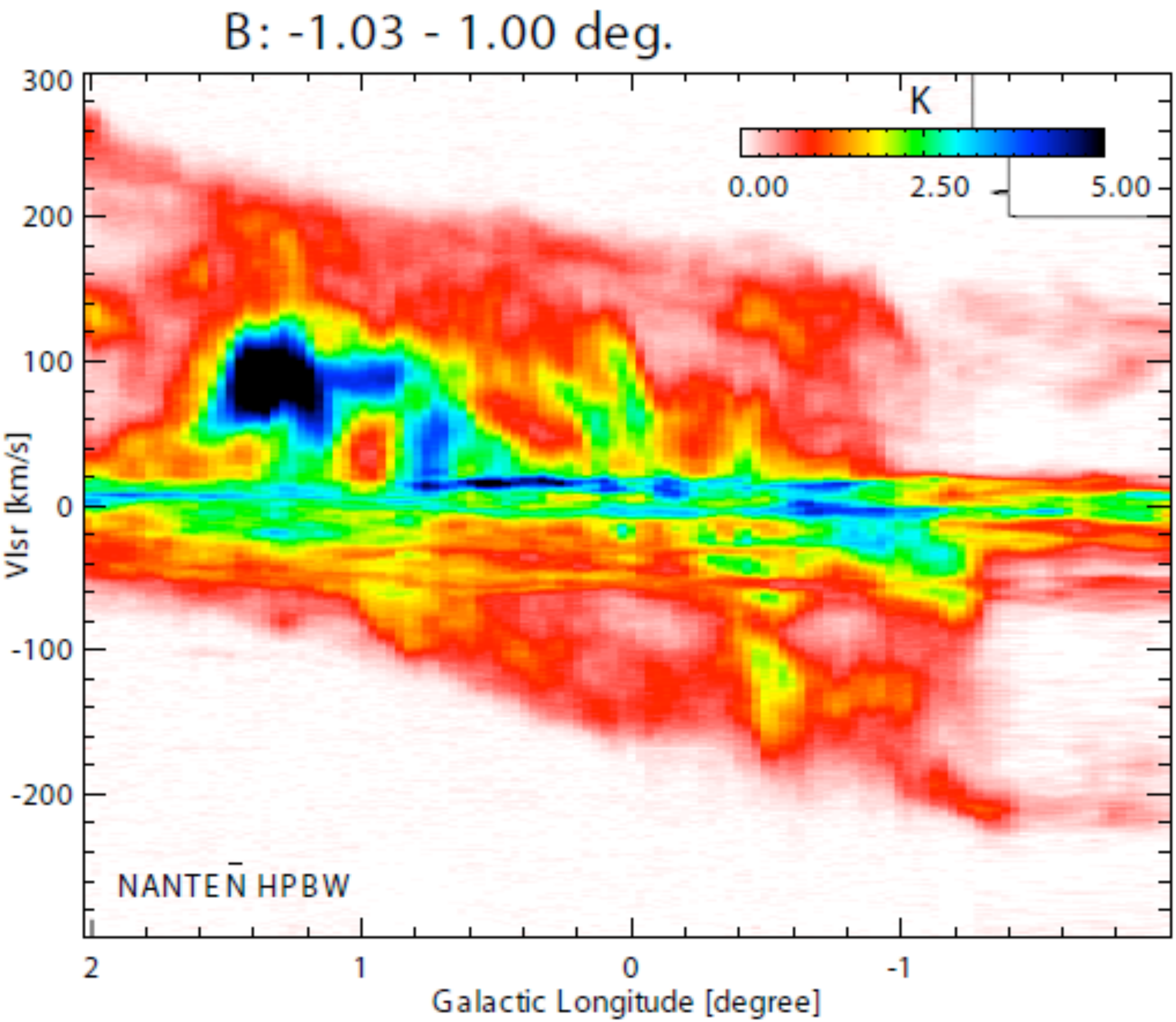
2000
1000
K km/s
0
0.5
0.0
-0.5
Galactic Latitude [degree]
2.0
1.0
0.0
-1.0
-2.0
Galactic Longitude [degree]
Vlsr: -299.7 - 299.6 km/s
NANTEN2 HPBW
100pc

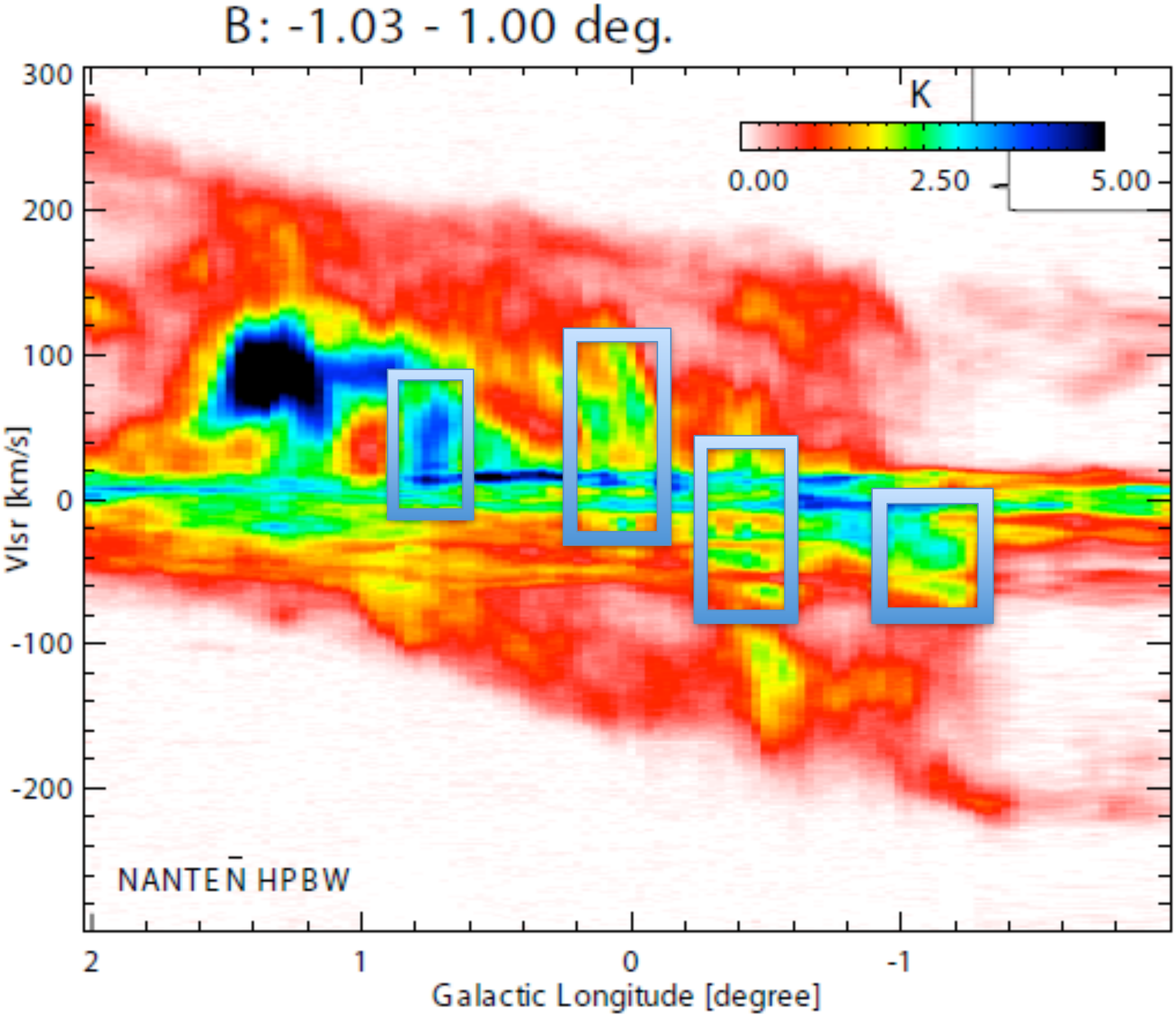


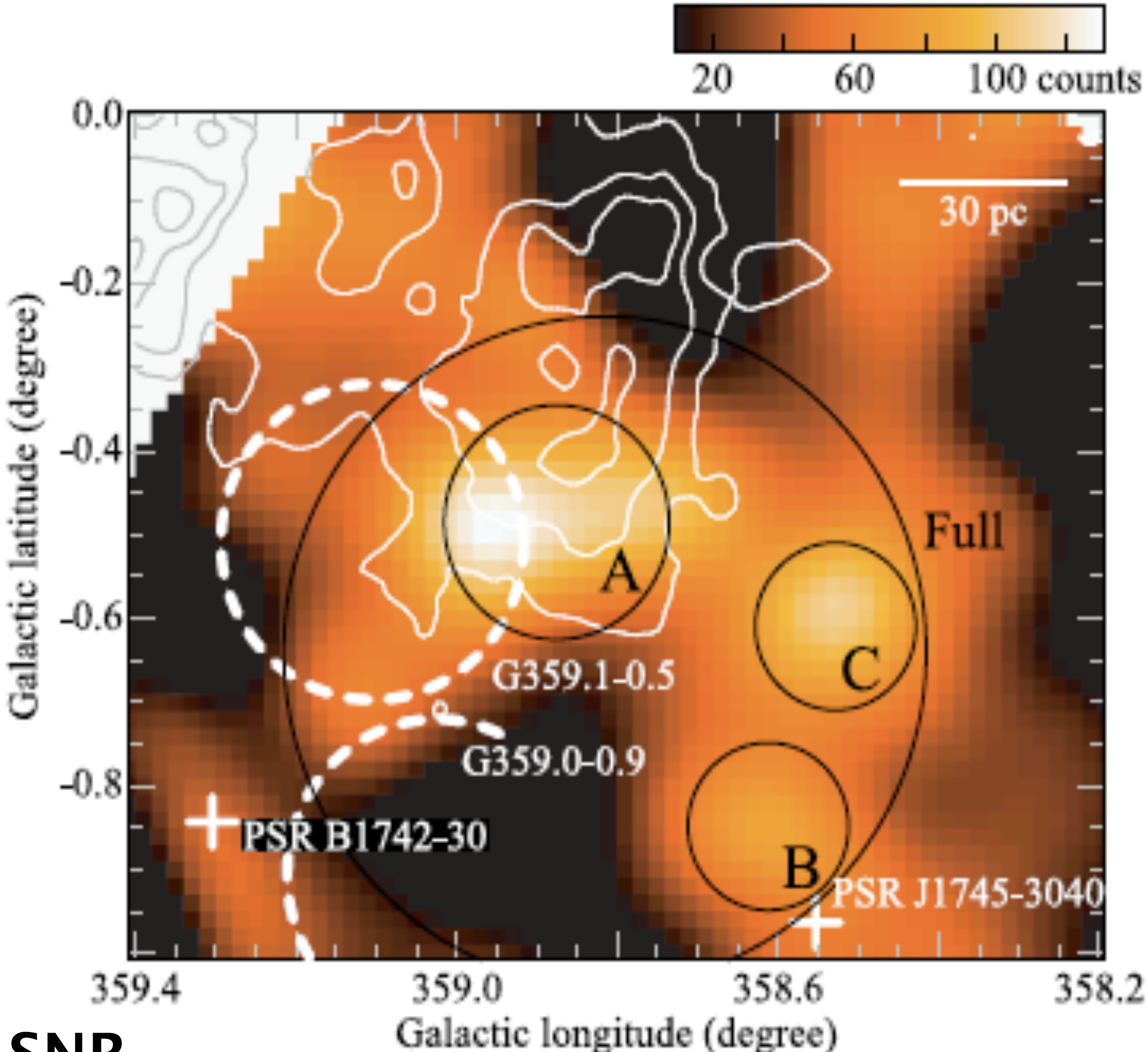
Galactic Latitude [degree]
0.5
0.0
-0.5
2.0
1.0
0.0
-1.0
-2.0
Galactic Longitude [degree]
Vlsr: -299.7 - 299.6 km/s
NANTEN2 HPBW
100pc

GC TeV gamma rays vs. CO



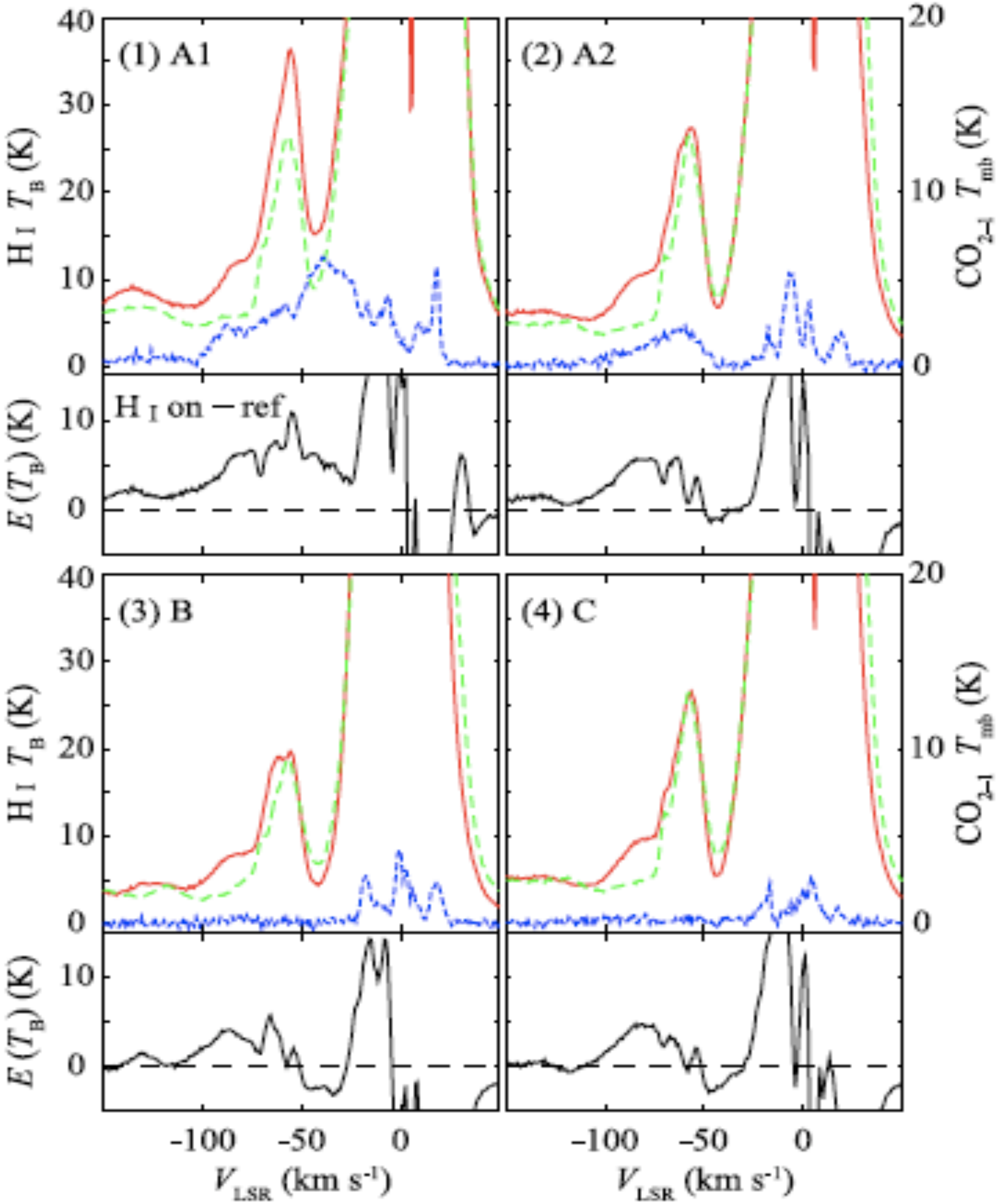

B: -1.03 - 1.00 deg.
K
0.00
2.50
5.00
300
200
100
0
-100
-200
Vlsr [km/s]
2
1
0
-1
Galactic Longitude [degree]
NANTEN HPBW


B: -1.03 - 1.00 deg.
K
0.00
2.50
5.00
300
200
100
0
-100
-200
Vlsr [km/s]
2
1
0
-1
Galactic Longitude [degree]
NANTEN HPBW



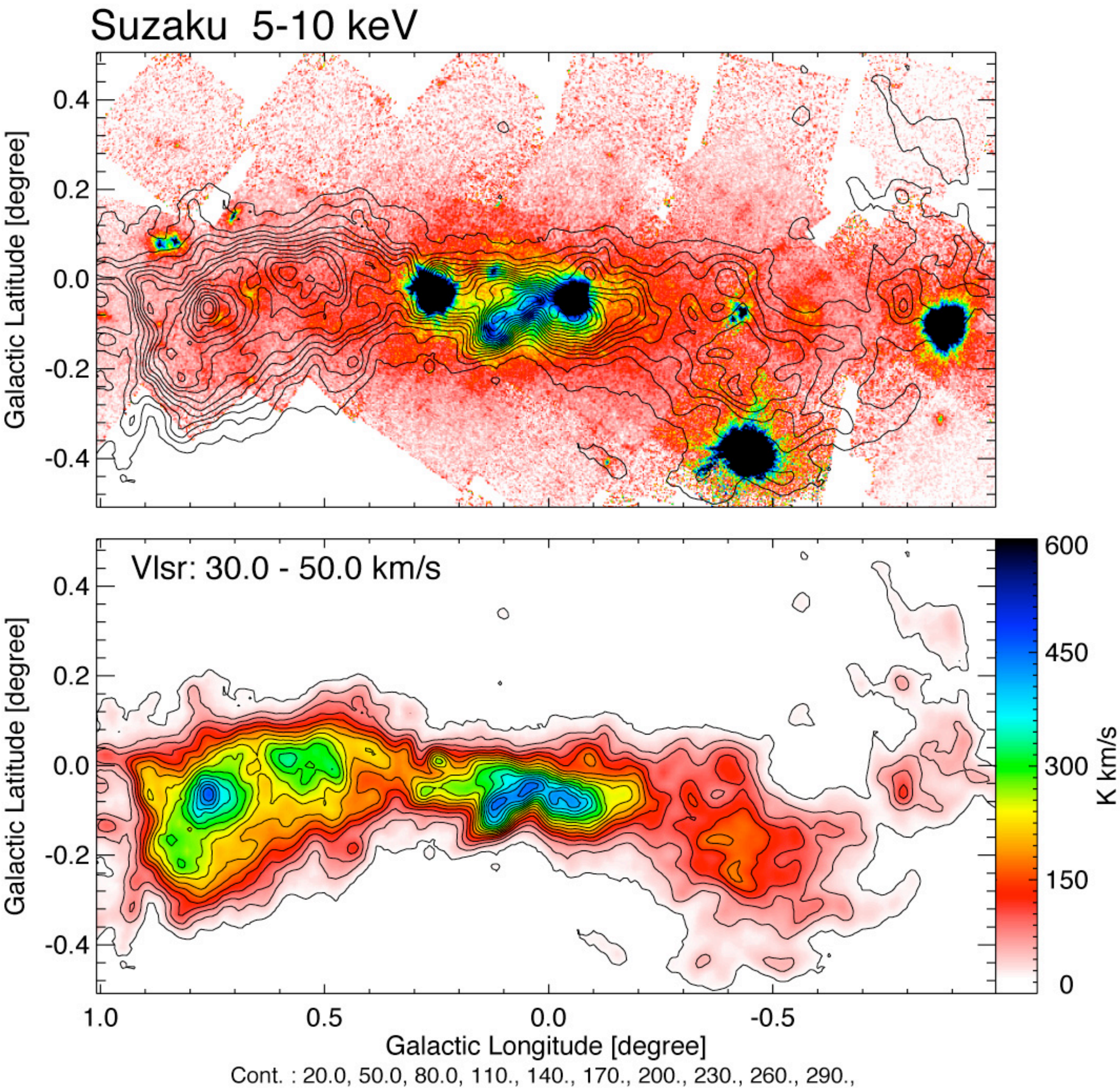
Dashed SNR
Orange HESS
White NANTEN2 CO

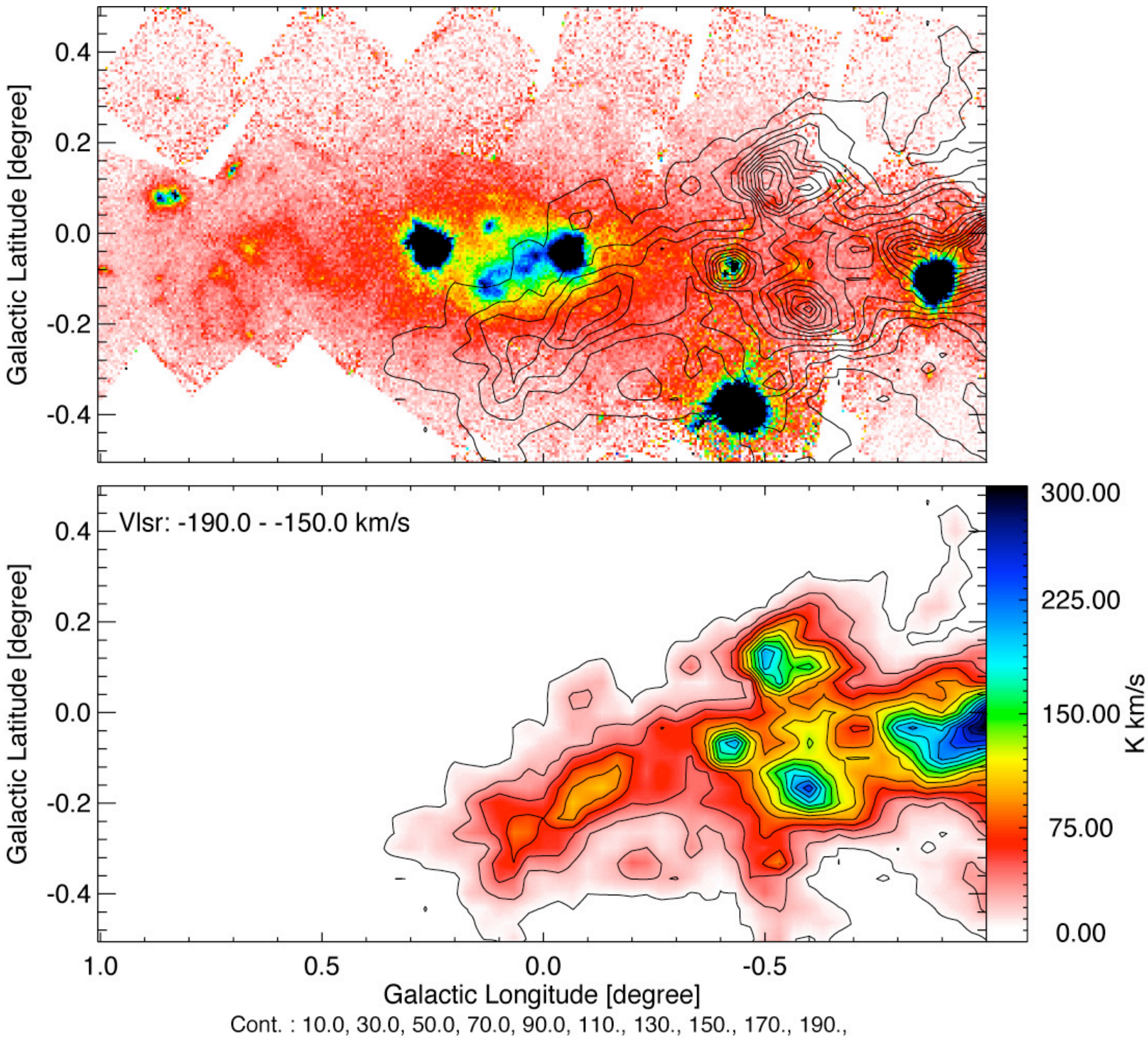
Hayakawa et al. 2011



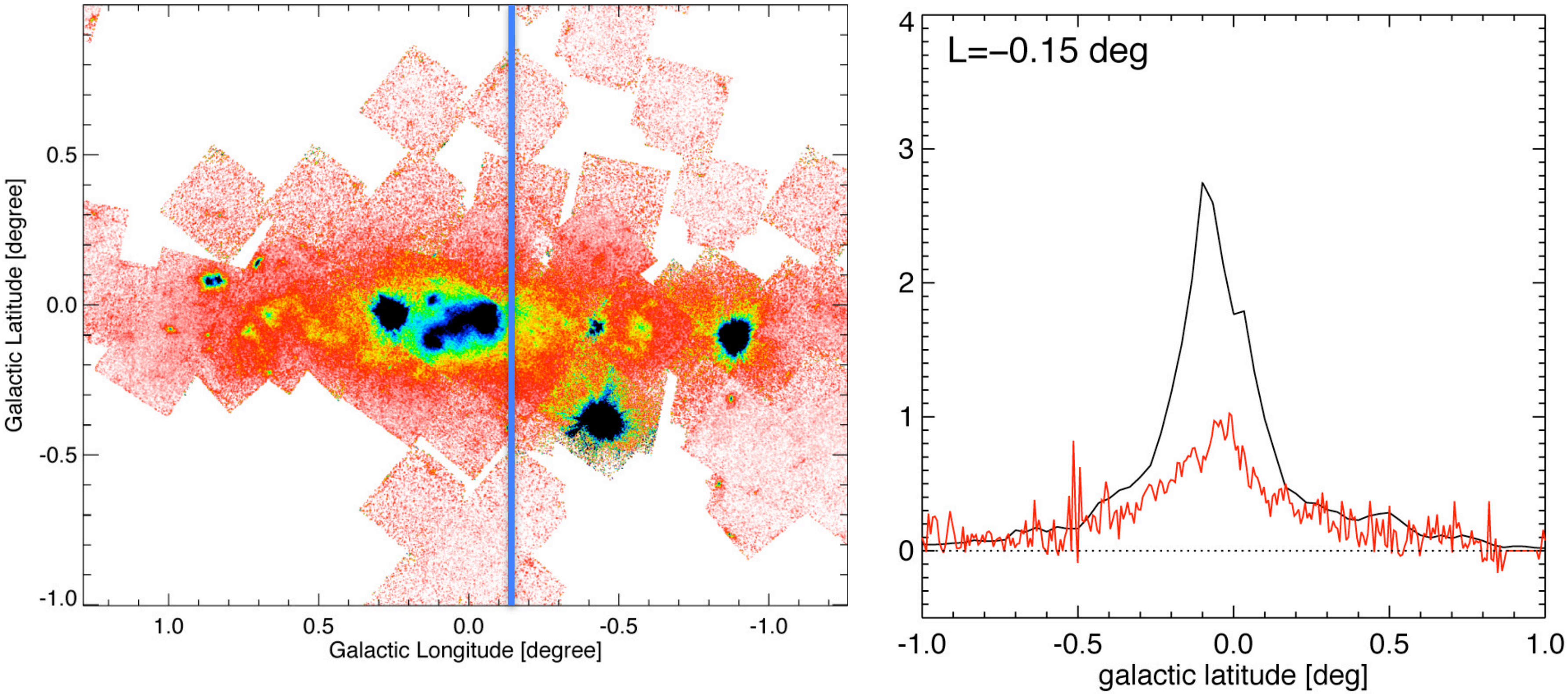
Red On source HI
Green Reference HI
Blue CO

Black Subtracted HI
[Cold dense HI]


Suzaku 5-10 keV
0.4
0.2
0.0
-0.2
-0.4
Galactic Latitude [degree]
Vlsr: 30.0 - 50.0 km/s
600
450
300
150
0
K km/s
1.0
0.5
0.0
-0.5
Galactic Longitude [degree]
Cont. : 20.0, 50.0, 80.0, 110., 140., 170., 200., 230., 260., 290.,



Galactic Latitude [degree]
0.4
0.2
0.0
-0.2
-0.4
Vlsr: -190.0 - -150.0 km/s
300.00
225.00
150.00
75.00
0.00
K km/s
1.0
0.5
0.0
-0.5
Galactic Longitude [degree]
Cont. : 10.0, 30.0, 50.0, 70.0, 90.0, 110., 130., 150., 170., 190.,



Black: CO J=1-0, Red: Suzaku 5-8 keV

No SNR, Large turbulence
2nd order Fermi acceleration in the Galactic centre

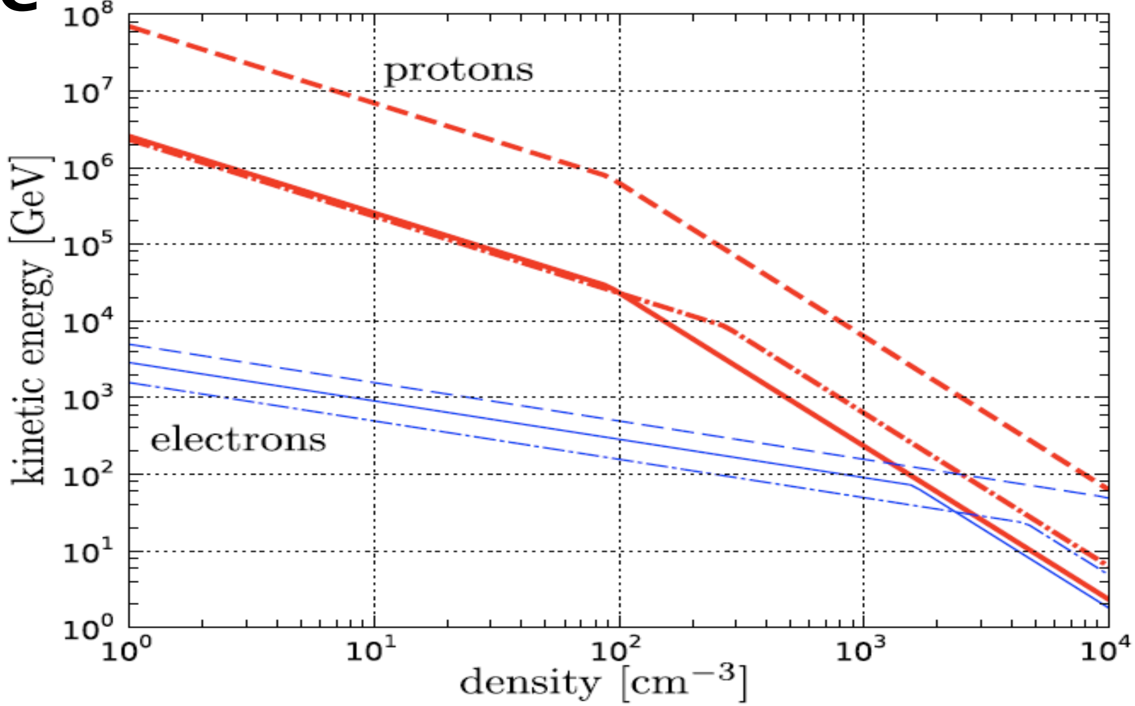
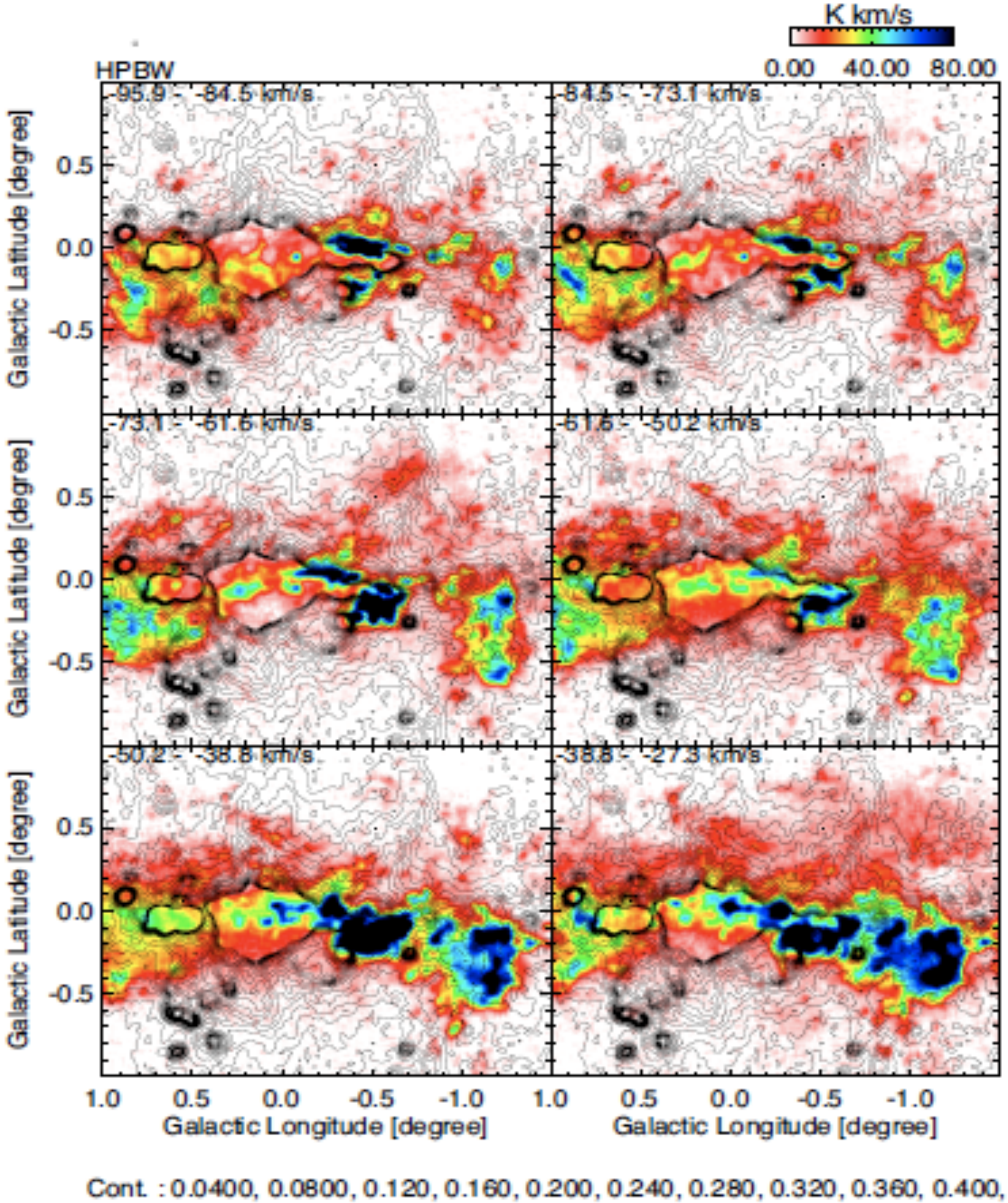
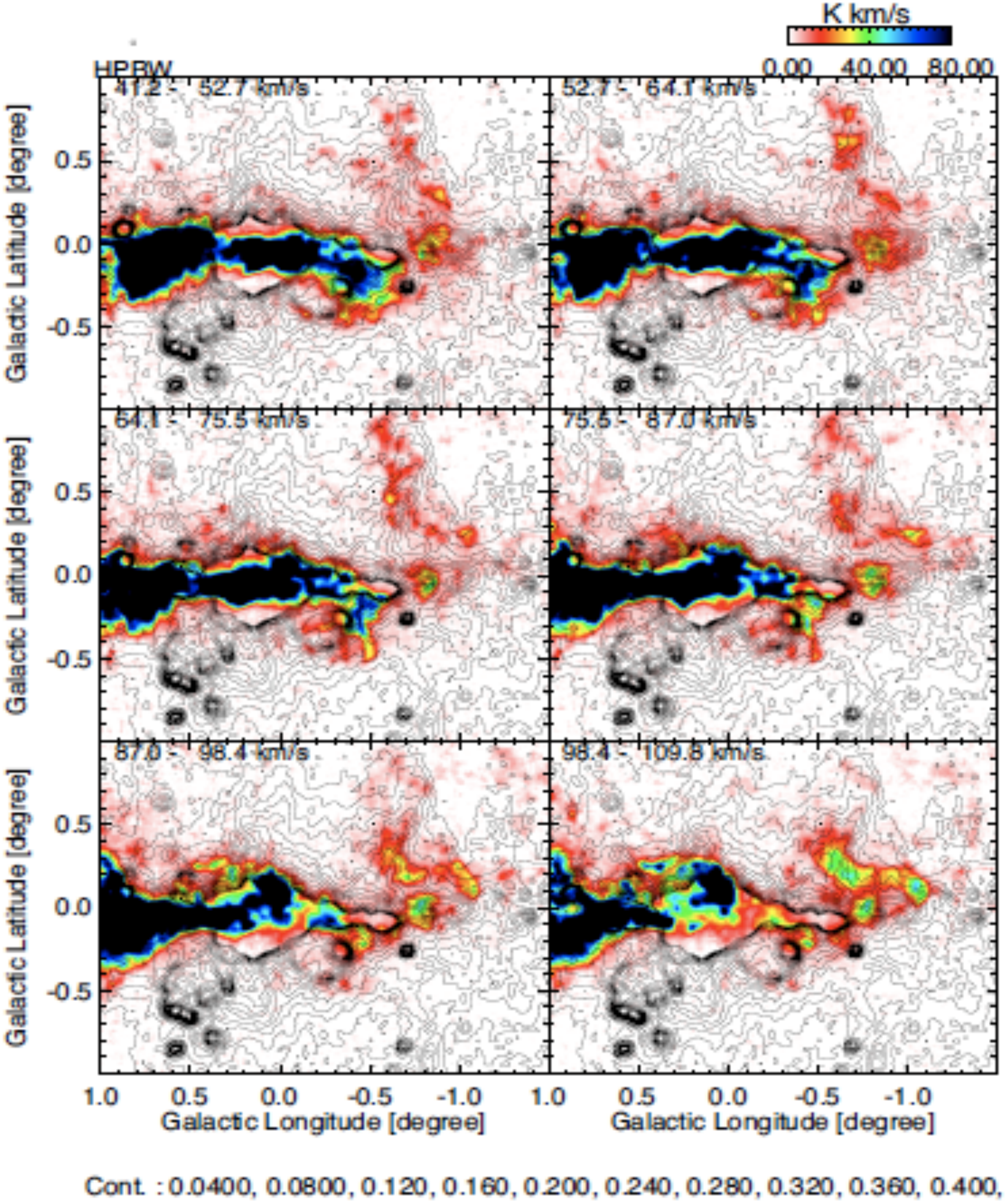
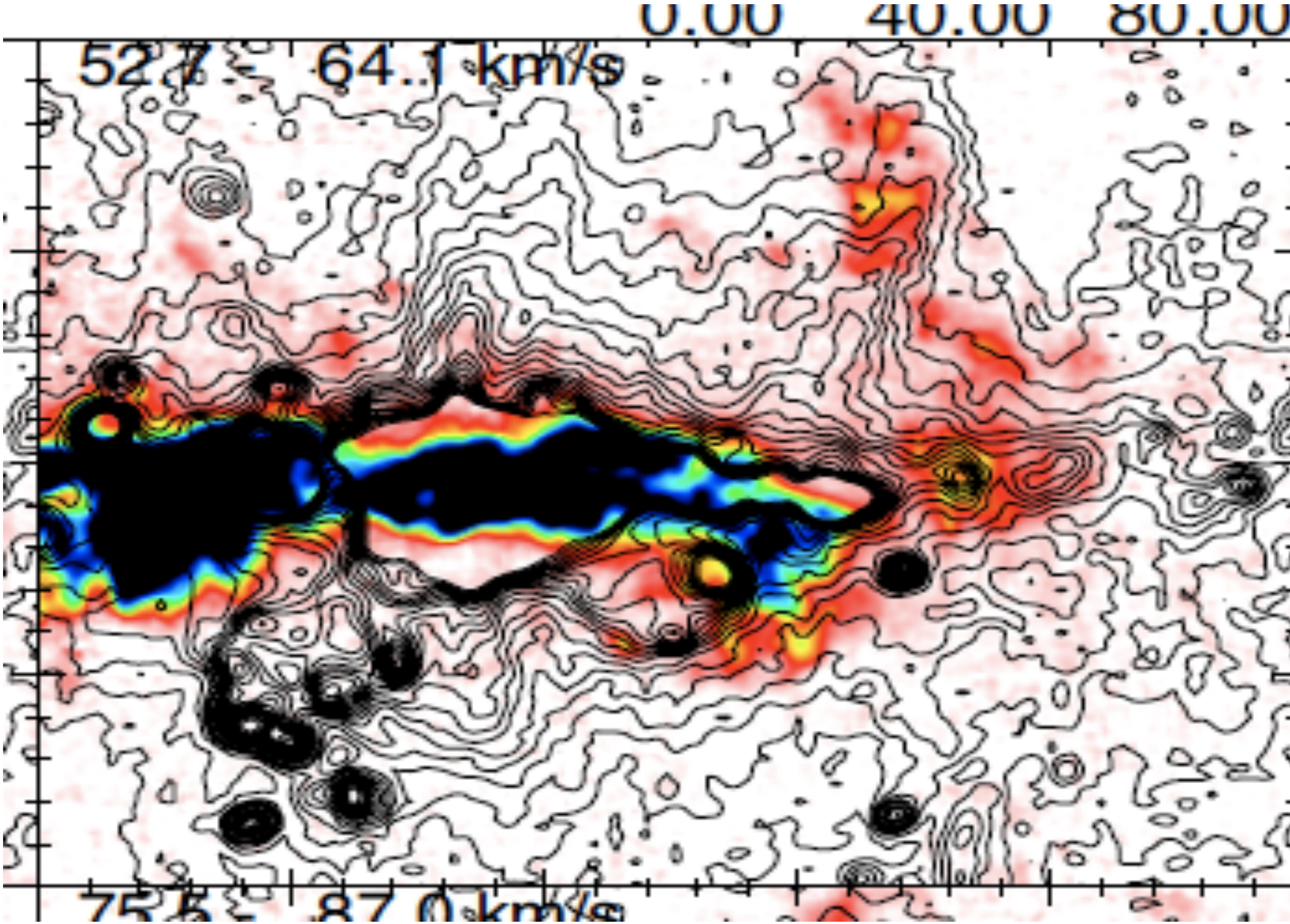


Fig. 1.— Maximum attainable energy by stochastic acceleration as a function of ambient density. Thick (upper three) and thin (lower three) lines represent the maximum energy for protons and electrons, respectively. Solid lines are for $\xi = 10$, $B = 100\,\mu$G, $V_{\rm wind} = 100$ km/s, while dashed lines are for $B = 300\,\mu$G with keeping other parameters constant. Dash dotted lines are for $\xi = 100$, $B = 300\,\mu$G, $V_{\rm wind} = 300$ km/s.

Amano et al. 2011


K km/s
0.00 40.00 80.00
HPBW
-95.9 - -84.5 km/s
-84.5 - -73.1 km/s
-73.1 - -61.6 km/s
-61.6 - -50.2 km/s
-50.2 - -38.8 km/s
-38.8 - -27.3 km/s
Galactic Latitude [degree]
Galactic Longitude [degree]
0.5
0.0
-0.5
1.0 0.5 0.0 -0.5 -1.0
Cont. : 0.0400, 0.0800, 0.120, 0.160, 0.200, 0.240, 0.280, 0.320, 0.360, 0.400,


K km/s
0.00 40.00 80.00
HPBW
41.2 - 52.7 km/s
52.7 - 64.1 km/s
64.1 - 75.5 km/s
75.5 - 87.0 km/s
87.0 - 98.4 km/s
98.4 - 109.8 km/s
Galactic Latitude [degree]
0.5
0.0
-0.5
1.0 0.5 0.0 -0.5 -1.0
Galactic Longitude [degree]
Cont. : 0.0400, 0.0800, 0.120, 0.160, 0.200, 0.240, 0.280, 0.320, 0.360, 0.400,


0.00
40.00
80.00
52.7 - 64.1 km/s
75.5 - 87.0 km/s

E. N. Parker 1966

discrete character of the interstellar gas is self-gravitation of the individual clouds,[8] but there is the problem that in many cases the cloud masses inferred from the observations do not seem to be large enough to maintain the cloud in equilibrium by self-gravitation alone (see Kahn and Dyson 1965). For instance, the self-gravitation of a spherical cloud with a diameter of 20 pc and a density of 10 hydrogen atoms/cm^3 can hold the cloud together only if the internal motions are 0.7 km/sec or less. A higher density of 100 atoms/cm^3 can contain internal motions of only 2.2 km/sec. But even the thermal velocities are this large, to say nothing of the 10-km/sec motions expected from collisions between clouds and from the passage of hot luminous stars through the region. So there is some question as to the means by which the apparent identity of the smaller, more tenuous, interstellar gas clouds is maintained. The new point arising in the galactic field configuration presented in this paper is that the self-gravitation of the individual gas clouds is supplemented, in the configuration shown in Figure 2, by the gravitational field of the Galaxy as a whole.

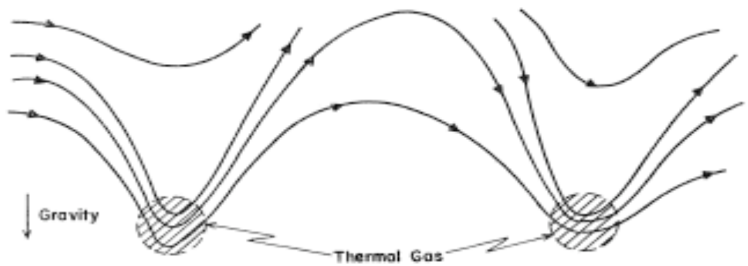


FIG 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

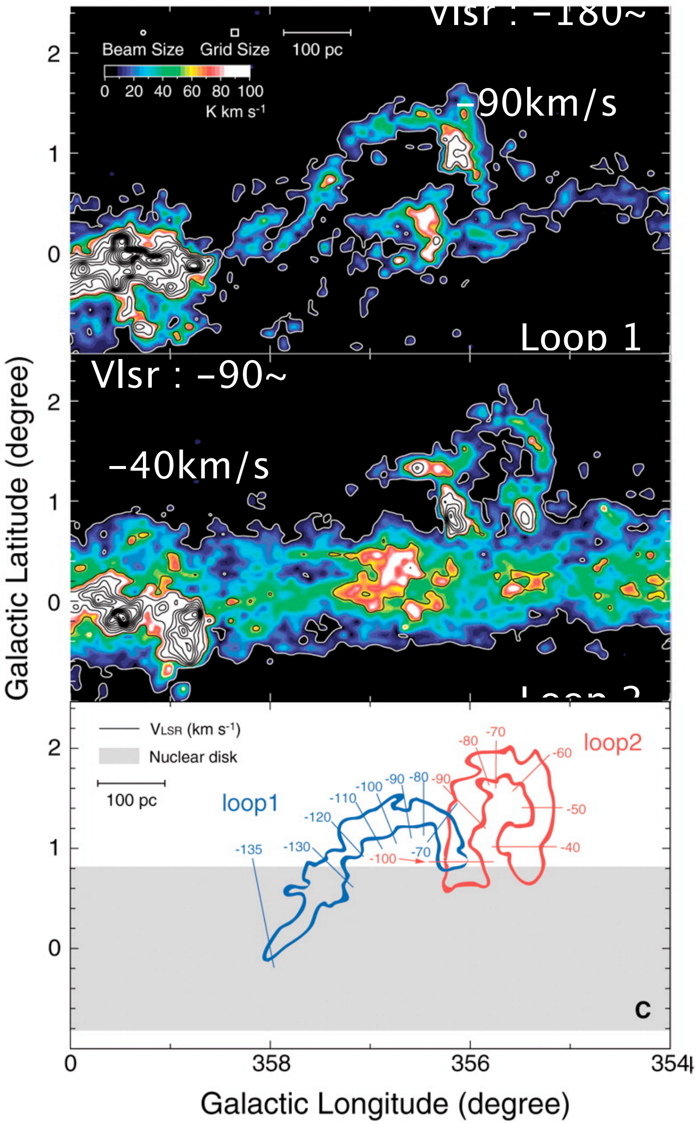
To illustrate the supplement to self-gravitation in a direct way, and to establish that the supplement may be large in many cases, consider two parallel, widely separated, infinitely long, slender cylinders of gas lying across the horizontal magnetic field B_0 and supported by the magnetic field in the large-scale gravitational field g. The entire region is filled with a tenuous conducting plasma, so that the hydromagnetic equations are the appropriate description of the system. To make the problem tractable, suppose that the pressure of the tenuous plasma is negligible compared to the pressure and weight of the cylinders of dense gas lying across the field. Then $\nabla \times \boldsymbol{B} = 0$, with $\boldsymbol{B} = -\nabla\psi$, $\nabla^2\psi = 0$, everywhere except in the dense cylinders. The field outside the cylinders has the same configuration and stresses as though the space were a vacuum. The solution of this hydromagnetic problem may be effected simply by noting that, if m is the mass per unit length of each cylinder, then the current I induced in each cylinder by the weight on the magnetic field is given by

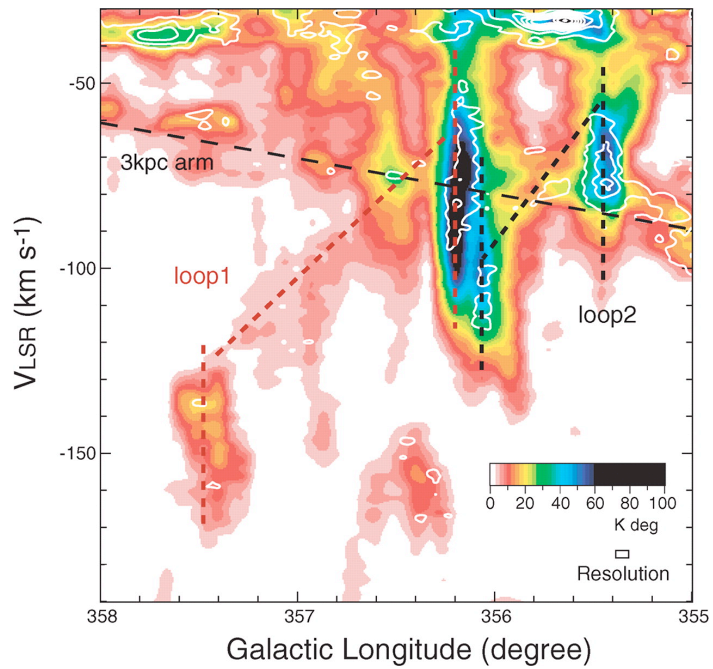
$$\frac{IB_0}{c} = m\,g\,.$$

[8] Alternatively it has been suggested (Savedoff and Spitzer 1950) that the region between clouds is filled with hot (10^4 °K) tenuous (0.1/cm^3) hydrogen, whose pressure confines the neutral clouds.

Molecular loops 1 & 2

(Fukui et al.2006)

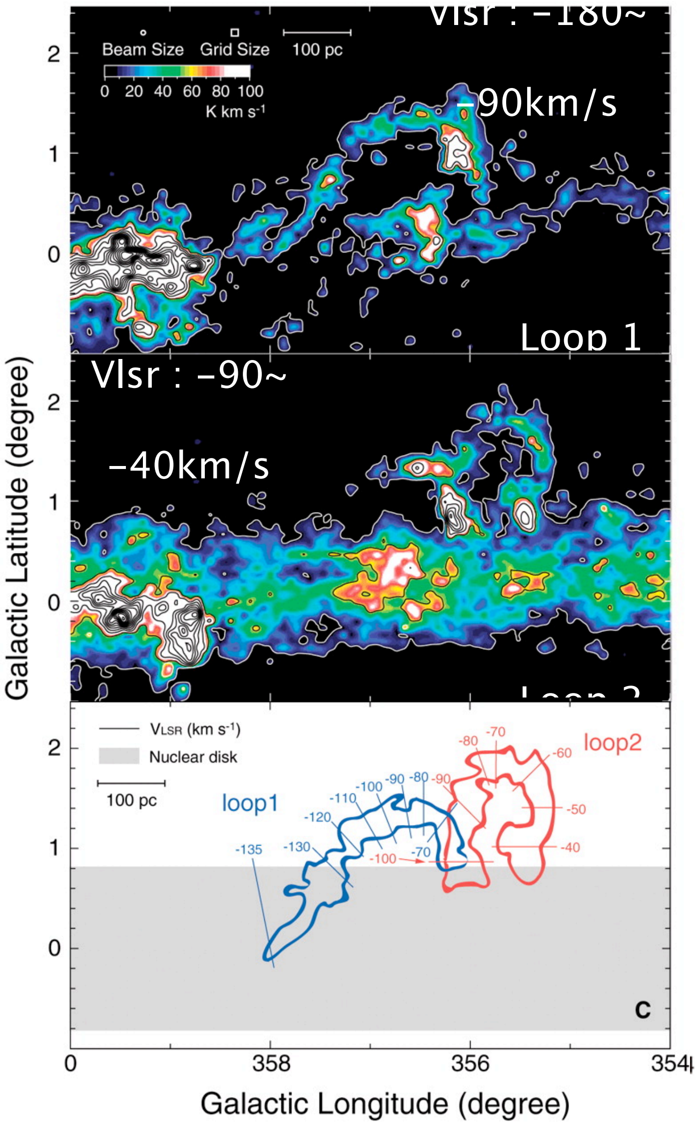


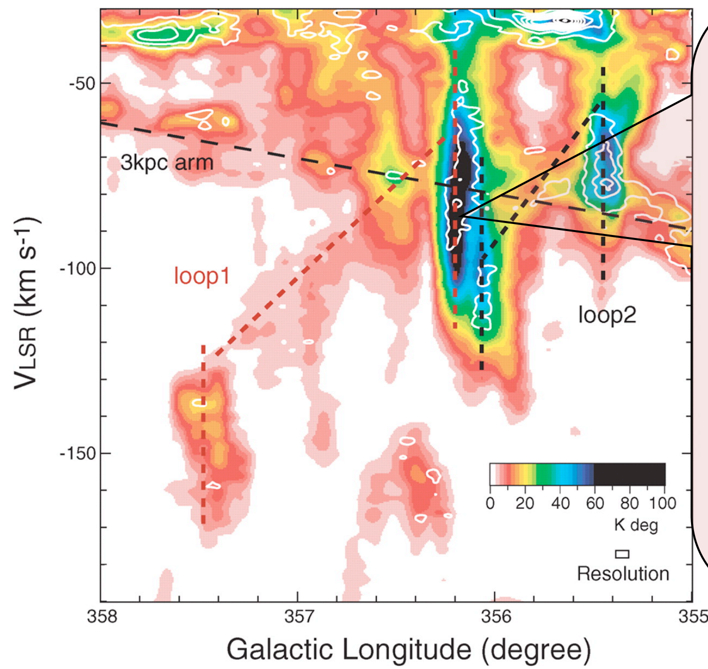


We were able to find these molecular loops in the galactic center due to large range and high resolution imaging by using NANTEN telescope.

Molecular loops 1 & 2

(Fukui et al.2006)





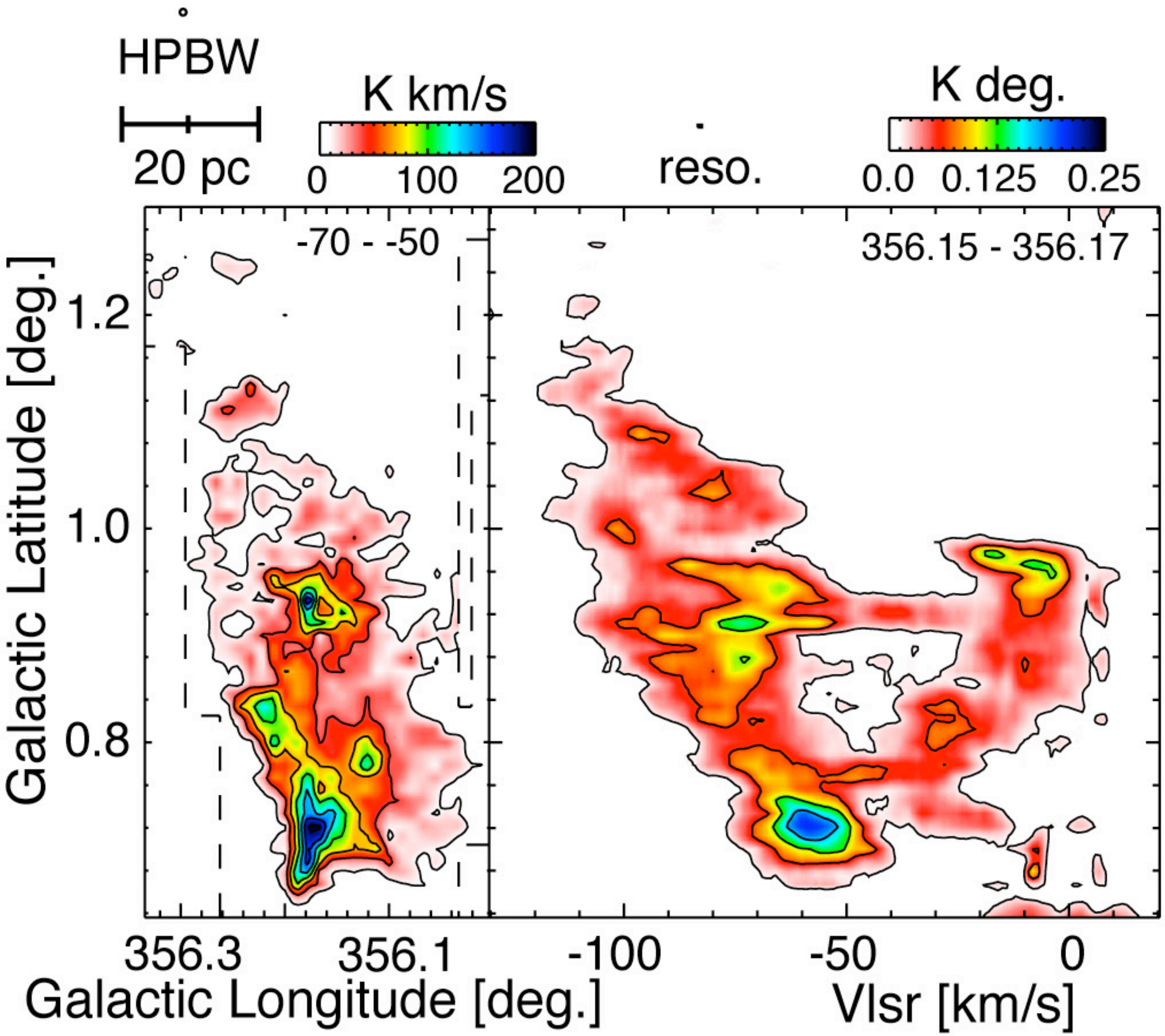
Loops' foot point has a broad velocity dispersion. (~40km/s)

Total mass：

~10^6 Msun

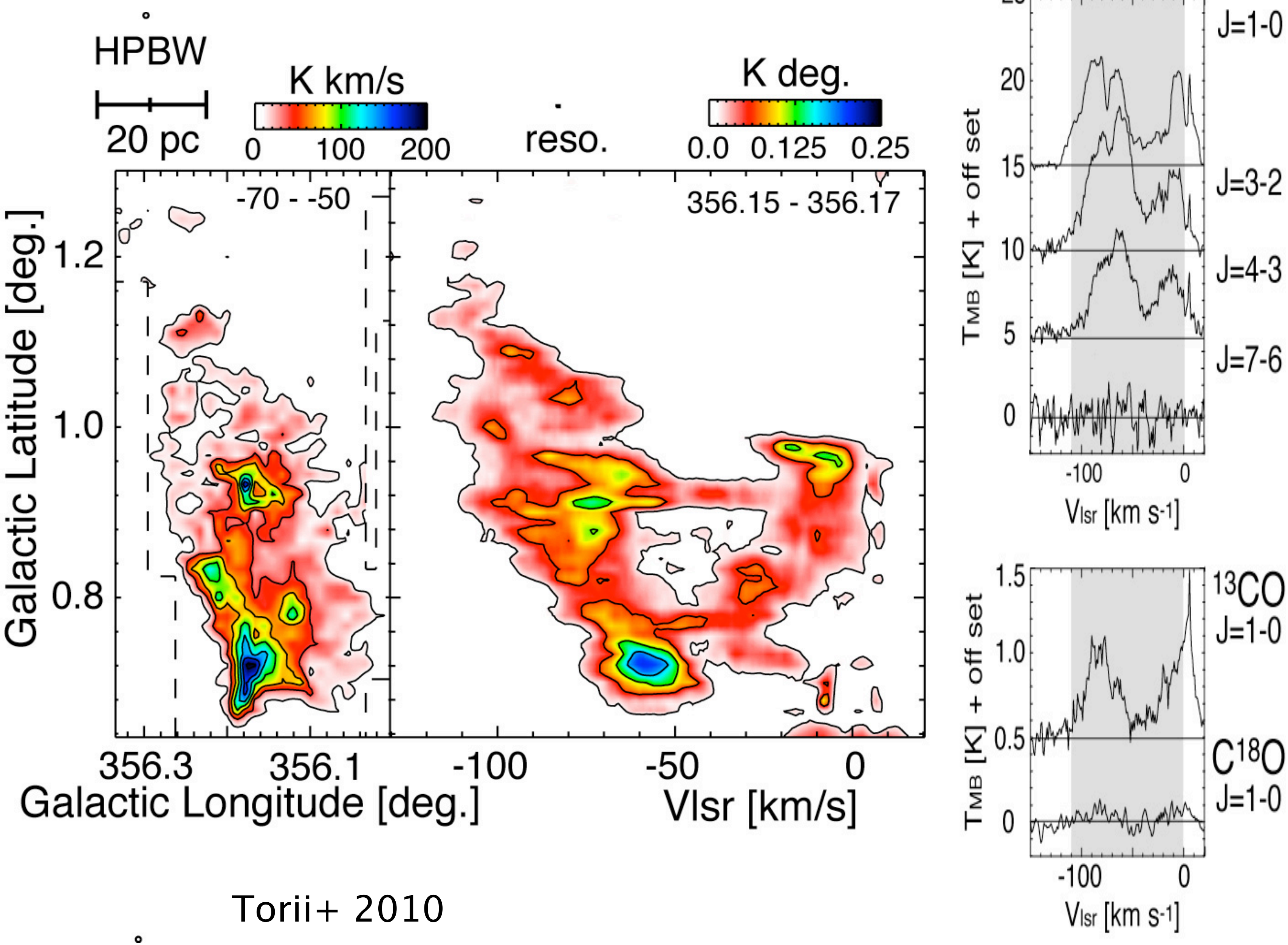
We were able to find these molecular loops in the galactic center due to large range and high resolution imaging by using NANTEN telescope.

U shape of foot point



Torii+ 2010

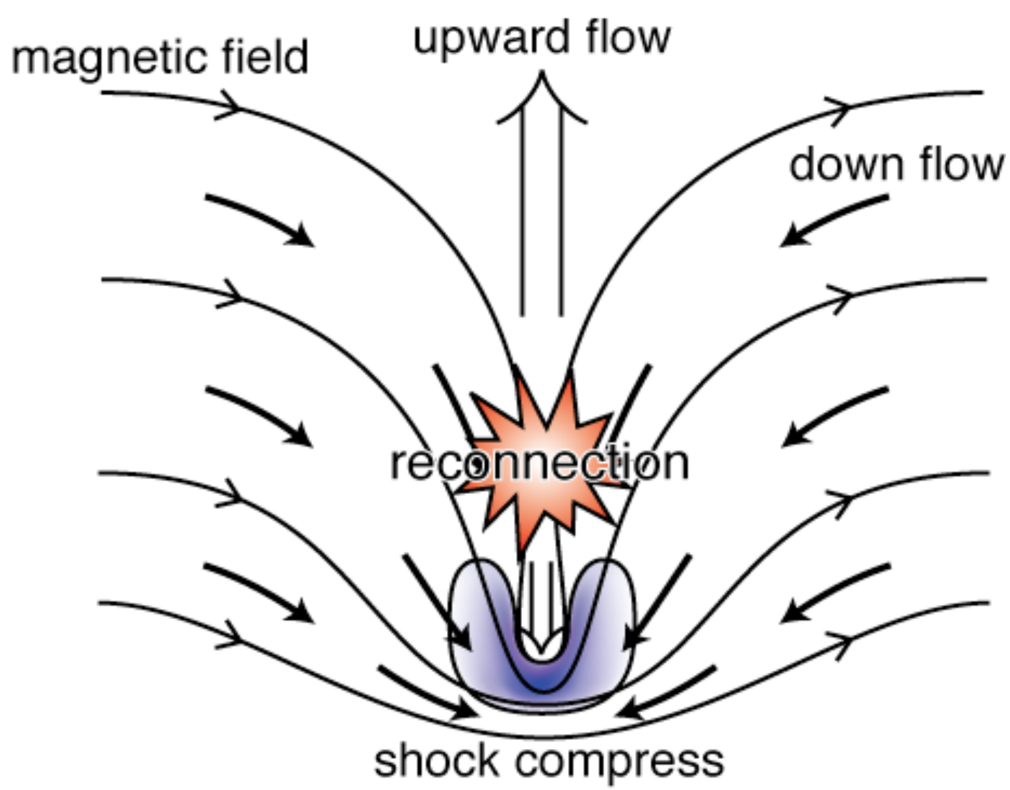
U shape of foot point

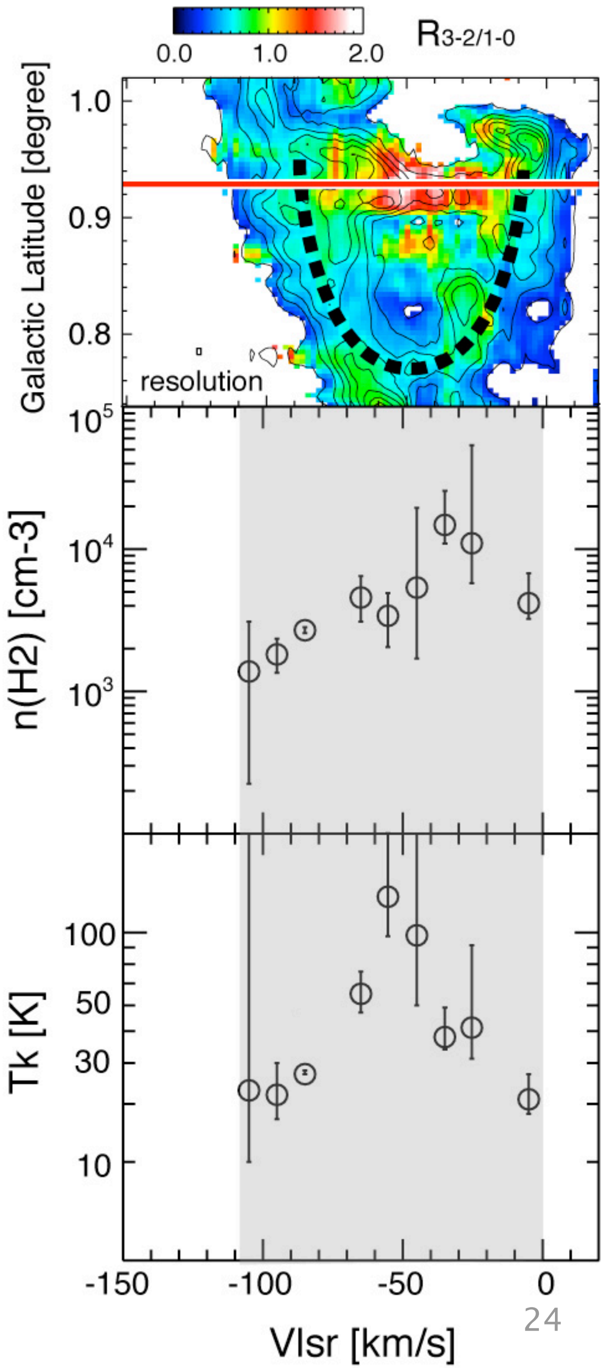


Torii+ 2010

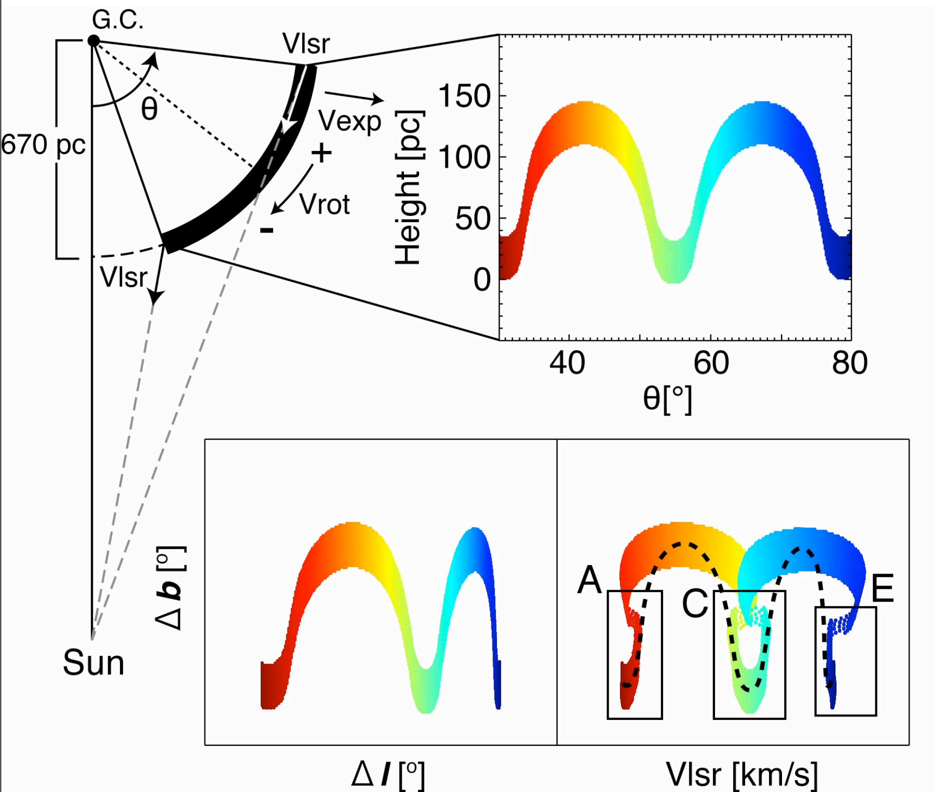
LVG analysis - Results -

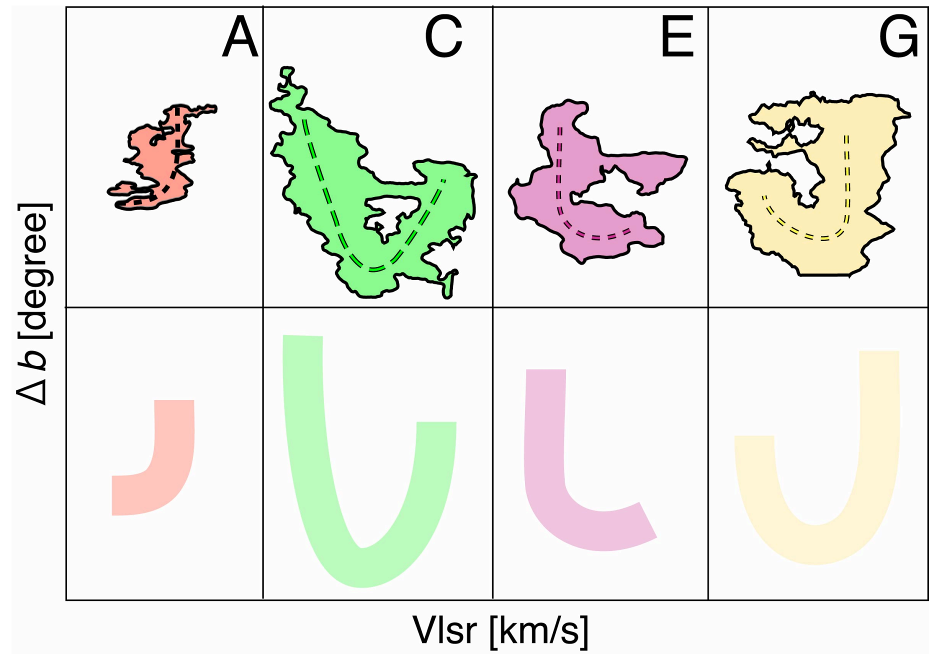
- Typically T ∼30–50 K, n∼10^3 /cm^3
- Broad emission : > 100 K
- Magnetic reconnection may offer a possible mechanism for the hot and broad gas component.



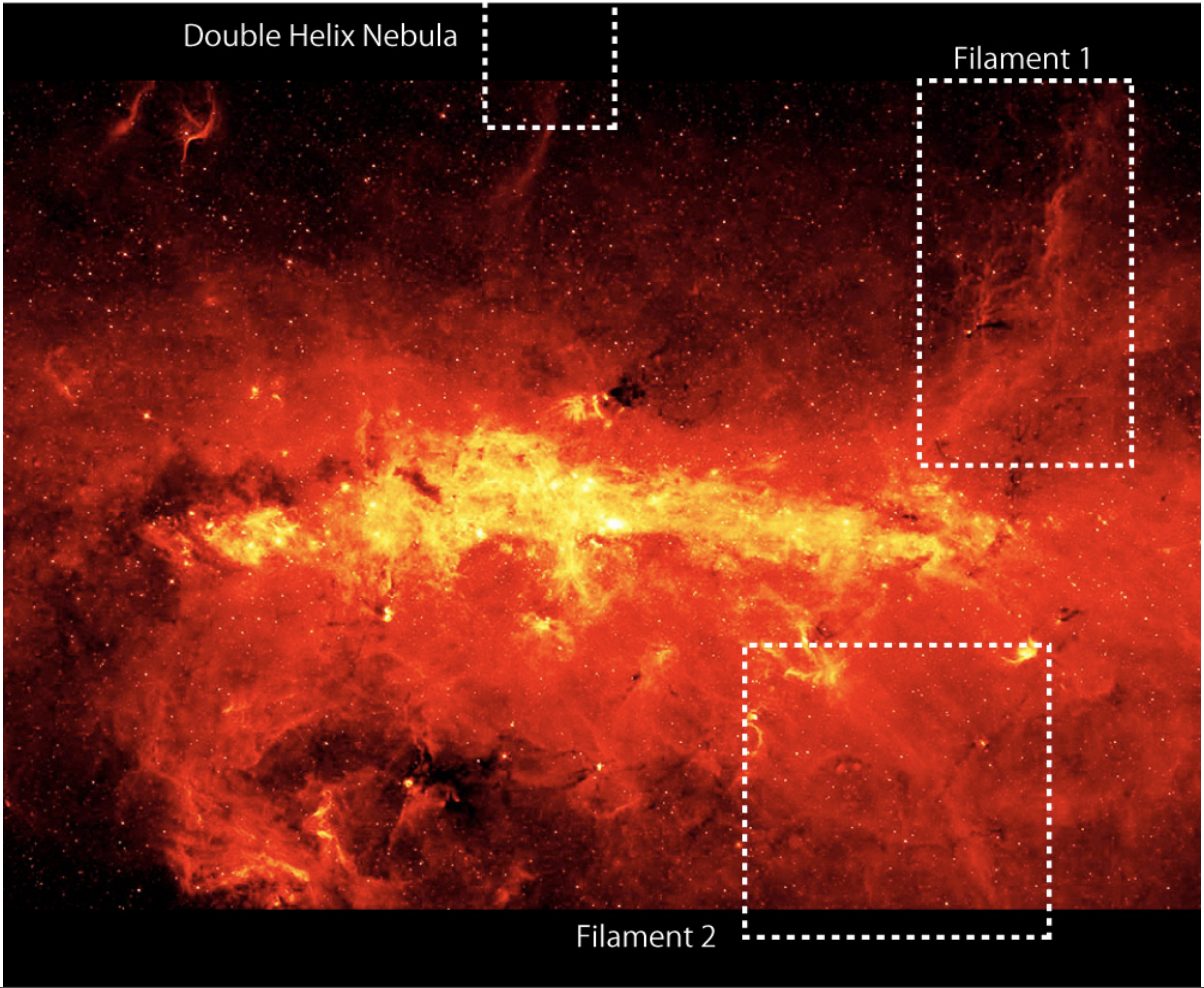


U/L shapes of foot points

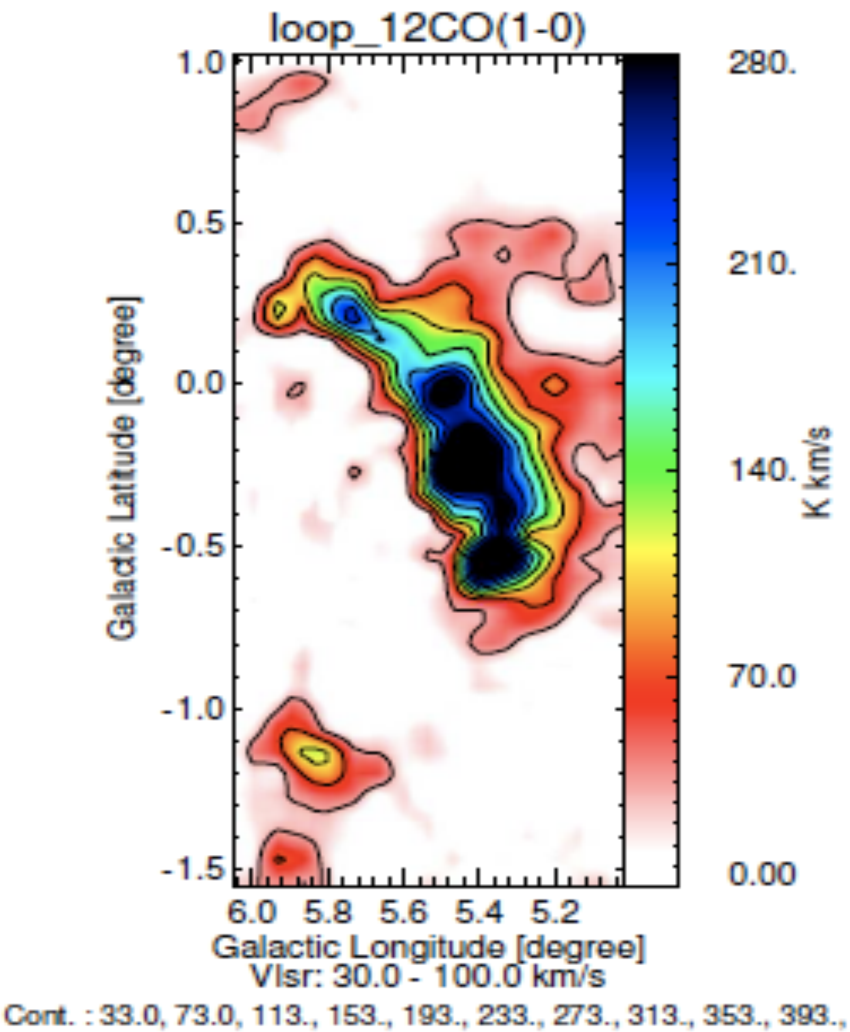




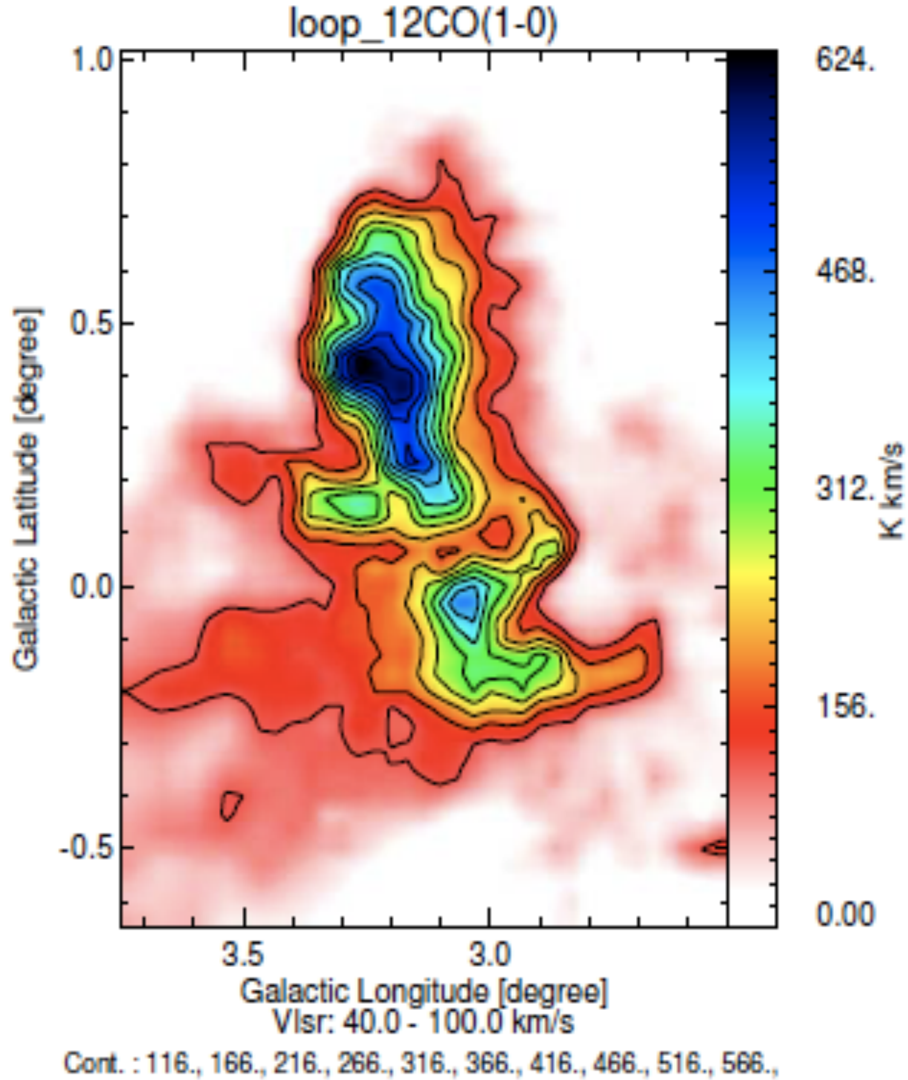
Kudo et al. 2010, Torii et al. 2010b, Fujishita et al. 2009
Takahashi et al. 2009


Double Helix Nebula
Filament 1
Filament 2

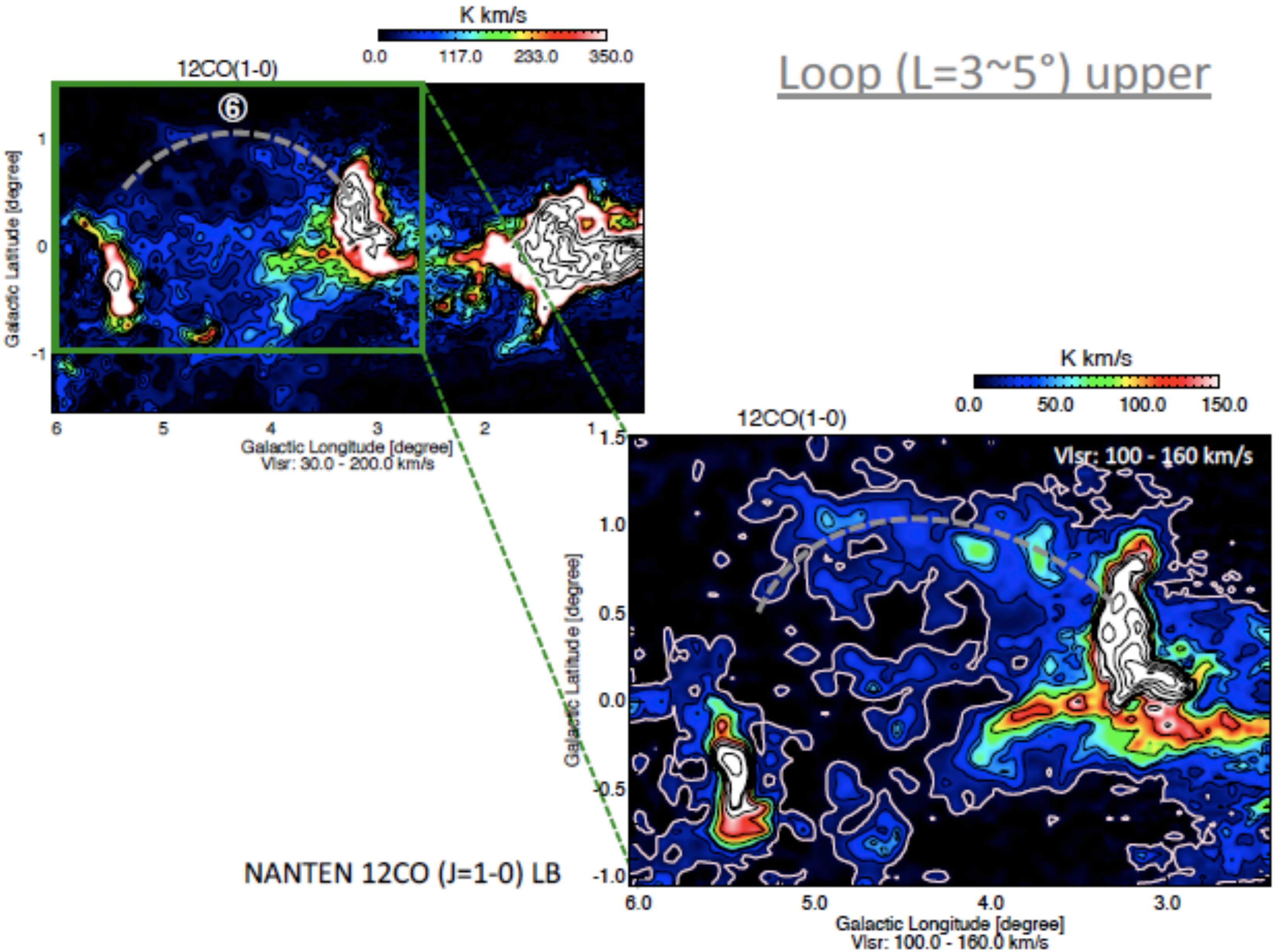
L=5.5 degree



L=3.0 degree

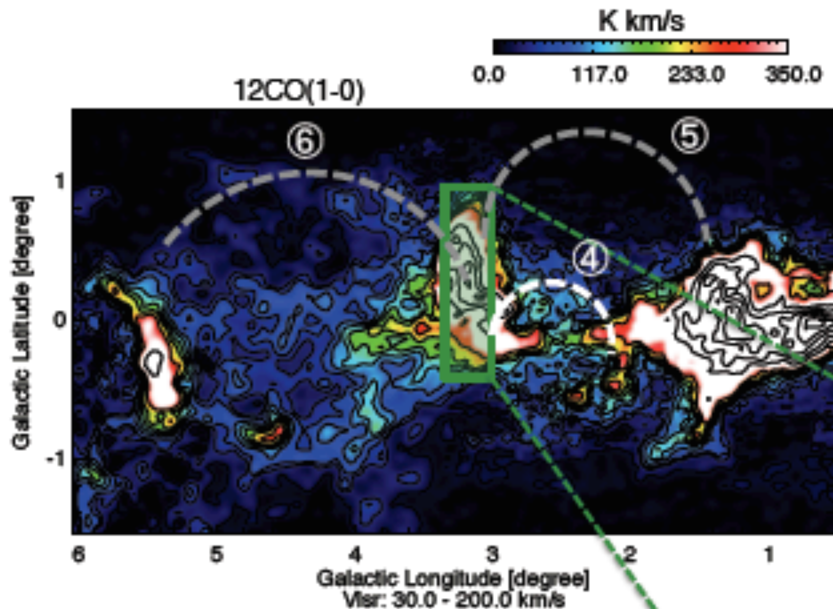


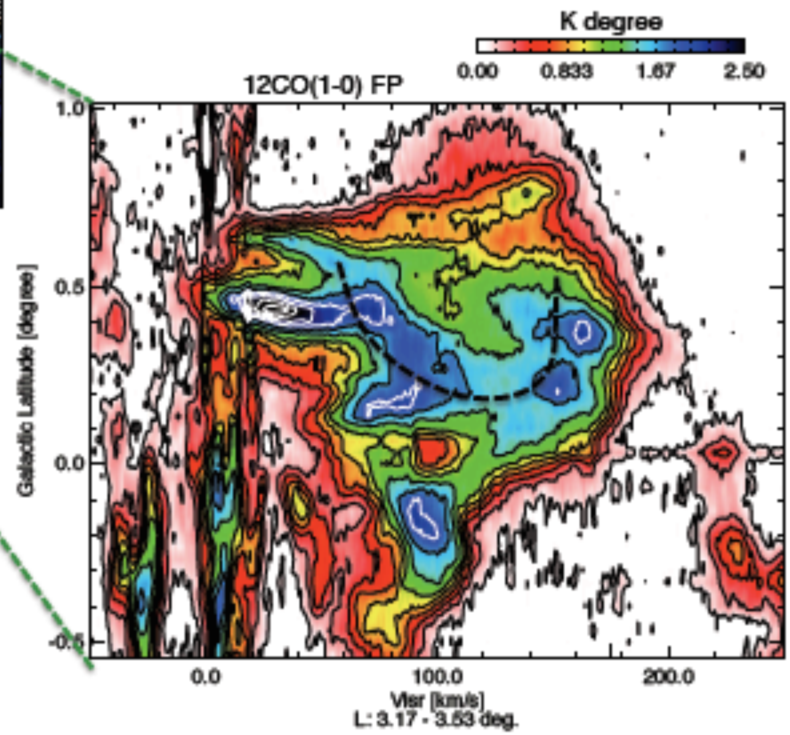
Loop (L=3~5°) upper



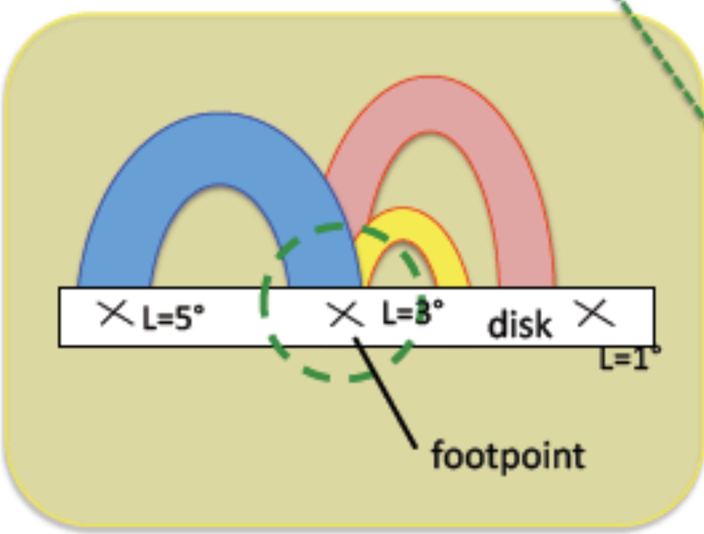
NANTEN 12CO (J=1-0) LB

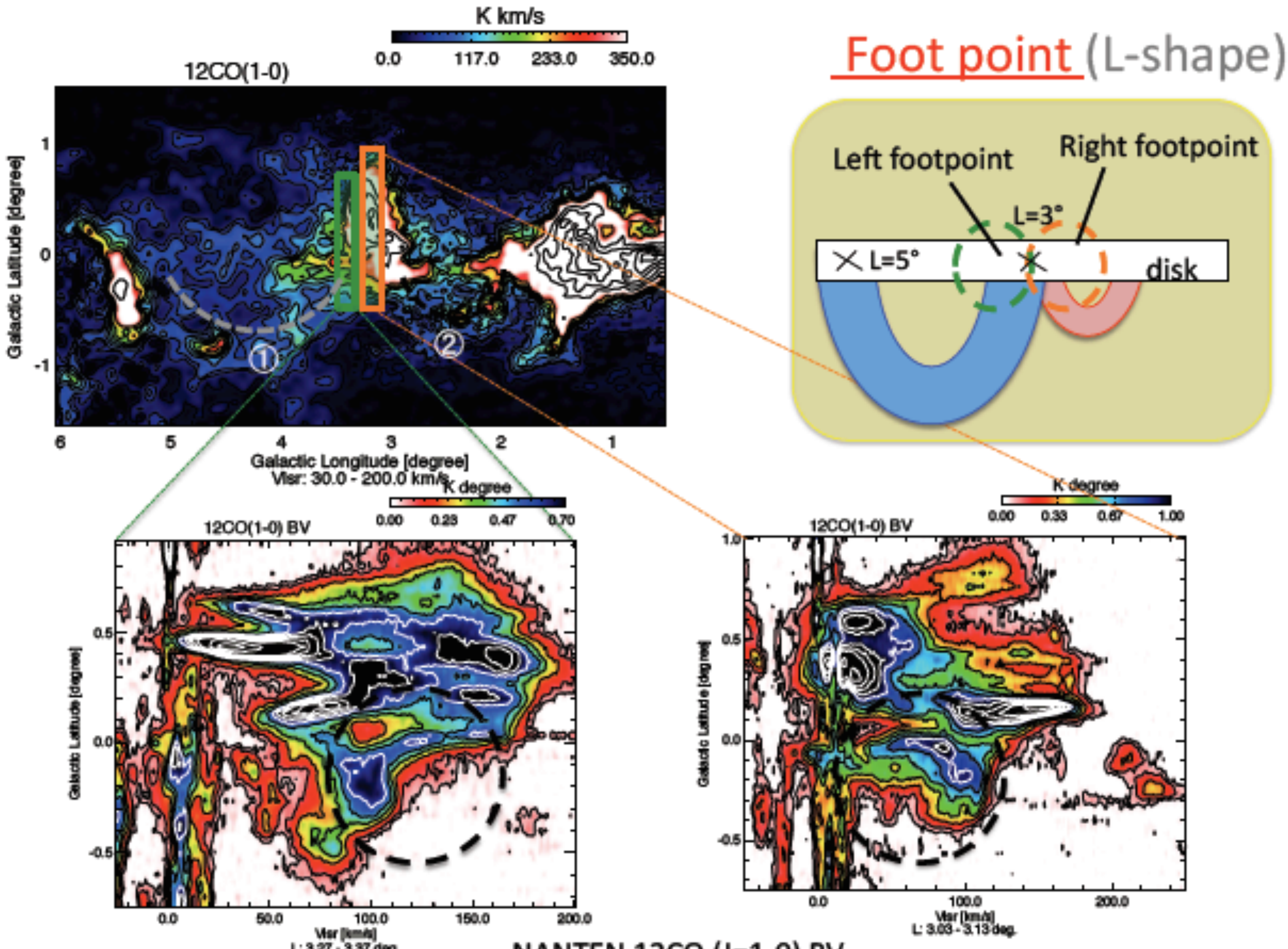
Foot point (U-shape)





NANTEN 12CO (J=1-0) BV

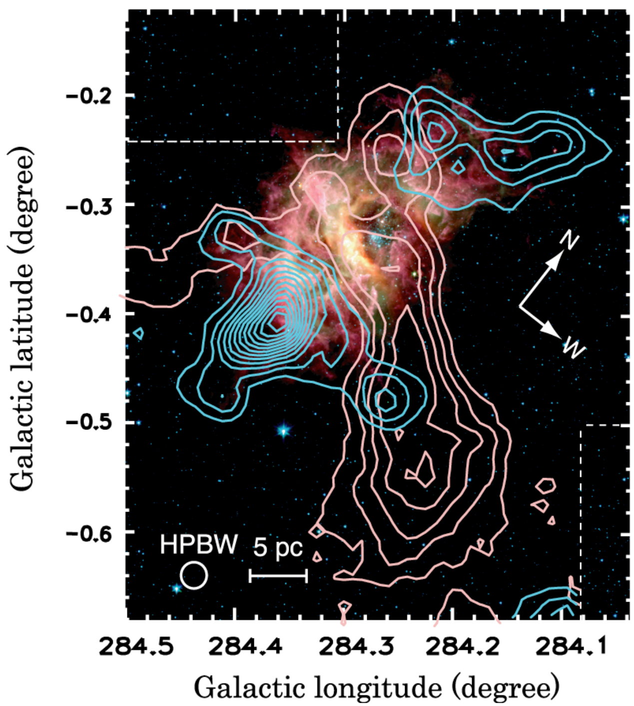


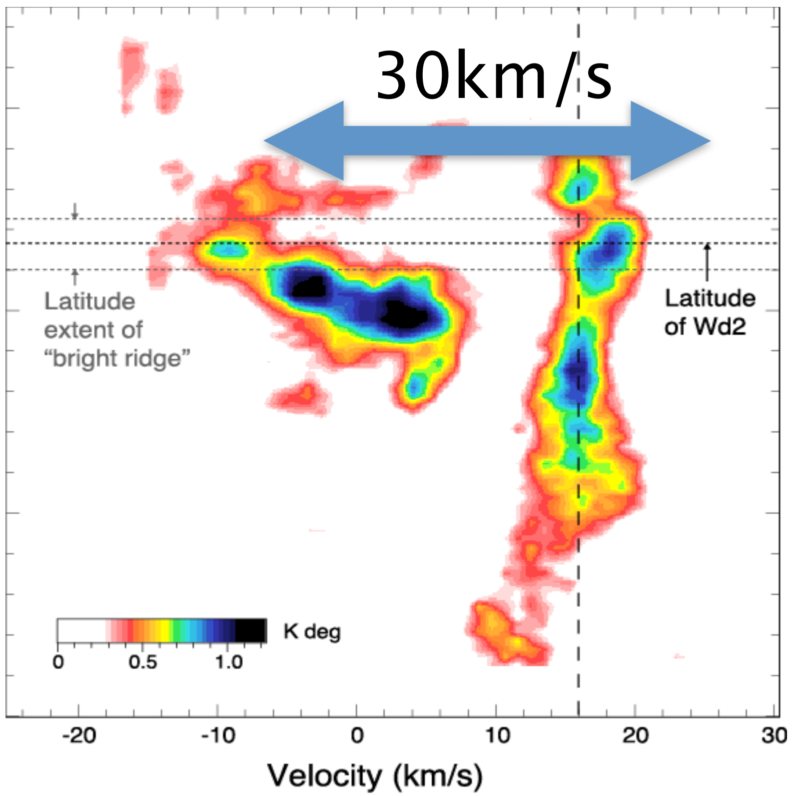


NANTEN 12CO (J=1-0) BV

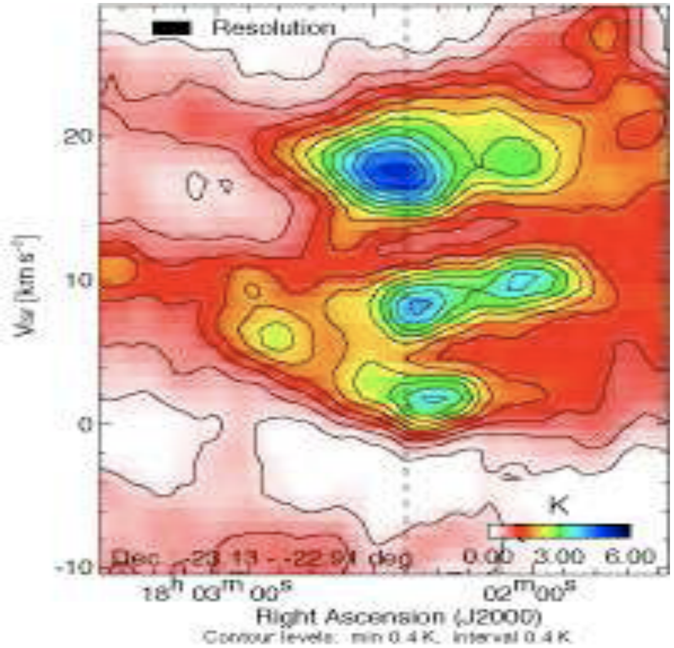
Cloud-cloud collision scenario

- A collision between two clouds trigger the star formation of the central O7.5 star (Torii et al. 2011)
- Same scenario as Westerlund 2 (Furukawa+09; Ohama+10)



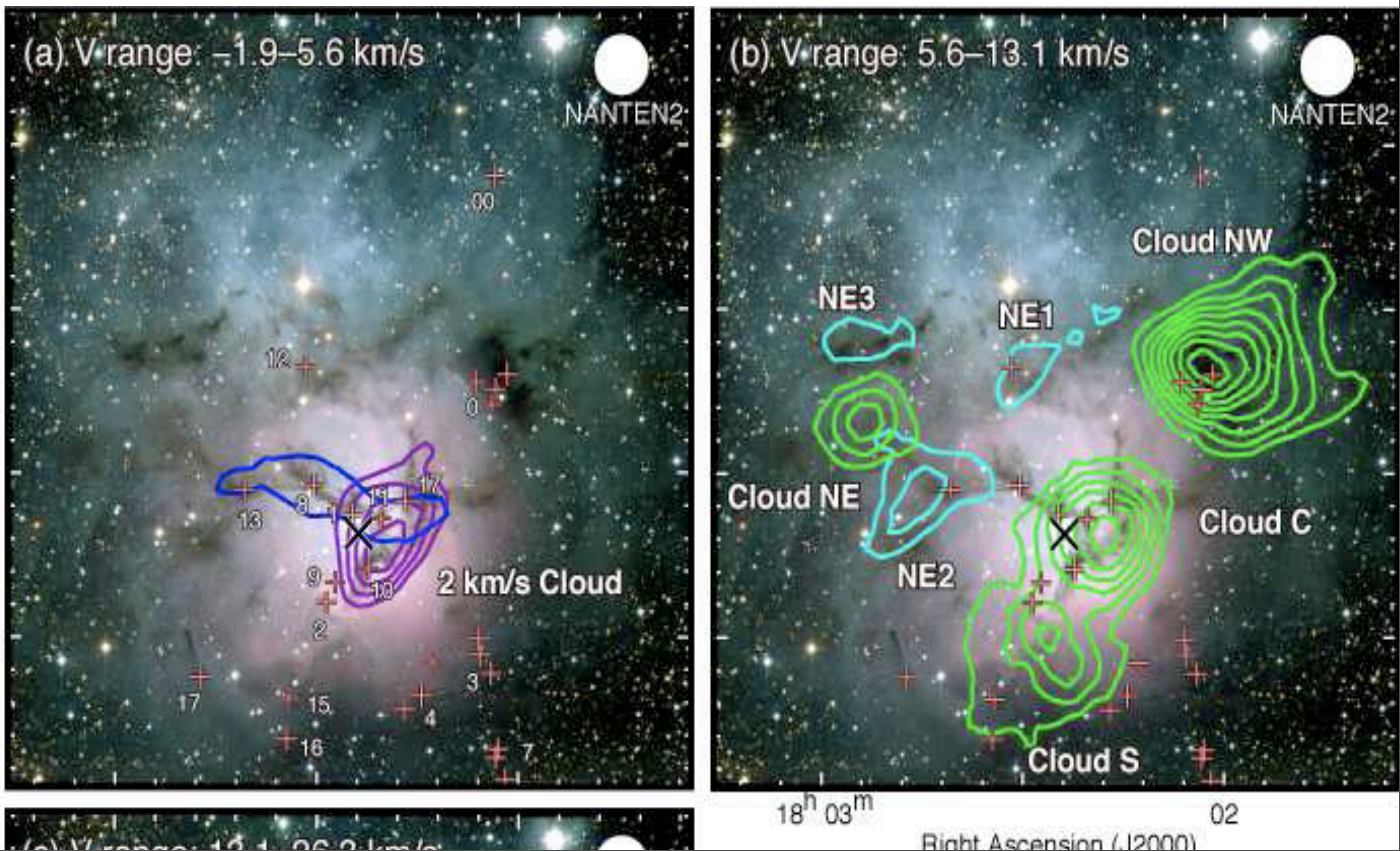


Cloud-cloud collision to form O star in M20



Torii et al. 2011

Cloud-cloud collision to form O star in M20



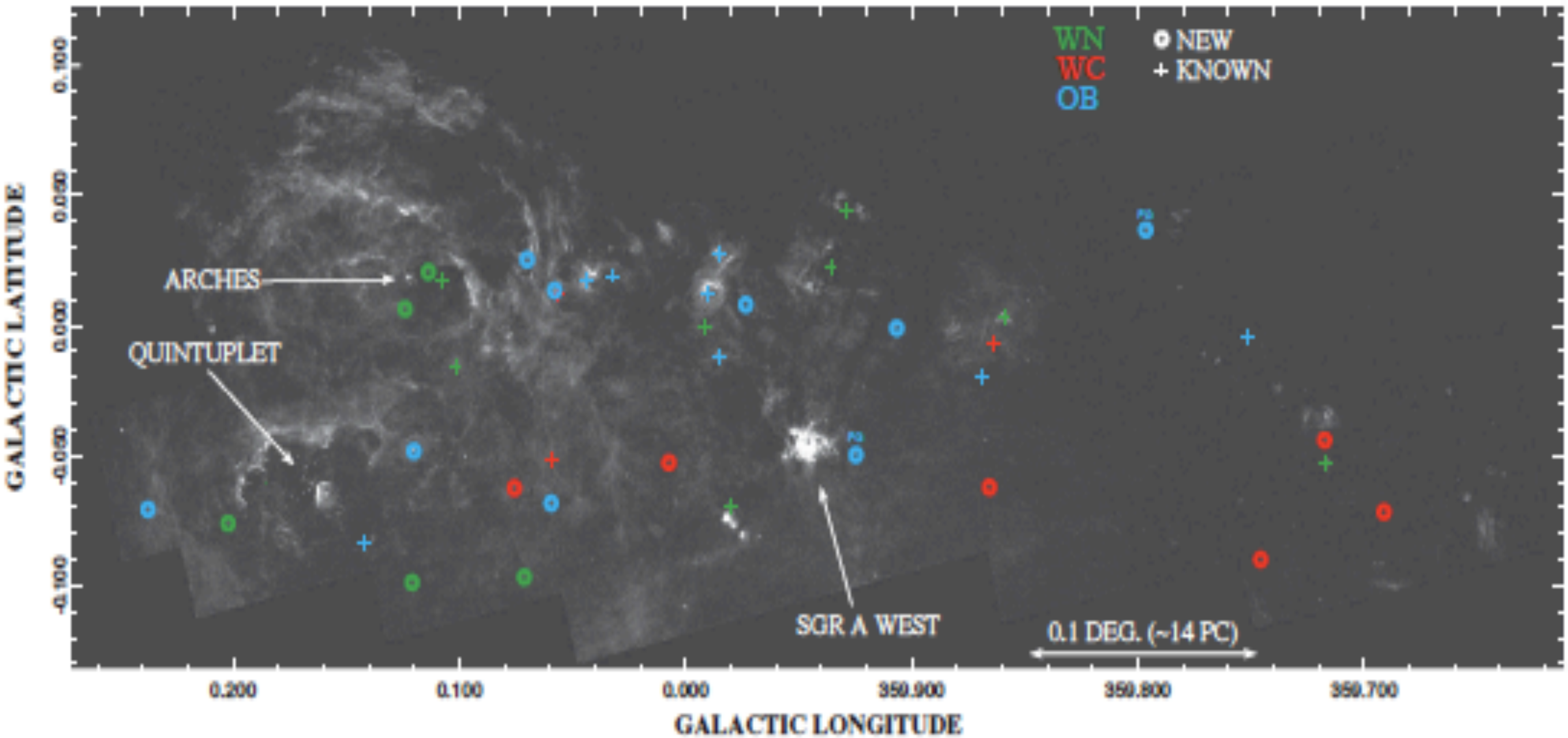


Fig. 10.— *HST*/NICMOS Pα survey image of the Galactic center region from Wang et al. (2010). The positions of the isolated massive stars are marked (i.e., those located outside of the known extent of the Arches, Quintuplet, or Central clusters) and color coded according to spectral type (see the image legend). The discoveries of this work (circles) are marked separately from the known sources (crosses). The two foreground O stars are labeled "FG". Bona fide cluster members are not marked.

Mauerhan et al. 2010

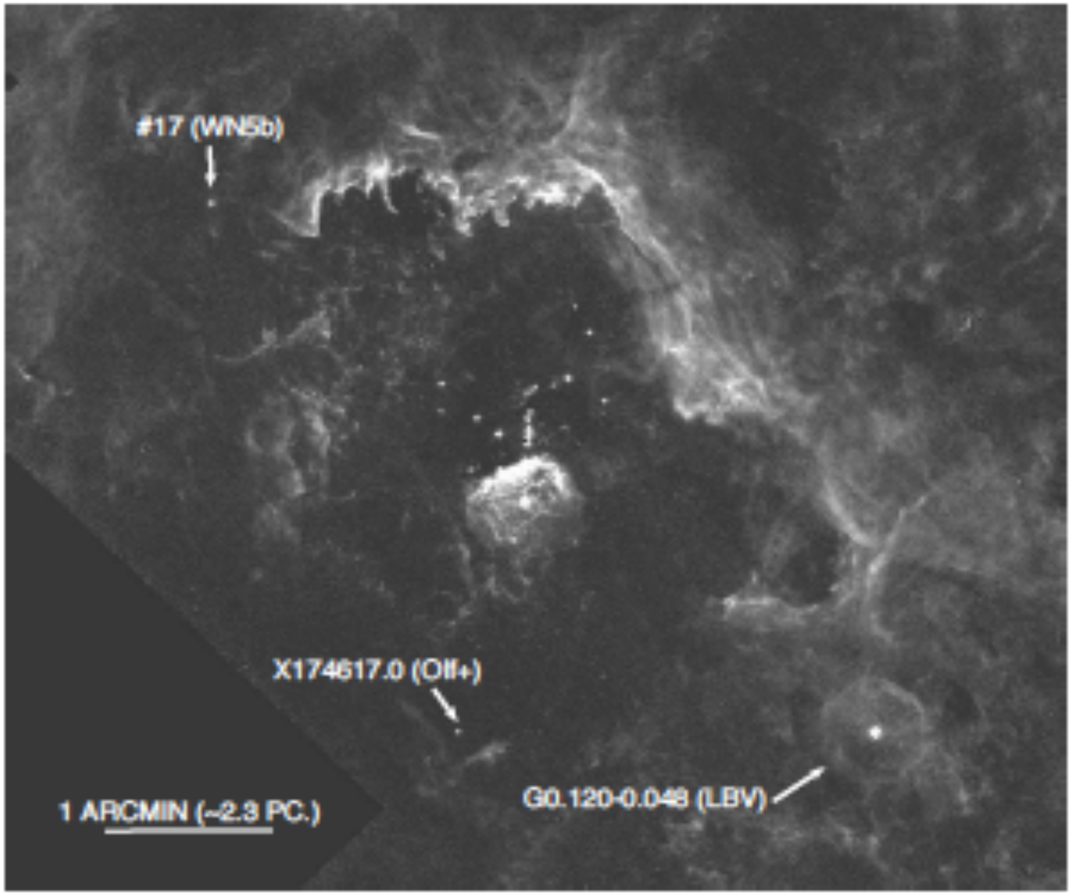
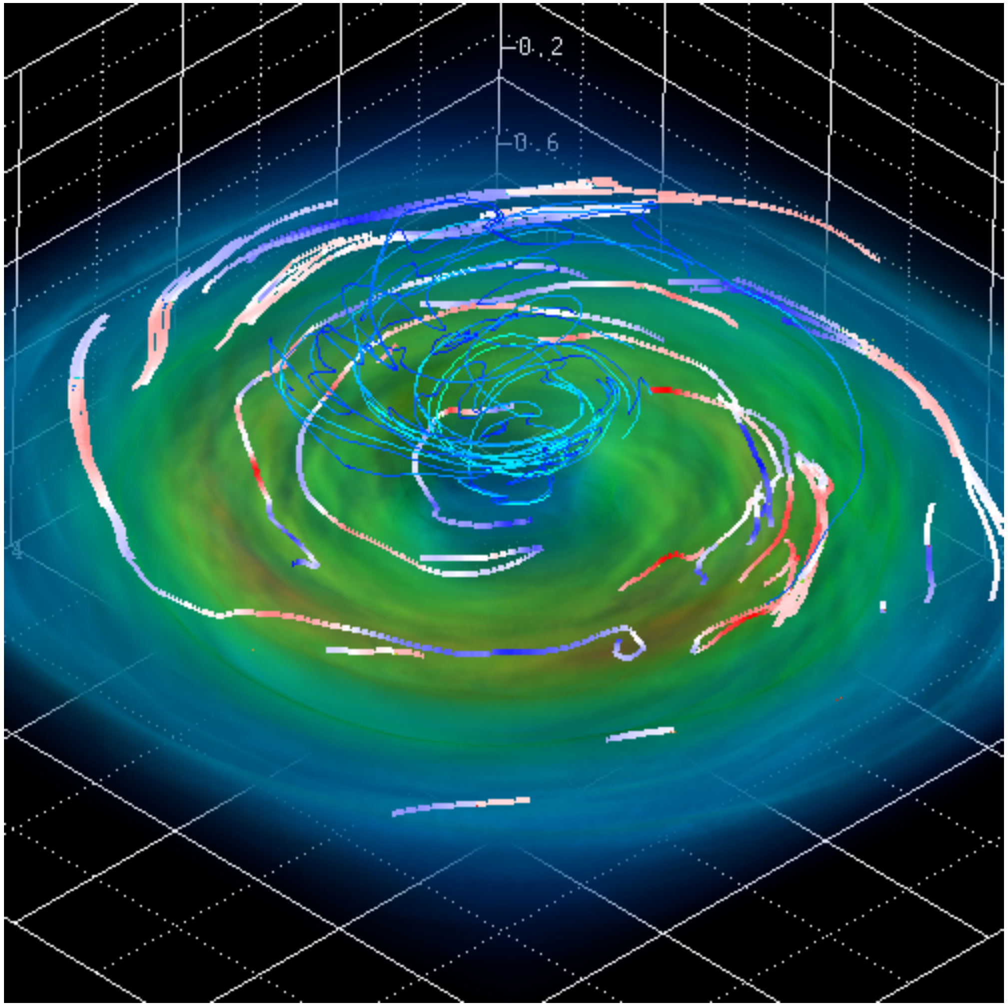


Fig. 9.— *HST*/NICMOS Pα survey image of the Sickle region from Wang et al. (2010), which contains the Quintuplet cluster and nearby isolated massive stars, including the O6If$^+$ X-ray source X174517.0 from Mauerhan, Muno, & Morris (2007), the LBV G0.120−0.048 from Mauerhan et al. (2010a), and the new WN5b star 17 of this work. All of the unmarked point sources are known massive stars spectroscopically identified in Figer et al. (1999). North is up and east is to the left in this image.

Formation of Magnetic Loops and Tower in the Galactic Centre



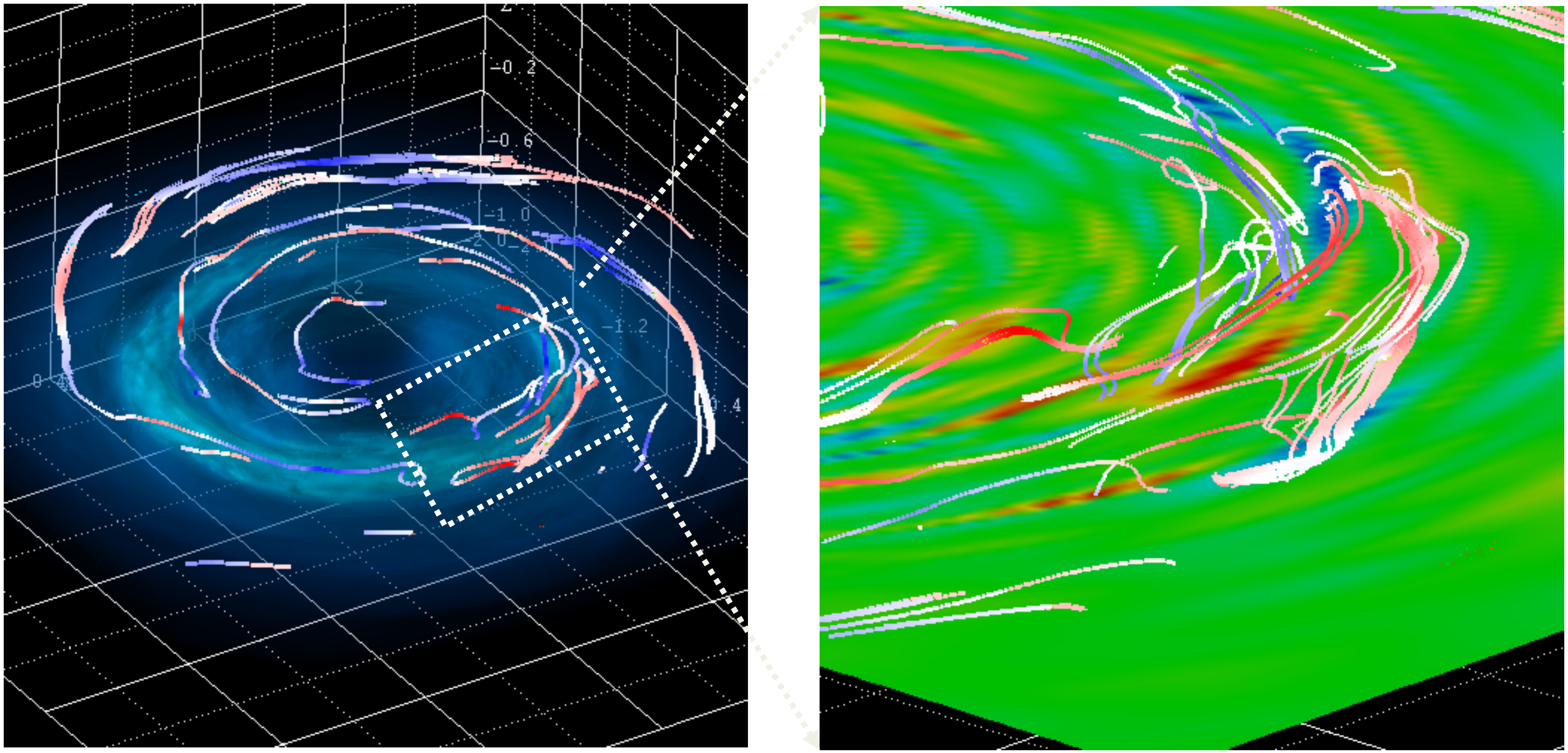
Machida et al. 2009

Global 3D MHD Simulations of Galactic Center Gas Disks

Molecular halo of the CMZ

- CO is the best tool to probe dense gas, small A_{10} coeff.
  CO only is sensitive to low density molecular gas (several x 100 cm^{-3})
- CMZ halo of 10^6 Mo over the CMZ
  [talk Kazufumi Torii]
- Molecular clouds toward DHN above Sgr A*
  [talk Rei Enokiya]
- High z of 200pc requires "wind" from the CMZ. Possible connection with the neutral wind by magnetic or stellar activity

Parker instability in the nuclear disk
(Machida et al. 2009)

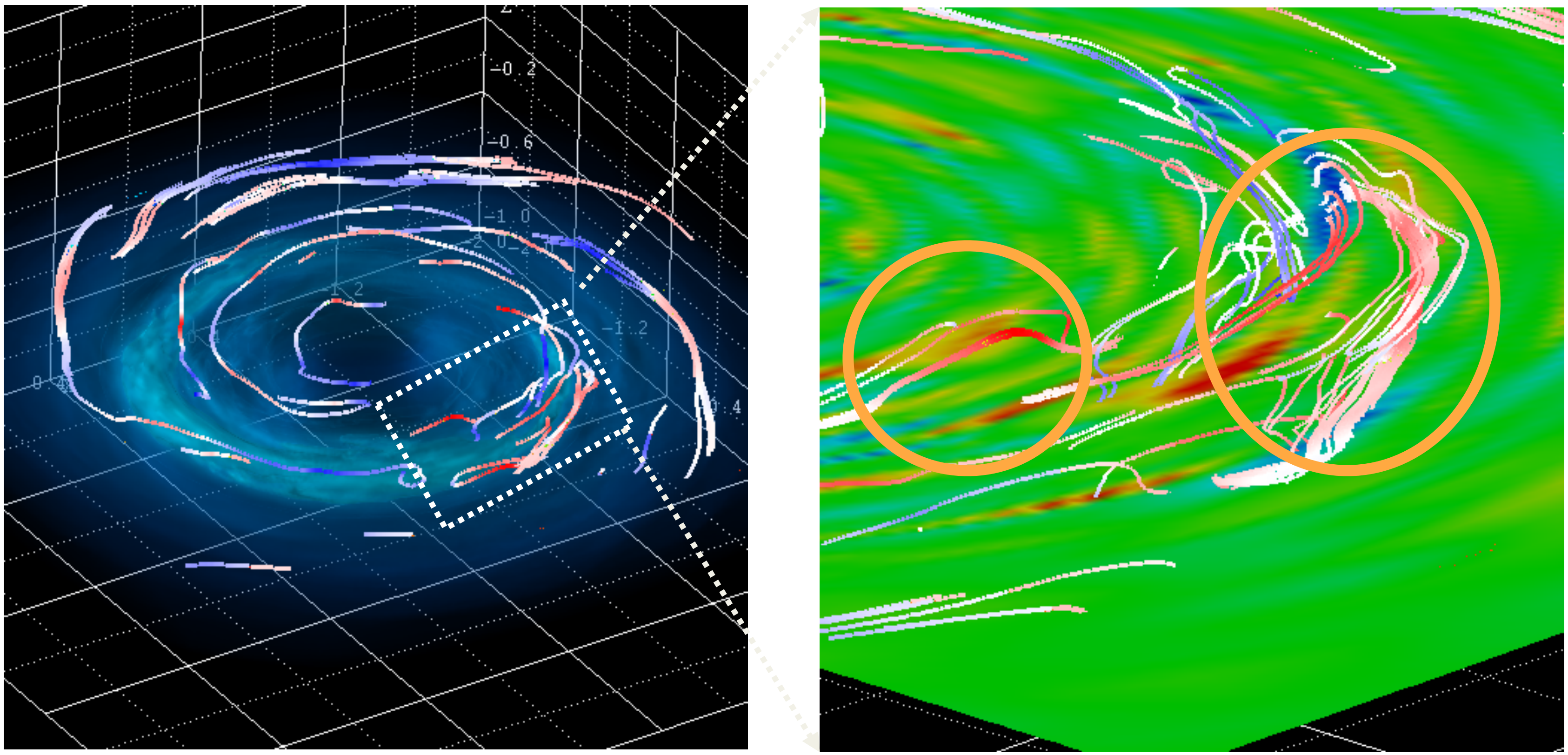


left)　Blue surface：　volume rendered image of the gas density

Curves：　Floating magnetic loops. Color depicts vertical velocity from minus to plus: blue – white –red.

right)　Enlarged figure of the left panel.　Curves are same on the left panel.

Parker instability in the nuclear disk
(Machida et al. 2009)



left) Blue surface： volume rendered image of the gas density

Curves： Floating magnetic loops. Color depicts vertical velocity from minus to plus: blue – white –red.

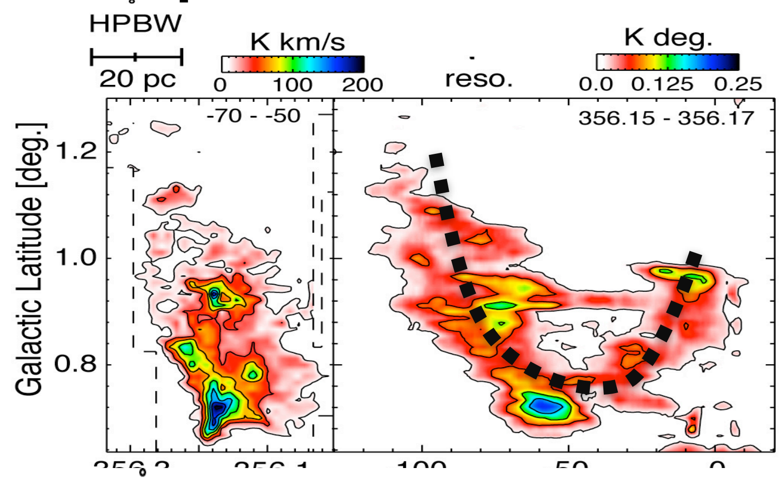
right) Enlarged figure of the left panel. Curves are same on the left panel.

NANTEN

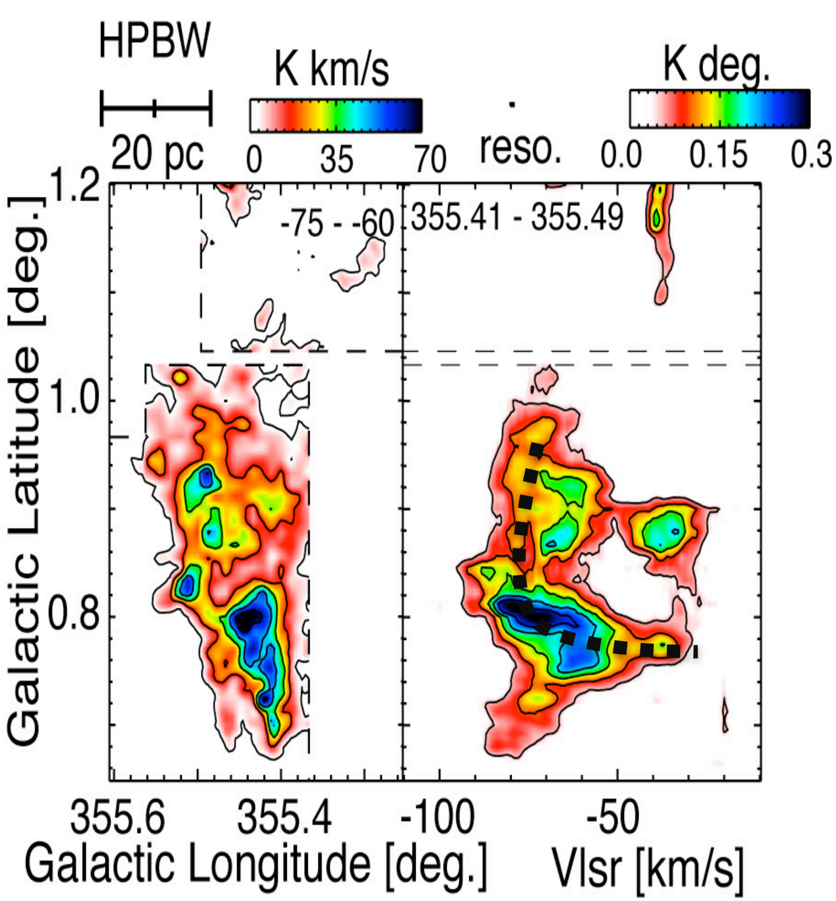
Submillimeter Observatory

U/L-shapes of foot points

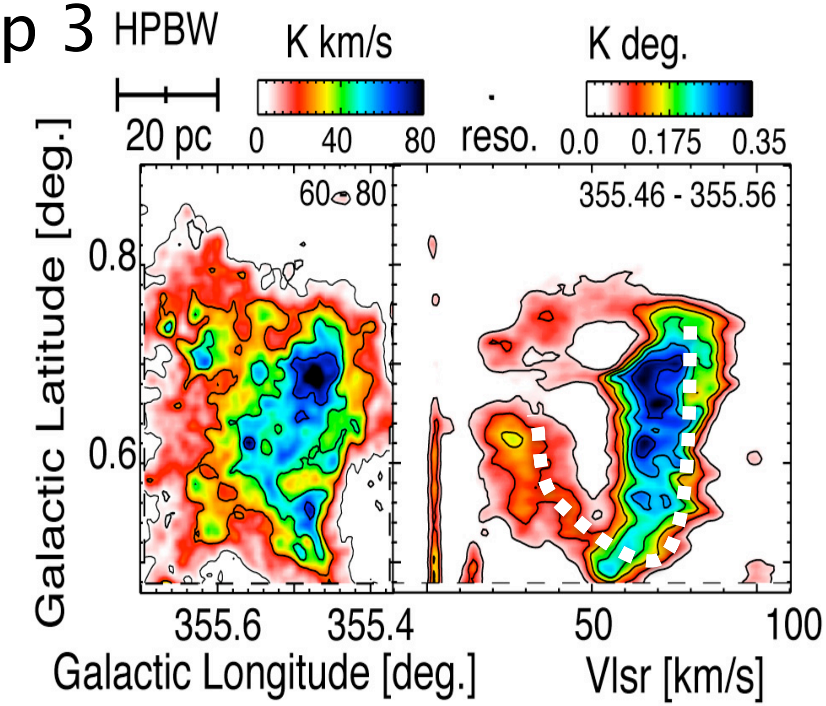
Loop1/2



Loop 2



Loop 3



The Galactic center; loop papers

Observations

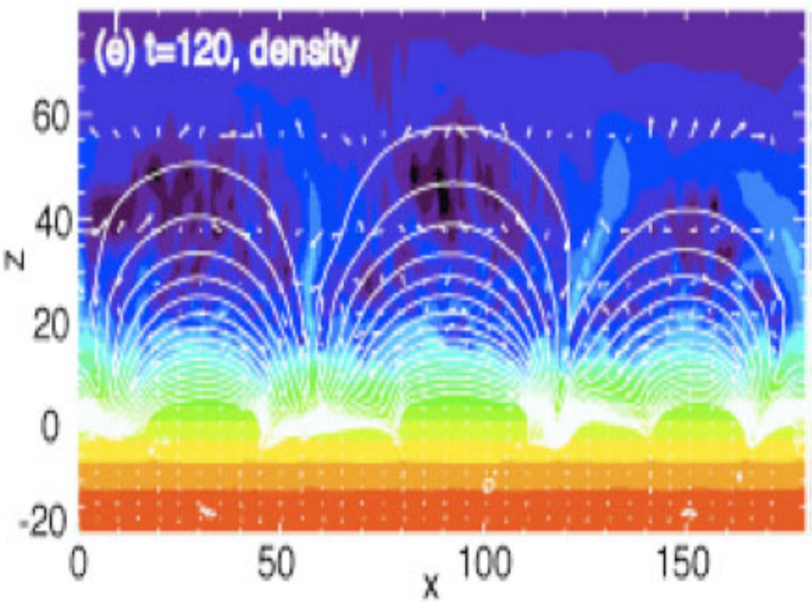
- Fukui et al. 2006 Science 314, 106 [loops1 & 2]
- Fujishita et al. 2009 PASJ 61, 1039 [loop3]
- Takeuchi et al. 2010 PASJ 62, 557 [star formation]
- Torii et al. 2010a PASJ 62, 675 [loop 1-2 CO7-6....foot point]
- Torii et al. 2010b PASJ 62, 1307 [loop 1-2 CO1-0]
- Kudo et al. 2010 PASJ 62, in press [loop 1-2 CO3-2/2-1]
- Riquelme et al. 2010 AA
  [shock tracers SiO, HCO+, etc.]

MHD theories

- Machida et al. 2009 PASJ 61, 411
  [3D numerical simulation]
- Takahashi et al. 2009 PASJ 61, 957
  [2D numerical simulation]

Collaborators

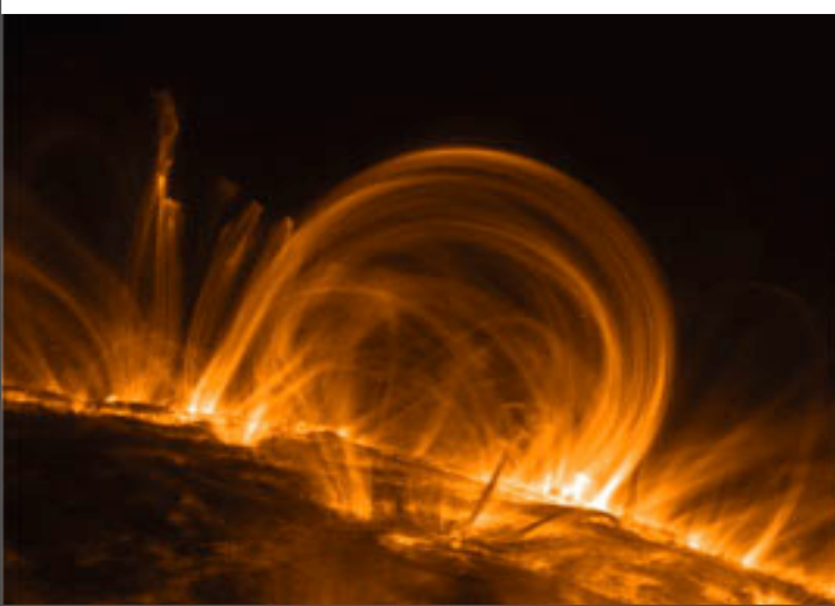
Torii,K., Kudo, N., Kawamura,A., Yamamot

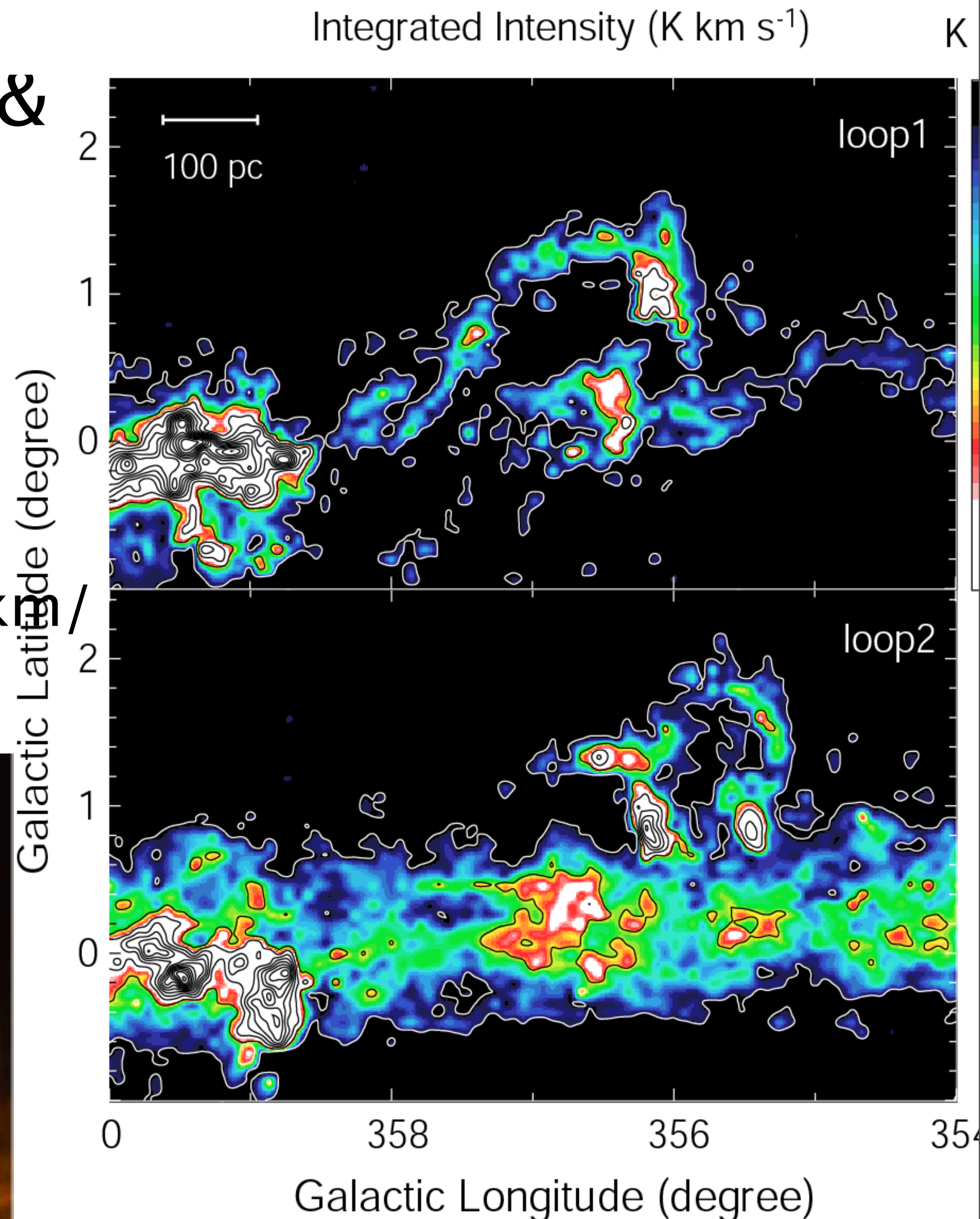


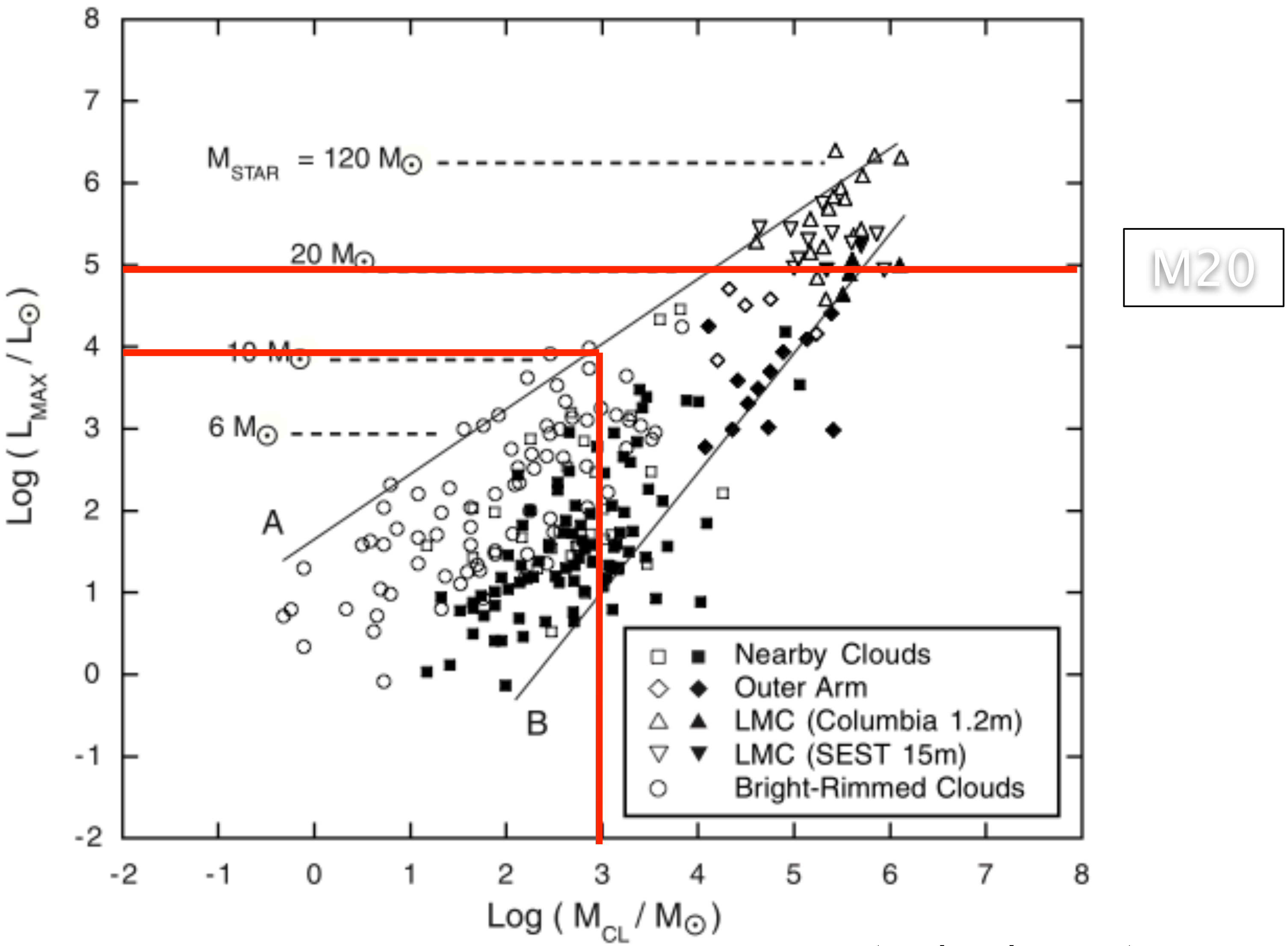
Molecular loops 1 & 2
(Fukui et al. 2006)

Two loop like structures in CO 1-0

Foot points with large velocity dispersion (~40km/s)



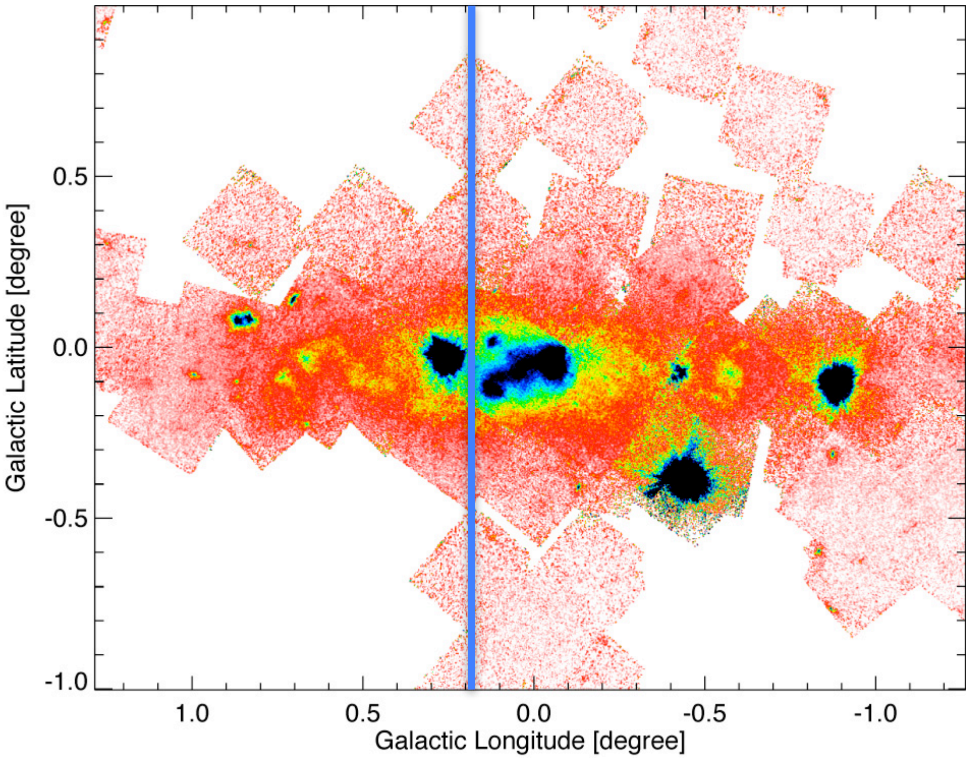


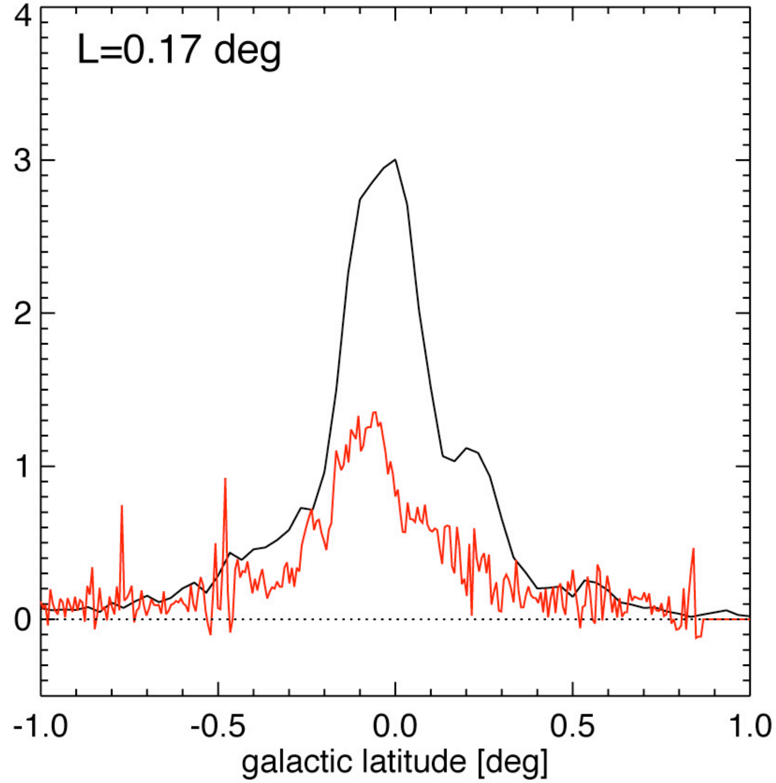


M20
M_{STAR} = 120 M⊙
20 M⊙
10 M⊙
6 M⊙
A
B
Nearby Clouds
Outer Arm
LMC (Columbia 1.2m)
LMC (SEST 15m)
Bright-Rimmed Clouds
Log (L_{MAX} / L⊙)
Log (M_{CL} / M⊙)

(Dobashi+01)

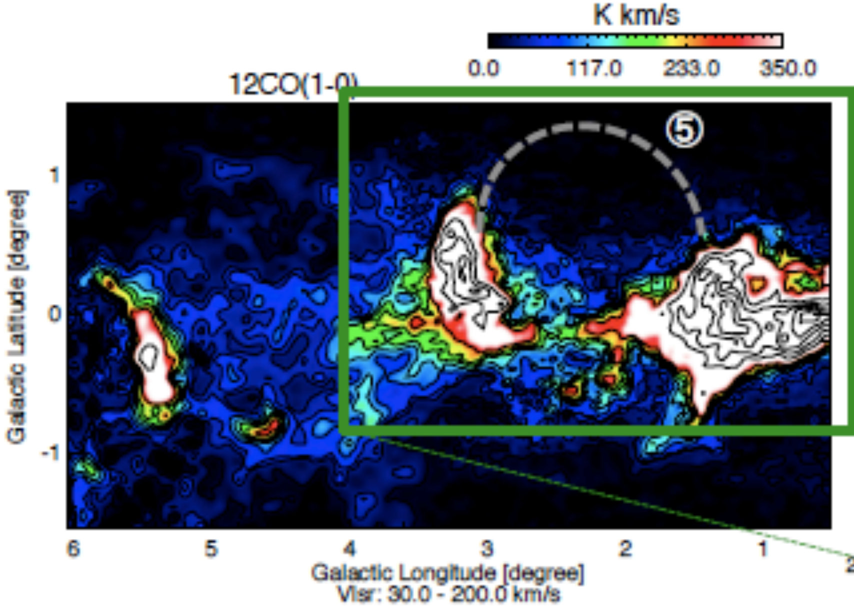
Vertical distributions

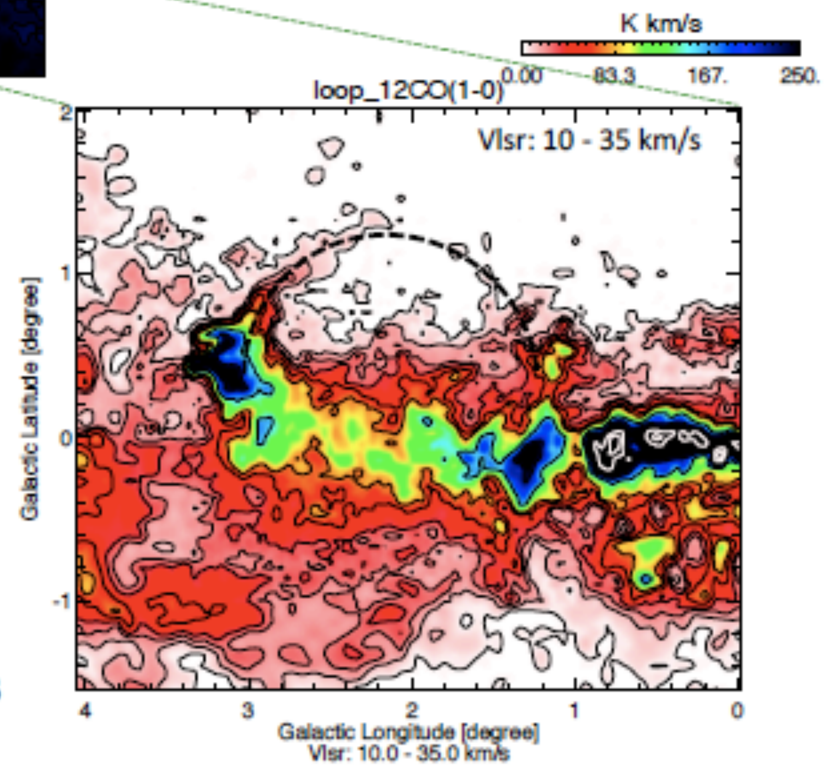




Black: CO J=1-0, Red: Suzaku 5-8 keV

Loop (L=1~3°) upper





NANTEN 12CO (J=1-0) LB