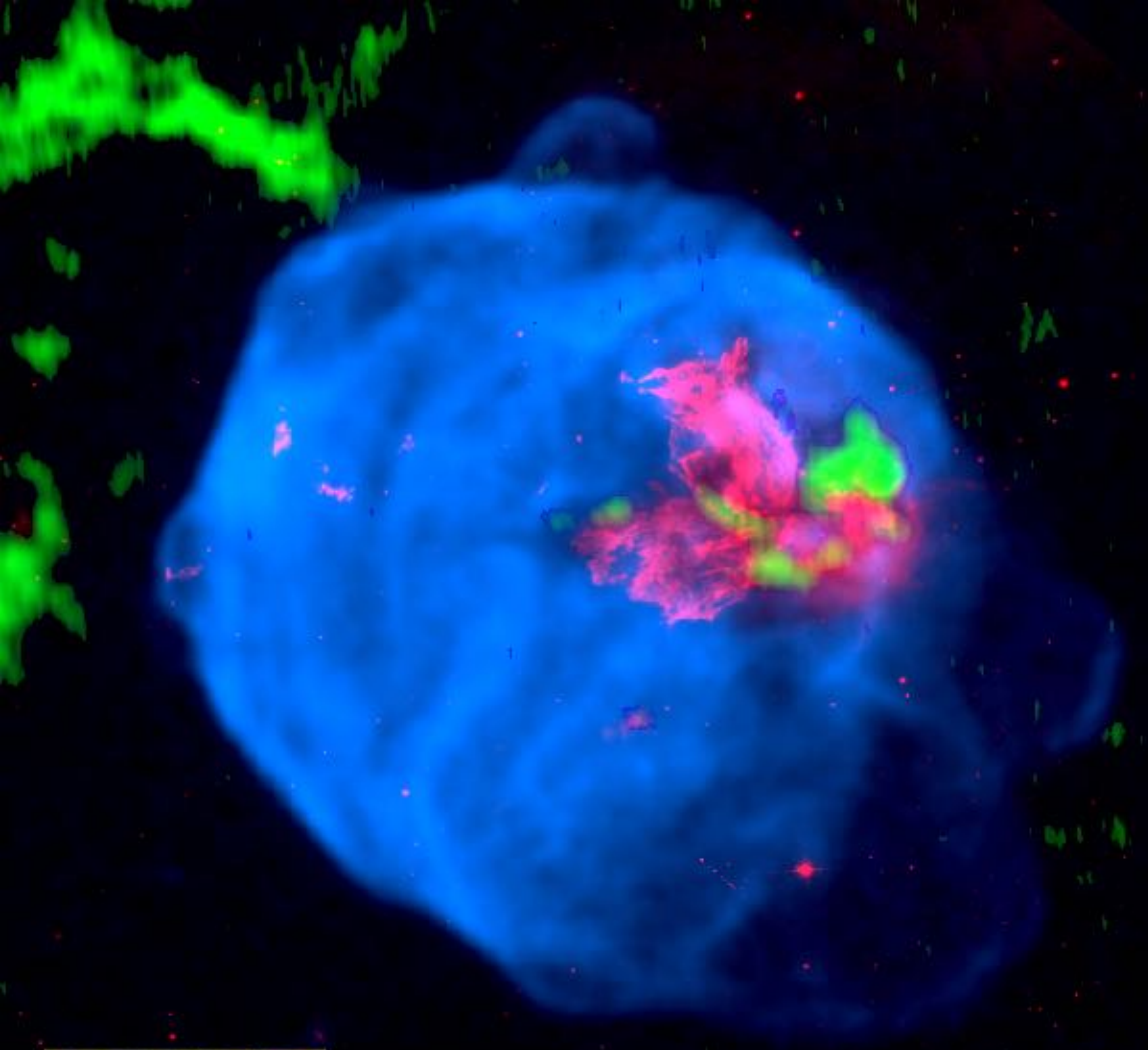
ALMA/45m/ASTE Users Meeting 2021
December 16, 2021, via zoom



ASTE Science I: Supernova Remnant

Hidetoshi Sano (NAOJ)

web URL

LMC SNR N63A

Red: HST Hα
Green: ALMA CO
Blue: Chandra X-ray

Sano et al. (2019), ApJ, **873**, 40

Collaborators

M. D. Filipović, G. Rowell, P. P. Plucinsky,, F. Aharonian, A. Sharda, F. Acero, P. Maggi, C. J. Law, R. Alsaberi, F. Voisin, N. Maxted, J. Vink, E. M. Reynoso, N. McClure-Griffiths, A. Kawamura, T. Minamidani, H. Yamaguchi, N. Mizuno, Y. Fukui, T. Onishi, K. Tachihara, A. Bamba, H. Matsumura, T. Inoue, S. Inutsuka, M. Aruga, Y, Yamane, K. Fujii, K. Tokuda, K. Tsuge, S. Asayama, S. Ishii, D. Iono, T.Kamazaki et al.

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ASTE Science I: Supernova Remnant

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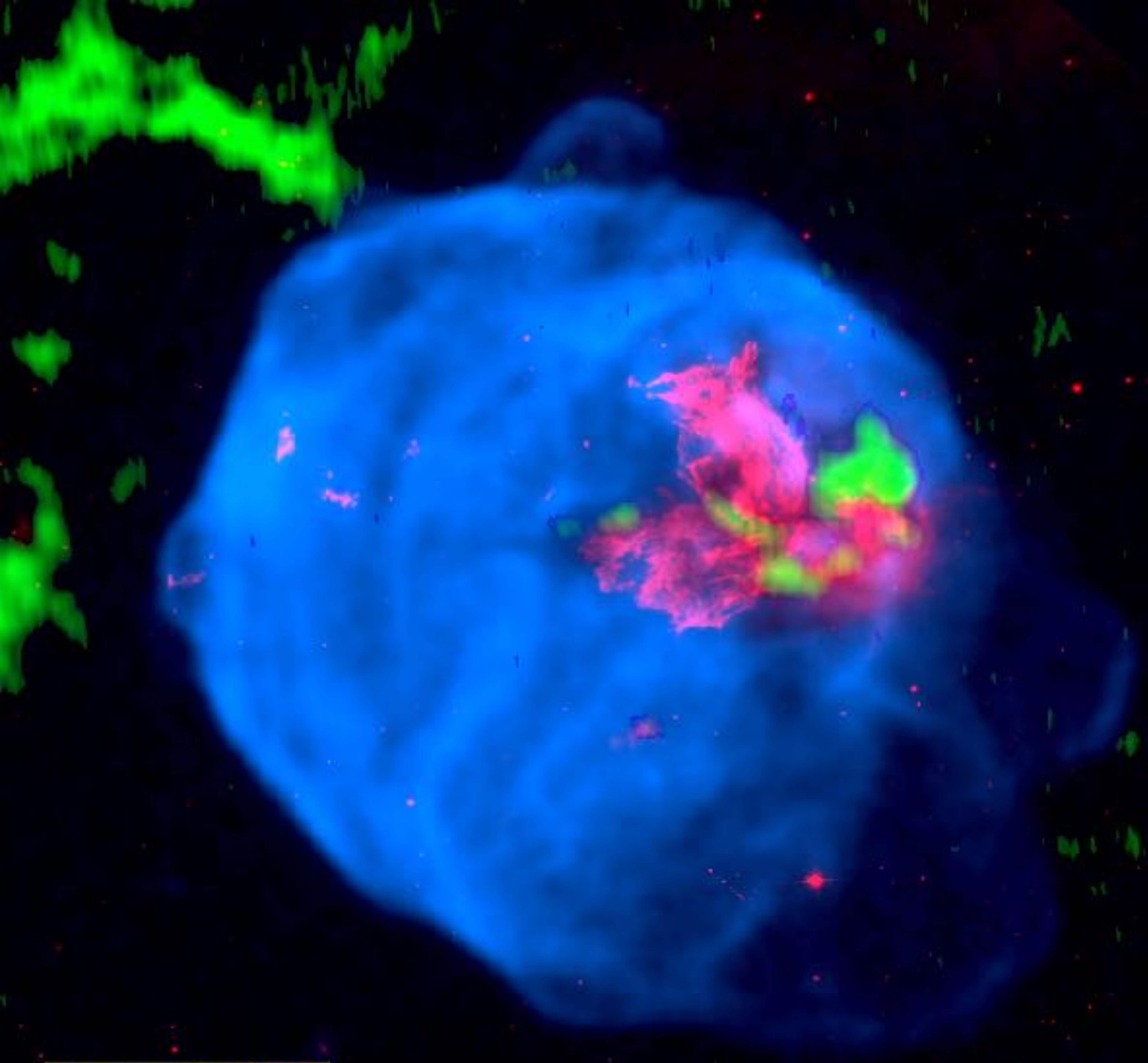

LMC SNR N63A

Red: HST Hα
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web URL

Contents:

1. **Introduction: Why supernova remnants?**
2. **ASTE & ALMA results of the Magellanic SNRs**
3. **Ongoing projects using the atomic carbon line [CI]**

Sano et al. (2018) ApJ, 867, 7; Yamane, Sano et al. (2018) ApJ, 864, 12; Sano et al. (2019a) ApJ, 873, 40; Sano et al. (2019b) ApJ, 881, 85; Sano et al. (2020a) ApJ, 902, 53; Sano & Fukui (2021) ApSS, 366, 58 [review article]; Yamane, Sano et al. (2021) ApJ, 916, 36

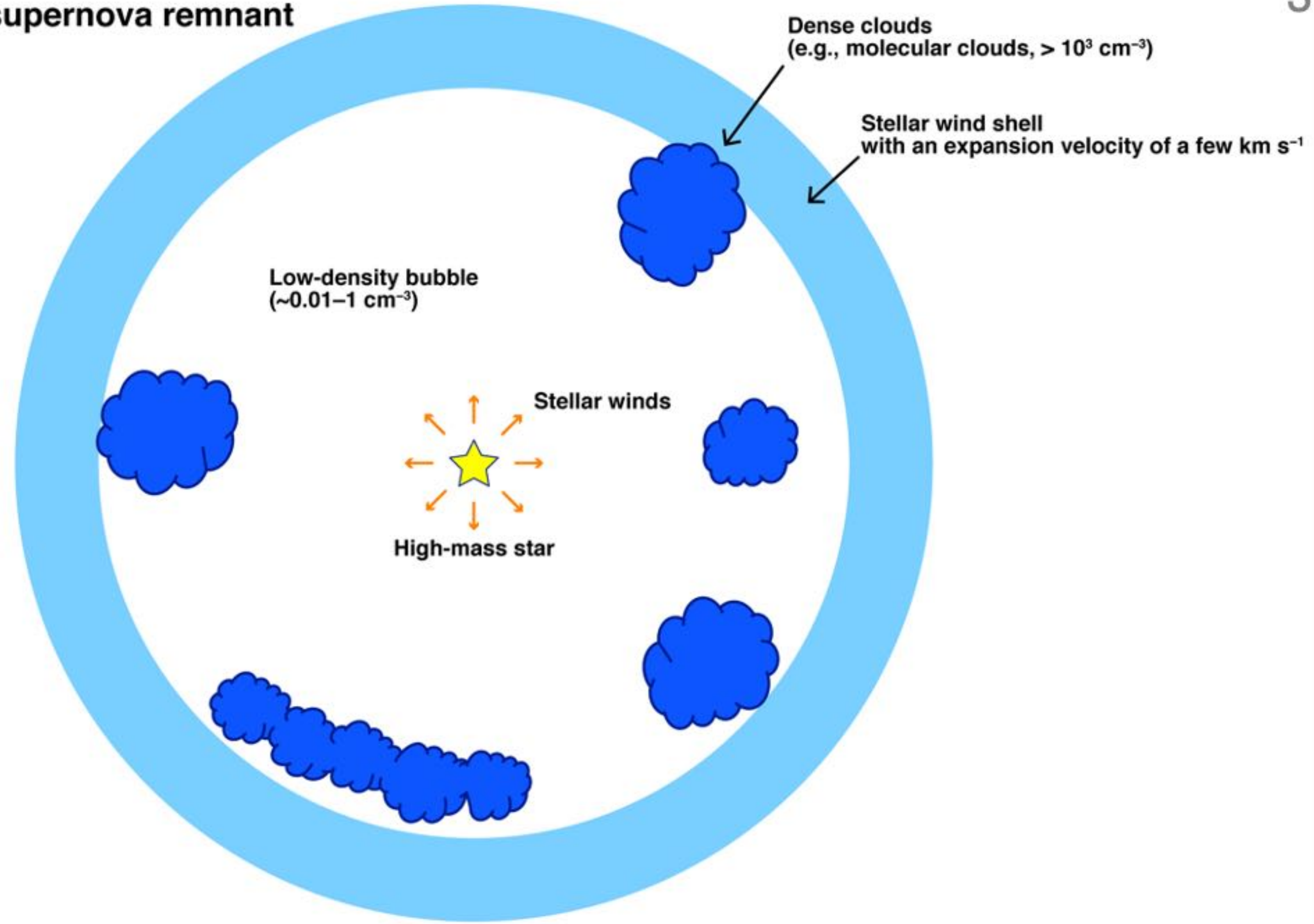
Why supernova remnants?

- Shockwaves, injection of heavy elements, and cosmic-ray production
  → SNRs hold a key to understanding the ISM and galaxy evolution (+ star formation)

- Bright in multi-wavelength from radio to gamma-rays
  → Multi-wavelength studies can reveal physical processes from various aspects

- More than 1000 SNRs in the Local Galaxies
  → We can statistically analyze and reveal their universality and diversity

Physical processes in a supernova remnant



Physical processes in a supernova remnant

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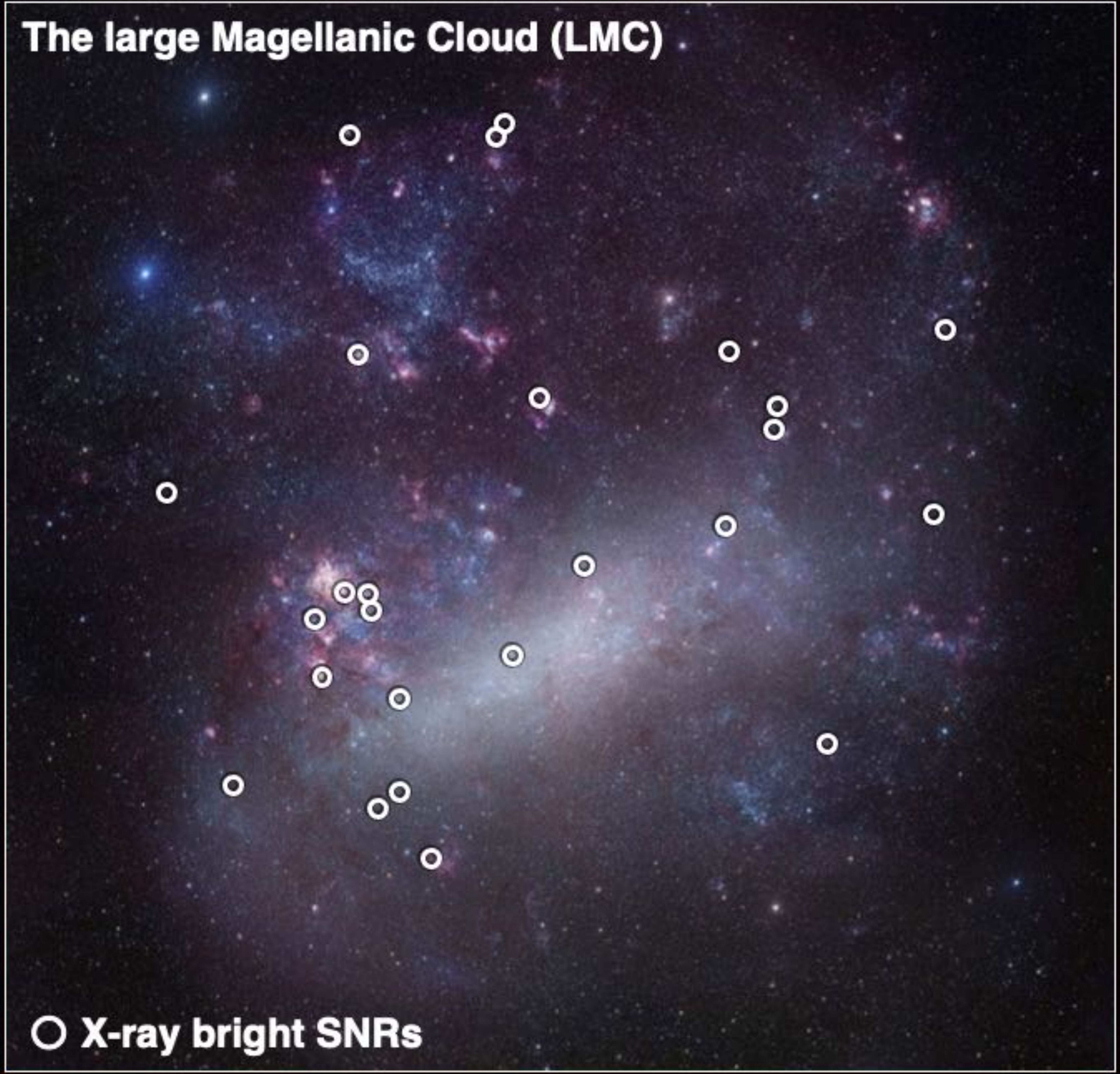
Physical processes in a supernova remnant
Dense clouds
(e.g., molecular clouds, > 10³ cm⁻³)
Forward shock
Stellar wind shell
with an expansion velocity of a few km s⁻¹
Yoshiike et al. (2013)
White (1994)
Partially heating of gas/dust with line broadening
+ chemical evolution of the ISM
Characteristic X-rays
Interstellar gas associated with supernova remnants are essential in understanding the low- and high-energy physical processes in the interstellar medium
Diffusive acceleration
via DSA
Thermal radiation
Gamma-rays
Network of Expanding Shells
GMC Collision
Dense HI Shell
Molecular Cloud
Inutsuka et al. (2015)
Molecular filament formation
by multiple shock compressions
Cosmic-ray proton
Gamma-rays
(Neutral pion decay)
ISM proton
(e.g., molecular clouds)

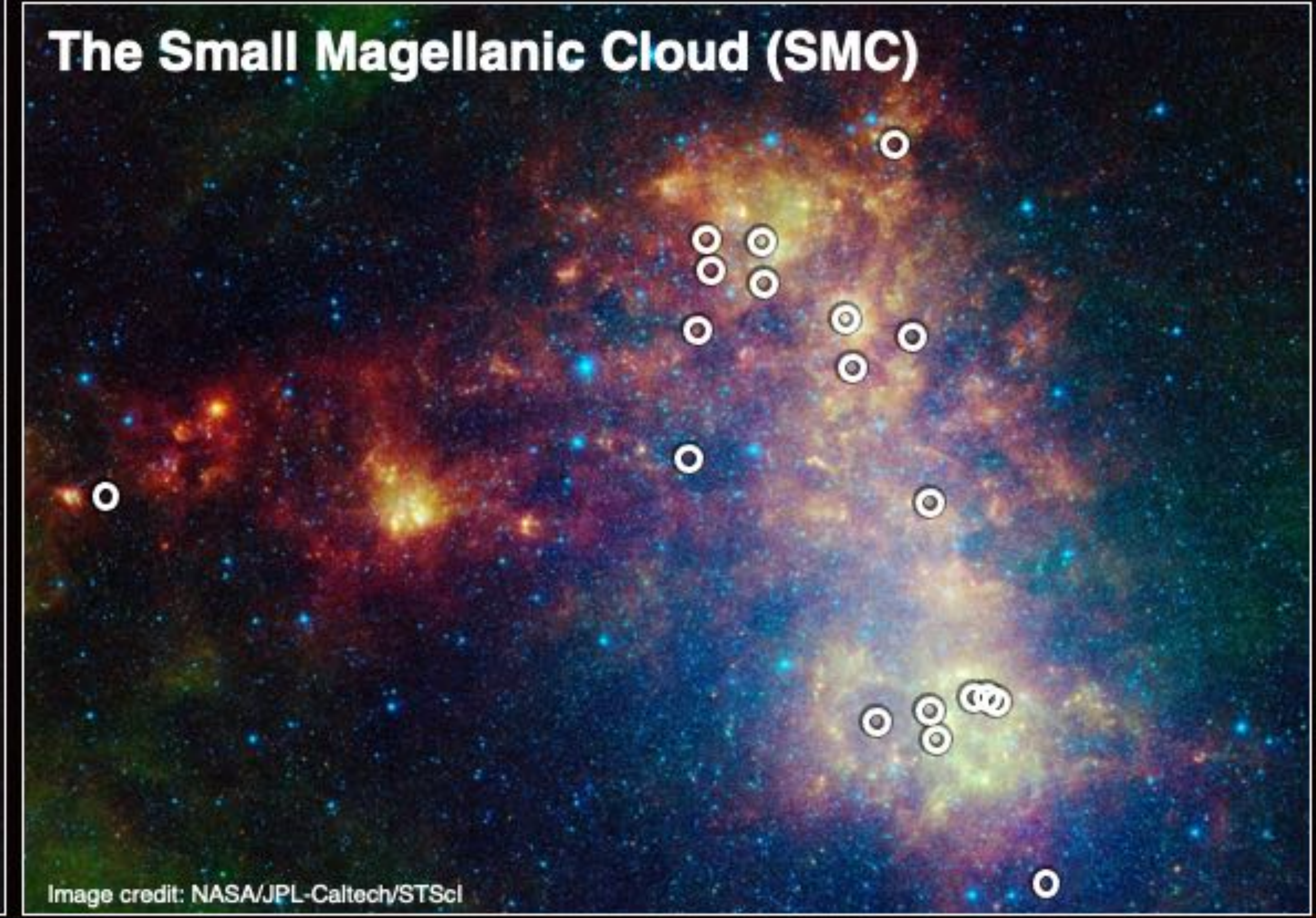
ASTE & ALMA CO observations of the Magellanic SNRs



1. **Well-known distance**
   50 ± 1.3 kpc for the LMC (Pietrzyński et al. 2013)
   ~ 60 kpc for the SMC (Hilditch et al. 2005)

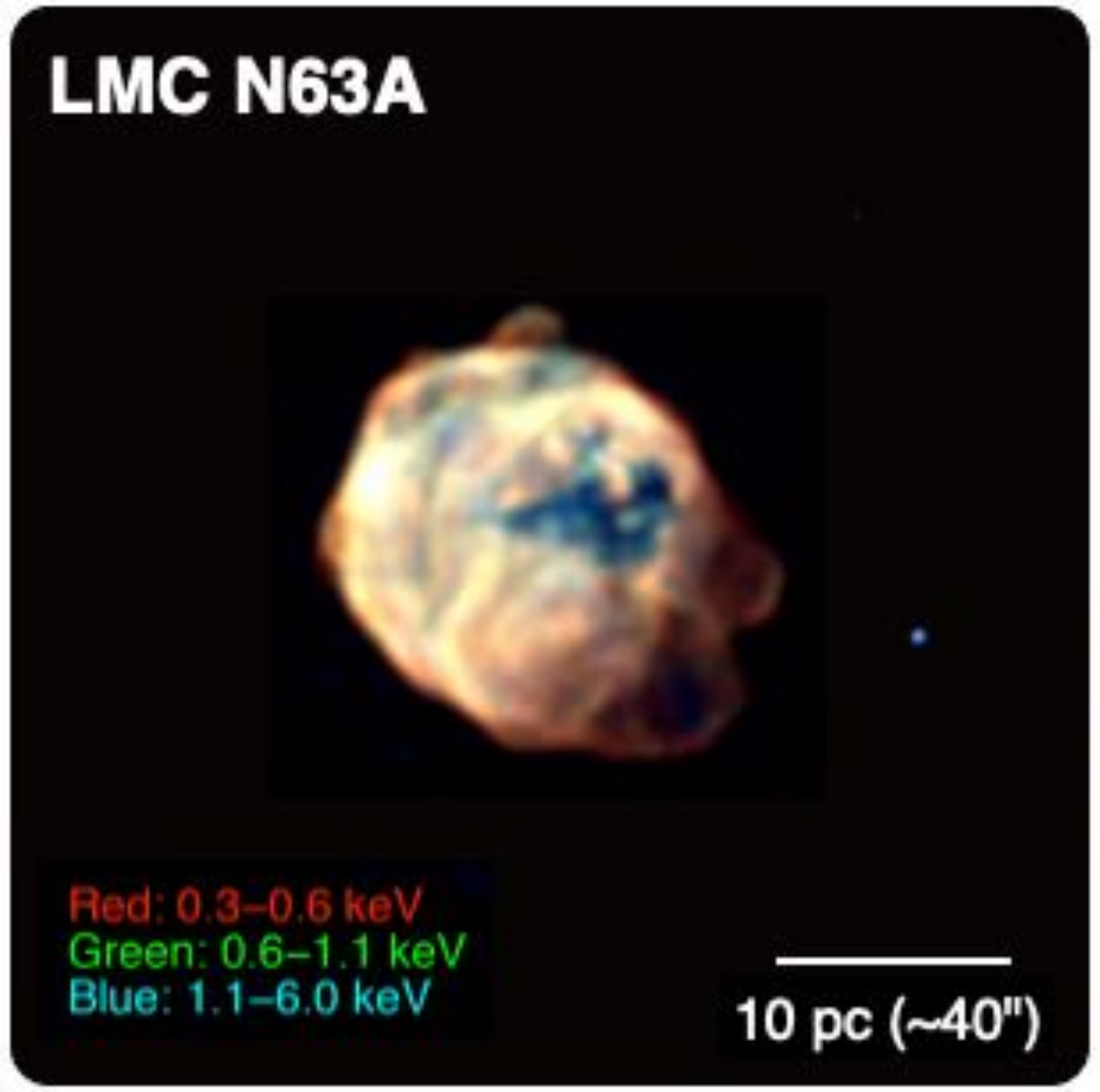
2. **Low ISM metallicity**
   ~0.3–0.5 $Z_\odot$ for the LMC (Westerlund 1997)
   ~0.05–0.2 $Z_\odot$ for the SMC, (Russell & Dopita 1992; Rolleston et al. 1999)

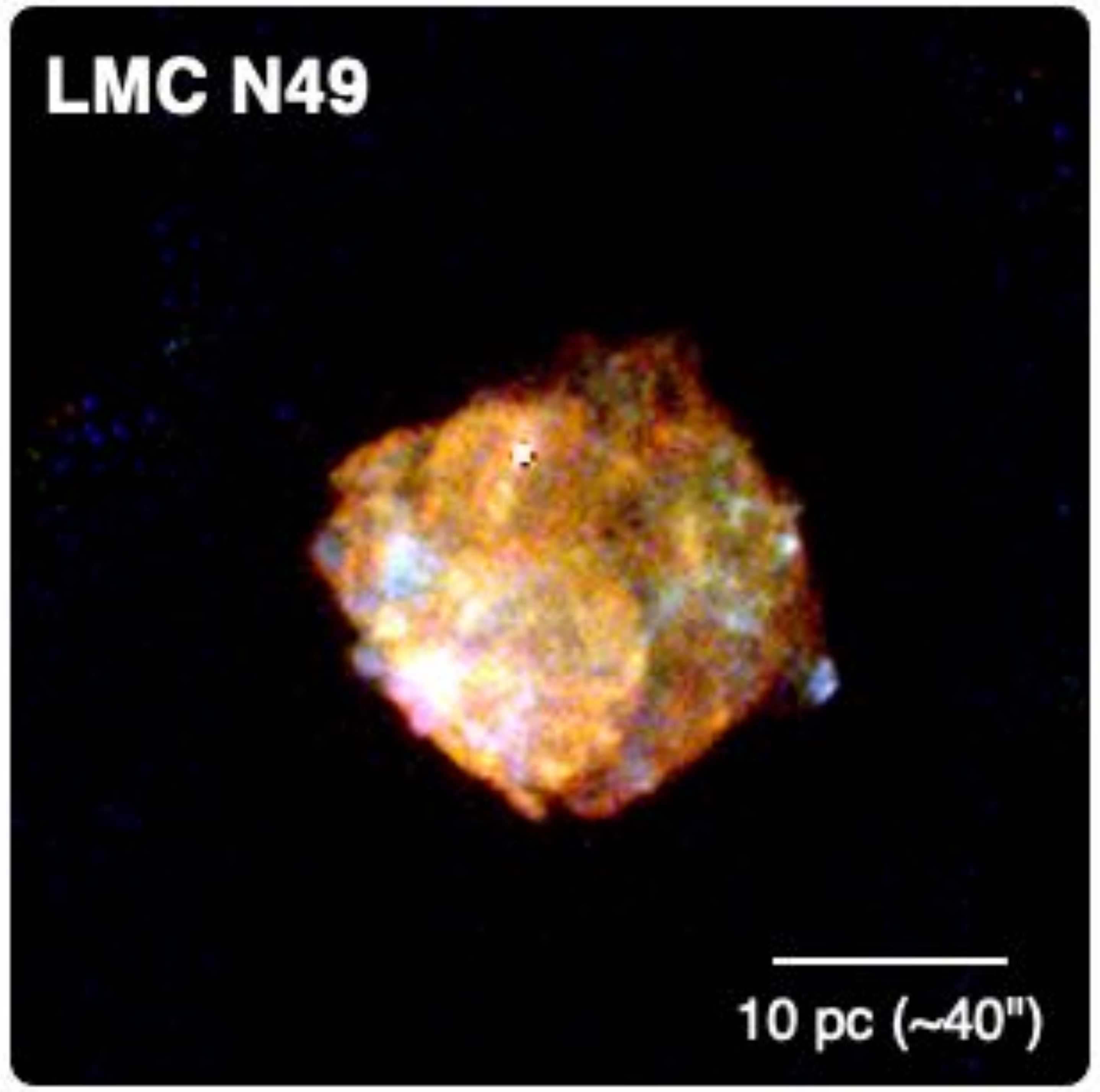
3. **Smaller contamination along the line of sight**

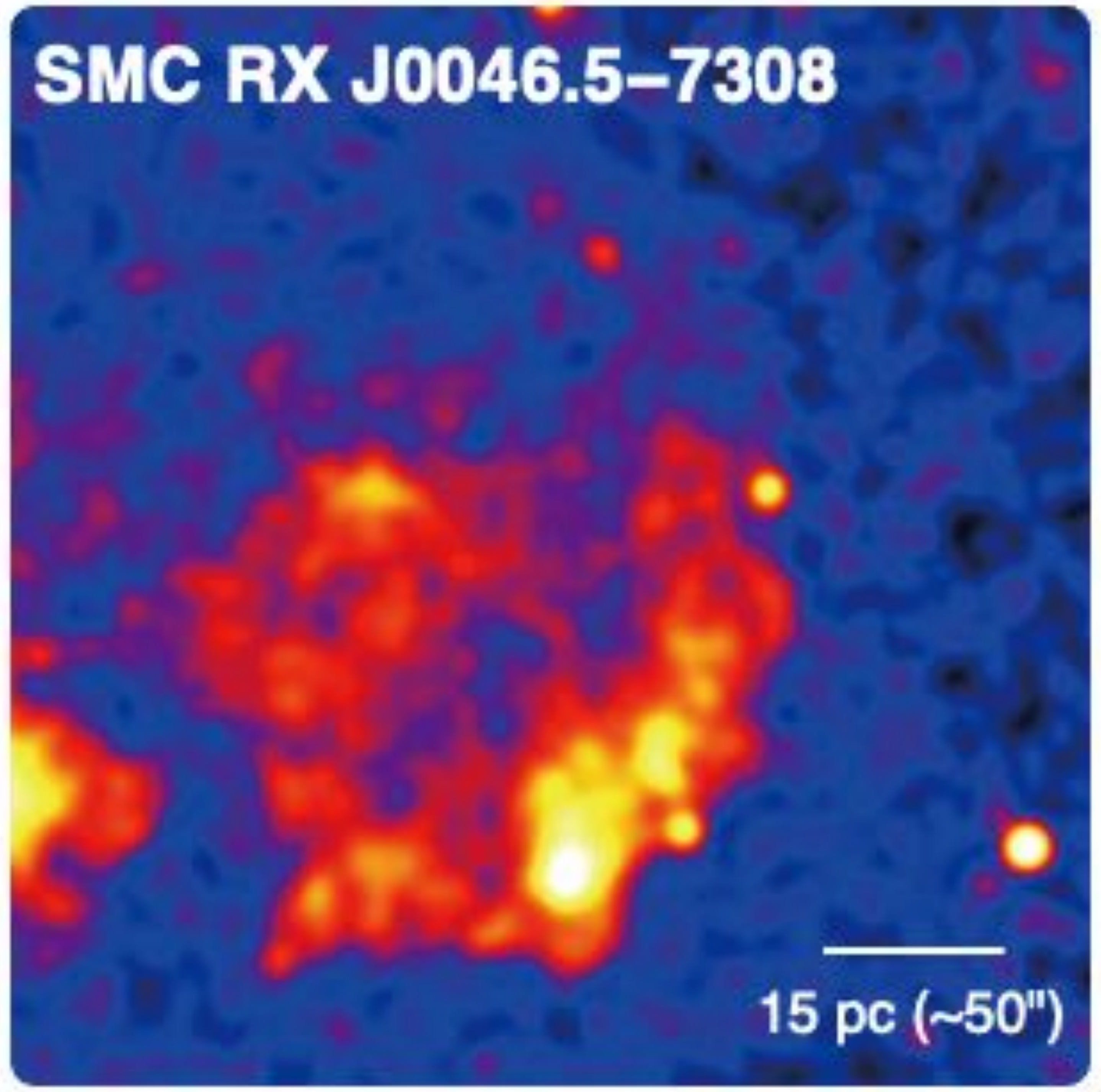


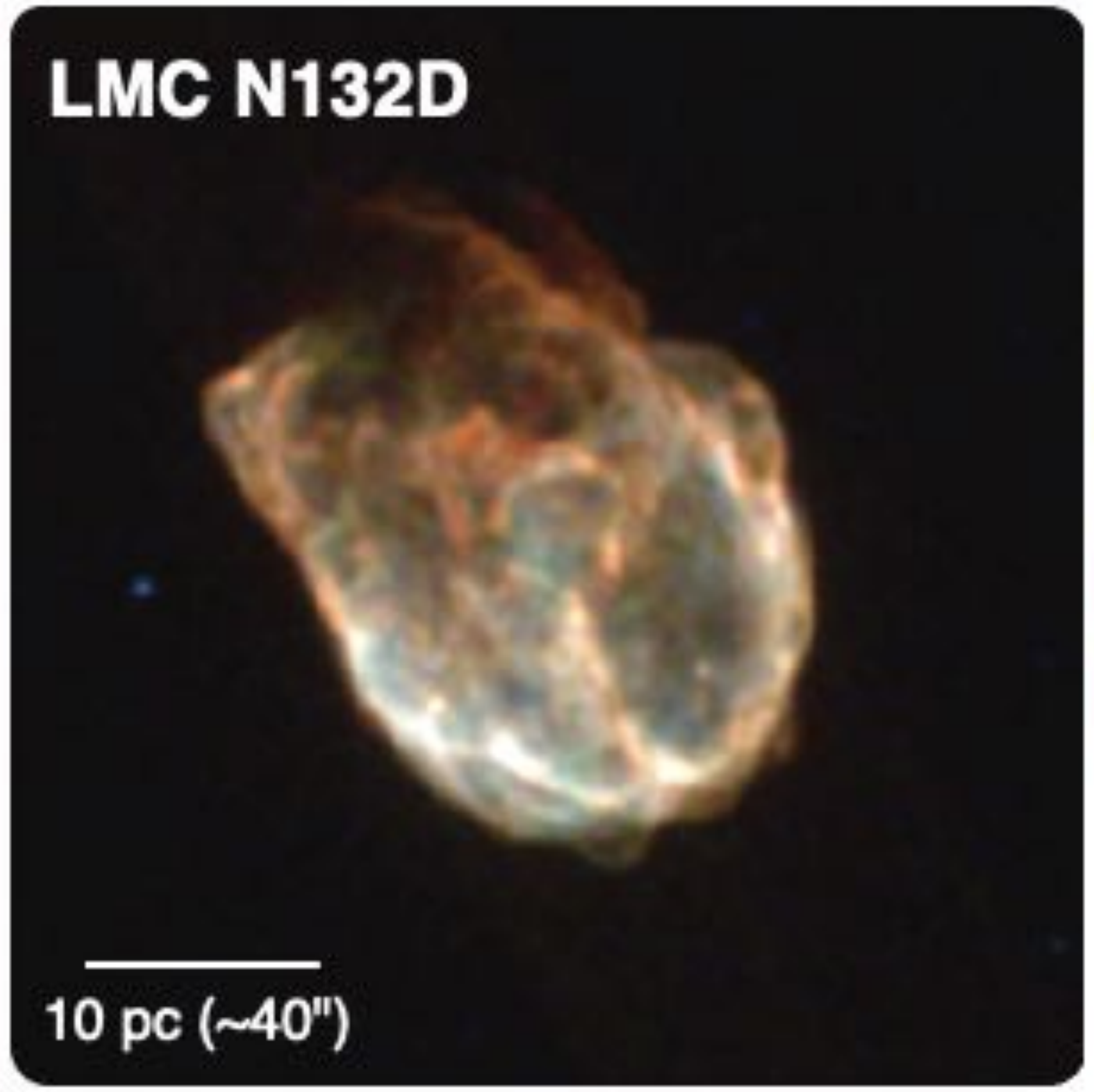
X-ray views of the Magellanic SNRs

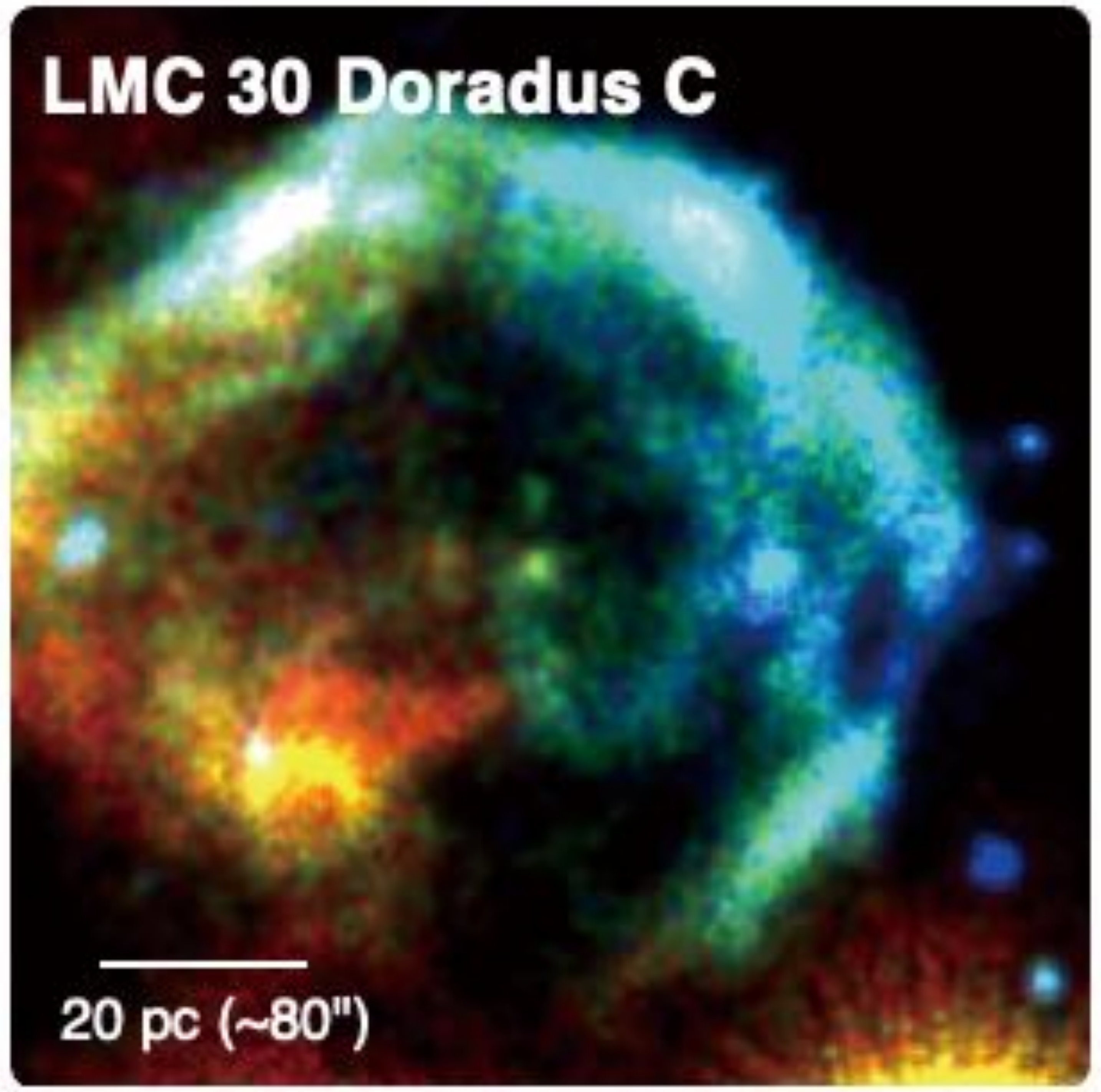
Images: X-ray images obtained using Chandra or XMM-Newton

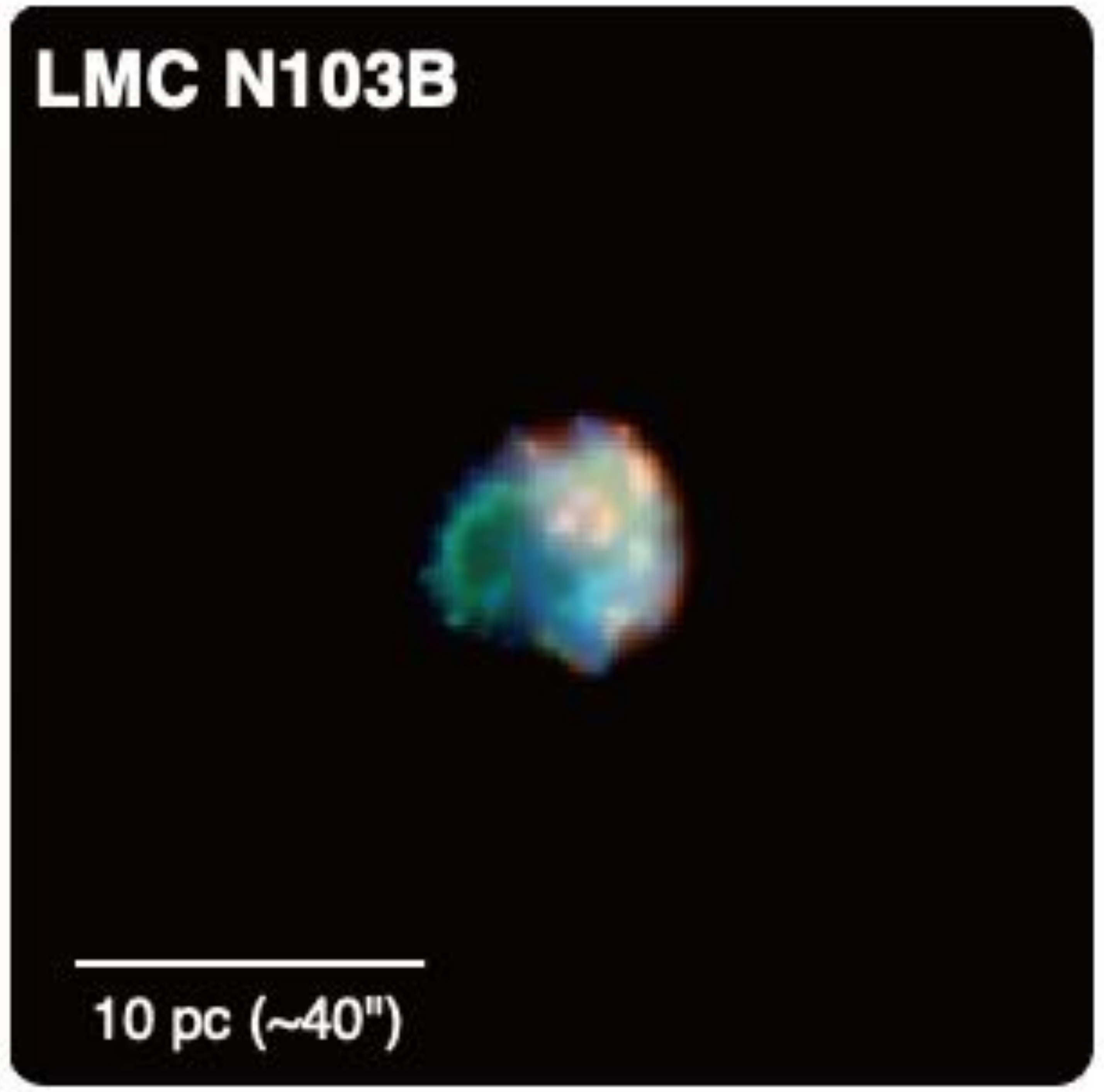








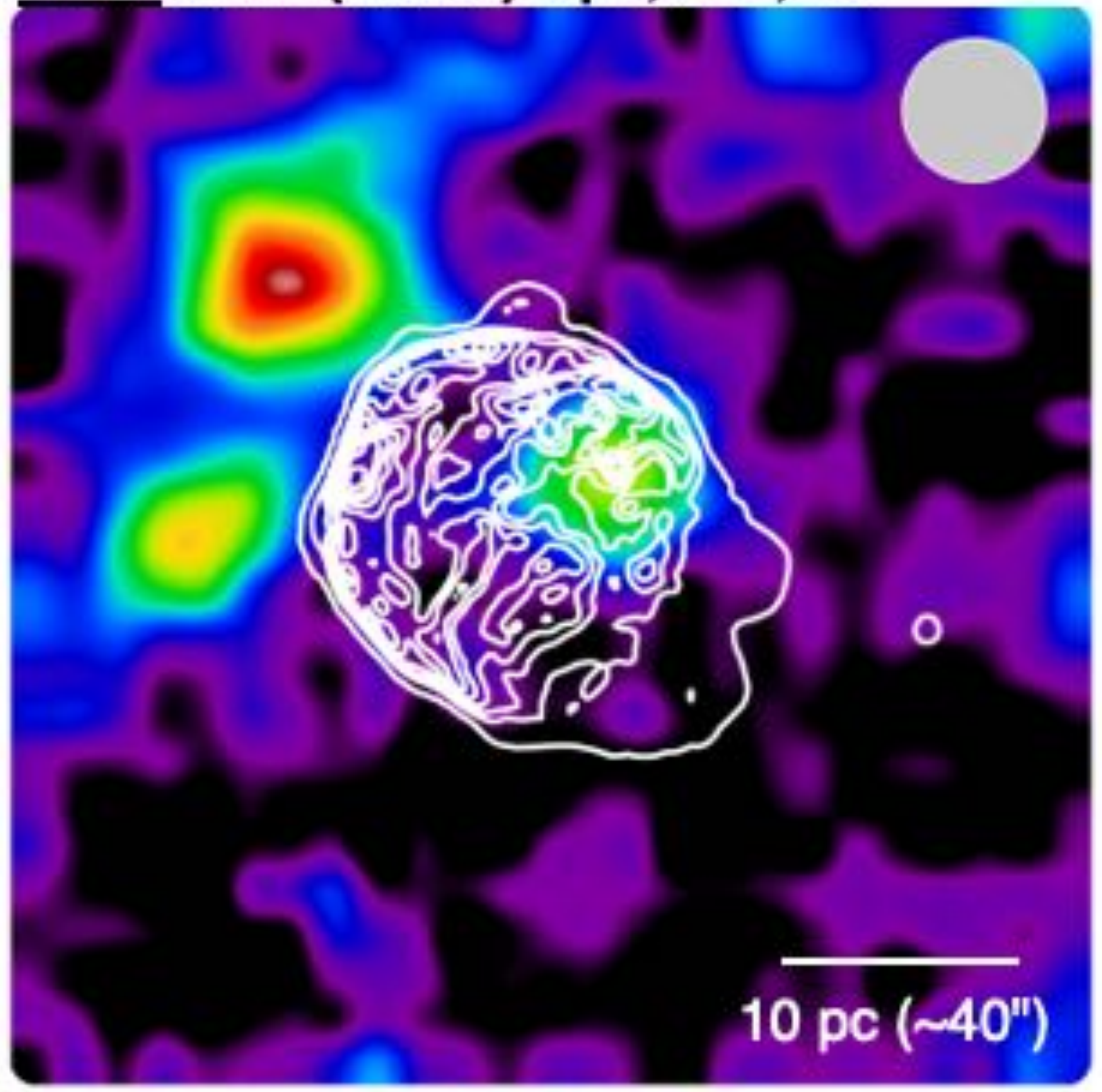




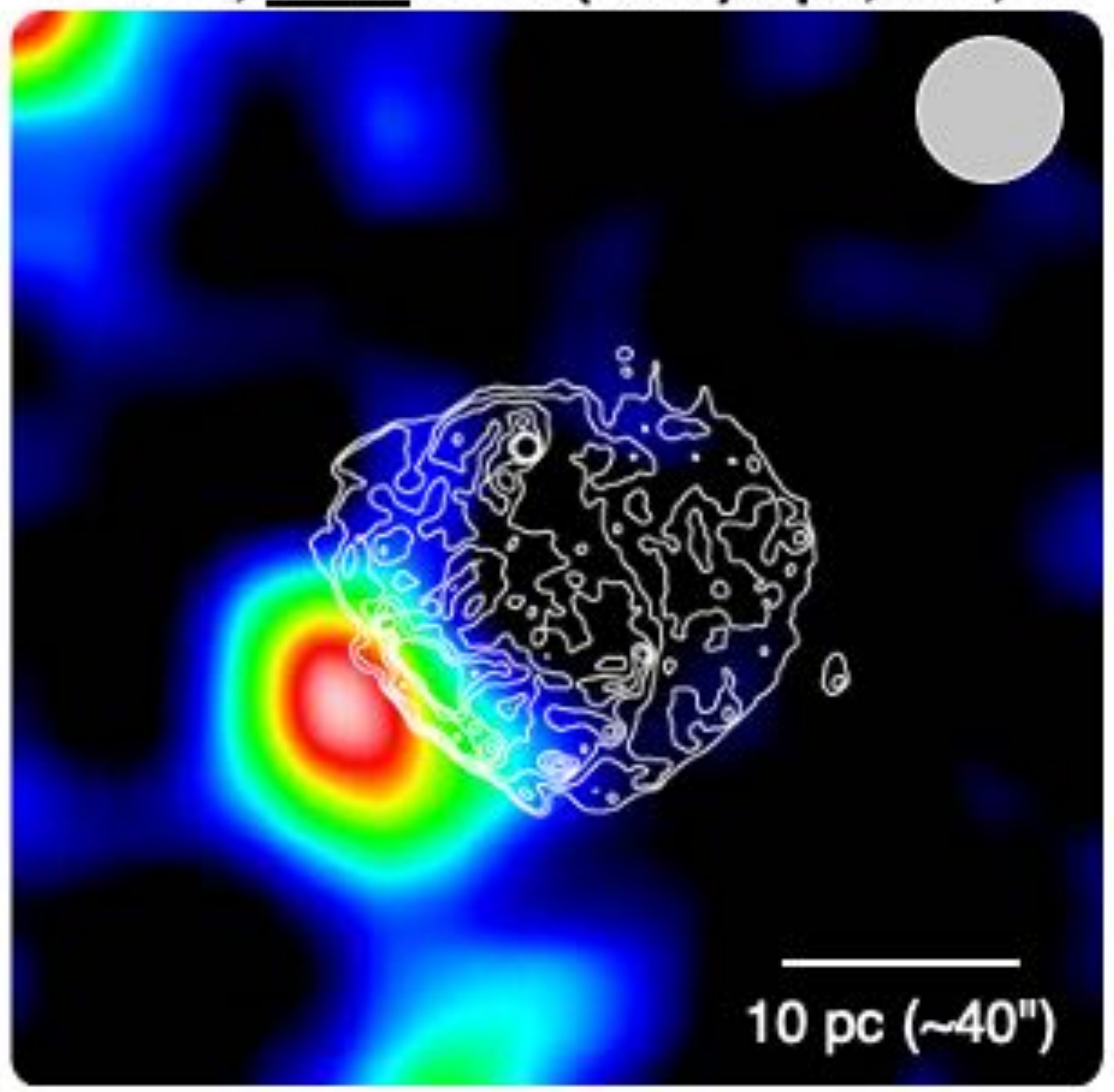
ASTE CO results toward the Magellanic SNRs

Image: ASTE ^{12}CO(J = 3–2)
Contours: *Chandra* X-rays

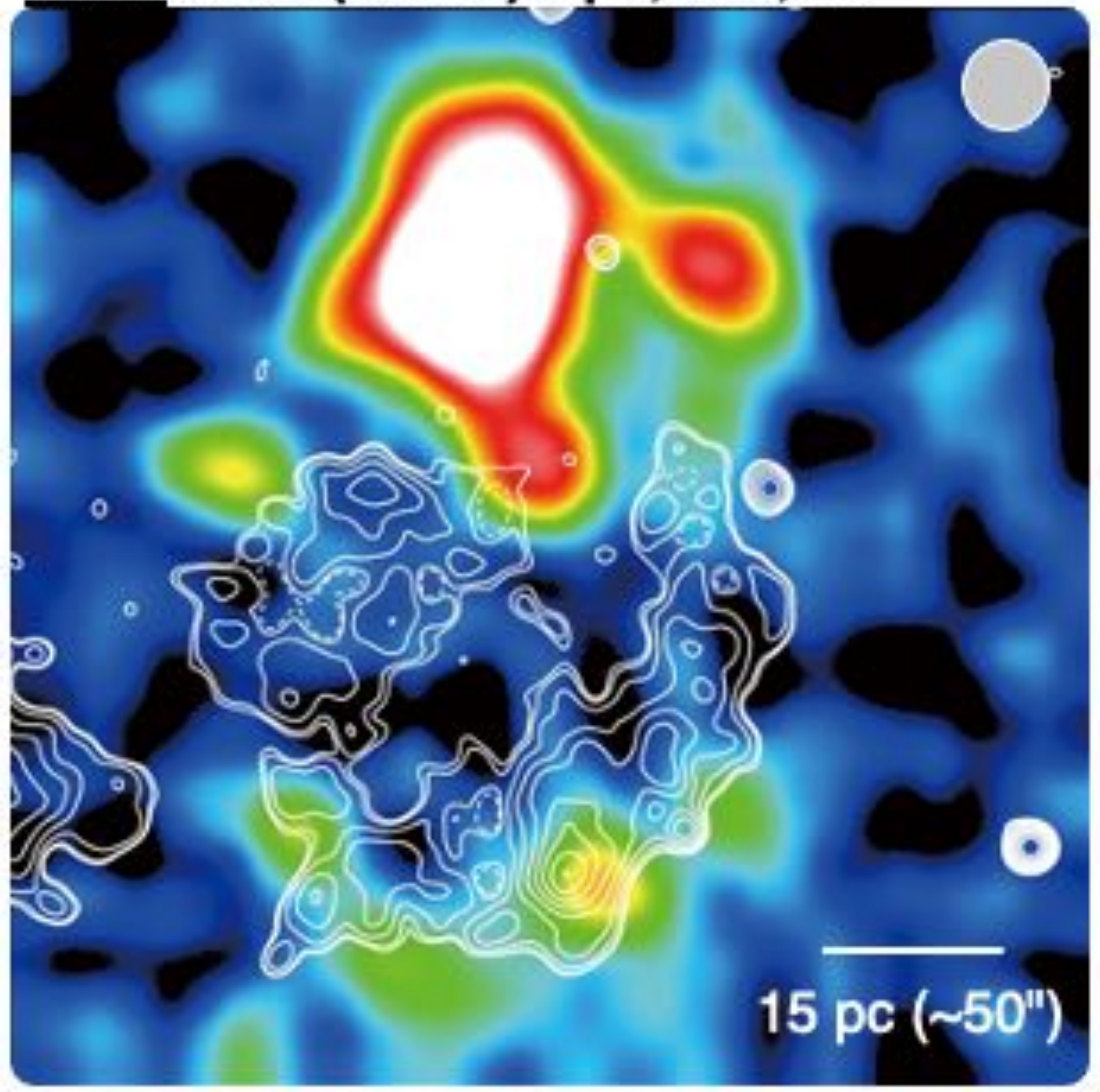
Sano et al. (2019a) ApJ, 873, 40

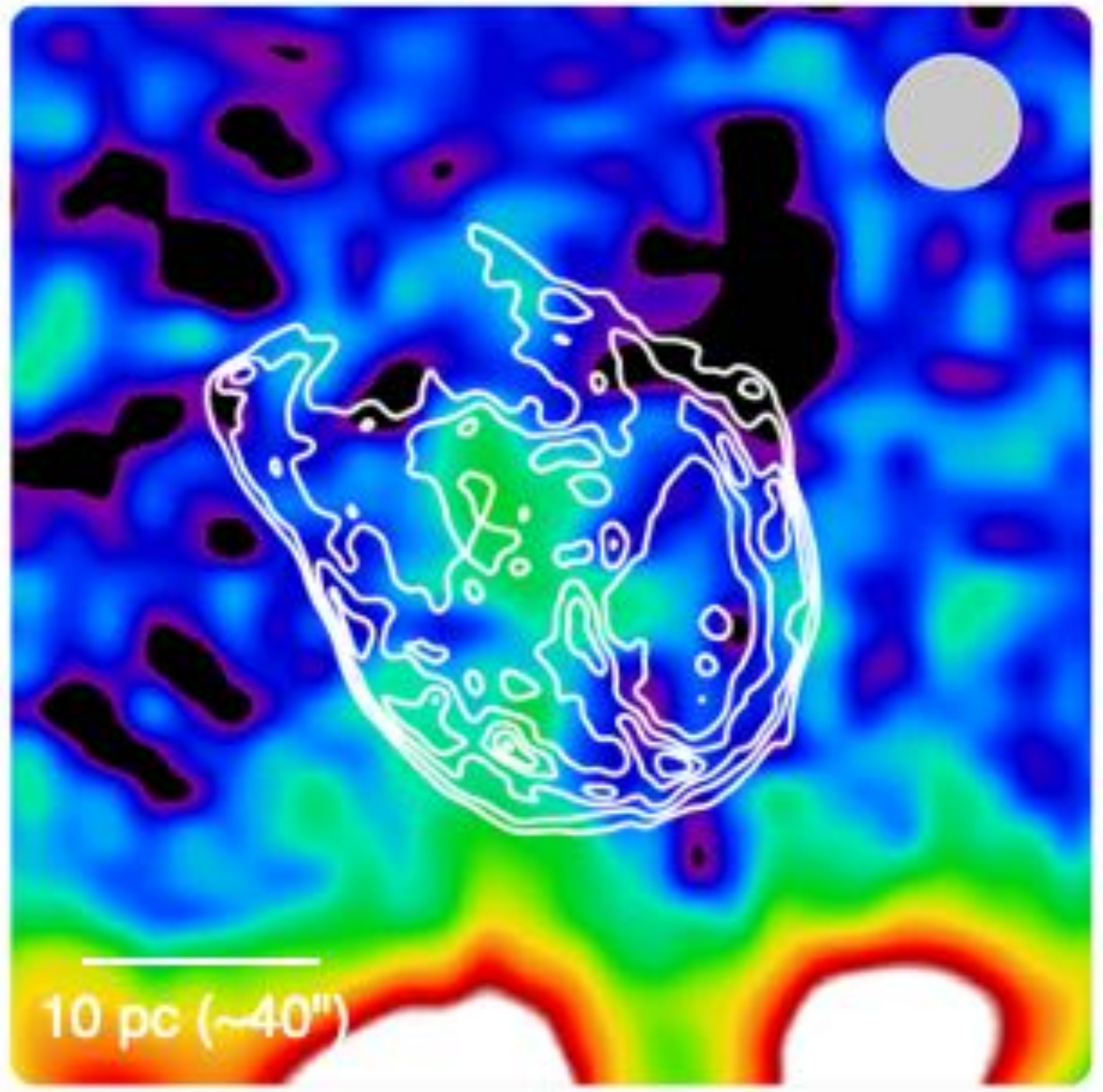


Yamane, Sano et al. (2018) ApJ, 864, 12

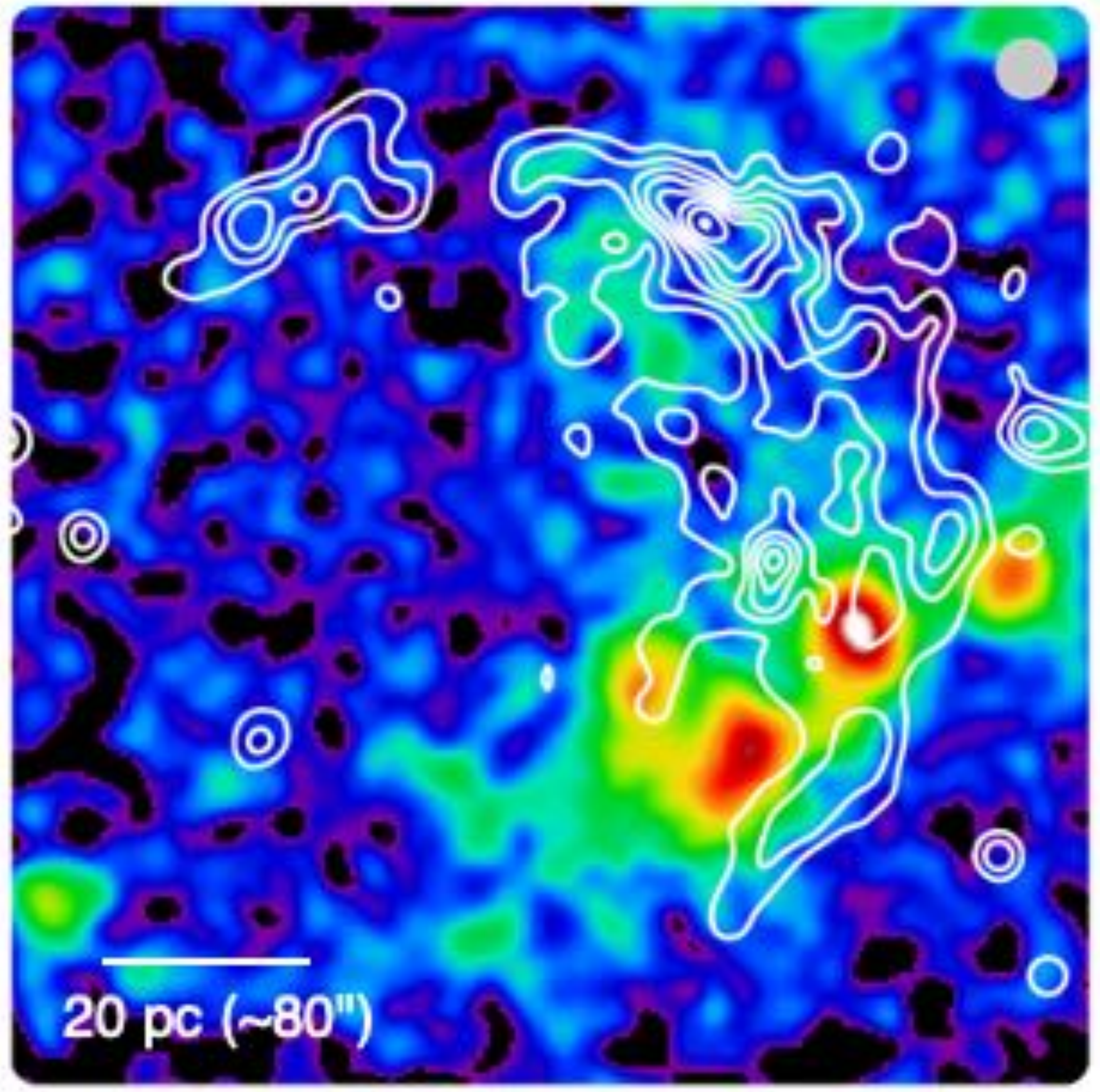


Sano et al. (2019b) ApJ, 881, 85

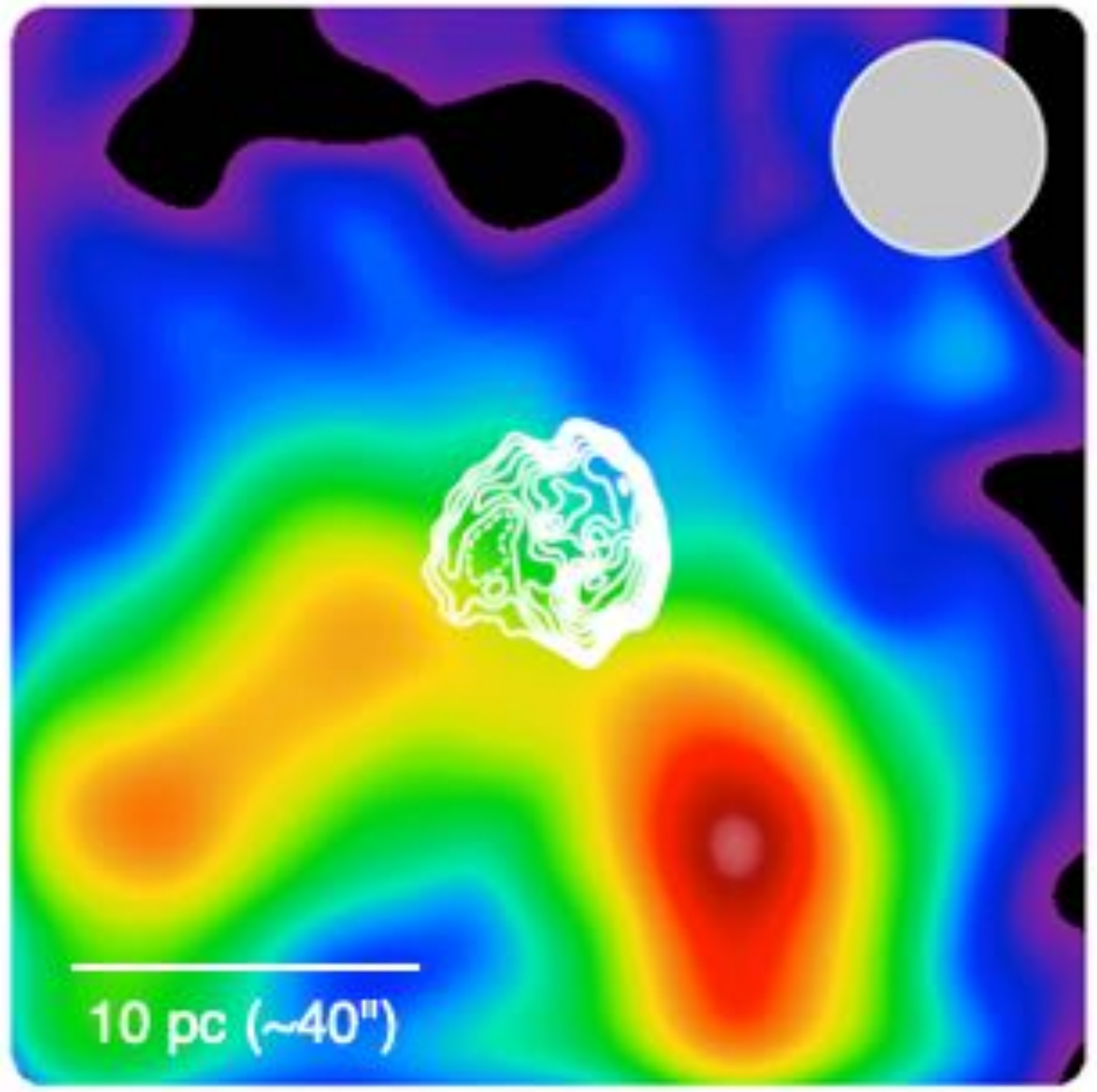




Sano et al. (2020) ApJ, 902, 53



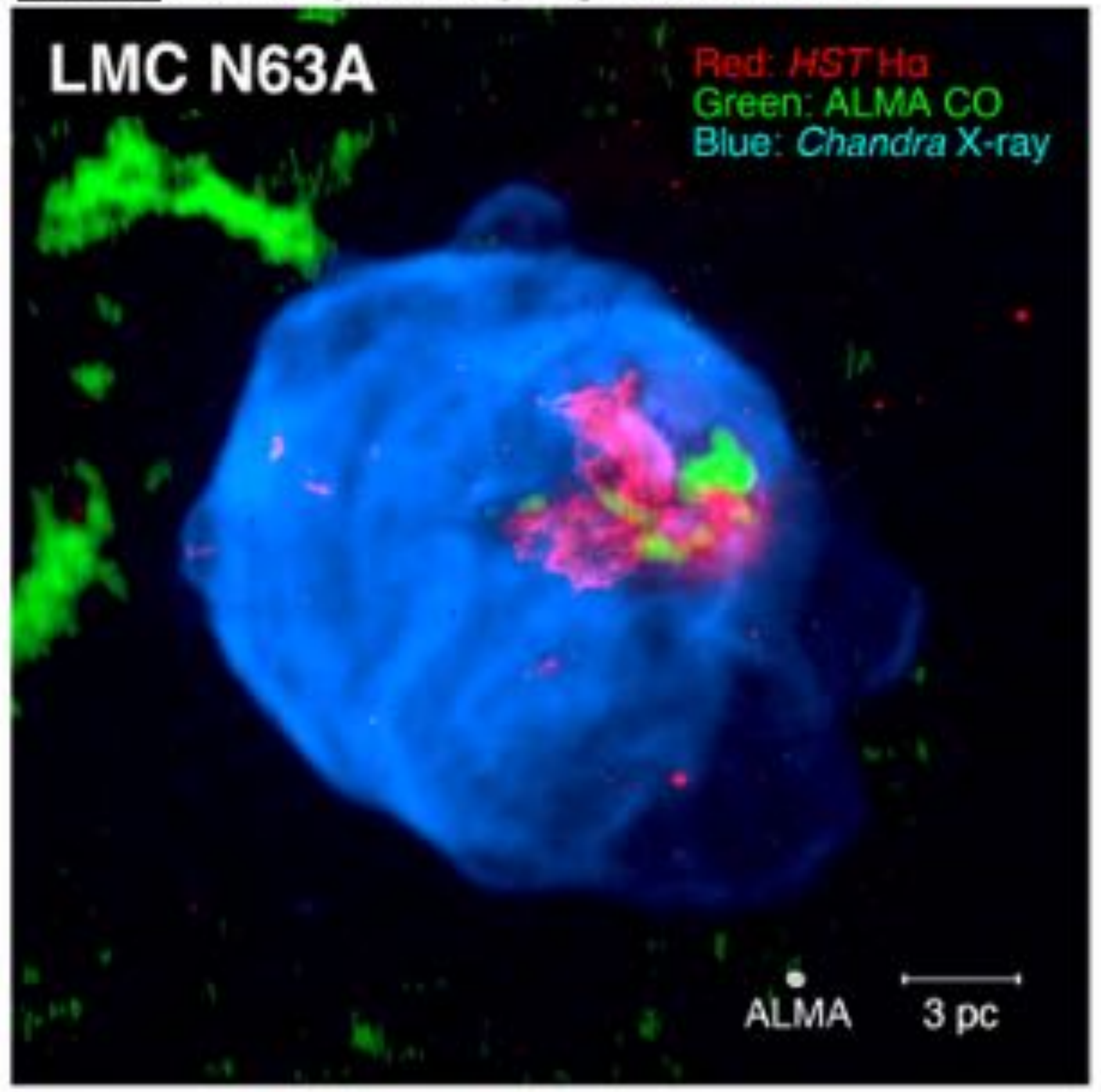
Yamane, Sano et al. (2021) ApJ, 916, 36



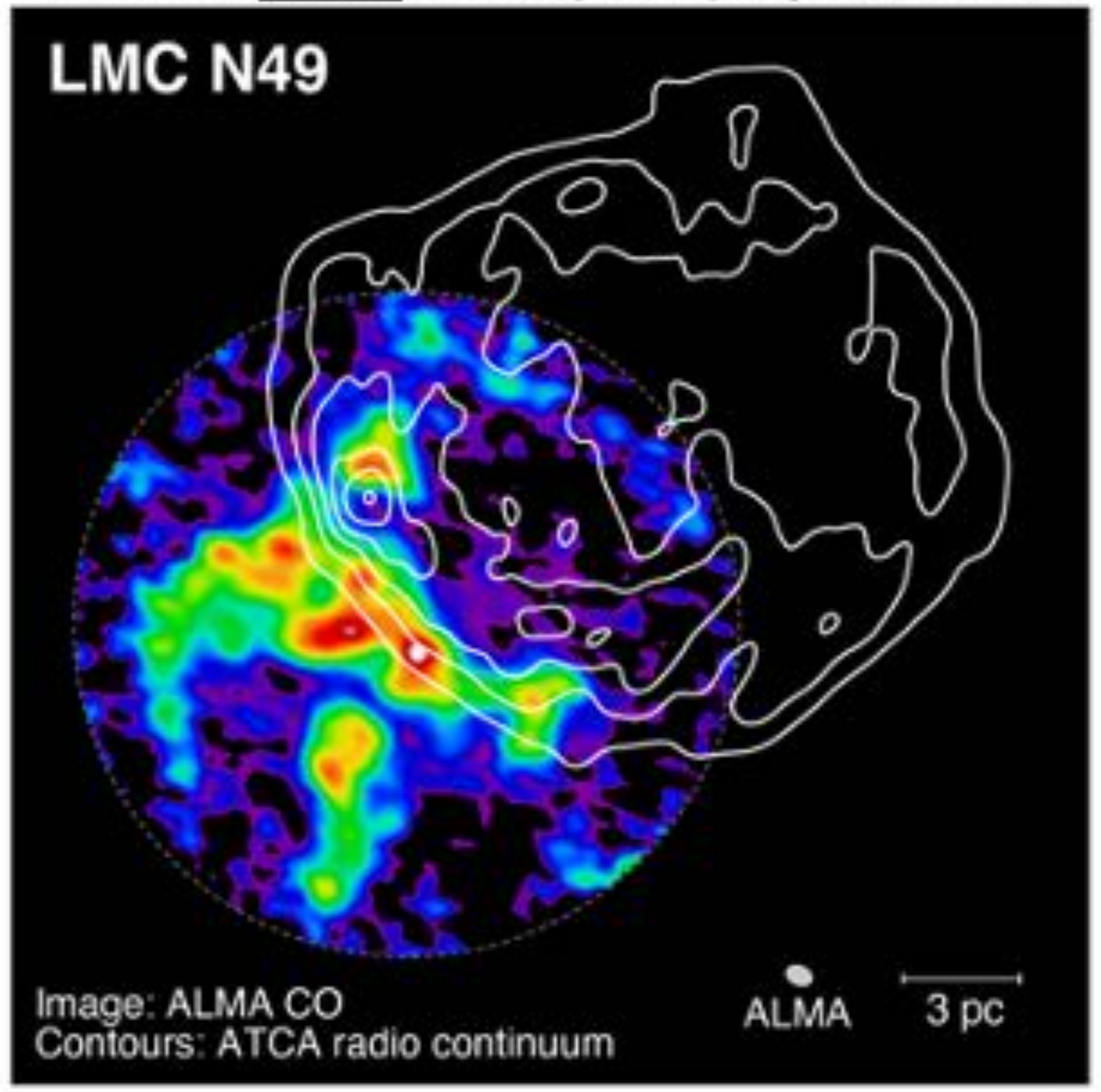
Sano et al. (2018) ApJ, 867, 7

ALMA CO results toward the Magellanic SNRs

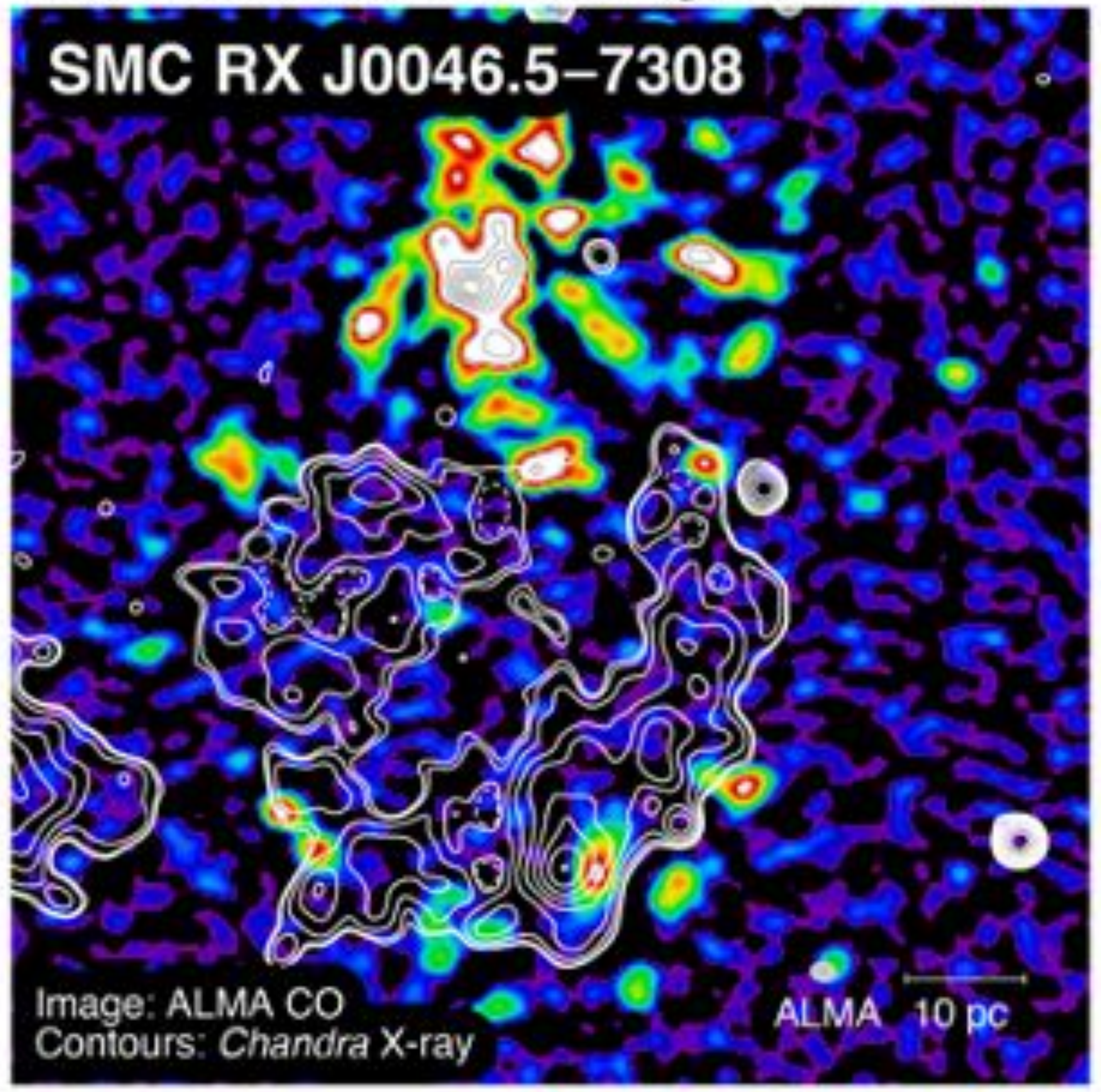
Sano et al. (2019a) ApJ, 873, 40

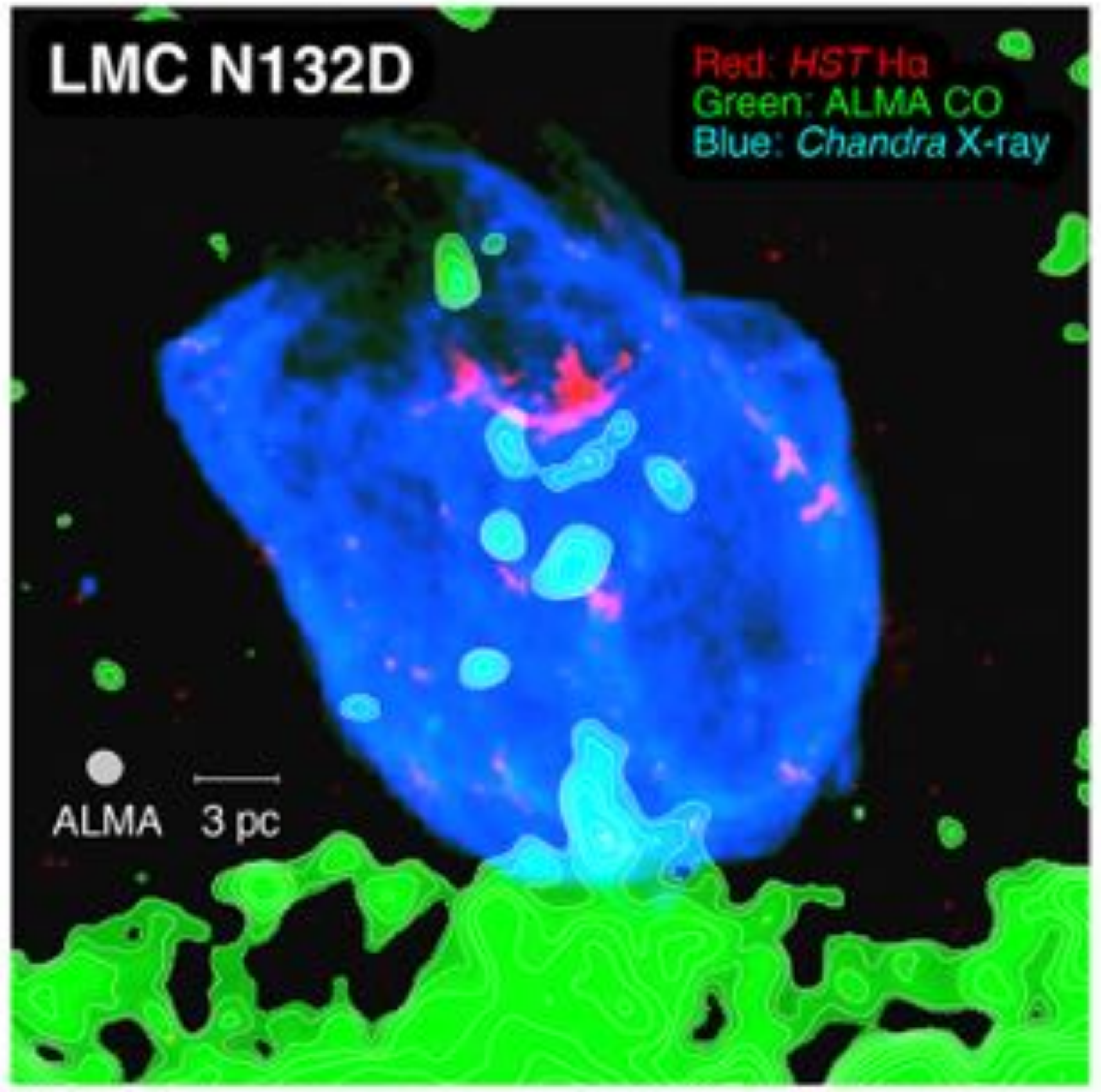


Yamane, Sano et al. (2018) ApJ, 864, 12



From archival data using ACA Band 6





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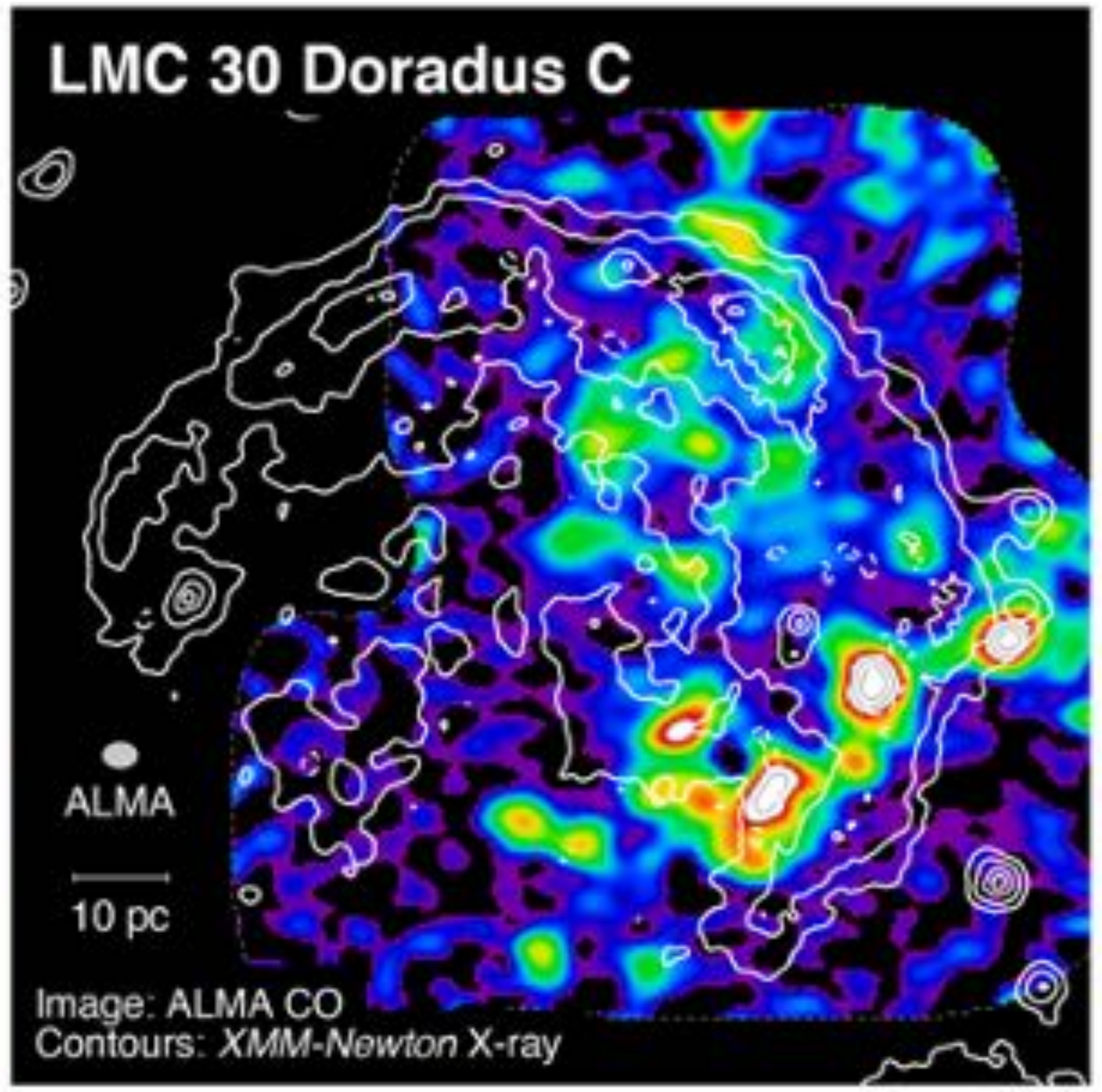
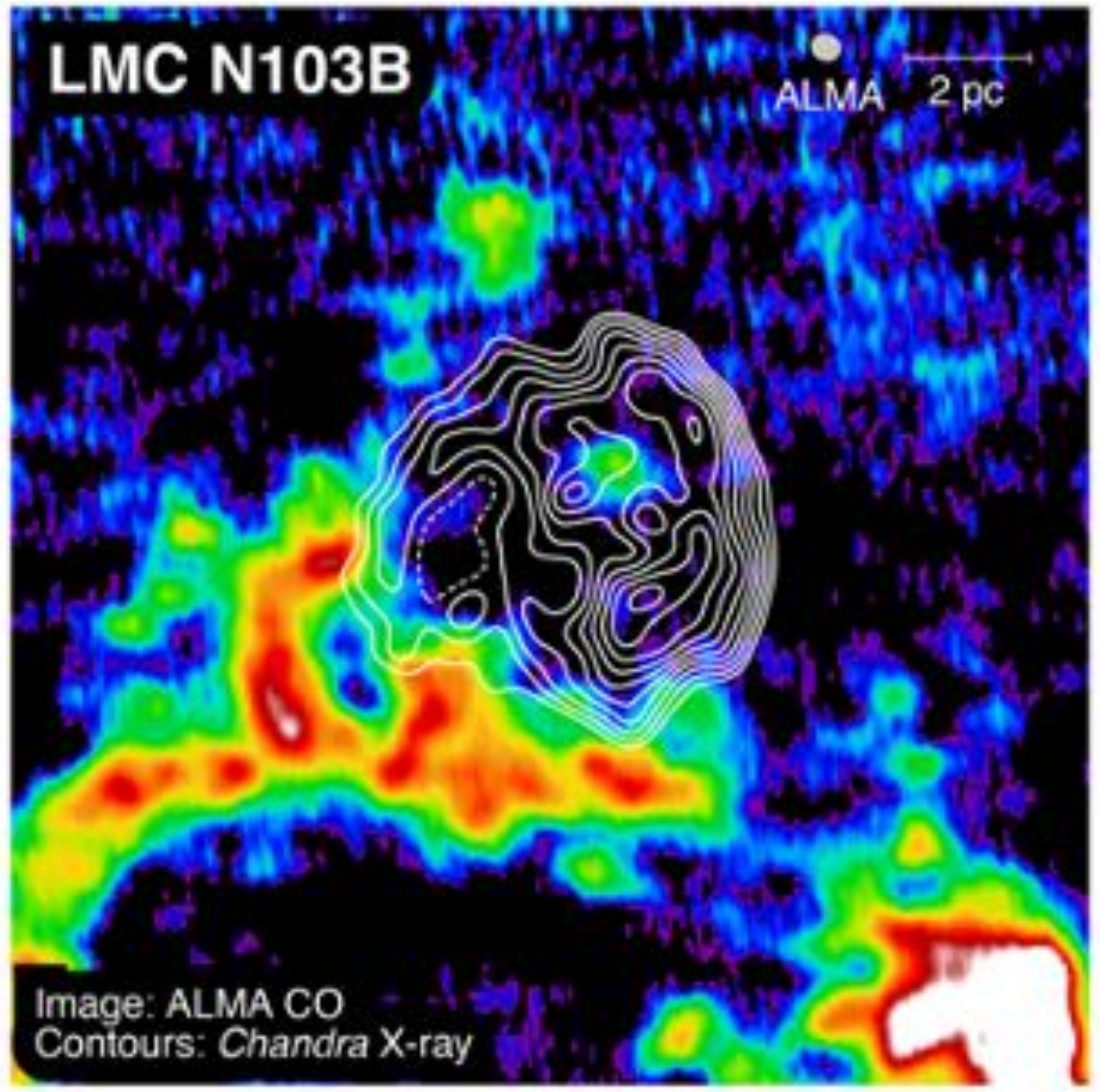
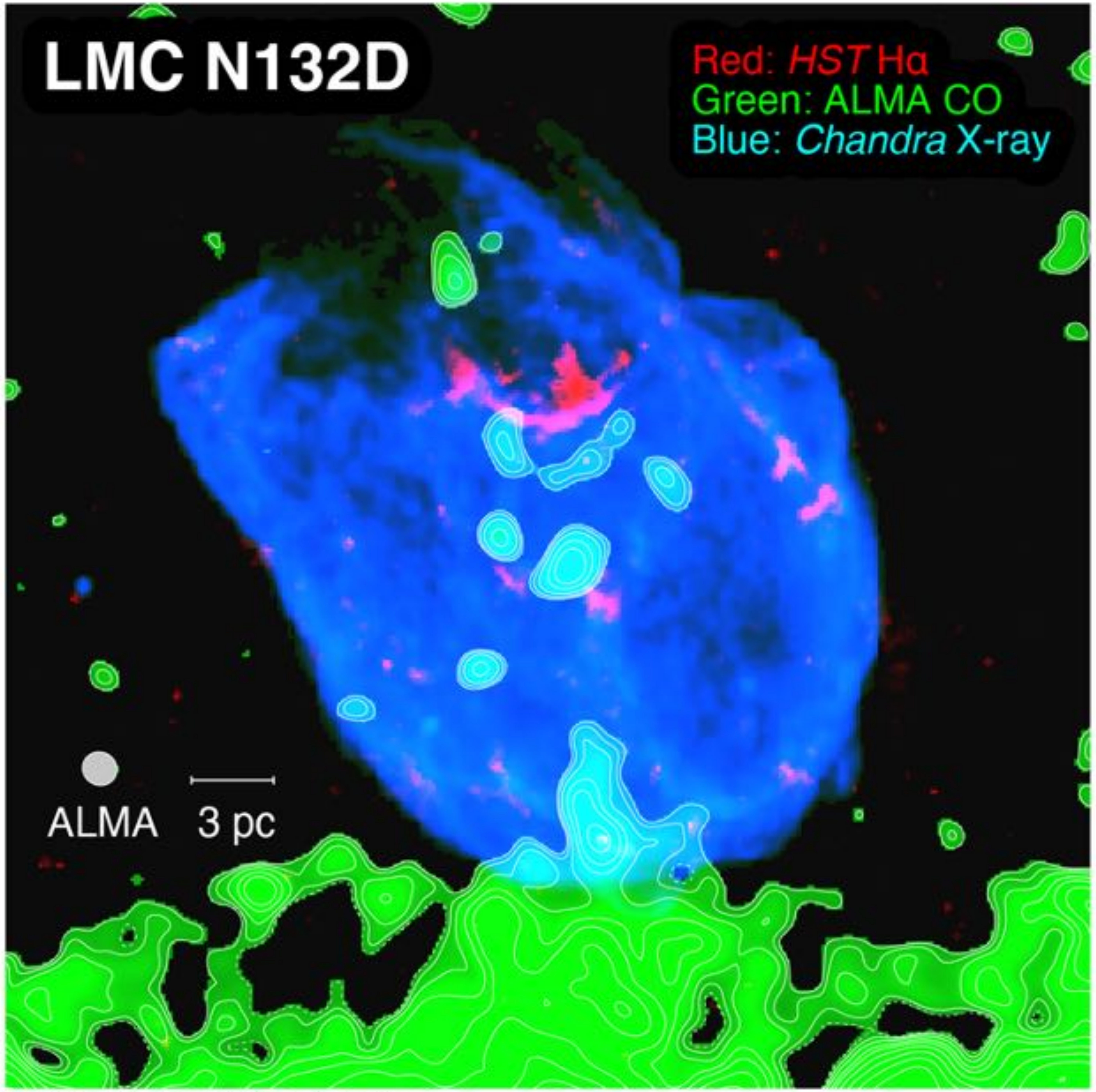


Yamane, Sano et al. (2021) ApJ, 916, 36



Sano et al. (2018) ApJ, 867, 7

CO J = 3–2/1–0 ratio confirms physical association of clouds



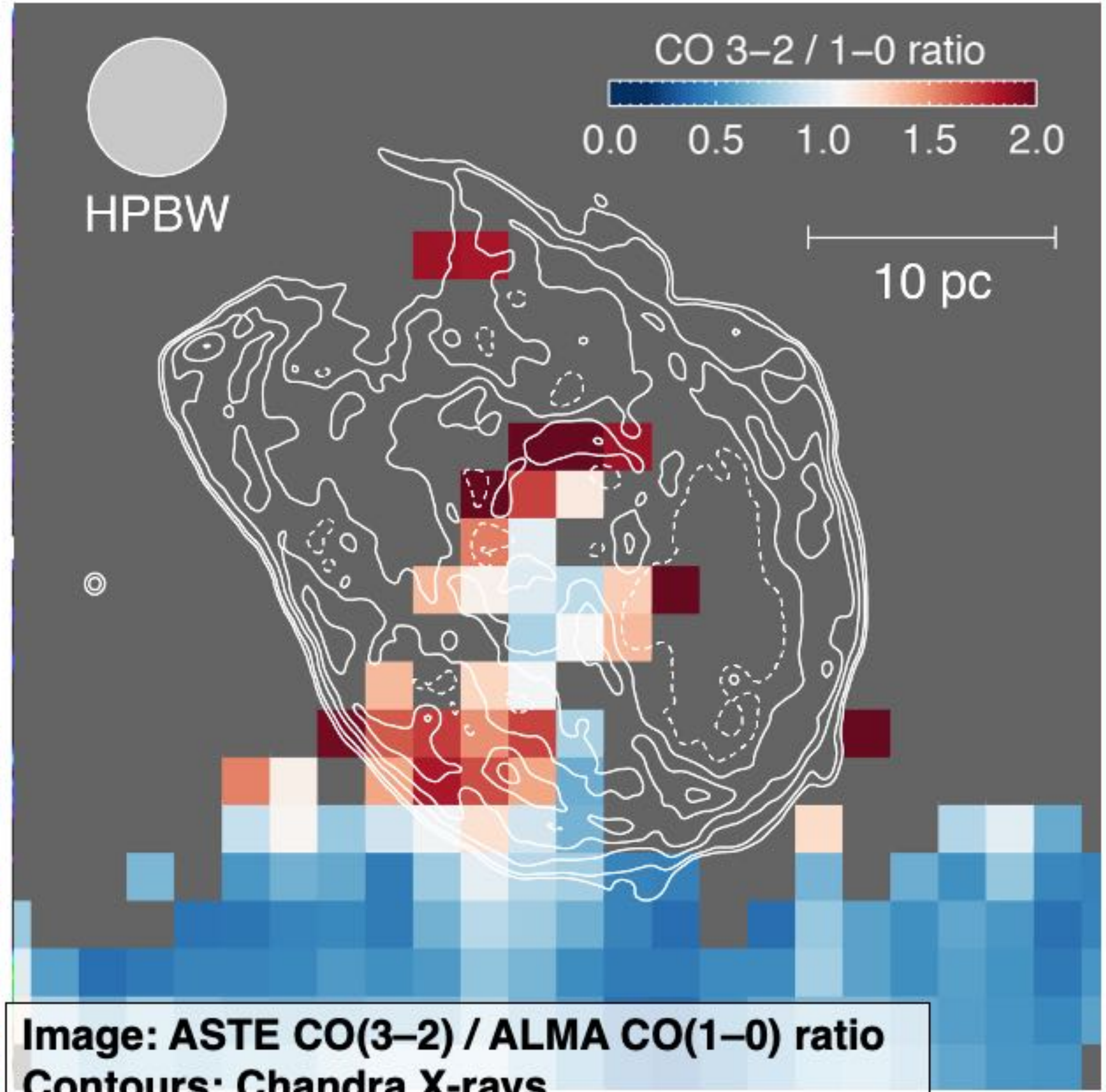
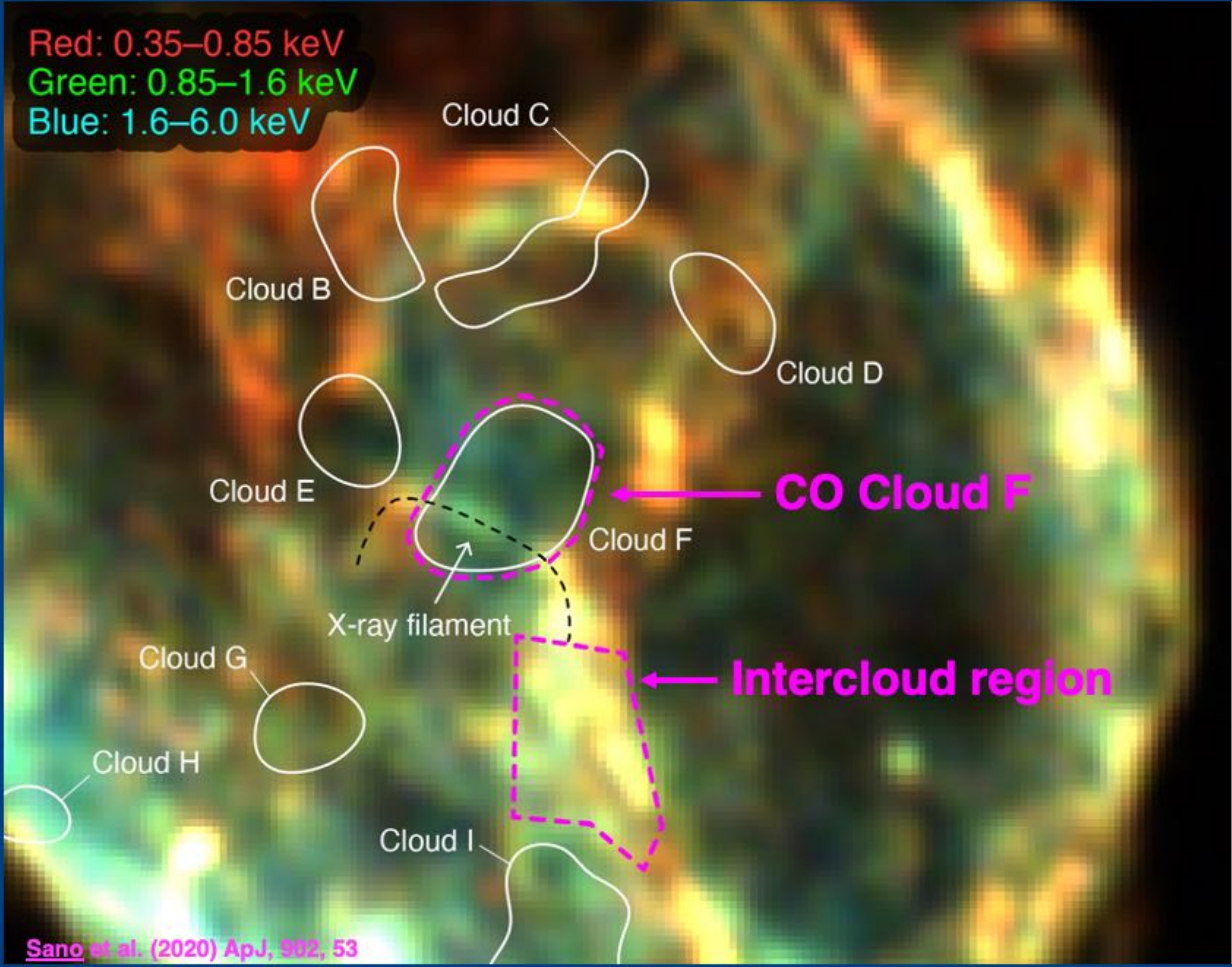


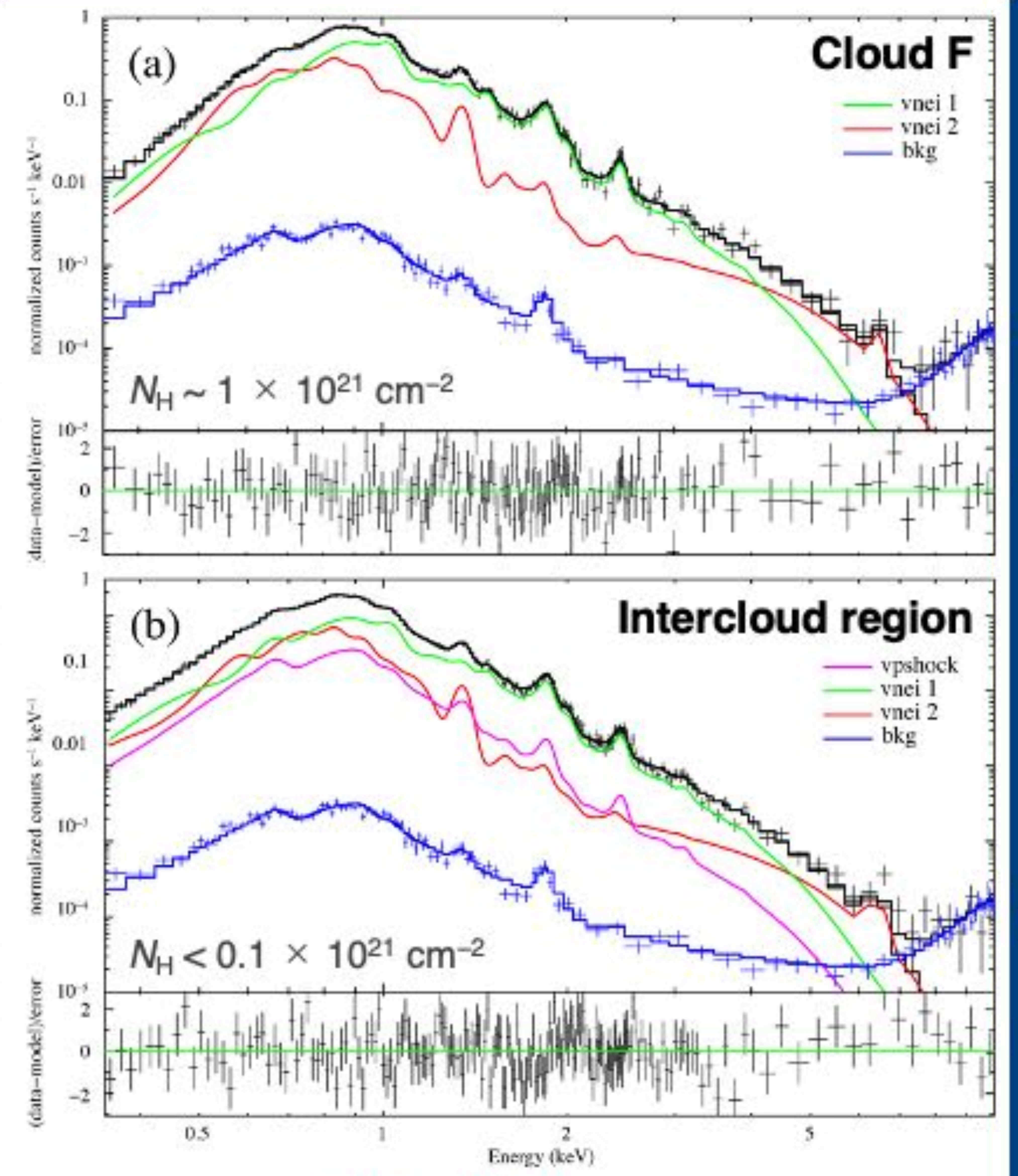
Image: ASTE CO(3–2) / ALMA CO(1–0) ratio
Contours: Chandra X-rays

Sano et al. (2020) ApJ, 902, 53

X-ray spectroscopy toward the shocked cloud & intercloud region



Sano et al. (2020) ApJ, 902, 53



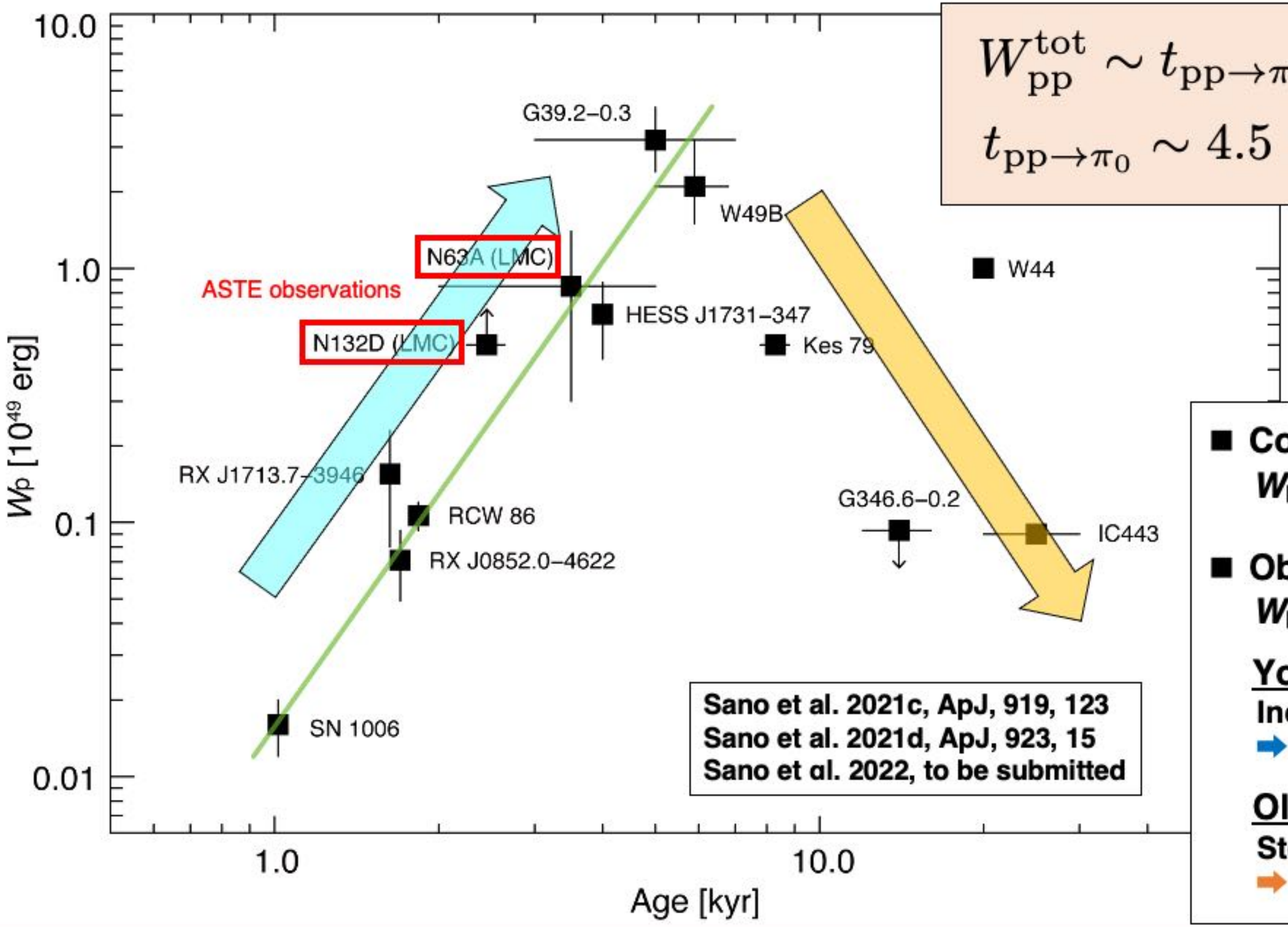
- Cloud F: CIE + NEI
- Intercloud: CIE + NEI + vpshock

Forward shock has been terminated in Cloud F

➡ The ISM based X-ray spectroscopy is needed

[科研費 国際共同研究強化(A) has benn accepted (PI: Sano)]

[Chandra Large proposal has been accepted, (PI: Plucinsky, Co-I: Sano)]



Sano et al. 2021c, ApJ, 919, 123
Sano et al. 2021d, ApJ, 923, 15
Sano et al. 2022, to be submitted

$$W_{\rm pp}^{\rm tot} \sim t_{{\rm pp}\rightarrow\pi_0} \times L_\gamma$$

$$t_{{\rm pp}\rightarrow\pi_0} \sim 4.5 \times 10^{15}\ (n/1\ {\rm cm}^{-3})^{-1}$$

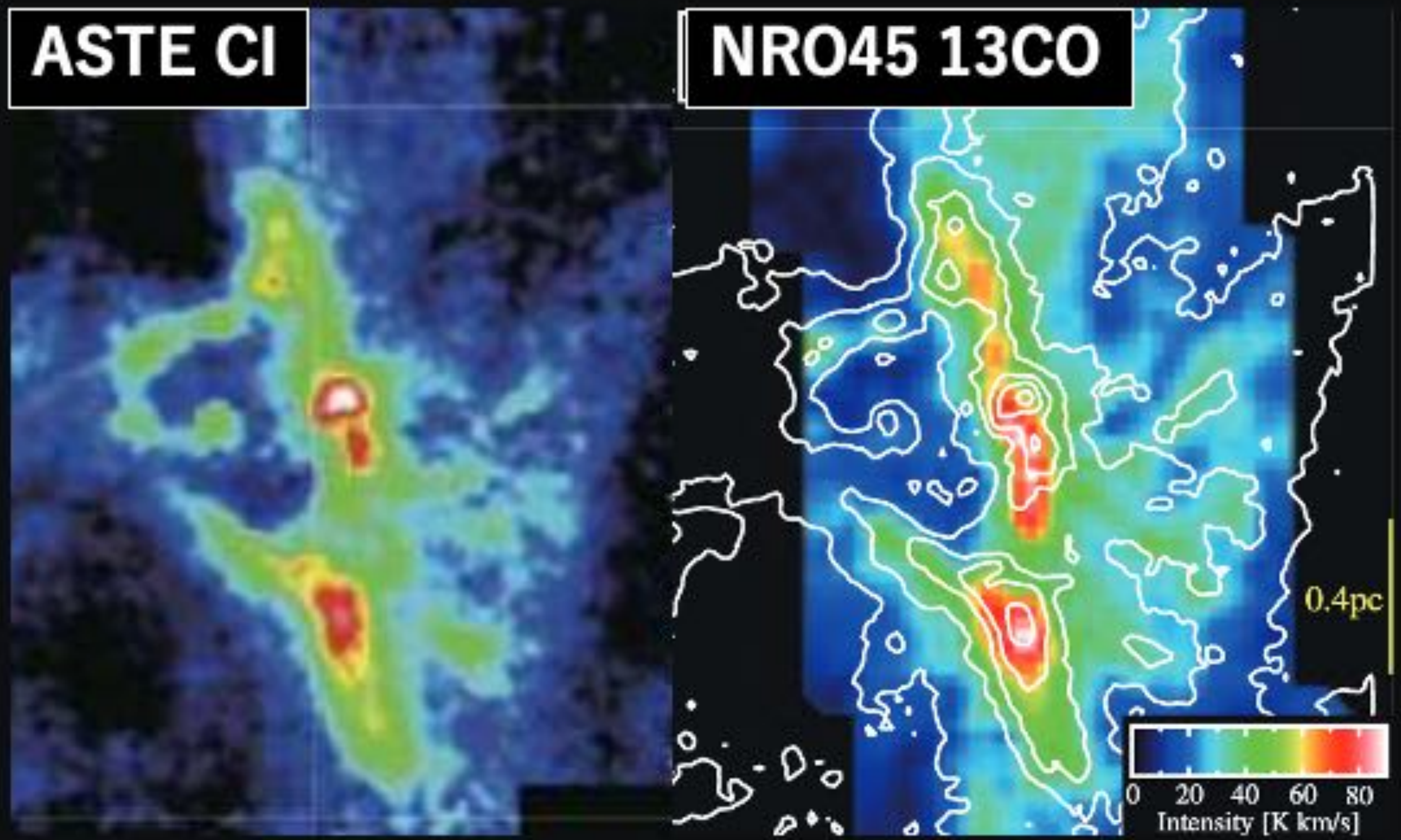
- **Conventional (theoretical) values**
  W_p ~10^{49}–10^{50} erg
- **Observational values (this work)**
  W_p ~10^{47} to more than 10^{49} erg

Young SNRs (age < 6000 yr)
Increasing *Wp* as a function of age
➡ time dependent evolution!?

Old SNRs (age > 8000 yr)
Steady Decreasing of *Wp*
➡ time dependent diffusion of CRs

Atomic carbon [CI] as a tracer of interstellar hydrogen

- <u>sub-millimeter lines</u>
  [CI] $^3P_1$–$^3P_0$: 492.161 GHz (Band 8)
  [CI] $^3P_2$–$^3P_1$: 809.344 GHz (Band 10)
- <u>critical density・optical depth</u>
  CI(1–0): ~500 cm^{-3}
  CI(2–1): ~3000 cm^{-3} @ 50 K ($\tau \ll 1$)
  (Zmuidzinas et al. 1988)
- CI enhancement in low-metal ISM & PDR
- Similar distribution to the ^{13}CO emission
  (e.g., Ikeda et al. 2002, Plume et al. 2000, Shimajiri et al. 2013)
- Indicator of the cloud evolution
  (e.g., Suzuki et al. 1992)
- A good tracer for the interstellar hydrogen gas!?
  (e.g., Papadopoulos et al. 2004; Walter et al. 2011; Alaghband-Zadeh et al. 2013; Jiao et al. 2019; Tachihara et al. 2008)



ASTE CI results of the Orion A molecular cloud
(Shimajiri et al. 2013)

Atomic carbon [CI] as a tracer of interstellar hydrogen

- <u>sub-millimeter lines</u>
  [CI] $^3P_1$–$^3P_0$: 492.161 GHz (Band 8)
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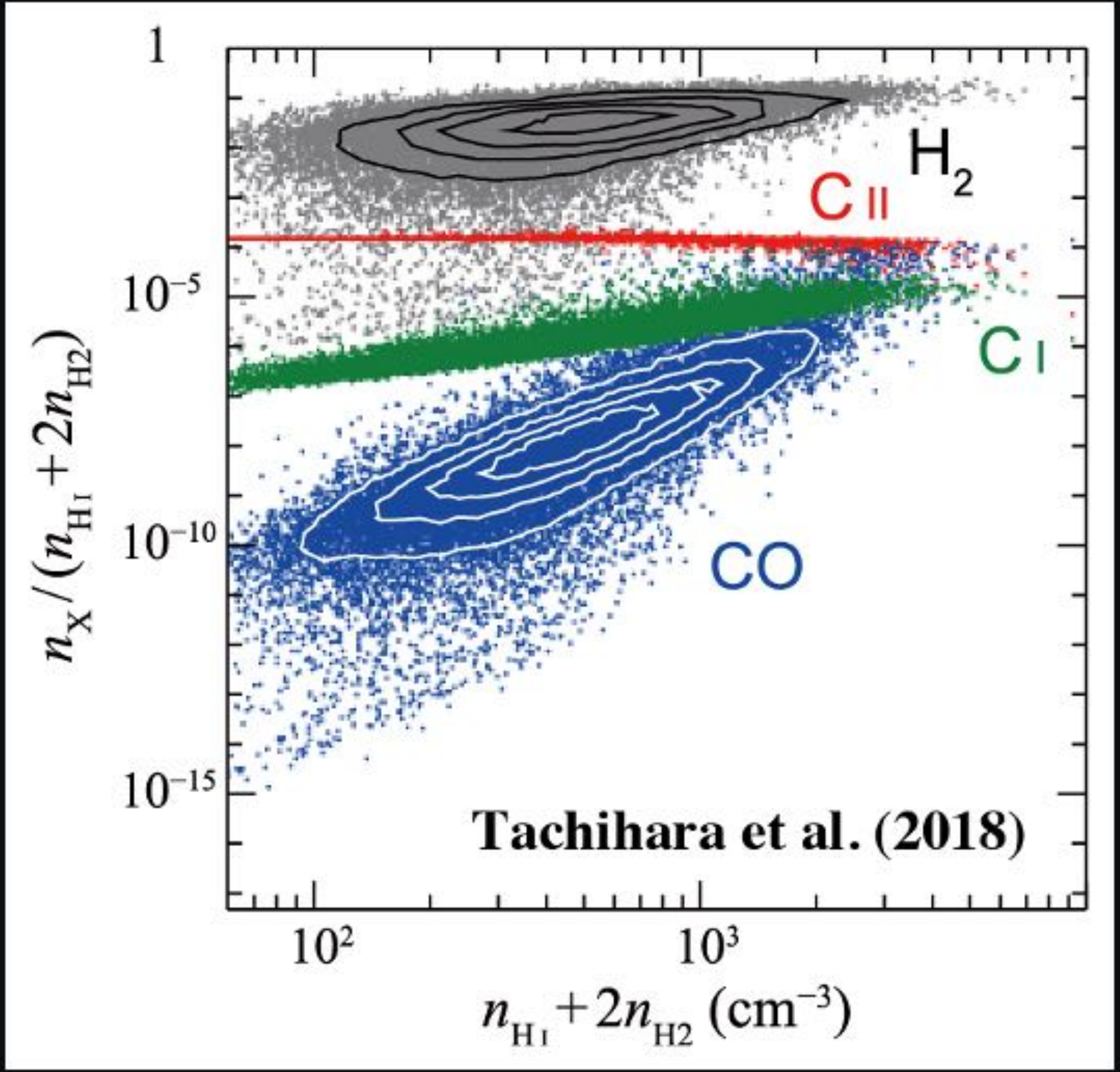
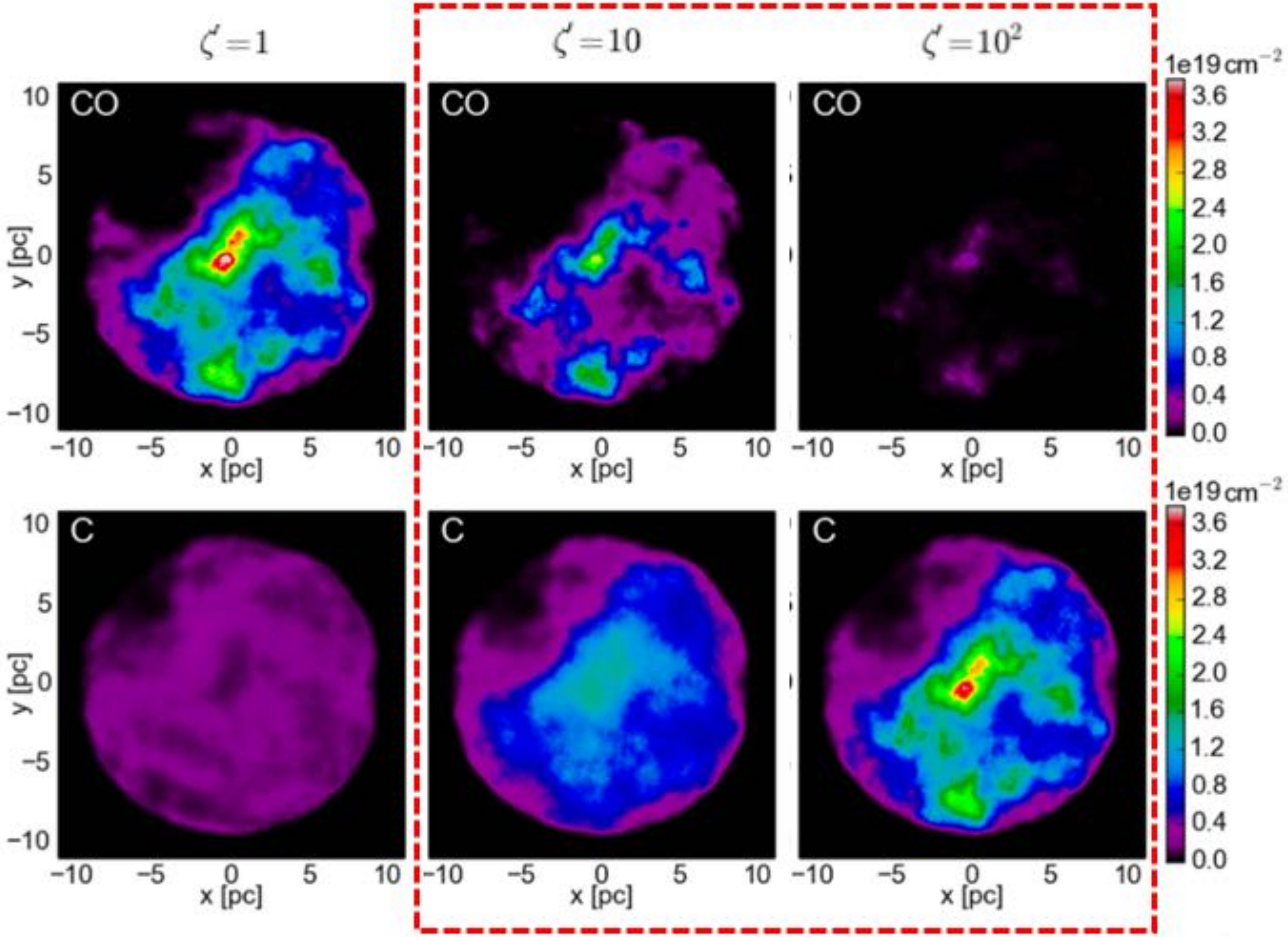


- A good tracer for the interstellar hydrogen gas!?
  (e.g., Papadopoulos et al. 2004; Walter et al. 2011; Alaghband-Zadeh et al. 2013; Jiao et al. 2019; Tachihara et al. 2008)

Cosmic-ray (CR) & shock induced enhancements of CI

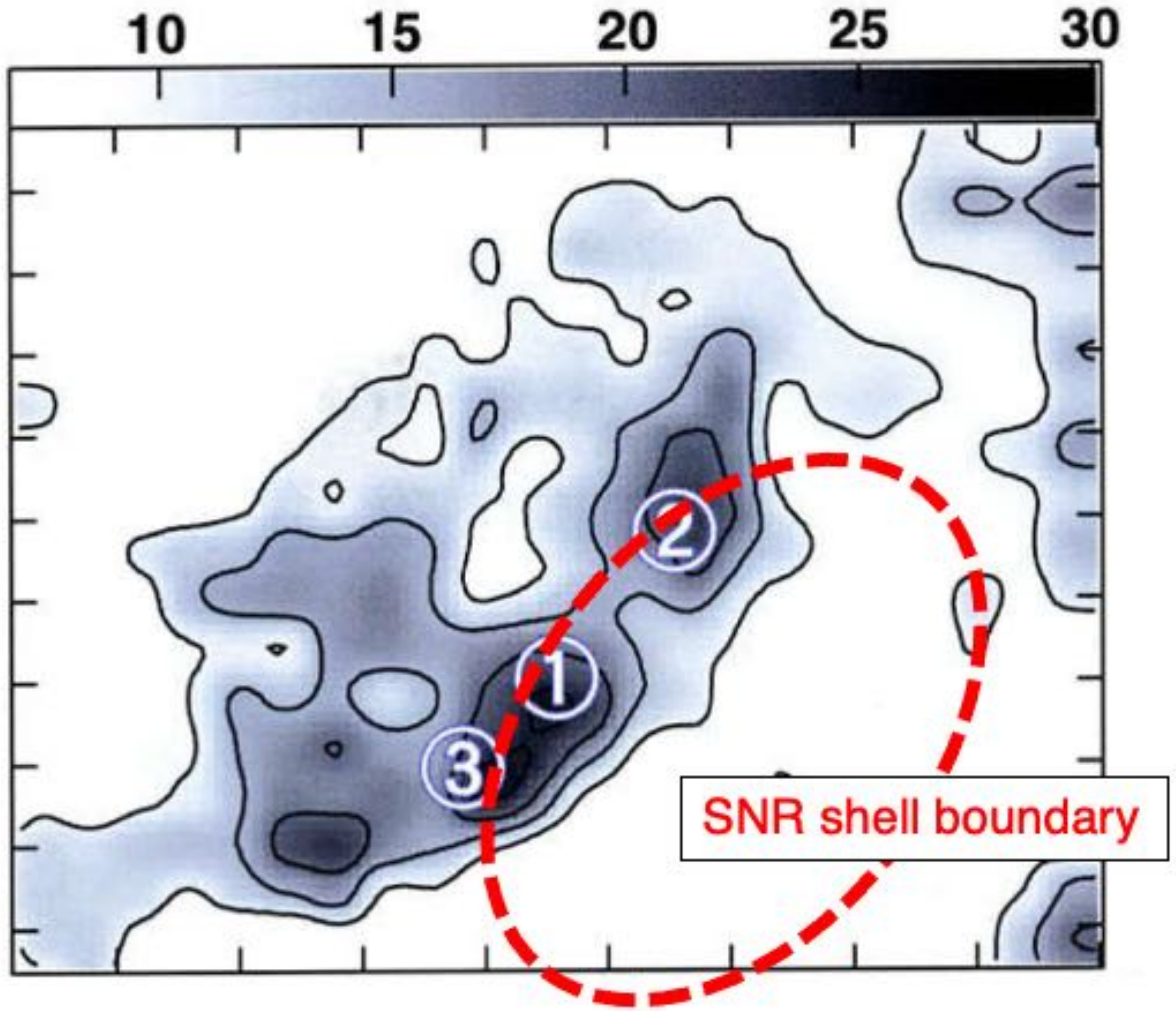
CR induced destruction of CO



ζ ~10–300 in the vicinity of SNRs
(Ceccarell et al. 2011; Vaupré et al. 2014)

Bisbas et al. (2015, 2017)

Shock destruction of CO

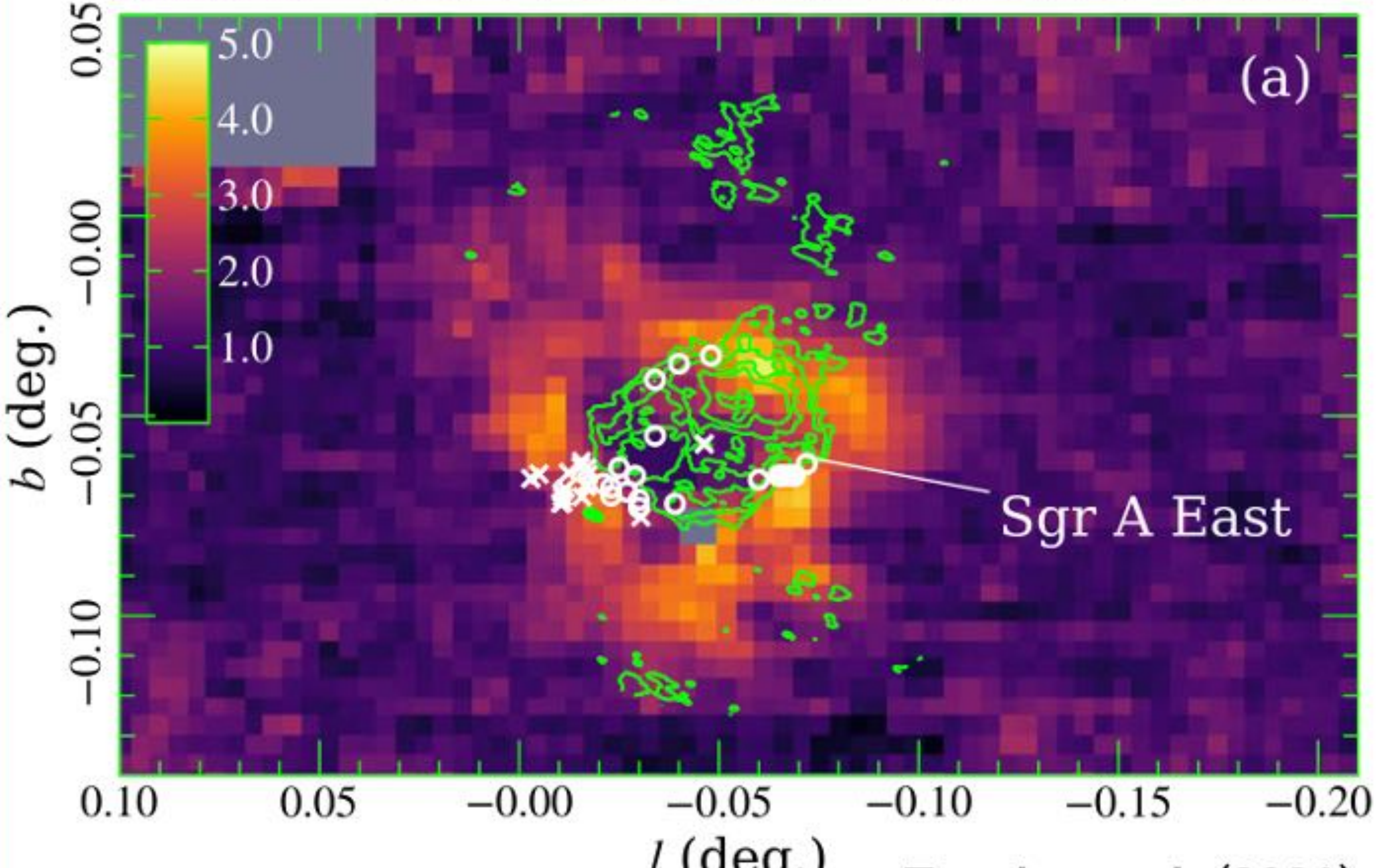


Arikawa et al. (1999)

Cosmic-ray (CR) & shock induced enhancements of CI

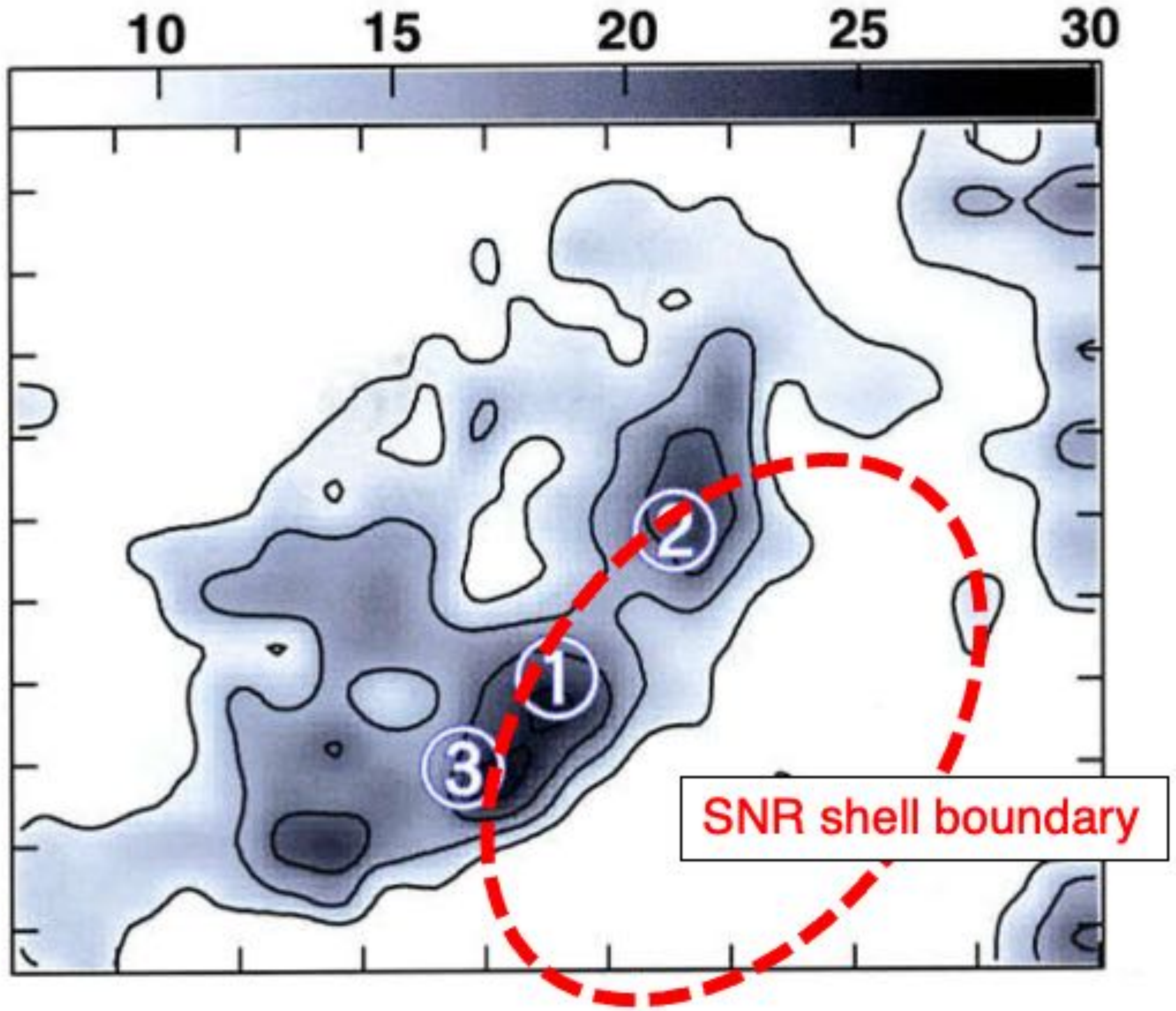
CR induced destruction of CO

[CI](1–0)–^{13}CO(2–1) excess map (contours: 6 cm RC)



Tanaka et al. (2021)

Shock destruction of CO



Arikawa et al. (1999)

CI observations of the LMC SNR N49

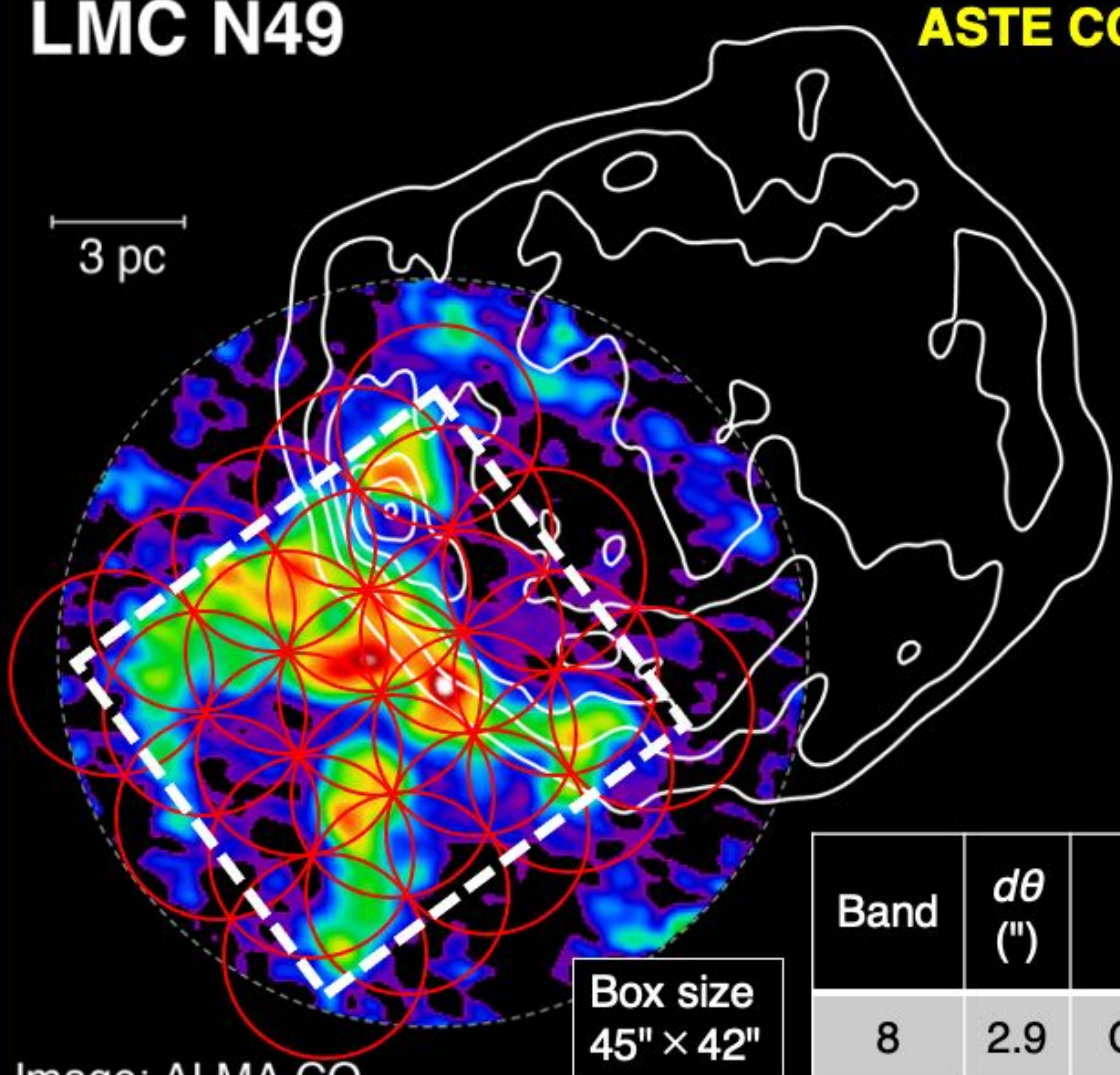


Image: ALMA CO
Contours: ATCA radio continuum

ASTE CO 3–2/1–0 ratio also confirmed cloud association

(Yamane, Sano et al. 2018, ApJ, 863, 55)

[case 1] CI/CO enhancement is seen whiten the shell
→ Shock induced destruction of CO is effective

[case 2] CI/CO gradient is seen in the GMC
→ CR induced CO destruction is effective

Diffusion length of cosmic-rays $l_{\rm diff}$

$$l_{\rm diff} = \sqrt{4\ D(E)\ t_{\rm age}} \sim 6\ {\rm pc}$$

$$E = 100\ {\rm MeV},\ t_{\rm age} = 4800\ {\rm yr},\ B = 10\ \mu{\rm G}$$

$$D(E) = 5 \times 10^{26}\ (E/\ 100\ {\rm MeV})^{0.5} (B/\ 10\ \mu{\rm G})^{-0.5}\ {\rm cm^2\ s^{-1}}$$

Band	$d\theta$ (")	Line	Time (12m)	Time (ACA)	$T_{\rm rms}$ (K)	$V_{\rm res}$ (km/s)	# of FoVs	LAS (")
8	2.9	CI $^3P_1$–$^3P_0$	0.0 h	17.4 h	0.2	0.3	23	40

ALMA Cycle 8 proposal has been accepted (#2021.1.00200.S, PI: H.Sano)

ASTE Band 10 observations of CI(2–1) emission toward RCW 38

Sano et al. (2022) to be submitted
with Asayama-san, Ishii-san
Iono-san, and Kamazaki-san

CI(1–0): Izumi et al. (2021)

- We can measure CI T_{ex} & N(CI) accurately using two CI lines by using ASTE.
- CI T_{ex} is roughly three times higher than CO T_{ex}.

➡ CI can unveil dense cloud components in the vicinity of the cluster.

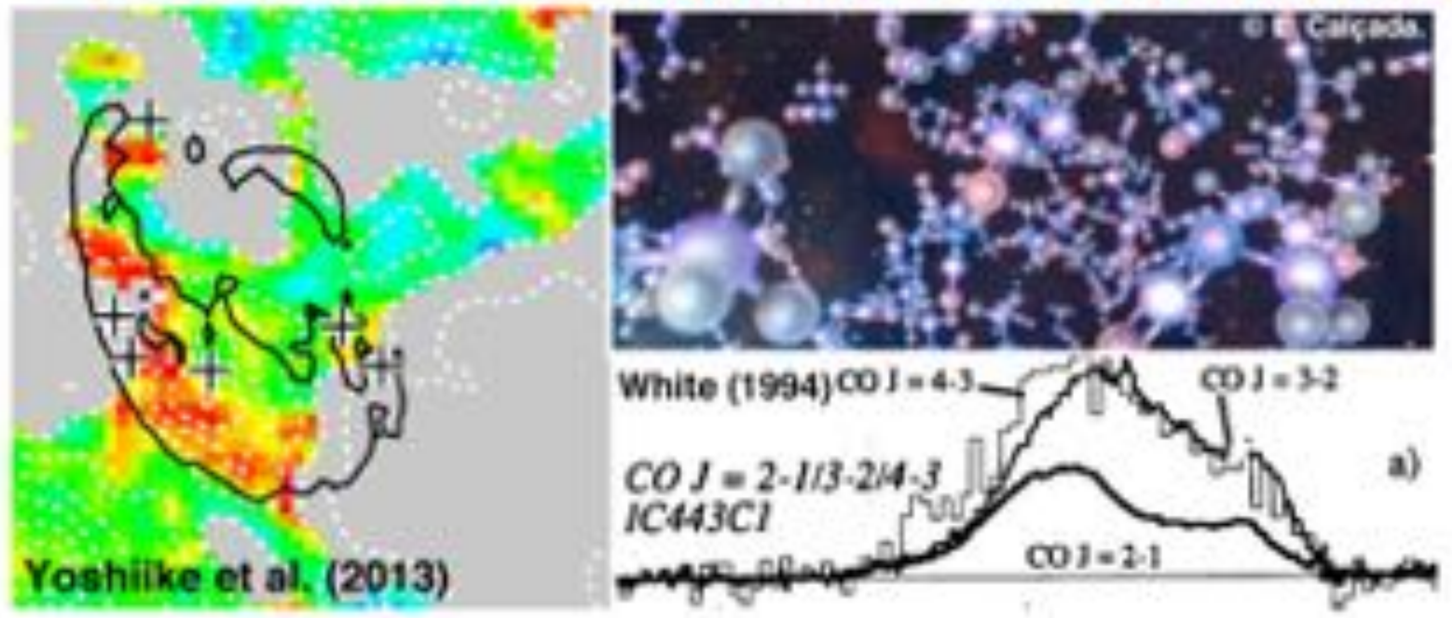
$$T_{ex} = 38.8\ \mathrm{K} / \ln\,[2.11/R].$$

R is the integrated intensity ratio between [CI] $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$.

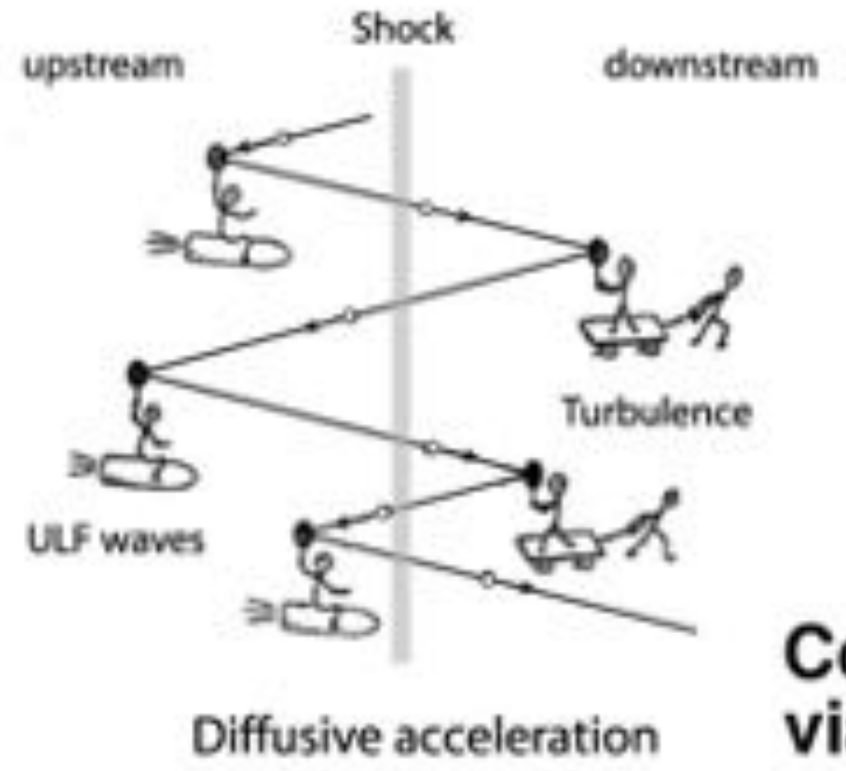
Summary

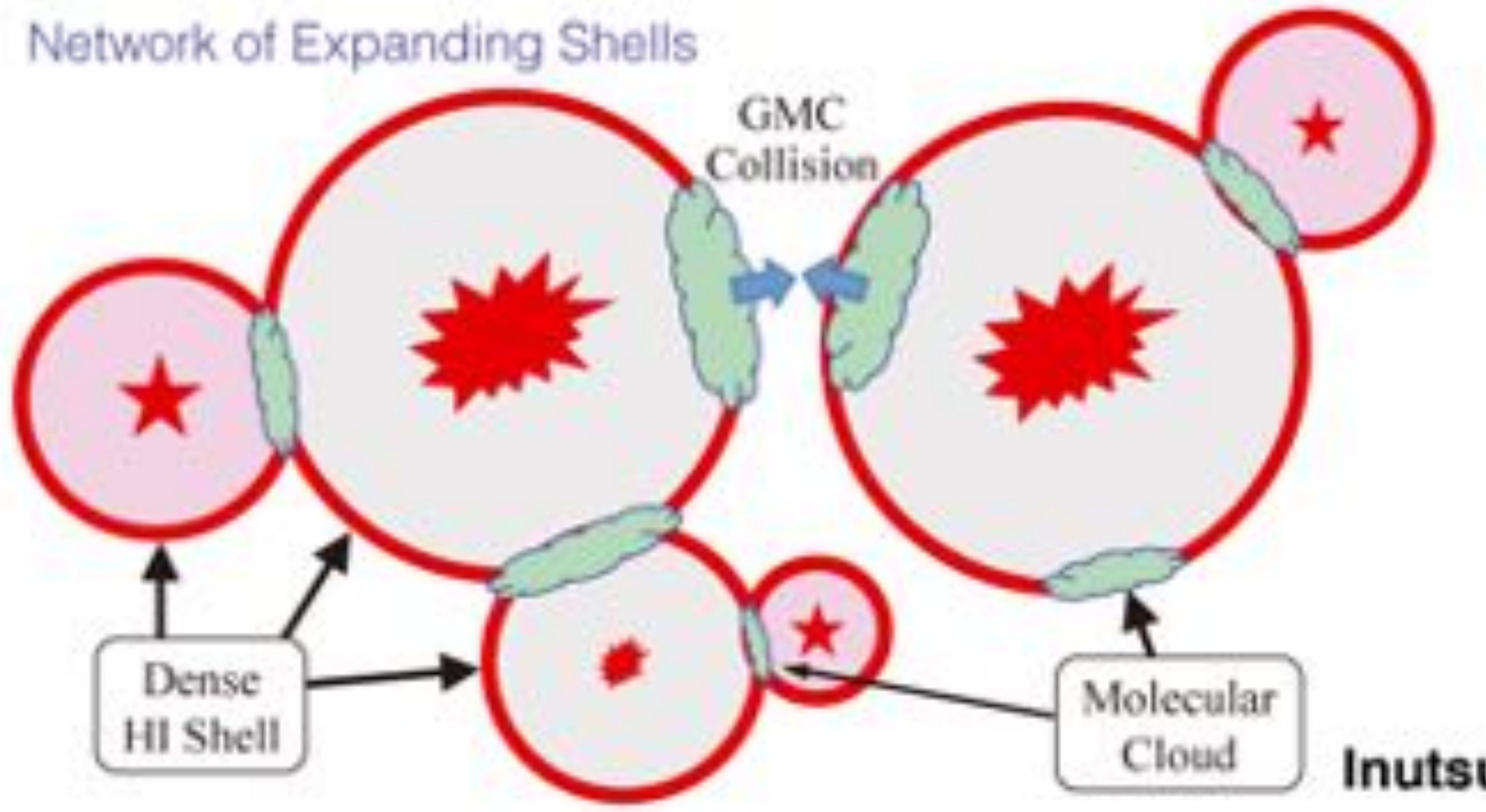
We can apply our knowledge of supernova remnants for studying nearby and high-z galaxies…!!

ASTE can reveal shock-heated gas using submm lines
➡ Combining study with ALMA is promising!!



Partially heating of gas/dust with line broadening
+ chemical evolution of the ISM
+ CI chemistry in the vicinity of SNRs





Inutsuka et al. (2015)