Using CO to study Our Galaxy

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Outline

- 1，ISM and CO surveys；
- 2，SNR-MC Interacting System；
- 3，Our Galaxy；
- 4，Summary；

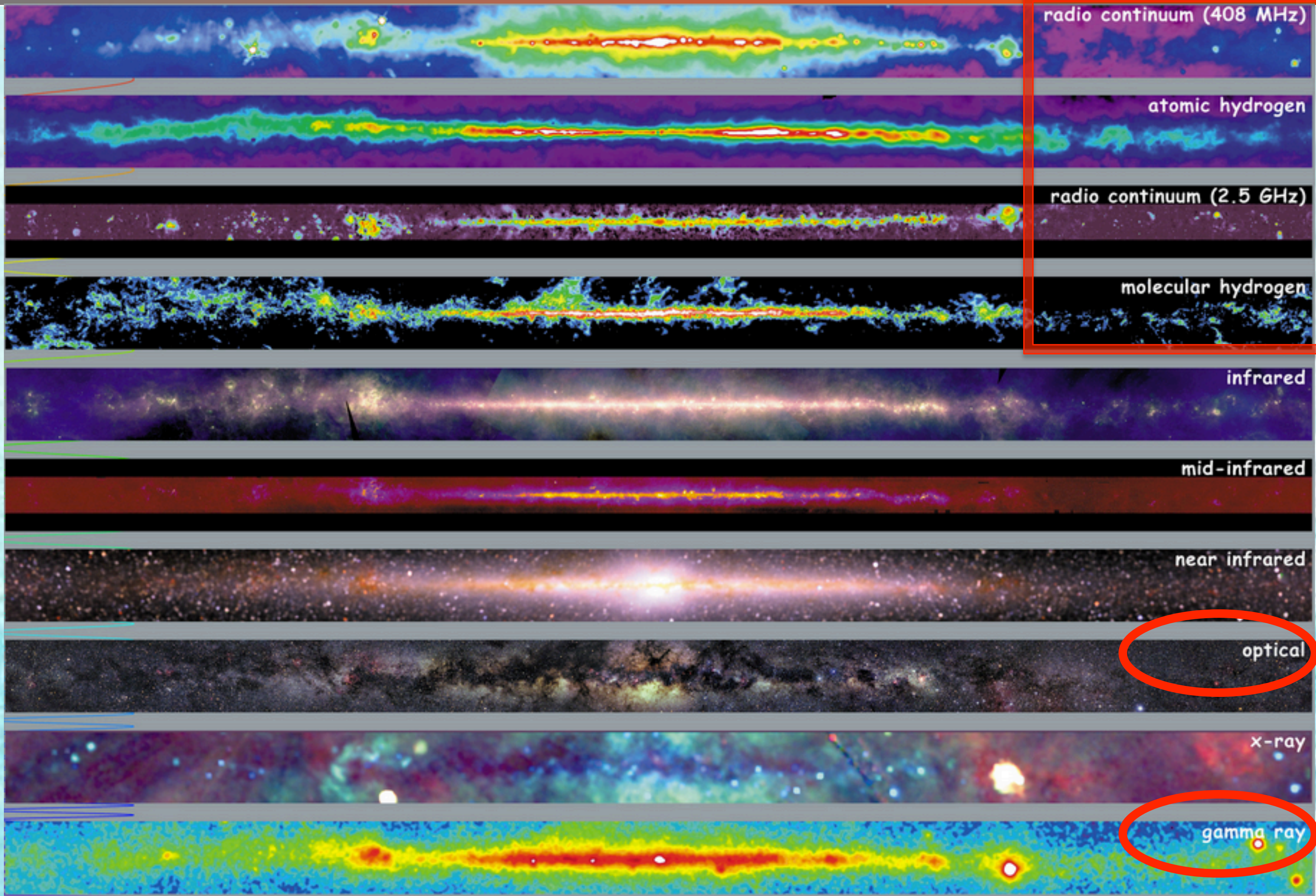
1，ISM and CO line；

Phase		n [cm^{-3}]	T[K]	M_{tot}[M$_\odot$]
atomic (HI)	cold	$\backsim 25$	$\backsim 100$	$1.5 \cdot 10^9$
	warm	$\backsim 0.25$	$\backsim 8000$	$1.5 \cdot 10^9$
molecular (H_2)		$\gtrsim 10^3$	$\lesssim 100$	10^9
ionized	HII	$\backsim 1 \cdots 10^4$	$\backsim 10000$	$5 \cdot 10^7$
	diffuse	$\backsim 0.03$	$\backsim 8000$	10^9
	hot	$\backsim 6 \cdot 10^{-3}$	$\backsim 5 \cdot 10^5$	10^8

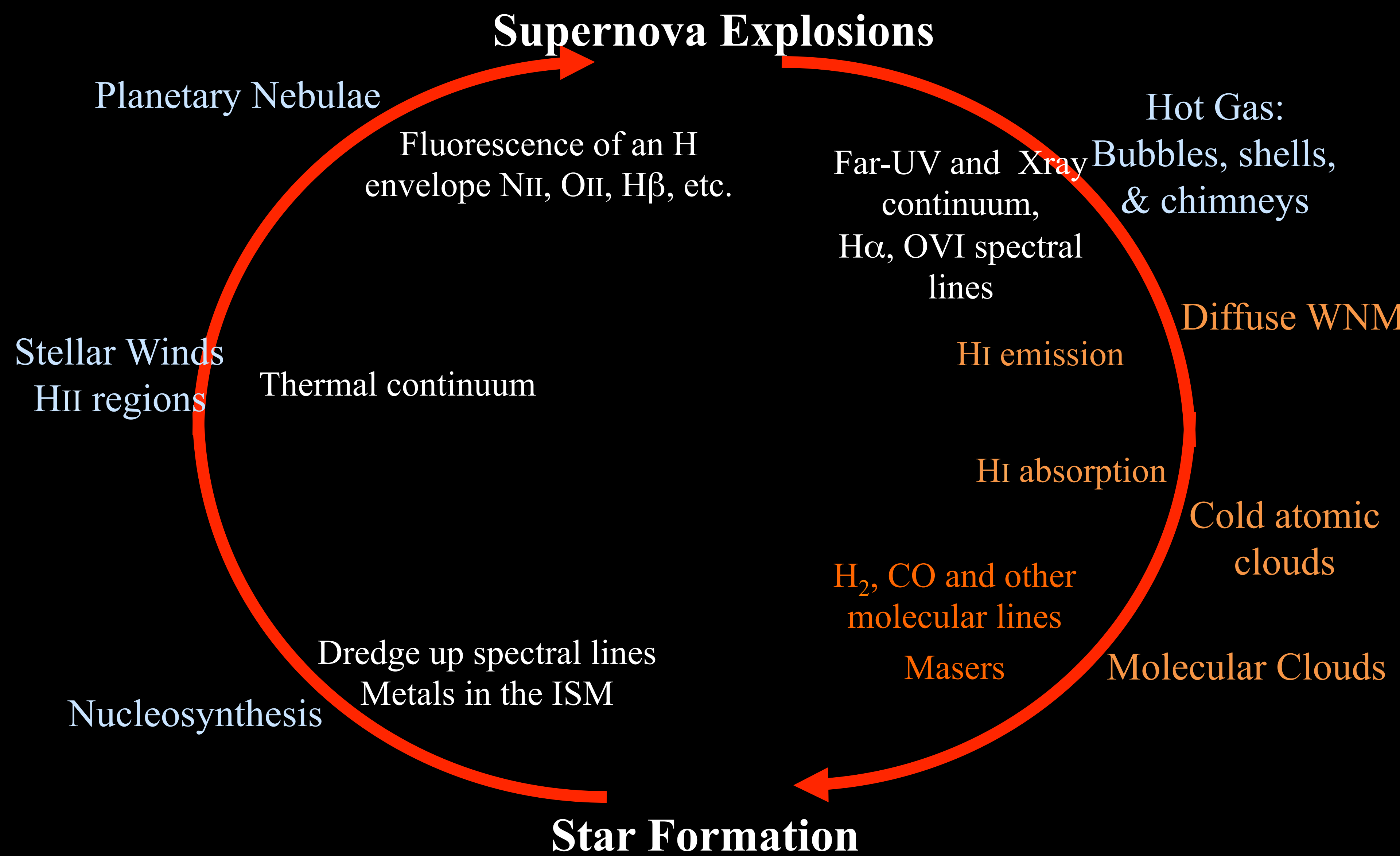
Second most abundant molecule in the ISM: ***CO***

Molecule	Transition	A_{ul}	ν_{ul} / GHz
^{12}CO	$1 \to 0$	$7.4 \cdot 10^{-8}$	111.271203
^{12}CO	$2 \to 1$	$7.1 \cdot 10^{-7}$	230.538001
^{13}CO	$1 \to 0$	$6.5 \cdot 10^{-8}$	110.201370
^{13}CO	$2 \to 1$	$6.2 \cdot 10^{-7}$	220.398714
C^{18}O	$1 \to 0$	$6.5 \cdot 10^{-8}$	109.782182
C^{18}O	$2 \to 1$	$6.2 \cdot 10^{-7}$	219.560319

Multi-wavelength Sky



The ISM Life Cycle



How do we detect the ISM?

Many tracers throughout the E-M spectrum

- Spectral emission lines
  - e.g. Hα (optical), HI (radio), ***CO (millimeters)***, recombination lines (H109α in the radio)
- Spectral absorption lines
  - e.g. HI, Ca, Na, Fe
- Thermal continuum emission
  - e.g. PAH emission (12μm), HII regions (radio, infrared, optical, millimeter, …), hot, diffuse plasma (Xray)
- Nonthermal continuum emission
  - e.g. synchrotron emission from the magnetoionic medium
- Absorption and Scattering
  - e.g. dust grains (Xray, UV, optical)
- Reflection
  - e.g. dust grains (optical light)

The Most Easily Observed Molecules in Space

- ***CO = Carbon Monoxide → Radio emission***

The Most Common Molecule in Space:

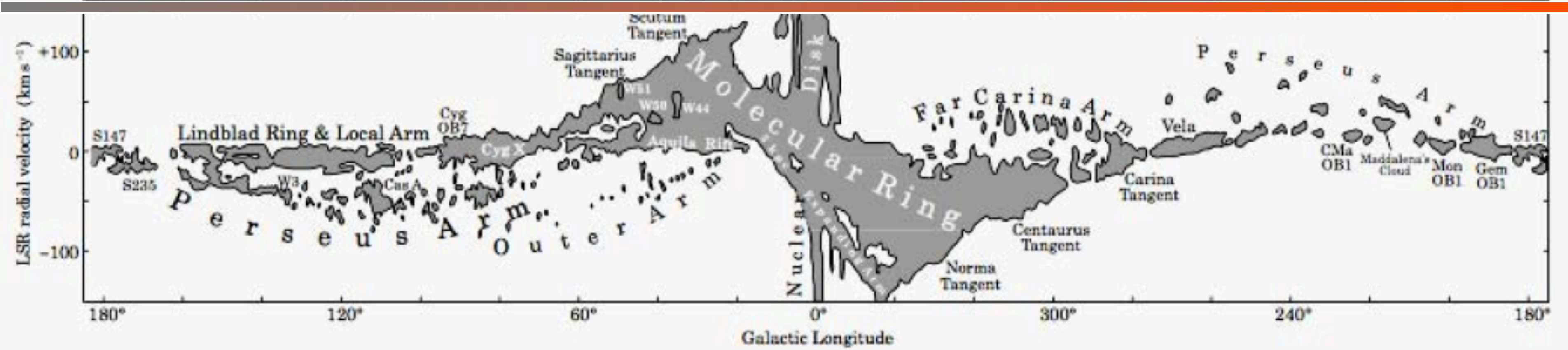
- H_2 = Molecular Hydrogen ➔ can be detected by far ultraviolet absorption and emission:

  \- very difficult to observe.

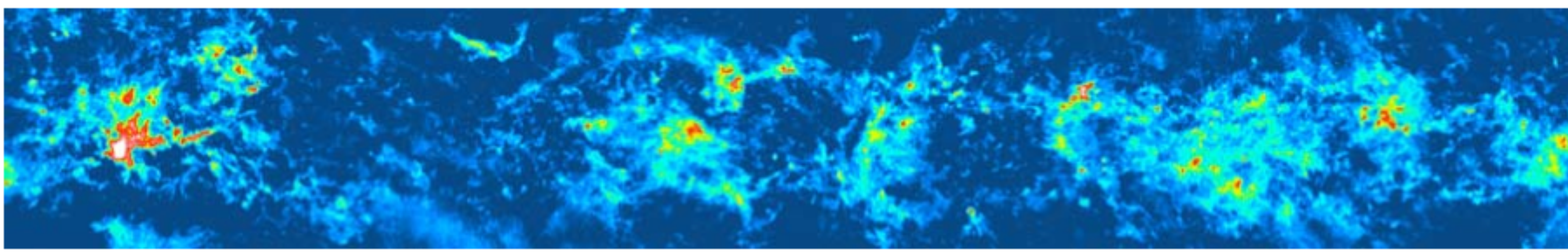
But: Where there's H_2, there's also CO - cloud may contain only 1 CO per 10,000 H_2,-- enough to see them;

Use CO as a tracer for H_2 in the ISM.

CO survey



CfA survey Dame et al. 2001



^{13}CO Galactic Ring Survey (46" resolution) www.bu.edu/galacticring

- CO emission lines show molecular cloud complexes.
- Stars apparently form in these dense regions.

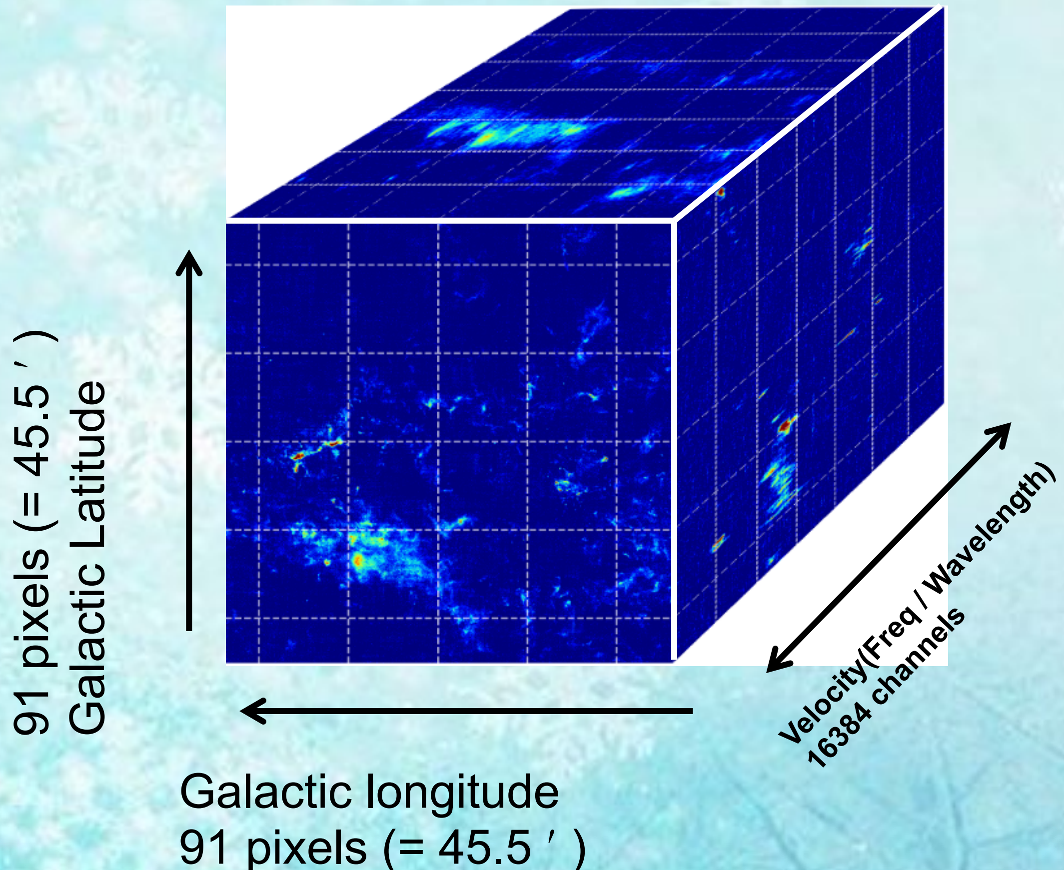
CO survey

Telescope: PMO-13.7m at Delingha
Resolution: 50-55″
Receiver： 3x3
Sensitivity: 60 K (SSB)
Spectrometers: 18× 1GHz, 16384ch
Spectral Resolution: 61 kHz (0.17km/s @ 110 GHz)
Velocity Coverage: 2700 km/s
Line Probes: $^{12}CO/^{13}CO/C^{18}O$ (J=1-0)
Line Sensitivity: 0.3-0.5 K by OTF
Sky Coverage: 15°×20°/yr

97°33′.6E
37°22′.4N
3200 m
PWV =3mm@winter

A color (multi-lines) survey is feasible !
➔ Color Image as a Scroll Painting

Milky Way Imaging Scroll Painting, MWISP



(a) Basic calibration;

(b) Bad channel rejection, speed correction, efficiency correction, position correction, ➔ data quality check;

(c) Regrid, baseline fitting, data sum ➔ Observation assistant manually checks whether the data quality is OK;

(d) If the baseline is not good and other bugs exist, manual inspection will intervene;

A large-scale, unbiased, and high-sensitivity triple-CO isotope line survey along the northern Galactic plane with unprecedented high-quality.

Many systematic scientific studies have been done based on MWISP.

Milky Way Imaging Scroll Painting, MWISP

- What is the content, general physics of MCs in our Milky Way?
- What is internal structural of MCs (cores and clumps) and its fragmentation process to star formation?
- How does the cloud evolution proceed over the time? What is the dynamic state of MCs and its governing processes?
- What kind of role the molecular gas play in Galactic dynamic processes, such as bubbles, SN explosion and other high-energy process?

Milky Way Imaging Scroll Painting, MWISP

- Discovery of new MCs and study on large-scale physical and chemical properties;

- Statistic distribution of MCs、sub-structures in different Galactic environment;

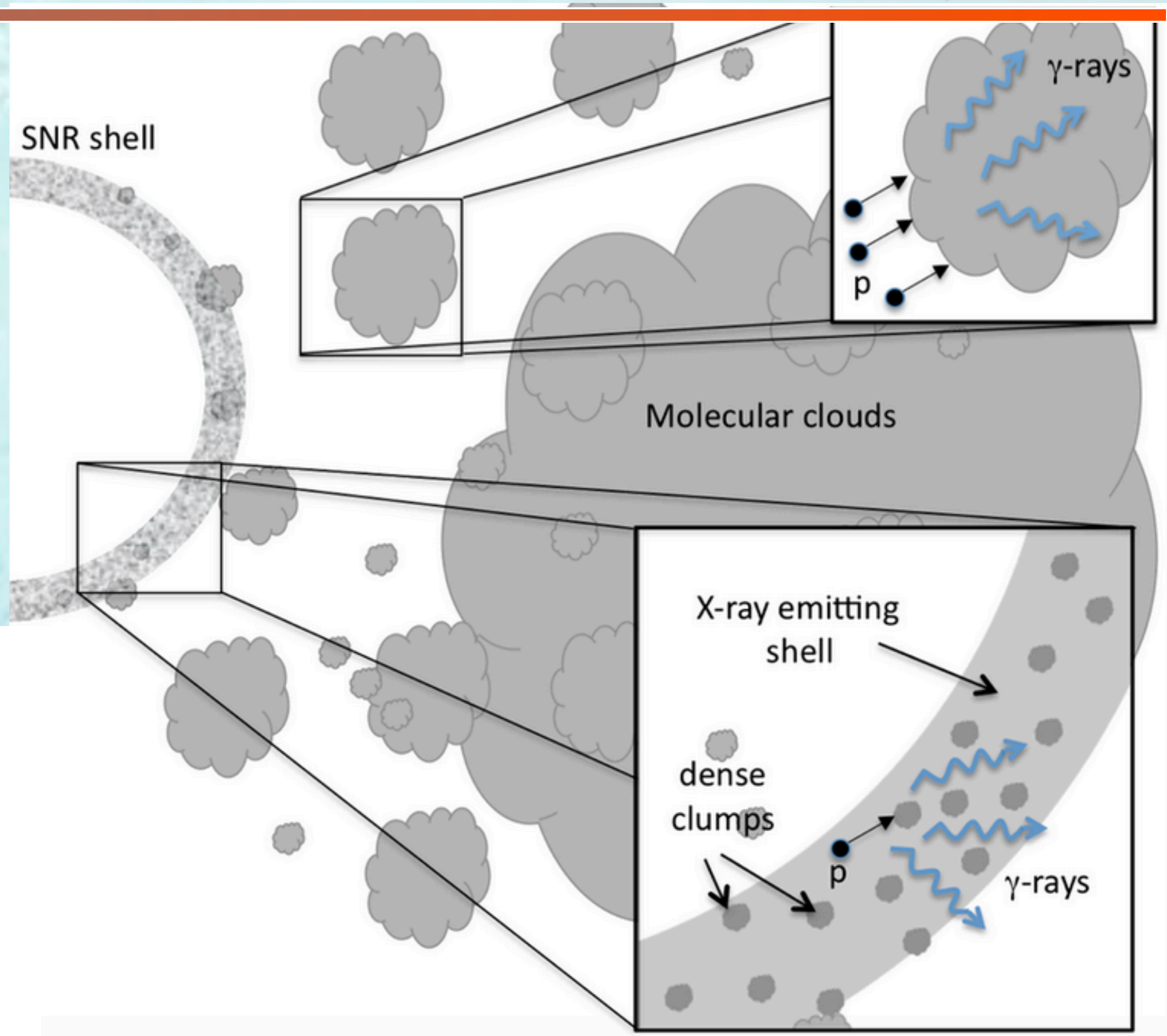
- Dynamical signatures of star forming processes, such as infall and outflow;

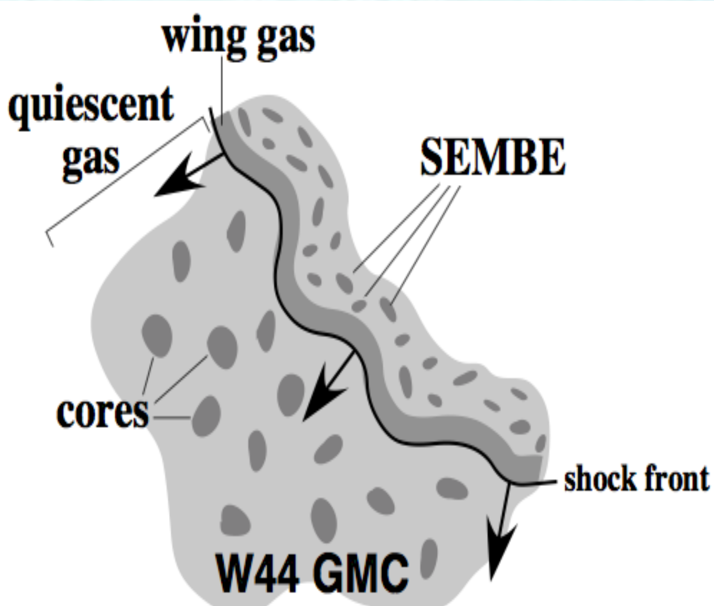
- New components and structures of our Milky Way as well as its motions: dynamical Interactions between MCs and other stellar components, such as bubbles, SNRs, PNs, HII regions, clusters, & CRs.

2，SNR-MC Interacting System

SEMBE:

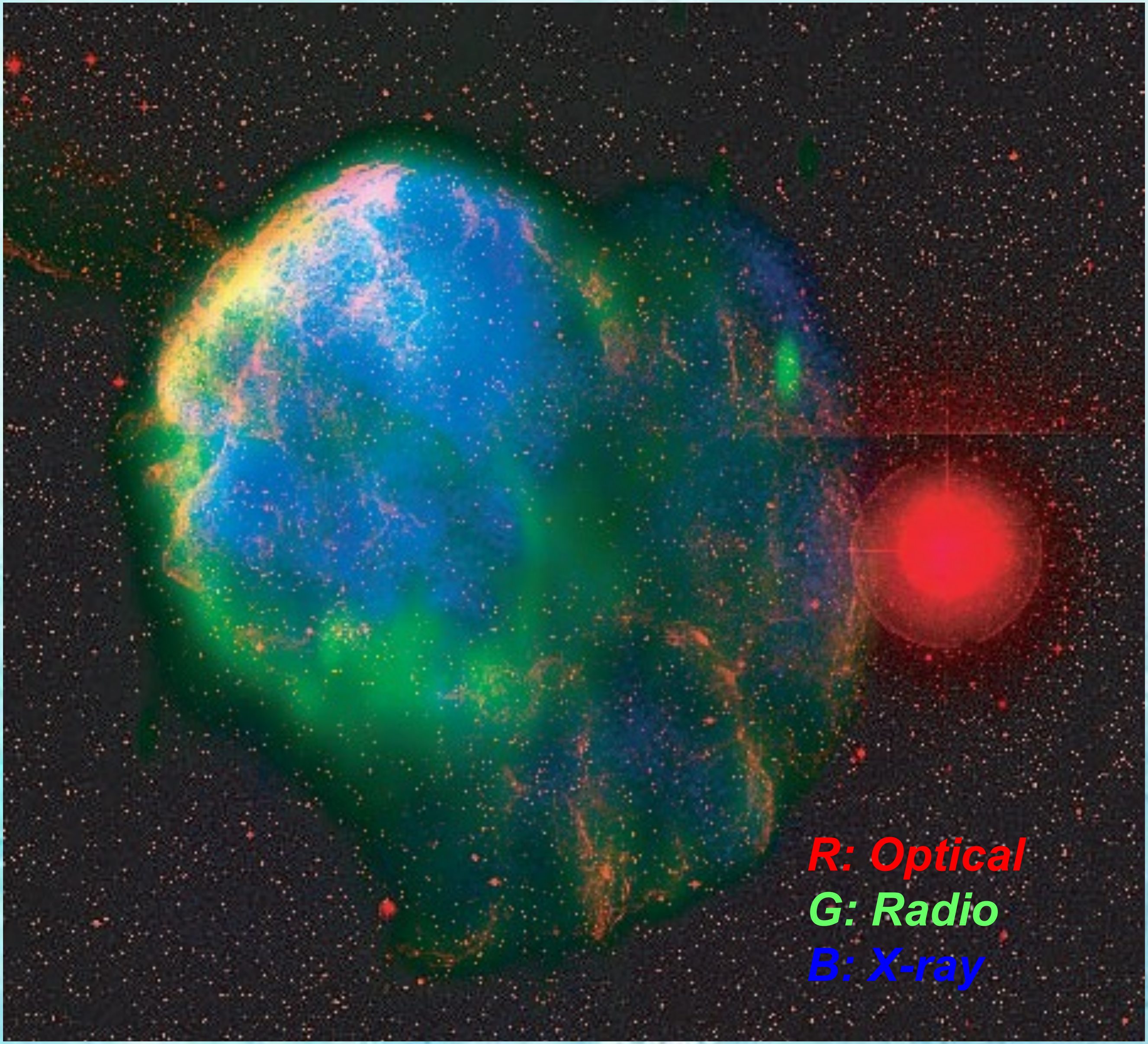
Spatially Extended Moderately Broad Emission





Sashida et al. 2013

Case 1: SNR IC443

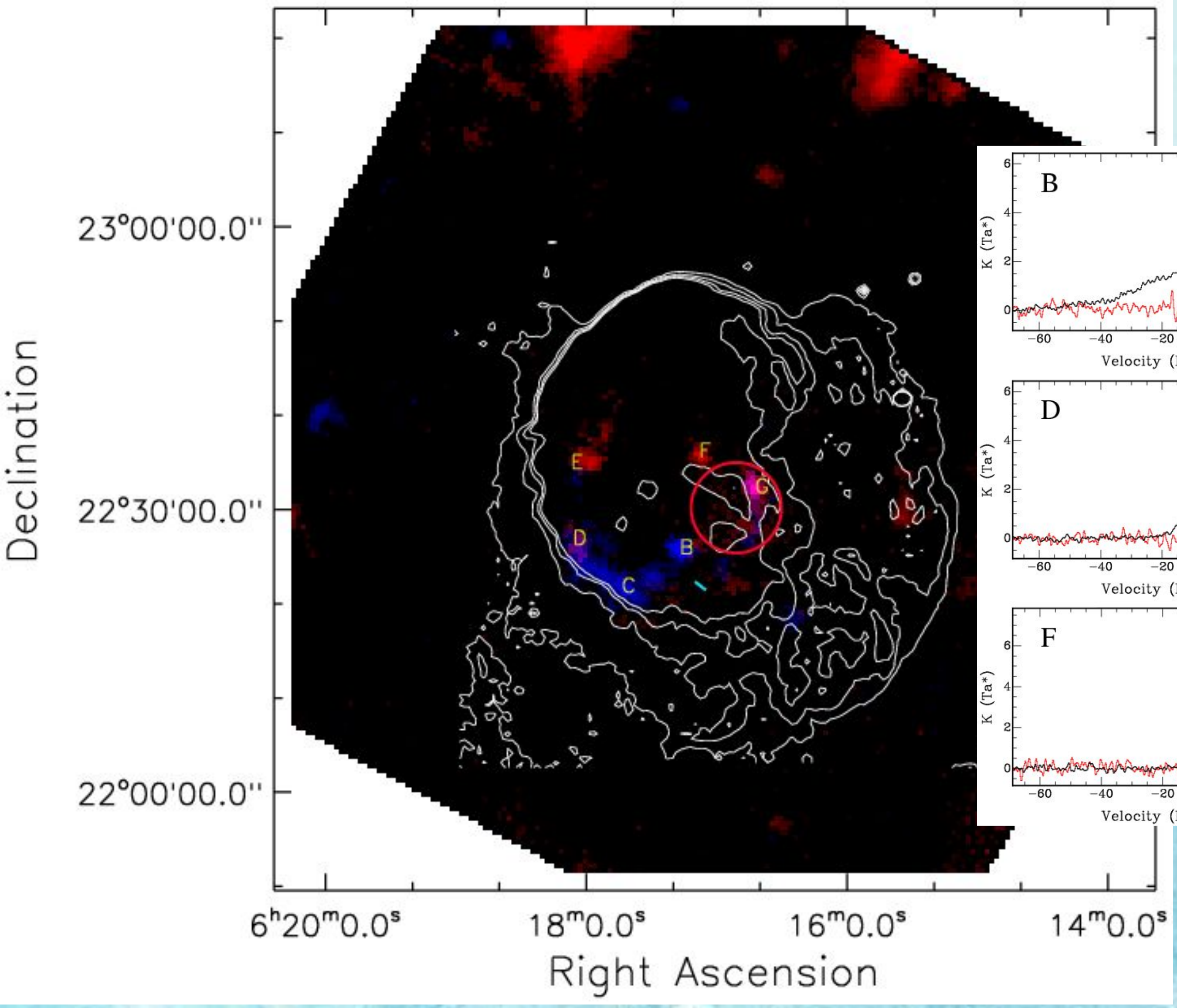


- SNR IC 443
- **d~1.6 kpc**
- R~16'—26'
- OH maser
- PWN (2'×1')
  G189.22+2.90
  (J0617+2221)

Fesen et al.1980
Frail et al. 1996
Rho et al. 2001
Gaensler et al. 2006
Castelletti et al. 2011

Case 1: SNR IC443

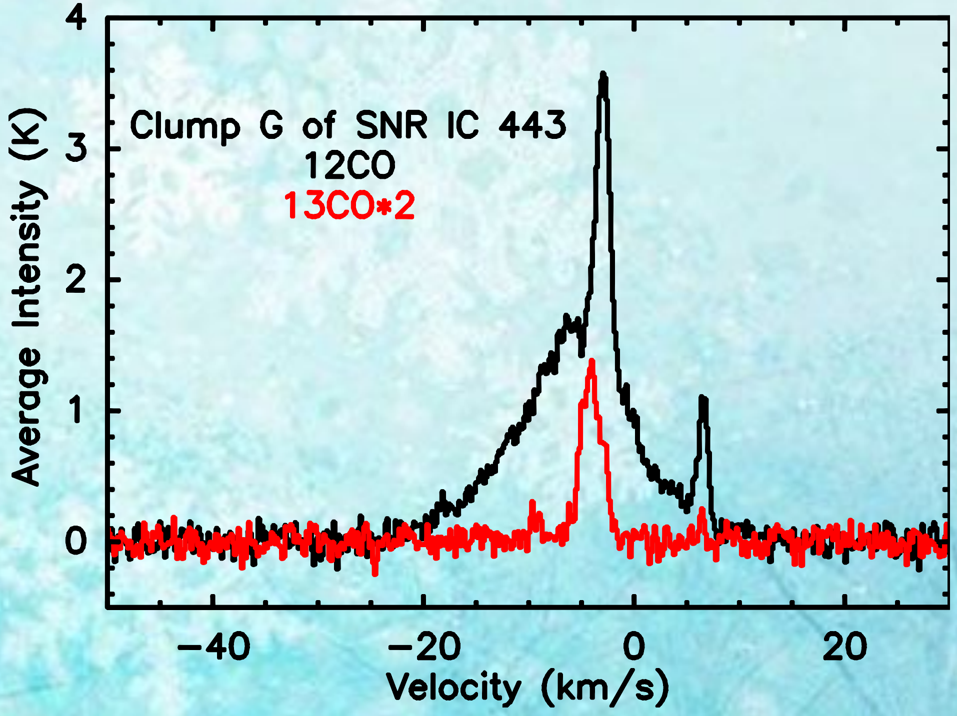
Shocked gas towards the SNR (*-50 to -9 km/s* & *0 to 4 km/s*)

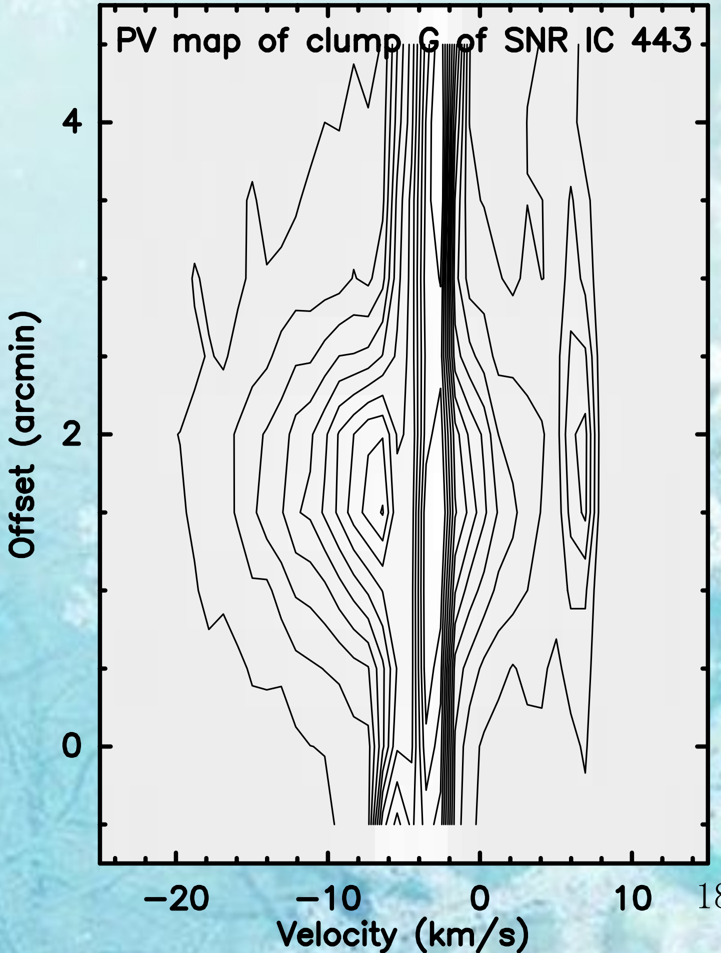


Su et al. 2014, ApJ

Case 1: SNR IC443

- A, The Spectral line (profile, line ratio, PV map, …)

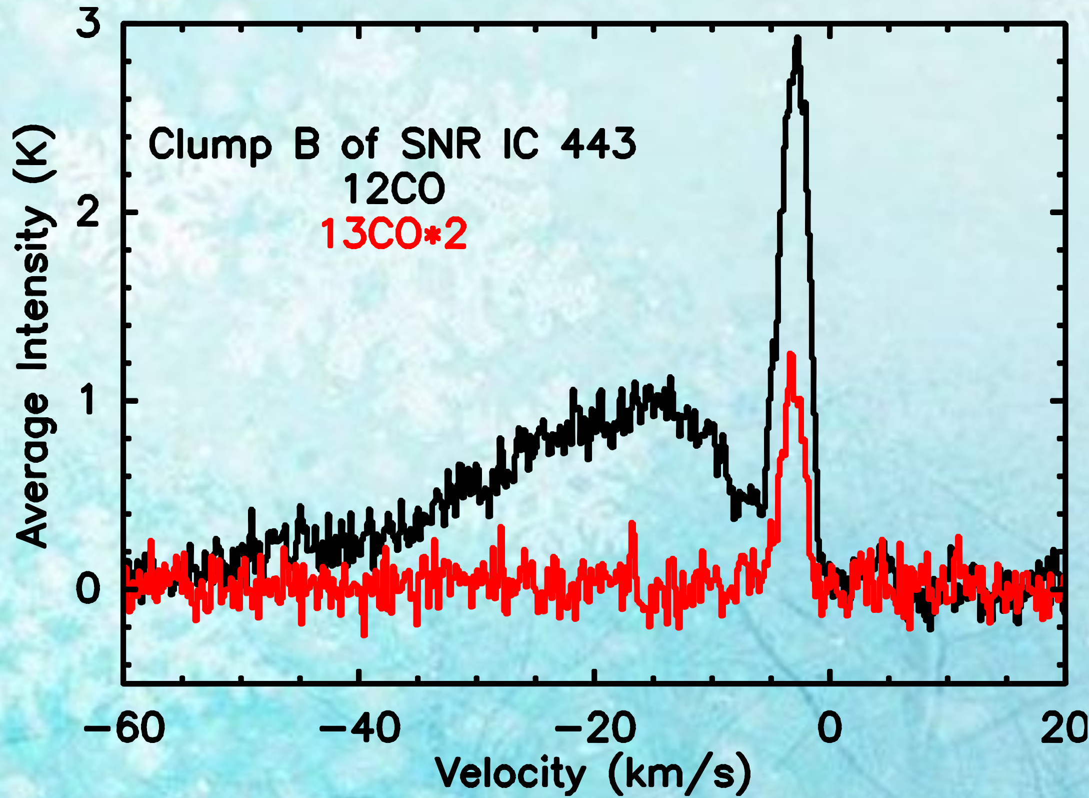


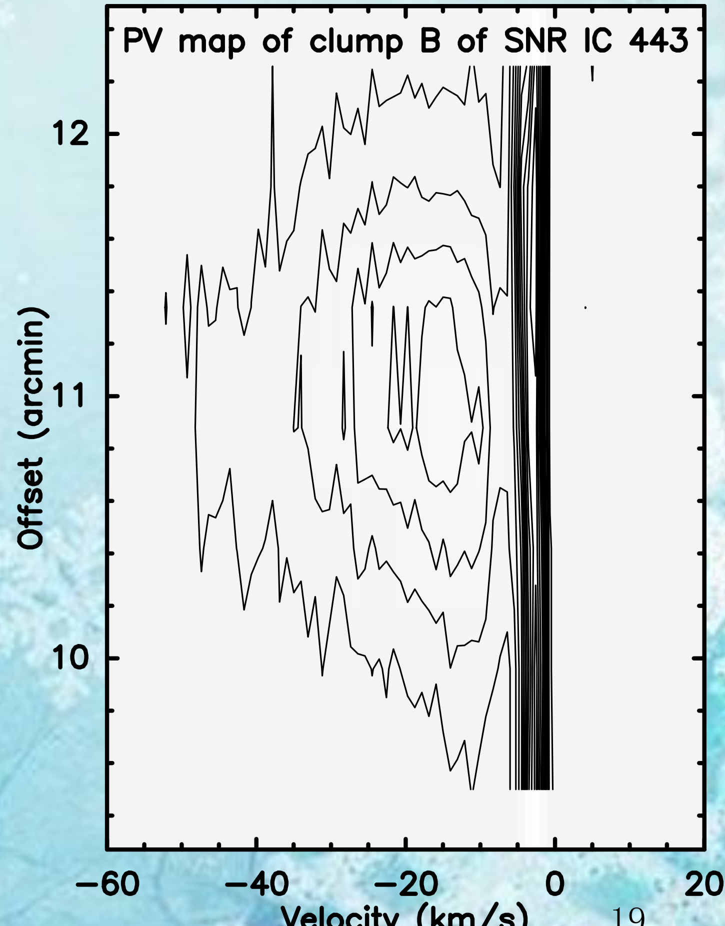


Su et al. 2014, ApJ

Case 1: SNR IC443

- B, The Spectral line (profile, line ratio, PV map, …)

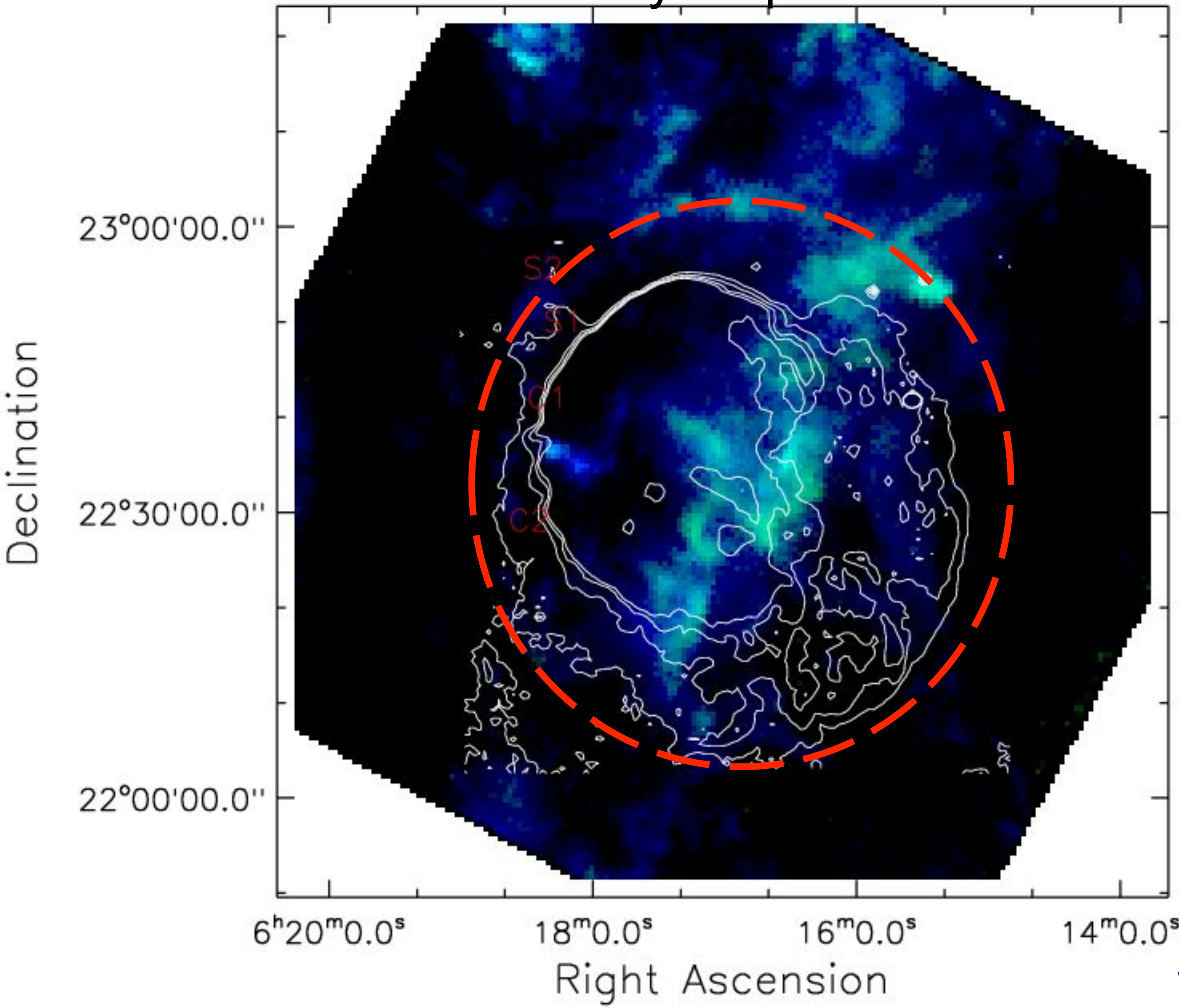




Su et al. 2014, ApJ

Case 1: SNR IC443

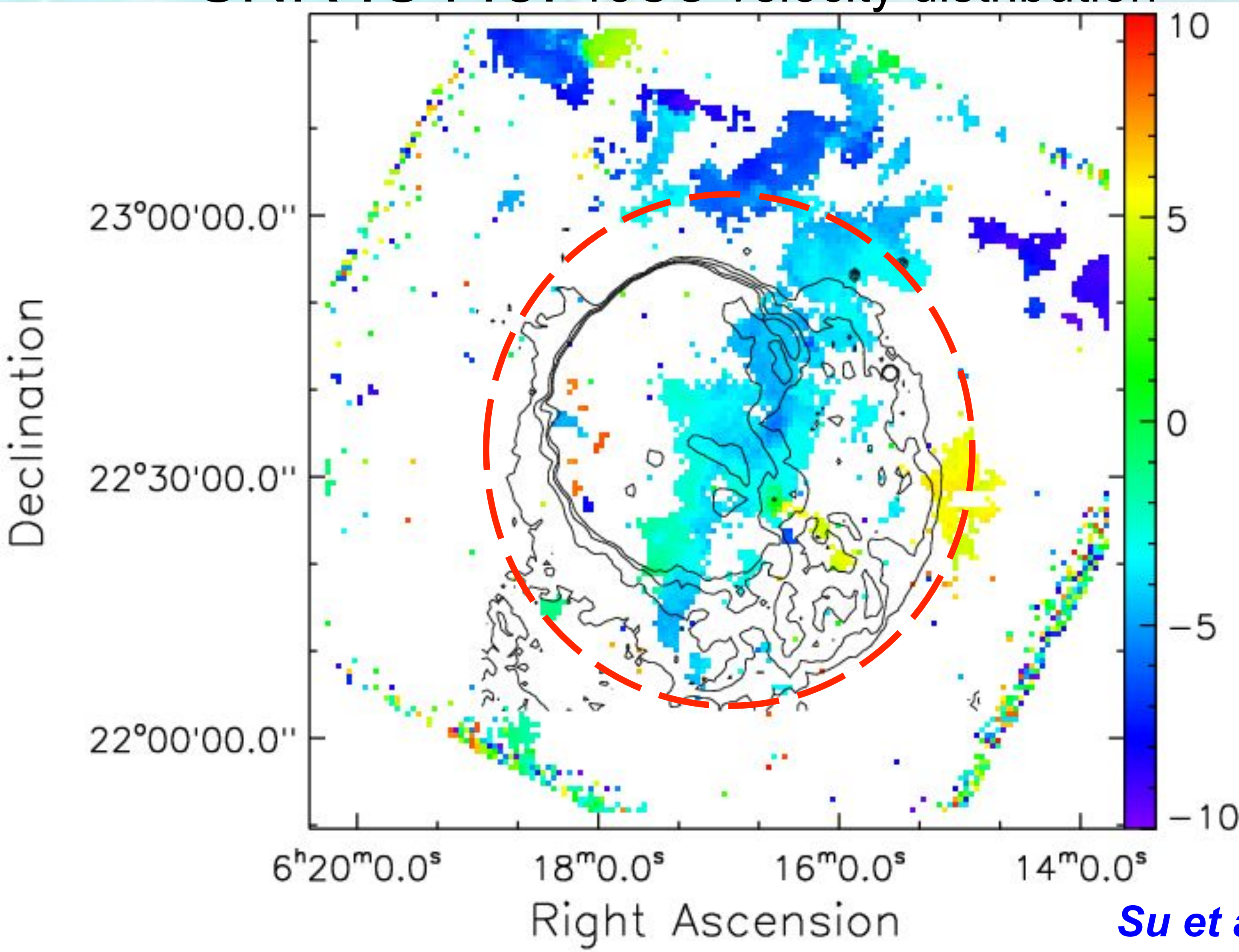
SNR IC443: Intensity map in -6 to -1 km/s (*12CO*+*13CO*)



Su et al. 2014, ApJ

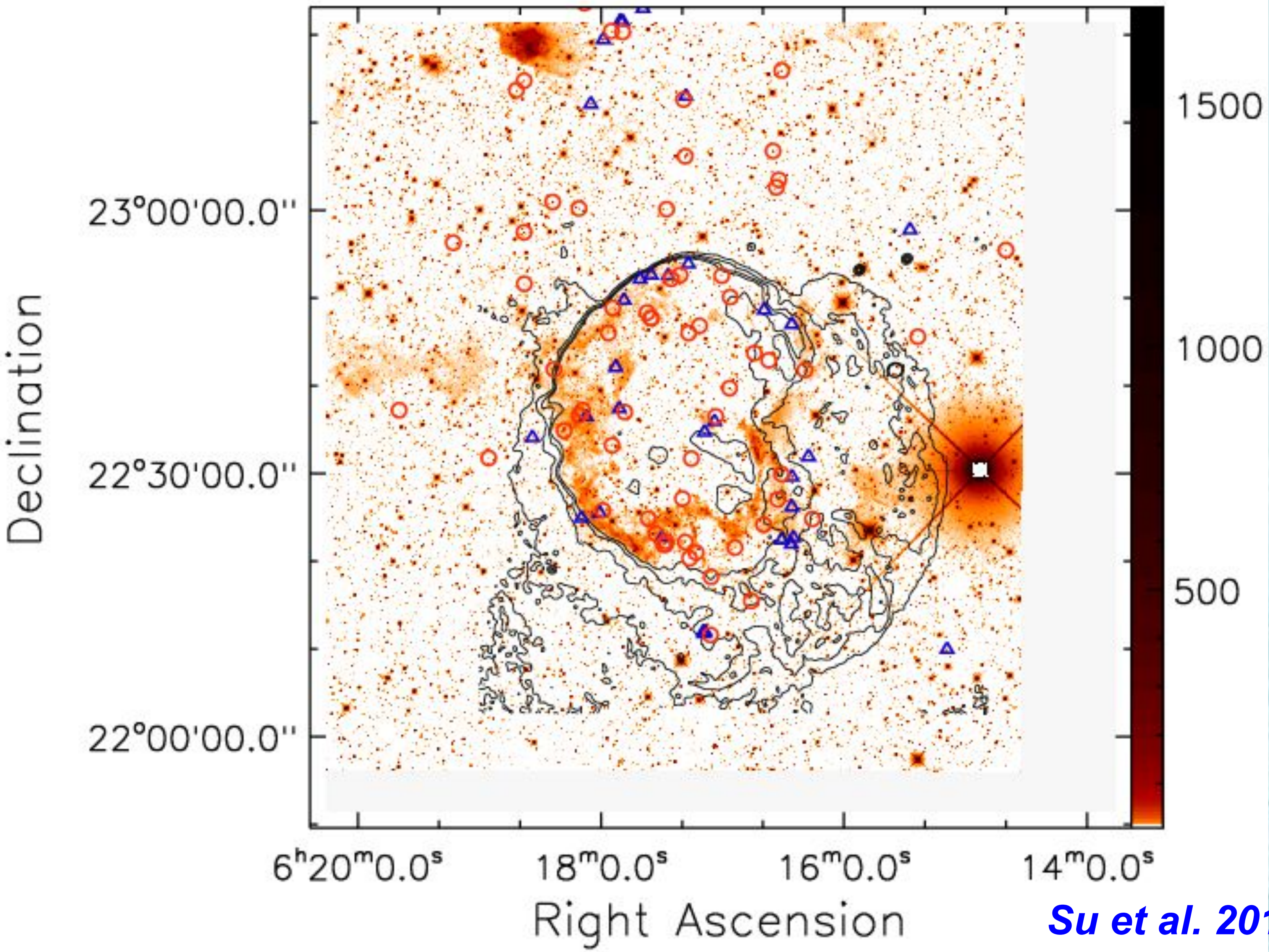
Case 1: SNR IC443

SNR IC443: 13CO velocity distribution



Su et al. 2014, ApJ

Case 1: SNR IC443



Su et al. 2014, ApJ

CO 1-0 line

$$T_0^{12} = 5.53[\frac{1}{e^{5.53/T_{ex}} - 1} - 0.148](1 - e^{-\tau_\nu})$$

$$T_0^{13} = 5.29[\frac{1}{e^{5.29/T_{ex}} - 1} - 0.164](1 - e^{-\tau_\nu})$$

where T_0^{12} and T_0^{13} is the peak radiation temperature of ^{12}CO (1-0) and ^{13}CO (1-0), respectively, and τ_ν is the optical depth;

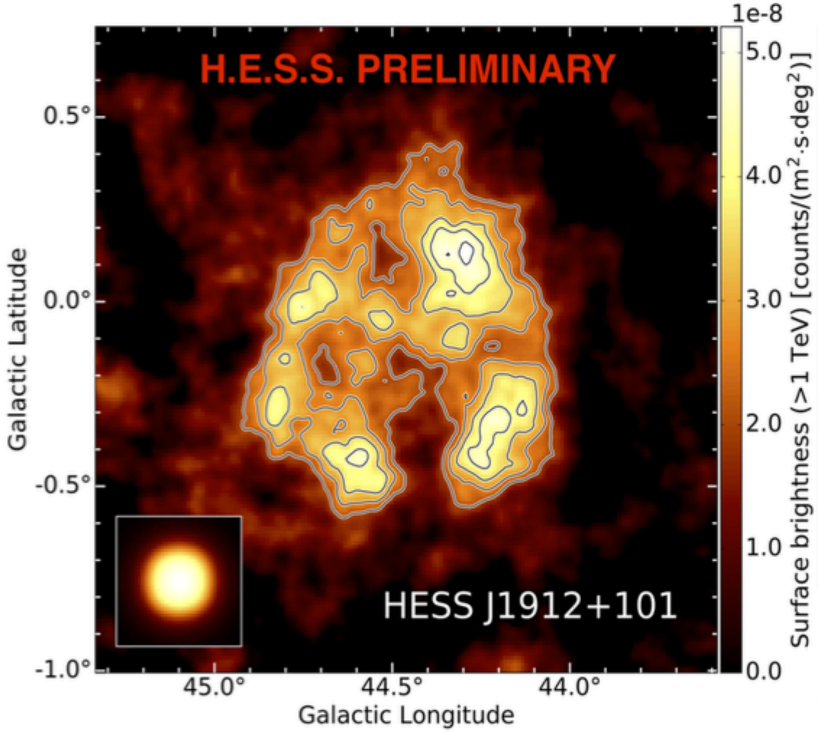
Exitation temperature (for Boltzmann population):

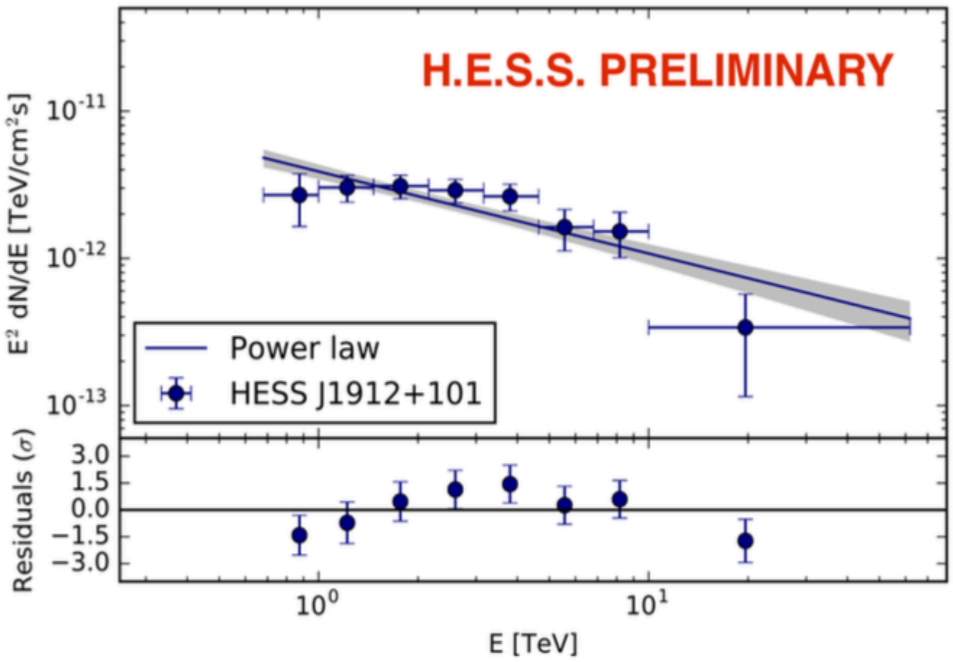
$$T_{\mathrm{ex}} = \frac{5.53}{\ln\left[1 + 5.53/(T_0^{12} + 0.82)\right]}$$

$$\tau_0^{13} = -\ln\left[1 - \frac{T_0^{13}}{5.29/(e^{5.29/T_{\mathrm{ex}}} - 1) - 0.87}\right]$$

$$\left[\frac{N^{13}}{\mathrm{cm}^{-2}}\right] = 2.42 \times 10^{14}\left[\frac{\Delta v}{\mathrm{km\ s^{-1}}}\right]\left[\frac{T_{\mathrm{ex}}}{\mathrm{K}}\right]\frac{\tau_0^{13}}{1 - e^{-5.29/T_{\mathrm{ex}}}}$$

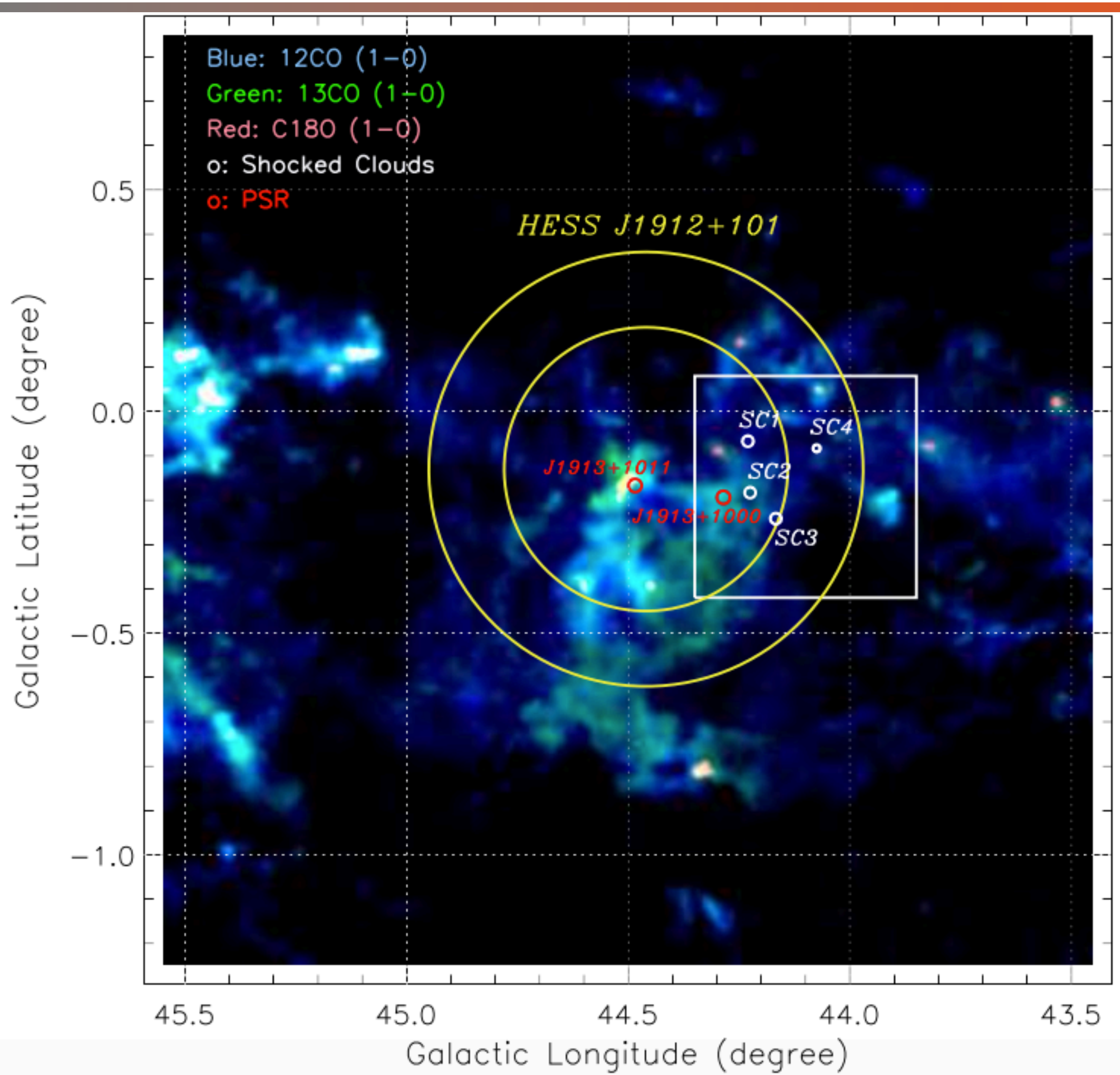
Case 2: Is HESS J1912+101 Associated with an Old SNR?





- ***(l=44.46d, b=-0.13d)***
- ***Radius=(0.32d, 0.49d)***
- ***No clear counterpart in multi-wavelength***

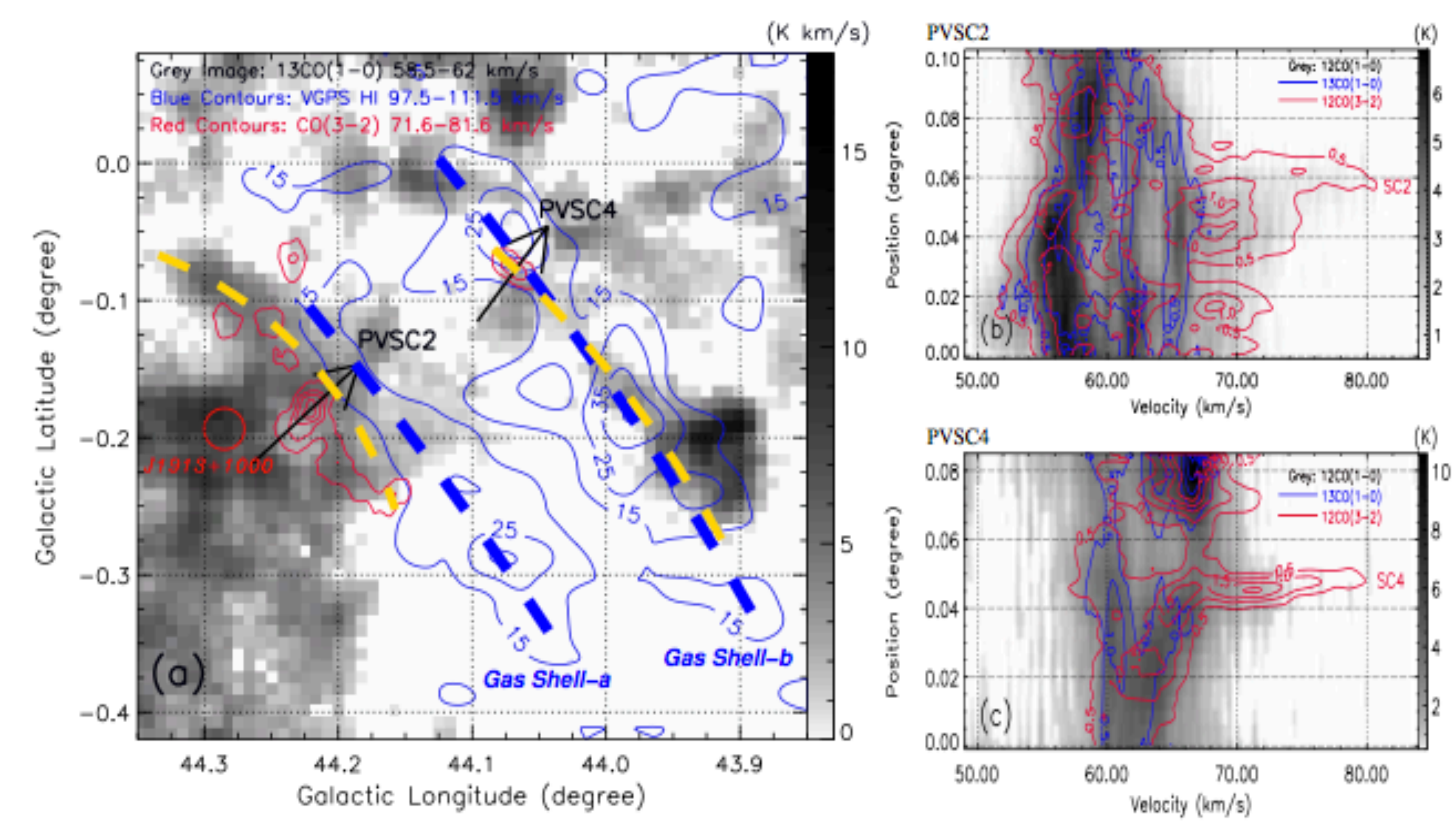
Case 2: Is HESS J1912+101 Associated with an Old SNR?



The shell-like TeV emission is from the decay of neutral pions produced by interactions between an old SNR at 4.1 kpc and the surrounding dense MCs at 60 km/s. PSR J1913+1011 is related to the SNR due to their comparable ages and distances.

Su et al. 2017, ApJ

Case 2: Is HESS J1912+101 Associated with an Old SNR?



- *13CO(1—0) shells at 58.5—62 km/s (Gold);*
- *High-velocity HI shells at 97.5—111.5 km/s (Blue);*
- *12CO shocked gas up to 80km/s (Partial shells);*

Su et al. 2017, ApJ

Case 3: SNR G150.3+4.5

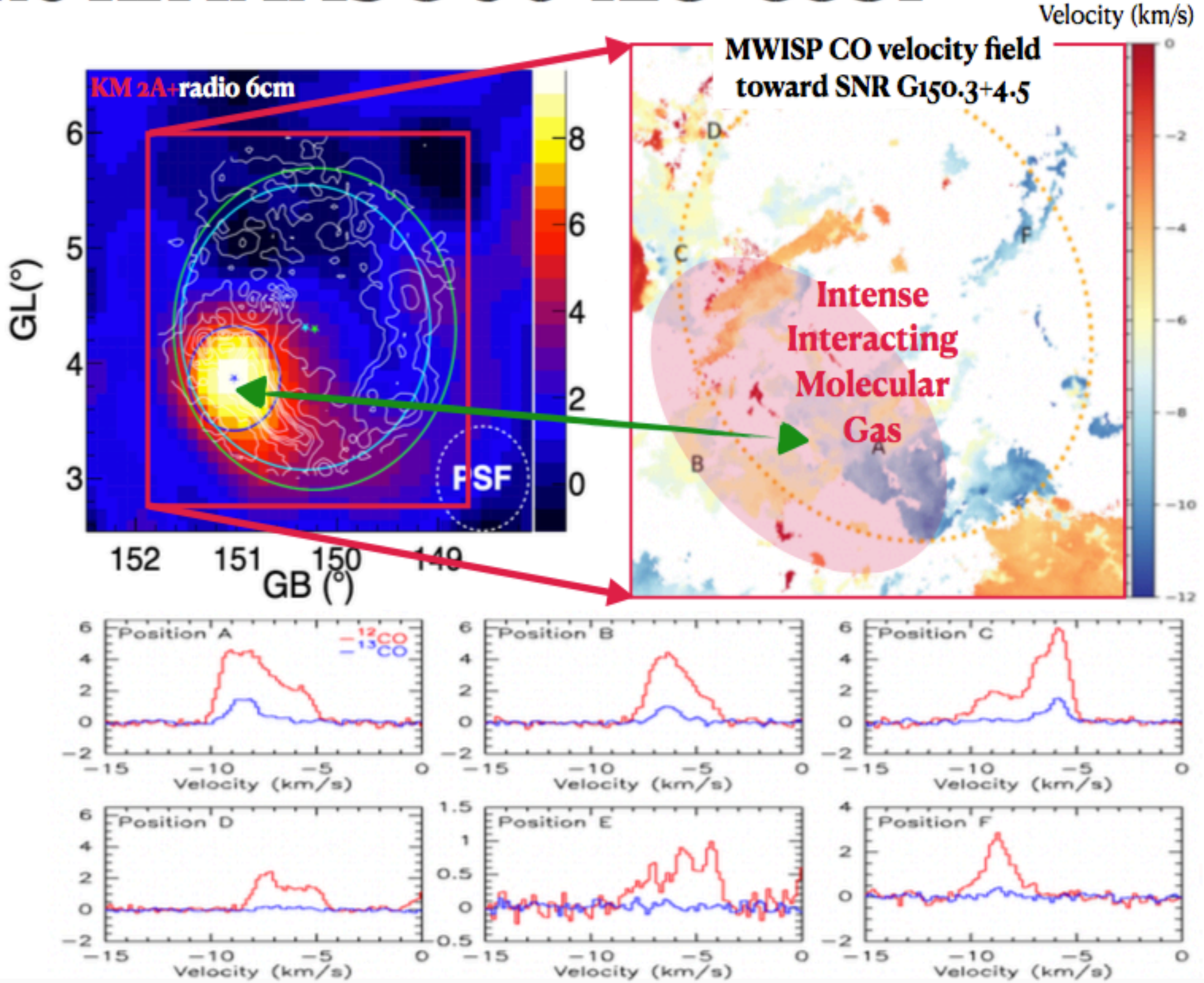
Origin of the 1LHAASO J0428+5531

1, A series of evidence show that 1LHAASO J0428+5531 is associated with the old SNR G150.3+4.5, including
(a) the spatial coincidence between them,
(b) the SED fitting of the SNR model,
(c) the convincing scenario of SNR-MCs interaction;

2, The SNR is interacting with the surrounding dense MCs based on the remarkable morphological and kinematic features of the molecular gas from the MWISP data;

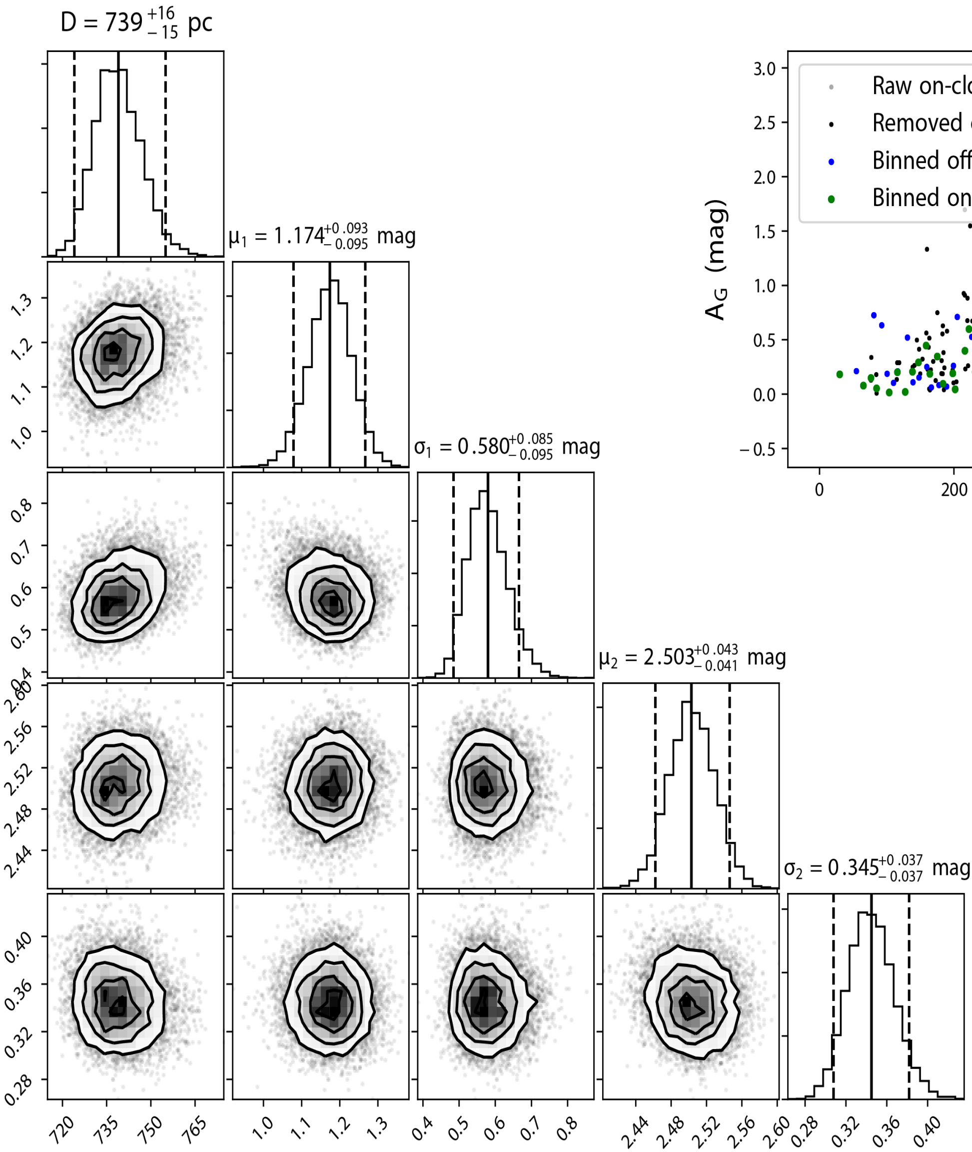
3, SNR G150.3+4.5 with an age of 10^4 yr is located at about 740\pm50 pc based on the Gaia data;

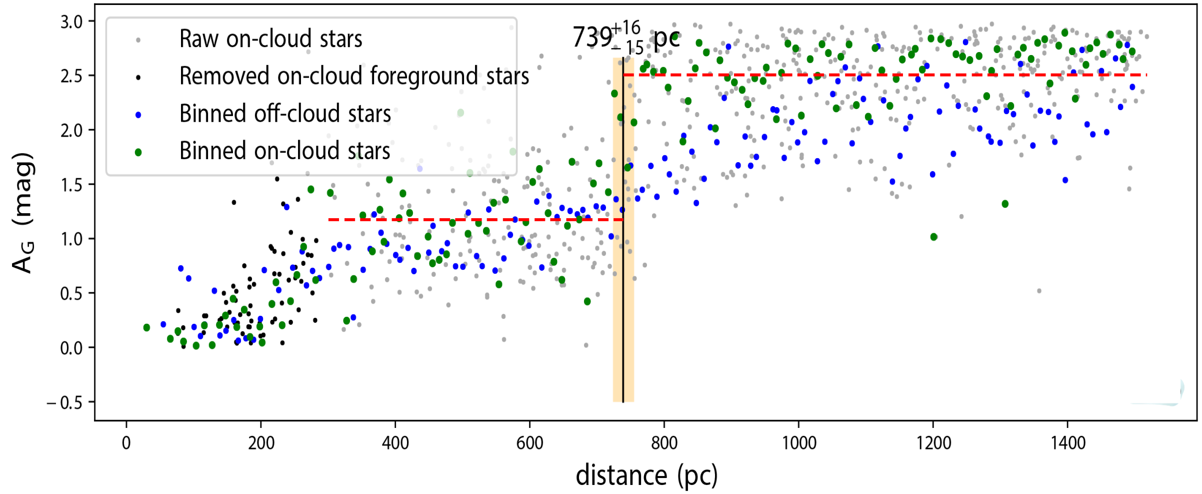
4, The VHE emission of 1LHAASO J0428+5531 almost certainly comes from the hadronic origin;

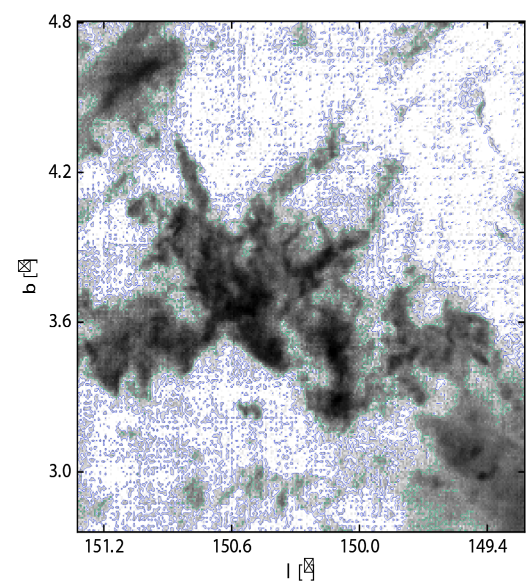


Feng, et al. 2024, A&A

Case 3: SNR G150.3+4.5





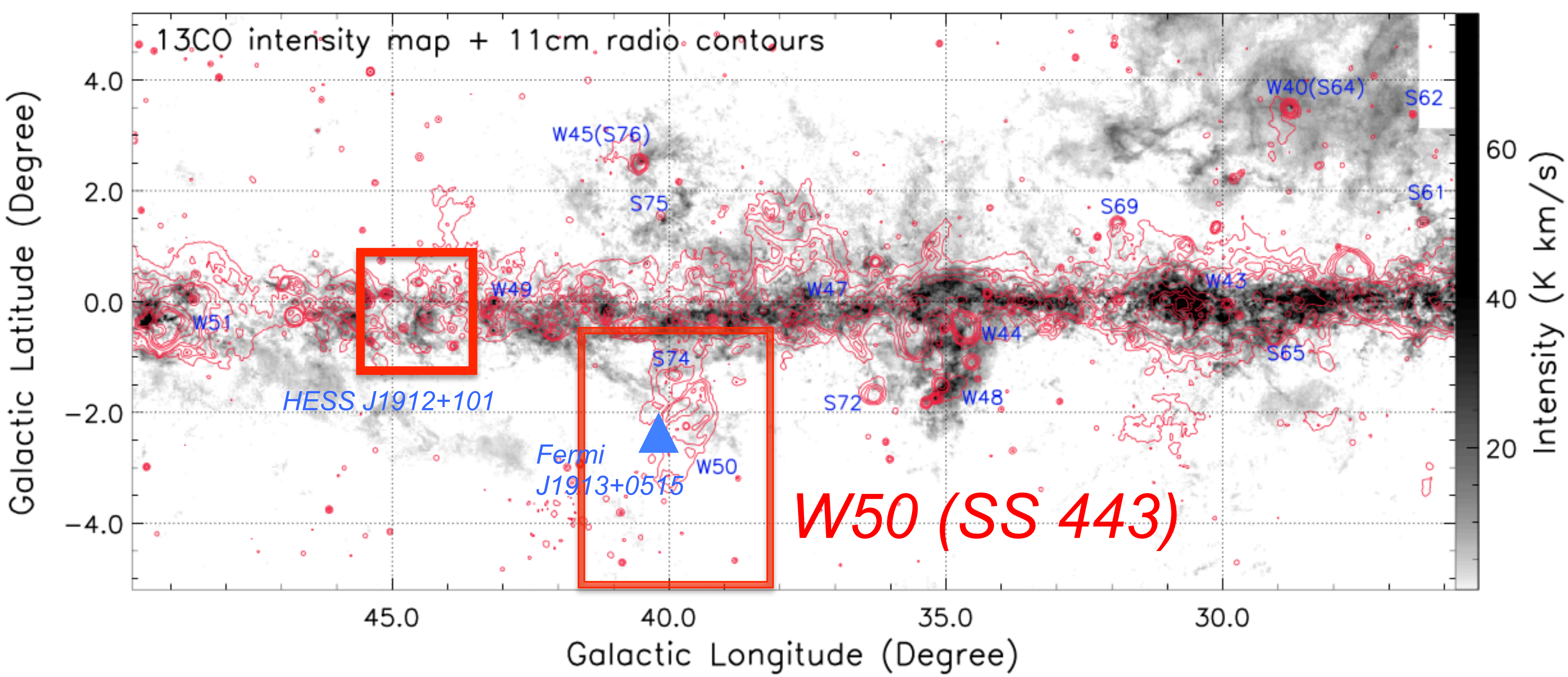


Feng, et al. 2024, A&A

Case 4: MCs vs. SFR

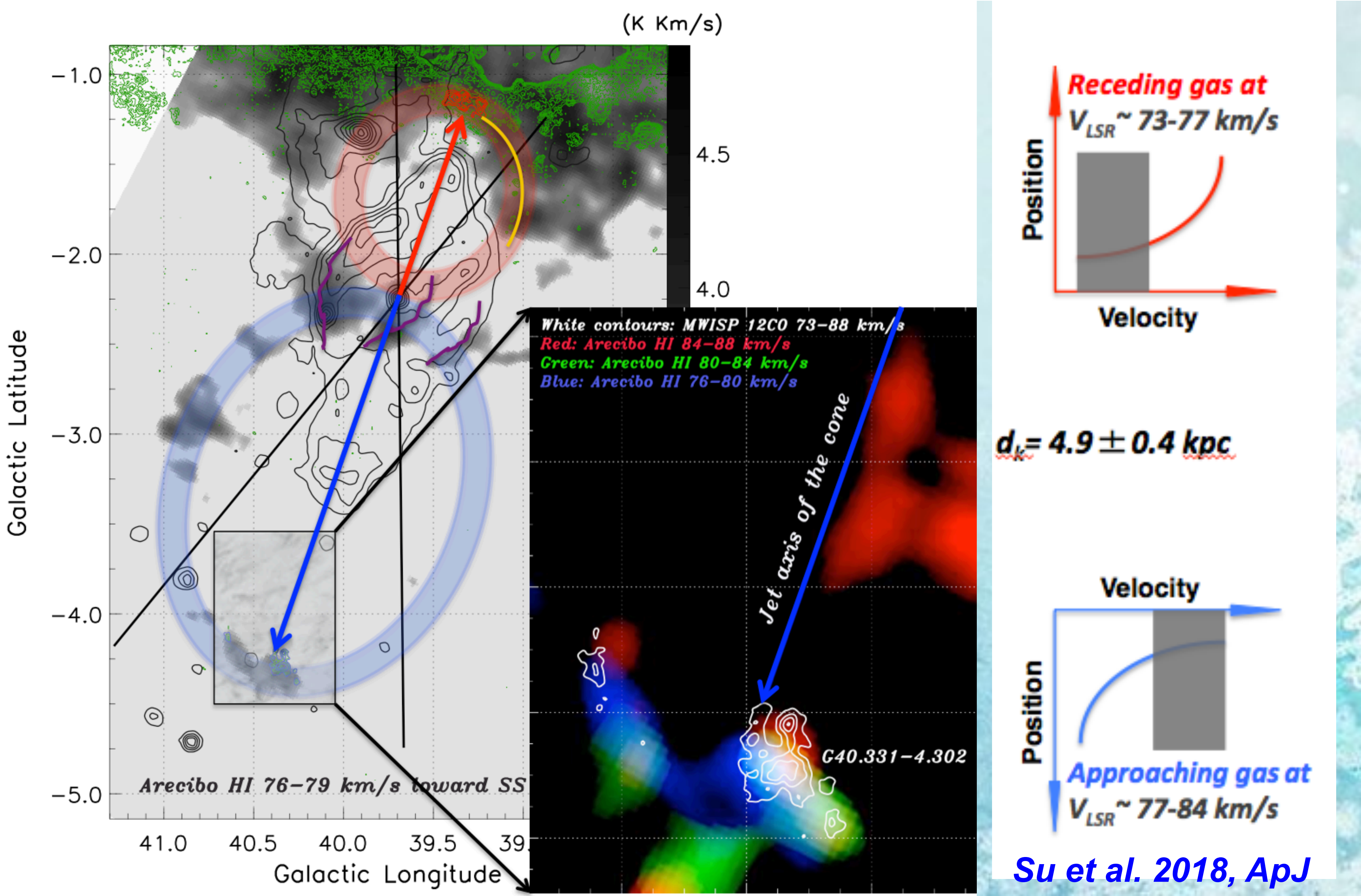
- High-energy sources are related to surrounding MCs;

Gray scale (0.9') ***Red contours (HPBW=4.3')***



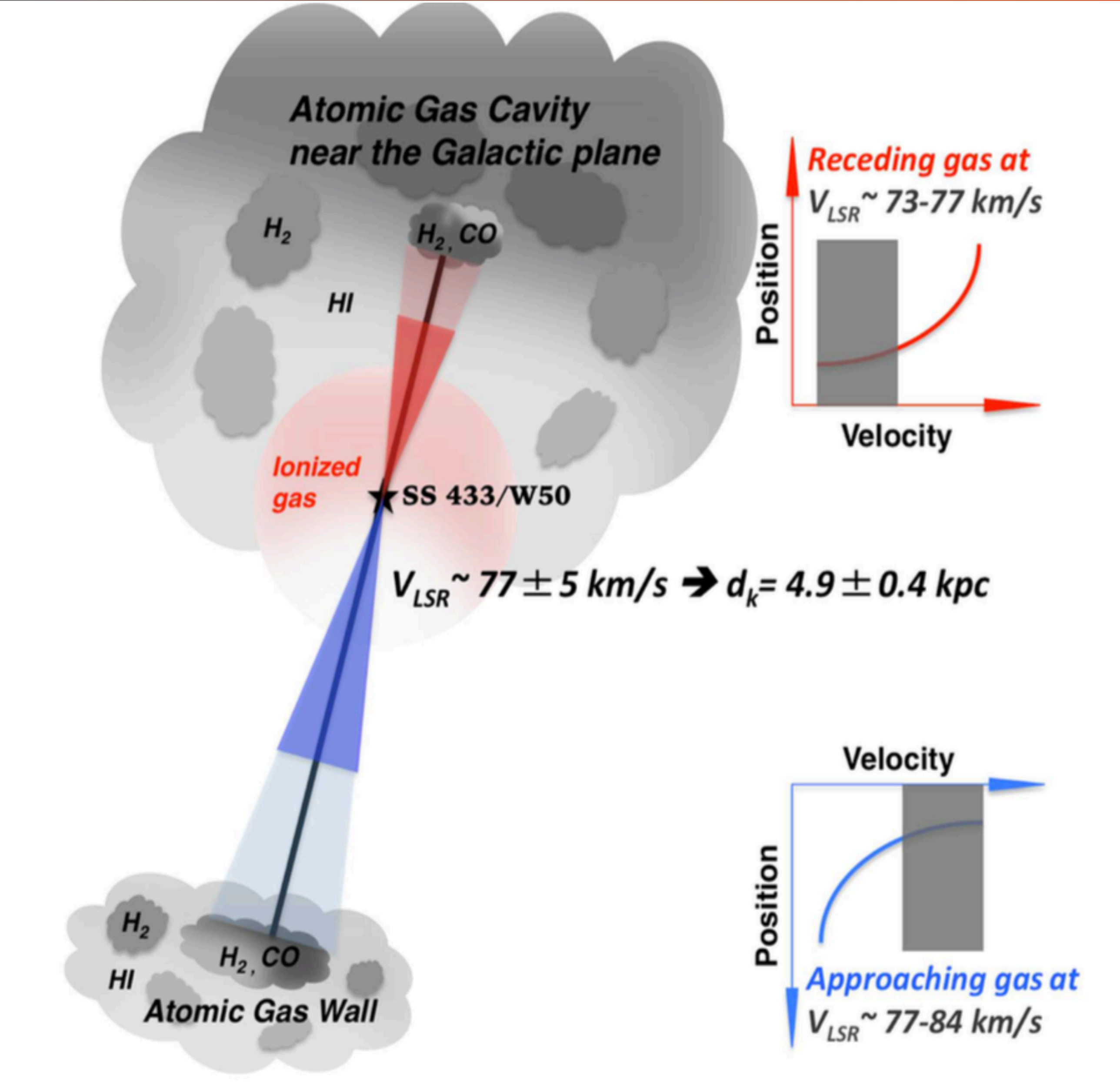
Su et al. 2019, ApJS

Case 4: SS 433/W50



Su et al. 2018, ApJ

Case 4: SS 433/W50



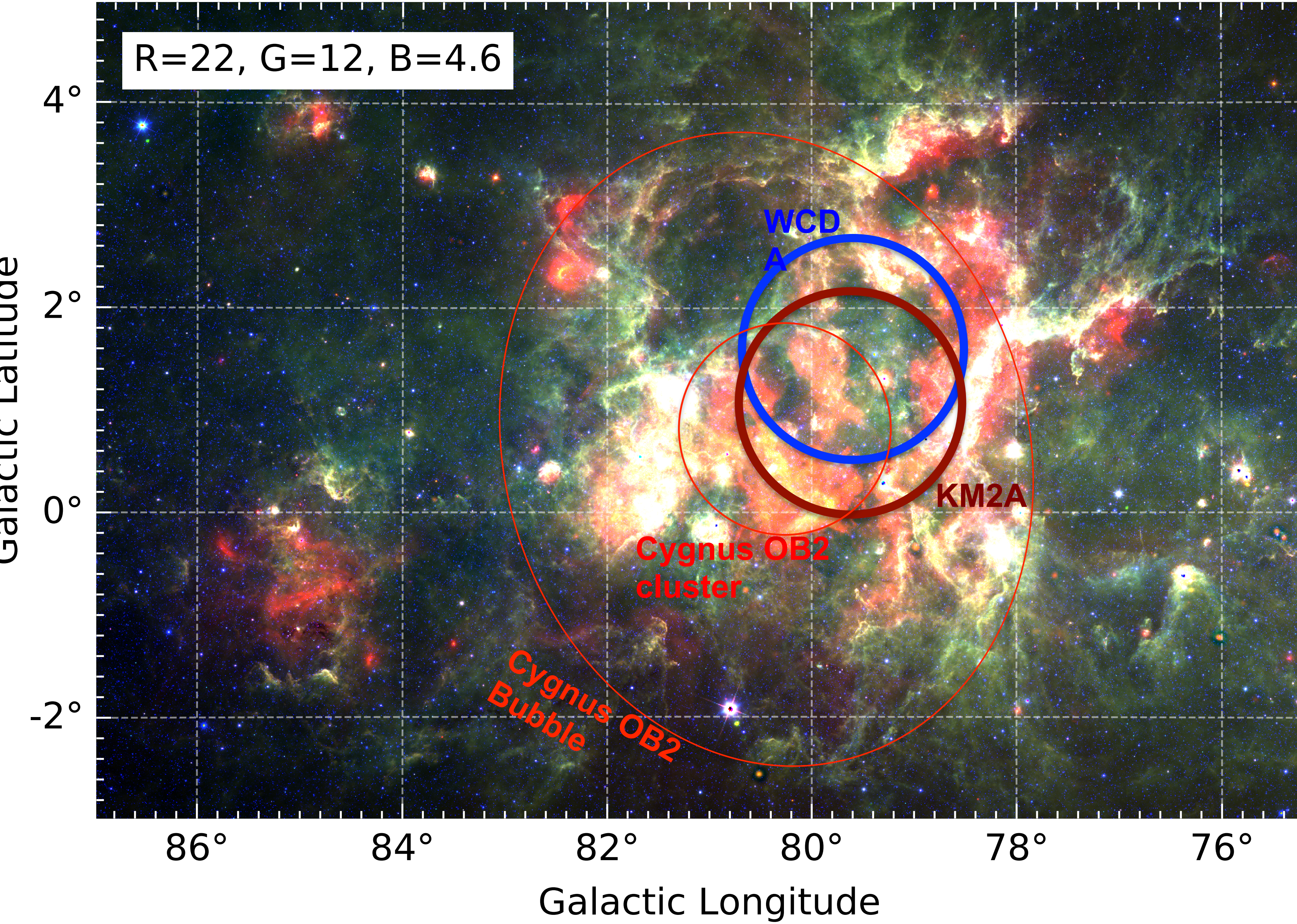
Evidence:
Spatial coincidence +
Kinematic features +
Anti-symmetry

Complements:
Velocity of Optical + atomic + MCs

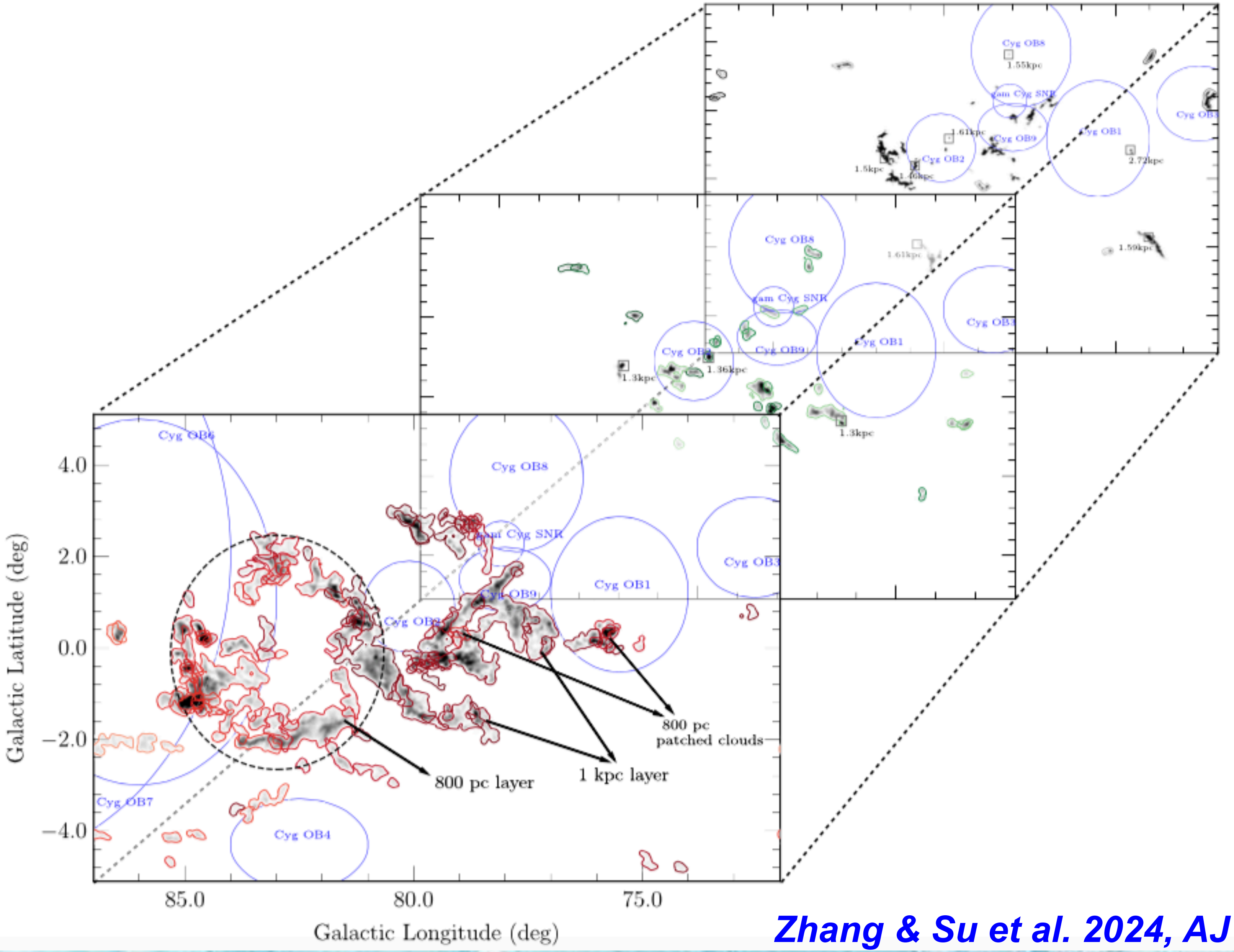
Other methods:
Proper motions of the radio jets/knots
➔ 4.5—5.5 kpc

The MCs are located at ~400 pc below the GP!
➔ Is it universal?

Su et al. 2018, ApJ

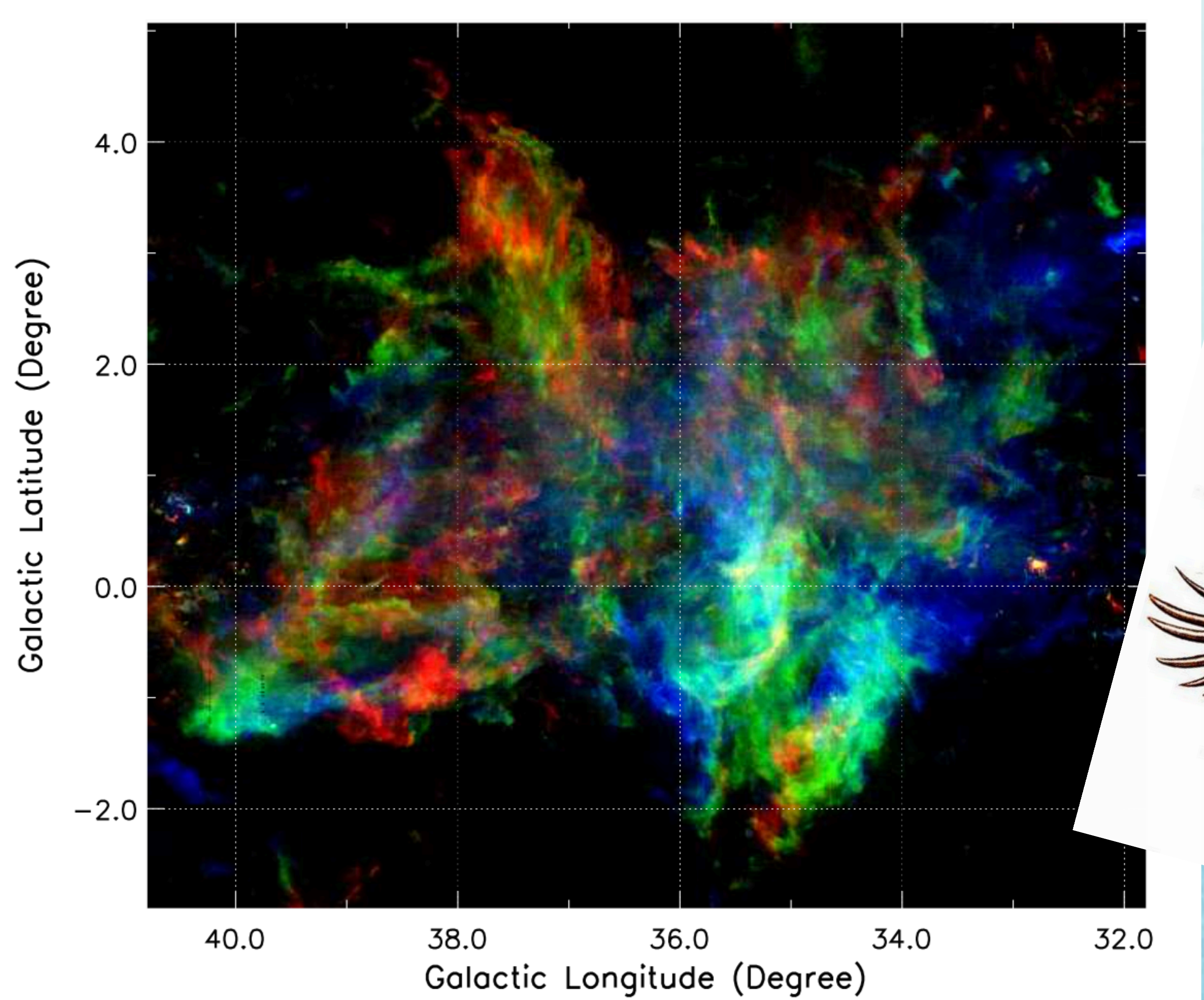

R=22, G=12, B=4.6
WCDA
KM2A
Cygnus OB2 cluster
Cygnus OB2 Bubble
Galactic Latitude
Galactic Longitude
4°
2°
0°
-2°
86°
84°
82°
80°
78°
76°

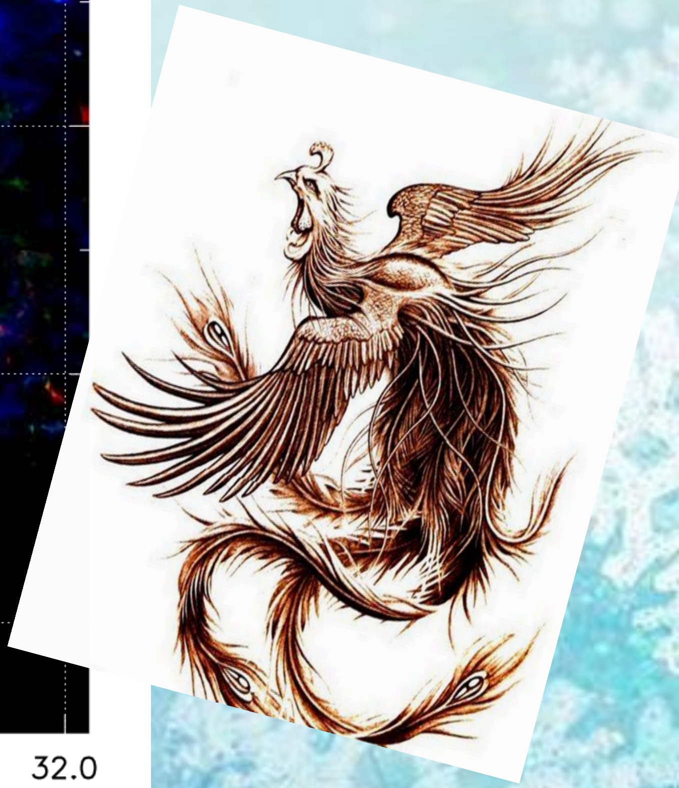
Case 4: Cygnus OB2



Zhang & Su et al. 2024, AJ

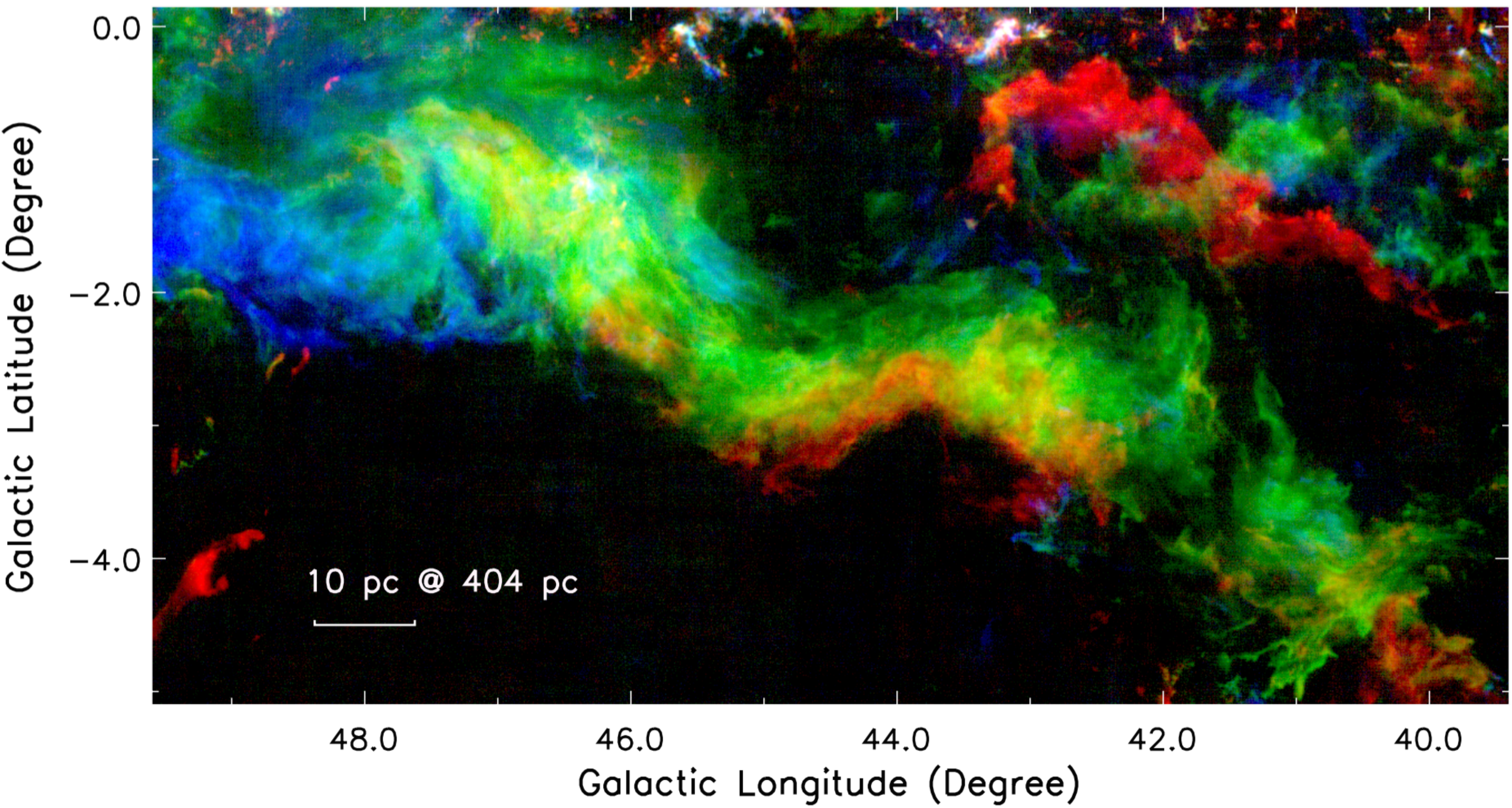
3，Our Galaxy；





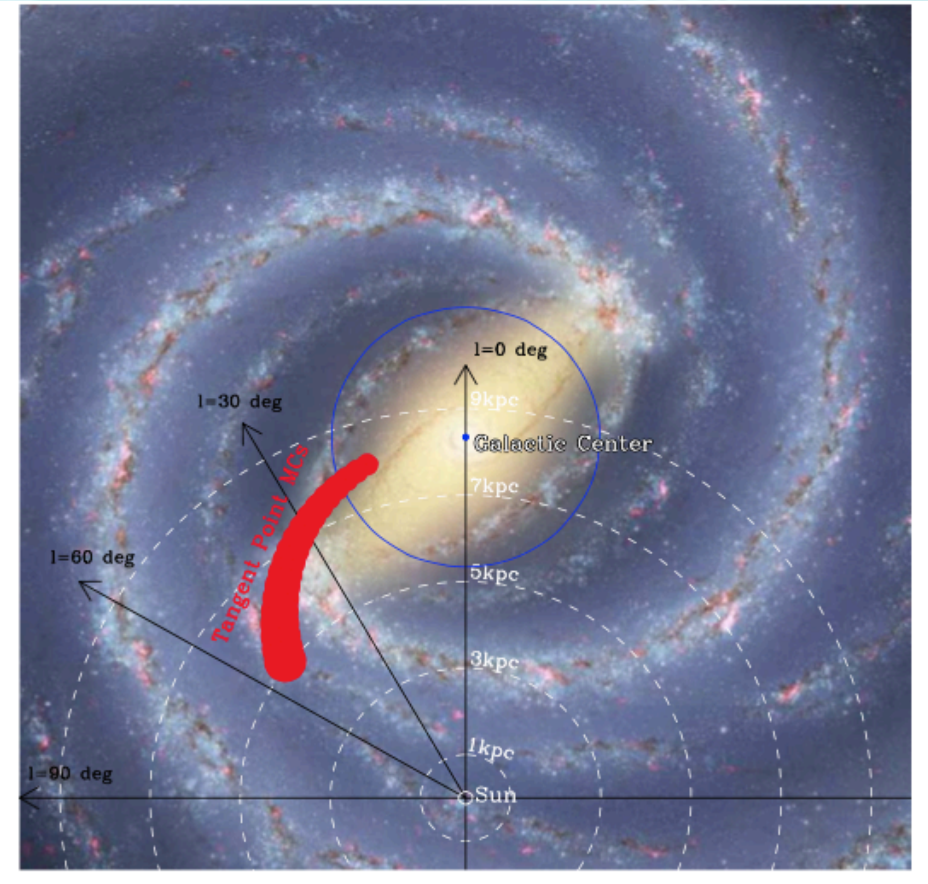
Su et al. 2020, ApJ

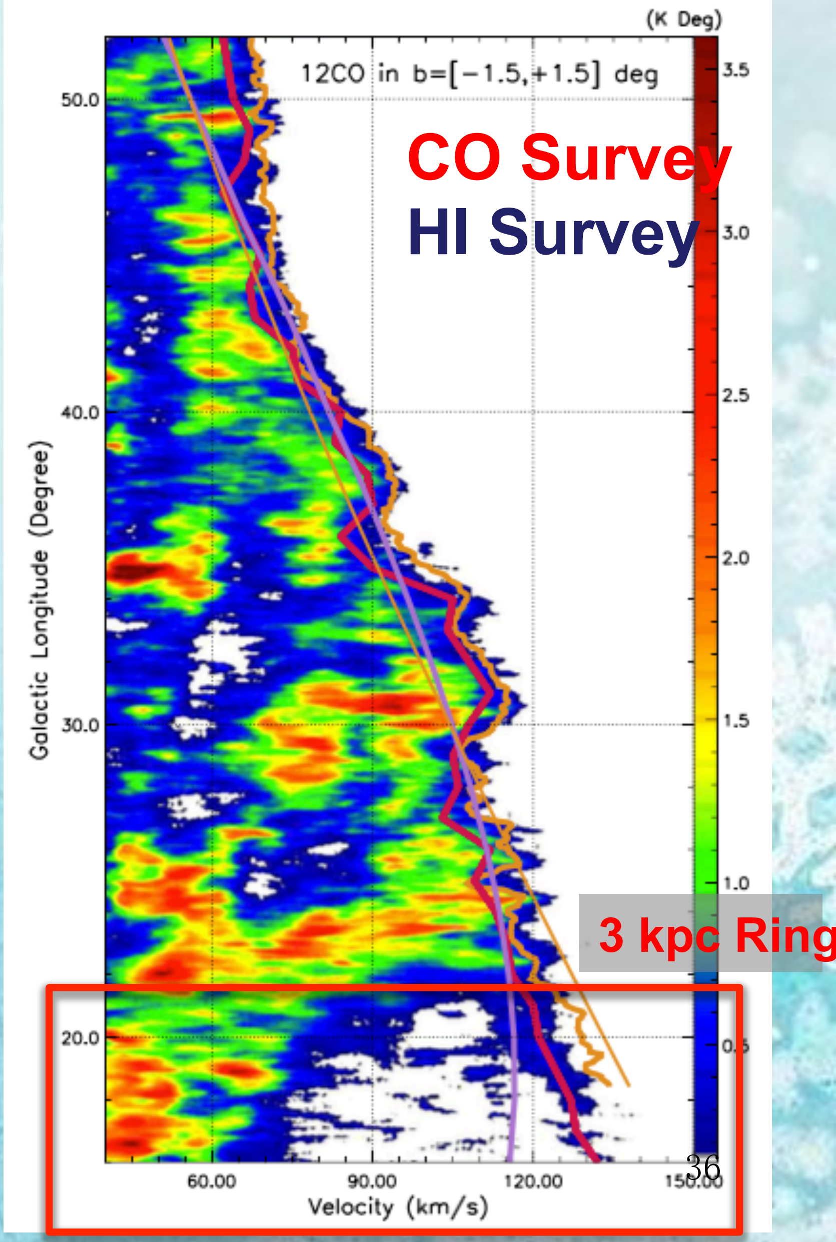
Case 5: Nearby MCs (hubs, filaments, …)



Su et al. 2020, ApJ

Case 6: Galactic structures

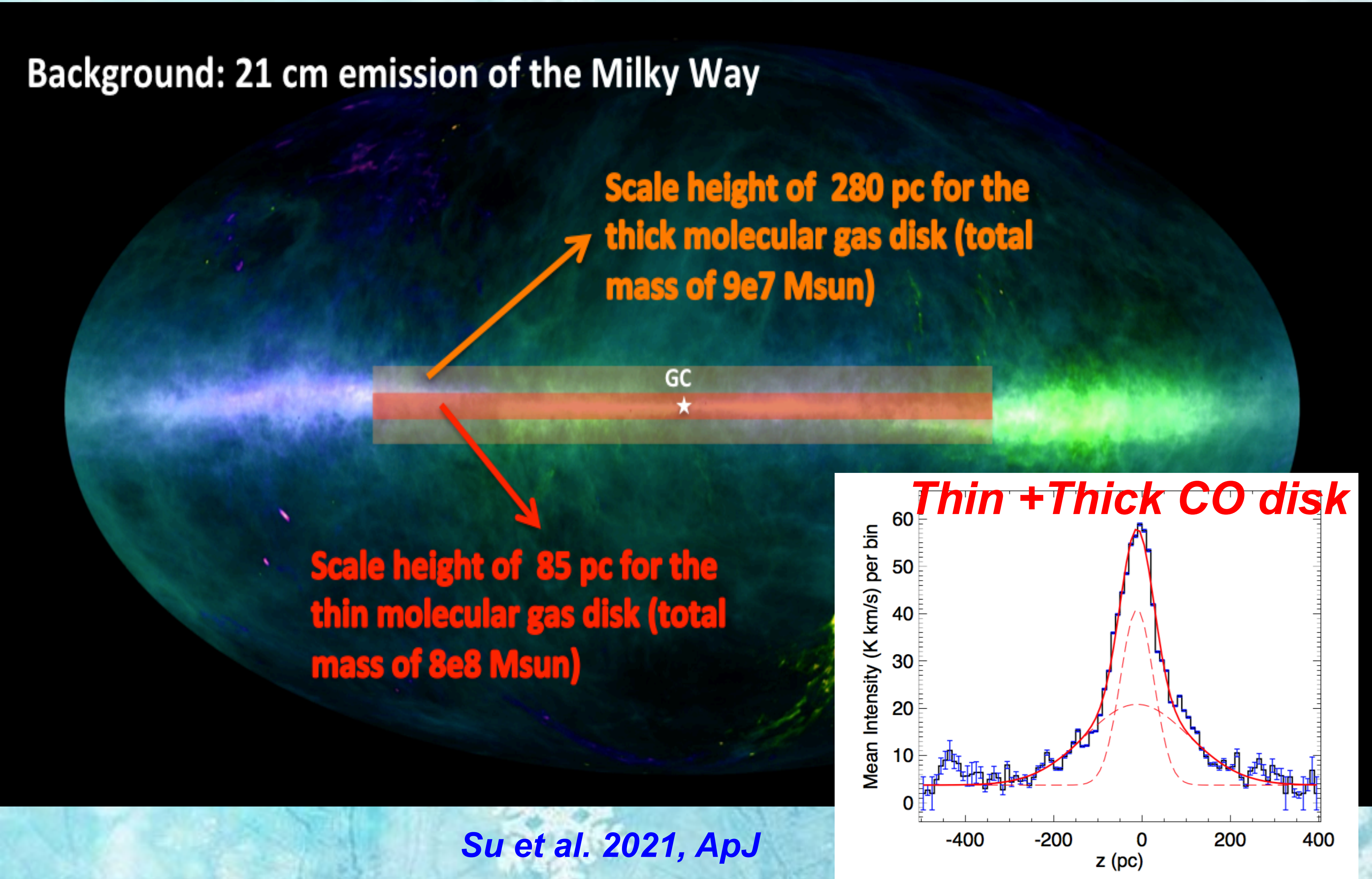




CO emission near the terminal velocity can **avoid the distance ambiguity** within the solar circle.

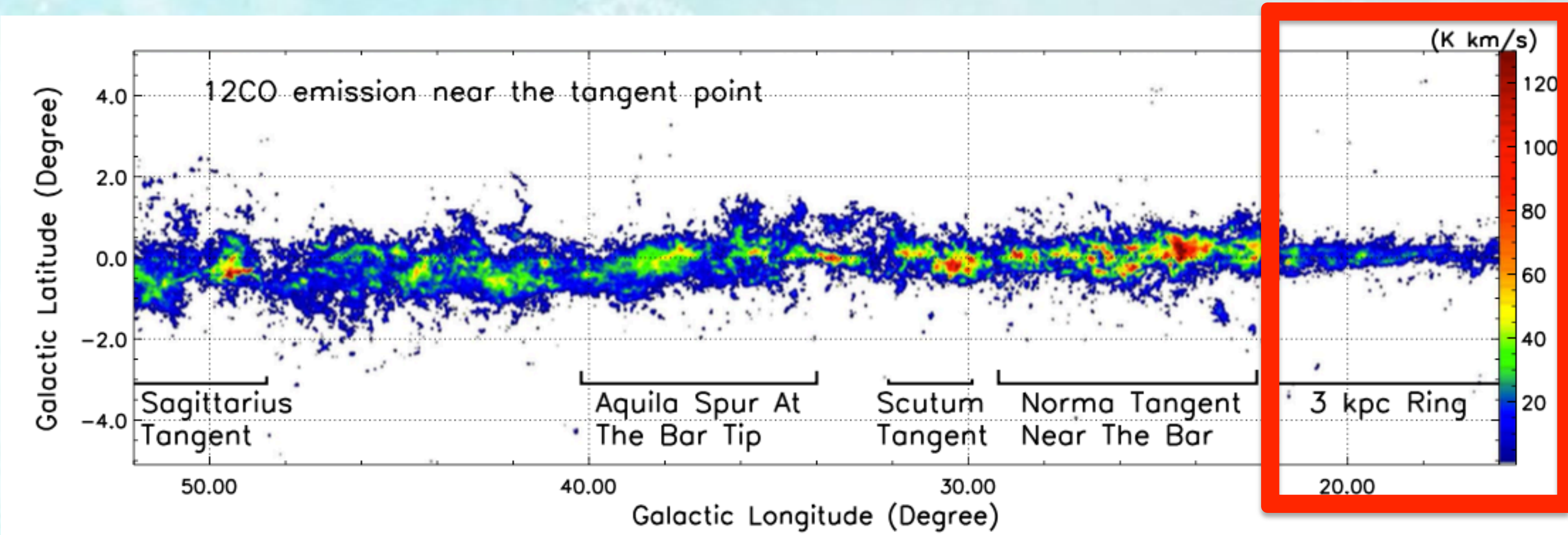
Su et al. 2021, ApJ

Case 6: Galactic structures



Su et al. 2021, ApJ

Case 6: Galactic structures

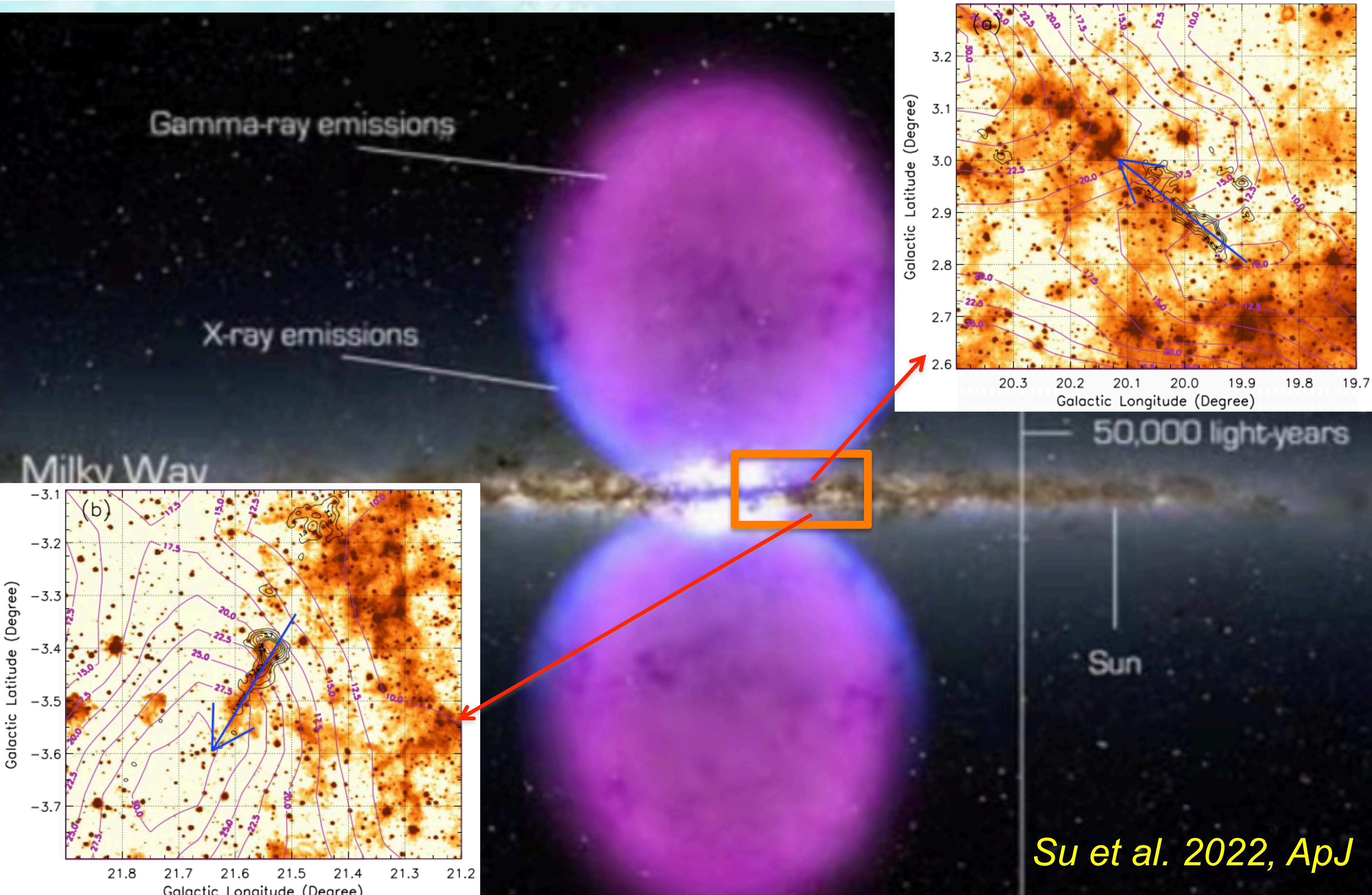


The 3-kpc Ring is probably related to the GC super bubble and/or the Galactic bar potential;

Surface Density of the thick disk=0.4 Msun/pc^2 ➔ 1% of the Baryons
Volume Density of the thick disk=0.0014 Msun/pc^3 or 0.02H_2/cm^3 ➔ 4%

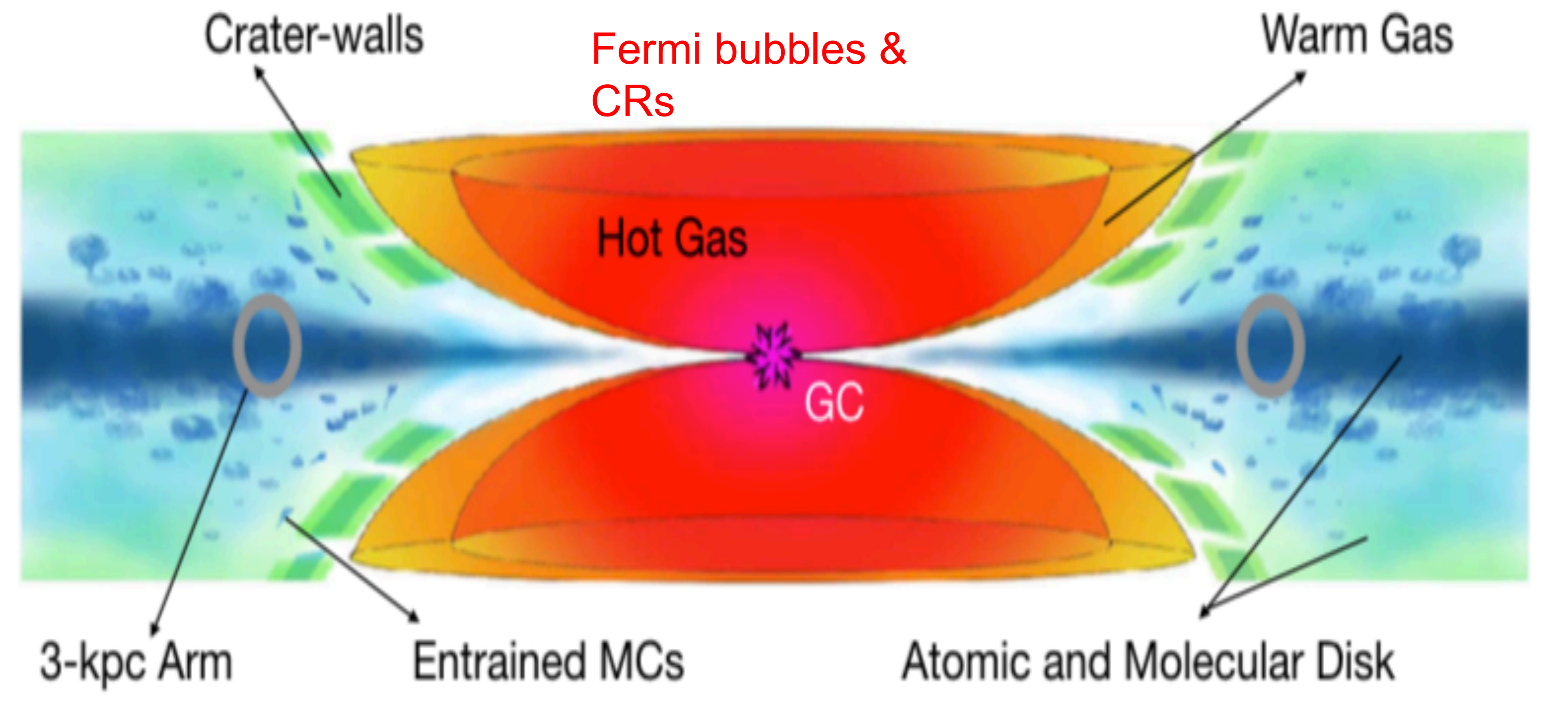
Su et al. 2021, ApJ

Case 6: Galactic structures



Su et al. 2022, ApJ

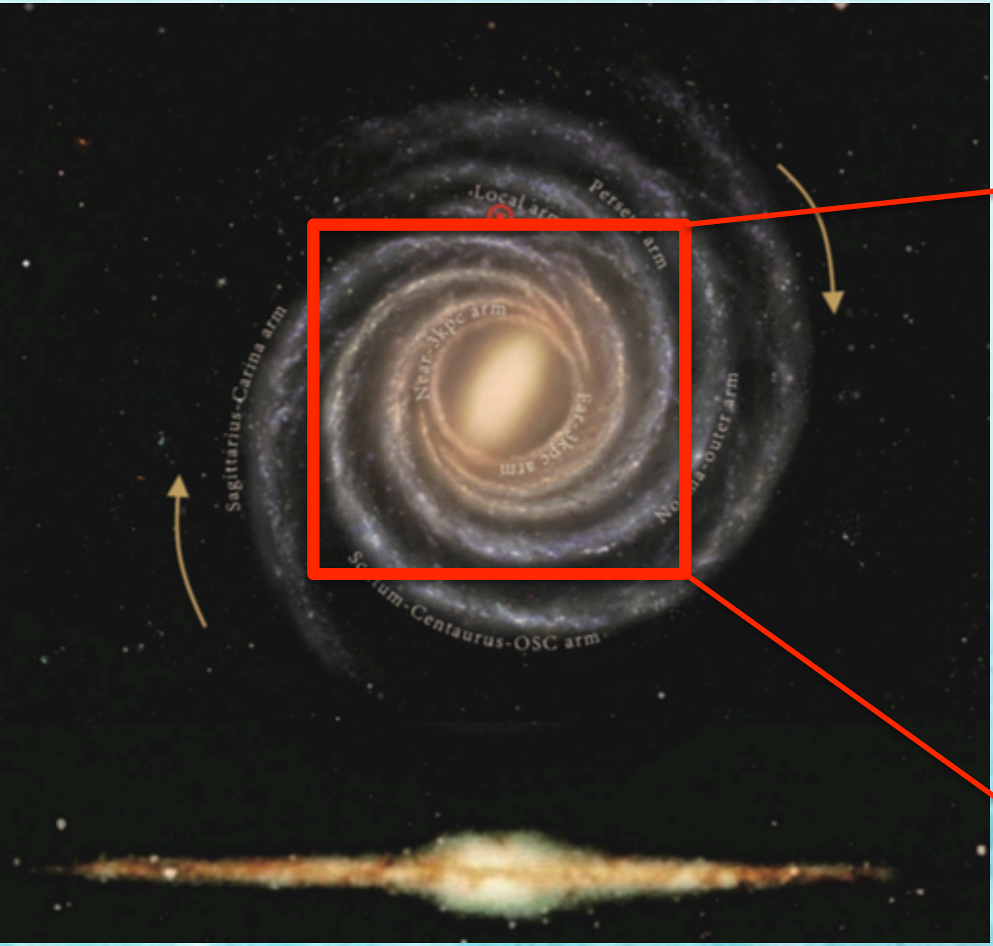
Case 6: Galactic structures

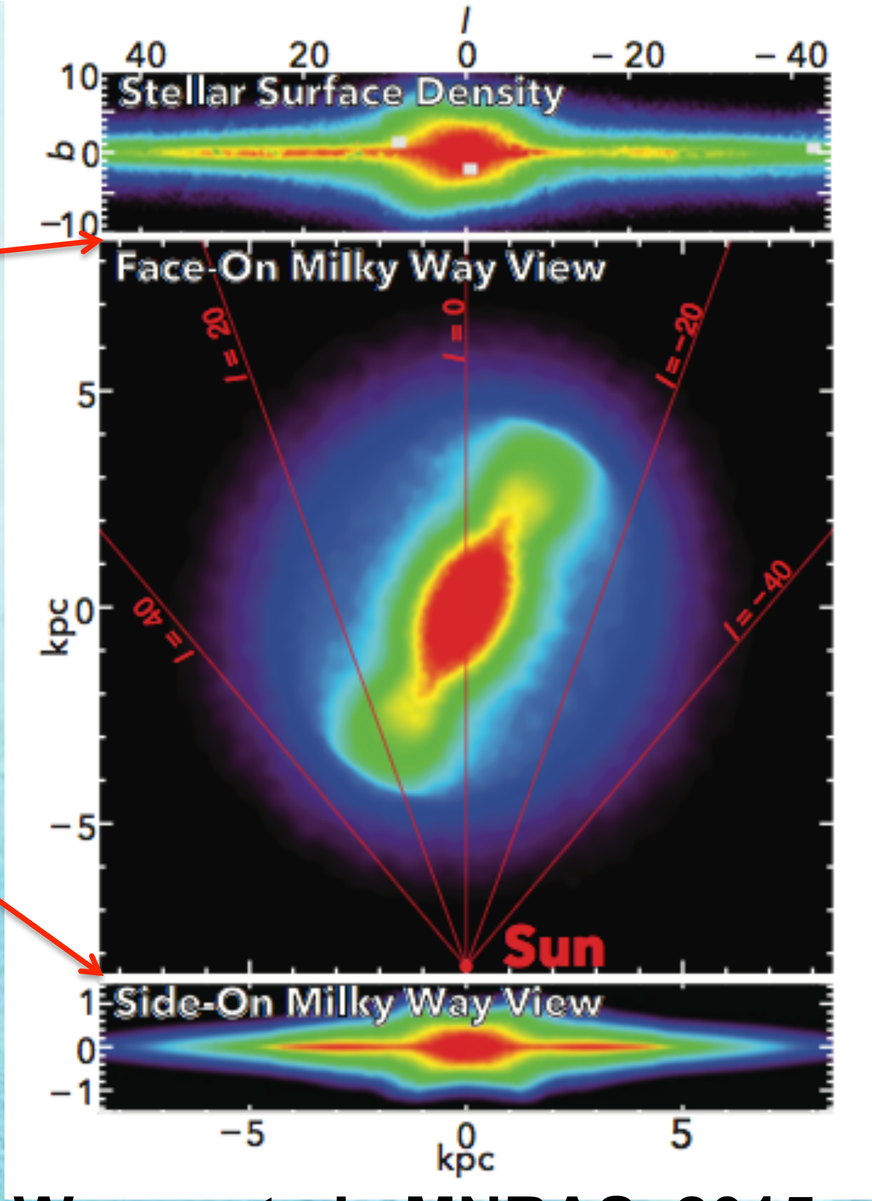


Intermittent nuclear activities of the Milky Way in the recent 3–6 Myr have a significant impact on the gaseous disk

Su et al. 2022, ApJ

Case 6: Galactic structures

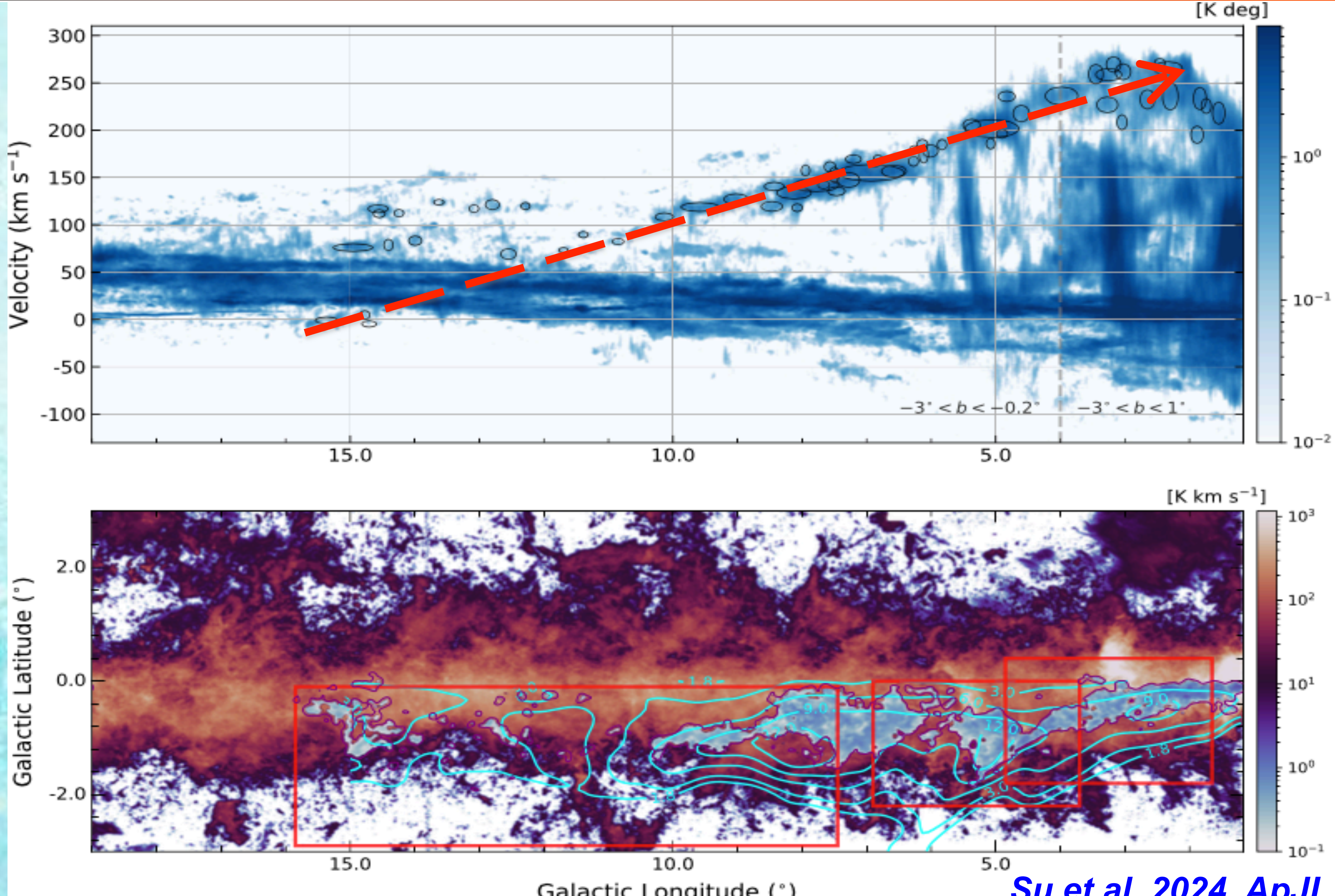




Shen et al., RAA, 2020

Wegg. et al., MNRAS, 2015

Case 6: Galactic structures



Su et al. 2024, ApJL

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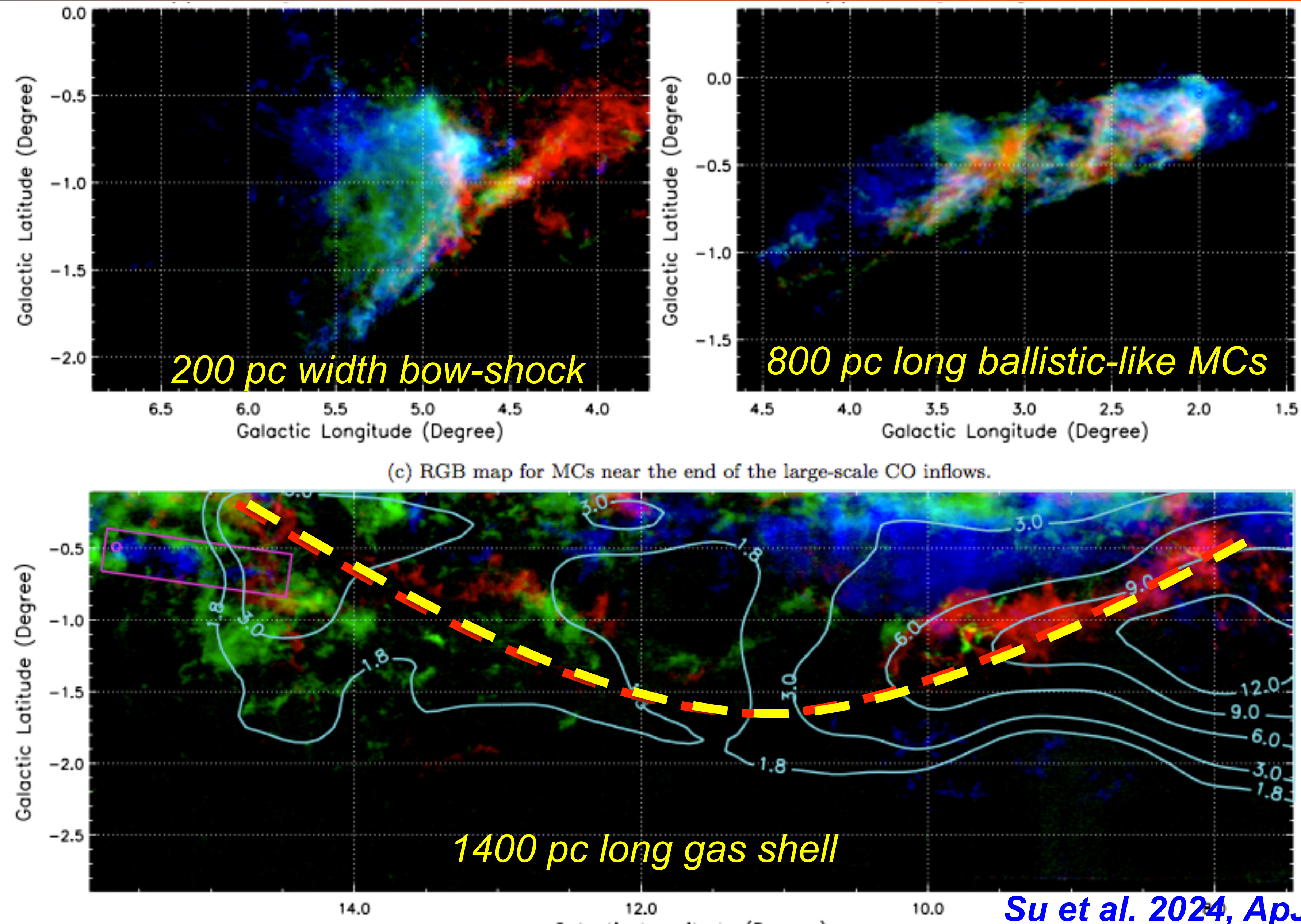
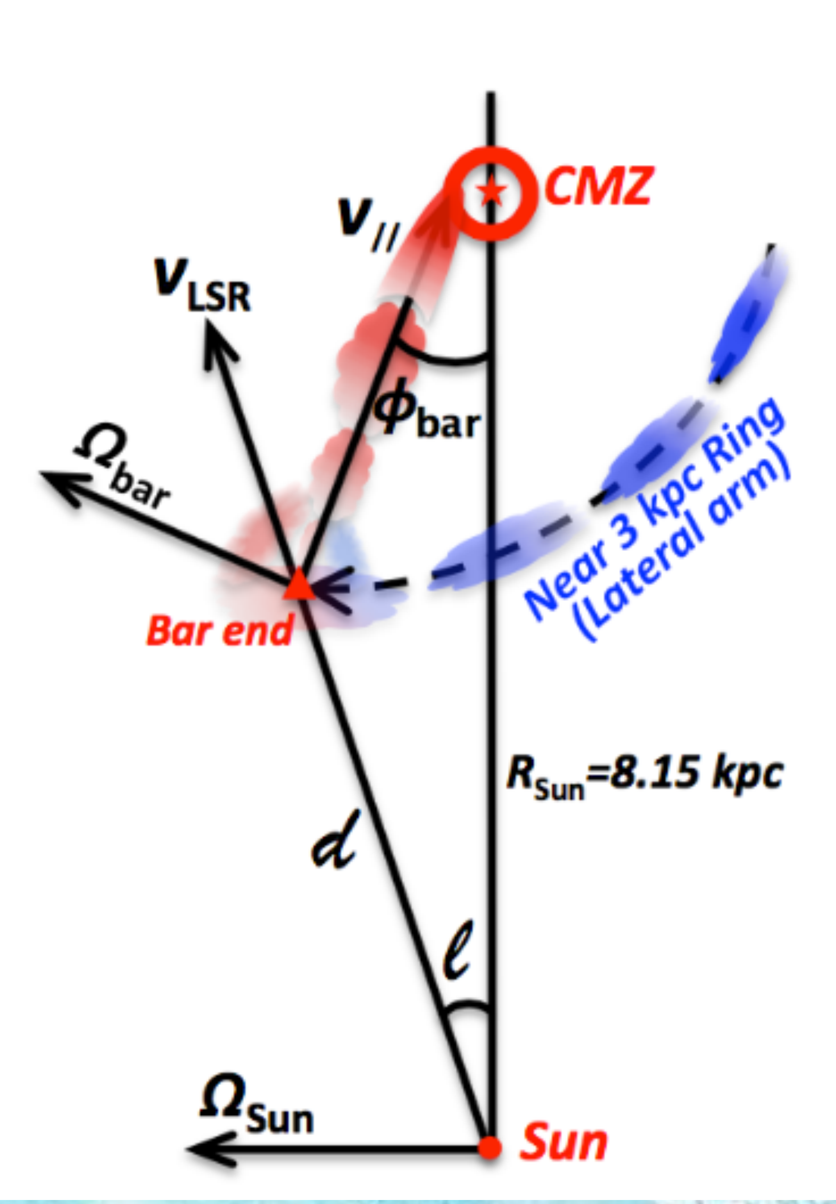


Su et al. 2024, ApJL

Case 6: Galactic structures



- 1, We reveal the large-scale gas inflows connecting the CMZ and the 3-kpc ring;

- 2, MCs are moving towards the CMZ based on bow-like, bright-edged MCs heading towards the GC, the corresponding wide CO broadening and the large-scale velocity gradient;

- 3, The parameters of the gas bar are well constrained;

- 4, The average gas inflow rate toward the Galactic is roughly comparable to the outflow's rate from the Galactic nuclear winds;

Su et al. 2024, ApJL


M82 @ 4 Mpc
R: Spitzer
G: Hubble
B: Chandra

4, Summary;

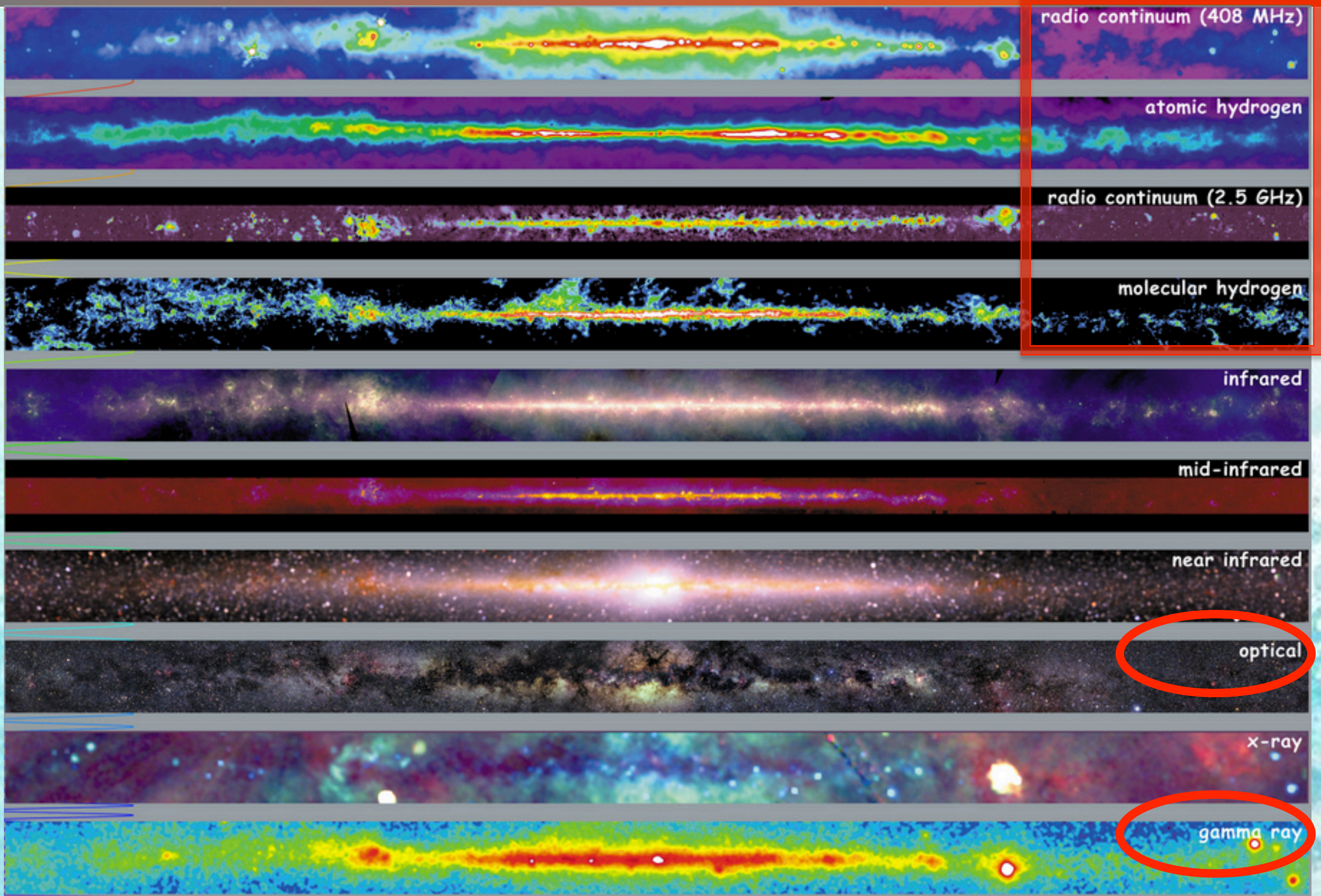
- **CO is a good tracer of molecular gas in the Milky Way;**

- **MWISP is a multi-tracer molecular-line survey along the northern Galactic plane with unprecedented high-quality (high sensitivity, high-frequency spectral resolution, and complete sampling with large sky area coverage).**

- **The MWISP survey will also provide indispensable support for millimeter-wave molecular data for multi-band collaborative research between various bands, e.g., FAST, LHAASO, WFST, CSST, etc.**

- **Many studies will benefit for the MWISP survey such as structures of the Milky Way, and some special cases (SNR-MCs, and other dynamic processes).**

Multi-wavelength Sky



4, Summary;

MWISP CO Data

数据使用政策:
http://www.radioast.csdb.cn/shujuzhengce.php

数据使用申请:
http://www.dlh.pmo.cas.cn/xzzq/sqb/
dlhproposal@pmo.ac.cn

Acknowledgements

- 银河画卷科学计划使用了紫金山天文台13.7望远镜开展北银道面$^{12}CO/^{13}CO/C^{18}O$多谱线巡天。感谢所有参与银河画卷巡天工作的同志们，青海观测站工作人员的长期努力。银河画卷计划得到国家重点研发计划（资助号2023YFA1608000&2017YFA0402701）和中国科学院前沿科学重点研究计划（资助号QYZDJ-SSW-SLH047）的资助。

- This research made use of the data from the Milky Way Imaging Scroll Painting (MWISP) project, which is a multi- line survey in in $^{12}CO/^{13}CO/C^{18}O$ along the northern galactic plane with PMO-13.7m telescope. We are grateful to all the members of the MWISP working group, particularly the staff members at PMO-13.7m telescope, for their long-term support. MWISP was sponsored by National Key R&D Program of China with grants 2023YFA1608000 & 2017YFA0402701 and by CAS Key Research Program of Frontier Sciences with grant QYZDJ-SSW-SLH047.