

cherenkov telescope array

The multi-wavelength and multimessenger context II

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with thanks to Marcos Santander



ICTP-SAIFR Advanced School 2023







- The Neutrino Gamma connection
- A primer on neutrino astronomy
- Overview of recent results
- The MM context of neutrinos

CTA coordination activities

The neutrino gamma connection



Connecting the puzzle



Gamma-rays are the cornerstone of multi-messenger astrophysics

© adapted from a slide by Johannes Knapp

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All messengers are connected and relate back to the same sources: logic behind the multi-messenger astrophysics



Anatomy of a relativistic astrophysical source











Towards the first MM SED

MWL/MM spectral energy distribution of **TXS 0506+056**

(IceCube, Fermi-LAT, MAGIC et al. **Science 2018)**





Connecting the puzzle



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Neutrino limit A - πproduction in CR interactions suggest potential links between neutrino and TeV-PeV gamma-ray sources. V

Neutrino limit B - If neutrino fluxes are related to UHECR, UHE neutrino limits could be higher, from large "cosmic-ray reservoirs"

Cosmogenic neutrinos -

Attenuation of CRs by the CMB (GZK cut-off) supress CRs above EeV and if detected would impose important constraints on UHECR physics.











Neutrinos: probe of deeper horizon, denser environments







A primer on neutrino astronomy



The MM context of neutrinos

Neutrinos interact via weak interaction (rare, hard to detect). The basic reactions are:

- $\circ n \longrightarrow p^+ + e^- + v_e$ typically in nuclear reactors where neutron-rich fragments from Uranium fission stabilize by neutron decay
- $\circ p^+ \longrightarrow n + e^+ + v_e$ typically for Solar Neutrinos where 4 protons fuse to produce ⁴He (2p, 2n), i.e. 2 p converted into 2 n
- $\circ p^+ + e^- > n + v_e$ typically in Supernovae, where protons and electrons fuse to produce neutrons.

But VHE (IceCube) neutrinos (also the case of accelerator neutrinos) originate in decay process from mesons produced in hadronic interactions:

•
$$\pi^+ \longrightarrow \mu^+ + \nu_{\mu}$$
 or $\pi^- \longrightarrow \mu^- + \nu_{\mu}$ from pion decay.

 $\circ \mu^+ \longrightarrow e^- + \nu_{\mu} + \nu_e$ or $\mu^- \longrightarrow e^- + \nu_e + \nu_{\mu}$ from muon decay.





Astrophysics with TeV neutrinos



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The technique is based on the use of km³ volumes of water or ice to detect neutrino interaction signals

Effective area : despite gigantic volumes of detectors, effective areas are low due to difficulty of detection (between 10-100 m^2 in the range 10-100 TeV)

Cf. Gamma-ray detectors : In space (Fermi-LAT) effective areas are relatively low, 1 m² @ 100 GeV, but fluxes are high; whereas in ground-based observatories effective areas reach 10⁵ m² in the TeV range (and compensate for the lower fluxes).

In principle, efective areas are sufficient to detect several events from a "1 Crab" TeV source, if emission is hadronic... (but beware of heavily absorbed sources, e.g. in binaries where intrinsic luminosities could be up to 100x brighter).













km³detectors

Antares & KM3Net: in the Mediterranean Sea (1999 -) Amanda & IceCube: in the South Pole (1995 -) 2010 - 1 km³! Currently in activity

> 1 km³ 5200 sensors, ~2 km deep in the ice Astrophysical VHE neutrinos are detected after traversing the Earth (E $\approx 10^{11}$ – 10^{15} eV)

How to distinguish signal astrophysical / background shower atmospheric neutrinos? Down vs. up-going

At energies $> 10^{15}$ eV astrophysical neutrinos dominate the flux...





The next Generation



Baikal GVD

Km3-detector with 10,000 sensors. In construction, Siberia, Lake Baikal

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km3-detector with 4,000 sensors 0.1° angular resolution (better than ice)

Approaching 10 km3 in volume > 5x sensitivity improvement

0.2° angular resolution

Deployment ongoing

















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Neutrinos create charged particles in interactions, which then produce the Cherenkov radiation detected.

Muon-tracks

better type of event for astronomy, with good localization ($< 1^{\circ}$) most common type of event, thanks to the long trajectories which cross the detector.

results from electron and tau neutrino interactions

Event has poor localization but good energy resolution and lower



IceCube Point source sensitivity









Phenomenology: Neutrinos

In 2013, IceCube detected the first set of 28 excess high-energy neutrinos of clear astrophysical (non-atmospheric) origin.





In 2017, first evidence (tentative) of a correlated photon-v emission from a blazar: **TXS 0506+056** (IceCube Coll. Science 2018)

o month-long gamma-ray high-state with 2 UHE neutrinos in coincidence at 3σ level o 3.5σ neutrino high-state in 2014-2015, with no electromagnetic counterparts o TXS 0506+056 is a blazar sequence outlier (Padovani+2019)





The neutrino sky

Arrival directions of most energetic neutrino events



ASTRO 2020 - High-energy Cosmic Neutrinos - Science White Paper

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TXS 0506+056 Galactic No evidence of clustering in high-energy neutrino direction, pointing towards an extragalactic origin (mostly)

km³-class detectors could in principle detect neutrino fluxes from TeV sources _{-180°} with flux superior to 1 Crab (2x10⁻¹¹ /cm².s) - Crab Nebula, Vela X, + a couple of Supernovae...

Blazars have been considered the potential sources if their gamma-ray flux is from hadronic origin, and potentially attenuated by absorption (intrinsic flux >> observed flux)











Overview of current status



High-energy Astrophysical neutrinos



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IceCube measured the 10 TeV - 10 PeV astrophysical neutrino flux

- Atmospheric origin excluded > 8 sigma
- Flux > 200 TeV follows a power law of index 2.2 2.8

Searches for astrophysical origin

- Astrophysical correlations with individual sub-PeV events
- Astrophysical ID of lower-energy neutrino clusters
- *Preferential use of cascade events







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High-energy Astrophysical neutrinos



The near-isotropic neutrino distribution favors an extragalactic origin



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The population of LAT GeV-emitting blazars is not the astrophysical

counterpart, as derived from limits from stacked signal estimations. Stacked search for neutrino emission from blazars in Fermi AGN catalogs.

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No neutrino emission detected. Upper limits at the level of 6-27% of all-sky flux.



Neutrino point sources?



First 10 years of data, circa 1 million candidate neutrino events, following

multiple tests: clustering, population cross-matching, stacking analysis.

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lottest spot (North



Equatorial

Analysis	Category	Pre-trial signifi- cance (p_{local})	Post-trial significanc
All-Sky	North	3.5×10^{-7}	9.9×10^{-2}
Scan	South	4.3×10^{-6}	0.75
Source List	North	1.8×10^{-5}	2.0×10^{-3}
	South	5.9×10^{-2}	0.55
Catalog	North	3.3×10^{-5}	4.8×10^{-4}
Fogulation	South	0.12	0.36
Stacking	SNR		0.11
Search	PWN	—	1.0
	UNID		0.4

3 \bigcap $-\log_{10}(p_{local})$









Seyfert Galaxy NGC 1068, with heavily obscured nucleus which is Compton thick

for gammaFKay9e This best fit time-integrated astrophysical power-law neutrino flux obtained using the 10 year I cal pre-trial p-value map around the most NGC 1068. The shaded regions represent the 1, 2 & 3σ error regions on the $int_{ullsses}$ have been been been been been been been boost in the pared to the γ and corresponding ν AGN outflow models and the Fermi the coordinates easily galaxy NGG at 0.141 from 3 $0.000 \text{ for a set start in the field set start in the field of the set start in the field of the set start is the set of the set start in the set of t$





We restricted our searcines to the northern Hemisphere from declination $\delta = -3^{\circ}$ to 81° , here IceCube is most sensitive to astrophys-

Current not cosmic muon shield and as a target material for neutrinos. Hence, by selecting only upward-



going events, we reduced the atmospheric muon background, which contributes <0.3% to our final event sample (25). Declinations higher than 81° are excluded because low-energy events from those directions are closely aligned ta with the strings of IceCube, complicating our distinction between the signal and background (26). The resulting loss of sky coverage is <1%.

A total of 670,000 neutrino-induced muon tracks pass the final event selection criteria (25). However, only a small fraction of these events originate from neutrinos produced in astrophysical sources. Most arse from the decay of particles (specifically mesons) that are produced in the interaction of cosmic rays with nuclei in Earth's atmosphere. To discriminate 20 utrinos that originate from individual astrophysical sources from the background of atmospheric and diffuse astrophysical neutrinos, we used a maximum-likelihood method and

40.2 likelihood ratio hypothesis testing, based on the estimated energy, direction, and angular uncertainty of each event (26). The median angular resolution of each neutrino arrival direction, composed of reconstruction uncertainty and

Pretriale A value, the angle betrosttrial A value, neu-(localisignification) is 1(2) obtal significance) 100 TeV, and 0.3° at 1 PeV. We assume any

5. point source emits a neutrino flux Φ_{ν}^{-2} (2.0 θ_{e}^{-2} 1 Scribed (5y2a) generalized powerlaw (4 nergy)

normalization energy $E_0 = 1$ TeV, where E_v is the neutrino energy and the spectral index γ and the flux normalization Φ_{a} are free narame-



Fig. 2. High-resolution scan around the most significant location. (**A**) High-resolution scan around the most significant location marked by a white cross, with contours showing its 68% (solid) and 95% (dashed) confidence regions. The red dot shows the position of NGC 1068, and the red circle is its angular size in the optical wavelength (61). (**B**) The distribution of the squared angular distance, $\hat{\psi}^2$, between NGC 1068 and the reconstructed event directions. We estimated the background (orange) and the signal (blue) from Monte Carlo simulations, assuming the best-fitting spectrum at the position of NGC 1068. The superposition of both components is shown in gray and the data in black. This representation of the result ignores the energy and angular uncertainty of the events.

peated under the same three spectral index tuple of μ_{ns} and γ fully determines the flux of hypotheses as the sky scan. muon neutrinos, $\Phi_{\nu_{\mu}+\bar{\nu}_{\mu}}$, at any given energy. vateromsthærdiærent sex Ses 06506Attanto 6 met Rok Scluding the selection The first search consists of three discrete scans of the hypotheses to be tested, were formuof Omobione Emishes is ign a. lated a priori. The performance of each method location of the most statistically significant was evaluated using simulations and randomexcesses of high-energy neutrino events. These ized experimental data (26). The local P values scans use three different hypotheses for the are determined as the fraction of back about the fracting about the fraction of back about the fractin spectral index: γ as a free parameter, γ fixed to only simulations that yield a test statistic greater than (or equal to) the test statistic obtained 2.0, and γ fixed to 2.5. The other two searches from the experimental data The global P values use a list of 110 preselected astronomical ob-

Beware of opaque EM sources!









potential dark EM origin of the neutrino flux ULISSES BARRES DE ALMEIDA - REPSAHER MARCH 2023 $E_{\nu}^{2}F_{\nu}(E_{\nu})$







Time-dependent searches

R. Abbasi et al. (IceCube) ApJ 911 (2021) 1, 67 arXiv/2012.01079



+ searches from flares from selected source catalogue of AGNs (3σ w/ 4 sources)





The Gamma-MM context of neutrinos





High-energy neutrino counterparts

Relativistic astrophysical sources are natural cosmic-ray accelerators and therefore expected to be multimessenger sources









IceCube 170922A - TXS 0506+056



The 290 TeV neutrino event detected by IceCube coincided with an increased activity of the blazar as recorded by Fermi-LAT and a first follow-up detection by MAGIC in the VHEs (3σ association).

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IceCube et al. 2018





IceCube 170922A - TXS 0506+056



The 290 TeV neutrino event detected by IceCube coincided with an increased activity of the blazar as recorded by Fermi-LAT and a first follow-up detection by MAGIC in the VHEs (3σ association).

Additionally, search through archival data revealed evidence for 13 +/- 5 excess events from the direction of TXS during for months in 2014-15, without counterpart gamma-ray flare





DE PESQUISA DO MCT

IceCube et al. 2018





Leecube 170922A - TXS 0506-656





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IceCube 170922A - TXS 0506+056



IceCube et al. 2018

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IceCube 170922A - TXS 0506+056



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Energetics of the SED

No straightforward theoretical explanation for the photon SED - neutrino association.

- General scenario would be photo-pion production - For v ~ 100 TeV, need $E_p \sim 200E_{14}\delta_1^{-1}$ TeV and $E_{ph} \sim 1.6E_{14}^{-1}\delta_1$ keV (X-rays)



(a) Proton synchrotron modeling of TXS 0506+056





But the model fits to SED either overestimate the X-ray photon component (e.g., Gao et al. 2018) or predict too high neutrino energies (e.g., Cerruti et al. 2018)

Energetics of the SED

No straightforward theoretical explanation for the photon SED - neutrino association.

- General scenario would be photo-pion production
 - For v ~ 100 TeV, need $E_p \sim 200E_{14}\delta_1^{-1}$ TeV and $E_{ph} \sim 1.6E_{14}^{-1}\delta_1$ keV (X-rays)
- But, the model fits to SED either overestimate the X-ray photon component (e.g., Gao et al. 2018) or predict too high neutrino energies (e.g., Cerruti et al. 2018)
- Detailed analysis by Reimer et al 2019 suggested that the 2014-15 neutrino flare and the gamma-ray emission from TXS 0506+056 could not have originated in the same process, from constraints derived on the development of photo-hadronic initiated EM cascades.
- More individual source coincidences are necessary to reinforce the statistical connection and provide further observational elements to guide and constrain theoretical modelling. 40





- IceCube (this work)







A closer look at the neutrino sky

Sky distribution of high-energy IceCube neutrinos P. Giommi et al. 2019

Virtual Observatory Data Tools

avenue – allows for a selection of best candidate counterparts by providing complete SED information on the sources.

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Cross-matching between blazar and neutrino catalogues VO tools, is a promising

Left: In this case showing the error regions and candidate counterparts for the 2016 triplet 1 TeV neutrino event (< 100s)

Right: and the corresponding SED for one of the 3HSP blazar counterpart candidates.

Most promising results in blazarneutrino cross-match

A marginal 2.8 σ excess on the positional coincidence between good localisation neutrinos events and the blazars from the 3HSP

Excess HBL coincidences between neutrino and 3HSP blazars.

Excess for gamma-ray detected HBLs in neutrino positions (1.3x 90% containment region), at the 3.6σ level, = 15 excess HBLs with respect to chance coincidence.

P. Giommi et al. 2019

CTA coordination activities

MM Neutrino Studies with CTA

Extragalactic / transient studies

- <u>Follow-up of sub-PeV astrophysical neutrino events</u>
- <u>Real-time correlation studies with active gamma-ray sources</u>

Galactic Searches

- Focus on hadronic emitters such as SNR, Novae, > 100 TeV
- And searches for correlations in diffuse emission

The Unknown Unknowns

- Dark sources or unidentified sources
- New types of objects like tidal disruptions

Deep astrophysical view of candidate sources

https://github.com/ChrisCFTung/FIRESONG

CTA strategy: Neutrino Target of Opportunity (NToO):

- <u>Transients</u>: CTA search for gamma-ray counterpart from a neutrino alert
- Steady sources: monitor hotspots exceeding IceCube sensitivity

FIRESONG

• Simulate a neutrino population according to source evolution and luminosity function

Density vs. Luminosity plot

- Steady sources: sources/Mpc³ vs. neutrino luminosity
- Transient sources: burst rates/Mpc³ (%flaring blazars) vs. neutrino flare luminosity
- IC-170922A: TXS 0506+056 (z = 0.3365) ullet**IC-190730A:** PKS 1502+106 (z = 1.84) IC-200107A: 3HSP J095507.9+355101 (z = 0.557) \bullet
- **IC-141209A:** GB6 J1040+0617 (z = 0.7351)

https://github.com/ChrisCFTung/FIRESONG

Steady Sources

Standard candles, follow the SFR evolution model of Madau & Dickinson (2014)

Local density $\rho = 10^{-12}$ to 10^{-5} Mpc⁻³ Luminosities: L_v = 5x10⁴⁷ to 10^{57} erg/year

Gamma-ray flux parametrised assuming $\,p\gamma\,$ interactions Ahlers & Halzen (2018)

Sources exceeding the IceCube sensitivity (Aartsen et al., IceCube Collaboration, (2019)) are used as seeds of the NToO for CTA

Assuming all the sources are always observable by CTA

Transient Sources

Standard candles and the flat cosmological evolution

Based on the neutrino flare model of TXS 0506+056 in 2014-2015 Halzen et al., ApJ 874 (2019)

Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

All the sources are assumed to have the same flare duration in their reference frame (110 days @z TXS)

Assuming IC Gold alerts and events always observable by CTA

https://github.com/ChrisCFTung/FIRESONG

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Steady Sources

1		Assuming these sources will be always obse	ervable by CTA:
20		At low-mid zeniths (20°-40°) CTA-N all sources up to p= 10 ⁻⁹ Mpc	detects
400	Probabil	Drastic performance loss, up to 6 at high zeniths (60°)	65% ,
	Detection	Magnetic field effect: 10-30% diff for low to high zeniths	erence
60) ⁰ Dete	For sources with flat redshift evolution trends are similar, but less pronotection probability	tion the unced
	as a	function of source	N Sergije
luminosity and local density			
	of so	ources, for 30 exposure	
	PoS(ICRC2021)975	

https://github.com/ChrisCFTung/FIRESONG

Steady Sources

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Steady Sources

Assuming these sources will be always observable by CTA:

At low-mid zeniths (20°-40°) CTA-N detects all sources up to ρ = 10⁻⁹ Mpc⁻³

Drastic performance loss, up to 65%, at high zeniths (60°)

Magnetic field effect: 10-30% difference for low to high zeniths

For sources with flat redshift evolution the trends are similar, but less pronounced

O. Sergijenko

https://github.com/ChrisCFTung/FIRESONG

CTA 30 mins obs; Flaring blazars

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Transient Sources (Flaring blazars)

Selecting IC Gold alerts (>50 %) and assuming observable conditions by CTA:

n probability grows while **F** decreases (as ted: flux of each flare is increasing)

bability is almost identical for 20° and 40° ifference < 1%), decreases by 4% for 60°

nagnetic field is minimal: <0.5% for CTA-S and up to 2% for CTA-N

Thank you for the attention!

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Zhen Cao

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Results on Fundamental Questions after 30 Years of Ground-Based Observations

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