Neutrinos from galactic sources

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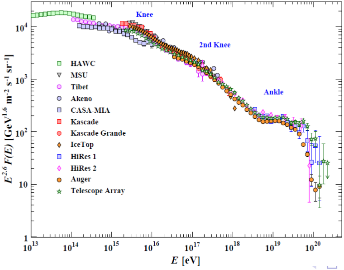
based on
P. Cristofari, VN, S. Gabici, arXiv:2105.12494 [astro-ph.HE], VN, arXiv:2012.02599 [astro-ph.HE]
VN, A. Neronov, L. Fusco, S. Gabici, D. Semikoz, arXiv:1910.09065 [astro-ph.HE]
see also F. Halzen, A. Kheirandish, VN, arXiv:1609.03072 [astro-ph.HE]
M.C. Gonzalez-Garcia, F. Halzen, VN, arXiv:1310.7194 [astro-ph.HE]

MSCA
Marie Skłodowska-Curie Actions

Cosmic-rays

- Cosmic-rays discovered in 1912 by Victor Hess
- The observed energy spectrum of *cosmic-rays* is described by a power law with spectral index of about 2.7 up to energies of a few PeV, where the spectrum gets steeper and a feature called the "knee" originates.
- The knee is believed to mark the maximum energy for cosmic-rays accelerated by *Galactic sources*, or the energy above which the effectiveness of the confinement within the Galaxy is reduced. *A.M. Hillas, J.Phys.Conf.Ser. 47 (2006) 168-177*



Cosmic-rays and neutrinos

- *Neutrinos* are particles that rarely interact with matter and do not feel the magnetic field
  $\Rightarrow$ they can carry information on the physics of acceleration of particles and on the most energetic and distant phenomena in the Universe

- Neutrinos can permit to discriminate unambiguously between *leptonic* and *hadronic* scenarios
  $\Rightarrow$ They are "smoking gun" signature of cosmic-rays accelerators

Calculation of neutrinos expected at KM3 detectors from specific *galactic* sources:

$\Rightarrow$ Milagro sources at IceCube *M.C. Gonzalez-Garcia, F. Halzen, V. Niro, arXiv:1310.7194 [astro-ph.HE]; F. Halzen, A. Kheirandish, VN, arXiv:1609.03072 [astro-ph.HE]*

$\Rightarrow$ Neutrinos from RX J1713.7-3946, Vela Junior, Milagro sources, Fermi Bubble

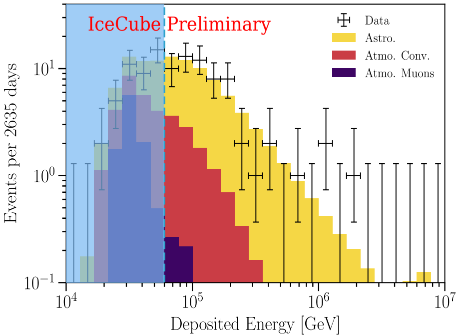
F. Vissani, F. Aharonian, arXiv: 1112.3911 [astro-ph.HE], F. Vissani, F. Aharonian, N. Sahakyan, arXiv: 1101.4842 [astro-ph.HE]

$\Rightarrow$ Neutrinos from eHWC J1825-134 source

VN, A. Neronov, L. Fusco, S. Gabici, D. Semikoz, arXiv:1910.09065 [astro-ph.HE]

Diffuse flux at IceCube

From the data collected in 7.5 years of running of the IceCube detector, 60 events were identified with deposited energy $E_{dep} > 60$ TeV.

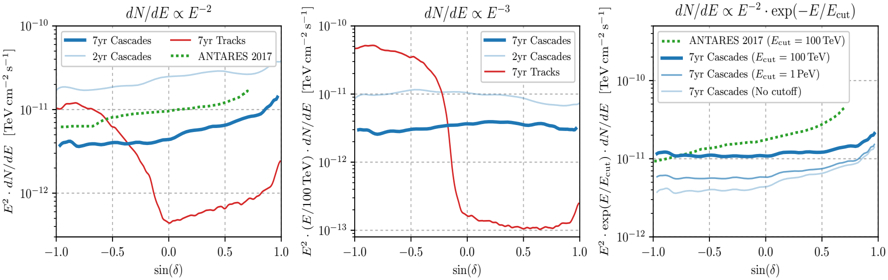


A. Schneider, arXiv:1907.11266 [astro-ph.HE], PoS-ICRC2019-1004

Moreover, a 3.5σ evidence is present for neutrino emission coming from the direction of the blazar TXS 0506+056

M. G. Aartsen et al., arXiv:1807.08794 [astro-ph.HE], Science 361 (2018) 6398

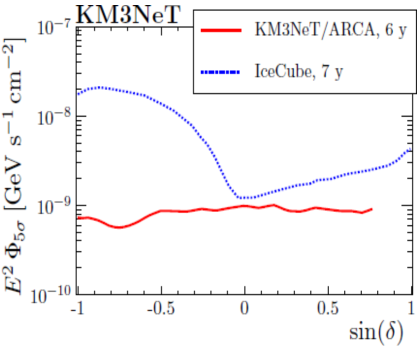
IceCube sensitivity to point-sources



M. G. Aartsen et al., arXiv:1907.06714 [astro-ph.HE]

The IceCube detector has an optimal sensitivity for sources located in the northern hemisphere, and is less sensitive to sources located in the southern sky, using tracks events.

KM3NeT sensitivity to point sources



5σ discovery potential for KM3NeT/ARCA for point-like sources with an E^{-2} spectrum and for 6 years of data-taking (red line).

The KM3NeT Collaboration, arXiv:1810.08499 [astro-ph.HE]

A multi-messenger approach

- A multi-messenger search is mandatory for the identification of the origin of cosmic neutrinos.
- Gamma-ray data are necessary to make correct estimations of neutrino fluxes from point-sources.
- The characteristic gamma-ray feature of a PeVatron include an hadronic, hard spectrum that extends until at least several tens of TeV.

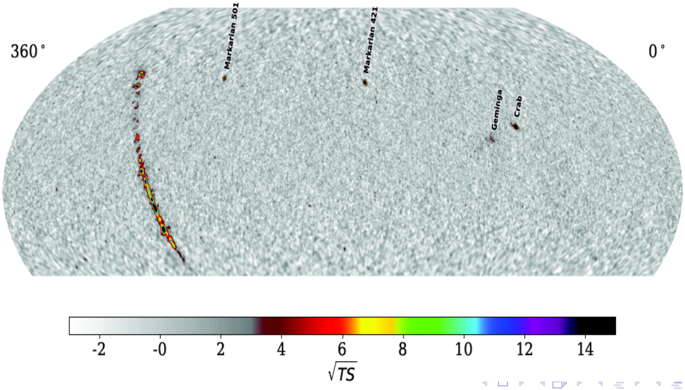
  $\Rightarrow$ a gamma-ray experiment with sensitivity to make detections up to about 100 TeV is of fundamental importance.

HAWC results

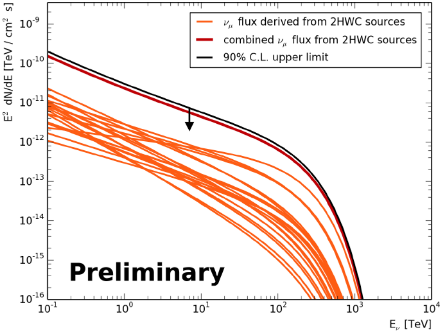
2HWC catalogue: first catalog of TeV gamma-ray sources realized with the High Altitude Water Cherenkov Observatory.

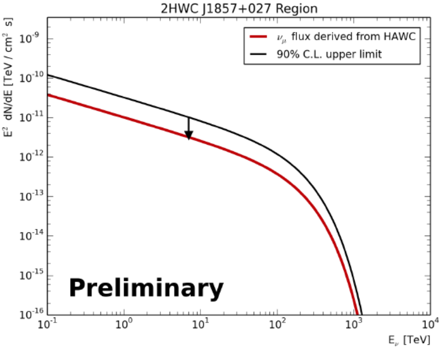
⇒ 39 very high energy gamma-ray sources identified. The fit has done using a power-law spectrum and considering two hypotheses: a point-source case and a uniform disk of fixed radius.

A.U. Abeysekara et al., arXiv:1702.02992v1 [astro-ph.HE]



IceCube and HAWC analysis

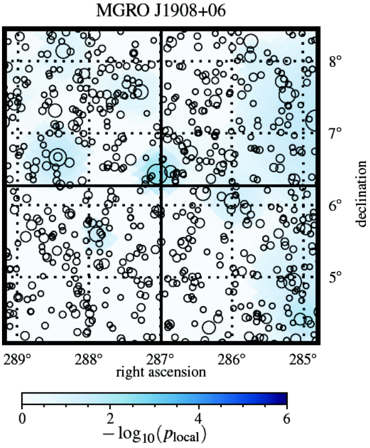




Left: Upper limit on the flux of high-energy muon neutrinos for the stacking search of non-PWN sources in the 2HWC catalogue (black line). Expected flux from each source (orange lines) and combined flux (red line).
Right: Upper limits on the flux of high-energy muon neutrinos (black line) and expected flux (red line), p-value $= 0.02$ *A. Kheirandish, J. Wood, arXiv:1908.08546 [astro-ph.HE]*

Search for point-like sources with 8 yrs of IceCube data

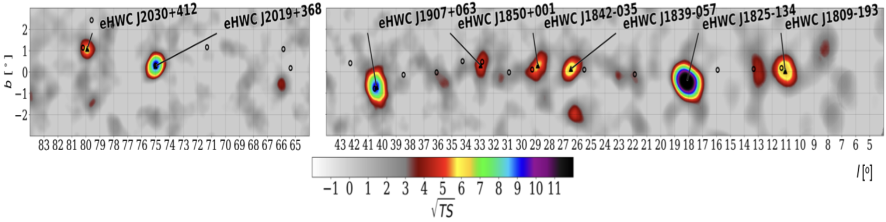
MGRO J1908+06 ⇒ 2HWC J1908+063



Local p-value landscapes around the source position of MGRO J1908+06, p-value $= 0.0088$ *M. Aartsen et al., arXiv:1811.07979 [astro-ph.HE]*

eHWC sources

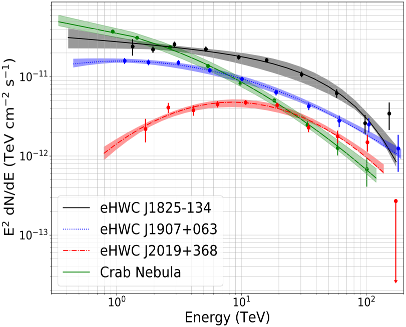
eHWC catalogue: gamma-ray sources emitting above 56 and 100 TeV with data from the HAWC Observatory



A. U.Abeysekara et al., arXiv:1909.08609 [astro-ph.HE]

Nine sources are observed above 56 TeV, all of which are likely Galactic in origin

eHWC sources



A. U.Abeysekara et al., arXiv:1909.08609 [astro-ph.HE]

eHWC J1825-134 source ⇒ Amongst the HAWC sources, it is the most luminous in the multi-TeV domain and therefore is one of the first that should be searched for with a neutrino telescope in the northern hemisphere

eHWC J1825-134 source

We will use for the analysis the spectrum reported in the eHWC catalogue, where a power-law with exponential cut-off fit was considered:

$$\frac{dN_\gamma}{dE_\gamma} = \phi_0 \left(\frac{E_\gamma}{10\ \mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\frac{E_\gamma}{E_{cut,\gamma}}\right),$$

with $E_{cut,\gamma}$ being the cut-off energy of the gamma-ray spectrum, α_γ the spectral index and ϕ_0 the flux normalization:

$$E_{cut,\gamma} = (61 \pm 12)\ \mathrm{TeV}, \qquad \phi_0 = (2.12 \pm 0.15) \times 10^{-13}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1},$$

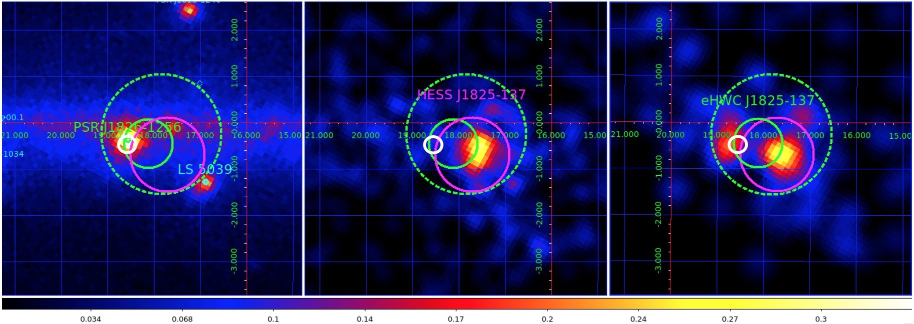
$$\alpha_\gamma = 2.12 \pm 0.06, \qquad \sigma_{\mathrm{ext}} = 0.53^\circ \pm 0.02^\circ,$$

where σ_{ext} is the extension of the source.

⇒ The sensitivity of HAWC to the high energy tail of the spectrum is of fundamental importance for the correct prediction of the neutrino flux.

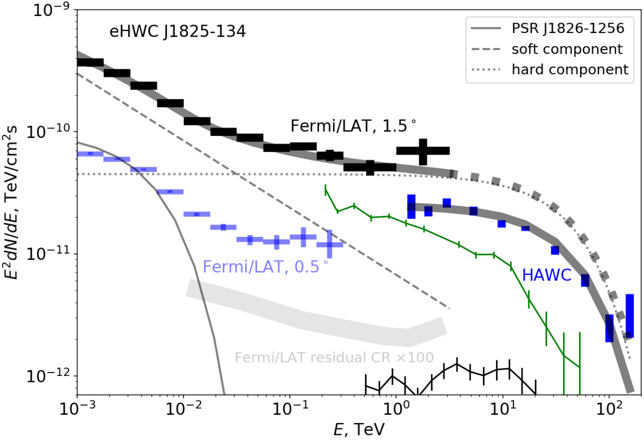
⇒ The eHWC J1825-134 overlaps with two HESS sources: the very bright HESS J1825-137 and the much weaker HESS J1826-130.

Fermi/LAT data



Fermi/LAT countmaps of the source region in 1-10, 100-300 and $>$ 300 GeV energy ranges (left to right). The 1-10 GeV and 100-300 GeV maps are smoothed with 0.3 degree Gaussian, the 300 GeV map is smoothed with 0.5 degree Gaussian.

eHWC J1825-134 region



Spectrum of eHWC J1825-134 region measured by Fermi/LAT compared to the HAWC and HESS spectral measurements.

Neutrino event rate

The event rate at KM3NeT detector can be described by:

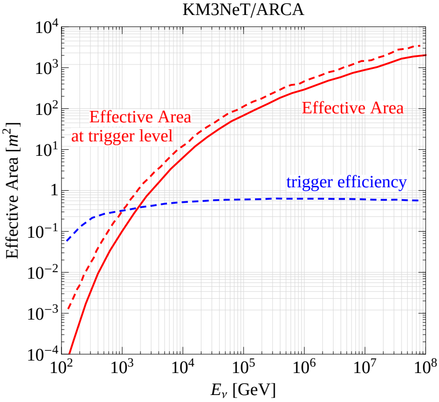
$$N_{\rm ev} = \epsilon_\theta \epsilon_v \, t \int_{E_\nu^{\rm th}} dE_\nu \, \frac{dN_\nu(E_\nu)}{dE_\nu} \times A_\nu^{\rm eff} \, ,$$

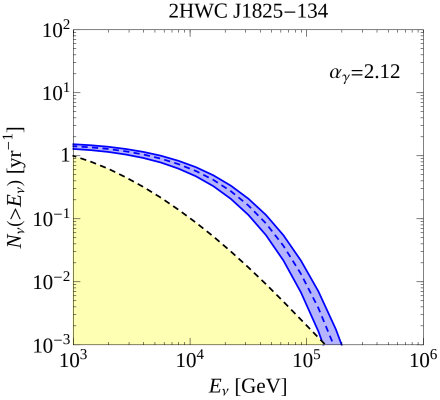
where a sum over neutrino and antineutrino contributions is implicit.

$\epsilon_v = 0.57$: visibility of the source,
$\epsilon_\theta = 0.72$: takes into account a reduction factor due to the fact that only a fraction of the signal will be detected if the source morphology is assumed to be a Gaussian of standard deviation σ_{ext} and the signal is extracted within a circular region of radius $\sigma_{\rm eff} = 1.6\sqrt{\sigma_{\rm ext}^2 + \sigma_{\rm res}^2}$.

$\sigma_{\rm res} \sim 0.1^\circ$: angular resolution of KM3NeT/ARCA.

Effective area and source eHWC J1825-134





Left: Effective area used in the analysis (red solid line), effective area at trigger level (red dashed line), and trigger efficiency (blue dashed); *Right:* number of events expected for the atmospheric background (yellow area) and for the source for the best-fit value of α_γ and different values of $E_{cut,\gamma}$.

Statistical significance

For the statistical significance of discovery, we use the total number of expected signal and bkg events and we compute the bkg-only p-value:

ATL-PHYS-PUB-2011-011, CMS-NOTE-2011-005

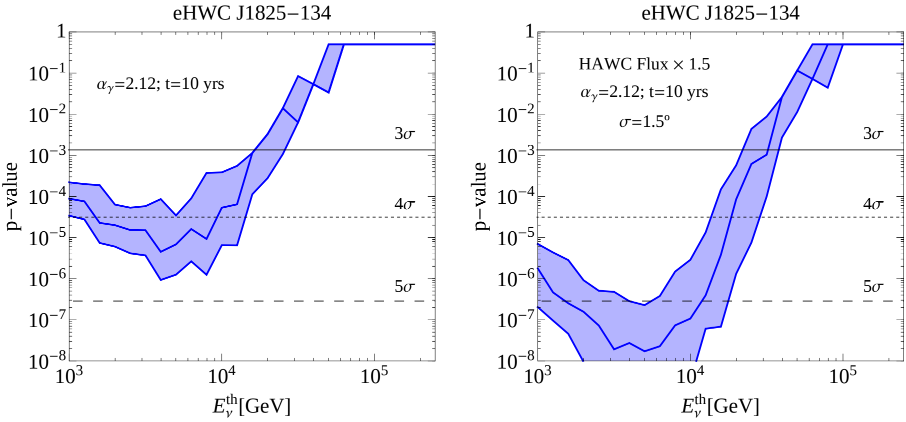
$$p_{\mathrm{value}} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{q_0^{obs}/2}\right)\right] \, ,$$

where q_0^{obs} is defined as

$$q_0^{obs} \equiv -2\ln \mathcal{L}_{b,D} = 2\left(Y_b - N_D + N_D \ln\left(\frac{N_D}{Y_b}\right)\right) \, ,$$

with N_D the estimated experimental data –generated as the median of a large sample of event numbers that are Poisson distributed around the expectation of signal plus bkg– and Y_b the theoretical expectation for the bkg.

eHWC J1825-134 source and extended region

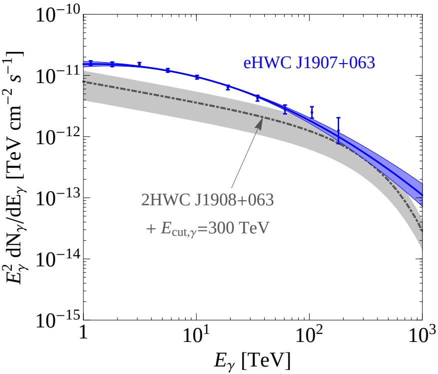


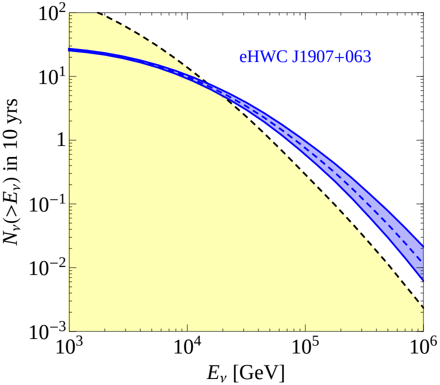
p-value for the best-fit value of α_γ and different values of $E_{cut,\gamma}$ for 10 years of running of the KM3NeT detector.

eHWC J1825-134 source and extended region

- About a 4 to 5σ detection has to be expected after ten years of observations, depending on the details of the considered scenario.
- The BAIKAL-GVD detector in the Baikal Lake will have the discovery potential similar to the KM3NeT detector.
- The cascade channels represent the most promising way to discover eHWC J1825-134 at the IceCube detector.
- Combined analysis of different KM3 detectors data could improve the sensitivity to this source.

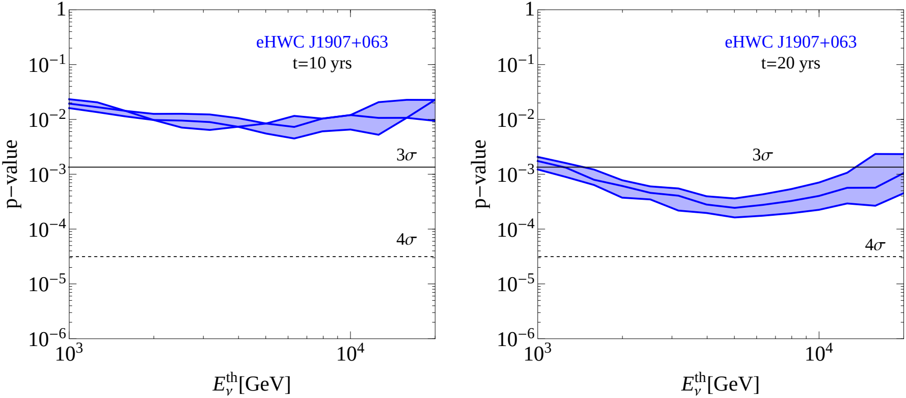
eHWC J1907+063





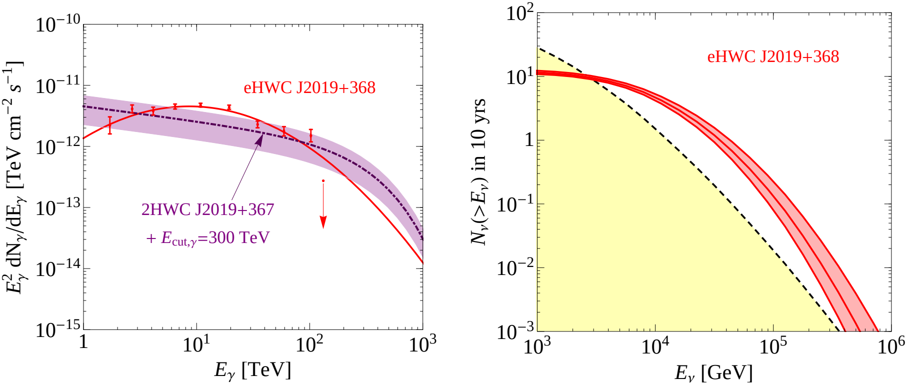
Left: Gamma-ray flux as reported in the eHWC (log parabola fit) and 2HWC catalogues. *Right:* Events rate expected at the IceCube detector in 10 years running time and atmospheric background (yellow area).

Statistical significance for eHWC J1907+063



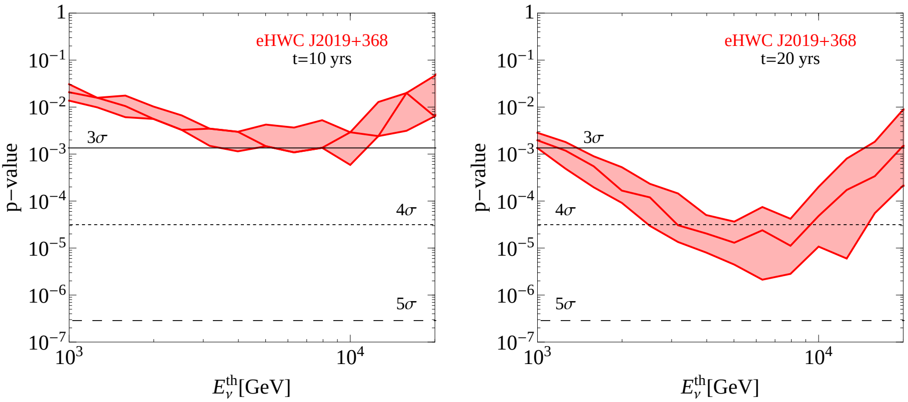
Statistical significance for 10 and 20 years running time for the eHWC J1907+063 source ($\sigma_{ext} = 0.67^\circ$). The IceCube point source analysis uses an unbinned likelihood method, that takes into account the energy distribution of the events with their individual angular uncertainties.

eHWC J2019+368



Left: Gamma-ray flux as reported in the eHWC (log parabola fit) and 2HWC catalogues. *Right:* Events rate expected at the IceCube detector in 10 years running time and atmospheric background (yellow area).

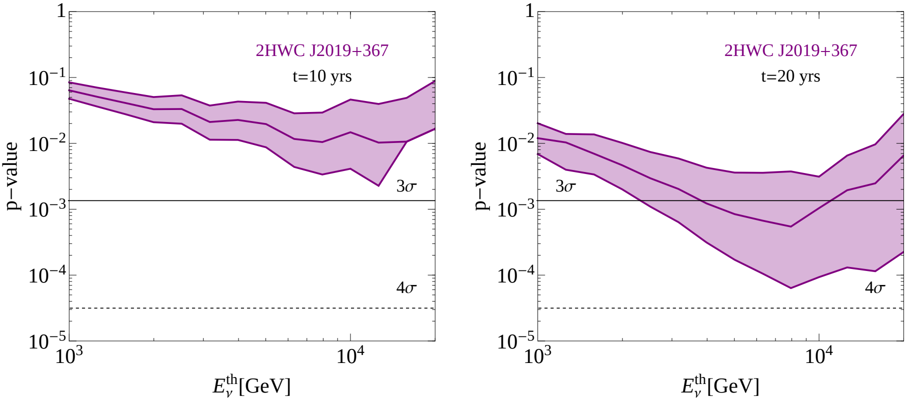
Statistical significance for eHWC J2019+368



Statistical significance for 10 and 20 years running time for the eHWC J2019+368 source ($\sigma_{ext} = 0.30^\circ$).

Statistical significance for 2HWC J2019+367

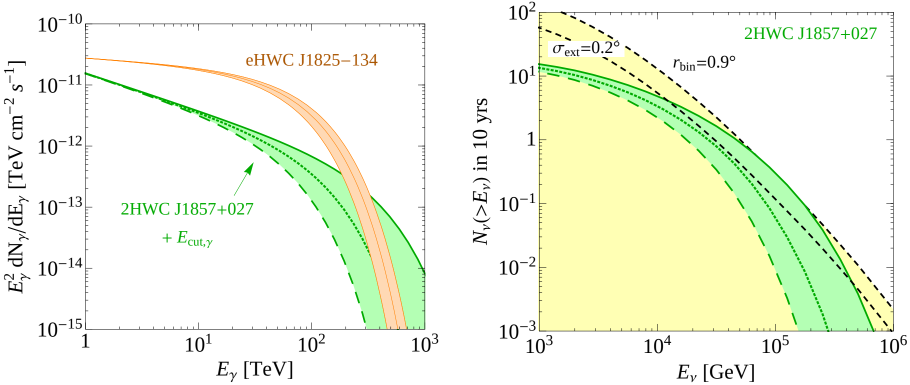
The 2HWC J2019+367 source belongs to the Cygnus region, that is a region of about 5°, where five 2HWC sources can be found.



Statistical significance for 10 and 20 years running time for the 2HWC J2019+367 source ($r_{bin} = 0.7^\circ$). The purple band: $E_{cut,\gamma} = 100,\ 150,\ 300$ TeV.

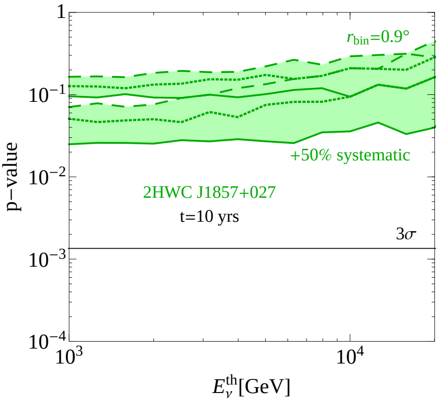
2HWC J1857+027

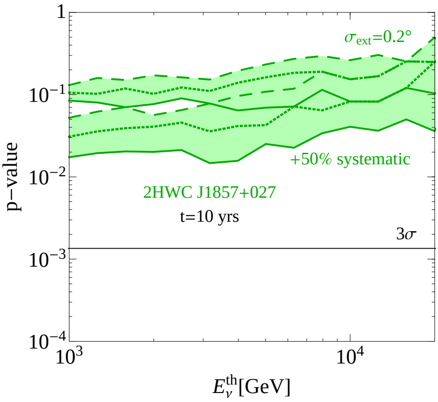
2HWC J1857+027 does not belong to the eHWC catalogue ⇒ emission above 56 TeV should be fainter than the emission from the sources in the eHWC catalogue.



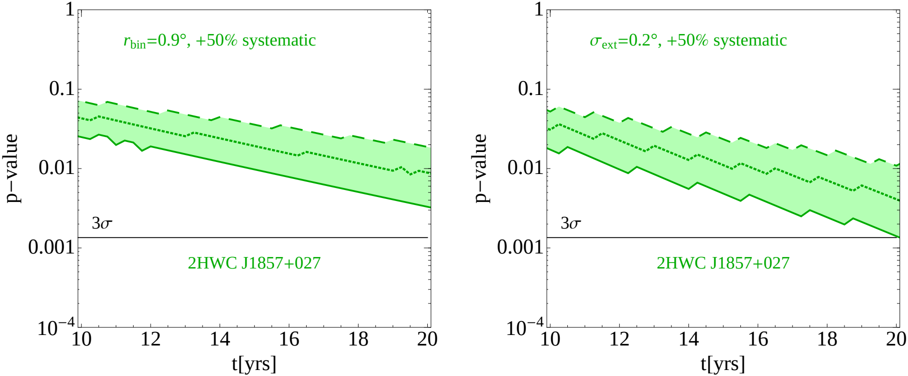
Left: Gamma-ray flux for $E_{cut,\gamma}$=50, 100, 300 TeV (green band).
Right: Events rate expected at the IceCube detector in 10 years running time and atmospheric background (yellow area).

2HWC J1857+027



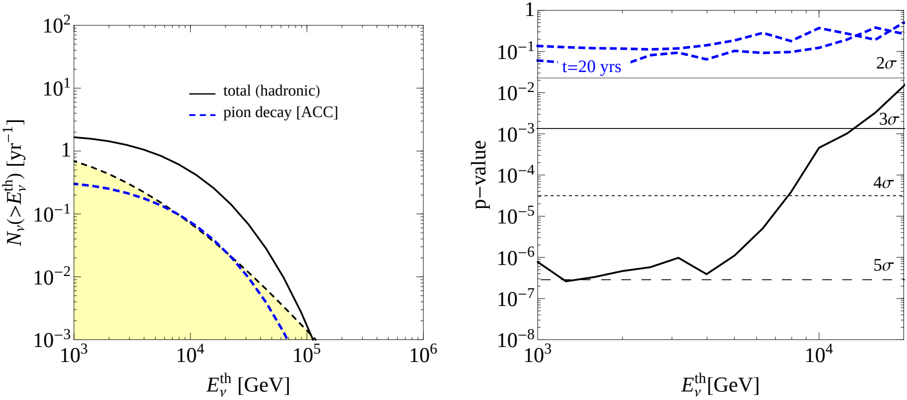


Statistical significance for 2HWC J1857+027



Dependence of the statistical significance on the running time for the 2HWC J1857+027 source ($r_{bin} = 0.9^\circ$) and for a gaussian morphology with $\sigma_{ext} = 0.2^\circ$.

Neutrinos from RX J1713.7-3946



Neutrinos and p-value from RX J1713.7-3946 at KM3NeT detector.

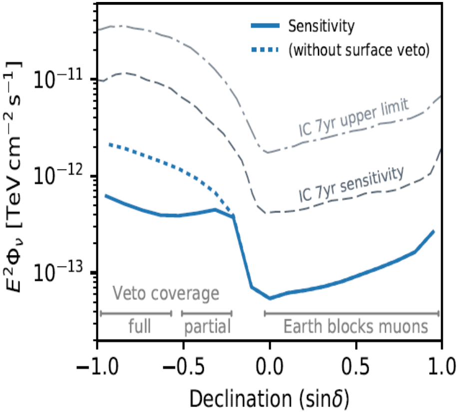
Conclusions

- A detection at 3σ or more at the IceCube detector for eHWC J1907+063 and eHWC J2019+368 expected within the next decade
- For 2HWC J2019+367 region, a detection at about 3σ for a neutrino energy threshold of 10 TeV
- The detection at about 3σ of 2HWC J1857+027 will depend on the specific value of the flux, on the extension and on the cut-off energy.
- Visibility of these sources at KM3NeT, ϵ_v= 0.47, 0.31, 0.49 for eHWC J1907+063, eHWC J2019+368, 2HWC J1857+027, respectively; at Baikal-GVD detector: ϵ_v = 0.46, 0.13; 0.48
- IceCube Gen2 with an effective area of about five times bigger than IceCube could improve the sensitivity to these sources dramatically

$\Rightarrow$ synergy between data from gamma-ray experiments and from neutrino telescopes

BACK-UP slides

Sensitivity to point sources: E^{-2} spectrum



IceCube-Gen2: the next-generation neutrino observatory for the South Pole, PoS(ICRC2017)991

Integrated sensitivity for an E^{-2} spectrum after 15 years of IceCube operation followed by 15 years of IceCube-Gen2.

Flux of neutrinos from gamma rays

Contribution from *pions*, *kaons* and *muons decay:*

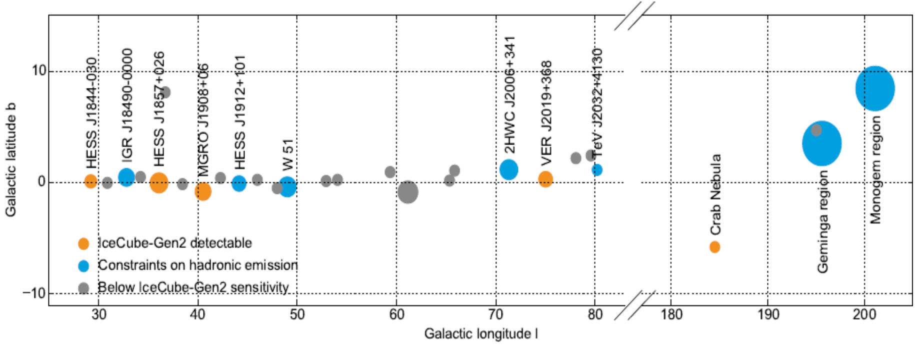
$$\phi_{\nu_\mu}[E] = 0.380\ \phi_\gamma[E/(1-r_\pi)] + 0.0130\ \phi_\gamma[E/(1-r_k)] + \int_0^1 \frac{dx}{x} k_{\nu_\mu}[x]\phi_\gamma[E/x]$$

$$\phi_{\bar\nu_\mu}[E] = 0.278\ \phi_\gamma[E/(1-r_\pi)] + 0.0090\ \phi_\gamma[E/(1-r_k)] + \int_0^1 \frac{dx}{x} k_{\bar\nu_\mu}[x]\phi_\gamma[E/x]$$

$$\begin{aligned}
k_{\nu_\mu}[x] &= x^2(15.34 - 28.93\ x) \quad x \le r_k = 0.0458 \\
&= 0.0165 + 0.1193\ x + 3.747\ x^2 - 3.981\ x^3 \quad r_k < x < r_\pi \\
&= (1-x)^2\ (-0.6698 + 6.588\ x) \quad x \ge r_\pi = 0.573 \\
k_{\bar\nu_\mu}[x] &= x^2(15.34 - 28.93\ x) \quad x \le r_k \\
&= 0.0251 + 0.0826\ x + 3.697\ x^2 - 3.548\ x^3 \quad r_k < x < r_\pi \\
&= (1-x)^2\ (0.0351 + 5.864\ x) \quad x \ge r_\pi = 0.573
\end{aligned}$$

F.L. Villante, F. Vissani, arXiv:0807.4151 [astro-ph]

IceCube-Gen2 sensitivity



M. Aartsen et al., arXiv: 2008.04323

Sensitivity of IceCube-Gen2 to hadronic emission of neutrinos by Galactic sources. Orange: sources that will be detected by IceCube-Gen2; Blue: the hadronic emission contribution can be constrained at the 90% C.L; gray: sources below the sensitivity of IceCube-Gen2.