Pursuing the Origin of the Gamma Rays in RX J1713.7-3946 Quantifying the Hadronic and Leptonic Components


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1. Cosmic-rays & Supernova Remnants

☑ It is a longstanding question how cosmic-ray (CR) protons are accelerated in interstellar space.

☑ Supernova remnants (SNRs) are the most likely candidates for acceleration because the high-speed shock waves offer an ideal site for the DSA [e.g.,1,2].

2. Hadronic gamma-rays from young SNRs

☑ TeV gamma-rays from young SNRs are mainly produced by relativistic CR protons and/or electrons close to PeV through two mechanisms, called hadronic or leptonic processes (Fig.1).

☑ Numerous attempts have been made to distinguish the two processes using broadband spectral modeling [e.g.,3]. In most cases, however, it is difficult to distinguish between hadronic and leptonic gamma-rays by the spectral modeling alone (Fig.1., [e.g., 3,4,5]).

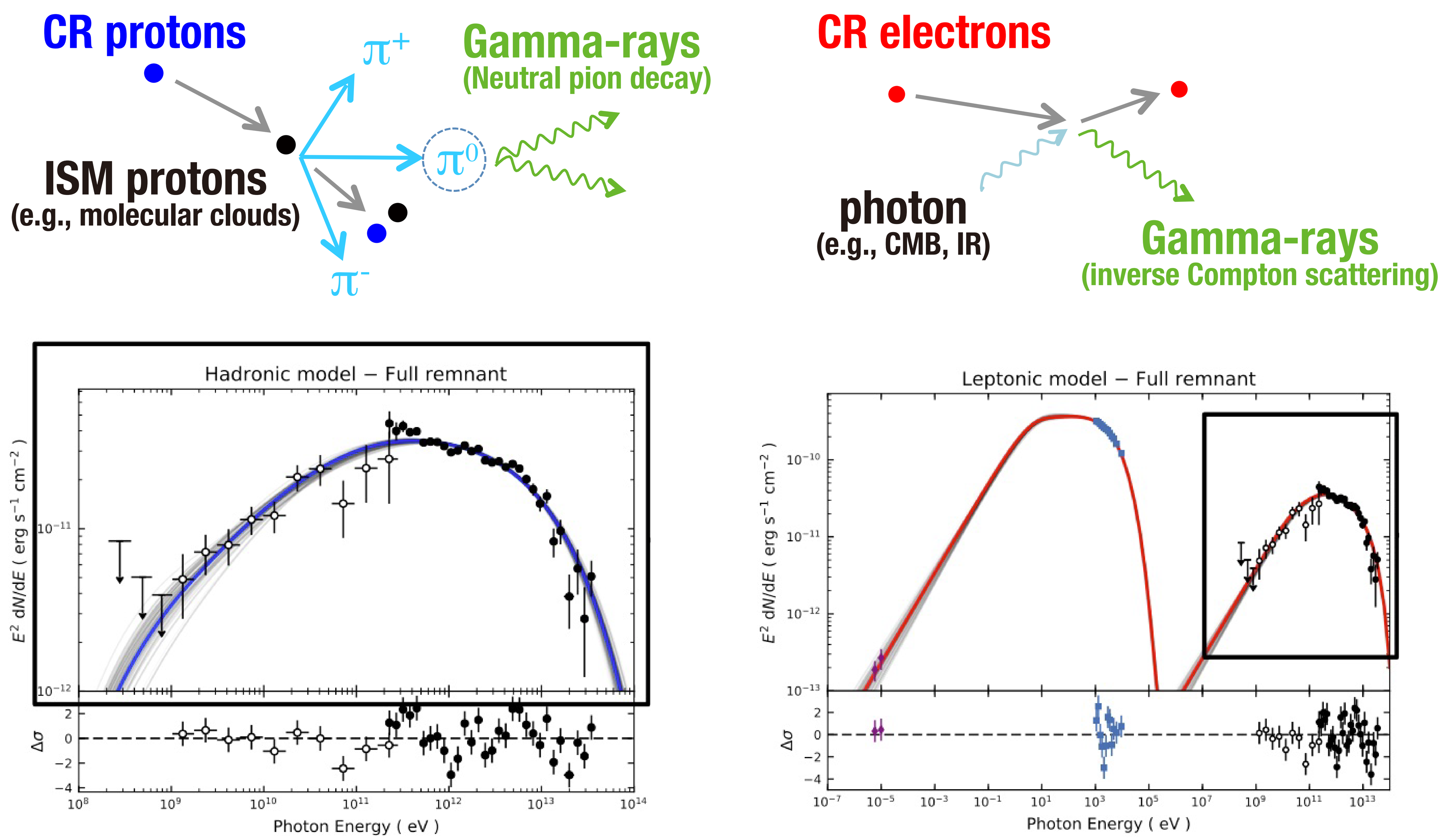


Fig. 1: (upper panels) Schematic images of hadronic and leptonic gamma-rays. (lower panels) Results of spectral modeling toward the TeV gamma-ray SNR RX J1713.7−3946 by H.E.S.S. collaboration et al. [3].

3. Spatial correspondence between the ISM protons & gamma-rays

☑ The hadronic gamma-ray flux is proportional to the target-gas density.

☑ We presented good spatial correspondence between TeV gamma-rays and ISM protons in the young SNRs RX J1713.7–3946, Vela Jr., HESS J1731-347, and RCW 86. This provides one of the essential conditions for gamma-rays to be predominantly of hadronic origin [6-9].

☑ The total energy of CR protons, ~10^{48}–10^{49} erg, derived using ISM density gives a lower limit.

Open question: How much do leptonic gamma-rays contribute to the total gamma-rays?

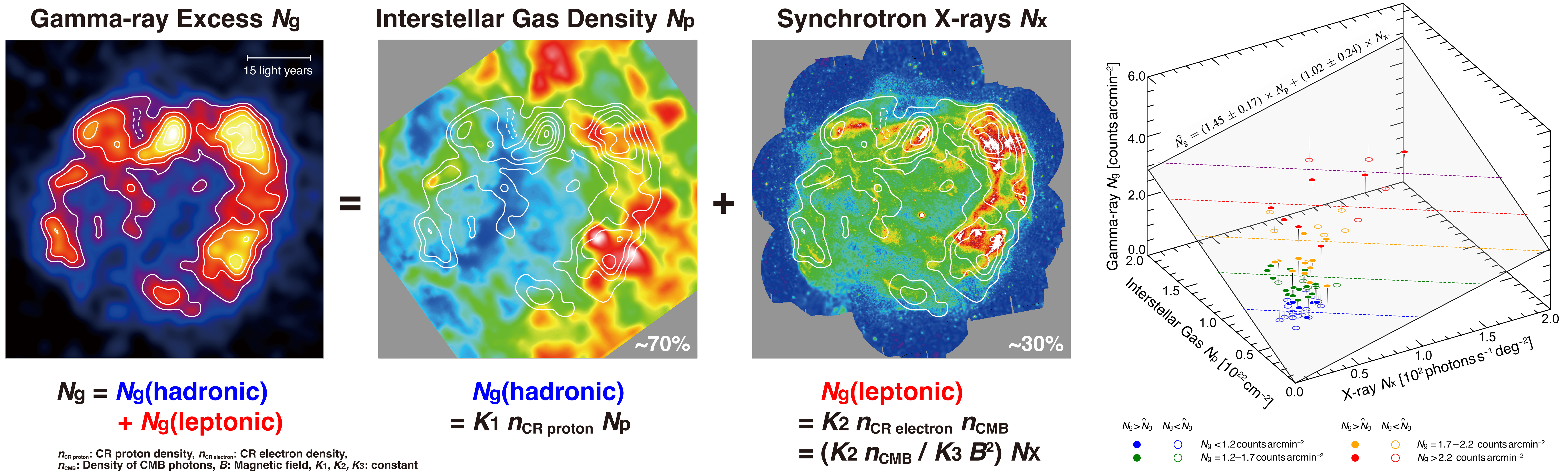
The gamma-rays from these SNRs are mainly of hadronic origin, while a contribution from the leptonic component was not excluded. We aim to quantify the hadronic and leptonic gamma-rays by imaging analysis of the gamma-ray, X-ray, and the ISM in RXJ1713.

4. A novel imaging analysis of radio, X-ray, and gamma-ray radiation in RXJ1713

☑ We propose a new methodology that assumes that the number of gamma-ray counts N_g is expressed as a linear combination of two terms: one (hadronic gamma-ray) is proportional to the ISM column density N_p and the other (leptonic gamma-ray) is proportional to the X-ray count N_x (see Fig.2, [10]).

☑ By fitting the expression to the data pixels, we find that the gamma-ray counts are well represented by a tilted flat plane in a 3D space of N_p–N_x–N_g. This plane illustrates that the total number of gamma rays N_g increases with N_p and N_x, respectively, which is consistent with the hybrid picture.

☑ The results show that the hadronic and leptonic components occupy (58–70)% and (25–37)% of the total gamma rays, respectively ➡ **Further support for the acceleration of the CR protons!**



$N_g = N_g(\text{hadronic}) + N_g(\text{leptonic})$

$N_g(\text{hadronic}) = K_1\, n_{\text{CR proton}}\, N_p$

$N_g(\text{leptonic}) = K_2\, n_{\text{CR electron}}\, n_{\text{CMB}} = (K_2\, n_{\text{CMB}} / K_3\, B^2)\, N_x$

$n_{\text{CR proton}}$: CR proton density, $n_{\text{CR electron}}$: CR electron density, n_{CMB}: Density of CMB photons, B: Magnetic field, K_1, K_2, K_3: constant

Fig. 2: (Left three images) Maps of the H.E.S.S. TeV gamma-rays N_g (left, $E > 2$ TeV, [3]), total interstellar proton column density N_p (middle, [6]), and the XMM-Newton synchrotron X-rays (right, E: 1.0–5.0 keV) in the SNR RX J1713.7−3946. (Right panel) 3D fitting of a flat plane in the N_p–N_x–N_g space with a pixel size of 4.8 arcmin. The data pixels are colored by the code in the figure according to N_g, and are shown by filled and open symbols for those above and below the plane. Each vertical line connects N_g and $\hat{N}_g$ where the hat symbol on $\hat{N}_g$ means that it is predicted by the regression. The blue, green, orange, red, and purple lines on the best-fit plane indicate $\hat{N}_g$ = 1.0, 1.5, 2.0, 2.5, and 3.0 cnt arcmin^{-2}, respectively.

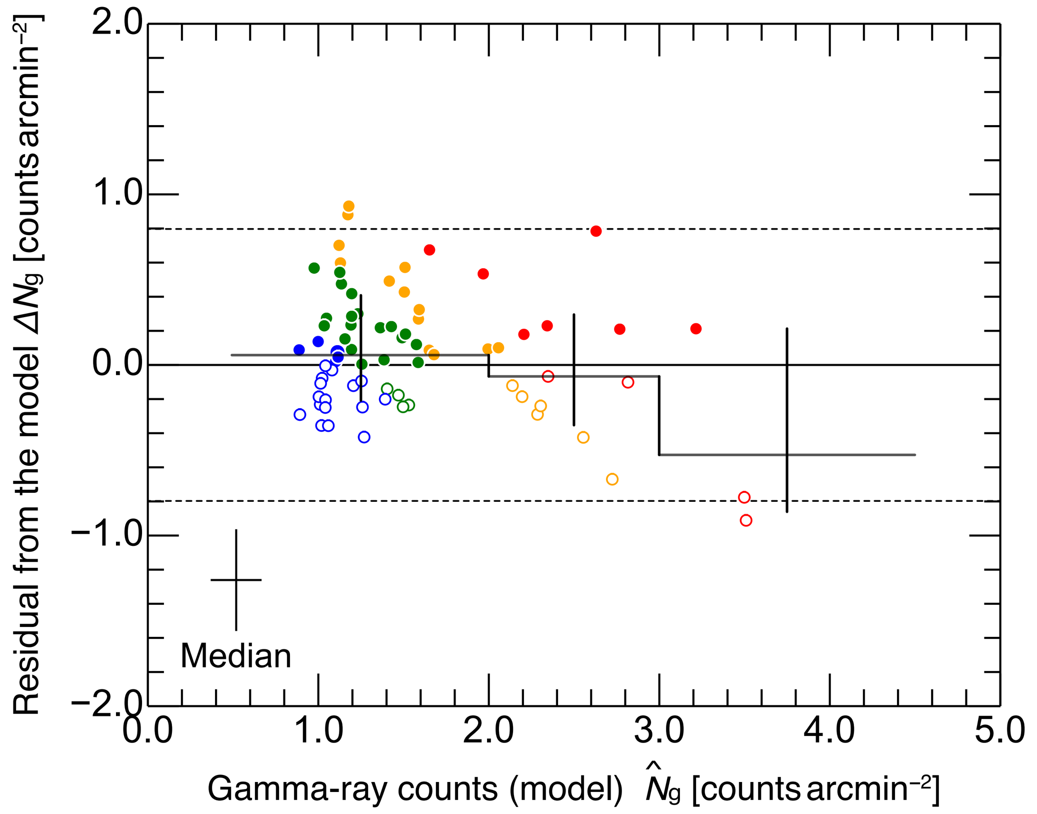


Fig. 3: Plot of the difference $\Delta N_g = N_g - \hat{N}_g$ with respect to $\hat{N}_g$. The averages of ΔN_g weighted with $\sigma(\Delta N_g)^{-2}$ are shown for three bins of $\hat{N}_g$ with the vertical error bars.

5. Discussion and Future Prospects

☑ There is a marginal hint that the gamma rays are suppressed at high gamma-ray counts (see Fig. 3), which may be ascribed to second-order effects including the **shock–cloud interaction** and the effect of penetration depth. **The shock–cloud interaction excites turbulence toward the dense cores and amplifies the magnetic field up to 100 μG ➡ Suppression of the leptonic gamma-rays**

☑ CR protons cannot penetrate into the dense cores because of their limited penetration depth around dense cores where the turbulent magnetic field reduces the CR diffusion. This reduces the hadronic gamma-rays toward the dense cores. Since Sano et al. (2020) [11] also showed clumpy clouds with a size of 0.01 pc scales, a high-resolution ISM study is needed to understand the gamma-ray spectra. **➡ Follow-up observations using ALMA and CTA will solve the issues**

☑ The methodology proposed in the present work has provided a new tool to quantify the leptonic and hadronic gamma-rays and will be applicable to the other gamma-ray bright SNRs. In any case, investigating the ISM associated with gamma-ray SNRs are crucial in understanding the origin of gamma-rays.

6. References

[1] Bell 1978, MNRAS, 182, 147, [2] Blandford & Ostriker (1978), ApJL, 221, 29, [3] H.E.S.S. Collaboration (2018), A&A, 612, A6, [4] H.E.S.S. Collaboration (2018), A&A, 612, A12, [5] Inoue et al. (2012), ApJ, 744, [6] Fukui et al. (2012), ApJ, 746, 82, [7] Fukui et al. (2017), ApJ, 850, 71, [8] Sano et al. (2019), ApJ, 876, 37, [9] Fukuda et al. (2014), ApJ, 788, 94, [10] Fukui et al. (2021), ApJ, 915, 84, [11] Sano et al. (2020), ApJL, 904, L24 ➡ see also the contributed talk #462 (7th July 2022, 16:00–16:15).