# Quantification of the hadronic and leptonic gamma-ray components in the TeV gamma ray supernova remnants RX J1713.7−3946 and RX J0852.0−4622

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**The extreme Universe viewed in very-high-energy gamma rays 2022**

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# The origin of the Galactic cosmic rays

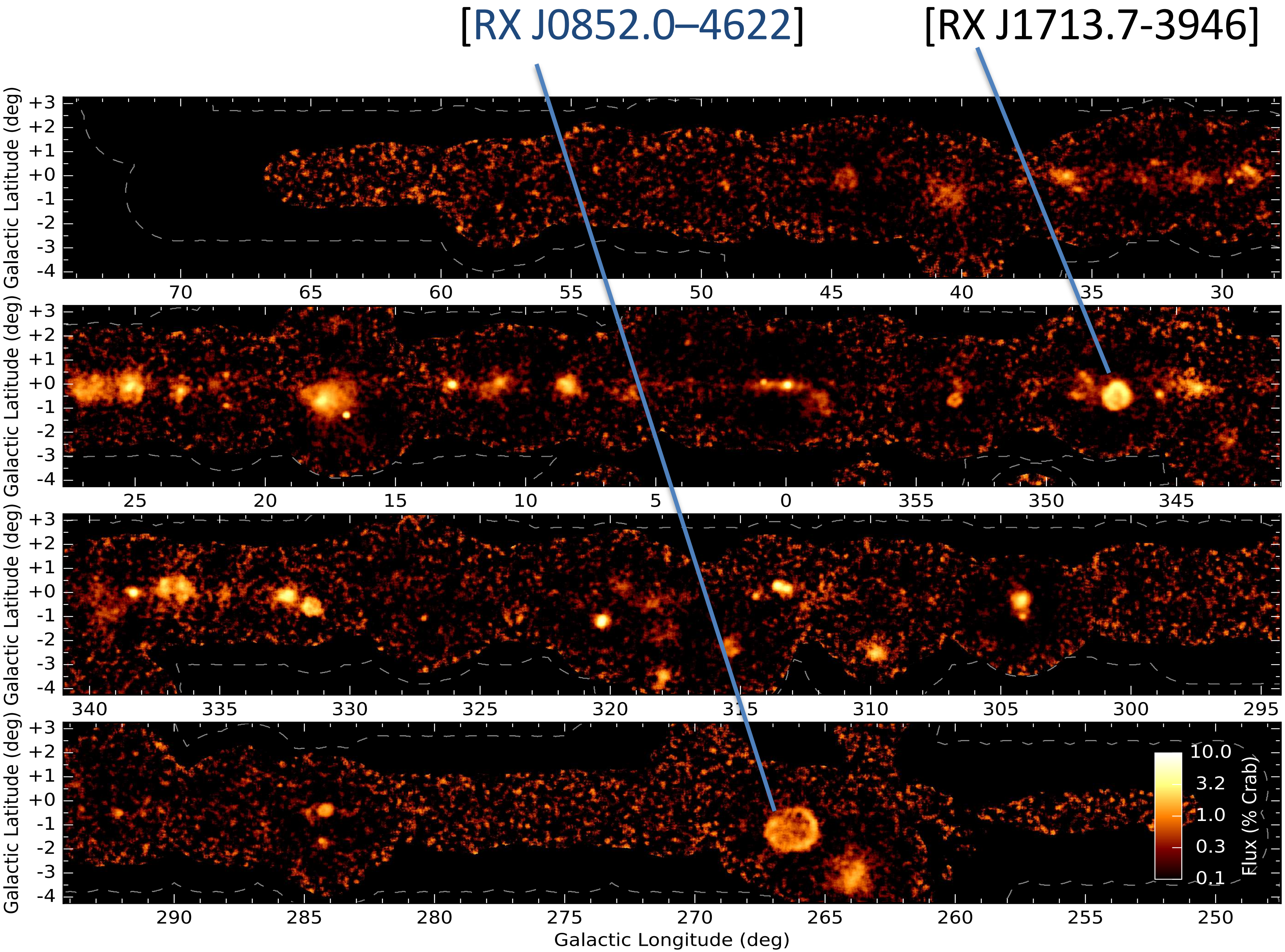
1912 Discovery of the cosmic rays by V. Hess

Cosmic ray protons are not easily identified
Interaction with low energy protons allows to probe CRs
— p-p collision creates pions, $\pi^0$, $\pi^+$, $\pi^-$
  $\pi^0$ decays into two gamma rays
  $\pi^+$, $\pi^-$ decay and produces neutrinos

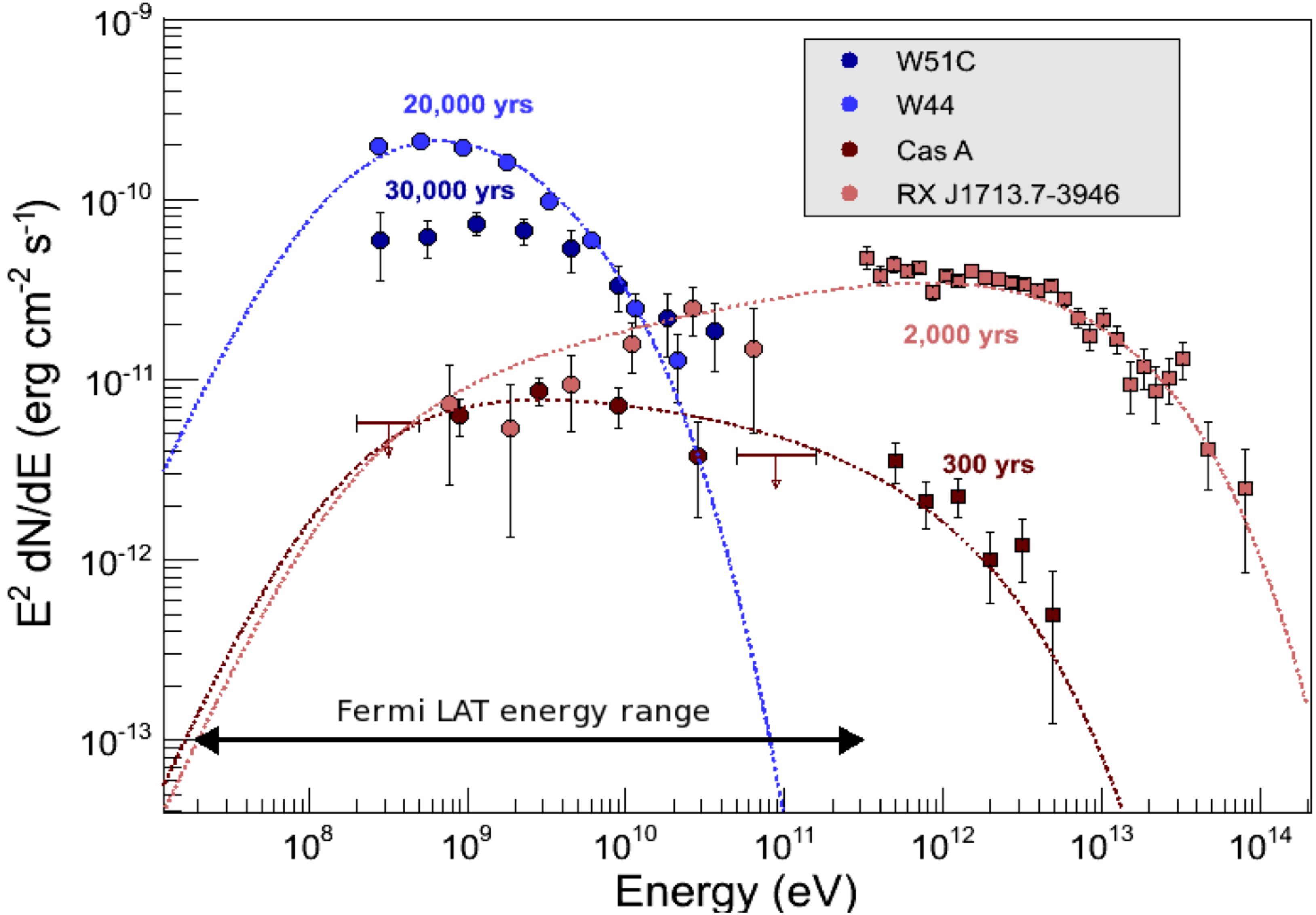
Two possible gamma ray origins must be disentangled
—hadronic : p-p collision
  CR protons produce gamma rays via neutral pion
  $CRp+p \rightarrow \pi^0 \rightarrow 2\gamma$
—leptonic : inverse Compton scattering
  CR electrons scatter low-energy photons(CMB)→ $\gamma$

Verification of the hadronic gamma rays is the key for the cosmic ray origin and calculated CR proton energy can test CR budget in our Galaxy

# The Galactic Plane  H.E.S.S. TeV gamma rays (2018)



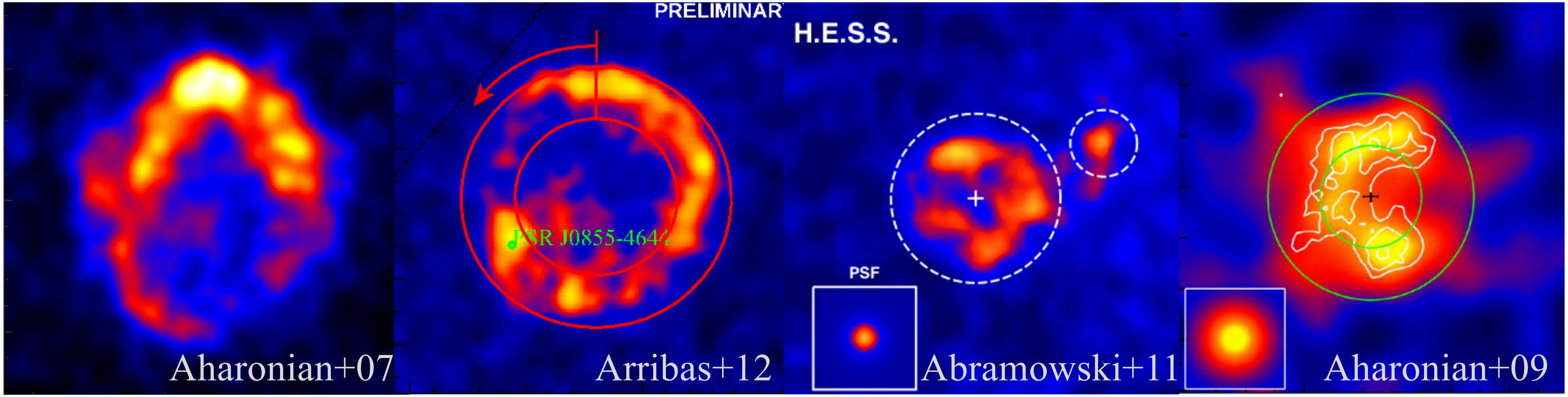
# SNRs emitting gamma-rays




Courtesy H. Tajima

# Four TeV Gamma-ray SNRs

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




| | RX J1713.7–3946 | RX J0852.0–4622 | HESS J1731–347 | RCW 86 |
|---|---|---|---|---|
| Diametr : | ~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 |

# Key observable quantities of young supernova remnants

SNR as the best candidate where DSA is working to accelerate CRs

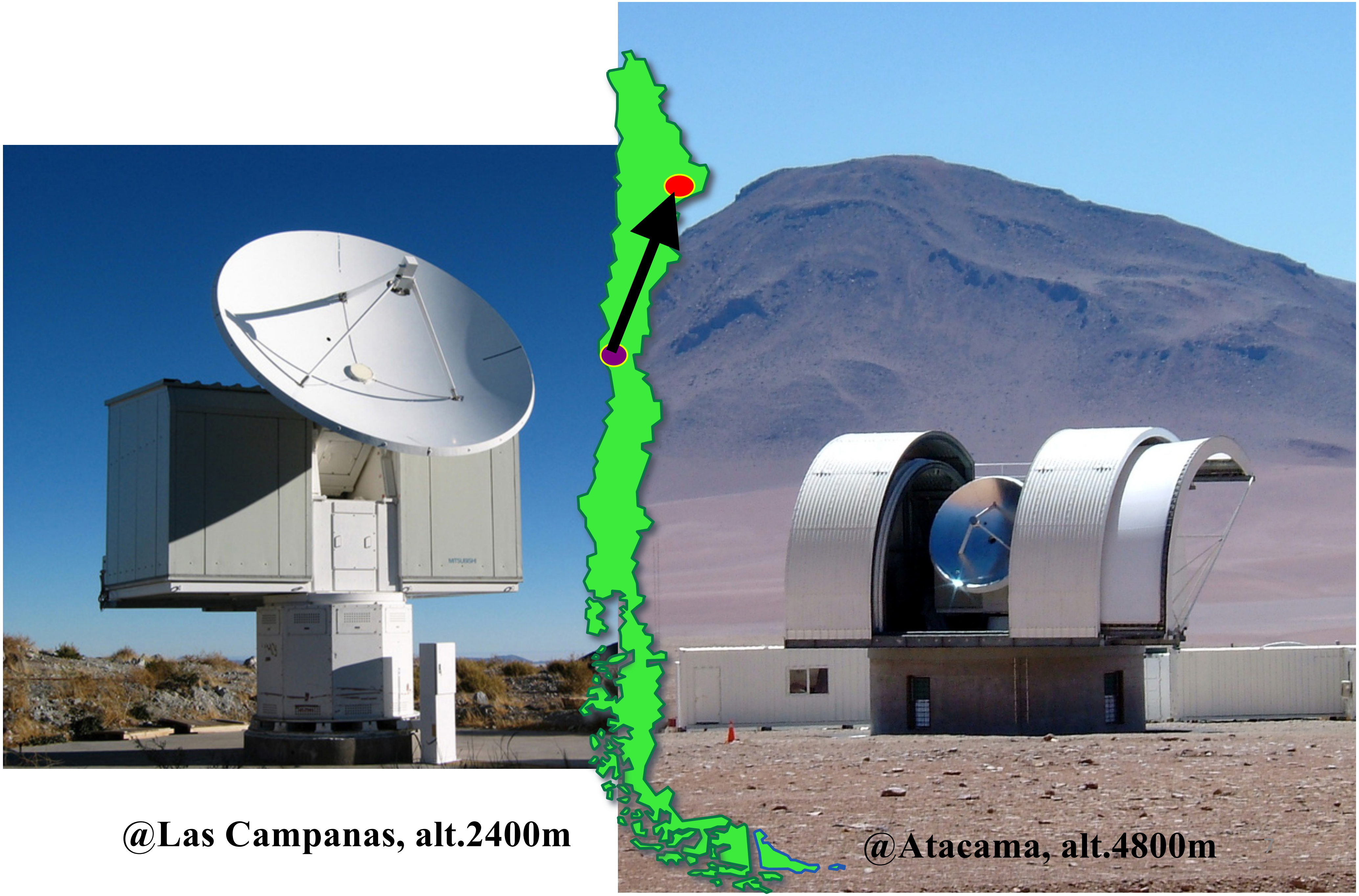
RX J1713.7-3946 and RX J0852.0–4622, the brightest gamma ray SNRs,
most promising object

Gamma rays (Ng in count);
GeV-TeV gamma rays observed with HESS, Veritas, MAGIC, Fermi, AGILE …

X rays (Nx in count);
Non-thermal X rays observed with Suzaku, XMM Newton, Chandra….

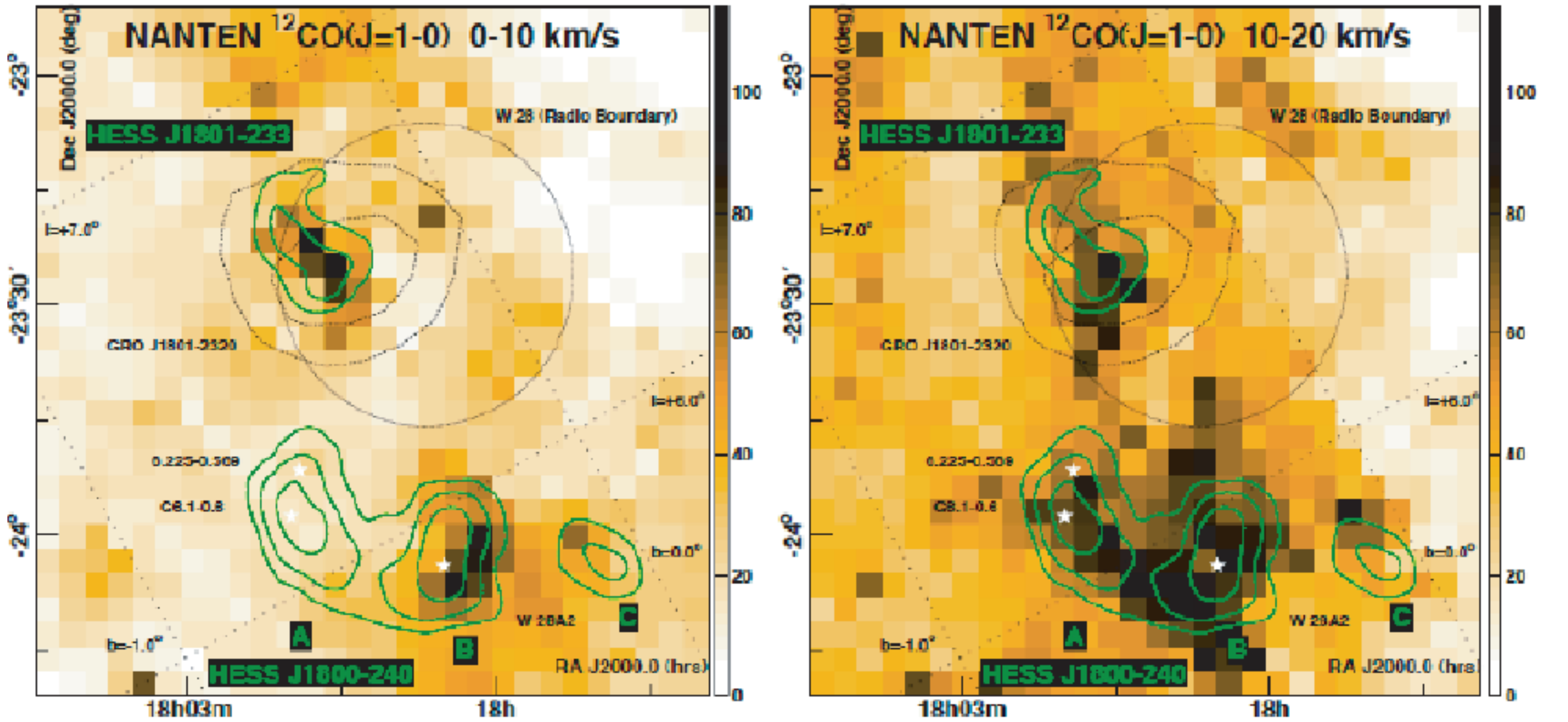
Interstellar protons (Np in column density);
NANTEN 4m telescope, Mopra 22 m telescope, ATNF etc.

# NANTEN & NANTEN2 since 1996



## H.E.S.S. TeV gamma rays vs. CO(J=1-0):

## small CO telescope is powerful for comparison with gamma rays




**Left: NANTEN 12CO(1-0) image (beam size : 2.7') of the W 28 region for VLSR=0 to 10 km/s with H.E.S.S. VHE γ ray significance contours overlaid (green) -levels 4,5,6σ. 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 12CO(1-0) image for VLSR=10 to 20 km/s.**

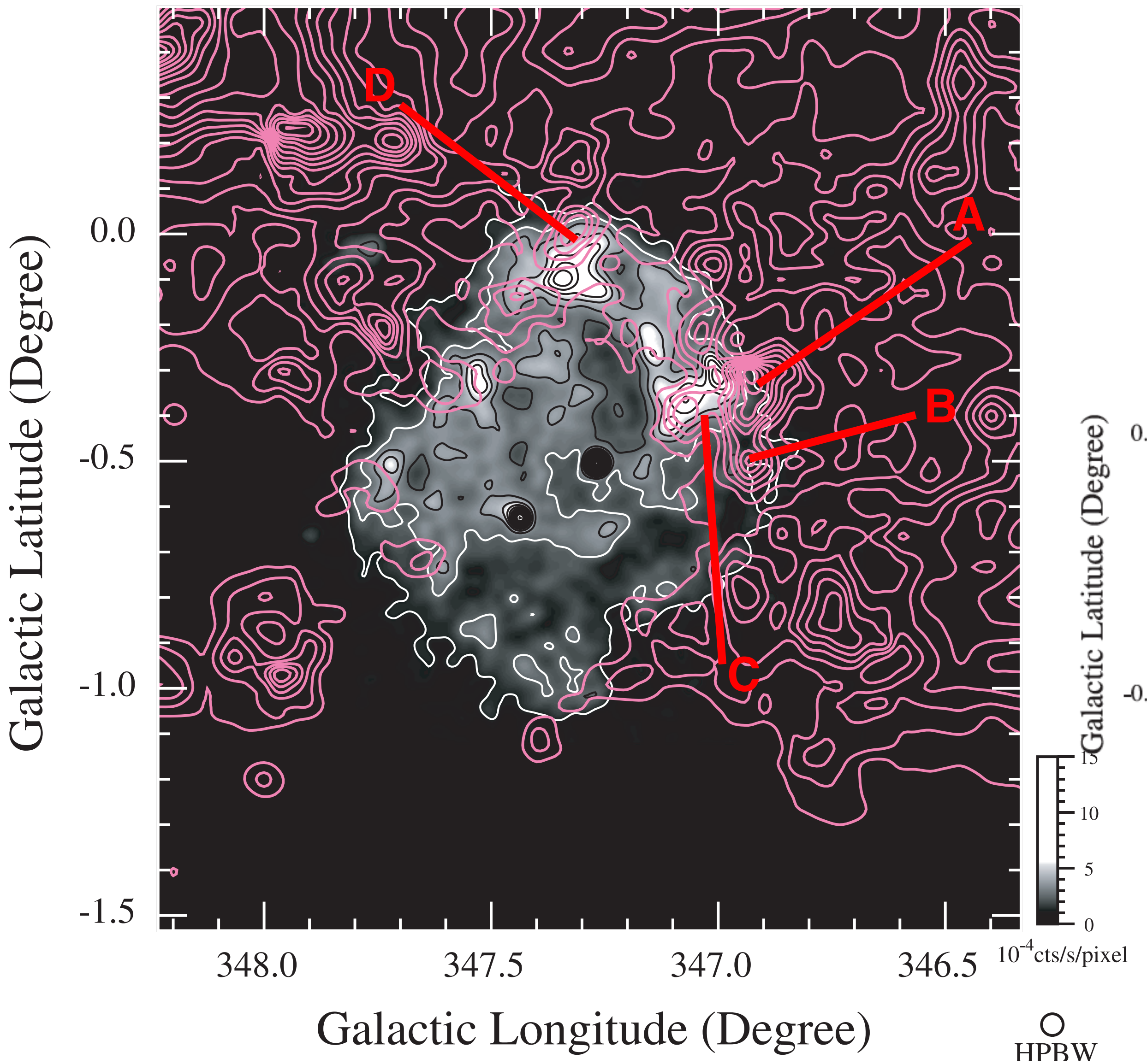
**(Aharonian, Fukui, Moriguchi et al. 2007)**

# RX J1713.7-3946, non-thermal X rays + gamma rays

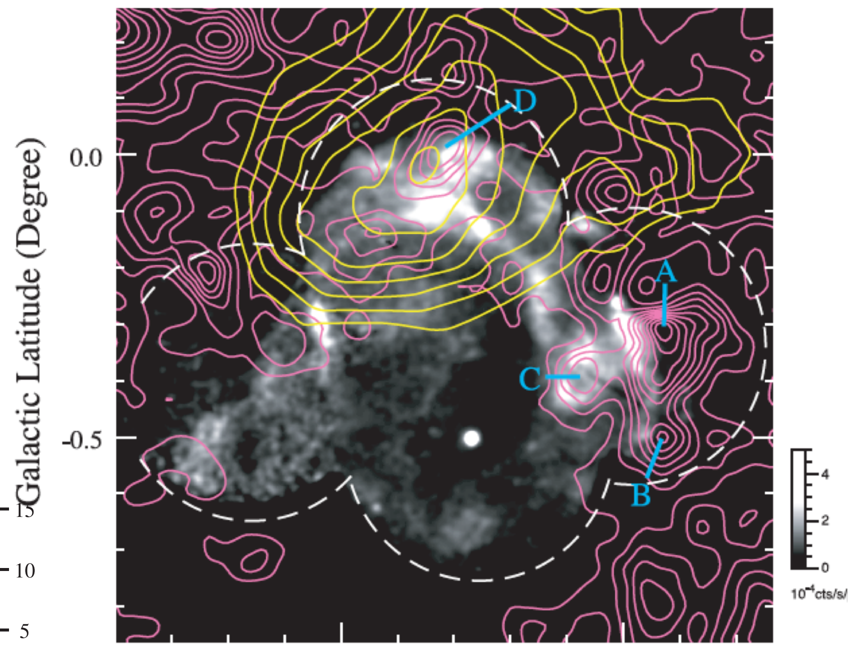
## First detection of CO associated

## [-11 km/s < $V_{LSR}$ < -3 km/s, distance 1kpc]

magenta NANTEN CO, grey ASCA X rays



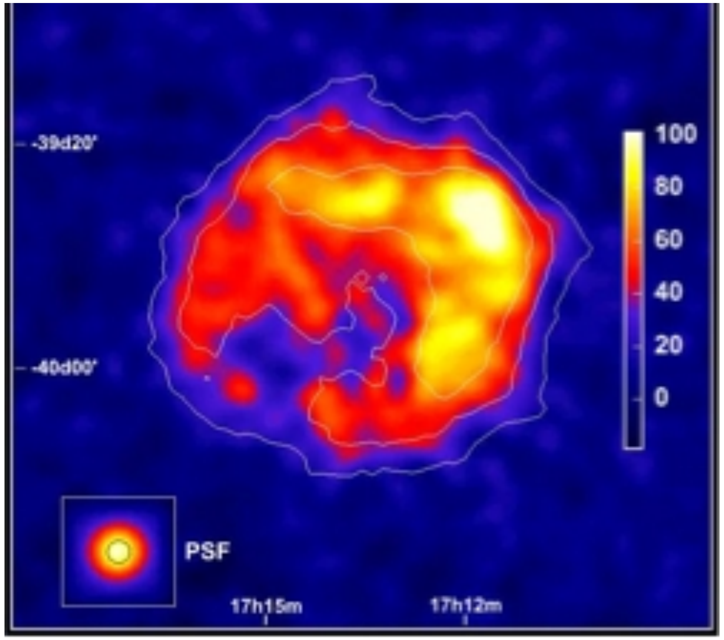

yellow TeV gamma-rays
Enomoto+ 2002



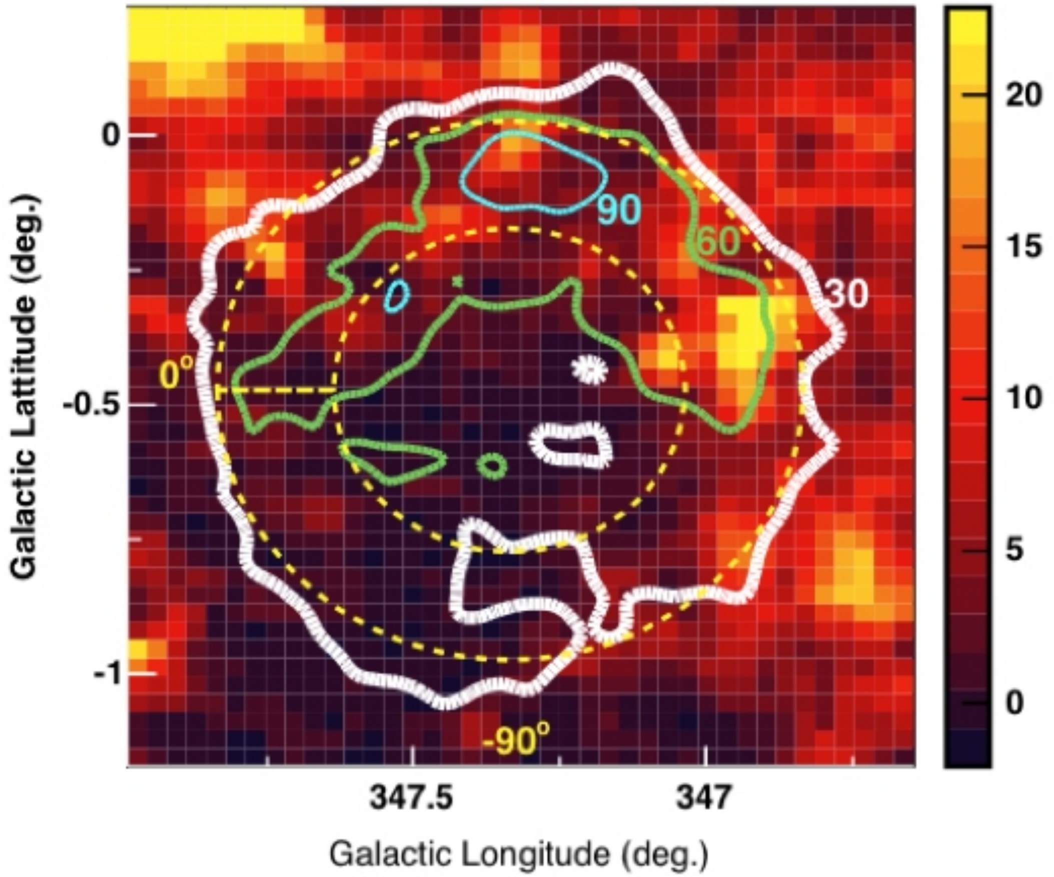

Fukui et al. 2003

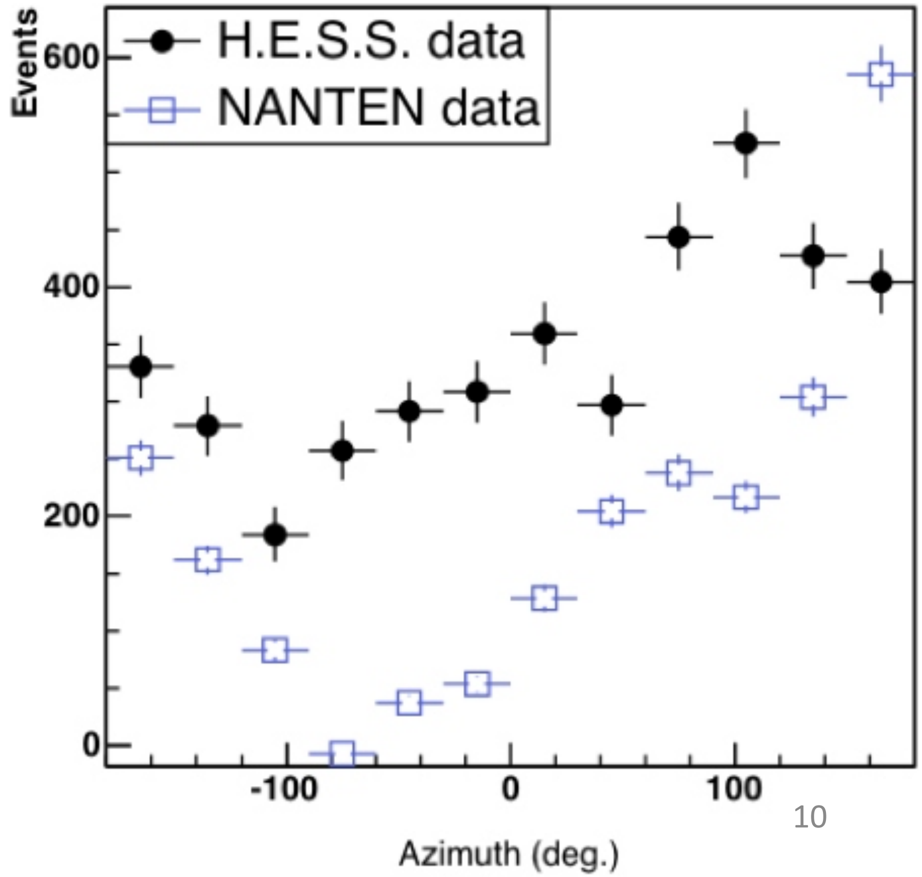
# RXJ1713 gamma-ray shell by H.E.S.S.

- TeV gamma ray shell-like structure: similar to X-rays
- No significant variation of spectrum index across the regions
- spatial correlation with surrounding molecular gas
- the correlation seems not complete




Aharonian+ 2006

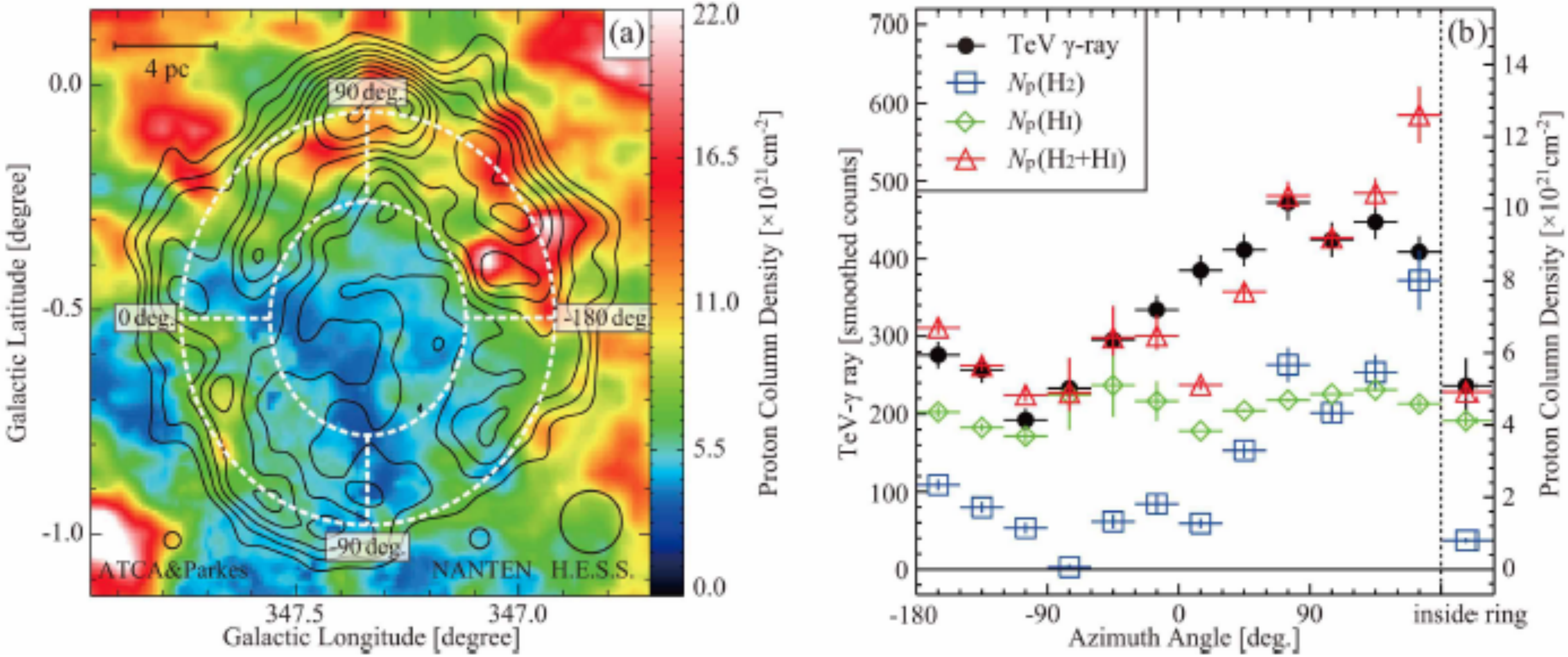


Interstellar protons HI+$H_2$ in RX J1713.7-3946

very similar to TeV gamma rays

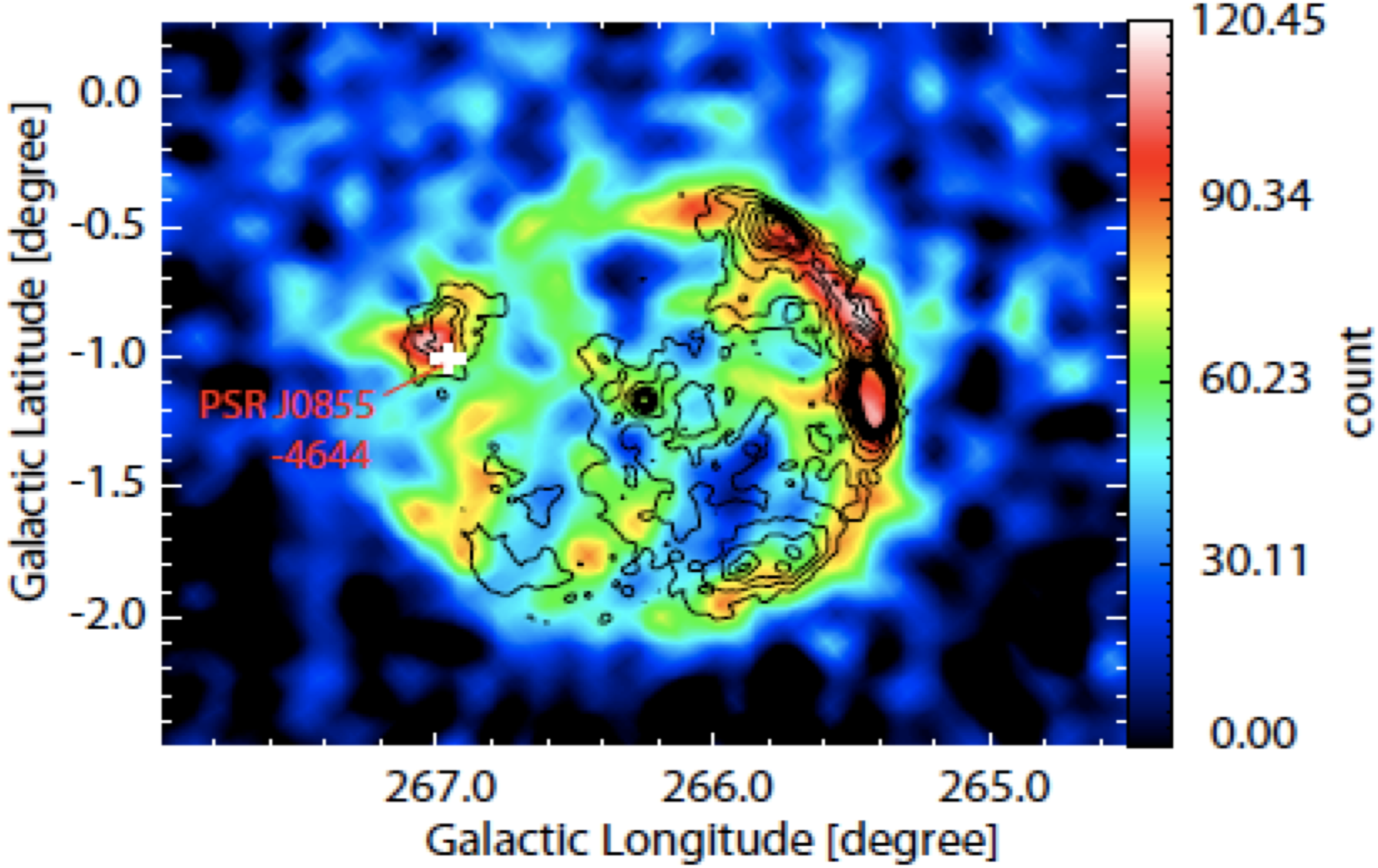
support hadronic scenario ?




HI + $2H_2$

Fukui et al. 2012

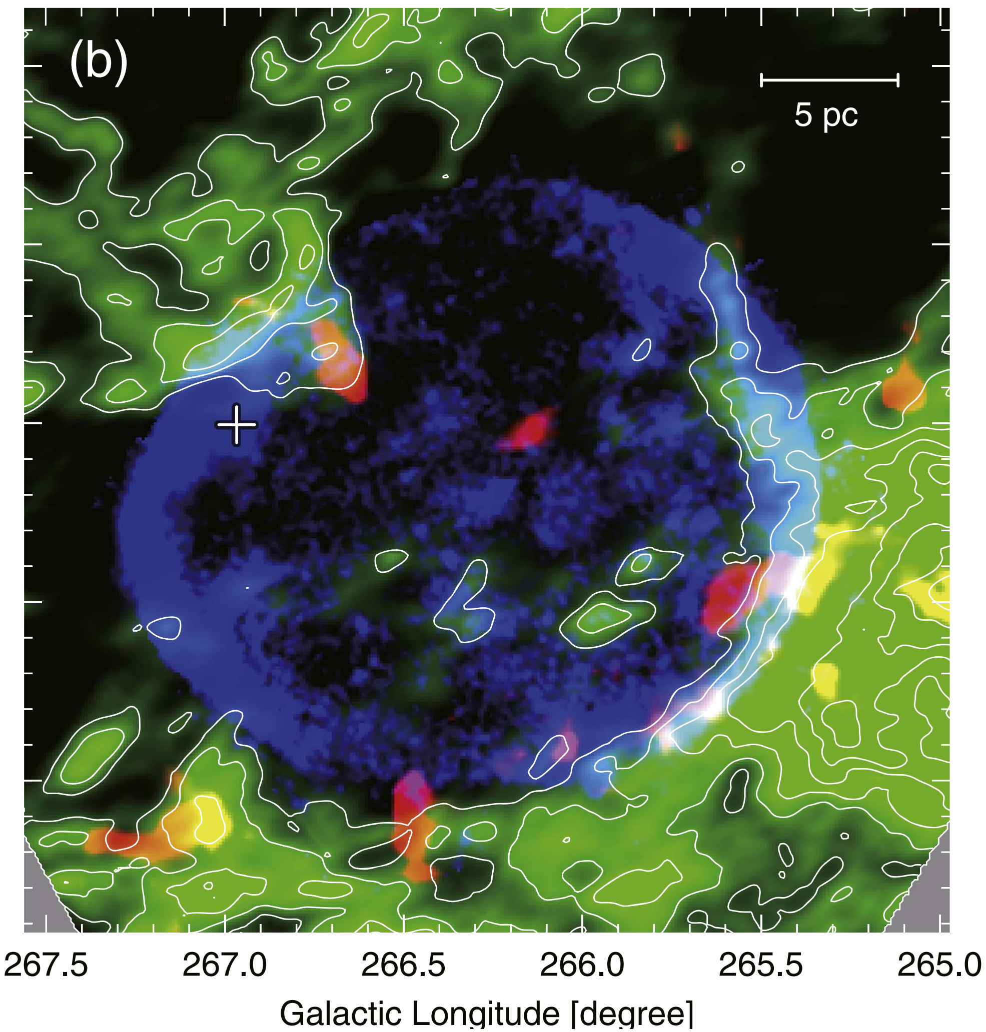
# TeV gamma-ray SNR RX J0852.0-4622

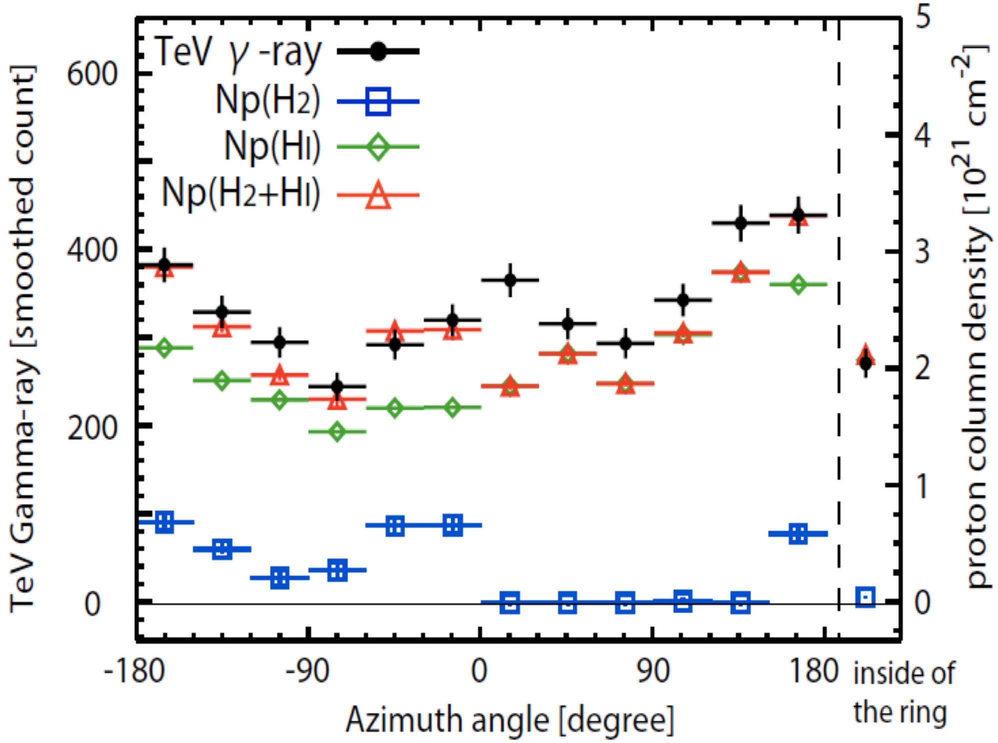



Fukui 2013 Color; TeV gamma rays, contour; X rays

# TeV gamma-ray SNR RX J0852
# ISM Proton and TeV gamma-ray Distributions
## Fukui+ 2017

Fukui et al.




gamma rays
ISM protons
good correspondence

# Fukui+ 2012, 2017 strength and weakness

- Fukui+ 2012, 2017 showed that the interstellar proton distribution is similar to TeV gamma rays. [HI + H2] is essential as target protons.
- Cosmic ray energy, estimated to be $10^{47\text{-}48}$ erg, can supply the Galactic cosmic rays, if CR escape and volume filling factor of interstellar protons are taken into account.
- The hadronic gamma ray is consistent with the SNR origin of CRs, but is not conclusive.
- Significant contribution of the leptonic origin is not excluded.
- Resolution is low, ~4 pc. Number of pixels is 10-20 (best data for RXJ1713 in 2008).

# the present work

RXJ1713 Fukui+ 2021 ApJ, 915, 84F
RXJ0852 Fukui+ 2023 preprint

TeV gamma rays (HESS Collaboration 2018) resolution 4pc→1.4pc etc.

Formulation: gamma rays **Ng** are combination of hadronic and leptonic components in each pixel;

Hadronic Ng is proportional to target protons **Np**

Leptonic Ng is proportional to non-thermal X ray count **Nx**

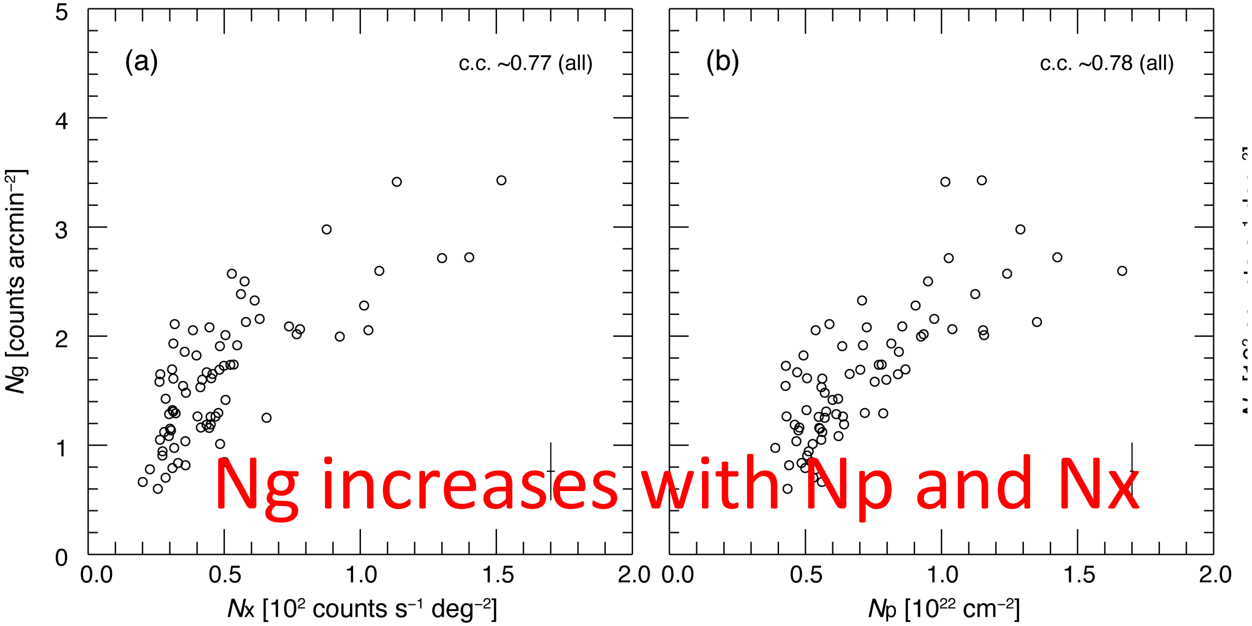
**Ng** (count) = a **Np** ($cm^{-2}$) + b **Nx** (count) : [hadronic]＋[leptonic]

- a: cross section of pp reaction, cosmic ray proton density
- b: inverse Compton scattering, depends on $B^{-2}$

# RXJ1713 and RXJ0852 Np-Nx-Ng correlation

## Nx-Ng

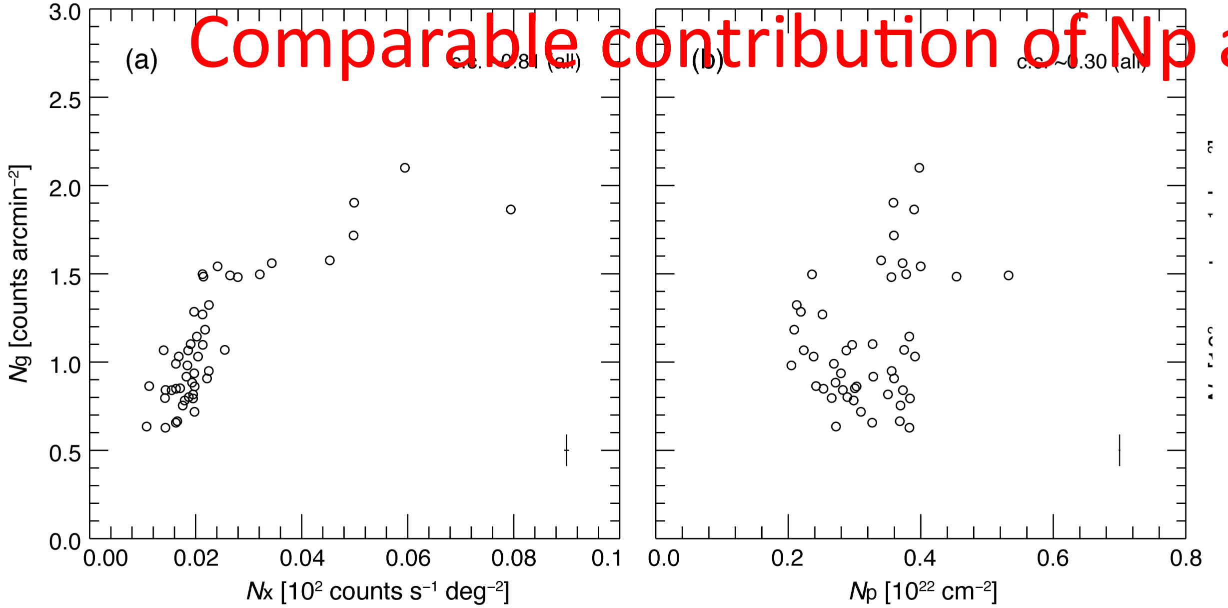
## Np-Ng



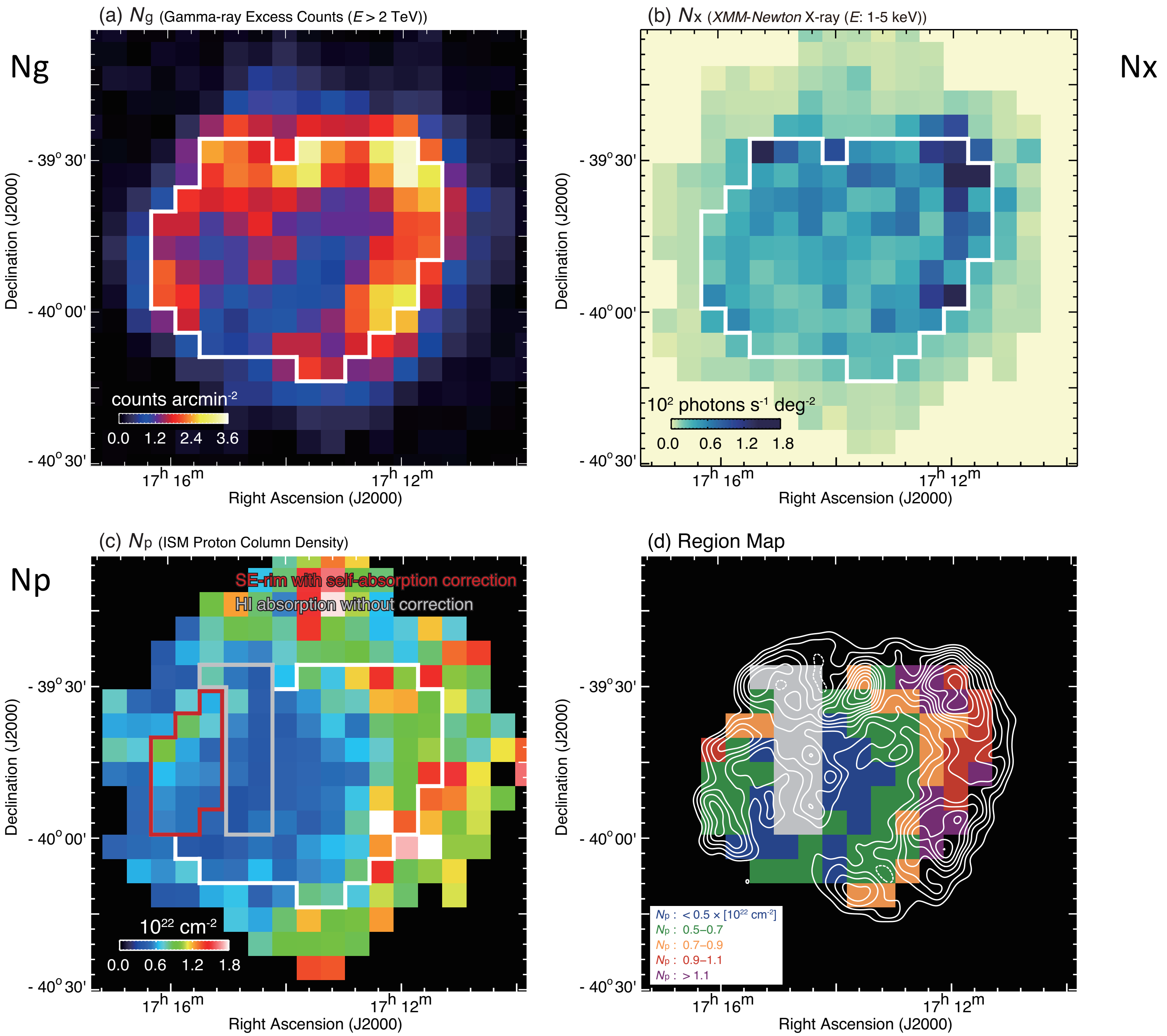

RXJ1713

Ng increases with Np and Nx

Comparable contribution of Np and Nx




RXJ0852

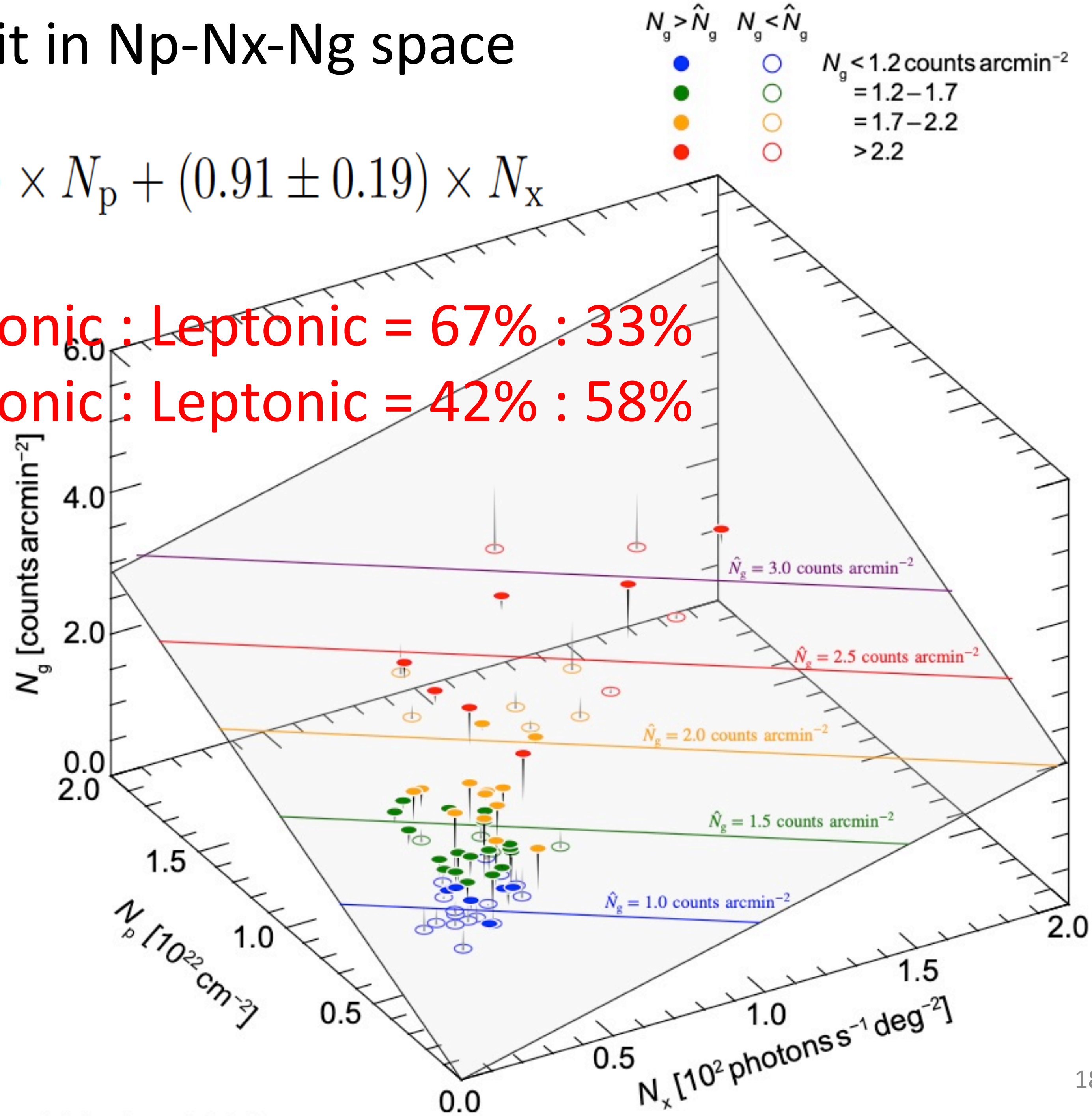

Ng
Nx
Np
(a) Ng (Gamma-ray Excess Counts (E > 2 TeV))
counts arcmin-2
0.0 1.2 2.4 3.6
(b) Nx (XMM-Newton X-ray (E: 1-5 keV))
10² photons s-1 deg-2
0.0 0.6 1.2 1.8
(c) Np (ISM Proton Column Density)
SE-rim with self-absorption correction
HI absorption without correction
10²² cm-2
0.0 0.6 1.2 1.8
(d) Region Map
Np : < 0.5 × [10²² cm-2]
Np : 0.5–0.7
Np : 0.7–0.9
Np : 0.9–1.1
Np : > 1.1
- 39° 30'
- 40° 00'
- 40° 30'
Declination (J2000)
17h 16m
17h 12m
Right Ascension (J2000)

# RXJ1713 3D fit in Np-Nx-Ng space

$$N_g = (1.57 \pm 0.14) \times N_p + (0.91 \pm 0.19) \times N_x$$

RXJ1713 Hadronic : Leptonic = 67% : 33%

RXJ0852 Hadronic : Leptonic = 42% : 58%




Fukui+ 2021

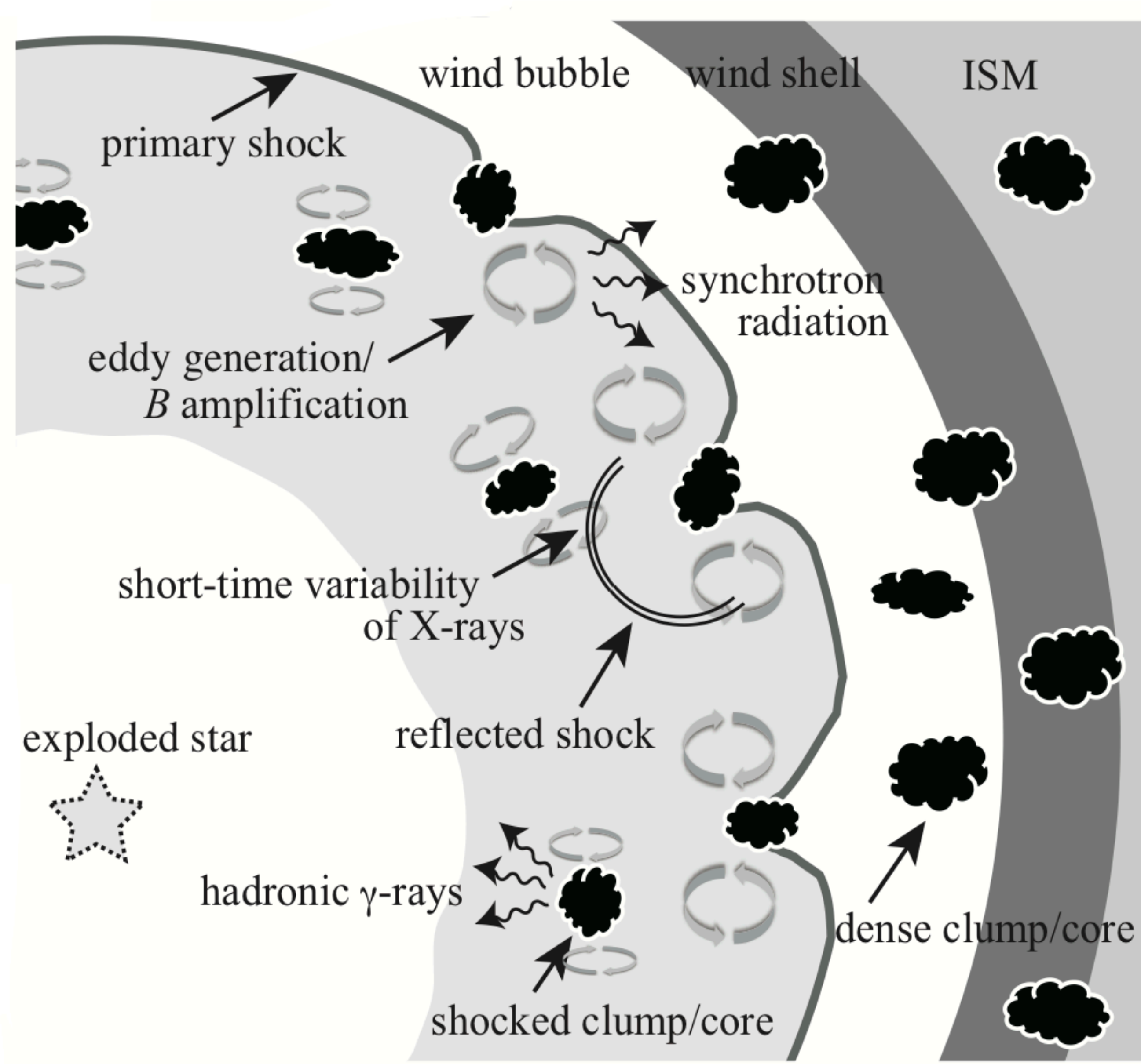
# RXJ0852 results various fitting scheme

Fukui, Aruga, Sano+ 2023

**Table 2.** Estimate of the hadronic- and leptonic-origin gamma-rays (RXJ0852)

| Model | $\langle \widehat{N}_{\rm g} \rangle$ | $\langle N_{\rm p} \rangle$ | Hadronic component | | $\langle N_{\rm x} \rangle$ | Leptonic component | |
|---|---|---|---|---|---|---|---|
| | | | $\widehat{N}_{\rm g}^{\rm hadronic}$ | $\widehat{N}_{\rm g}^{\rm hadronic}/\langle \widehat{N}_{\rm g} \rangle$ | | $\widehat{N}_{\rm g}^{\rm leptonic}$ | $\widehat{N}_{\rm g}^{\rm leptonic}/\langle \widehat{N}_{\rm g} \rangle$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 1 all region | $1.06 \pm 0.02$ | 0.32 | $0.43 \pm 0.08$ | $(41 \pm 7)\%$ | 0.02 | $0.63 \pm 0.08$ | $(59 \pm 7)\%$ |
| $\Delta N_{\rm g} > 0$ (shell) | $1.17 \pm 0.03$ | 0.30 | $0.43 \pm 0.09$ | $(37 \pm 8)\%$ | 0.02 | $0.74 \pm 0.09$ | $(63 \pm 8)\%$ |
| $\Delta N_{\rm g} \leq 0$ (inner) | $0.98 \pm 0.02$ | 0.34 | $0.38 \pm 0.05$ | $(38 \pm 6)\%$ | 0.03 | $0.60 \pm 0.06$ | $(62 \pm 6)\%$ |
| 2 all region | – | – | $0.41 \pm 0.06$ | $(38 \pm 5)\%$ | – | $0.68 \pm 0.06$ | $(62 \pm 5)\%$ |
| $\Delta N_{\rm g} \geq 0.1$ | $1.22 \pm 0.04$ | 0.29 | $0.48 \pm 0.11$ | $(39 \pm 9)\%$ | 0.02 | $0.74 \pm 0.11$ | $(61 \pm 9)\%$ |
| $0.1 > \Delta N_{\rm g} > -0.1$ | $1.10 \pm 0.01$ | 0.33 | $0.47 \pm 0.04$ | $(43 \pm 3)\%$ | 0.02 | $0.63 \pm 0.04$ | $(57 \pm 4)\%$ |
| $\Delta N_{\rm g} \leq -0.1$ | $0.89 \pm 0.02$ | 0.36 | $0.42 \pm 0.05$ | $(47 \pm 6)\%$ | 0.02 | $0.47 \pm 0.05$ | $(53 \pm 6)\%$ |
| 3 all region | – | – | $0.46 \pm 0.05$ | $(42 \pm 4)\%$ | – | $0.63 \pm 0.05$ | $(58 \pm 4)\%$ |

Note— Columns (1): model name; (2), (3) and (6): spatial averages of observed $N_{\rm g}$ (counts arcmin$^{-2}$), $N_{\rm p}$ ($10^{22}$ cm$^{-2}$) and $N_{\rm x}$ ($10^2$ photons s$^{-1}$ degree$^{-2}$); (4) and (7): predicted values of hadronic- and leptonic-origin gamma-rays (counts arcmin$^{-2}$); (5) and (8): fraction of the hadronic and leptonic components.


wind bubble
wind shell
ISM
primary shock
synchrotron
radiation
eddy generation/
B amplification
short-time variability
of X-rays
reflected shock
exploded star
hadronic γ-rays
dense clump/core
shocked clump/core

Inoue+ 2012

# Hadronic dominant broad band spectrum

Zirakashvili & Aharonian 2010

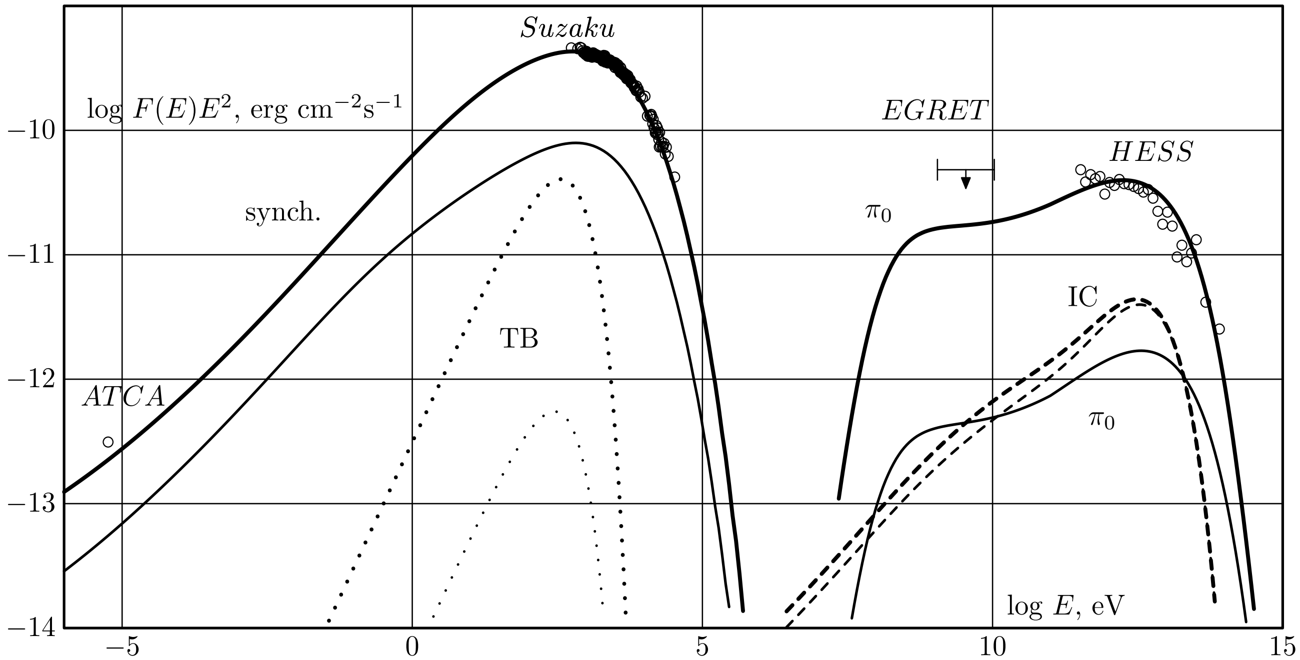



Fig. 6.— The results of modeling of of nonthermal radiation of RX J1713.7-3946 within the hadronic scenario of gamma-ray production. The following basic parameters are used: $t = 1620$ yr, $D = 1.2$ kpc, $n_H$ =0.09 cm$^{-3}$, $E_{SN} = 2.7 \cdot 10^{51}$ erg, $M_{ej} = 1.5M_{\odot}$, $M_A^f = M_A^b = 23$, $\xi_0 = 0.05$, the electron to proton ratios at the forward and reverse shocks $K_{ep}^f = 10^{-4}$ and $K_{ep}^b = 1.4 \cdot 10^{-3}$. The calculations lead to the following values of the magnetic fields and the shock speeds at the present epoch: the magnetic field downstream of the forward and reverse shocks $B_f = 127$ $\mu$G and $B_b = 21$ $\mu$G respectively, the speed of the forward shock $V_f = 2760$ km s$^{-1}$, the speed of the reverse shock $V_b = -1470$ km s$^{-1}$. The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), IC emission (dashed line), gamma-ray emission from pion decay (solid line on the right), thermal bremsstrahlung (dotted line). The input of the reverse shock is shown by the corresponding thin lines. Experimental data in gamma-ray (HESS; Aharonian et al. 2007a) and X-ray bands (Suzaku; Tanaka et al. 2008), as well as the radio flux $22 \pm 2$ Jy at 1.4GHz (ATCA; Acero al. 2009) from the whole remnant are also shown.

# Leptonic dominant broad band spectrum

Zirakashvili & Aharonian 2010 ApJ 708, 965Z

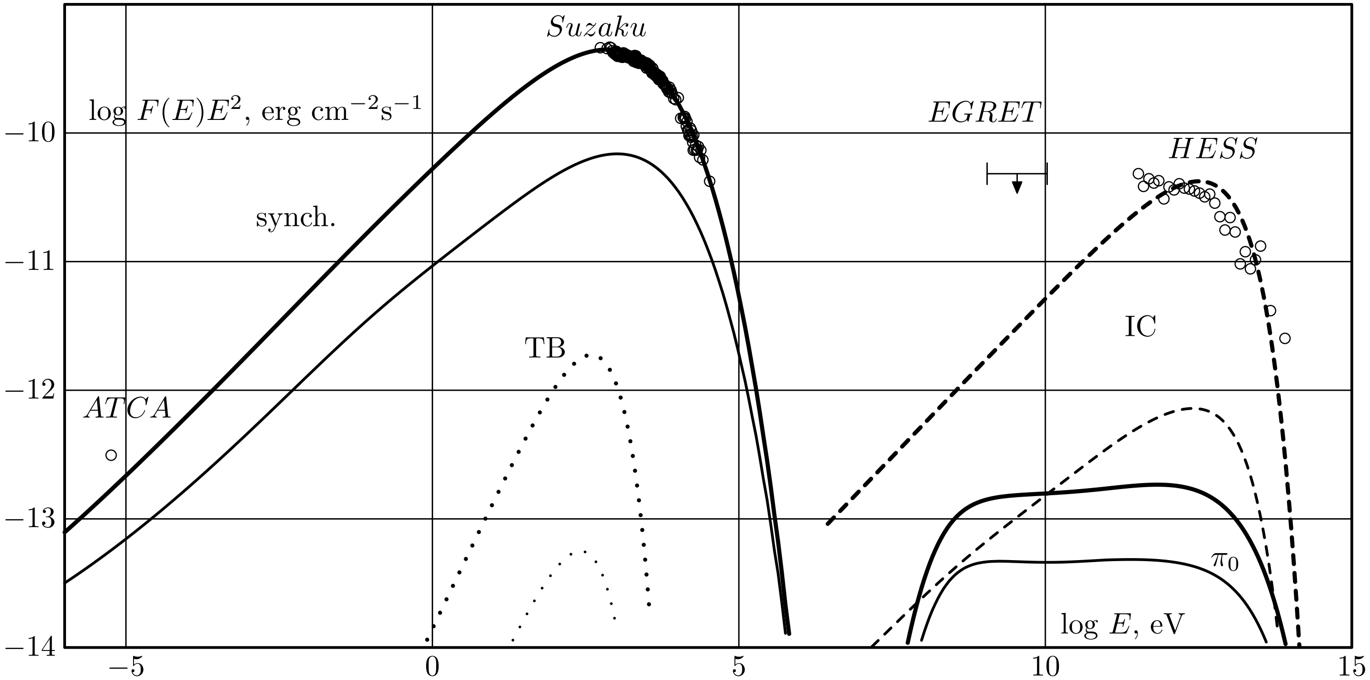



Fig. 8.— Broad-band emission of RX J1713.7-3946 for the leptonic scenario of gamma-rays with a non-modified forward shock. The principal model parameters are: $t$ = 1620 yr, $D$ = 1.5 kpc, $n_H$ =0.02 cm$^{-3}$, $E_{SN} = 1.2 \cdot 10^{51}$ erg, $M_{ej} = 0.74 M_\odot$, $M_A^f = 69$, $M_A^b = 10$, $\xi_0 = 0.1$, $K_{ep}^f = 2.3 \cdot 10^{-2}$, $K_{ep}^b = 9 \cdot 10^{-4}$. The calculations lead to the following values of the magnetic fields and the shock speeds at the present epoch: the magnetic field downstream of the forward and reverse shocks $B_f = 17$ $\mu$G and $B_b = 31$ $\mu$G, respectively, the speed of the forward shock $V_f = 3830$ km s$^{-1}$, the speed of the reverse shock $V_b = -1220$ km s$^{-1}$. The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), IC emission (dashed line), gamma-ray emission from pion decay (solid line on the right), thermal bremsstrahlung (dotted line). The input of the reverse shock is shown by the corresponding thin lines.

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