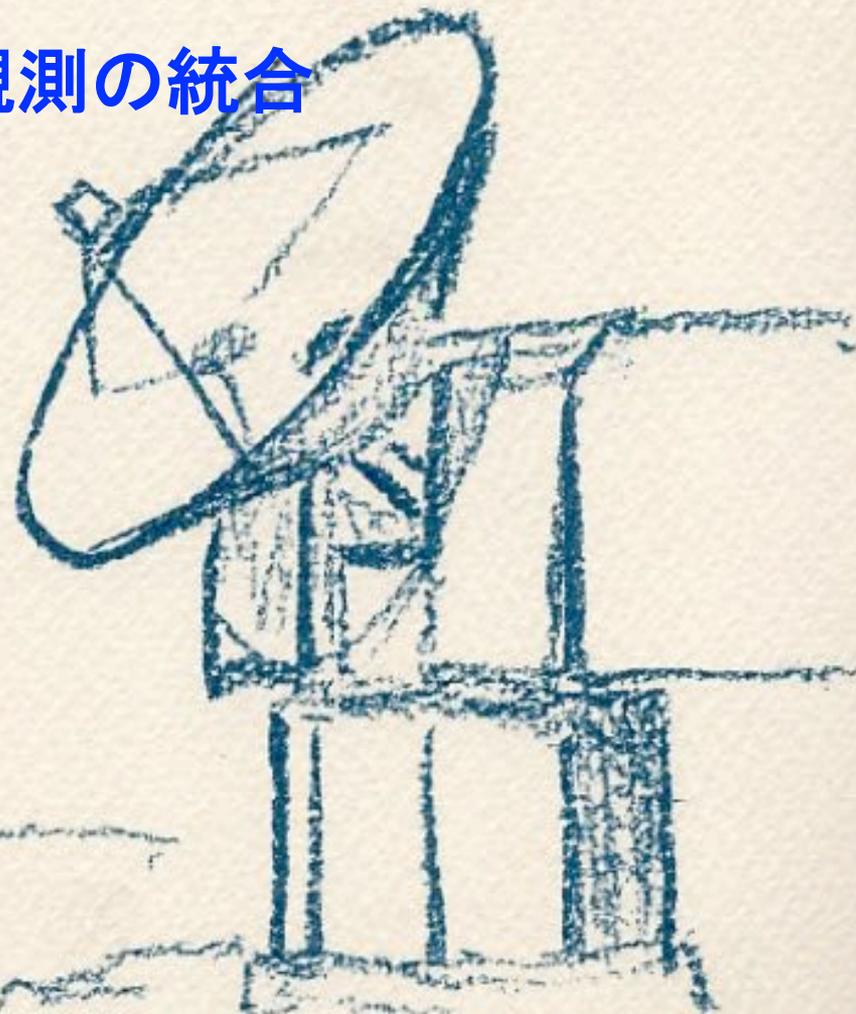


多波長観測で切り拓く高エネルギー天文学

ガンマ線—X線—星間物質観測の統合 による超新星残骸の解明

名古屋大学
福井康雄



CTA企画セッション、日本天文学会秋季年会 甲南大学
2015年 9月9日—11日

Y.F.

ガンマ線起源の解明を目指す CTA ⇒宇宙線の起源の解明に直結

ガンマ線の発生:

ハドロン起源 pp反応、 π 粒子、ガンマ線⇒陽子成分の起源

レプトン起源 逆コンプトン散乱など

超新星残骸が有力な候補 高速の衝撃波面

ガンマ線観測装置:

HESS, MAGIC, VERITAS etc.

CTA: 角度分解能と感度が鍵、飛躍的な向上

「銀河系内・局所群で基本過程を解明し、遠方宇宙にも拡張する」

ガンマ線起源の解明を目指す CTA ⇒宇宙線の起源の解明に直結

星間物質との比較が本質的に重要

理由1 星間陽子は、ハドロン起源ガンマ線発生 of 標的粒子

———星間水素の精密な定量

理由2 衝撃波と星間物質の相互作用が、粒子加速・磁場/乱流増幅に効く

———分解能の高いX線データが重要

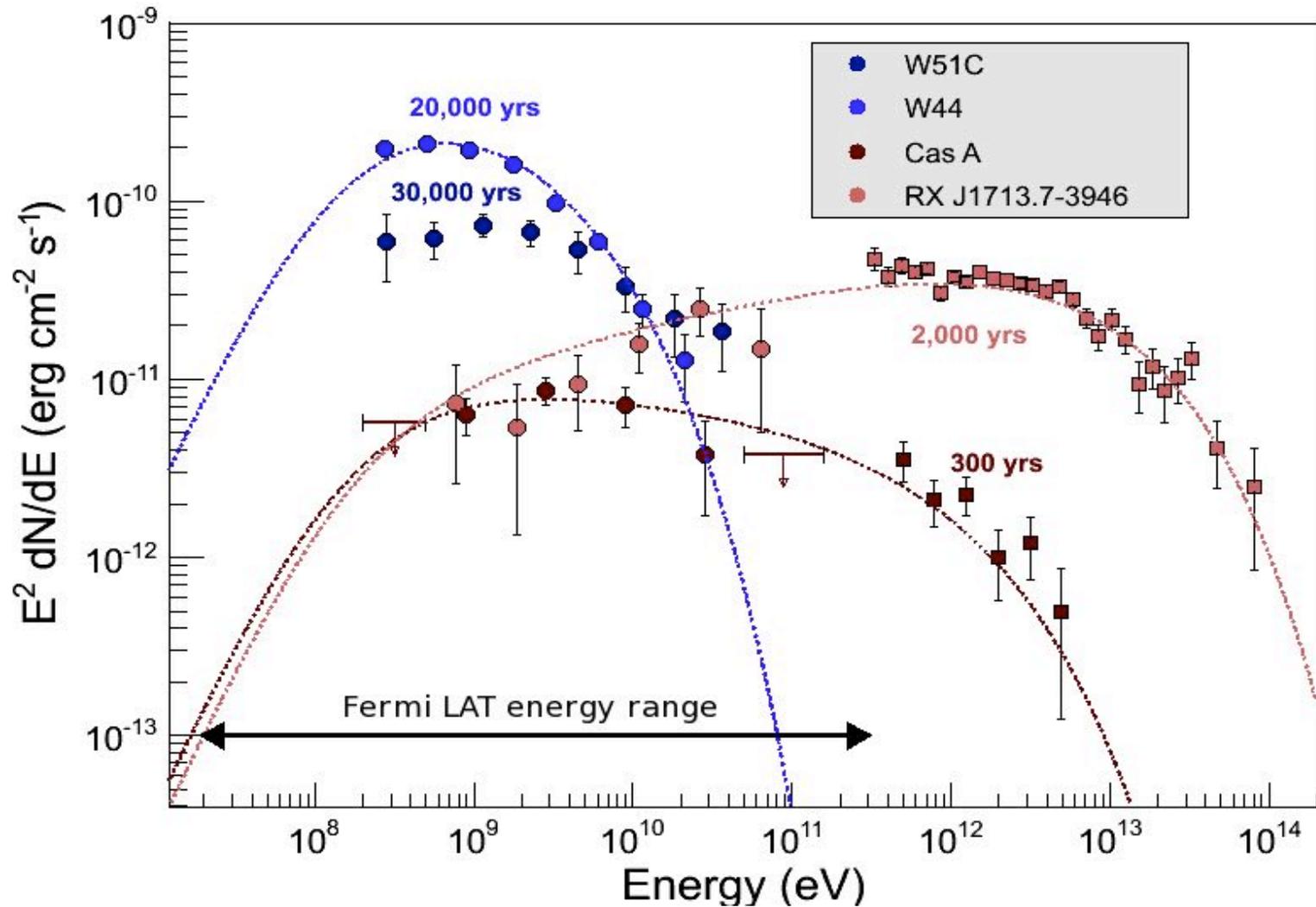
ガンマ線観測装置:

HESS, MAGIC, Veritas etc.

CTA: 角度分解能と感度が鍵、飛躍的な向上

「銀河系内・局所群で基本過程を解明し、遠方宇宙にも拡張する」

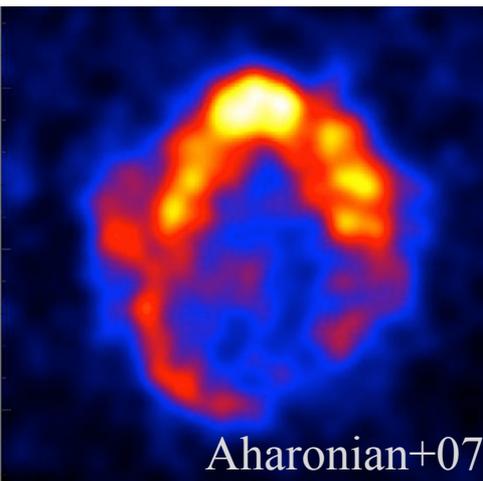
SNRs emitting gamma-rays



Four TeV Gamma-ray SNRs

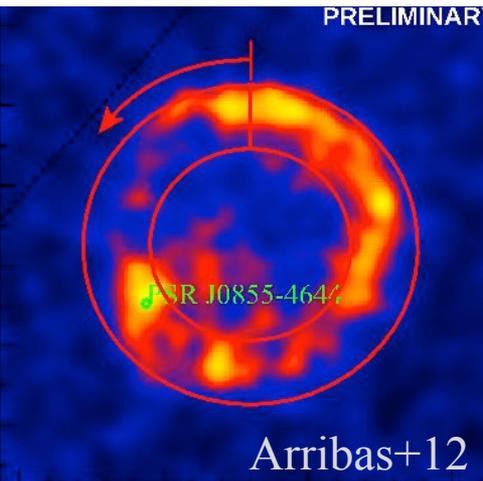
- 4 TeV gamma ray SNRs age 2000yrs
- They are interacting with ISM

RX J1713.7-3946



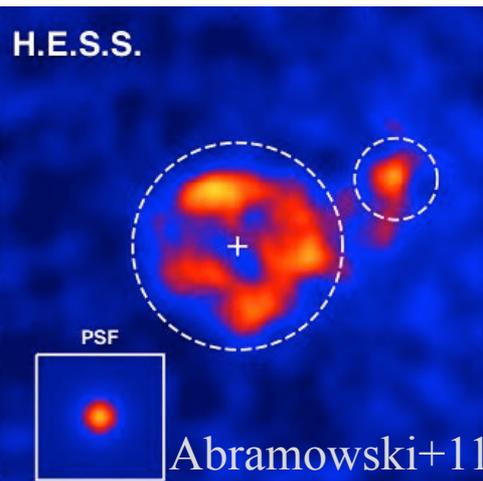
dimater: ~1 deg.
 age: ~1600 yr
 ISM: rich CO + cold H_I
 X-rays: pure synchrotron

RX J0852.0-4622



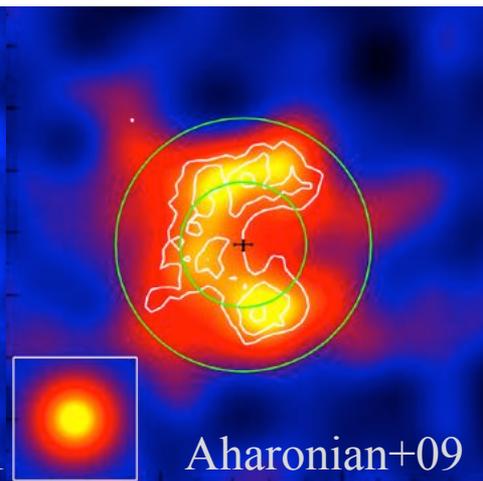
~2 deg.
 ~1700-4300 yr
 rich H_I + little CO
 pure synchrotron ?

HESS J1731-347



~0.5 deg.
 ~3600-7200 yr
 rich CO + H_I cavity
 pure synchrotron

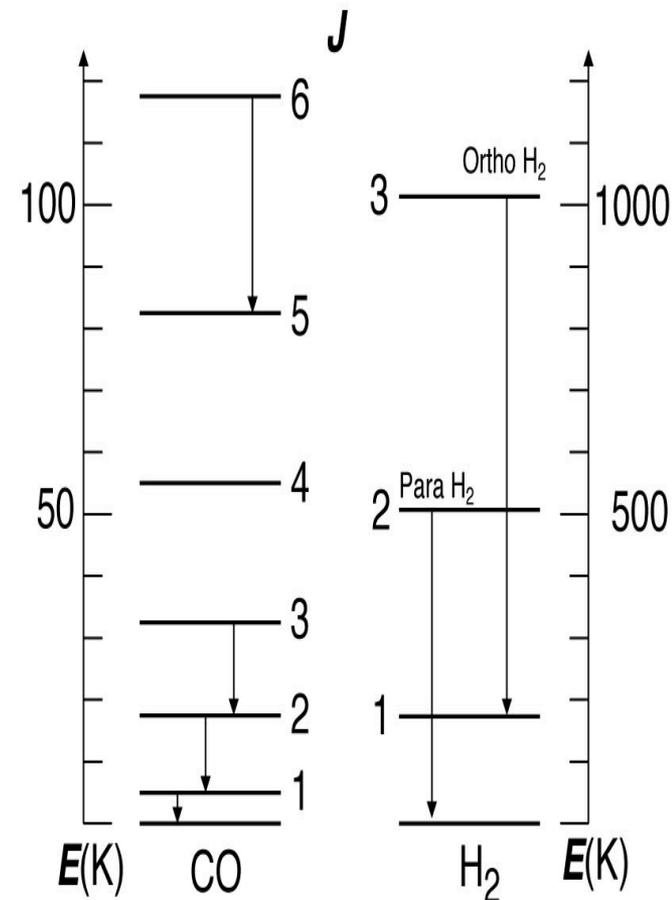
RCW 86



~0.5 deg.
 ~1800 yr
 rich H_I + little CO
 thermal + non-thermal

CO transitions to probe molecular hydrogen

- Hydrogen molecules are not observable in radio. Too high energy levels. Only in absorption.
- 2.6mm Carbon monoxide CO emission is observed in rotational transitions.
NANTEN2, Mopra, ASTE
- ^{12}CO vs. ^{13}CO :
 ^{12}CO is important to trace all molecular gas.
- In addition, HI 21cm emission to probe atomic hydrogen
GASKAP, SKA



NANTEN & NANTEN2

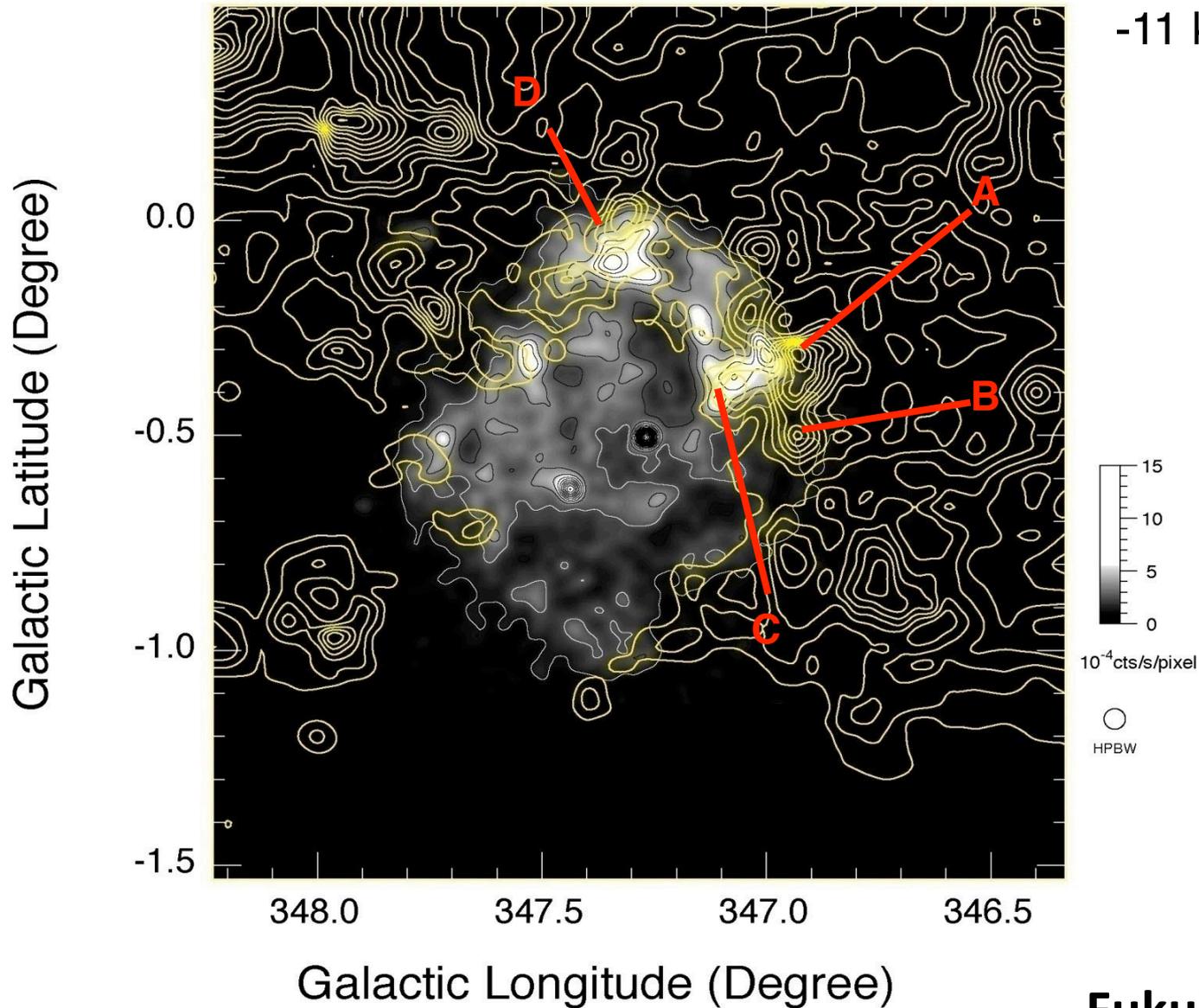


@Las Campanas, alt.2400m



@Atacama, alt.4800m

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



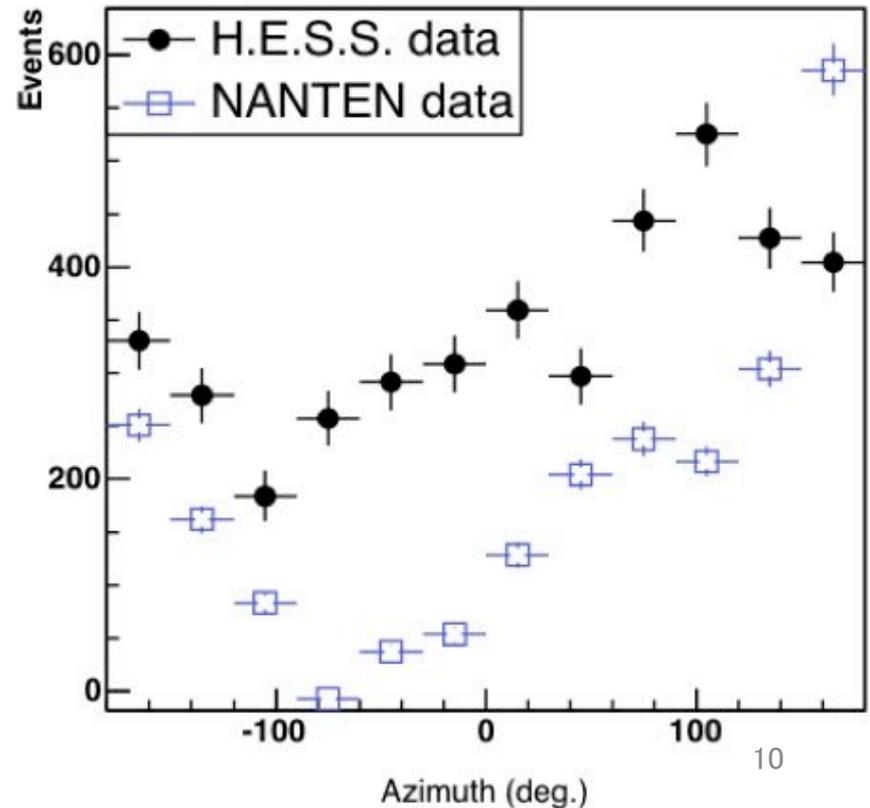
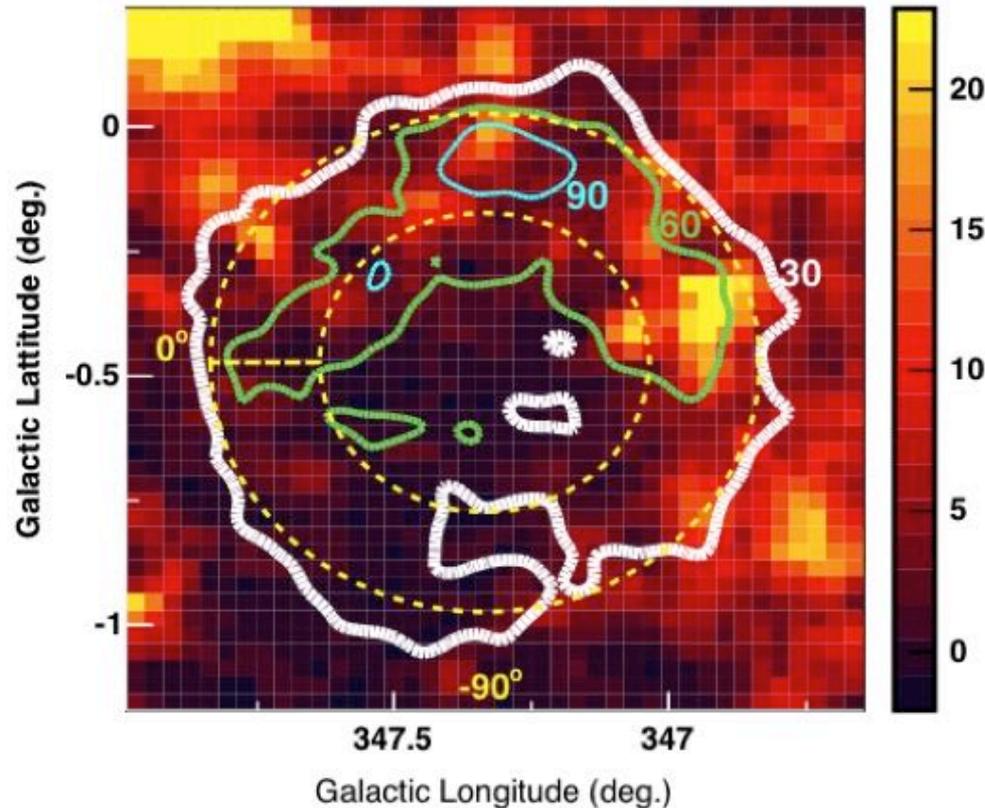
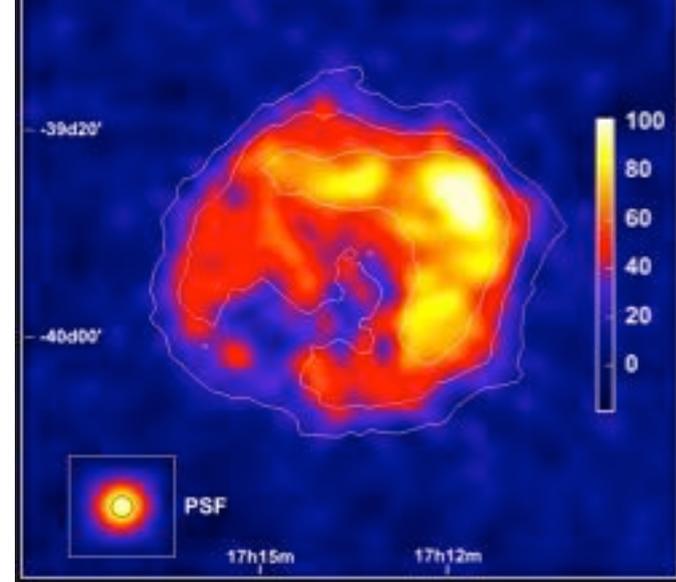
$-11 \text{ km/s} < V_{\text{LSR}} < -3 \text{ km/s}$

Fukui et al. 2003

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

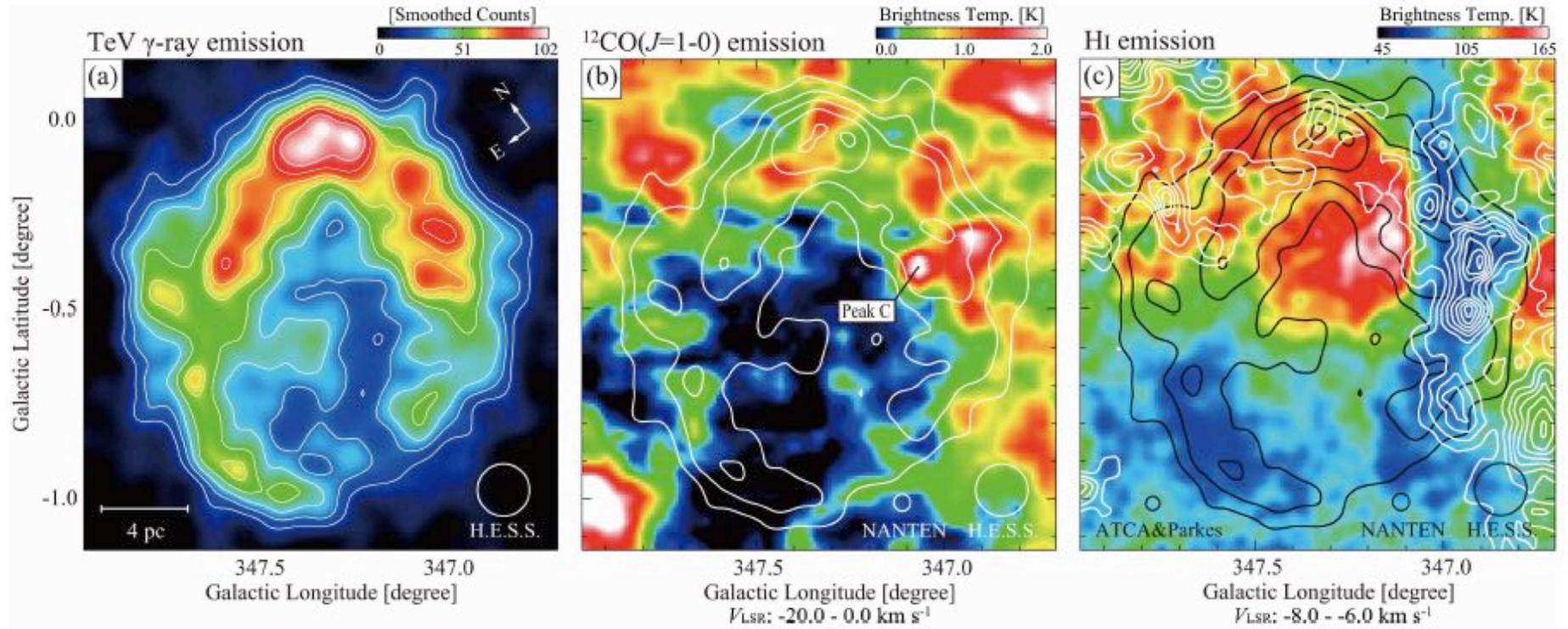
- Shell-like structure: similar with X-rays
- No significant variation of spectrum index across the regions
- spatial correlation with surrounding molecular gas

Aharonian et al. 2005



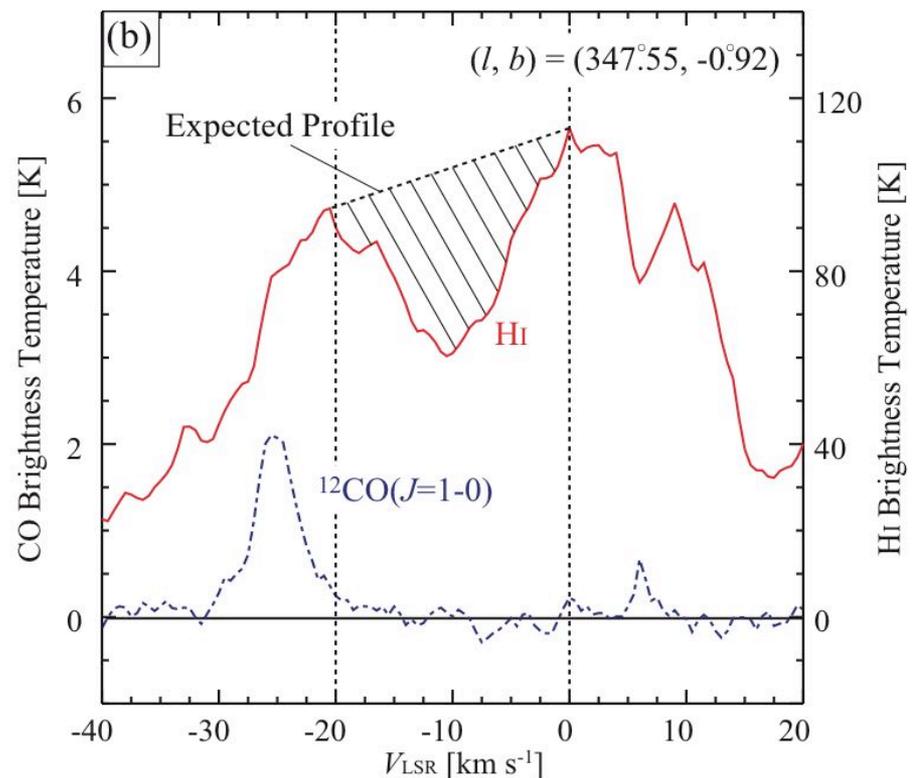
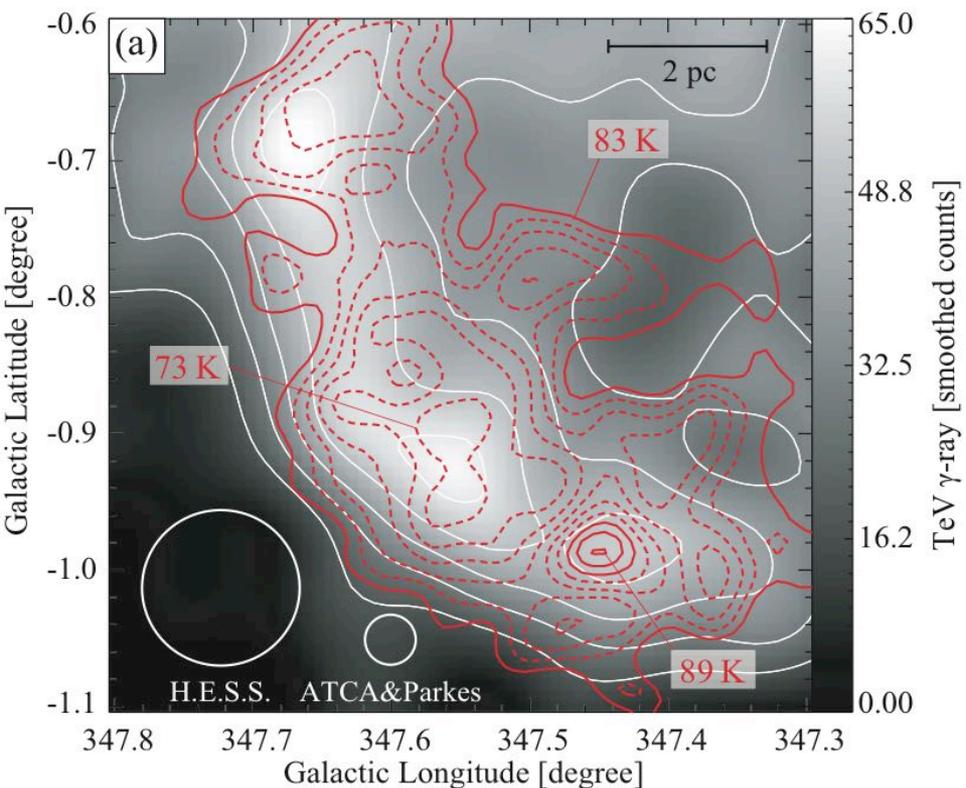
RX J1713.7-3946

3



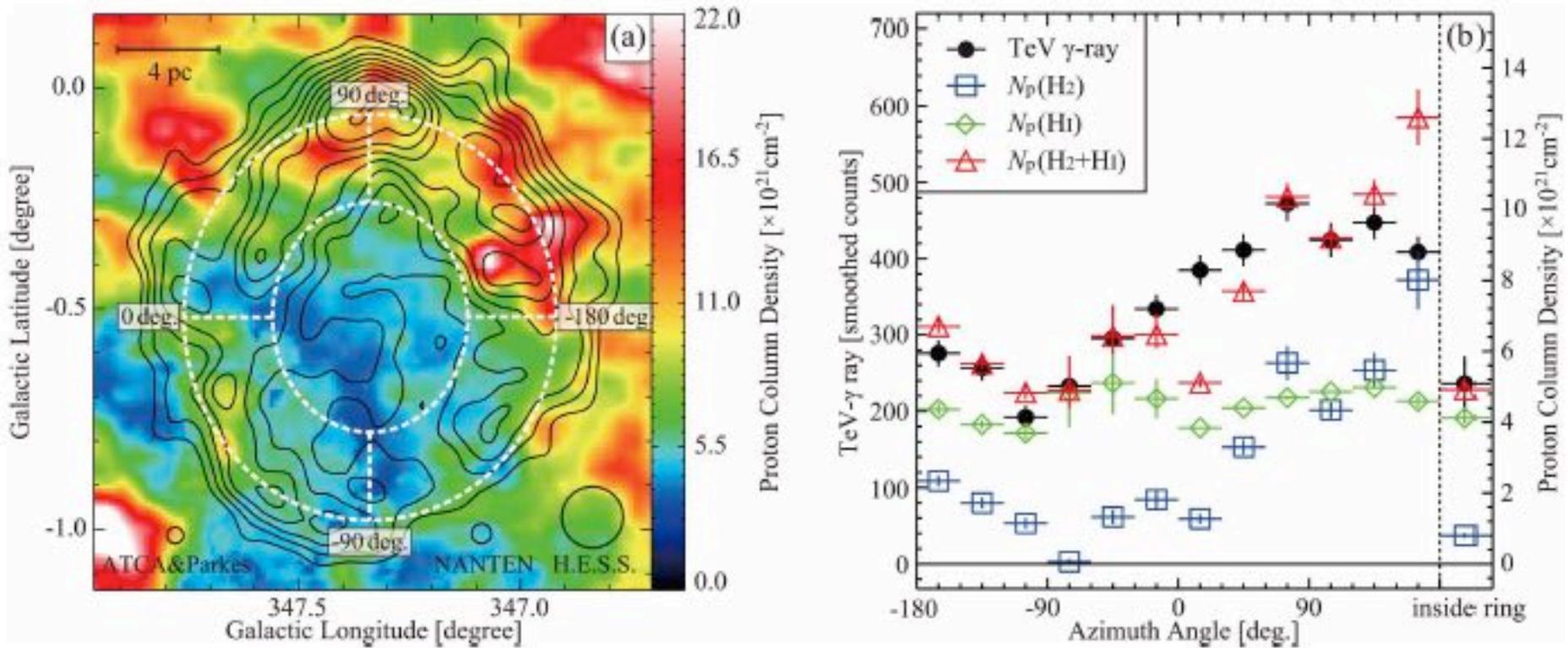
Fukui et al. 2012, ApJ, 746, 82

Dark HI SE Cloud (Self-Absorption)



ISM protons in RX J1713.7-3946

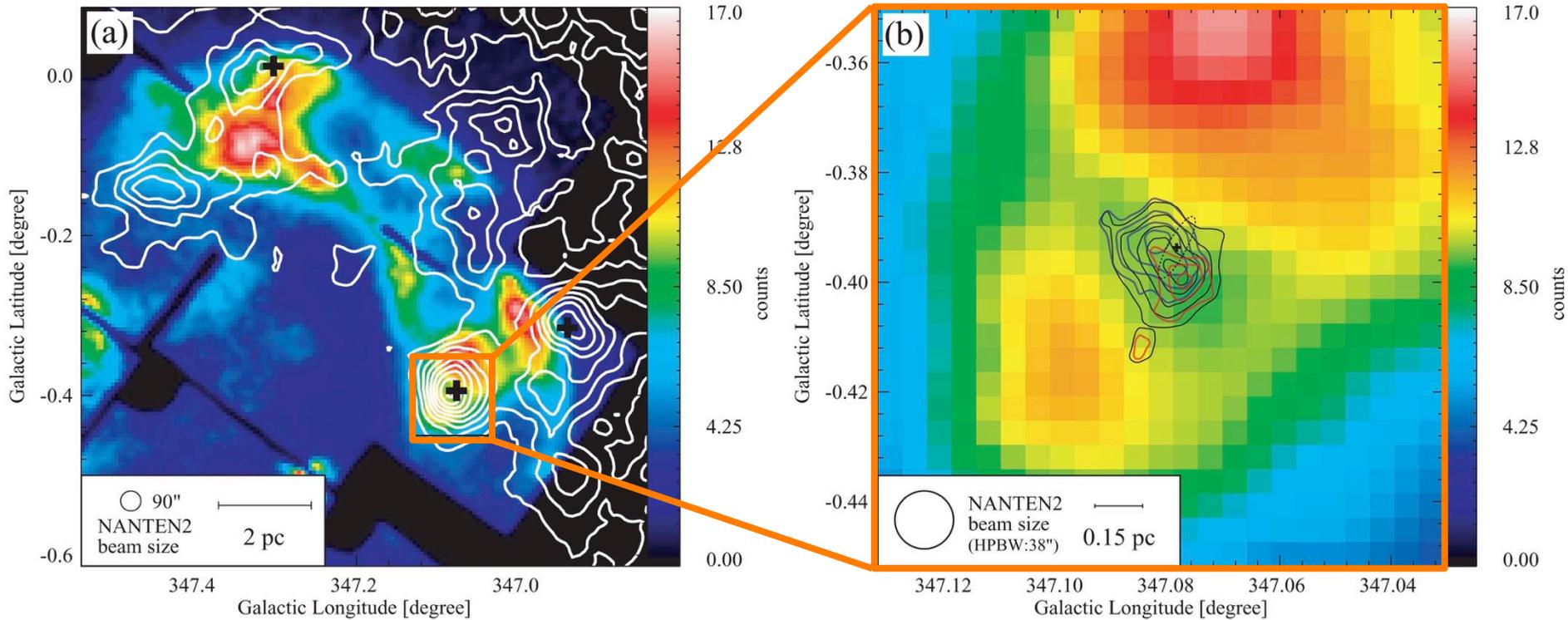
Support hadronic scenario



HI + 2H₂

Fukui et al. 2012

Shock propagation into dense gas



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

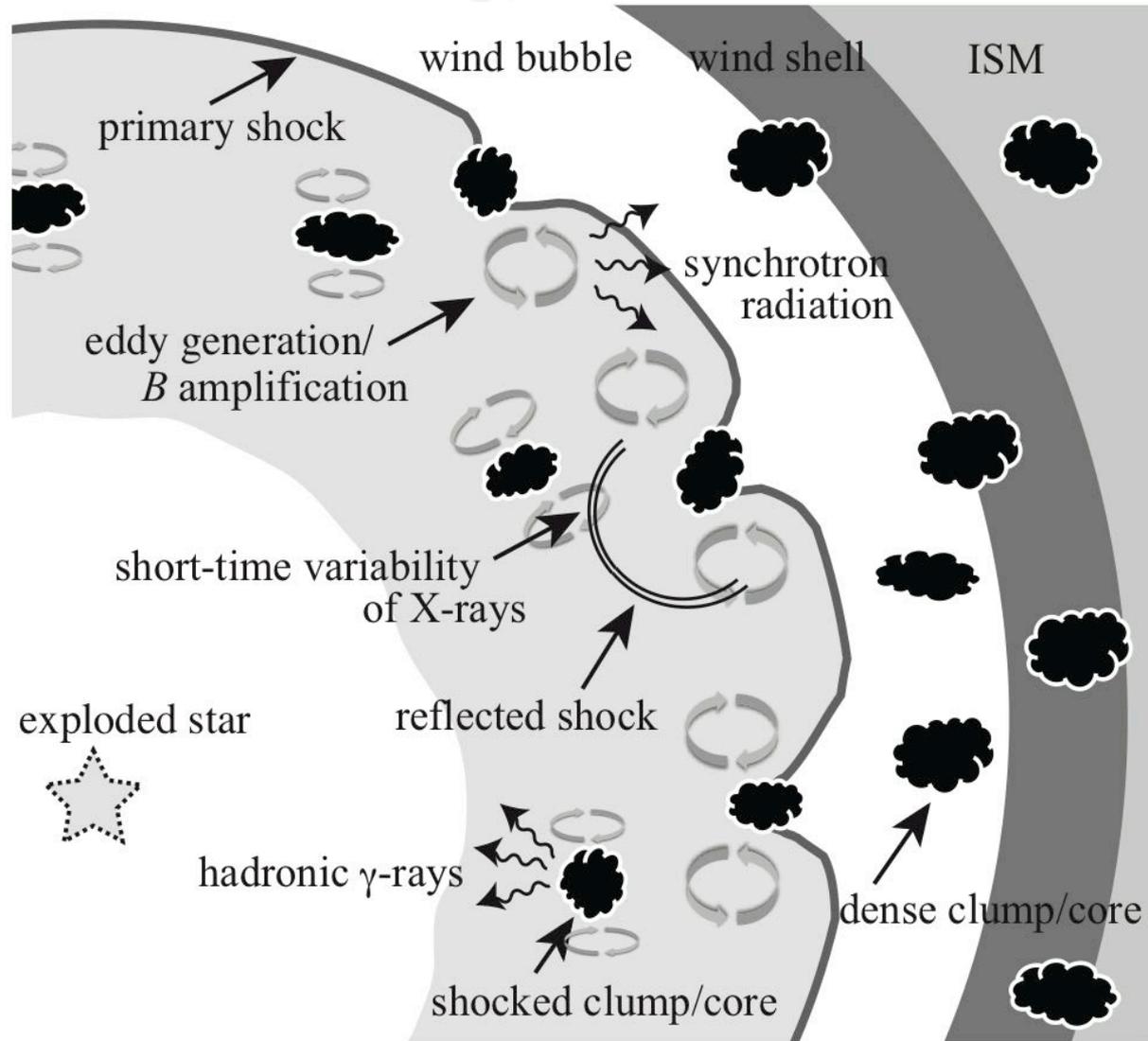
n : density of clump

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

10^4 cm^{-3} , $t \sim 1000 \text{ yrs}$

Penetrating Depth = 0.03 pc

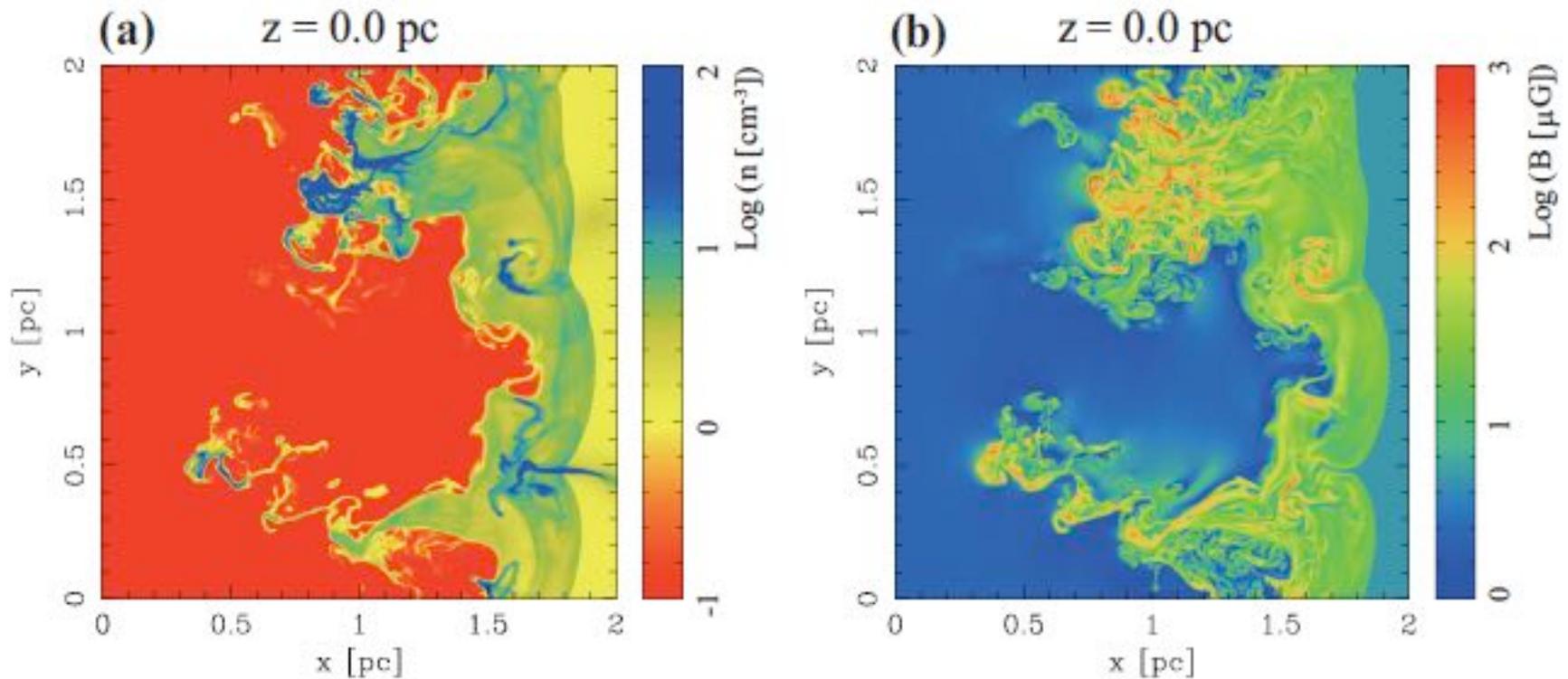
Sano et al. 2010



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

MHD simulations of shock-cloud interaction

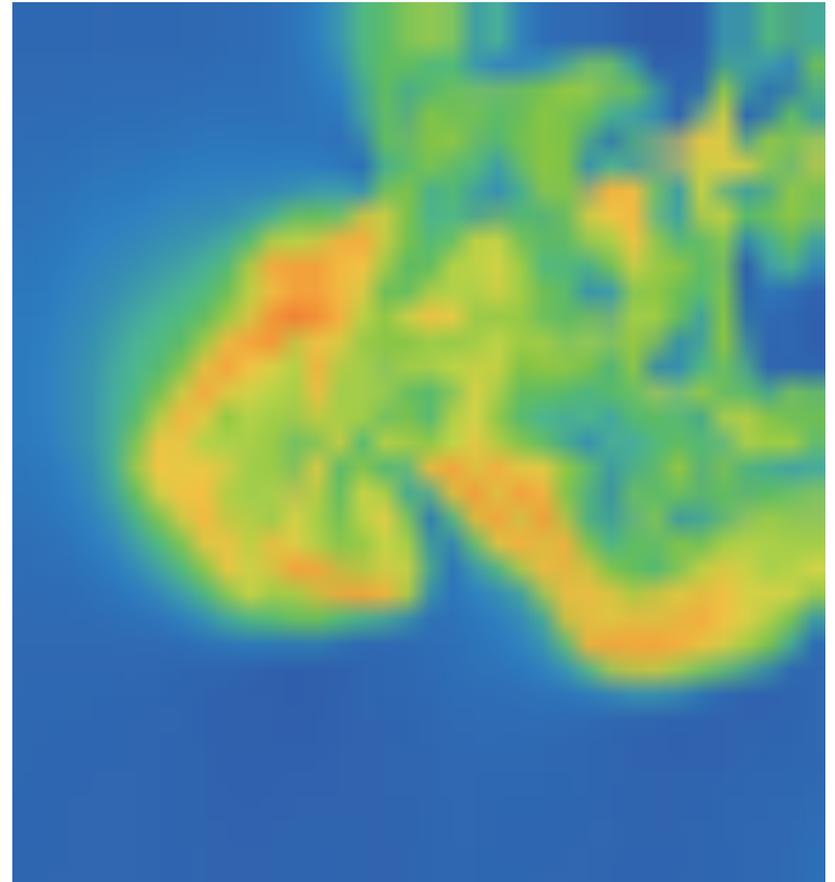
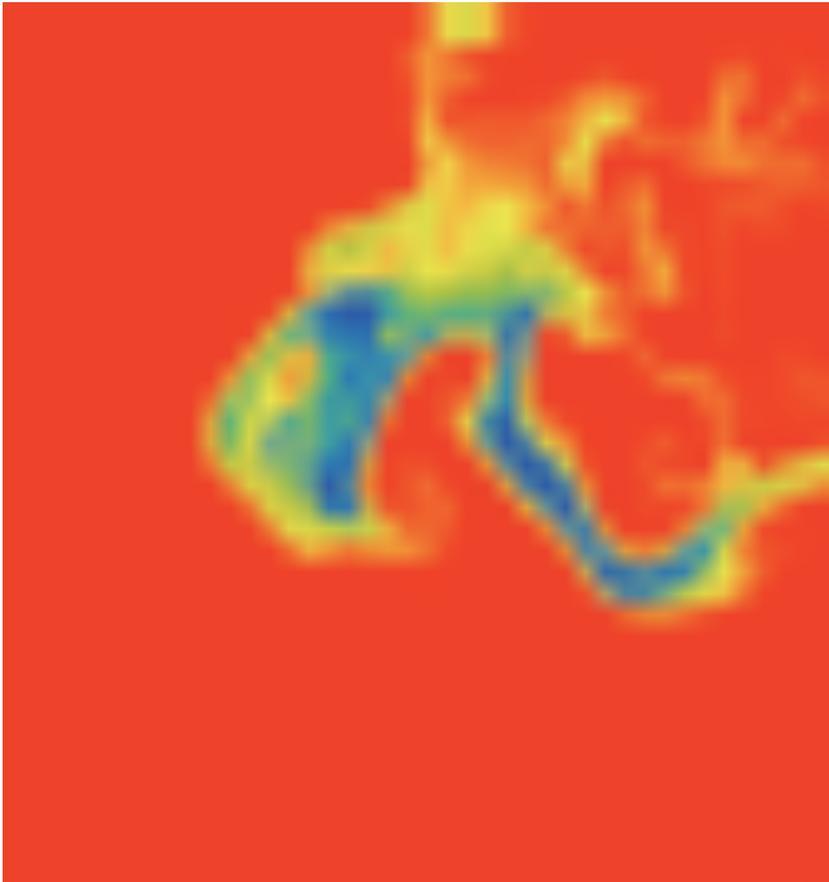
density vs. magnetic field



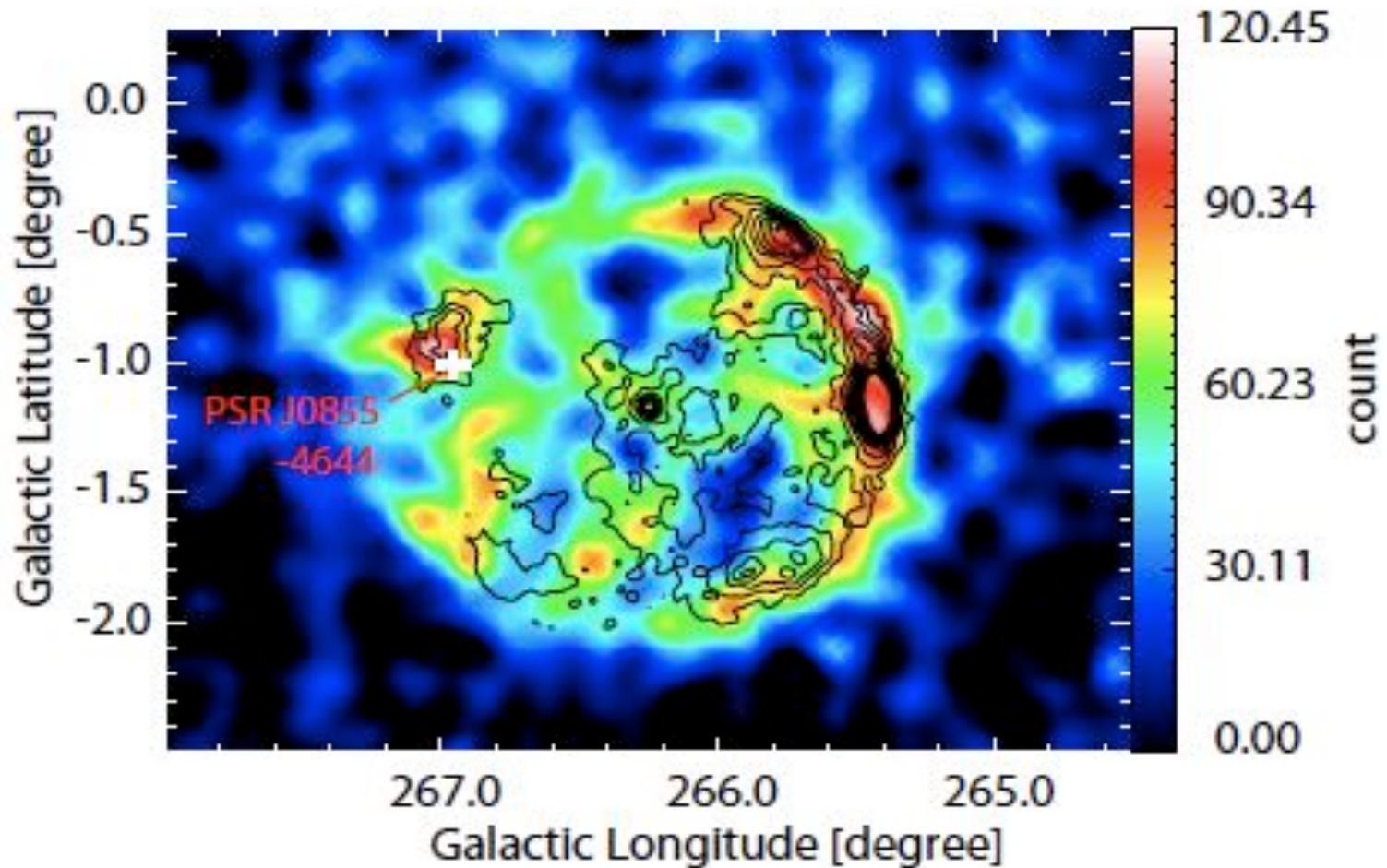
Inoue+ 2010

density vs. magnetic field

[sub-pc scale]



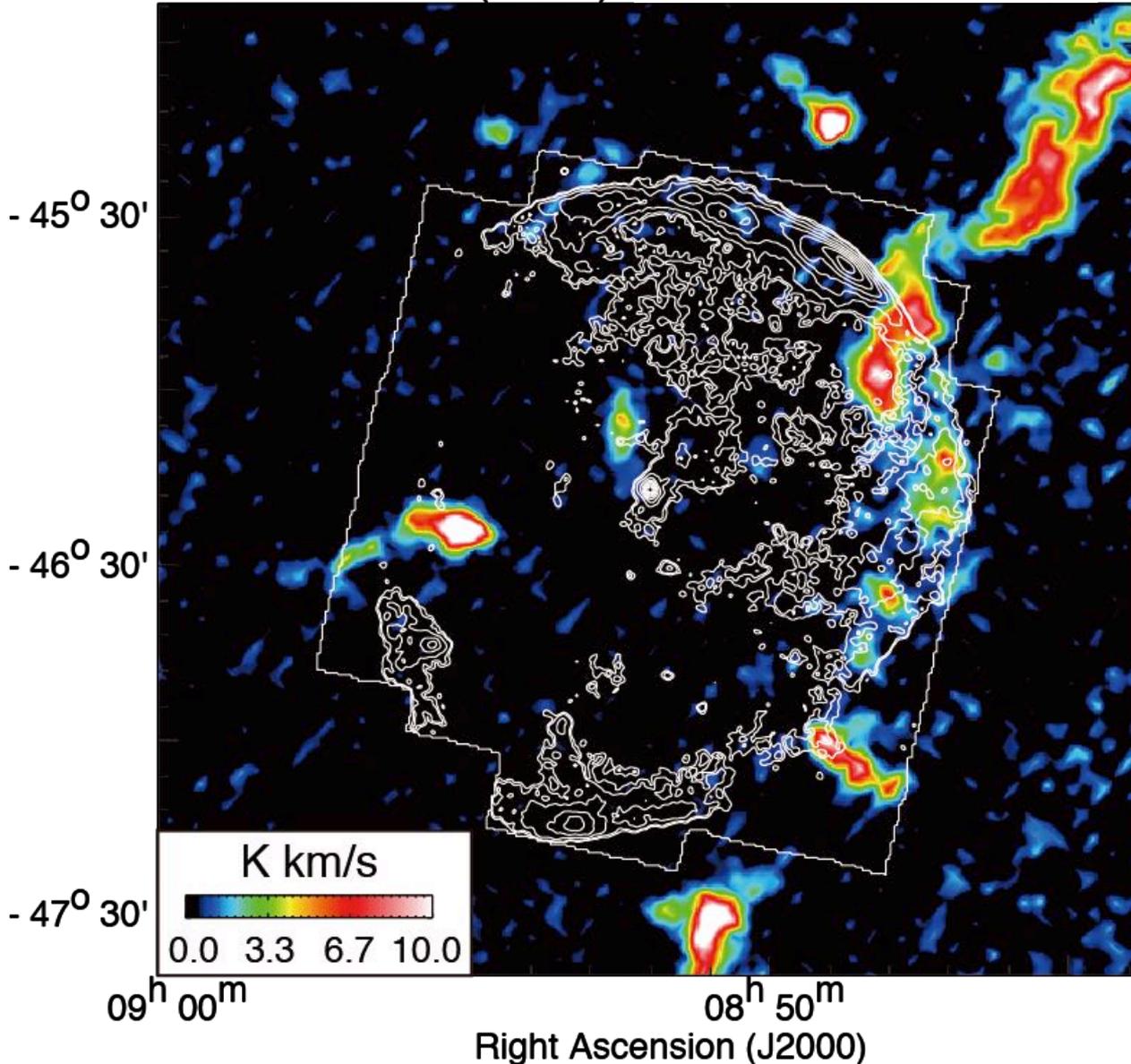
TeV gamma-ray SNR RX J0852.0-4622



Color TeV gamma rays contour X rays

RX J0852: CO distribution (interact with the SNR)

NANTEN2 12CO($J=1-0$)



■ CO vs. X-rays

good spatial correspondence between the CO and X-rays

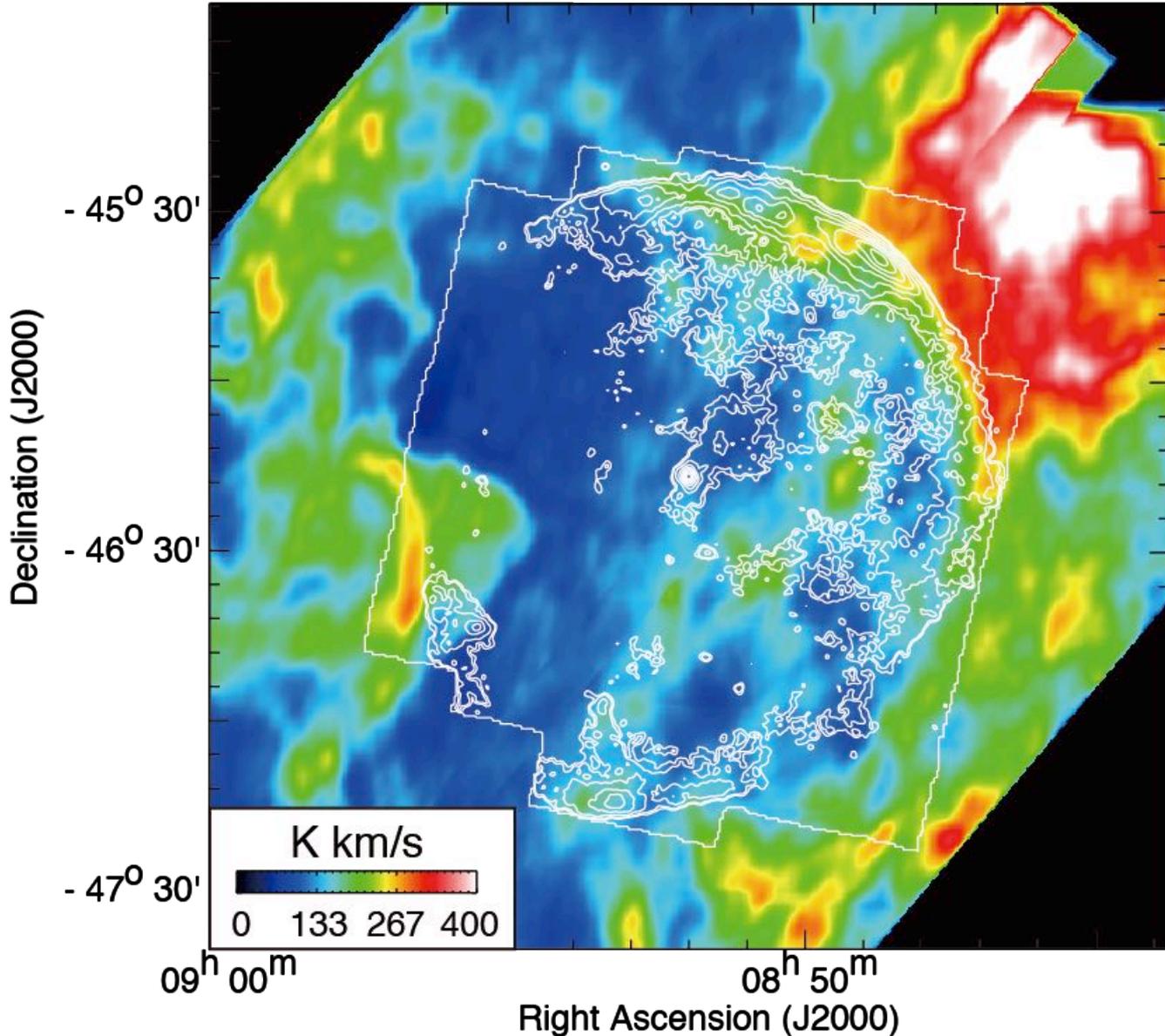


Interacting with the SNR

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

RX J0852: HI distribution (interact with the SNR)

ATCA & Parkes HI



■ HI vs. X-rays

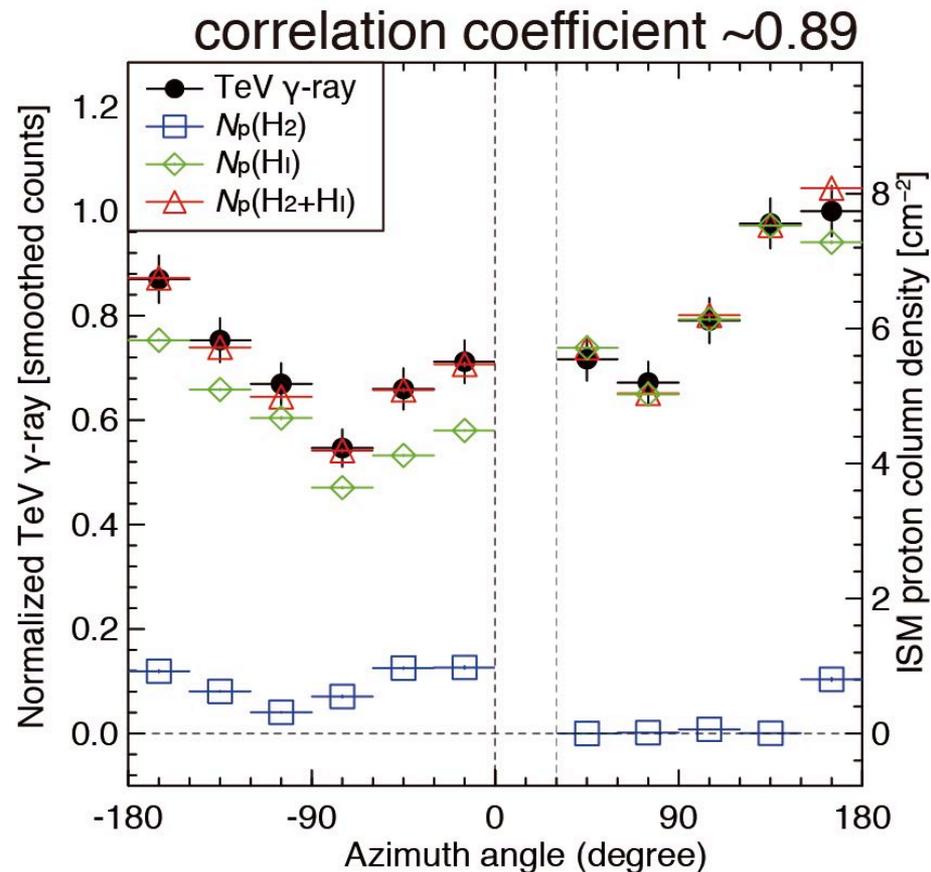
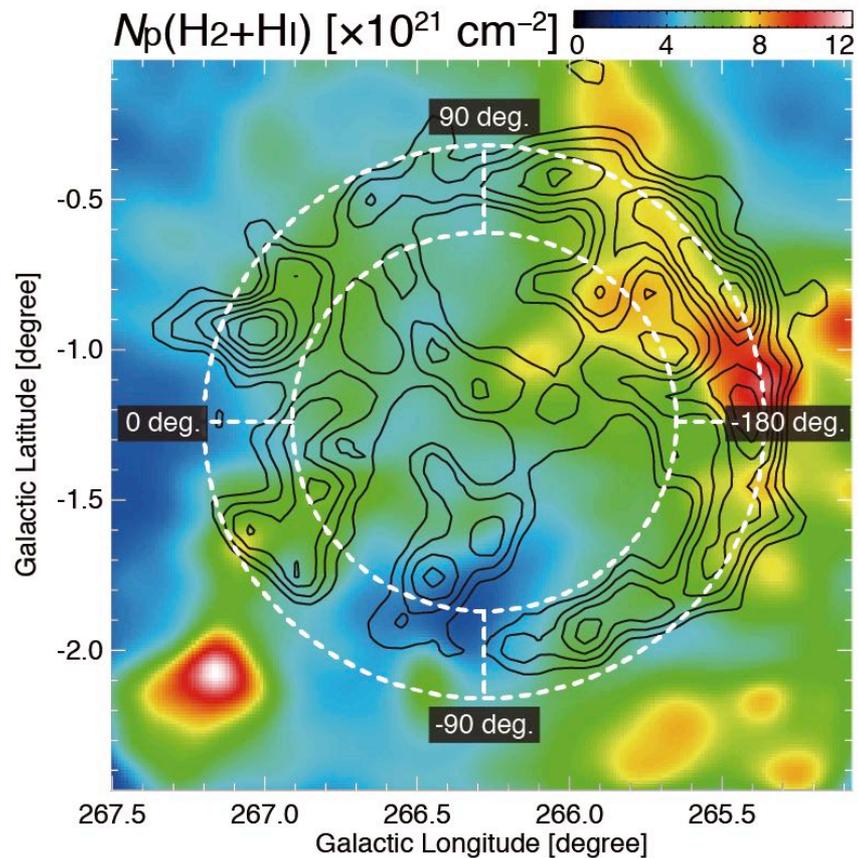
HI wind bubble at
same velocity in CO



ISM cavity created
by the progenitor

Image: HI I. I.
(V_{lsr} : 28-34 km/s)
contours: X-ray (1-5 keV)

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

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) ($10^{34} \text{ erg s}^{-1}$)	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%

RXJ0852

Fermi LAT

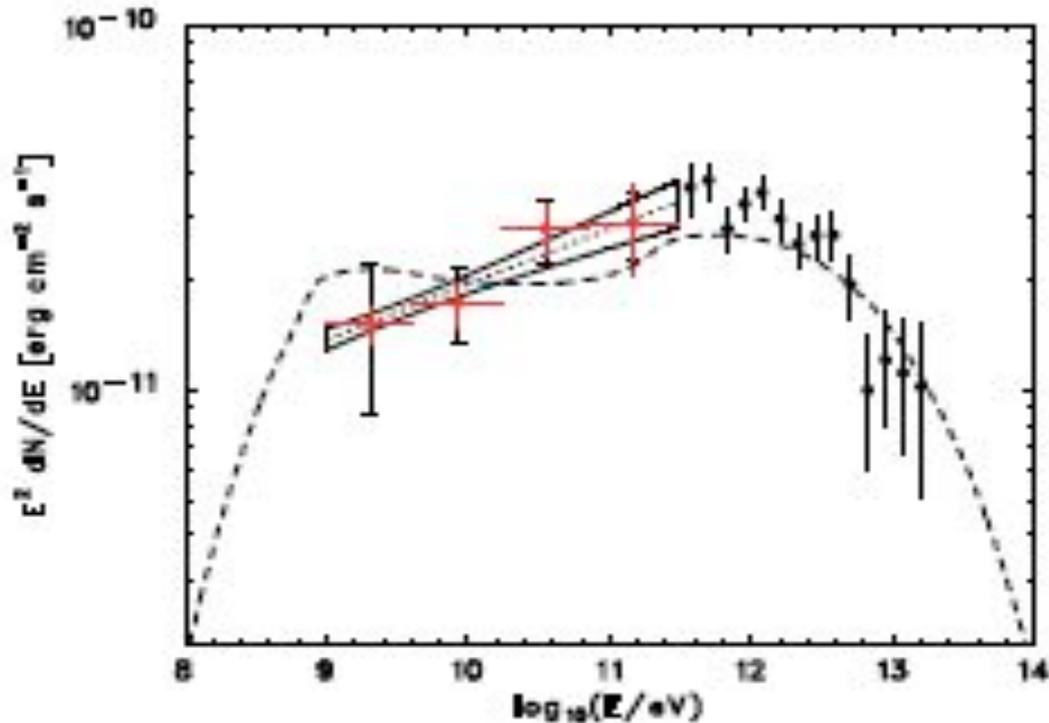
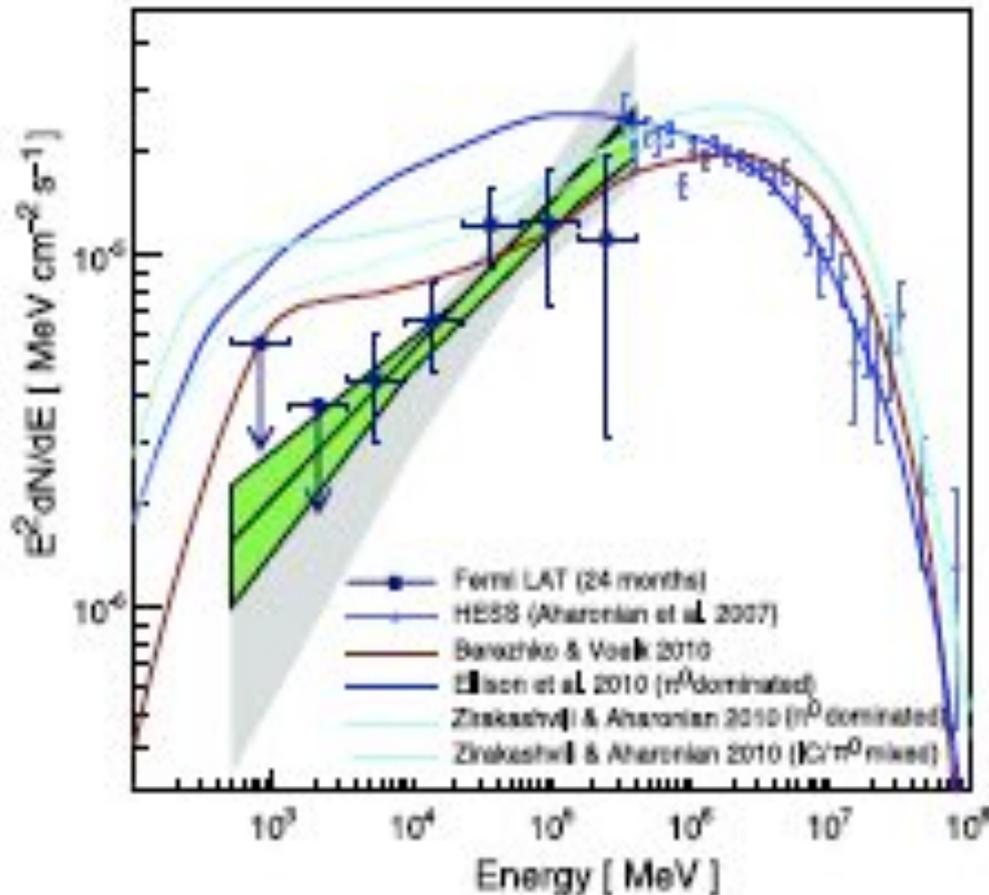


Figure 2. *Fermi* LAT spectral energy distribution (SED) in 1–300 GeV with the H.E.S.S. SED by Aharonian et al. (2007b) plotted together. For the *Fermi* LAT points, the vertical red lines and the black caps represent statistical and systematic errors, respectively. The dotted line indicates the best-fit power law obtained from the maximum likelihood fit for the entire 1–300 GeV band. The butterfly shape shows the 68% confidence region. The dashed curve is the π^0 -decay spectrum by Berezhko et al. (2009).

Gamma-ray spectrum of RXJ1713

Abdo et al. 2011



The hard spectrum is not unique to the leptonic scenario

The hard spectrum is explained by energy dependent penetration of CR protons into dense molecular gas.

Hadronic γ -ray spectrum for dense cloud cores

Gabici 2007, Zirakasivili Aharonian 2010,
Inoue, Inutsuka, Yamazaki, Fukui 2012

- accelerated particles in the cavity diffuse into clouds and pions are created

- diffusion length: $\kappa_{\text{dif}} = 4 \eta l_{g,p} c/3\pi$ (Skilling 1975)

$$\begin{aligned} l_{\text{dif}} &\simeq (\kappa_{\text{dif}} t)^{1/2} \\ &= 0.1 \eta^{1/2} \left(\frac{E}{10 \text{ TeV}} \right)^{1/2} \left(\frac{B}{100 \mu\text{G}} \right)^{-1/2} \left(\frac{t_{\text{age}}}{10^3 \text{ yr}} \right)^{1/2} \text{ pc} \end{aligned}$$

- mass of the cloud penetrated by CR particles (\propto number of gamma rays)

Dense cloud cores [$\rho \propto r^{-2}$]

$$M = \int_{R-l_{\text{dif}}}^R 4\pi r^2 \rho_0 r^{-2} dr = 4\pi \rho_0 l_{\text{dif}}$$

- Photon spectrum: $N(E) \propto M(E) E^{-p} \propto E^{1/2-p} = E^{-1.5}$ for $p = 2$

→ The same with the leptonic spectrum by IC

→ Hadronic scenario is consistent with the Fermi spectrum

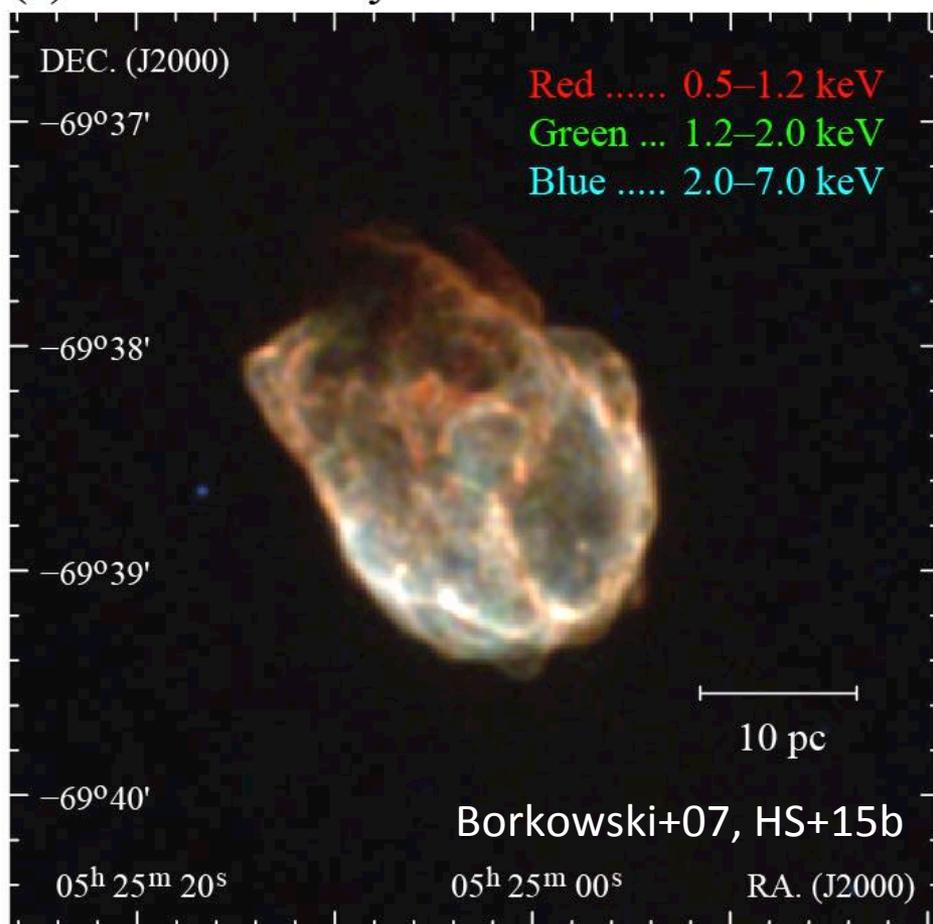
Magellanic SNR N132D

大マゼラン雲 ($d \sim 50$ kpc) にある、若い重力崩壊型 SNR (~ 3150 yr)

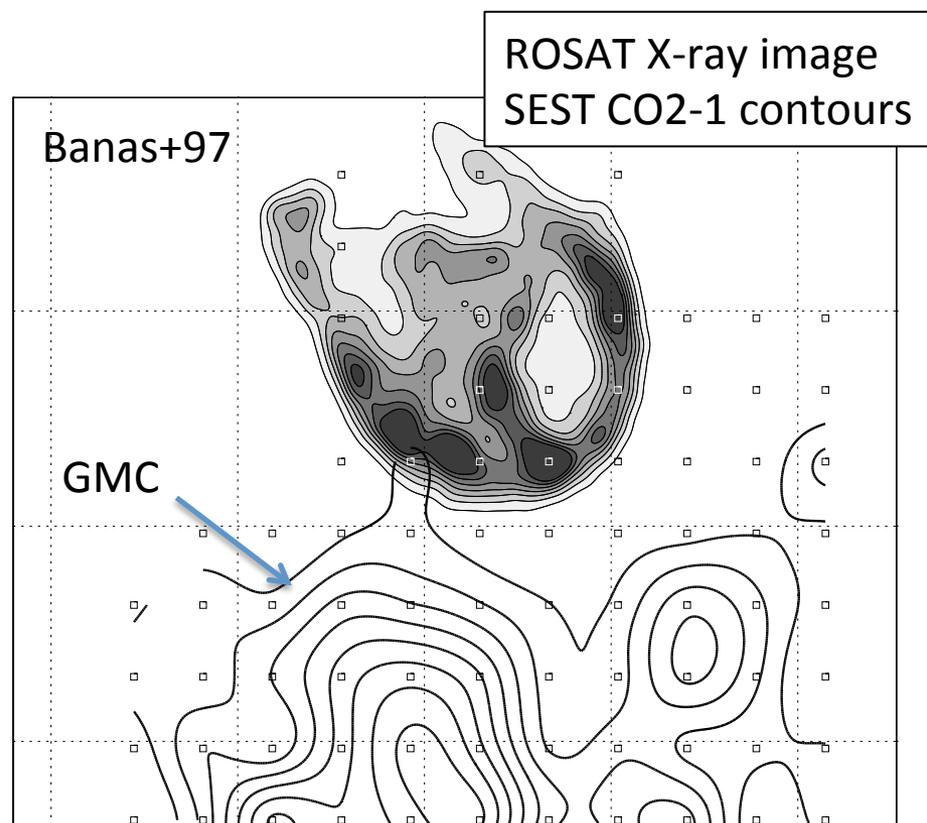
【特徴】 X線で明るい、TeV ガンマ線検出、GMC との相互作用？

(e.g., Morse+95, Banas+97, Borkowski+07, H.E.S.S. Col.+15)

(a) *Chandra* X-rays

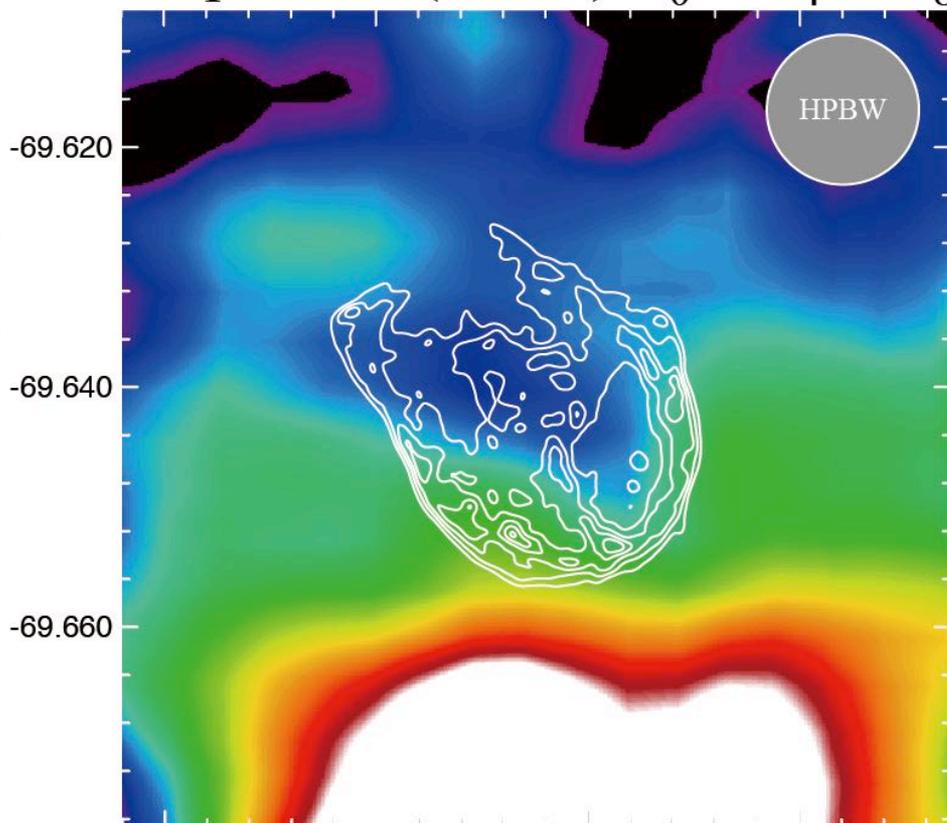


衝撃波相互作用と宇宙線研究 ◎



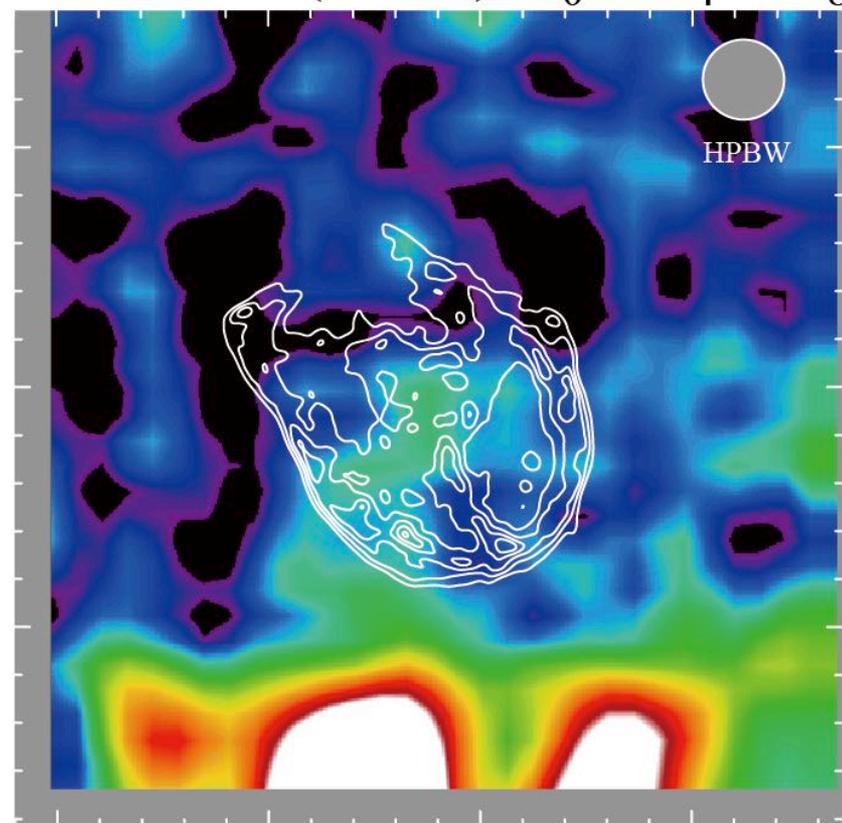
観測結果 (CO & HI の空間分布)

Mopra $^{12}\text{CO}(J=1-0)$ 0 4 8



Right Ascension (J2000) [degree]
Declination (J2000) [degree]
Vlsr: 254.9 - 267.6 km/s

ASTE $^{12}\text{CO}(J=3-2)$ 0 4 80

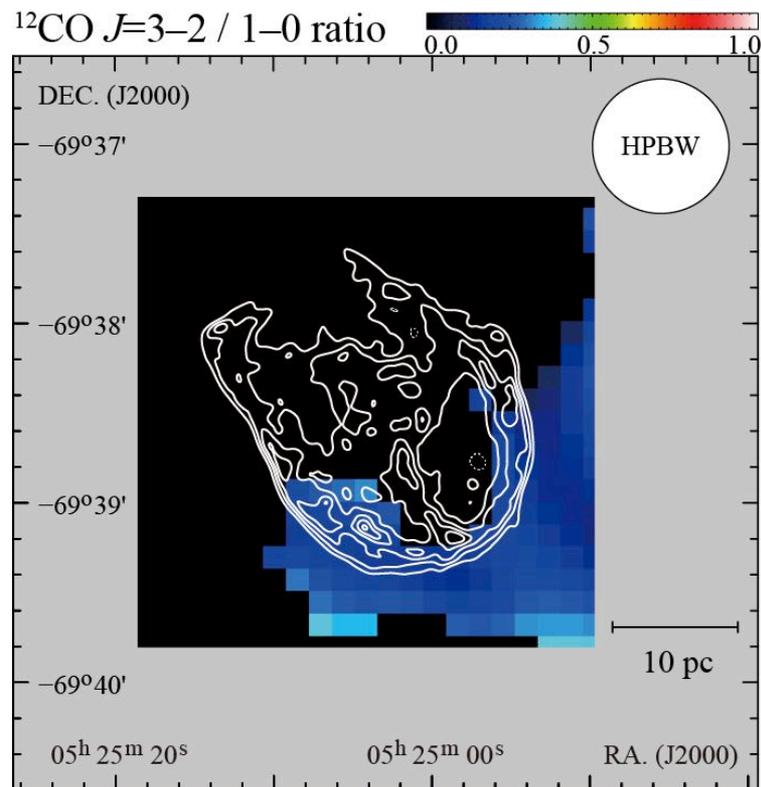
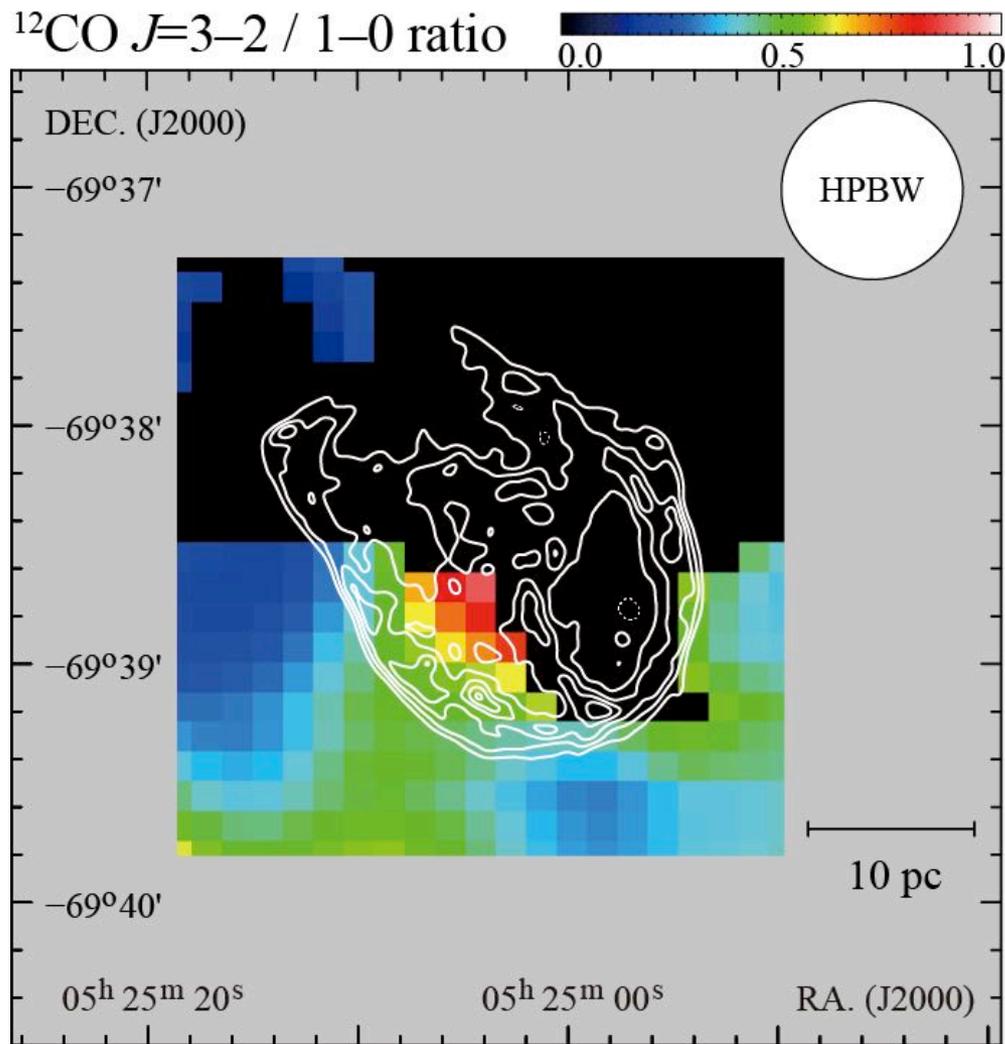


Right Ascension (J2000) [degree]
Declination (J2000) [degree]
Vlsr: 254.9 - 267.6 km/s

コントア: *Chandra* X線 (0.5-7.0 keV)

- 南側でX線シェルと一致。特に、南東側で CO 1-0, 3-2 共に強い
質量 $\sim 10,000 M_{\odot}$ (分子雲)、 $> 6,000 M_{\odot}$ (原子ガス)

CO 3-2/1-0 強度比



↑ 相互作用していない分子雲の例

← 相互作用している分子雲 (256-266 km/s)

コントア: *Chandra* X線 (0.5-7.0 keV)

■ SNR 南東側で、有意な比の上昇を確認 (> 0.8)

➡ HS+15bで特定した分子雲は、確かに相互作用+衝撃波加熱

議論2: 宇宙線陽子のエネルギー

- H.E.S.S. によって、N132D から TeV ガンマ線検出 (HESS Col.+15)
 - ➔ 数 TeV 以上の宇宙線陽子 and/or 電子起源
 - TeVガンマ線 と ISM 分布の一致 ➔ 陽子起源ガンマ線 (不可)
 - 宇宙線陽子の全エネルギー W_{pp} 推定 (可能)

(H.E.S.S. Collaboration+15)

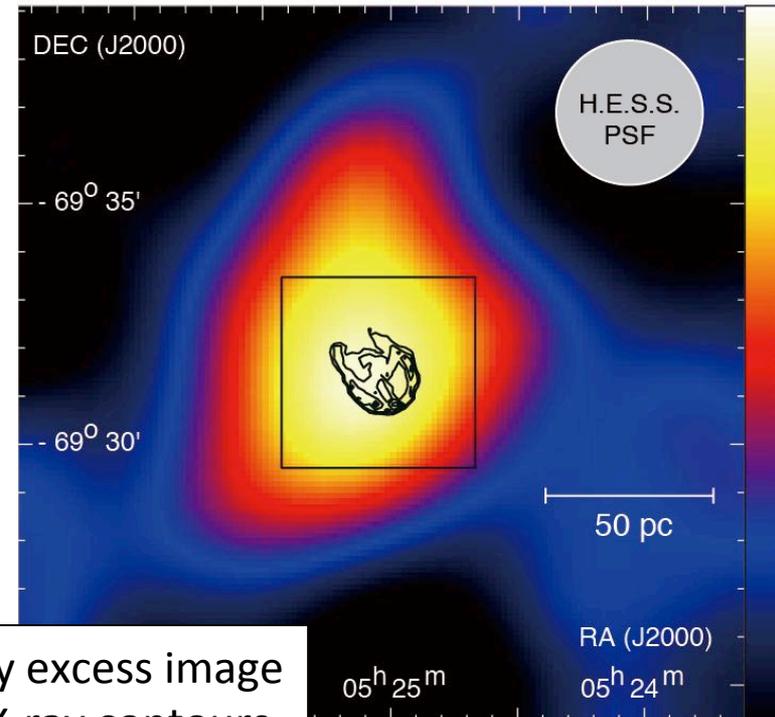
$$W_{pp} = 10^{52} \left(n_H / 1 \text{ cm}^{-3} \right)^{-1} \left(d / 50 \text{ kpc} \right)^{-2}$$

↑
星間ガス密度

↑
SNRまでの距離

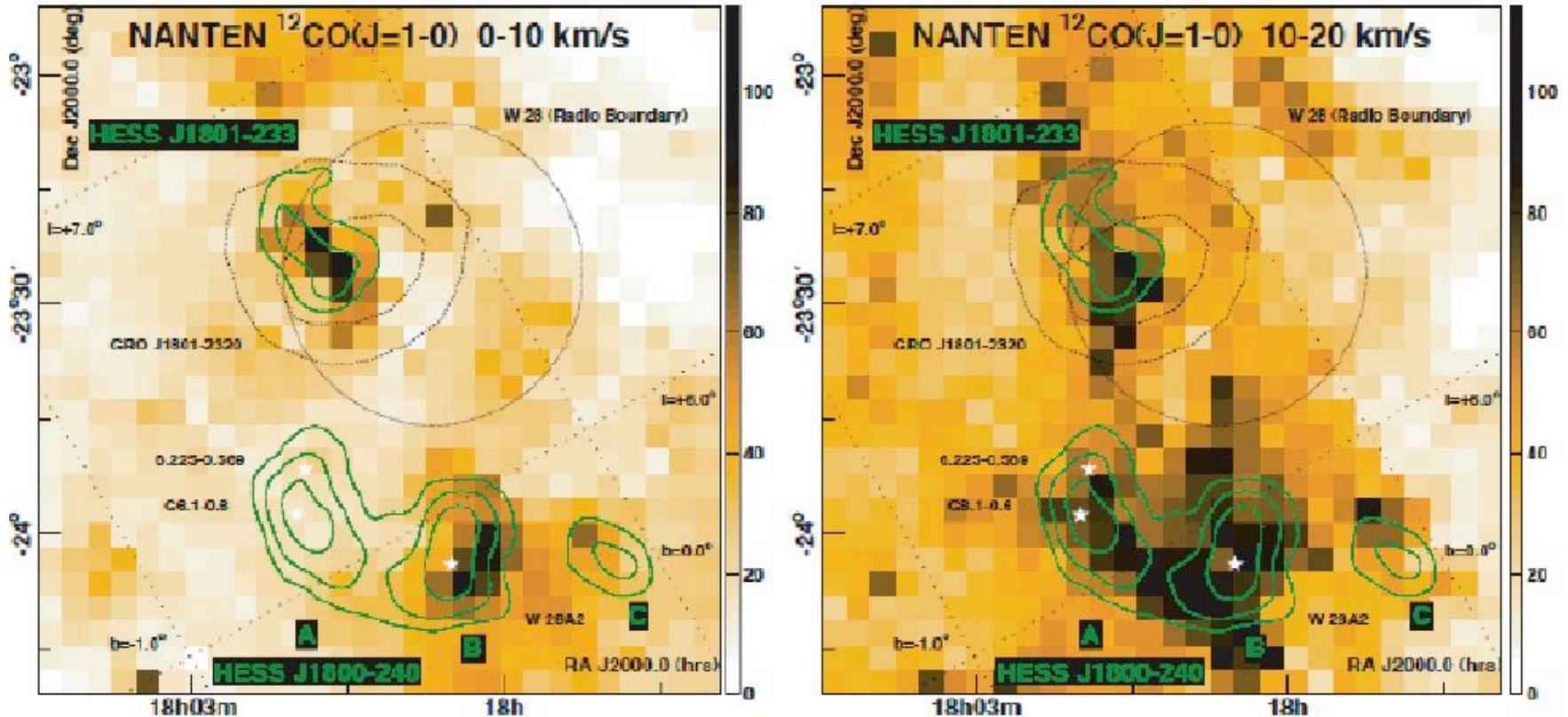
$d = 50 \text{ kpc}$, 星間ガス密度 $n_H \sim 90 \text{ cm}^{-3}$

$$W_{pp} \sim 1 \times 10^{50} \text{ erg}$$



HESS γ -ray excess image
Chandra X-ray contours

TeV γ vs. CO(J=1-0)



Left: NANTEN $^{12}\text{CO}(1-0)$ image (beam size : $2.7'$) of the W 28 region for VLSR=0 to 10 km/s with VHE γ ray significance contours overlaid (green) -levels $4, 5, 6\sigma$. The radio boundary of W 28, the 68% and 95% location contours of GRO J1801—2320 and the location of the HII region W 28A2 (white stars) are indicated.

Right: NANTEN $^{12}\text{CO}(1-0)$ image for VLSR=10 to 20 km/s.

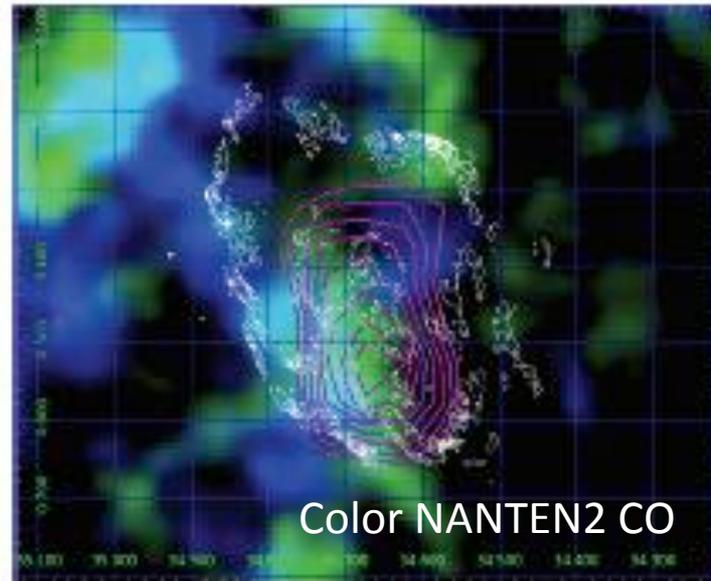
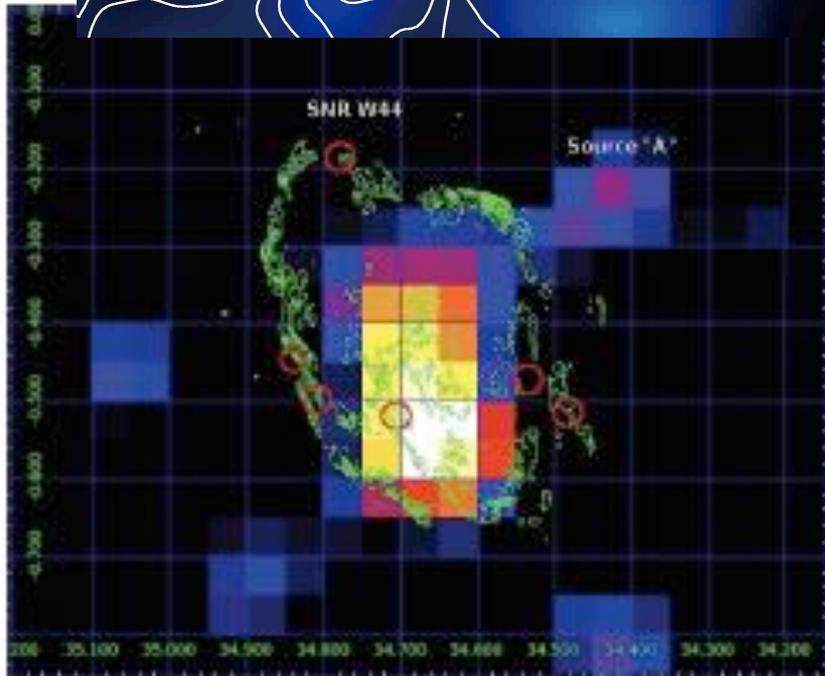
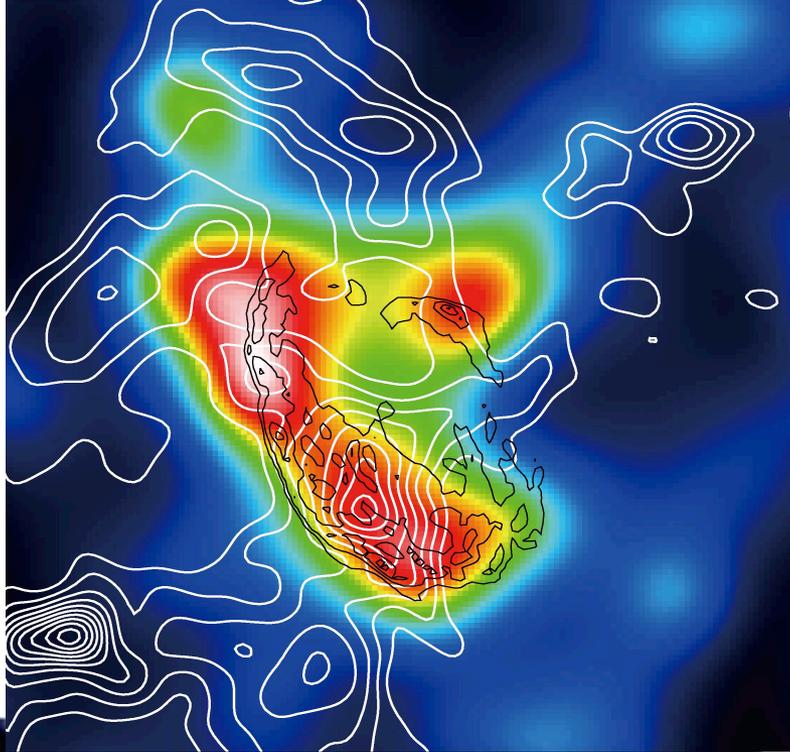
(Aharonian et al. 2007)

W44 GeV gamma & CO

Fermi/NANTEN2 results

New AGILE/NANTEN2 results

Cardillo+ 2013



ガンマ線の起源の解明を目指す CTA

⇒超新星残骸における宇宙線起源の解明に直結:まとめ

- 1 銀河系内 TeVガンマ線超新星残骸で標的水素を特定、
水素分子と水素原子の和が効く

ハドロン起源卓越—RXJ1713(佐野講演),RXJ0852(Vela Jr.岡本講演),
HESSJ1731(福田講演),W28(吉池講演), W44

- 2 マゼラン雲の超新星残骸、分子雲サーベイ(藤井講演Q39)

当面、X線分布との対応—N132D, 30Dor C(馬場崎講演Q23,24),N49 etc.

—X線との比較による星間物質の特定

—CTA: 角度分解能と感度が鍵、飛躍的な向上によって一桁を超えるサンプル増

—“ガンマ線スペクトルの空間分布”

宇宙線陽子と星間物質の詳細比較⇒加速理論との比較

「銀河系内・局所群で詳細を解明し、遠方宇宙に拡張する」