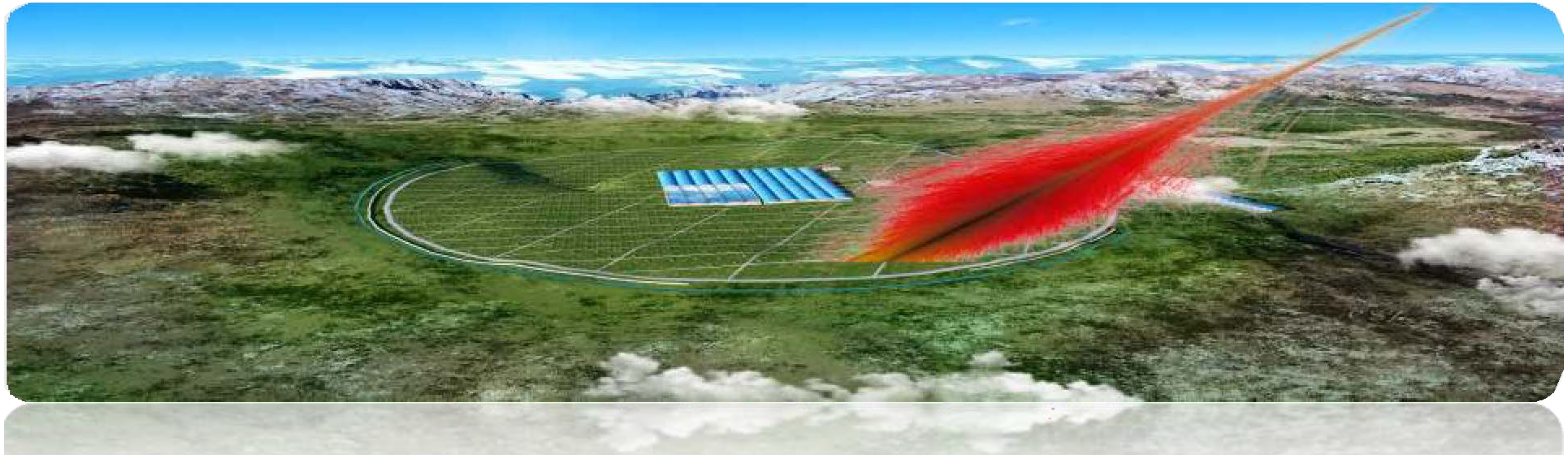
Recent Results from The Large High Altitude Air Shower Observatory (LHAASO)

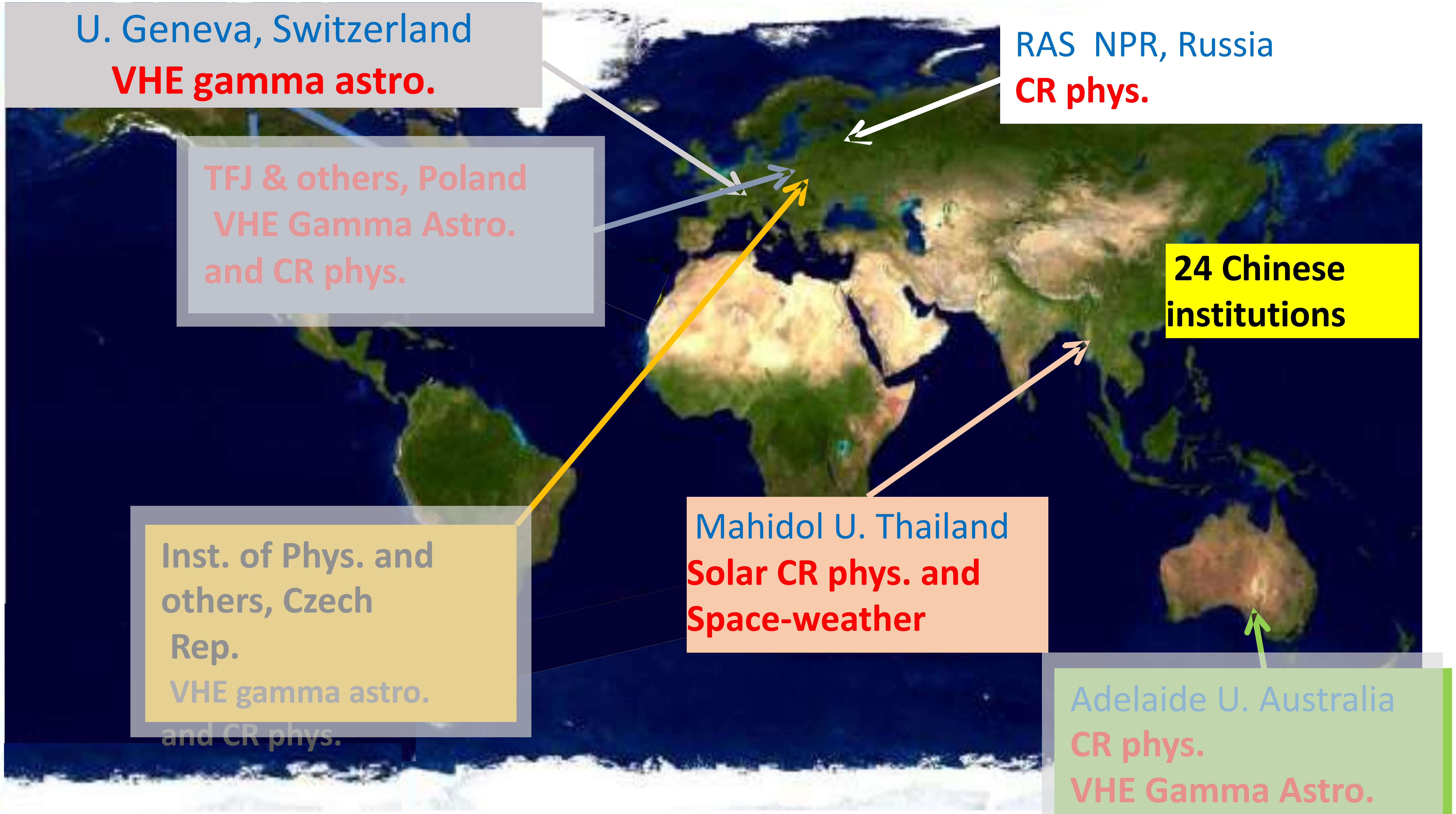
Jordan Goodman
Erice Summer 2022

Talk Overview

- Large High Altitude Air Shower Observatory (LHAASO)
  - Disclaimer - I am not a LHAASO collaborator. (More of an envious admirer)!
  - All the material in this talk was taken from public sources or given to me by Zhen Cao
- There are many similarities between HAWC and LHAASO
  - Cost in not one of them!



LHAASO Collaboration (by country)



Yi Zhang

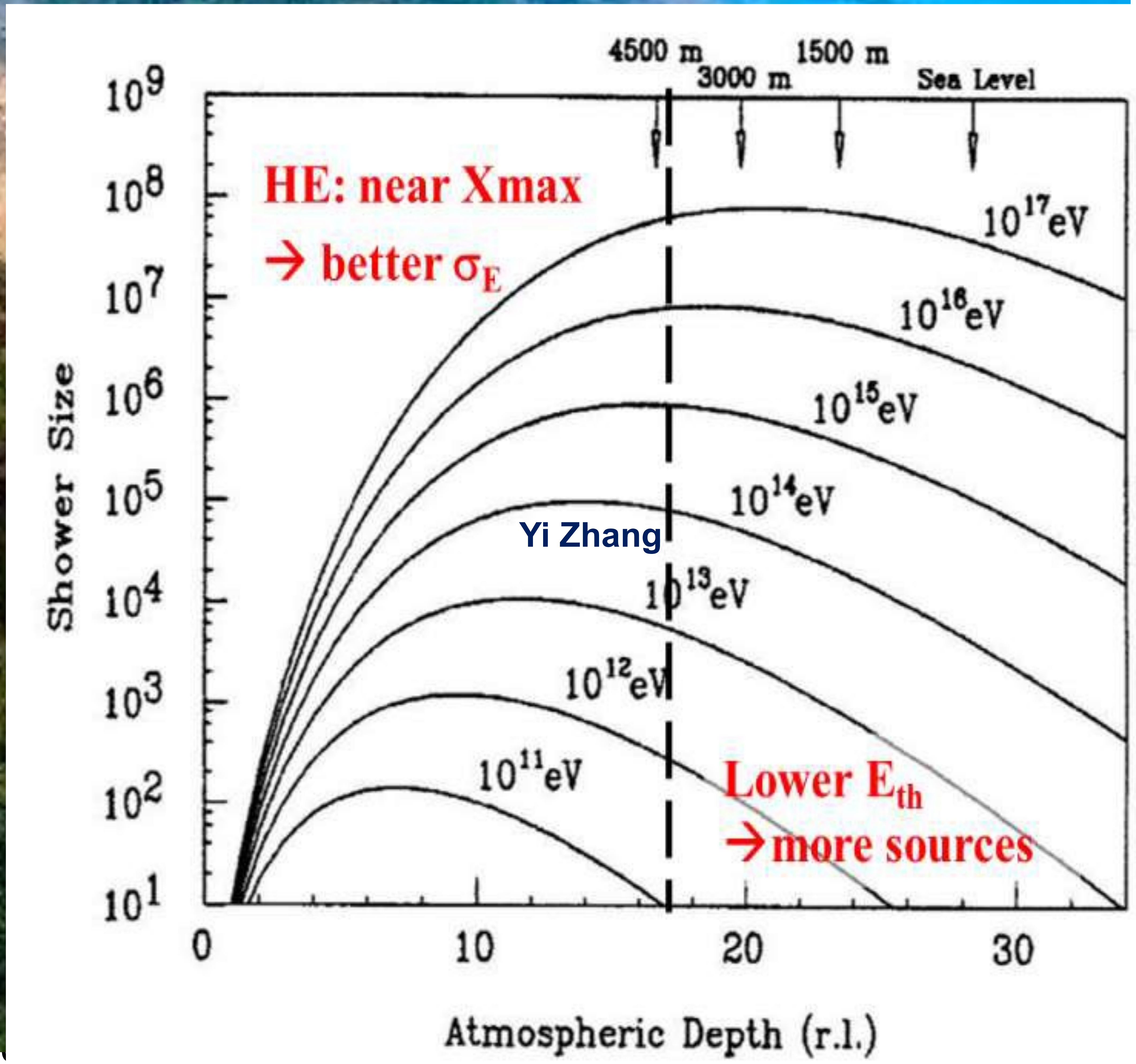
LHAASO Coll. Chinese institutions

Yi Zhang

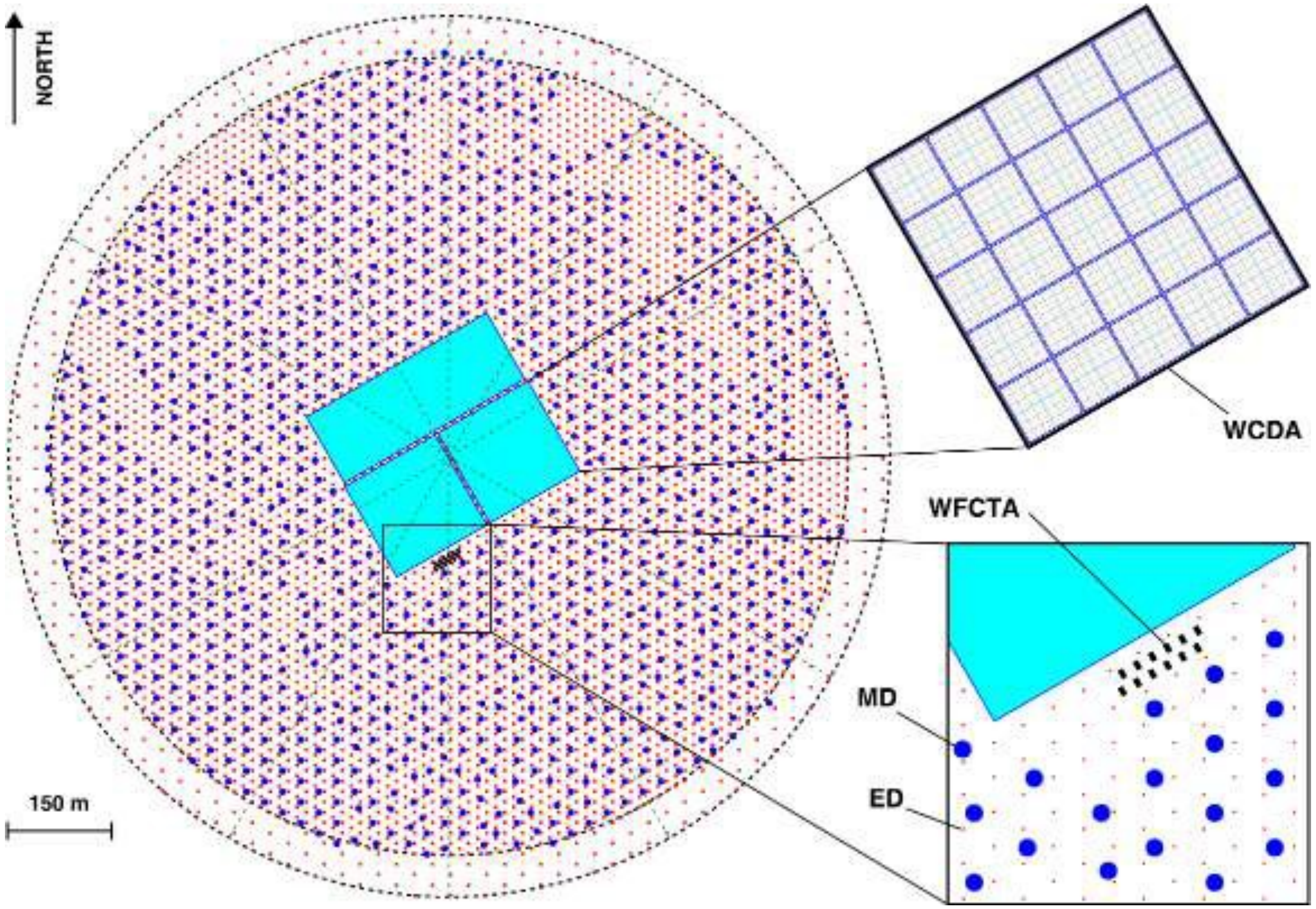
Where is LHAASO

Mt. Haizi (4410 m a.s.l., 29º21’ 27.6” N, 100º08’19.6” E), Sichuan, China

Yi Zhang



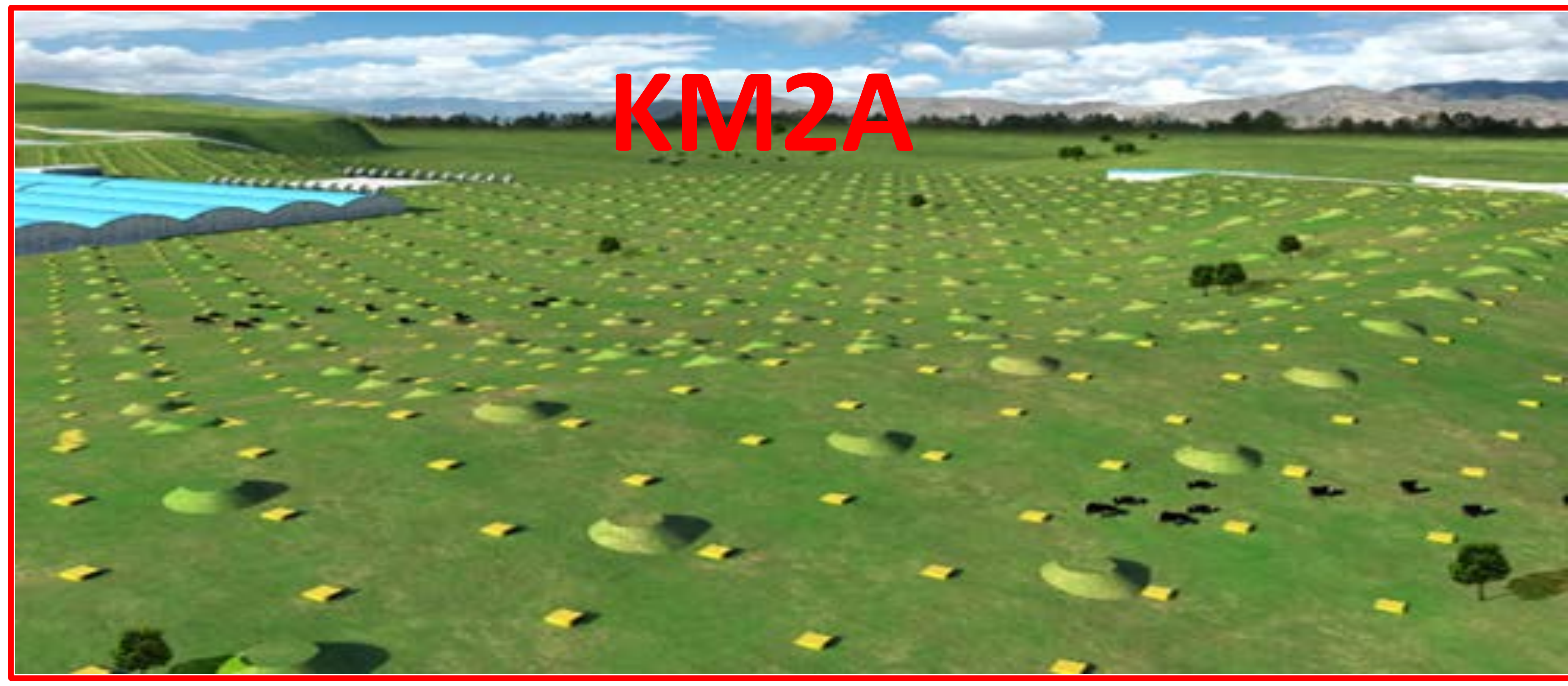
A Large area EAS array covering 1.3 km²



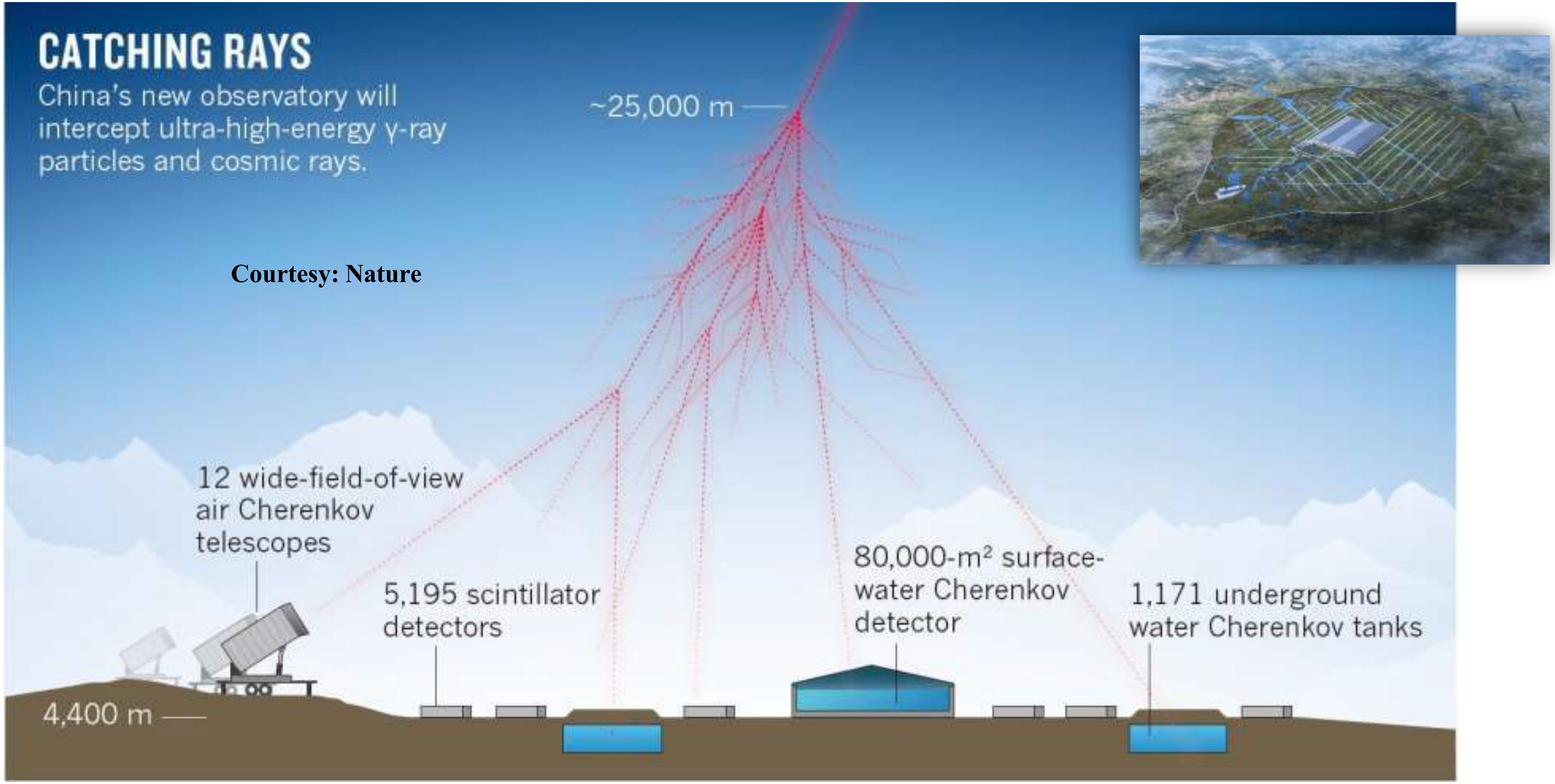
- 5242 Electron Detectors (ED)s
  - 1 m² each
  - 15 m spacing
- 1188 Muon Detectors (MD)s
  - 36 m² each
  - 30 m spacing
- 3120 Water Cherenkov Det. WCDs
  - 25 m² each
- 18 Wide Field Cherenkov Telescopes WFCTs

Main goals of LHAASO

- TeV gamma-ray survey → WCDA (100 GeV-30 TeV)
  - AGN, GRB, survey new source, …
- >20 TeV gamma-ray survey →KM2A (10TeV-1PeV)
  - SNR, PWN, Superbubble, diffuse around 100TeV, …
- Individual nuclei spectra →WFCTA (10TeV to EeV)
  - Different configures
  - Combined with WCDA, WCDA++, KM2A
- Benefit regions:
  - Anisotropy, Solar physics, dark matter, EBL, IGMF, Lorentz invariance, hadronic interaction, …



Hybrid Detection of EASs by LHAASO



Courtesy: Nature

LHAASO birds-eye View from a drone — May. 2021

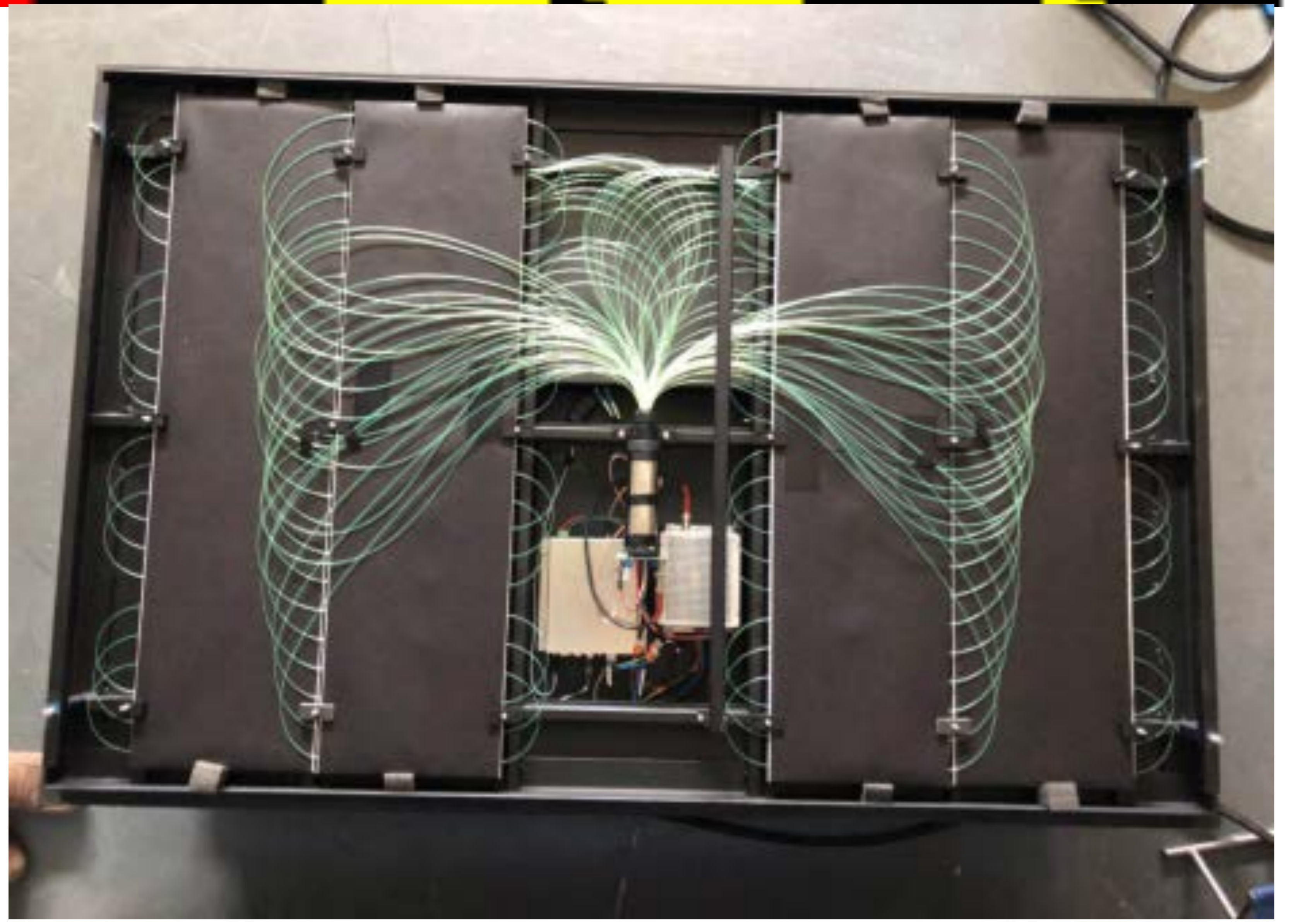
Living Space

Building the Experiment

Three Gorges Dam - $22B

LHAASO birds-eye View from a drone

KM2A Electromagnetic particle Detectors



Scintillator Detector Unit

1/2 ED array, 2365 EDs started 2019-12

3/4 ED array, 3978 EDs (total 5242),

started operation 6/12/2020

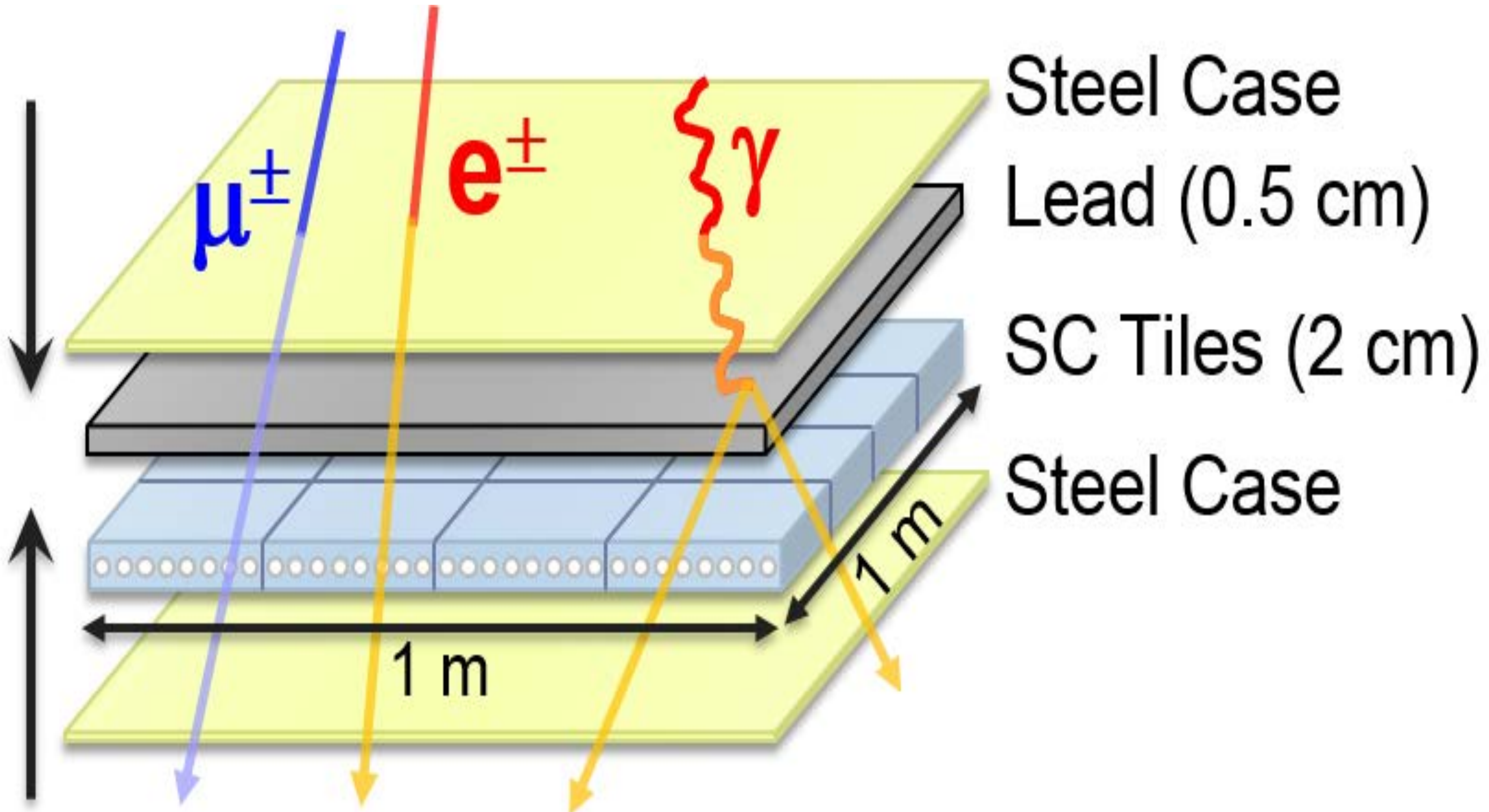
Trigger rate ~ 1900Hz,

1.45TB one day

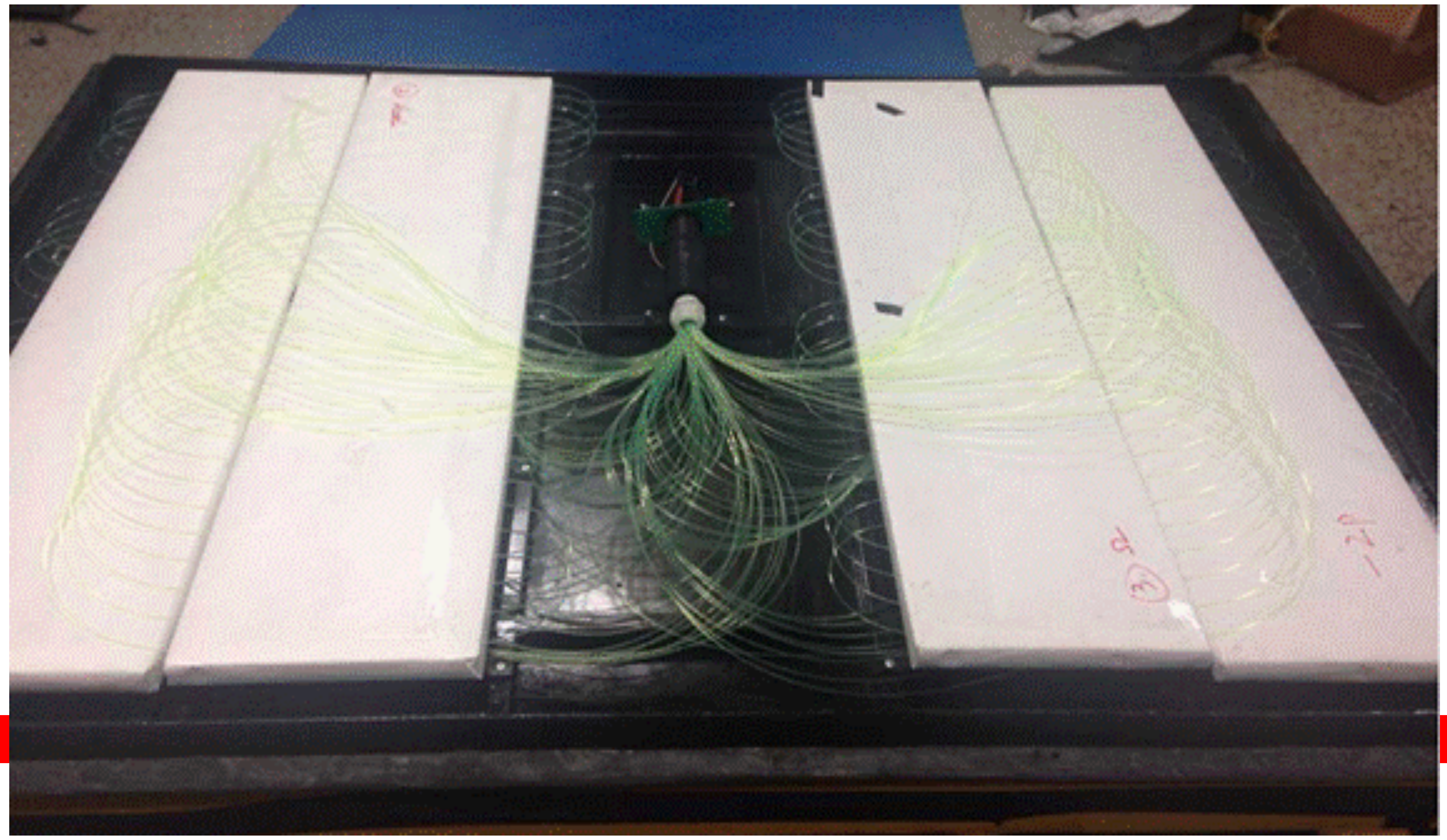
ED Specifications	
Detection area	1m×1m; 5mm Lead covered
Detection efficiency	> 95%
Time resolution	< 2ns
Dynamic range	1~10000 particles/m^2; 25%@1 particle, 5%@10000 particles
single channel rate	<2kHz@working Gain
Stable operation	> 20yrs (4410m, 0.6atm., ±25°C)

KM2A

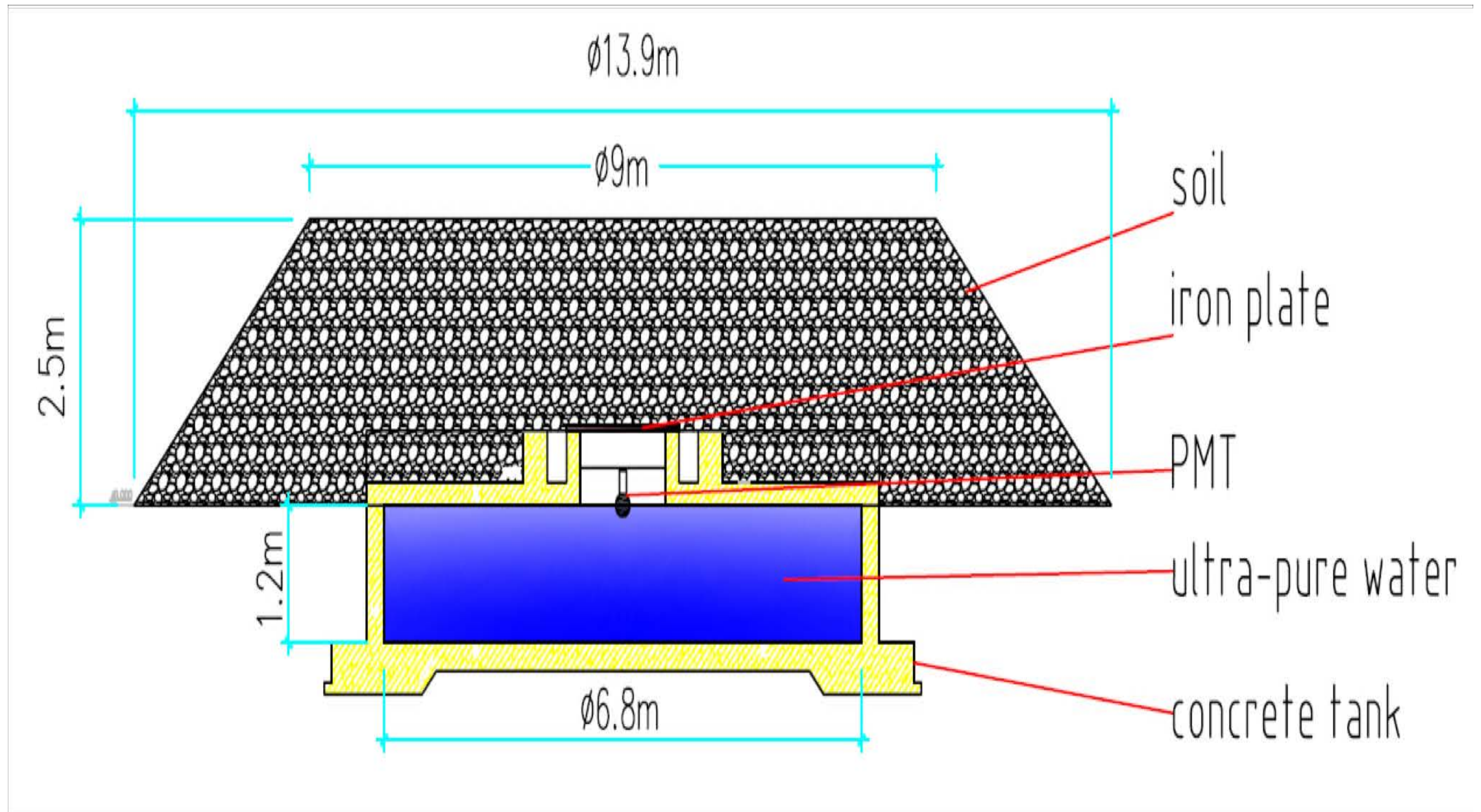
ED



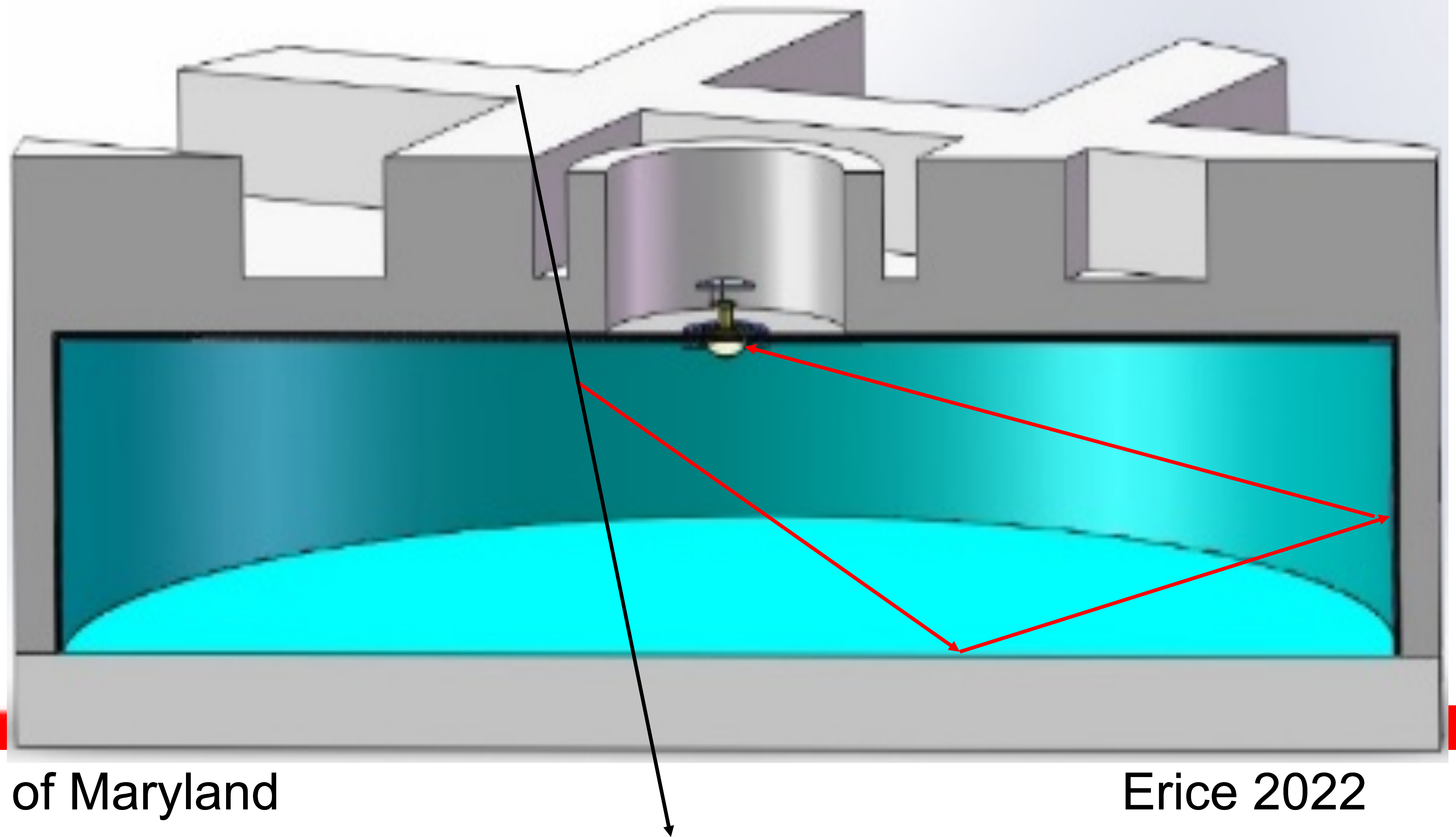
Steel Case
Lead (0.5 cm)
SC Tiles (2 cm)
Steel Case
1 m
1 m



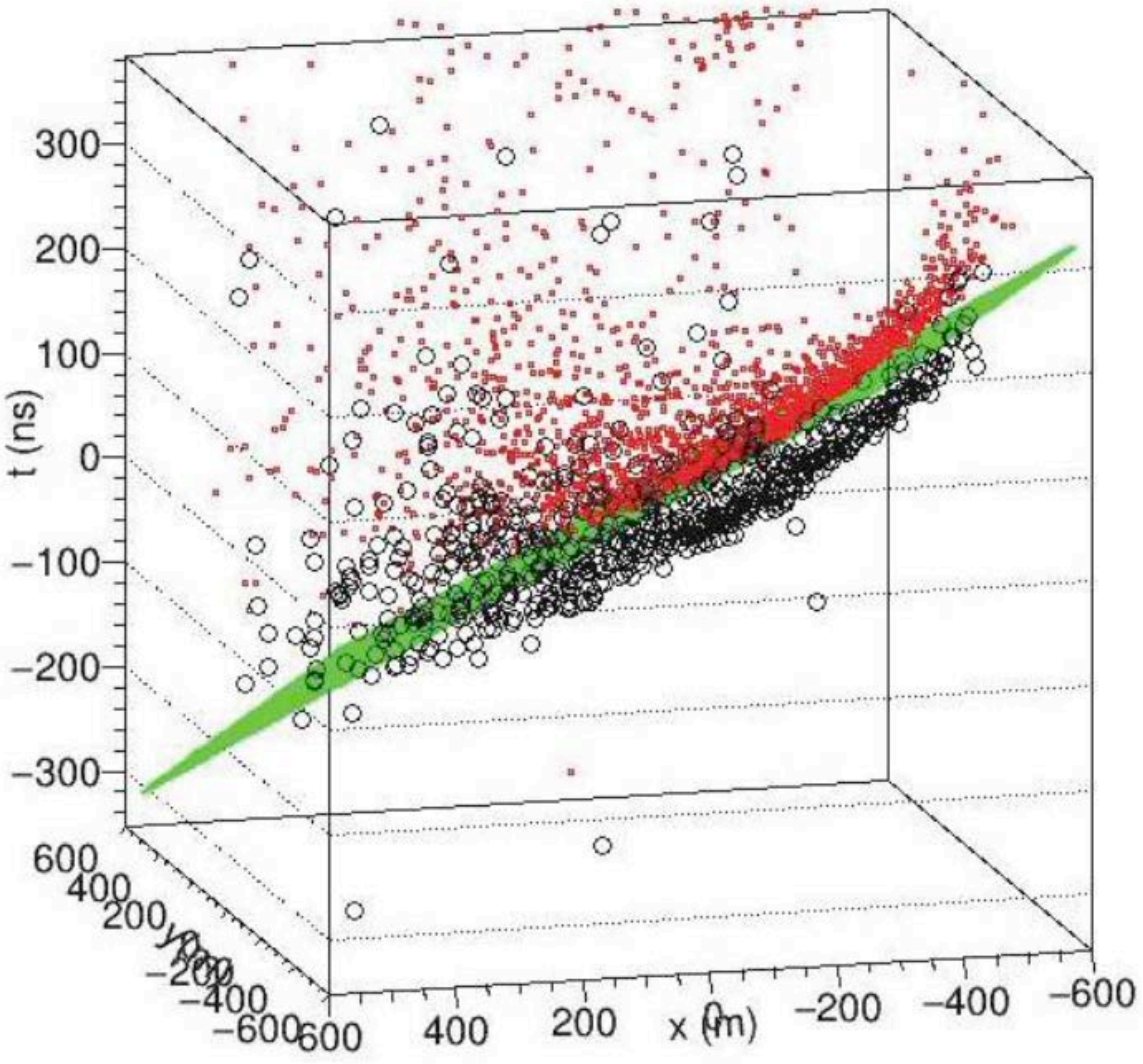
MD



ø13.9m
ø9m
2.5m
1.2m
ø6.8m
soil
iron plate
PMT
ultra-pure water
concrete tank

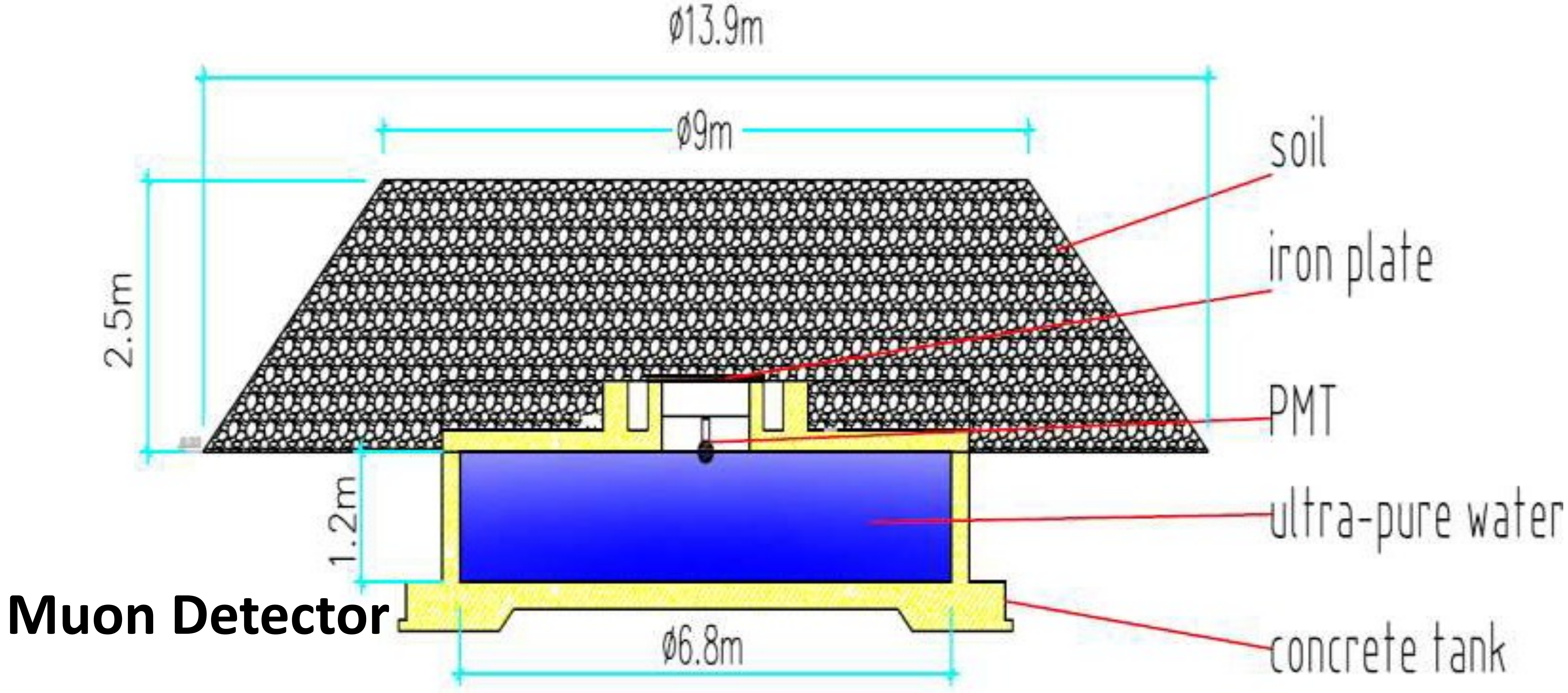


KM2A



Secondary particles of an EAS detected by the ED array. The green plane is EAS front plane. The red squares are the fired ED. The black circles are the fired MD. The second front is caused by MD's dead time.

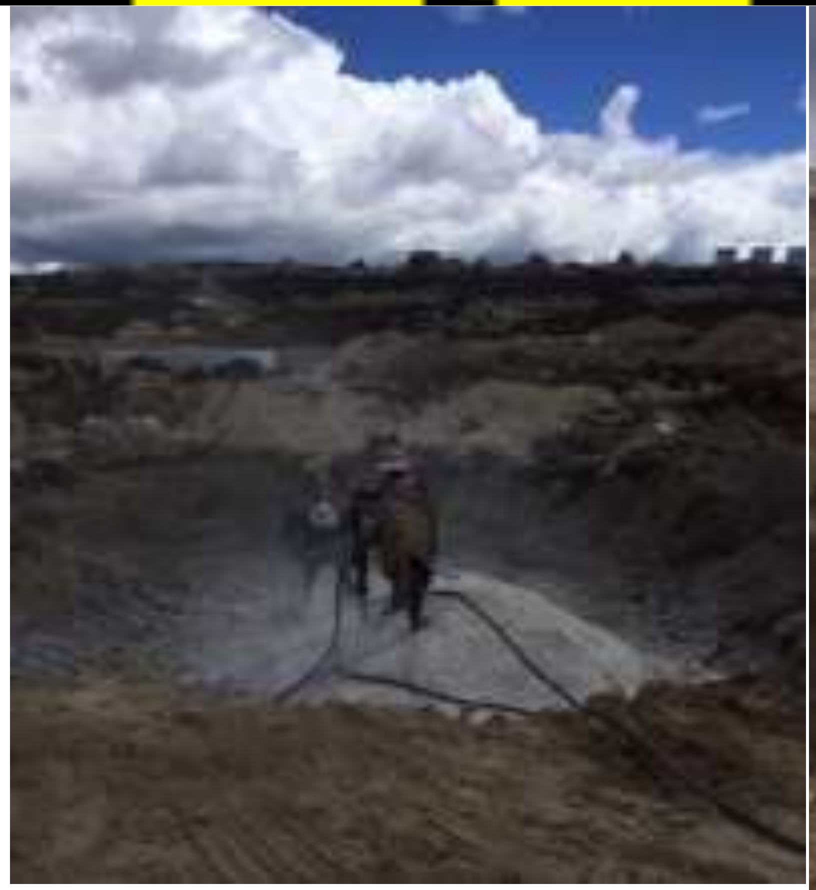
KM2A Muon Detector array



1/2 MD array, 592 MDs (total 1188) started operation from 12/2019

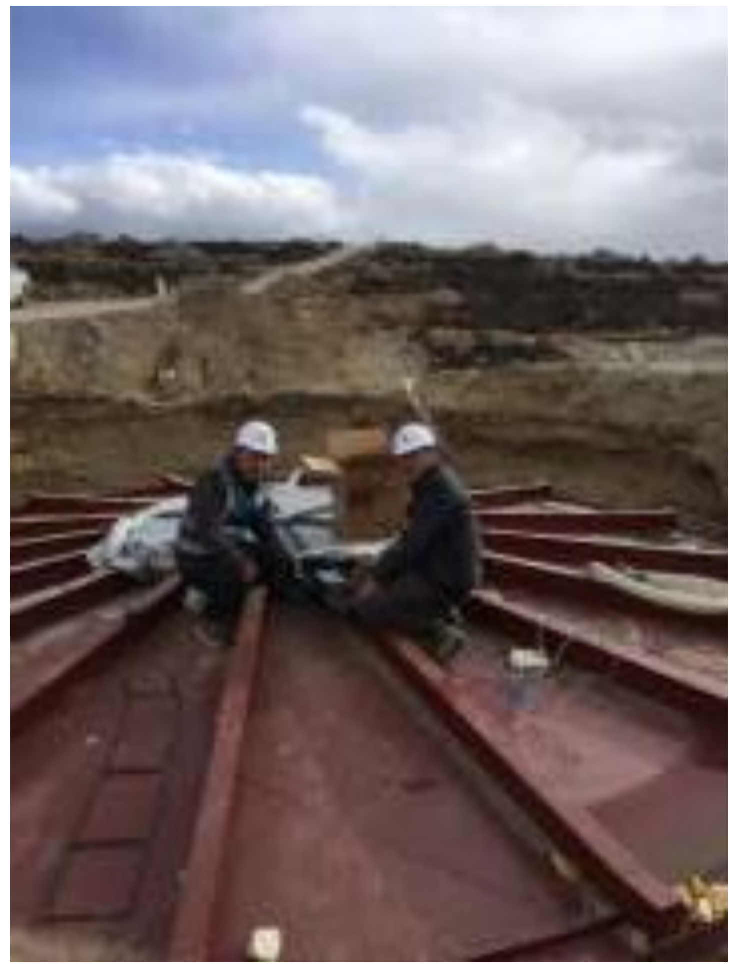
3/4 MD array, 914 MDs (total 1188) started operation from 12/2020

Installation of a Muon Detector

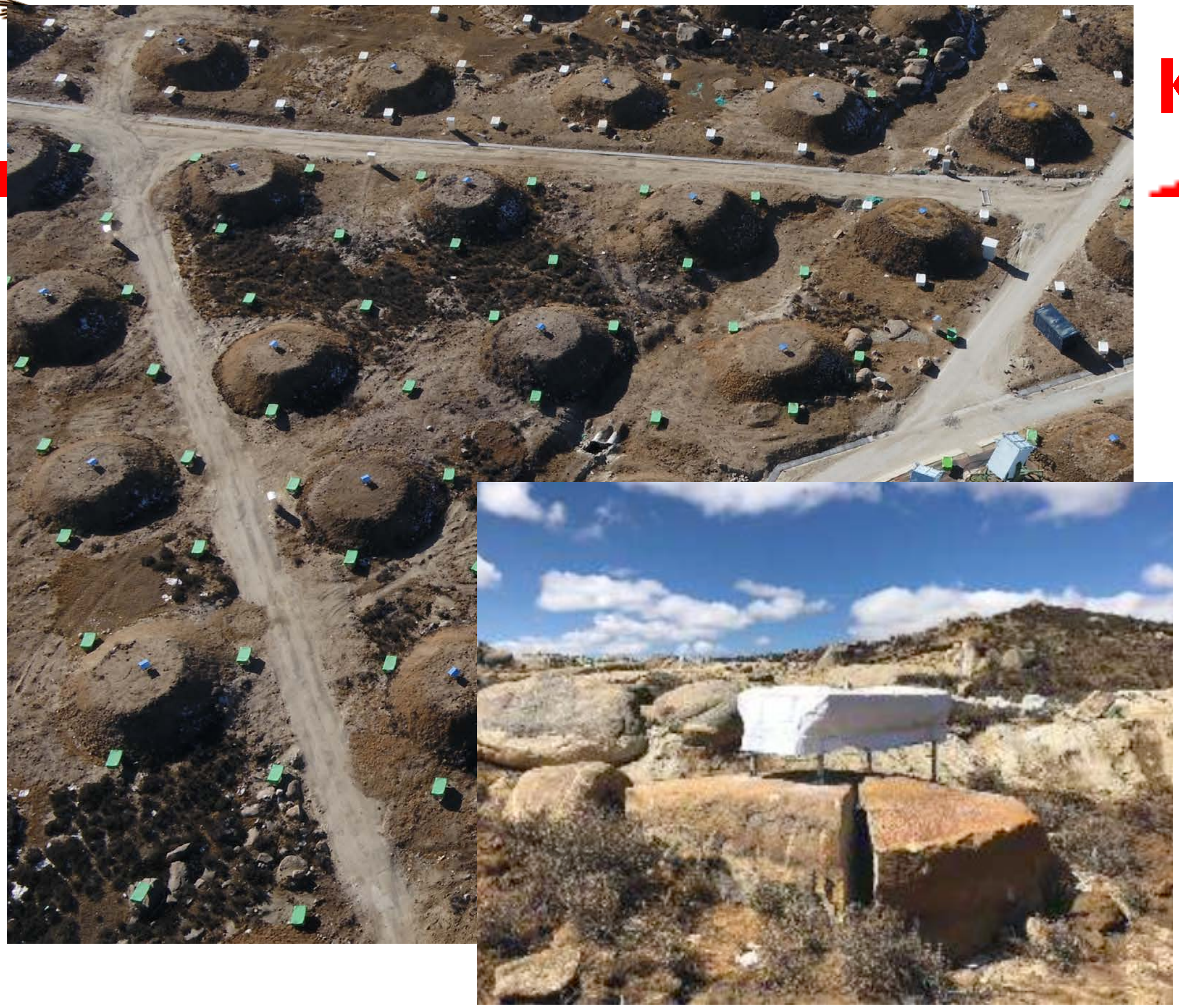



Foundation pit treatment → Fabrication of side wall and bottom plate → Head cover mounting → Install insulation →





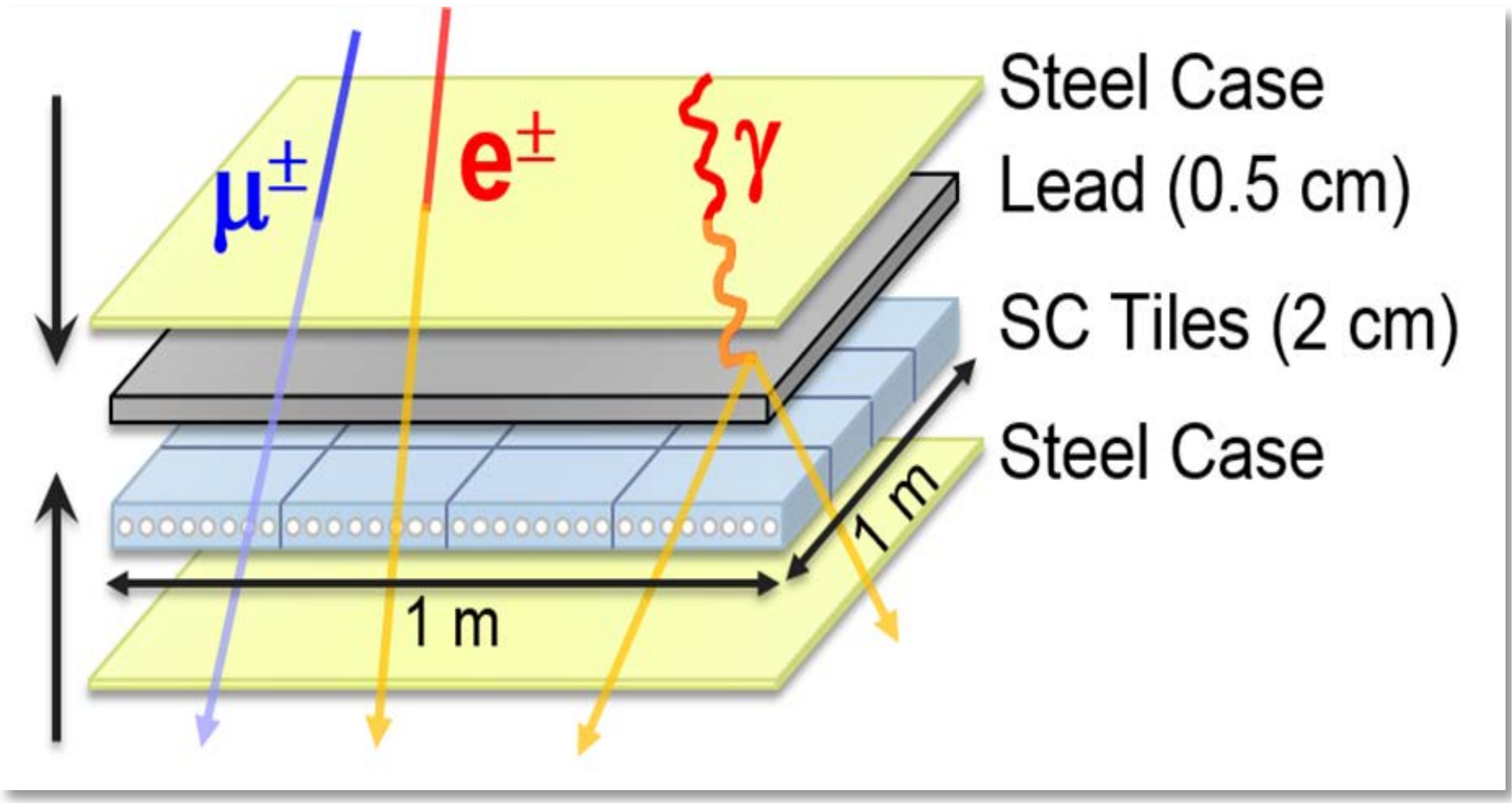

Install liner and PMT → ultrapure water infusion → debug → Covering soil → intergrated test



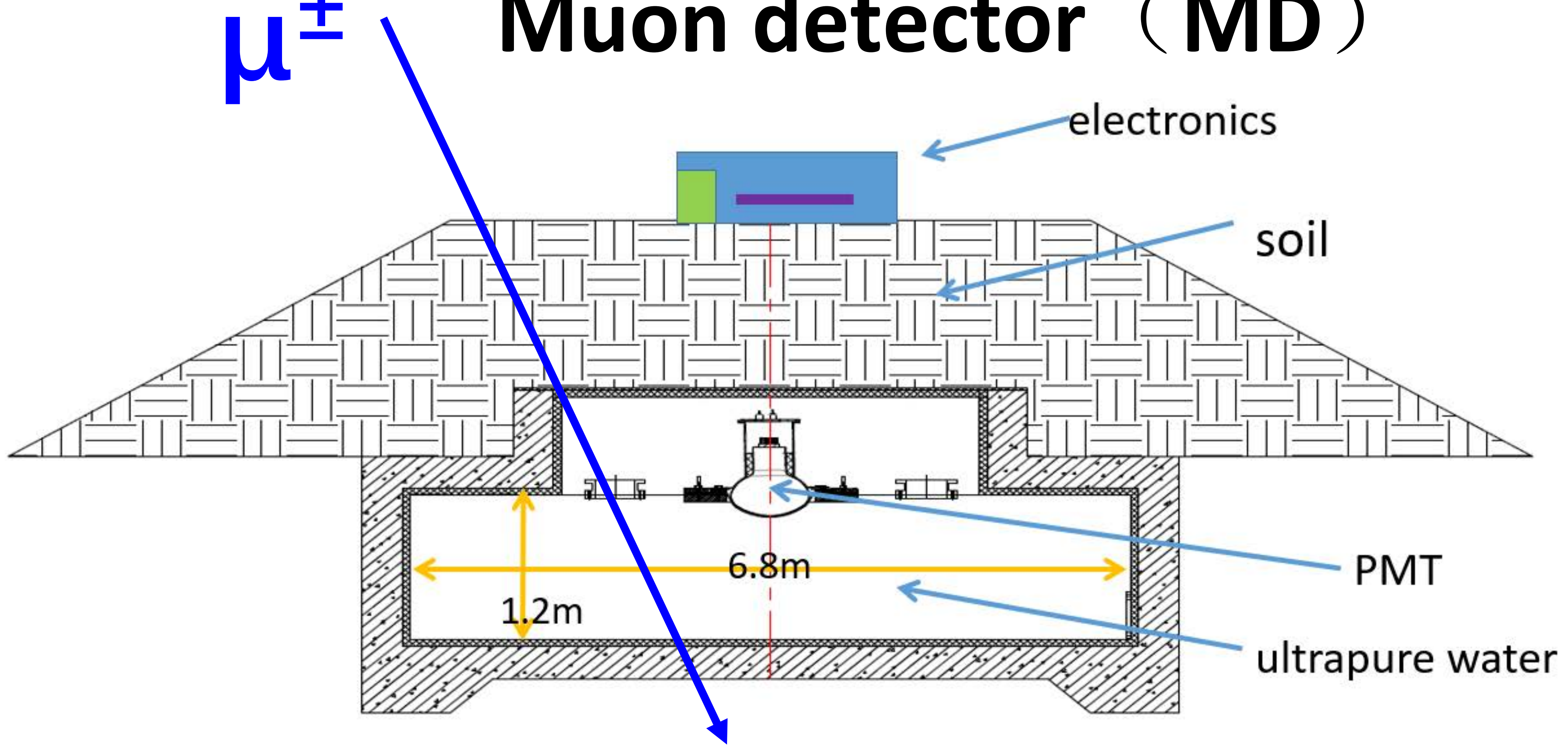
KM2A: 1.36 $(km)^2$

- ➢ 5195 EDs
  - $1\ m^2$ each
  - 15 m spacing
- ➢ 1188 MDs
  - $36\ m^2$ each
  - 30 m spacing

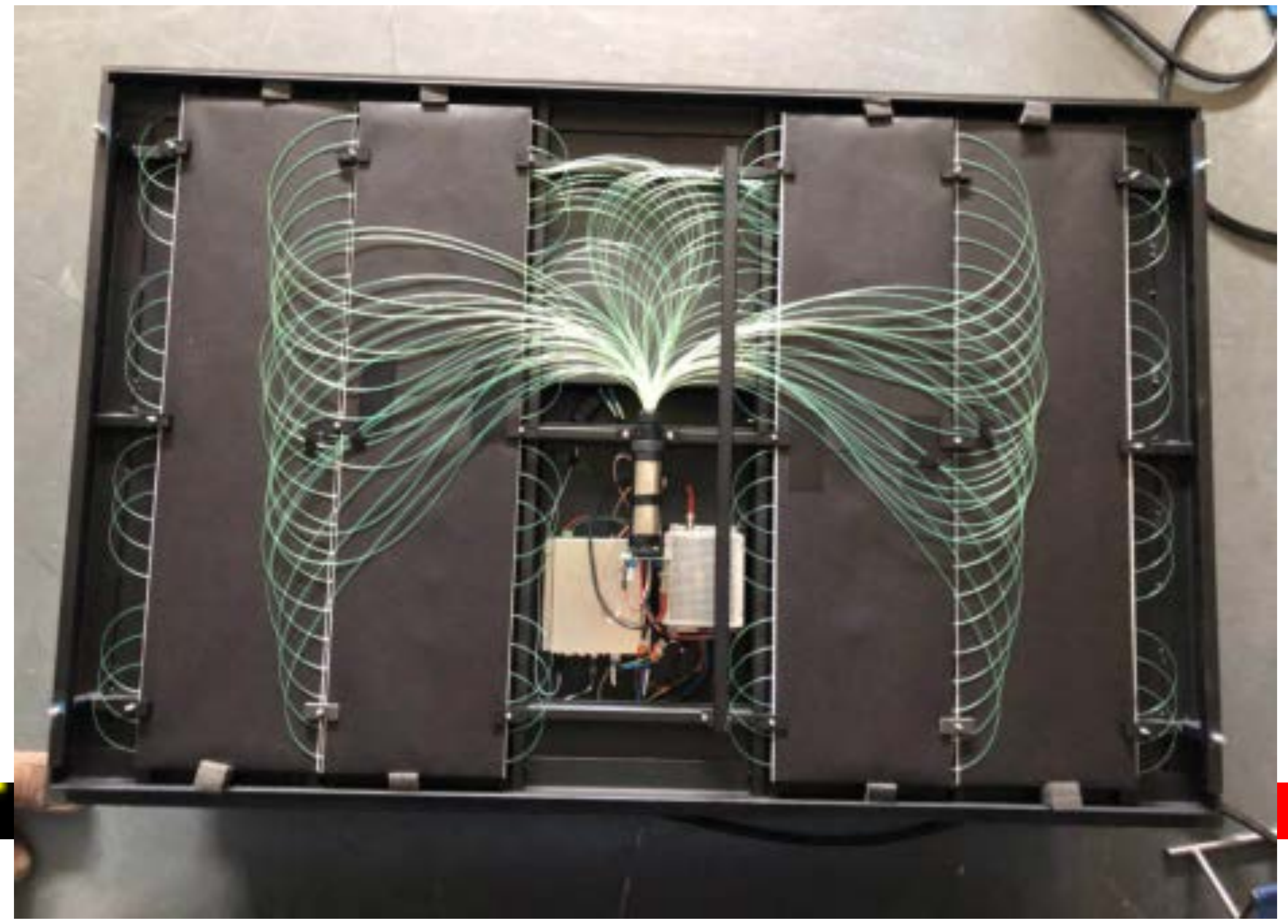
Scintillator Detectors （ED）



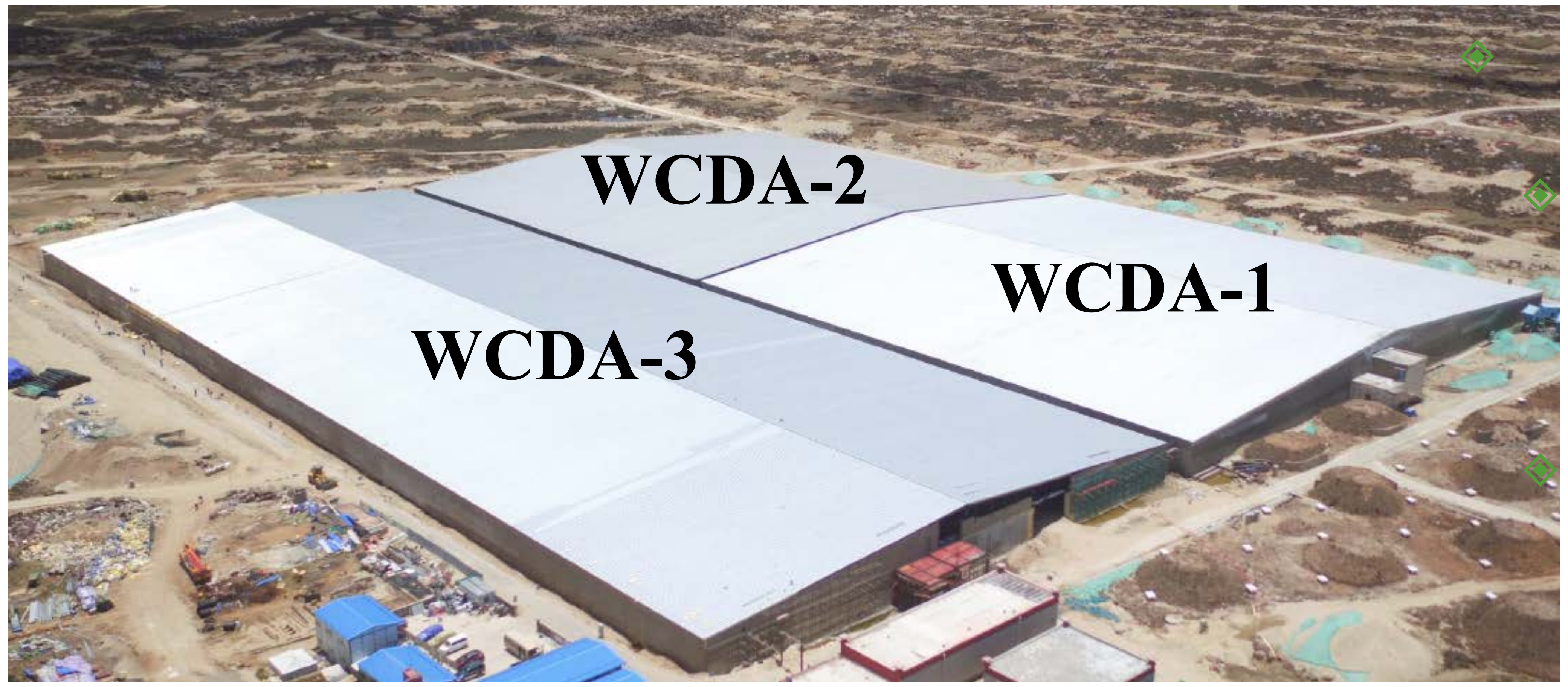
Muon detector（MD）



Inner View of one ED



Water Cherenkov Detector Array (WCDA)



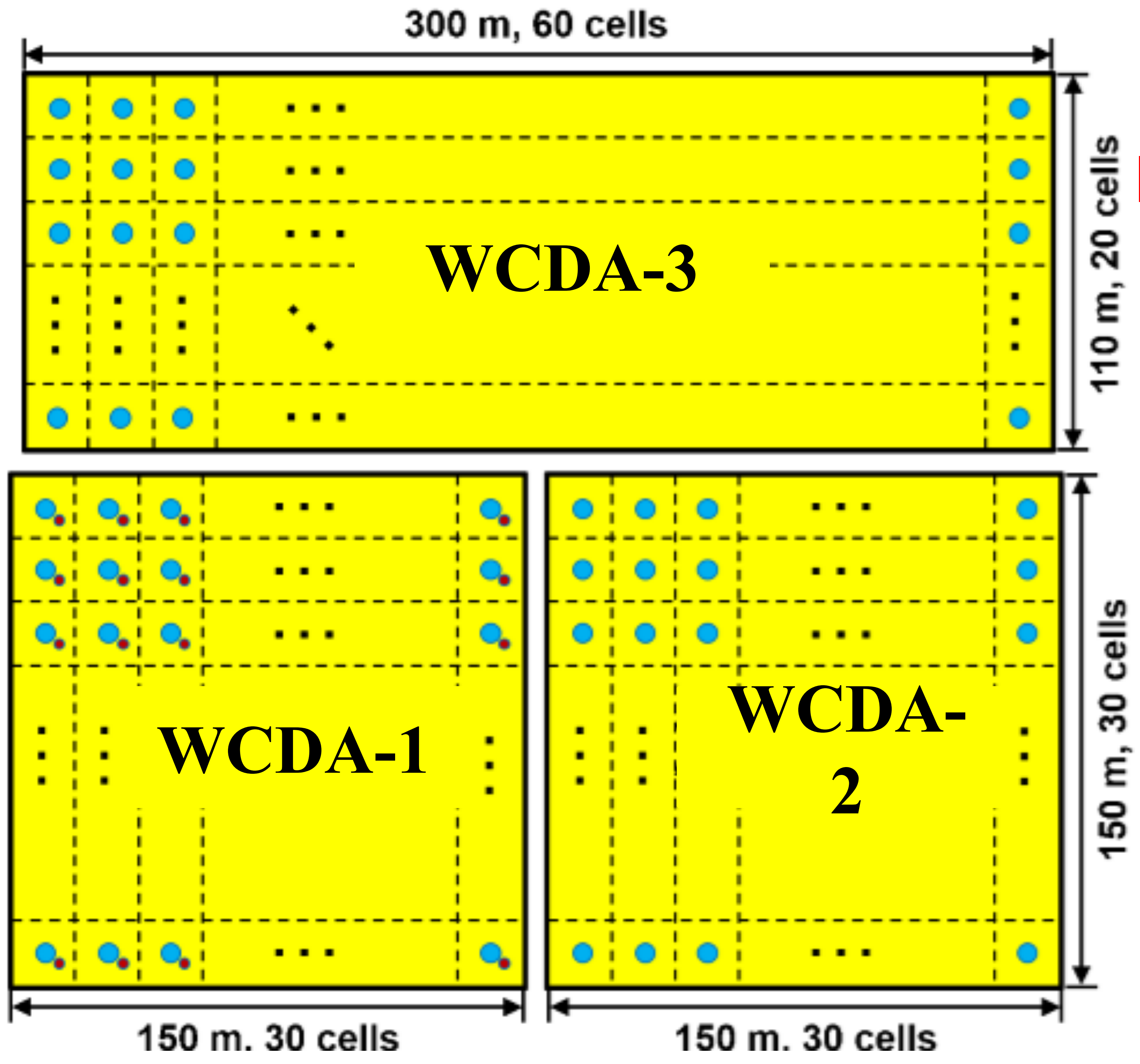
Energy rang

WCDA-1

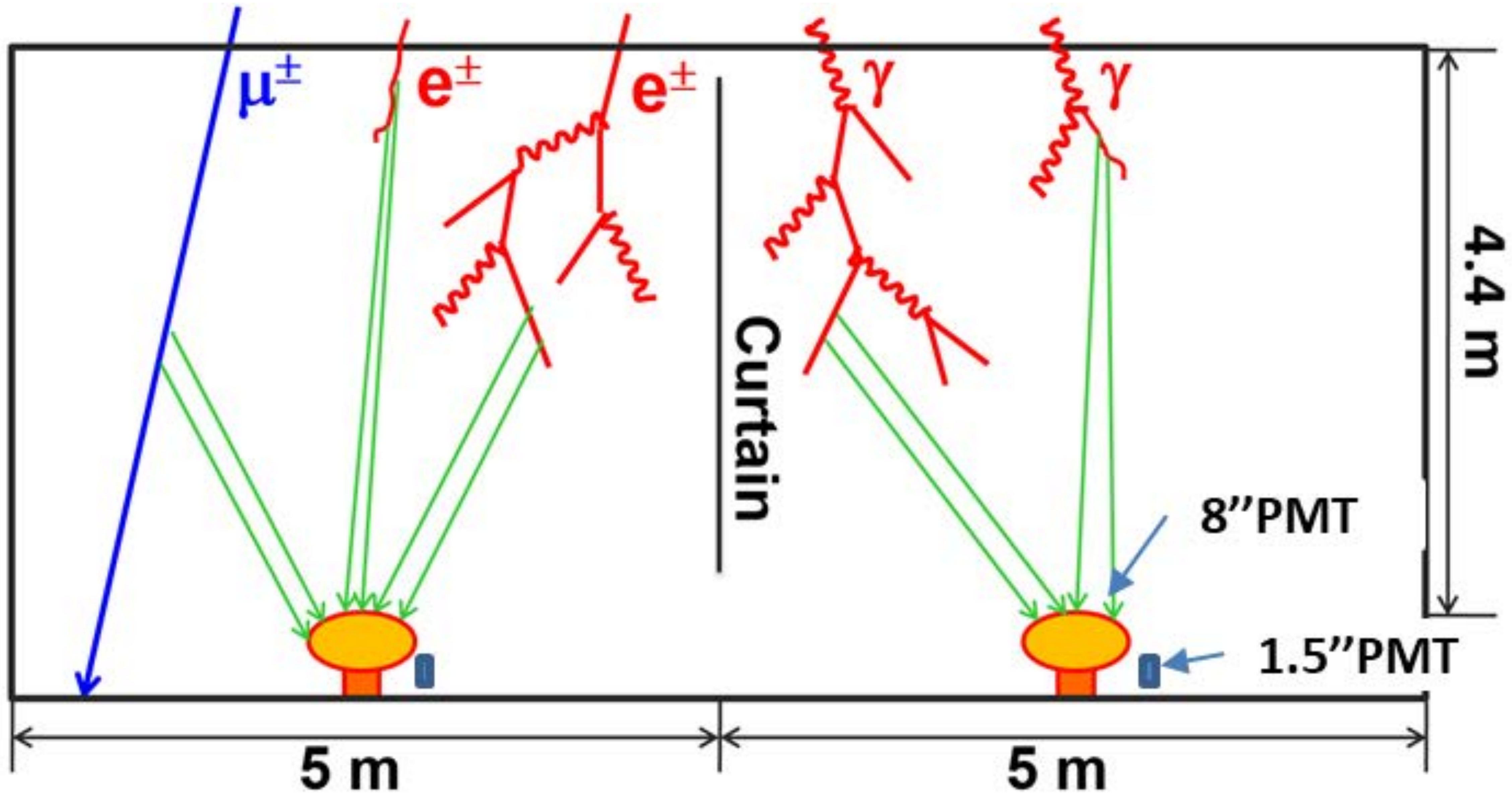
- 300 GeV – 10 PeV

WCDA-2 and WCDA-3

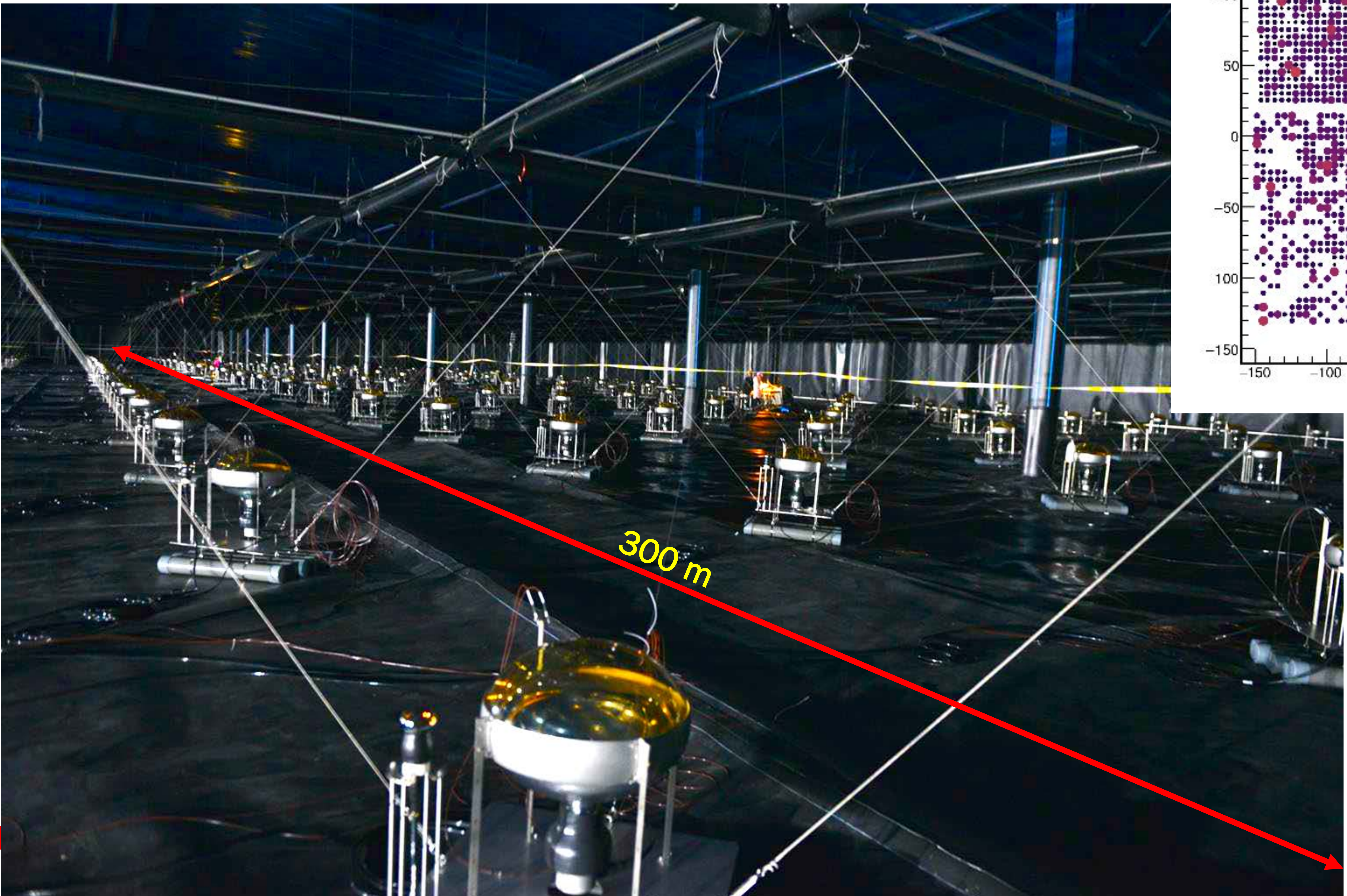
- 100 GeV - 10 TeV

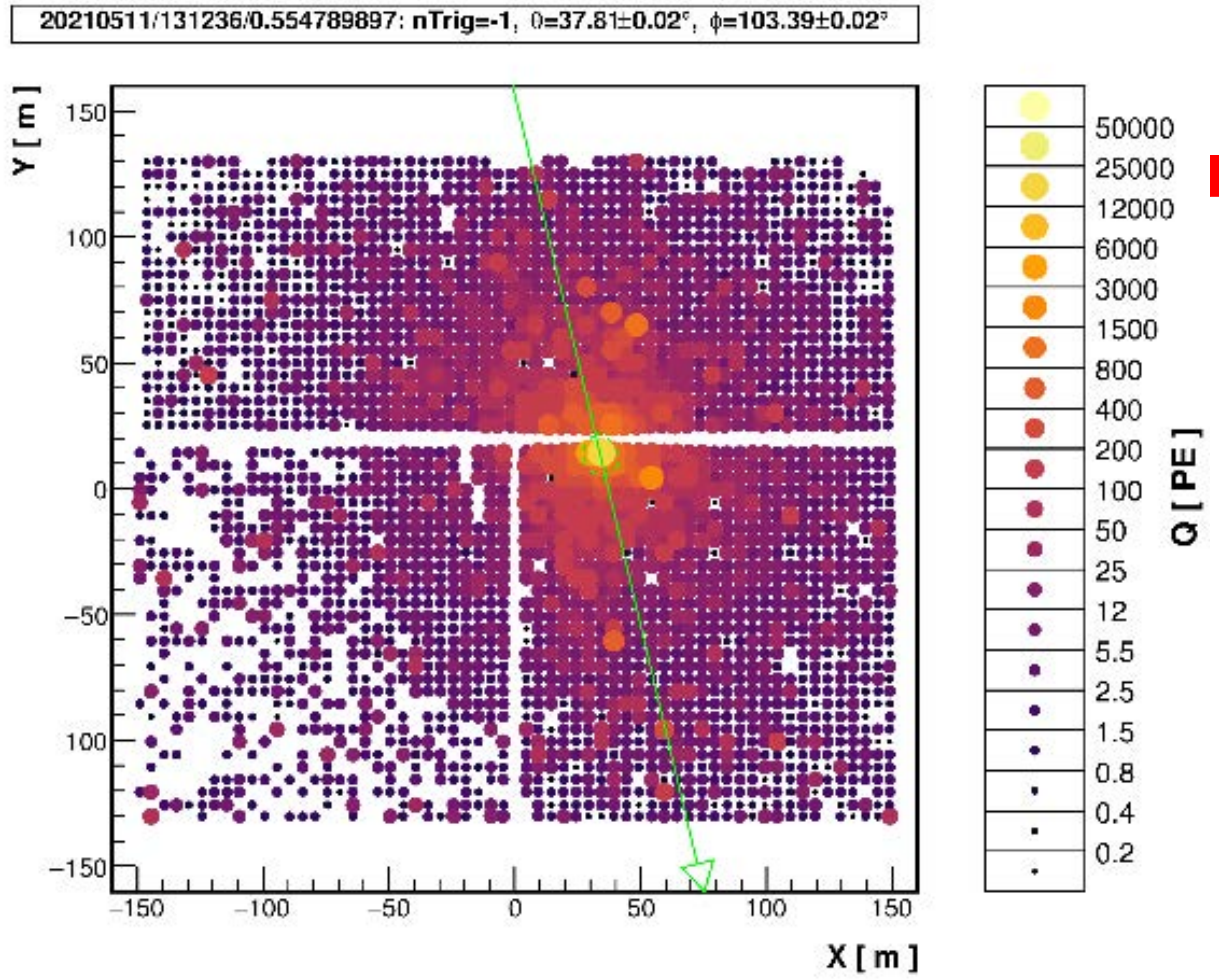


- ➢ Total area: $78,000m^2$ (HAWC 22,000m^2)
- ➢ Total units: 3,120
- ➢ Unit size: $5m\times5m\times4.4m$
- ➢ Two type of PMTs in each pool:
  - 8 inches and 1.5 inches for WCDA-1
  - 20 inches and 3 inches for WCDA-2 and WCDA-3



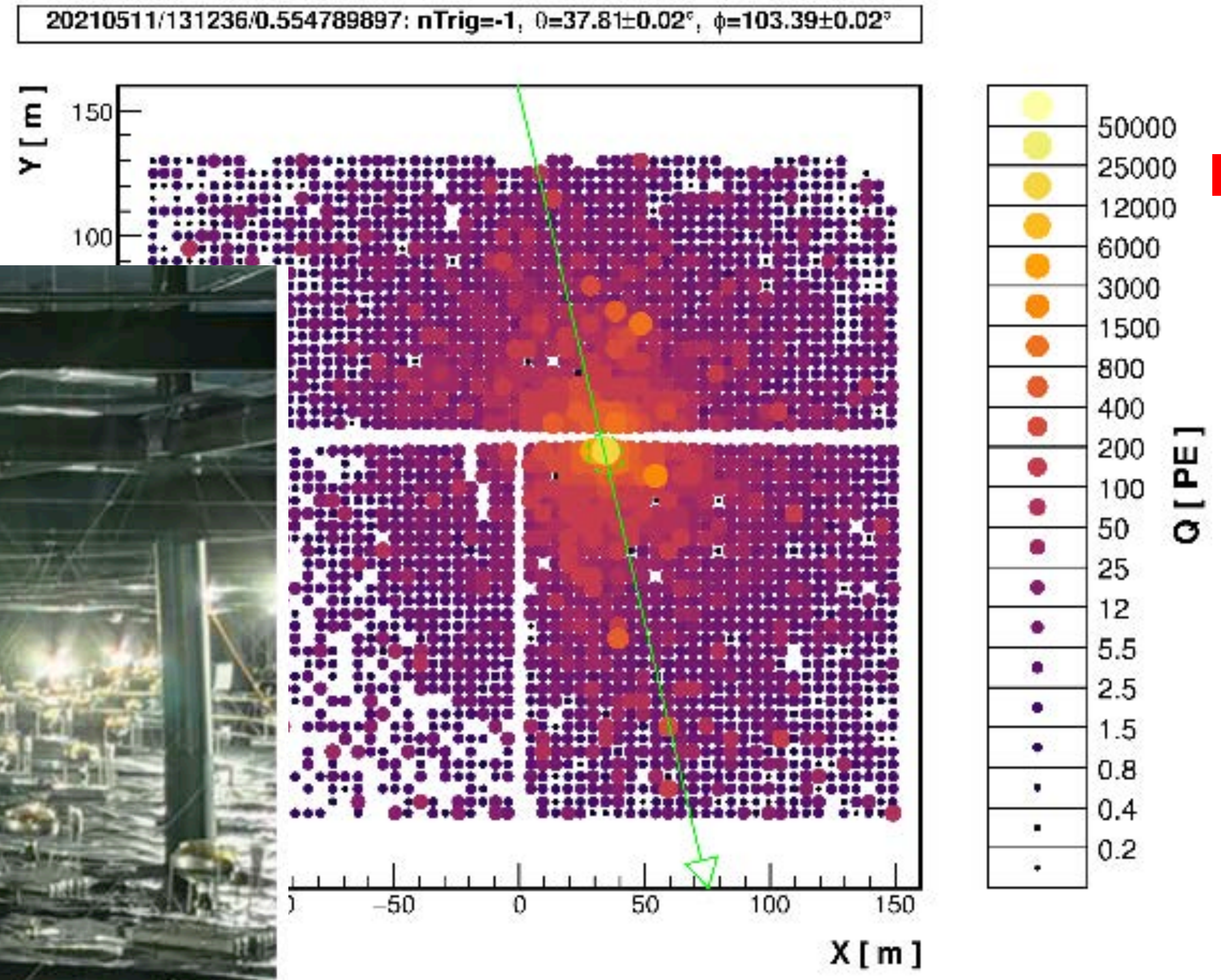
Inside of WCDA-3





- WCDA-1 started operating in April 2019
- WCDA-2 started operating in January 2020
- WCDA-3 started operating in March 2021

Inside of WCDA-3



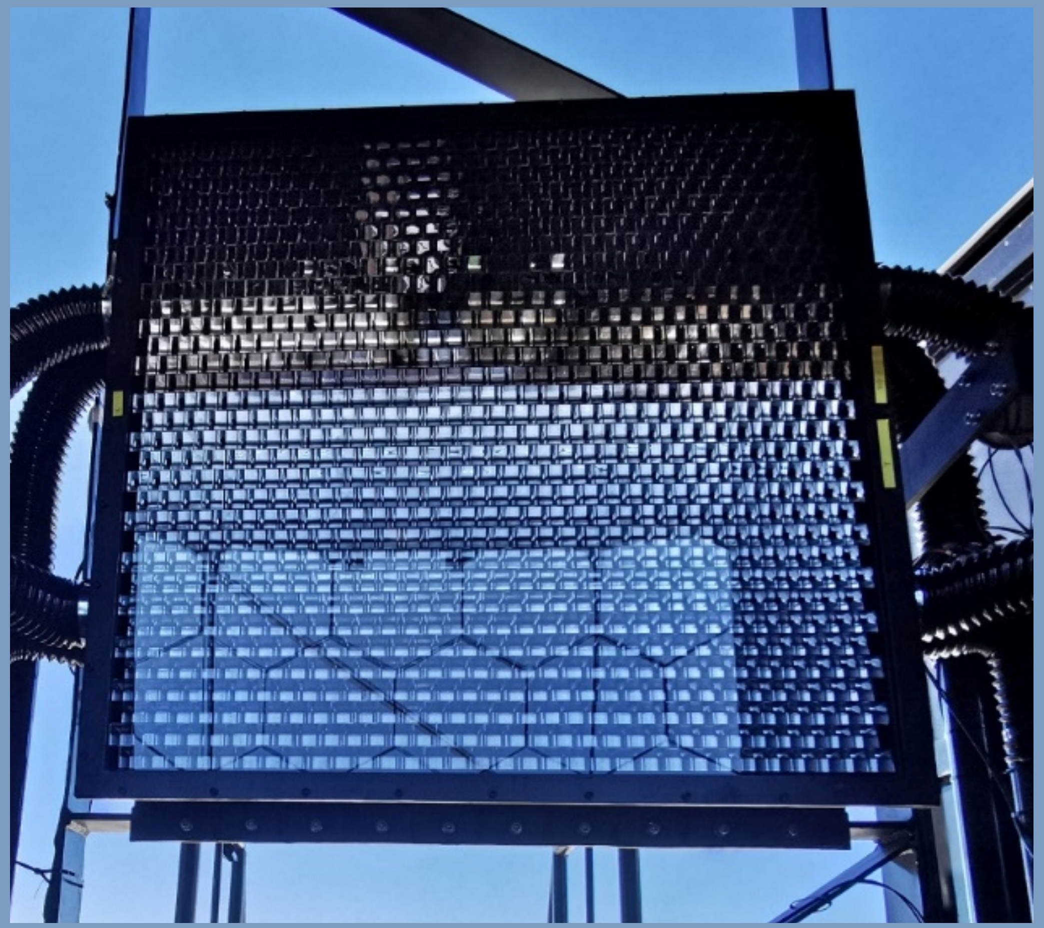
- WCDA-1 started operating in April 2019
- WCDA-2 started operating in January 2020
- WCDA-3 started operating in March 2021

Wide Field of View Cherenkov Telescope (WFCTA)

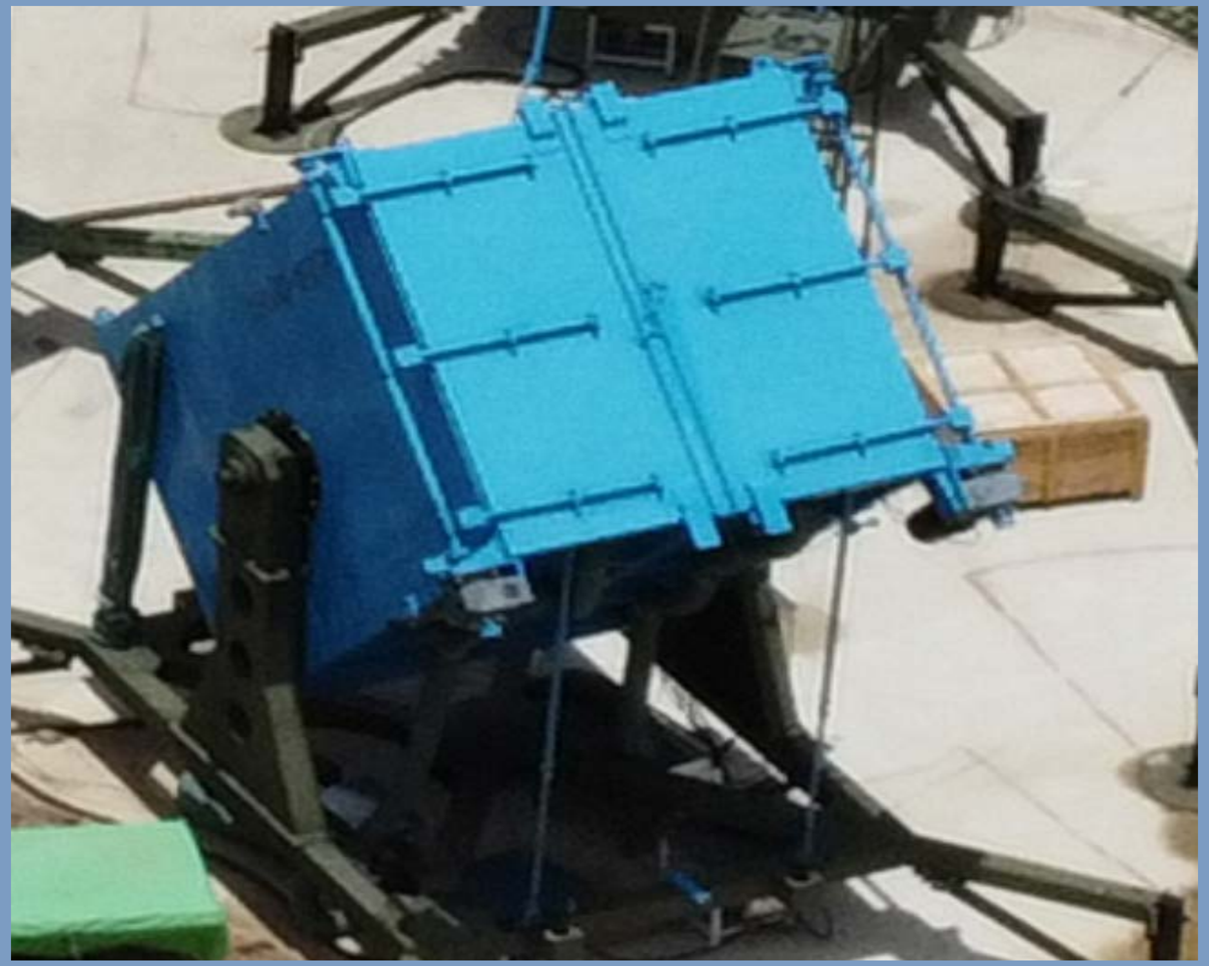
◆ Telescope parameters:

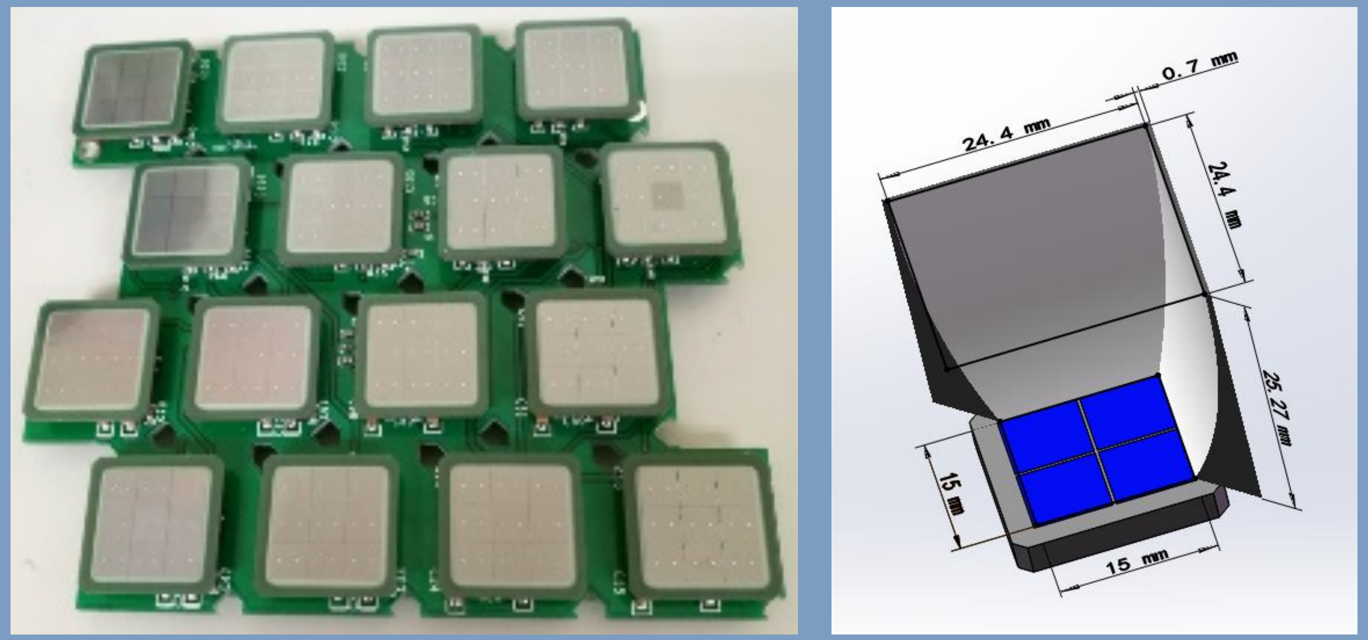
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: $16^\circ \times 16^\circ$
- Pixel size: 0.5°

Mirror



SiPM camera

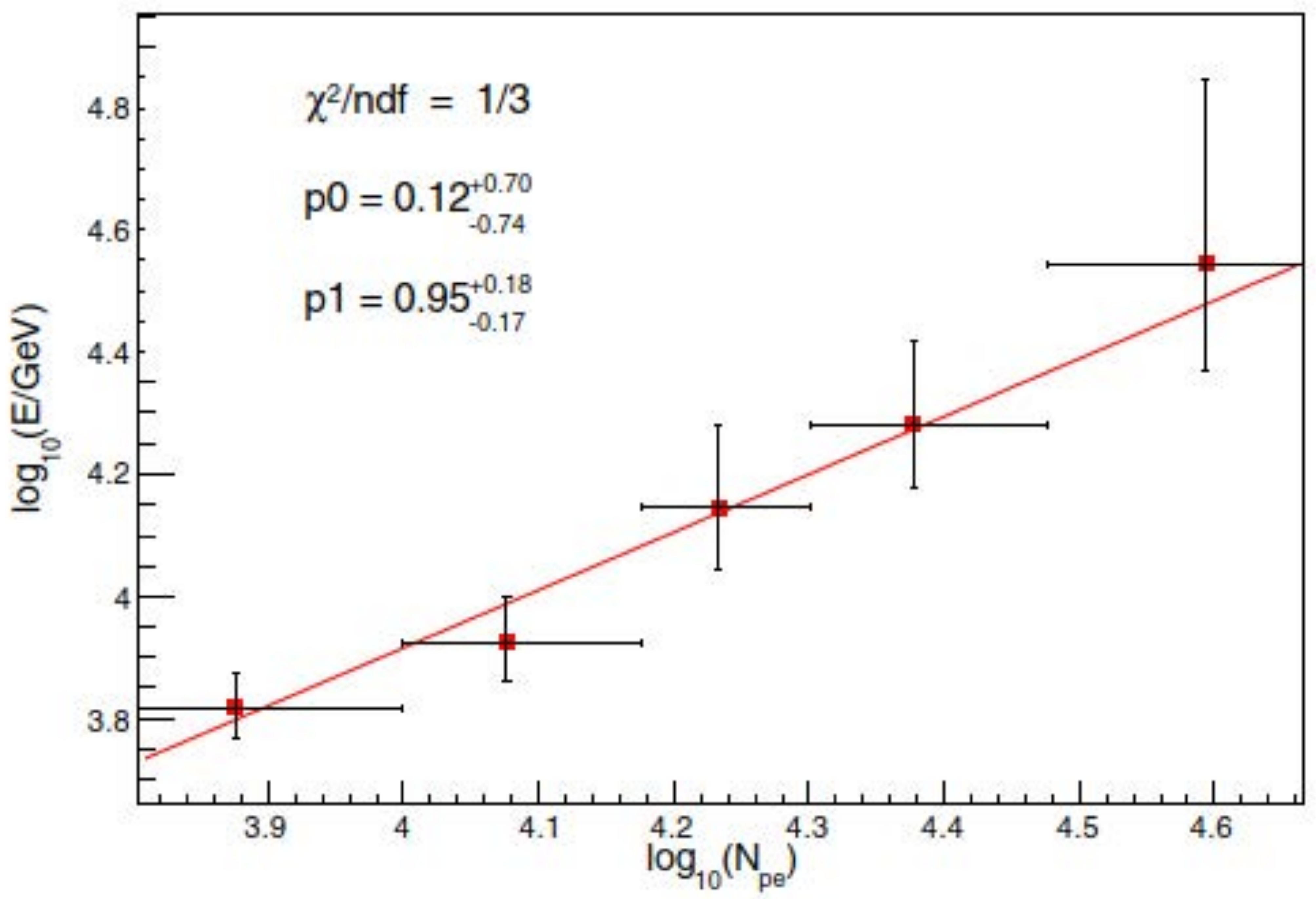




SiPM and Winstone cone

Absolute energy scale with WCDA-1

- In the energy range from 1 TeV to 50 TeV, the cosmic rays are dominated by protons and helium nuclei.
- The ratio of protons and helium nuclei can be obtained from CREAM and DAMPE.
- The trigger efficiency of WCDA-1 for protons and helium is obtained from simulation.



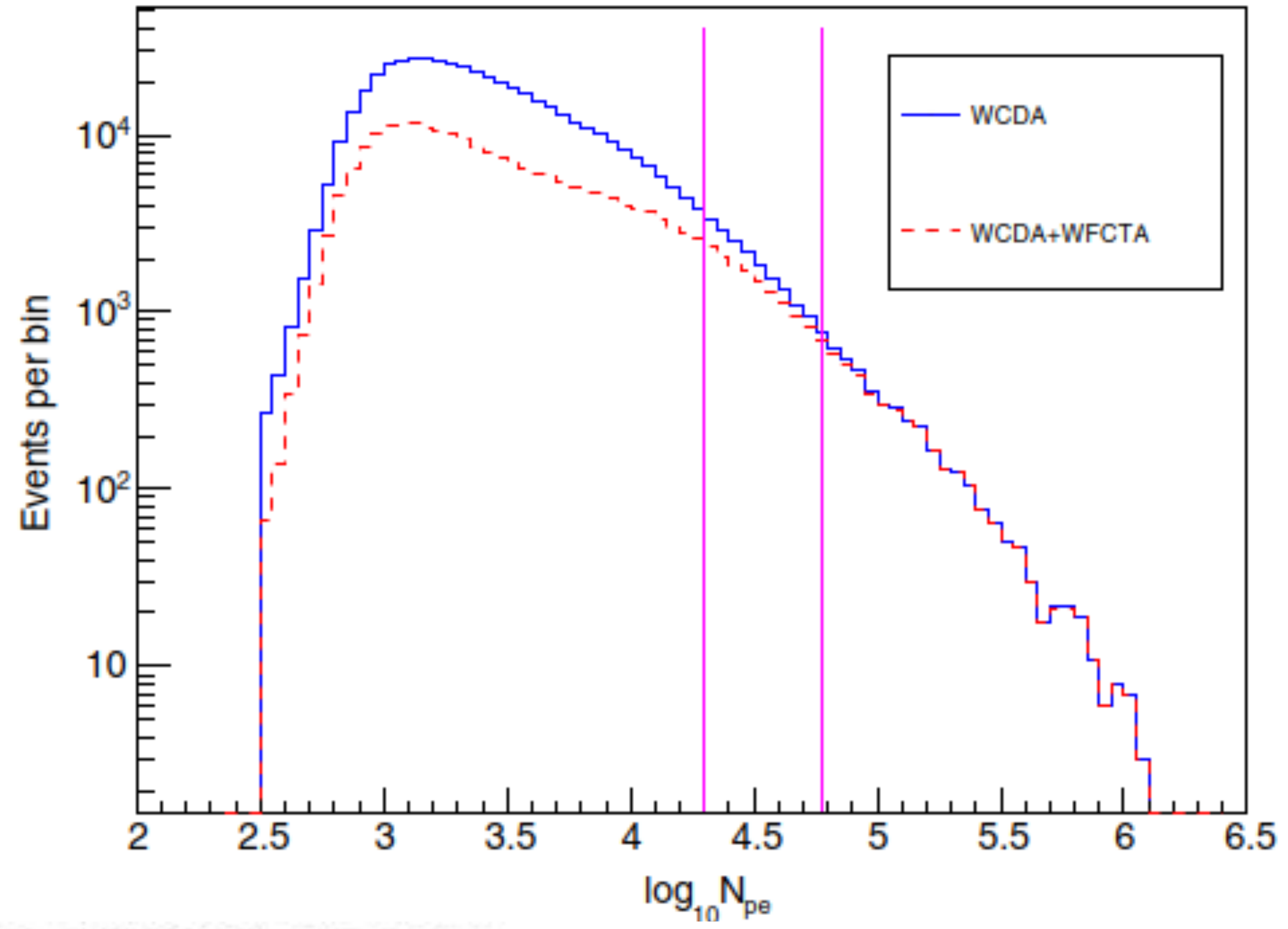
- System uncertainties:
  - Uncertainty caused by 10% changing of the ratio of protons and helium nuclei is about 3%.
  - Uncertainty from different hadronic models (EPOS-LHC vs. QGSJET-II04) is less than 2%.
  - An uncertainty of 4% is caused by the energy and angular resolution.

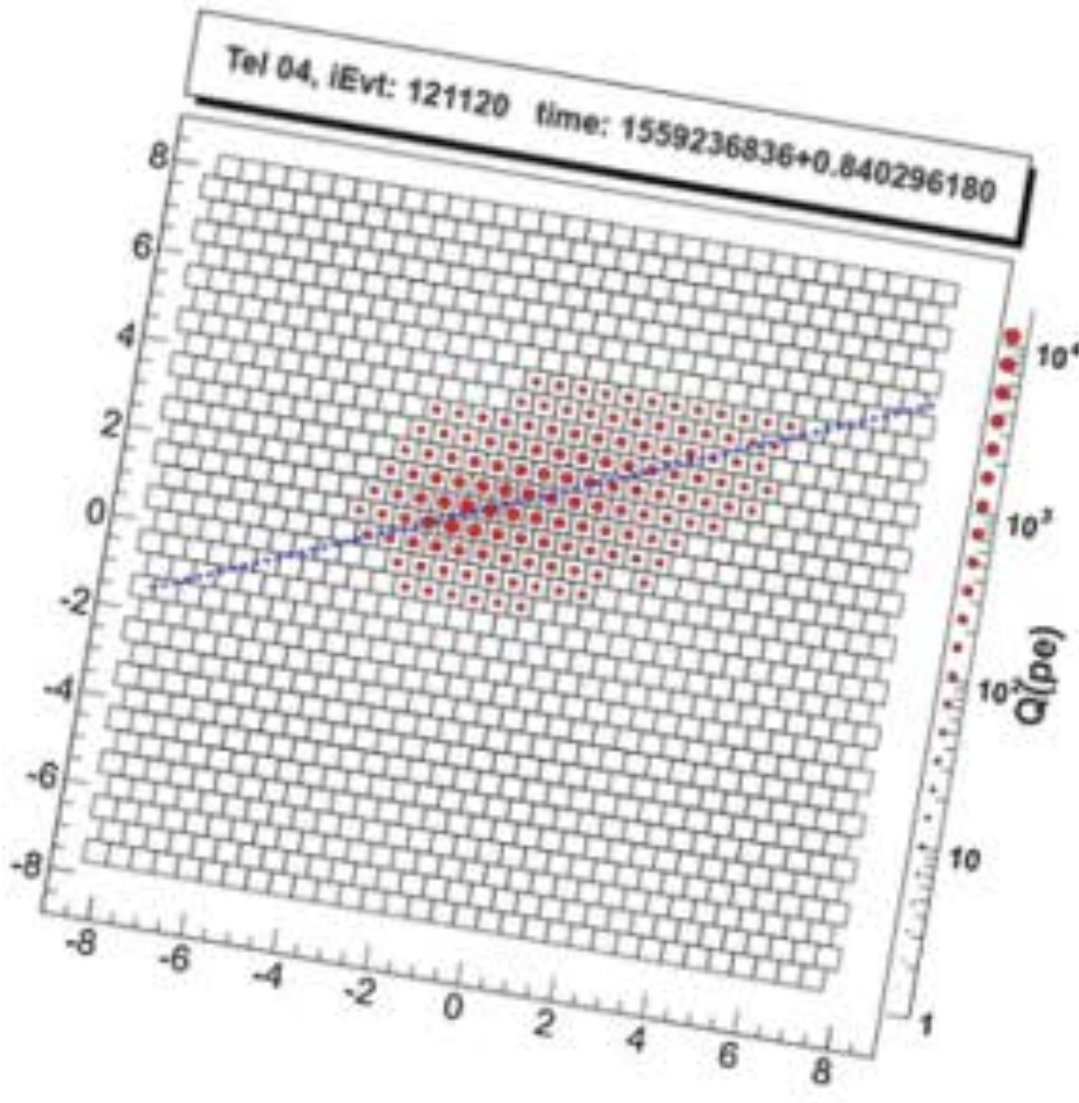
$$E(GeV) = aN_{pe}^{b}$$
$$a = 1.33^{+5.26}_{-1.06}$$
$$b = 0.95 \pm 0.17$$

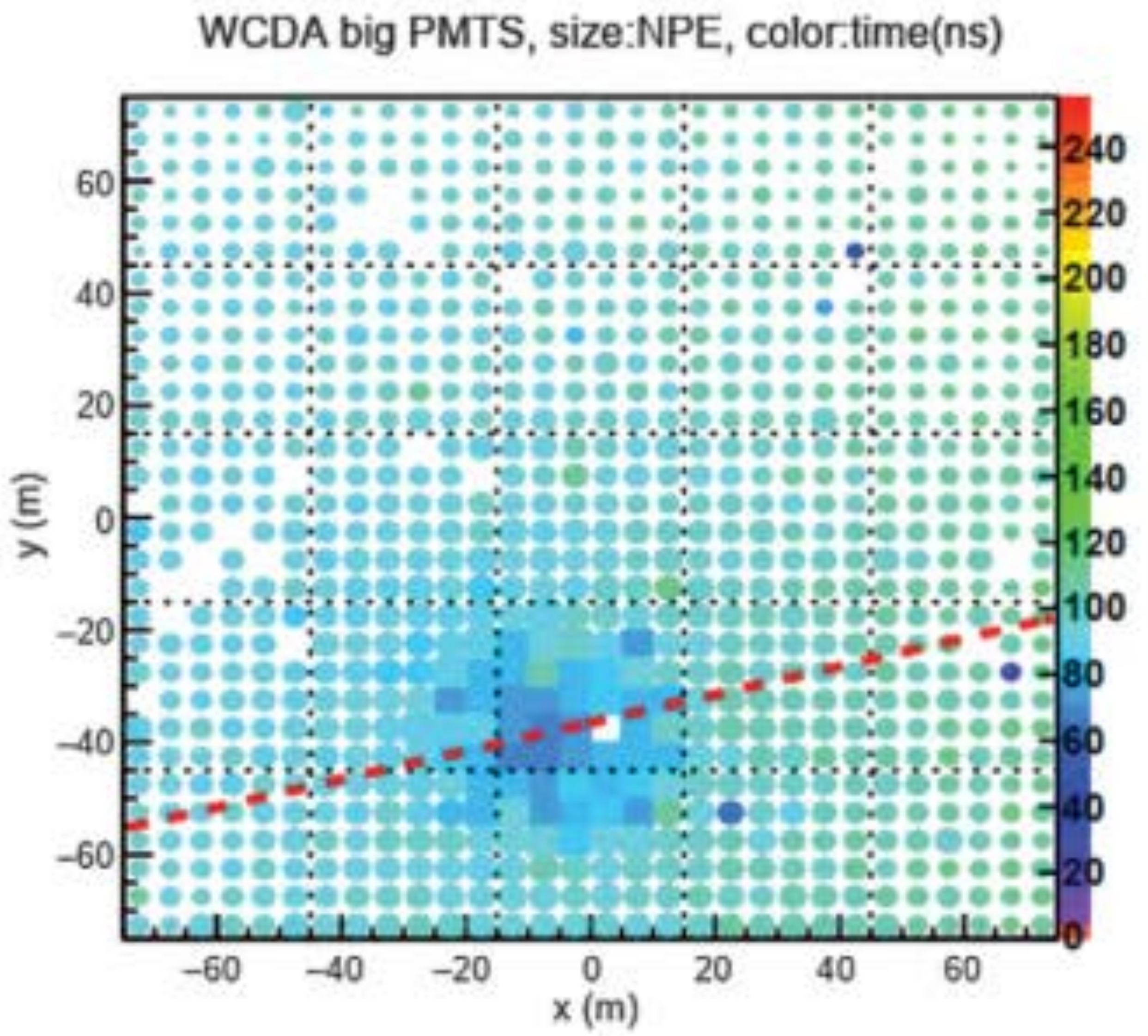
Absolute energy scale propagates from WCDA to WFCTA

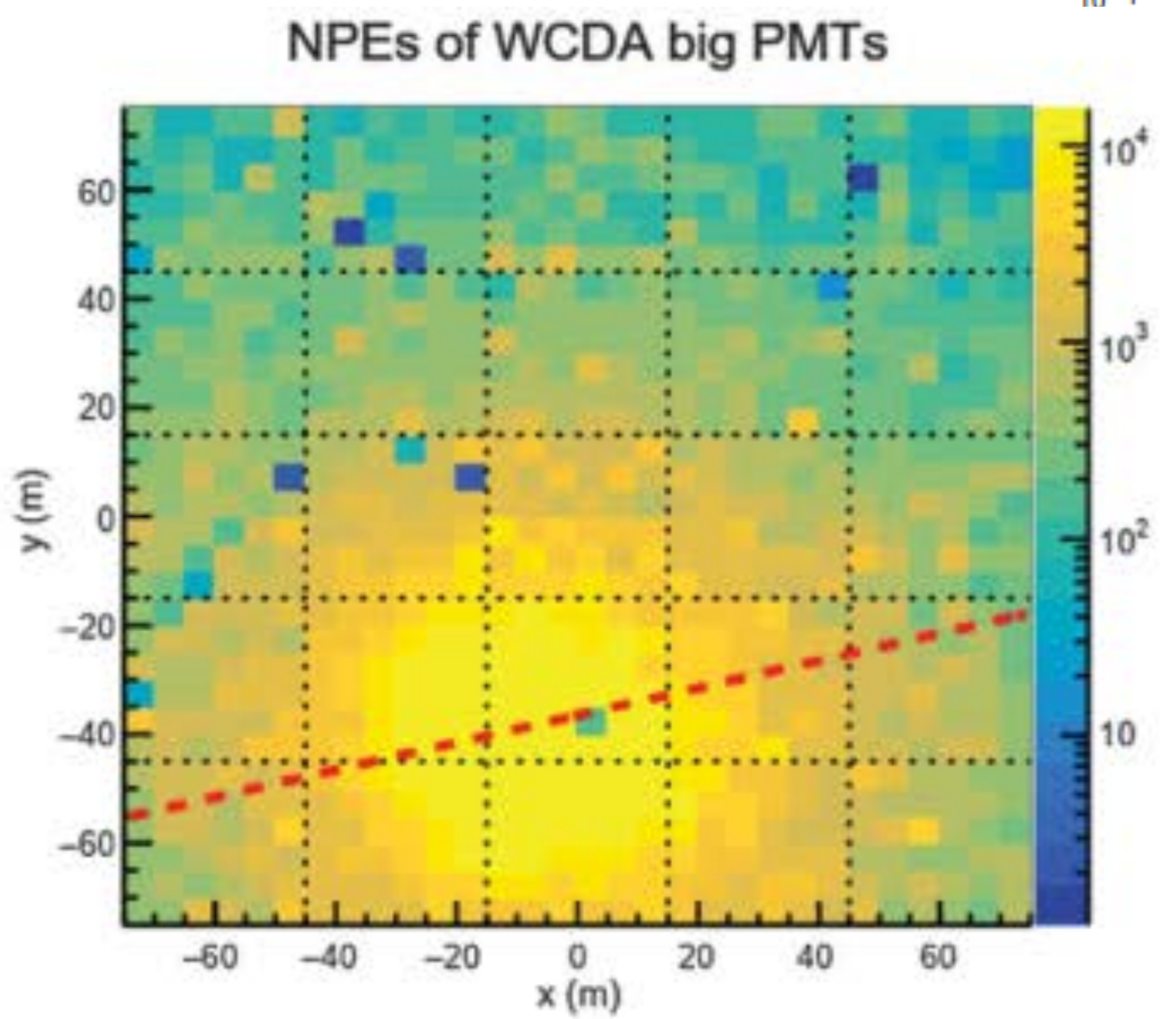
- It is impossible for WFCTA to measure Moon shadow shifts directly.
- The absolute energy scale obtained by WCDA-1 can be propagated to WFCTA by using common-triggered events.
- Data Set of WCDA-1+WFCTA:
  - telescope FoV: 22°<Zenith angles <38°
  - $N_{hit}>200$
  - $20k<N_{pe}<60k$
  - shower cores inside WCDA-1:

  $|core_x|<55$ m, $|core_y|<55$ m







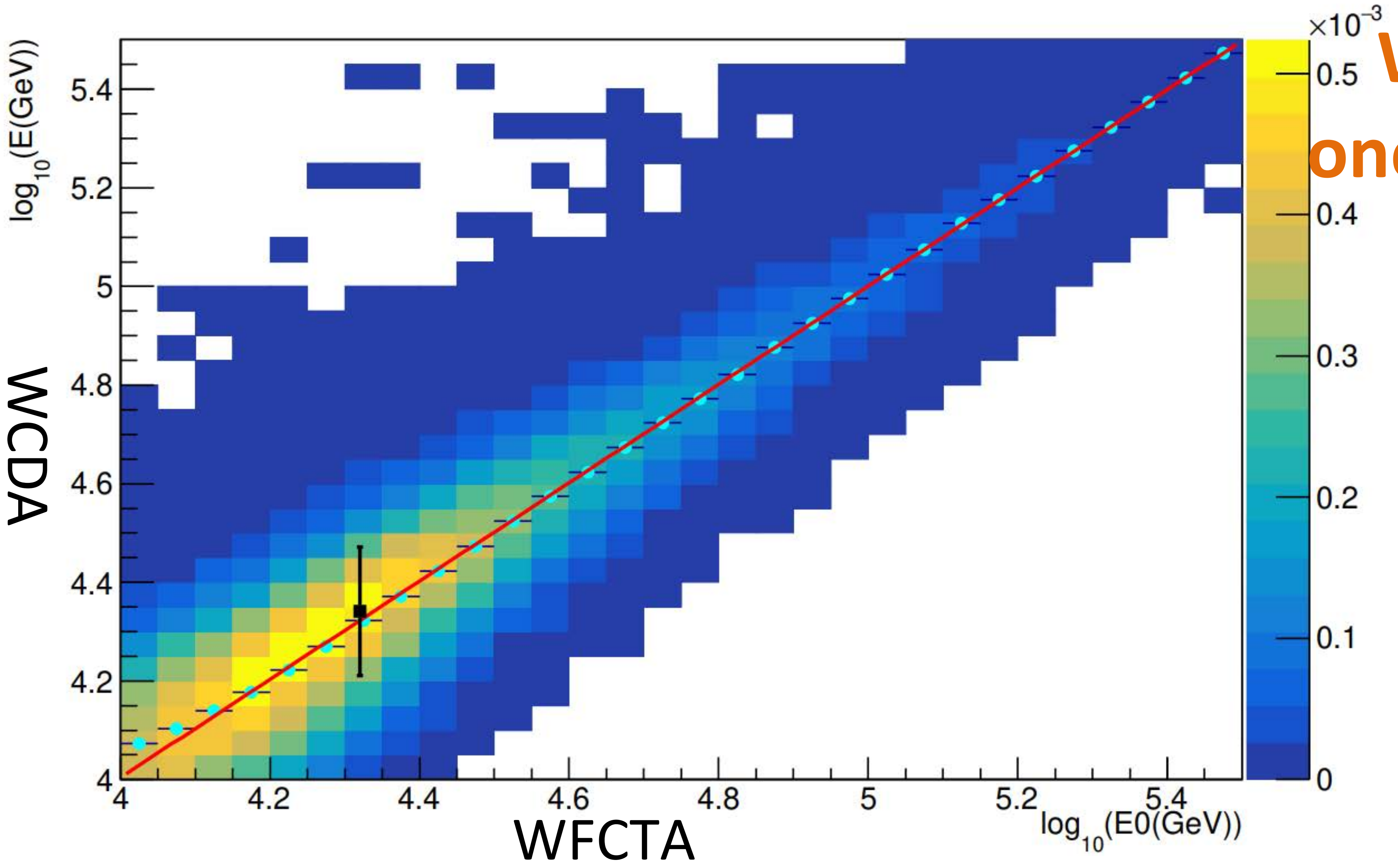


Absolute energy scale of WFCTA

➢And then the absolute energy scale obtained by WCDA is propagated to WFCTA by using the common trigger events.

- The energy reconstructed by WFCTA is 21.9 ±0.1 TeV;
- 23.4±0.1±1.3 TeV by the formula of the absolute energy scale.
- The two energies are consistent with each other within uncertainties.

➢ **It is the first time that Cherenkov telescopes have the absolute energy scale.**

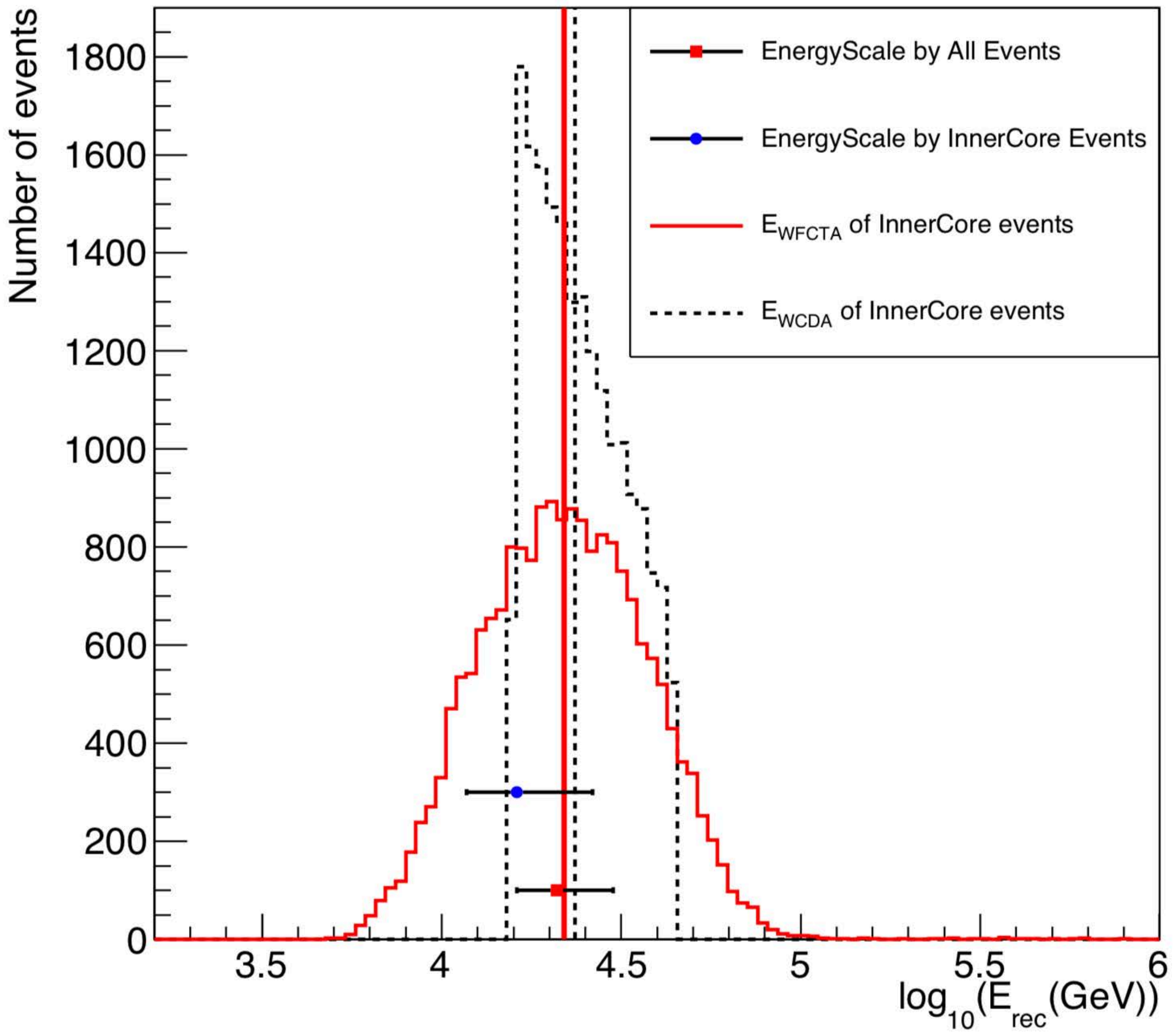


WCDA Calibration result (8 months, one pool)：

✓ 21.0 ±6.5 TeV for all events

✓ 16.2 ±6.2 TeV for shower core falling inside WCDA.

✓ The uncertainty largely dominated by the low statistics. After 4 years, the uncertainty will be < 10%.



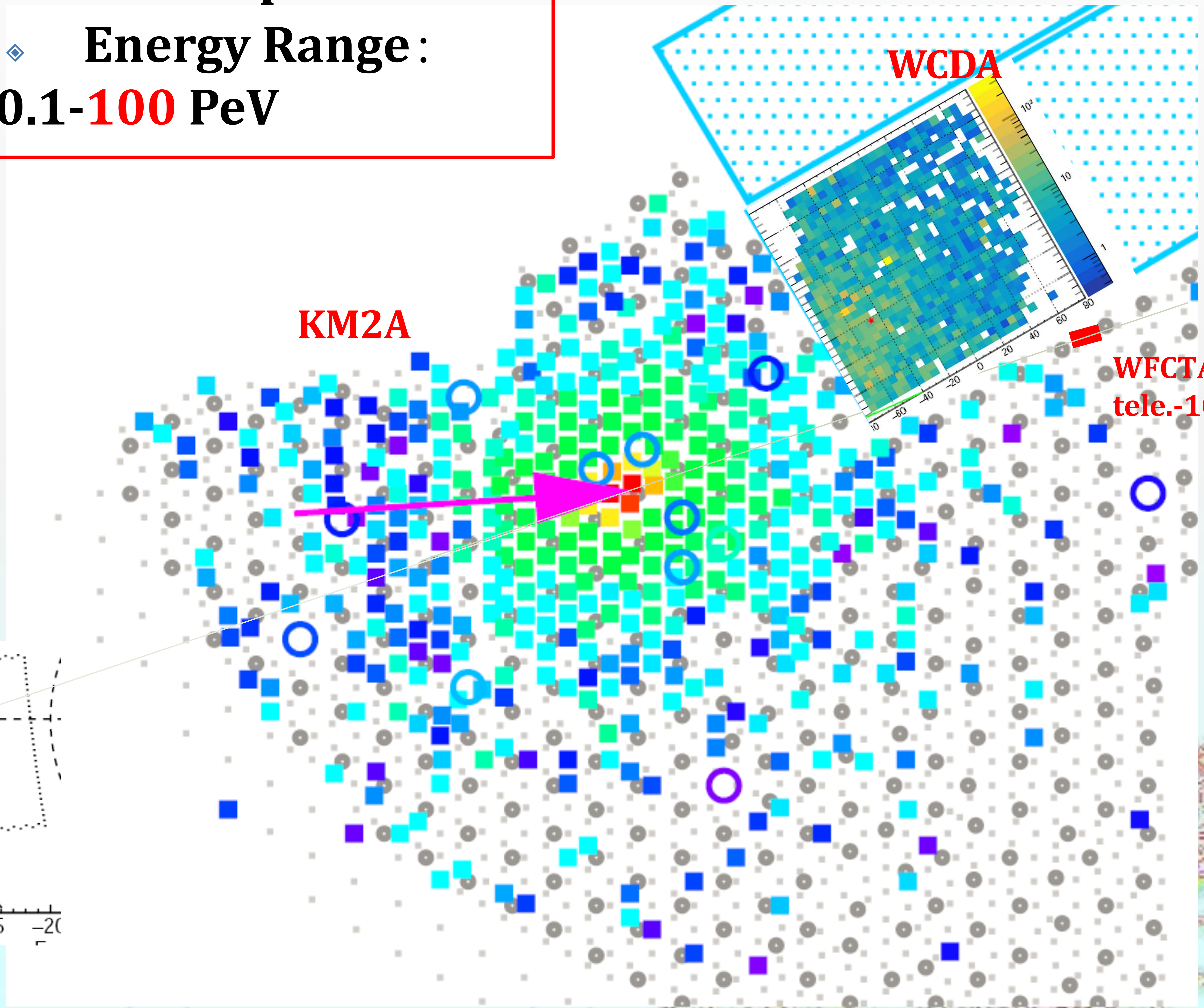
LHAASO Collaboration, PHYS. REV. D 104, 062007 (2021)

Wide FoV C-Telescope Array (WFCTA)

Cross-checking inside Collaboration

- **Telescopes**: 18
- **Energy Range**:

0.1-100 PeV



WFCTA measured the event simultaneously

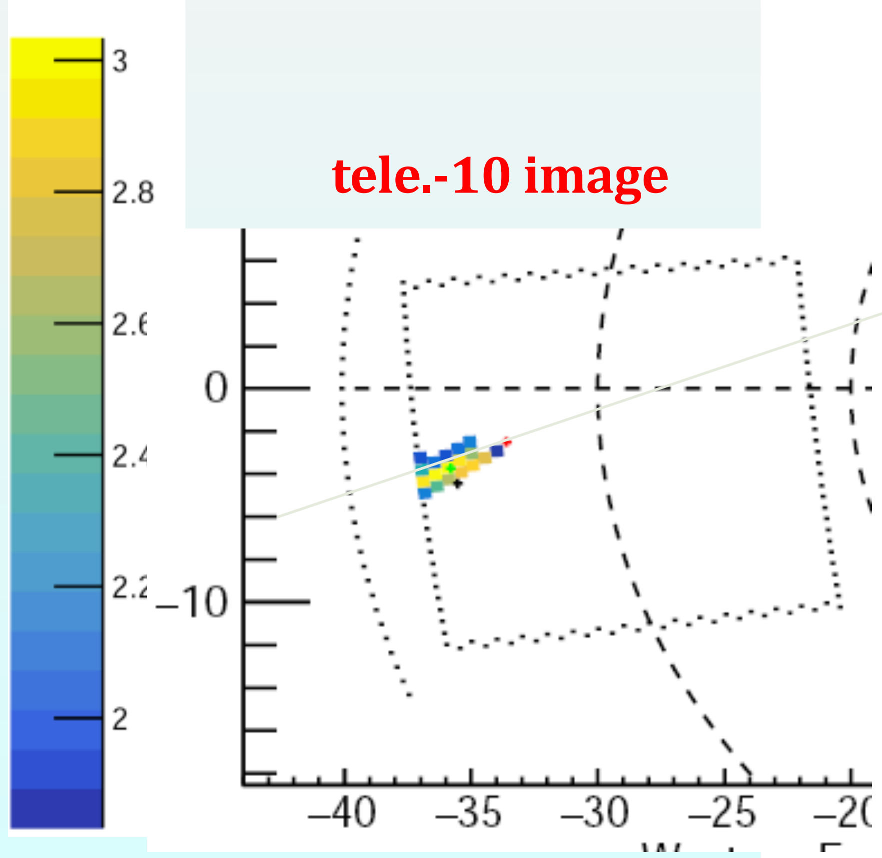
L/W~2.6, N_{pe}~9100 in 11 pixels

- Energy：0.9±0.2 PeV
- KM2A measured the event

$N_{particle}$~4574 in 395 EDs

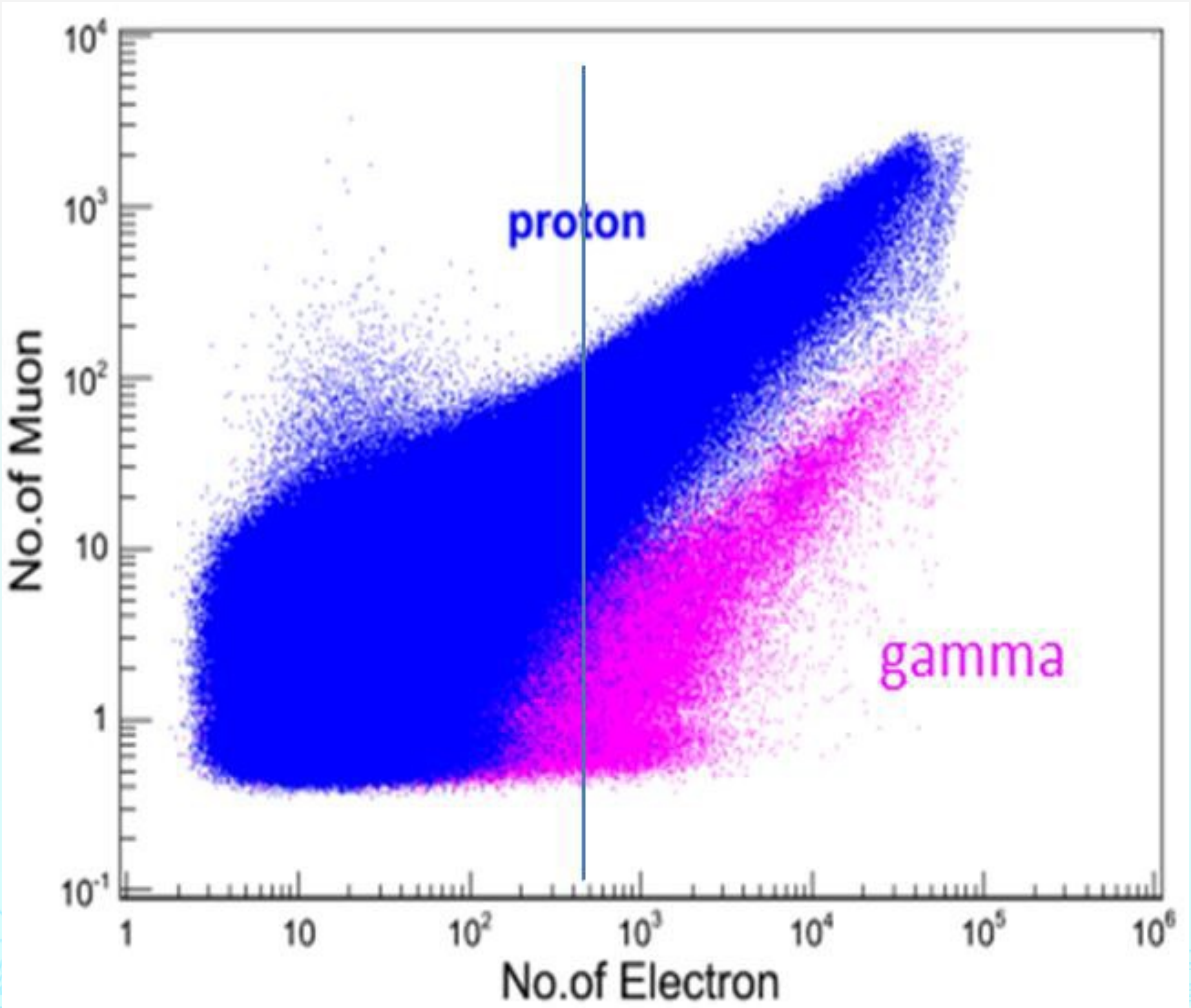
- Energy： 0.9±0.1 PeV
- Chance probability: <0.1%

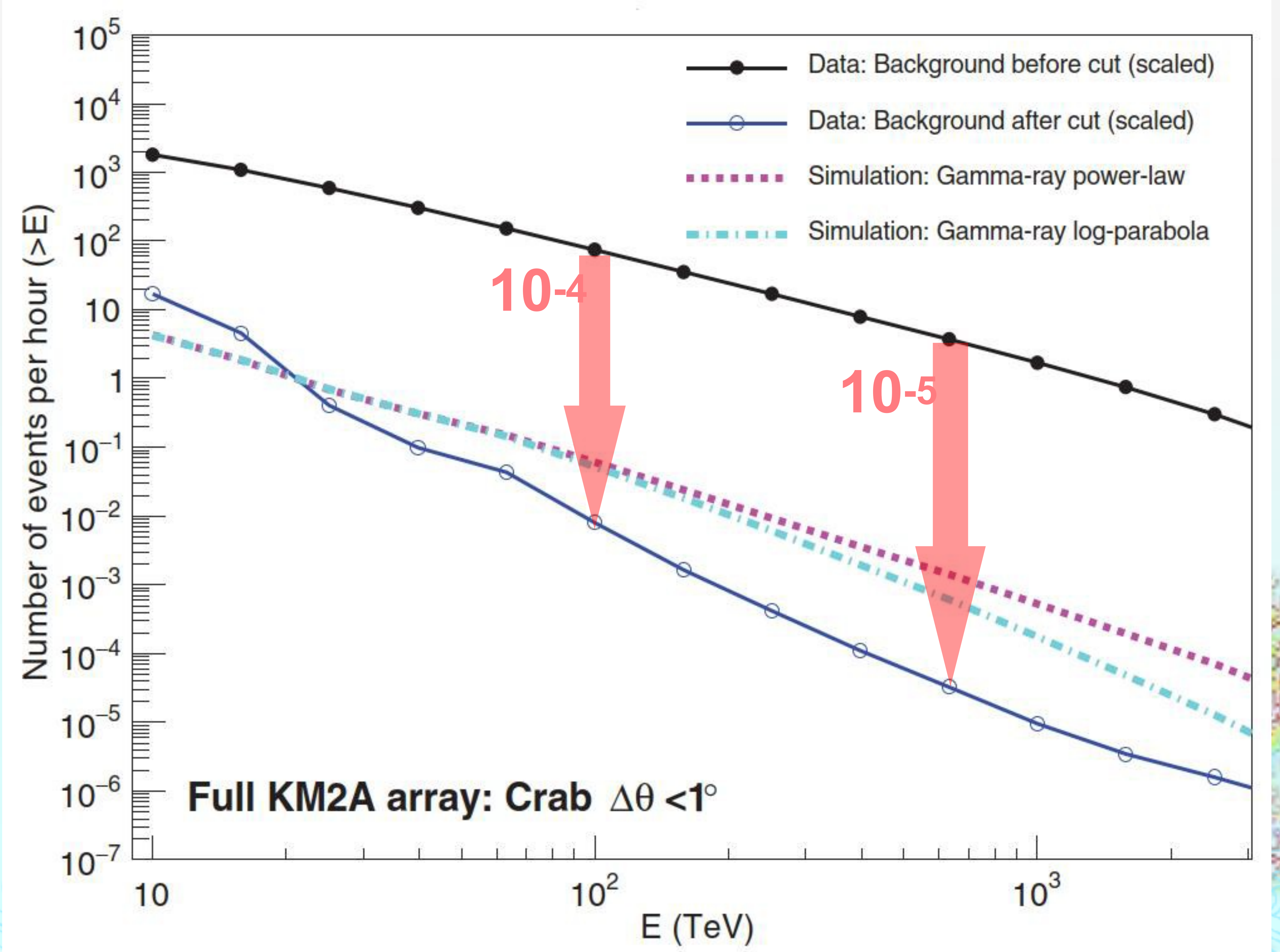
N_{μ}~15 in 11 MDs



Background rejection

- Counting number of measured muons in a shower
- Cutting on ratio N_μ/N_e<**1/230**
- BG-free (N_γ>10N_{CR}) Photon Counting
  for showers E>100 TeV from the Crab

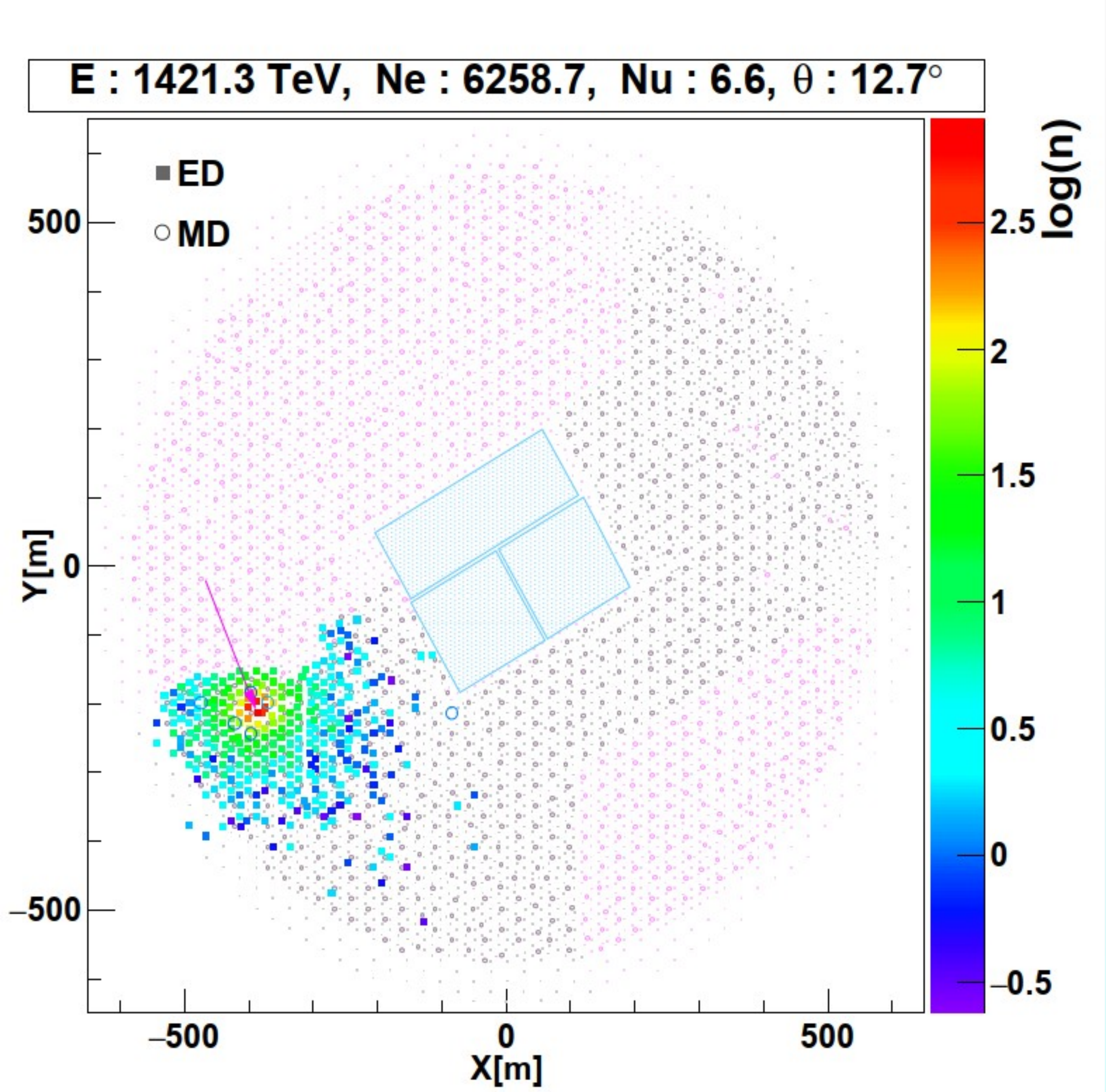


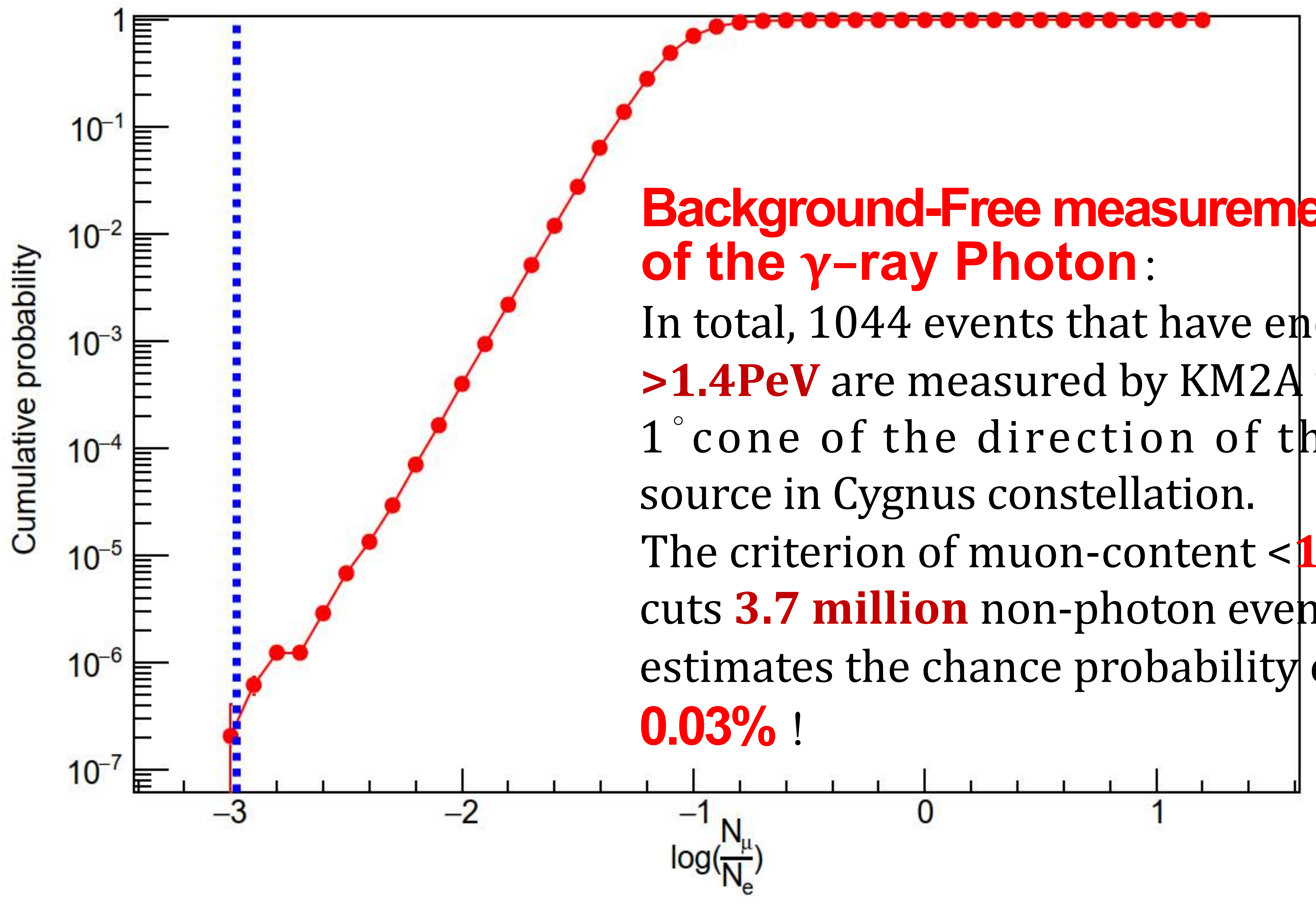


1.4 PeV Photon

from Cygnus Direction Record by KM2A

LHAASO, Nature, 594, p.33-36, 2021





Background-Free measurement of the γ–ray Photon:

In total, 1044 events that have energy **>1.4PeV** are measured by KM2A in 1°cone of the direction of the source in Cygnus constellation.

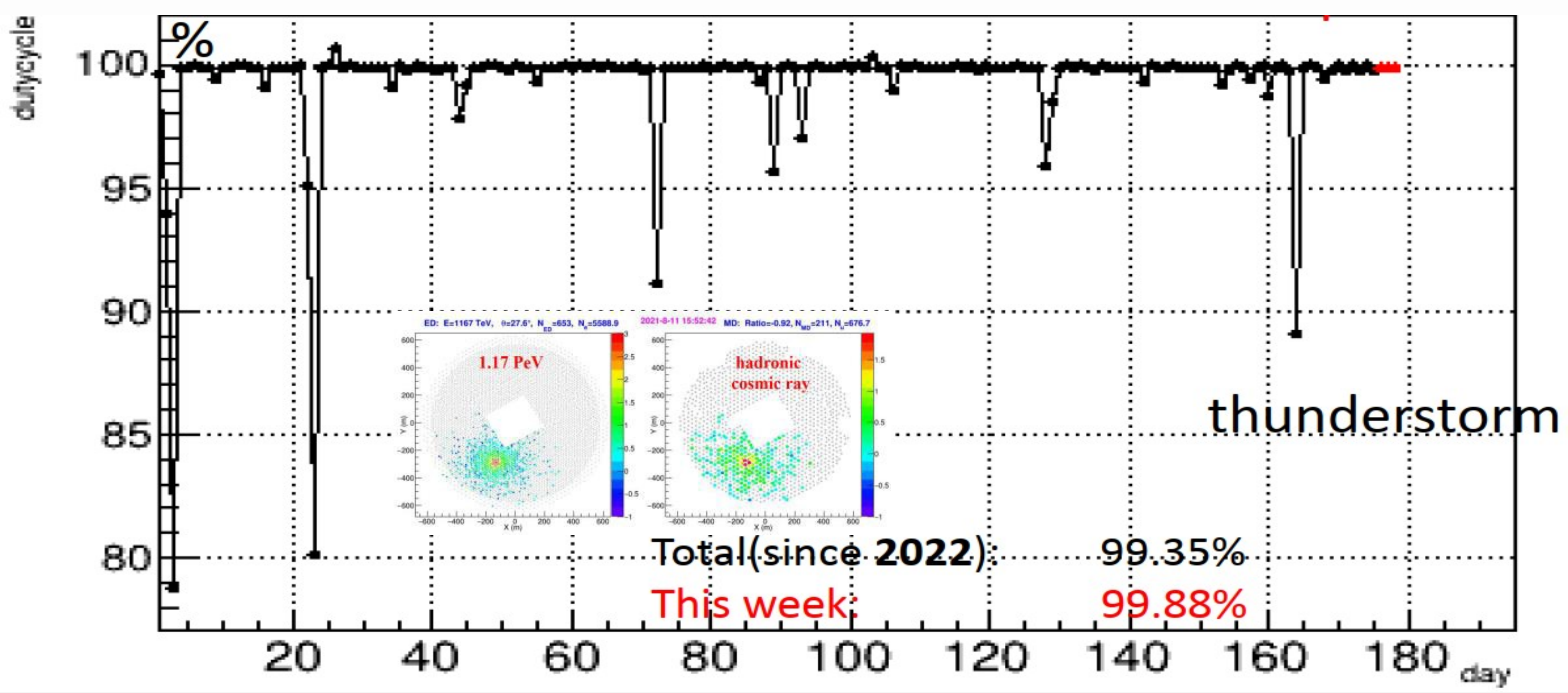
The criterion of muon-content <**1/941** cuts **3.7 million** non-photon events, thus estimates the chance probability of **0.03%** !

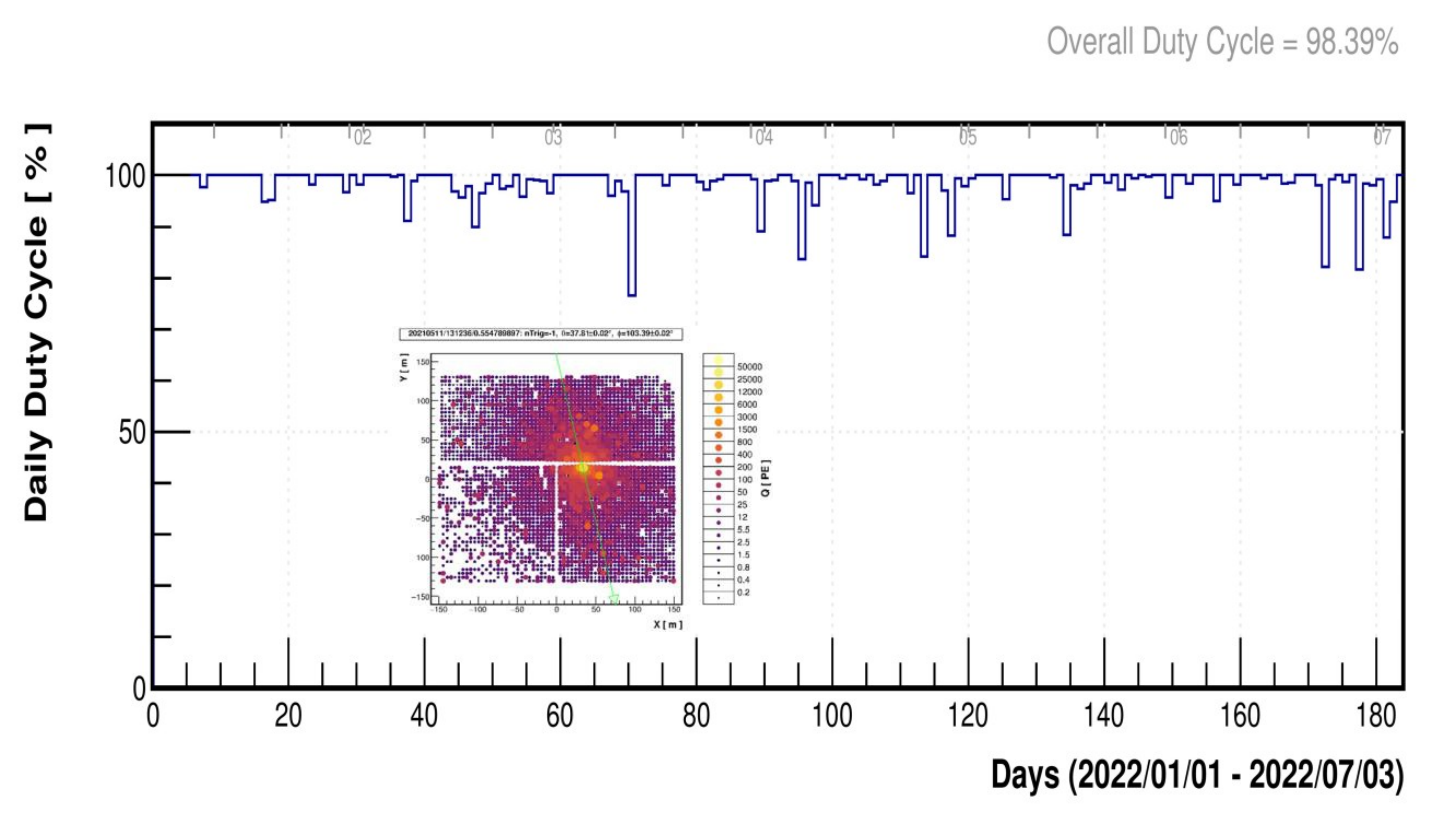
Operation

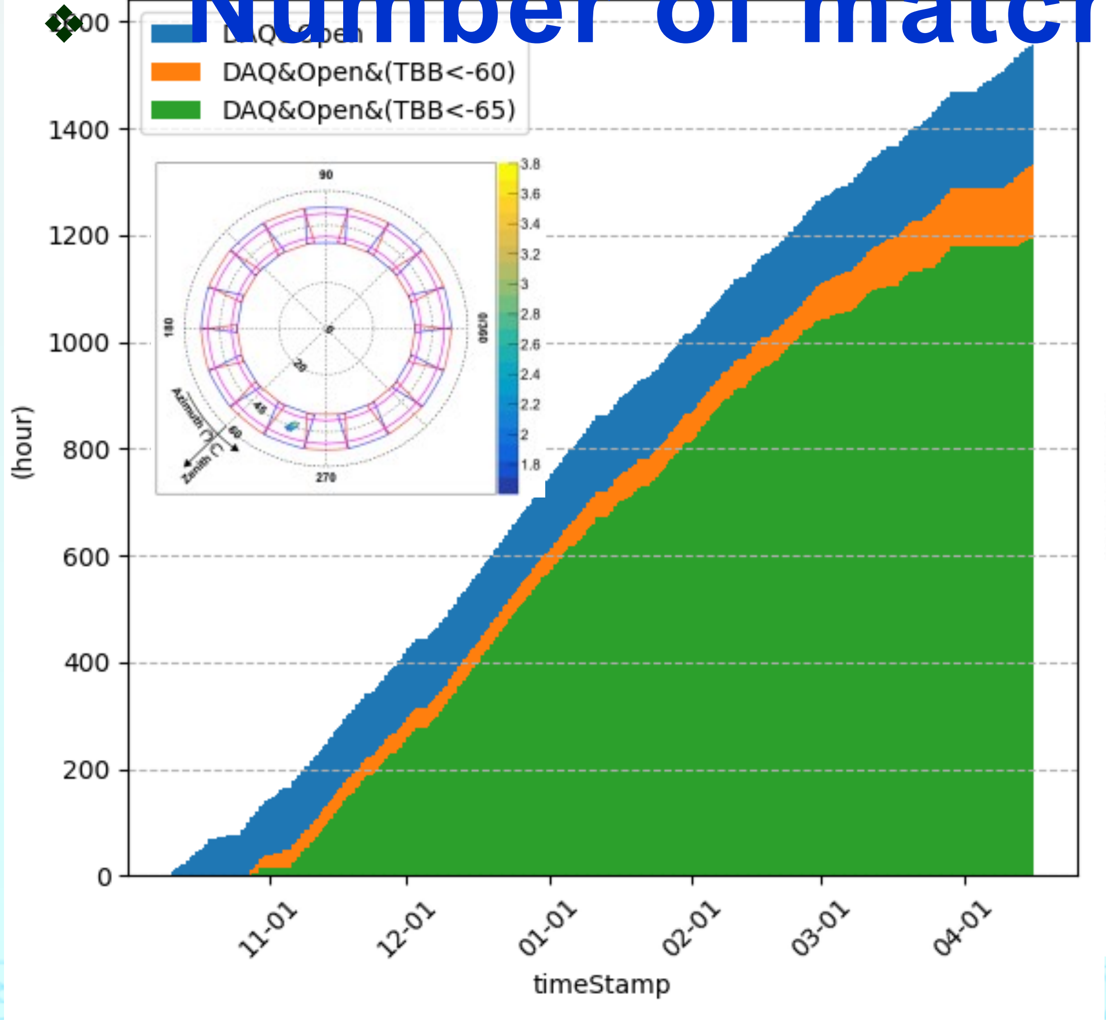
- The duty cycle of KM2A is >99.4%
- Event rate 2×10^8 /day

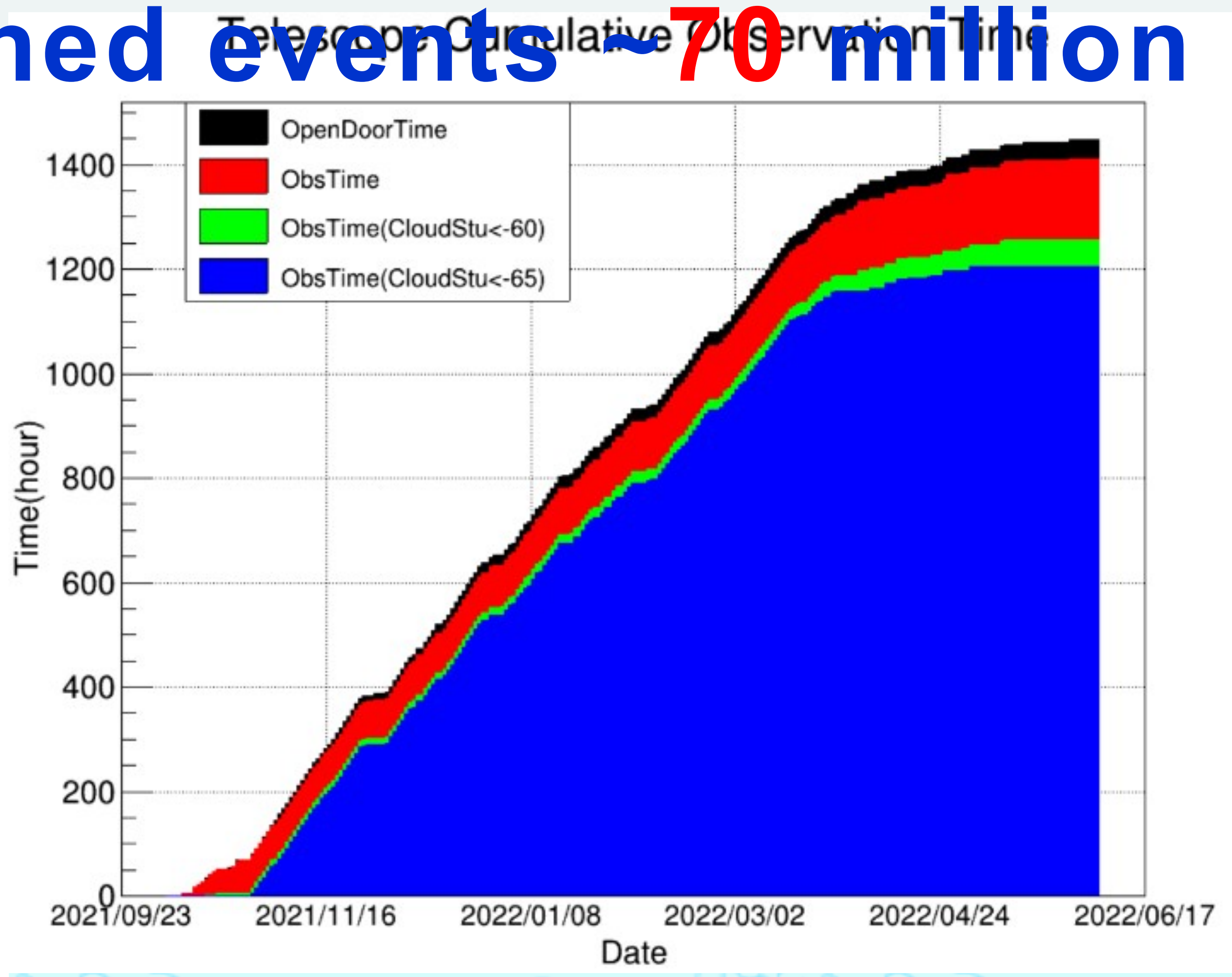
- The duty cycle of WCDA is 98.4%
- Event rate 3×10^9 /day

- Data acquisition time of WFCTA >1400 hrs
- Number of matched events ~70 million

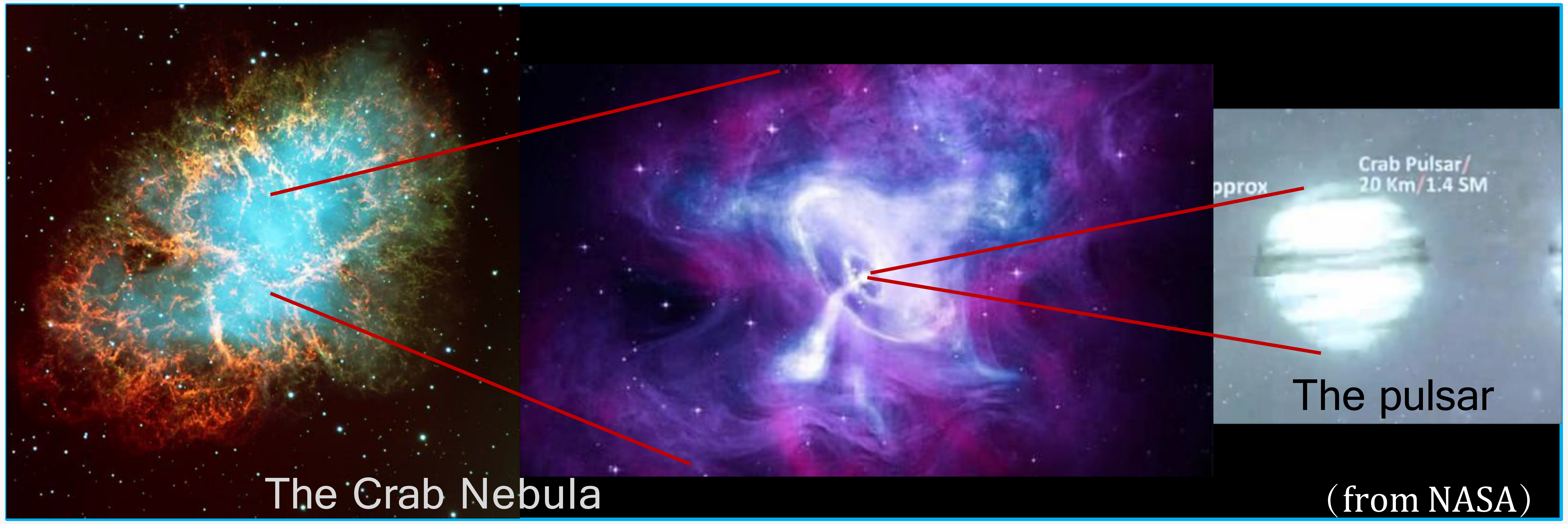






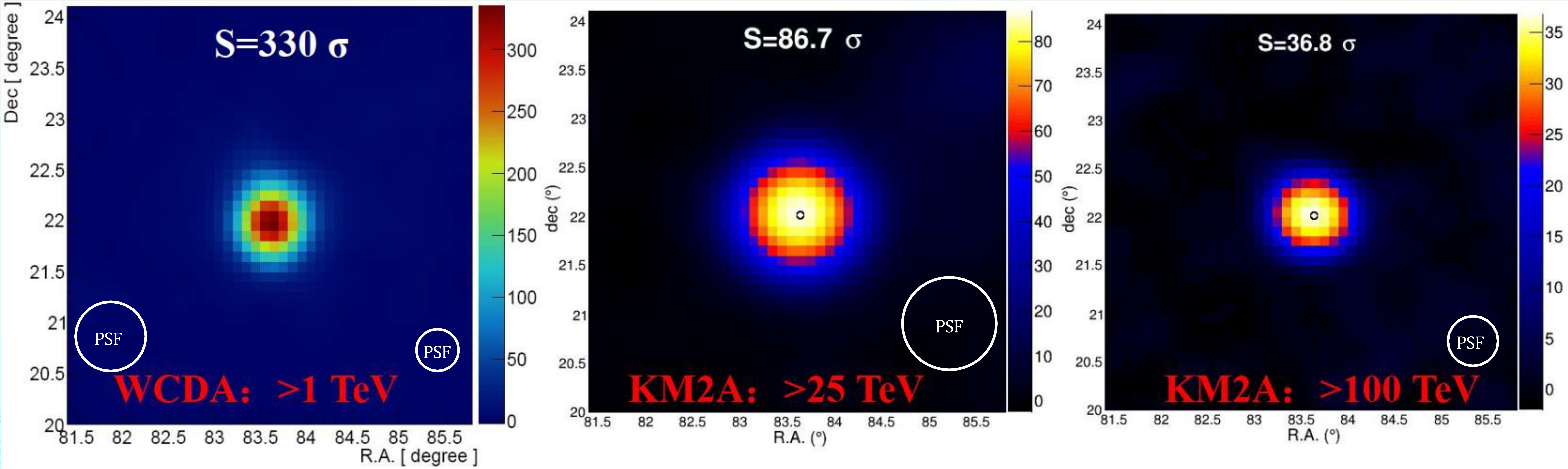


Standard candle for γ–ray Observation



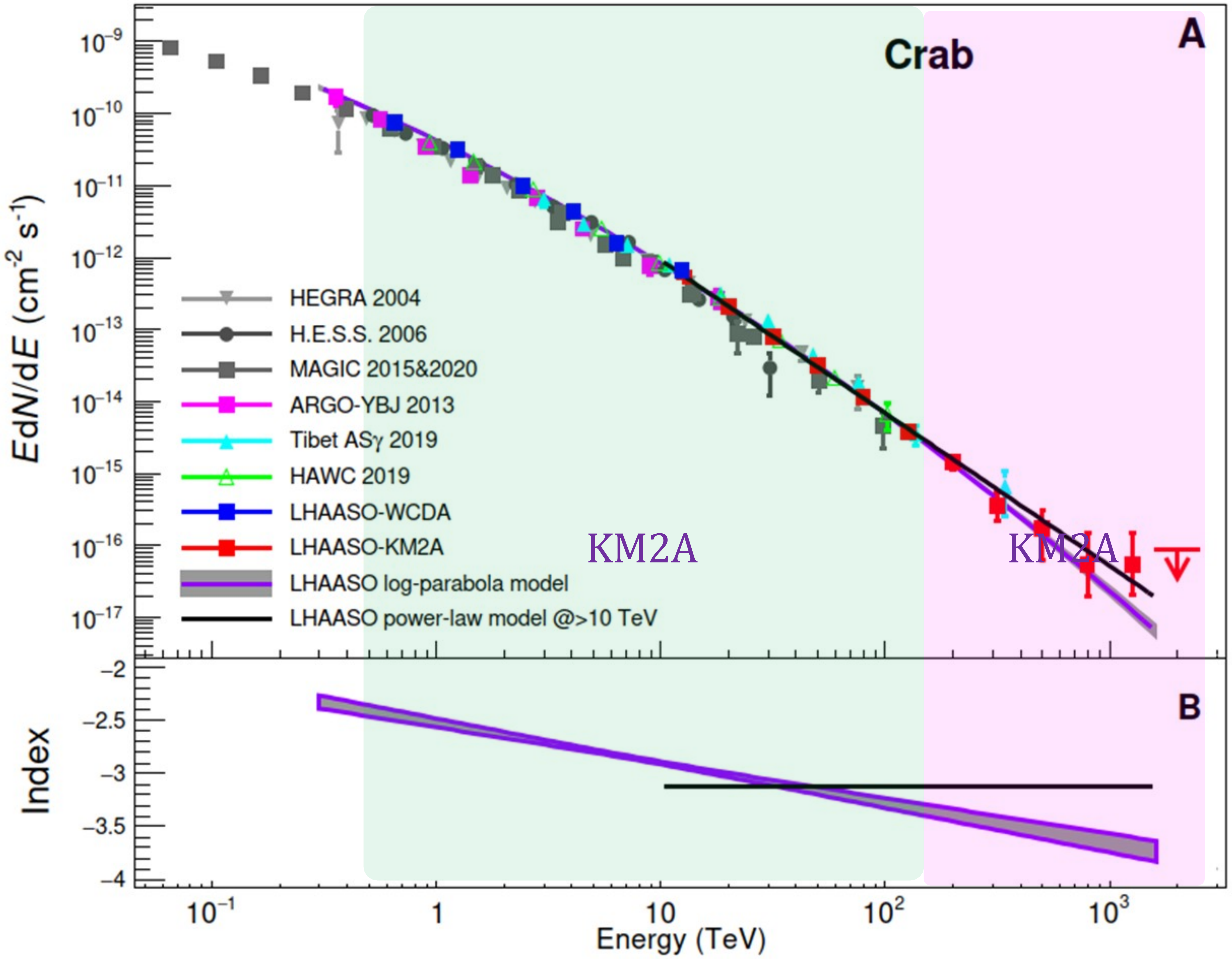
The coverage of 3.5 orders of magnitudes of energy

1 - 12 TeV	25-100 TeV	0.1-1.2 PeV
PSF: 0.22°	0.30°	0.15°
Pointing accuracy: 0.01°		

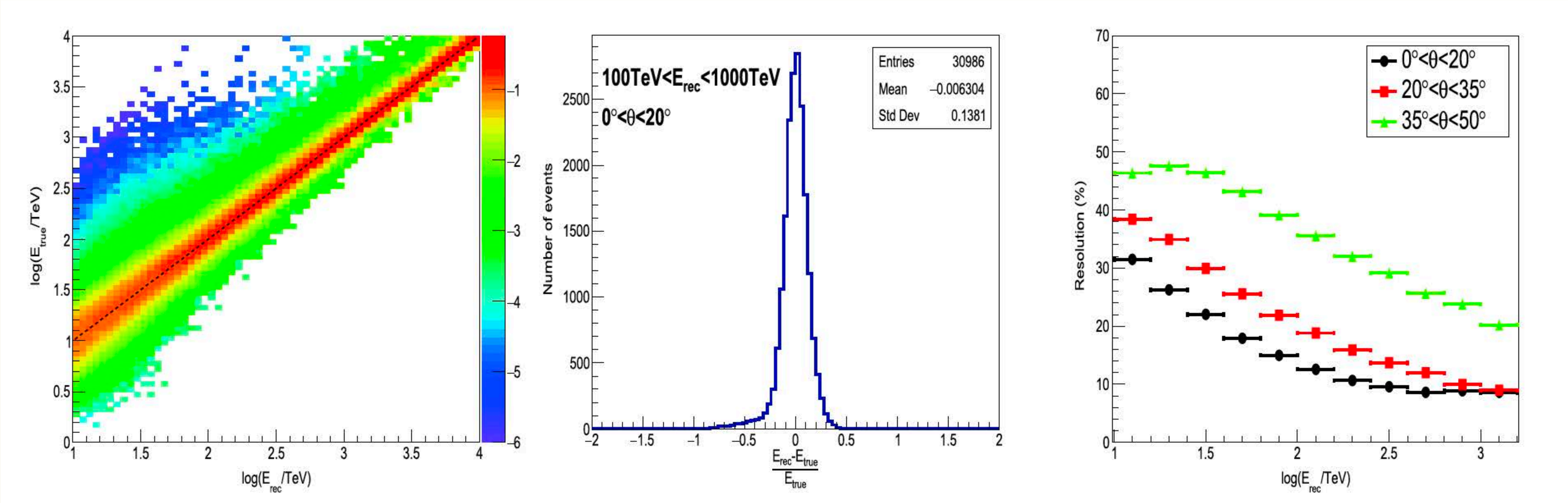


SED of the Crab

- LHAASO:
  - Covering 3.5 decades of energy
  - Agreeing with other experiments below 100 TeV
  - Self cross-checking between WCDA & KM2A
- LHAASO-KM2A:
  - Unique UHE SED
  - A PeVatron without ambiguity
  - Clear origin: a well-known PWN
- An extreme e-accelerator:
  - 2.3 PeV electrons
  - in ~0.025 pc compact region
  - accelerating efficiency of 15% (1000× better than SNR shock waves)



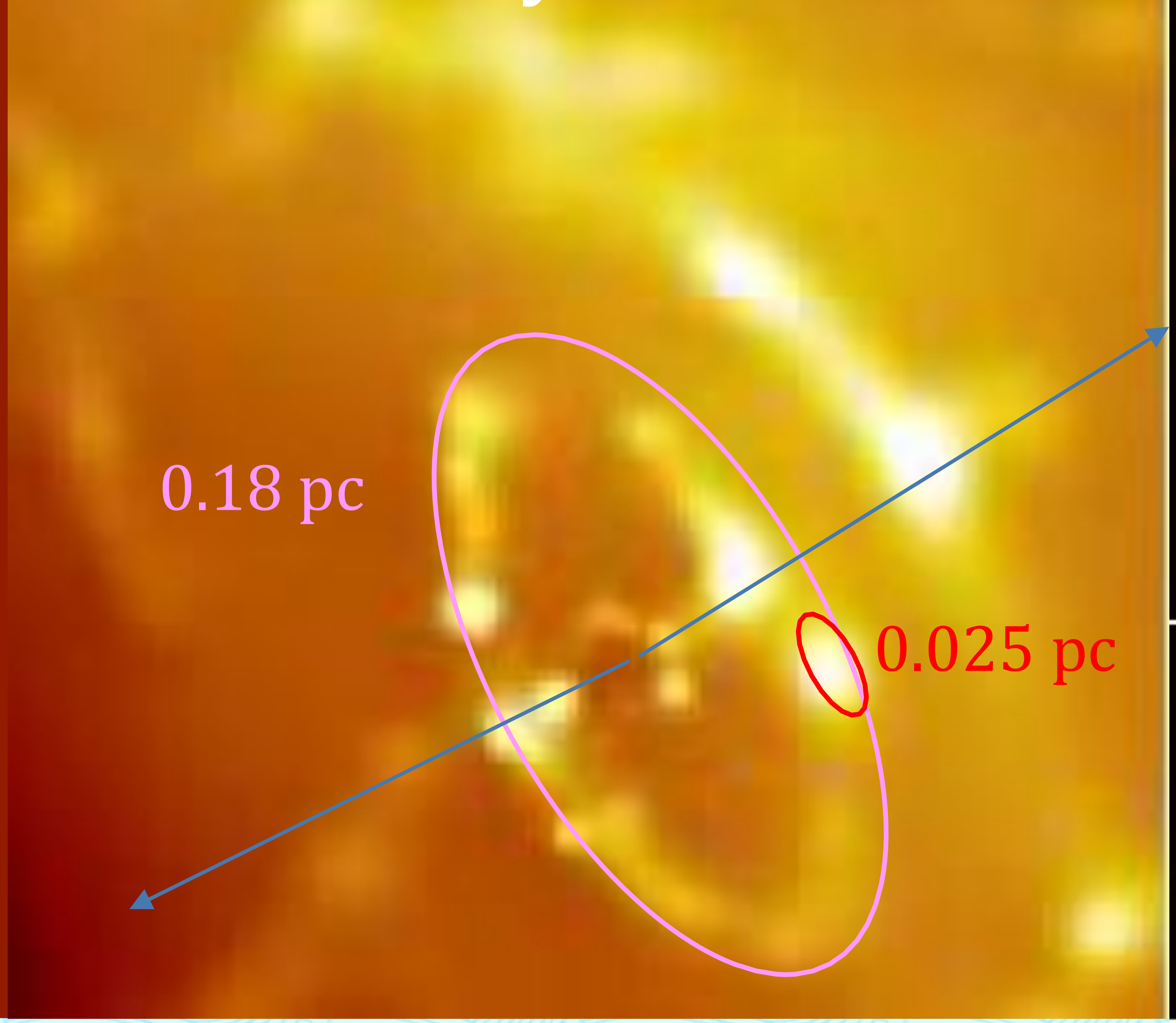
Energy reconstruction of KM2A

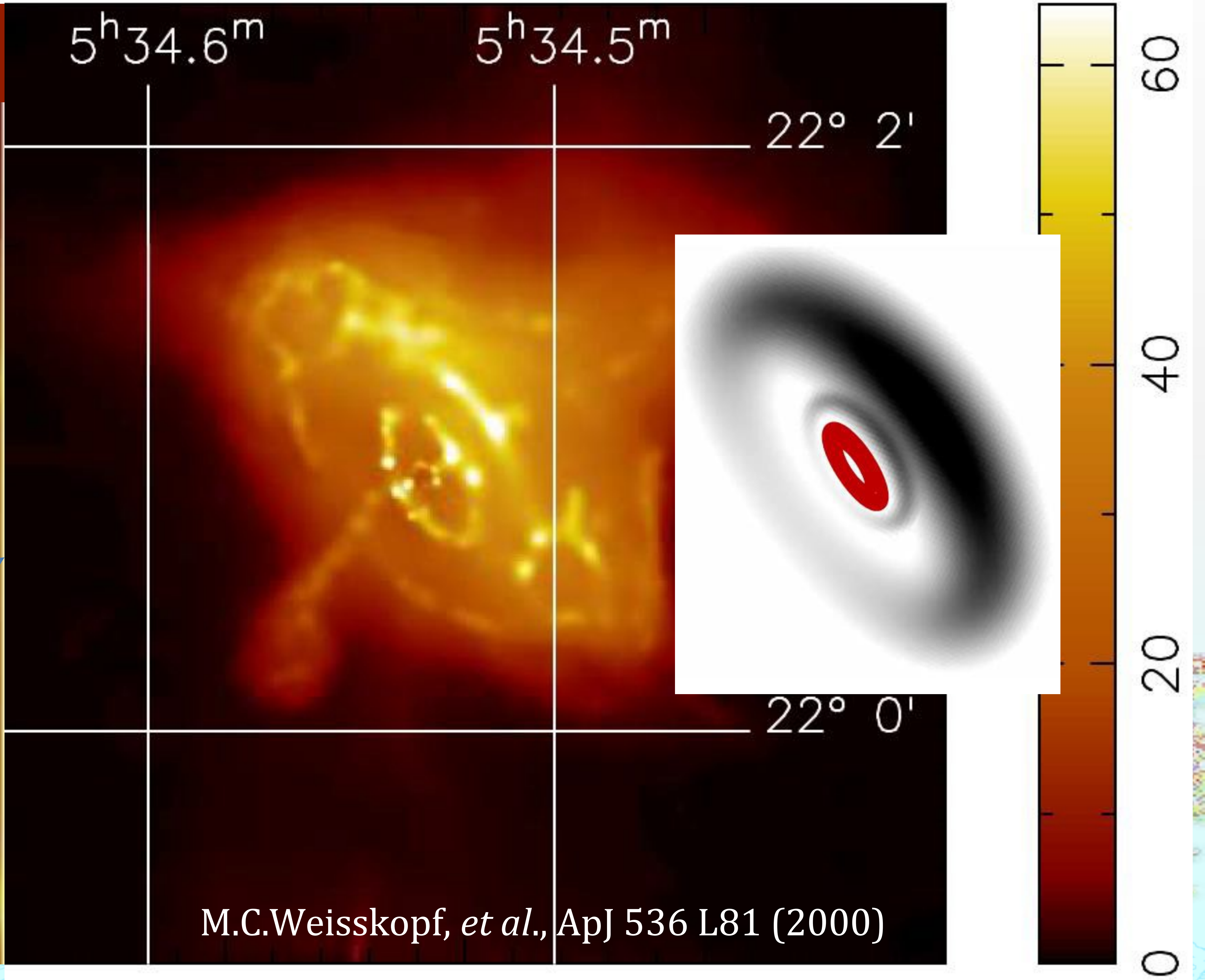


- The energy resolution is better than 14% for photons above 100 TeV arriving from a zenith angle of <35.

Inner ring, jets and knots

- Chandra has observed many knots in between the pulsar and the inner ring
- They are apparently in the region that ~PeV photons may be emitted by electrons



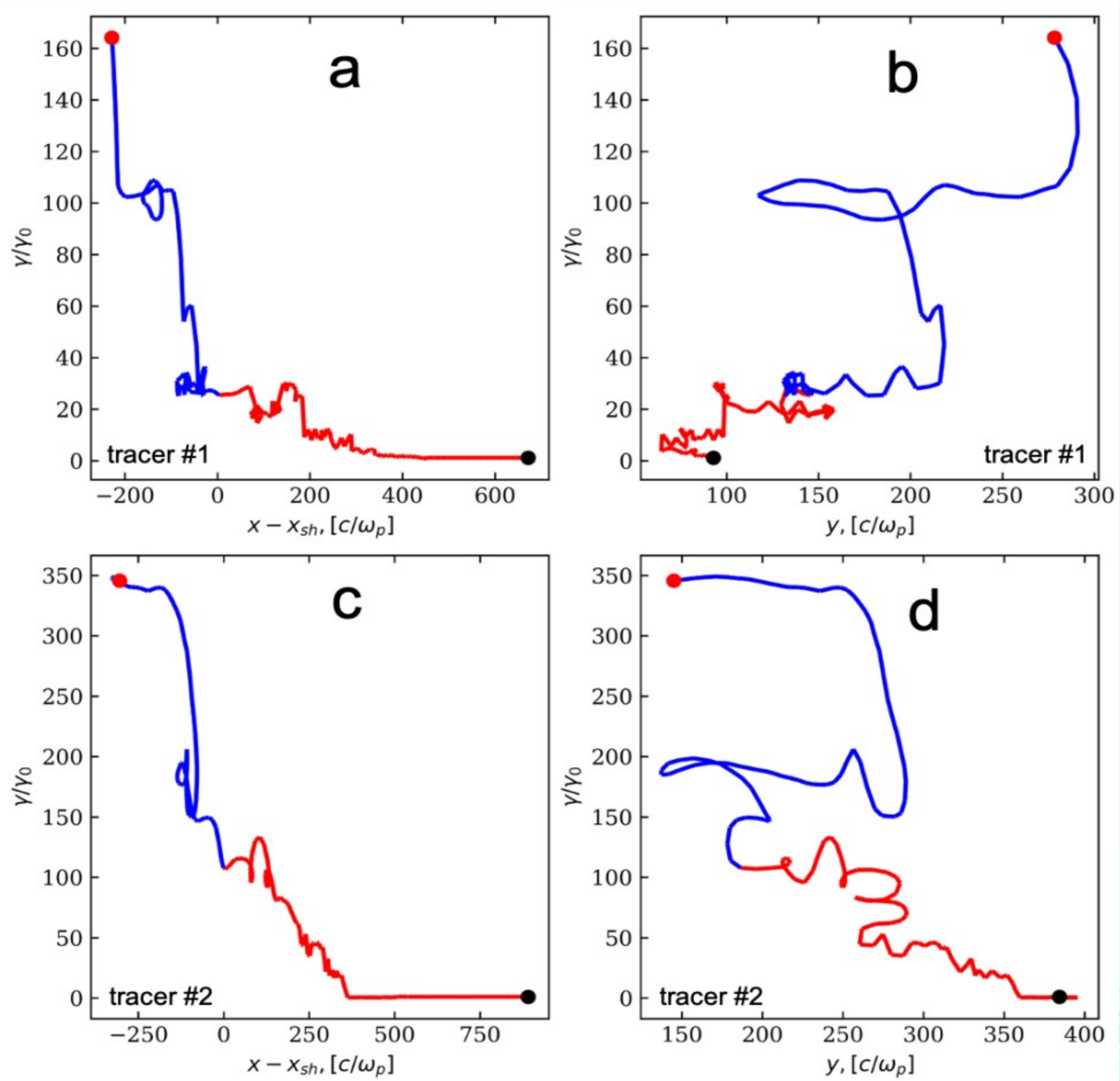


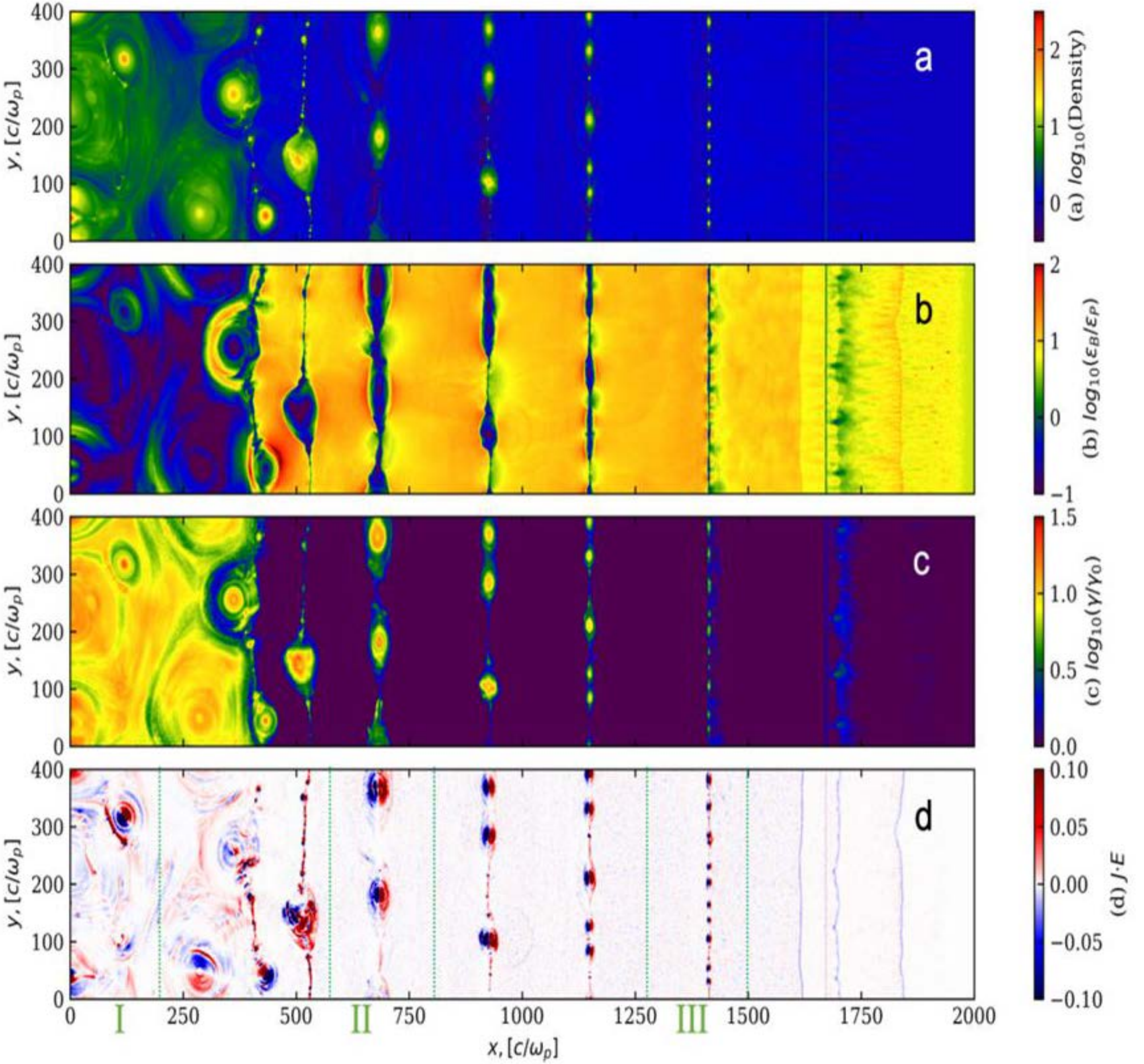
M.C.Weisskopf, *et al.*, ApJ 536 L81 (2000)

LHAASO
高海拔宇宙线观测站

MHD PIC Simulation

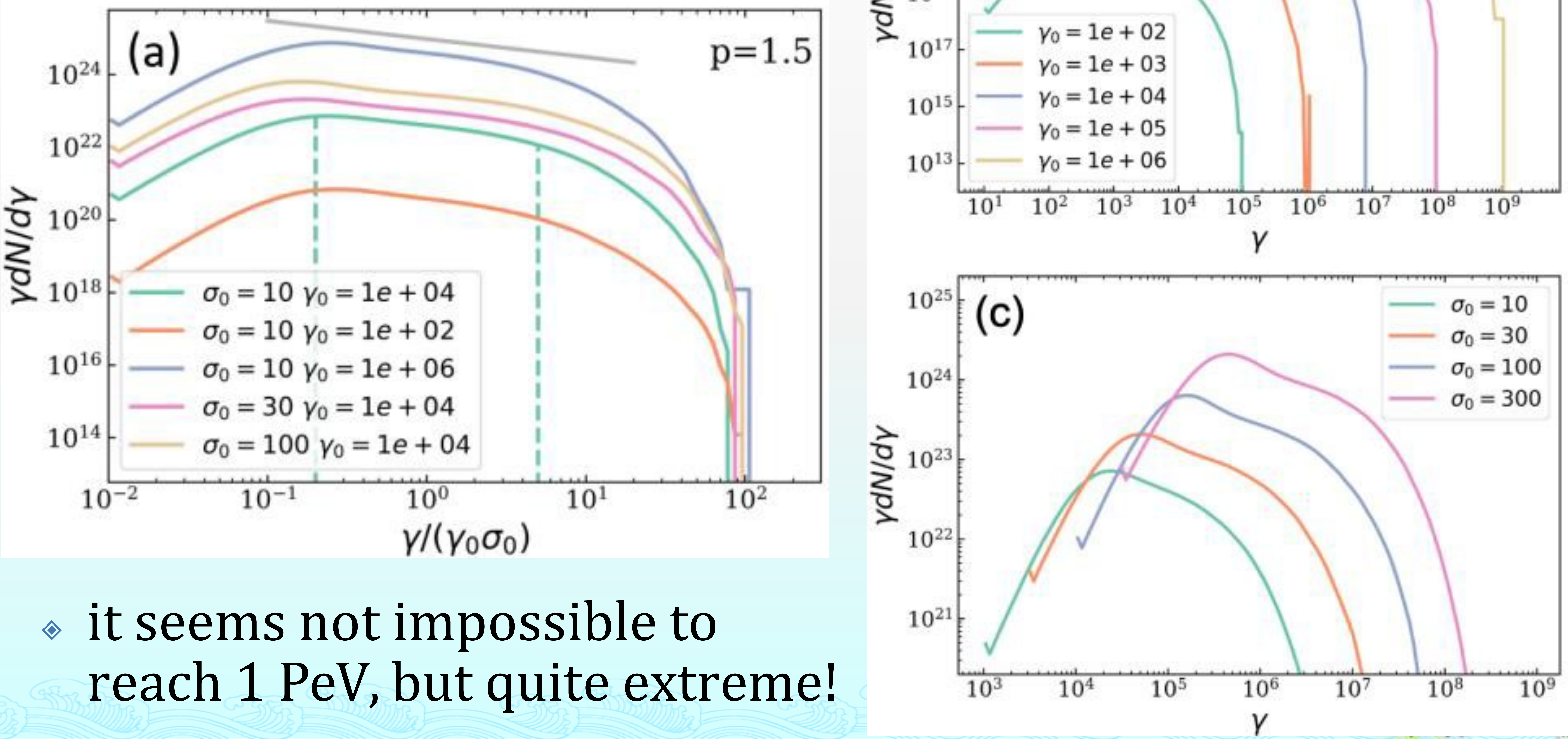
Yingchao Lu et al., ApJ 908, 2, 147 (2021)





Electron E-Spectrum

Yingchao Lu et al., ApJ 908, 2, 147 (2021)



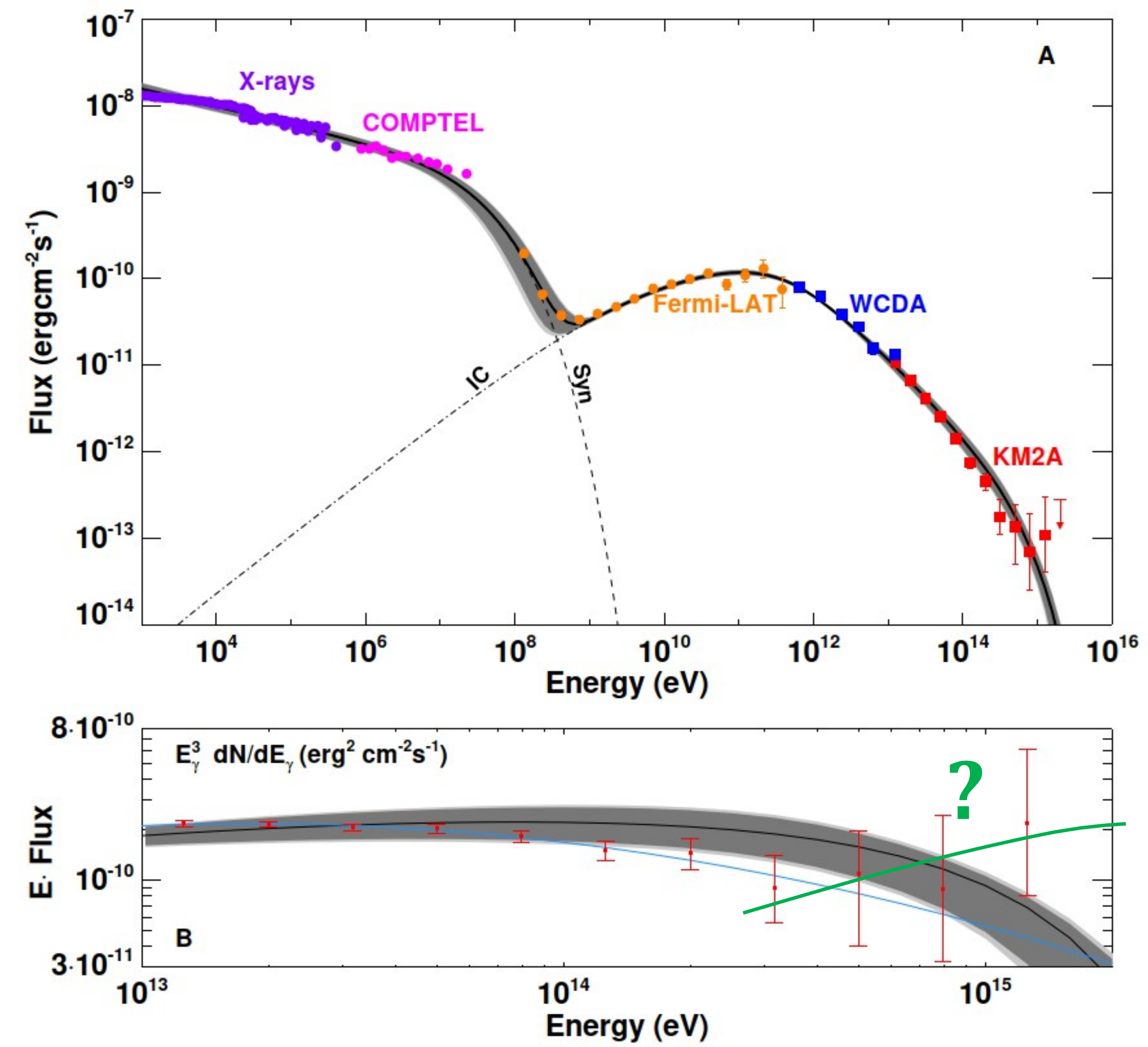
- it seems not impossible to reach 1 PeV, but quite extreme!

LHAASO 高海拔宇宙线观测站

SED of the Crab: Extreme E-accelerator

LHAASO, Science, DOI10.1126/science.abg5137, 2021

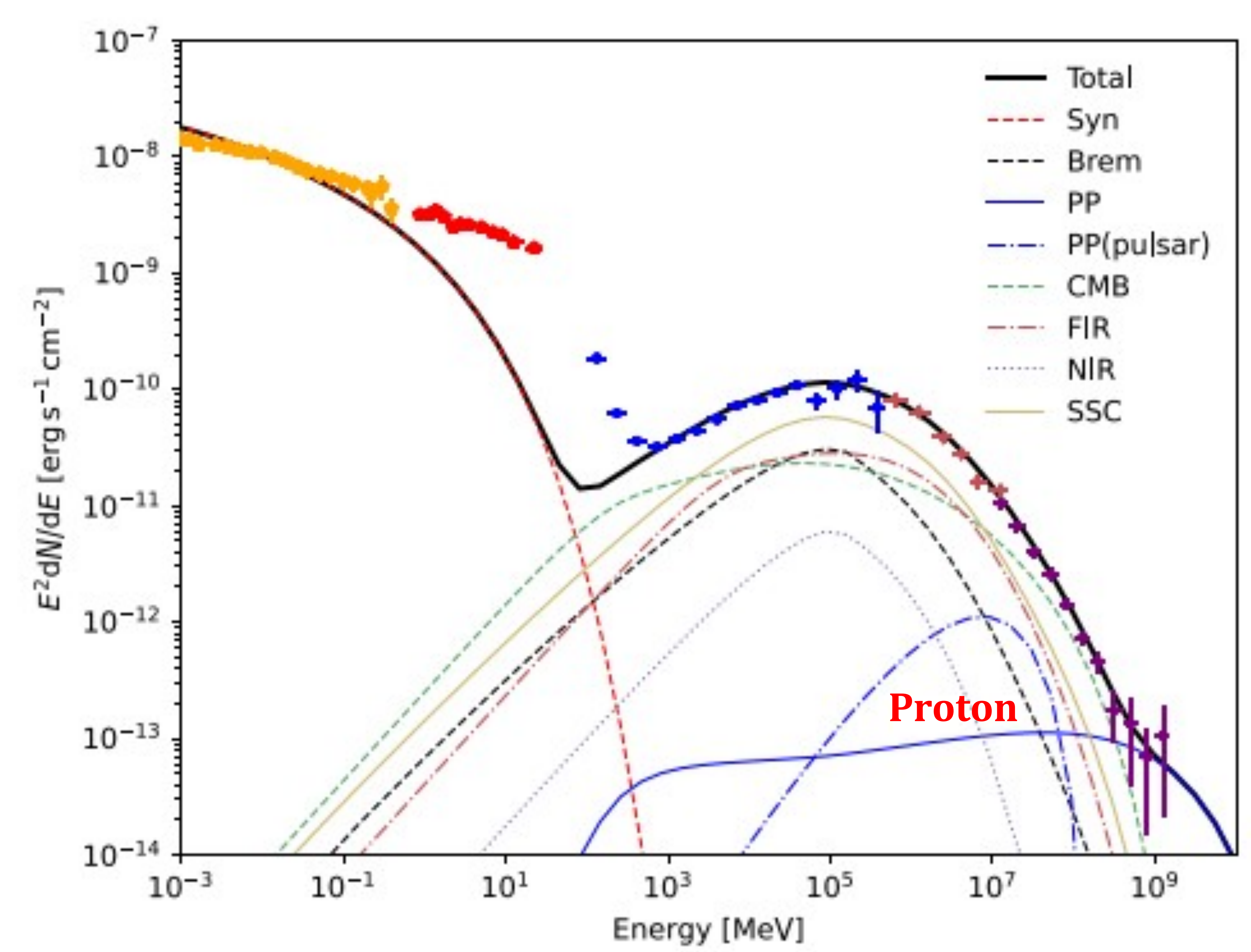
- **Perfect interpretation of one-zone electronic origin up to 50TeV**
- **Reasonable extension up to 1 PeV, with a deviation of 4 σ**
- **Can not rule out proton origin of photons ~1.1 PeV, yet**

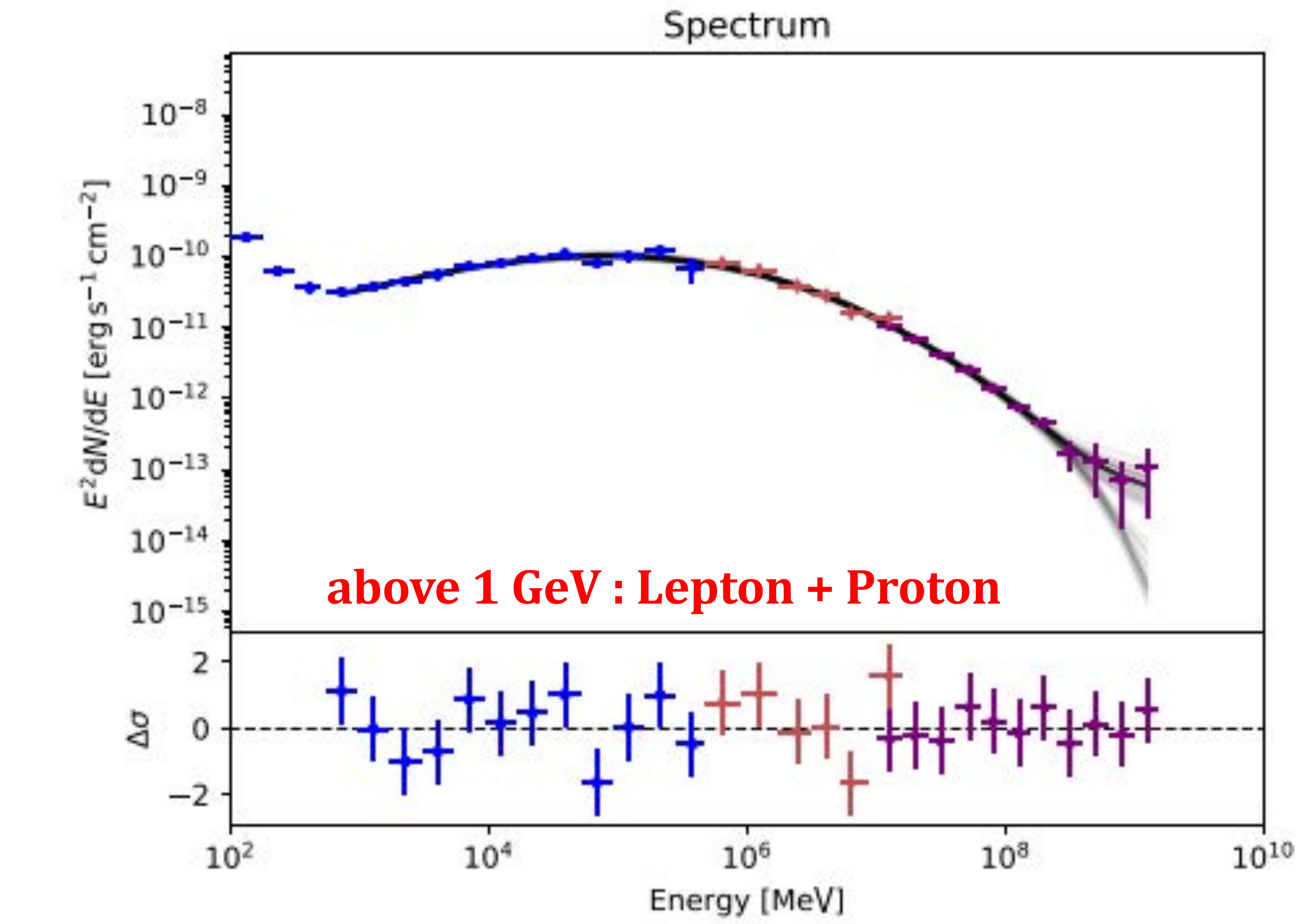


Seems to be a better interpretation

- Relaxing the tension of 2.3 PeV electron’s acceleration
- Origin of CRs above the knee: a Super-PeVatron

L. Nie et al., ApJ, **924** 42, arXiv:2201.03796





Discovery in KM2A Survey

Our Galaxy is full of PeVatrons

LHAASO, Nature, 594, p.33-36, 2021

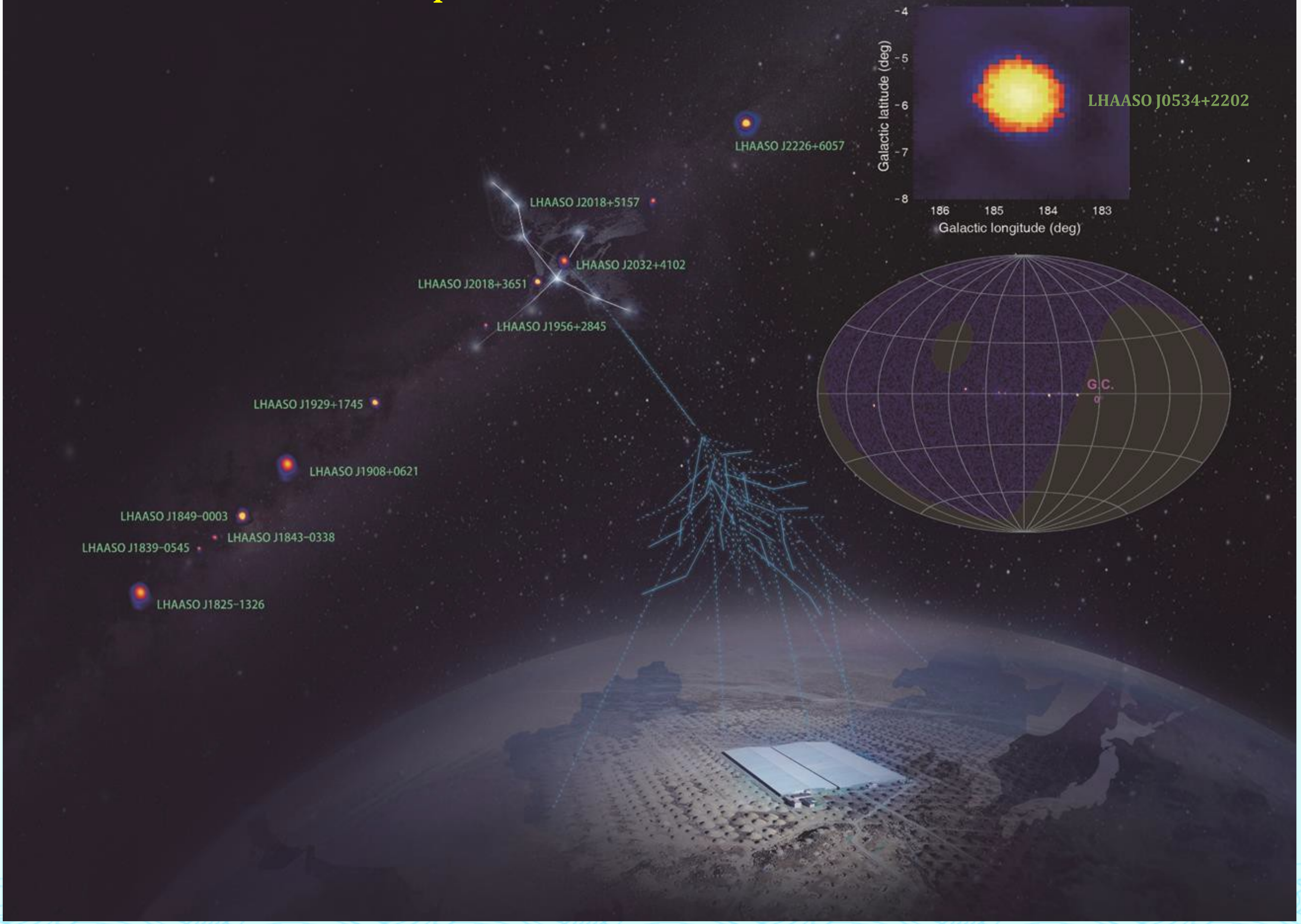


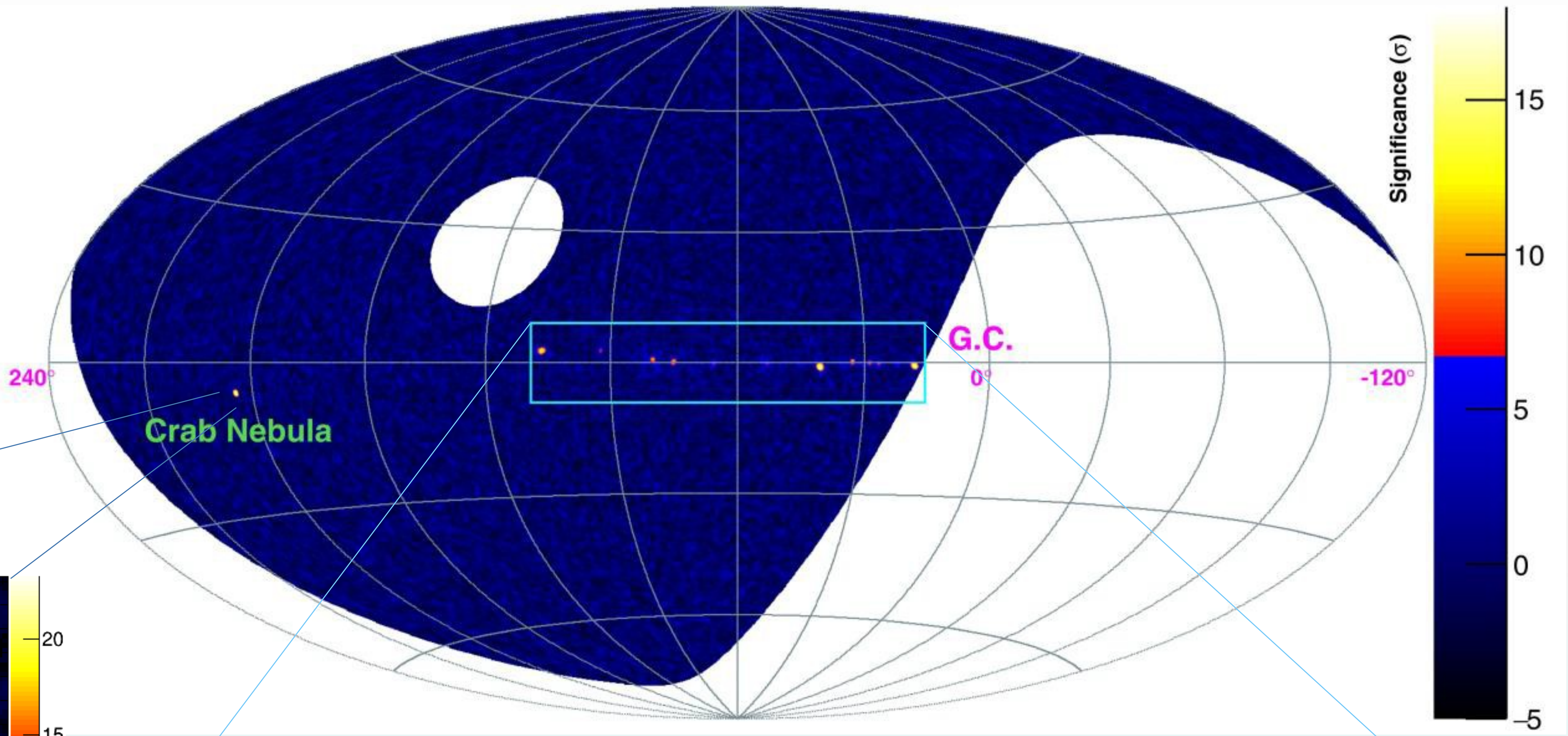
Table 1 | UHE γ-ray sources

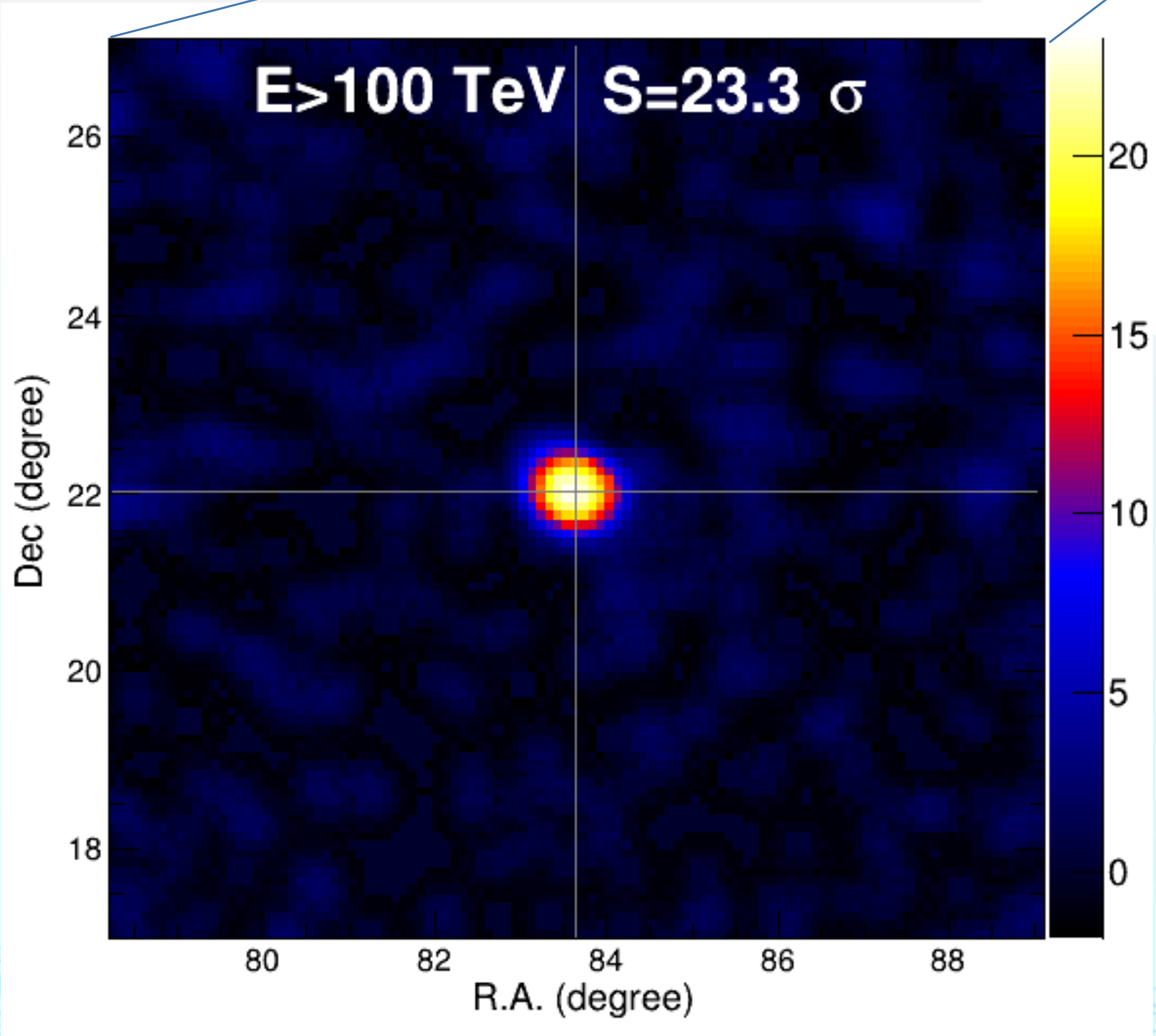
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26^{+0.16}_{-0.10}$	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	$0.71^{+0.16}_{-0.07}$	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	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)

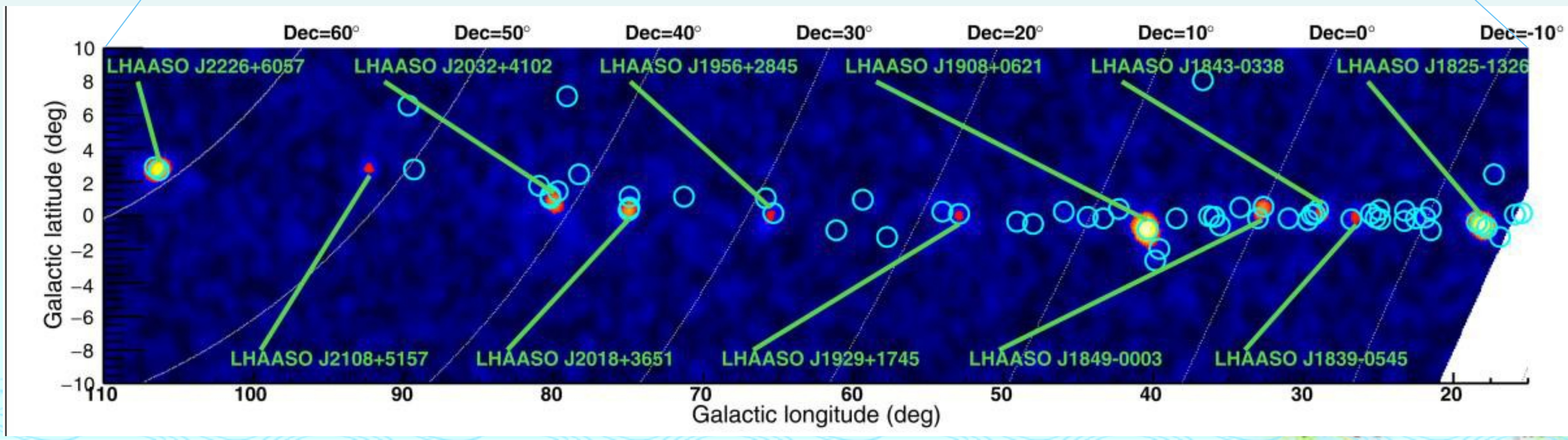
12 PeVatrons are discovered

- ◆ **High Standard： significance >7σ**
- ◆ **BG-free： Cosmic Ray background rejection rate $<10^{-4}$**
- ◆ **High Statistics： 530 UHE photons**
- ◆ **Multiple Type of Sources**

UHE γ–ray (0.1-1 PeV) Sky Map







LHAASO sky map (E>100TeV)

Significance > 7-sigma

Table 1 | UHE γ-ray sources

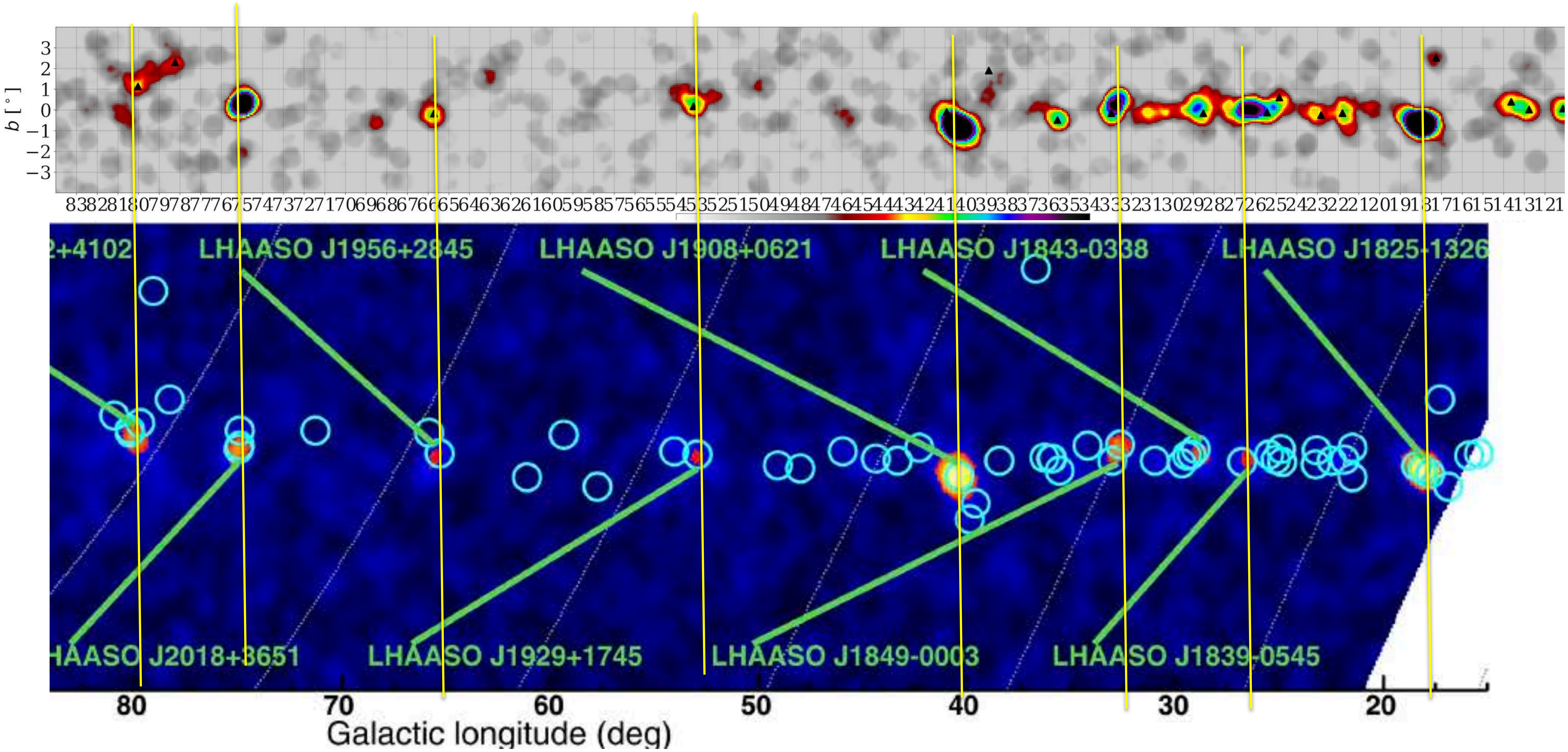
Source name		RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	Crab	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	1825 region	276.45	−13.45	16.4	0.42 ± 0.16	$\boxed{3.57(0.52)}$
LHAASO J1839-0545		279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338		280.75	−3.65	8.5	$0.26^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003		282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	MGRO1908	287.05	6.35	17.2	0.44 ± 0.05	$\boxed{1.36(0.18)}$
LHAASO J1929+1745		292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	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	Cygnus OB	308.05	41.05	10.5	$\boxed{1.42 \pm 0.13}$	0.54(0.10)
LHAASO J2108+5157		317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	Boomerang	336.75	60.95	13.6	0.57 ± 0.19	$\boxed{1.05(0.16)}$

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.

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

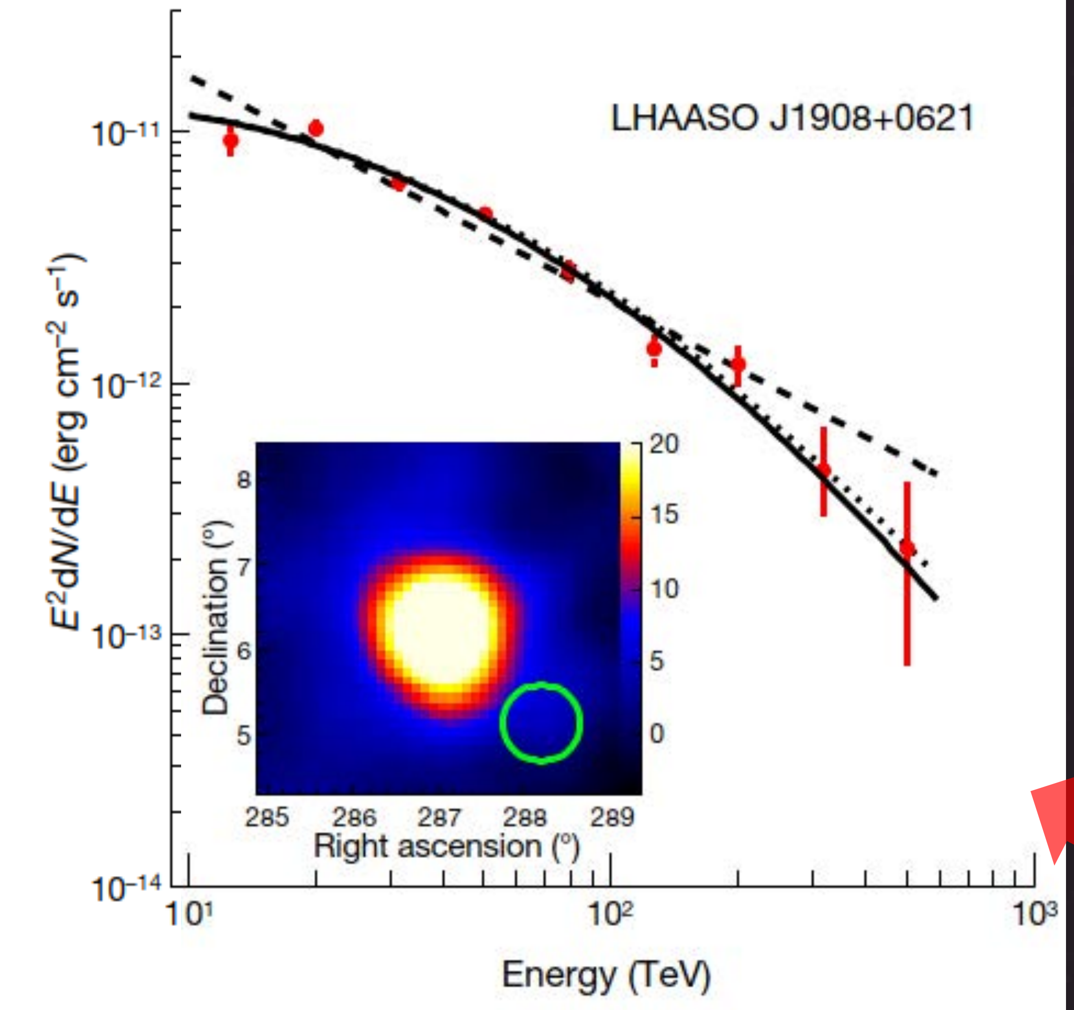
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	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}	

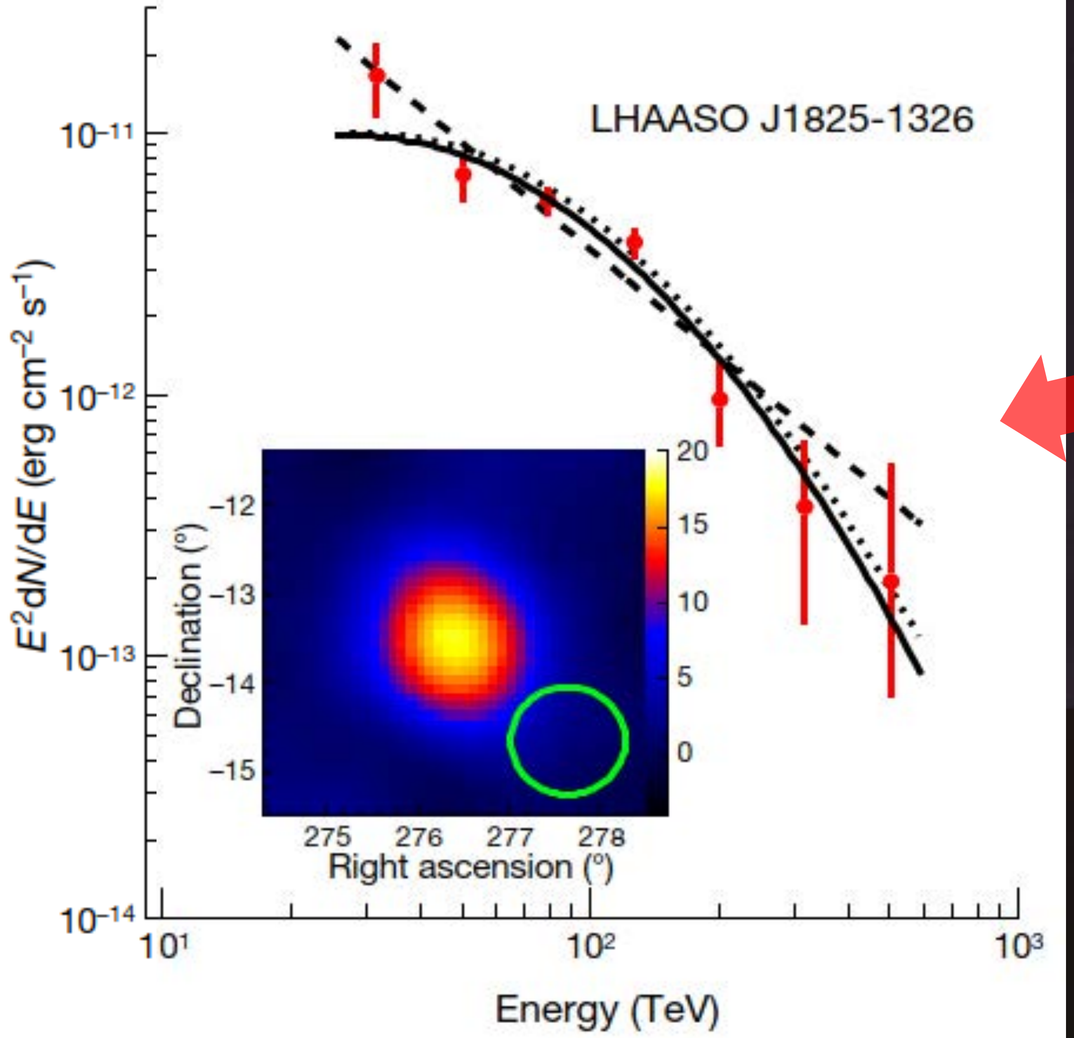
HAWC LHAASO Comparison

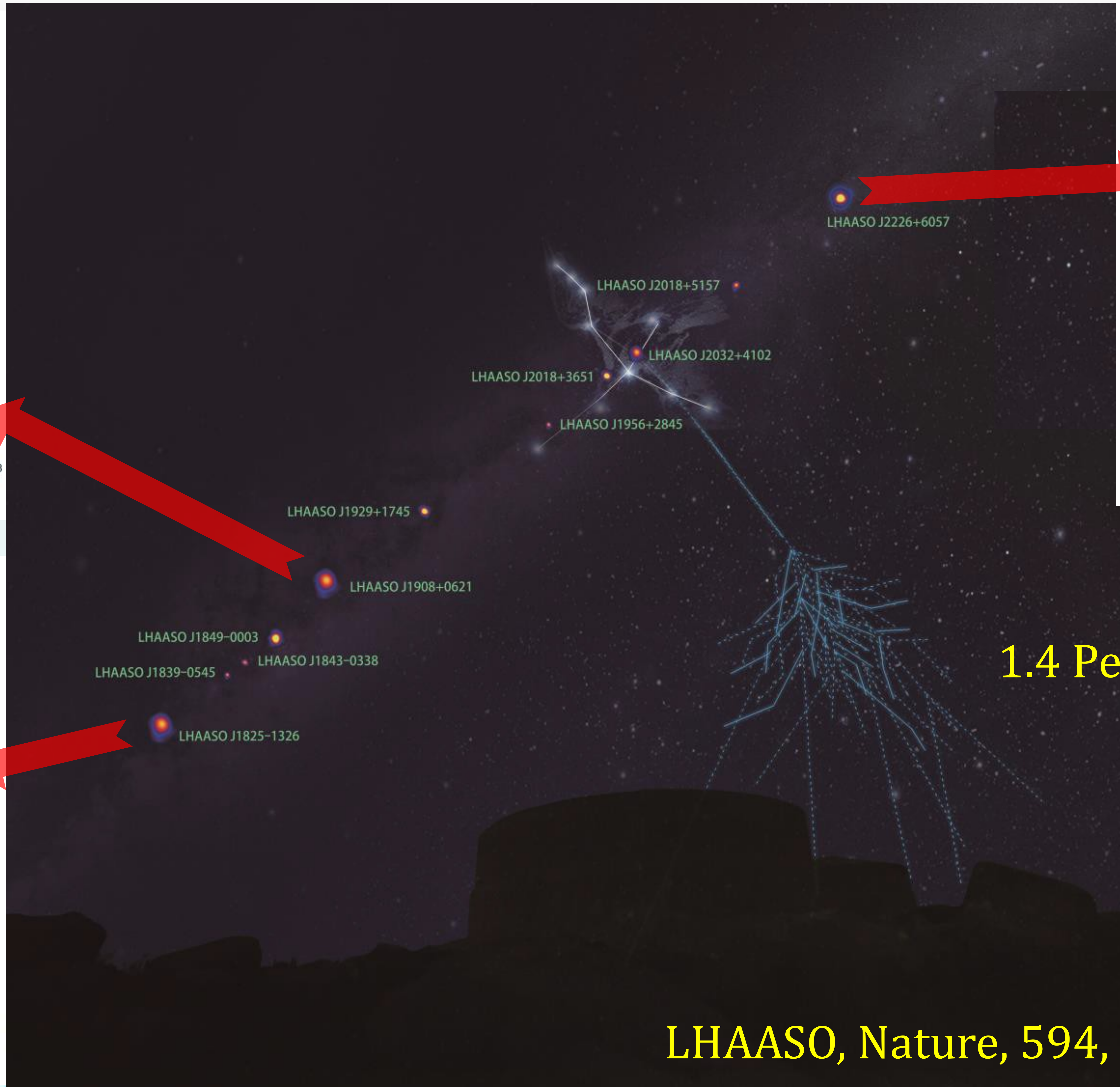


KM2A Survey

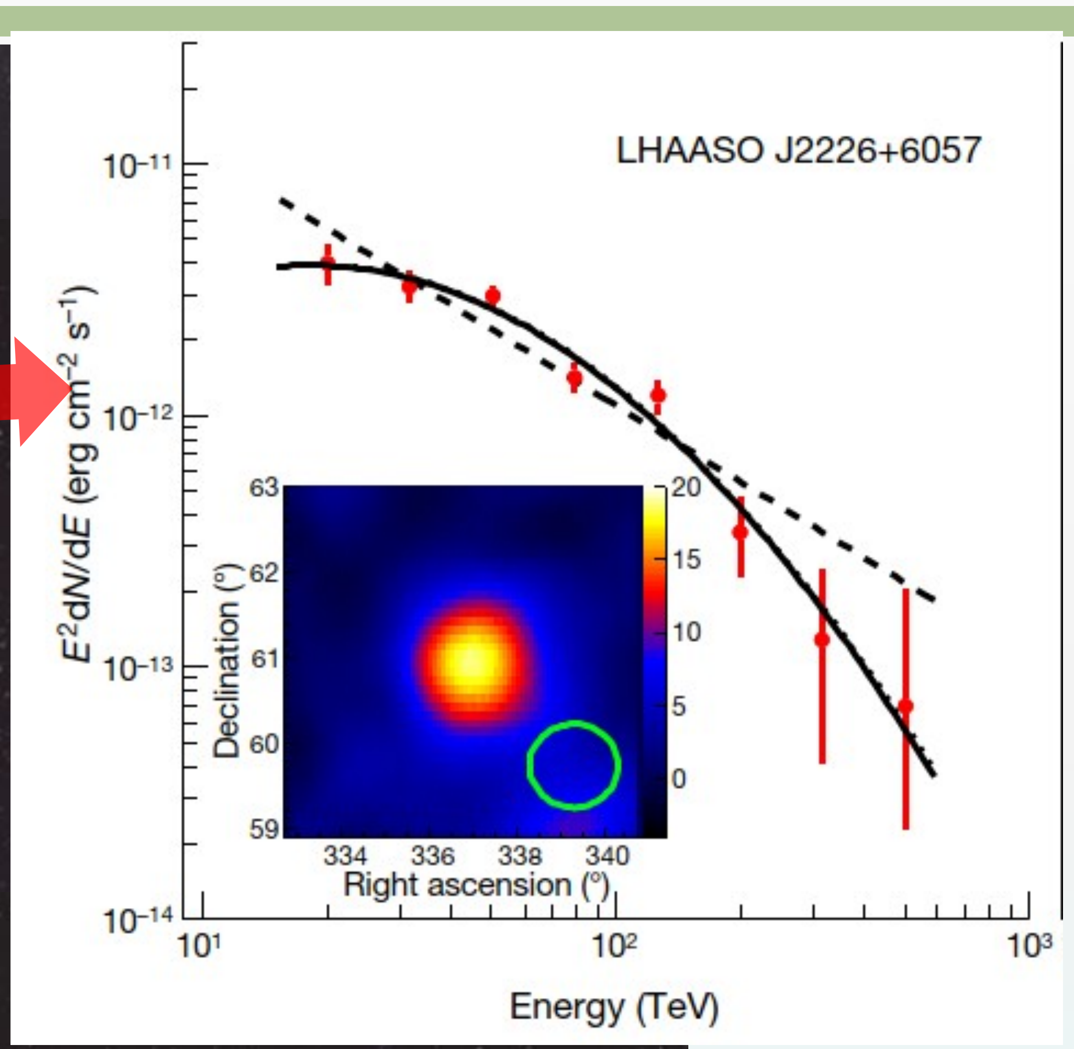
Do not observe clear cut-off up to ~1 PeV







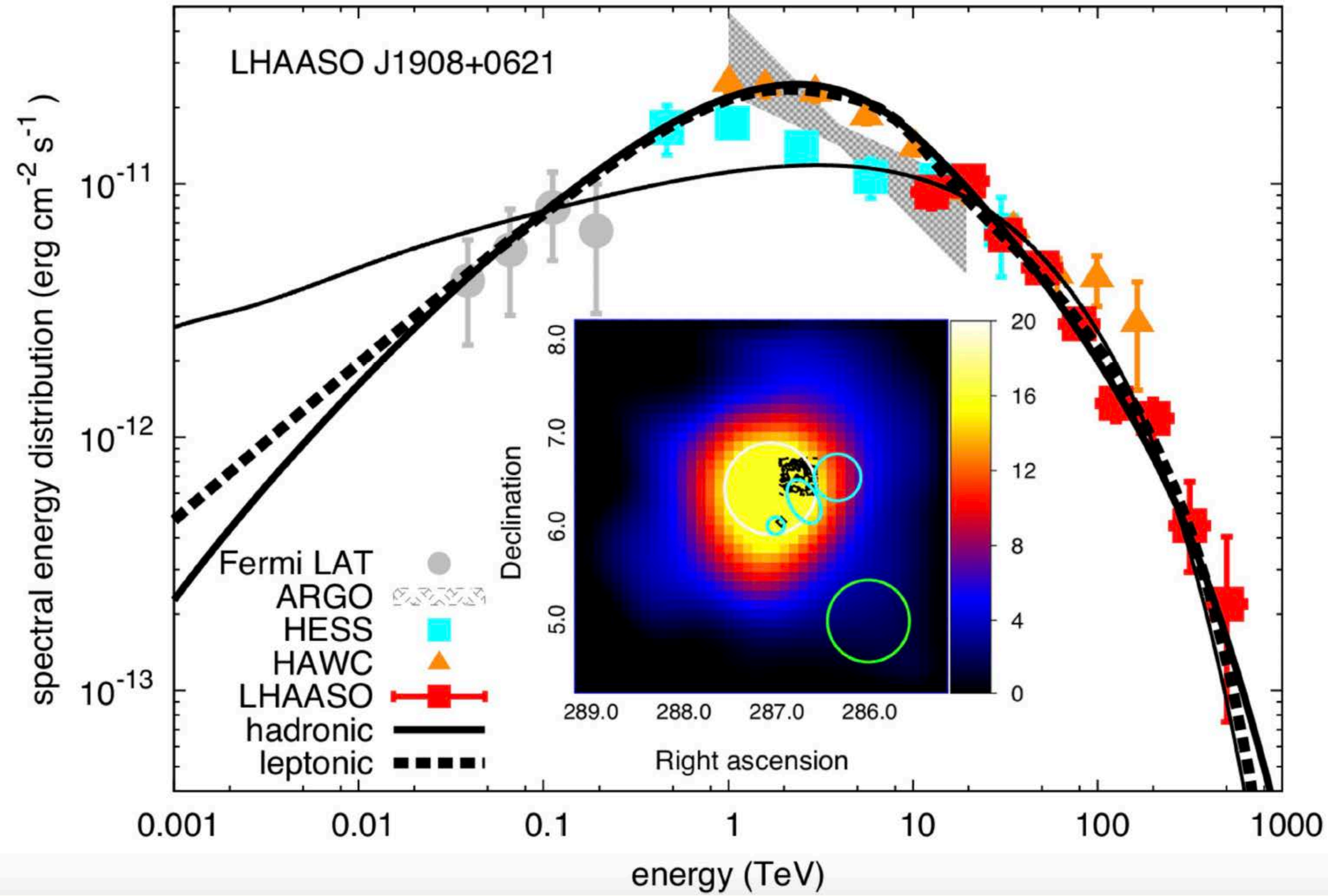
LHAASO, Nature, 594, p.33-36, 2021



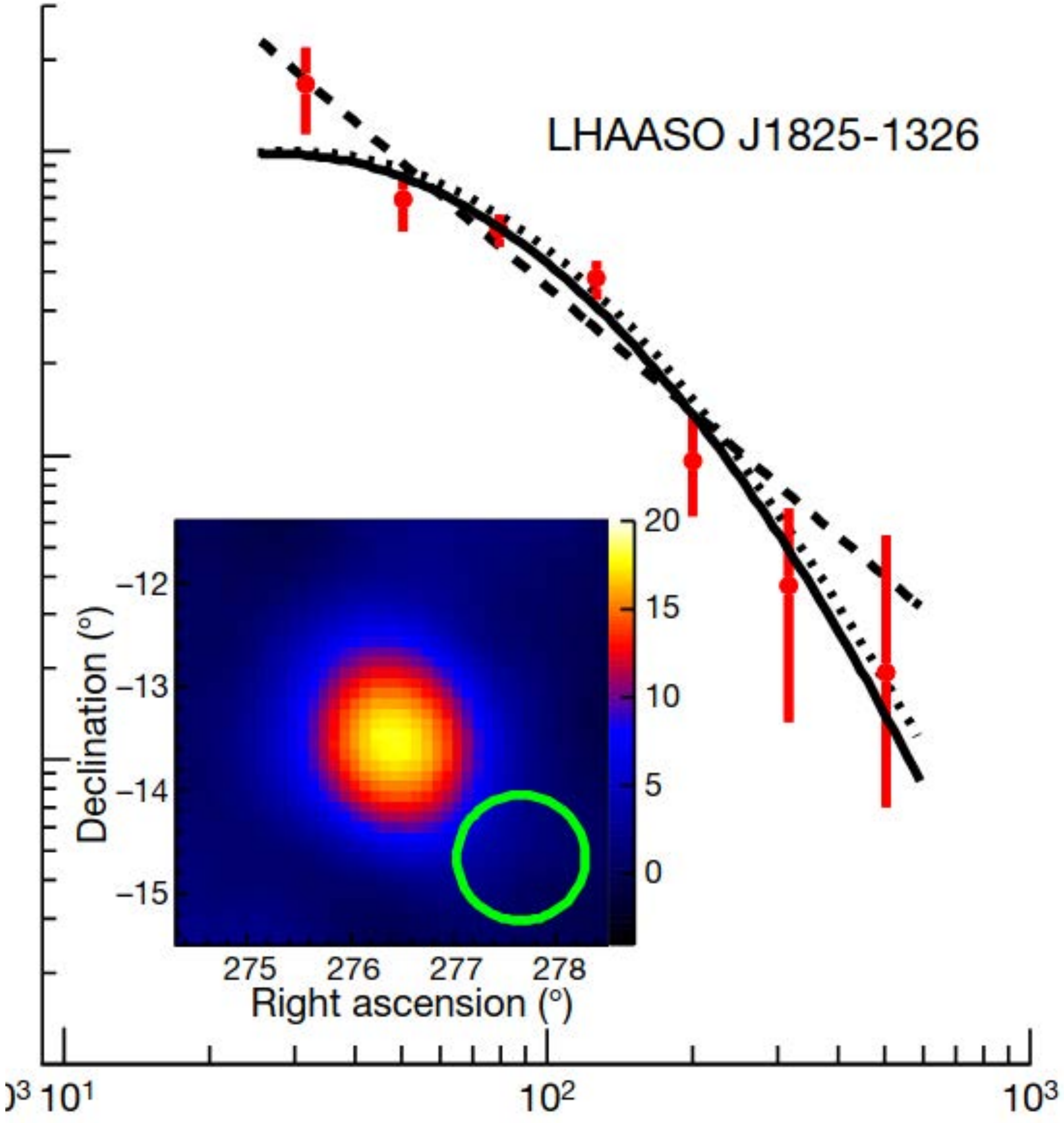
Three brightest PeVatrons

- No trend of cut-off in SED of γ−ray sources
- Updates using newer data show continuous extension to higher energies

E_{max} (PeV) 0.57 +- 0.19 0.44 +- 0.55 0.42 +- 0.16


LHAASO J1908+0621
spectral energy distribution (erg cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
0.001
0.01
0.1
1
10
100
1000
energy (TeV)
Fermi LAT
ARGO
HESS
HAWC
LHAASO
hadronic
leptonic
Declination
8.0
7.0
6.0
5.0
289.0
288.0
287.0
286.0
Right ascension
20
16
12
8
4
0

LHAASO J1825-1326



2021Natur.594...33C

>100 TeV:

sign=16.4σ （Extension=0.3°)

R.A.=276.45°

Decl.−13.45°

The 68% contamination angle is 0.62°

for LHA ASO J1825-1326

HESS J1825-137

PSR B1823-13 (PSR J1826-1334)

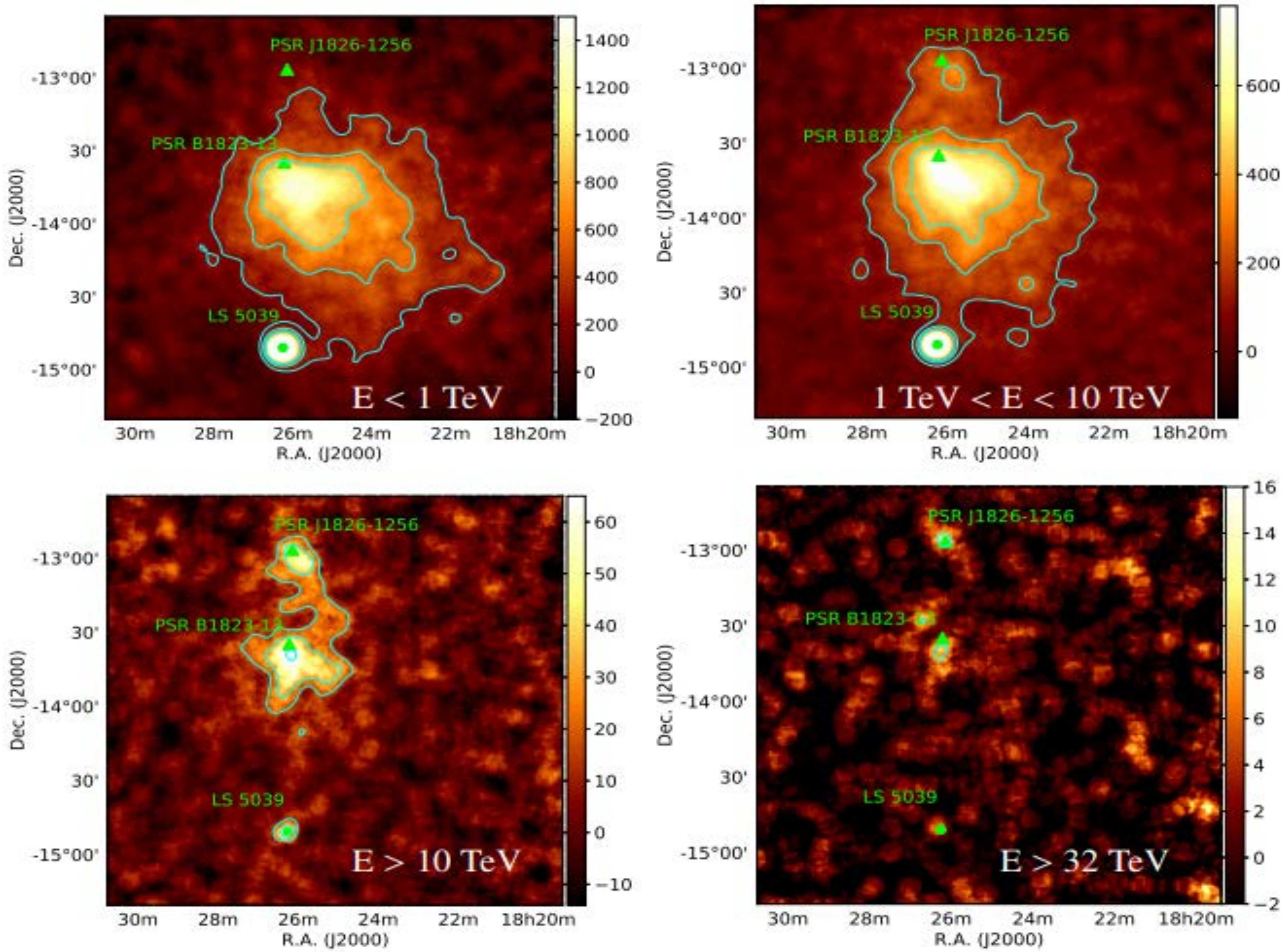
RA: 18 h 26 m 13.06 s
Dec: −13° 34'48.1"

Age $\tau = 2.14\times 10^{4}$ yr

$\dot{E}=2.8\times 10^{36}\ \mathrm{erg\ s^{-1}}$

period $P = 0.1015$ s

Distance:~ 4 kpc



H.E.S.S. Collaboration 2019

HESS J1826-130

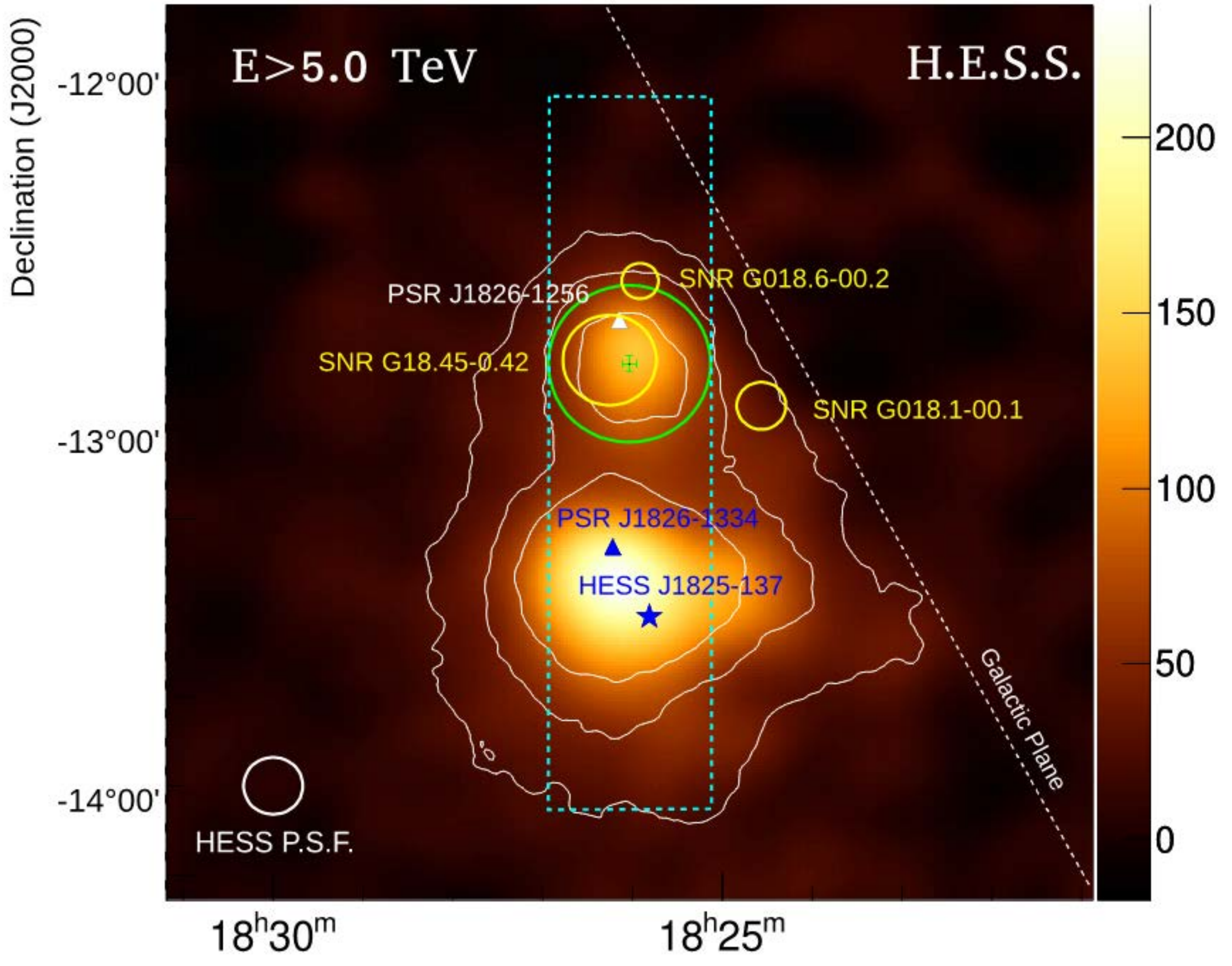
The Fermi/LAT detected the radio-quiet γ -ray pulsar PSR J1826 − 1256

RA: 276.54°
Dec: −12.94°

Age $\tau = 1.44\times 10^4$ yr

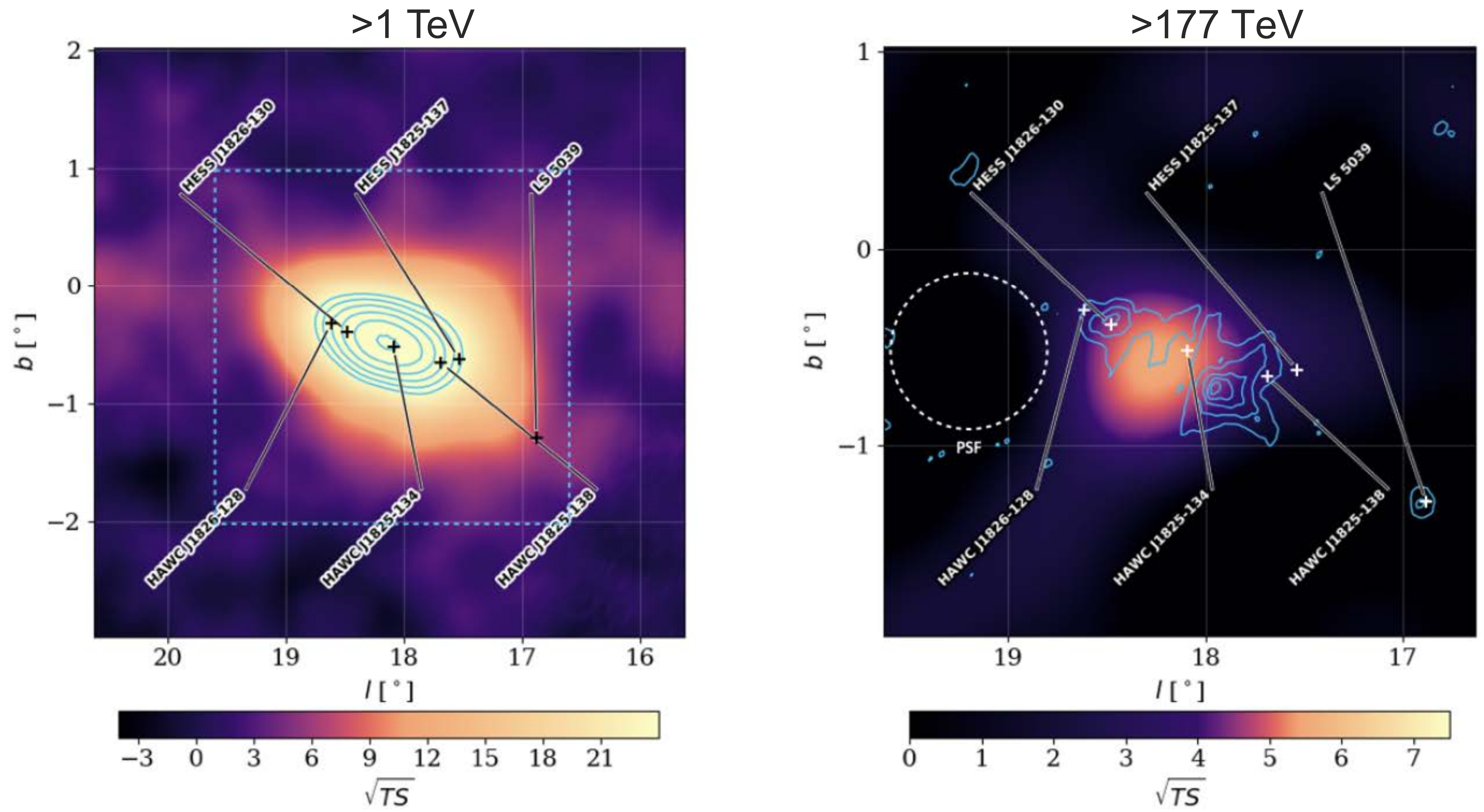
$\dot{E}=3.6\times 10^{36}$ erg s^{-1}

PSR J1826-1256 to HESS J1825-137
Distance： 0.64°



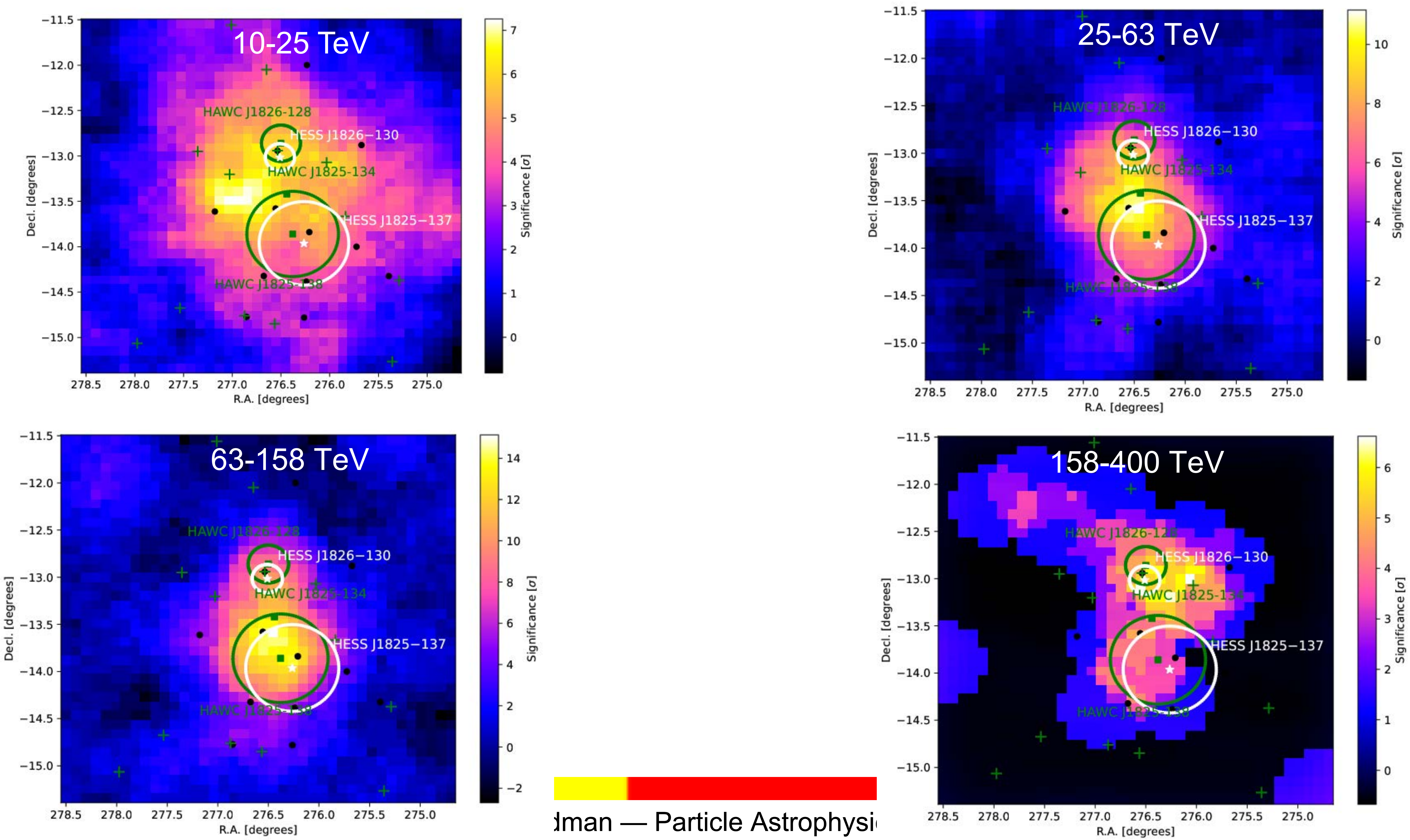
H.E.S.S. Collaboration 2020

eHWC J1825-134

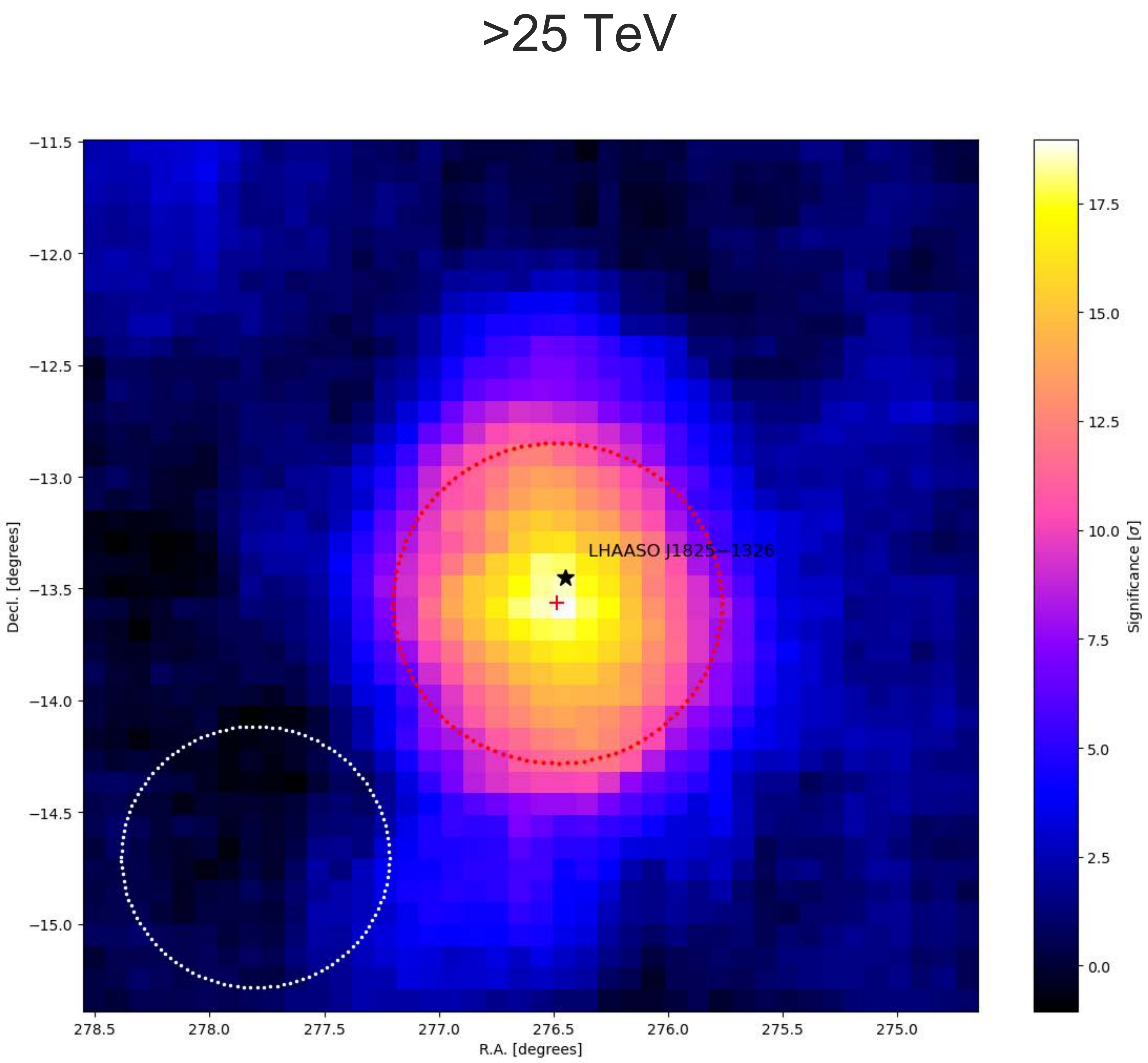


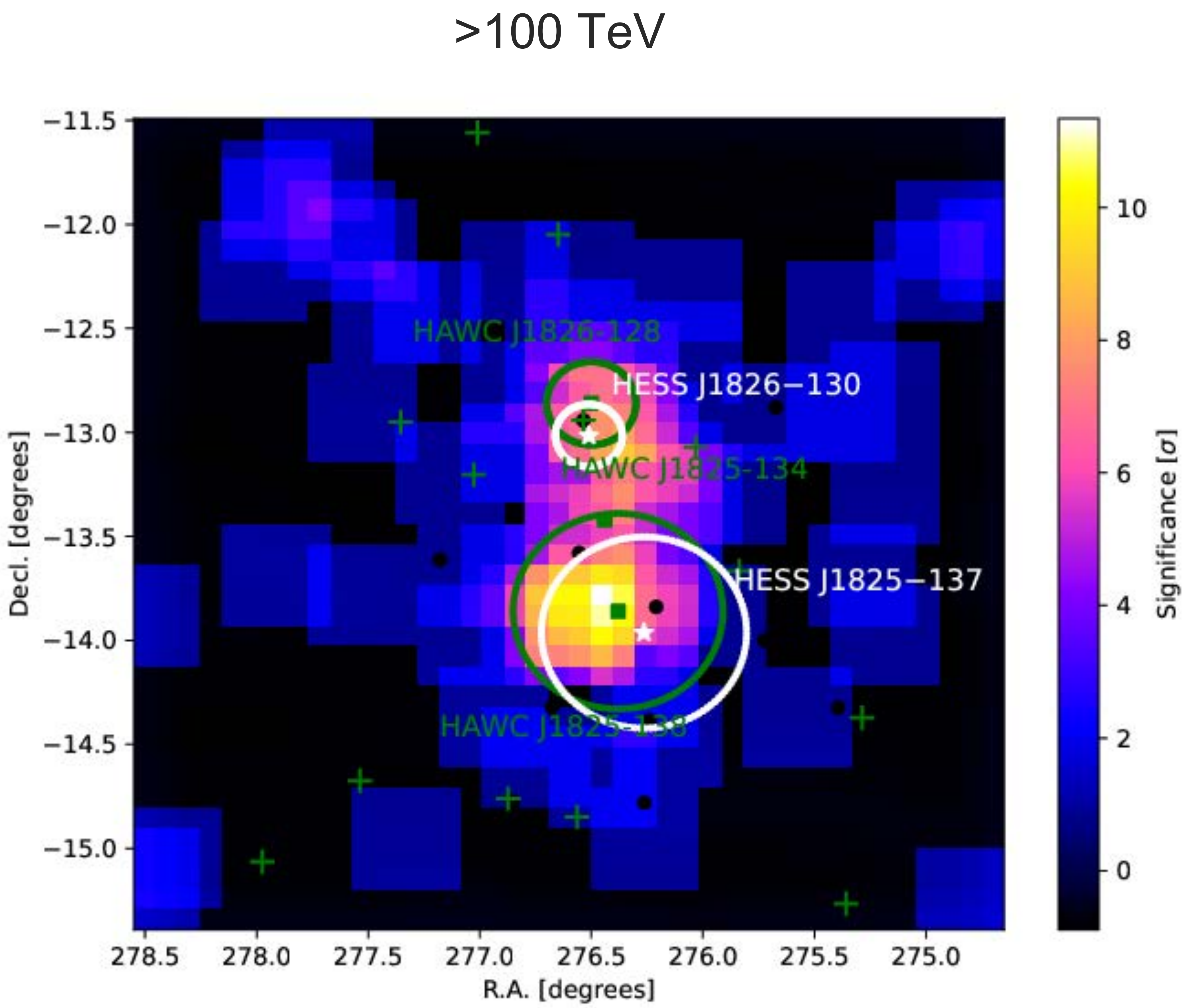
Albert et al. 2021

J1825-134 Energy dependent morphology



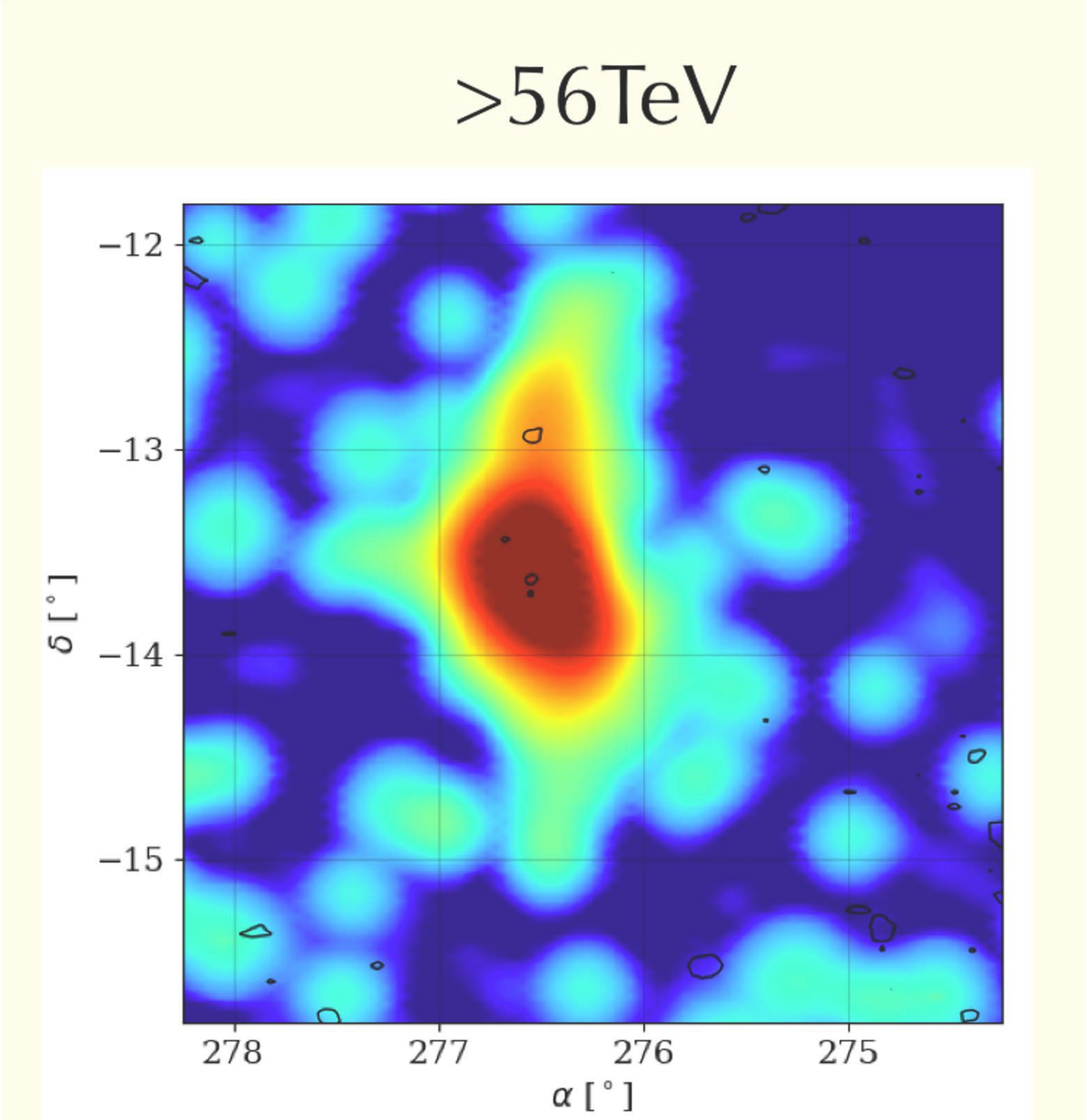
J1825-134 >25 TeV & >100 TeV morphology





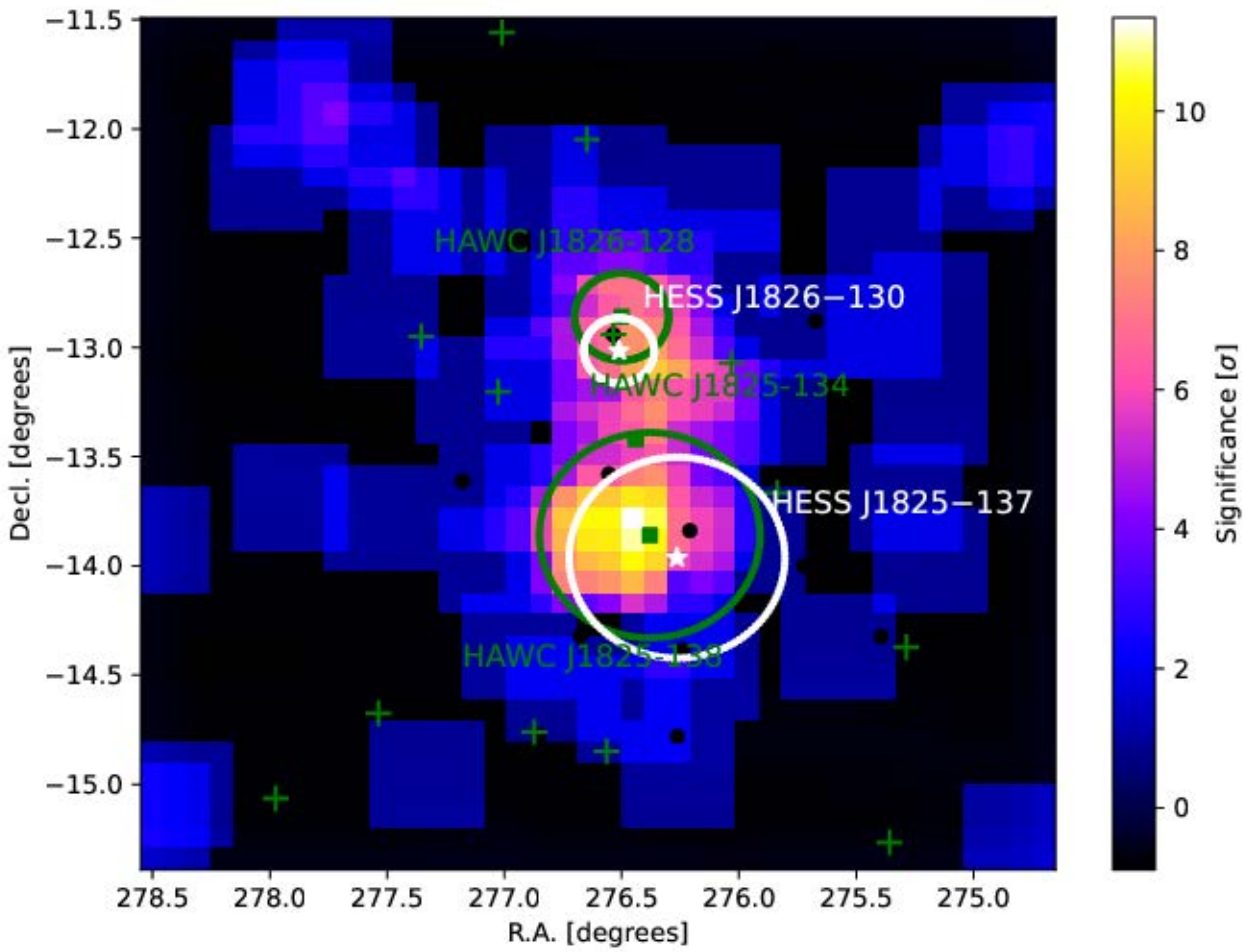
J1825-134 >25 TeV & >100 TeV morphology

HAWC



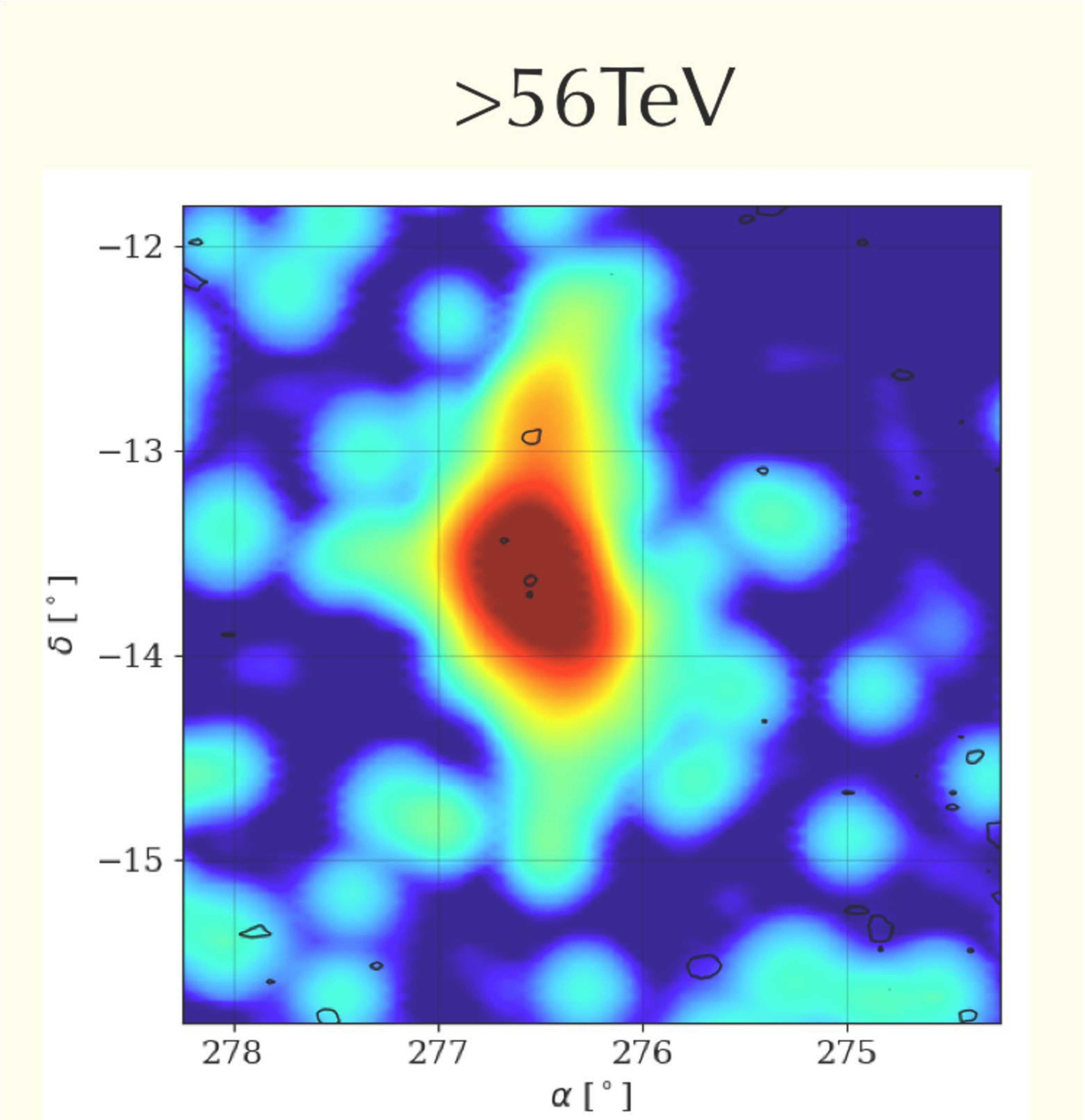
LHAASO

>100 TeV

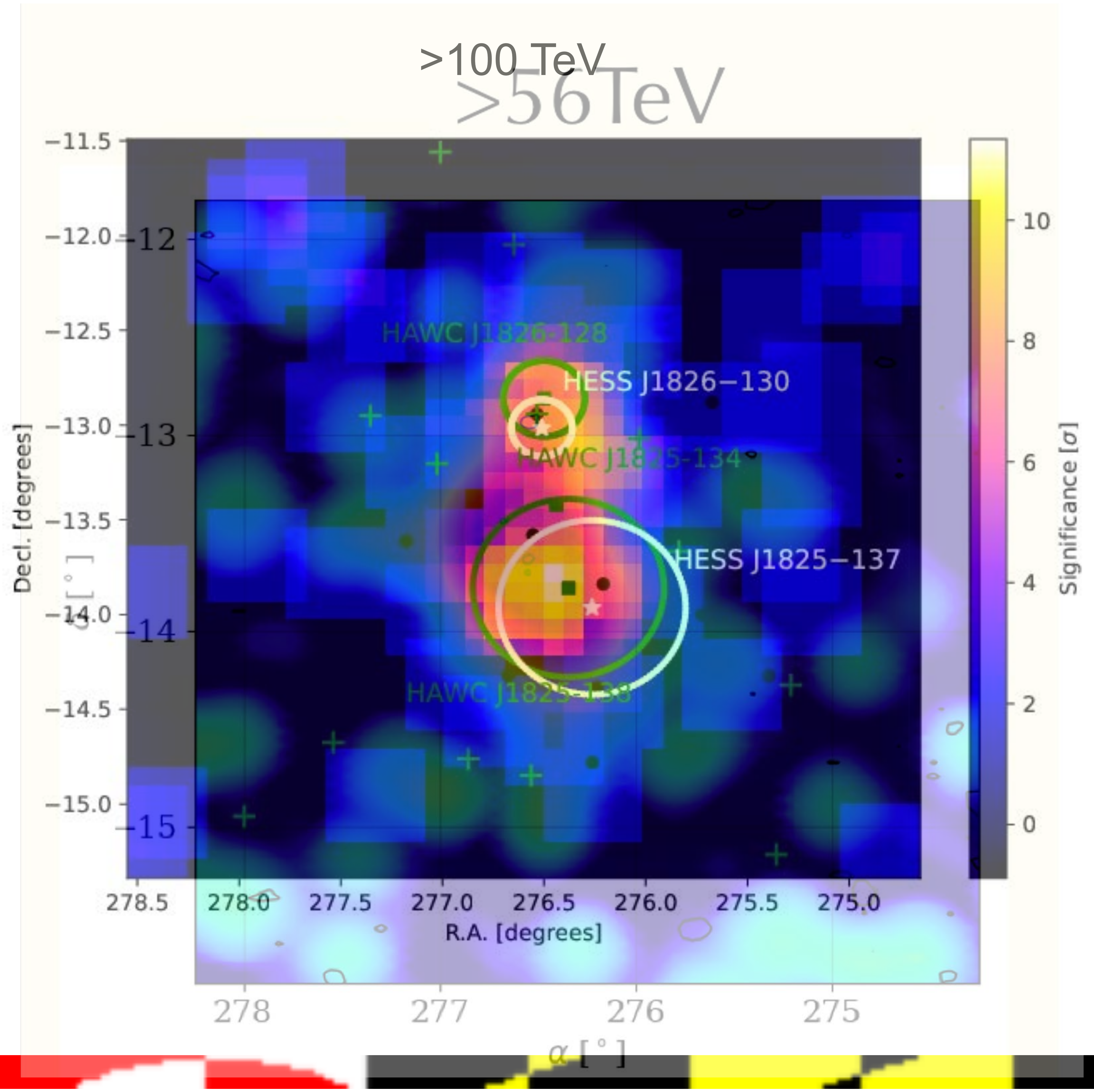


J1825-134 >56 TeV & >100 TeV morphology

HAWC

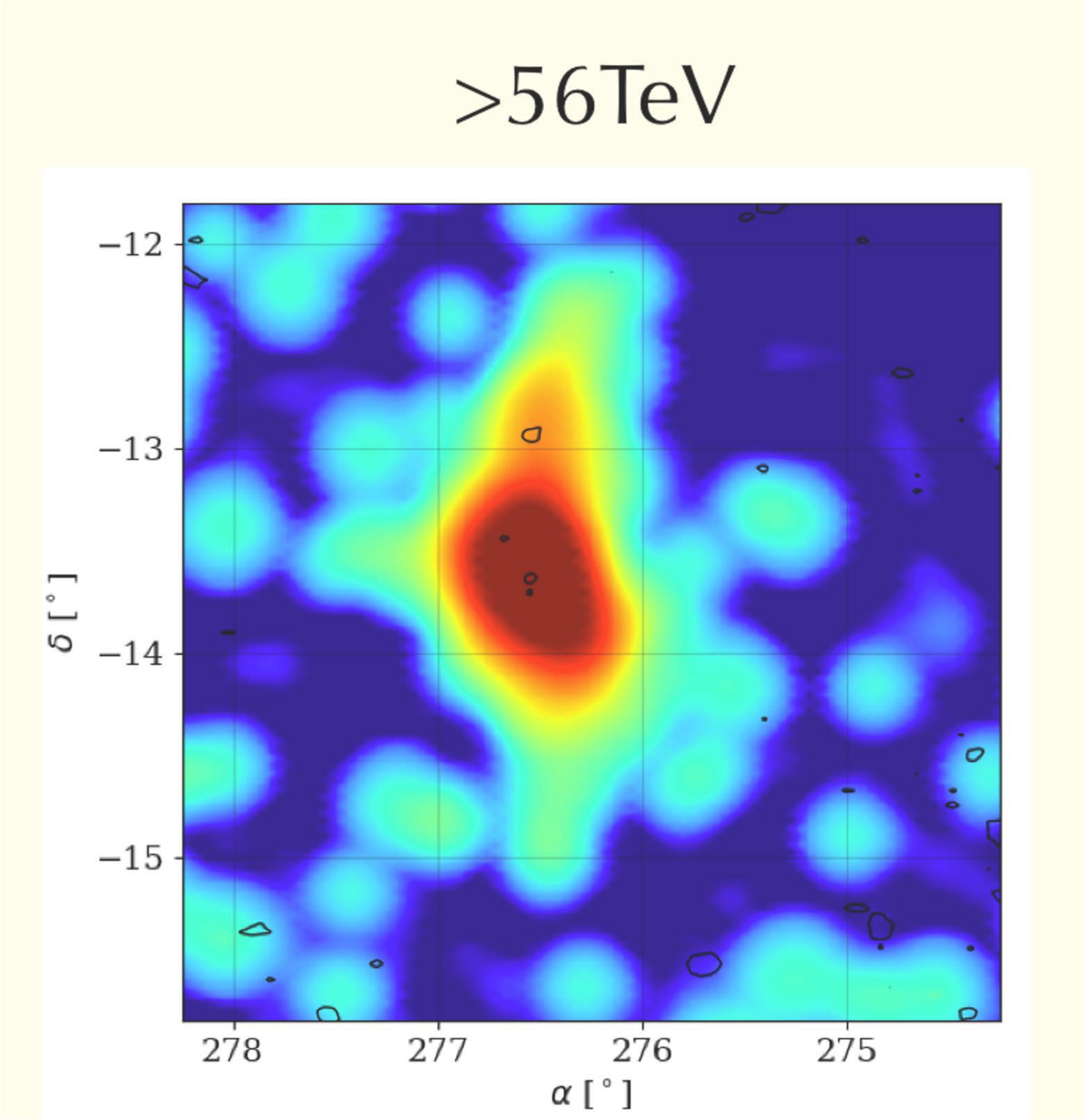


LHAASO

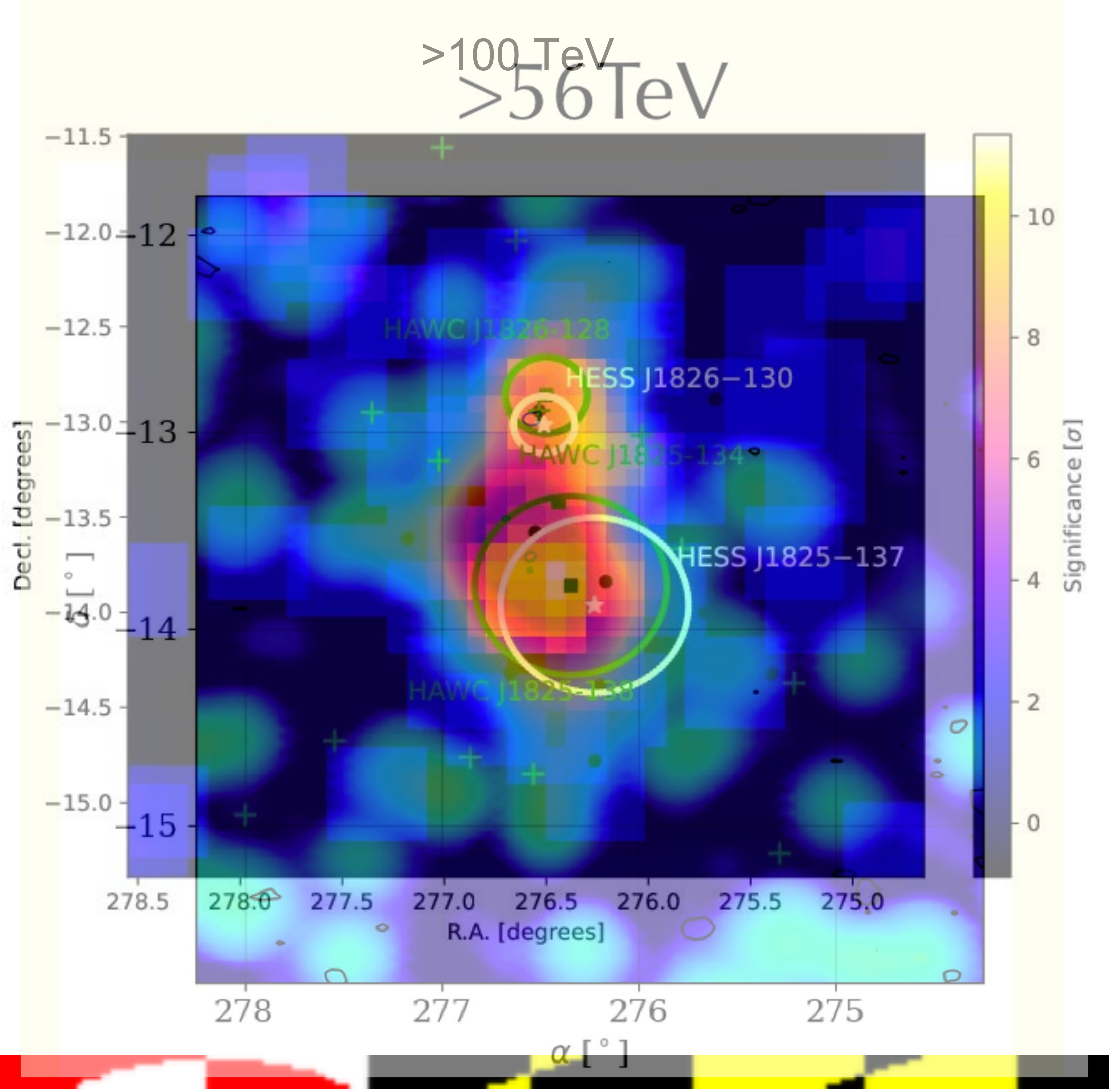


J1825-134 >56 TeV & >100 TeV morphology

HAWC

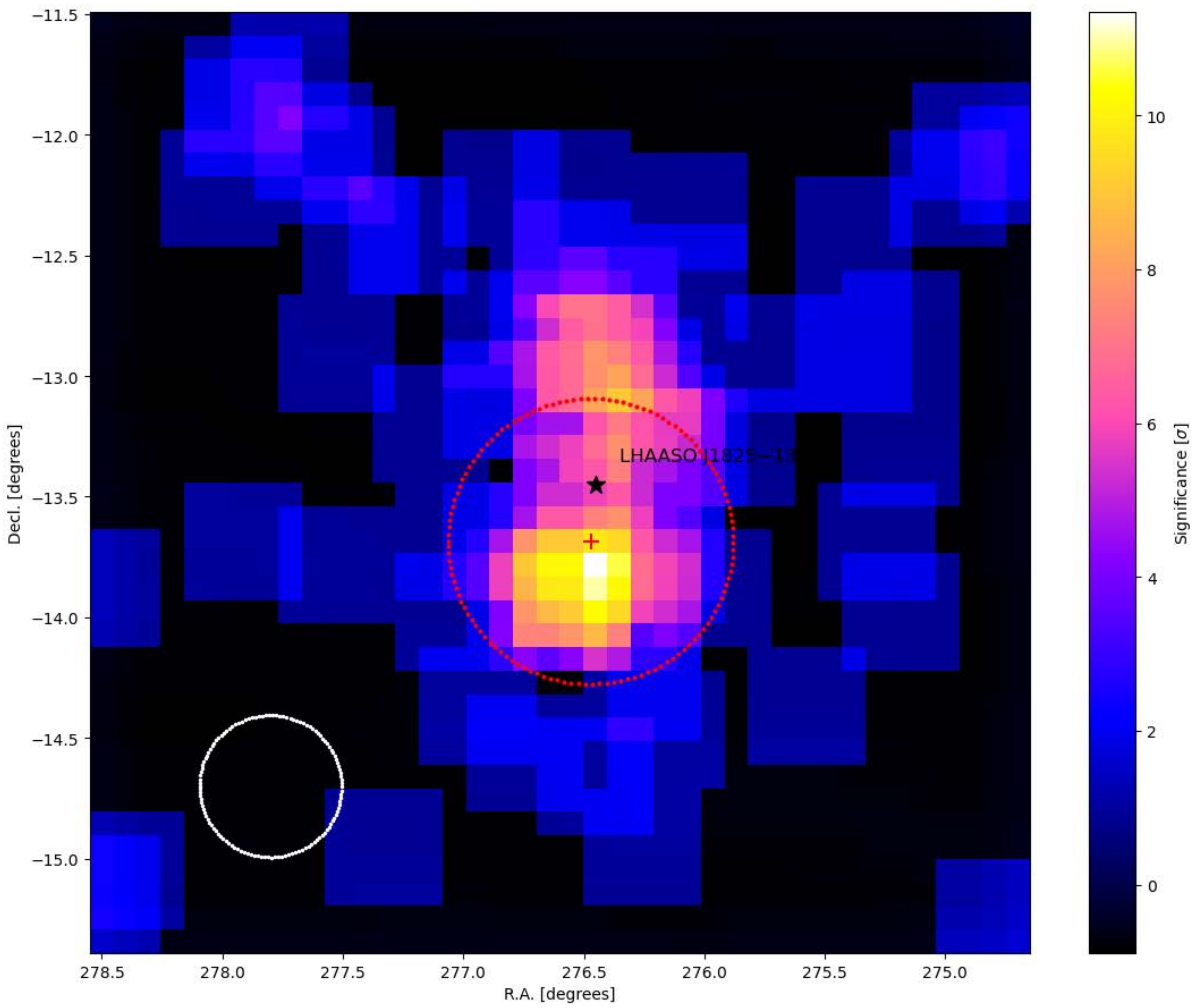


LHAASO



>100 TeV morphology

sign=16.4σ
Extension=0.3°
R.A.=276.45°
Decl.−13.45°



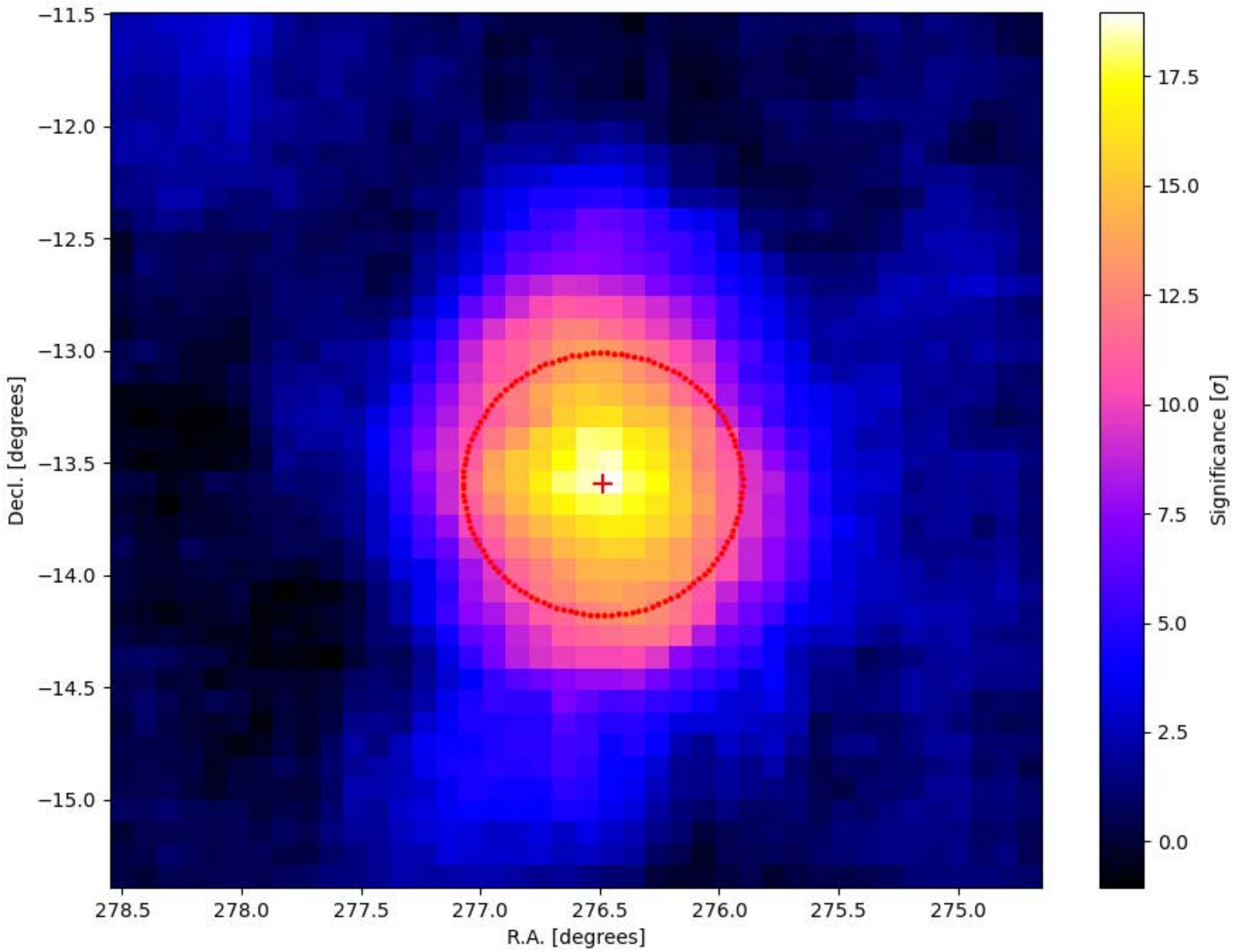
sign=15.0σ
Extension=0.34
ra = 276.47° +0.12° -0.15°
dec = -13.69° +0.33° -0.18°

Morphology test: point-like source

ra = 276.49° +/-0.03°
Dec = -13.59°+/-0.04°
PSF(σ)=0.387°

-loglikelihood:
L0=1684.56
L1=1470.97
TS: 427.18

>25 TeV



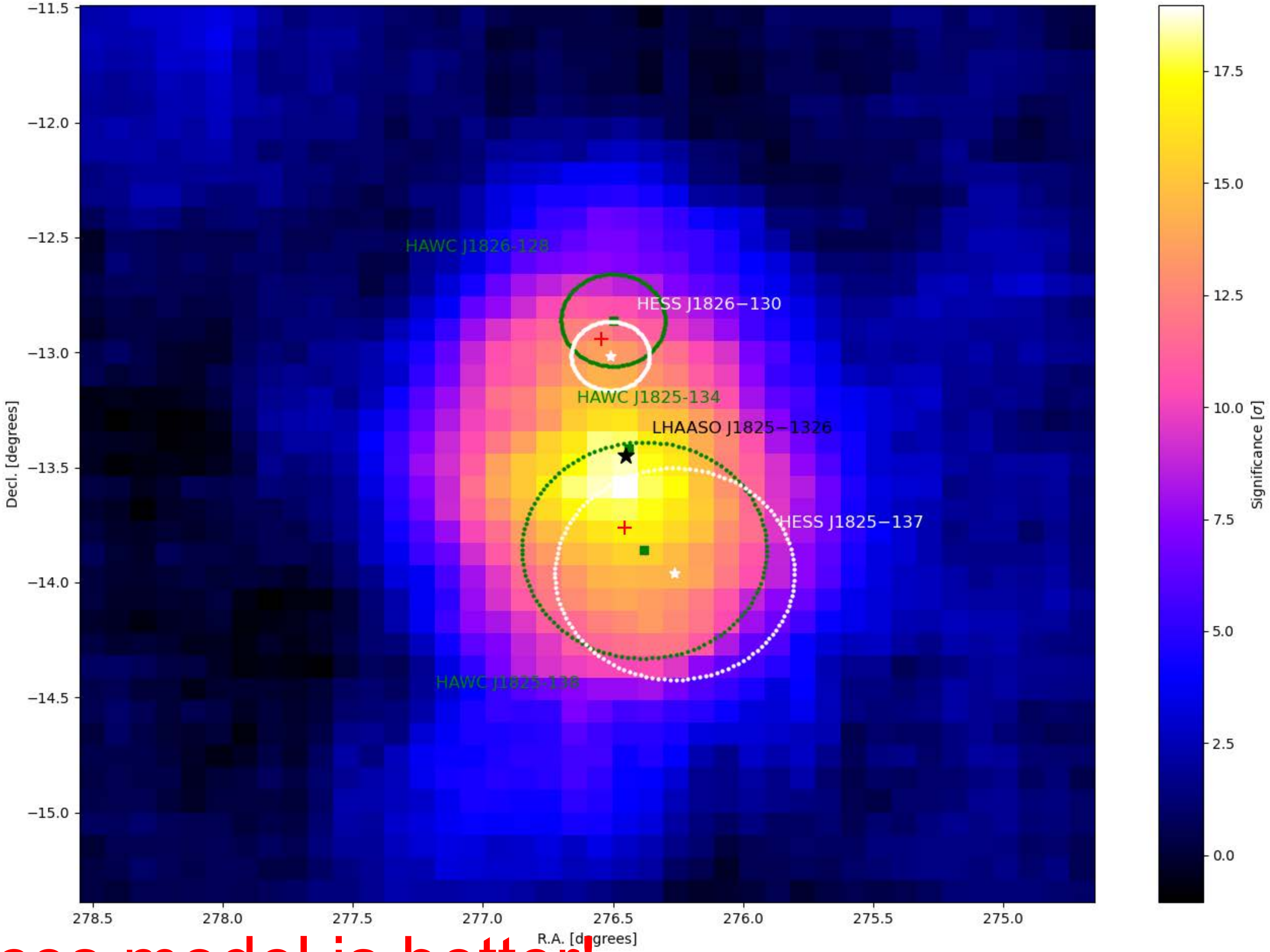
Morphology test: two point-like sources

ra = 276.46° +/-0.04°
Dec = -13.76°+0.05°-0.06°

ra = 276.54° +/-0.06°
Dec = -12.94°+0.10°-0.11°

-loglikelihood:
L0=1684.56
L1=1454.14
TS_2pts=33.67

TS_ext<TS_2pts



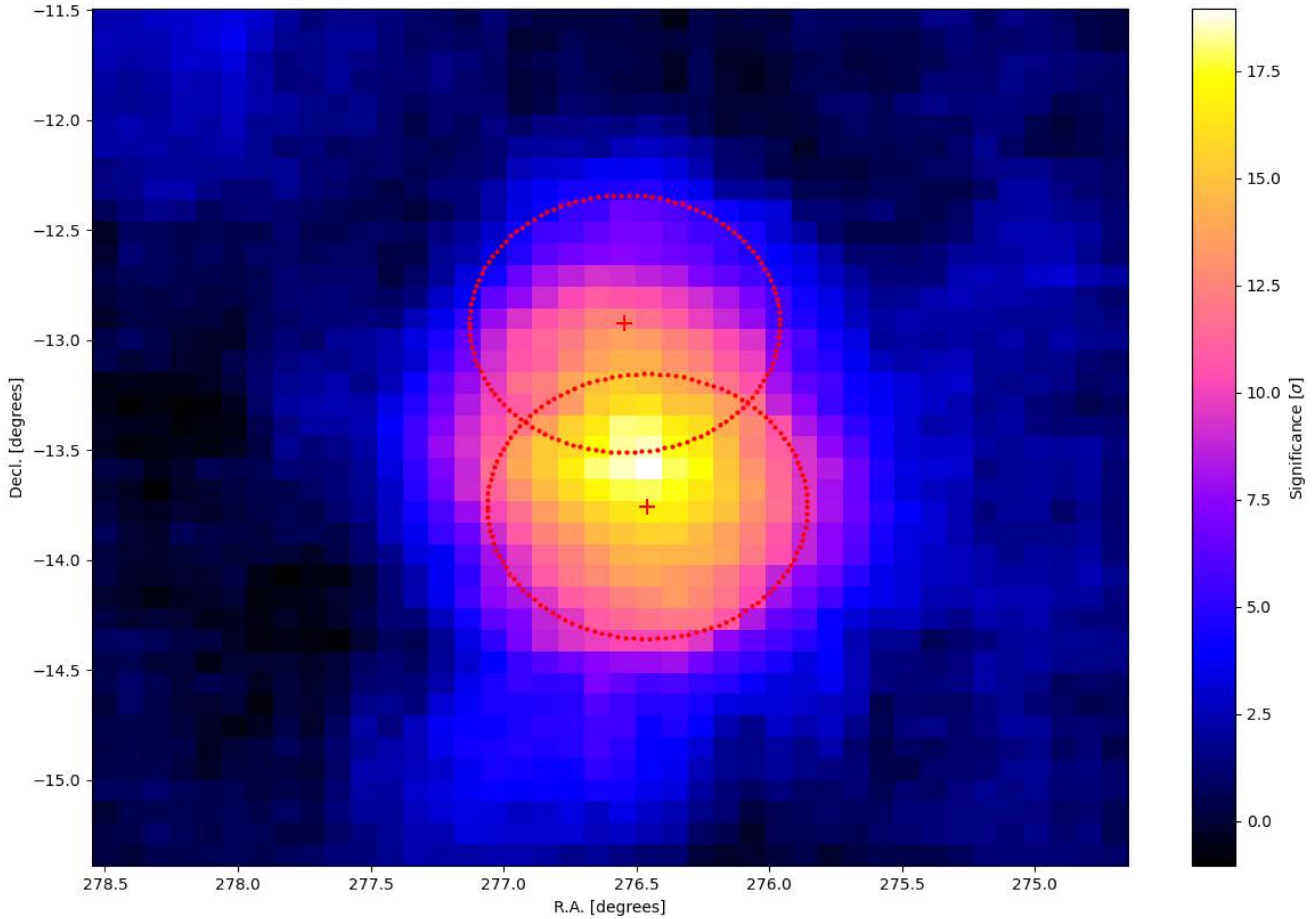
Two sources model is better!

Morphology test: 2-D Gaussian+PS

TS_ext=0.68
sigma_ul=0.33°
(95%)

TS_ext=0.41
sigma_ul=0.25°(95%)

Two point-like sources!

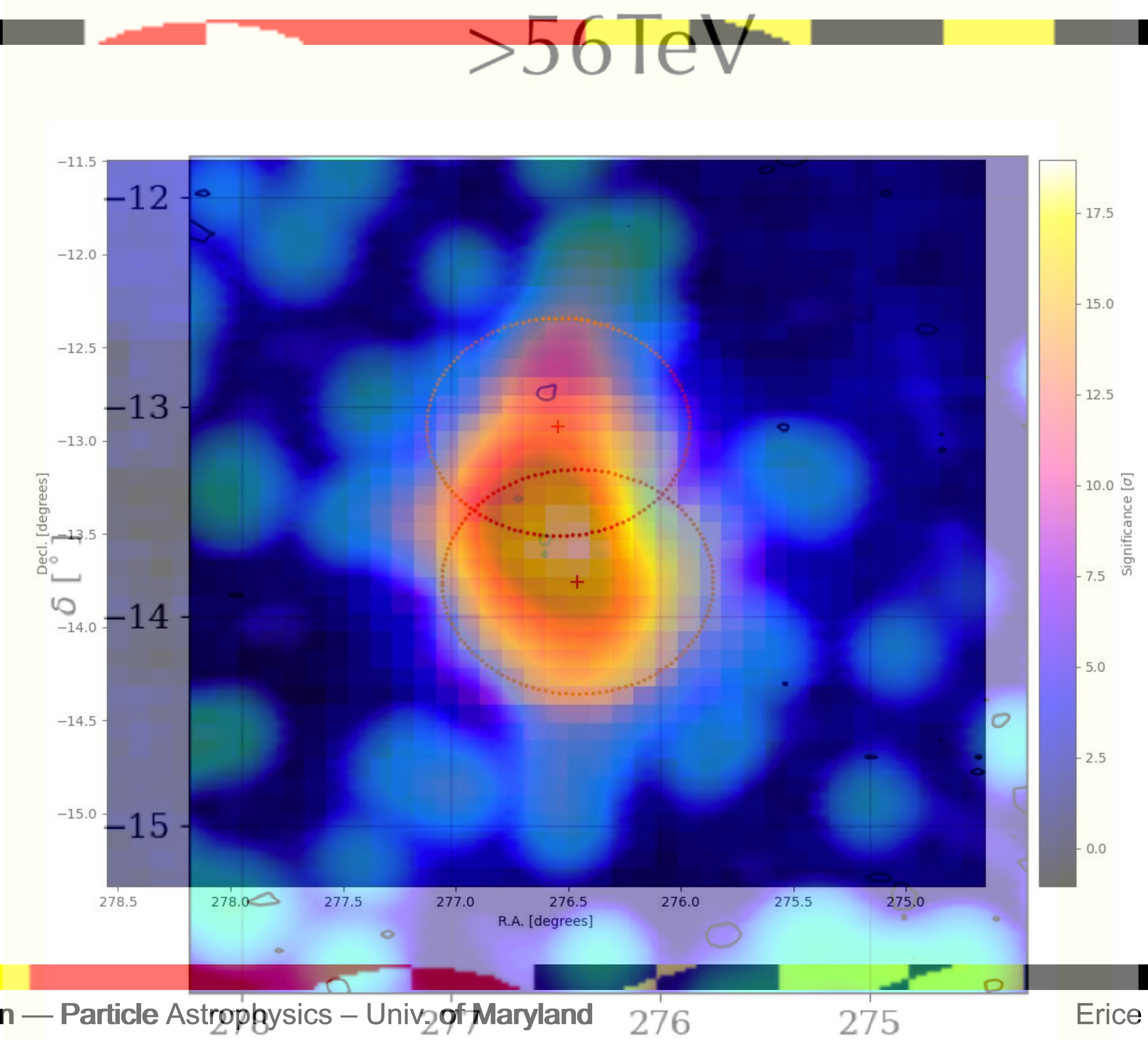


Morphology test: 2-D Gaussian+PS

TS_ext=0.68
sigma_ul=0.33°
(95%)

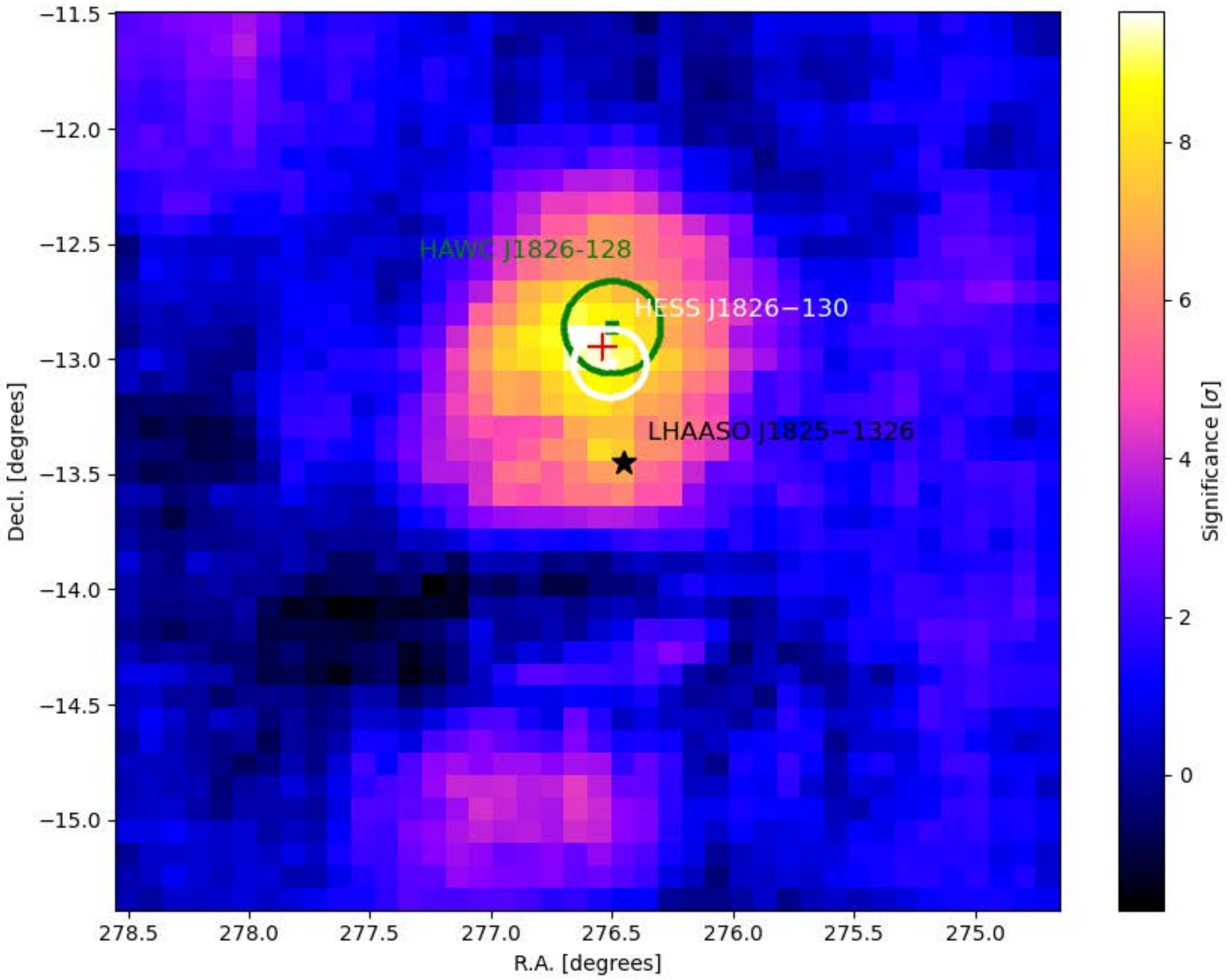
TS_ext=0.41
sigma_ul=0.25°(95%)

Two point-like sources!



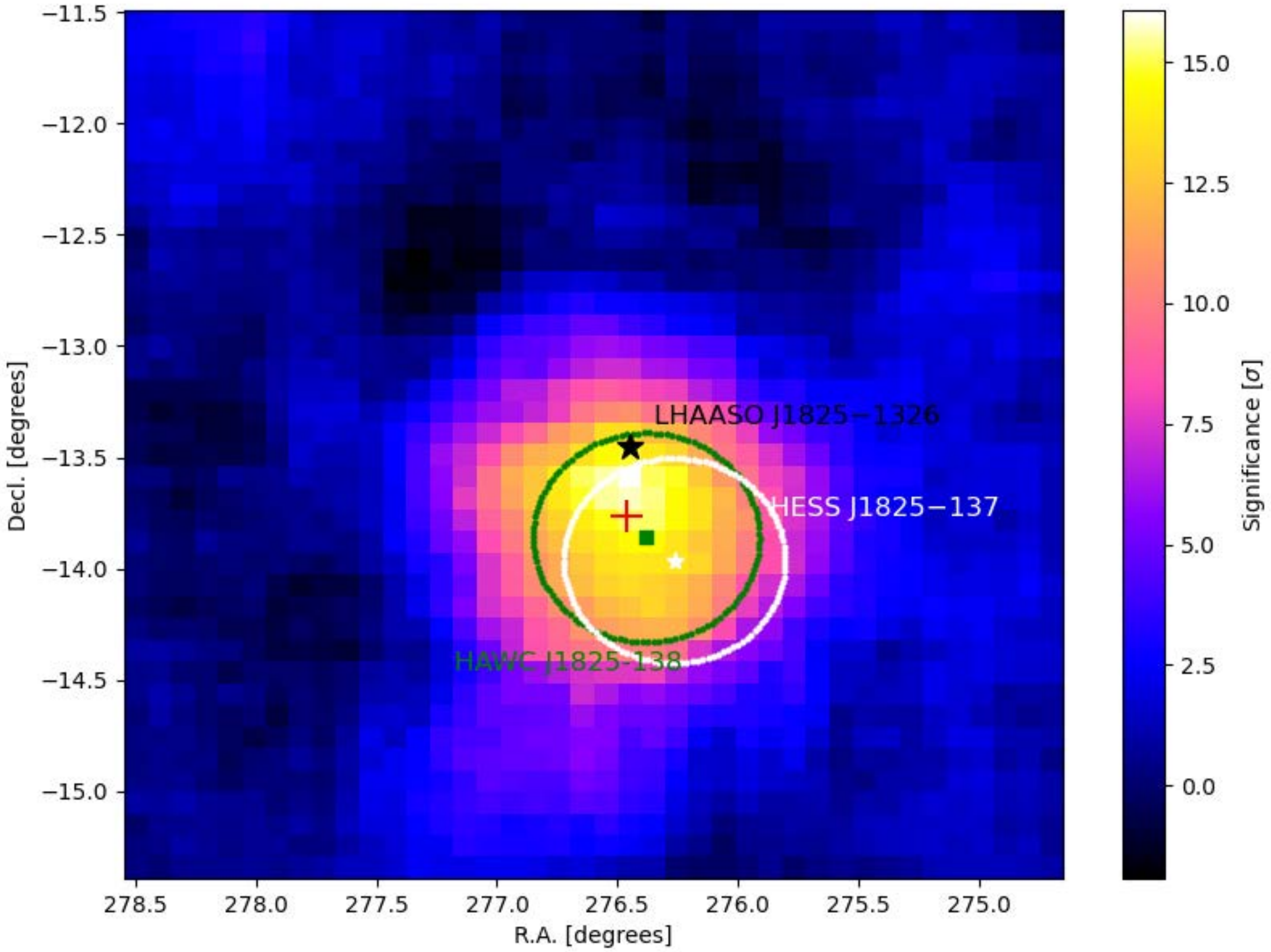
LHAASO J1826-1256 & J1825-1345(>25 TeV)

LHAASO J1826-1256



TS=214.08

LHAASO J1825-1345



TS=393.73

LHAASO J1826-1256 & J1825-1345(>100 TeV)

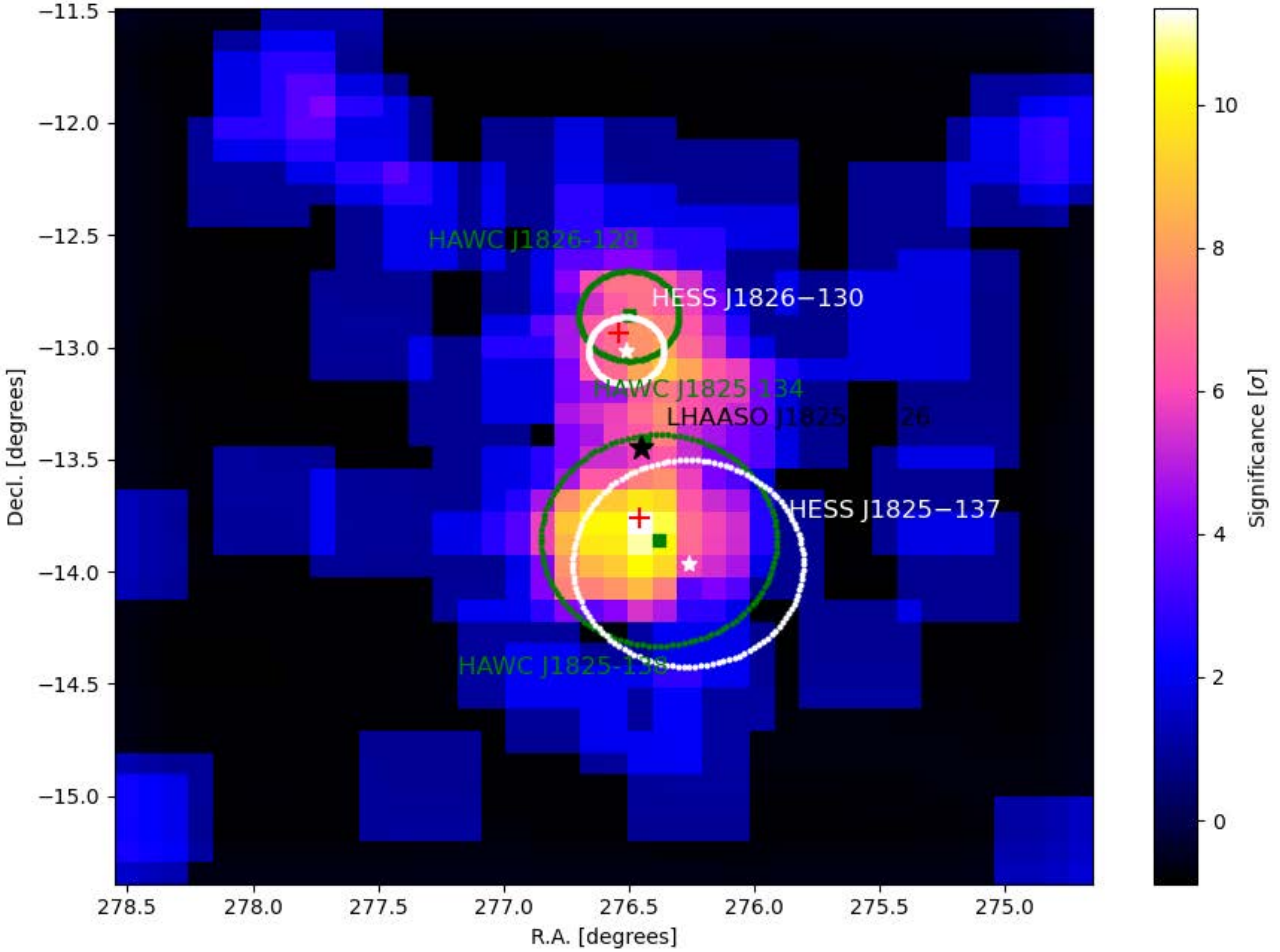
LHAASO J1825-1326

LHAASO J1826-1256

TS=100.95

LHAASO J1825-1345

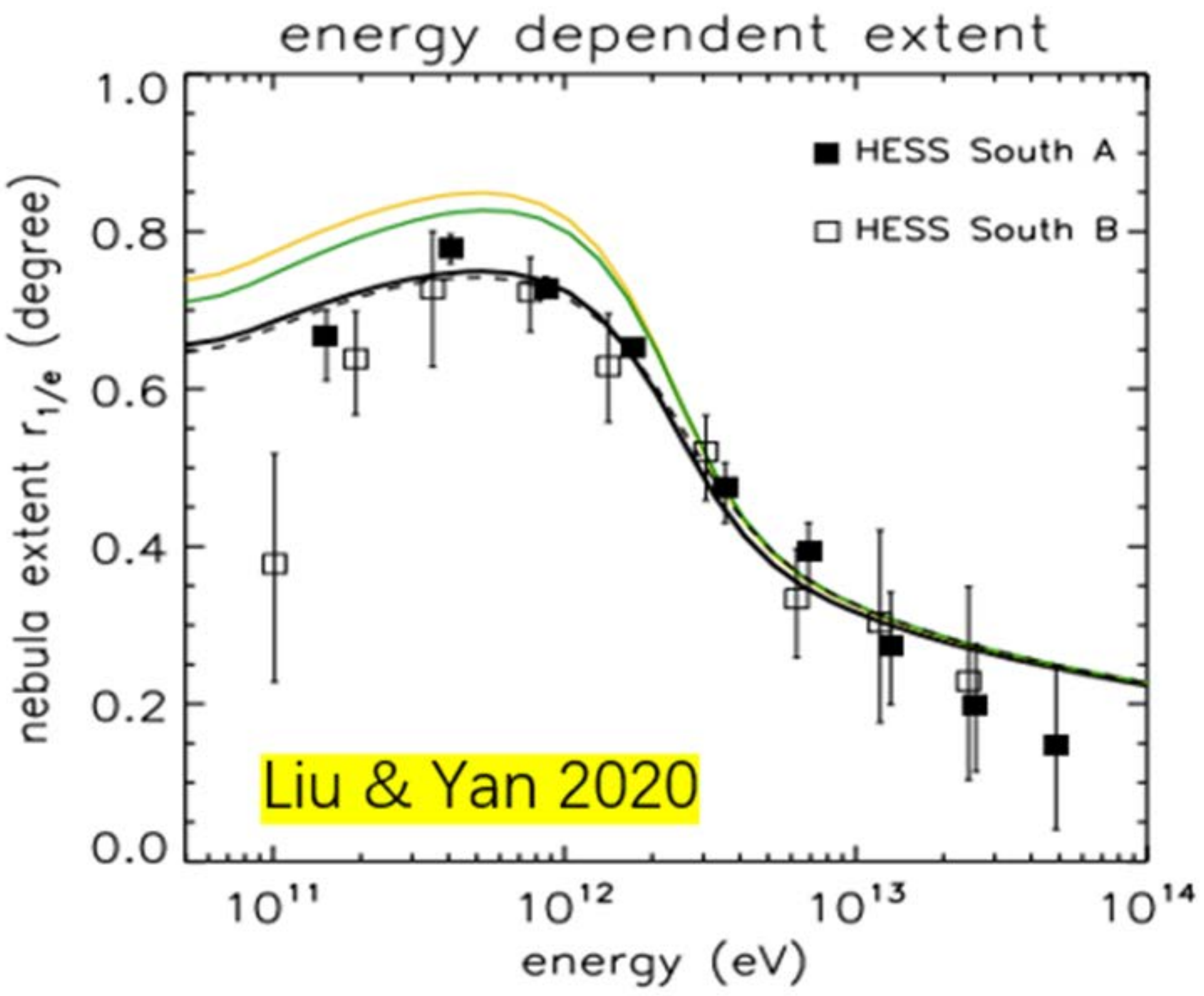
TS=164.88



Summary

Two UHE sources:
LHAASO J1825-1345 & LHAASO J1826-1256
Associated with HESS and observation,

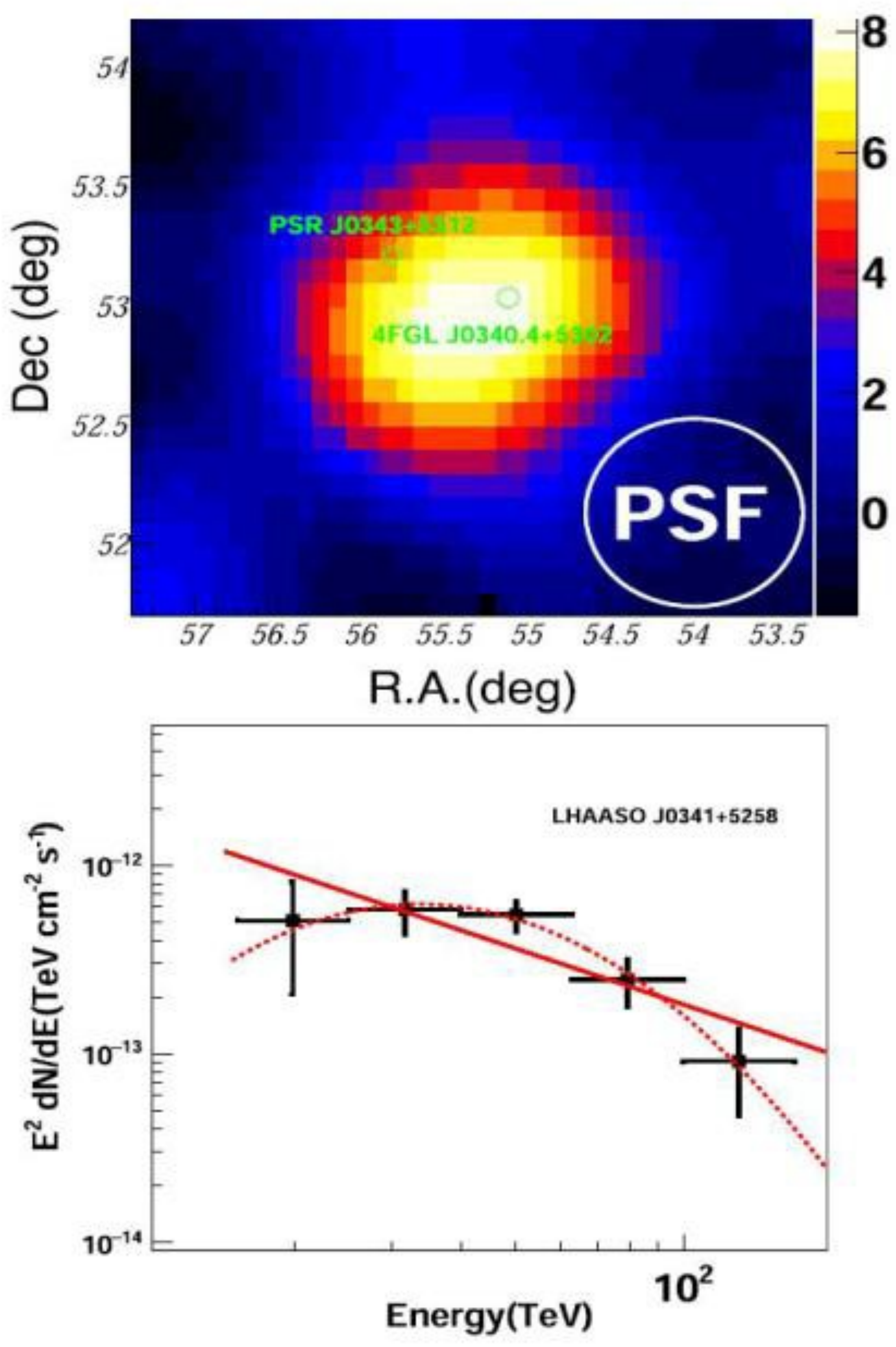
HESS J1825-137



New Source Discovery

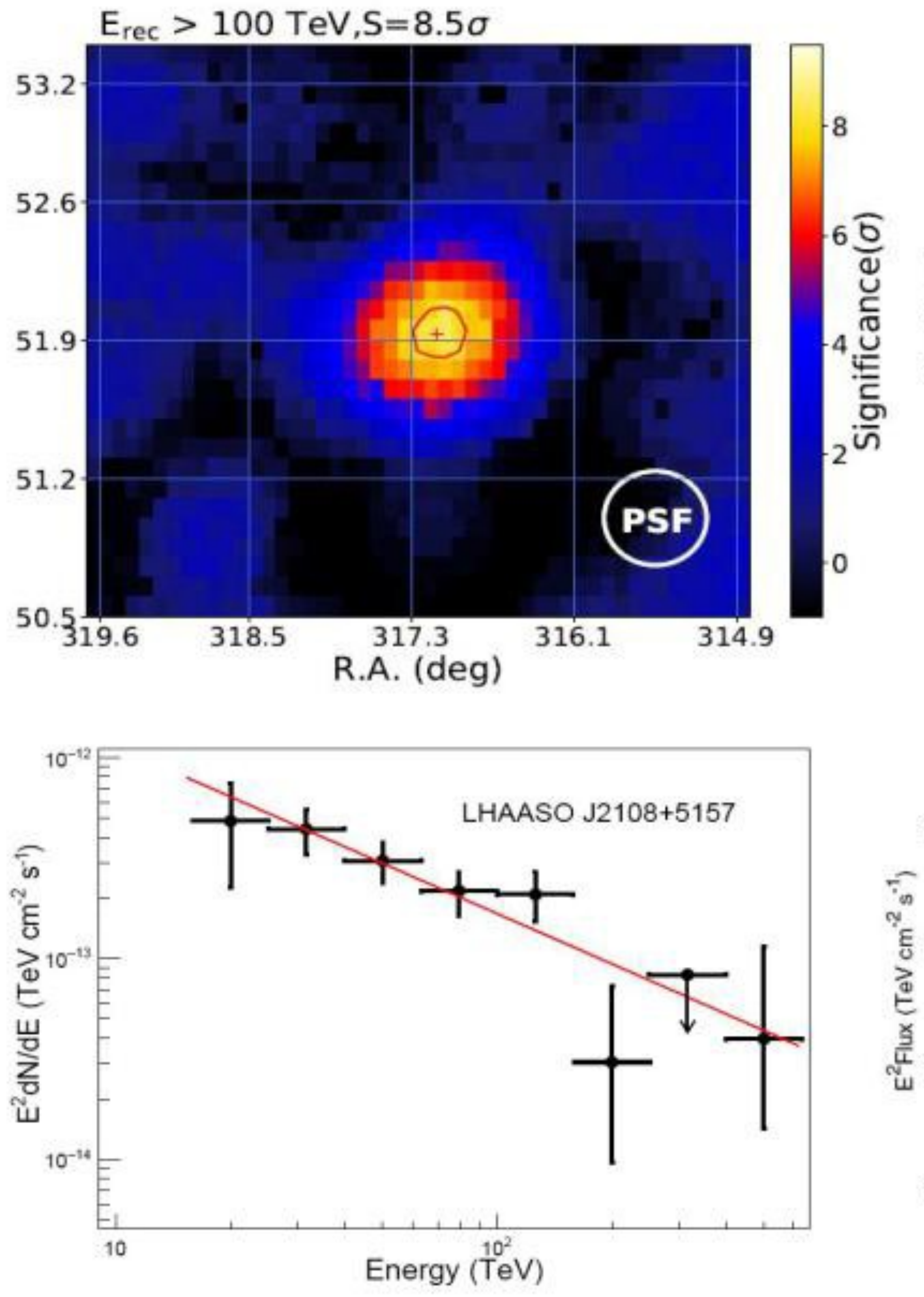
- WCDA has accumulated data for 16 months
- KM2A for 12 months
- LHAASO catalog Ver-1 will be published soon with many new VHE/UHE sources discovered

LHAASO J0341+5258



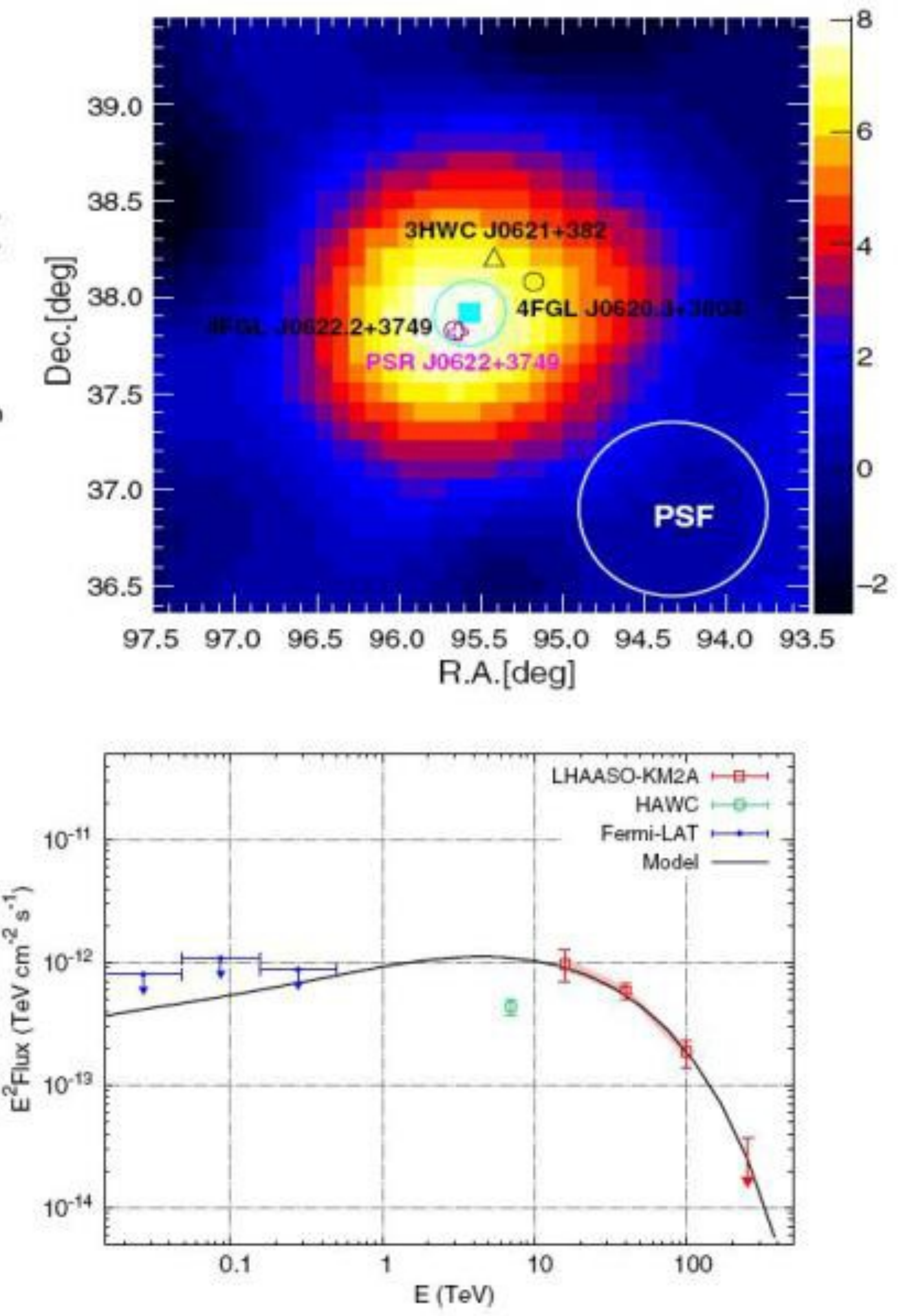
ApJL 917:L4 (2021)

LHAASO J2108+5157

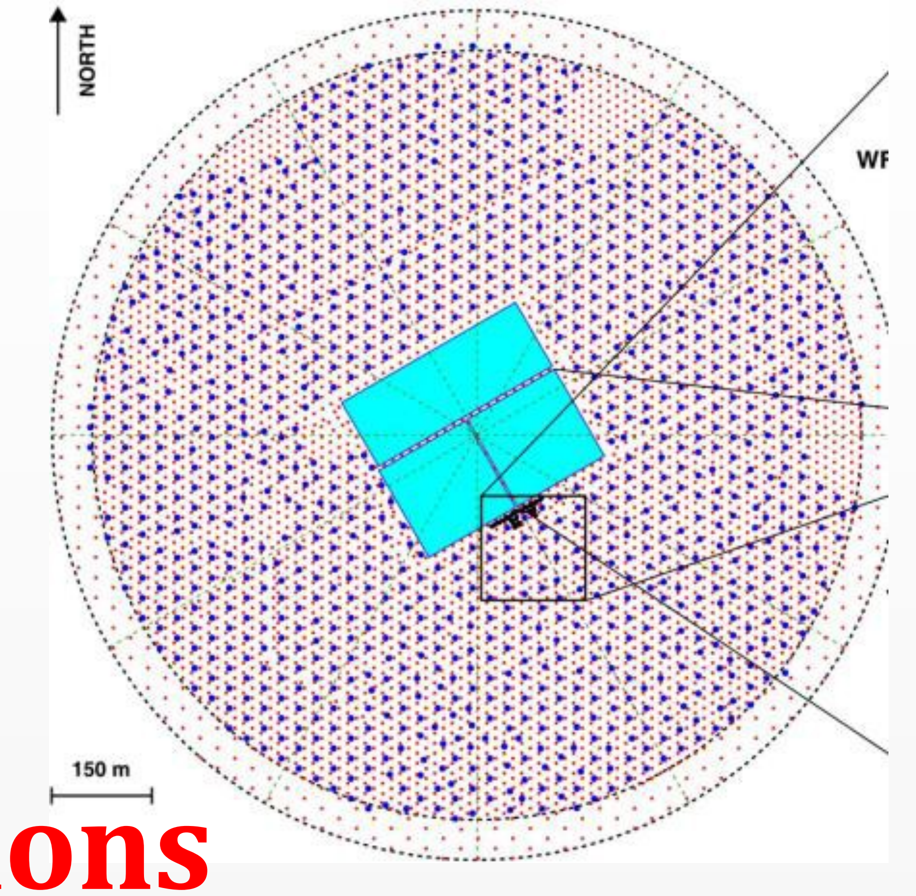


ApJL 919:L22 (2021)

Halo of PSR J0622 + 3749



PRL 126:241103 (2021)

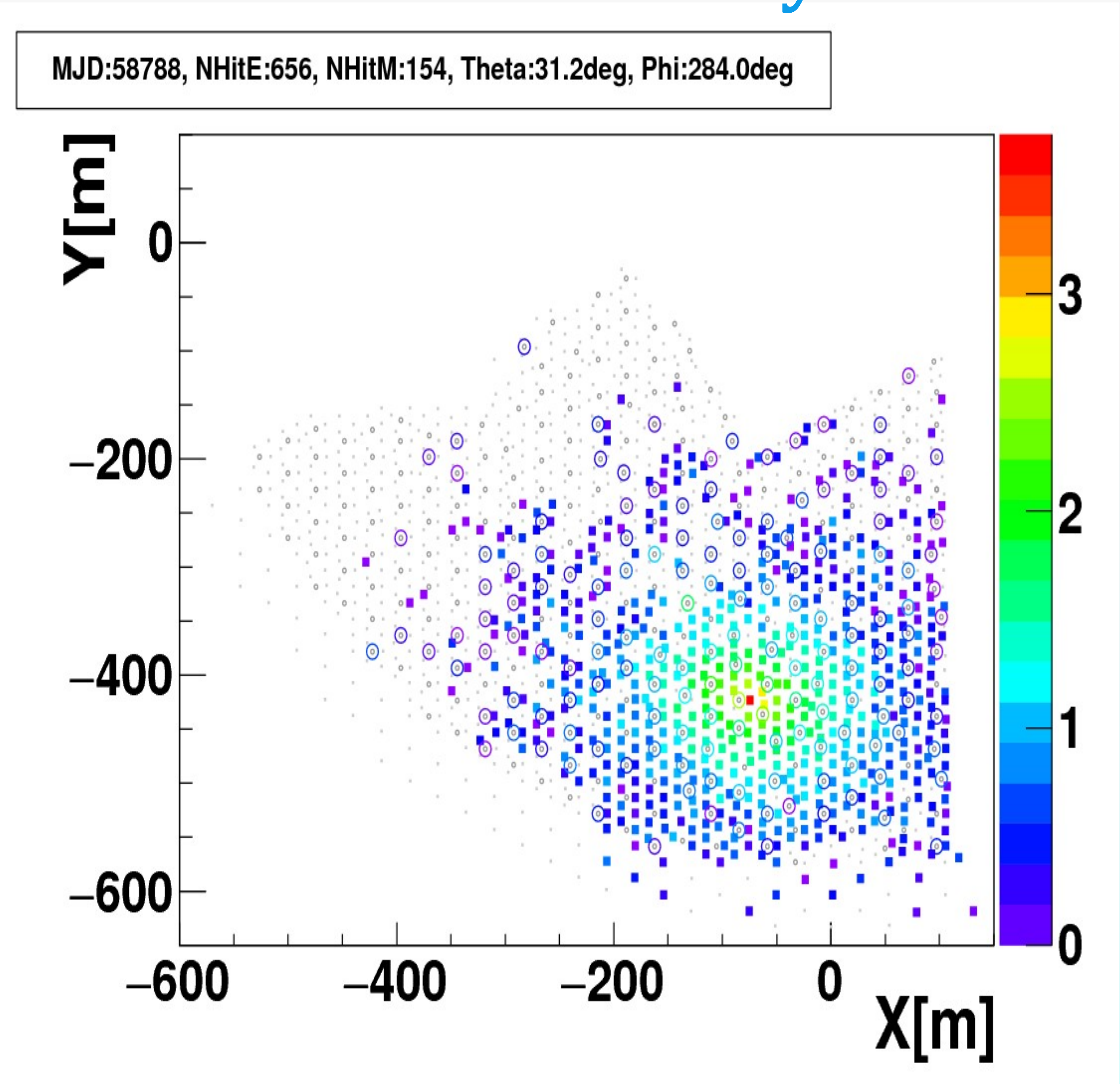


KM2A

Selection of γ–rays out of CR background

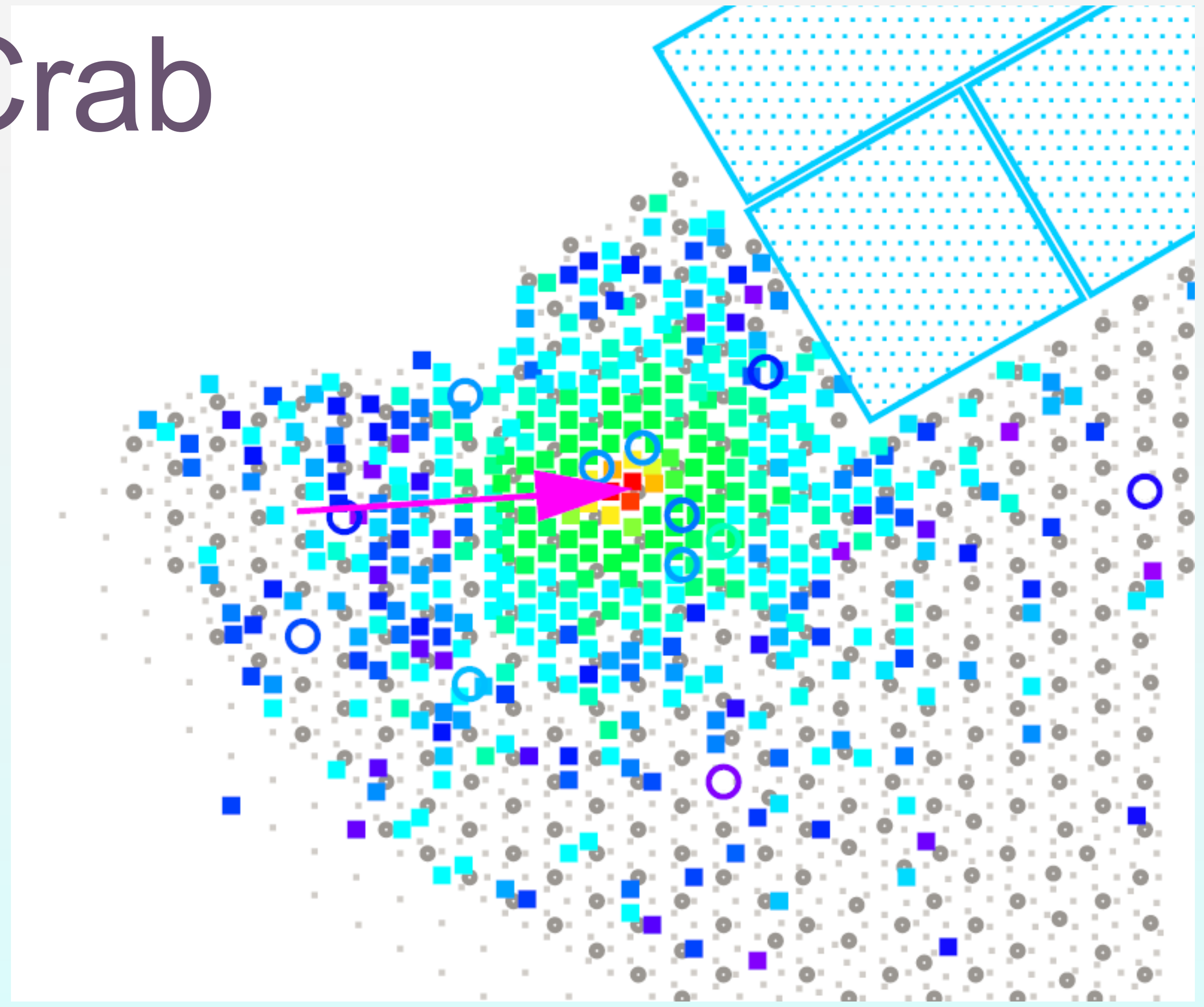
Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons



~ 1 PeV γ–ray event： very few muons

~1 PeV from the Crab



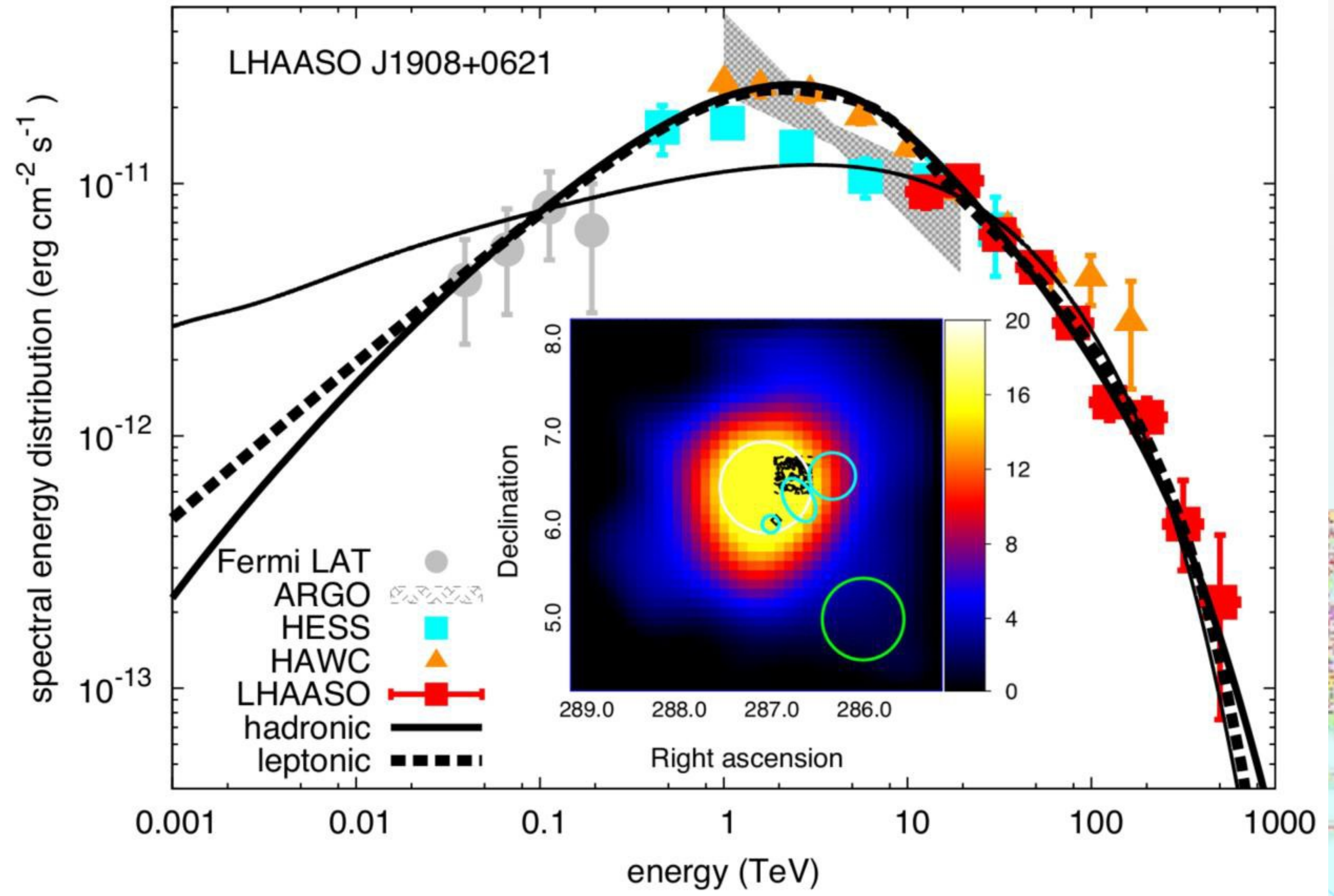
- **Area：**
  1.3 km²
- **Detectors：**
  5242 ED
  1188 MD
- **Energy Range：**
  0.01-10 PeV

Discovery Using KM2A Onset of UHE γ–ray Astronomy

E > 0.1 PeV: all types of candidates

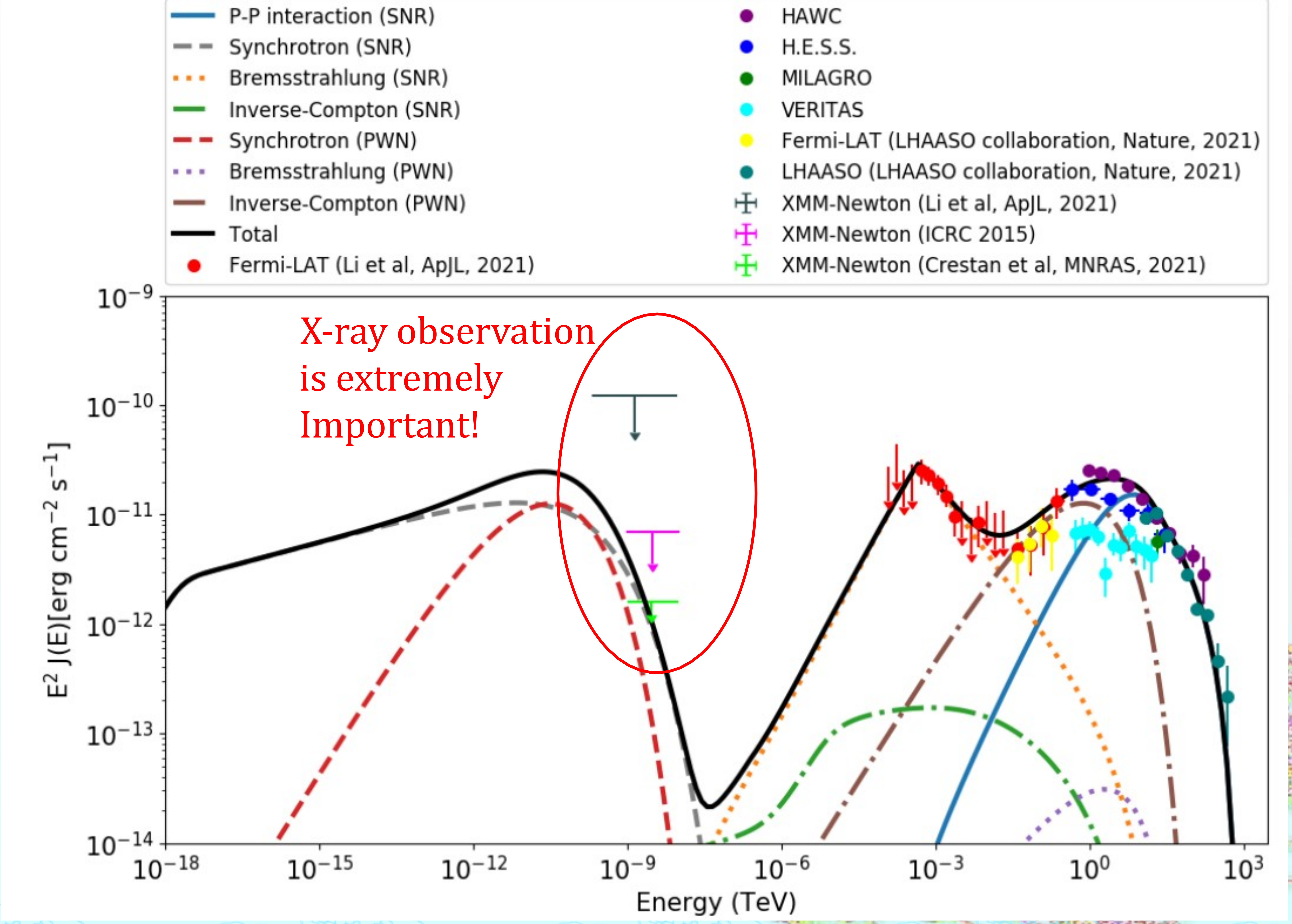
- **Spectroscopy: 15% resolution**
- **Morphology: 0.25° PSF**

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}	



LHAASO J1908+0621

- Multi Wavelength analysis reveals more exciting features
- Hadronic process dominates the UHE emission ?
- SNRs may be still strong candidates for PeVatrons



Agnibha De Sarkar, Nayantara Gupta, accepted by APJ, arXiv:2205.01923

Exploring Lorentz Invariance Violation

In the superluminal LIV

$$\gamma \rightarrow e^- e^+$$

$$\alpha_0 \le \frac{4m_e^2}{E_\gamma^2 - 4m_e^2},$$

$$E_{LIV}^{(1)} \ge 9.57 \times 10^{23}\text{eV}\left(\frac{E_\gamma}{\text{TeV}}\right)^3,$$

$$E_{LIV}^{(2)} \ge 9.78 \times 10^{17}\text{eV}\left(\frac{E_\gamma}{\text{TeV}}\right)^2.$$

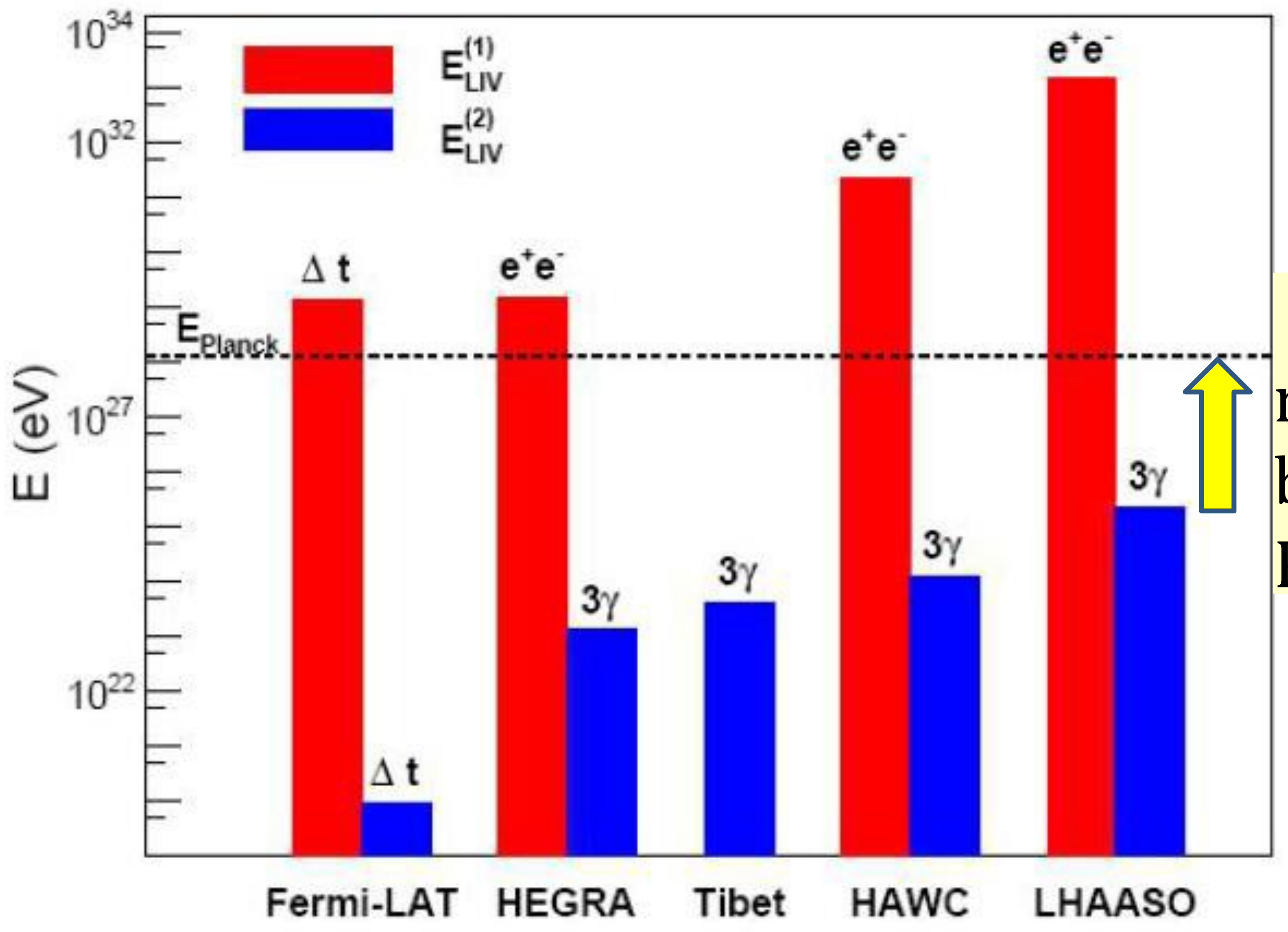
$$\gamma \rightarrow 3\gamma$$

$$\Gamma_{\gamma\to 3\gamma} = 5 \times 10^{-14}\frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

$$E_{LIV}^{(2)} > 3.33 \times 10^{19}\text{eV}\left(\frac{L}{\text{kpc}}\right)^{0.1}\left(\frac{E_\gamma}{\text{TeV}}\right)^{1.9}.$$

New CLs method

Source	L (kpc)	$E_{\max}$ (PeV)	$E_{\rm cut}^{95\%}$ (PeV)
J0534+2202	2.0	0.88	$0.75^{+0.043}_{-0.043}$
J2032+4102	1.4	1.42	$1.14^{+0.06}_{-0.06}$



3 orders of magnitudes below the Planck-scale

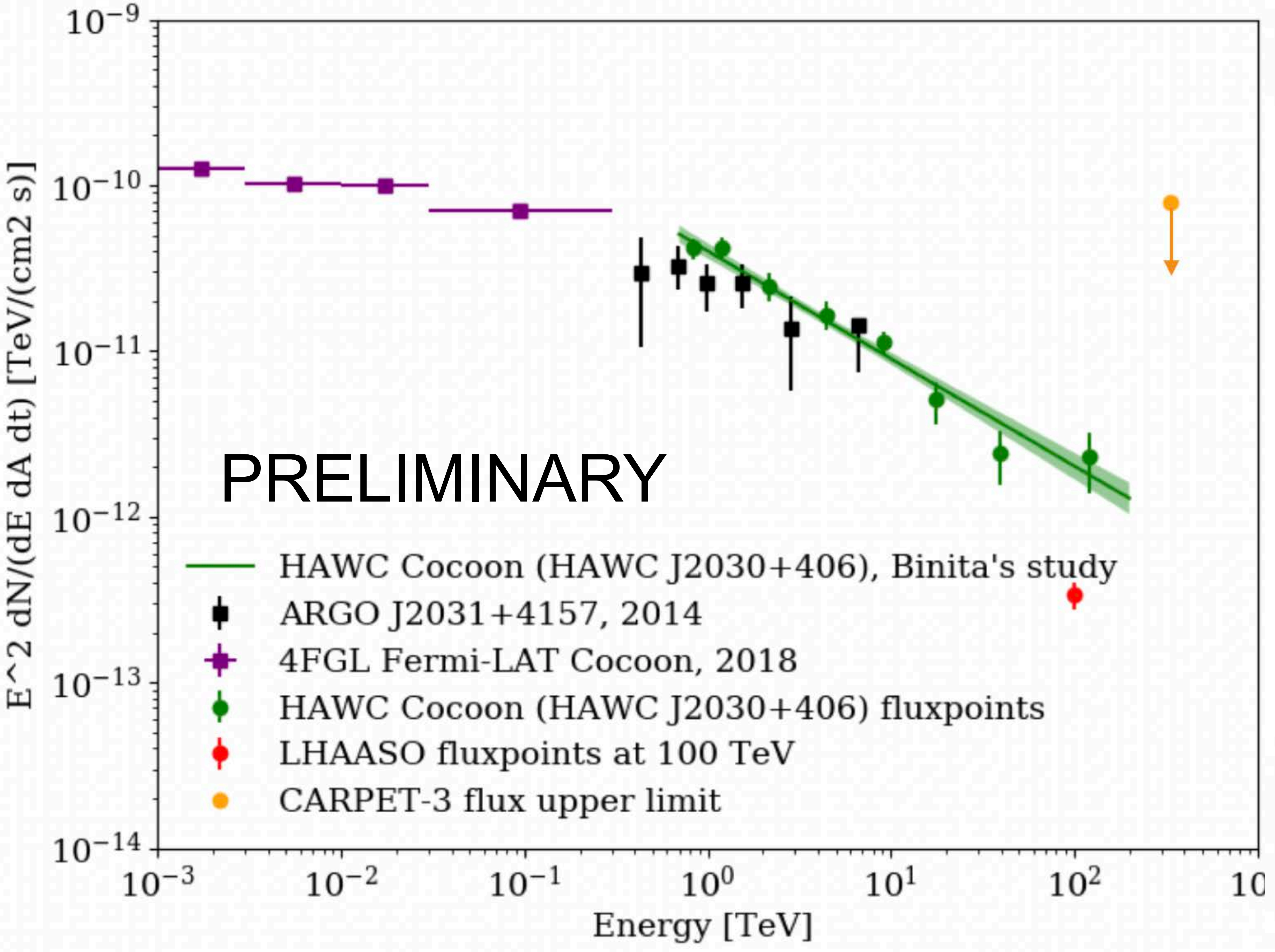
LHAASO Coll., Phys.Rev.Lett. 128 (2022) 5, 051102, Phys.Rev.Lett. 126 (2022) 051102

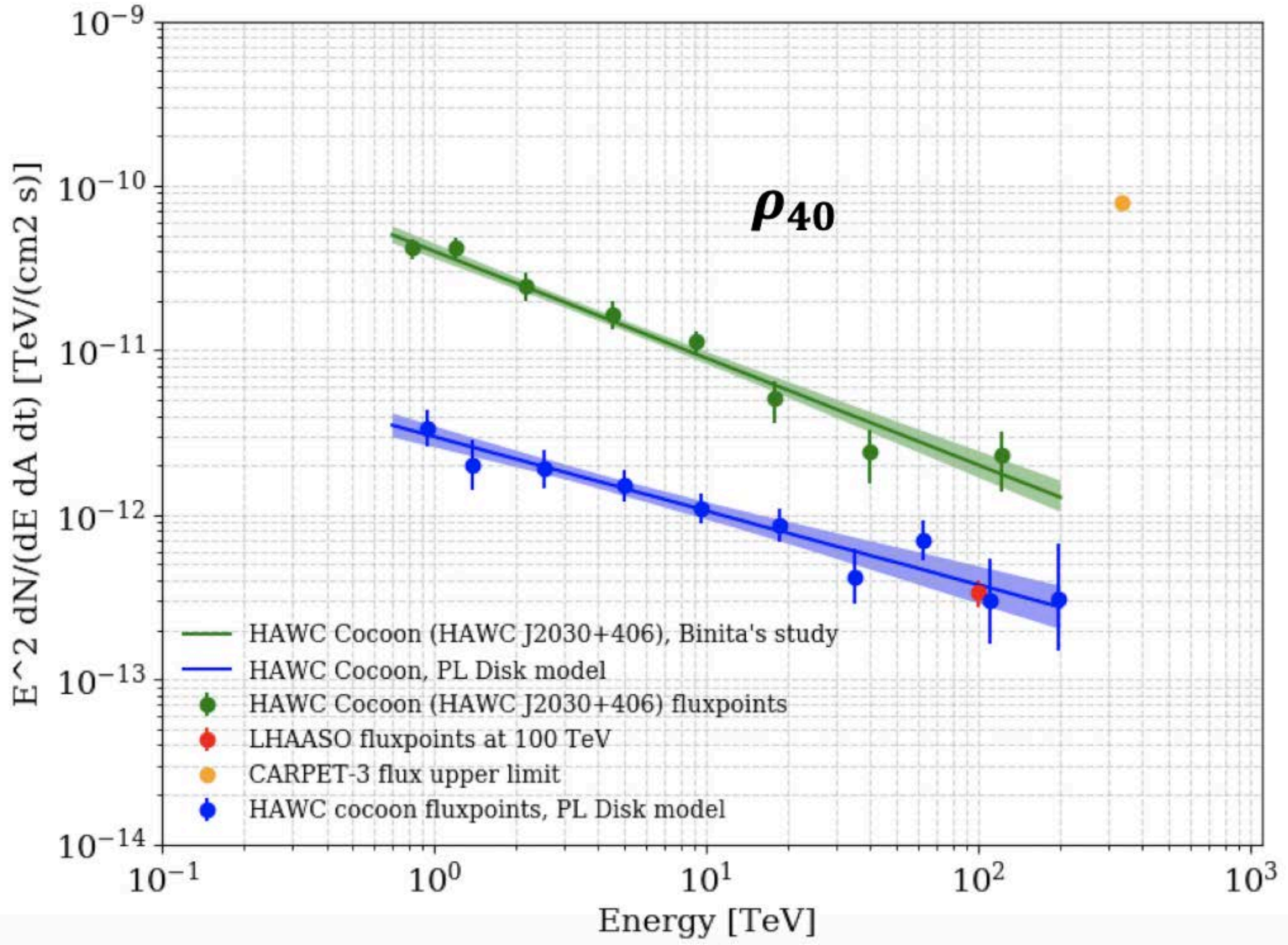
Summary

- **LHAASO is completely built, and in full operation since July 2021**
- **Open-up "UHE (>0.1 PeV) Astronomy"**
  1. **12 PeVatrons are discovered in our galaxy**
  2. **A photon at 1.4 PeV is recorded toward Cygnus constellation**
- **First Discoveries：**
  1. **Our galaxy is full of PeVatrons accelerating particles over 1 PeV**
  2. **Potential CR origins: many type of candidates**
  3. **The Crab: extreme e-PeVatron emitting 1.1 PeV γ posing challenges**
  4. **Many new sources are discovered**
- **Fundamental rules, e.g. LIV, are tested in extreme condition**
- **Precision Measurements of individual species CRs around knees will be measured at first time**

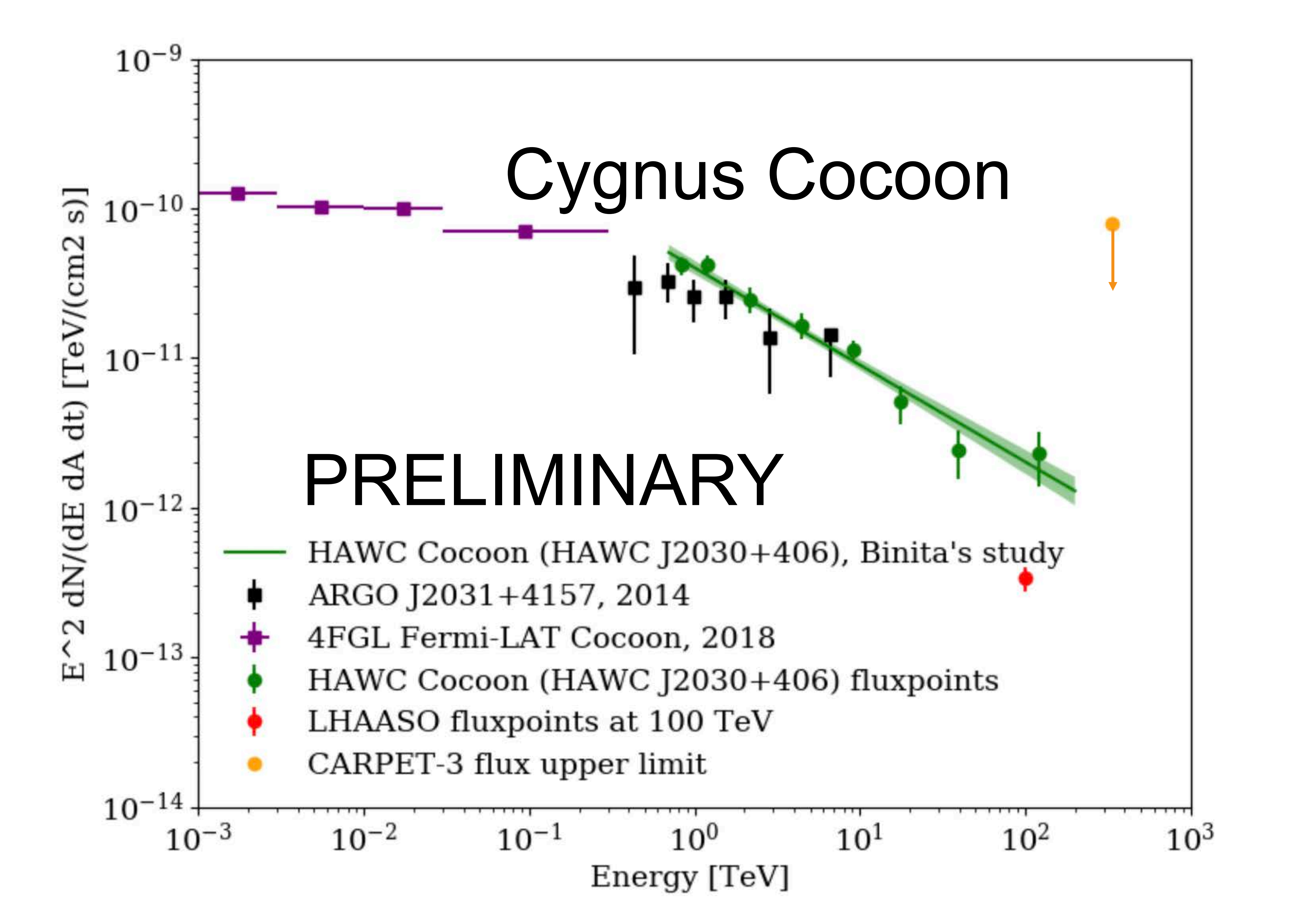
Some comparisons

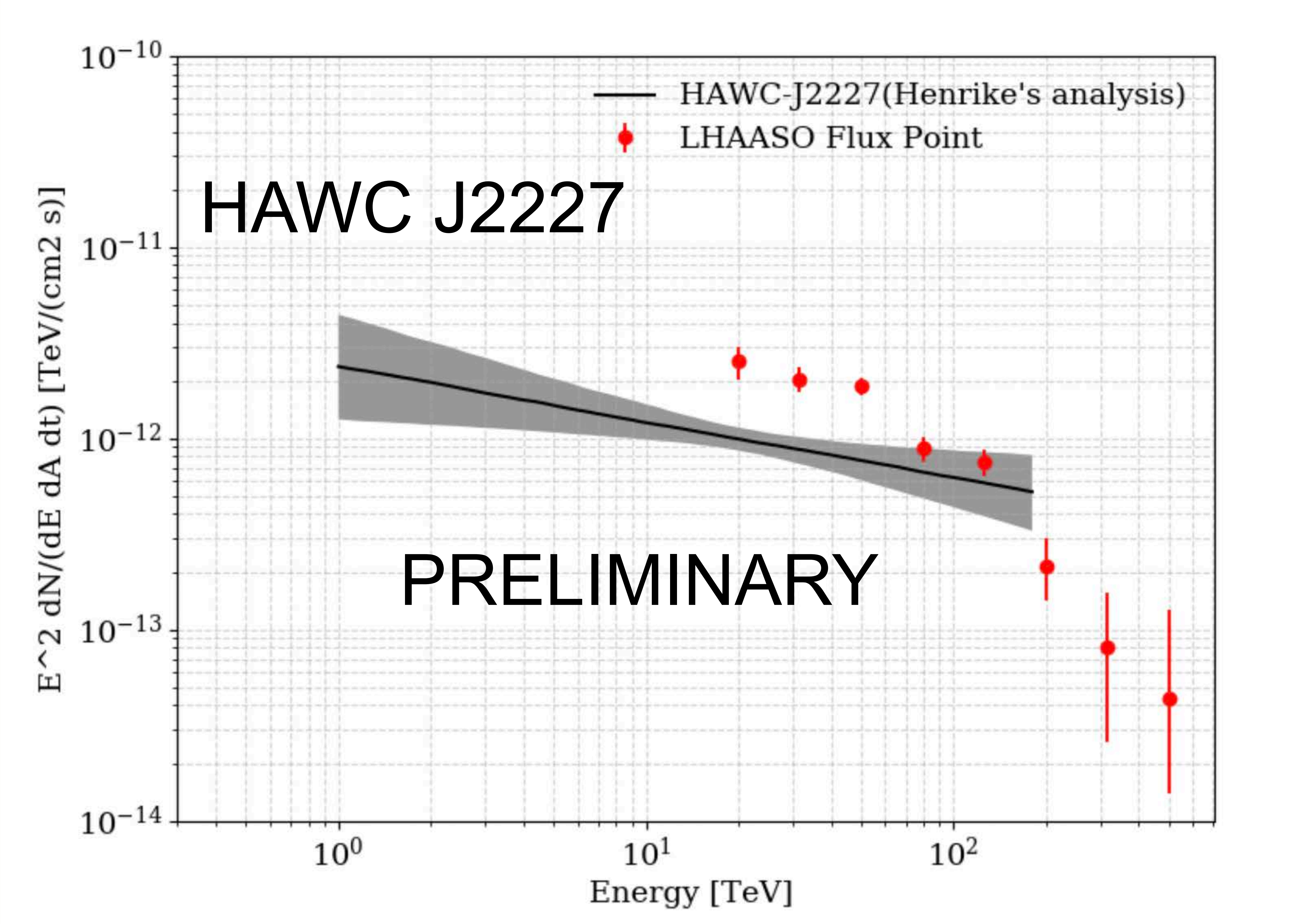
Cygnus Cocoon





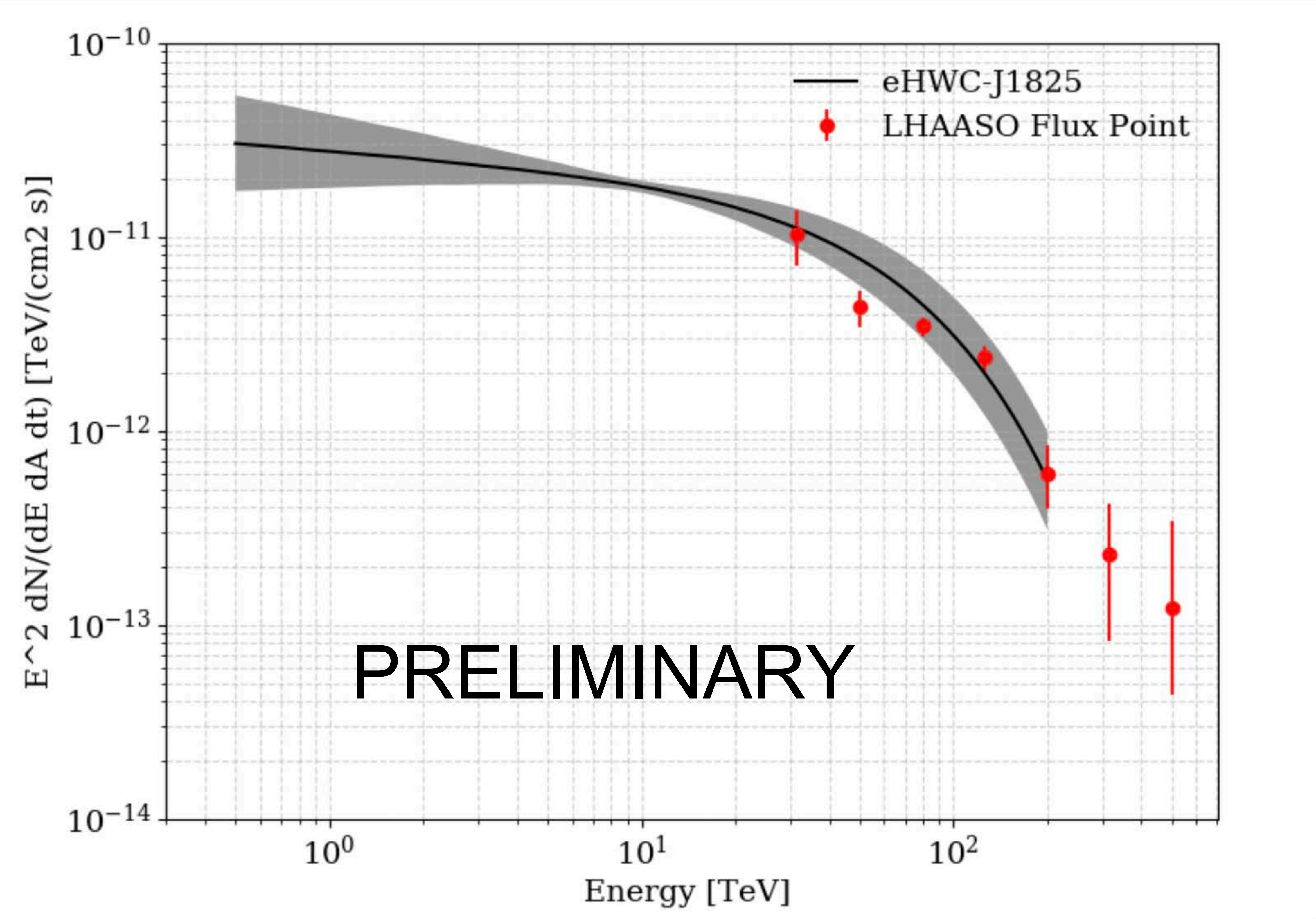
Some comparisons

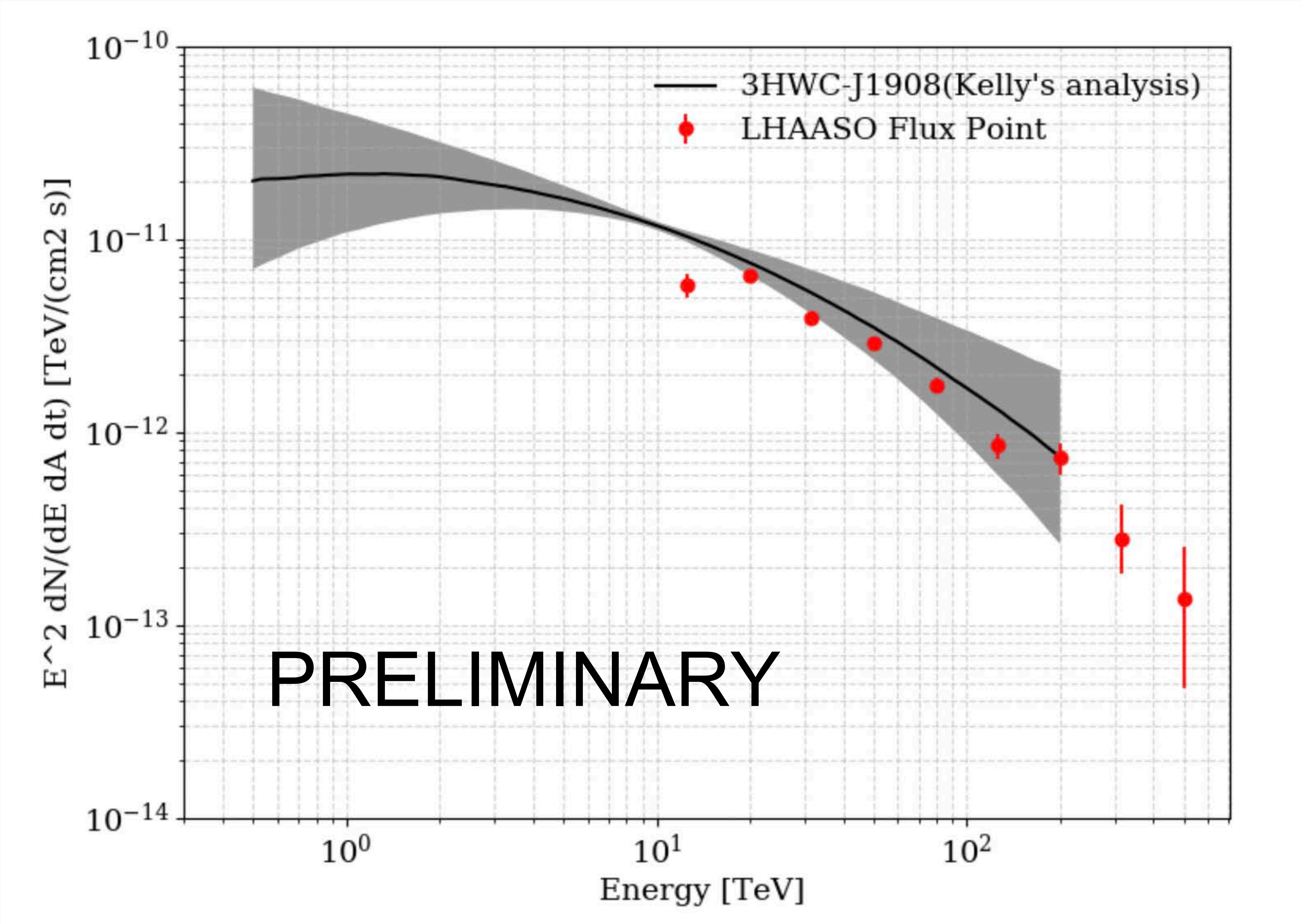




HAWC + VERITAS joint analysis

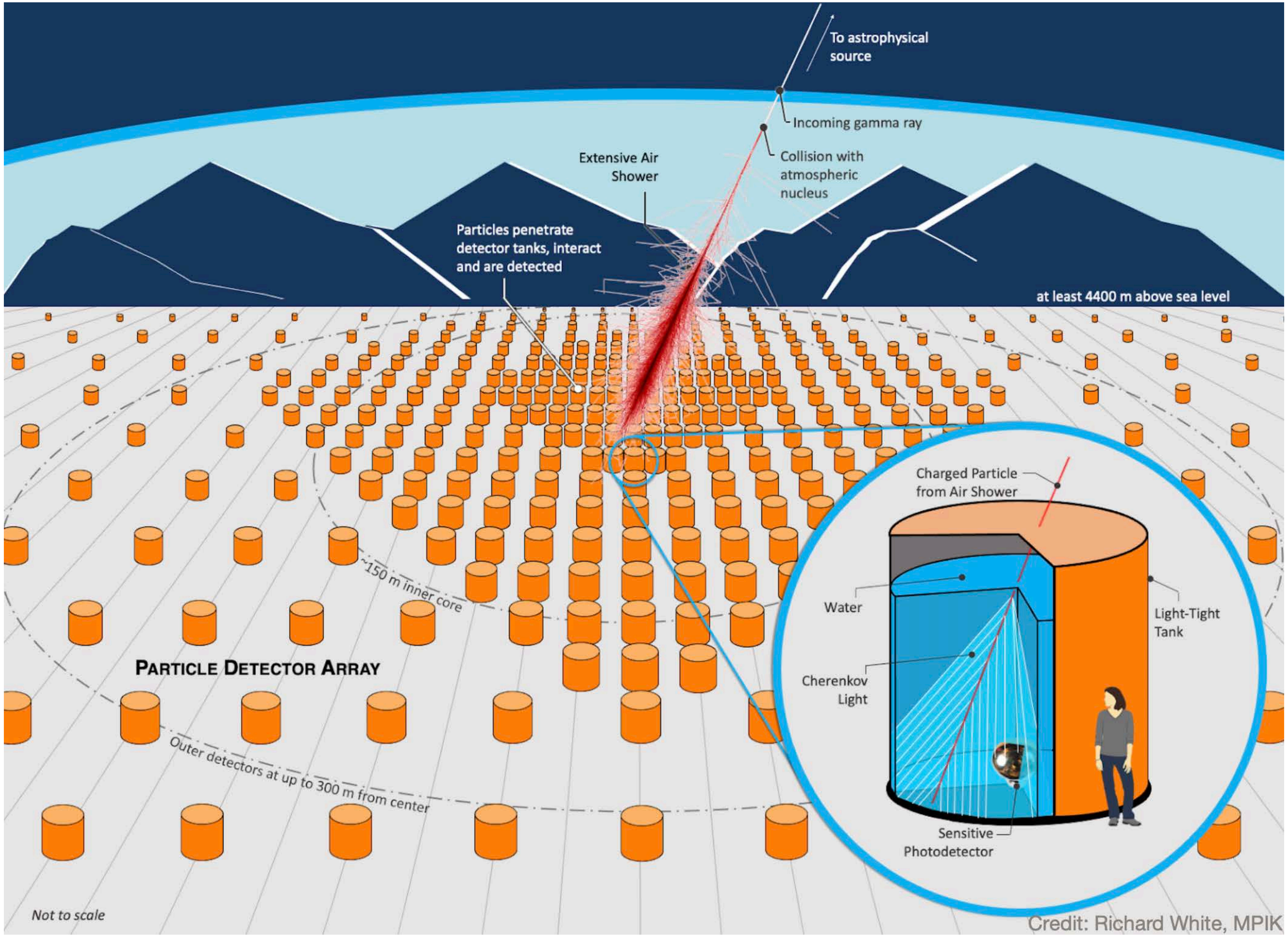
Some comparisons



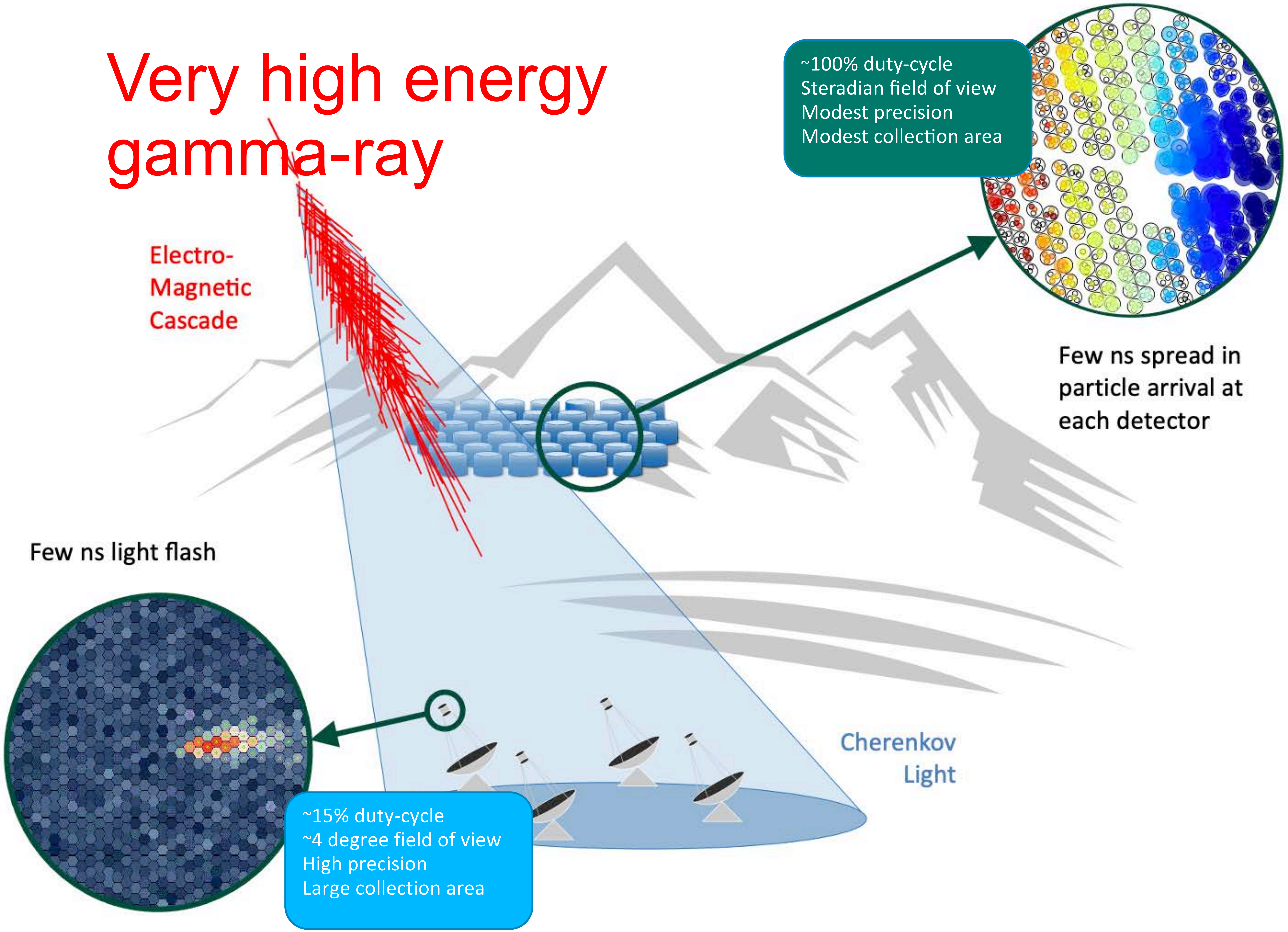


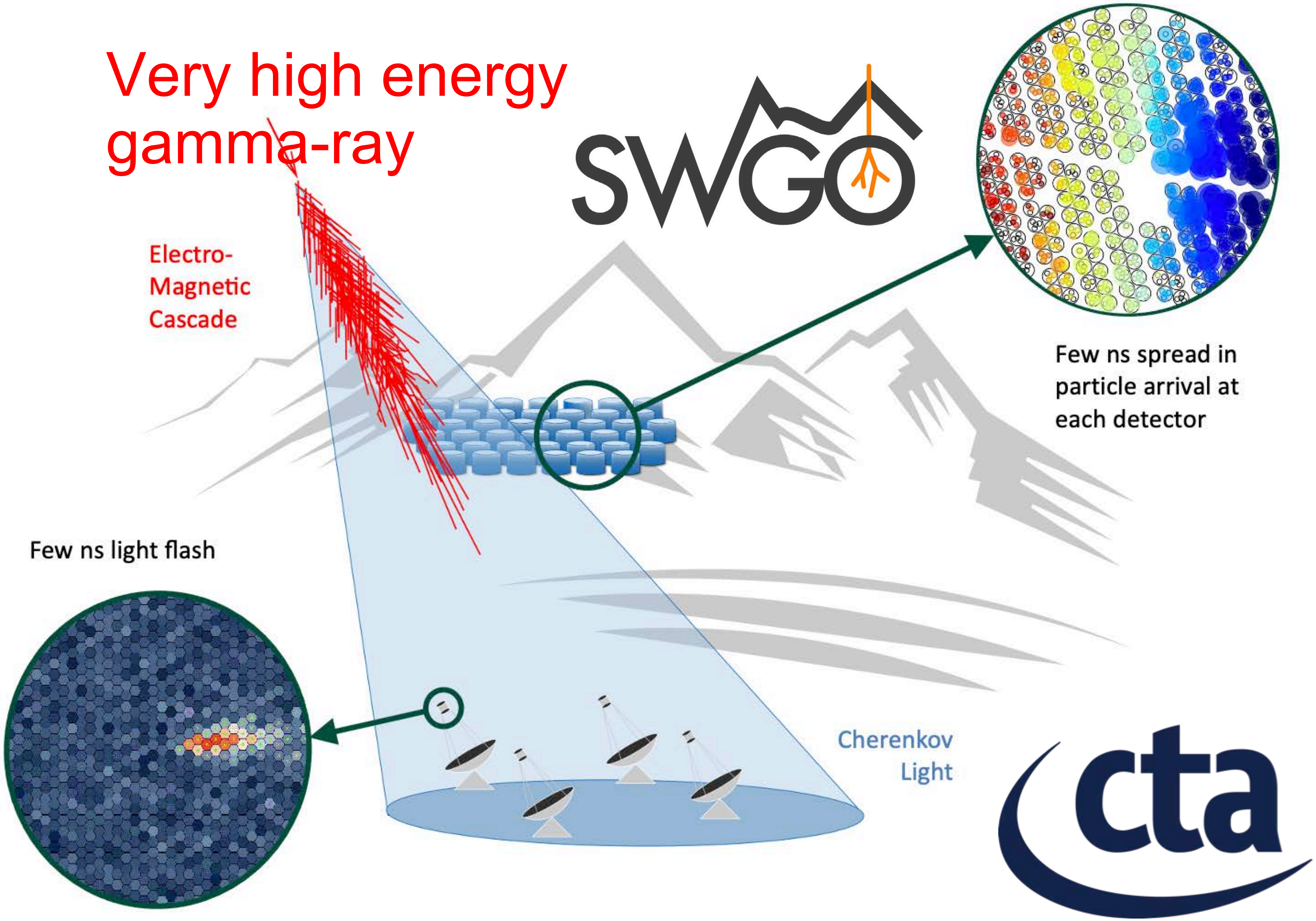
The Future

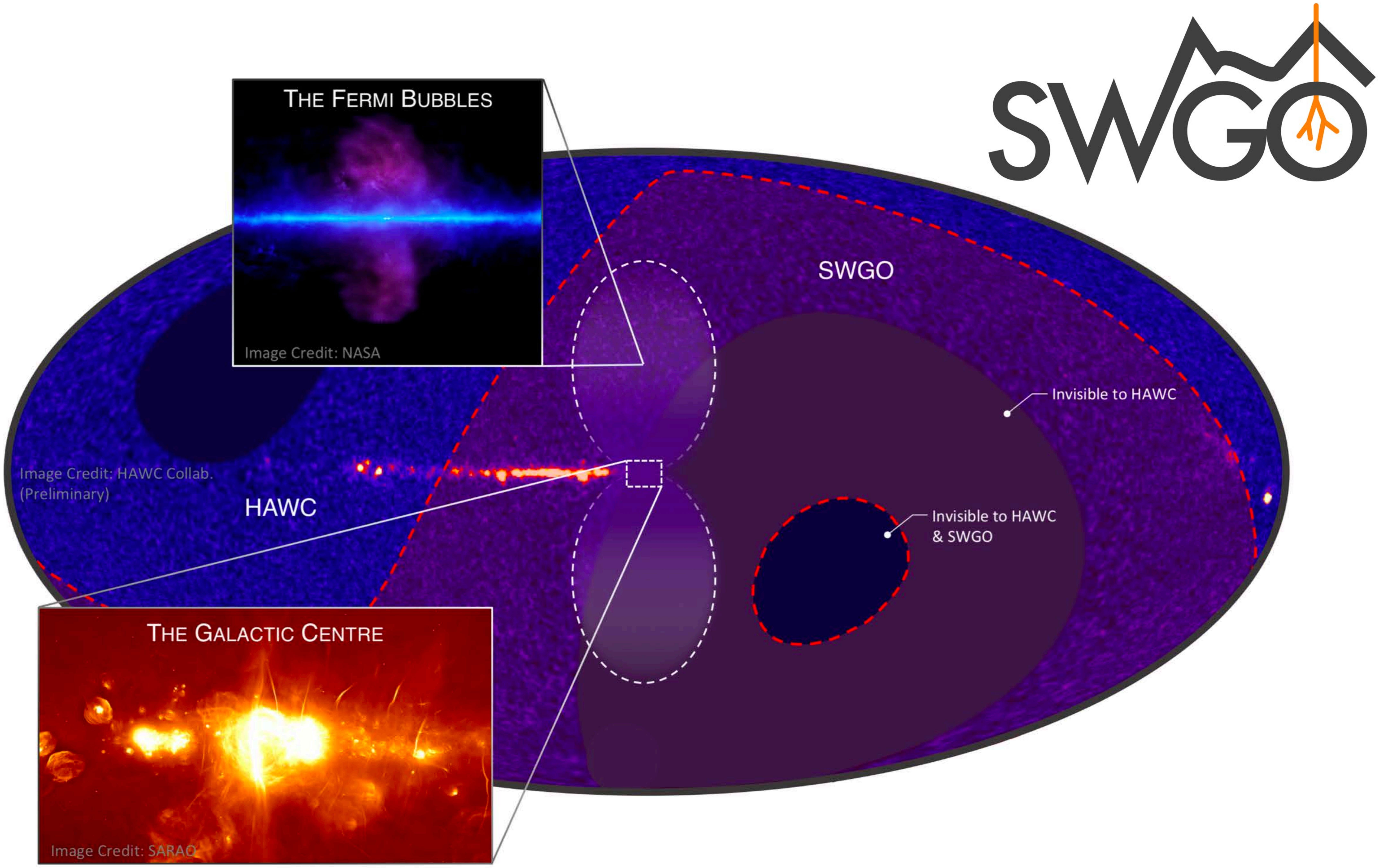
The Southern Wide-field Gamma-ray Observatory



Credit: Richard White, MPIK


Very high energy gamma-ray
Electro-Magnetic Cascade
~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area
Few ns spread in particle arrival at each detector
Few ns light flash
Cherenkov Light
~15% duty-cycle
~4 degree field of view
High precision
Large collection area


Very high energy gamma-ray
SWGO
Electro-Magnetic Cascade
Few ns spread in particle arrival at each detector
Few ns light flash
Cherenkov Light
cta



SWGO
The Fermi Bubbles
Image Credit: NASA
SWGO
Invisible to HAWC
Image Credit: HAWC Collab.
(Preliminary)
HAWC
Invisible to HAWC
& SWGO
The Galactic Centre
Image Credit: SARAO

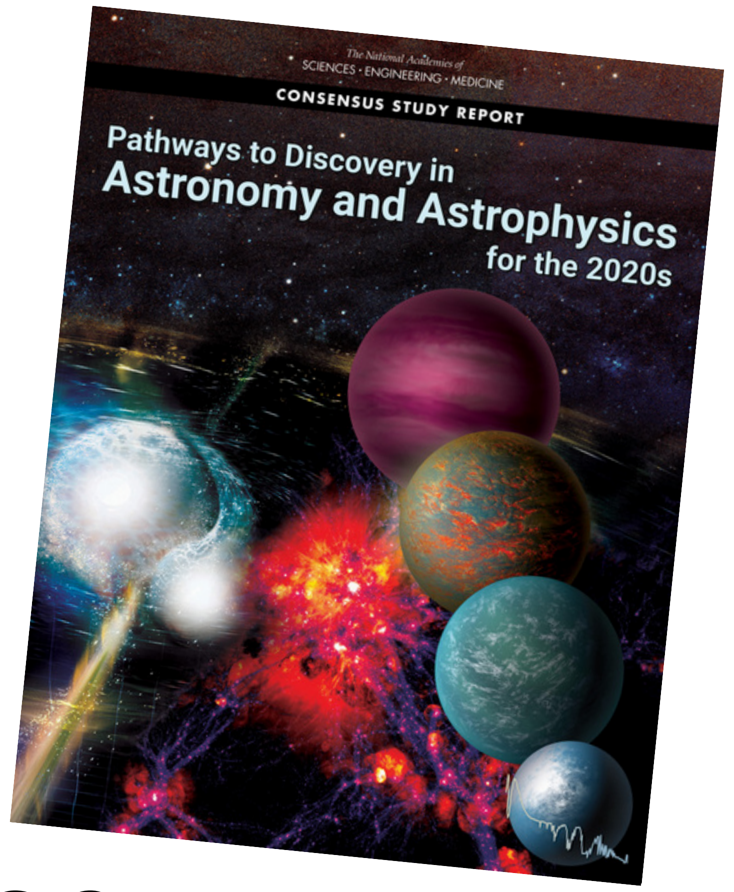
Status & Plan

		SWGO R&D Phase Milestones
✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
✓	M3	Reference Configuration & Options Defined
	M4	Site Shortlist Complete
✓	M5	Candidate Configurations Defined
	M6	Performance of Candidate Configurations Evaluated
	M7	Preferred Site Identified
	M8	Design Finalised
	M9	Construction & Operation Proposal Complete

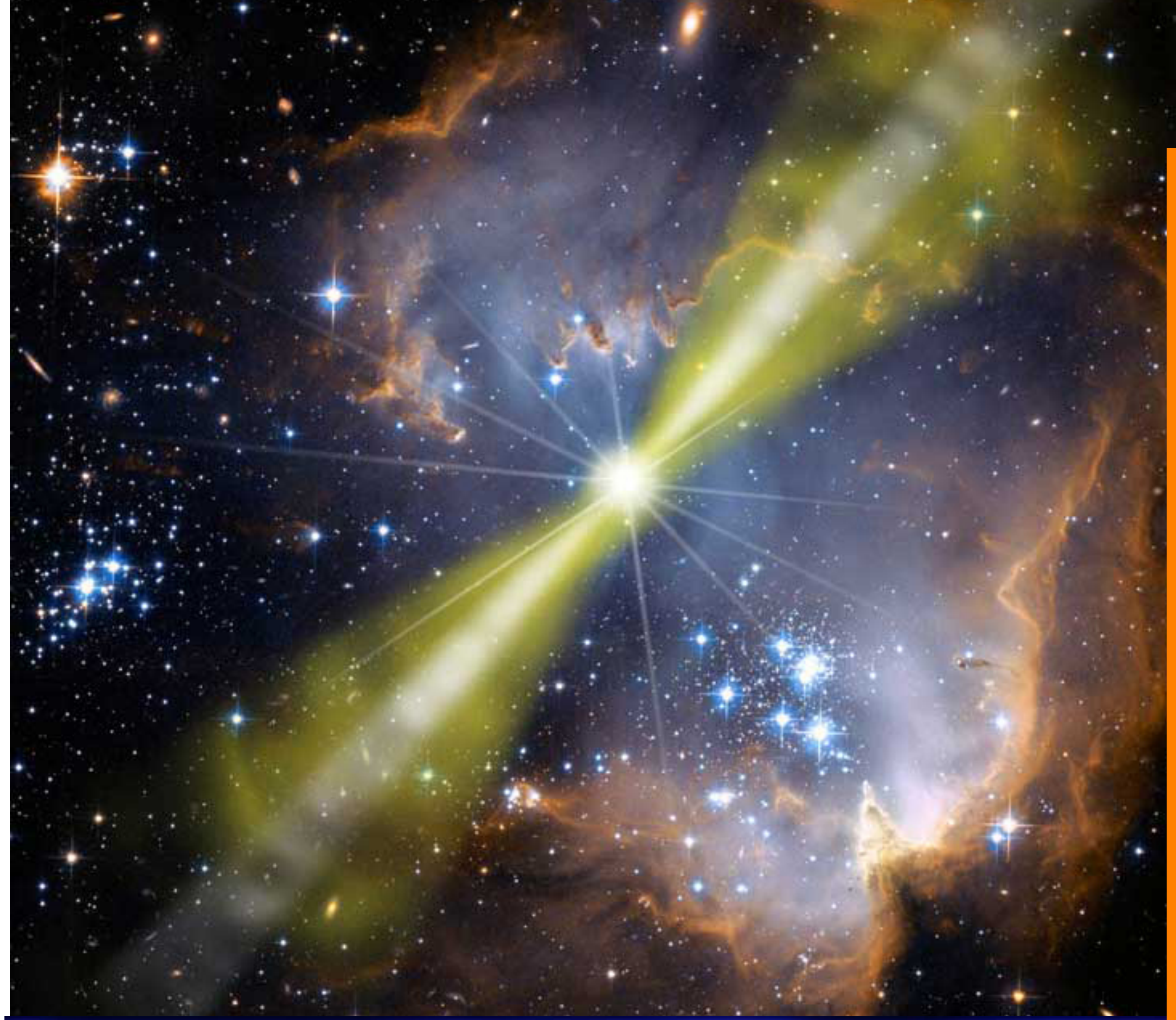
- SWGO partners
  - 47 institutes in 12 countries*
  - + supporting scientists

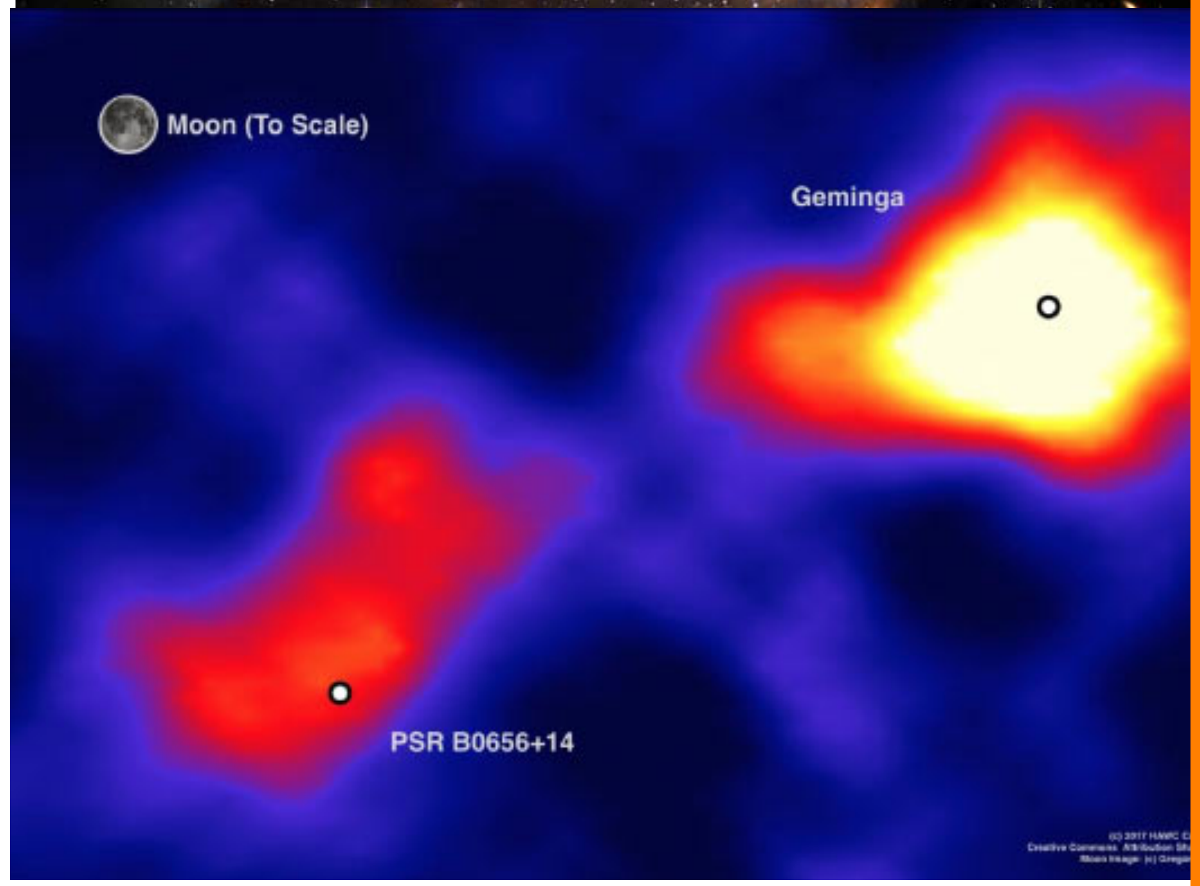
R&D Phase
- Kick off meeting Nov 2019
- Expected completion 2023
  - Site and Design Choices made
- Then:

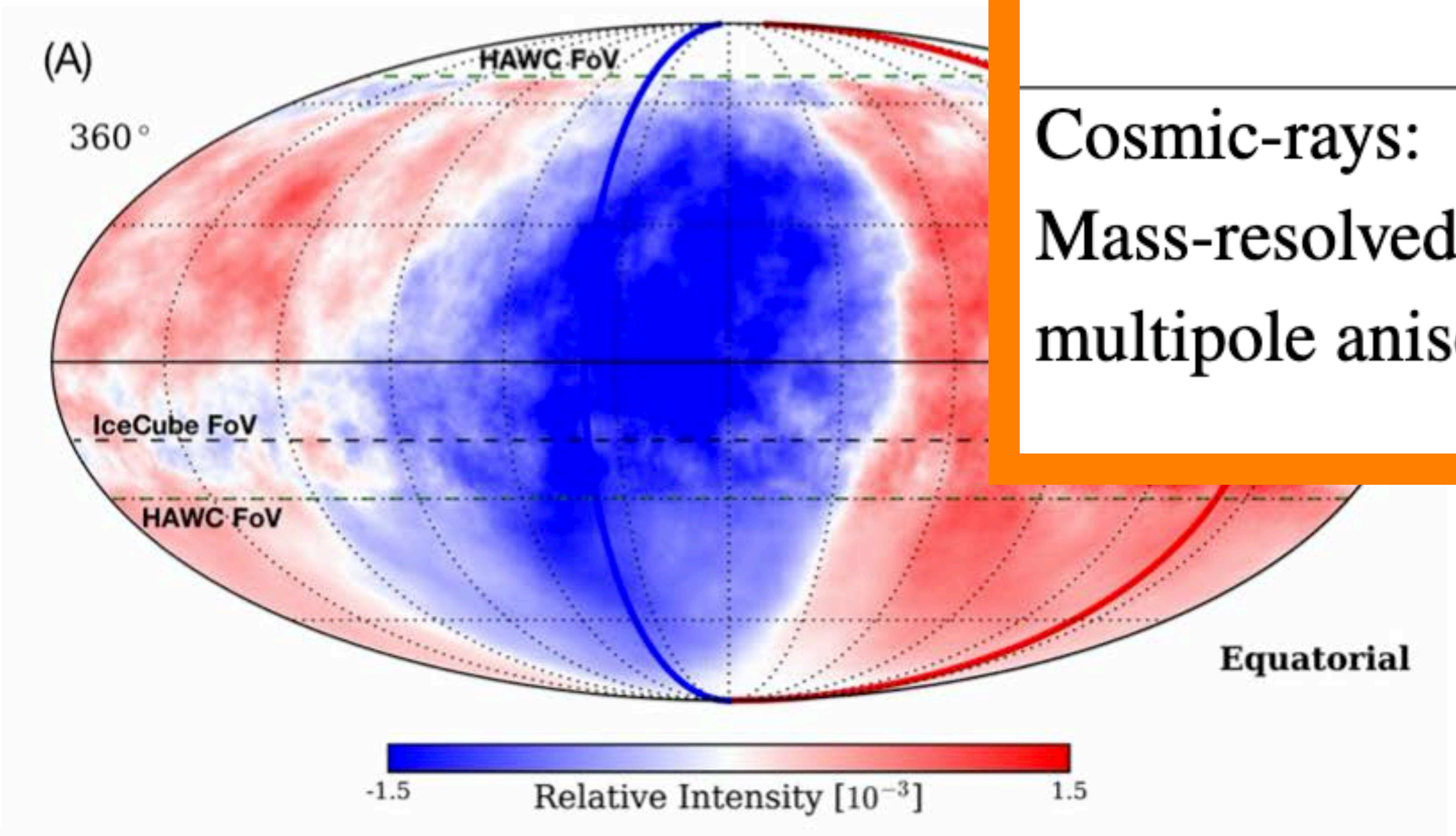
Preparatory Phase
- Detailed construction planning
- **Engineering Array**



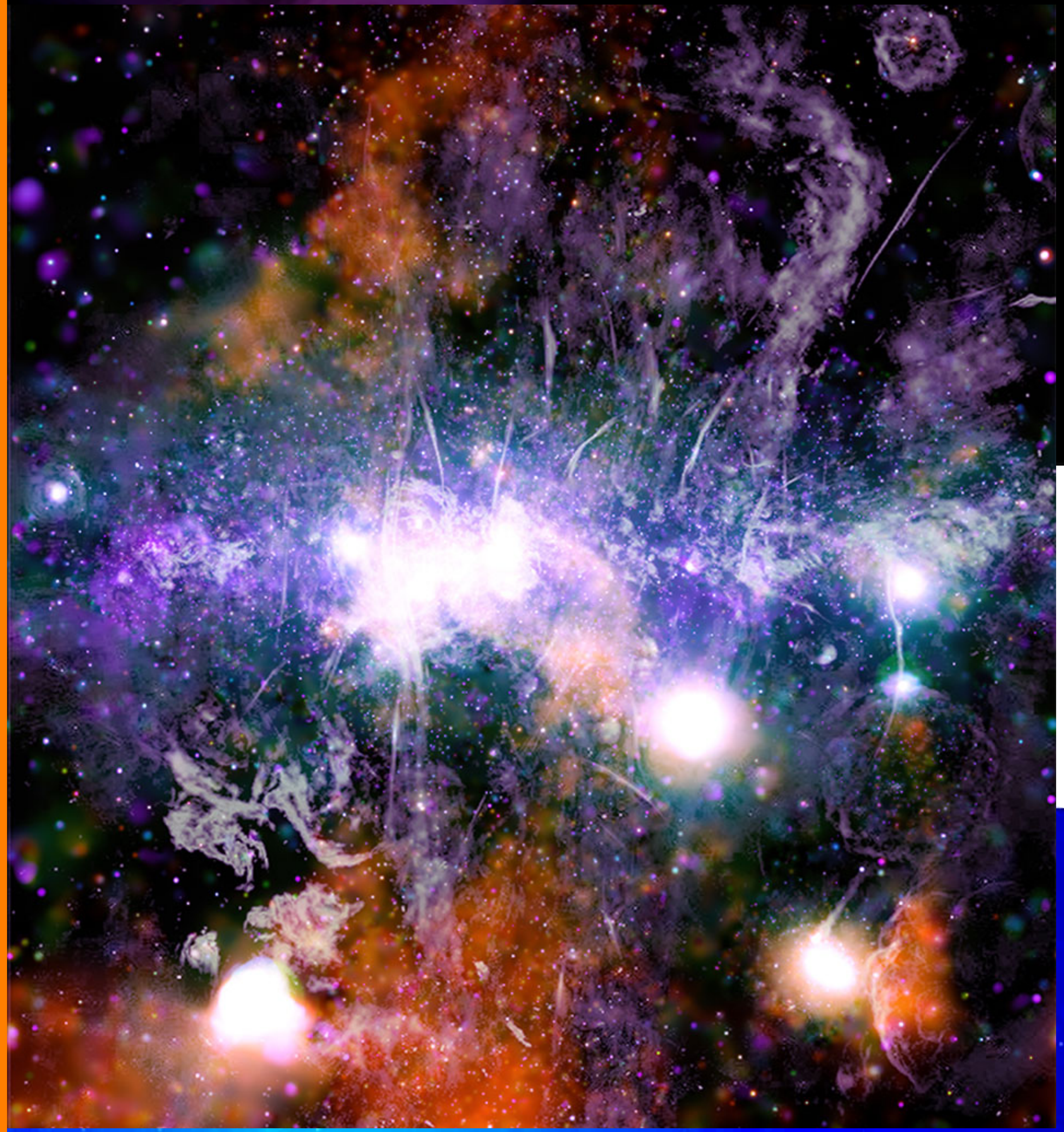
(Full) Construction Phase
- 2026+

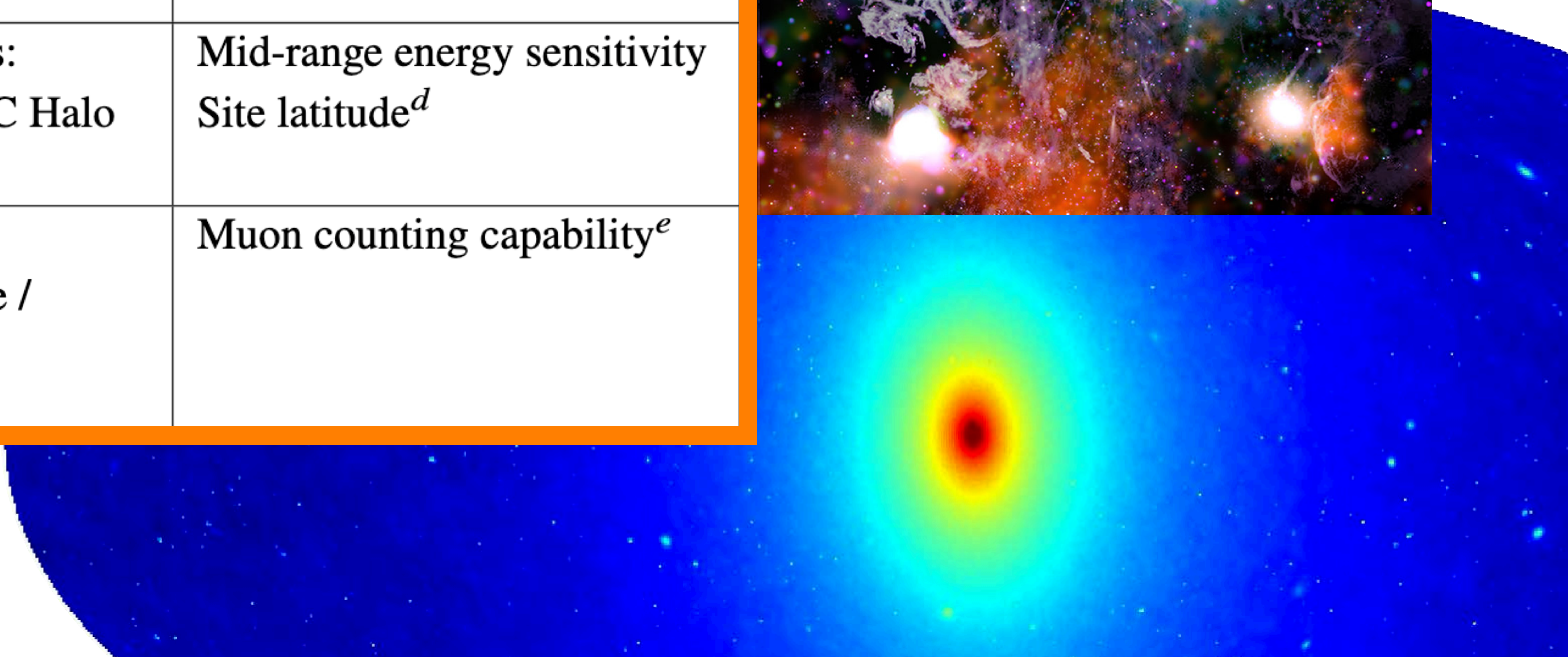






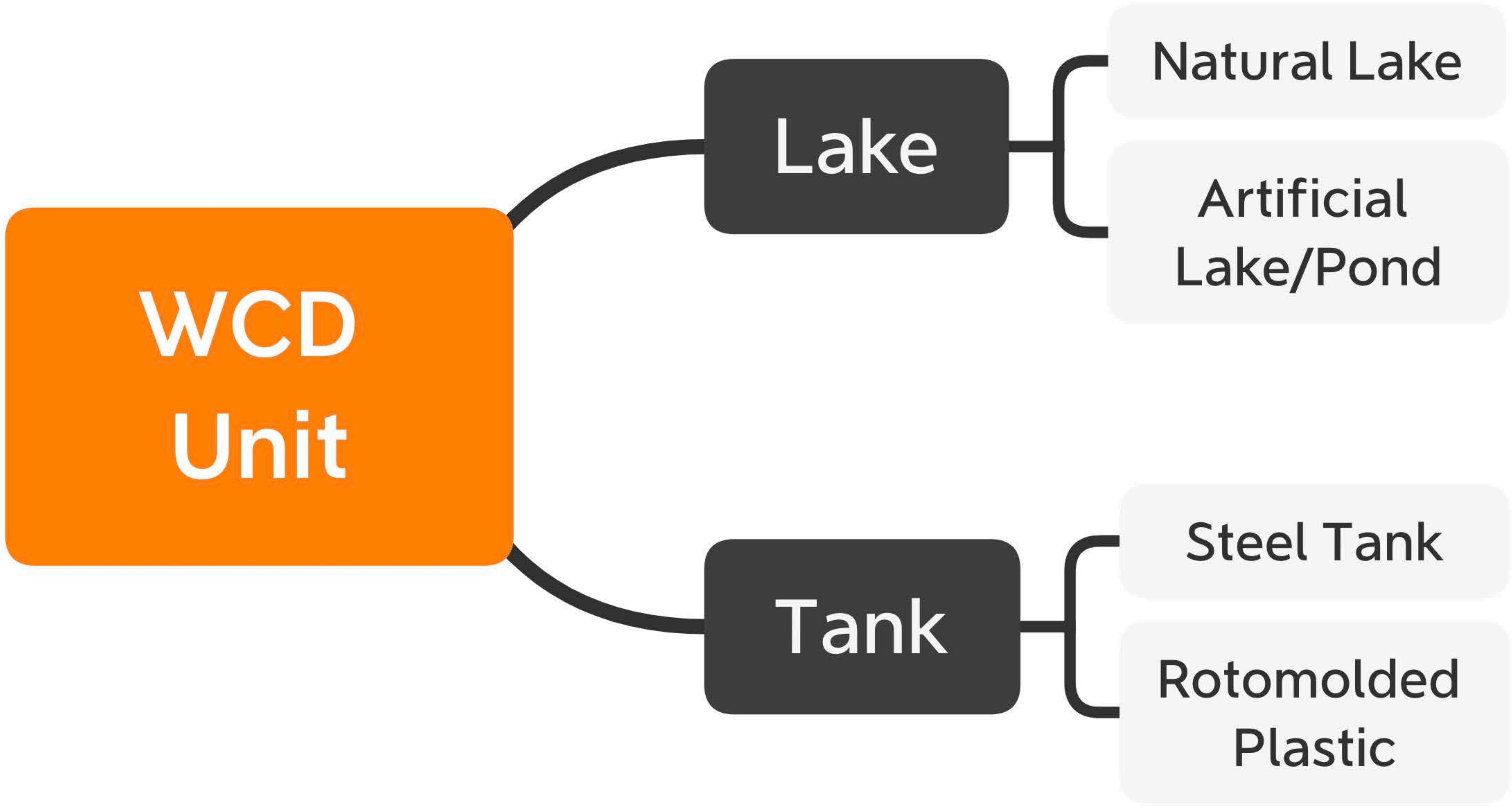
Science Case	Design Drivers
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude[a]
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution[b]
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution[c]
Diffuse Emission: Fermi Bubbles	Background rejection
Fundamental Physics: Dark Matter from GC Halo	Mid-range energy sensitivity Site latitude[d]
Cosmic-rays: Mass-resolved dipole / multipole anisotropy	Muon counting capability[e]

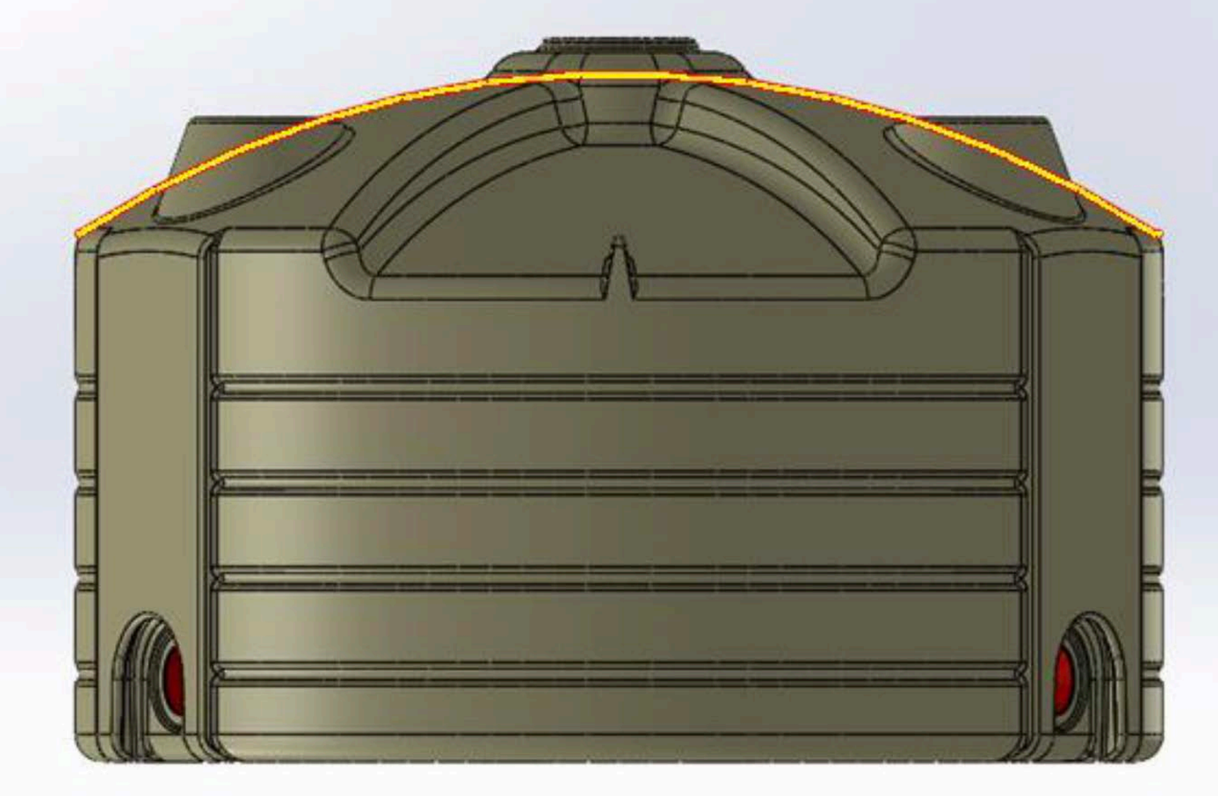


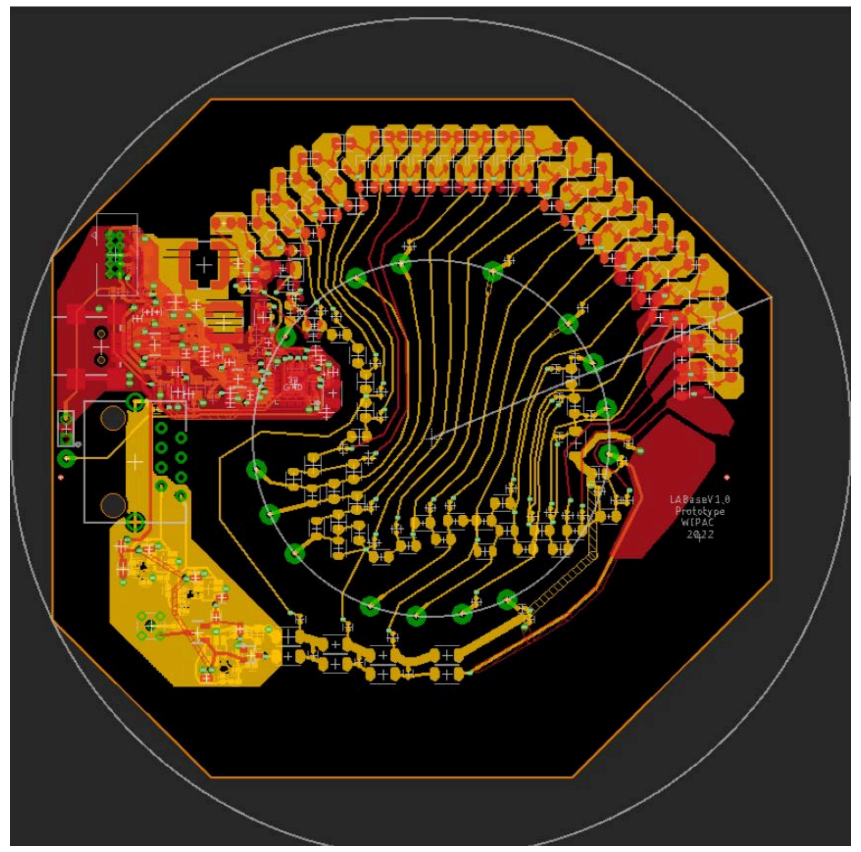



Bolivia 4.7k
Chile 4.8 k
STATE OF ACRE
Peru
Lima
13º S
Lake Sibinacocha (Peru)
Yanque (Peru)
Imata (Peru)
Chacaltaya (Bolivia)
Bolivia
Cochabamba
AAP Pajonal (Chile)
24º S
Alto Tocomar (Argentina...
Chile
Argentina 4.8 k
Peru 4.9 k

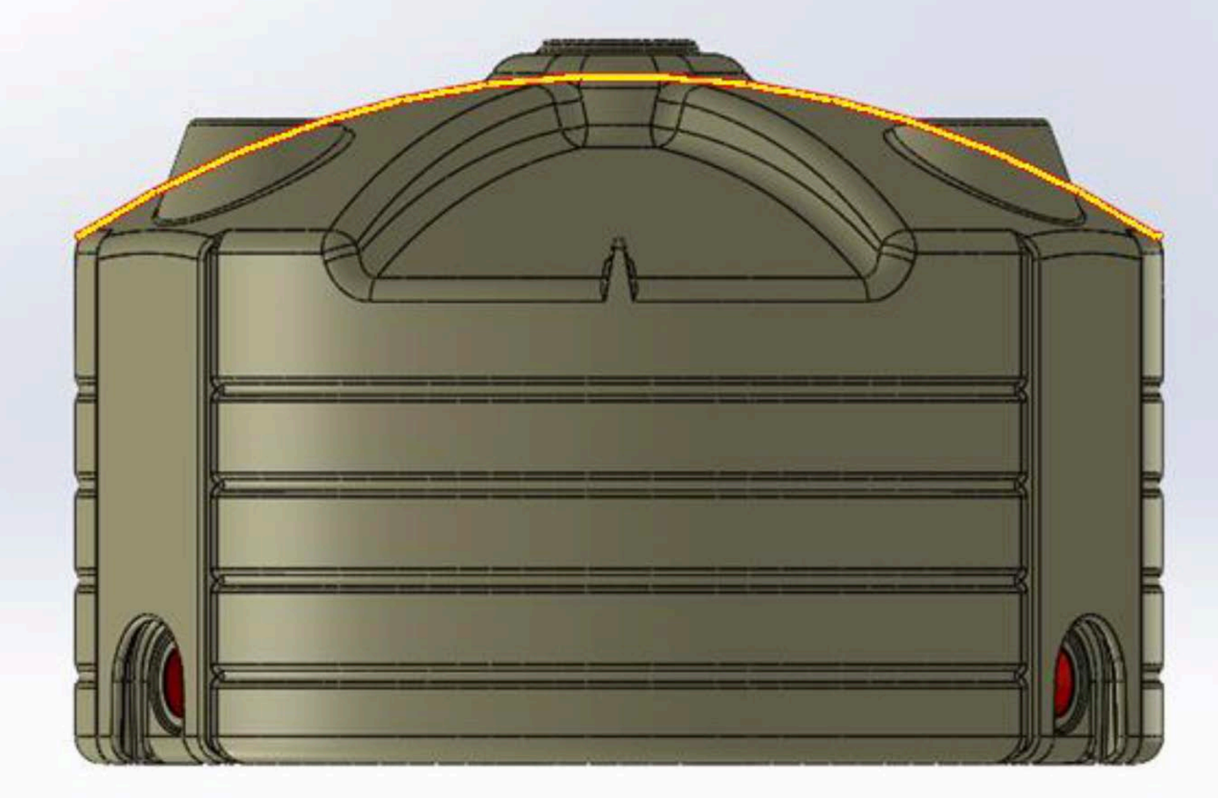

Bolivia 4.7k
Chile 4.8 k
Argentina 4.8 k
Peru 4.9 k
STATE OF ACRE
Peru
Lima
13º S
Cusco
Lake Sibinacocha (Peru)
Yanque (Peru)
Imata (Peru)
Chacaltaya (Bolivia)
Bolivia
Cochabamba
Santa Cr
de la Sier
AAP Pajonal (Chile)
24º S
Alto Tocomar (Argentina...
Chile
Site shortlisting: September 2022
Site team visits: October 2022
Preferred Site identified: Autumn 2023
On-site prototyping activities: from 2022

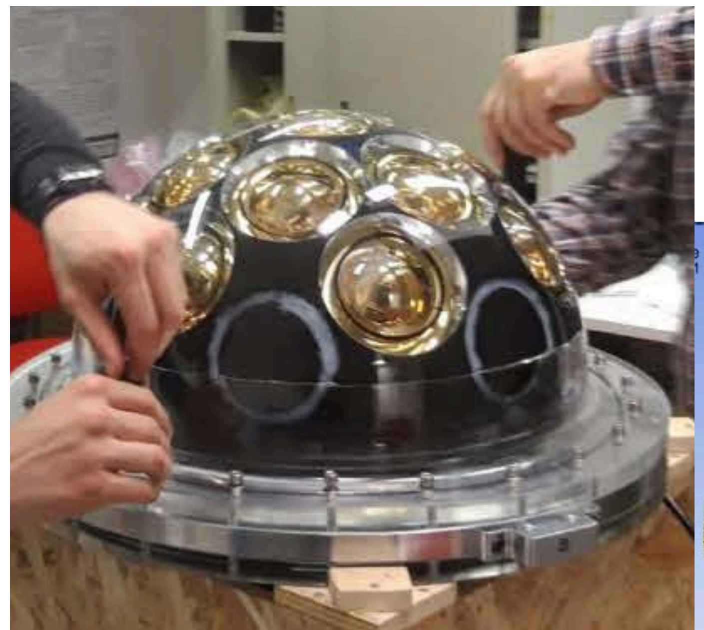

WCD Unit
Lake
Natural Lake
Artificial Lake/Pond
Tank
Steel Tank
Rotomolded Plastic



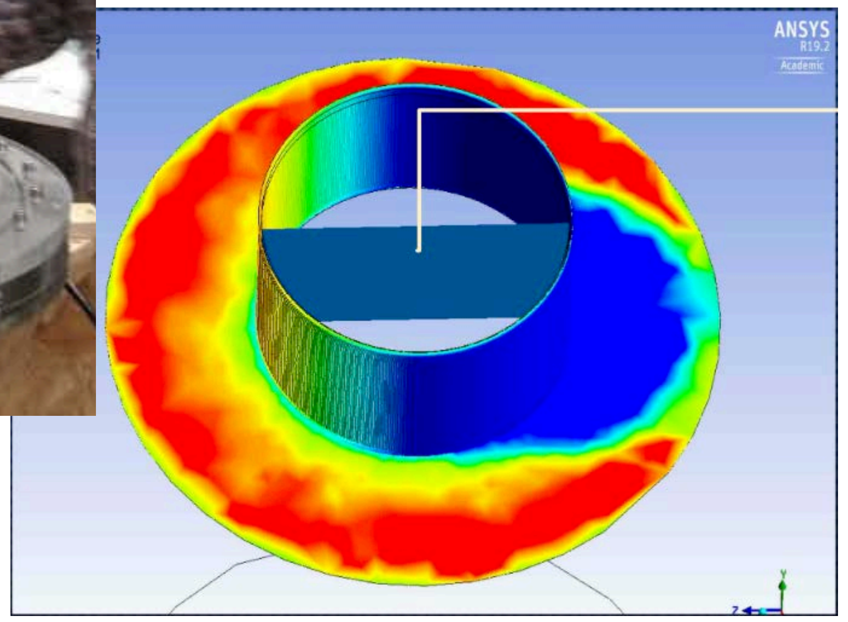


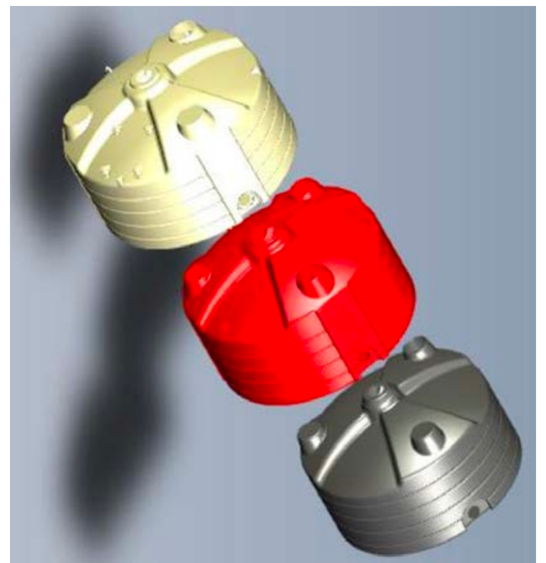
- **WCD Unit**
  - **Lake**
    - Natural Lake
    - Artificial Lake/Pond
  - **Tank**
    - Steel Tank
    - Rotomolded Plastic

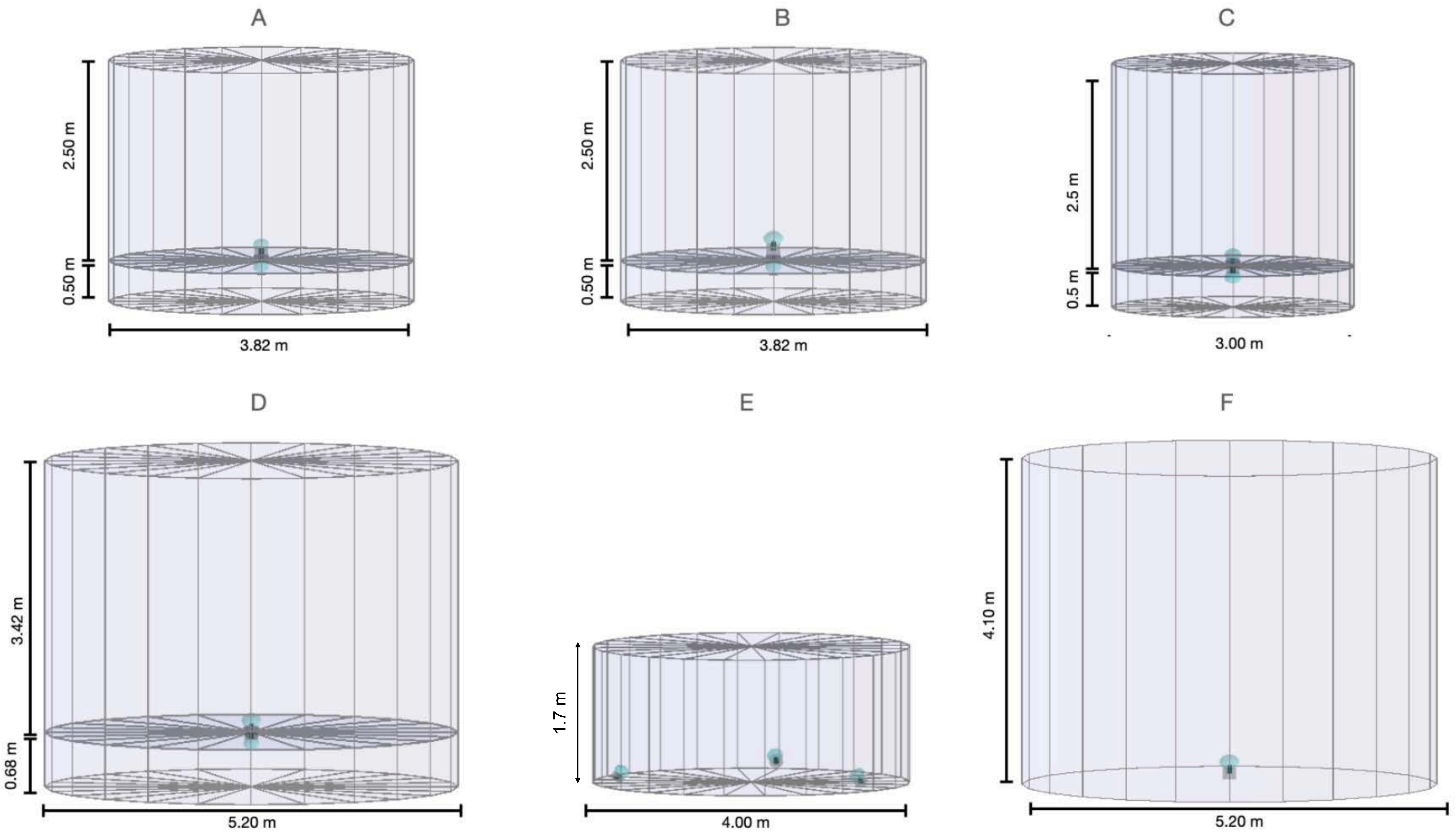




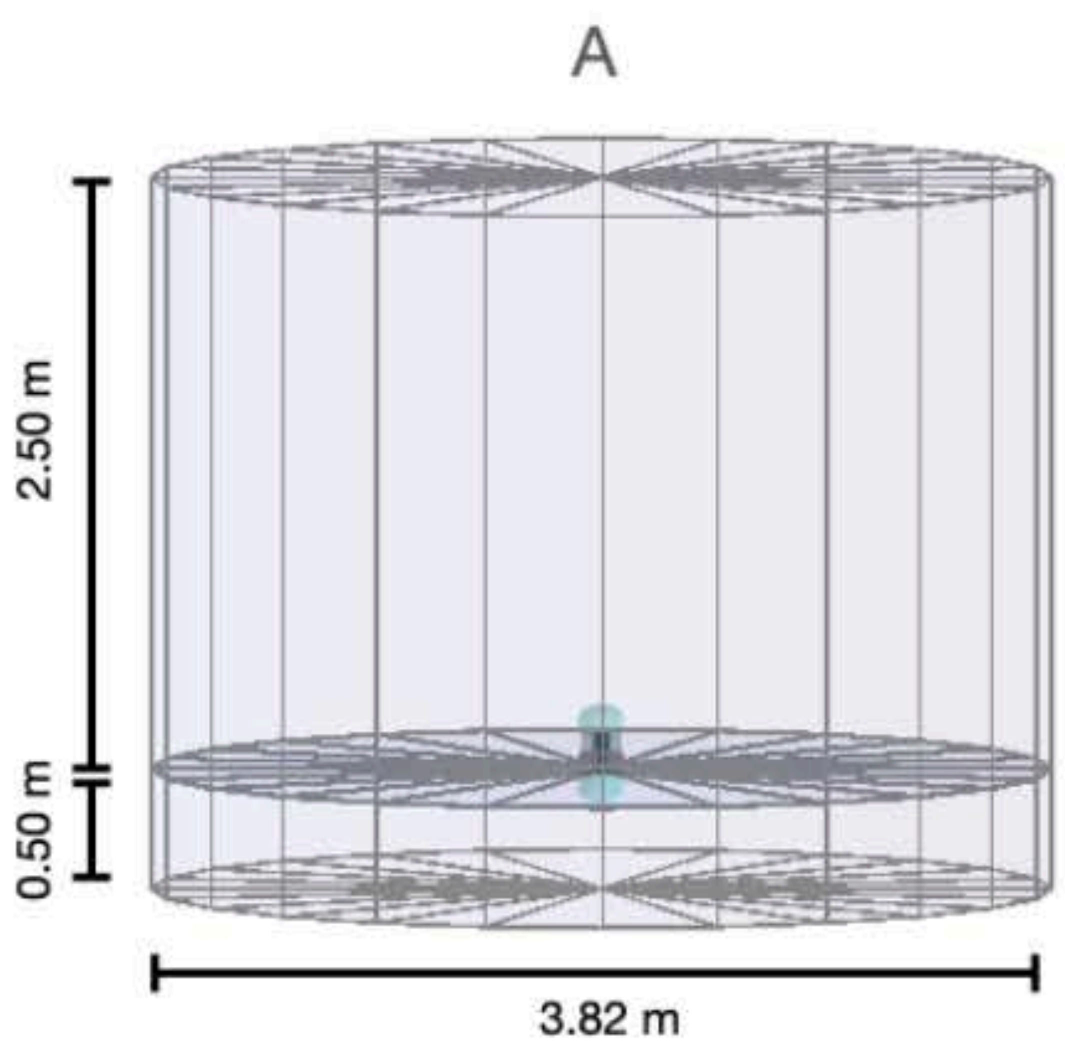
*cooperation with KM3NeT, MoU in prep.



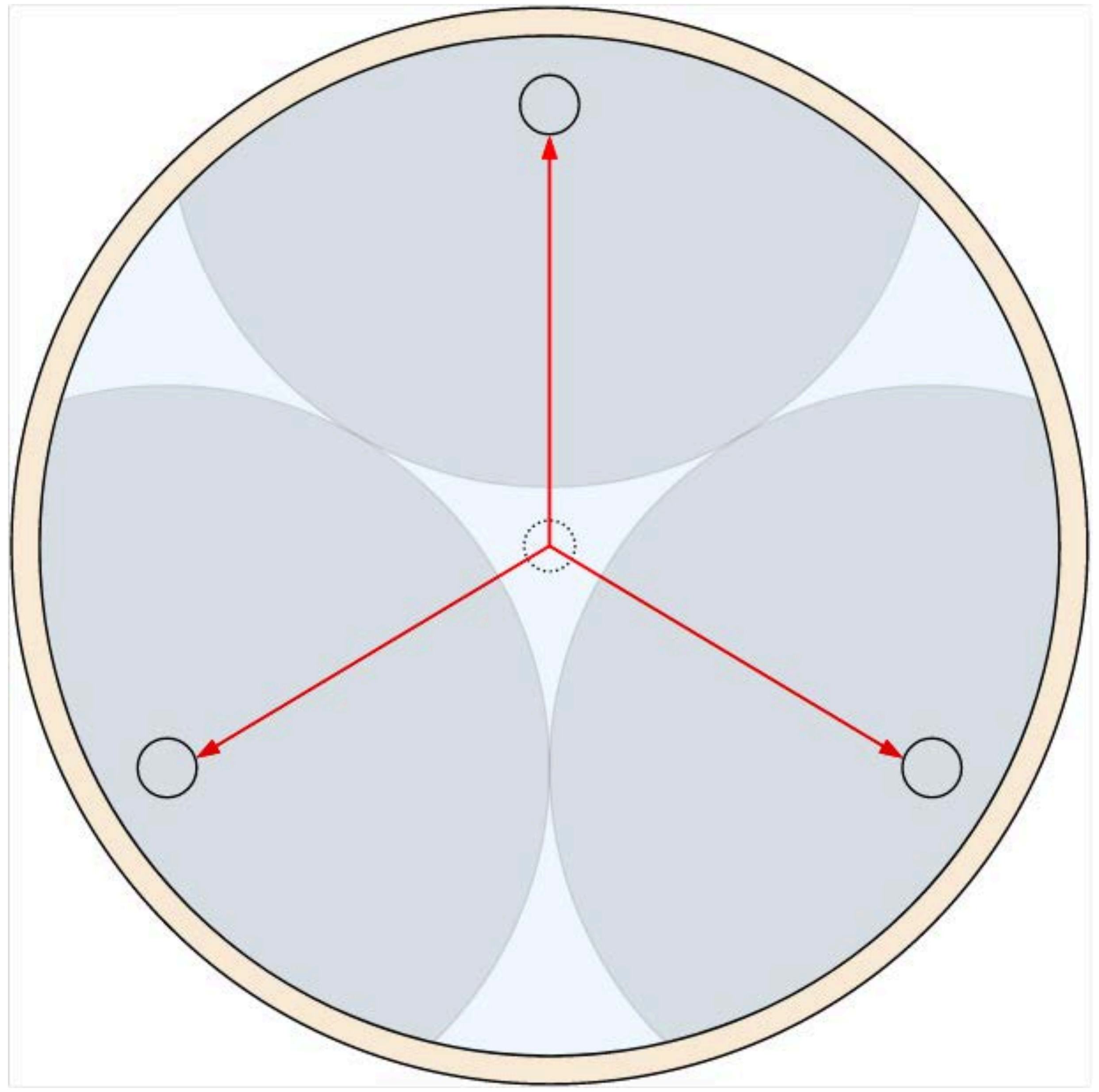


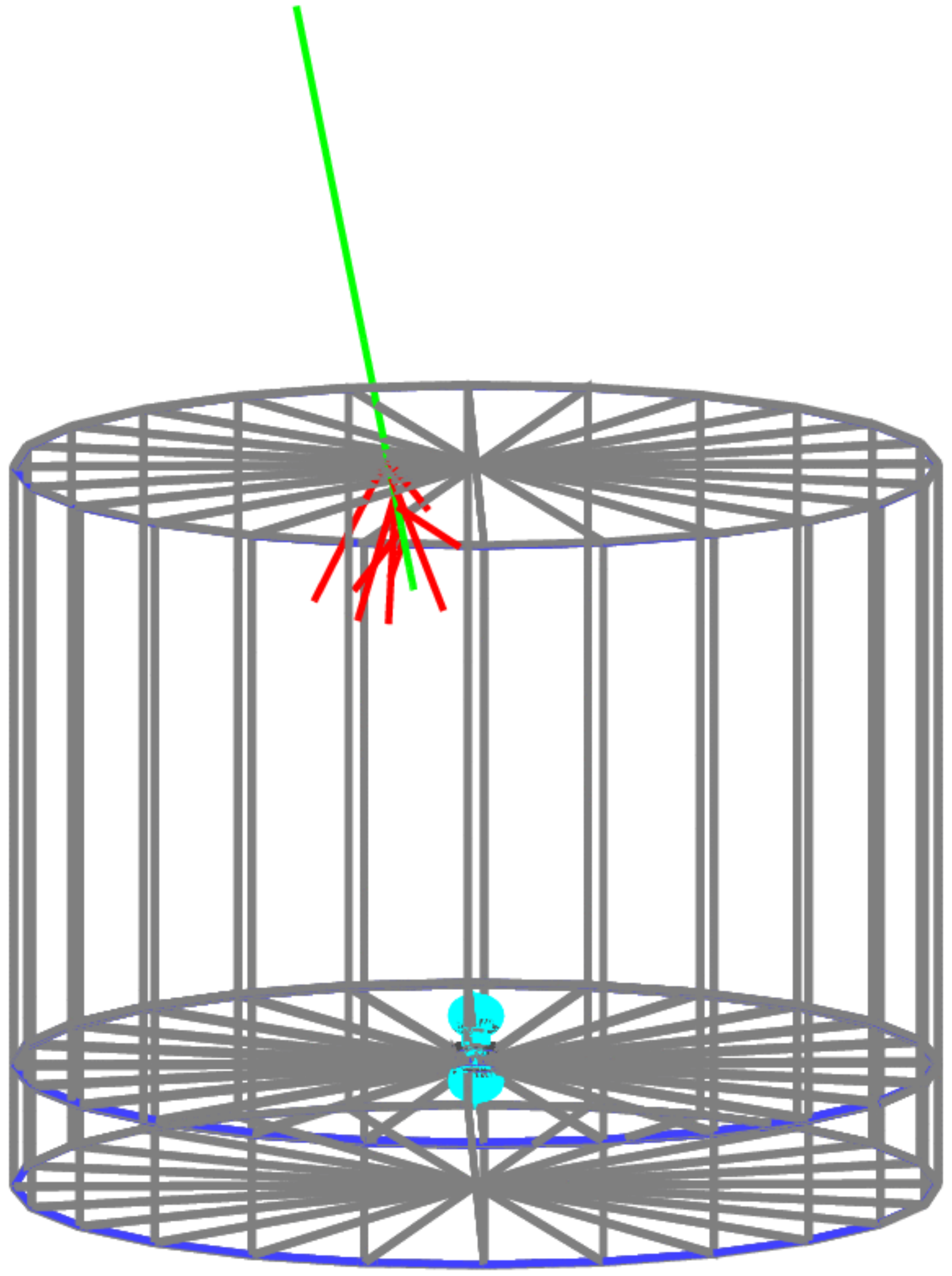


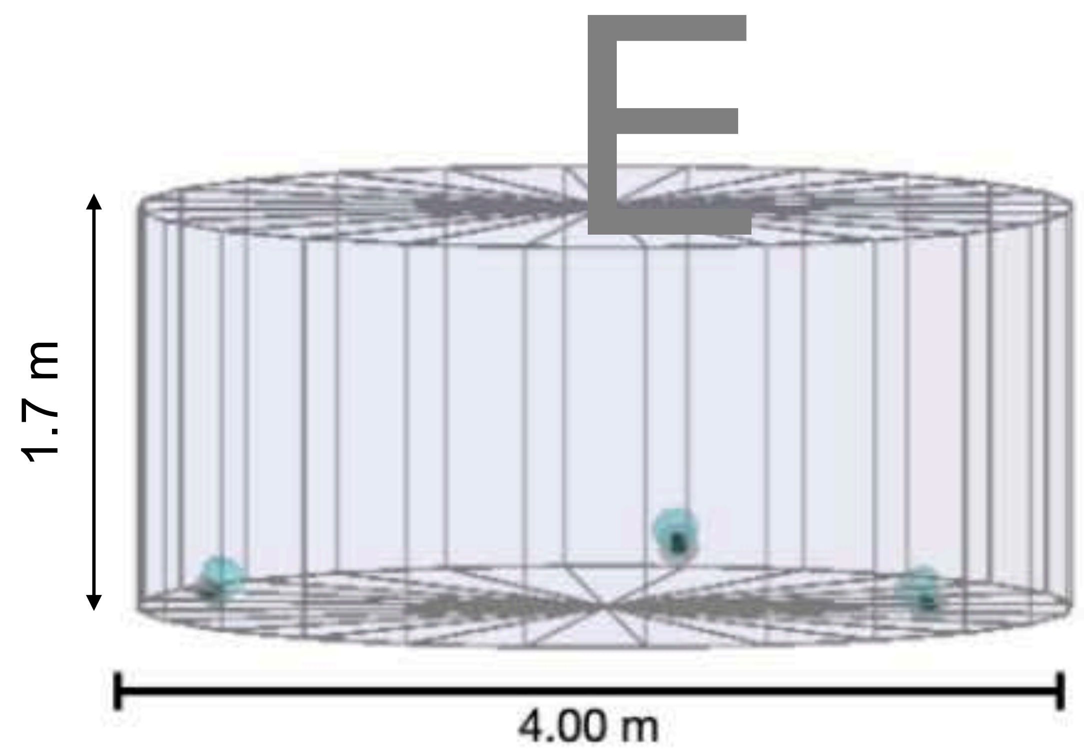
A
2.50 m
0.50 m
3.82 m
B
2.50 m
0.50 m
3.82 m
C
2.5 m
0.5 m
3.00 m
D
3.42 m
0.68 m
5.20 m
E
1.7 m
4.00 m
F
4.10 m
5.20 m

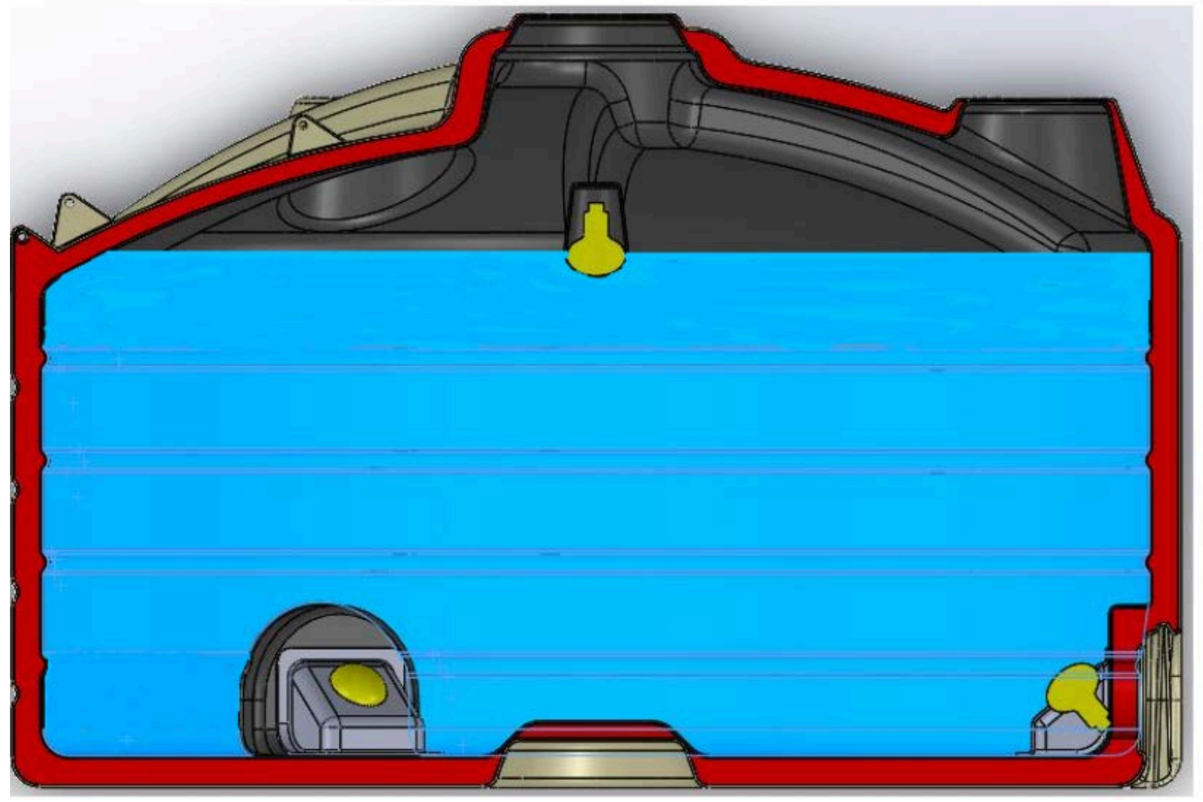


Muon identification a key element of background rejection – two approaches under evaluation

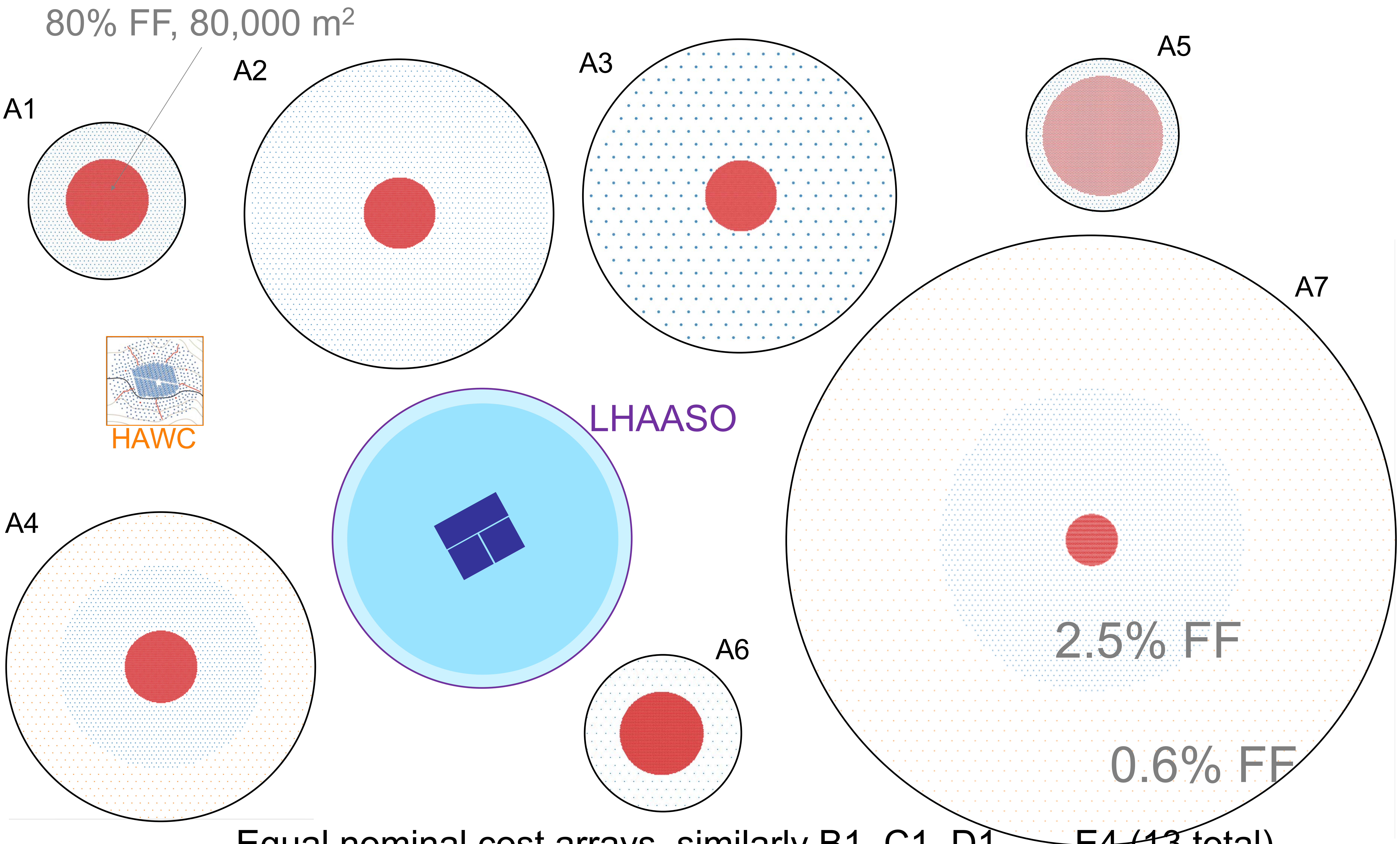




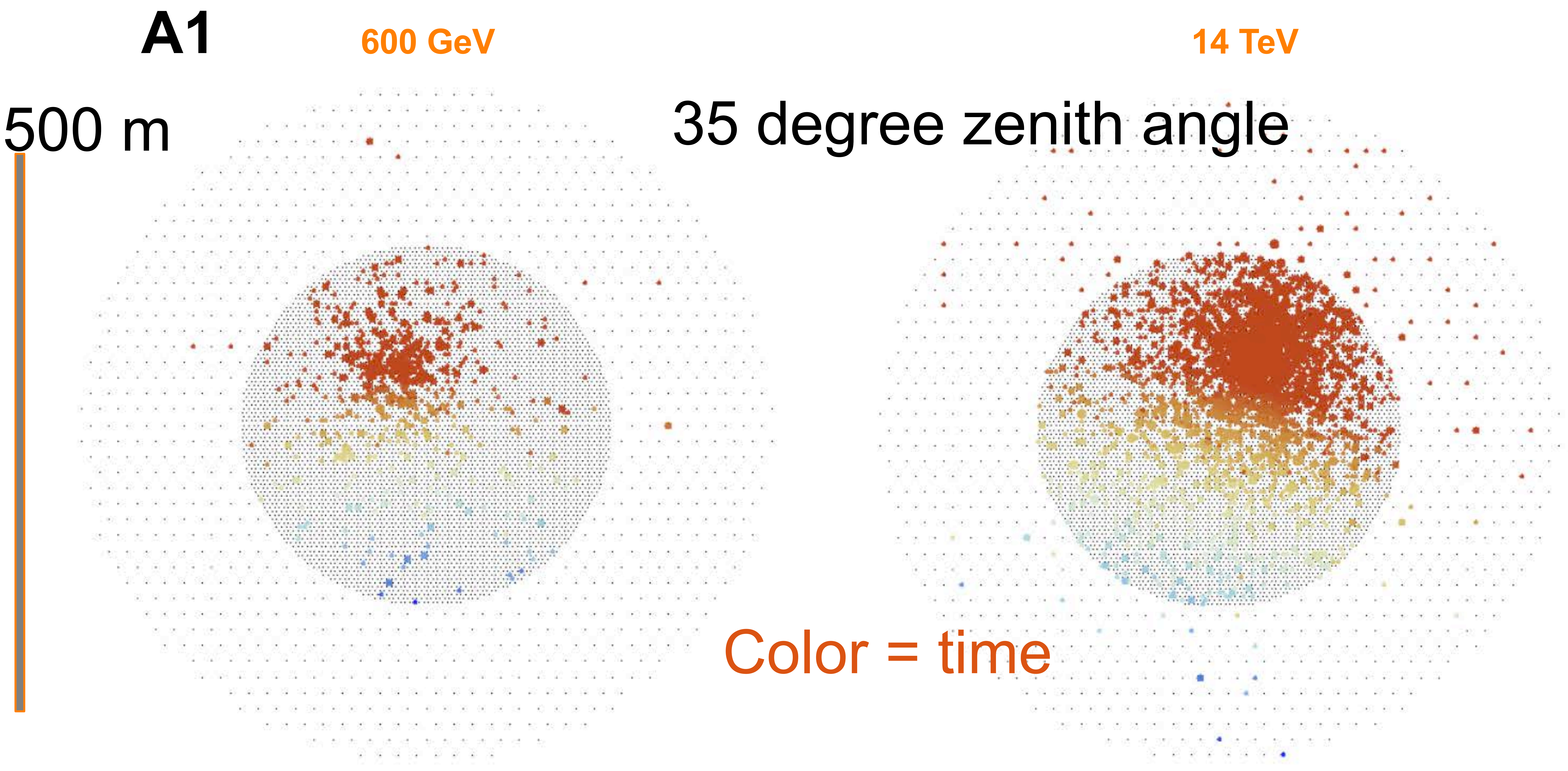




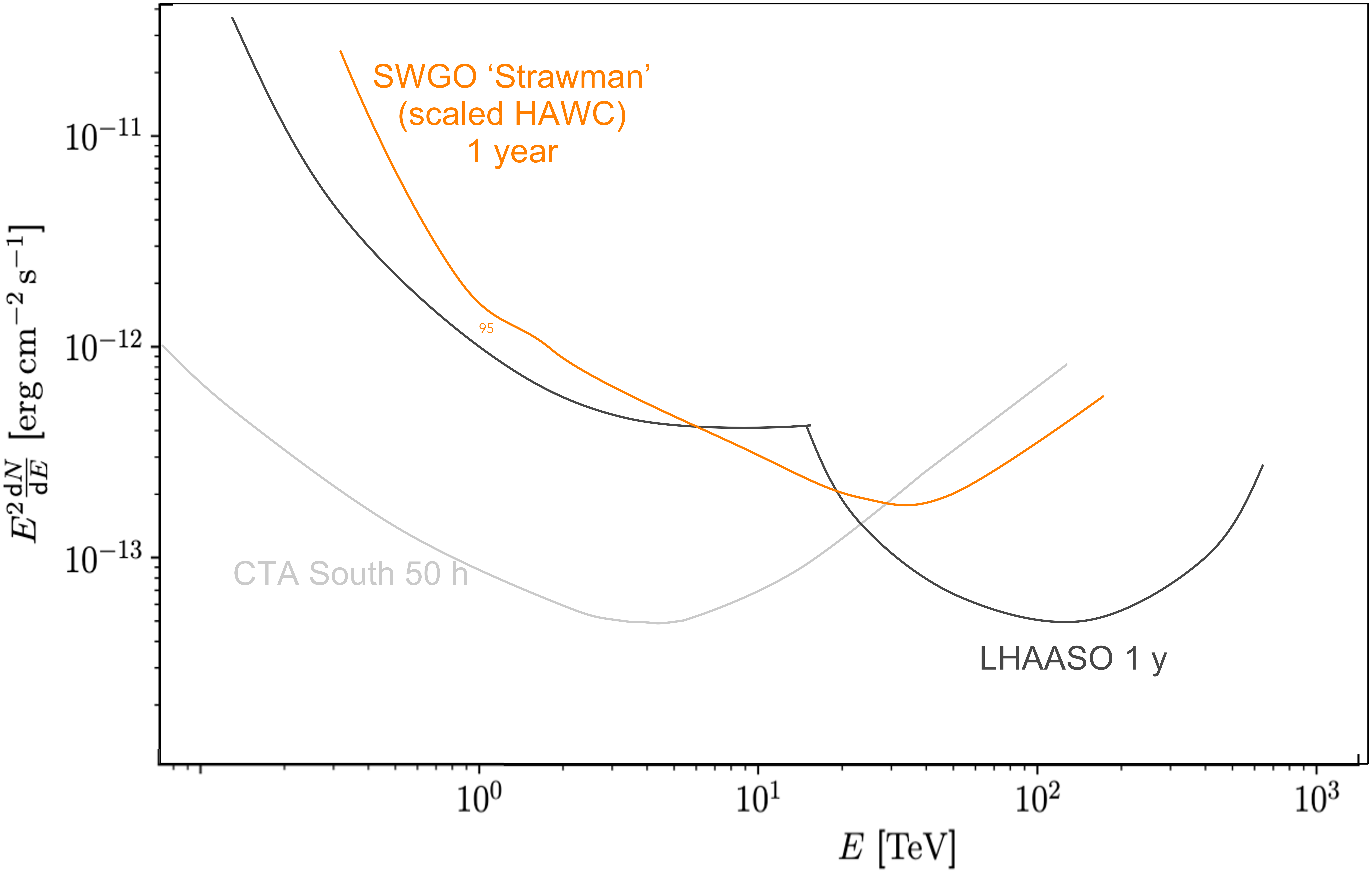
Samridha Kunwar

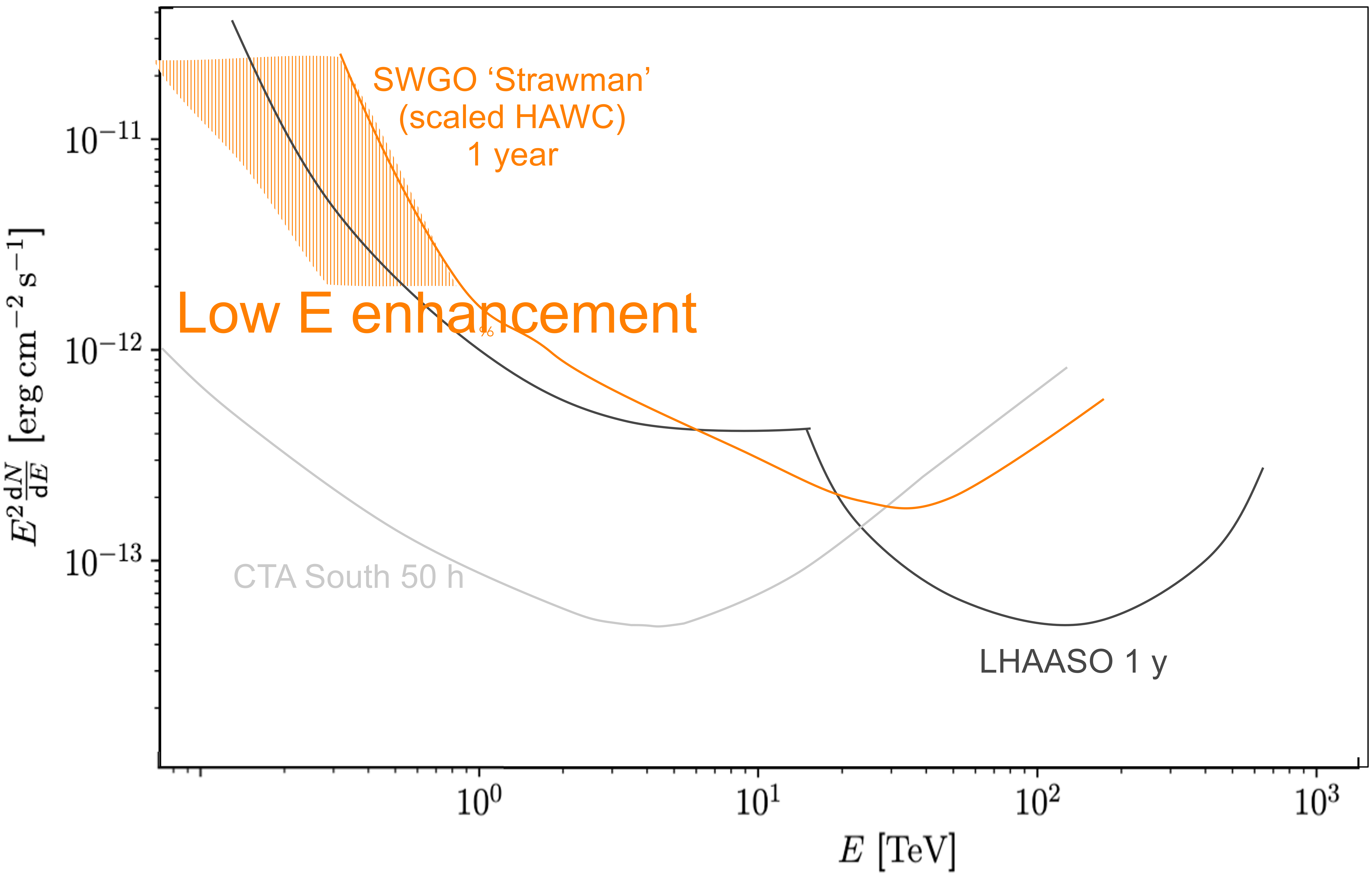


Equal nominal cost arrays, similarly B1, C1, D1, …, E4 (13 total)

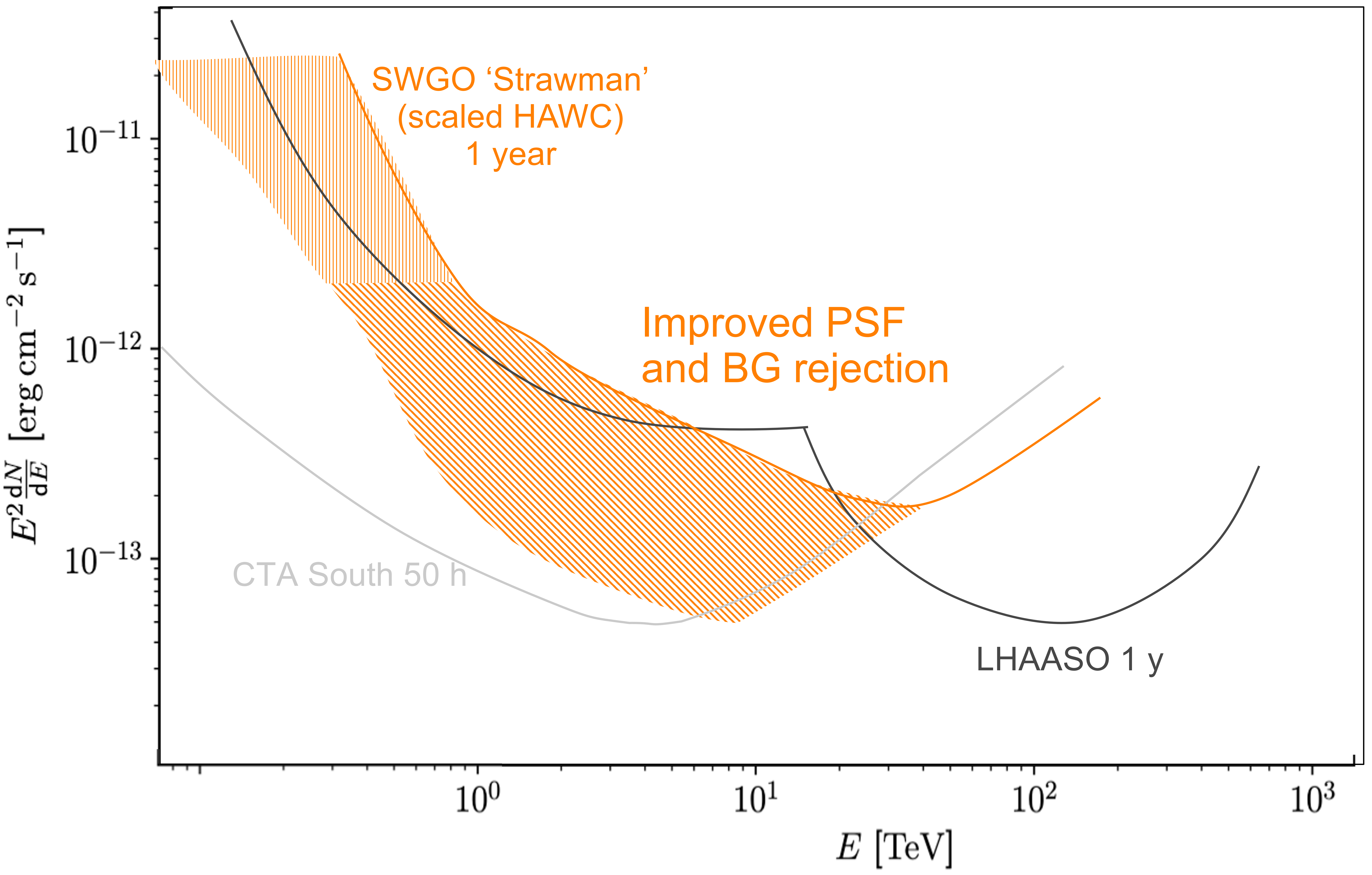


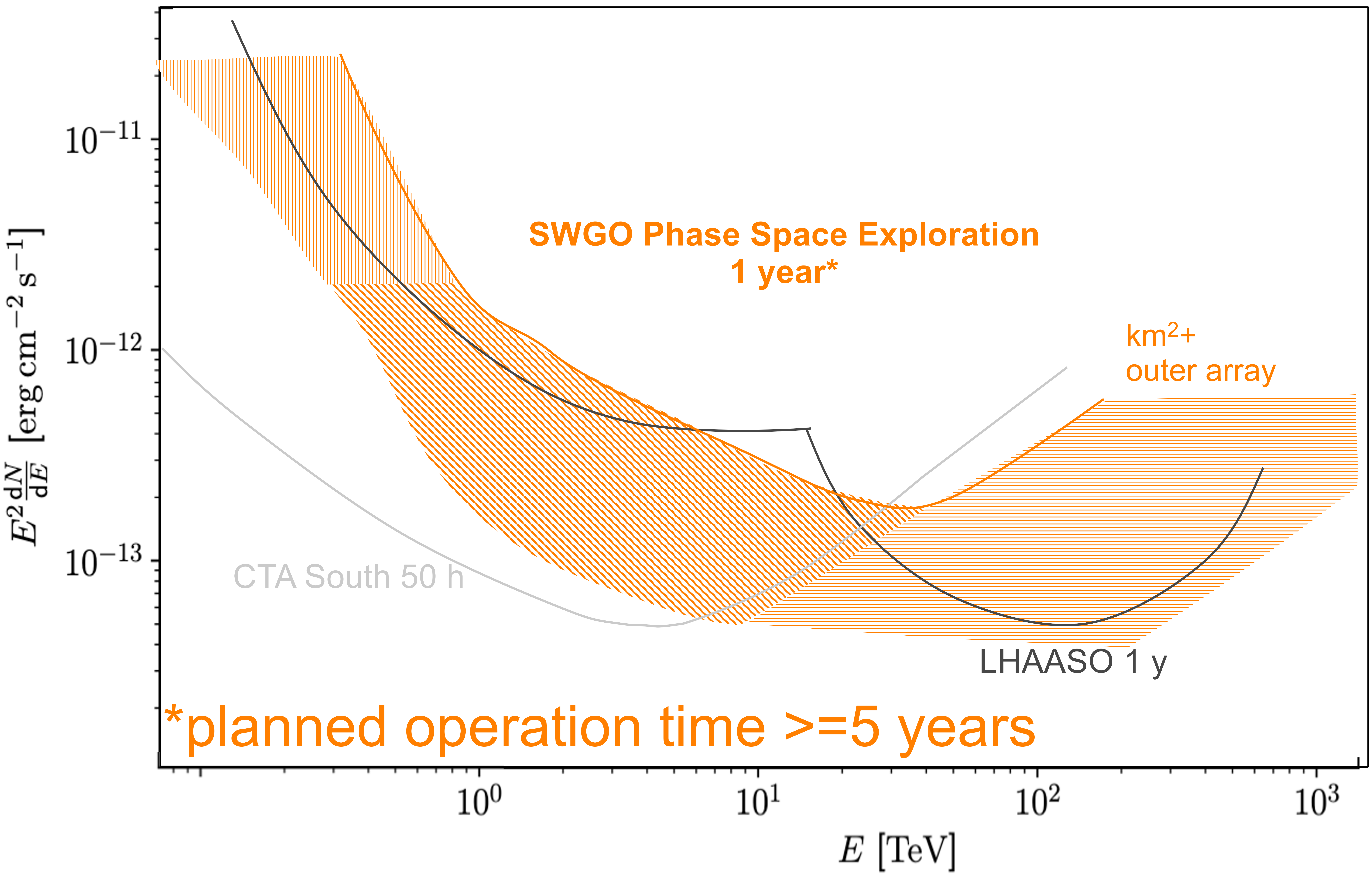
- Larger detector array and increased altitude w.r.t. HAWC
  - → Very precise measurements possible even below 1 TeV

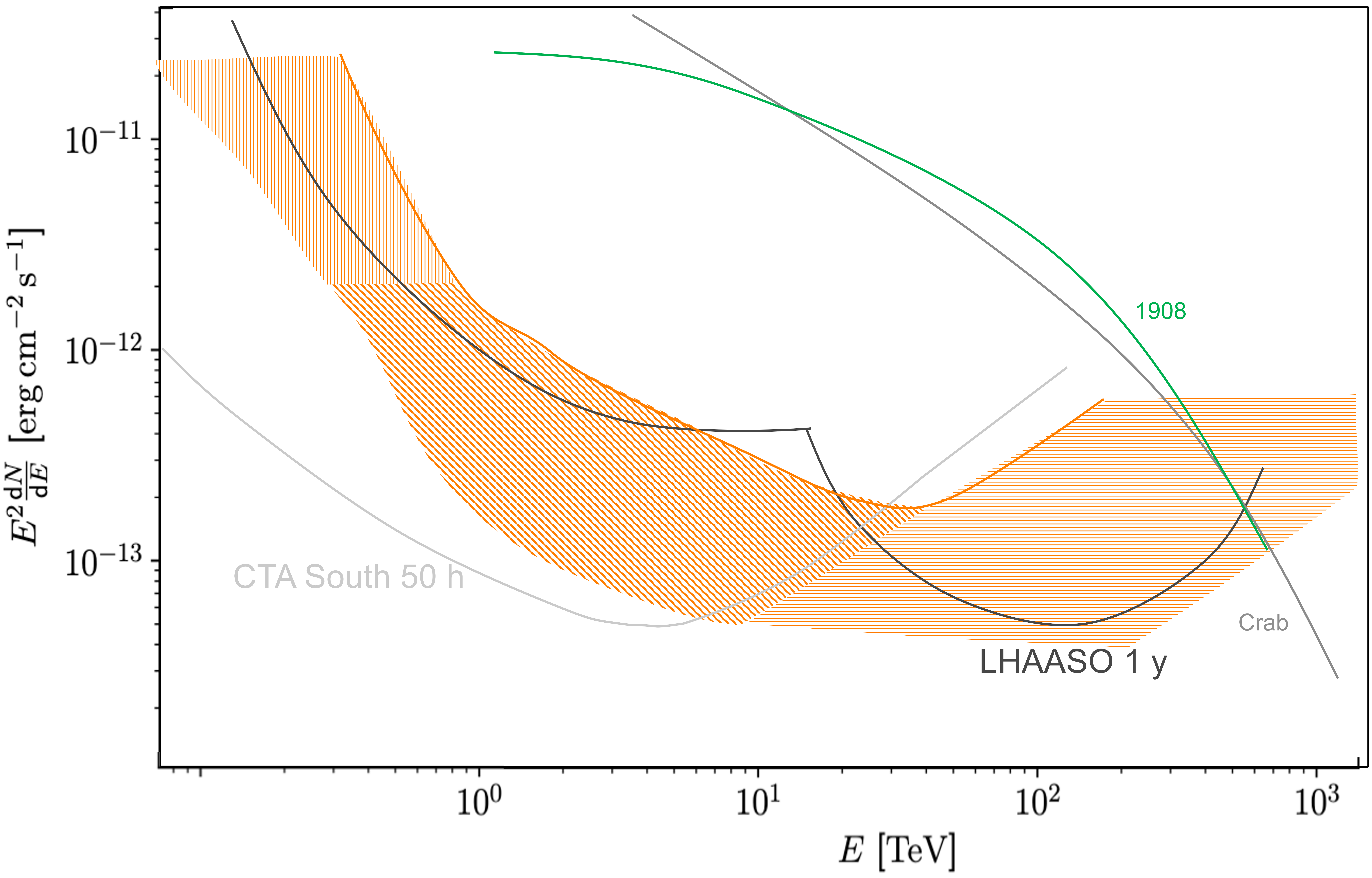

SWGO 'Strawman'
(scaled HAWC)
1 year
CTA South 50 h
LHAASO 1 y
10^{-11}
10^{-12}
10^{-13}
$E^2 \frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^0
10^1
10^2
10^3
E [TeV]



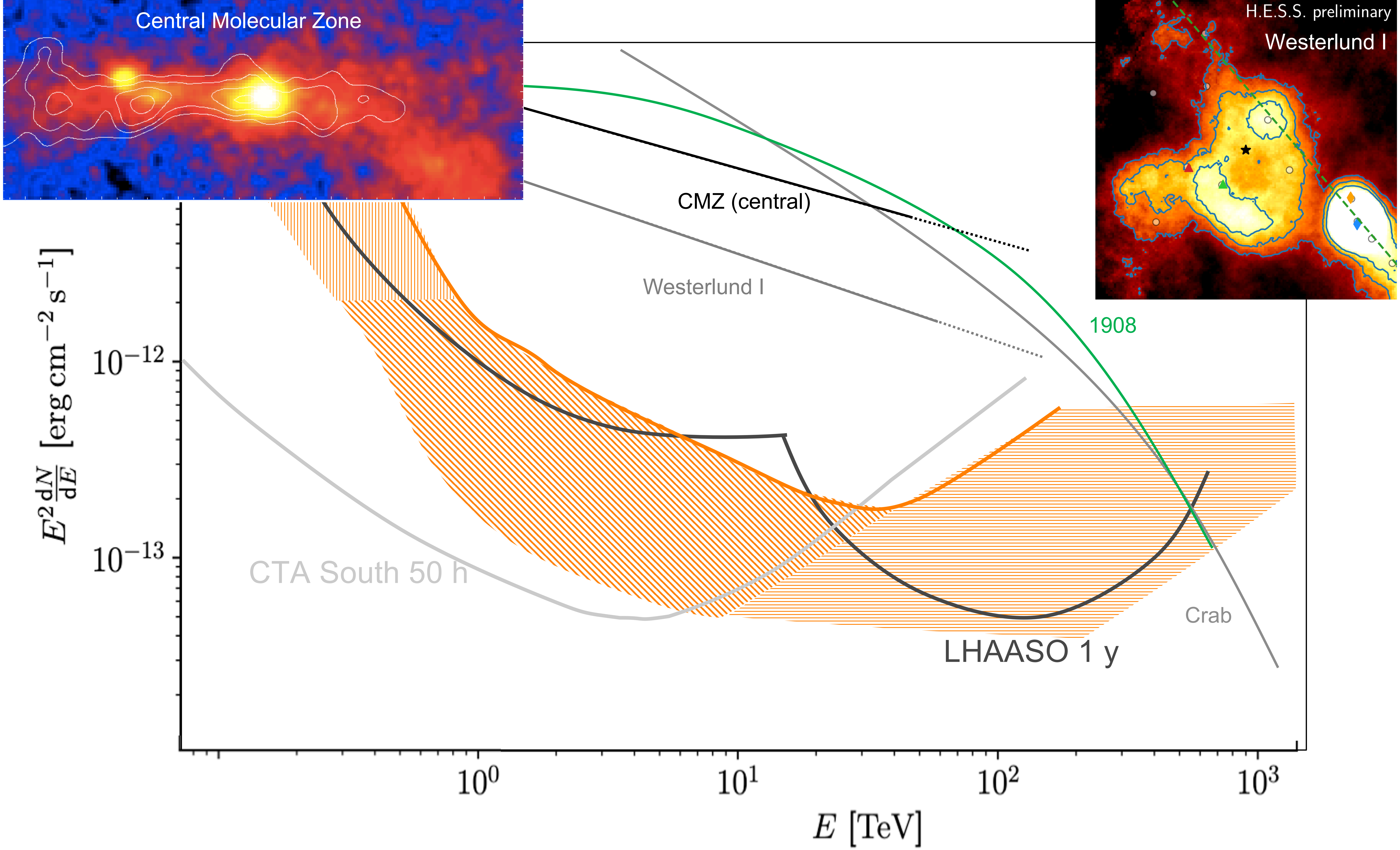
SWGO 'Strawman'
(scaled HAWC)
1 year
Low E enhancement
CTA South 50 h
LHAASO 1 y
$E^2 \frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^{-11}
10^{-12}
10^{-13}
10^0
10^1
10^2
10^3
E [TeV]


SWGO 'Strawman'
(scaled HAWC)
1 year
Improved PSF
and BG rejection
CTA South 50 h
LHAASO 1 y
10^{-11}
10^{-12}
10^{-13}
$E^2\frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^0
10^1
10^2
10^3
E [TeV]

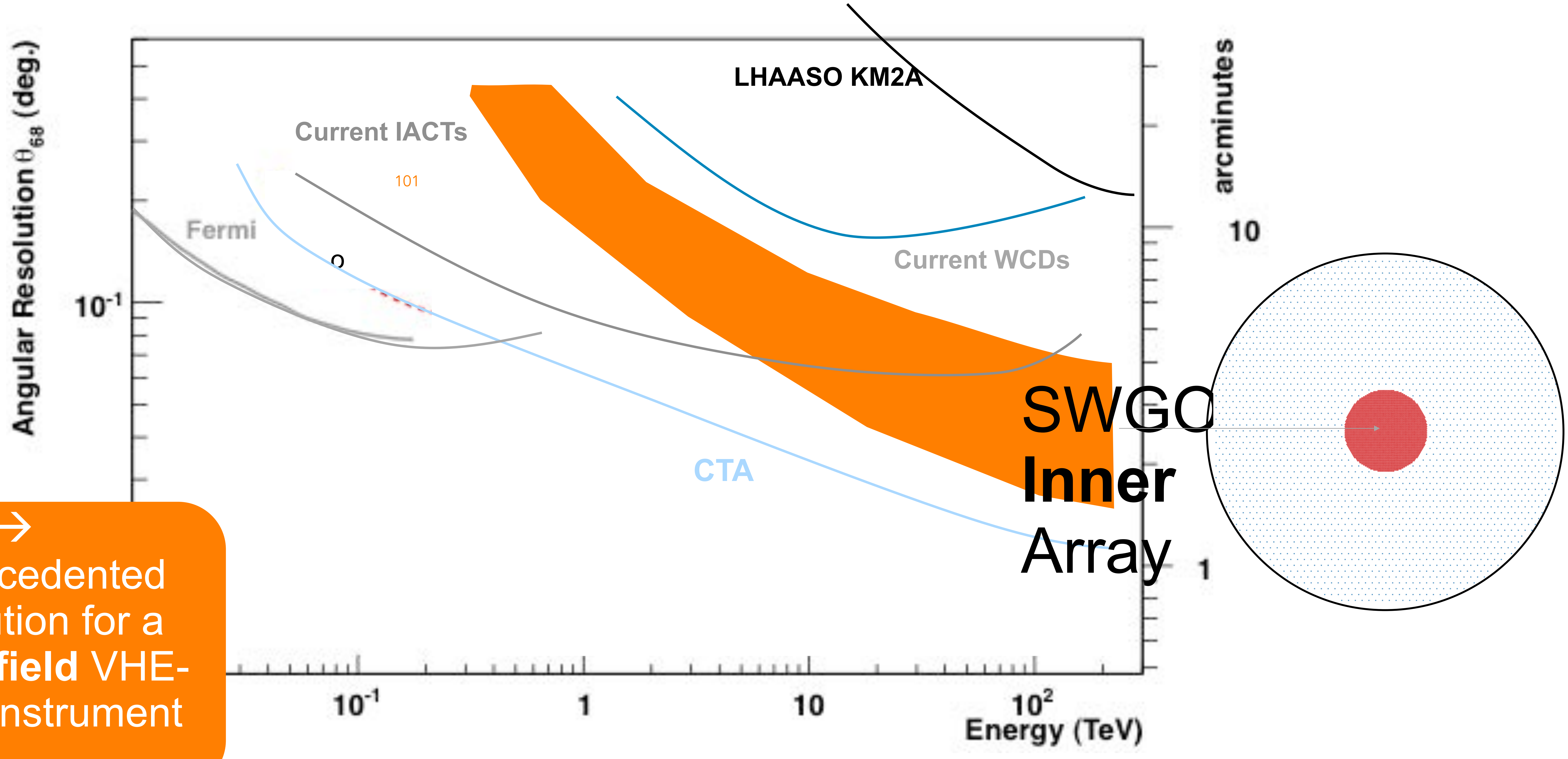

SWGO Phase Space Exploration
1 year*
km^2+
outer array
CTA South 50 h
LHAASO 1 y
*planned operation time >=5 years
$E^2 \frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^{-11}
10^{-12}
10^{-13}
10^0
10^1
10^2
10^3
E [TeV]



$E^2 \frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^{-11}
10^{-12}
10^{-13}
10^0
10^1
10^2
10^3
E [TeV]
1908
CTA South 50 h
Crab
LHAASO 1 y


Central Molecular Zone
H.E.S.S. preliminary
Westerlund I
CMZ (central)
Westerlund I
1908
CTA South 50 h
LHAASO 1 y
Crab
10^{-12}
10^{-13}
$E^2 \frac{\mathrm{d}N}{\mathrm{d}E}$ [erg cm^{-2} s^{-1}]
10^0
10^1
10^2
10^3
E [TeV]

Resolution?



Goal → unprecedented resolution for a **wide field** VHE-UHE instrument

Neutrino Synerg

SWGO+LHAASO

Full sky map of TeV-PeV γ emission

Strongly complements new generation of **neutrino instruments**

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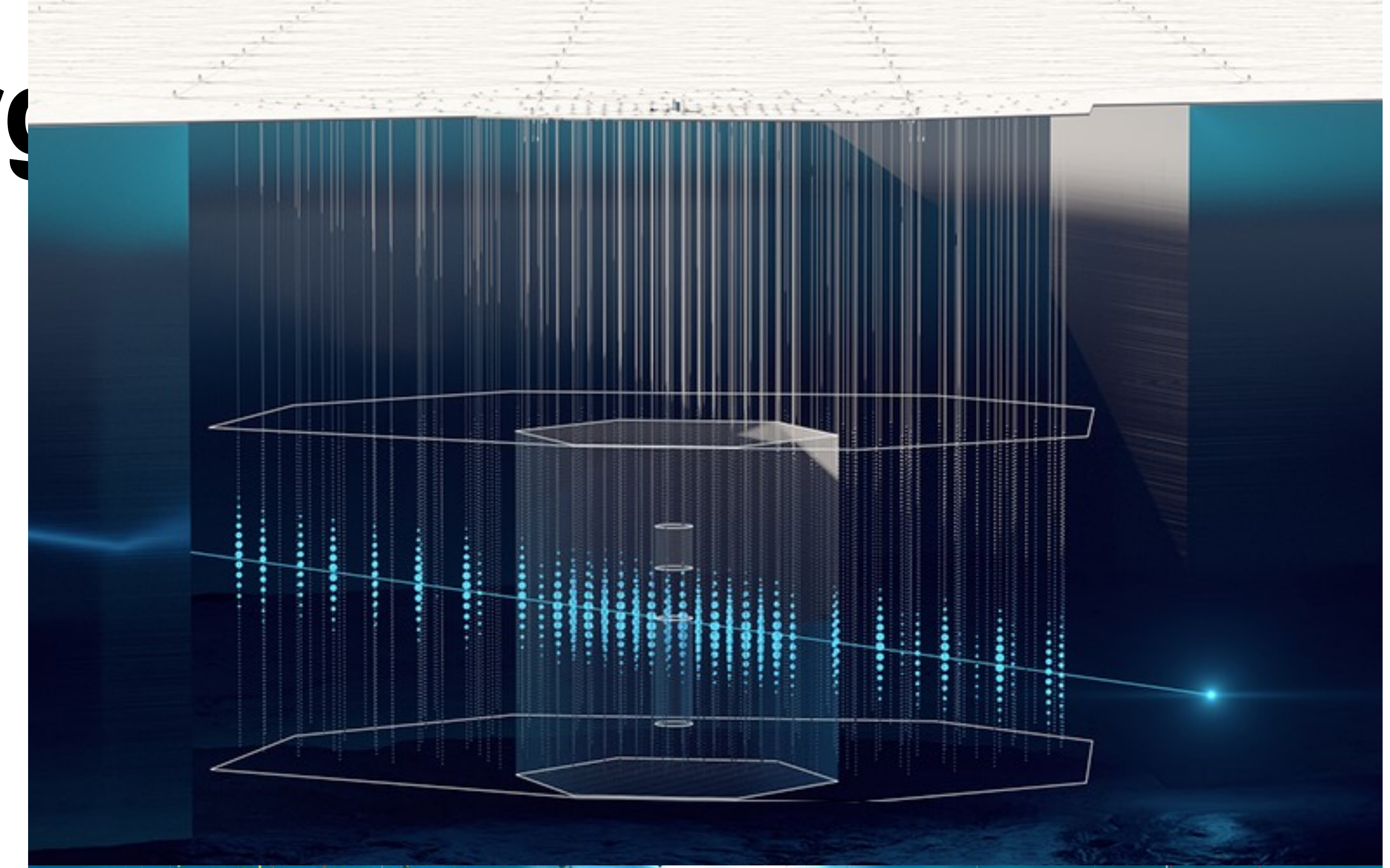
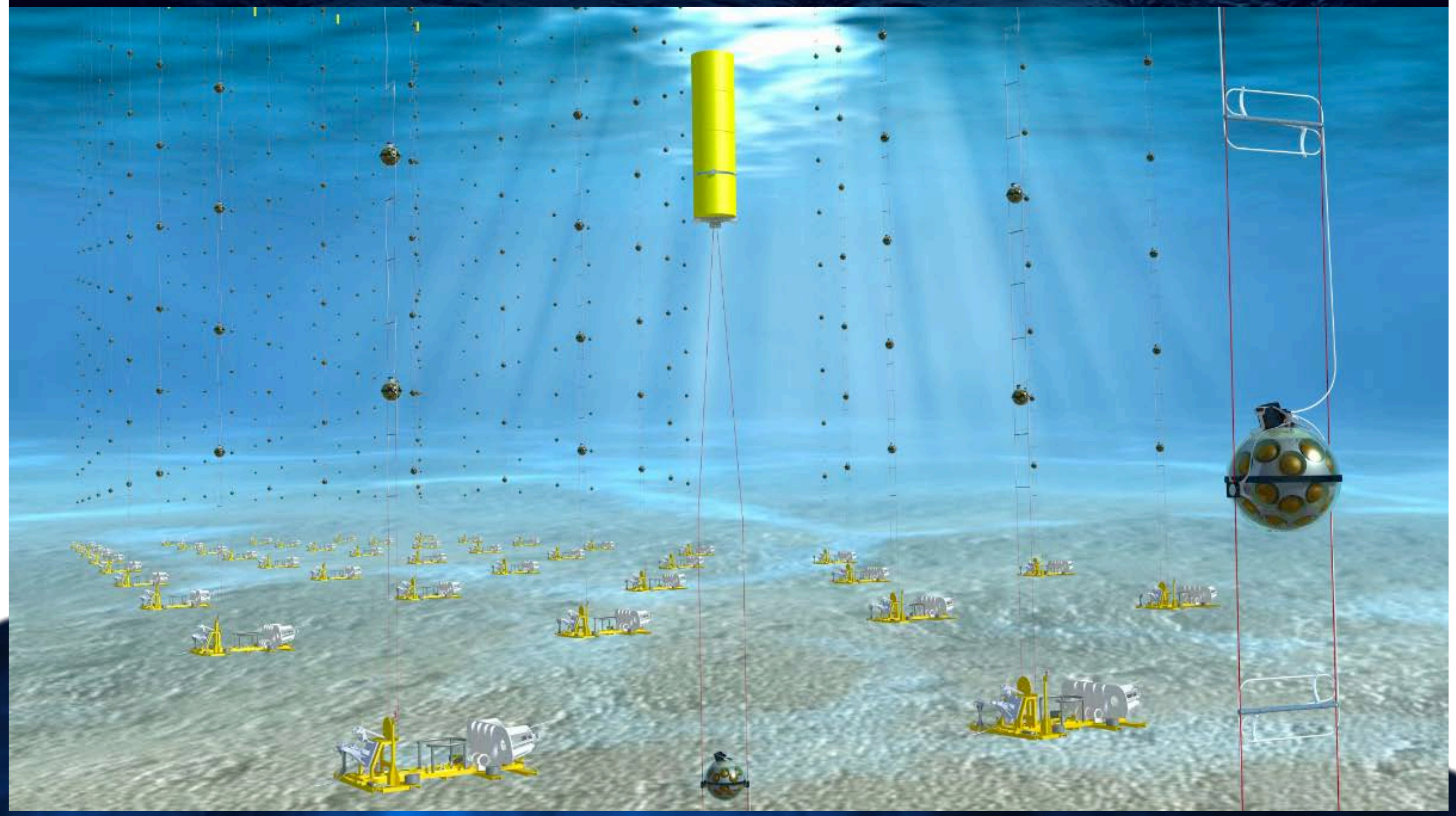
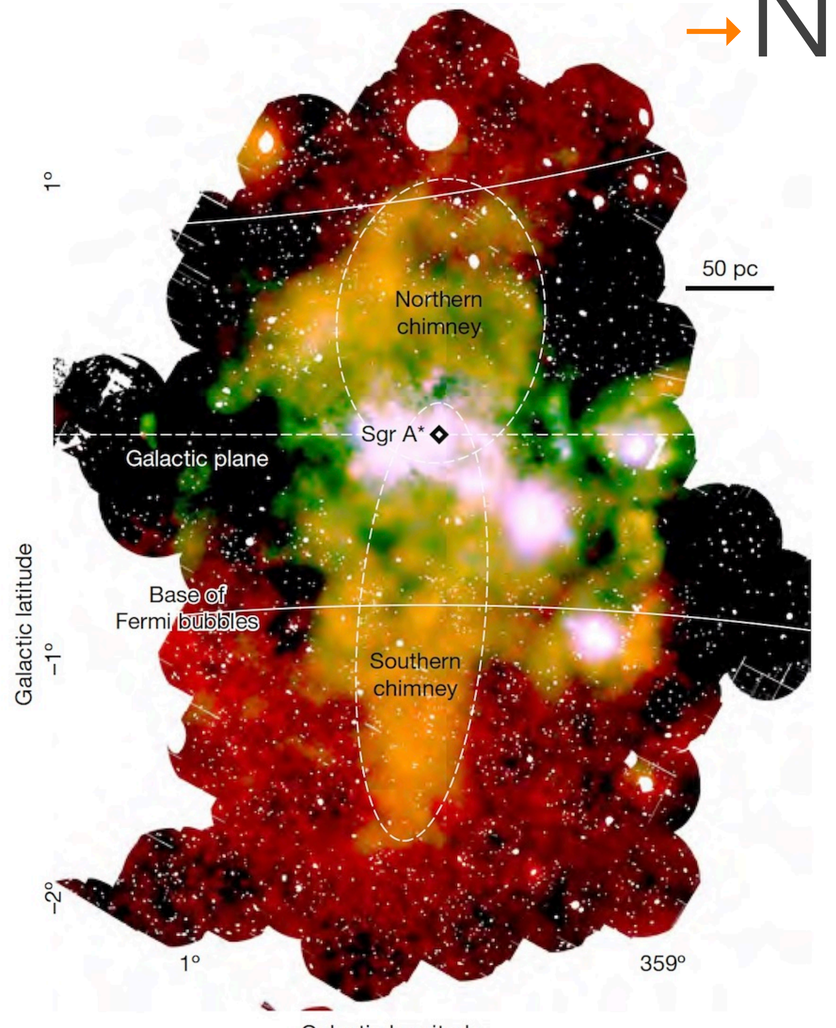
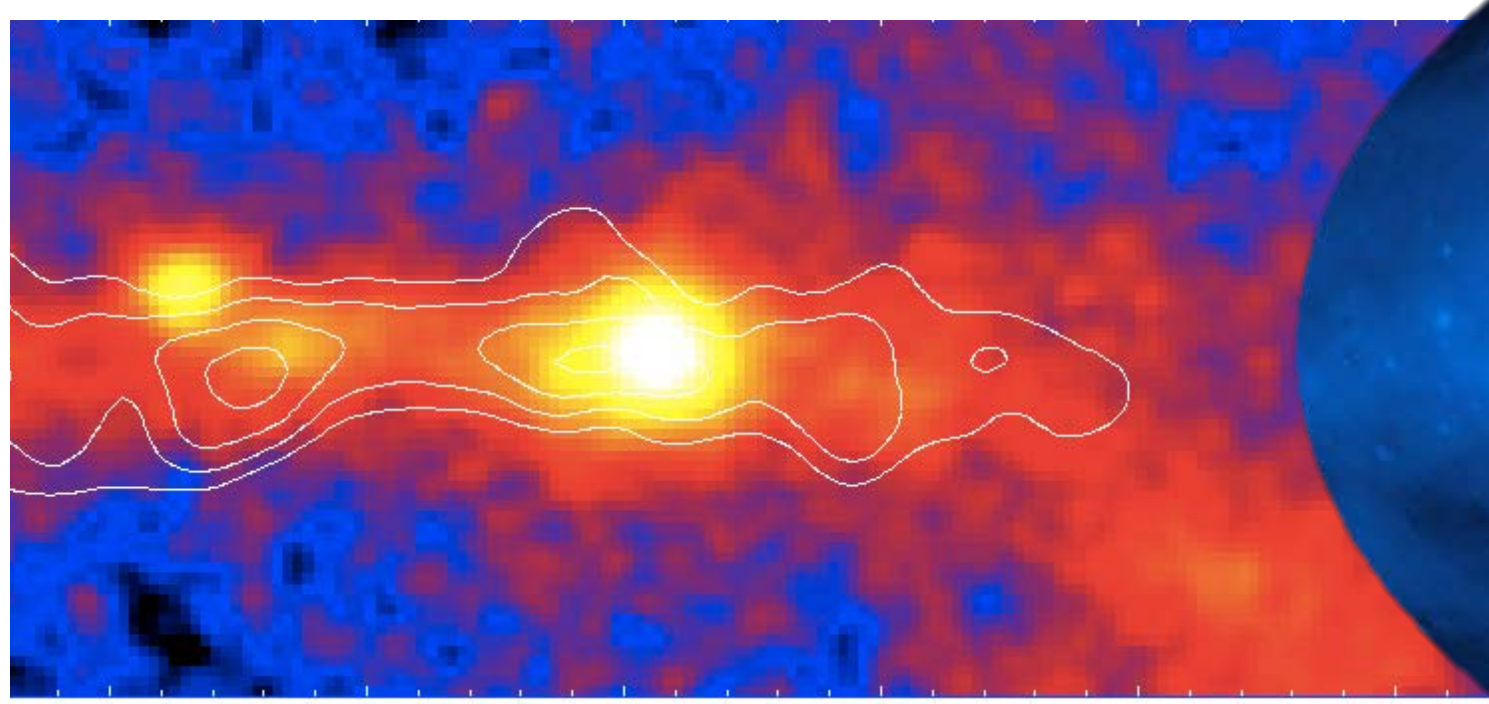
Mapping out diffuse emission / separating IC from pion decay emission, Dark Matter search +++

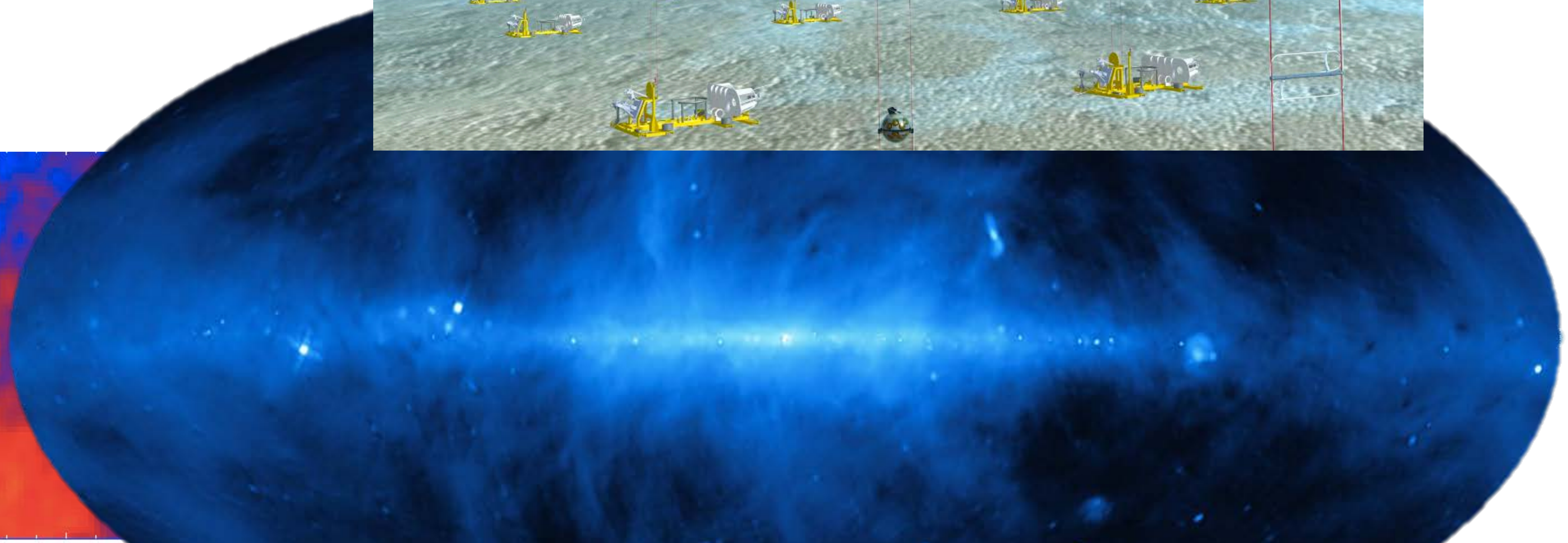
→Nearby transients/flares



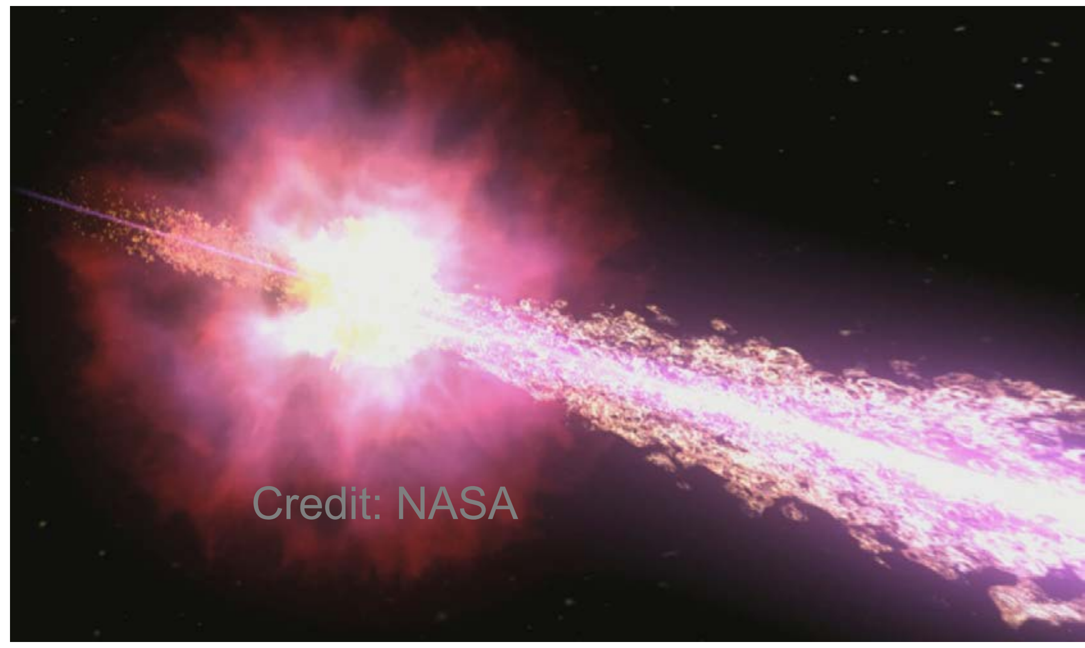








Transients



Instantaneous / short-timescale sensitivity of ground-particle detectors is much worse than IACTs! Especially at low E!!

So why are they still interesting for transients?

100% duty cycle → higher rate of high luminosity and/or nearby events (nearby bursts are very important → GWs, EBL systematics, ++)

Zero observation delay - can potentially catch events with fluxes many orders of magnitude higher

No need to trigger!

Blind searches and can check offline for 'slow' alerts

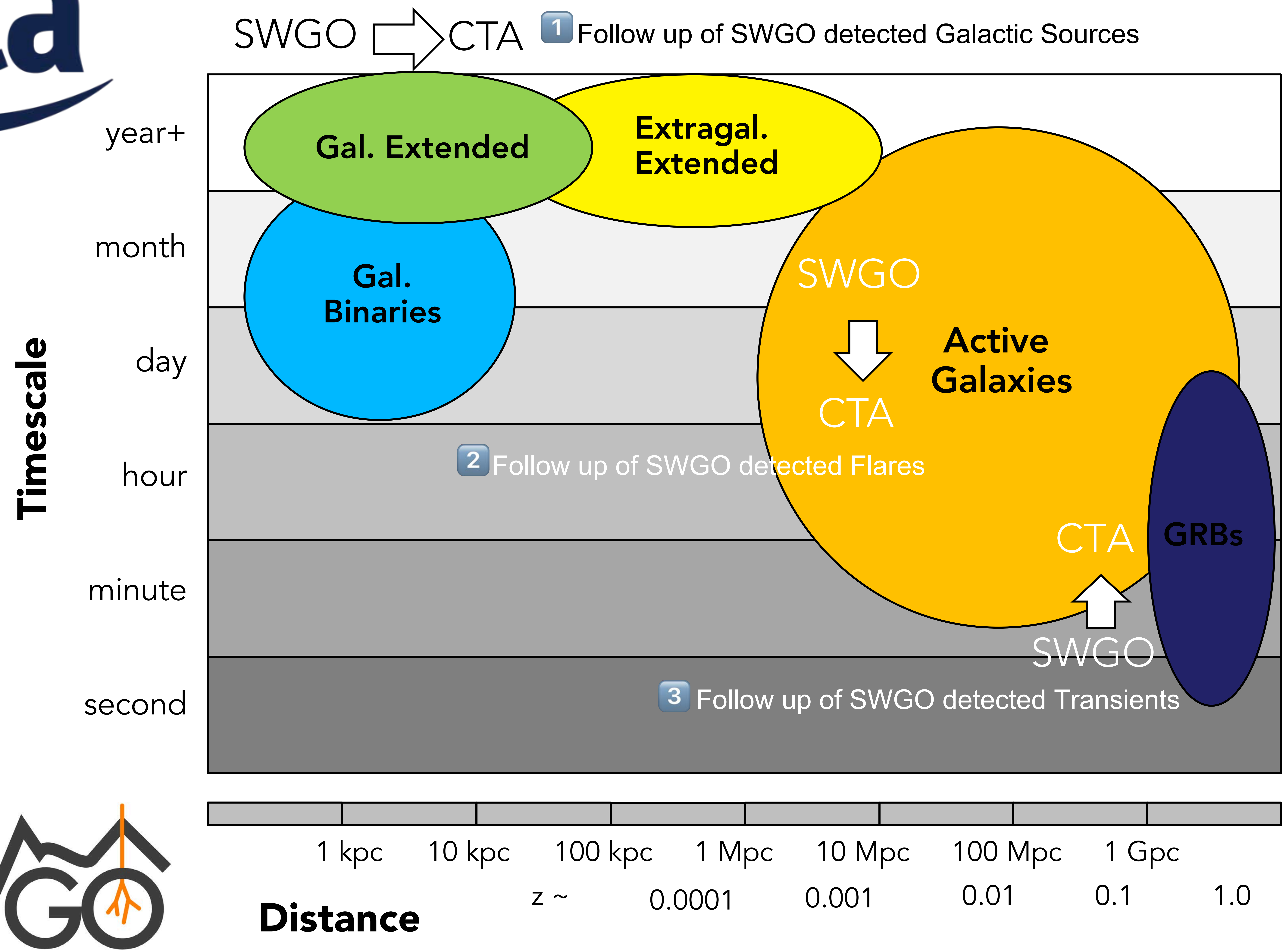
e.g. afterglow triggers from optical and radio → look back!

e.g. cubesats ++ many new / near future alert sources which can come **hours late**

Fermi: 1 GeV
CTA/SWGO: few 100 GeV

Order of magnitude **1 minute sensitivity**: Fermi-LAT: 10^{-7}, SWGO: 10^{-9}, CTA: 10^{-11} erg/cm^2/s

SWGO can bring the 10s deg^2 error boxes (GBM, GW) down to arcmin size


SWGO
CTA
1 Follow up of SWGO detected Galactic Sources
year+
month
day
hour
minute
second
Timescale
Gal. Extended
Extragal. Extended
Gal. Binaries
SWGO
CTA
Active Galaxies
2 Follow up of SWGO detected Flares
CTA
GRBs
SWGO
3 Follow up of SWGO detected Transients
1 kpc
10 kpc
100 kpc
1 Mpc
10 Mpc
100 Mpc
1 Gpc
z ~
0.0001
0.001
0.01
0.1
1.0
Distance