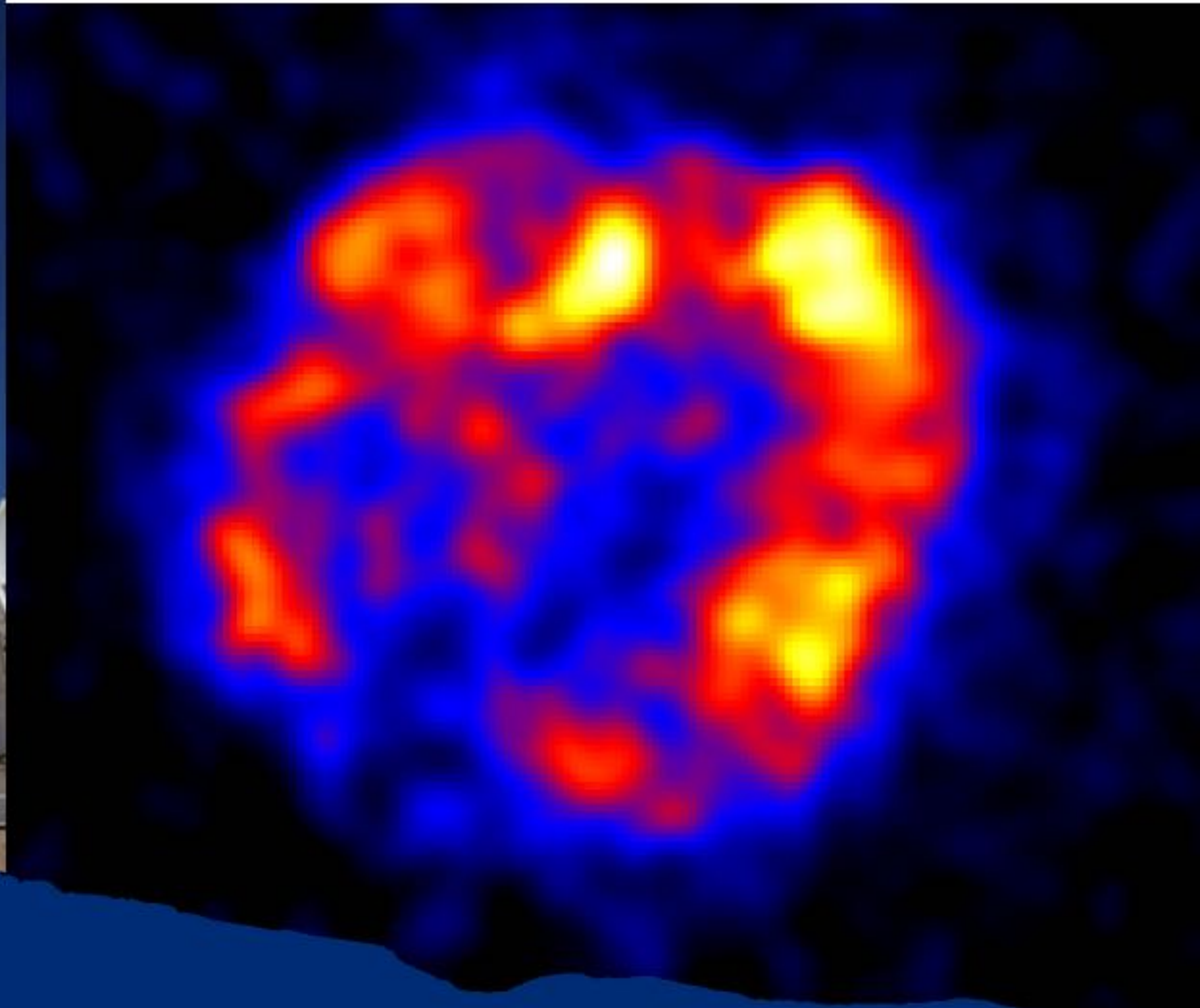
ALMA (©NAOJ)



多波長観測で探る
超新星残骸の高エネルギー現象

佐野栄俊 Hidetoshi Sano (岐阜大学)

東海国立大学機構 MAKE NEW STANDARDS. | 岐阜大学

マルチメッセンジャー天文学の展開
2023年11月2日(木) 11:30–11:45
@東京大学柏キャンパス図書館メディアホール

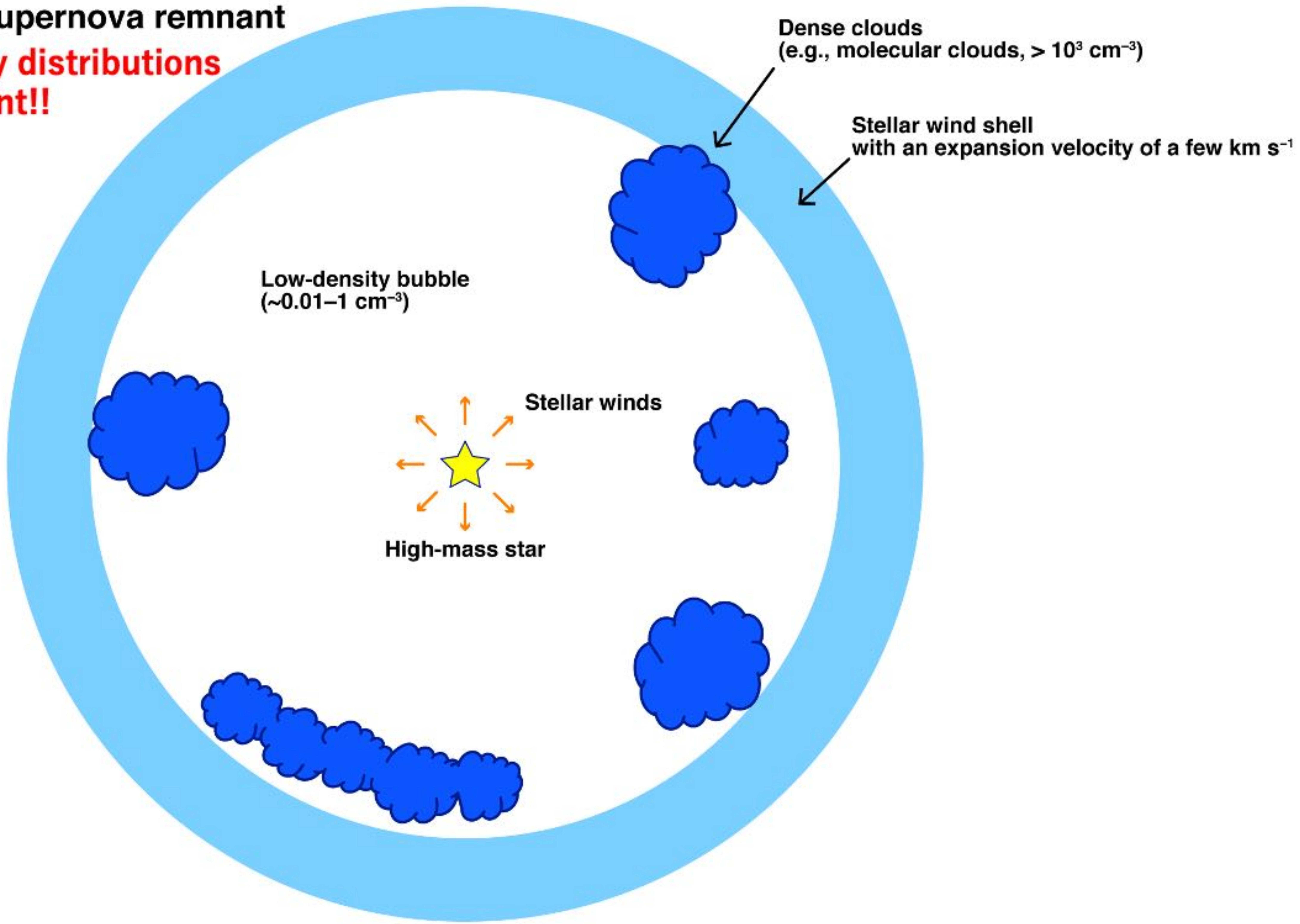
Why supernova remnants?

- Shockwaves, injection of heavy elements, and cosmic-ray production
  → SNRs hold a key to understanding the ISM and galaxy evolution (+ star formation)
- Bright in multi-wavelength from radio to gamma-rays
  → Multi-wavelength studies can reveal physical processes from various aspects

Radio (21 cm, 3 mm)
Infrared (22 μm)
Optical (656.28 nm)
X-rays (1 nm)
Gamma-rays (1 am)
SNR RCW 86
Atomic hydrogen
Molecular hydrogen
Stars (embedded within dust)
Interstellar dust
Stars
Plasma (~10^4 K)
Plasma (~10^7 K)
Heavy elements
Cosmic-ray electrons
Radioisotope
Cosmic-ray electrons & protons
Radio Astronomy
Infrared Astronomy
Optical Astronomy
X-ray Astronomy
Gamma-ray Astronomy
collaborate
collaborate
collaborate
We newly established a strong collaboration

Physical processes in a supernova remnant

Inhomogeneous & clumpy distributions of the clouds are important!!



Physical processes in a supernova remnant

Physical processes in a supernova remnant

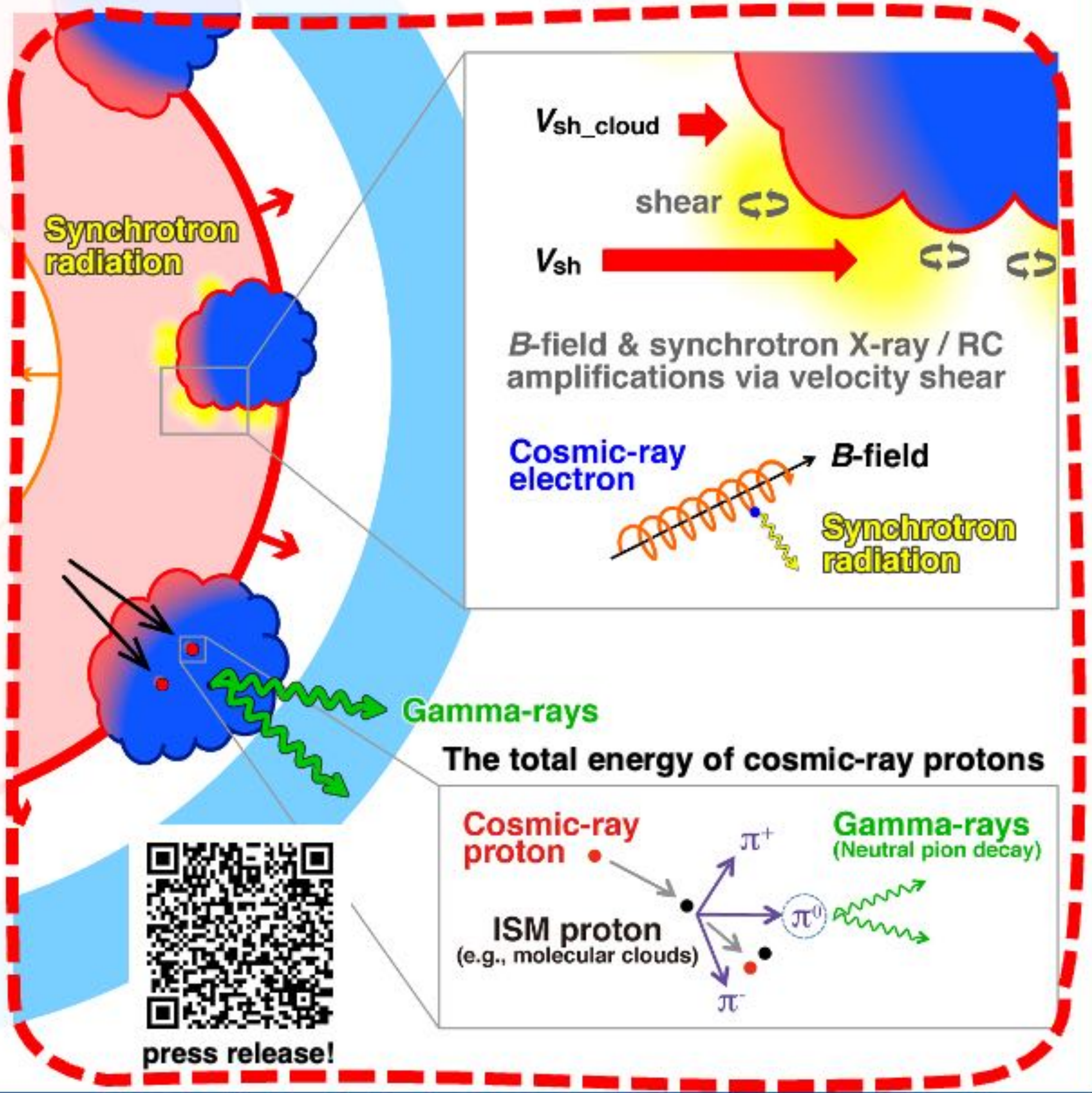
Interstellar gas associated with supernova remnants are essential in understanding the low- and high-energy physical processes in the interstellar medium

① The origin of cosmic-rays

Fukui, Sano et al. (2012), ApJ
Fukui, Sano et al. (2017), ApJ
Sano et al. (2019a), ApJ, 876, 37
Sano et al. (2021a), ApJ, 919, 123
Sano et al. (2021b), ApJ, 923, 15
Sano & Fukui (2021), Ap&SS, 366, 58 [review paper]
Fukui, Sano et al. (2021), ApJ, 915, 84
Sano et al. (2022), ApJ, 933, 157 etc..

② Thermal/non-thermal X-rays via shock-cloud interactions

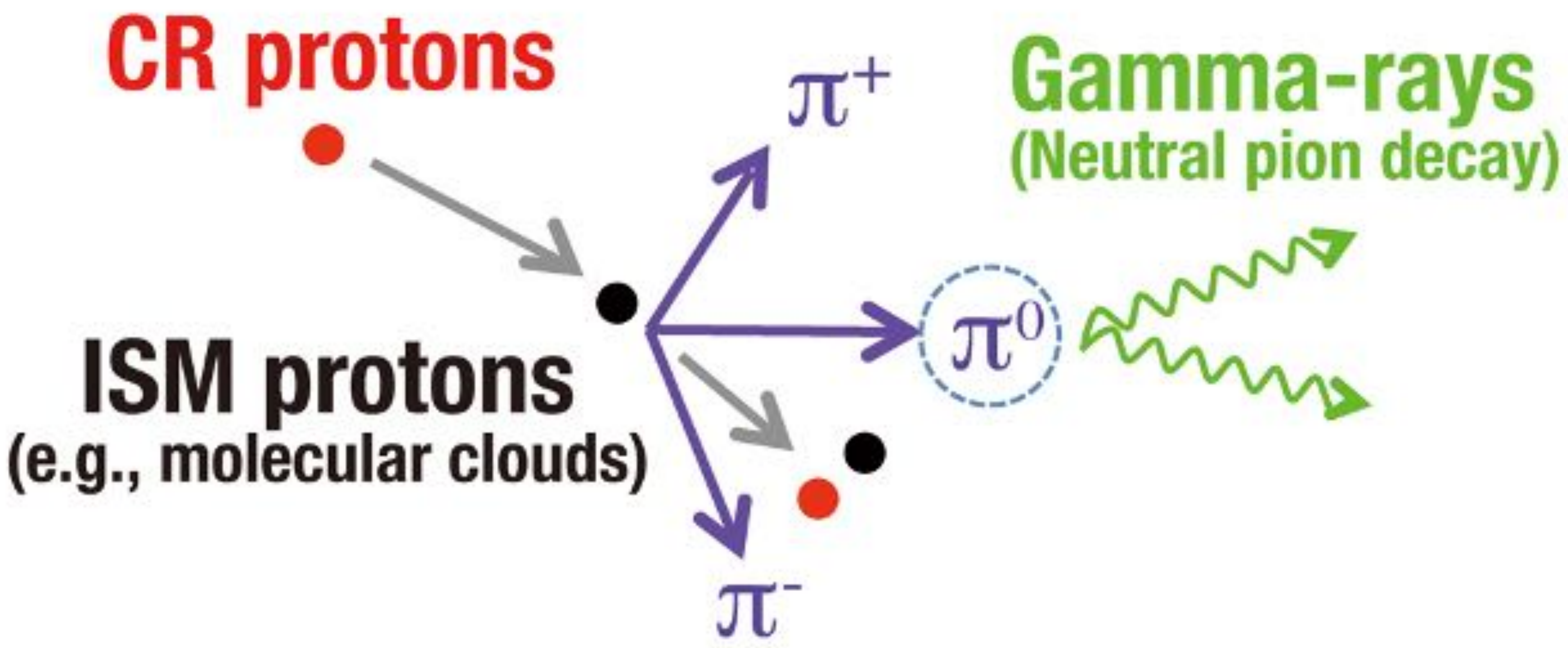
Sano et al. (2010), ApJ, 724, 59
Sano et al. (2013), ApJ, 778, 59
Sano et al. (2015), ApJ, 799, 175
Sano et al. (2017), JHEAp, 15, 1
Sano et al. (2018), ApJ, 867, 7
Sano et al. (2019b), ApJ, 873, 40
Sano et al. (2019c), ApJ, 881, 85
Sano et al. (2020a), ApJL, 904, L24
Sano et al. (2020b), ApJ, 902, 53 etc..

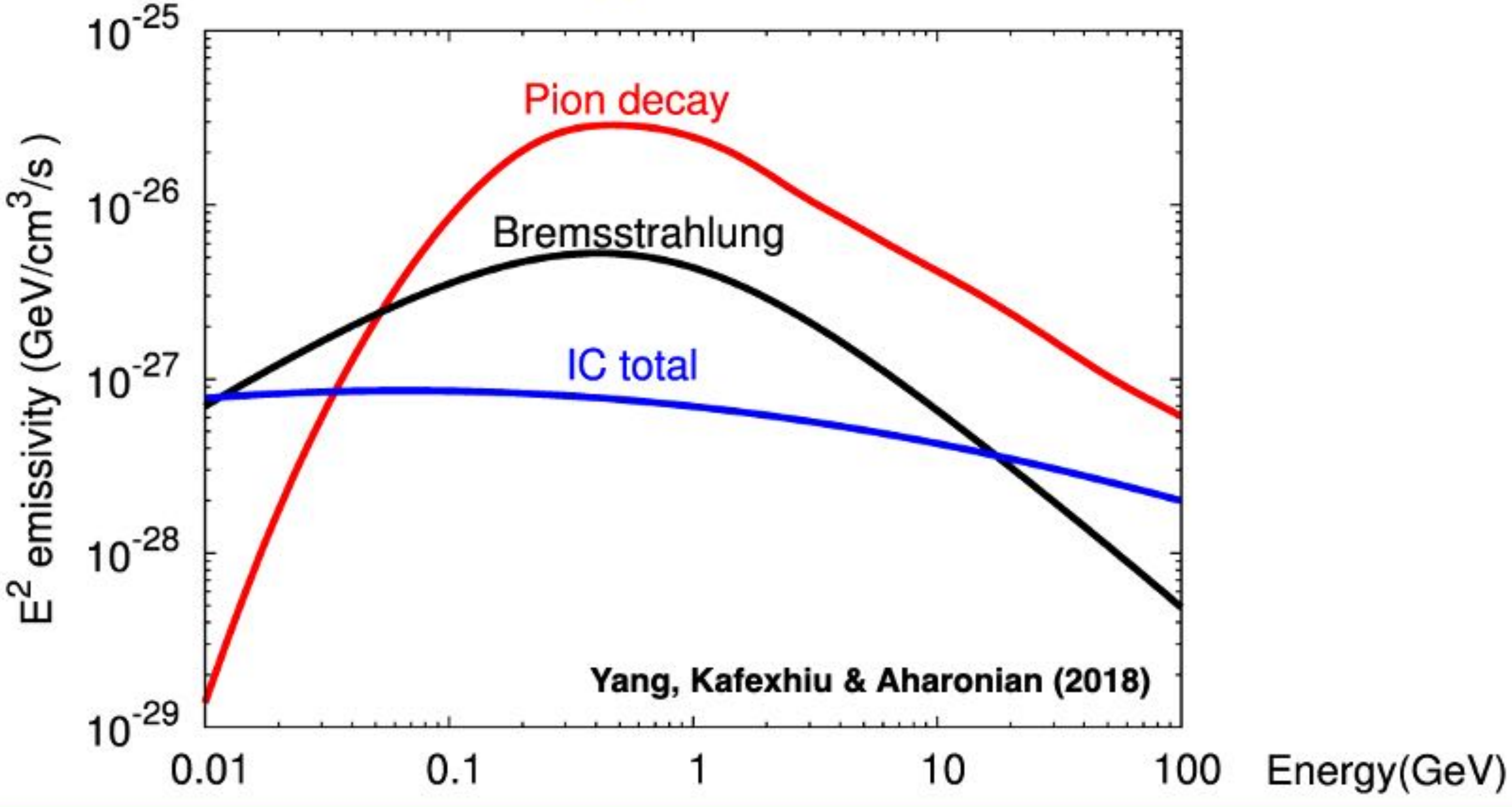


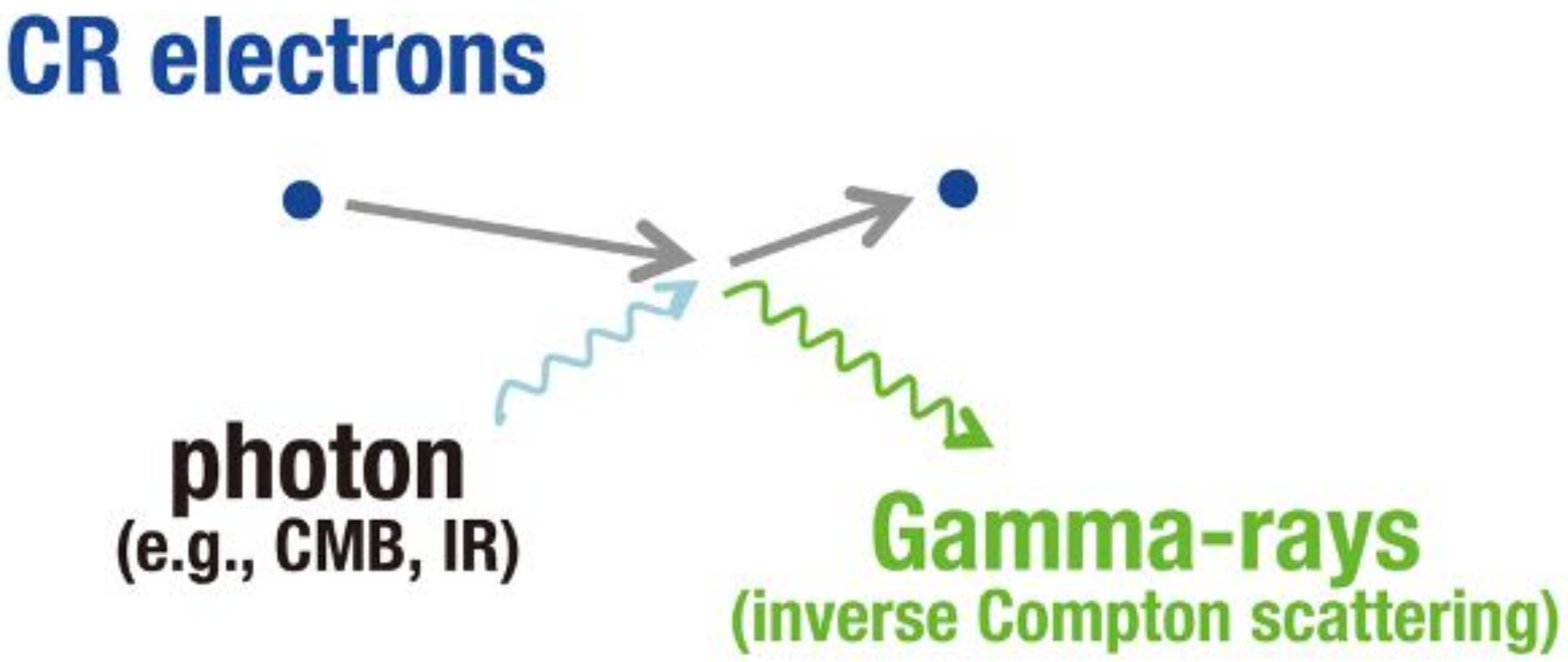
Gamma-ray supernova remnants as CR accelerators

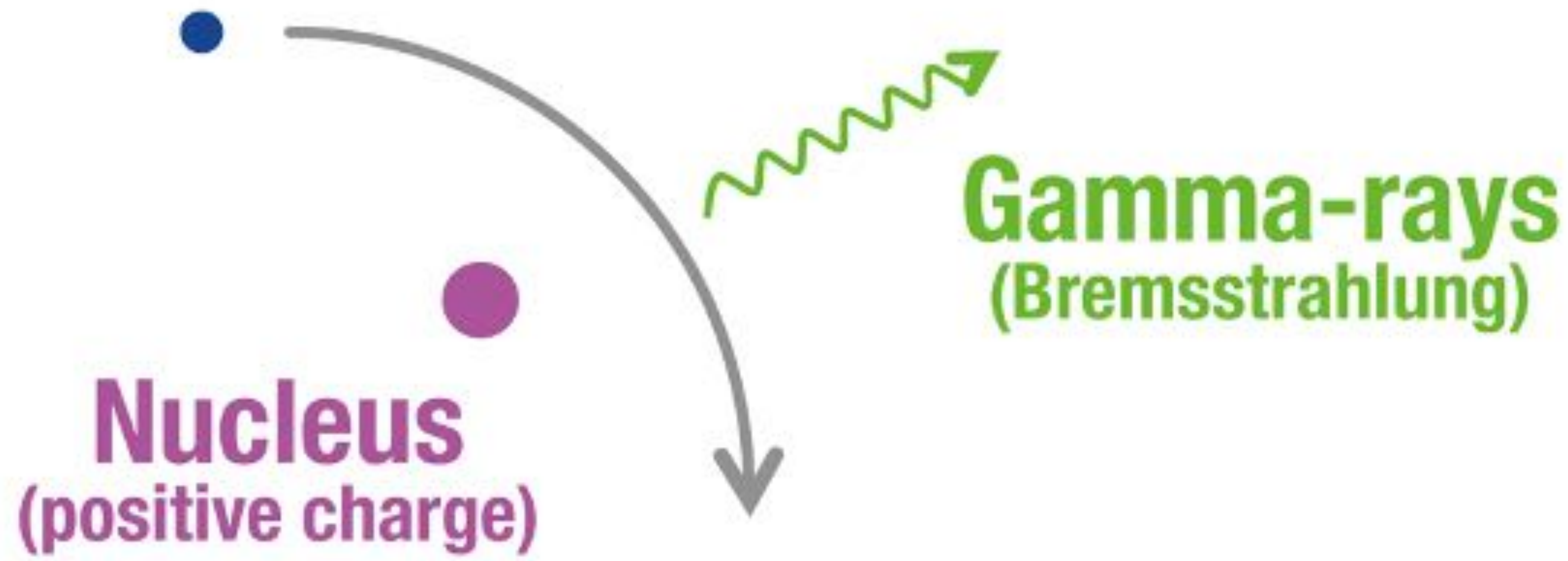
RX J1713.7-3946 (H.E.S.S. Collaboration et al. 2018a)
HESS J1731–347 (H.E.S.S. Collaboration et al. 2011)
W44 (Giuliani et al. 2011)

Hadronic vs. Leptonic Gamma-rays

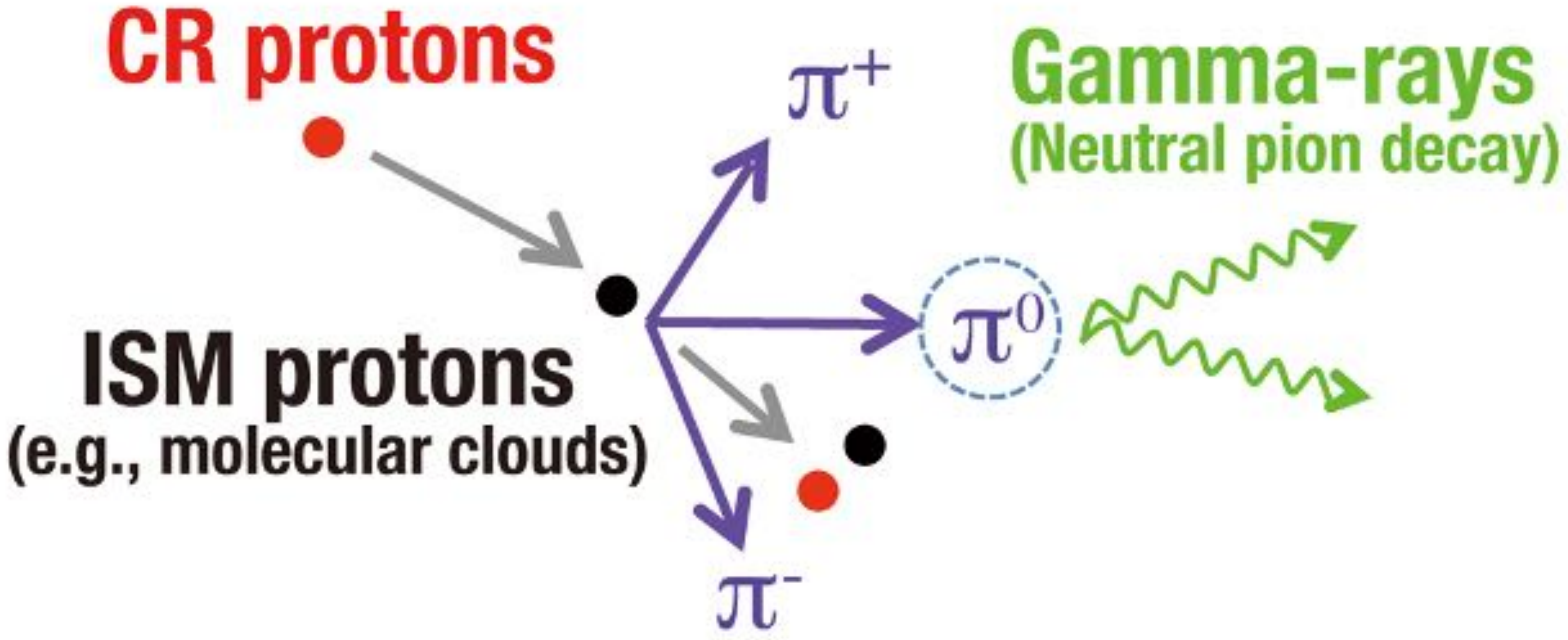


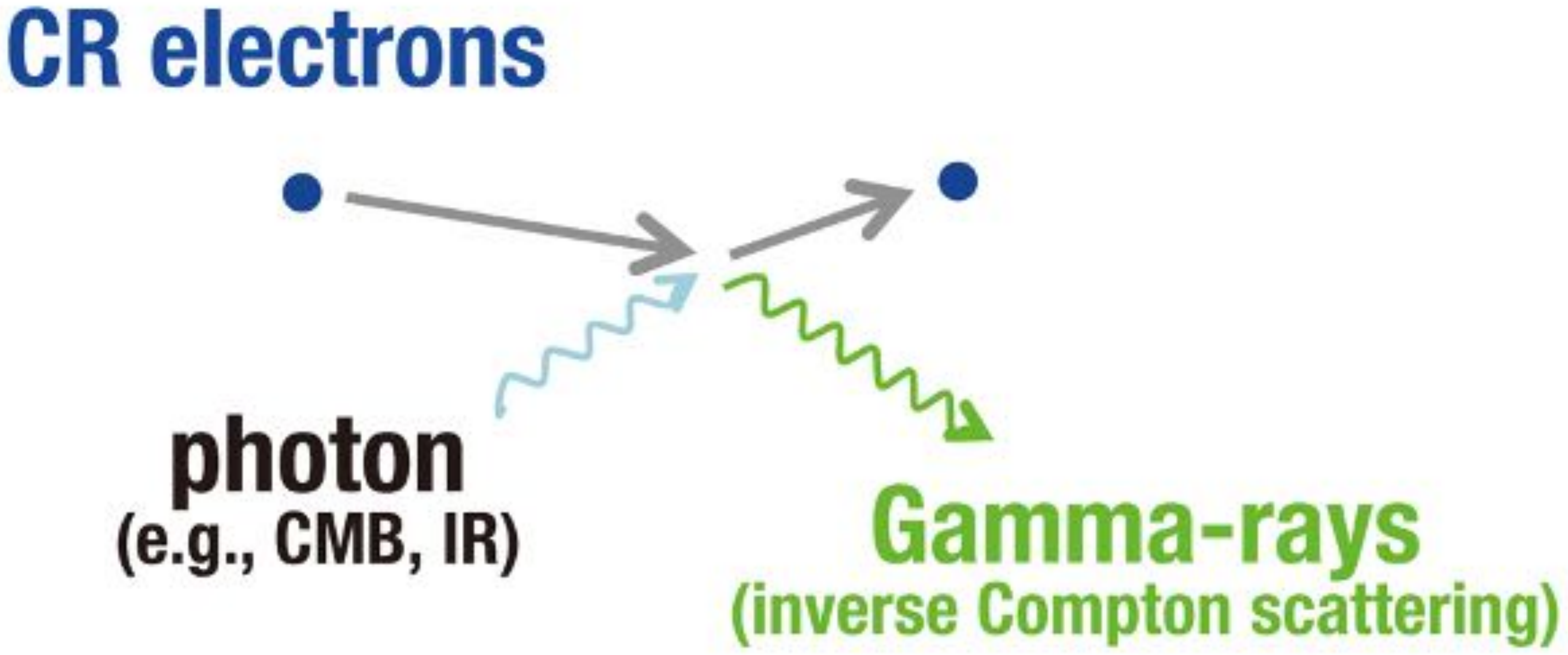


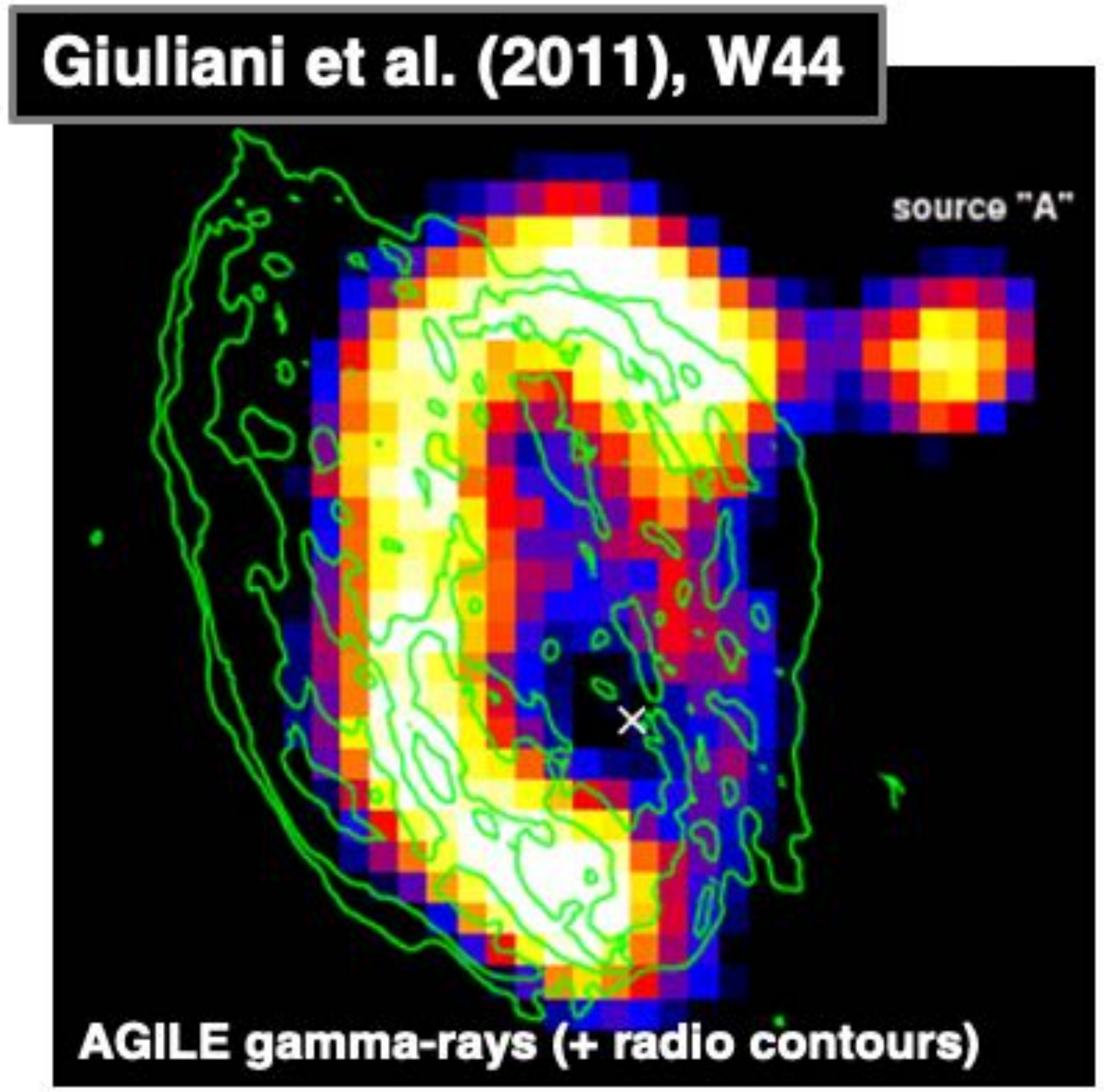


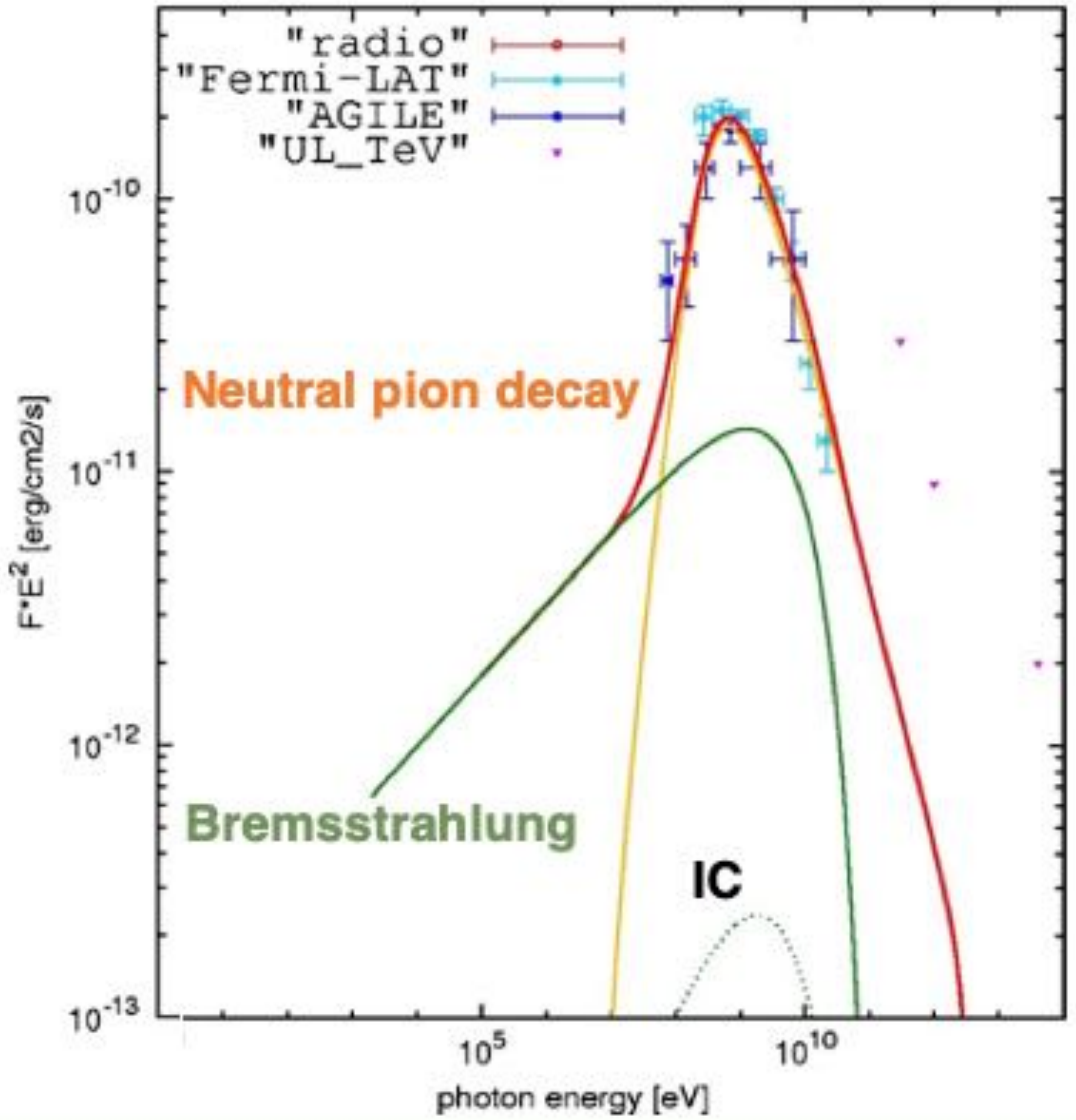


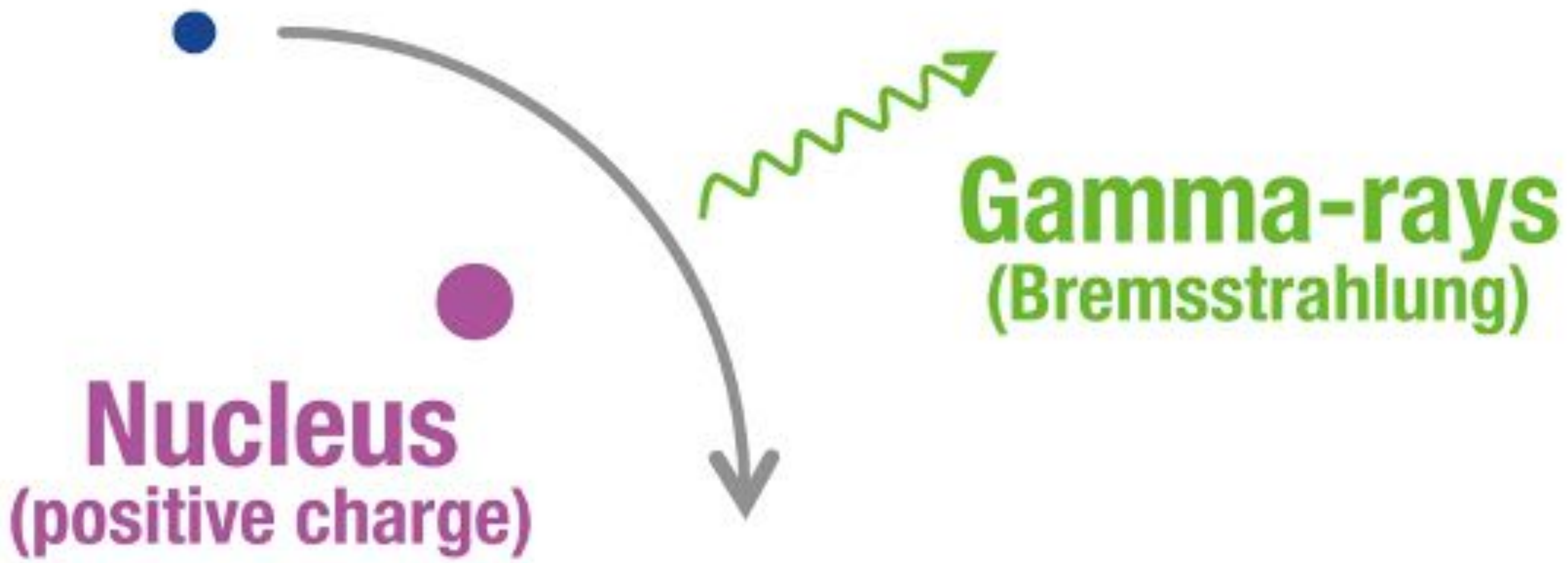
Low-energy gamma-rays are distinguishable





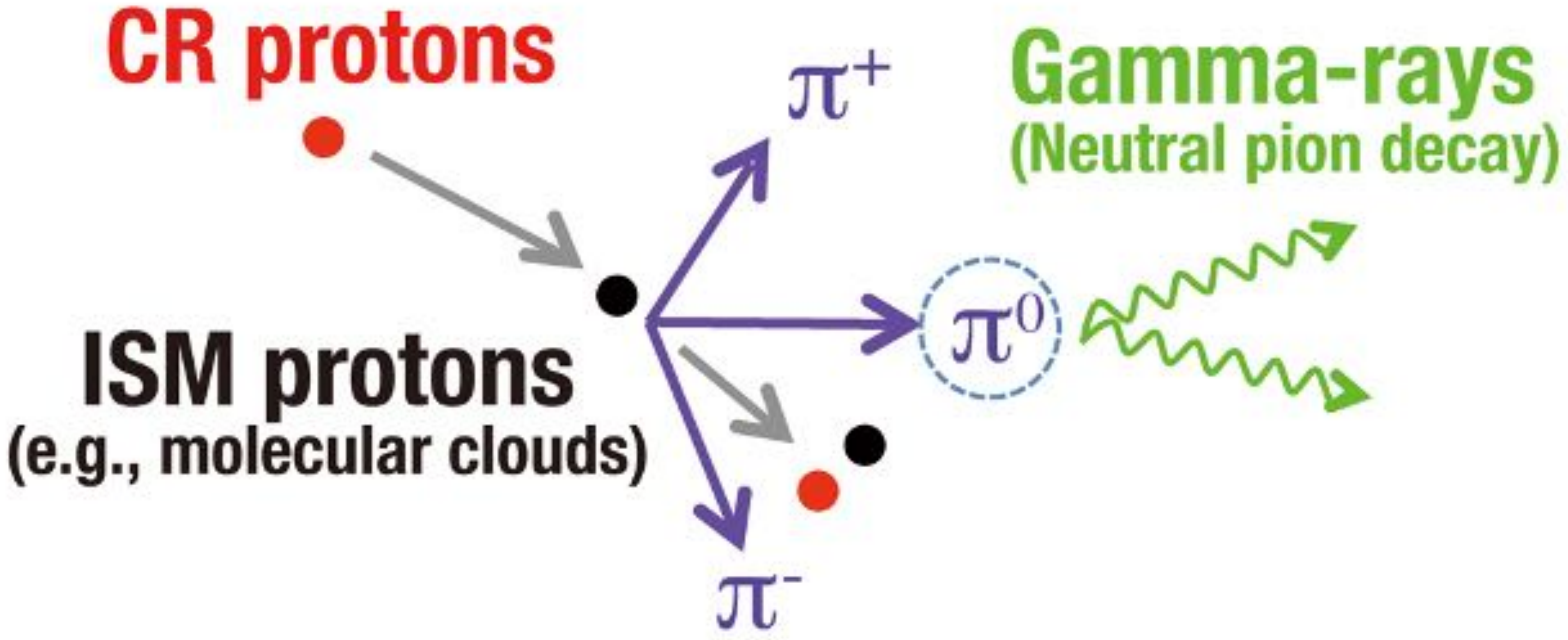


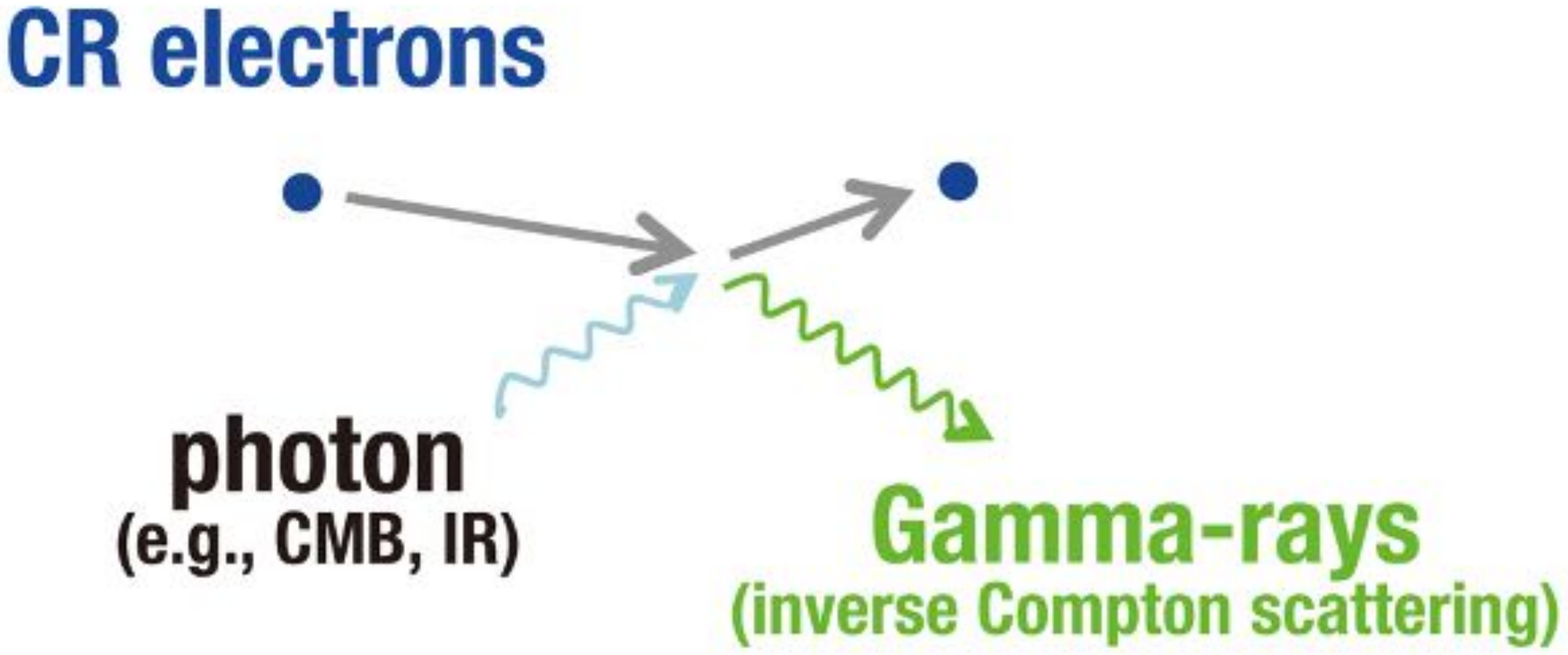


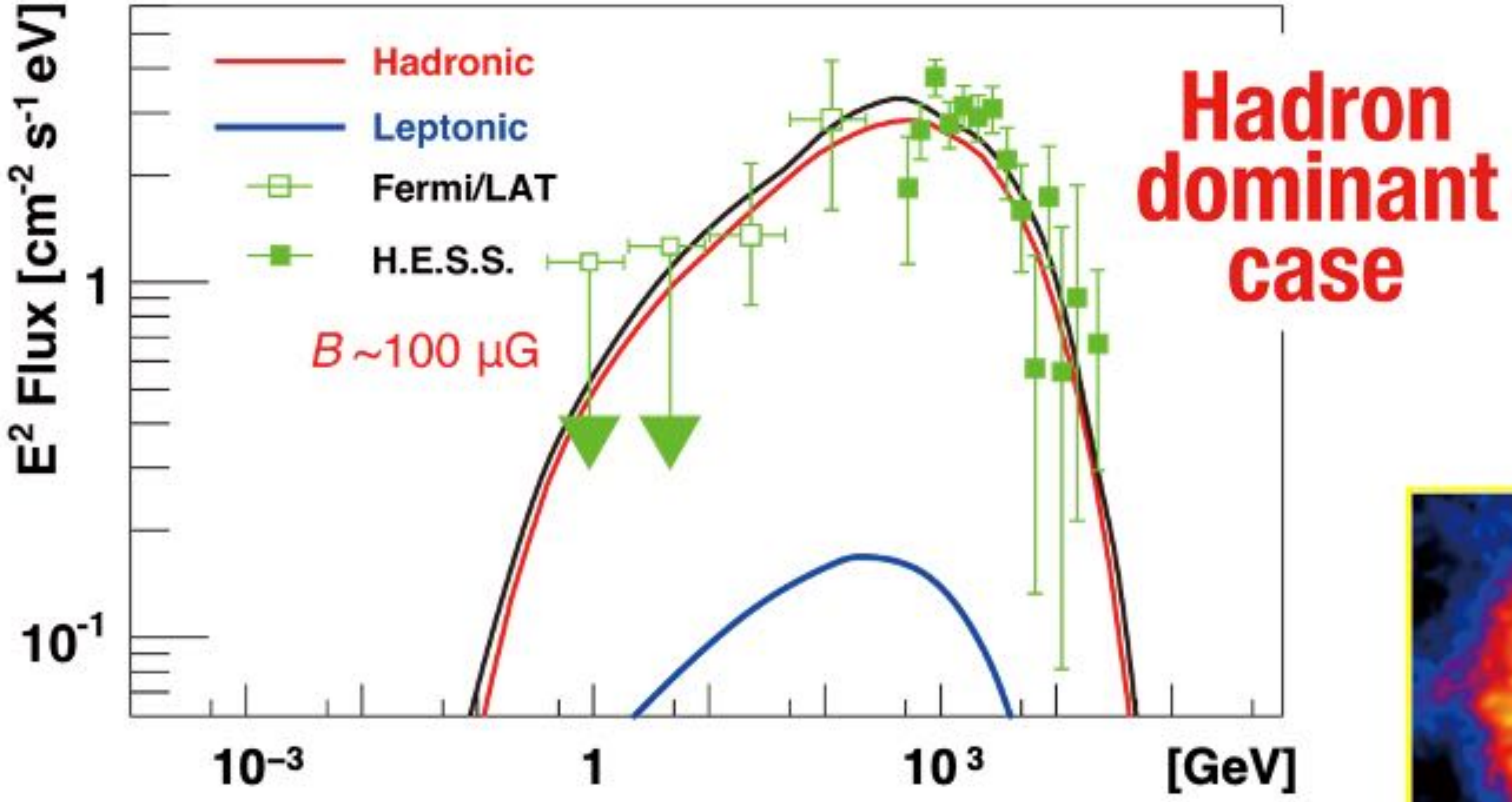


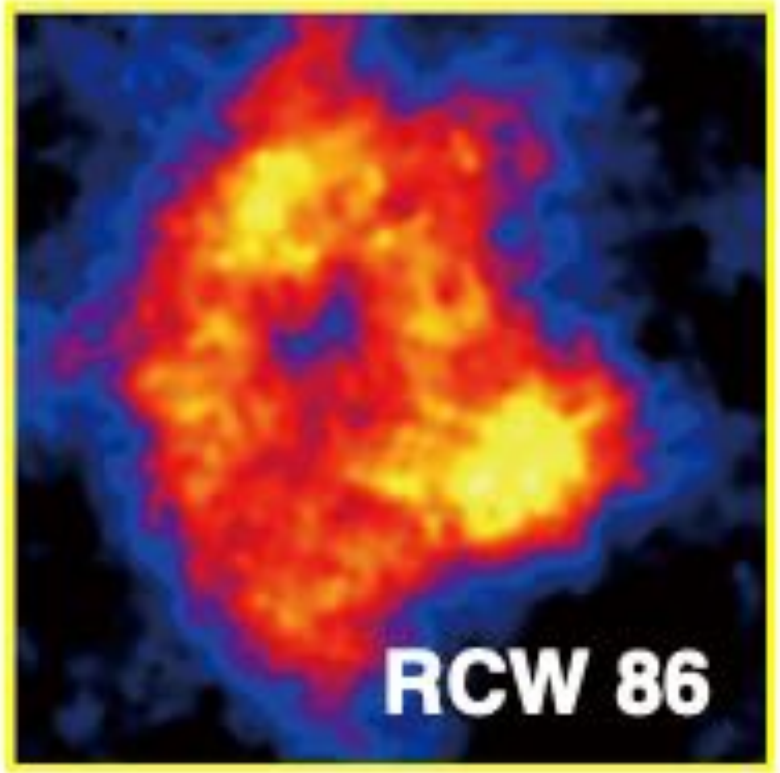
Subsequent Fermi observations confirmed the pion-decay bump (W44 & IC 443, Ackermann et al. 2013, Science, 339, 807)

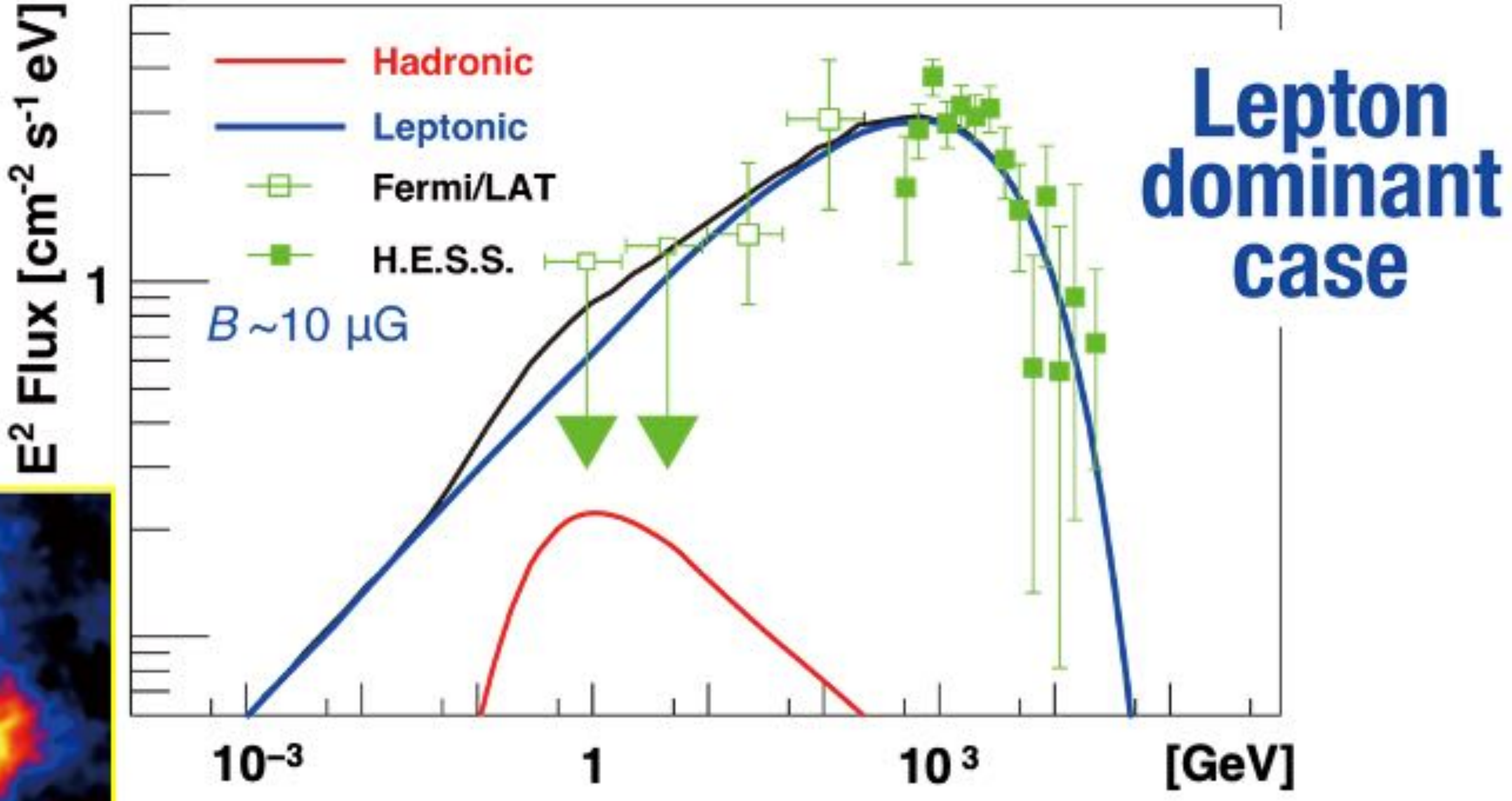
Hadronic vs. Leptonic Gamma-rays in young TeV bright SNRs





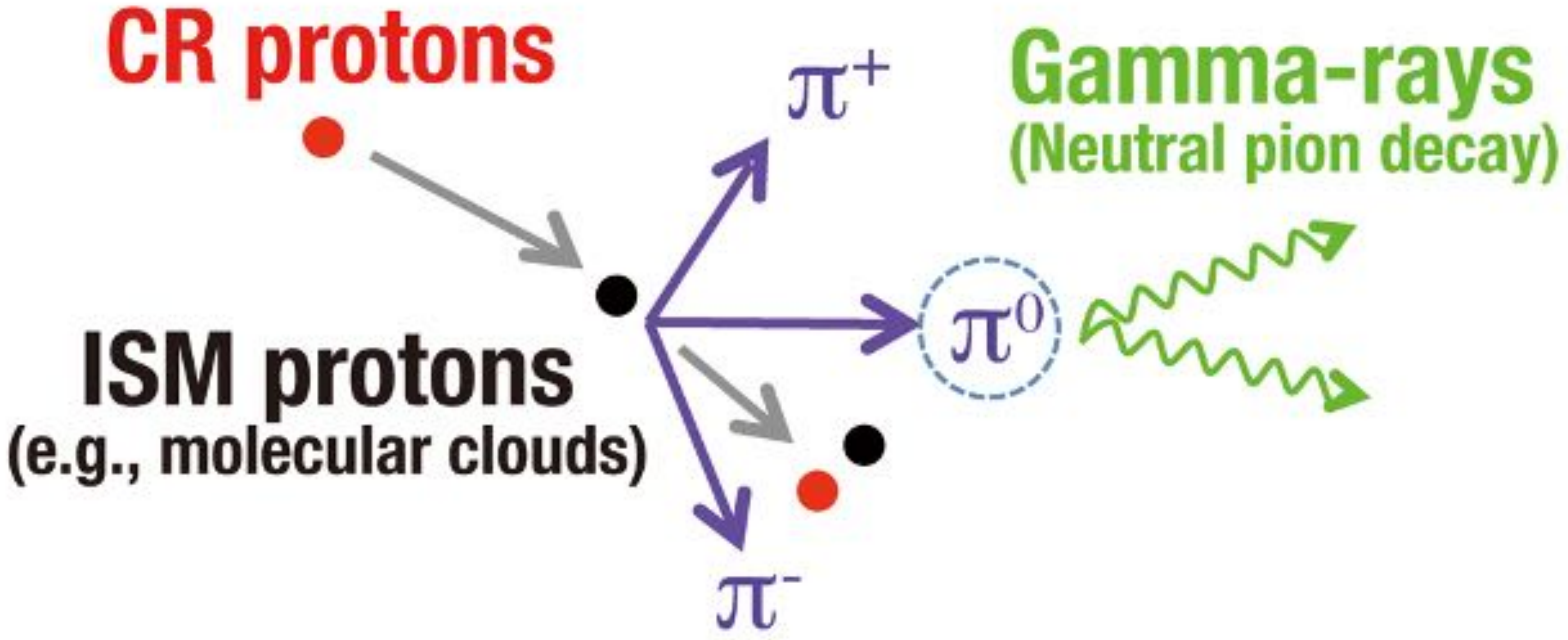






Gamma-ray spectra from RCW 86 (H.E.S.S. Collaboration et al. 2018b)

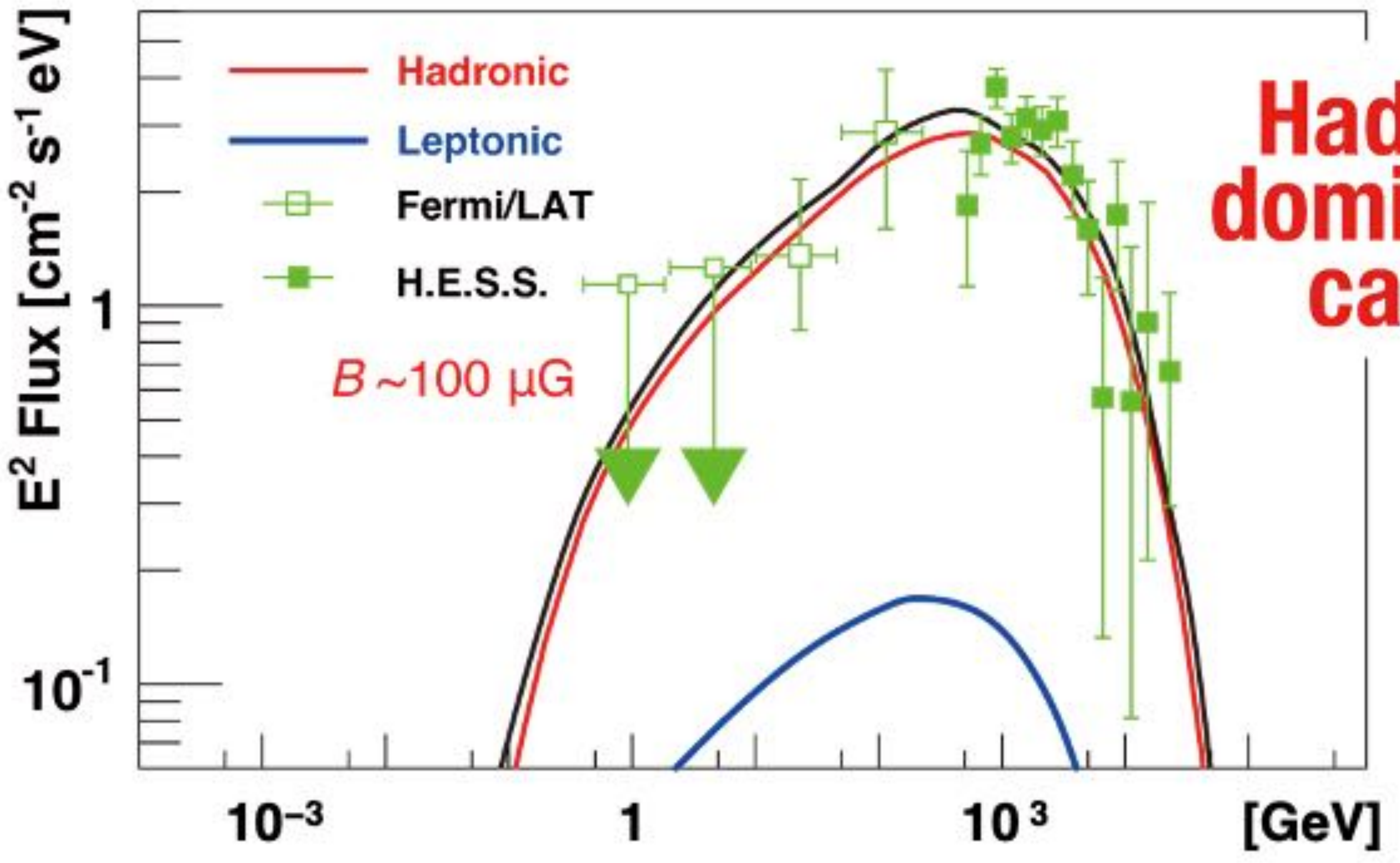
Hadronic vs. Leptonic Gamma-rays in young TeV bright SNRs



$$F \propto \frac{W_p n}{d^2}$$

(W_p: total energy in accelerated protons; n: gas density; d: distance to the SNR)

Gamma-ray flux ∝ ISM proton density



Gamma-ray spectra from RCW 86 (H.E.S.S. Collaboration et al. 2018b)

Hadron dominant case

Molecular Hydrogen H_2

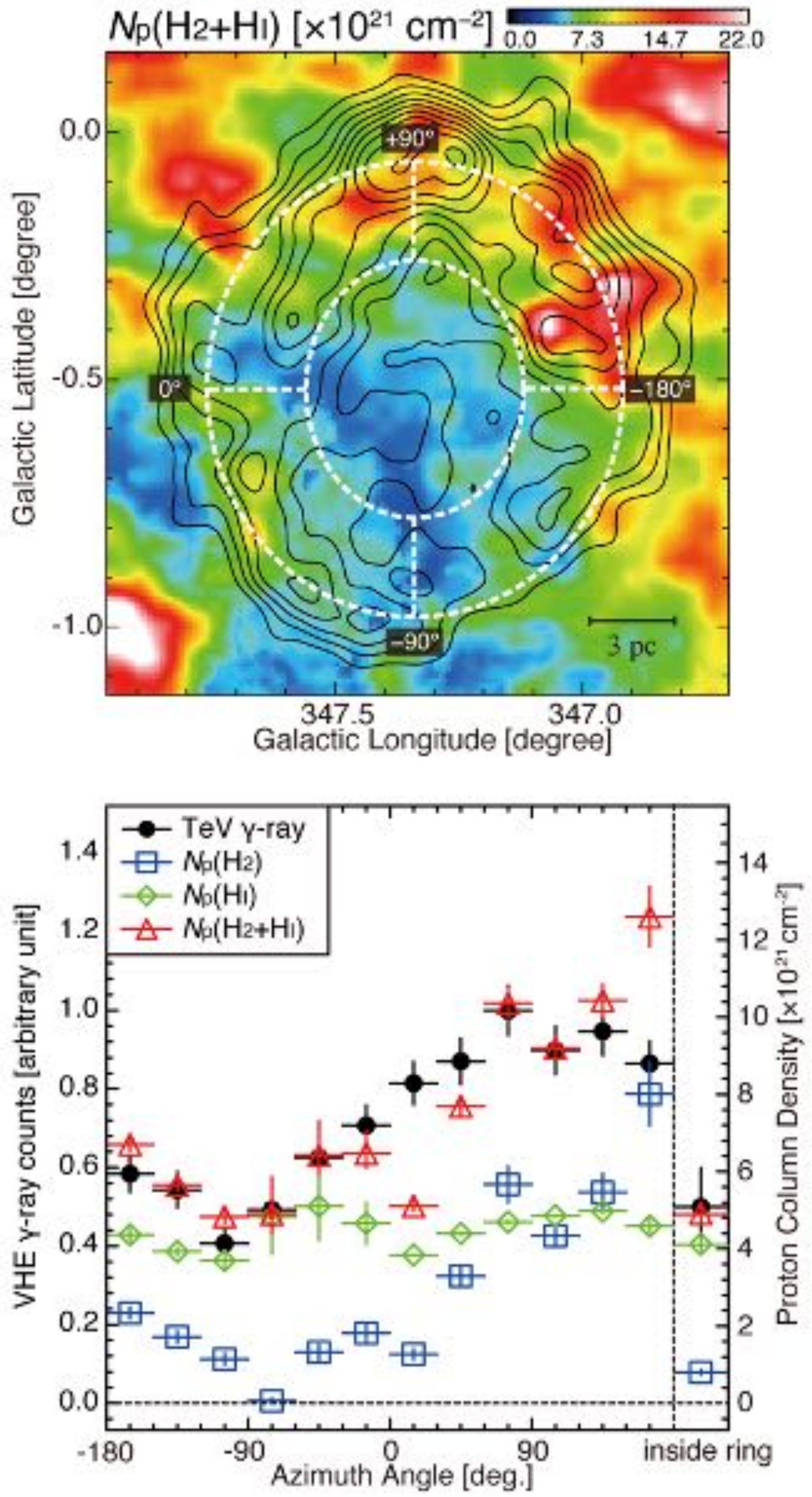
- traced by CO 2.6 mm line emission
- Density > 1000 cm^{-3}, T_k ~10 K

Atomic Hydrogen HI

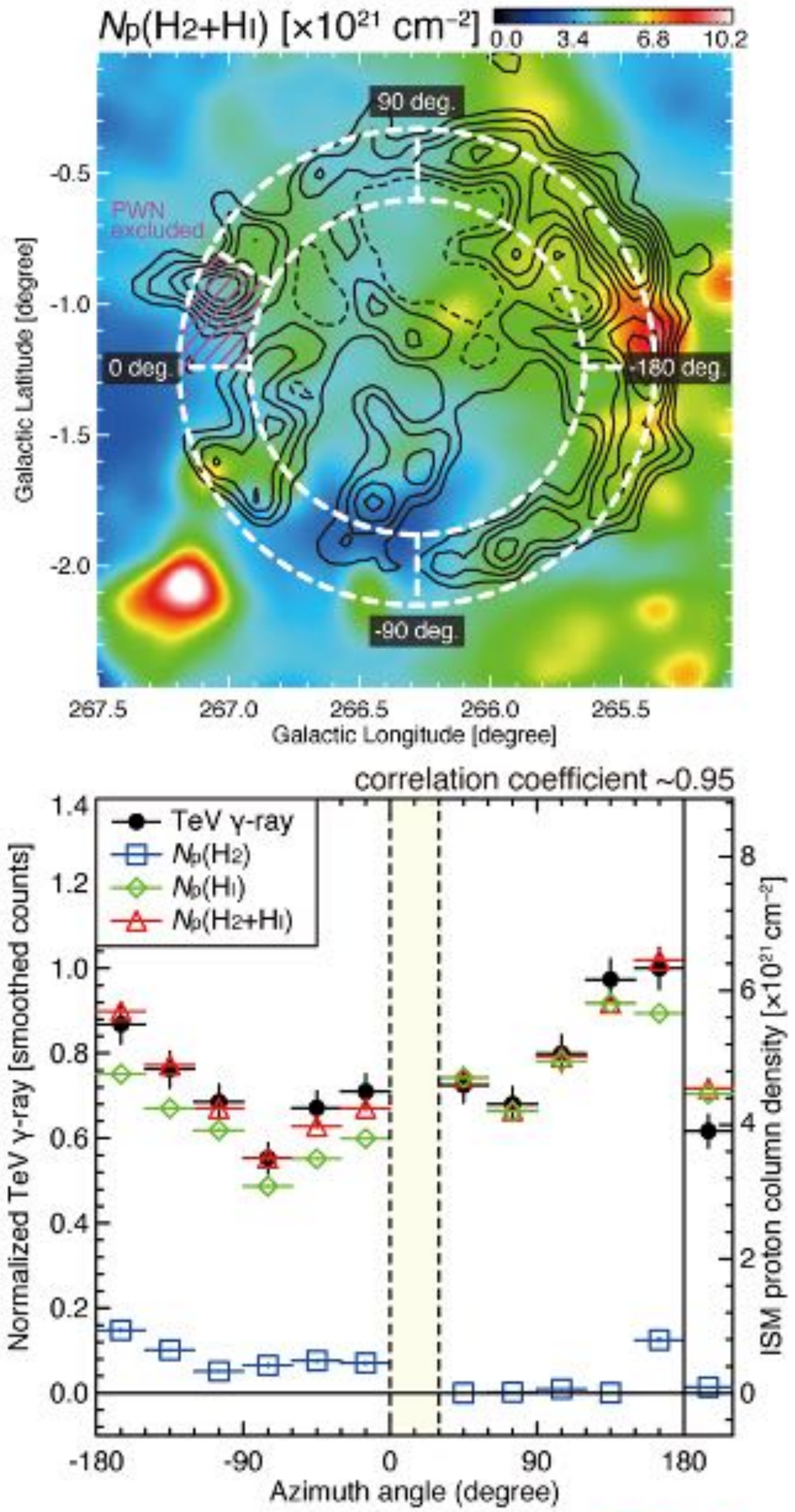
- traced by HI 21 cm line emission
- Density ~ 1–100 cm^{-3}, T_k ~ 40–100 K

Spatial correlation between the ISM & Gamma-rays (2012–)

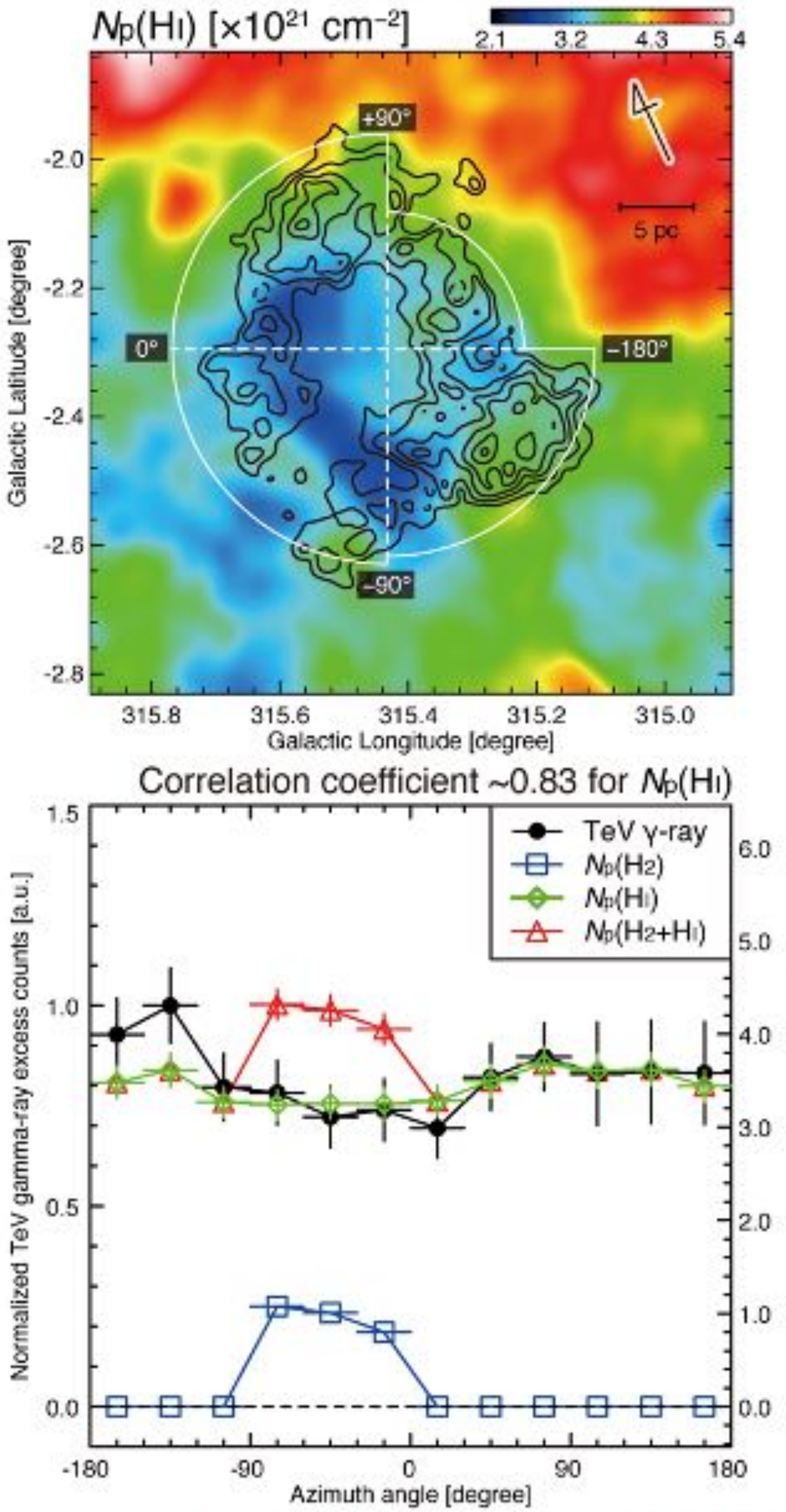
RX J1713.7−3946



Vela Jr.



RCW 86



HESS J1731−347

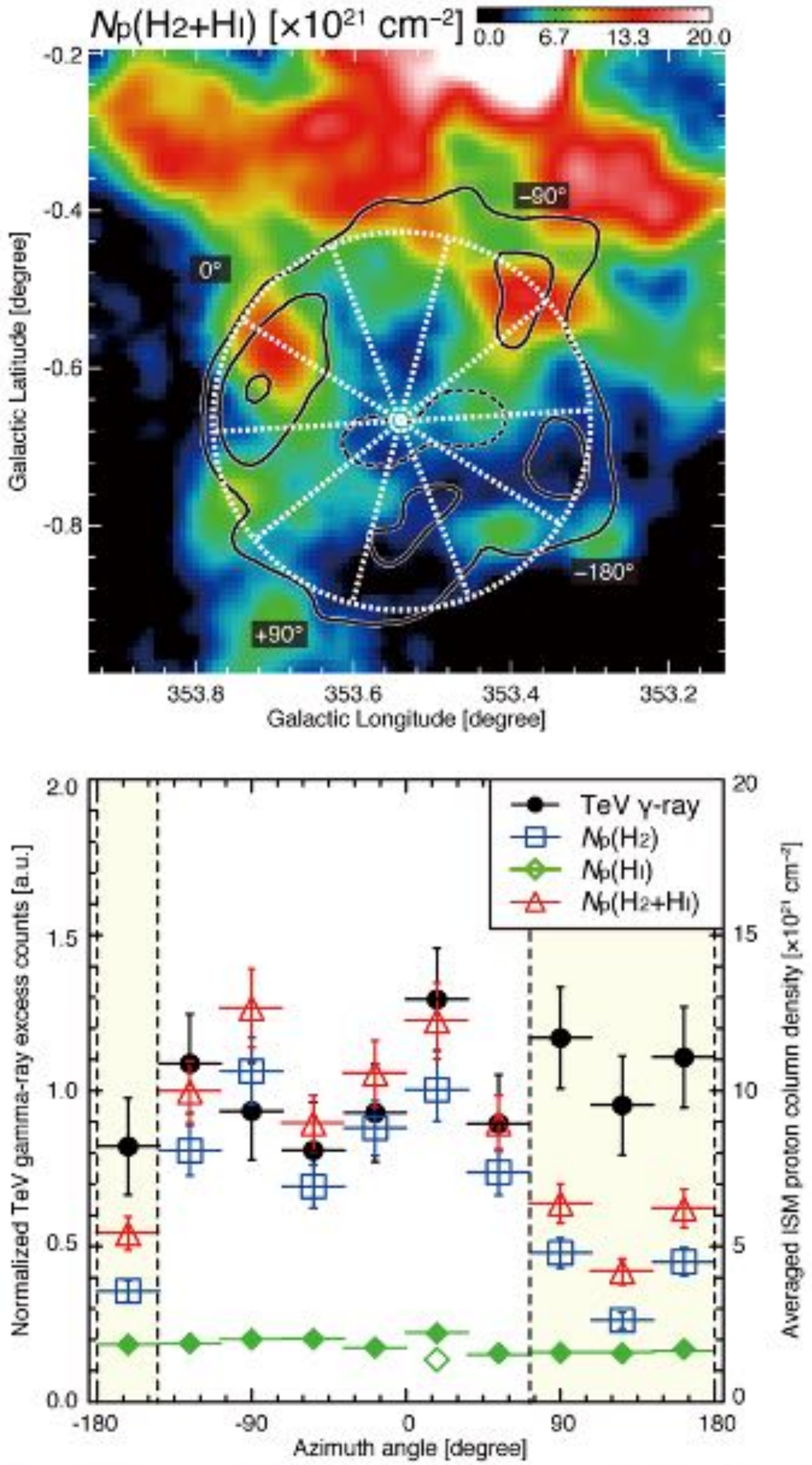


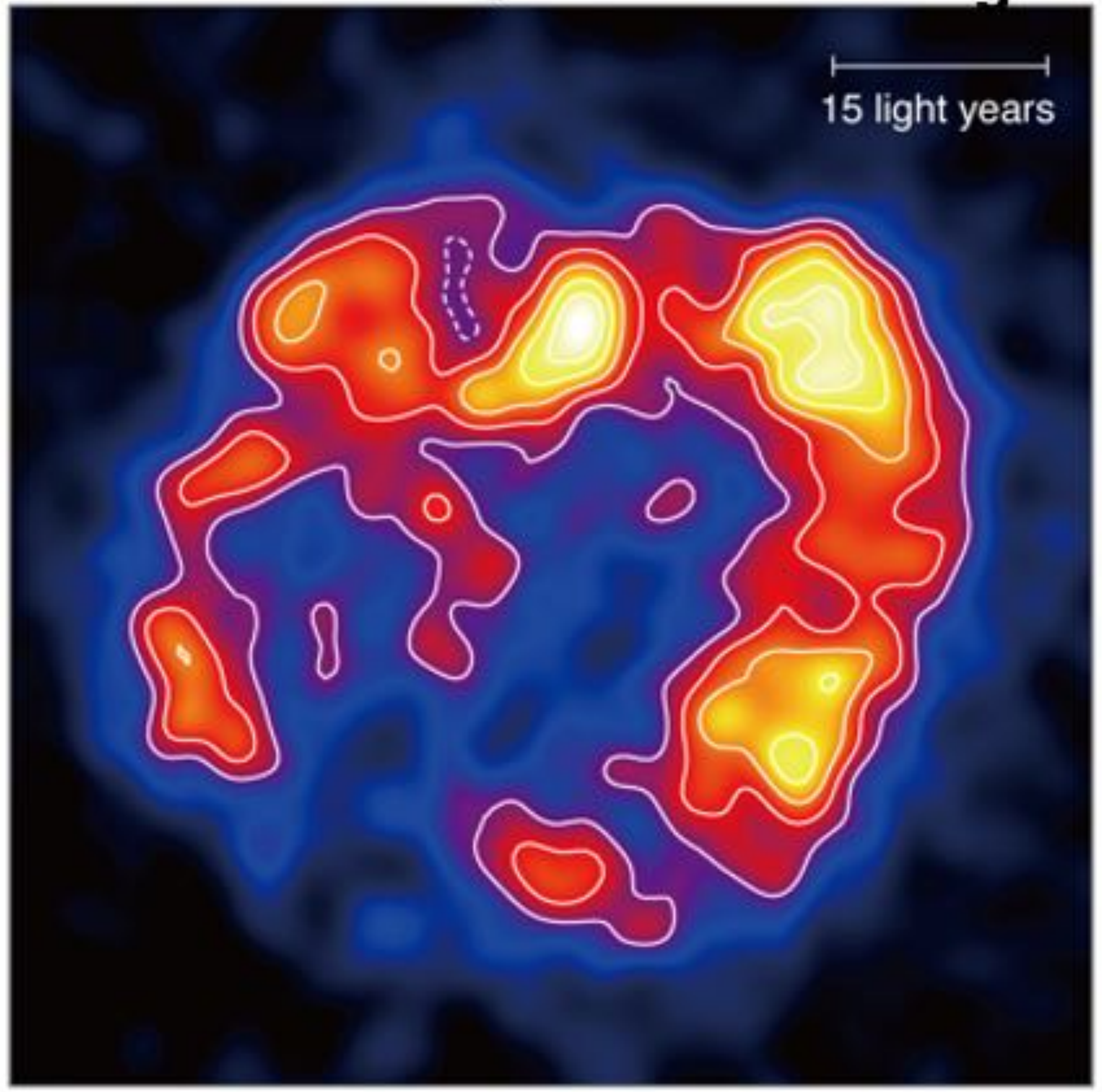
Image: ISM protons $N_p(H_2 + H_I)$, Contours: H.E.S.S. TeV gamma-rays

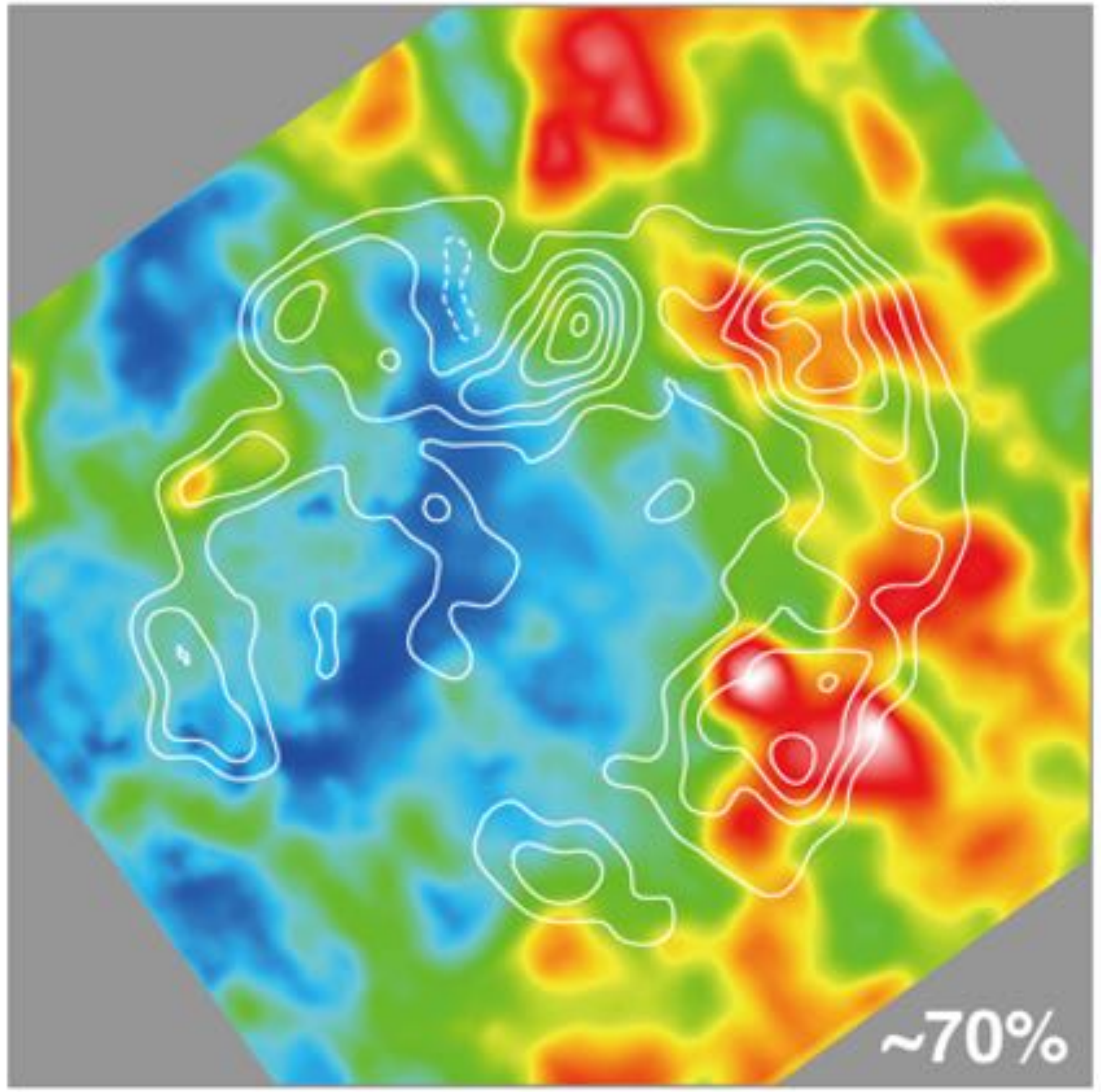
Total energy of accelerated CR protons ~10^{48}–10^{49} erg (compatible with a conventional value)

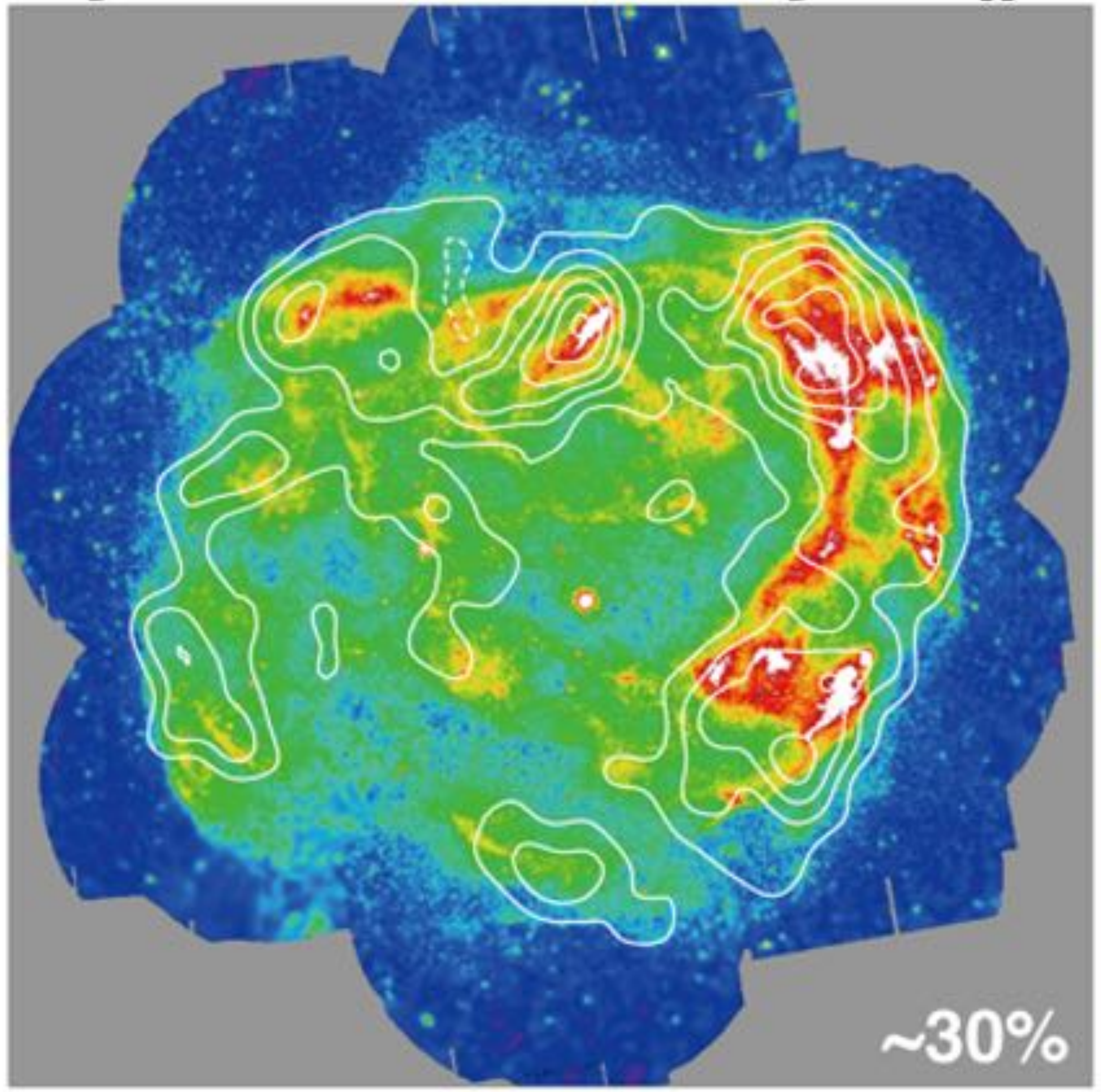
Fukui et al. 2012 ApJ, 746, 82; Fukui et al. 2017, ApJ, 850, 71; Sano et al. 2019, ApJ, 876, 37; Fukuda et al. 2014, ApJ, 788, 94

Quantifying hadronic and leptonic gamma-rays (2021)

Gamma-ray Excess N_g = **Interstellar Gas Density N_p** + **Synchrotron X-rays N_x**







Fukui, Sano et al. 2021, ApJ, 915, 84

$N_{g} = N_{g\_hadronic} + N_{g\_leptonic}$

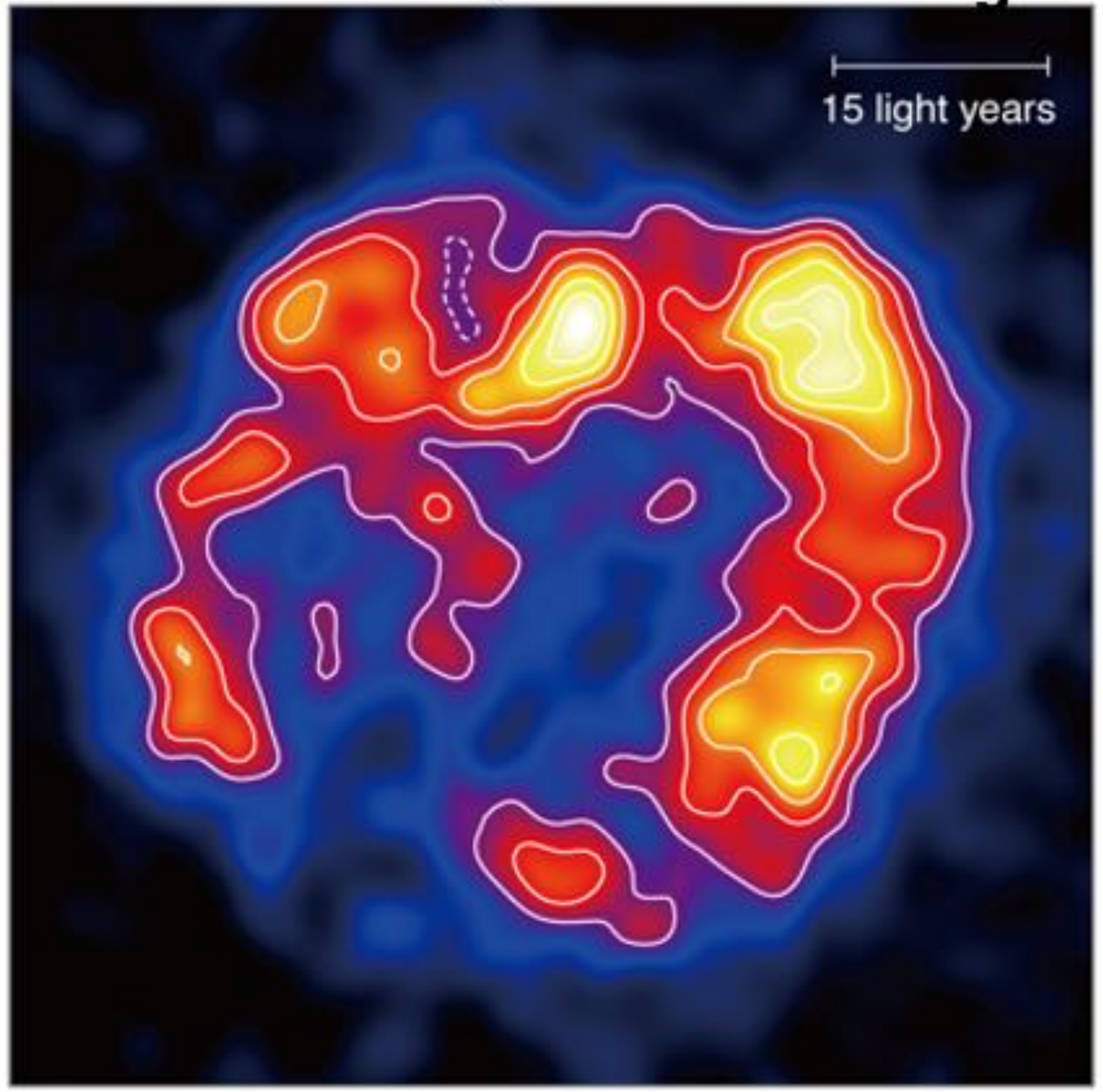
$N_{g\_hadronic} = K_1 \ n_{CR\,proton} \ N_p$

$N_{g\_leptonic} = K_2 \ n_{CR\,electron} \ n_{CMB} = (K_2 \ n_{CMB} / K_3 B^2) \ N_x$

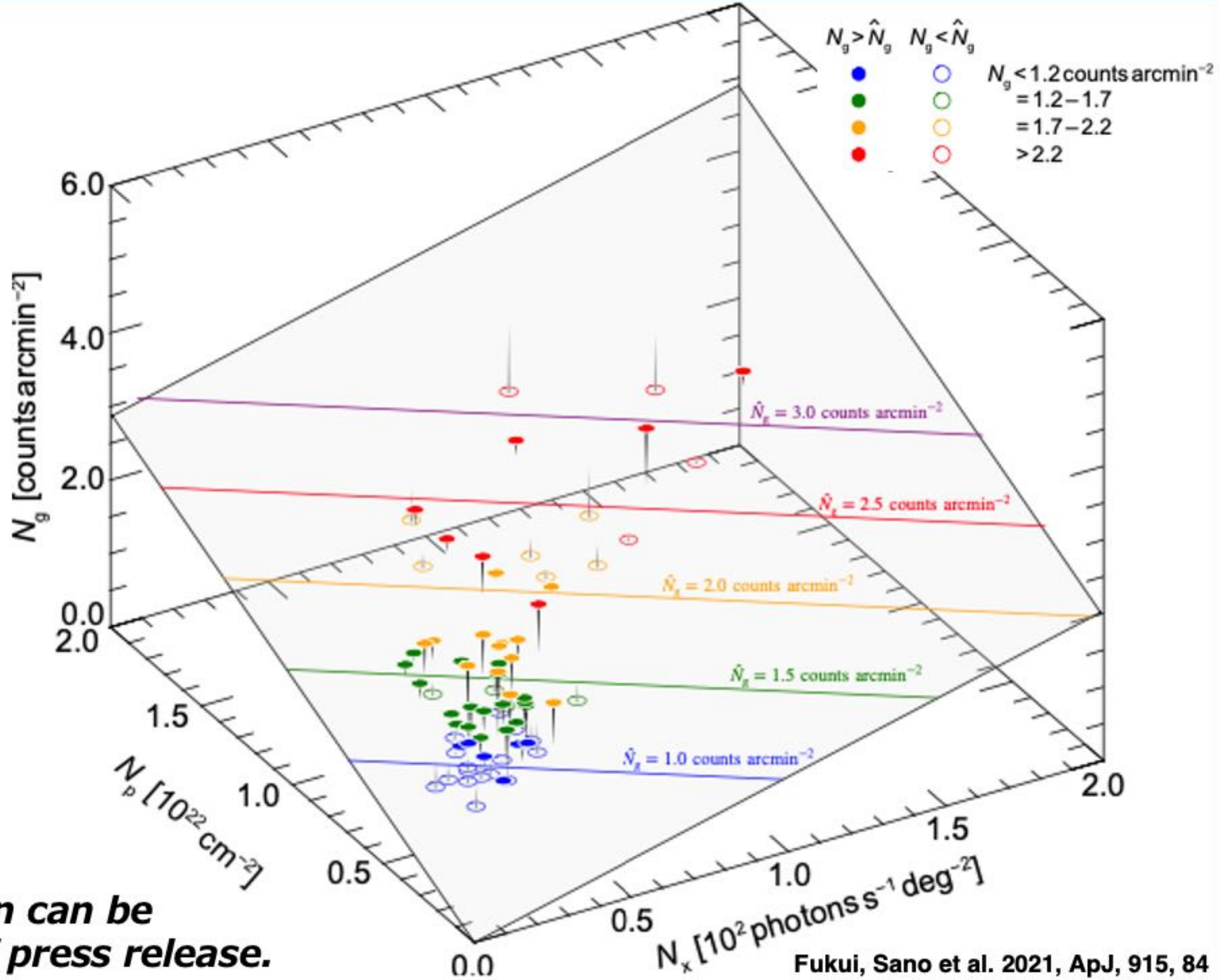
$n_{CR\,proton}$: CR proton density
$n_{CR\,electron}$: CR electron density
n_{CMB} : density of CMB photons
B : magnetic field
K_1, K_2, K_3 : constant

Quantifying hadronic and leptonic gamma-rays (2021)

Gamma-ray Excess N_g



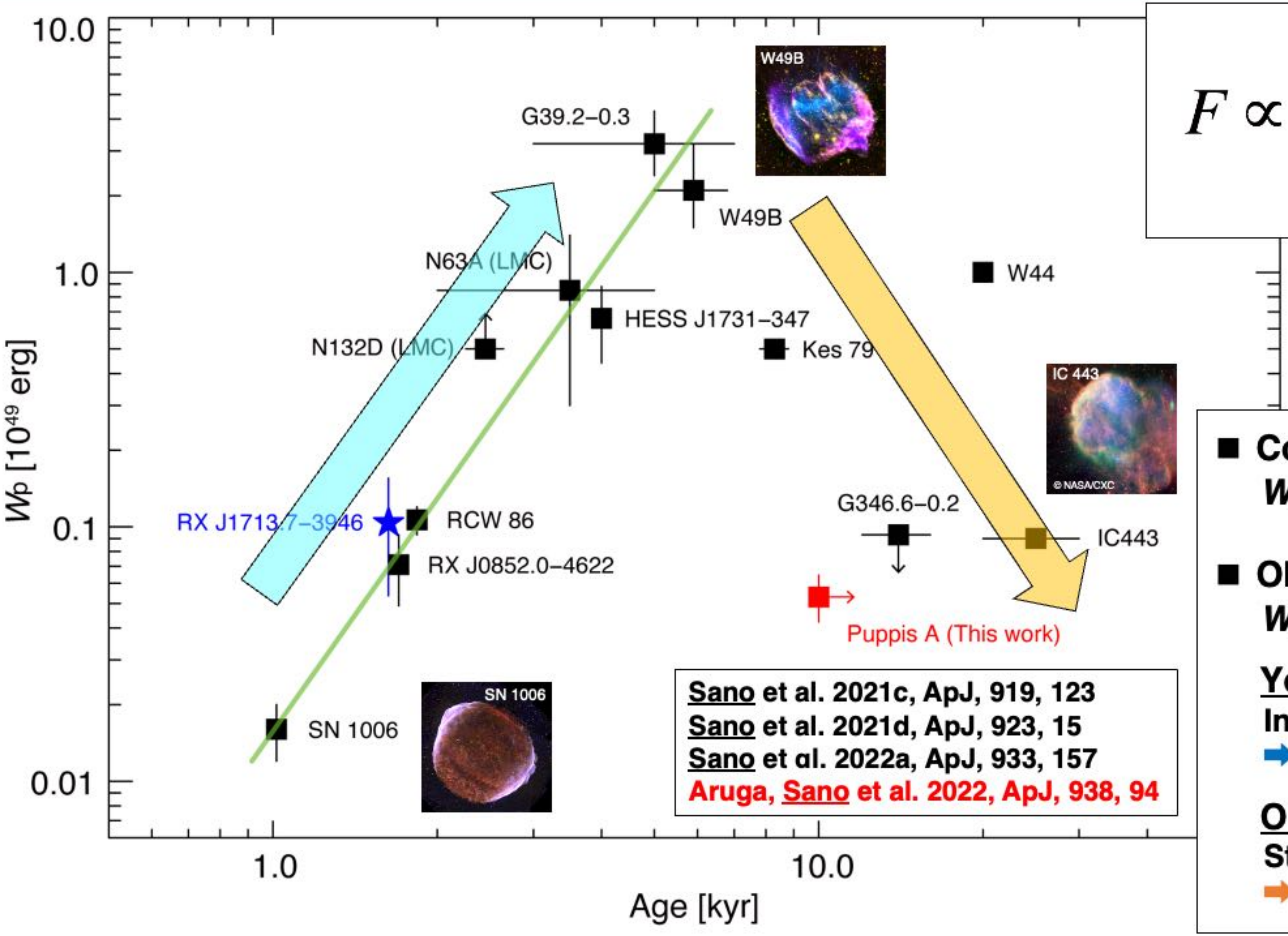
$N_{g\_hadronic}$: $N_{g\_leptonic}$ = 7 : 3



Fukui, Sano et al. 2021, ApJ, 915, 84

More detailed information can be found in the web page of press release.

Total energy of accelerated cosmic-ray protons W_p (2021–)



<u>Sano</u> et al. 2021c, ApJ, 919, 123
<u>Sano</u> et al. 2021d, ApJ, 923, 15
<u>Sano</u> et al. 2022a, ApJ, 933, 157
Aruga, <u>Sano</u> et al. 2022, ApJ, 938, 94

$$F \propto \frac{W_p n}{d^2}$$

(W_p: total energy in accelerated protons
n: gas density
d: distance to the SNR)

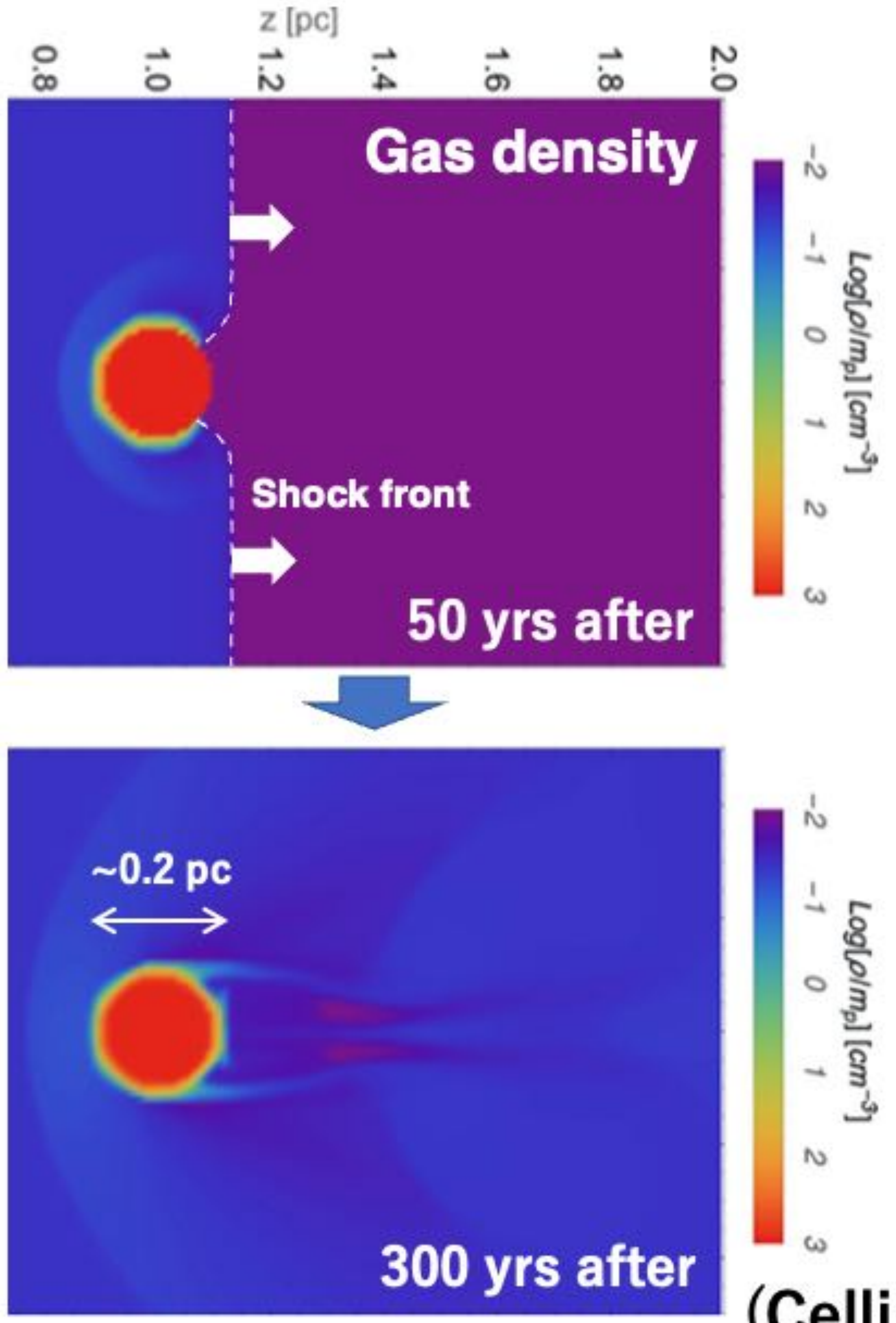
- **Conventional (theoretical) values**
  W_p ~10^{49}–10^{50} erg
- **Observational values (this work)**
  W_p ~10^{47} to more than 10^{49} erg

<u>Young SNRs (age < 6000 yr)</u>
Increasing W_p as a function of age
➡ time dependent evolution!?

<u>Old SNRs (age > 8000 yr)</u>
Steady Decreasing of W_p
➡ time dependent diffusion of CRs

Molecular clouds can survive shock erosion (e.g., Celli+2019)

MHD simulation of shock-cloud interaction (density contrast ~10^5)
➡ Clouds will not be destructed and/or thermalized immediately...!!!



(Celli et al. 2019)

$$V_{\rm cloud} = V_0\sqrt{n_{\rm cloud}/n_0} = 0.003\ V_0$$

(e.g., Sano et al. 2010)

$V_{\rm cloud}$ ... Shock velocity in cloud
V_0 .... Initial shock velocity
$n_{\rm cloud}$ ... Density of clouds
n_0 .... Density inside a bubble

Cloud crossing time ~2×10^4 yr
($V_0 = 3000$ km s^{-1}, $n_{\rm cloud}/n_0 = 10^5$, size = 0.2 pc)

$$k_{\rm B}T = \frac{3}{16}m_{\rm p}V_{\rm cloud}^2$$

$$= 2\times10^{-4}\left(\frac{V_0}{3000\ {\rm km\ s^{-1}}}\right)^2\left(\frac{n_0}{0.01\ {\rm cm^{-3}}}\right)\left(\frac{n_{\rm cloud}}{10^3\ {\rm cm^{-3}}}\right)^{-1}\ {\rm keV}$$

(Inoue et al. 2012)

Decelerated shocks in cloud cannot emit bright thermal X-rays...

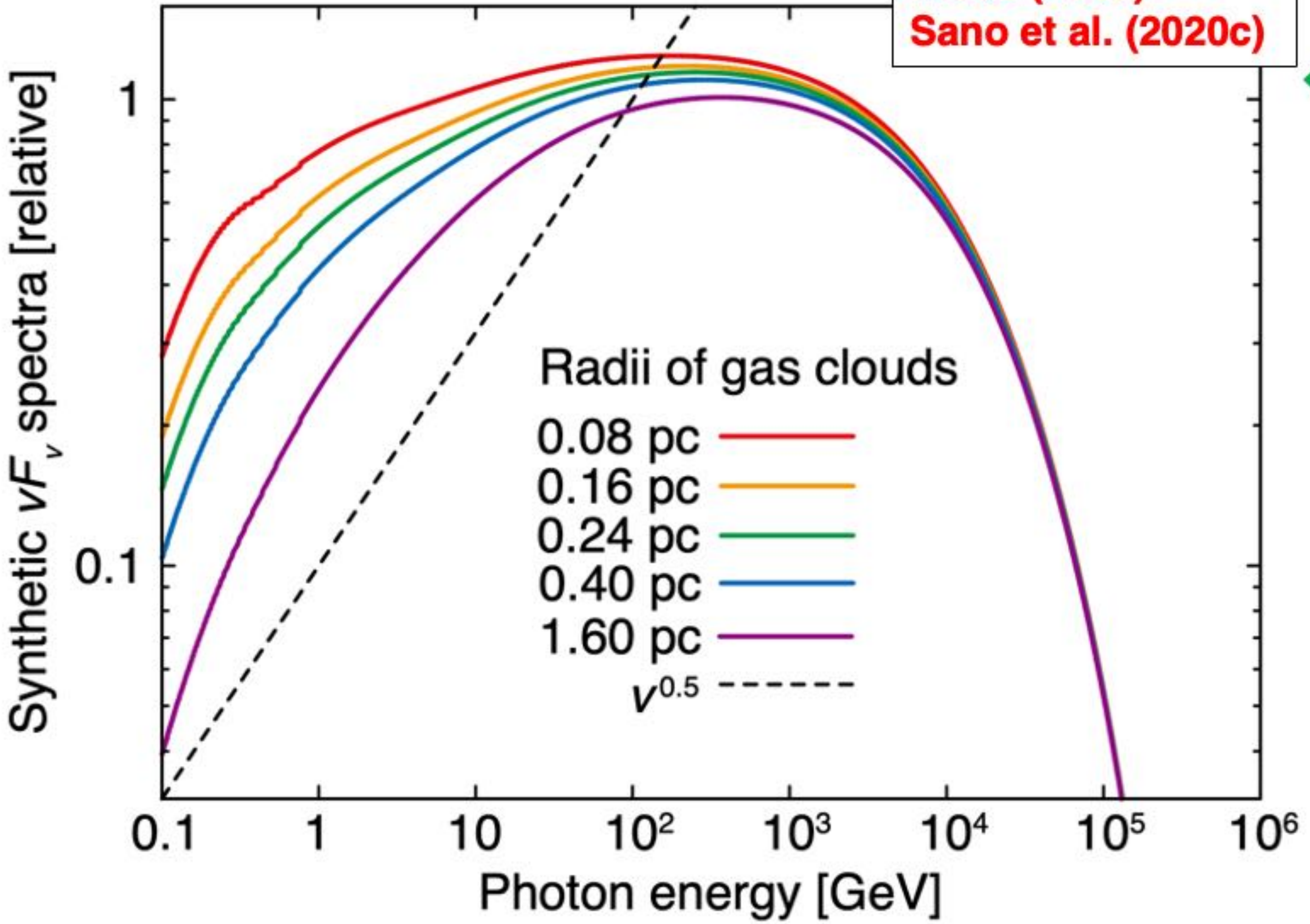
Cloudlets cause gamma-ray spectral moderation

$$l_{\rm pd} \simeq (\kappa_{\rm d}\, t)^{1/2} = 0.1\, \eta^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2} \left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2}\ {\rm pc},$$

$l_{\rm pd}$: penetration depth,
η: gyro factor,
E: CR proton energy,
B: magnetic field,
$t_{\rm age}$: SNR age

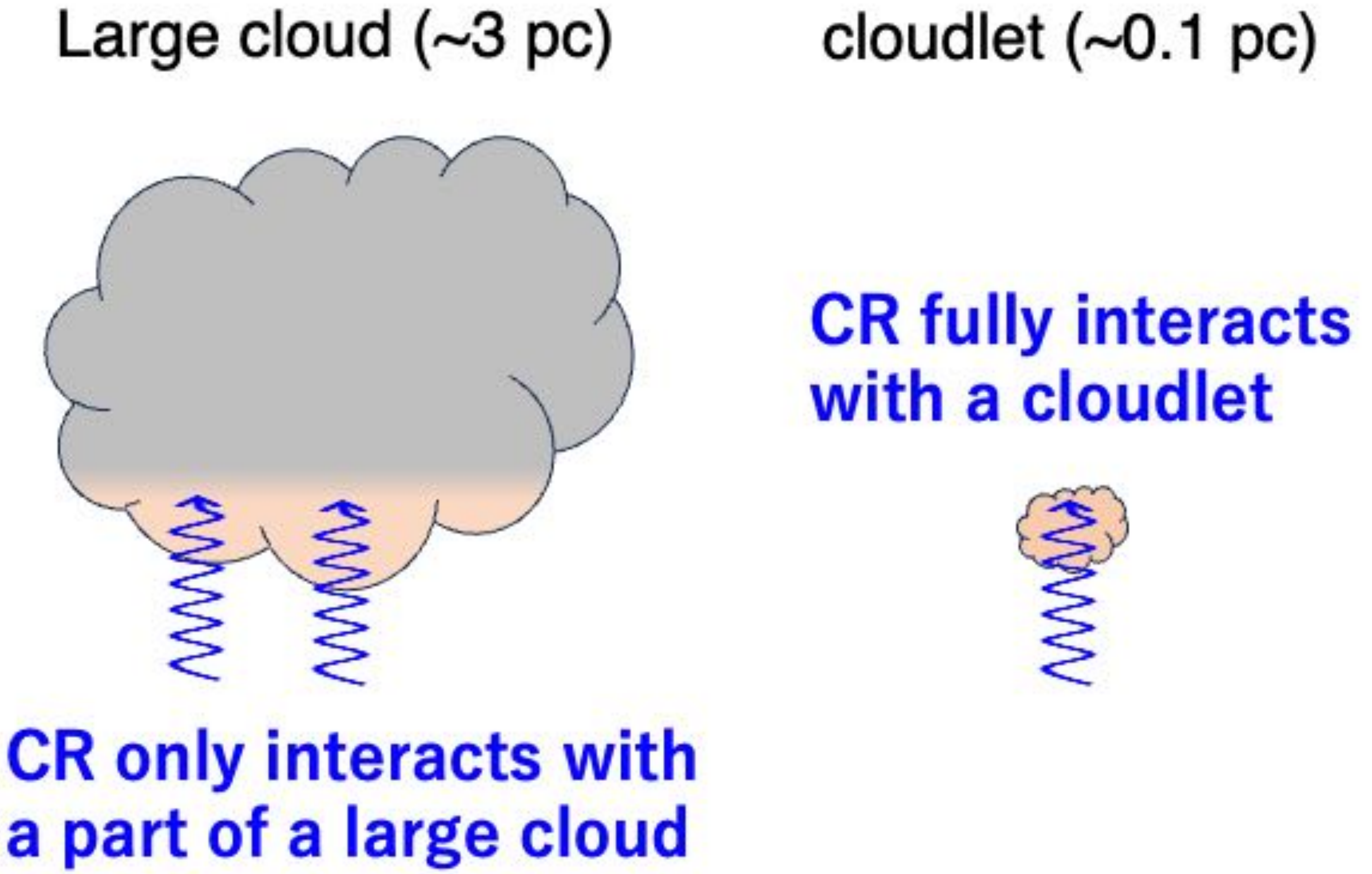
Inoue et al. (2012)

Inoue (2019)
Sano et al. (2020c)

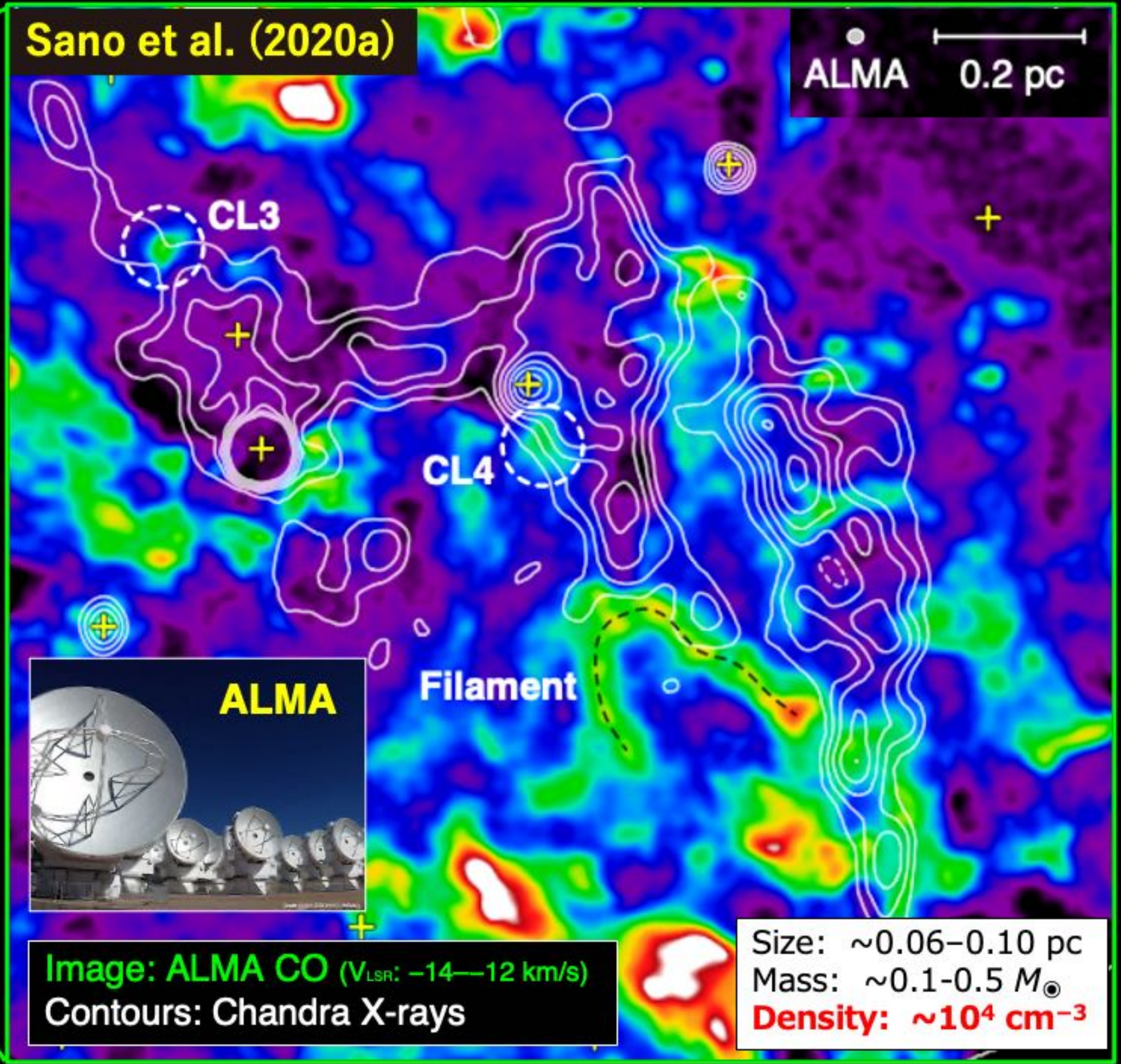


← **γ-ray spectral moderation**

Low-energy CRs cannot penetrate dense clouds (= reducing effective target mass)



Spatially resolved many cloudlets toward the NW of RXJ1713!!



Size: ~0.06–0.10 pc
Mass: ~0.1-0.5 $M_{\odot}$
Density: ~10^4 cm^{-3}

Multi-messenger astronomy for supernova remnants

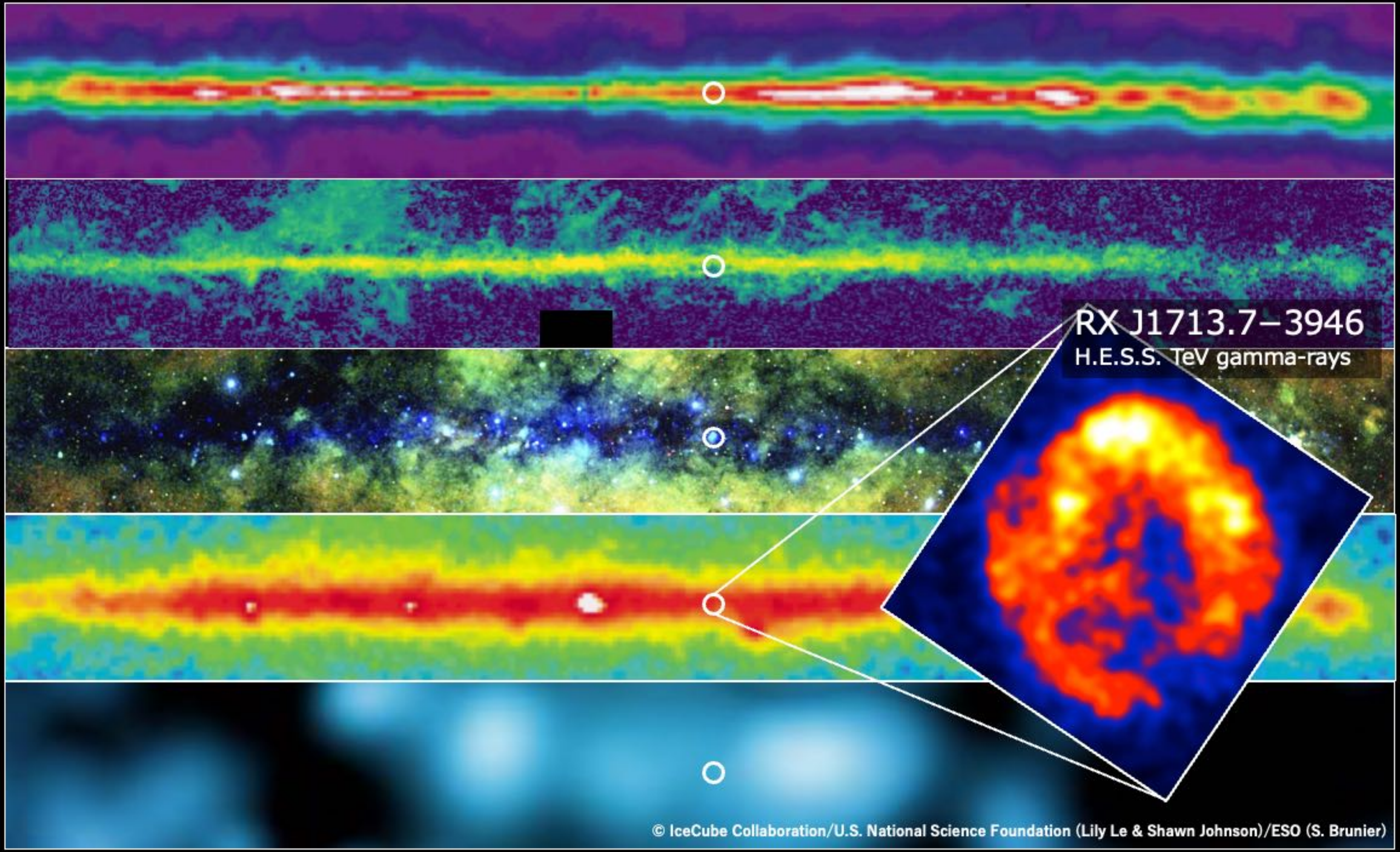
センチ波 (HI)
Dwingeloo

ミリ波 (分子雲)
NANTEN 4-m

エックス線
eROSITA

ガンマ線
Fermi-LAT

ニュートリノ
IceCube



Interstellar gas associated with supernova remnants (SNRs)

Shock interaction with **inhomogeneous and clumpy clouds** is important in understanding the high- and low-energy processes in interstellar space.

→ ***CR acceleration, γ-/X-ray spectral moderation, magnetic-field amplification etc...***