Interstellar Medium in the Middle-aged SNRs

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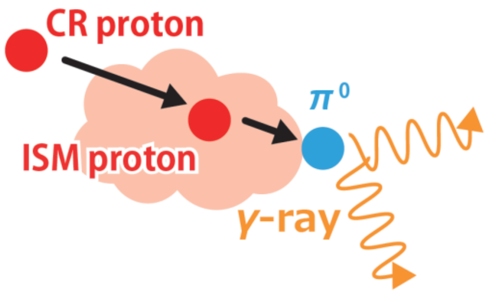
SNR: Origin of Galactic CRs ?



- Observe γ-ray produced by hadronic process
  - p(CR) + p(ISM) → π^0 + … , π^0 → 2γ
- Two approaches:

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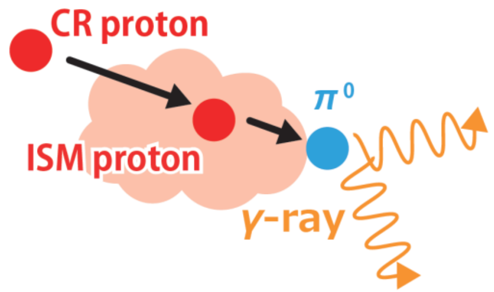

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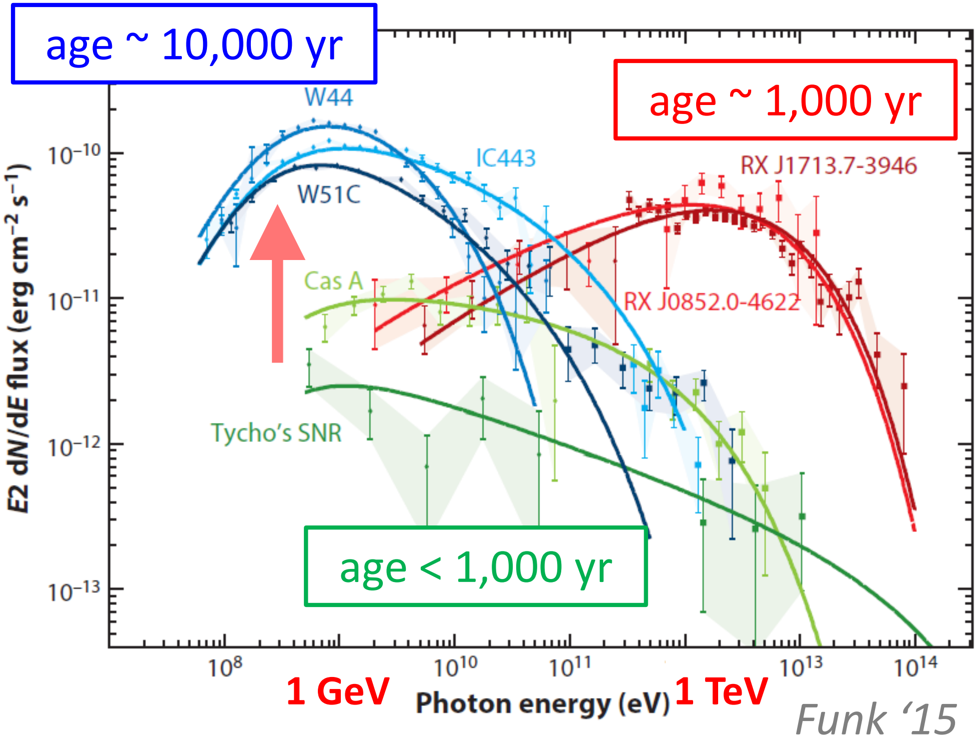

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   - Direct evidence
   - Useful for middle-aged SNRs
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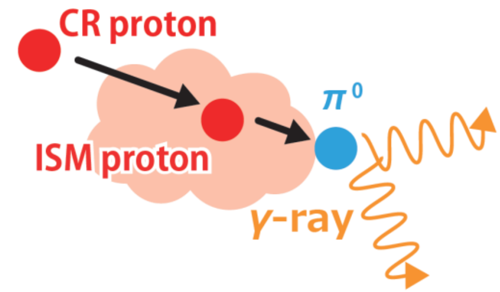

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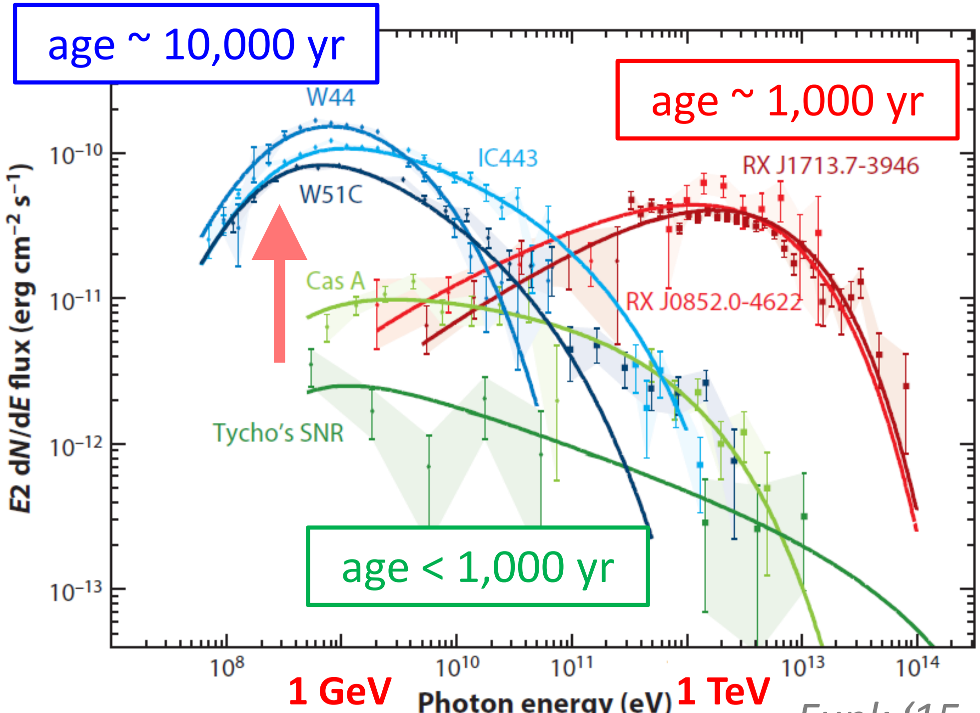
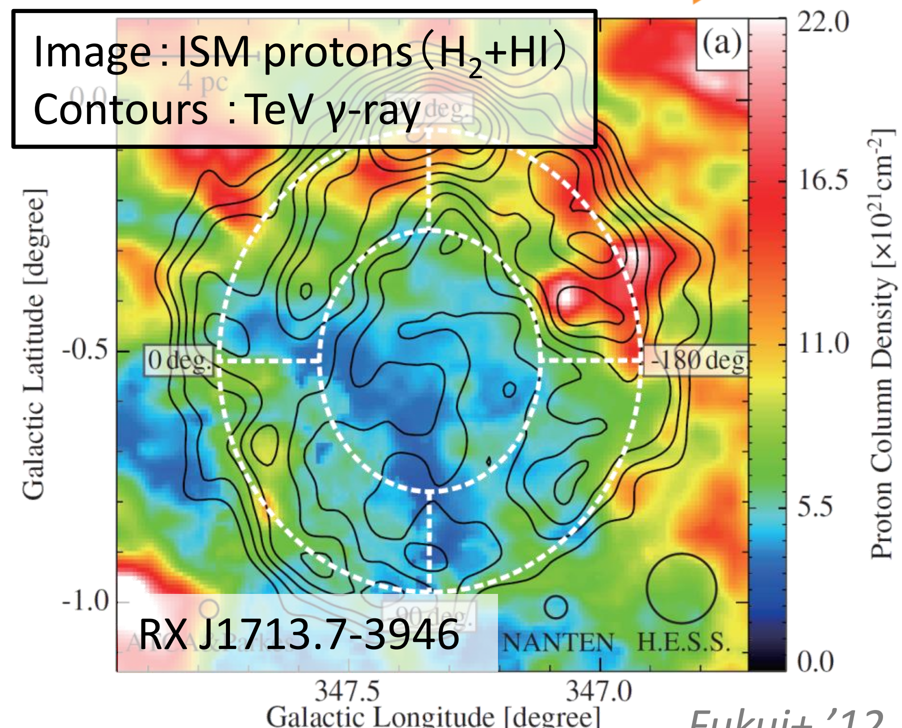


Funk '15



Fukui+ '12

1. Characteristic spectral break
   - Direct evidence
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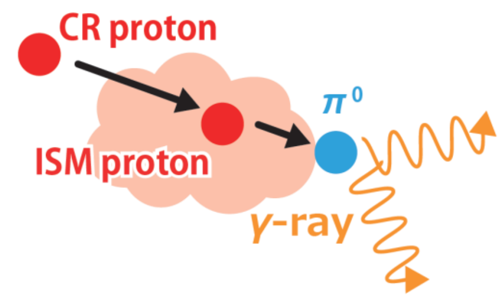
   - NO information about ISM proton
2. Spatial correlation: ISM proton and γ
   - Useful for young TeV γ-rays
   - Available mass of ISM proton
     - enable to estimate *Wp*

SNR: Origin of Galactic CRs ?



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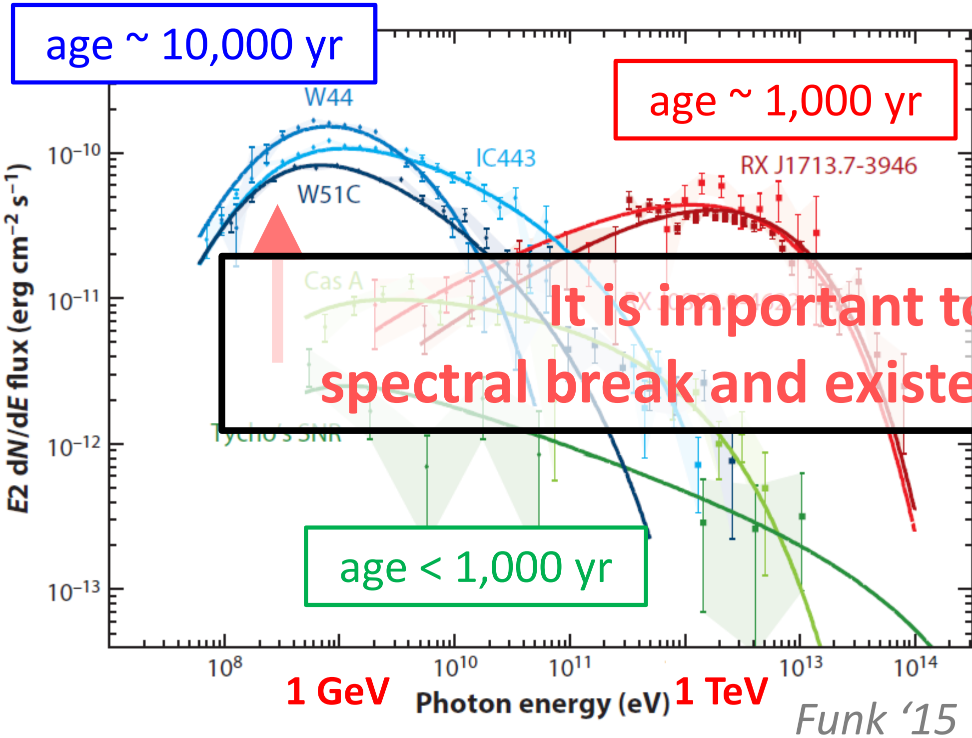

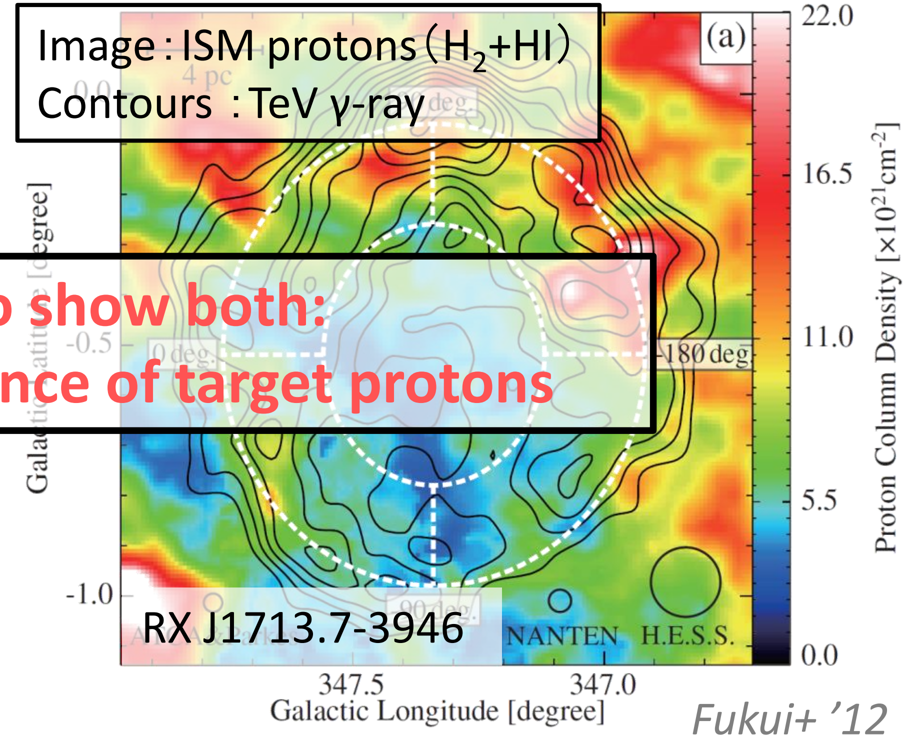

It is important to show both:
spectral break and existence of target protons

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Middle-aged SNRs: W44, IC 443

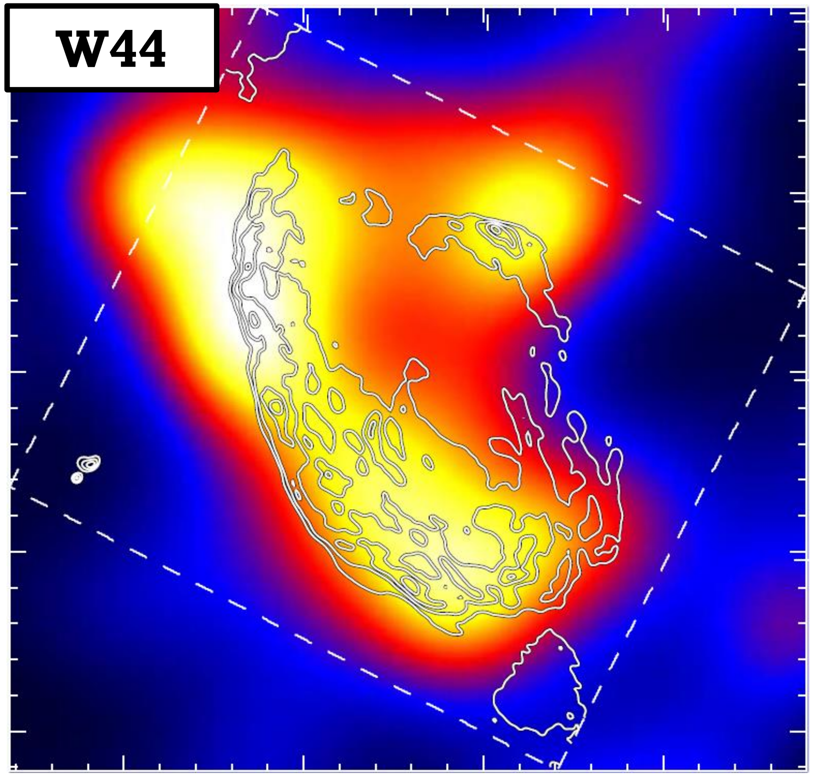


Image: GeV γ-ray (Fermi-LAT)
Contours: 1.4 GHz conti. (VLA)

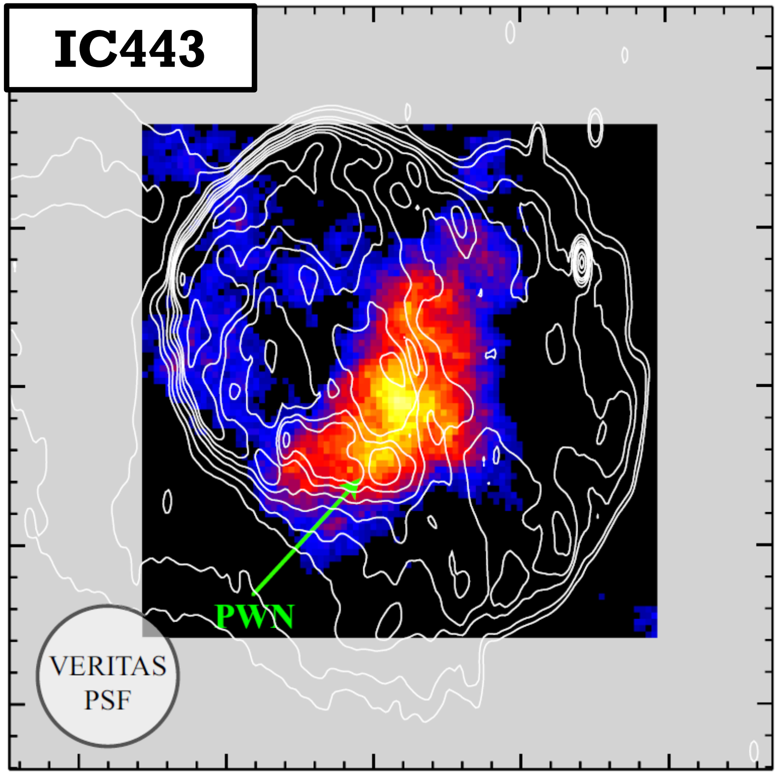


Image: TeV γ-ray (VERITAS)
Contours: 1.4 GHz conti.
(DRAO Synthesis Telescope)

- Spectral break was confirmed by *AGILE* and *Fermi*-LAT
  Giuliani+ '11, Ackermann+ '13
- This work: Analyzed ISM (CO, HI, Dust) data to identify the target protons for the hadronic γ–rays.

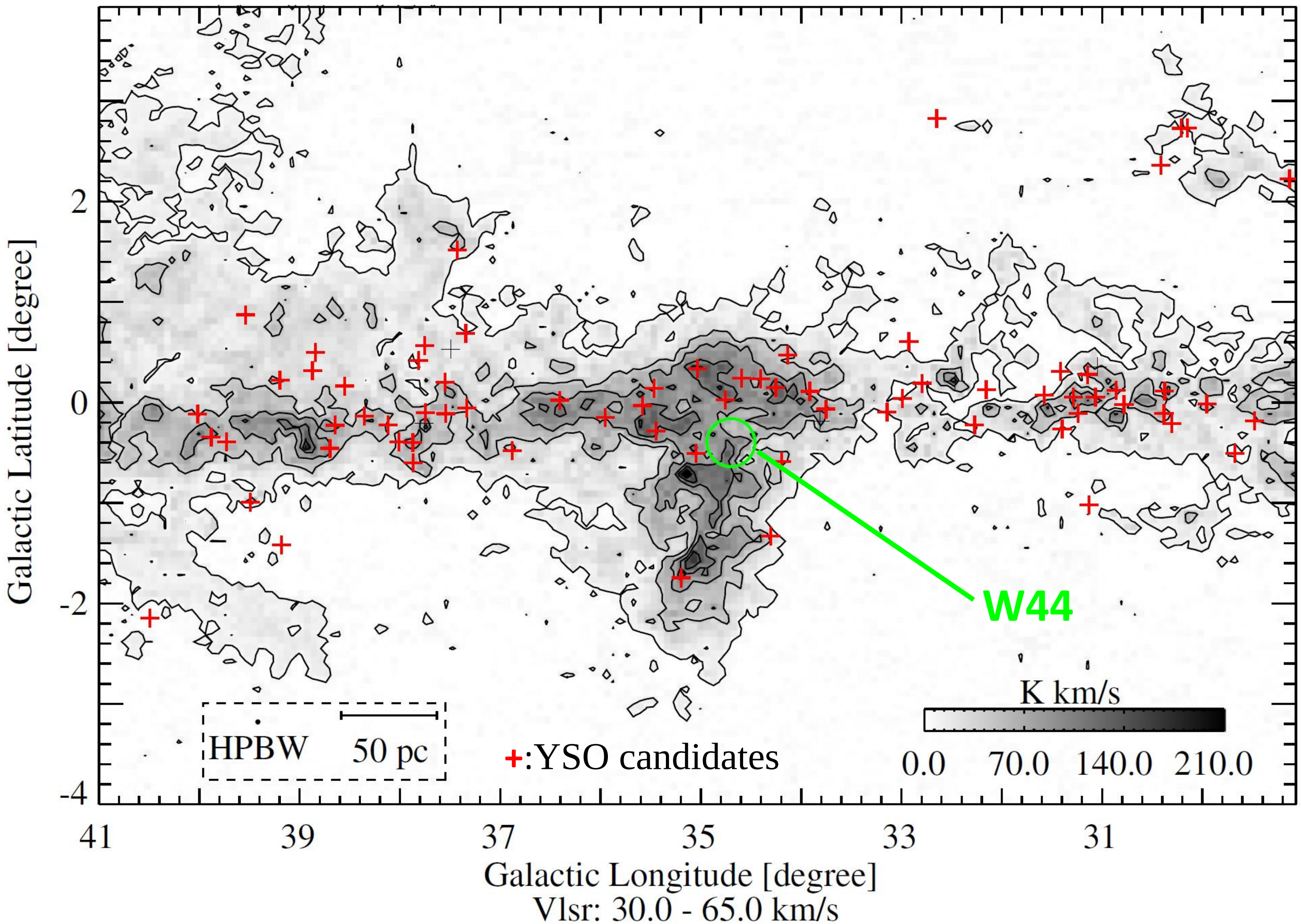
NANTEN2 telescope

- Location: Chile, Atacama (alt. 4,850m)
- Frequencies:
  - ✓ 100 GHz: CO(J = 1–0)
    HPBW ~ 2.7'
    → ~ 2.3 pc (at W44)
    → ~ 1.1 pc (at IC 443)
  - ✓ 200 GHz: CO(J = 2–1)
    HPBW ~ 1.5'
    → ~ 1.3 pc (at W44)
    → ~ 0.65 pc (at IC 443)

- Advantages
  - ✓ Moderate beam size
    Good for observing large area and/or many objects.
  - ✓ Multi-line observation
    Investigate for physical properties of ISM

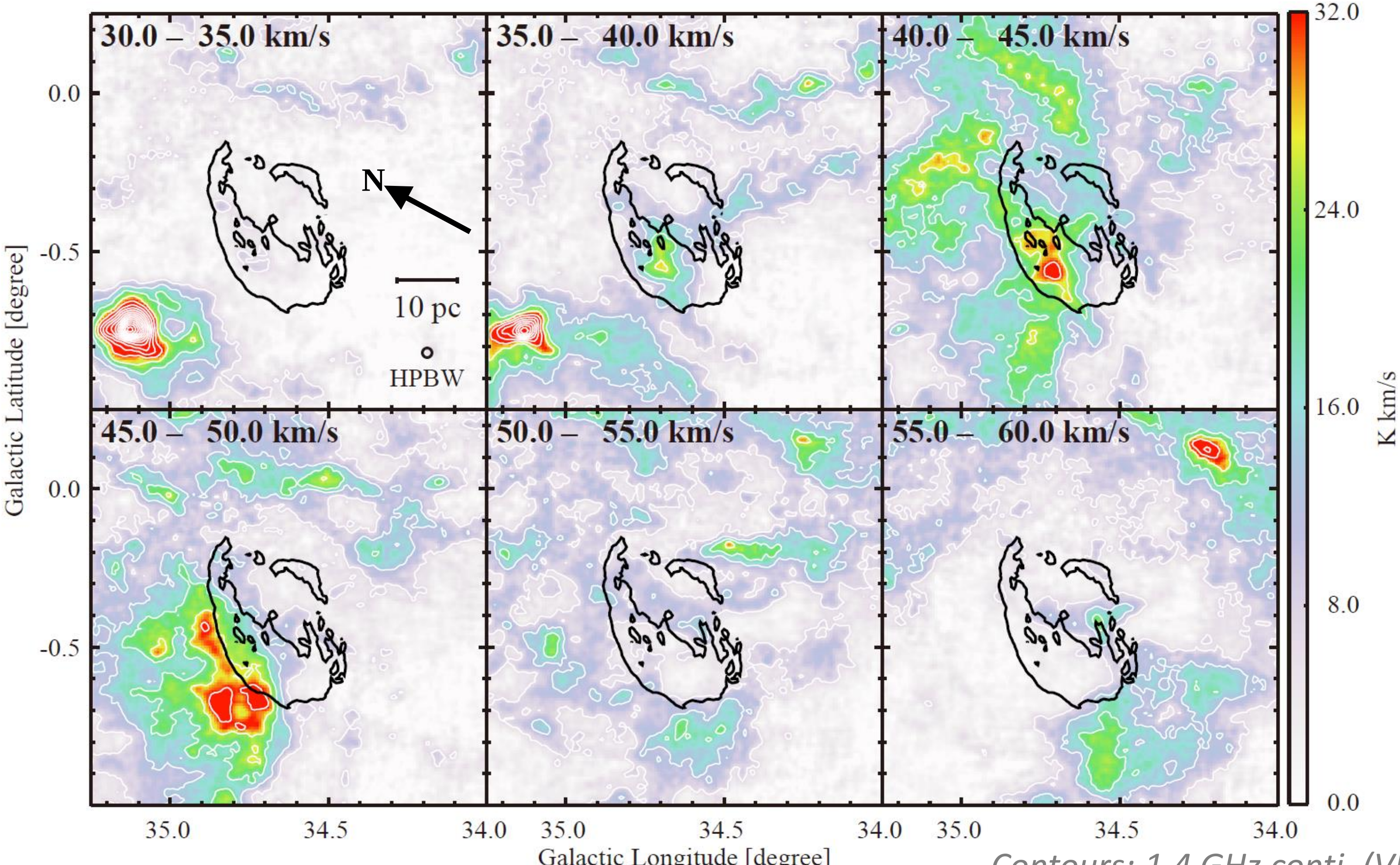
W44: Yoshiike et al. 2013

- † Large scale distribution of ^{12}CO(J=1–0) by NANTEN
  - ‡ W44 is embedded in “Molecular Ridge”.



W44: Yoshiike et al. 2013

- † Velocity Channel Map of ^{12}CO(J=2–1): 30 - 60 km/s, 5 km/s interval
  - ‡ V = 40 – 50 km/s : GMC is located at Eastern-side
  - ‡ V = 50 – 60 km/s : Clouds surround the shell



Contours: 1.4 GHz conti. (VLA)

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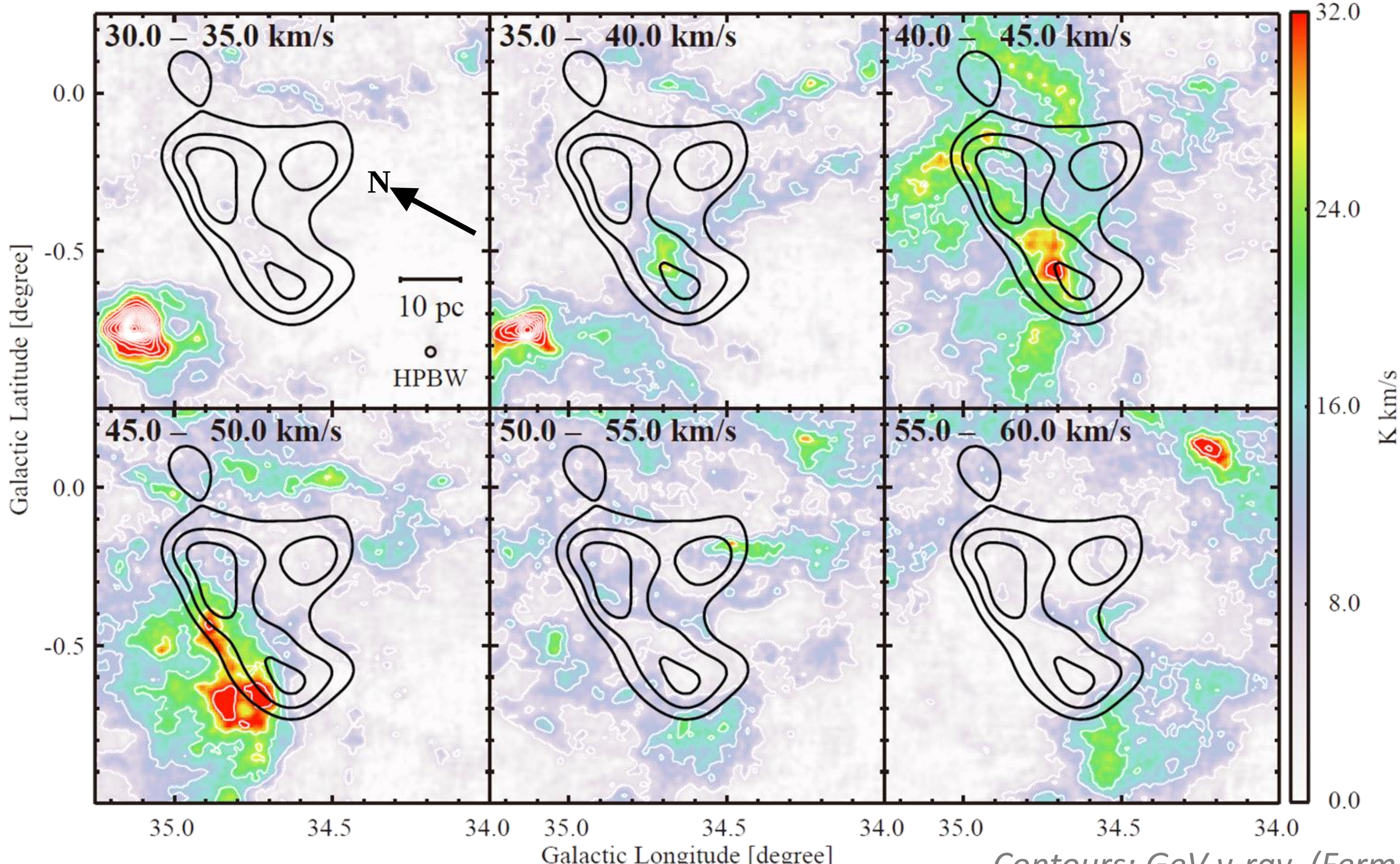
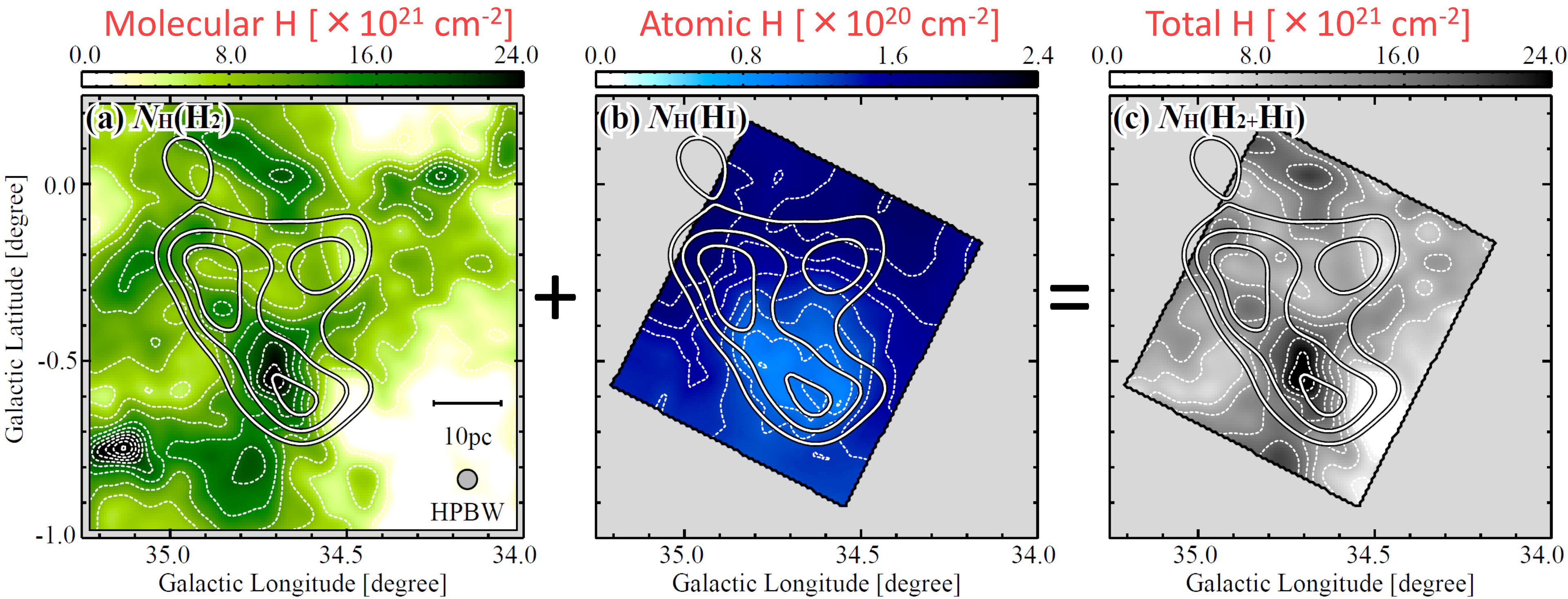
- † Velocity Channel Map of ^{12}CO(J=2–1): 30 - 60 km/s, 5 km/s interval
  - ‡ V = 35 – 45 km/s : Candidate of the target protons



Contours: GeV γ-ray (Fermi-LAT)

W44: Yoshiike et al. 2013

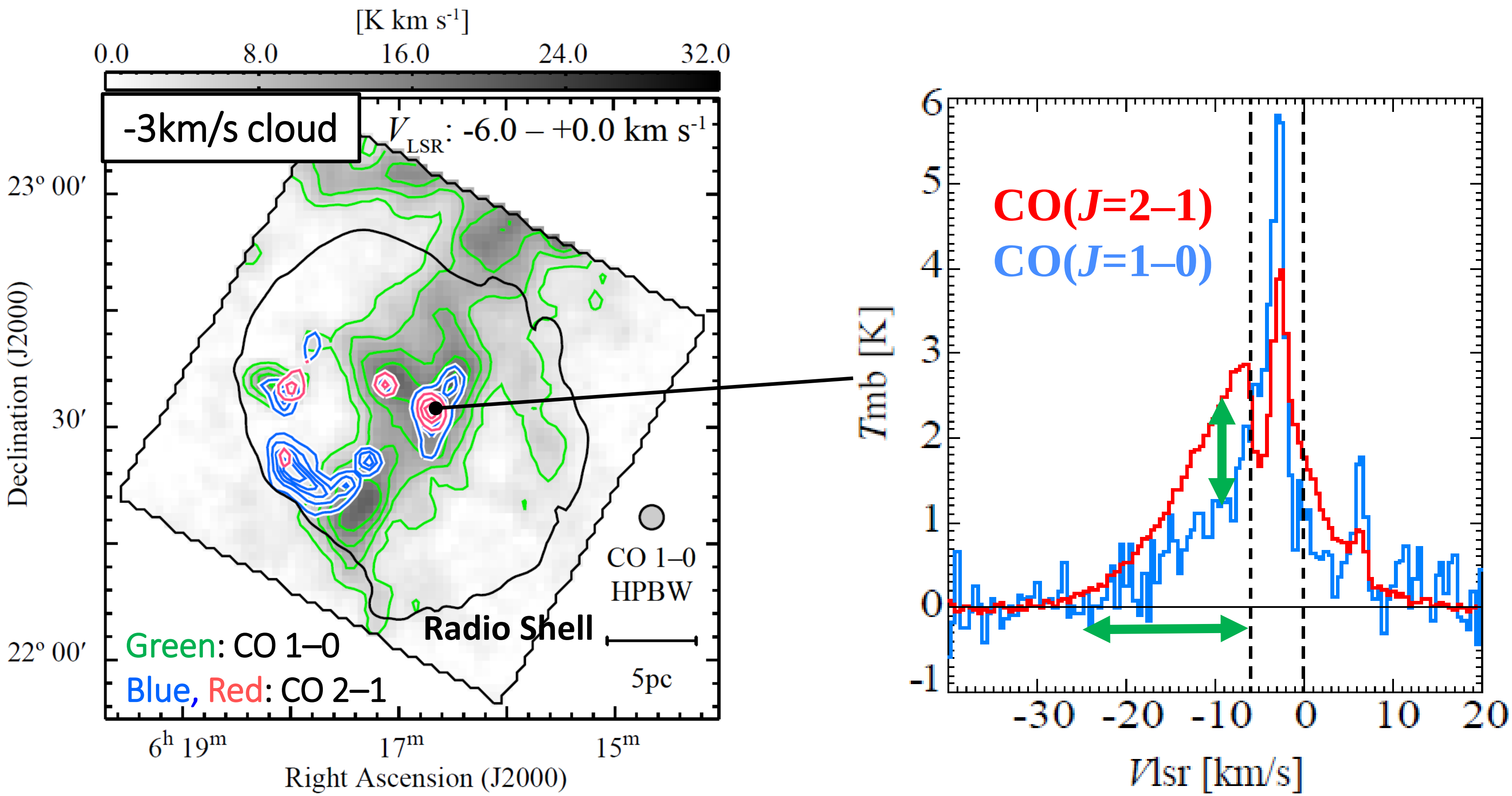
- Distribution of ISM proton column density



- Target protons are dominated by molecular gas: $n(H_2):n(HI) \sim 10 : 1$
  - different situation from young SNRs: $n(H_2):n(HI) \sim (0–1) : 1$
- $n_p \sim 200$ cm^{-3}, $W_p \sim 10^{49}$ erg ($\sim 1\,\% \times E_{SN}$)

IC 443: Molecular Gas Distribution

- Narrow component: -3 km/s clouds
- Clumps: (Blue) -18 – -6 km/s, (Red) 0 – +10 km/s
  - Broad wings + High intensity ratio of CO 2–1/1–0
    - → Interaction with SNR shock



IC 443: Gas Location relative to the SNR

- Spatial Comparison: Soft X-ray (0.4–0. 75 keV) vs CO (*J*=1–0)
- X-ray shows anti-correlation with -3km/s cloud
  - -3km/s clouds is located in front of IC443

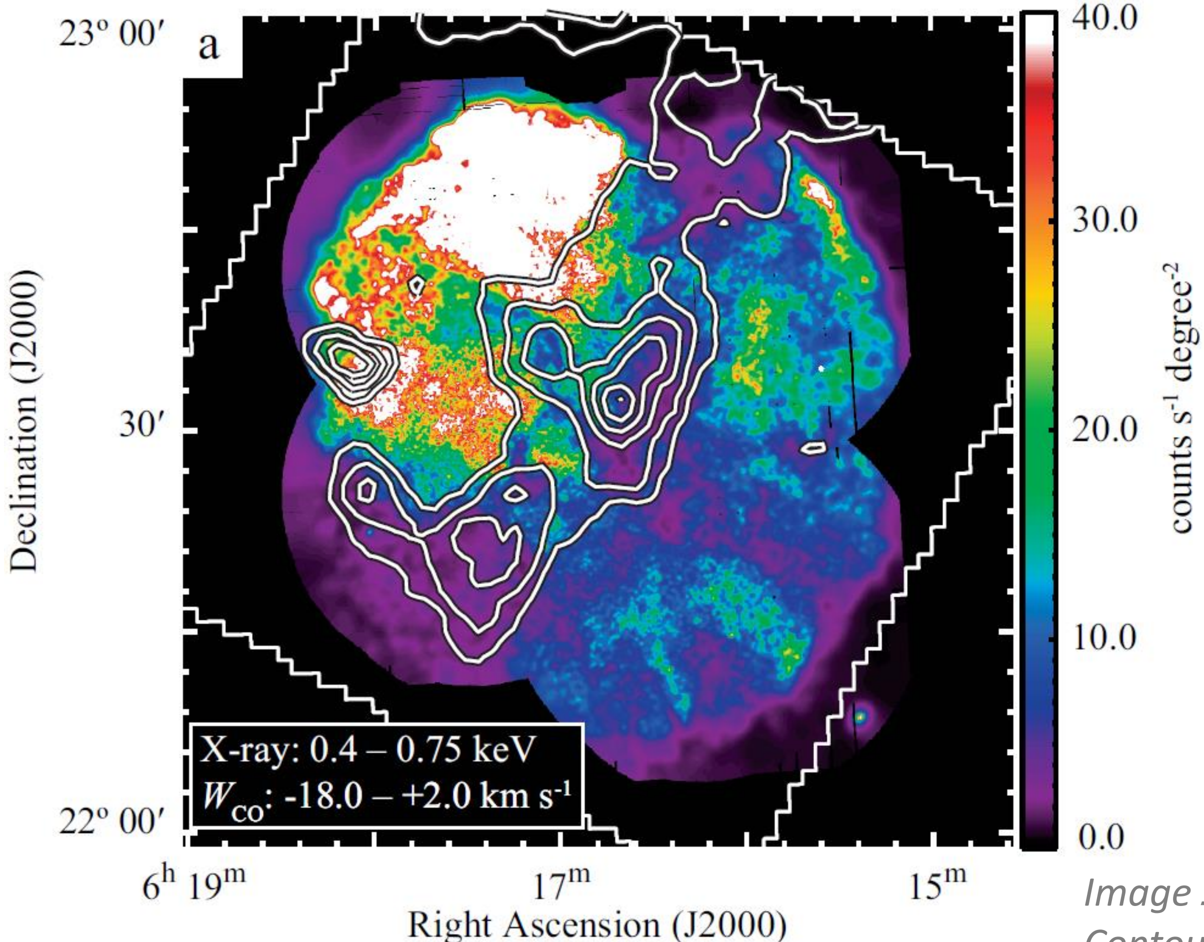
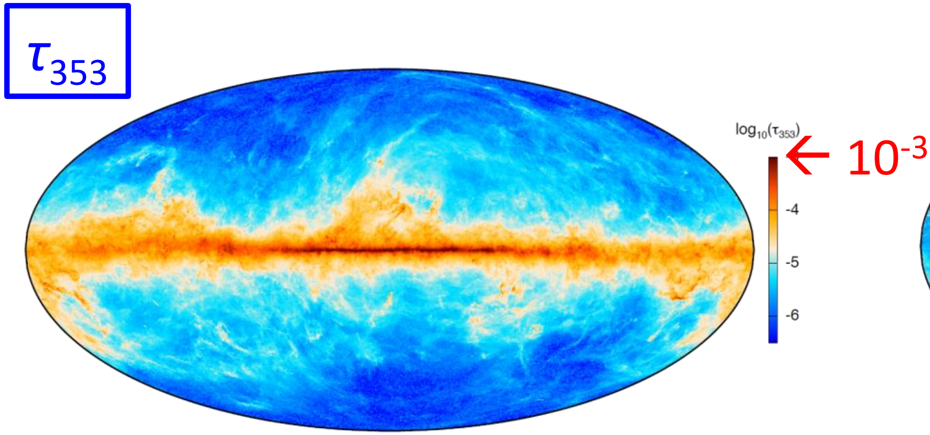


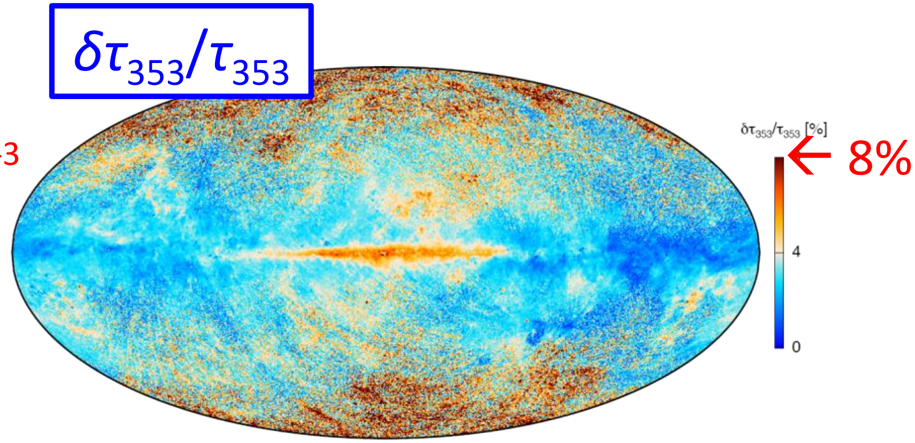
Image :XMM-Newton
Contours :CO(J=1–0)

τ_{353}: Tracer of Hydrogen

- Dust opacity at 353 GHz, τ_{353} (*Planck/IRAS*)
  - $\tau_{353} \lesssim 10^{-3}$, $\delta\tau_{353}/\tau_{353} \lesssim 10$ %
  - Good tracer of interstellar hydrogen

Fukui+ '14 (MBM 53, 54, 55 + HLCG 92-35), '15 (All-sky), '17 (MHD simulation)





Planck Collaboration+ '14

- Okamoto+ '17 derived the relation between N_H and τ_{353} in the Perseus clouds.

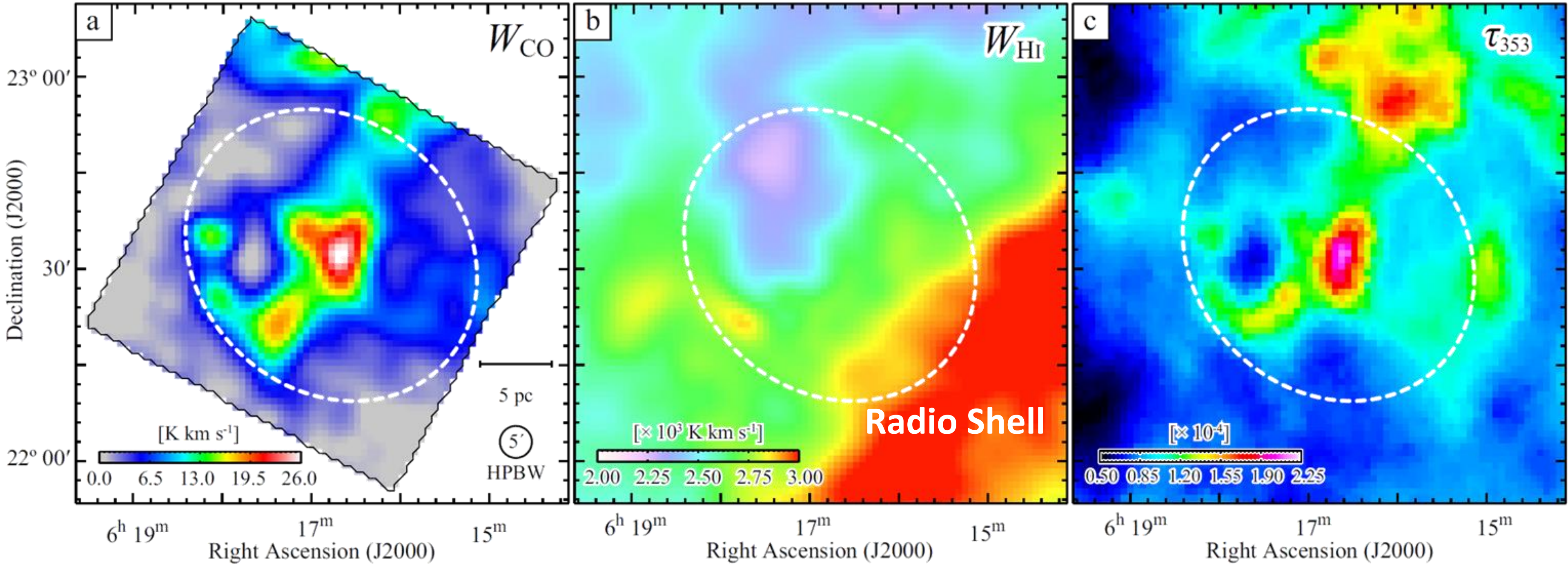
$$N_H = (9.0 \times 10^{24}) \times (\tau_{353})^{1/1.3}\,(\mathrm{cm}^{-2})$$

τ_{353}: Tracer of Hydrogen

- CO and τ_{353}: similar spatial distributions
- HI: a low contrast and more extended distribution
  → Corresponds to a diffuse part of τ_{353}.

τ_{353} is useful as the tracer of H in IC 443 region !

CO(1–0) Integrated Intensity	HI Integrated Intensity	Dust opacity at 353 GHz



X-factor (X_{CO}) in IC 443

- X-factor: X_{CO} ($\equiv N(H_2) / W_{CO}$)
  - Typical value in the Galaxy: (1–3) × 10^{20} cm^{-2}/(K km/s)

e.g., see Bolatto+ '13, Table 1

- **Total H column density from τ_{353}** *Okamoto+ '17*
  - $N_H = (9.0 \times 10^{24}) \times \tau_{353}^{1/1.3}$ (cm^{-2})

- **X_{CO} in IC 443**
  - ✓ H_2 column density

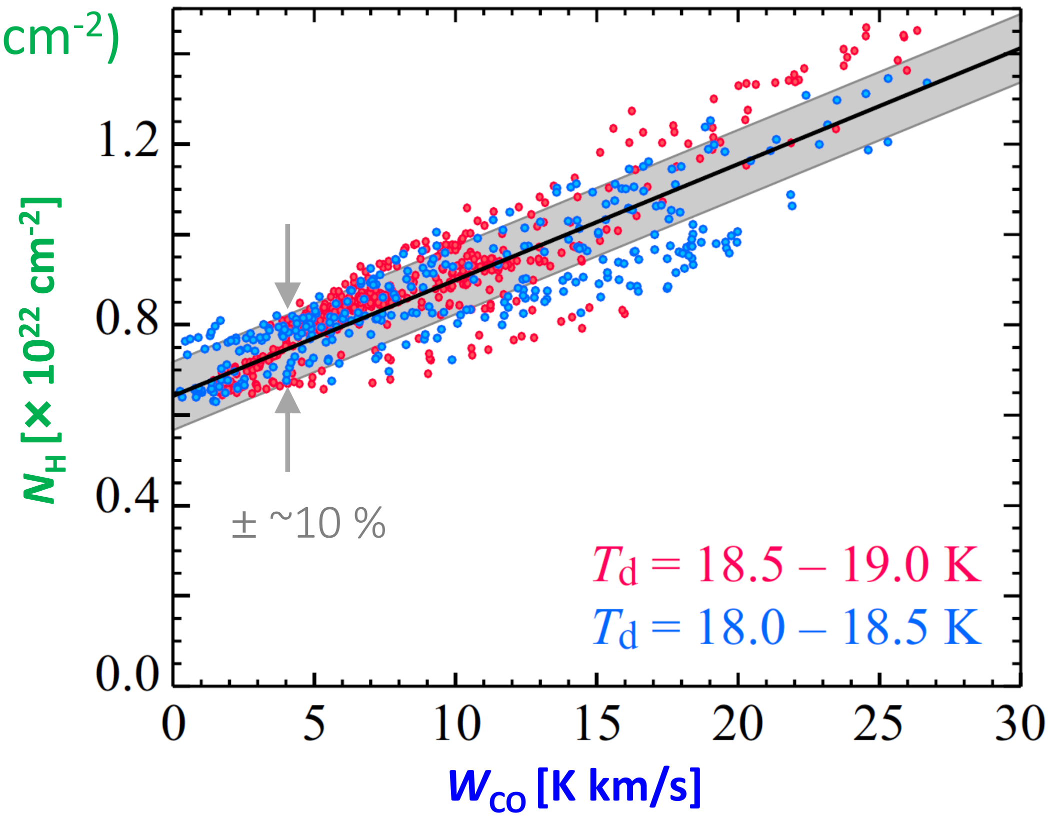
    $N(H_2) = X_{CO} \times W_{CO}$
  - ✓ Total H column density

    $N_H = 2 \times N(H_2) + N(HI)$

→ $N_H = (2 \times X_{CO}) \times W_{CO} + N(HI)$

X_{CO} = Slope/2

= **1.2 × 10^{20} cm^{-2}/(K km/s)**



Using points with W_{CO} > 3σ in Shell

IC 443: Target Protons and CR Proton Energy

- Good correspondence between molecular cloud and γ-ray peaks
- Mass: 580 $M_\odot$ / Size ~ 4pc
  - n_p: 680 cm^{-3}
- γ-ray Flux (0.1 – 100 GeV)
  - $F_\gamma = 502.1 \times 10^{-12}$ erg cm^{-2} s^{-1}

    Fermi LAT 3rd Source Catalog (*Acero+ '15*)
- Total CR Proton Energy
  - $W_p \sim 9 \times 10^{47} (n_p/680\ \mathrm{cm}^{-3})^{-1}$ erg

cf. *Ackermann+ '13*

$W_p \sim 4 \times 10^{49} (n_p/20\ \mathrm{cm}^{-3})^{-1}$ erg

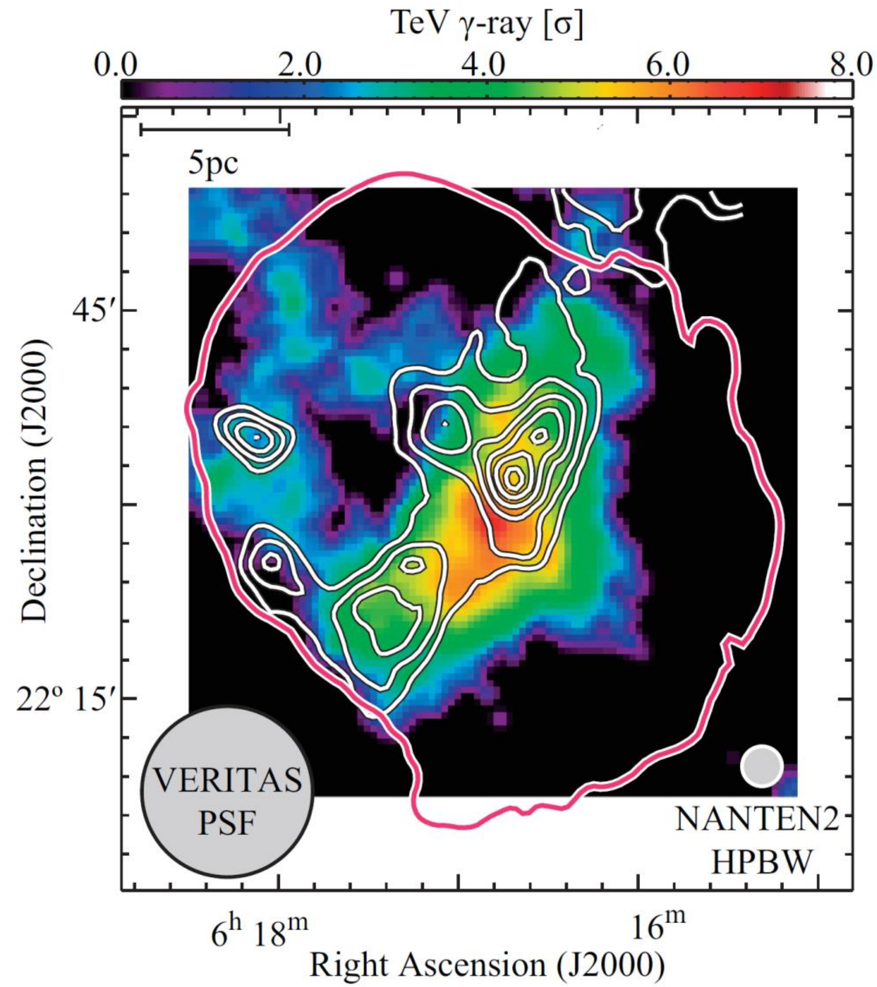


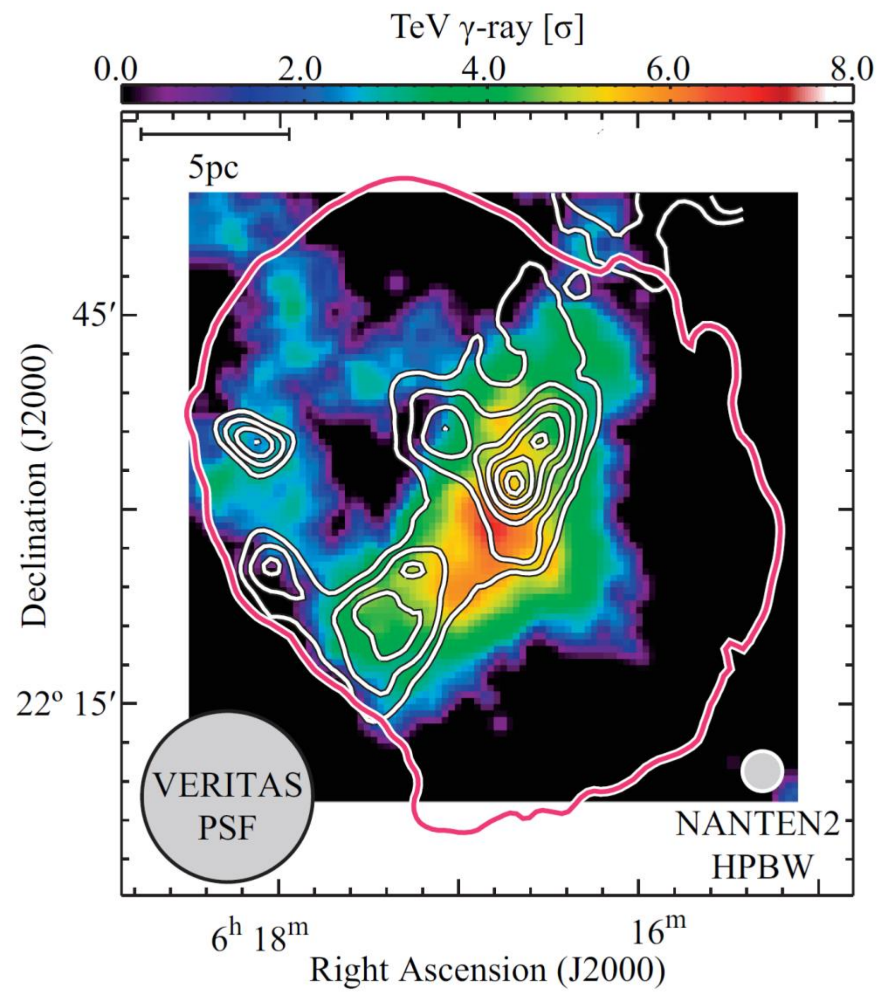
Image: TeV γ-ray (VERITAS)
Contours
White :CO(J=1–0) (-18 – +2 km/s)
Red :1.4 GHz radio conti.
(DRAO Synthesis Telescope)

Energy Budget for CRs

Efficiency of CR acceleration

- † $W_p \sim 9 \times 10^{47}$ erg
  - ‡ 0.1 % of E_{SN}

    ⇔ 1 – 10 % is required
- † NON-uniform proton distribution
  - ‡ γ-rays reflect only a part of total CR protons.



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- NON-uniform proton distribution
  - γ-rays reflect only a part of total CR protons.
- Escape of CRs from SNR

	W44	W28
W_{esc}	(0.3—3) × 10^{50} erg	> 2 × 10^{49} erg

W44; Uchiyama+ '12, W28; Hanabata+ '14

- True W_p could archive 1 – 10 % of E_{SN}
- CR energy of this work provides reasonable lower limit.

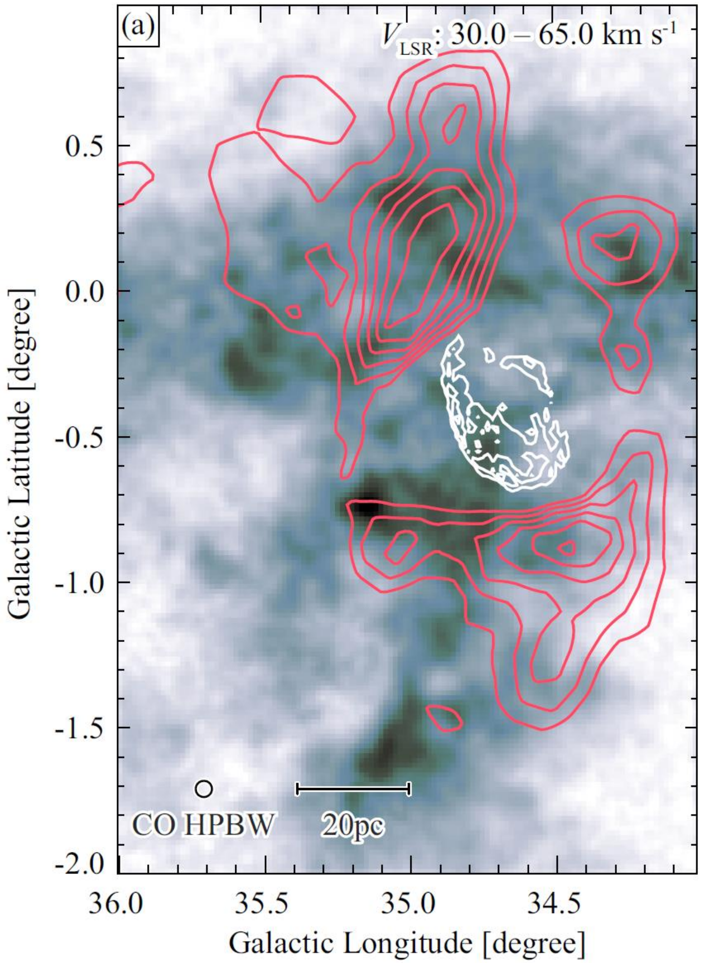

Image : CO(J=1-0) (NANTEN2)
Contours
red : GeV γ-ray (Fermi-LAT)
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Contribution of Molecular and Atomic Proton

- Analysis of W44, IC443 (, and W28)
  - Molecular gas is a major target in middle-aged SNRs.
  - H_2 : HI ~ 10 : 1

- Young SNRs show different trend:

	RX J1713.7 -3946	RX J0852.0 -4622	HESS J1731 -347	RCW 86
Age (yr)	1,000	1,700	4,000	1,800
$M(H_2)$:M(HI)	1 : 1	0.1 : 1	4 : 1	0 : 1

RX J1713.7-3946; *Fukui et al. (2012)*, RX J0852.0-4622; *Fukui (2013), Fukui et al. (2017)*
HESS J1731-347; *Fukuda et al. (2014)*, RCW86; *Sano et al. in prep*

- *Is this a universal trend ? , What makes this difference ?*
  - More samples (Age, Type, surrounding)
    - Galactic and also Magellanic SNRs.
  - MHD simulation of shock propagation into ISM for $t \sim 10^4$ yr

Conclusion

- † W44 and IC443 actually have target protons for hadronic γ–rays.
- † Determined the X_{CO} more accurately for IC 443 using dust data.
- † $W_p \sim 10^{48} - 10^{49}$ erg, 0.1 – 1 % of E_{SN}
  - Low efficiency can be explained by the non-uniform distribution of the target protons and escape of CRs.
  - γ–ray observation not only toward SNR but also its surroundings is important.
- † Target protons tend to be dominated by H_2 in Middle-aged SNRs.
  - Increase samples using large-scale Galactic CO survey data:
    - *COHRS*: JCMT 15m *Dempsy+ '13*
    - *The Mopra Galactic Plane CO Survey*: Mopra 22m
    - *NASCO*: NANTEN2 4m
    - *FUGIN*: Nobeyama 45m *Umemoto+ '17*