

NANTEN

Submillimeter Observatory  
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# Molecular Clouds Observations with NANTEN2

## - NASCO project and Gamma-ray SNRs -

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5:Seoul National Univ.、 6:INAF/ISAF-Milano









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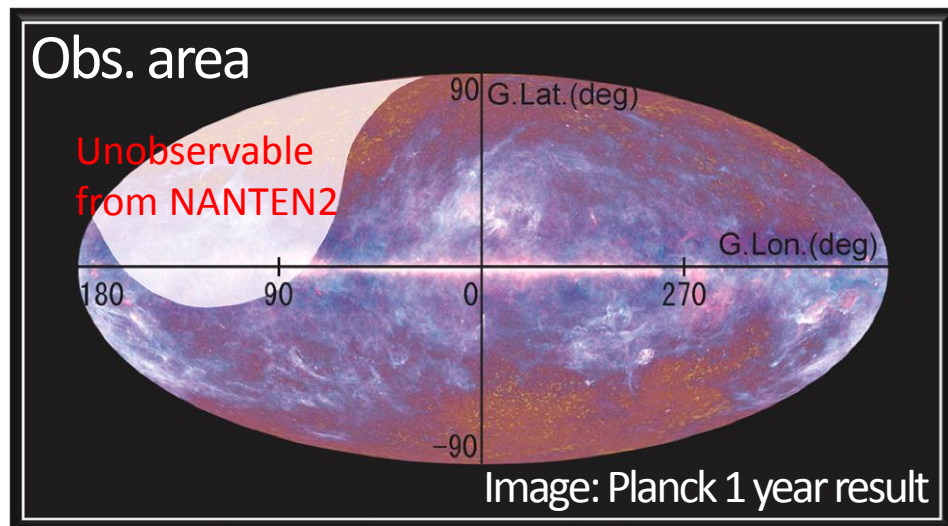
- What is NANTEN2?
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# What is NANTEN2?

- **Location** : Atacama, Chile (alt. 4,850m) *NANTEN* = Southern sky  
南天
- **Goal** : To investigate **large scale** distributions, structure, dynamics, and chemistry of ISM in the Milky Way and nearby galaxies
- **Way** : Multi line observations in CO and CI
  - 100GHz :  $^{12,13}\text{CO}(J=1-0)$  low freq. receiver (Nagoya Uni.)
  - 200GHz :  $^{12,13}\text{CO}(J=2-1)$
  - 500GHz :  $\text{CO}(J=4-3)$ ,  $\text{CI}(^3\text{P}_1-^3\text{P}_0)$  500/800GHz receiver (*SMART*) (Universität zu Köln)
  - 800GHz :  $^{12}\text{CO}(J=7-6)$ ,  $\text{CI}(^3\text{P}_2-^3\text{P}_1)$
- **International collaboration**
  -  Nagoya U., Osaka Prefecture U.
  -  Universität zu Köln, Universität Bonn
  -  The University of New South Wales, Sydney, Macquarie and so on
  -  Universidad de Chile     Seoul National U.
  -  Swiss Federal Institute of Technology Zurich

# NAnten Super CO survey as Legacy

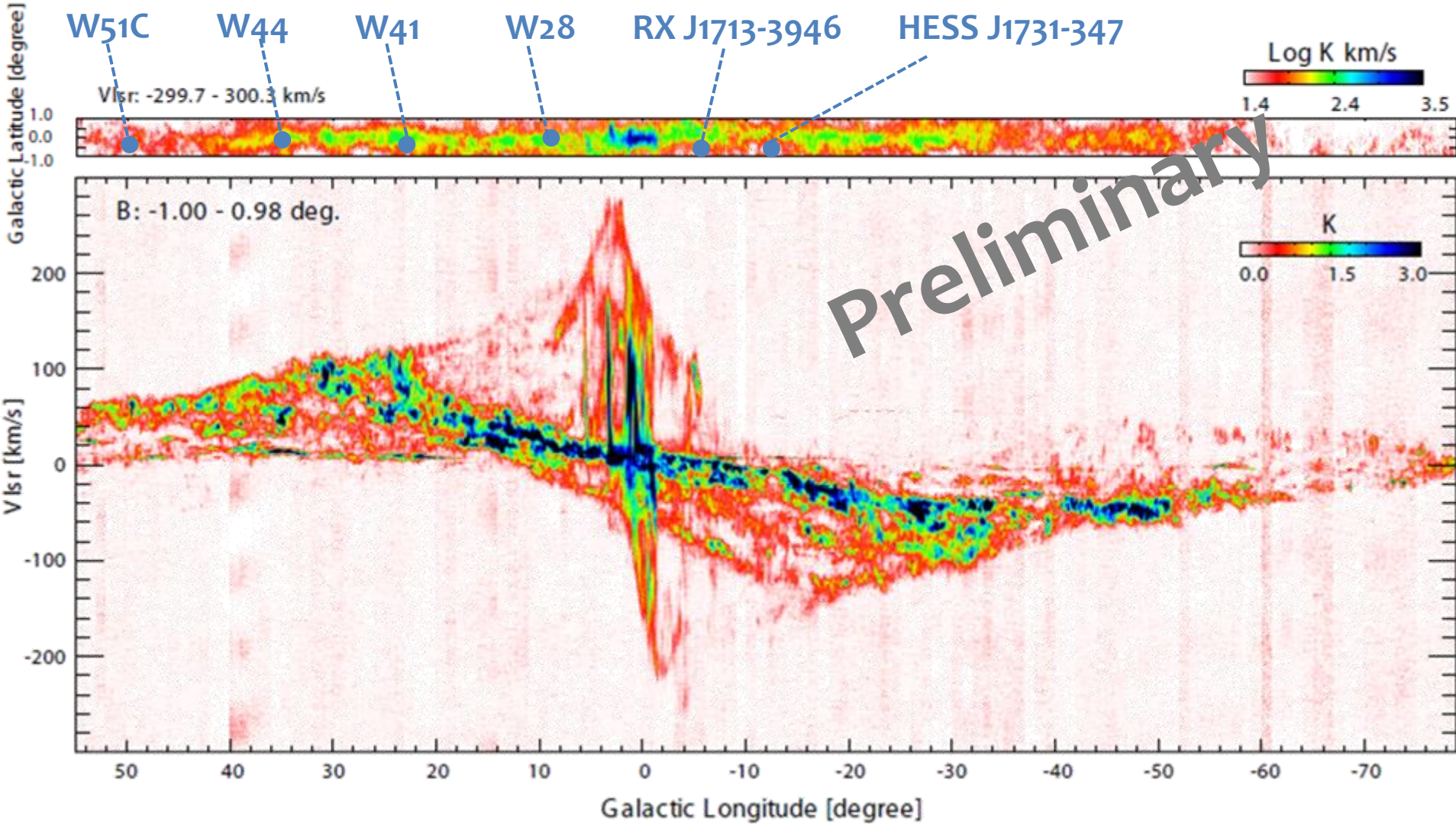
- New Survey with OTF by NANTEN"2"  $^{12}\text{CO}$  and  $^{13}\text{CO}(J=1-0)$  simultaneously.
- Start in 2015
- Covering 70% area of whole sky
- Collaborative study with Planck team



Survey Name	Coverage (deg)	HPBW (')	Grid (')	Vel cov. (km/s)	Vel reso. (km/s)	Total points (million)
NGPS	$200 < L < 60, B <  10 $	2.6	4-8	$\pm 300$	1.0	1.1
NASCO	70% of sky	2.6	1	$\pm 1300$	0.16	20



# Early result in 2011-2012 [ $^{12}\text{CO}(J=1-0)$ ]

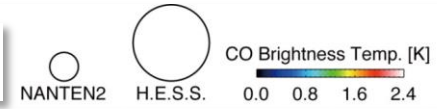


Total observation time:  $\sim 1000$  h , Data point:  $\sim 100,000 \times 16,000$  !



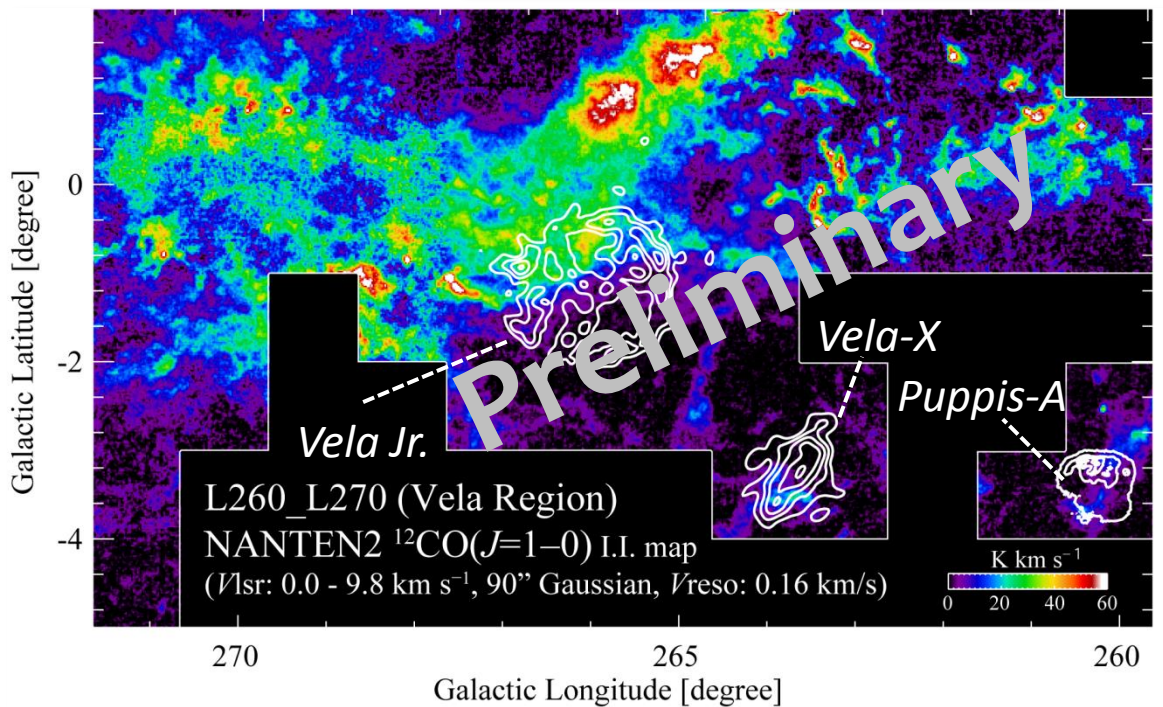
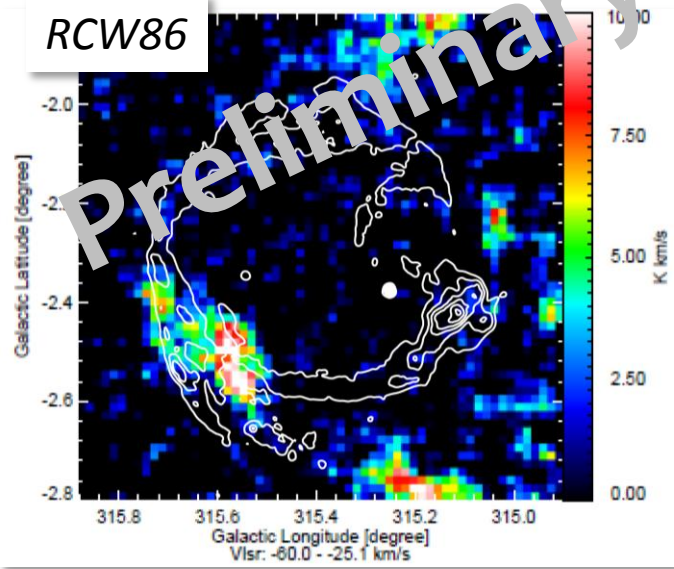
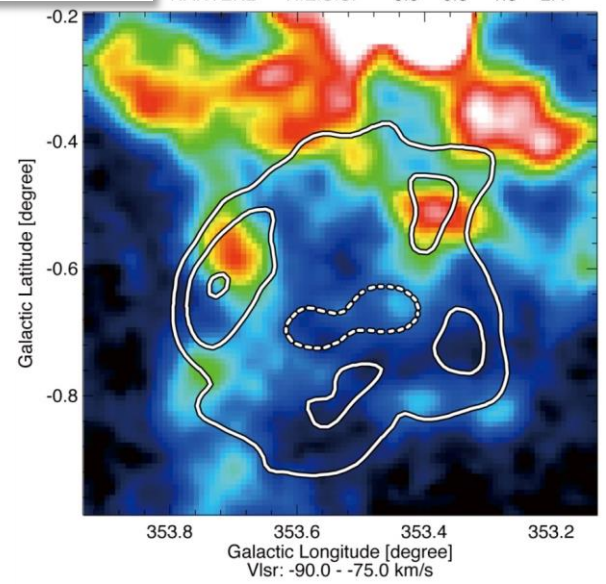
# SNR Observations

HESS J1731-347

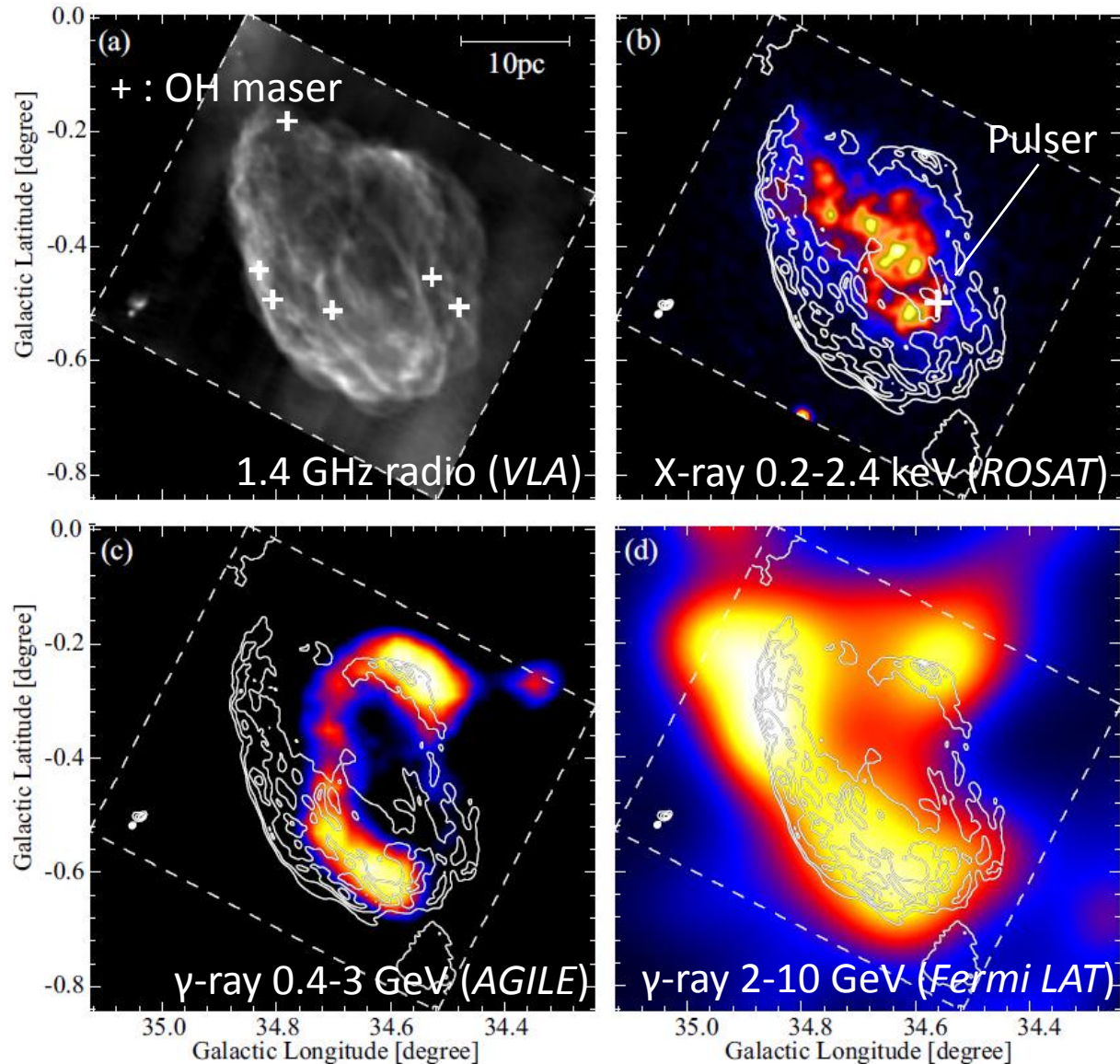


## Target

- Vela region
  - Sano+ '13 inprep.
- RCW86
- HESS J1731-347
  - Fukuda+ '13 submitted
- RX J1713-3946
  - Sano+ '13 inprep.
- W28
- W41
- **W44 (this talk)**
  - Yoshiike+ '13
- **IC443 (this talk)**
- W51C

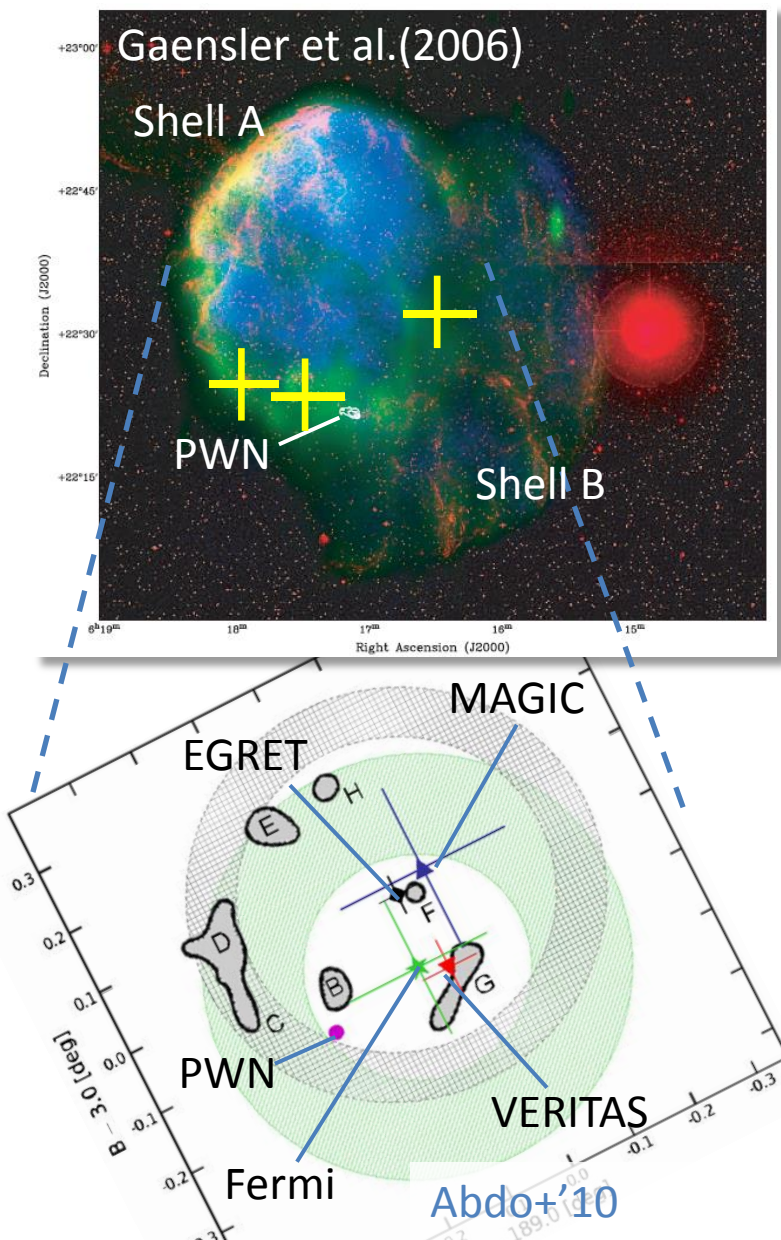


- Age  $\sim 20,000$  yr  
= Middle-aged SNR  
(e.g., Harrus et al. 1997)
- Distance  $\sim 3$  kpc  
(e.g., Caswell et al. 1975)
- OH Maser (Shock tracer)  
(Claussen et al. 1997)
- Interaction with ISM  
(Seta et al. 1998, 2004;  
Koo & Heiles 1995)
- GeV  $\gamma$ -ray  
(Abdo et al. 2010;  
Giuliani et al. 2011)





# SNR IC443



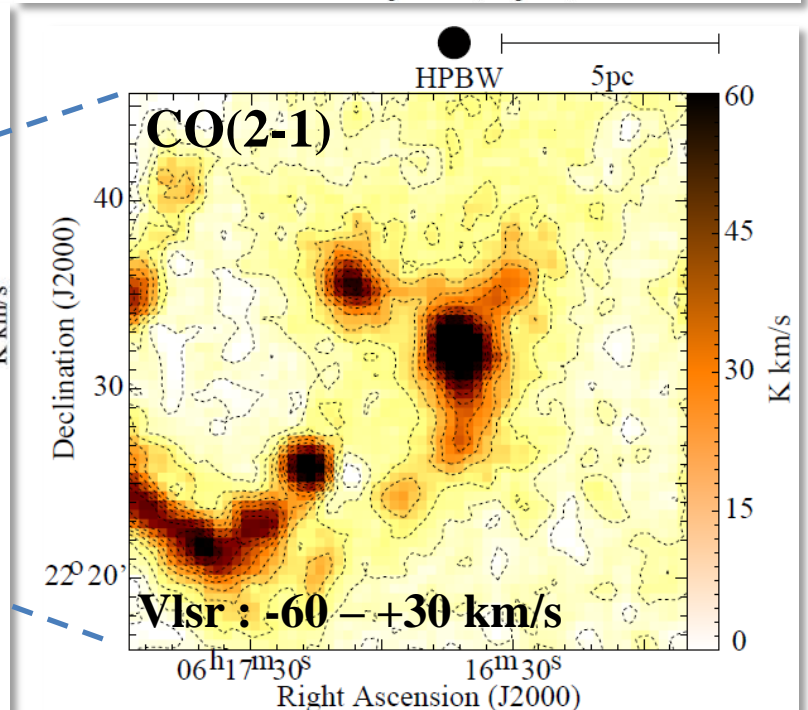
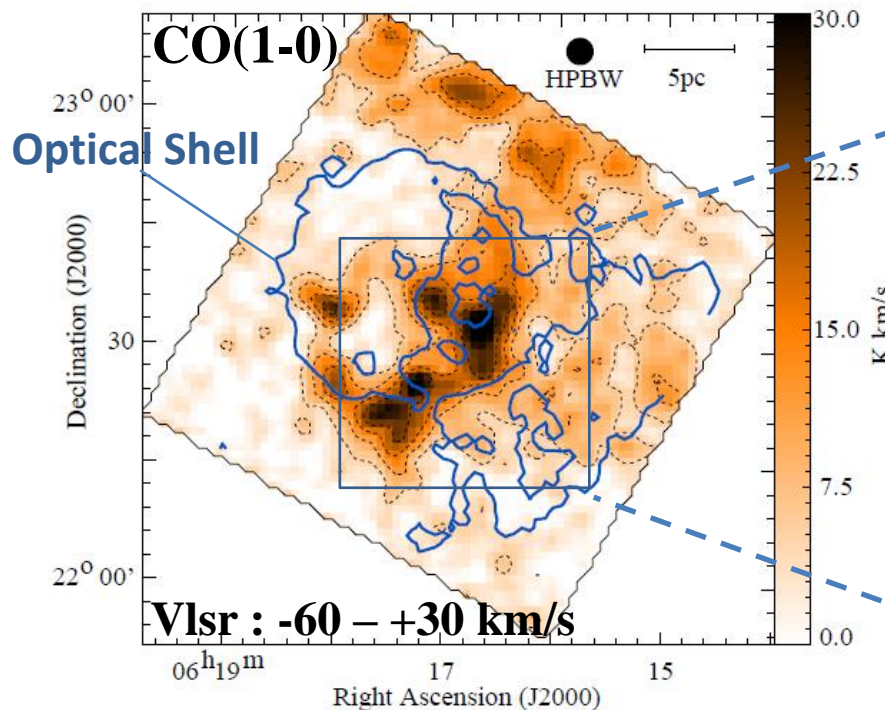
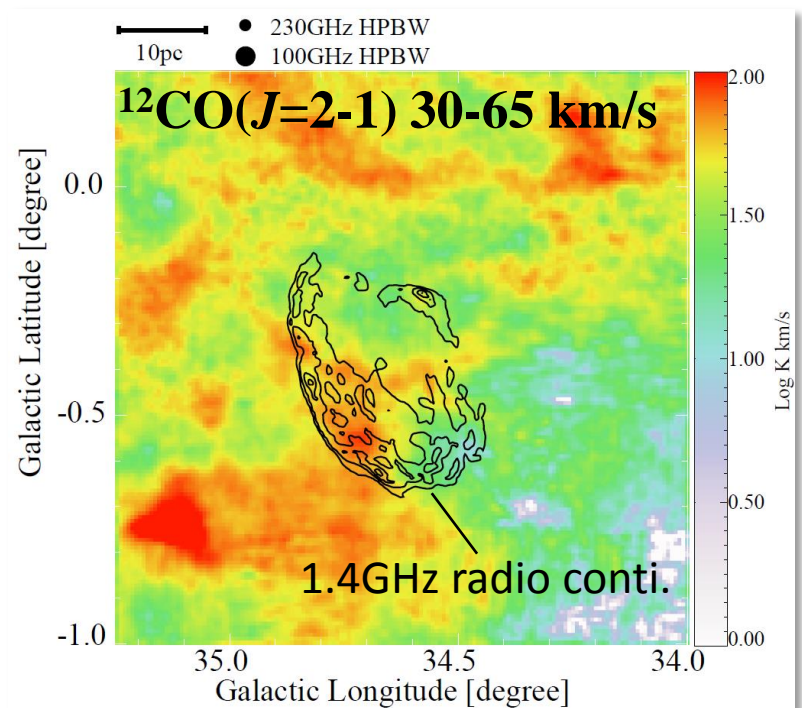
← Red:Optical / Green:1.4 GHz / Blue:X-ray

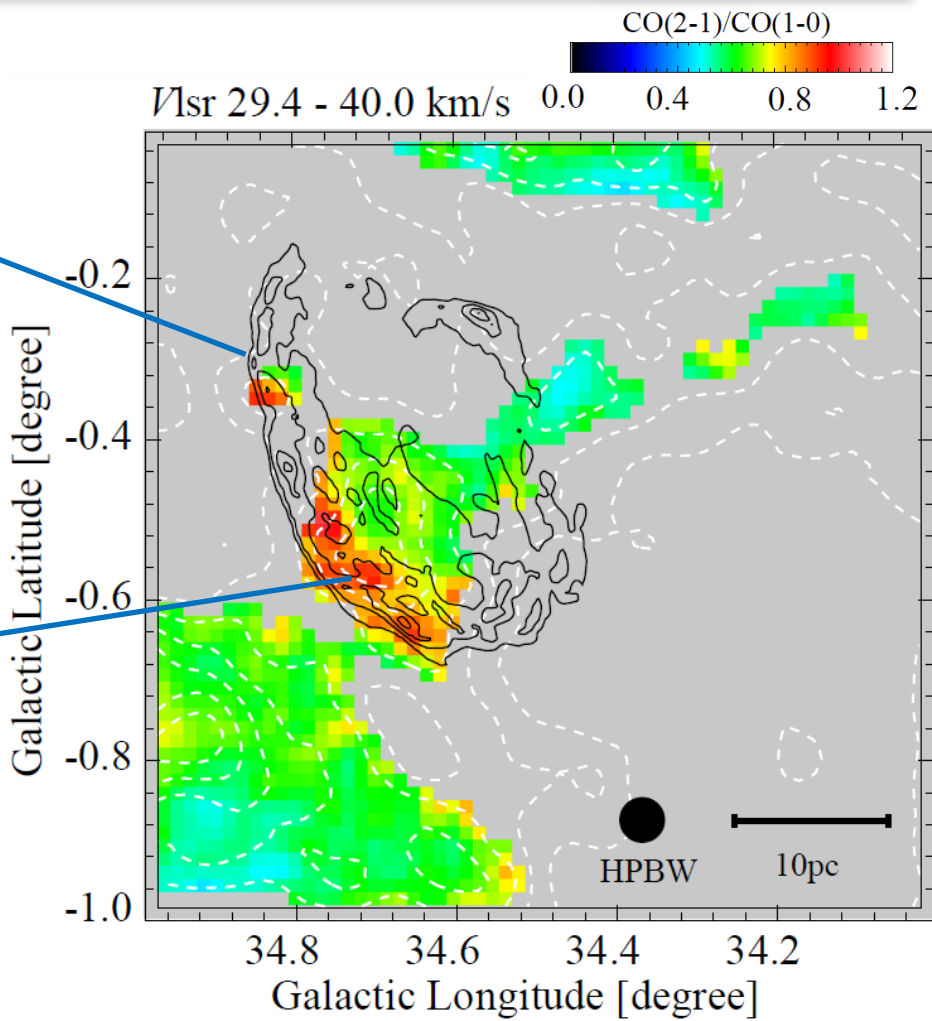
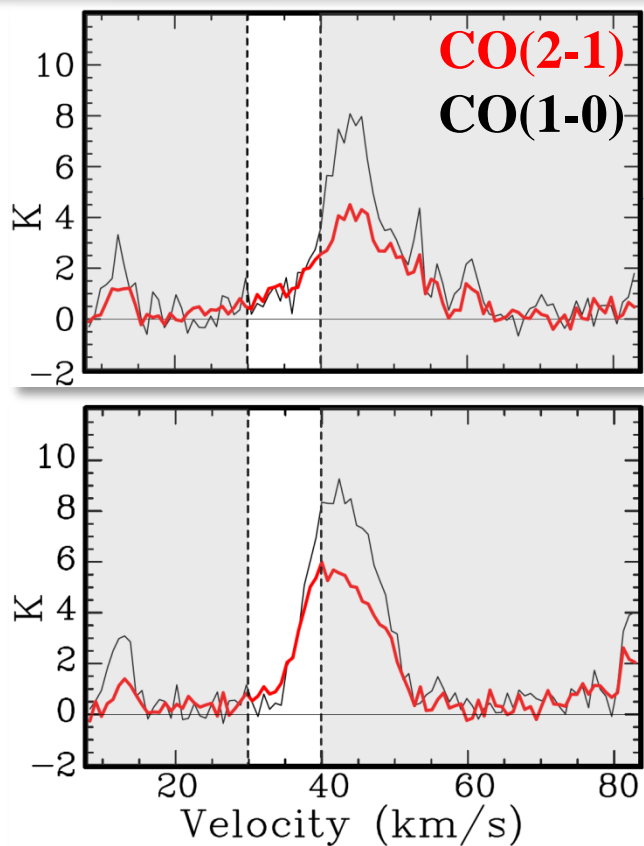
- Shell A and B
- Age :  $4 \times 10^3$  yr (Troja+'08)  
 $\sim 2 \times 10^4$  yr (Lee+'08)
- Distance : 1.5 kpc (Welsh & Sallmen 2003)
- Mixed-Morphology SNR
- Interaction with ISM, OH maser (crosses)  
 (Koo & Moon 1997, Denoyer 1979, Hewitt+'06)
- Gamma-ray
  - TeV : MAGIC<sup>1</sup>, VERITAS<sup>2</sup>  
 (1: Albert+'07, 2: Acciari+'09)
  - GeV : Fermi<sup>3</sup>, AGILE<sup>4</sup>  
 (3: Abdo+'10, 4: Tavani+'10)
- Pulsar Wind Nebula  
 (CXOU J061705.3 + 222127)
  - Chandra (Olbert+'01)
  - XMM (Bocchnino+'01)



# Observations

- Object : W44, IC443
- Telescope : NANTEN2
- @ Chile Atacama
- Line :  $^{12}\text{CO}(J=1-0)$ ,  $^{12}\text{CO}(J=2-1)$ 
  - Upper right : W44  $^{12}\text{CO}(2-1)$
  - lower left : IC443  $^{12}\text{CO}(1-0)$
  - lower right : IC443  $^{12}\text{CO}(2-1)$



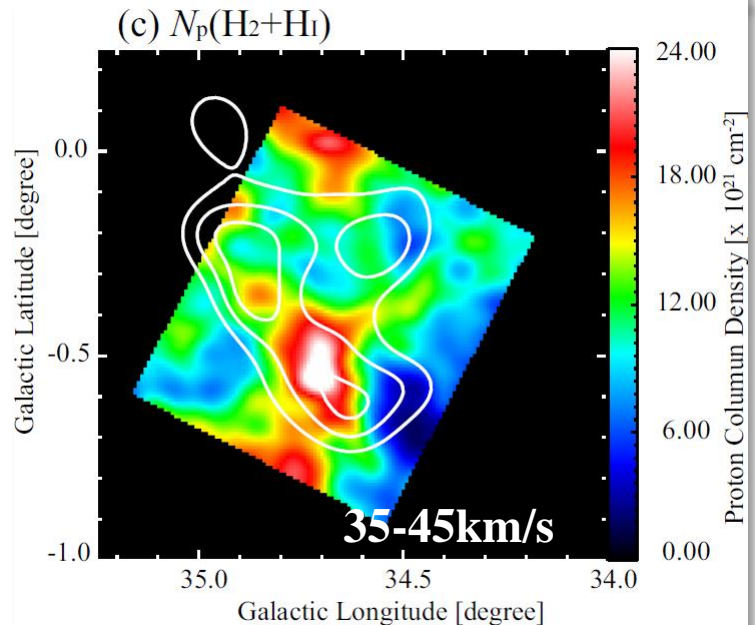
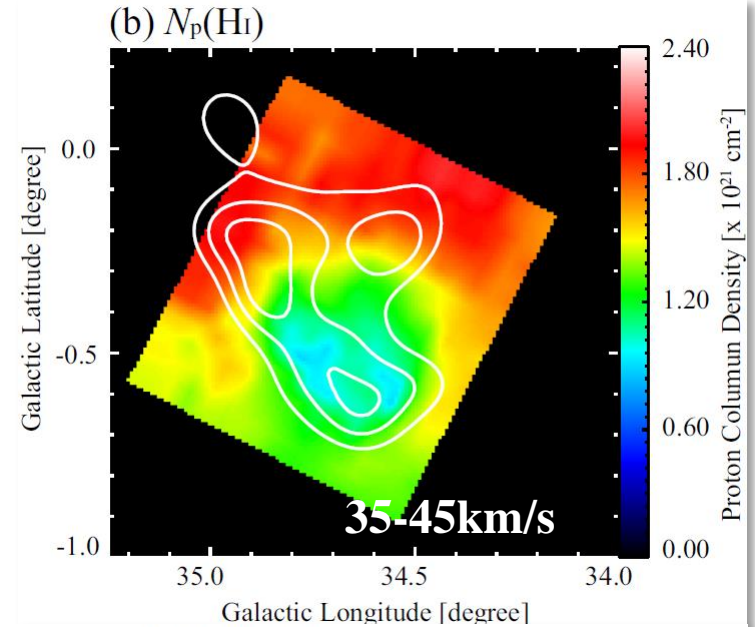
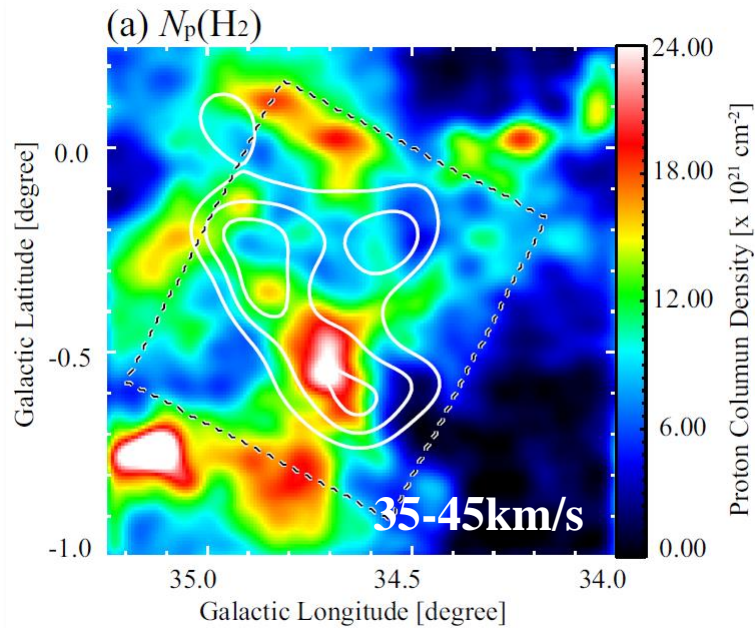


• The ratios are enhanced around  $\sim 1.0$  along the eastern shell.

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

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

# W44 Distribution of Total ISM Protons



$$(a) N_p(\text{H}_2) = 2 \times X_{\text{CO}} \int T_{mb} dv [\text{cm}^{-2}]$$

$$- X_{\text{CO}} = 1.56 \times 10^{20} \text{ cm}^{-2} / (\text{K km/s})$$

(Hunter + '97)

$$- \text{CO}(2-1)/\text{CO}(1-0) = 0.6$$

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

Absorptions are interpolated.

$$(c) N_p(\text{H}_2 + \text{HI}) = N_p(\text{H}_2) + N_p(\text{HI}) [\text{cm}^{-2}]$$

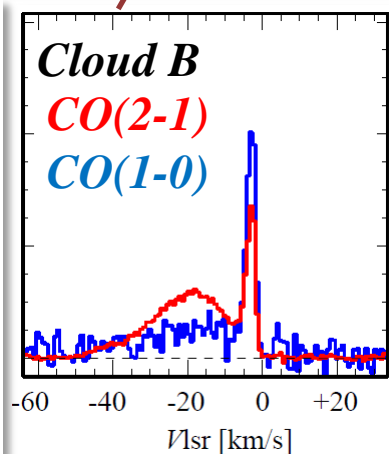
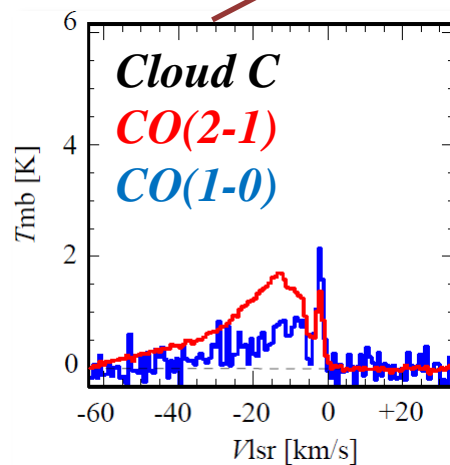
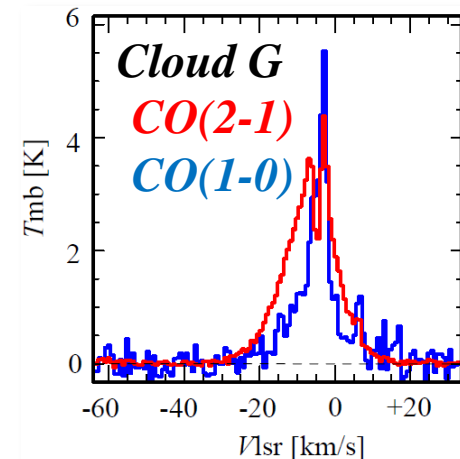
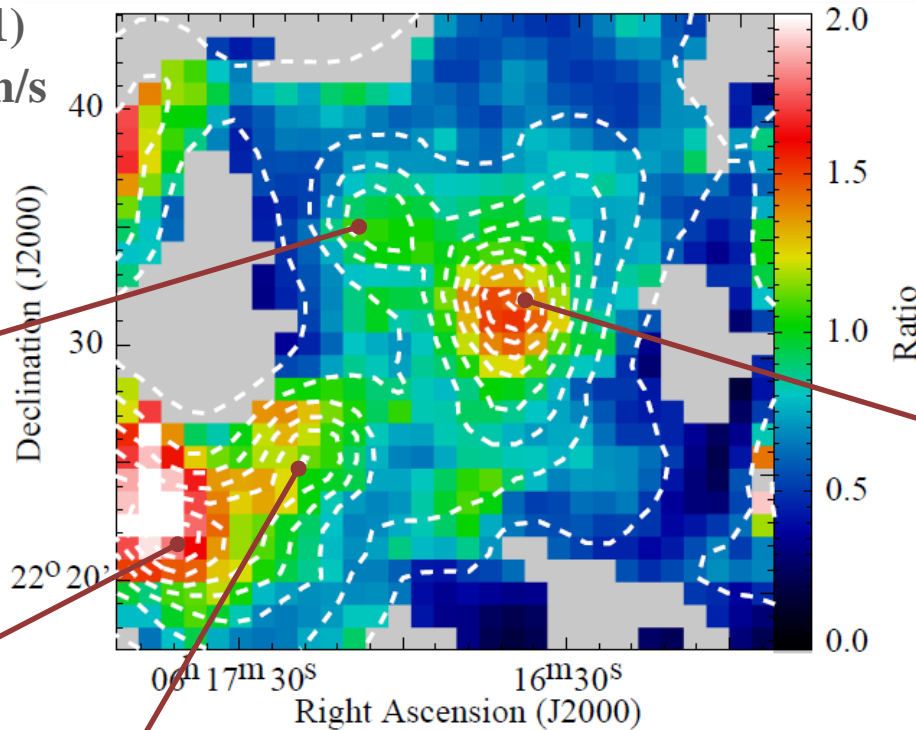
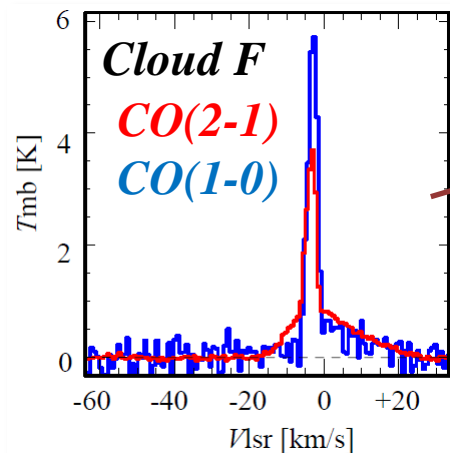


# IC443 CO(2-1)/CO(1-0)

● —  
HPBW 2pc

Contours ...  $^{12}\text{CO}(2-1)$

-60 — +30 km/s



- Shocked Gas
  - The ratios are enhanced in each MCs ( 1 ~ 3 )
  - Large velocity width
- Mass of Shocked Gas[-60:-6km/s]

~ 900  $M_{\odot}$

# IC443 Comparison with Gamma-ray

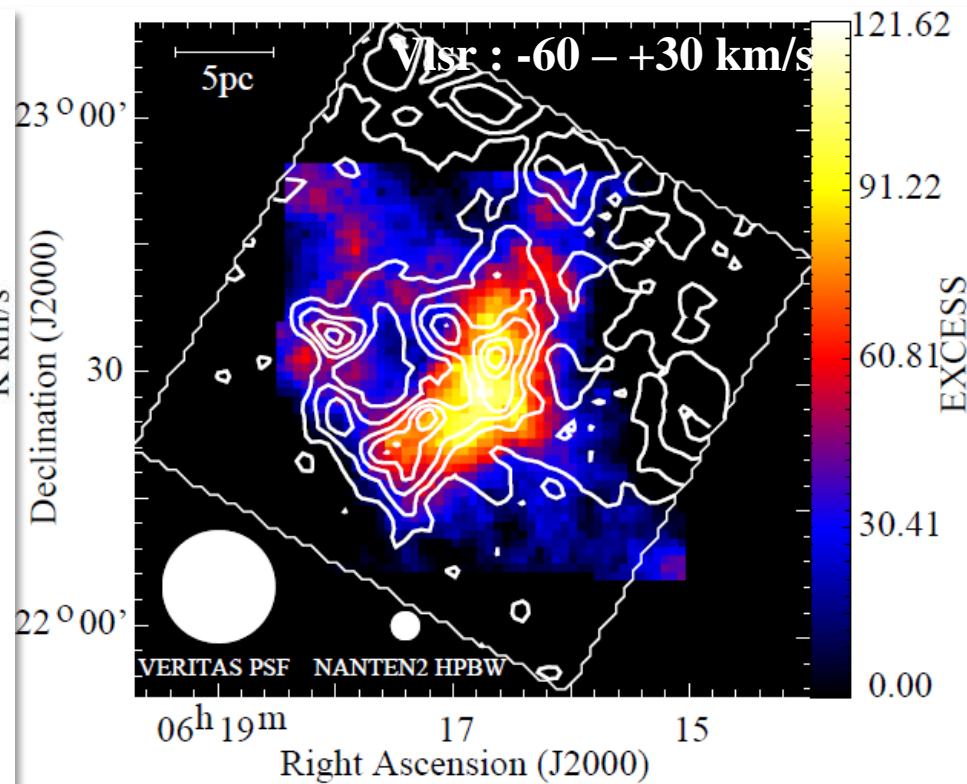
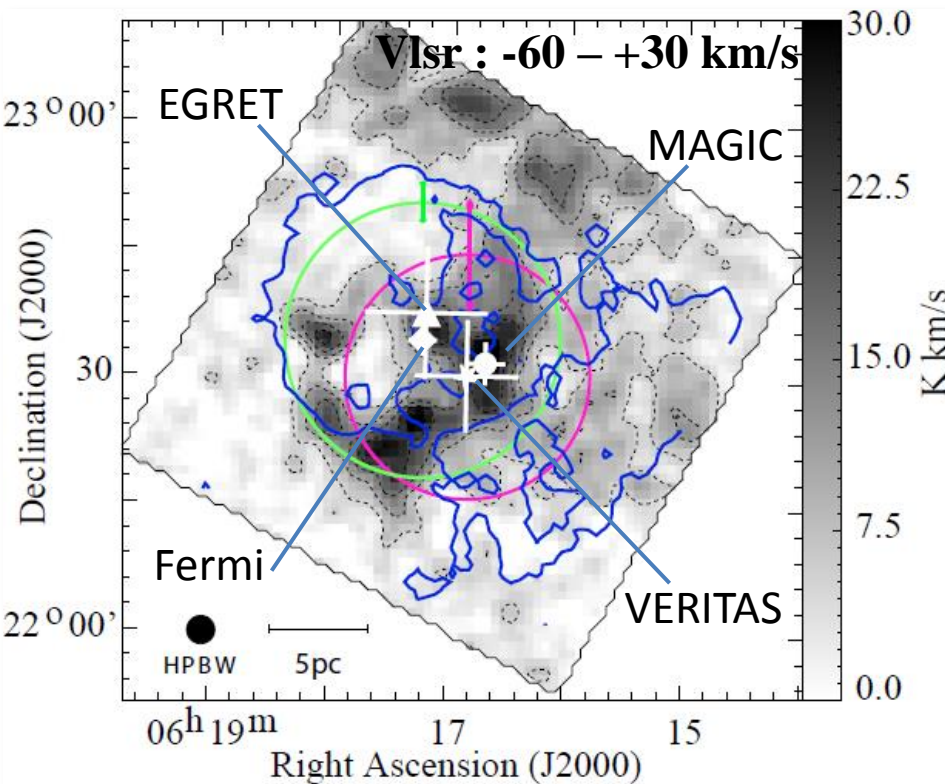


Image : NANTEN2 CO(1-0)

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 <sup>14</sup>

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

A:Yoshiike +'13, B: Aharonian et al.2008, C : Giuliani et al.2010

$$W_p \approx \tau_p \times L_\gamma \text{ [erg]}, \tau_p \approx 4.5 \times 10^{13} \times (n / 100 \text{cm}^{-3})^{-1} \text{ [s]}$$

- $W_p \sim 10^{49}$  erg
- ■ 1% of the kinematic energy released per SNR,  $10^{51}$  erg
- $> \sim 10^{48}$  erg (young SNR  $\sim 1,000$  yr, RXJ 1713 (Fukui+ '12))

This is consistent for explaining the average interstellar CR energy density of  $0.5 \text{ eV cm}^{-3}$

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



# Summary

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- *NASCO* project
  - New survey of molecular cloud covering 70 % of whole sky.
  - Compared with multi-wavelength results.
    - Planck, Herschel, Suzaku, Fermi, AGILE etc
  - We observed the Galactic plane  $55 > l > -80$  and  $-1 < b < 1$  in 2011 and 2012 including some gamma-ray SNRs.
- W44, IC443
  - Shocked Gas
    - High line ratio and large velocity width.
    - Location is Corresponds to that of gamma-ray .
  - Total proton energy  $\sim 10^{49}$ erg > young SNR
    - Can explain the average CR energy density.