cherenkov telescope array

Neutrino Target of Opportunity program for the Cherenkov Telescope Array

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for the CTA Consortium
&
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for the FIRESONG Team

TEV PARTICLE ASTROPHYSICS 25 - 29 October 2021

Cosmic Messenger Connection

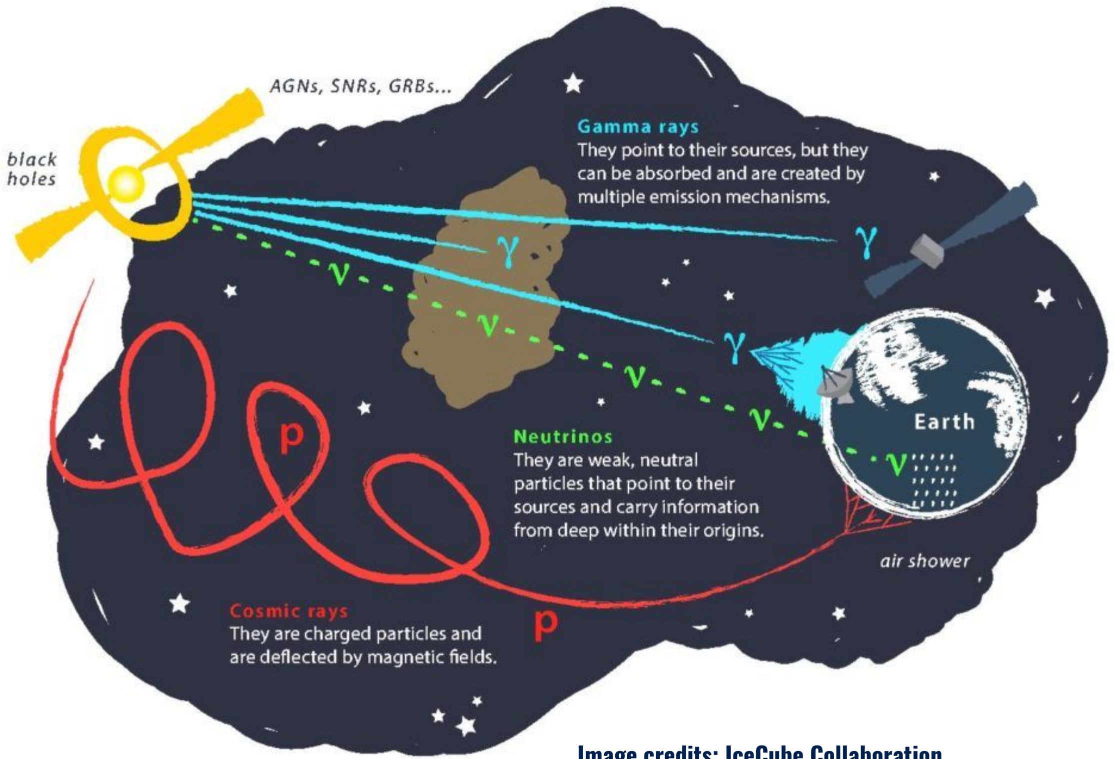
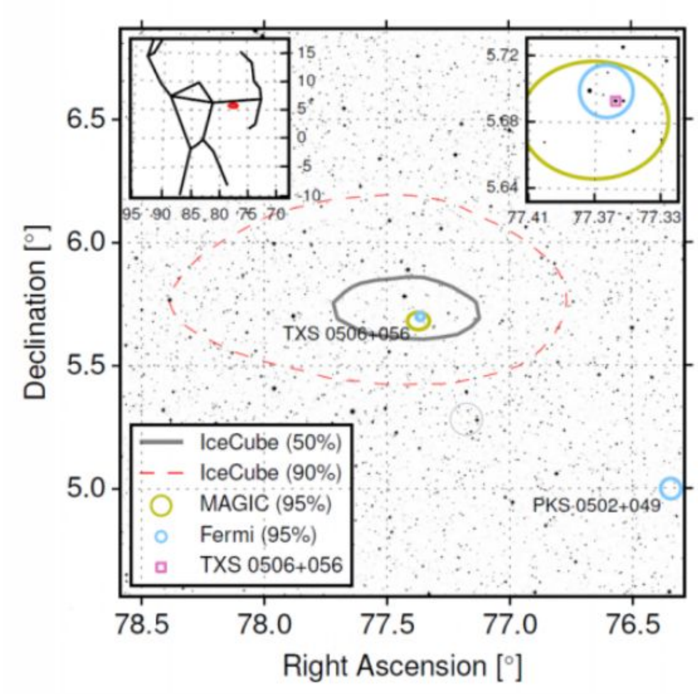


Image credits: IceCube Collaboration

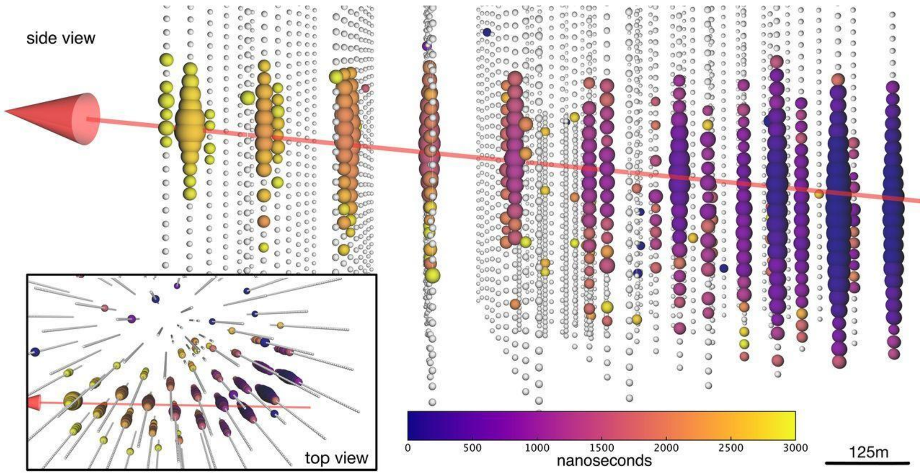
The neutrino/gamma-ray connection is expected if the hadronic processes occur in astrophysical sources (such as AGNs)

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

Motivation: IceCube-170922A & TXS 0506+056



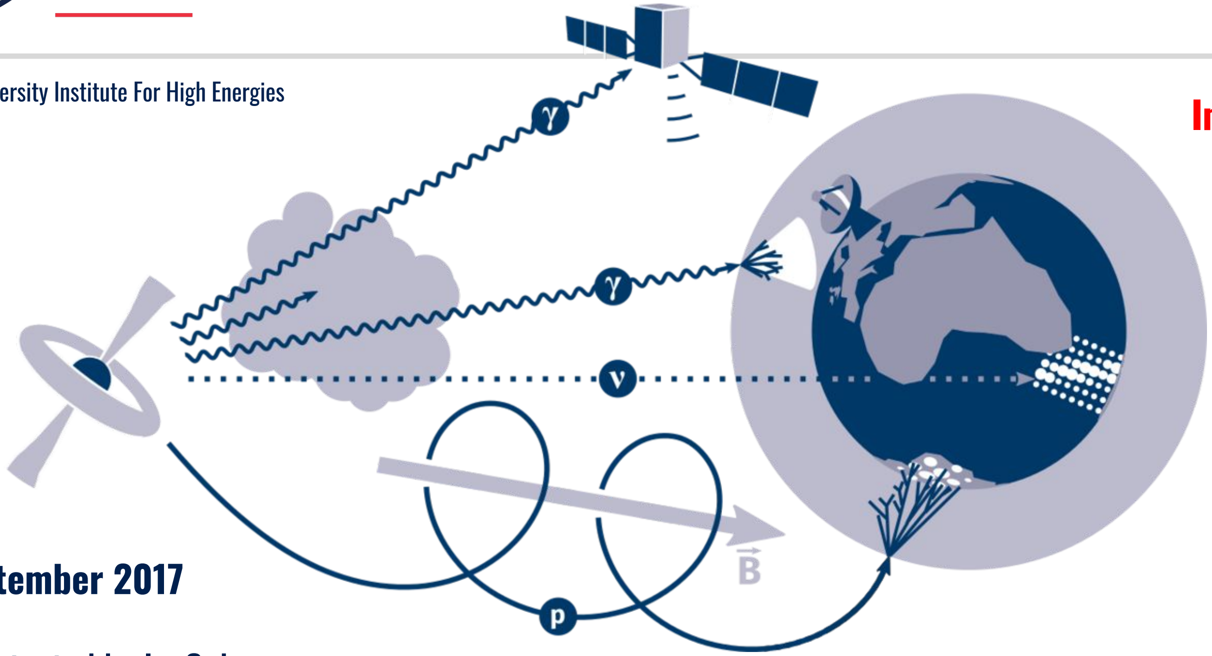
Science 361, eaat1378 (2018)



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)

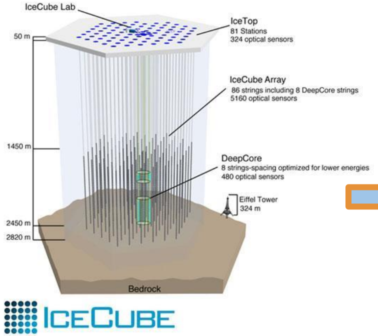
CTA can look for the gamma-ray counterpart to a neutrino source alert and also monitor the hot-spots exceeding the IceCube (IC) sensitivity

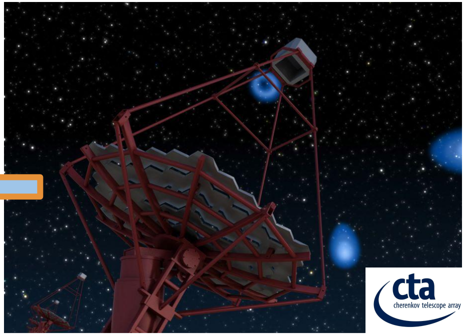
SIMULATIONS:

Hadronic contributions: pγ process

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

Transient Sources - Alerts coming from the flaring blazar sources





Different CTA configurations to be tested:

Omega configuration*

Alpha configuration**

High NSB (x5 NSB; moon observations)

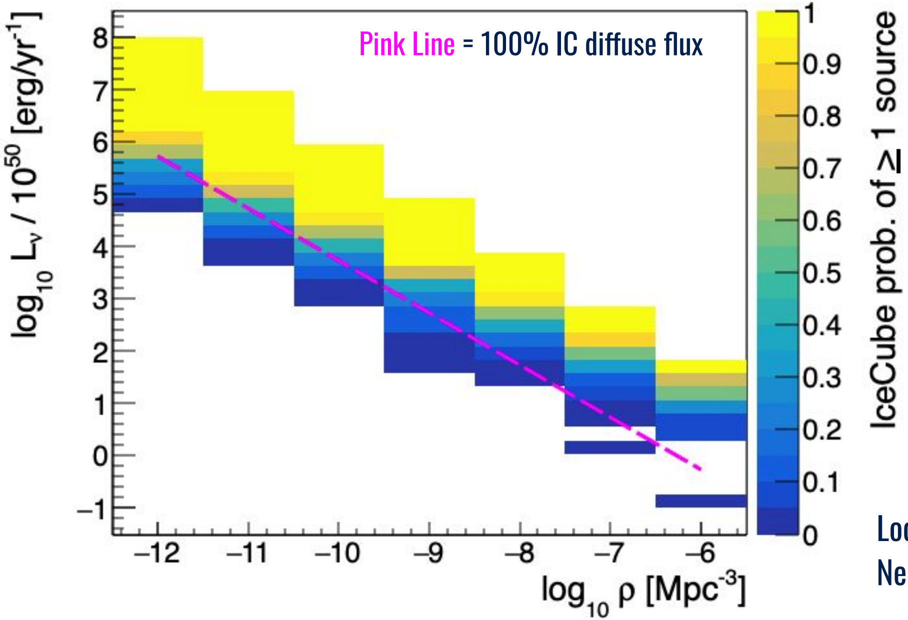
*prod3b-v2 IRFs: https://zenodo.org/record/5163273

** 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_ν (neutrino flux @100 TeV) & θ (declination)

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FIRESONG Simulations

Steady Sources

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

Local density ρ = 10^{-12} to 10^{-5} Mpc^{-3}
Luminosities: L_ν = 5×10^{47} 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)

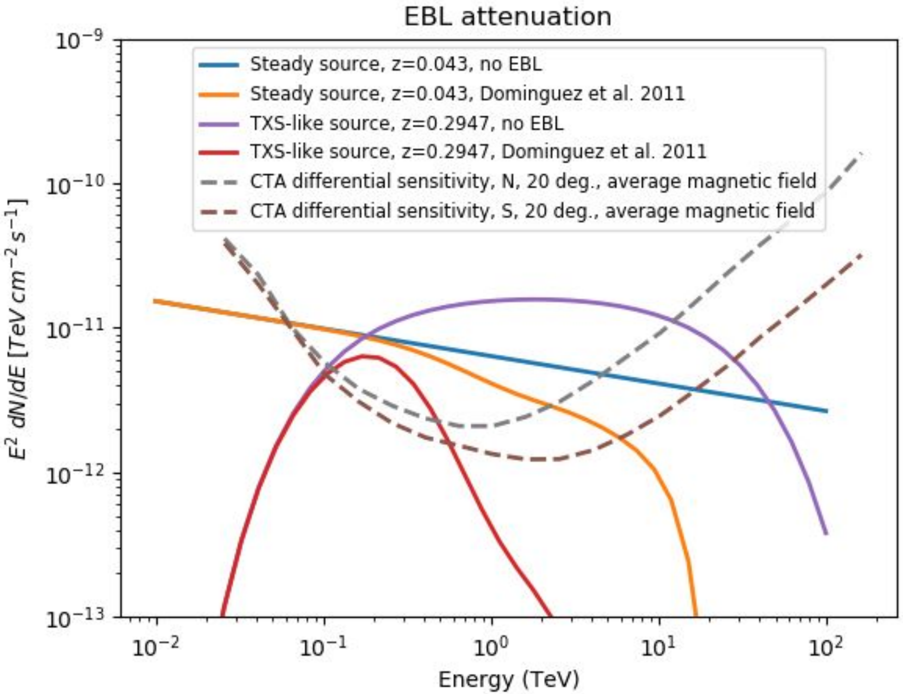
Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

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

CTA follow-up observations

Energy spectra vs CTA Omega configuration differential sensitivity for the detected sources



SIMULATIONS: ctools-1.6.2 with prod3b-v2 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 (~5σ)

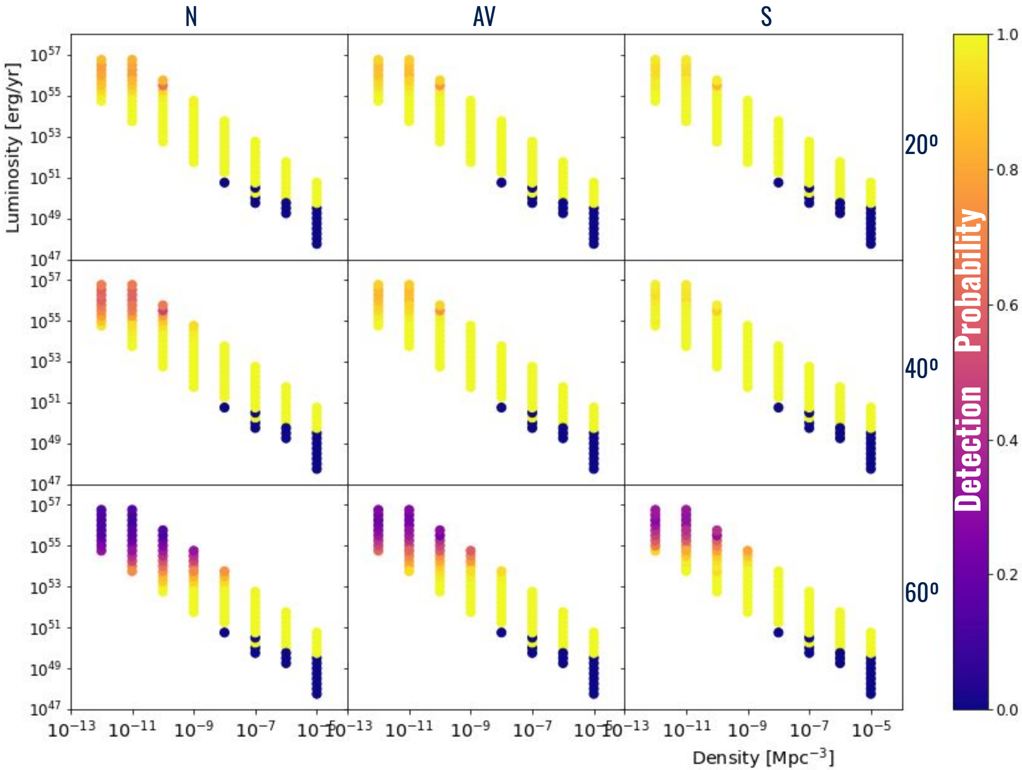
$$TS = 2\left(\ln L(M_s + M_b) - \ln L(M_b)\right)$$

$\ln L(M_s + M_b)$ log-likelihood of: Source + Background

$\ln L(M_b)$ log-likelihood of: Background only

Results: Steady Sources

CTA-N; 30 min obs; SFR evolution



Assuming these sources will be always observable by CTA:

At low-mid zeniths (20º-40º) CTA-N detects all sources up to $\rho = 10^{-9}$ Mpc^{-3}

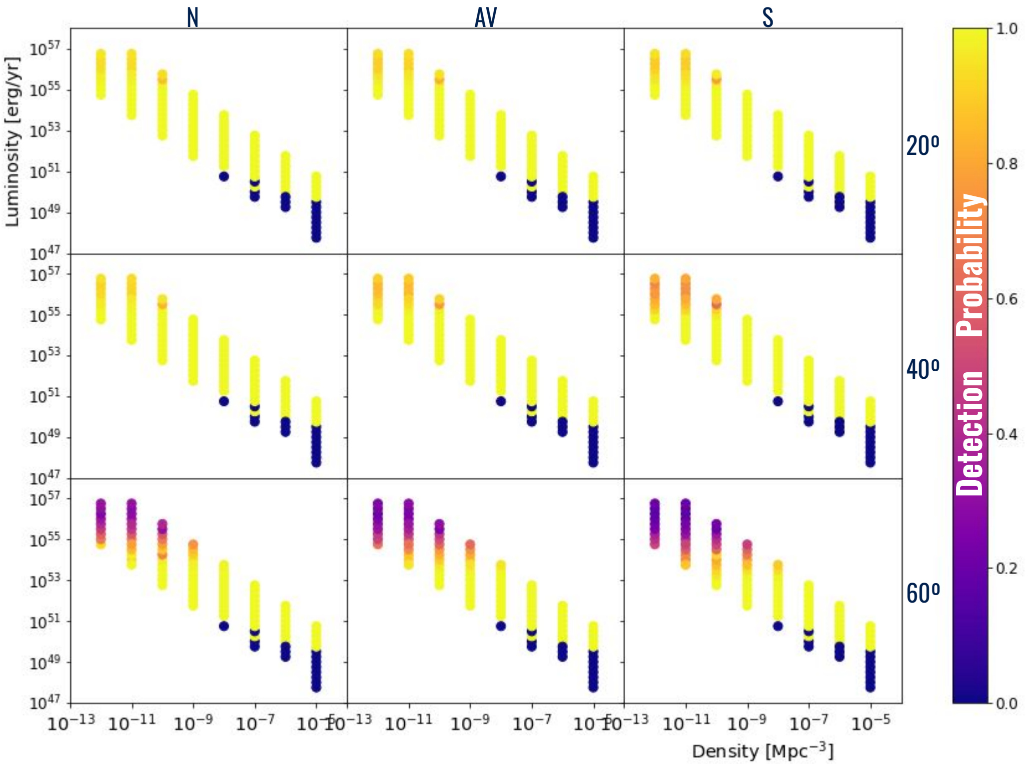
Drastic performance loss, up to 65%, at high zeniths (60º)

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

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

Results: Steady Sources

CTA-S; 30 mins obs; SFR evolution & standard candles



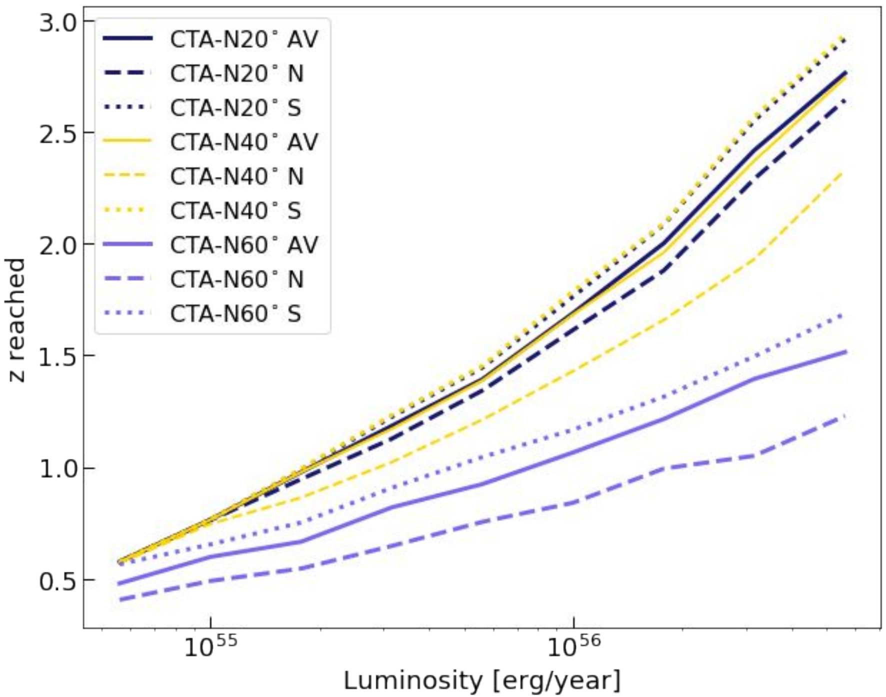
The CTA-S array shows the similar response as CTA-N (within 10% for average azimuth).

Main differences are:

- Higher performance loss: up to 70% at high zeniths (60°)
- Smaller influence of the magnetic field effect: 5% to 15% difference in detection probability for the North/South azimuth directions for low to high zeniths

Results: Redshift reach

CTA-N; 30 min obs; SFR evolution; $\rho = 10^{-12}$ Mpc-3



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 low densities and high luminosities (for $\rho = 10^{-12}$ Mpc^{-3} up to z~2.8)

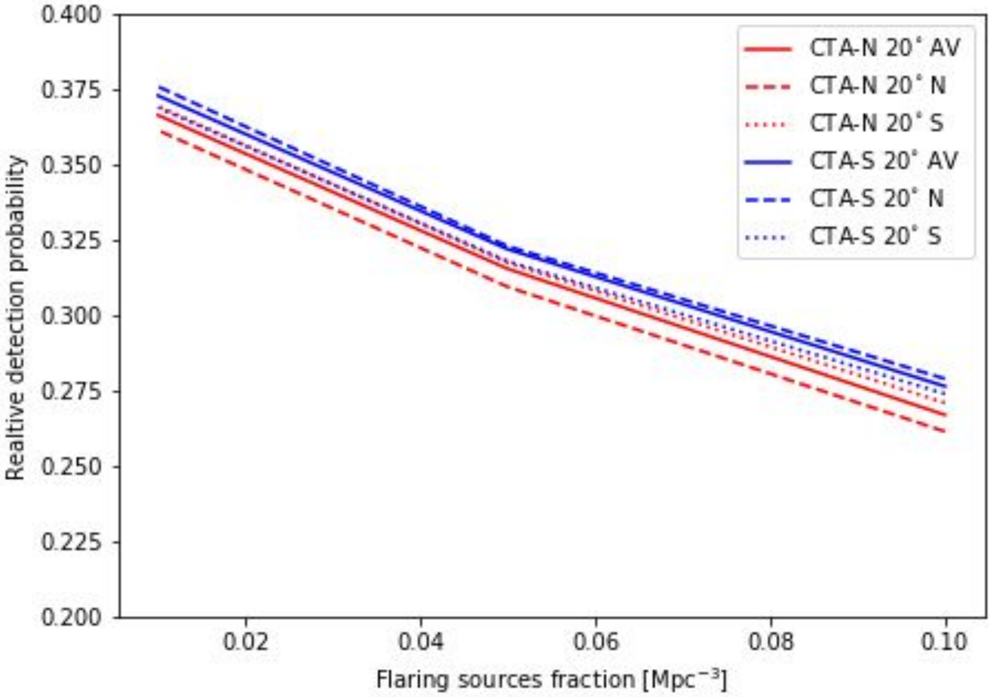
Redshift reach goes down at higher zeniths: for 20° and 40° the redshift reach is similar, but there is a huge drop at 60°

There is a cut in redshift coming from the IceCube preselection effect

Sources with the flat cosmological evolution follow the same trend, but the redshift reach is lower than for the SFR evolution

Results: Transient Sources (Flaring blazars)

CTA 30 mins obs; Flaring blazars



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

CTA detection probability grows while **F** decreases (as expected: flux of each flare is increasing)

Detection probability is almost identical for 20º and 40º zenith IRFs (difference < 1%), decreases by 4% for 60º

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

Conclusions and Outlook

CTA will enhance our understanding of the high energy universe and play a key role in the multi-messenger astronomy.

CTA prospects are particularly promising for the flaring blazars case, up to 37% chances of detection with 30 mins observations.

Results also show the high CTA detection probability for steady sources in certain parameter space regions.

In future, we plan to investigate:

- Longer observation times, especially for steady sources (5 hrs, 50 hrs)
- Different durations for transient sources: 100s to few hours
- Include CTA visibility constraints for steady and transient sources
- Include the effect of delays introduced by the alert system and the telescope re-pointing
- More configurations: results for the sub-arrays and the high night sky background (NSB) are being analysed

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Thanks for your attention

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BACKUP SLIDES

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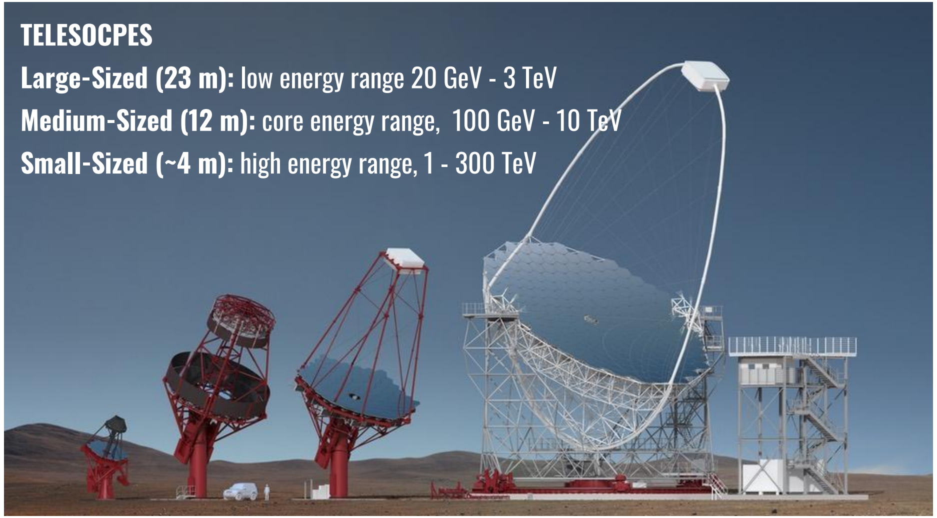
CTA Array Configurations



ALPHA CONFIGURATION

Northern site: 4 LSTs and 9 MSTs

Southern site: 14 MSTs and 37 SSTs

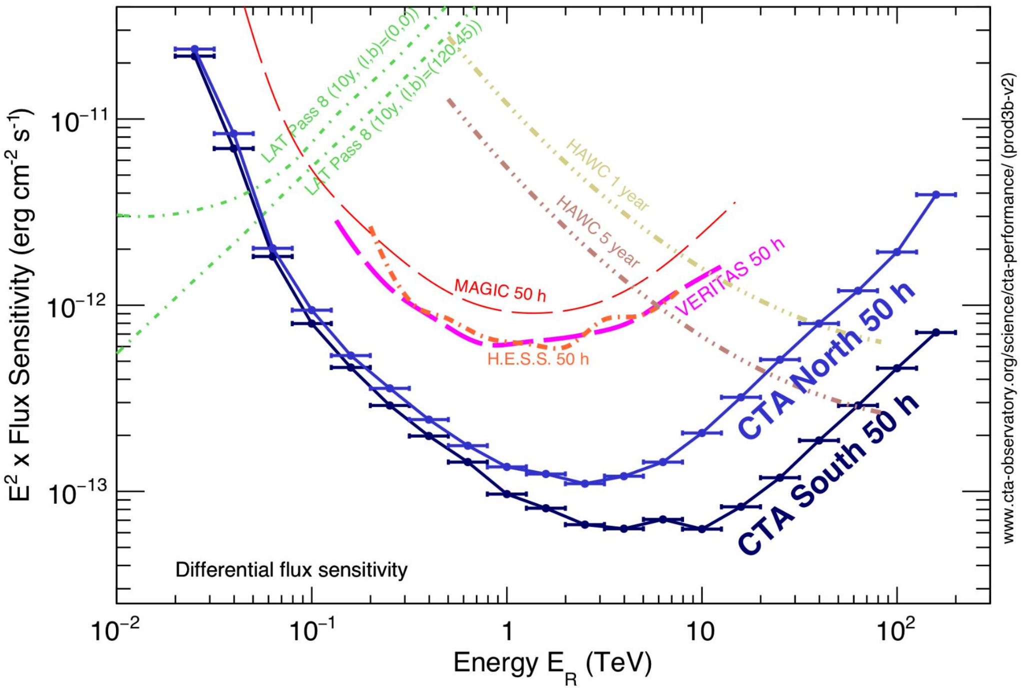
OMEGA CONFIGURATION

Northern site: 4 LSTs, 15 MSTs
Roque de los Muchachos Observatory, La Palma, Spain

Southern site: 4 LSTs, 25 MSTs, 70 SSTs
Paranal Observatory, Atacama desert, in Chile

CTA Performance (Omega configuration)

Sensitivity



Angular Resolution