Observation of an astrophysical gamma-ray source HESS J1843-033 with the Tibet air shower array and its muon detector array

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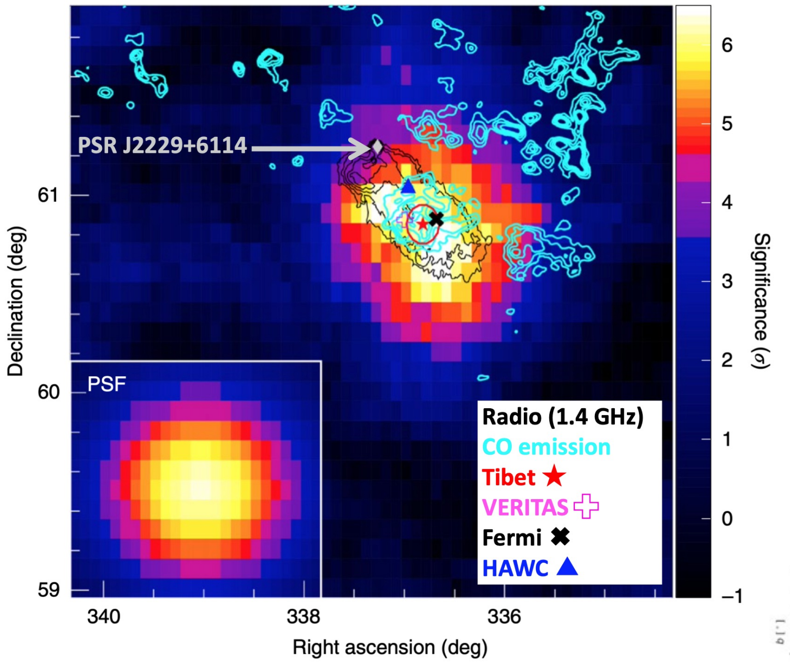
TeVPA 2023

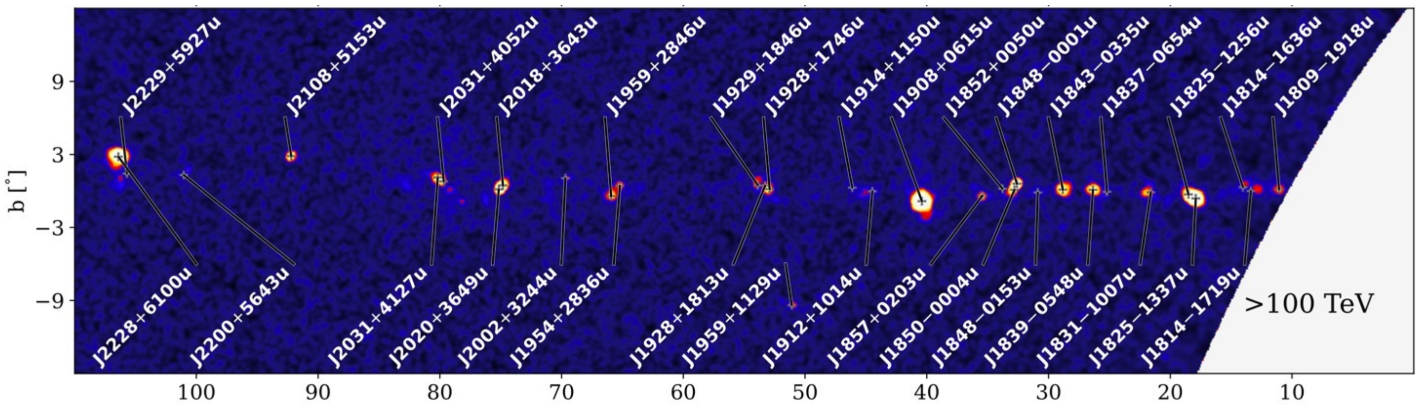
Sub-PeV Gamma-Ray Astronomy

1. Amenomori et al., Nat. Astron. Lett (2021)
2. Amenomori et al., PRL 126, 141101,(2021)
3. Cao et al., arXiv:2305.17030v1 (2023)
4. Malone et al., ICRC2023, 698 (2023)

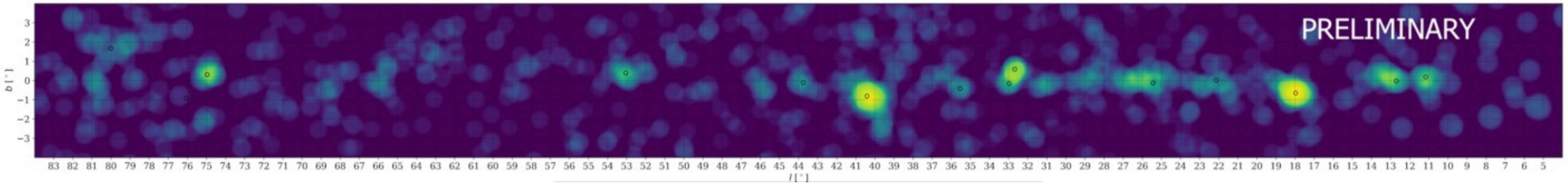
SNR G106.3+2.7 (E >10 TeV)[1]



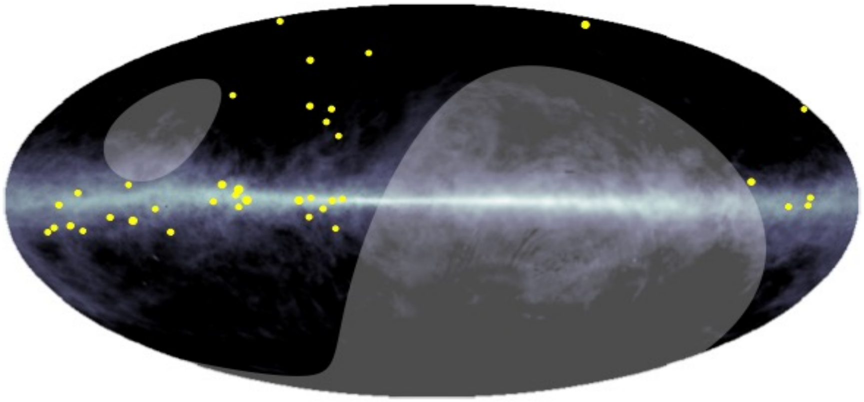
LHAASO sky map (E > 100 TeV)[3]



HAWC sky map (E > 100 TeV)[4]



Diffuse gamma rays (E > 400 TeV)[2]



- ✓ Catalog of several tens of sub-PeV gamma-ray sources
- ✓ Sub-PeV Galactic diffuse gamma rays

=> PeVatrons somewhere in the Galaxy, but

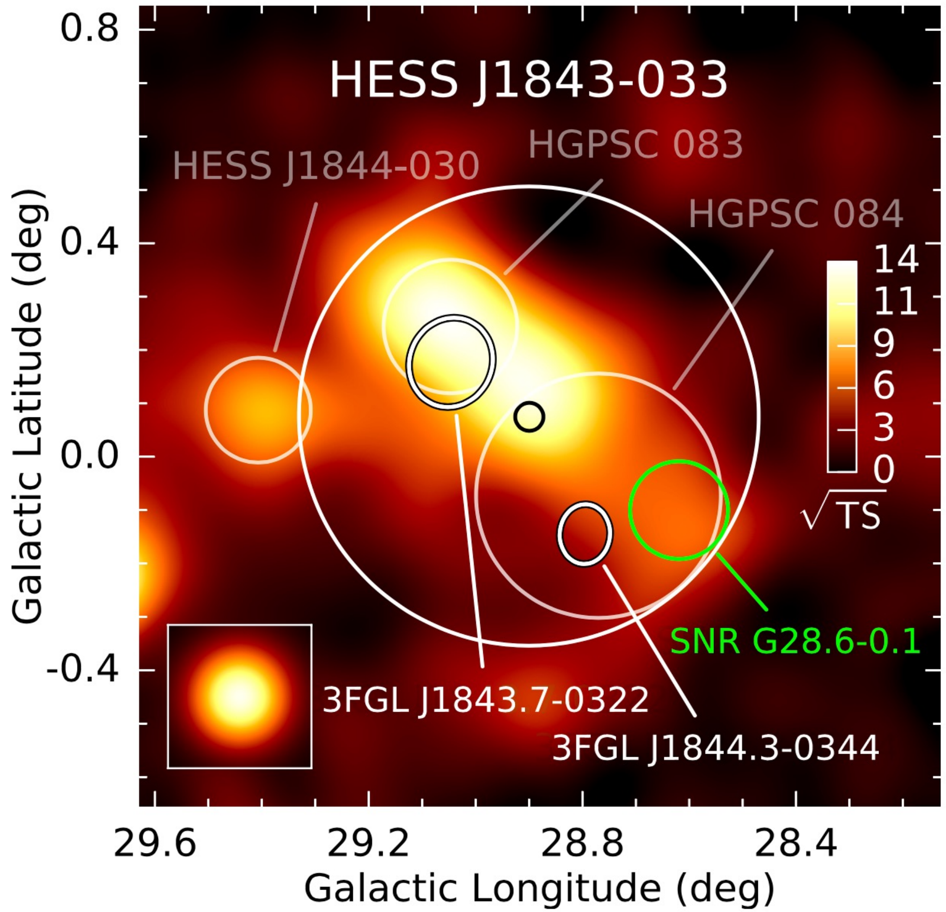
Where? Which is a PeVatron? How many PeVatrons?

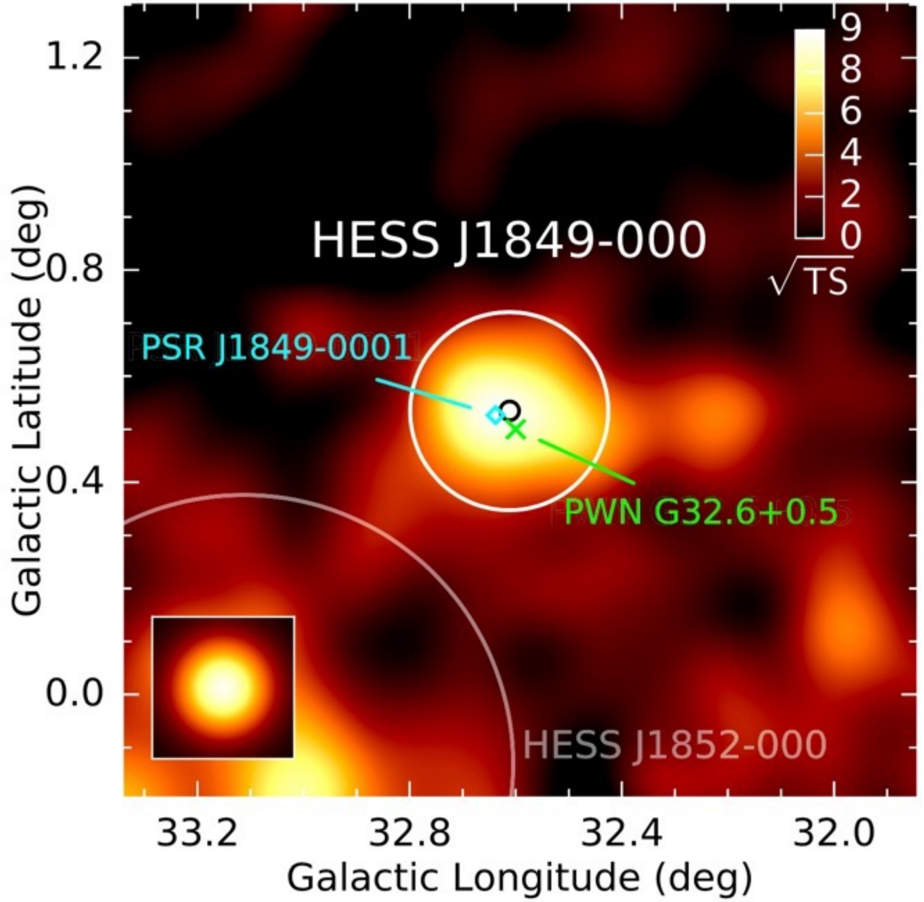
=> Detailed studies of individual sources would be crucial

Studied Source : HESS J1843-033 & HESS J1849-000

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, PRL 124, 021102 (2020)
3. Cao+, Nature 594, 33 (2021)
4. H.E.S.S. Collaboration, A&A 612, A2 (2018)

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

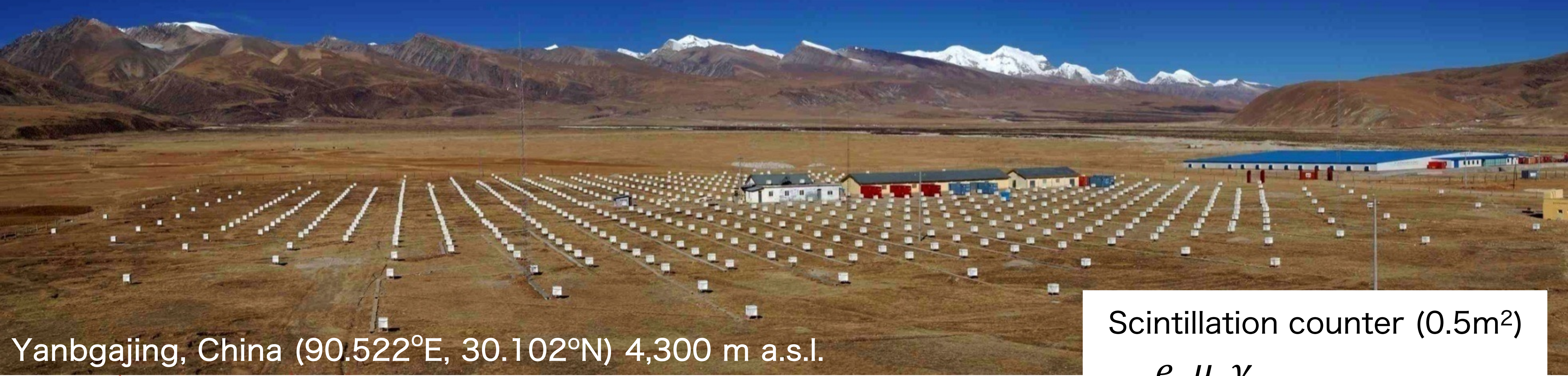


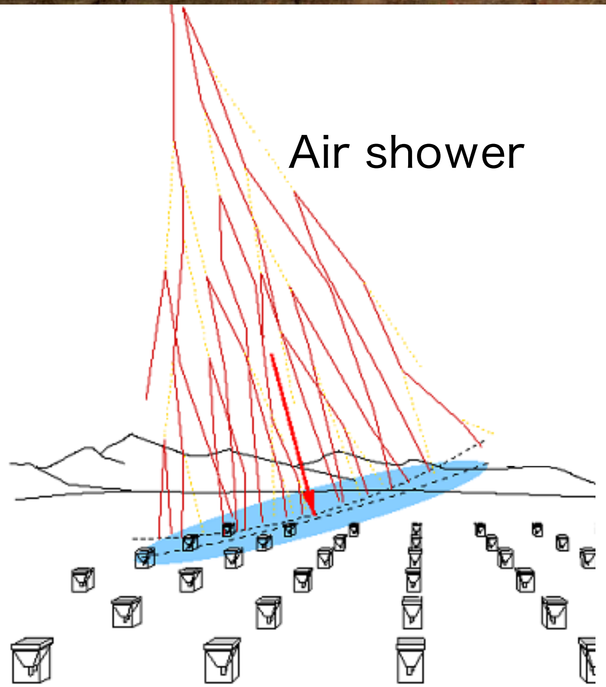


- ✓ Unidentified γ-ray source w/ complex morphology[1]
- ✓ IntF(> 1TeV) ~ 3×10^{-12} cm^{-2} s^{-1} & Γ ~ 2.2[1]
- ✓ Nearby HAWC (>56TeV)[2] & LHAASO (>100TeV)[3] src.s

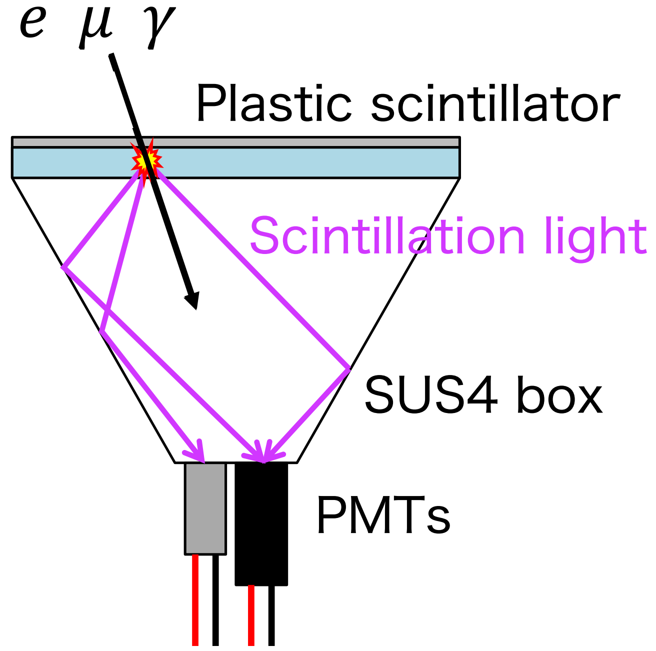
- ✓ Middle aged PWN[1,4]
- ✓ IntF(> 1TeV) ~ 6×10^{-13} cm^{-2} s^{-1} & Γ ~ 2.0[1]
- ✓ Nearby HAWC[2] & LHAASO[3] src.s

Tibet Air Shower Array (AS array)

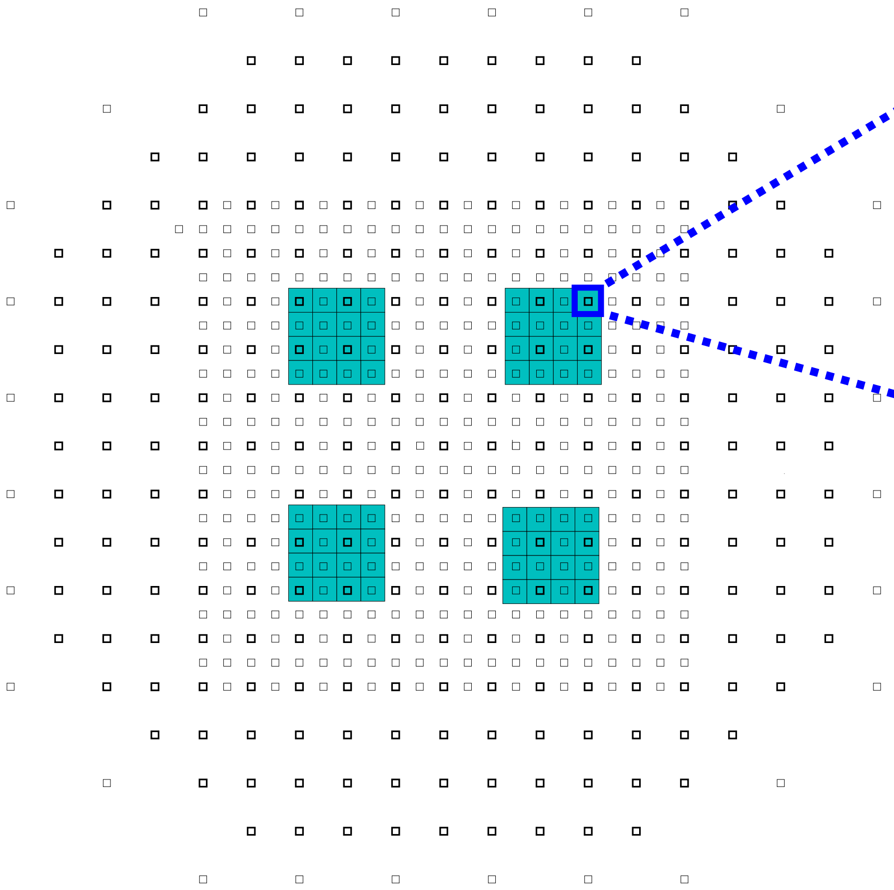




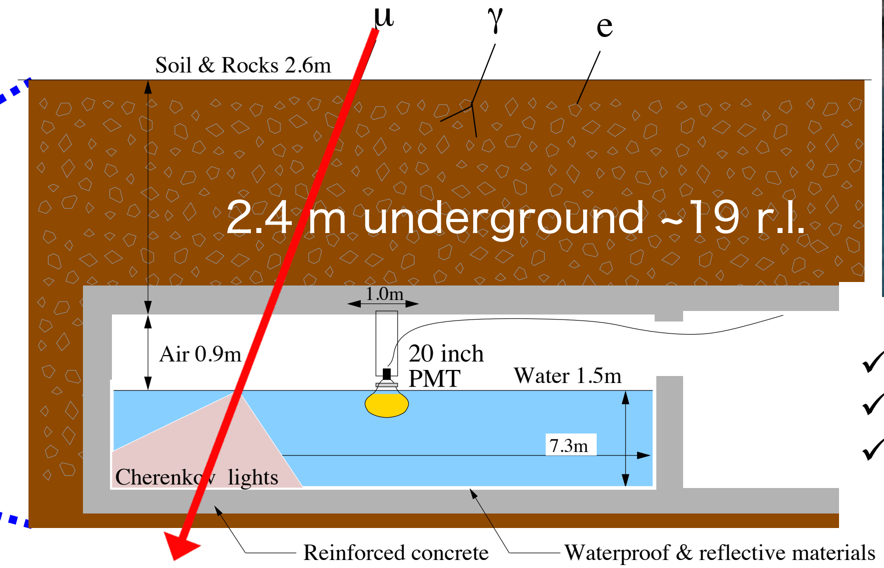
- ✓ Operating since 1991
- ✓ AS array 65,700 m^2
  - ・597 × 0.5 m^2 scintillation counter
  - ・Energy & direction reconstruction
- ✓ Angular resolution : ~0.2° @ 100TeV γ
- ✓ Energy resolution : ~20% @ 100TeV γ

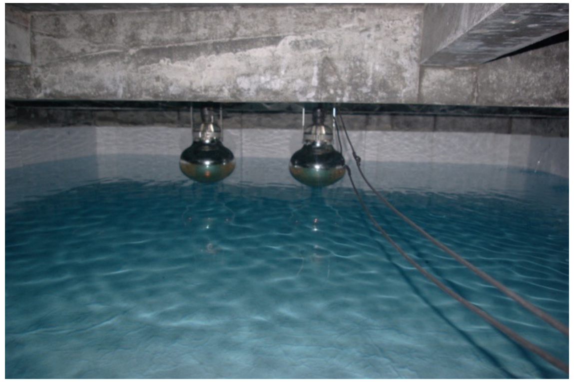


Underground Muon Detector Array (MD Array)

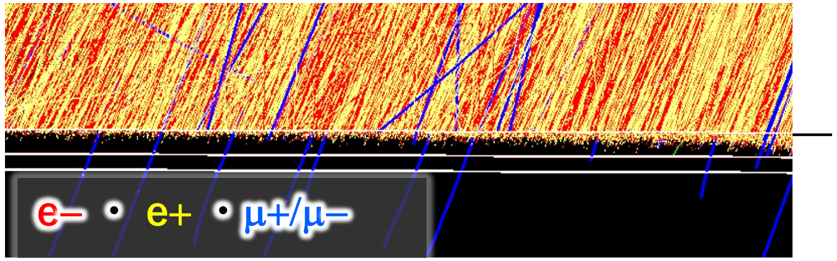


MD : 3400m²



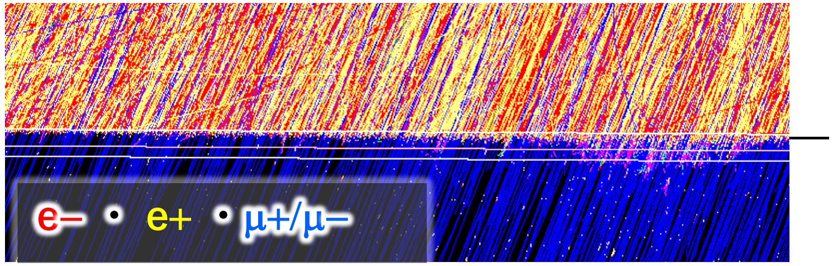


- ✓ 50m² / cell
- ✓ 1.5m-depth water layer
- ✓ A 20-inch PMT suspended to catch Cherenkov light



200TeV γ shower

Few muons (~1 μ)



200TeV CR shower

Many muons (~100 μ)

Rejection power for background CRs : > 99.9% @ E > 100TeV
γ-ray survival ratio : ~ 90% @ 〃

Tibet ASγ Collaboration

M. Amenomori[1], Y. W. Bao[2], X. J. Bi[3], D. Chen[4], T. L. Chen[5], W. Y. Chen[3], Xu Chen[4], Y. Chen[2], Cirennima[5], S. W. Cui[6], Danzengluobu[5], L. K. Ding[3], J. H. Fang[3,7], K. Fang[3], C. F. Feng[8], Zhaoyang Feng[3], Z. Y. Feng[9], Qi Gao[5], Q. B. Gou[3], Y. Q. Guo[3], Y. Y. Guo[3], Y. Hayashi[10], H. H. He[3], Z. T. He[6], K. Hibino[11], N. Hotta[12], Haibing Hu[5], H. B. Hu[3], K. Y. Hu[3,7], J. Huang[3], H. Y. Jia[9], L. Jiang[3], P. Jiang[4], H. B. Jin[4], K. Kasahara[13], Y. Katayose[14], C. Kato[10], S. Kato[15], I. Kawahara[14], T. Kawashima[15], K. Kawata[15], M. Kozai[16], Labaciren[5], G. M. Le[17], A. F. Li[3,9,18], H. J. Li[5], W. J. Li[3,10], Y. Li[4], Y. H. Lin[3,7], B. Liu[19], C. Liu[3], J. S. Liu[3], L. Y. Liu[4], M. Y. Liu[5], W. Liu[3], H. Lu[3], T. Makishima[14], Y. Masuda[10], S. Matsuhashi[14], M. Matsumoto[10], X. R. Meng[5], Y. Meng[3,7], A. Mizuno[15], K. Munakata[10], Y. Nakamura[15], H. Nanjo[1], C. C. Ning[5], M. Nishizawa[20], R. Noguchi[14], M. Ohnishi[15], S. Okukawa[14], S. Ozawa[21], X. Qian[4], X. L. Qian[22], X. B. Qu[23], T. Saito[24], M. Sakata[25], T. Sako[15], T. K. Sako[15], T. Sasaki[11], J. Shao[3,9], T. Shibasaki[26], M. Shibata[14], A. Shiomi[26], H. Sugimoto[27], W. Takano[11], M. Takita[15], Y. H. Tan[3], N. Tateyama[11], S. Torii[28], H. Tsuchiya[29], S. Udo[11], R. Usui[14], H. Wang[3], S. F. Wang[5], Y. P. Wang[5], Wangdui[5], H. R. Wu[3], Q. Wu[5], J. L. Xu[4], L. Xue[8], Z. Yang[3], Y. Q. Yao[4], J. Yin[4], Y. Yokoe[15], Y. L. Yu[3,7], A. F. Yuan[5], L. M. Zhai[4], H. M. Zhang[3], J. L. Zhang[3], X. Zhang[2], X. Y. Zhang[8], Y. Zhang[3], Yi Zhang[30], Ying Zhang[3], S. P. Zhao[3], Zhaxisangzhu[5], X. X. Zhou[9] and Y. H. Zou[3,7]

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27 Shonan Institute of Technology, Japan.
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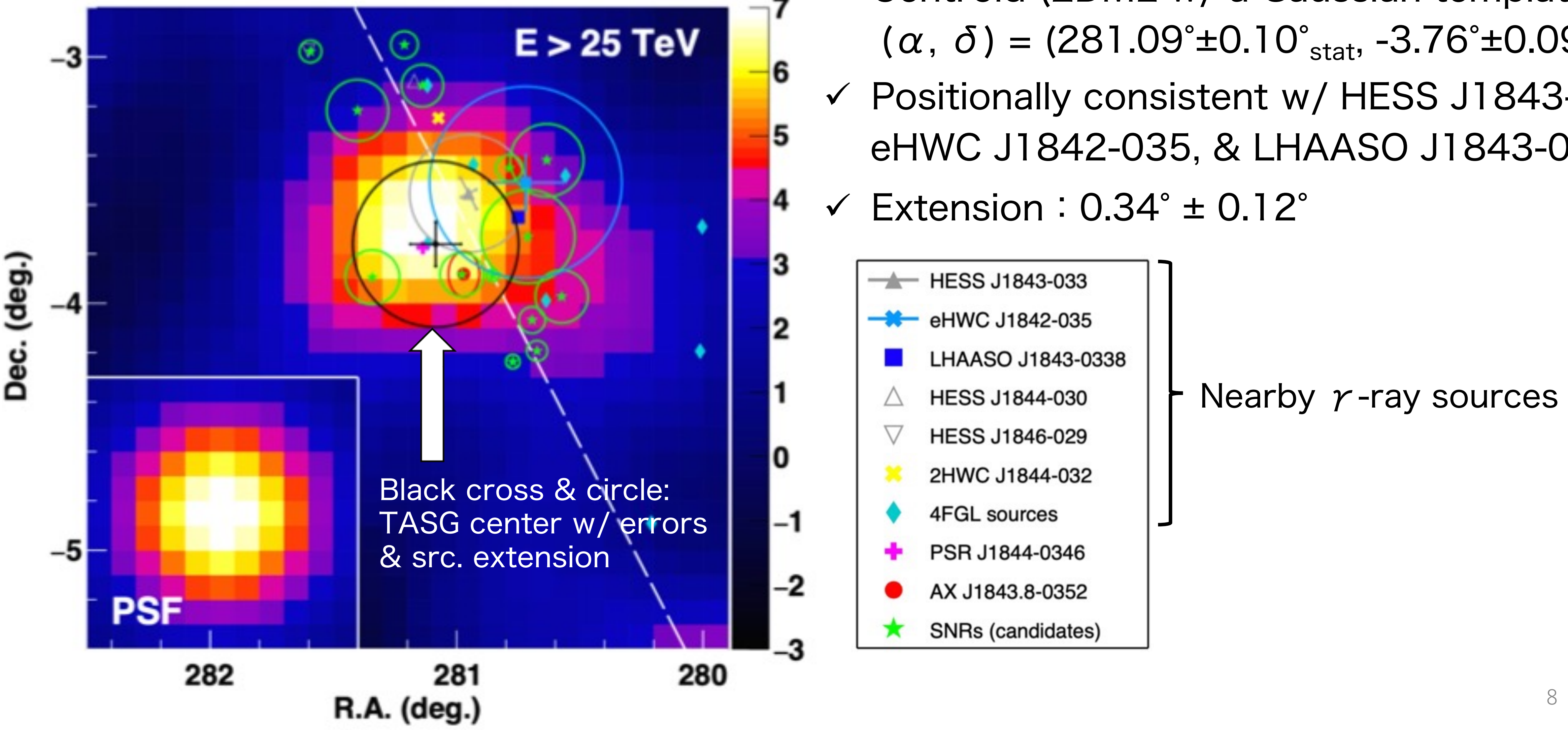
30 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.

Study of the HESS J1843-033 region

Amenomori, Kato et al., ApJ 932, 120 (2022)

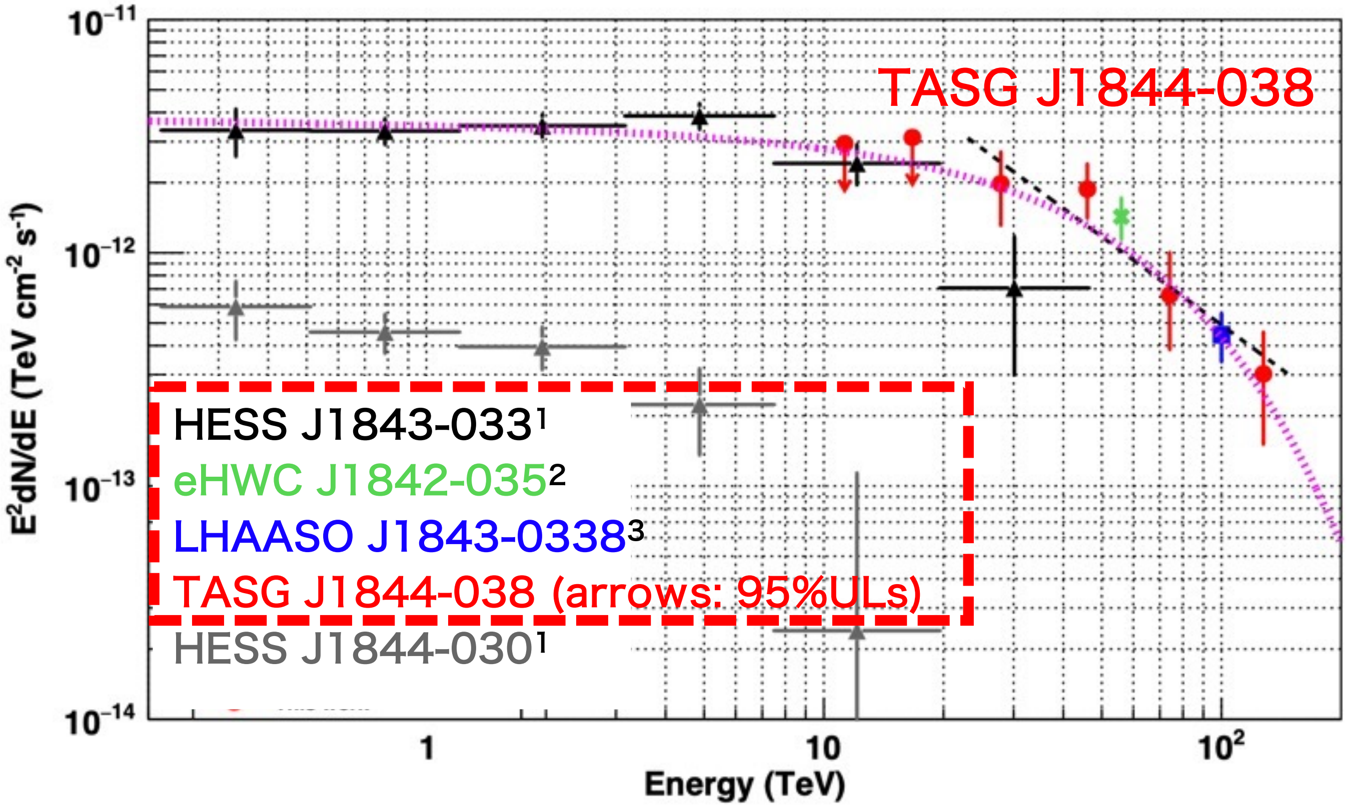
Detection of a New γ-Ray Source TASG J1844-038

Significance map
(PSF smoothed, E > 25 TeV)



- ✓ 6.2σ detection @ E > 25 TeV
- ✓ Centroid (2DML w/ a Gaussian template) : $(\alpha, \delta) = (281.09^\circ \pm 0.10^\circ_{stat}, -3.76^\circ \pm 0.09^\circ_{stat})$
- ✓ Positionally consistent w/ HESS J1843-033, eHWC J1842-035, & LHAASO J1843-0338
- ✓ Extension : $0.34^\circ \pm 0.12^\circ$

Energy Spectrum



- ✓ 1^{st} measurement in 25TeV<E<130TeV
- ✓ Power-law function fits well
- ✓ Smooth connection to HESS, eHWC & LHAASO sources
  => They have common origin?
- ✓ Cutoff in E_{cut} = 50TeV?

Power-law fit :
(25TeV < E < 130TeV)

$$\frac{dN}{dE} = (9.70 \pm 1.89)\times 10^{-16} \left(\frac{E}{40\ \text{TeV}}\right)^{-3.26\pm 0.30} \text{TeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1} \quad (\chi^2/\text{d.o.f.} = 2.1/2)$$

PL + exp. cuoff :
(HESS, LHAASO, TASG, 300GeV < E < 130 TeV)

$$\frac{dN}{dE} = (3.57 \pm 0.26)\times 10^{-12} \left(\frac{E}{1\ \text{TeV}}\right)^{-2.02\pm 0.06} \exp\left(-\frac{E}{E_{cut}}\right) \text{TeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1} \quad (\chi^2/\text{d.o.f.} = 10.4/8)$$

E_{cut} = 49.5 ± 9.0TeV

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

Association of TASG J1844-038 w/ SNR G28.6-0.1

SNR G28.6-0.1

- ✓ Radio complex seen in 20 cm continuum[1]
- ✓ Non-thermal keV X-ray src AX J1843.8-0352[2]
- ✓ Electrons accelerated up to >100TeV[3]
- ✓ Age[2] : < 2.7 kyr
- ✓ Distance[4] : 9.6±0.3 kpc
- ✓ Magnetic field[3] : 6~8 μG

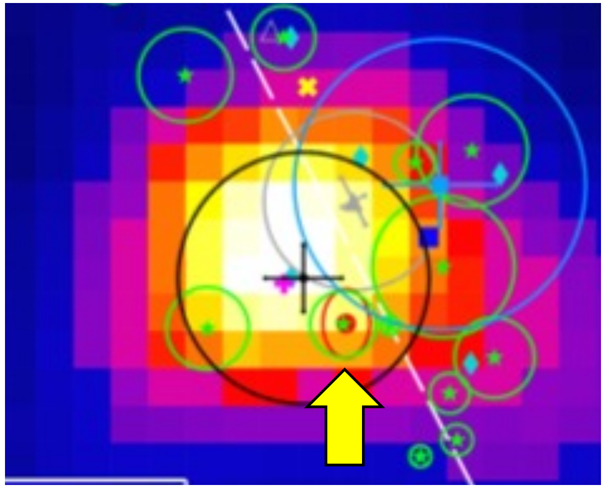
If the γ rays (E > 25TeV) are of leptonic origin…

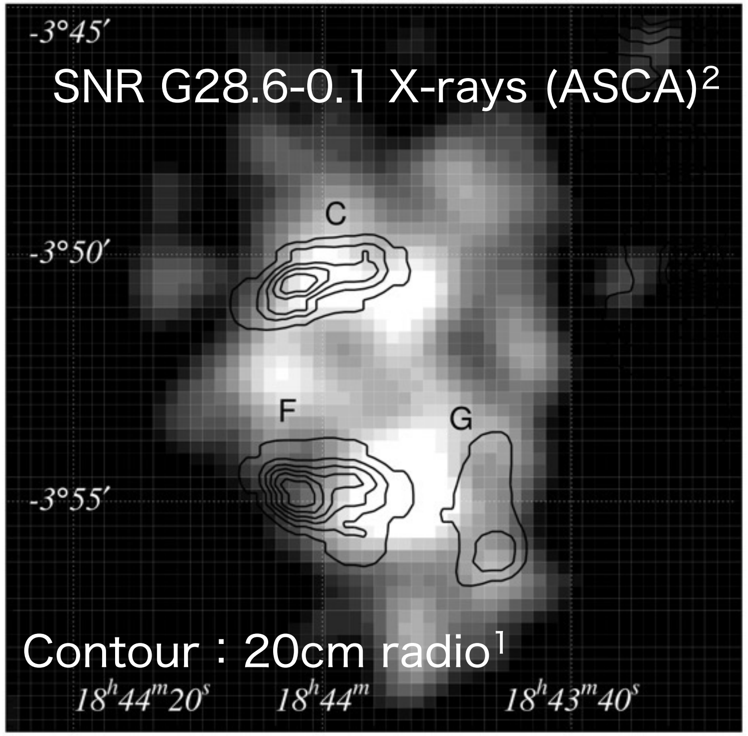
X- & γ rays have the same parent $e^{\pm}$ w/ E ~ 100TeV if ICS off CMB works

=> X- & γ-ray extensions should thus be the same

! Extension of γ-rays (0.34°±0.12°) is larger than the X-ray extension (4.5')[3] at a 2.3σ level

=> Hadronic contribution to the γ-ray emission??

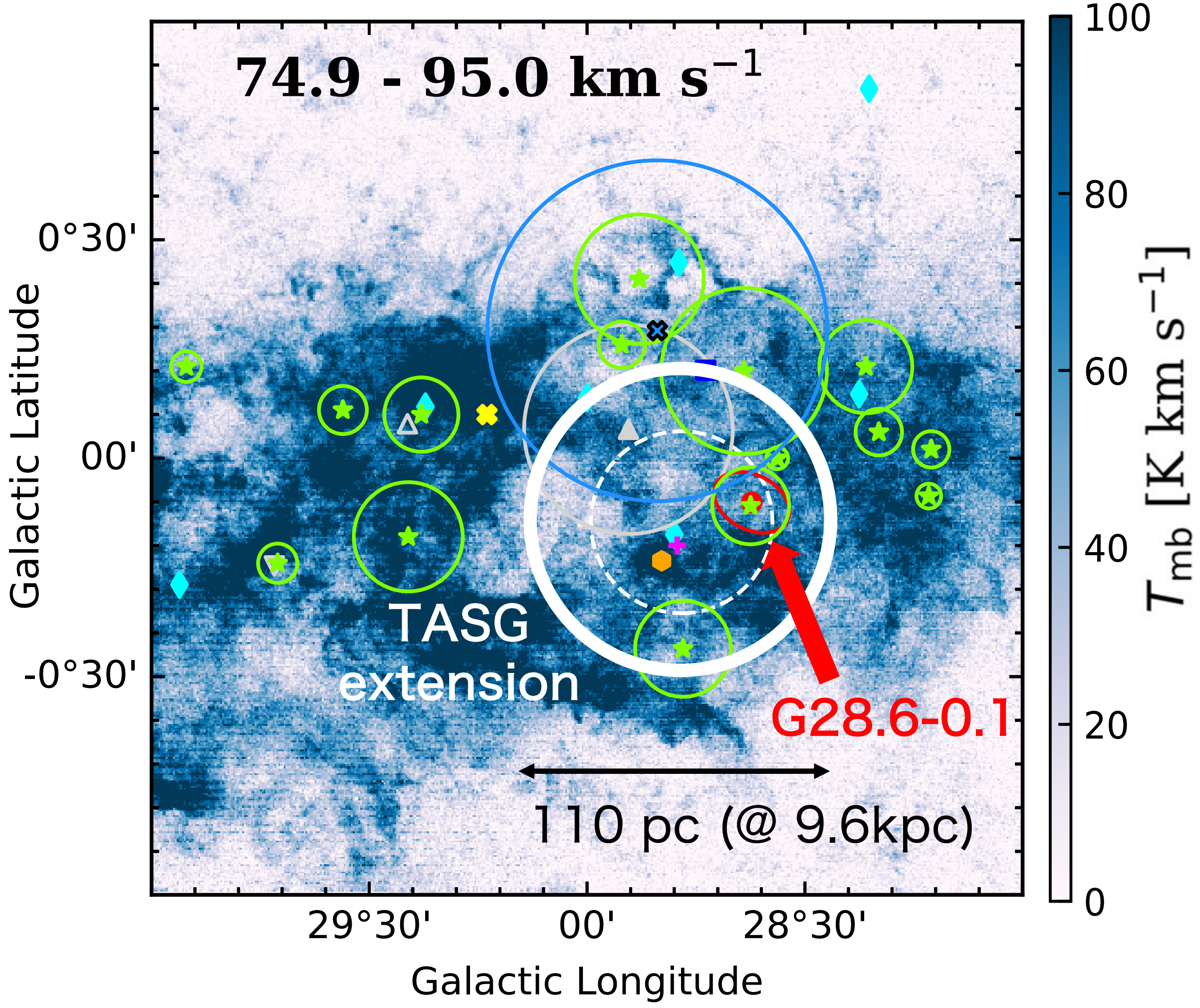




1. Helfand+, ApJ 341, 151 (1989)
2. Bamba+, PASJ 53, L21 (2001)
3. Ueno+, ApJ 588, 338 (2003)
4. Ranasinghe & Leahy, MNRAS 477, 2243 (2018)

Association of TASG J1844-038 w/ SNR G28.6-0.1

Molecular gas seen in ^{12}CO (J=1-0) using archive data (FUGIN[1])



- ✓ SNR-Cloud interaction found[1] in ~ 86 km s^{-1}
  => Protons accelerated by the SNR diffuse & interact w/ the cloud?
- ✓ Gas w/ ~50 K km s^{-1} in the source region can provide n_p ~ 30 cm^{-3}
- ✓ Wp < 0.1 × 10^{51} erg @ 9.6 kpc :

$$W_p(E > 1\,\mathrm{TeV}) \sim 6 \times 10^{49} \left(\frac{n_p}{10\,\mathrm{cm}^{-3}}\right)^{-1} \mathrm{erg}$$

- ✓ $E_{p,max}$ ~ 10 $E_{\gamma,max}$ = 500TeV
  => SNR G28.6-0.1 is a PeVatron candidate

1. Ranasinghe & Leahy, MNRAS 477, 2243 (2018)
2. Umemoto+, PASJ 69, 5 (2017)

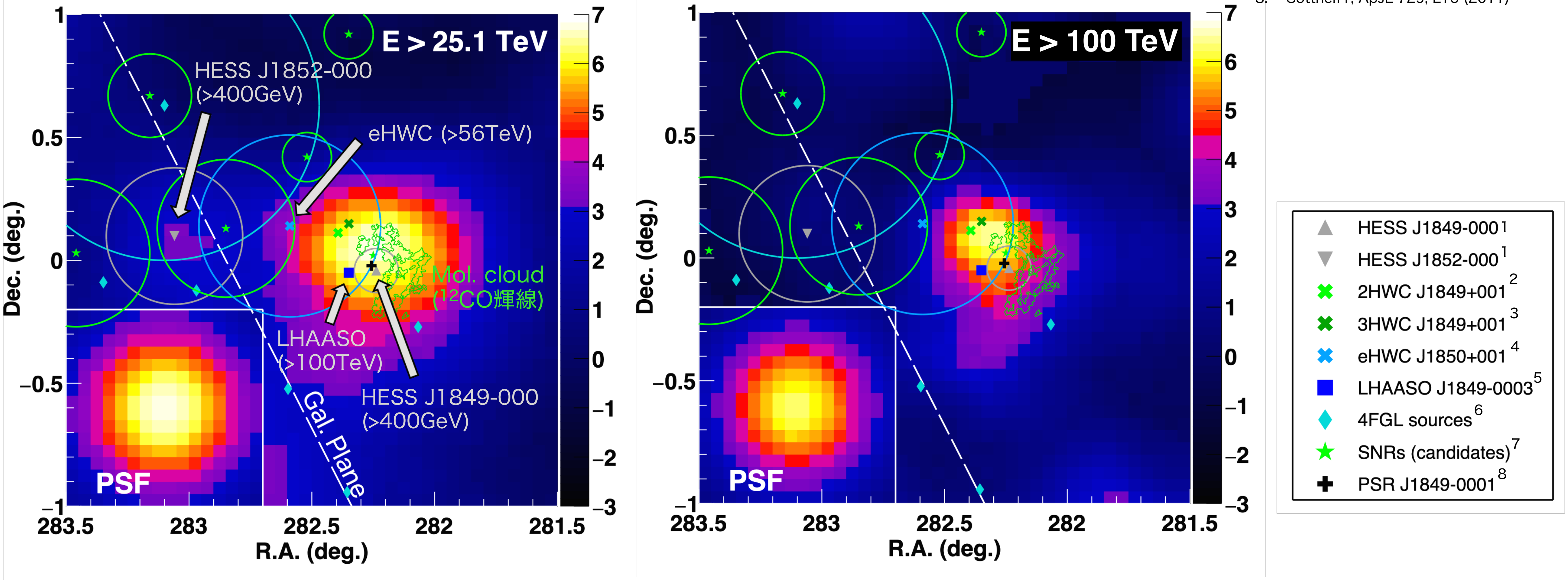
Study of HESS J1849-000

Amenomori, Kato et al., ApJ 954, 200 (2023)

Detection of γ Rays from HESS J1849-000

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)

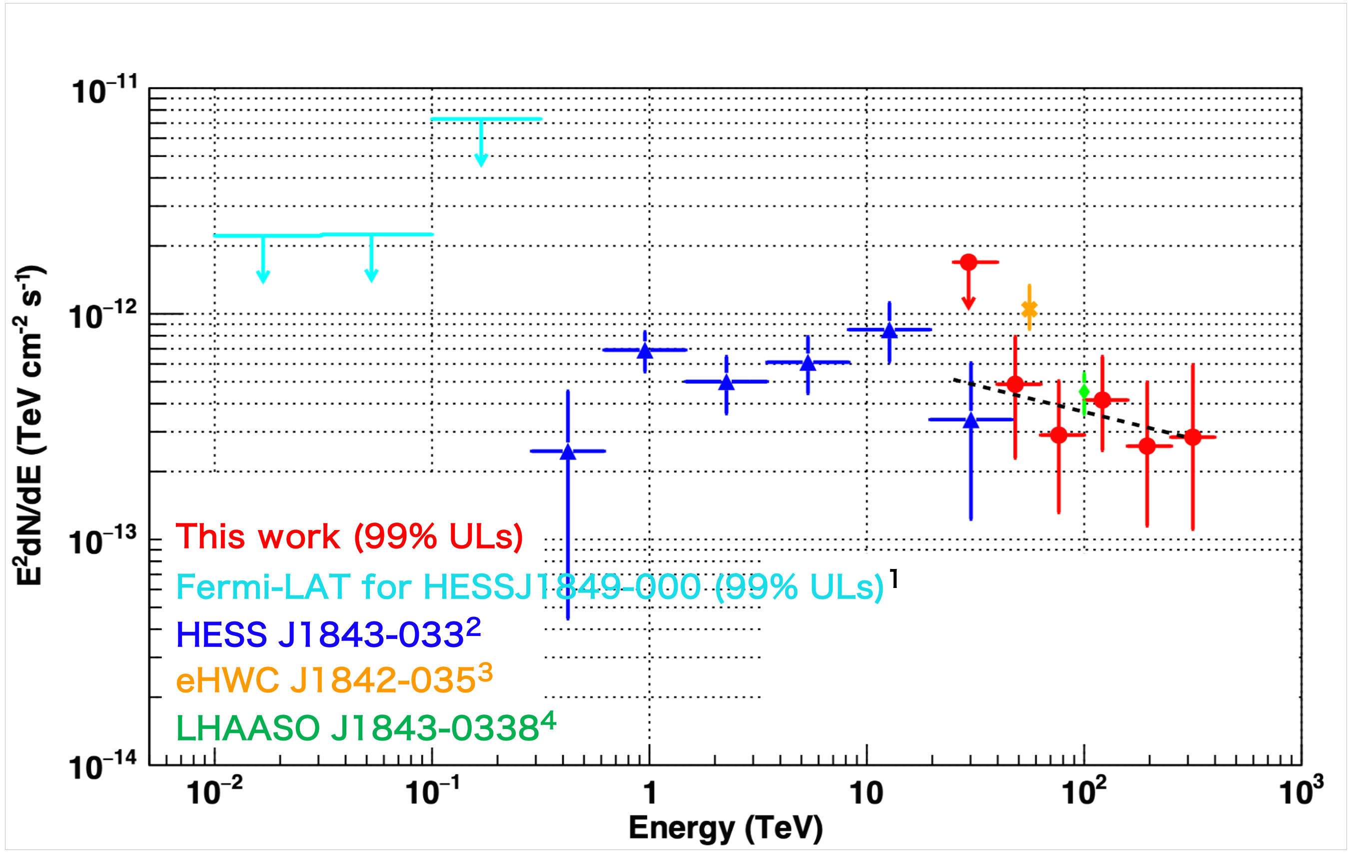
Significance map
(smoothed w/ PSF)



- ✓ Detection significance : <u>4.0 σ @ E > 25TeV & 4.4 σ @ E > 100 TeV</u>
- ✓ From the toy MC simulation, the position unc. of the bright region @ E > 100 TeV is 0.22°
  => Positionally consistent w/ HESS J1849-000
- ✓ Deviation from HESS J1852-000[1] : 3.0 σ @ E > 100 TeV => Unlikely the source

Energy Spectrum

1. Acero+, ApJ 773, 77 (2013)
2. H.E.S.S. Collaboration, A&A 612, A1 (2018)
3. Abeysekara+, PRL 124, 021102 (2020)
4. Cao+, Nature 594, 33 (2021)
5. Amenomori+, ApJ 692, 61 (2009)



- ✓ 1st spectral measurement b/w 40TeV < E < 320TeV
- ✓ Smoothly connected to the H.E.S.S. measurement
- ✓ Giving consistent flux levels w/ HAWC & LHAASO
- ✓ Systematic error :
  1. Energy estimation 12%[5]
     => Flux 27%
  2. Contamination by HESS J1852-000
     => Flux < 20% @ 95% C.L.

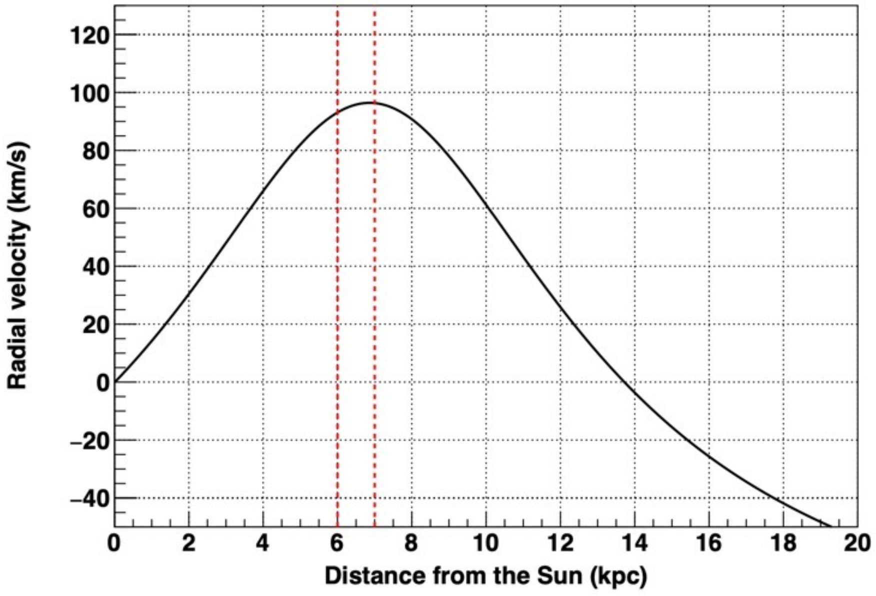
PL fit :
(40TeV < E < 320TeV)

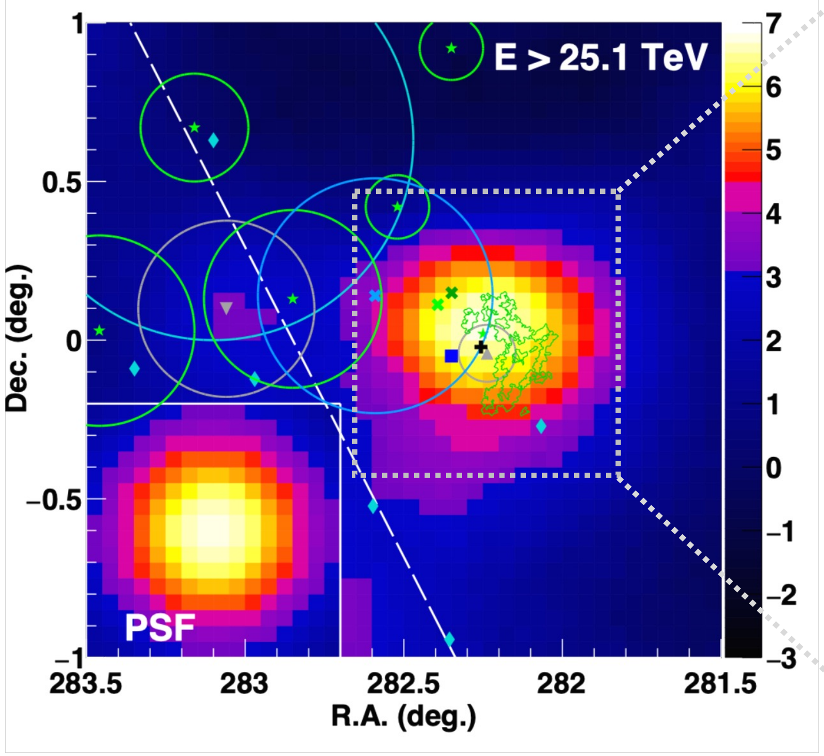
$$\frac{dN}{dE} = (2.86 \pm 1.44)\times10^{-16}\left(\frac{E}{40\ \mathrm{TeV}}\right)^{-2.24\pm0.41}\ \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}}$$

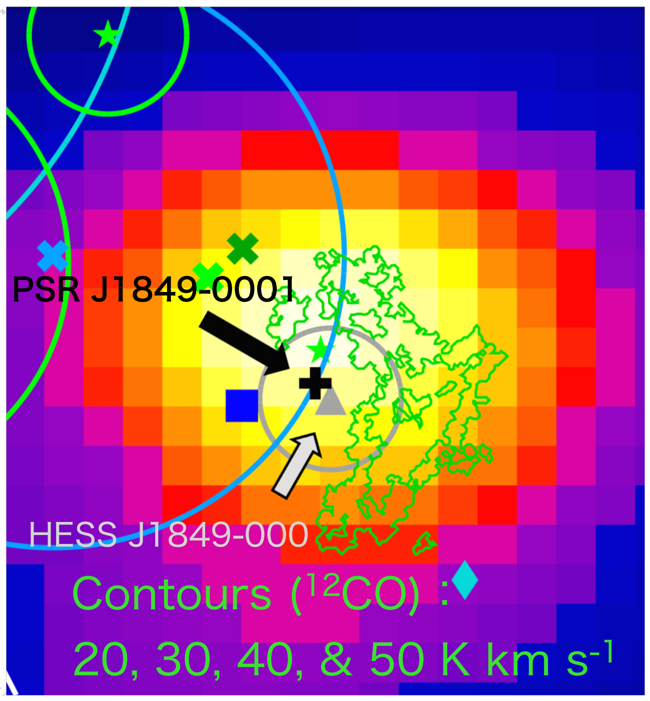
$(\chi^2/\mathrm{d.o.f.} = 0.5/3)$

Detection of a Molecular Cloud

Distance-velocity map



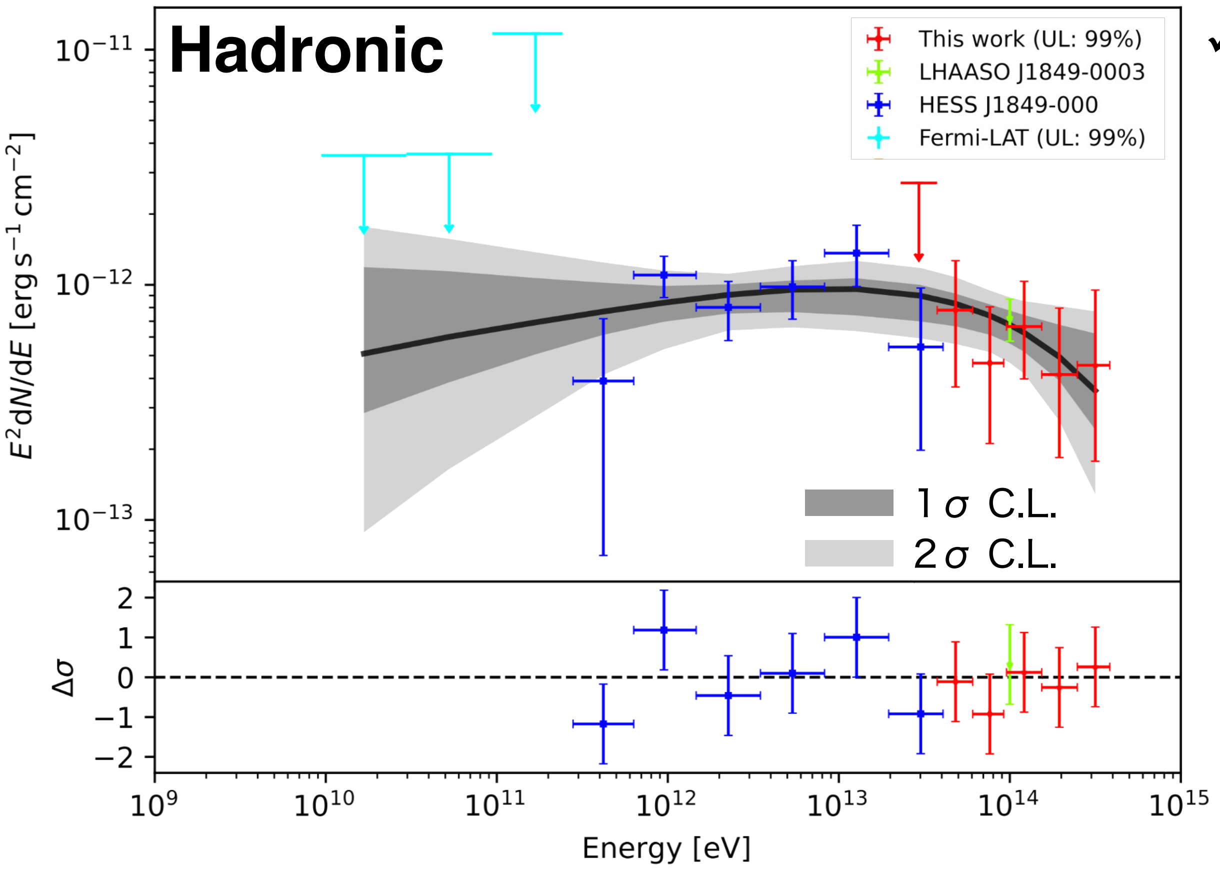




- ✓ Analysis of archive ^{12}CO (J=1-0) data (FUGIN[1])
- ✓ Assumed istance : 7 kpc[2]
- ✓ Integration of velocity range of 93-100 km s^{-1}
  => A ~20 pc size cloud w/ T_b ~20 K km s^{-1} @ the west of HESS J1849-000
- ✓ Overlap b/w γ-ray emission & cloud
- ✓ Gas density : np = Xco T_{mb} / R ~ 70 cm^{-3} (Xco = 2×10^{20} cm^{-2} (K km $s^{-1})^{-1}$)[3]
  => Can provide the gas density of ≳ 10 cm^{-3}

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

Modeling of the Spectrum (Hadronic Scenario, Naima[1])



✓ Assumptions :

- π^0-decay γ-rays from collisions of gas & CR p's
- Gas density = 10 cm^{-3}
- PL + exp. cutoff for CR protons :

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

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

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

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

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

Possible acceleration of CR protons beyond PeV

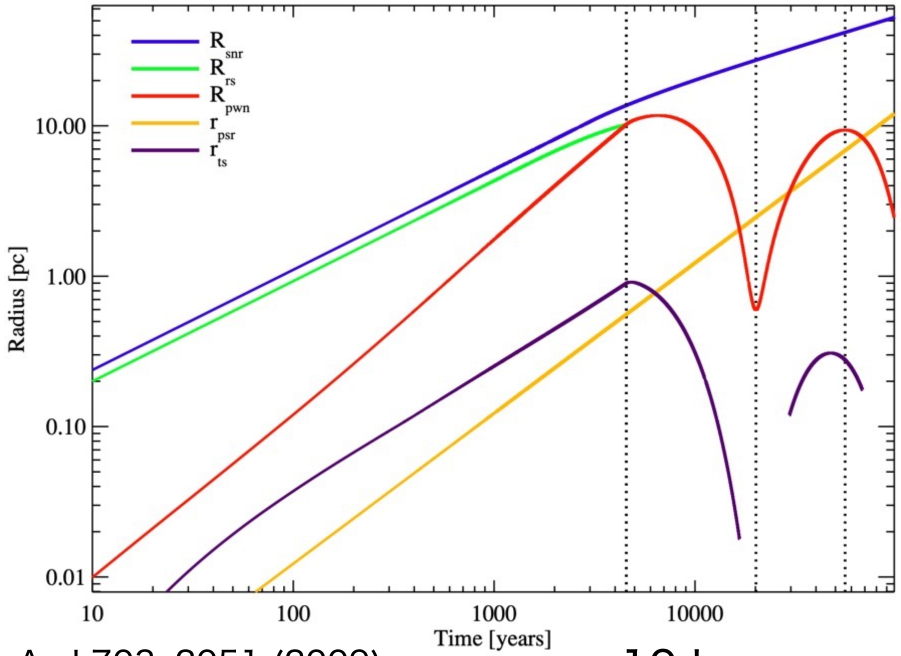
1. Zabalza, PoS(ICRC2015) 922 (2015)

Possible Acceleration Mechanism of PeV CRs

✓ CR acceleration in a PWN-SNR composite system[1,2] ??

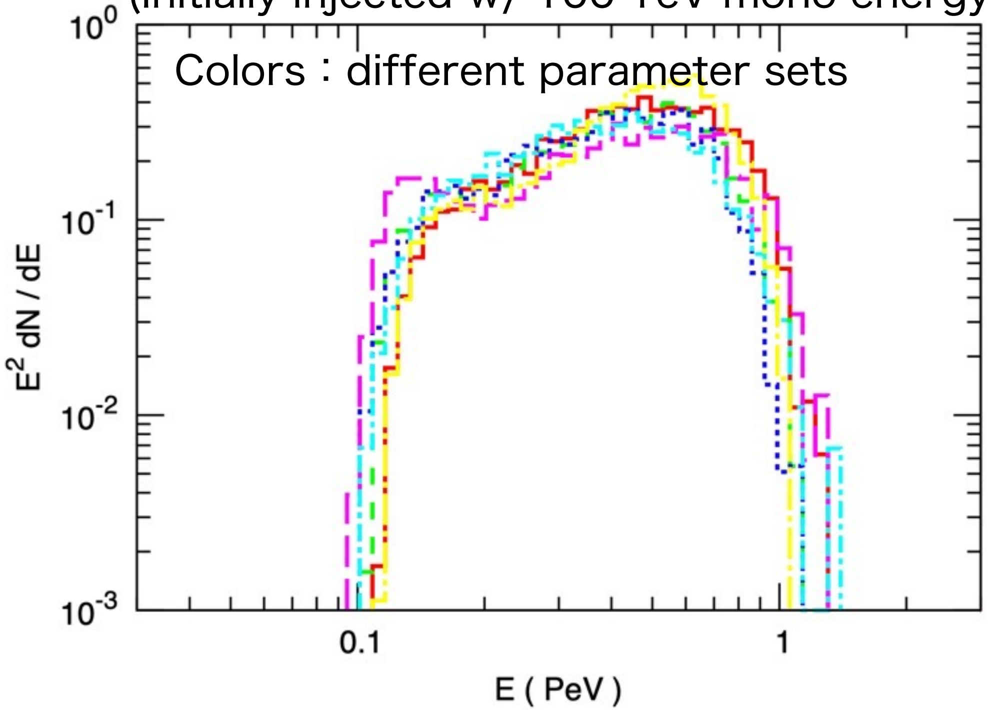
- CR protons pre-accelerated up to ~100 TeV in the SNR FS are re-accelerated up to ~ 1 PeV in the PWN compressed by the SNR reverse shock
- $\sim 10^{49}$ erg is given to the accelerated particles[1]
- PWN is compressed to ~10% of the original size[1,2]
- *B* of the PWN is amplified up to ~ 100 μG[1]
  => compact synchrotron X-ray emission by $e^{\pm}$ of PWN origin??

Evolution of the size of the system



10 kyr

Energy spectrum of CR protons[2]
(Initially injected w/ 100 TeV mono energy)



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

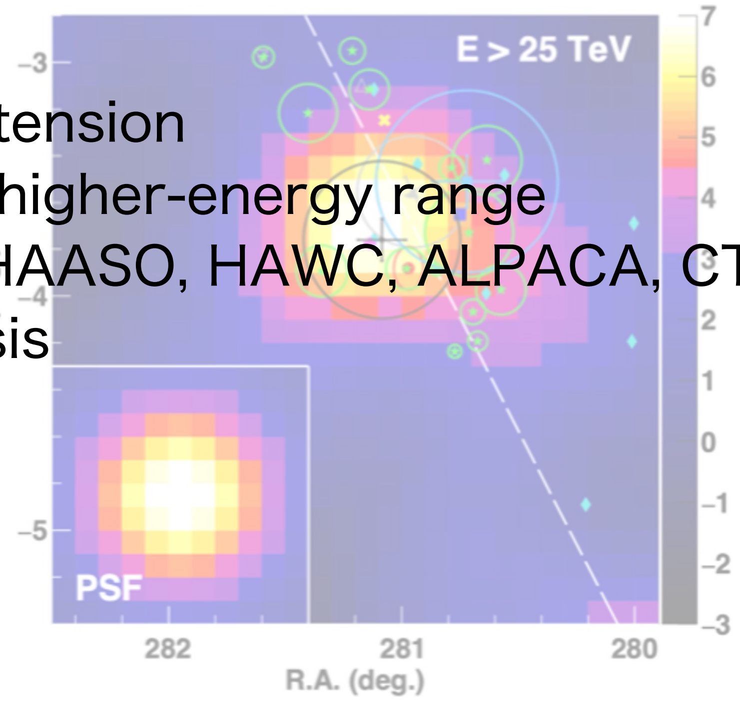
Summary

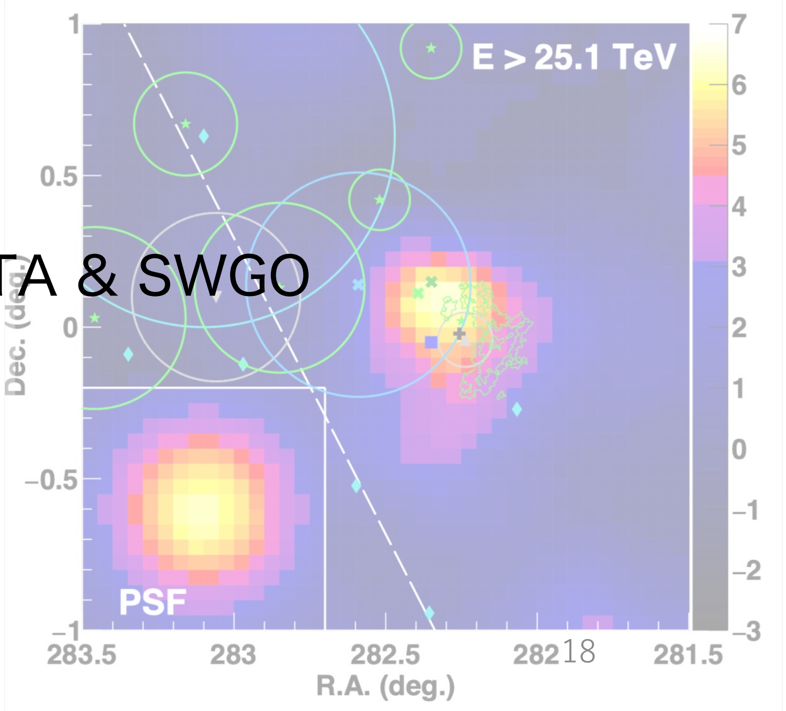
- ✓ Study of HESS J1843-033 & HESS J1849-000 by the Tibet AS array + MD array
- ✓ Detection of mol. clouds near the both sources ($n_p > 10\ cm^{-3}$)
- ✓ PeVatron scenarios are considered (leptonic origin is not ruled out) :

  HESS J1843-033 => SNR G28.6-0.1?? ($E_{p,\ max}$ ~ 500 TeV)

  HESS J1849-000 => Composite system of PWN & SNR?? ($E_{p,\ max} \gtrsim$ 1 PeV)

- ✓ Future work :
  1. Accurate determination of extension
  2. Spectral measurement in the higher-energy range
  3. Further detailed studies by LHAASO, HAWC, ALPACA, CTA & SWGO
  4. Radio to X-ray spectral analysis
  5. Neutrino observation

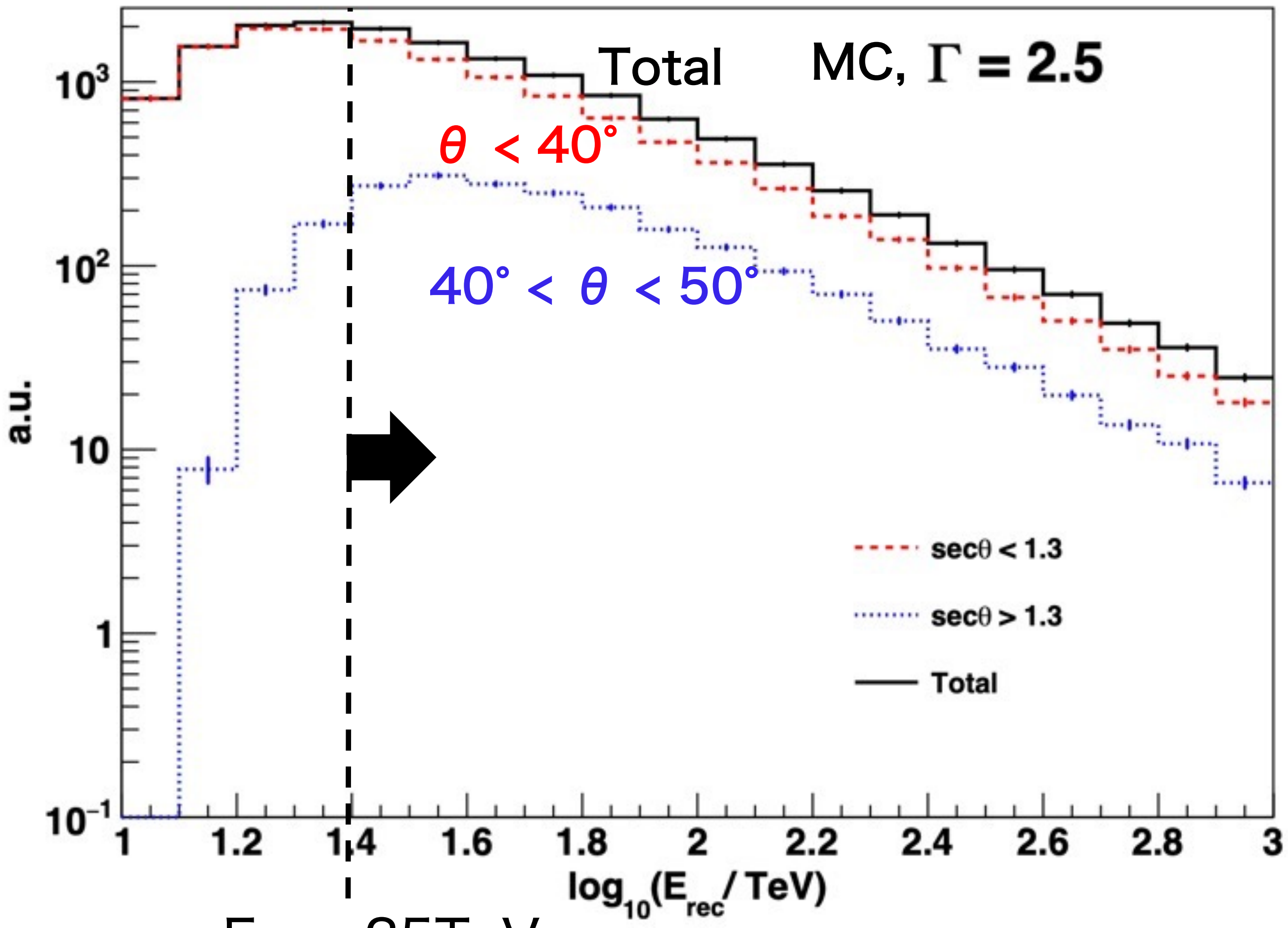




Backup Slides

Extension of the Analyzed Zenith-Angle Range up to 50°

Distribution of MC gamma events (before MD cut)



E_{th} = 25TeV

- ✓ HESS J1843-033 & HESS J1849-000 have
  1. a low flux level (~10% Crab @ E > 1TeV[1])
  2. large meridian zenith (~ 30°) & low exposure

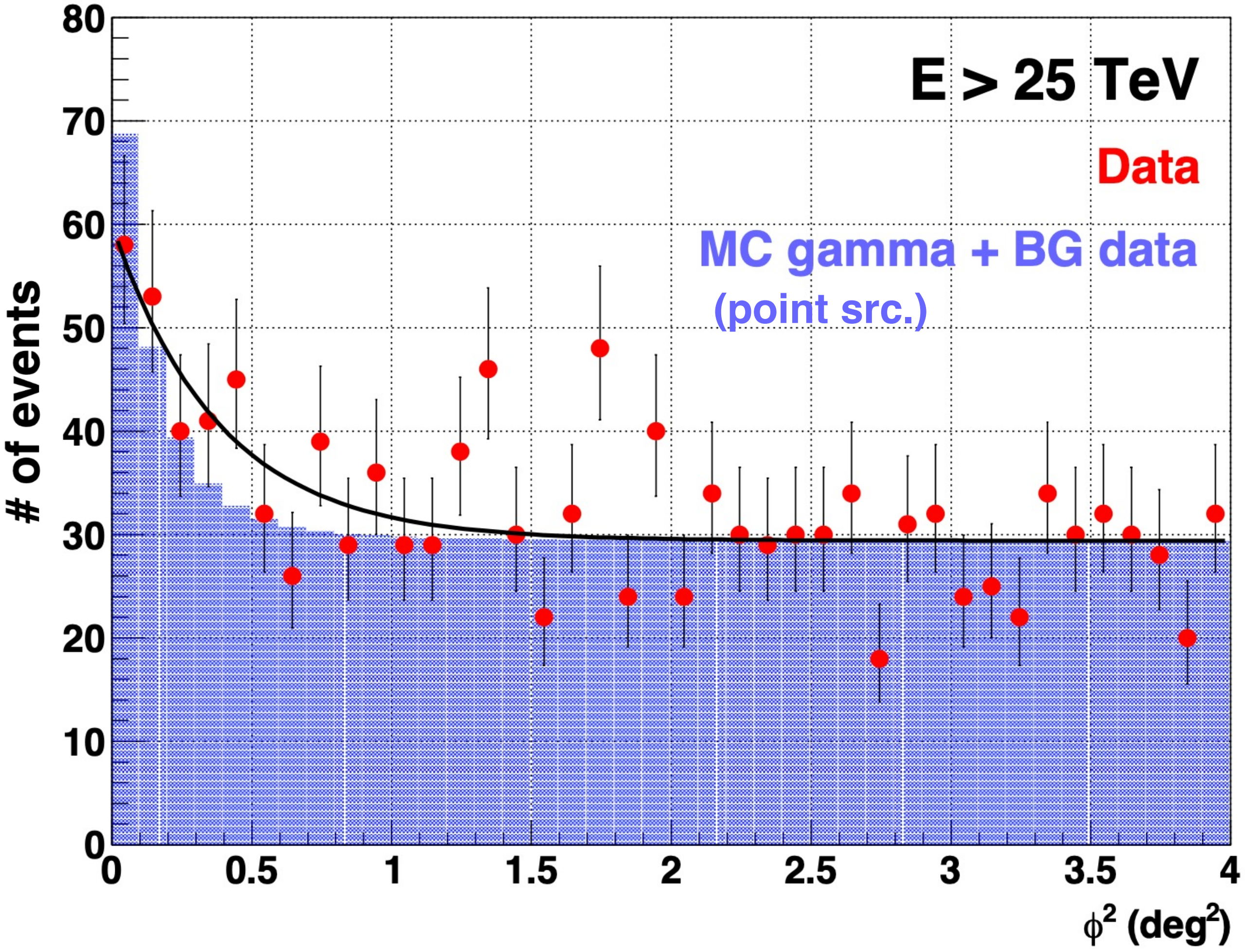
⇒ Need for the increase of statistics by **extending the analyzed zenith-angle range up to 50°**

(The conventional analysis adopted θ<40°)

- ✓ Improvement of event statistics by ~30% @ E > 25TeV

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

Extension of TASG J1844-038



ϕ: Angular distance b/w the centroid & events

✓ Fit of a Gaussian :

$$G(\phi^2; A, \sigma_{\rm ext}) = A \exp\left(- \frac{\phi^2}{2(\sigma_{\rm ext}^2 + \sigma_{\rm psf}^2)} \right) + N_{\rm bg}$$

$\sigma_{\rm psf}$ = 0.28° : PSF radius, $N_{\rm bg}$ = 29.4 : # of BG events

=> Extension $\sigma_{\rm ext}$ = 0.34° ± 0.12° (χ^2 / d.o.f. = 39.5 / 38)

✓ Extension consistent w/

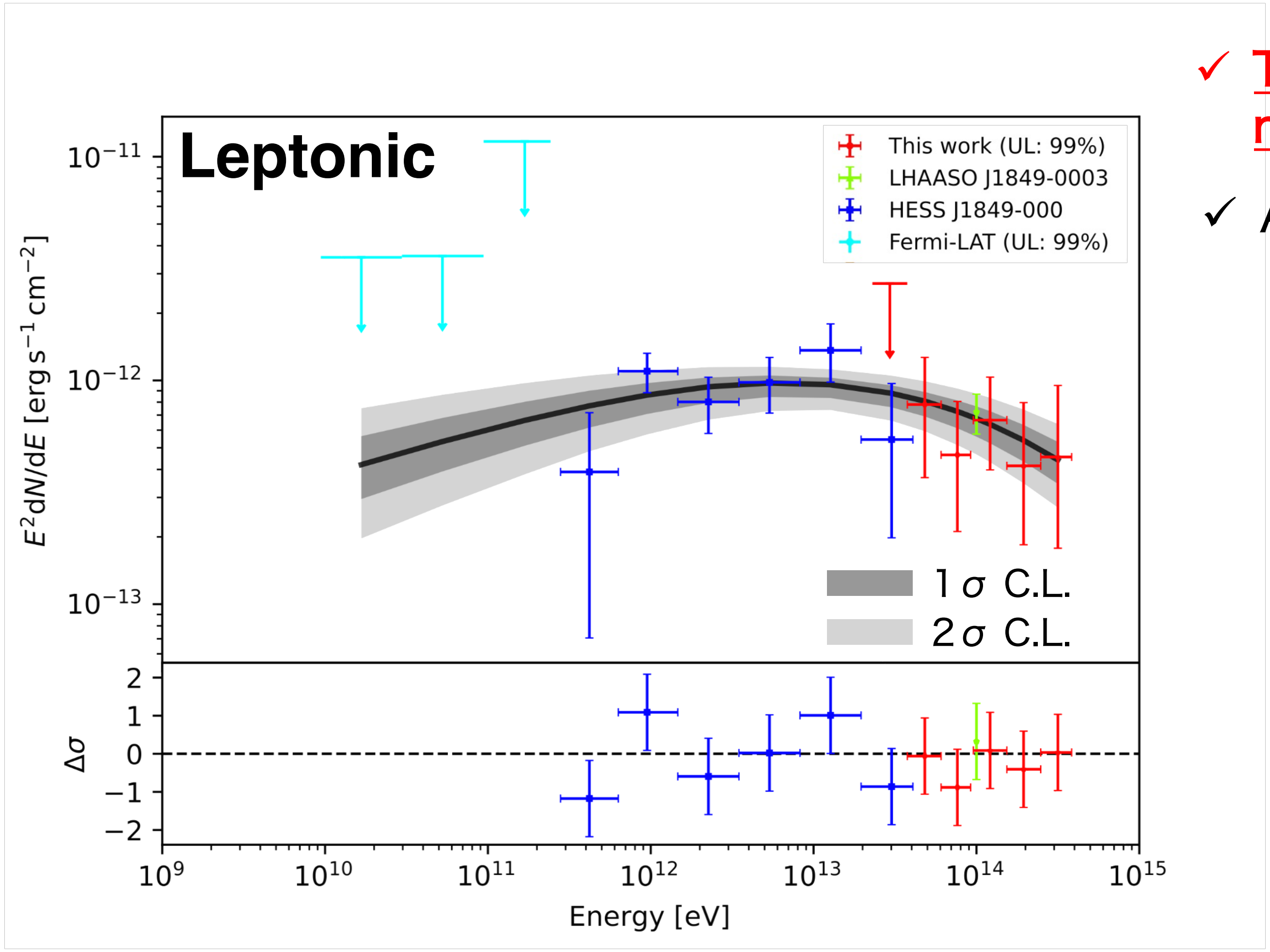
HESS J1843-033 (0.24°±0.06° @ E > 400 GeV)[1]

eHWC J1842-035 (0.39°±0.09° @ E > 56 TeV)[2]

=> TASG J1844-038 is concluded as extended

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, PRL 124, 021102 (2020)

Leptonic Modeling of the HESS J1849-000 spectrum (Naima[1])



✓ **The first spectral modeling including the results in the sub-PeV range**

✓ Assumptions：

- Inverse Compton Scattering by HE $e^{\pm}$
- Radiation field：determined from the GALPROP calculation[2,3]

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

- PL spectrum for HE $e^{\pm}$：

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

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

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

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

Cutoff energy：> 740 TeV @ 95% C.L.

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