東京大学宇宙線研究所「共同利用成果発表会」 2023年 2月 22日

チベット高原での
高エネルギー宇宙線の研究

加藤 勢 (東京大学宇宙線研究所)
For the Tibet ASγ Collaboration

Tibet ASγ Collaboration

M. Amenomori[1], S. Asano[2], Y. W. Bao[3], X. J. Bi[4], D. Chen[5], T. L. Chen[6], W. Y. Chen[4], Xu Chen[4,5], Y. Chen[3], Cirennima[6], S. W. Cui[7], Danzengluobu[6], L. K. Ding[4], J. H. Fang[4,8], K. Fang[4], C. F. Feng[9], Zhaoyang Feng[4], Z. Y. Feng[10], Qi Gao[6], A. Gomi[11], Q. B. Gou[4], Y. Q. Guo[4], Y. Y. Guo[4], Y. Hayashi[2], H. H. He[4], Z. T. He[7], K. Hibino[12], N. Hotta[13], Haibing Hu[6], H. B. Hu[4], K. Y. Hu[4,8], J. Huang[4], H. Y. Jia[10], L. Jiang[4], P. Jiang[5], H. B. Jin[5], K. Kasahara[14], Y. Katayose[11], C. Kato[2], S. Kato[15], I. Kawahara[11], T. Kawashima[15], K. Kawata[15], M. Kozai[16], D. Kurashige[11], Labaciren[6], G. M. Le[17], A. F. Li[4,9,18], H. J. Li[6], W. J. Li[4,10], Y. Li[5], Y. H. Lin[4,8], B. Liu[19], C. Liu[4], J. S. Liu[4], L. Y. Liu[5], M. Y. Liu[6], W. Liu[4], X. L. Liu[5], Y.-Q. Lou[20,21,22], H. Lu[4], X. R. Meng[6], Y. Meng[4,8], K. Munakata[2], K. Nagaya[11], Y. Nakamura[15], Y. Nakazawa[23], H. Nanjo[1], C. C. Ning[6], M. Nishizawa[24], R. Noguchi[11], M. Ohnishi[15], S. Okukawa[11], S. Ozawa[25], L. Qian[5], X. Qian[5], X. L. Qian[26], X. B. Qu[27], T. Saito[28], Y. Sakakibara[11], M. Sakata[29], T. Sako[15], T. K. Sako[15], T. Sasaki[12], J. Shao[4,9], M. Shibata[11], A. Shiomi[23], H. Sugimoto[30], W. Takano[12], M. Takita[15], Y. H. Tan[4], N. Tateyama[12], S. Torii[31], H. Tsuchiya[32], S. Udo[12], H. Wang[4], Y. P. Wang[6], Wangdui[6], H. R. Wu[4], Q. Wu[6], J. L. Xu[5], L. Xue[9], Z. Yang[4], Y. Q. Yao[5], J. Yin[5], Y. Yokoe[15], N. P. Yu[5], A. F. Yuan[6], L. M. Zhai[5], C. P. Zhang[5], H. M. Zhang[4], J. L. Zhang[4], X. Zhang[3], X. Y. Zhang[9], Y. Zhang[4], Yi Zhang[33], Ying Zhang[4], S. P. Zhao[4], Zhaxisangzhu[6], X. X. Zhou[10] and Y. H. Zou[4,8]

1 Department of Physics, Hirosaki Univ., Japan.
2 Department of Physics, Shinshu Univ., Japan.
3 School of Astronomy and Space Science, Nanjing Univ., China.
4 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS, China.
5 National Astronomical Observatories, CAS, China.
6 Department of Mathematics and Physics, Tibet Univ., China.
7 Department of Physics, Hebei Normal Univ., China.
8 Univ. of Chinese Academy of Sciences, China.
9 Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong Univ., China.
10 Institute of Modern Physics, SouthWest Jiaotong Univ., China.
11 Faculty of Engineering, Yokohama National Univ., Japan.
12 Faculty of Engineering, Kanagawa Univ., Japan.
13 Faculty of Education, Utsunomiya Univ., Japan.
14 Faculty of Systems Engineering, Shibaura Institute of Technology, Japan.
15 Institute for Cosmic Ray Research, Univ. of Tokyo, Japan.
16 Polar Environment Data Science Center, Joint Support-Center for Data Science Research, Research Organization of Information and Systems, Japan.
17 National Center for Space Weather, China Meteorological Administration, China.
18 School of Information Science and Engineering, Shandong Agriculture Univ., China.
19 Department of Astronomy, School of Physical Sciences, Univ. of Science and Technology of China, China.
20 Department of Physics and Tsinghua Centre for Astrophysics (THCA), Tsinghua Univ., China.
21 Tsinghua Univ.-National Astronomical Observatories of China (NAOC) Joint Research Center for Astrophysics, Tsinghua Univ., China.
22 Department of Astronomy, Tsinghua Univ., China.
23 College of Industrial Technology, Nihon Univ., Japan.
24 National Institute of Informatics, Japan.
25 National Institute of Information and Communications Technology, Japan.
26 Department of Mechanical and Electrical Engineering, Shangdong Management Univ., China.
27 College of Science, China Univ. of Petroleum, China.
28 Tokyo Metropolitan College of Industrial Technology, Japan.
29 Department of Physics, Konan Univ., Japan.
30 Shonan Institute of Technology, Japan.
31 Research Institute for Science and Engineering, Waseda Univ., Japan.
32 Japan Atomic Energy Agency, TJapan.
33 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.

令和 4年度チベット実験関係
共同利用研究採択課題一覧

F 9 チベット高原での高エネルギー宇宙線の研究（継続）

(瀧田正人　東京大学宇宙線研究所)

F10 チベット空気シャワーアレイによる10TeV宇宙線強度の恒星時日周変動の観測（継続）

(宗像一起　信州大学理学部)

F11 Knee領域一次宇宙線組成の研究（継続）

(片寄祐作　横浜国立大学大学院工学研究院)

F12 宇宙線による太陽の影を用いた太陽周辺磁場の時間変動の研究（継続）

(西澤正己　国立情報学研究所情報社会相関研究系)

チベットグループ共同利用研究経費執行状況

研究費：　申請額 795.6万円　→　配分額 180万円

Tibet空気シャワー観測装置、YAC空気シャワーコア観測装置、地下ミューオン観測装置の維持・運転に必要な経費の一部に使用。

旅費：　申請額 980万円　→　配分額 240万円

宇宙線研での研究打ち合わせ等に使用。

ご支援、どうもありがとうございました！

Activities in the 2022 FY

International conferences：

1. The 21st International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI2022), 2022/5/23-27 1 talk
2. International Conference on High Energy Physics (ICHEP2022), 2022/7/6-13 1 talk
3. COSPAR2022, 2022/7/16-24 3 talks
4. European Cosmic Ray Symposium (ECRS2022), 2022/7/25-29 2 talks
5. TeV Particle Astrophysics (TeVPA2022), 2022/8/8-12 1 talk
6. The 15th Asia Pacific Physics Conference (APPC15), 2022/8/21-26 1 talk
7. Neutrino Oscillation Workshop (NOW2022), 2022/9/4-11 1 talk
8. Cosmic Rays in the Multi-Messenger Era, 2022/12/5-7 1 talk
9. Theory Meeting Experiments (TMEX2023), 2023/1/5-11 1 talk

Domestic conferences：

1. 日本物理学会秋季大会, 2022/9/6-8, 2 talks
2. 日本天文学会秋季年会, 2022/9/13-15, 2 talks
3. 日本物理学会春季大会, 2023/3/22-25予定, 2 talks

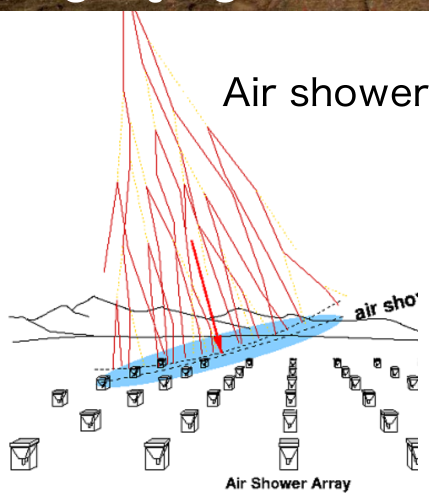
Refereed papers：

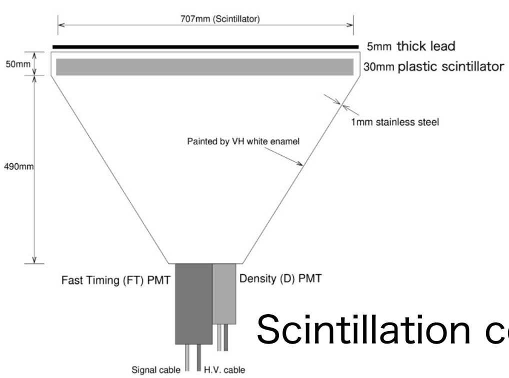
1. “Measurement of the Gamma-Ray Energy Spectrum beyond 100 TeV from the HESS J1843-033 Region”, Amenomori et al., ApJ 932,120(2022)
2. “Sensitivity of the large muon detector with the Tibet air-shower array to measure the primary proton spectrum between 40 and 630 TeV”, Kurashige et al., PTEP 093F01 (2022)

Tibet Air Shower Array

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

Air shower

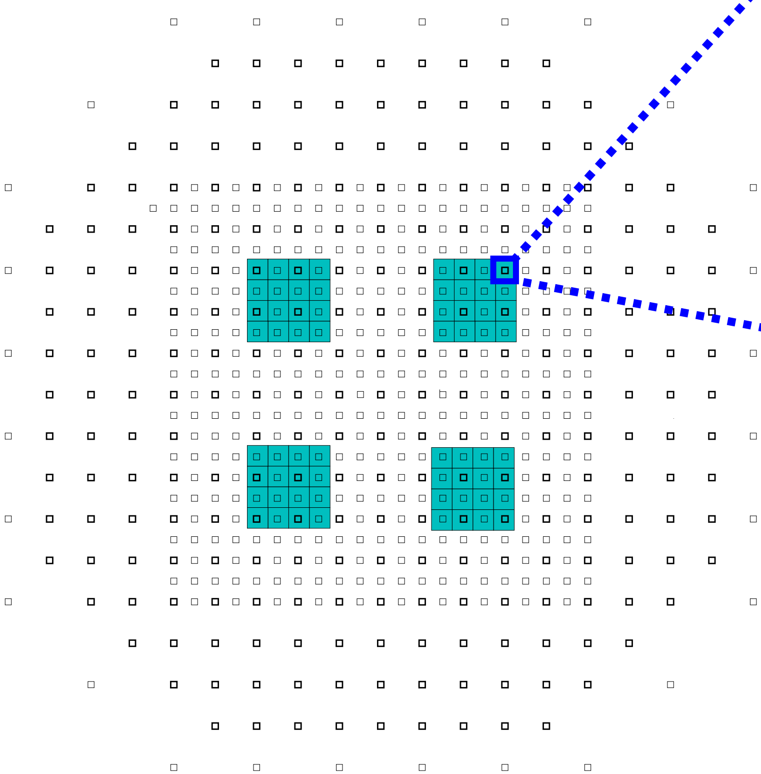




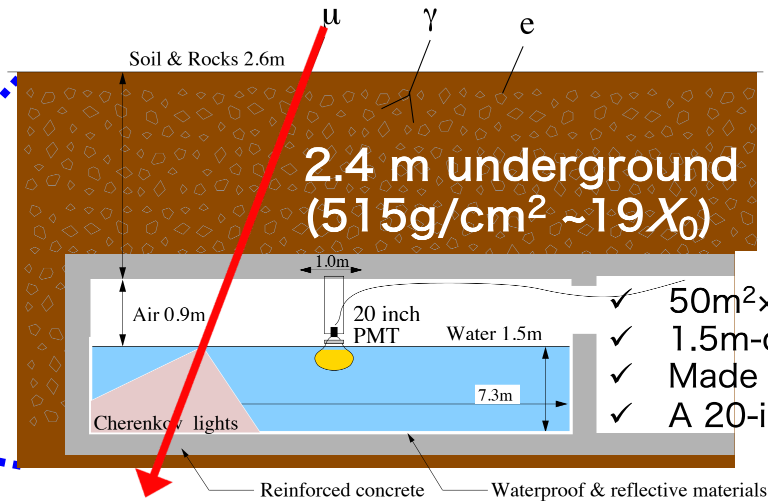
Scintillation counter

- ✓ Scintillation counters ($0.5m^2$) arranged over $65{,}700m^2$
- ✓ Observation of air shower ptcl.s to determine the energy & incoming direction of primary CRs
- ✓ Wide F.O.V. (~ 2 sr) & continuous operation
- ✓ Physics :
  CR physics in the TeV-PeV range
  γ-ray astronomy in the TeV-sub-PeV range

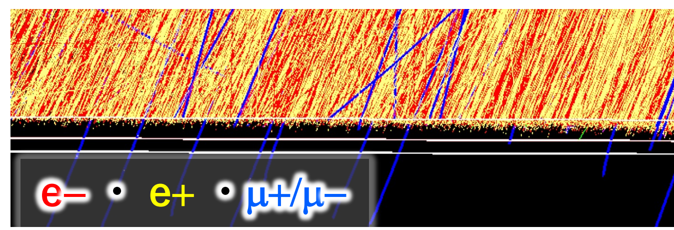
Underground Muon Detector Array (MD Array)



MD：3400m²

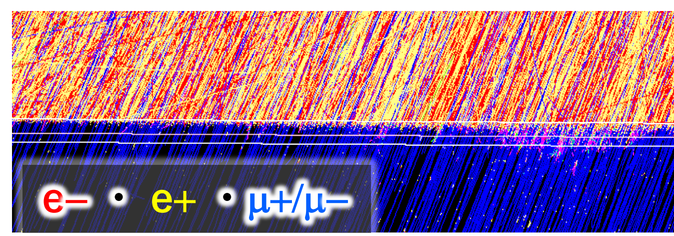


- ✓ 50m²×2.4m
- ✓ 1.5m-depth water layer
- ✓ Made of concrete
- ✓ A 20-inch PMT suspended



200TeV γ shower

Few muons (~1μ)



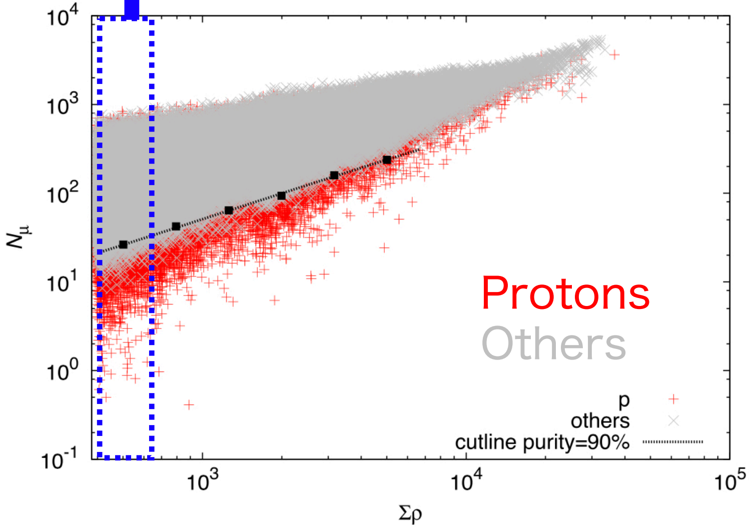
200TeV CR shower

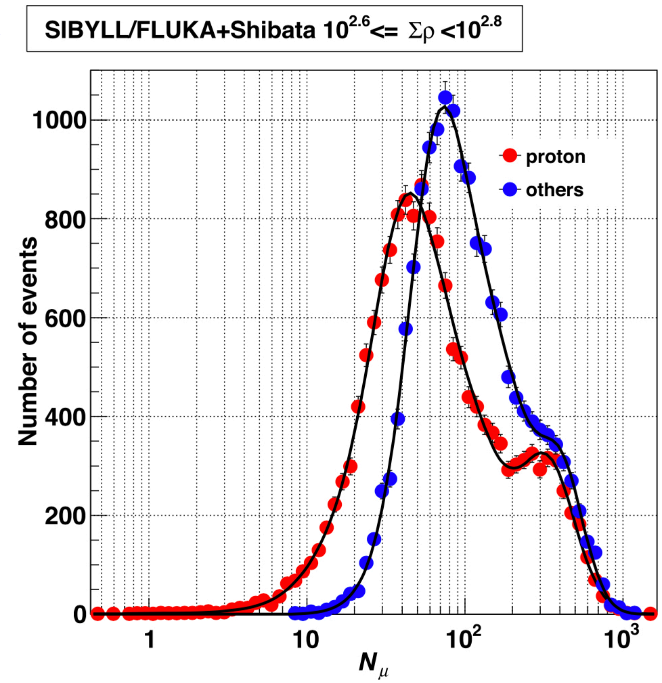
Many muons (~100μ)

Quantification of the shower muon component leads to
good γ/h separation
Rejection power for BGCRs： >99.9% @ E>100TeV
γ-ray survival ratio：~90% @ 〃

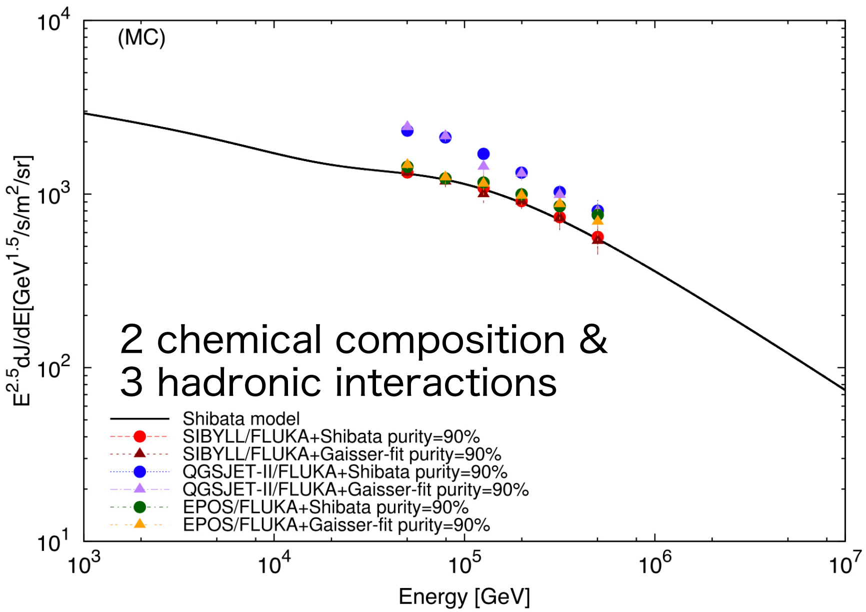
“Sensitivity of the large muon detector with the Tibet air-shower array to measure the primary proton spectrum between 40 and 630 TeV”, Kurashige et al., PTEP 093F01 (2022)

To measure the proton spectrum around the sub-PeV range





$\Sigma\rho$: # of shower ptcl.s detected w/ the AS array
ΣN_μ : # of muons detected w/ the MD array

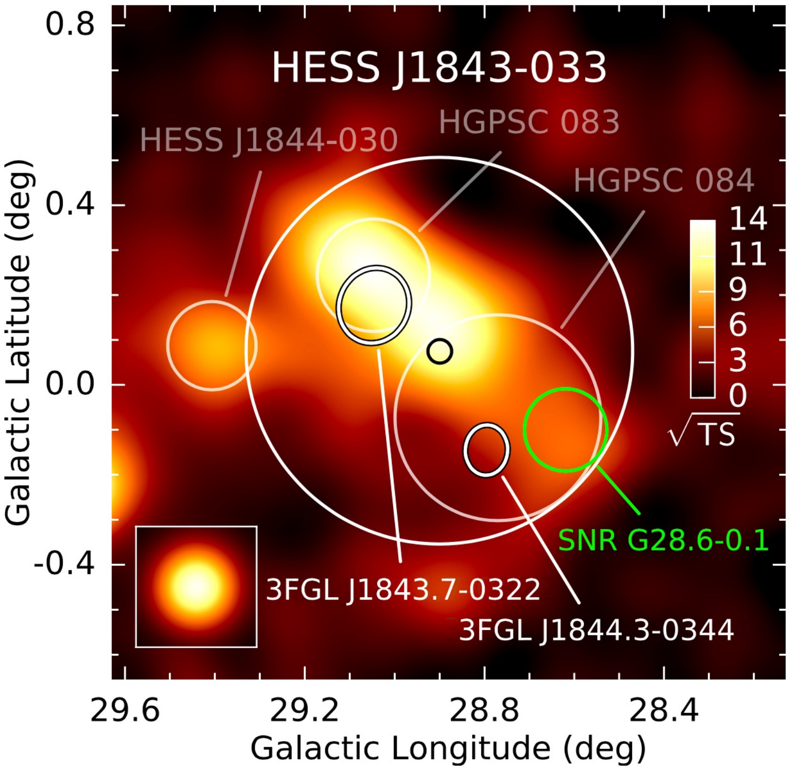


- ✓ Proton showers have few muons
  => Proton spectrum can be measured based on the cut using ΣN_μ
- ✓ Systematic errors of the spectrum is evaluated w/ an MC simulation :
  1 : Chemical composition (~10%)
  2 : Hadronic interaction (~30%)

“Measurement of the Gamma-Ray Energy Spectrum beyond 100 TeV from the HESS J1843-033 Region”, Amenomori et al., ApJ 932,120(2022)

HESS J1843-033

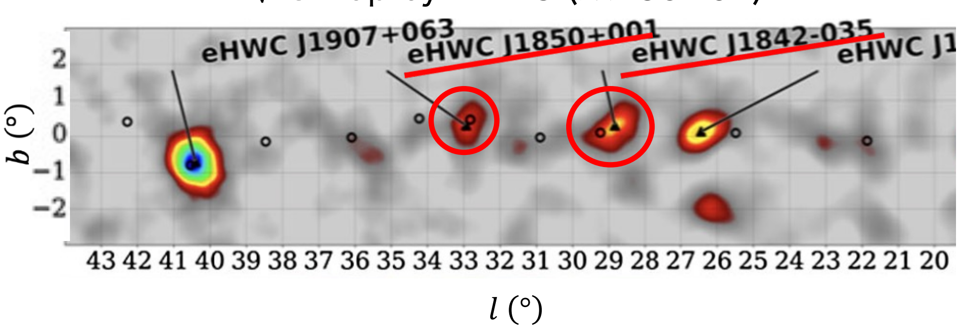
$\sqrt{TS}$ map by H.E.S.S. (E > 400GeV)[2]



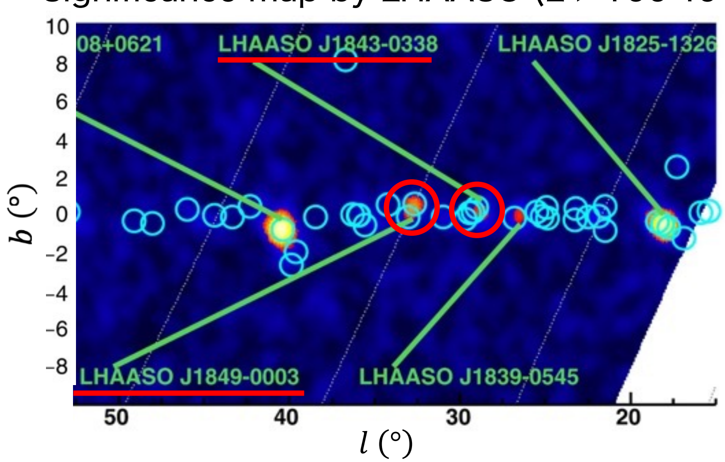
- ✓Detected by H.E.S.S.[1,2]
- ✓Unidentified src.
- ✓Nearby objects：SNR G28.6-0.1 & PSR J1844-0346
- ✓The spectrum is measured in E < 30TeV[2]
- ✓Sub-PeV spectrum is not measured
- ✓Nearby src.s detected by HAWC & LHAASO[3,4]

1. Hoppe, S. 2008, ICRC (Mérida), 30, 579
2. H.E.S.S. Collaboration, A&A 612, A1 (2018)
3. Abeysekara+, PRL 124, 021102 (2020)
4. Cao+, Nature 594, 33 (2021)

$\sqrt{TS}$ map by HAWC (E > 56 TeV)[3]

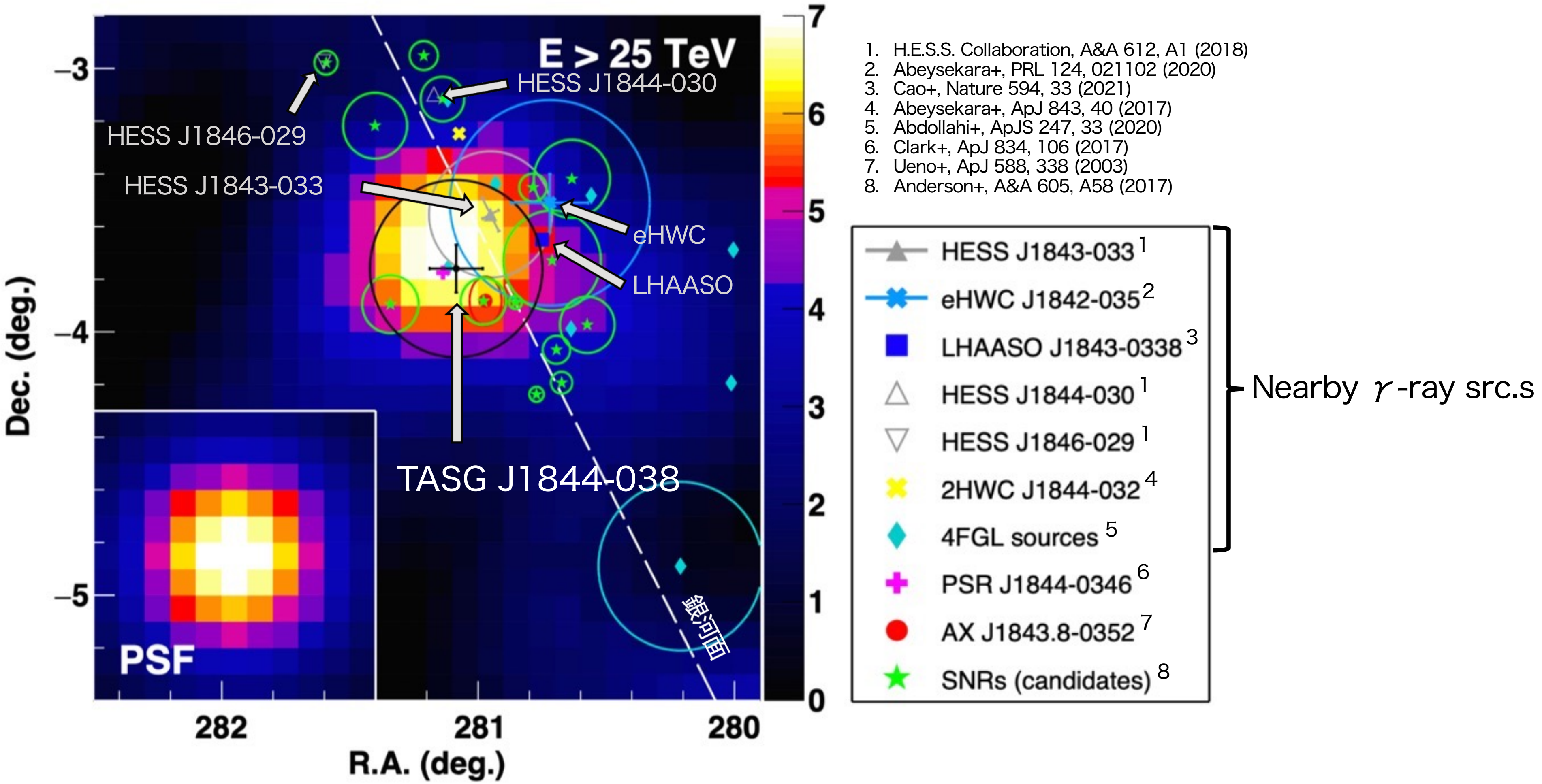


Significance map by LHAASO (E > 100 TeV)[4]



Detection of a New γ-Ray Src. TASG J1844-038

Significance map of the ROI
(smoothed w/ the PSF)



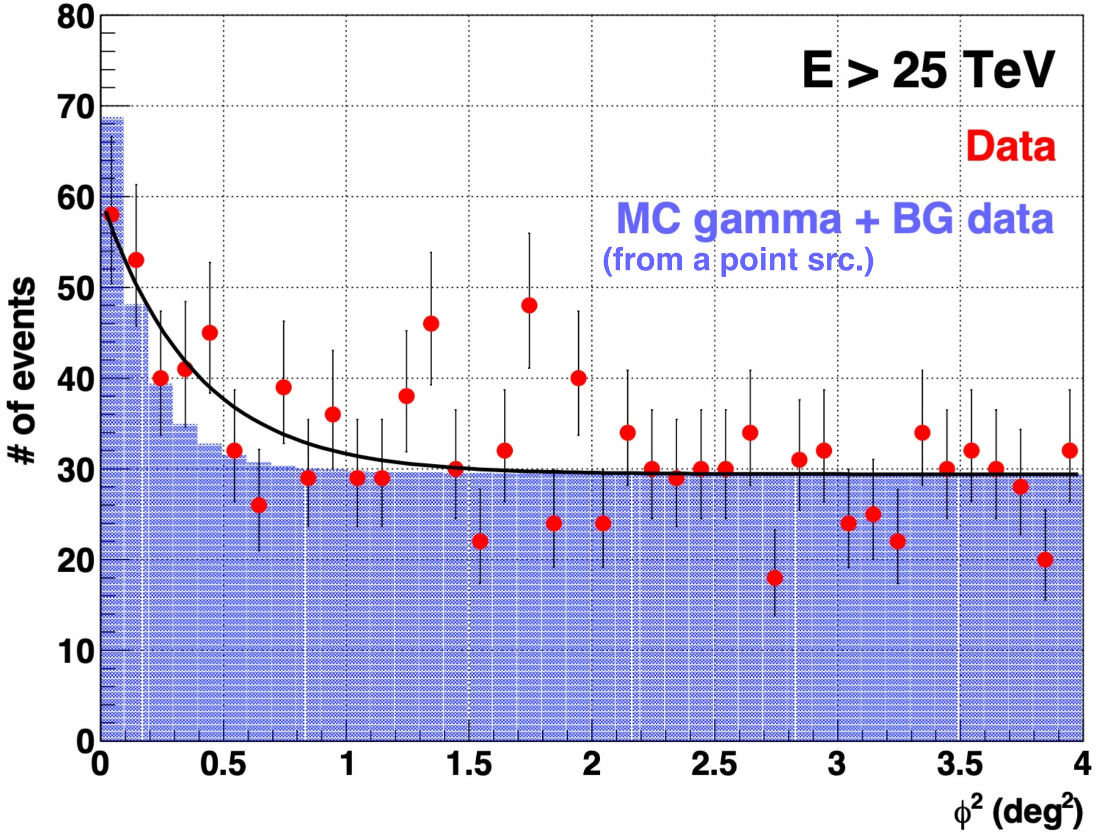
1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, PRL 124, 021102 (2020)
3. Cao+, Nature 594, 33 (2021)
4. Abeysekara+, ApJ 843, 40 (2017)
5. Abdollahi+, ApJS 247, 33 (2020)
6. Clark+, ApJ 834, 106 (2017)
7. Ueno+, ApJ 588, 338 (2003)
8. Anderson+, A&A 605, A58 (2017)

✓ TASG J1844-038 is detected (6.2σ @ E > 25TeV) near HESS J1843-033

✓ The src. position is ：(α, δ) = $(281.09^\circ \pm 0.10^\circ_{stat}, -3.76^\circ \pm 0.09^\circ_{stat})$

✓ Positionally consistent w/ HESS J1843-033, eHWC J1842-035, & LHAASO J1843-0338

Extension of TASG J1844-038



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

ϕ: distance b/w the TASG J1844-038 position & the direction of each event

✓ A Gaussian is fitted to the distribution :

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

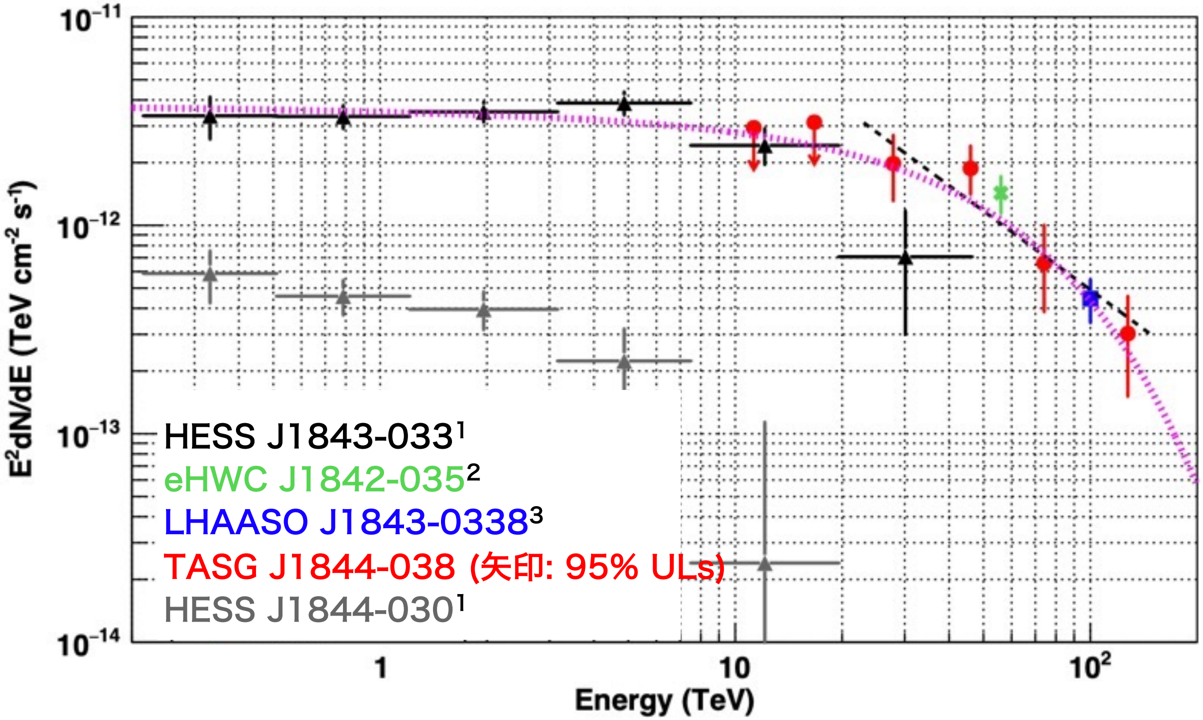
σ_{psf} = 0.28° : PSF radius
N_{bg} = 29.4 : # of BG events

=> Src. extension : σ_{ext} = 0.34° ± 0.12°

(χ^2 / d.o.f. = 39.5 / 38)

✓ The extension is consistent w/ HESS J1843-033 (0.24°±0.06°, E > 400 GeV)[1] & eHWC J1842-035 (0.39°±0.09°, E > 56 TeV)[2]

Energy Spectrum



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

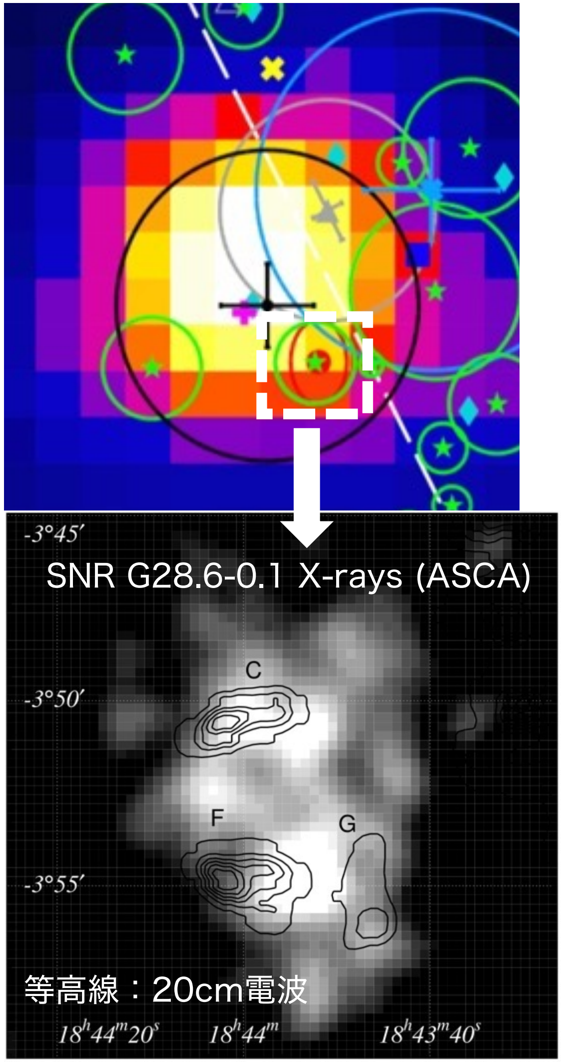
- ✓ The energy spectrum is **Measured in 25TeV<E<130TeV FTFT**
- ✓ Fitted w/ a PL function

$$\frac{dN}{dE} = (9.70 \pm 1.89)\times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-3.26\pm0.30} \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}} \quad (\chi^2/\mathrm{d.o.f.} = 2.1/2)$$

- ✓ The origin of the γ rays is common b/w TASG, HESS, eHWC & LHAASO?
- ✓ Fit of the PL + exponential cutoff to the spectra b/w TASG, HESS & LHAASO implies E_{cut} = 50TeV

$$\frac{dN}{dE} = (3.57 \pm 0.26)\times 10^{-12} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-2.02\pm0.06} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right) \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}} \quad (\chi^2/\mathrm{d.o.f.} = 10.4/8)$$

Discussion：Association w/ SNR G28.6-0.1



SNR G28.6-0.1

- ✓ Radio complex (@20 cm)[1]
- ✓ keV X-ray src AX J1843.8-0352[2] (non-thermal emission)
- ✓ 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…

- Parent electrons of the X- & γ rays should be the same if ICS off CMB works
- X- & γ-ray Extensions should thus be the same

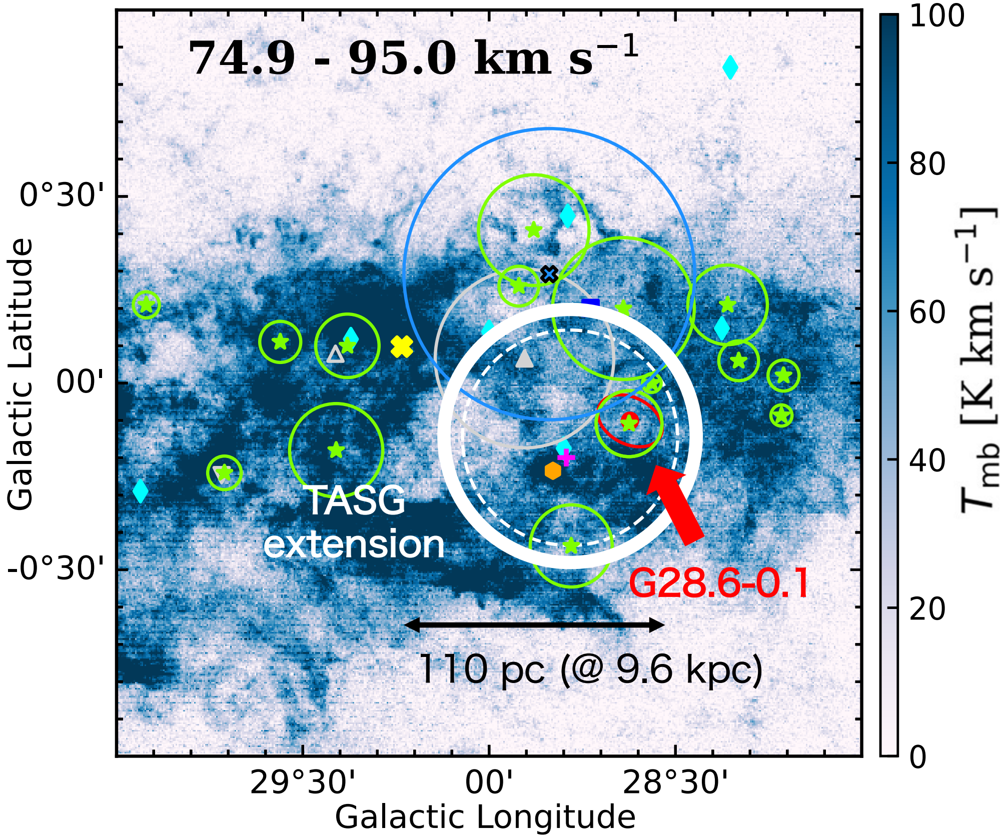
! Extension of γ-rays (0.34°±0.12°) is larger than the X-ray extension[3] (4.5’) at a 2.3σ level

Contribution to the γ-ray emission from hadrons??

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)

Discussion：Study of the Molecular-Cloud Distribution

Molecular clouds seen in ^{12}CO (J=1-0)



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

✓ G28.6-0.1 interacts w/ molecular clouds in the 86 km s^{-1} channel[1]

✓ radio archive data[2] of the Nobeyama observatory is analyzed in 75-95 km s^{-1}

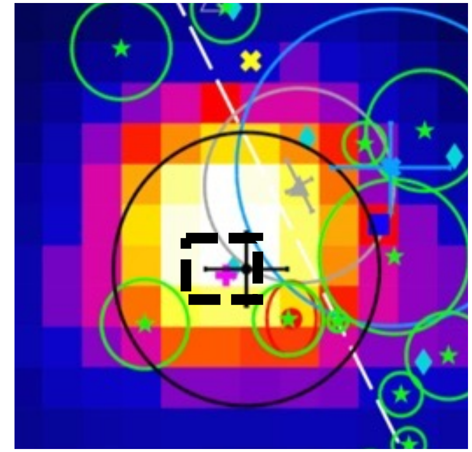
✓ Clouds w/ ~50 K km s^{-1} in the TASG src can provide n_p ~ 30 cm^{-3} @ 9.6 kpc

✓ Total CR energy to explain the γ-ray flux： $W_p(E > 1\,\mathrm{TeV}) \sim 6 \times 10^{49} \left(\frac{n_p}{10\,\mathrm{cm}^{-3}}\right)^{-1}$ erg can be covered by <10% of the energy released by an SNR (10^{51} erg)

✓ Maximum energy of CR protons：$E_{p,max}$ ~ 10 $E_{\gamma,max}$ = 500TeV

✓ SNR G28.6-0.1 can be a PeVatron candidate

Discussion : Association w/ PSR J1844-0346



PSR J1844-0346[1]

- ✓ γ-ray pulsar (3FGL J1844.3-0344[2], 4FGL J1844.4–0345[3])
- ✓ P = 113 ms, $E_{sp} = 4.2\times10^{36}$ erg s^{-1}, τ_c = 12 kyr
- ✓ Compact non-thermal X-rays from the magnetosphere[4]?
- ✓ No PWN-like radio & X-ray emission[5]
- ✓ Pseudo distance[6] : 4.3 kpc

? γ rays from the PWN of the PSR?

- ✓ ICS off CMB by electrons accelerated up to ~100 TeV?
- ✓ Total energy of electrons can be covered by ~10% of the E_{sp} if B ~ 3 μG[7]
- ✓ Characteristics of the TeV emission from HESS J1843-033 is very similar to those of TeV PWNs[8] assuming the 4.3 kpc distance

? No PWN-like radio & X-ray emission[5]

- Weak magnetic field??
- Low surface brightness??
- The emission is not of leptonic origin…??

=> Deep obs. in the radio & X-ray ranges & theoretical studies required

1. Clark+, ApJ 834, 106 (2017)
2. Acero+, ApJS 218, 23 (2015)
3. Abdollahi+, ApJS 247, 33 (2020)
4. Dmitry+, MNRAS 476, 2177 (2018)
5. Devin+, A&A 647, A68 (2021)
6. Parkinson+, ApJ 725, 571 (2010)
7. Sudoh+, JCAP08(2021)010
8. H.E.S.S. Collaboration, A&A 612, A2 (2018)

Summary

- ✓ Sky region around HESS J1843-033 is observed by the Tibet AS array & the MD array
- ✓ A new γ-ray src. TASG J1844-038 is detected a 6.2σ level @ E > 25TeV
- ✓ Src. position : (α, δ) = (281.09°±0.10°$_{stat}$, -3.76°±0.09°$_{stat}$)
- ✓ Src. extension : 0.34° ± 0.12°
- ✓ Energy spectrum is measured b/w 25TeV < E < 130TeV for the first time :

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (9.70 \pm 1.89) \times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-3.26 \pm 0.30} \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}}$$

- ✓ Src. association w/ SNR G28.6-0.1 :

  CRs accelerated by the SNR up to ~ 500TeV interact w/ molecular clouds w/ 50 K km s^{-1} producing the observed γ rays?

- ✓ Src. association w/ PSR J1844-0346 :

  Electrons accelerated by the PWN of the PSR up to ~ 100TeV produce the γ rays through ICS off CMB?

- ✓ Deep X-ray & radio observations are needed