H.E.S.S. realtime follow-ups of IceCube high-energy neutrino alerts Federica Bradascio IJCLab — Université Paris-Saclay

Journée SFP 2025: Astroparticules et synergies multi-messagers LPNHE — March 20, 2025

Multimessenger astronomy

MULTIMESSENGER SOURCE

COSMIC RAYS

Charged particles, deflected by magnetic fields

@J.A. Aguilar & J. Yang

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GRAVITATIONAL WAVES

GAMMA RAYS

Point to their sources, but can be absorbed and created by multiple emission mechanisms

air shower

Earth

NEUTRINOS

Weak, neutral particles, point to their sources, Not deflected, not absorbed

Astrophysical neutrino telescopes



How to search for neutrino sources?





How to search for neutrino sources?

ATMOSPHERIC BACKGROUND * O(10⁵) v yr⁻¹

Muon neutrino events using **9.5yr** of IceCube data





ATMOSPHERIC BACKGROUND O(10⁵) v yr⁻¹

Muon neutrino events using 9.5yr of IceCube data



Follow-up of astrophysical neutrino events Realtime alert system

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Alert of single high-energy muon track events with high probability of being astrophysical $(E \gtrsim 100 \text{ TeV})$ distributed to ground and space-based observatories for rapid follow-ups

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H.E.S.S.

Array of 5 Imaging Atmospheric Cherenkov Telescopes to detect VHE gamma rays from ~30 GeV to 100 TeV

H.E.S.S. Target of Opportunity (ToO) program Fully automatised neutrino ToO alert system since 2012

- ~20 hours/year of deep observations of few (~5/yr) candidates
 - Extension of observations for potential signal or interesting MWL info
- Rapid response time
 - Automatic re-pointing for immediate observations of P_{astro} > 50% events if conditions permit (e.g., dark night, favorable weather)
 - Observations typically occur within a few days if immediate conditions are not met

H.E.S.S. Target of Opportunity (ToO) program Fully automatised neutrino ToO alert system since 2012

Alert IC-211208A

Blazar PKS0735+178 in flaring state in radio, X-ray, optical and γ -ray at ~2.0° from v best-fit position

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Neutrino event (171 TeV) detected on Dec 8, 2021 with $P_{astro} = 50.2\%$

PKS 0735+178 MWL observations

H.E.S.S. observations for ~16h (3.8h of data) from Dec 8 to Dec 15

Lepto-hadronic model marginally consistent with v event

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Summary

- Realtime and MWL searches complement clustering methods in identifying neutrino sources
- H.E.S.S. actively involved in neutrino follow-up programs since 2012
 - Observations of flaring blazar PKS 0735+178 in spatial and temporal coincidence with IC-211208A
- Follow-up of KM3NeT neutrinos will provide a unique view of the Southern Sky, optimally covered by H.E.S.S.
- Expertise gained will contribute to CTAO

Backup

Why astronomy with neutrinos? Neutrinos are smocking gun signature of hadronic processes

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Why astronomy with neutrinos? To observe the extragalactic universe beyond PeV energies

Neutrino detection principle

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15 m

High-energy gamma-rays **Detection principle**

H.E.S.S. (2002) Khomas Highland, Namibia

Single neutrino public alert stream Neutrino alerts with 50% and 30% probability of being astrophysical

Goal: find electromagnetic counterpart to the neutrino event

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Gamma-ray Follow-Up (GFU) private stream

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Neutrino multiplets (*flares*) from pre-defined source list: 339 sources from 3LAC/3FHL and TeVCAT

[T. Kintscher, PhD thesis, 2020, doi:10.18452/21948]

Goal: determine changes in the source state

H.E.S.S. Target of Opportunity (ToO) program Pointing strategy: All IC error region often covered thanks to large FoV

RIGHT ASCENSION

Searches over entire Region of Interest (neutrino error) without prior source candidates

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RIGHT ASCENSION

Searches focused on source(s) if candidates (e.g. GFU alerts)

This talk: alerts received in 2021-2024

TXS 0506+056IceCube v event IC-170922A (290 TeV) observed in coincidence with flaring gamma-ray blazar

Chance correlation can be rejected at the 3σ -level

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[IceCube, PoS (ICRC2019) 1021; Science 361(2018)6398]

TXS 0506+056

Multi-wavelength observations

[IceCube++, Science 361 (2018) 6398] Photon SED can be modeled by lept

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Photon SED can be modeled by lepton-hadronic or proton-synchrotron models

PKS 0735+178 multiwavelength observations

Modelling of the SED to reproduce the neutrino detection

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PKS 0735+178 multiwavelength observations

First attempt at modelling the SED using only leptonic model (SSC)

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PKS 0735+178 multiwavelength observations

Leptonic model (SSC) alone cannot reproduce SED!

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PKS 0735+178 multiwavelength observations

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PKS 0735+178 multiwavelength observations

GFU PKS 0625-35

H.E.S.S. detection of blazar PKS 0625-35 (3.5o) during IceCube neutrino flare but no flux variation observed

[FB for H.E.S.S. & IceCube, PoS(ICRC2023)1546]

GFU PKS 0829+046

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Flare of 8 neutrinos with $E_{max} = 2$ TeV for ~8 days (3.03 σ pre-trial)

H.E.S.S. observed on Dec 30th, 2021 for 2 nights (~4.7h) \Rightarrow ULs in [0.22, 100] TeV

Gold neutrino event detected on Apr 25, 2022 with $P_{astro} = 17\%$

• H.E.S.S. observations triggered automatically in less than 70 seconds

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IC-220425A

IC-220425A

- H.E.S.S. observations triggered automatically in less than 70 seconds
 - Updated neutrino position outside FOV
- ~75 minutes moonlight observations
- No detection, ULs between 0.37 and 100 TeV

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Gold neutrino event detected on Apr 25, 2022 with $P_{astro} = 17\%$

GFU 1ES0229+200

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Flare of 4 neutrinos with $E_{max} = 1.3$ TeV for ~1.2 days (3.09 σ pre-trial)

H.E.S.S. observed on Aug 27th, 2022 for 5 nights (~8h) \Rightarrow no variation in MWL SED

IC-211125A

- Potentially associated to 2 sources:
 - Nova AT2021 afpi detected by MASTER
 - AGN Fermi-LAT 4FGL J0258.1+2030
- H.E.S.S. observations between both sources for 4 nights
- Total of ~5 hours data
- No significant excess in the FoV on both sources

Bronze neutrino event detected on Nov 25, 2021 with $P_{astro} = 39\%$

IC-211125A

Contemporaneous MWL observations on 4FGL J0258.1+2030

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Source detected only in X-ray, ULs in γ -ray (95% C.L. assuming E^{-2} spectrum)

IceCube neutrino alert follow-ups Some numbers...

- 275 alerts since 2011
 - 16 followed-up by HESS since 2015
- 5 GFU alerts followed-up
- 3 publications (TXS 0506+056, PKS) 0735+17, Joint IACTs follow-ups in internal reviews), ~6 conference proceedings

IceCube cumulative number of alerts as a function of time

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Neutrino event signature

Tracks

 $\nu_{\mu} + N \rightarrow \mu + X$

Good angular resolution 0.1-1 deg Neutrino astronomy

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Cascades

 $\nu_X + N \rightarrow \nu_X + X, \ \nu_e + N \rightarrow e + X$ Fully active calorimeter **Good energy resolution ~15%**

Neutrino event signature

Tracks

 $\nu_{\mu} + N \rightarrow \mu + X$

Good angular resolution 0.1-1 deg Neutrino astronomy

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H.E.S.S. realtime follow-ups of IceCube high-energy neutrino alerts — Journée SFP 2025

Cascades

 $\nu_X + N \to \nu_X + X, \quad \nu_e + N \to e + X$

Fully active calorimeter Good energy resolution ~15%

The atmospheric background

