Potential PeV cosmic ray acceleration in the middle-aged pulsar-wind nebula HESS J1849-000

Kato Sei (加藤 勢)
ICRR, Univ. of Tokyo

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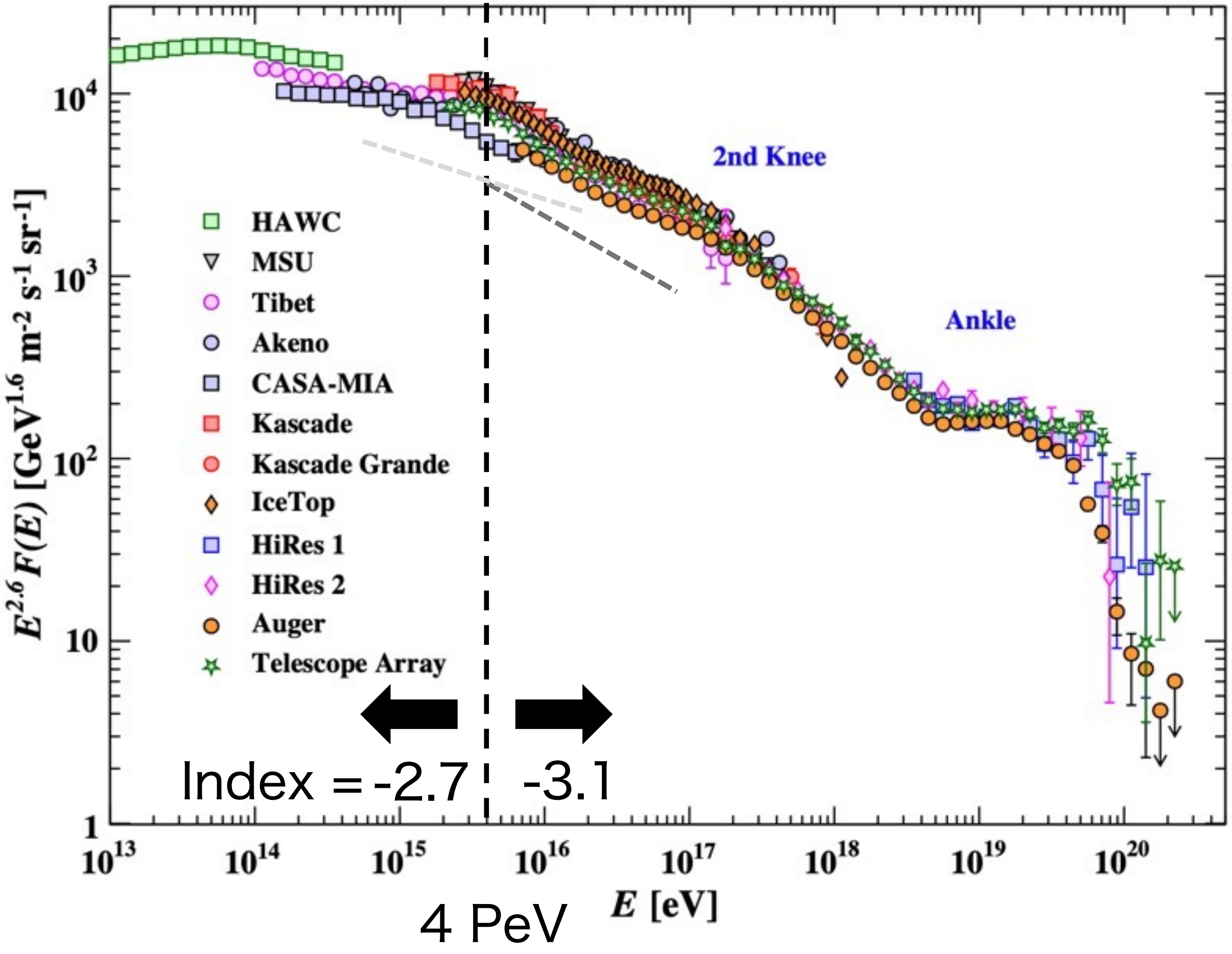
Introduction

Bend seen in the CR energy spectrum：Knee

CR energy spectrum observed @ Earth



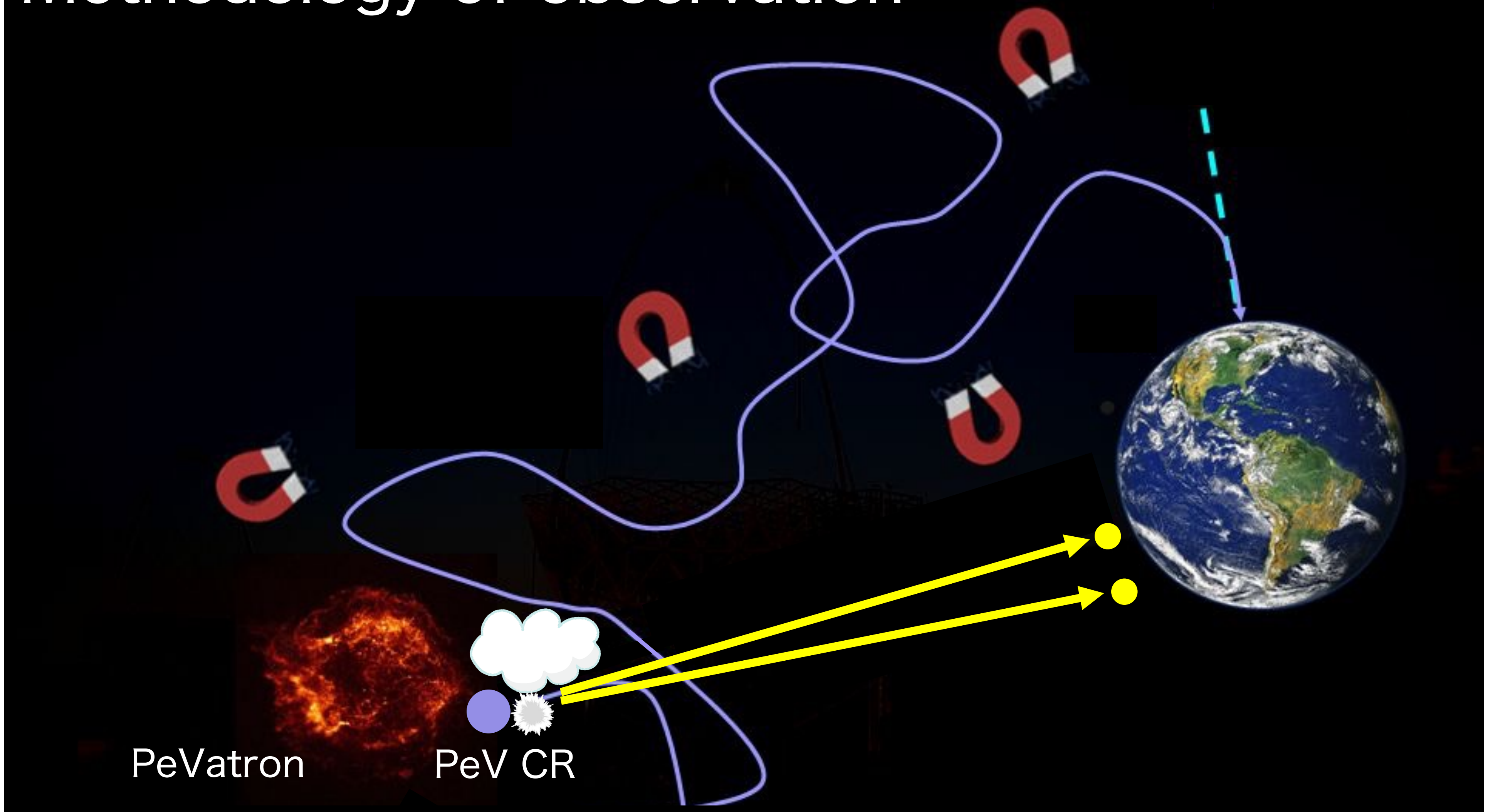
Index = -2.7 -3.1

4 PeV

- ✓ Origin of the Knee ??
- ✓ CRp acceleration limit in our Galaxy ??
- ✓ PeV CR accelerators: ***PeVatrons***
- ✓ Only a few promising candidate sources[2,3] …

1. Zyla et al. Prog. Theor. Exp. Phys. 2021, 083C01 (2021)
2. Amenomori et al., Nat. Astron 5, 460 (2021)
3. Cao et al., Science Bulletin 69, 449 (2024)

Methodology of observation

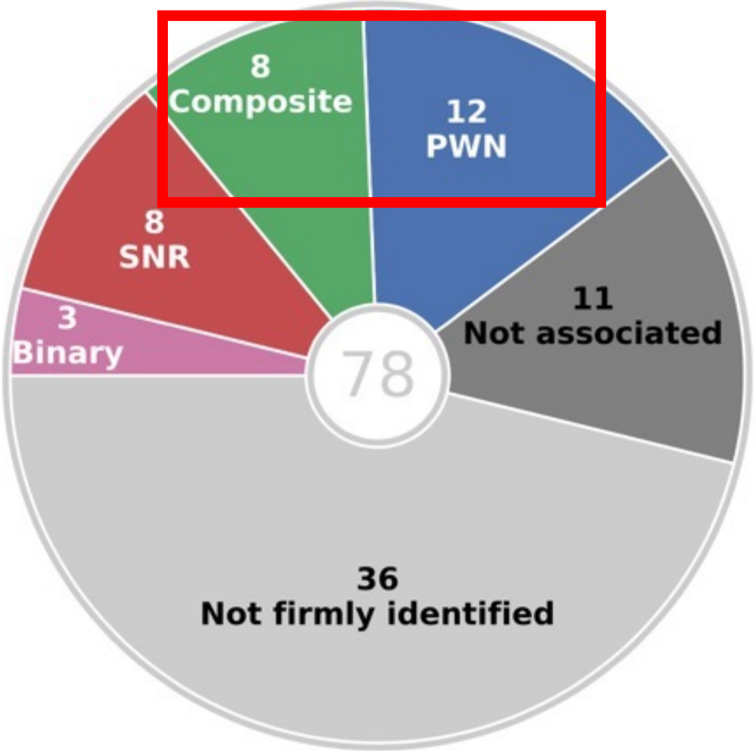


- ! PeVatrons cannot be localized from the CR obs.
- ✓ $\pi 0 \rightarrow 2\gamma$ from CR-gas collisions
- ✓ Sub-PeV (E > 100 TeV) γ rays & ISM gas

Gamma-Ray Sources Associated w/ Pulsar Wind Nebulae

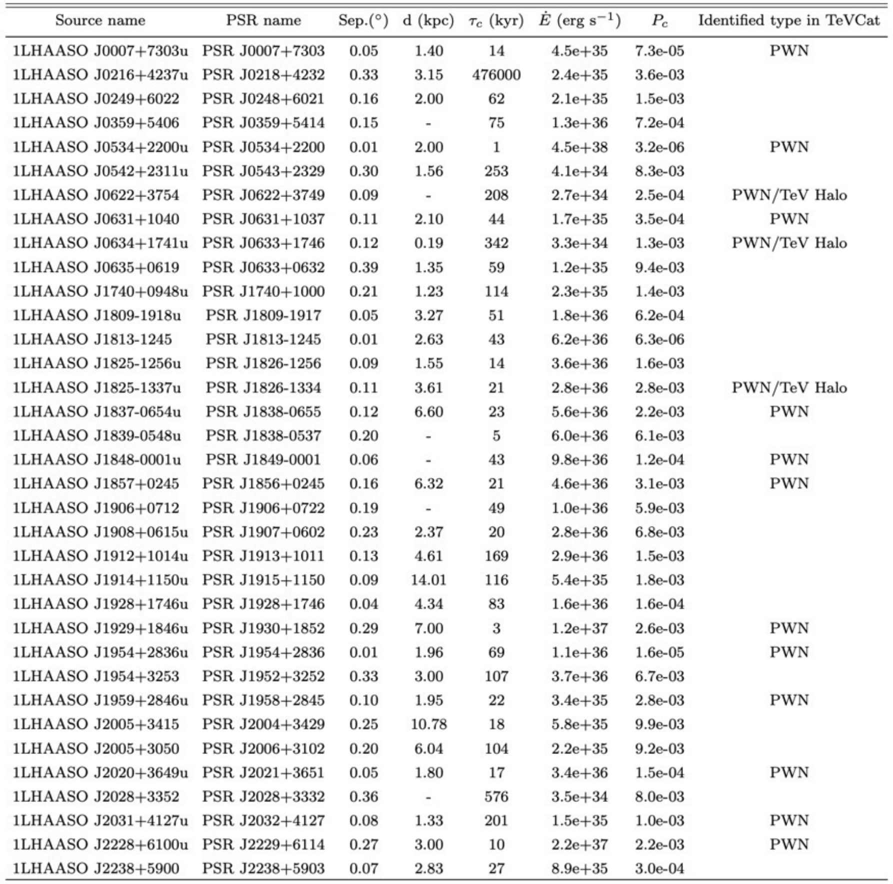
H.E.S.S. Gal. Plane Survey[1]

20/78 sources are associated w/ PWNe



35 1LHAASO sources associated w/ PSRs[2]

15 sources w/ identified PWNe/TeV Halo



Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	-	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

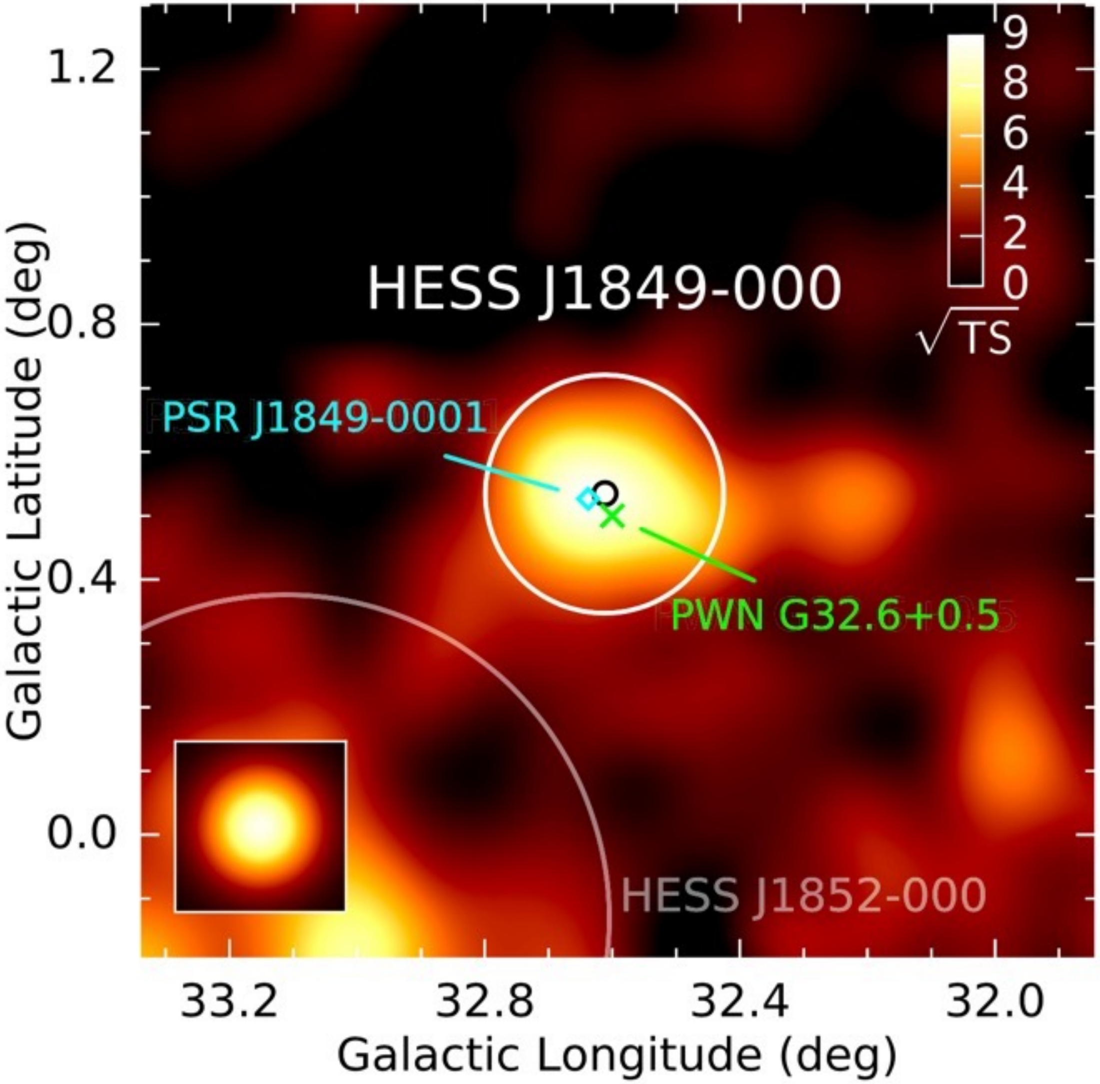
✓ PWNe could occupy a large fraction of VHE/UHE src.s

✓ Potential CR acceleration theoretically discussed[3,4,5,6]

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. arXiv:2305.17030v2 (2023)
3. Cheng et al., ApJ 300, 500 (1986)
4. Zhang et al., MNRAS 497, 3477–3483 (2020)
5. Liu & Wang, ApJ 922, 221 (2021)
6. Spencer et al., PoS(ICRC2023)690

HESS J1849–000

$\sqrt{TS}$ maps @ E > 400GeV (H.E.S.S.[1])



✓ PSR J1849–0001 in the center of TeV γ-ray emission
=> Middle aged pusar-wind nebula (PWN)[1,2]

✓ IntF(> 1TeV) = 2.3% Crab & Γ ~ 2.0[1]

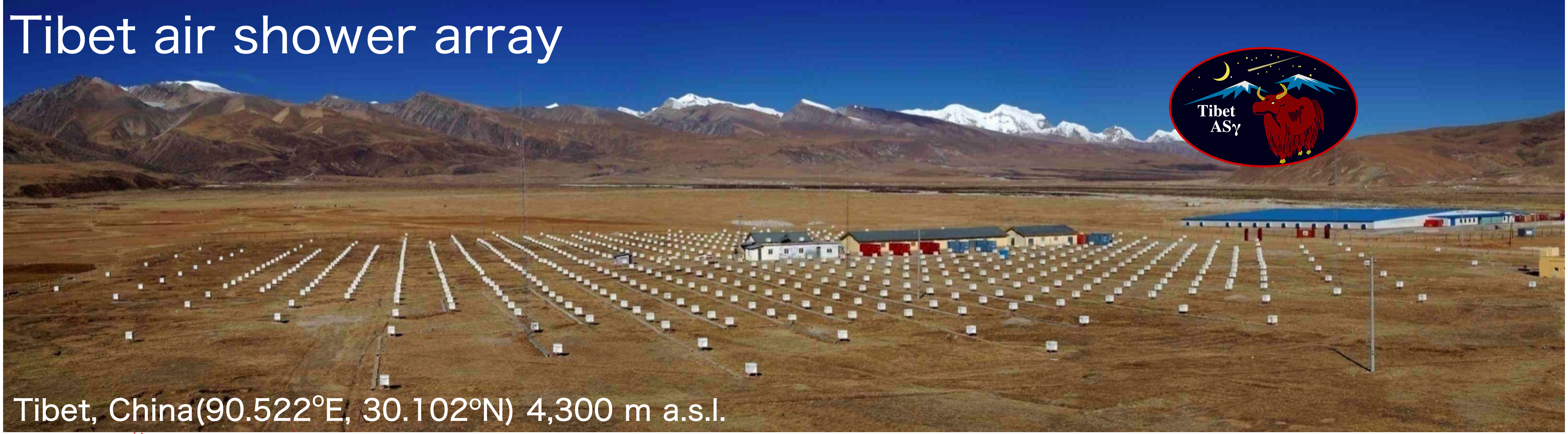
✓ Nearby HAWC (>56TeV)[3] & LHAASO (>100TeV)[4,5] src.s

! No detailed study of the origin of the γ-ray emission

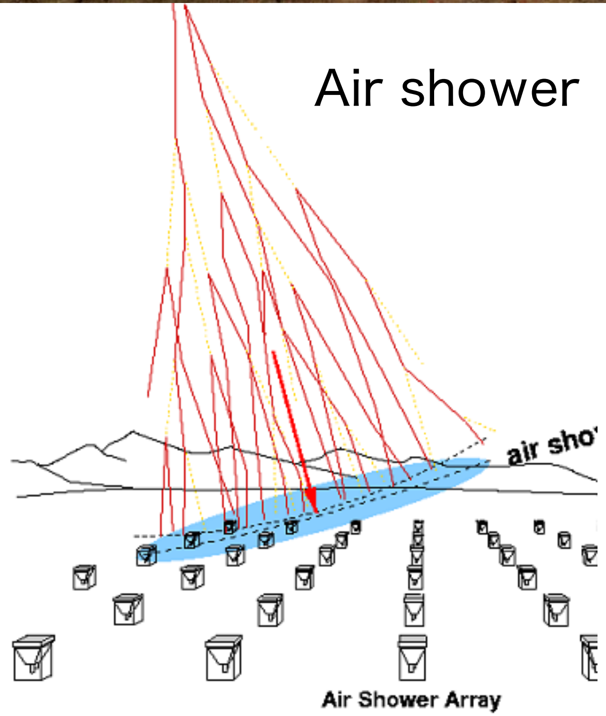
1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. H.E.S.S. Collaboration, A&A 612, A2 (2018)
3. Abeysekara et al., PRL 124, 021102 (2020)
4. Cao et al., Nature 594, 33 (2021)
5. Cao et al., arXiv:2305.17030v2 (2023)

Experiment & Data Analysis

Tibet air shower array

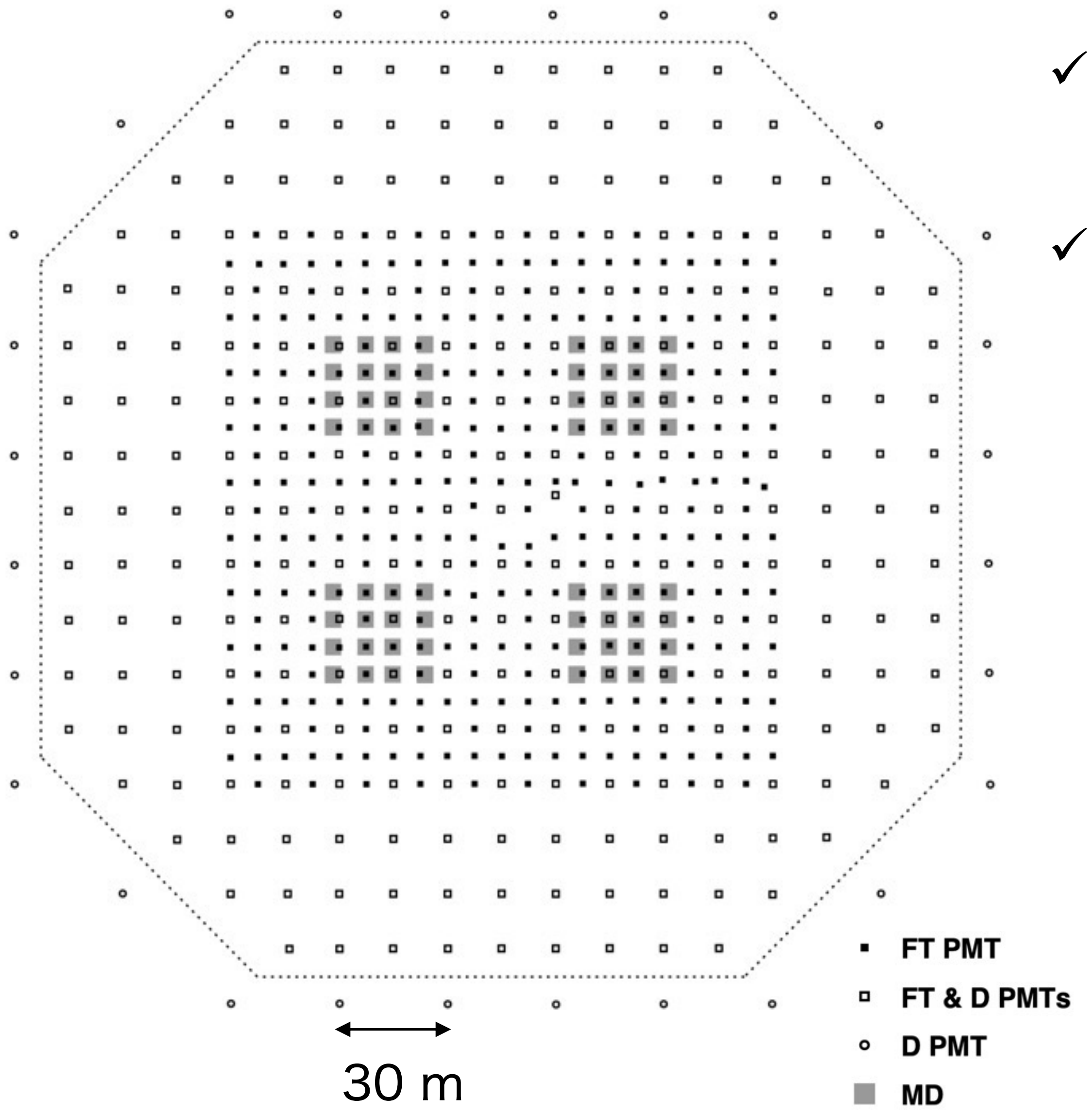


Tibet, China(90.522°E, 30.102°N) 4,300 m a.s.l.

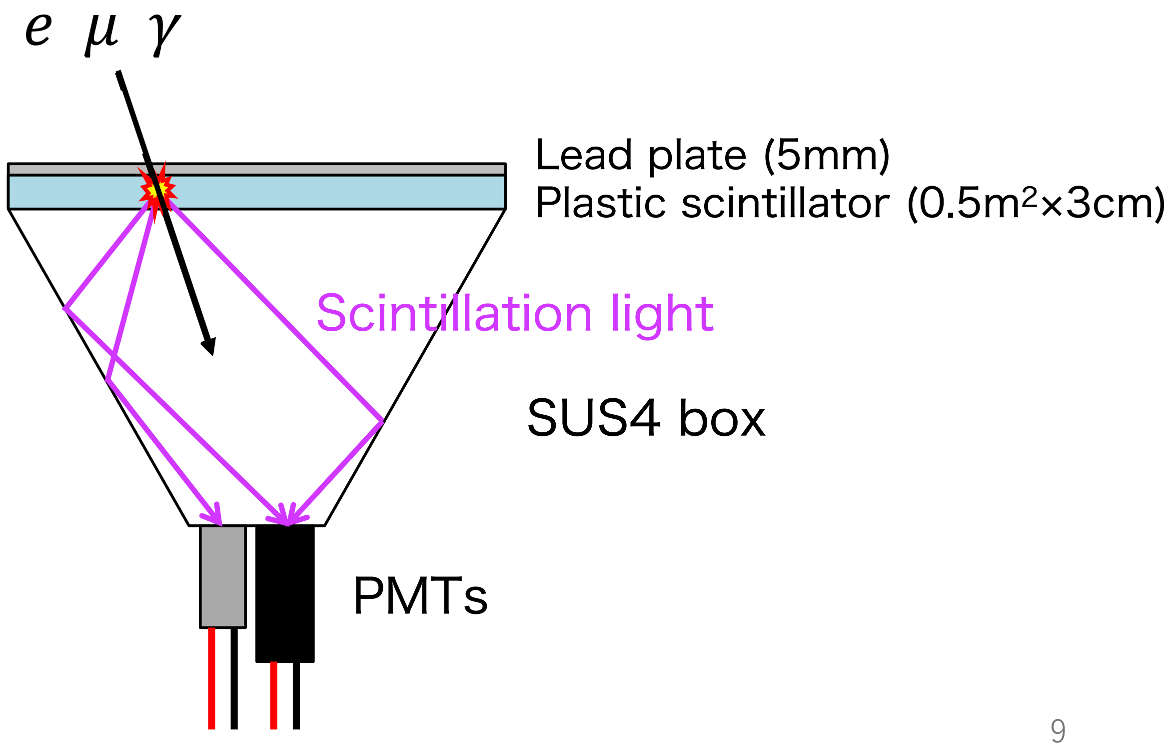


- ✓ Operating since 1990
- ✓ Observation of air showers produced by CR-atm. collisions
  => Reconstruction of energy & arrival direction
- ✓ Wide F.O.V. (~ 2 sr) & high duty cycle (>90%)
- ✓ Angular resolution : 0.2° for 100TeV γ
- ✓ Energy resolution : 20% for 100TeV γ

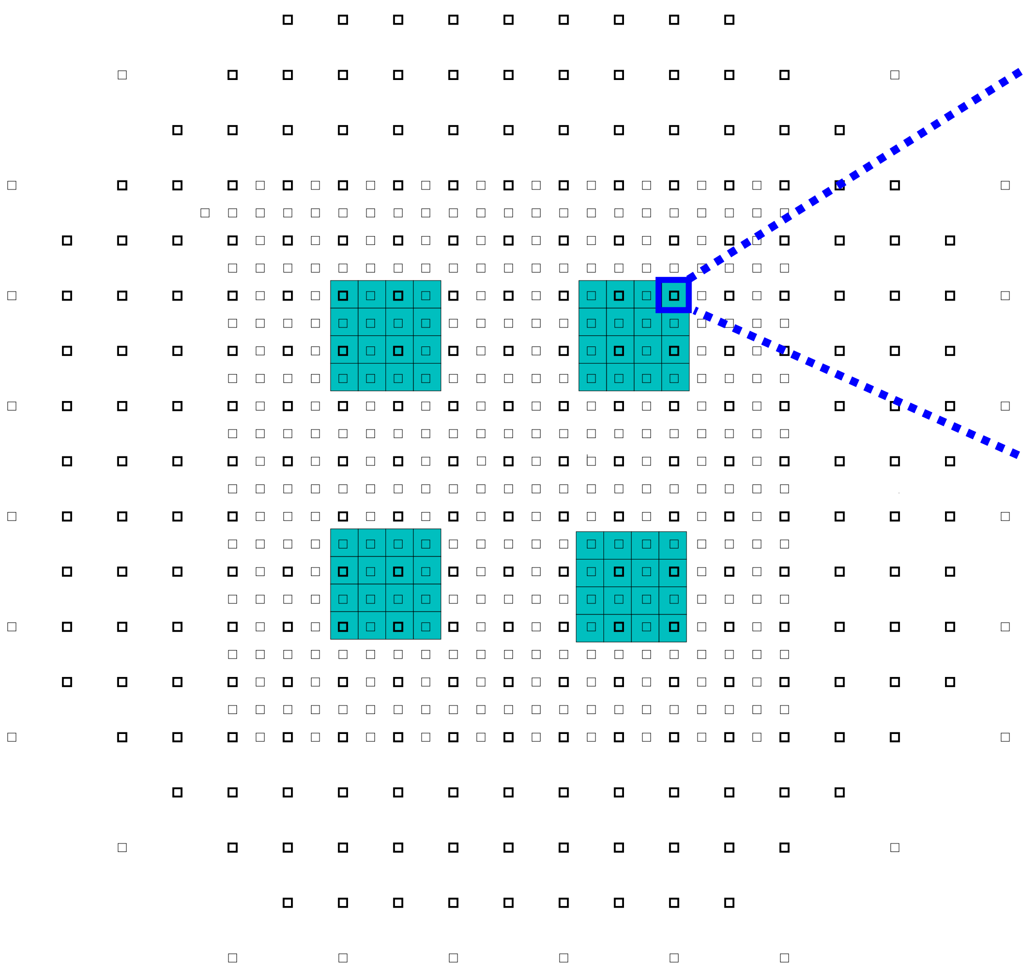
Tibet air shower array



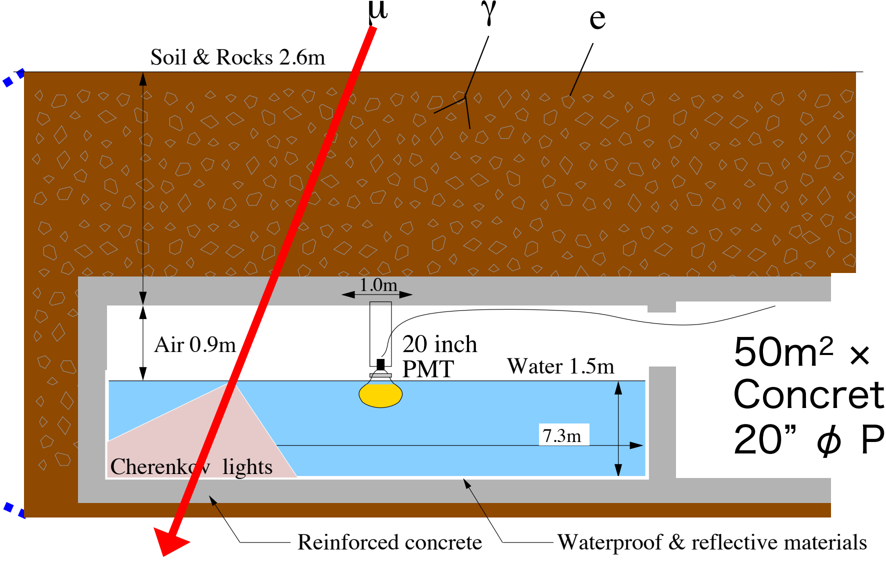
- ✓ Geometrical area : 65,700 m^2
  (597 × 0.5m^2 scintillation detectors)
- ✓ Real-time calibration of cable lengths & sngl. peak
  => Good angular & energy resolutions



Underground muon detector array (MD array)

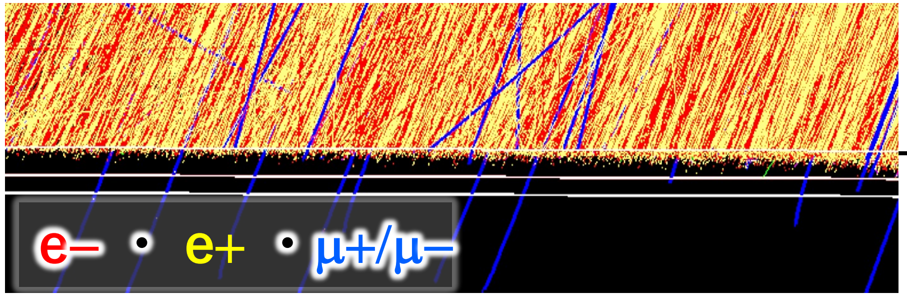


MD : 3400m²



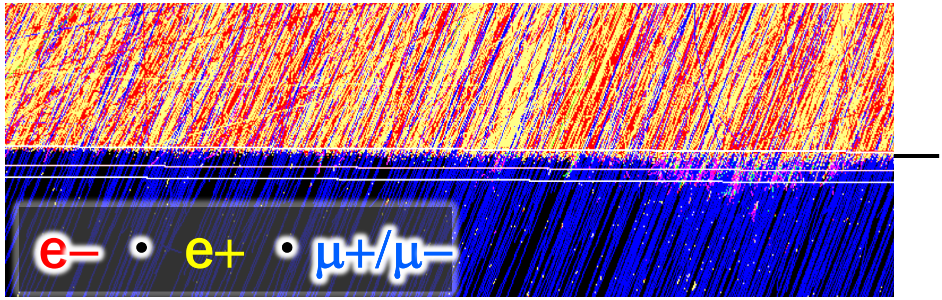
2.4 m soil overburden (515g/cm² ~19X_0)

50m² × 2.4m (1.5m water depth)
Concrete + Tyvek sheet
20” ϕ PMT (HAMAMATSU R3600)



200TeV γ shower

Few muons (~1μ)

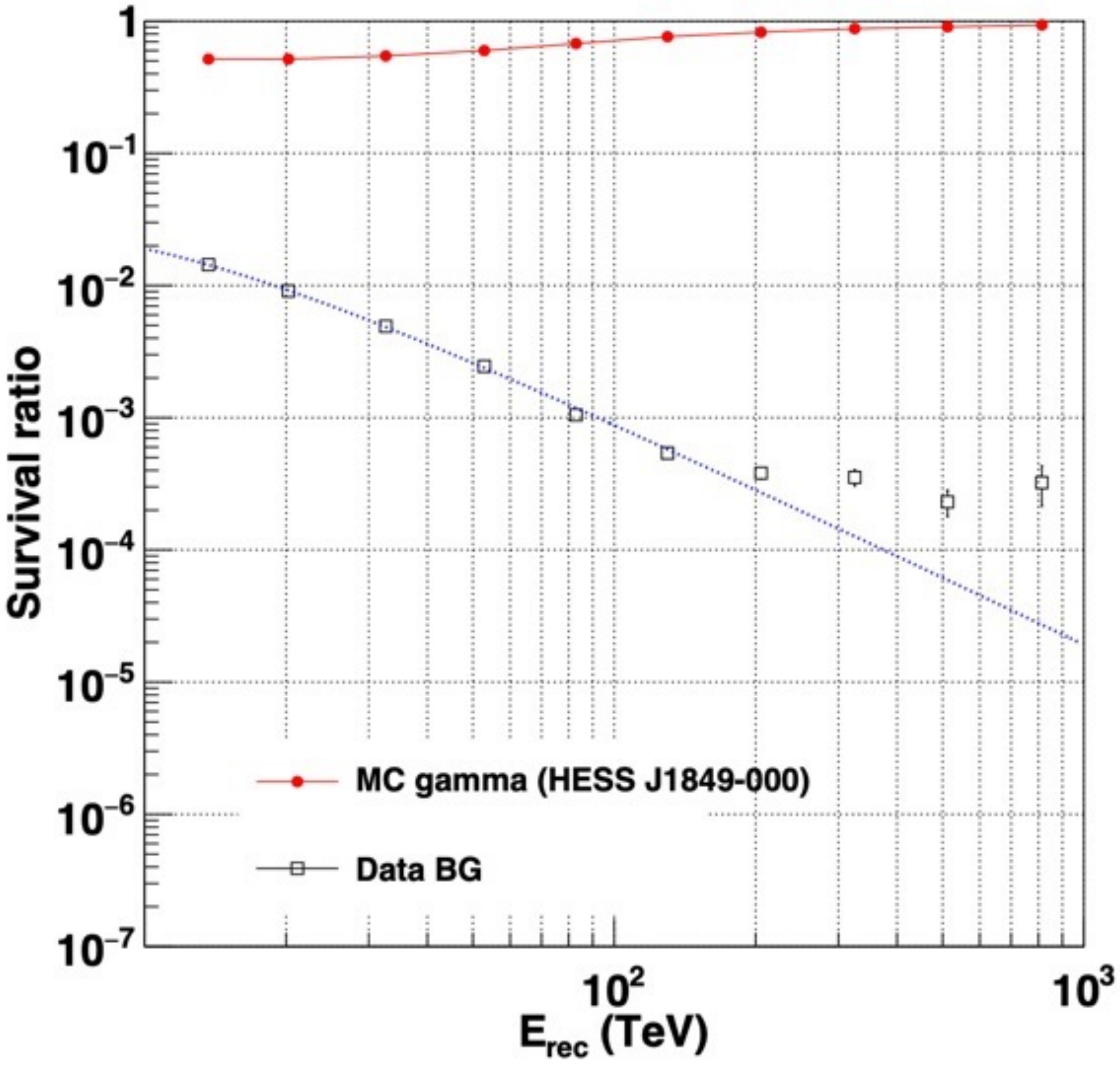


200TeV CR shower

Many muons (~100μ)

Discrimination b/w γ & CR showers by counting shower muons

Survival ratio of γ & CR events after the MD cut



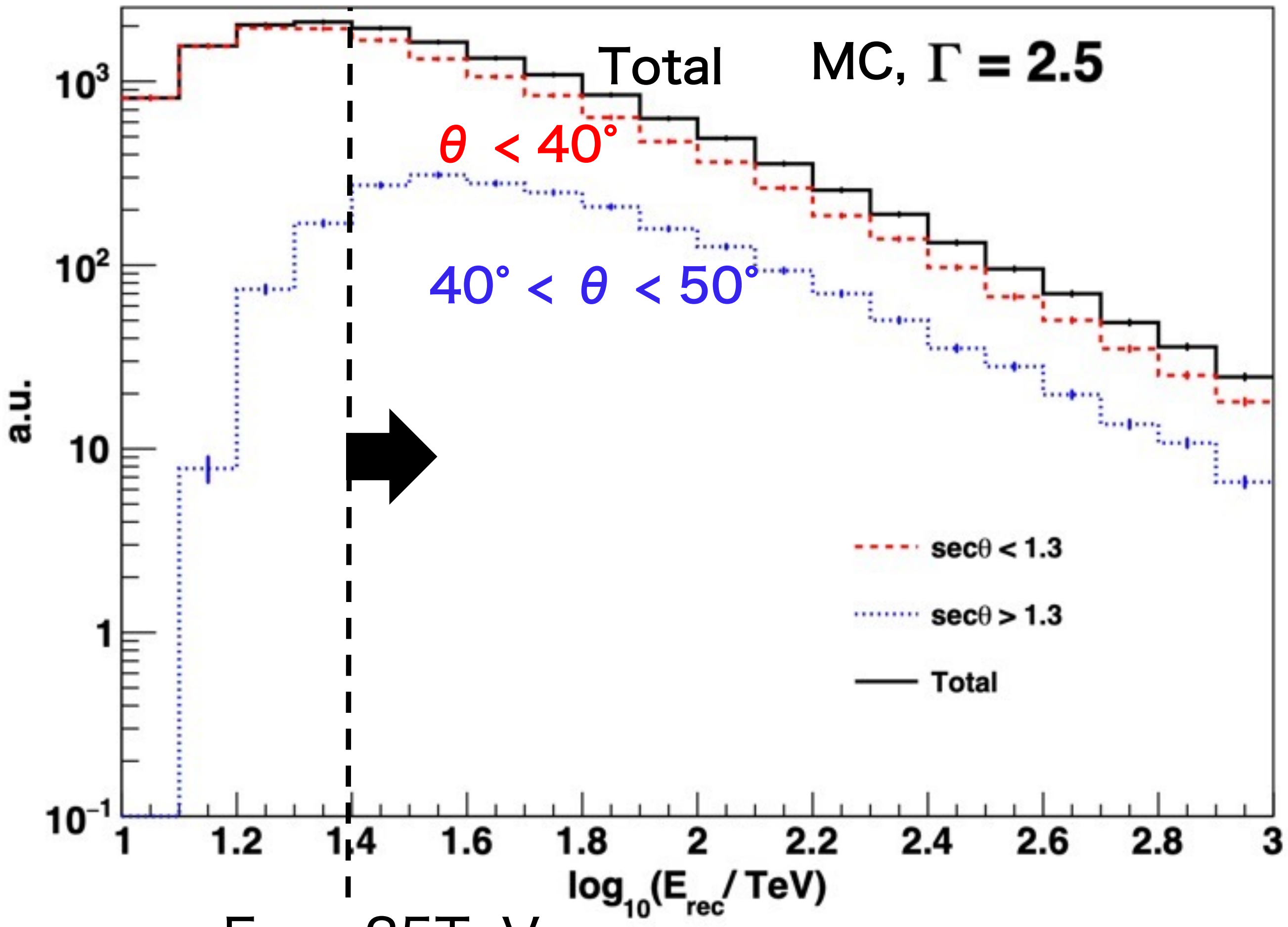
γ rays from HESS J1849-000

BGCRs from the ROI

	$E > 25$ TeV	$E > 100$ TeV
γ-ray survival ratio	$> 55\%$	$> 76\%$
BG rejection power	$> 99\%$	$> 99.9\%$

Analysis of the Zenith-Angle Range up to 50°

Distribution of MC gamma events (before MD cut)



E_{th} = 25TeV

✓ HESS J1849-000 has

1. a low flux level (~2% Crab @ E > 1TeV^{1})
2. large meridian zenith (~ 30°) & low exposure

⇒ Need for the increase of statistics by **extending the analyzed zenith-angle range up to 50°**

(In the conventional analysis θ<40°)

✓ Improvement of event statistics by ~30% @ E > 25TeV & not deteriorating the sensitivity

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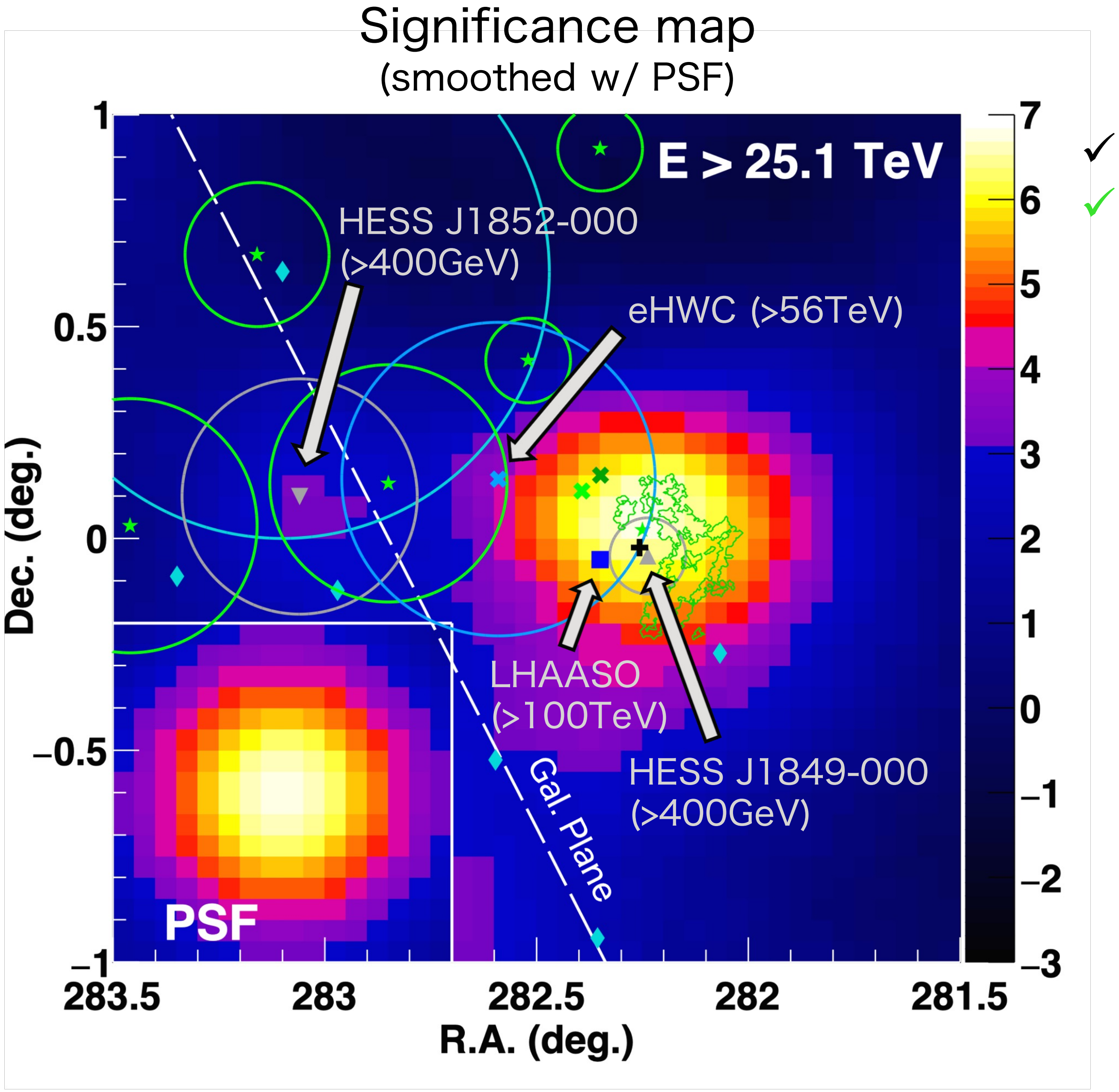
1. H.E.S.S. Collaboration, A&A 612, A1 (2018)

Results

Detection of γ Rays from HESS J1849−000 @ E > 25 TeV

Significance map
(smoothed w/ PSF)



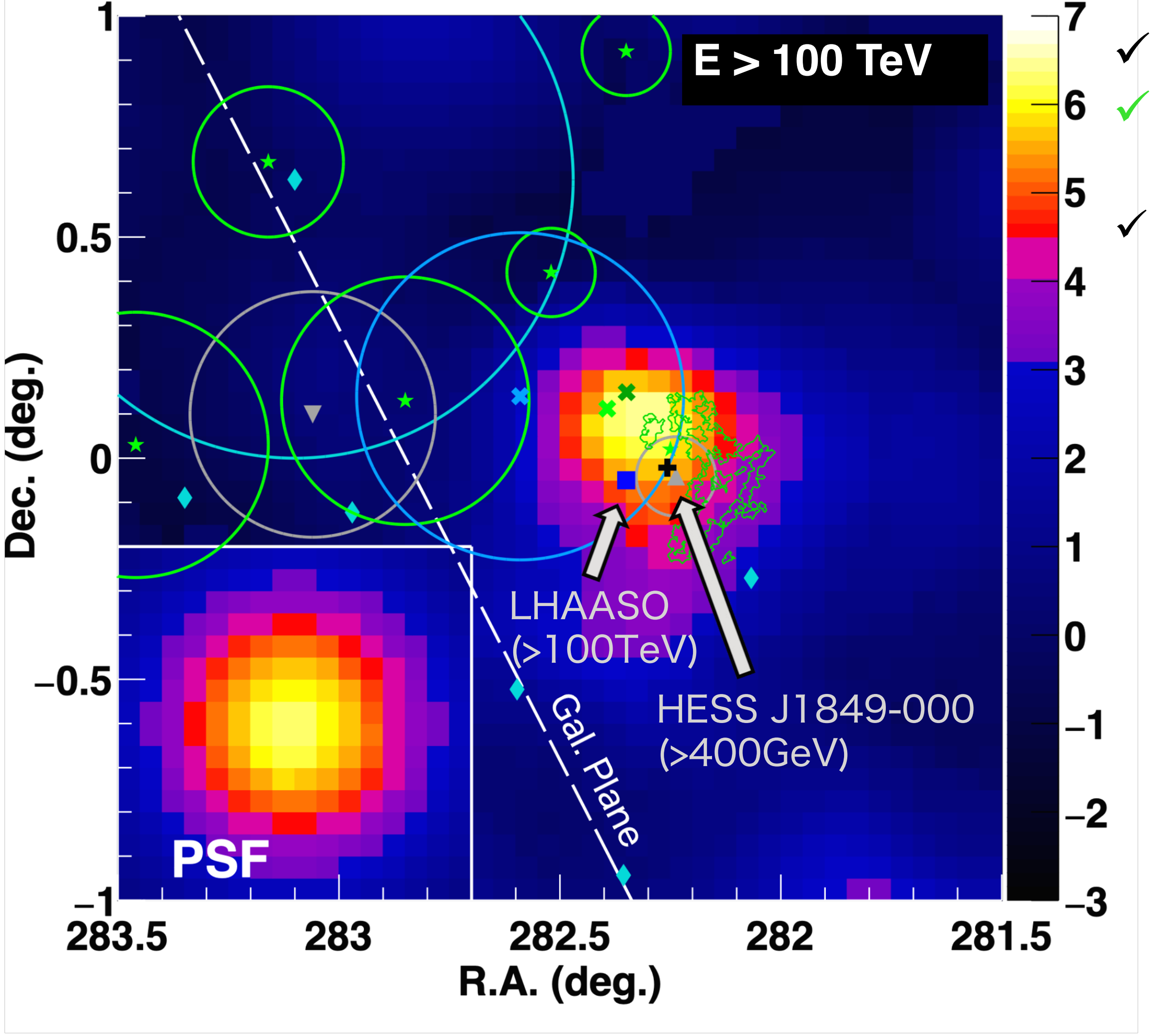
- ✓ 4.0σ detection @ E > 25TeV
- ✓ Green contour : Mol. Cloud found in this study

▲ HESS J1849-000 [1]
▼ HESS J1852-000 [1]
✖ 2HWC J1849+001 [2]
✖ 3HWC J1849+001 [3]
✖ eHWC J1850+001 [4]
■ LHAASO J1849-0003 [5]
◆ 4FGL sources [6]
★ SNRs (candidates) [7]
✚ PSR J1849-0001 [8]

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, ApJ 843, 40 (2017)
3. Albert+, ApJ 905, 76 (2020)
4. Abeysekara+, PRL 124, 021102 (2020)
5. Cao+, Nature 594, 33 (2021)
6. Abdollahi+, ApJS 247, 33 (2020)
7. Anderson+, A&A 605, A58 (2017)
8. Gotthelf+, ApJL 729, L16 (2011)

Detection of γ Rays from HESS J1849−000

Significance map
(smoothed w/ PSF)



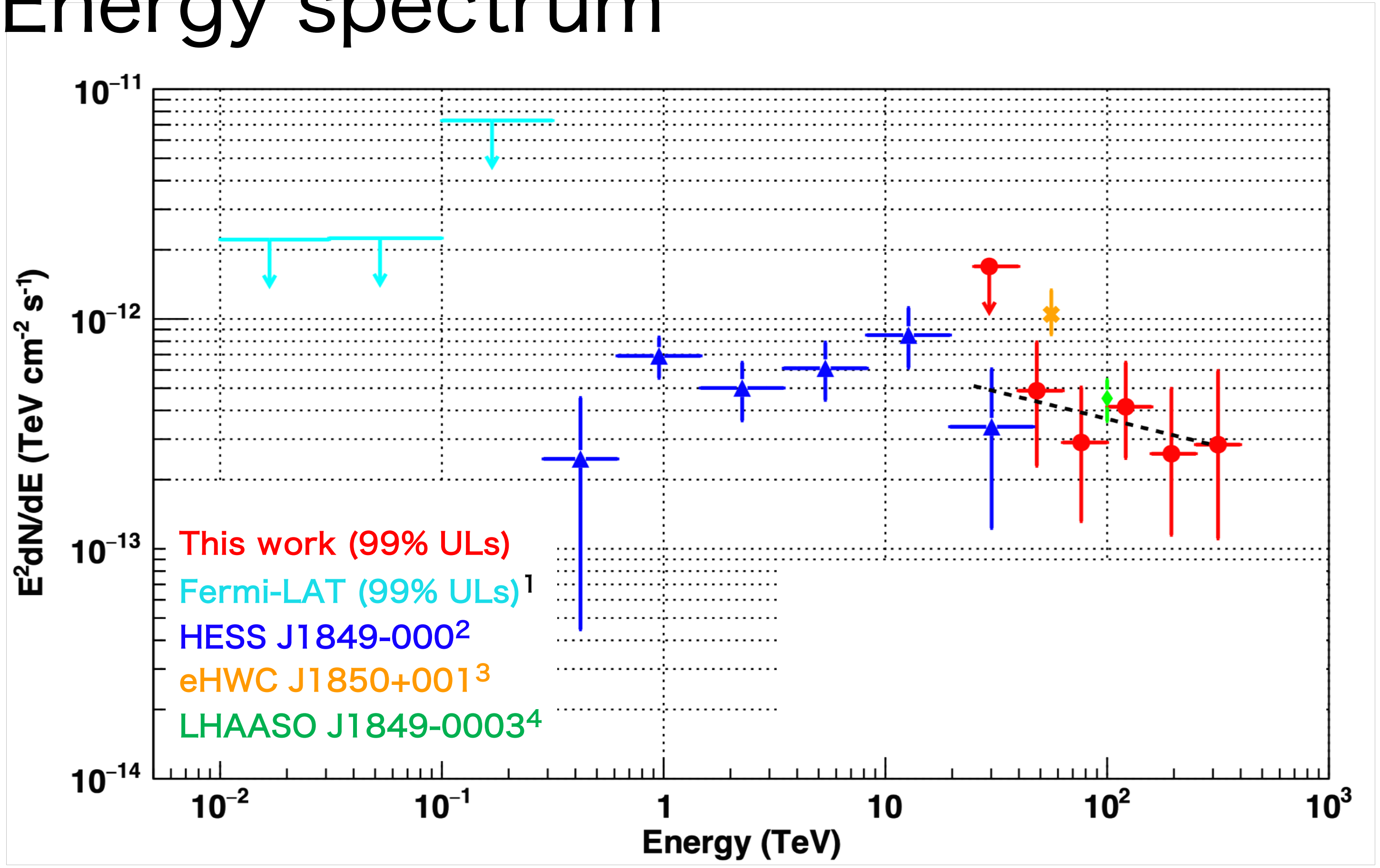
- ✓ 4.4σ detection @ E > 100TeV
- ✓ Green contour : Mol. Cloud found in this study
- ✓ Position unc. (68%) : 0.22°

  Positionally consistent w/ HESS J1849−000

▲ HESS J1849-000 [1]
▼ HESS J1852-000 [1]
✖ 2HWC J1849+001 [2]
✖ 3HWC J1849+001 [3]
✖ eHWC J1850+001 [4]
■ LHAASO J1849-0003 [5]
♦ 4FGL sources [6]
★ SNRs (candidates) [7]
✚ PSR J1849-0001 [8]

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, ApJ 843, 40 (2017)
3. Albert+, ApJ 905, 76 (2020)
4. Abeysekara+, PRL 124, 021102 (2020)
5. Cao+, Nature 594, 33 (2021)
6. Abdollahi+, ApJS 247, 33 (2020)
7. Anderson+, A&A 605, A58 (2017)
8. Gotthelf+, ApJL 729, L16 (2011)

Energy spectrum



- ✓ 1st measurement of spectrum in 40TeV < E < 320TeV
- ✓ Modeled w/ a power-law func.
- ✓ Connects w/ HESS J1849−000[1] & LHAASO J1849−0003[2]
- ✓ No significant cutoff sign

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, PRL 124, 021102 (2020)
3. Cao+, Nature 594, 33 (2021)
4. Acero+, ApJ 773, 77 (2013)

Power-law fit :
(40TeV < E < 320TeV)

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (2.86 \pm 1.44)\times 10^{-16}\left(\frac{E}{40\ \mathrm{TeV}}\right)^{-2.24\pm 0.41} \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \quad (\chi^2/\mathrm{d.o.f.} = 0.5/3)$$

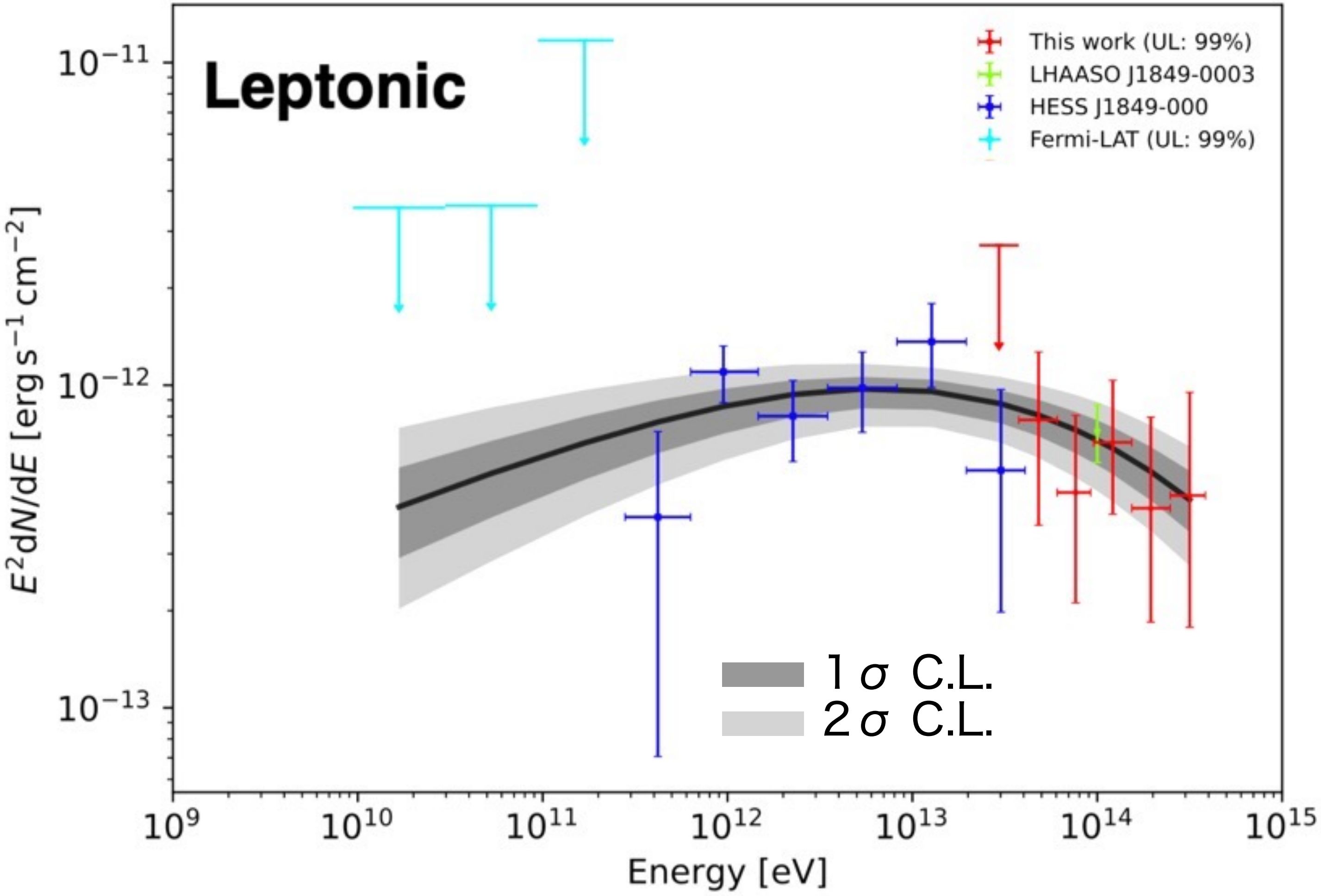
✓ Systematic uncertainties :

- Absolute energy scale uncertainties 12% => Normalization 27%
- Contamination from a nearby source HESS J1852−000 => Normalization < 20% @ 95 C.L.

Discussion

Leptonic emission model (Naima[1])

1. Zabalza, PoS(ICRC2015) 922 (2015)
2. Porter+, ApJ 846, 67 (2017)
3. Vernetto & Lipari PRD 94, 063009 (2016)
4. Gotthelf+, ApJL 729, L16 (2011)



$\log_{10} N_0 = 31.98^{+0.06}_{-0.07}$

$\alpha_e = 2.46^{+0.08}_{-0.07}$

We(>100GeV) = $2.8^{+1.0}_{-0.7} \times 10^{47}$ erg

✓ **First spectral modeling including the sub-PeV energy range**

✓ Assumptions：

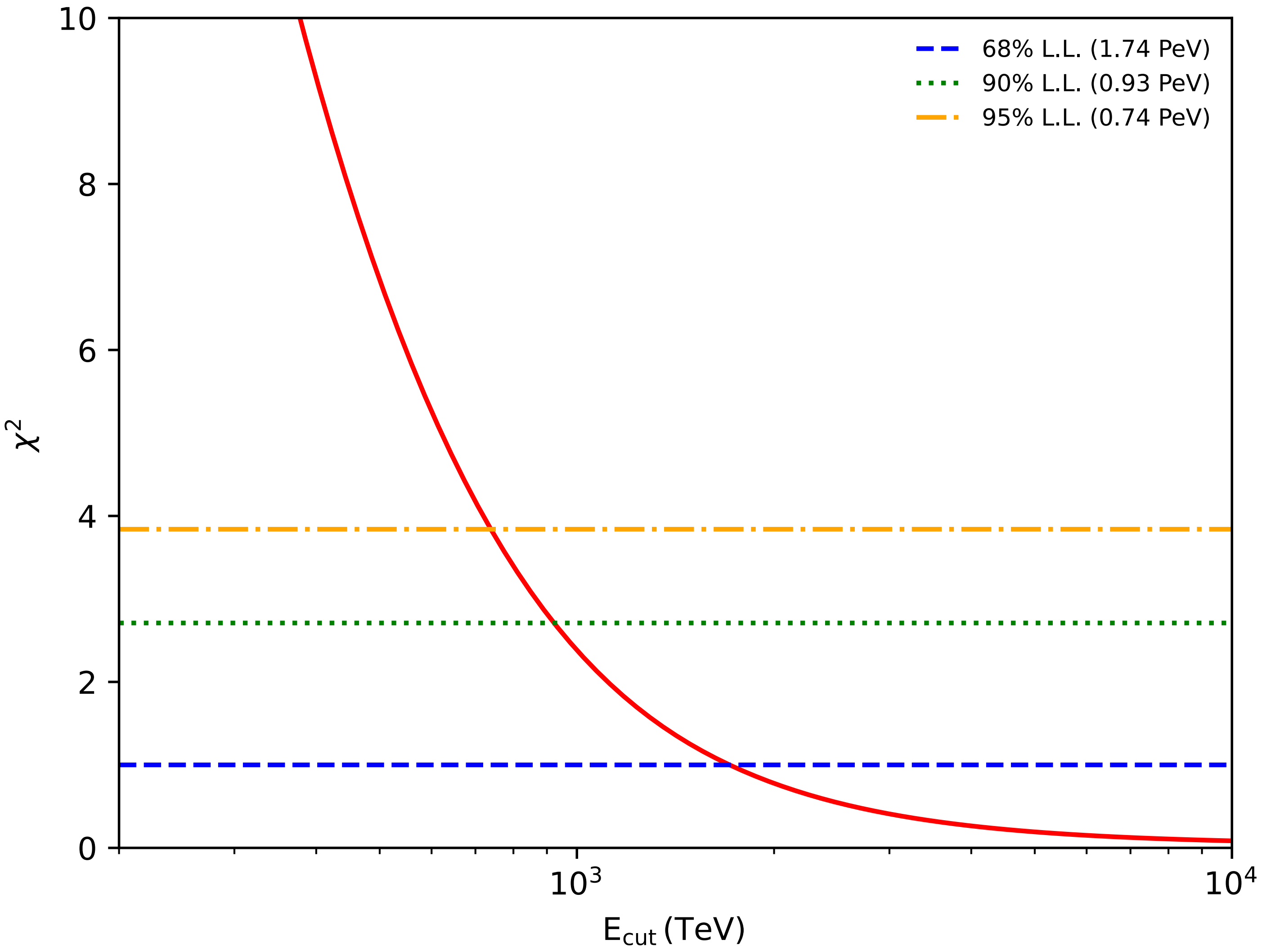
- Inverse Compton scattering by e± following a simple PL func.：

$$\frac{dN_e}{dE} = A_e \left(\frac{E}{10\ \mathrm{TeV}} \right)^{-\alpha_e} \mathrm{eV}^{-1}$$

- Interstellar radiation field[2,3] (assuming a distance of 7kpc[4])：

ISRF	Energy density (eV cm^{-3})
CMB (2.7 K)	0.26
FIR (20 K)	0.75
NIR (3,000 K)	1.26

Lower limit on the cutoff energy of electrons



$$\chi^2 = -2\left(\ln \mathcal{L}_{\mathrm{ECPL,\,max}} - \ln \mathcal{L}_{\mathrm{PL,\,max}}\right)$$

E_{cut} > 740 TeV (95% C.L.)

Extremely high, but not impossible
(c.f., the Crab Nebula)

Association : PSR J1849–0001

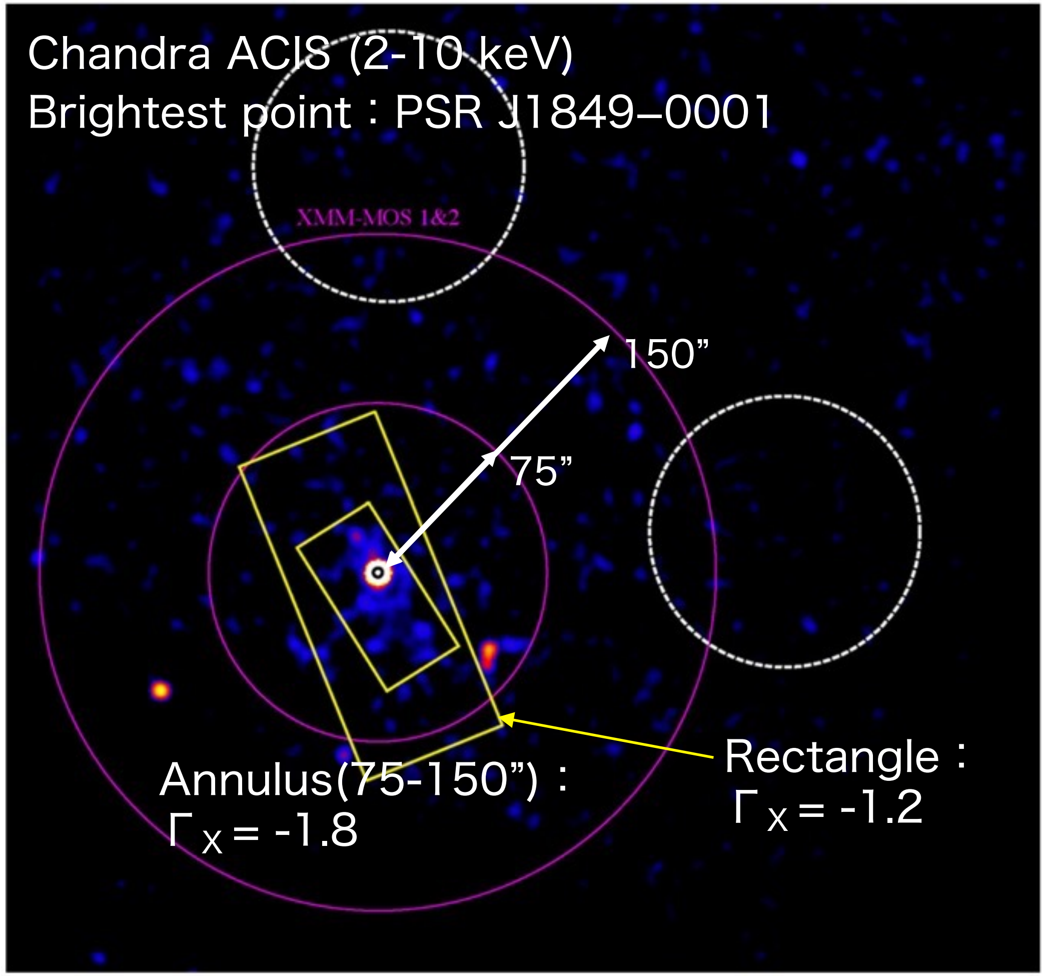
PSR J1849–0001[1]

X-ray pulsar

P = 38.5 ms, $E_{sp} = 9.8\times10^{36}$ erg s^{-1}, τ_c = 42.9 kyr

Extended keV X rays(75”) => Synchrotron PWN

Distance : 7 kpc

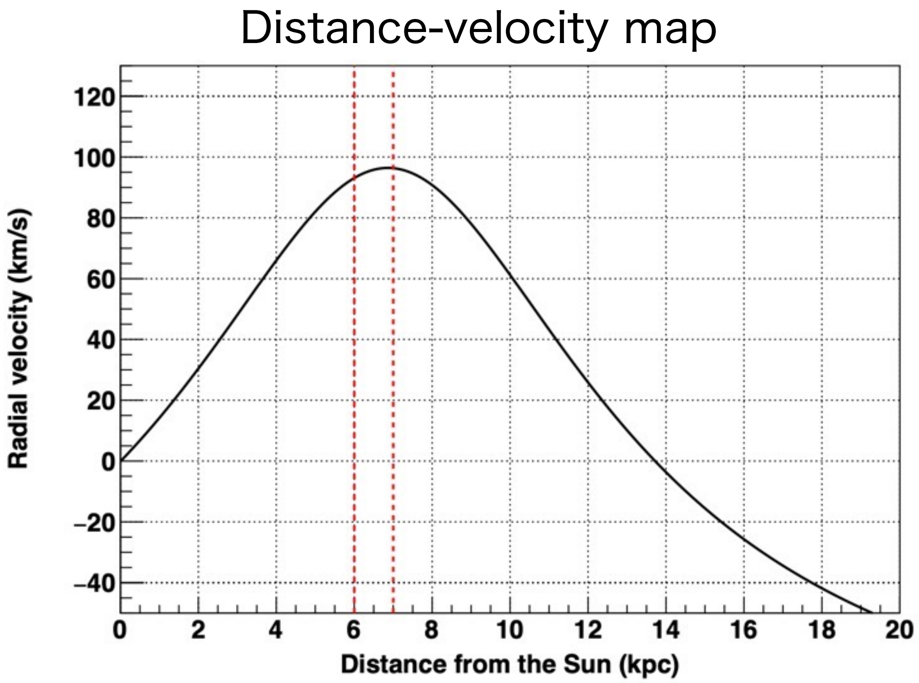


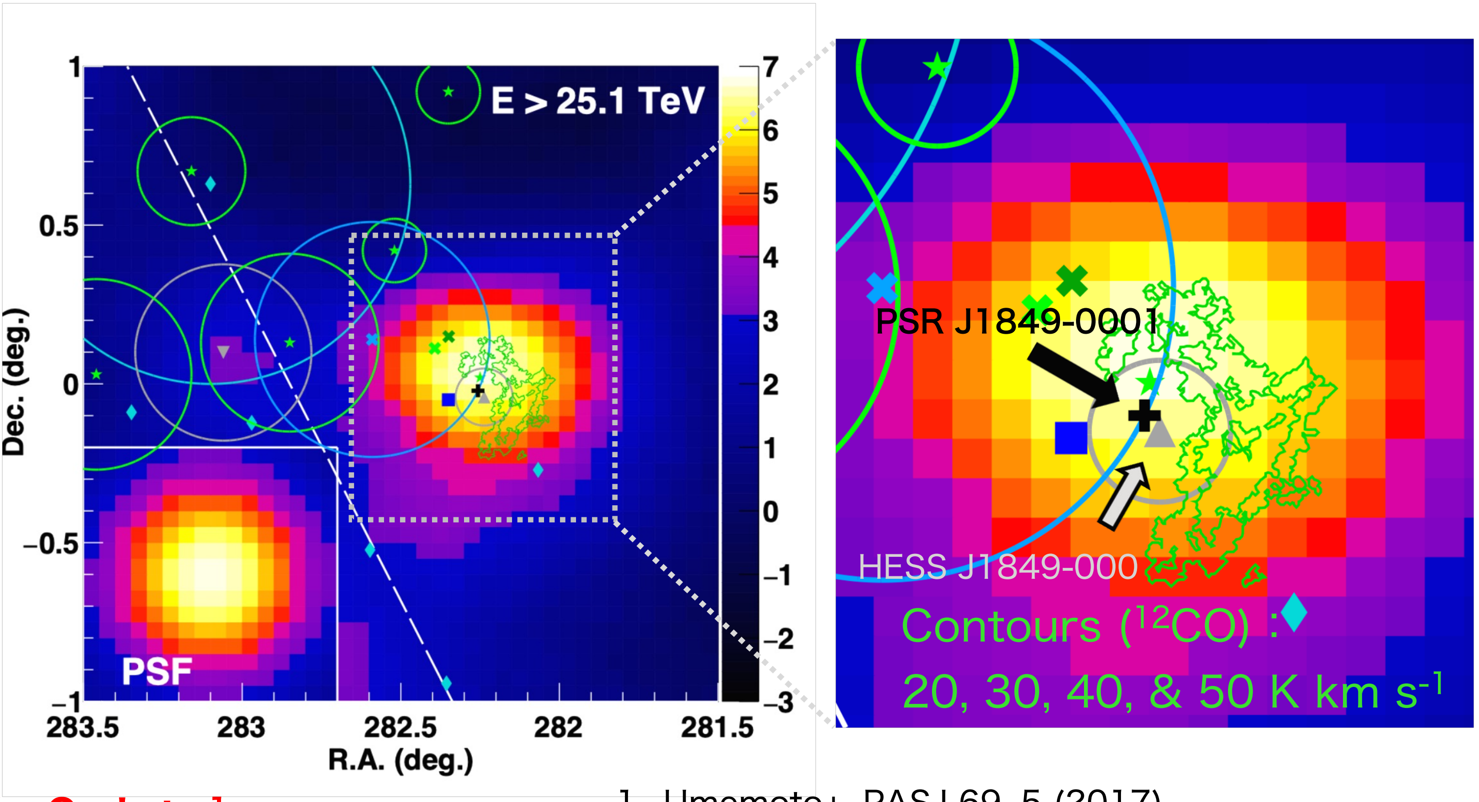
- ✓ γ rays is also a PWN of PSR J1849–0001??
- ✓ We(>100GeV) = 0.03 $E_{sp}\tau_c$. Energetics OK
- ✓ Synchrotron keV X-rays :
  Cooling effect is seen[3]; photon index Γ_X = -1.2 -> -1.8
  as going distant from the PSR
- ✓ $\Gamma_X = (-1 + \Gamma_e) / 2 = (-1 -2.5) / 2 = -1.8$
  => e± producing ICS γ rays are already cooled??
- ✓ Γ_e of e± before cooling : Γ_e = -1.5. Much harder than the standard shock acceleration (-2.0[5])
  => Efficient acceleration by interaction b/w e± & shock waves[6,7]??

Radio ~ hard X-ray obs. & high-statistics γ-ray obs. are needed to determine the e± spectrum

1. Gotthelf+, ApJL 729, L16 (2011)
2. Terrier+, AIP Conf. Proc. 1085, 312 (2008)
3. Kuiper & Hermsen, MNRAS 449, 3827 (2015)
4. Vleeschower+, Nucl. Part. Phys. Proc 297-299, 102 (2018)
5. Gaisser+, Cambridge Univ. Press (2016)
6. Malkov, ApJ 511, L53 (1998)
7. Berezhko & Ellison, ApJ 526, 385 (1999)

Hadronic emission model：Molecular cloud





1. Umemoto+, PASJ 69, 5 (2017)
2. Gotthelf+, ApJL 729, L16 (2011)
3. Bolatto+, Ann. Rev. Astron. Astrophys 51, 207 (2013)

- ✓ Analysis of archive FUGIN ^{12}CO J=1–0 data[1]
- ✓ Assumed distance：7 kpc[2]
- ✓ Integration in 93–100 km s^{-1} (6-7 kpc)

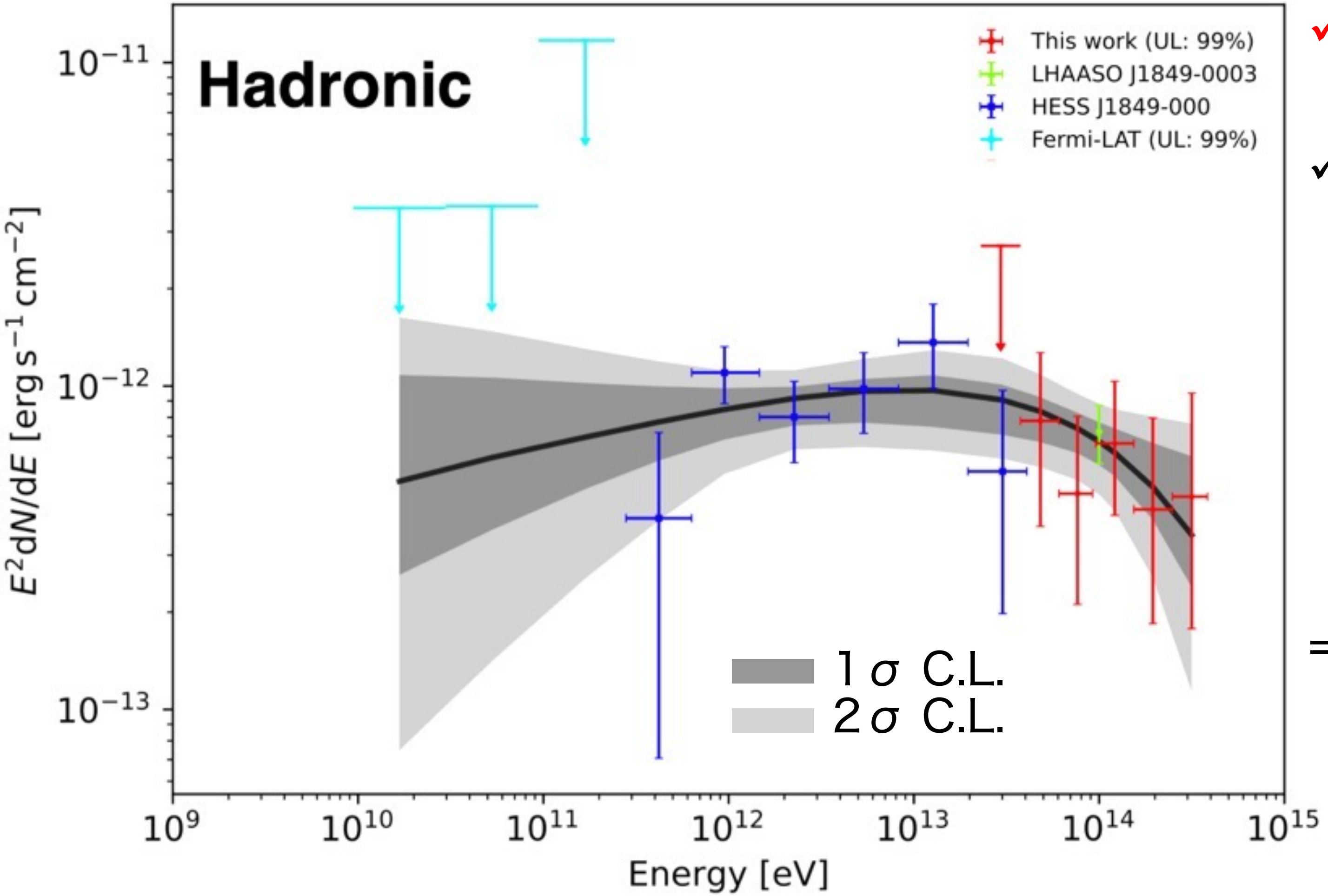
  => Molecular cloud w/ ~20 pc size (T_B ~20 K km s^{-1}) @ the west side of HESS J1849–000
- ✓ If the cloud size along the l.o.s. is ~ 20 pc, the gas density is

$$n_p = X_{co}\, T_{mb} / R \sim 70 \text{ cm}^{-3} \quad (X_{co} = 2\times10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1})^{3}$$

> 10 cm^{-3} can be provided

Hadronic emission model (Naima[1])

[1]. Zabalza, PoS(ICRC2015) 922 (2015)



- ✓ First spectral modeling including the sub-PeV energy range
- ✓ Assumptions：
  - $\pi^0 \to 2\gamma$ from CRp-gas collisions
  - $n_p = 10\ \mathrm{cm}^{-3}$
  - CRp spectrum：

$$\frac{dN_\mathrm{p}}{dE} = A_\mathrm{p}\left(\frac{E}{10\ \mathrm{TeV}}\right)^{-\alpha_\mathrm{p}} \exp\left(-\frac{E}{E_\mathrm{p,cut}}\right) \mathrm{eV}^{-1}$$

=>

$$\log_{10} A_\mathrm{p} = 33.93^{+0.09}_{-0.11}$$

$$\alpha_\mathrm{p} = 2.01^{+0.12}_{-0.21}$$

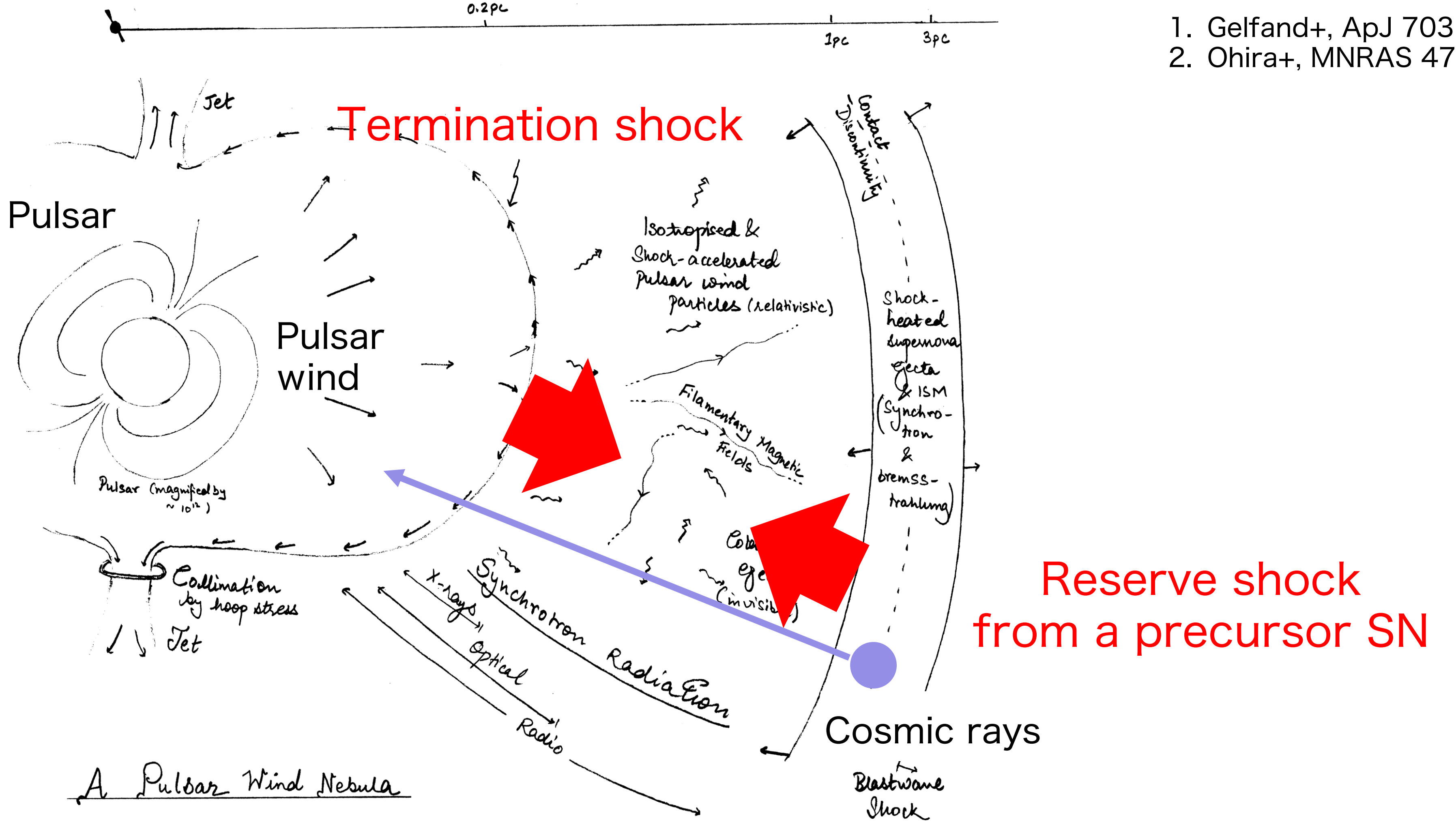
$$\log_{10}(E_\mathrm{p,\,cut}/\mathrm{TeV}) = 3.73^{+2.98}_{-0.66}$$

Wp(1TeV<E<10PeV) = $(1.1 \pm 0.2) \times 10^{49}$ erg

Possible acceleration of CR protons beyond PeV

PeV CR acceleration in a PWN-SNR composite system

1. Gelfand+, ApJ 703, 2051 (2009)
2. Ohira+, MNRAS 478, 926 (2018)

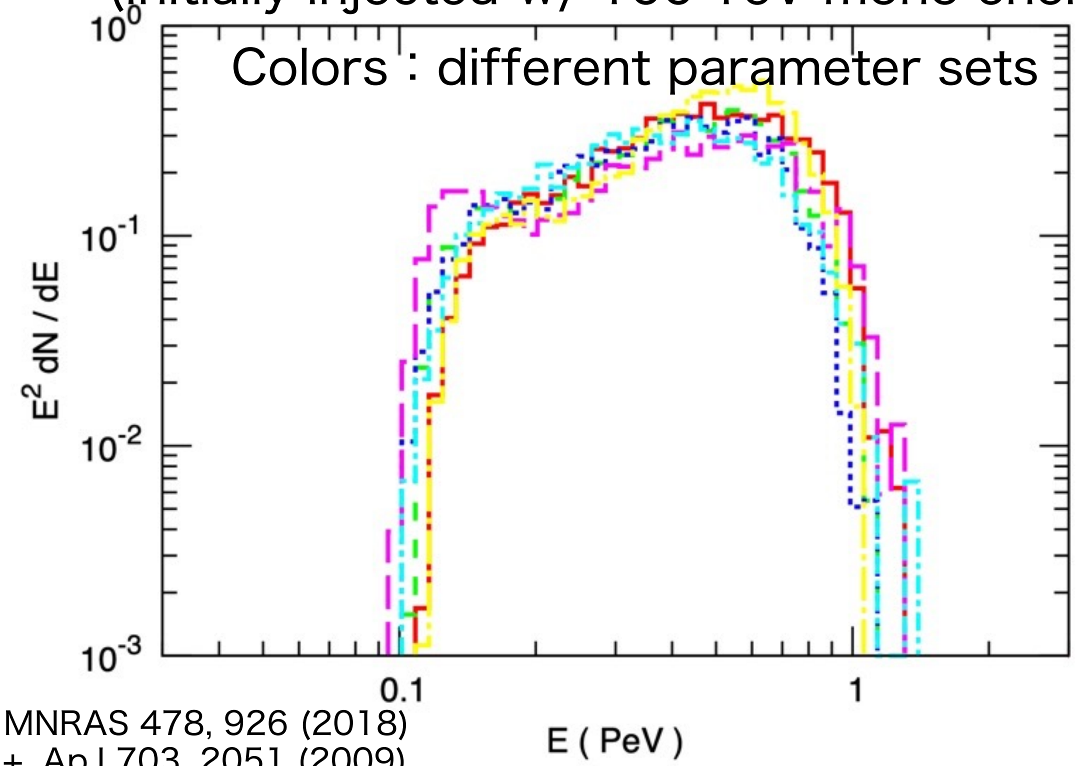


- ✓ CRp's accelerated up to ~100 TeV in the SNR FS could be re-accelerated up to ~ 1 PeV in the PWN compressed by the SNR reverse shock[1,2]

PeV CR acceleration in a PWN-SNR composite system

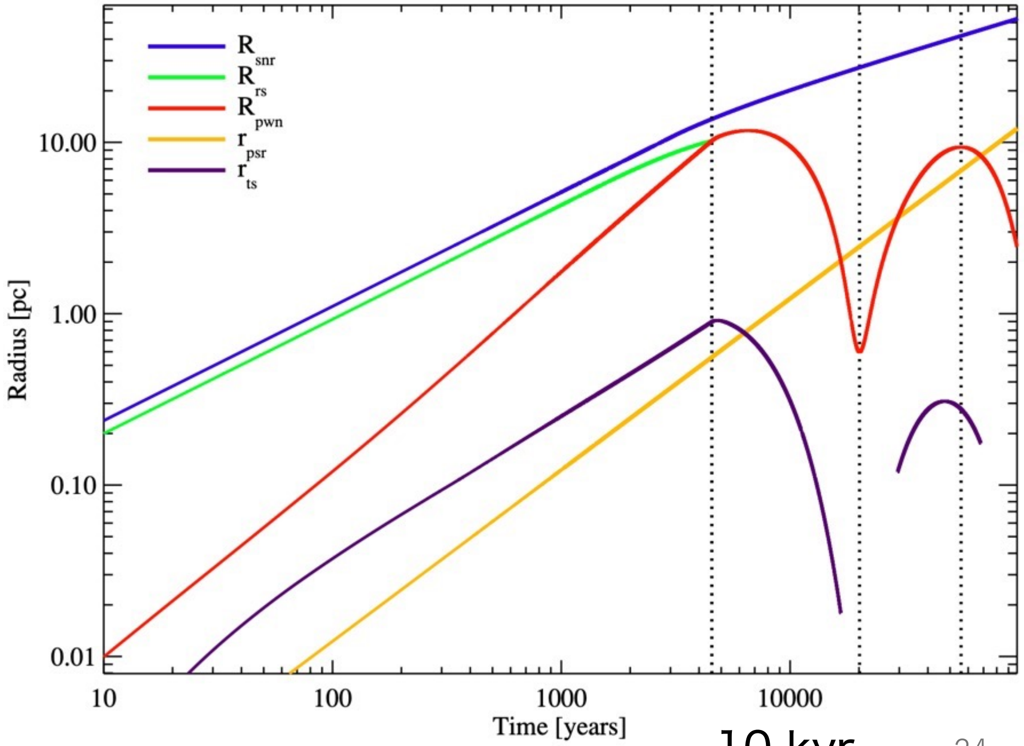
- PeV CR can be produced irrespective of environmental parameters[1]
- ~10^{49} erg is given to the accelerated particles[2]
- B of the compressed PWN is amplified up to ~ 100 μG[2]
  => compact synchrotron X-ray emission by $e^{\pm}$ of PWN origin??
- Compression of PWN takes place @ ~ 10 kyr aft. SN => Invisible SNR

Energy spectrum of CR protons[1]
(Initially injected w/ 100 TeV mono energy)



Colors : different parameter sets

Evolution of the size of the system[2]



10 kyr

1. Ohira+, MNRAS 478, 926 (2018)
2. Gelfand+, ApJ 703, 2051 (2009)

PeV CR acceleration in a PWN-SNR composite system

✓ Problems of the PWN-SNR scenario：

- Simple PL + Exp. cutoff CR spectrum can be realized in such a complex system??
- There should be $e^{\pm}$ of PWN origin. γ-ray spectrum from CR + $e^{\pm}$??
- No evidence for existence of SNR => Radio obs. (gas temp., ionization degree…)
- CRs w/ 10^{49} erg can really be confined within the compressed PWN??

✓ Future observations：

- Neutrino obs. w/ IceCube-Gen2[3] => Constraint on γ-ray flux from hadrons
- Accurate measurement of sub-PeV γ-ray energy spectrum

Summary

- ✓ Obs. of UHE γ up to 320 TeV w/o clear cutoff from PWN HESS J1849−000

  Detection significance : 4.0 σ @ > 25TeV & 4.4 σ @ > 100TeV

- ✓ 1st spectral measurement in 40 TeV < E < 320 TeV

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (2.86 \pm 1.44)\times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-2.24\pm 0.41} \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

- ✓ Detection of ~20 pc size MC @ the west side of the src. n_p ~ 70 cm^{-3}
- ✓ Leptonic scenario : ICS $e^{\pm}$ efficiently accelerated by PWN ?? ($\Gamma_e = -1.5$)
- ✓ Hadronic scenario : PeV CR acceleration in a PWN-SNR composite system??

  Further theoretical & observational studies needed