The origin of gamma rays in RXJ1713.7-3946 and the other shell like SNRs; Evidence for γ-ray production dominated by the hadronic process

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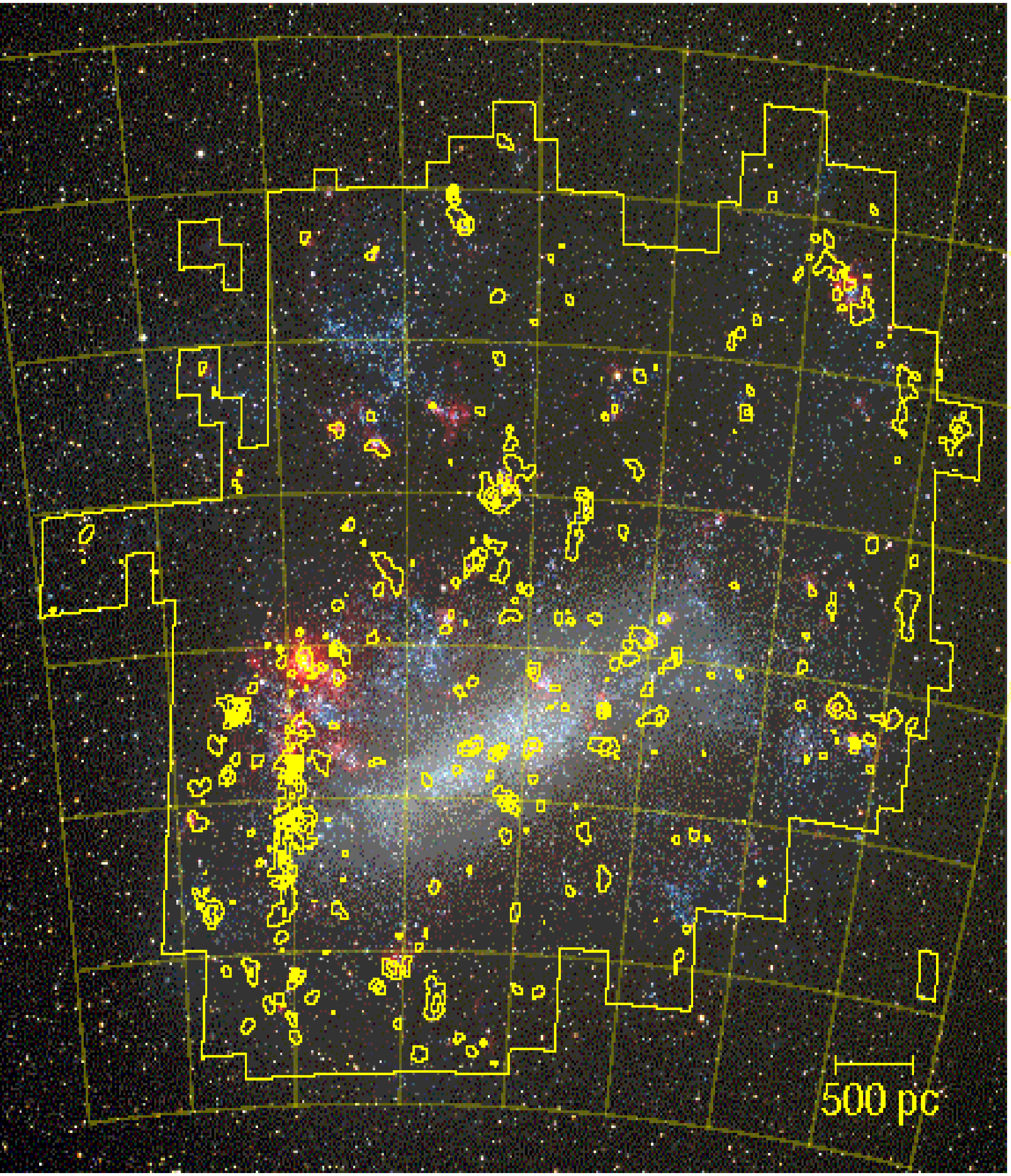
IAU331 "SN1987A, 30 yrs later"
La Reunion, February 20-24, 2017

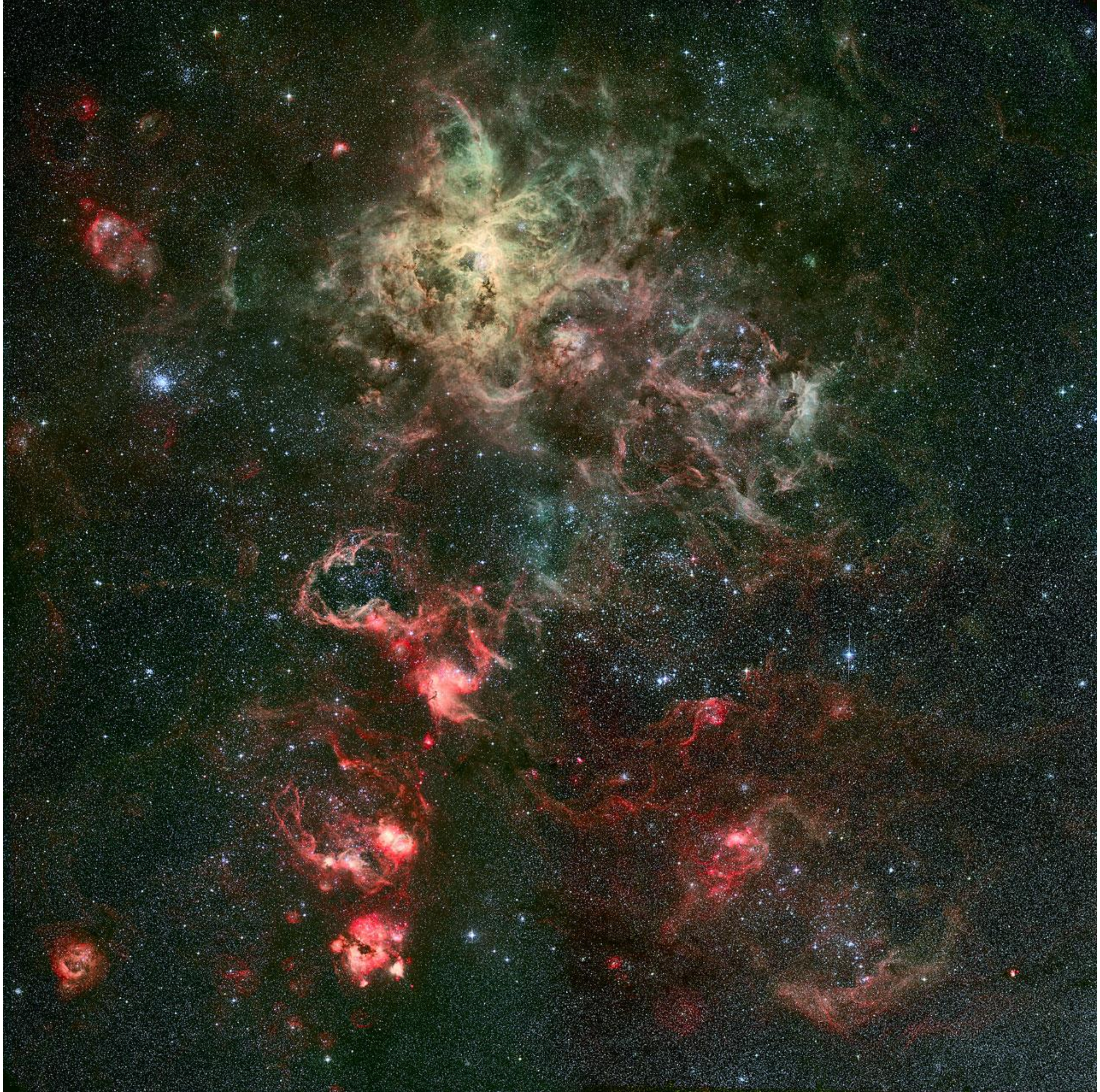
NANTEN 2nd survey of GMCs in the LMC (Fukui et al. 2008)



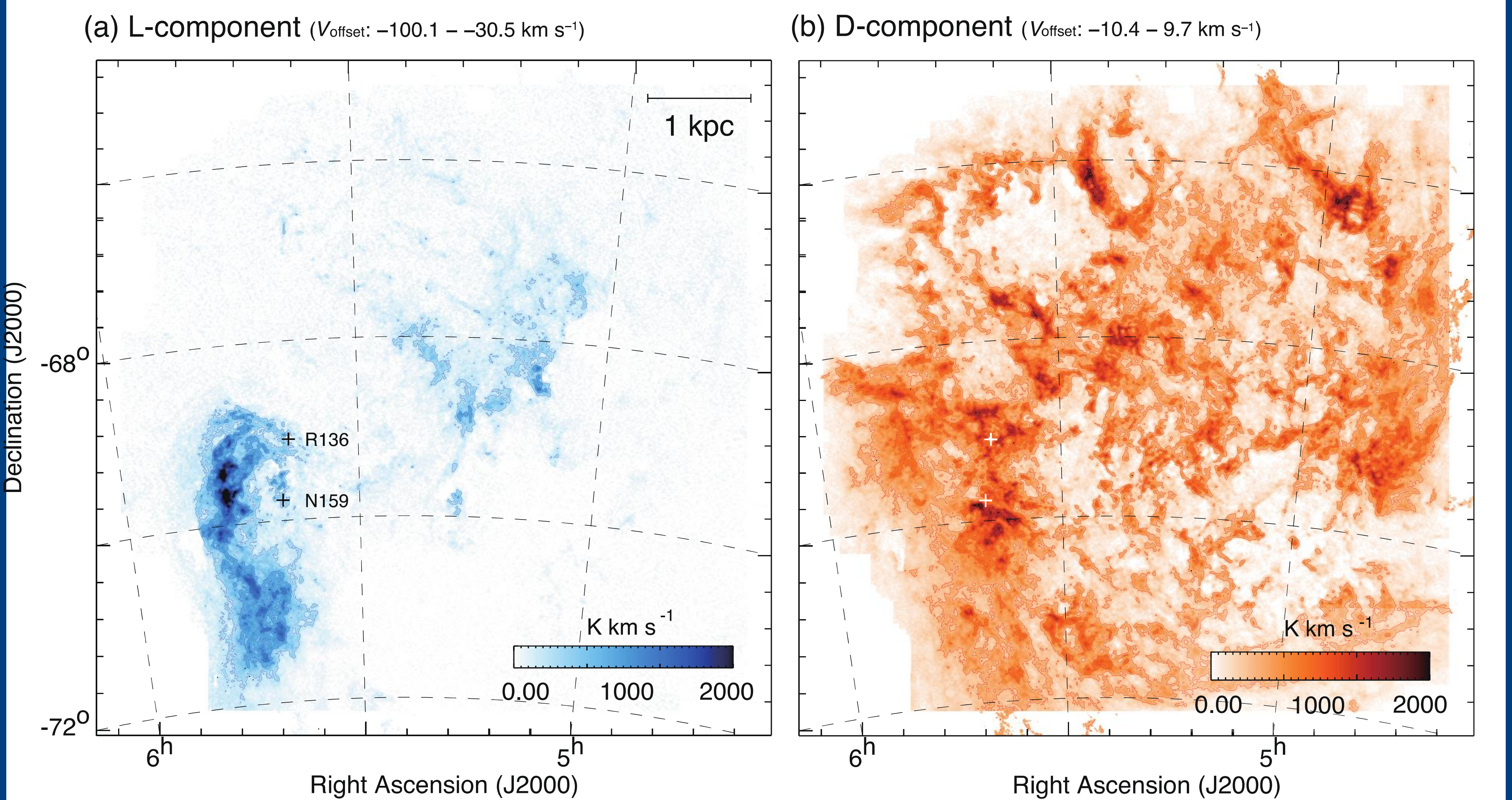
- **Contours: CO J=1-0**
- **270 GMCs**
- **X_{LMC} ~ 9 × 10^{20} cm^{-2} / [K km s^{-1}] ~ 3 X_G is used (Mizuno et al. 2001))**

($X = N(H_2)/ I_{CO} = M/L_{CO}$)

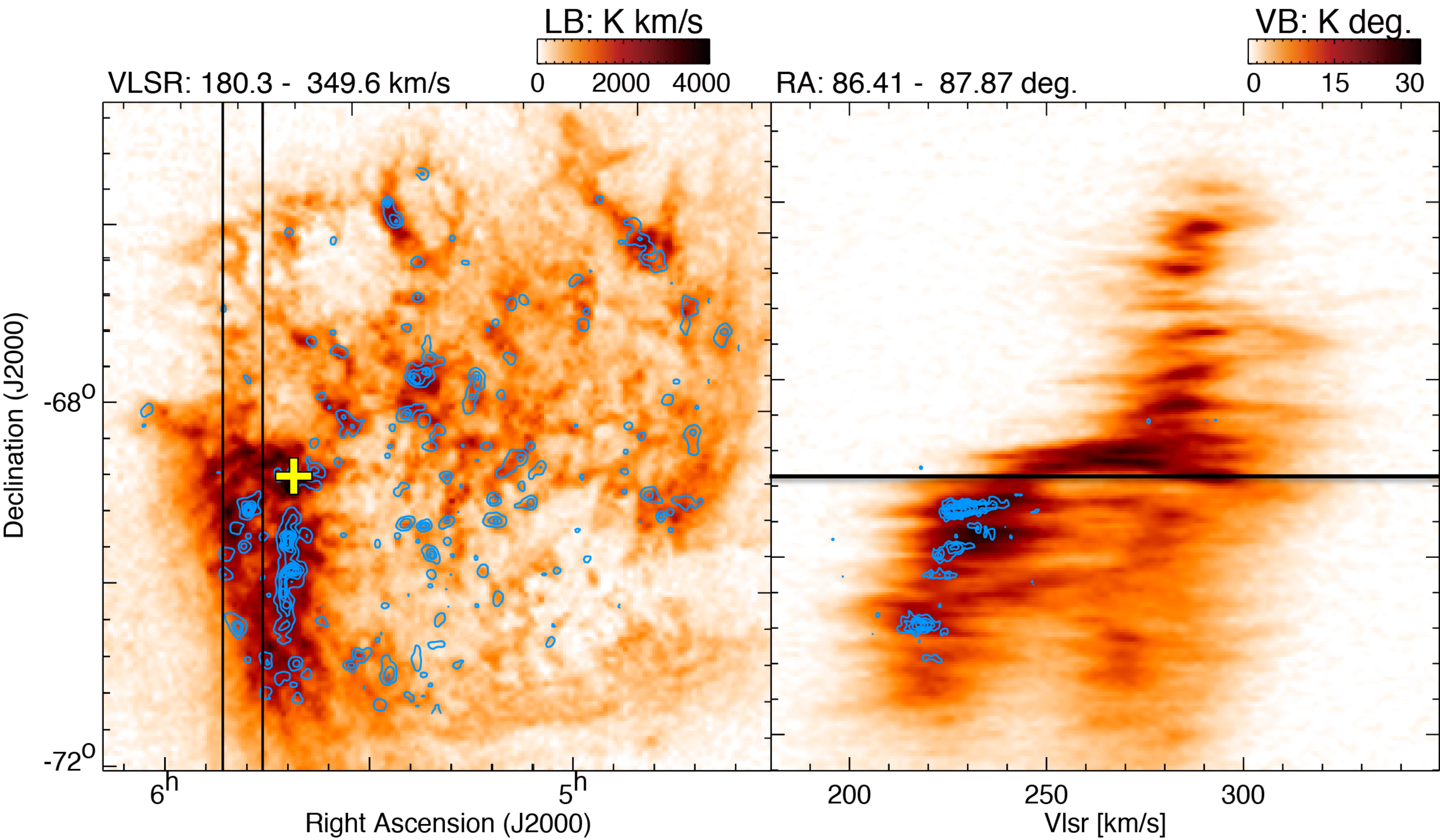
Mass : 6 × 10^4 – 6 × 10^6 Mo
Size (radius) : 30 - 150 pc
Line width (FWHM) : 3 – 17 km s^{-1}



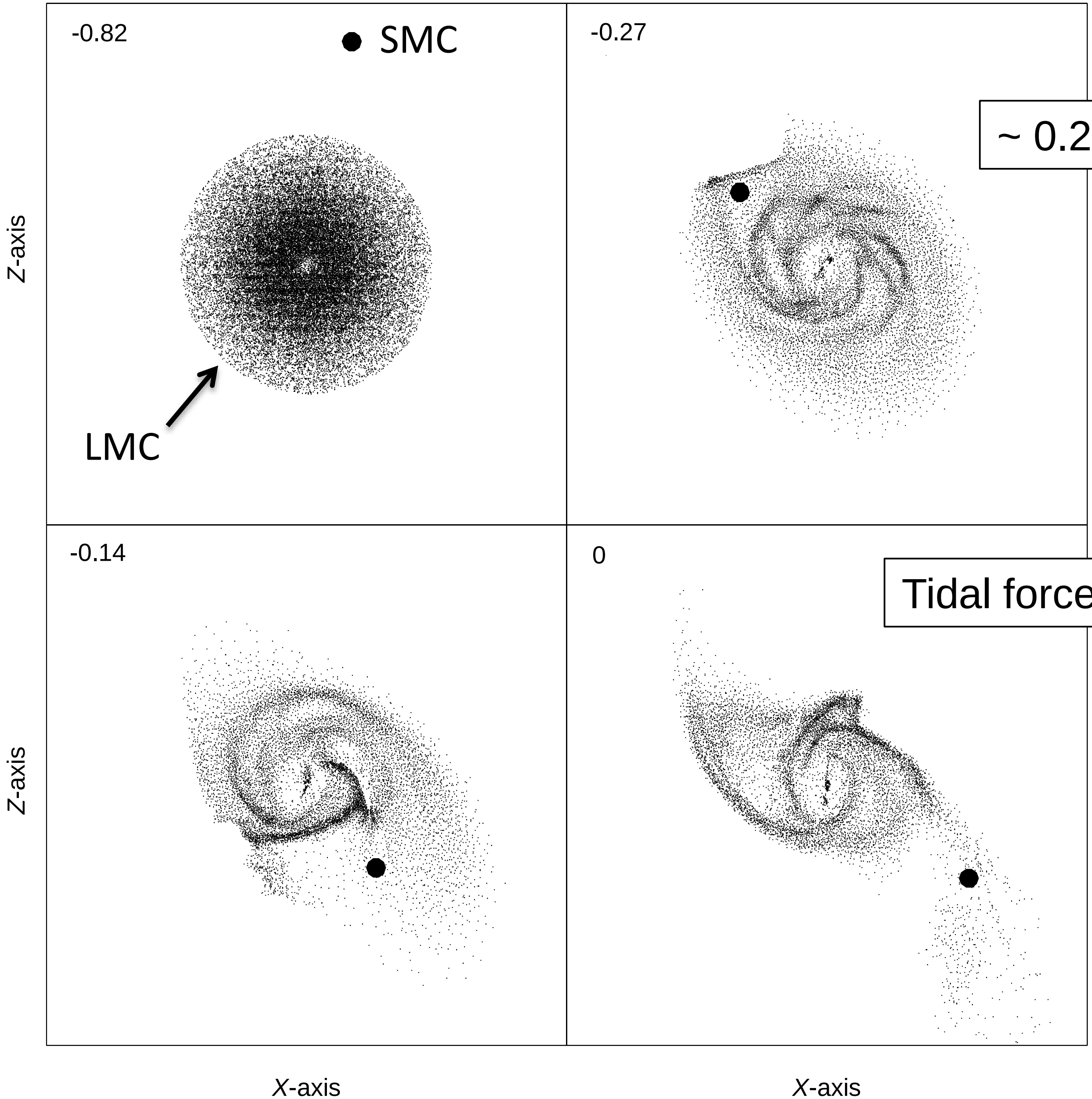
Separation of L- & D-components



Fuku et al. 2017, soon appear in astroph


LB: K km/s
VLSR: 180.3 - 349.6 km/s
0
2000
4000
VB: K deg.
RA: 86.41 - 87.87 deg.
0
15
30
Declination (J2000)
-68°
-72°
6h
5h
Right Ascension (J2000)
200
250
300
Vlsr [km/s]

Previous Study: Tidal interaction between the LMC & SMC



~ 0.2 Gyr close encounter

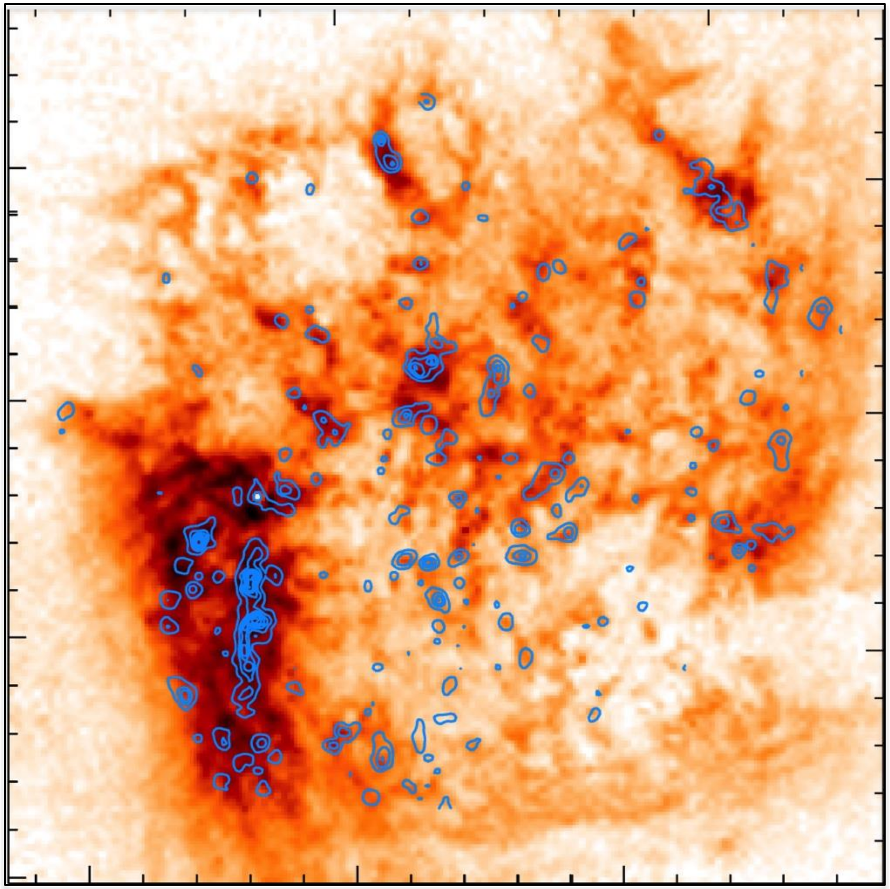
Tidal force agitates HI

e.g.,
Murai & Fujimoto 80
Fujimoto & Murai 84
Fujimoto & Noguchi 90

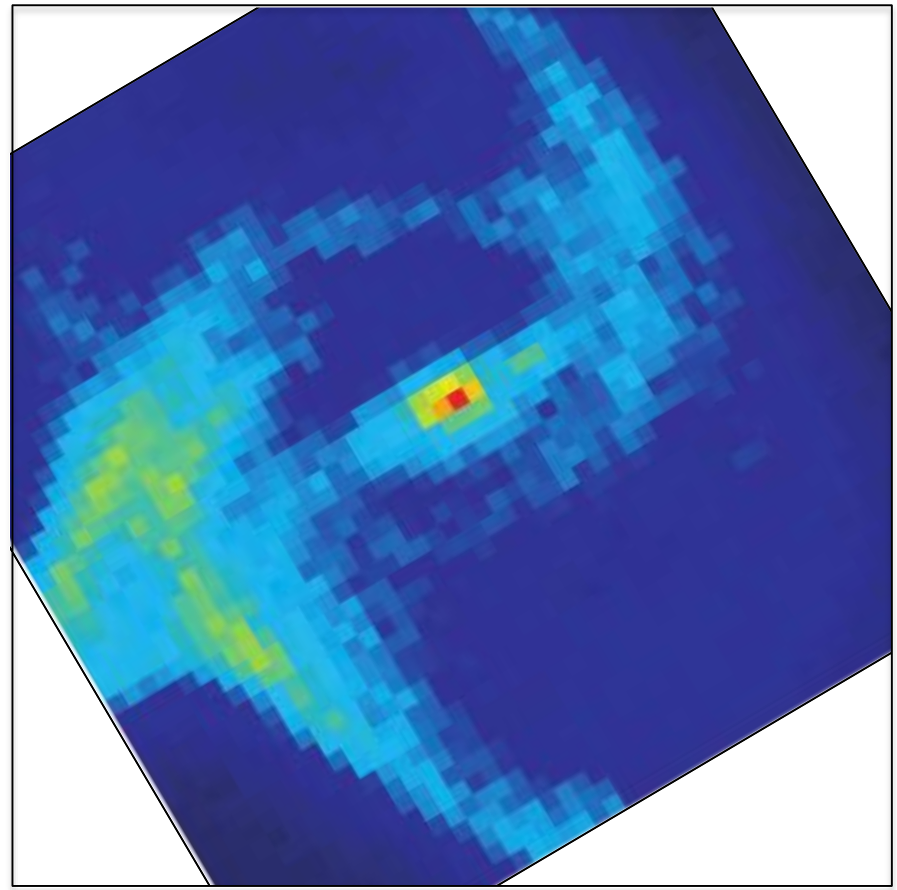
Bekki & Chiba 07

Previous Study: Tidal interaction between the LMC & SMC

observations（image HI, contour CO）



simulation（gas density）



Bekki, Chiba 2007

Interstellar molecular clouds and gamma-rays
The origin of the cosmic rays is SNR?- Yes.

Interstellar Medium ISM

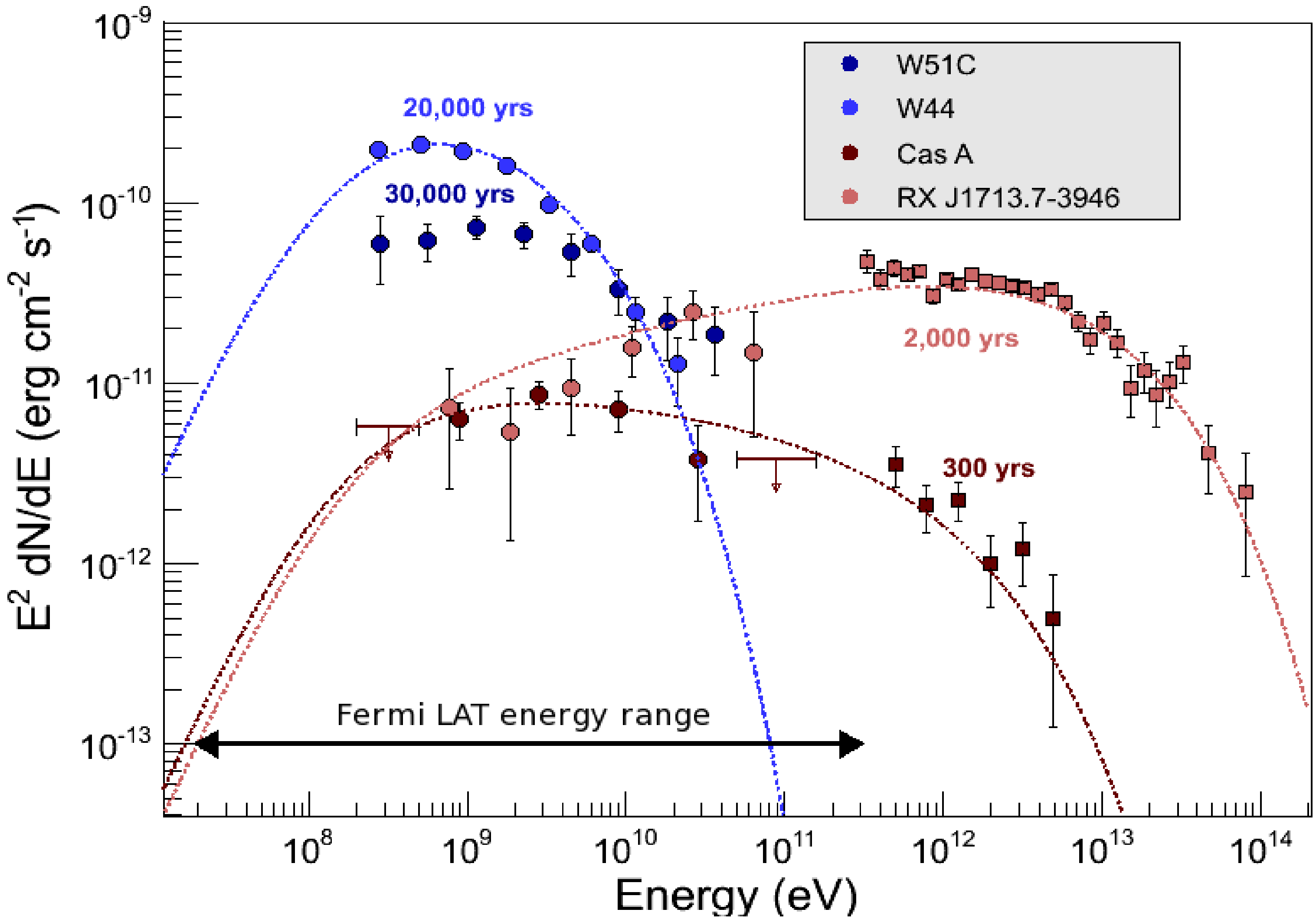
- Molecular clouds: dense neutral gas H_2 (2.6mm CO)
  - density 10^3 cm-3 or higher, Tk=10-20K
- Atomic clouds: dense atomic gas HI (21cm HI)
  - density 1-100 cm-3, Ts=20-100K

Gamma-rays produced by

1) Hadronic scenario:
   - cosmic ray CR proton - ISM proton reaction,
   neutral pions decay into gamma rays
2) Leptonic scenario
   - CR electrons, Inverse Compton (IC) process, CMB etc.

Gamma-rays (0.1GeV-100TeV) observed by HESS, MAGIC, VERITAS, Fermi, AGILE and CTA[2016-]

SNRs emitting gamma-rays

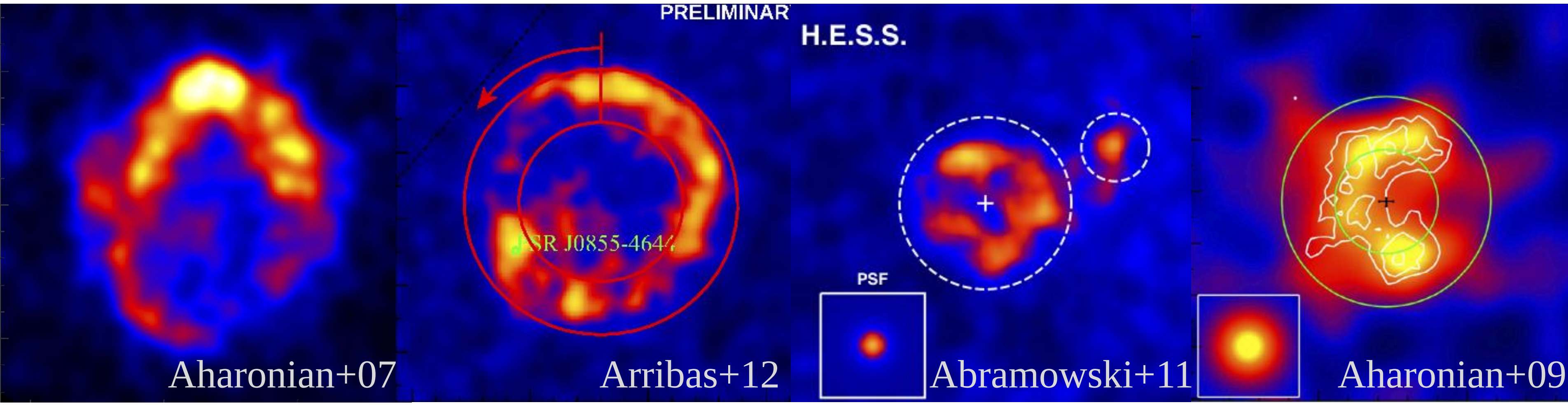


Courtesy H. Tajima

Four TeV Gamma-ray SNRs

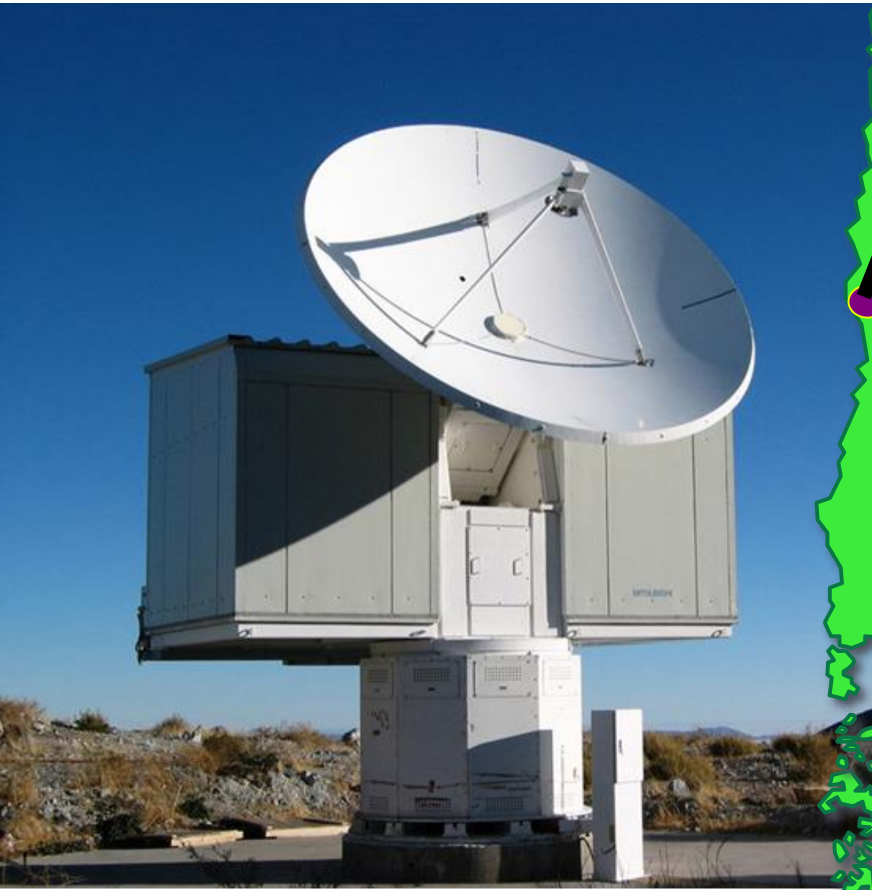
- 4 TeV gamma ray SNRs age 2000yrs
- They are interacting with ISM

RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86

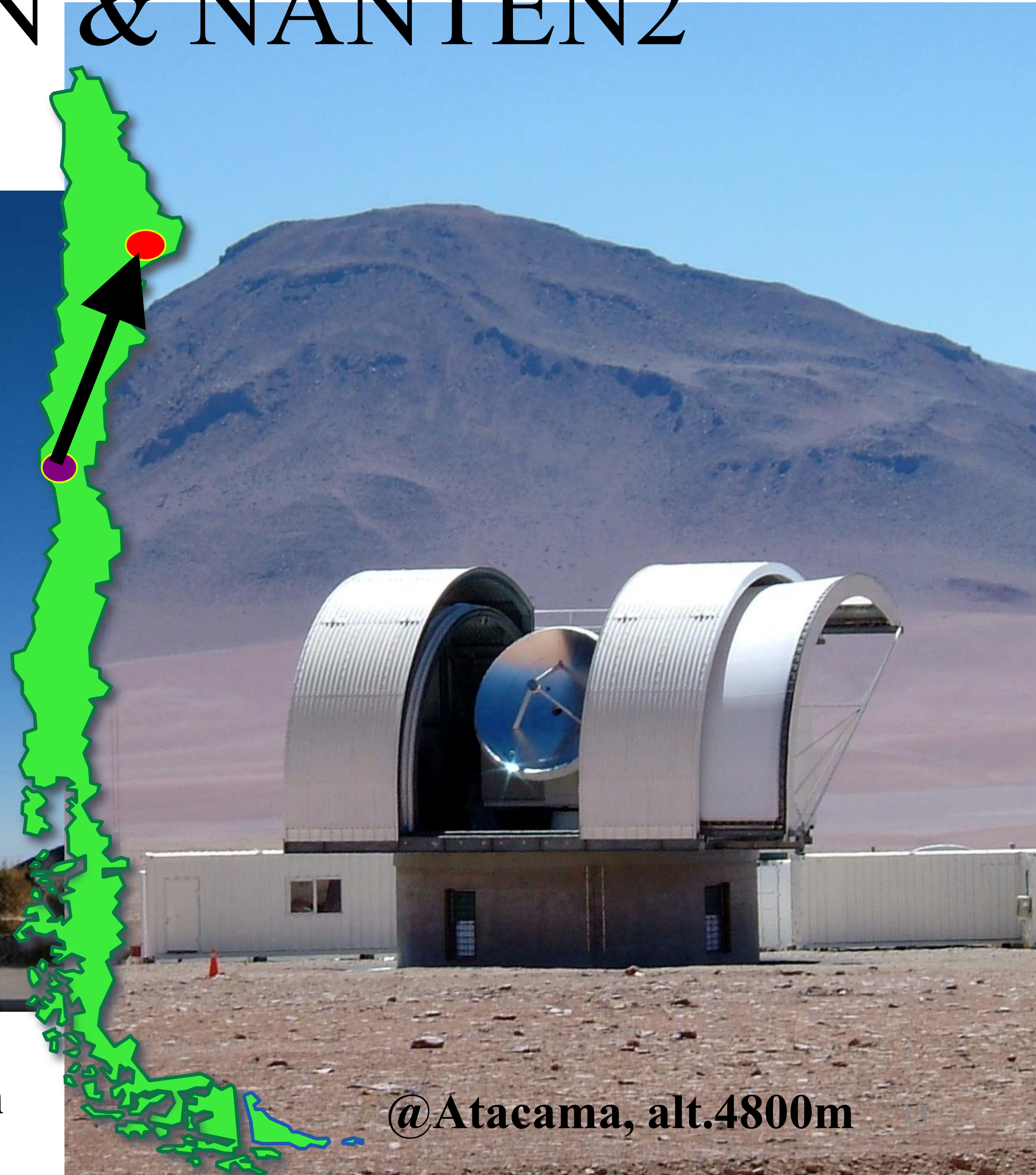


diamter: ~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
age: ~1600 yr	~1700−4300 yr	~3600−7200 yr	~1800 yr
ISM: rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays: pure synchrotron	pure synchrotron ?	pure synchrotron	thermal + non-thermal

NANTEN & NANTEN2



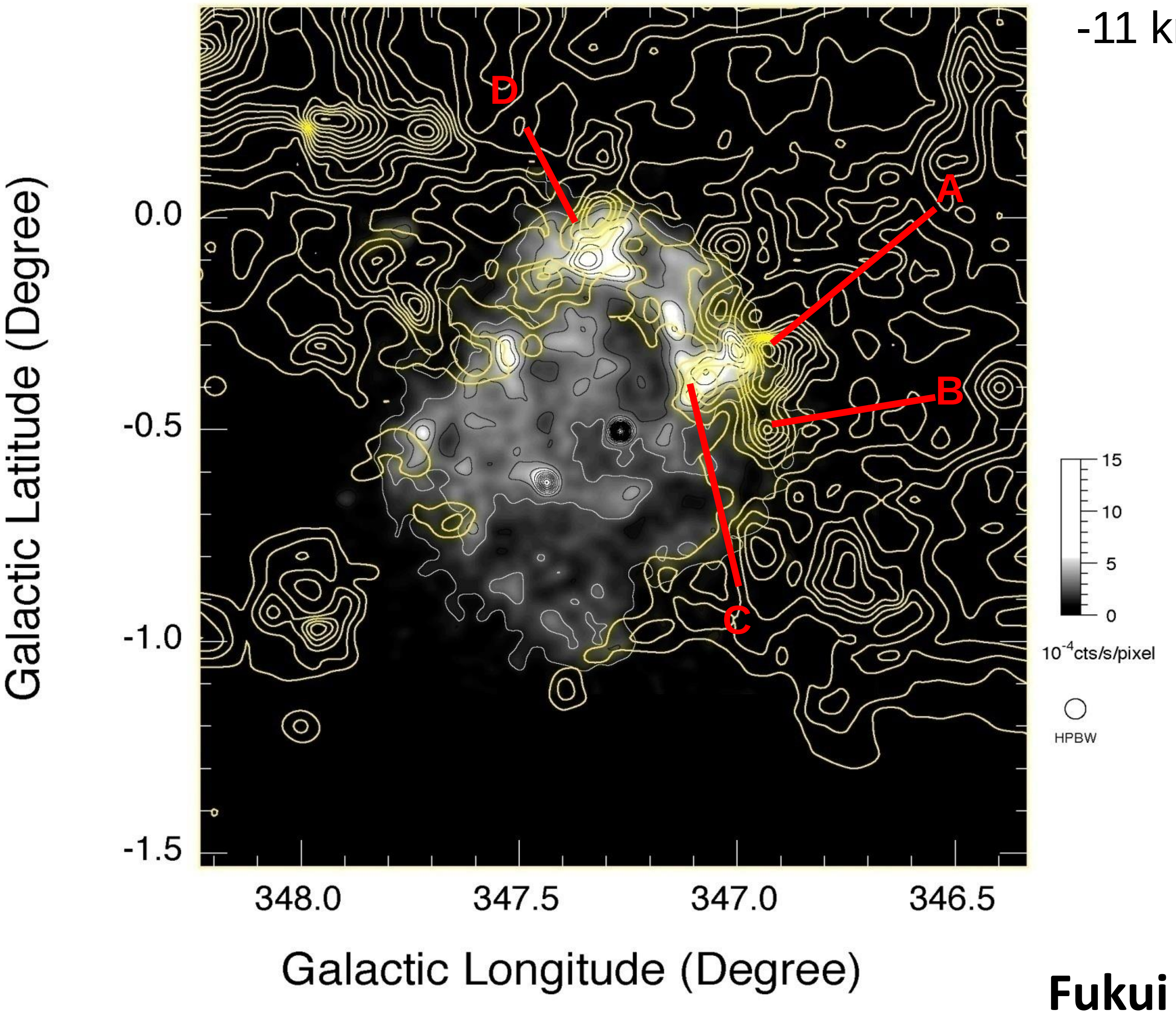
@Las Campanas, alt.2400m



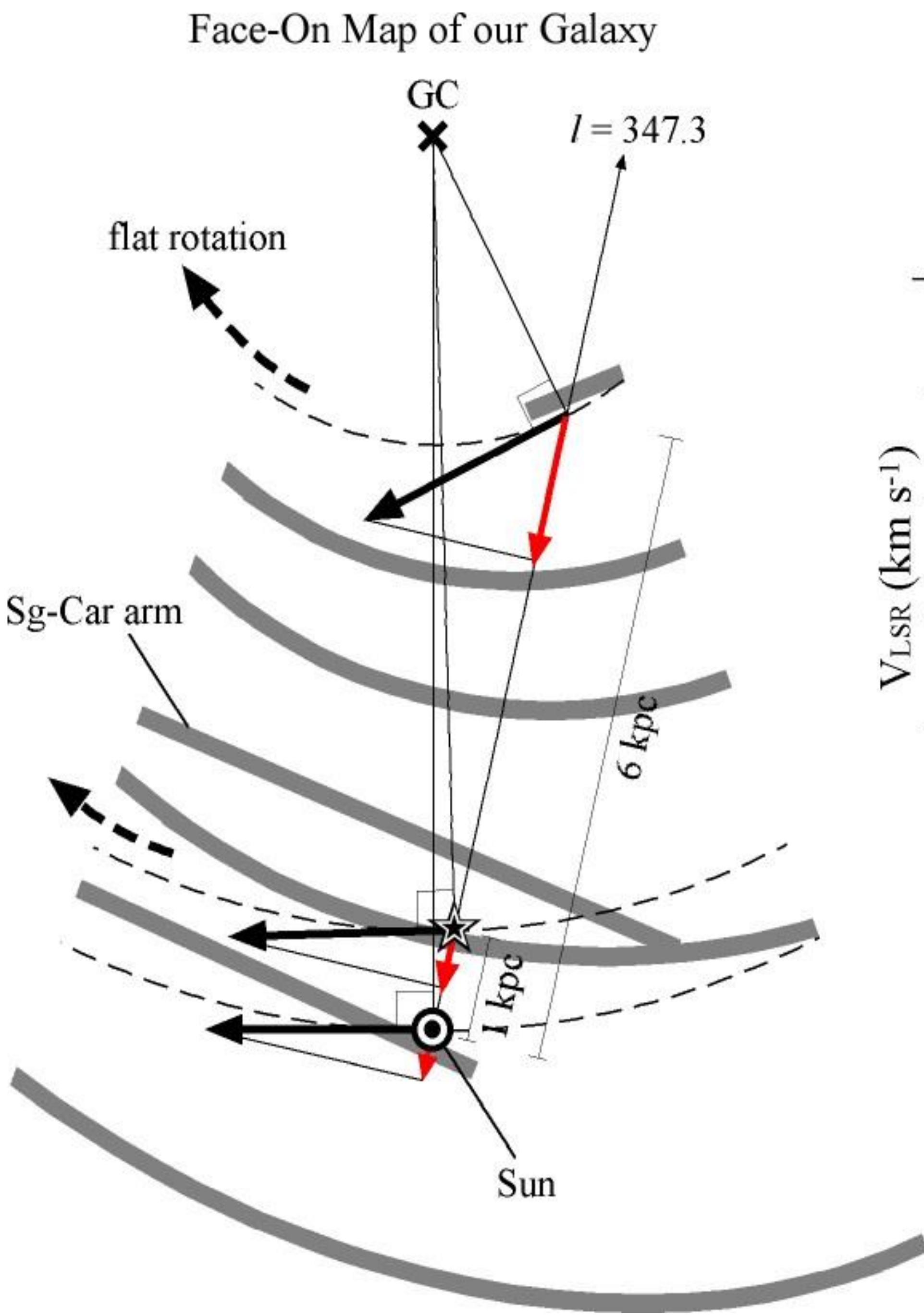
@Atacama, alt.4800m

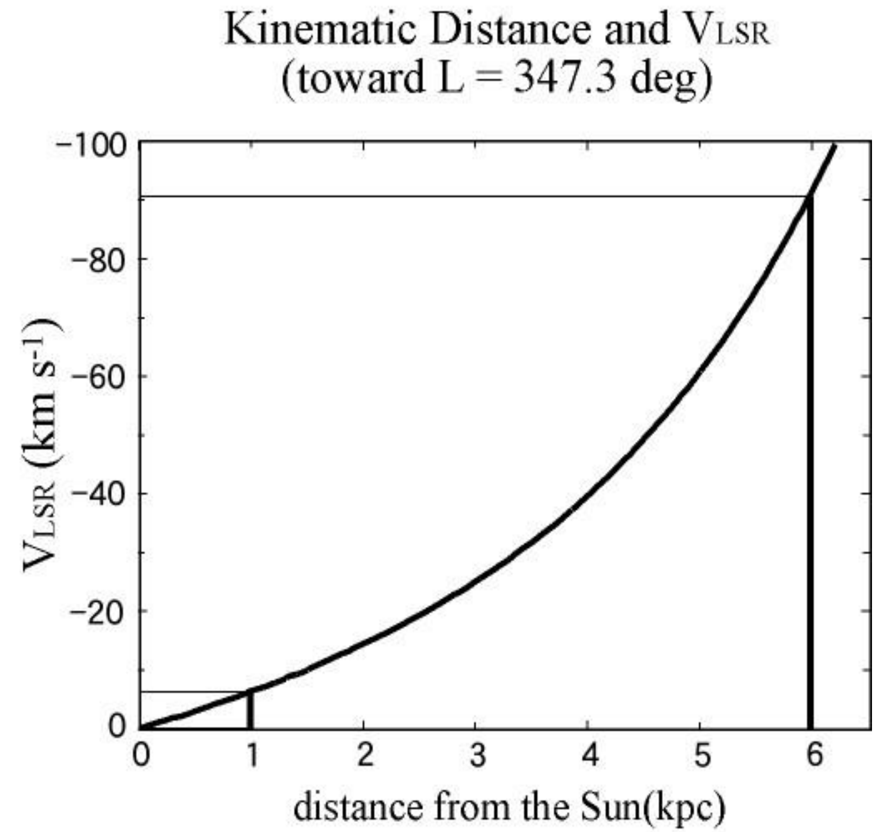
RX J1713.7-3946: $^{12}CO(J=1-0)$ with X-rays

-11 km/s < V_{LSR} < -3 km/s



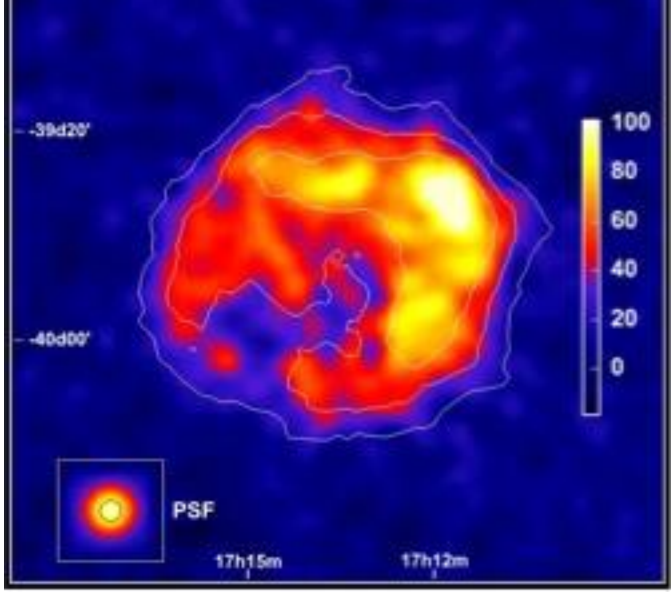
Fukui et al. 2003


Face-On Map of our Galaxy
GC
l = 347.3
flat rotation
Sg-Car arm
6 kpc
1 kpc
Sun

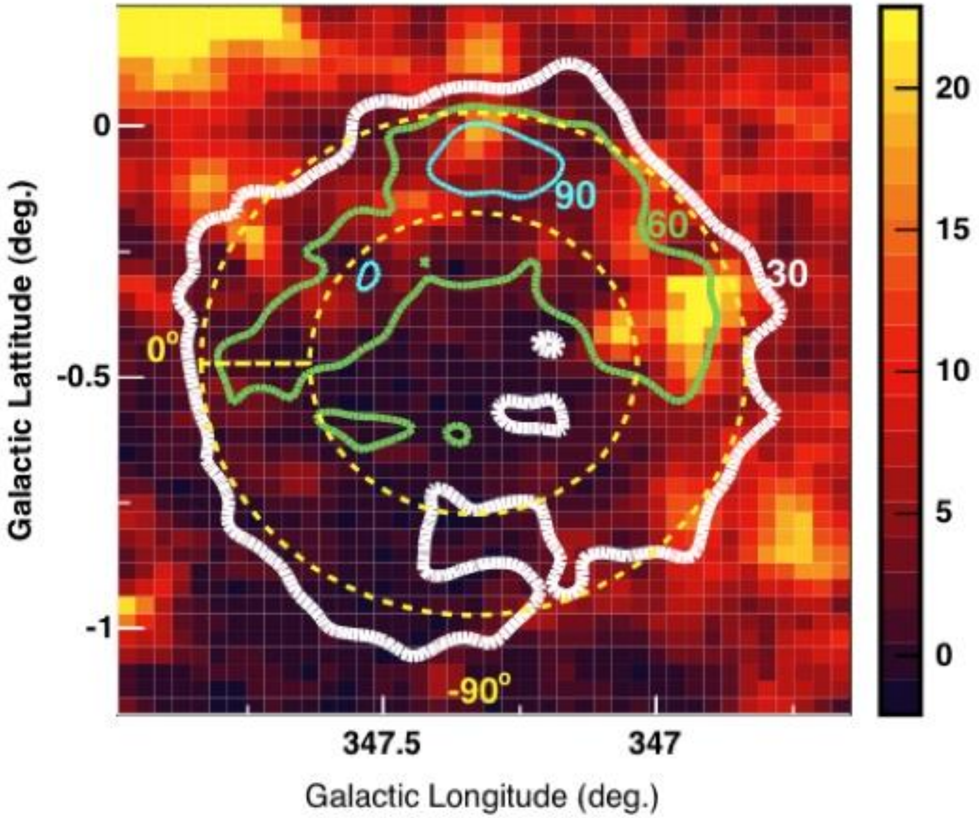

Kinematic Distance and VLSR
(toward L = 347.3 deg)
VLSR (km s-1)
-100
-80
-60
-40
-20
0
0
1
2
3
4
5
6
distance from the Sun(kpc)

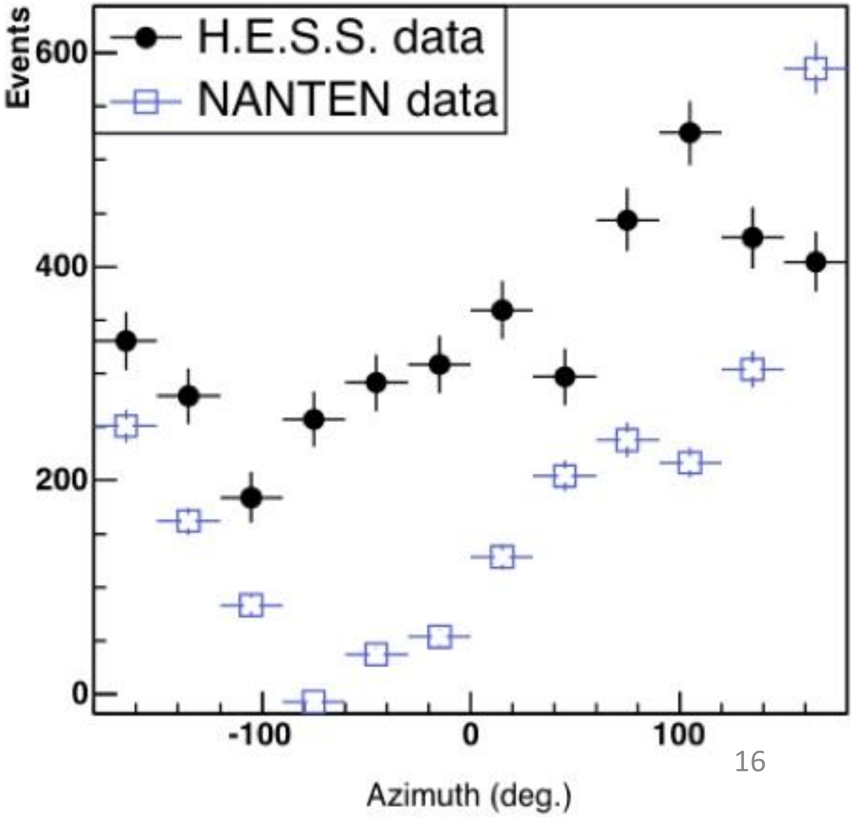
SNR G347.3-0.5 (RXJ1713.7-3946)

- Shell-like structure: similar with X-rays
- No significant variation of spectrum index across the regions
- spatial correlation with surrounding molecular gas

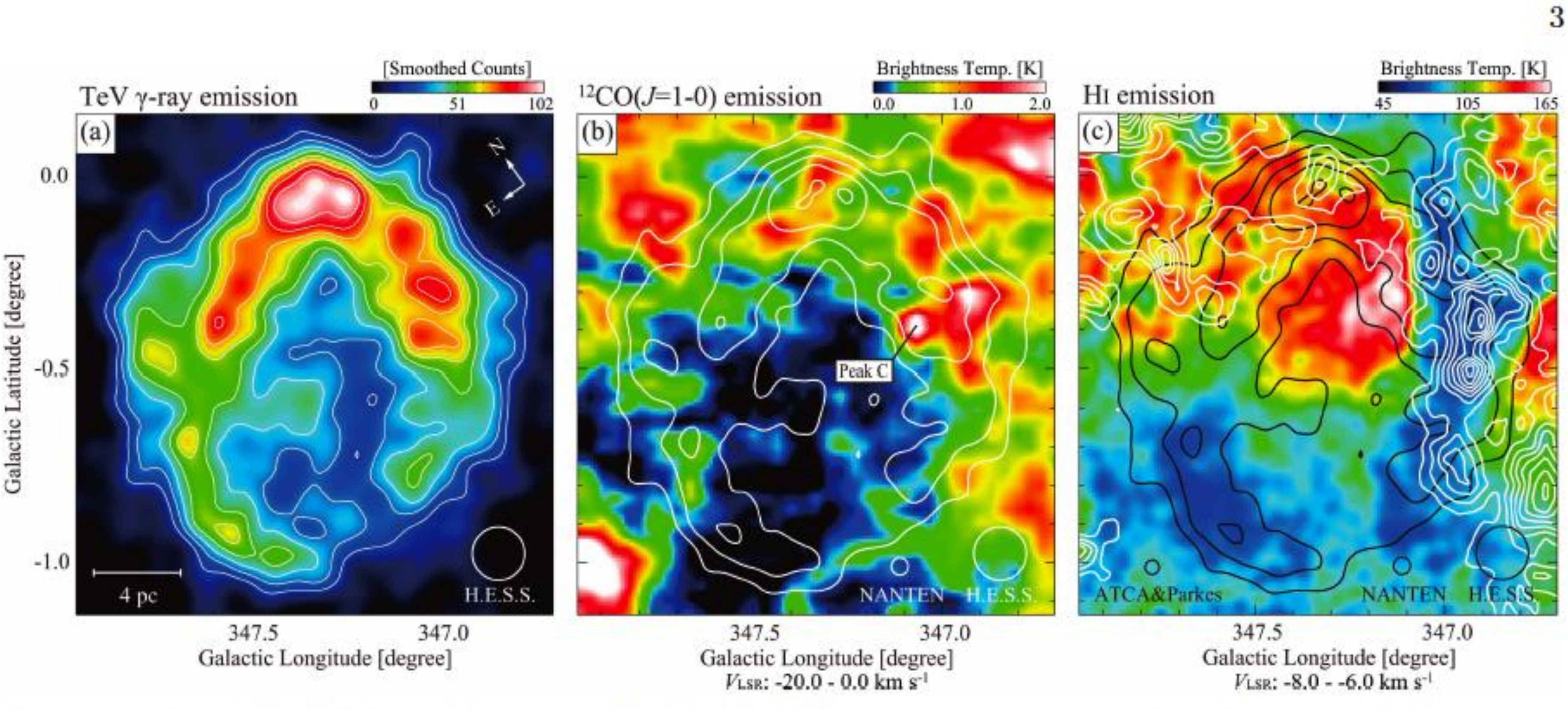


Aharonian et al. 2005



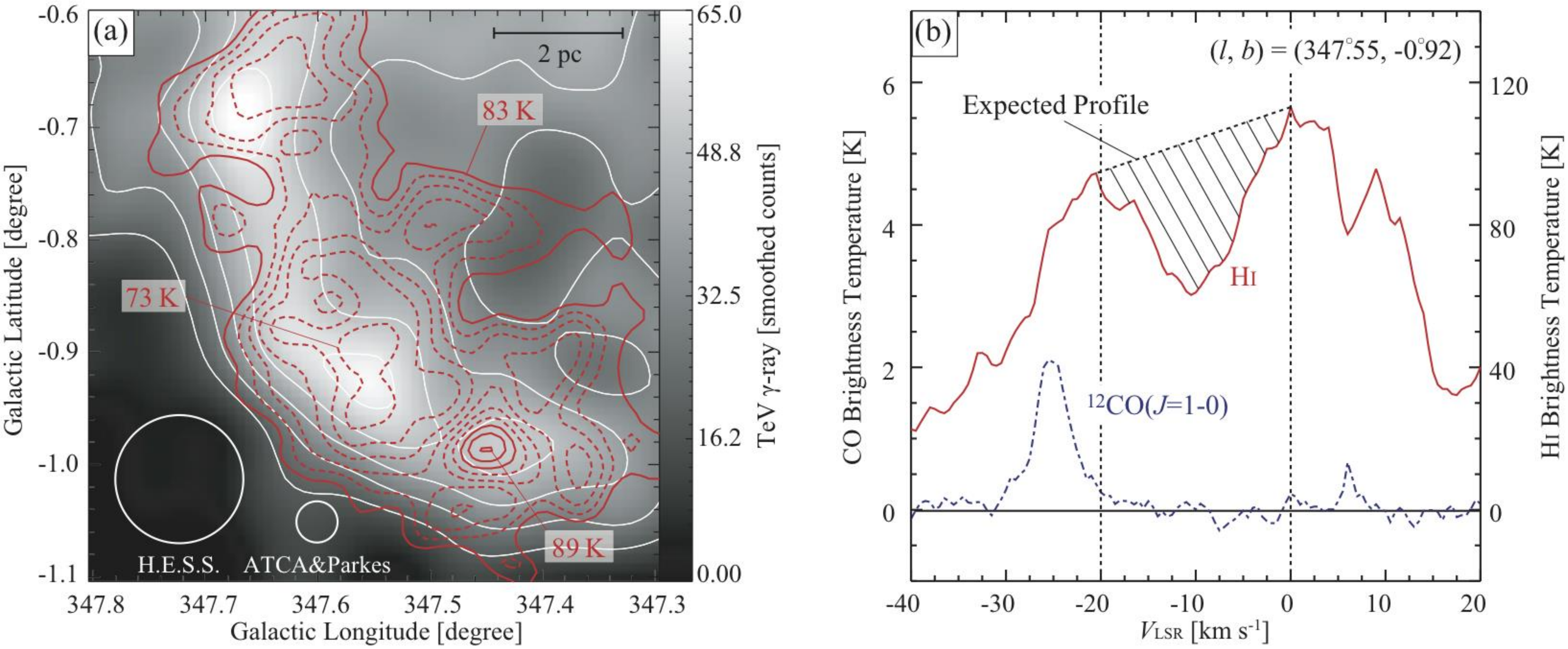


RX J1713.7-3946

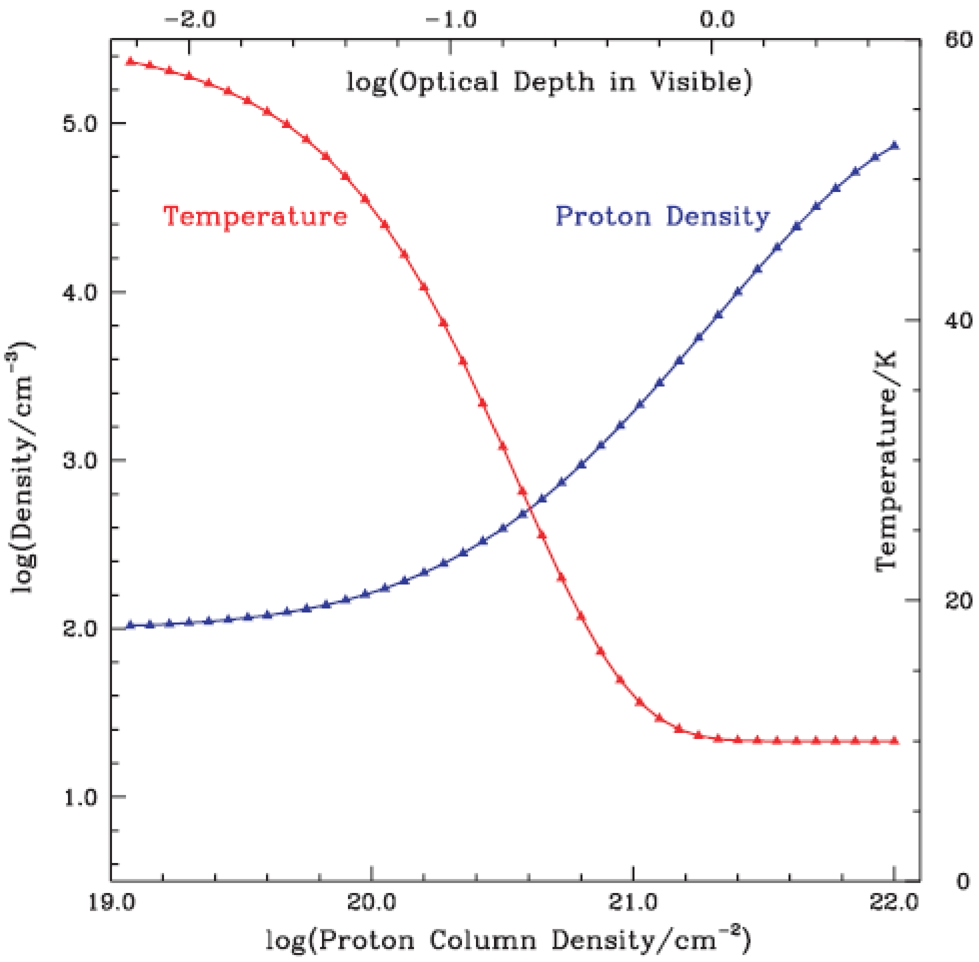


Fukui et al. 2012, ApJ, 746, 82

Dark HI SE Cloud (Self-Absorption)

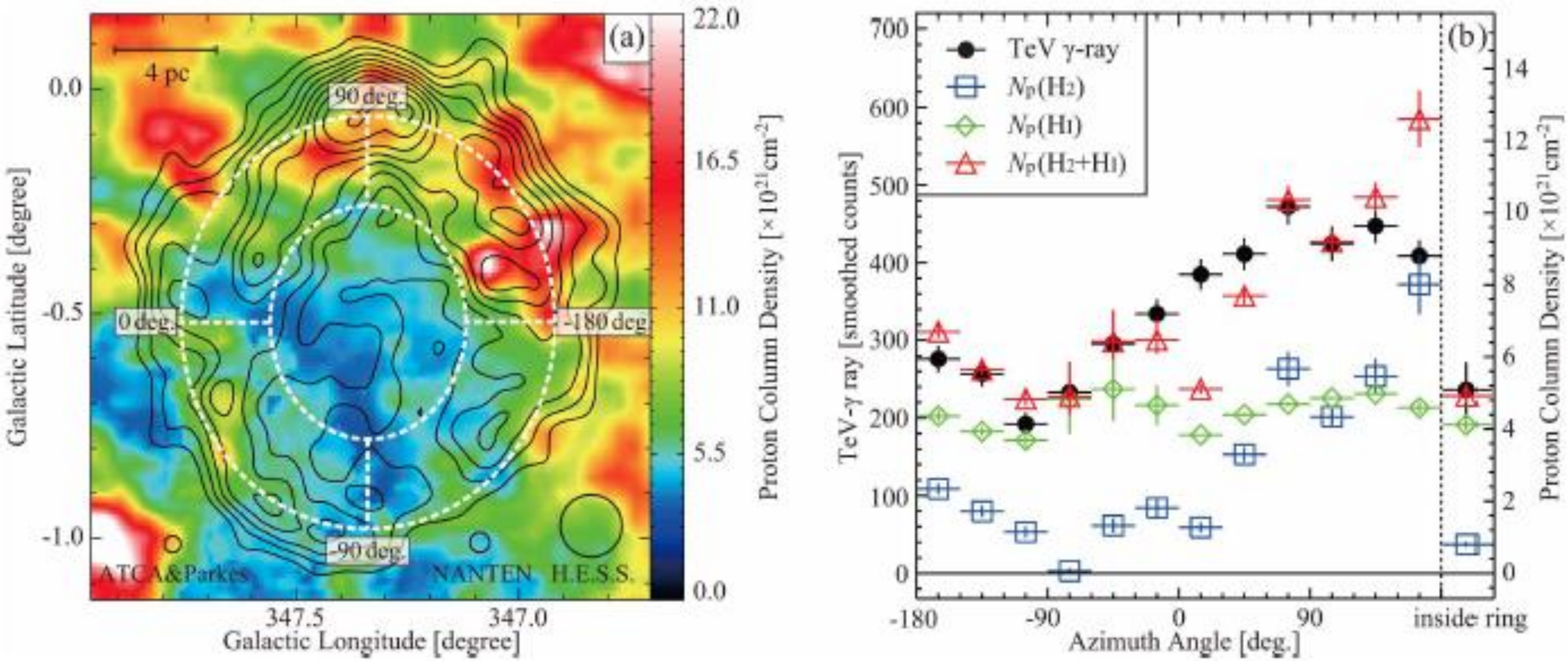


HI becomes dark at higher density



Goldsmith et al. 2007

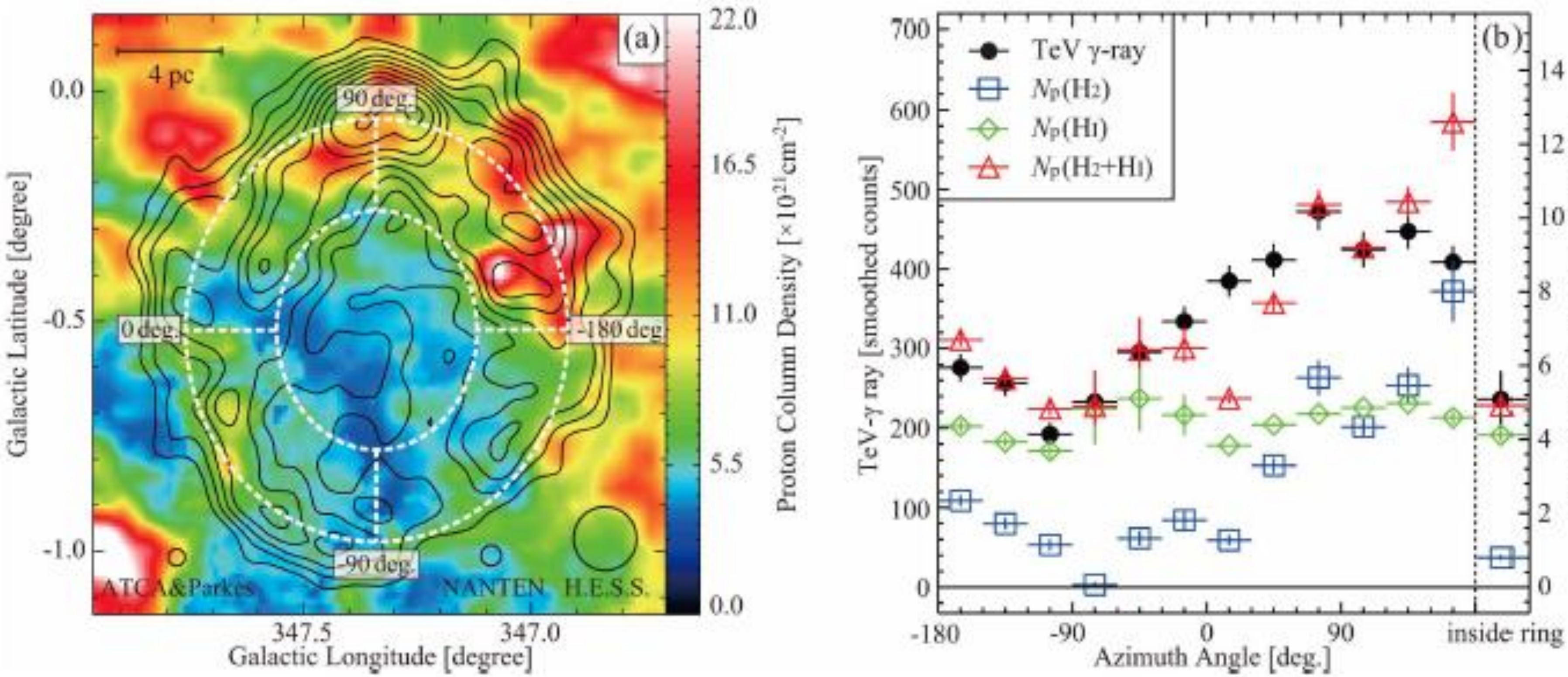
ISM protons in RX J1713.7-3946



HI + $2H_2$

Fukui et al. 2012

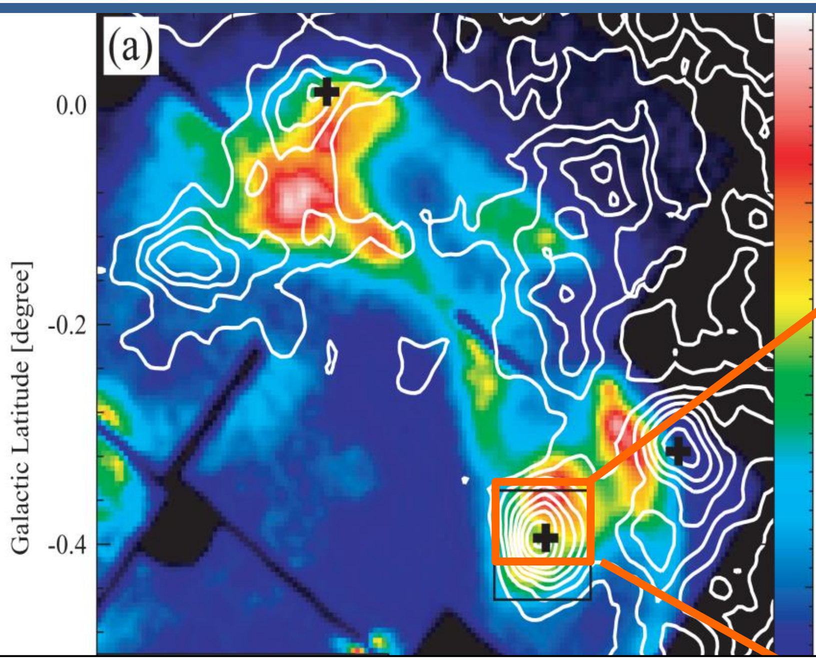
ISM protons in RX J1713.7-3946
Support hadronic scenario

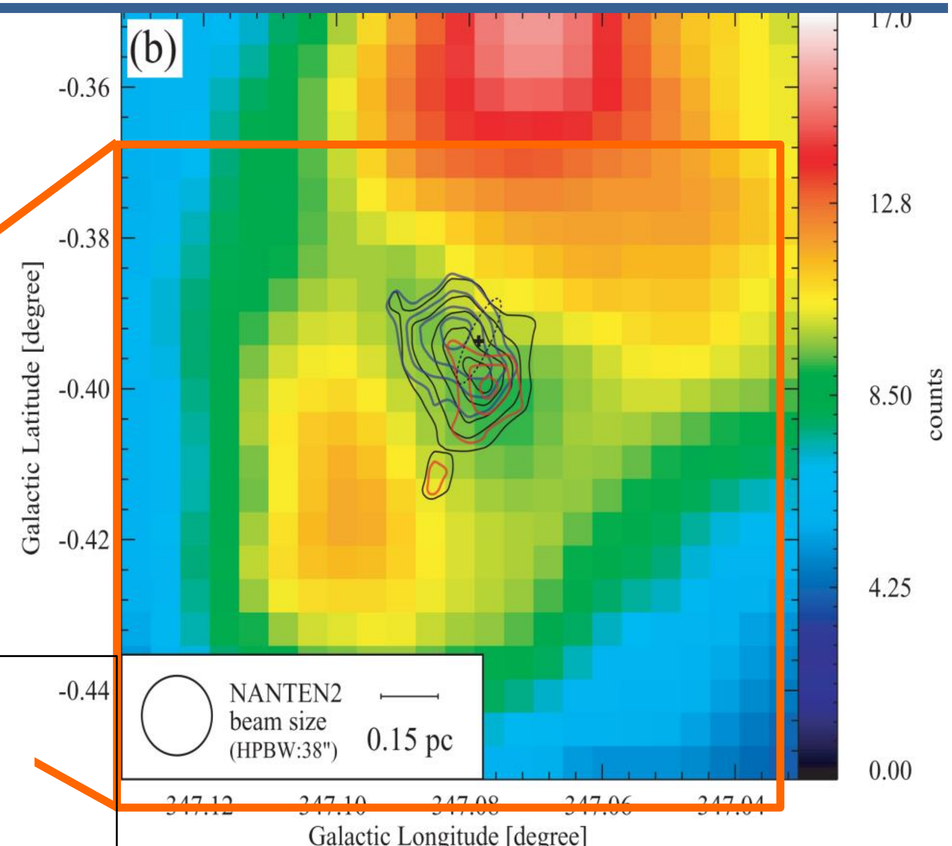


$HI + 2H_2$

Fukui et al. 2012

Shock propagation into dense gas





$$V_{\rm sh} \sim 3000\ {\rm km\ s^{-1}} / \sqrt{n/n_0}$$

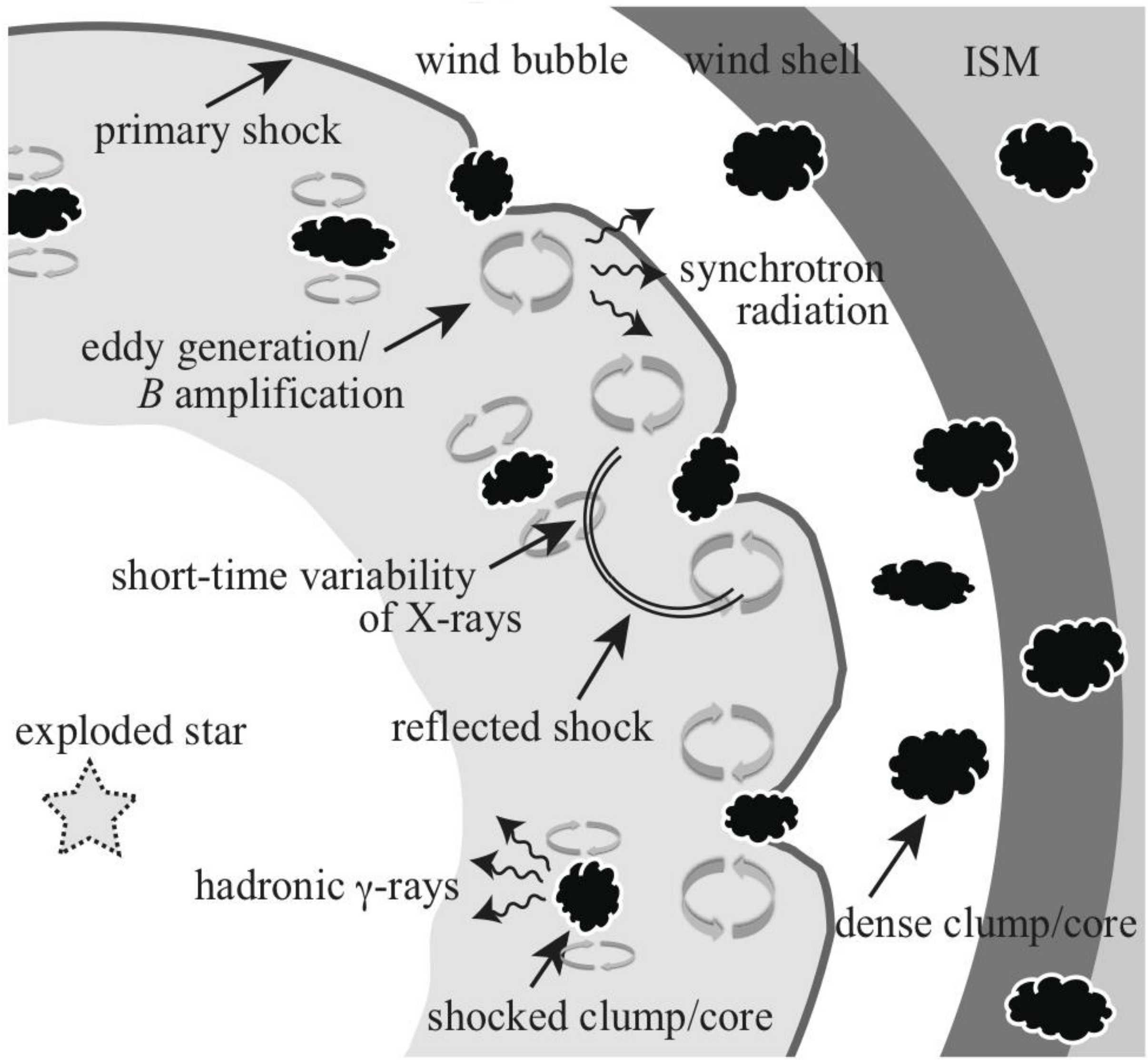
n : density of clump

n_0 : ambient density (=1 cm^{-3})

10^4 cm^{-3}, t~1000yrs

Penetrating Depth = 0.03 pc

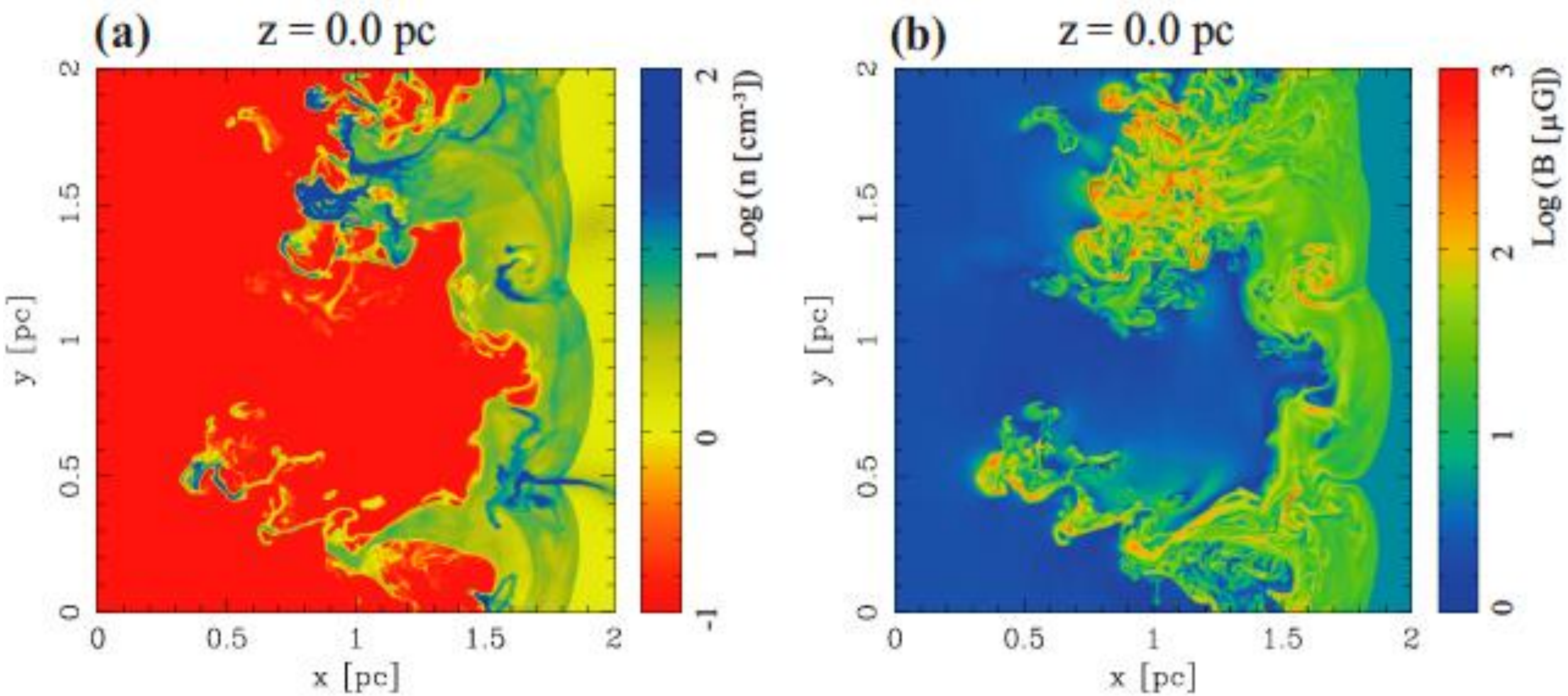
Sano et al. 2010



Inoue, Yamazaki, Inutsuka, Fukui 2012, ApJ, 744, 71

MHD simulations of shock-cloud interaction

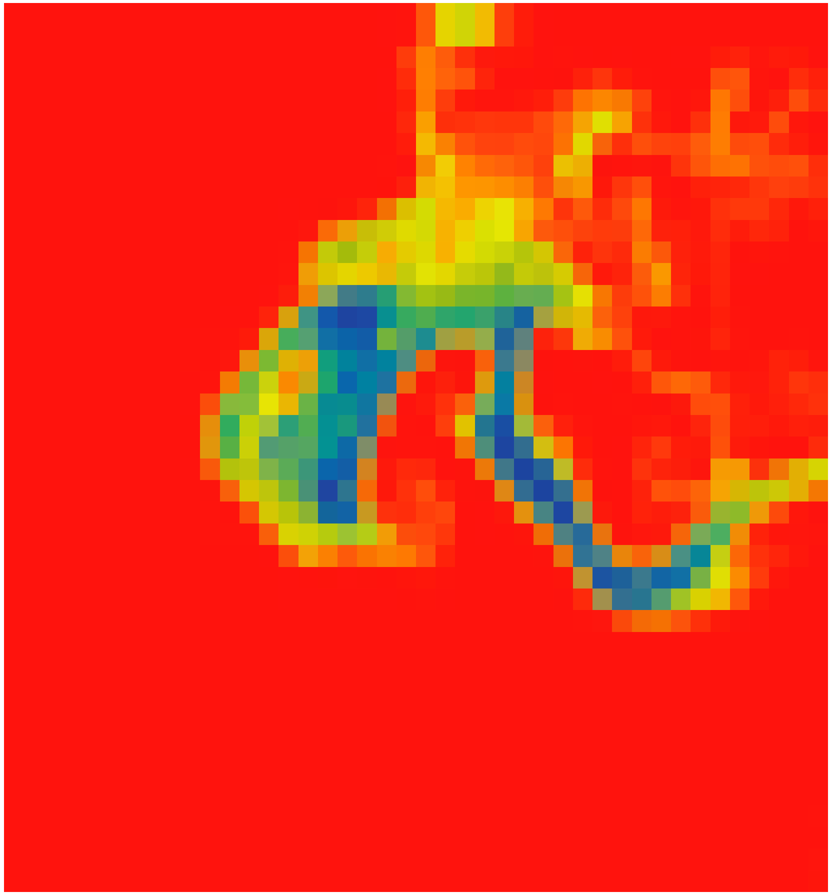
density vs. magnetic field

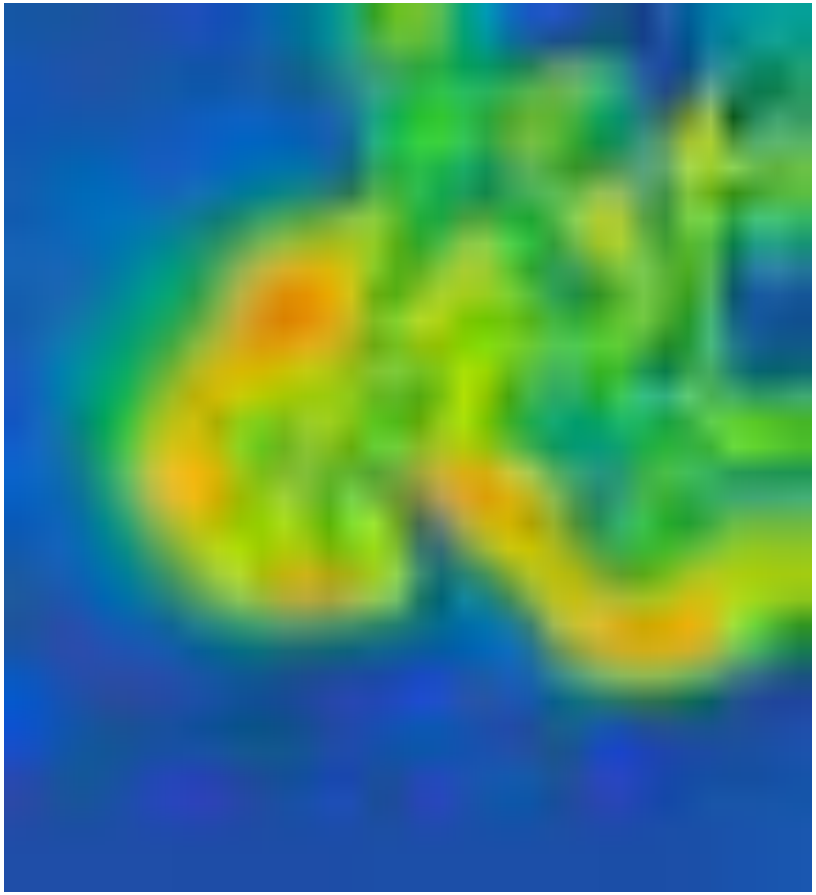


Inoue+ 2010

density vs. magnetic field

[sub-pc scale]





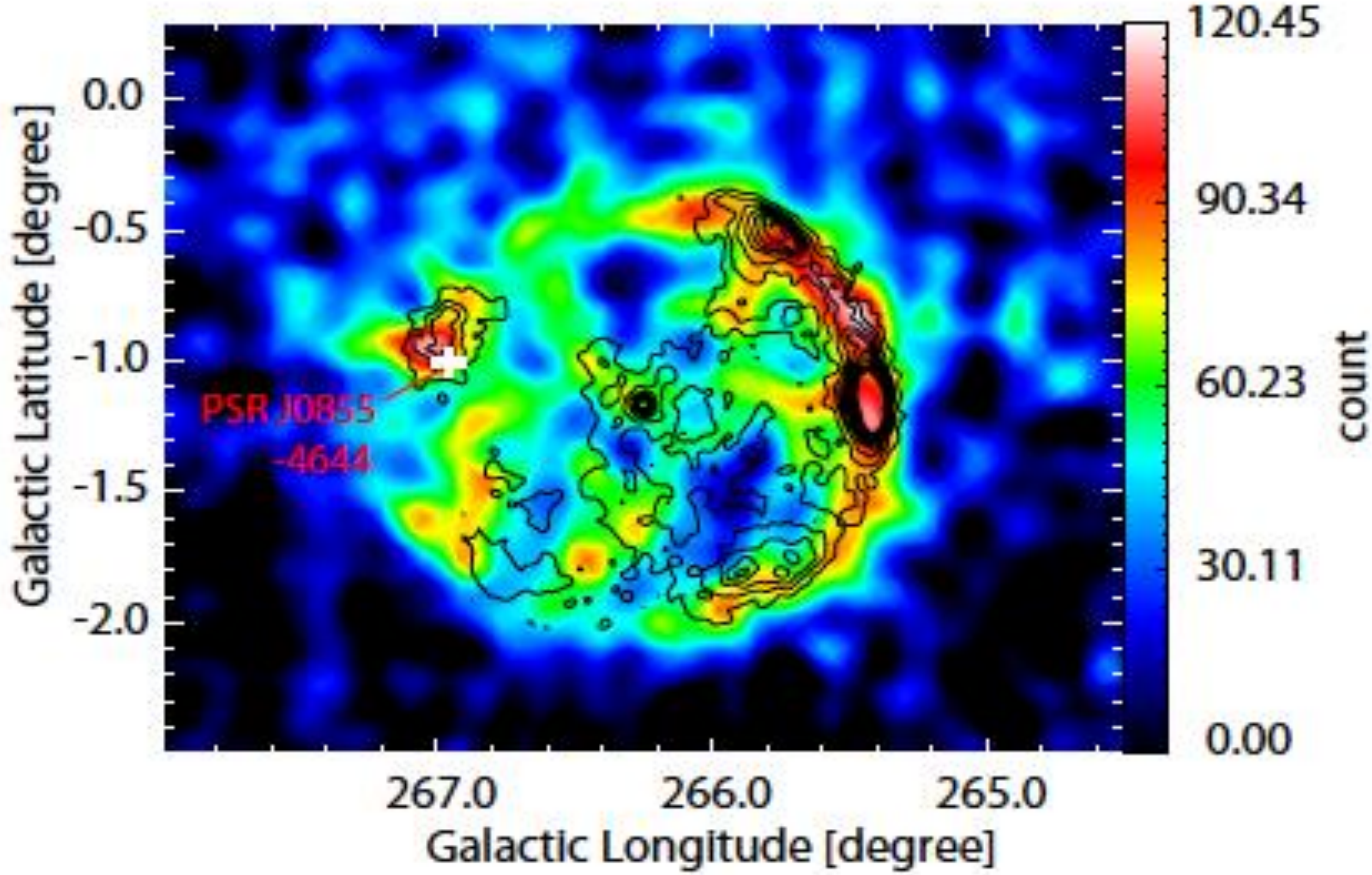
SNR RXJ1713 summary

Gamma-rays corresponds well with interstellar H nuclei, CO+HI, allowing detailed identification of target protons in a density range from 100 to 10^3 cm^{-3}. The gas is highly clumpy.

Wp ~ 10^{48}erg for 100cm^{-3}: gamma rays ~ Wp x ISM

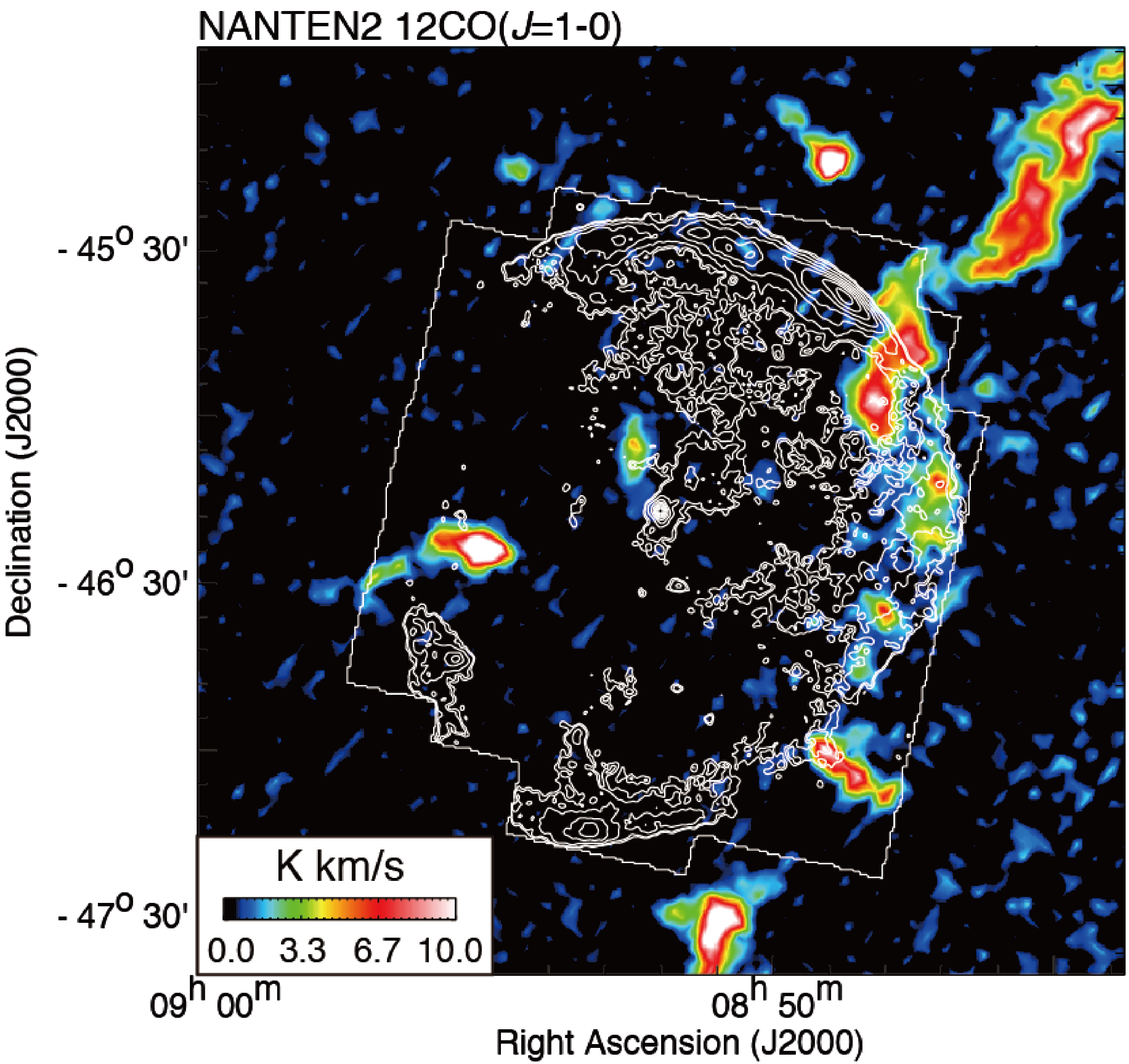
- Hadronic origin is consistent with the spatial correspondence
- Careful analysis of dense atomic and molecular gas, HI and CO, yields total ISM protons
- Shock-cloud interaction causes gas turbulence and strong B field up to mG

TeV gamma-ray SNR RX J0852.0-4622



Color TeV gamma rays   contour X rays

RX J0852: CO distribution (interact with the SNR)



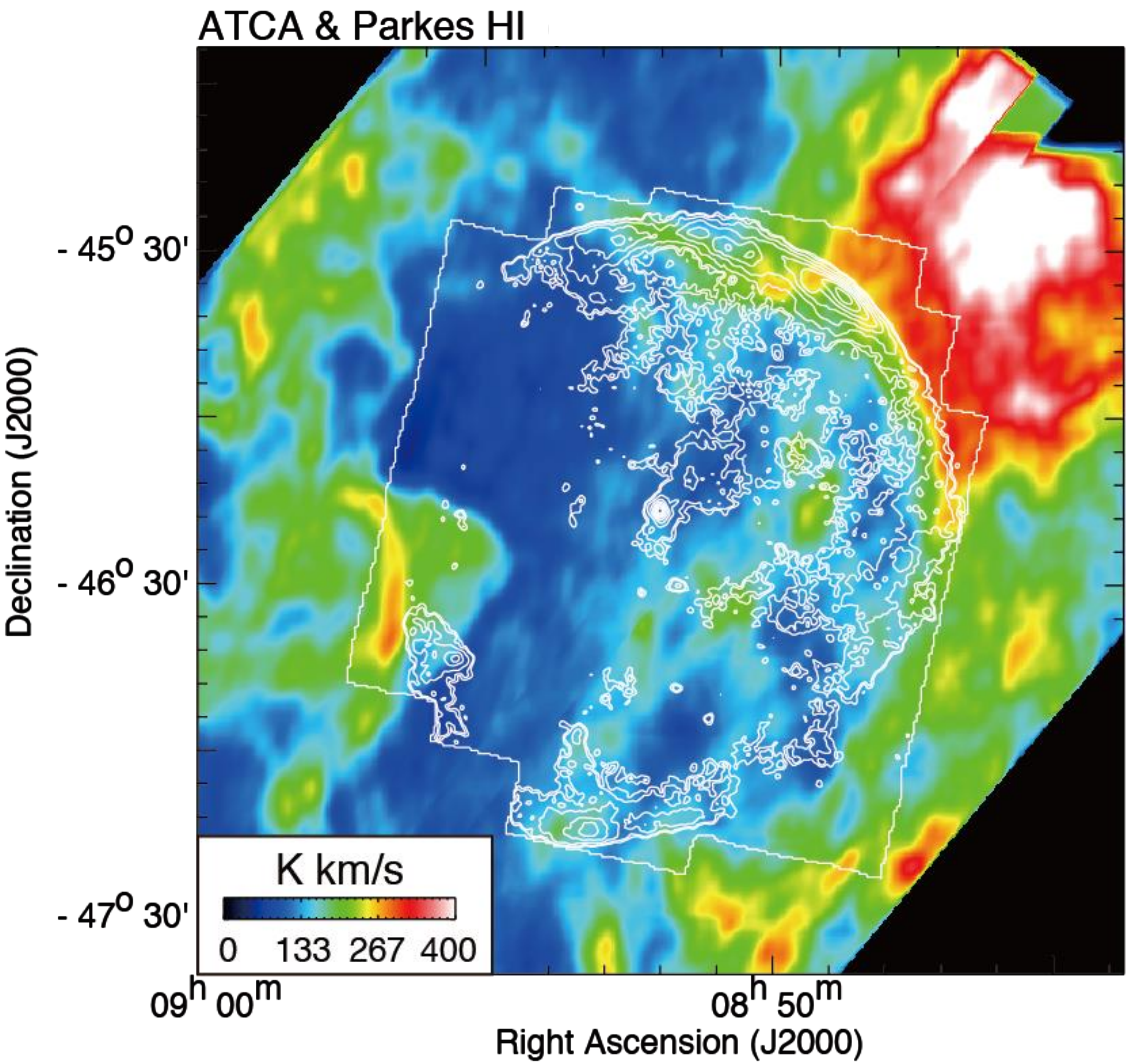
■ CO vs. X-rays

good spatial correspondence between the CO and X-rays

Interacting with the SNR

image: CO(1-0) I.I.
(Vlsr: 24-33 km/s)
contours: X-ray (1-5 keV)

RX J0852: HI distribution (interact with the SNR)



- HI vs. X-rays

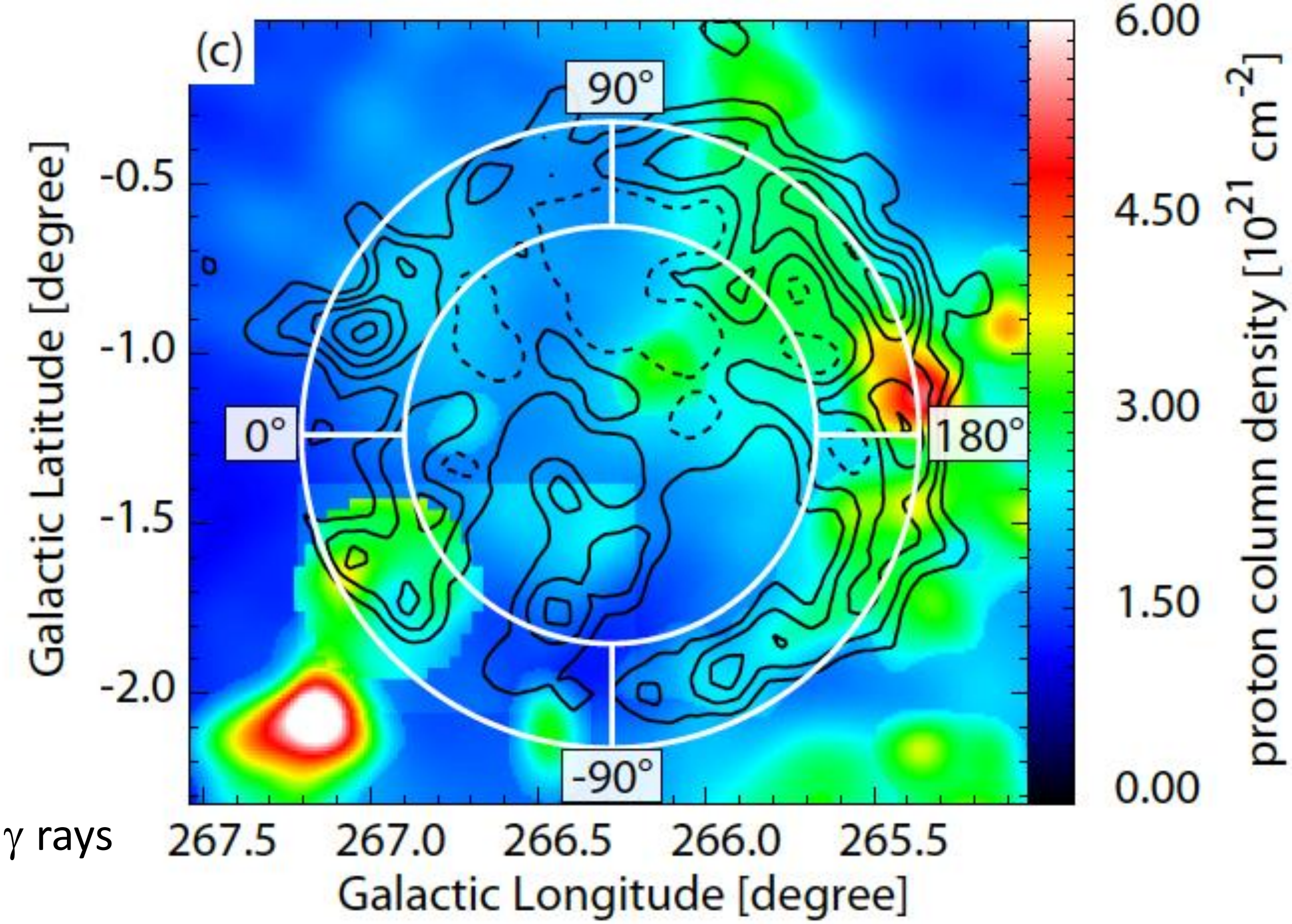
HI wind bubble at same velocity in CO

ISM cavity created by the progenitor

Image: HI I. I. (Vlsr: 28-34 km/s)
contours: X-ray (1-5 keV)

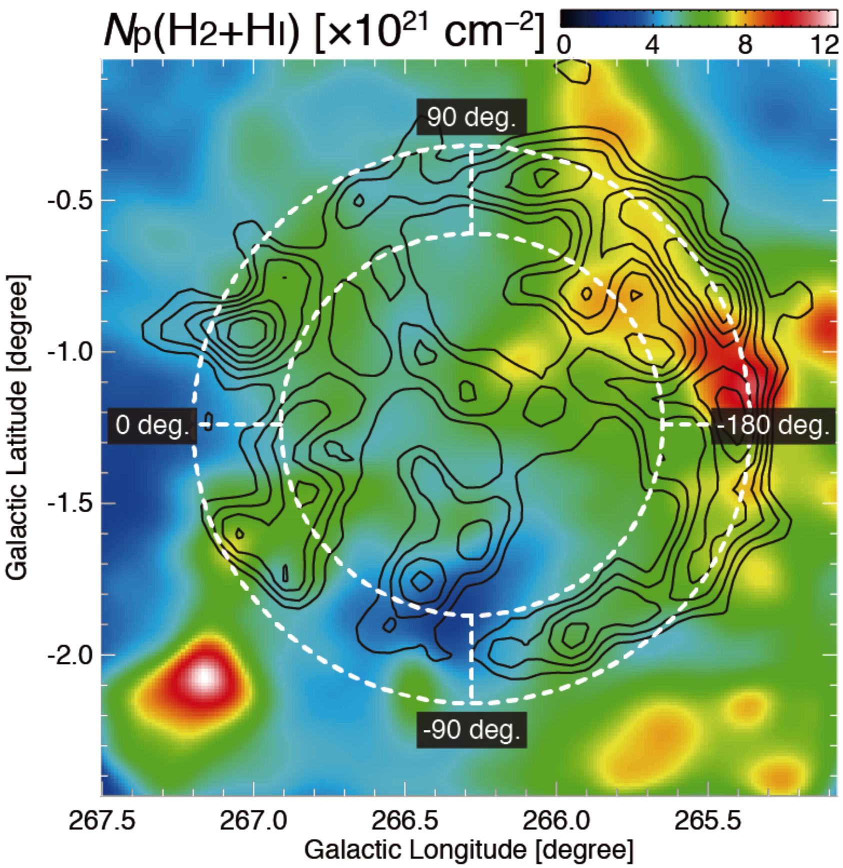
TeV gamma-ray SNR RX J0852
ISM Proton Column Density Distributions

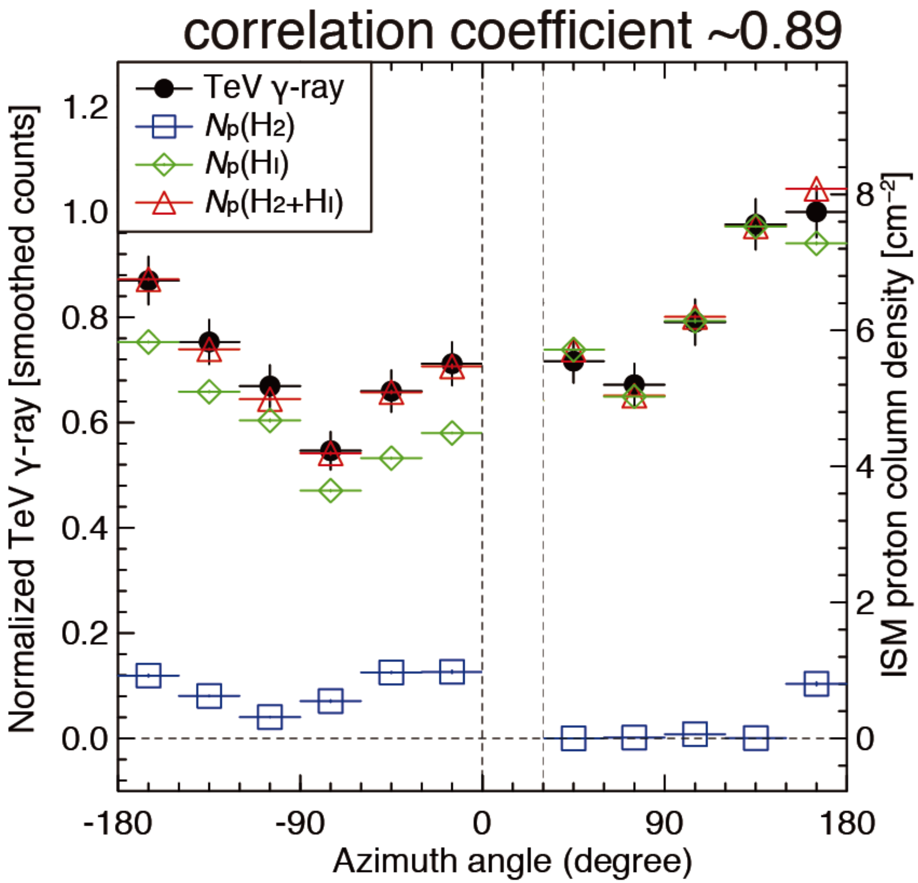
Fukui et al. 2013, in prep.



Color: $HI+2H_2$
Contour : TeV γ rays

Vela Jr. total ISM protons & TeV γ-rays (optically thick HI corrected)

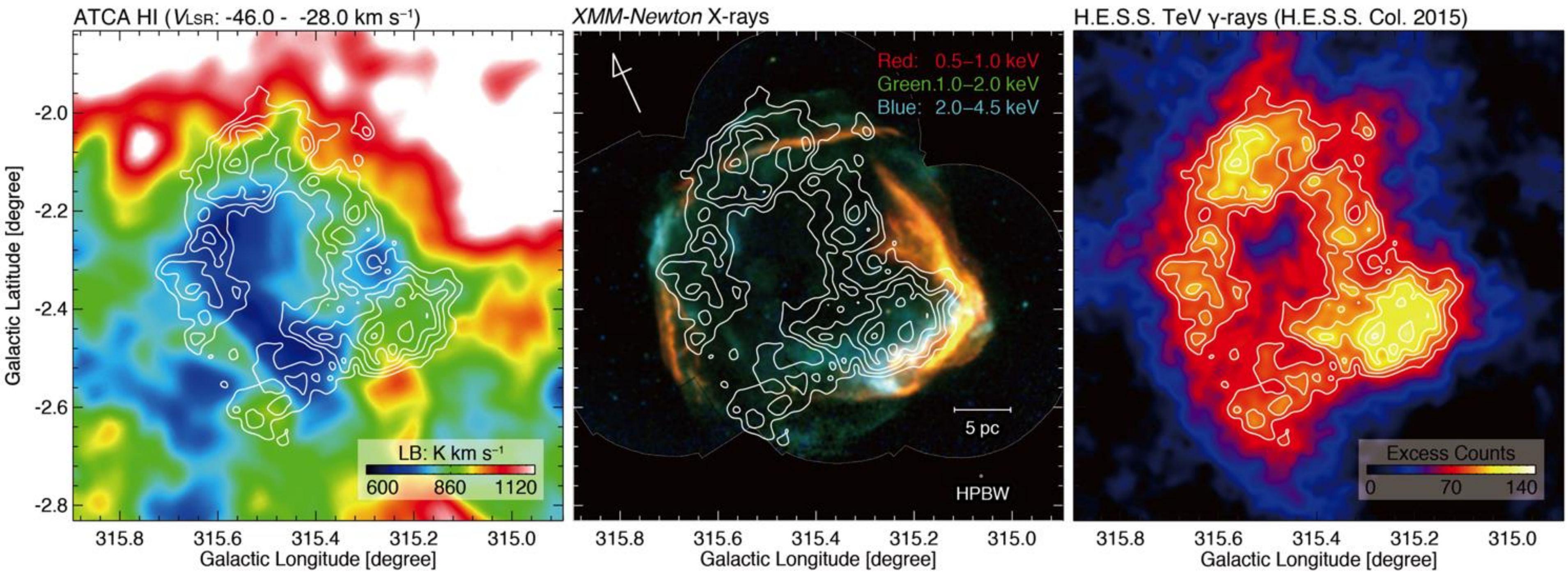




(left) Image: Total interstellar proton column density, contours: TeV γ-rays (Aharonian+07)
(Right) Azimuthal plots

Fukui, Sano+15 in prep.

RCW 86: γ-ray and ISM (preliminary)



Images: (left) ATCA HI integrated intensity, (middle) XMM-Newton X-ray three color, (right) H.E.S.S. TeV Gamma-rays
Contours: H.E.S.S. TeV Gamma-rays (lowest: 75 excess counts, interval: 10 excess counts)

- TeV Gamma-ray intensity increases around the inner wall of the HI cavity.
- Diffuse HI gas (green) is well correlated with the TeV gamma-ray peaks.
- In the northeast region, the peak of synchrotron X-ray is anti-correlated with the TeV gamma-ray peak.

Sano+16b in prep.

Magellanic SNR N132D （Mopra CO1-0, Sano+15b）

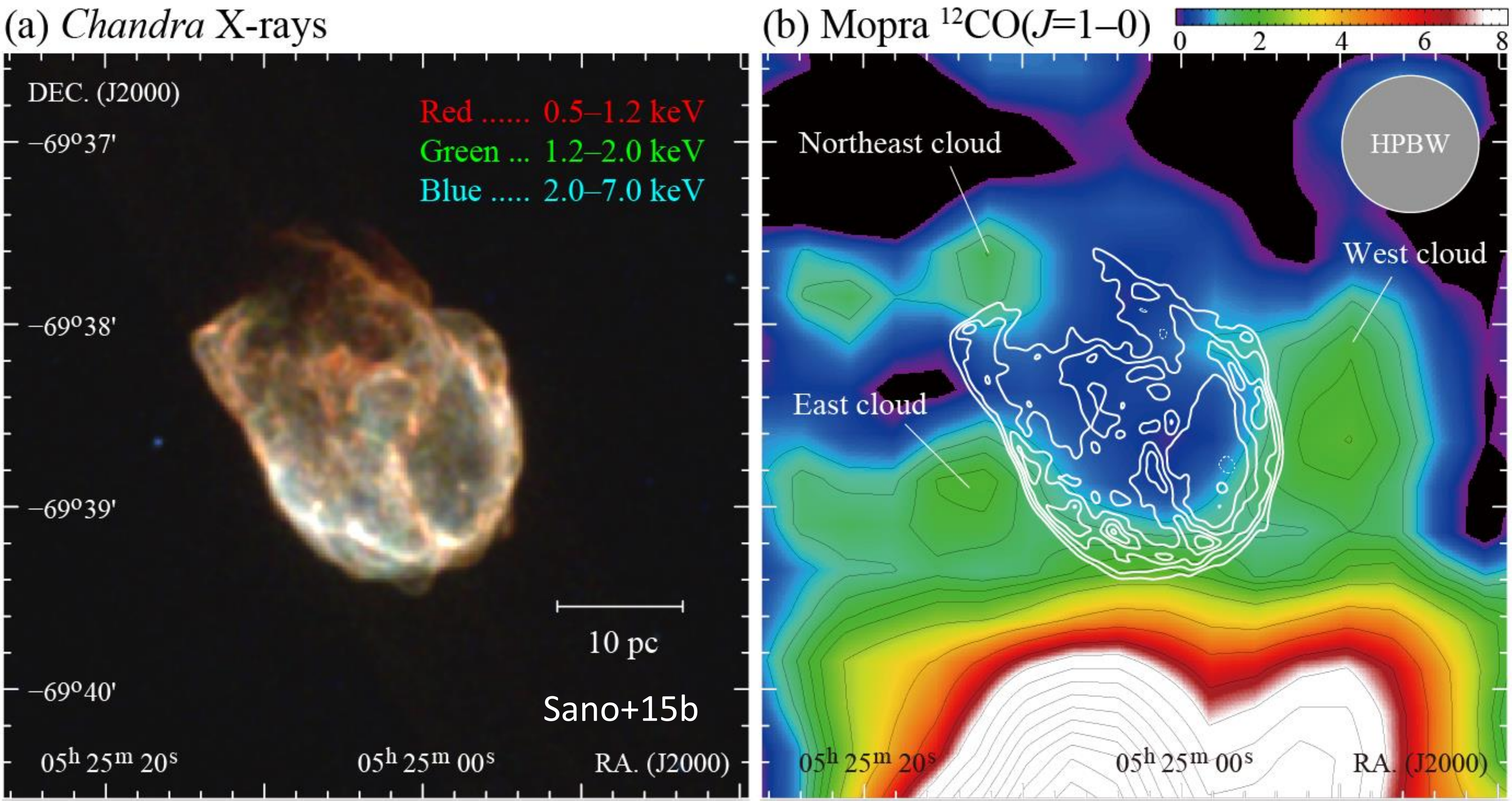
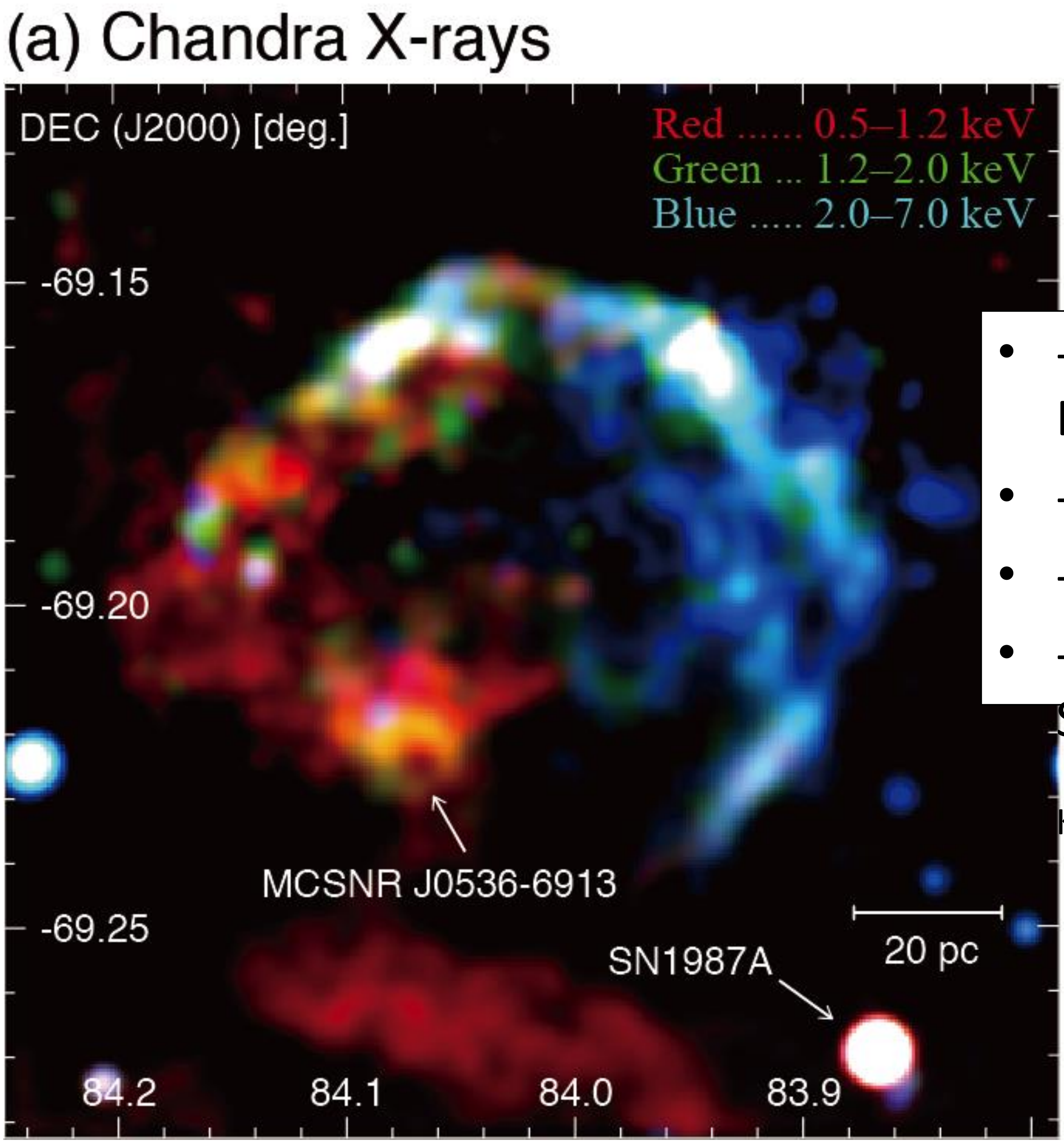


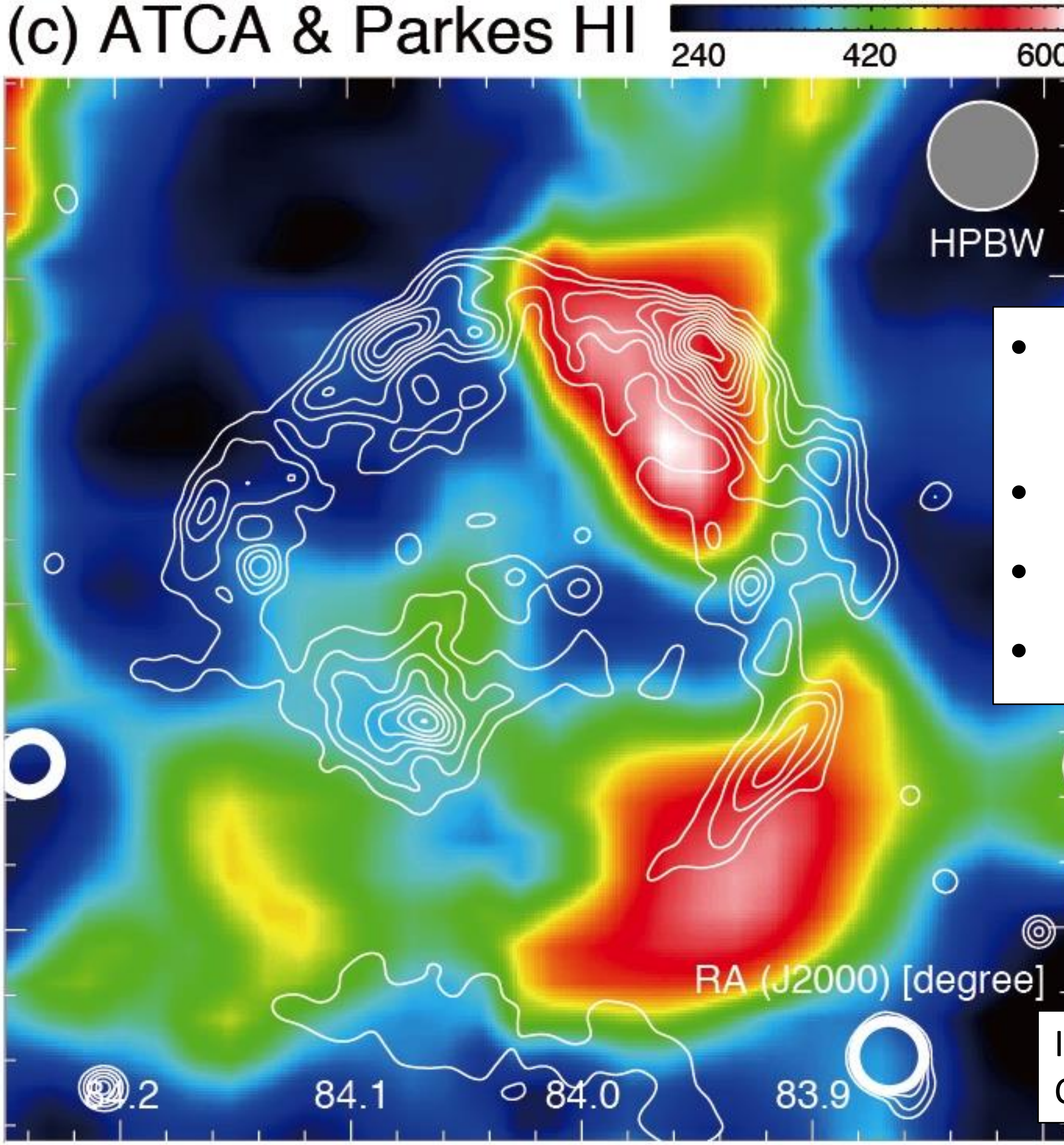
Image: (a) Chandra X-rays, (b) Mopra CO 1-0 (MAGMA: Wong+11)
Contours: Chandra X-rays (0.5-7.0 keV)

30 Dor C



- - Superbubble in 30 Dor
- - Non-thermal X-rays
- - TeV Gamma-rays
- - Containing young SNR
  (Age: 2.2–4.9 kyr, Kavanagh+14)

30 Dor C



- - Superbubble in 30 Dor
- - Non-thermal X-rays
- - TeV Gamma-rays
- - Containing young SNR

(Age: 2.2–4.9 kyr, Kavanagh+14)

Image: HI (Kim+03)
Contours : X-rays (0.5-7.0 keV)

Comparison of young SNRs

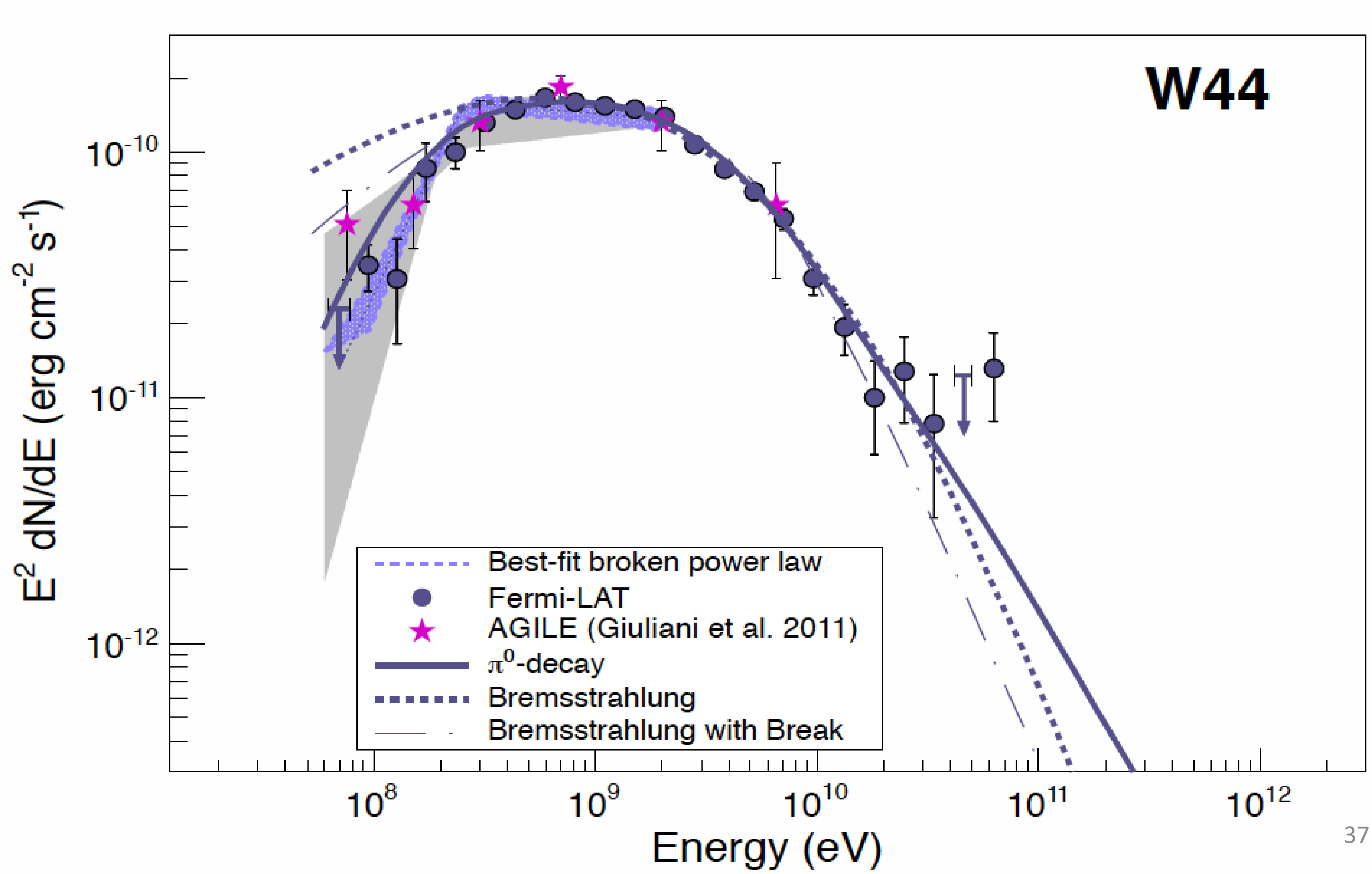
Table 1
A Comparison of RX J0852.0-4622, RX J1713.7-3946, and HESS J1731-347

	RXJ0852.0 – 4622[a]	RXJ1713.7 – 3946[b]	HESSJ1731 – 347[c]
Distance (kpc)	0.7	1	5.2[d]
Radius (pc)	13	9	22
Age (years)	1700	1600	4000
Atomic proton mass ($10^4\ M_\odot$)	1	1	1.3
Molecular proton mass ($10^4\ M_\odot$)	0.1	1	5.1
Total proton mass ($10^4\ M_\odot$)	1.1	2	6.4
Average density (cm^{-3})	40	100	60
L_γ (1–10 TeV) (10^{34} erg s^{-1})	0.63	0.81	2.8
Total CR proton energy	$\sim 10^{48}$	$\sim 10^{48}$	$\sim 10^{49}$

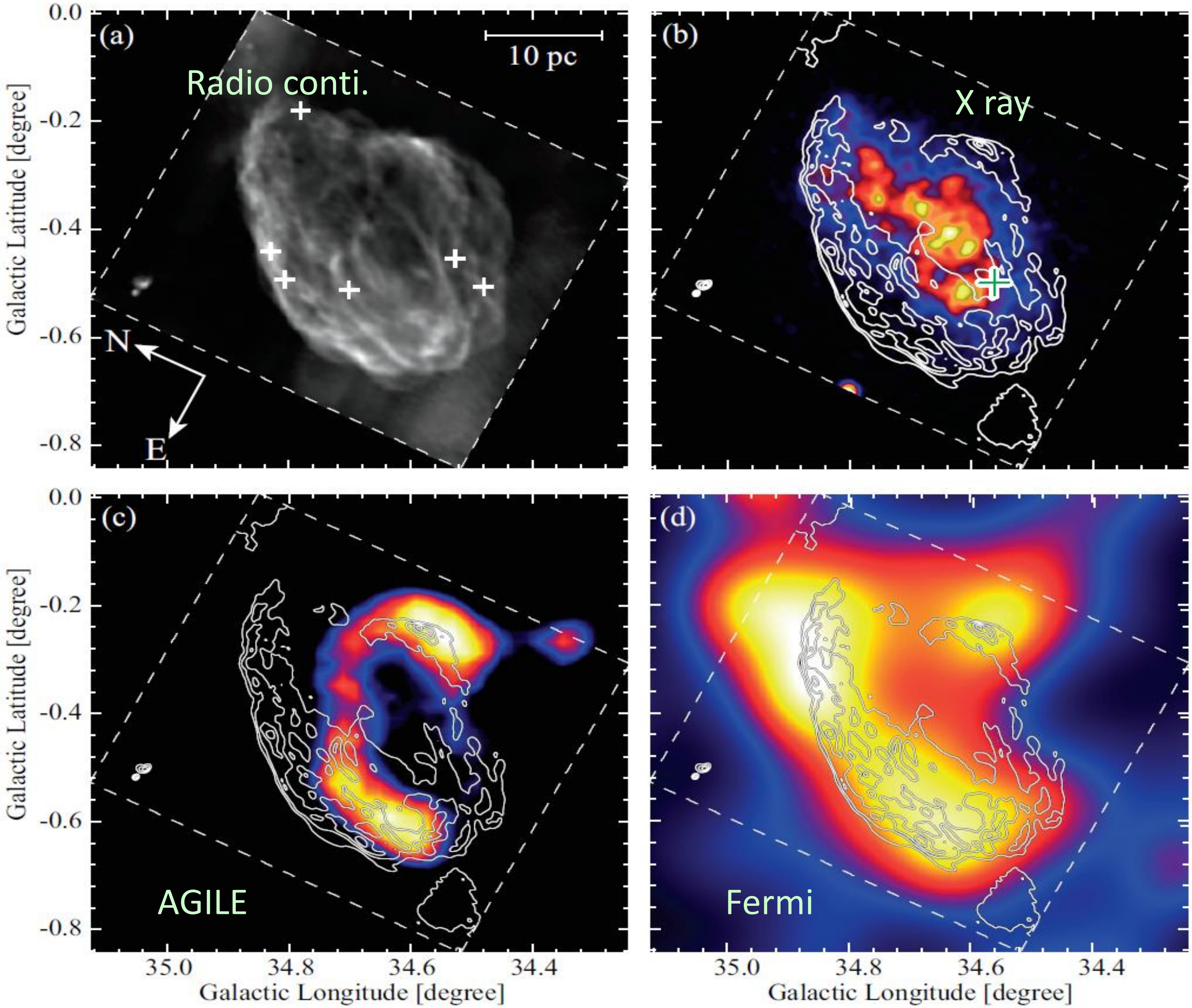
If the γ -rays are produced predominantly by the hadronic process,

- Total CR protons energy $10^{48} - 10^{49}$ erg
- CR acceleration efficiency 0.1% - 1%

W44 Fermi/AGILE results
pion bump, but low resolution, for lower energy CRs

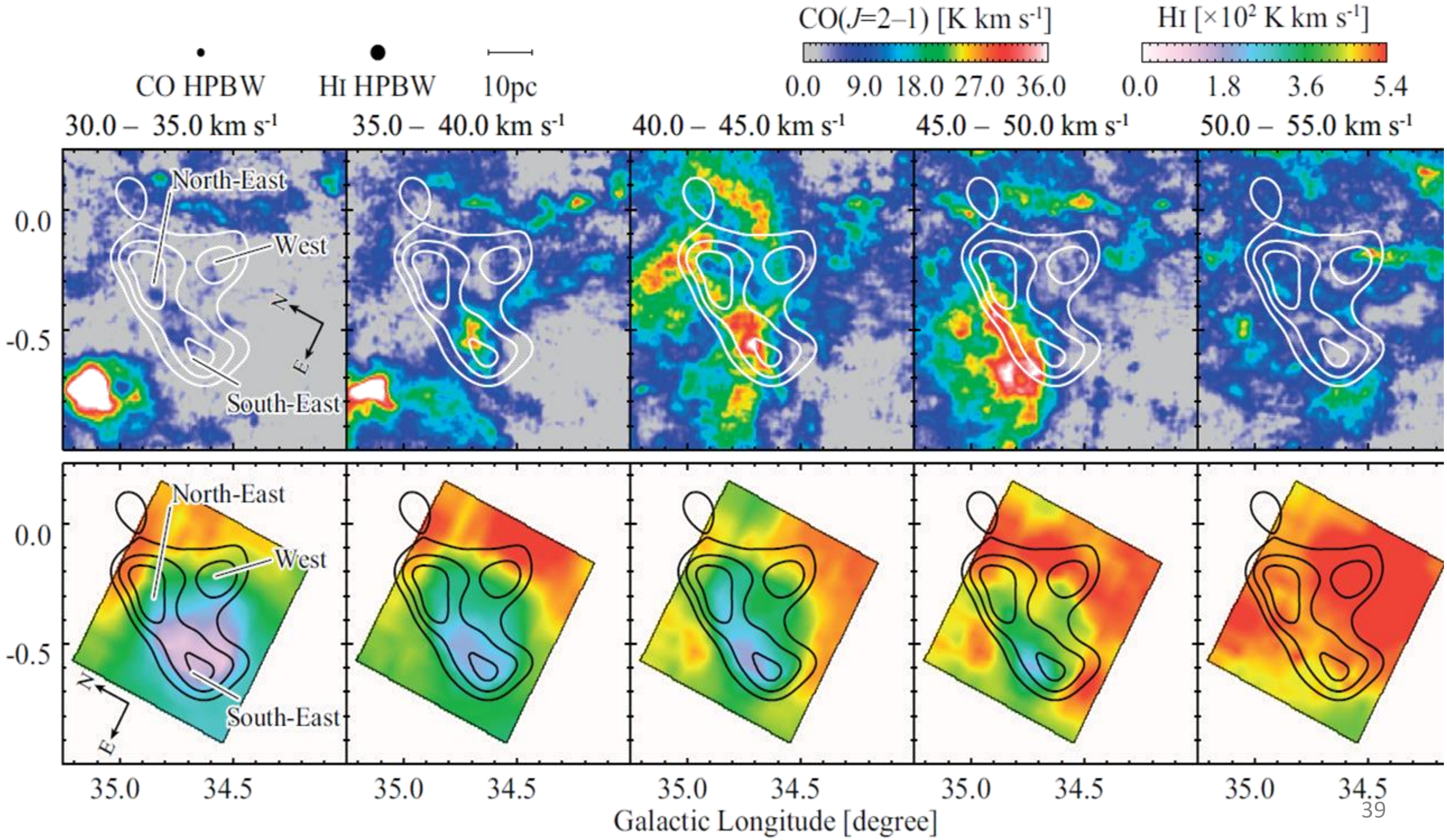


W44

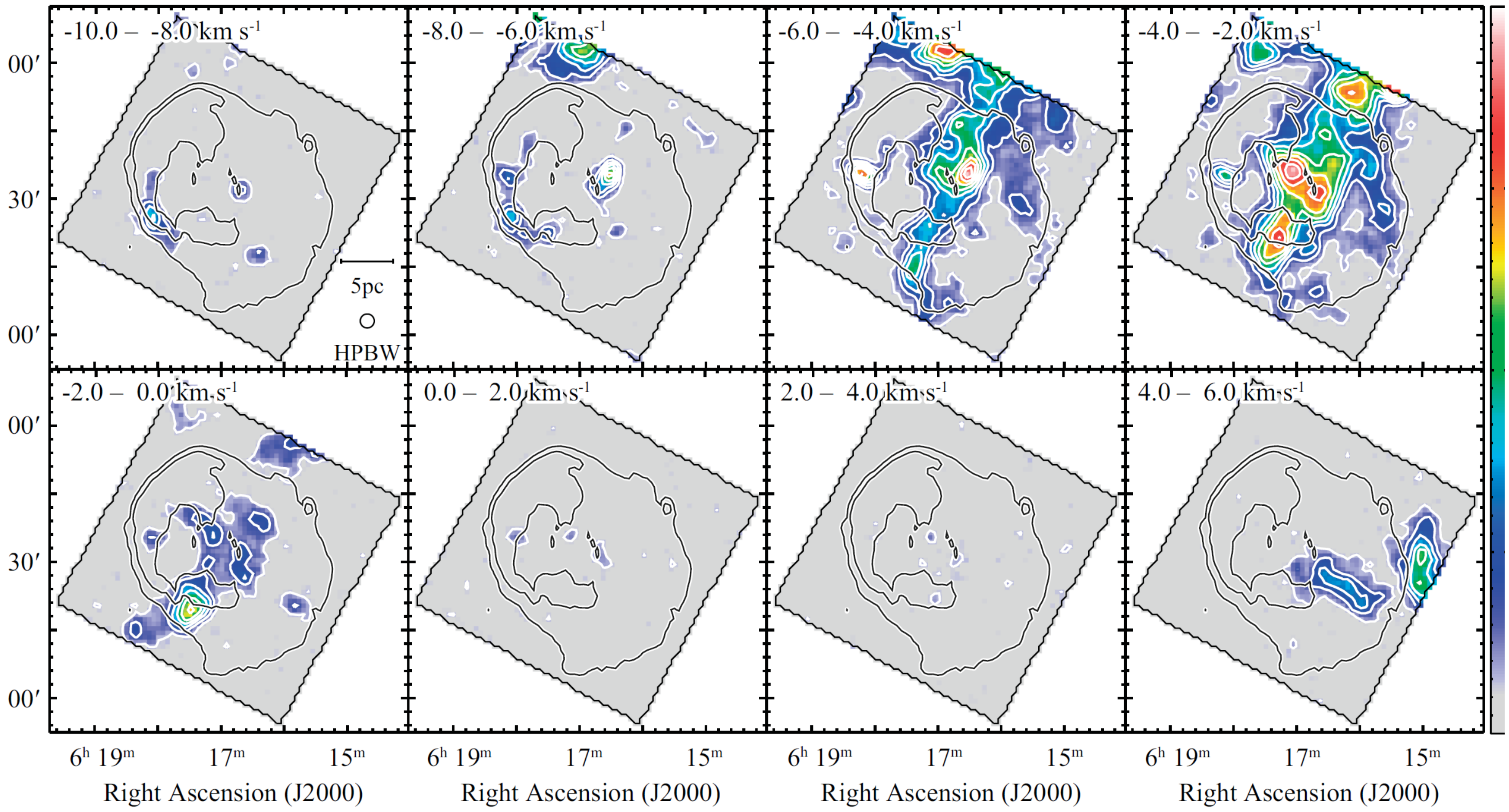


Yoshiike+ 2017

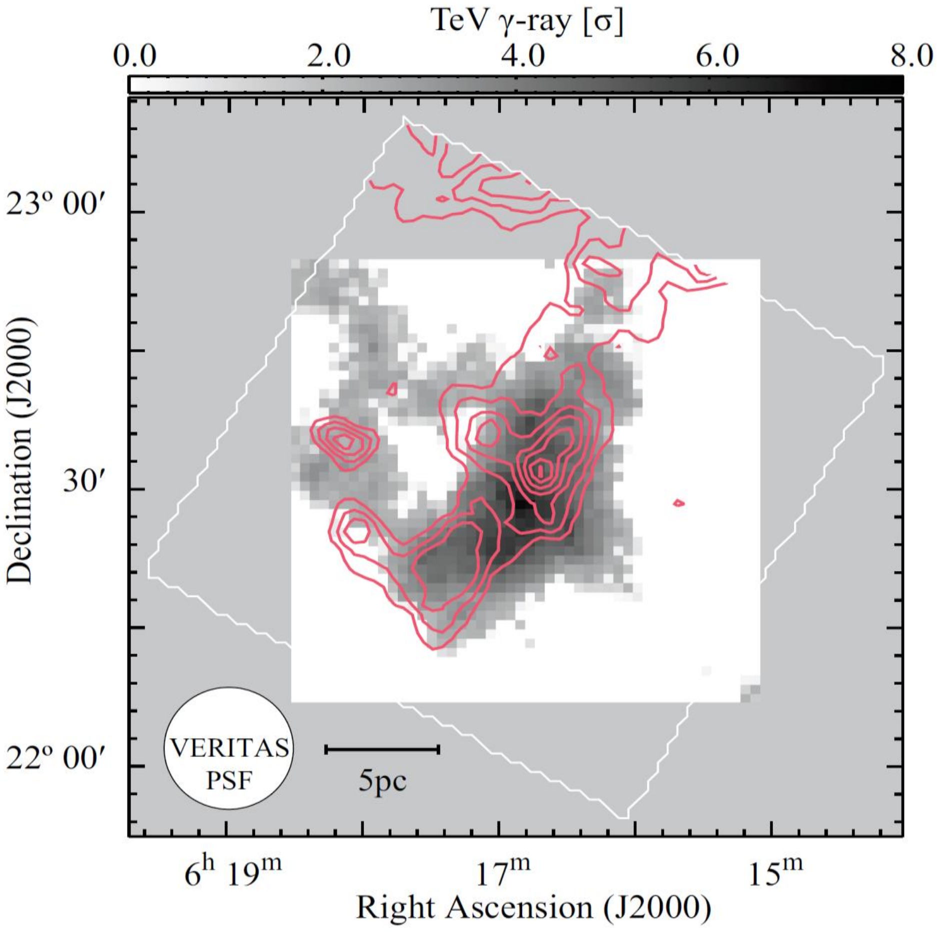
W44 CO and HI Yoshiike et al. 2017



IC443 CO and HI Yoshiike et al. 2017



IC443 Wp~8e47 erg



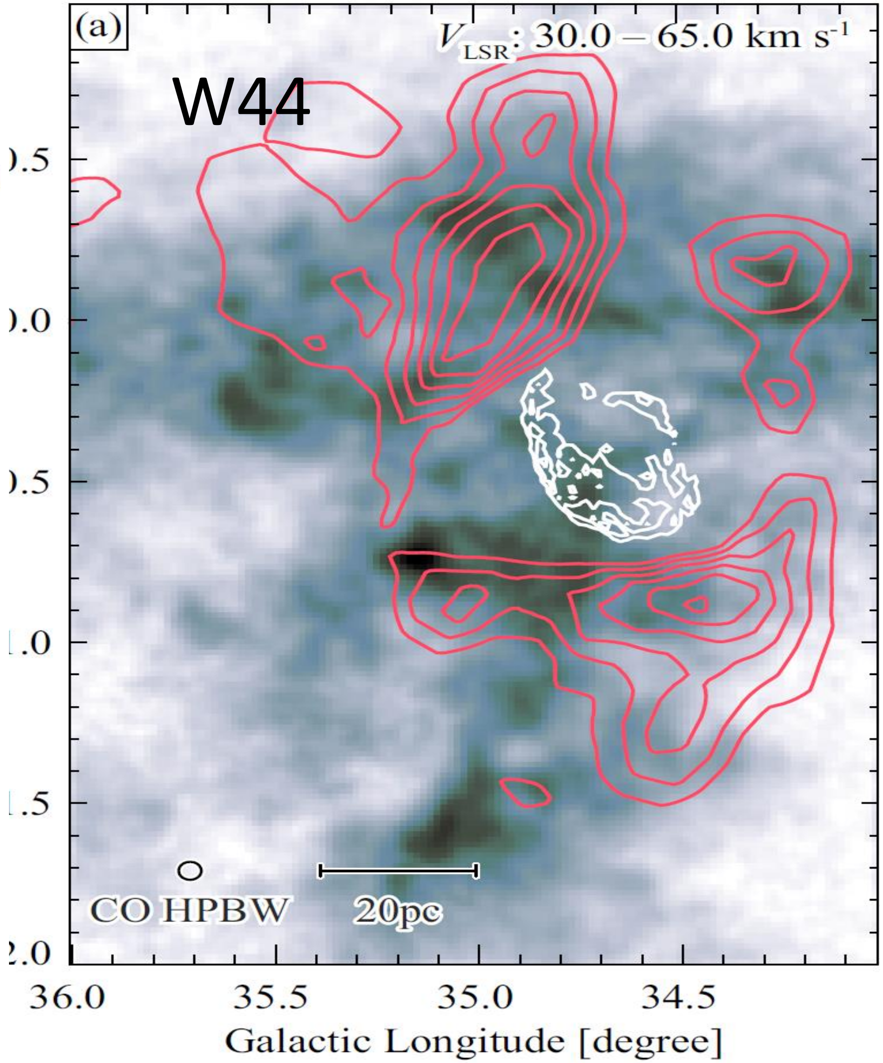


Image VERITAS
Contour CO

Escaping CR
Uchiyama et al. 2012

Summary

- TeV gamma ray SNRs:
  hadonic dominant, target both H2 and HI
- GeV gamma ray SNRs:
  hadronic with target H2

- Target should be directly identified, HI plus CO
  ---for high density, shock-cloud interaction
  B field amplified —
  CR electrons decrease by synchrotron loss
  then, hadronic dominates

- CR energies 10^48-10^49 erg, secure lower limits
- Escaping, low filling factor of target ISM
- SNRs are the most important CR source in the Galaxy

CTA will provide excellent images to demonstrate the correspondence soon