中国科学技术大学
University of Science and Technology of China

LHAASO
高海拔宇宙线观测站

Discovery of Ultra High Energy Gamma-ray Sources by LHAASO

Ruizhi Yang
University of Science and Technology of China
On behalf of LHAASO collaborations

Outline

1. Intro of LHAASO

2. Highlights of LHAASO results

3. Summary and prospect

LHAASO collaborations

中国科学技术大学
University of Science and Technology of China

- 274 Scientists

- 32 institutions
- from 5 countries

Zhen Cao[1,2,3], F. Aharonian[4,5], Q. An[6,7], Axikegu[8], L. X. Bai[9], Y. X. Bai[1,3], Y. W. Bao[10], D. Bastieri[11], X. J. Bi[1,2,3], Y. J. Bi[1,3], H. Cai[12], J. T. Cai[11], Zhe Cao[6,7], J. Chang[13], J. F. Chang[1,3,6], B. M. Chen[14], E. S. Chen[1,2,3], J. Chen[9], Liang Chen[1,2,3], Liang Chen[15], Long Chen[8], M. J. Chen[1,3], M. L. Chen[1,3,6], Q. H. Chen[8], S. H. Chen[1,2,3], S. Z. Chen[1,3], T. L. Chen[16], X. L. Chen[1,2,3], Y. Chen[10], N. Cheng[1,3], Y. D. Cheng[1,3], S. W. Cui[14], X. H. Cui[17], Y. D. Cui[18], B. D'Ettorre Piazzoli[19], B. Z. Dai[20], H. L. Dai[1,3,6], Z. G. Dai[7], Danzengluobu[16], D. della Volpe[21], X. J. Dong[1,3], K. K. Duan[13], J. H. Fan[11], Y. Z. Fan[13], Z. X. Fan[1,3], J. Fang[20], K. Fang[1,3], C. F. Feng[22], L. Feng[13], S. H. Feng[1,3], Y. L. Feng[13], B. Gao[1,3], C. D. Gao[22], L. Q. Gao[1,2,3], Q. Gao[16], W. Gao[22], M. M. Ge[20], L. S. Geng[1,3], G. H. Gong[23], Q. B. Gou[1,3], M. H. Gu[1,3,6], F. L. Guo[15], J. G. Guo[1,2,3], X. L. Guo[8], Y. Q. Guo[1,3], Y. Y. Guo[1,2,3,13], Y. A. Han[24], H. H. He[1,2,3], H. N. He[13], J. C. He[1,2,3], S. L. He[11], X. B. He[18], Y. He[8], M. Heller[21], Y. K. Hor[18], C. Hou[1,3], H. B. Hu[1,2,3], S. Hu[9], S. C. Hu[1,2,3], X. J. Hu[23], D. H. Huang[8], Q. L. Huang[1,3], W. H. Huang[22], X. T. Huang[22], X. Y. Huang[13], Z. C. Huang[8], F. Ji[1,3], X. L. Ji[1,3,6], H. Y. Jia[8], K. Jiang[6,7], Z. J. Jiang[20], C. Jin[1,2,3], T. Ke[1,3], D. Kuleshov[25], K. Levochkin[25], B. B. Li[14], Cheng Li[6,7], Cong Li[1,3], F. Li[1,3,6], H. B. Li[1,3], H. C. Li[1,3], H. Y. Li[7,13], J. Li[1,3,6], K. Li[1,3], W. L. Li[22], X. R. Li[1,3], Xin Li[6,7], Xin Li[8], Y. Li[9], Y. Z. Li[1,2,3], Zhe Li[1,3], Zhuo Li[26], E. W. Liang[27], Y. F. Liang[27], S. J. Lin[18], B. Liu[7], C. Liu[1,3], D. Liu[22], H. Liu[8], H. D. Liu[24], J. Liu[1,3], J. L. Liu[28], J. S. Liu[18], J. Y. Liu[1,3], M. Y. Liu[16], R. Y. Liu[10], S. M. Liu[8], W. Liu[1,3], Y. Liu[11], Y. N. Liu[23], Z. X. Liu[9], W. J. Long[8], R. Lu[20], H. K. Lv[1,3], B. Q. Ma[26], L. L. Ma[1,3], X. H. Ma[1,3], J. R. Mao[29], A. Masood[8], Z. Min[1,3], W. Mitthumsiri[30], T. Montaruli[21], Y. C. Nan[22], B. Y. Pang[8], P. Pattarakijwanich[30], Z. Y. Pei[11], M. Y. Qi[1,3], Y. Q. Qi[14], B. Q. Qiao[1,3], J. J. Qin[7], D. Ruffolo[30], V. Rulev[25], A. Sáiz[30], L. Shao[14], O. Shchegolev[25,31], X. D. Sheng[1,3], J. Y. Shi[1,3], H. C. Song[26], Yu. V. Stenkin[25,31], V. Stepanov[25], Y. Su[32], Q. N. Sun[8], X. N. Sun[27], Z. B. Sun[33], P. H. T. Tam[18], Z. B. Tang[6,7], W. W. Tian[2,17], B. D. Wang[1,3], C. Wang[33], H. Wang[8], H. G. Wang[11], J. C. Wang[29], J. S. Wang[28], L. P. Wang[22], L. Y. Wang[1,3], R. N. Wang[8], W. Wang[18], W. Wang[12], X. G. Wang[27], X. J. Wang[1,3], X. Y. Wang[10], Y. Wang[8], Y. D. Wang[1,3], Y. J. Wang[1,3], Y. P. Wang[1,2,3], Z. H. Wang[9], Z. X. Wang[20], Zhen Wang[28], Zheng Wang[1,3,6], D. M. Wei[13], J. J. Wei[13], Y. J. Wei[1,2,3], T. Wen[20], C. Y. Wu[1,3], H. R. Wu[1,3], S. Wu[1,3], W. X. Wu[8], X. F. Wu[13], S. Q. Xi[1,3], J. Xia[7,13], J. J. Xia[8], G. M. Xiang[2,15], D. X. Xiao[16], G. Xiao[1,3], H. B. Xiao[11], G. G. Xin[12], Y. L. Xin[8], Y. Xing[15], D. L. Xu[28], R. X. Xu[26], L. Xue[22], D. H. Yan[29], J. Z. Yan[13], C. W. Yang[9], F. F. Yang[1,3,6], J. Y. Yang[18], L. L. Yang[18], M. J. Yang[1,3], R. Z. Yang[7], S. B. Yang[20], Y. H. Yao[9], Z. G. Yao[1,3], Y. M. Ye[23], L. Q. Yin[1,3], N. Yin[22], X. H. You[1,3], Z. Y. You[1,2,3], Y. H. Yu[22], Q. Yuan[13], H. D. Zeng[13], T. X. Zeng[1,3,6], W. Zeng[20], Z. K. Zeng[1,2,3], M. Zha[1,3], X. X. Zhai[1,3], B. B. Zhang[10], H. M. Zhang[10], H. Y. Zhang[22], J. L. Zhang[17], J. W. Zhang[9], L. X. Zhang[11], Li Zhang[20], Lu Zhang[14], P. F. Zhang[20], P. P. Zhang[14], R. Zhang[7,13], S. R. Zhang[14], S. S. Zhang[1,3], X. Zhang[10], X. P. Zhang[1,3], Y. F. Zhang[8], Y. L. Zhang[1,3], Yi Zhang[1,13], Yong Zhang[1,3], B. Zhao[8], J. Zhao[1,3], L. Zhao[6,7], L. Z. Zhao[14], S. P. Zhao[13,22], F. Zheng[33], Y. Zheng[8], B. Zhou[1,3], H. Zhou[28], J. N. Zhou[15], P. Zhou[10], R. Zhou[9], X. X. Zhou[8], C. G. Zhu[22], F. R. Zhu[8], H. Zhu[17], K. J. Zhu[1,2,3,6], and X. Zuo[1,3]

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LHAASO site

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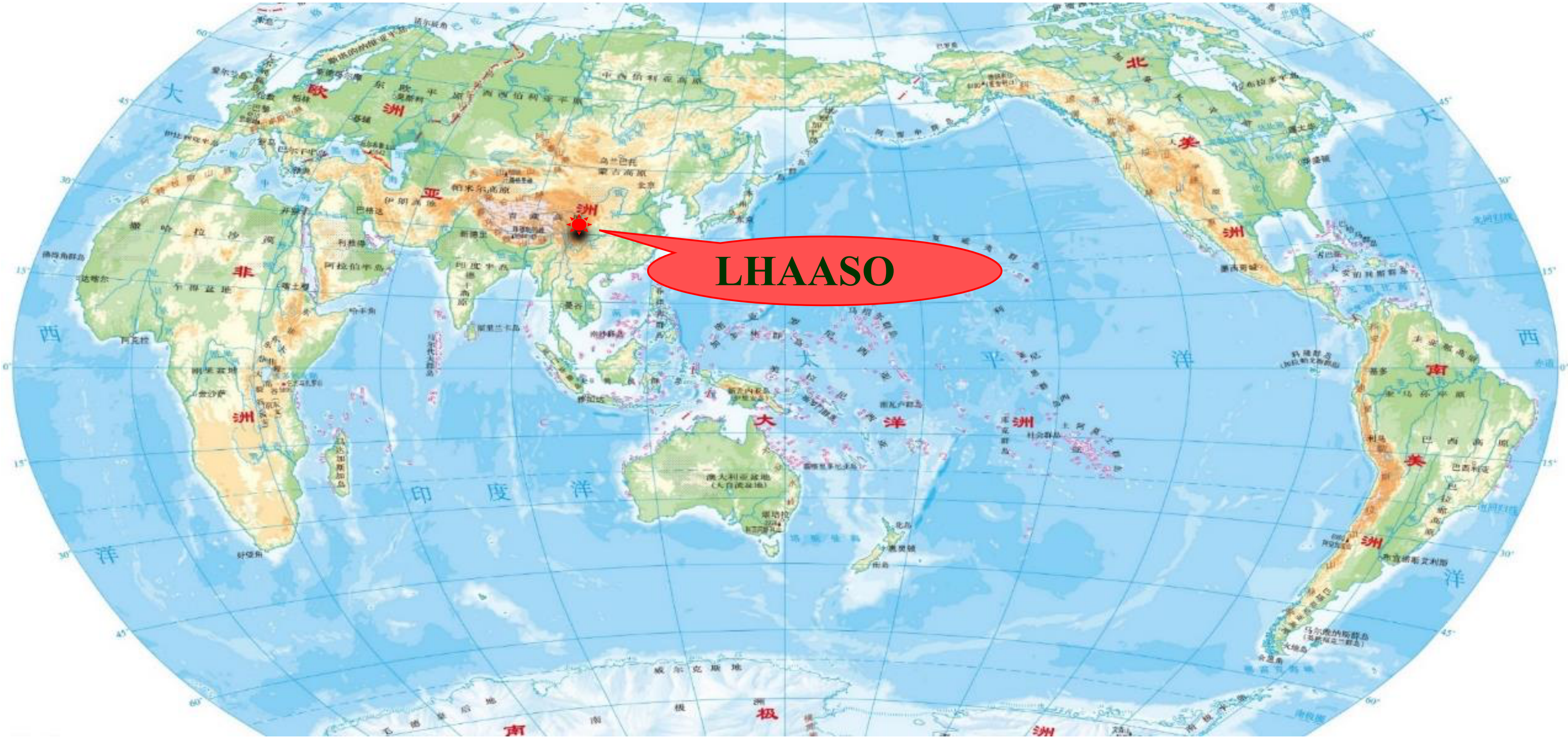
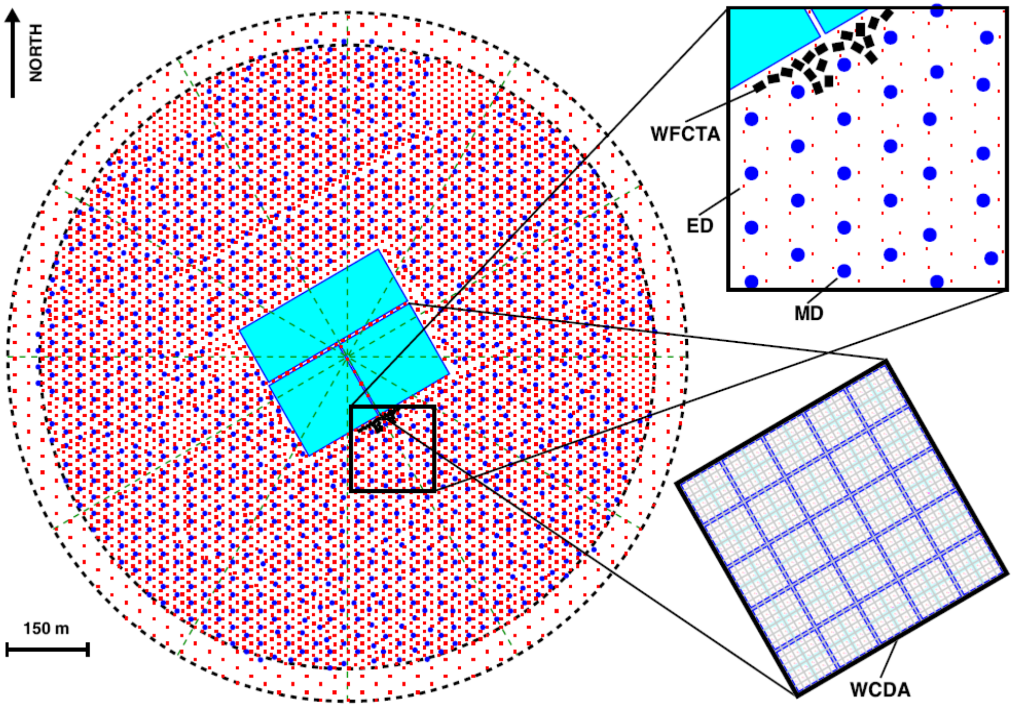
- Haizi Mountain, Sichuan province, China
- Location： 29°21’27.6” N, 100°08’19.6” E
- Altitude： 4410 m a.s.l.
- 10 km from Yading Airport



LHAASO layout

All detectors are in DAQ since 2021-7-19



1.3 km^2

- **5195 EDs**
  - 1 m^2 each
  - 15 m spacing
- **1188 MDs**
  - 36 m^2 each
  - 30 m spacing

KM2A

- **3120 WCDs**
  - 25 m^2 each

WCDA

- **18 WFCTs**

WFCTA

LHAASO sub-arrays

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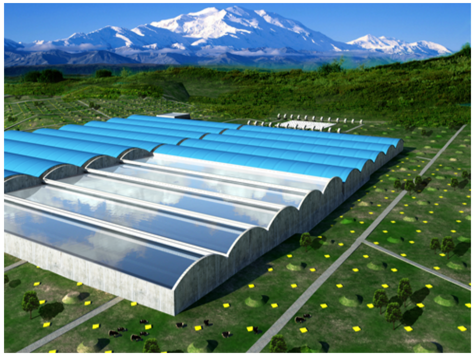
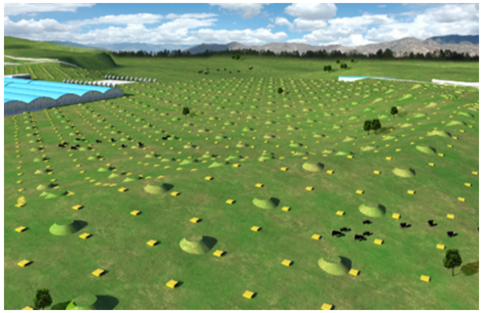
- **WCDA (100 GeV-30 TeV)**
  - VHE (>0.1TeV) γ-ray astronomy

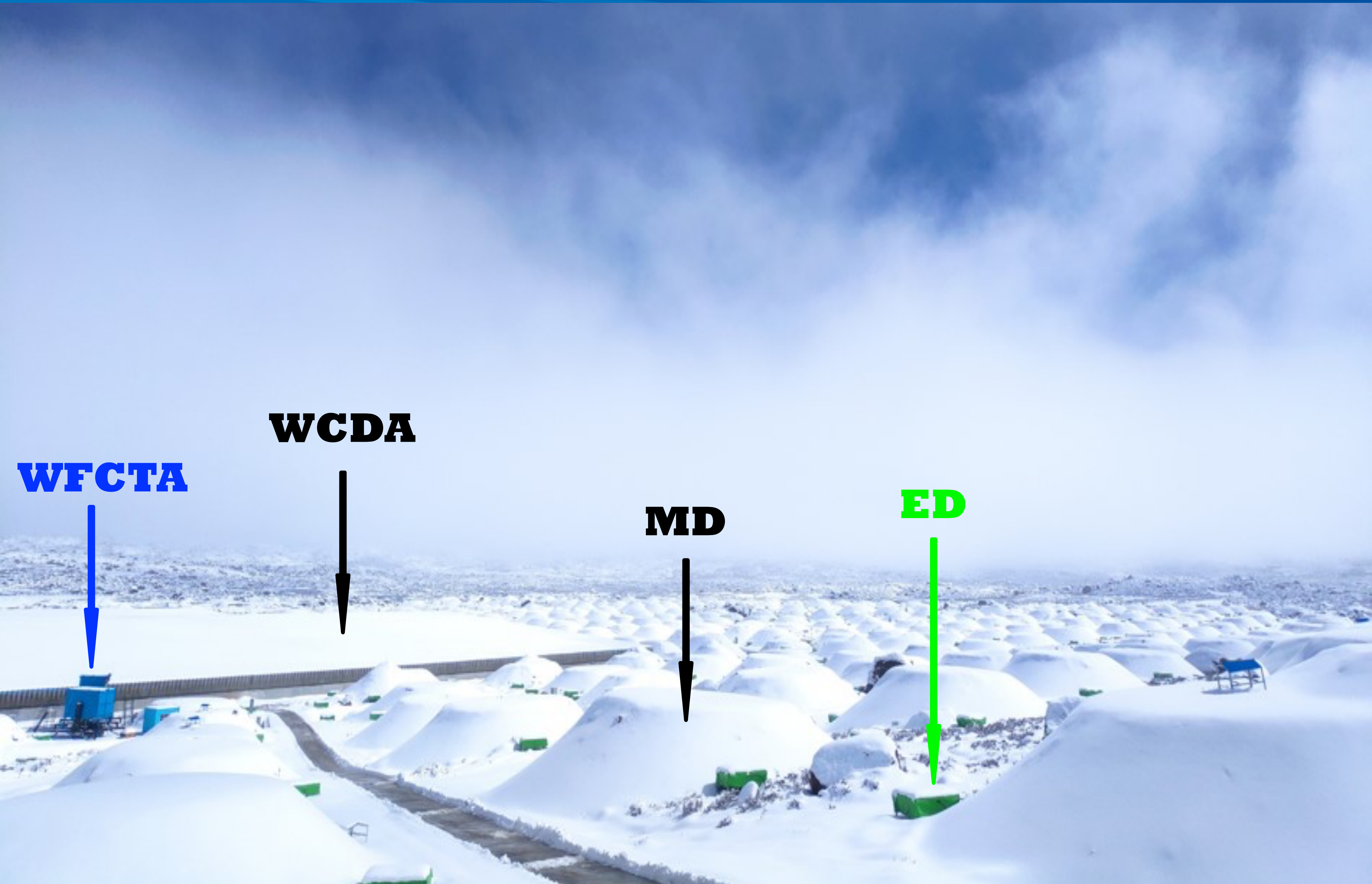


- **KM2A (10 TeV-10 PeV)**
  - UHE (>0.1PeV) γ-ray astronomy



- **WFCTA (10TeV to 1 EeV)**
  - Combined with WCDA, and KM2A
  - Individual nuclei spectra

LHAASO sub-arrays



LHAASO FOV

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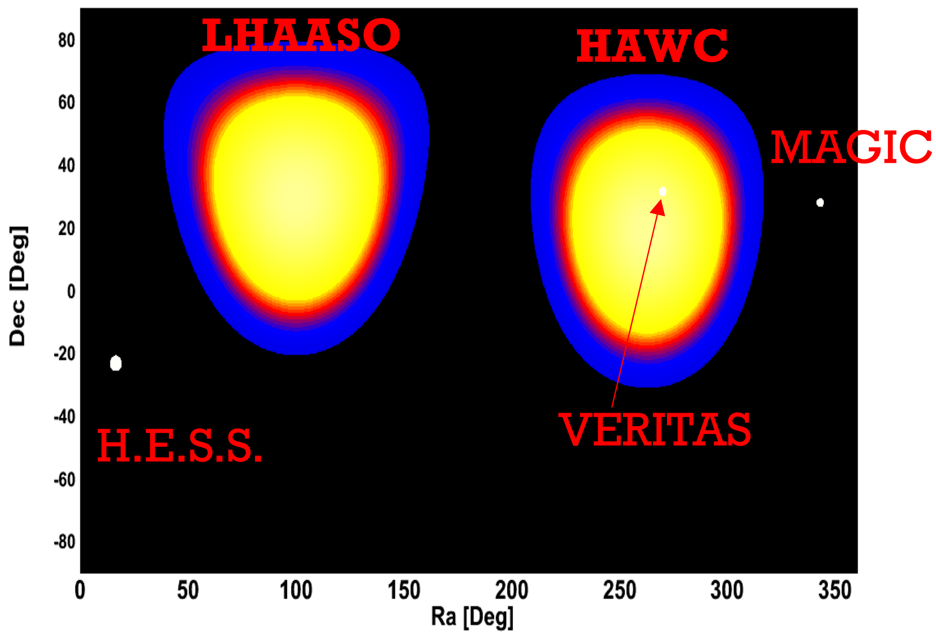
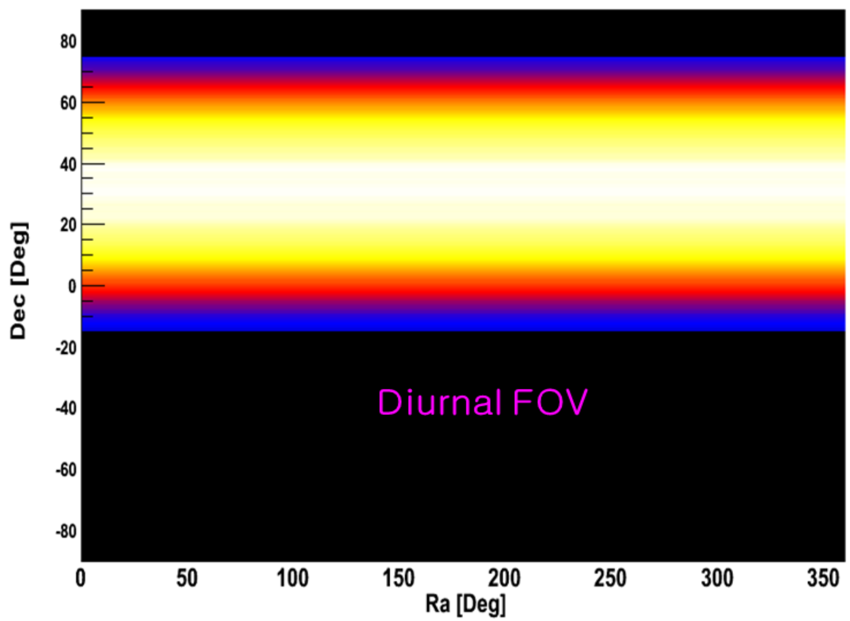
- **High duty cycle: ~100% running time**
- **Large FOV:**
  - **1/7 of the sky at any time**
  - **60% of the sky in a diurnal observation**





Extensive air shower

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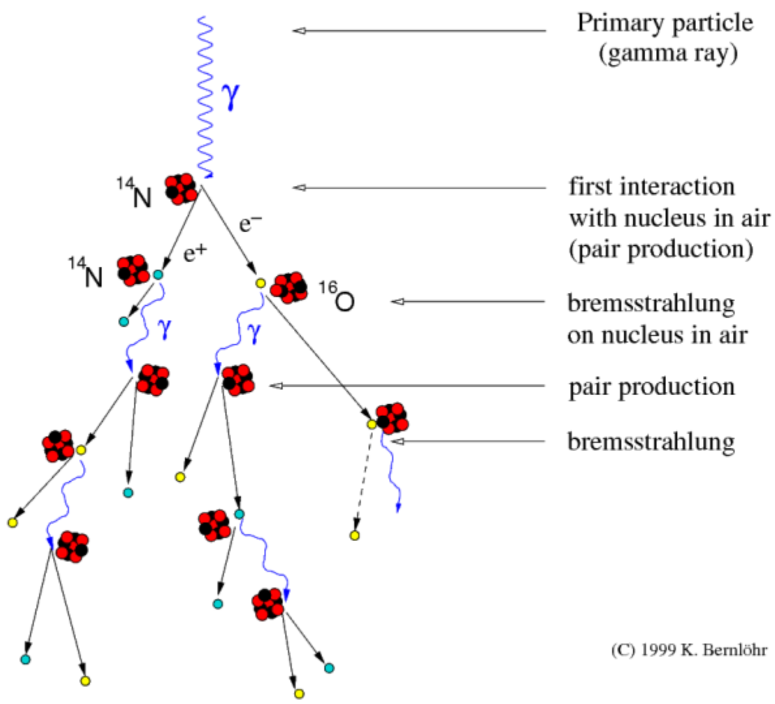
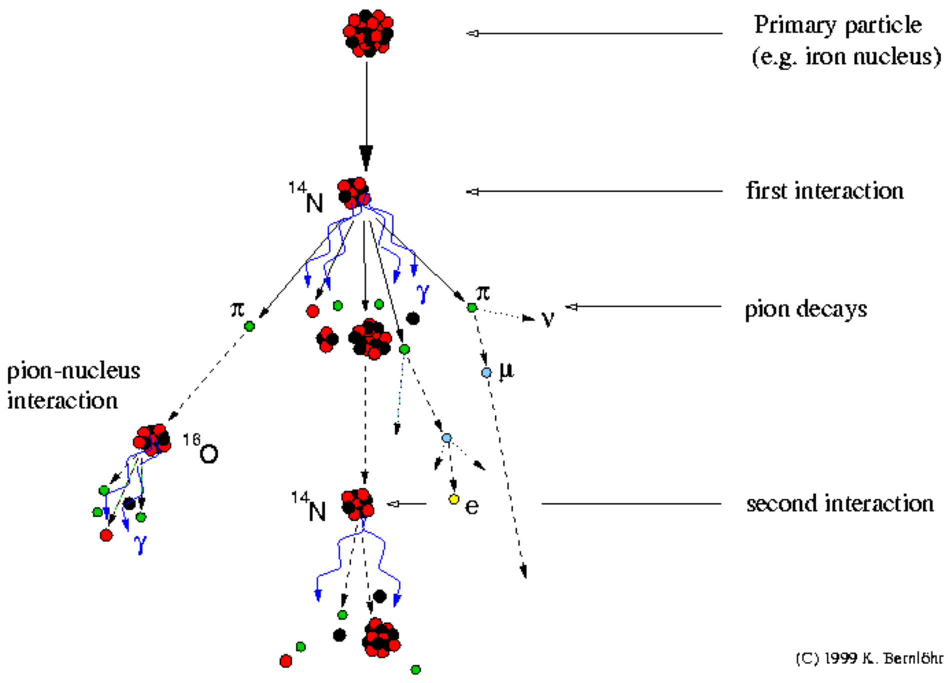
Development of gamma–ray air showers



Development of cosmic-ray air showers



γ-ray/cosmic ray discrimination

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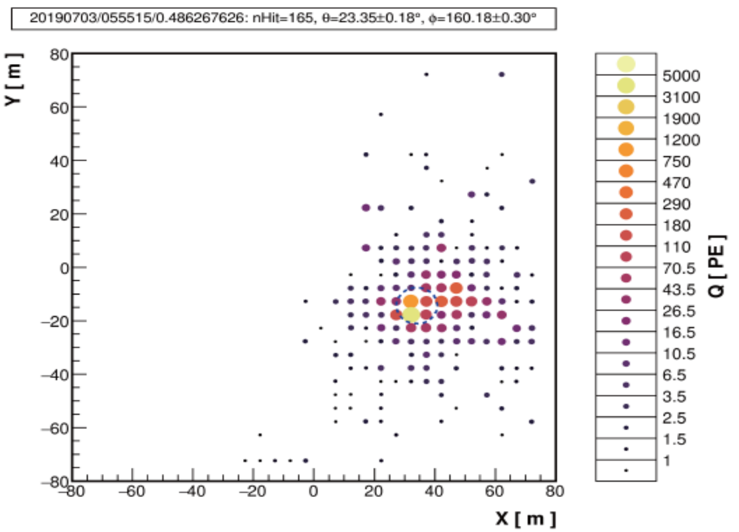
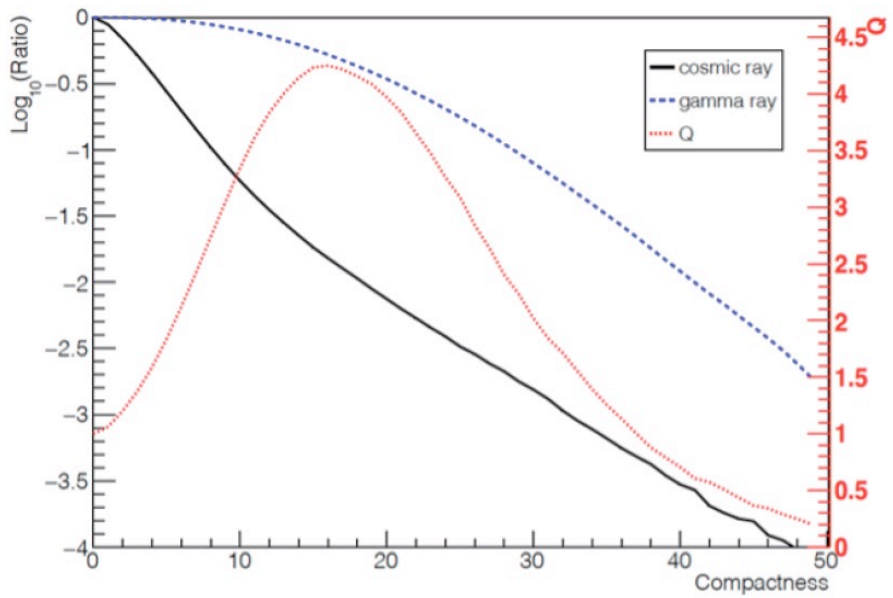
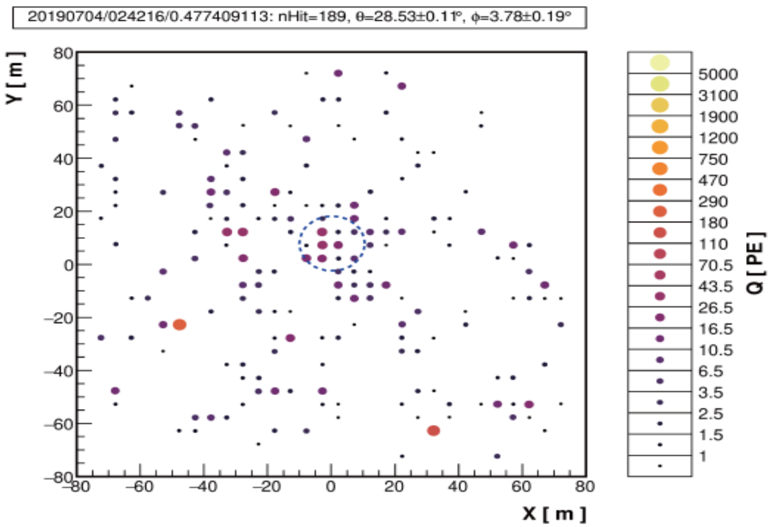


WCDA γ/P separation





Chinese Physics C 45: 085002 (2021)

γ-ray/cosmic ray discrimination

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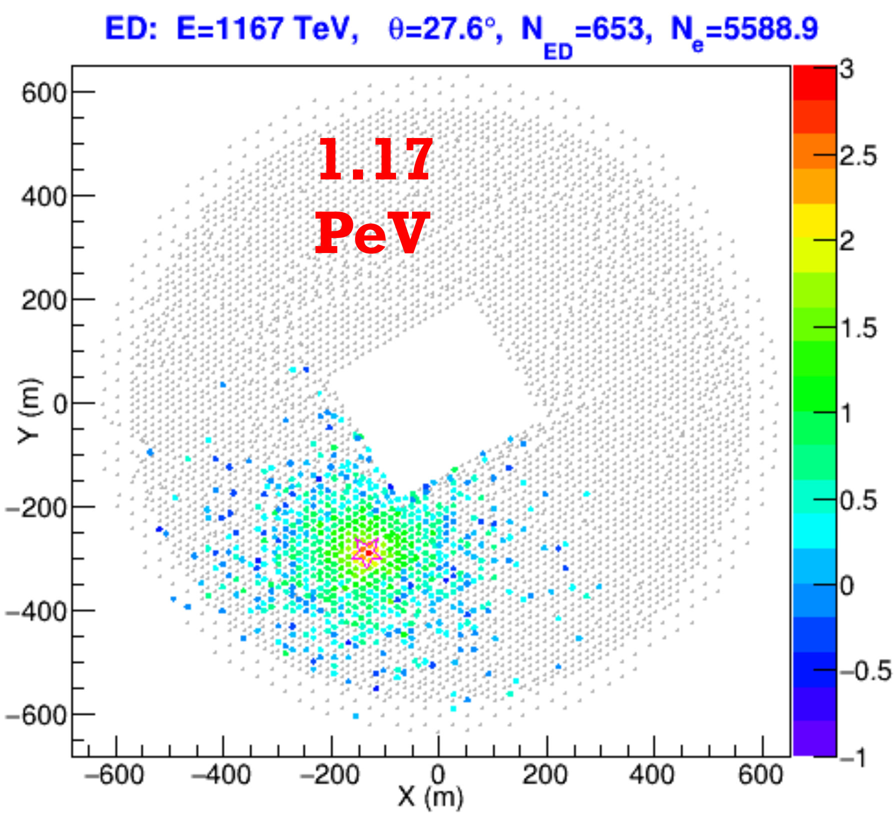
KM2A γ/P separation

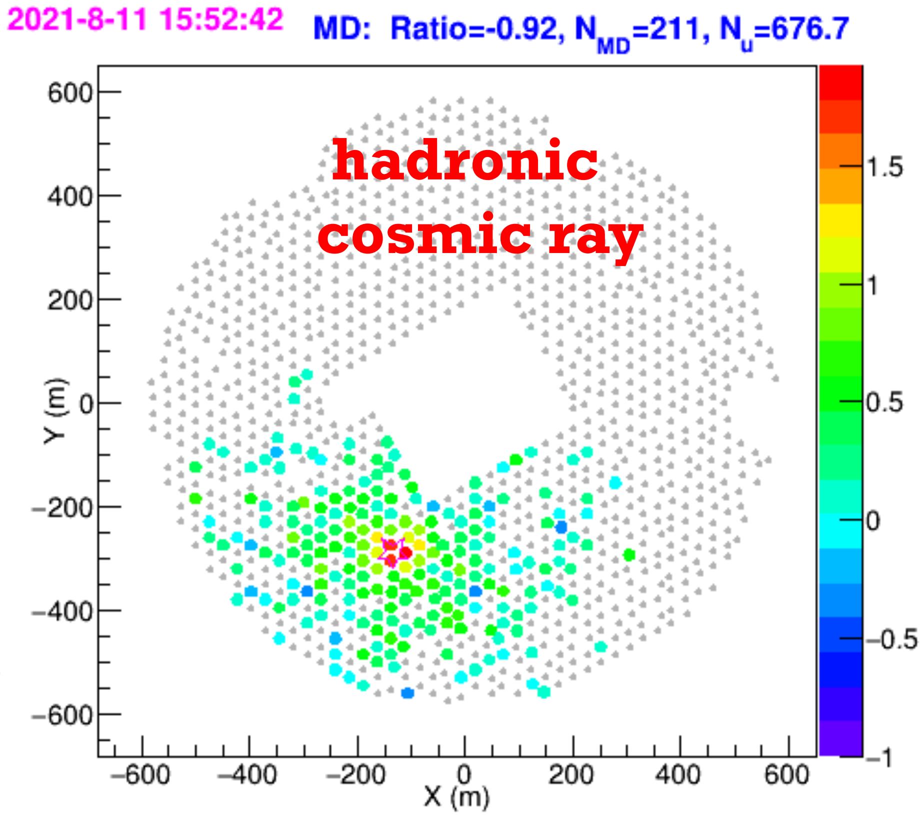
ED array

Reconstruct the direction, core, energy of events

MD array

Discriminate gamma-ray/cosmic ray





γ-ray/cosmic ray discrimination

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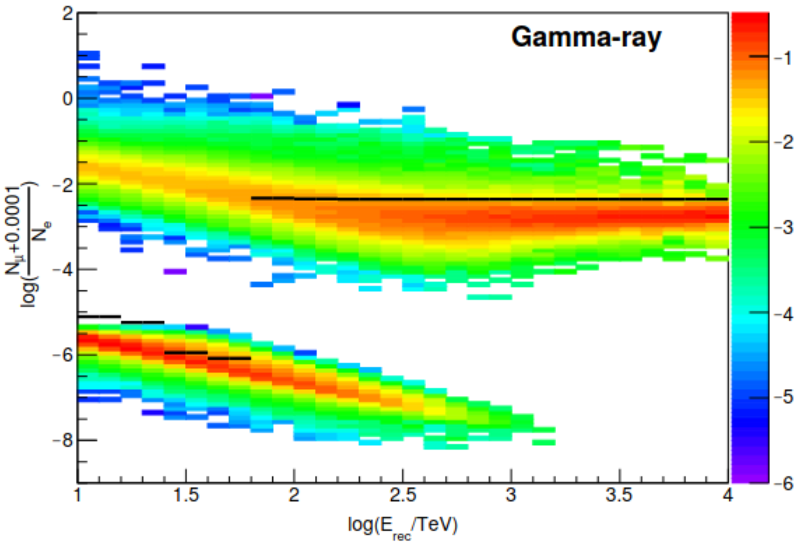
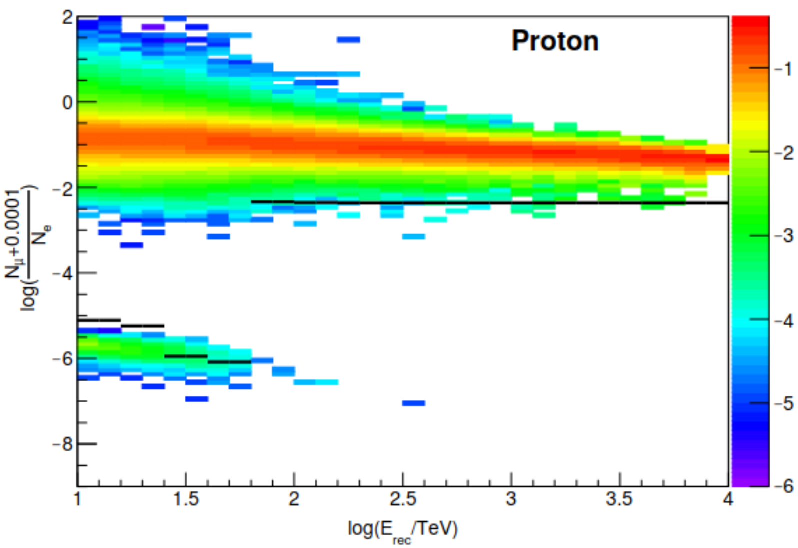
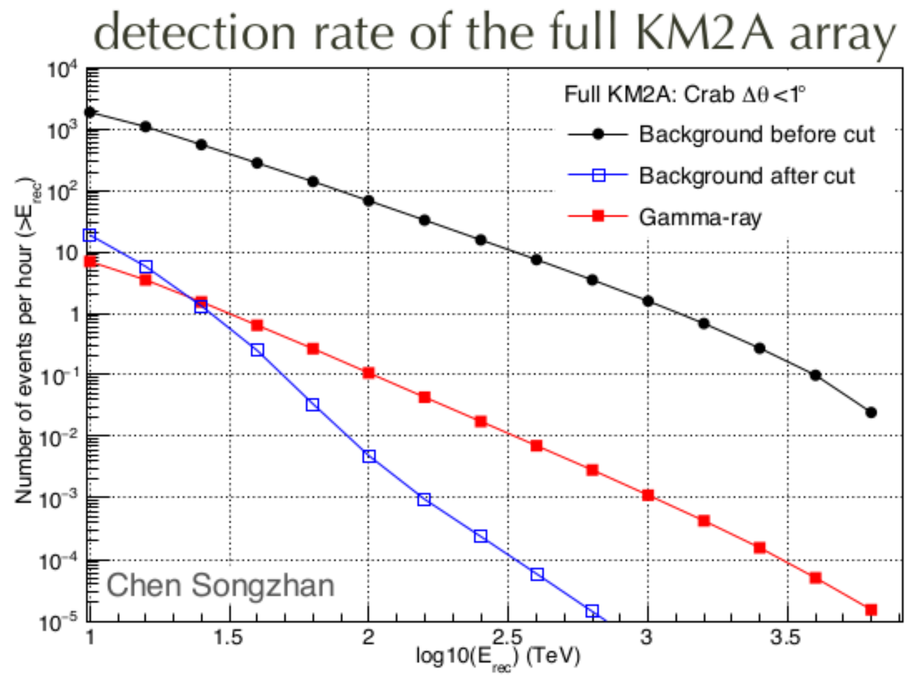
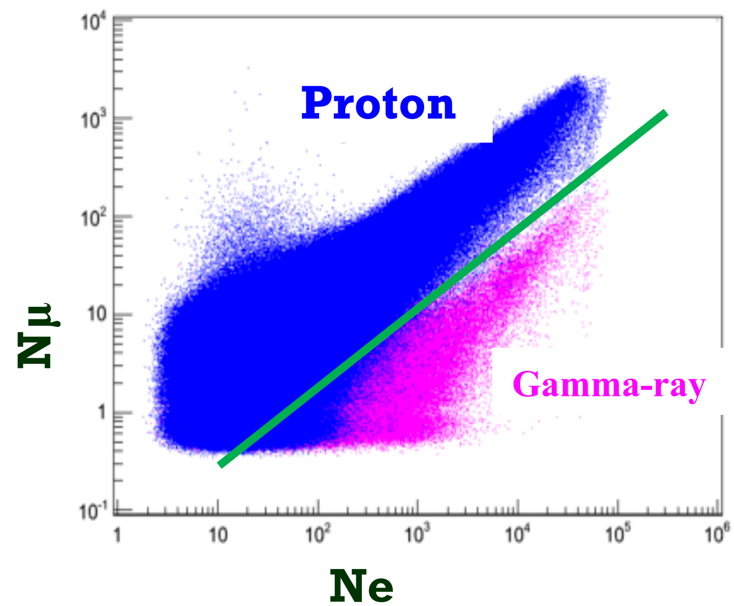


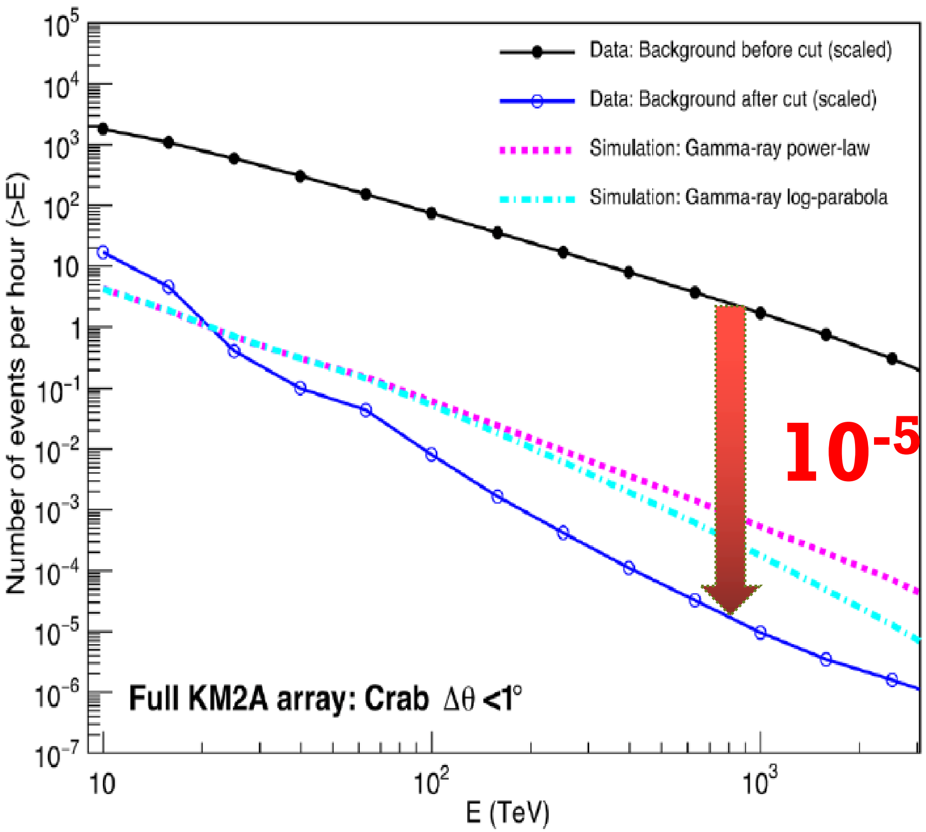




- Large effective area
- efficient background rejection (gamma-proton separation)

γ-ray/cosmic ray discrimination





Cosmic ray rate before cut

Gamma-ray rate

Cosmic ray rate after cut

LHAASO Sensitivities

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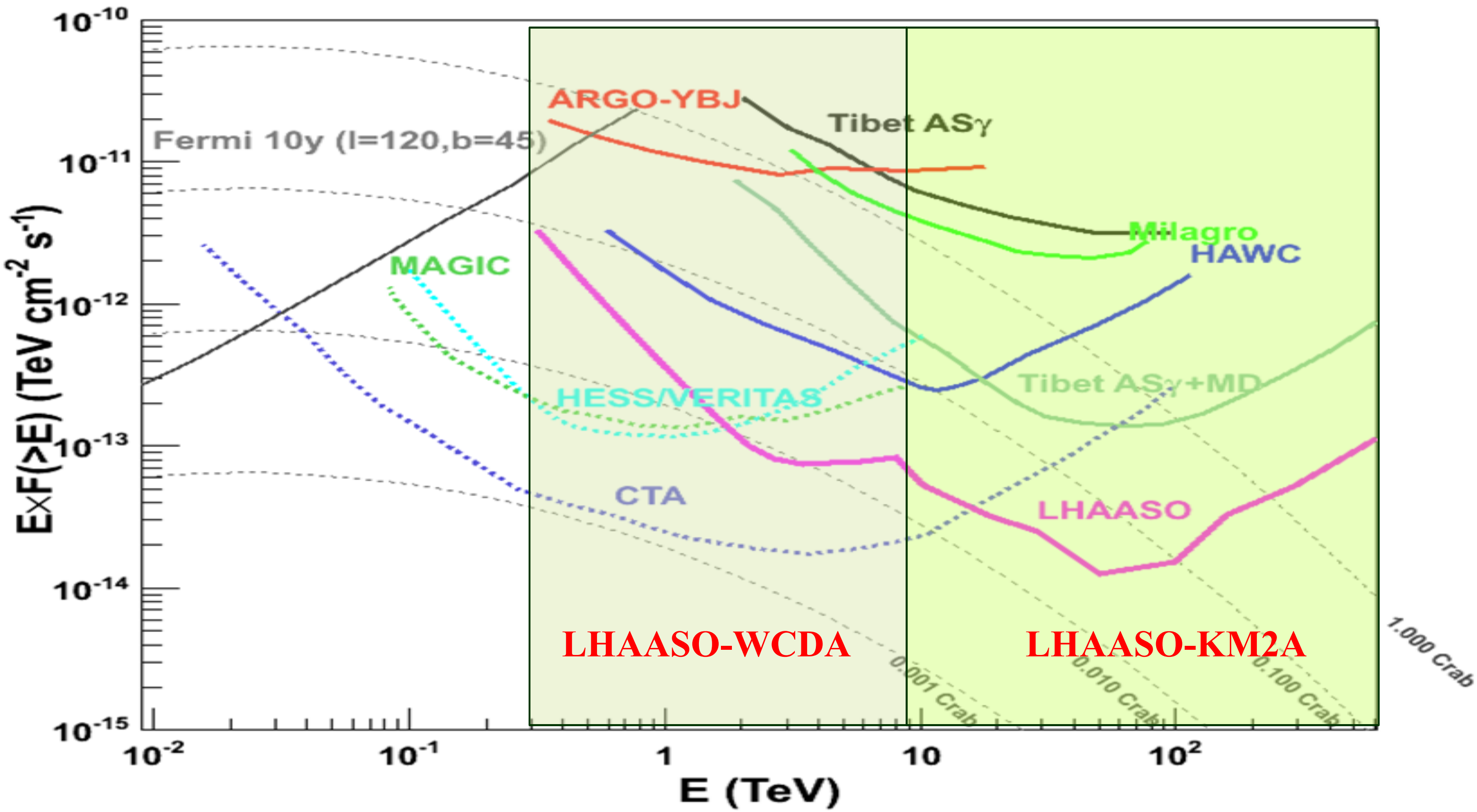

Unprecedented sensitivities above 20 TeV

Angular resolution (KM2A)

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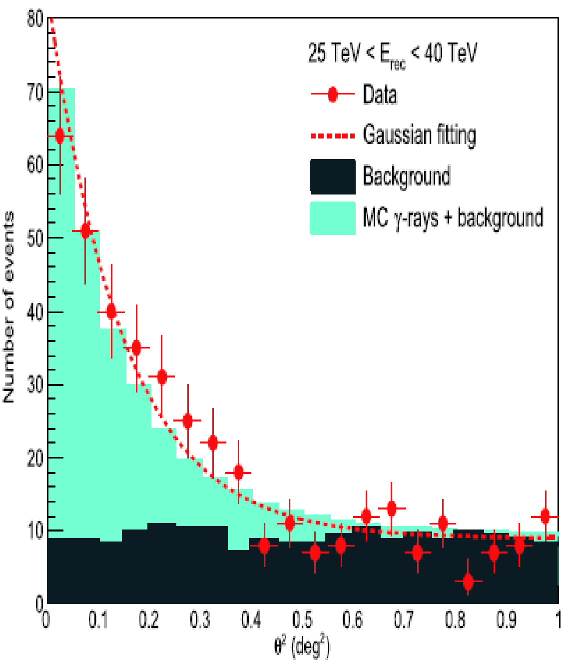
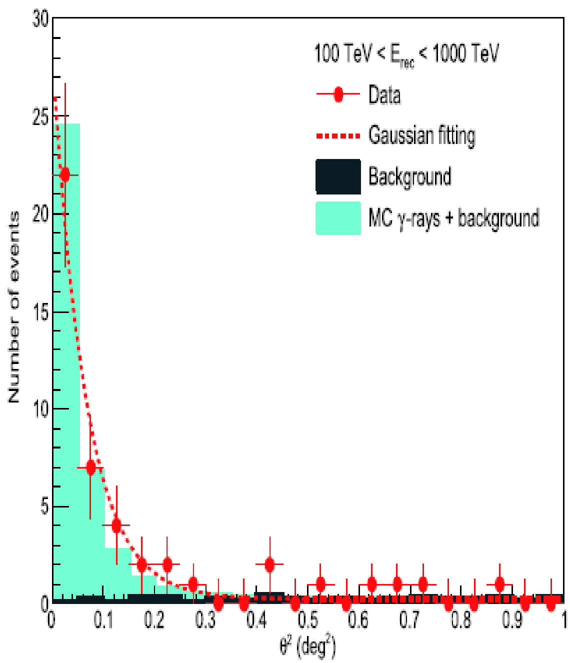
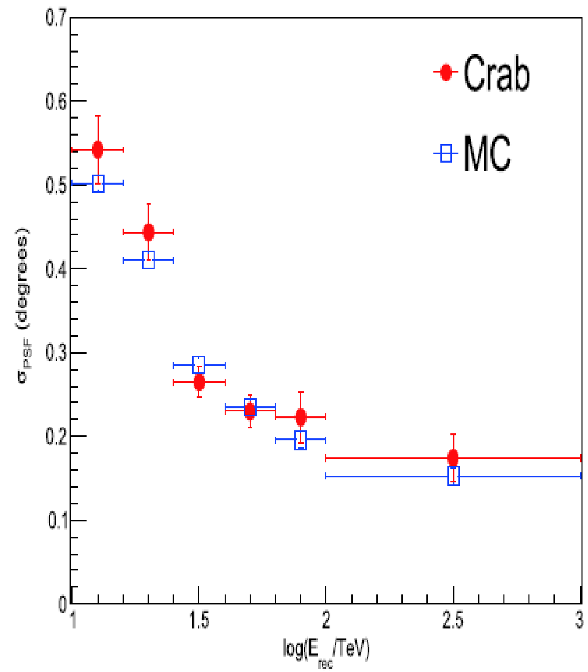
- **The angular resolution measured using standard candle Crab Nebula is consistent with MC prediction.**







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Energy resolution (KM2A)

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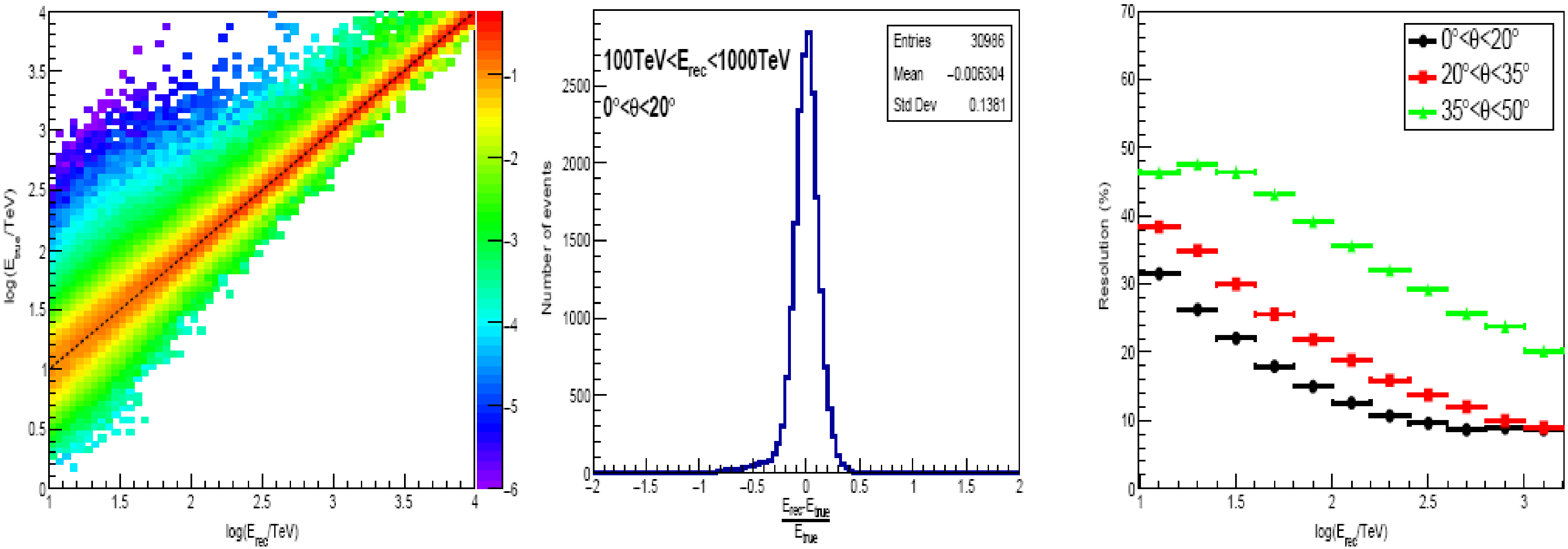
- **θ<20°: 24% @ 20 TeV, 13% @ 100 TeV**



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Highlights on recent results

Scientific objective: PeVatron hunting

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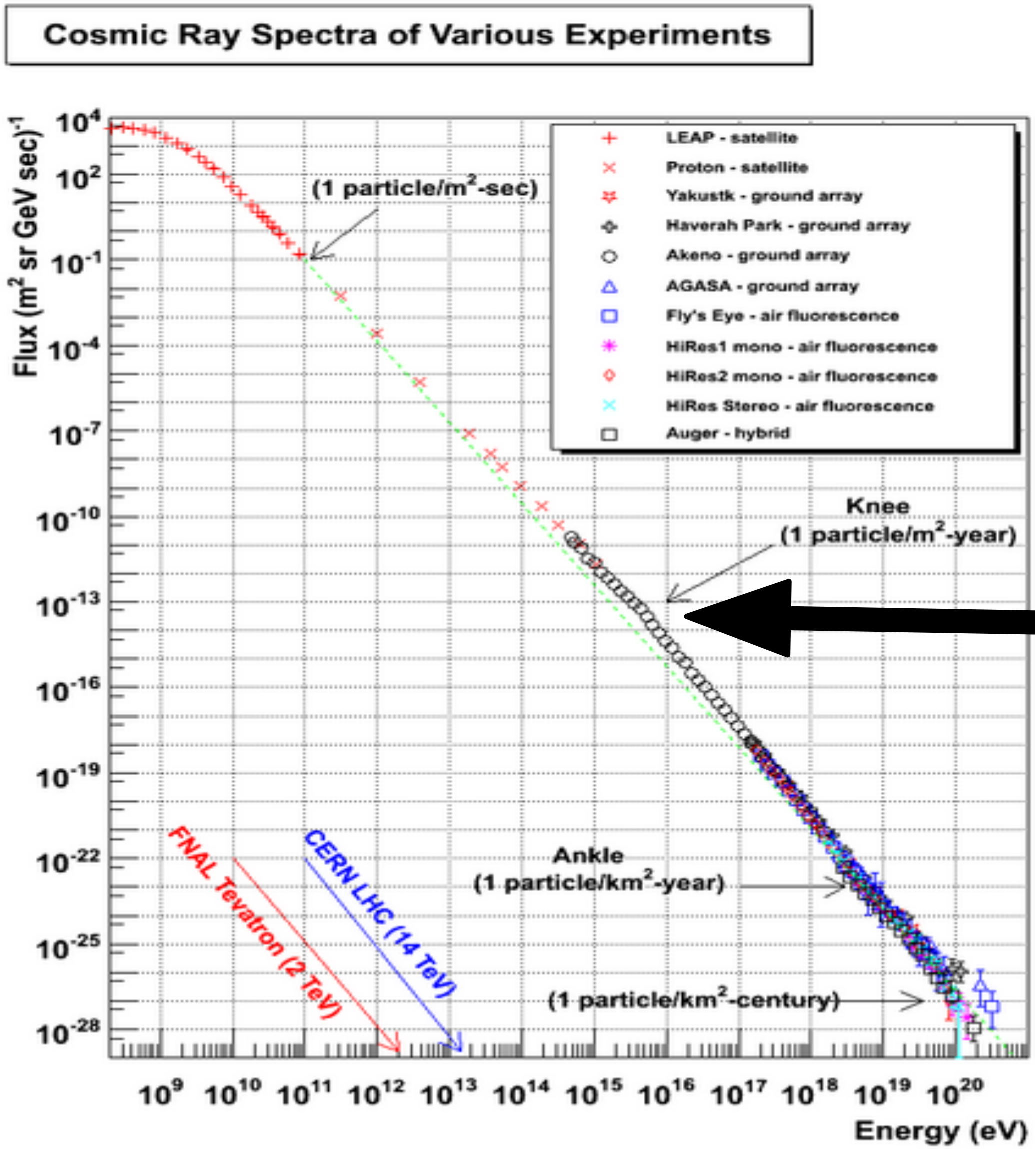

Knee: GCR at least to PeV

Searching for (proton) PeVatron

https://www.physics.utah.edu/~whanlon/spectrum.html

PeVatron identification

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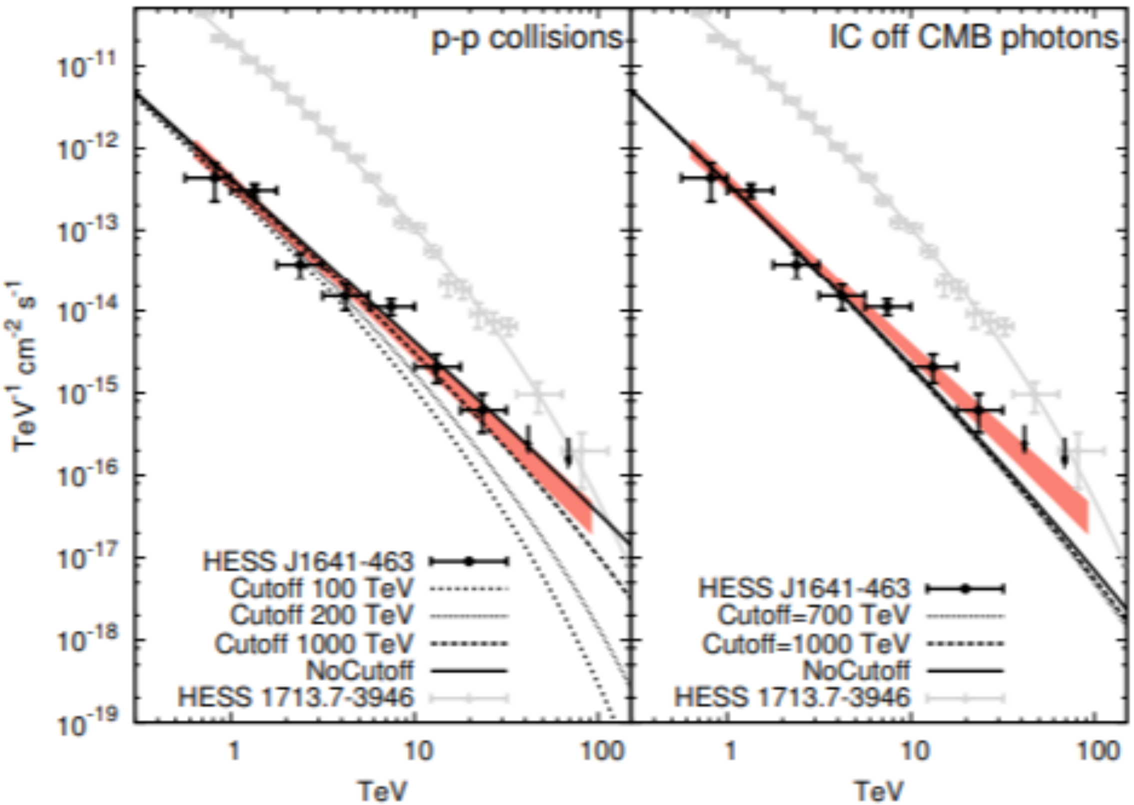
- **Hard gamma-ray spectrum without cutoff can hardly be addressed in leptonic model (cooling and KN effects).**

- **no-cutoff in the gamma-ray spectrum up to 25 TeV => no-cutoff in the parent proton spectrum up to ~ PeV.**



Hess J1641-463
(H.E.S.S collaboration 2016)

Galactic plane survey

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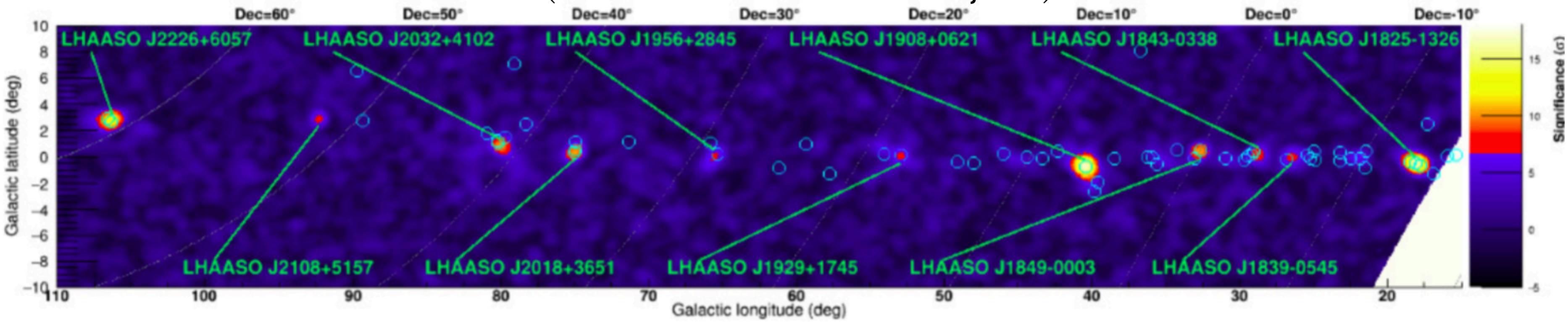
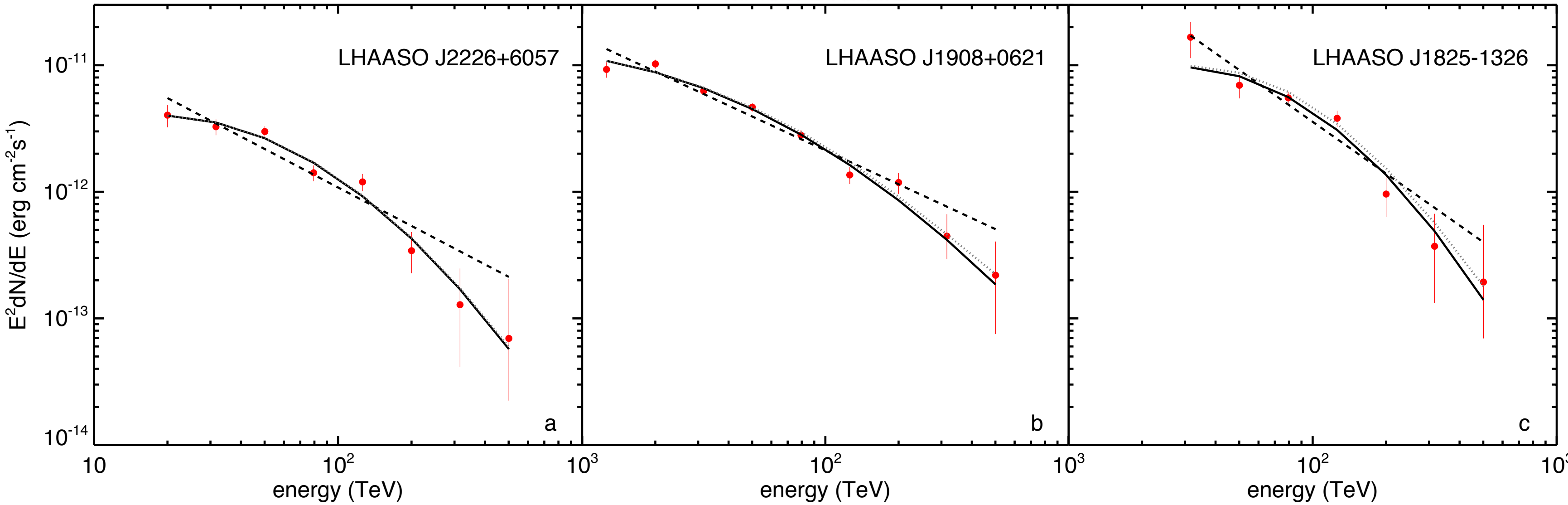
12 UHE sources detected （Cao et.al Nature 594, 33）





11 Months data of Half KM2A-array
Definitely PeVatrons (hadronic or leptonic)
The Galaxy full of powerful accelerators

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11 (Update:1.1PeV)	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13 (Cygnus region)	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Highest energy photon

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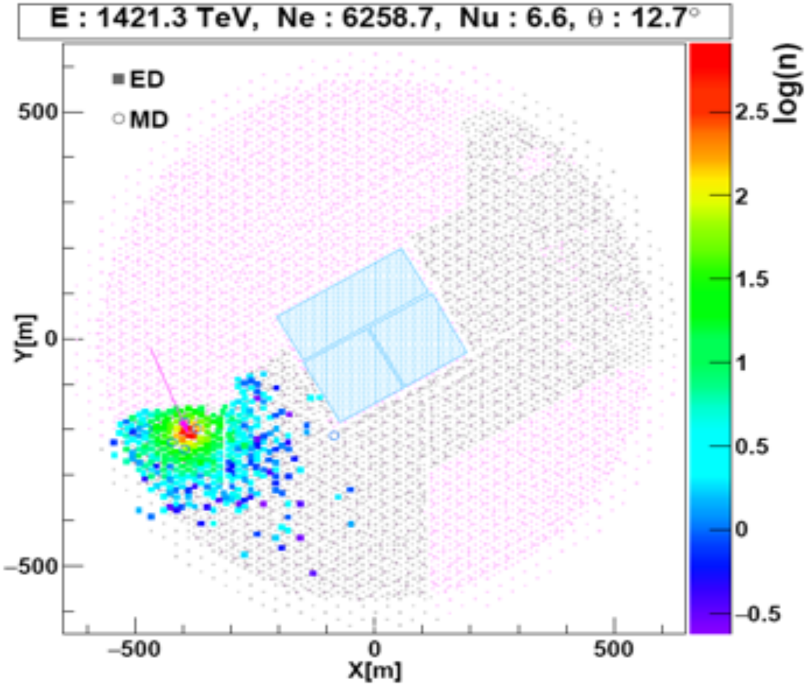
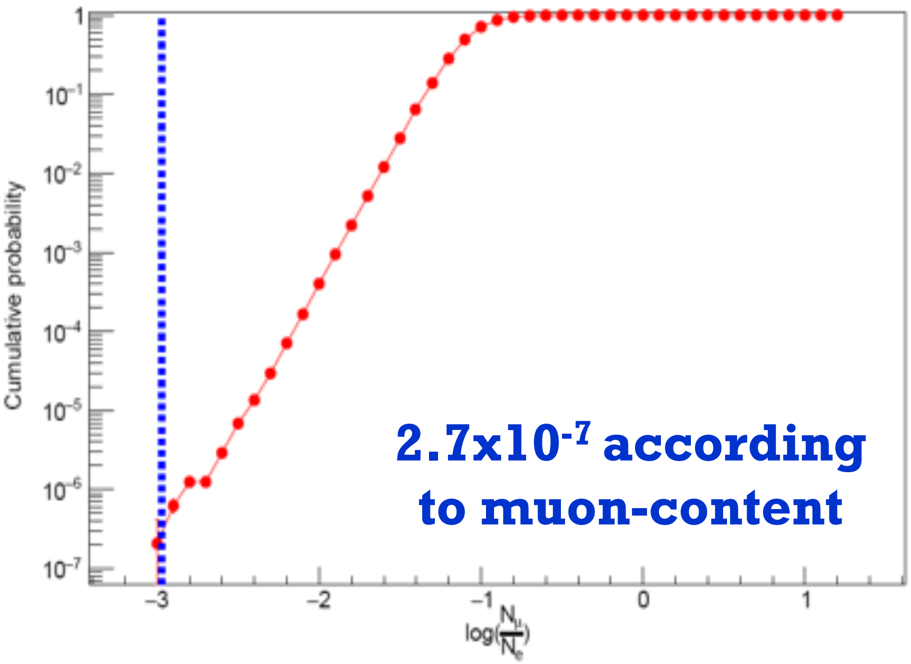
- **1.42±0.13 PeV from the Cygnus region**
- **Chance probility due to cosmic ray background 0.028%.**



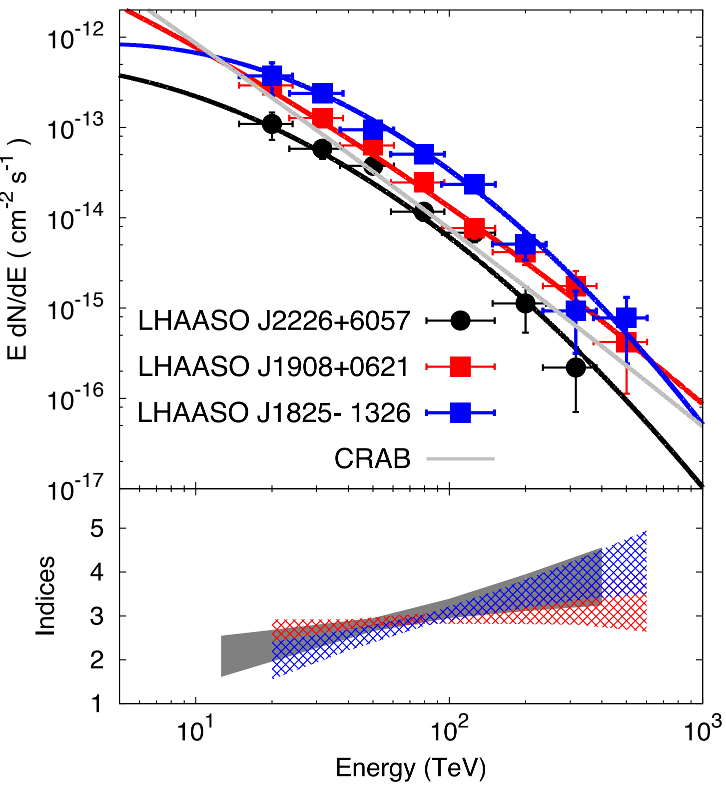


2.7×10^{-7} according to muon-content

Nature 594:33-36 (2021)

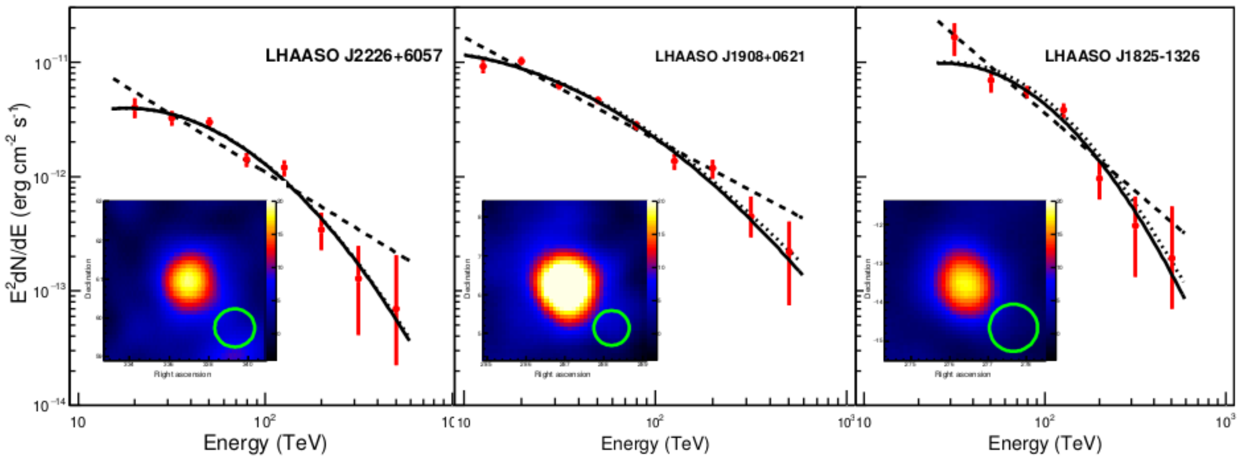
Three brightest sources

			distance	age	power
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	~ 10 – 20[j]	—
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}



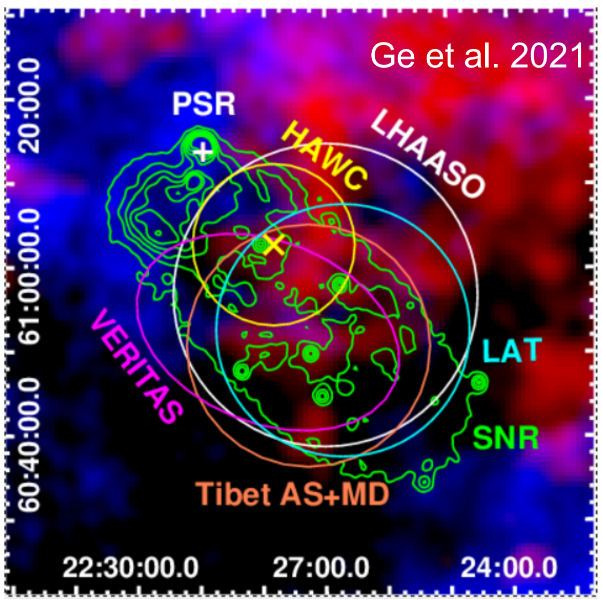
- spectral softening above 100 TeV
- No significant cutoff
- extended sources

Three brightest sources

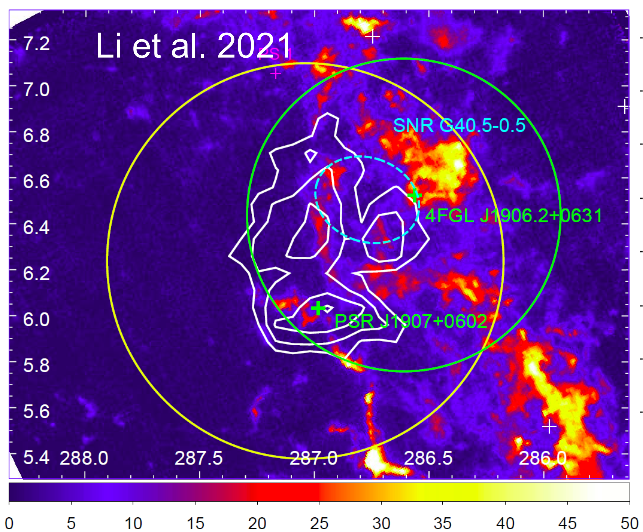


Complex regions

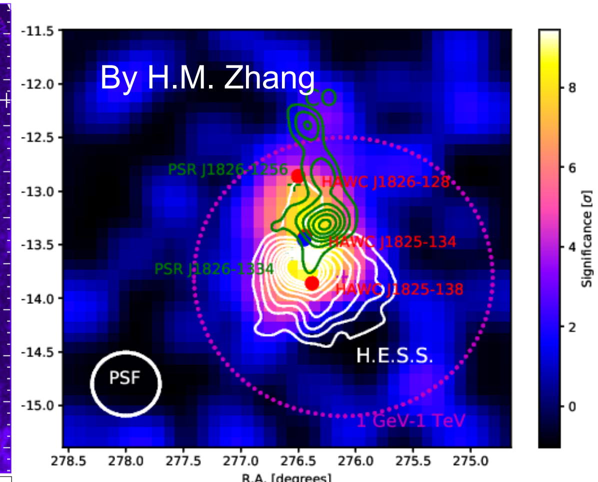
J2226+6057



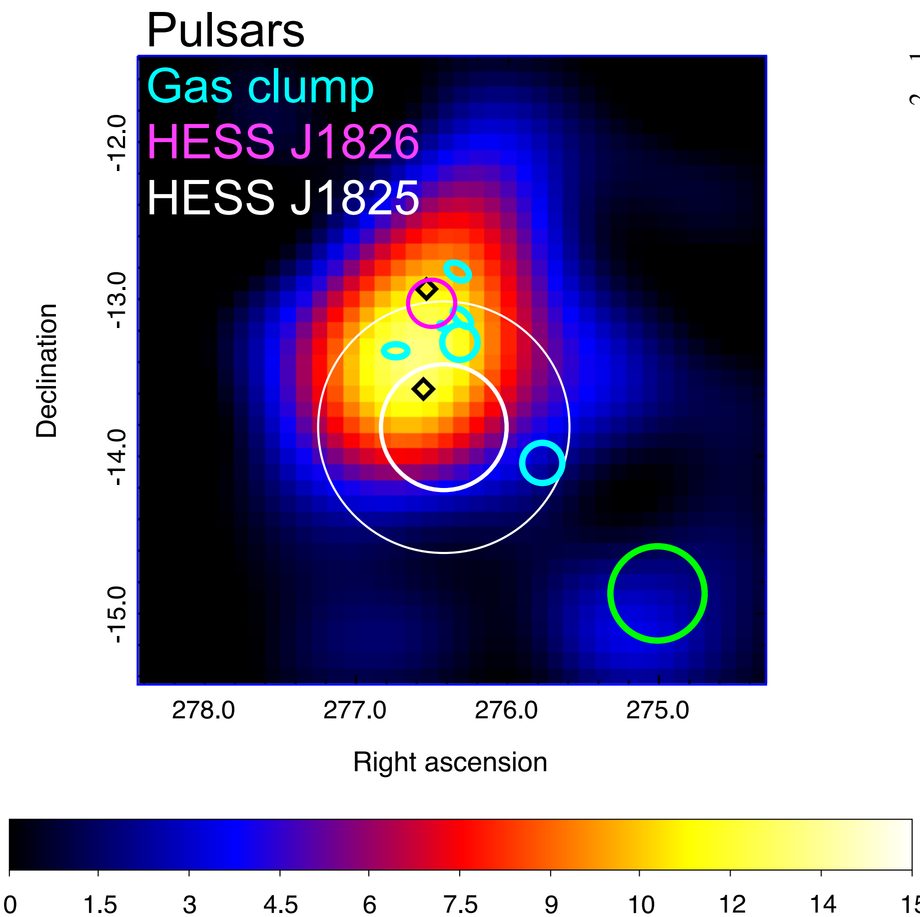
J1908+0621

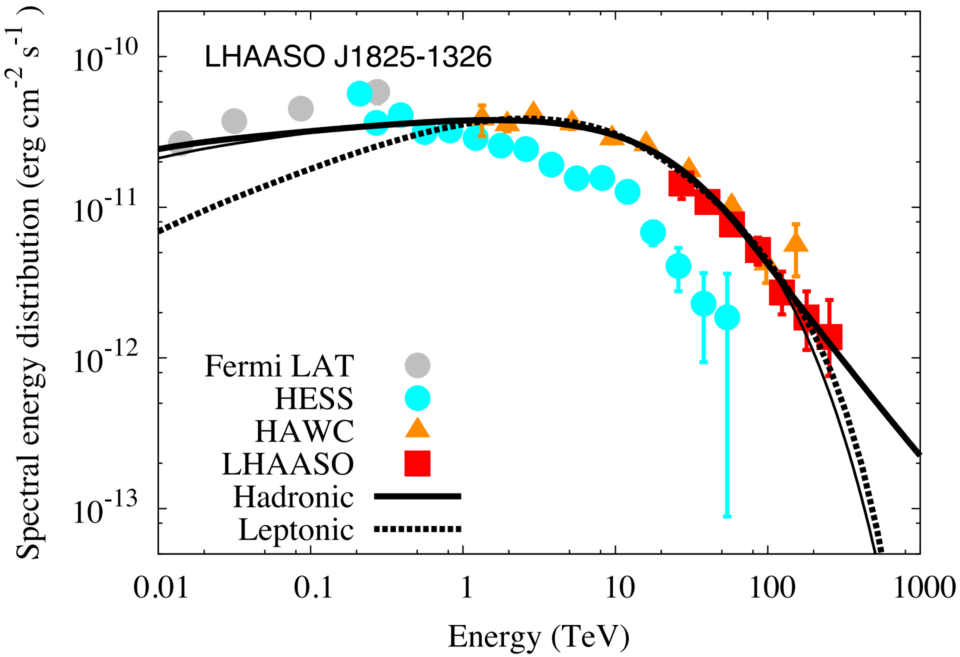


J1825-1326



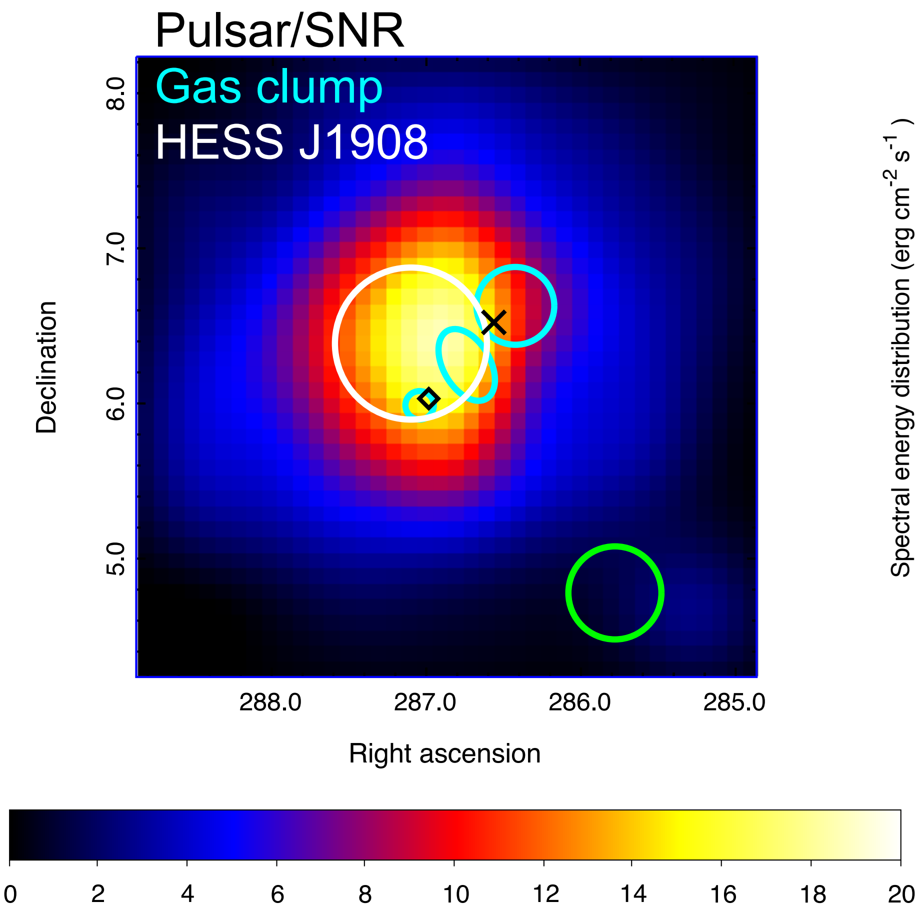
LHAASO J1825

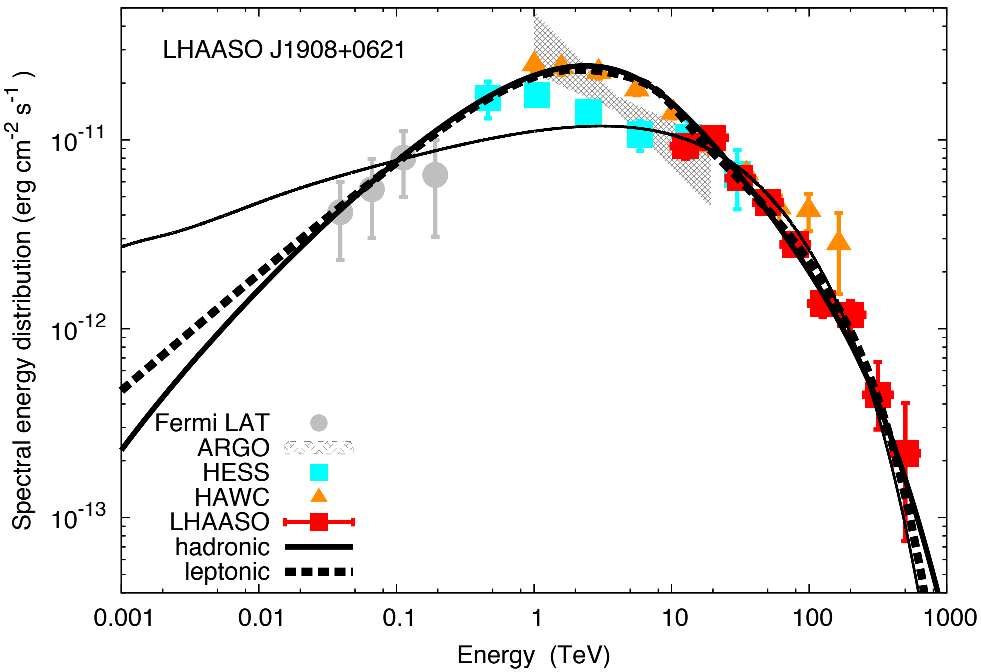




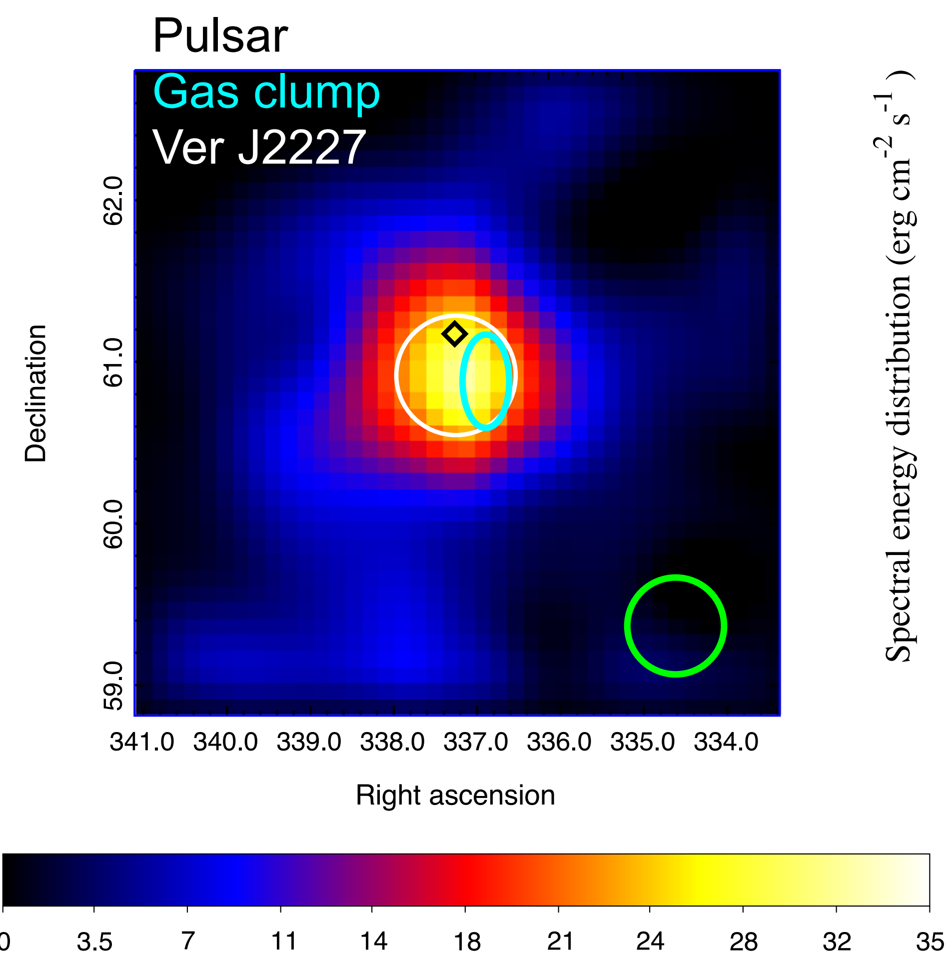
- BPL for protons : index 2.0 and 3.4 below and above 120 TeV
- PLEC for electrons: injection index of 2.07 cutoff ~ 600 TeV

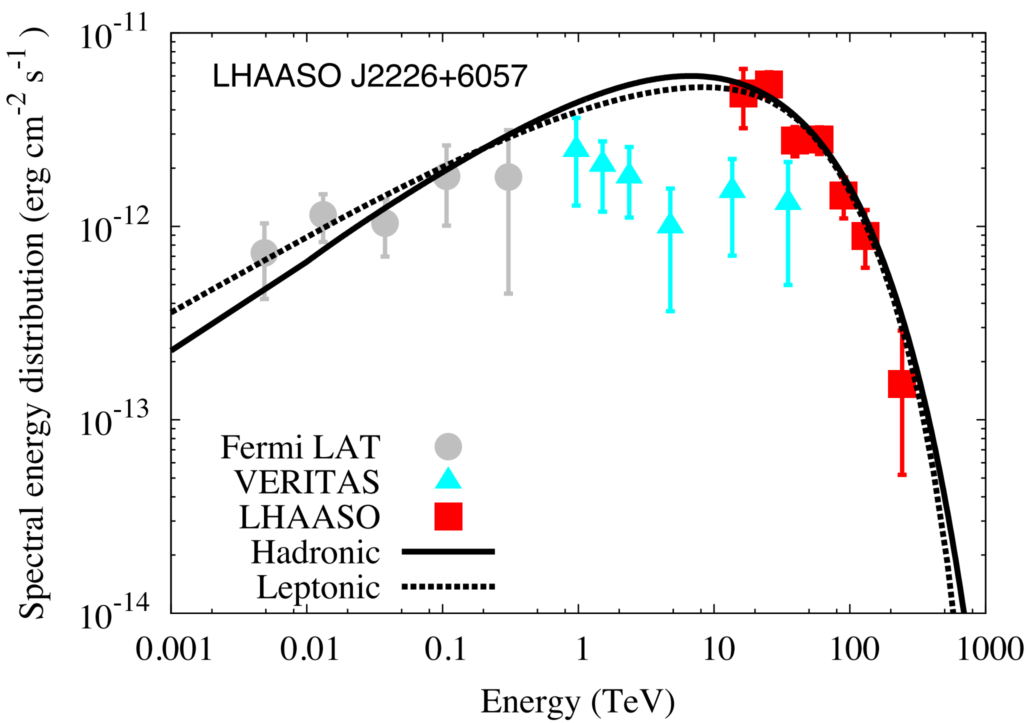
LHAASO J1908





LHAASO J2226

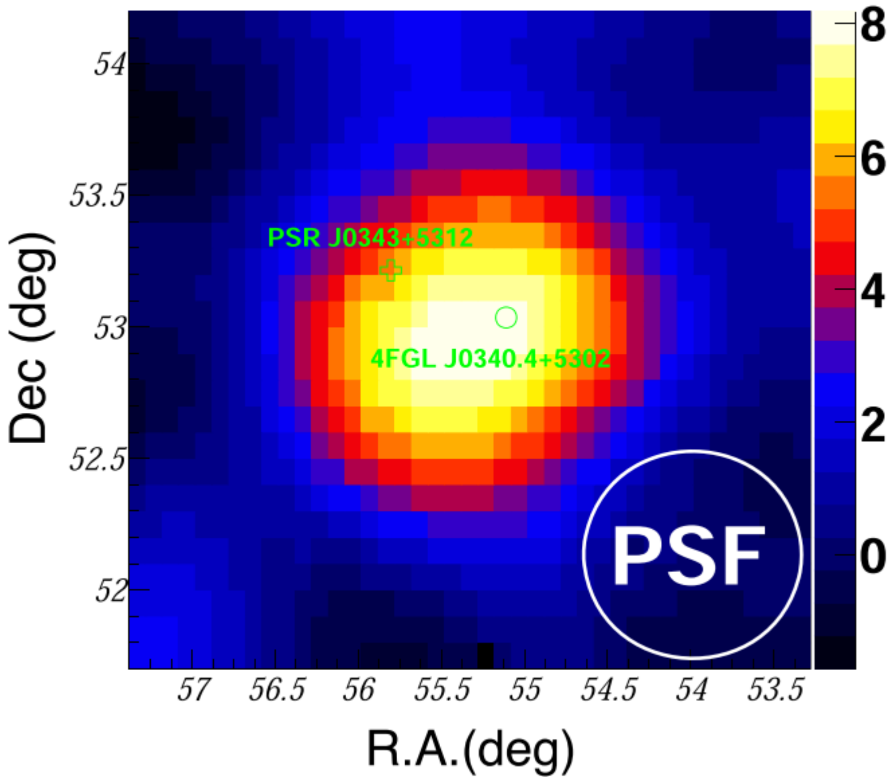


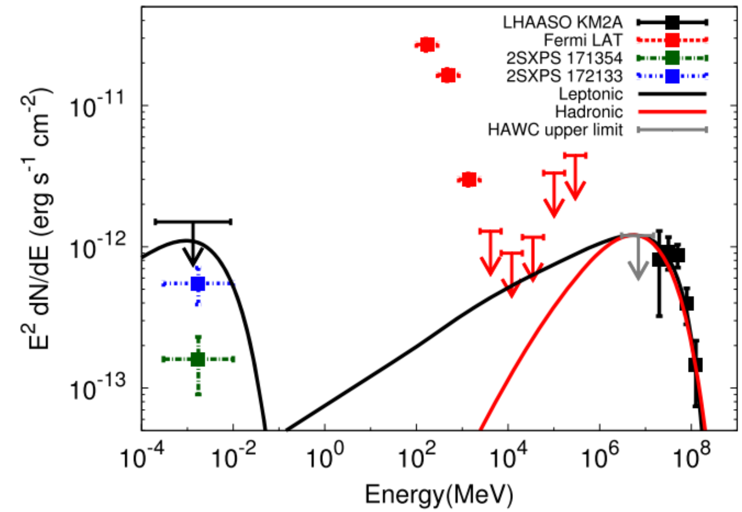


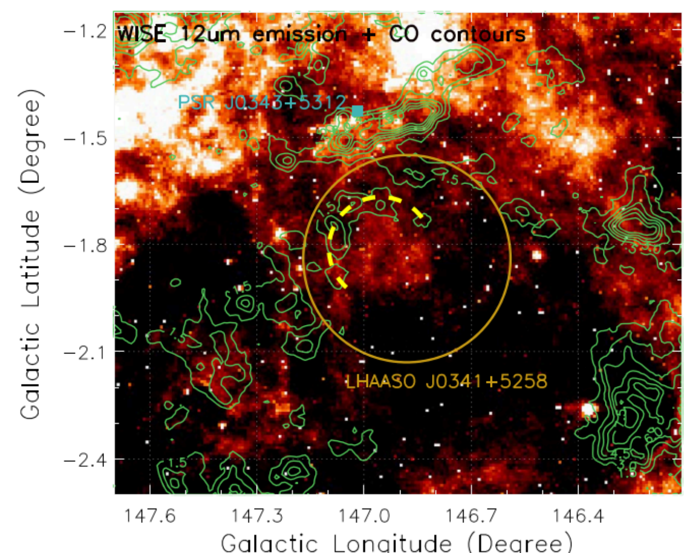
Need to understand the discrepancy between IACT and EAS

Two New sources

LHAASO J0341+5258 (ApJL 917, L4)







Two New sources

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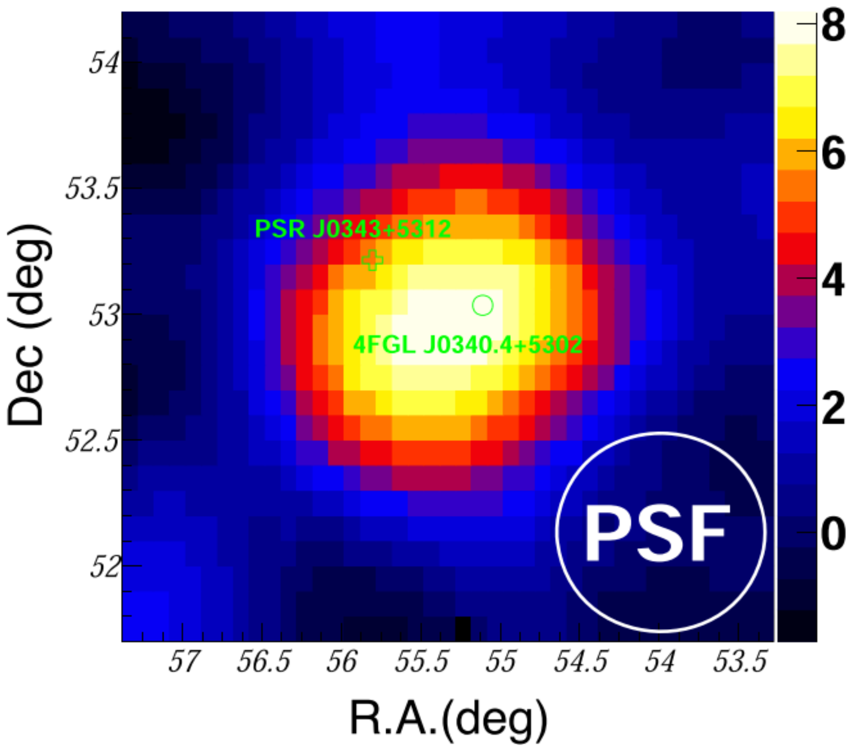
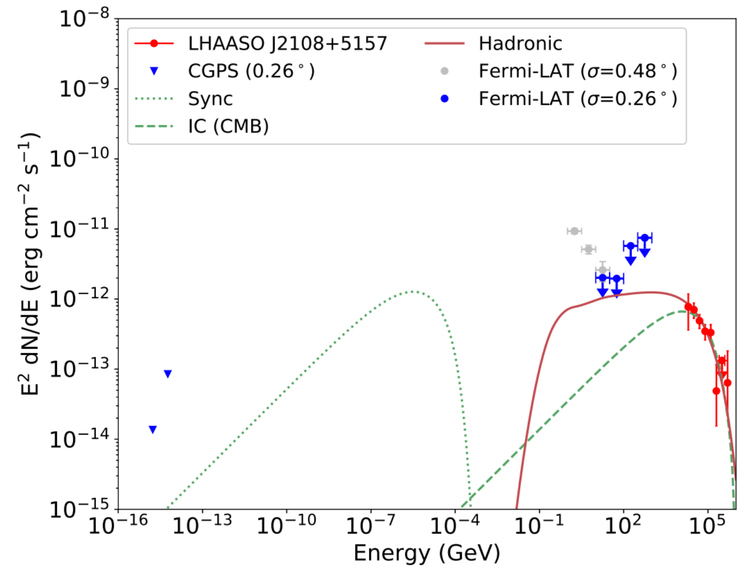
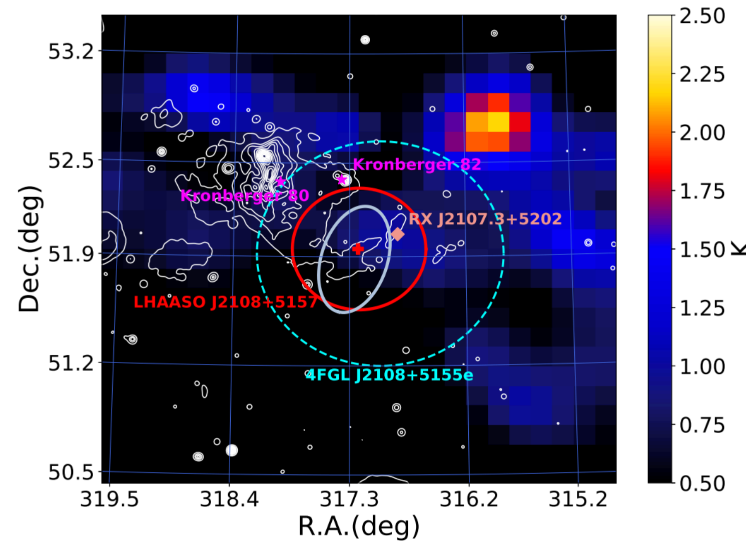
LHAASO J2108+5157 (ApJL accepted)







- Show discovery ability of LHAASO
- nearly No counterpart in other wavelength
- Soft GeV gamma-ray spectrum

Pulsar related sources

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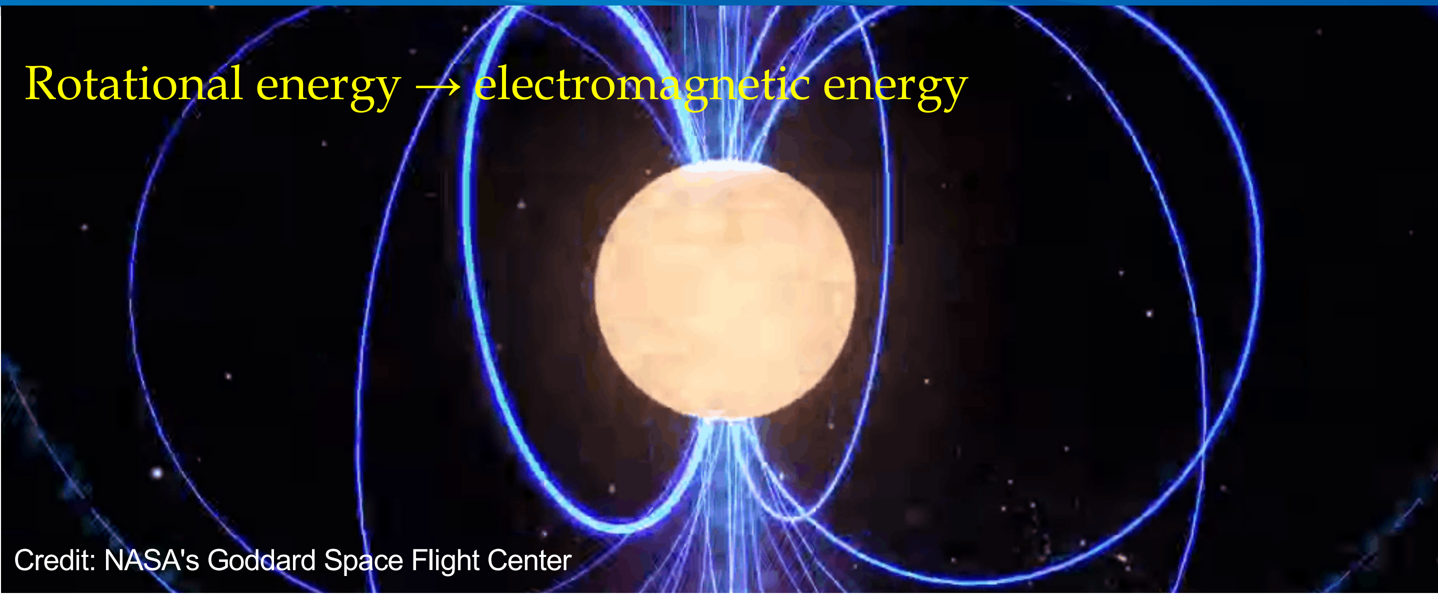

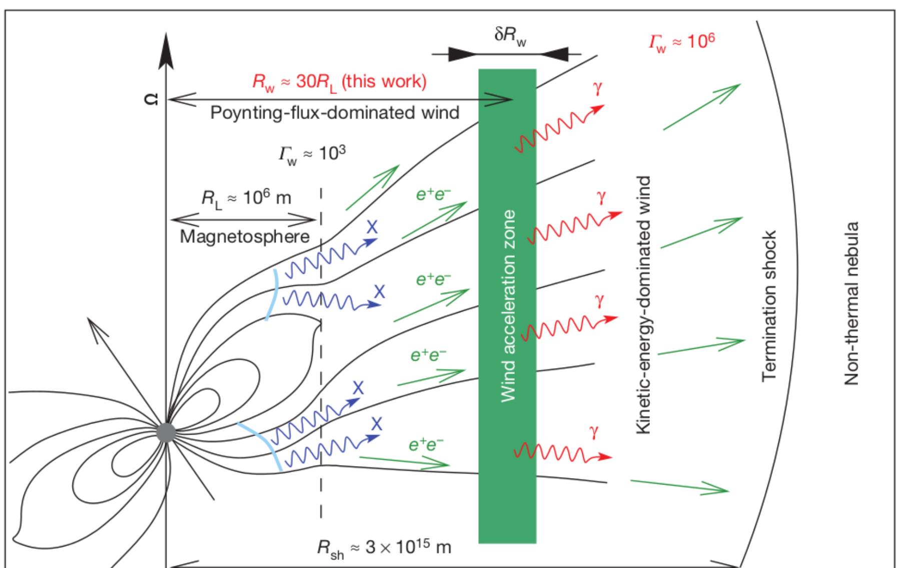

- Pulsar can produce GeV emission through curvature radiation
- Pulsed emission also found up to 1 TeV, possible IC emission of cold wind (Aharonian 2012)

Pulsar related sources

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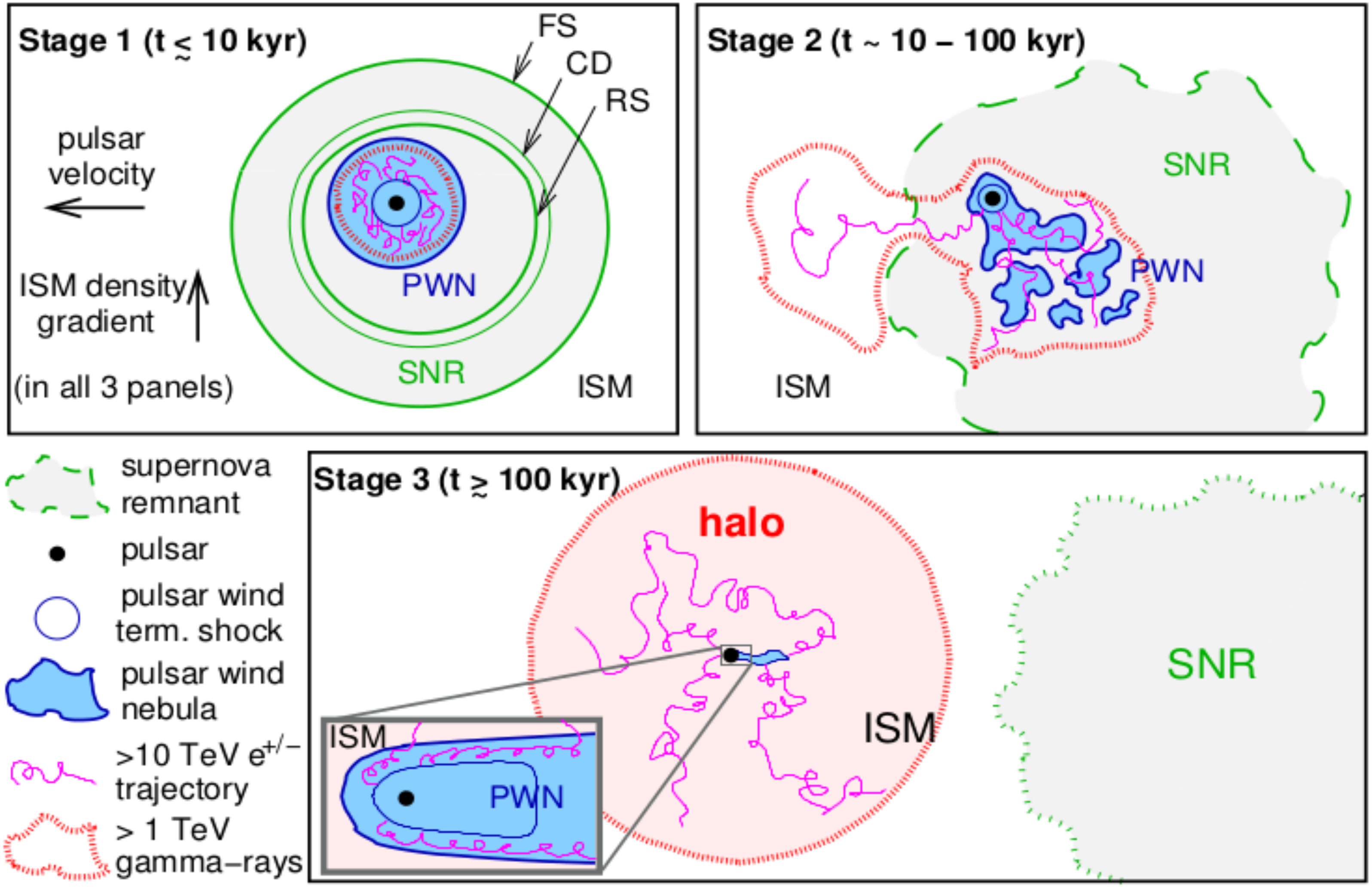
- Pulsar wind nebular (PWN) and Pulsar halo



Giacinti et al 2020

Crab as electron PeVatron

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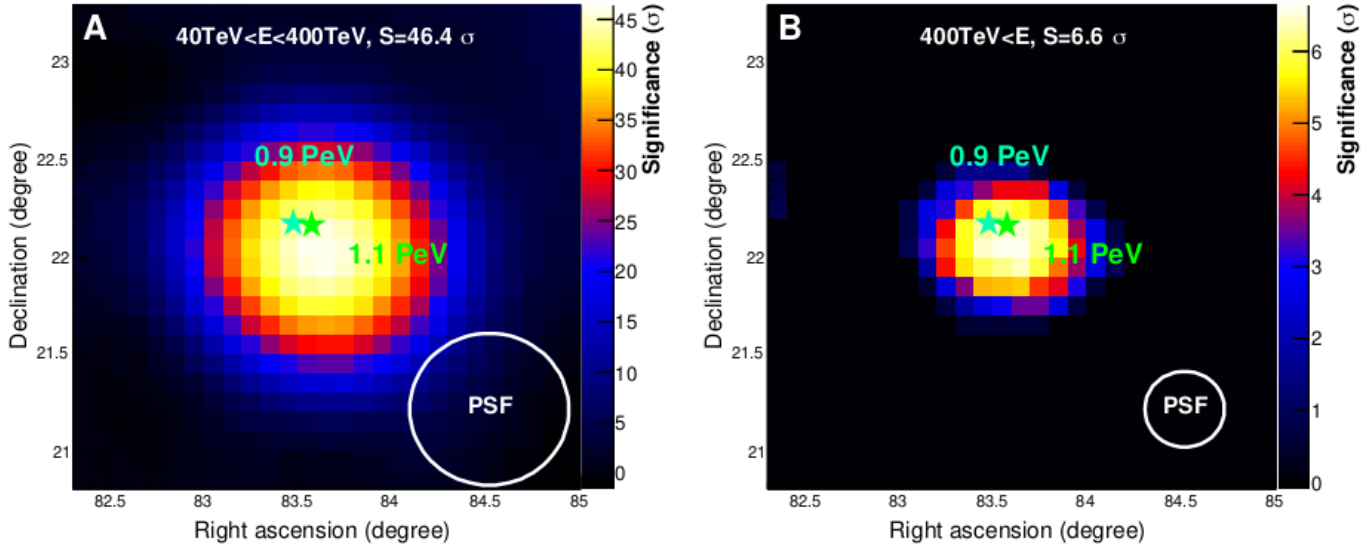

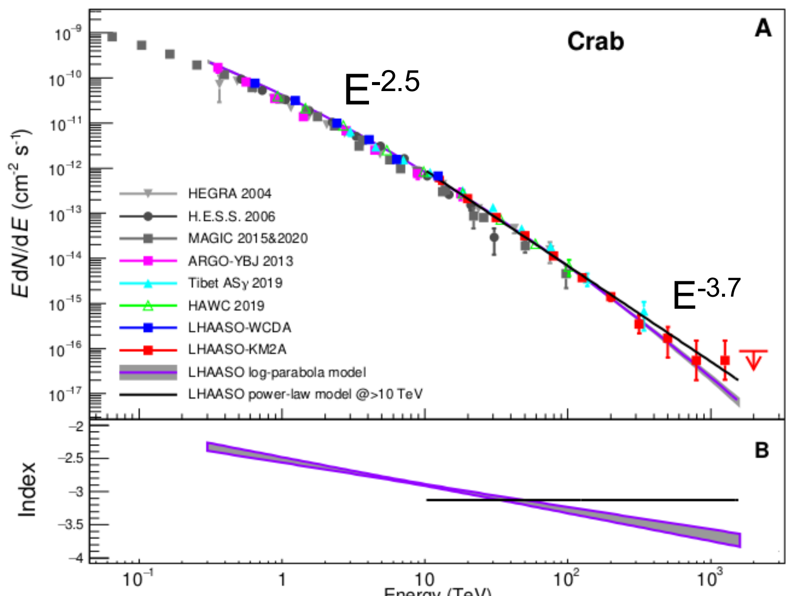

LHAASO collaboration
Science 373, 425

Crab as electron PeVatron

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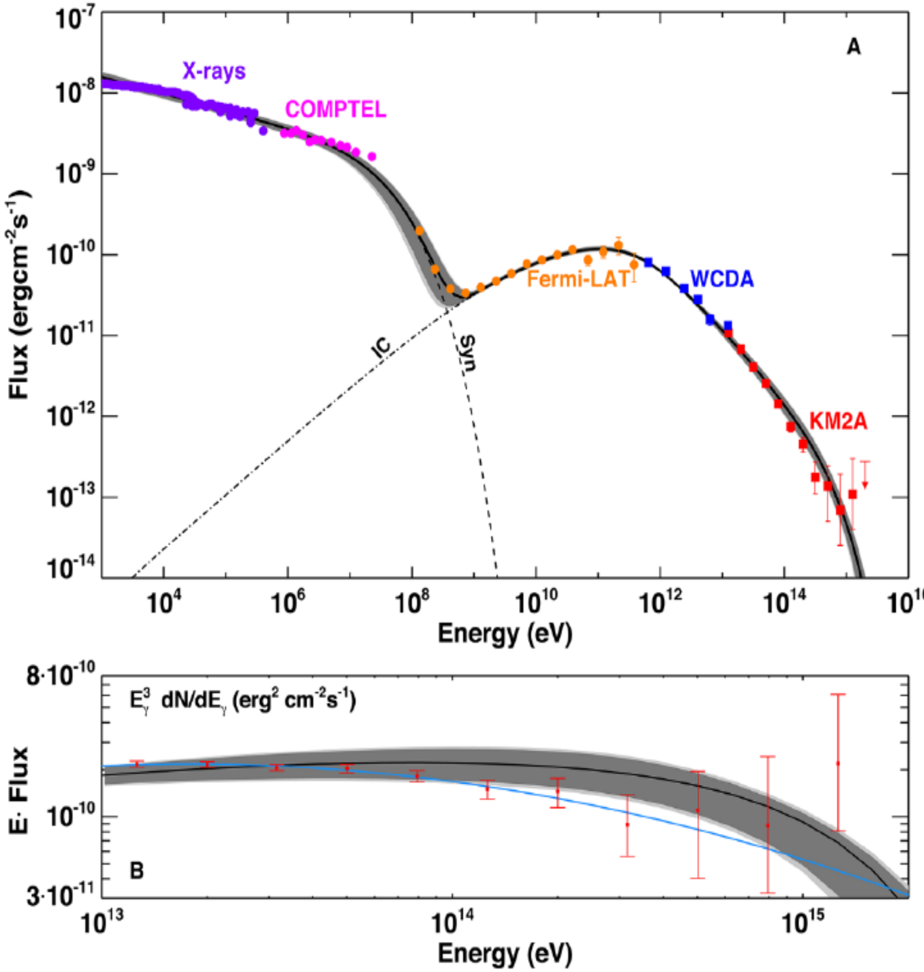
- **An extreme e-accelerator:**
  - **2.3 PeV electrons**
  - **In 0.025—0.1 pc core region**
  - **accelerating efficiency of 15% (1000×SNR shock)**
- **Perfect interpretation of one-zone model up to 50 TeV, while a deviation of 4σ at higher energy.**
- **1~ 2 PeV photon per year.**



Science 373:425-430 (2021)

Crab as electron PeVatron

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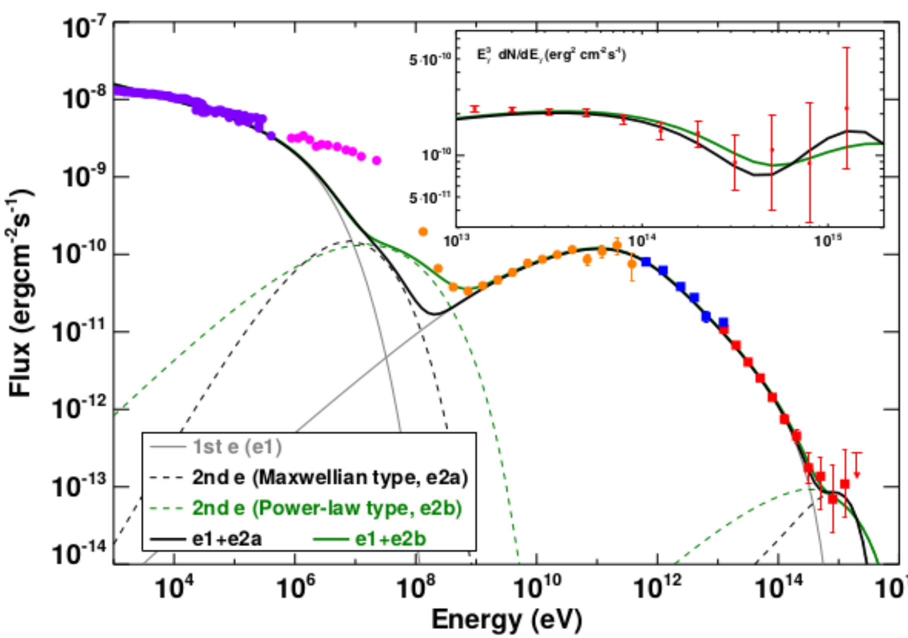
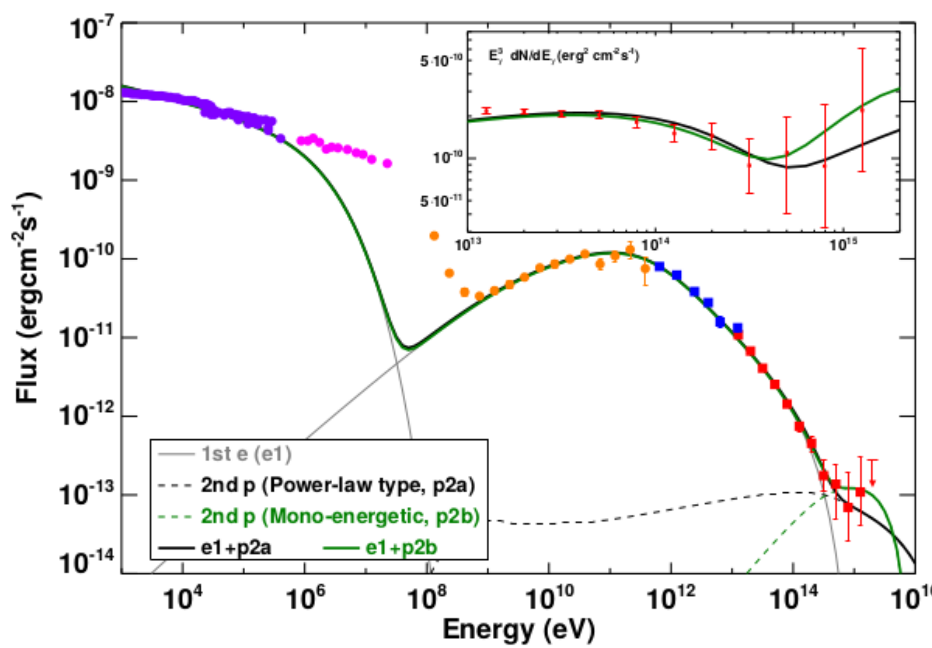
2 Leptonic components

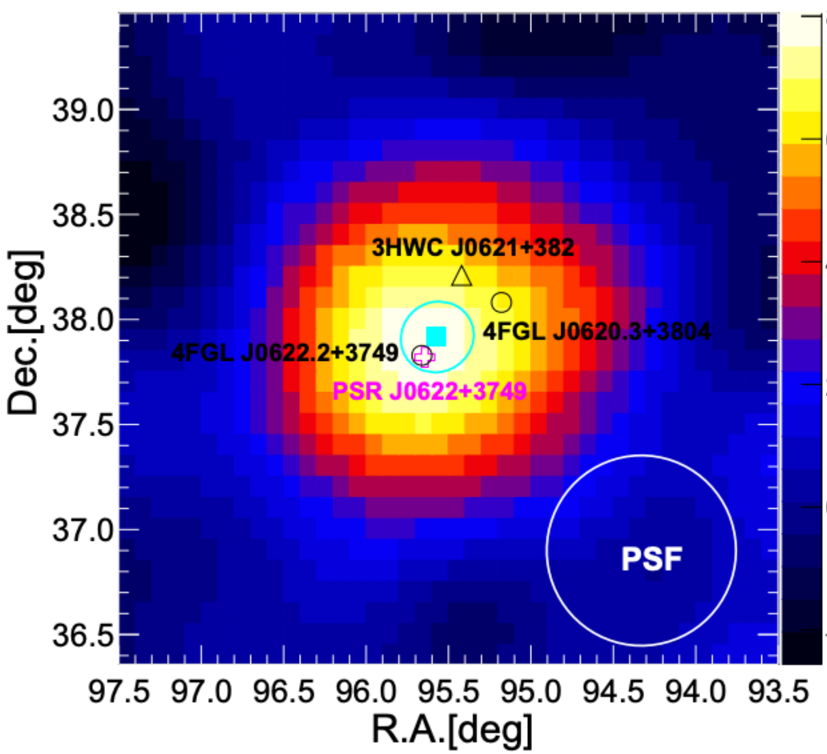


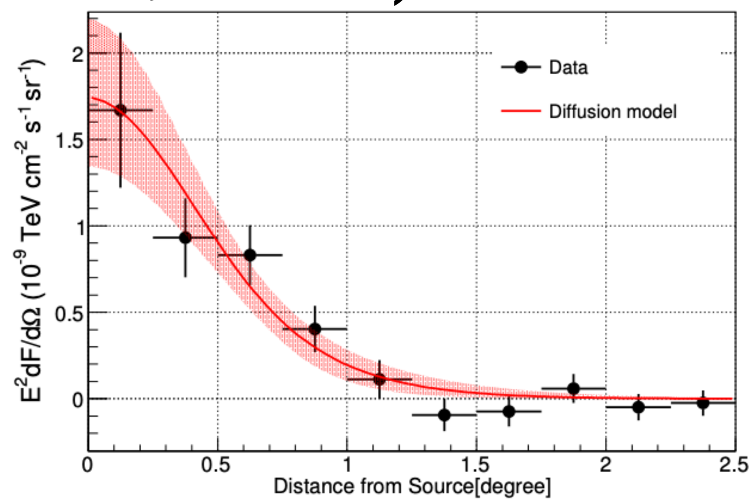
Leptonic+Hadronic component

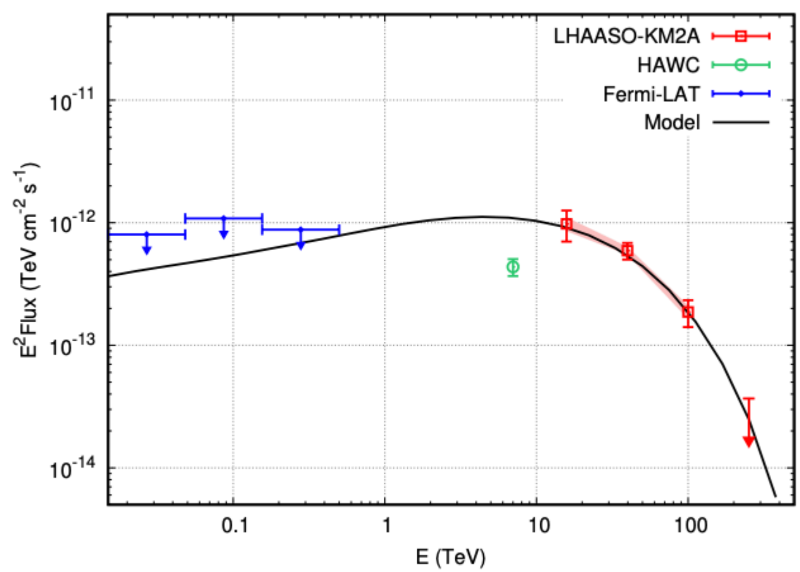


New pulsar halo

LHAASO J0622 + 3749 (PRL 126, 241103)







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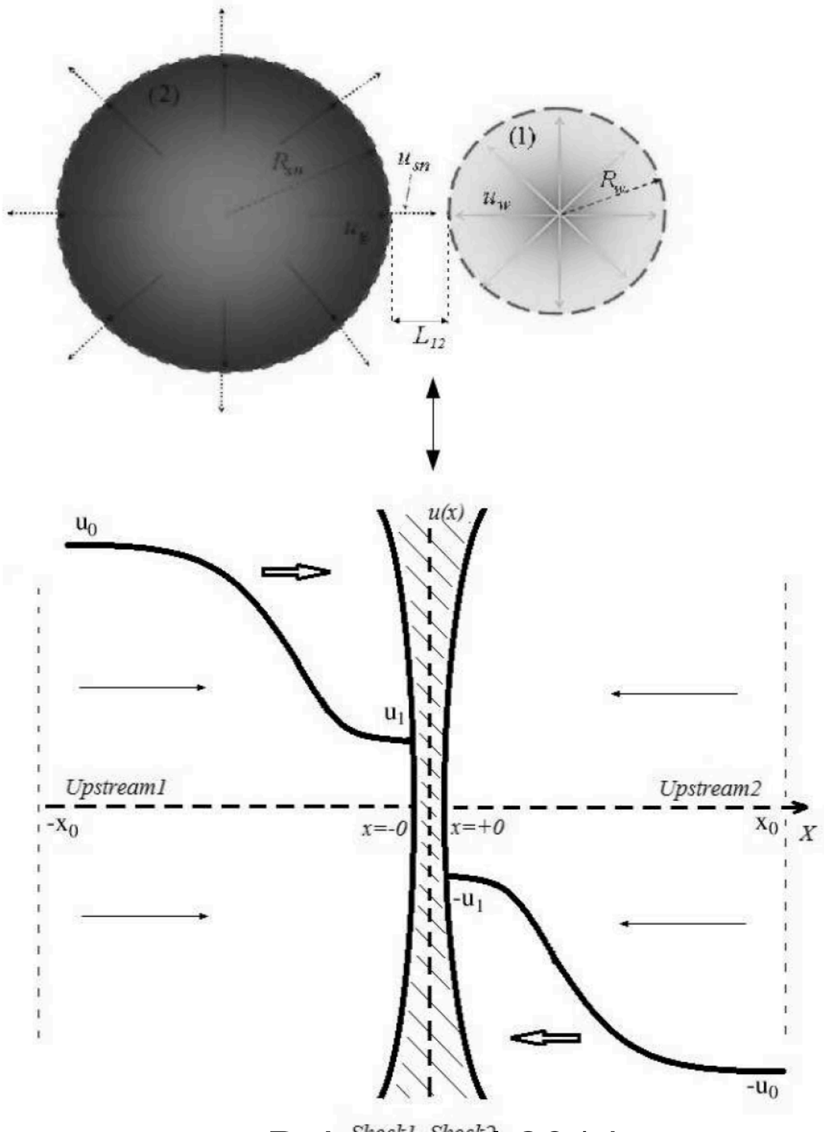
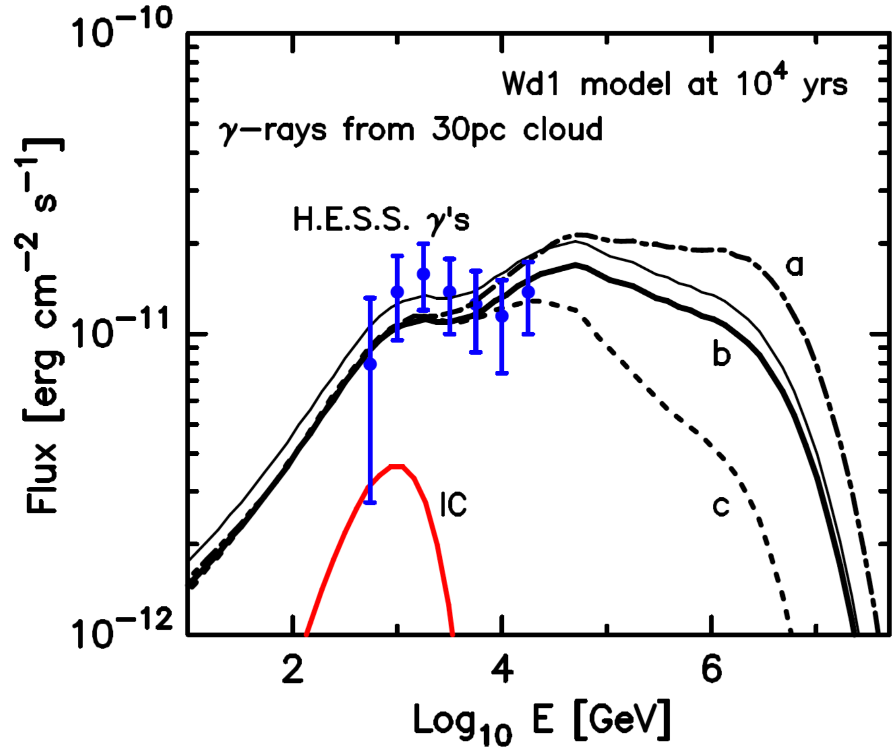
Summary and Prospect

PeVatron hunting: Cygnus region

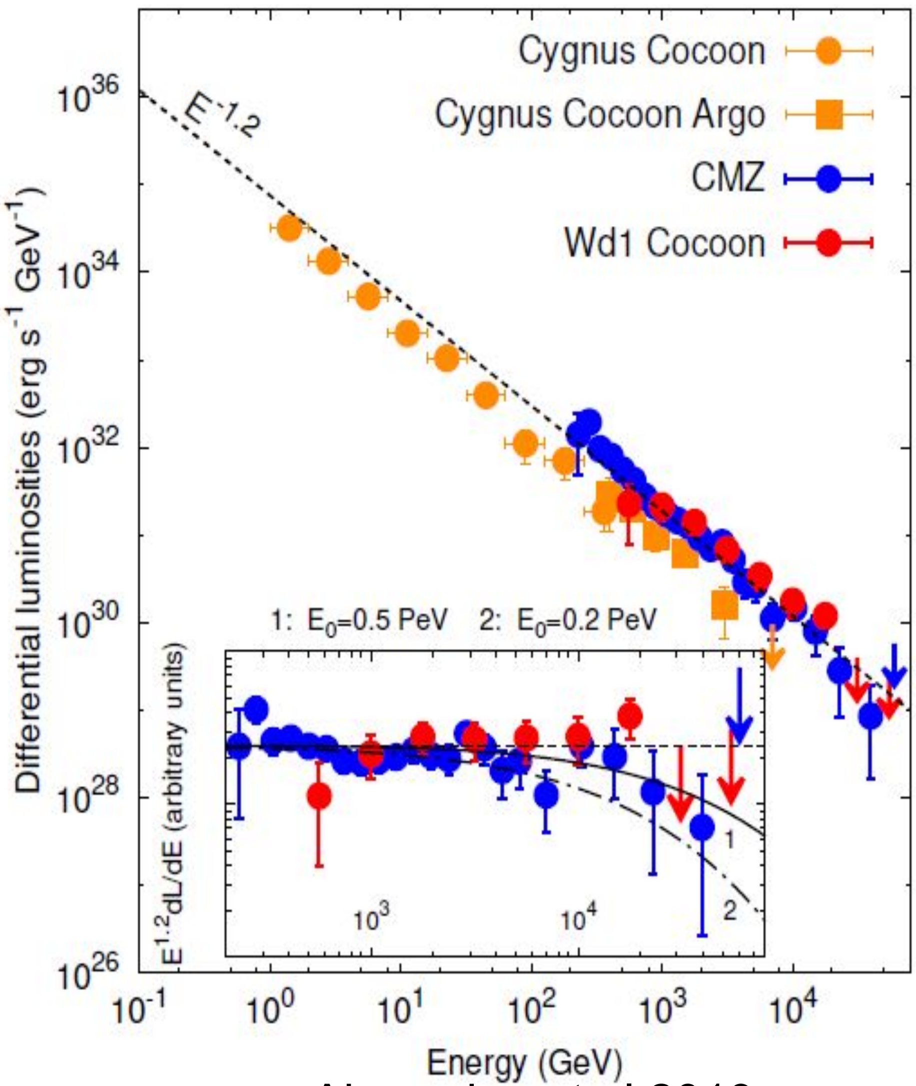


Bykov et.al 2014



- One promising site: SNR shock colliding with wind termination
- Can accelerate to PeV

PeVatron hunting: Cygnus region



Aharonian et.al 2019

- 1.4 PeV photons from Cygnus region, most promising Proton PeVatron!
- Spectrum extended from GeV to PeV
- Waiting for accumulation of data

future of LHAASO

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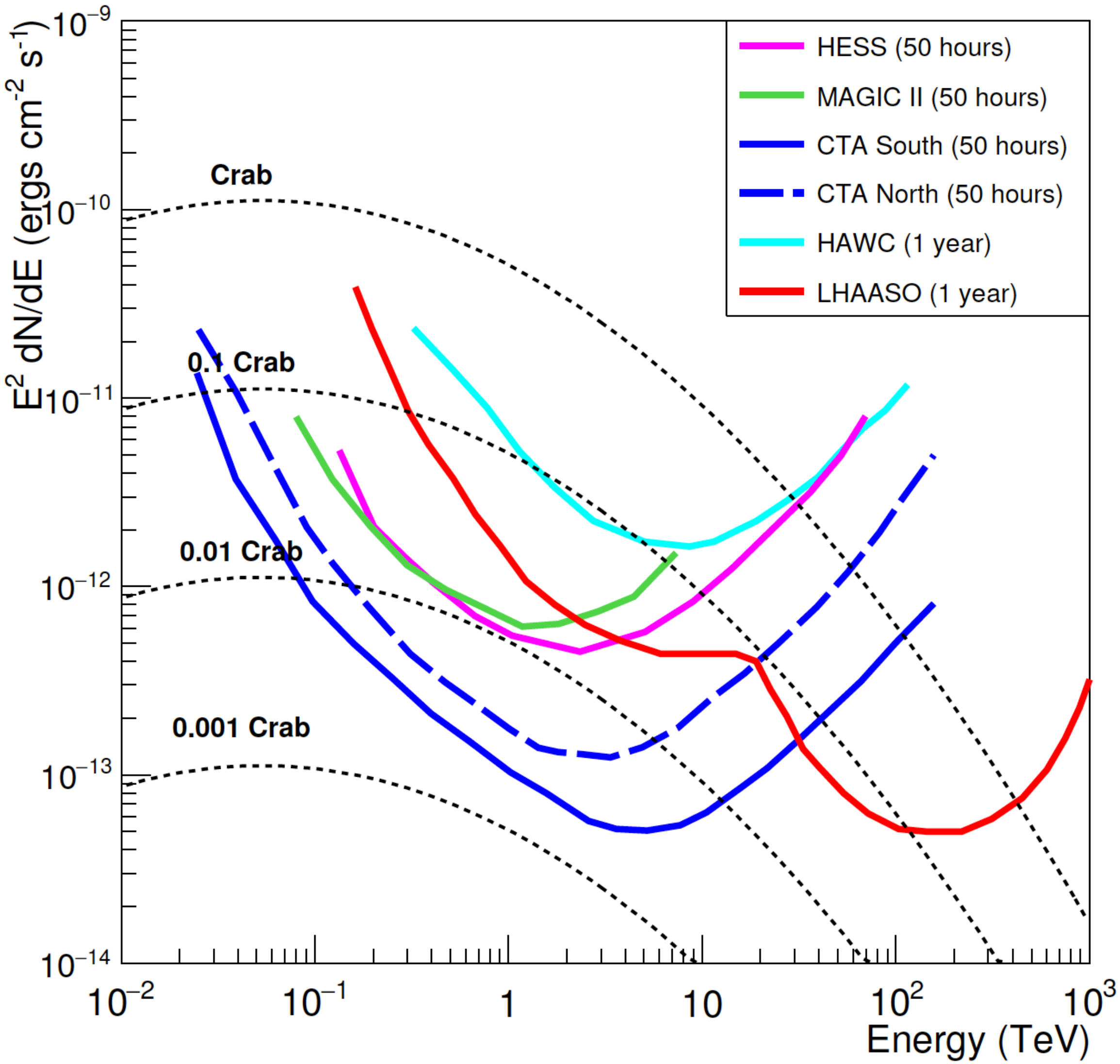


Data accumulation of LHAASO and Multi-wavelength observations

Unprecedented above 20 TeV

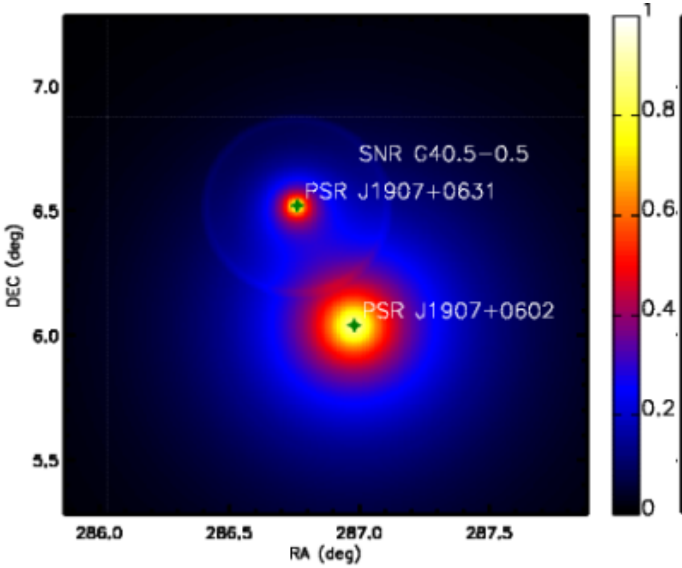
ideal PeVatron hunter

But limited angular resolution

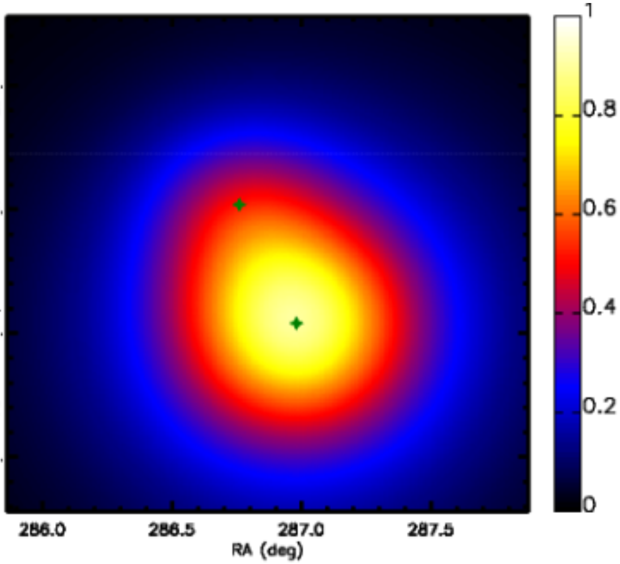
IACTs

(Imaging Air Cherenkov telescope arrays) IACTs can provide angular resolutions as good as 0.05 degree

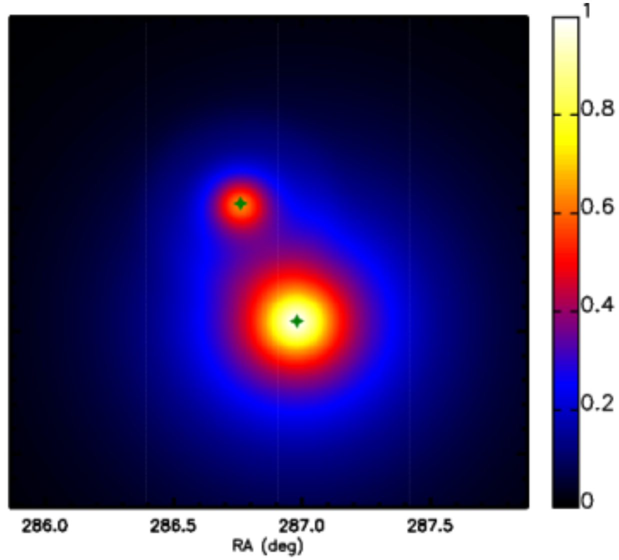
Important in crowded environment



Intrinsic distributions



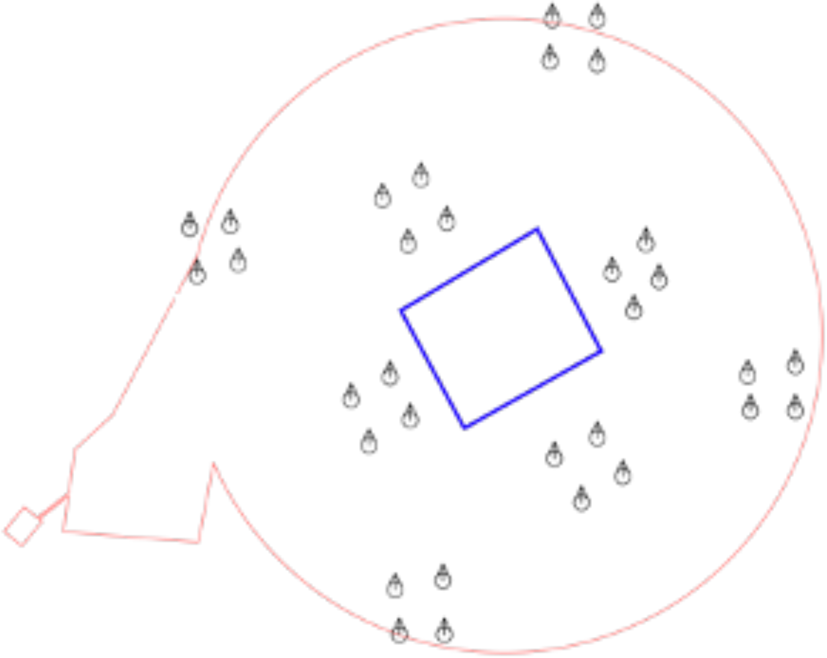
Observation by LHAASO



Observation of IACTs

IACTs in LHAASO site

6m telescope



8 X 4 arrays in LHAASO site

First light soon!

Predicted sensitivities

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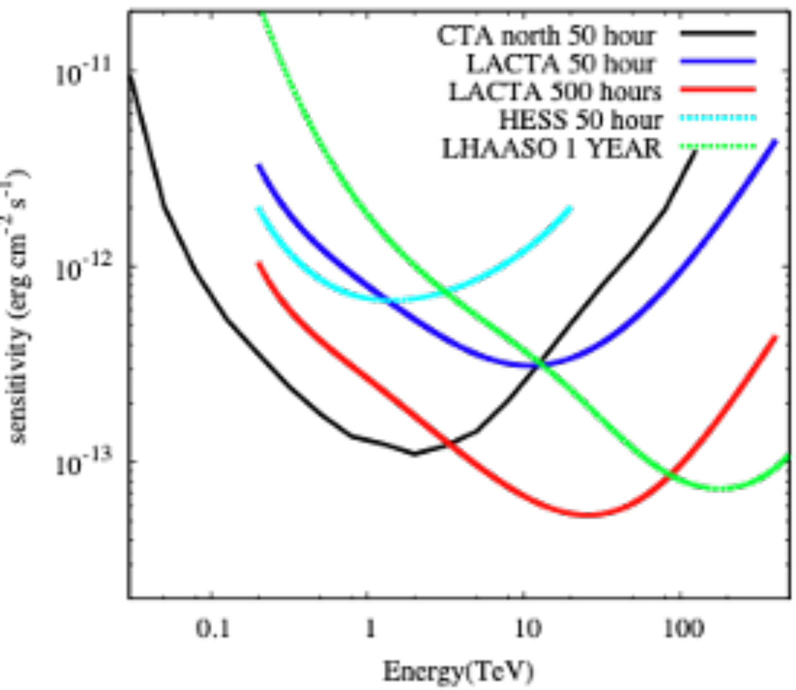
Synergy with LHAASO
Use MD to improve the gamma/p separation
Detailed morphology study of PeVatrons, TeV halo, PWN…



target	R.A	DEC	Exposure per year	Photon number above 50 TeV	Photon number above 100TeV
Crab	83.55	22.05	1090	400	100
LHAASO J1908	287.05	6.35	913	800	110
Cygnus Cocoon	308.05	41.05	1190	200	100
LHAASO J1825	276.45	-13.45	600	1000	350
LHAASO J2226	336.75	60.95	1267	600	140
W43	282.35	-0.05	833		75

Conclusion

- LHAASO already show great power in gamma-ray astronomy, especially in PeVatron study

- A lot of future tasks for LHAASO: Cygnus region, diffuse gamma-ray, high energy transients, direct measurement of CRs, indirect dark matter search…….

- WCDA will also release interesting results soon!

- Further project: Imaging Air Cherenkov array in LHAASO site

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Thanks!

Crab as electron pevatron

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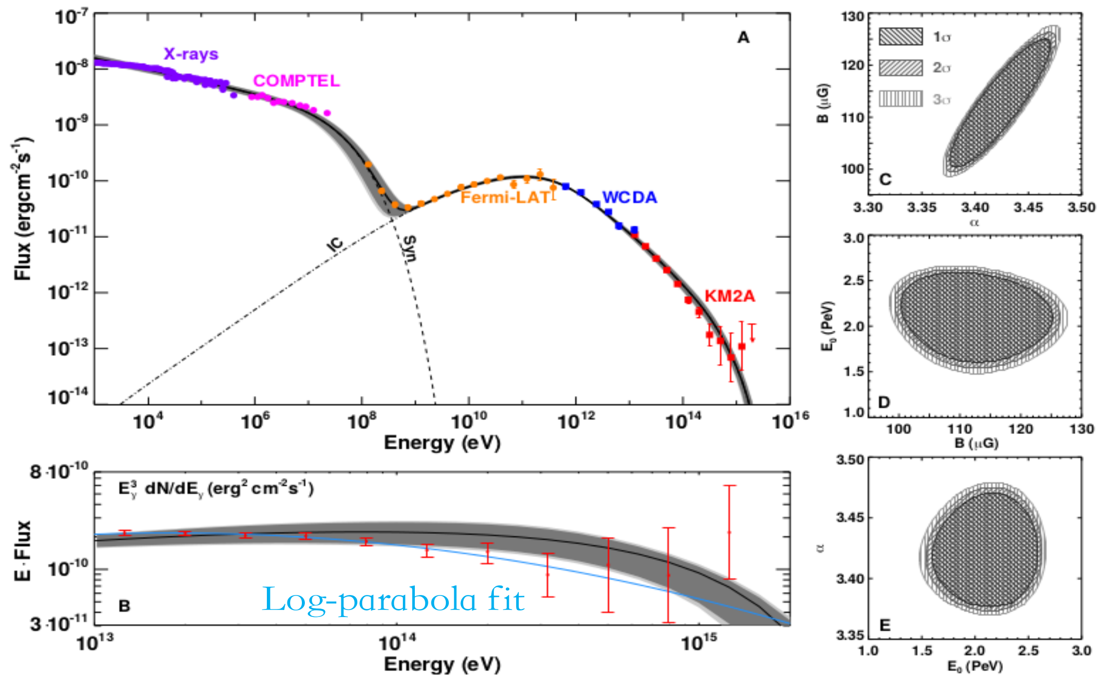
Standard One-Zone Model



$E_e = 2.15\ (E_\gamma/1\mathrm{PeV})^{0.77}$ Inverse Compton scattering on CMB

$\dot{E}_e = e\mathcal{E}c = \eta eBc$

$\eta = \mathcal{E}/B$ acceleration efficiency

$\dot{E}_{e,\mathrm{syn}} = \sigma_T (E_e/m_e c^2)^2 B^2 c/6\pi$ Synchrotron loss rate

Extreme acceleration efficiency

$\eta = 0.14(B/100\mu\mathrm{G})(E_\gamma/1\ \mathrm{PeV})^{1.54}$

$\dot{W}_{e,\mathrm{PeV}} = 2\times10^{36}(B/100\mu\mathrm{G})^2\mathrm{erg/s}$