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SINCE 2002

Shock-cloud interaction in the Galactic/Magellanic supernova remnants: Evidence for cosmic-ray acceleration

Hidetoshi Sano (Nagoya University)

28 March 2018 @ Bamberg

Interstellar Medium in the Nearby Universe (ISM2018)

Main Collaborators:
Y. Yamane, S. Yoshiike, T. Nagaya, K. Tachihara, G. Rowell, F. Voisin, N. Maxted, M. Filipovic, K. Grieve, E. Reynoso, T. Inoue, S. Inutsuka, T. Tanaka, A. Bamba, H. Uchida, and Y. Fukui

To understand CR acceleration & X-/γ-rays in SNRs, detailed study of the ISM is important

- **Shock-cloud interaction**

  B field amplification around ISM clumps, CR electrons rapidly dump & synchrotron X-ray enhancement (Sano+10, 13, 15, 17a; Inoue+09, 12)

- **Cosmic-ray origin**

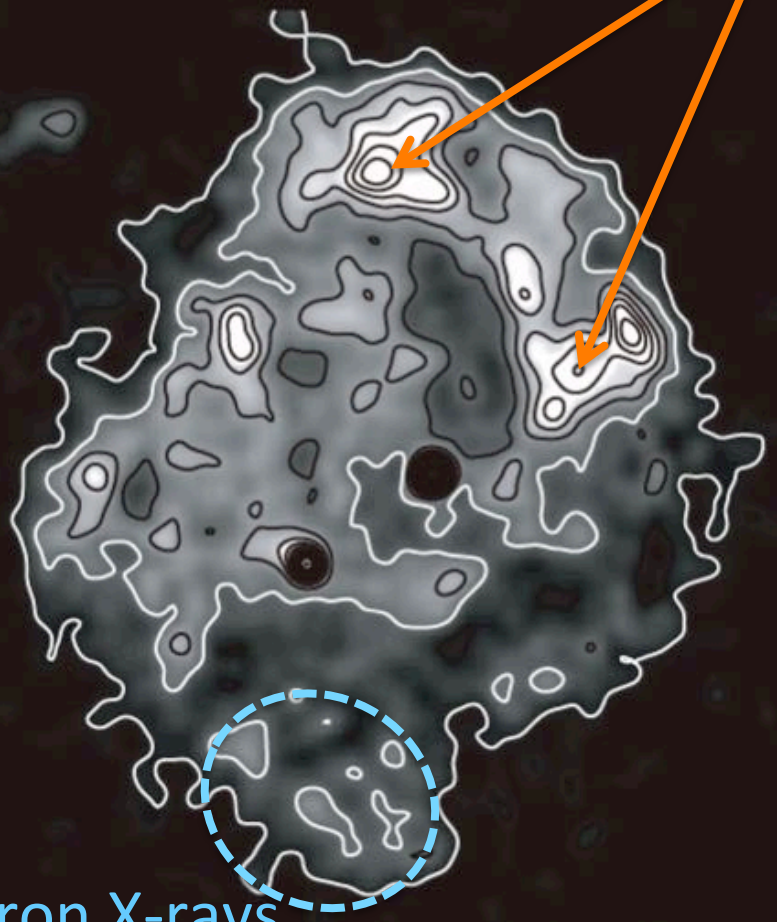
  Good spatial correspondence between the ISM & hadronic γ-rays (Fukui+12, 13, 17; Fukuda+14; Sano+18 in prep.)

- **Toward the Cherenkov Telescope Array (CTA) era**

  Identifying the ISM associated with the Galactic/Magellanic SNRs (Sano+17b,c; Kuriki+17; Yamane+18 to be submitted)

Supernova remnant RX J1713.7–3946

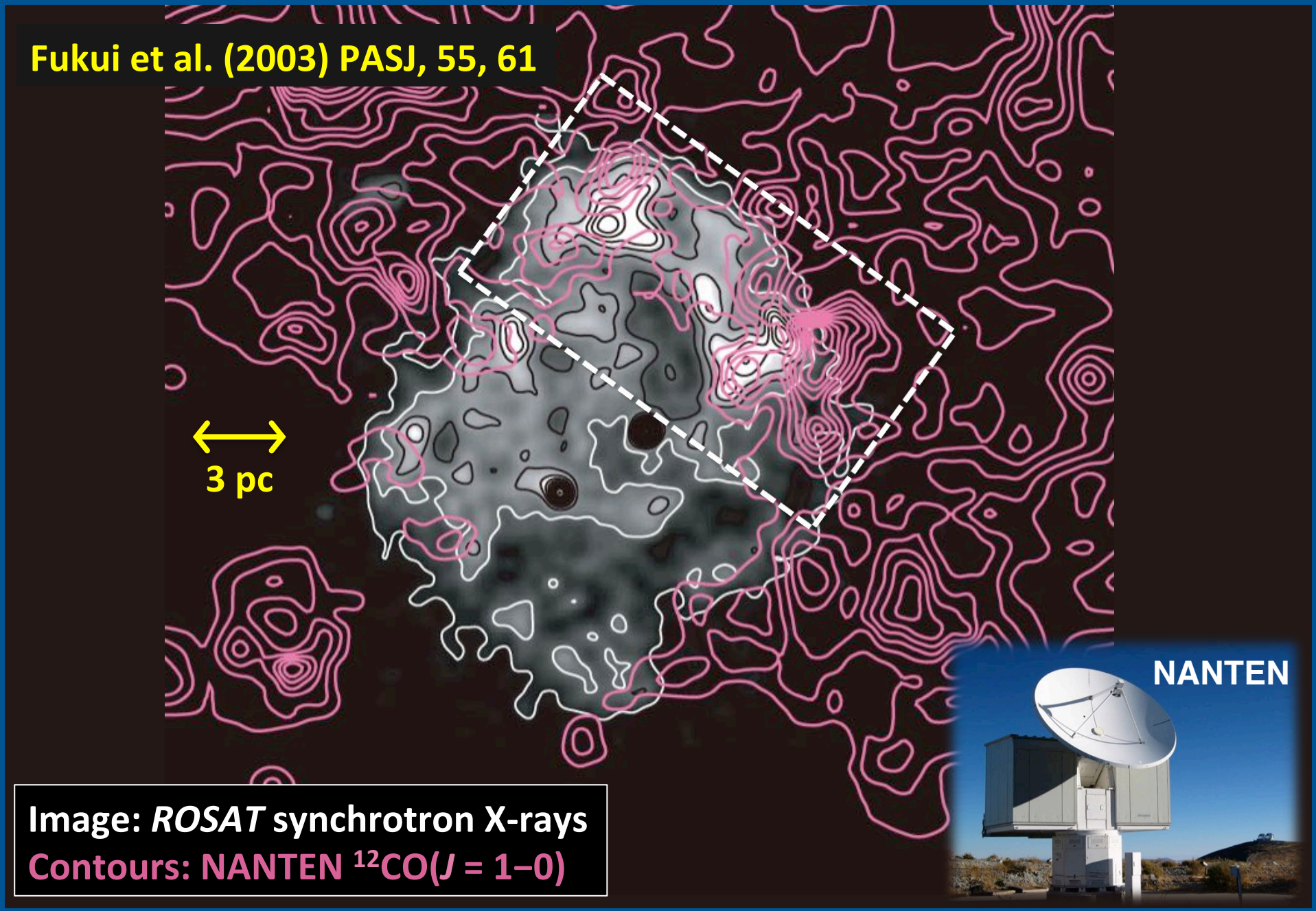
Fukui et al. (2003) PASJ, 55, 61



- Age: ~1,600 yr
- Distance: ~1 kpc
- Size: ~19 pc
- Core-collapse SNR

Image: *ROSAT* synchrotron X-rays

Supernova remnant RX J1713.7–3946



Supernova remnant RX J1713.7–3946

Fukui et al. (2003) PASJ, 55, 61
Sano et al. (2010) ApJ, 724, 59
Sano et al. (2013) ApJ, 778, 59

Image: *Suzaku* synchrotron X-rays (5–10 keV)
Contours: NANTEN2 ^{12}CO(J = 2–1)

Supernova remnant RX J1713.7–3946

Fukui et al. (2003) PASJ, 55, 61
Sano et al. (2010) ApJ, 724, 59
Sano et al. (2013) ApJ, 778, 59
Sano et al. (2015) ApJ, 799, 175

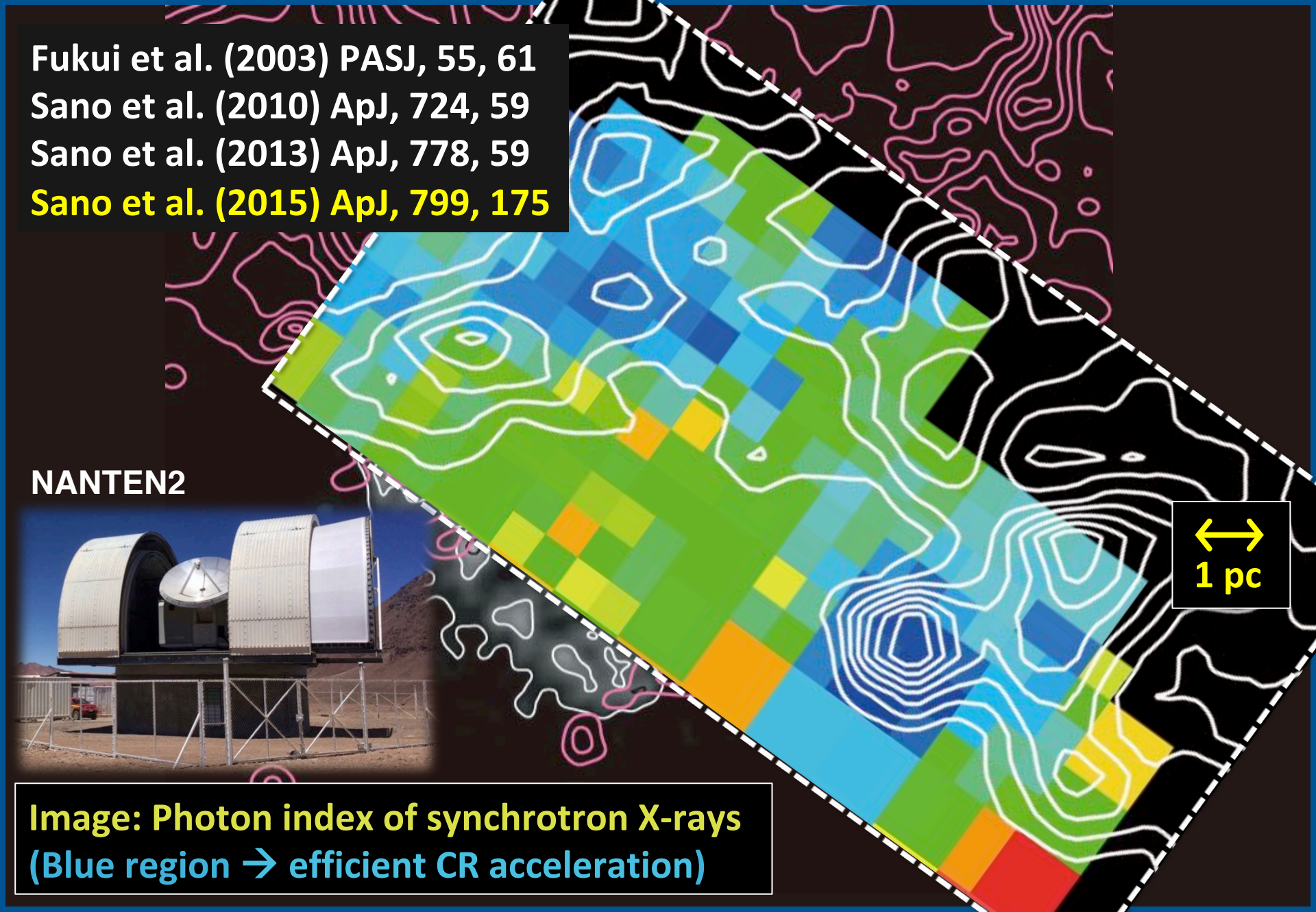
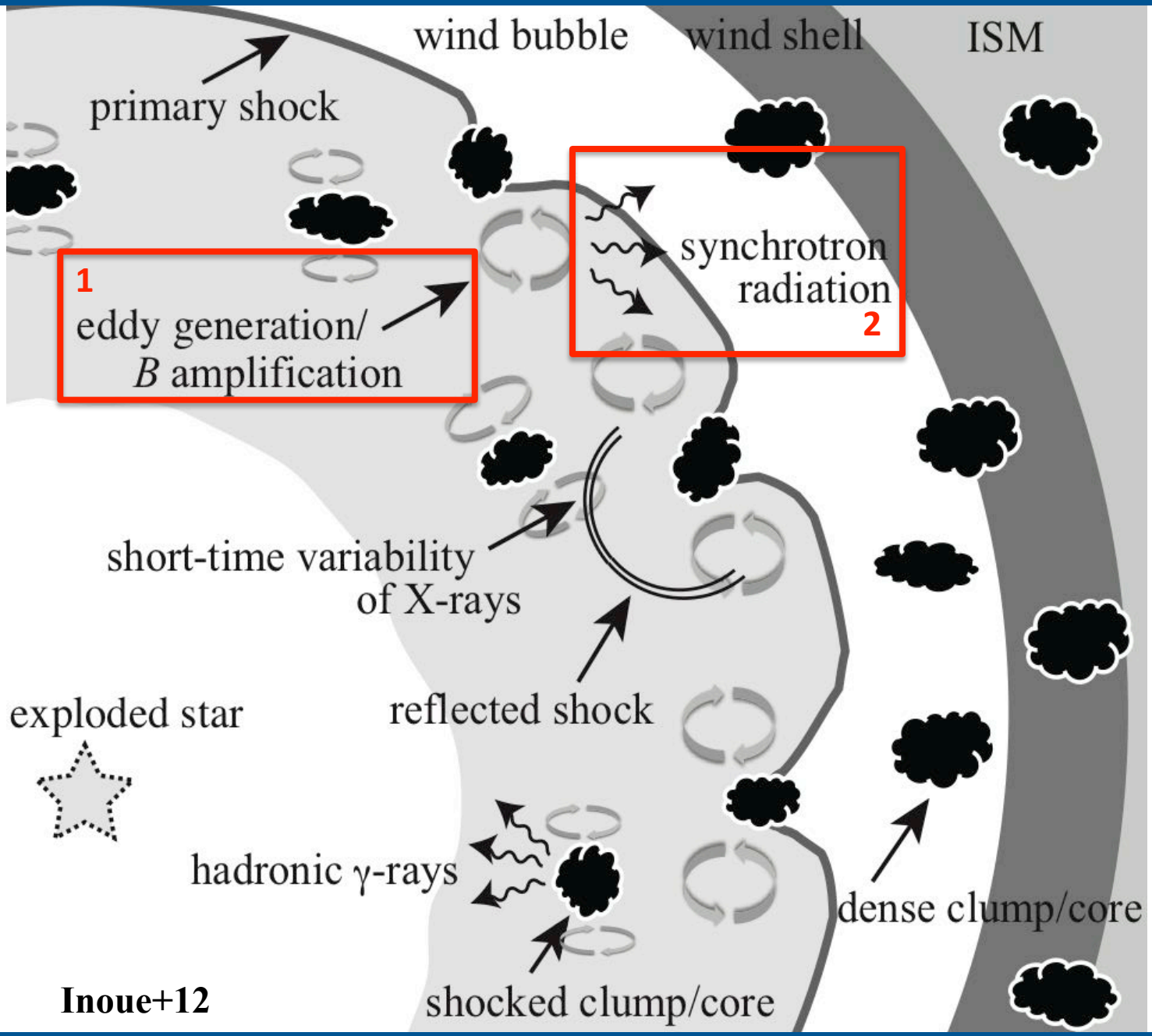


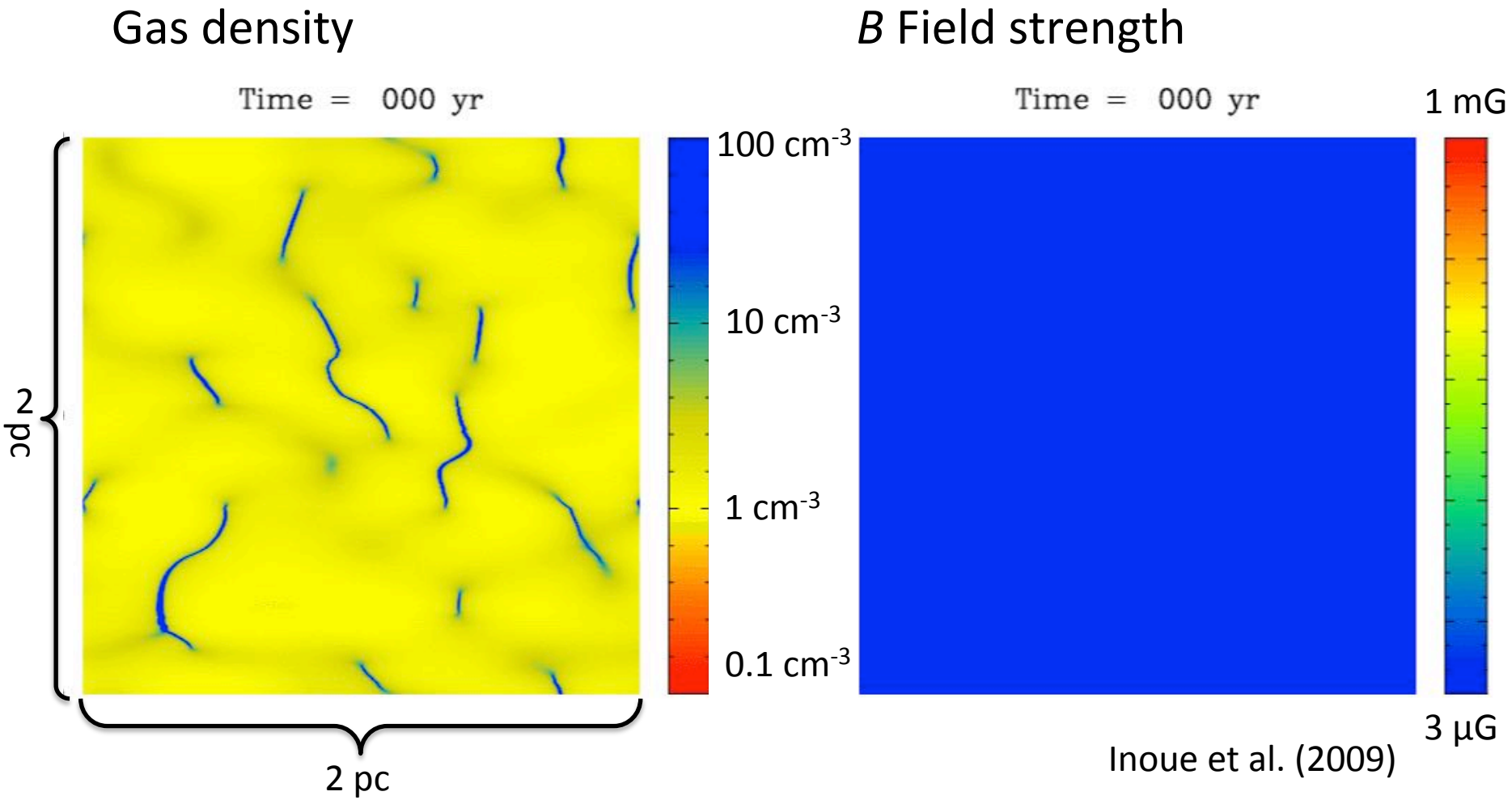
Image: Photon index of synchrotron X-rays
(Blue region → efficient CR acceleration)

Shock interaction with gas clumps



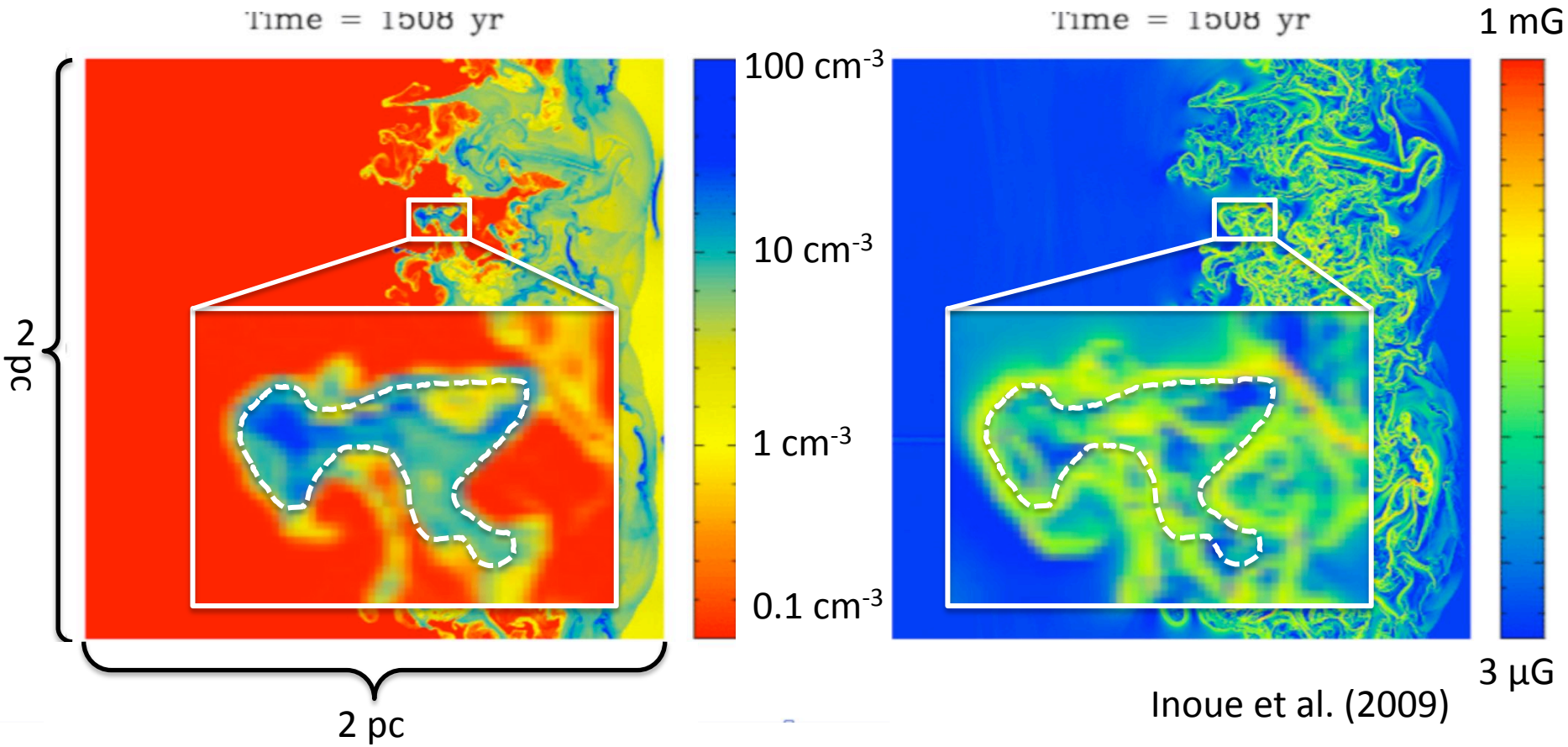
Inoue+12

Shock interaction with gas clumps: MHD simulation



Inoue et al. (2009)

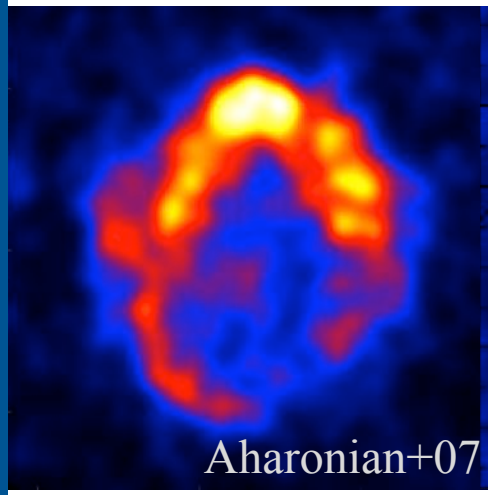
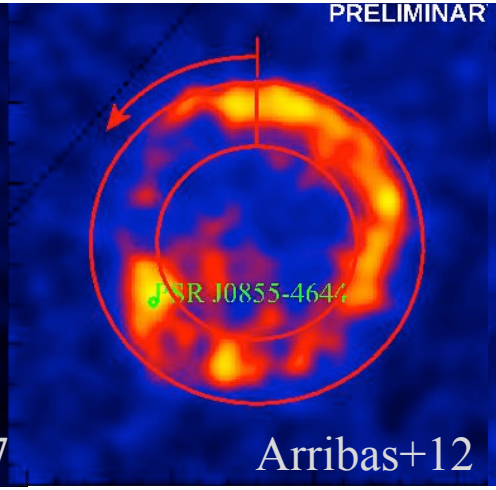
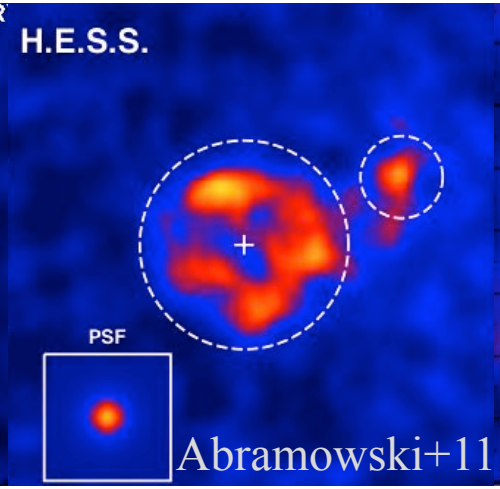
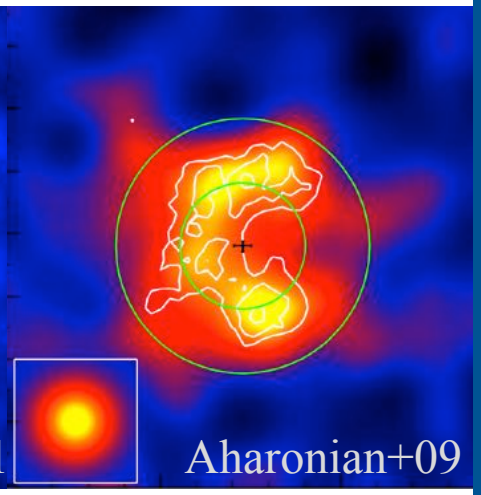
Shock interaction with gas clumps: MHD simulation



- *B* field are amplified around the CO-like clump
- Maximum *B* field strength reaches ~1 mG
  (Averaged *B* field: ~30–40 μG in the down stream)

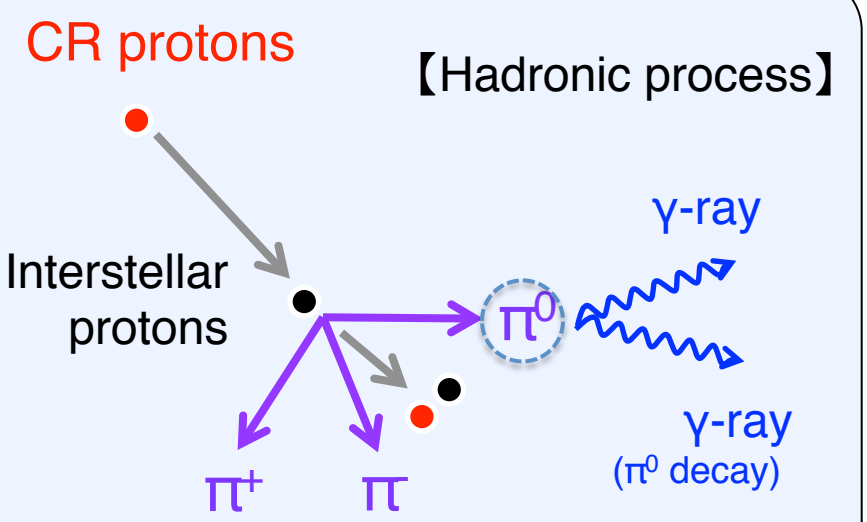
Young TeV gamma-ray SNRs

- four well-known TeV gamma-ray SNRs (age ~ 2,000 yrs)
- The SNRs are interacting with ISM.

RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
			
Aharonian+07	Arribas+12	Abramowski+11	Aharonian+09
diameter: ~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
age: ~1600 yr	~1700−4300 yr	~3600−7200 yr	~1800 yr
ISM: rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays: pure synchrotron	pure synchrotron?	pure synchrotron	thermal + non-thermal

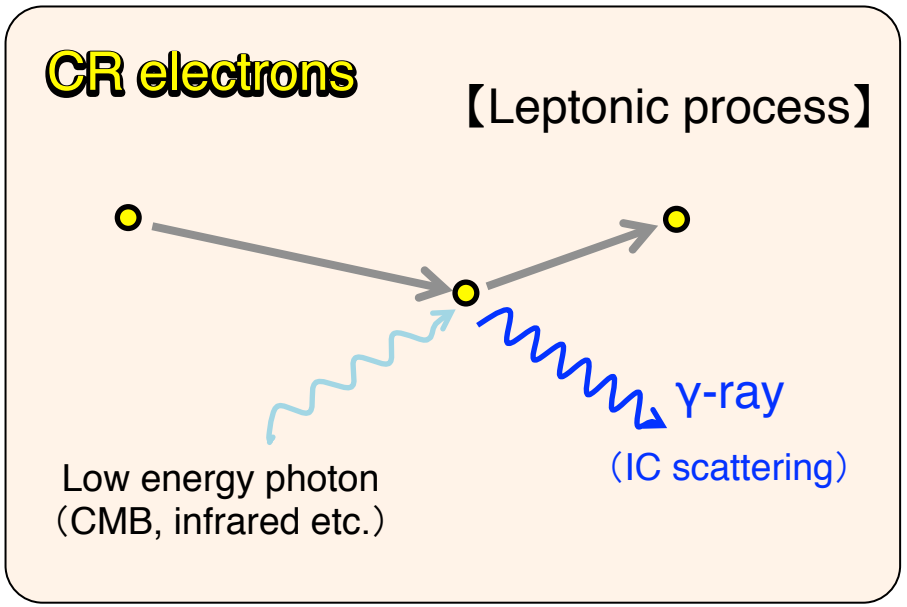
Radiative processes of gamma-rays in the young SNRs

- Gamma-rays (hadronic: p-p interaction, leptonic: IC scattaring)
  → It is difficult to distinguish the processes by spectra analysis alone



$$F \propto \frac{W_p n}{d^2}$$

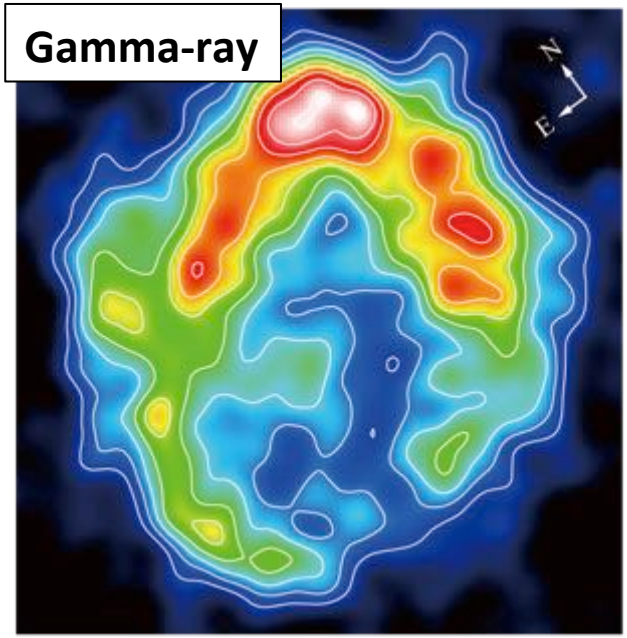
W_p: total energy in accelerated protons
n: gas density
d: distance to the SNR



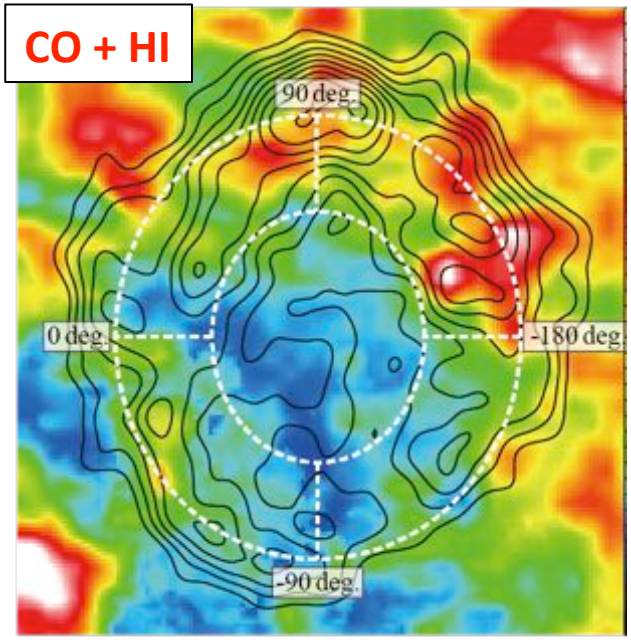
If the hadronic process is working,
→ **gamma-ray flux ∝ gas density**

Evidence for CR proton acceleration（Fukui+12）

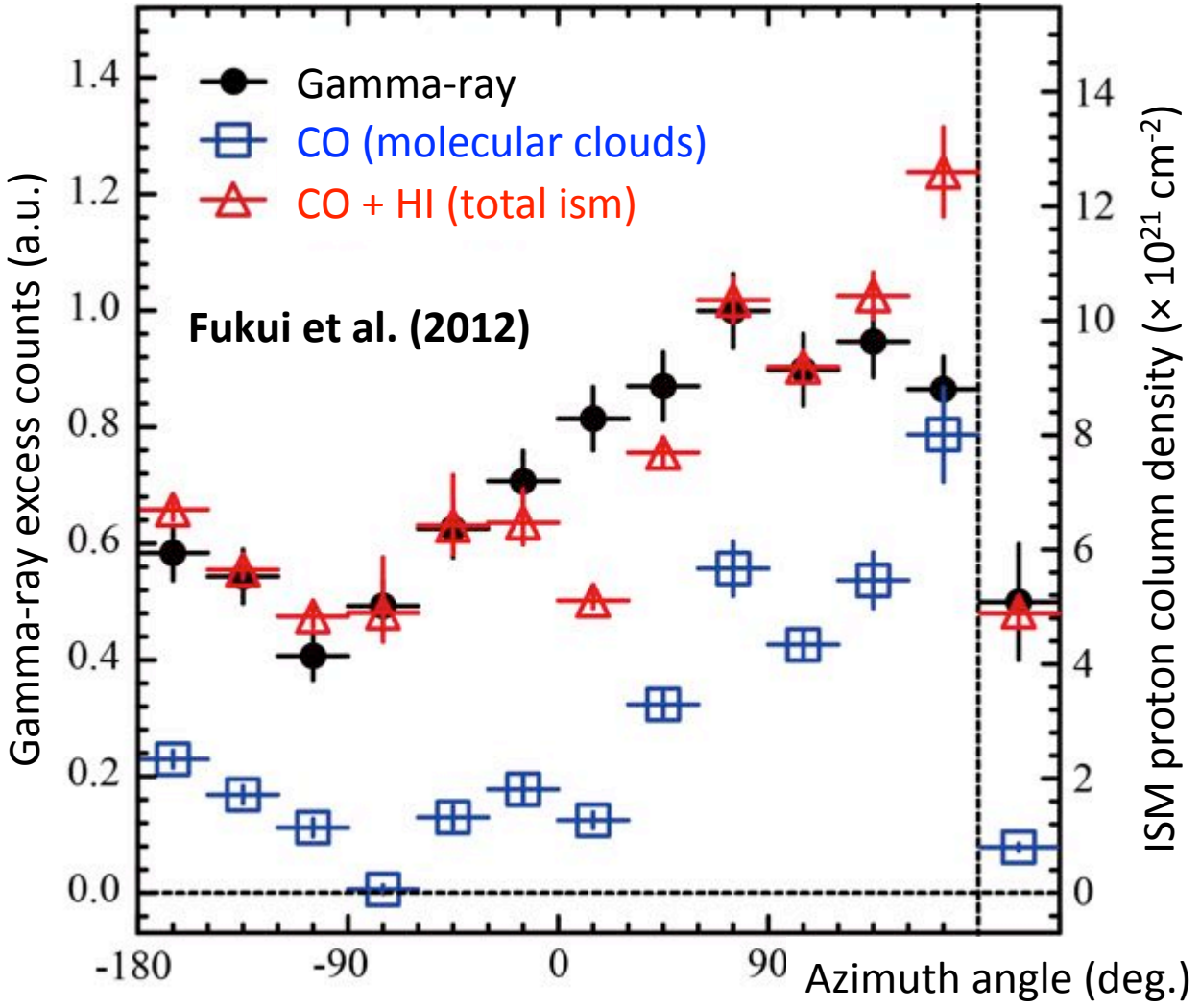
Gamma-ray



CO + HI

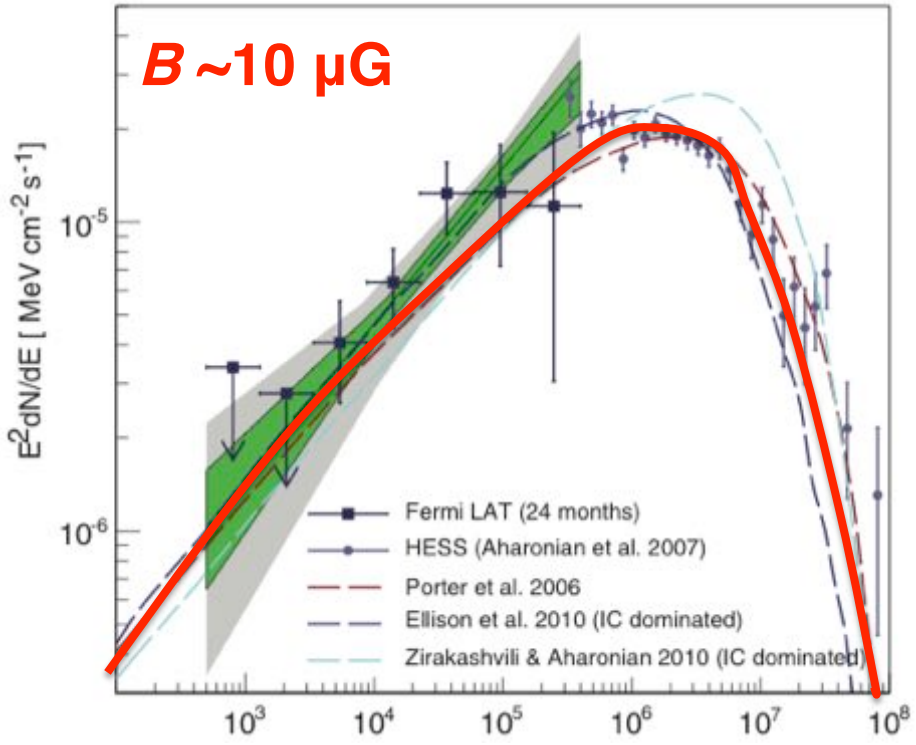


Spatial correspondence between the interstellar protons & TeV gamma-rays

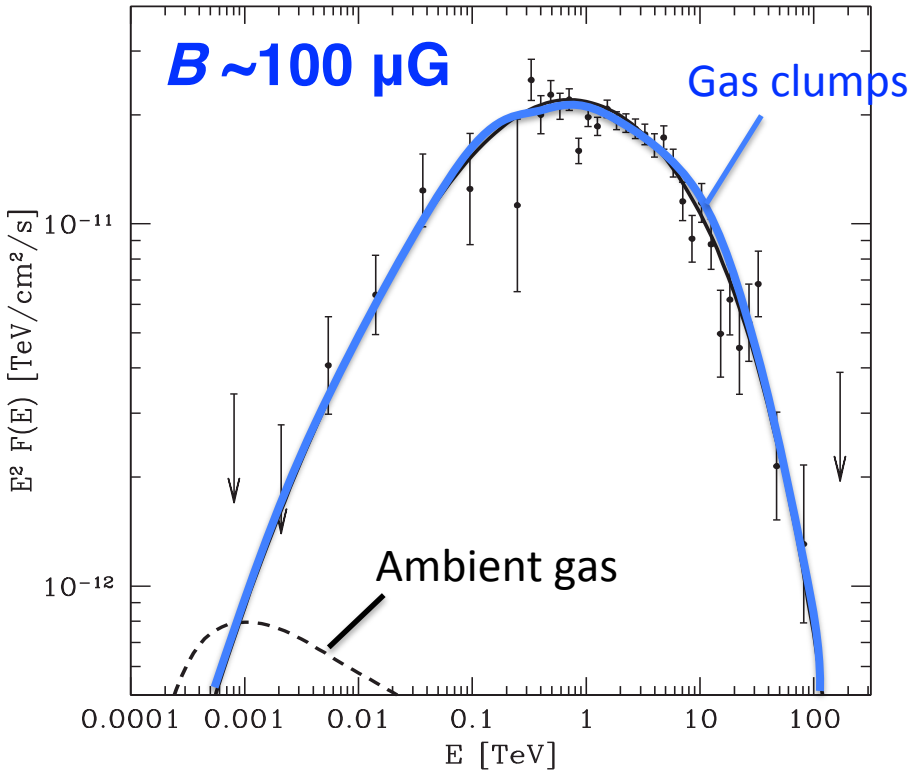


Interpretation of the gamma-ray spectra of RXJ1713

Leptonic model (Abdo+11)
→ Low *B* field needed



Hadronic model (Gabici+14)
→ High *B* field needed



RXJ1713

Energy of CRs ↓ E | ***B* field strength** ↓ B | SNR age ↓ $t_{\rm age}$

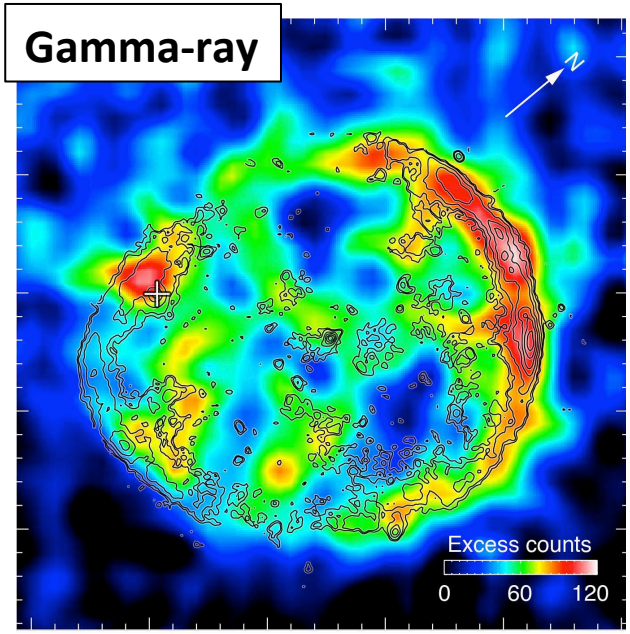
$$l_{\rm pd} \simeq (\kappa_{\rm d}\, t)^{1/2} = 0.1\,\eta^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2} \left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2} {\rm pc},$$

↑ Penetration depth　　↑ Gyro factor

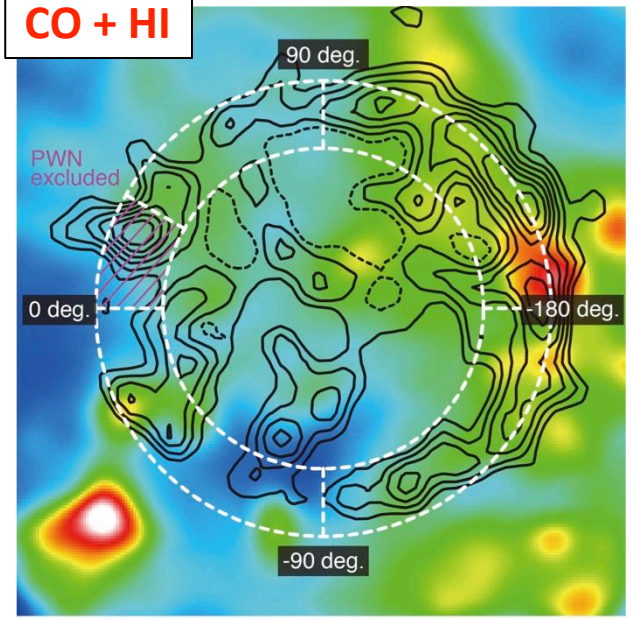
Inoue+12

Interstellar gas in Vela Jr.（Fukui+17, ApJ, 850, 71）

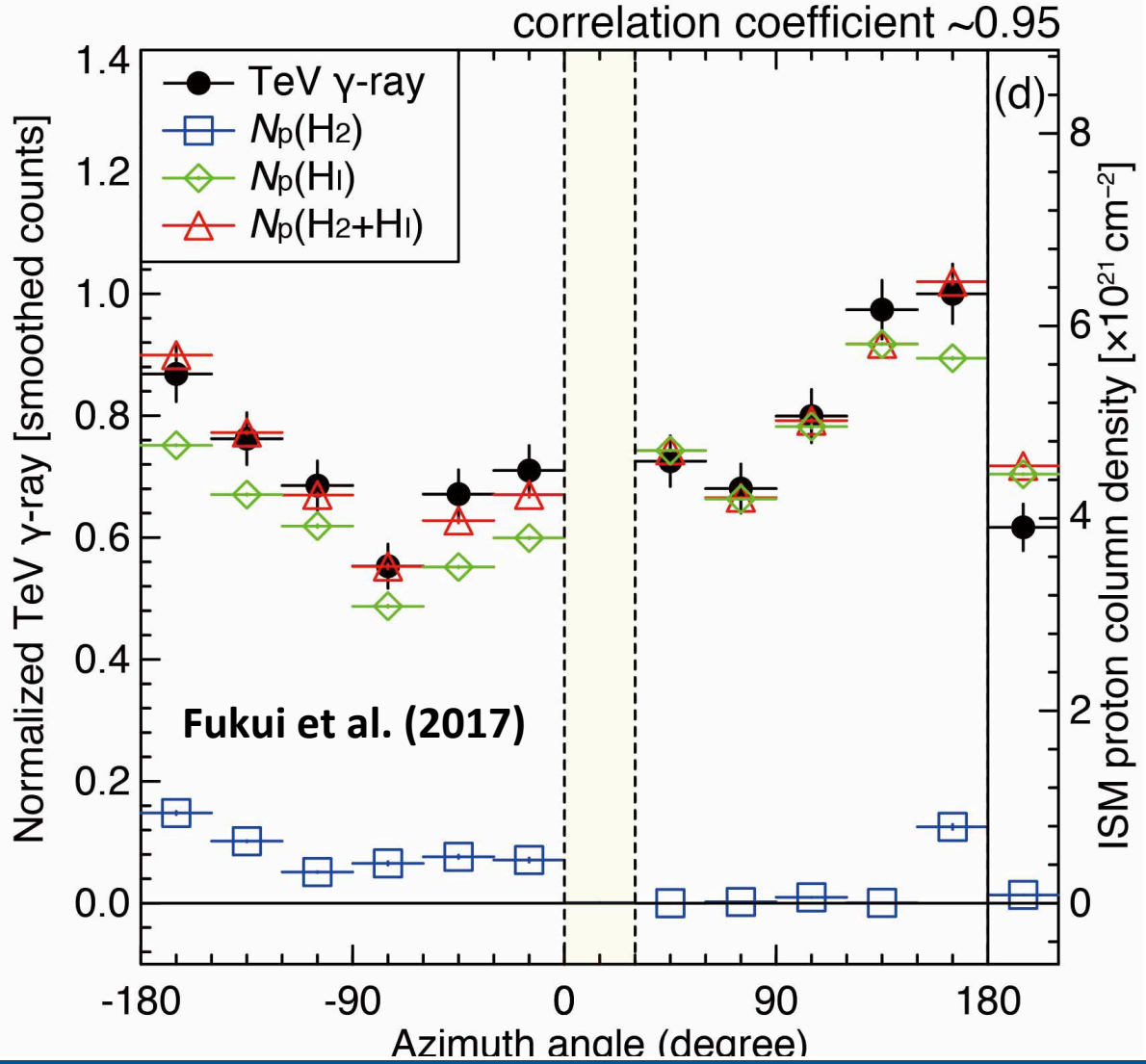
Gamma-ray



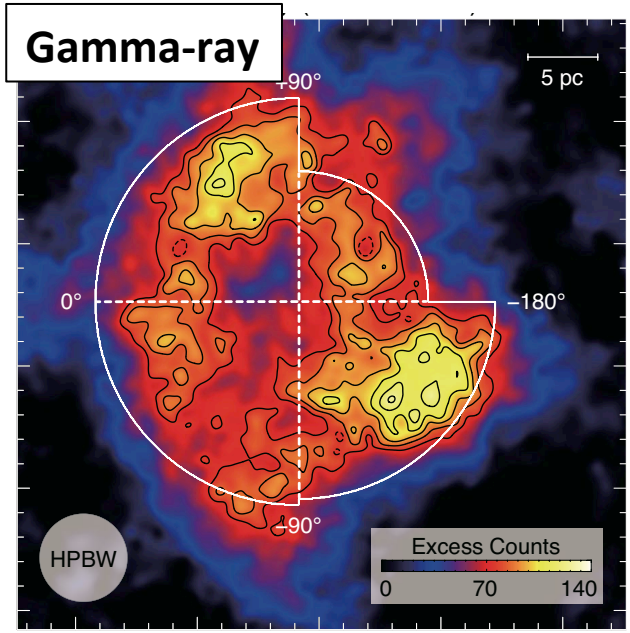
CO + HI

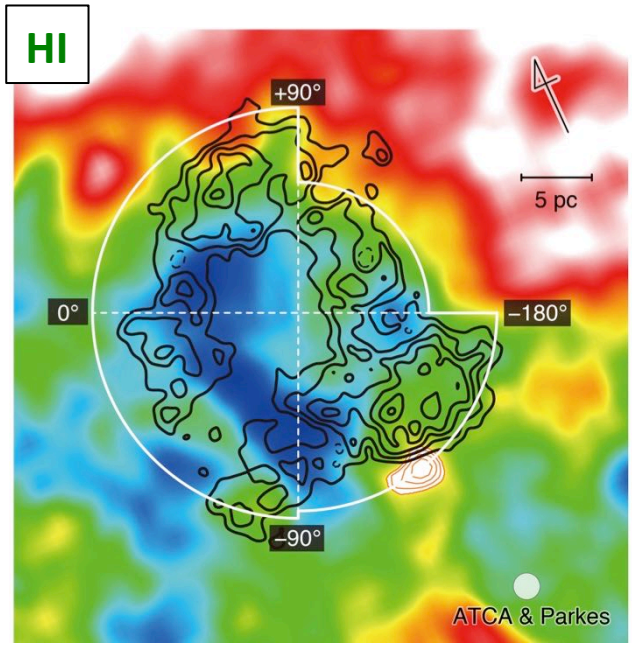


Spatial correspondence between the interstellar protons & TeV gamma-rays

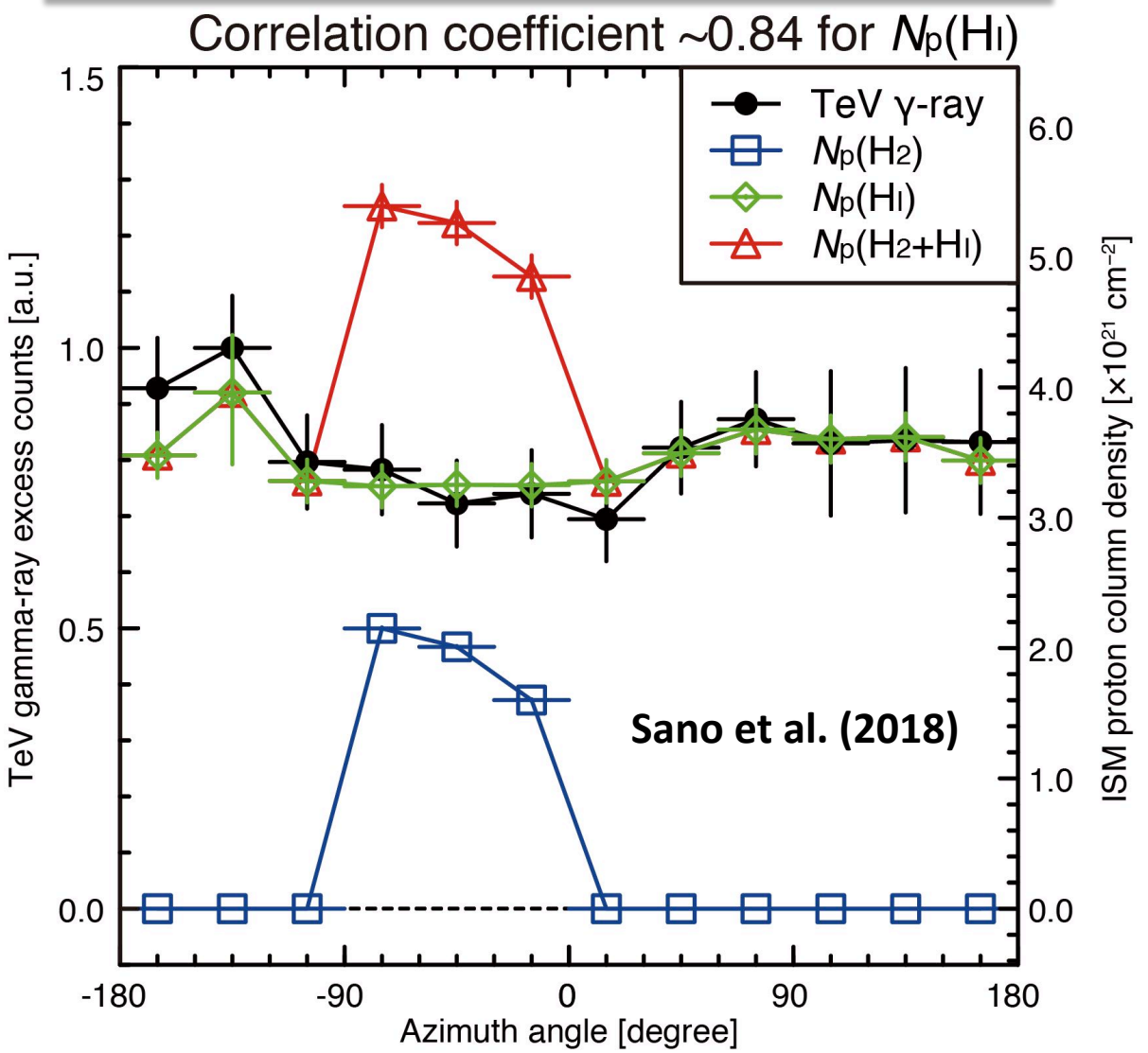


Interstellar gas in RCW 86（Sano+18 to be submitted） 15





Spatial correspondence between the *N*p(HI) & TeV gamma-rays



Total energy of CRs in the young gamma-ray SNRs

$$W_{\rm pp}^{\rm tot} \sim t_{\rm pp\to\pi_0} \times L_\gamma$$
$$t_{\rm pp\to\pi_0} \sim 4.5\times10^{15}\ (n/1\ {\rm cm}^{-3})^{-1}\ {\rm s}$$

Theoretical value of $W_{\rm pp}$ ~10^{49}–10^{50} erg

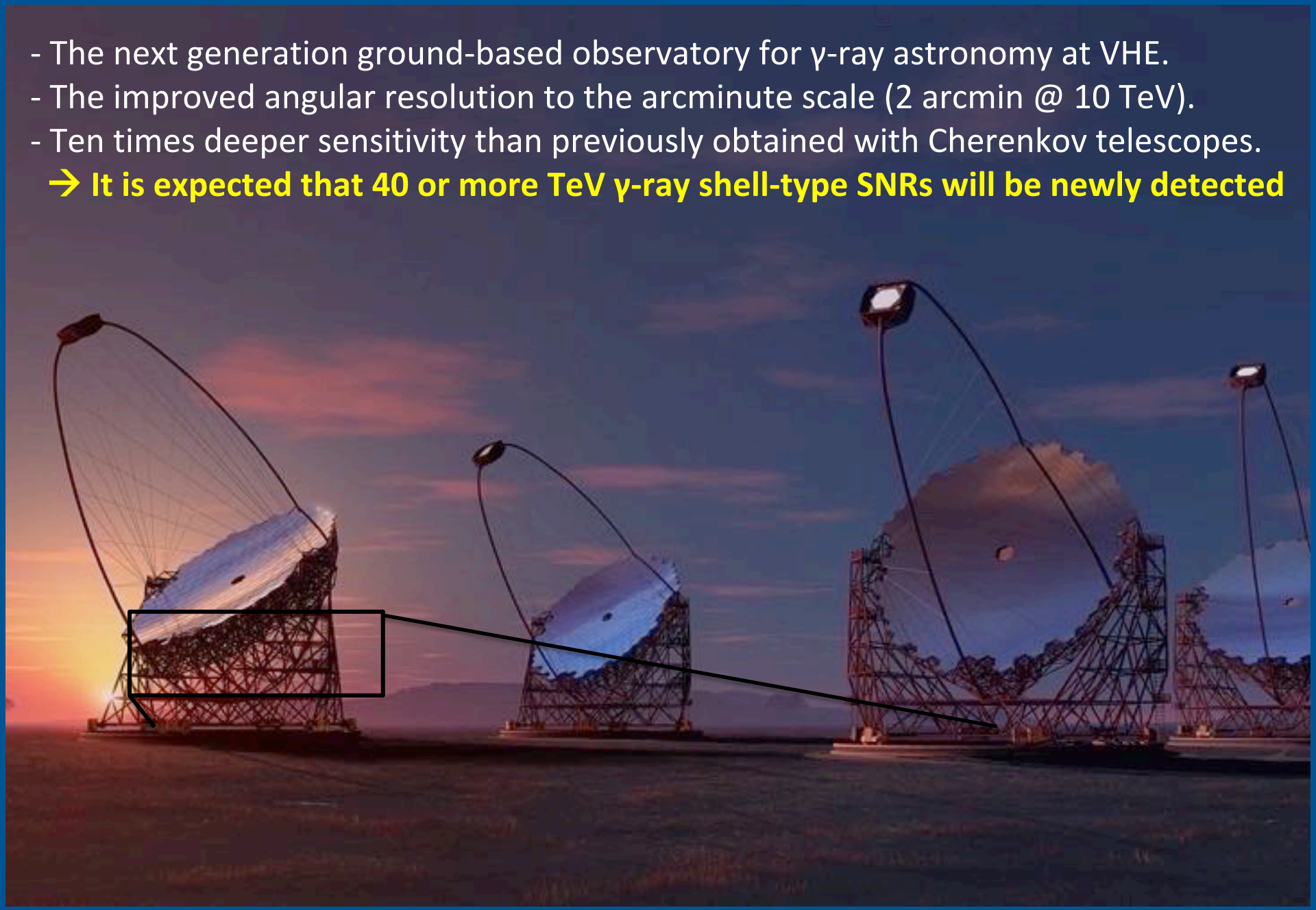
	Fukui+12	Sano+18	Fukui+17	Fukuda+14
	RX J1713	RCW 86	Vela Jr.	HESS J1731
Age (yr)	1600	1800	2400	4000
Distance (kpc)	1	2.5	0.75	5.2
Radius (pc)	8.2	7.5	5.9	11
Atomic mass (10^4 $M_\odot$)	1.1	2.0	2.5	1.3
Molecular mass (10^4 $M_\odot$)	0.9	-----	0.1	5.1
Total ISM mass (10^4 $M_\odot$)	2.0	2.0	2.6	6.4
ISM density (cm^{-3})	130	75	100	60
$W_{\rm pp}$ (10^{48} erg)	**0.4**	**1.2**	**0.7**	**7**
SNR Type	CC	Type Ia	CC?	CC

- A safety lower limit of $W_{\rm pp}$ is ~10^{48-49} erg for young TeV SNRs

Cherenkov Telescope Array (CTA)

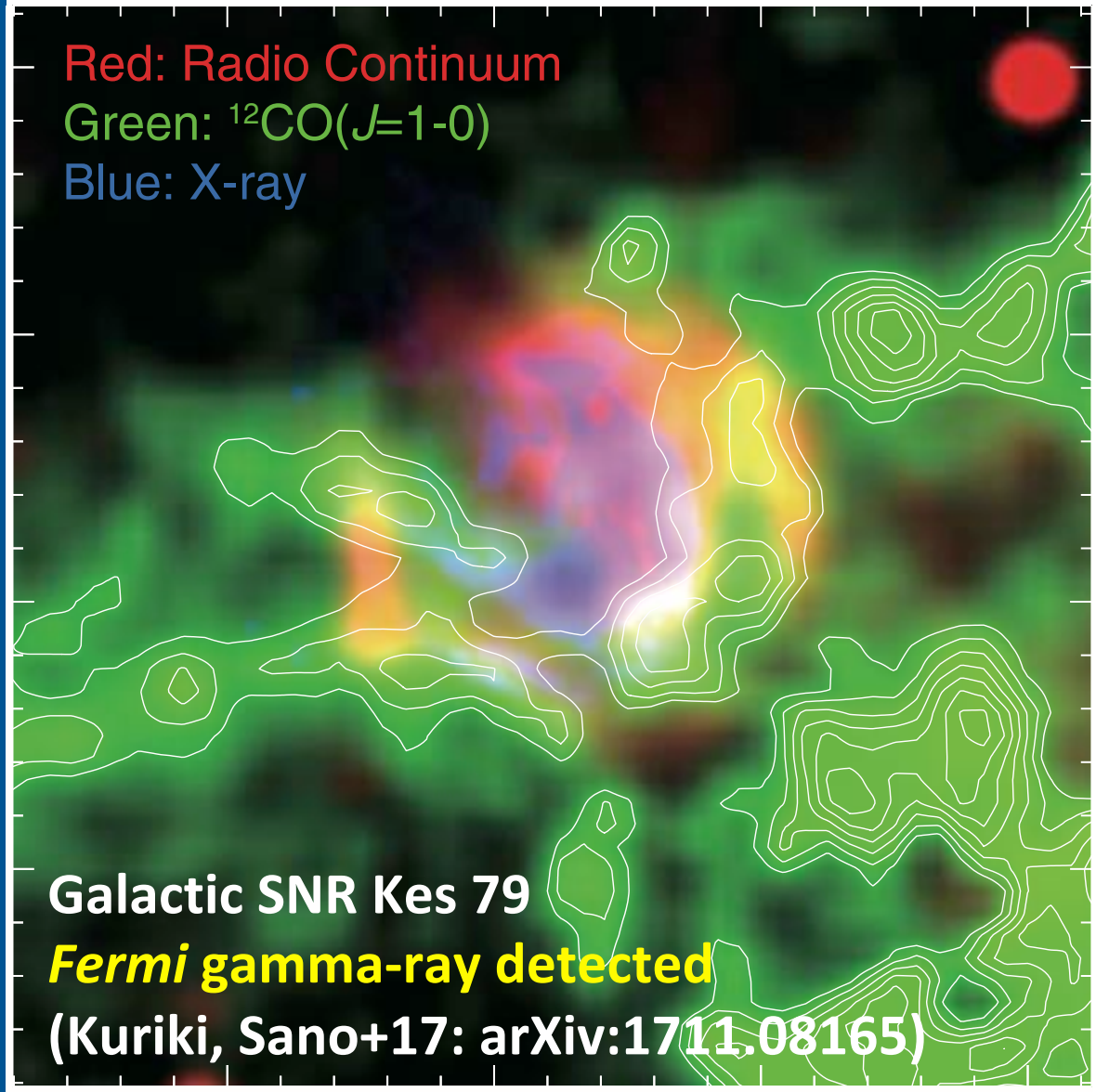
- The next generation ground-based observatory for γ-ray astronomy at VHE.
- The improved angular resolution to the arcminute scale (2 arcmin @ 10 TeV).
- Ten times deeper sensitivity than previously obtained with Cherenkov telescopes.

→ **It is expected that 40 or more TeV γ-ray shell-type SNRs will be newly detected**



Investigating the ISM associated with X-ray bright SNRs

■ **CO surveys using NANTEN2, Mopra & NRO 45-m are useful !!**



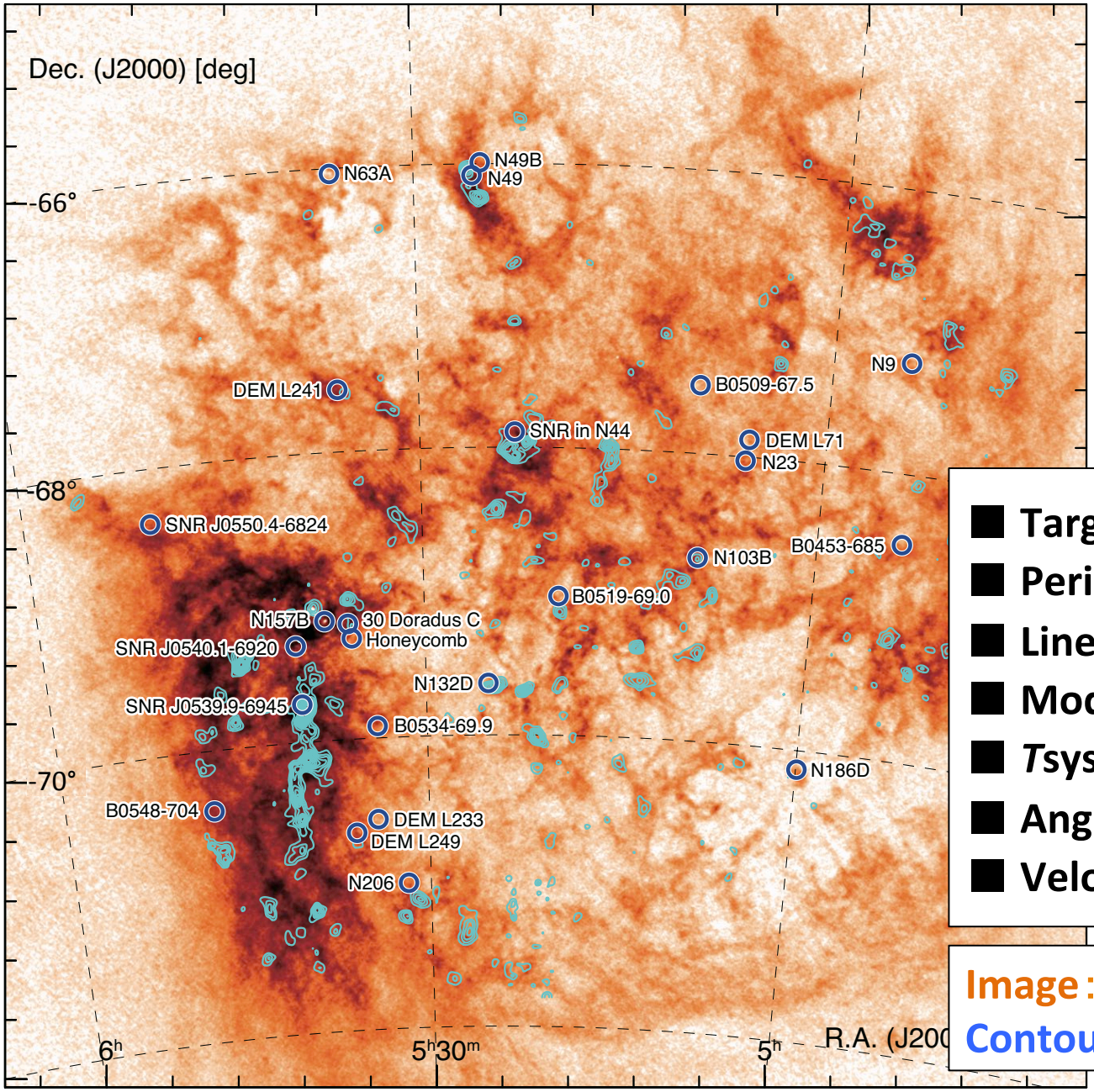
■**Coverage**
$10° < l < 50°$, $|b| < 1°$ (inner)

■**Lines**
^{12}CO, ^{13}CO, C^{18}O J = 1–0

■**Sensitivity**
^{12}CO: ~1.5 K, ^{13}CO,C^{18}O: ~0.7 K

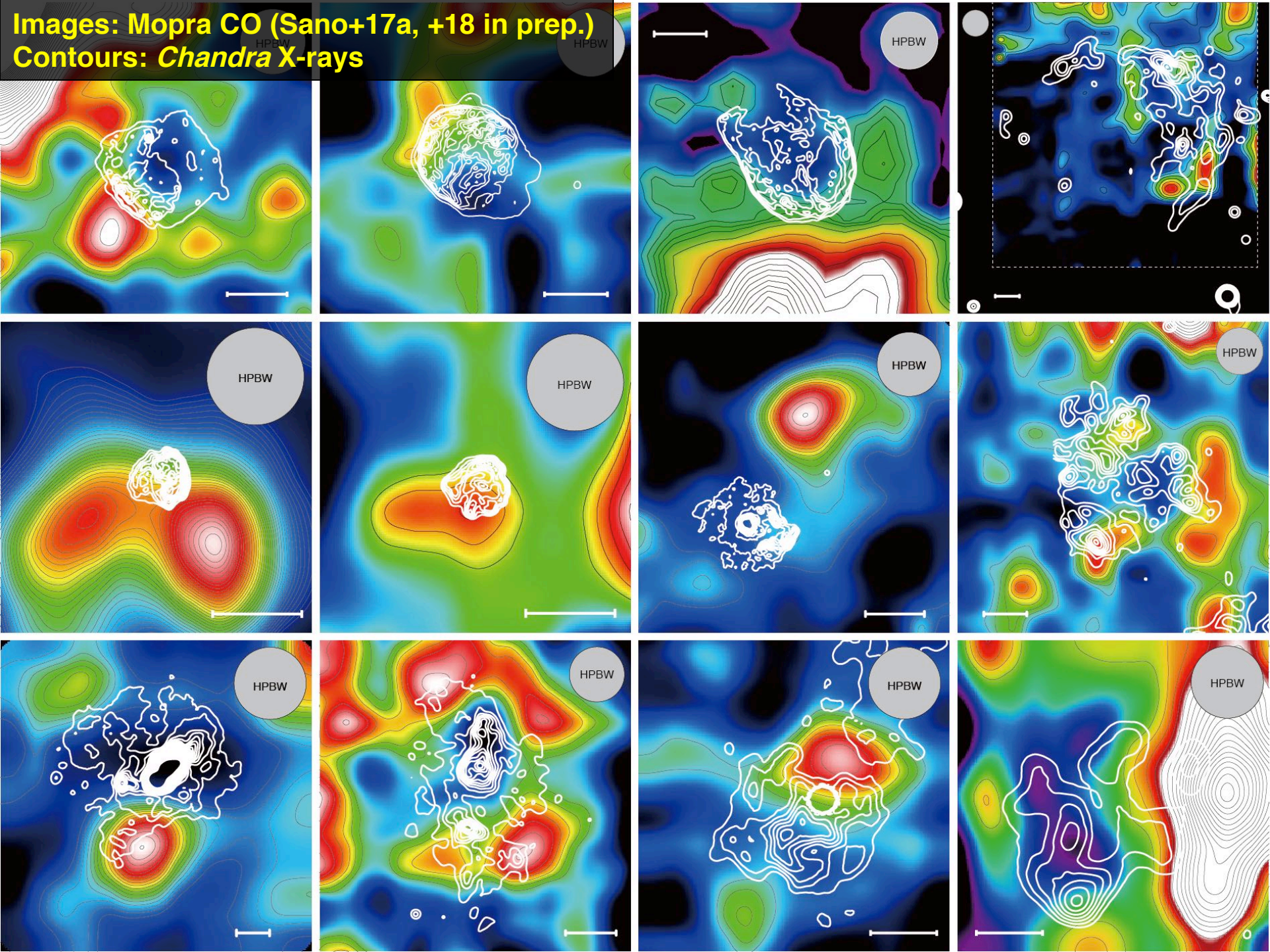
■**Resolution**
Angular resolution ~20 arcsec
Channel resolution ~0.65 km s^{-1}

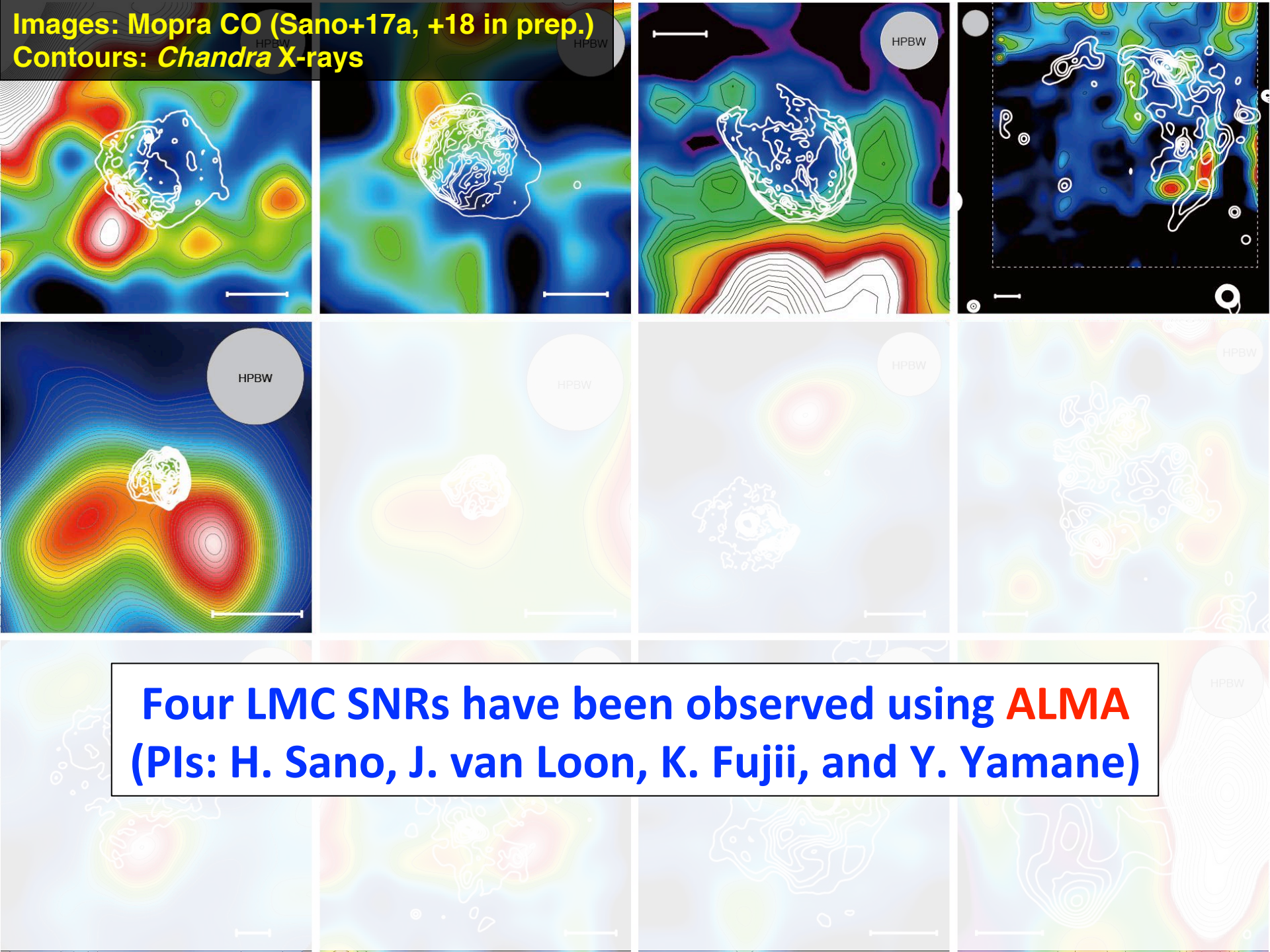
CO survey of Magellanic SNRs (Sano+17a, +18 in prep.)



- **Target**: X-ray bright SNRs
- **Period**: 2013/7–2015/5
- **Line**: 12CO(J = 1–0)
- **Mode**: On-the-fly (OTF)
- ***T*sys**: ~600–1000 K
- **Angular reso.**: ~45" (~11 pc)
- **Velocity reso.**: ~0.088 km s^{-1}

Image : ATCA & Parkes HI
Contours : NANTEN ^{12}CO *J* = 1–0


Images: Mopra CO (Sano+17a, +18 in prep.)
Contours: *Chandra* X-rays
HPBW


Images: Mopra CO (Sano+17a, +18 in prep.)
Contours: *Chandra* X-rays
HPBW
HPBW
HPBW
HPBW
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HPBW
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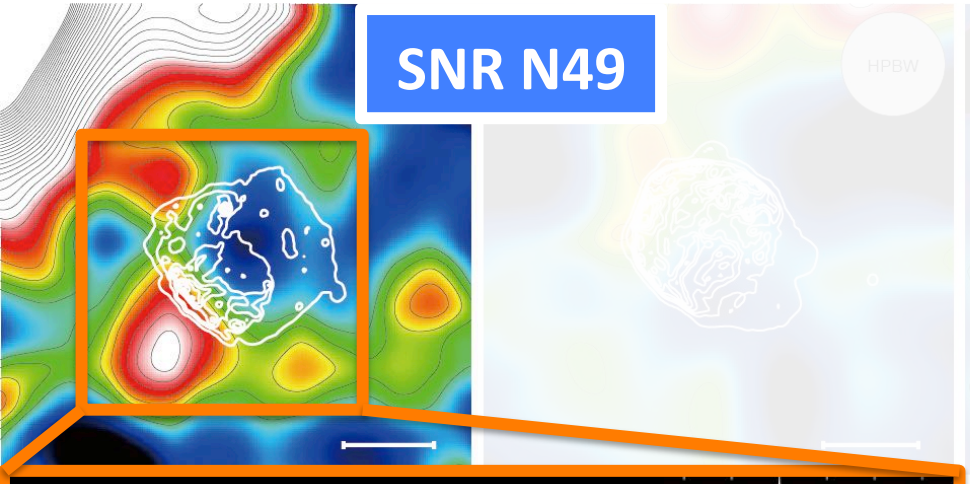
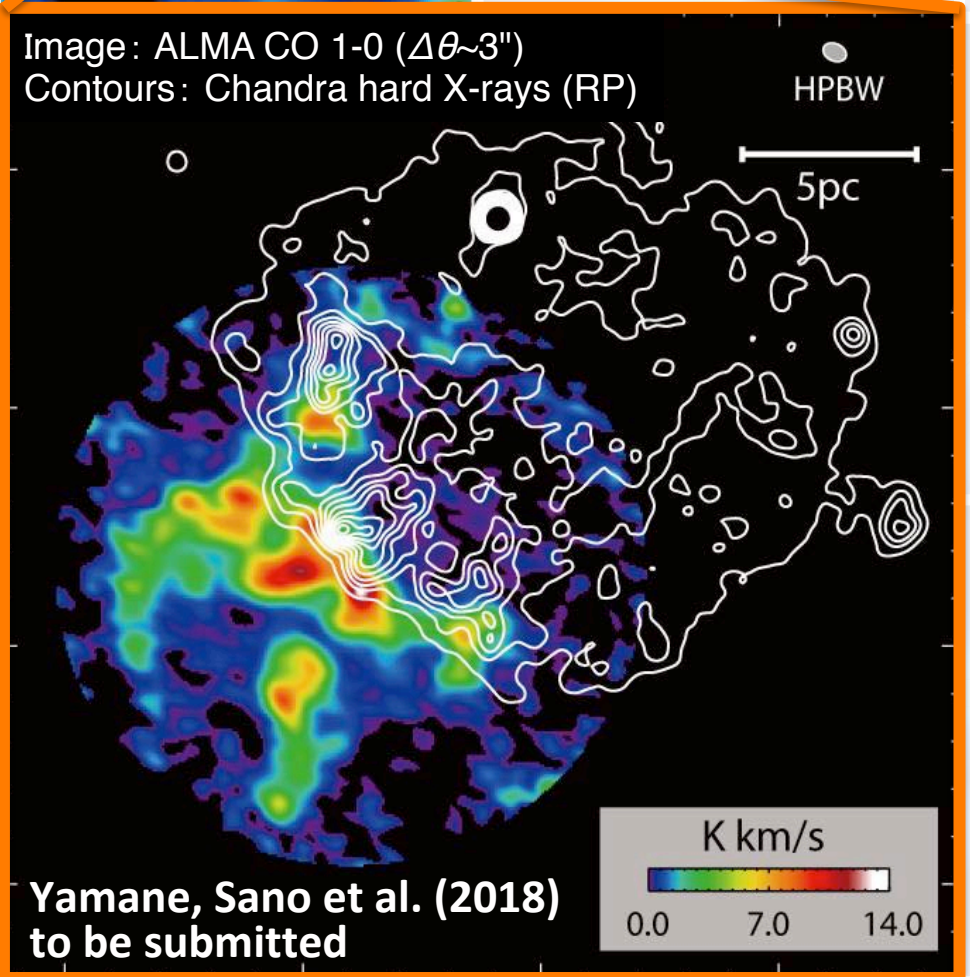
HPBW
Four LMC SNRs have been observed using ALMA
(PIs: H. Sano, J. van Loon, K. Fujii, and Y. Yamane)

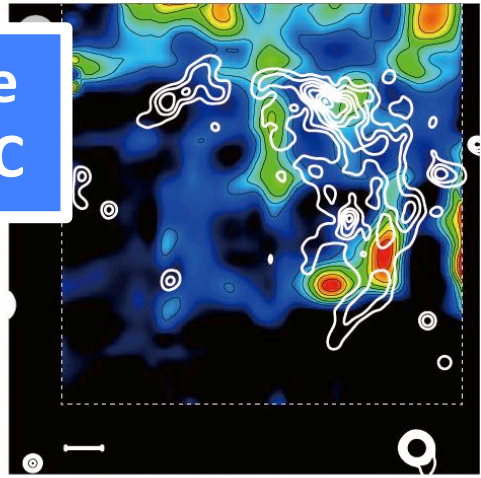
SNR N49

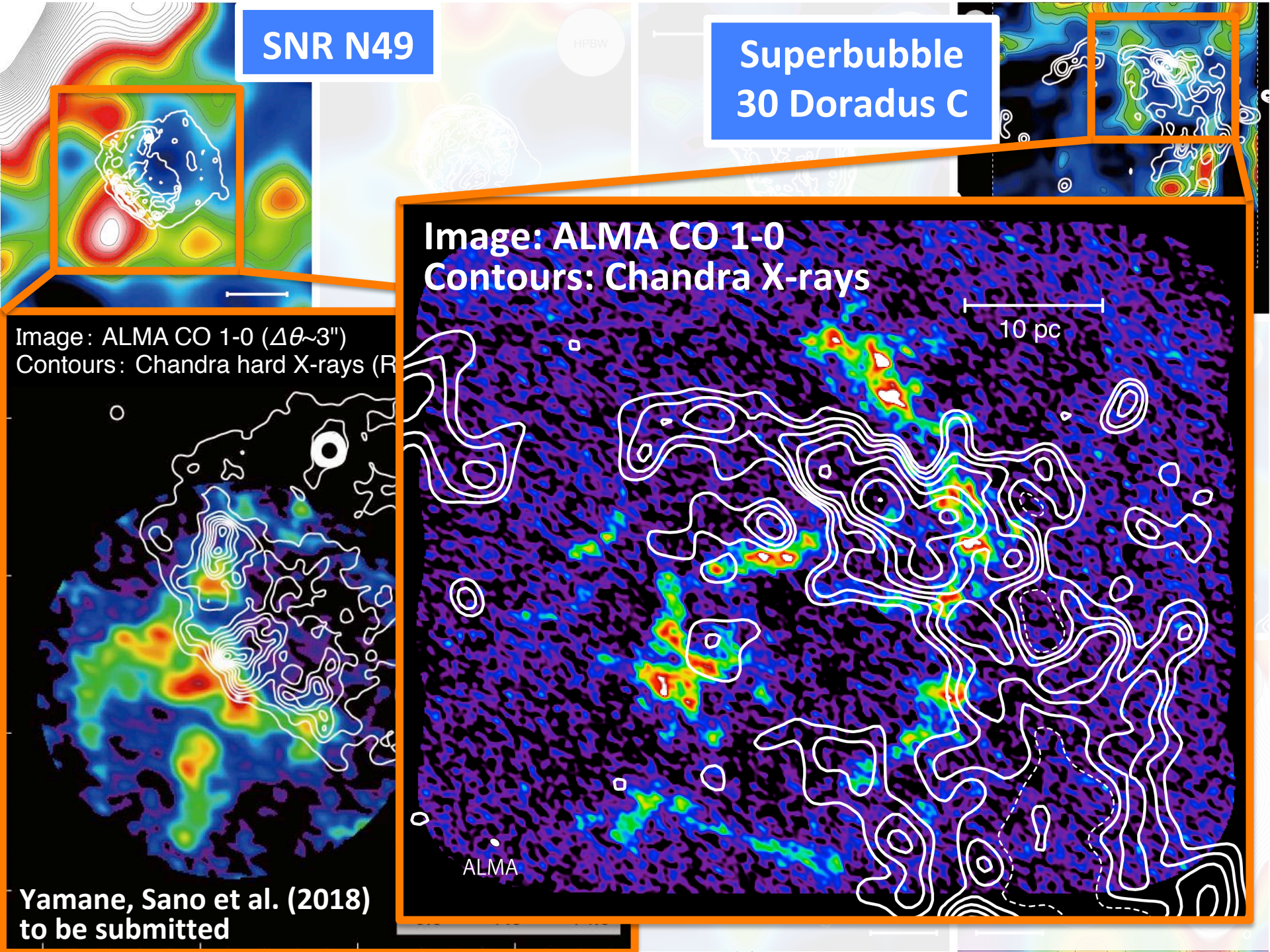




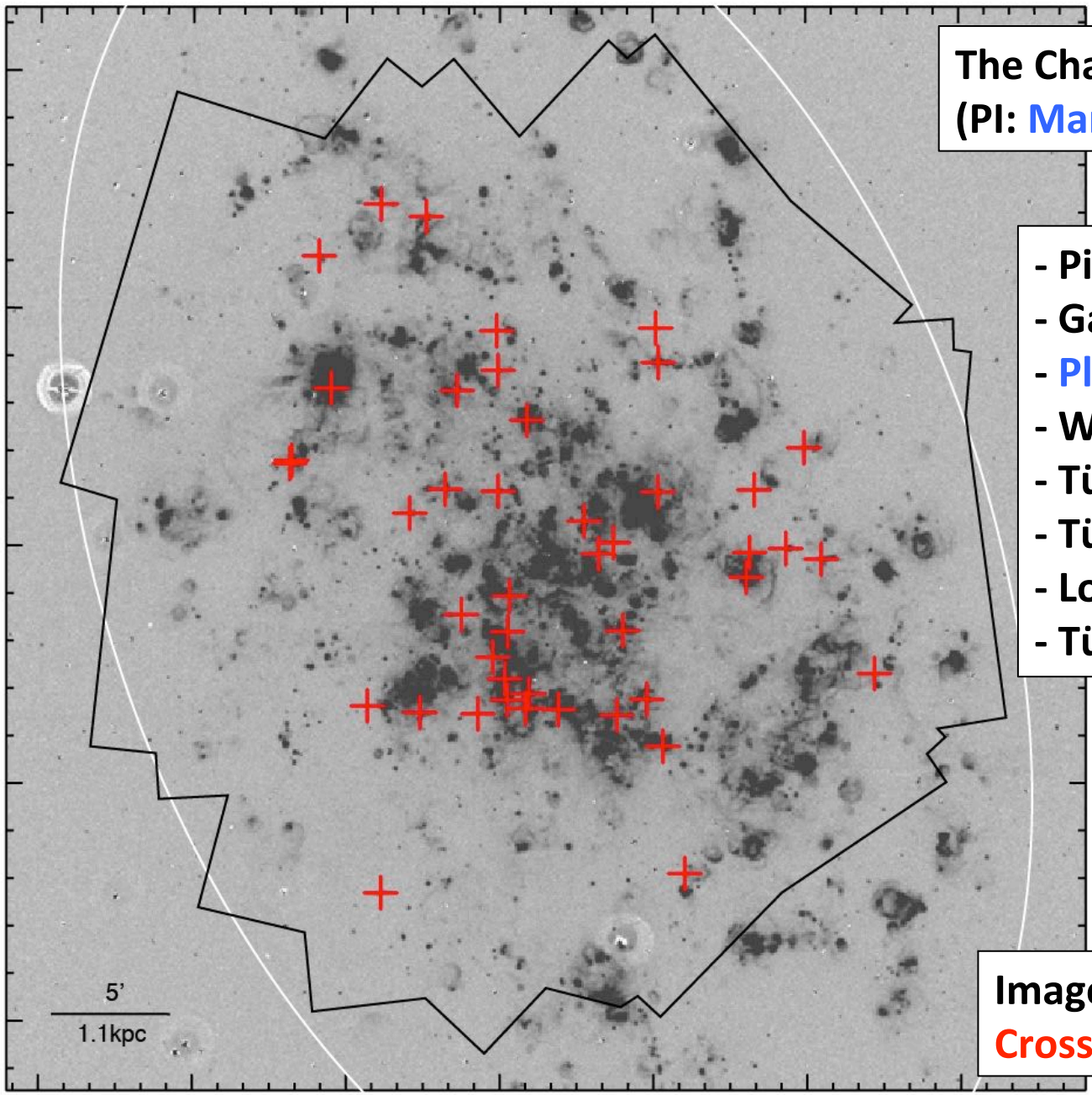
Yamane, Sano et al. (2018)
to be submitted

Superbubble 30 Doradus C




SNR N49
Superbubble
30 Doradus C
Image: ALMA CO 1-0
Contours: Chandra X-rays
10 pc
ALMA
Image: ALMA CO 1-0 (Δθ~3")
Contours: Chandra hard X-rays (R
Yamane, Sano et al. (2018)
to be submitted

X-ray Bright SNRs in M33

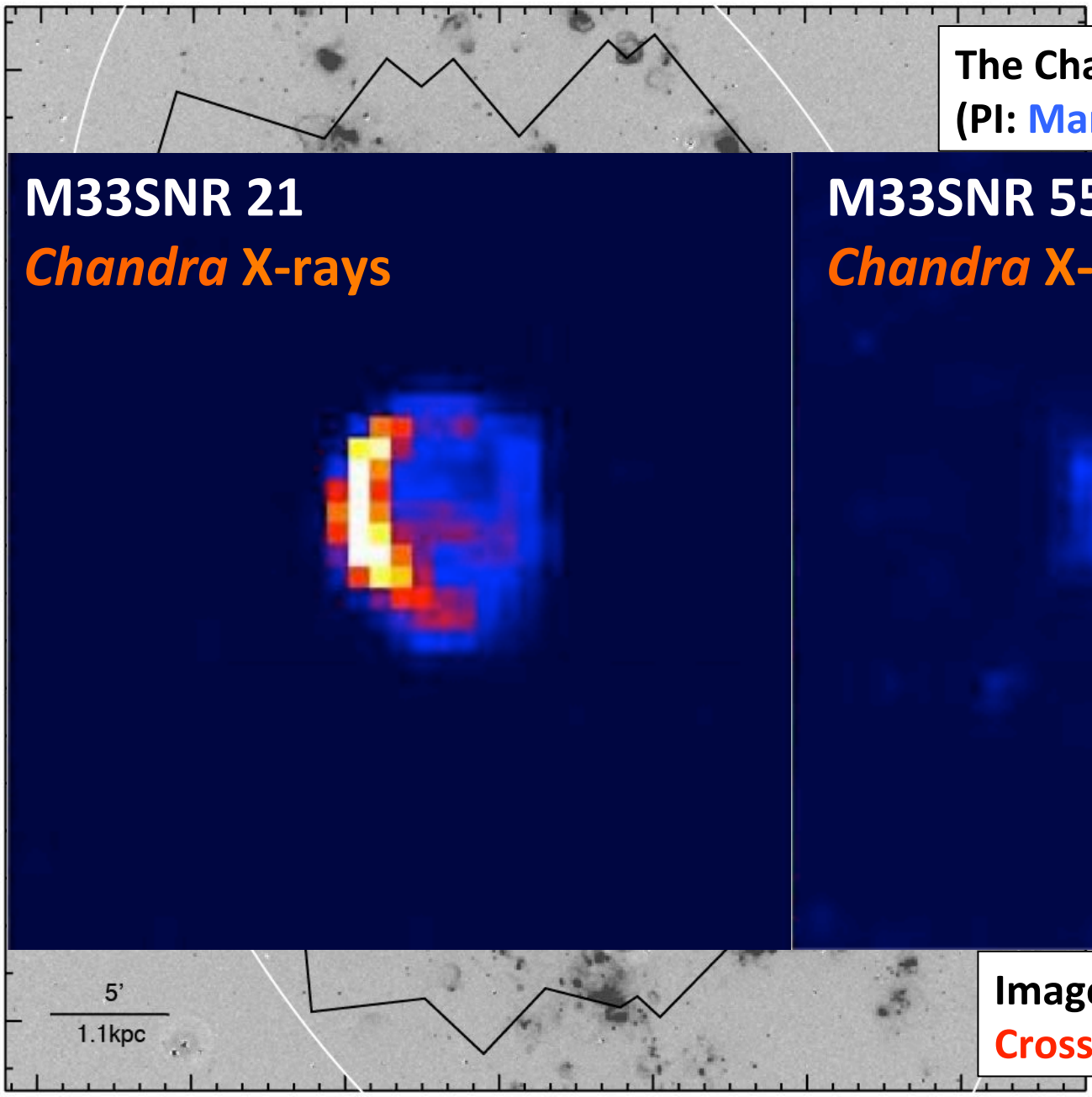


The Chandra ACIS Survey of M33
(PI: Manami Sasaki)

- Pietsch+06 (M33 X-7)
- Gaetz+07 (M33SNR 21)
- Plucinsky+08 (First Look)
- Williams+08 (Transient)
- Tüllmann+08 (NGC 604)
- Tüllmann+09 (IC131)
- Long+10 (SNRs)
- Tüllmann+11 (Src Catalog)

Image : Optical
Crosses : X-ray SNRs (Long+10)

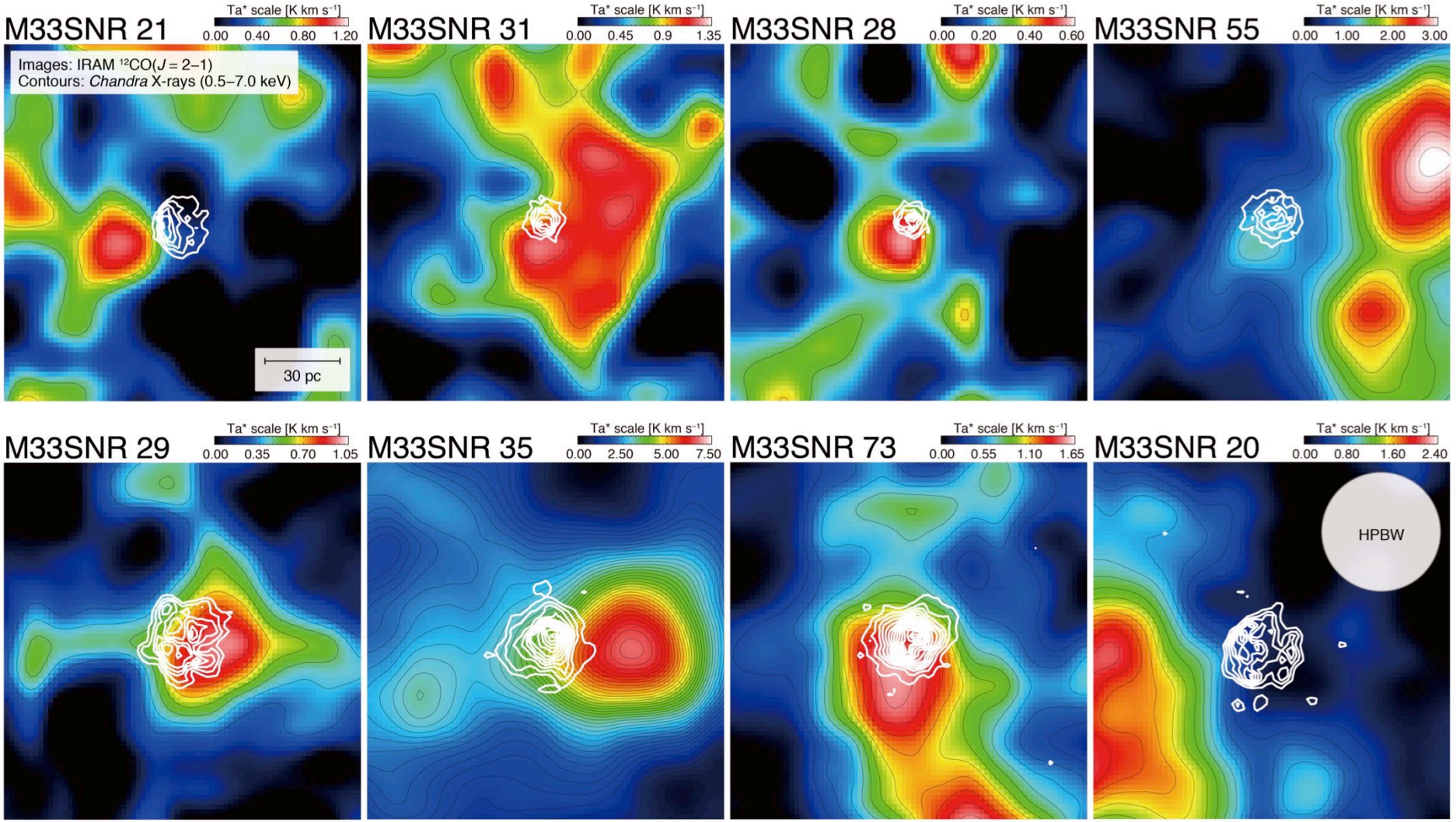
X-ray Bright SNRs in M33



Molecular gas associated with X-ray Bright SNRs in M33

Extremely Preliminary Results

Sano, Fukui, Sasaki, Knies et al.



- All X-ray brightest SNRs in M33 are possibly associated with GMCs
  → ALMA observation will reveal CO clumps associated with the SNRs.

Summary

- **Young SNRs & interstellar gas**
  - Candidate for the Galactic cosmic-ray accelerator
  - Molecular cloud (> 1000 cm^{-3}), Atomic cloud (~1–100 cm^{-3})
- **Shock-cloud interaction**
  - Enhancement of the turbulence & *B* field around the gas clumps
  - Gas distribution may control the synchrotron X-ray spectra
- **Good spatial correspondence between the ISM & gamma-rays**
  - CR protons are accelerated over 1 TeV in the young SNRs
- **Science toward the CTA era**
  - CO surveys are useful to identify MCs with gamma-ray SNRs
  - CO surveys of Magellanic & M33 SNRs are ongoing!!

Interstellar gas associated with SNRs plays an essential role in understanding the origins of X-, γ-rays and CRs !!