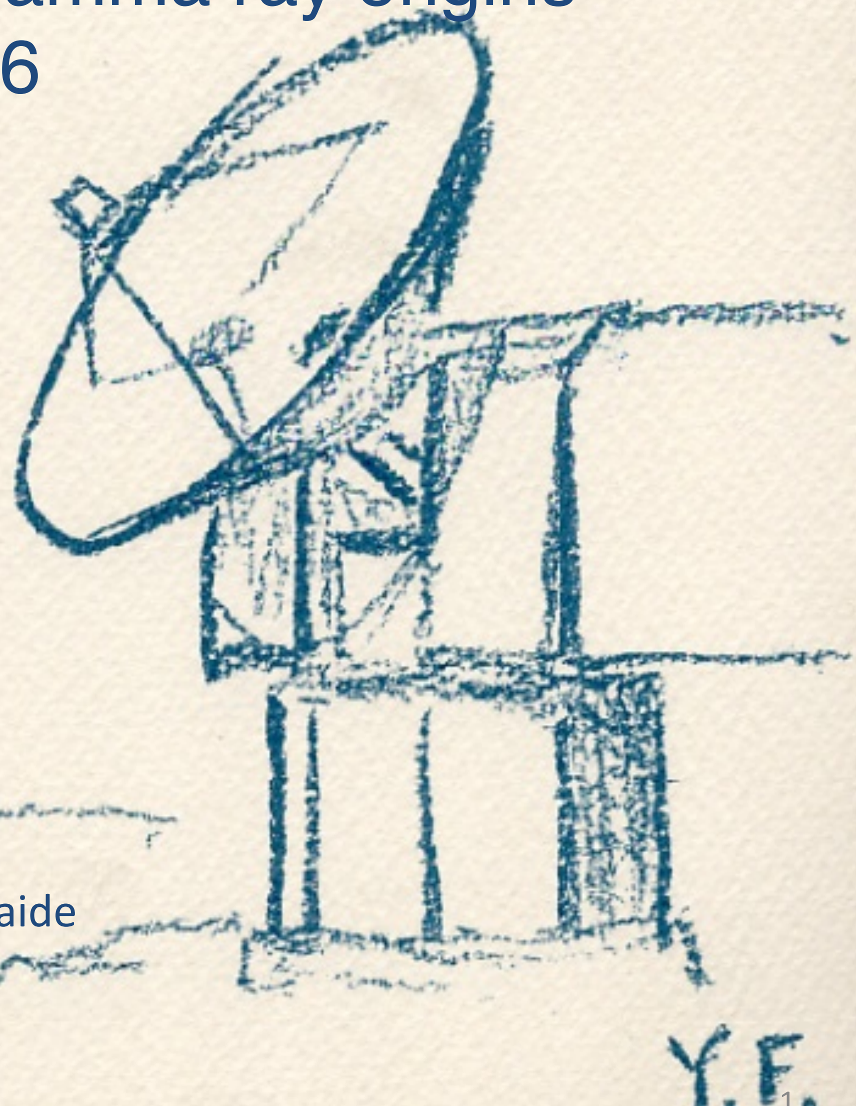
An attempt to separate the gamma ray origins in the SNR RX J1713.7–3946



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"The extreme Universe viewed in very-high-energy gamma rays 2020" December 3-4, 2020

The origin of the Galactic cosmic rays

1912 Discovery of the cosmic rays by V. Hess

Two possible origins;

－Hadronic ：p-p collision, CR protons don not radiate

$p+p \rightarrow \pi^0 \rightarrow 2\gamma$

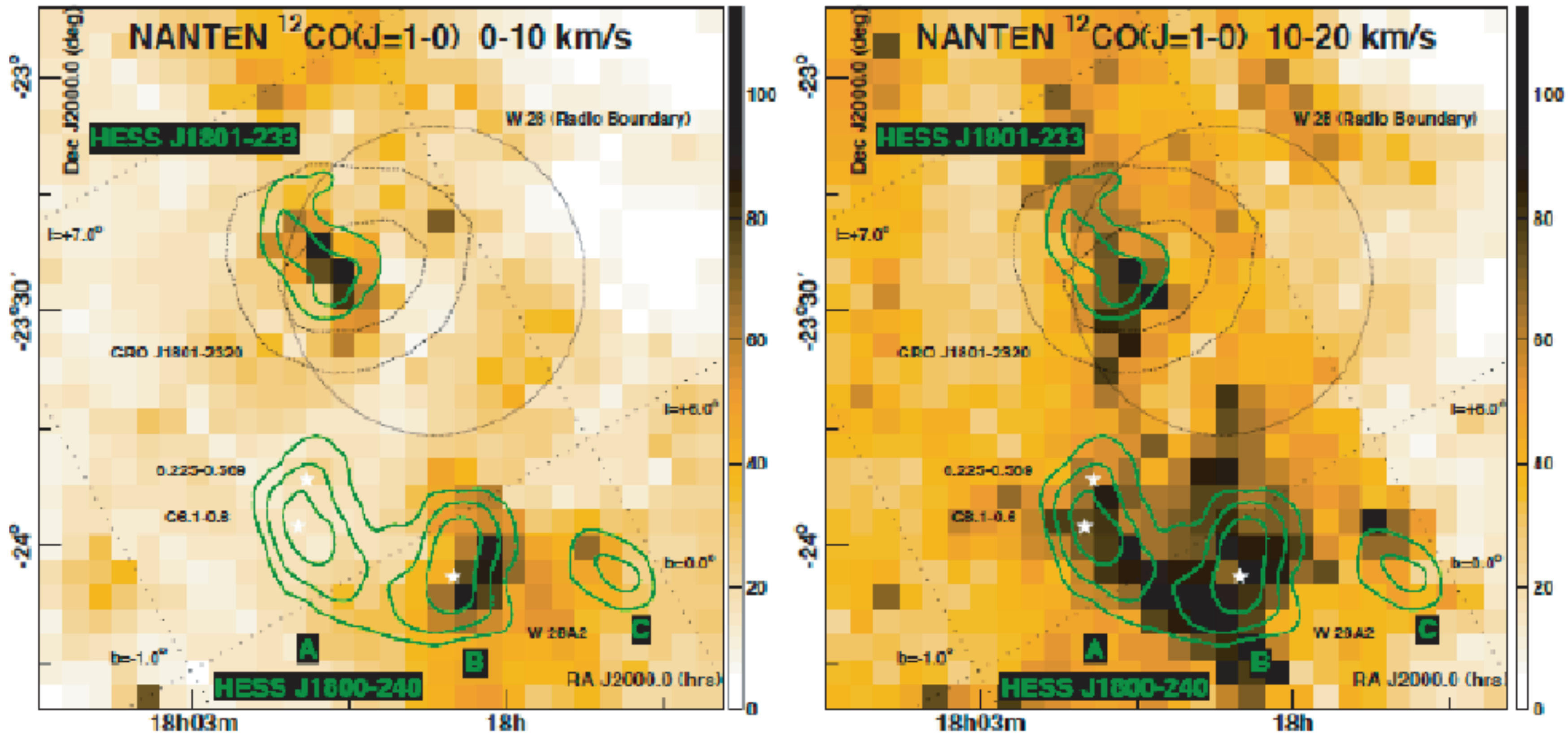
－leptonic origin：inverse Compton scattering

CR electrons + low-energy photons(CMB)$\rightarrow\gamma$

－electrons/protons in CRs is ~10^-2

Proof of CR protons is crucial

TeV γ vs. CO(J=1-0)



Left: NANTEN 12CO(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 4,5,6σ. 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, Morigiuchi et al. 2007)

The origin of the gamma rays

The hadronic origin can be established in the spectrum?

- Low energy cut off in the π^0 decay in the GeV band, not the highest energy

AGILE collaboration: Giuliani, Gardillo, Tavani, Fukui et al. 2011

—W44 : middle aged

- Fermi collaboration 2012 etc.

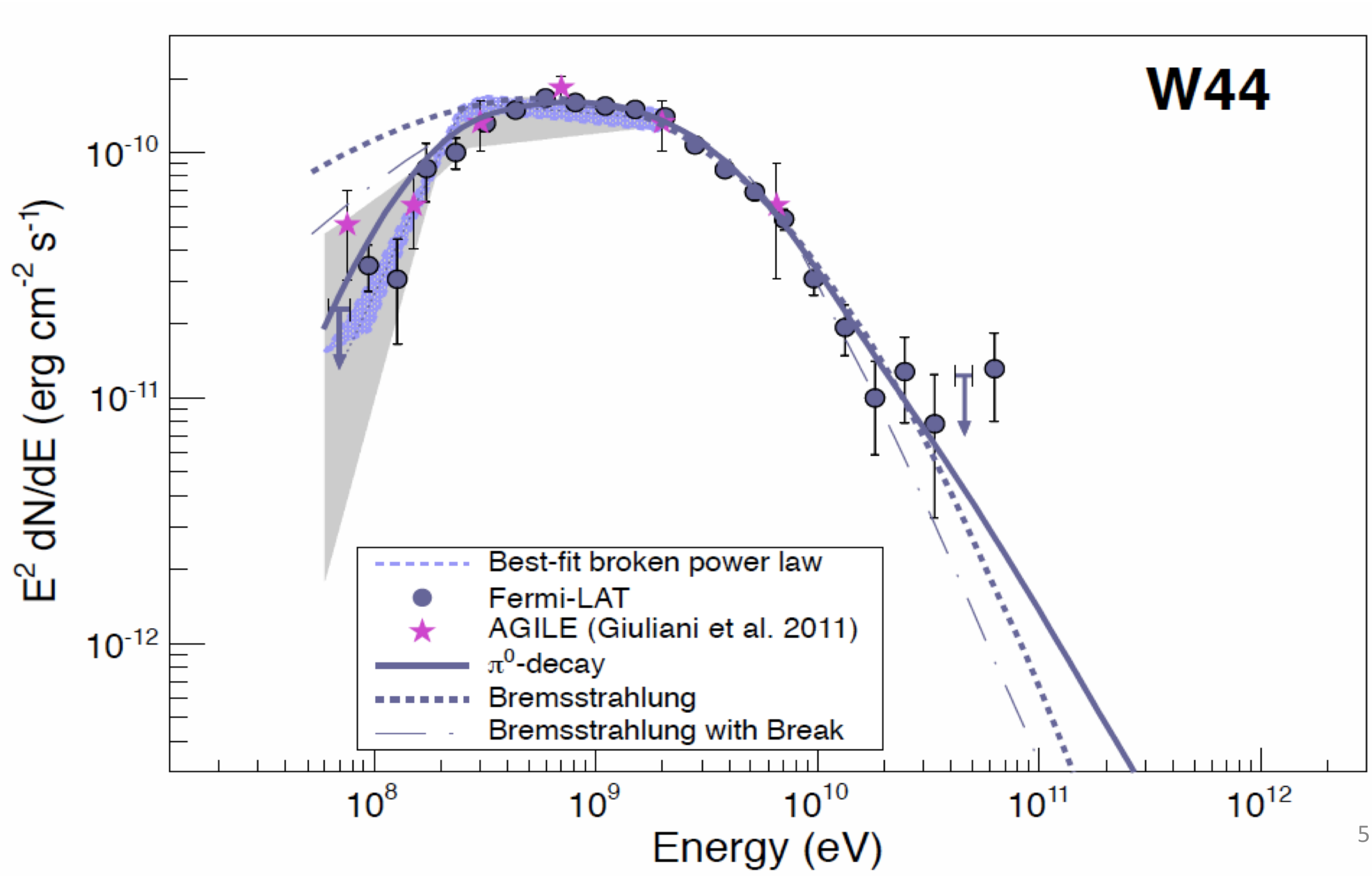
—W44, IC443

- Spatial correspondence between gamma rays and the interstellar protons

—RXJ1713 .7–3946 young TeV gamma SNR age 1600 yr

—Fukui et al. 2012, Inoue, Yamazaki, Inutsuka, Fukui 2012

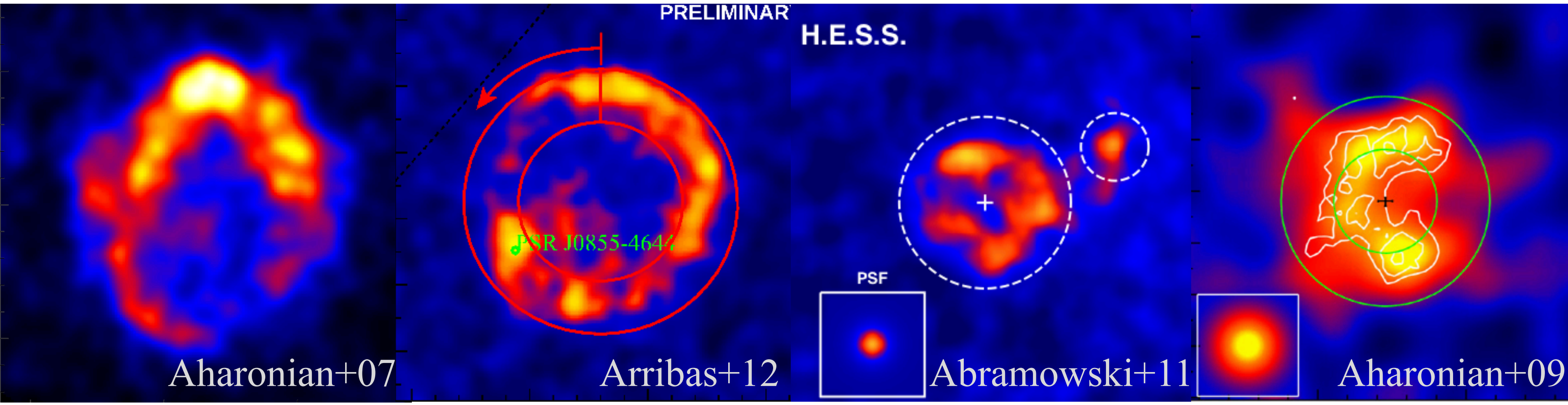
W44 Fermi results



Four TeV Gamma-ray SNRs

- Young SNRs with an age ~2000 yr
  → each SNR is interacting with the ISM (Interstellar Medium)

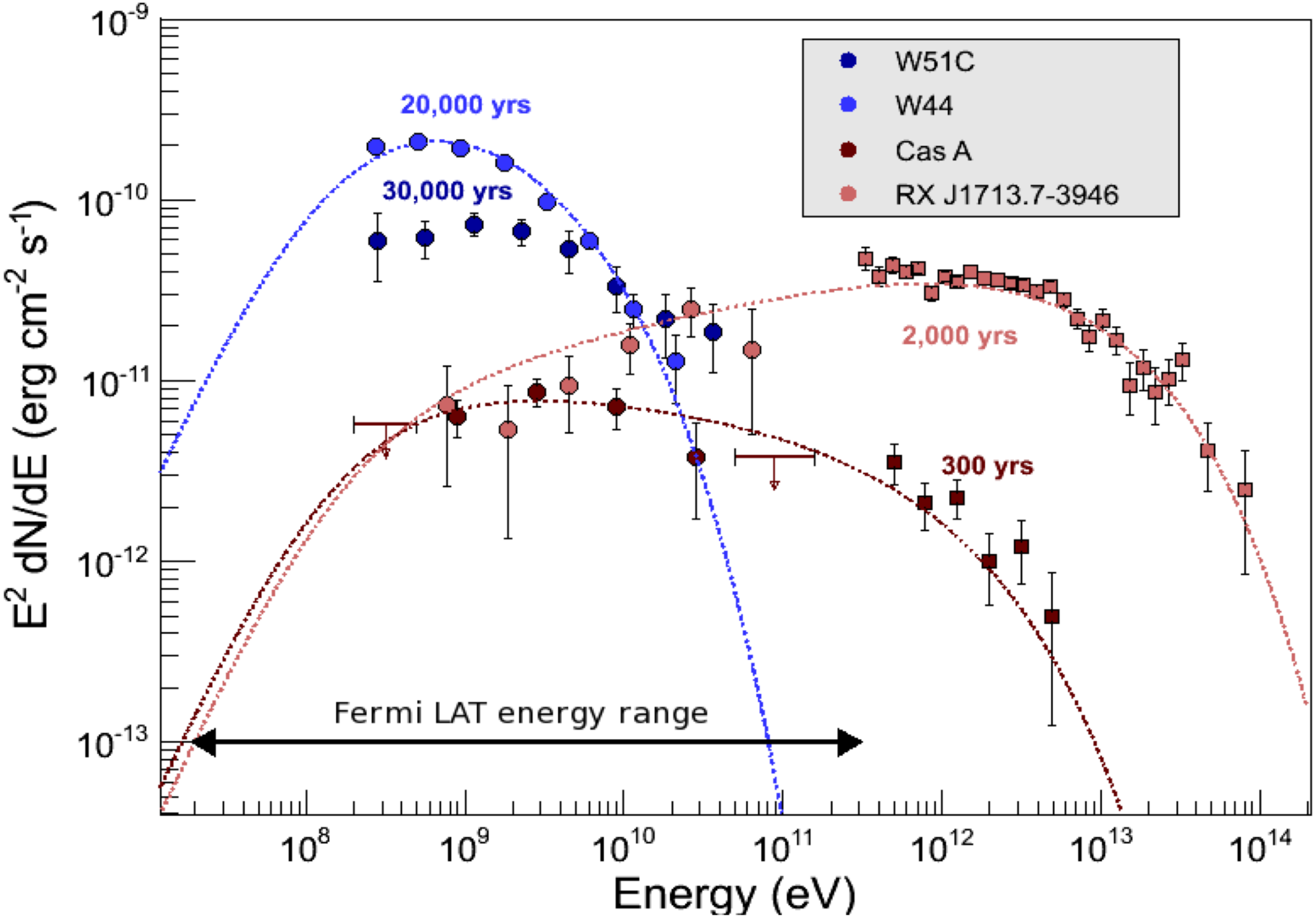
RX J1713.7–3946 | RX J0852.0–4622 | HESS J1731–347 | RCW 86



	RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
diameter:	~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 H I	rich H I + little CO	rich CO + H I cavity	rich H I + little CO
X-rays:	pure synchrotron	pure synchrotron ?	pure synchrotron	thermal + non-thermal

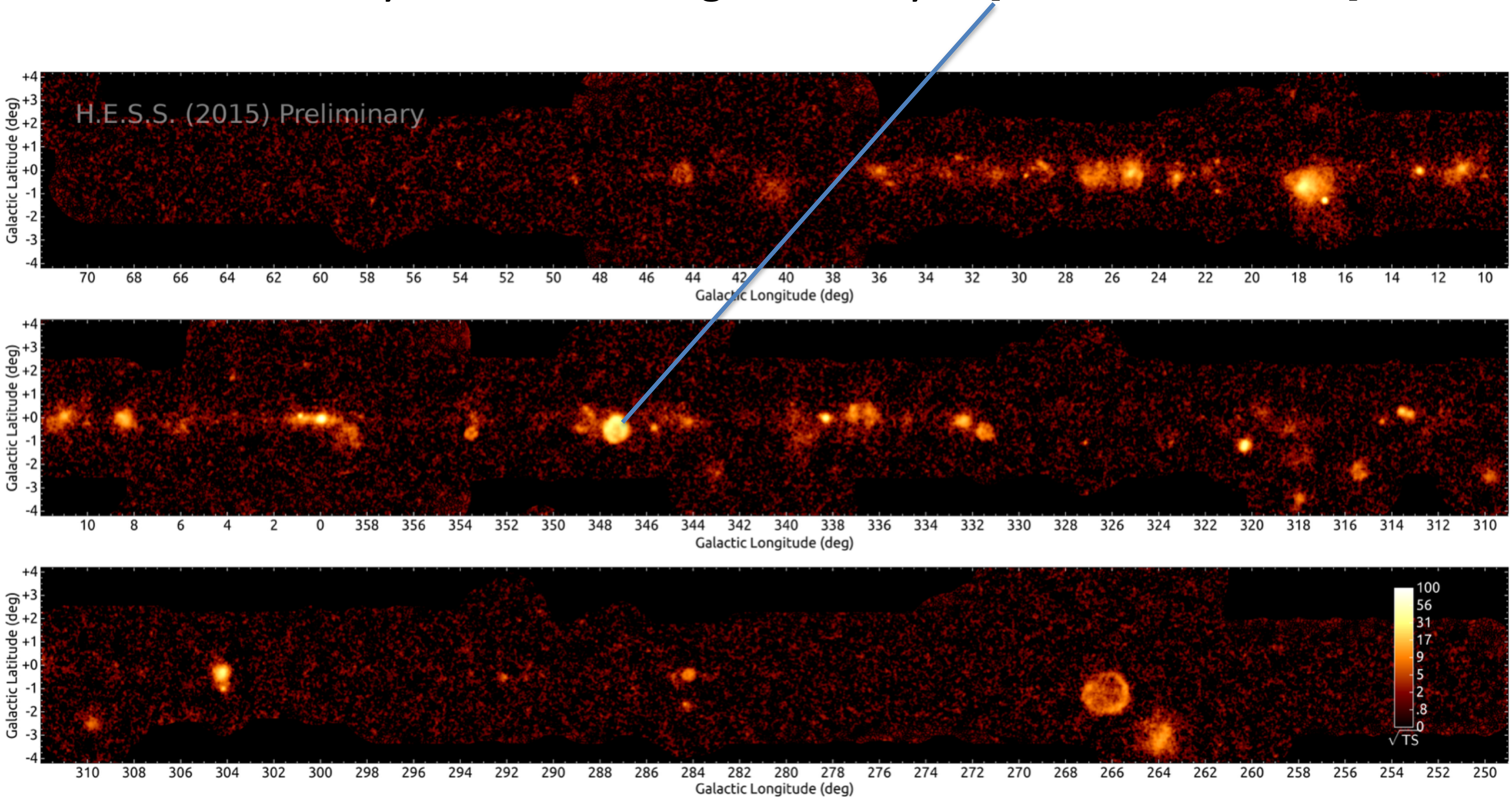
- SNR-ISM correlation, shock-cloud interaction and p-p reaction

SNRs emitting gamma-rays

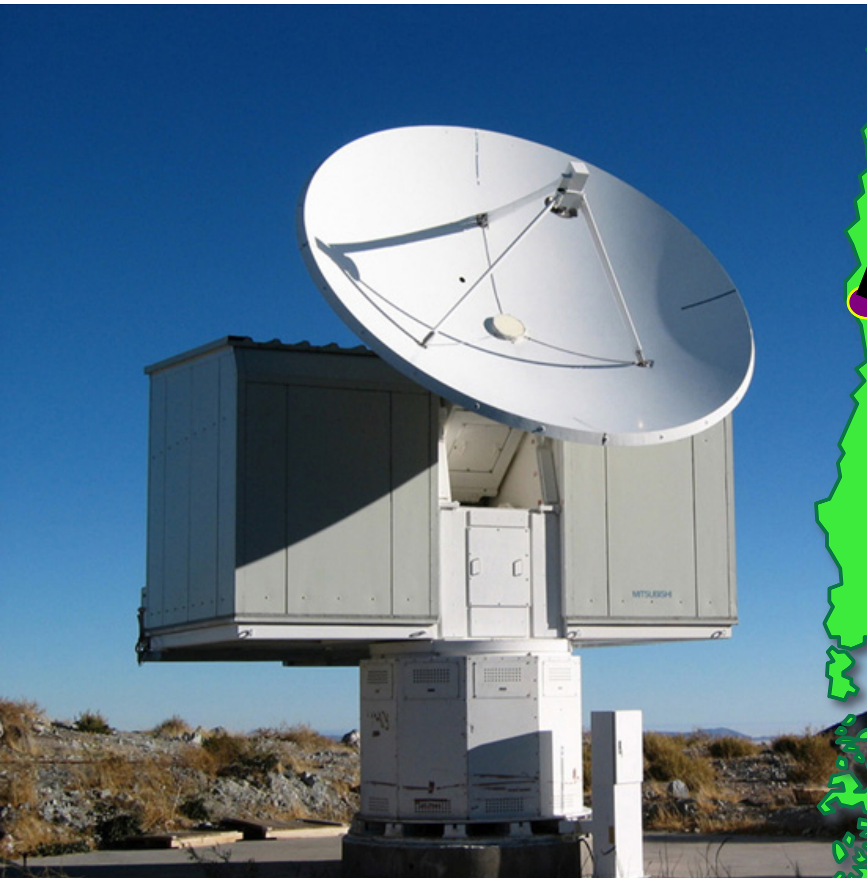


Courtesy H. Tajima

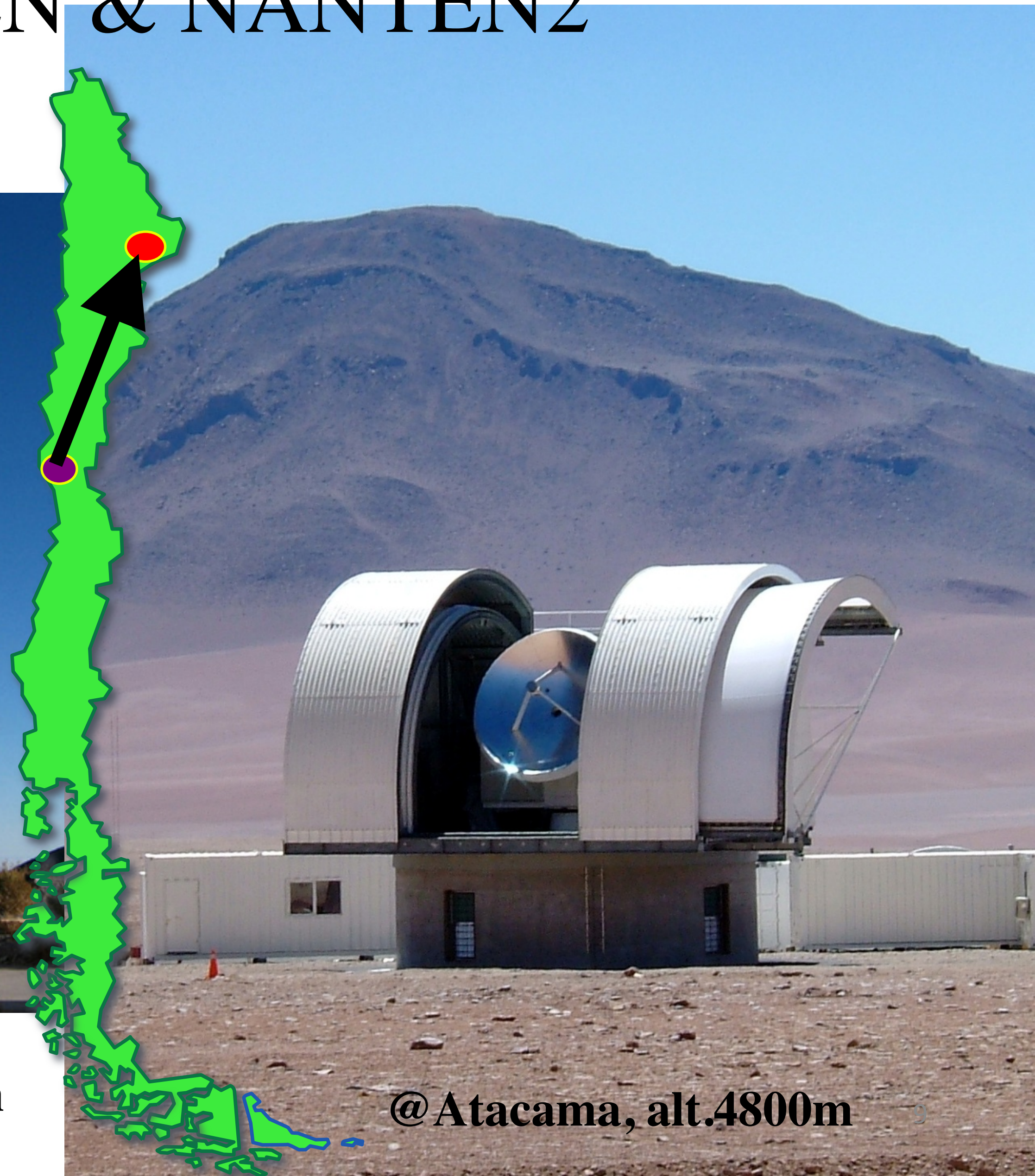
The Galaxy, H.E.S.S. TeV gamma ray [RX J1713.7-3946]



NANTEN & NANTEN2



@Las Campanas, alt.2400m

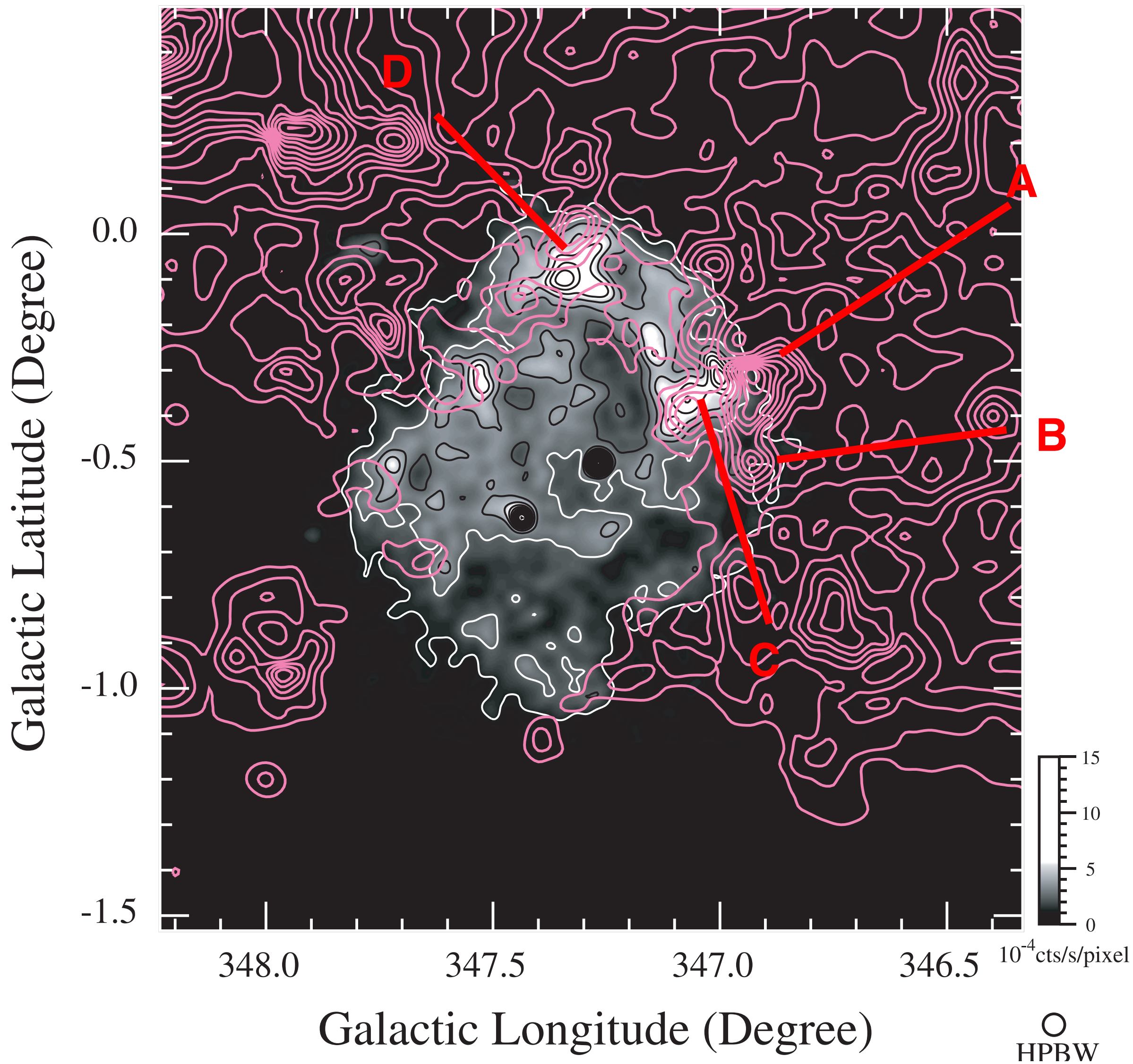


@Atacama, alt.4800m

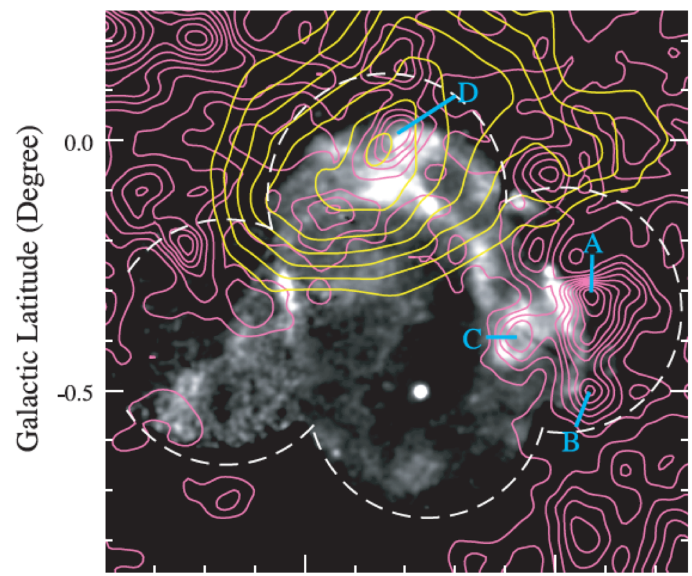
RX J1713.7-3946: ^{12}CO(J=1-0) with X-rays

pink CO, grey X ray

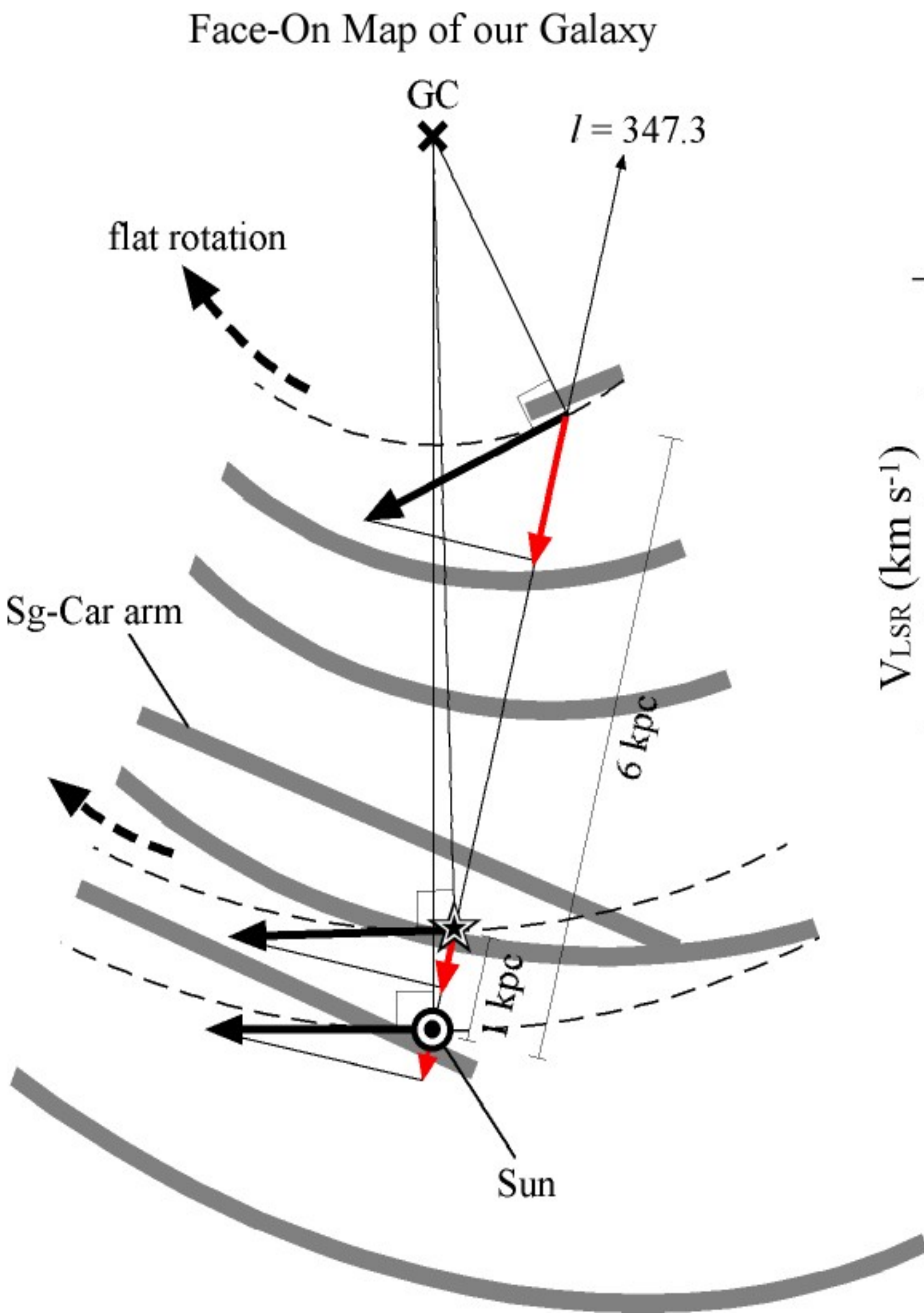
-11 km/s < V_{LSR} < -3 km/s



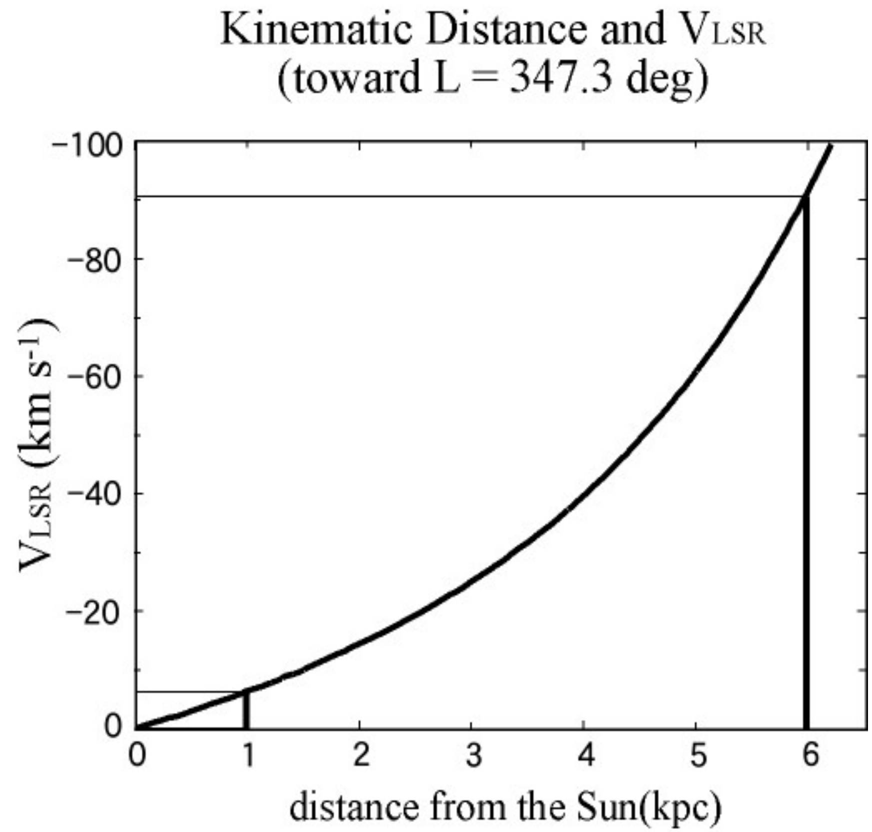
yellow TeV γ-rays



Fukui et al. 2003



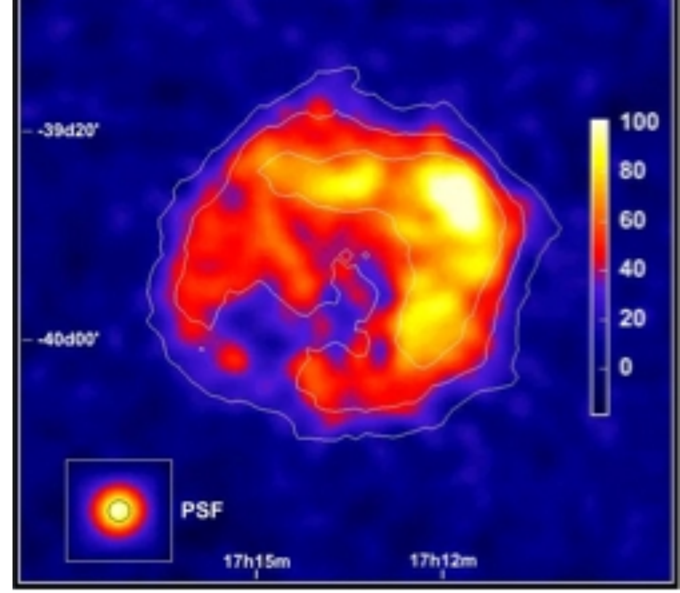
Face-On Map of our Galaxy
GC
l = 347.3
flat rotation
Sg-Car arm
6 kpc
1 kpc
Sun



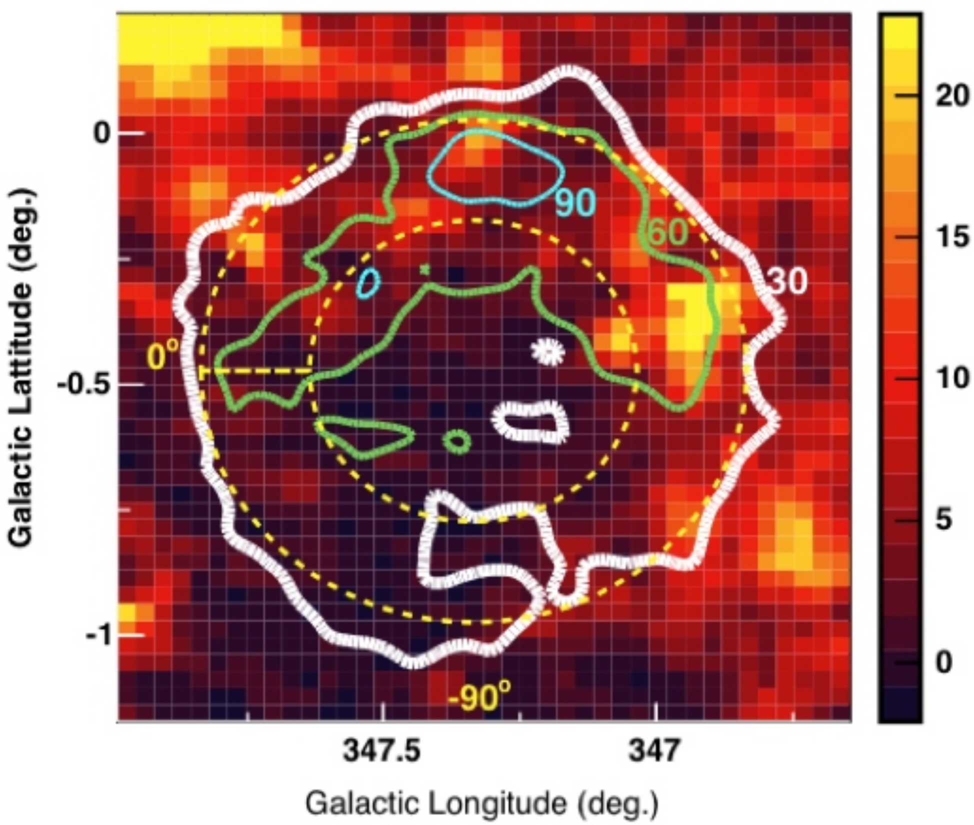
Kinematic Distance and VLSR
(toward L = 347.3 deg)
VLSR (km s-1)
−100
−80
−60
−40
−20
0
0
1
2
3
4
5
6
distance from the Sun(kpc)

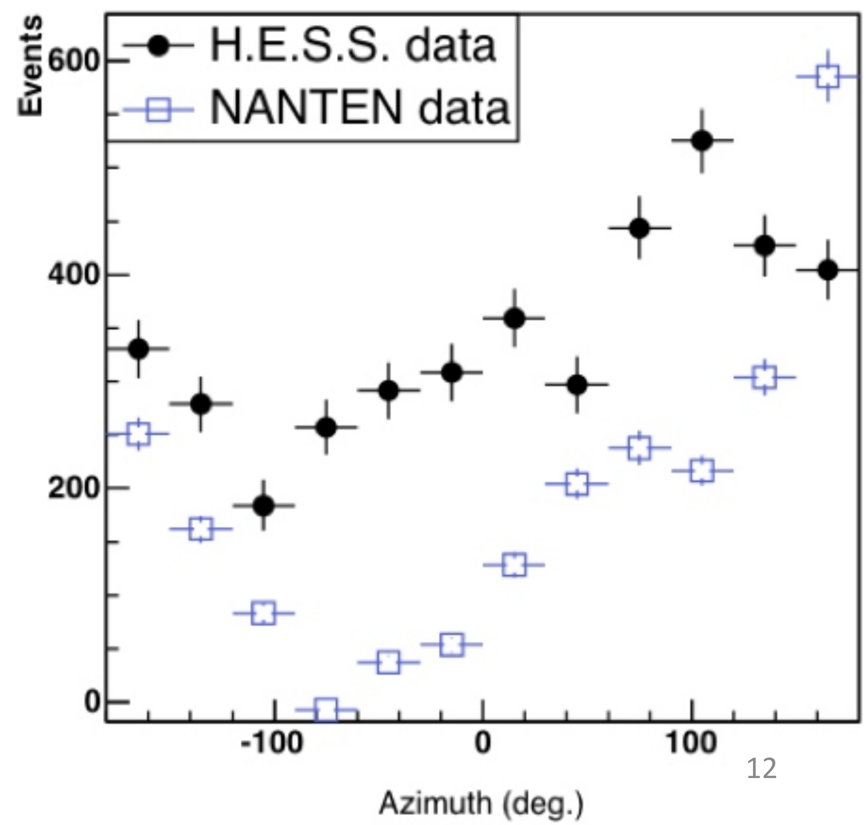
SNR G347.3-0.5 (RX J1713.7-3946)

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

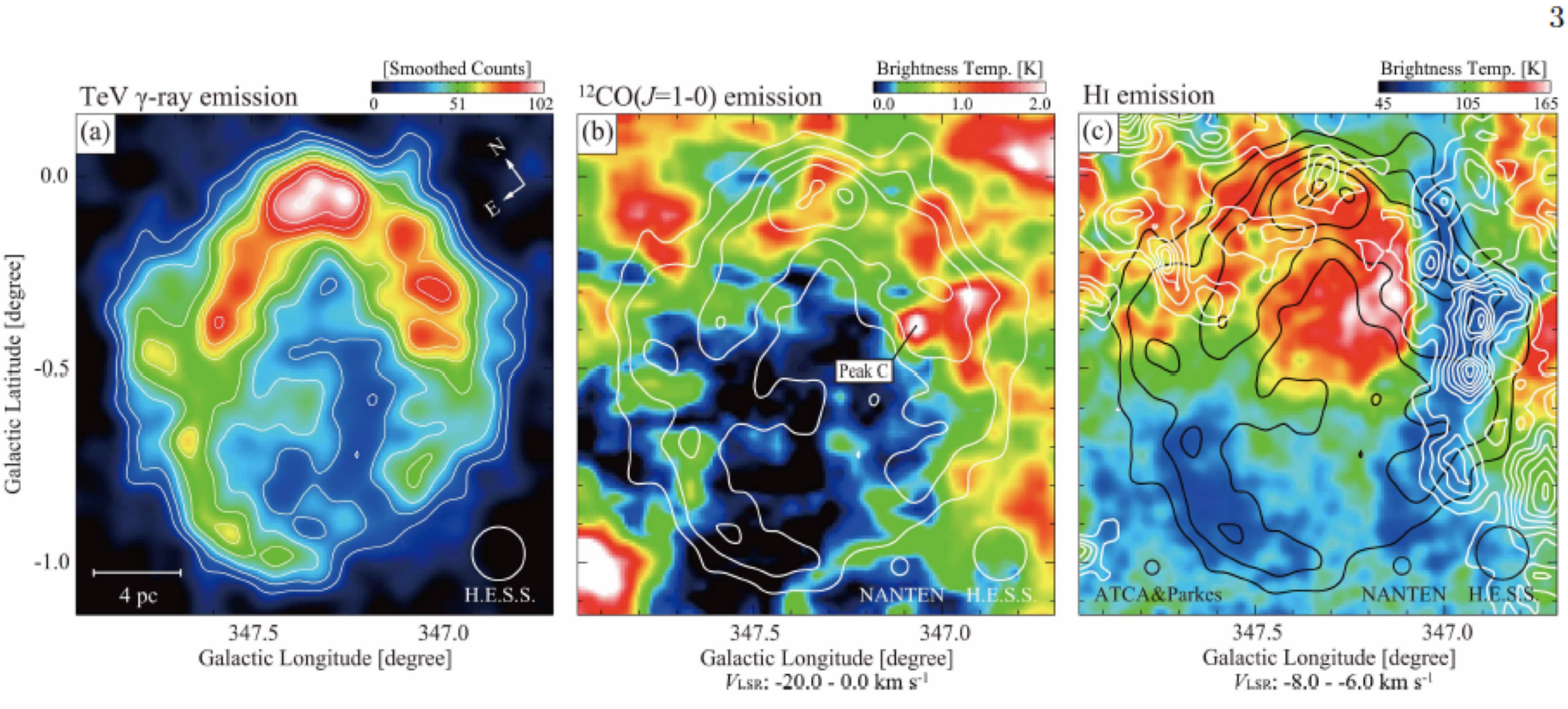


Aharonian et al. 2005



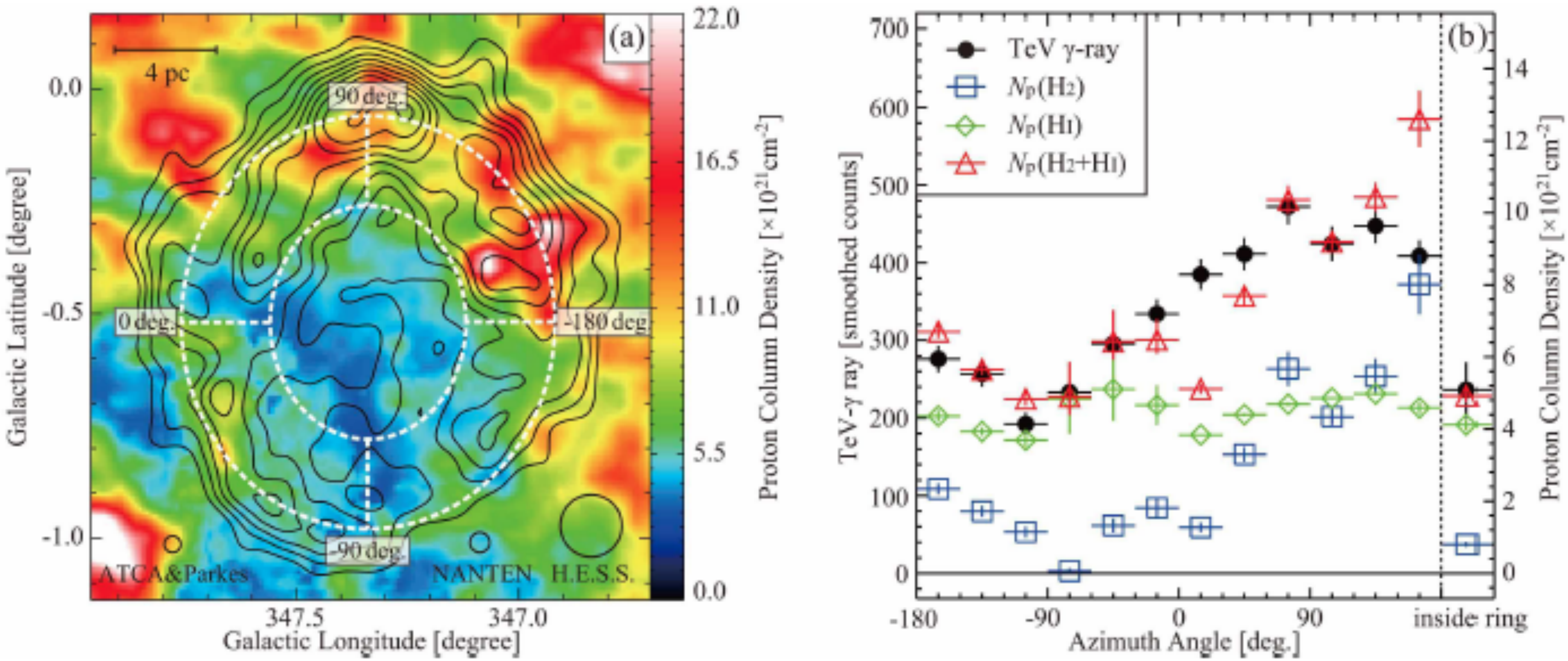


RX J1713.7-3946



Fukui et al. 2012, ApJ, 746, 82

ISM protons in RX J1713.7-3946
Support hadronic scenario
NO leptonic?

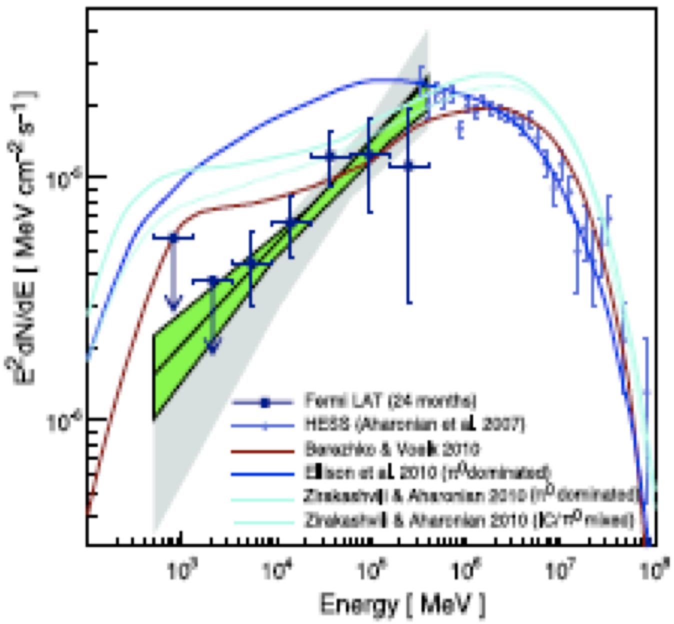


HI + $2H_2$

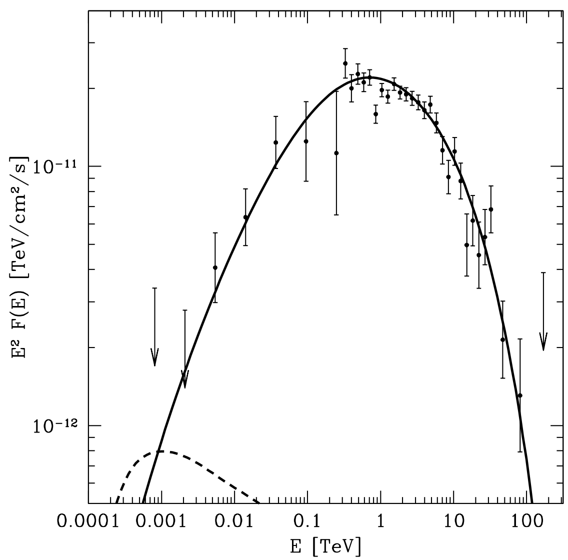
Fukui et al. 2012

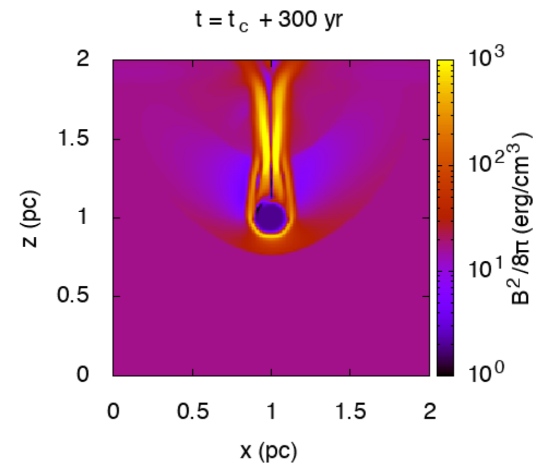
Gamma-ray spectrum of RX J1713

Abdo et al. 2011



S. Gabici and F. A. Aharonian





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.
(Inoue, Yamazaki, Inutsuka, Fukui 2012, Gabici&Aharonian 2014, Celli+ 2018)

New hybrid analysis

H.E.S.S. Collaboration 2018

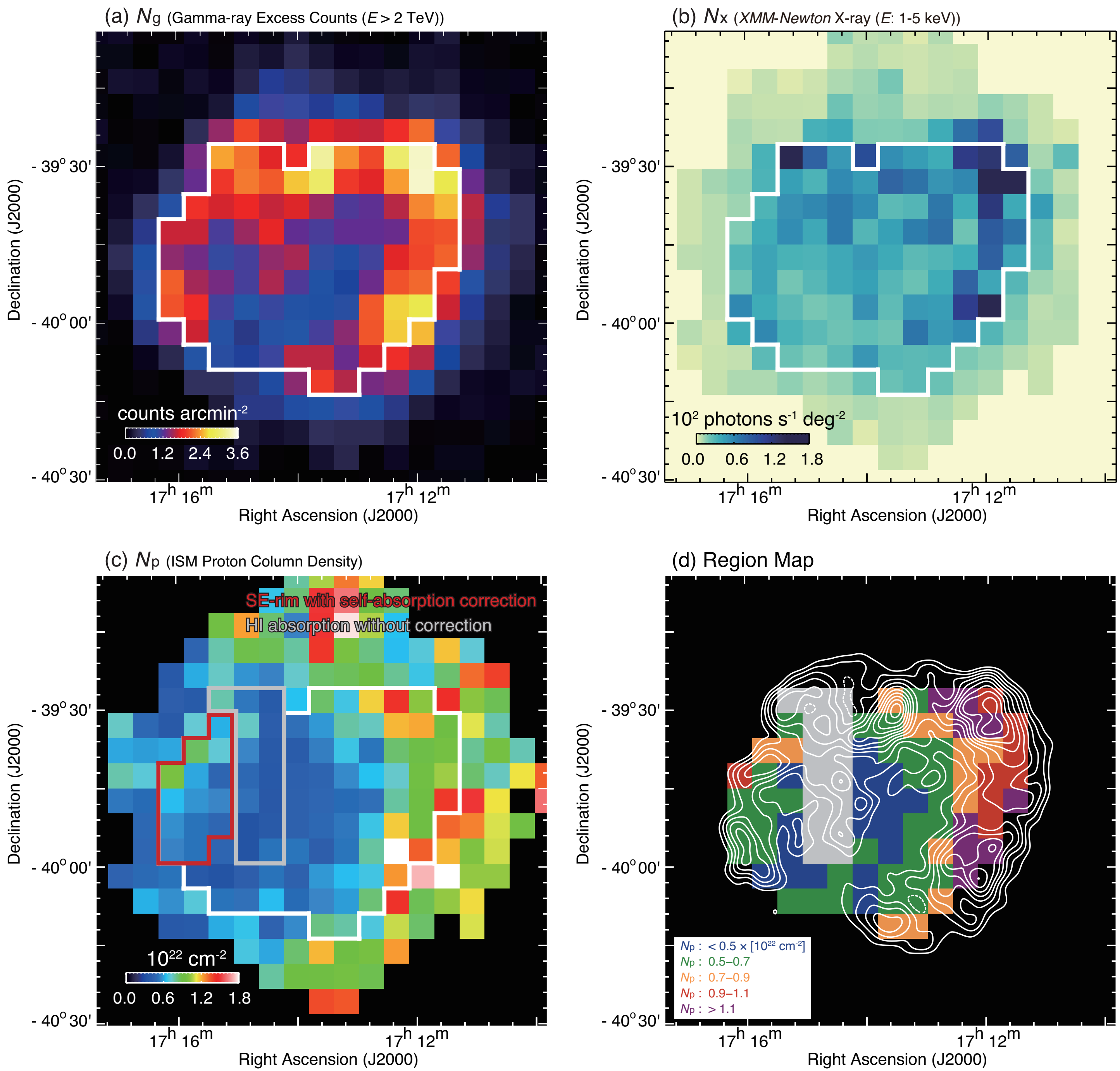
- TeV gamma rays (more than 250 GeV, 10-yr accumulation)
  spatial resolution 4pc→1.4pc
  —Detailed analysis with X rays, the spectrum is explicable either by the hadronic or leptonic origin

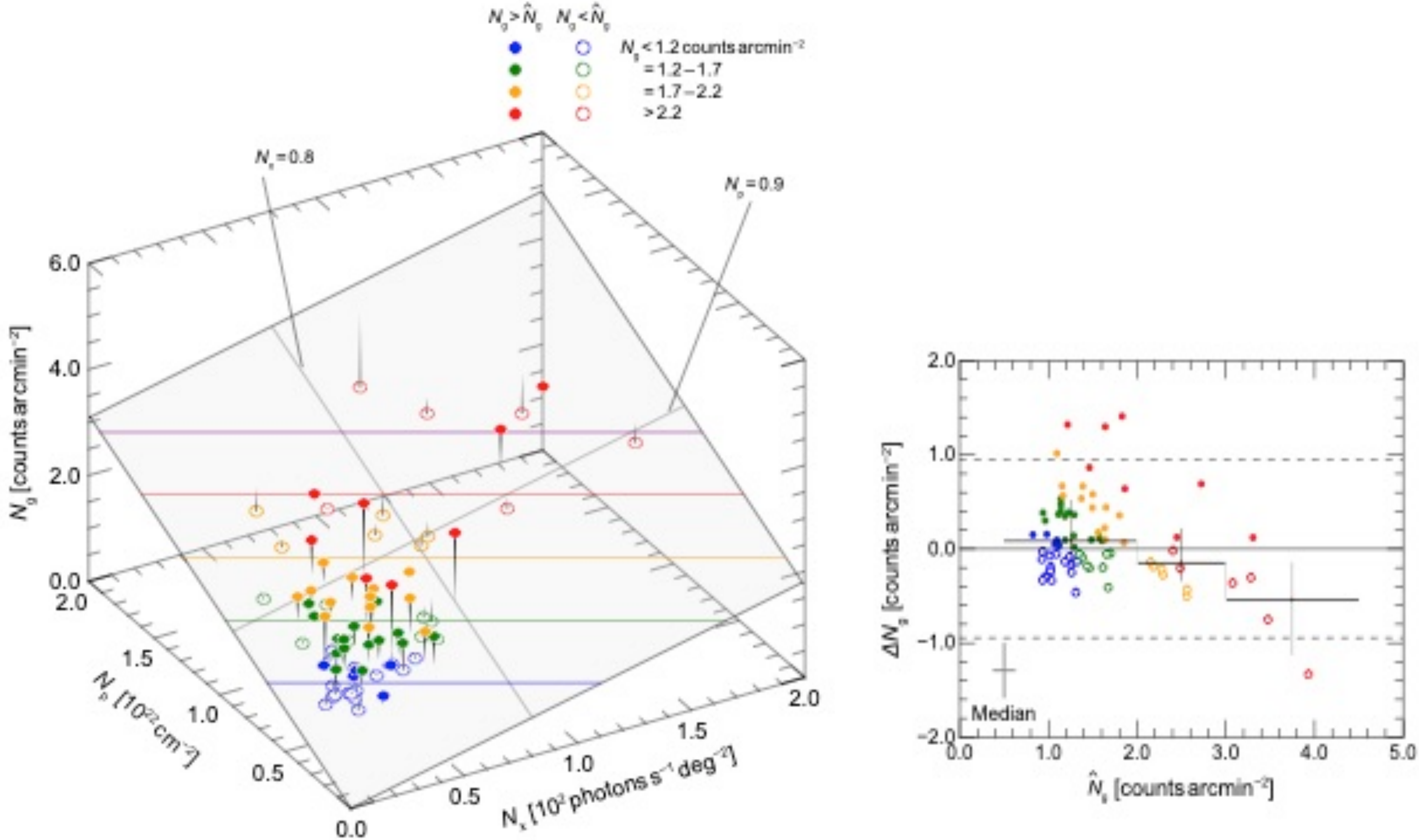
Fukui et al. 2021

- Gamma rays Ng(excess counts arcmin^-2), interstellar protons Np(10^22 cm^-2), non-thermal X rays Nx(100 phtons s-^-1 degrees^-2)
- Assume two linear terms proportional to Np and Nx

  Ng = a x Np + b x Nx : hadronic origin＋ leptonic origin

  fitting in a 3D space


(a) Ng (Gamma-ray Excess Counts (E > 2 TeV))
(b) Nx (XMM-Newton X-ray (E: 1-5 keV))
(c) Np (ISM Proton Column Density)
SE-rim with self-absorption correction
HI absorption without correction
(d) Region Map
counts arcmin-2
10² photons s-1 deg-2
10²² cm-2
Np : < 0.5 × [10²² cm-2]
Np : 0.5–0.7
Np : 0.7–0.9
Np : 0.9–1.1
Np : > 1.1
Declination (J2000)
Right Ascension (J2000)



$$\hat{N}_{\rm g} = (1.57 \pm 0.14) \times N_{\rm p} + (0.91 \pm 0.19) \times N_{\rm x},$$

Hadronic origin: Leptonic origin = (67±6)%: (27±8)%

Hadronic dominant (Zirakashvili & Aharonian 2010)

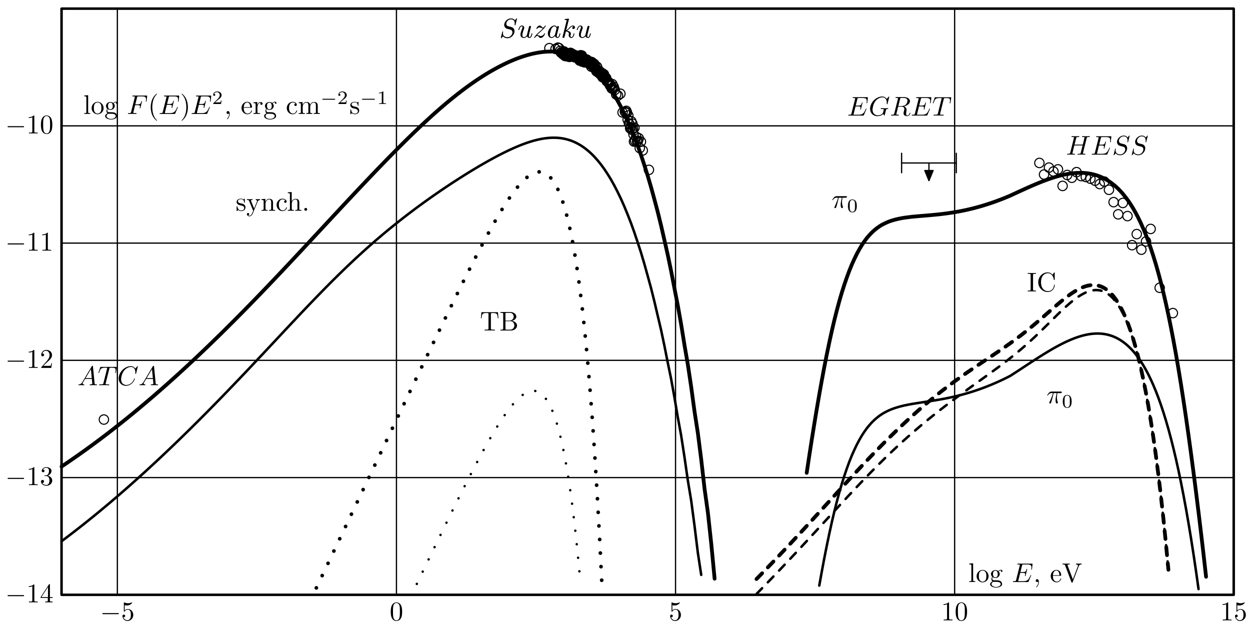


Fig. 6.— The results of modeling of of nonthermal radiation of RX J1713.7-3946 within the hadronic scenario of gamma-ray production. The following basic parameters are used: $t = 1620$ yr, $D = 1.2$ kpc, n_H =0.09 cm^{-3}, $E_{SN} = 2.7 \cdot 10^{51}$ erg, $M_{ej} = 1.5M_{\odot}$, $M_A^f = M_A^b = 23$, $\xi_0 = 0.05$, 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 $B_f = 127$ μG and $B_b = 21$ μG 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 ± 2 Jy at 1.4GHz (ATCA; Acero al. 2009) from the whole remnant are also shown.

Leptonic dominant (Zirakashvili & Aharonian 2010)

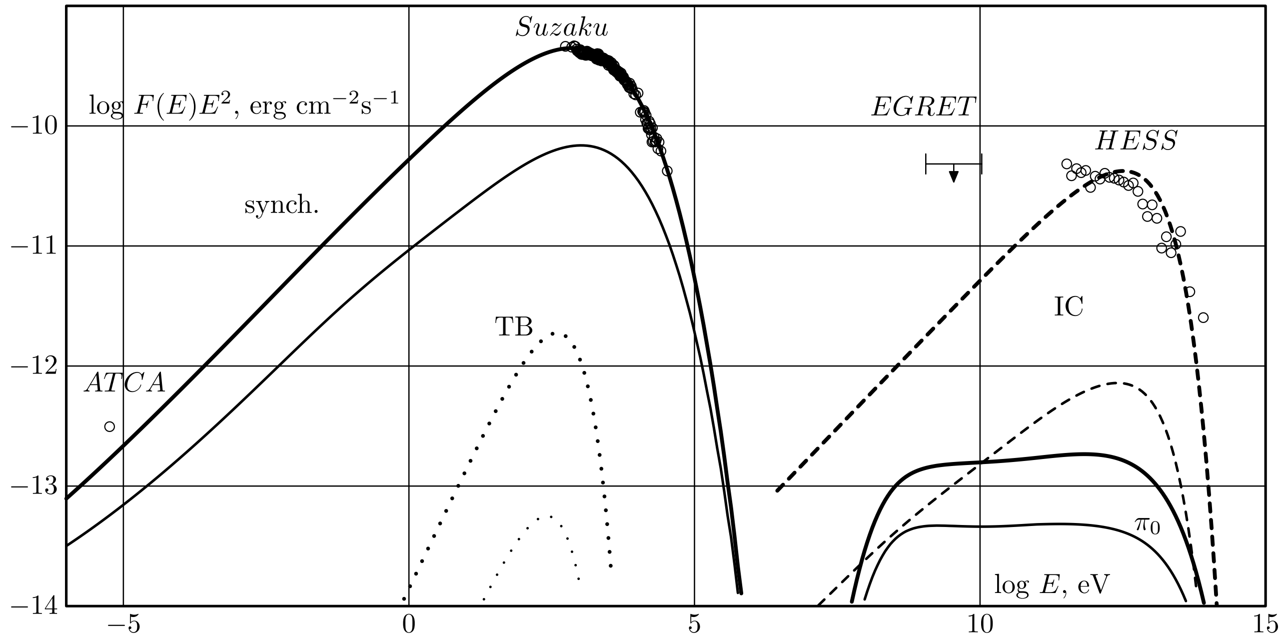


Fig. 8.— Broad-band emission of RX J1713.7-3946 for the leptonic scenario of gamma-rays with a non-modified forward shock. The principal model parameters are: $t = 1620$ yr, $D = 1.5$ kpc, n_H =0.02 cm^{-3}, $E_{SN} = 1.2 \cdot 10^{51}$ erg, $M_{ej} = 0.74 M_\odot$, $M_A^f = 69$, $M_A^b = 10$, $\xi_0 = 0.1$, $K_{ep}^f = 2.3 \cdot 10^{-2}$, $K_{ep}^b = 9 \cdot 10^{-4}$. 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 $B_f = 17$ μG and $B_b = 31$ μG, 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.

Hybrid origin (Zirakashvili & Aharonian 2010)

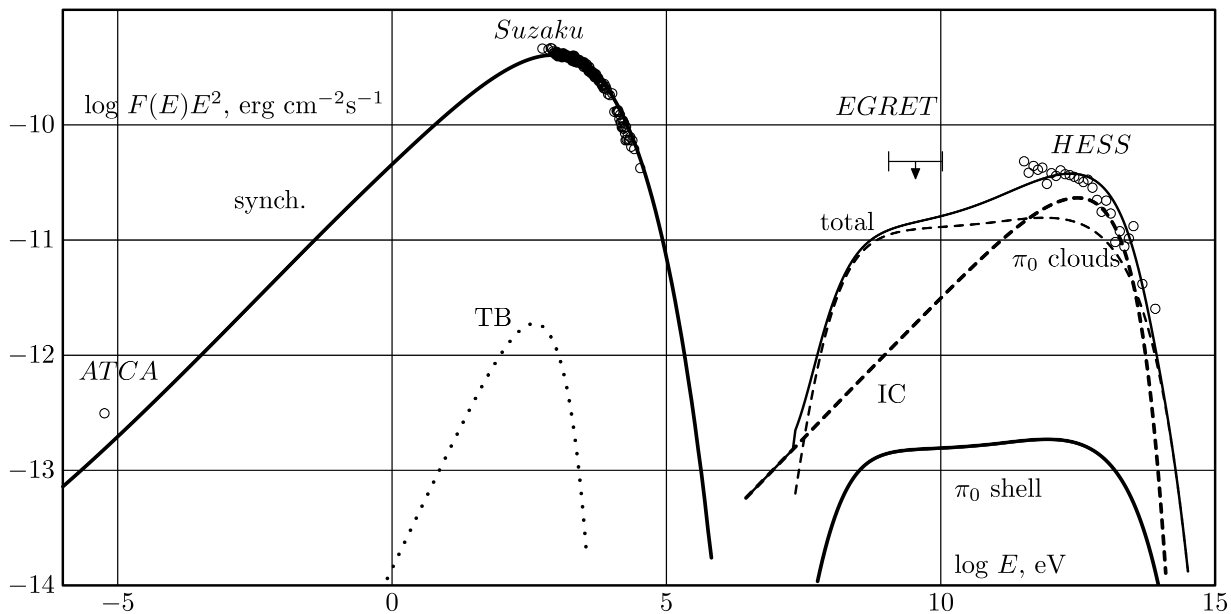
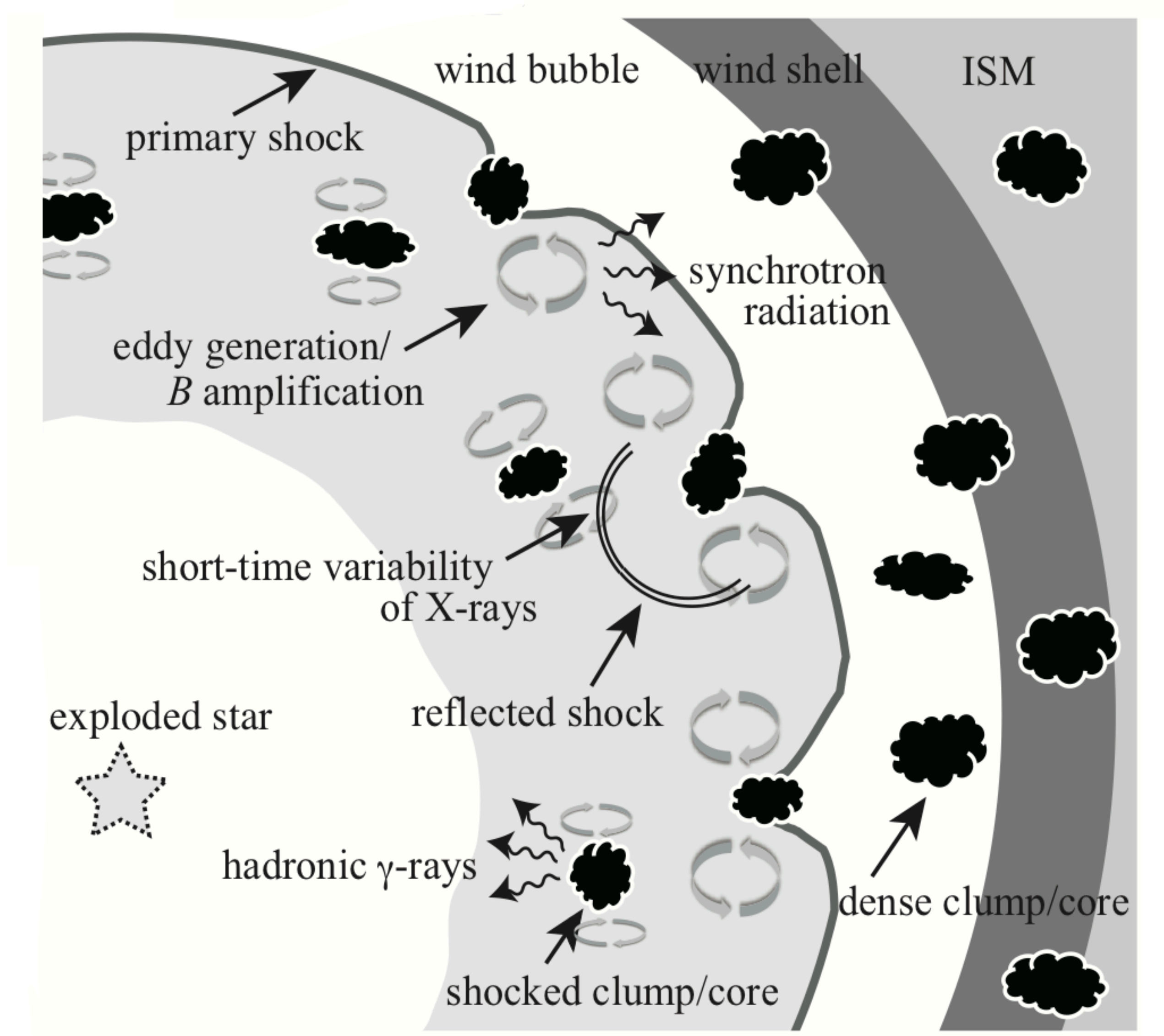


Fig. 14.— Broad-band emission of RX J1713.7-3946 for the composite scenario of gamma-rays with a non-modified forward shock and dense clouds. The principal model parameters are: t = 1620 yr, D = 1.5 kpc, n_H =0.02 cm^{-3}, $E_{SN} = 1.2 \cdot 10^{51}$ erg, $M_{ej} = 0.74 M_\odot$, $M_A^f = 55$, $M_A^b = 10$, $\xi_0 = 0.1$, $K_{ep}^f = 1.4 \cdot 10^{-2}$, $K_{ep}^b = 9 \cdot 10^{-4}$. 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 $B_f = 22$ μG and $B_b = 31$ μG, 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), thermal bremsstrahlung (dotted line), IC gamma-ray emission of the entire remnant including forward and reverse shocks (dashed line), hadronic component of gamma-rays from the remnant's shell (solid line on the right) as well as from dense clouds assuming the factor of 120 enhancement of the flux (thin dashed line). We also show the total gamma-ray emission from the entire remnant including the dense clouds (thin solid line).



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

Summary：Gamma rays are of hybrid origin

Hadronic vs. leptonic in RX J1713

-Hadronic origin: Leptonic origin = (67±6)%: (27±8)%

first separation of the two origins, hadronic dominant

ーFukui+12 showed the hadronic component,

but too low spatial resolution, nearly three times coarser than the present H.E.S.S. data, to confirm the leptonic component

The large amount of the ISM protons (10^4 Mo) causes the significant hadronic component

ISM evolution in Myr vs. shock waves expansion in kyr

Future broad applications of the method to the other SNRs with CTA results, quantification of the gamma ray origin