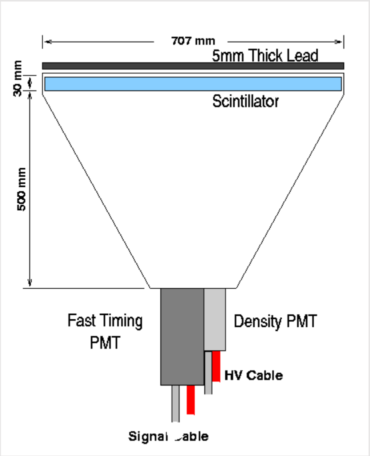
チベット空気シャワーアレイを用いた超高エネルギーガンマ線観測の解析結果報告

加藤勢 for the Tibet ASγ collaboration

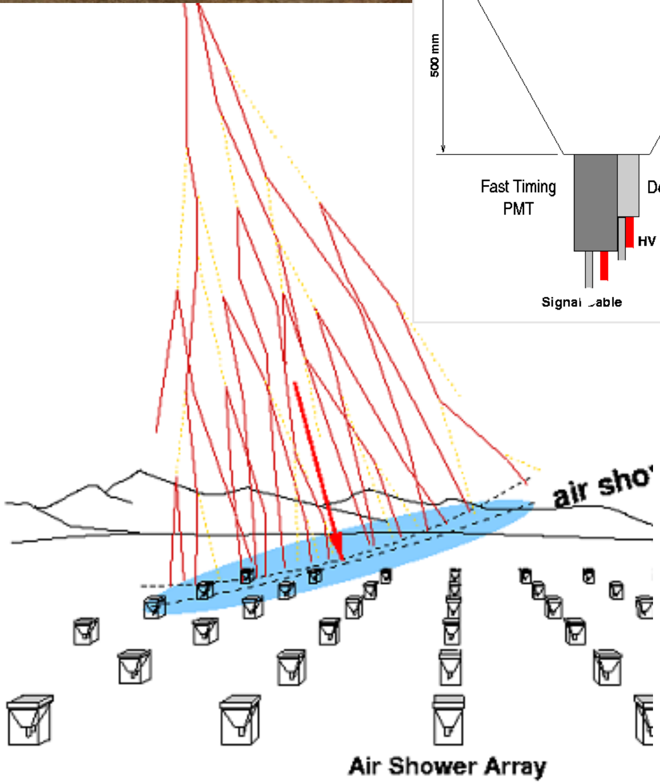
Tibet Air Shower Array



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

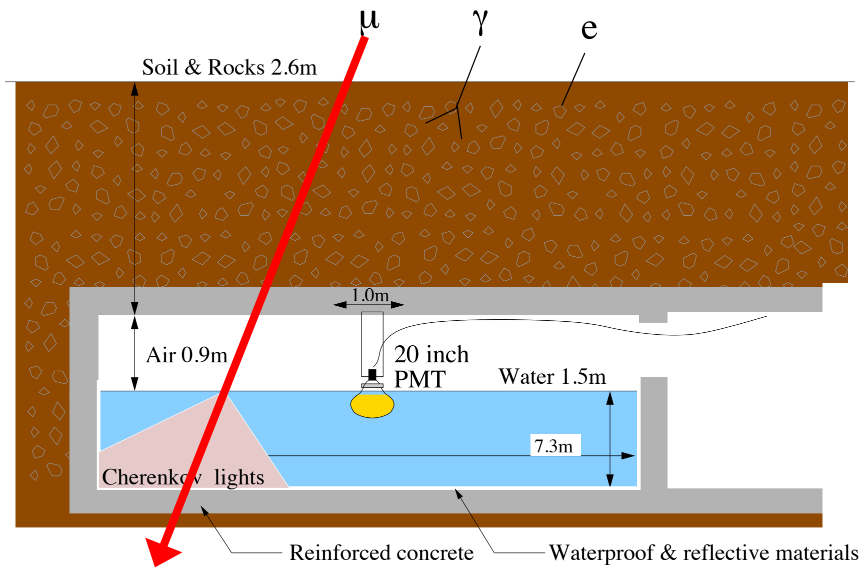
scintillation counters	0.5 m^2 x 597
area	~65,700 m^2
angular resolution	~0.5°@10TeV
	~0.2°@100TeV
energy resolution	~40%@10TeV
	~20%@100TeV

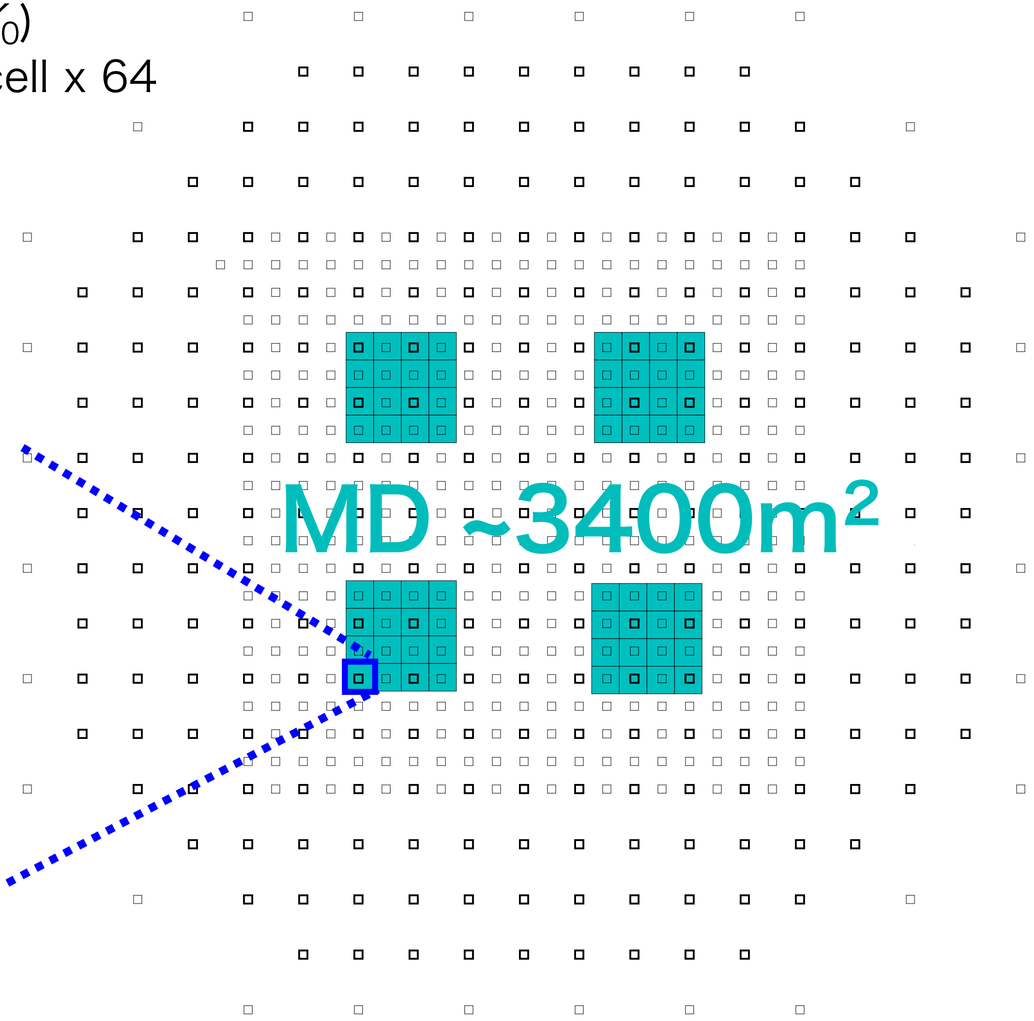
2nd particles timing ➡ arrival direction
2nd particles energy deposit ➡ primary energy



Water Cherenkov Muon Detector Array

- ✓ 2.4m underground (515g/cm^2 ~19X_0)
- ✓ 7.35m x 7.35m x 1.5m-deep water cell x 64
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + Tyvek sheets





Measurement of number of muons in air showers
➡ γ／CR discrimination

The Tibet ASγ Collaboration

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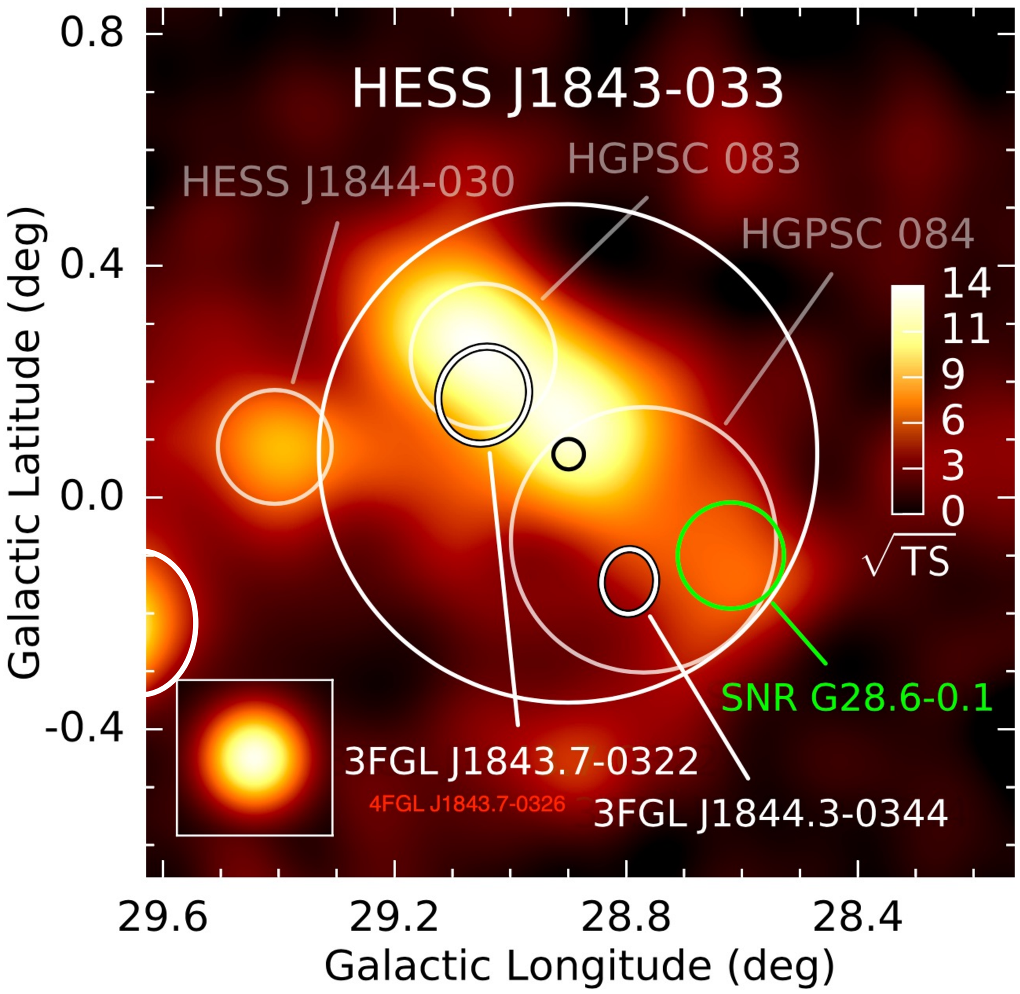
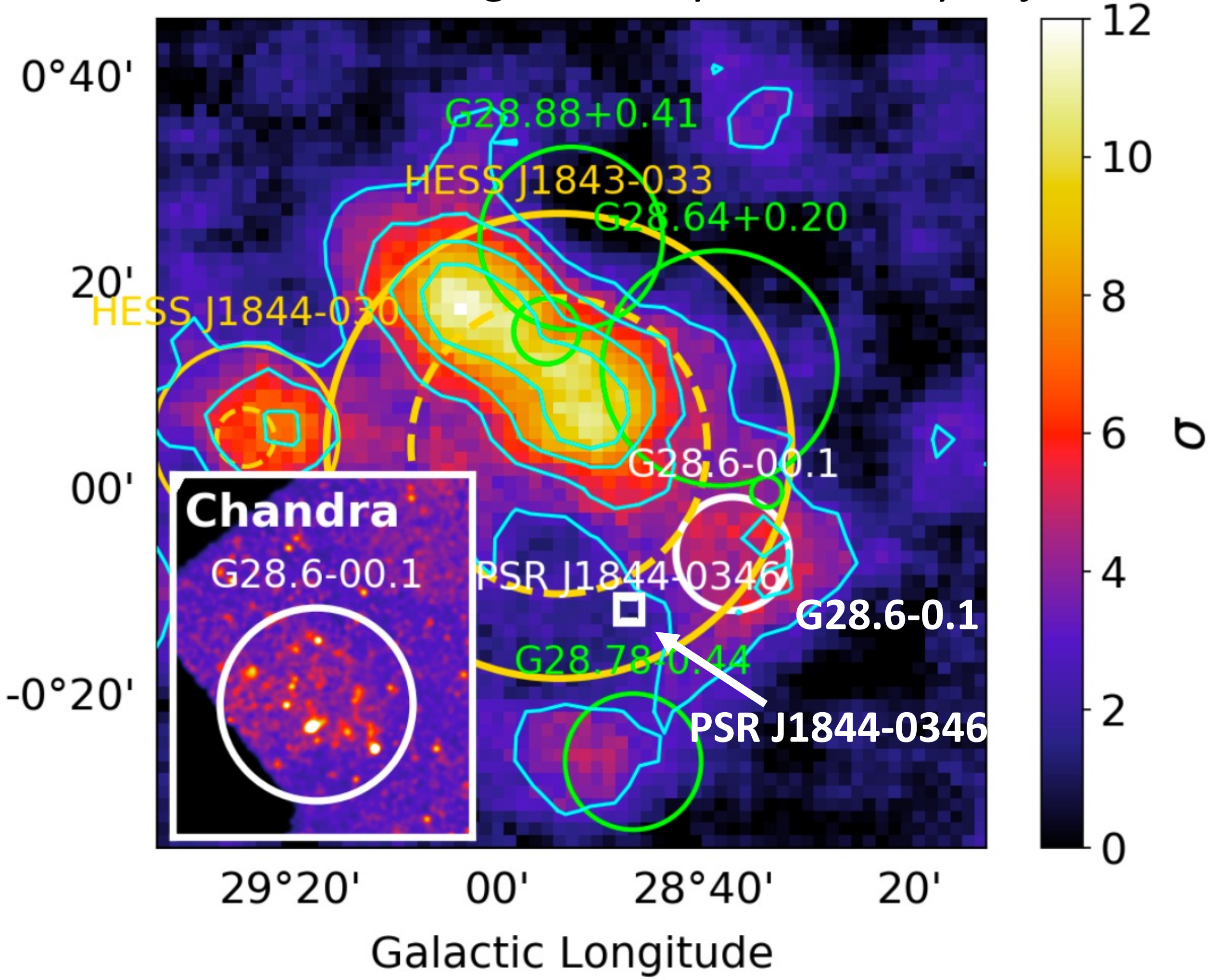
UNID TeV gamma-ray source HESS J1843-033

H.E.S.S. Galactic plane survey



HESS collaboration, A&A 612, A1 (2018)

Contour of TeV gamma rays w/ nearby objects



J. Devin et al., A&A 647, A68 (2021)

*

- Origin of the gamma-ray emission is not established
- eHWC J1842-035* & LHAASO J1843-0338** are also discovered near HESS J1843-033
- Energy spectrum in E > 30 TeV is not drawn yet

*A. U. Abeysekara et al., PRL 124, 021102 (2020)
**Z. Cao et al., Nature, 594, 33 (2021)

Analysis of gamma rays from the HESS J1843-033 region

- Data taken from 2014 February to 2017 May (719 live days) is used

- Event selection criteria: the same as Amenomori et al., PRL 123, 051101 (2019) expect that

  1. zenith < 50 deg to improve statistics because the meridian zenith of HESS J1843-033 is ~= 33 deg at the Tibet site, &

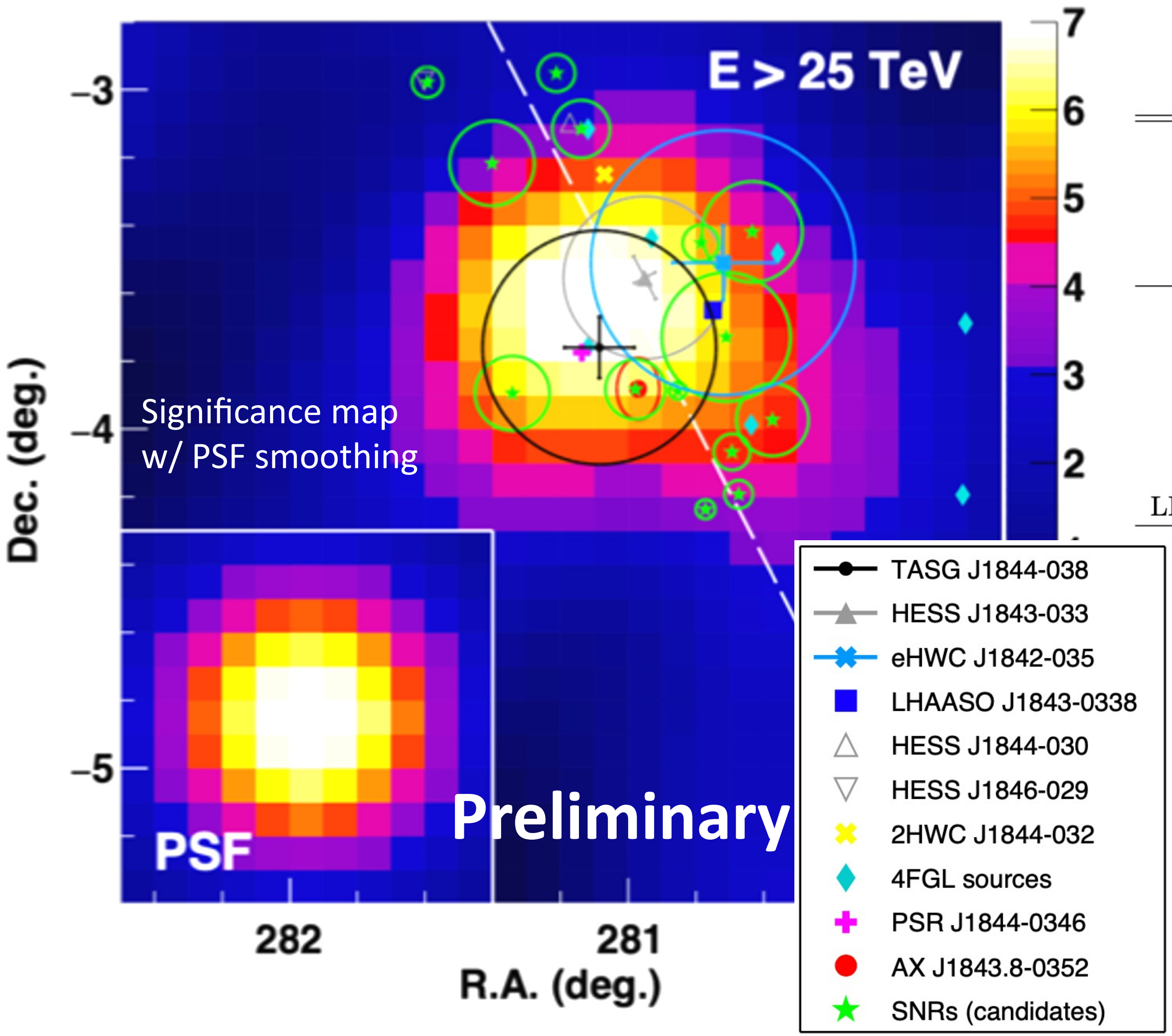
  2. MD cut: $\Sigma N\mu < 1.8\times10^{-3} (\Sigma\rho/m^{-2})^{1.1}$ or $\Sigma N\mu < 0.4$ (optimized for this analysis)

  ($\Sigma\rho$: Sum of # density recorded by each detectors of the AS array)

- # of events after the selection: $\sim 1.4\times10^{7}$ events

Results (1): Source detection (6.2 σ above 25 TeV)

Cross: positional uncertainty of a src
Circle: extension of a src



Source name: TASG J1844-038

Src center:

$$(\alpha,\, \delta) = (281.^\circ09 \pm 0.^\circ10,\, -3.^\circ76 \pm 0.^\circ09)$$

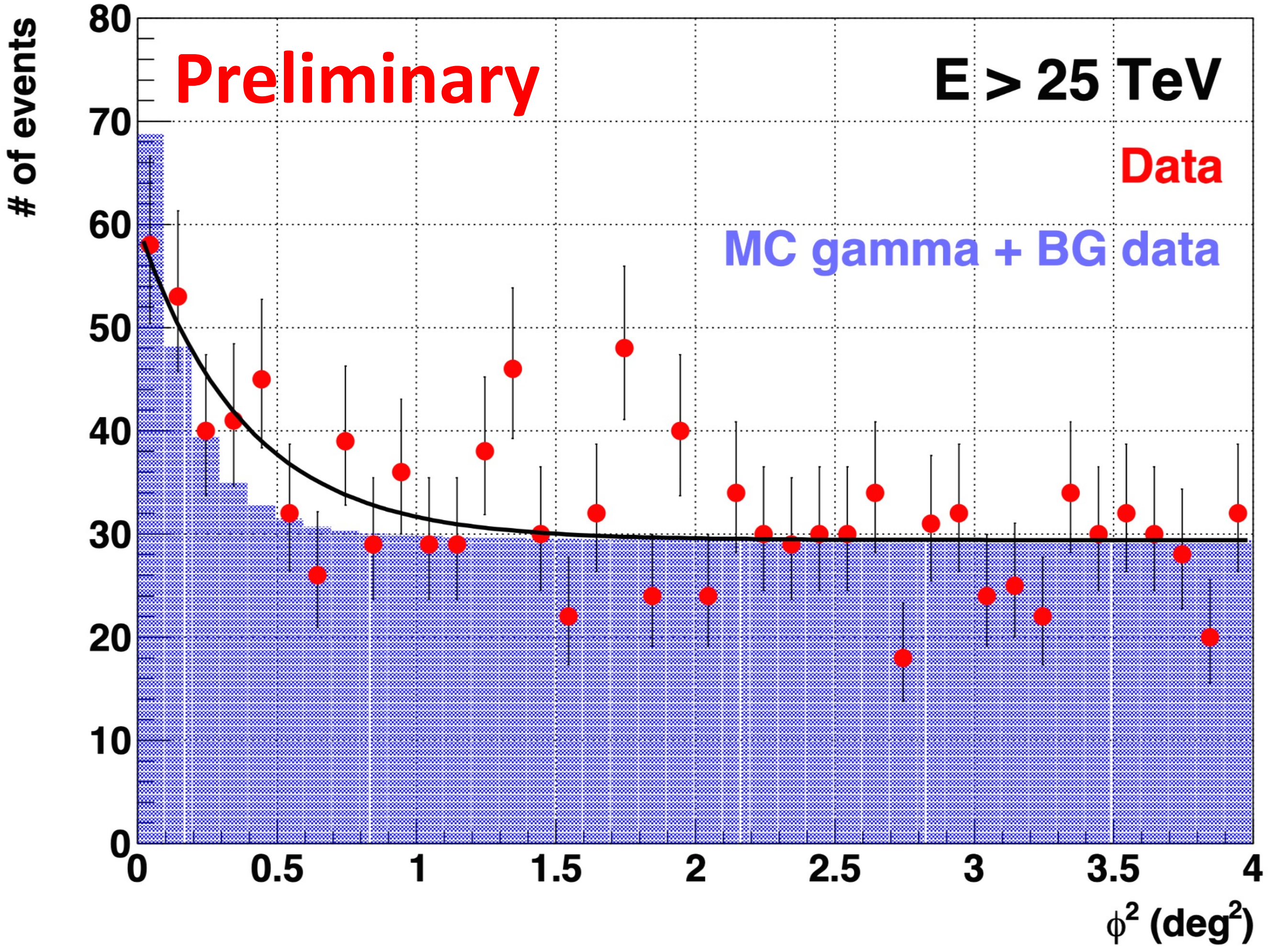
Source name	$\alpha(^\circ)$	$\delta(^\circ)$	$R_{0.68}$ †$(^\circ)$	Extension $(^\circ)$	Angular distance to TASG J1844-038 $(^\circ)$
TASG J1844-038	281.09	−3.76	0.21	0.35 ± 0.11	-
HESS J1843-033	280.95	−3.55	0.12	0.24 ± 0.06	0.25 $(1.0\,\sigma)$
HESS J1844-030	281.17	−3.10	0.023	0.02 ± 0.013	0.67 $(3.2\,\sigma)$
HESS J1846-029	281.60	−2.97	0.015	0.01 ± 0.013	0.94 $(4.5\,\sigma)$
eHWC J1842-035	280.72	−3.51	0.30	0.39 ± 0.09	0.44 $(1.2\,\sigma)$
LHAASO J1843-0338	280.75	−3.65	0.16	-*	0.35 $(1.4\,\sigma)$

† For $R_{0.68}$, see HESS collaboration, A&A 612, A1 (2018)
* The source extension is not published

- The position of TASG J1844-038 is consistent w/ those of HESS J1843-033, eHWC J1842-035, & LHAASO J1843-0338
- On the other hand, TASG J1844-038 seems to deviate from HESS J1844-030 & HESS J1846-029

Results (2): ϕ^2 distribution

$\phi2$: The square of the angle between the center of TASG J1844-038 and the event direction



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

where σ_{psf} = 0.27°: PSF radius &

N_{bg} = 29.4: # of BG

$\Rightarrow$ A = 30.5 ± 8.5

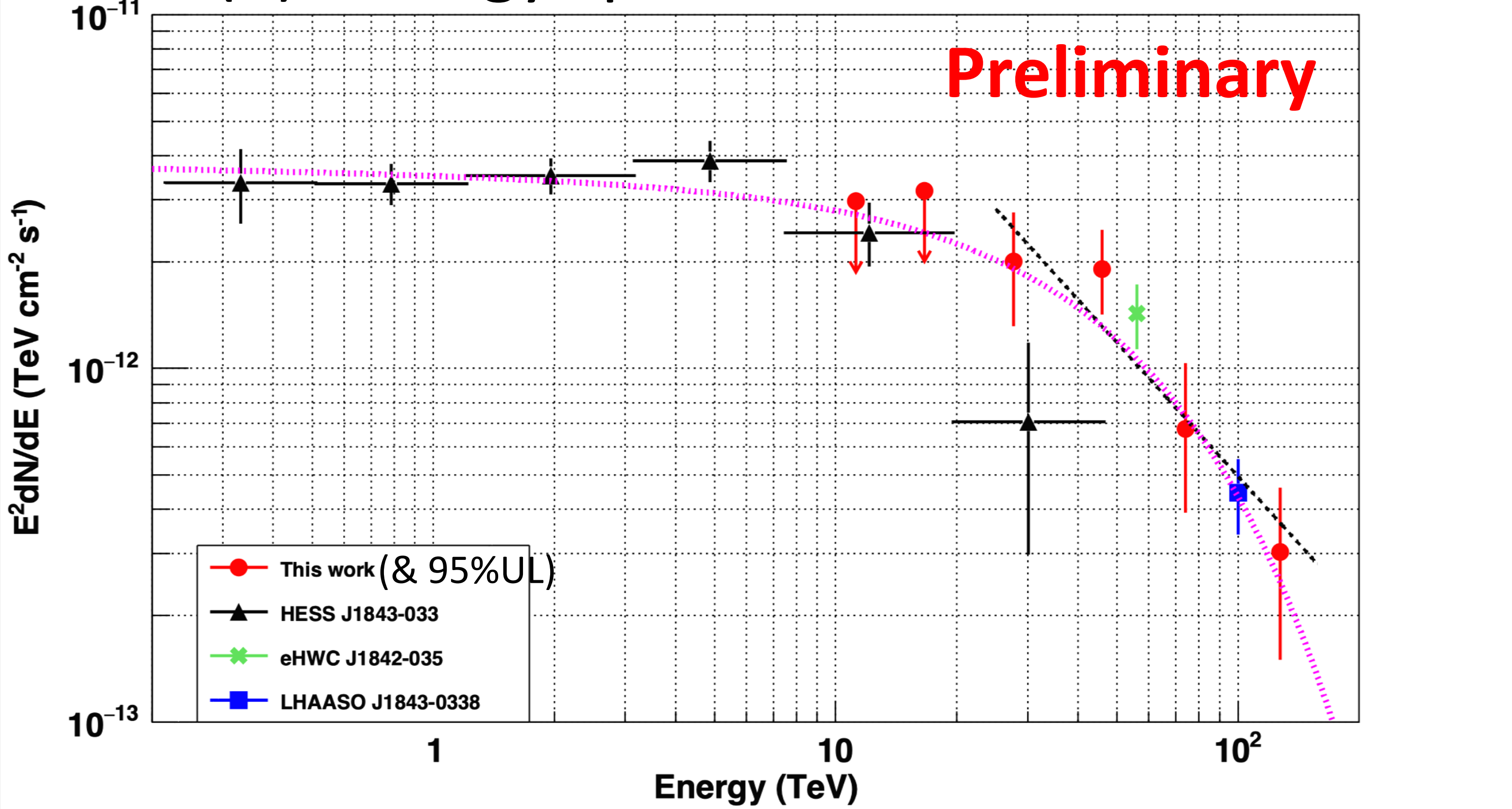
σ_{ext} = 0.35° ± 0.11° (χ^2 / d.o.f. = 39.5 / 38)

Consistent w/

HESS J1843-033: 0.24° ± 0.06° (E > 400 GeV)

eHWC J1842-035: 0.39° ± 0.09° (E > 56 TeV)

Results (3): Energy spectrum



* Simple PL fit to the combined spectra is rejected at the 5.0 σ level (χ^2/d.o.f. = 47.3/9)

- Black dashed line (best-fit PL for this work in 25TeV < E < 130TeV):

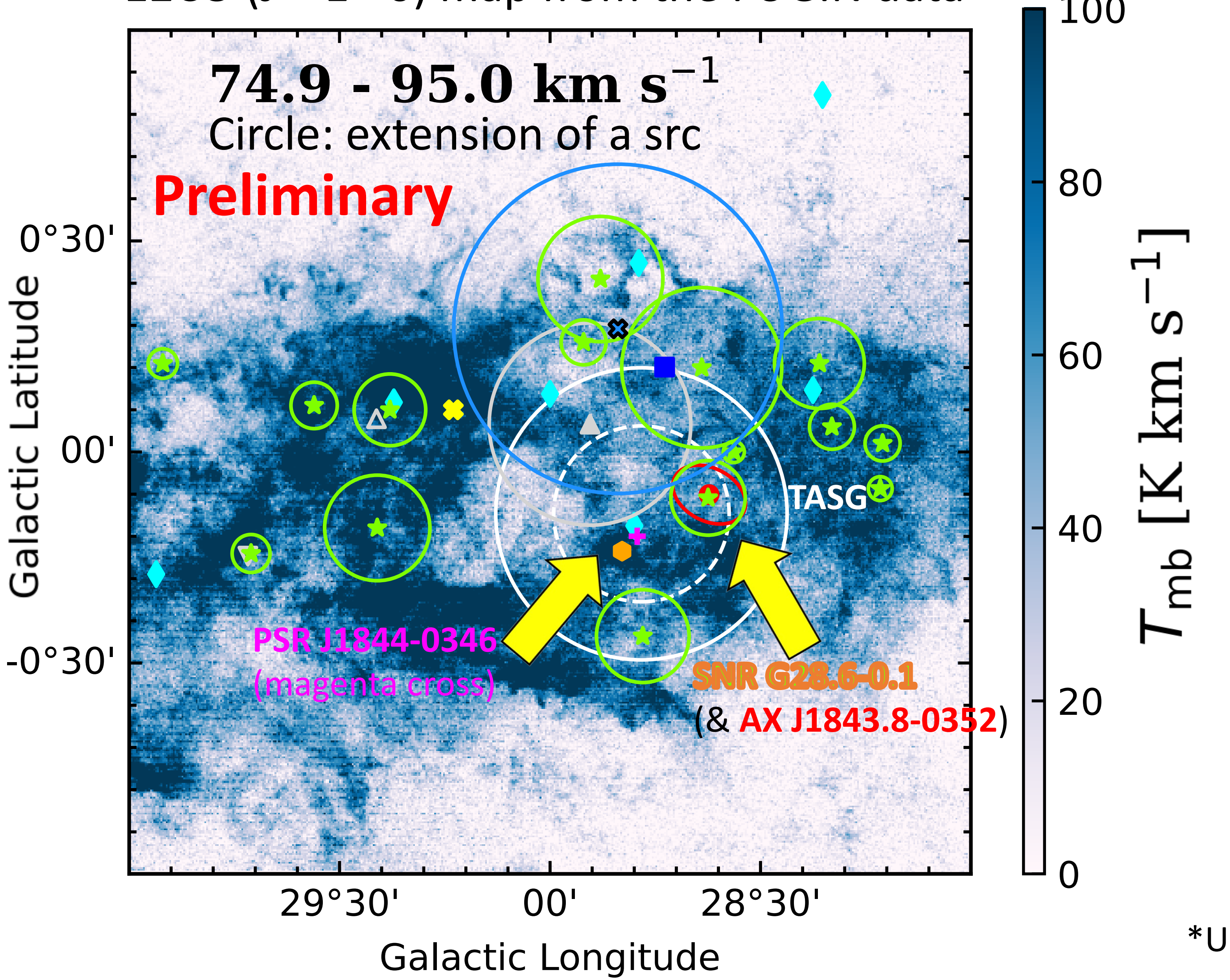
$$\frac{dN}{dE} = (9.78 \pm 1.91)\times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-3.26\pm 0.30}\ \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}} \quad (\chi^2/\mathrm{d.o.f.} = 2.2/2)$$

- Magenta dotted curve: ECPL fit to the combined spectra of H.E.S.S., LHASSO, & Tibet*:

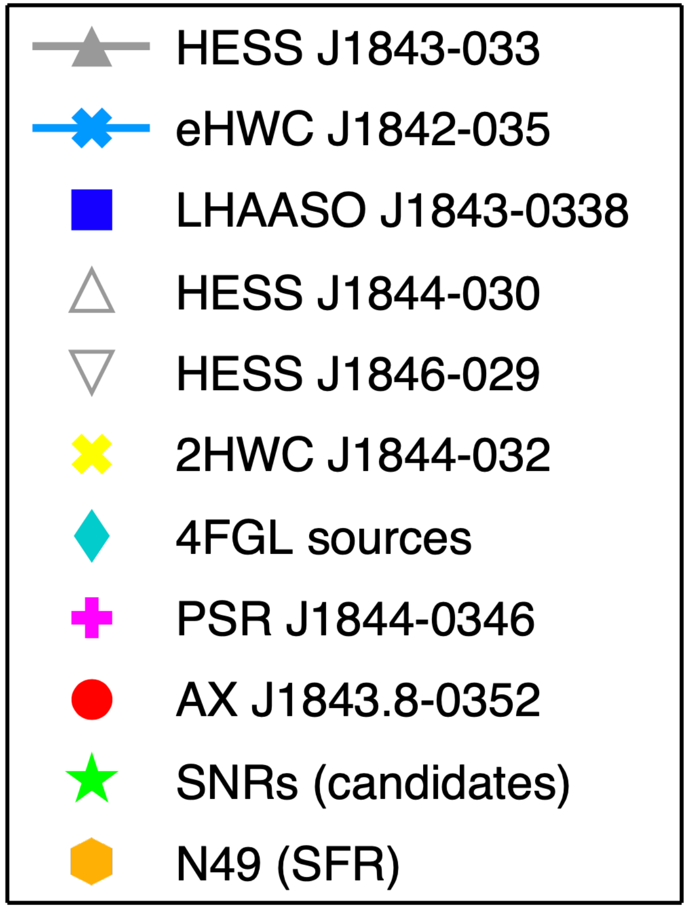
$$\frac{dN}{dE} = N_0 \left(\frac{E}{\mathrm{TeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right) \quad \text{with} \quad N_0 = (3.57 \pm 0.26)\times 10^{-12}\ \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}},$$
$$\Gamma = 2.02 \pm 0.06,\ \&\ E_{\mathrm{cut}} = 49.5 \pm 9.0\ \mathrm{TeV}\ (\chi^2/\mathrm{d.o.f.} = 10.5/8)$$

Discussion (1): Association w/ nearby sources

12CO (J = 1 - 0) map from the FUGIN data*



Solid white: extension of TASG J1844-038
Dashed white: positional unc. (68% C.L.)



*Umemoto et al., PASJ 69, 78 (2017)

Discussion (1): Association w/ SNR G28.6-0.1 (1)

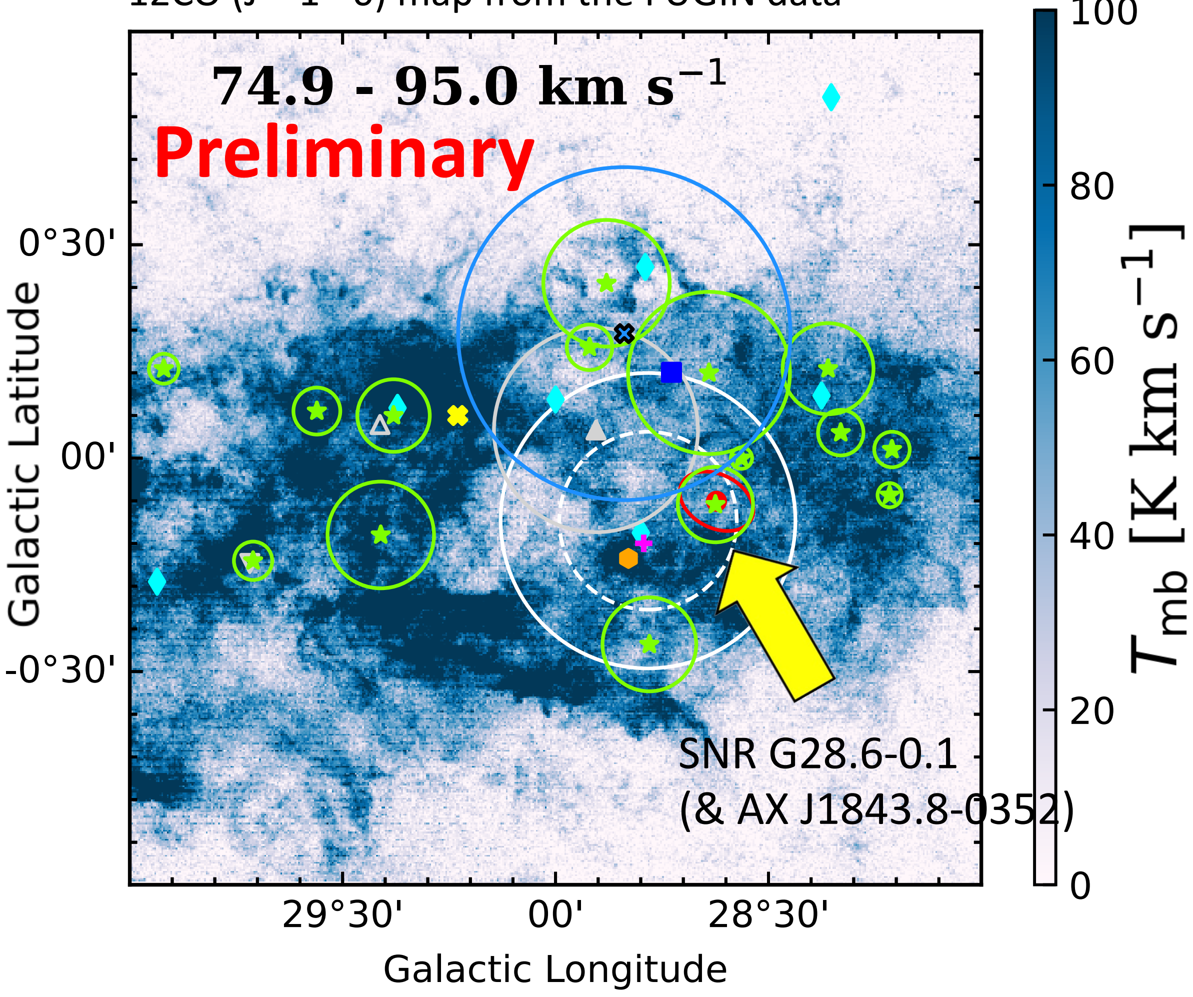
- SNR G28.6-0.1
  - Radio C/P: regions C & F of a radio complex G28.60-0.13 (Helfand et al., ApJ 341, 15, 1989)
  - X-ray C/P: AX J1843.8-0352 (Bamba et al., PASJ 53, 21, 2001)
    => Synchrotron emission by HE electrons accelerated by a shell-type SNR
  - Distance: 9.6±0.3 kpc (Ranasinghe & Leahy, MNRAS 477, 2243, 2018)
  - Age: 2.7 kyr (Bamba et al. 2001) or 19 kyr (Ranasinghe & Leahy 2018)

- Size of TASG J1844-038 (radius of 0.35°±0.11°) is larger than that of AX J1843.8-0352 (mean diameter of 9' *) at the 2.5 σ level *Ueno et al., ApJ 588, 338 (2003)

  ⇒ If the association b/w TASG J1844-038 and SNR G28.6-0.1 is assumed, this possible discrepancy suggests the contribution of gamma rays of hadronic origin
  (because extension of gamma- & X-ray sources should be the same if the both are of leptonic origin)

Discussion (1): Association w/ SNR G28.6-0.1 (2)

12CO (J = 1 - 0) map from the FUGIN data



1. MCs overlapped w/ TASG J1844-038
2. Max. energy of accelerated protons: ≃ 500TeV
3. Average of the estimated ages is ≃ 10 kyr

=> Similar system to a PeVatron candidate G106.3+2.7*
Could have been a PeVatron in the past ??

Calculation of the diffusion time of CR protons:

$$\tau_{diff}^{**} = \frac{R_{cl}^2}{6D(E)} \sim 1.2 \cdot 10^4 \chi^{-1} \left(\frac{R_{tot}}{20\ \mathrm{pc}}\right)^2 \left(\frac{E}{\mathrm{GeV}}\right)^{-0.5} \left(\frac{B}{10\ \mu\mathrm{G}}\right)^{0.5} \mathrm{yr}$$

=> $\tau_{diff}\,(R = \text{TASG J1844–038}, E > 250\ \text{TeV}) \lesssim 2.0\ \text{kyr}$

$\tau_{diff}\,(R = \text{HESS J1843–033}, E \simeq 10\ \text{TeV}) \simeq 4.9\ \text{kyr}$

(assuming χ=0.1 & B = 10μG)

*Amenomori et al., Nature Astron. 5, 460 (2021) **Gabici et al., Astrophys Space Sci 309, 365 (2007)

Discussion (2): Association w/ PSR J1844-0346

- PSR J1844-0346
  - Gamma-ray pulsar discovered by Einstein@home project (Clark et al. ApJ 834, 106 (2017))
  - $P = 113$ ms, $\tau_c = 12$ kyr, $\dot{E} = 4.2\times10^{36}$ erg s^{-1}, & $B_s = 4.2\times10^{12}$ G
  - Pseudo distance: 4.3 kpc (Devin et al., A&A 647, A68 (2021))

- HESS J1843-033
  - Energy Flux(1–10TeV) $= 1.1\times10^{-11}$ erg cm^{-2}s^{-1} (HESS collaboration, A&A 612, A1 (2018))

    => Luminosity(1-10TeV) $= 2.4\times10^{34}$ erg s^{-1}
  - Size: $\backsimeq$ 18 pc
  - Spectral index of $\simeq 2.0$ (from the ECPL fit)

  $\Rightarrow$ Similar to the properties of typical TeV pulsar wind nebulae (HESS collaboration A&A 612, A2 (2018))

- ICS off CMB is plausible ?
  - Energy of parent electrons for gamma rays w/ ≈ 50 TeV: ≈ 90 TeV
  - Diffusion coefficient: assuming one in the Geminga environment (Abeysekara et al., Science 358, 911(2017)),

    $D(E = 90\ \mathrm{TeV}, B = 3\mu\mathrm{G}) = 4.4\times10^{27}\ \mathrm{cm^2\ s^{-1}}$ => $\tau_{\mathrm{diff}}(E = 90\ \mathrm{TeV}) \backsimeq 7.8$ kyr
  - Cooling time by sync. w/ B = 3 μG & ICS off CMB: $\tau_{\mathrm{cool}}(E = 90\ \mathrm{TeV}) \backsimeq 11$ kyr

  => Naturally explain the extension of TASG J1844-038

Summary

- Gamma rays from the HESS J1843-033 region is observed by the Tibet air shower array
- Detection of TASG J1844-038 above 25 TeV w/ a 6.2 σ level
  - Position $(\alpha, \delta) = (281.^\circ09 \pm 0.^\circ10, -3.^\circ76 \pm 0.^\circ09)$ consistent w/ HESS J1843-033, eHWC J1842-035, & LHAASO J1843-0338
  - Extension 0.35° ± 0.11°
- Energy spectrum is measured in 25 TeV < E < 130 TeV for the 1st time:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (9.78 \pm 1.91) \times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-3.26 \pm 0.30} \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

  - Cutoff @ 49.5 ± 9.0 TeV in the combined spectra of HESS J1843-033, LHAASO J1843-0338, & TASG J1844-038
- Possible association w/ SNR G28.6-0.1 or PSR J1844-0346
  - If SNR G28.6-0.1 is assumed to be the counterpart,
    - Contribution from π^0-decay gamma rays from CR protons w/ $E \lesssim 500$ TeV accelerated by the SNR & interacting w/ the adjacent MCs ?

    => Could have been a PeVatron in the past (note some similarities w/ SNR G106.3+2.7)
  - If PSR J1844-0346 is assumed to be the counterpart,
    - emission from a TeV PWN generated by ICS off CMB by electrons w/ $E_e \lesssim 90$ TeV ?

The research is submitted to *Astrophysical Journal Letters* last week