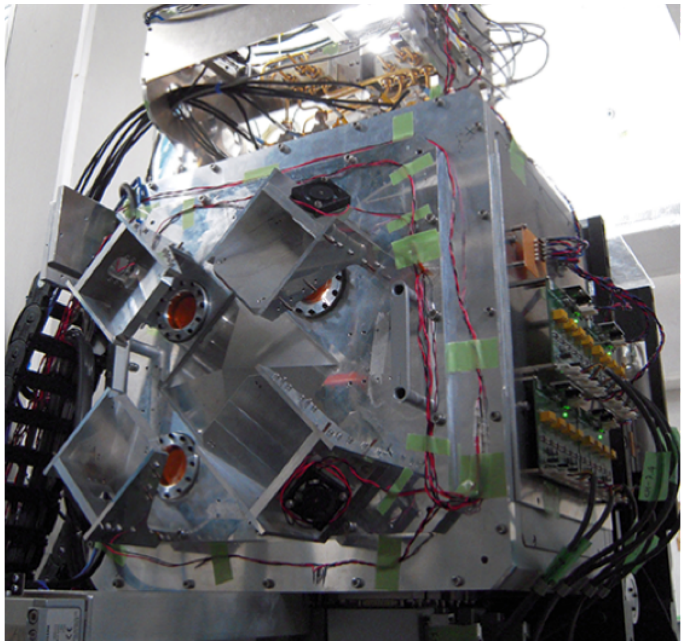
FUGINが見た分子雲衝突;
Cloud-cloud collisions with the FUGIN data

Kazufumi Torii（NAOJ/NRO）

- Fujita, S, Kohno, M., Nishimura, A., Fukui, Y. (Nagoya Univ.), Kuno, N.(Univ. of Tsukuba), Matsuo, M., Umemoto,T., Minamidani, T. (NRO), and other FUGIN members

Nobeyama 45m telescope and FOREST receiver



Nobeyama 45m telescope

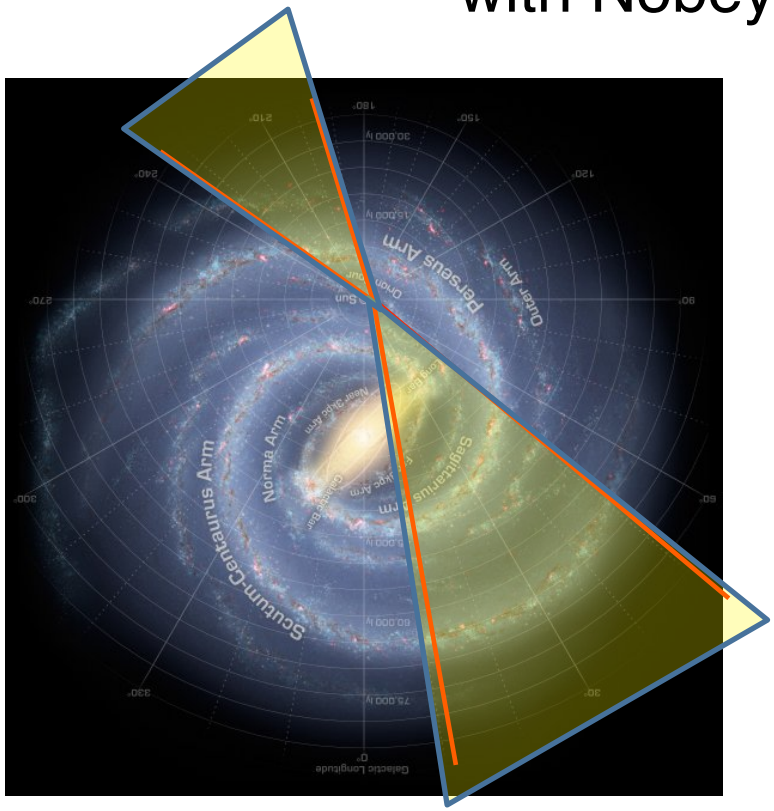
- Diameter: 45m
- Beam size@115GHz: ~15”

FOREST (FOur-beam REceiver System on the 45-m Telescope)

- Minamidani et al. 2016, Proc. SPIE
- 80–116GHz
- 4 beams x 2 pols. x 2 SBs = 16 IFs
- Tsys ~ 150K@110GHz, ~ 250K@115GHz
- IF 4–11GHz → simultaneous 12CO, 13CO, C18O observation
- SPW mode (2016–): CO three isotopes can be obtained at 0.1 km/s resolution at minimum

FUGIN project

FOREST Unbiased Galactic plane Imaging survey with Nobeyama 45-m telescope



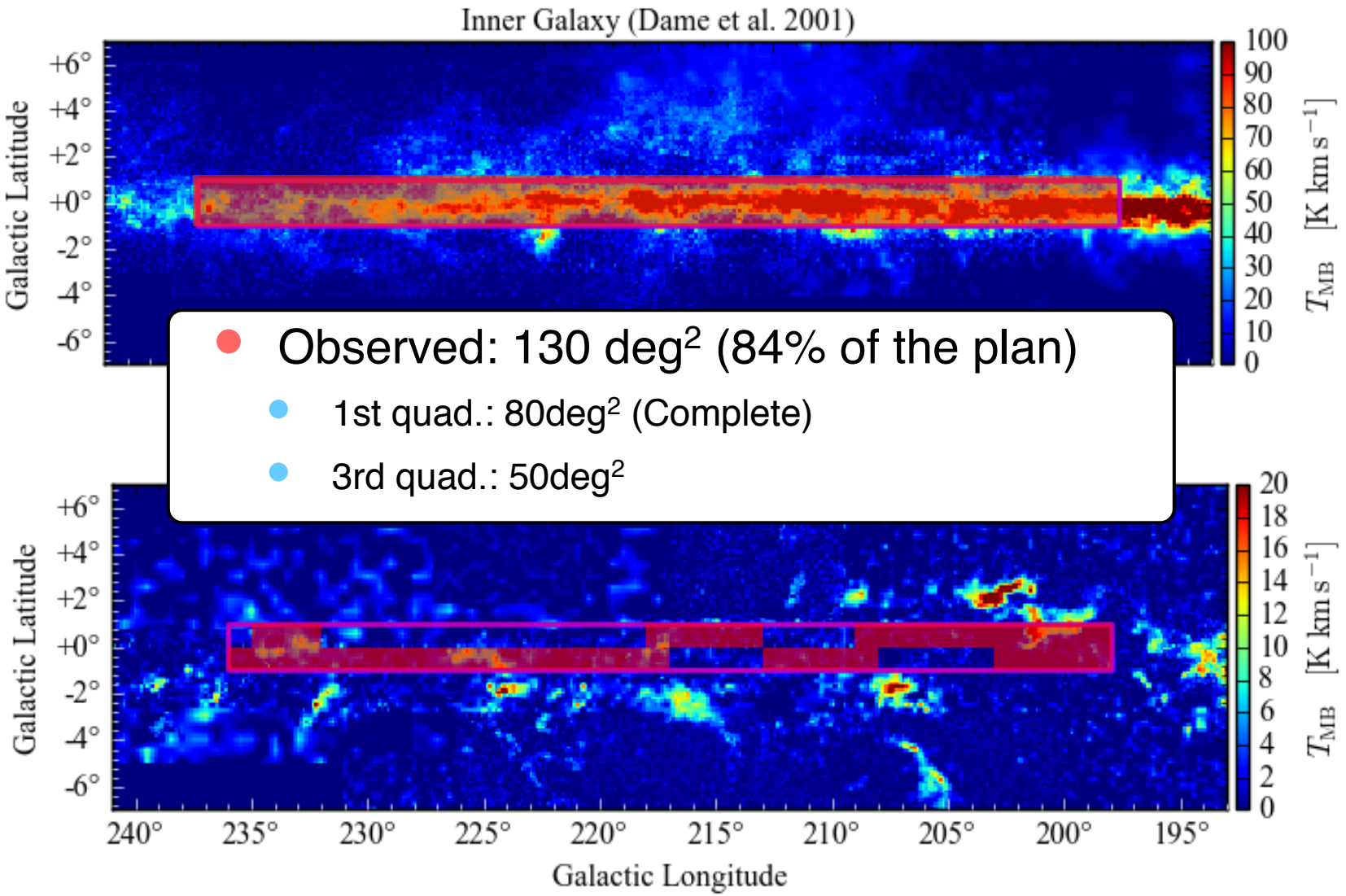
Large-scale ^{12}CO, ^{13}CO, C^{18}O J=1-0 observations in the Galactic Plane

- 1st quad.: l ~ 10° – 50°, b < l1°l
- 3rd quad: l ~ 198° – 236°, b< l1°l
- effective beam sizes: 20”
- ch resolution: ~0.65km/s (effective: 1.3km/s)
- Trms(Tmb): 0.7K@13CO & C18O, 1.5K@12CO
- Data (fits cube) will be public in 2018

Aims

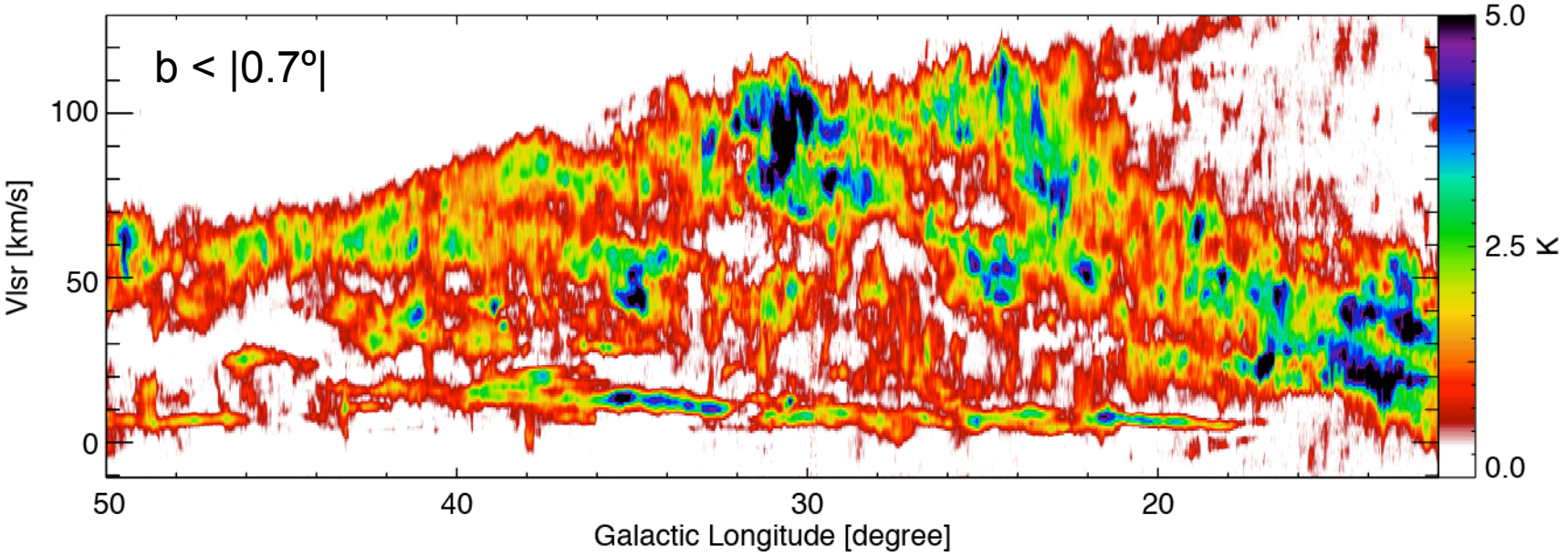
- Understanding ISM and star formation in the MW.
- Understanding the galactic structures in the MW.
- Constructing a bridge between the MW and galaxies.

Observed regions



magenta: planned, red: observed

Studies on GMCs with the FUGIN data



1. W33 (Kohno et al. accepted to PASJ, arXiv:1706.07964)
2. M17 (Nishimura et al. accepted to PASJ, arXiv:1706.06956; Yamagishi et al. 2016)
3. Spitzer bubble N18 (Torii et al., arXiv:1706.07164)
4. Spitzer bubble N35 + α (Torii et al., arXiv:1710.08564)
5. W51 (Fujita et al., arXiv: 1711.01695)

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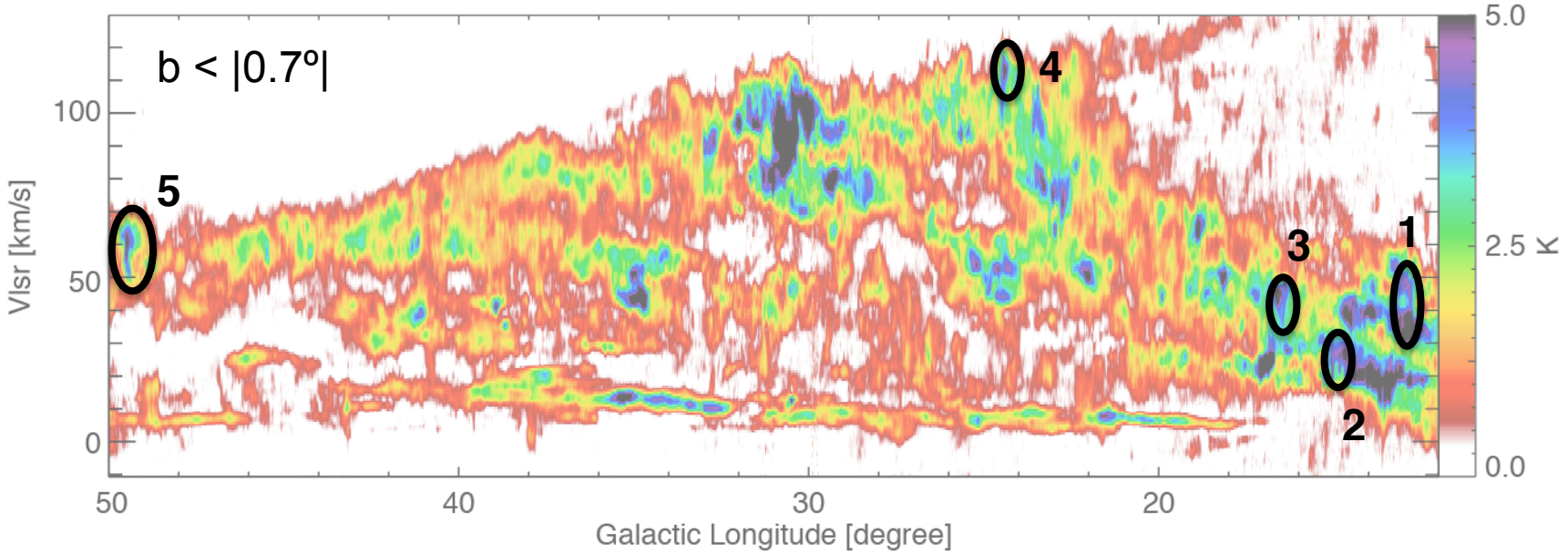

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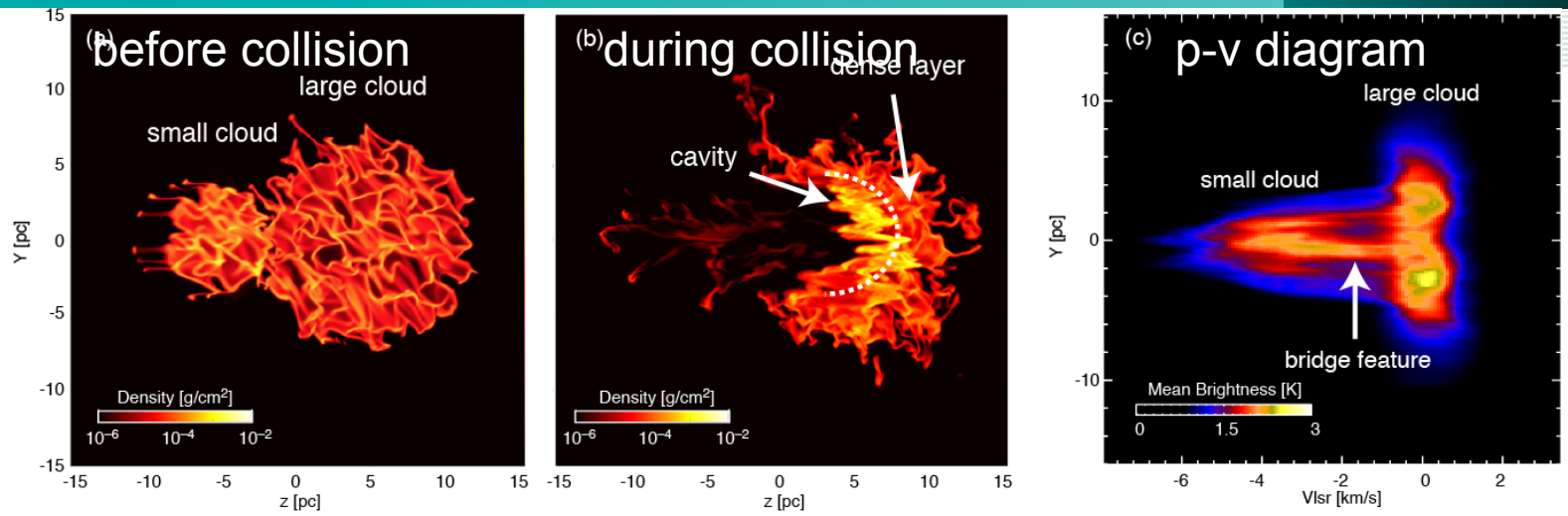
Cloud-cloud collisions

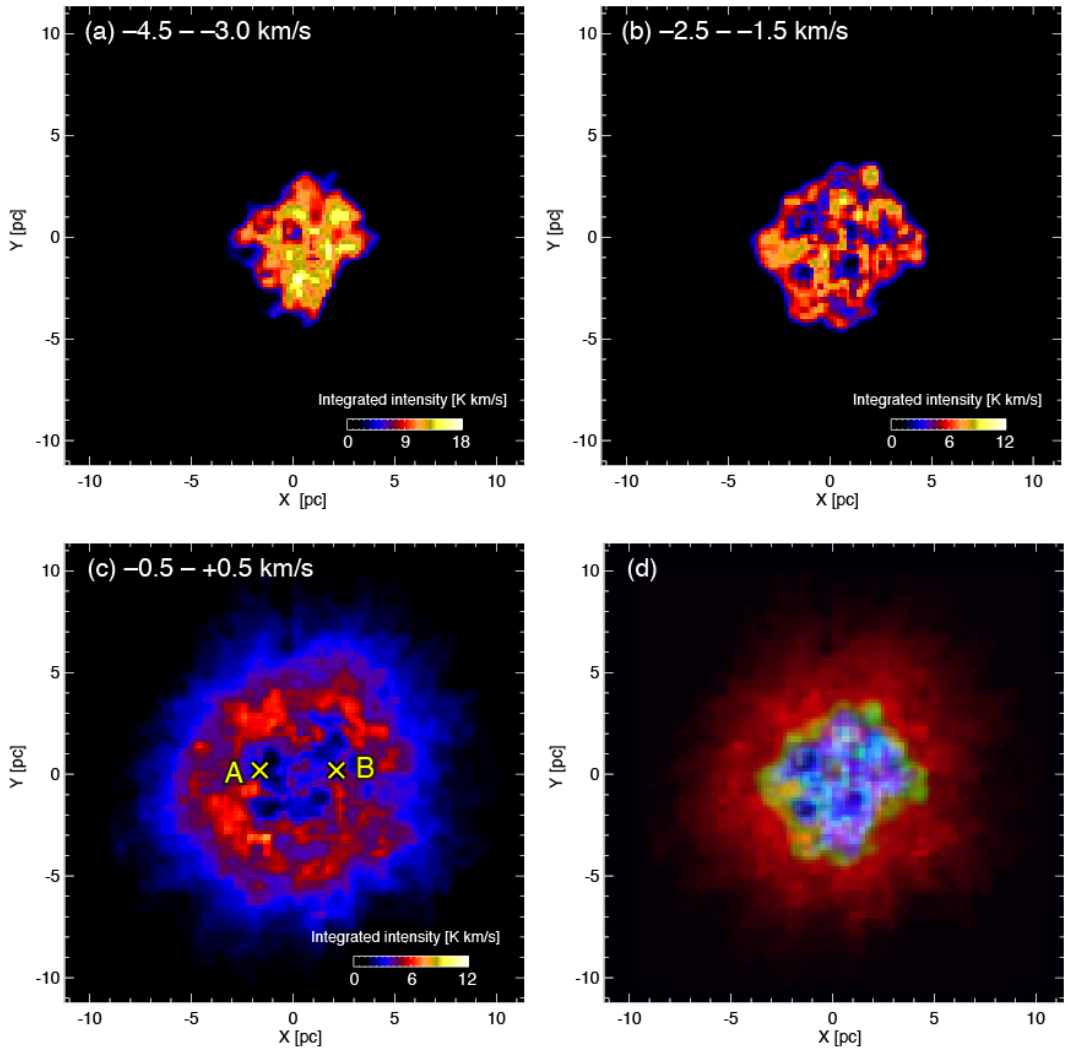
- Trigger of (massive) star formation
  - NGC1333 (Loren 1976); SgrB2 (Hasegawa+1994)
  - Galactic super star clusters (Furukawa+2010, Fukui+2014, 2016)
  - HII regions (Torii+2011, 2015, 2017, Ohama+2017a, 2017b, etc.)
  - Colliding velocities: ~10–30 km/s
  - CCC-driven star formation is dominated by massive GMCs having masses > $10^{5.5}$ $M_{\odot}$, which accounts for a few 10% of the total star formation in the MW (Kobayashi et al. 2017)
- Merger/coagulation of clouds
  - Frequency o collisions in MW-like galaxies ~ 7–10 Myr (Tasker & Tan 11; Dobbs+15).
  - Collision cooling to form giant clumps in gas-rich galaxy disk (Li 2017).
  - Little impact on the evolution of ISMs (Dobbs+15).

Cloud-cloud collision (CCC) model



- Takahira+14: Simulations of CCC between two dissimilar clouds.
- Haworth+15a, 15b: Synthetic CO J=1-0 observations with a radiative transfer code using the Takahira et al.'s data, in which the observer viewing angle is set to parallel to the colliding axis.
- When a smaller cloud drives into a larger cloud, a cavity is created on the larger cloud.
- In a position-velocity diagram, two velocity peaks separated by emissions with intermediate intensities (= broad bridge features) are observed.
- Bridge features are observable as long as the collision continues.

Cloud-cloud collision (CCC) model

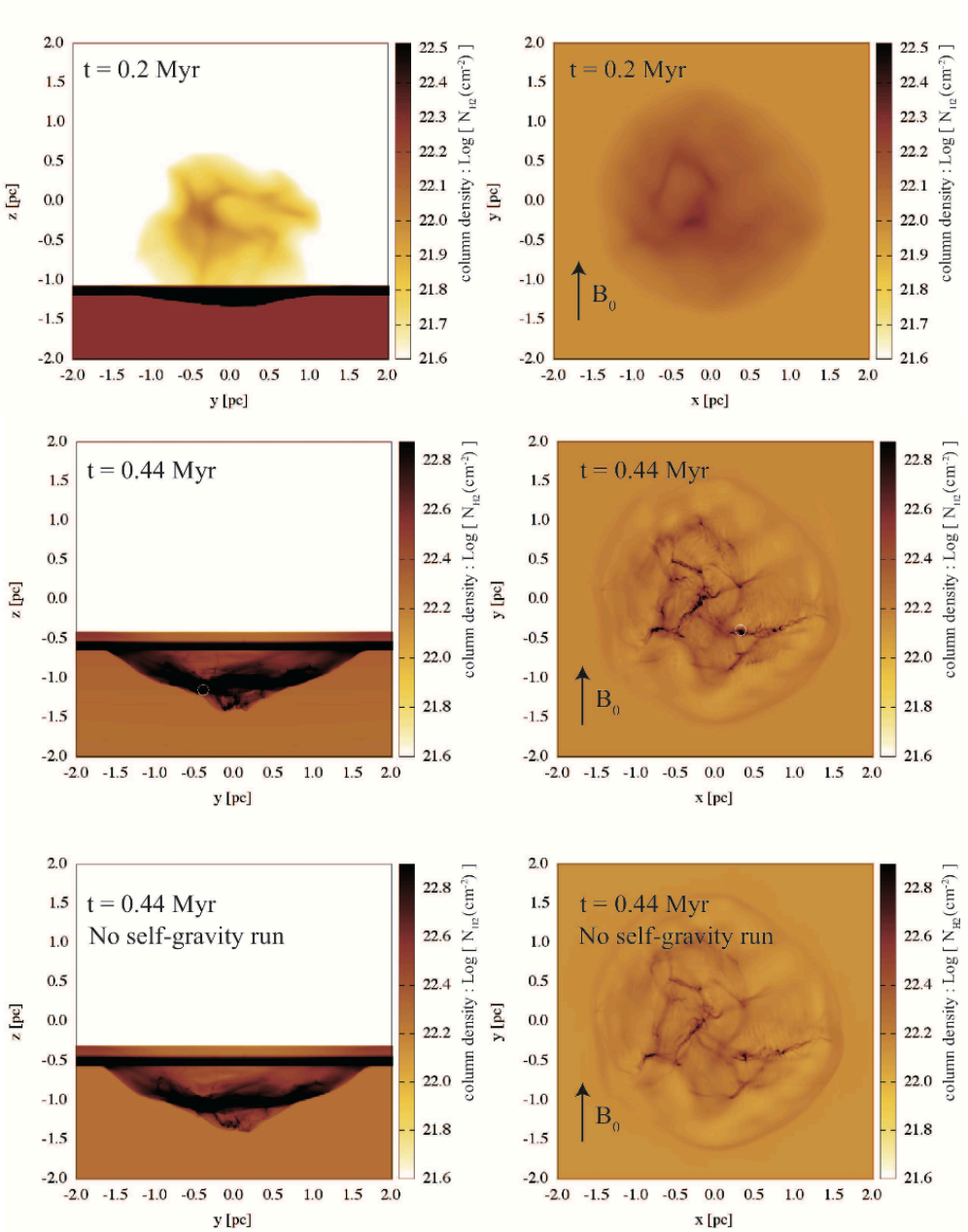


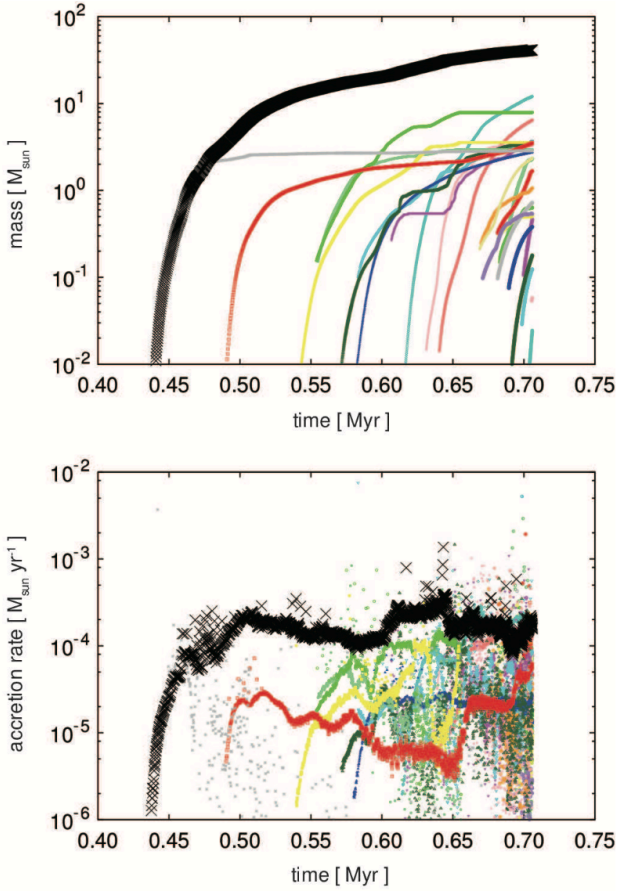
Torii+2017a

Spatial distributions of the two colliding clouds and bridge features with the synthetic CO J=1-0 data.

- The larger cloud with a cavity shows a ring-like gas distribution.
- The inner radius corresponds to the radius of the smaller cloud, showing a <u>complementary distribution</u> between the two velocity clouds.

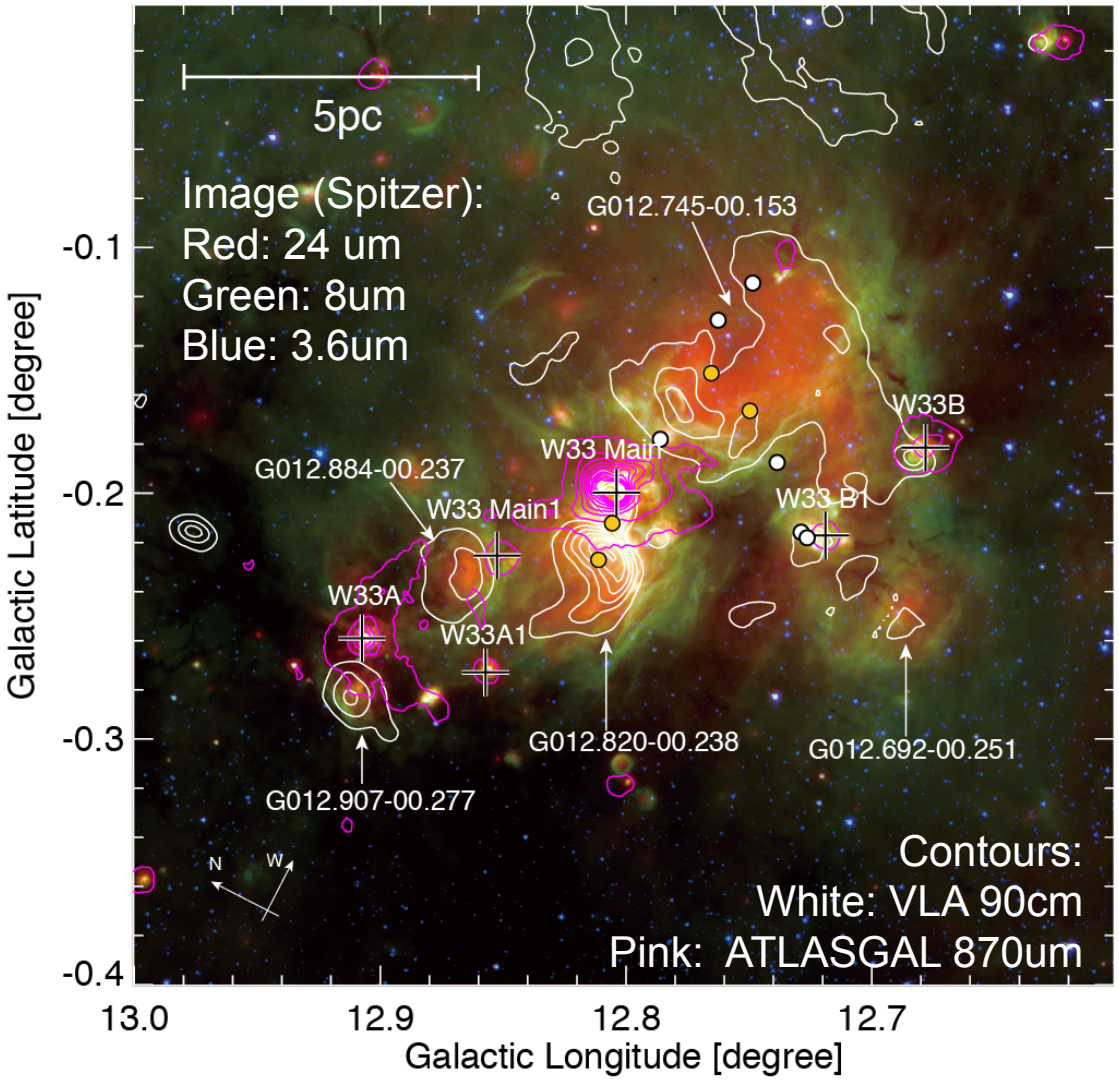
MHD numerical calculations (Inoue+2017)





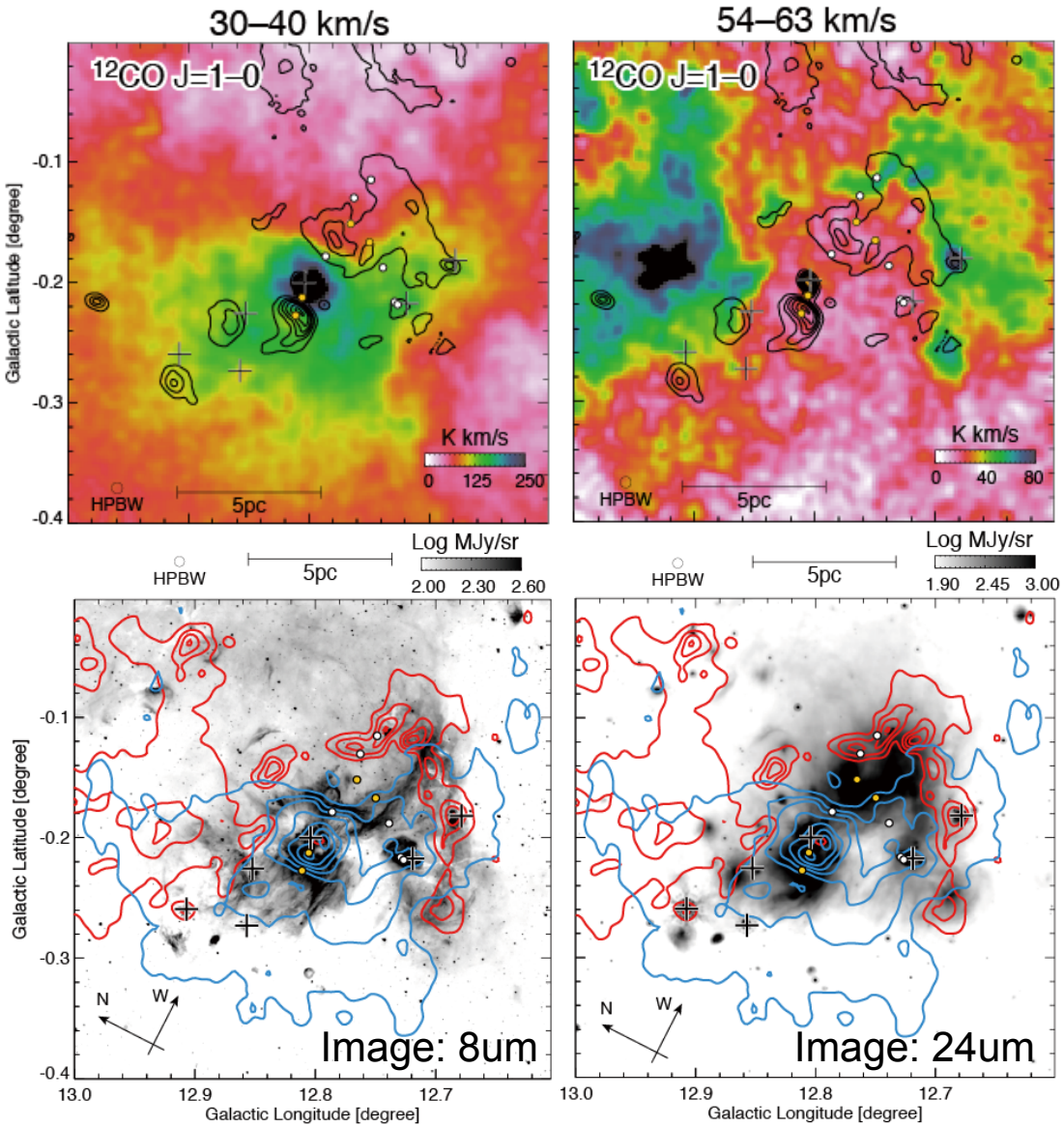
- Formation of filaments within the colliding layer.
- Dense clumps with high Mdot are formed.

W33 (Kohno et al. arXiv:1706.07964)



- Massive star forming region complex with a total bolometric luminosity of ~8x10^5 Lo.
- Dust clumps/cores, which include hot cores, compact HII regions, and massive outflows.
- HII regions and O stars.
- Parallaxial distance: 2.4kpc (Immer et al. 2013)
- Multiple velocity molecular gas components between 30–60 km/s.

W33 (Kohno et al. arXiv:1706.07964)



35km/s vs 58km/s

Two velocity clouds

35 km/s cloud

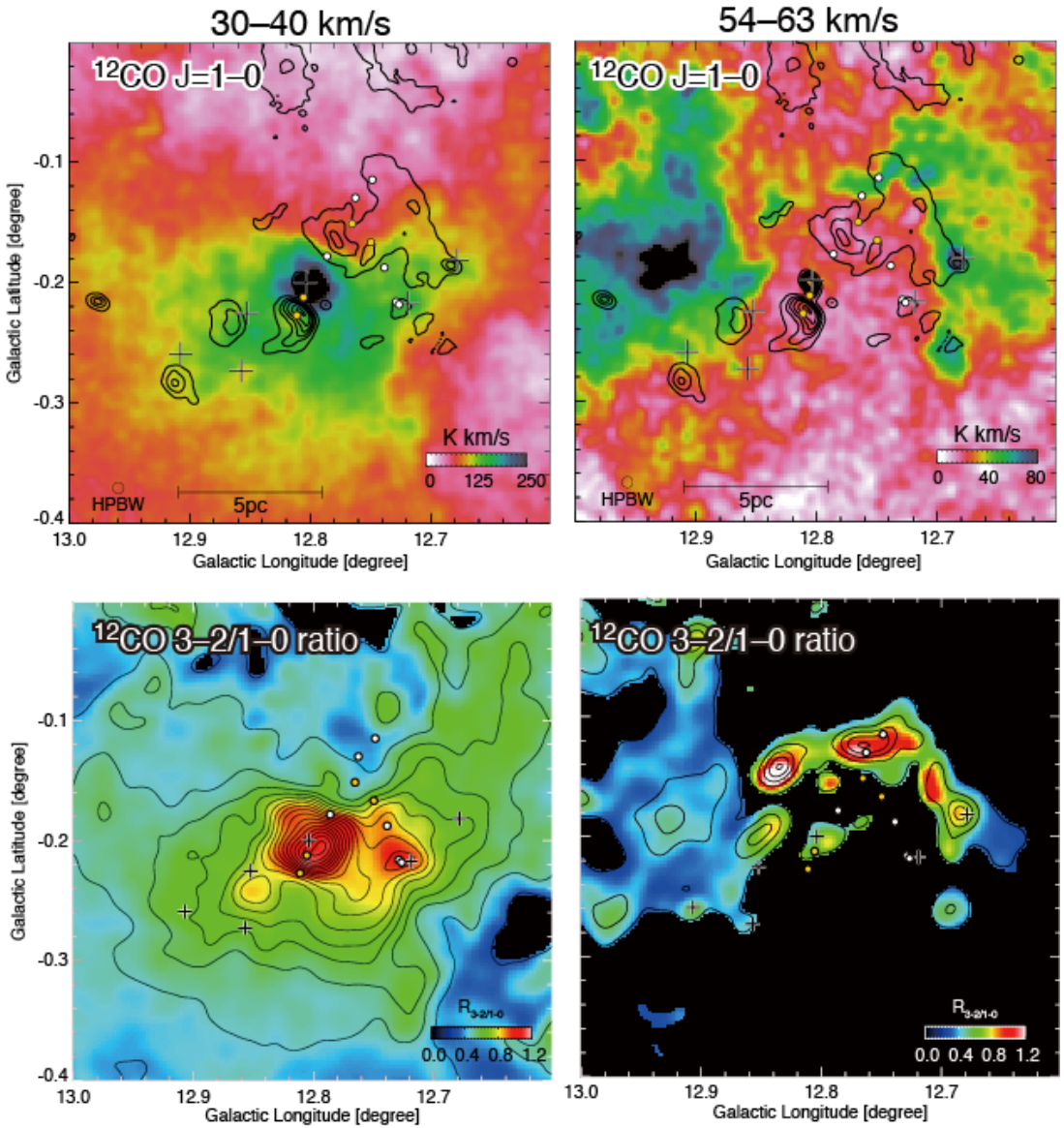
- ~5x10^4 Mo
- Spatially correlated with almost all of the dust clumps and HII regions in W33
- High CO 3-2/1-0 ratios

58 km/s cloud

- ~2x10^4 Mo
- Arch-like structure which surrounds W33
- dense gas clump in W33B
- High CO 3-2/1-0 ratios

<– heating by W33

W33 (Kohno et al. arXiv:1706.07964)



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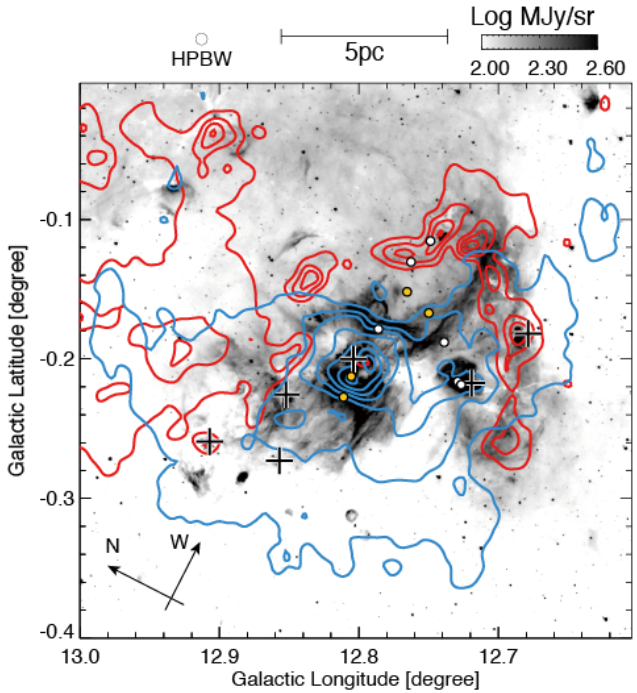
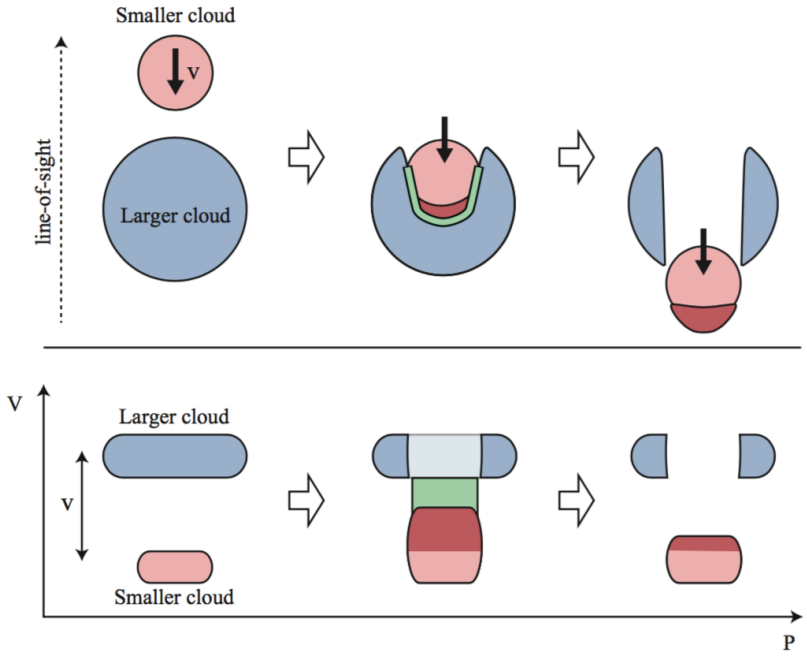
CCC in W33





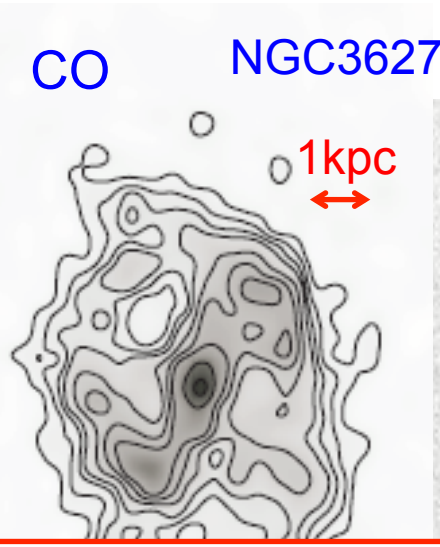
- Collision between two molecular clouds with different sizes at a relative velocity of ~23 km/s.
- As the smaller cloud is much dense than the larger cloud, the smaller cloud has punched the larger cloud.
- Collisional timescale ~ 1 Myr.

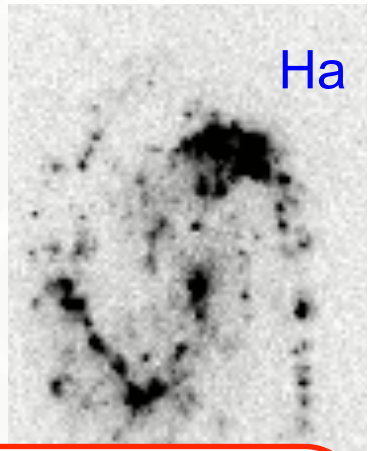
CCCs with the FUGIN data

- Roles of CCCs on evolution of ISM as well as star formation in the MW.
  - GMC formation?
  - Contribution to the global star formation rate.
- Variation depending on the location in the MW.
- Driving source of the cloud-cloud velocity dispersions.
  - Related to the galactic structures?
  - or stellar feedbacks?

- FUGIN provides
  - Large area coverage at high spatial resolution.
  - Diagnostics of the high- and low-density structures.

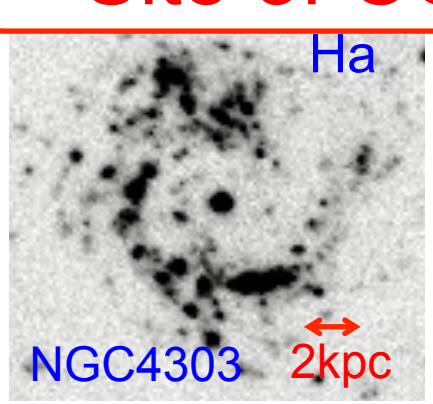
Barred spiral galaxies

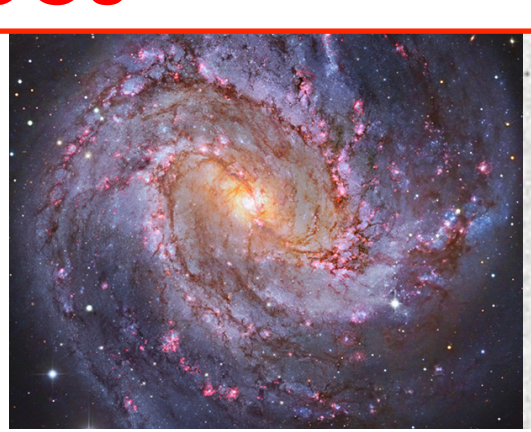


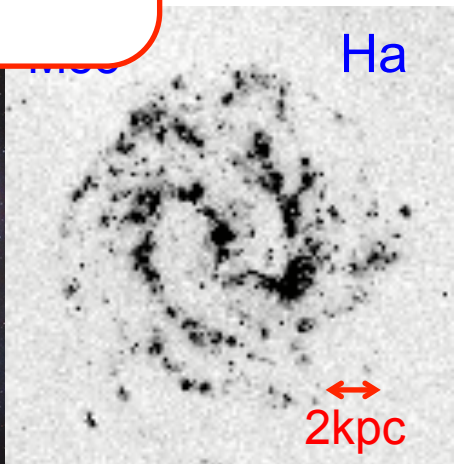


Bar-end:

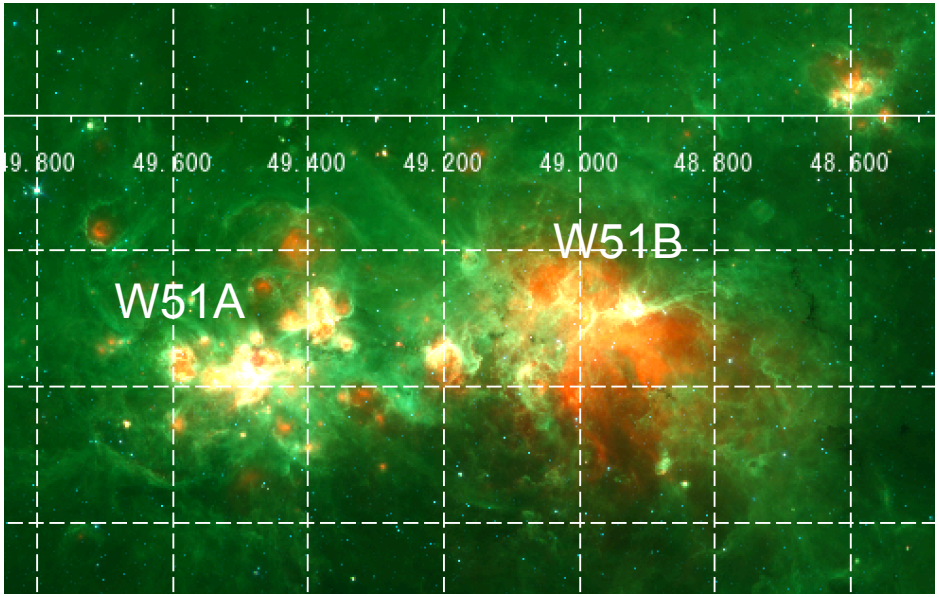
- mini-starburst at kpc scale
- Site of CCCs

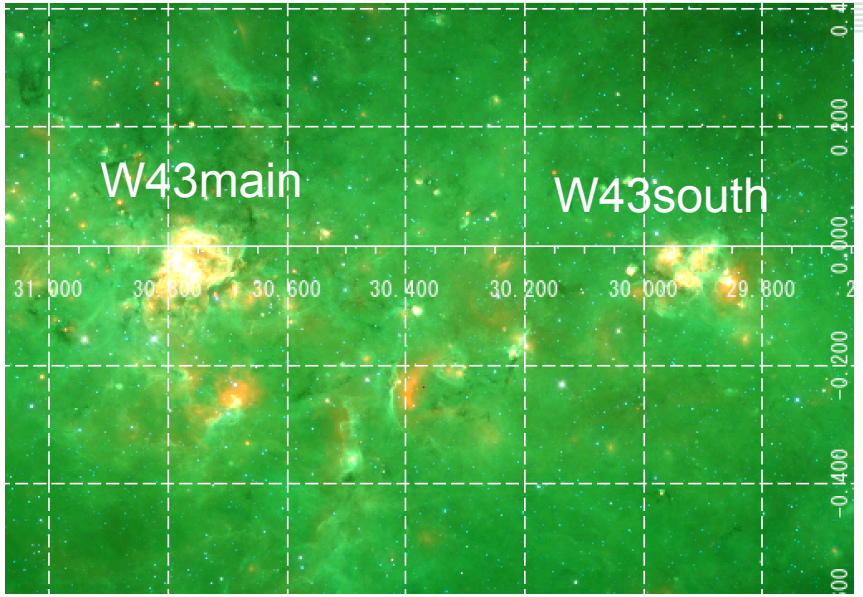






Galactic mini-starbursts at the bar-end





W51

D : ~5.4kpc (parallax)

L_{bol}: ~ $10^{6.7}$ $L_{\odot}$

GMC

size : ~100pc

mass : ~10^{6} $M_{\odot}$

W43

D : ~5.5kpc (parallax)

L_{bol}: ~ $10^{5.9}$ $L_{\odot}$

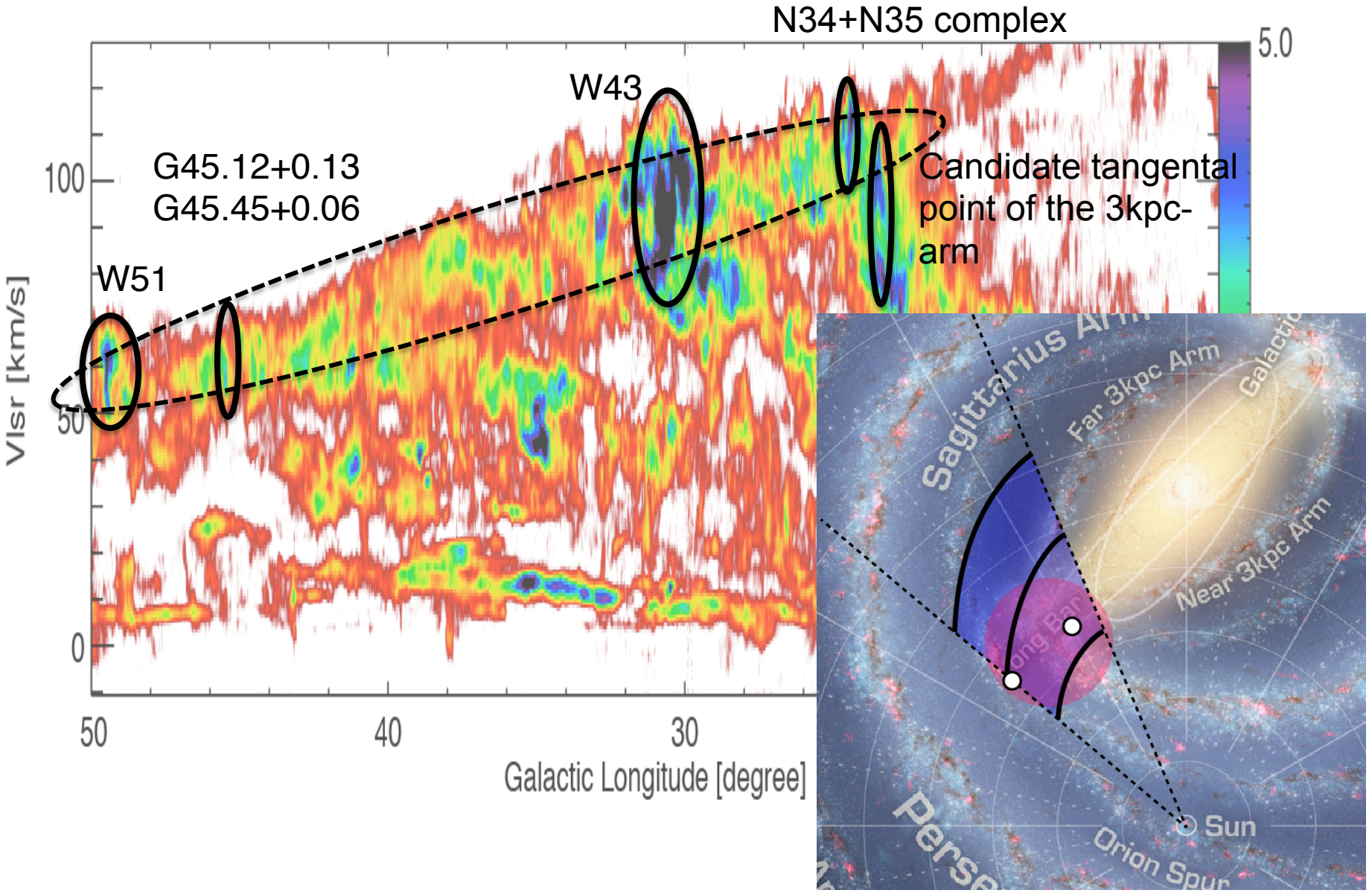
GMC

size: >100pc

mass : ~10^{7} $M_{\odot}$

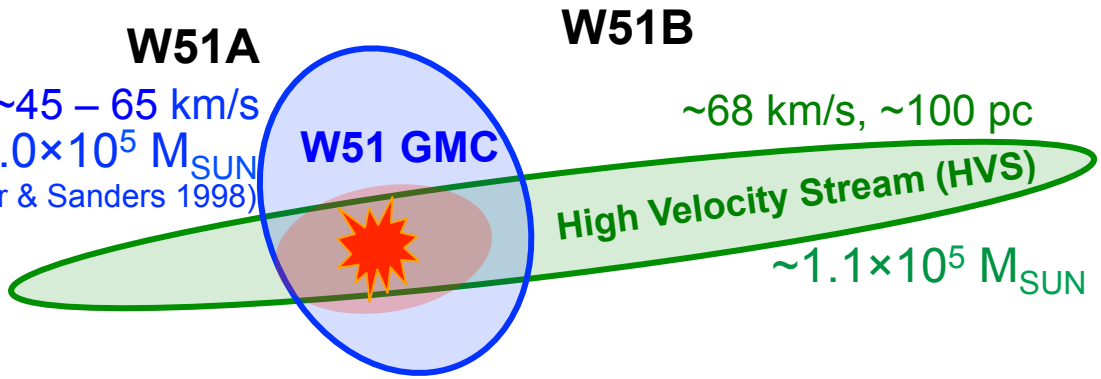
c.f., L_{galaxy} ~ 0.76x10^{8} Lo (Urquhart+2014)

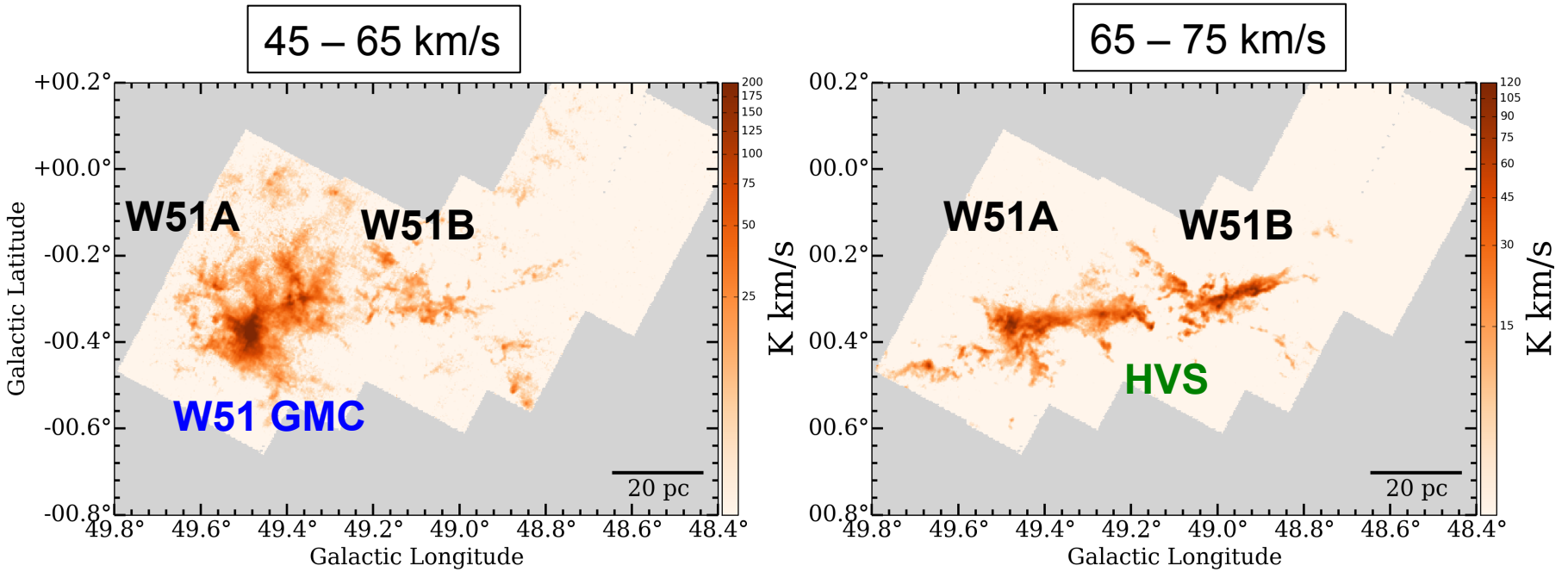
High-mass star forming regions in the bar-end



W51 and two GMCs

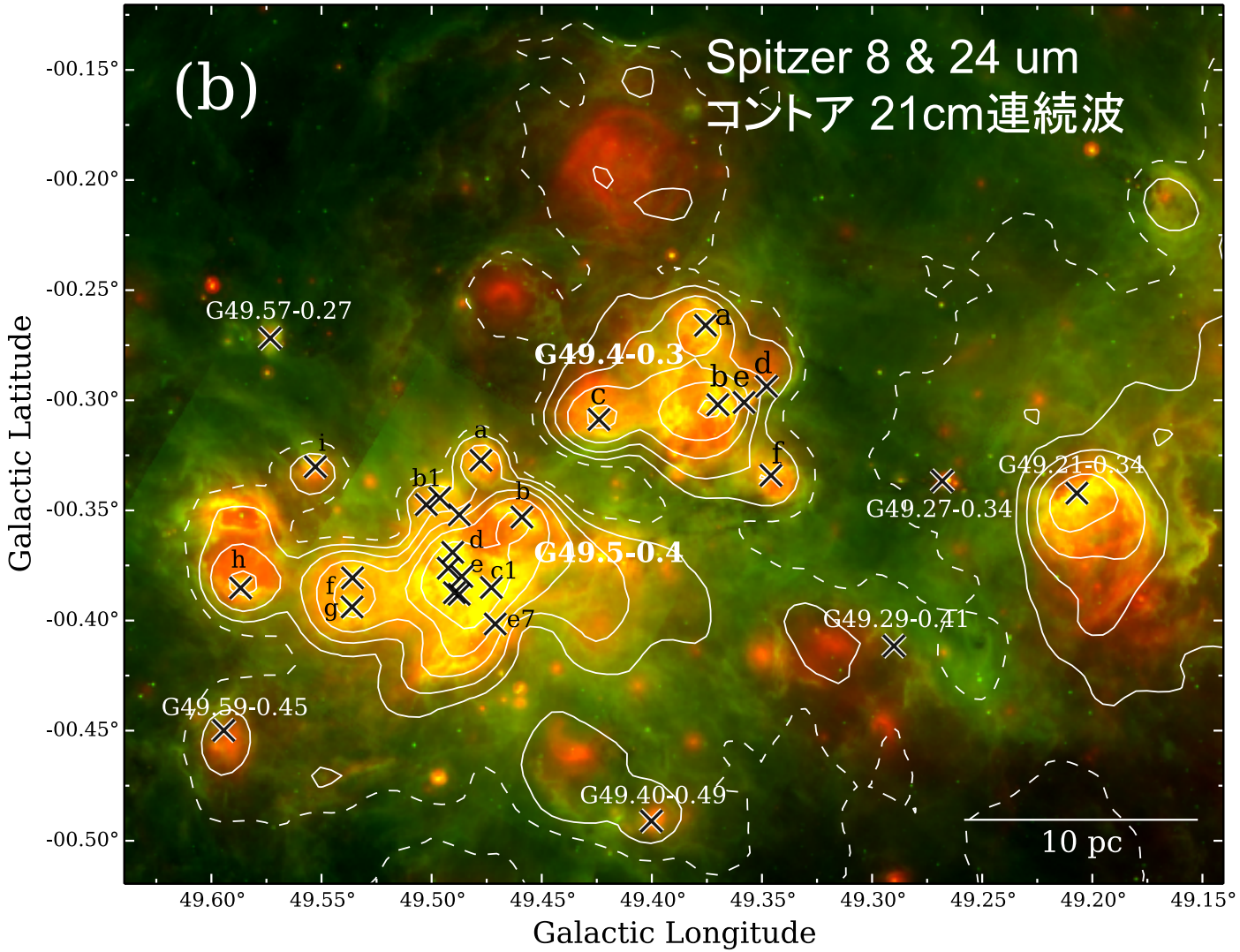
- Two large components
  - W51 GMC &
  - High Velocity Stream (HVS)





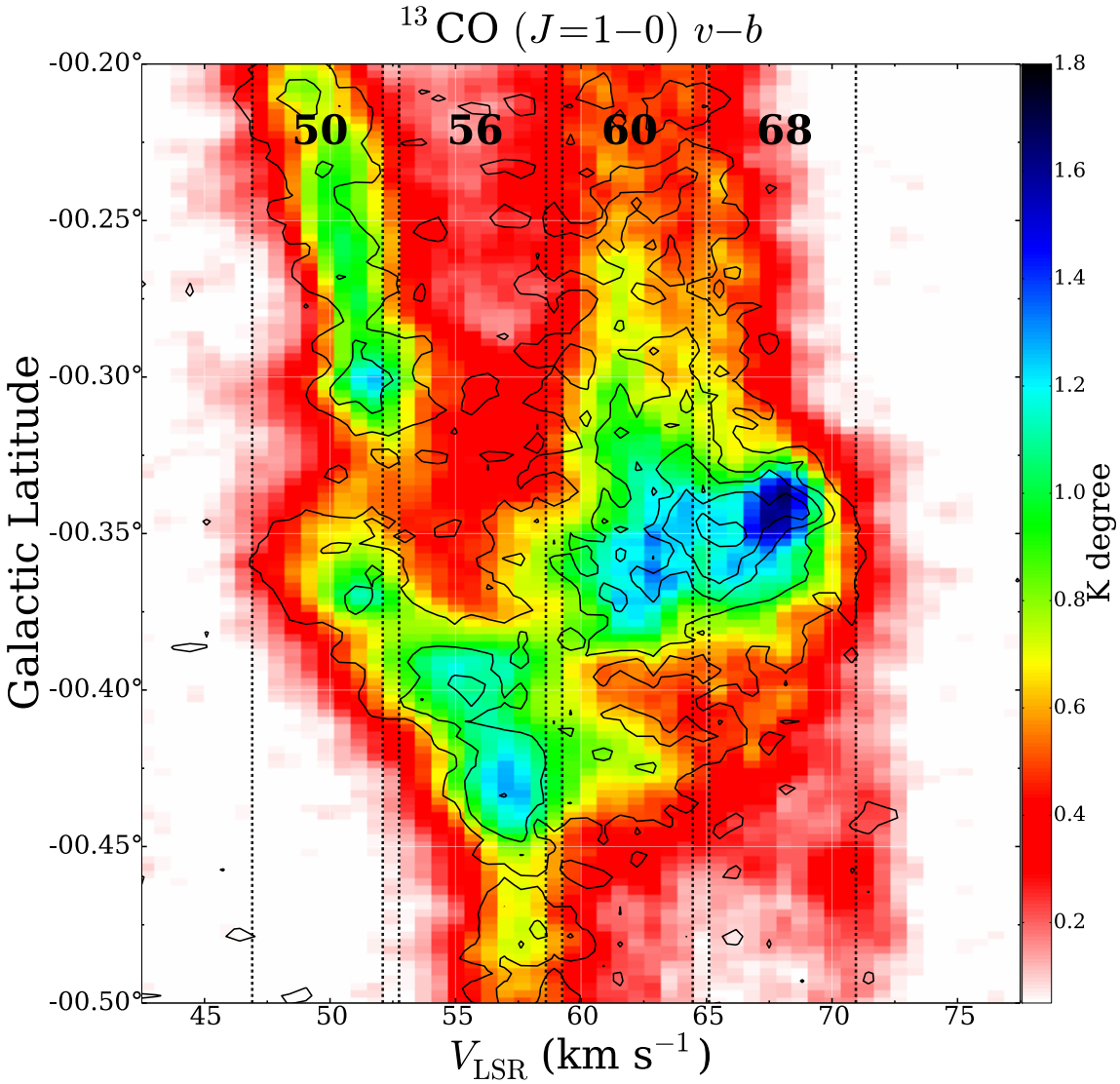
JCMT ^{13}CO (3–2) (Parsons+ 2012)

GMC in W51A

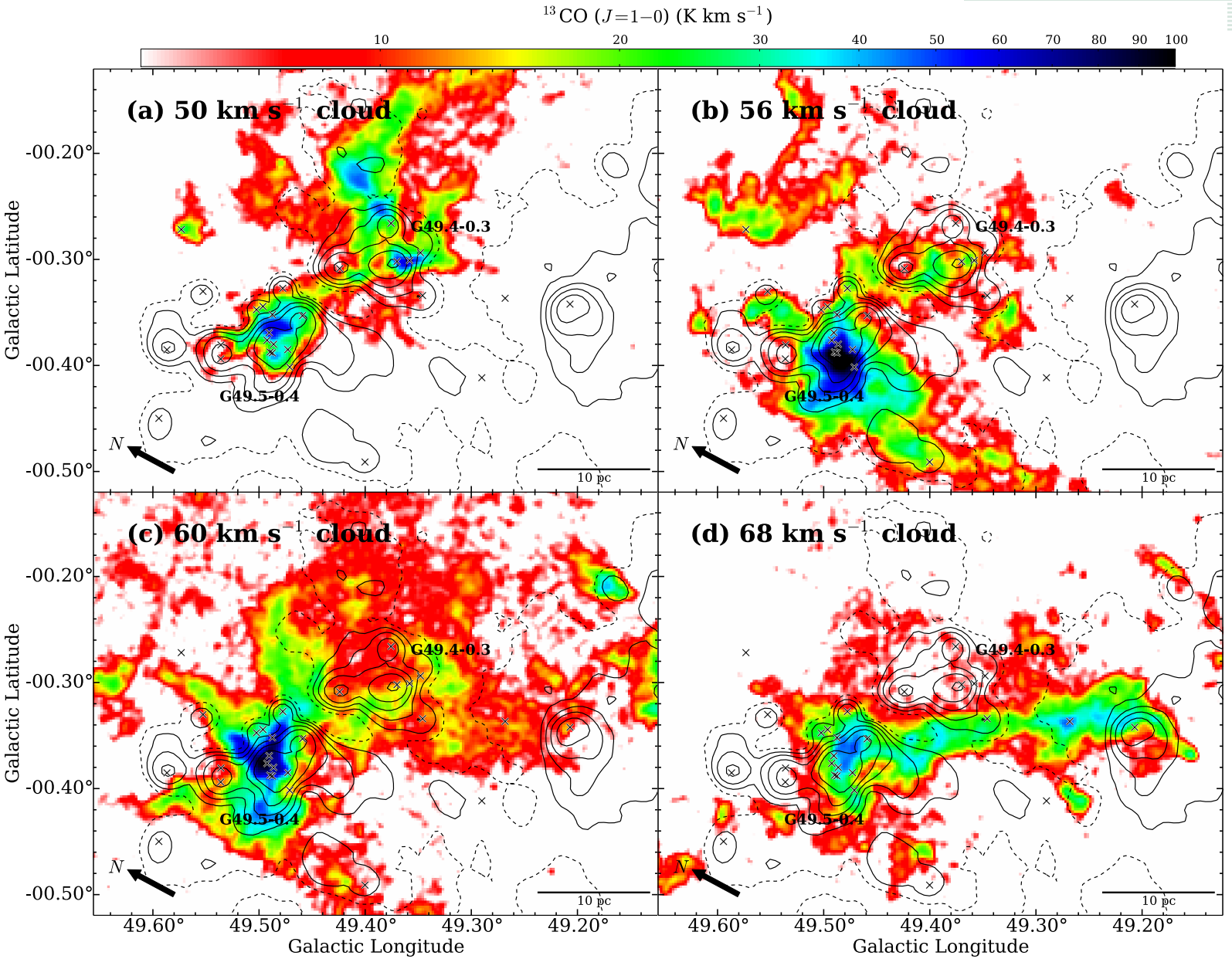


Fujita+2017 submitted

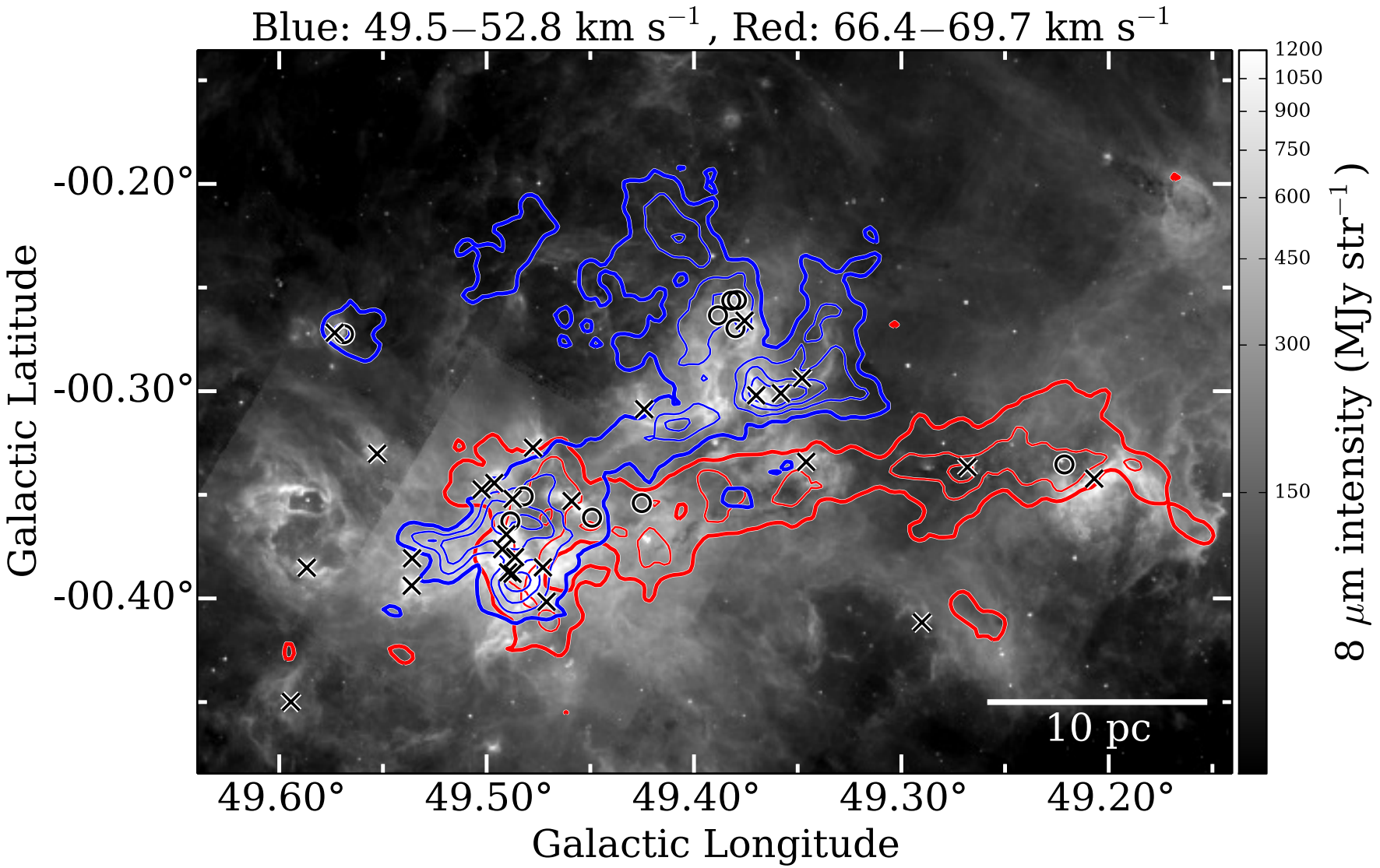
GMC in W51A


^{13}CO (J=1–0) v–b
50
56
60
68
-00.20°
-00.25°
-00.30°
-00.35°
-00.40°
-00.45°
-00.50°
Galactic Latitude
45
50
55
60
65
70
75
$V_{\rm LSR}$ (km s^{-1})
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
K degree

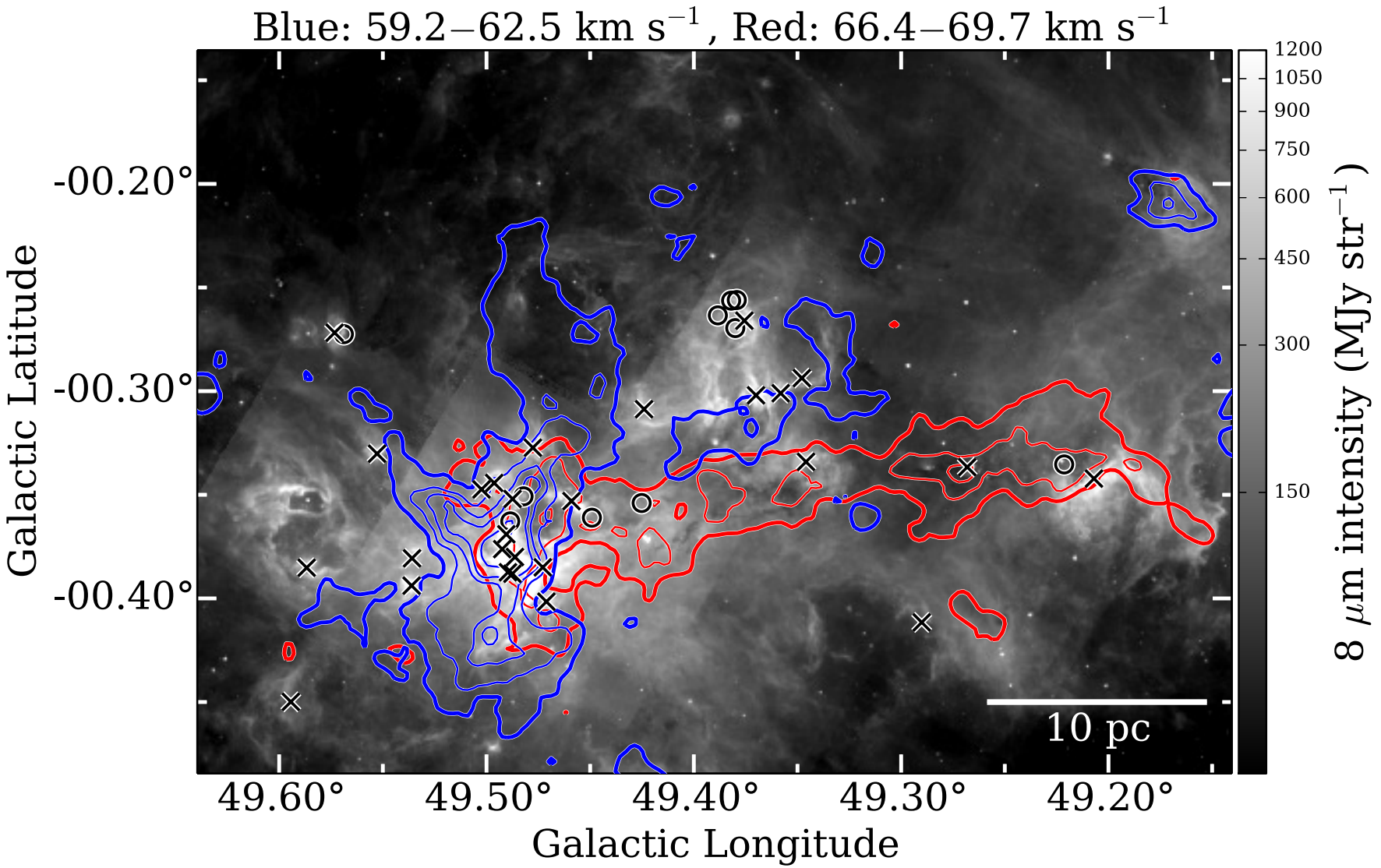
GMC in W51A


^{13}CO (J=1–0) (K km s^{-1})
10
20
30
40
50
60
70
80
90
100
(a) 50 km s^{-1} cloud
(b) 56 km s^{-1} cloud
(c) 60 km s^{-1} cloud
(d) 68 km s^{-1} cloud
G49.4-0.3
G49.5-0.4
N
10 pc
Galactic Latitude
-00.20°
-00.30°
-00.40°
-00.50°
Galactic Longitude
49.60°
49.50°
49.40°
49.30°
49.20°

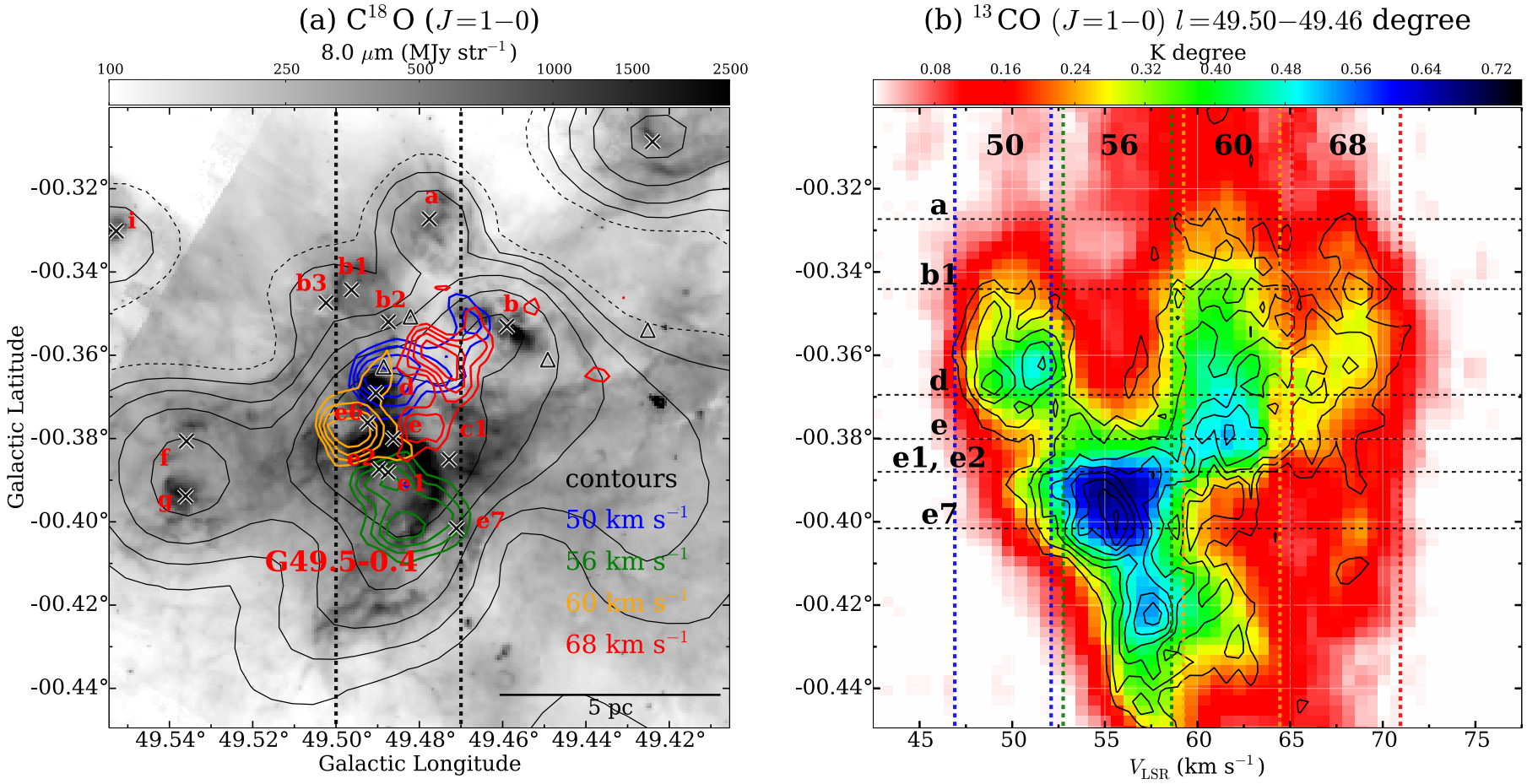
GMC in W51A


Blue: 49.5−52.8 km s^{-1}, Red: 66.4−69.7 km s^{-1}
-00.20°
-00.30°
-00.40°
Galactic Latitude
49.60°
49.50°
49.40°
49.30°
49.20°
Galactic Longitude
10 pc
1200
1050
900
750
600
450
300
150
8 μm intensity (MJy str^{-1})

GMC in W51A

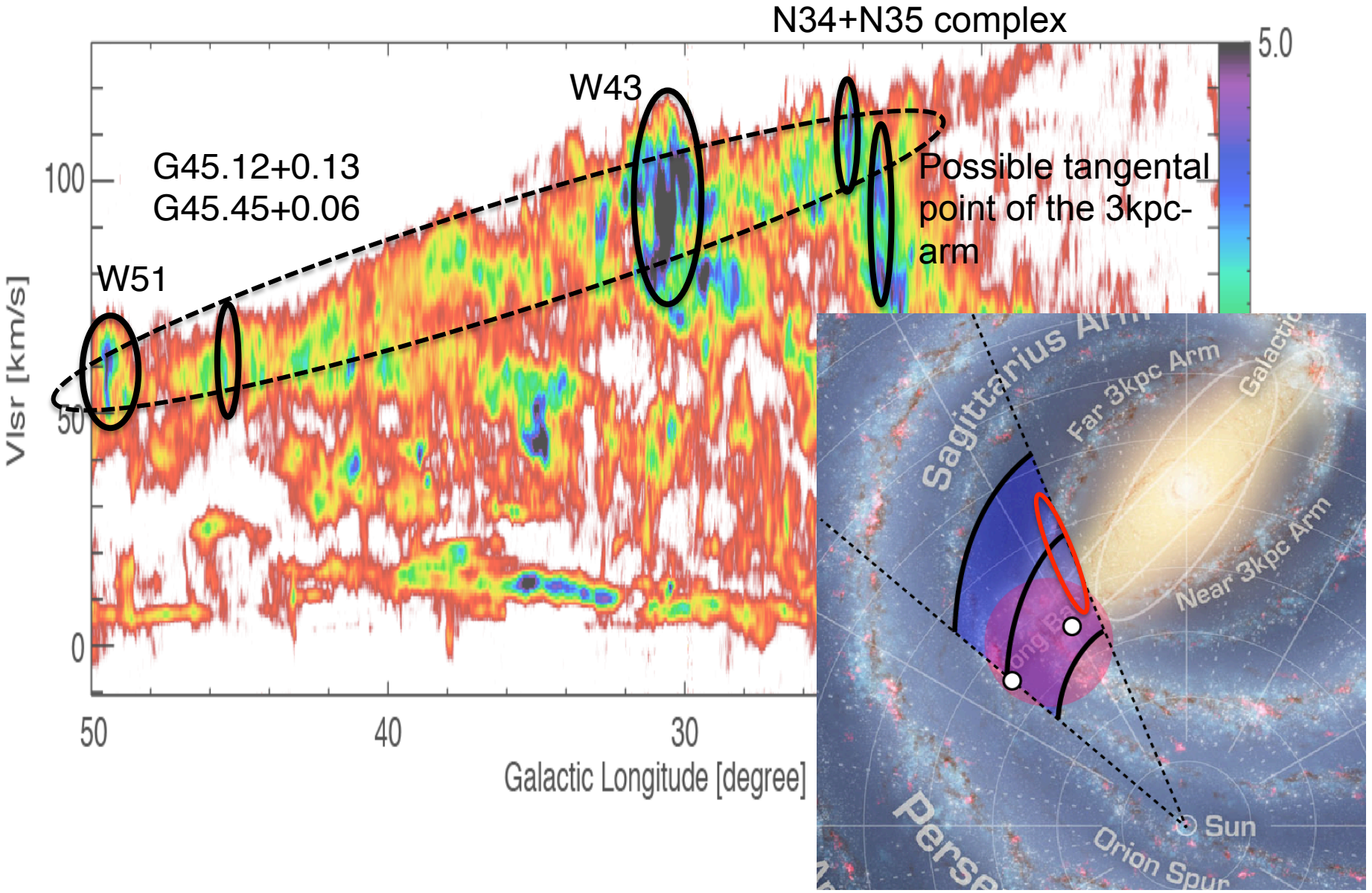

Blue: 59.2−62.5 km s^{-1}, Red: 66.4−69.7 km s^{-1}
-00.20°
-00.30°
-00.40°
Galactic Latitude
49.60°
49.50°
49.40°
49.30°
49.20°
Galactic Longitude
10 pc
1200
1050
900
750
600
450
300
150
8 μm intensity (MJy str^{-1})

GMC in W51A

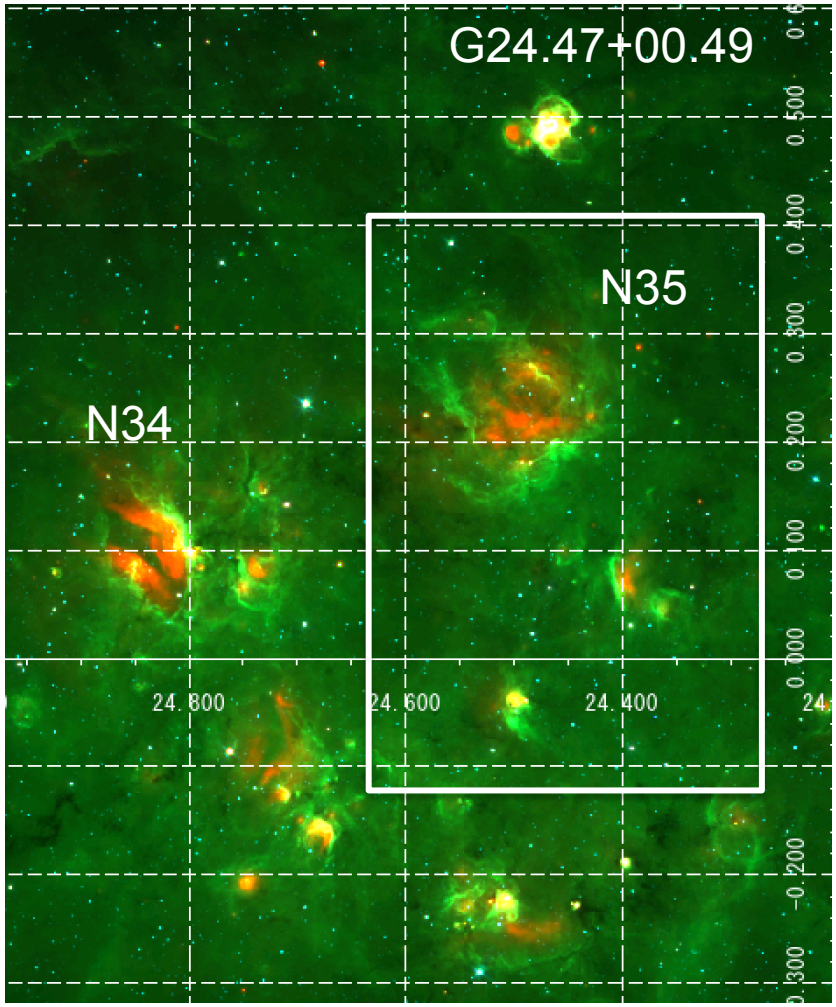


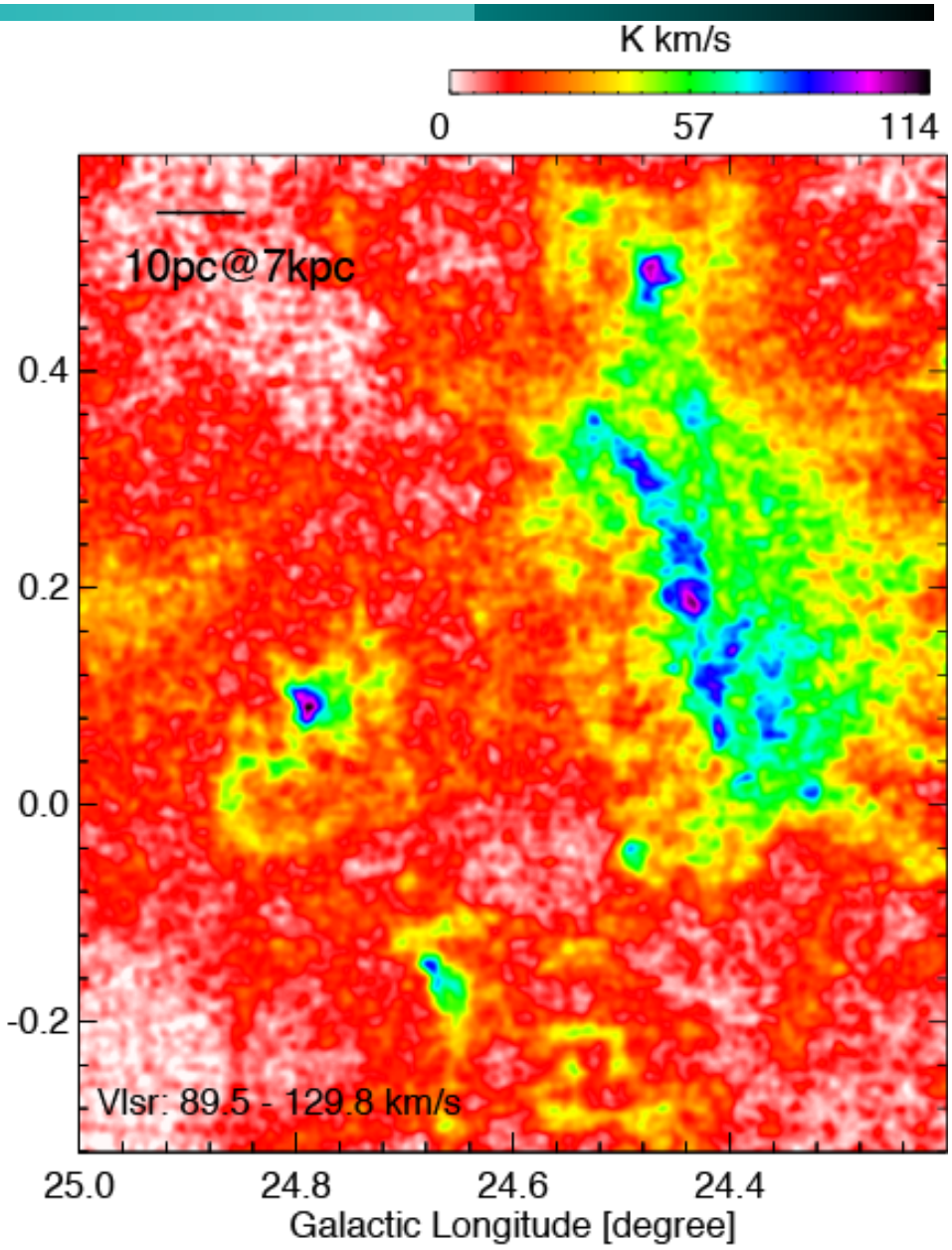
- Four dense clumps having different velocities over ~15km/s are concentrated within the central 2-3 pc.
- Triggering star formation via multiple collisions?

High-mass star forming regions in the bar-end

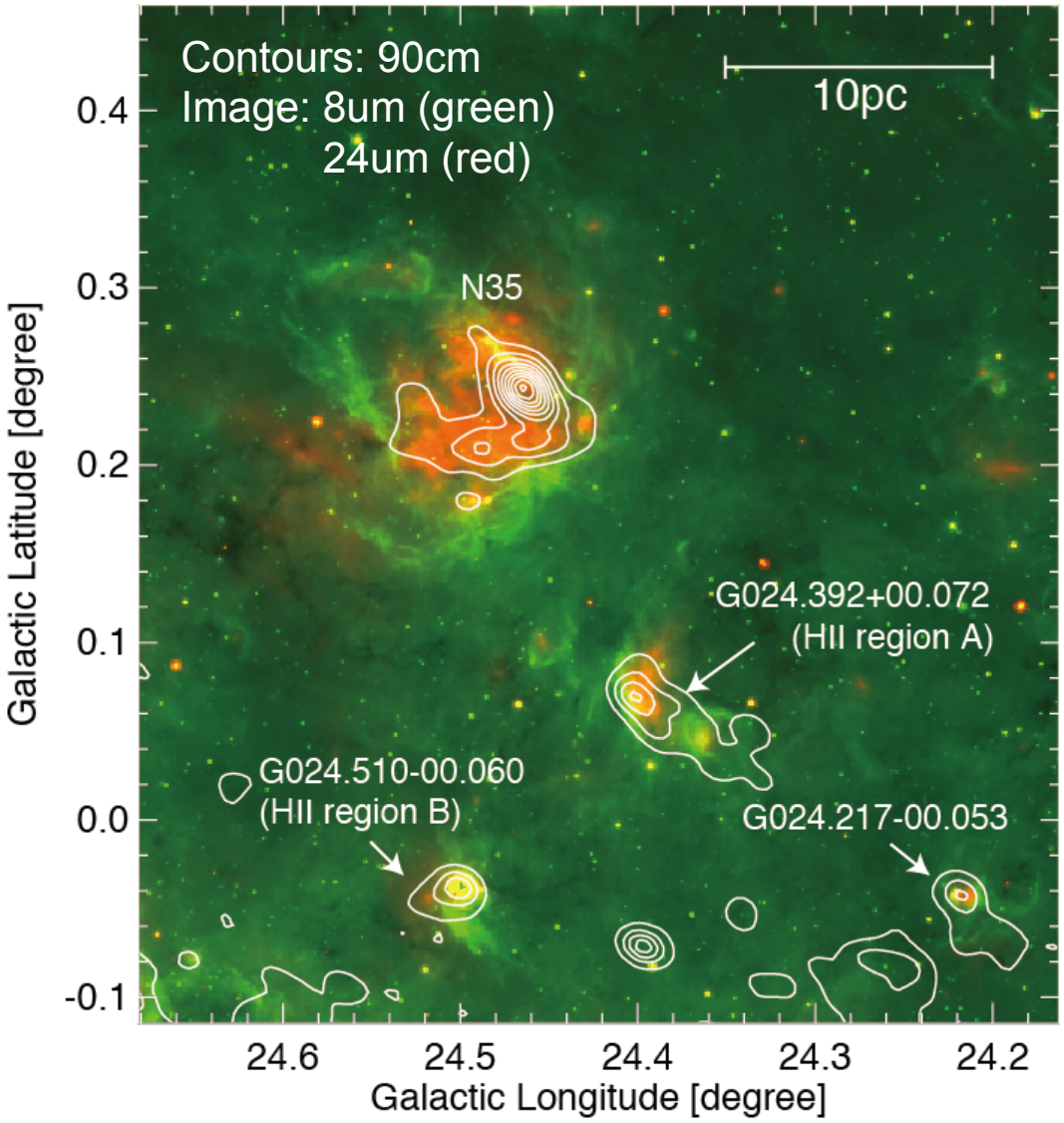


Spitzer bubbles N34 & N35, etc.



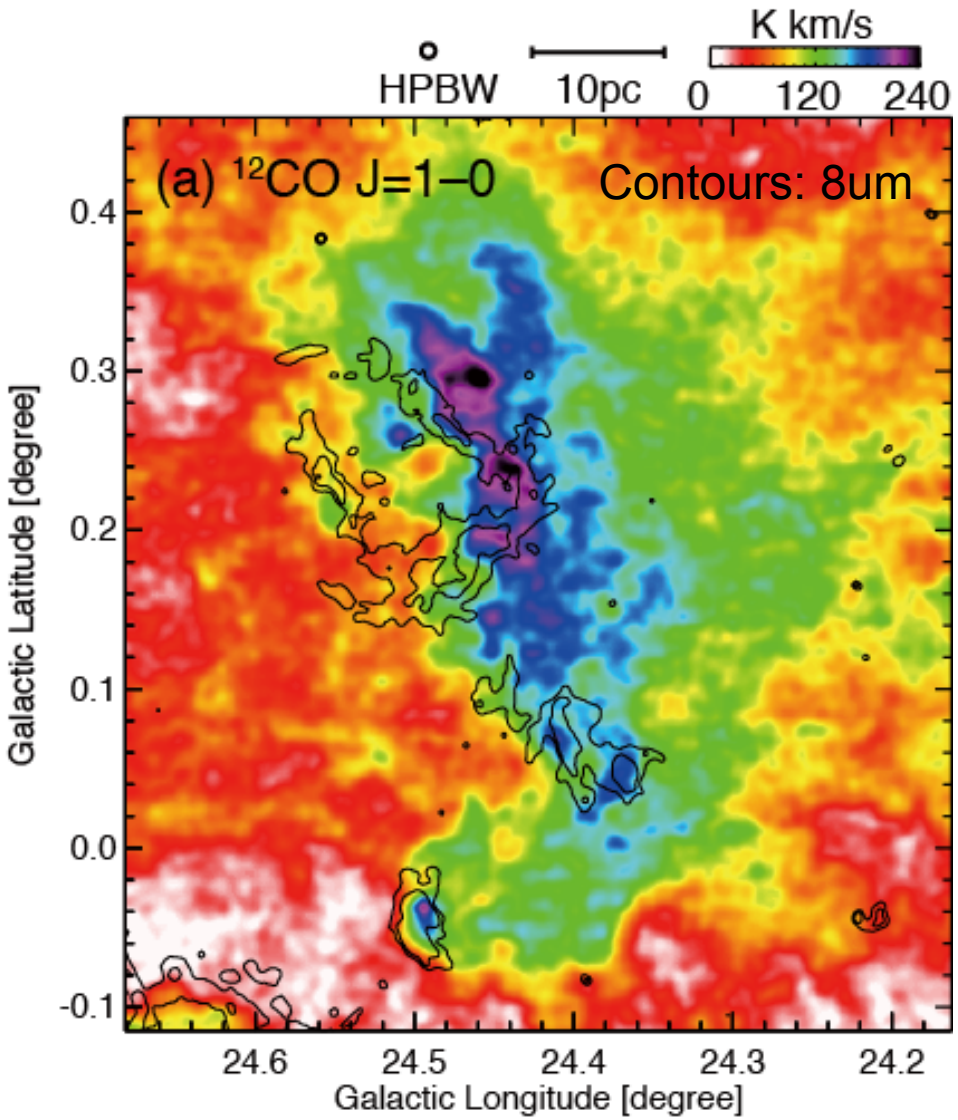


N35 and nearby HII regions (Torii+, arXiv:1710.08564)



- Distance: ~6–8kpc
- N35: Ring-like 8um structure which surrounds an HII region
- Total infrared luminosity of N35: ~10^6 Lo (Hattori+17)
- Spectral types of the exciting stars estimated from Nly (assuming single object):
  - N35: O4V
  - HII region A: O6
  - HII region B: O7

Spitzer bubble N35 and nearby HII regions

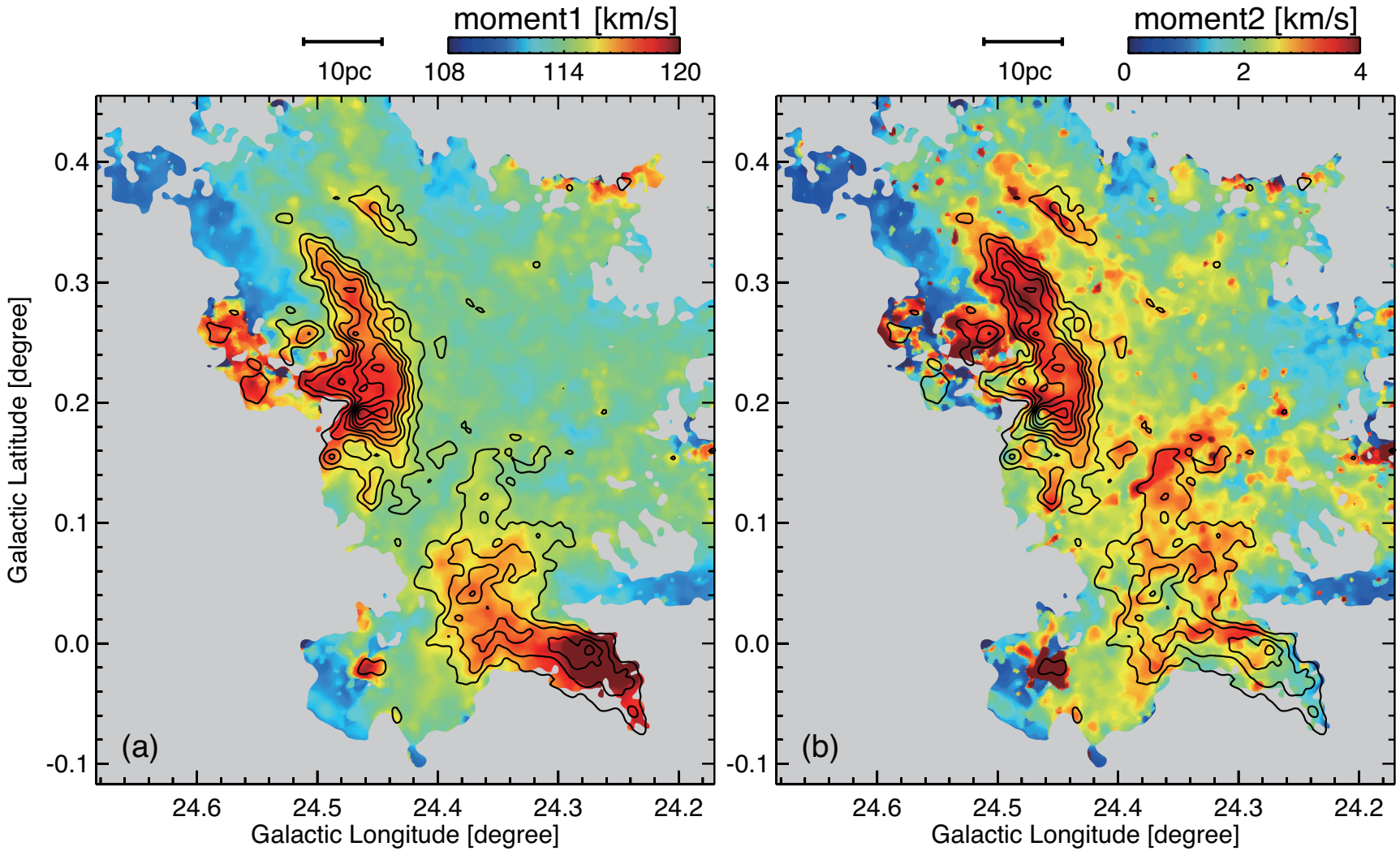


GMC associated with the three HII regions

- Size: 30pc x 40pc
- Mass: ~10^6 Mo

The HII regions are located at the eastern rim of the GMC.

Two velocity components in the GMC



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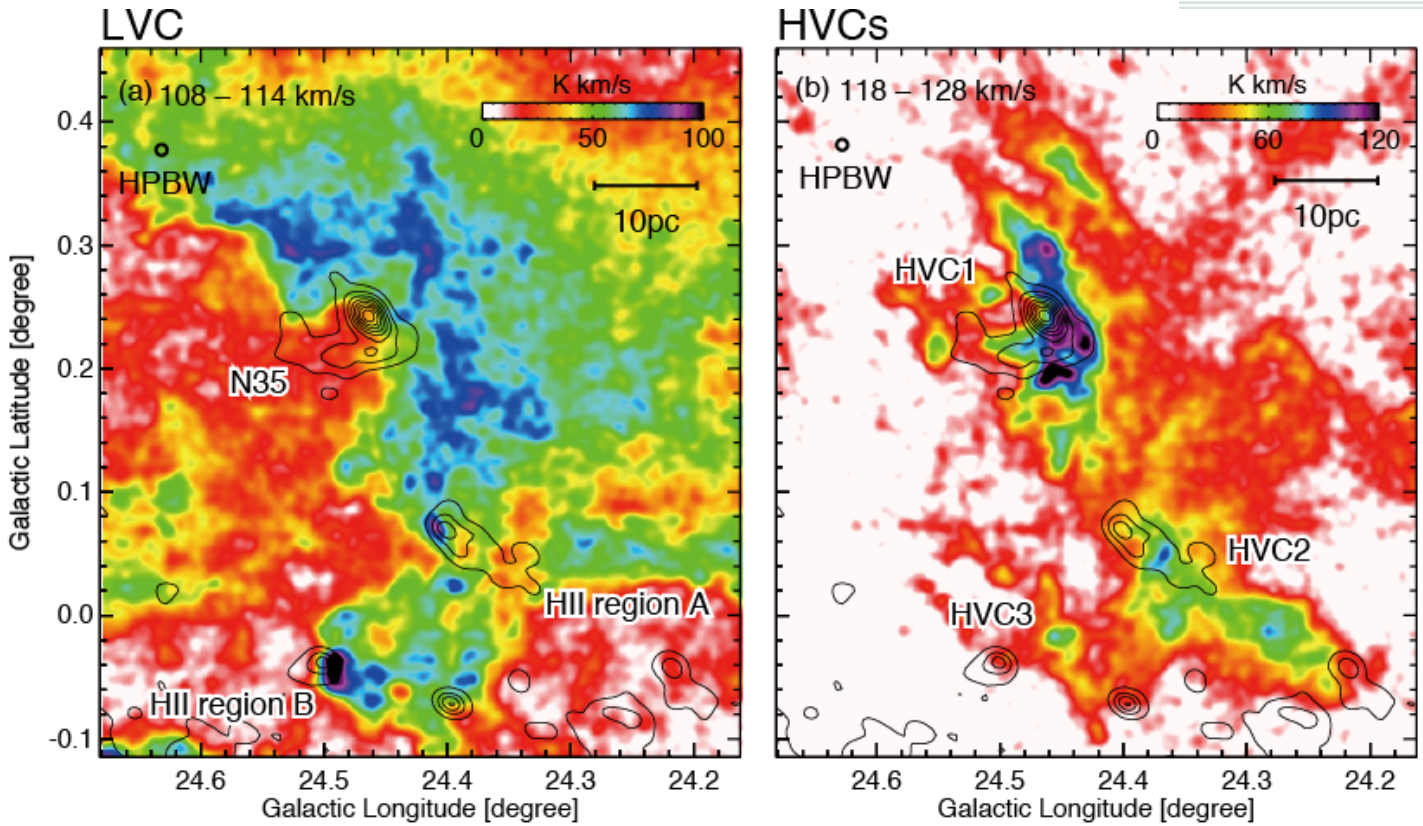
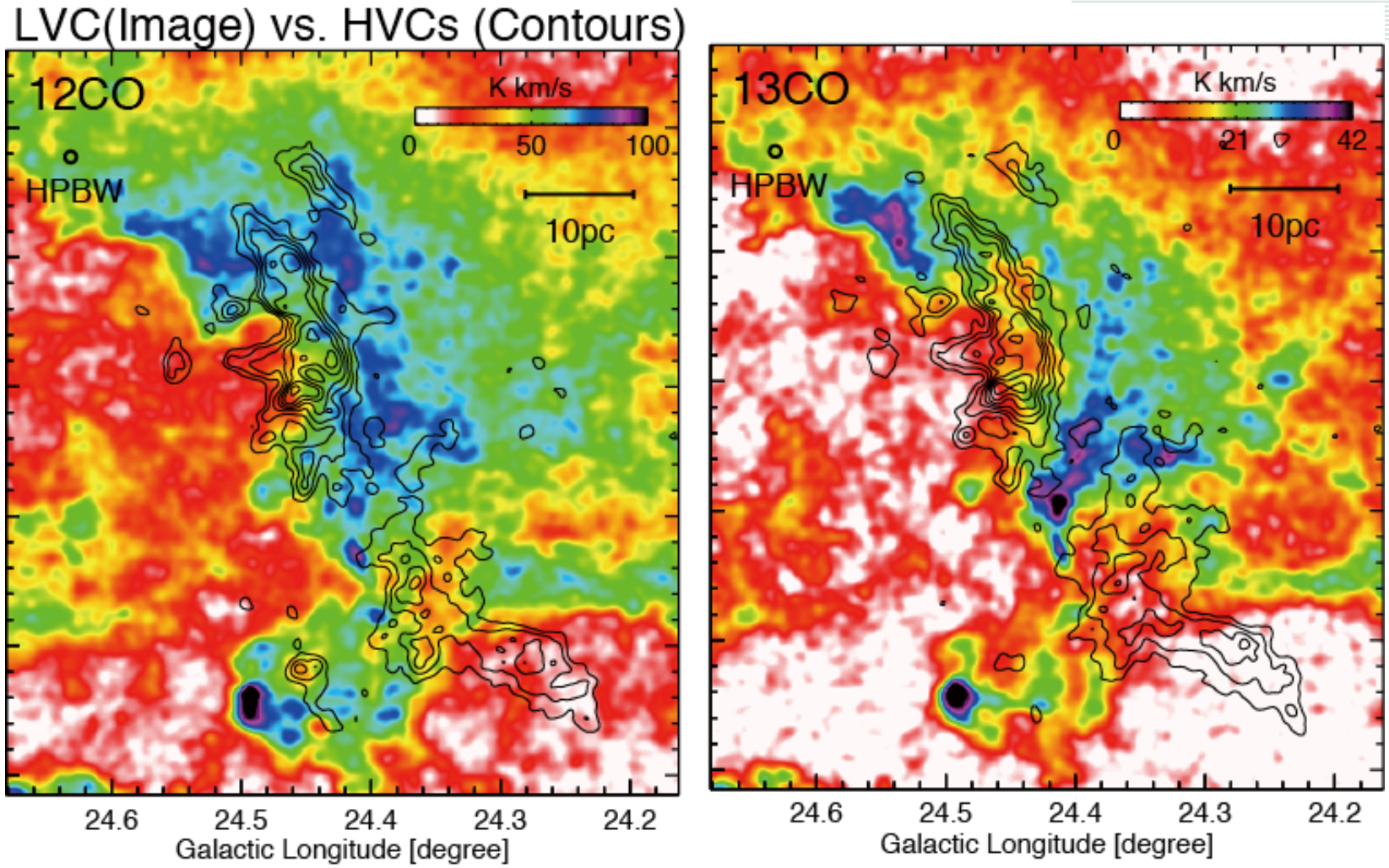
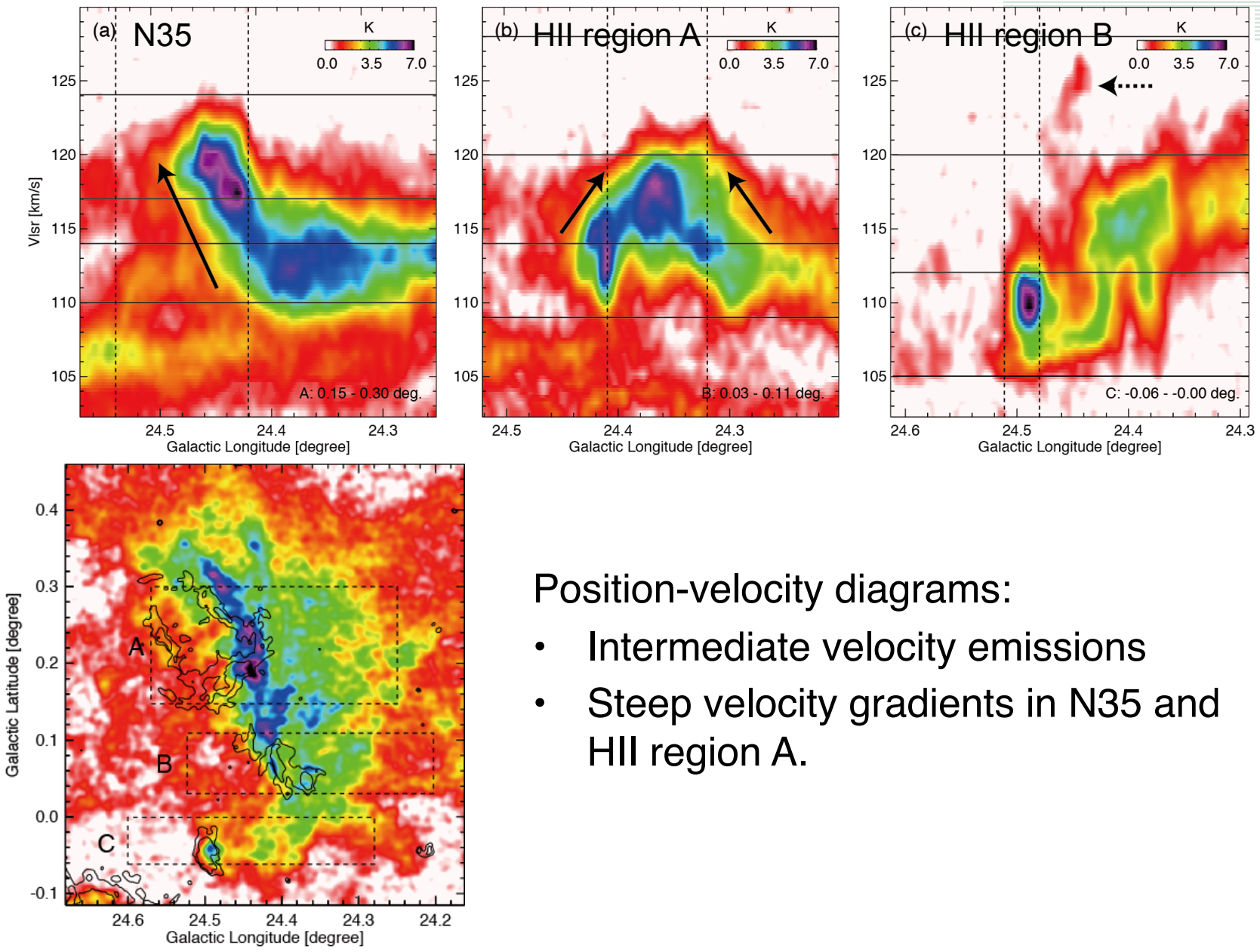


- Lower velocity component (LVC):
  - includes the majority of gas in the GMC (~10^6 Mo, order of 10^{22} cm^{-2})
- Higher velocity components (HVCs):
  - three distinct components with masses 10^4–10^5 Mo at order of 10^{22} cm^{-2}
- Velocity separations: ~ 10km/s

Two velocity components in the GMC



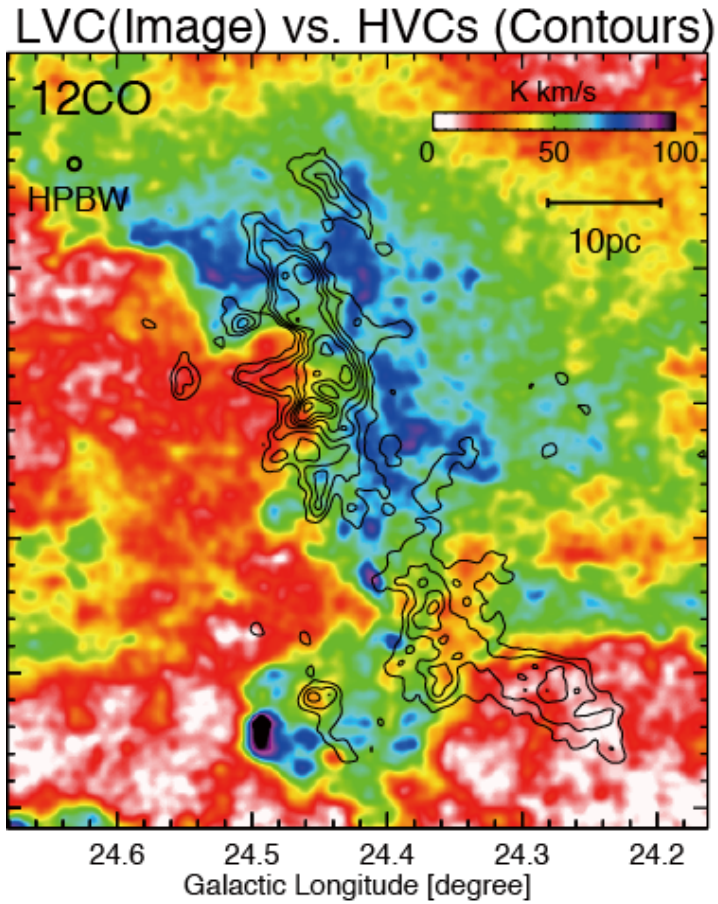
- Complementary distributions between LVC and HVCs

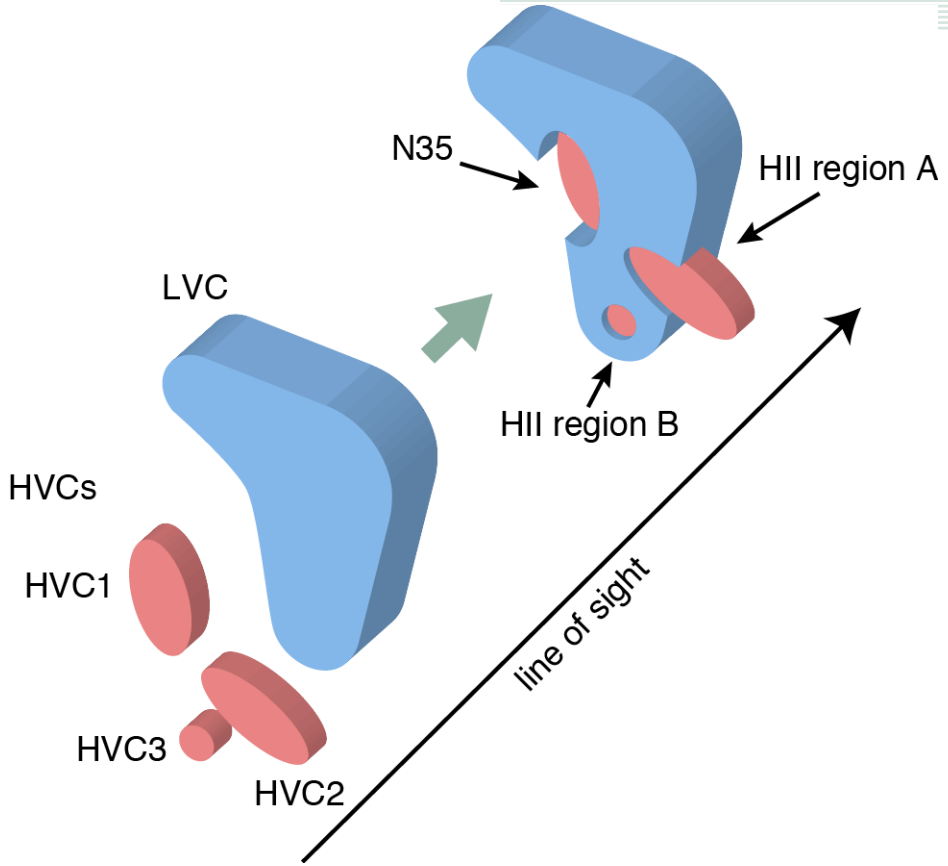


Position-velocity diagrams:

- Intermediate velocity emissions
- Steep velocity gradients in N35 and HII region A.

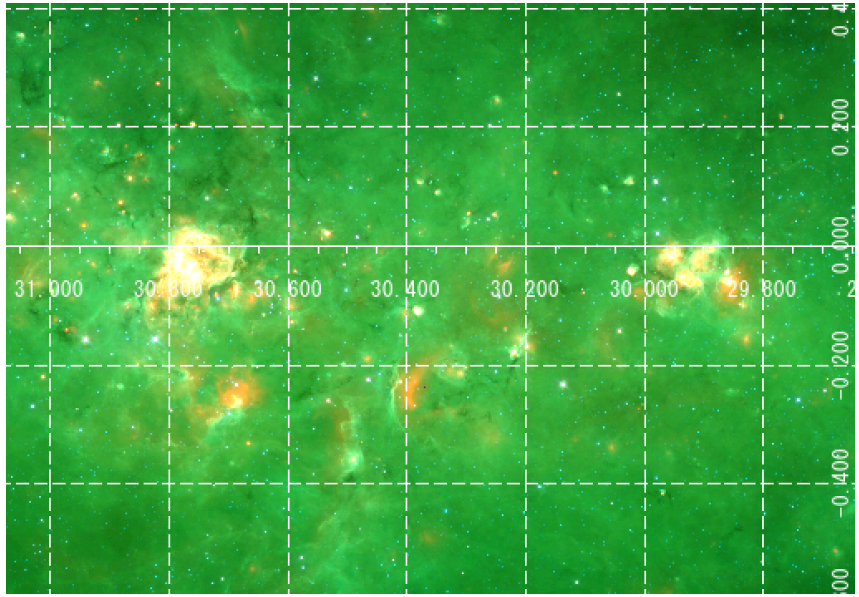
CCCs between LVC and HVCs

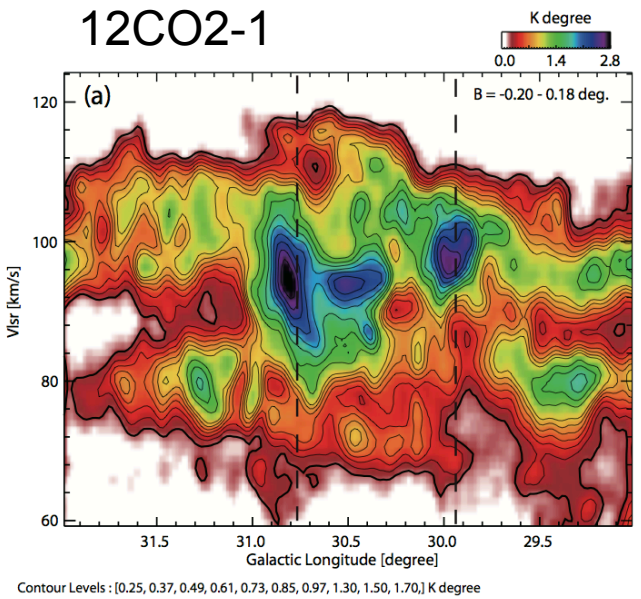


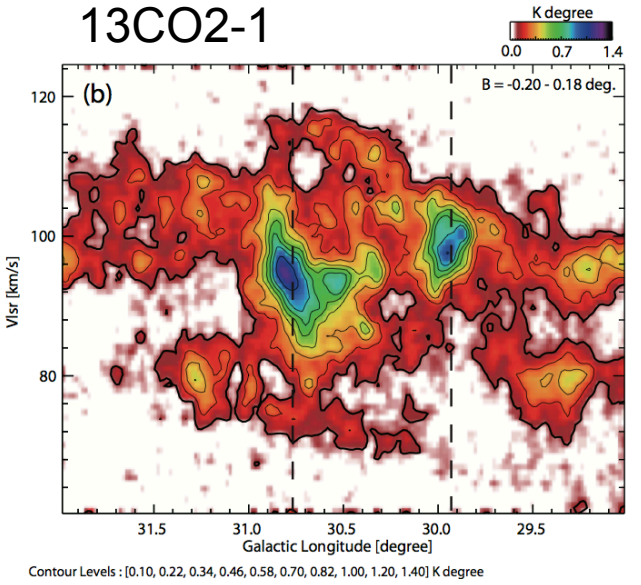


- Collisions between a large GMC with 10^6Mo with smaller clouds.
- Timescales: ~2–3 Myr for N35, 0.2–0.3 Myr for HII regions A & B.

Future prospects (W43)



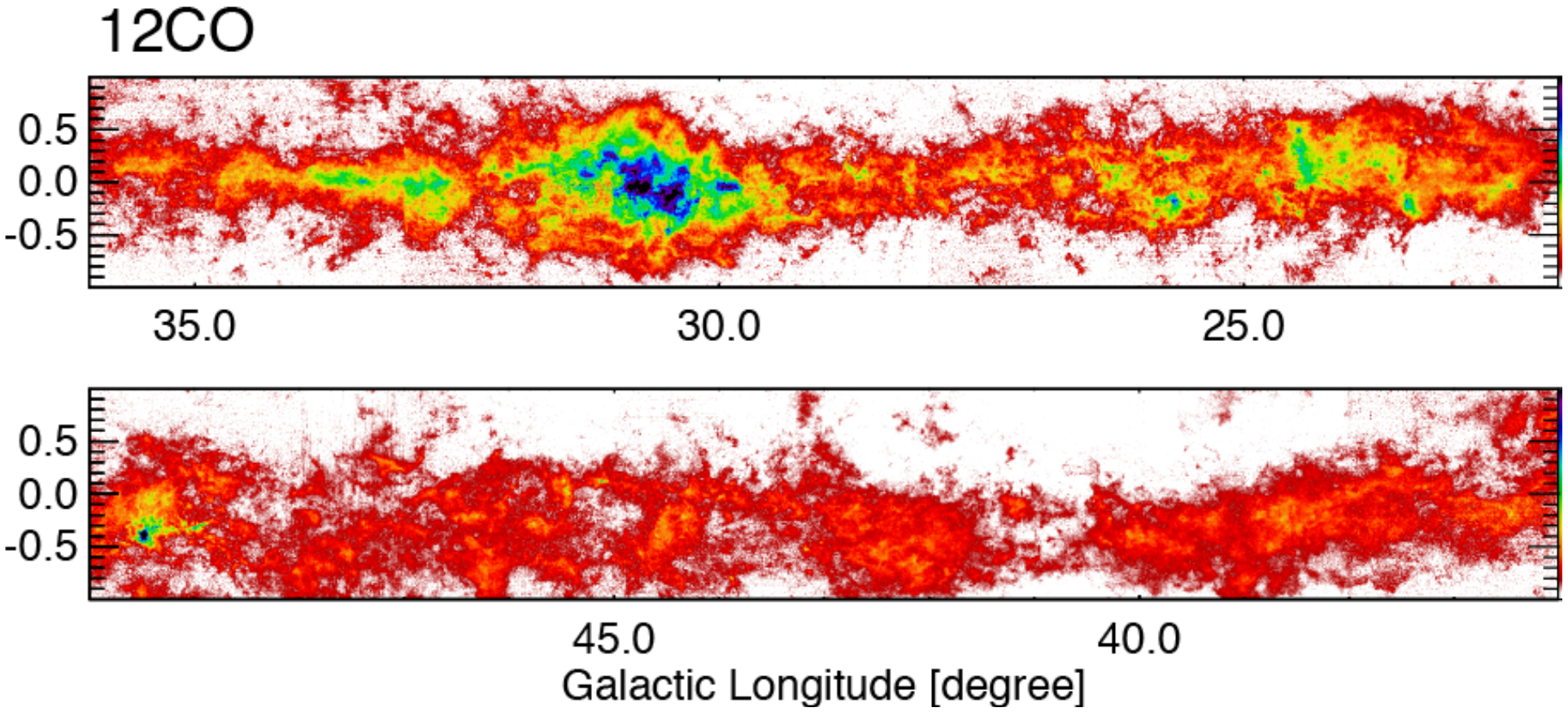




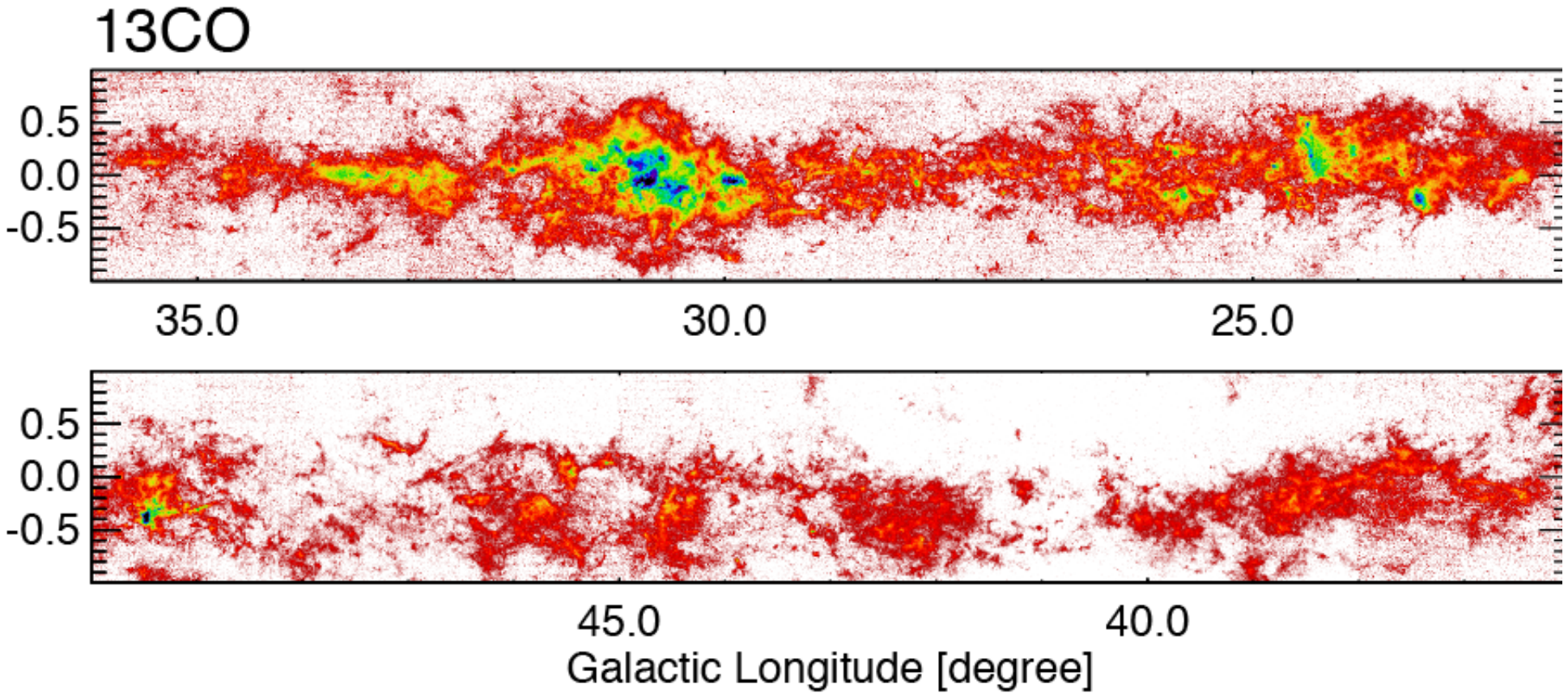
- Multiple velocity components at ~80km/s and ~100km/s.
- Broad velocity emission toward W43 main and W43 south

(Kiridoshi, Master thesis 2016, Osaka Pref. Univ.)

Future prospects (Bar-end region??)



Future prospects (Bar-end region??)

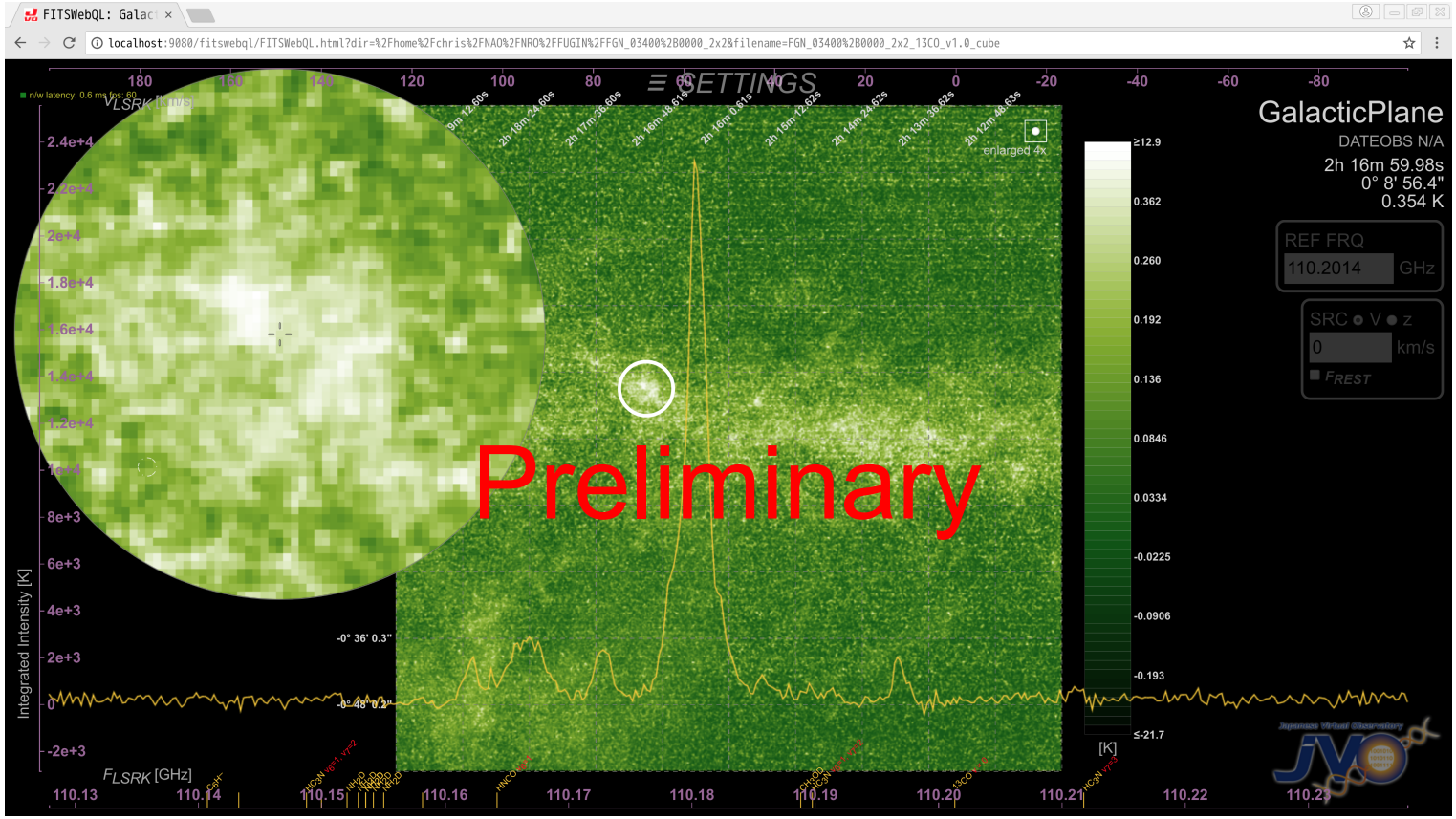


Future prospects

- Identify molecular clouds, including distances, and check associations of signs of star formation
- Global properties of gas
  - Intensity ratio variations, e.g., CO J=3-2/J-1-0, 12CO/13CO.
  - PDF, Brightness distribution index (BDI, Sawada+12)
- Diagnose physical properties of the individual clouds
  - Dynamics of the clouds
  - Cloud evolution based on a statistical study, e.g., cloud mass function, fraction of dense gas, etc.
  - Frequency of cloud-cloud collision
- Comparisons with the numerical calculations

FUGIN data release

- 2018.6.1: open to the public
- 3D fits, 2D fits (Integrated intensities), r.m.s 2D map
- JVO operated by ADC, NAOJ
- Some useful catalogs, e.g., clouds, clumps, filaments, etc.



Special thanks: Shirasaki, Y., Zapart C., M. Oishi (ADC/NAOJ)