Gamma-ray observations in the vicinity of supernova remnants G106.3+2.7 and HB9

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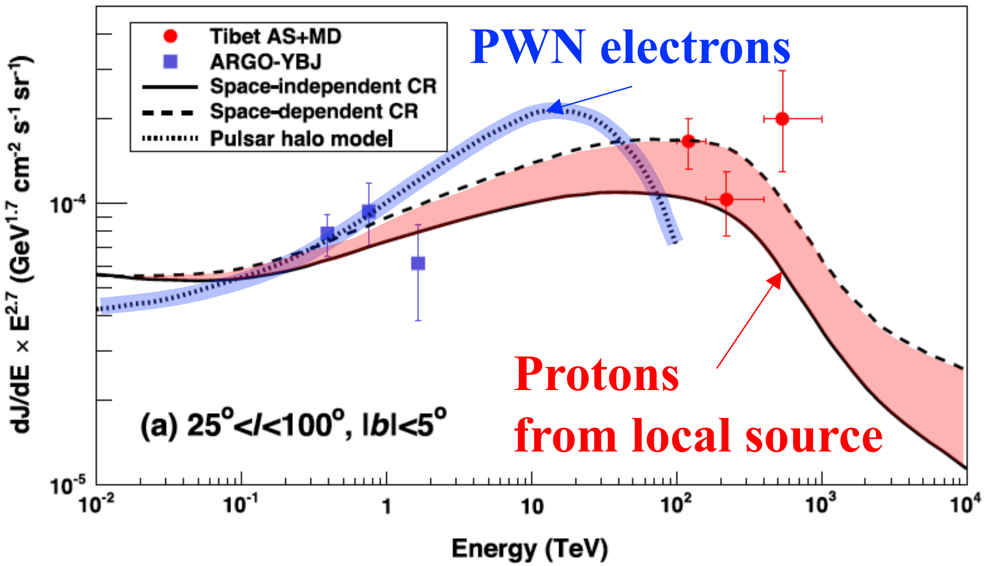
PeVatron SNR search

CRs up to PeV are accelerated in Supernova remnant (SNR)?

→ PeV protons emit ~100 TeV gamma rays via the neutral pion decay.

Detection of 100 TeV γ rays from Galactic diffuse emission
[Tibet Collab., 2021]



☑ Electrons from PWNe cannot explain the 100-TeV flux?
→ Support for Galactic PeVatrons

100-TeV source catalog
[LHAASO Collab., 2021]

* Blue: PWN, Red: SNR, Green: star formation region

Almost PWNe?

Name	Associated source (< 1.0°)
J0534+2202	PSR J0534+2200
J1825−1326	PSR J1826−1334, PSR J1826−1256
J1839−0545	PSR J1837−0604, PSR J1838−0537
J1843−0338	SNR G28.6−0.1
J1849−0003	PSR J1849−0001, W43
J1908+0621	SNR G40.5−0.5, PSR J1907+0602, PSR J1907+0631
J1929+1745	PSR J1928+1746, PSR J1930+1852, SNR G54.1+0.3
J1956+2845	PSR J1958+2846, SNR G66.0−0.0
J2018+3651	PSR J2021+3651, Sh 2-104
J2032+4102	Cygnus OB2, PSR J2032+4127, SNR G79.8+1.2
J2108+5157	-
J2226+6057	SNR G106.3+2.7, PSR J2229+6114

There is no conclusive observational evidence.

My Study

Q. Why we can't find SNR PeVatron?

Reason 1: Although LHAASO already detect the emissions from SNR PeVatron, we cannot resolve the emission mechanism.

→ Detailed γ-ray observations with better angular resolution can discover them?

Reason 2: Only young SNR (< 1 kyr) can produce PeV CR, and they already escaped from SNR at the early stage.
Thus, the observation opportunity is few?

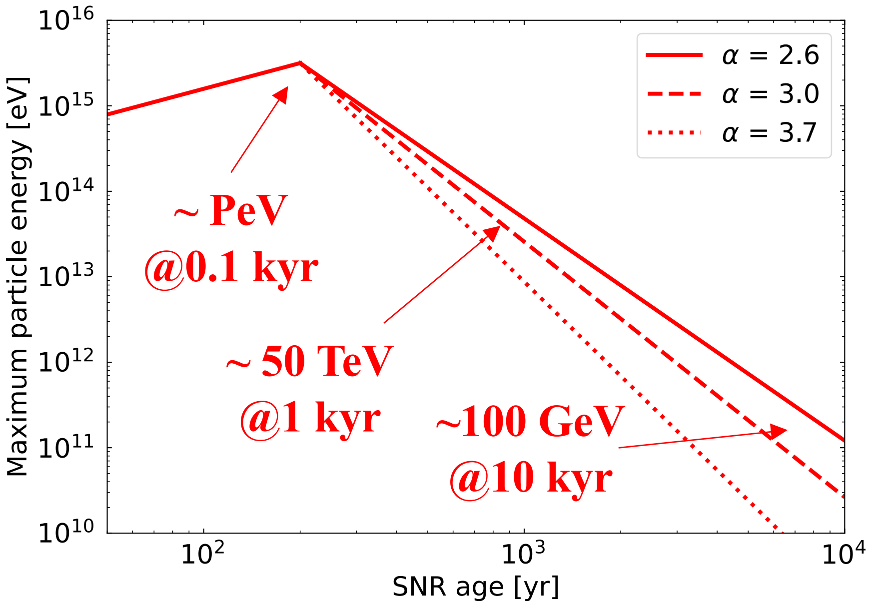
→ Measure the time evolution of the maximum acceleration energy of SNRs.

Approach using γ-ray observations

LHAASO 100 TeV sources

Name	Associated source (<1°)
J0534+2202	PSR J0534+2200 (Crab)
… ≈	…
J2226+6057	**SNR G106.3+2.7, PSR J2229+6114**

E_{max} vs t_{age} [based on Ohira+2011]



MAGIC γ-ray observation of LHAASO J2226+6057/ SNR G106.3+2.7

[MAGIC Collab.: H. Abe, TO et al.,, A&A in press, arXiv: 2211.15321]

SNR G106.3+2.7 / Boomerang PWN

☺ **One of the PeVatron candidate**

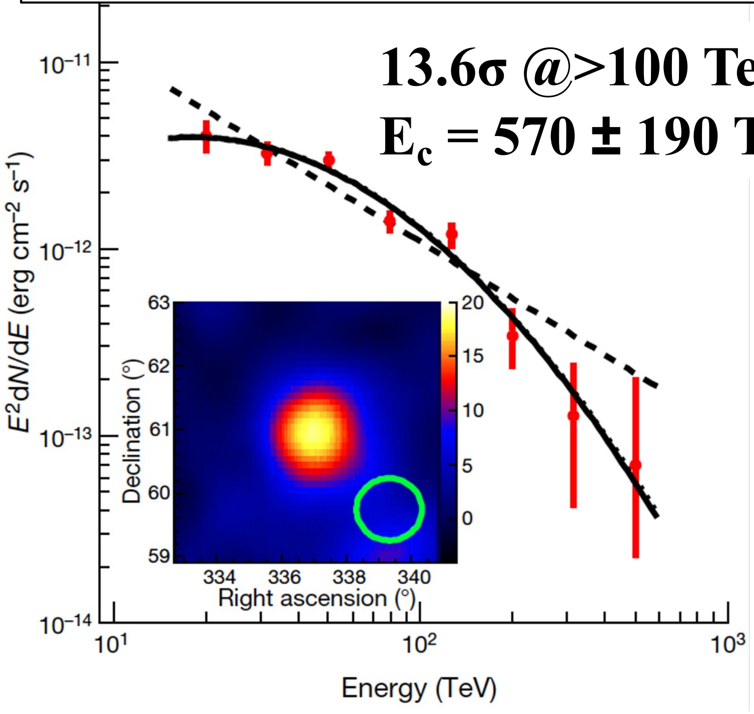
HAWC, TibetASγ, and LHAASO detected 100 TeV γ-ray emission [Albert+ 2020; Amenomori+ 2021; Cao+2021]

☹ **PWN & SNR complex (Boomerang PWN & SNR G106.3+2.7)**

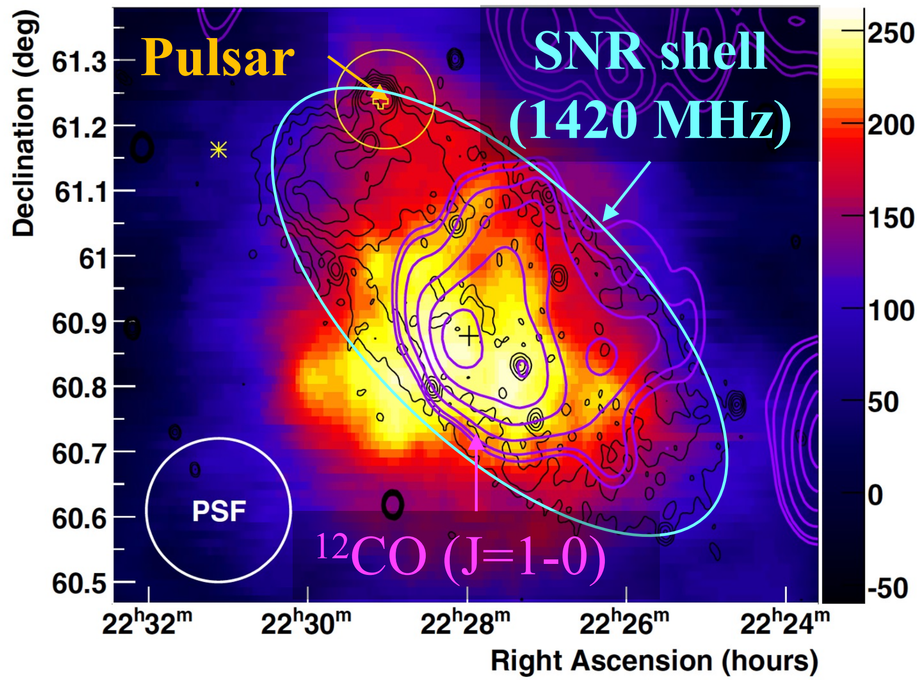
SNR age: 4-10 kyr [Halpern+2001, Kothes+2006]

Origin of the VHE emission is unclear. PWN or SNR? hadronic or leptonic?

LHAASO spectrum [Cao+2021]



VERITAS >0.63 TeV [Acciari+2009]

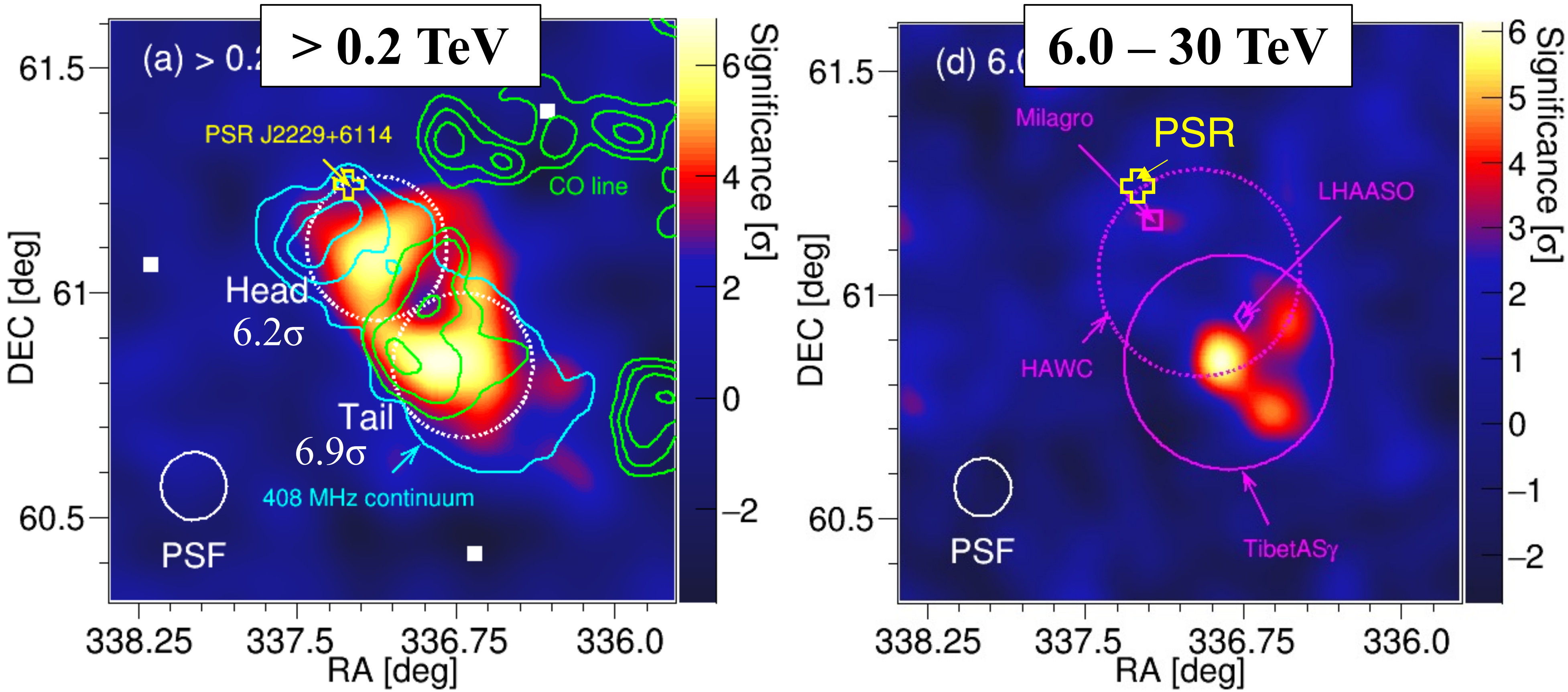


MAGIC observations

The MAGIC observations were performed with better angular resolution than previous γ ray observations in the vicinity of SNR G106.3+2.7.

	VERITAS (pre-upgrade) [Acciari+2009]	**MAGIC [This work]**
Observation period	2008	2017 – 2019
Observation time	**33.4 hr**	×3.6 → **122 hr**
Analysis threshold	0.63 TeV	0.2 TeV
68%-containment radius of PSF	**0.11°**	→ **0.084° (>0.2 TeV)** **0.072° (> 1 TeV)**

MAGIC skymap

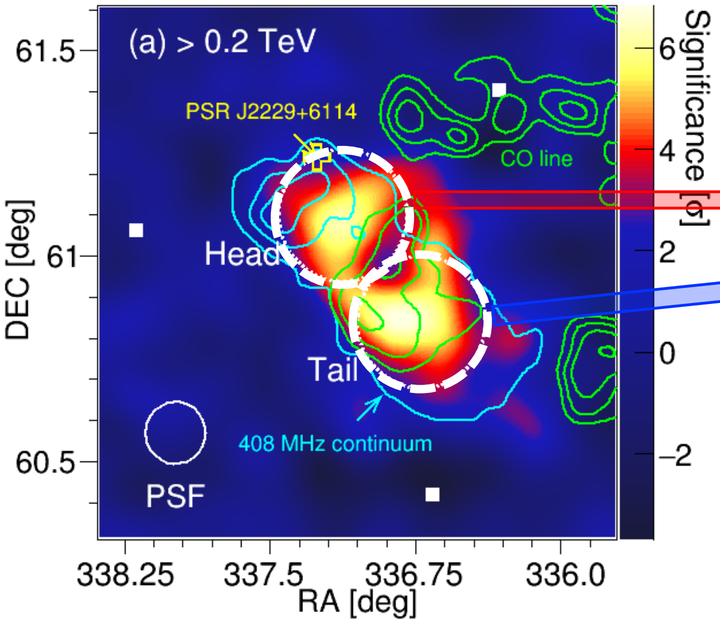


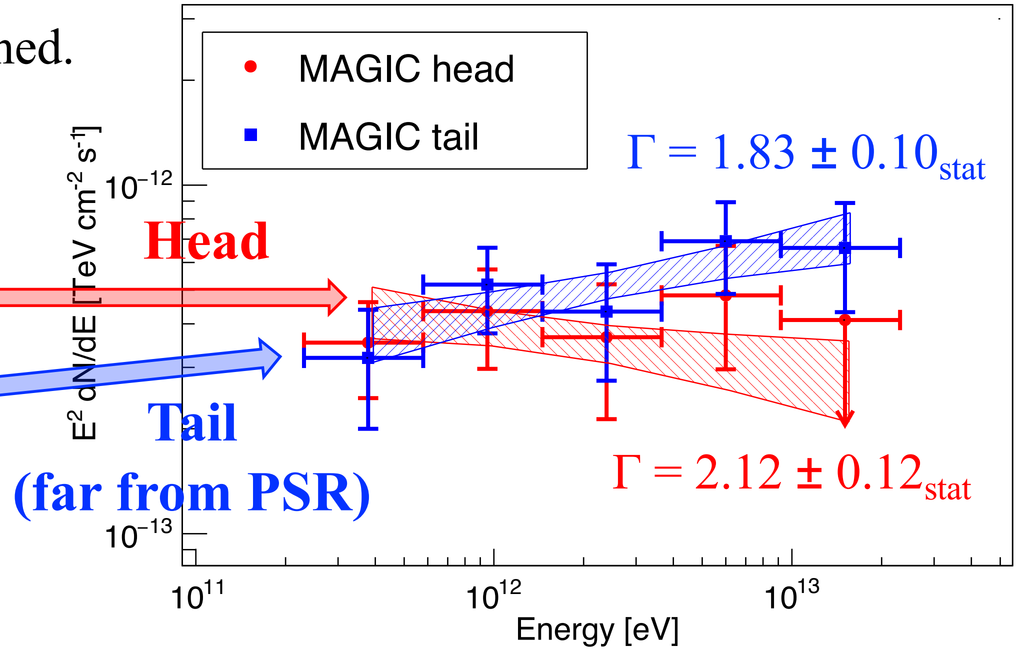
☑ γ-ray emission > 0.2 TeV extends along with radio continuum emissions, named Head & Tail by Joncas & Higgs (1990).

☑ High energy emissions are offset (0.47 ± 0.03 deg) from the pulsar position.
- The position is in good agreement with other experiments.
- Extension (0.14 ± 0.09 deg) is consistent with Tibet ASγ (0.24 ± 0.10 deg).

Energy spectrum of SNR G106.3+2.7

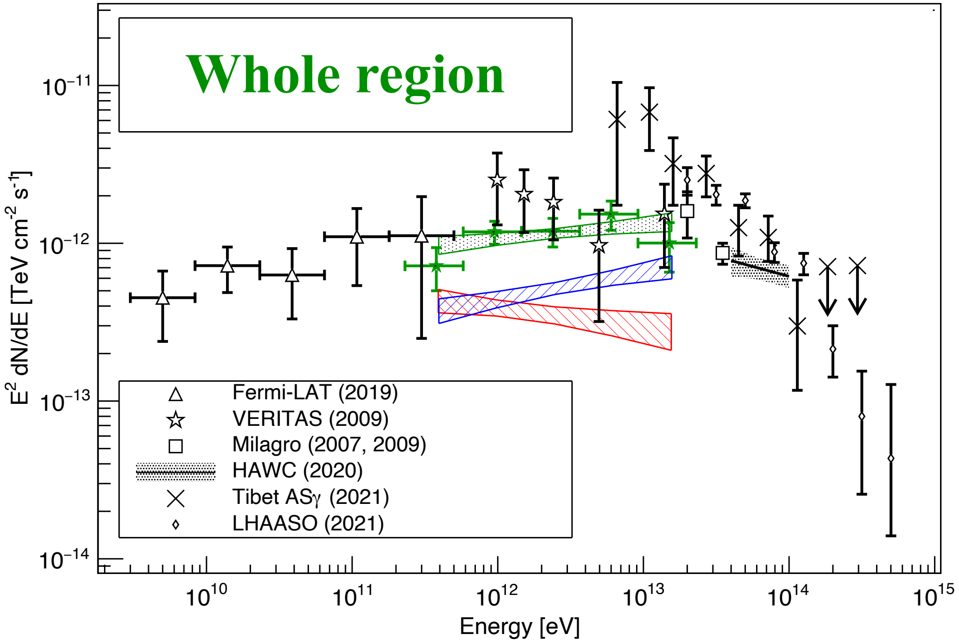
Two regions, Head & Tail, are newly defined.





☑ The spectra of Two regions are similar but at ~10 TeV, Head has lower flux.

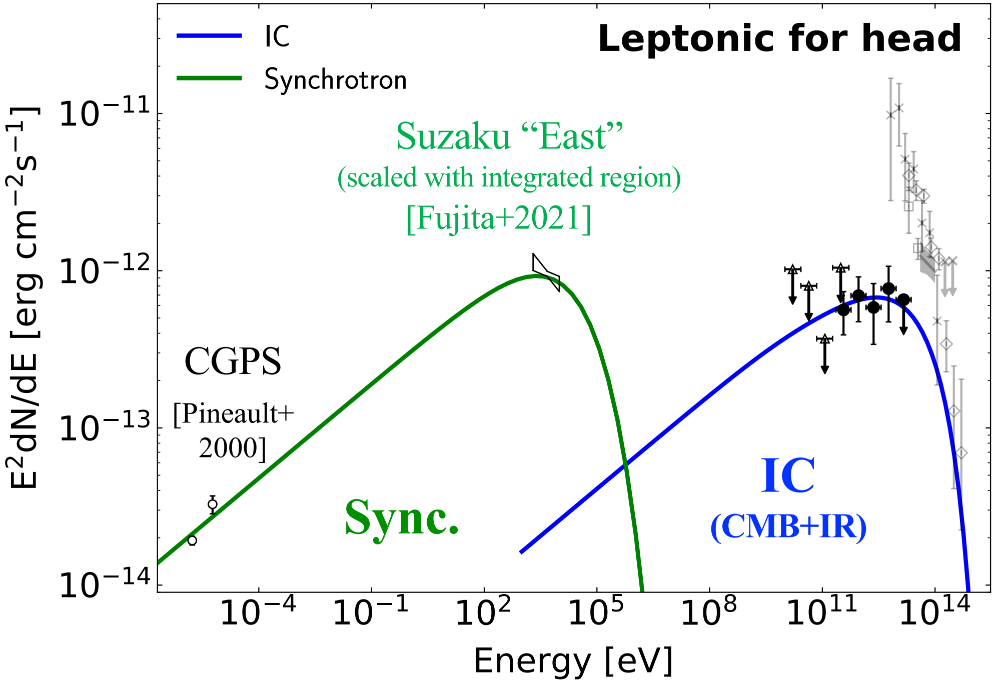
→ **MAGIC-Tail is a promising counterpart of the 100 TeV source.**



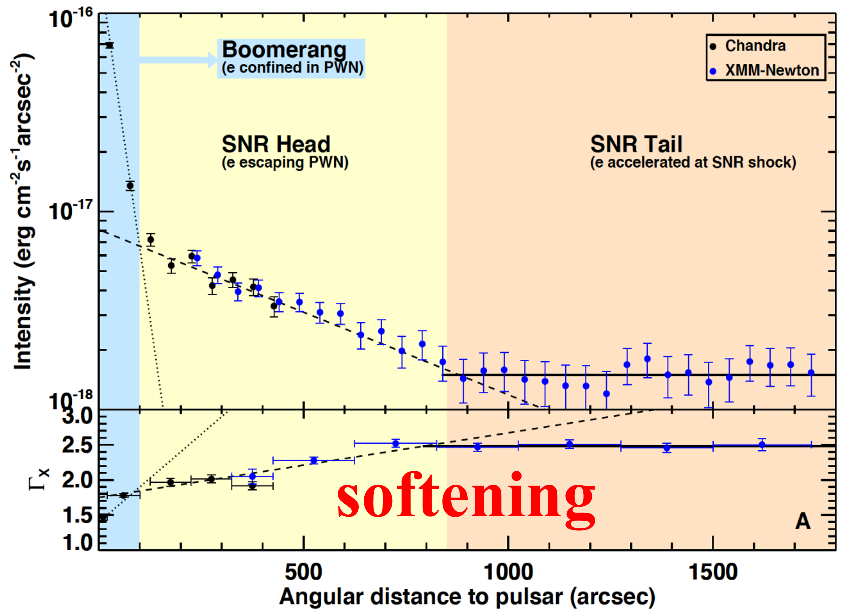
☑ Our result is consistent with VERITAS within 1σ uncertainty.

Modelling result **-Head (near PSR)-**

Modeling with naima [Zabalza 2015]



X-ray 1D profile [Ge+2021]

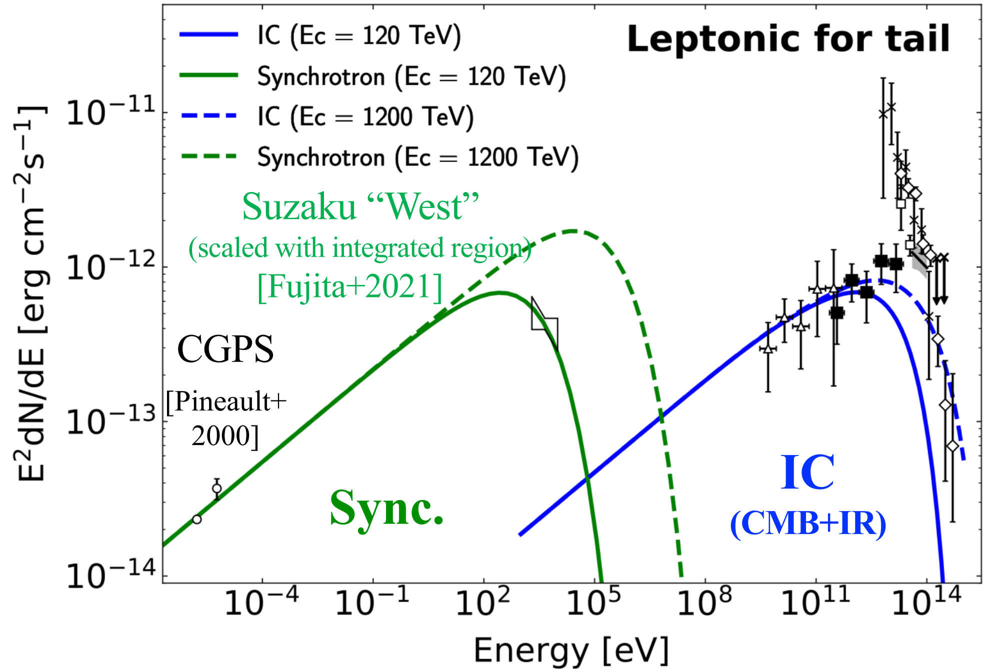


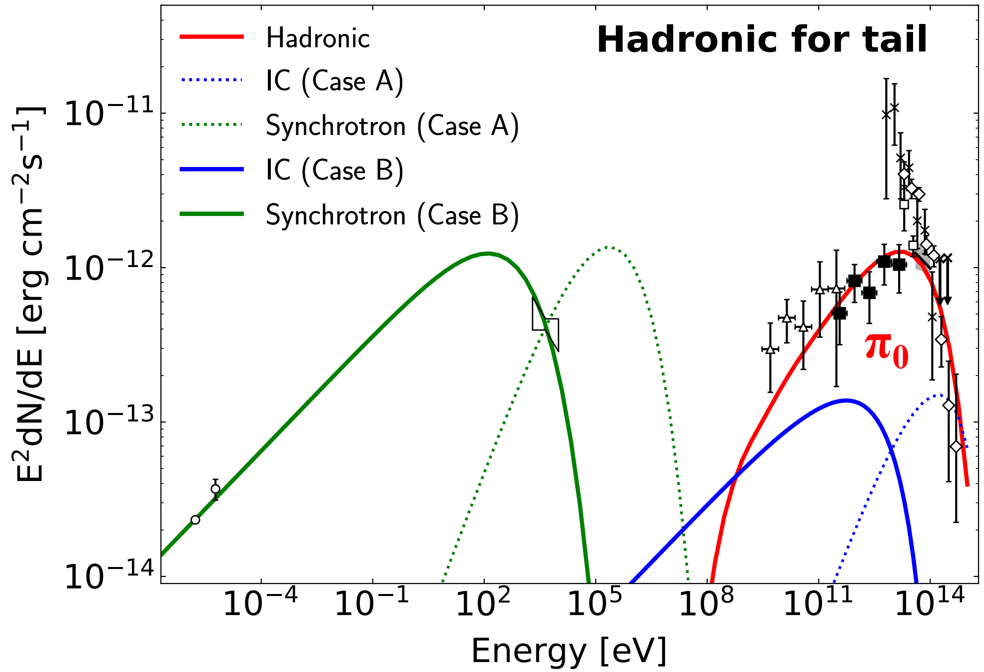
	α_e	$E_{cut, e}$	W_e (>1 GeV)	B
Leptonic	2.6	360 TeV	1.4×10^{47} erg	3 μG

☑ Leptonic emission can reproduce the MWL spectrum in the head region.

☑ X-ray results for the head region (Ge+2021, Fujita+2021) suggest the synchrotron emission originates in the Boomerang PWN.

Modelling result **-Tail-**





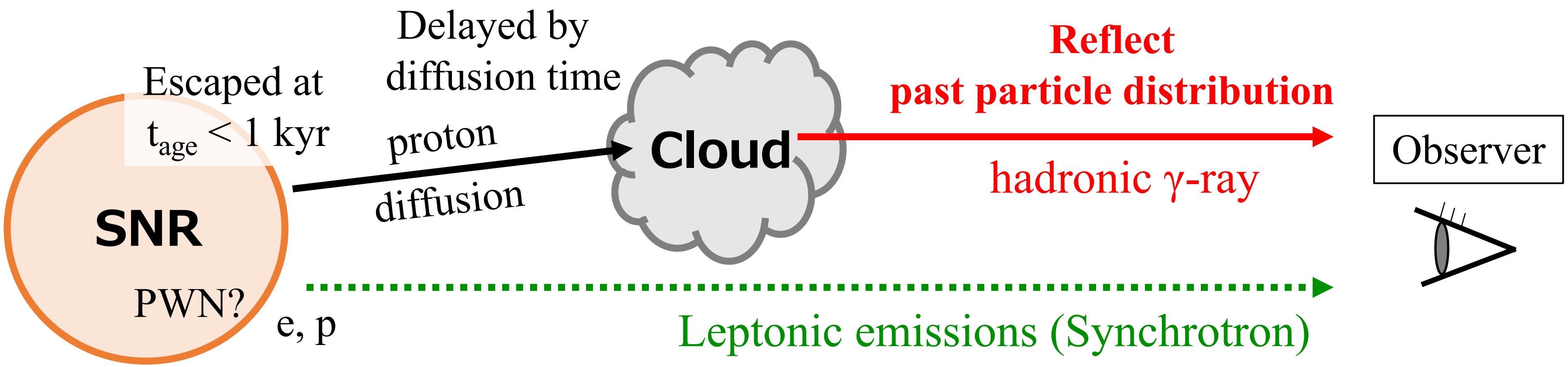
	α_e	$E_{cut, e}$	W_e (>1 GeV)	B	α_p	$E_{cut, p}$	W_p (>1 GeV)	N_{gas}
Leptonic	2.6	120 TeV (1.2 PeV)	1.6×10^{47} erg	3 μG	-	-	-	-
Hadronic	2.5	35 TeV	2.0×10^{46} erg	10 μG	1.7	1 PeV	8.2×10^{45} erg	200 cm^{-3}

Leptonic: Electrons of SNR-tail can reproduce the MAGIC spectrum
but if assume gamma-ray > 10 TeV is only from tail, in tension.

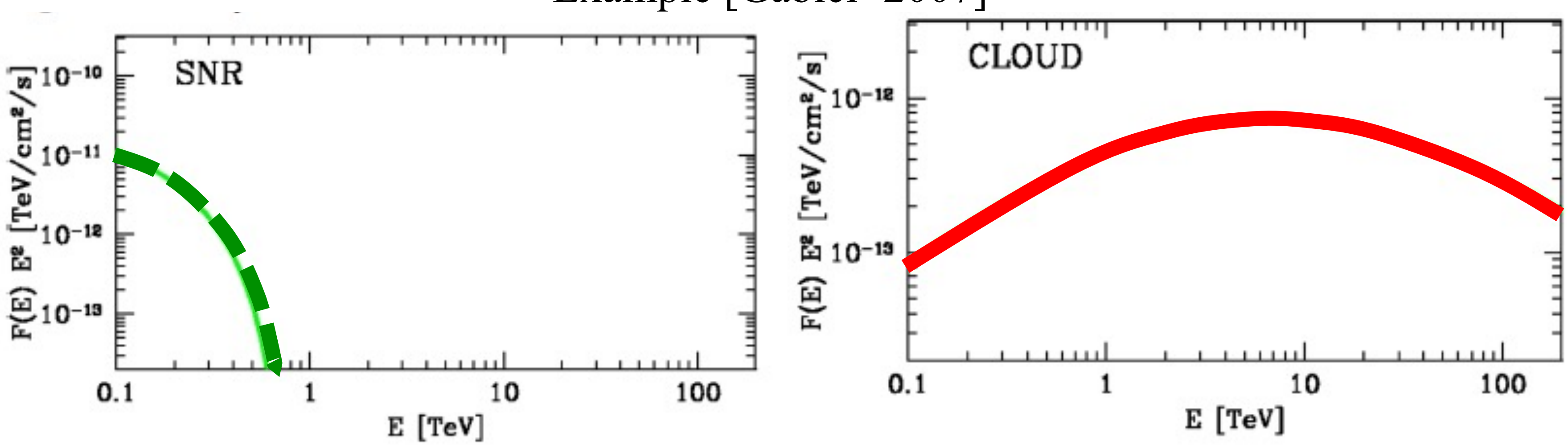
Hadronic: PeV proton is not expected in middle-aged SNR (4—10 kyr).
To reproduce the radio-X band, required different electron distribution from protons.

Interpretation for Tail: CR-escape scenario

☑ Protons escaped from SNR in the past can explain
~ 1 PeV energies and the hard index at the middle-aged SNR (4-10 kyr).



Example [Gabici+2007]



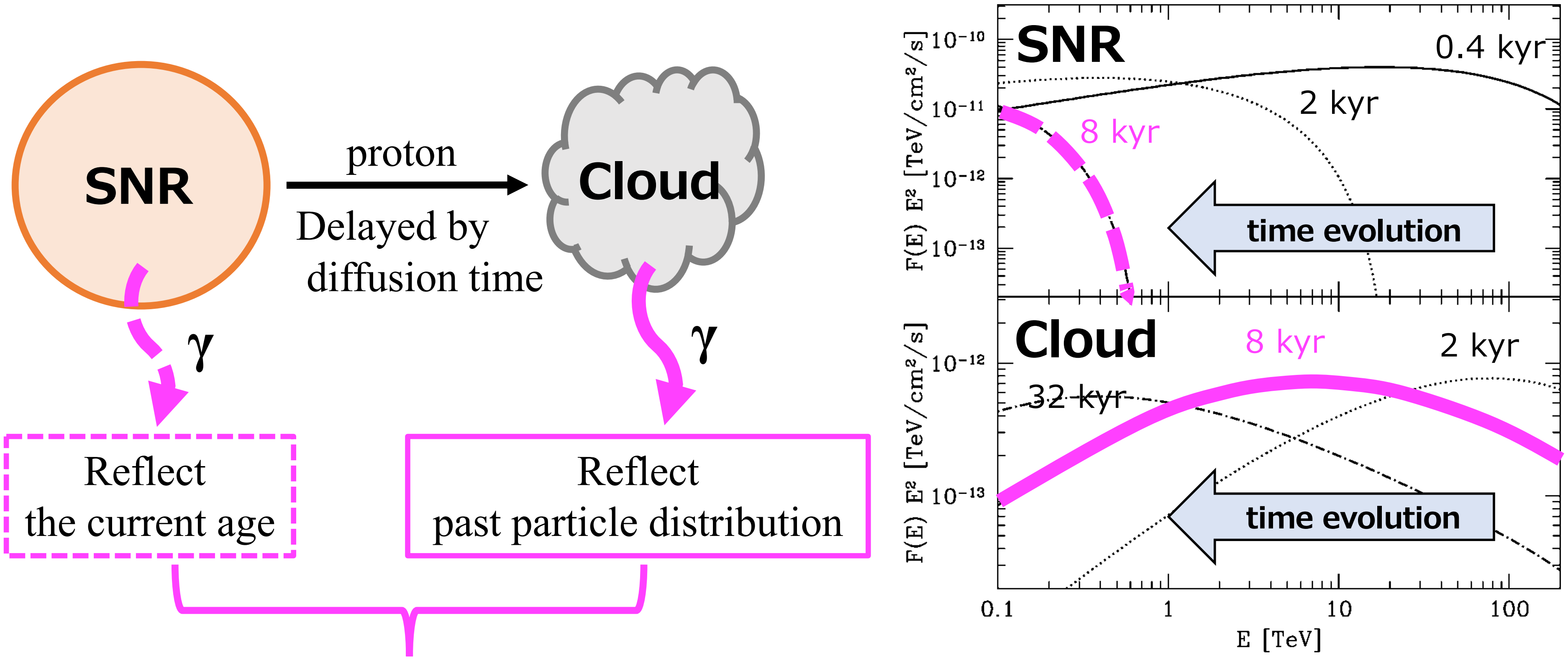
☑ The difference in the distribution between electron & proton suggests
they come from the different location (i.e., shell and cloud)?

Measurement of time evolution of the maximum acceleration energy by DSA in SNRs

[TO and W. Ishizaki., 2022, PASJ, arXiv: 2203.03240]

How to measure at a single SNR

Example of Gamma-ray spectra assuming SNR was PeVatron [Gabici et al., 2007]



Once we observe the spectra in more than two of these region (e.g., SNR+Cloud or two Clouds),
we can trace the time evolution of the particle distribution on a single SNR.

It is important that SNR and Cloud do not overlap in line of sight.

Object of interest: SNR HB9 (G160.9+2.6)

6.6 kyr (Dynamical age), Distance from Earth: 0.8±0.4 kpc [Leahy & Tian, 2007]

Advantage 1

GeV γ-ray emission from SNR radio shell was already detected [Araya 2014]

↓

Present distribution can be obtained.

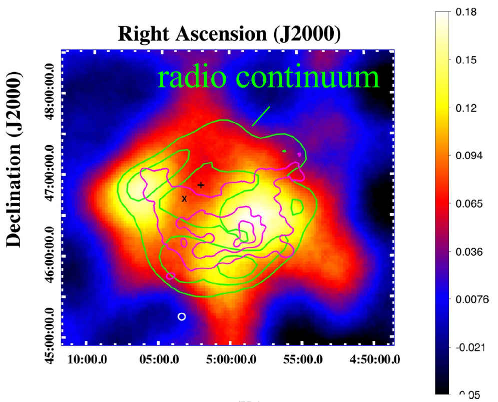
Advantage 2

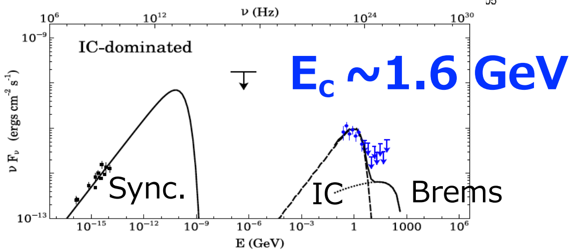
CO clouds exist w/o overlapping with the SNR shell radially [Sezer+2019]

↓

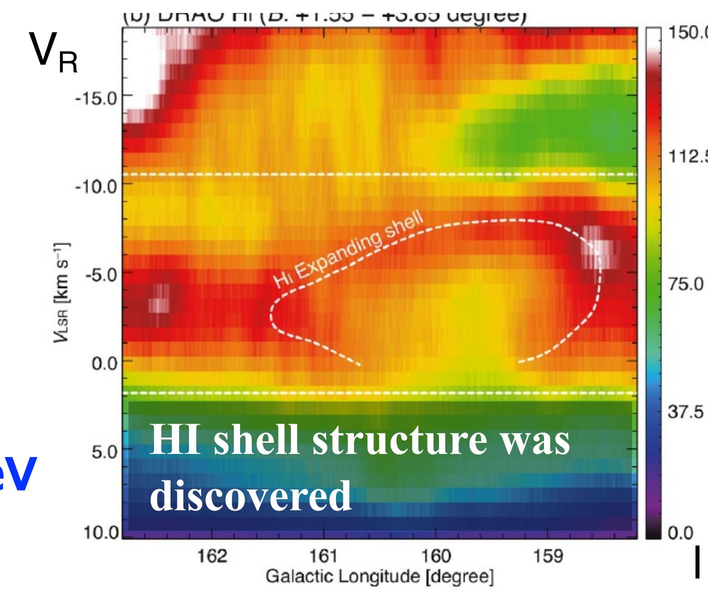
Past distribution can be examined.

Fermi-LAT γ-ray map

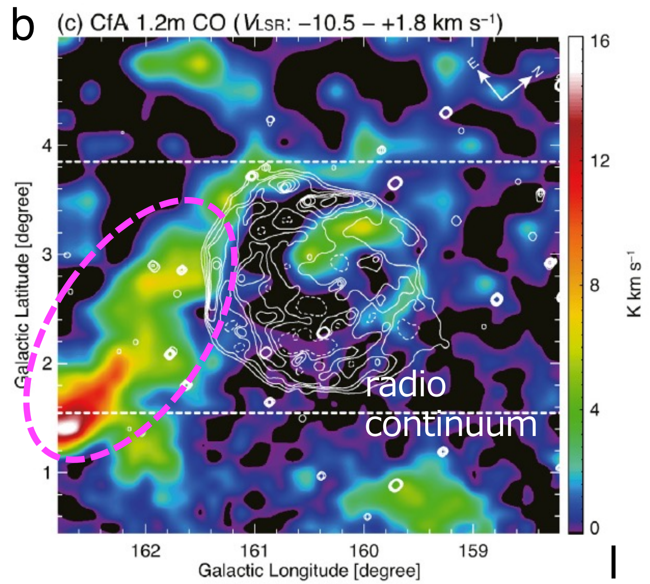




HI line pos.–velo. diagram



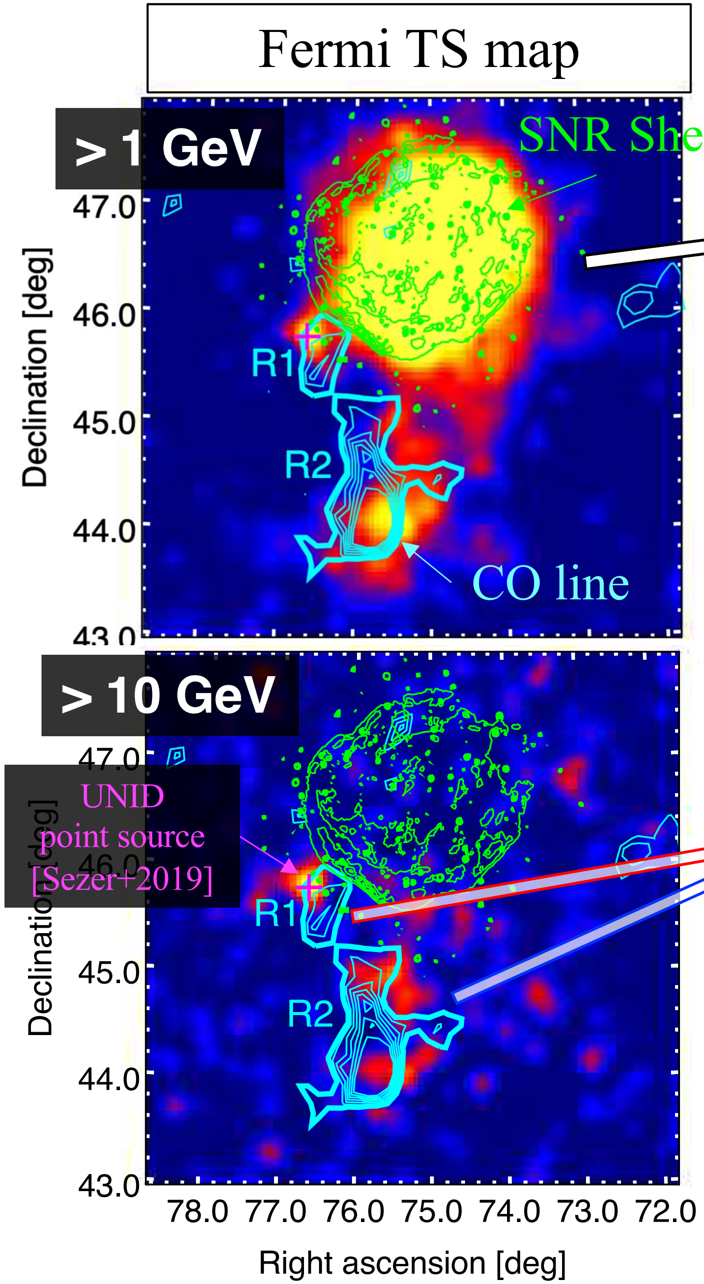
^{12}CO (J=1-0) map

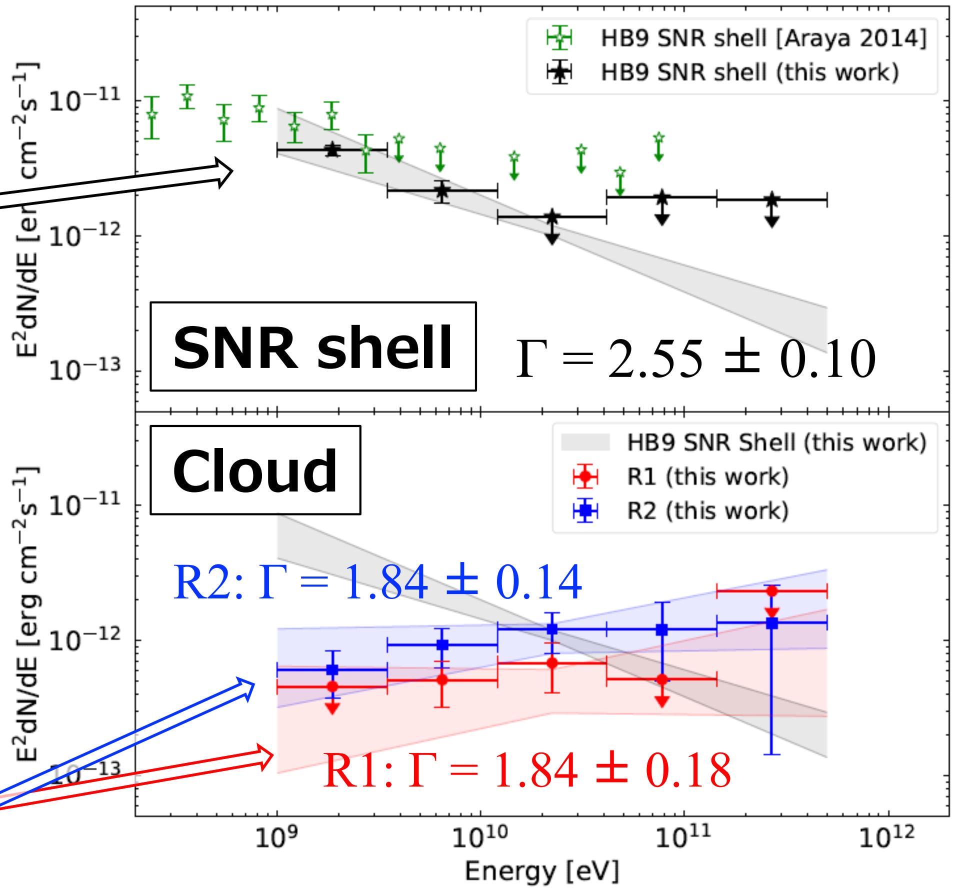


No γ-ray detection at the CO cloud regions

[This work] Analyze the 12-yr *Fermi*-LAT data

12-yr *Fermi*-LAT data analysis





☑ **GeV emissions outside Shell were found.**
→ Spatial correlation with Cloud (> 6σ)

☑ Energy spectra at Cloud are harder than that of Shell.

Model of "delayed" γ-ray emission

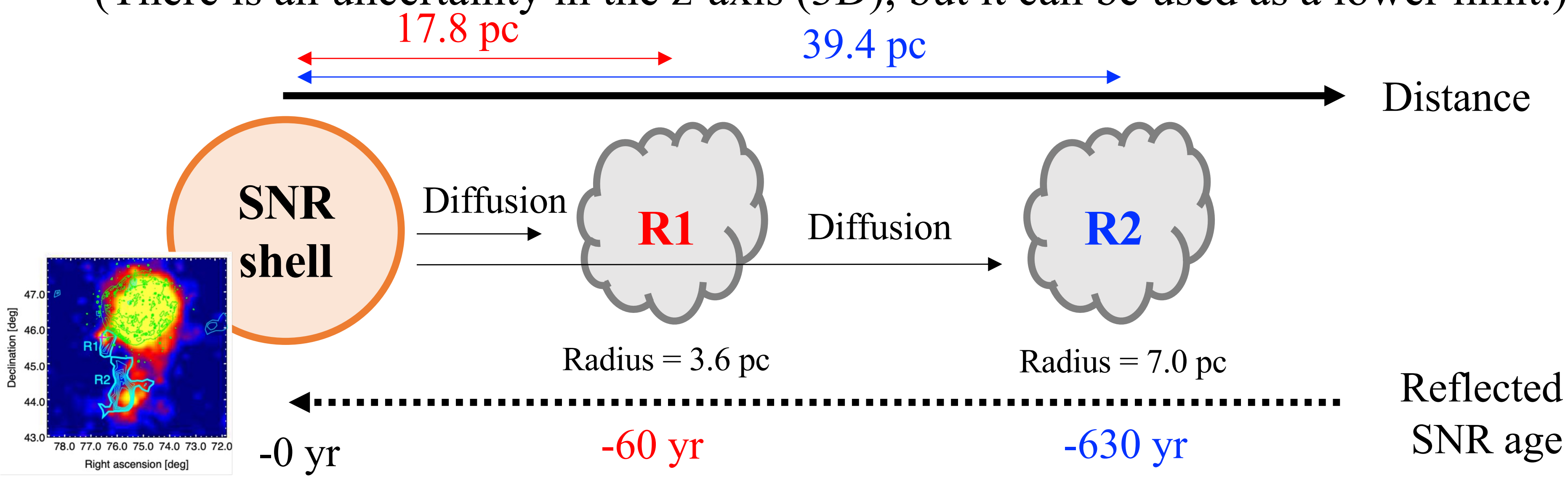
☑ Solve CR distribution escaping from SNR by the diffusion equation with 1D spherical symmetry [Gabici+2007, 2009, Ohira+ 2011]

$$\frac{\partial f_{p,\mathrm{out}}}{\partial t}(t,r,E) - D_{\mathrm{ISM}}(E)\Delta f_{p,\mathrm{out}}(t,r,E) = q_{p,s}(t,r,E), \quad (3)$$

☑ Maximum energy of injected CRs varies as a power-law function of age: E_{now} is estimated with the observation data (300 GeV).

$$E_{\mathrm{esc}}(t) = E_{\max}\left(\frac{t}{t_{\mathrm{Sedov}}}\right)^{-\alpha},$$

☑ Distance b/w SNR & Cloud: adopt the 2D distance obtained from radio data (There is an uncertainty in the z-axis (3D), but it can be used as a lower limit.)

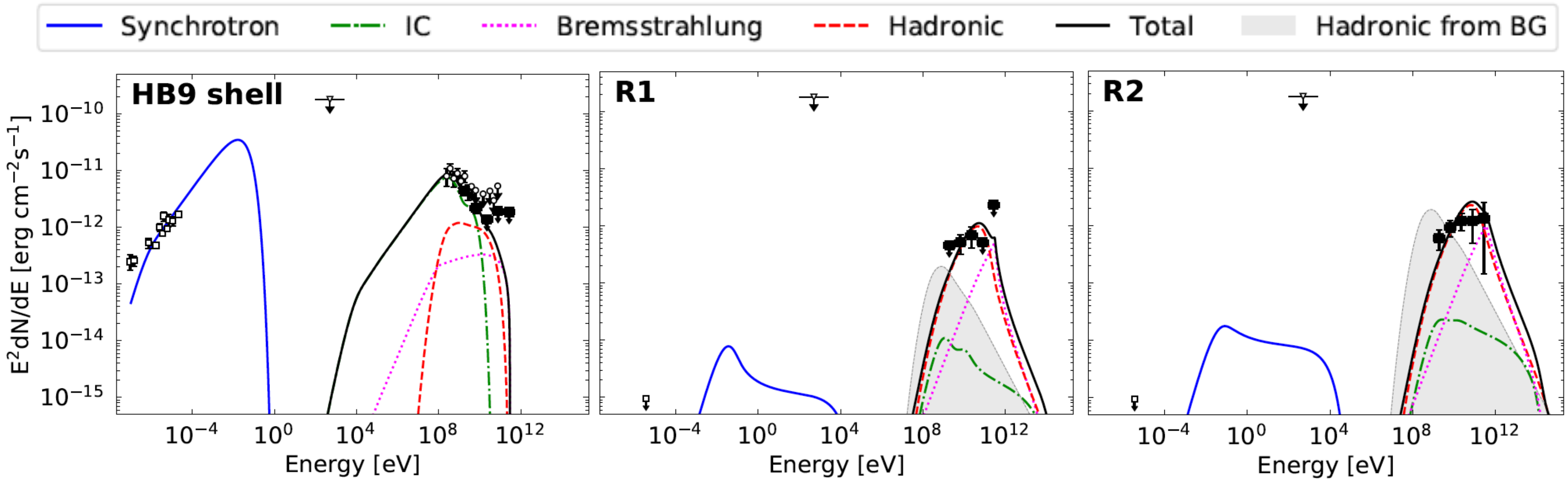


(6.6 kyr at present)

☑ Diffusion coefficient: $D(E) = D_0 E^{\delta}$

Modelling result with delayed γ rays

Both spectra of Shell & Cloud can be reproduced simultaneously.



Shell: Synchrotron (B=8 μG)
+ IC (CMB + dust)

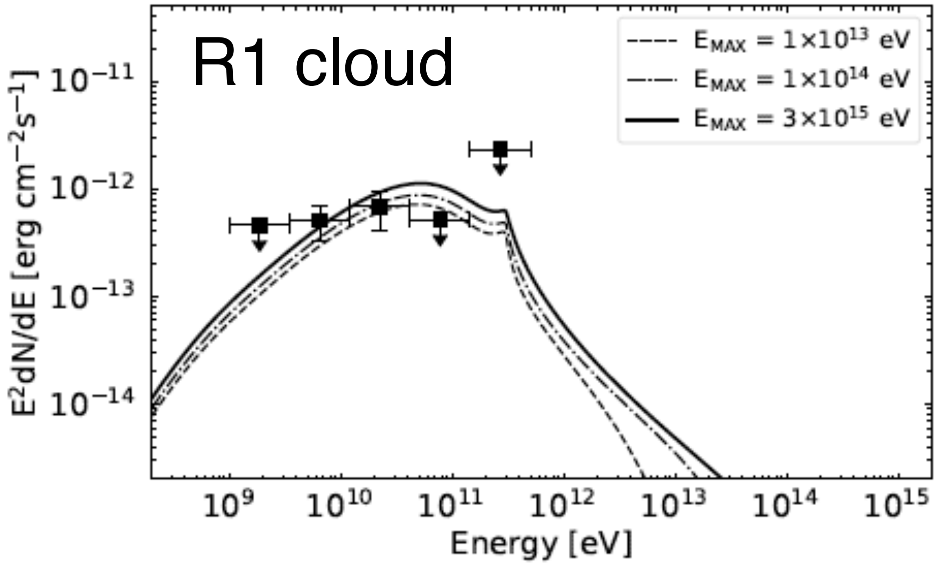
Cloud: π^0 decay (+ electron Brems)
(n_{gas} = 150 cm^{-3} for R1, 200 cm^{-3} for R2)

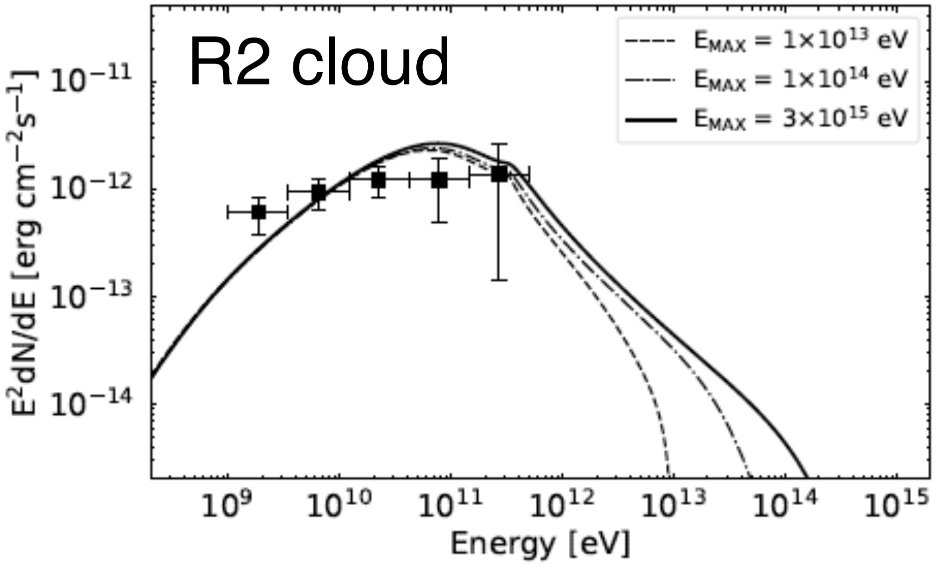
<u>Model parameters</u>

- Total energy of the supernova explosion: $E_{SN} = 0.3 \times 10^{51}$ erg [Leahy+2007]
- ISM density: $n_{ISM} = 0.06$ cm^{-3} [Leahy+2007]
- Electron-to-proton ratio: $K_{ep} = 2\%$
- $D(E) = D_0E^{\delta} = 3\times10^{28} (E/10\ GeV)^{1/3}$ cm^2/s ~ Galactic mean
- **E_{now} = 300 GeV at the current shell & E_{max} = 3 PeV at entering Sedov phase**

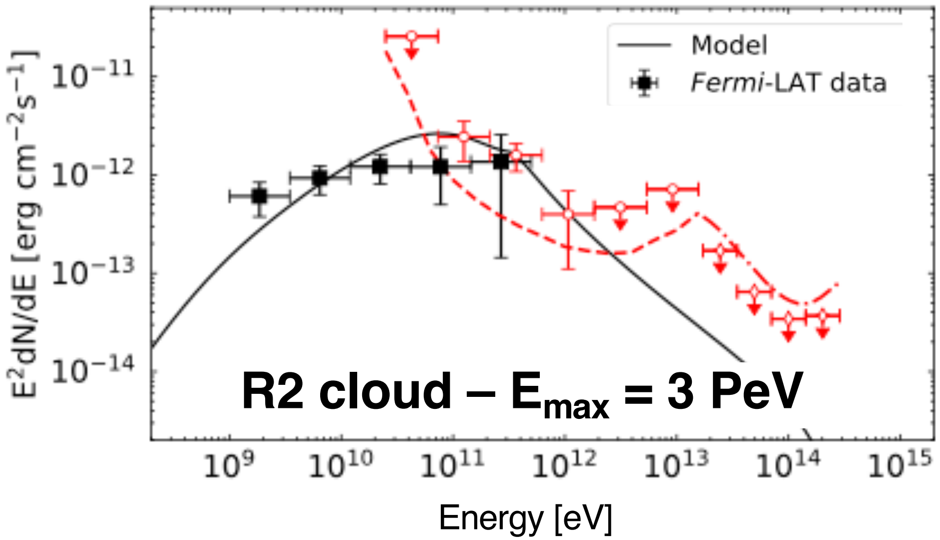
Model dependency on E_{max} @t_{Sedov}

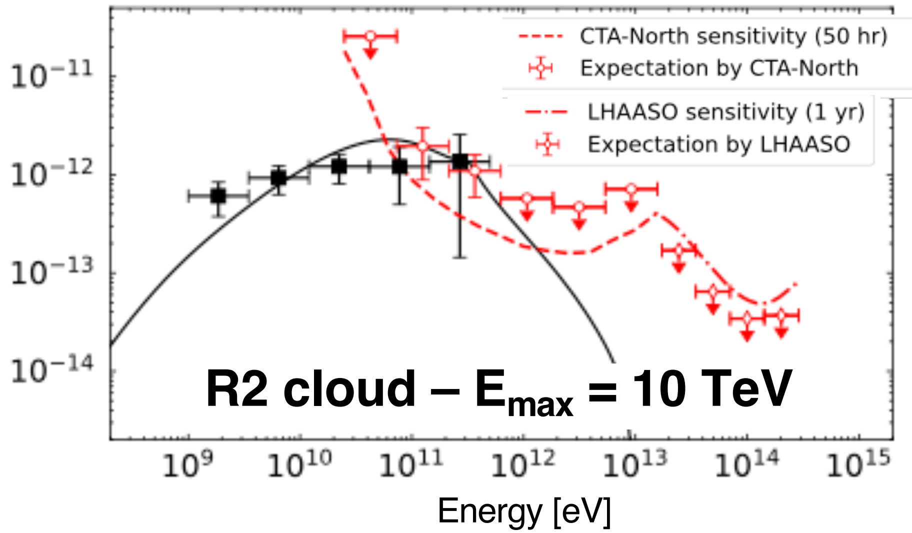
E_{max} : 3 PeV, 100 TeV, 10 TeV → lower limit ≳ 10 TeV





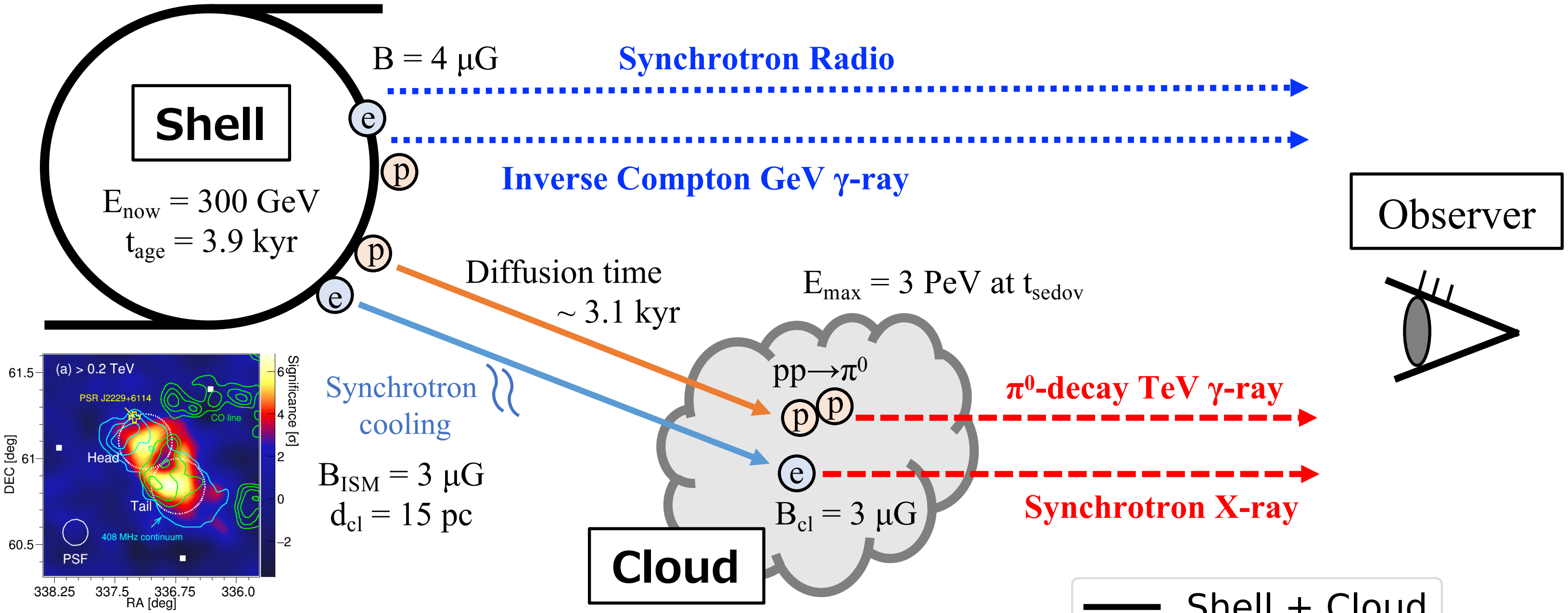
☑ We need TeV-PeV observations to determine the model parameter.



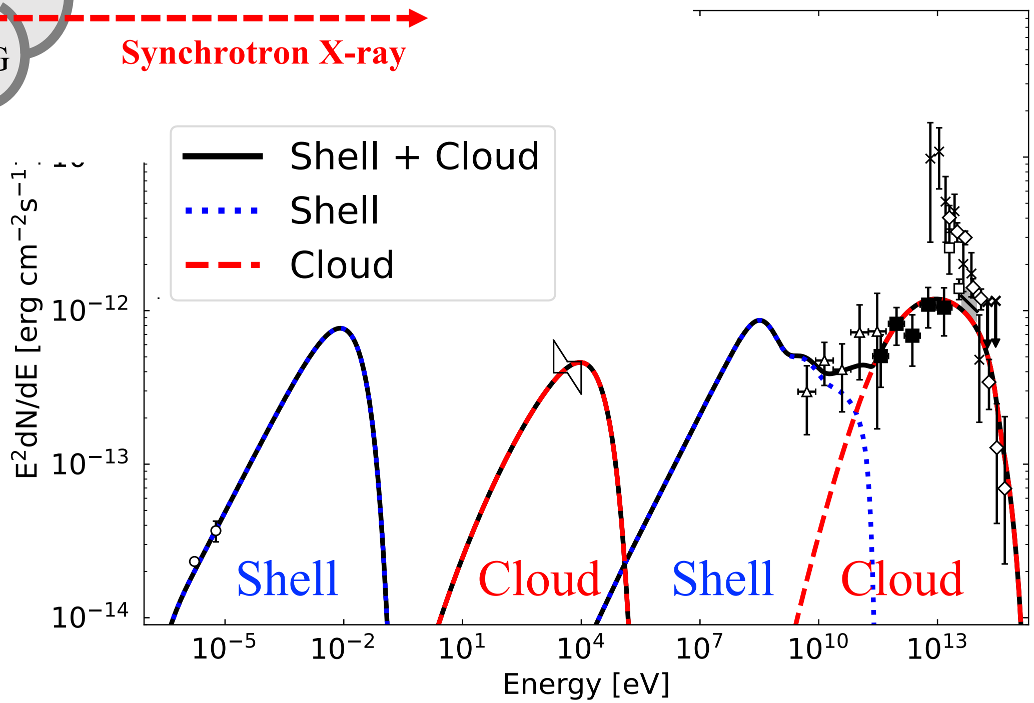


Delayed γ-ray model for G106.3+2.7–Tail

Apply to the SED of MAGIC–Tail region with 2-zone (Shell + Cloud) model



SED can be reproduced with the model assuming the time-evolution of E_{max} in the SNR.



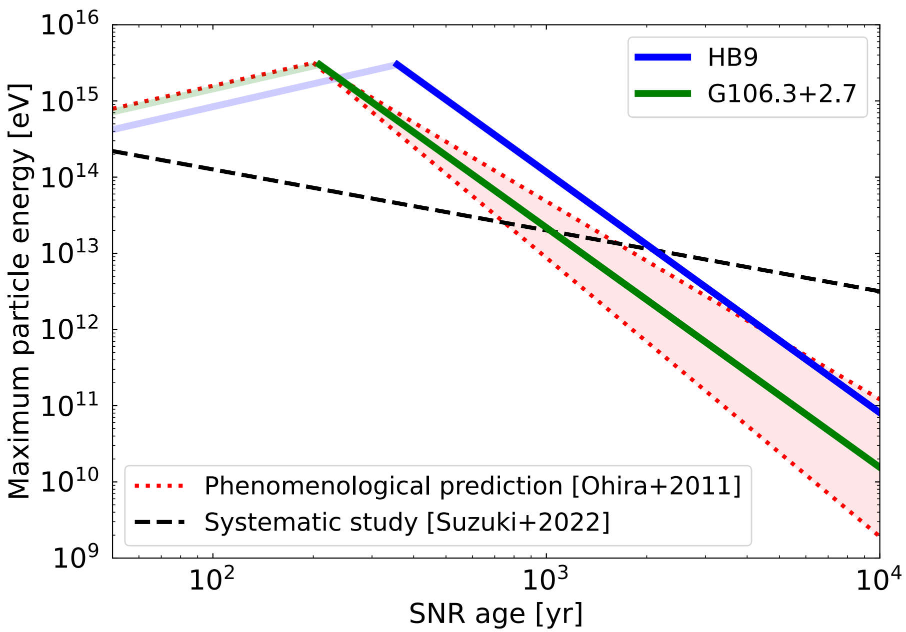
Comparison of obtained model parameters

	HB9	G106.3+2.7 – Tail
Explosion energy (E_{SN})	3.0×10^{50} erg	1.0×10^{50} erg
Maximum CR energy at t_{sedov}	3 PeV (> 10 TeV)	3 PeV (500 TeV−5 PeV)
Temporal decay index of $E_{max} \propto t_{age}^{-\alpha}$	3.2	3.2
Age of SNR	6600 yr	3900 yr
Diffusion coefficient at 10 GeV	3×10^{28} cm^2s^{-1}	2×10^{26} cm^2s^{-1}

☑ Both allow acceleration up to PeV.

☑ Temporal decay index in this work is consistent with the phenomenological prediction (α = 2.6−3.7; Ohira+2011).

☑ Diffusion coefficient varies by two orders of magnitude.



CR luminosity

Calculate the amount of PeV protons escaped from SNRs
→ Convert to Lumosity by multiplying SN rate = 0.03 yr^{-1} [e.g., Tammann+1994]

$$N_{\rm esc}(E) = \begin{cases} \frac{\eta(2-p_{\rm esc})E_{\rm SN}}{E_{\rm now}^2} \times \left[\left(\frac{E_{\rm max}}{E_{\rm now}}\right)^{2-p_{\rm esc}} - 1\right]^{-1} \times \left(\frac{E}{E_{\rm now}}\right)^{-p_{\rm esc}} & p_{\rm esc} \neq 2 \\ \frac{\eta E_{\rm SN}}{\ln(E_{\rm max}/E_{\rm now})} E^{-2} & p_{\rm esc} = 2 \end{cases}$$

$$L_{\rm SNR} \sim N_{\rm esc}(E) \times E^2 \times ({\rm SN\ rate}).$$

☑ Compare with the CR luminosity measured at Earth (L_{CR}) [e.g., Dermer 1986]

Name	$L_{\rm SNR}$(10 TeV) [erg s^{-1}]	$L_{\rm SNR}/L_{\rm CR}$ at 10 TeV	$L_{\rm SNR}$(1 PeV) [erg s^{-1}]	$L_{\rm SNR}/L_{\rm CR}$ at 1 PeV
HB9	2.88×10^{39}	1.08	4.56×10^{38}	0.54
G106.3+2.7	1.03×10^{39}	0.39	1.03×10^{39}	1.22

☑ Luminosity of protons escaped from SNRs (L_{SNR}) agrees with CR measurements at Earth (L_{CR}) within a factor of 3.
→ SNR paradigm for PeV CR origin is supported well.

Conclusion

Q. Why we can't find SNR PeVatron?

Reason 1: Hidden in 100-TeV γ-ray sources where its origin is unclear.

↓

Precise γ-ray observations of SNR G106.3+2.7 with the MAGIC telescopes strongly suggest proton acceleration up to PeV in the SNR.

[MAGIC Collab.: H. Abe, TO et al.,, A&A in press, arXiv: 2211.15321]

Reason 2: E_{max} in SNRs depends on its age. PeV CRs are produced only by young SNRs (t_{age} < 1 kyr). Observation opportunities for SNR PeVatron are few.

↓

We newly proposed the measurement method for the time-evolution of E_{max}.

First successful application to the real observation data (HB9)

[TO and W. Ishizaki., 2022, PASJ, arXiv: 2203.03240]

Luminosity of runaway protons from SNRs (calculated with obtained model, e.g., temporal decay index ~ 3) agrees with CR observations at Earth.

A. We can interpret with the time-evolution scenario for SNRs. SNR paradigm for CR origin is supported well

CTA and LHAASO/ALPACA observations will provide a robust conclusion.