Ultra-High Energy Gamma-ray Sources Revealed by Large High-Altitude Air Shower Observatory (LHAASO)

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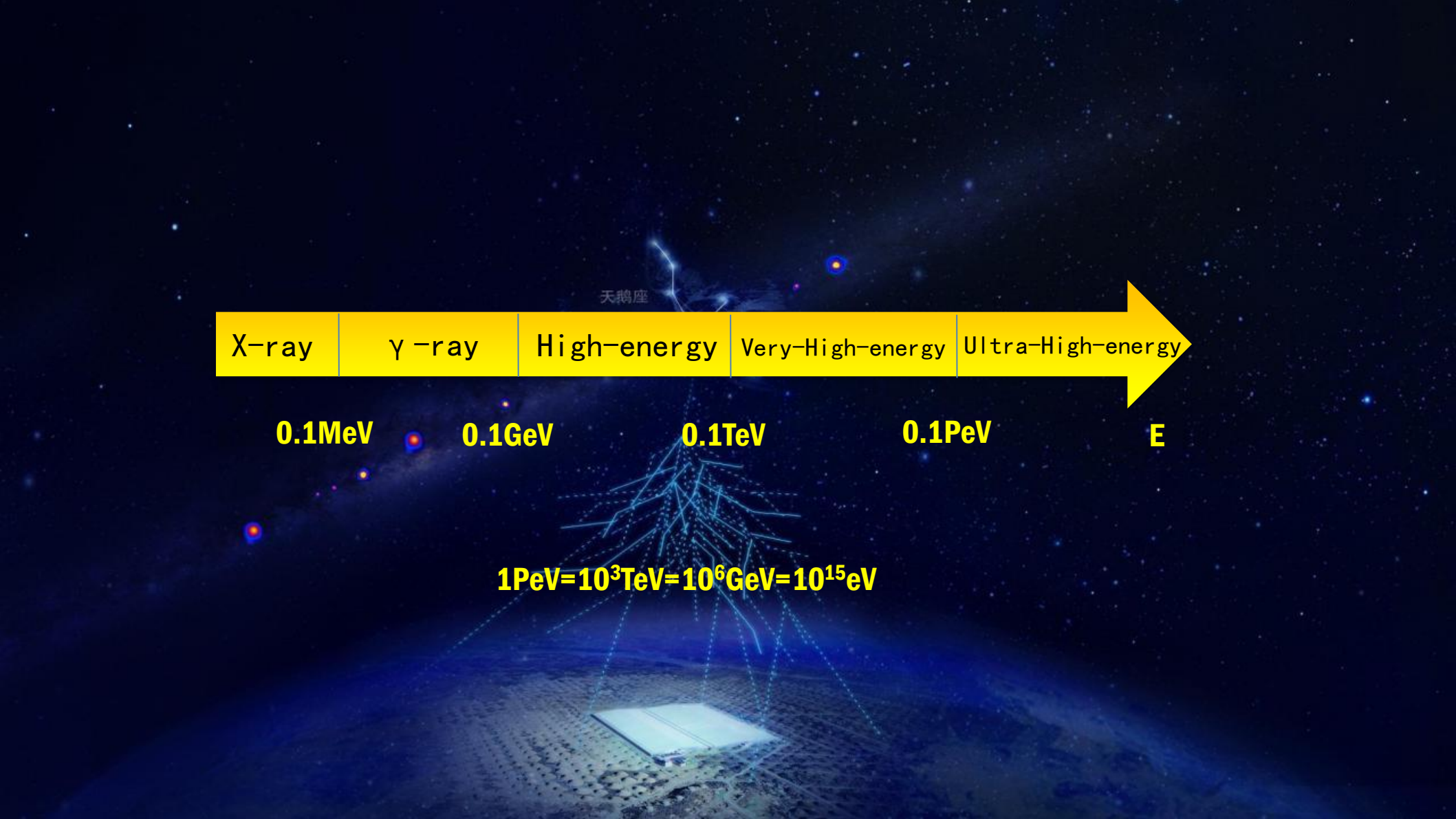
20-22.09.2022, Town Hall KM3NeT Meeting, Catania, Italy

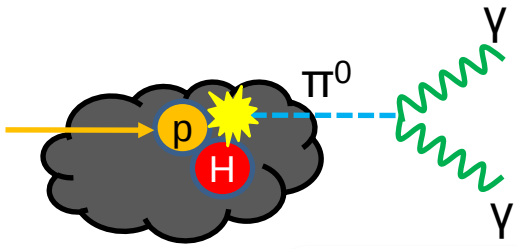
Outline

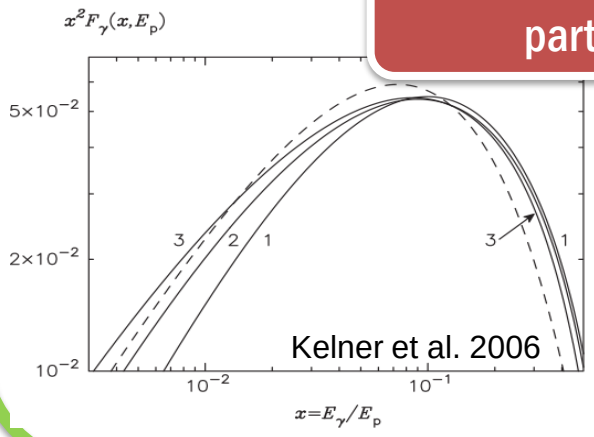
- A brief Introduction to UHE gamma-ray astronomy and LHAASO
- Two brightest UHE gamma-ray sources
  - LHAASO J1908+0621
  - LHAASO J1825-1326
- Summary


X-ray
γ-ray
High-energy
Very-High-energy
Ultra-High-energy
0.1MeV
0.1GeV
0.1TeV
0.1PeV
E
1PeV=10³TeV=10⁶GeV=10¹⁵eV

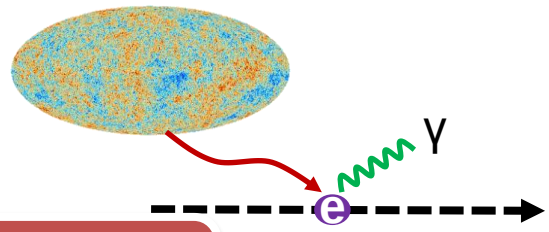
UHE Gamma ray radiation mechanism

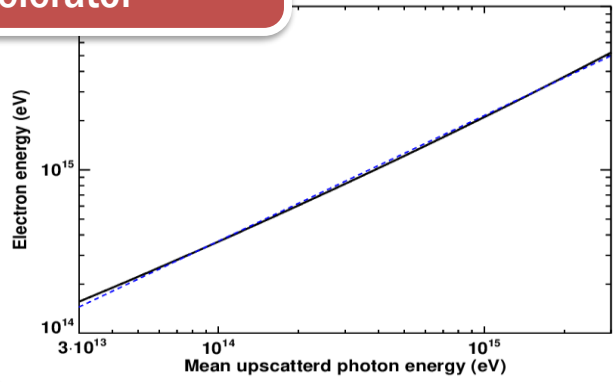
Proton-proton collision



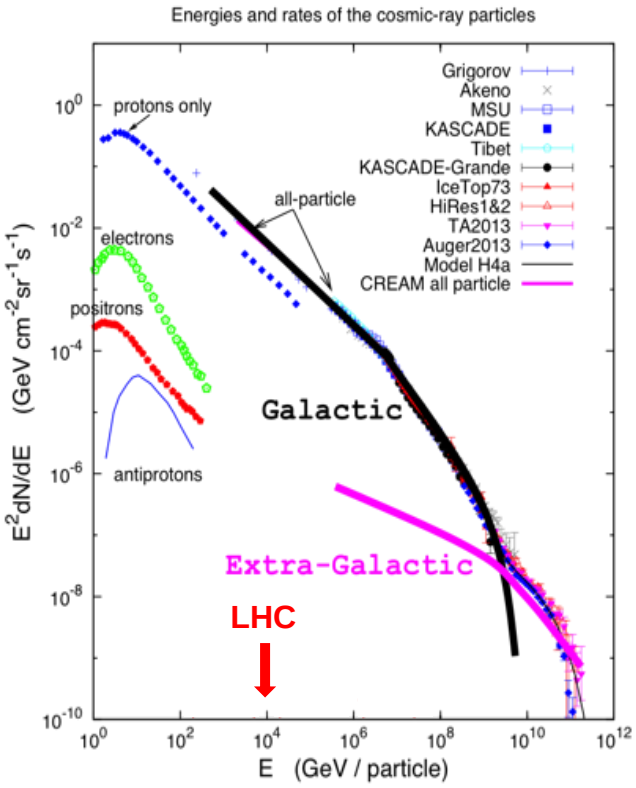


Inverse Compton scattering





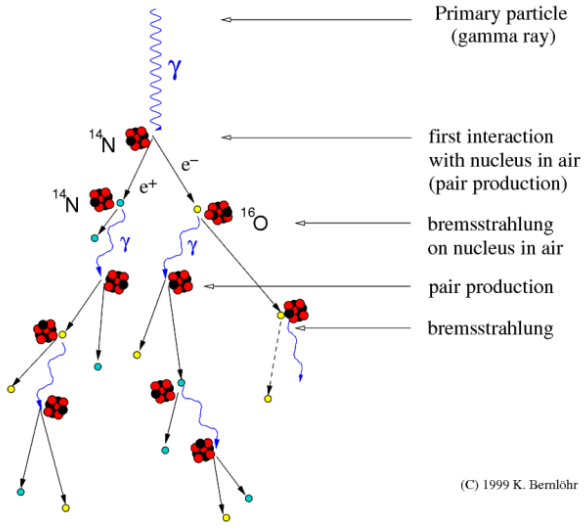
UHE emission is the probe of PeV particle accelerator



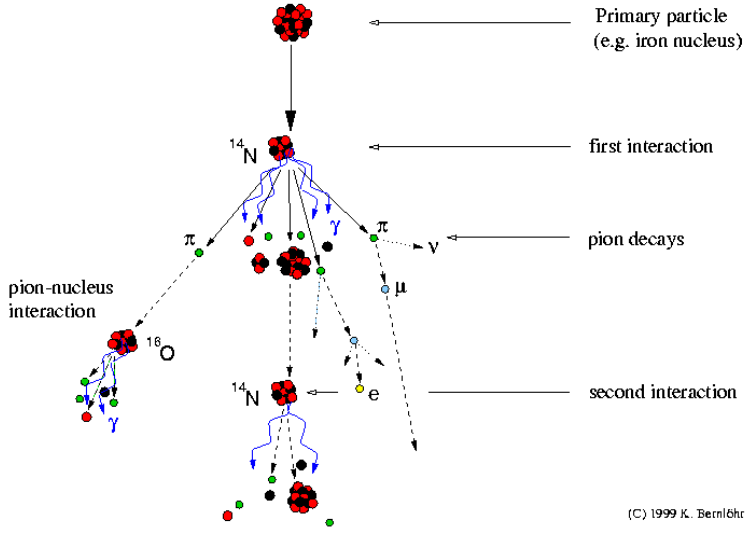
- Solution to the century puzzle of CR origin
- Probe of non-thermal Universe
- Gate to new physics

Extensive Air Shower

Development of gamma–ray air showers



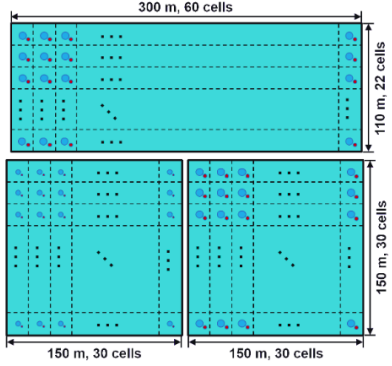
Development of cosmic-ray air showers

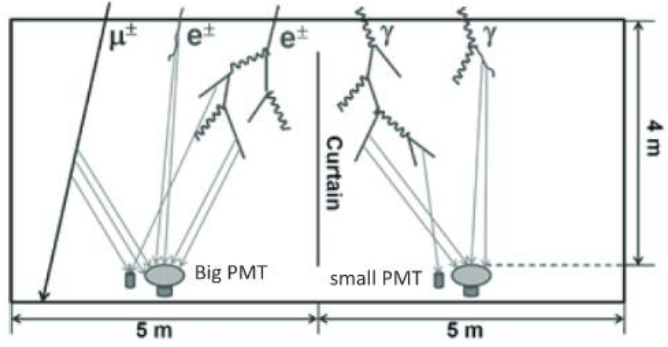


Indirect Detection – Event Reconstruction

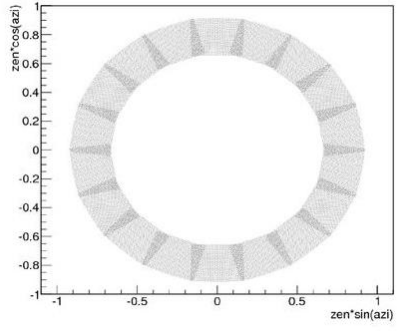
Water Cherenkov Detector Array

78,000m^2





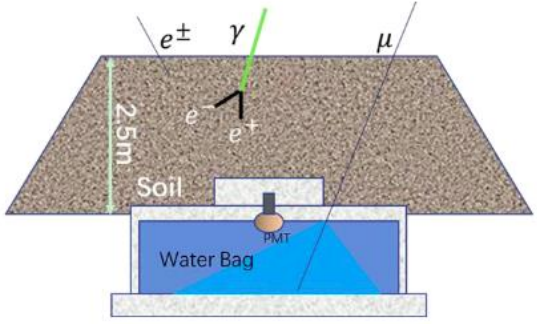
Wide Field Cherenkov
Telescope Array



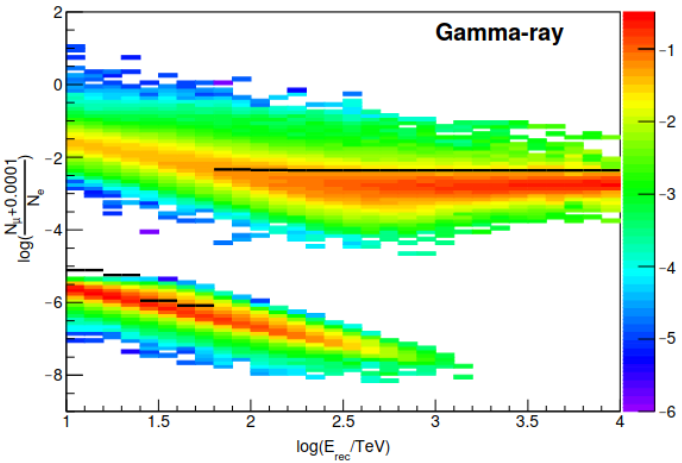
KiloMeter
Square(=2)
Array

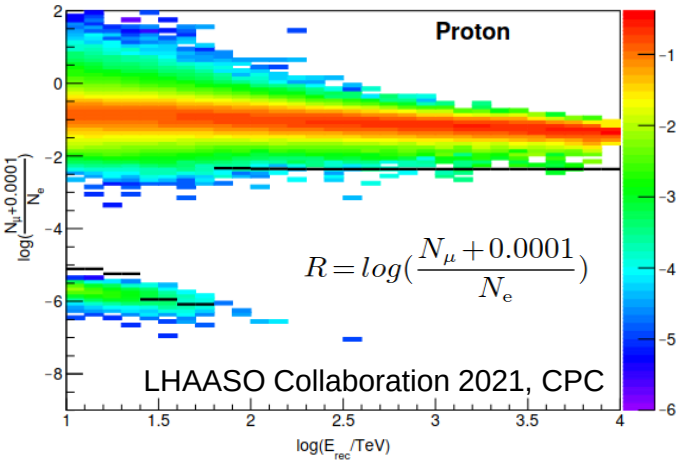
1188 Muon Detectors

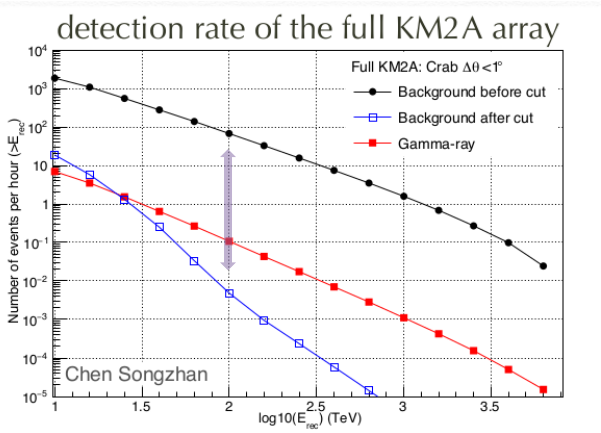
5195 Electron Detectors

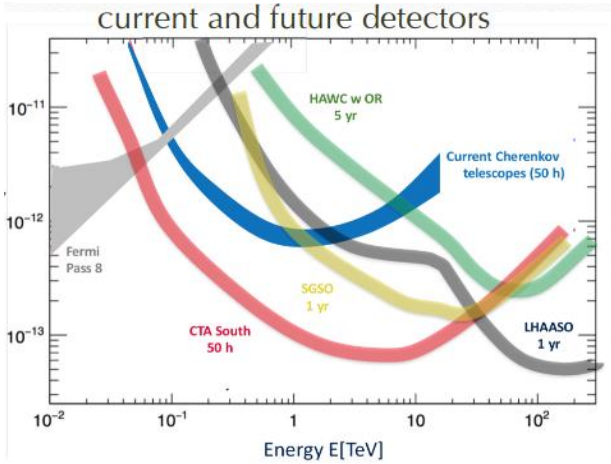


Sensitivity





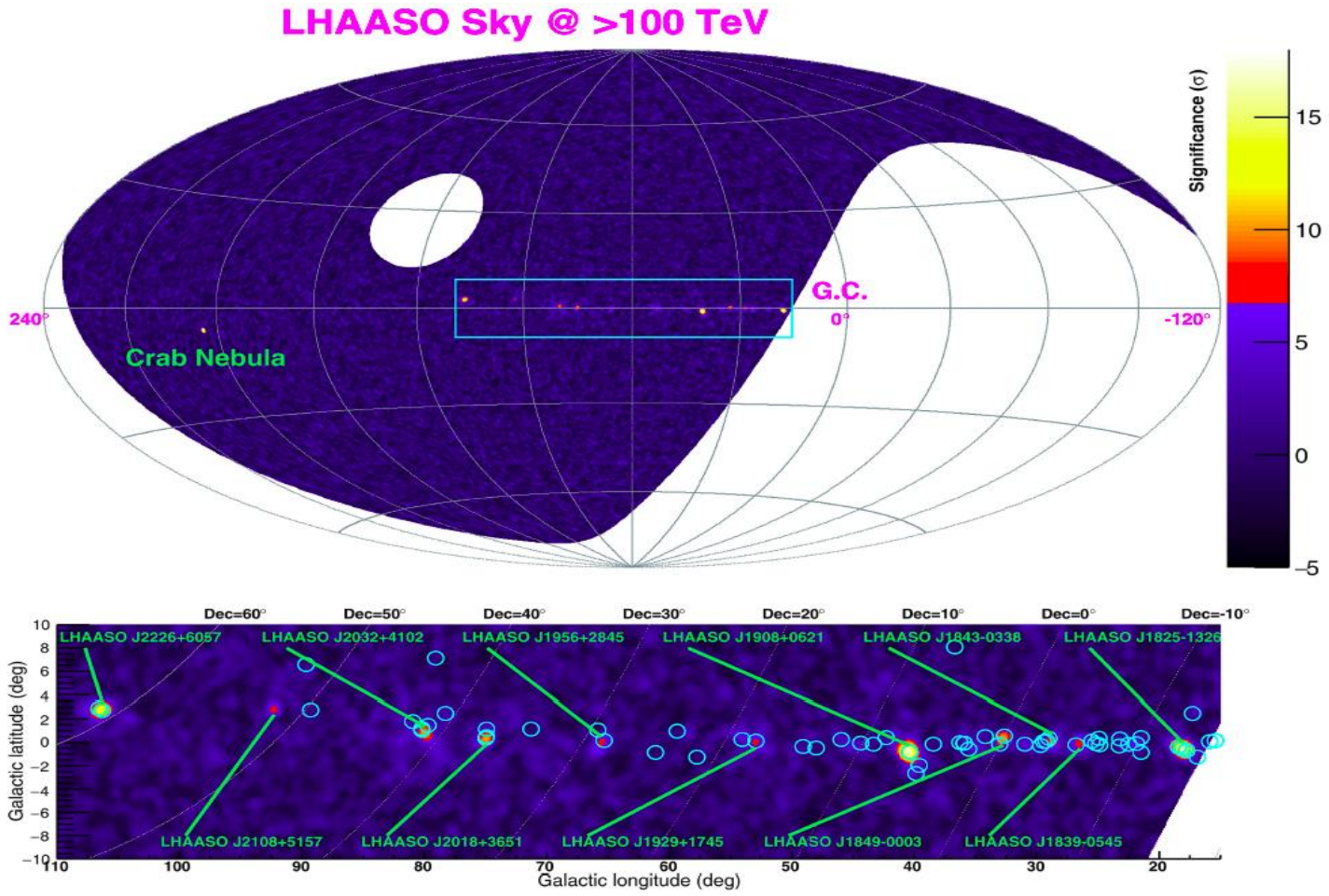




1. Large collection area

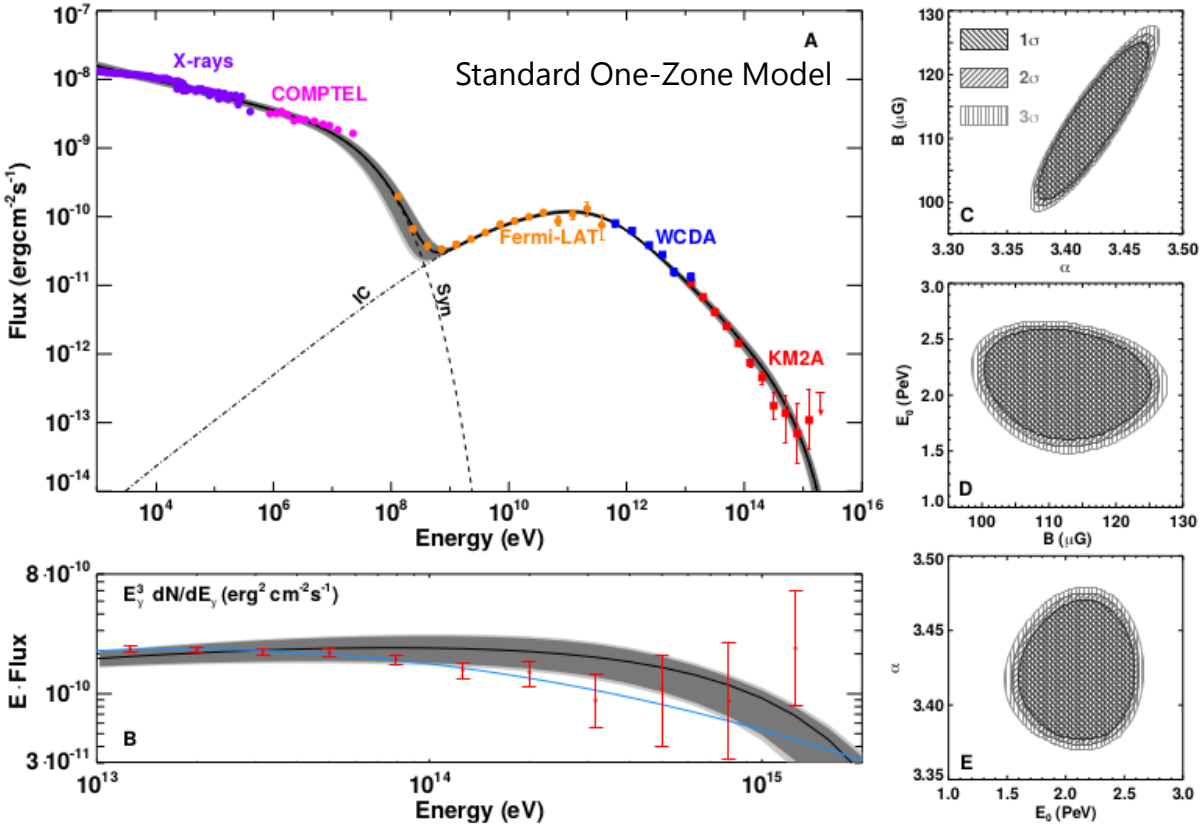
2. Strong background rejection power

LHAASO's first results



LHAASO Collaboration 2021, Nature

LHAASO's measurement on Crab Nebula

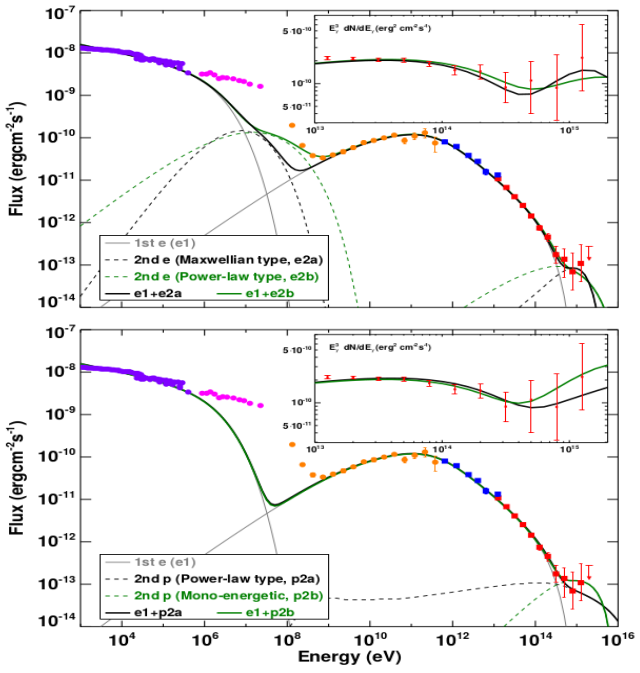


LHAASO Collaboration 2021, Science

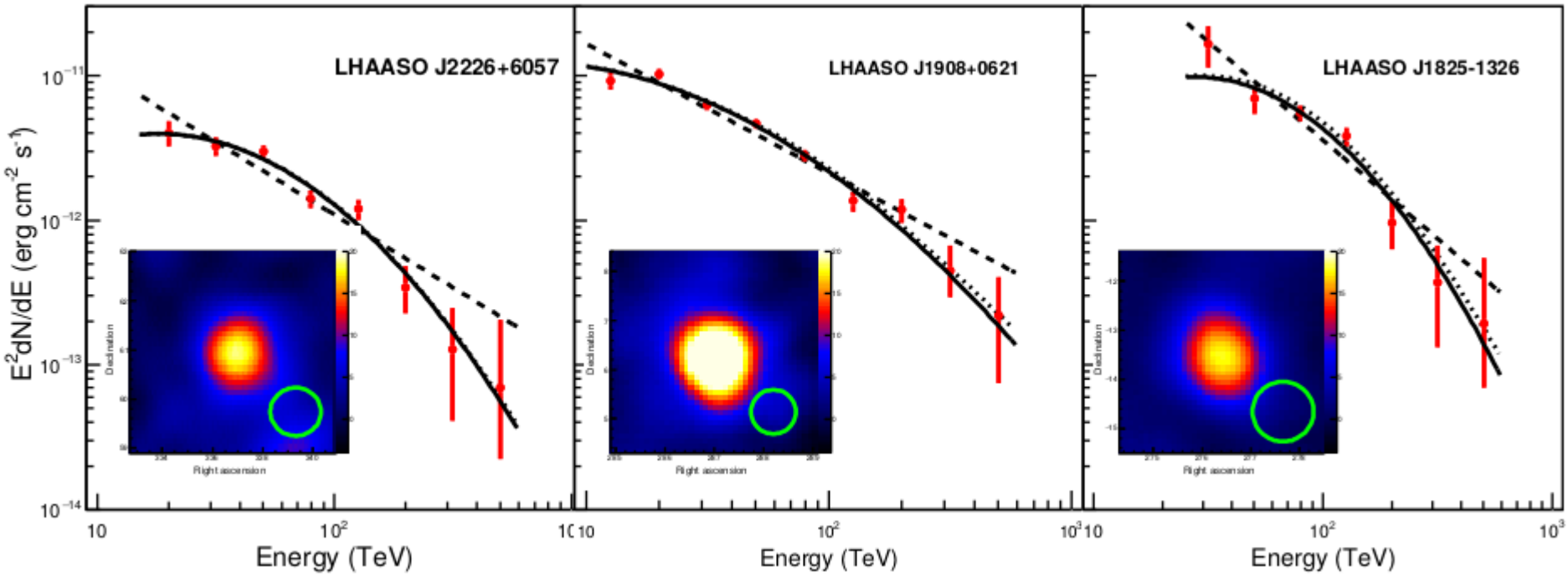
Extreme acceleration efficiency

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

$$(\eta = \frac{\mathcal{E}}{B} < 1)$$



Three brightest sources at 100TeV



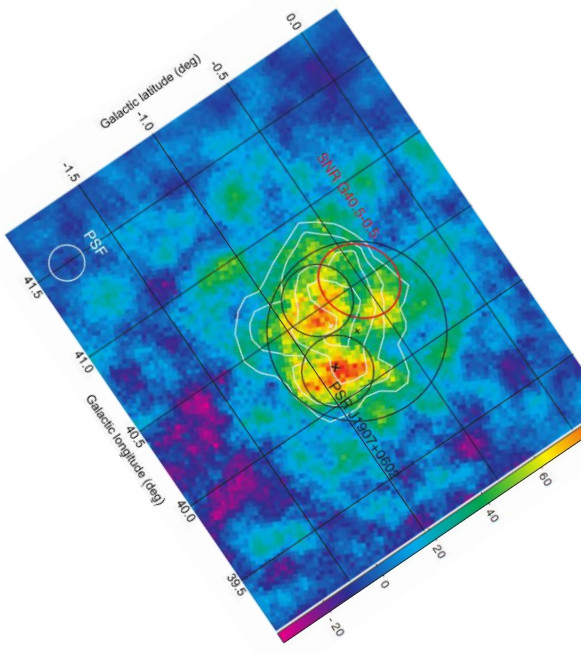
1. Extended Sources

2. Pulsars+SNRs+MC

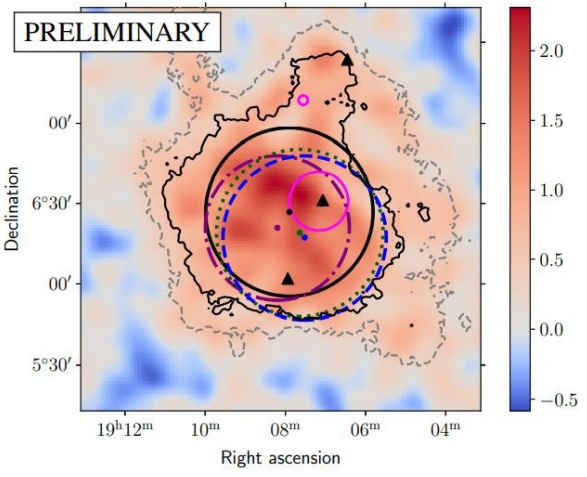
3. No cutoff feature

LHAASO J1908+0621

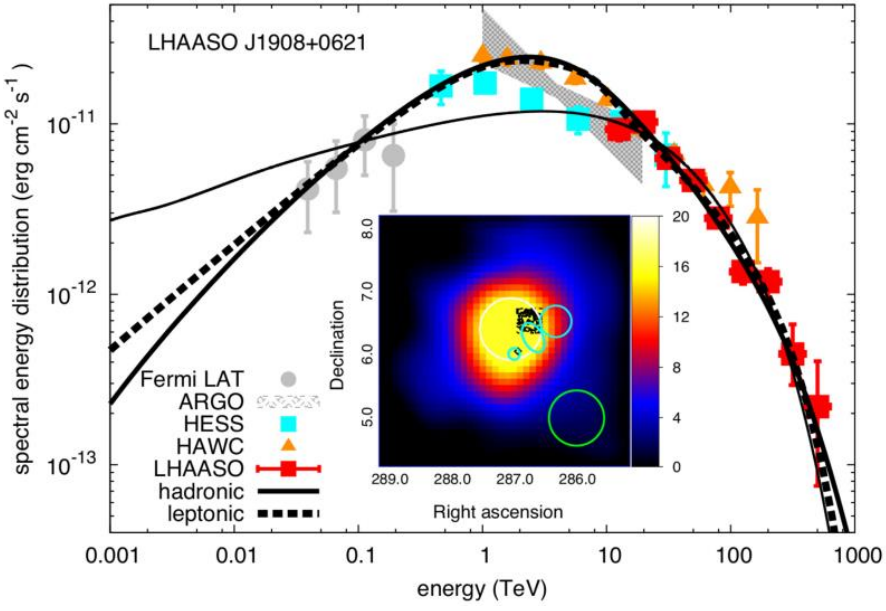
			Distance (kpc)	Age (kyr)	Luminosity (erg/s)	Counterparts
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10-20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063

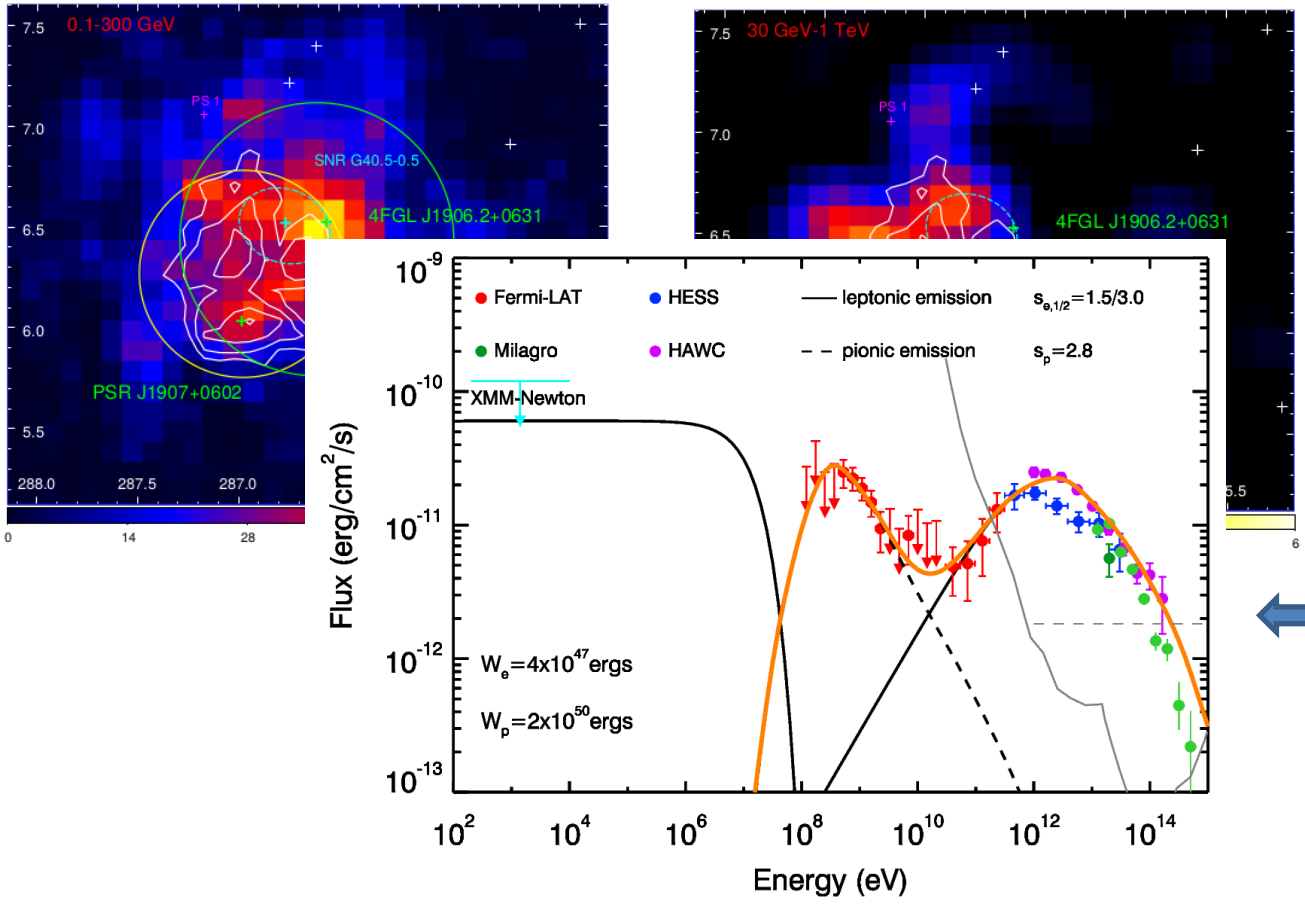


VERITAS Collaboration 2014



Kostunin et al. 2022





Li, RYL, de Oña Wilhelmi et al. 2021, ApJL

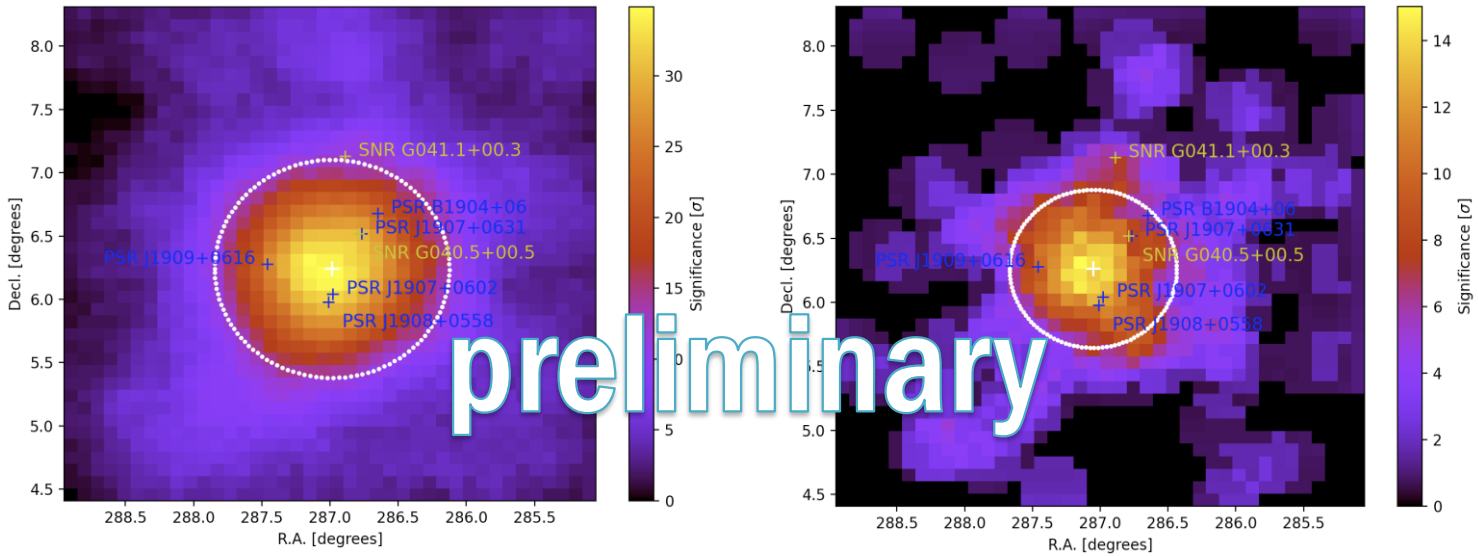
Hadronic gamma-ray UL from IceCube 10yr PS UL

$$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} = 5.7 \times 10^{-13} \left(\frac{E_{\nu_\mu}}{1\mathrm{TeV}}\right)^{-2} \ \mathrm{TeV^{-1}cm^{-2}s^{-1}}$$

IceCube Collaboration 2020, PRL

See also
Crestan et al. 2021
HAWC Collaboration 2022
De Sarkar & Gupta 2022

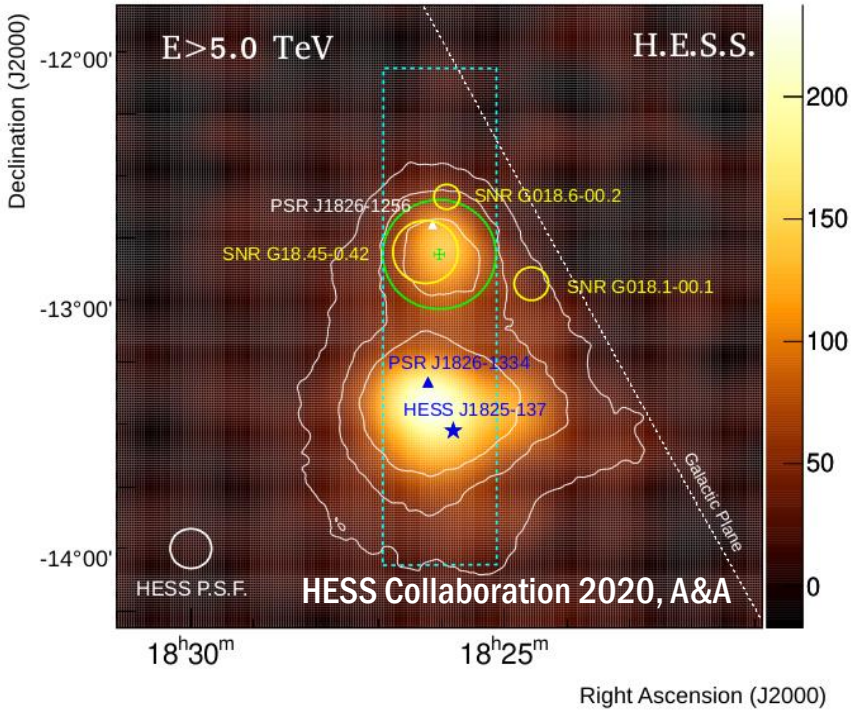
LHAASO Update (Preliminary)

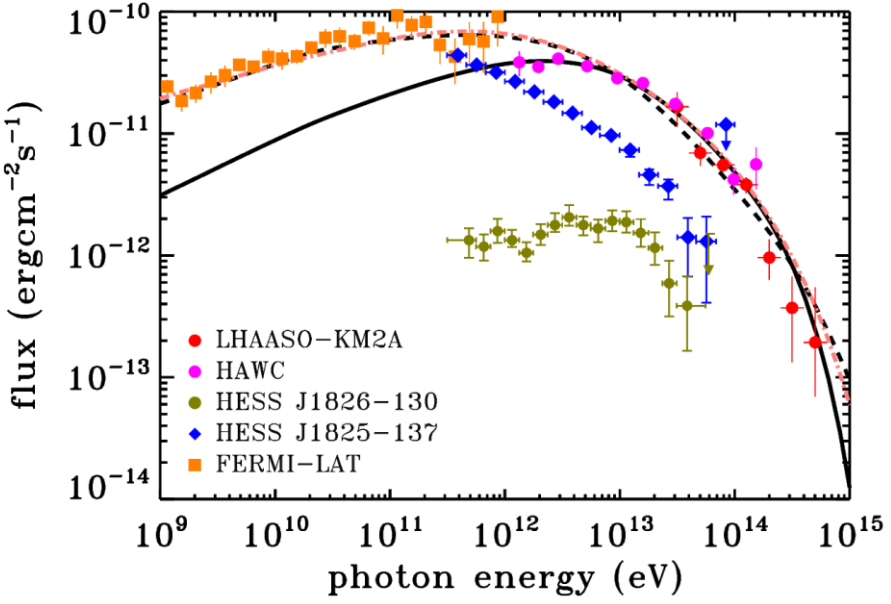


Energy	Template	Ra	Dec	PSF	σ
>25TeV	1 Gauss	286.99 ± 0.01	6.24 ± 0.01	0.31	0.62 ± 0.01
>100TeV	1 Gauss	287.06 ± 0.05	6.26 ± 0.06	0.16	0.42 ± 0.05

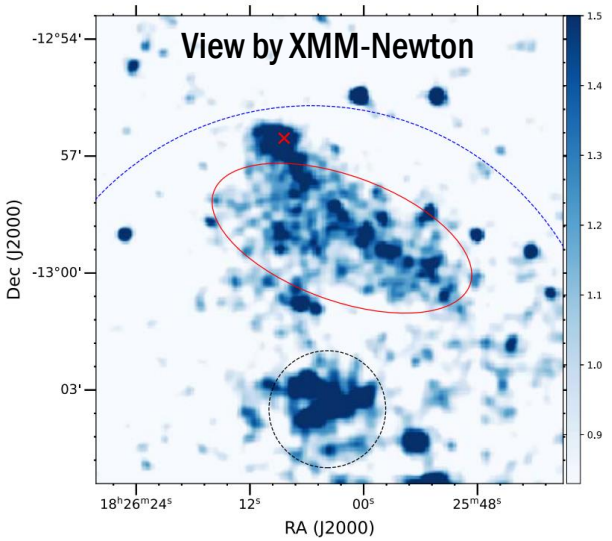
LHAASO J1825-1326

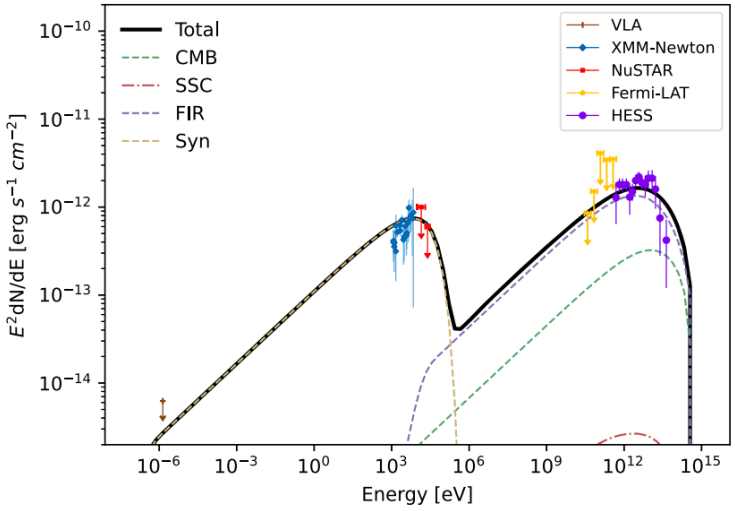
			Distance (kpc)	Age (kyr)	Luminosity (erg/s)	Counterparts
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^{d}	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134





HESS J1826-130





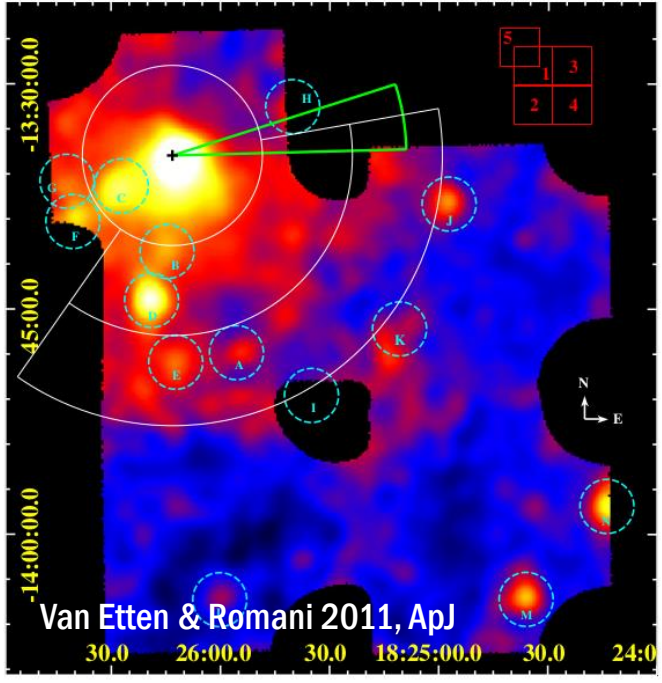
Potential leptonic PeVatron

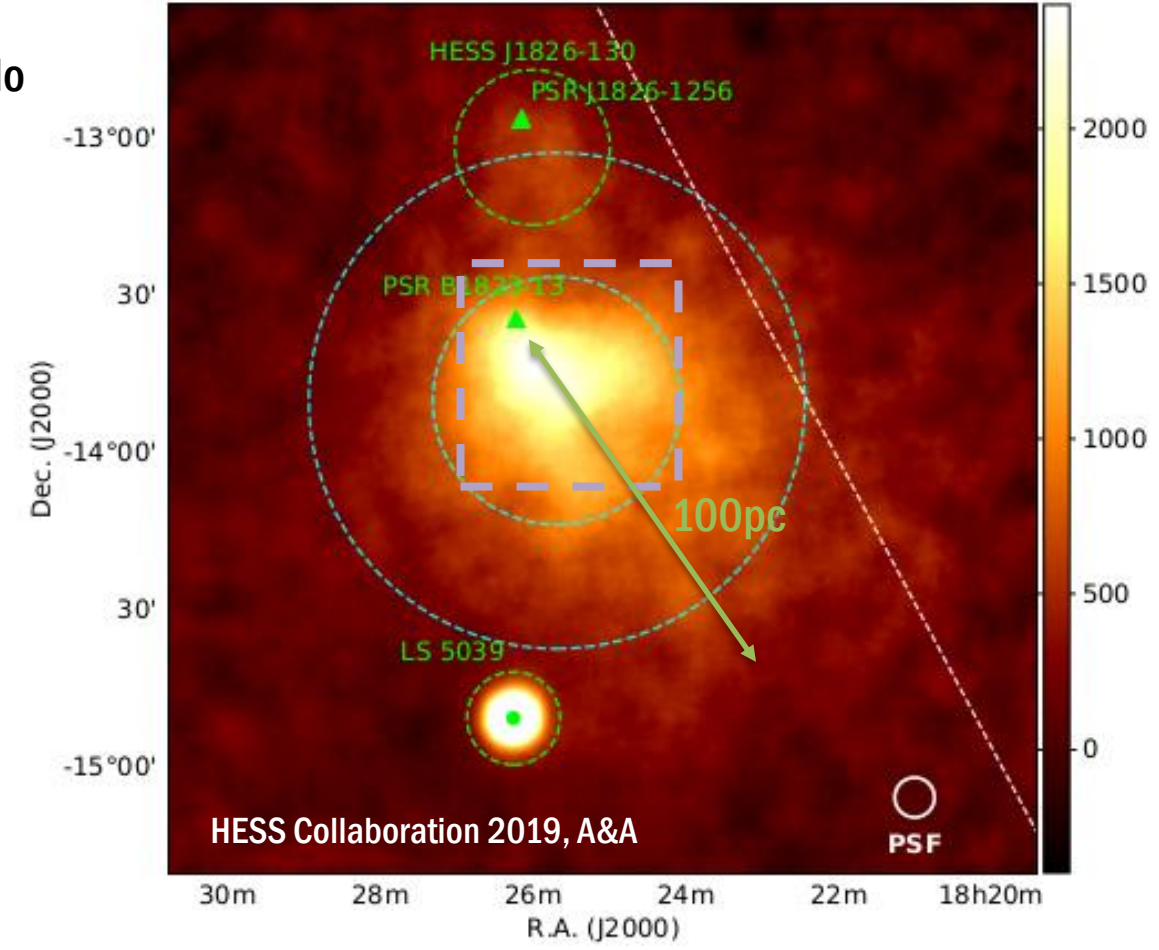
Cannot exclude (partial) hadronic origin of gamma rays

Burgess et al. 2022, ApJ

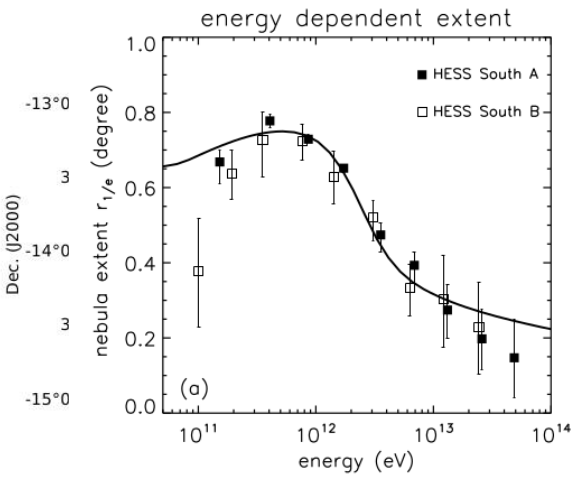
HESS J1825-137

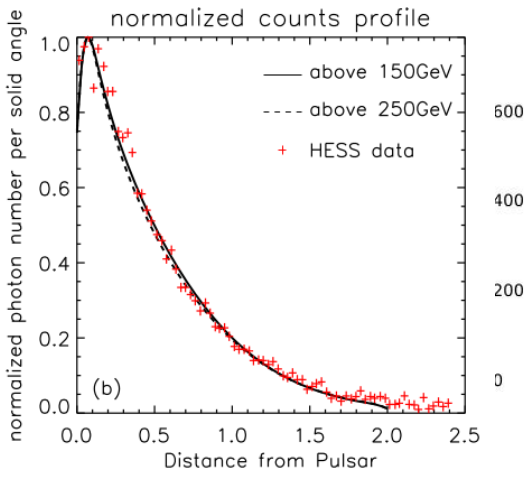
Compact nebula + diffuse nebula + extended halo

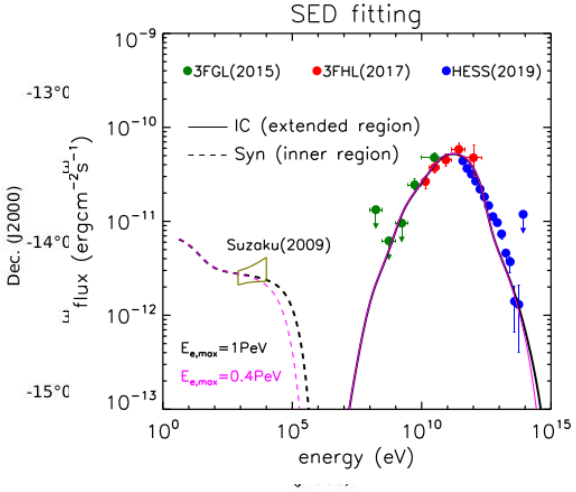


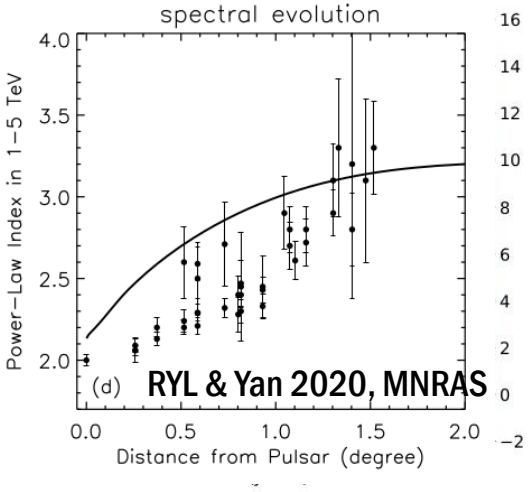


Consistent with leptonic origin





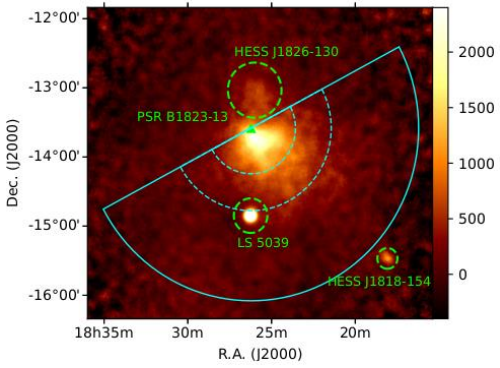


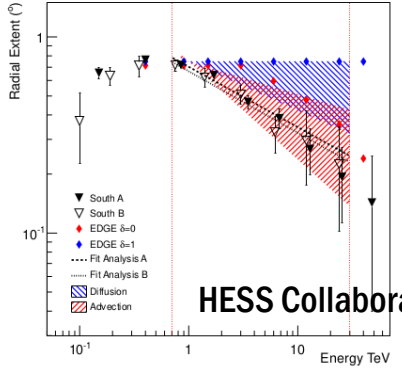


RYL & Yan 2020, MNRAS

Size shrinking at higher energies

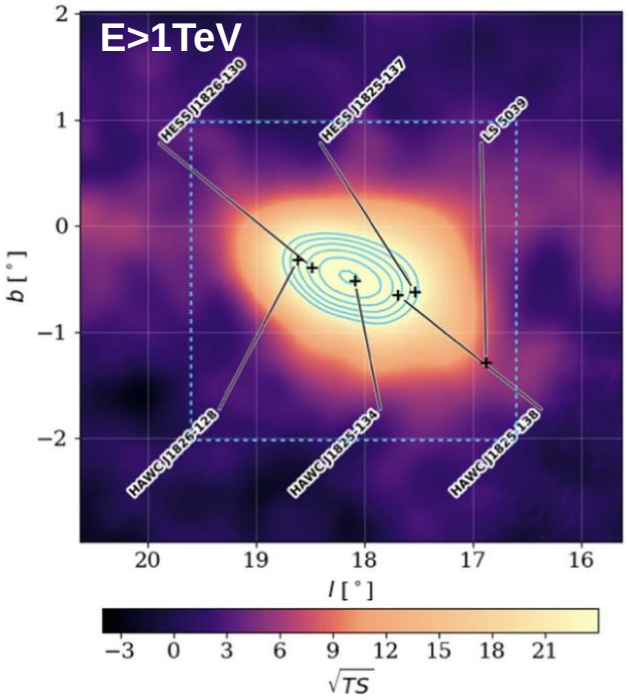
$t_{cool} \sim E^{-1}$

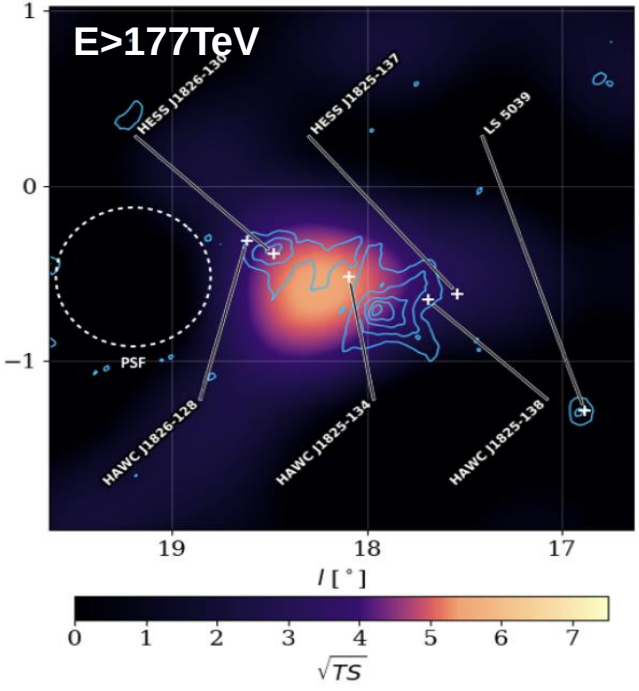




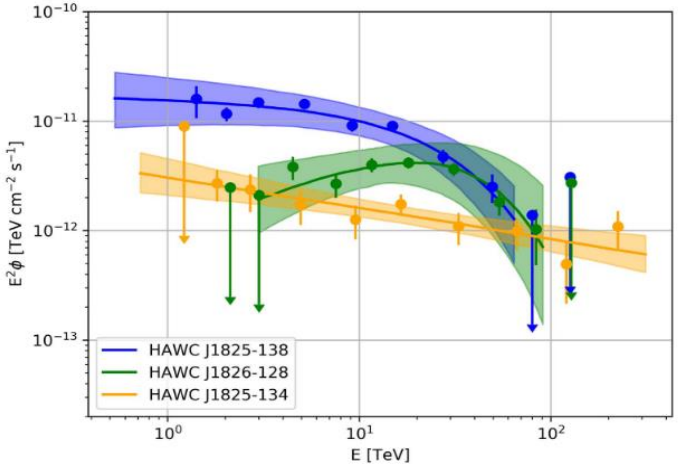
HESS Collaboration 2019, A&A

A hadronic component?





HAWC Collaboration 2021, ApJ

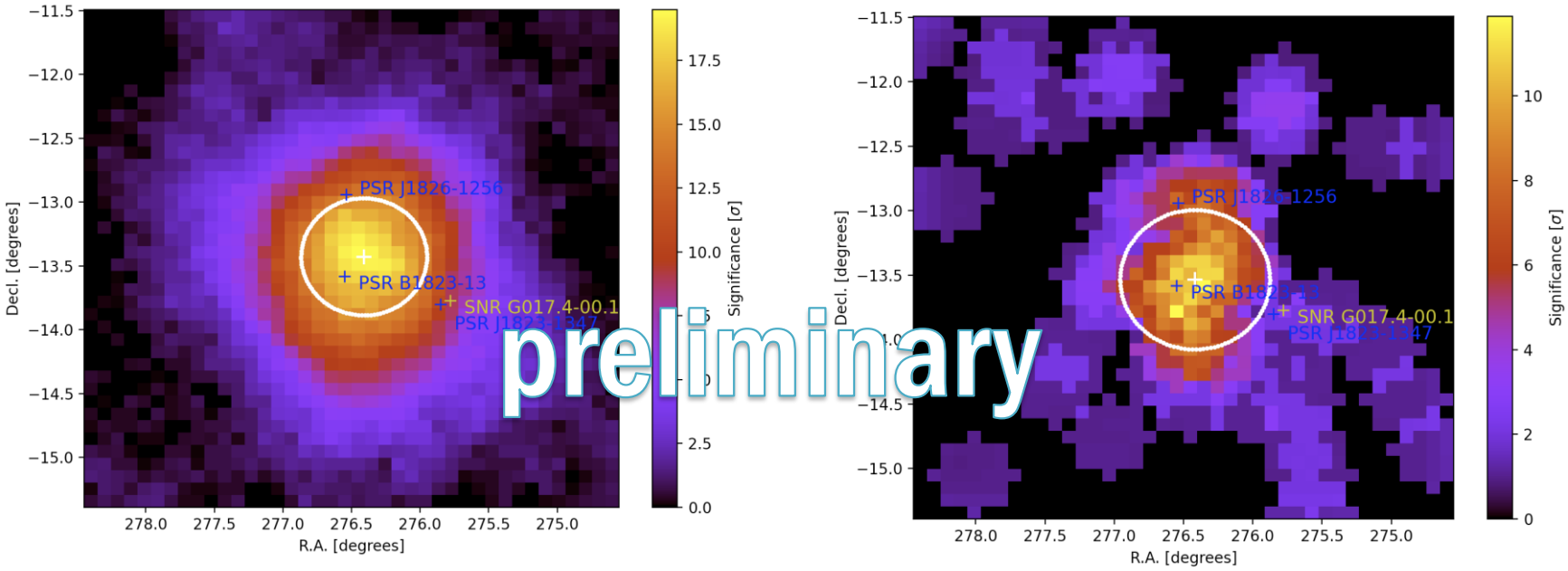


Hadronic component?

Source Name	R.A.(°)	Decl. (°)	Width (°)	ϕ_0 (cm^{-2} TeV^{-1} s^{-1})	α	$E_{\rm cut}$ (TeV)	TS
HAWC J1825-138	$276.38\ ^{+0.04}_{-0.04}$	$-13.86\ ^{+0.05}_{-0.05}$	$0.47\ ^{+0.04}_{-0.04}\ ^{+0.02}_{-0.05}$	$4.5^{+1.4}_{-1.0}\ ^{+1.1}_{-2.0} \times 10^{-14}$	$2.02\ ^{+0.15}_{-0.15}\ ^{+0.19}_{-0.27}$	$27^{+9}_{-7}\ ^{+12}_{-4}$	142
HAWC J1826-128	$276.50\ ^{+0.03}_{-0.03}$	$-12.86\ ^{+0.04}_{-0.04}$	$0.20\ ^{+0.03}_{-0.03}\ ^{+0.00}_{-0.02}$	$2.7^{+1.1}_{-0.8}\ ^{+1.3}_{-1.4} \times 10^{-14}$	$1.2^{+0.4}_{-0.4}\ ^{+0.4}_{-0.5}$	$24^{+10}_{-7}\ ^{+15}_{-7}$	83
HAWC J1825-134	$276.44^{+0.03}_{-0.03}$	$-13.42\ ^{+0.04}_{-0.04}$	...	$4.2^{+0.8}_{-0.7}\ ^{+1.1}_{-1.5} \times 10^{-15}$	$2.28\ ^{+0.12}_{-0.12}\ ^{+0.10}_{-0.04}$	...	38

See also
Niro et al. 2021, PRD
Dzhatdoev et al. 2022, ApJ

LHAASO Update (Preliminary)



Energy	Template	Ra	Dec	psf	σ
>25TeV	1 Gauss	276.41 ± 0.03	-13.43 ± 0.04	0.39	0.48 ± 0.03
>100TeV	1 Gauss	276.42 ± 0.12	-13.52 ± 0.16	0.19	0.40 ± 0.1

Summary

- LHAASO has detected 12 UHE gamma-ray sources in Galaxy and the number is increasing with exposure time.

- Two brightest UHE gamma-ray sources, LHAASO J1908+0621, LHAASO J1825-1326
  - no clear cutoff feature in spectra
  - extended; shrinking as energy goes up

- No clue for more than one sources yet from 3D likelihood analysis. Spatially associated with SNRs and energetic pulsars, MCs.

- The high-energy neutrino detection will be a smoking gun.