Observation of multi-ten TeV to sub-PeV gamma rays from the HESS J1843-033 region with the Tibet air shower array

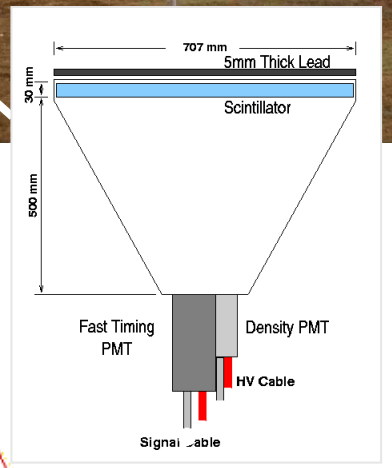
Kato Sei (ICRR) for the Tibet ASγ collaboration

This presentation is based on

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

(https://doi.org/10.3847/1538-4357/ac6ef4)

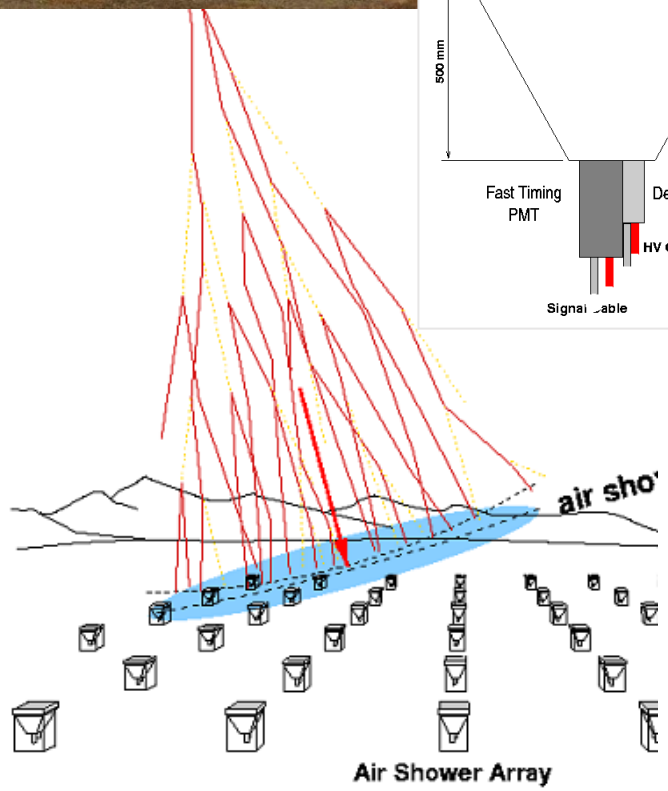
Tibet Air Shower Array



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

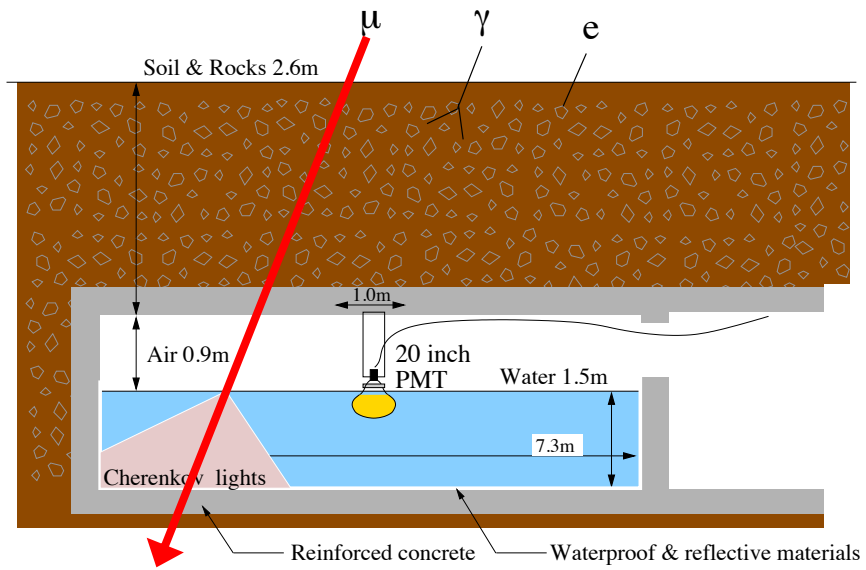
- scintillation counters 0.5 m² x 597
- area ~65,700 m²
- angular resolution (gamma rays) ~0.5° @ 10TeV
  ~0.2° @ 100TeV
- energy resolution (gamma rays) ~40% @ 10TeV
  ~20% @ 100TeV

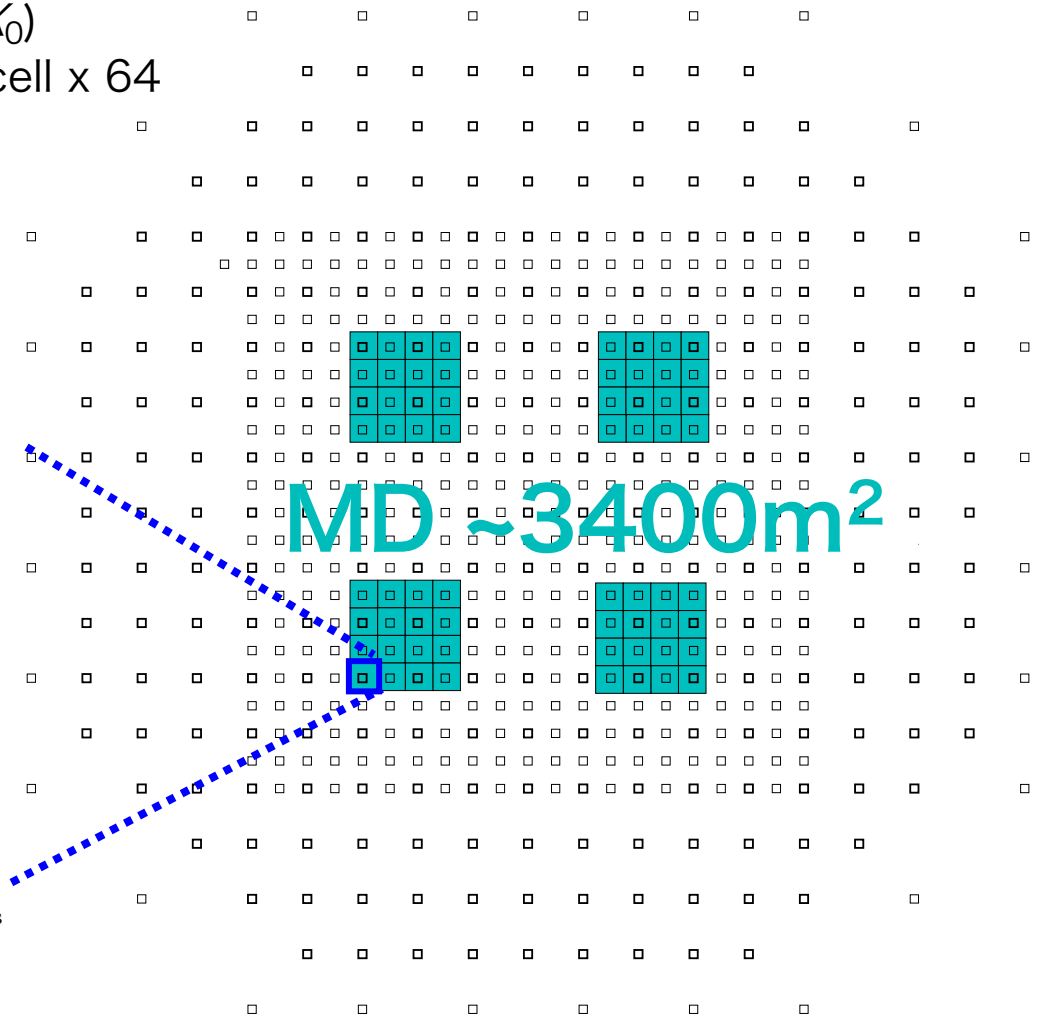
2nd particles timing ➡ arrival direction
2nd particles energy deposit ➡ primary energy



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

Tibet ASγ Collaboration

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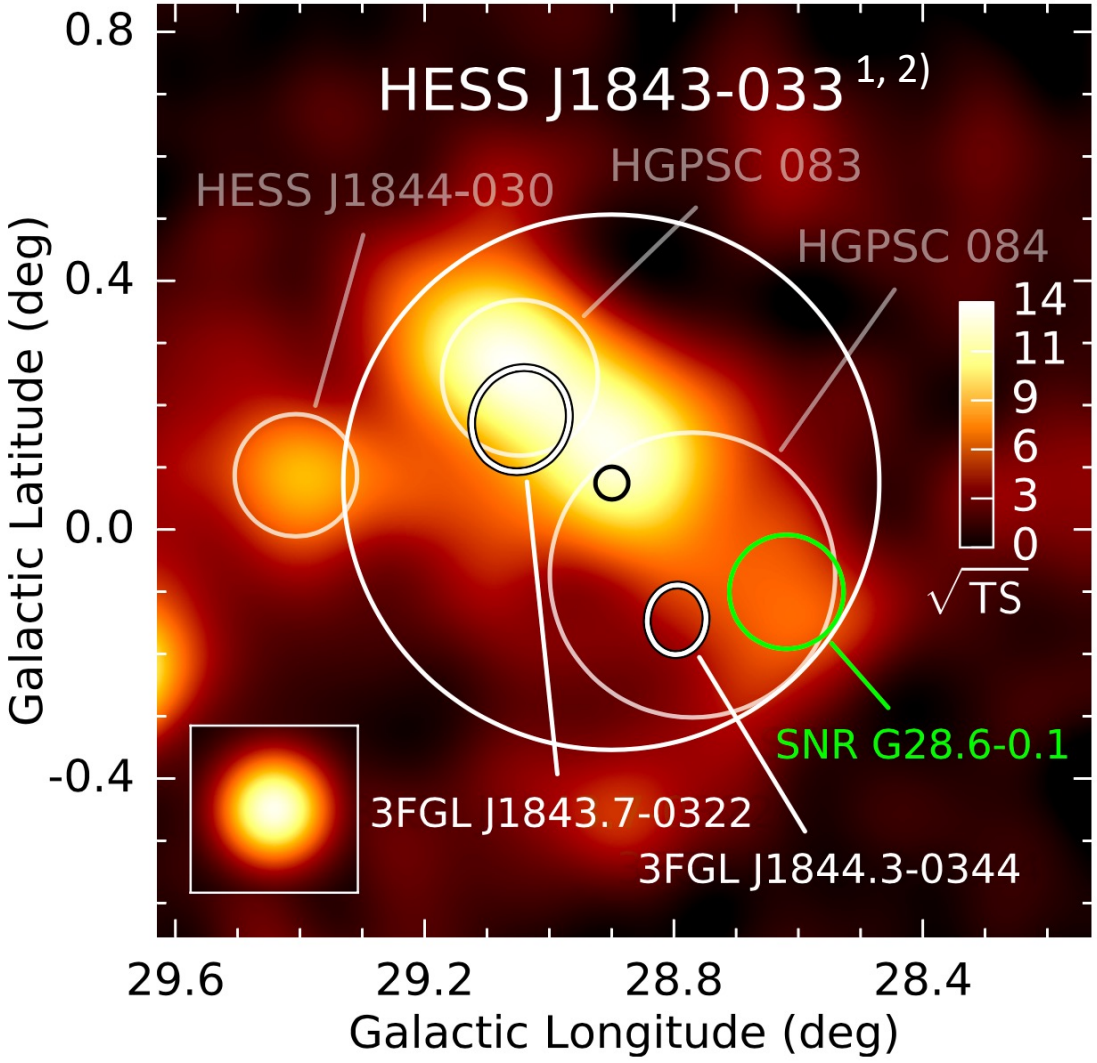
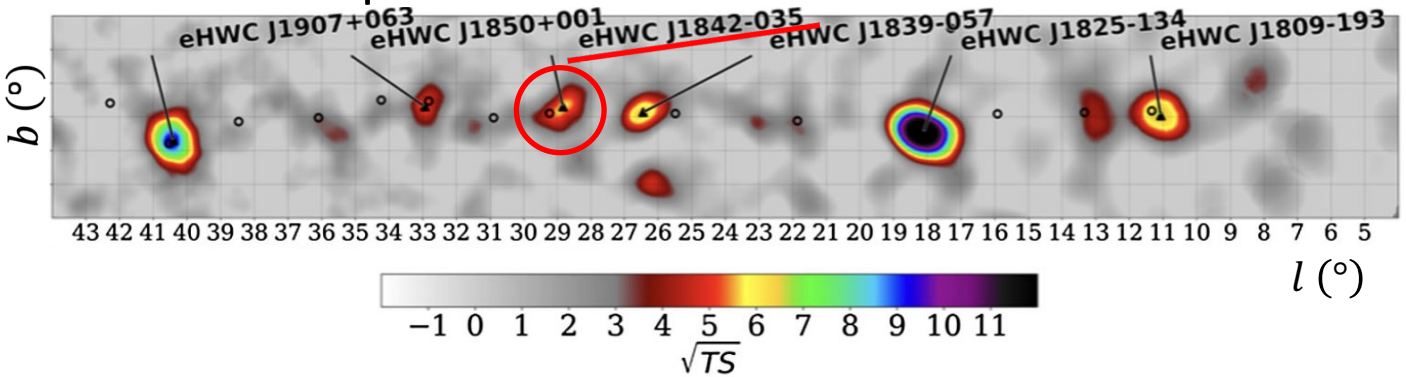
HESS J1843-033: Unidentified TeV gamma-ray source



HAWC TS map above E > 56 TeV[3]



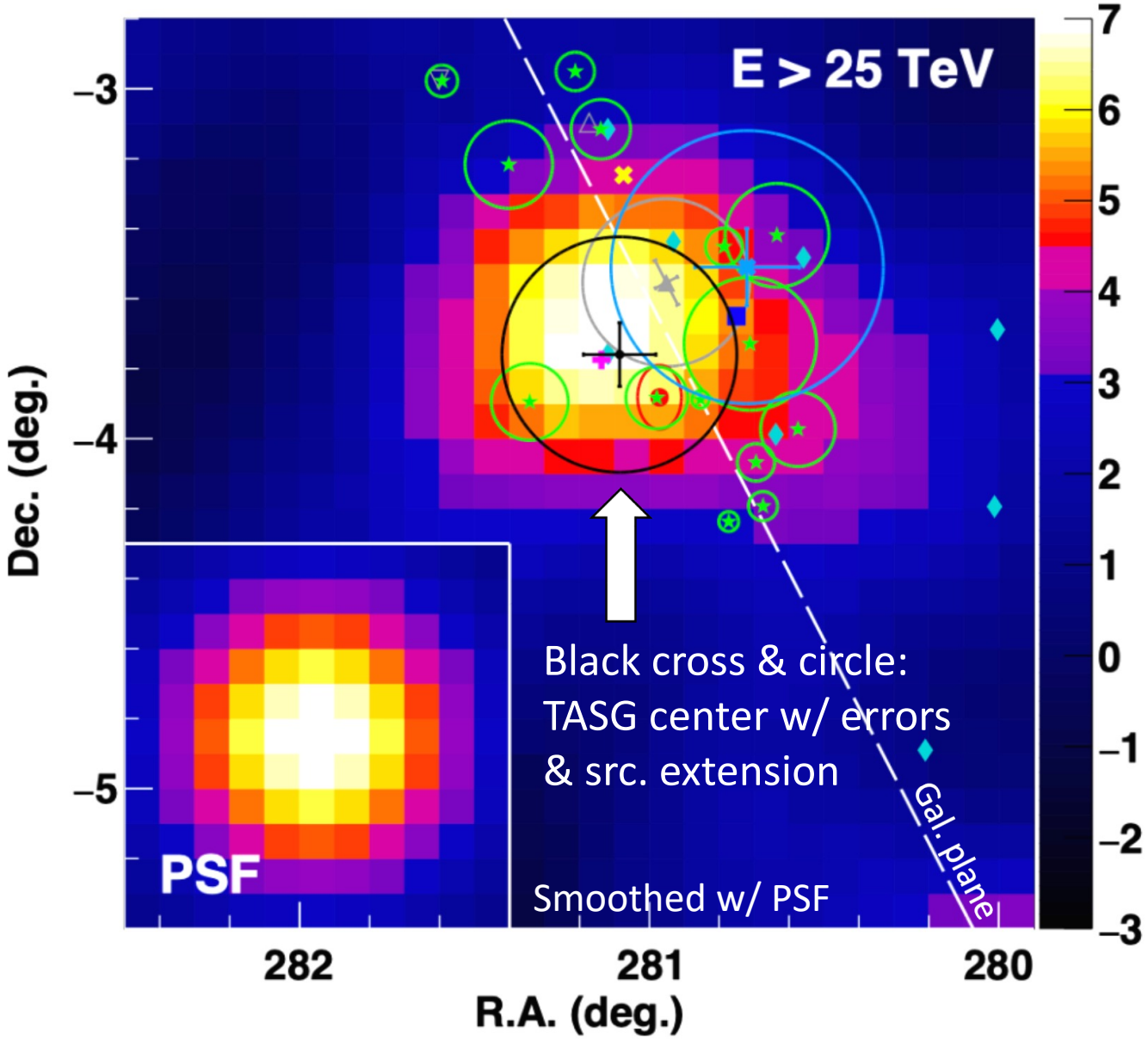
- Nearby gamma-ray sources:

  eHWC J1842-035[3] in E > 56 TeV &

  LHAASO J1843-0338[4] @ E = 100 TeV
- Gamma-ray emission mechanism is not known
- Energy spectrum is not measured above 30 TeV

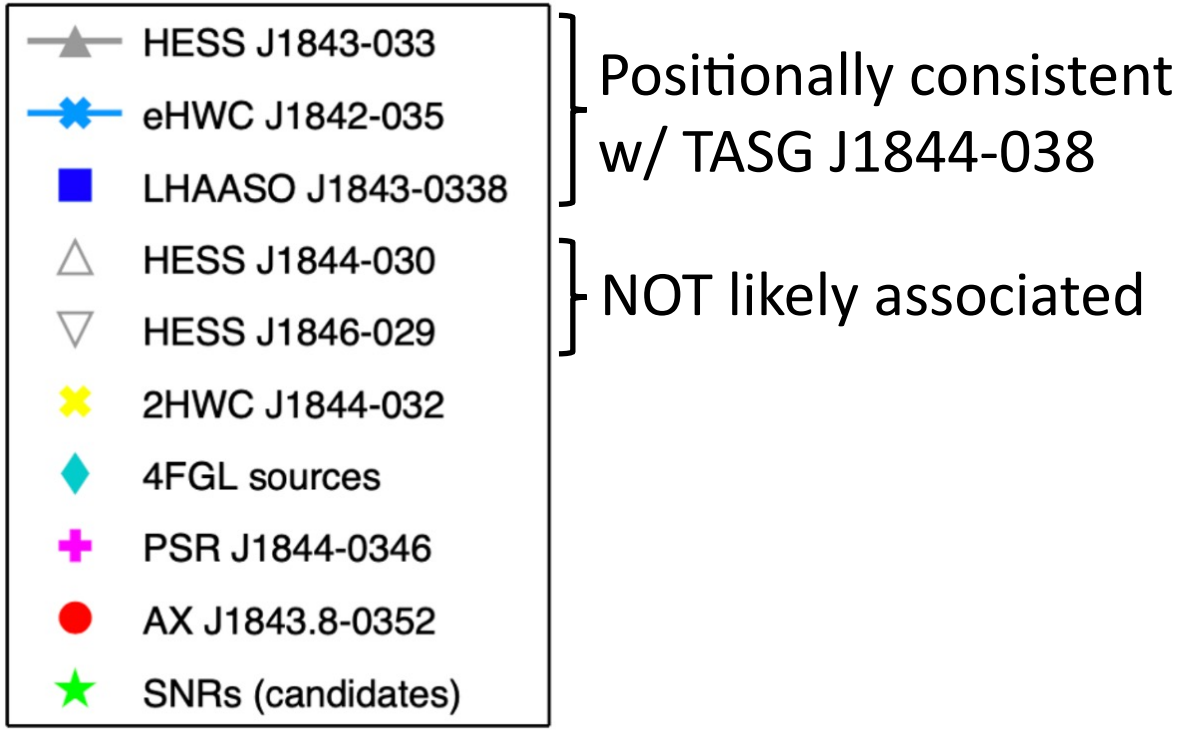
1) Hoppe, Proc. of ICRC 2007 (2008)
2) H.E.S.S. collaboration, A&A 612, A1 (2018)
3) Abeysekara et al., PRL 124, 021102 (2020)
4) Cao et al., Nature, 594, 3 (2021)

Results (1): Source detection: TASG J1844-038



- Used data: 2014 Feb. to 2017 May (719 live days)
- Li & Ma[1)] significance: 6.2σ (E > 25 TeV)
- Source center in the J2000 coordinates:

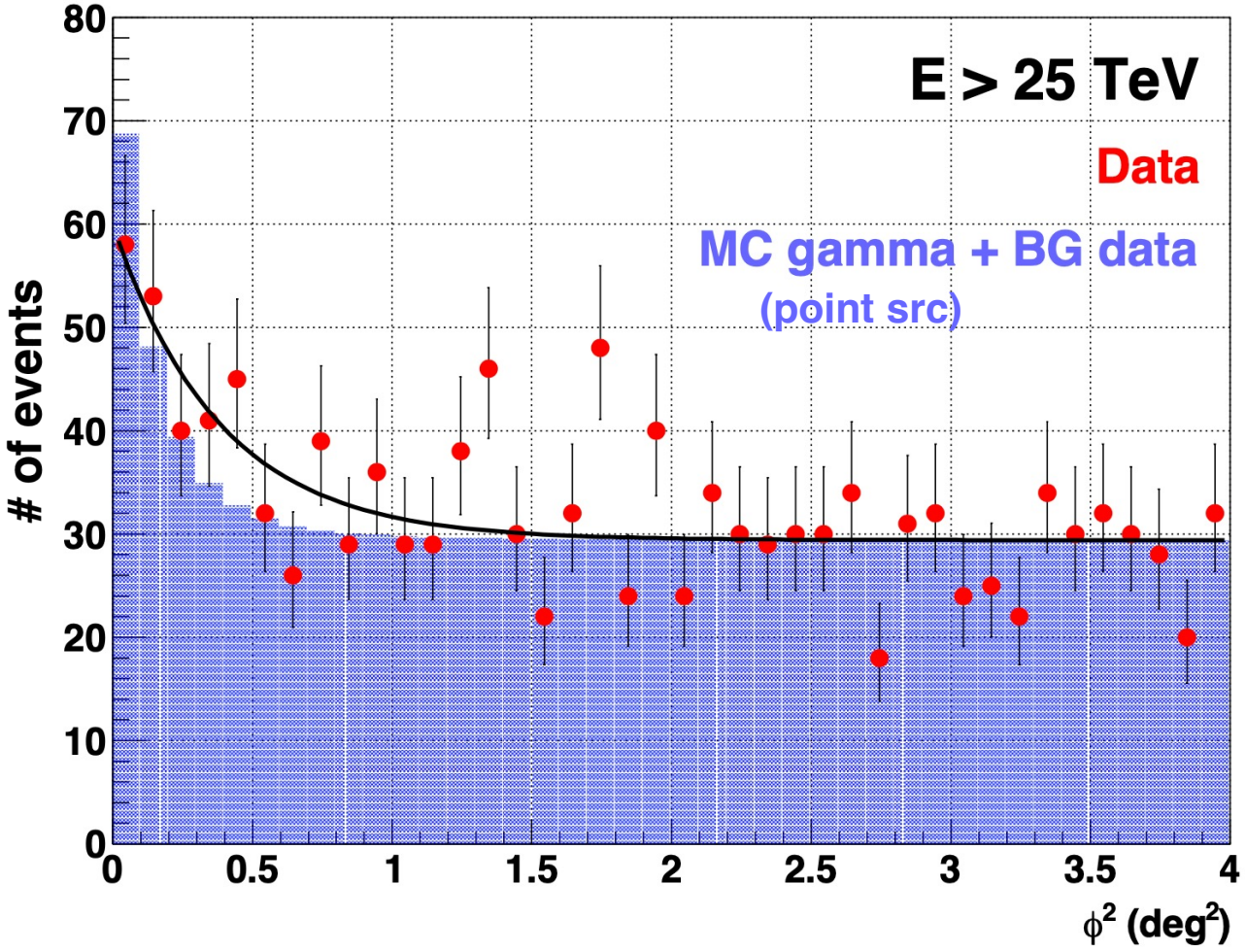
$$(\alpha,\ \delta) = (281.^\circ09 \pm 0.^\circ10,\ -3.^\circ76 \pm 0.^\circ09)$$



1) Li & Ma, ApJ 272, 317 (1983)

Results (2): ϕ^2 distribution of the TASG J1844-038 region

ϕ2: The square of the angle b/w the source center and incoming direction of events



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

where σ_{psf} = 0.28°: PSF radius and

N_{bg} = 29.4 : # of BG.

⇒ Source extension: σ_{ext} = 0.34° ± 0.12°

(χ^2 / d.o.f. = 39.5 / 38)

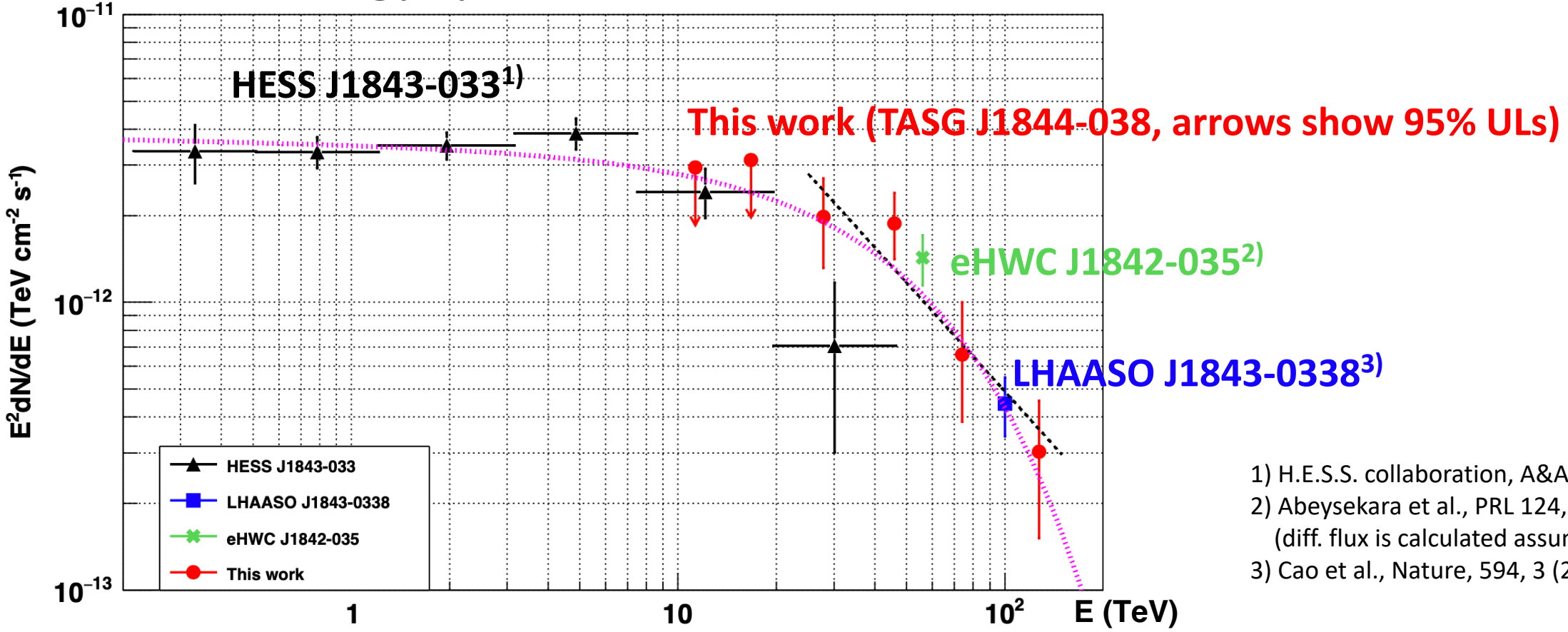
The extension is consistent w/

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

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

1) H.E.S.S. collaboration, A&A 612, A1 (2018)
2) Abeysekara et al., PRL 124, 021102 (2020)

Results (3): Energy spectrum



1) H.E.S.S. collaboration, A&A 612, A1 (2018)
2) Abeysekara et al., PRL 124, 021102 (2020)
(diff. flux is calculated assuming Γ=2.7)
3) Cao et al., Nature, 594, 3 (2021)

PL fit to this work :

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

(Black dashed in 25 TeV < E < 130 TeV)

$(\chi^2/\mathrm{d.o.f.} = 2.1/2)$

ECPL fit to HESS, LHAASO & this work:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{\mathrm{TeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

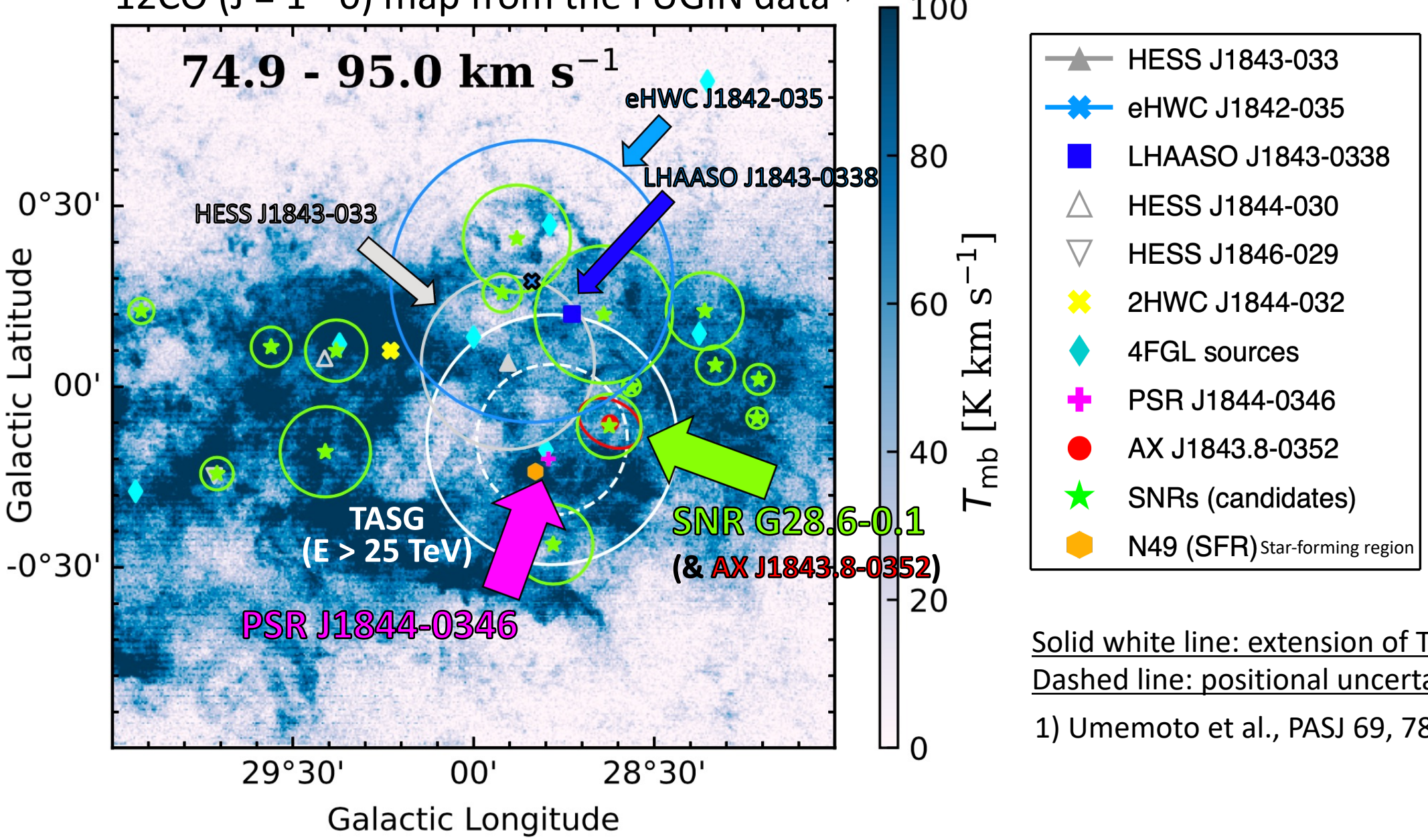
(Magenta dotted)

where $N_0 = (3.57 \pm 0.26)\times 10^{-12}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$,

$\Gamma = 2.02 \pm 0.06$ & $E_{\mathrm{cut}} = 49.5 \pm 9.0$ TeV $(\chi^2/\mathrm{d.o.f.} = 10.4/8)$.

Discussion: Association of TASG J1844-038 w/ nearby objects

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



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

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

Discussion (1): Association of TASG J1844-038 w/ SNR G28.6-0.1 (1)

SNR G28.6-0.1

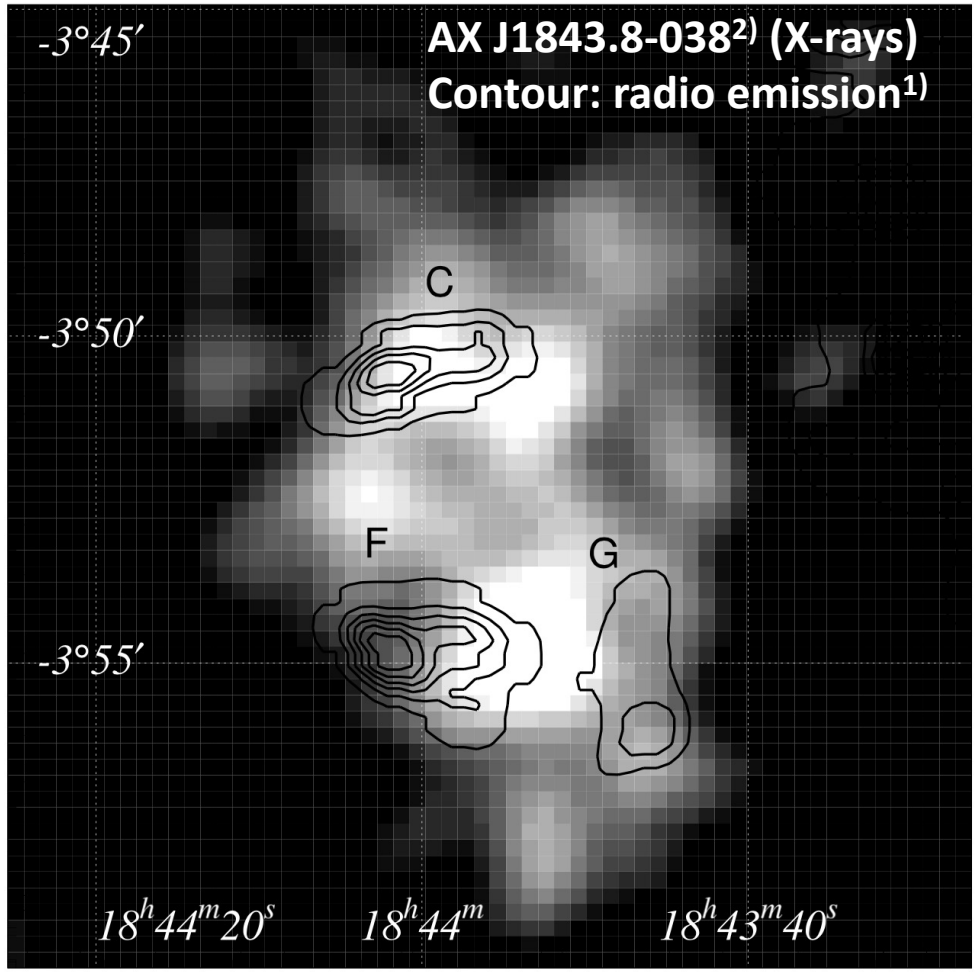
– Nonthermal radio[1)] & X-rays[2)] by electron synchrotron radiation
– Shell-type SNR[2)]
– Distance: 9.6±0.3 kpc[3)]
– Age: 2.7 kyr[2)] or 19 kyr[3)]

TASG J1844-038's radius: $\sigma = 0.34° \pm 0.12°$

AX J1843.8-0352's radius (X-rays): $\sigma_{mean} = 4.5'$[4)]

Discrepancy in their extensions at the 2.3 σ level

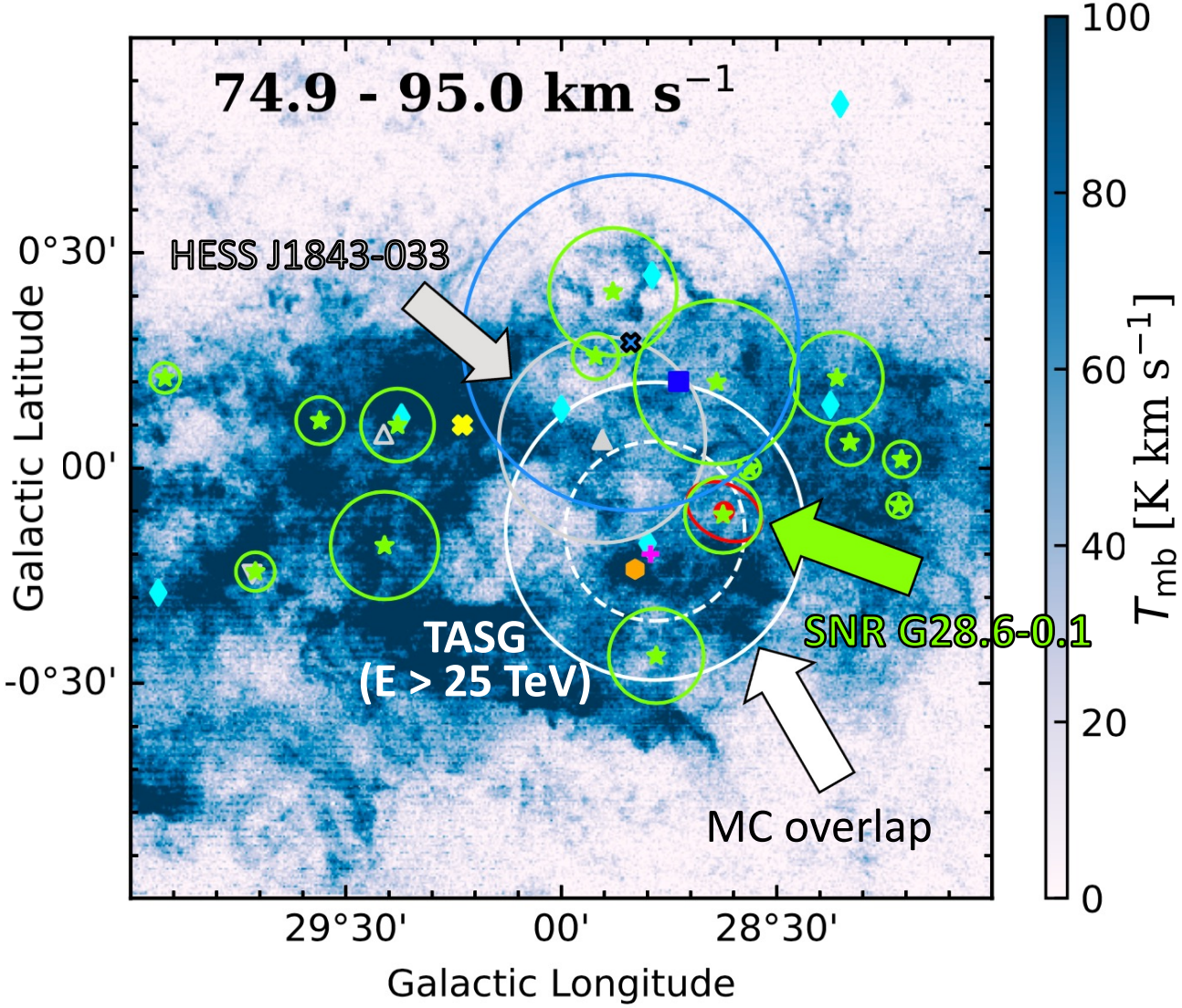
=> Contribution of gamma ray of hadronic origin ?
(CR interaction w/ ambient molecular clouds ?)



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

Discussion (1): Association of TASG J1844-038 w/ SNR G28.6-0.1 (2)

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



Several resemblances to SNR G106.3+2.7[2)]:

1. Overlapping molecular clouds (MCs),
2. Max. energy of CR protons: ≃ 500TeV, &
3. Average of the estimated ages is ≃ 10 kyr.

=> **Could have been a PeVatron in the past??**

Diffusion time of CR protons through MCs[3)]:

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

where R, size of MCs & χ , suppression factor.

Assuming χ = 0.1 & B = 10μG ($n_H \sim 100$ cm^{-3}),

$$\tau_{\rm diff}\,(R_{\rm TASG}, E_{\rm CR} > 250\ {\rm TeV}) \lesssim 2.0\ {\rm kyr}\ \&$$

$$\tau_{\rm diff}\,(R_{\rm HESS}, E_{\rm CR} \simeq 10\ {\rm TeV}) \simeq 4.9\ {\rm kyr}.$$

Acceptable compared w/ the SNR's age

1) Umemoto et al., PASJ 69, 78 (2017)
2) Amenomori et al., Nat. Astron. 5, 460 (2021)
3) Gabici et al., Astrophys. Space Sci. 309, 365 (2007)

Discussion (2): Association of TASG J1844-038 w/ PSR J1844-0346

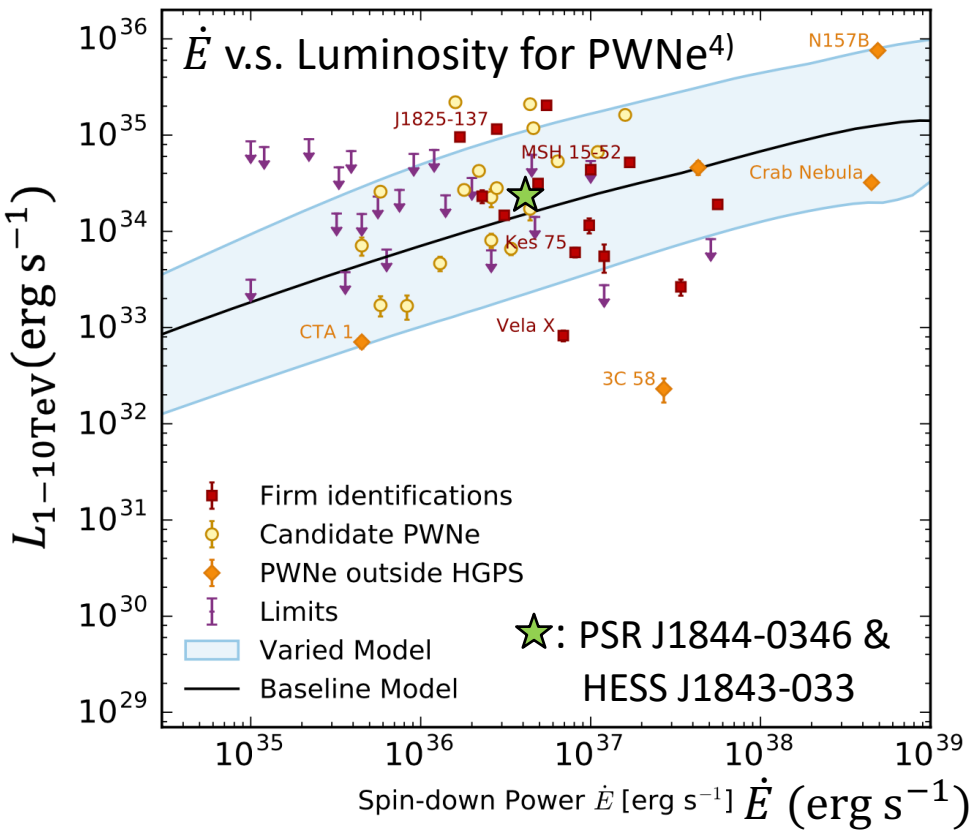
PSR J1844-0346

- Gamma-ray PSR discovered by the Einstein@home project[1)]
- P = 113 ms, τ_c = 12 kyr & $\dot{E}$ = 4.2 × 10^{36} erg s^{-1}
- Pseudo distance: 4.3 kpc[2)]

HESS J1843-033[3)]

- L (1 TeV < E < 10 TeV) = 2.4 × 10^{34} erg s^{-1} [3)] (@ 4.3 kpc)
- Size: ≃ 18 pc (@ 4.3 kpc)
- Spectral index: ≃ 2.0 (from the ECPL fit in this work)

=> has characteristics typical for TeV PWNe[4)].



ICS off CMB is acceptable

- $e^{\pm}$ w/ E ≈ 90 TeV scatters off CMB up to $E_{\gamma,\,cutoff}$ ≈ 50 TeV[5)].
- Size of TASG J1844-038: ≃ 26 pc (@ 4.3 kpc)
- Assuming the Geminga-like env.[6)] w/ B = 3 μG, D = 4.4 × 10^{27} cm^2 s^{-1}, τ_{diff} ≃ 8 kyr
- Cooling time of $e^{\pm}$ by sync. & ISC[5)]: τ_{cool} ≃ 11 kyr

  => $\tau_{\mathrm{diff}} < \tau_{\mathrm{cool}}$ & $\tau_{\mathrm{diff}} < \tau_c$

1) Clark et al., ApJ 834, 106 (2017)
2) Devin et al., A&A 647, 68 (2021)
3) H.E.S.S. collaboration, A&A 612, A1 (2018)
4) H.E.S.S. collaboration, A&A 612, A2 (2018)
5) Hinton & Hofmann, Ann. Rev. of Astron. & Astrophys. 47, 523 (2009)
6) Abeysekara et al., Science 358, 911 (2017b)

Summary

- Gamma rays from the HESS J1843-033 region 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: 0.34° ± 0.12°
- Energy spectrum measured in 25 TeV < E < 130 TeV for the 1st time
  - Our results is fitted w/ $\mathrm{d}N/\mathrm{d}E = (9.70 \pm 1.89)\times10^{-16}(E/40\ \mathrm{TeV})^{-3.26\pm0.30}\mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.
  - Combined spectra b/w HESS, LHAASO & TASG implies a cutoff @ 49.5 ± 9.0 TeV.
- Source association w/ nearby objects
  - If SNR G28.6-0.1 is assumed to be the source, possibly π^0-decay gamma rays from CR protons w/ $E \lesssim 500$ TeV contribute to the total emission and the SNR could have been a PeVatron in the past.
  - If PSR J1844-0346 is assumed to be, the emission can be well explained by ICS off CMB by electrons w/ $E \lesssim 90$ TeV accelerated by a TeV PWN.

Thank you

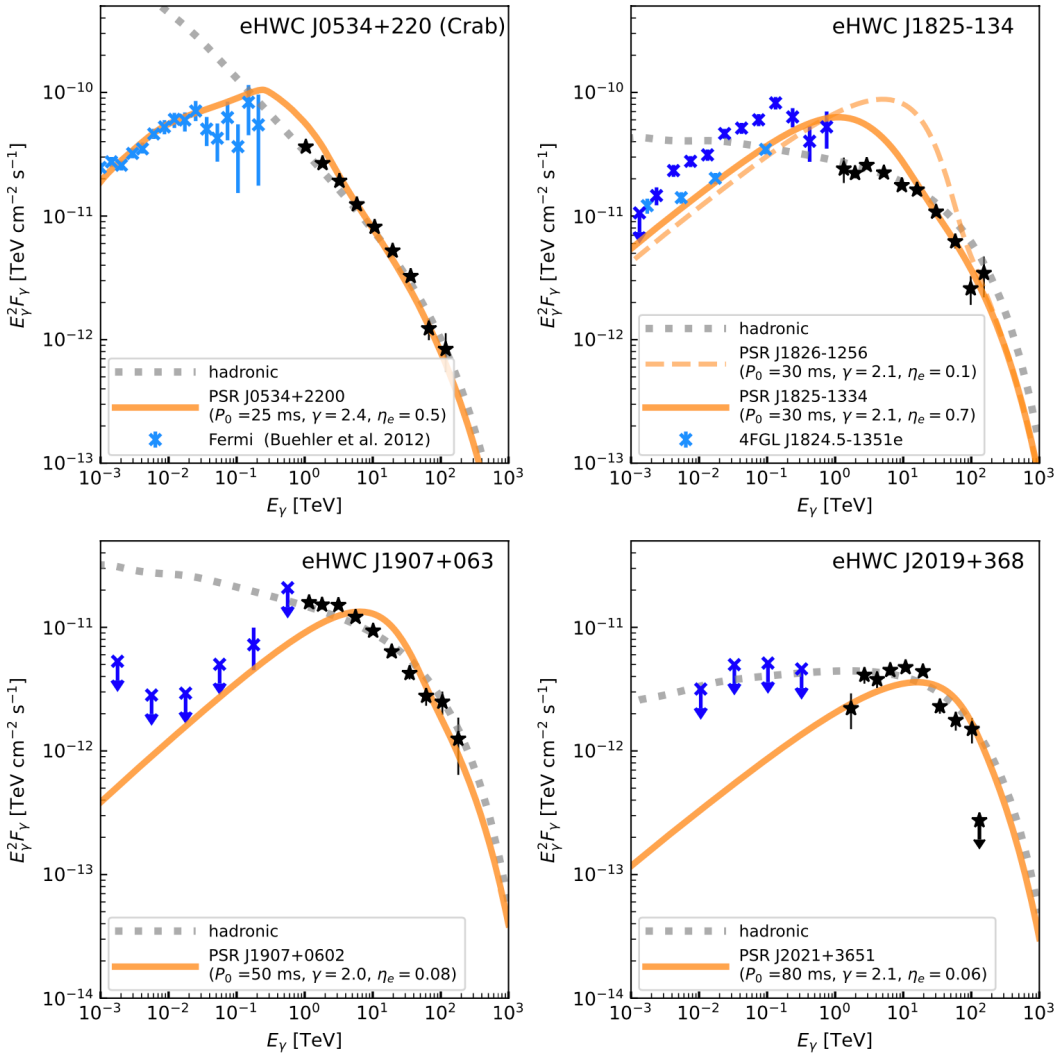
Feel free to ask a question or send me an email to
katosei@icrr.u-tokyo.ac.jp

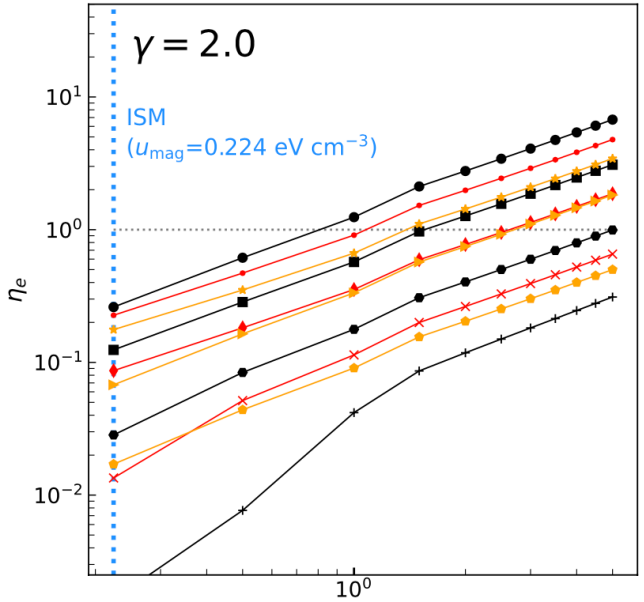
If you are interested in my presentation, please also read
"Measurement of the Gamma-Ray Energy Spectrum beyond 100 TeV from the HESS J1843-033 Region",
Amenomori et al., ApJ 932, 120 (2022)
(https://doi.org/10.3847/1538-4357/ac6ef4)

Back-up slides

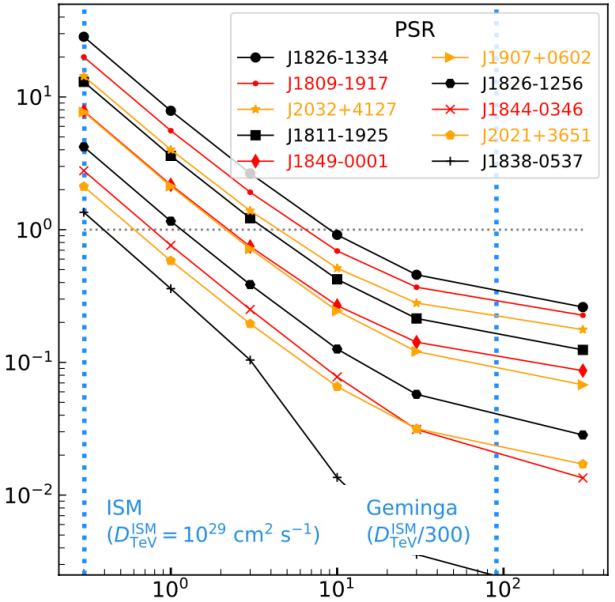
Theoretical research (1)

Sudoh et al. (2021): All eHWC sources are TeV PWN or TeV halo powered by nearby pulsars





B energy density (eV cm^{-3})



Diffusion time scale @ 1 TeV (cm^2 s^{-1})

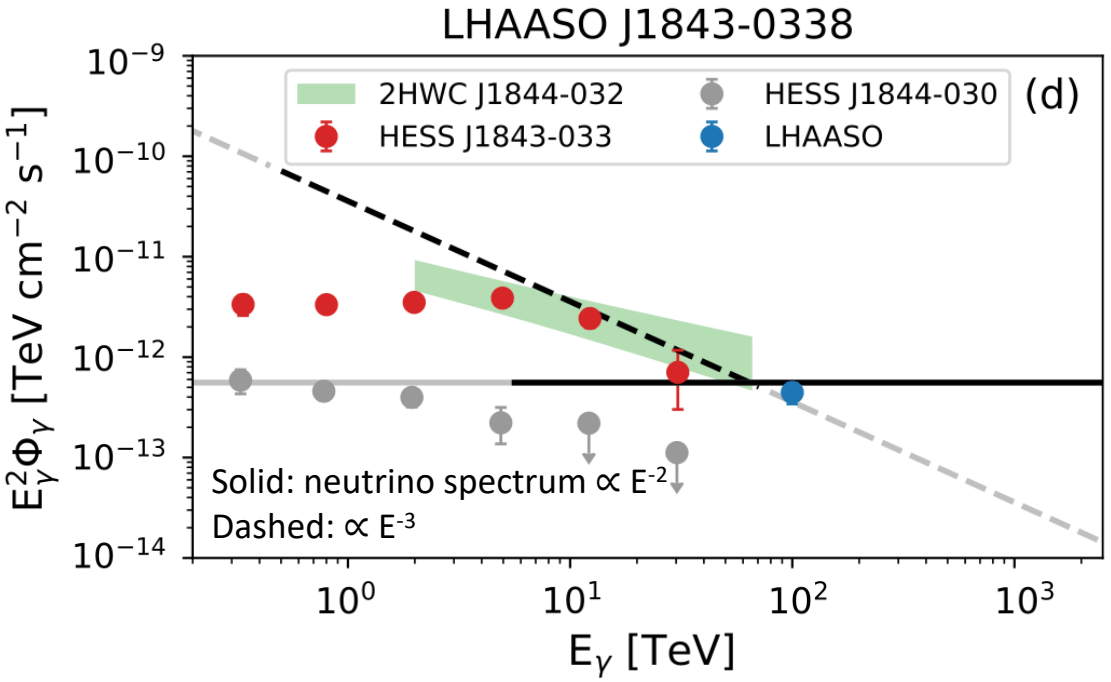
Fit result for HESS J1843-033 is not shown in their paper

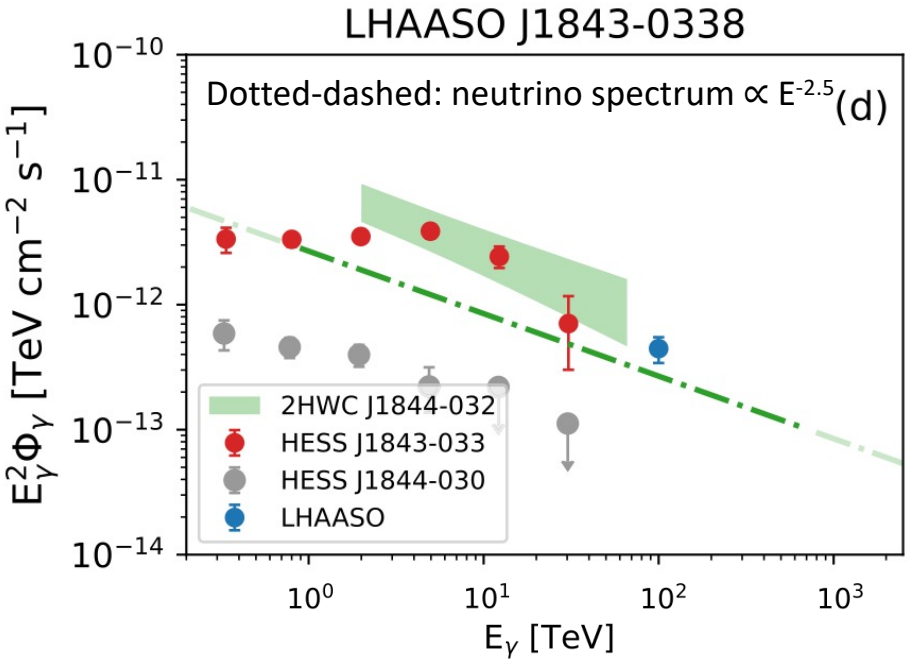
Theoretical research (2)

Huang & Li (2022): Ratio of hadronic gamma-ray flux to the total flux using the observation results of neutirinos

$$\Phi_\gamma^{\mathrm{UL}}(100\ \mathrm{TeV}) = \frac{1}{2}\Phi_{\nu_\mu+\bar{\nu}_\mu}^{\mathrm{UL}}(E_\nu)\left(\frac{50\ \mathrm{TeV}}{E_\nu}\right)^{-\gamma}$$

90% upper limit on hadronic gamma-ray flux





- In these theoretical works (Sudoh et al and Huang & Li), association between gamma-ray sources remains unclear (not evaluated clearly) because energy spectrum in 30TeV<E<100TeV is not measured systematically
- Discussion by experimentalists is not enough (only vague deduction for the association is made)

Data analysis for gamma rays from the HESS J1843-033 region

- Used data: 2014 Feb. to 2017 May (719 live days)

- Event selection criteria: the same as the Crab std. cut (Amenomori et al., PRL 123, 051101, 2019) EXCEPT for the following two points:

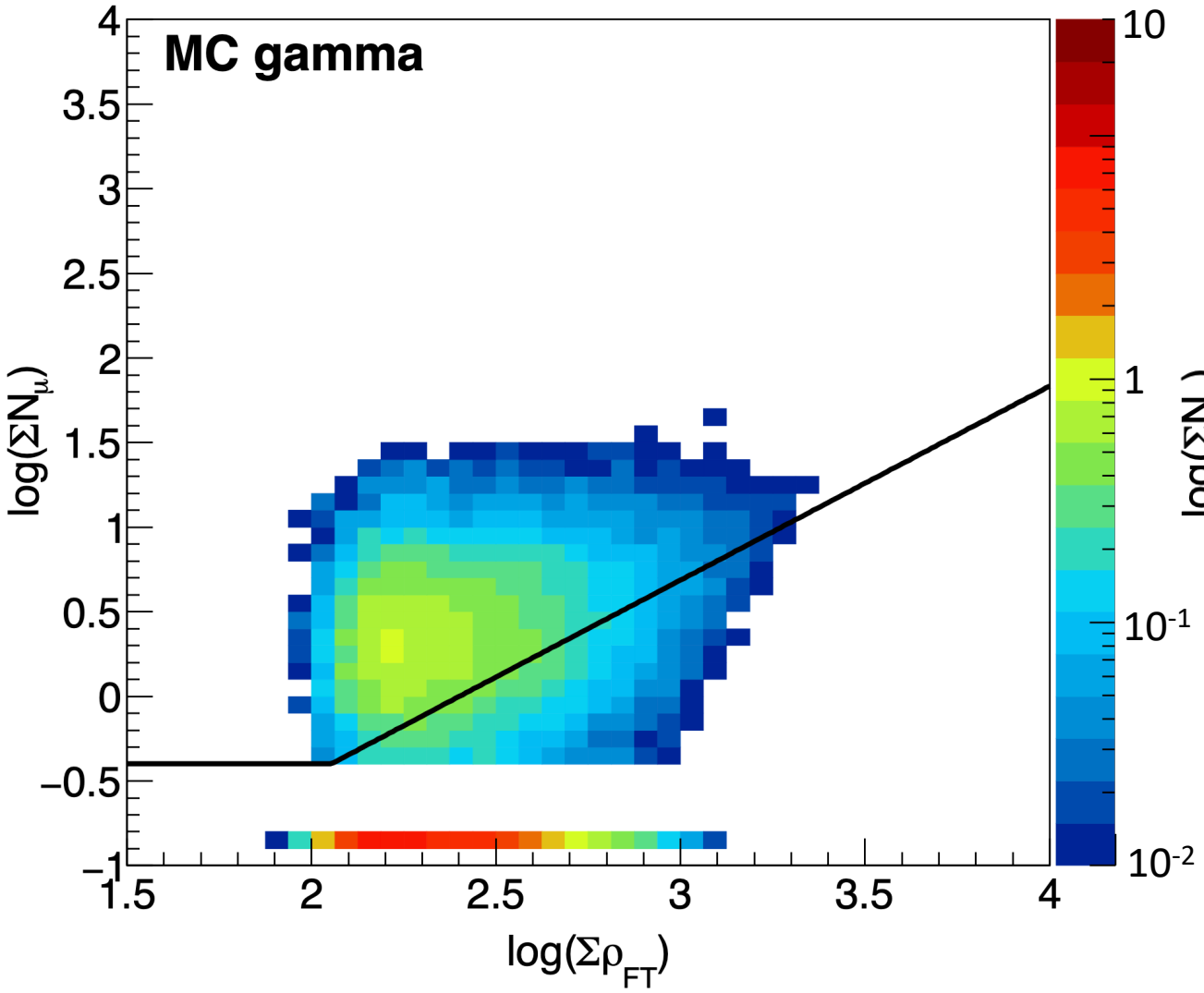
  1. zenith < 50 deg to improve statistics ($\mathrm{zenith}_{\mathrm{meridian}} = 33\ \mathrm{deg}$), and

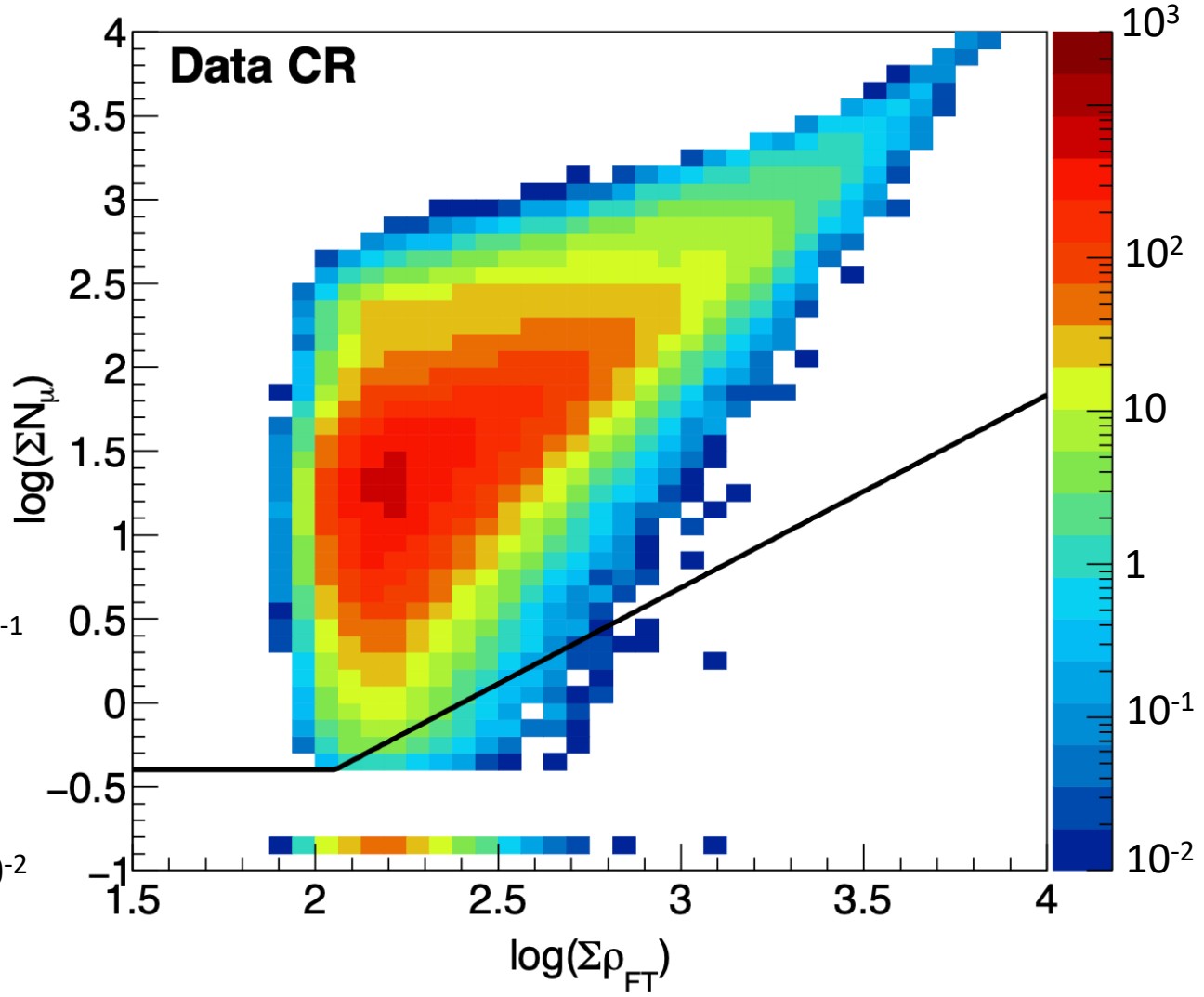
  2. Optimized MD cut: $\Sigma N\mu < 1.8\times10^{-3}\ (\Sigma\rho/m^{-2})^{1.1}$ or $\Sigma N\mu < 0.4$.

  (Σρ: Sum of # density recorded by each detectors of the AS array)

- # of events after the selection: 1.4×10^{7} events

Optimum MD cut line (1): Cut-line formula

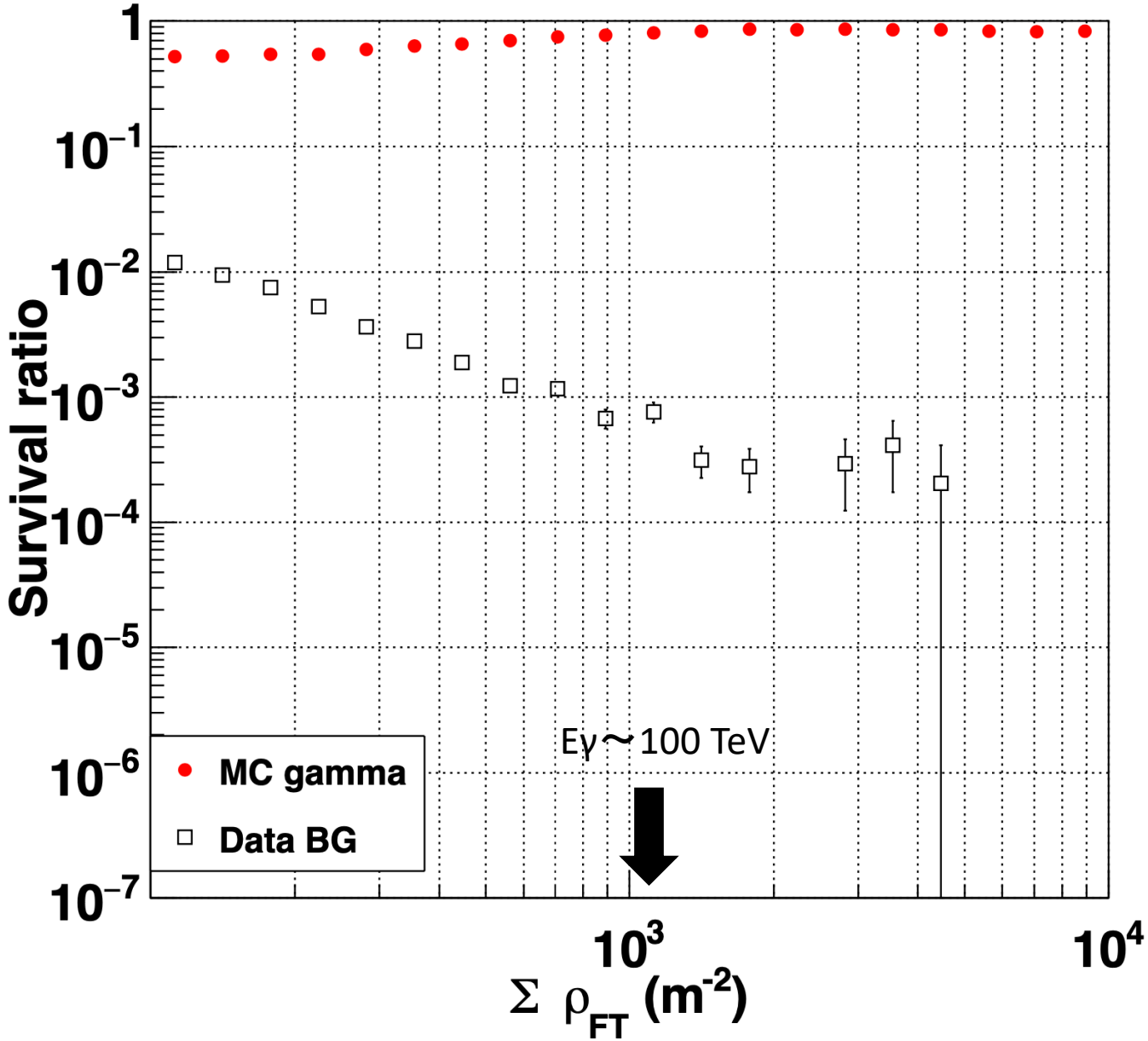




$$\Sigma N\mu < 1.8 \times 10^{-3} (\Sigma\rho/m^{-2})^{1.1} \text{ or } \Sigma N\mu < 0.4$$

Optimum MD cut line (2): Survival ratio of gamma rays & BGCRs

Gamma & BG survival ratio



@ Eγ～100 TeV

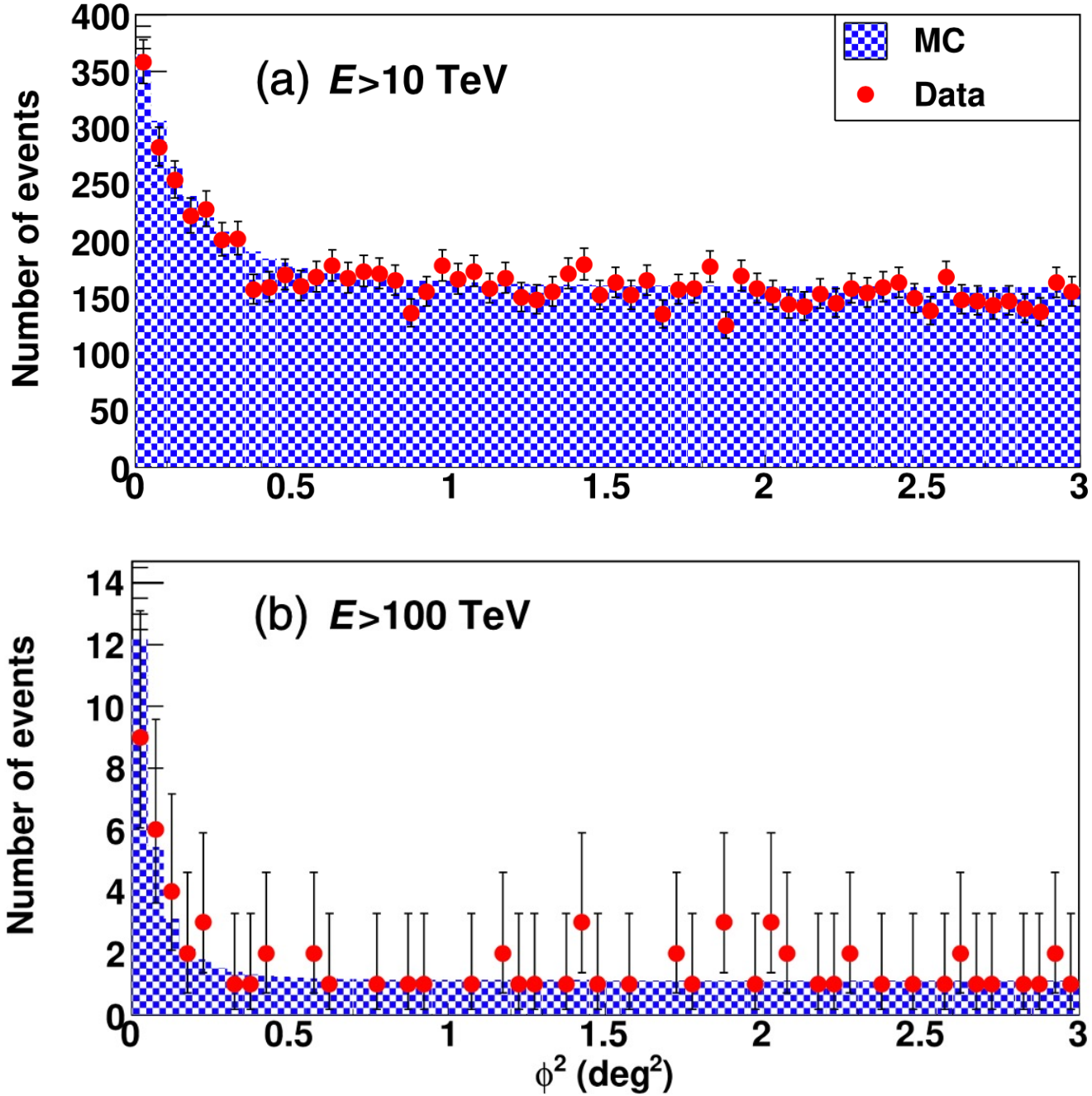
Gamma survival ratio: ≃81%

BG rejection power: ≳99.9%

Point spread function

ϕ^2 distribution for the Crab Nebula

(Amenomori et al., PRL 123, 051101, 2019)



Estimation of positional unertainty of a gamma-ray source

- For TASG J1844-038, eHWC J1842-035, & LHAASO J1843-0338：

  Positional uncertainty is evaluated in terms of the error radius $R_{0.68}$ w/ the 68% C.L. as in *HESS collaboration, A&A 612, A1 (2018)*, but using uncertainties of α & δ instead of *l* & *b*;

$$R_{0.68} = f_{0.68}\sqrt{\Delta\alpha_{\rm stat}^2 + \Delta\alpha_{\rm sys}^2 + \Delta\delta_{\rm stat}^2 + \Delta\delta_{\rm sys}^2}$$

where $f_{0.68} = \sqrt{-2\ln(1-0.68)}$ (A. A. Abdo et al. ApJS, 183, 46, 2009b) and

$\Delta\alpha_{\rm stat\ (sys)}$ & $\Delta\delta_{\rm stat\ (sys)}$ are the statistical (systematic) uncertainties of α & δ, respectively.

- HESS sources：

  There $R_{0.68}$'s are cited from *HESS collaboration, A&A 612, A1 (2018):*

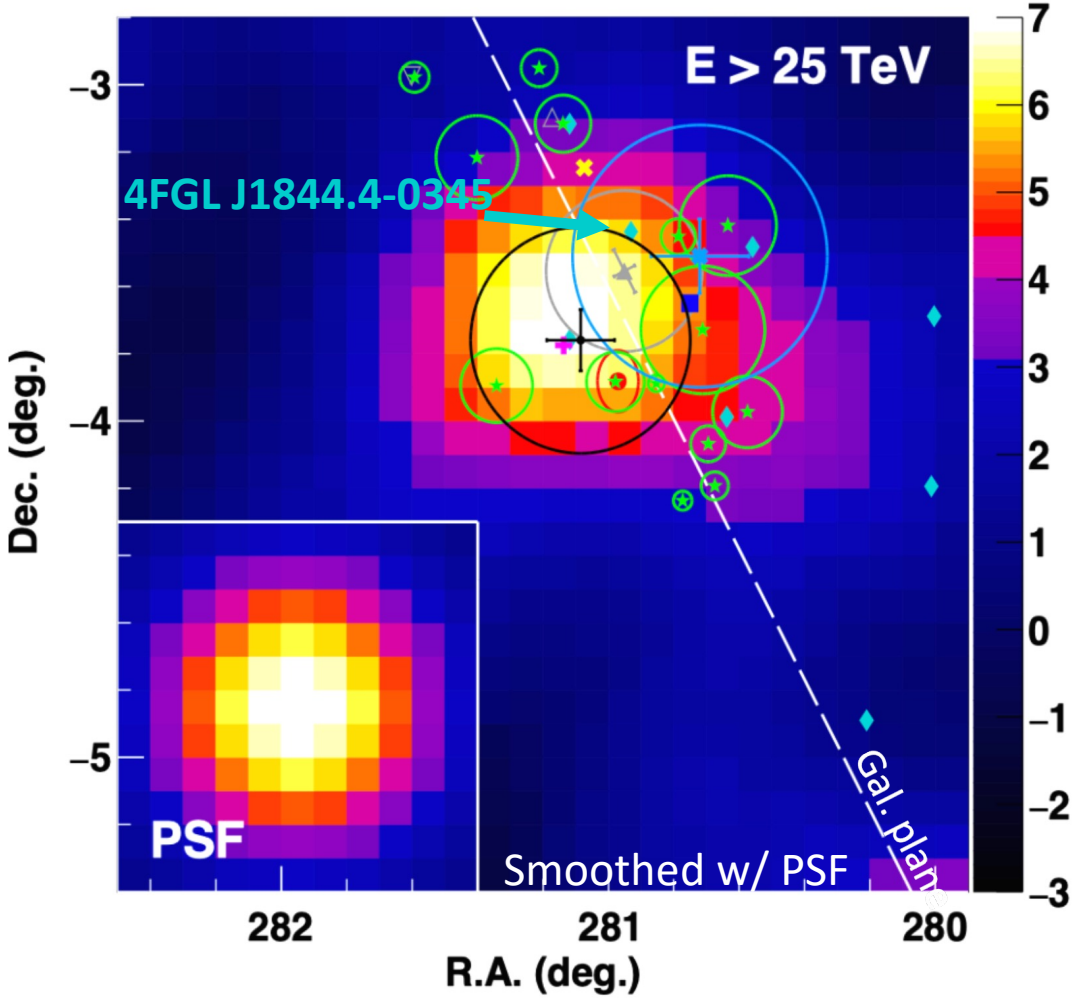
Relation of the TASG position to nearby gamma-ray sources

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 $(1.4\,\sigma)$

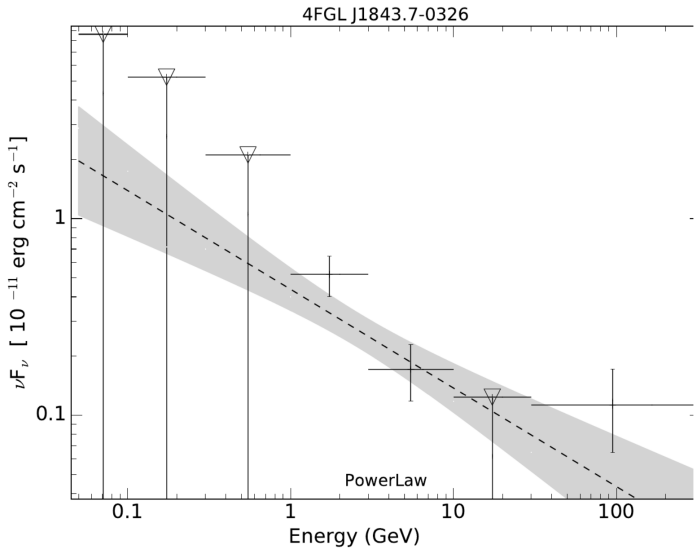
† For $R_{0.68}$, see HESS collaboration, A&A 612, A1 (2018)
* The source extension is not published

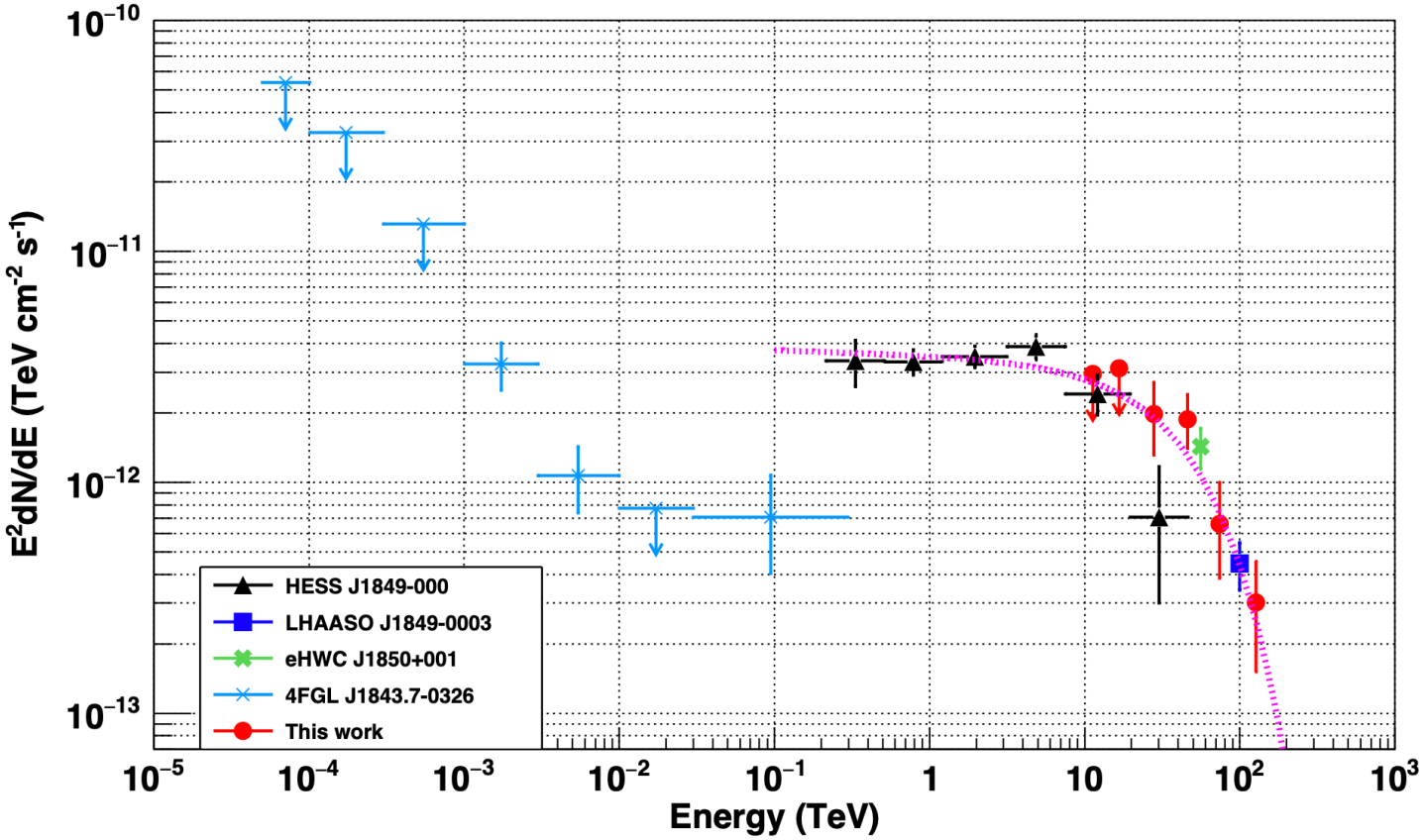
- The position of TASG J1844-038 is
  1. consistent w/ those of HESS J1843-033, eHWC J1842-035, and LHAASO J1843-0338, but
  2. deviated from HESS J1844-030 and HESS J1846-029.

4FGL J1843.7-0326 (cataloged as a point source)

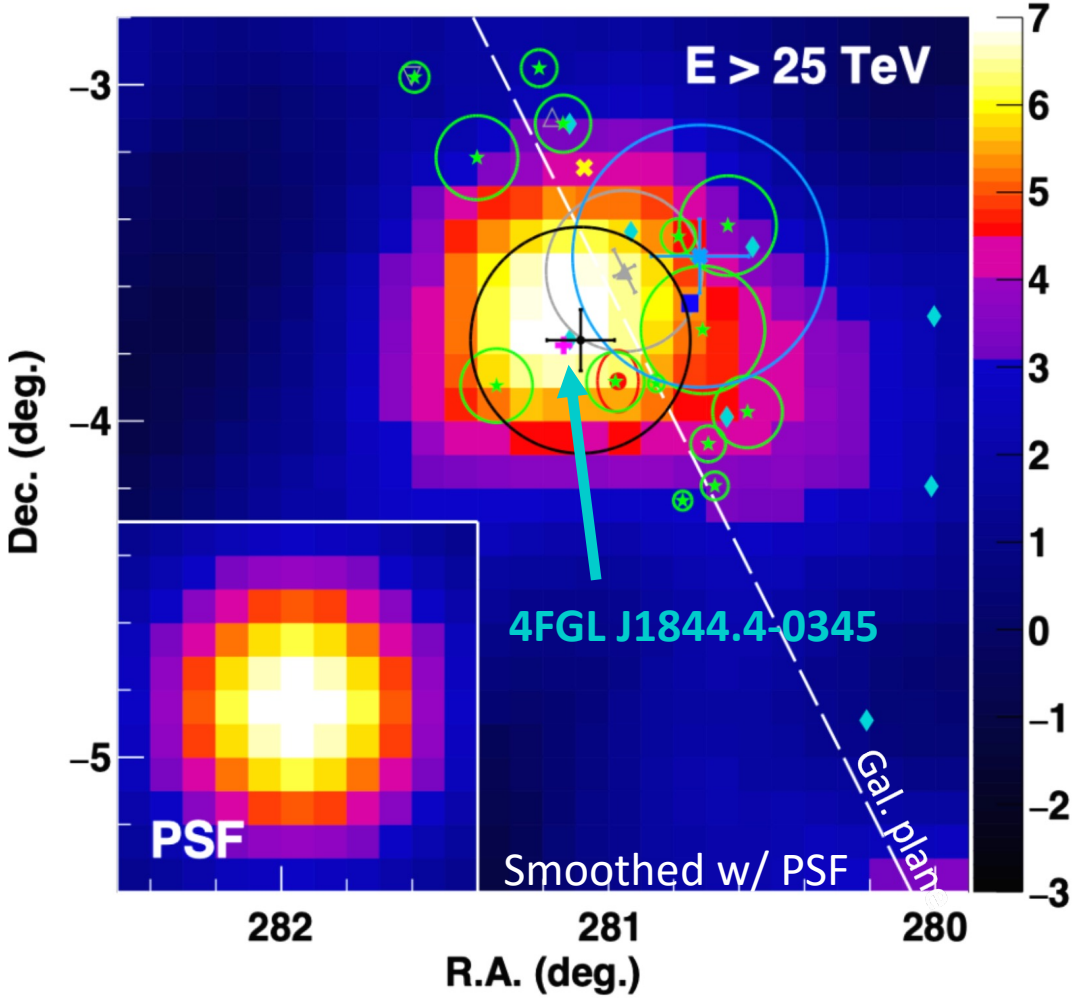


4FGL sources

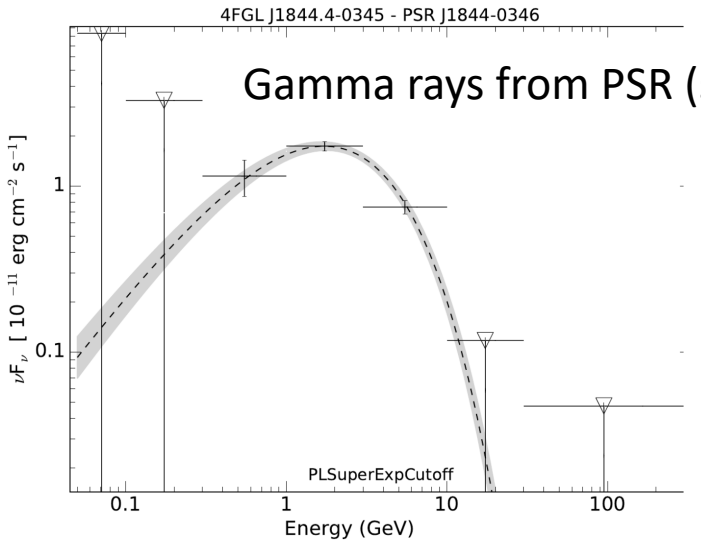


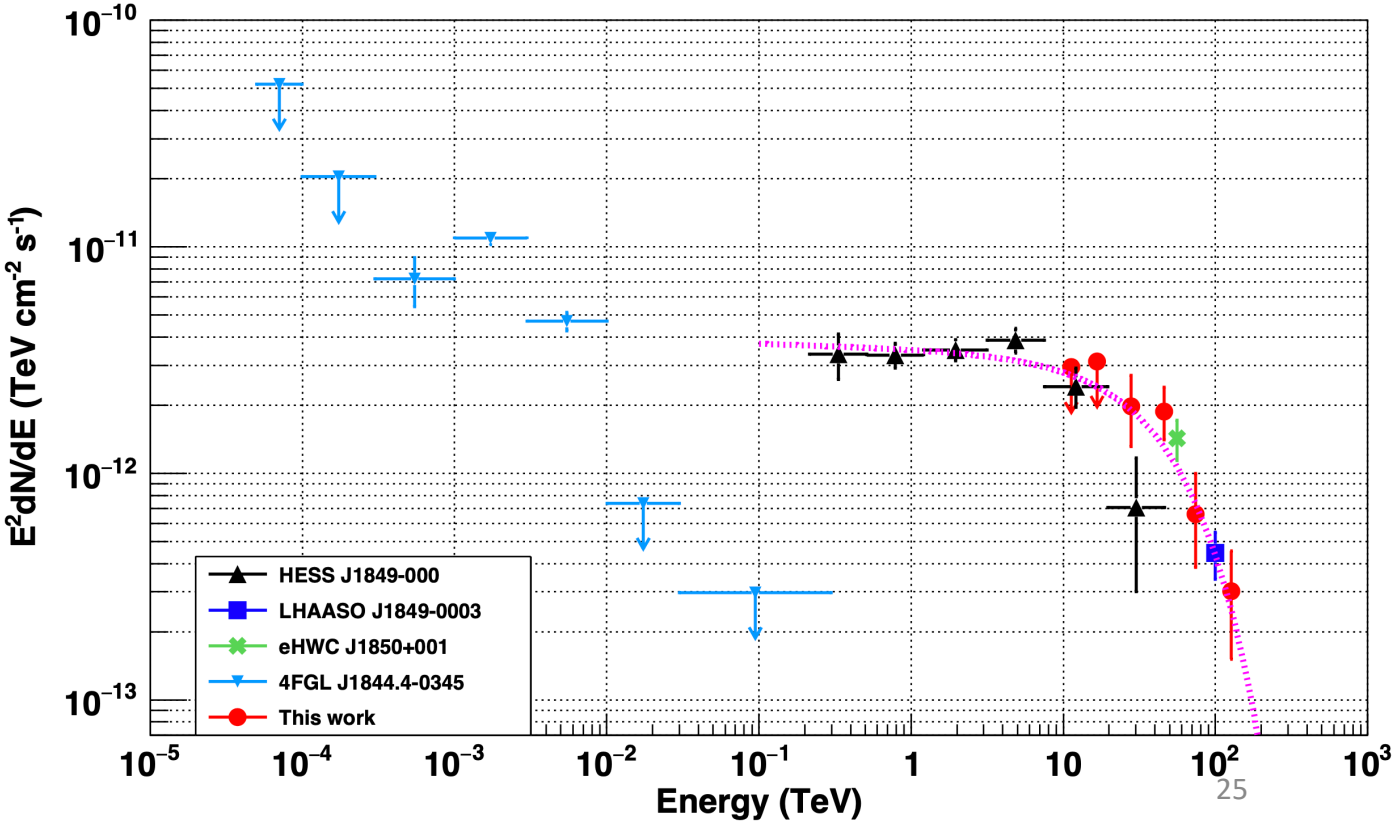


4FGL J1844.4-0345

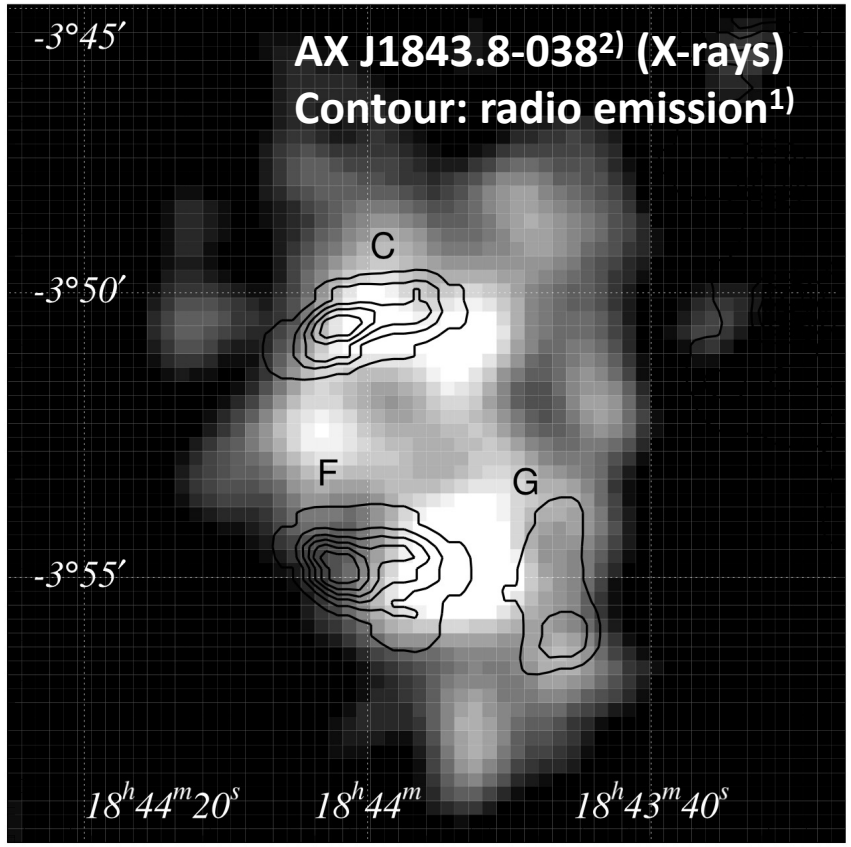


4FGL sources





Multi-wavelength flux (radio & X-ray bands) (1): The SNR G28.6-0.1 region



(a) Radio flux[2, 3)] @ 6 cm: 0.9 Jy
21 cm: 2.1 Jy

(b) X-ray observation[4)]

TABLE 1
BEST-FIT MODEL PARAMETERS FOR AX J1843.8−0352

Parameter	Power Law			NEI
	Observation 1	Observation 2	Observation 1+2	Observation 1+2
Photon index	$2.4^{+1.1}_{-0.9}$	$2.1^{+0.4}_{-0.4}$	$2.1^{+0.4}_{-0.3}$	...
kT (keV)	...	...	...	$5.4^{+3.5}_{-1.6}$
Abundance[a]	...	...	...	$0.17^{+0.17}_{-0.14}$
log [$n_e t$ (cm^{-3} s)]	...	...	...	$11.1^{+0.4}_{-0.7}$
N_H (10^{22} cm^{-2})	$4.7^{+2.8}_{-1.8}$	$3.7^{+0.7}_{-0.6}$	$3.8^{+0.7}_{-0.6}$	$3.5^{+0.6}_{-0.5}$
Absorbed flux[b] (10^{-14} ergs cm^{-2} s^{-1} arcmin^{-2})	2.3	3.1	3.1[c]	3.0[c]
Unabsorbed flux[d] (10^{-14} ergs cm^{-2} s^{-1} arcmin^{-2})	3.6	4.3	4.3[c]	4.1[c]
χ^2/dof	18.9/27	48.1/52	68.1/81	65.3/79

NOTE.—The errors correspond to 90% confidence.
[a] Assuming the solar abundance ratio (Anders & Grevesse 1989).
[b] Observed flux per unit area (arcmin^2) in the energy band 2.0–10.0 keV.
[c] The fluxes of observations 1+2 are calculated from the normalizations for the spectrum of observation 2, which covers the whole of AX J1843.8−0352.
[d] Absorption-corrected flux per unit area (arcmin^2) in the energy band 2.0–10.0 keV.

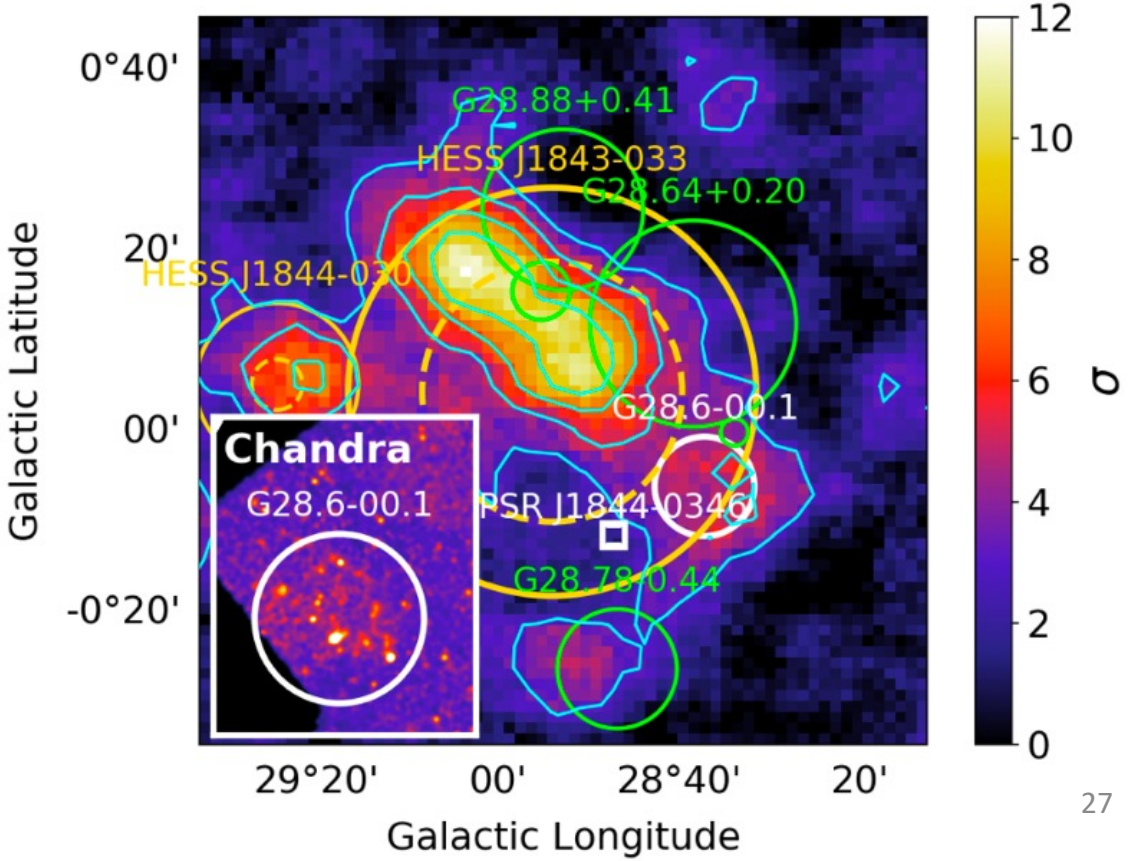
1) Bamba et al., PASJ 53, L21 (2001)
2) Altenhoff et al., A&AS 35, 23 (1979)
3) Helfand et al., ApJ 341, 151 (1989)
4) Ueno et al., ApJ 588, 338 (2003)

Multi-wavelength flux (radio & X-ray bands) (1): The PSR J1844-0346 region

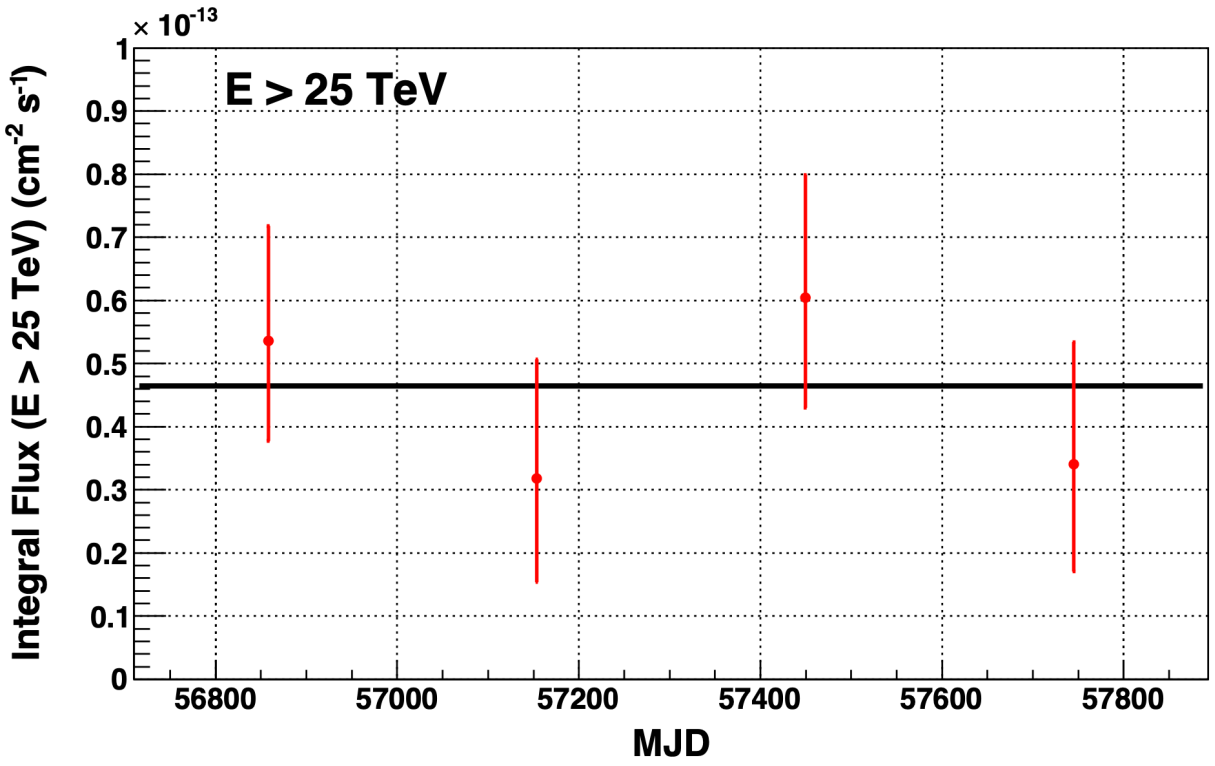
According to Devin et al., A&A 647, A68 (2021),

We also explored the archival multiwavelength data toward the pulsar PSR J1844−0346 and we did not find any radio or X-ray counterpart that could indicate a possible PWN. Radio data from MAGPIS and infrared data from *Spitzer* show a bright extended emission southeast of PSR J1844−0346.···

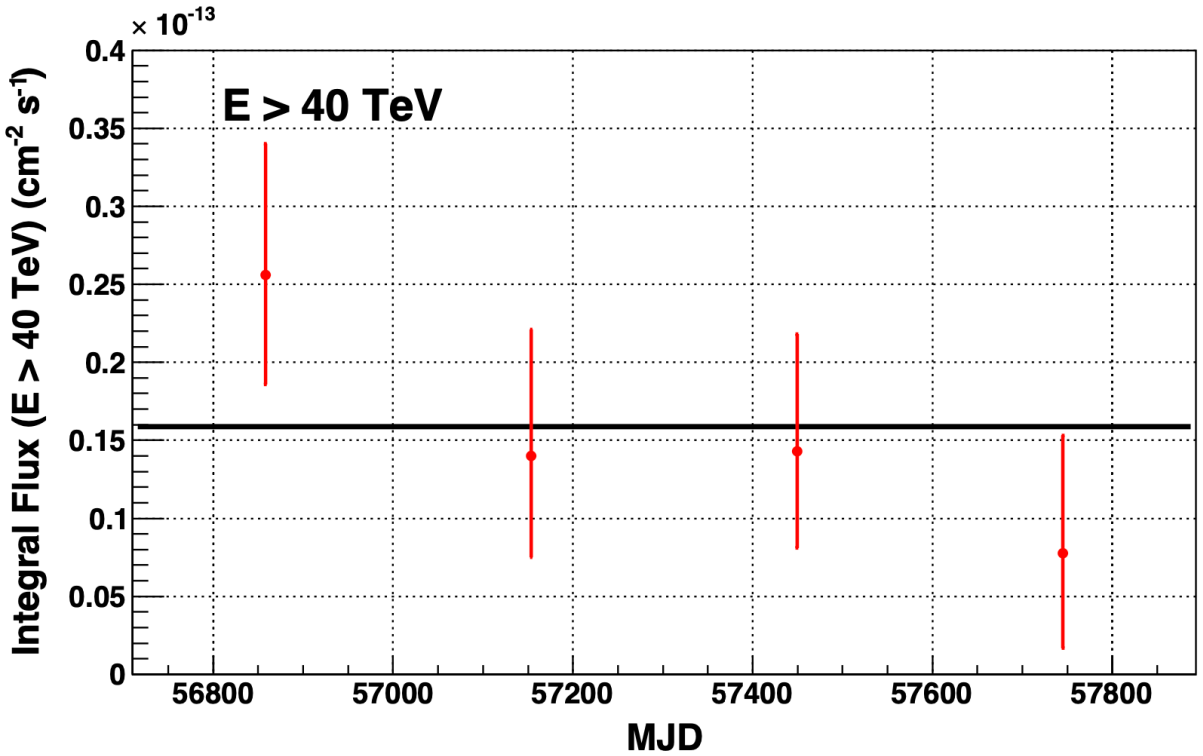
Significance map of gamma-ray emission → observed by HESS (Devin et al., 2021)



Results (4): Time variation of the integral flux



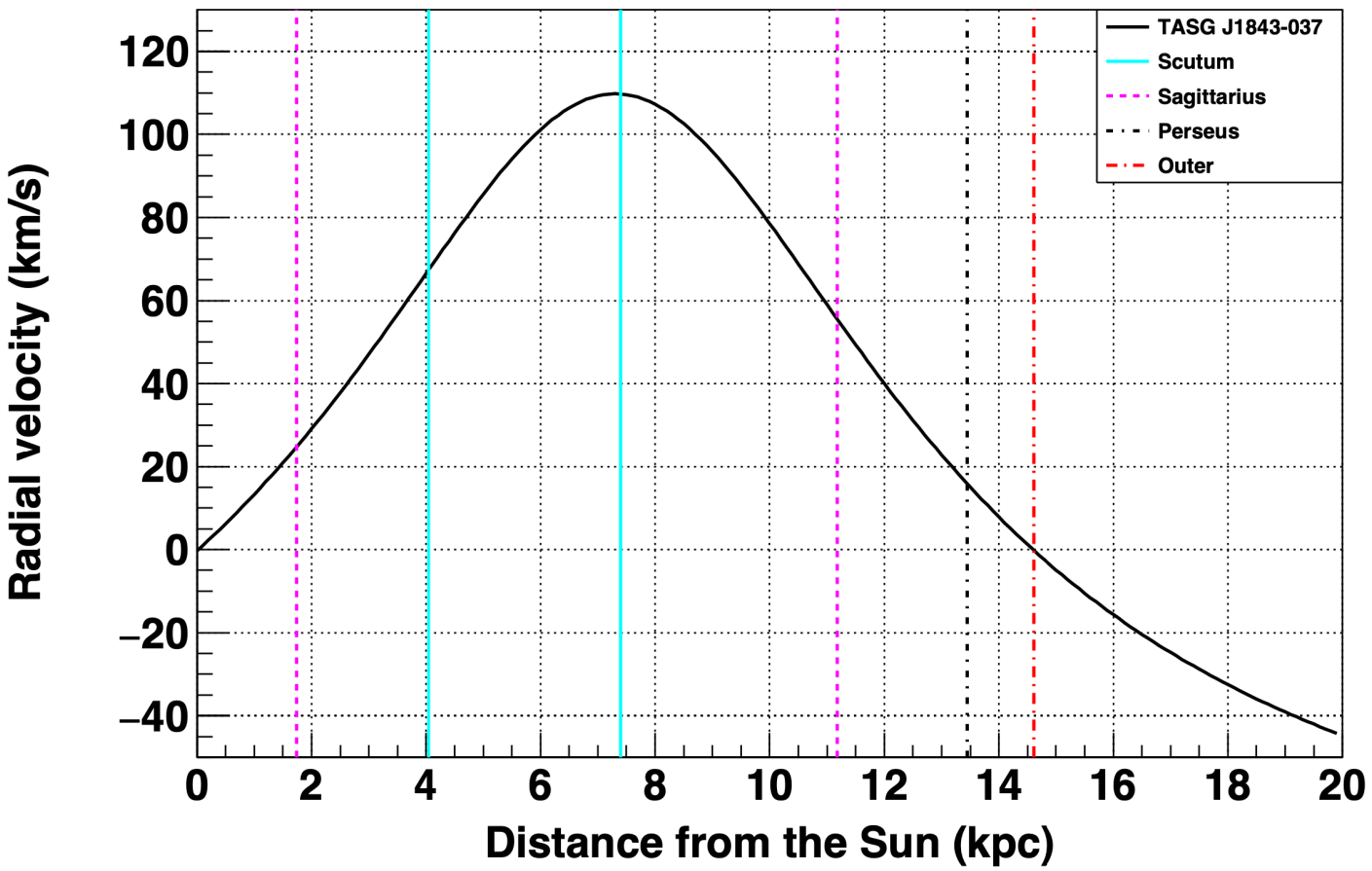
Consistent w/ stable @ $(4.65 \pm 0.89)\times10^{-14}$ cm^{-2} s^{-1}
$(\chi^2 = 1.9/3)$

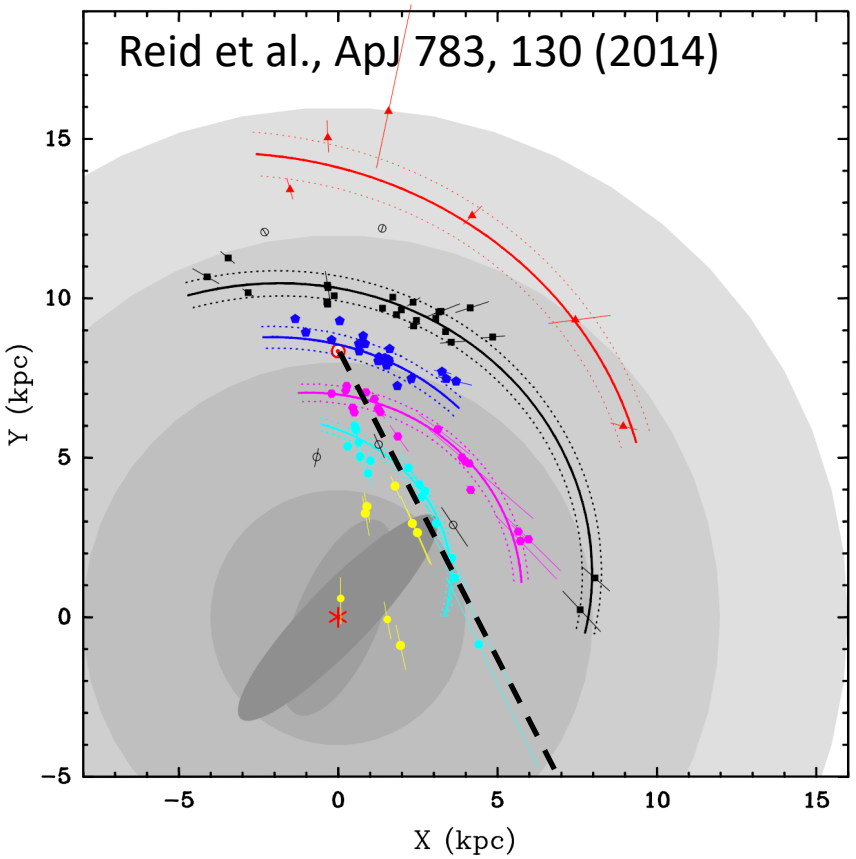


Consistent w/ stable @ $(1.59 \pm 0.38)\times10^{-14}$ cm^{-2} s^{-1}
$(\chi^2 = 3.2/3)$

No variation of the flux by ~30 % in $\lesssim$ 1 yr time scale is found

Distance-Vrad relation in the direction of TASG J1844-038 (*l* = 28.8 deg)

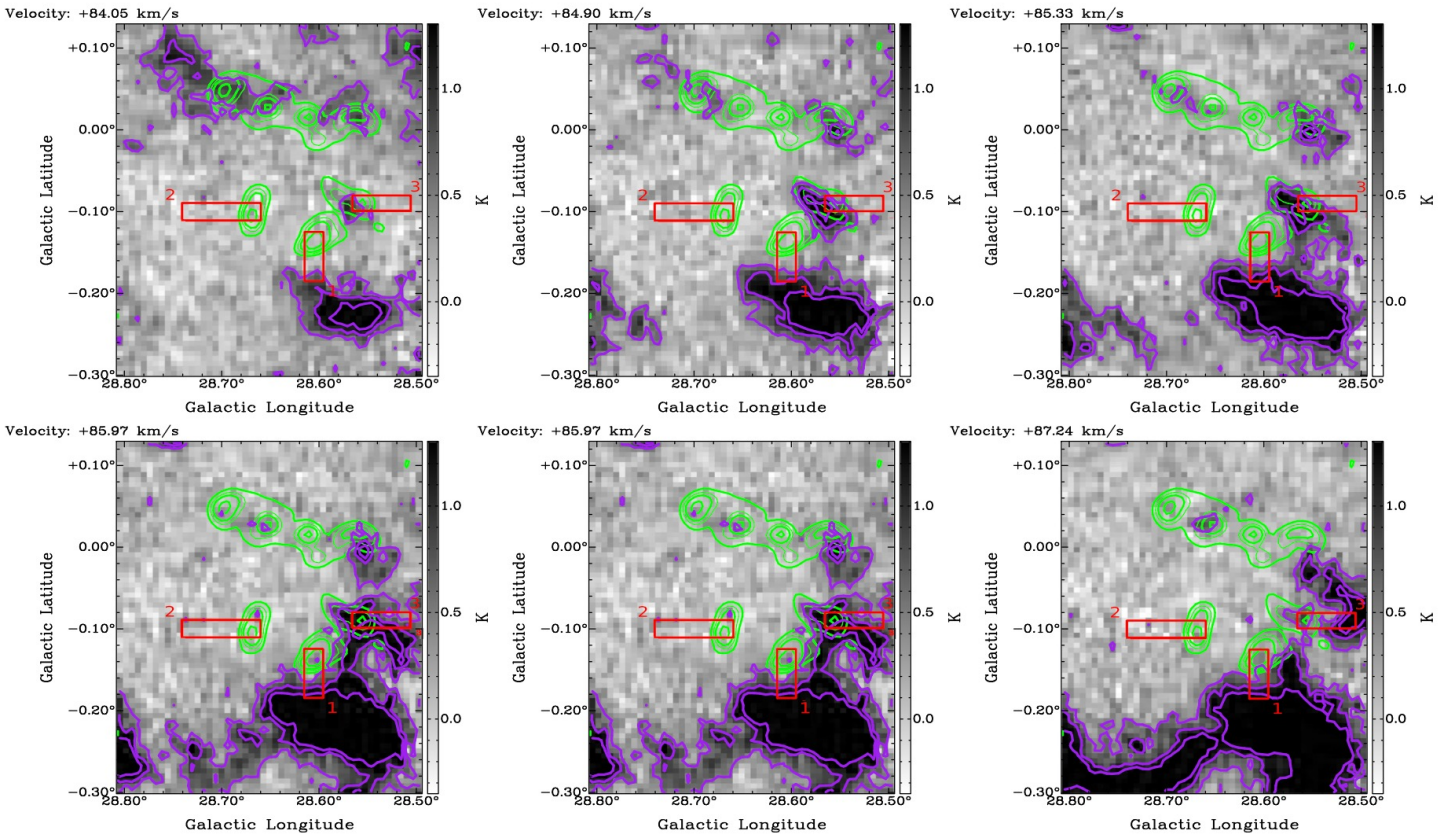




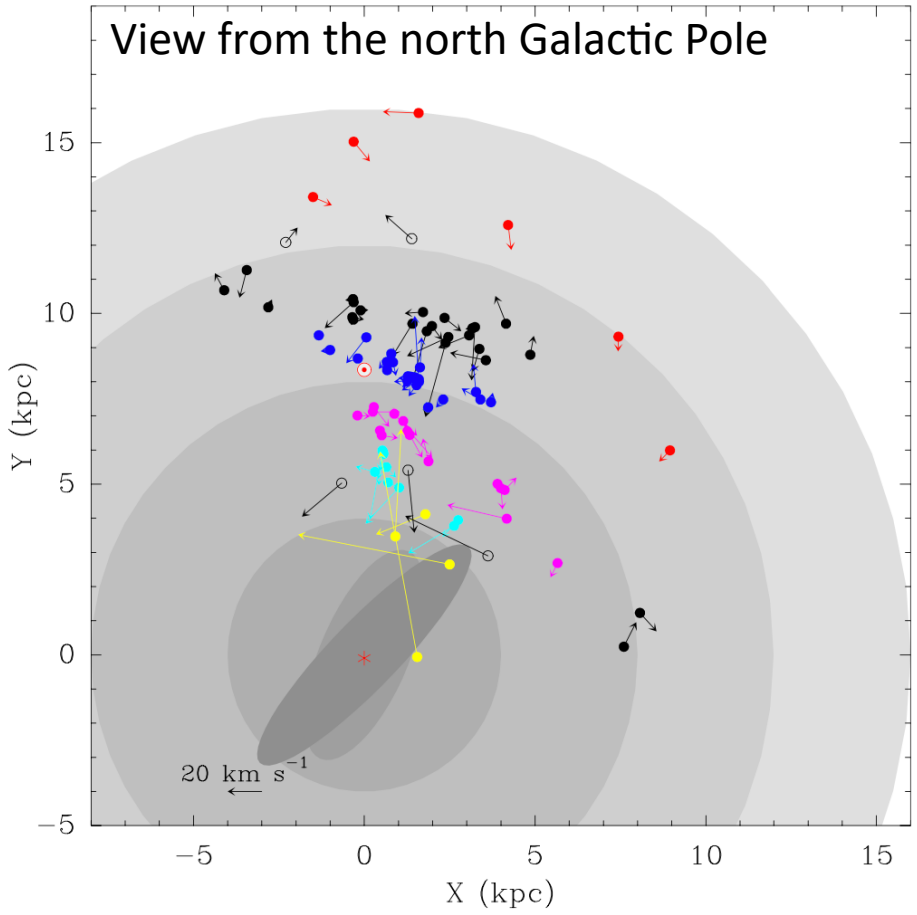
$$\ln(R/R_{\rm ref}) = -(\beta - \beta_{\rm ref})\tan\psi$$

Arm	N	$\beta_{\rm ref}$ (β Range) (deg)	$R_{\rm ref}$ (kpc)	Width (kpc)	ψ (deg)
Scutum	17	27.6 (+3 → 101)	5.0 ± 0.1	0.17 ± 0.02	19.8 ± 2.6
Sagittarius	18	25.6 (−2 → 68)	6.6 ± 0.1	0.26 ± 0.02	6.9 ± 1.6
Local	25	8.9 (−8 → 27)	8.4 ± 0.1	0.33 ± 0.01	12.8 ± 2.7
Perseus	24	14.2 (−21 → 88)	9.9 ± 0.1	0.38 ± 0.01	9.4 ± 1.4
Outer	6	18.6 (−6 → 56)	13.0 ± 0.3	0.63 ± 0.18	13.8 ± 3.3

Interval of the integration over the velocity range



Ranasinghe & Leahy, MNRAS 477, 2243 (2018)

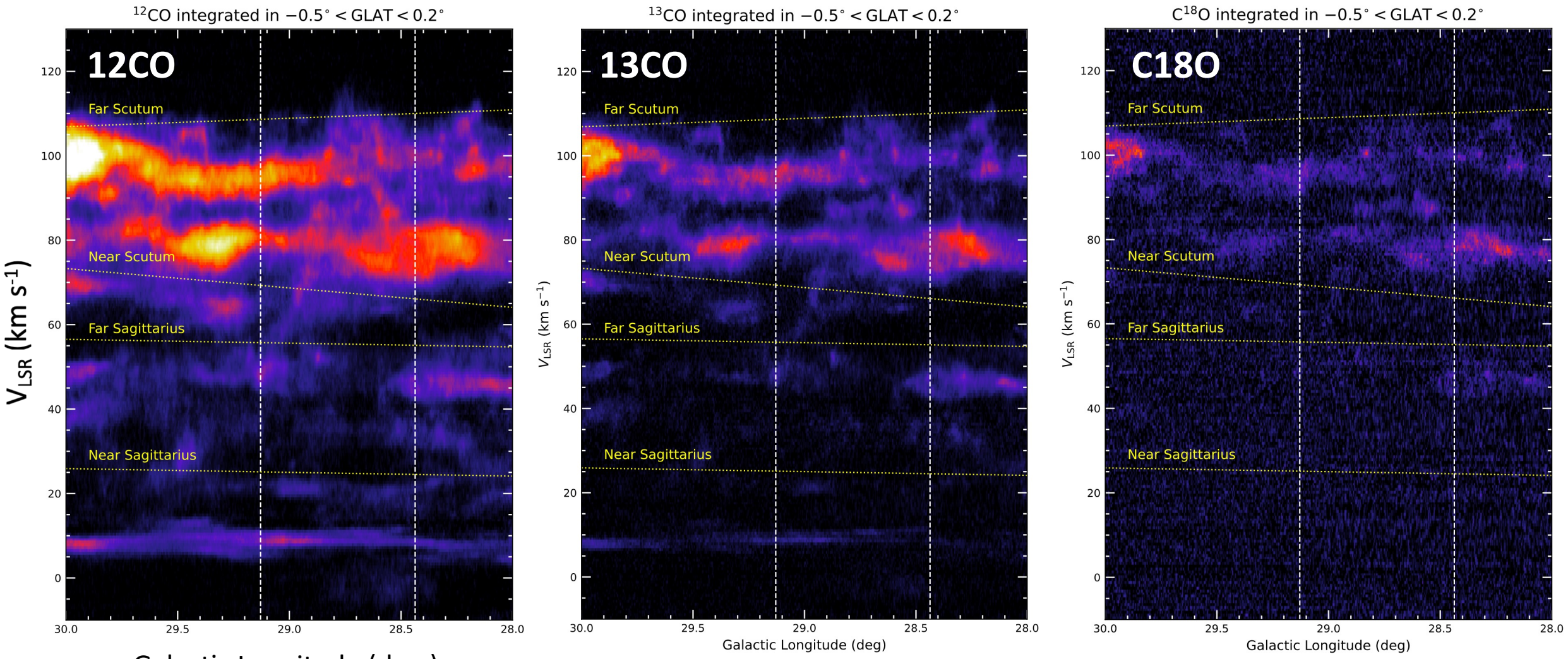


Reid et al., ApJ 783, 130 (2014)

- SNR G28.6-0.1 are interacting w/ molecular clouds in the v ≃ 85 km/s channels (left)
- On the other hand, generally celestial objects in the Galaxy have their peculiar motion w/ ~20 km/s (right)
- We determine the interval of integration over the velocity range of 20 km/s centered at 85 km/s

Comparison b/w 12CO, 13CO and C18O

Galactic longitude v.s. V_{LSR}



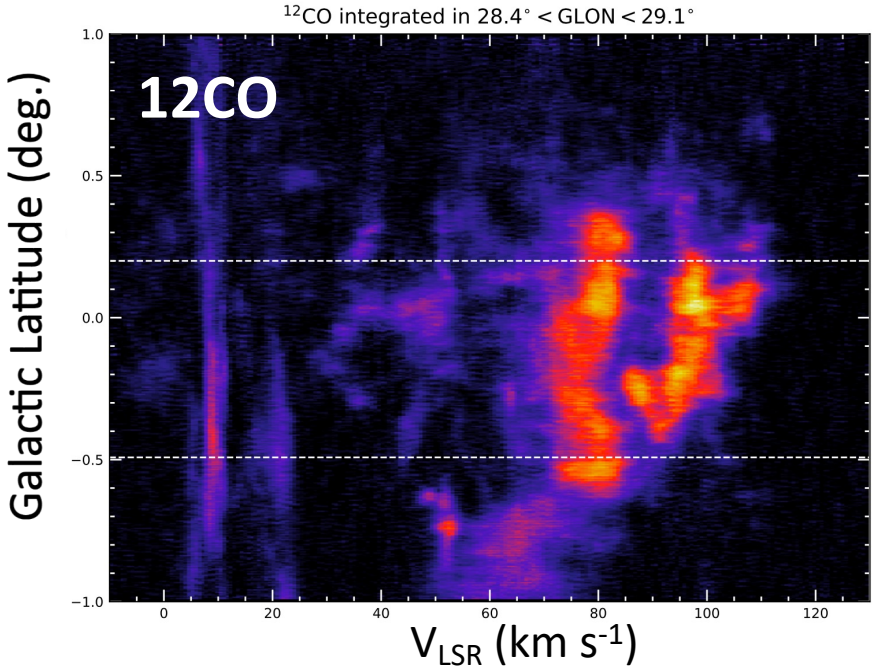
Galactic Longitude (deg.)

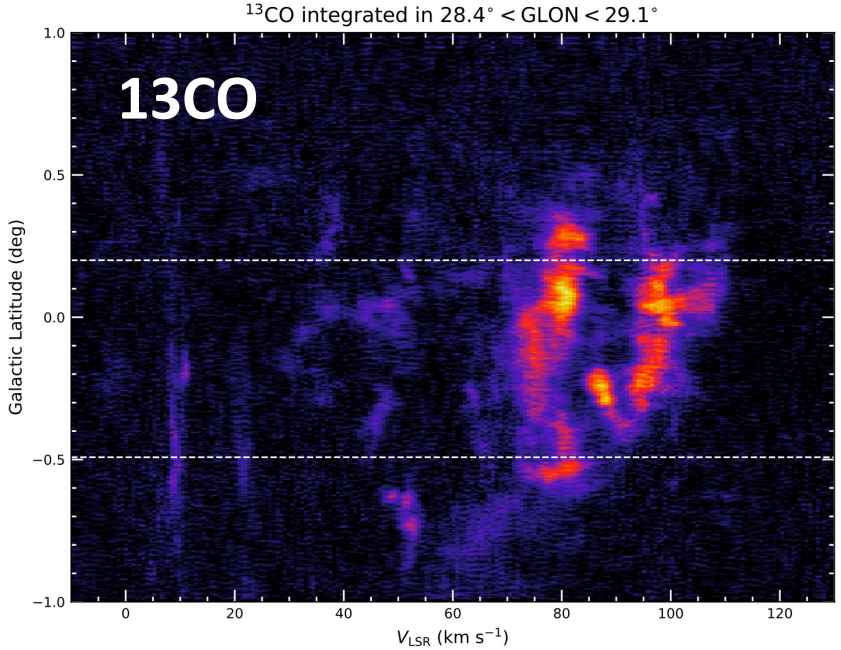
↑

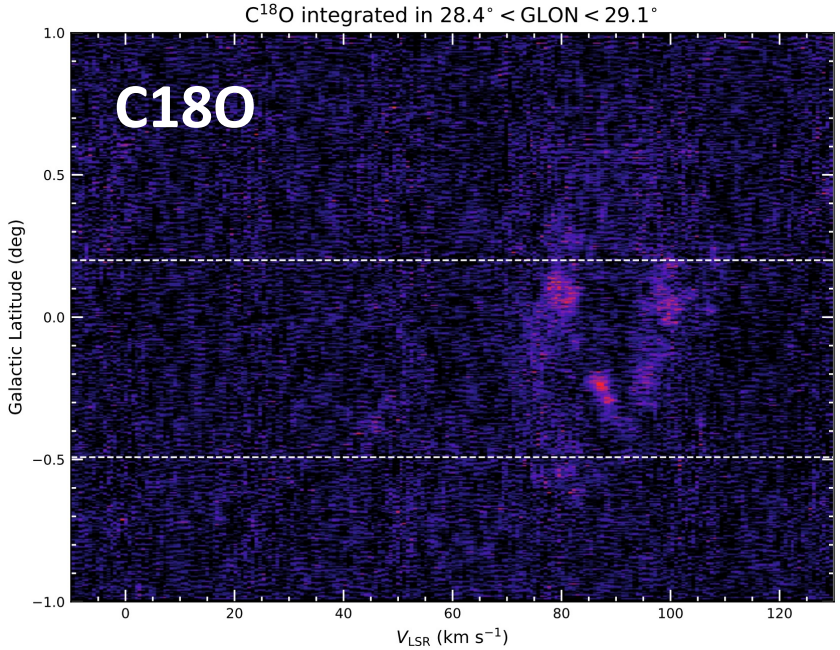
29.0

Comparison b/w 12CO, 13CO and C18O

VLSR-GLON







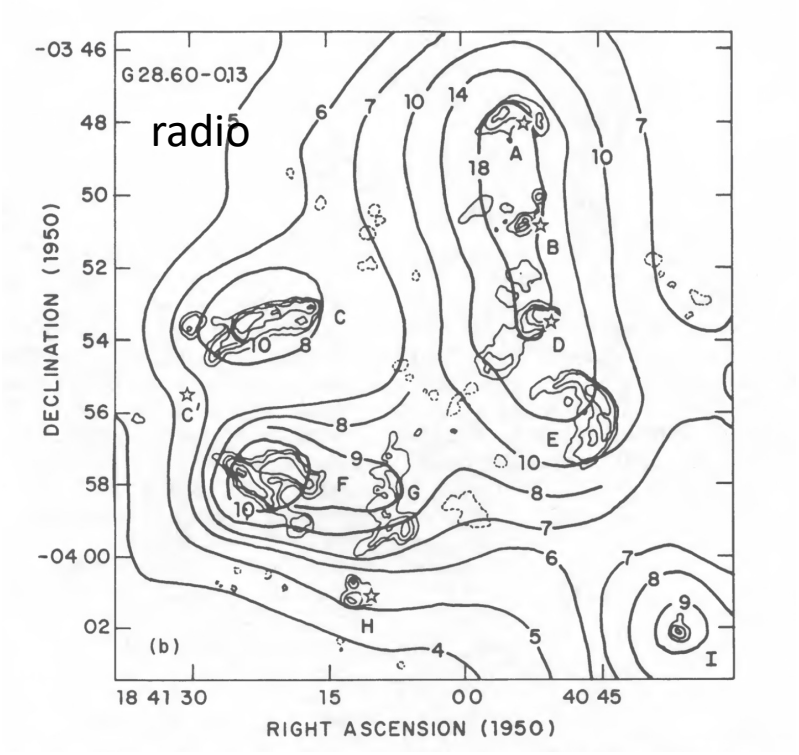
Modeling the gamma-ray emission (hadronic scenario)

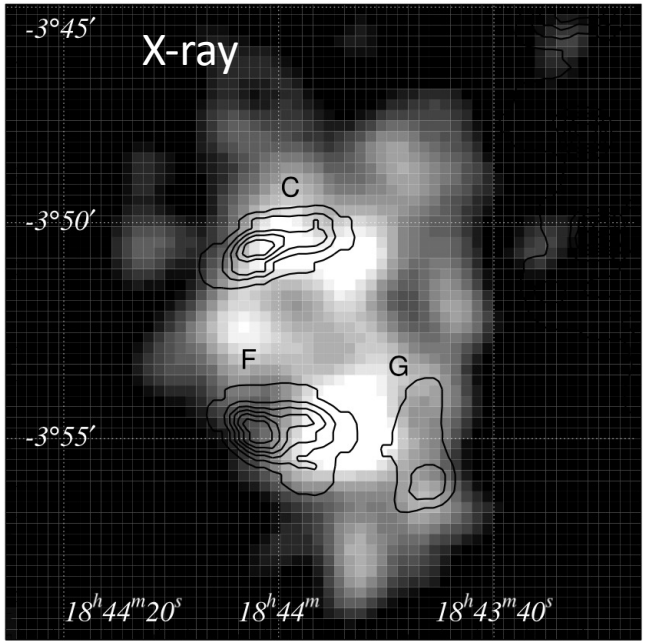
SNR G28.6-0.1

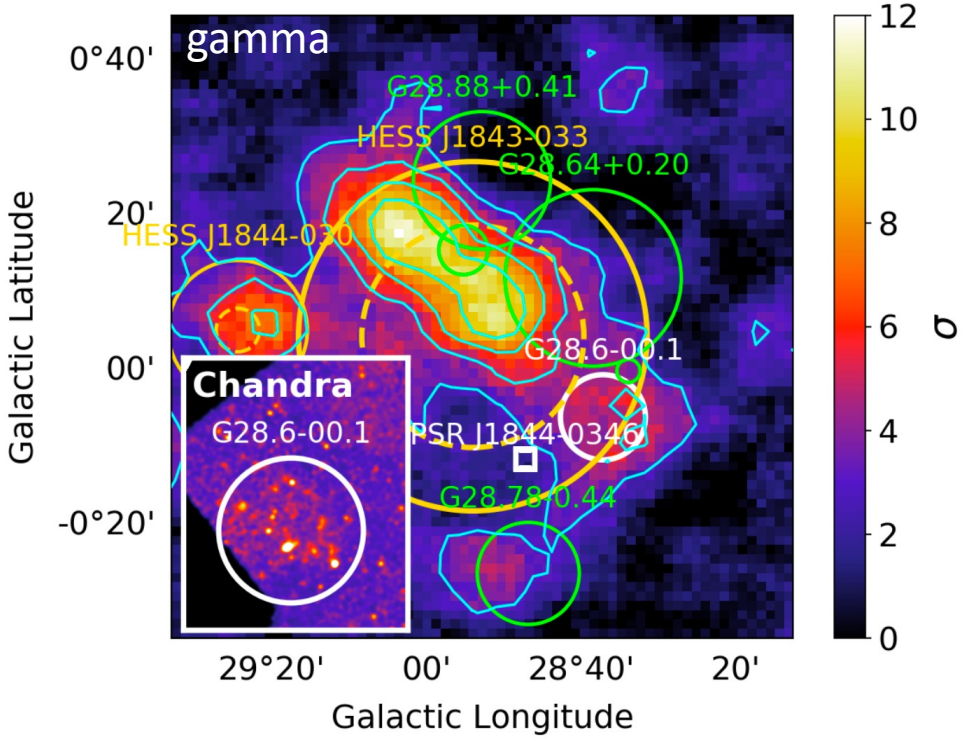
distance: 7 kpc (Bamba et al 2001), 9.6±0.3 kpc (Ranasinghe and Leahy 2018)

age: 2.7 kyr (Bamba et al 2001), 19 kyr (Ranasinghe and Leahy 2018)

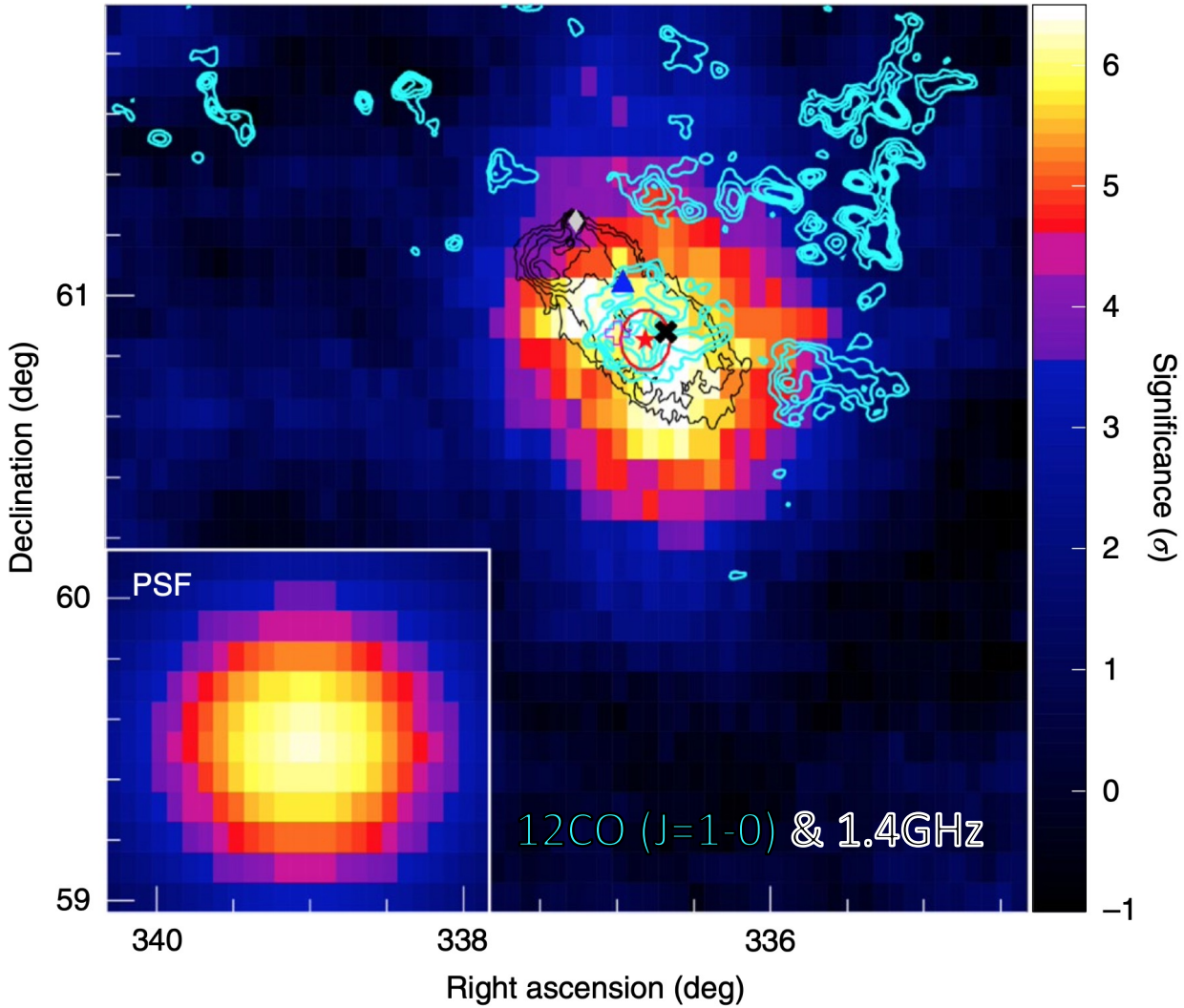
Non-thermal radio & X (Helfand et al 1989 & Bamba et al 2003) & TeV gamma (Devin et al 2021) are observed



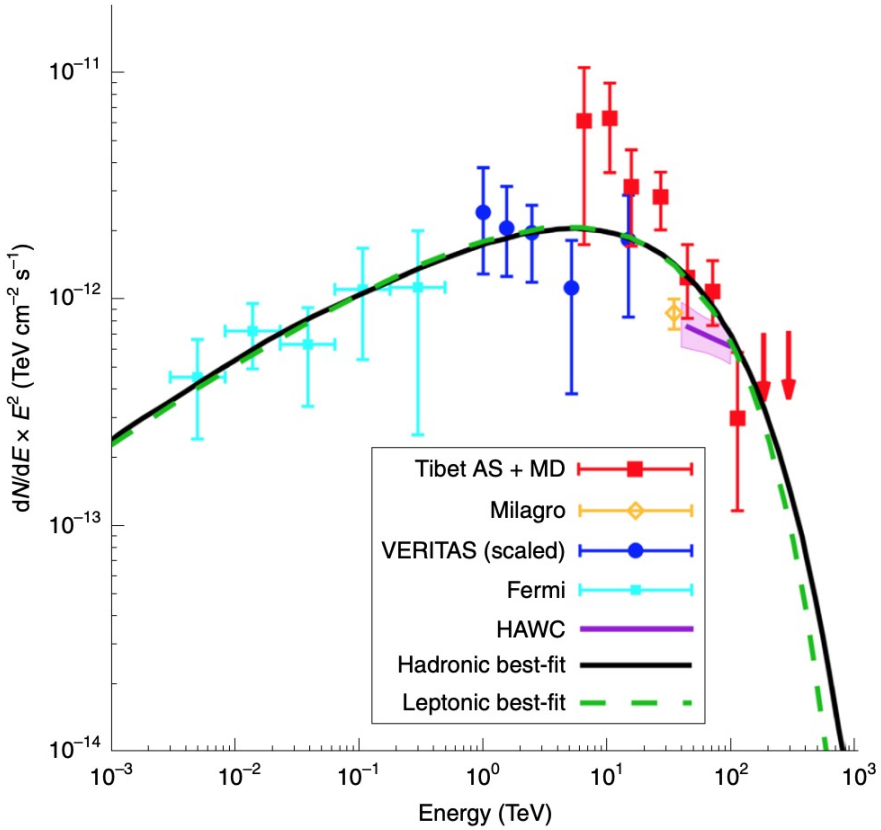




SNR G106.3+2.7: A PeVatron candidate (Amenomori et al., Nat. Astron. 5, 460 (2021)



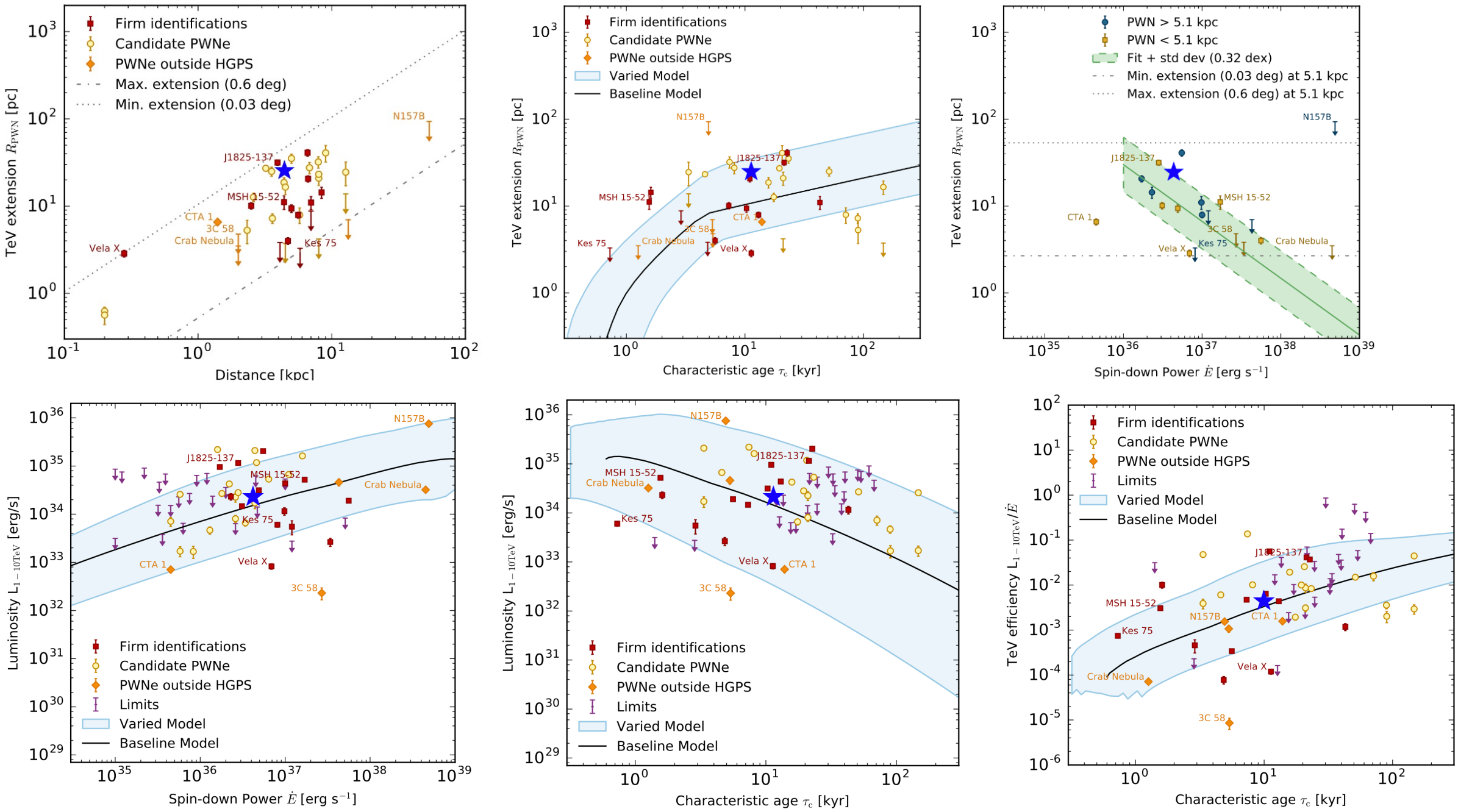
- age: ~ 10 kyr?
- distance: ~800 kpc?



	α	$E_{\rm cut}$ (TeV)	$W^{\ddagger}_{e/p}$ (10^{47} erg)	B (μG)	χ^2/ndf
leptonic	$2.30^{+0.08}_{-0.07}$	190^{+127}_{-66}	$1.4^{+1.8}_{-0.7}$	$8.6^{+3.4}_{-2.5}$	12.8/15
hadronic	$1.79^{+0.08}_{-0.09}$	499^{+382}_{-180}	$5.0^{+0.7}_{-0.6}$	—	13.0/14

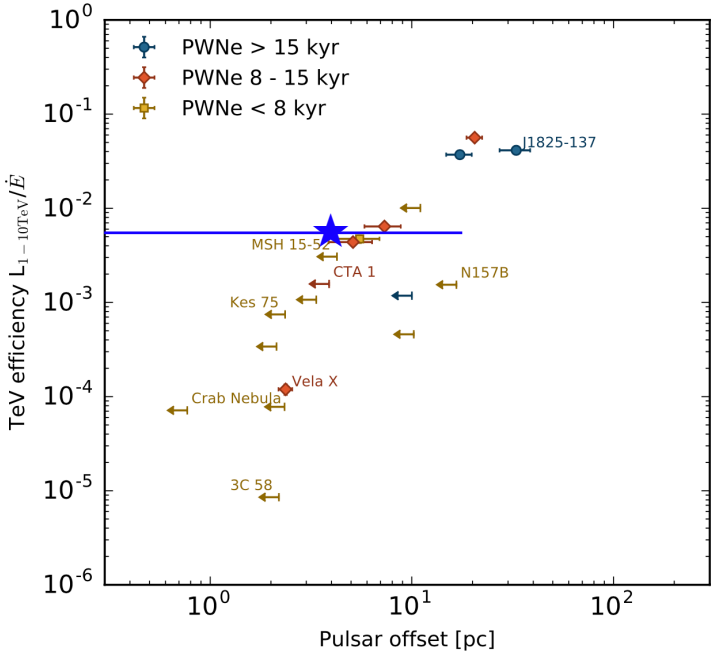
Association w/ PSR J1844-0346: TeV PWN?? (1)

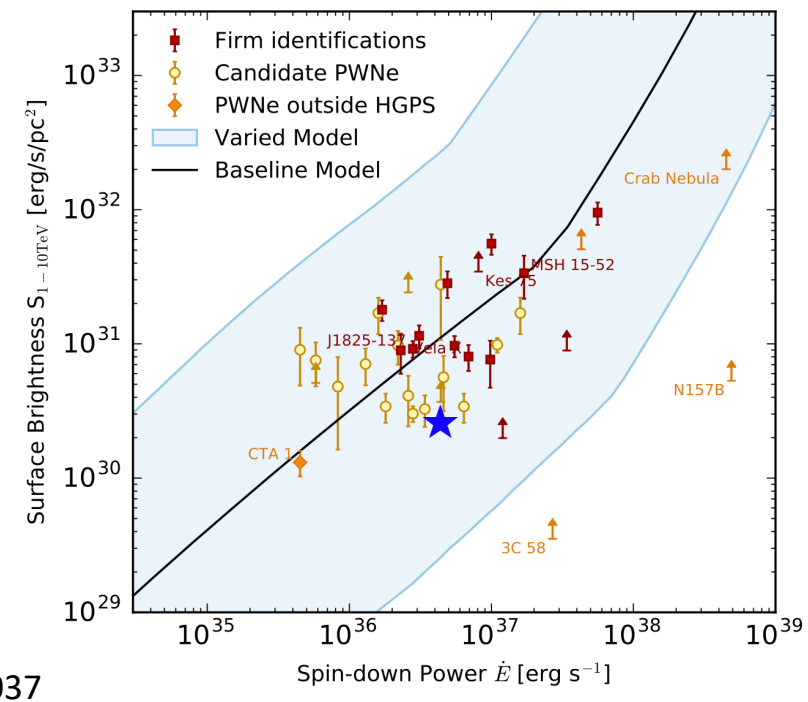
H.E.S.S. collaboration, A&A 612, A2 (2018)

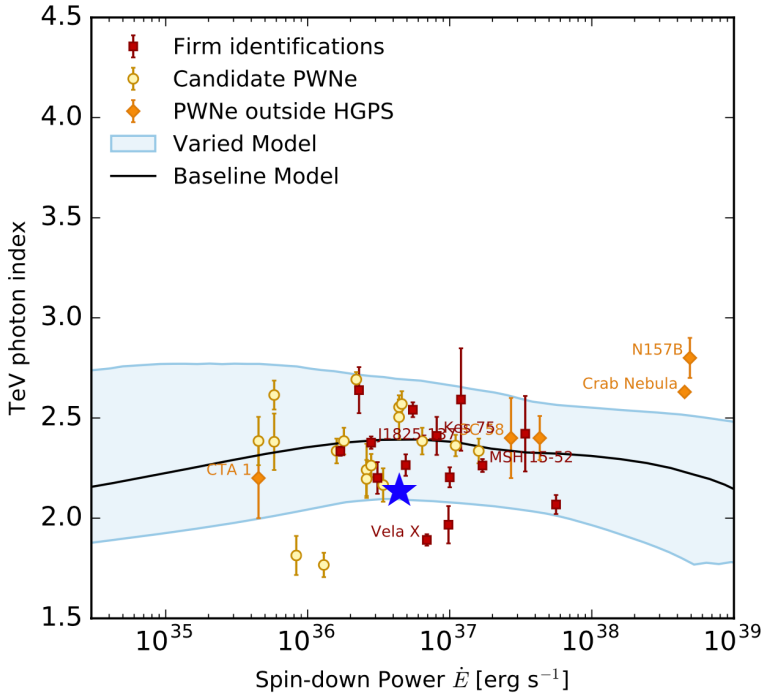


Association w/ PSR J1844-0346: TeV PWN?? (2)

H.E.S.S. collaboration, A&A 612, A2 (2018)







Error: Uncertainty on the position of TASG J1843-037

Surface brightness = Luminosity / ($4\pi \times R_{pwn}^2$) = 2.4×10^{34} erg s^{-1} / ($4\pi \times 26$pc^2) = 2.8×10^{30} erg s^{-1} pc^{-2}

Photon index: 2.15 (H.E.S.S. collaboration, A&A 612, A1, 2018) or 2.02 from our result on the ECPL fit

Statistical research on PWNe

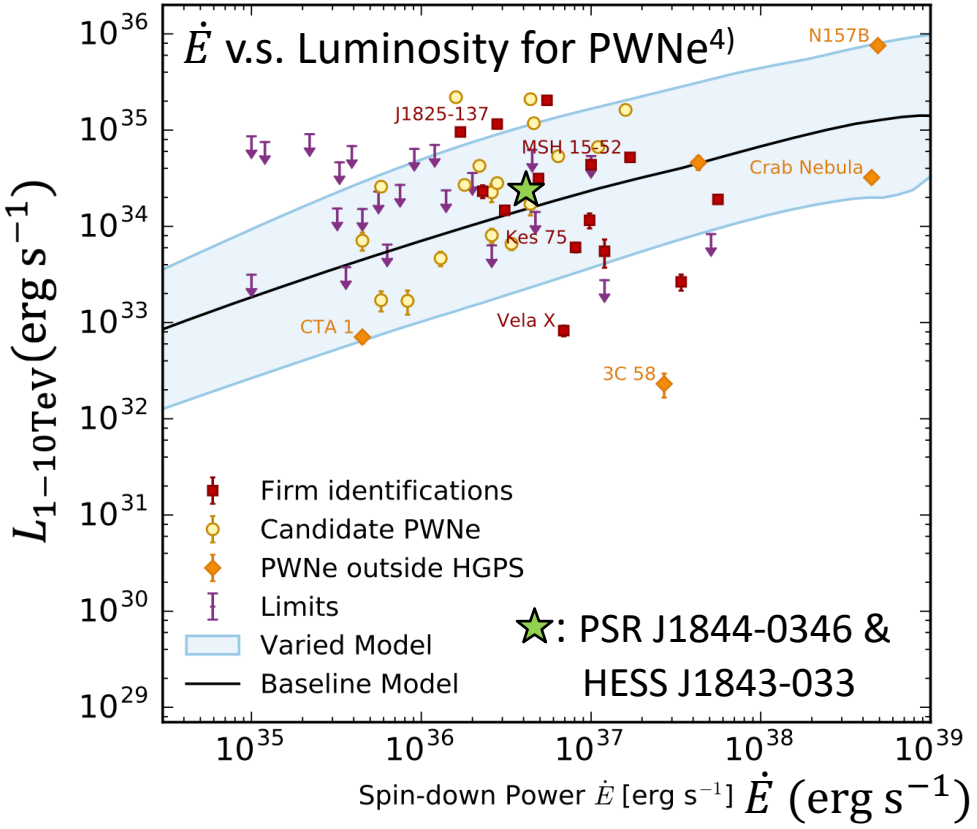
H.E.S.S. collaboration, A&A 612, A2 (2018)

Firm identification:

Table 1. HGPS sources considered as firmly identified pulsar wind nebulae in this paper.

HGPS name	ATNF name	Canonical name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	R_{PWN} (pc)	$L_{1-10\,TeV}$ (10^{33} erg s^{-1})
J1813−178[1]	J1813−1749		37.75	5.60	4.70	<2	2.07 ± 0.05	4.0 ± 0.3	19.0 ± 1.5
J1833−105	J1833−1034	G21.5−0.9[2]	37.53	4.85	4.10	<2	2.42 ± 0.19	<4	2.6 ± 0.5
J1514−591	B1509−58	MSH 15−52[3]	37.23	1.56	4.40	<4	2.26 ± 0.03	11.1 ± 2.0	52.1 ± 1.8
J1930+188	J1930+1852	G54.1+0.3[4]	37.08	2.89	7.00	<10	2.6 ± 0.3	<9	5.5 ± 1.8
J1420−607	J1420−6048	Kookaburra (K2)[5]	37.00	13.0	5.61	5.1 ± 1.2	2.20 ± 0.05	7.9 ± 0.6	44 ± 3
J1849−000	J1849−0001	IGR J18490−0000[6]	36.99	42.9	7.00	<10	1.97 ± 0.09	11.0 ± 1.9	12 ± 2
J1846−029	J1846−0258	Kes 75[2]	36.91	0.728	5.80	<2	2.41 ± 0.09	<3	6.0 ± 0.7
J0835−455	B0833−45	Vela X[7]	36.84	11.3	0.280	2.37 ± 0.18	1.89 ± 0.03	2.9 ± 0.3	0.83 ± 0.11*
J1837−069[8]	J1838−0655		36.74	22.7	6.60	17 ± 3	2.54 ± 0.04	41 ± 4	204 ± 8
J1418−609	J1418−6058	Kookaburra (Rabbit)[5]	36.69	10.3	5.00	7.3 ± 1.5	2.26 ± 0.05	9.4 ± 0.9	31 ± 3
J1356−645[9]	J1357−6429		36.49	7.31	2.50	5.5 ± 1.4	2.20 ± 0.08	10.1 ± 0.9	14.7 ± 1.4
J1825−137[10]	B1823−13		36.45	21.4	3.93	33 ± 6	2.38 ± 0.03	32 ± 2	116 ± 4
J1119−614	J1119−6127	G292.2−0.5[11]	36.36	1.61	8.40	<11	2.64 ± 0.12	14 ± 2	23 ± 4
J1303−631[12]	J1301−6305		36.23	11.0	6.65	20.5 ± 1.8	2.33 ± 0.02	20.6 ± 1.7	96 ± 5

Counterpart?: eHWC J1850+001 abv. 56 TeV & LHAASO J1849-0003 @100 TeV



PWNe outside HGPS (firmly identified):

Table 3. Pulsar wind nebulae outside the HGPS catalogue.

Canonical name	ATNF name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	R_{PWN} (pc)	$L_{1-10\,TeV}$ (10^{33} erg s^{-1})
N157B[1]	J0537−6910	38.69	4.93	53.7	<22	2.80 ± 0.10	<94	760 ± 80
Crab Nebula[2]	B0531+21	38.65	1.26	2.00	<0.8	2.63 ± 0.02	<3	32.1 ± 0.7
G0.9+0.1[3]	J1747−2809	37.63	5.31	13.3	<3	2.40 ± 0.11	<7	46 ± 7
3C 58[4]	J0205+6449	37.43	5.37	2.00	<2	2.4 ± 0.2	<5	0.23 ± 0.06
CTA 1[5]	J0007+7303	35.65	13.9	1.40	<4	2.2 ± 0.2	6.6 ± 0.5	0.71 ± 0.10

Candidate PWNe: Other than firmly identified PWNe, safisfy $\dot{E}$ / d2 > 10^{34} erg s^{-1} kpc^{-2} & $\theta_{PSR\text{-}TeV\gamma}$ < 0.5 deg & τ_c < 10^7 yr.

This list includes HESS J1908+063 for which eHWC J1907+063 and LHAASO J1908+0621 can be a counterpart.

Limits: PRSs (w/ $\dot{E}$ > 10^{35} erg s^{-1}) that coincide w/ a firm PWN HGPS src. or do not have a nearby HGPS src.

This list includes HESS J1841-055 for which eHWC J1839-057 and LHAASO J1839-0545 can be a counterpart.