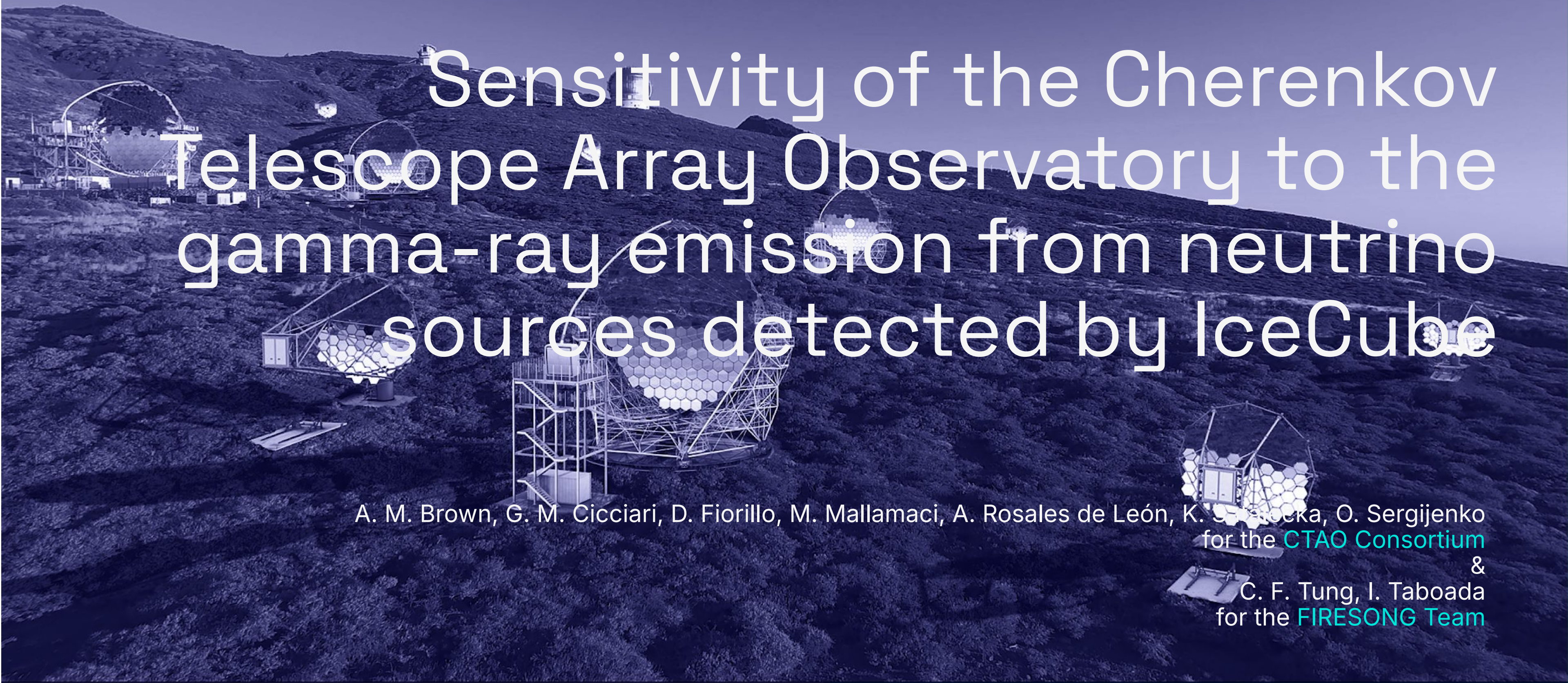


Cherenkov Telescope Array Observatory

# Sensitivity of the Cherenkov Telescope Array Observatory to the gamma-ray emission from neutrino sources detected by IceCube

A. M. Brown, G. M. Cicciari, D. Fiorillo, M. Mallamaci, A. Rosales de León, K. Satalecka, O. Sergijenko
for the CTAO Consortium
&
C. F. Tung, I. Taboada
for the FIRESONG Team

# Cosmic Messenger Connection

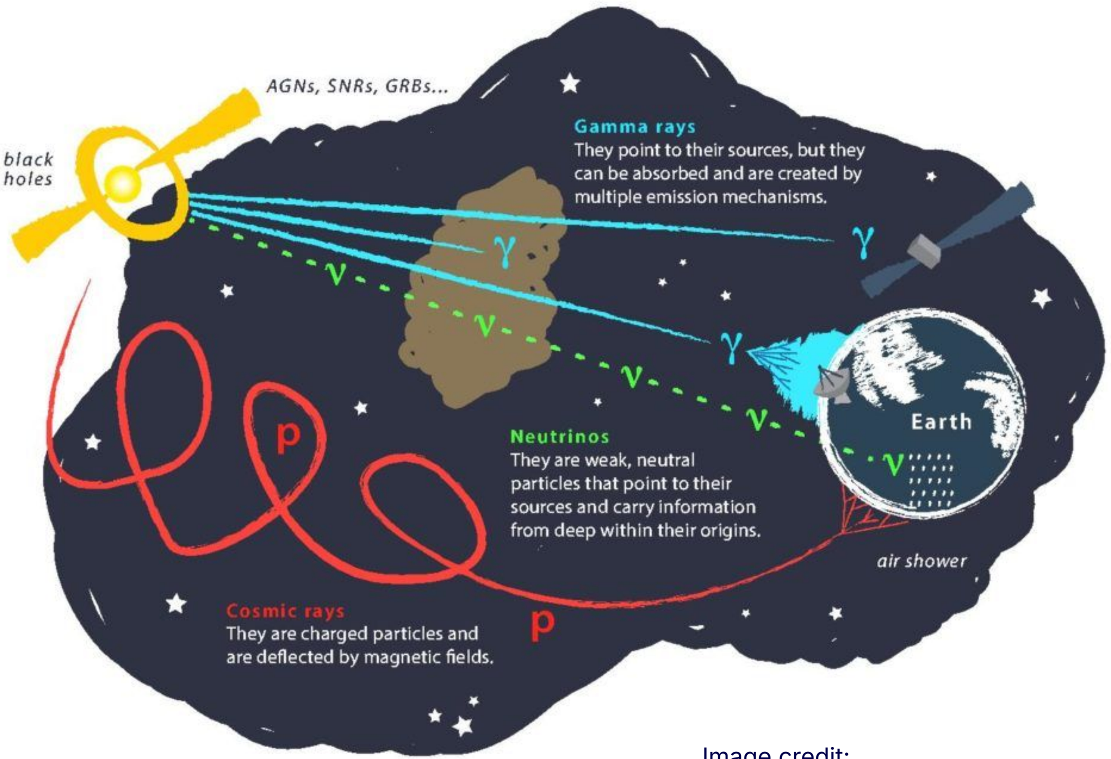
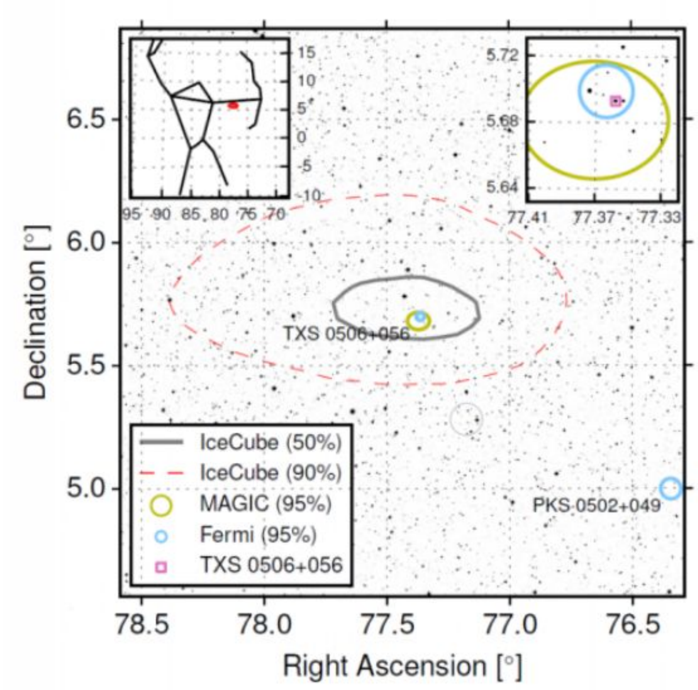



Image credit:
IceCube Collaboration

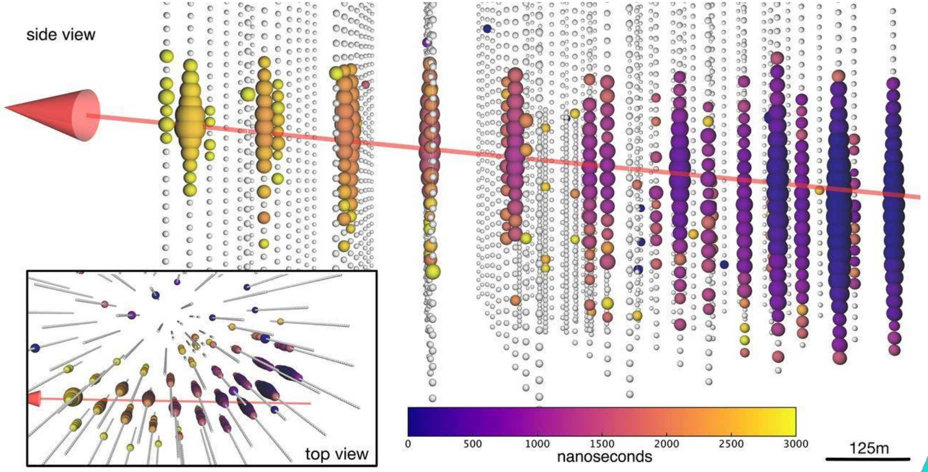
The neutrino/gamma-ray connection is expected if the hadronic processes occur in astrophysical sources (such as AGNs)

Neutrinos are considered to be the perfect cosmic messengers and the ‘smoking gun’ for hadronic interactions

# Motivation:
# IceCube-170922A & TXS 0506+056



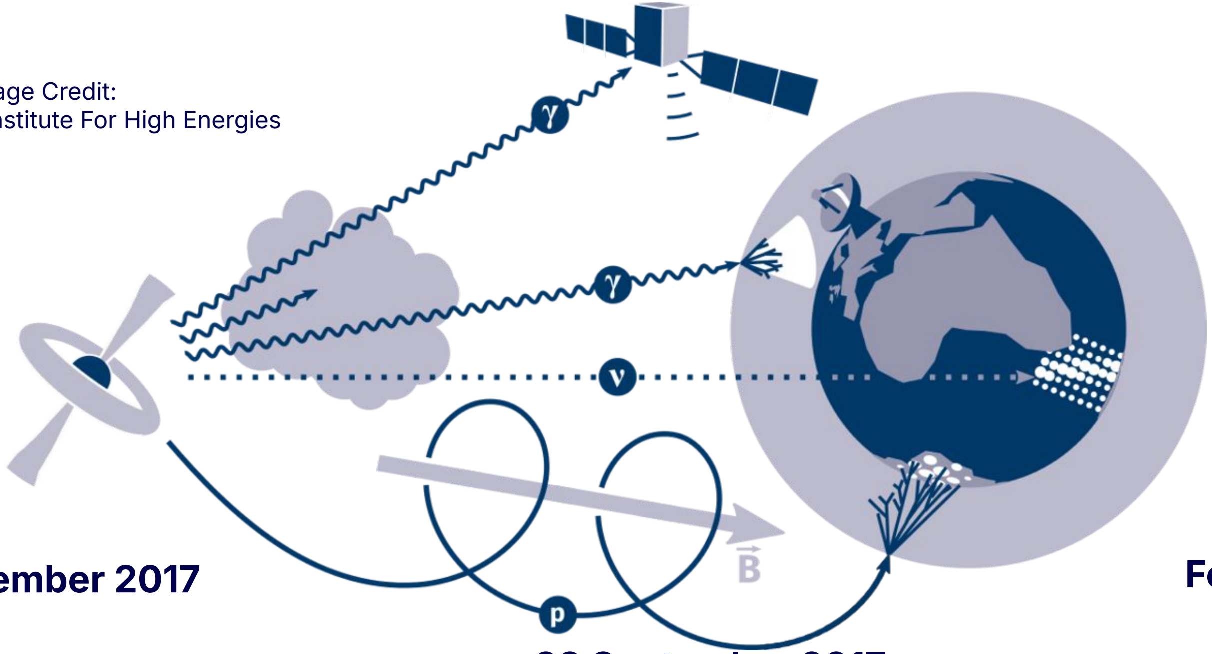

The IceCube Collaboration et al. Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. Science 361, eaat1378 (2018)




In 2017 the IceCube Collaboration detected a muon neutrino event with the reconstructed energy of 290 TeV during a flaring period of the source TXS 0506+056 at the significance level of 3σ

# IceCube-170922A & TXS 0506+056

Image Credit:
Inter-University Institute For High Energies




**Improved IC alert system:**

Gold alerts: 50%
Bronze alerts: 30%
astrophysical origin

Blaufuss et al. (2019)

**22 September 2017**

muon track detected by IceCube.
An alert that was distributed worldwide within 1 min of the detection

**28 September 2017**

Fermi-LAT Collaboration reported the blazar TXS 0506+056, a γ-ray source 0.1° from the neutrino direction, to be in flaring state

**Follow-up Observations:**

23 Sep: H.E.S.S. and VERITAS
24/28 Sep: MAGIC
HAWC, AGILE,
Radio, Optical and X-rays

# Neutrino Target of Opportunity (NToO)

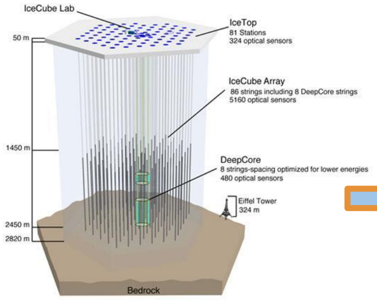
CTAO can look for the gamma-ray counterpart to a neutrino source alert and also monitor the hot-spots exceeding the IceCube (IC) sensitivity

**SIMULATIONS:**

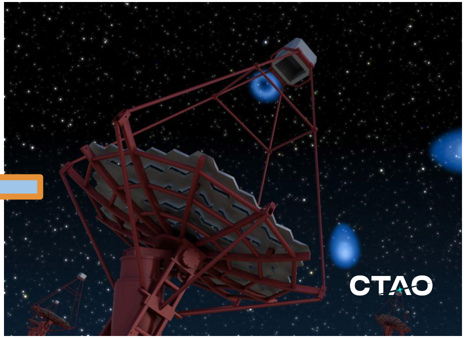
Hadronic contributions: pγ process

**Steady Sources** - Looking for an excess point above the IC limit

**Transient Sources** - Alerts coming from the flaring blazar sources




ICECUBE




Different CTAO configurations are tested:

Omega configuration*

Alpha configuration**

High NSB (x5 NSB; moon observations)

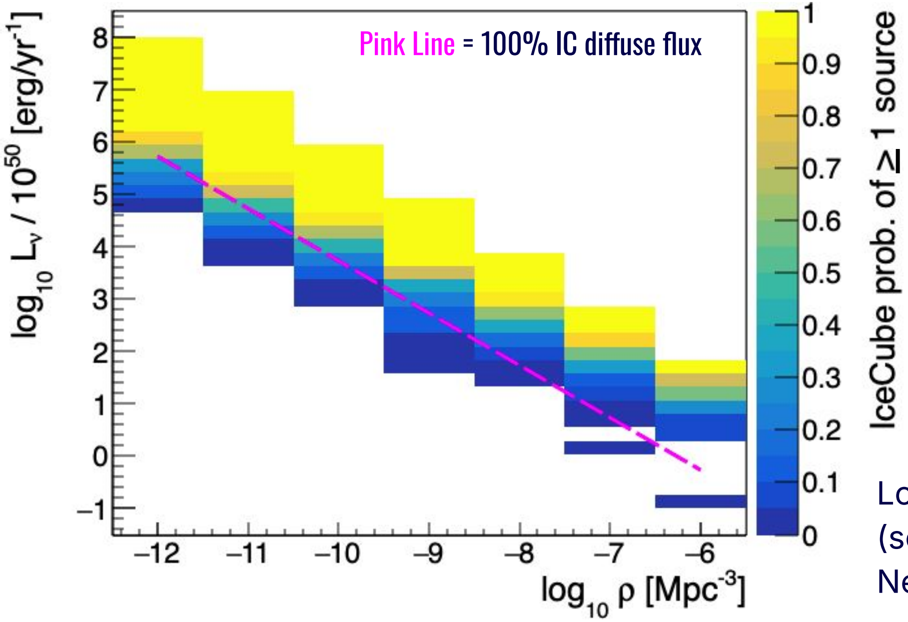
*prod3b-v2 IRFs: https://zenodo.org/record/5163273

** latest prod5-v0.1 IRFs: https://zenodo.org/record/5499840

# FIRESONG

FIRst Extragalactic Simulation Of Neutrinos and Gamma rays

## Steady Sources




Tung et al., JOSS, 6(61), 3194 (2021)

*https://github.com/ChrisCFTung/FIRESONG*

Simulates a neutrino population, given:
Source evolution (e.g. star formation rate)
Luminosity function (e.g. standard candle)

Density vs Luminosity

**Steady Sources**

Local source density (sources/Mpc$^3$)
Neutrino luminosity

**Transient Sources**

Local burst density rate (% flaring blazars )
Neutrino flare luminosity

**Output:** z (redshift), $A_\nu$ (neutrino flux @100 TeV) & $\theta$ (declination)

# FIRESONG Simulations

CTAO

## Steady Sources

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

Local density $\boldsymbol{\rho}$ = $10^{-12}$ to $10^{-5}$ $Mpc^{-3}$
Luminosities: $L_\nu = 5\times10^{47}$ to $10^{57}$ erg/year

Gamma-ray flux parametrised assuming pγ interactions
Ahlers & Halzen (2018)

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

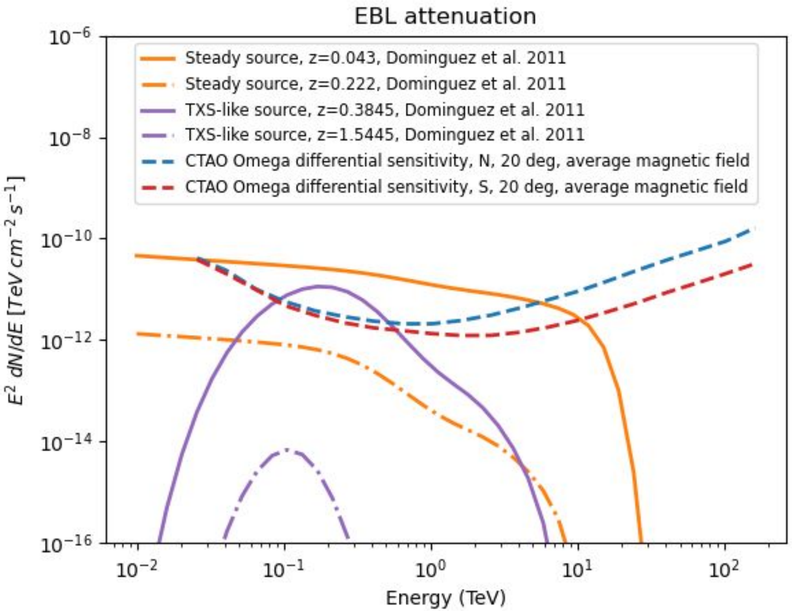
Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

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

Assuming IC Gold alerts

# CTAO follow-up observations

Energy spectra vs CTAO Omega configuration differential sensitivity




SIMULATIONS:

ctools with prod3b-v2/prod5-v0.1 IRFs

Zenith angles:

20º/40º/60º and Average/N/S B-field

Right ascension (RA) assigned randomly

Energy range: 0.03 - 200 TeV

Observation duration: 30 min

EBL absorption by Dominguez et al. 2011

Source is detected if the test statistic TS ≥ 25 (~5$\sigma$)

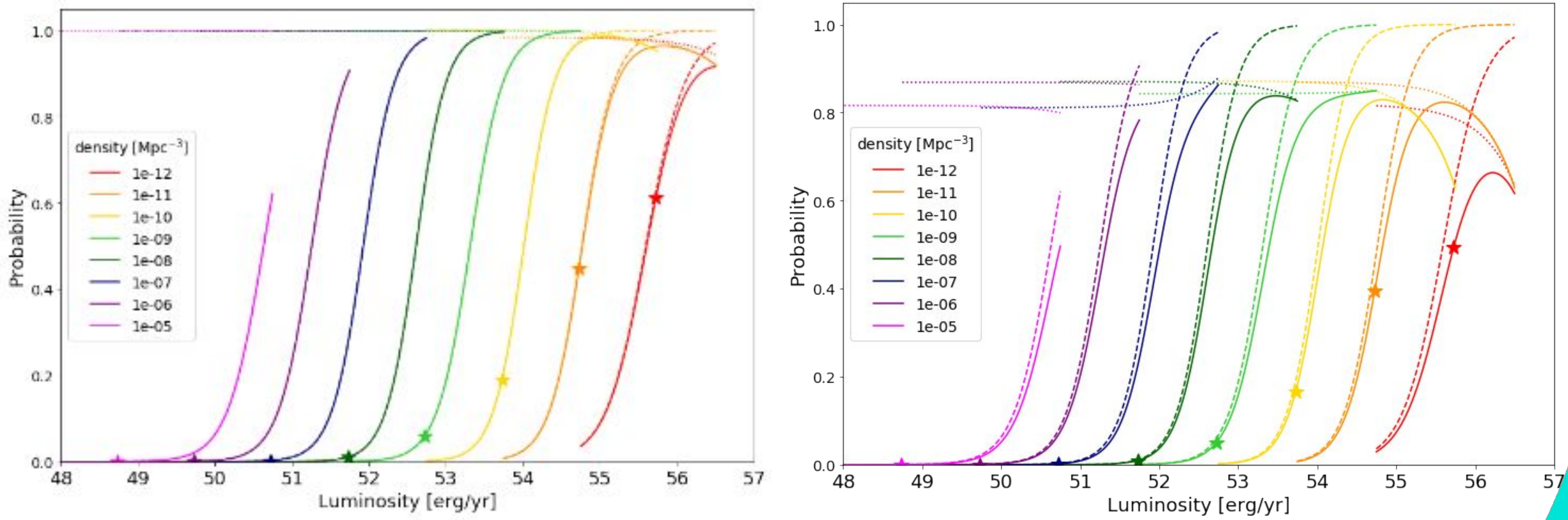
$$TS = 2\left(\ln L(M_s + M_b) - \ln L(M_b)\right)$$

log-likelihood of:

Source + Background: $\ln L(M_s + M_b)$

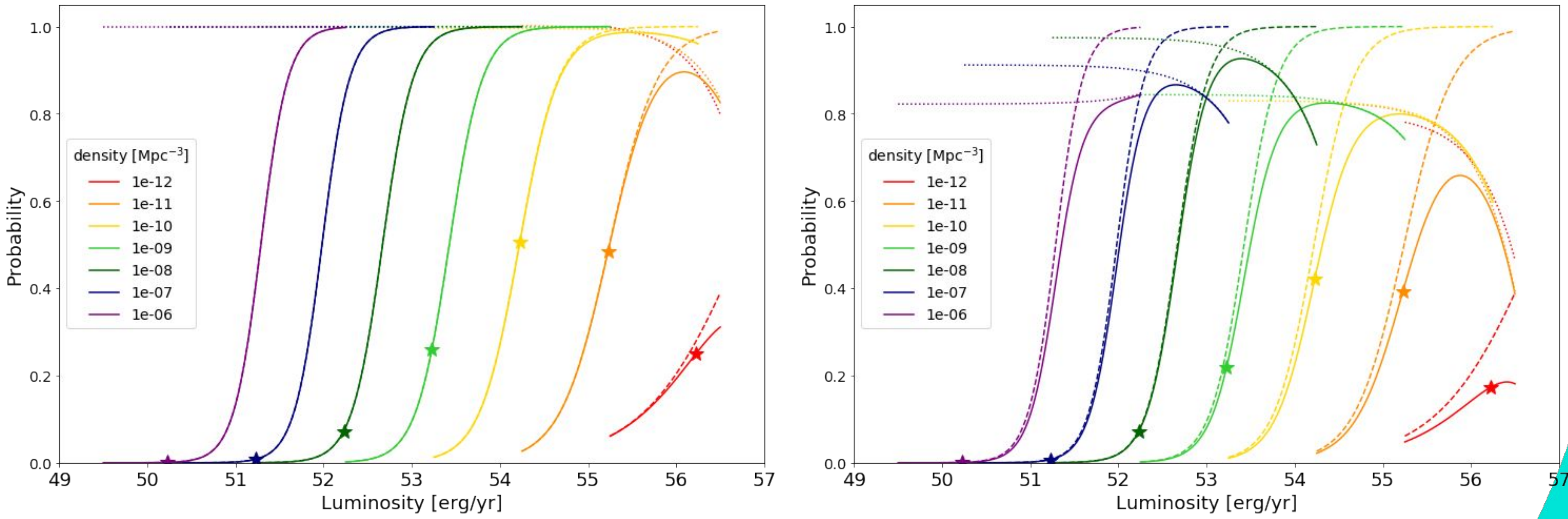
Background only: $\ln L(M_b)$

# Steady sources




Detection probability as a function of source luminosity for sources following the SFR evolution for 30 min observations with CTA-N Omega (left) and CTA-S Omega (right), including visibility constraints. The colored lines represent different local densities from 1e−12 to 1e−6 Mpc$^{-3}$. Dashed lines show the IceCube detection probability, dotted lines - the CTAO detection probability, and solid lines - the combined one. The stars mark the source populations saturating the neutrino diffuse flux, as measured by IceCube.

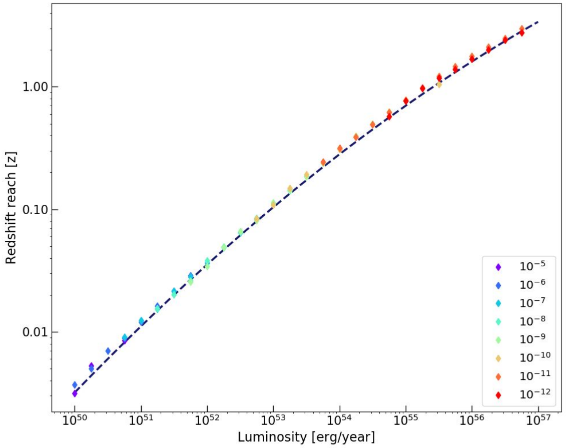
# Steady sources



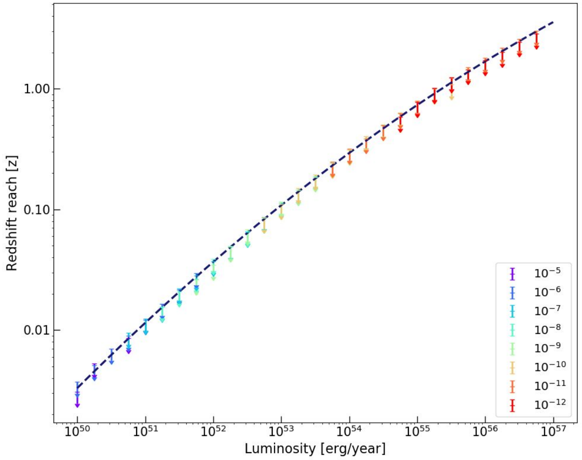

Detection probability as a function of source luminosity for sources following the flat evolution for 30 min observations with CTA-N Omega (left) and CTA-S Omega (right), including visibility constraints. The colored lines represent different local densities from 1e−12 to 1e−6 $Mpc^{-3}$. Dashed lines show the IceCube detection probability, dotted lines - the CTAO detection probability, and solid lines - the combined one. The stars mark the source populations saturating the neutrino diffuse flux, as measured by IceCube.

# Results: Redshift reach

CTA-N Omega, SFR evolution

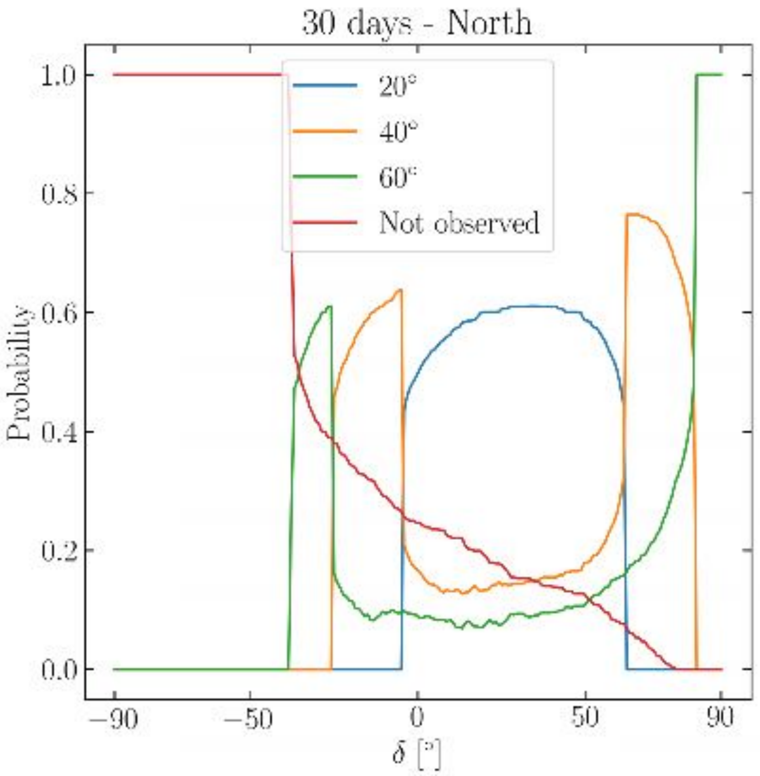



CTA-S Omega, SFR evolution



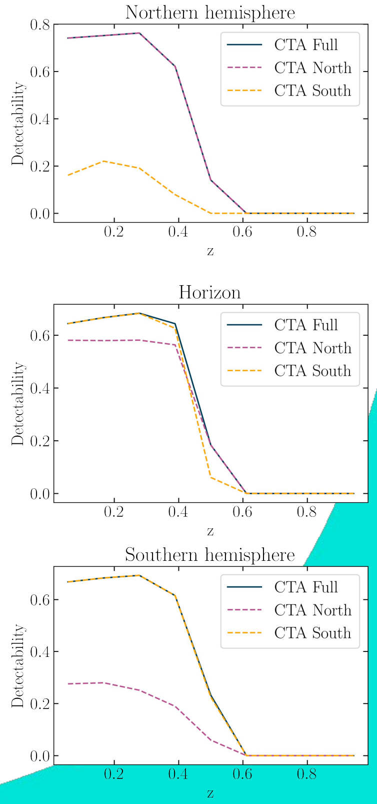

The redshift reach is defined as the maximum redshift up to which 90% of sources are detected (cut the last decile). Highest redshift reach is obtained at high luminosities (for $\rho = 10^{-11}$ Mpc$^{-3}$ up to z~3.0). Each coloured point represents the redshift reach of a different simulated population in the parameter space of local source density vs source luminosity. The dotted line is the best fit curve of the redshift reach points in the log-log space.

# Transient Sources (Flaring blazars)

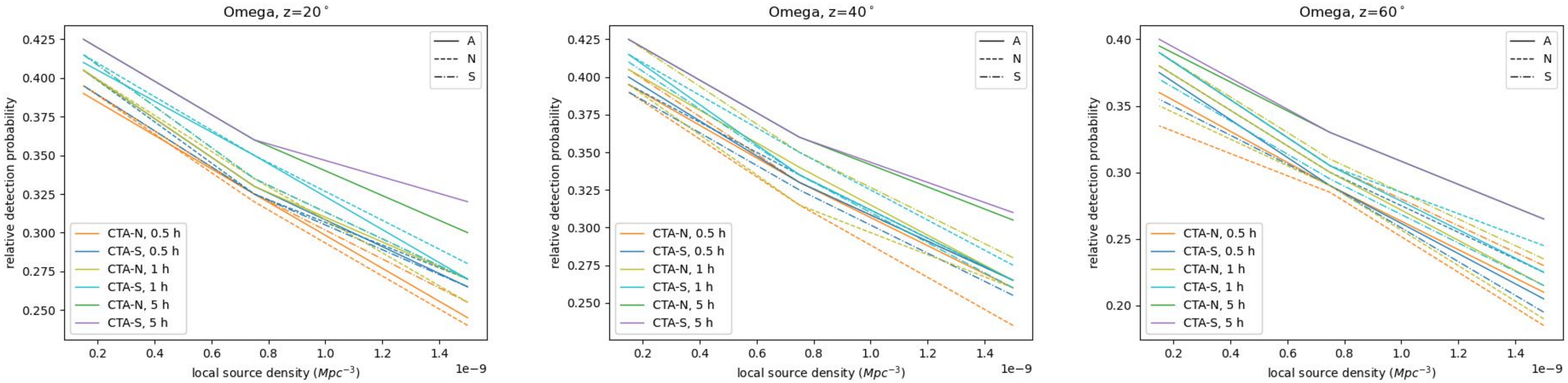



Left: Probability of observation of the alert at CTA-N in different zenith bins as a function of the alert declination. The case of no observation corresponds to a zenith angle larger than 66°.

Right: Fraction of detected alerts at CTA-N Omega, CTA-S Omega and either of the two arrays as a function of the redshift for alerts originating from the Northern hemisphere (top), horizon (middle), and Southern hemisphere (bottom). The source number density is fixed to 1.5e−9 $Mpc^{-3}$.

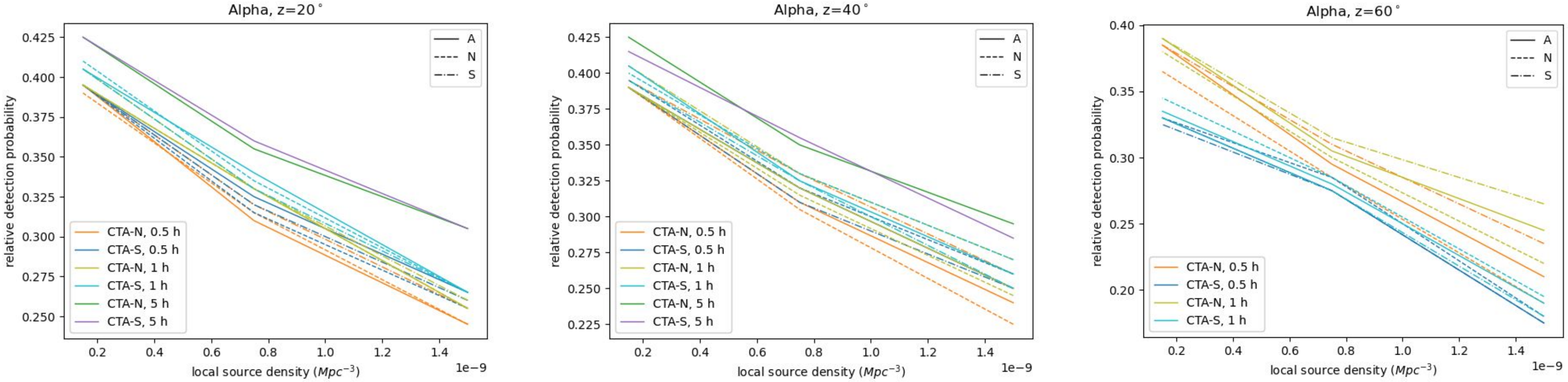


# Transient Sources (Flaring blazars)




Detection probability for flaring blazars observed with the CTAO Omega configuration for different durations of observation and geomagnetic field configurations

# Transient Sources (Flaring blazars)




Detection probability for flaring blazars observed with the CTAO Alpha configuration for different durations of observation and geomagnetic field configurations

# Conclusions and Outlook

- CTAO will enhance our understanding of the high energy universe and play a key role in the multi-messenger astronomy.
- CTAO prospects are particularly promising for the flaring blazars case, up to 37% chances of detection with 30 mins observations. Despite the transient character of the emission, thanks to a long (82 days in source frame) duration of the flare the observations do not have to be immediate. We investigate the possibility to perform the observation up to 1 month after the neutrino alert during a night with the best source visibility (dark night, lowest possible zenith angle). Using this strategy ~2.4 - 3.4 neutrino flaring sources could be detected per year by CTAO, with the majority of them located near the celestial equator, where the IceCube sensitivity is the highest.
- Results also show the high CTAO detection probability for steady sources in certain parameter space regions.

# Thanks for your attention!

olga.sergijenko.astro@gmail.com