Ultra-high-energy gamma rays from pulsar-wind nebulae and their contributions to Galactic gamma-ray emission

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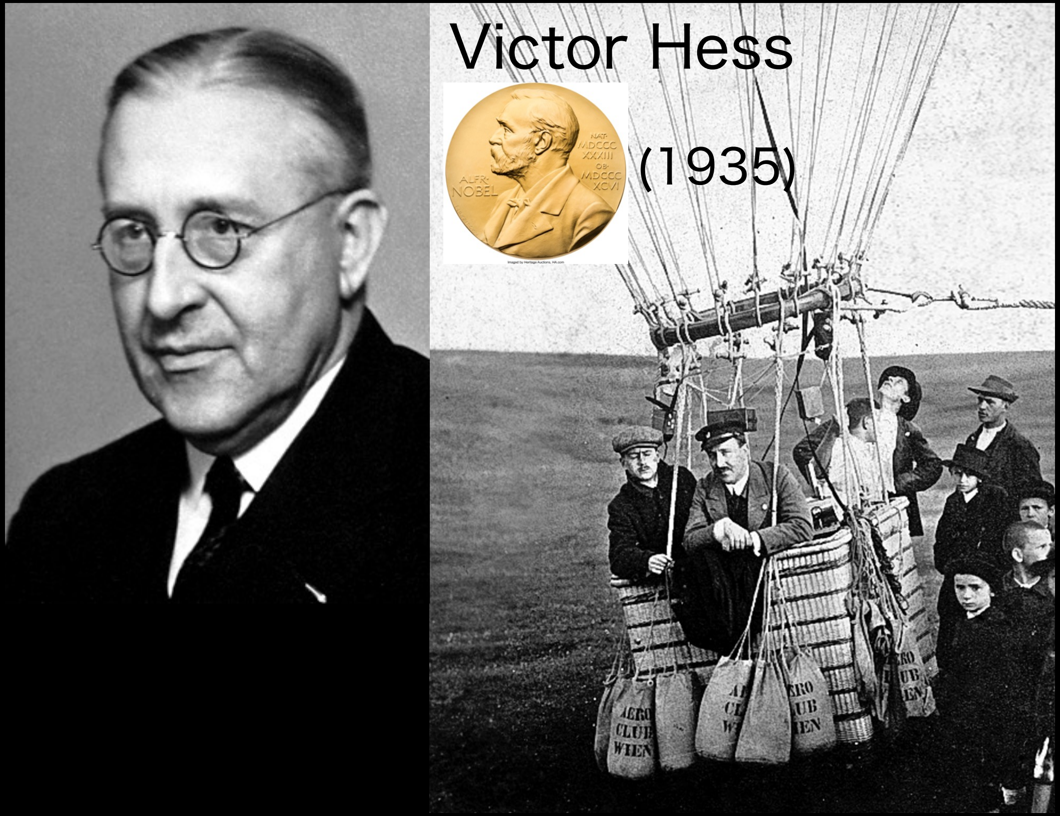
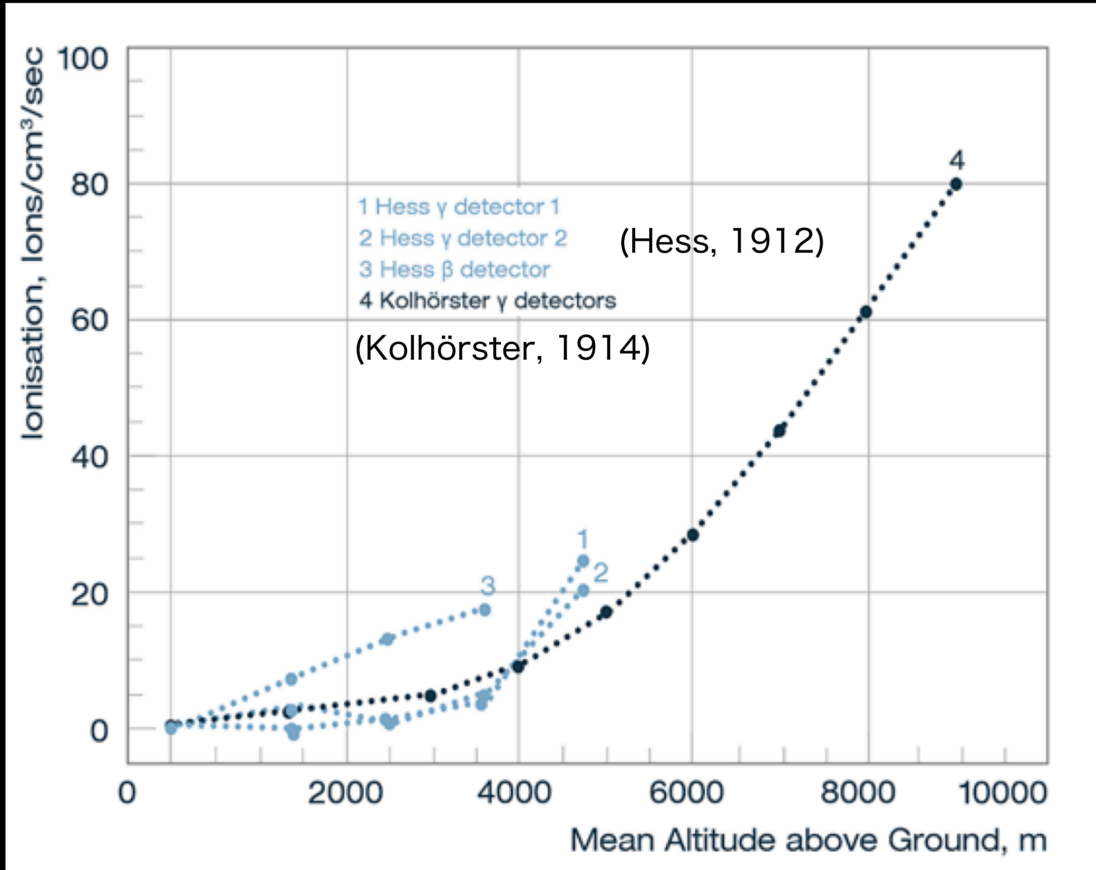
Cosmic Rays (CRs)

- ✓High energy H, He, Fe, ⋯
- ✓Important piece that affects the evolution of Galaxies

$$\varepsilon_{CR} \sim \varepsilon_{B} \sim \varepsilon_{gas} \sim 1 \text{ eV cm}^{-3}$$

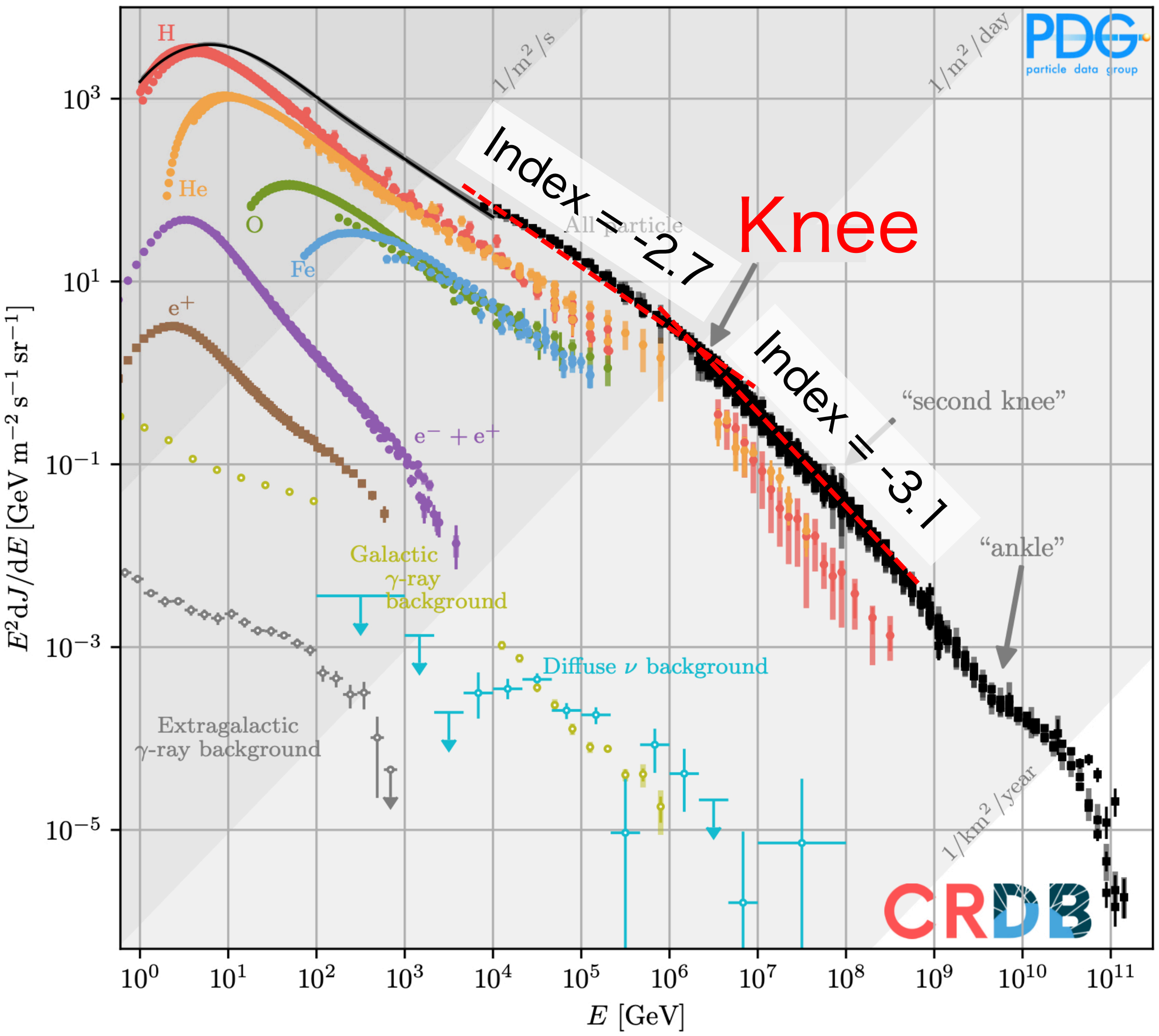




V. F. Hess (translated by Angelis & Schultz), Arxiv 1808.02927 (2018)

Knee Feature @ 4 PeV = 4×10^{15} eV in the CR spectrum

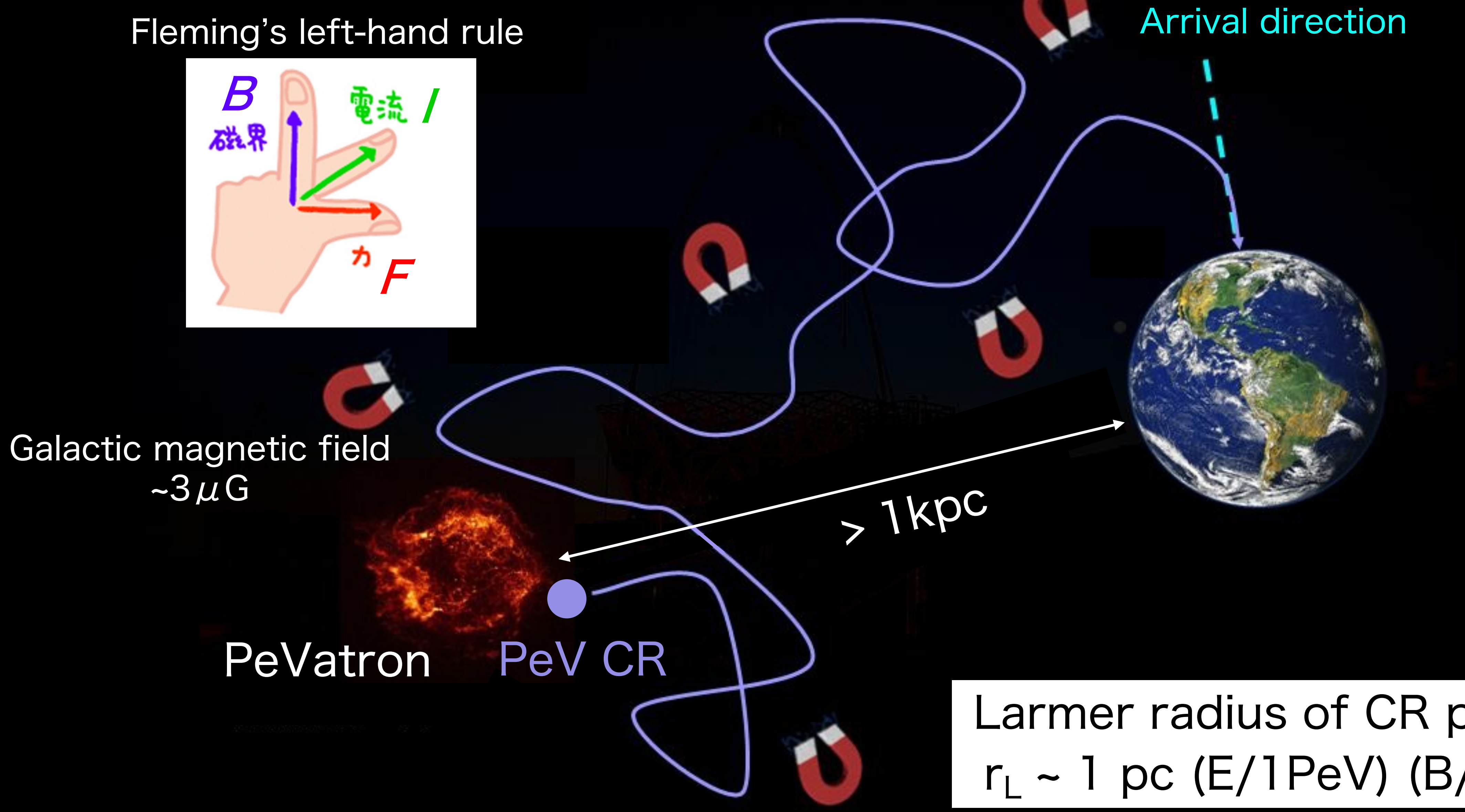
All particle CR energy spectrum (black)



- Differential spectral index changes -2.7 → -3.1
- Acceleration limit of Galactic CR protons?
  Obs. of Galactic diffuse gamma rays
  => PeV CR(proton) acceleration in MW
  Obs. of CR mass composition
  => Light composition (p & He)
- Search for Galactic PeV CRp accelerators
  PeVatrons

Amenomori et al., PRL 126, 141101 (2021)
Cao et al., PRL 132, 131002 (2024)

CR Observation Does NOT Help You Search For PeVatrons



Larmer radius of CR proton
$r_L \sim 1\ \mathrm{pc}\ (E/1\mathrm{PeV})\ (B/\mu G)^{-1}$

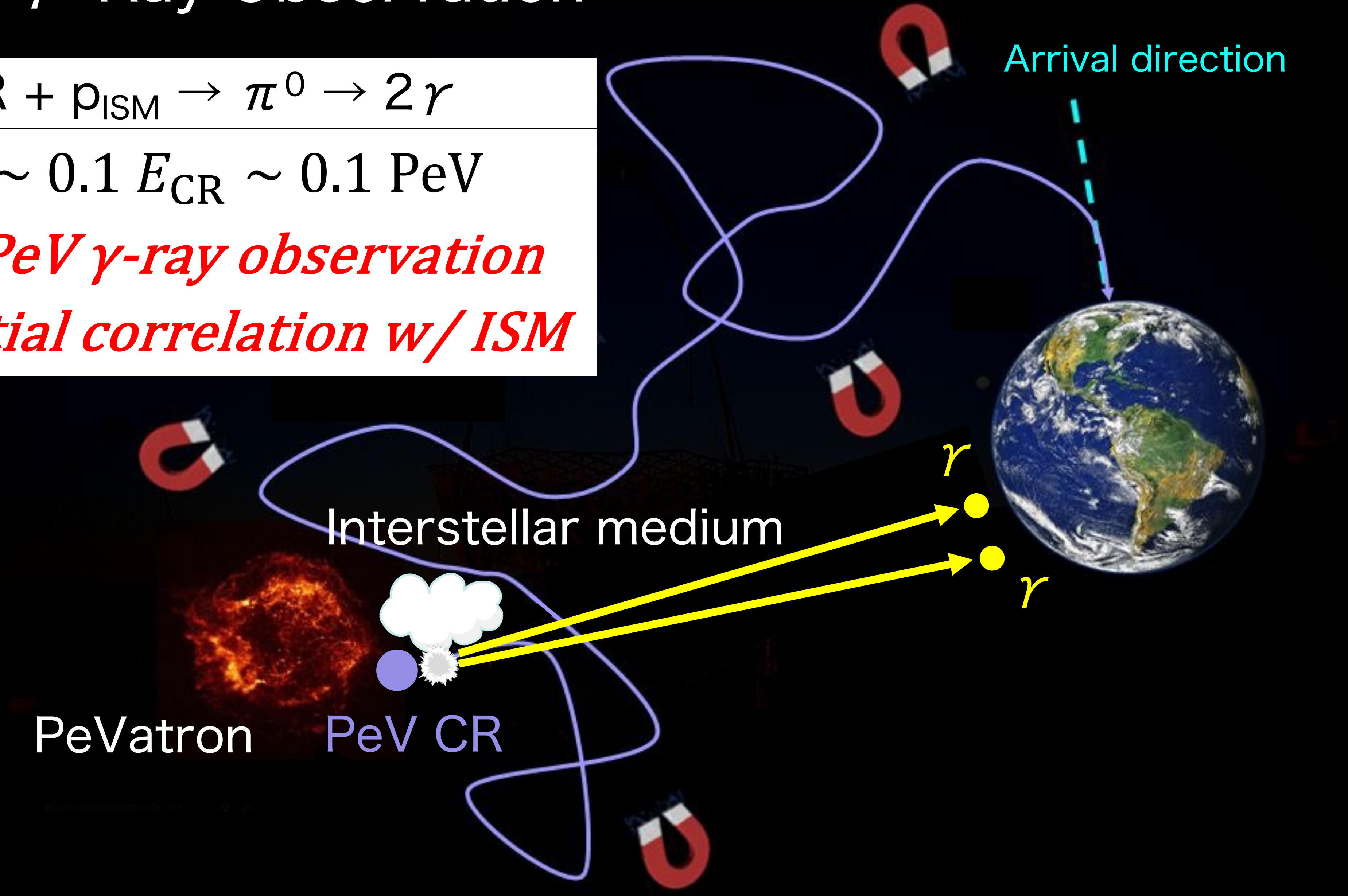
Sub-PeV γ-Ray Observation

$$\mathrm{CR} + \mathrm{p_{ISM}} \rightarrow \pi^0 \rightarrow 2\gamma$$

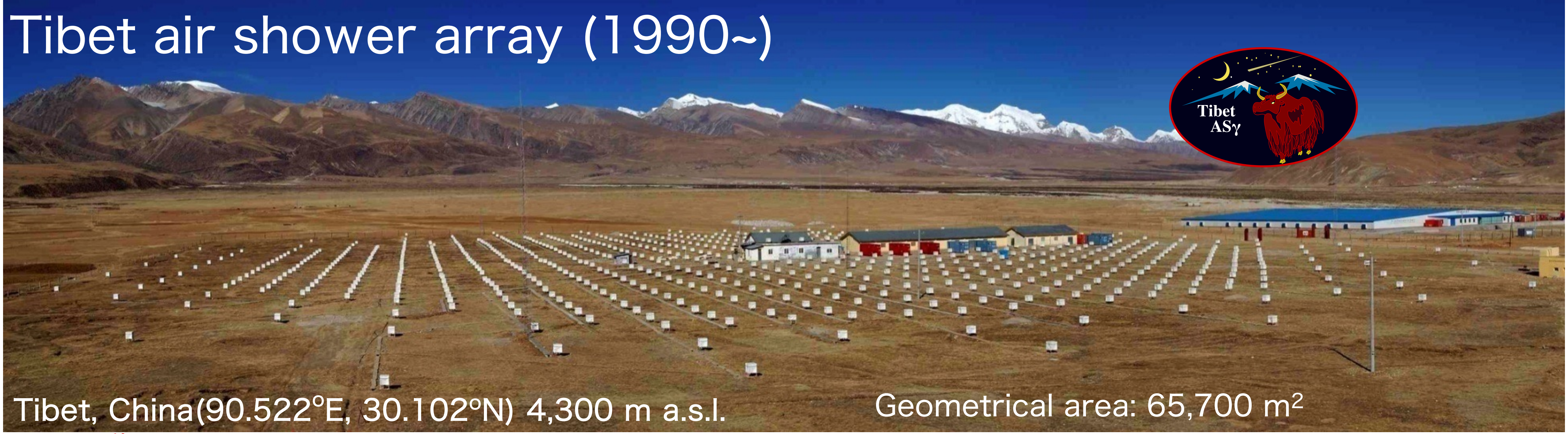
$$E_\gamma \sim 0.1\ E_{\mathrm{CR}} \sim 0.1\ \mathrm{PeV}$$

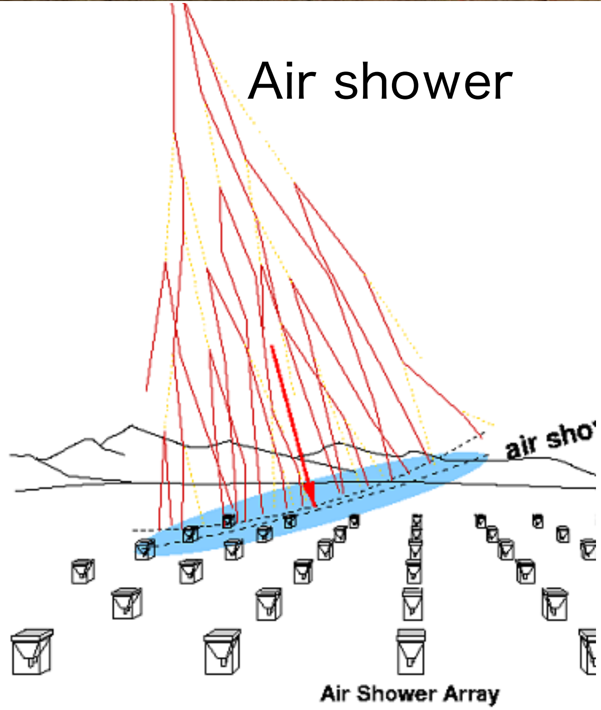
Sub-PeV γ-ray observation

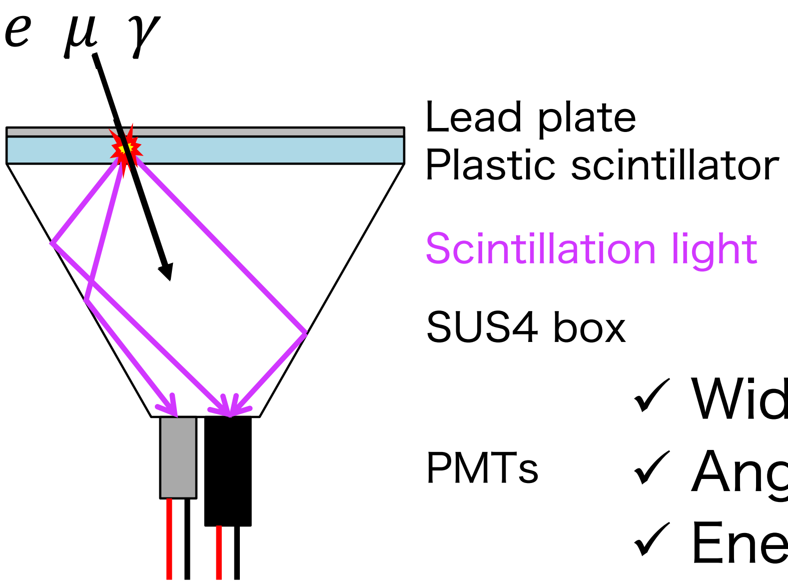
& Spatial correlation w/ ISM



Tibet air shower array (1990~)

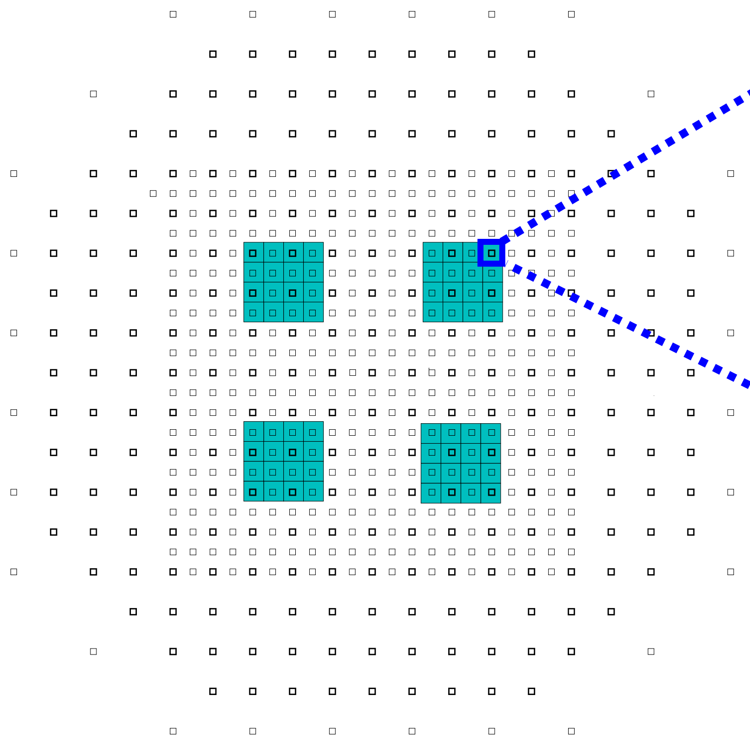


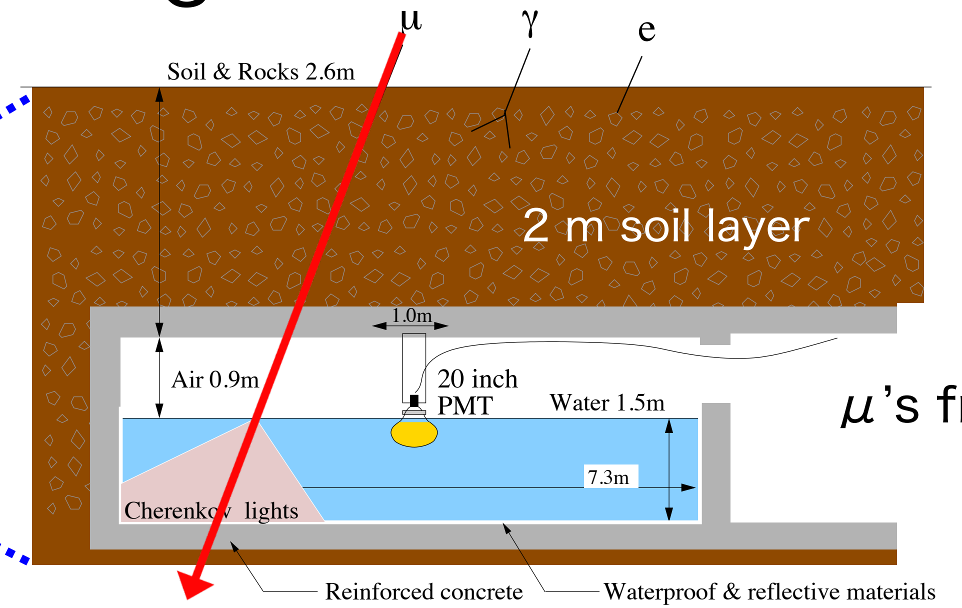




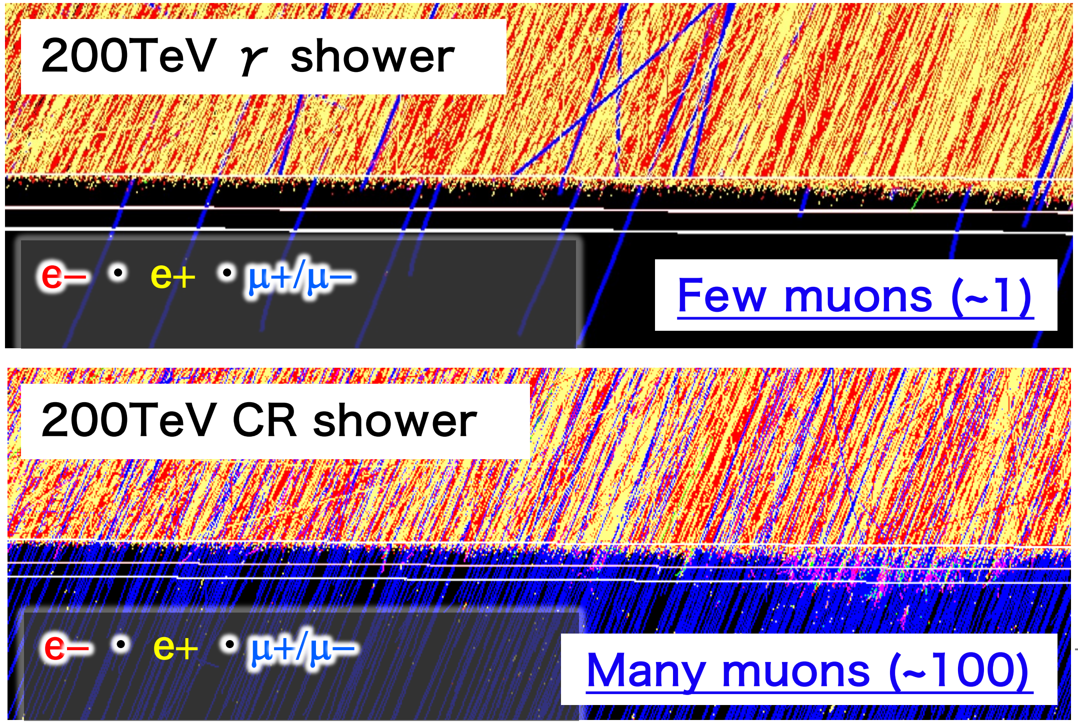
- ✓ Wide F.O.V. (~ 2 sr) & high duty cycle (>90%)
- ✓ Angular resolution : 0.2° for 0.1 PeV γ
- ✓ Energy resolution : 20% for 0.1 PeV γ

BG Rejection w/ an Underground Muon Detector Array





μ's from the decay of mesons



BG rejection : >99.9% @ sub-PeV

Sensitivity to γ : improvement by > 10

PeV CR acceleration in pulsar wind nebula?
UHE gamma rays from HESS J1849−000

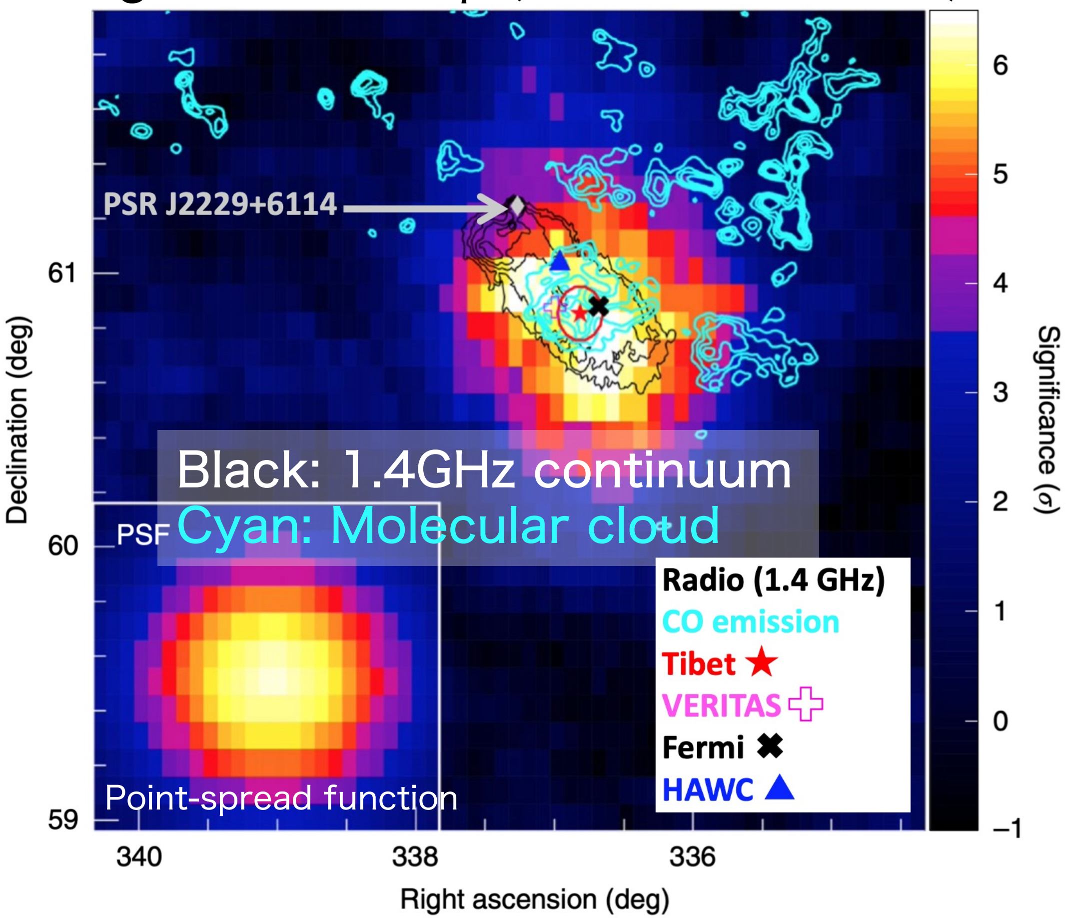
Amenomori, Kato et al., ApJ 954, 200 (2023)

Is Supernova Remnant Really Representative of PeVatron?

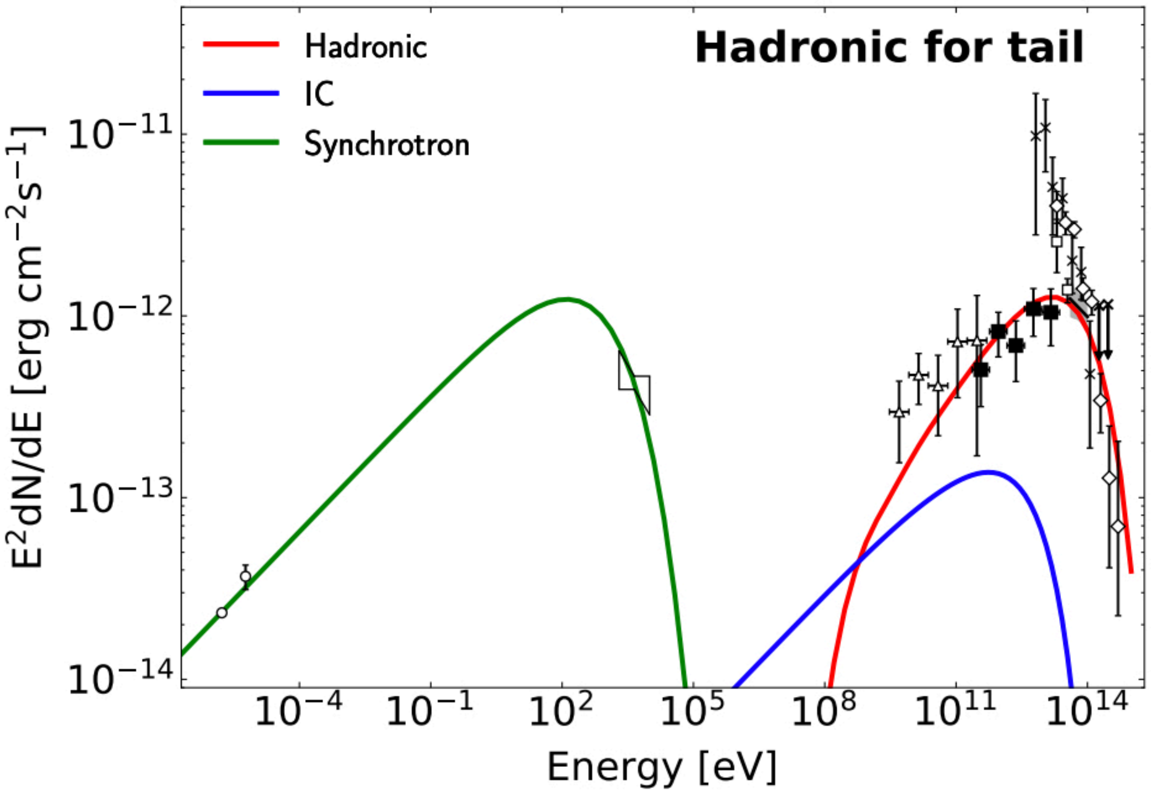
Promising case: SNR G106.3+2.7

1. M. Amenomori et al., Nat. Astron. Lett, 5, 460 (2021)

Significance map (Tibet, E >10 TeV[1])



Modeling of the γ-ray energy spectrum

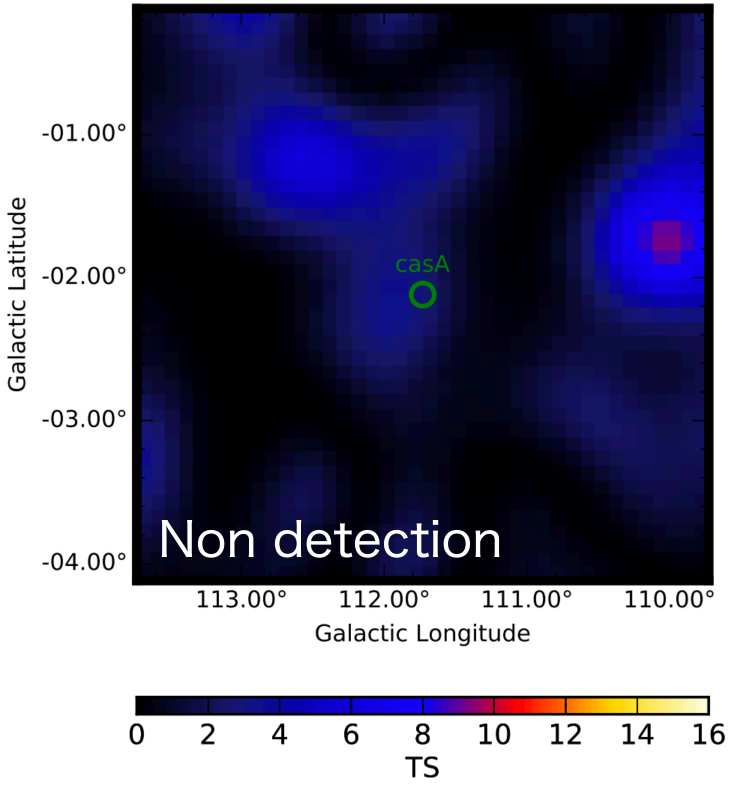


- ✓ SNR G106: discovered in radio continuum (1.4GHz)
- ✓ Gamma-ray emission coming from a molecular cloud
- ✓ Hadronic modeling gives $E_{p,cut}$ ~ 1PeV

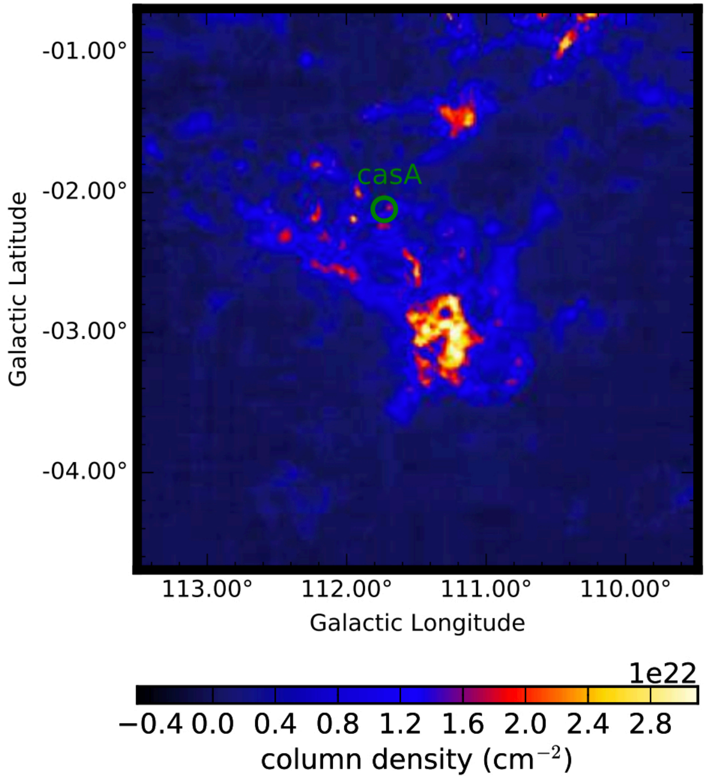
Is Supernova Remnant Really Representative of PeVatron?

Doubtful case: Cassiopeia A (age ~350 yrs)

LHAASO γ-ray obs. E > 25TeV

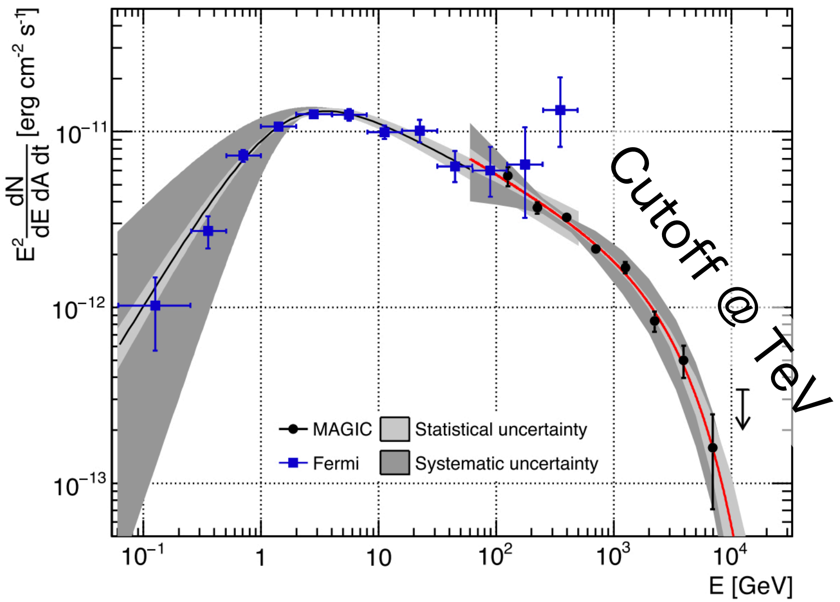


Molecular clouds



Cao et al., ApJL 961, L43 (2024)

MAGIC spectral measurement



MAGIC Collab. MNRAS 472, 2956 (2017)

Active young SNRs are NOT a factory of PeV CRs?

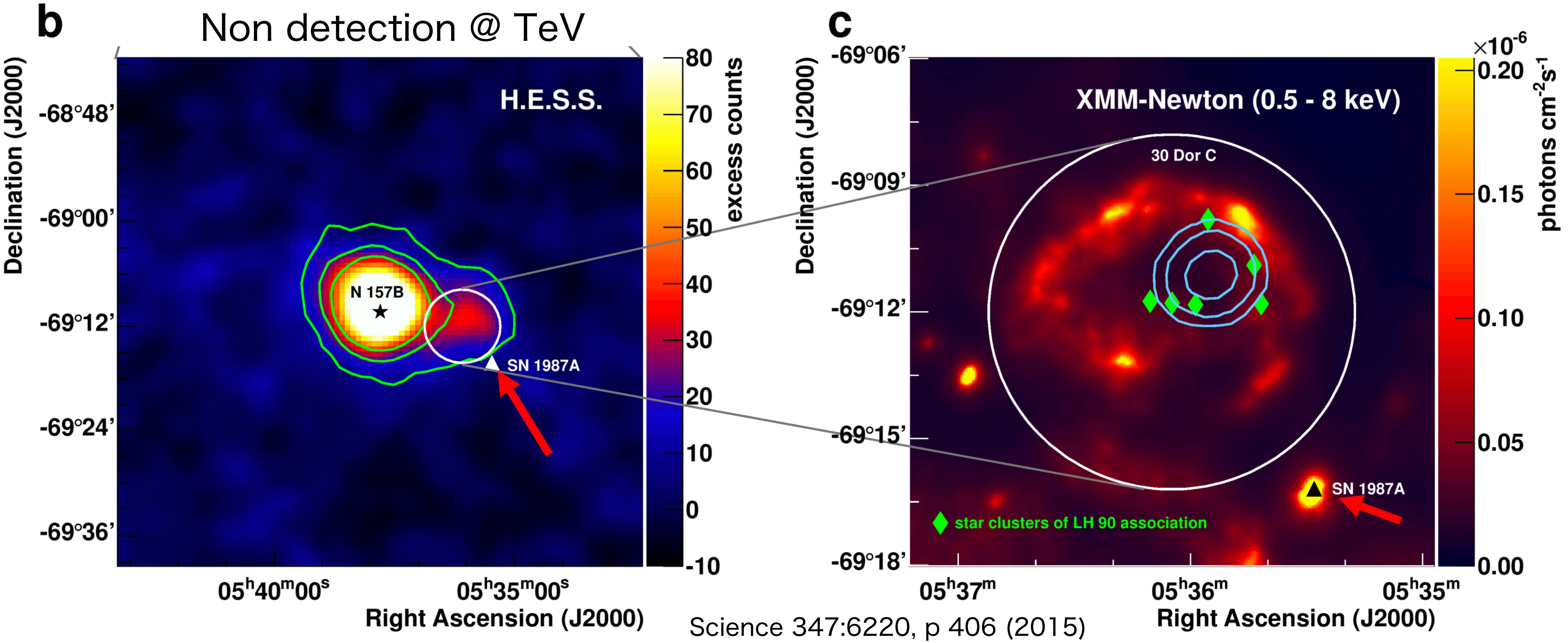
Is Supernova Remnant Really Representative of PeVatron?

Doubtful case: 1987A

Slide from N. Komin, IAUS 331: SN 1987A, 30 Years Later

- **not detected**
- gamma ray flux
  F (>1 TeV) < 5 x 10^{-14} $cm^{-2}s^{-1}$
  - 99% confidence level
- gamma ray luminosity
  L (>1 TeV) < 2.2 10^{34} erg/s
- at predicted level
  [Berezhko, Ksenofont

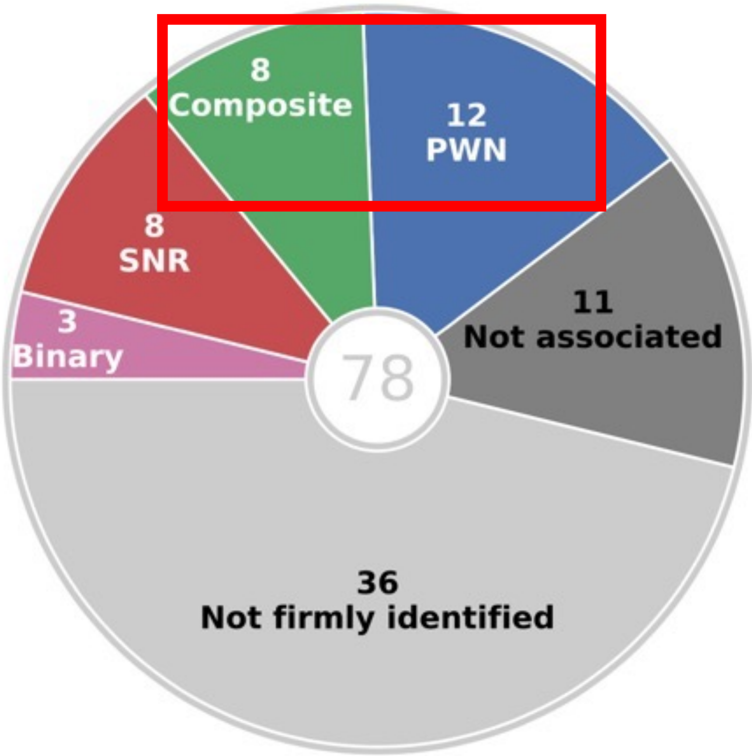
Non detection @ TeV



Science 347:6220, p 406 (2015)

Why Pulsar Wind Nebula (PWN)?

H.E.S.S. Gal. Plane Survey[1] (E > 100GeV)
<u>20/78 sources are associated w/ PWNe</u>



35(/90) 1LHAASO sources associated w/ PSRs[2]
<u>15 sources w/ identified PWNe/TeV Halo</u>

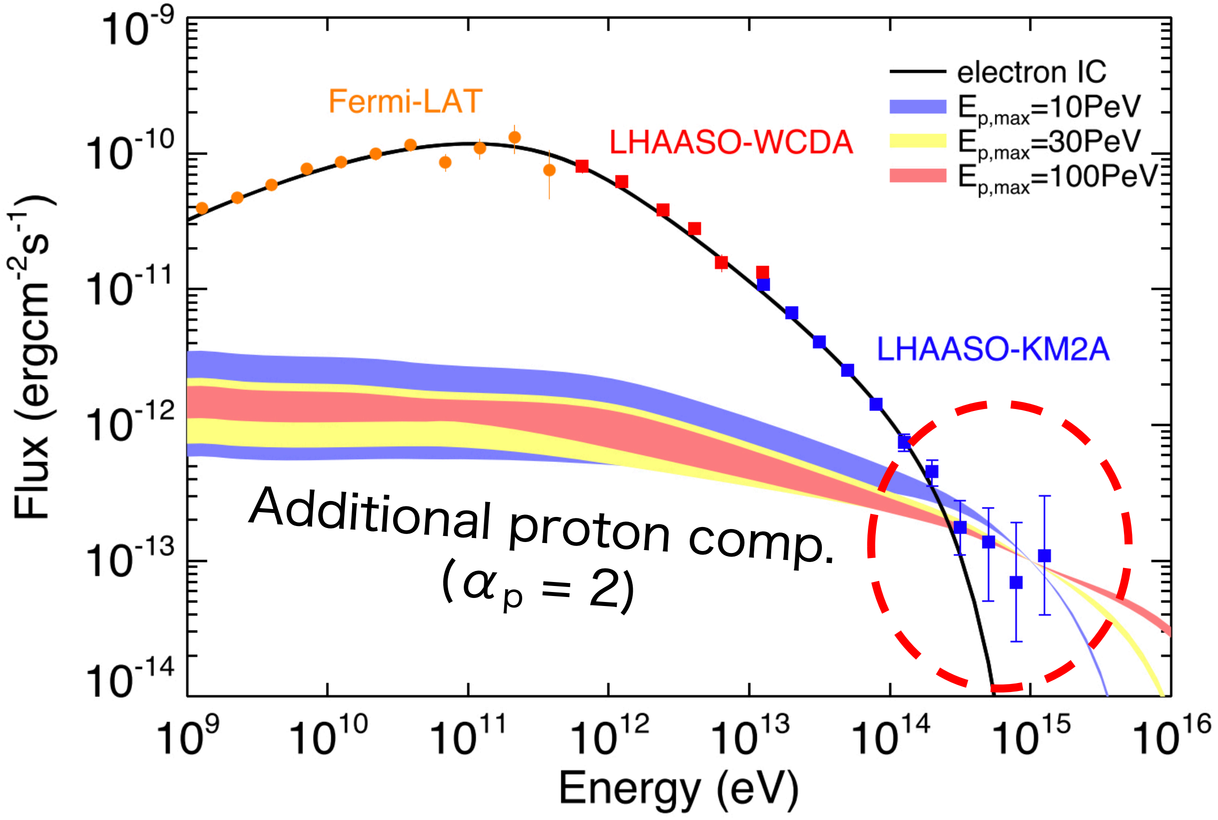
Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
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 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

CR Acceleration in the Crab PWN?

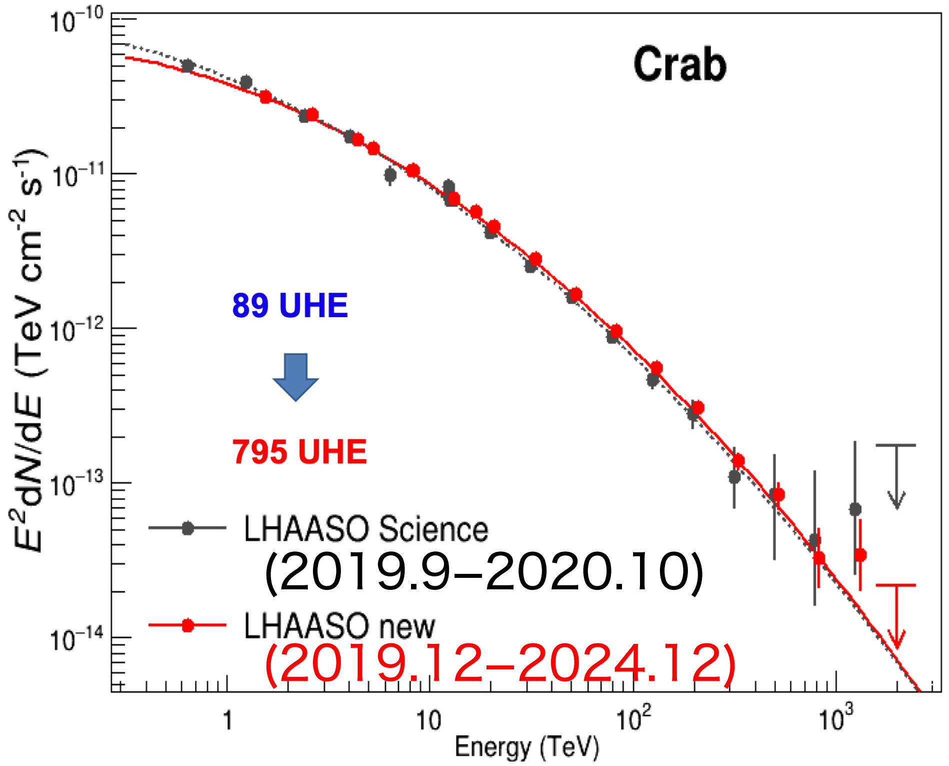
Modeling of the Crab γ-ray spectrum



Liu & Wang, ApJ 922, 221 (2021)

Updated spectrum (LHAASO)

From Chen, 2nd LHAASO symposium (2025)

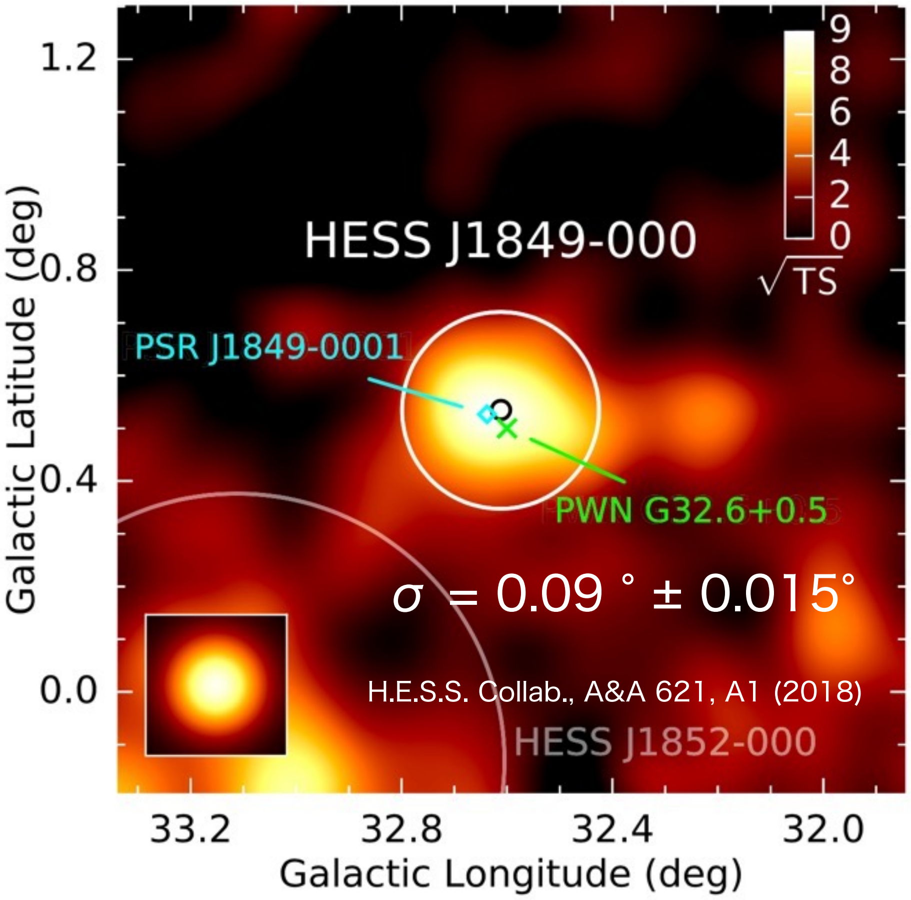


- ✓ Slight hardening of the spectrum needs protons?
- ✓ 2nd electron component w/ α ~ 1.5 can also explain the data
- ✓ Updated data points are milder than before

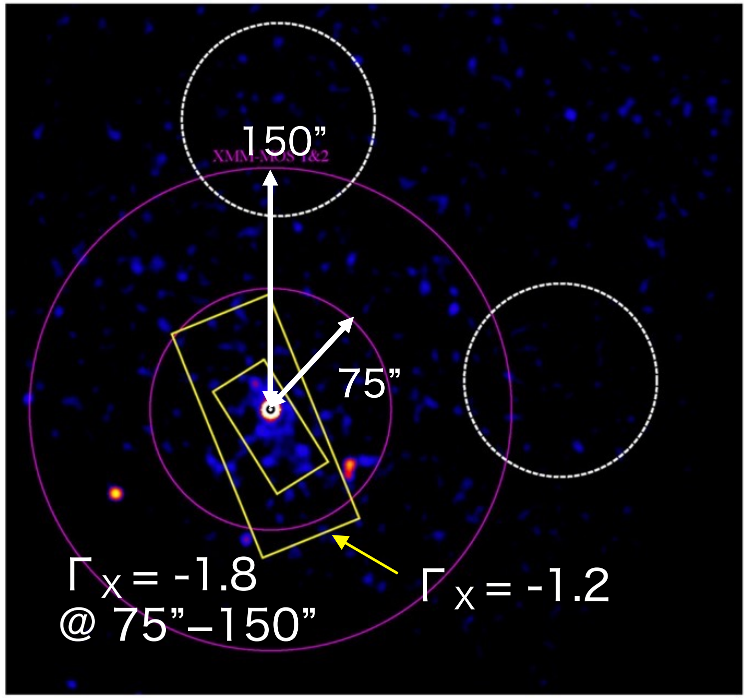
See also LHAASO Collab. Science (2021), Aharonian & Atoyan (1998), Nie et al., ApJ (2022), …

HESS J1849−000: A Middle Aged PWN

Significance map (> 400GeV)

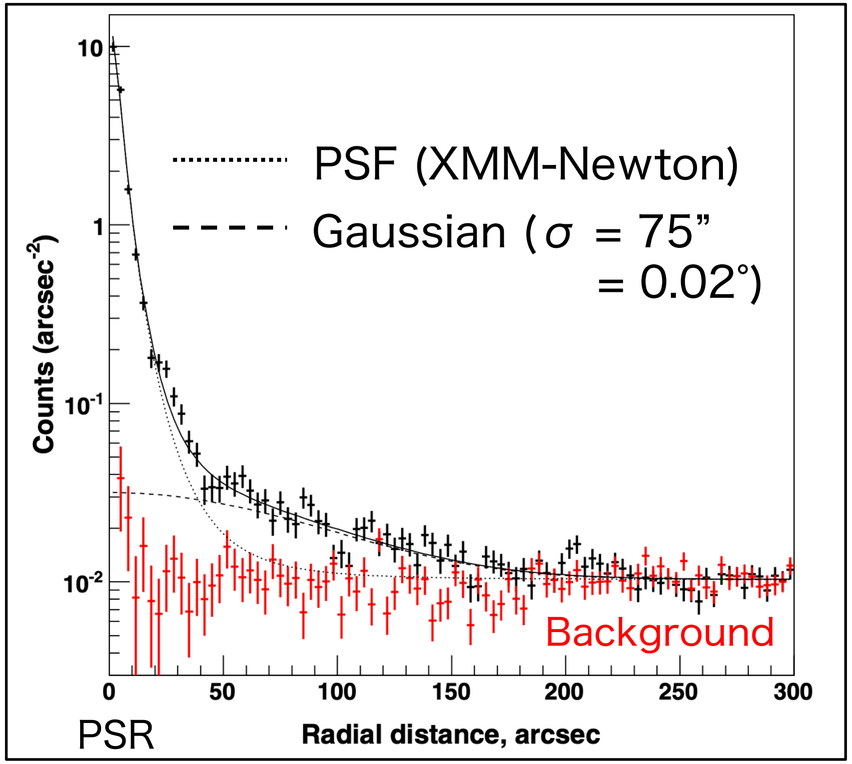


Chandra ACIS (2-10 keV)



Kuiper & Hermsen, MNRAS 449, 3827 (2015)

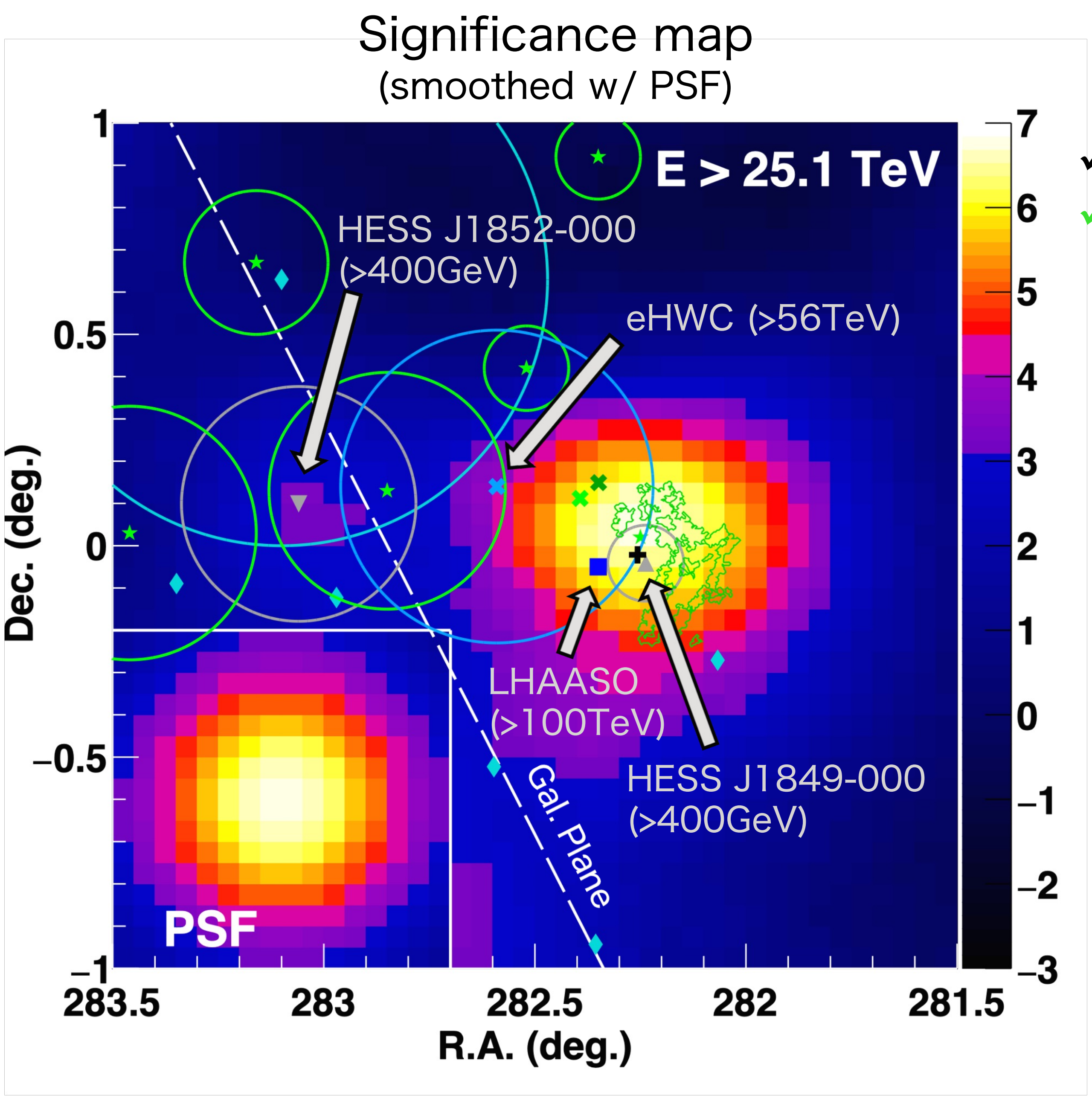
X-ray radial profile (0.2-10keV)



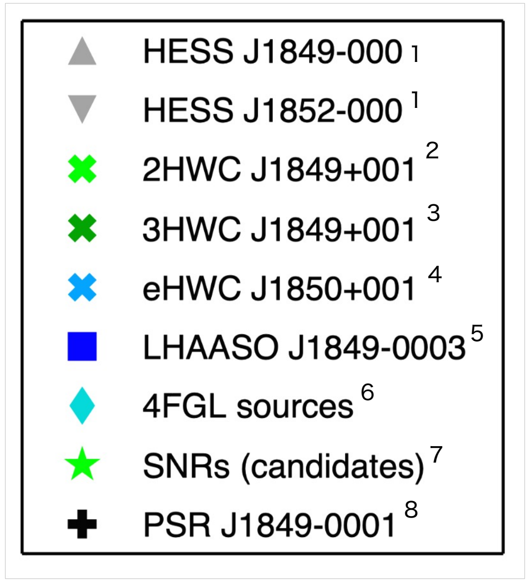
Gotthelf et al., ApJL 729, L16 (2011)

- ✓ P = 38.5 ms, E_{spin} = 9.8×10^{36} erg s^{-1}, τ_c = 42.9 kyr, B = 7.5×10^{11} G
- ✓ Distance = 7 kpc from the X-ray spectral analysis (Gotthelf et al., 2011)
- ✓ X-ray observations found a PWN & synchrotron cooling
- ! No detailed spectral study of sub-PeV gamma rays & the origin of the γ-ray emission

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



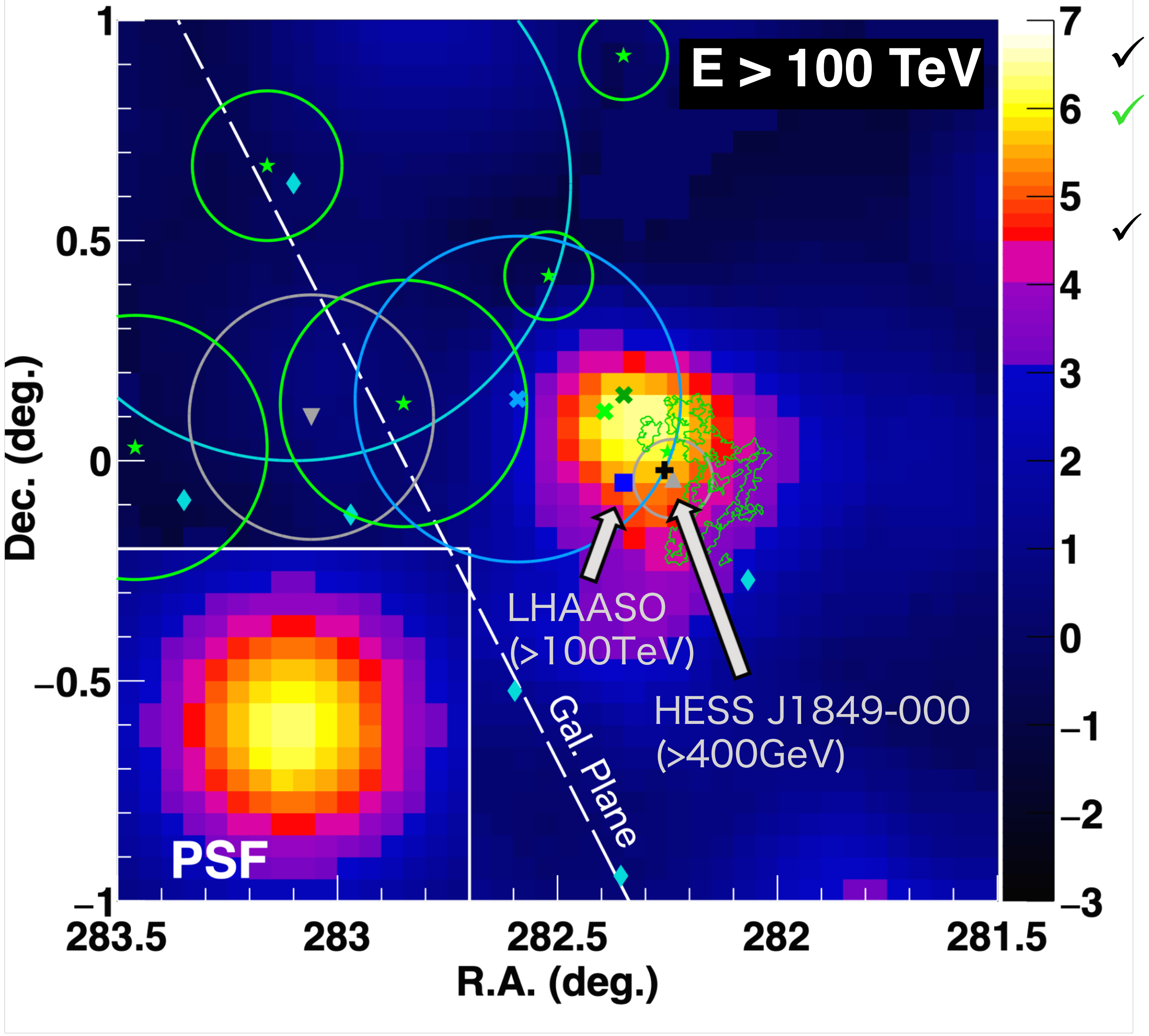
- ✓ 4.0 σ detection @ E > 25TeV
- ✓ Green contour : Mol. Cloud found in this study



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)

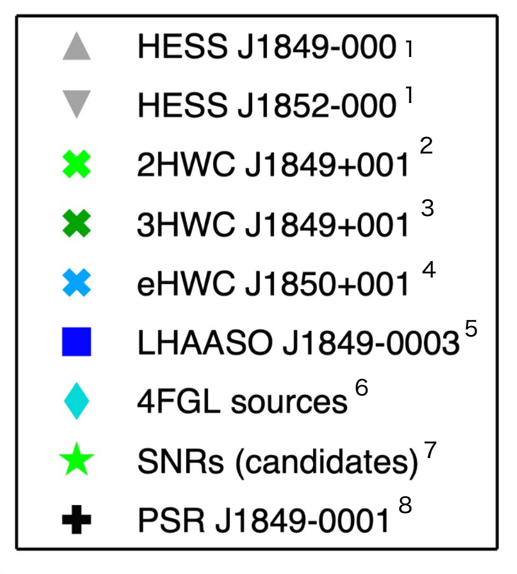
Detection of γ Rays from HESS J1849−000 @ > 100 TeV

Significance map
(smoothed w/ PSF)



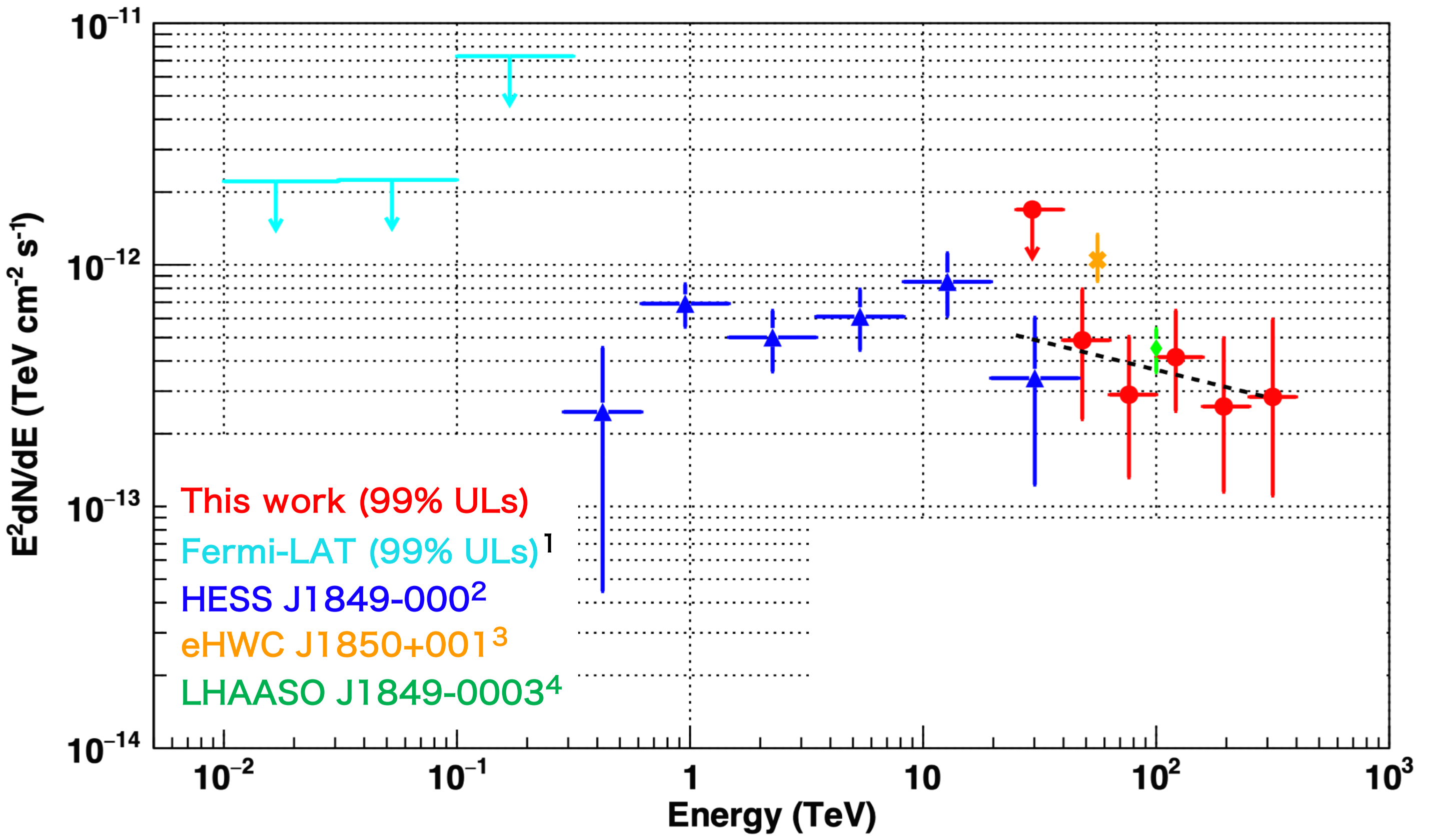
- ✓ 4.4σ detection @ E > 100TeV
- ✓ Green contour : Mol. Cloud found in this study
- ✓ Position unc. (68%) : 0.22°

  Positionally consistent w/ HESS J1849−000



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)

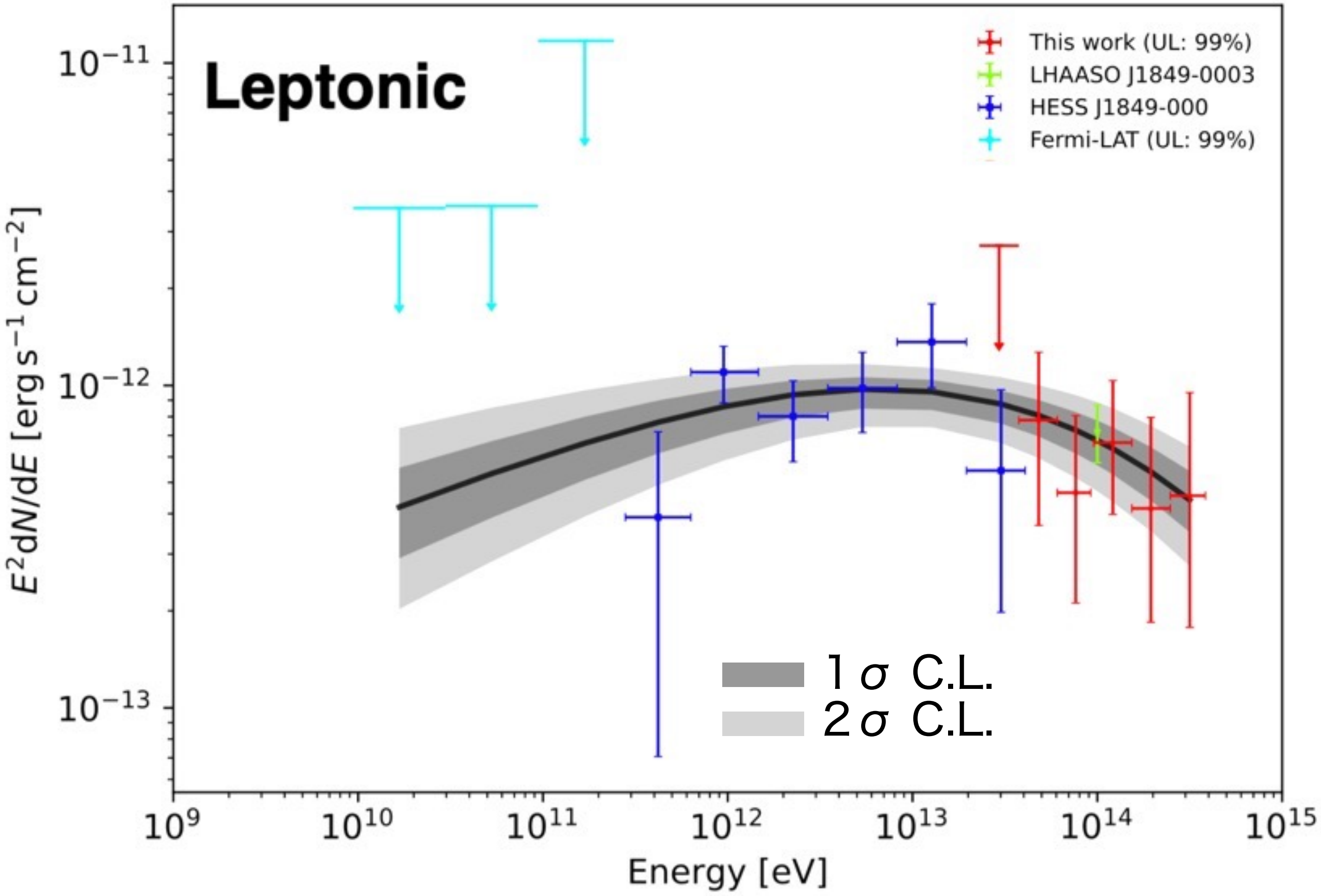
$$\frac{dN}{dE} = (2.86 \pm 1.44)\times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-2.24\pm 0.41} \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}} \quad (\chi^2/\mathrm{d.o.f.} = 0.5/3)$$

✓ Systematic uncertainties :

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

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

$E_{e,\,max}$ > 0.74 PeV

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

✓ Assumptions：

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

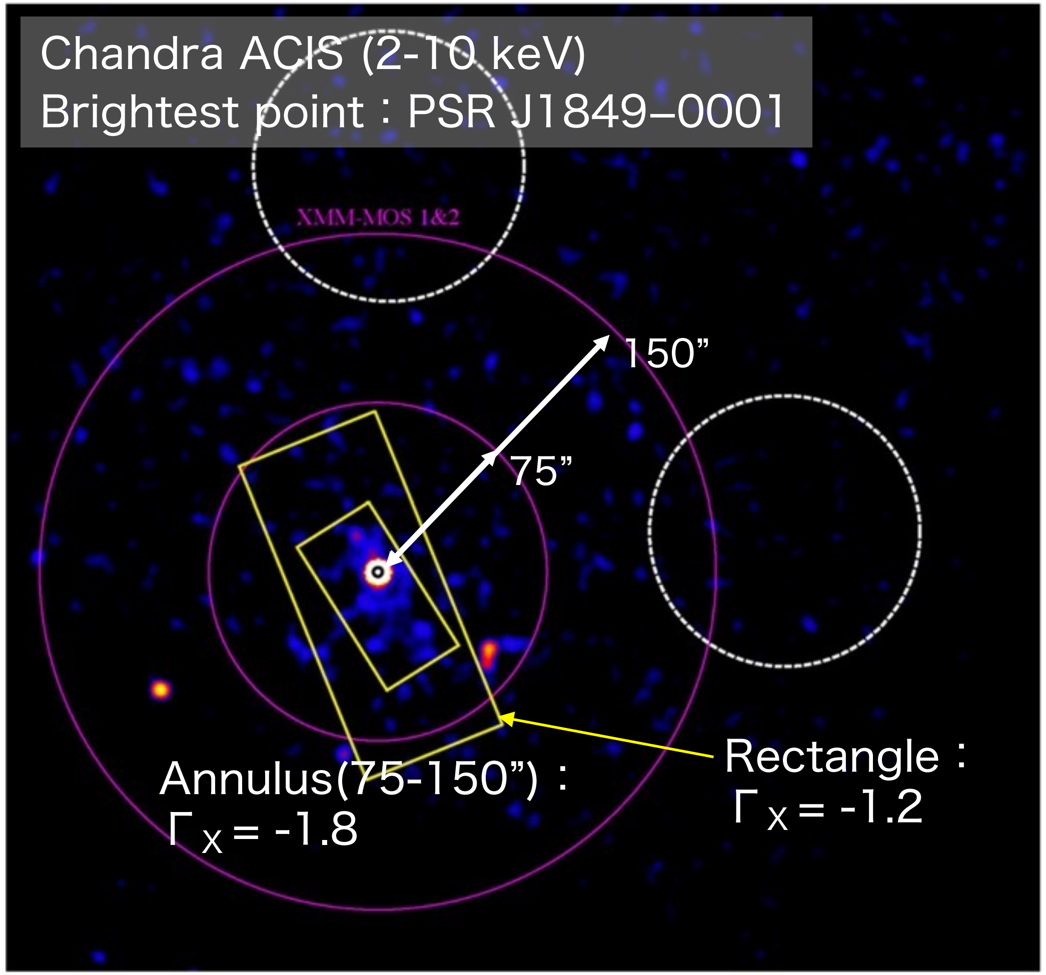
$$\frac{dN_e}{dE} = A_e \left(\frac{E}{10\ \mathrm{TeV}} \right)^{-\alpha_e} \mathrm{eV}^{-1}$$

- 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

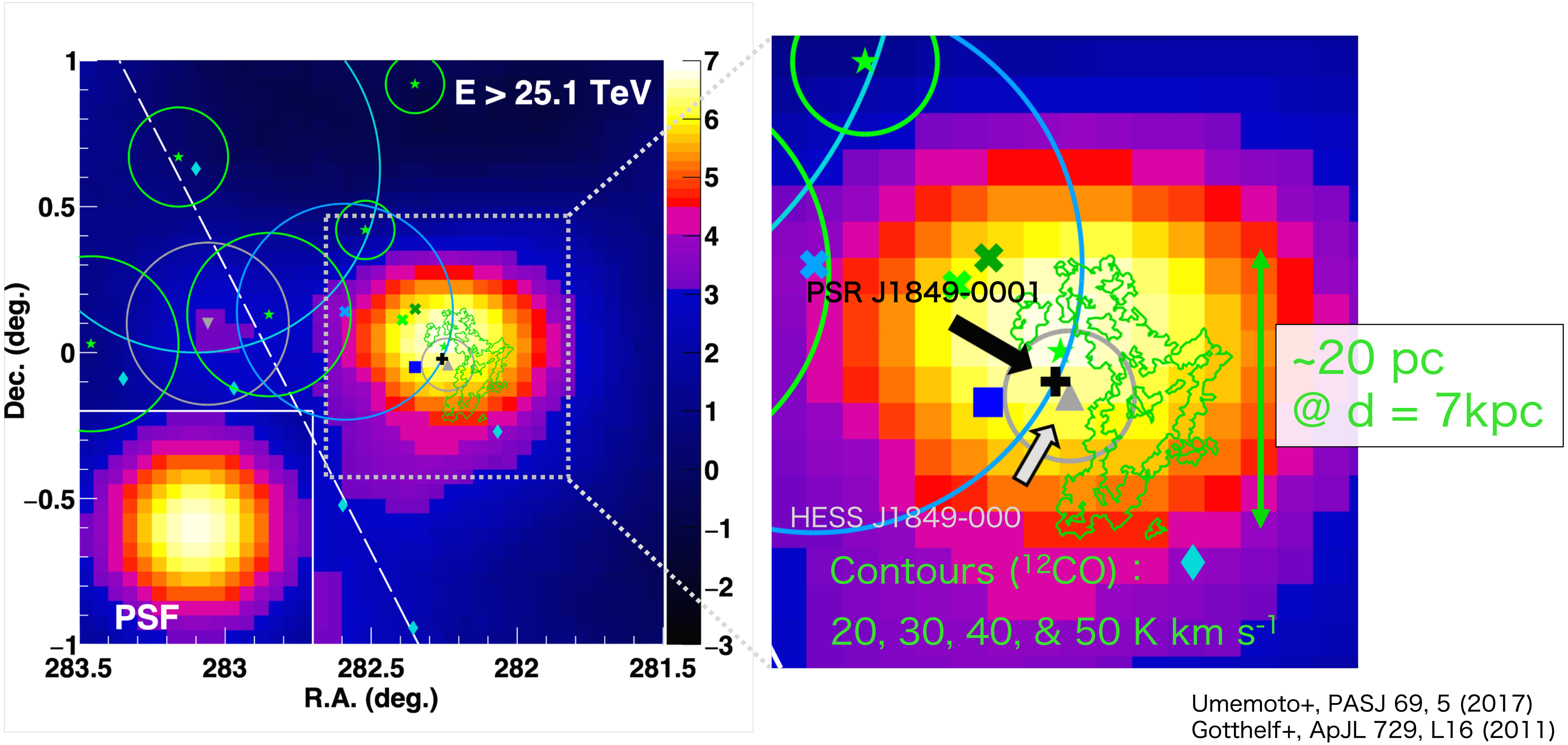
Association : PSR J1849−0001

- ✓ We(>100GeV) = 0.03 $E_{sp} \tau_c$. Energetics OK
- ✓ Synchrotron keV X-rays :
  Cooling effect is seen; photon index $\Gamma_X = -1.2 \to -1.8$ as going distant from the PSR
- ✓ $\Gamma_X = (-1 + \Gamma_e) / 2 = (-1 - 2.5) / 2 = -1.8$
  => $e^{\pm}$ producing ICS γ rays are already cooled??
- ✓ Γ_e of $e^{\pm}$ before cooling = −1.5
  Much harder than the diffusive shock acceleration
  => Magnetic reconnection?
  Efficient acceleration from non-linear effects??
- ✓ B ~ 2μG (If we include X-ray & γ-ray data under a one-zone model)
  Too low?



Kuiper & Hermsen, MNRAS 449, 3827 (2015)
Malkov, ApJ 511, L53 (1998)
Berezhko & Ellison, ApJ 526, 385 (1999)
Sironi & Spitkovsky, ApJL 783, L21 (2014)

Discovery of Molecular Clouds



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

✓ Analysis of archive FUGIN survey data of ^{12}CO (J=1–0)

✓ Assumed distance = 7 kpc[2]

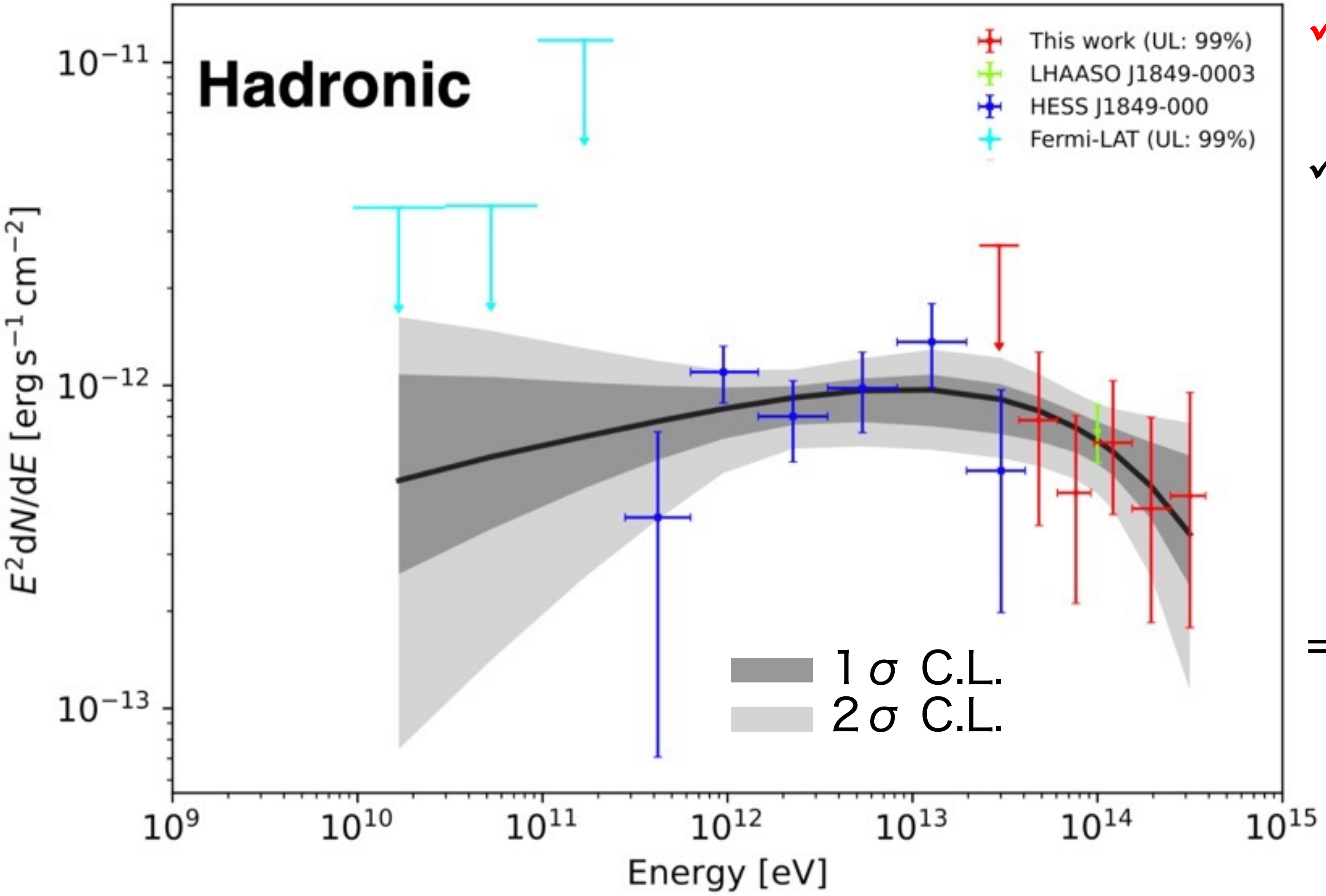
✓ Integrated range = 93–100 km s^{-1} (6-7 kpc)

$$n_p = X_{co}\, T_{mb} / R \sim 70\ cm^{-3}$$

$X_{co} = 2\times10^{20}\ cm^{-2}\ (K\ km\ s^{-1})^{-1}$
$R \sim 20$ pc

Hadronic Emission Model (Naima[1])

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



- ✓ **First spectral modeling including the sub-PeV energy range**
- ✓ Assumptions：
  - $\pi^0 \rightarrow 2\gamma$ from CRp-gas collisions
  - $n_p = 100\ \mathrm{cm}^{-3}$
  - CRp spectrum：

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

=>

$$\log_{10} A_p = 33.93^{+0.09}_{-0.11}$$

$$\alpha_p = 2.01^{+0.12}_{-0.21}$$

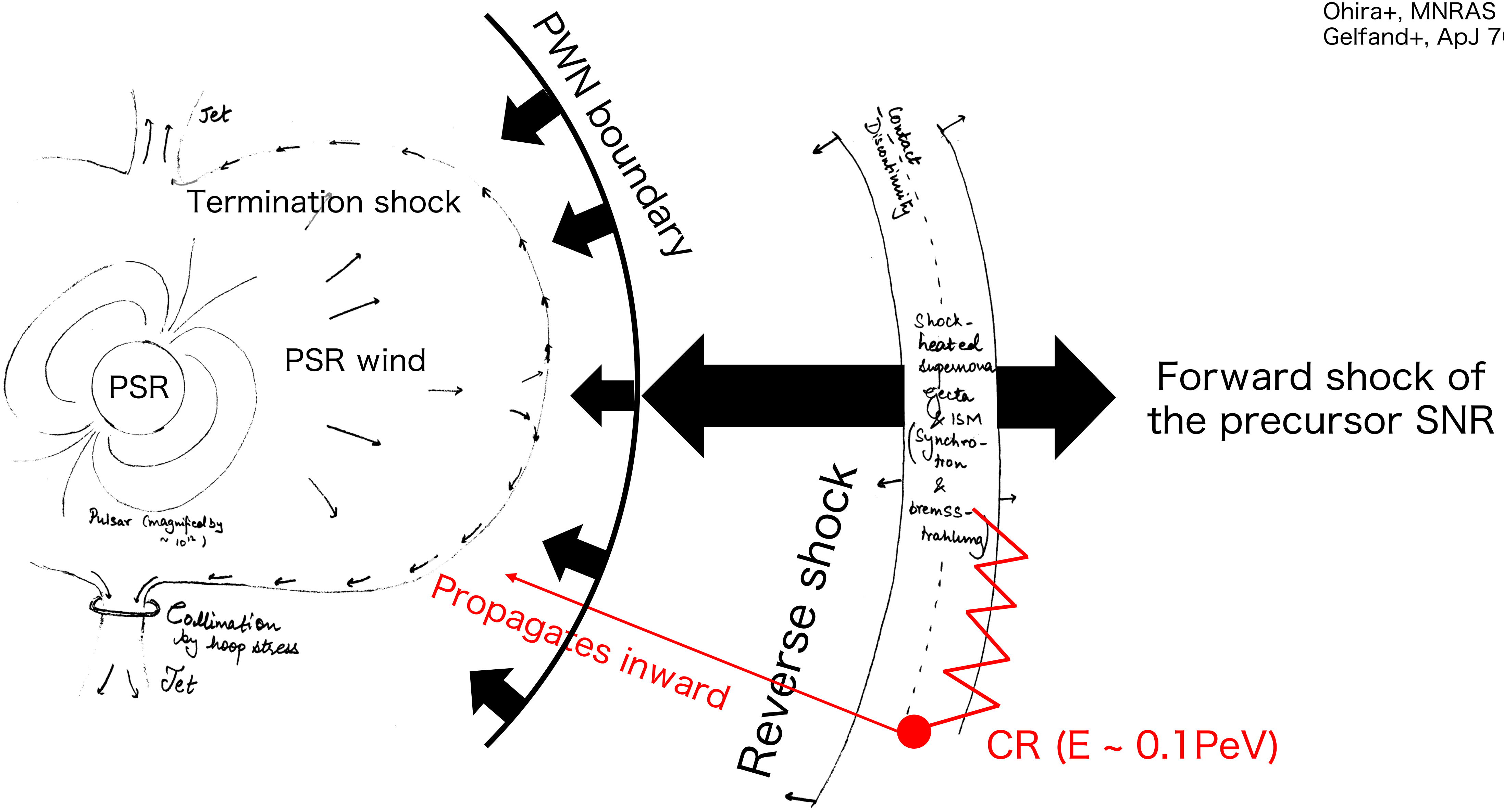
$$\log_{10}(E_{p,\mathrm{cut}}/\mathrm{TeV}) = 3.73^{+2.98}_{-0.66}$$

W_p(1TeV<E<10PeV) = (1.1± 0.2) × 10^{48} erg

Possible acceleration of CR protons beyond PeV

PeV CR Acceleration in a PWN-SNR Composite System?

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

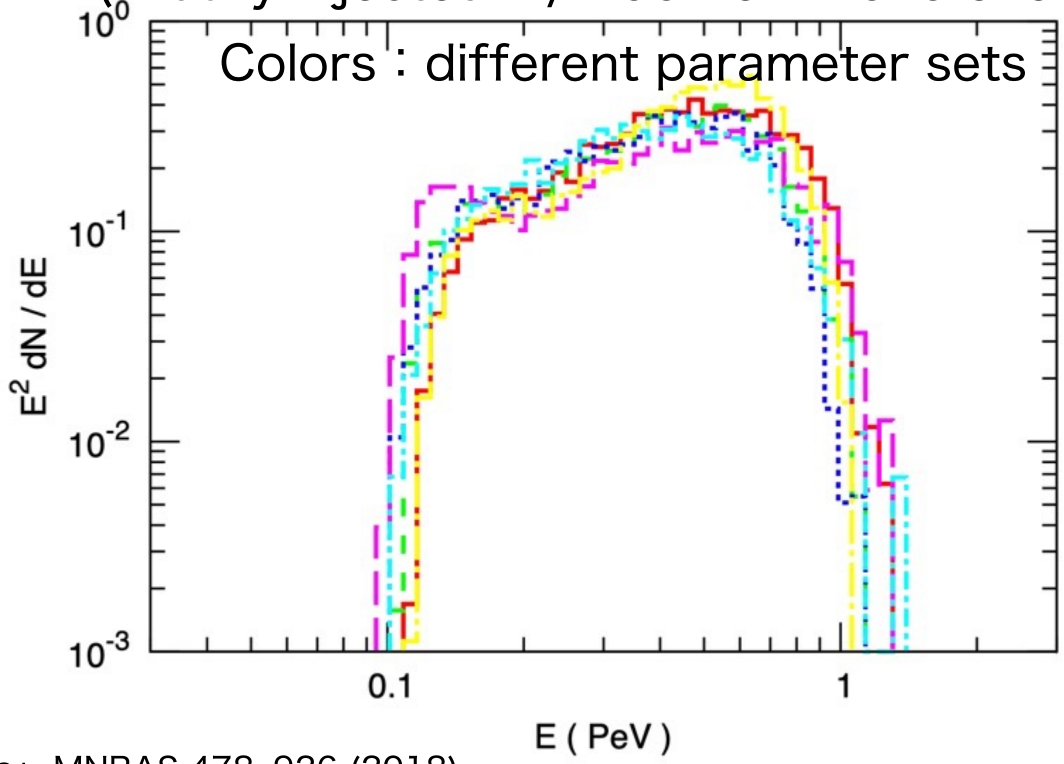


Adiabatic compression of PWN by RS can produce PeV CRs?

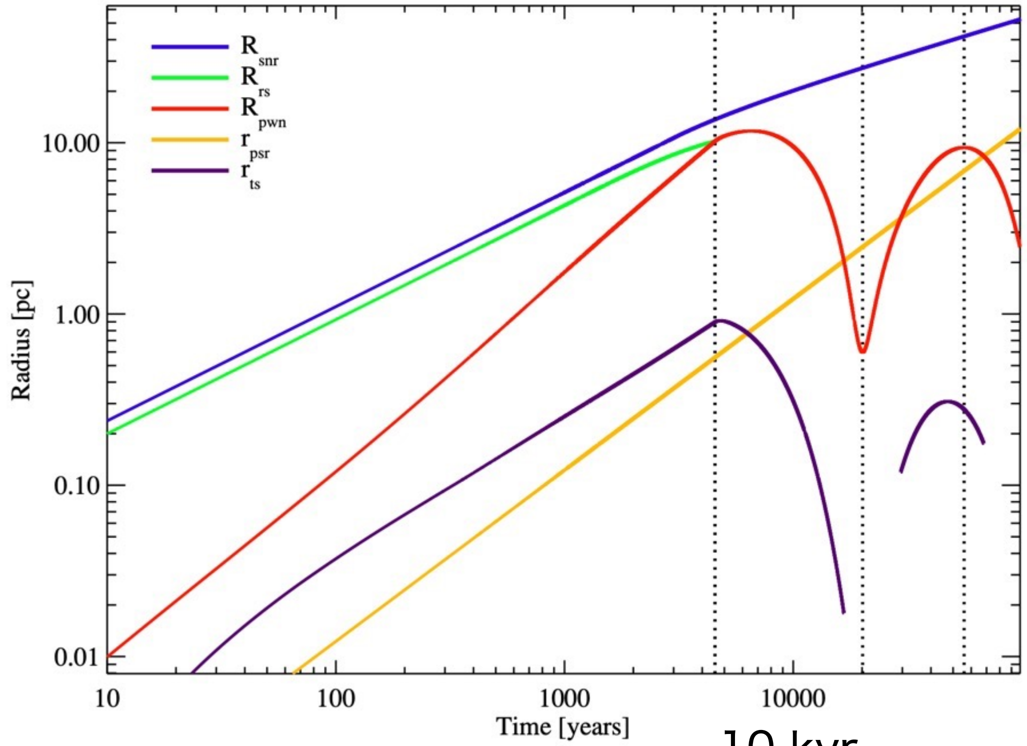
PeV CR acceleration in a PWN-SNR composite system

- PeV CR can be produced irrespective of environmental parameters[1]
- ~10^{48} erg is given to the accelerated particles[2]
- Compression of PWN takes place @ ~ 10 kyr aft. SN => Invisible SNR

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



Evolution of the size of the system[2]



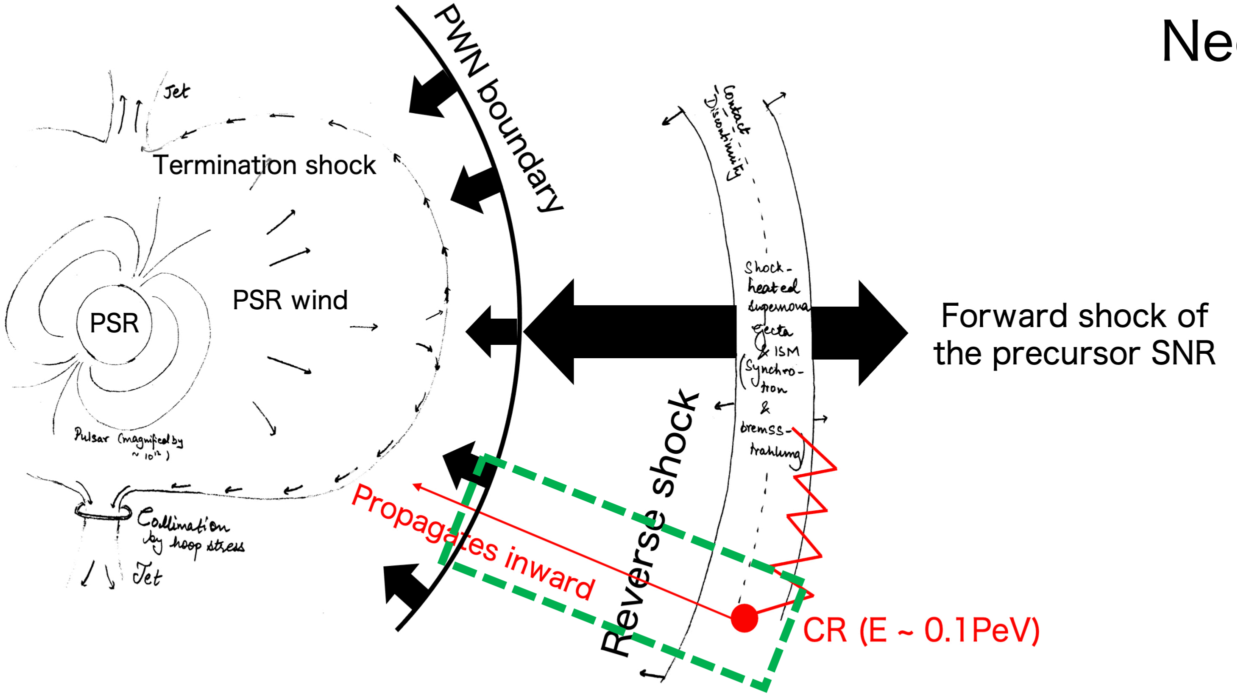
10 kyr

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

Caveats

? Can CRs really propagate through SNR FS – RS to reach PWN?
& its energy dependence?
So, the CR energy spectrum in PWN? Is it really $\Gamma = 2$?
=> Study of turbulence in shocked ejecta

? *B* of the compressed PWN is amplified up to ~ 100 μG^2
=> X-ray flux far exceeding the observation? (if UHE $e^{\pm}$ are in PWN)



Needed observations:
- Sub-PeV γ obs. w/ more statistics
- Neutrinos

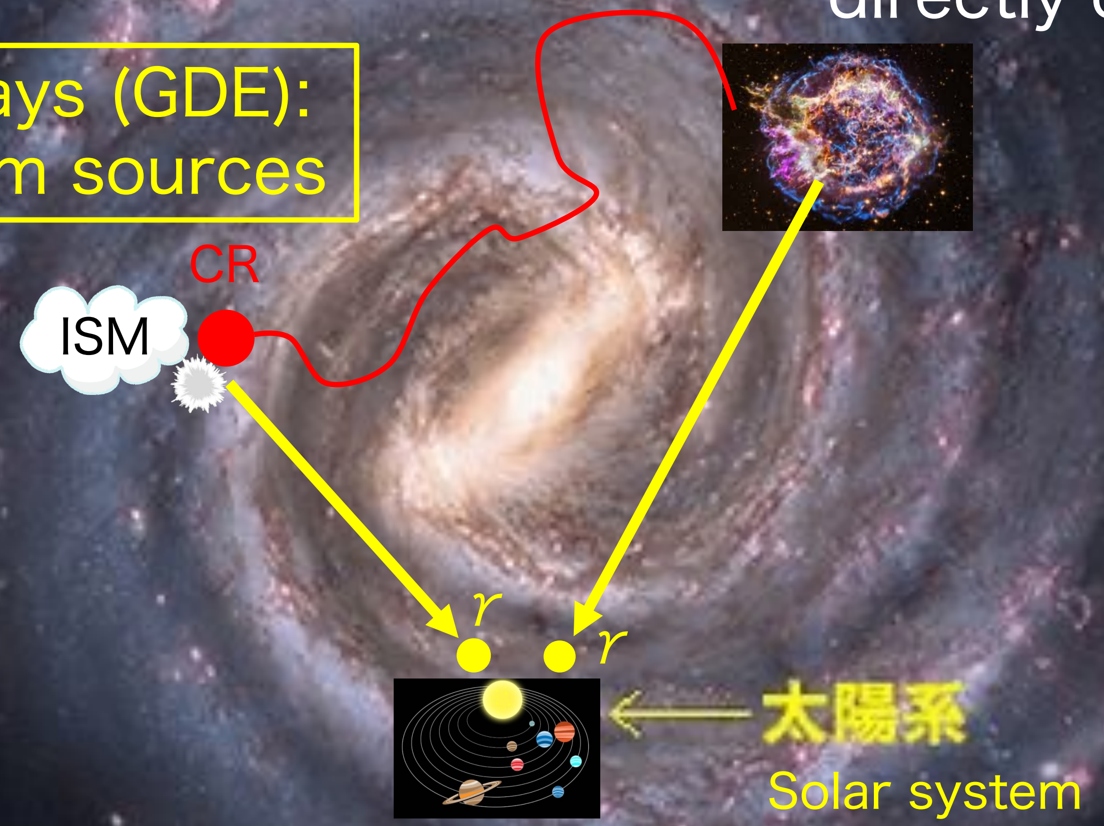
The origin of the sub-PeV Galactic gamma-ray emission?

Kato et al., ApJL 961, L13 (2024)
Kato et al., ApJL 977, L3 (2024)
Kato et al., ApJ 984, 98 (2025)

Sub-PeV Galactic Diffuse Gamma-Ray Emission (GDE)

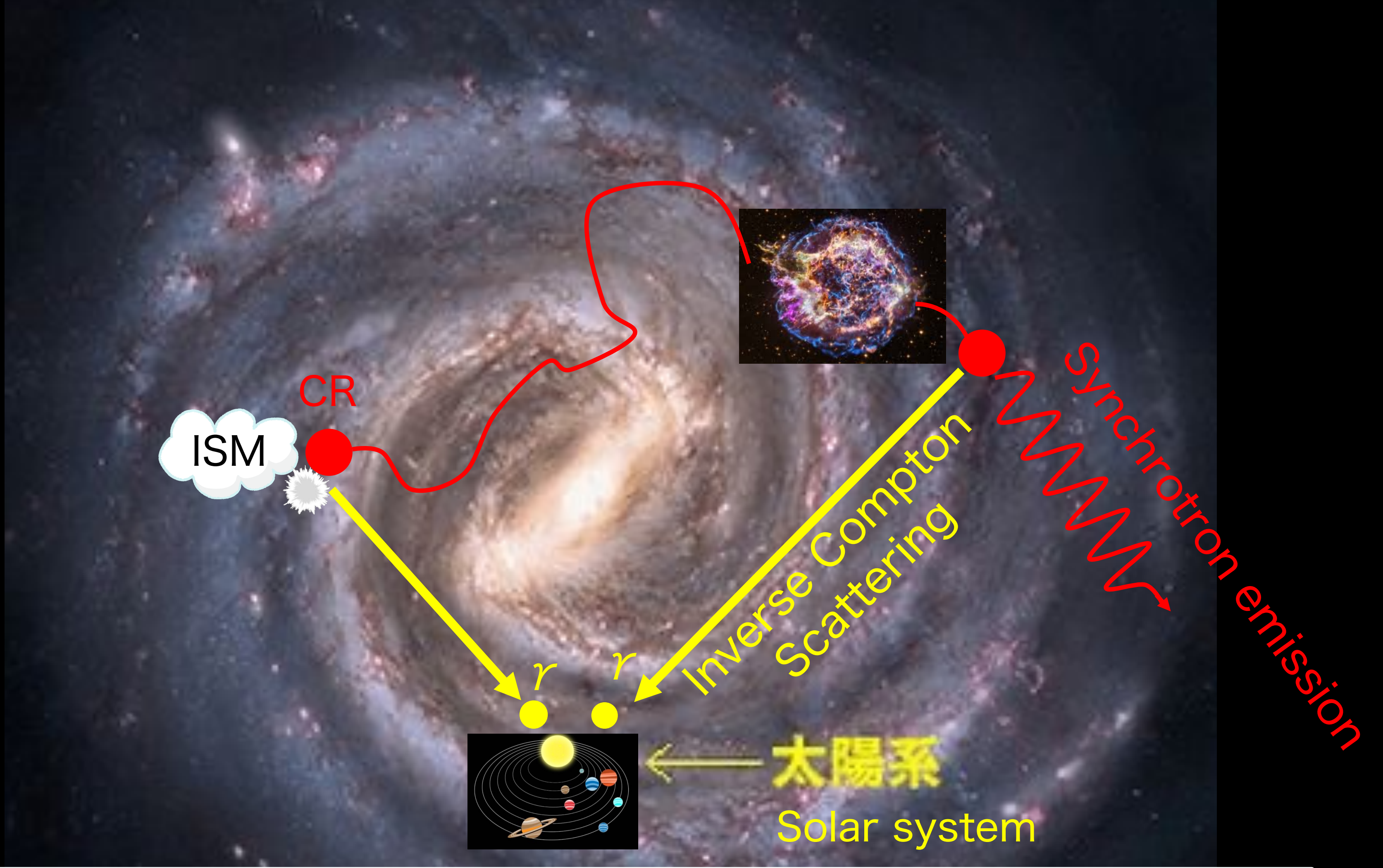
① Source gamma rays:
directly coming from sources

② Diffuse gamma rays (GDE):
Coming away from sources



✓ Extended along Gal. Plane & No source counterpart
✓ Key to study the PeVatron properties & distribution, CR propagation, ⋯

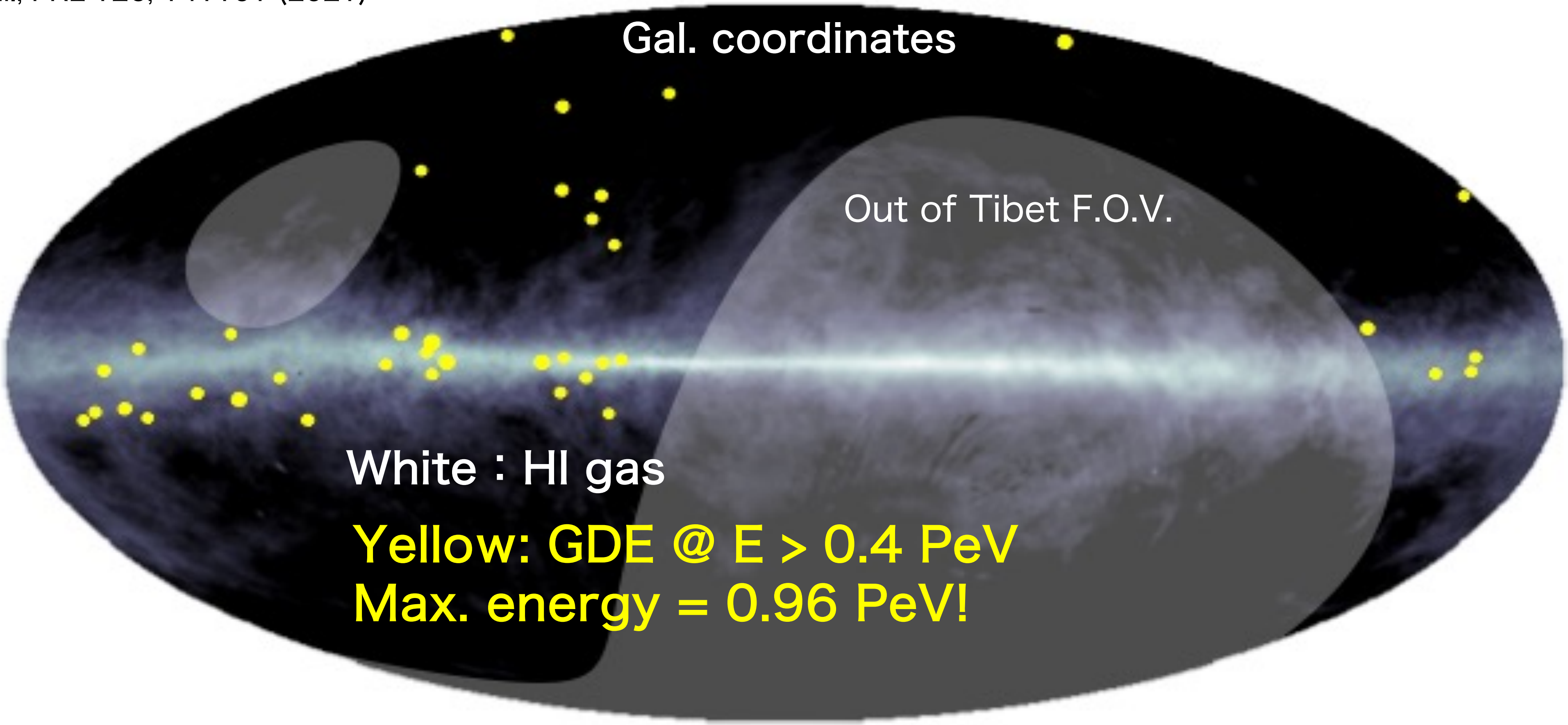
Leptonic Emission in Sub-PeV GDE



Electrons cannot go far away from their sources.
Their contribution can be removed by adopting an appropriate source masking scheme.

Detection of Sub-PeV GDE by Tibet ASγ

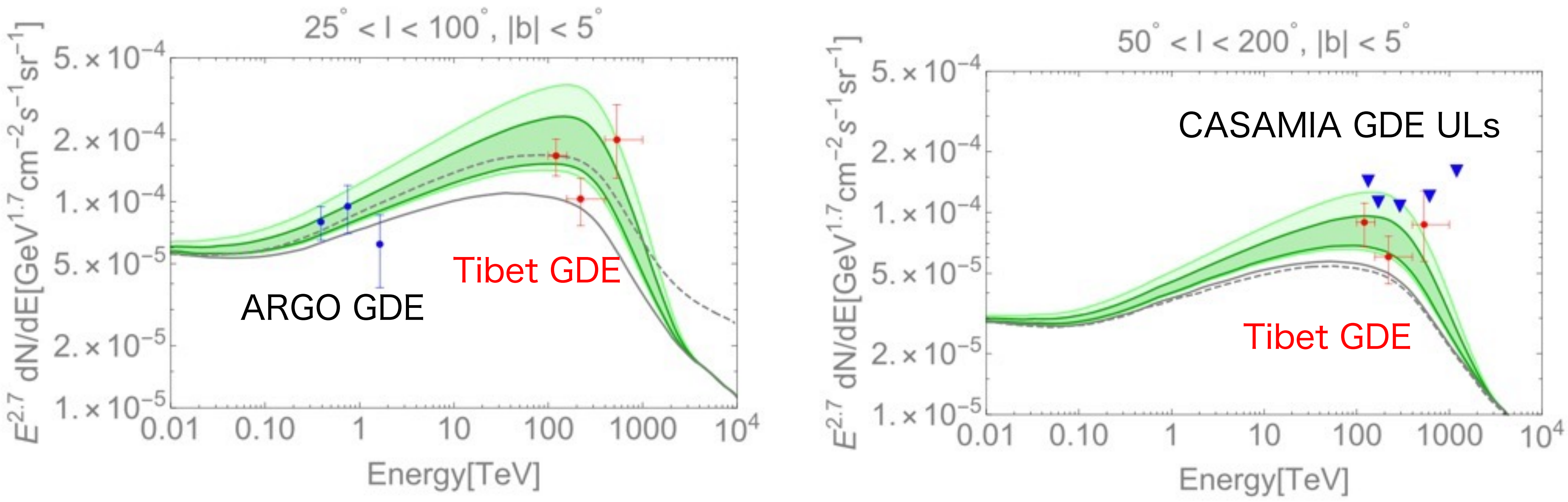
Amenomori et al., PRL 126, 141101 (2021)



- ✓ 23 GDE events @ E > 0.4 PeV in $|b| < 10°$
  Estimated BGCR are 2.7 events => 5.9σ detection!!
- ✓ Masking of TeVCat sources (2021) by circular regions w/ r = 0.5°
- ✓ Evidence of Galactic origin of PeV CRs!

TeVCat ≡ A catalog of TeV γ-ray sources (>10^{11} eV)

Contamination of Tibet GDE from (Unresolved) Sources?



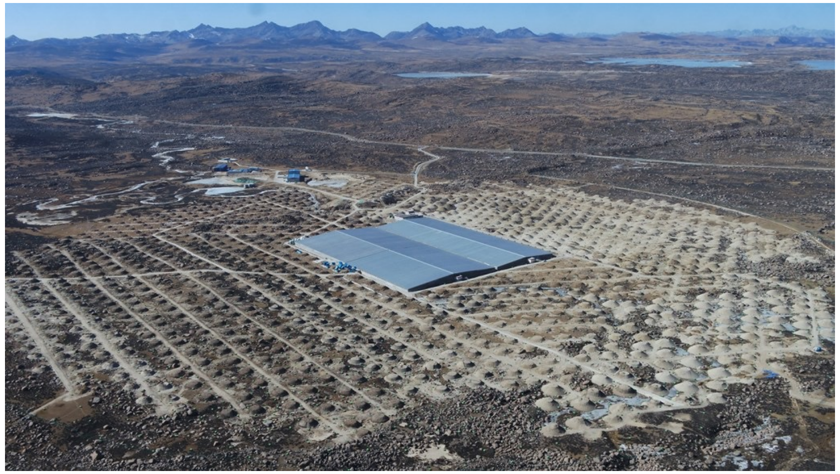
Vecchiotti et al., ApJ 928, 19 (2022)

Theoretical models:
Black: GDE
Green: GDE + contribution from unresolved sources

Unresolved source ≡ gamma-ray source not detected yet by current observatories due to the sensitivity limit

Let's Check Using an Up-To-Date γ-Ray Source Catalog

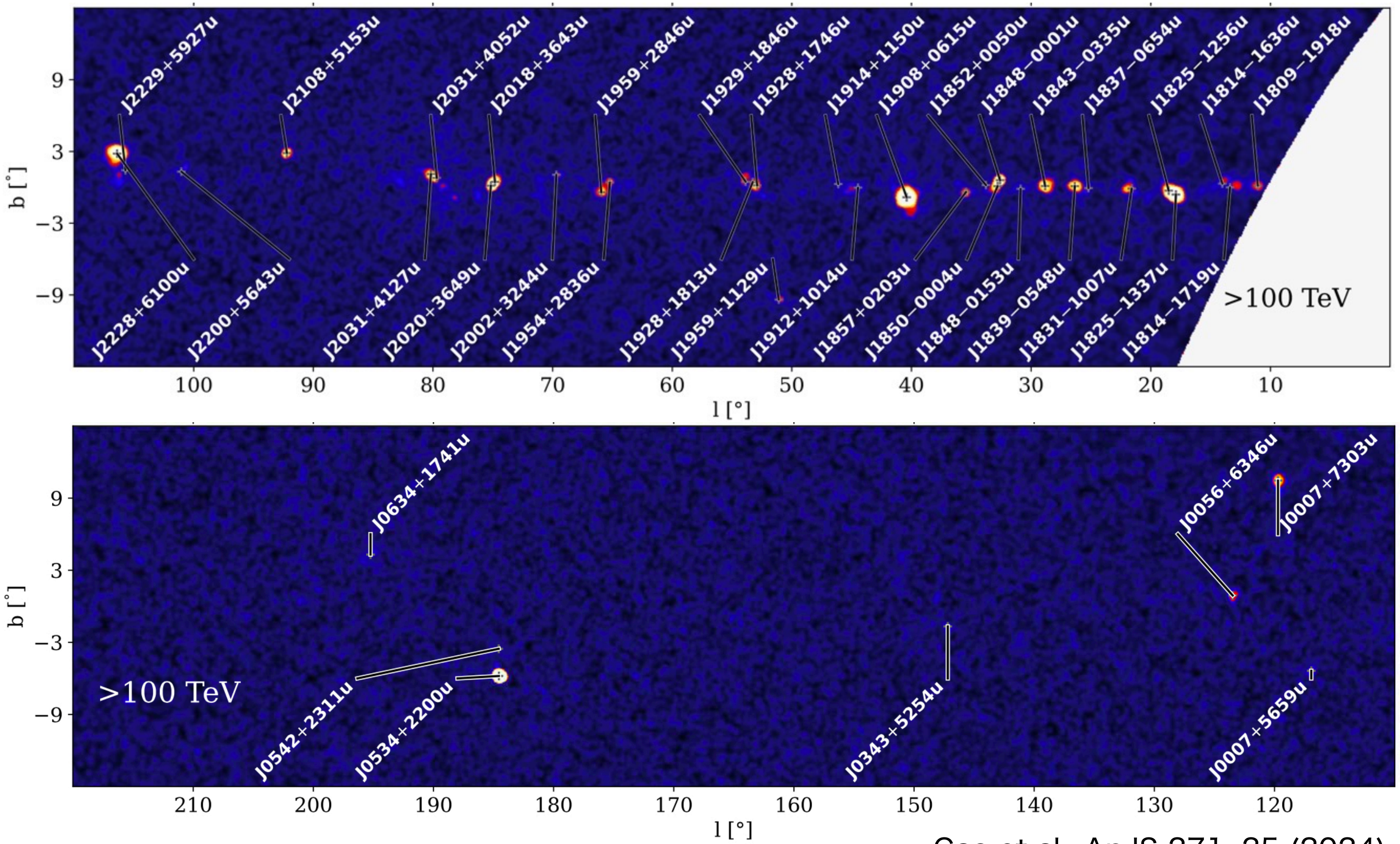
LHAASO: 1,000,000 m^2



> 10 × Tibet ASγ

1st LHAASO catalog (2024)

43 γ-ray sources @ E > 0.1PeV

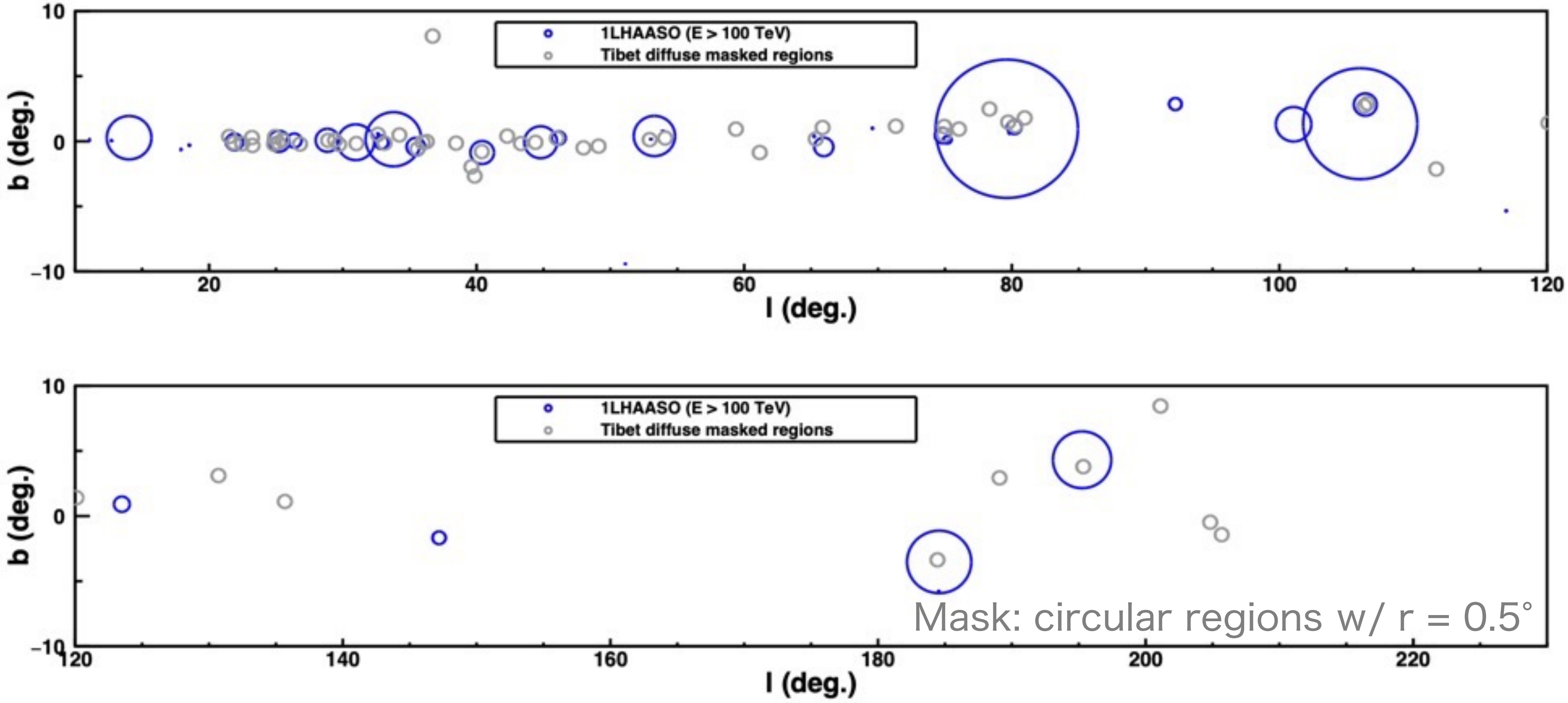


Cao et al., ApJS 271, 25 (2024)

1st LHAASO catalog helps us study the source contamination of Tibet GDE

To Study the Origin of Tibet Sub-PeV GDE

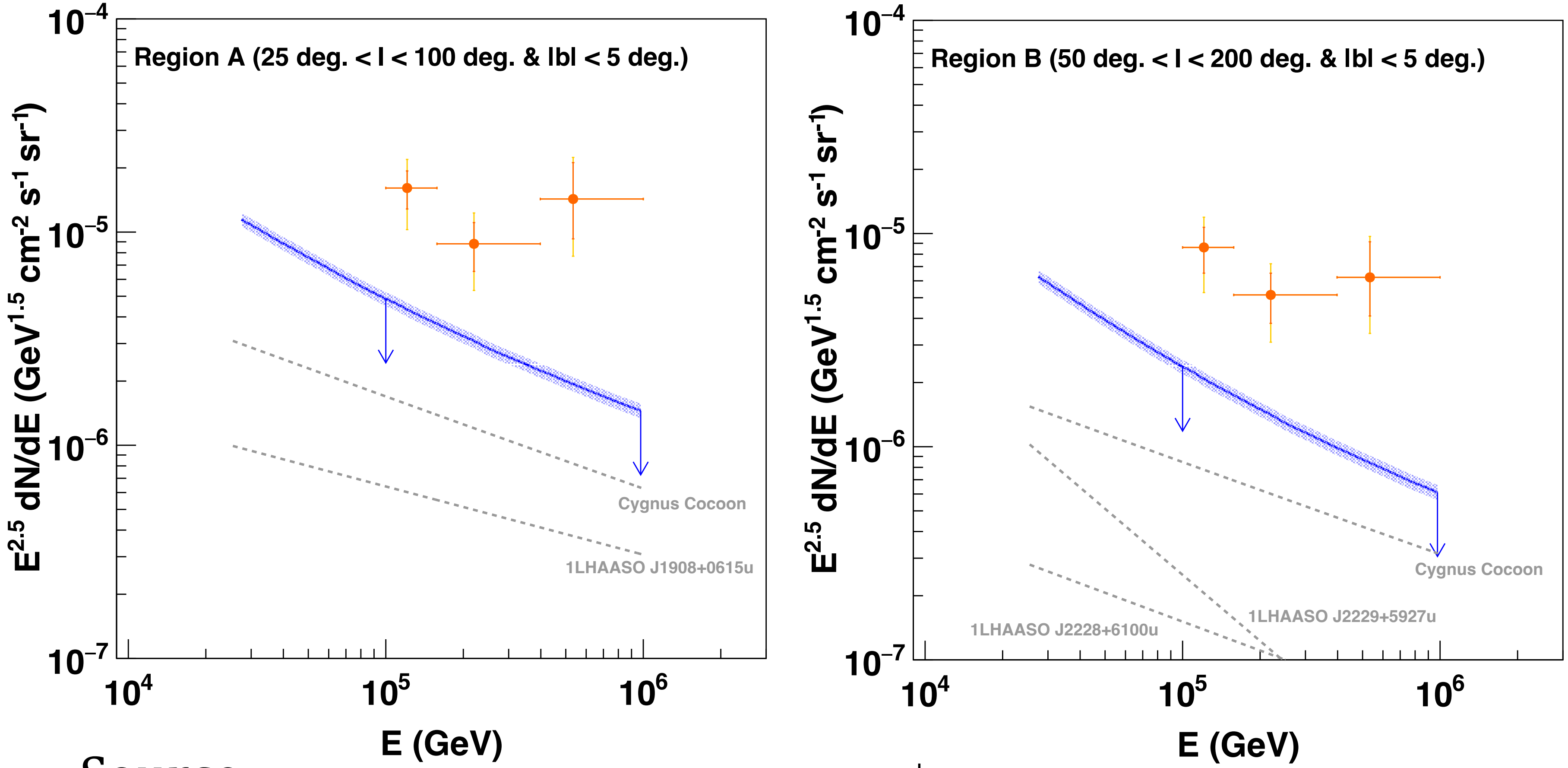
95% extension of 1st LHAASO catalog sources (@ > 0.1 PeV) & Tibet source masking



Tibet masked regions should be properly accounted for to estimate the source contamination of Tibet GDE

Estimated Contamination of the Tibet GDE Flux from Sources

S.K. et al., ApJL 977, L3 (2024)



Tibet GDE flux (stat. & syst.)

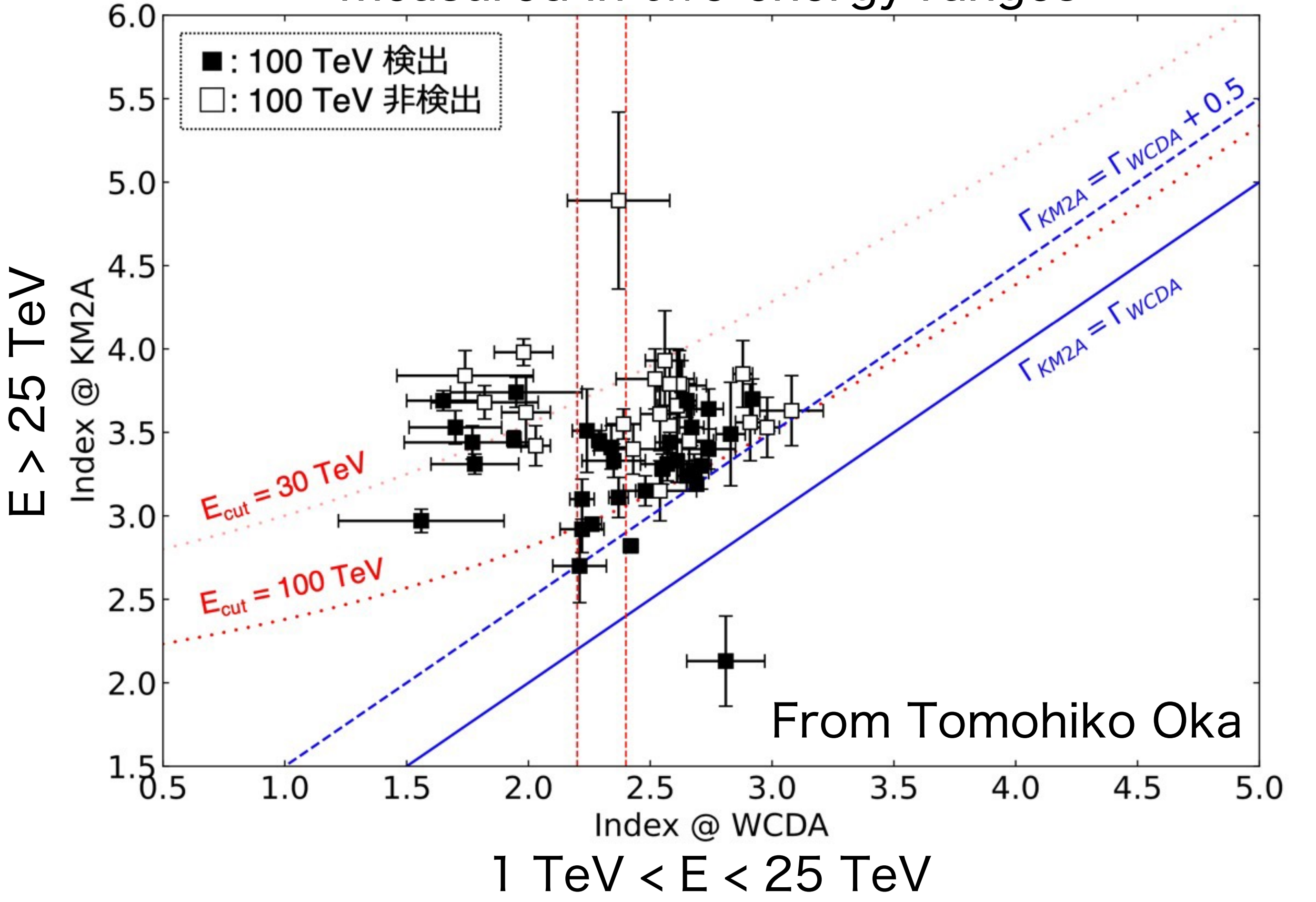
Upper limit of 1LHAASO(>100TeV)

$\frac{\text{Source}}{\text{Tibet GDE}}$	Region A (25°<l<100° & |b|<5°)	Region B (50°<l<200° & |b|<5°)
121 TeV	< 26.9%±9.9%	< 24.1%±9.5%
220 TeV	< 34.8%±14.0%	< 27.4%±11.1%
534 TeV	$< 13.5\%^{+6.3\%}_{-7.7\%}$	$< 13.5\%^{+6.2\%}_{-7.6\%}$

Source contamination is subdominant

Why Our Estimate Should be Regarded as UL @ E > 0.1PeV?

PL spectral Indices of the 1st LHAASO sources
measured in two energy ranges

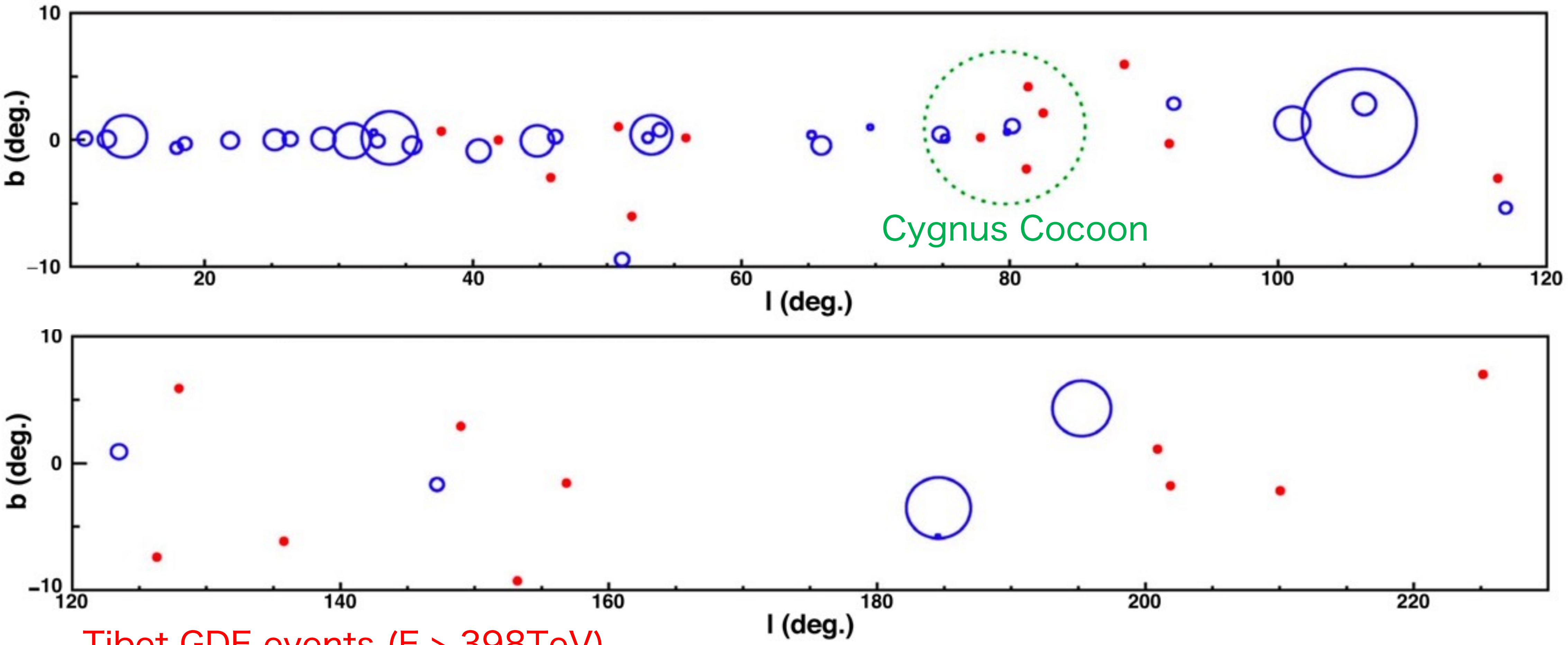


Our estimate is made by extrapolating the best-fit PL spectra measured by KM2A (E > 25TeV).
However, many of the sources have a softening @ E = O(10TeV).

<u>Therefore, the extrapolation should overestimate the source flux @ E > 0.1PeV</u>

Tibet GDE Events @ > 0.4PeV & LHAASO Sources @ > 0.4PeV

S.K. et al., ApJL 961, L13 (2024)



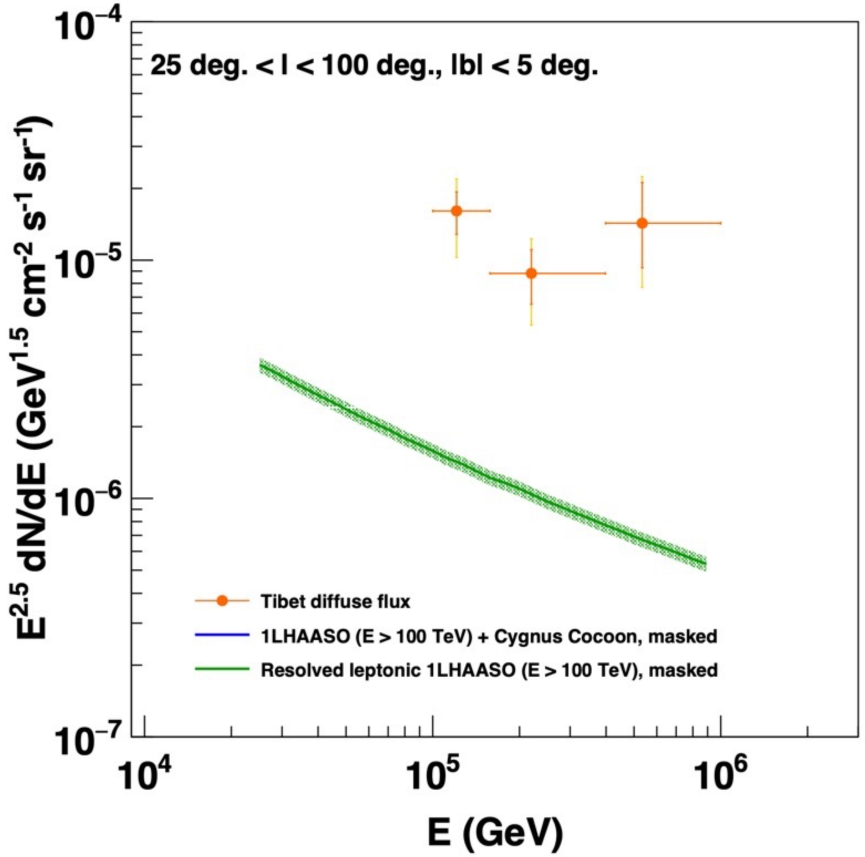
Tibet GDE events (E > 398TeV)

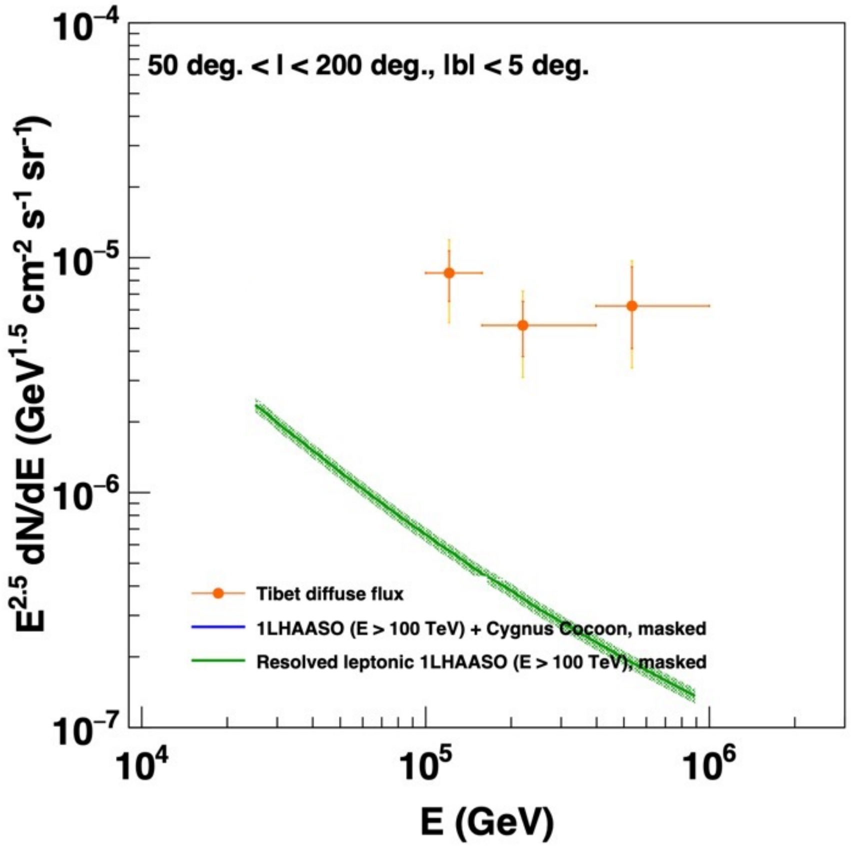
95% containment extension of the LHAASO sources detected @ 0.1PeV

No overlap b/w Tibet GDE events @ >398TeV & sub-PeV LHAASO sources

Supporting that the Tibet events are truly GDE

Estimated Contamination from Leptonic Sources (PWNe)

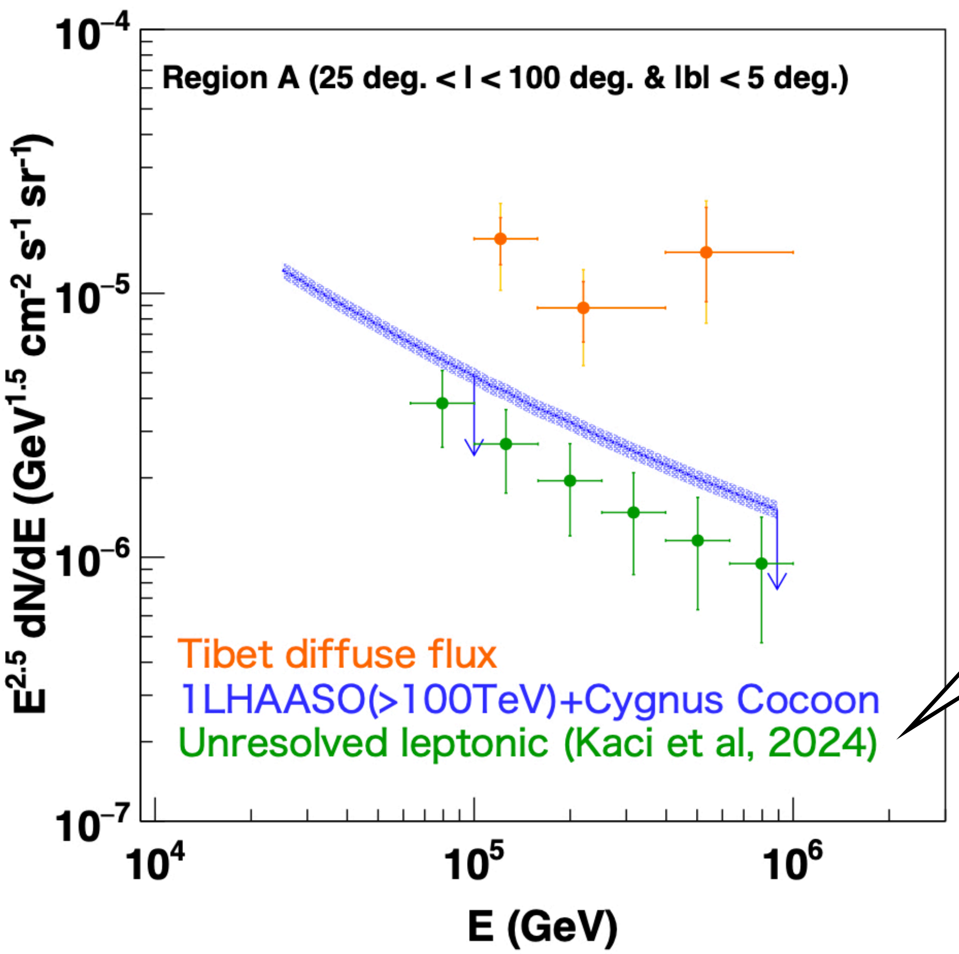




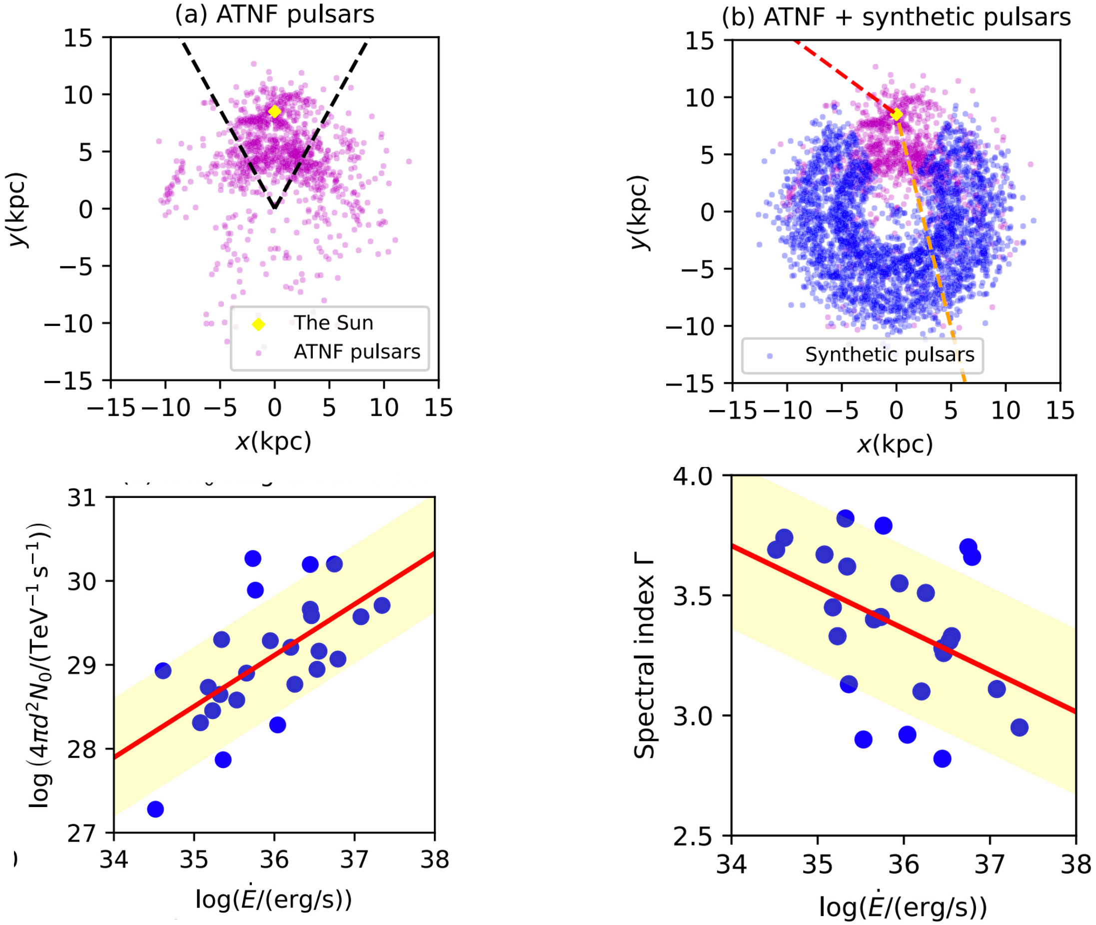
Contamination from the 1st LHAASO sources spatially associated w/ PSRs is
$< 9\%$ @ $E > 0.1$PeV in ($25^\circ < l < 100^\circ$ & $|b| < 50^\circ$)
$< 7\%$ @ $E > 0.1$PeV in ($50^\circ < l < 200^\circ$ & $|b| < 50^\circ$)

Leptonic resolved-source fraction is subdominant

Estimated Contamination from Leptonic Sources (PWNe)



Kaci et al., ApJL 975, L6 (2024) estimated the γ-ray flux from unresolved sources associated w/ PSRs in a data-driven way



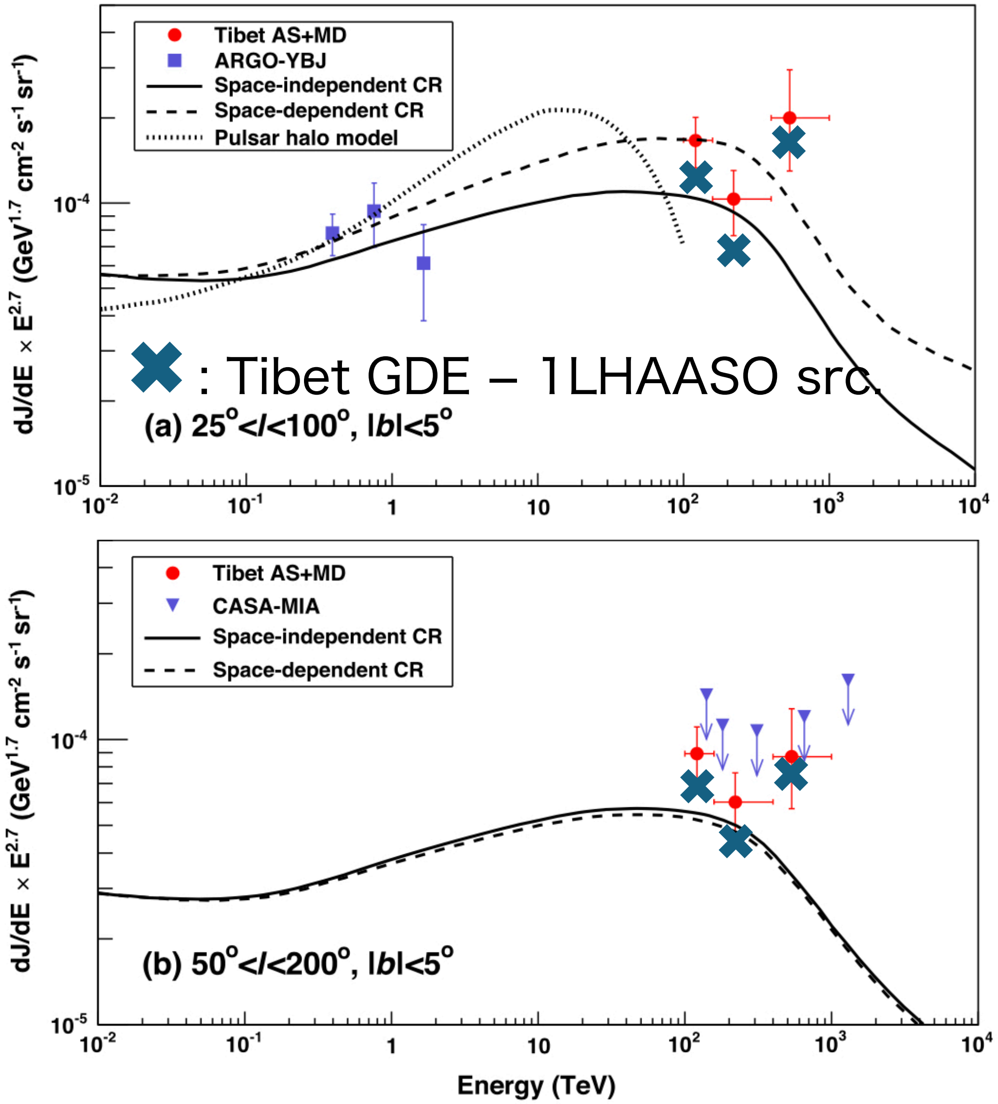
Tibet mask is not considered => strict UL

< 17% @ E > 0.1PeV in (25° < l < 100° & |b| < 5°)

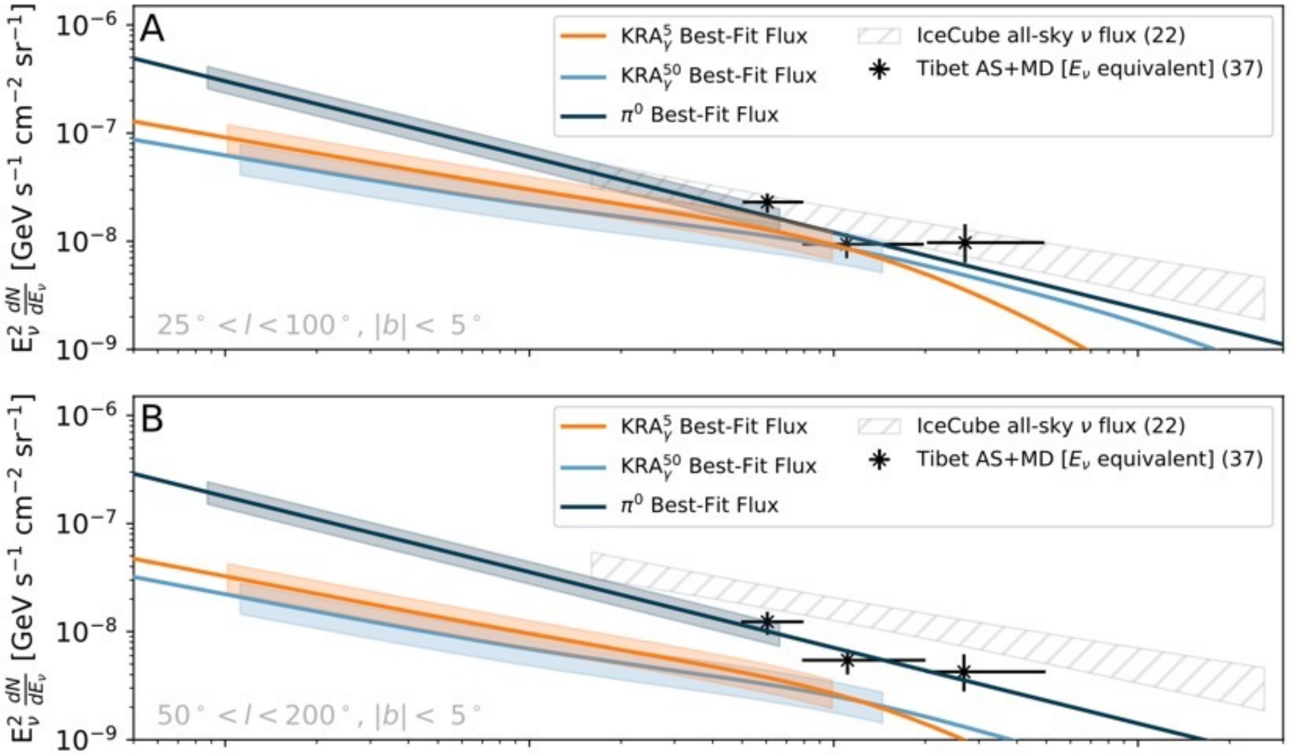
<u>Leptonic unresolved-source fraction is subdominant</u>

Nature of the Tibet GDE Flux

S.K. et al., ApJL 977, L3 (2024)



IceCube Galactic ν & Tibet GDE[2]



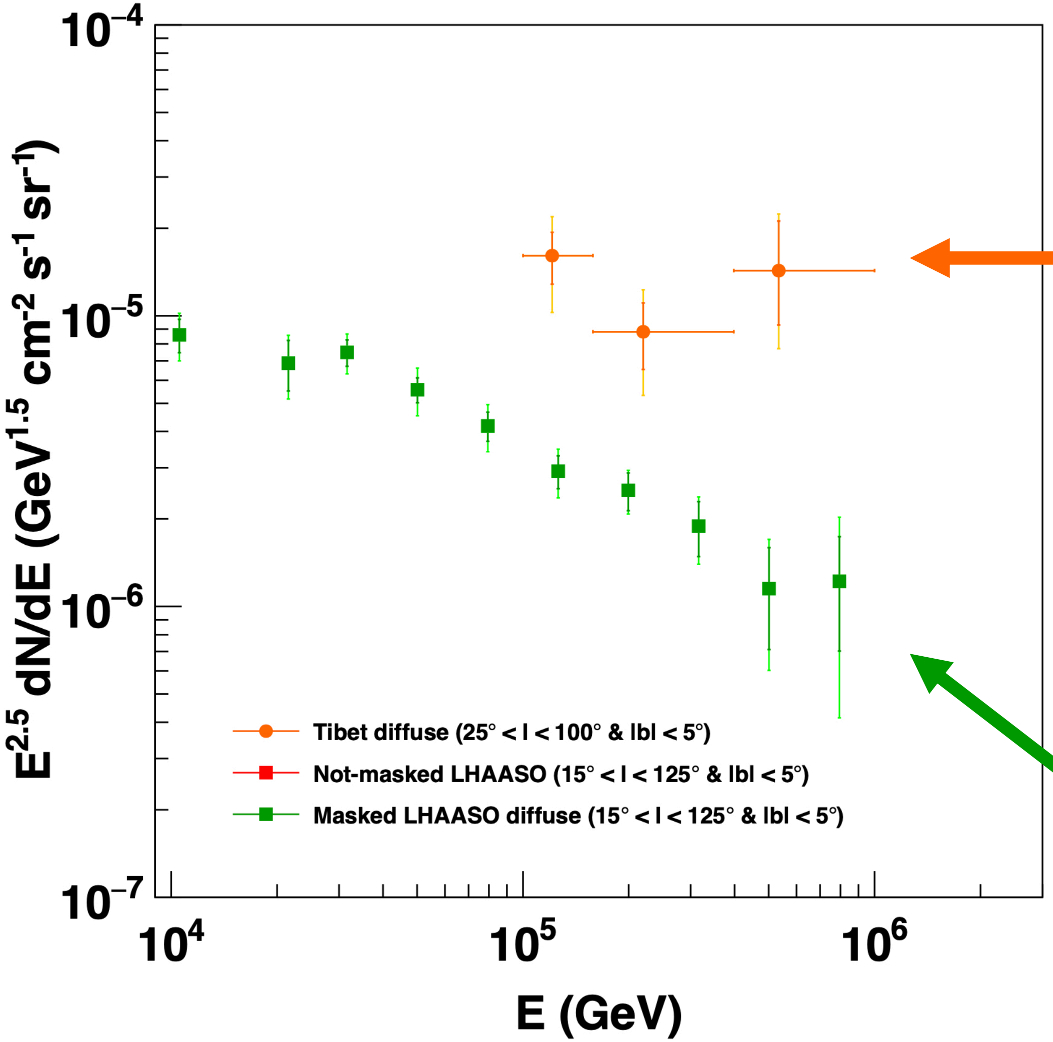
IceCube Collaboration, Science 380, 1338 (2023)

Consistent w/ ICν flux (π^0 model)

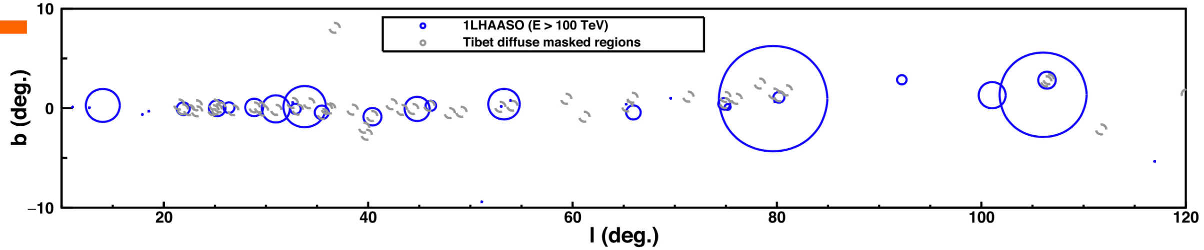
Black solid & dashed lines:
Lipari & Vernetto PRD 98, 043003 (2018) (leptonic fraction < 5% @ > 0.1PeV)

Supporting the hadronic diffusive origin of Tibet GDE

Comparison of Tibet & LHAASO GDE Observations

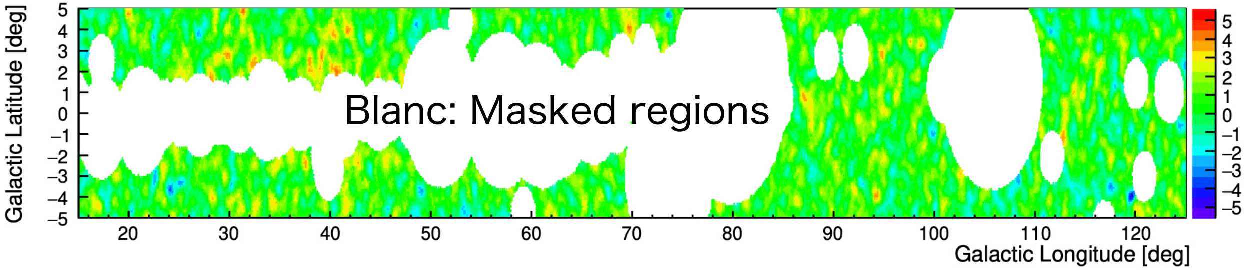


Tibet masked GDE flux: gray
(25° < l < 100° & |b| < 5°)



Amenomori et al., PRL, 126, 141101 (2021)

LHAASO masked GDE flux
(15° < l < 125° & |b| < 5°)



Cao et al., PRL 134 081002 (2025)

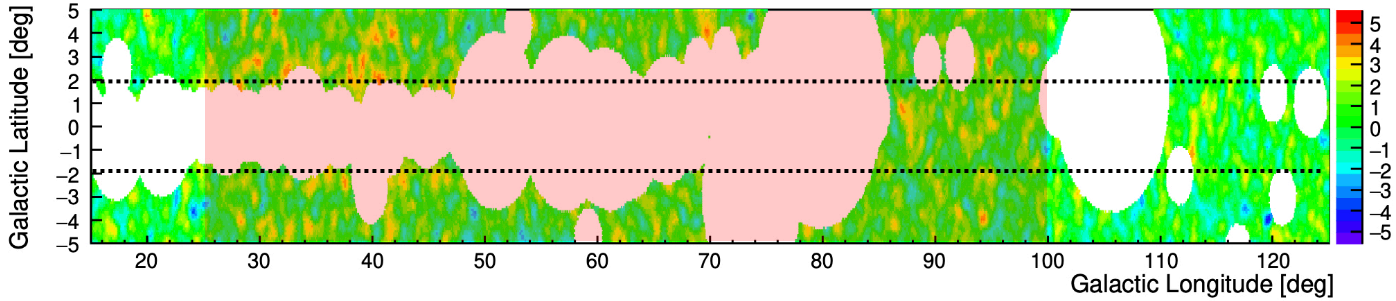
Discrepancy by a factor of ~ 5 @ 100 TeV,
but their different masking schemes should be accounted for

Consistency with the LHAASO GDE Measurements

S.K. et al., ApJL 977, L3 (2024)

$$\frac{\text{Tibet GDE } (25^\circ < l < 100^\circ, |b| < 5^\circ) - \text{Source}}{\text{LHAASO GDE}^{1} \; (15^\circ < l < 125^\circ, |b| < 5^\circ)} = 3,\ 2,\ \&\ 7 \text{ @ } 120\text{TeV},\ 220\text{TeV},\ \&\ 530\text{TeV}$$

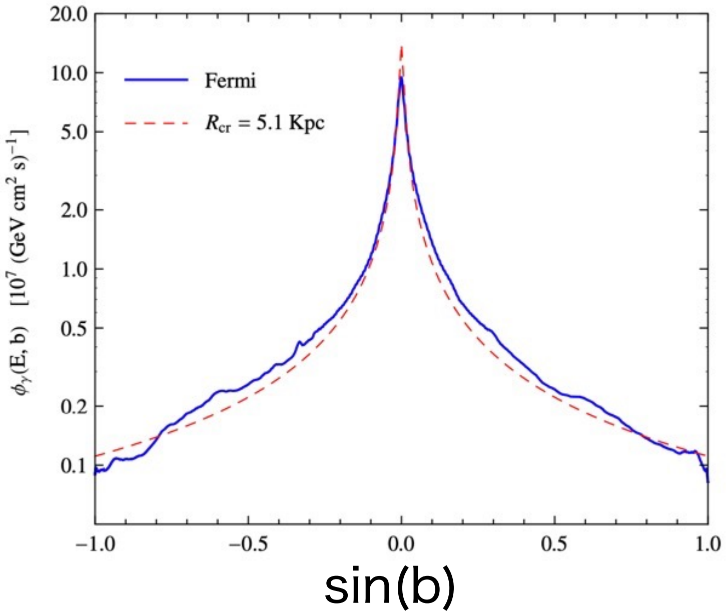
LHAAASO masking in the inner Galaxy[1]



: Tibet region A (25° < l < 100° & |b| < 5°)

LHAASO masks most of the region w/i |b| < 2°

1. Cao et al., PRL 134 081002 (2025)
2. Lipari & Vernetto, PRD 98, 043003 (2018)



GDE latitudinal distribution* by Lipari & Vernetto (2018)[2]

*The distribution is Integrated over |l| < 180°

Using the theoretical prediction,

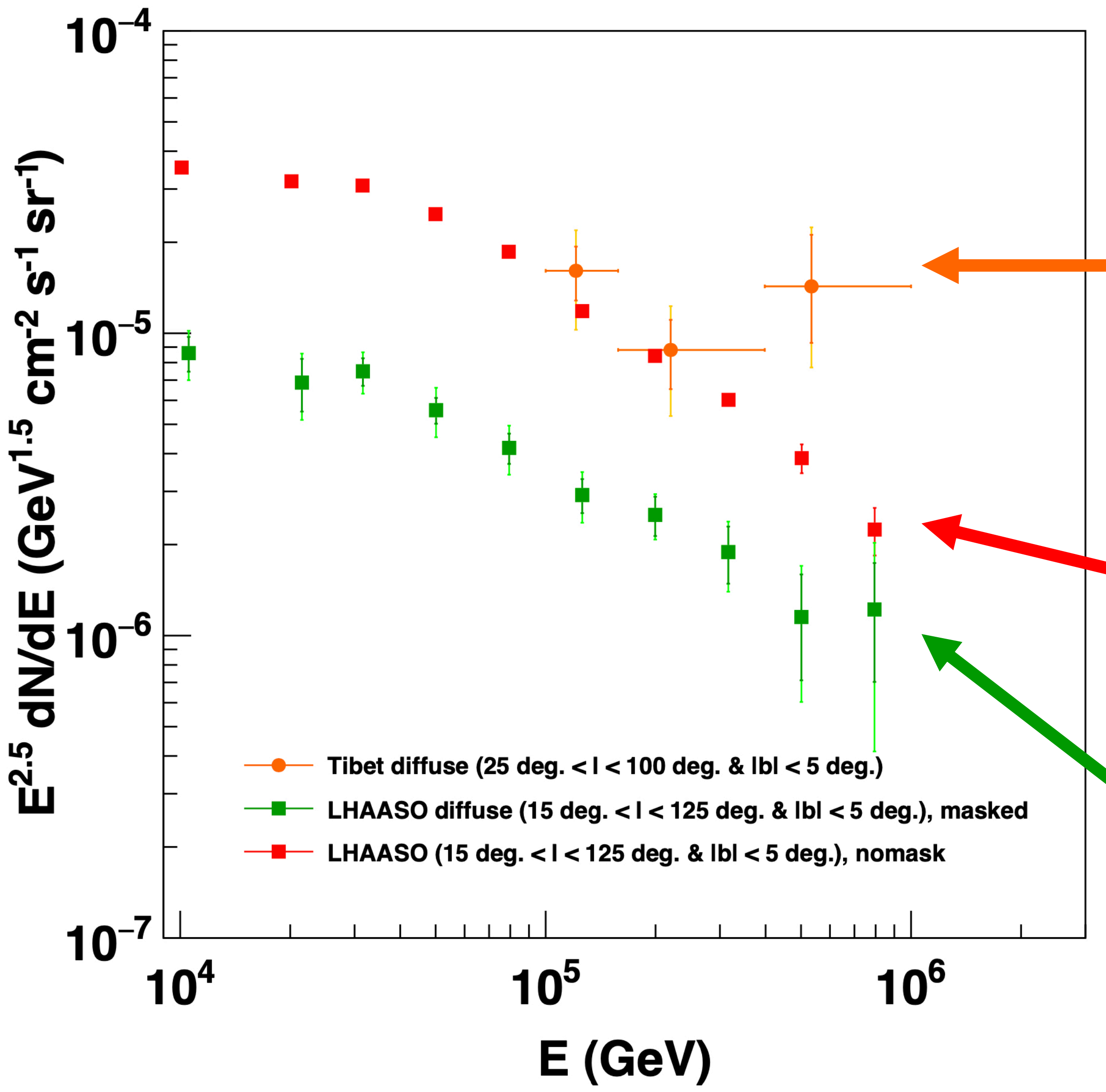
Flux(|b|<5°) ÷ Flux(2°<|b|<5°) ~ 3

~ Tibet region A ~ LHAASO inner Gal. plane

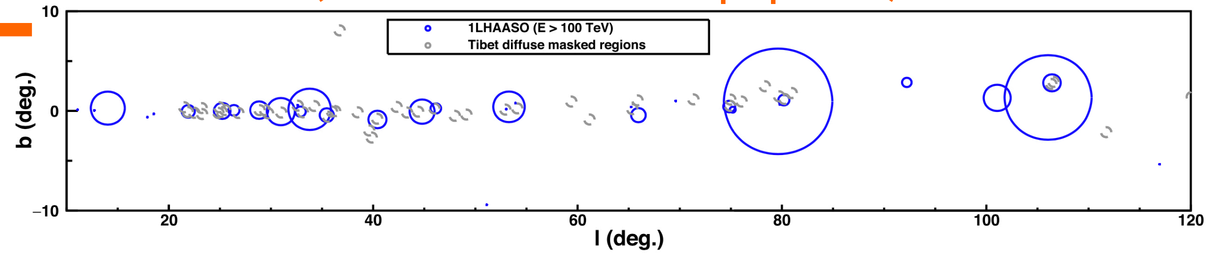
Larger source masking scheme by LHAASO likely loses a lot of GDE flux

Sub-PeV Galactic γ Rays Dominated by GDE?

S.K. et al., ApJ 984, 98 (2025)



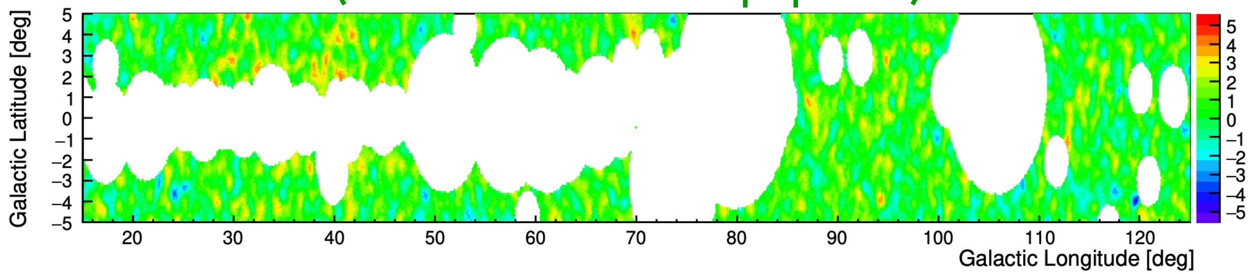
Tibet masked GDE flux: gray
(25° < l < 100° & |b| < 5°)



Amenomori et al., PRL, 126, 141101 (2021)

Not-masked LHAASO flux
(15° < l < 125° & |b| < 5°)

LHAASO masked GDE flux
(15° < l < 125° & |b| < 5°)

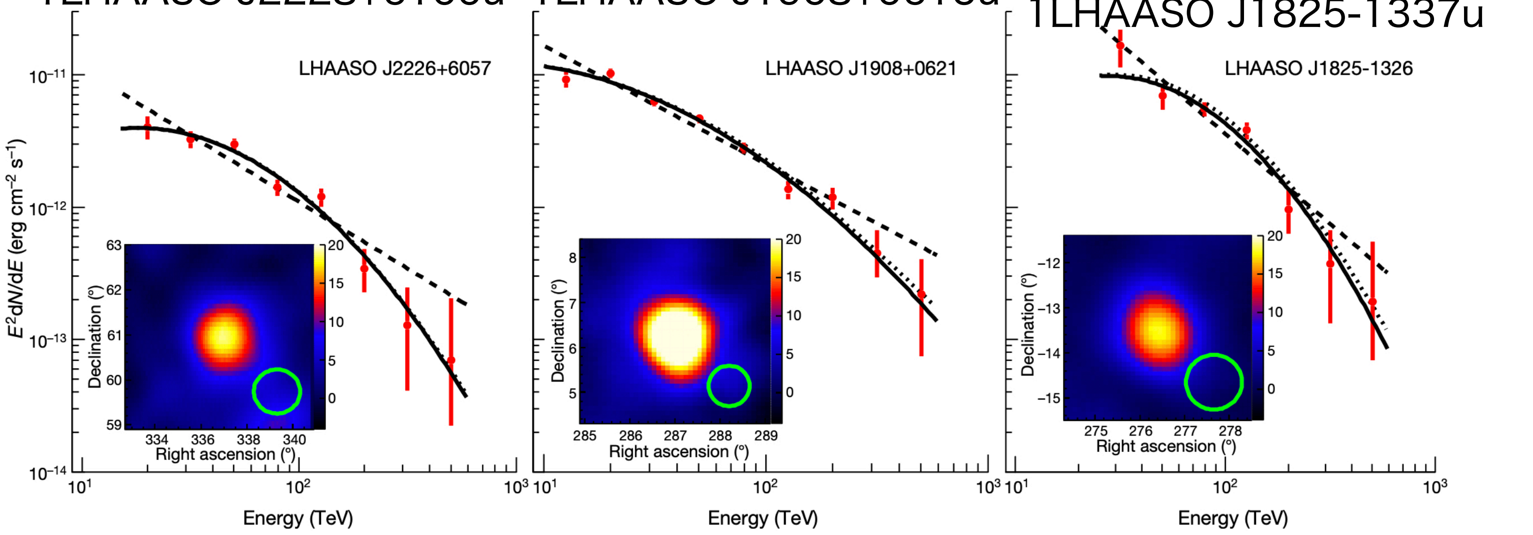


Cao et al., PRL 134 081002 (2025)

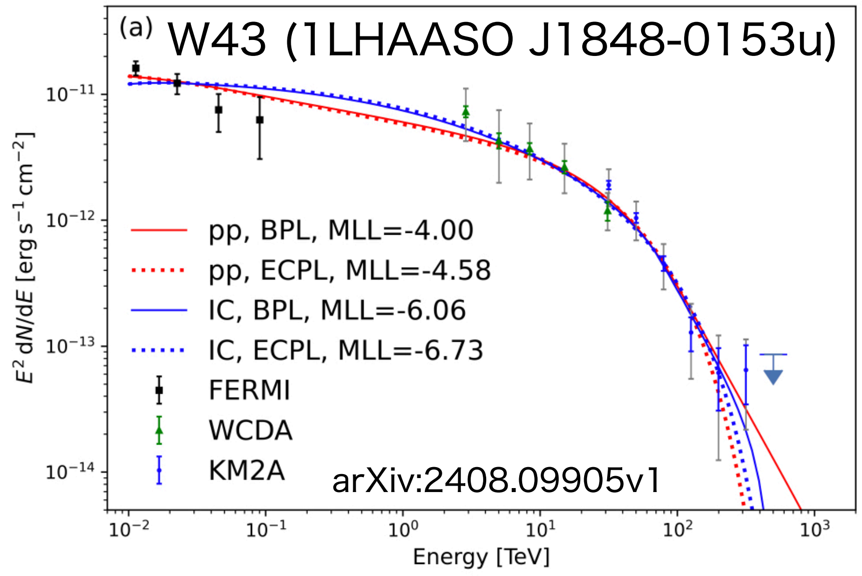
Tibet GDE = Not-masked LHAASO flux

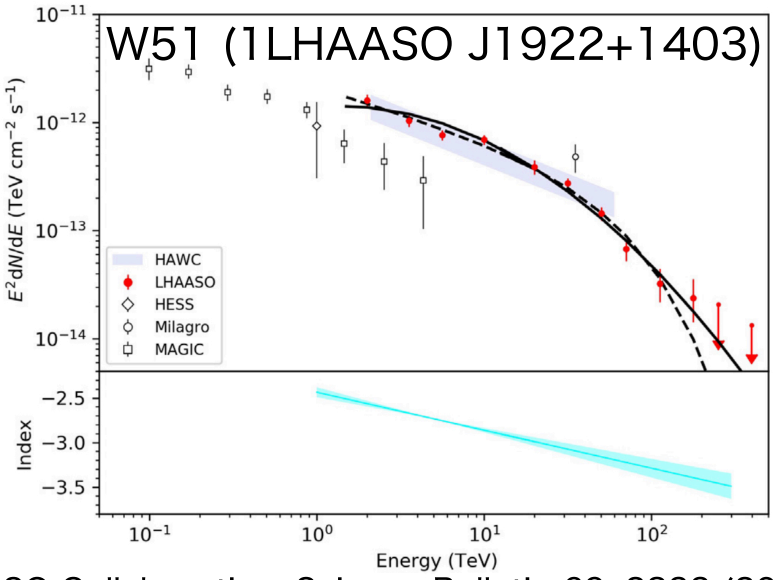
Energy Spectra of Individual 1st LHAASO Catalog Sources

1LHAASO J2228+6100u   1LHAASO J1908+0615u   1LHAASO J1825-1256u & 1LHAASO J1825-1337u



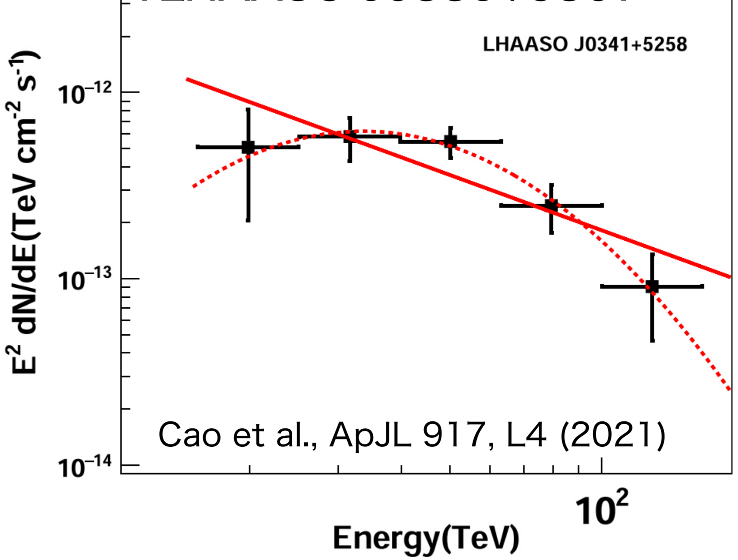
Cao et al., Nature 594, 33 (2021)





LHAASO Collaboration, Science Bulletin 69, 2833 (2024)

1LHAASO J0343+5254u & 1LHAASO J0339+5307

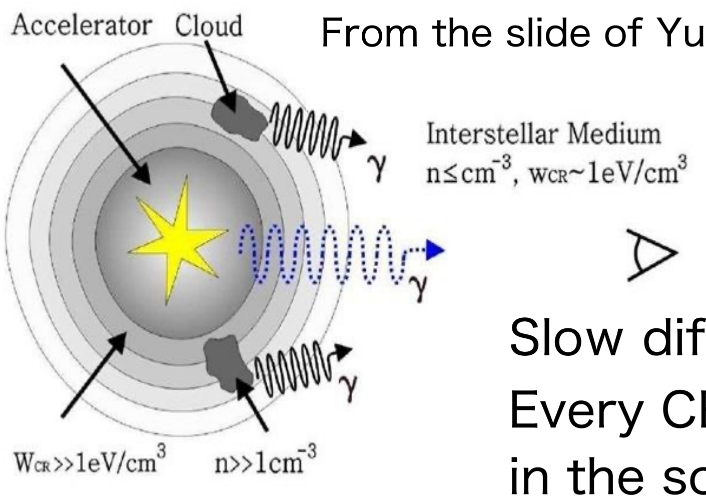


Cao et al., ApJL 917, L4 (2021)

Many gamma-ray sources have a spectral break @ O(10TeV)

Spectral studies of more sources needed

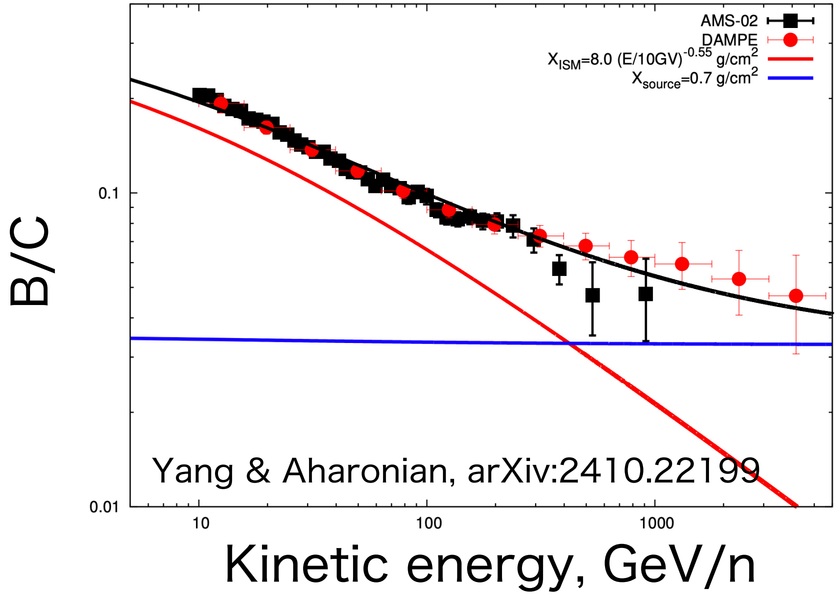
Contamination from Very Extended Sources?

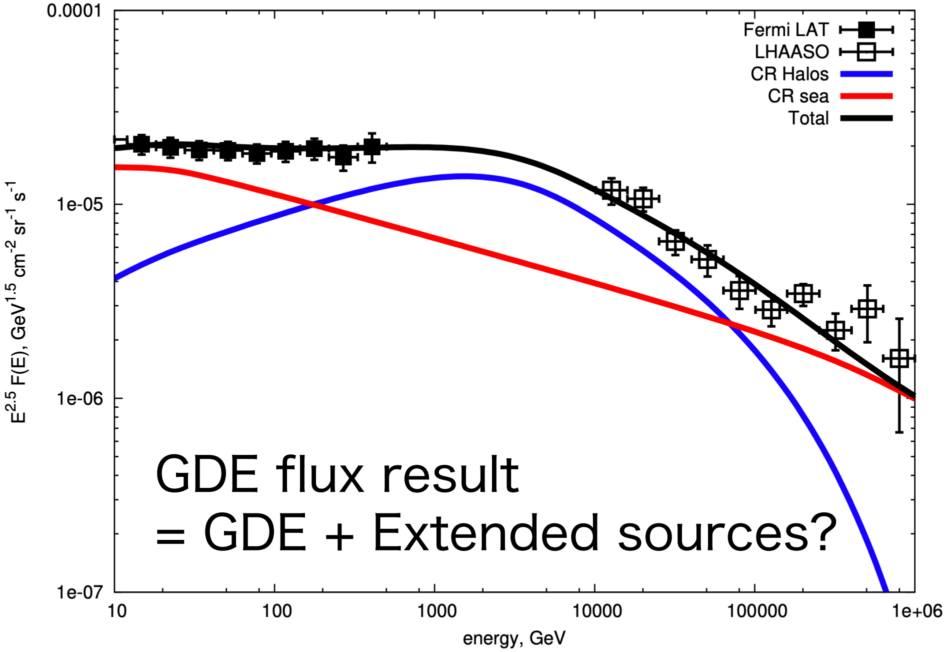


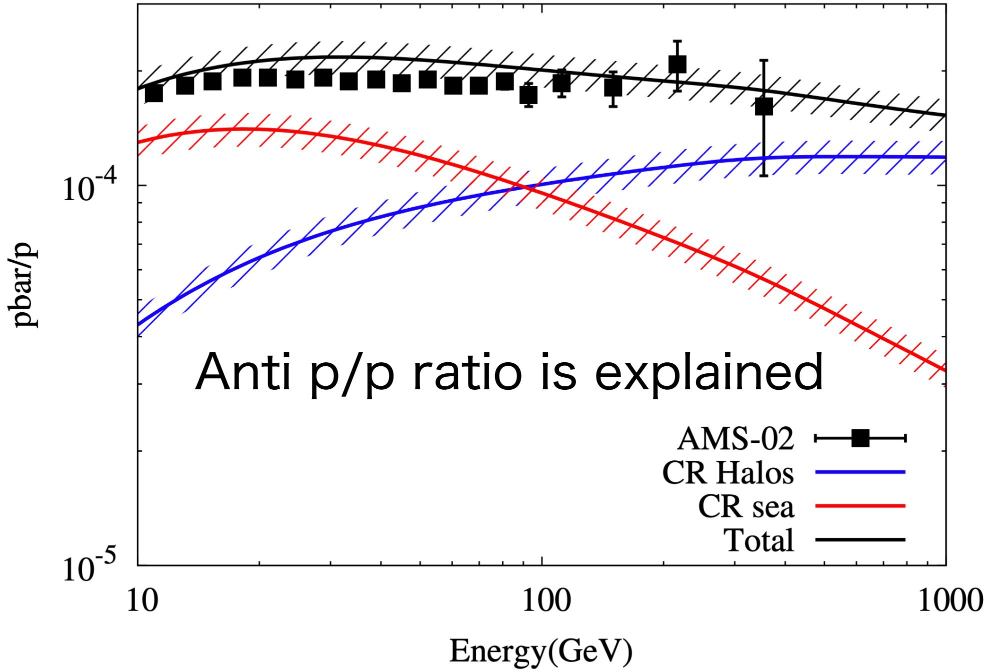
From the slide of Yuan (TMEX2025)

Slow diffusion in the source vicinity?

Every CR experience 0.7 g/cm^2 in the source vicinity?







Summary

✓ PWN as a candidate for the origin of the Knee CRs (~PeV)

✓ Sub-PeV γ-ray observation of a middle-aged PWN HESS J1849−000

=> PeV CR in a PWN-SNR composite system? (More study needed)

✓ PWNe largely contribute to the total sub-PeV Galactic γ-ray emission?

=> NO (regardless of resolved/unresolved PWN)

✓ The Galactic sub-PeV γ-ray emission is dominated by diffuse γ rays (Like in the GeV range)

✓ Contribution from yet-unresolved sources? NOT clear

✓ Contamination from undetectable very extended sources?

=> More study of the effect of HE phenomena on ISM is needed