NANTEN2 observations

- NASCO project and Gamma-ray SNRs -

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NANTEN2 Workshop @ Adelaide 03.Feb.2014

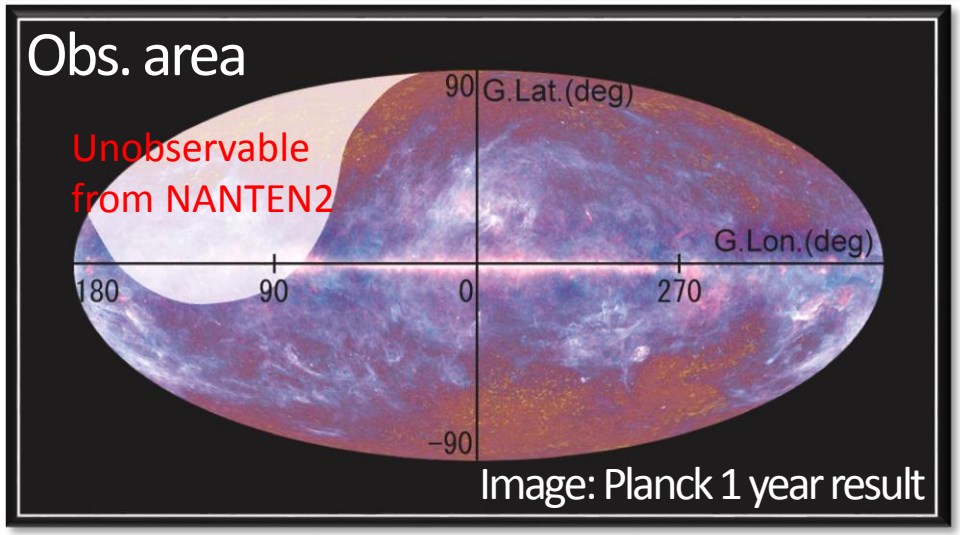
CONTENTS

- **NASCO project**
  - **Brief introduction and results of pilot observation**
- **Results of recent SNR study in Nagoya group**

  … from the aspect of ISM role in high-energy phenomena
  - **1. TeV Shell-Type SNRs**
    - ✓ **RX J1731.1-3947, Vela Jr., HESS J 1731.7-3946**
  - **2. Middle-aged SNRs**
    - ✓ **W44, IC443**
- **Summary**

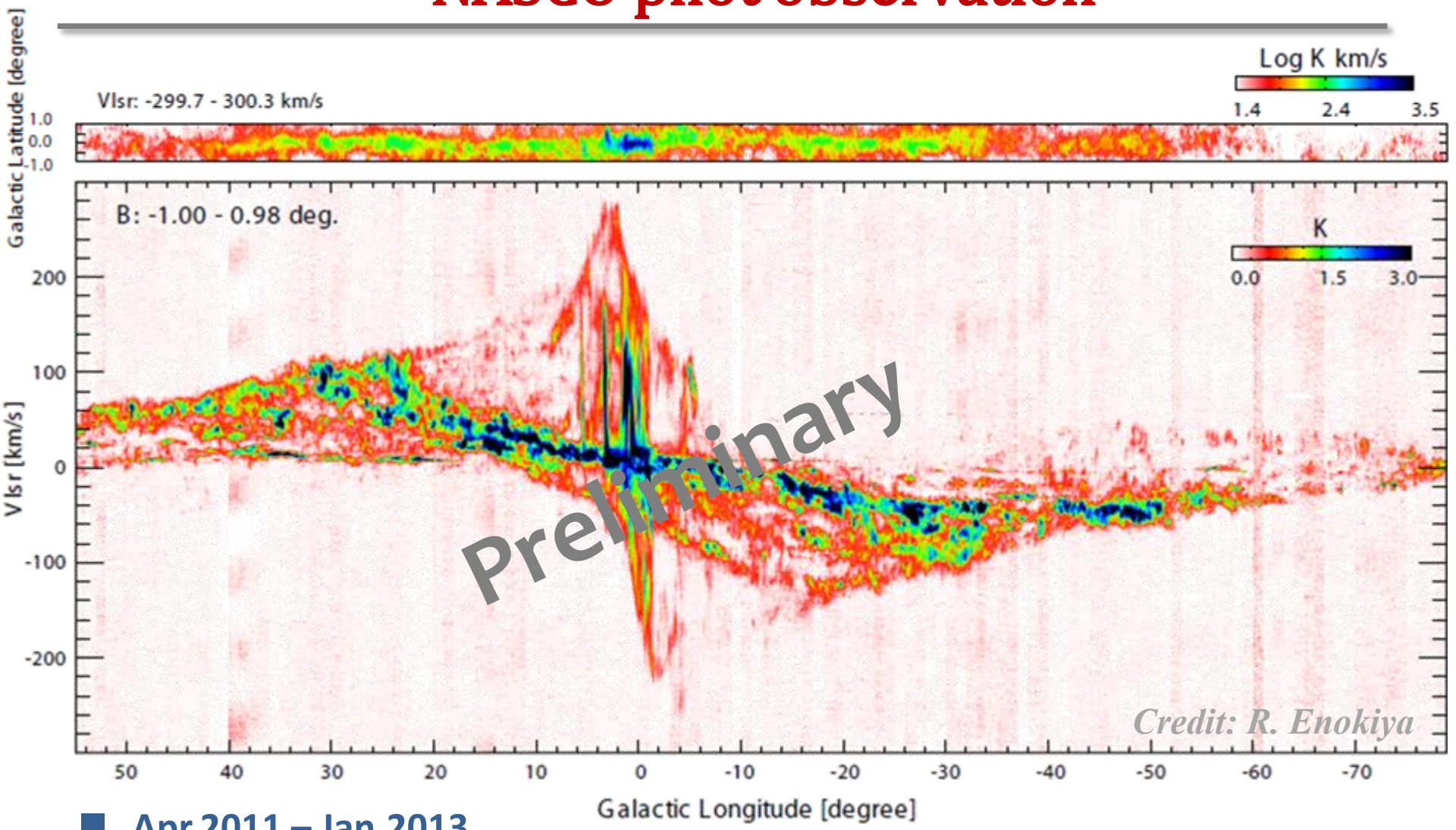
*NA*nten *S*uper *CO* survey as Legacy

- New Survey of molecular clouds by NANTEN2
  ^{12}CO and ^{13}CO(J=1-0) simultaneously.
- Start in 2015
- Covering 70% area of whole sky
- Collaborative study with Planck team



Survey Name	Coverage (deg)	HPBW (')	Grid (')	Vel. cov. (km/s)	Vel. reso. (km/s)	Total points (million)
NGPS	-160<L<60, B<|10|	2.6	4-8	±300	1.0	1.1
NASCO	70% of sky	2.6	1	±1300	0.16	20

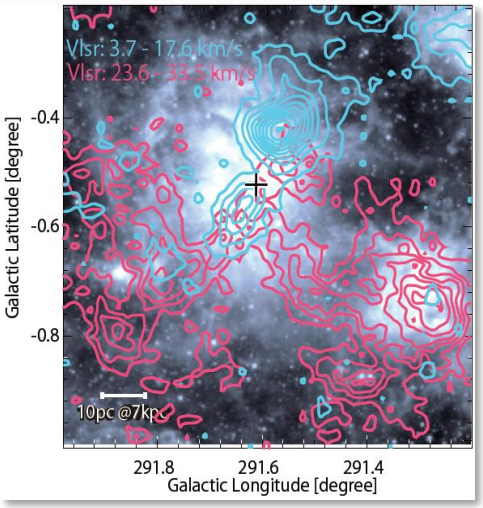
NASCO pilot observation

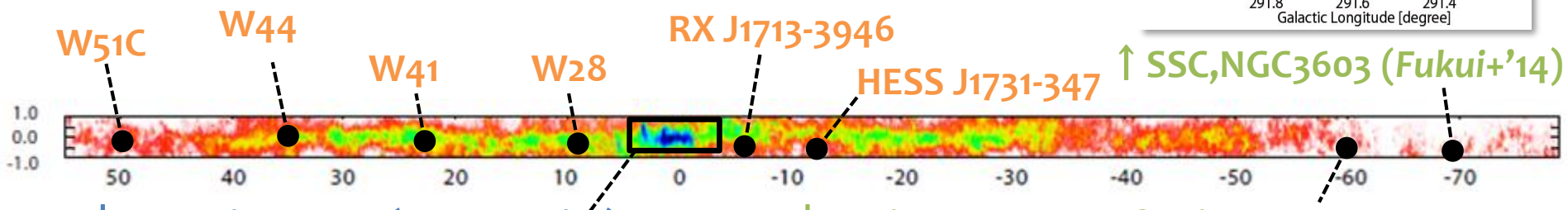


- Apr.2011 – Jan.2013
- Simultaneous observation of ^{12}CO,^{13}CO(1-0) by single pixel receiver
- Total observation time: ~ 1000 h , Data points: ~ 100,000 x 16,000 !

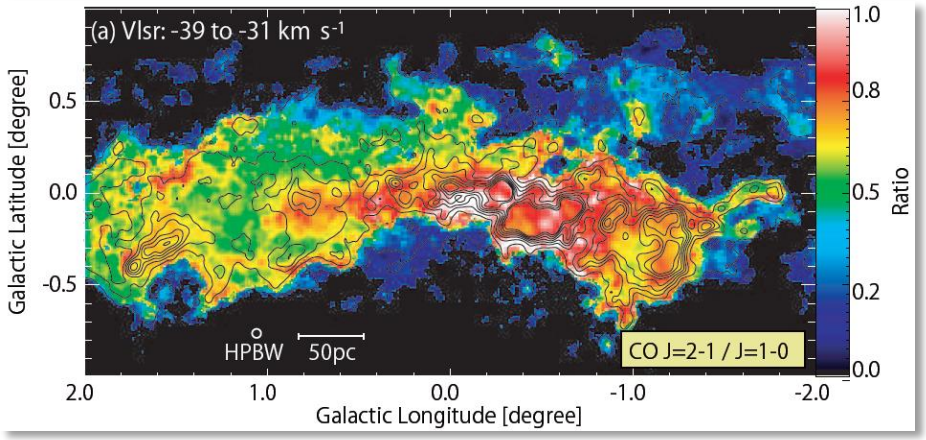
NASCO pilot observation

- **Studies from Pilot Observation**
  - Galactic Center
  - High-mass Star Formation via Cloud-Cloud Collision
    - ✓ Spitzer Bubbles (# of samples ~ 50)
    - ✓ Super Stellar Cluster (SSC)
  - Gamma-ray SNRs

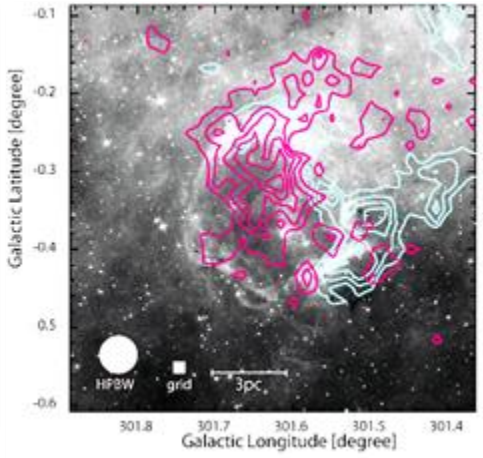


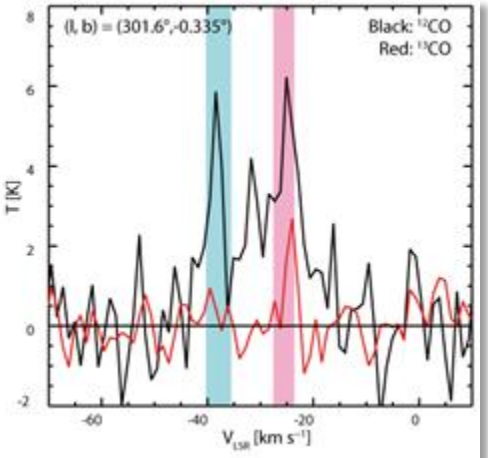


↓ Galactic Center (*Enokiya* +'14)



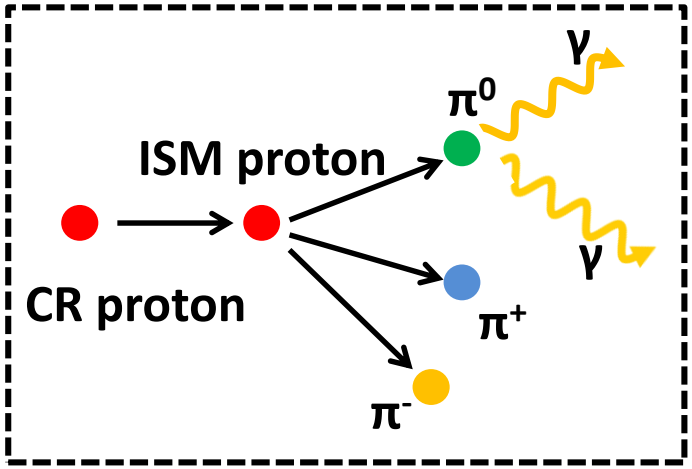
↓ Typical example of Spitzer bubble, S167





SNR Studies in Nagoya Radio Group

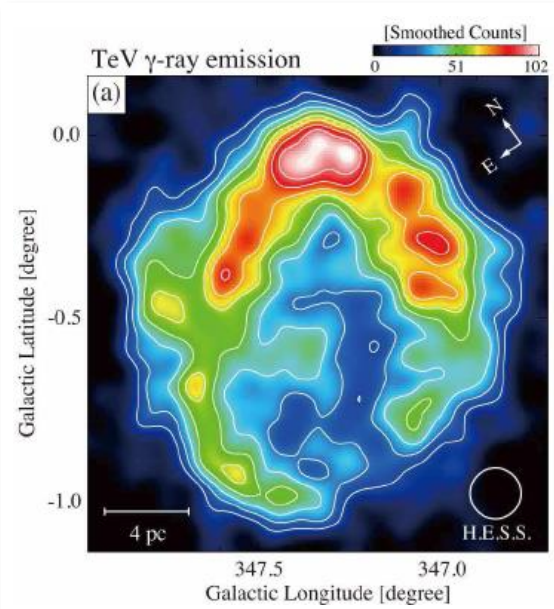
- **Main Members**
  - Hidetoshi SANO
    - ✓ *RX J1713, Vela Jr., etc*
  - Satoshi YOSHIIKE
    - ✓ *Middle-aged SNR (W44, IC443..)*
  - Tatsuya FUKUDA
    - ✓ *HESS J1731-347*

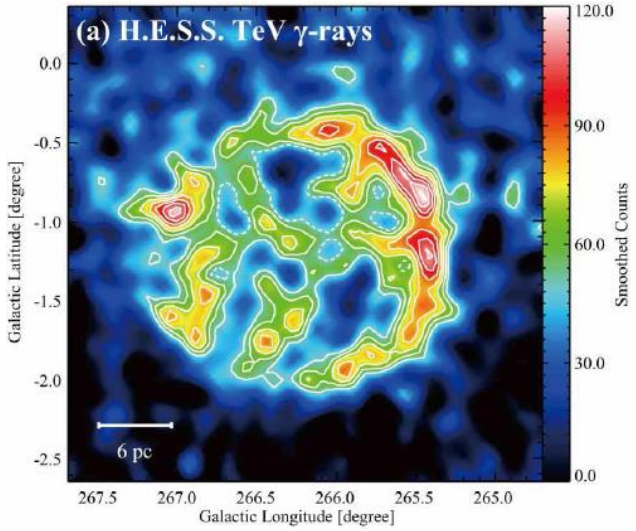


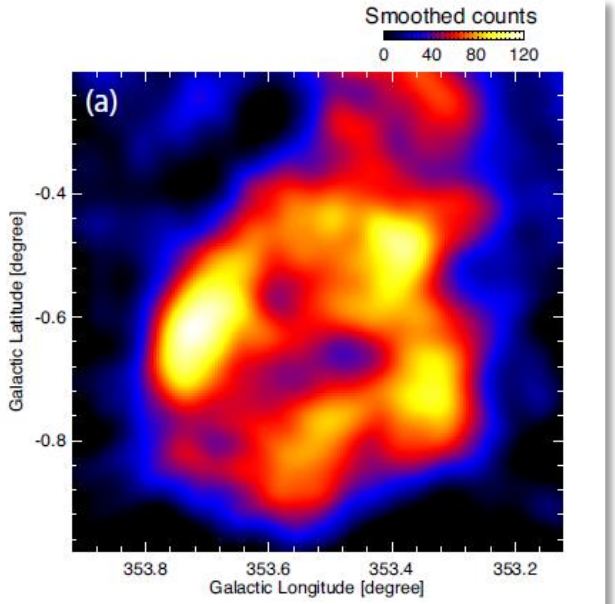
- **Topics of SNR Study**
  - Are SNRs origin of cosmic-rays (CRs), especially CR protons ?
    - ✓ ISM can be the target to produce γ-ray via the hadronic process.
    - ✓ Good spatial correlation between γ-ray and ISM
  - Do SNRs produce the energy density of the Galactic CRs?
    - ✓ 1-10% of E_{SN}~10^{51} erg is needed.
  - How dose the shock interaction with ISM affect its environment?

1. TeV Shell-Type SNR

- **RX J1713-3946**
- **Vela Jr.**
- **HESS J1731-347**



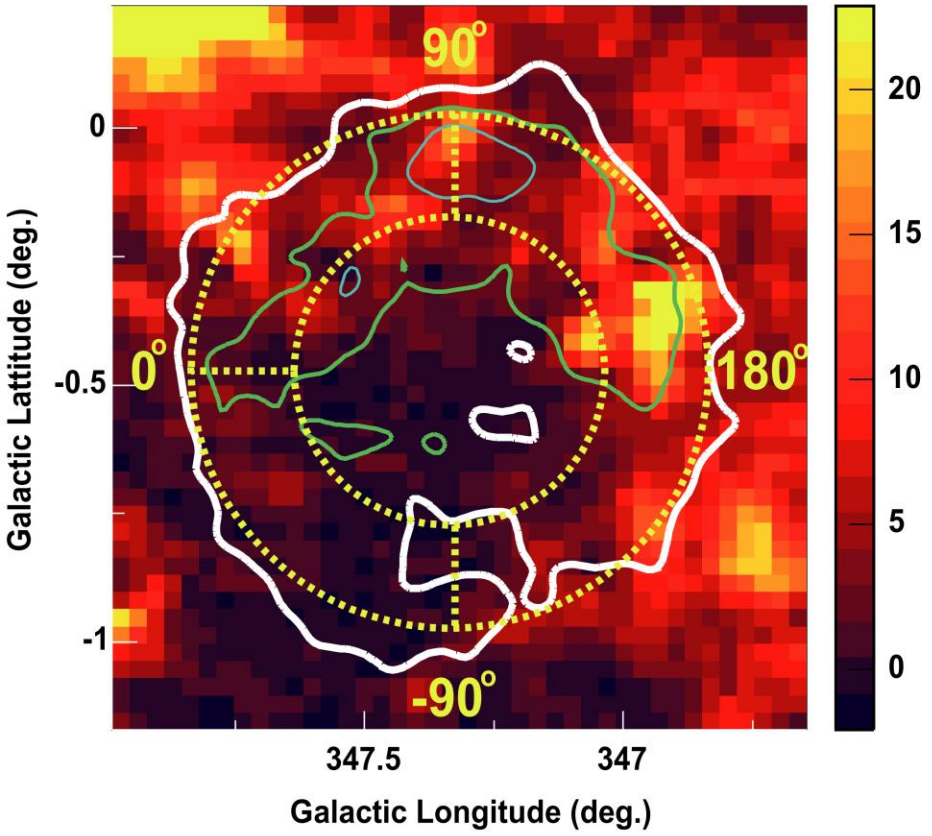


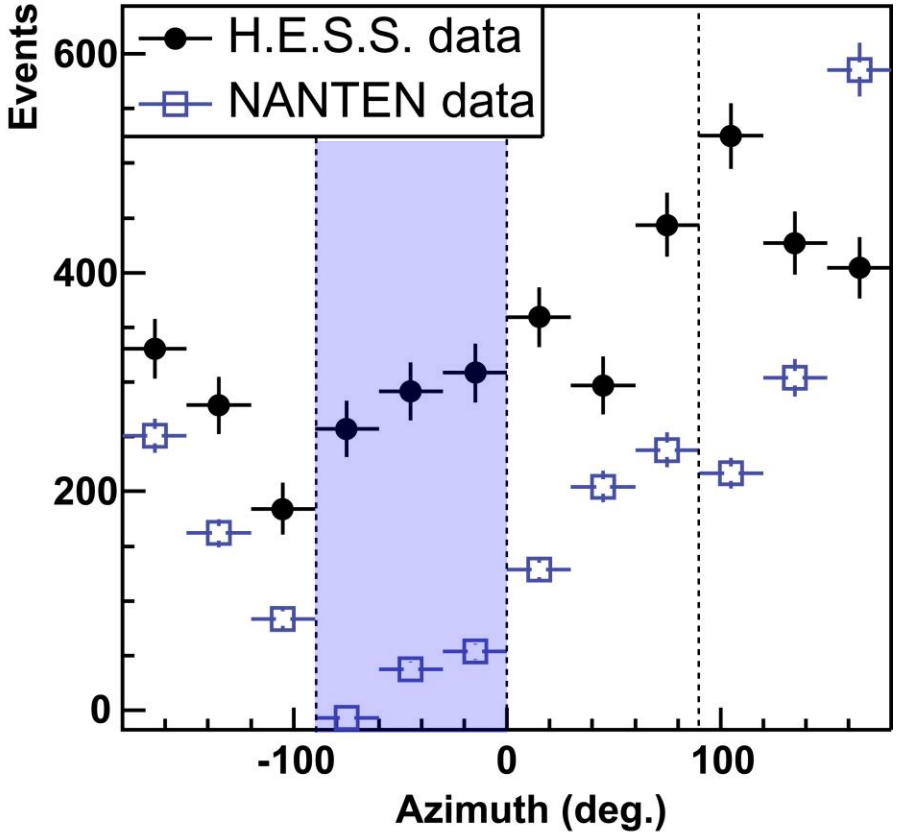


- Age ~ a few 10^3 yr (young)
- Shell-like γ-ray distribution
- Bright in TeV γ-ray
  - Detectable by Atmospheric Cherenkov Telescopes

RXJ1713 CO distribution (Aharonian+06)

- Azimuthal plot (H.E.S.S. VHE γ-rays and NANTEN CO)
  - The global trend between the CO and γ-rays is similar to each other
  - However, the correlation is not complete in the SE-rim (-100–0 deg)





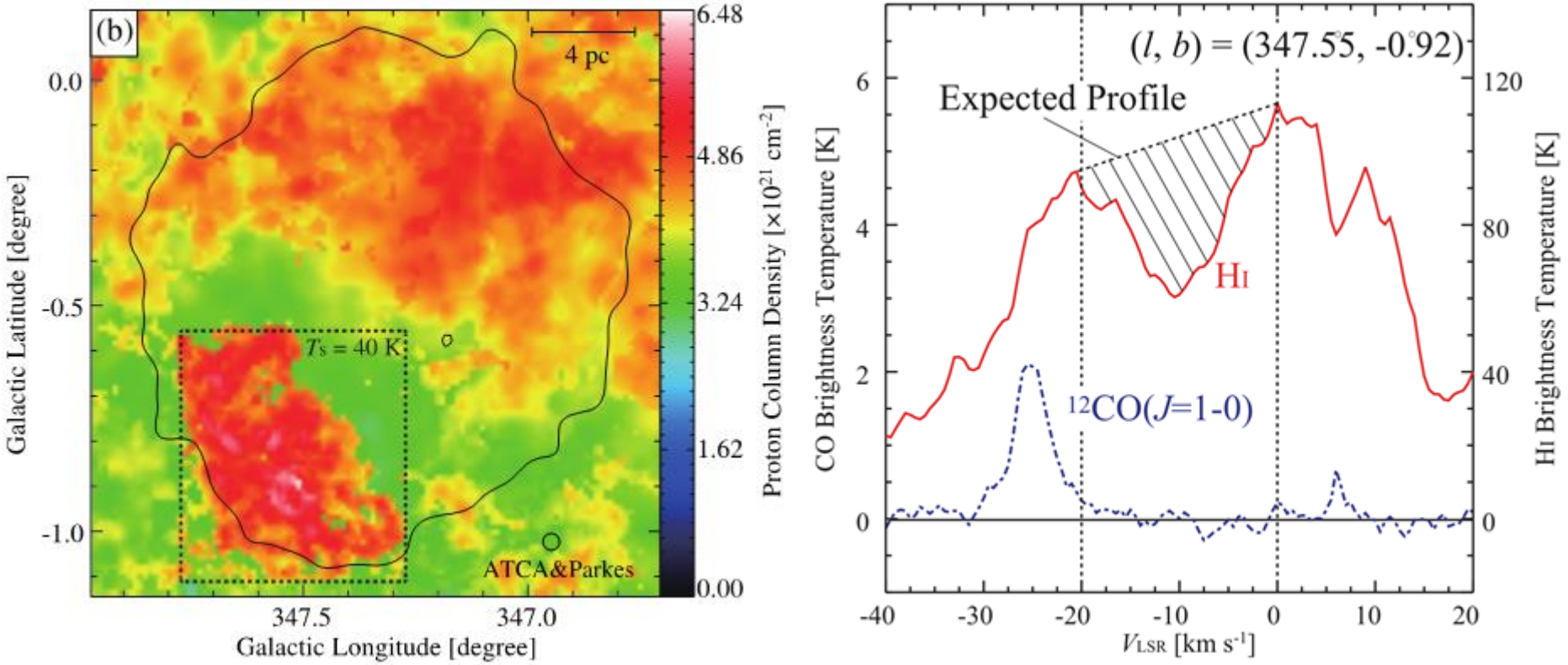
Credit: H. Sano

RXJ1713 Dark HI SE Cloud (Optically thick HI)

Fukui+'12

Image: (a) Tau map, (b) absorption-corrected HI column density

Contours: VHE gamma-ray boundary

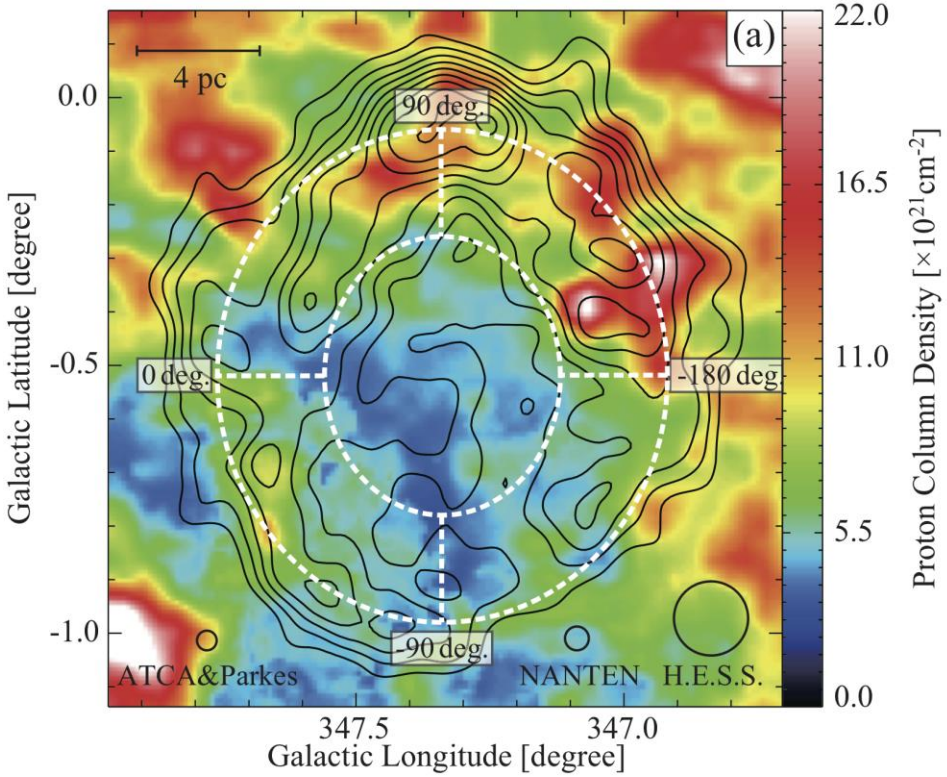


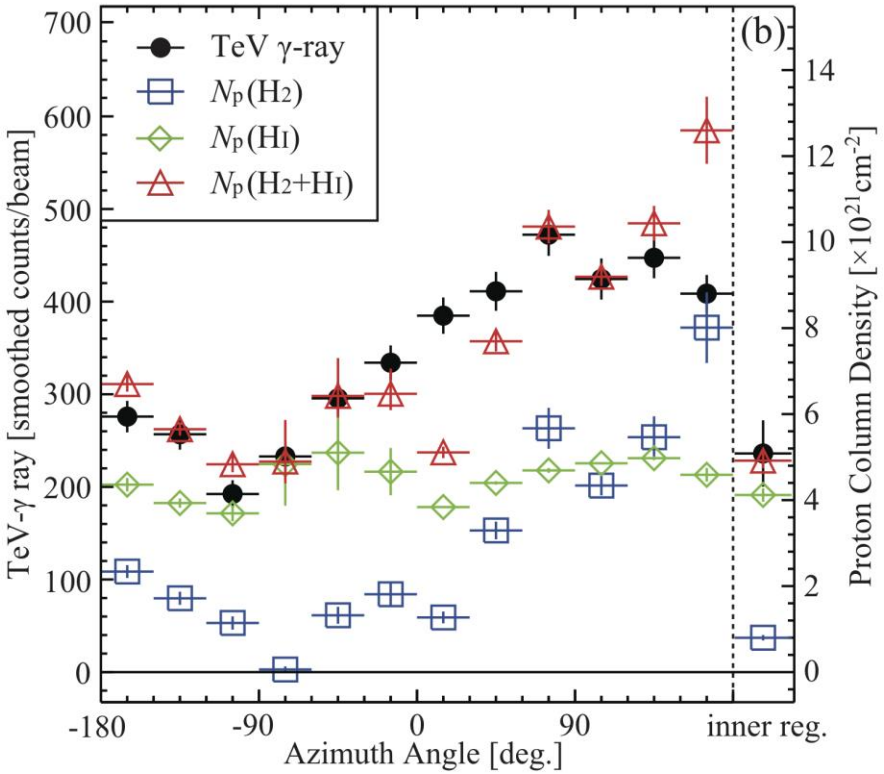
■ Optically thick HI (N_H~100 cm^{-3}, T_s ~40 K) ⇒ tau > 0.5

Credit: H. Sano

RXJ1713 Total Interstellar Gas (Fukui+12)

- Azimuthal plot (H.E.S.S. VHE γ-rays and Total ISM Gas)
  - H2 mass ~ HI mass (H2: $0.9 \times 10^4\ M_\odot$, HI: $1.1 \times 10^4\ M_\odot$)
  - **Total CR proton energy: ~10^{48} erg (~0.1 %)**



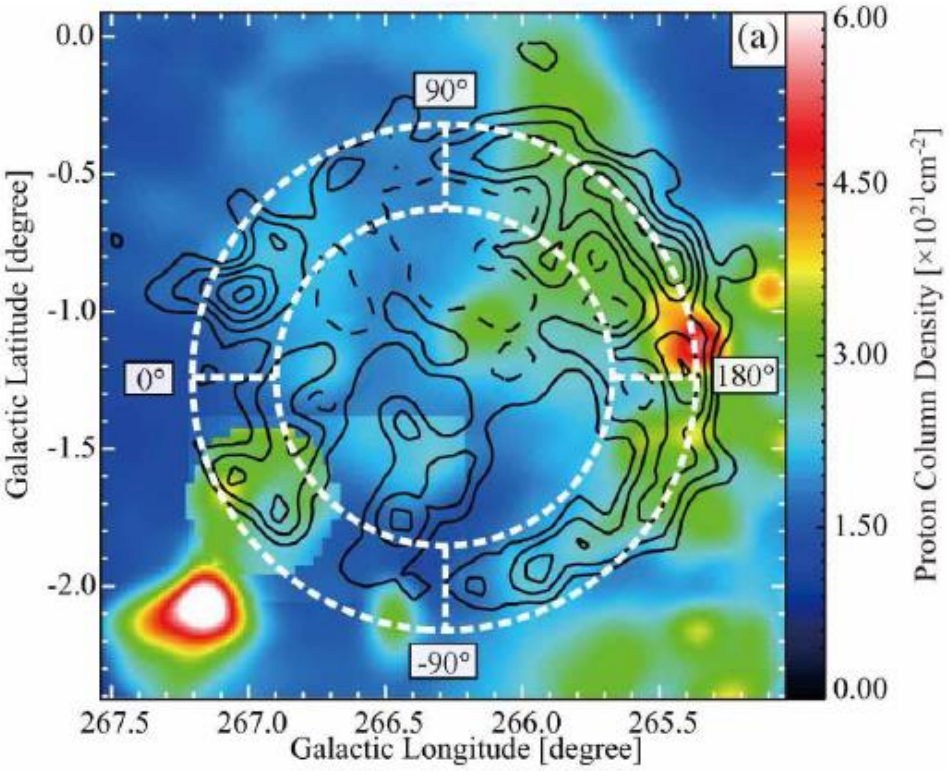


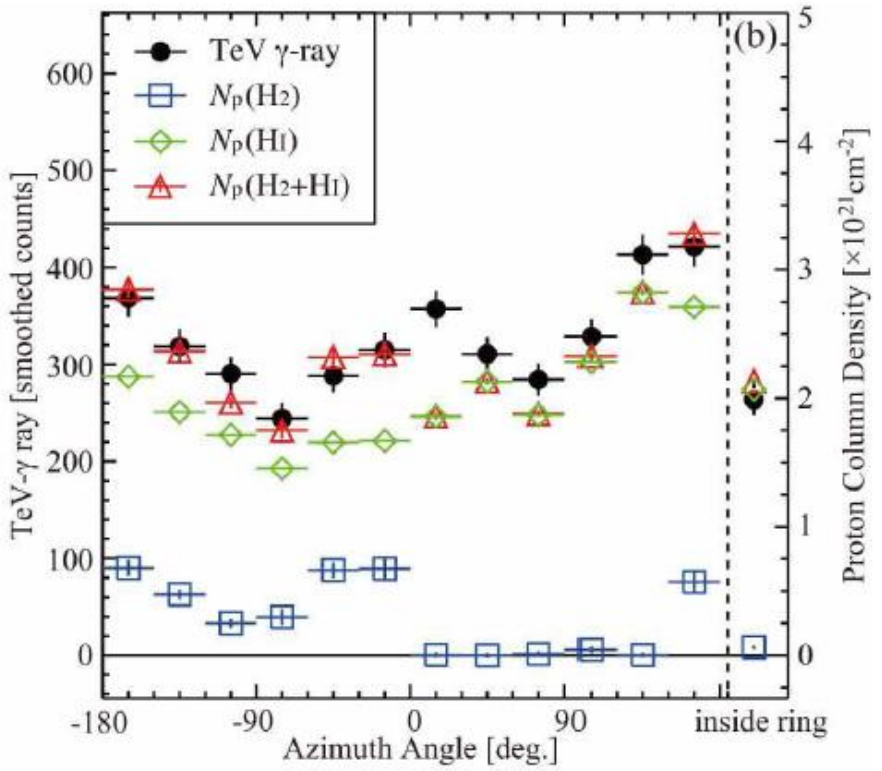
Evidence for the CR proton acceleration

Credit: H. Sano

Vela.Jr Total Interstellar Gas (Fukui13)

- Azimuthal plot (H.E.S.S. VHE γ-rays and Total ISM Gas)
  - H2 mass < HI mass (H2: $0.1 \times 10^4\ M_\odot$, HI: $1.0 \times 10^4\ M_\odot$)
  - **Total CR proton energy: ~10^{48} erg (~0.1 %)**

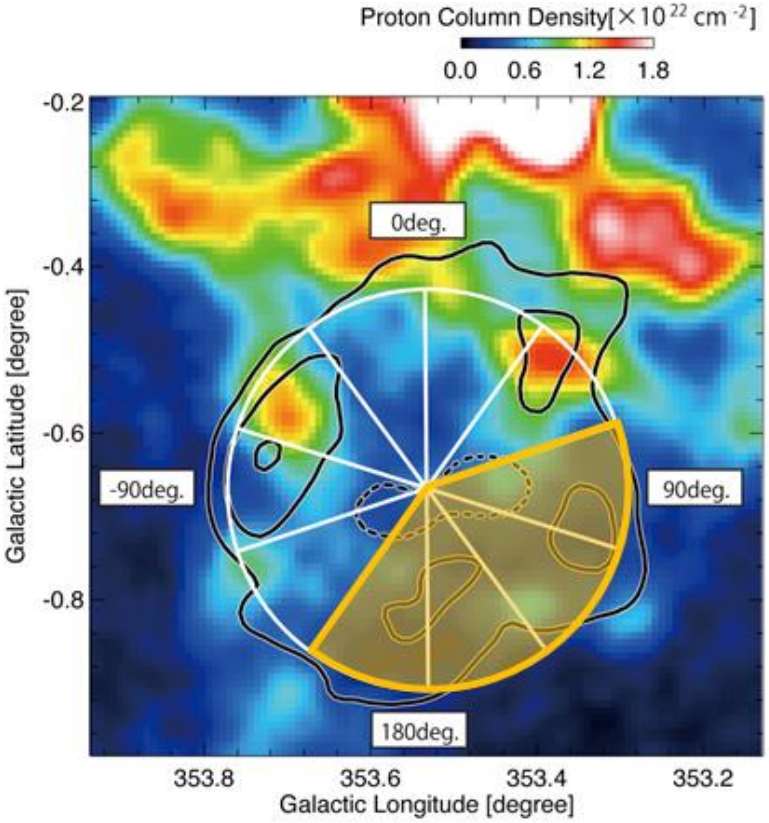


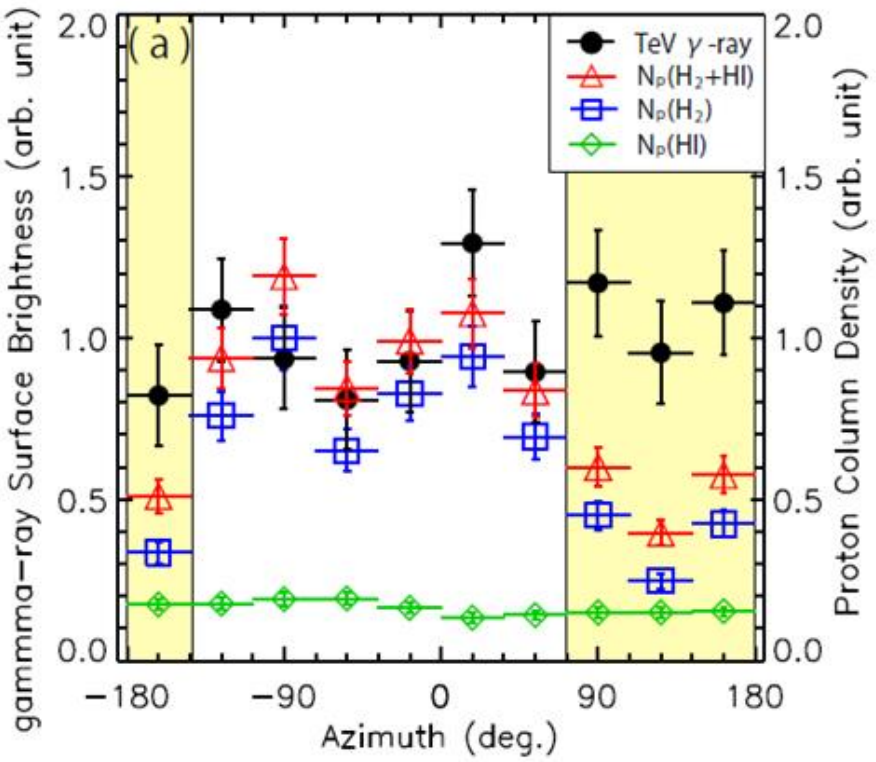


Credit: H. Sano

HESS J1731-347 Total Interstellar Gas (Fukuda+ submitted to ApJ)

- Azimuthal plot (H.E.S.S. VHE γ-rays and Total ISM Gas)
  - H_2 mass > HI mass (H_2: $5.1 \times 10^4\ M_\odot$, HI: $0.13 \times 10^4\ M_\odot$)
  - **Total CR proton energy: ~10^{49} erg (~1 %)**
- The origin of γ-rays may be mixture of hadronic and leptonic origin.





Credit: H. Sano

RXJ1713 Synchrotron X-rays & CO

- Clumpy ISM (created by progenitor of SNR) + SNR blast waves
  ⇒ Good spatial correlation (pc scale) and anti-correlation (sub pc scale)

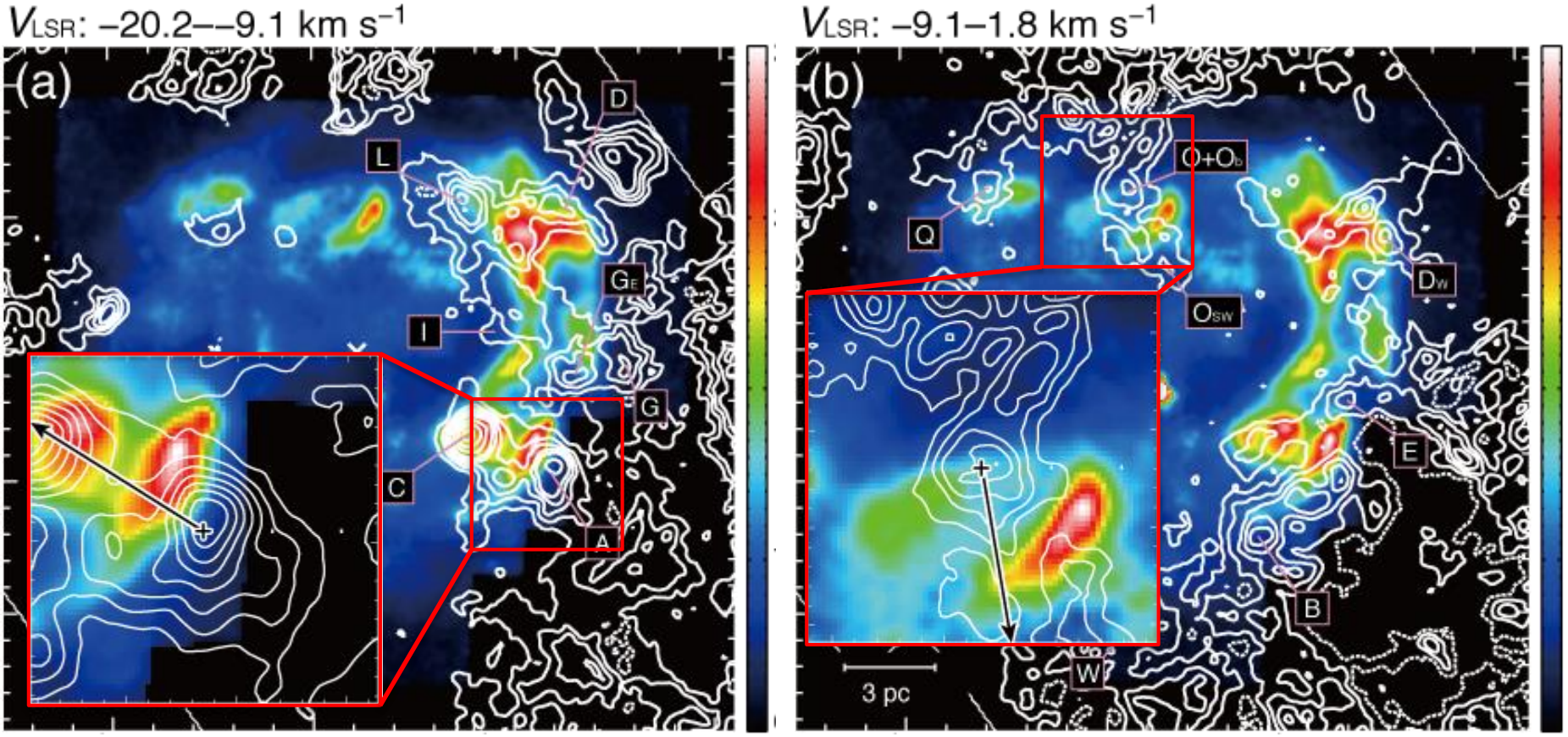
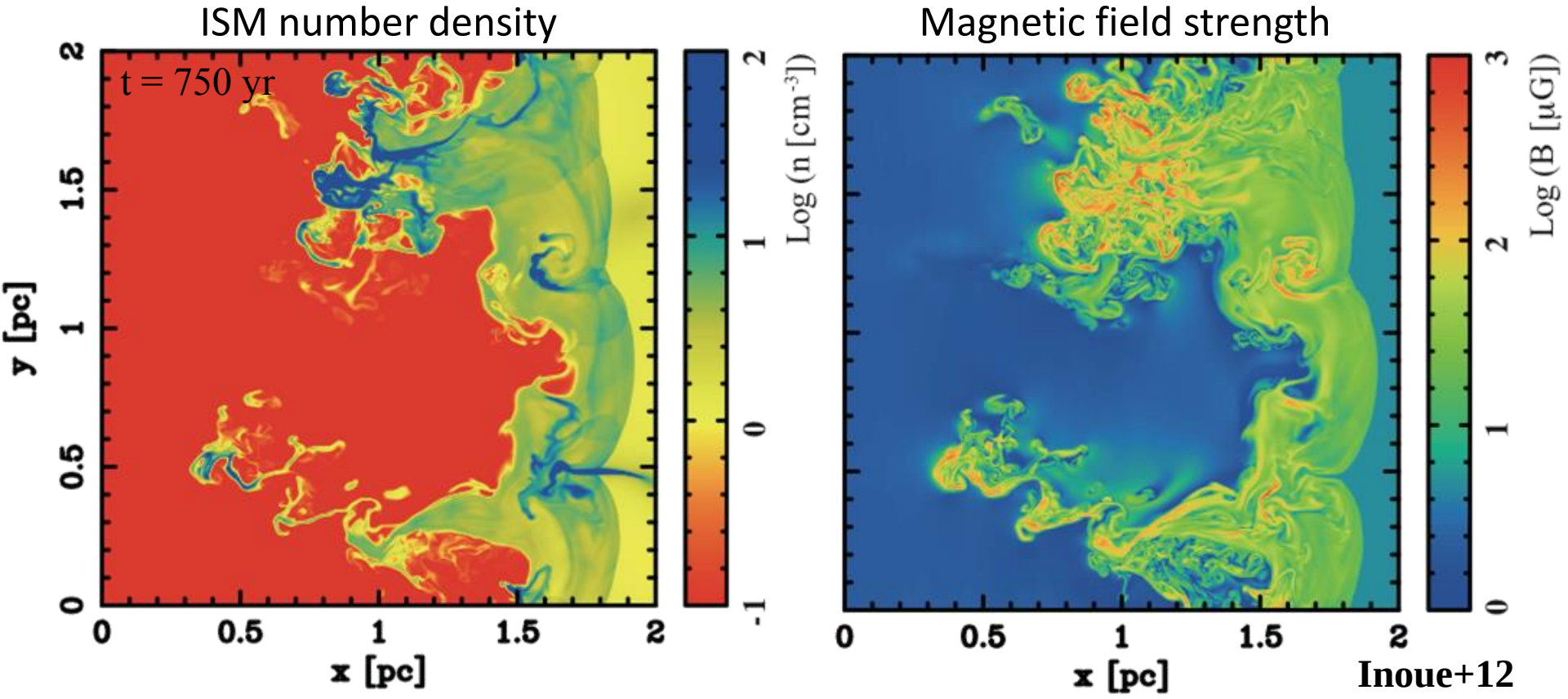


Image: *Suzaku* 5–10 keV, Contours: ^{12}CO(J=2–1) intensity (two velocity ranges) **Sano+10, Sano+13**

Credit: H. Sano

MHD Simulation

- Magnetic field amplification in the down stream（Inoue+12）
  ⇒ The shock waves propagate into the clumpy ISM formed by thermal instability



MHD results explain the spatial distribution between the CO and X-rays

Credit: H. Sano

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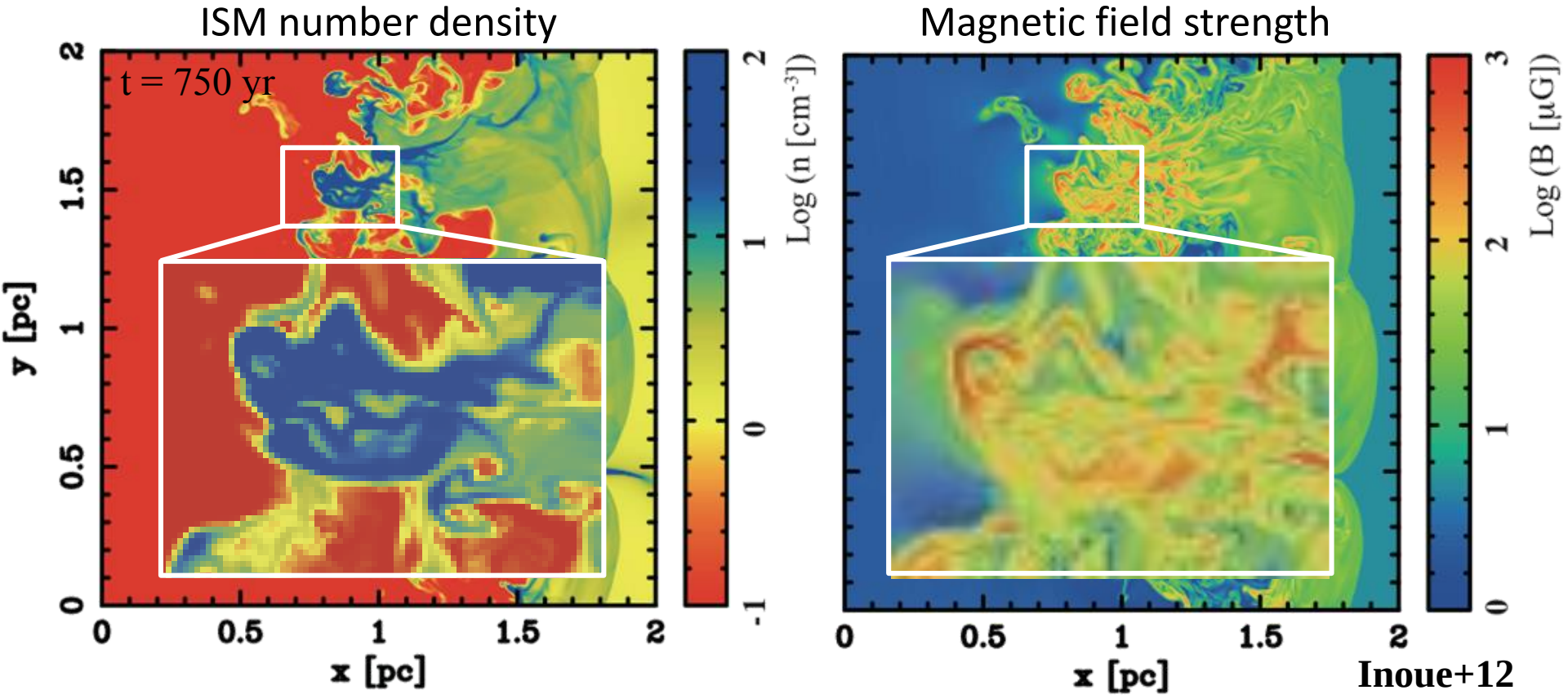

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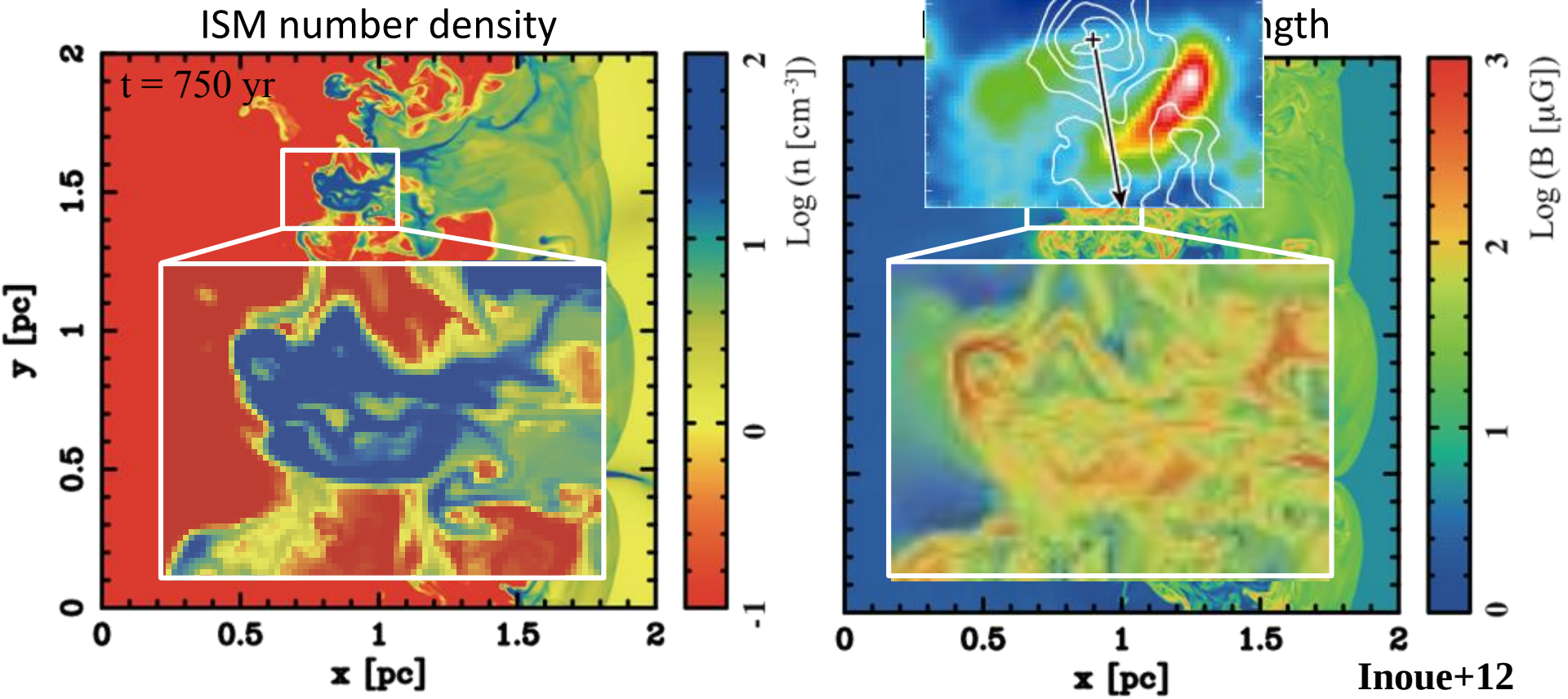
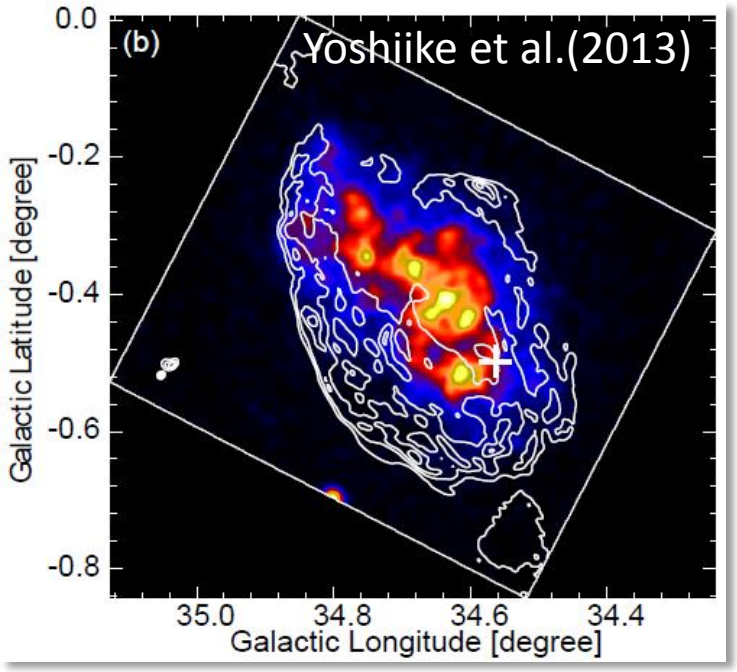


MHD results explain the spatial distribution between the CO and X-rays

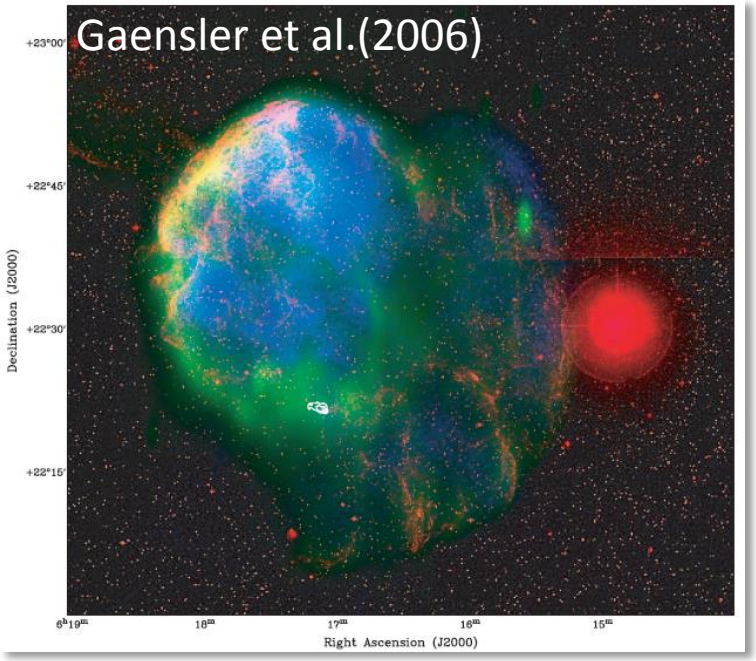
Credit: H. Sano

2. Middle-aged SNR

■ W44



■ IC443

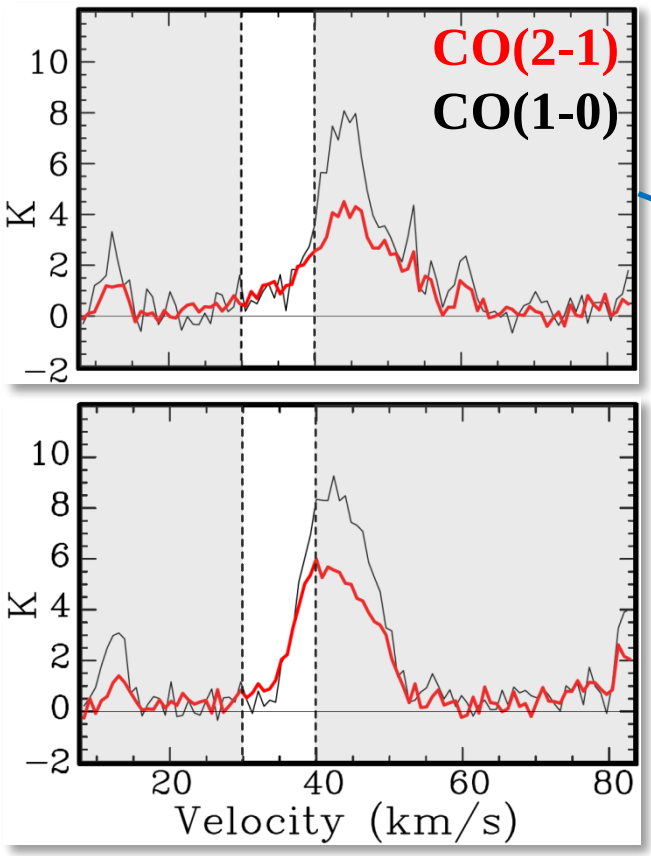


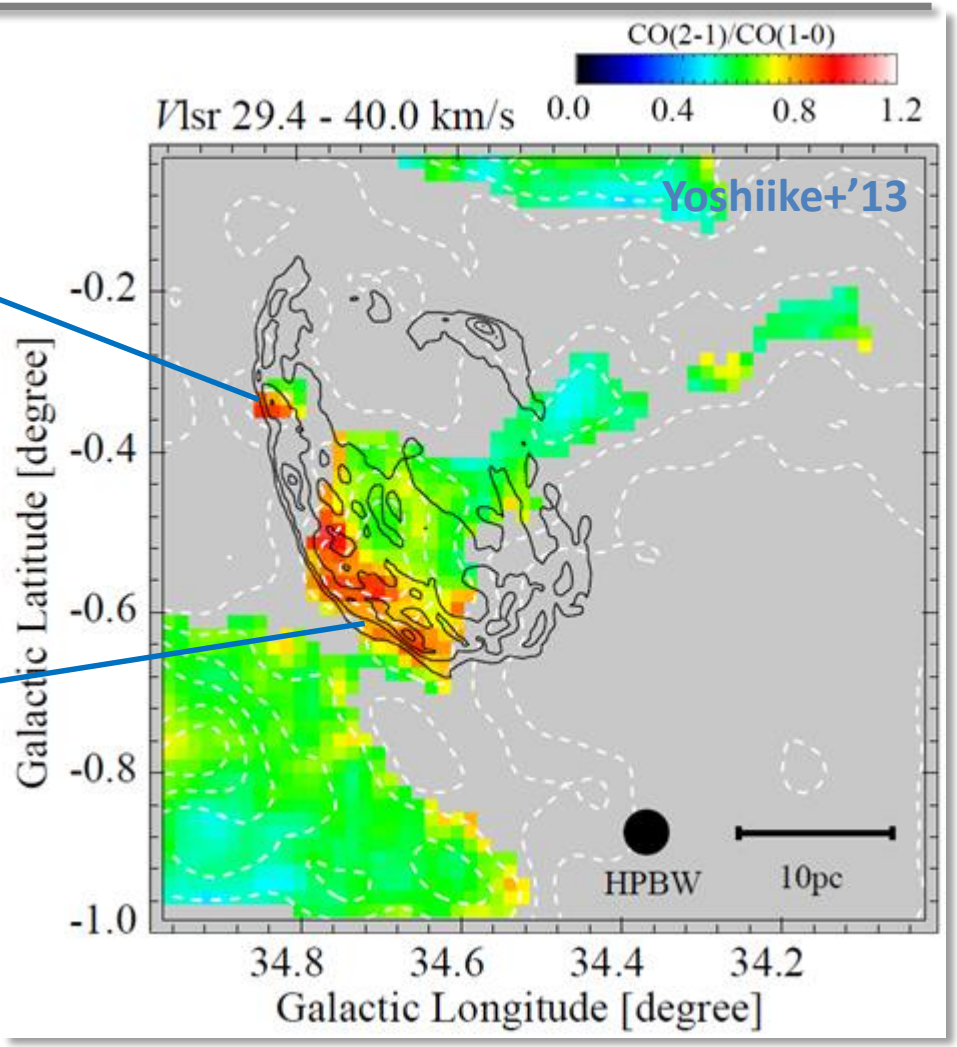
- Contours : Radio continuum (1.4GHz by *VLA*)
- Image : X-ray (0.4-2.4 keV by *ROSAT*)

Red:Optical / Green:1.4 GHz / Blue:X-ray

- **Age ~ 10,000 yr**
- **Interaction with ISM**
- **Brighter in GeV γ-ray rather than TeV**
  - **Identified as a extended source by Fermi-LAT**

^{12}CO(2-1)/^{12}CO(1-0) in W44



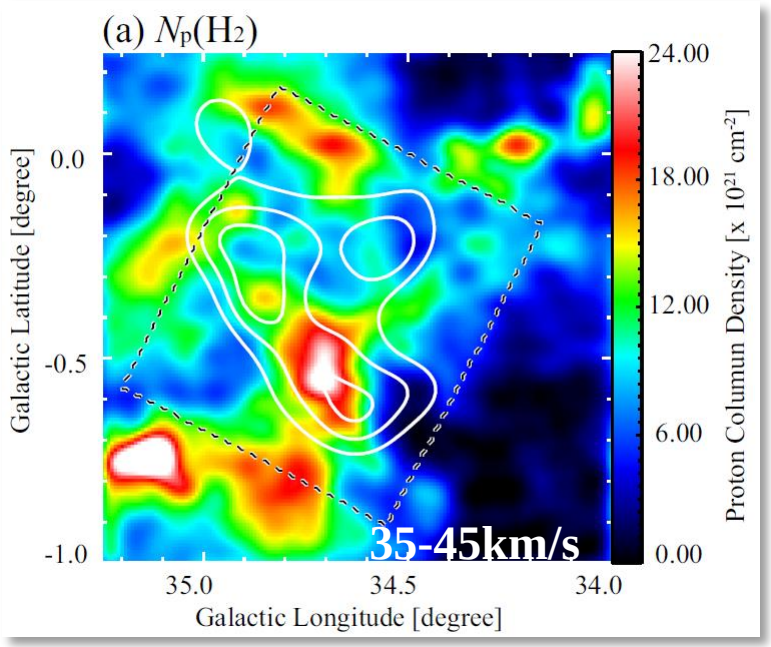


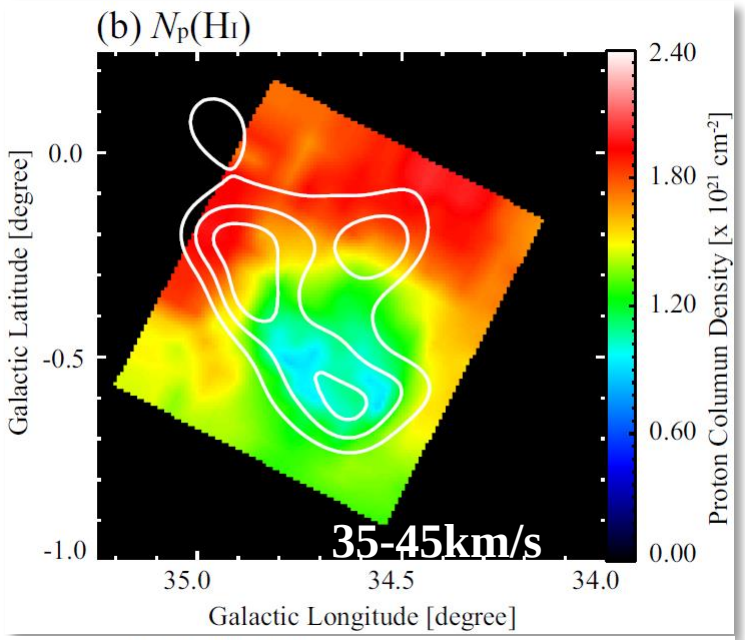
- **The ratios are enhanced around ~ 1.0 along the eastern rim.**

→ **indicates the molecular cloud is compresses and/or heated .**

Image … ^{12}CO(J=2-1)/ ^{12}CO(J=1-0)
Contours … Solid : 1.4GHz Radio Conti. (*VLA*)
Dashed : ^{12}CO(J=2-1) Integrated Intensity

Comparison between γ–ray and ISM





Yoshiike+'13

$$(a)\, N_p(H_2) = 2 \times X_{CO} \int T_{mb}\, dv\ [cm^{-2}]$$

- Xco = 1.56 x 10^{20} cm^{-2}/(K km/s)

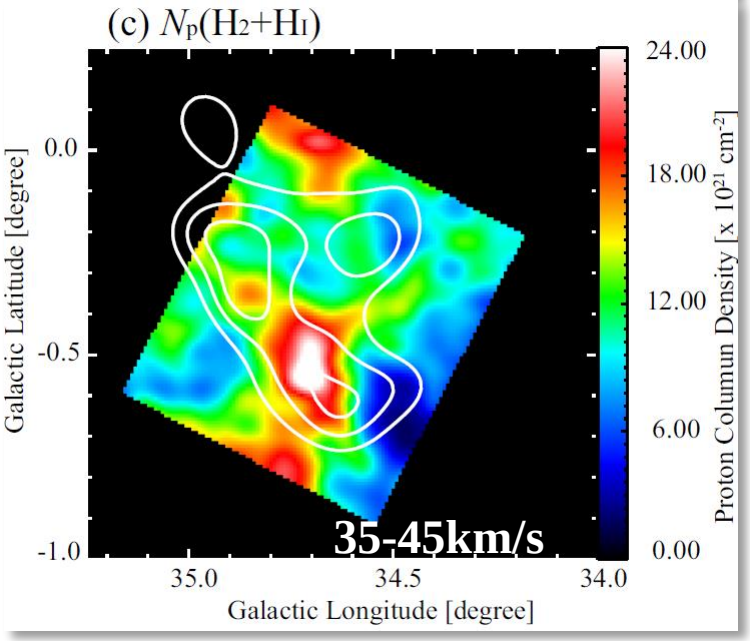
(Hunter +'97)

- CO(2-1)/CO(1-0) = 0.6

$$(b)\, N_p(HI) \cong 1.823 \times 10^{18} \int T_L\, dv\ [cm^{-2}]$$

Absorptions are interpolated.

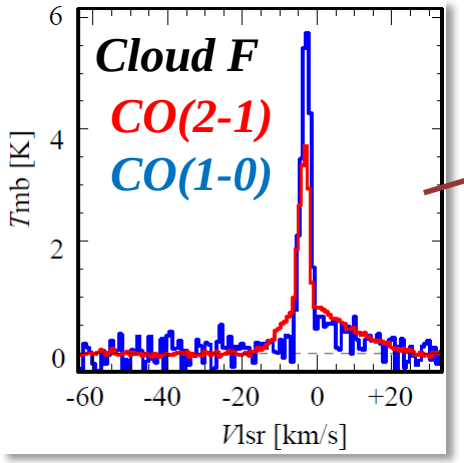
$$(c)\, N_p(H_2 + HI) = N_p(H_2) + N_p(HI)\ [cm^{-2}]$$

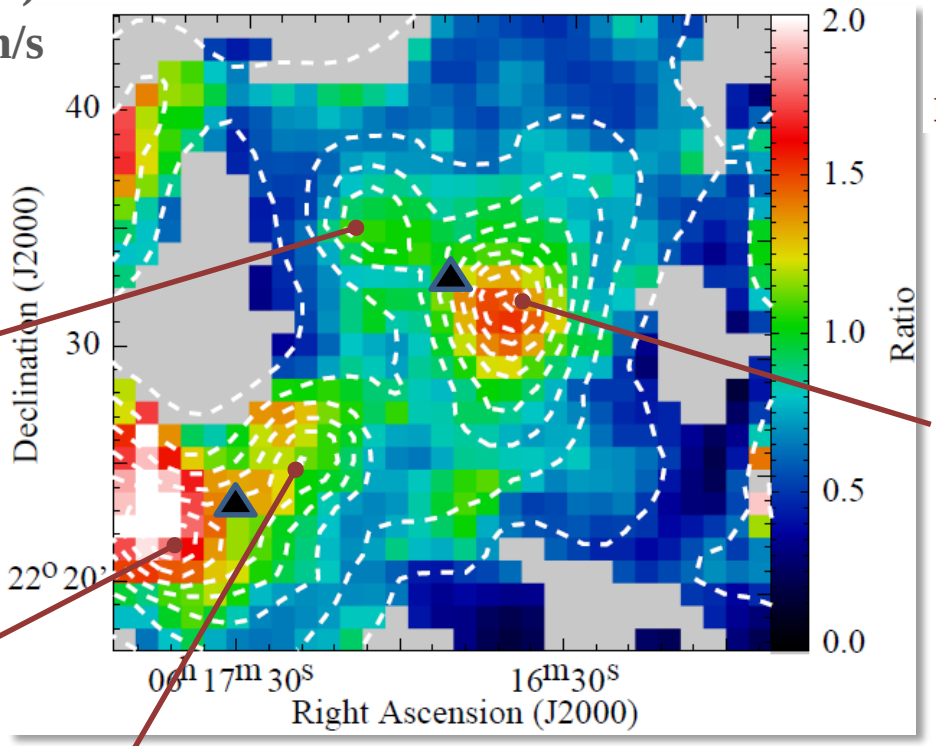


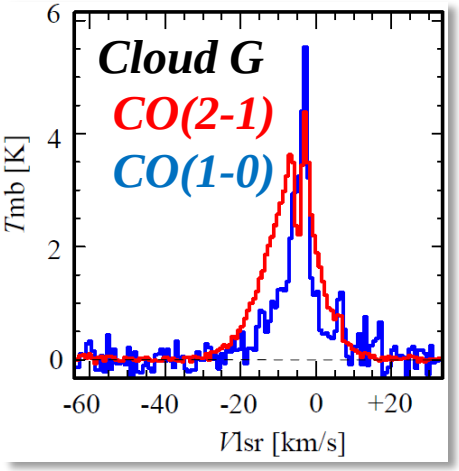
$^{12}CO(2-1)/^{12}CO(1-0)$ in IC443

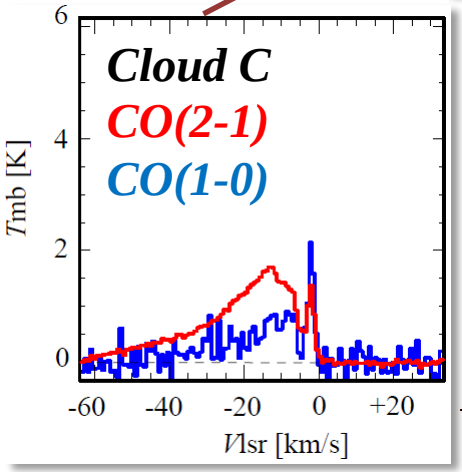
Contours … $^{12}CO(2-1)$
-60 — + 30 km/s

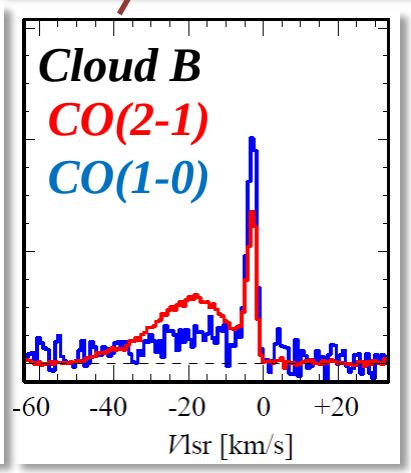
▲ … OH maser





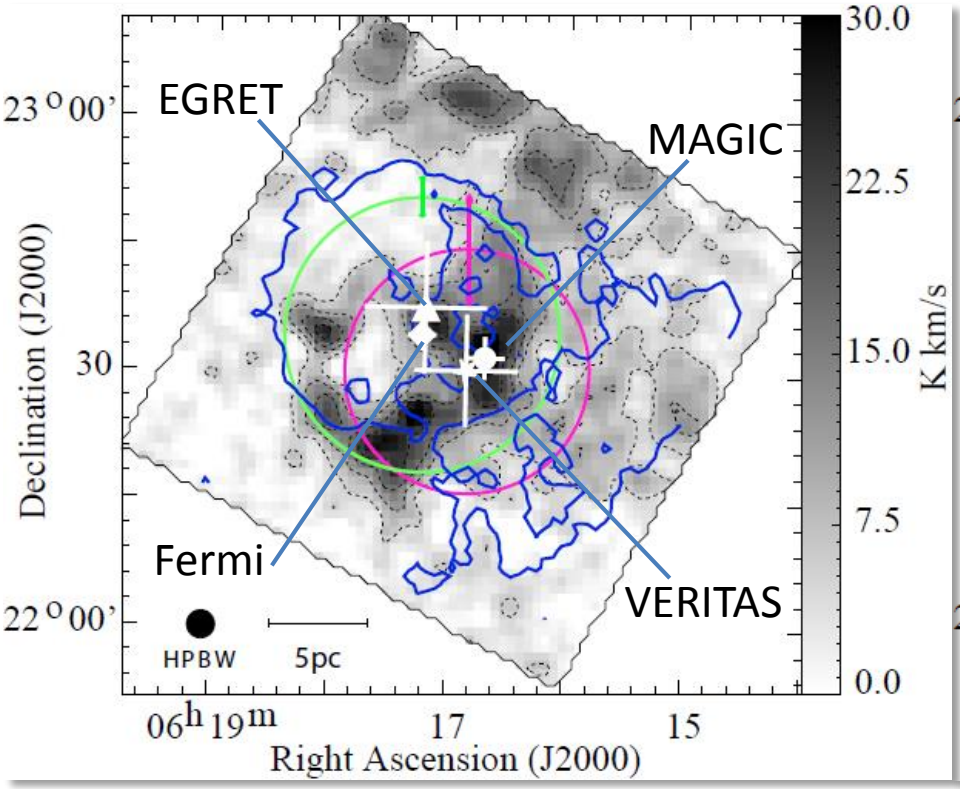






- Central region of Shell
- The ratios are enhanced in each MCs (2-1/1-0 ~ 1 - 3)
- Large velocity width < 60 km/s

Comparison between γ–ray and ISM



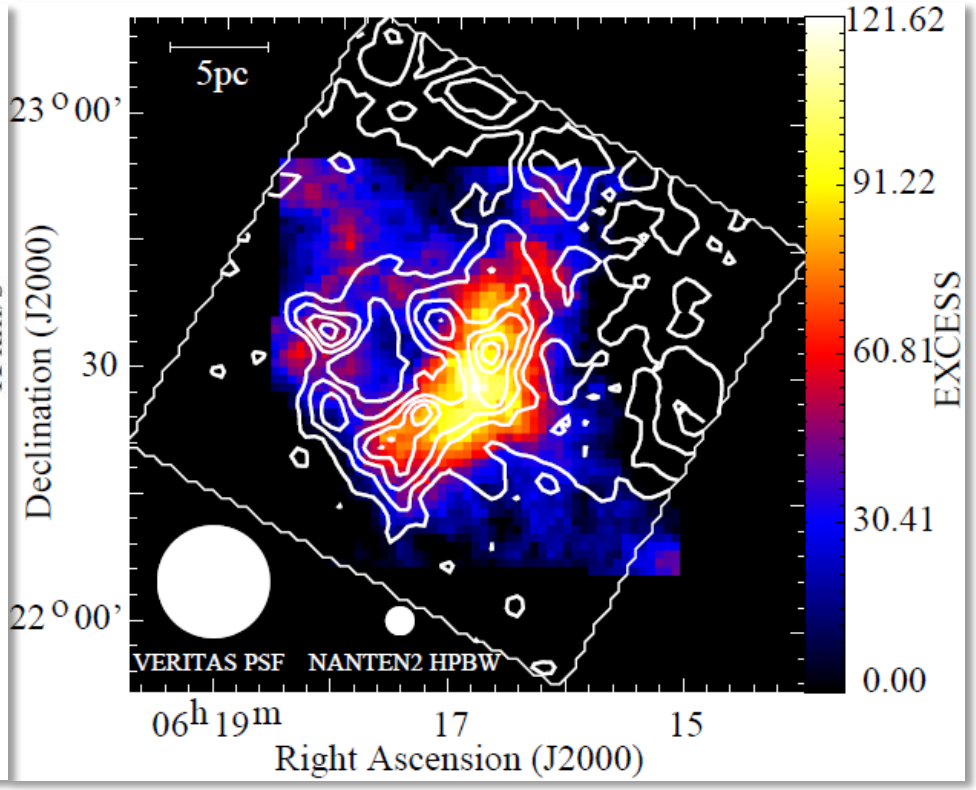


Image : NANTEN2 CO(1-0)
Blue Contour : DSS Optical
○ : Extension of the VERITAS sources
○ : Extension of the Fermi sources

Image : VERITAS 0.3 -2 TeV
(Acciari et al.2009)
White Contour: NANTEN2 CO(1-0)

Comparison between Middle-aged SNRs

SNR	age [x 10^4 yr]	distance [kpc]	Lγ [10^{35}Jy/s]	Proton density [cm^{-3}]	Total CR Proton Energy [erg]
IC 443	0.4 – 2	1.5	1.3	120	> 5 x 10^{48}
W44	2	3	5.9	200 [A]	> 1 x 10^{49} [A]
W28	4.5	~ 2	1	1,000 [B]	3 x 10^{49} [C]
W51C	5.8	6	13	---	5 x 10^{49}(n/100)$^{-1}$

A:Yoshiike +'13, B: Aharonian+'08, C : Giuliani+'10

$$W_p \approx \tau_p \times L_\gamma\,[\mathrm{erg}],\ \tau_p \approx 4.5\times10^{13}\times(n/100\mathrm{cm}^{-3})^{-1}\,[\mathrm{s}]$$

- W_p ~ 10^{49} erg
  - 1% of the kinematic energy released per SNR, 10^{51} erg

This is reasonable lower limit with taking into account CR escape. ***W28(Aharonian+'08), W44(Uchiyama+'12)***

  - > ~ 10^{48} erg (young SNR, RXJ 1713, Vela Jr)

This may suggest the CR energy to be increased over 10^3 to 10^4 yrs.

Summary

- **Are SNRs origin of cosmic-rays (CRs), especially CRs protons ?**
  - **TeV Shell-Type SNR (RXJ 1713, Vela Jr)**
    - ✓ **Good spatial correlation between γ-ray and "total" ISM proton (H_2+HI).**
  - **Middle-aged SNR (W44, IC443)**
    - ✓ **The position of shocked gas corresponds with γ-ray.**
  - **These γ-ray should be produced via "hadronic" origin.**
- **Do SNRs produce the energy density of the Galactic CRs?**
  - **Total CR proton Energy : W_P**
    - ✓ **Middle-age SNR ~ 10^{49}erg**
    - ✓ **W_P ~ 10^{49} ~ 0.01*E_{SN} would be a lower limit because of CRs escaping (e.g., W44, W28).**
- **How dose the shock interaction with ISM affect its environment?**
  - **Anti-correlatiton between X-ray and ISM in sub-pc scale (RXJ1713)**
  - **Interaction with clumps excites turbulence.**
    - **→ Amplification of B field**
    - **→ Enhancement of the synchrotron X-ray**