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Interstellar Gas toward Young Gamma-Ray SNRs

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2017/12/18（Mon.）@ Kashiwa, University of Tokyo
The extreme Universe viewed in very-high-energy gamma-rays 2017

Outline

To understand the CR acceleration in SNRs, detailed study of the ISM is important

Molecular cloud (H_2): $n > 1000$ cm^{-3}
Atomic cloud (HI): $n \sim$ 1- several 100 cm^{-3}

- **Shock-cloud interaction**
  - *B* field amplification around ISM clumps affects CR electron & synchrotron X-ray enhancement (e.g., Sano+10,13,17, Inoue+12)
- **Hadronic Gamma-rays**
  - The ISM is a target of the CRs accelerated in SNR shock
    → Accurate estimation of the ISM is crucial
- **SNR science toward the CTA era**
  - Identifying the ISM associated with SNRs using CO survey data!!

Supernova & Supernova Remnant (SNR)

- An explosion that occurs during the death of massive star or white dwarf(s)
- The shock waves are as fast as 3,000 km s^{-1}, which accelerate cosmic-rays
- The surrounding ISM holds a key to understand physical processes of SNR

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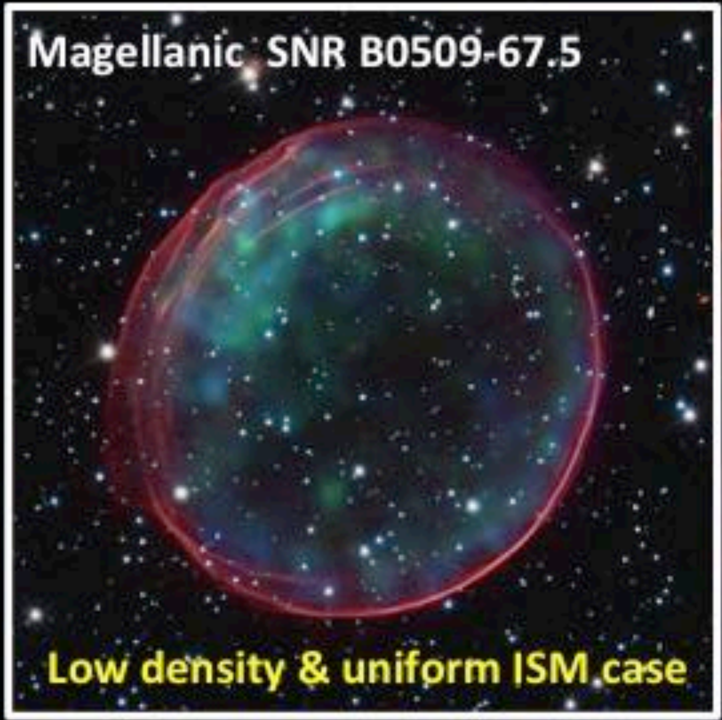

Young Shell type SNR RX J1713.7–3946

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

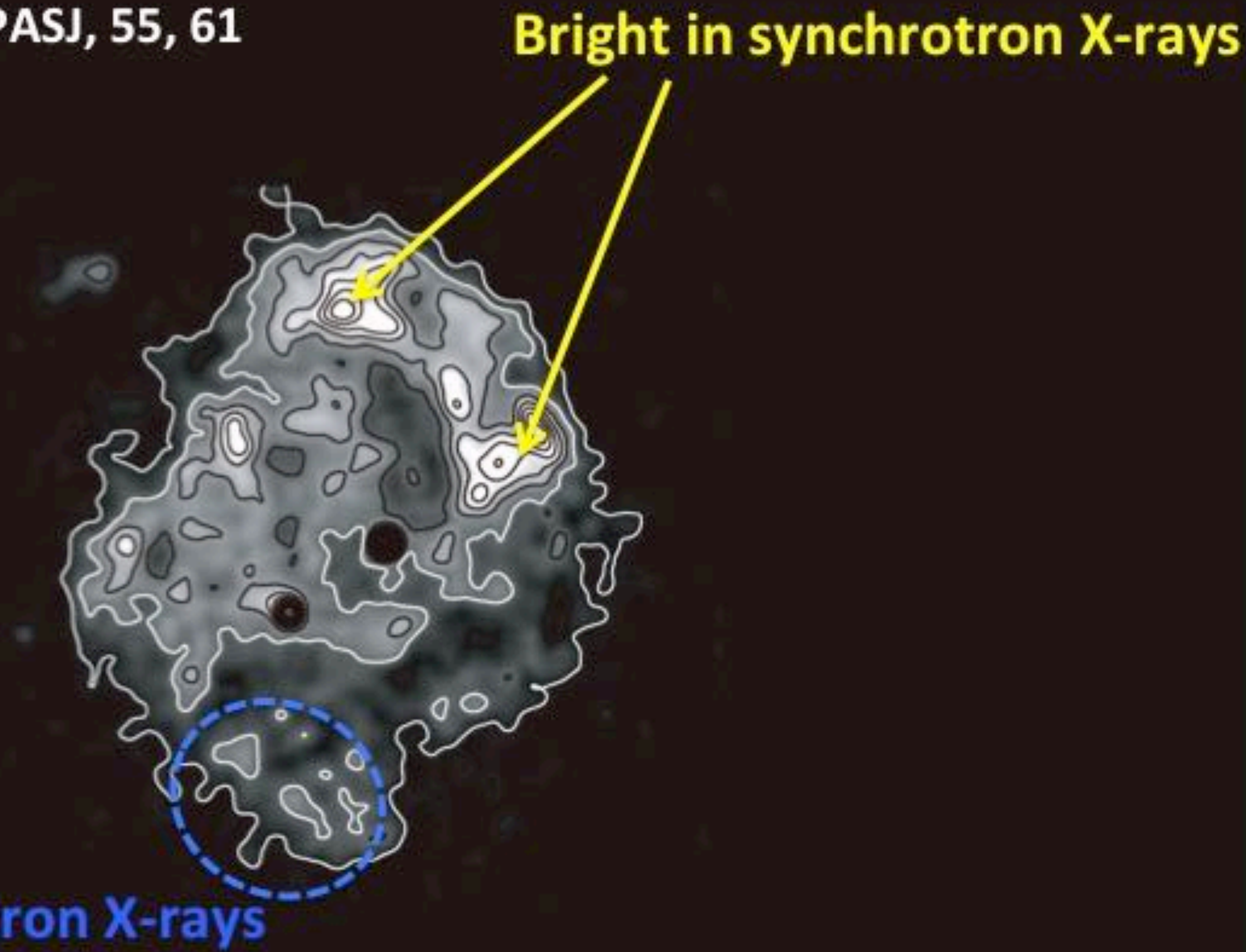

Image: ROSAT synchrotron X-rays

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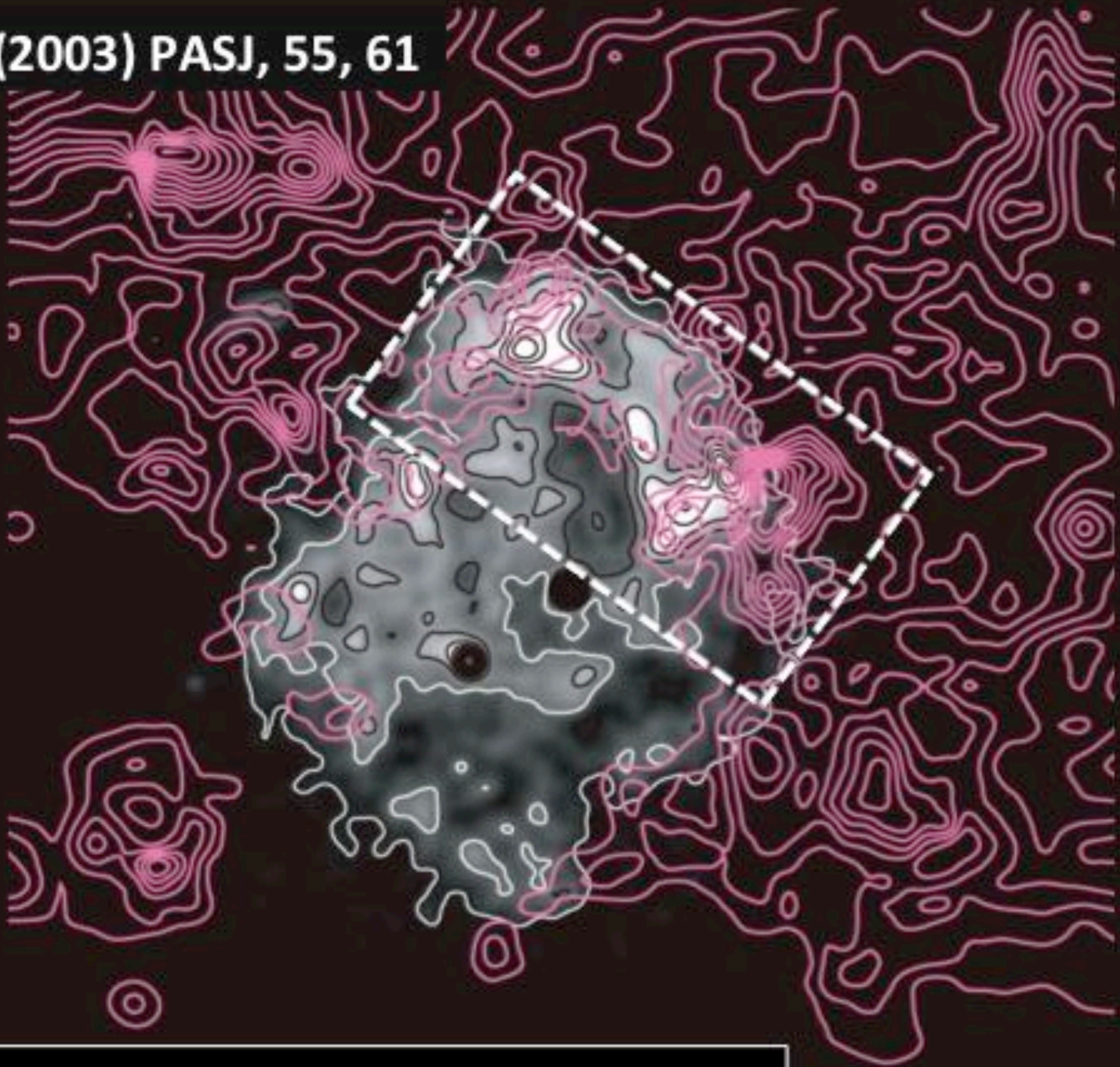
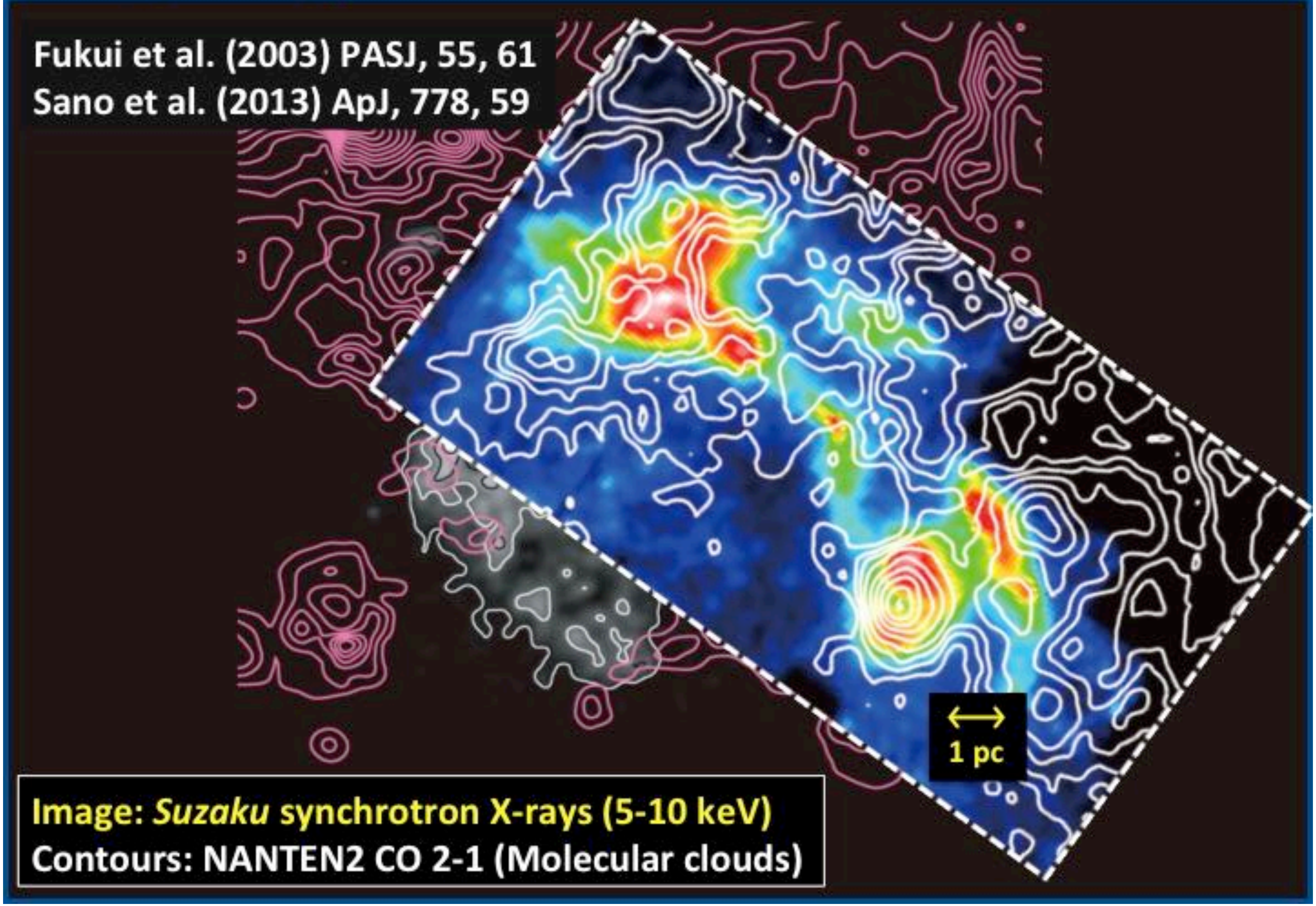


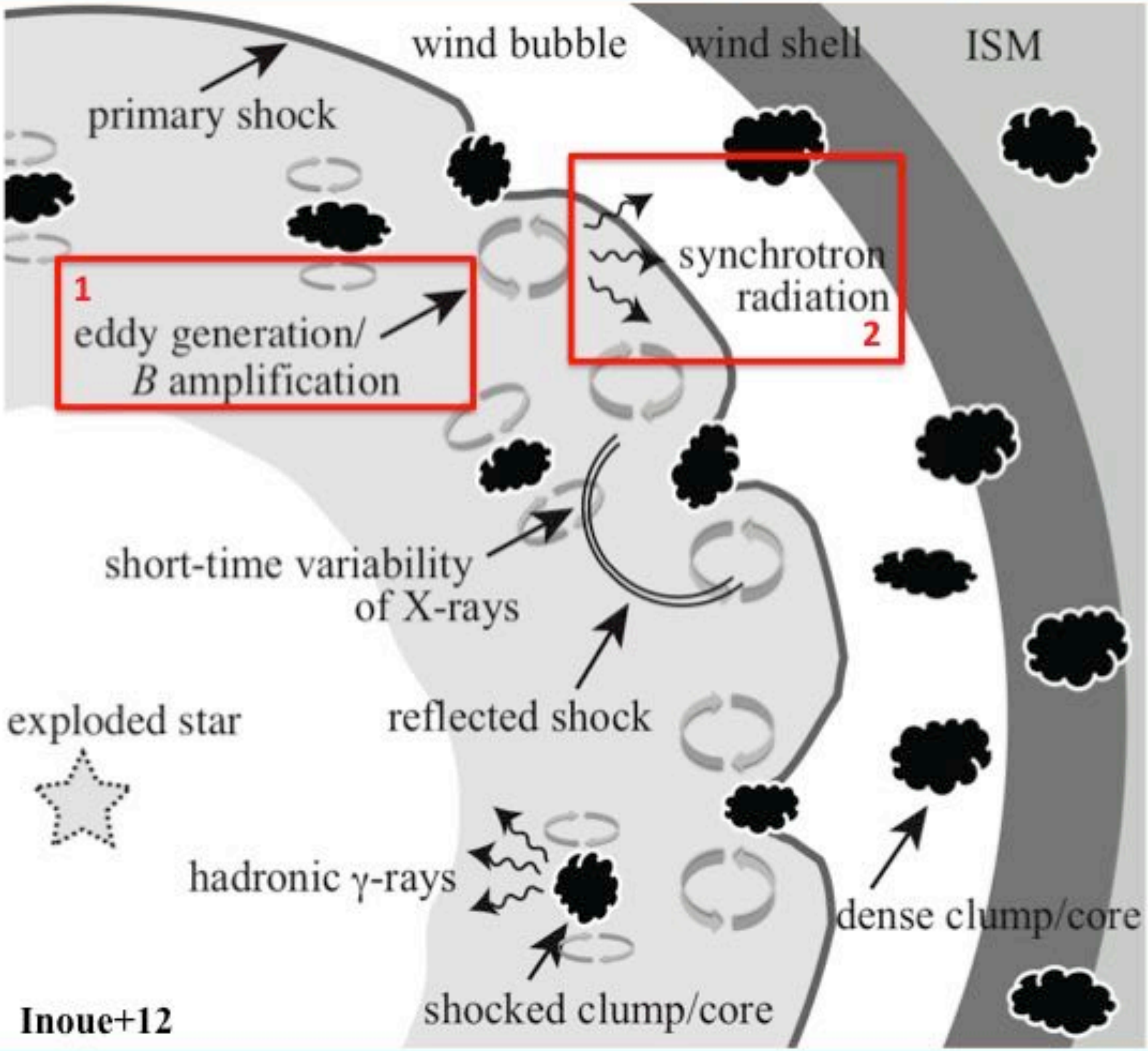
Image: ROSAT synchrotron X-rays

Contours: NANTEN CO 1-0 (Molecular clouds)

Young Shell type SNR RX J1713.7–3946

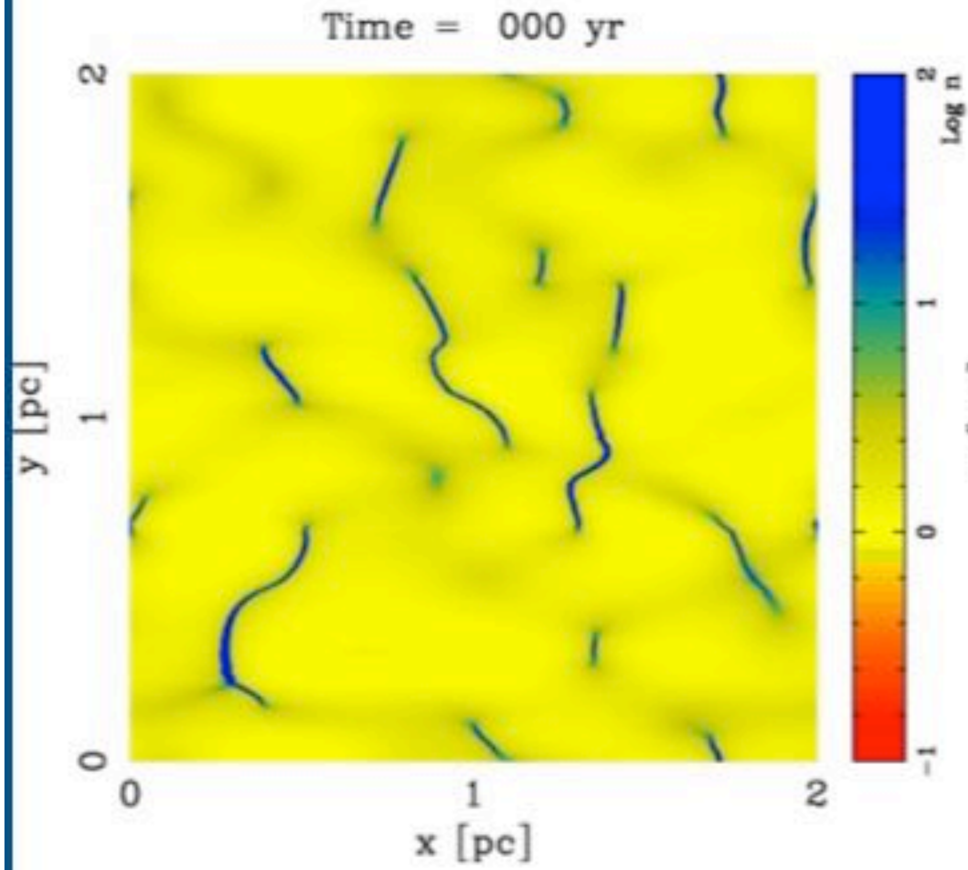


Shock interaction with the inhomogeneous gas

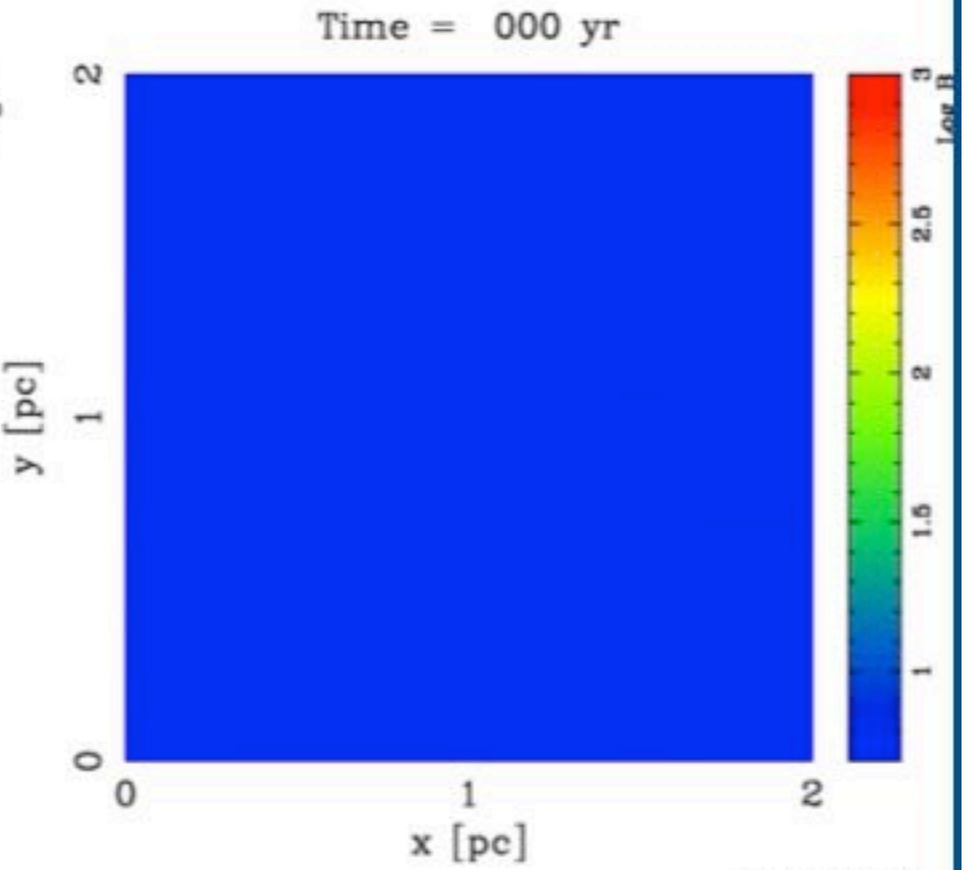


Shock-cloud Interaction: MHD simulation

Gas density



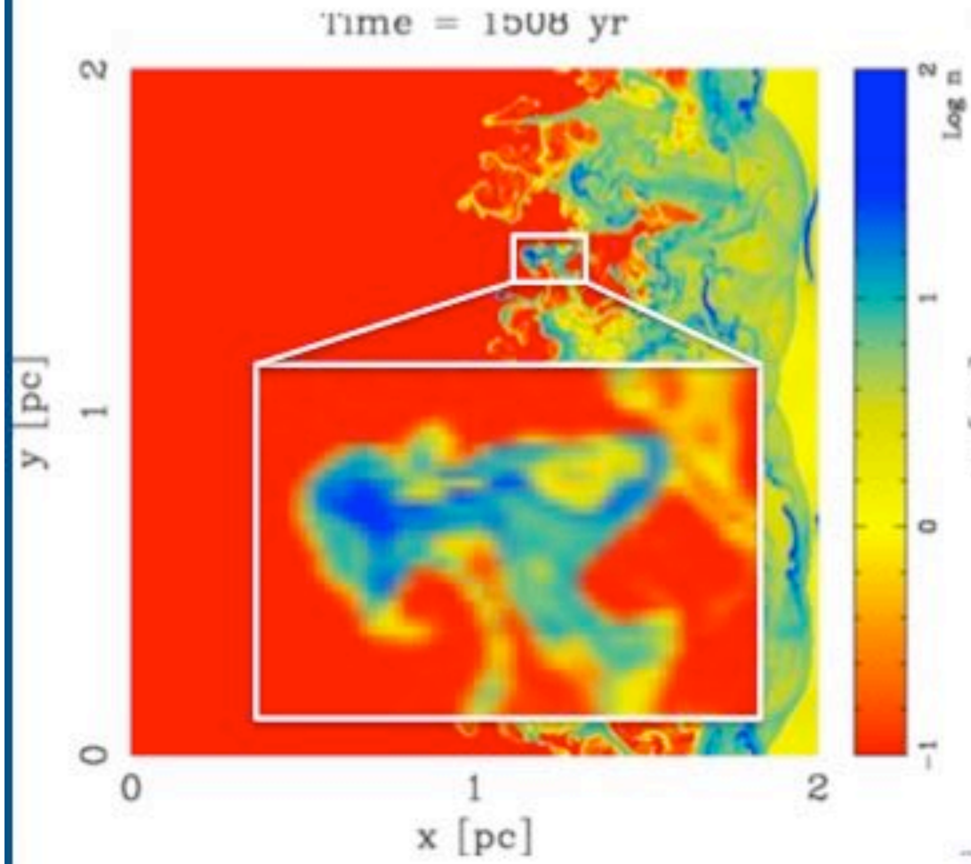
B Field strength



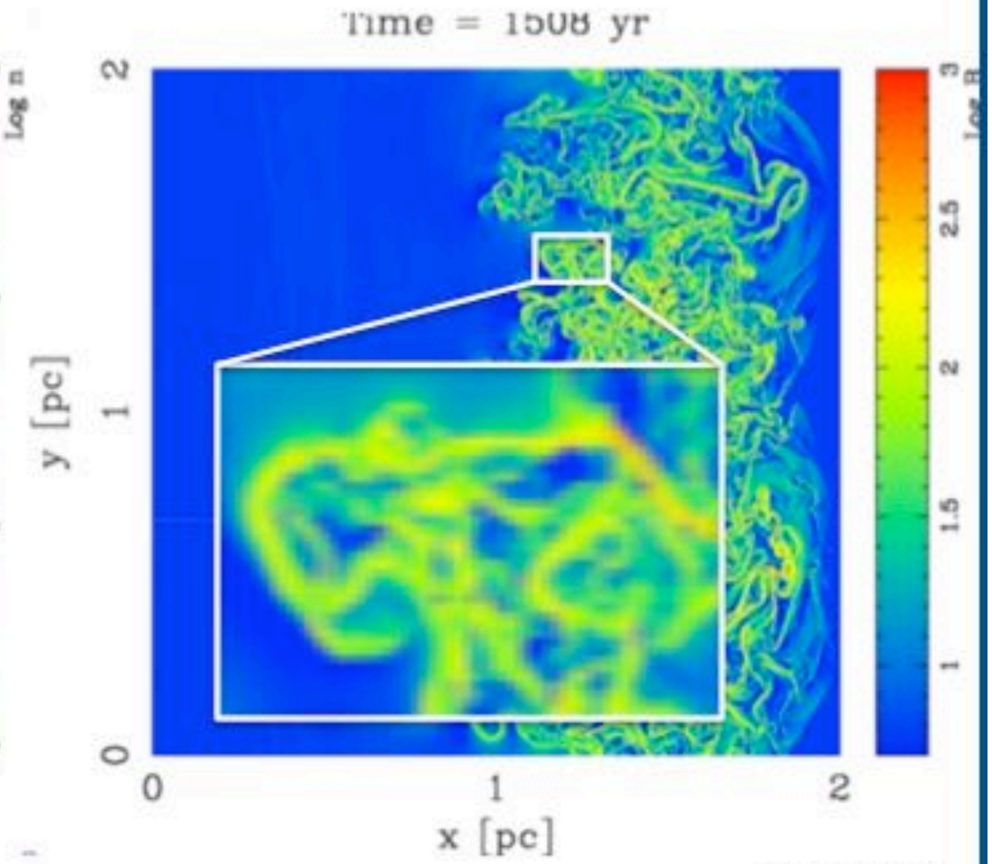
Inoue+12

Shock-cloud Interaction: MHD simulation

Gas density



B Field strength

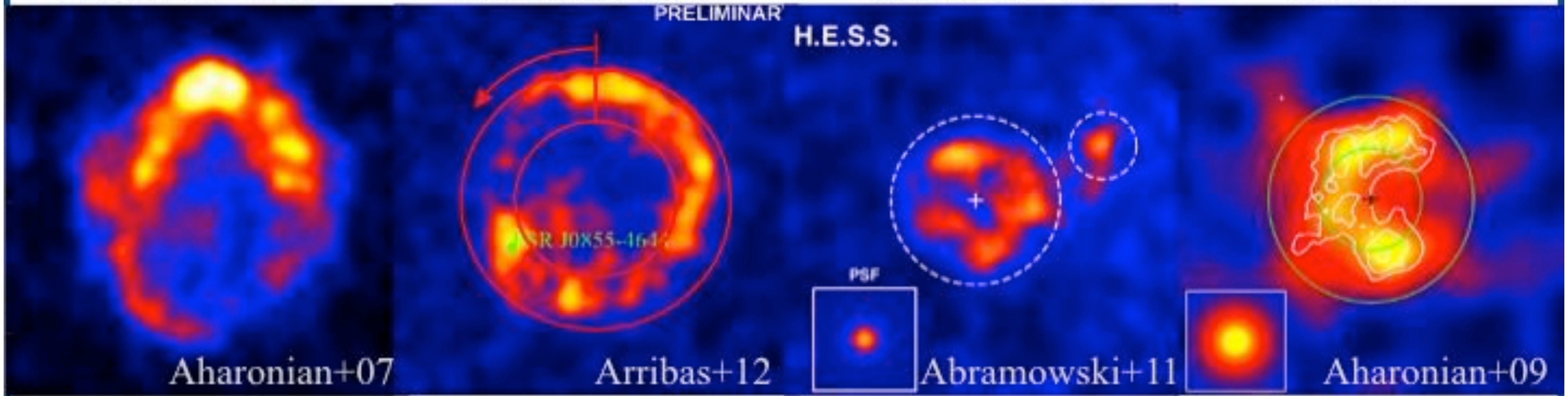


Inoue+12

- *B* field is amplified around CO-like clumps
- Maximum *B* field strength reaches ~1 mG
  (Averaged *B* field becomes ~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.

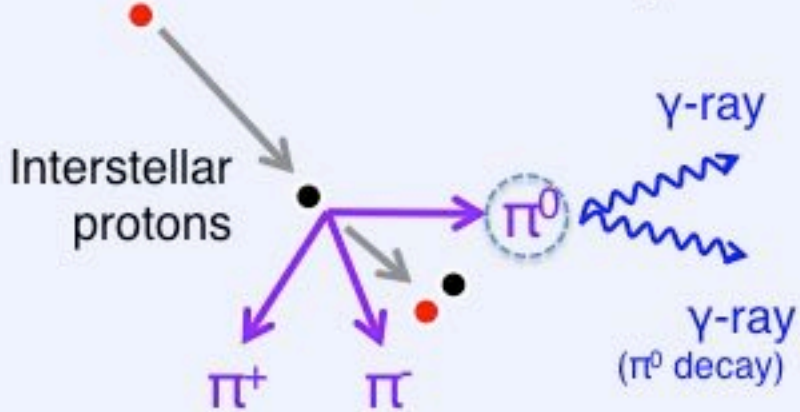


RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
diameter: ~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
age: ~1600 yr	~1700–4300 yr	~3600–7200 yr	~1800 yr
ISM: rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays: pure synchrotron	pure synchrotron?	pure synchrotron	thermal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

Radiative processes of gamma-rays in the young SNRs

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

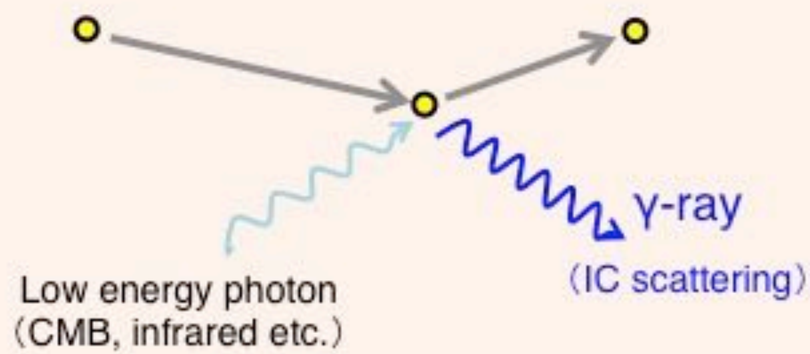
CR protons 【Hadronic process】



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

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

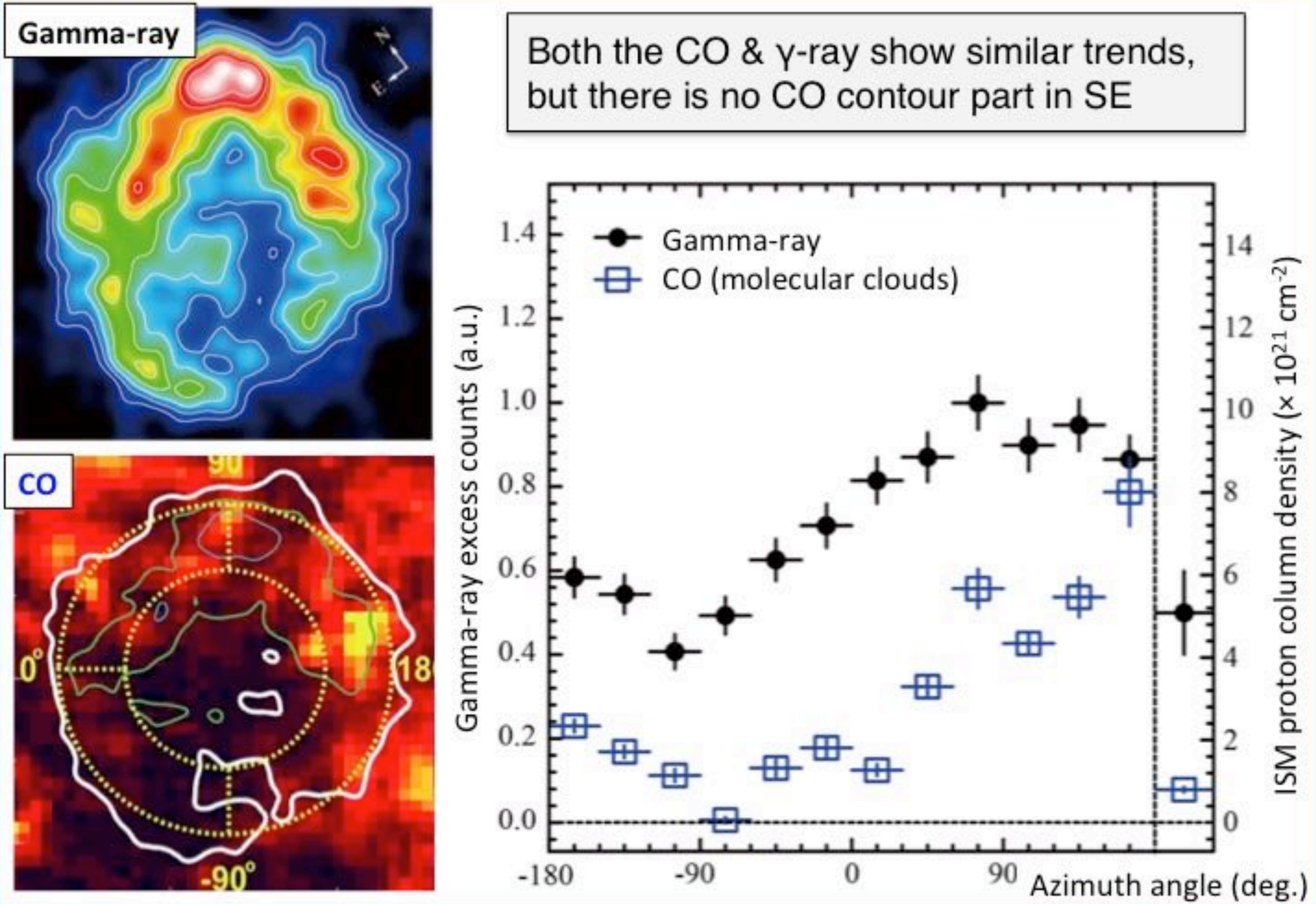
CR electrons 【Leptonic process】



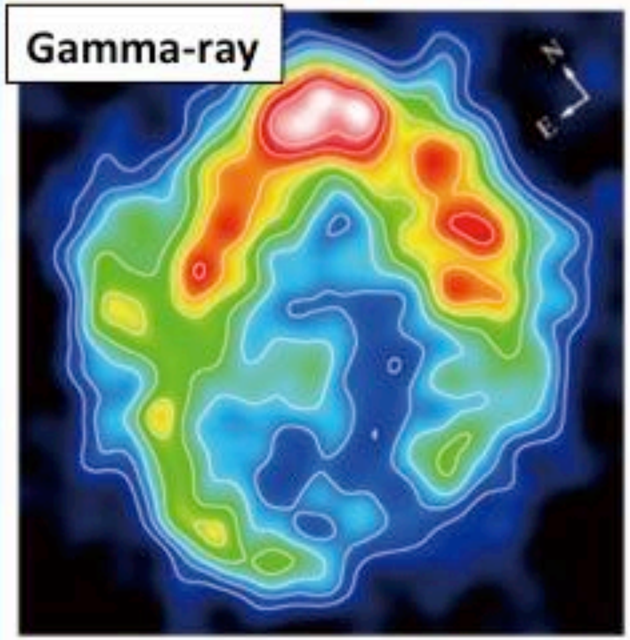
If the hadronic process is working,
→ **gamma-ray flux ∝ gas density**

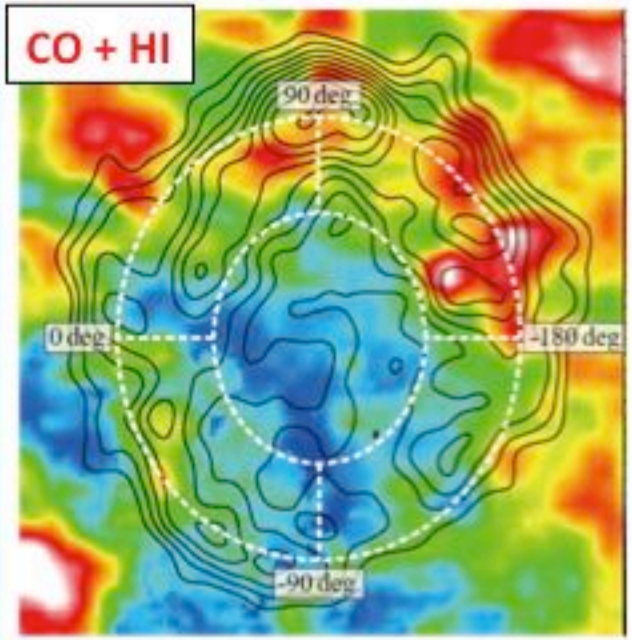
TeV gamma-rays & molecular clouds (Aharonian+06)

Both the CO & γ-ray show similar trends, but there is no CO contour part in SE

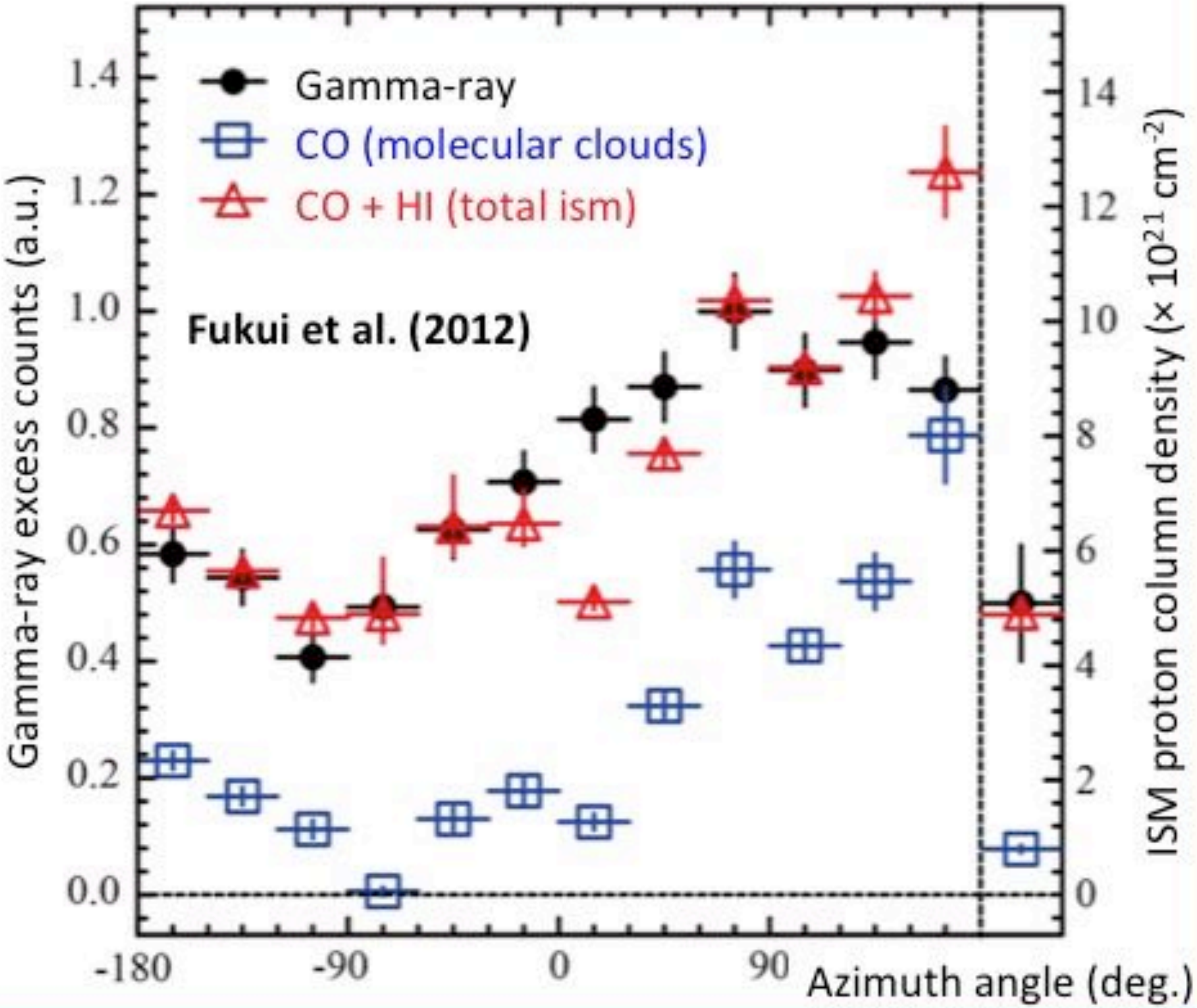


Hadronic γ-rays: Evidence for CR proton（Fukui+12）



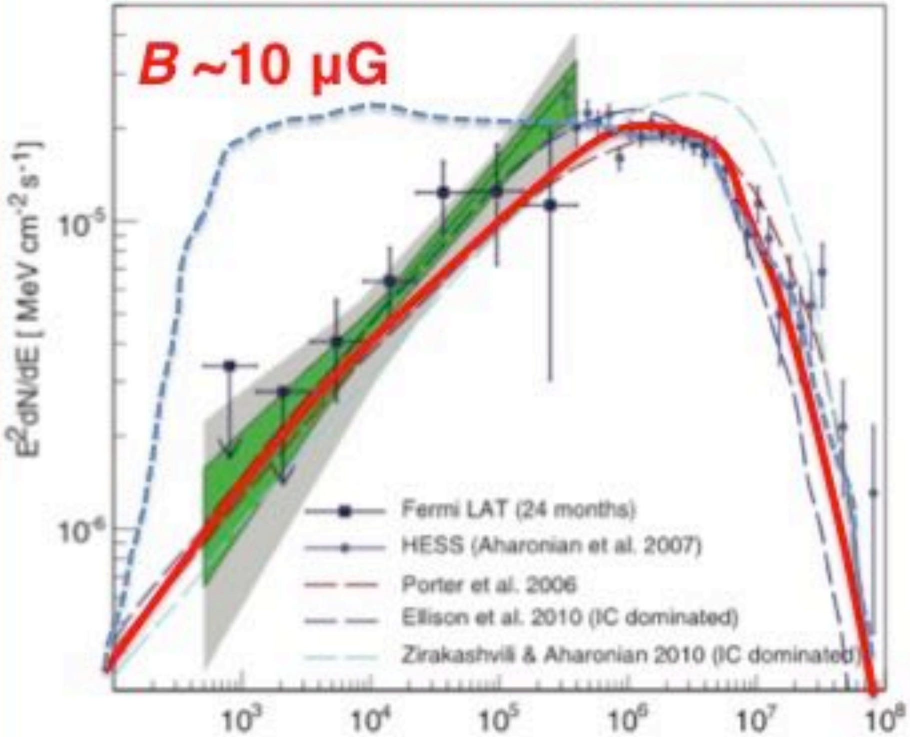


Spatial correspondence between the interstellar protons & TeV gamma-rays

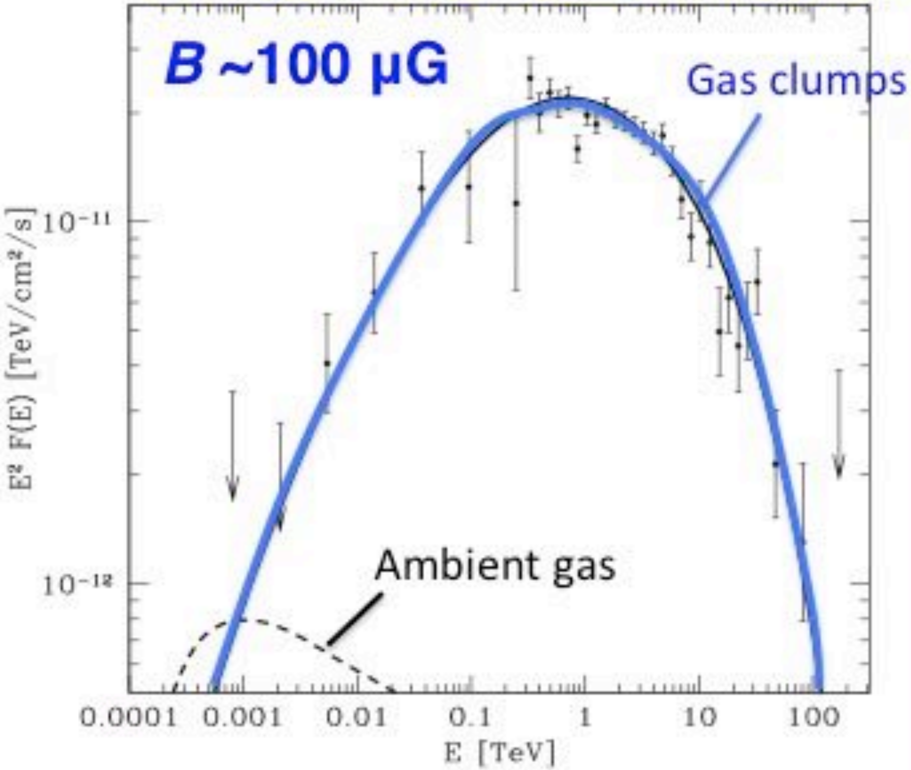


Interpretation of the gamma-ray spectra of RXJ1713

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



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



RXJ1713

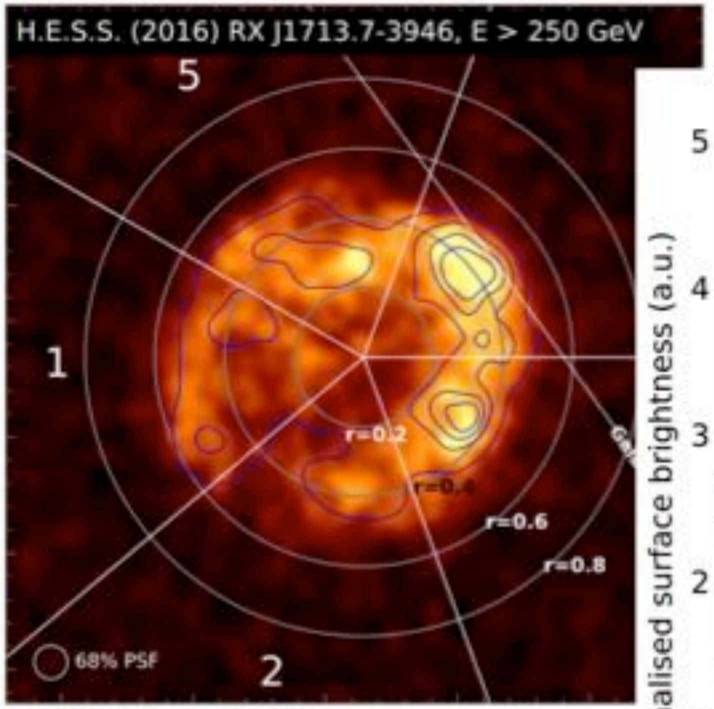
Energy of CRs; *B* field strength; SNR age

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

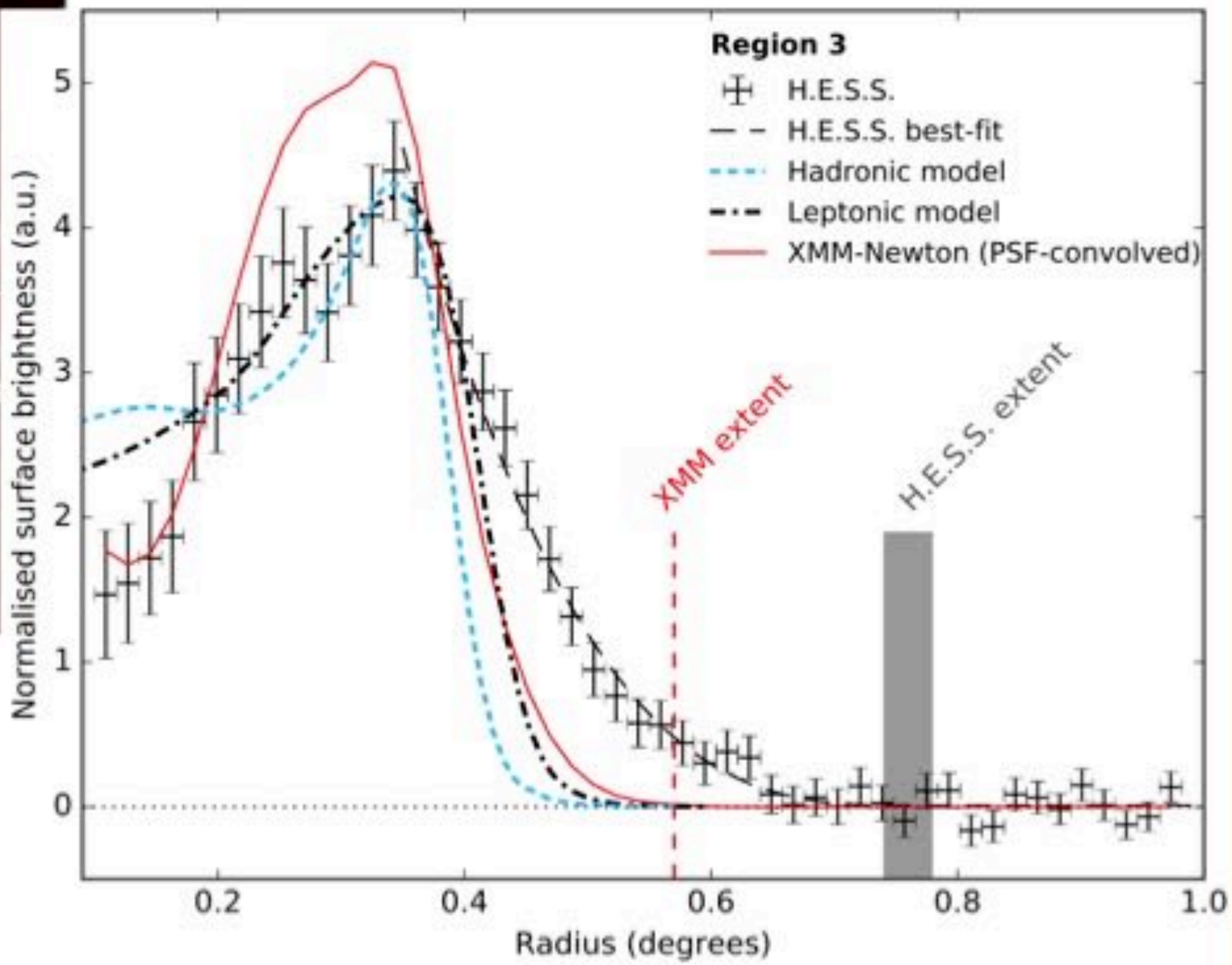
Inoue+12

Penetration depth; Gyro factor

New RX J1713.7–3946 image by using H.E.S.S.

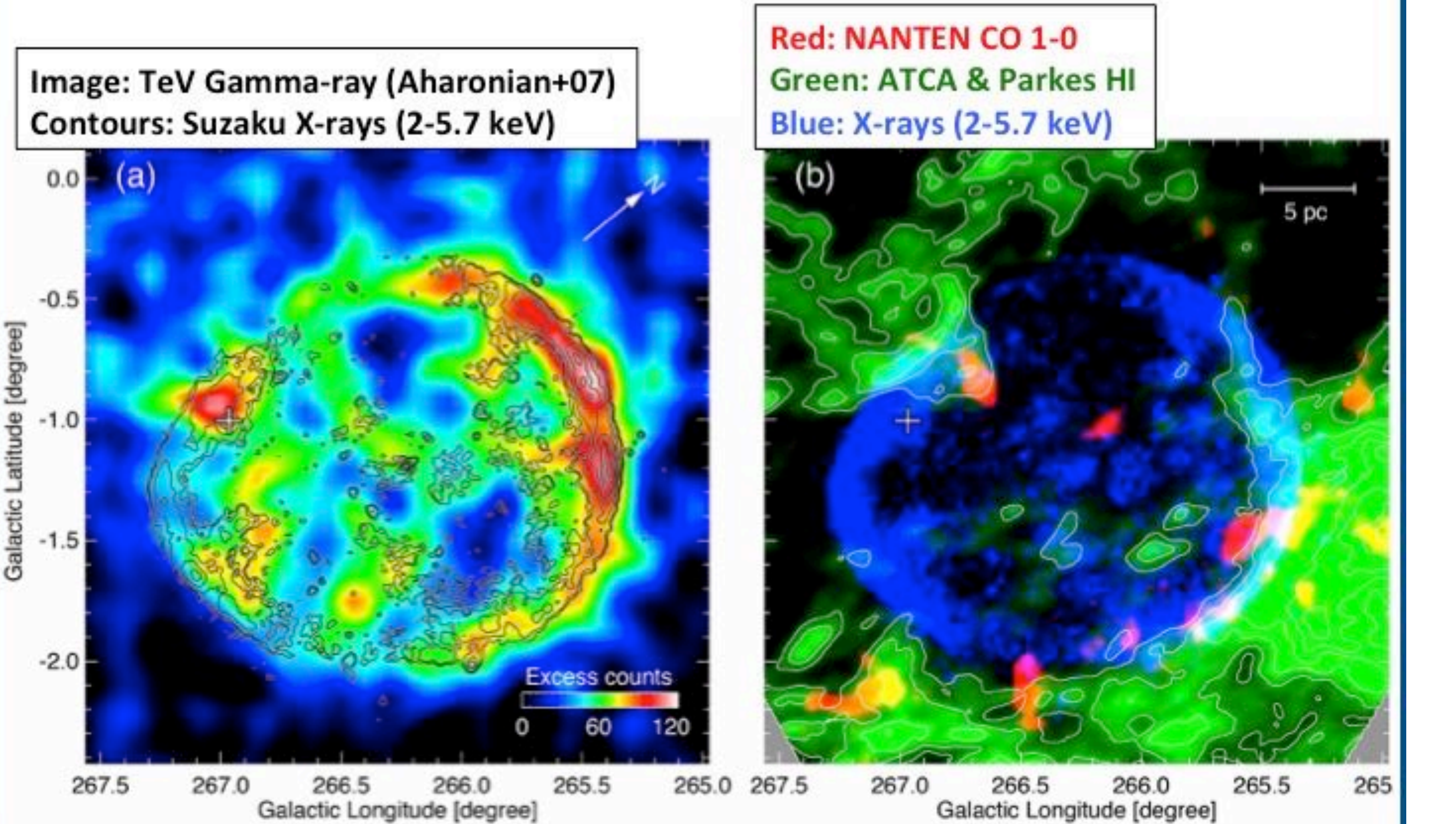


HESS Col. + 2017
RXJ1713 New image of VHE



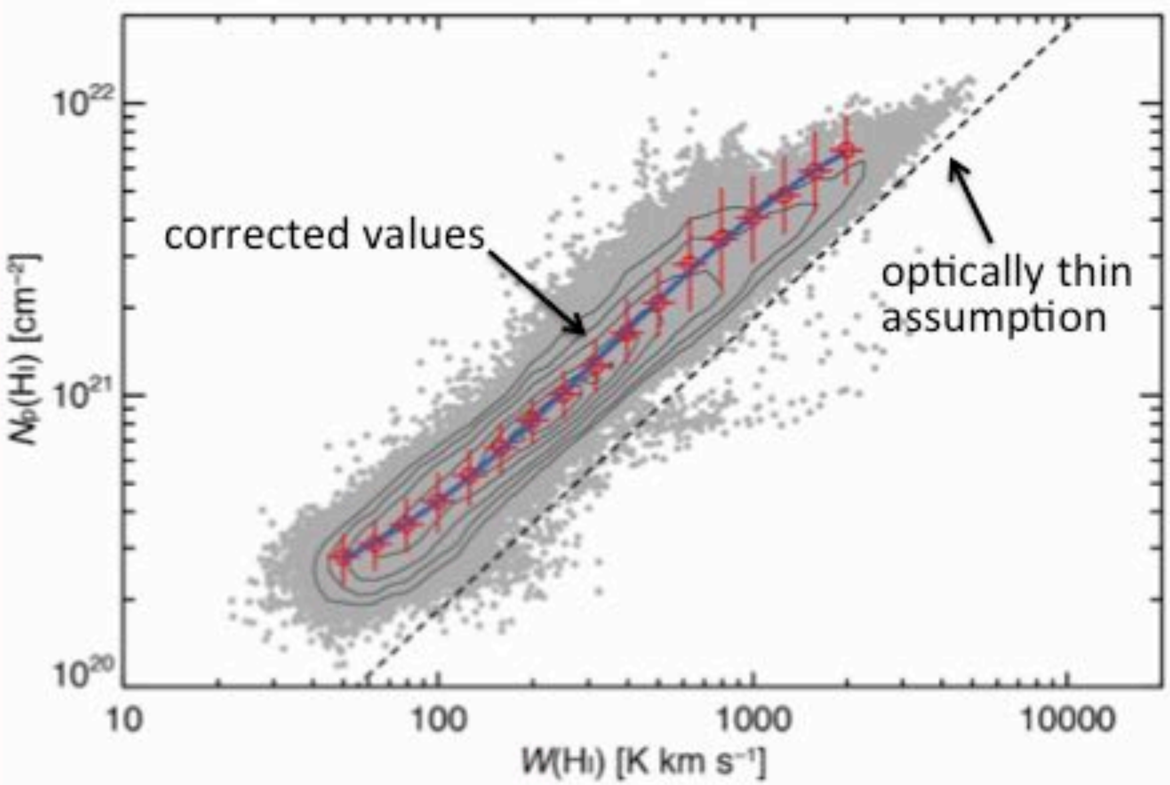
- Comparing the gamma-ray to the XMM-Newton X-ray image of RX J1713, they find significant differences between these two energy regimes!!
  → Originated by escaped CR protons?

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



Correction for the optical thick HI (see Fukui+15,16,17)

- ***Planck* tau$_{353}$ vs. W(HI)**
  - We derived conversion factor between the W(HI) and Np(HI) using the *Planck* tau353 data (see Fukui+15, 16; Okamoto+17).



$$N_H = (9.0 \times 10^{24}) \times (\tau_{353})^{1/1.3}\ (\mathrm{cm}^{-2})$$

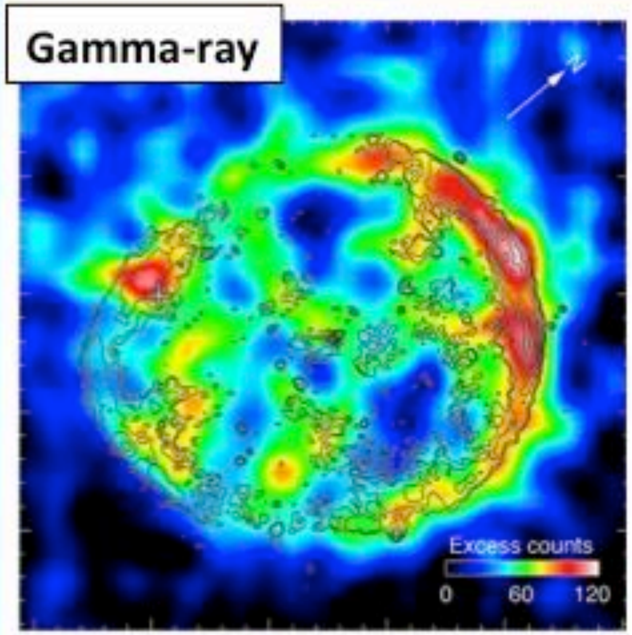
Okamoto et al. (2017) ApJ 838, 132

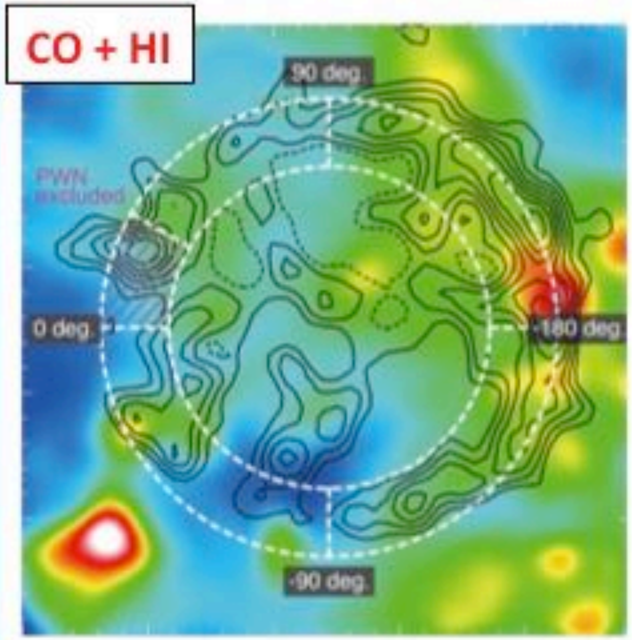
Step 1
We estimate the W(HI) range

Step 2
Estimating a conversion factor form W(HI) to *N*(H) using least-squares fitting

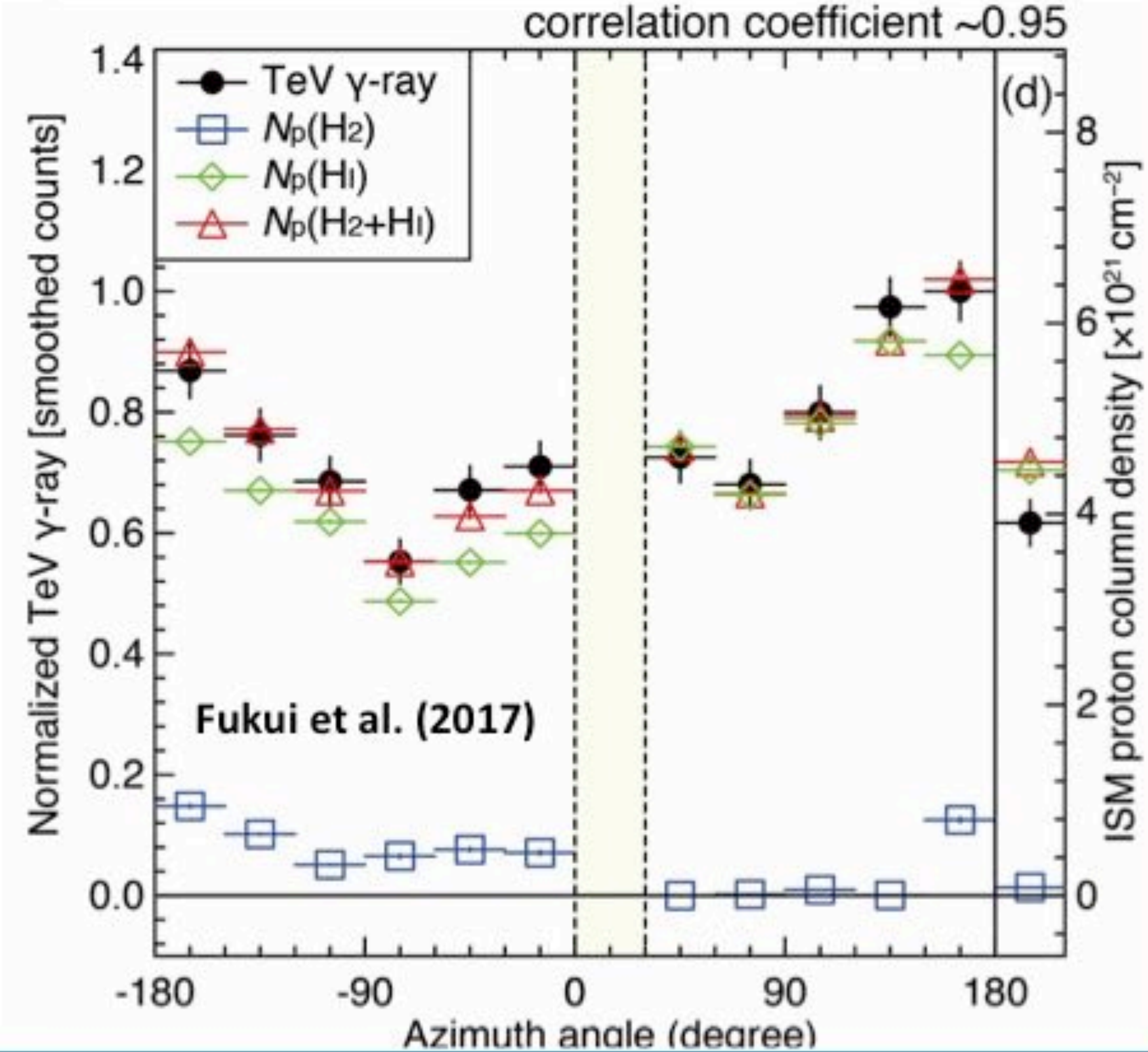
Step 3
We apply the correction

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



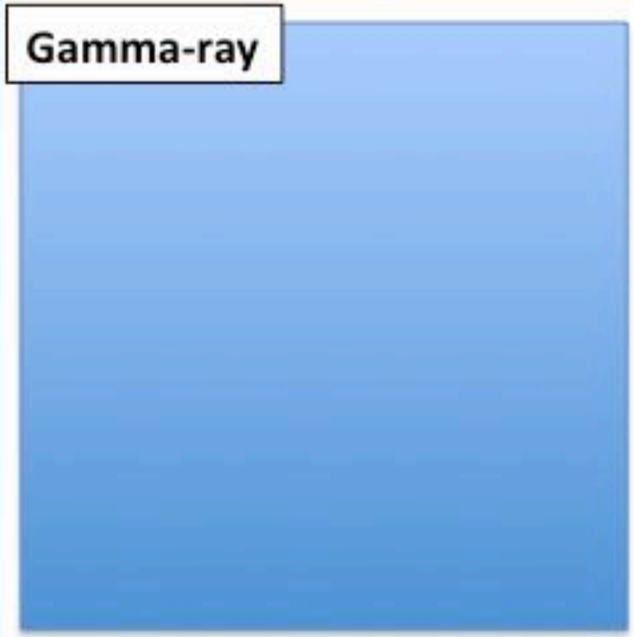


Spatial correspondence between the interstellar protons & TeV gamma-rays



Interstellar gas in RCW 86 (Sano+18 in prep.)

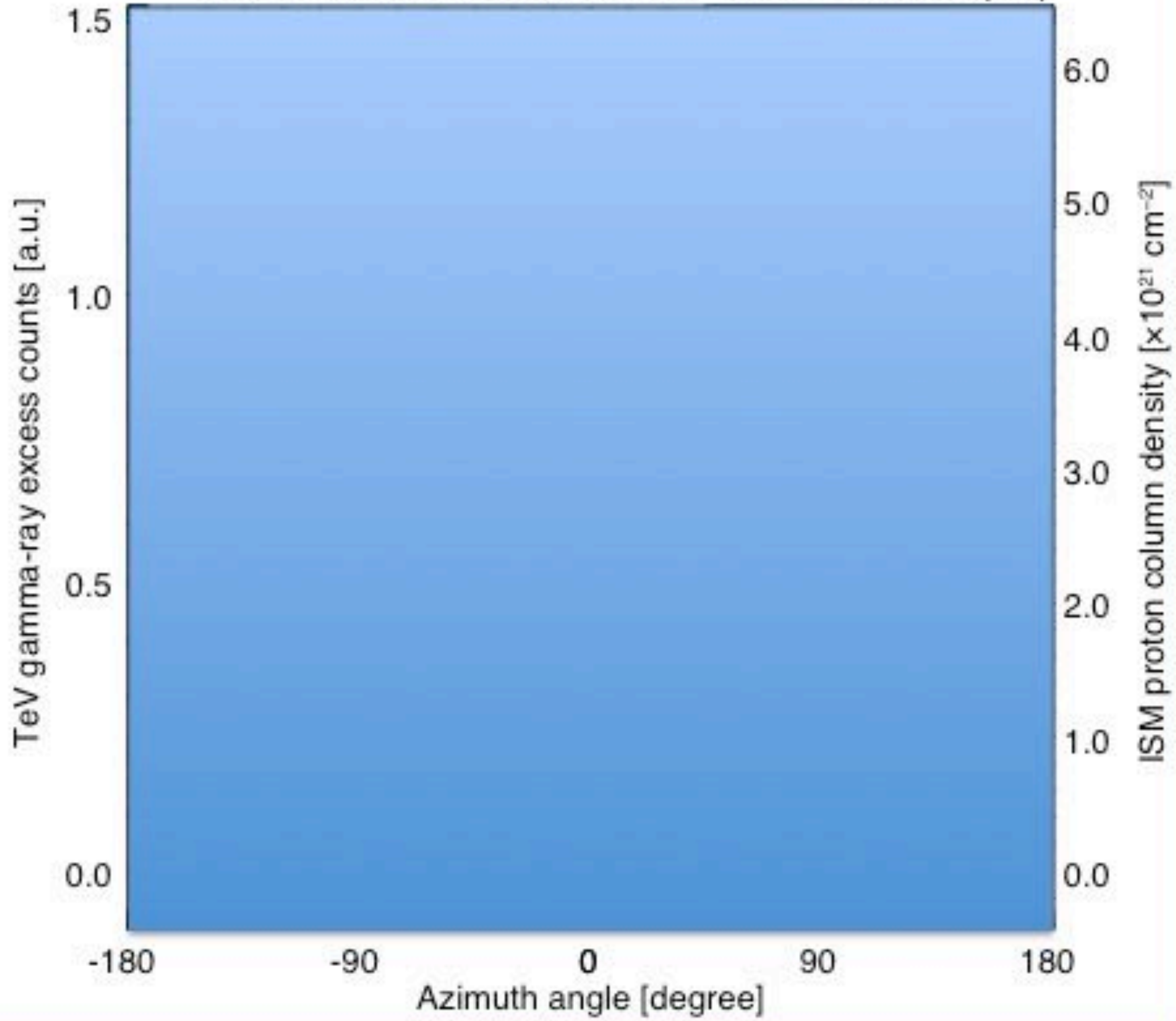
Gamma-ray



HI

Spatial correspondence between the N_p(HI) & TeV gamma-rays

Correlation coefficient ~0.74 for N_p(HI)

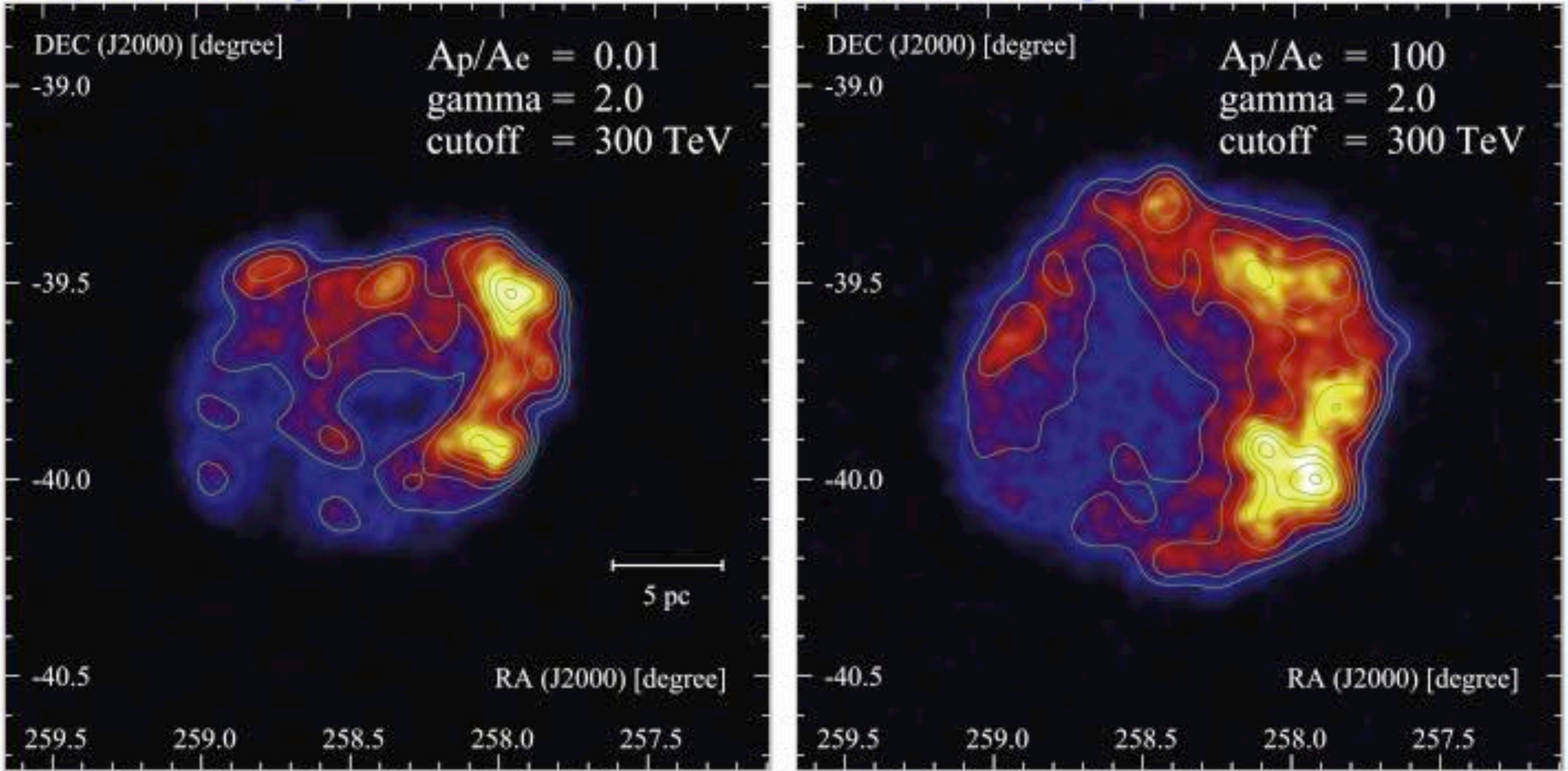


Cherenkov Telescope Array (CTA)

- 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.

Cherenkov Telescope Array (CTA)

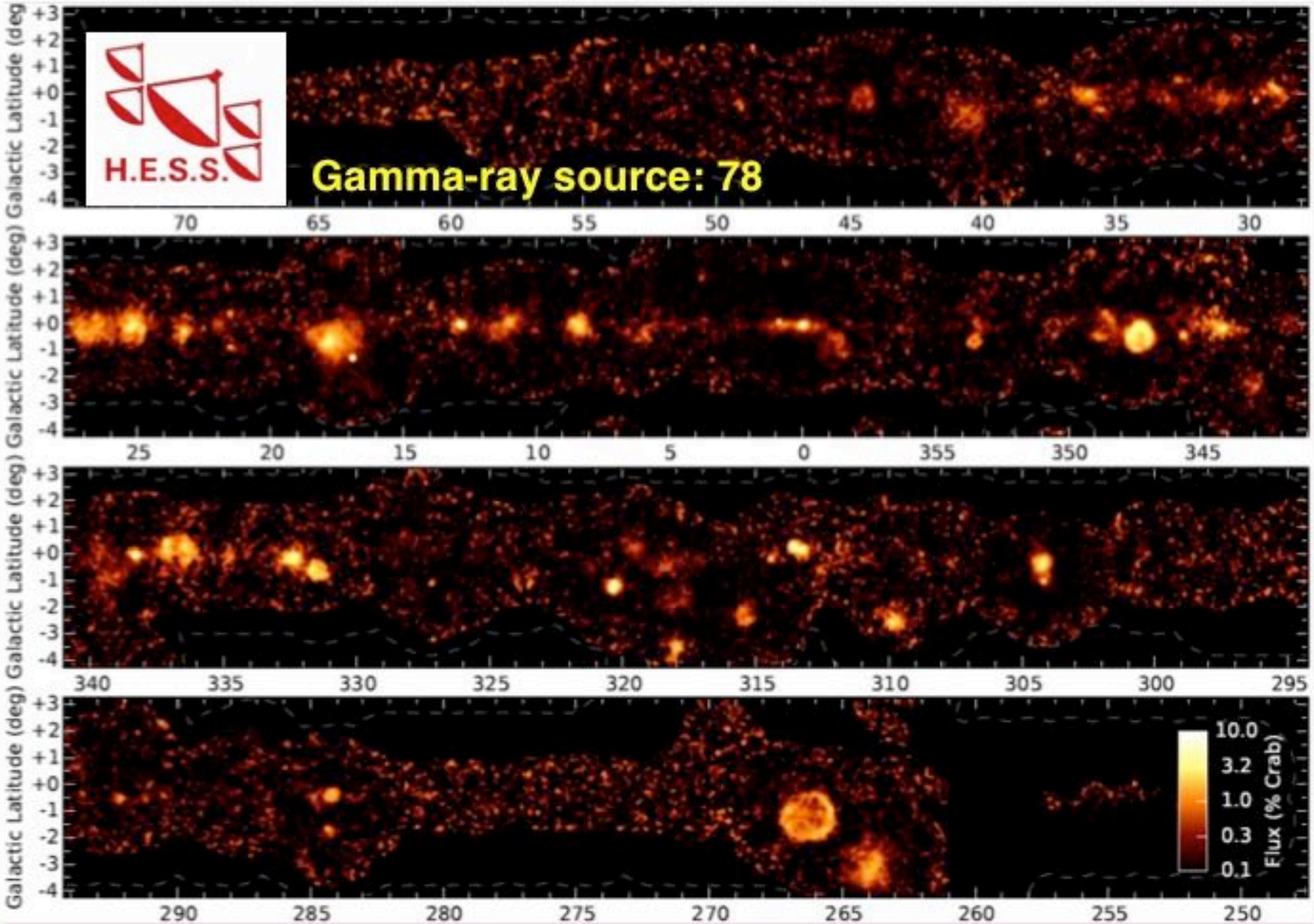
Leptonic origin | Hadronic origin



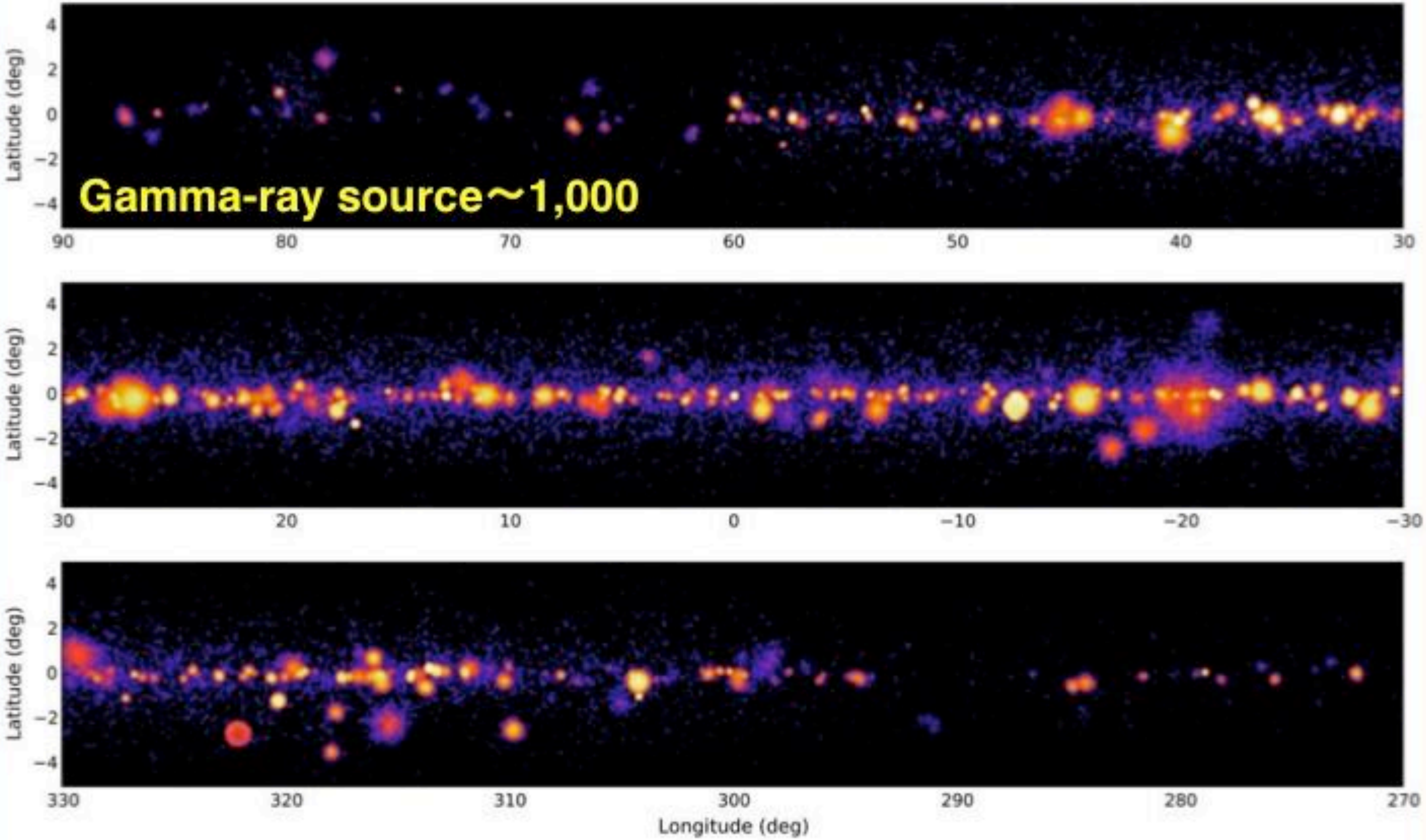
Acero+17（Corresponding authors: Nakamori, Katagiri, Sano, Yamazaki, Ohira）

- We simulated the gamma-ray morphologies with the CTA
- The origin of gamma-rays can be distinguished by morphological studies

Current VHE gamma-ray map（HESS Col.+17）



VHE gamma-ray map using CTA (simulated)



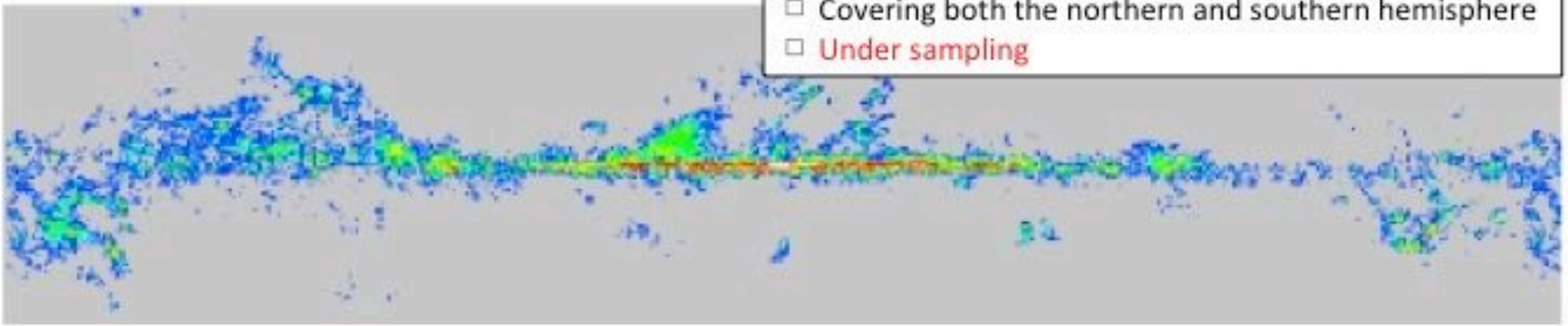
It suggests that ~ 40 gamma-ray SNRs will be newly detected!!

→ We can compare them with our interstellar gas data

CO surveys in the Galactic plane

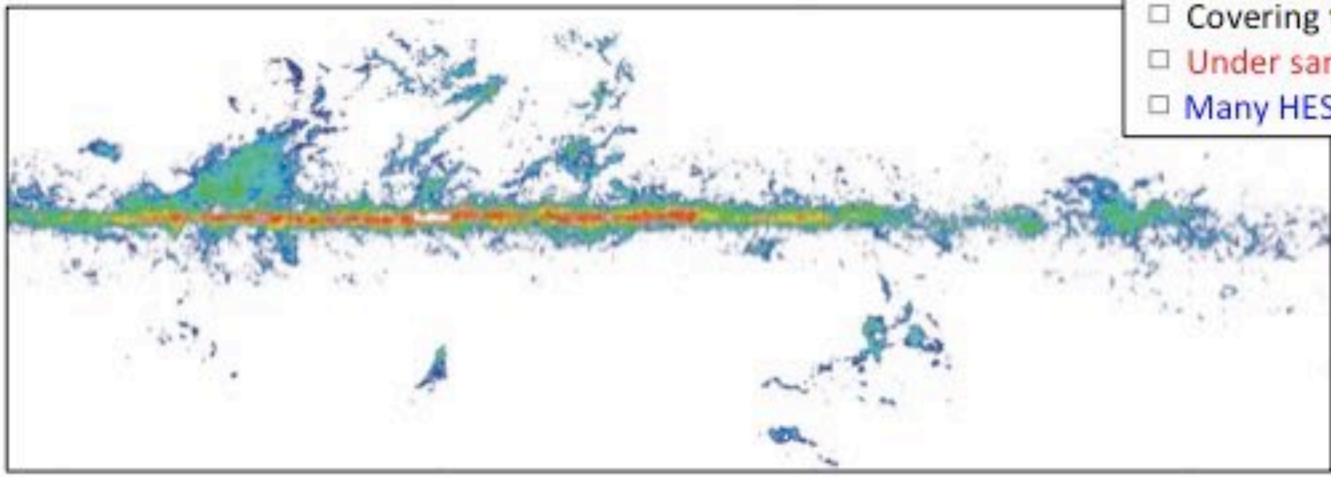
■ CfA 1.2 m (Dame+2001)

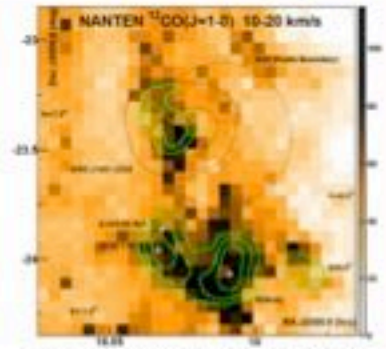
- □ Poor angular resolution (~8.8')
- □ Covering both the northern and southern hemisphere
- □ Under sampling



■ NANTEN 4 m (Mizuno & Fukui 2004)

- □ Better angular resolution (~2.6')
- □ Covering the southern hemisphere
- □ Under sampling
- □ Many HESS TeV & NANTEN CO papers





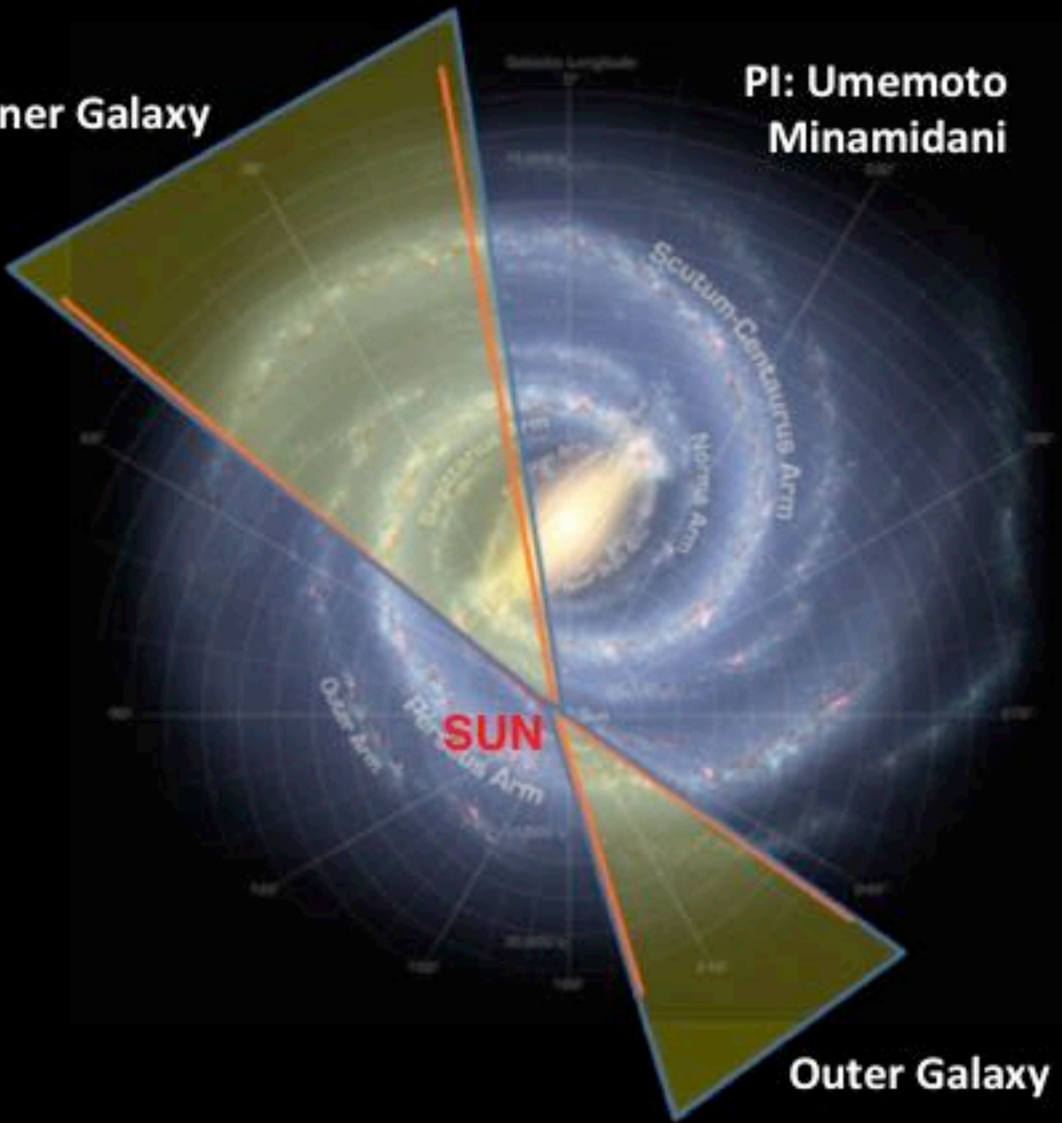
e.g., W28 (Aharonian+2008)

■ New CO Surveys

- NANTEN2 Super CO Survey as Legacy (NASCO)
- The Mopra Southern Galactic Plane CO Survey
- **Nobeyma 45-m CO Survey (FUGIN)**

Nobeyama CO Galactic Plane Survey (FUGIN)

FOREST Unbiased Galactic Plane Imaging survey with Nobeyama 45-m telescope (FUGIN)



■**Coverage**

$10° < l < 50°$, $|b| < 1°$ (inner)

■**Lines**

^{12}CO, ^{13}CO, $C^{18}O$ $J = 1–0$

■**Sensitivity**

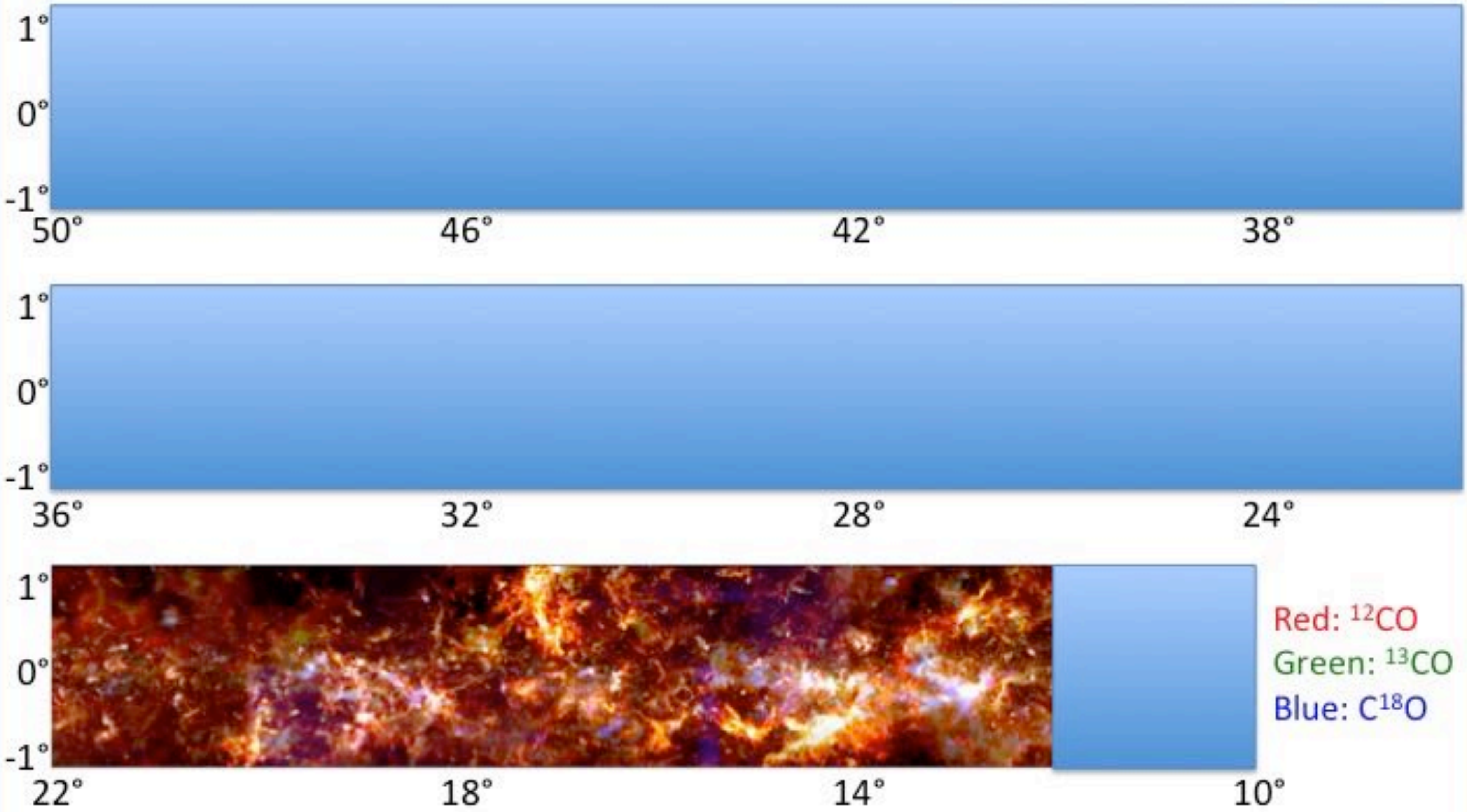
^{12}CO: ~1.5 K, ^{13}CO,$C^{18}O$: ~0.7 K

■**Resolution**

Angular resolution ~20"

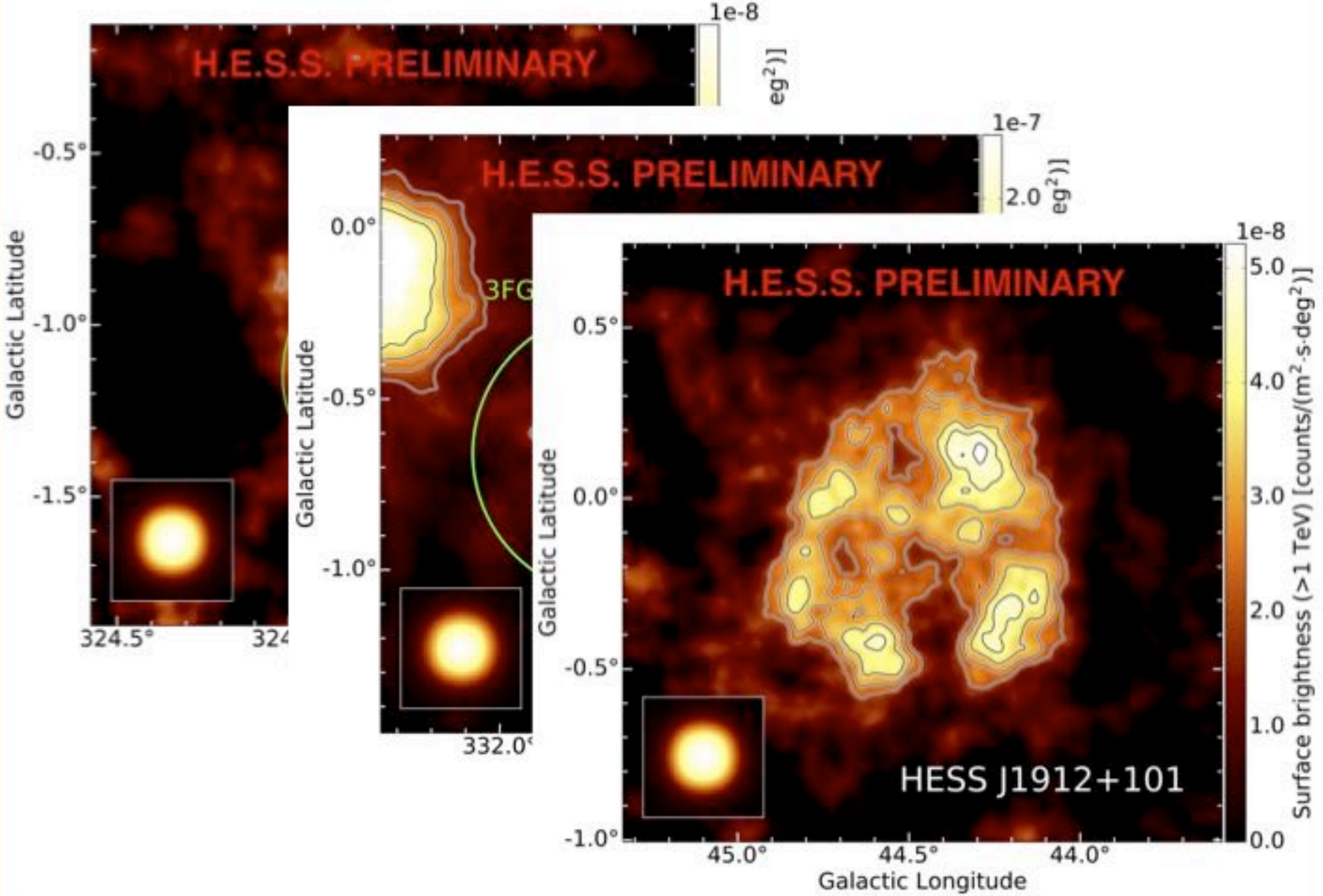
Channel resolution ~0.65 km/s

Nobeyama CO Galactic Plane Survey (FUGIN)



You can download the cube data from mid of 2018 at JVO web page
https://jvo.nao.ac.jp/index-e.html

New TeV shell SNRs (Gottschall+16)



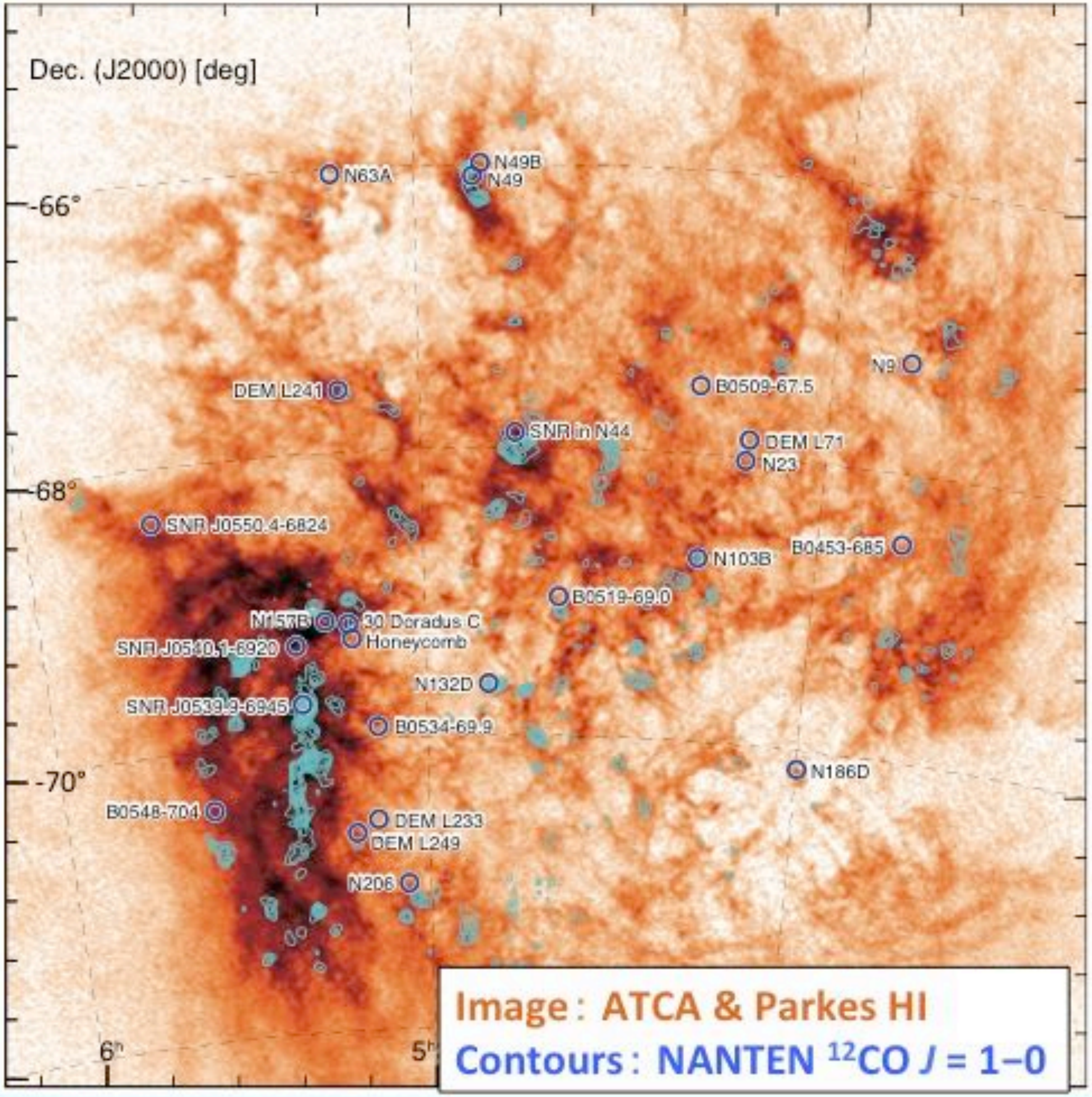
HESS J1912+101 with FUGIN CO (Sano+ in prep.)

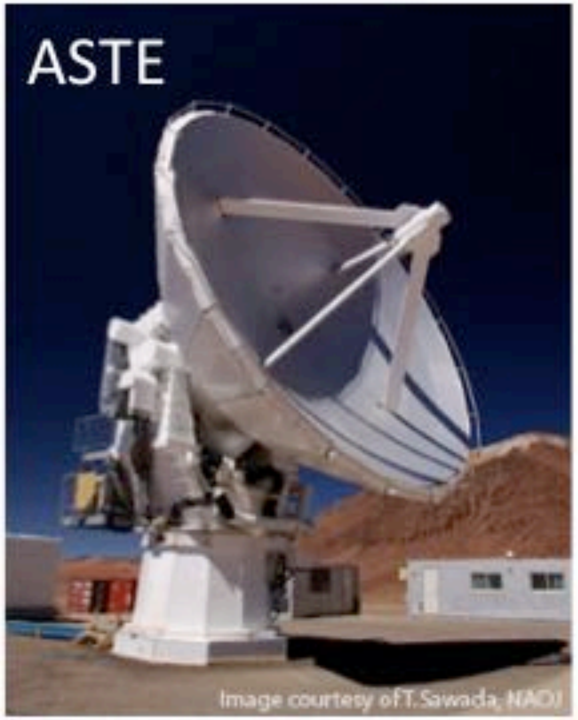
Image: FUGIN CO, Contours: TeV γ-rays

Preliminary

Sano, Fukui, Rowell+

CO surveys of the Magellanic SNRs (Sano+17a,b)





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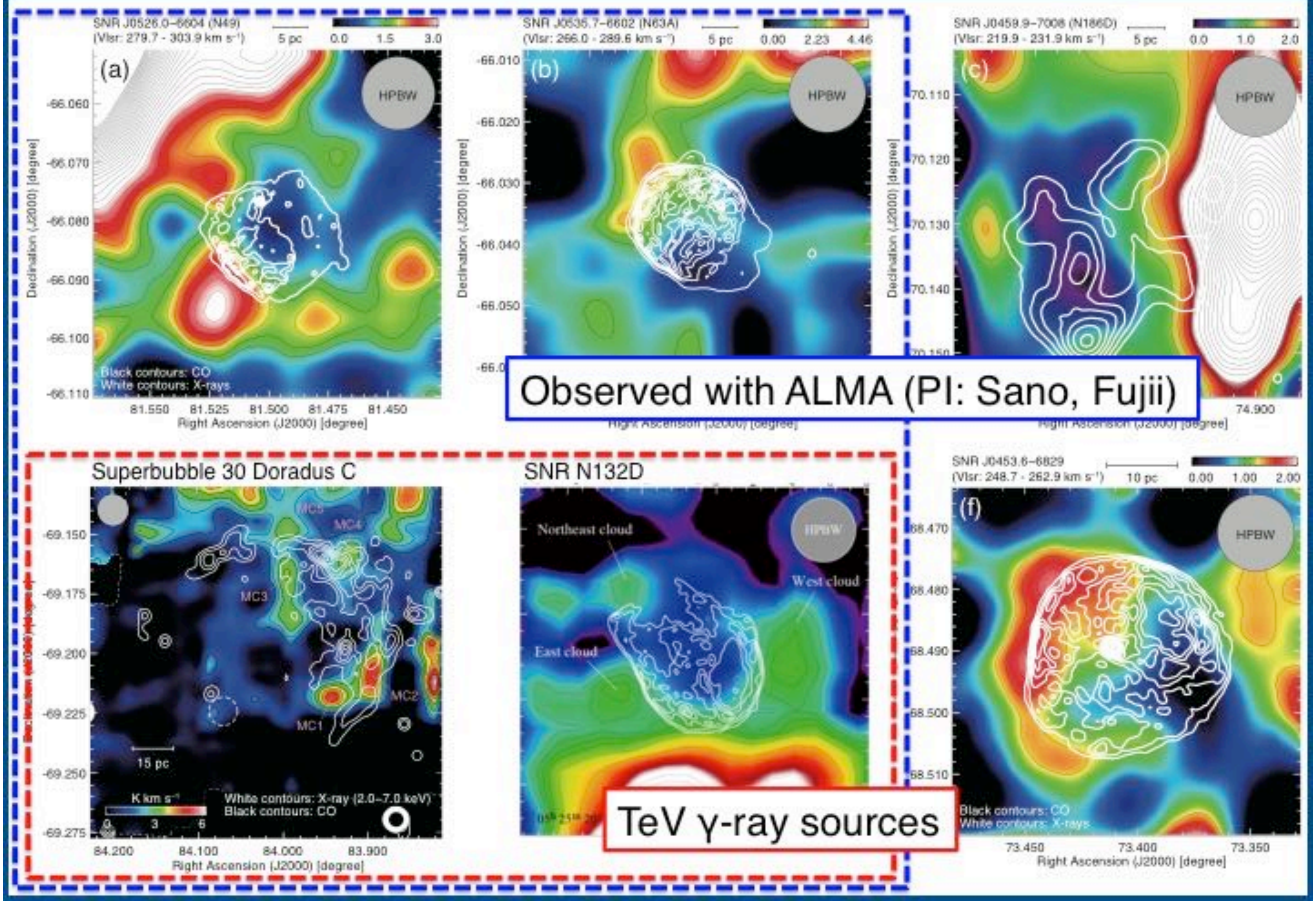

Summary

- **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 MC with gamma-ray SNRs
  - HESS J1912 provides 5th evidence for acceleration of CR protons

Interstellar gas associated with the SNR and numerical calculations are important to understand the origins of X-, γ-rays & CR