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

Recent scientific results from 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

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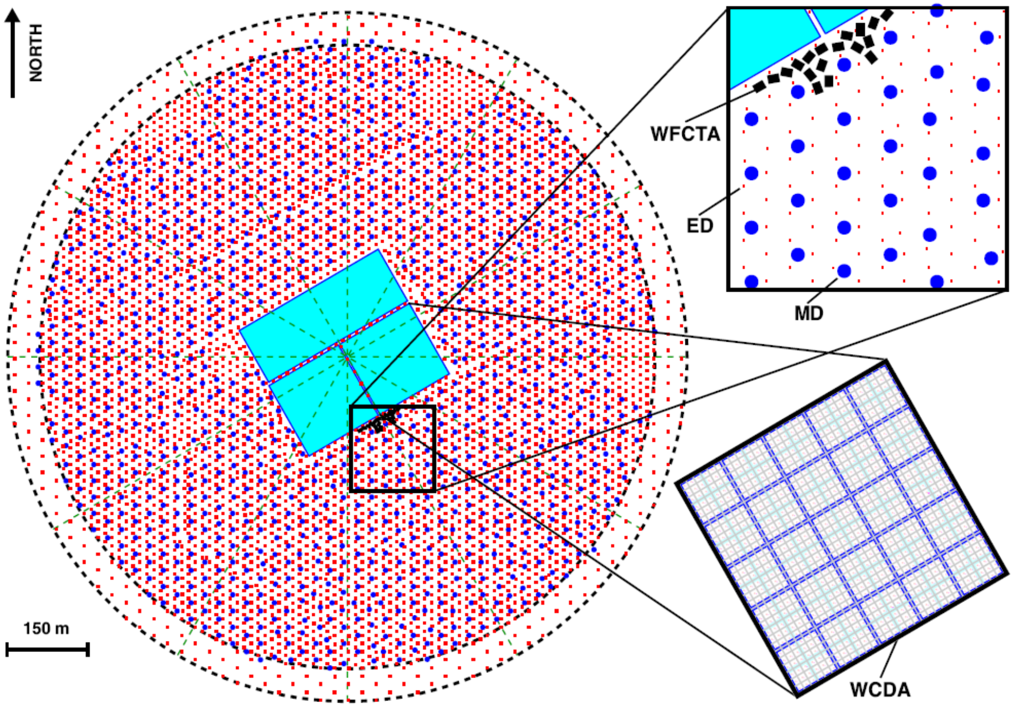
- Haizi Mountain, Sichuan province, China
- Location： 29°21’27.6” N, 100°08’19.6” E
- Altitude： 4410 m a.s.l.
- 10 km from Yading Airport

LHAASO layout

All detectors are in DAQ since 2021-7-19



1.3 km²

- 5195 EDs
  - 1 m² each
  - 15 m spacing
- 1188 MDs
  - 36 m² each
  - 30 m spacing

KM2A (EDs and MDs)

- 3120 WCDs
  - 25 m² each

WCDA

- 18 WFCTs

WFCTA

LHAASO layout

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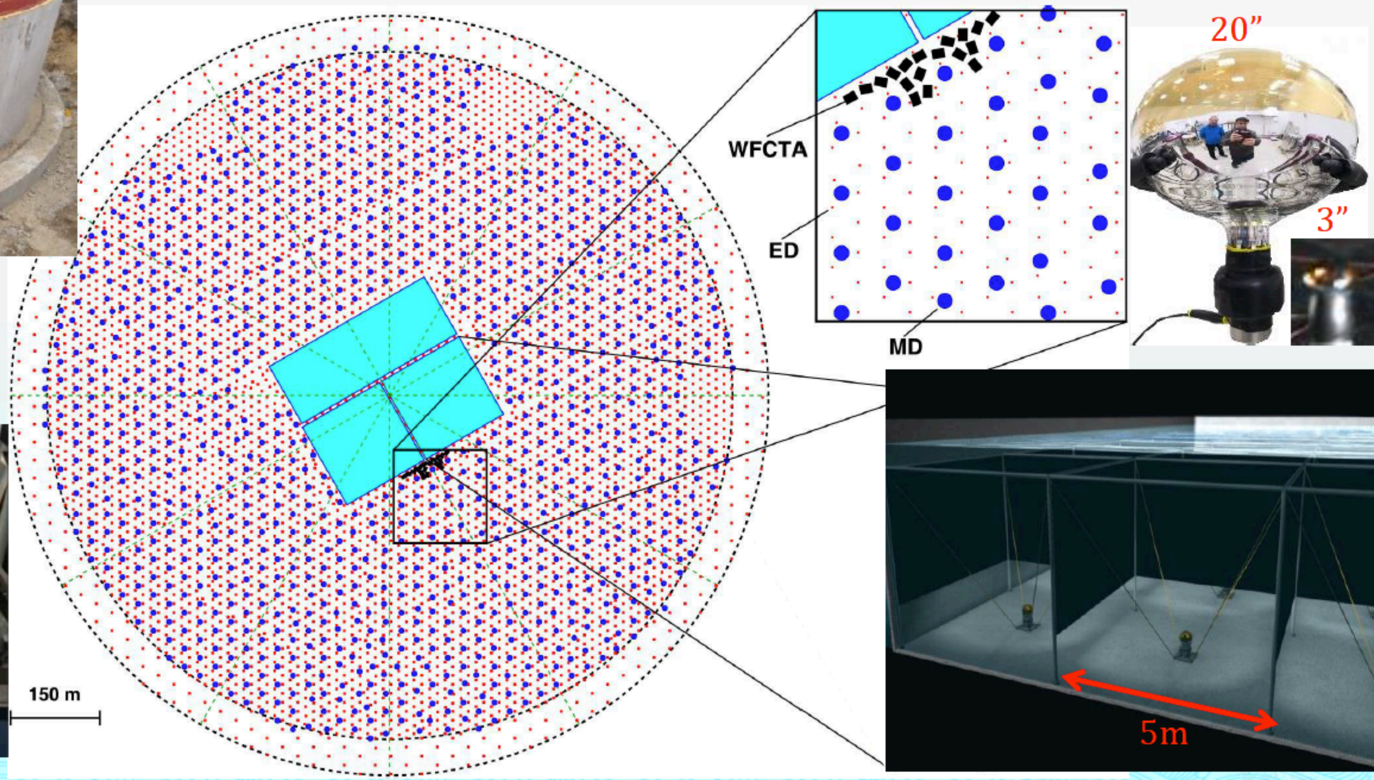
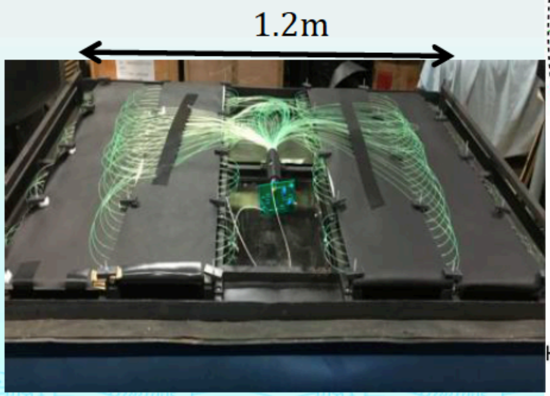
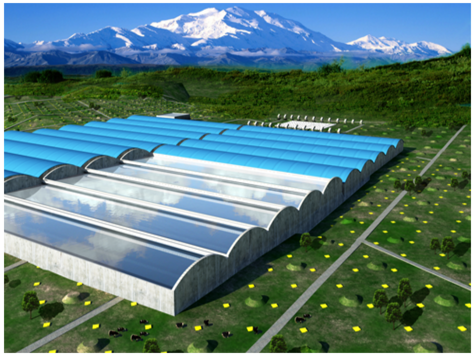
LHAASO Layout

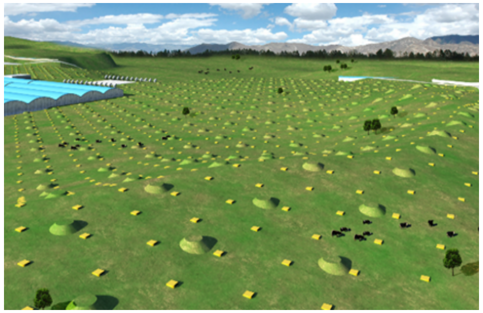




LHAASO sub-arrays

- **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

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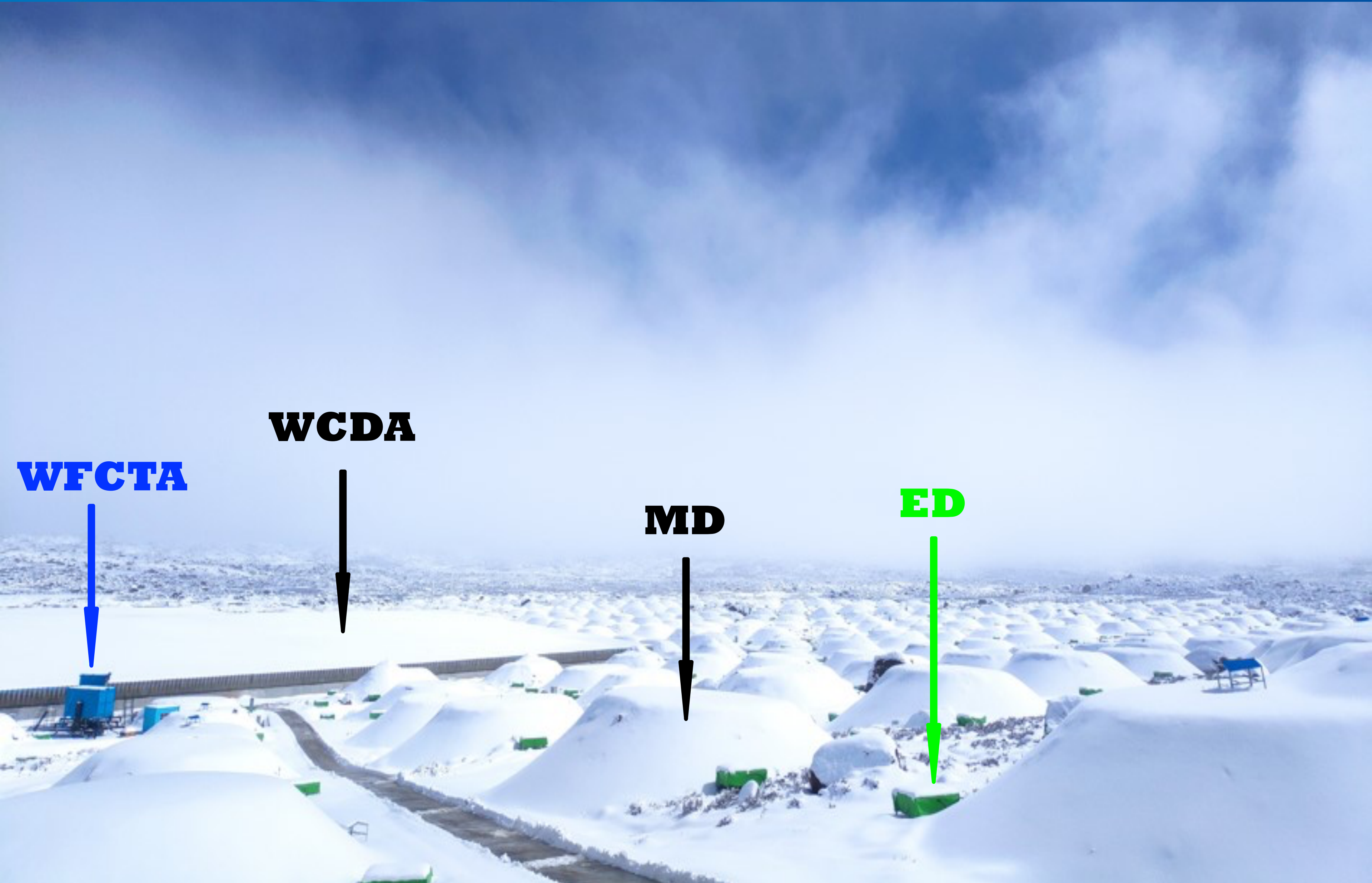
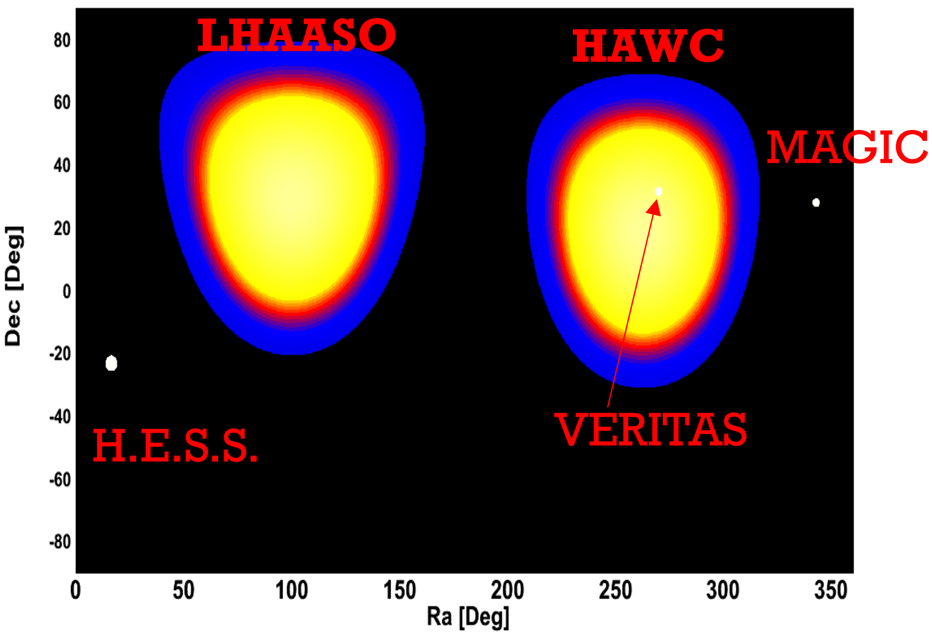
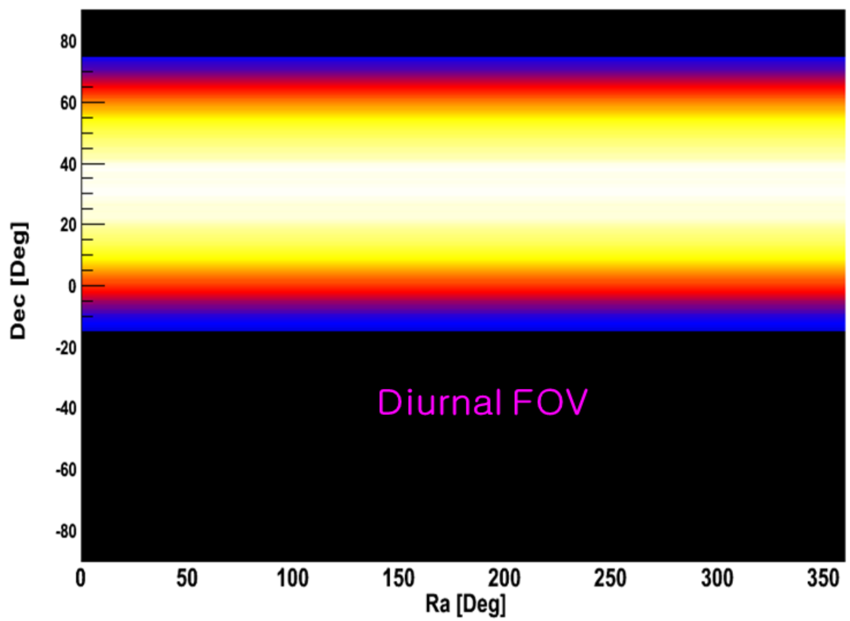


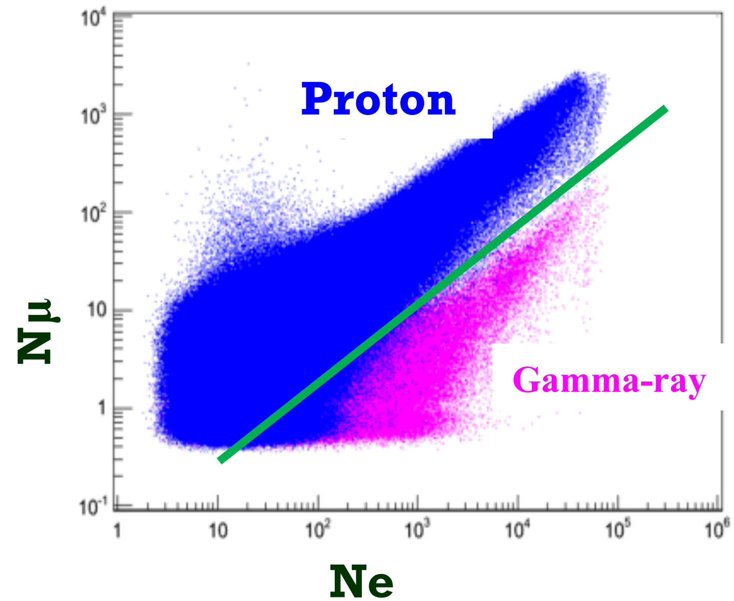
LHAASO FOV

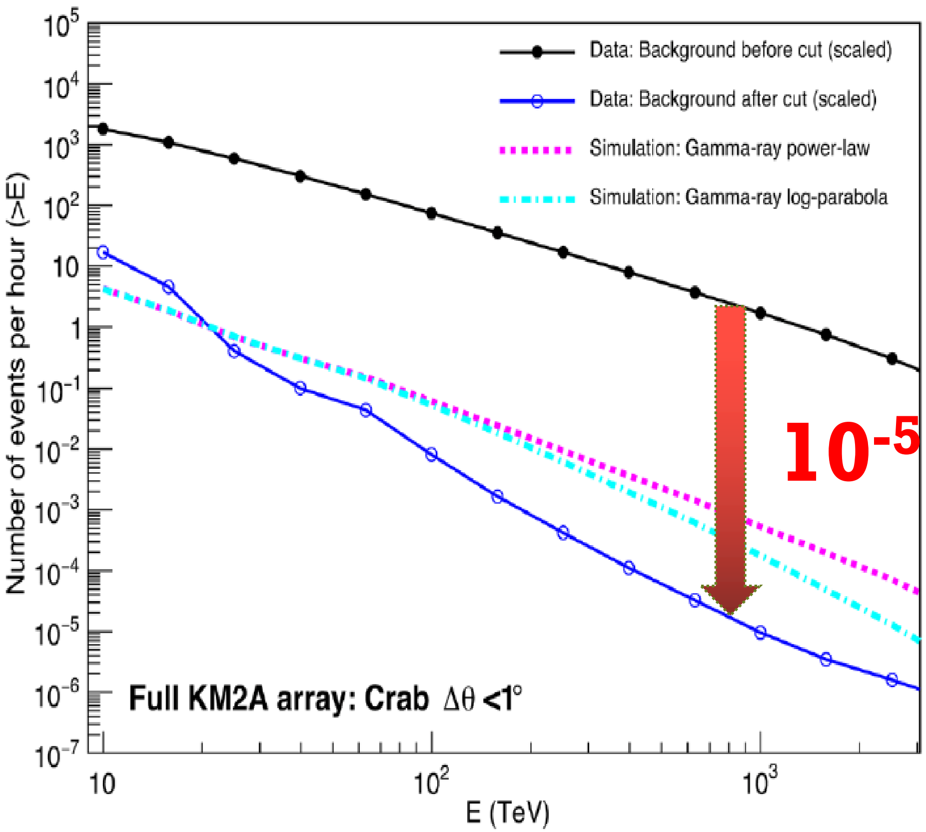
- **High duty cycle: ~100% running time**
- **Large FOV:**
  - **1/7 of the sky at any time**
  - **60% of the sky in a diurnal observation**





γ-ray/cosmic ray discrimination





Cosmic ray rate before cut

Gamma-ray rate

Cosmic ray rate after cut

LHAASO Sensitivities

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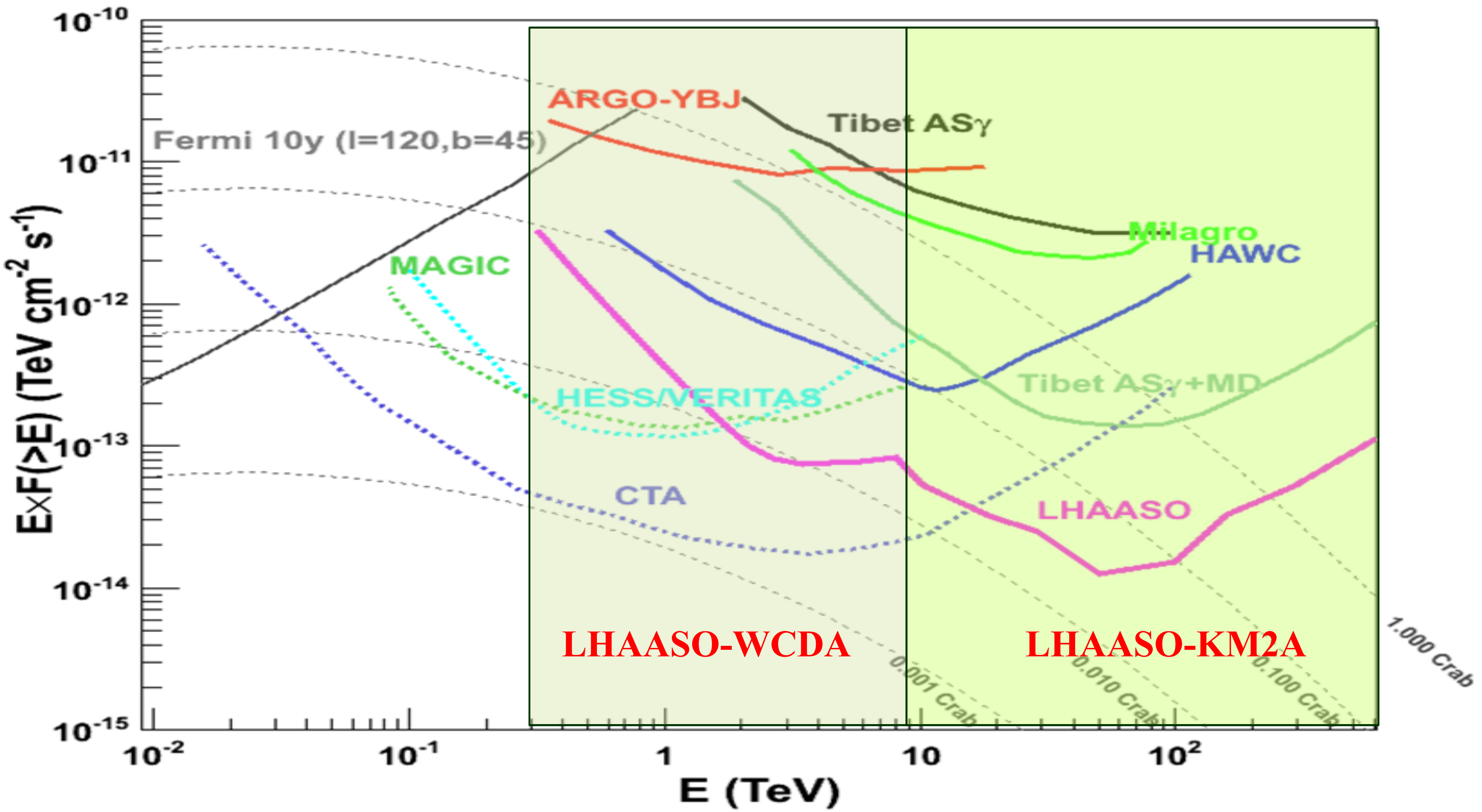

Unprecedented sensitivities above 20 TeV

Angular resolution (KM2A)

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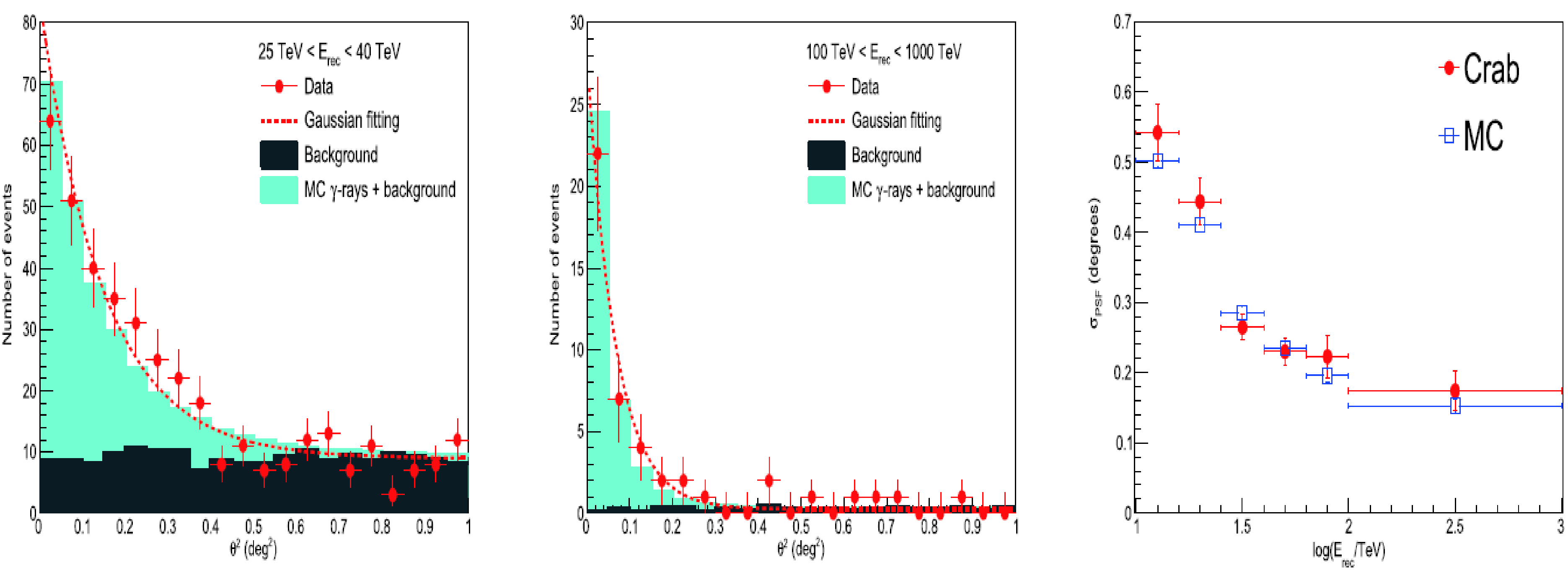
- **The angular resolution measured using standard candle Crab Nebula is consistent with MC prediction.**



Chinese Physics C 45： 025002 (2021)

Energy resolution (KM2A)

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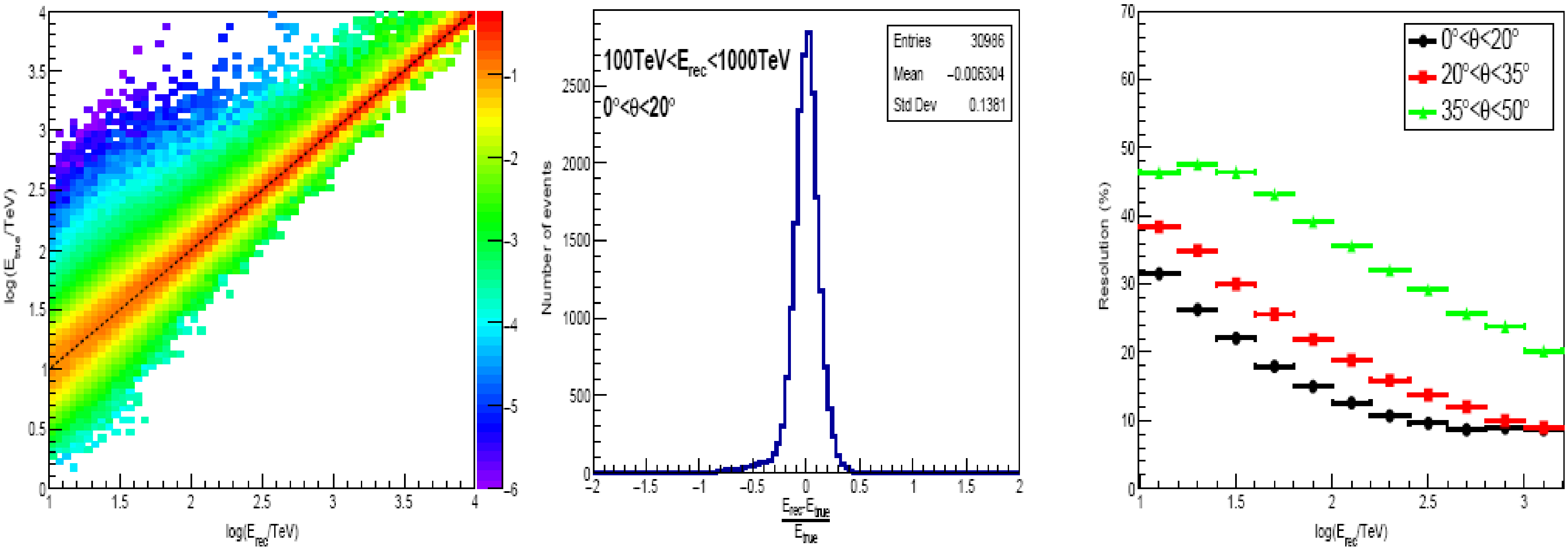
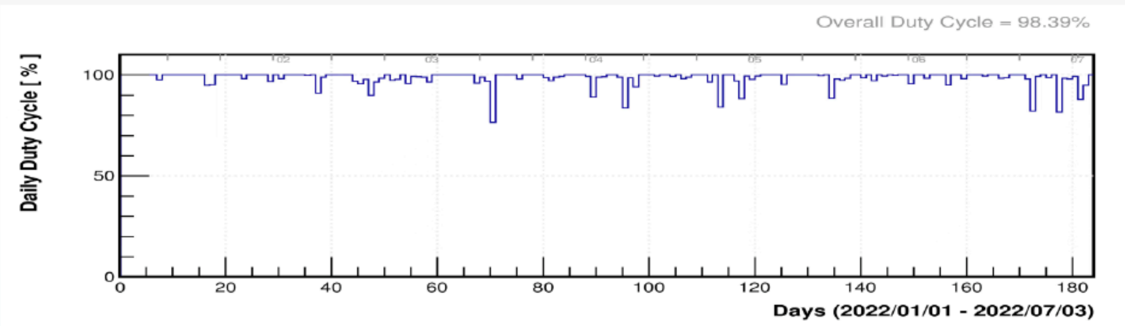
- **θ<20°: 24% @ 20 TeV, 13% @ 100 TeV**

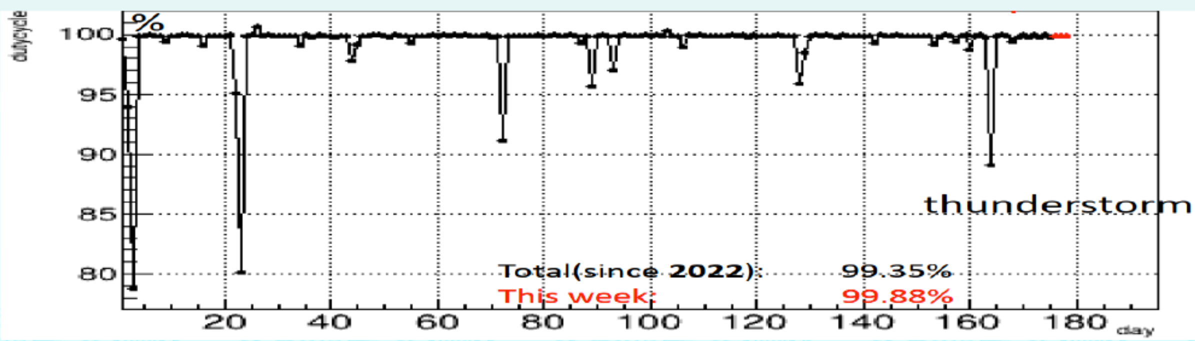


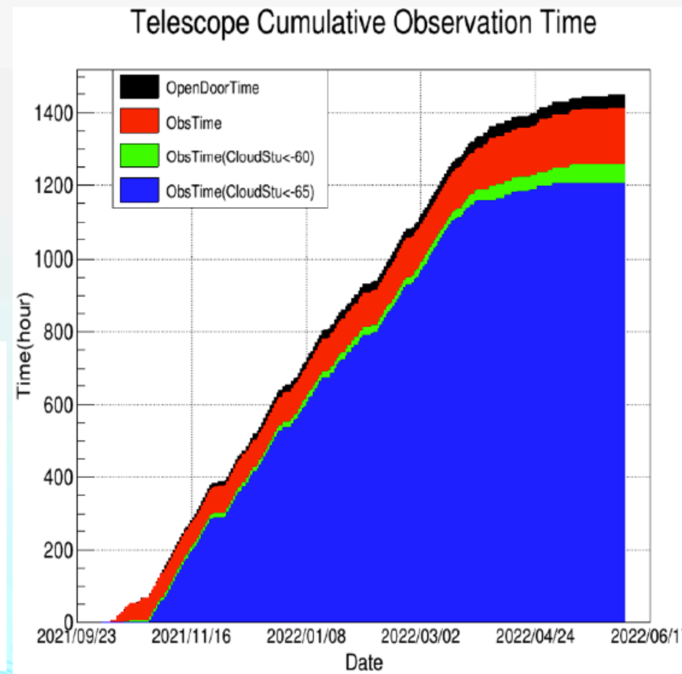
Chinese Physics C 45：025002 (2021)

Operation of LHAASO

- KM2A is operated with >99.4% duty cycle and event rate 2×10^8 /day
- WCDA is operated with 98.4% and event rate 3×10^9 /day
- Data acquisition time of WFCTA >1400 hrs and number of matched events ~70 million







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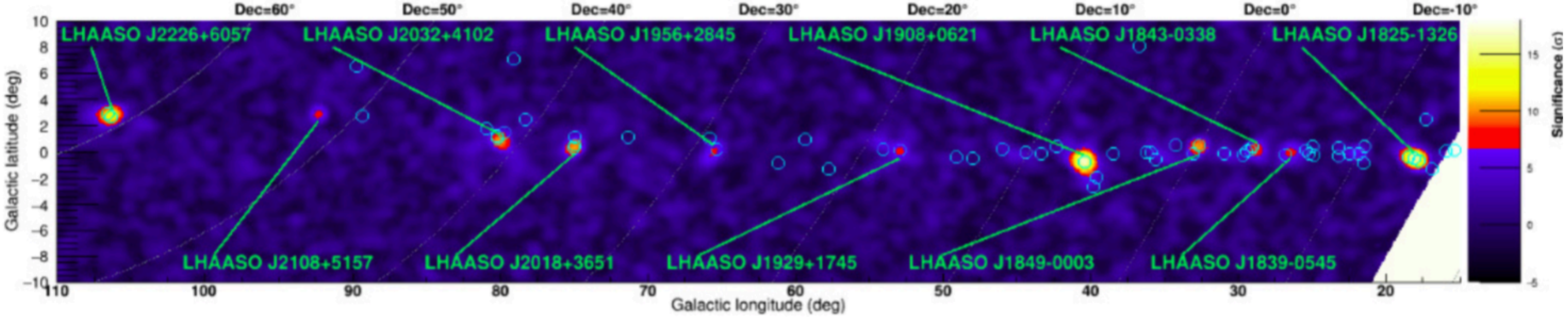
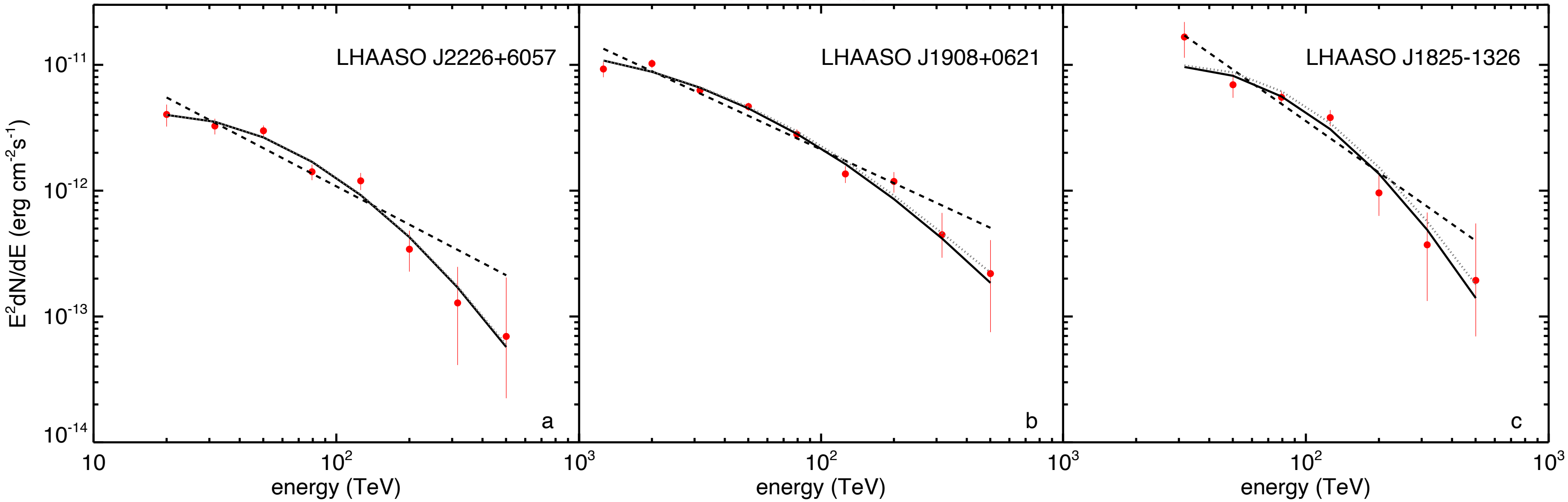
Highlights on recent results

Galactic plane survey

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	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	[illegible]	[illegible]	1.42 ± 0.13	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)

Update:1.1PeV

Cygnus region

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	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[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	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	3.3 ± 0.3[m]/4.0 ± 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]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

Highest energy photon

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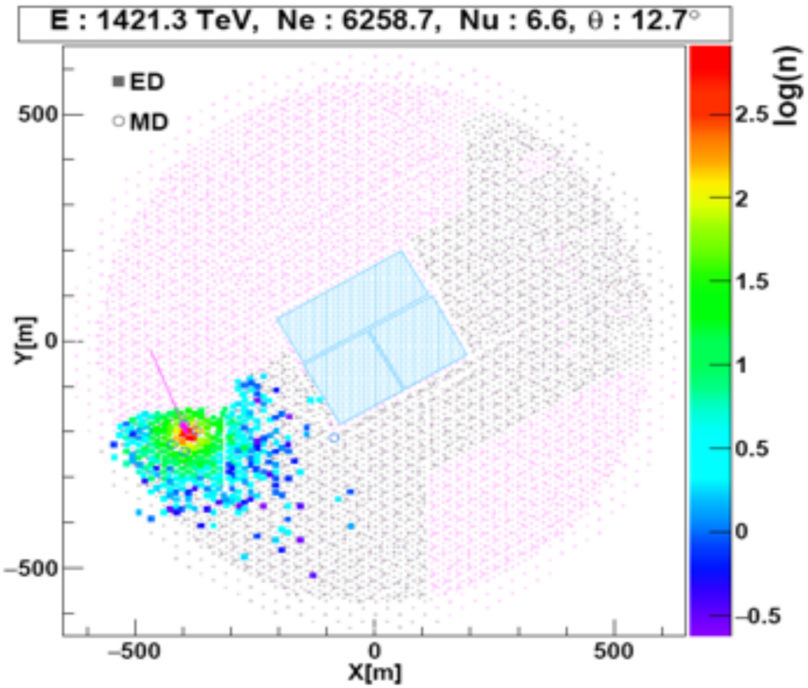
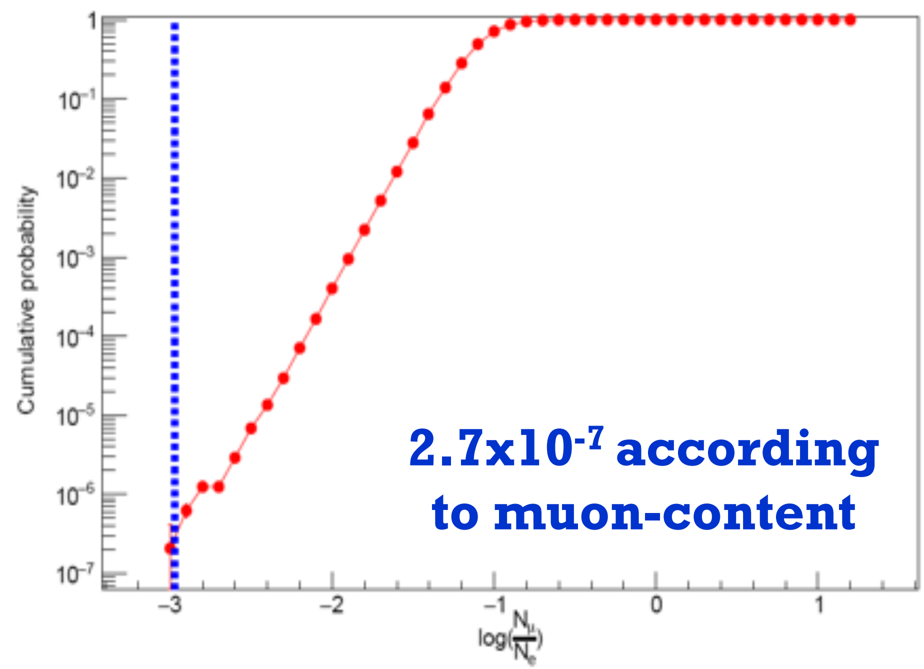
- **1.42±0.13 PeV from the Cygnus region**
- **Chance probility due to cosmic ray background 0.028%.**





Nature 594:33-36 (2021)

LHAASO VIEW ON CYGNUS

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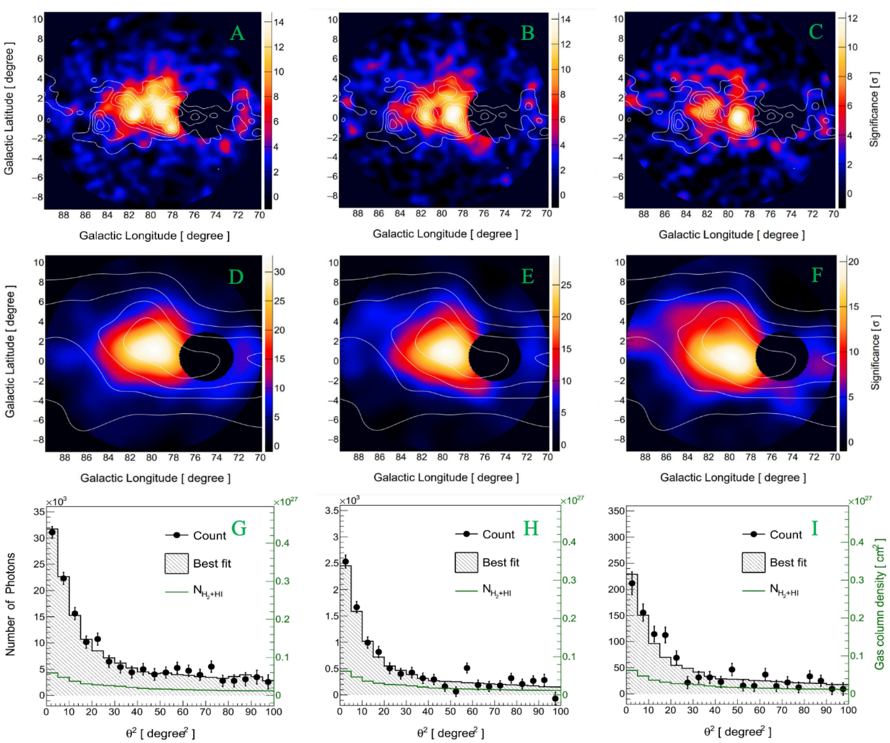
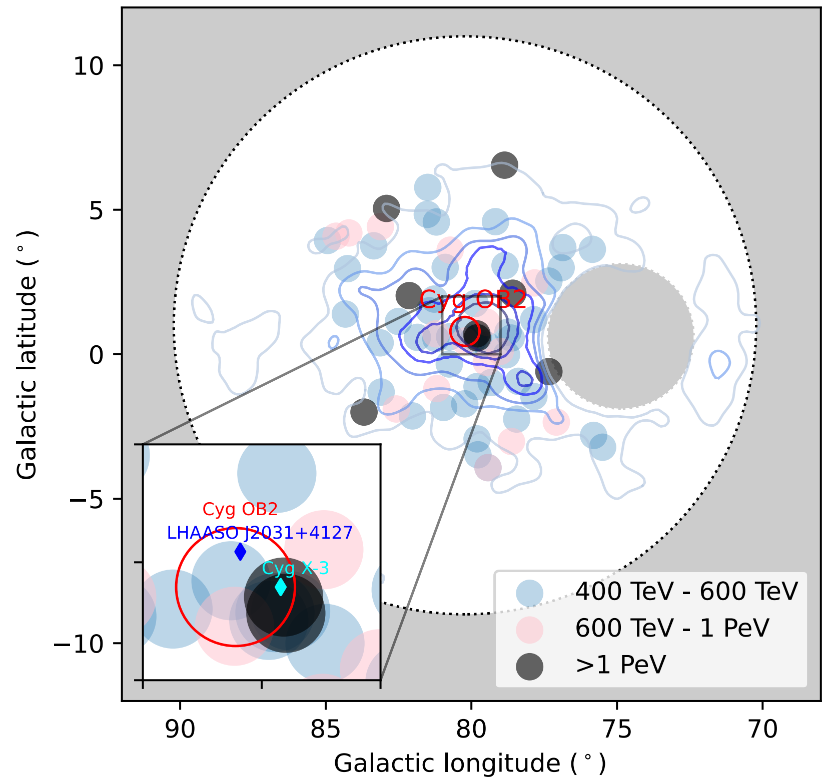




Huge bubble beyond ~10 degrees (200 pc)

Concentration of UHE photons in the central region

(LHAASO collaboration, Science Bulletin 69,449)

Schematic fitting of observations

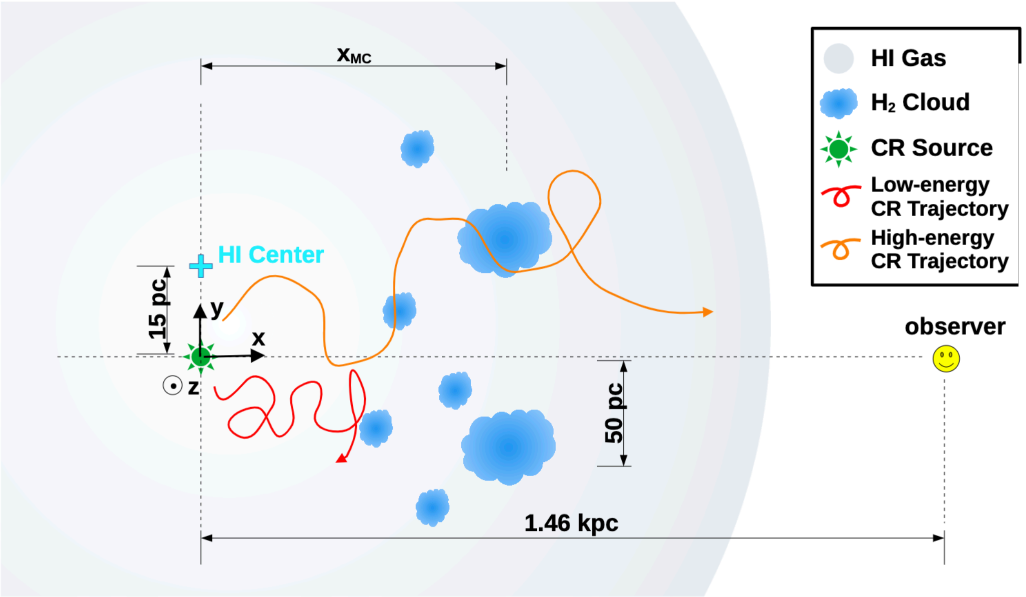
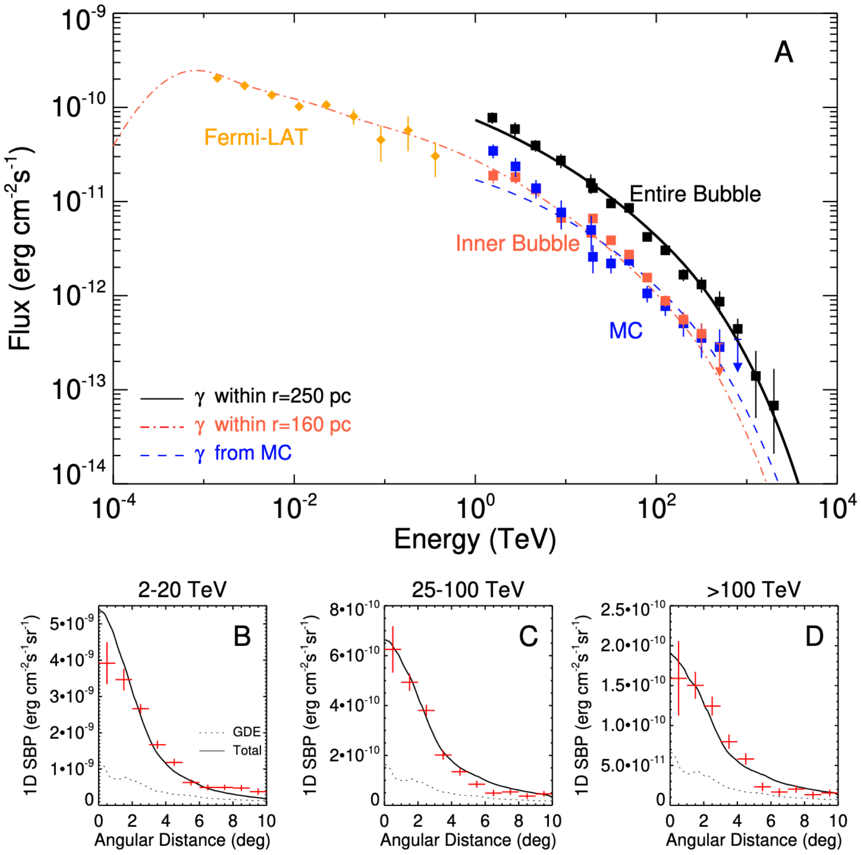


Figure 9: An illustrative sketch (not to scale) of the model.



- Central continuous injection of CRs up to PeV
- Slow diffusion near the source (1/100 of fiducial value)
- Harder spectra from Molecular clouds

GRB 221009A

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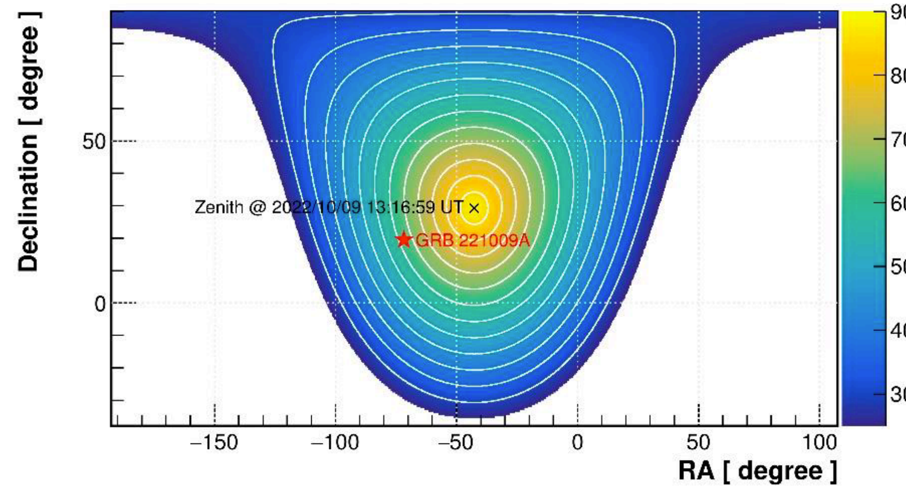
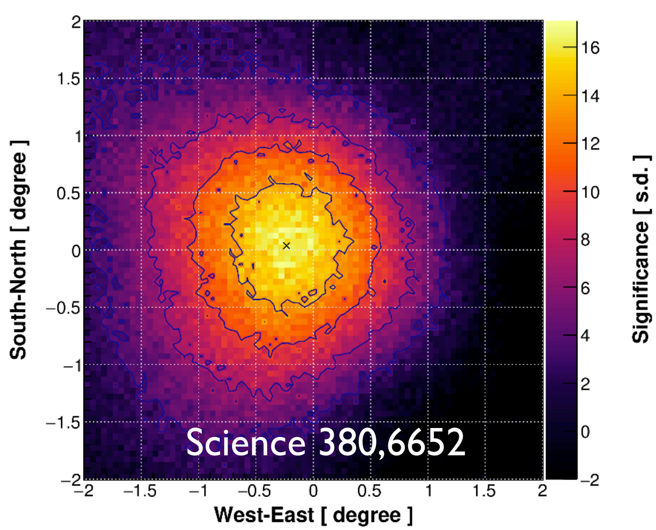
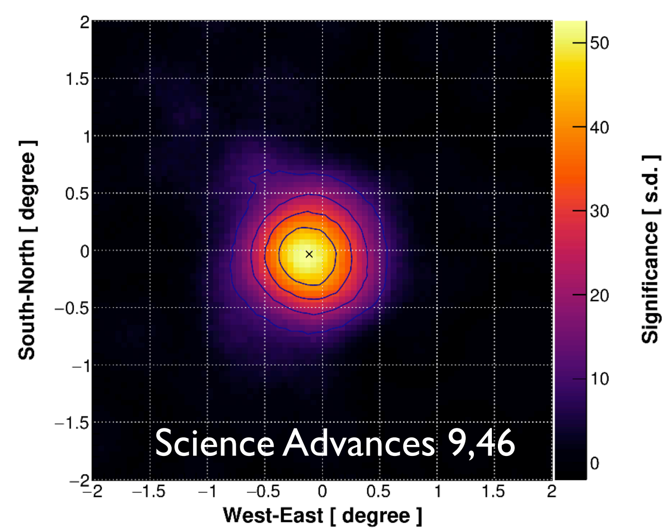
- LHAASO detected the brightest GRB ever
- >64,000 photons recorded above 300 GeV(WCDA), Significance >131σ
- >140 photons above 3TeV(KM2A), Significance >18σ
- Photon energy: Emax >10 TeV



E=0.5 TeV



E=3 TeV



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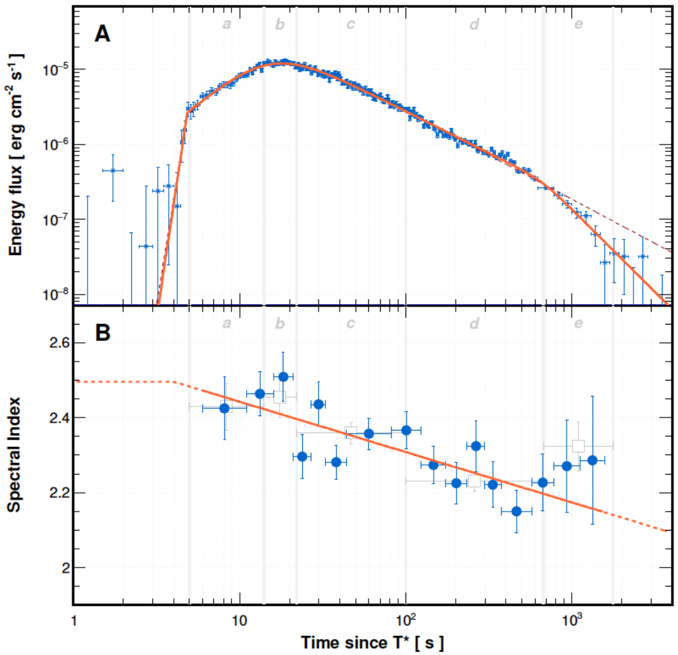
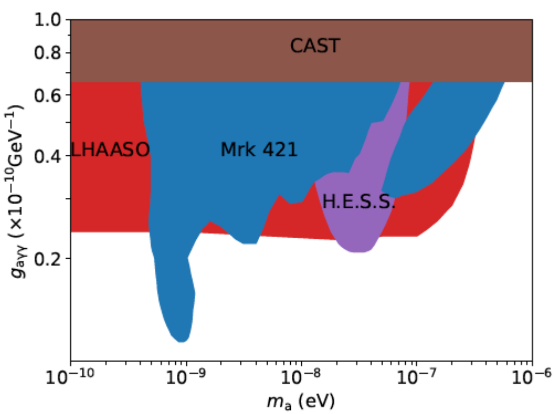
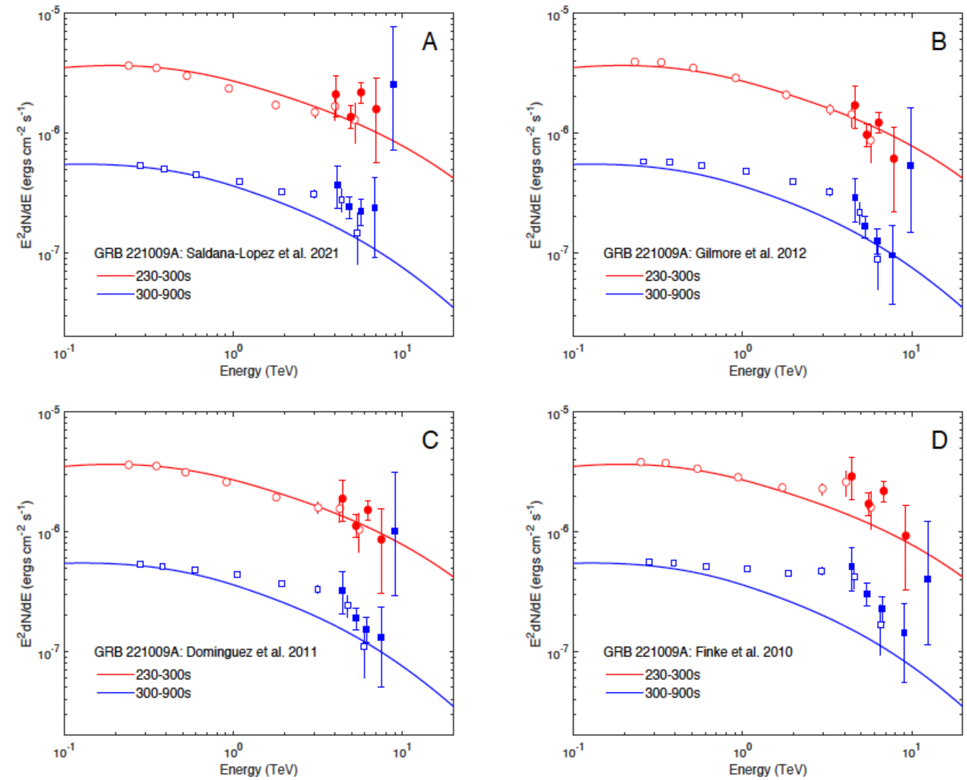
Jet break observed, jet opening angle ~0.8 degree



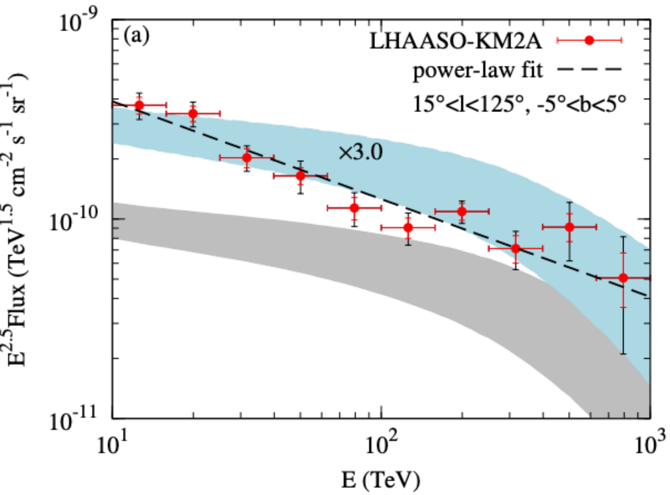


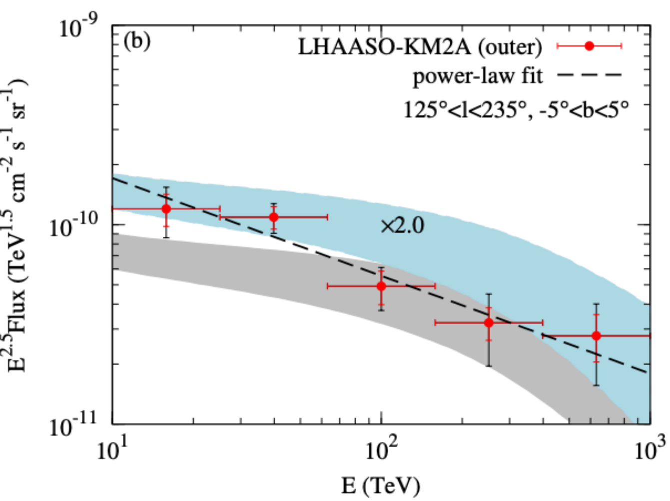


KM2A results reveal：

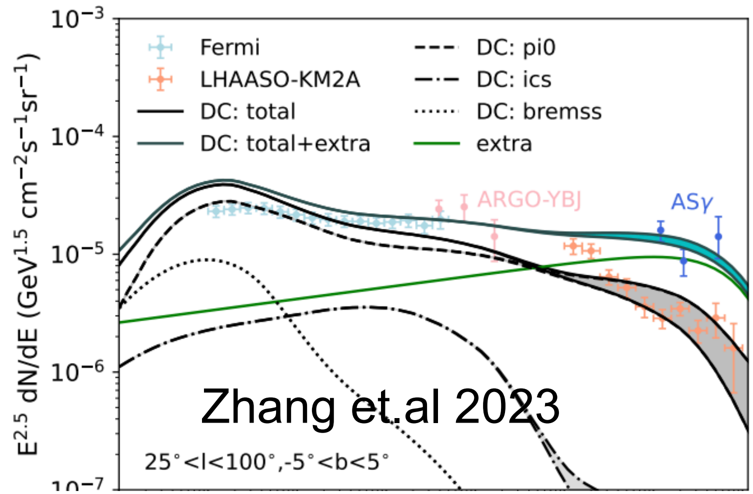
- tension with SSC model
- set stringent limit on Axion-gamma coupling

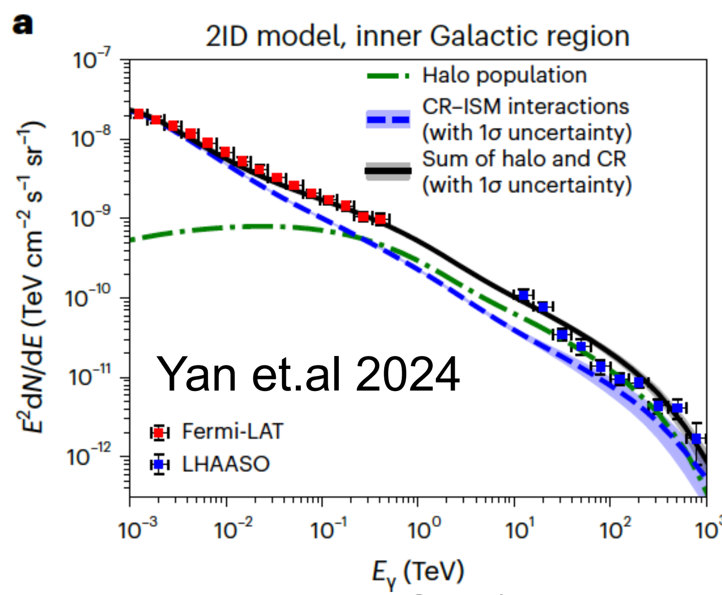
Diffuse gamma-ray emission





Phys. Rev. Lett. 131, 151001 (2023)
`Excess' revealed in multi-TeV band



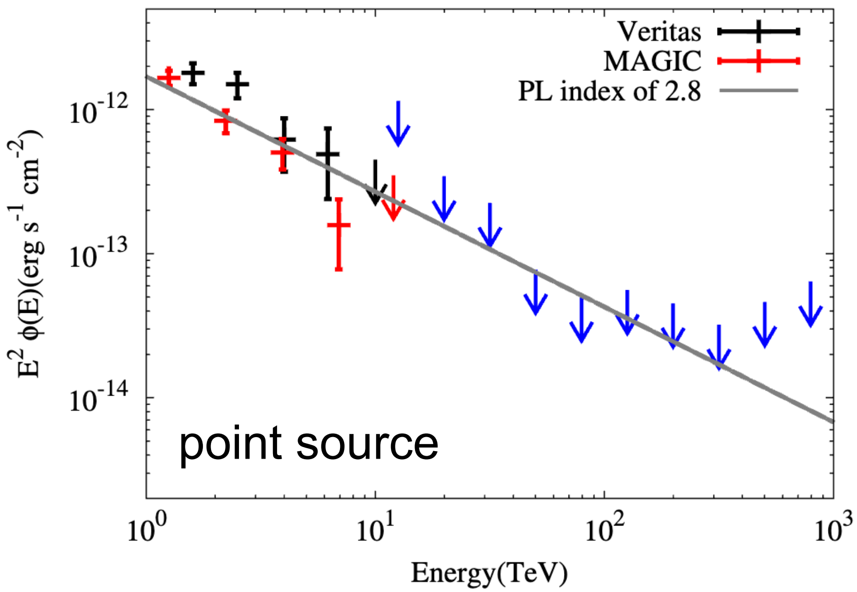


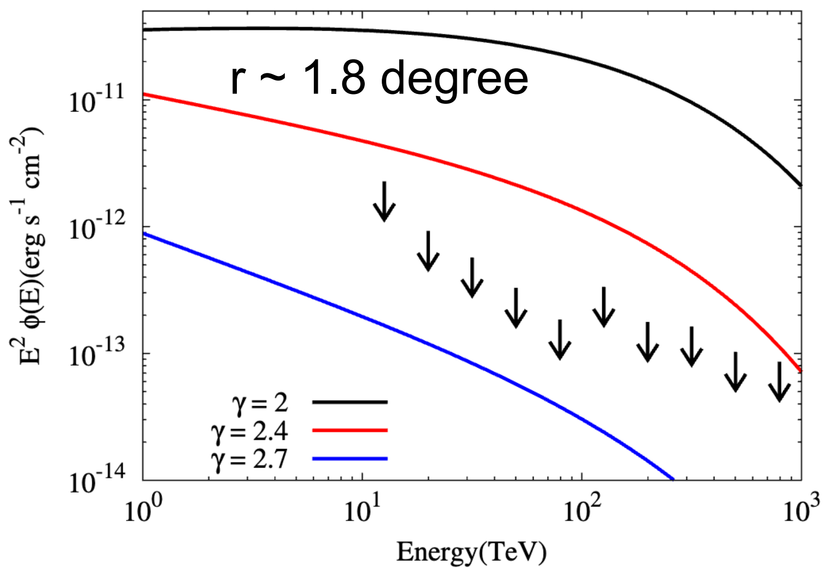
A new component in GDE? From Pulsar halos?

Upper limit on SNR Cas A

Using KM2A upper limit to constrain the total CR injected by Cas A

LHAASO collaboration, ApJL, 961, 43

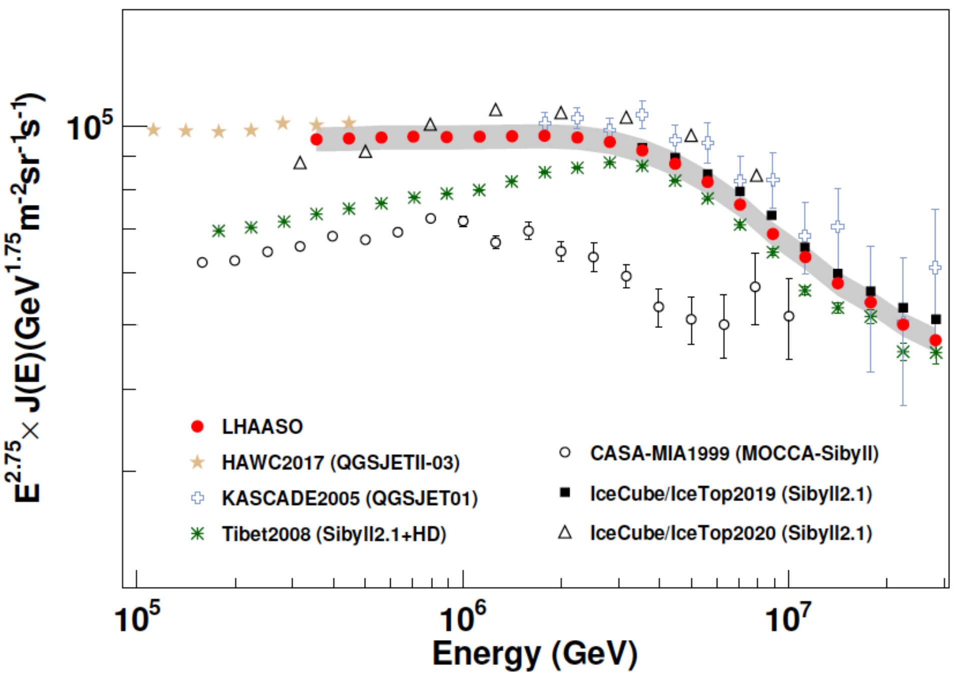


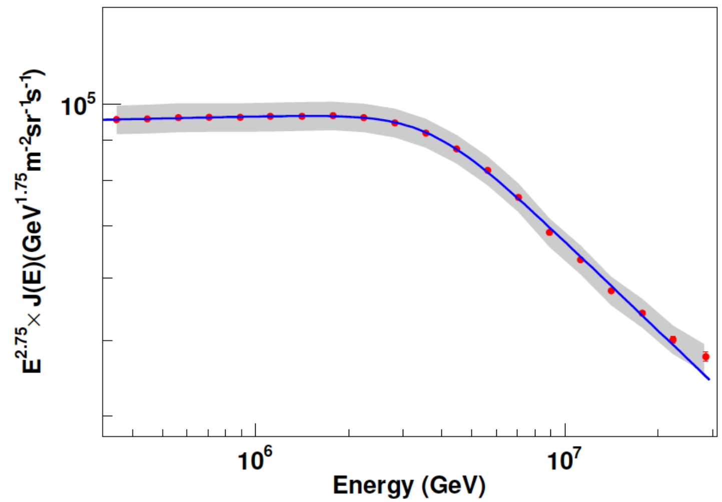


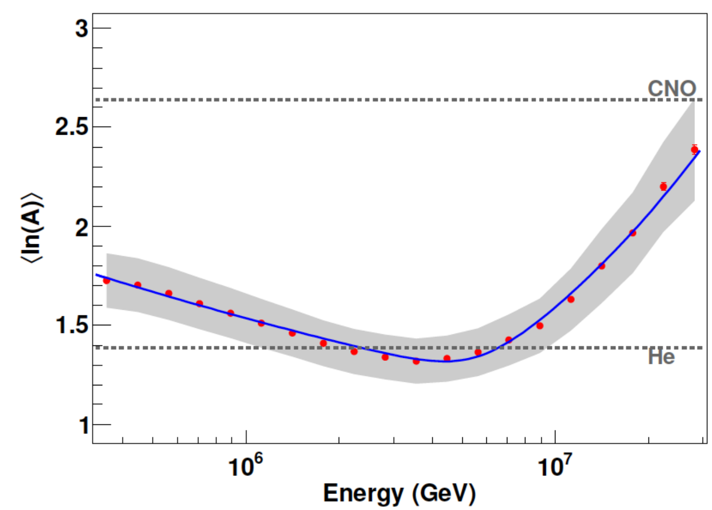
- Stringent upper limit was set for the total VHE CRs injected by Cas A since explosion
- hints for other candidates of PeVatrons

CR all particle spectrum

LHAASO collaboration, PRL, 132, 131002







- knee at ~ 3.7 PeV
- decreasing of mean logarithmic mass at knee region

Prospect

Three brightest sources

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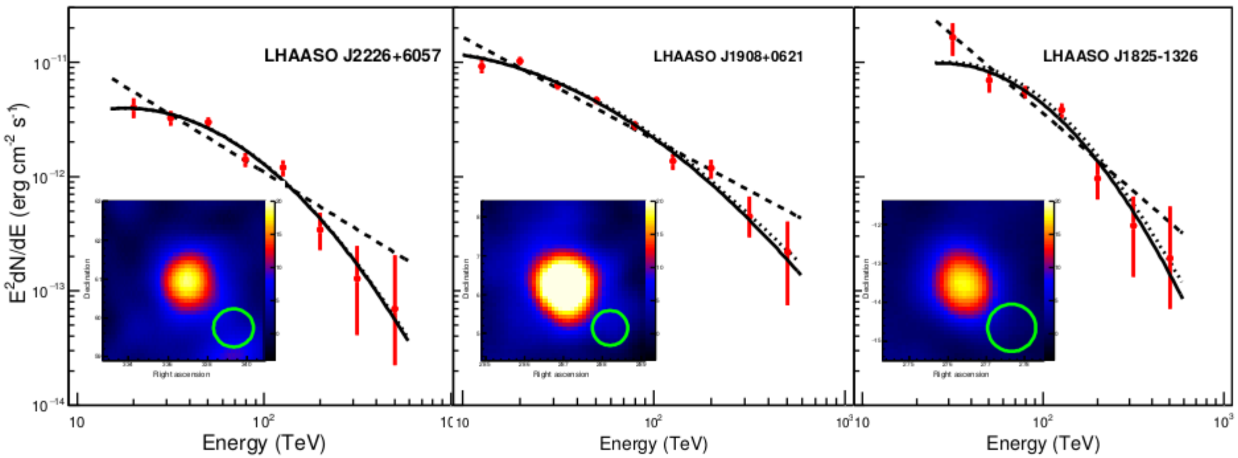
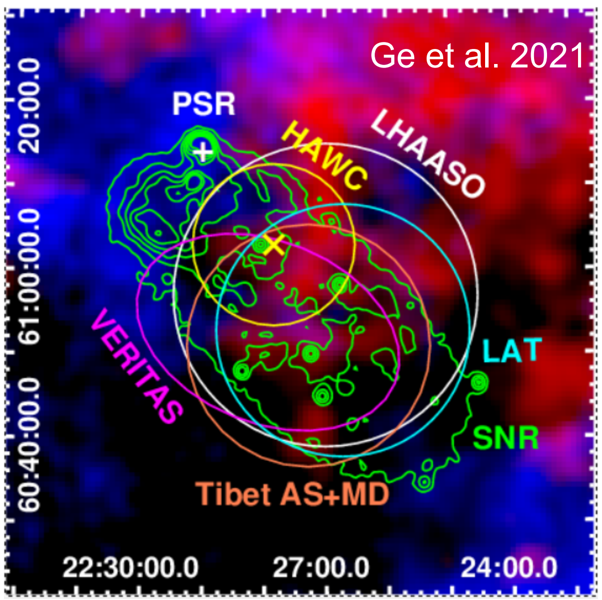


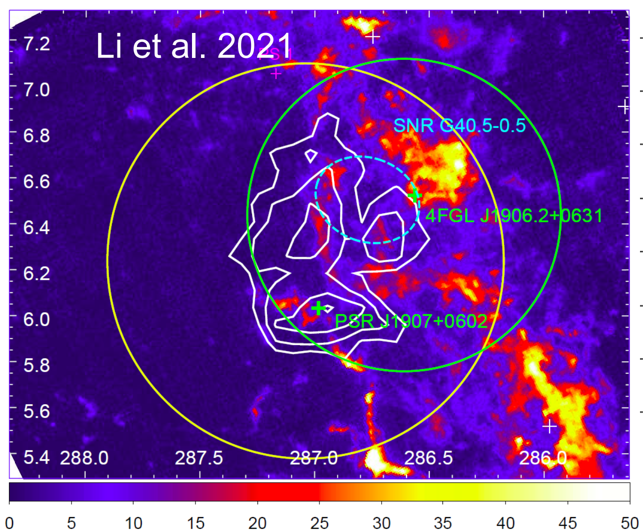
Complex regions

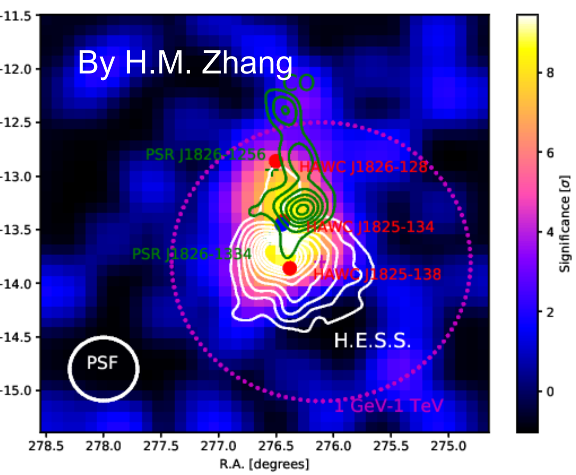
J2226+6057

J1908+0621

J1825-1326







Other on-going work

- bright sources: J1908, J1825, SNR G106….
- Proton/Helium spectrum at knee region
- Detection of Microquasars
- SS433
- Geminga halo
- detailed structure of Galactic diffuse emission
- Indirect search for DM
- Unexpected new sources,.etc.

future of LHAASO

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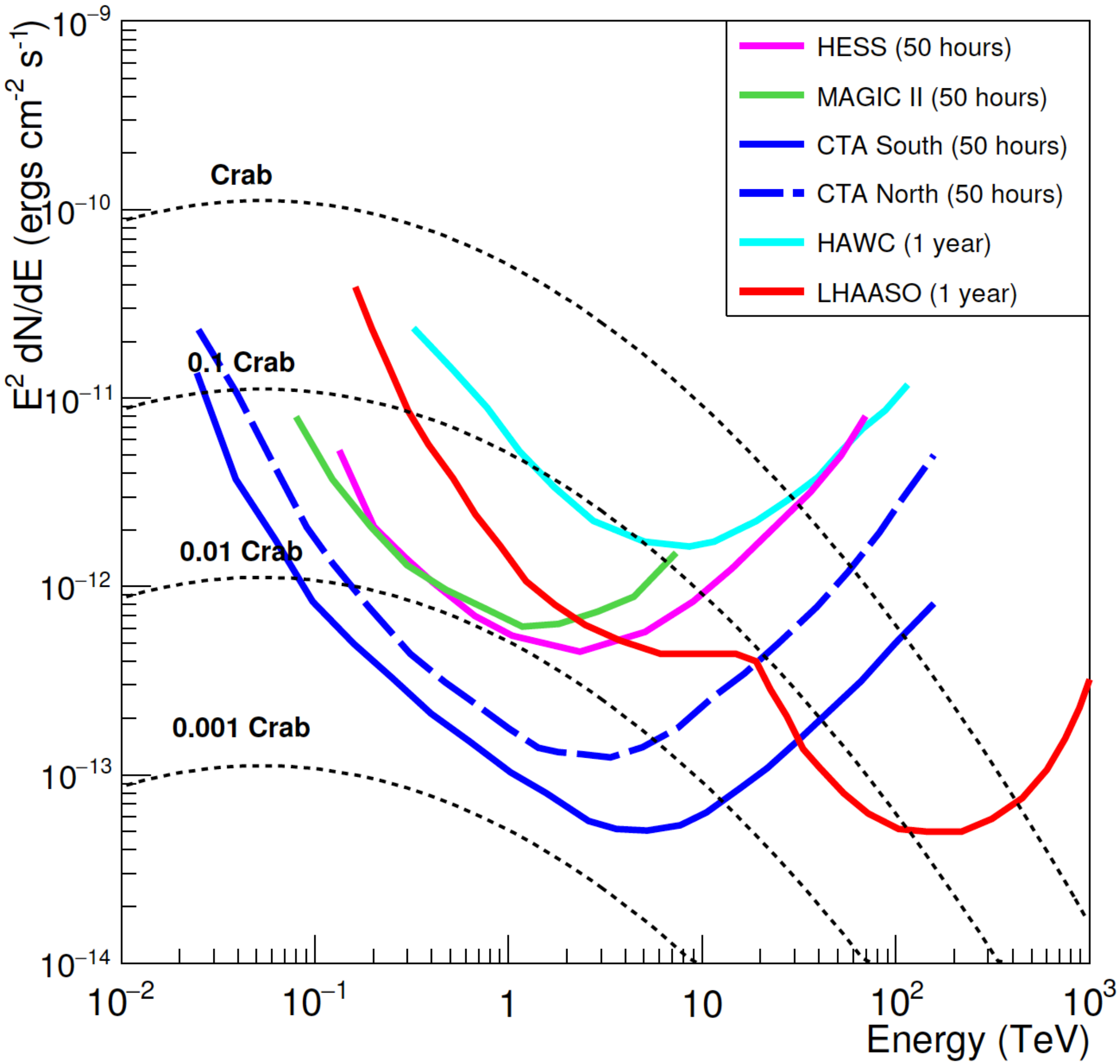


Data accumulation of LHAASO and Multi-wavelength observations

Unprecedented above 20 TeV

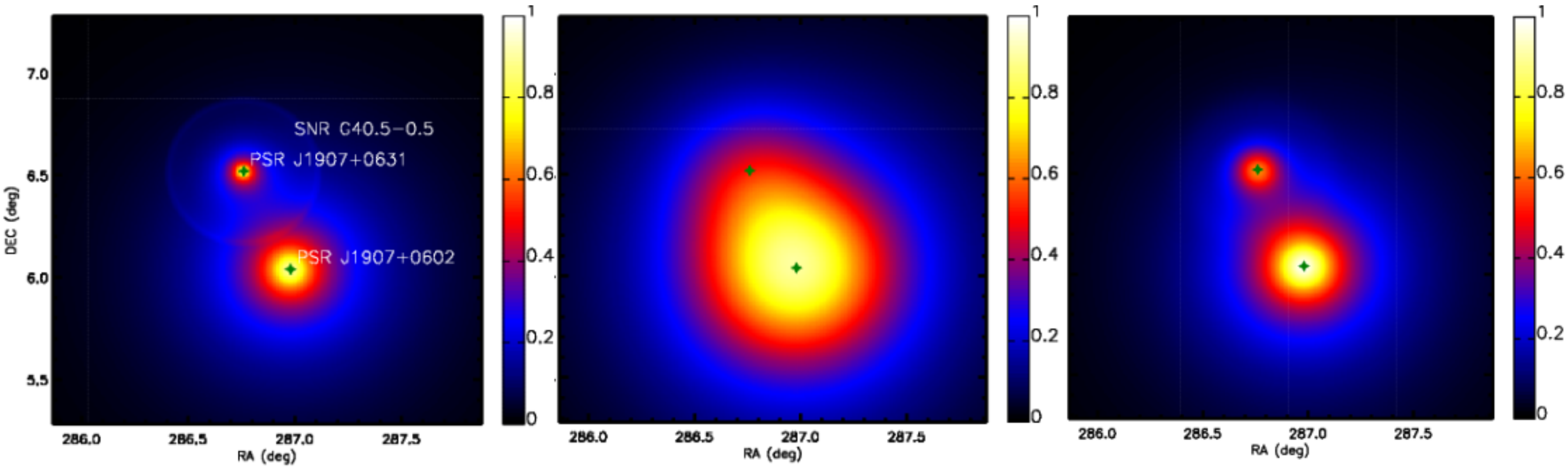
ideal PeVatron hunter

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 (LACT)

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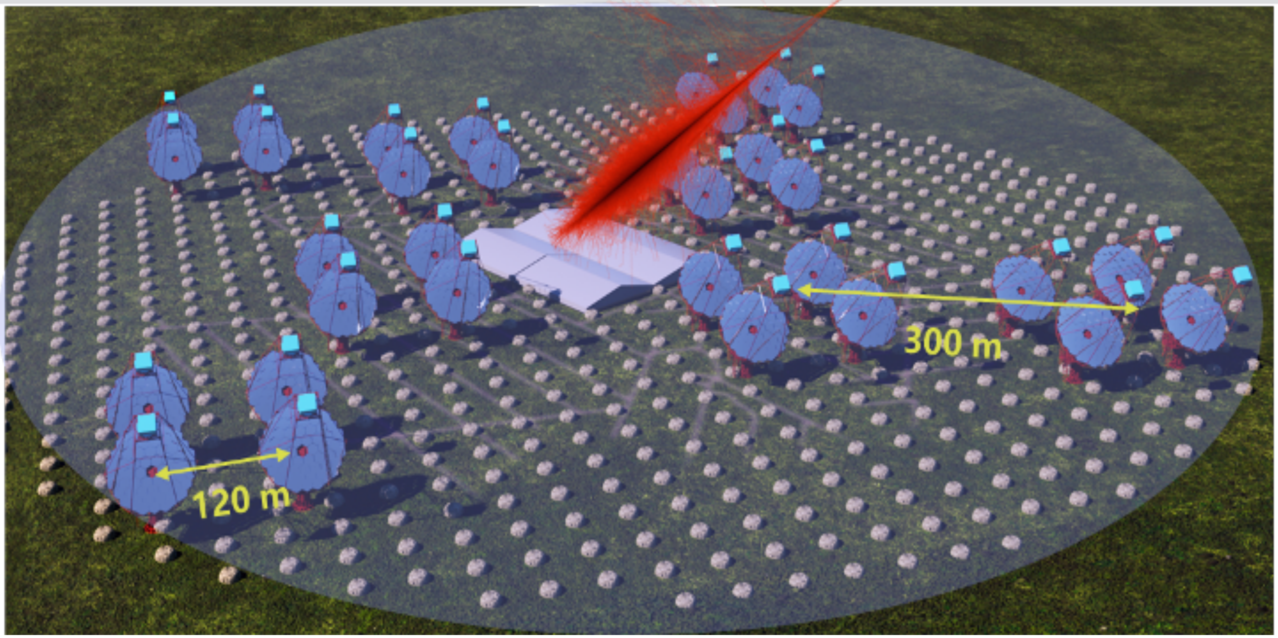

- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon!

See also Poster ID-016

Predicted sensitivities

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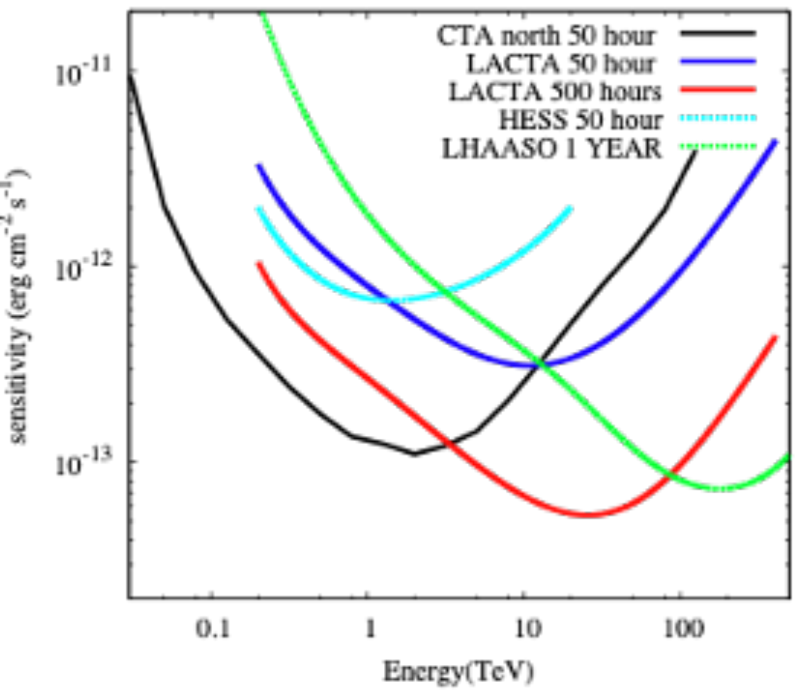
Synergy with LHAASO
Use MD to improve the gamma/p separation
Detailed morphology study of PeVatrons, TeV halo, PWN…



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

Synergy with LHAASO-KM2A

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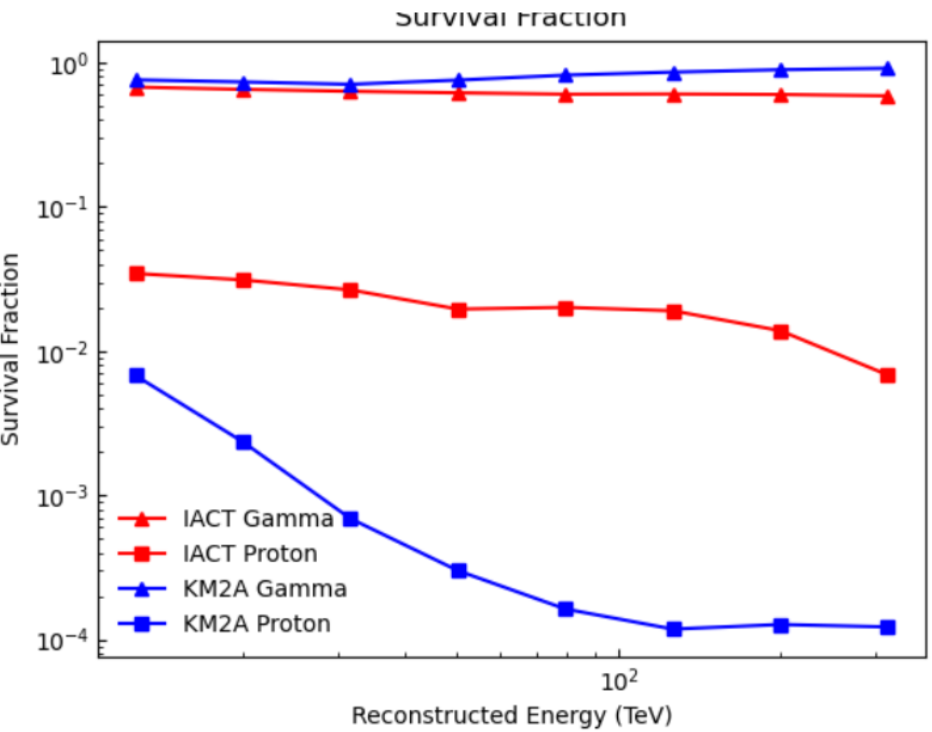
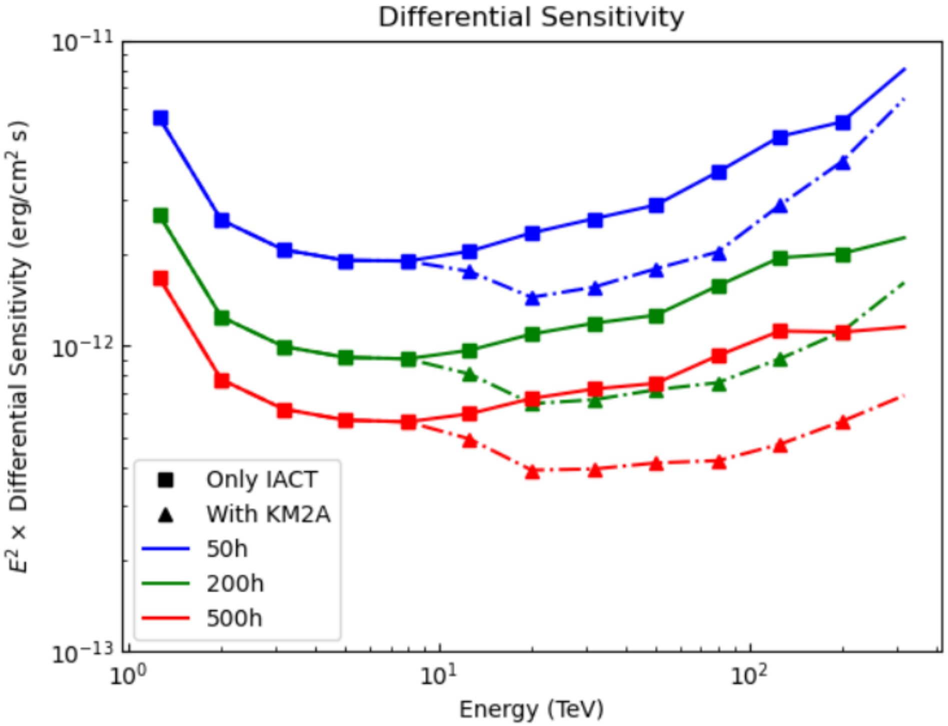


Using KM2A for gamma/p separation



Sensitivity of LACT can be significantly improved above 10 TeV

Conclusion

- LHAASO already show great power in gamma-ray astronomy, especially in PeVatron study and time domain astronomy
- A lot of future tasks for LHAASO: PeVatron identification, diffuse gamma-ray, high energy transients, direct measurement of CRs, indirect dark matter search…….
- Further project: Imaging Air Cherenkov array (LACT) in LHAASO site

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LHAASO
高海拔宇宙线观测站

Thanks!