Credit Spitzer Cocoon Legacy

HAWC PeVatrons

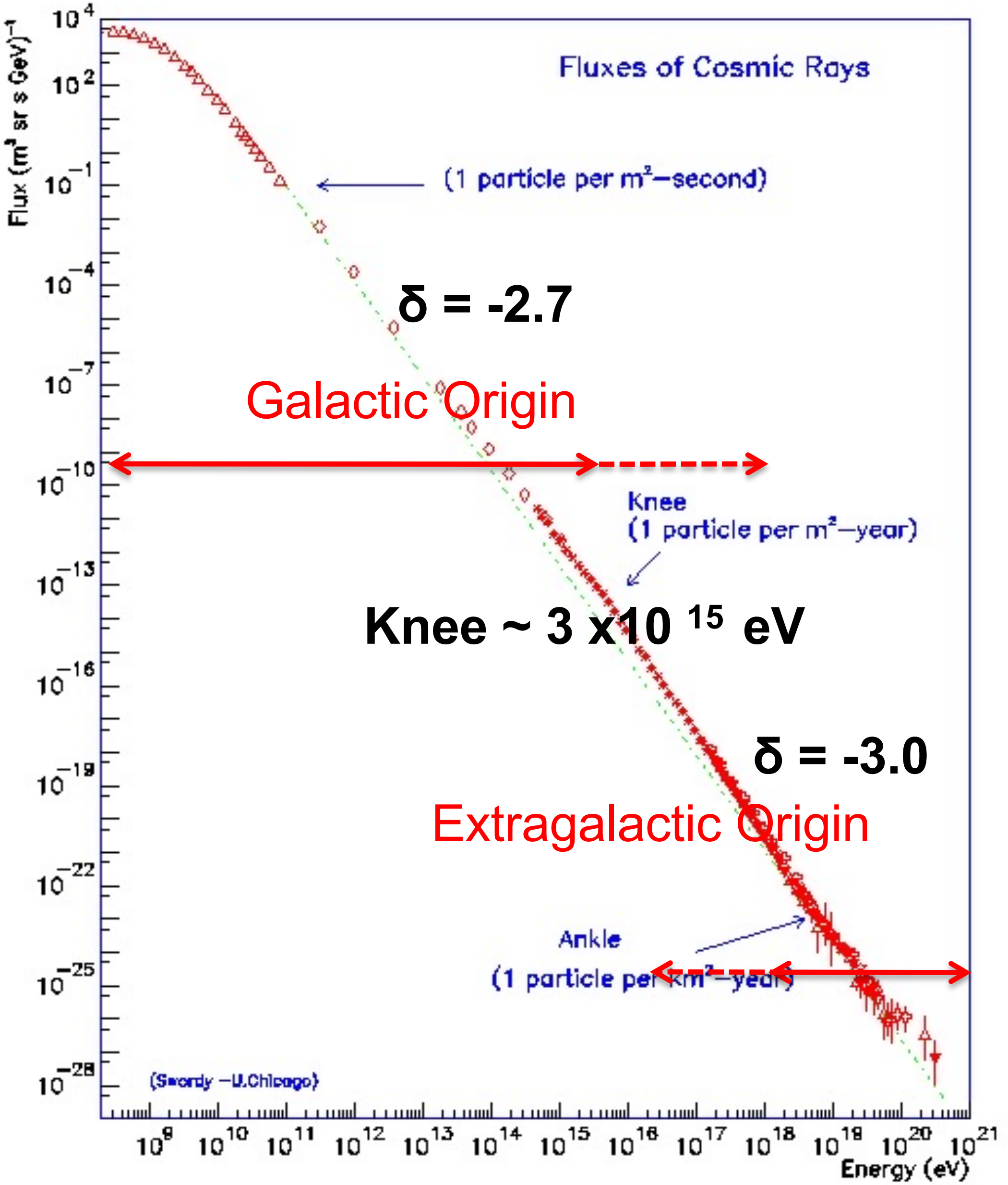
KM3NeT Town Hall Meeting 2022, Catania

Sabrina Casanova, IFJ-PAN, Krakow

Searching for the Galactic PeVatrons

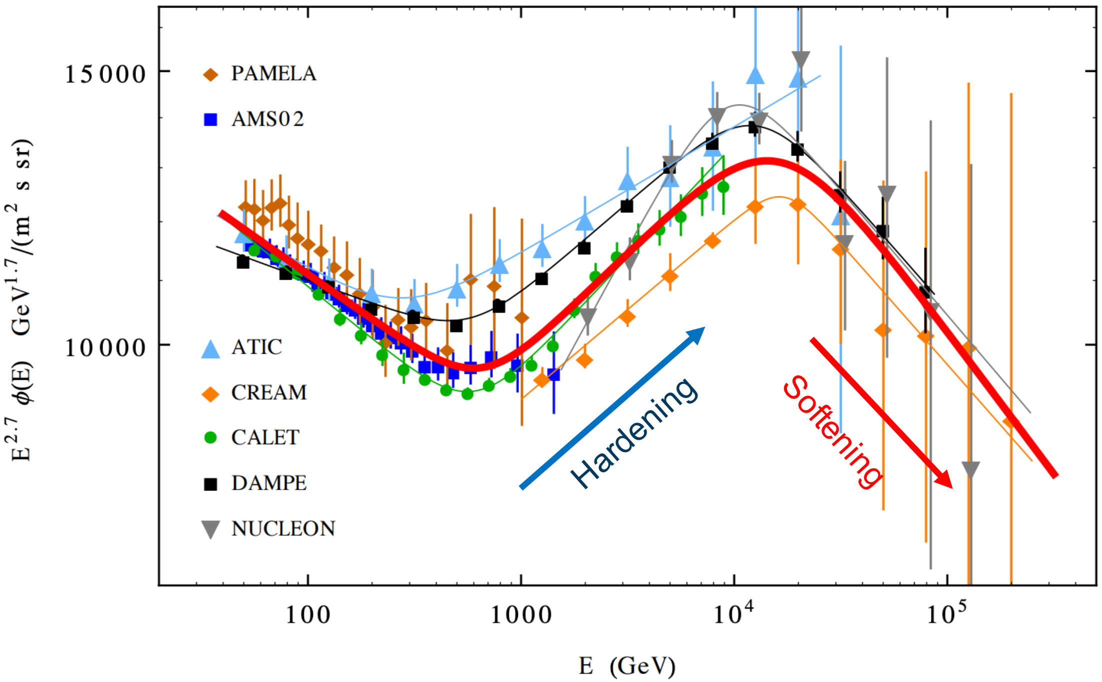
- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least to the knee at PeV
- The knee for protons at about 400-500 TeV (ARGO Collaboration 2015)

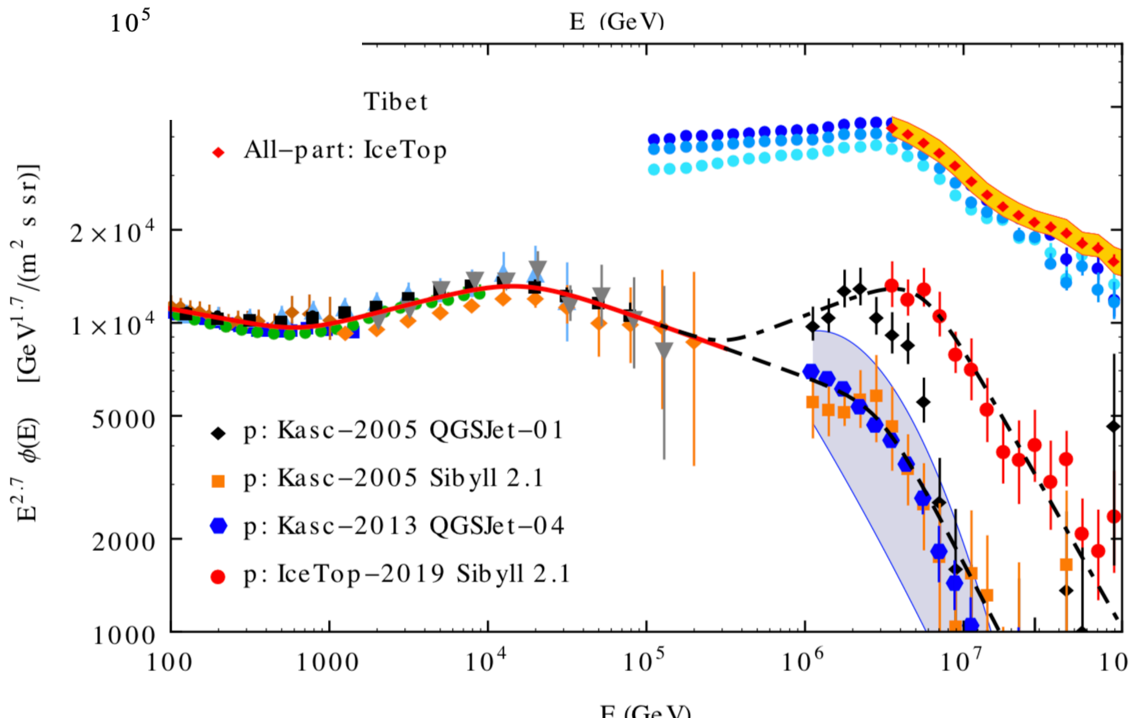
. Cronin, T. Gaisser, S. Swordy, Sci. Amer. 276 (1997) 44.



Several features in the CR spectrum

Lipari & Vernetto 2019





More classes of CR sources contribute to the knee ?

Direct Messangers of PeVatrons

$$CRs + gas \rightarrow \pi_0 \rightarrow \gamma\gamma\ (\sim 0.1\ PeV)$$

$$CRs + gas \rightarrow \pi^-\pi^+ \rightarrow \upsilon$$

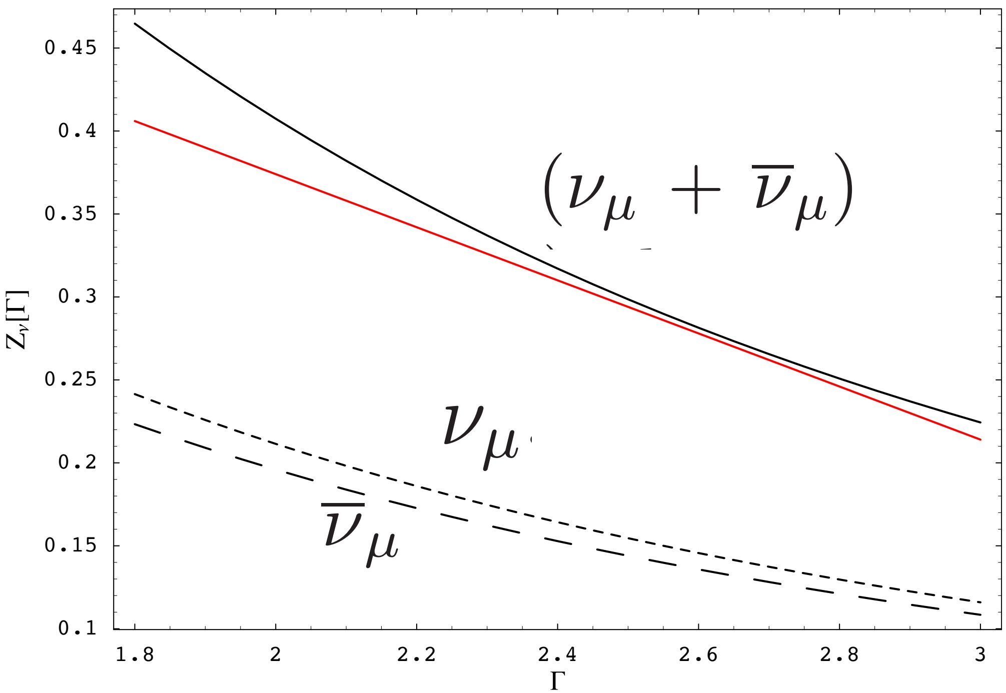
PeVatrons emits multi-TeV to hundred TeV γ-rays and νs

γ detected in hundreds TeVatrons and few PeVatrons
γ degeneracy leptonic-hadronic
γ γγ absorption within and outside sources

ν difficult to detect even with 1 km^2
ν unique identification of hadronic processes
ν no absorption – no spectral deformation

Neutrino flux from γ flux

Villante & Vissani, 2008



$$\Phi_\gamma \propto E^{-\Gamma}$$

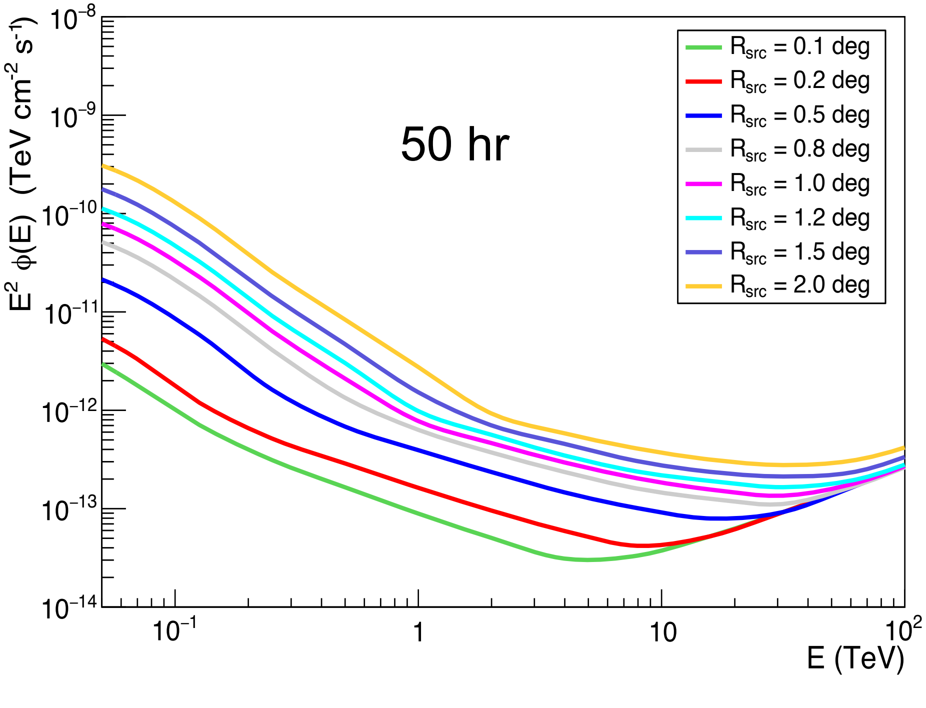
$$\Phi_\nu[E] = Z_\nu[\Gamma] \cdot \Phi_\gamma[E]$$

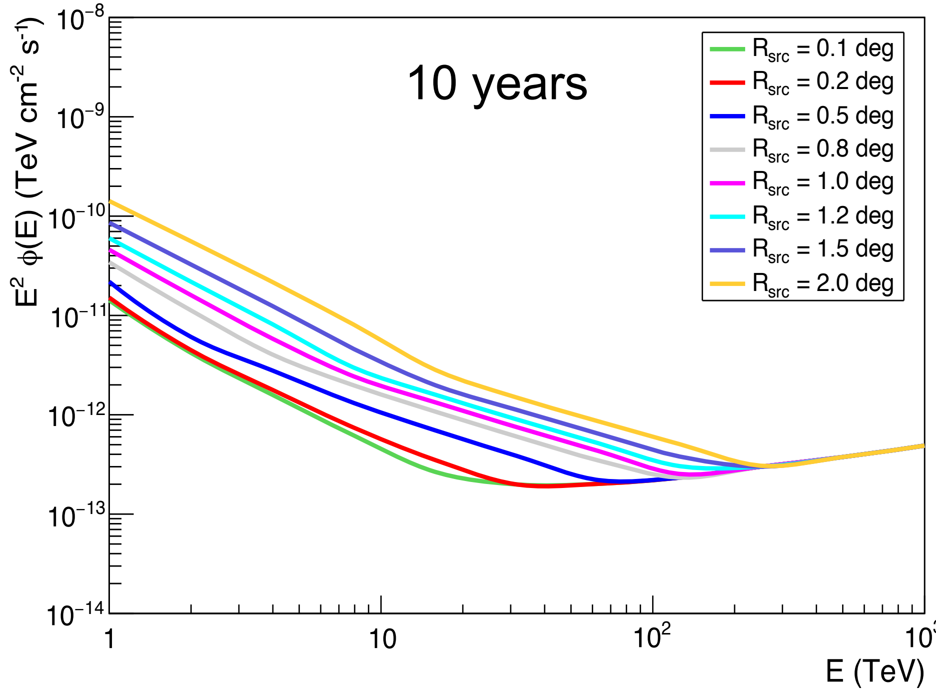
- Neutrino flux roughly the same
- Neutrino flux shifted to lower energies
- Cutoff shifted by a factor 0.59 for a -2 spectrum
- Best range : 10-100 TeV

Lipari 2006, Villante&Vissani, Kappes2007,…

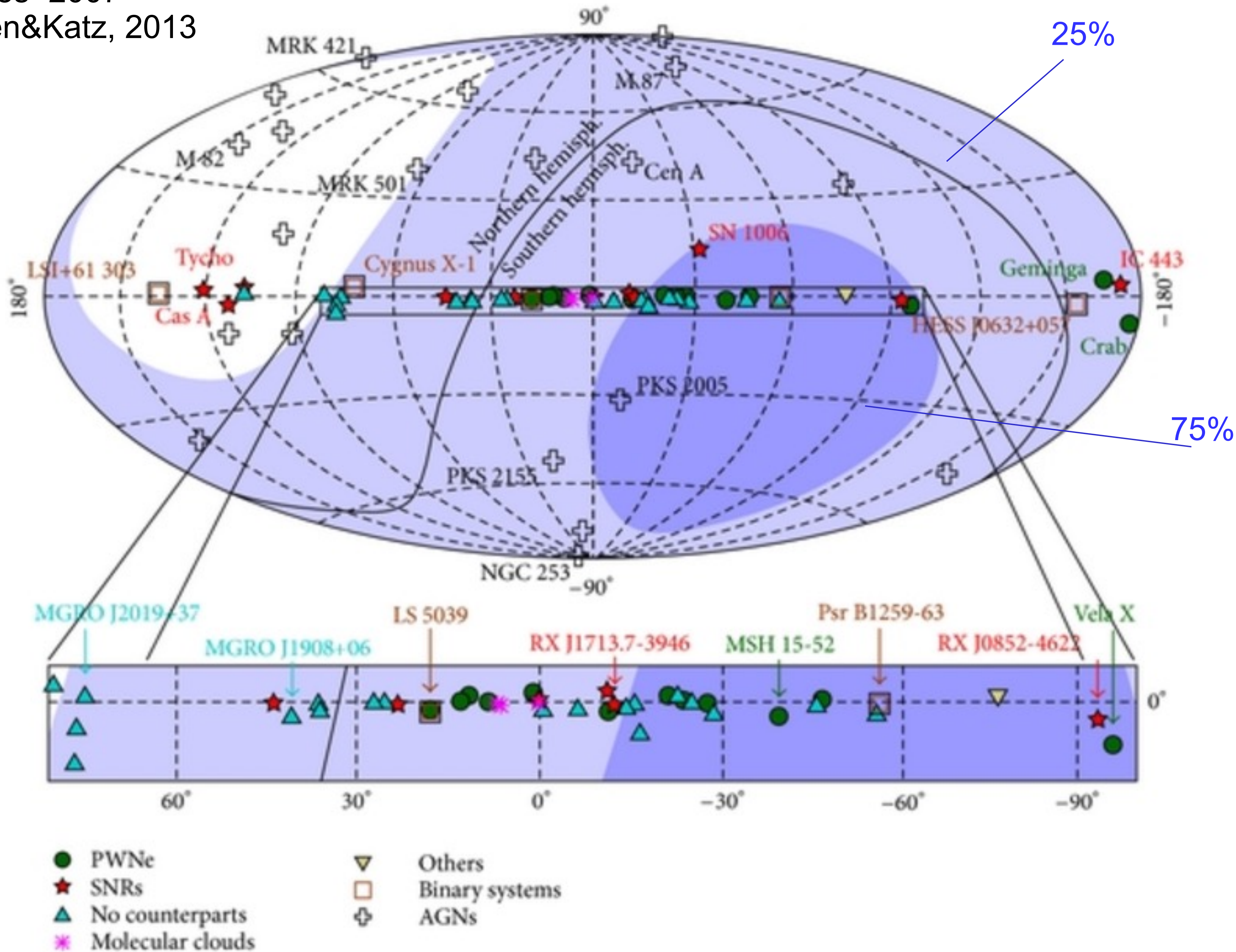
Minimum detectable flux in ν and γ

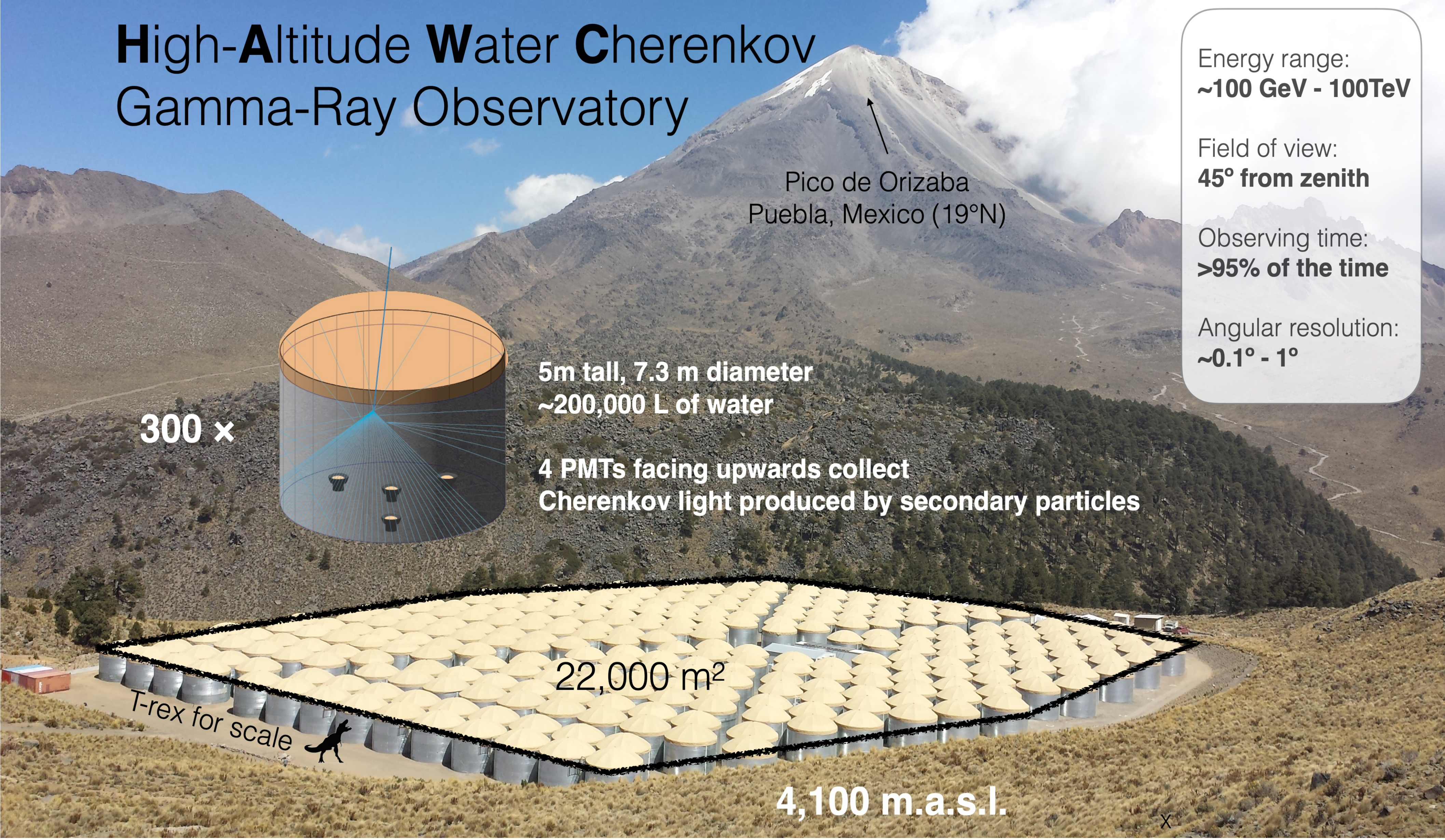
Ambrogi+2018





Kappes+2007
Halzen&Katz, 2013





- Site: Sierra Negra, Mexico, 19° N, 4,100 m altitude.
- Inaugurated **March 2015**.
- **Instantaneous FOV 2sr. Daily 8sr (66% of the sky).**

HAWC Water Cherenkov Detectors

- The WCDs are filled with 200,000 l of purified water. The particles from the shower induce **Cherenkov** light in **water,** detected by the 4 PMTs.

Steel frame construction

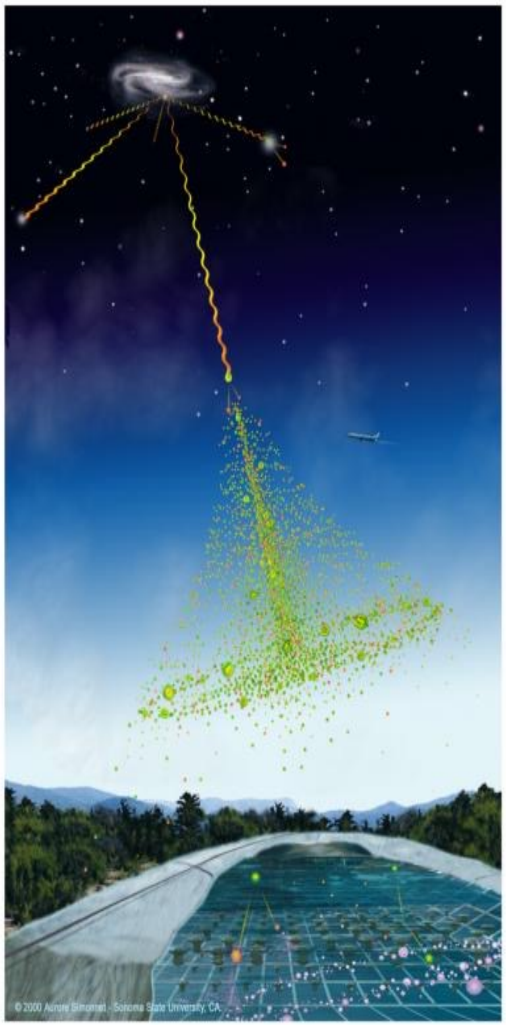
Large plastic bag container

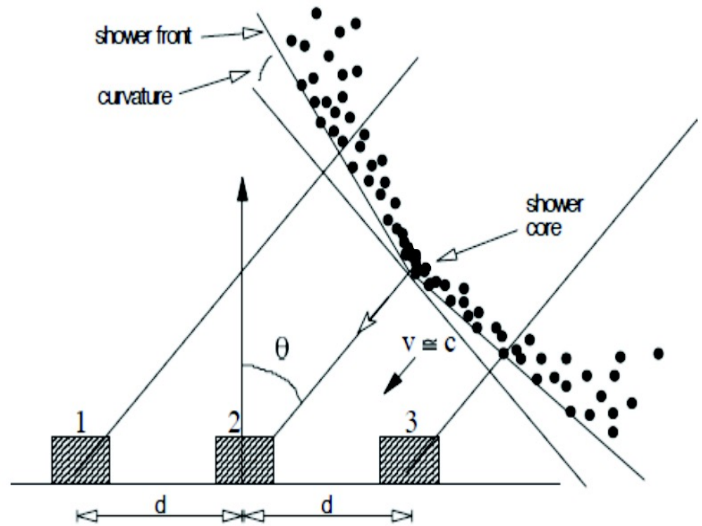
Water trucks filling the tanks

8-inch 10-inch PMTs

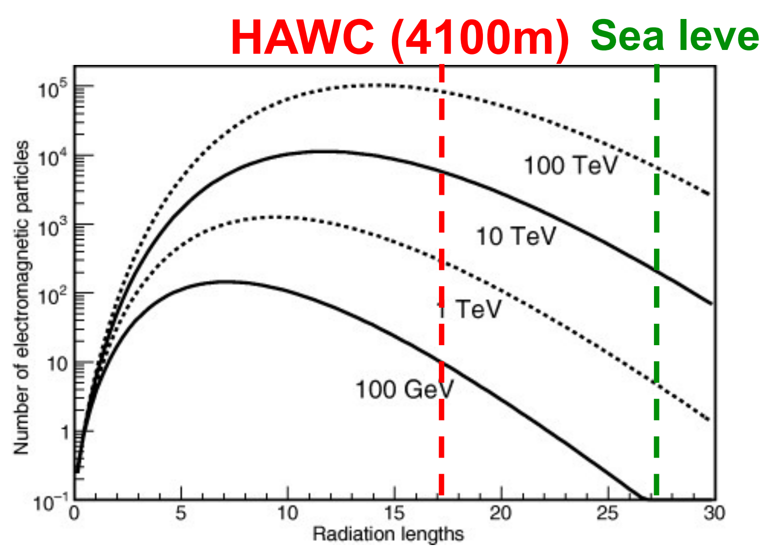
3900 tanker truck trips needed

Detection Technique





- The particle detectors are tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- High altitude means closer to the shower maximum



The reconstruction of the events Involves determining:

Direction of the Event

Likelihood of an event to be γ

Size of the Event

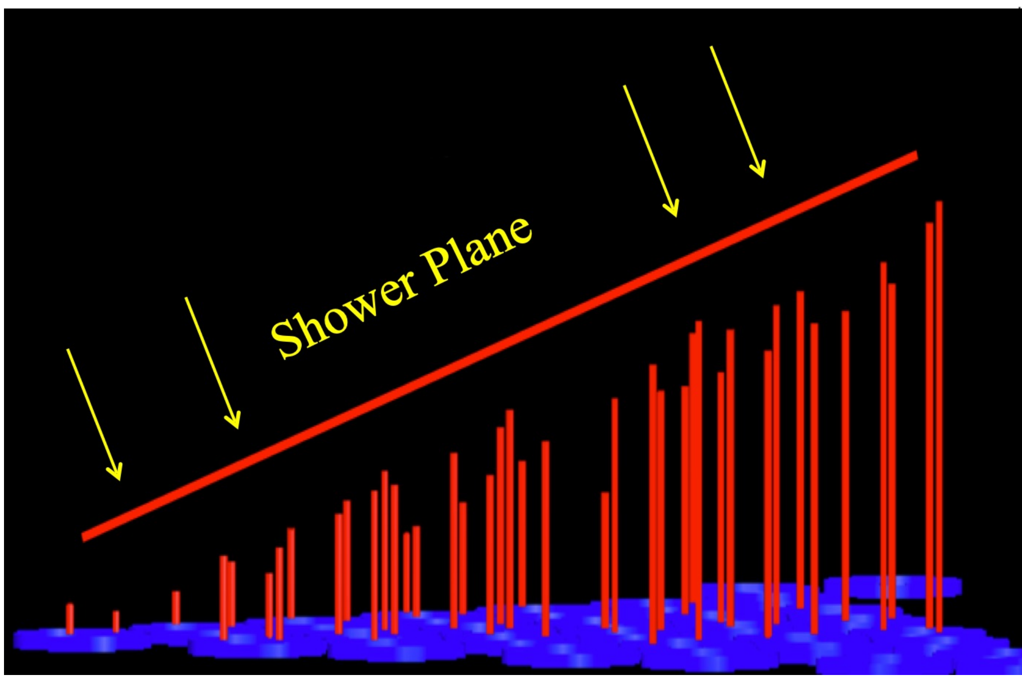
Direction reconstruction

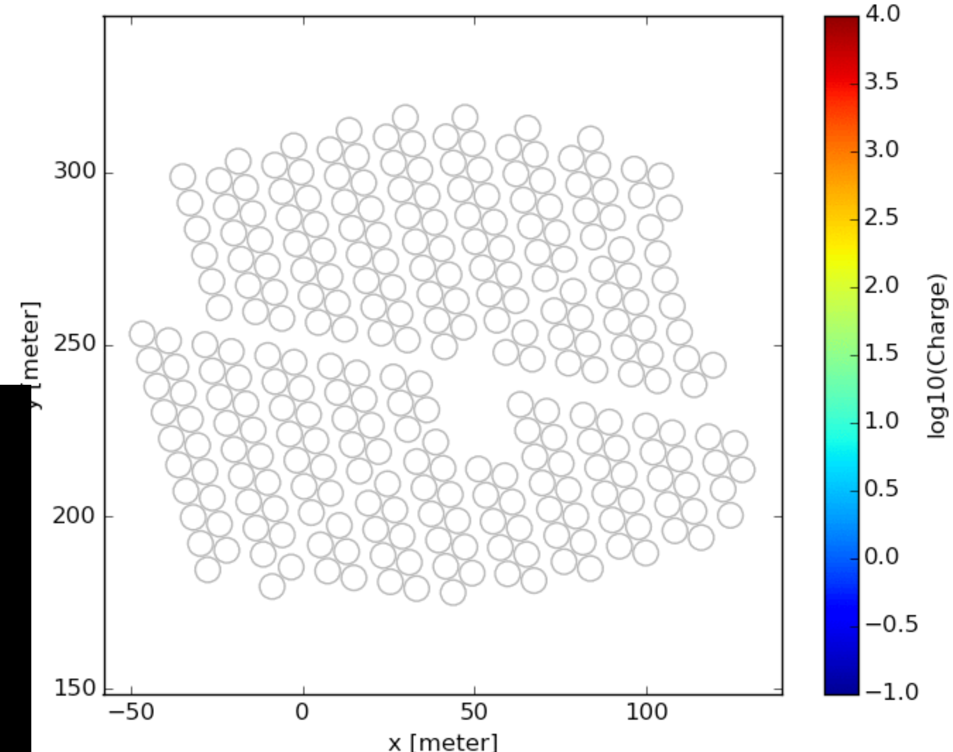
The concentration of secondary particles is highest along the trajectory of the original primary particle, termed the air shower core.

Determining the position of the core on the ground is key to reconstructing the direction

At first order, we fit a plane to the relative timing of each PMT

Sub-nanosecond precision is needed

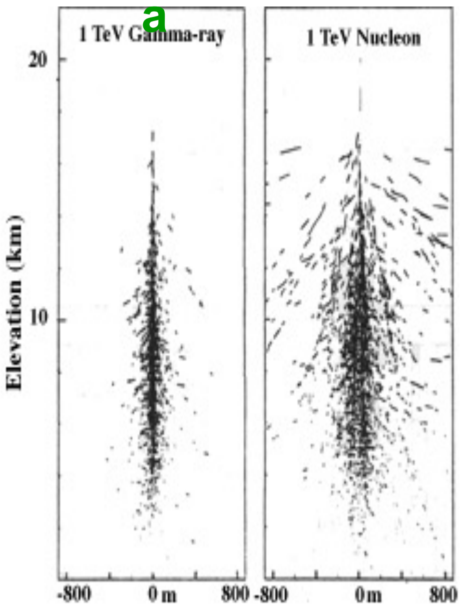




Gamma-Hadron Separation

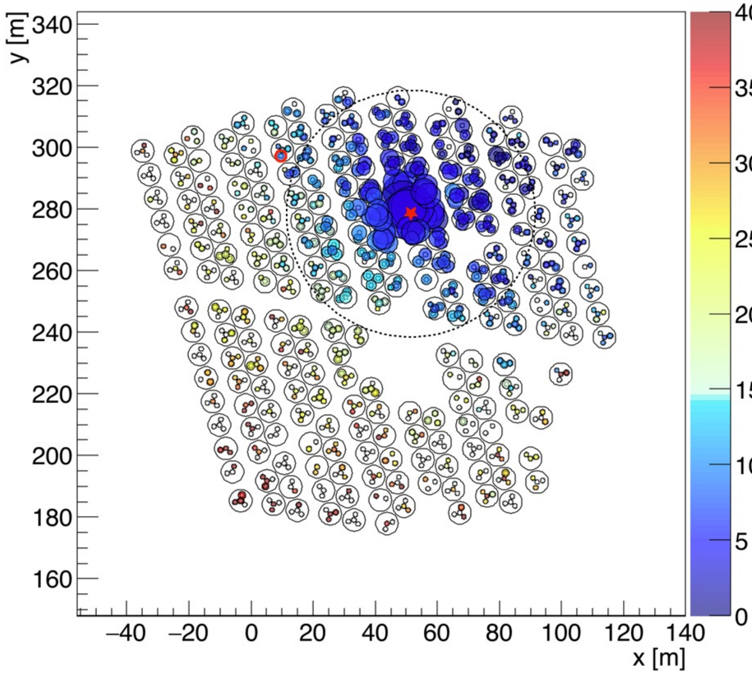
Simulation

Gamma   Hadron



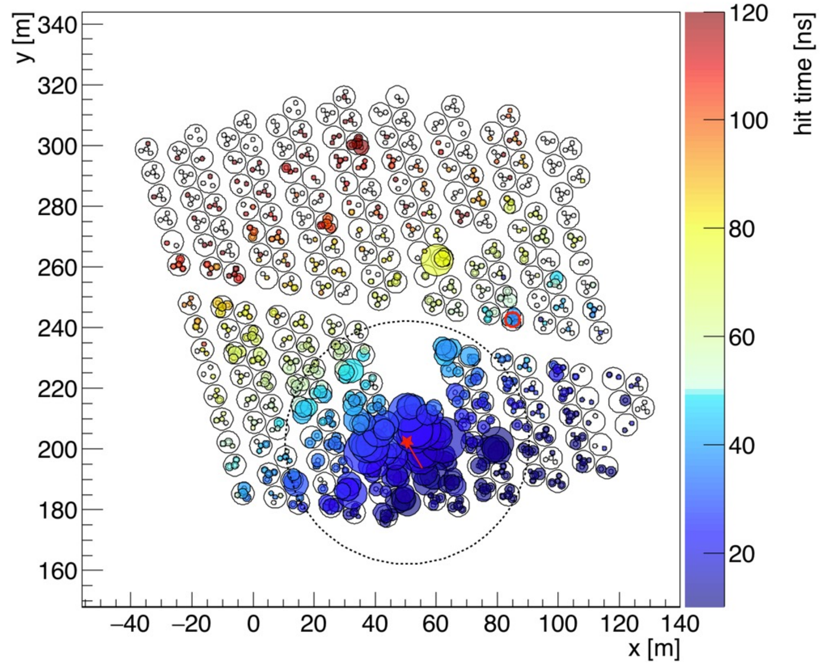
HAWC Data

Likely Gamma Ray



HAWC Data

Hadron Shower

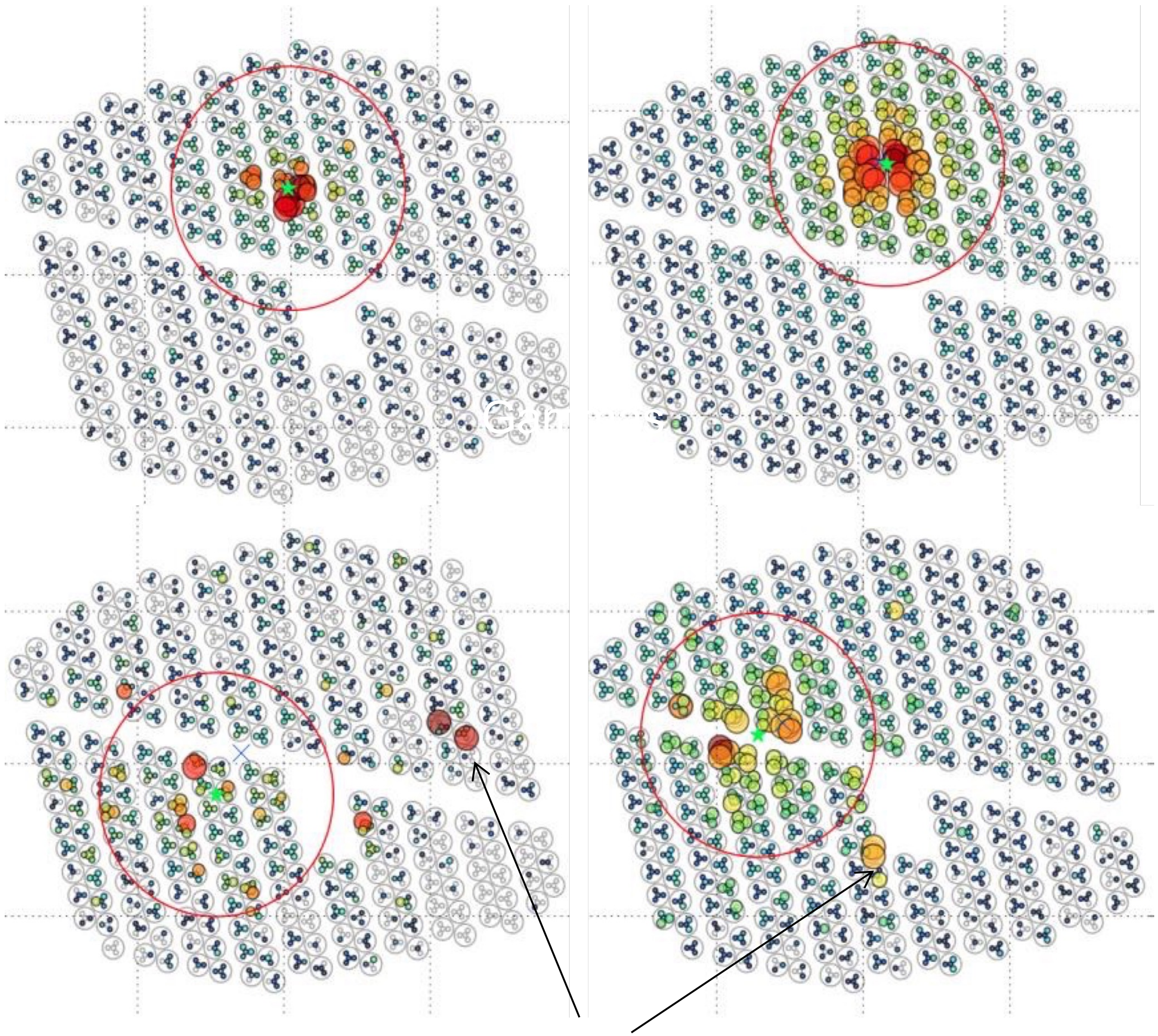


- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- Gamma/hadron can be discriminated based on the event footprint on the detector: gamma-ray showers are more compact, cosmic rays showers tend to "break apart”
- Showers appear quite different particularly above several TeV..

Montecarlo Shower Simulation

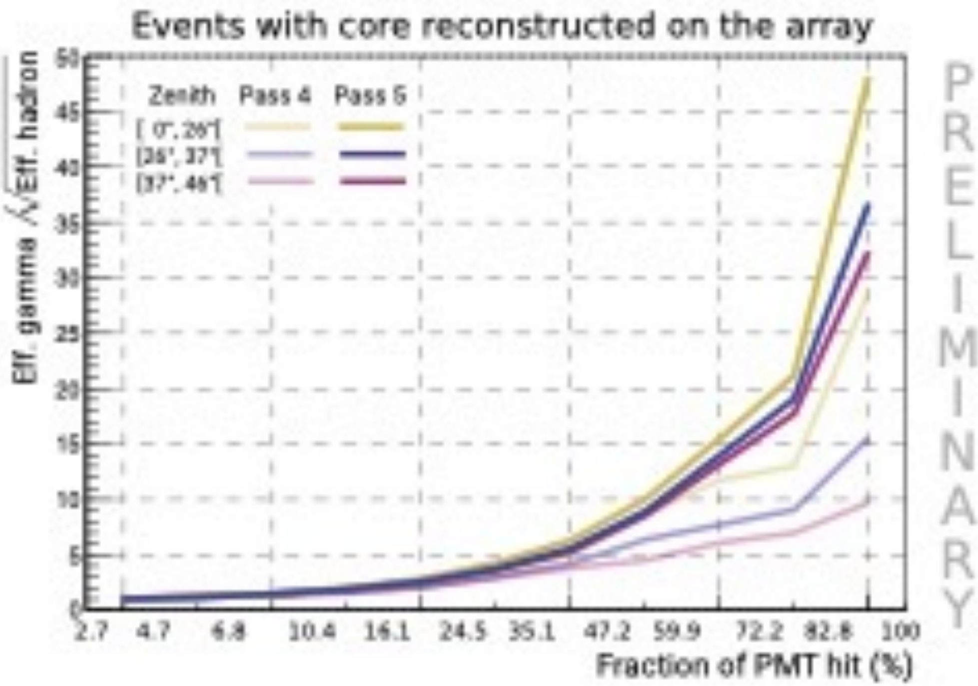
Gammas

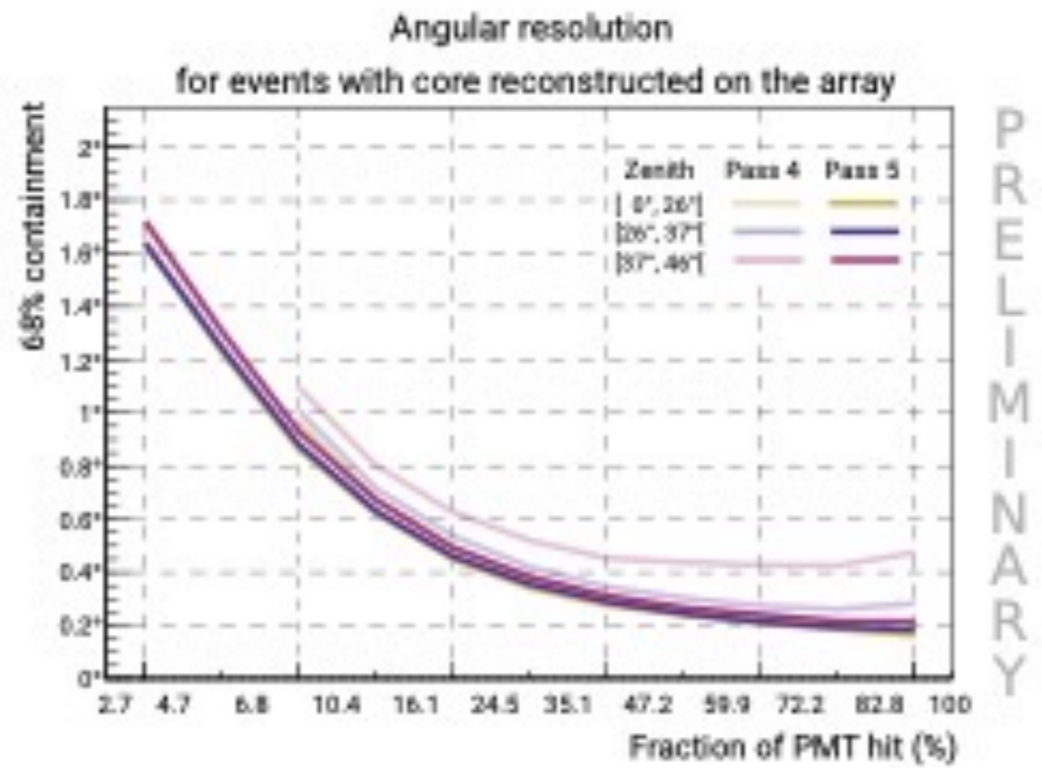
Protons



Energy deposited away from the core

Pass 5 reconstruction





$$Q = \frac{\mathrm{Efficiency}_{\mathrm{gammas}}}{\sqrt{\mathrm{Efficiency}_{\mathrm{hadrons}}}}$$

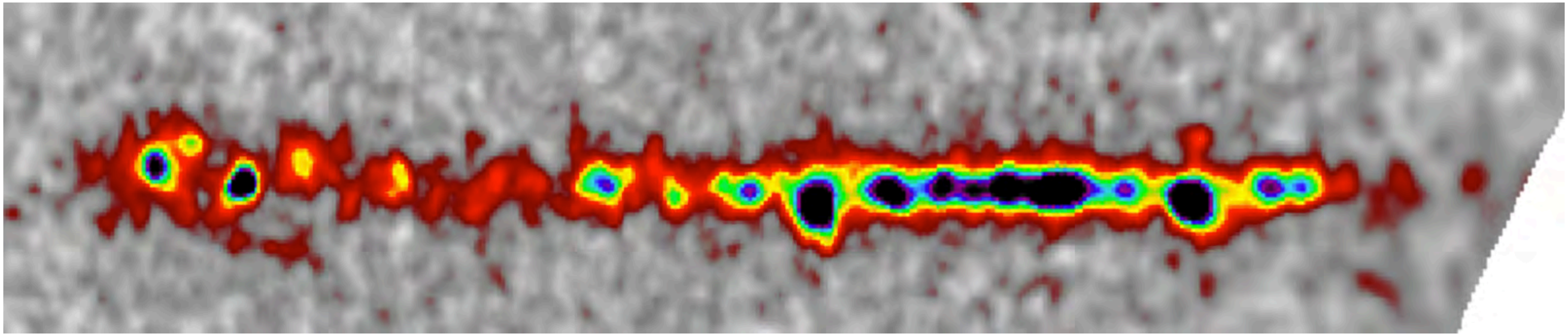
Large Events - Much improved background rejection

Better Angular Resolution - doesn't degrade at high zenith angles

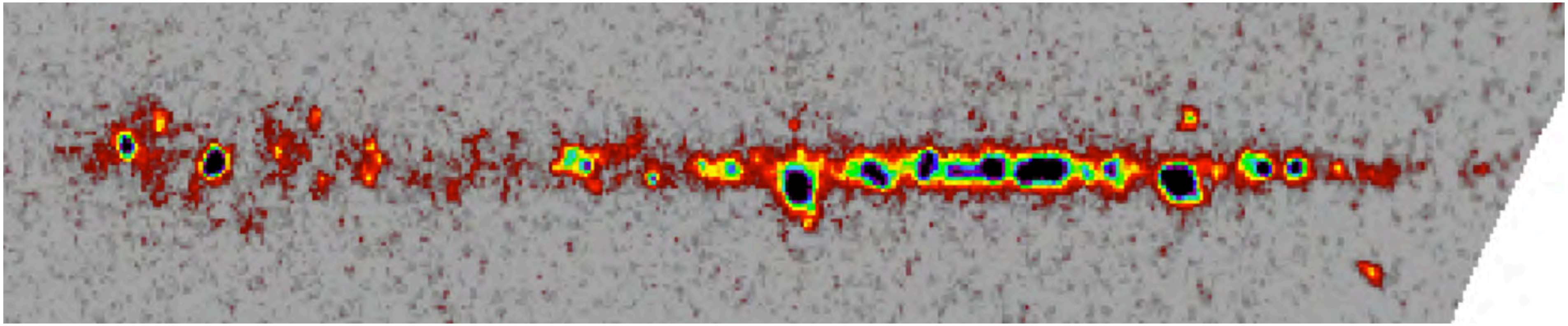
Wider FOV - Previous 45° now 60°

HAWC Pass 5 Maps

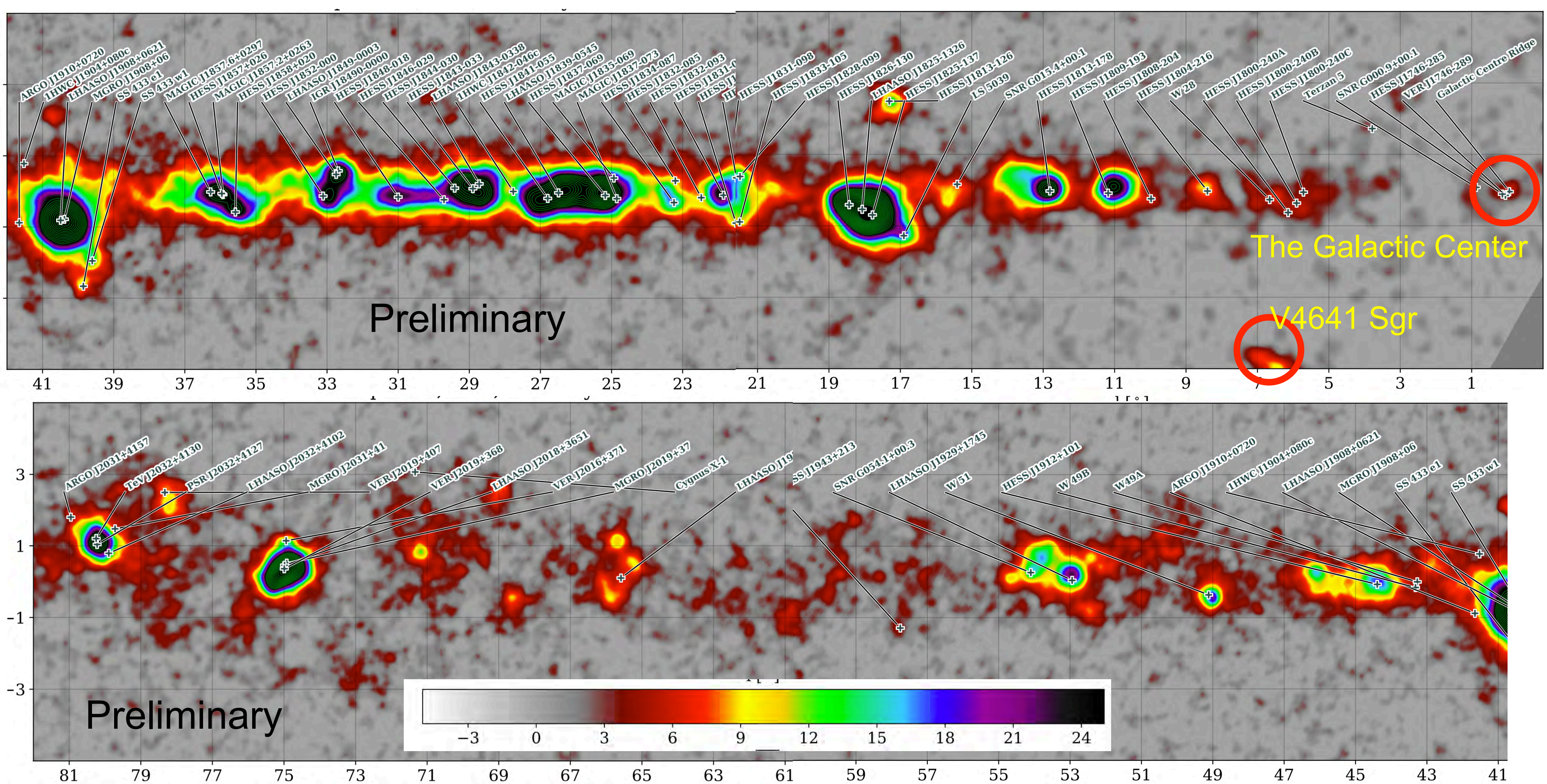
Pass 4



Pass 5

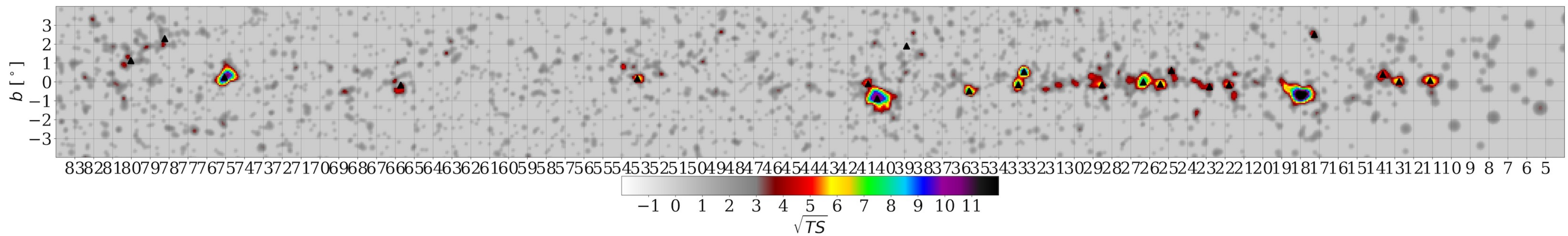


HAWC Pass 5 – 2090 days maps

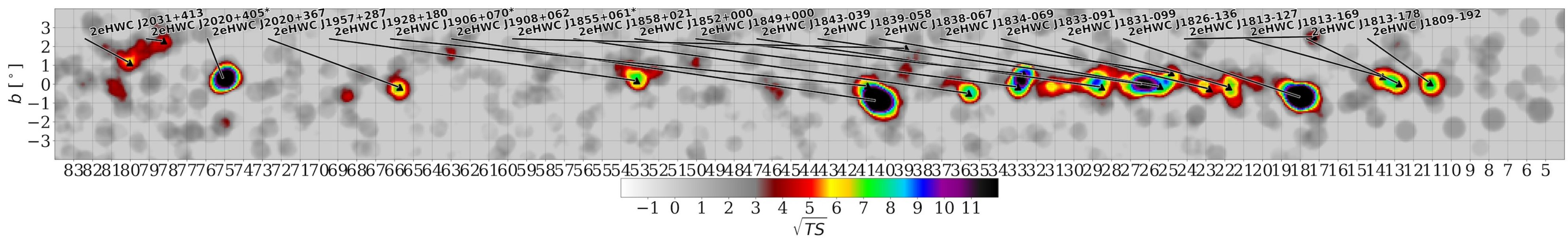


Sources above 56 TeV

Point source map



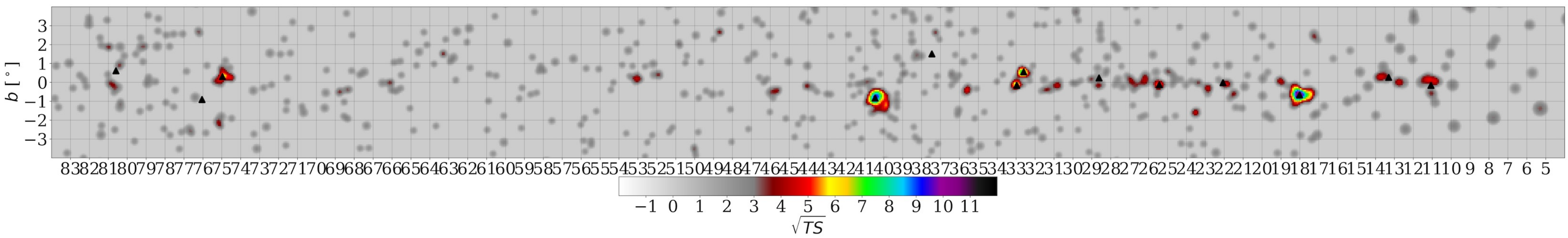
0.5 degree extended map



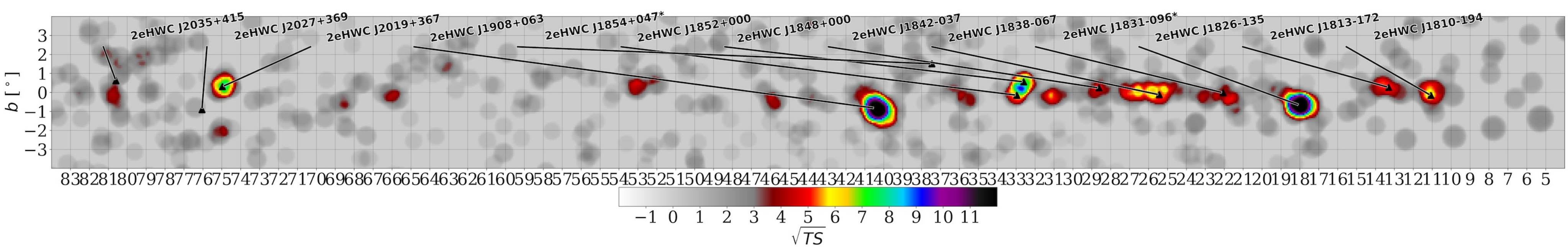
More than half unidentified and mostly extended

Sources above 100 TeV

Point source map



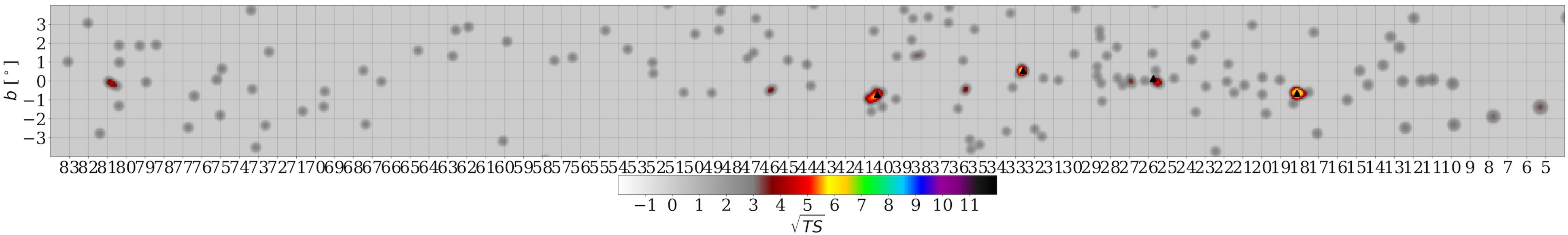
0.5 degree extended map



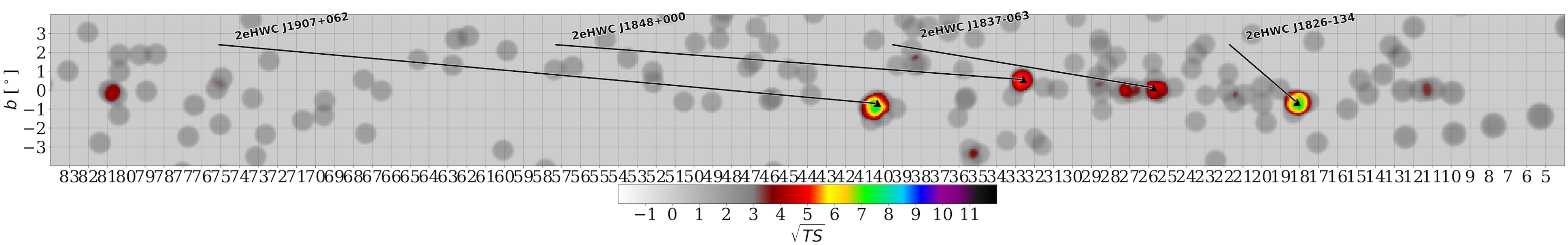
More than half unidentified and mostly extended

Sources above 177 TeV

Point source map

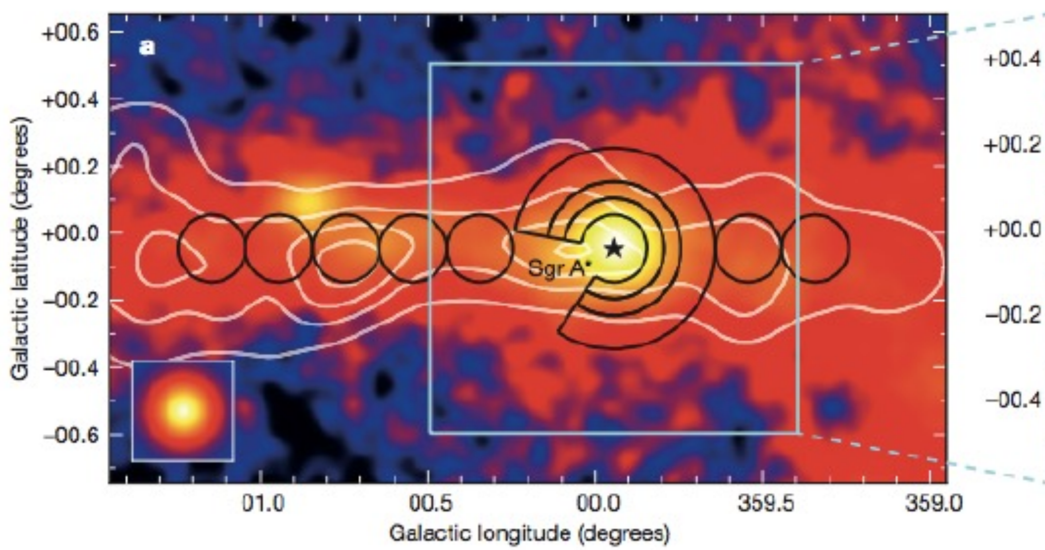


0.5 degree extended map

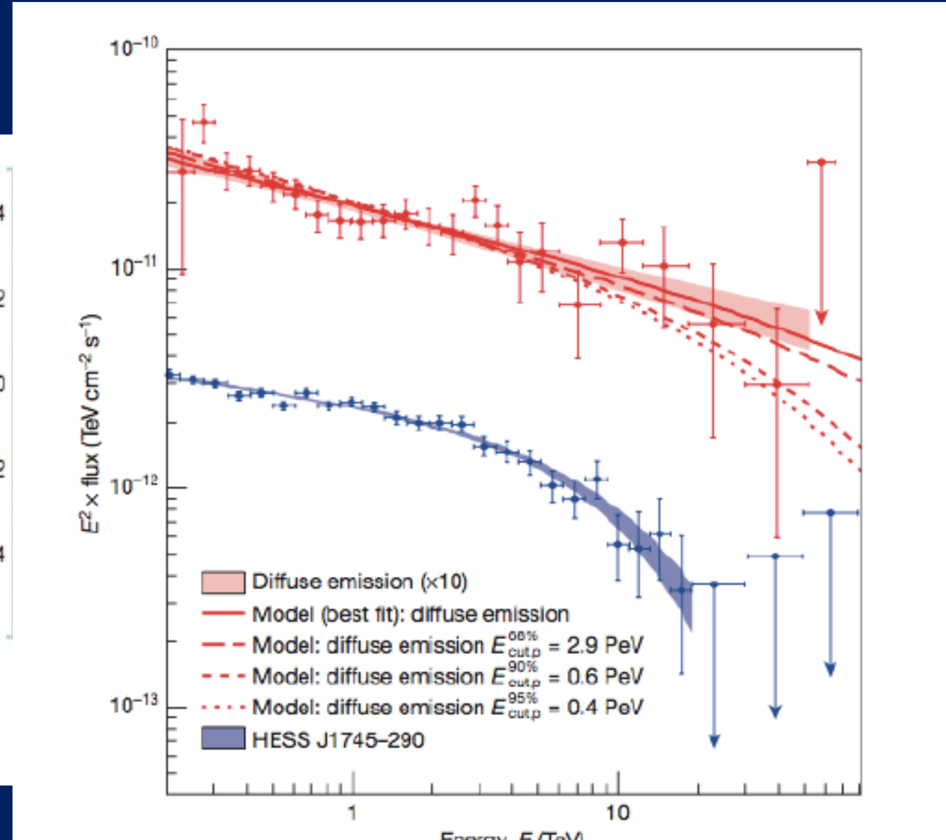


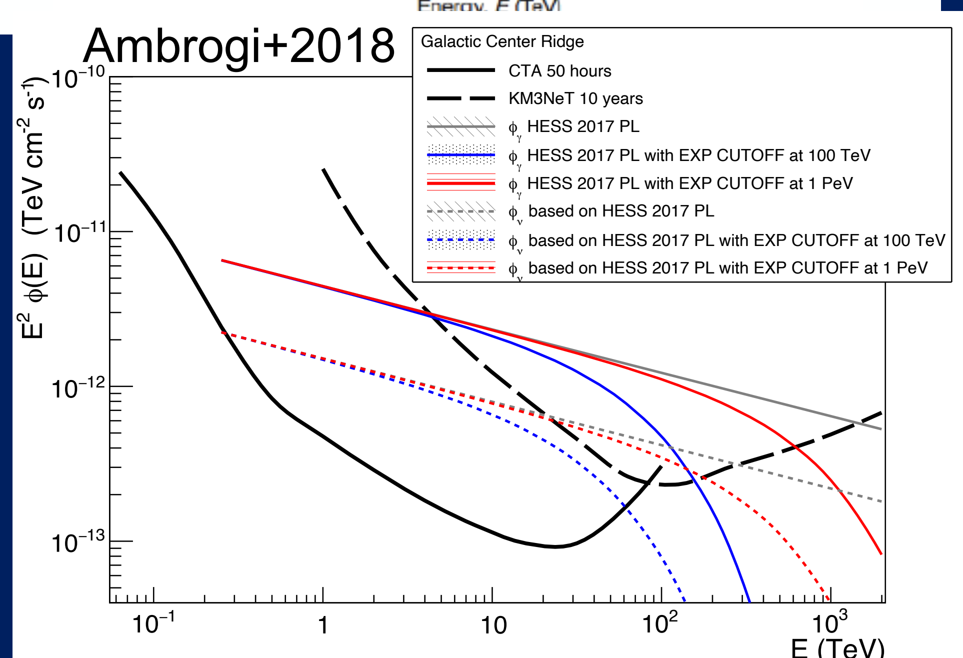
More than half unidentified and mostly extended

GC PeVatron



HESS Coll, Nature2016

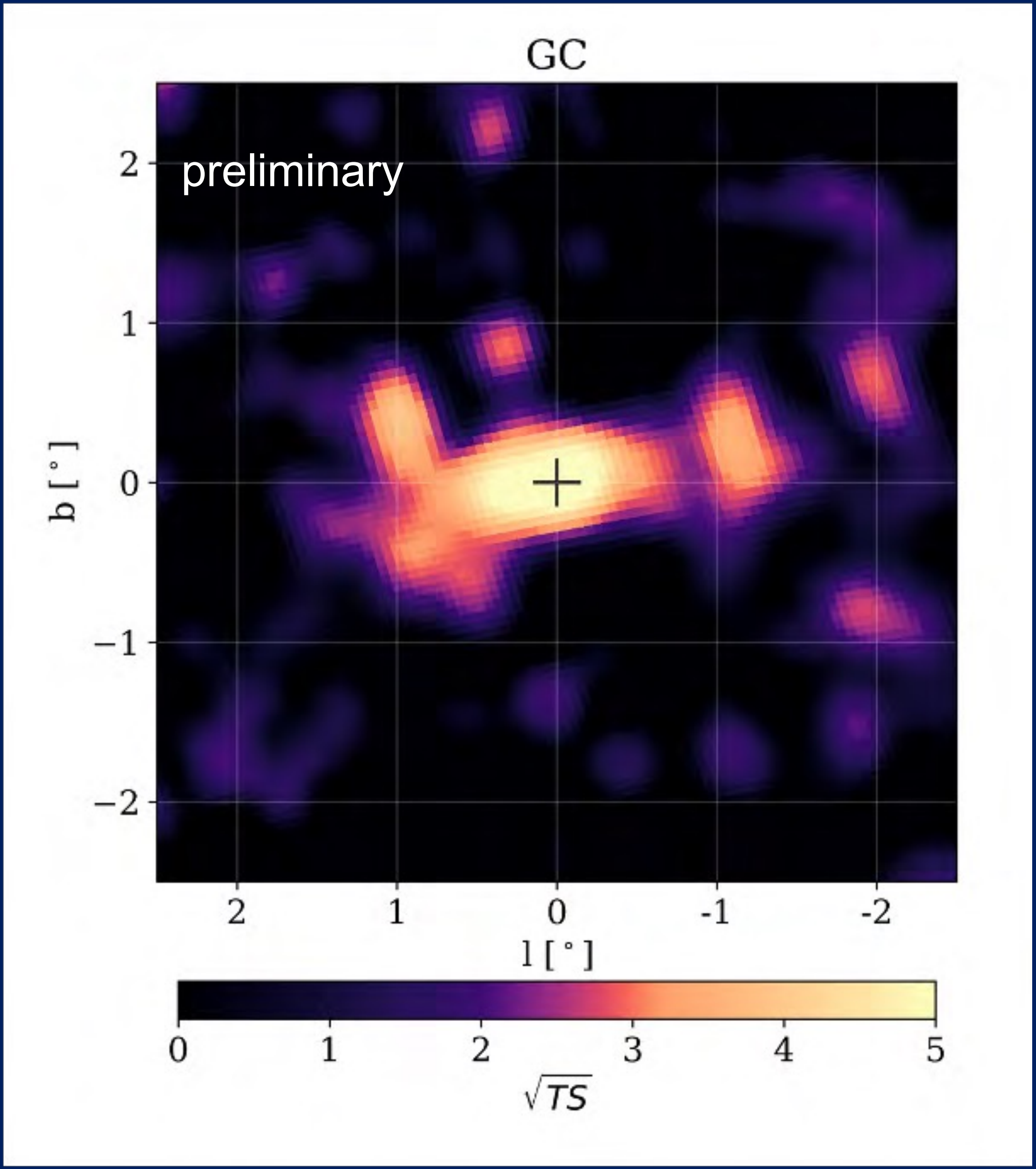




- Point-like, central source on top of extended (2 x 1 deg) ridge emission coincident with CMZ
- Central point source: cutoff @ 10 TeV
- Diffuse emission from interactions of CRs (from central BH or SFRs)
- Diffuse Emission : cutoff @ ?…

- 100 TeV photons might not escape the GC ridge
- neutrinos could be the only messenger

HAWC View of the Galactic Centre Ridge



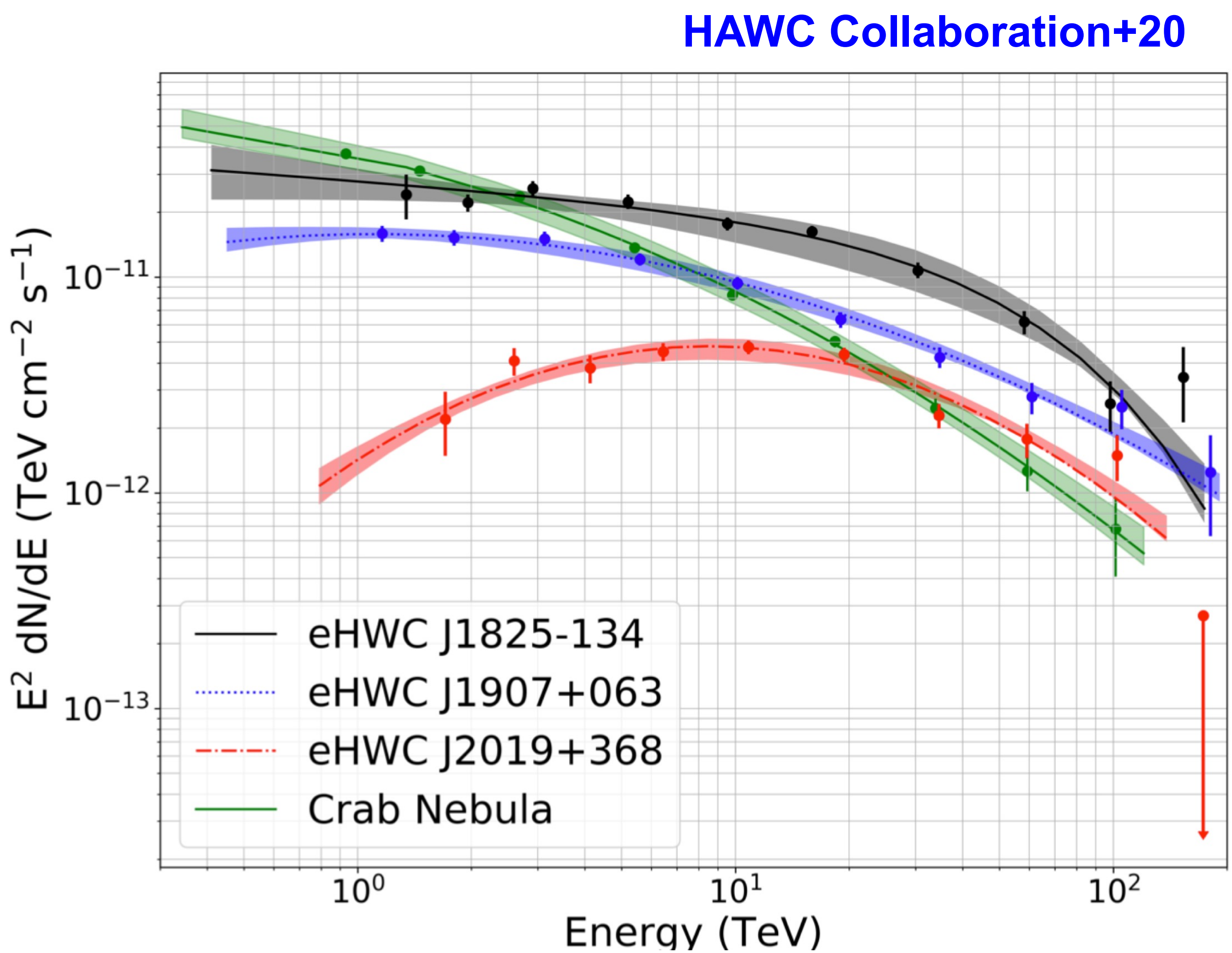
- 6 σ detection in Pass 5
- HAWC and HESS fluxes compatible
- **No spectral cutoff**
- Maximum γ energy detected in HAWC

1 sigma: 69.57 TeV

2 sigma: 50.17 TeV

3 sigma: 34.24 TeV

The Galaxy above 100 TeV: Spectra

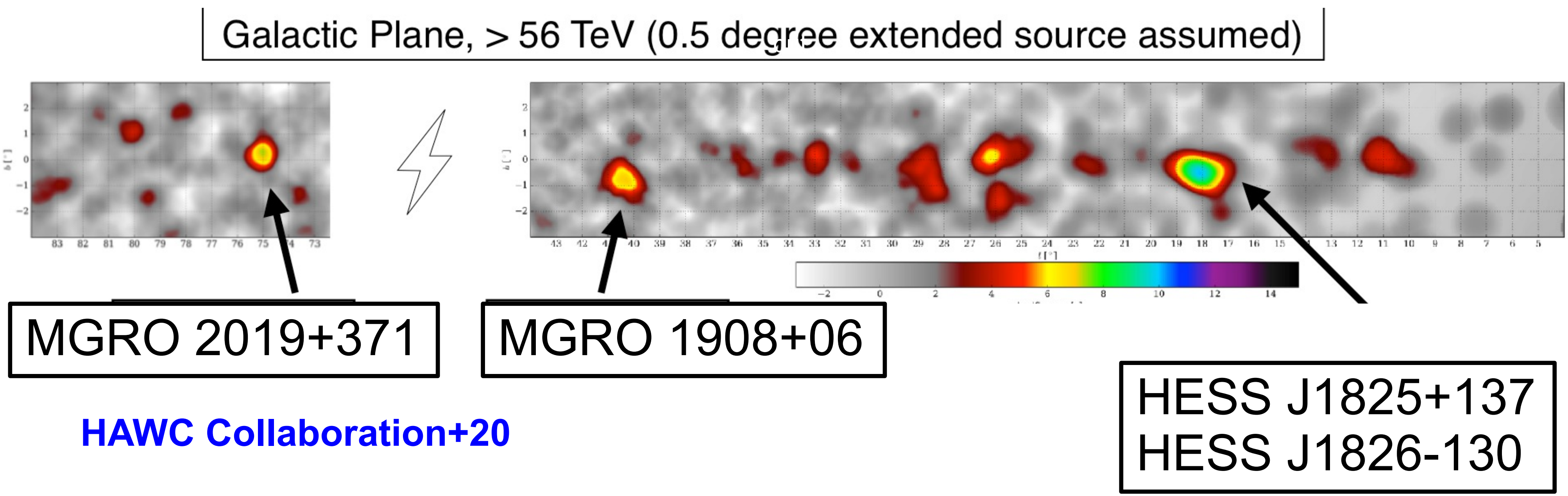


Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 $(10^{-13}$ TeV cm^2 s$)^{-1}$	α	E_{cut} (TeV)	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 $(10^{-13}$ TeV cm^2 s$)^{-1}$	α	β	PL diff
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

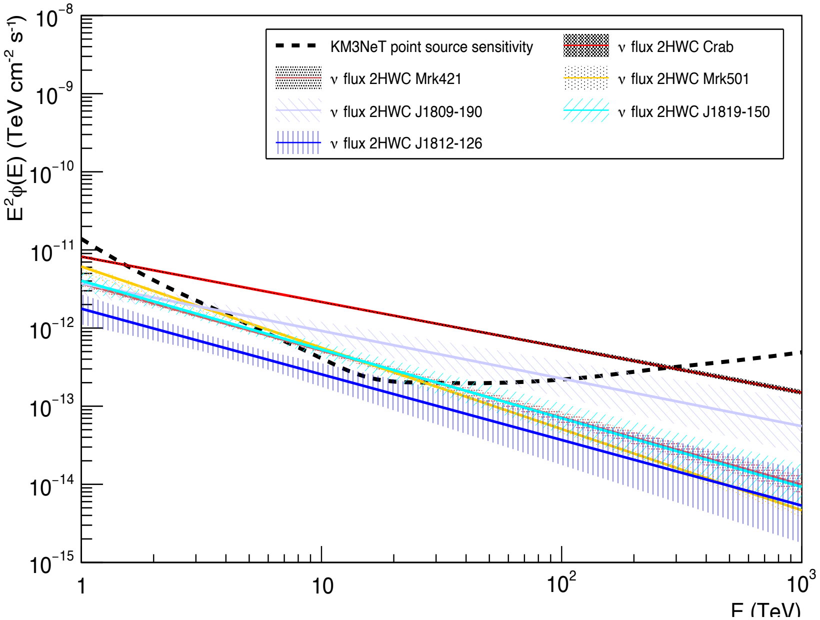
The Galaxy above 56 TeV

Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{TS}$ > 56 TeV	nearest 2HWC source	Distance to 2HWC source(°)	$\sqrt{TS}$ > 100 TeV
eHWC J0534+220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534+220	0.02	4.44
eHWC J1809-193	272.46 ± 0.13	-19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809-190	0.30	4.82
eHWC J1825-134	276.40 ± 0.06	-13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825-134	0.07	7.33
eHWC J1839-057	279.77 ± 0.12	-5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837-065	0.96	3.06
eHWC J1842-035	280.72 ± 0.15	-3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844-032	0.44	2.70
eHWC J1850+001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849+001	0.20	3.04
eHWC J1907+063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908+063	0.16	7.30
eHWC J2019+368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019+367	0.02	4.85
eHWC J2030+412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031+415	0.34	3.07

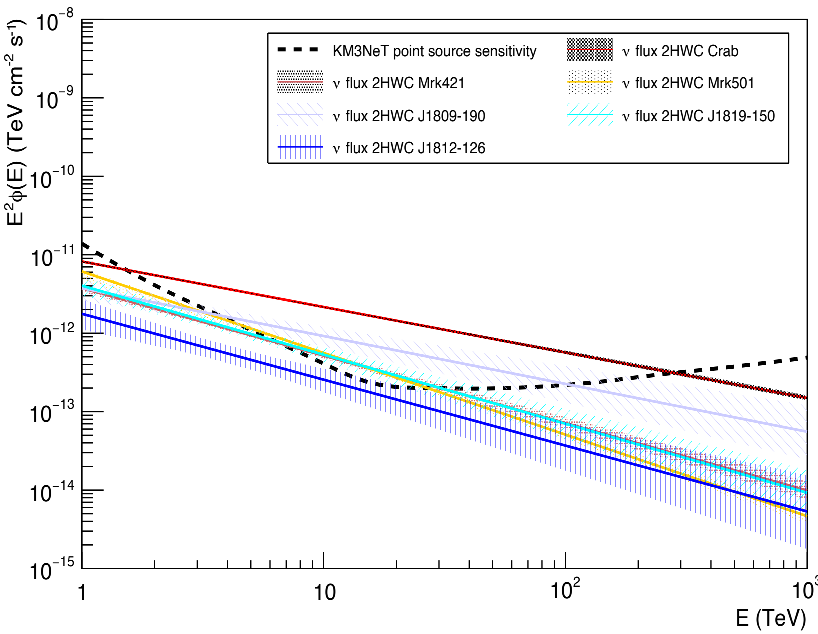


HAWC Collaboration+20

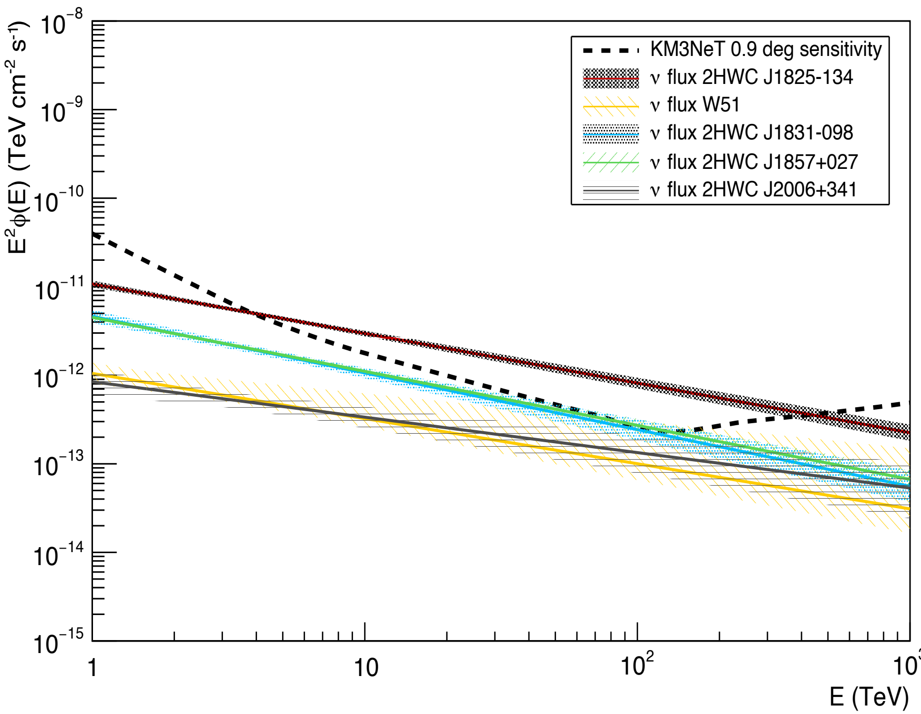
Visibility of bright HAWC PeV candidates



Ambrogi+2018

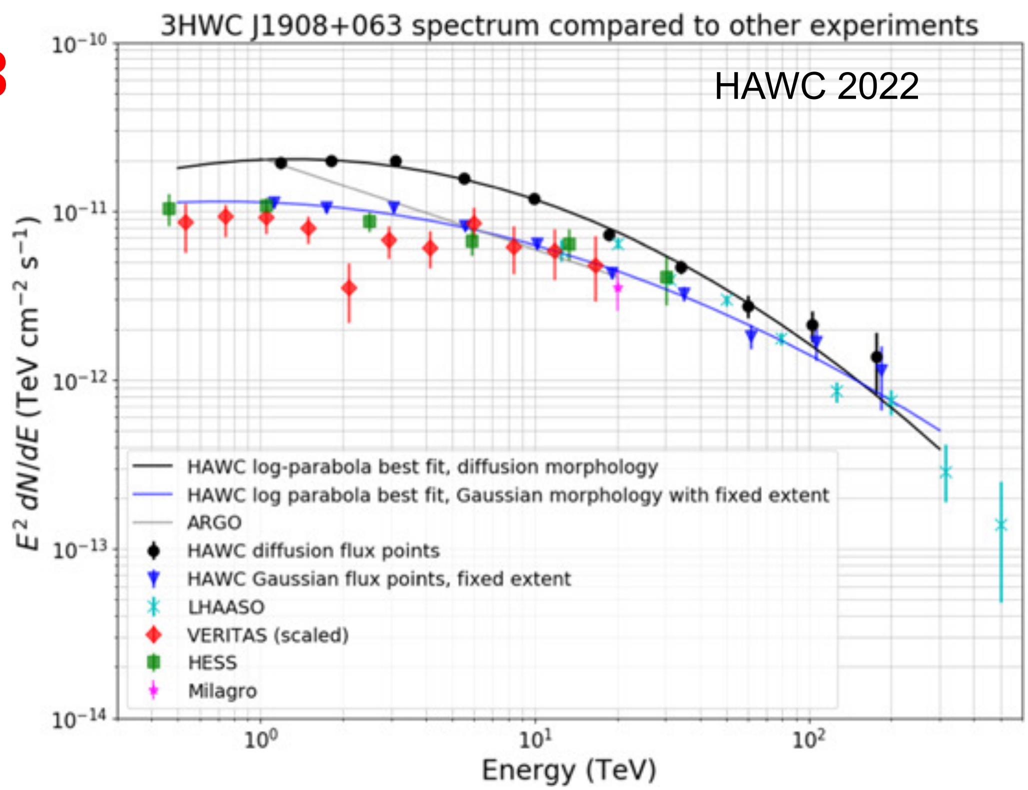


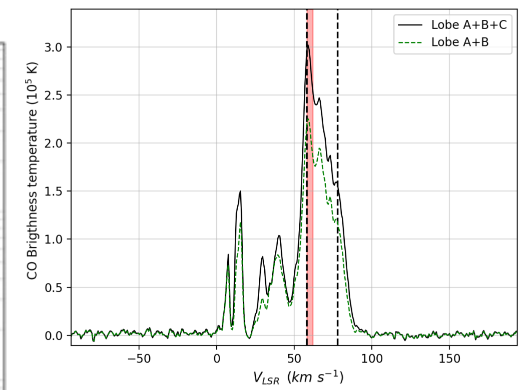
(a)

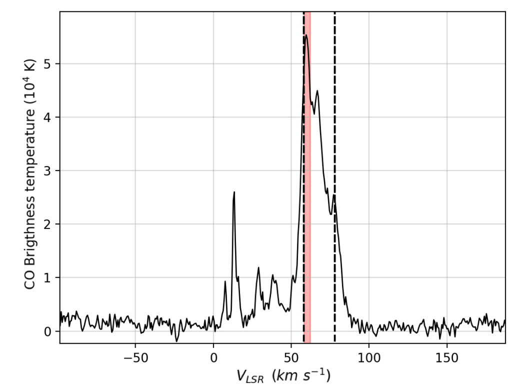


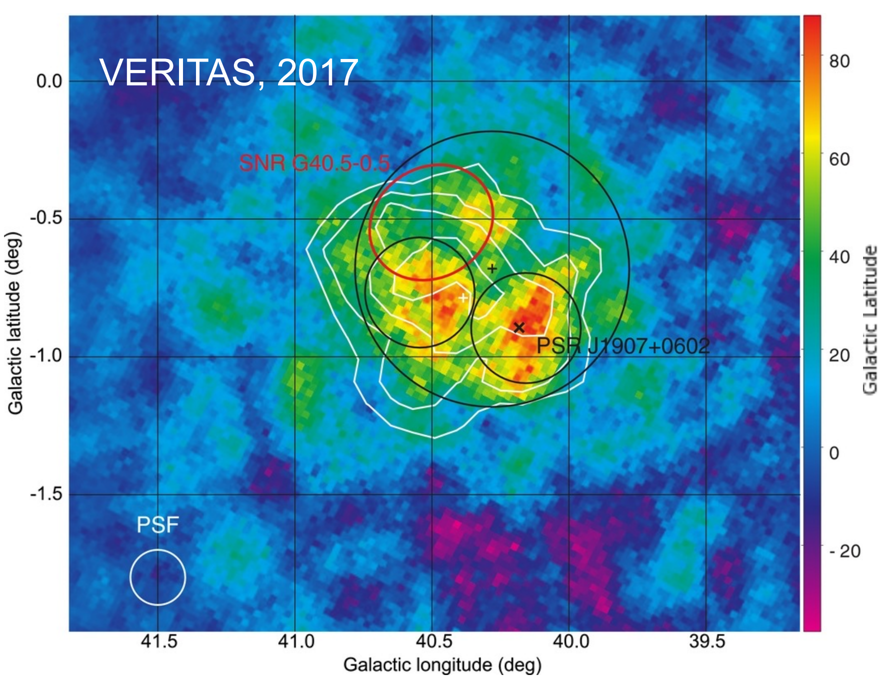
HAWC J1908 +063

l= 40° b= -0.79°

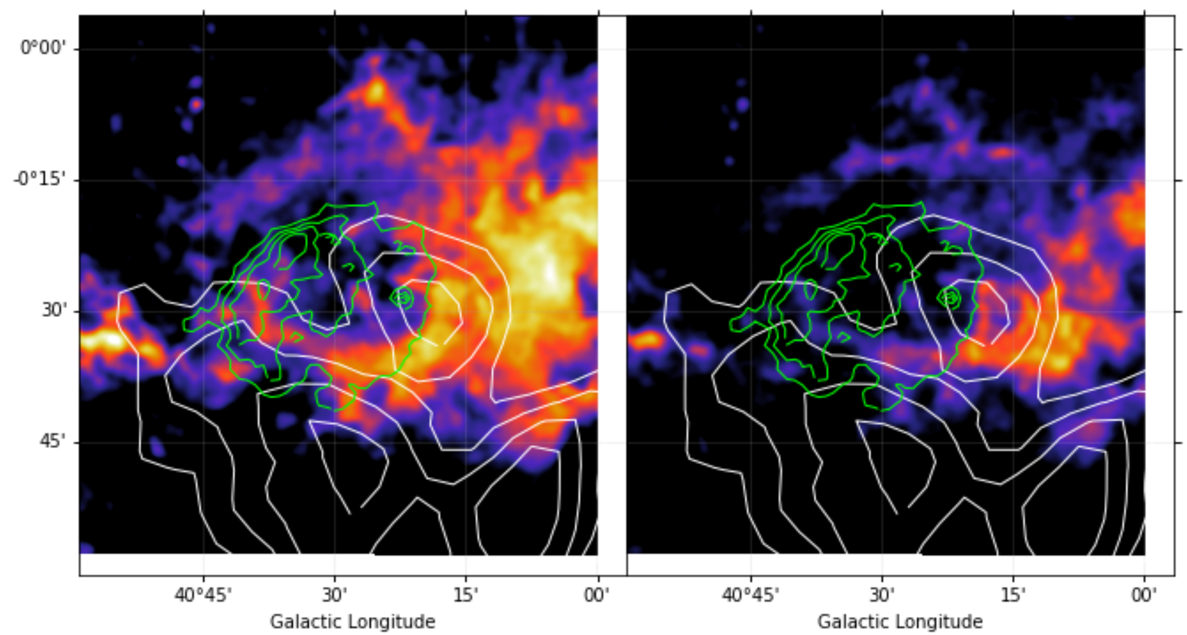




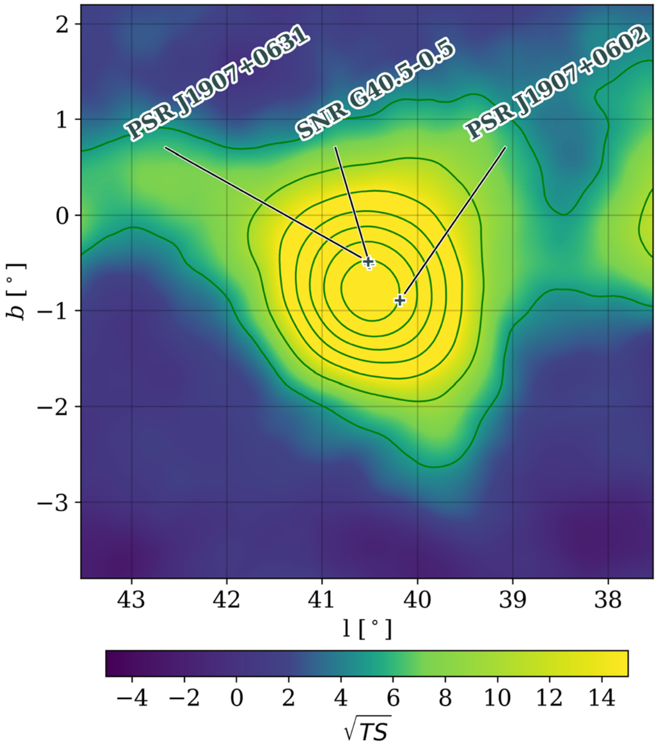


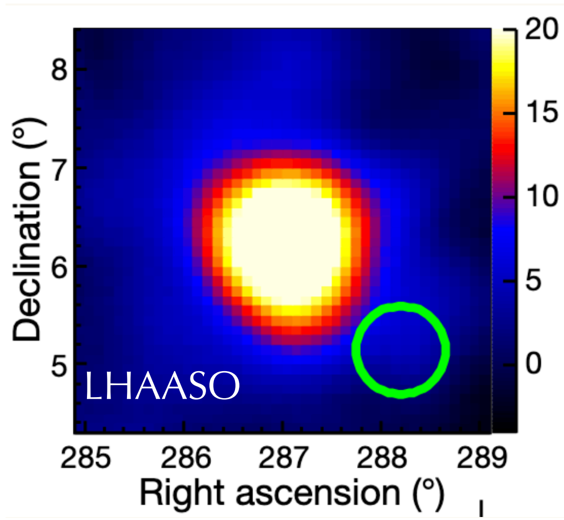


Crestan+ 2021

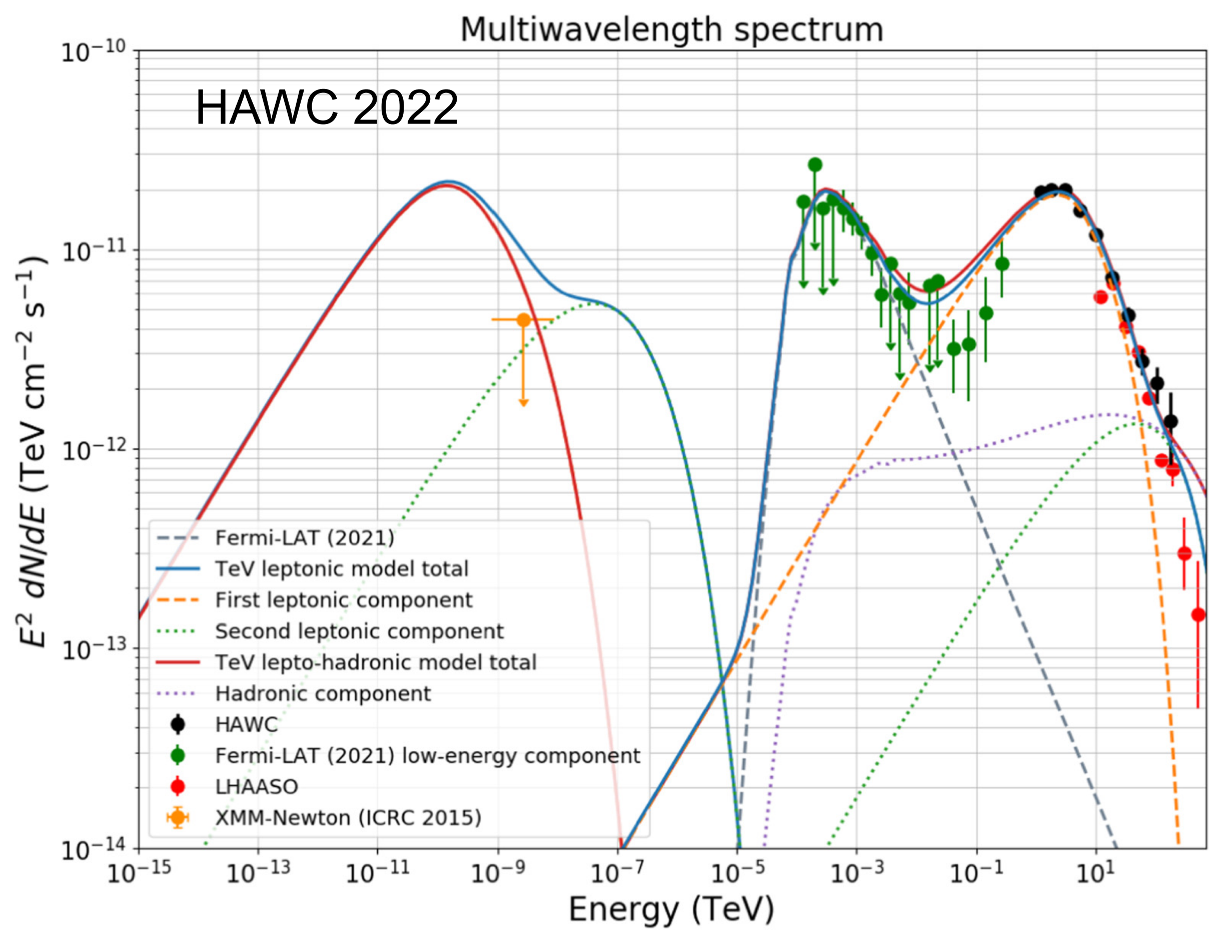


HAWC J1908+063





$\sim 7.5 \times 10^{-13}\ (\mathrm{TeV\ cm^2\ s})^{-1}$.



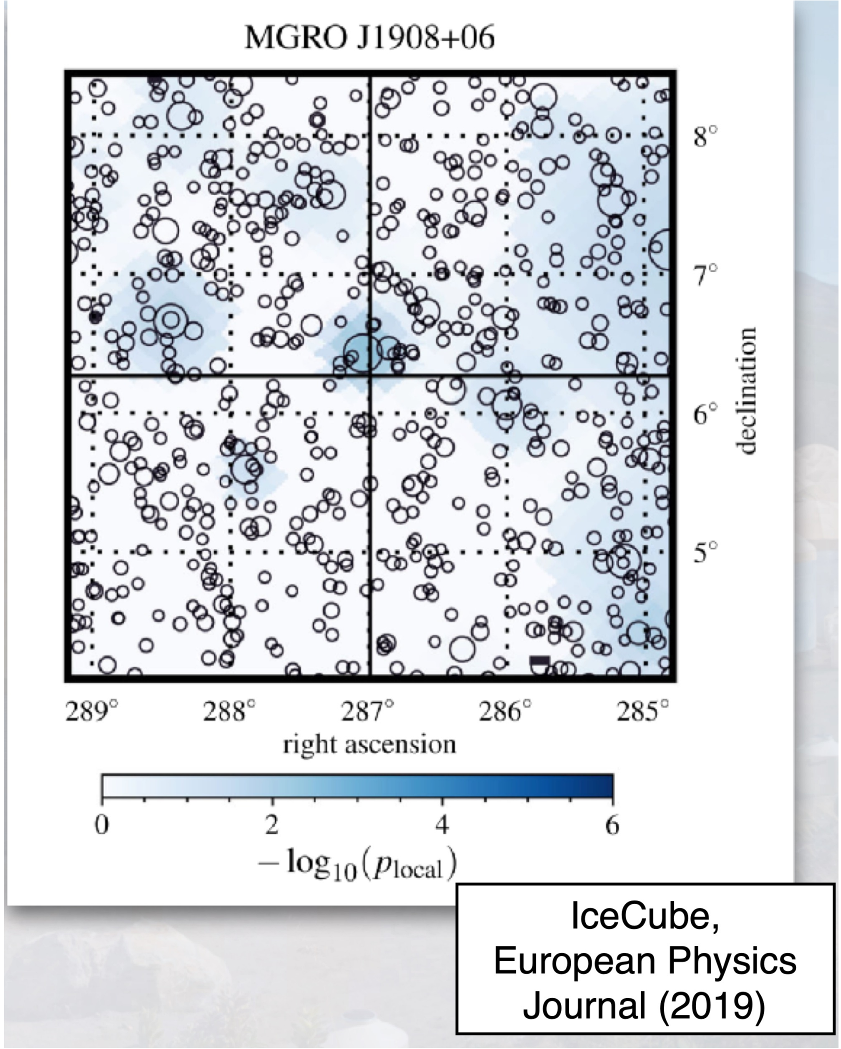
HAWC > 220 TeV, LHAASO 440 TeV

HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

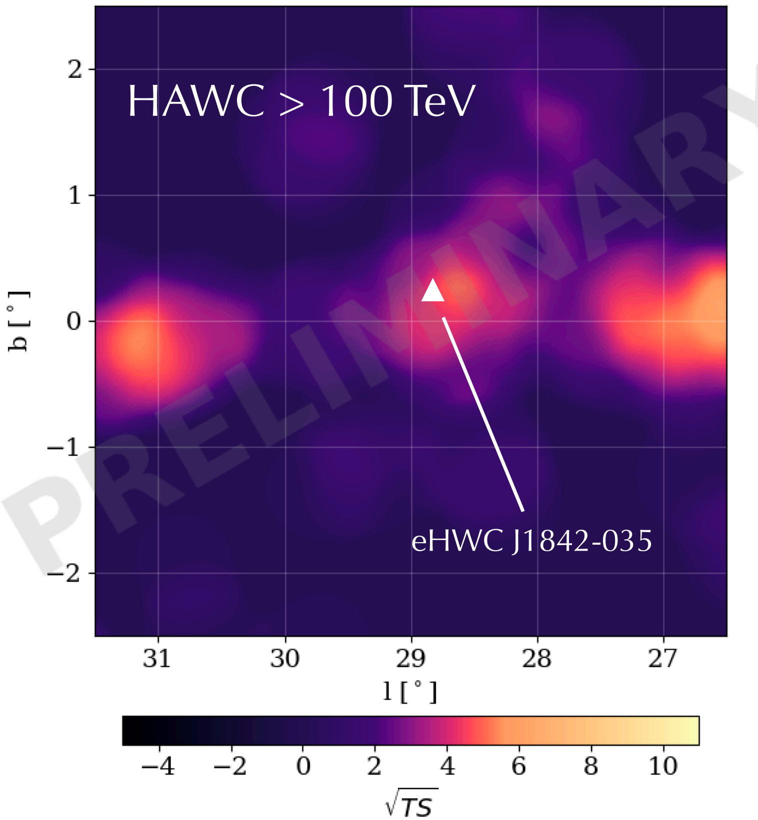
Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

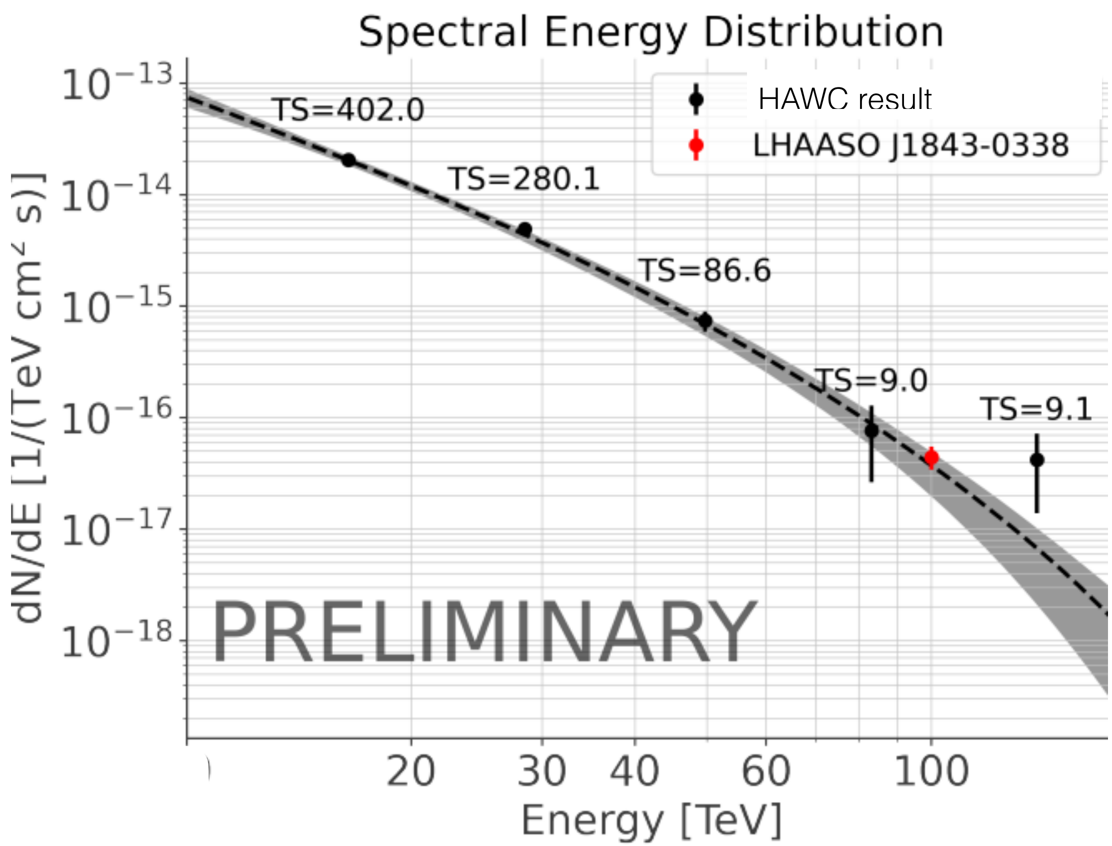
J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



IceCube, European Physics Journal (2019)

eHWC J1842-035



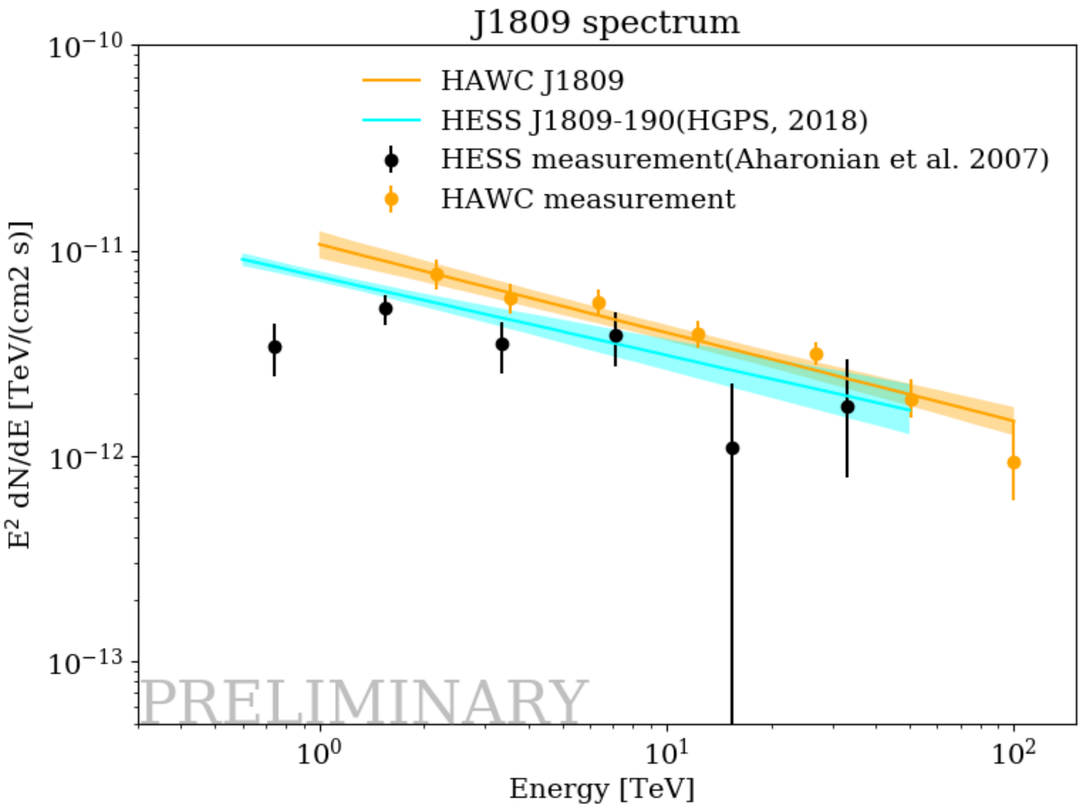


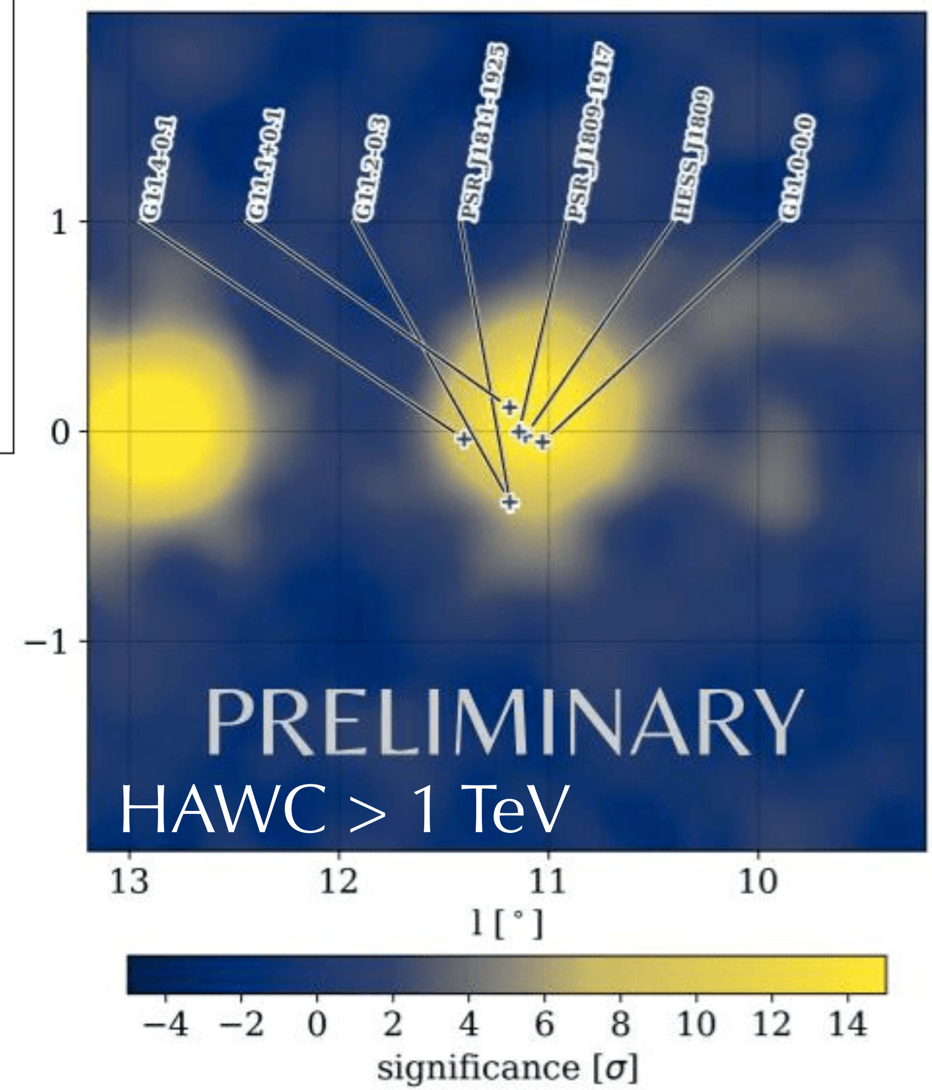
Complex morphology , 0.3-0.4 deg

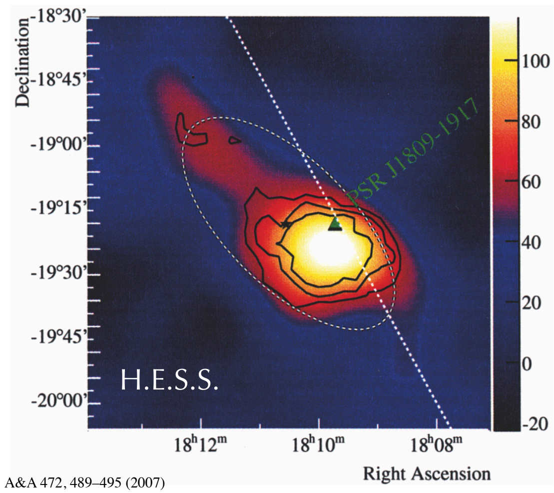
Maximum energy in HAWC > 100 TeV

Study ongoing

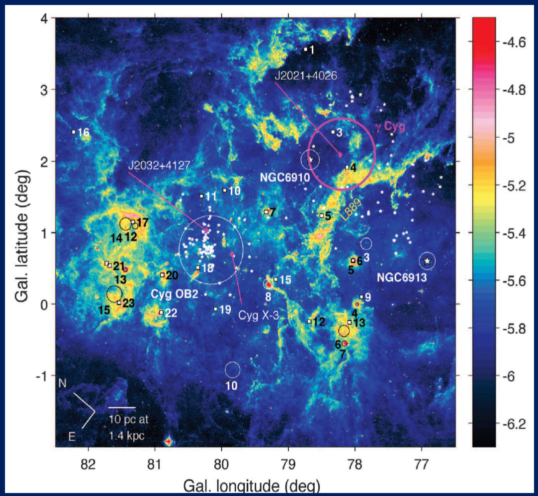
HESS J1809 -1917

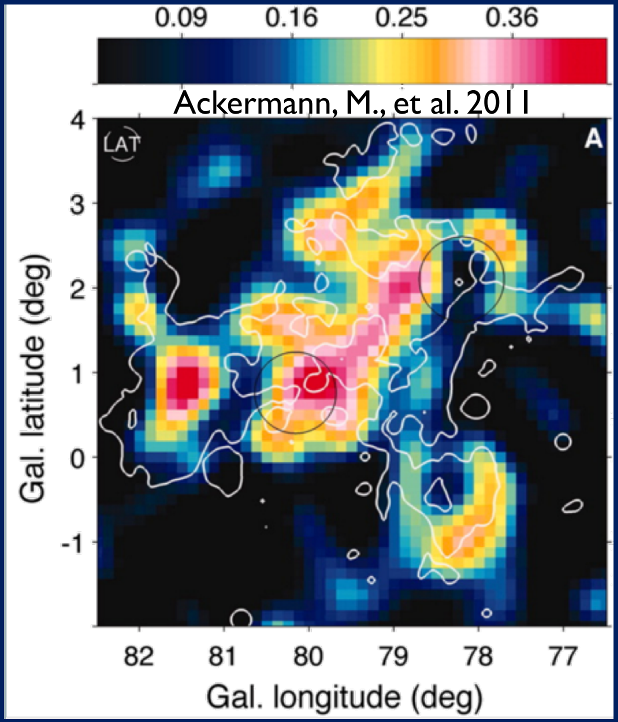




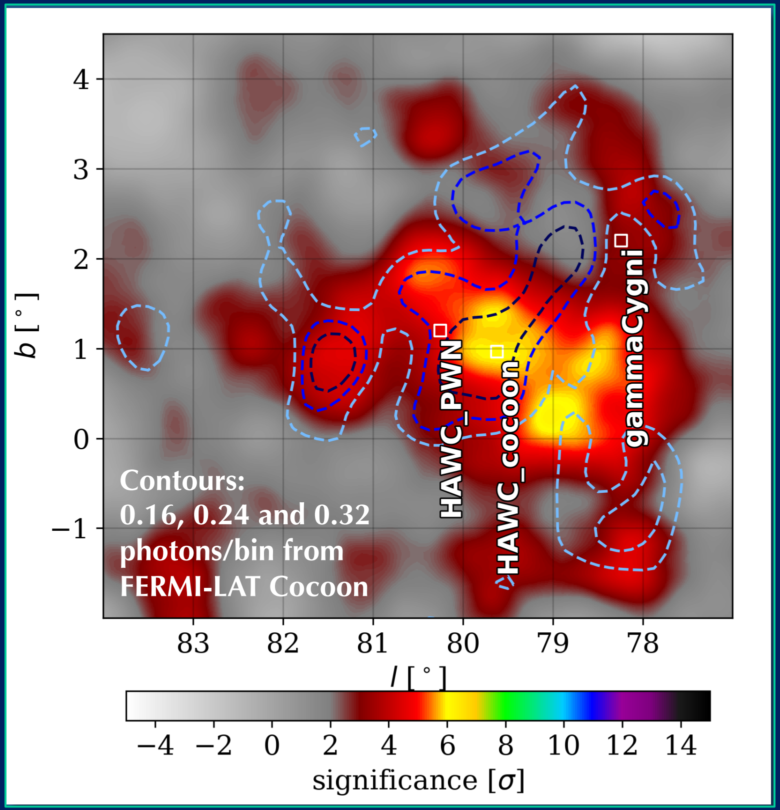


Fermi - Argo -HAWC-LHAASO cocoon





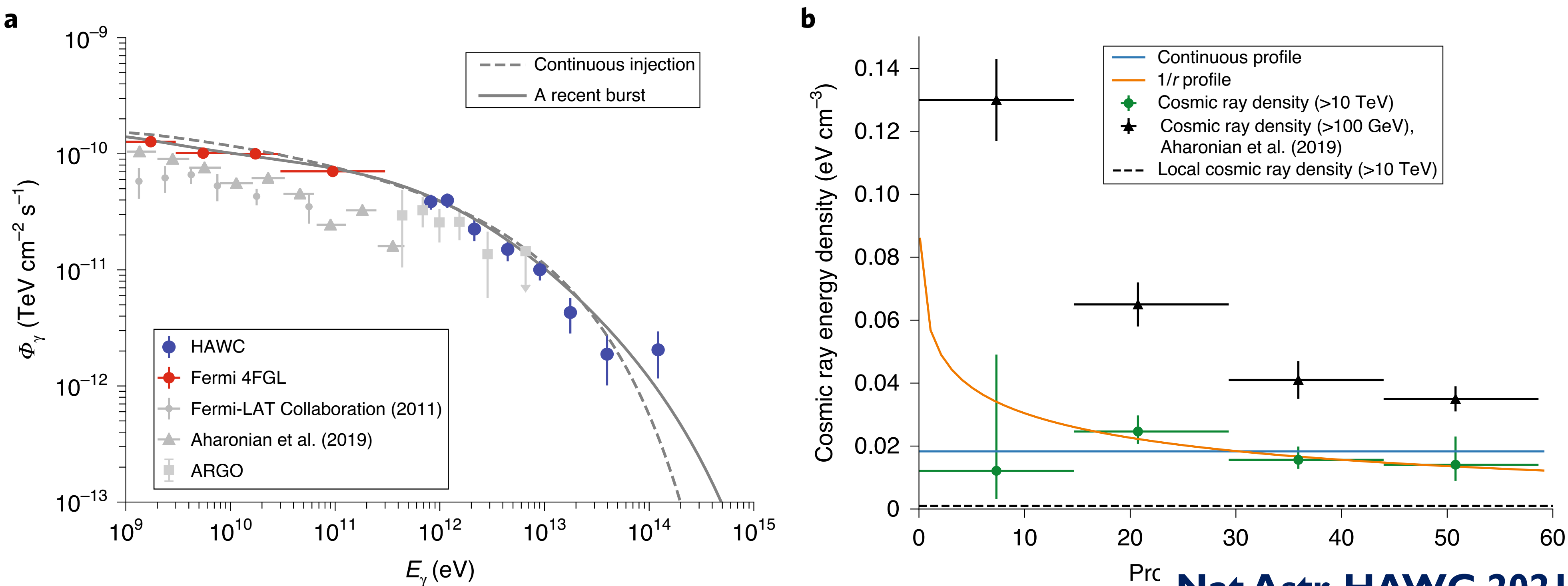
HAWC significance map of the Cygnus Cocoon



Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

HAWC Coll, NatAstr 2021

Cocoon Spectrum and morphology



Nat Astr, HAWC 2021

Unique SFR seen from GeV to PeV energies

Spectral break with respect to Fermi datapoints

CR density > 10 TeV higher than local CR in the whole region

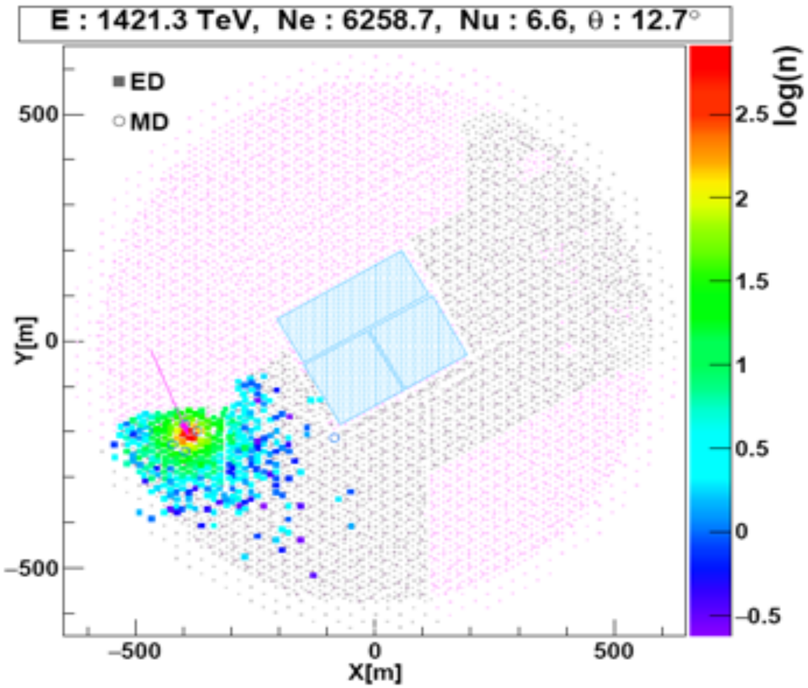
1/r profile would suggest a continous injection. A constant profile would suggest a recent burst event happened less than 0.1 Myr

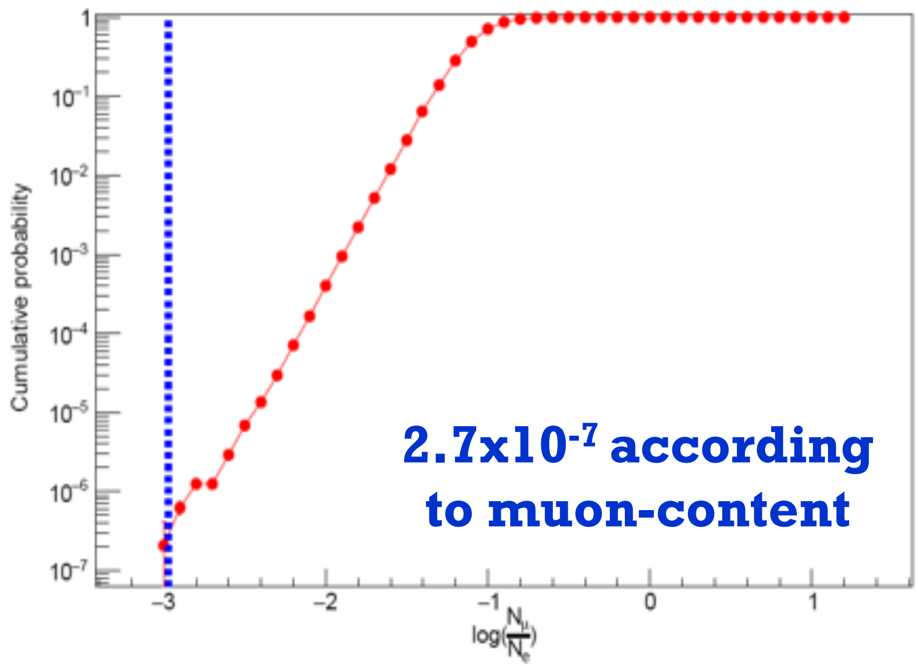
10000 CygOB2 would be required for CRs Galactic population

Highest energy photon

University of Science and Technology of China

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

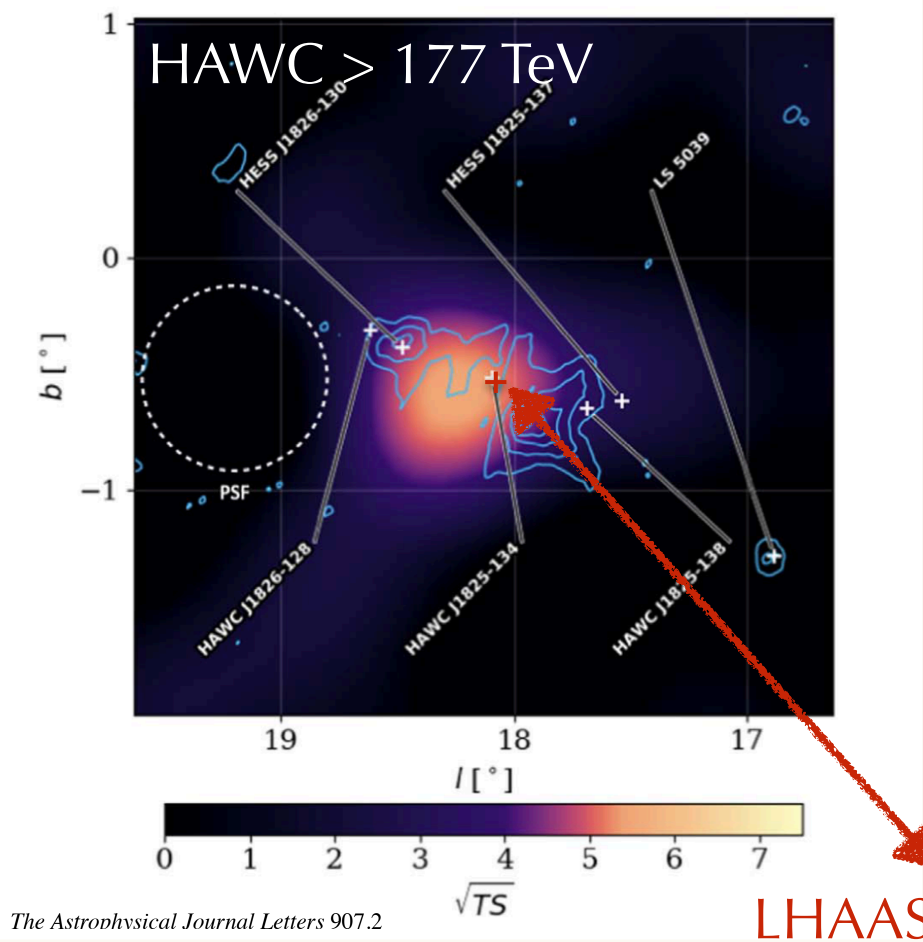


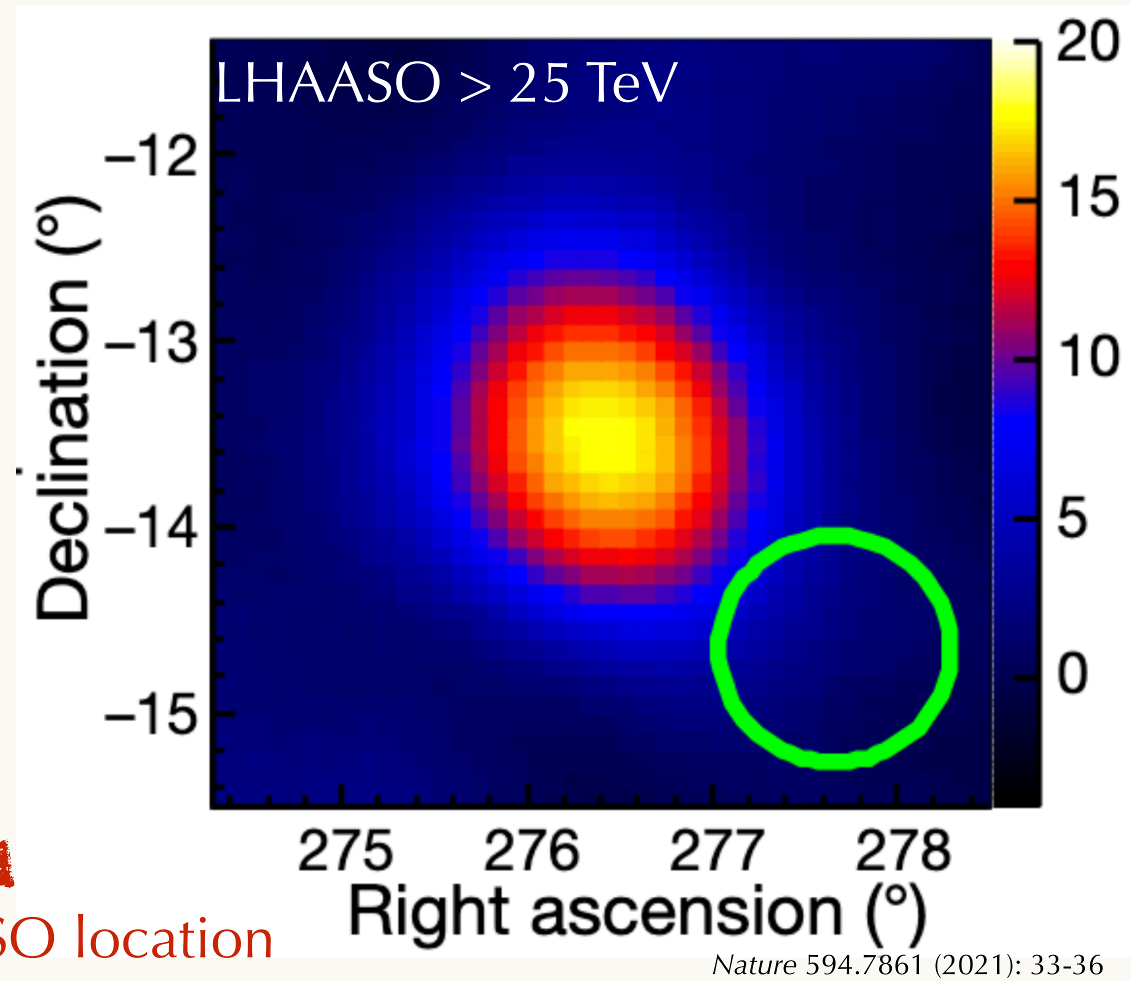


Nature 594:33-36 (2021)

Slide by Ruizhi Yang

eHWC J1825-134



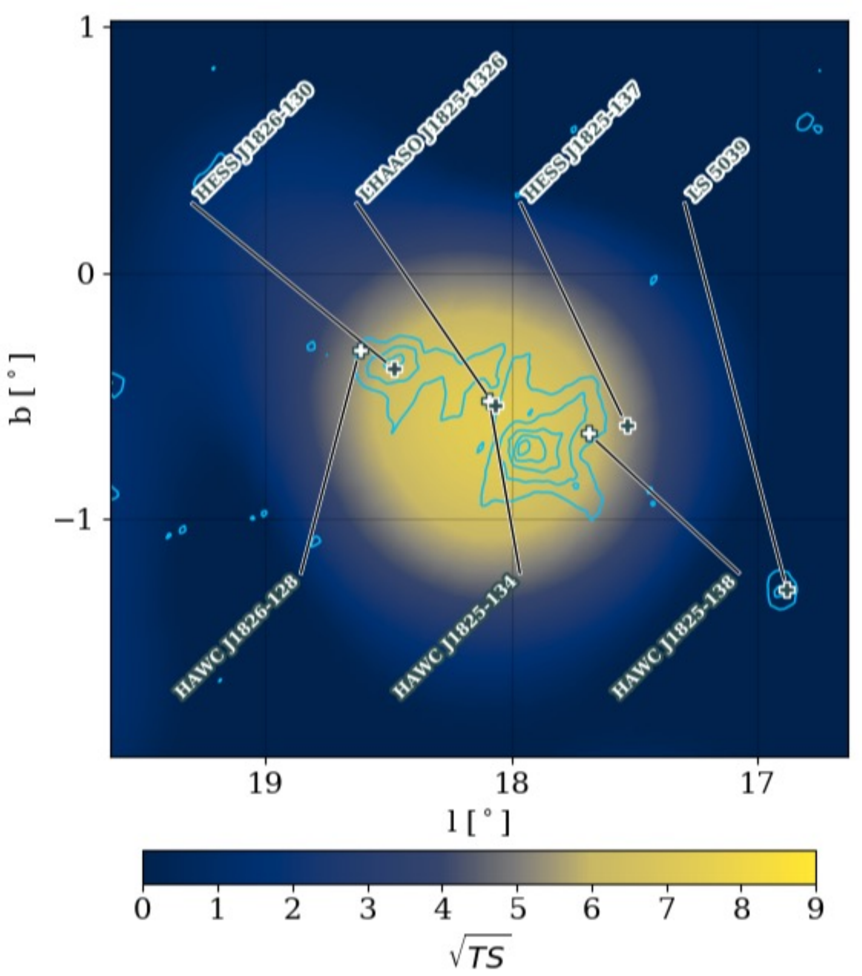


LHAASO location

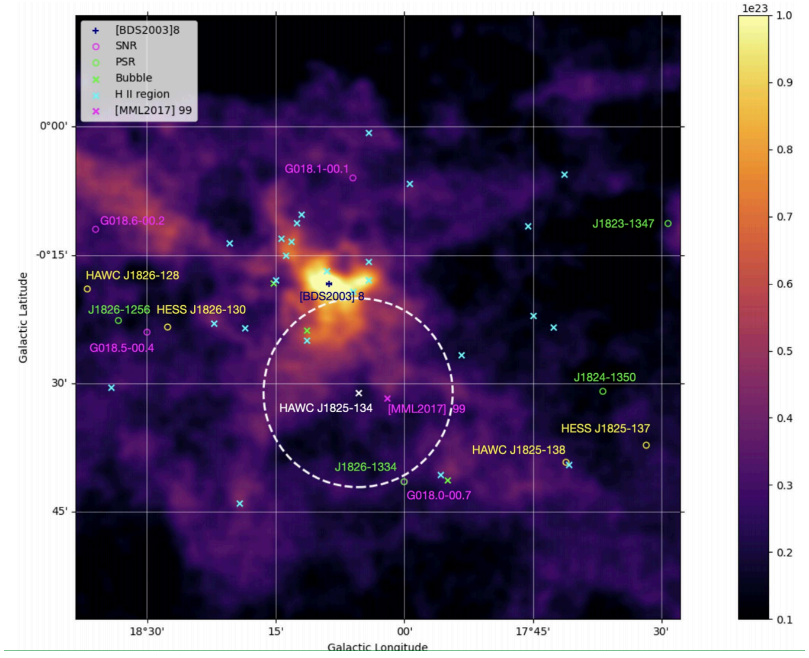
	HAWC	LHAASO
Location	**R.A. 276.44° Dec. -13.42°**	**R.A. 275.45° Dec. -13.45°**
Morphology	2 extended sources + 1point source	0.3 ° extension template
Maximum measured energy	>200 TeV	420 TeV
Origin of TeV emission	Proton accelerated by SFR Electron accelerated by PSR J1826-1334	

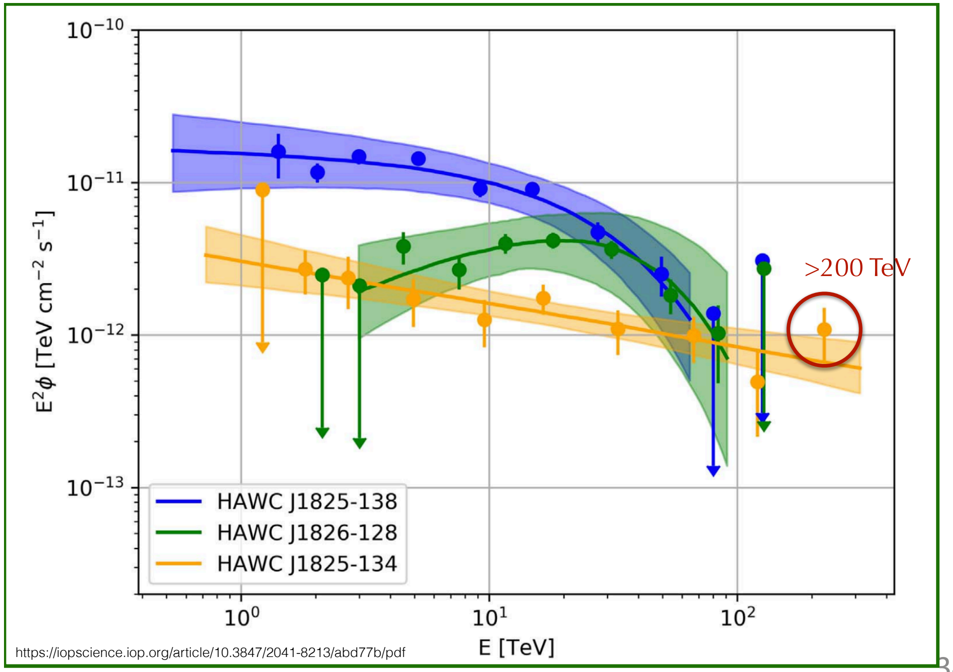
HAWC J1825-134

HAWC Coll ApJL 2021

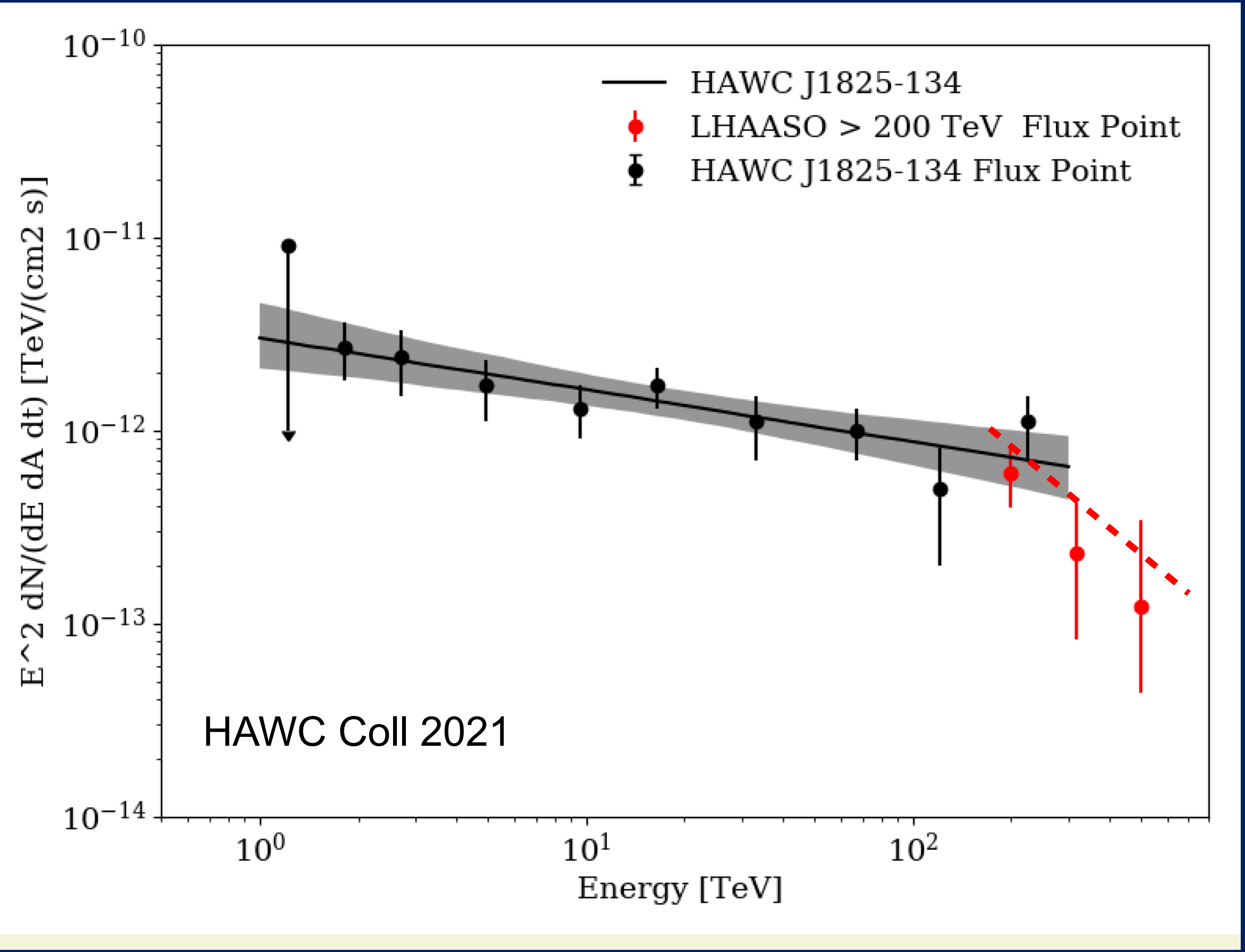


Above 177 TeV





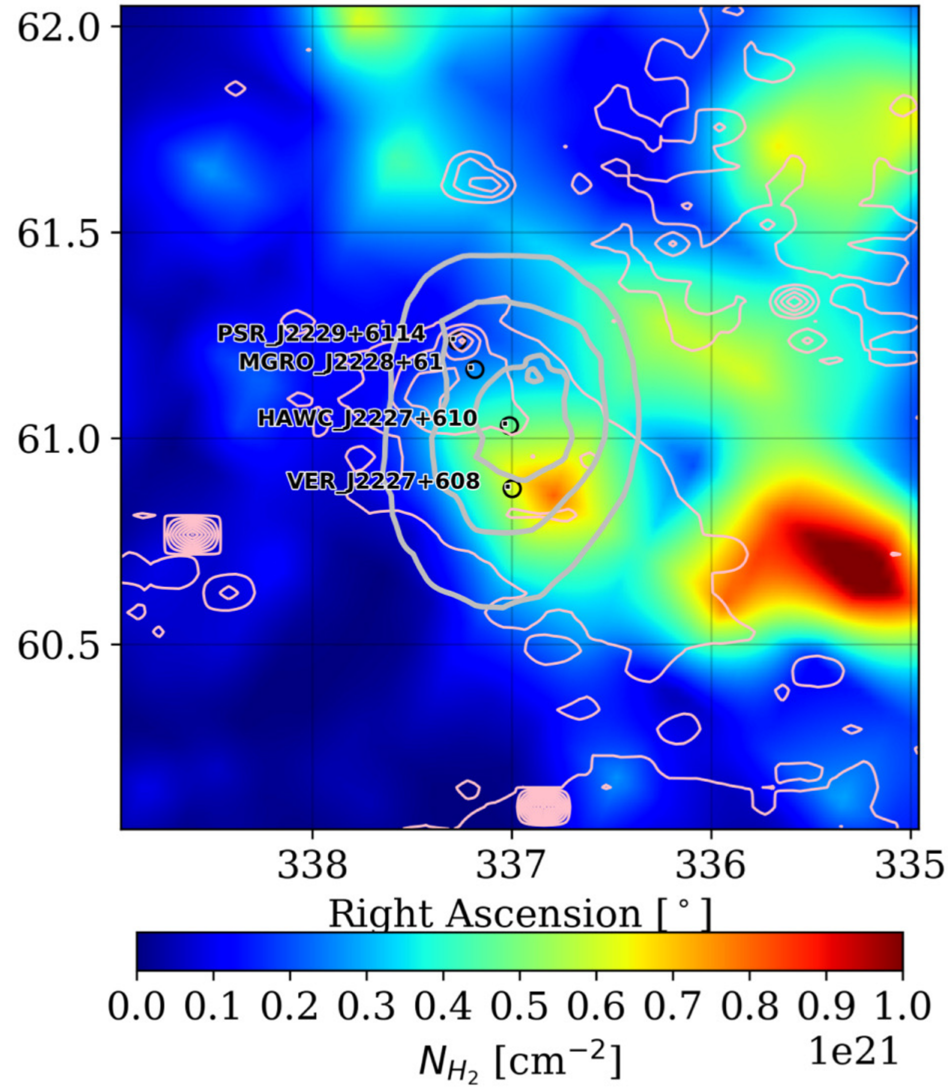
HAWC J1825-134 and LHAASO J1825-136 above 200 TeV



SNR G106.3+2.7: Galactic PeVatron ?

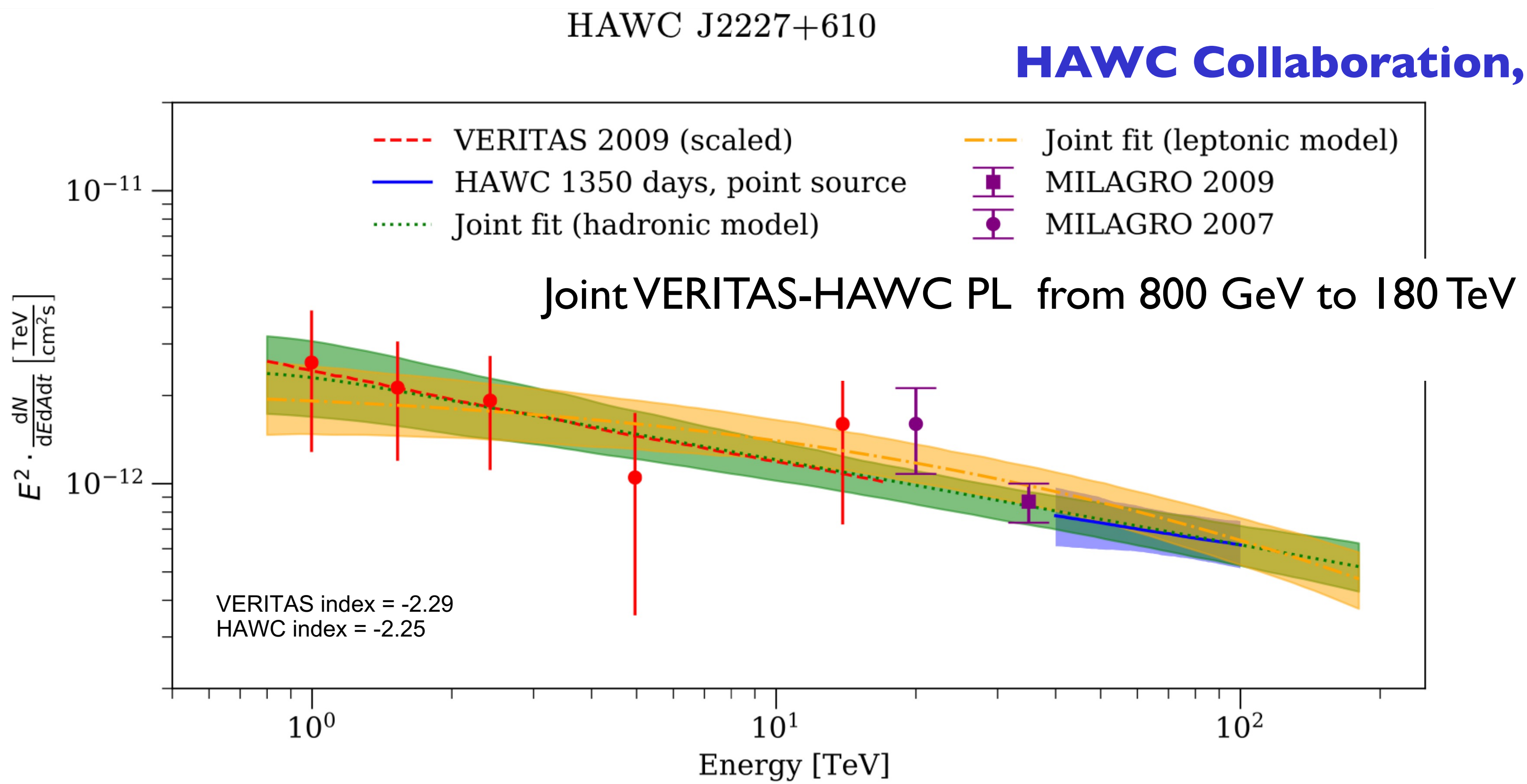
HAWC Collaboration, ApJL 2020

- SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV – 16 TeV)
- HAWC emission pointlike, morphology compatible with VERITAS source and coincident with a region of high gas density



G106.3+2.7 : a Galactic PeVatron?

HAWC Collaboration, ApJL 2020

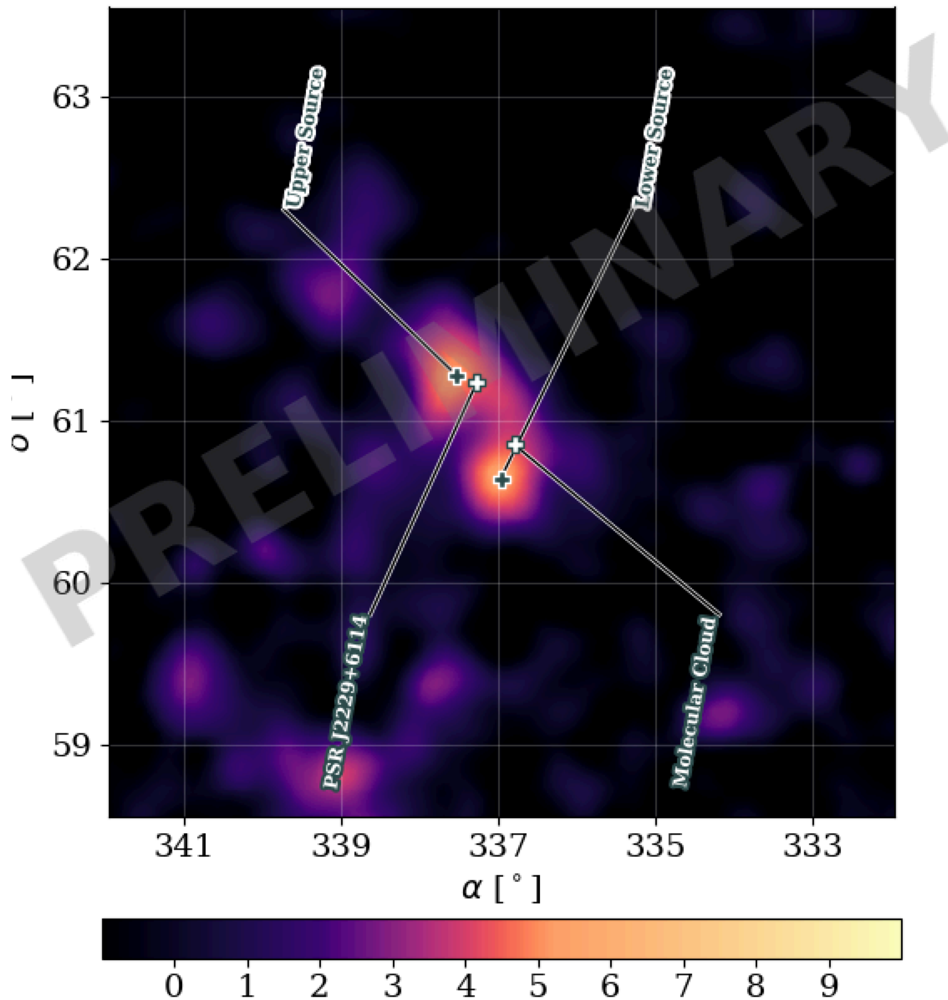


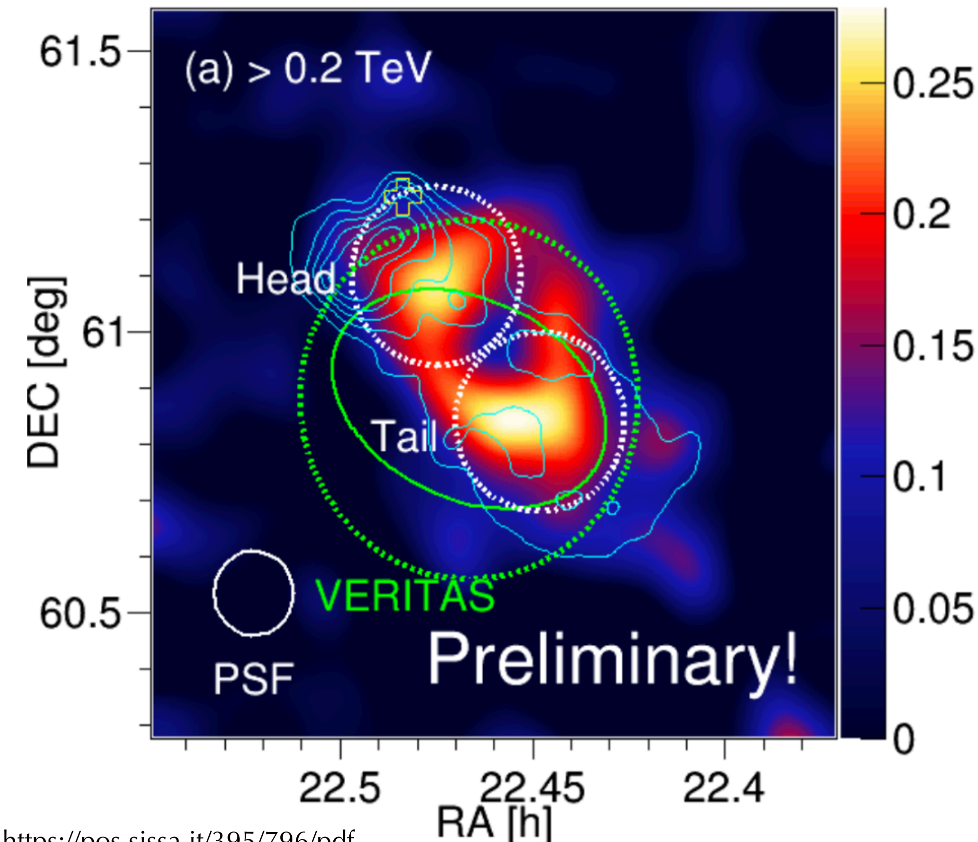
Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

$W_p = 10^{48} (n/50)^{-1}$ erg

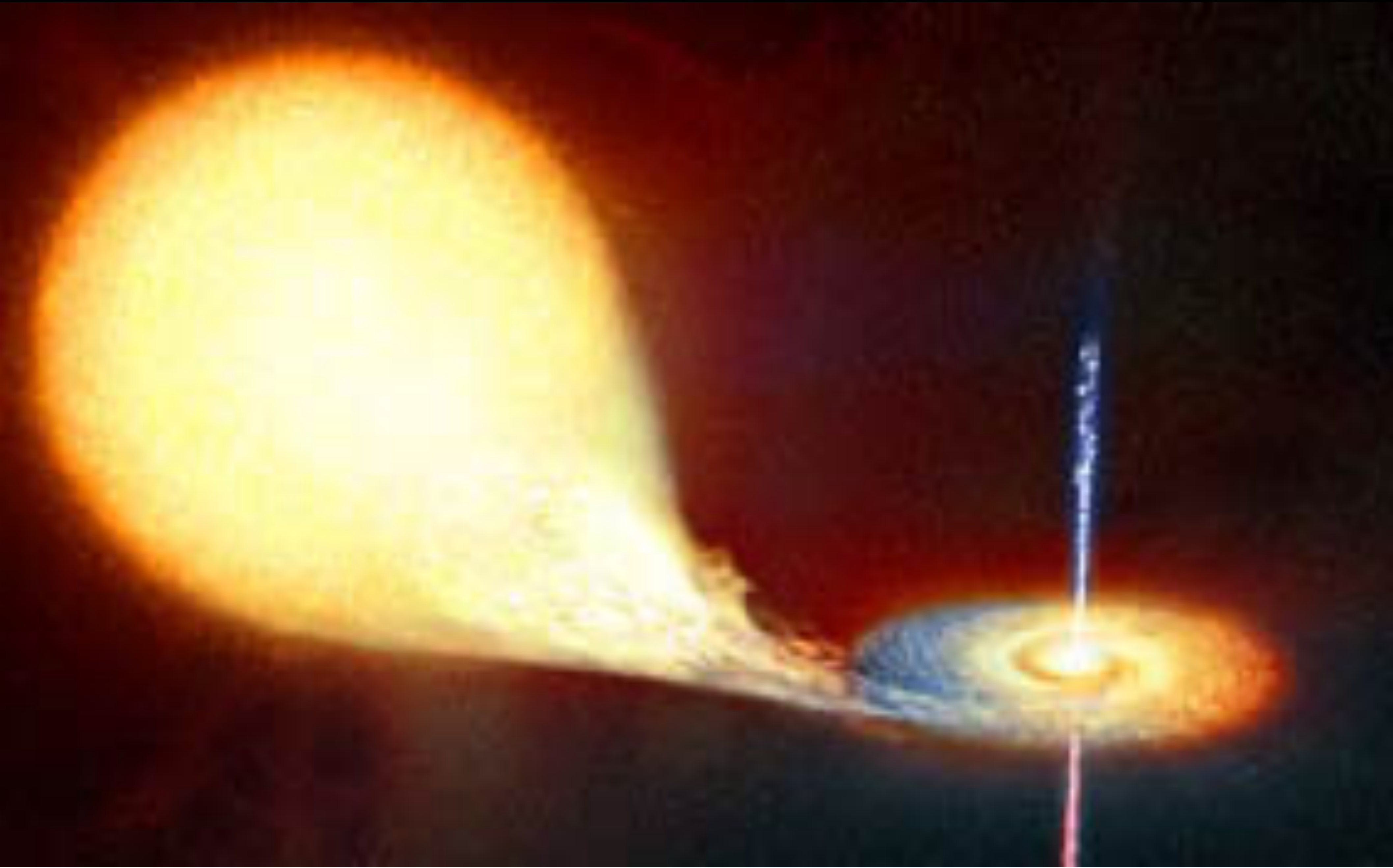
HAWC J2227+ 610 (Boomerang region)

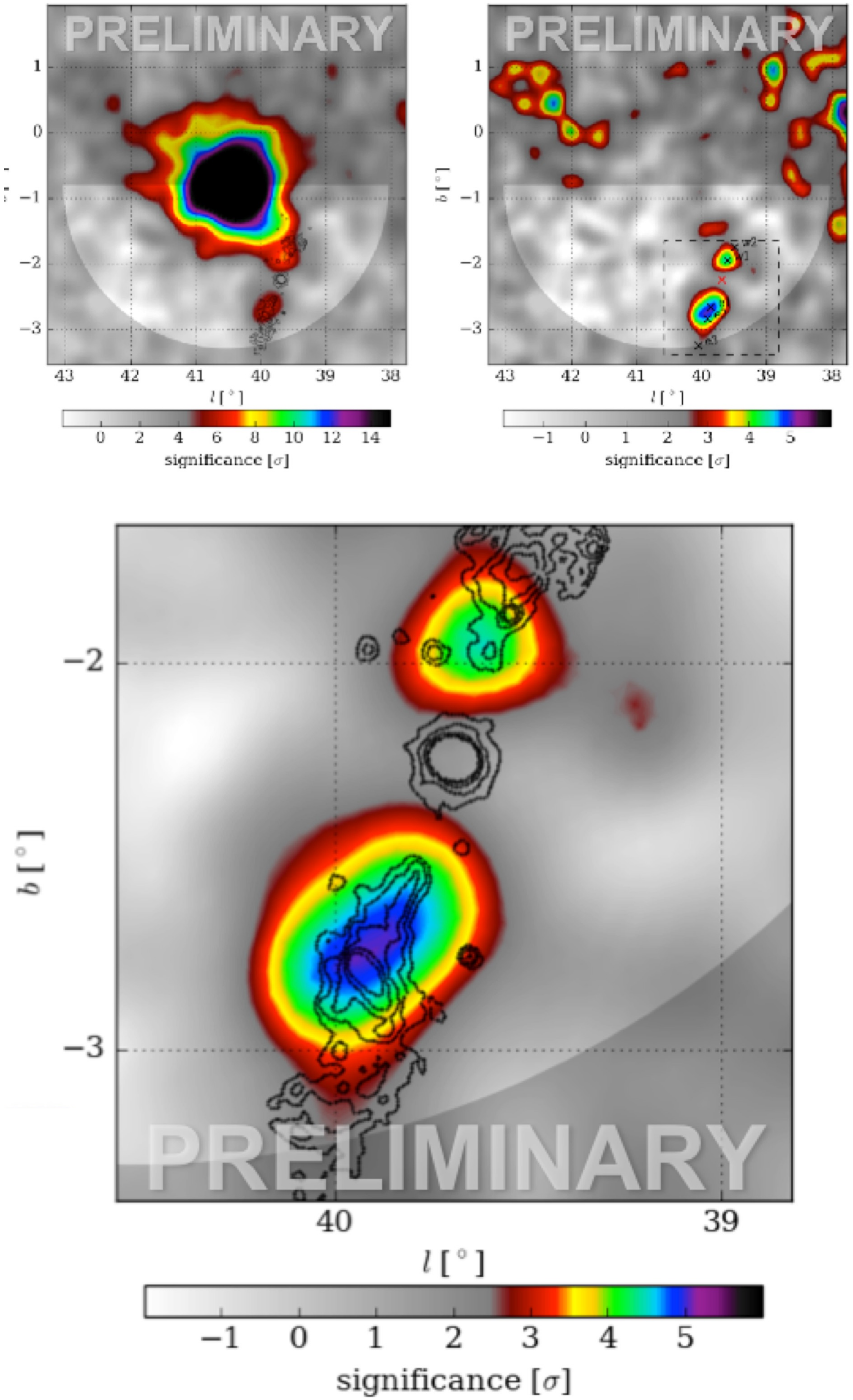




https://pos.sissa.it/395/796/pdf

HAWC detection of microquasars



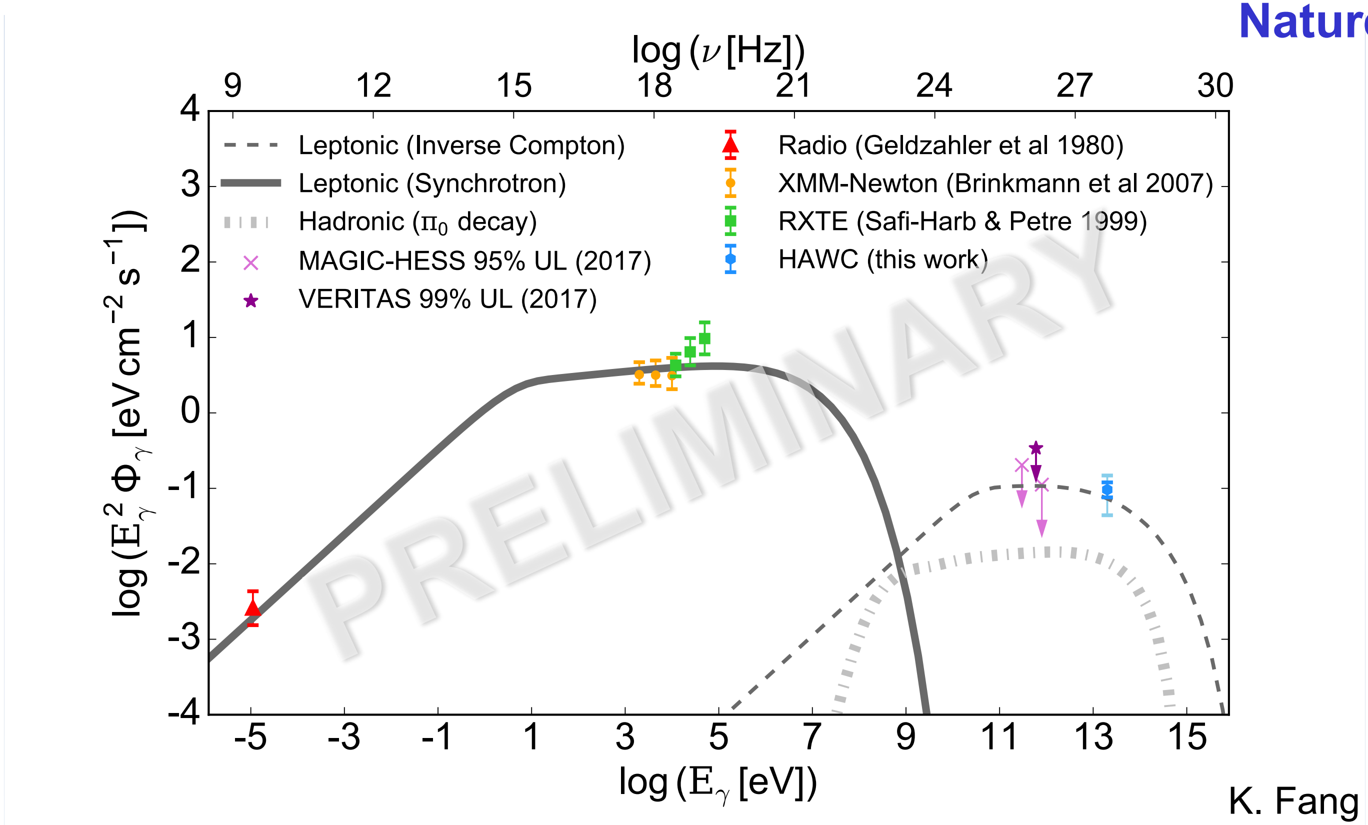


Microquasars as gamma-ray sources: SS433 Lobes

- SS 433 is a Galactic micro-quasar observed in radio-X-rays.
- SS433 is a binary system formed by a Supergiant 30 solar masses star and a compact object, either a neutron star or a black hole
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula and produce western and eastern X-ray lobes
- SS433 jet : 10^{39-40} erg/s
- SS433 jet speed roughly c/4
- Baryon loaded
- Particle acceleration is believed to occur at the lobes where strong radiation is expected to be emitted at GeV and TeV energies

Origin of the emission (e1)

Nature, HAWC Coll 2018



- IC scattering off CMB photons, scattering off optical and infrared suppressed electron acceleration
- Electrons of at least 130 TeV required in a magnetic field of 16microGauss
- Hadronic emission assumes 10% conversion of jet energy into protons and 0.05 cm-3 density

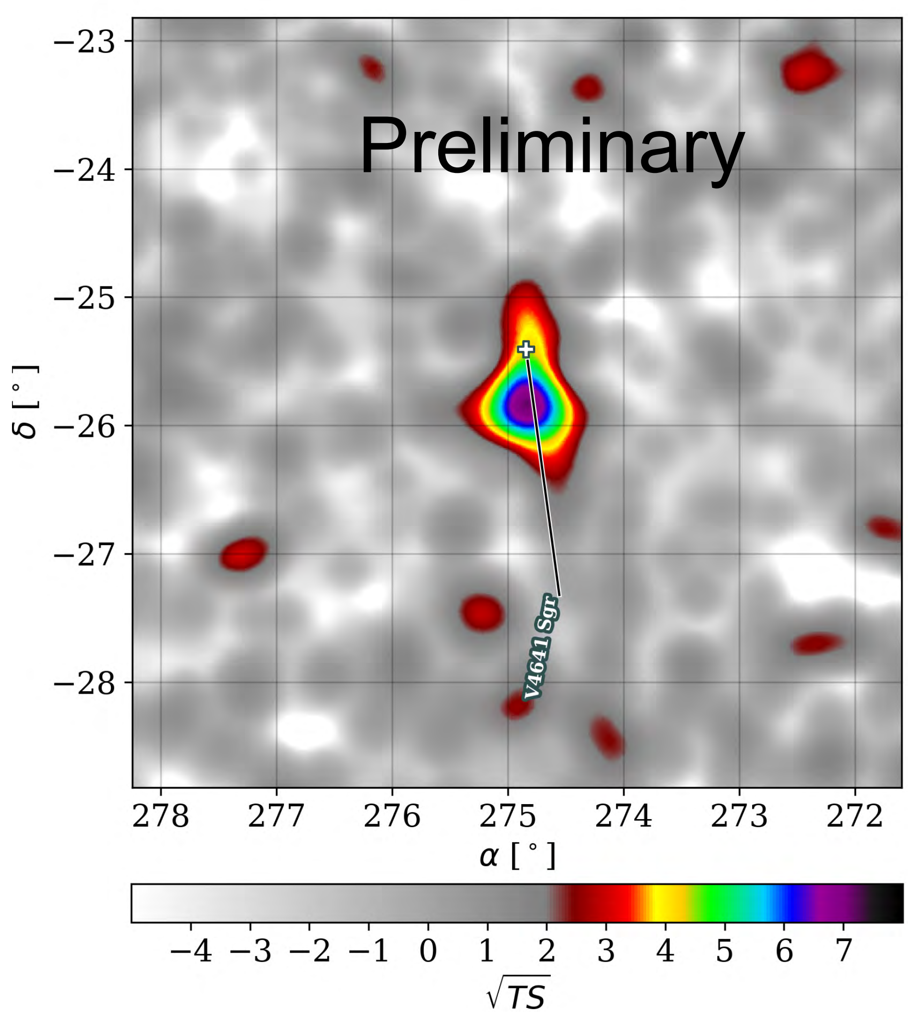
The closest known microquasar : V4641 Sagitarii

Newly discovered Tea micro- quasar
One of the fastest superluminal jets in the Milky Way galaxy
– Implies jet point toward us – but radio jet is very small

9.7σ in Pass 5 Median E~25 TeV
High zenith angle for HAWC

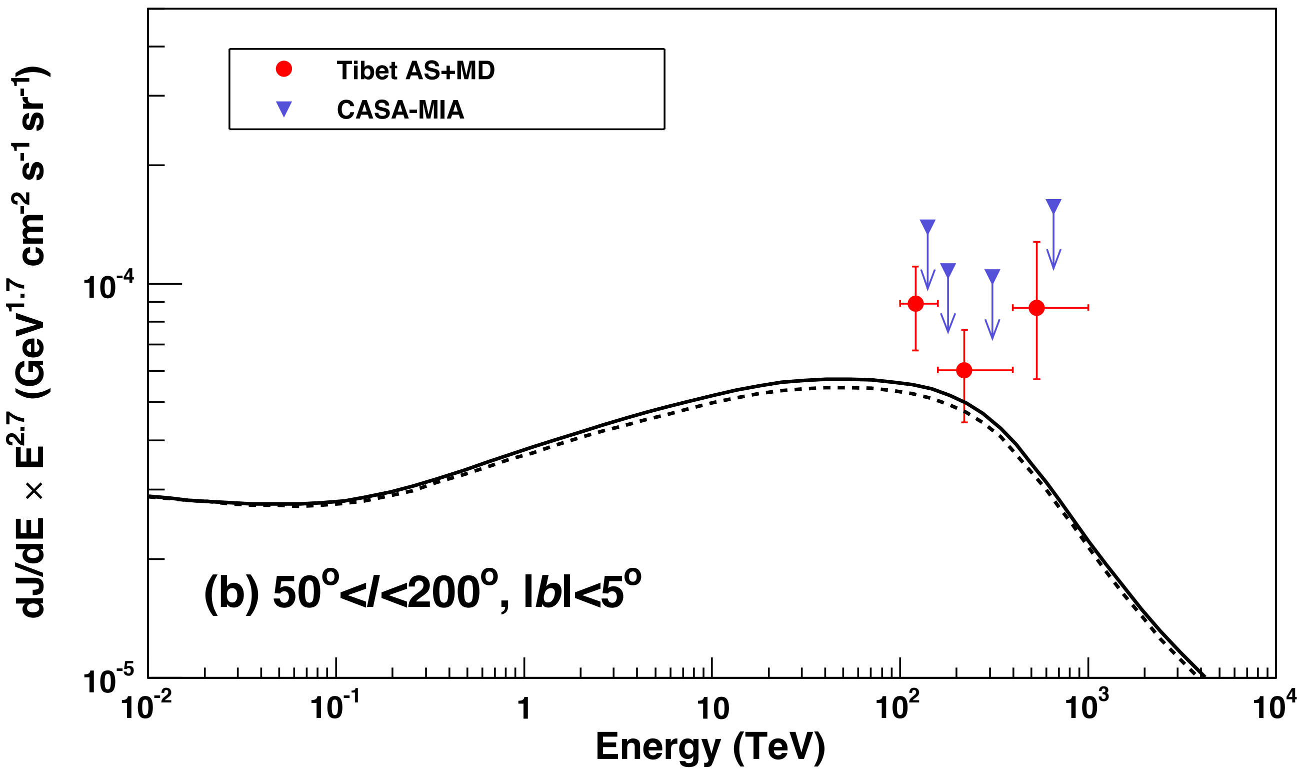
– 45o off zenith
– Extent appears <0.25o

Highest energy measured 180 TeV



Diffuse γ-rays at hundred TeVs

Amenomori+21, Tibet AS



- The fractional source contribution to the diffuse component is estimated to be 13%.
- All events above 398 TeV observed more than 0.5 deg apart from known sources. PeV electrons cannot easily explain such emission
- Above 398 TeV 4 out of 10 events are detected within 4◦ from the centre of the Cygnus cocoon If these 4 events are simply excluded, the observed flux at the highest energy agrees with the model prediction.

Conclusions and outlook

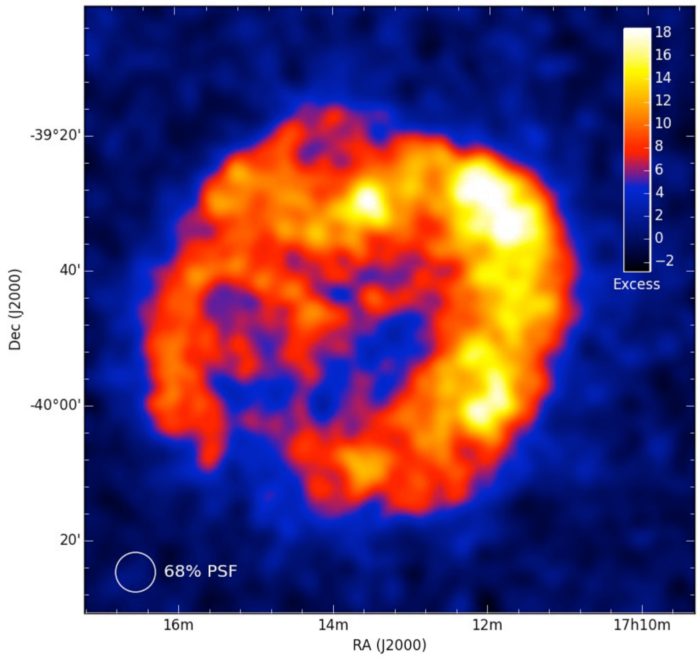
- Both target analysis and discoveries in blind survey searches brought recently new insights in the search for the Galactic PeVatrons
- We have **not yet** pinned down the origin of PeV particles but we now know that the Galaxy is rich in multi-TeV up to PeV gamma-ray sources
- Both hadronic and leptonic mechanisms possible in most cases
- Gamma-ray sources such as microquasars might be suffering from absorption
- Neutrino observatories have the potential to pin down the most extreme Galactic accelerators. The flux of the brightest gamma-ray sources known is close to the minimum detectable flux by Km3Net but it seems that there are some possibilities.

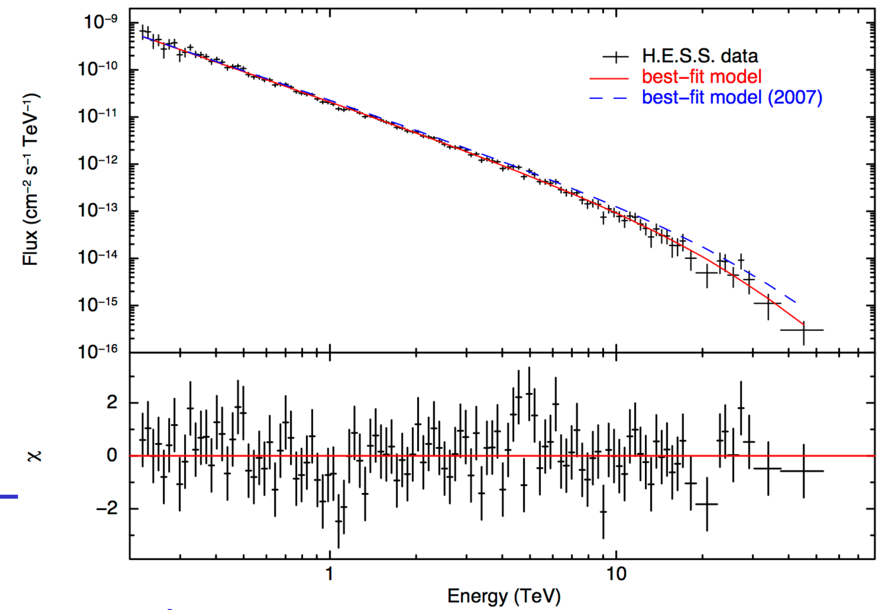
First Suspects : Young SNRs

Theoretically: efficient CR acceleration mechanism

Energetically: energy budget – 10^{51} erg – to sustain the Gal CR population

RXJ1713-3946
HESS Collaboration+16





Young (~1.5 kyr) and nearby (~1 kpc) SNR

First, and brightest resolved TeV shell

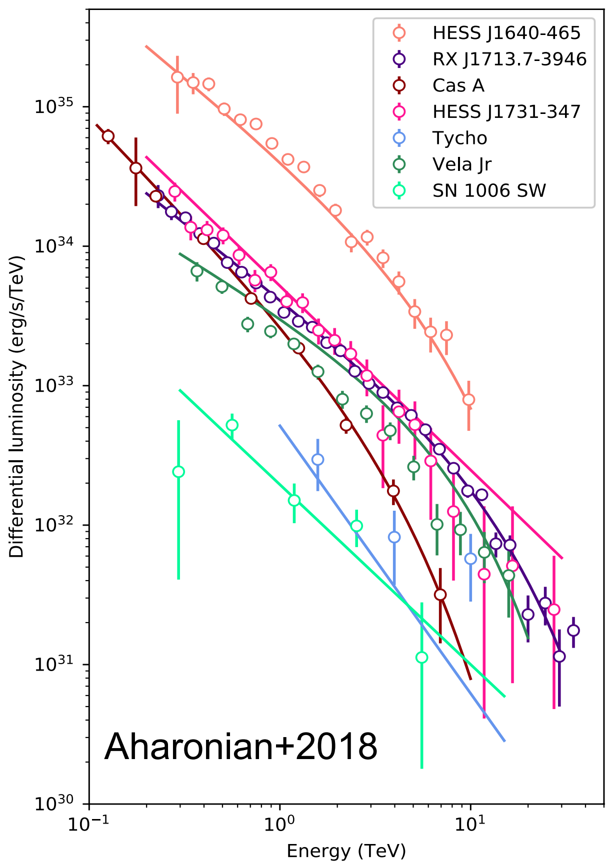
10 years of H.E.S.S. data. (> 27 000 γ's)

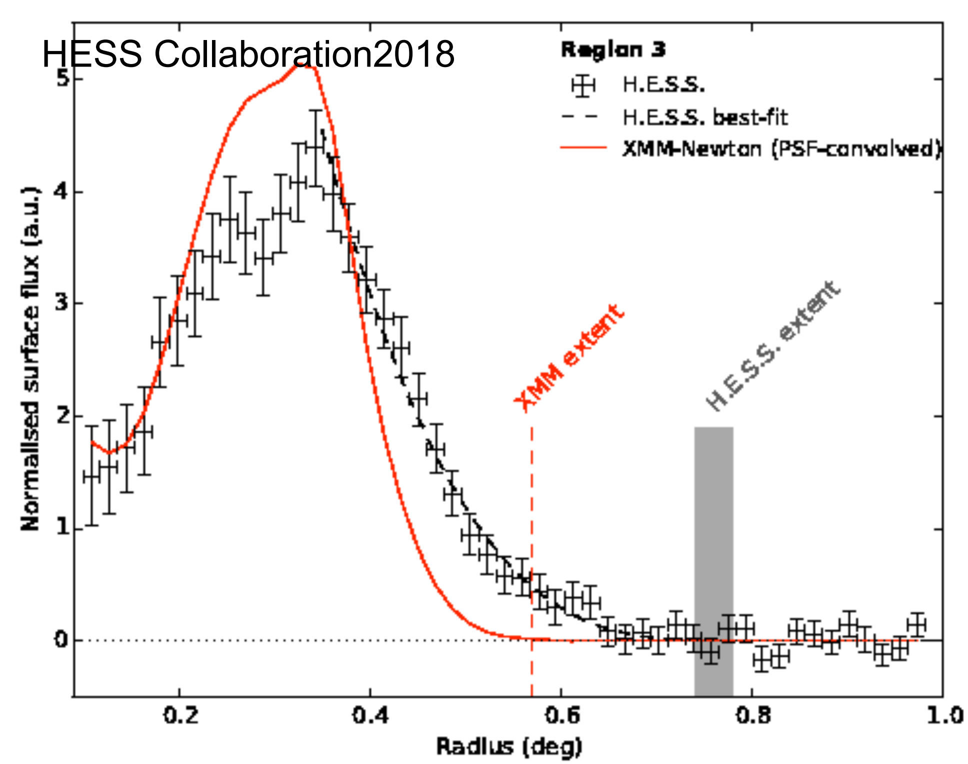
Spectrum up to ~50 TeV: cuts off ~ 12 TeV

Spectra of young SNRs

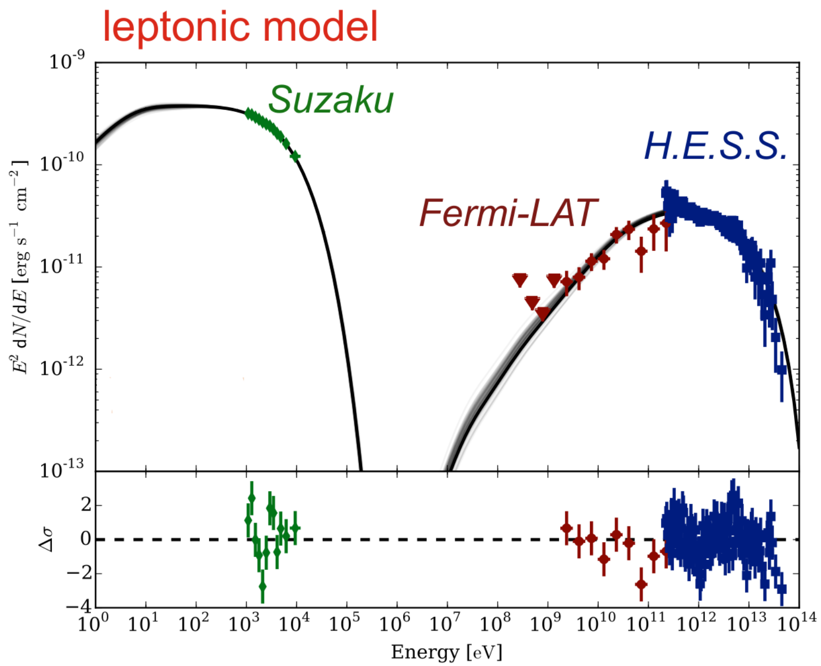
- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee

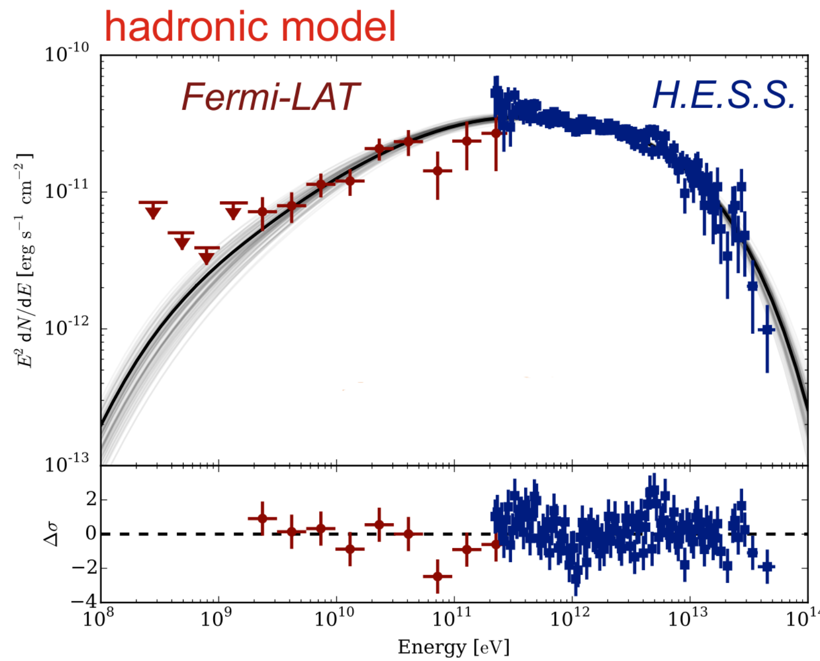
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs

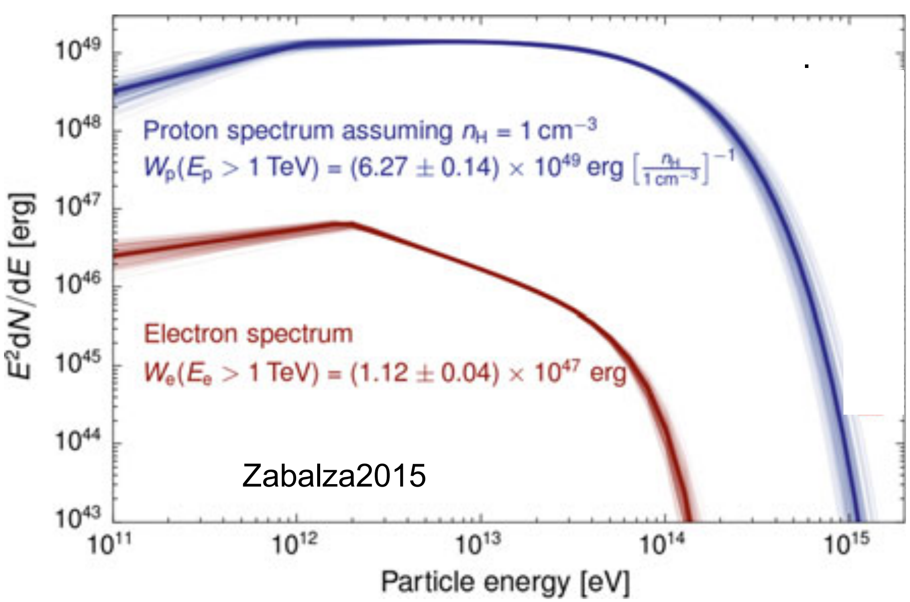




Hadronic or leptonic ?







Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons in unknown because of the uncertainty in the estimate of the gas density and of the B-field

Neutrino flux from γ fluxes

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \nu_\mu/\nu_e \simeq 2$$

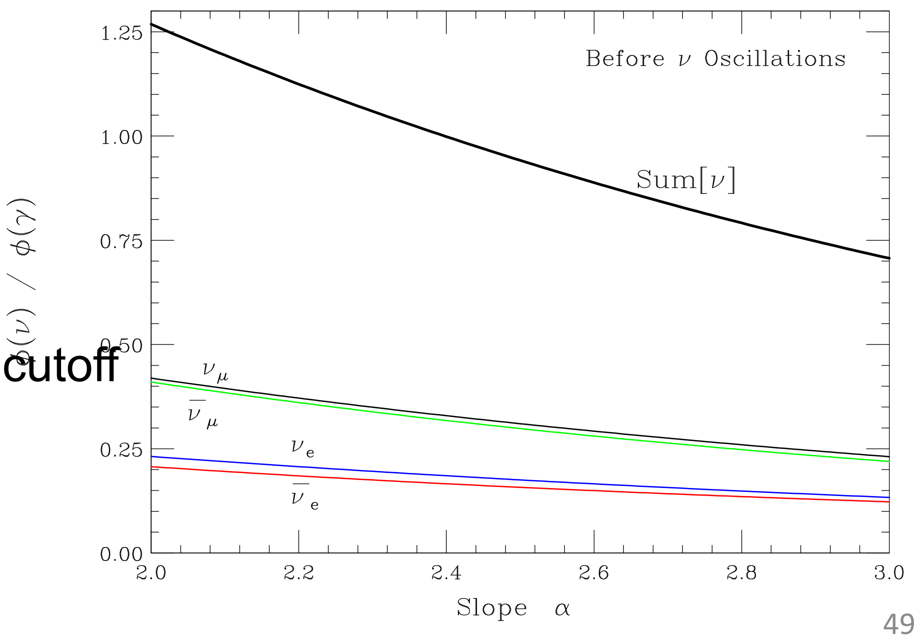
$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

$$\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} = \{1, 1, 1\}$$

A flux of roughly 10^-11 can be detected-dangerously close to the brightest gamma-ray sources known
Some gam ray sources might suffer internal and external absorption
Best range 10-100 TeV

Lipari 2006



Feynman scaling for inclusive
φcr ≃ Kcr E−α -> φnu ≃ Knu E−α
if interaction energy independent
If CR cutoff -> gradual steepening for E > 0.01 Ecutoff
Flux roughly the same
Cutoff energy about 0.5 Cutoff energy in gamma

Neutrino flux from γ fluxes

Kappes+2007

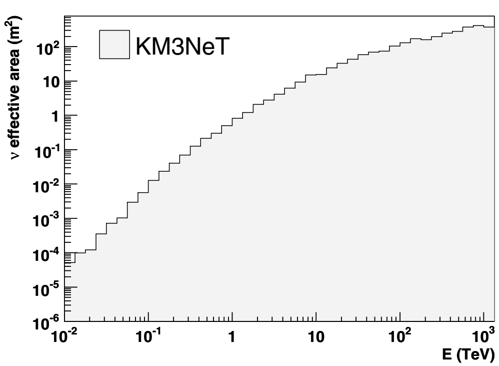
$$\frac{\mathrm{d}N_p}{\mathrm{d}E_p} = k_p \left(\frac{E_p}{1\,\mathrm{TeV}}\right)^{-\alpha} \exp\left(-\frac{E_p}{\epsilon_p}\right)$$

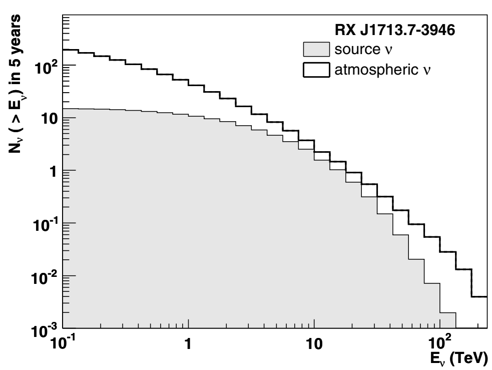
$$\frac{\mathrm{d}N_{\gamma/\nu}}{\mathrm{d}E_{\gamma/\nu}} \approx k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,\mathrm{TeV}}\right)^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

$k_\nu \approx (0.71 - 0.16\alpha)\, k_\gamma$

$\Gamma_\nu \approx \Gamma_\gamma \approx \quad \alpha - 0.1$

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} = \int \mathrm{d}E_\nu \, A_\nu^{\mathrm{eff}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}$$





	Type	Dia. (°)	$E_\nu > 1$ TeV Source	Bkg	$E_\nu > 5$ TeV Source	Bkg
	PWN	0.8	9 − 23	23	5 − 15	4.6
−4622	SNR	2.0	7 − 15	104	1.9 − 6.5	21
−3946	SNR	1.3	7 − 14	41	2.6 − 6.7	8.2
5−137	PWN	0.5	5 − 10	9.3	2.2 − 5.2	1.8
a	PWN	< 0.1	4.0 − 7.6	2.0	1.1 − 7.2	1.1
3−631	NCP	0.3	0.8 − 2.3	11	0.1 − 0.5	2.1
IFC) †	Binary	0.1	0.3 − 0.7	2.5	0.1 − 0.3	0.5

ν sensitivity and γ sensitivity

Ambrogi,Celli, Aharonian2018