Detecting Gamma-Ray Counterparts of High-Energy Neutrino Sources with CTAO: Prospects and Simulations

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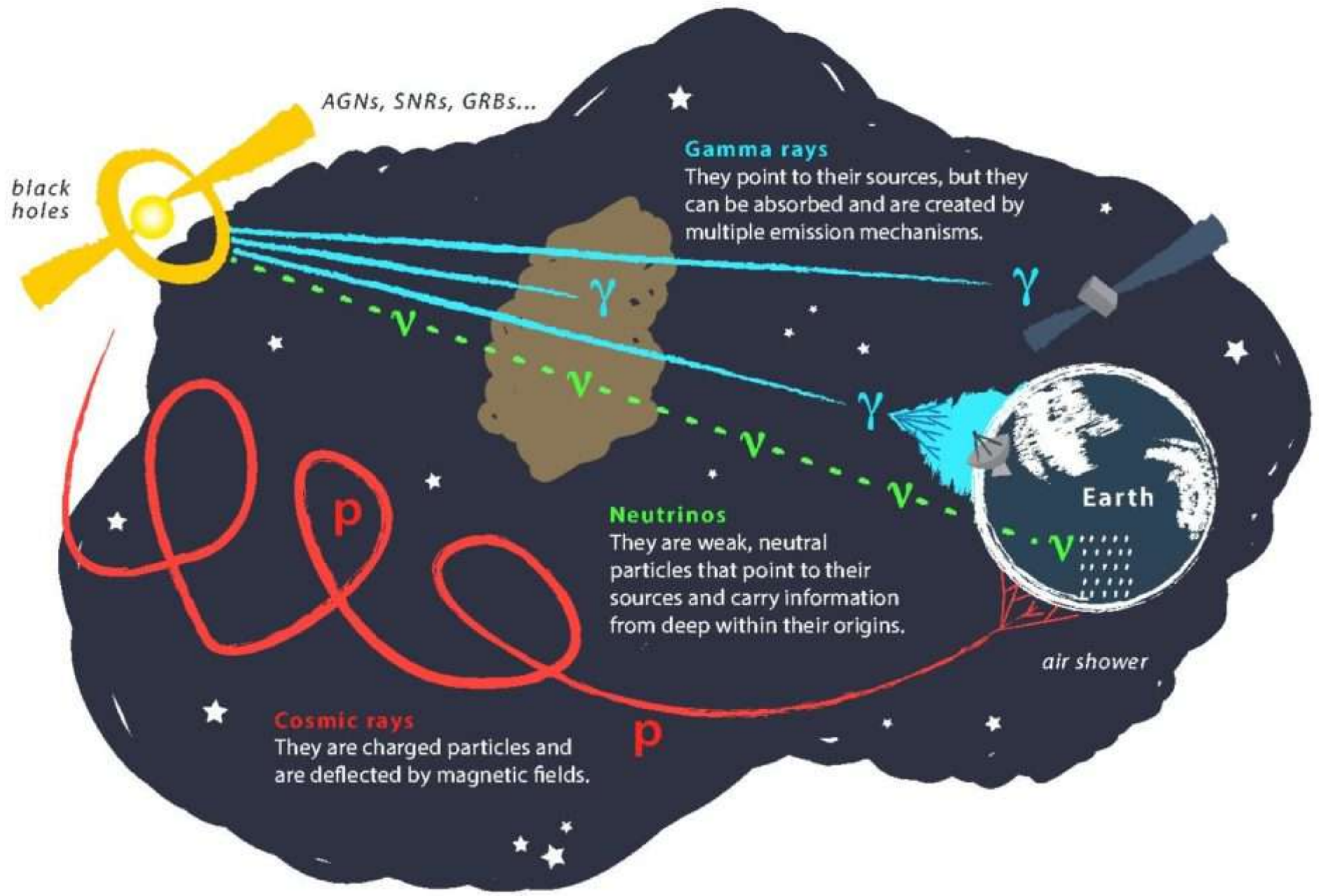
G.Ferrara, G. Marsella

Cosmic Messenger Connection



IceCube-170922A & TXS 0506+056

22 September 2017
IceCube detects muon track

Global alert sent
in < 1 min

23 September 2017
H.E.S.S. & VERITAS follow-ups

24 / 28 September 2017
MAGIC, HAWC, AGILE (Radio, Optical, X-rays)

28 September 2017
Fermi-LAT: blazar TXS 0506+056 in flaring state (0.1° from neutrino direction)

Neutrino Target of Opportunity

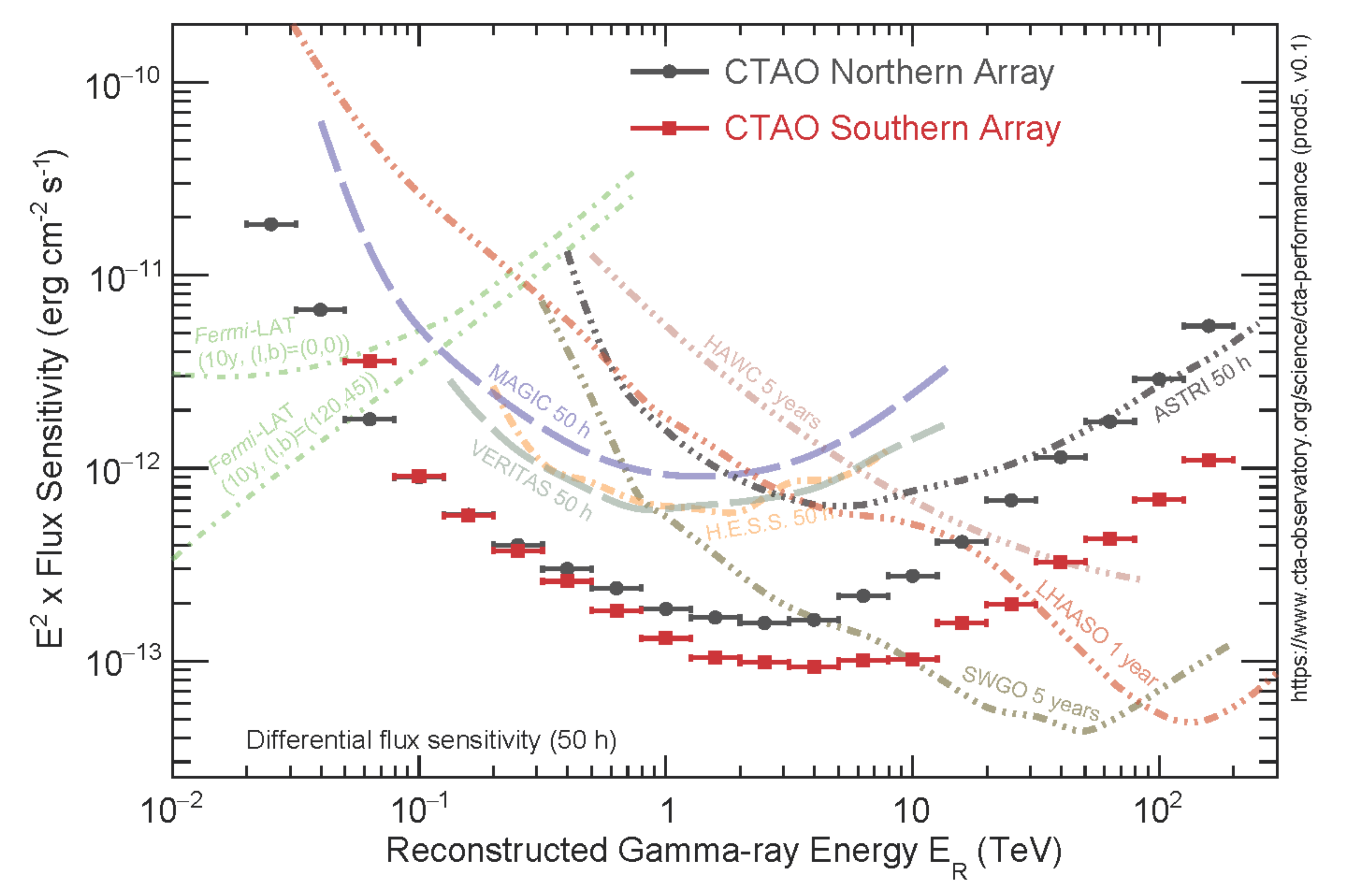
CTAO can look for the gamma-ray counterpart to a neutrino source alert and also monitor the hot-spots exceeding the IceCube (IC) sensitivity

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

1. **Neutrino Simulations** – FIRESONG python code
2. **Neutrino Telescope Filter** – Discovery potential of Neutrino Telescope
3. **Gamma Simulations** – EBL model and Alpha configuration of IRFs
4. **CTA performance** – CTAO detection probability

The Cherenkov Telescope Array Observatory (CTAO)



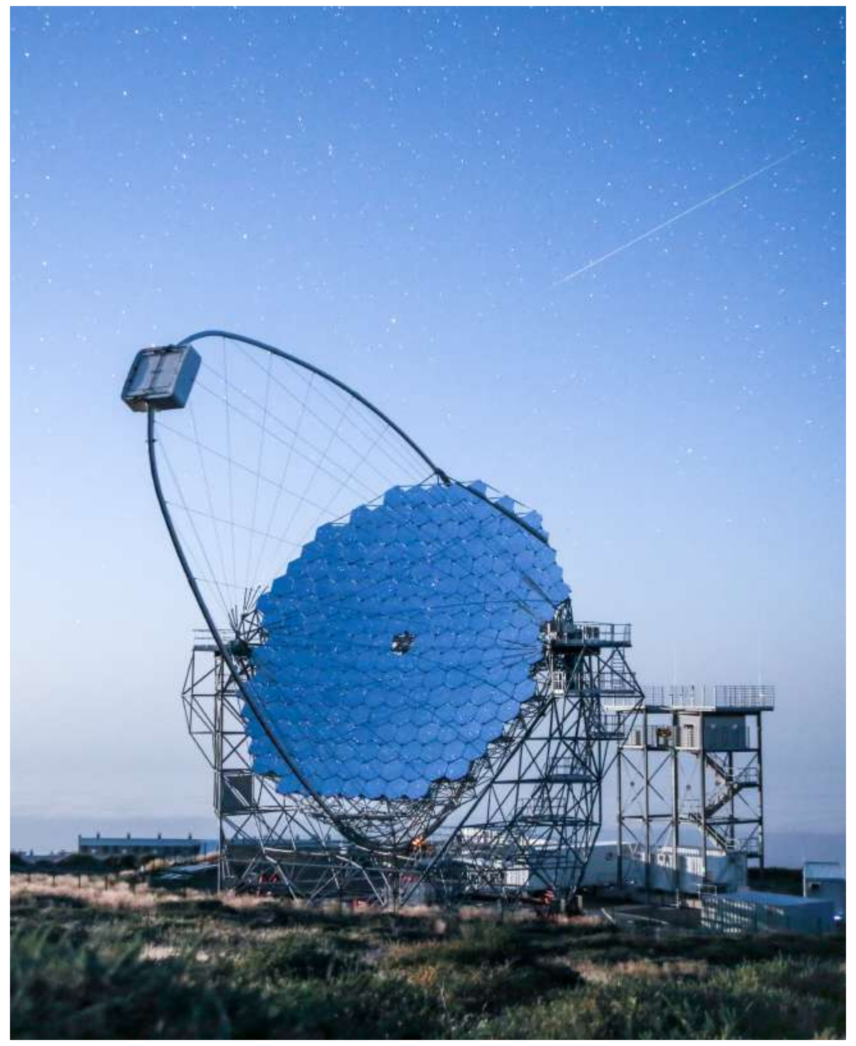
CTAO flux sensitivity for the Northern and Southern arrays, on axis, for 50 h observation time, including the sensitivity of other gamma-ray instruments, credit: CTAO

The "Alpha Configuration" of CTAO

- **CTAO Northern Array:** 4 Large-Sized Telescopes (LSTs) and 9 Medium-Sized Telescopes (MSTs)
- **CTAO Southern Array:** 14 Medium-Sized Telescopes (MSTs) and 37 Small-Sized Telescopes (STSs)

Size	Diameter	Energy range
SST	4 m	5 TeV - 300 TeV
MST	12 m	150 GeV - 5 TeV
LST	23 m	20 Gev - 150 GeV

energy ranges:
from **20 GeV** to **300 TeV**

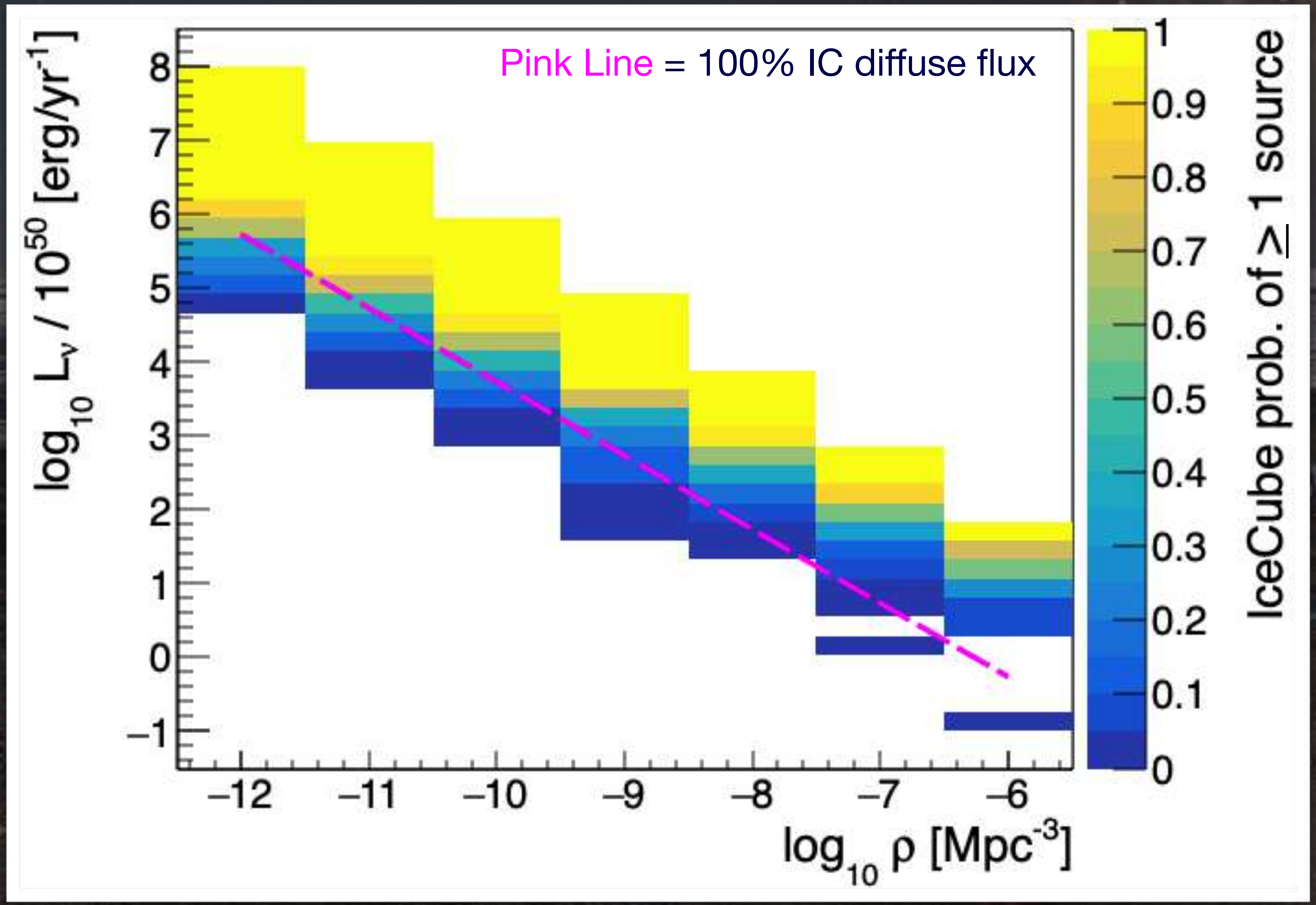


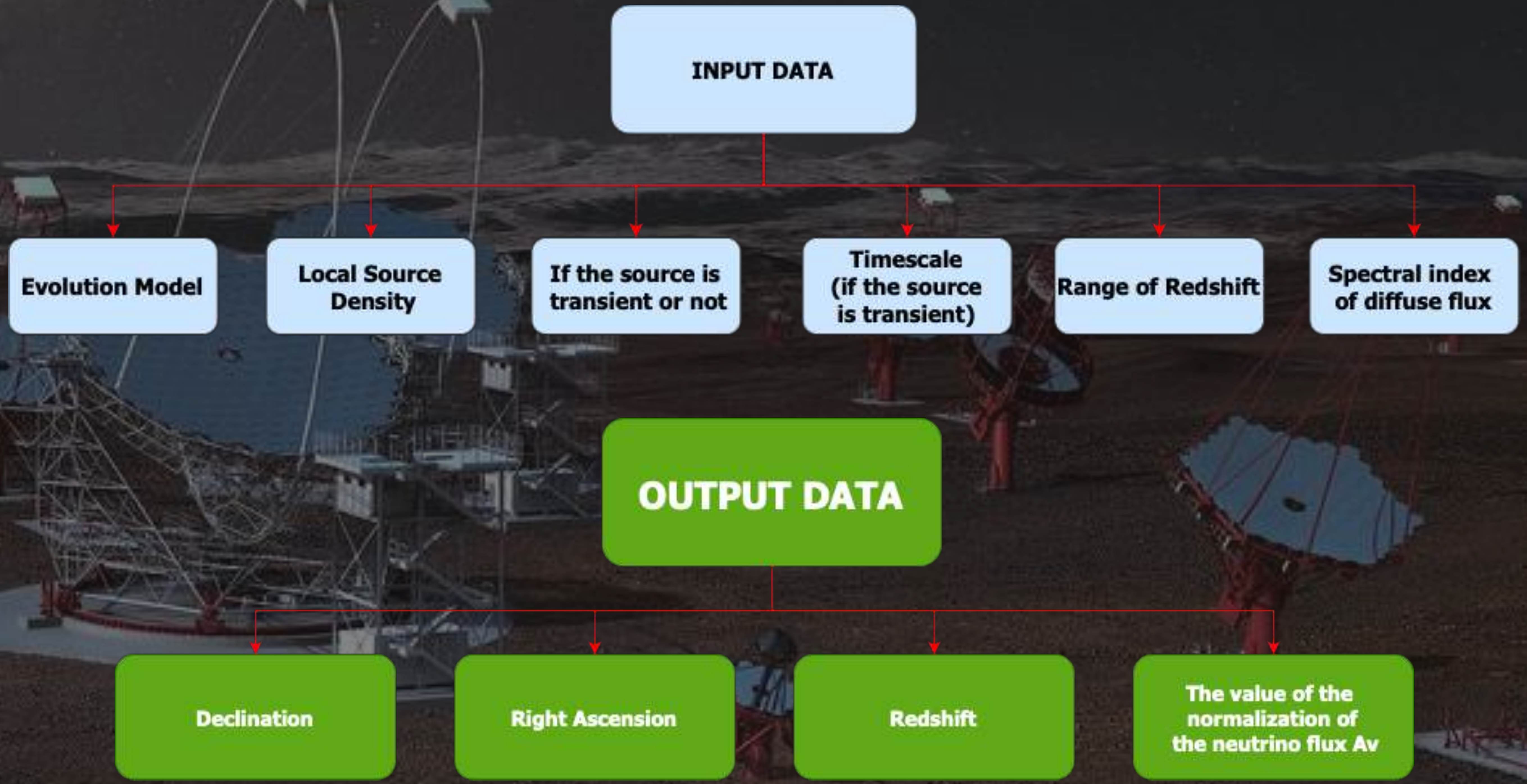
credit: Tomohiro Inada

FIRESONG

(FIRst Extragalactic Simulation Of Neutrinos and Gamma rays)

Tung et al., JOSS, 6(61), 3194 (2021)
https://github.com/ChrisCFTung/FIRESONG





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CTAO
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FIRESONG Simulations

Steady Sources

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

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

Local density $\boldsymbol{\rho} = 10^{-12}$ to 10^{-5} Mpc^{-3}

Luminosities: $L_\nu = 5\text{x}10^{47}$ to 10^{57} erg/year

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)

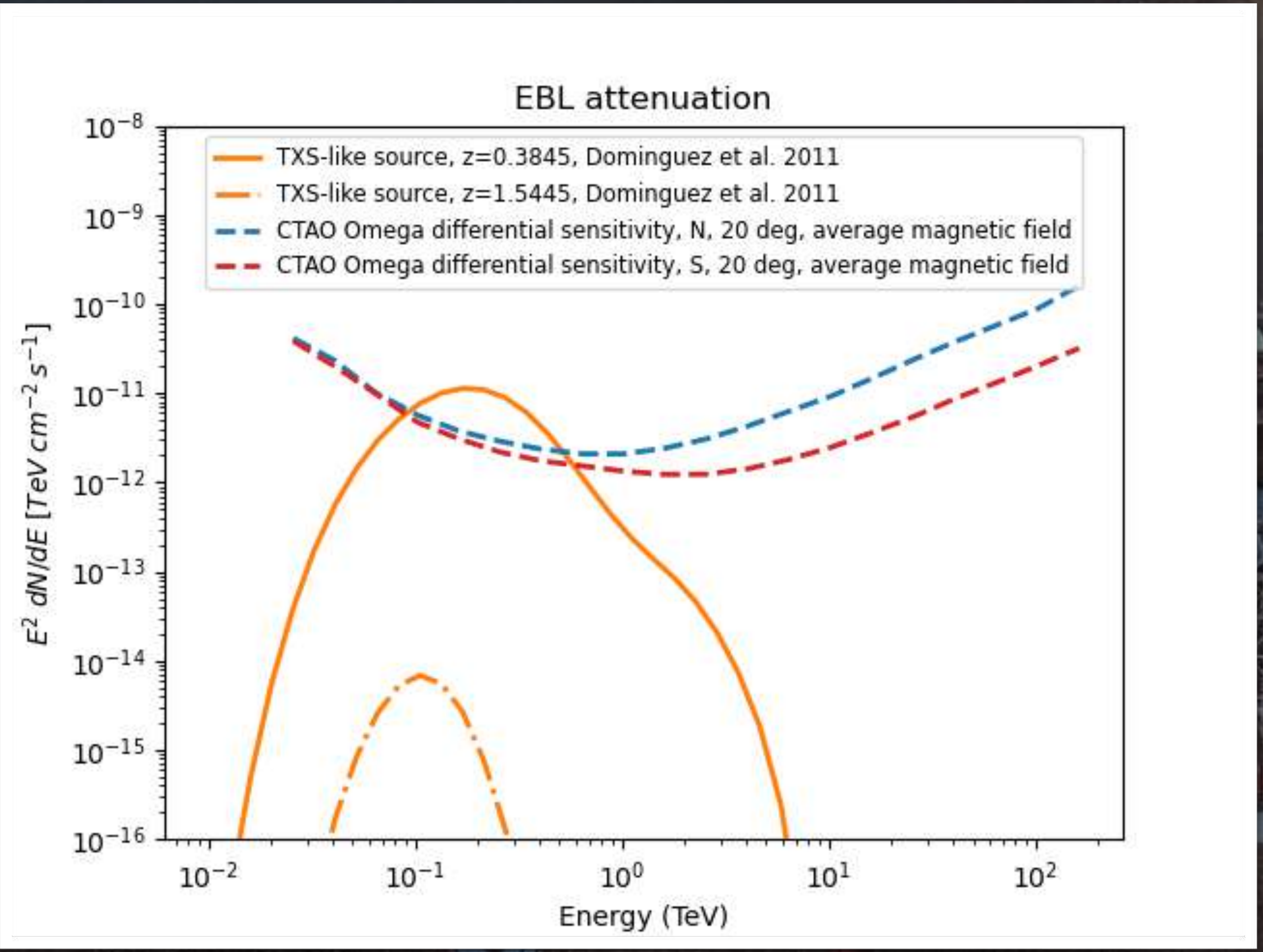
Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

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 (https://arxiv.org/abs/1606.00393) with prod3b-v2/prod5-v0.1 IRFs

Zenith angles:
20°/40°/60° 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

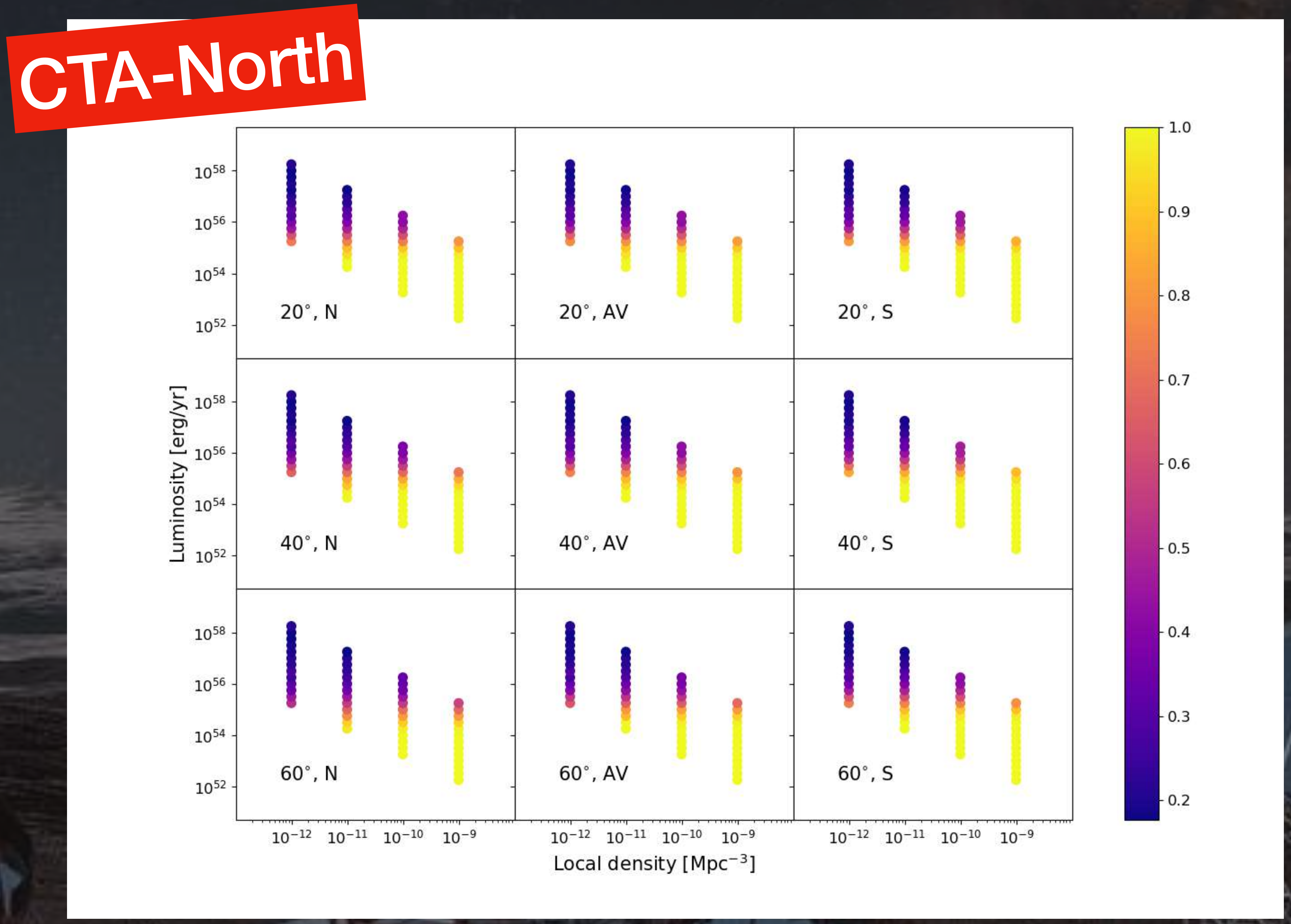
Source is detected if the test statistic TS ≥ 25 (~5σ)

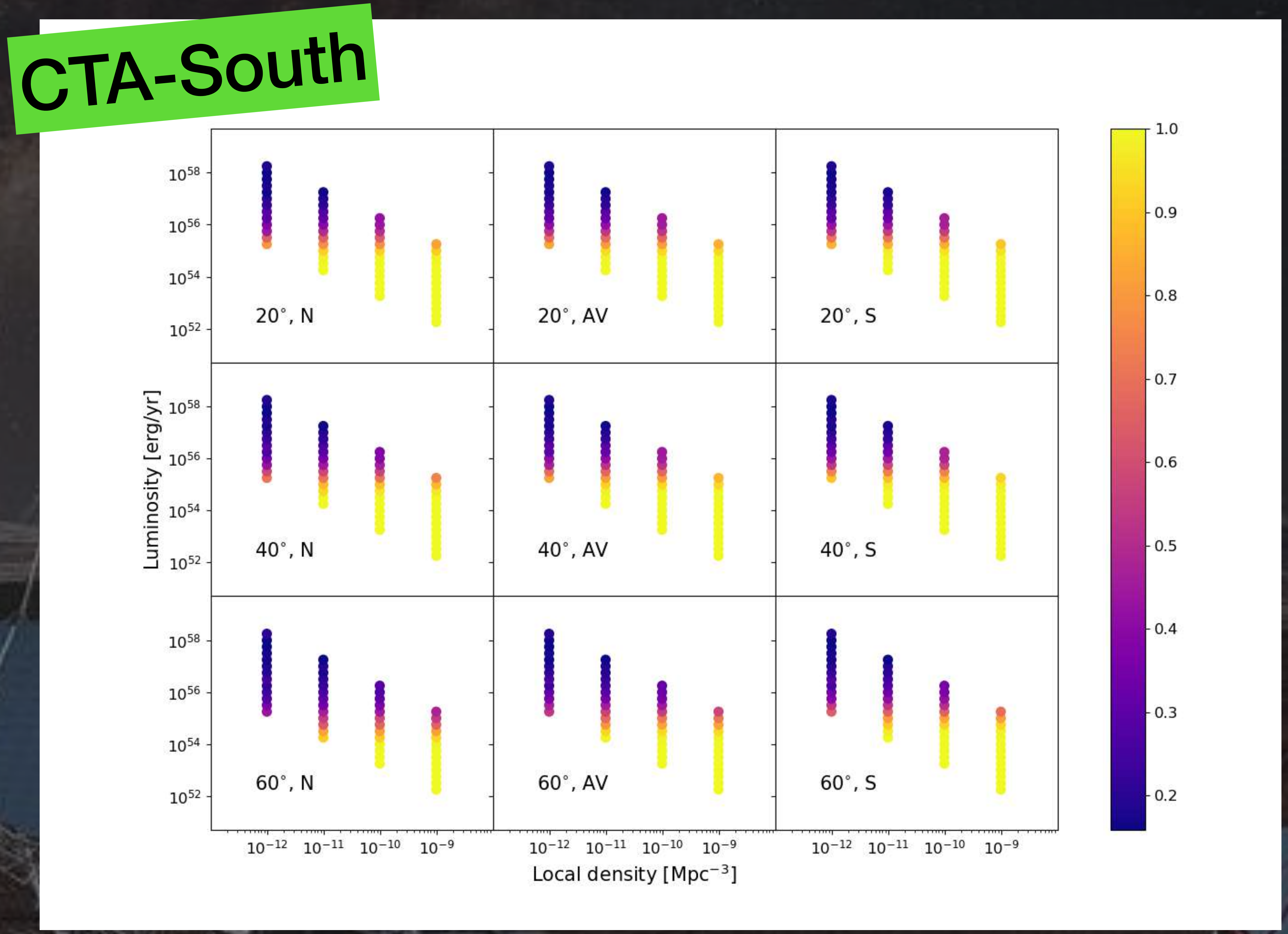
log-likelihood of: $\mathrm{TS} = 2\left(\ln L(M_s + M_b) - \ln L(M_b)\right)$

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

Background only $\ln L(M_b)$

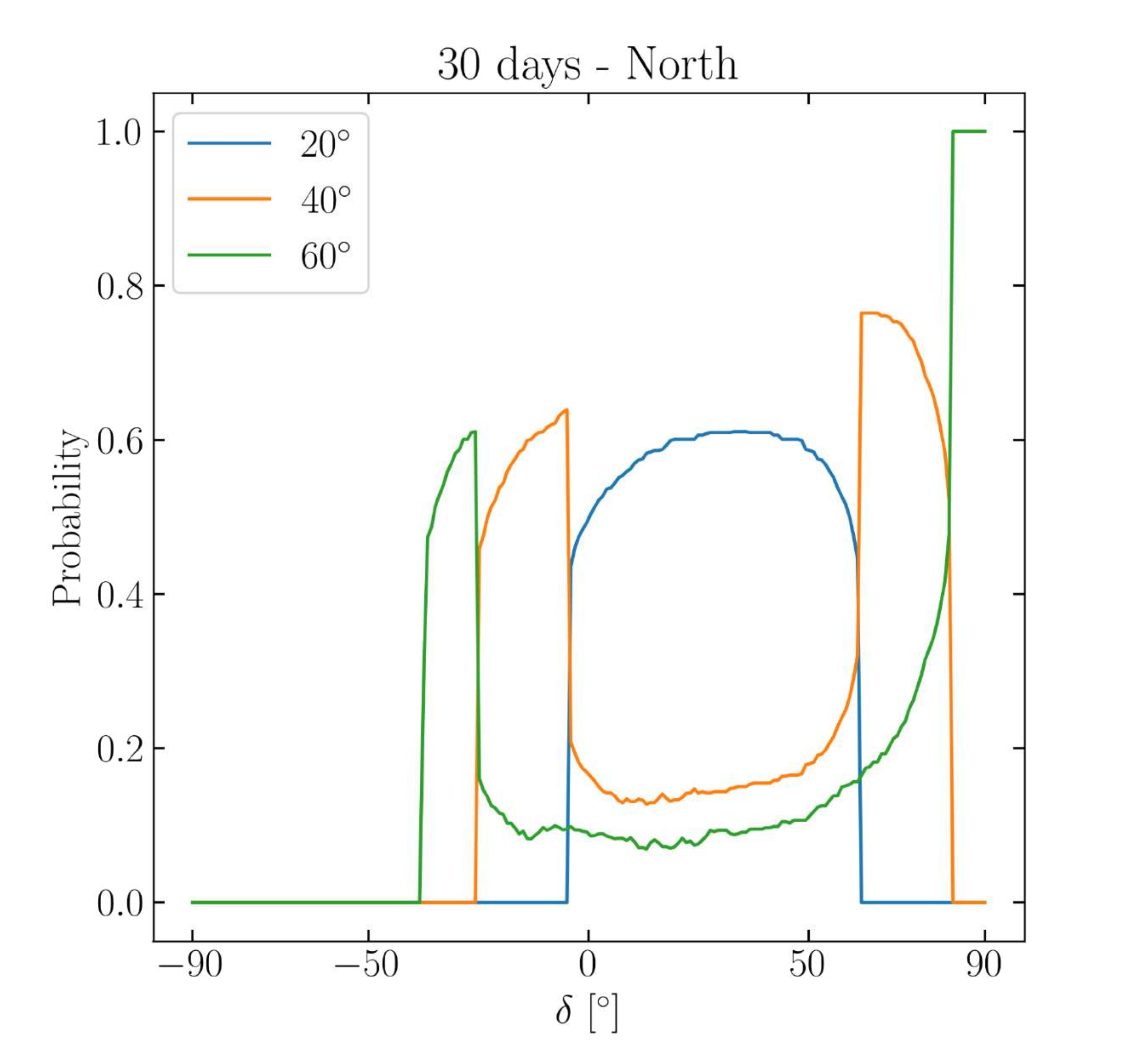
Steady Sources





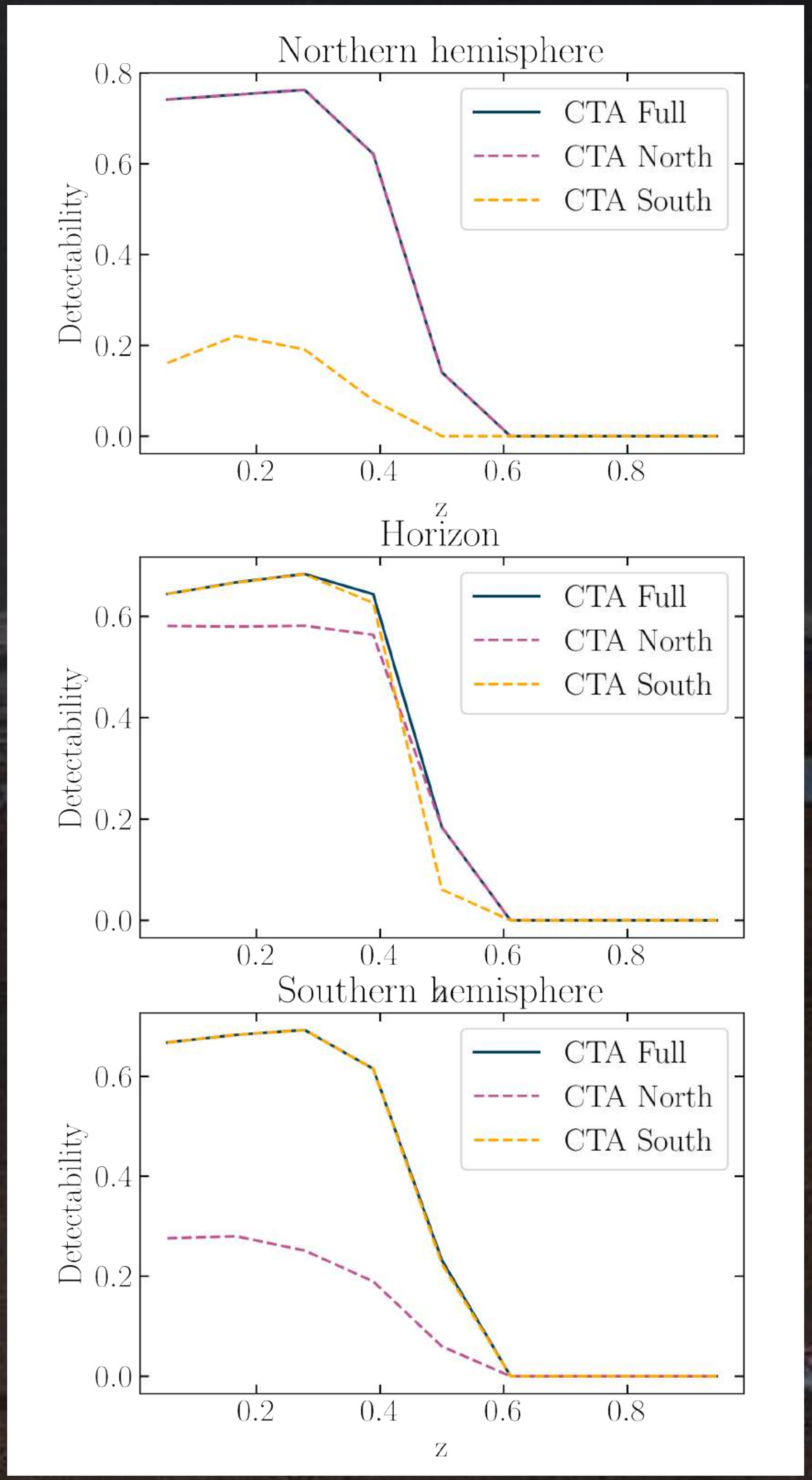
Detection probability as a function of source luminosity and local density for sources with flat redshift evolution (NoEvolution) for 30 min observations with CTAO-N Alpha (left) and CTAO-S Alpha (right). The plots in rows from top to bottom represent results for zenith angles 20°, 40° and 60°, while the columns show different magnetic field alignments: North, average and South (from left to right).

Transient Sources (Flaring blazars)



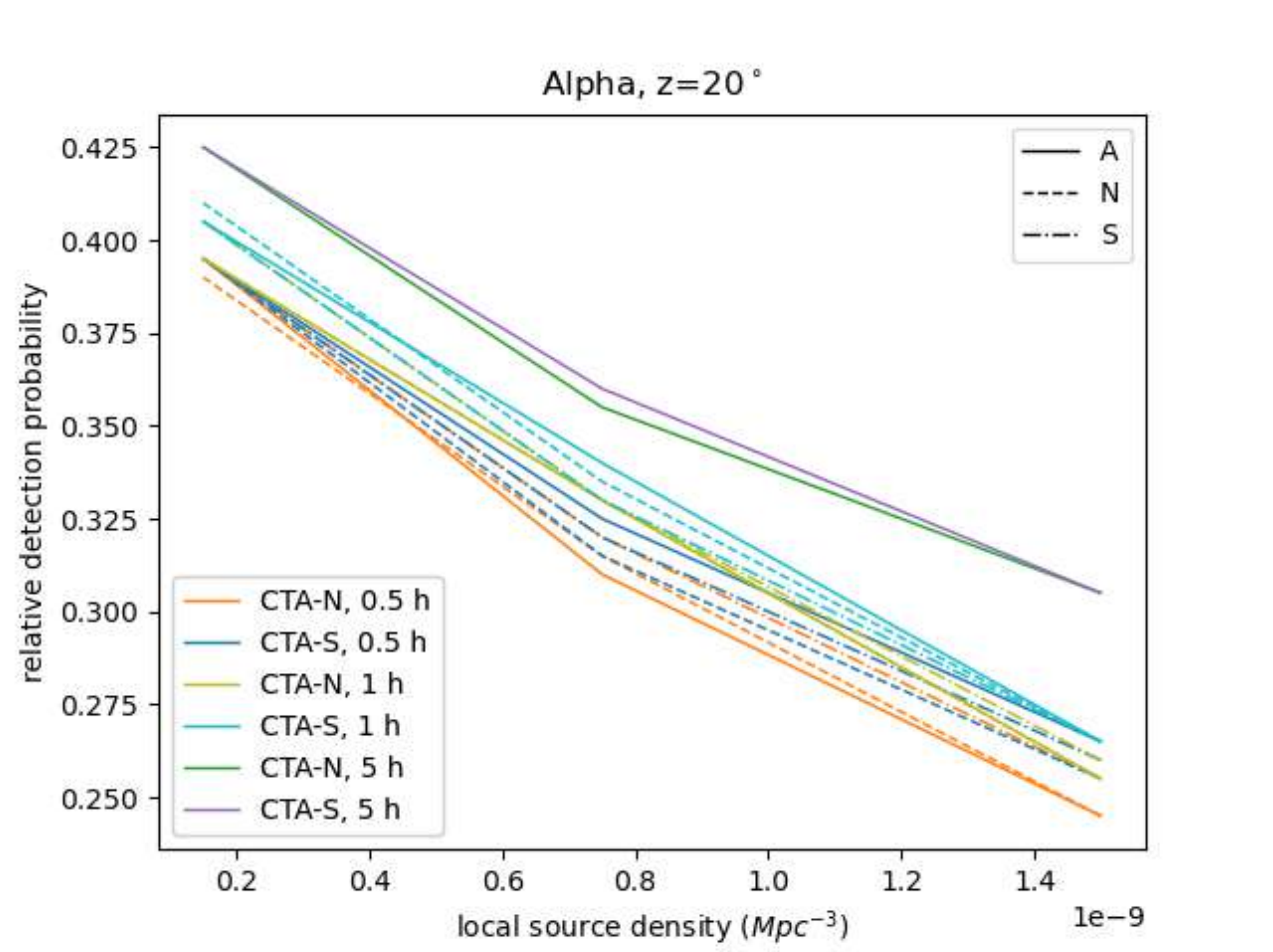
Left: Probability of observation of the alert at CTAO-N in different zenith bins as a function of the alert declination. The case of no observation corresponds to a zenith angle larger than 66○.

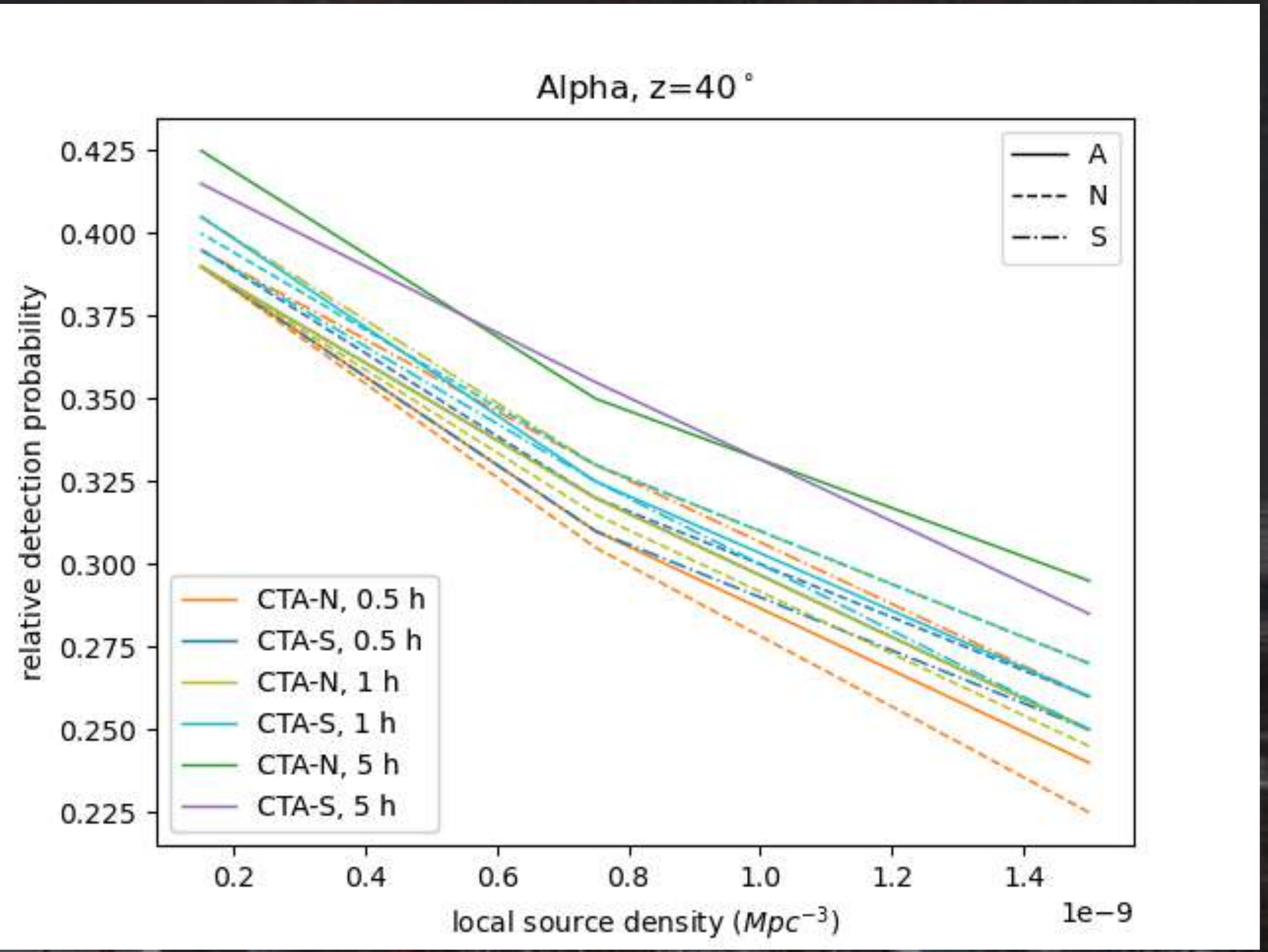
Right: Fraction of detected alerts at CTAO-N Omega, CTAO-S Omega and either of the two arrays as a function of the redshift for alerts originating from the Northern hemisphere (top), horizon (middle), and Southern hemisphere (bottom). The source number density is fixed to 1.5x10^{-9} Mpc^{-3}.

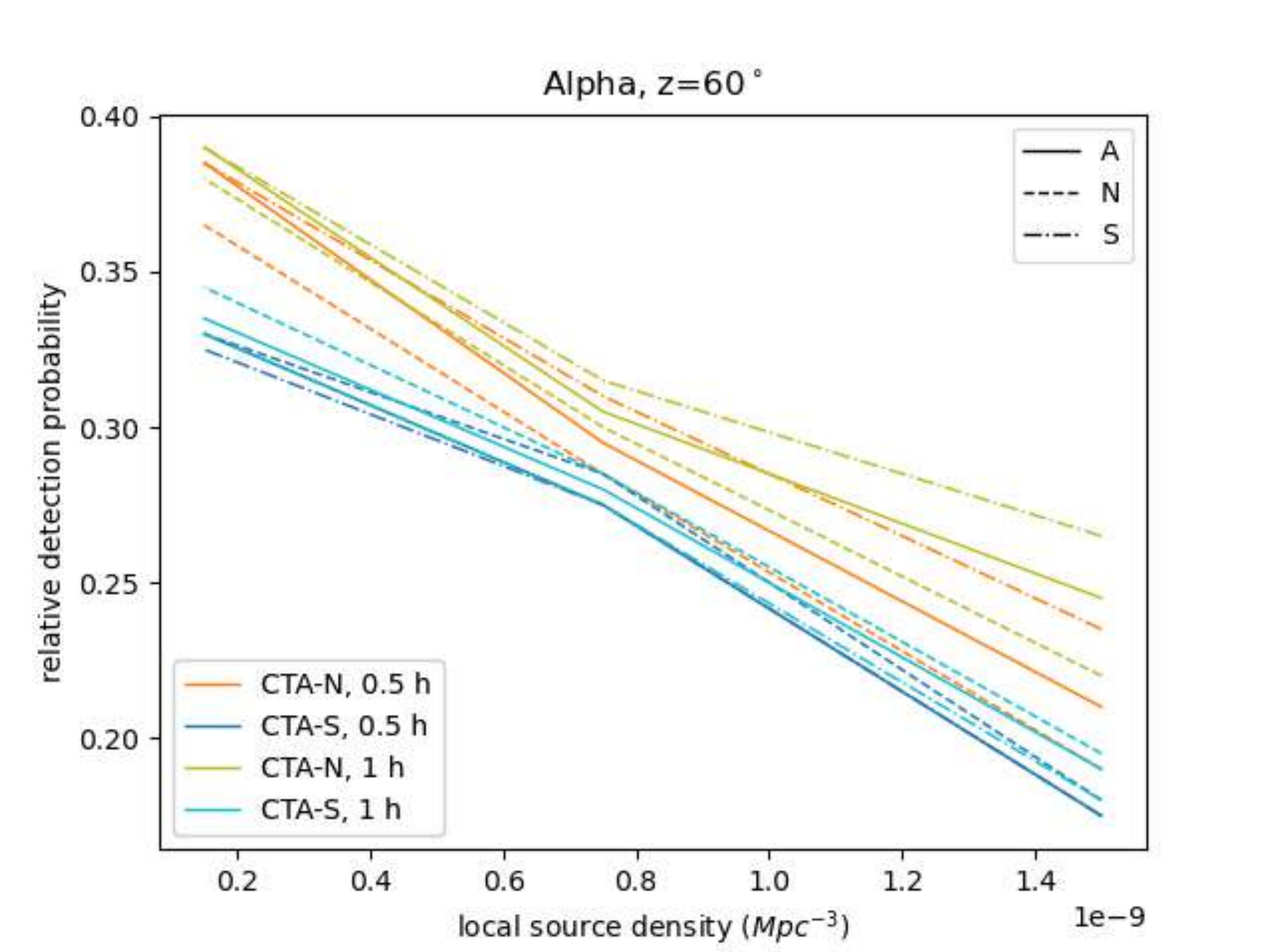


Transient Sources (Flaring blazars)

CTAO Alpha





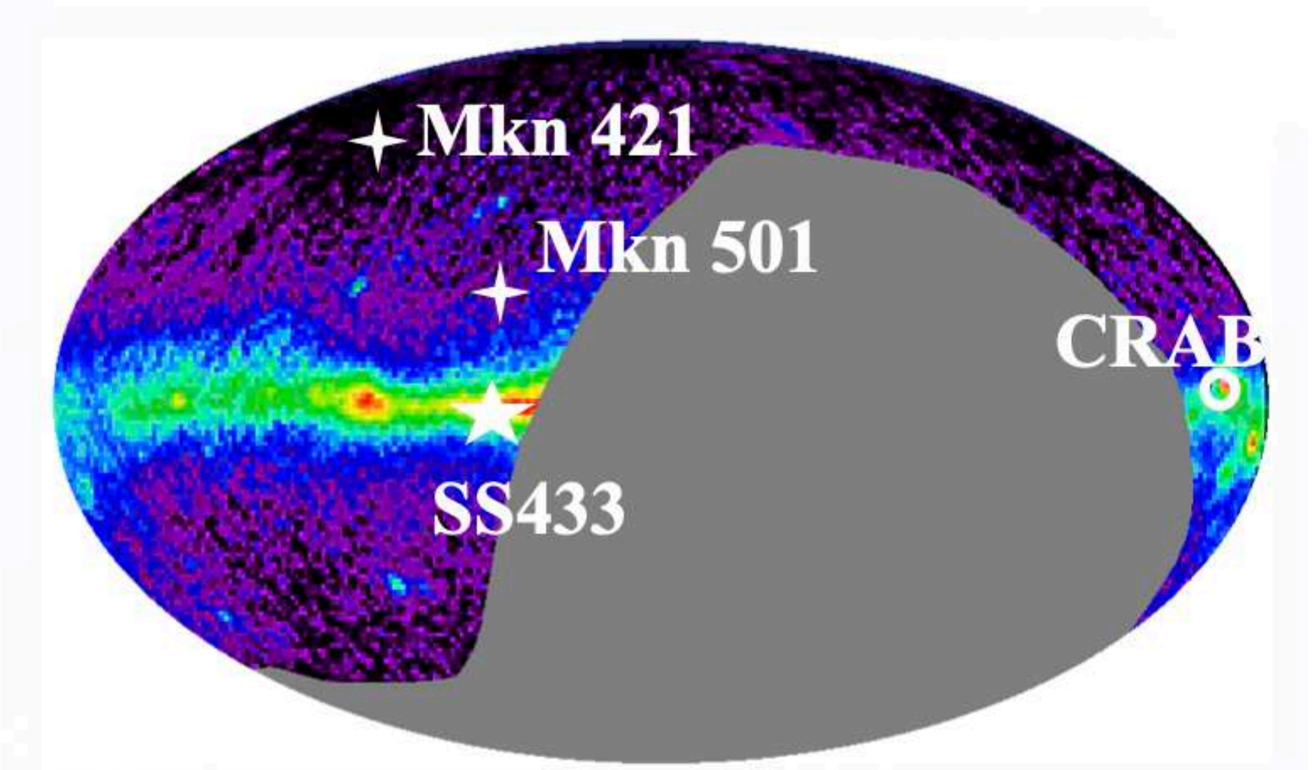


Detection probability for flaring blazars observed with the CTAO Alpha configuration for different durations of observation and geomagnetic field configurations

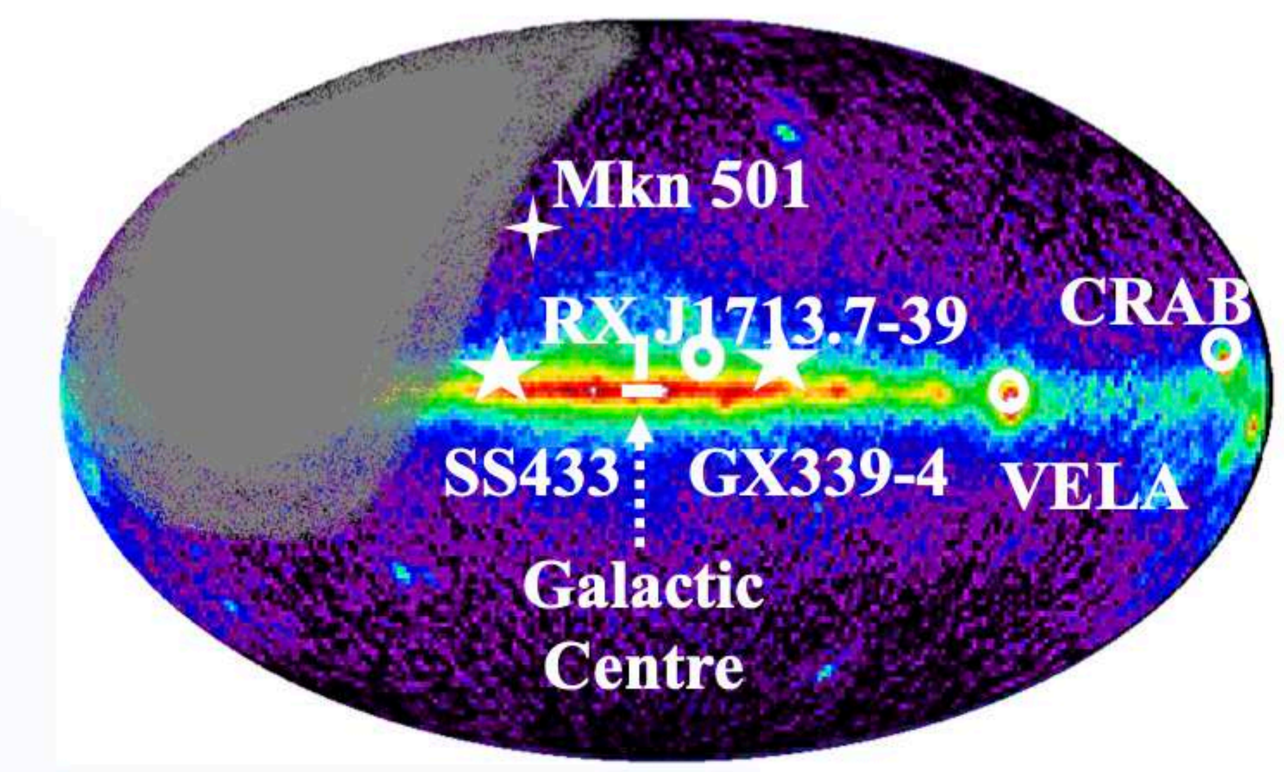
From IceCube to KM3NeT: Expanding the Neutrino Sky

IceCube	KM3NeT
2017 breakthrough	Mediterranean location
Real-time alerts	Better angular resolution
	Southern sky visibility

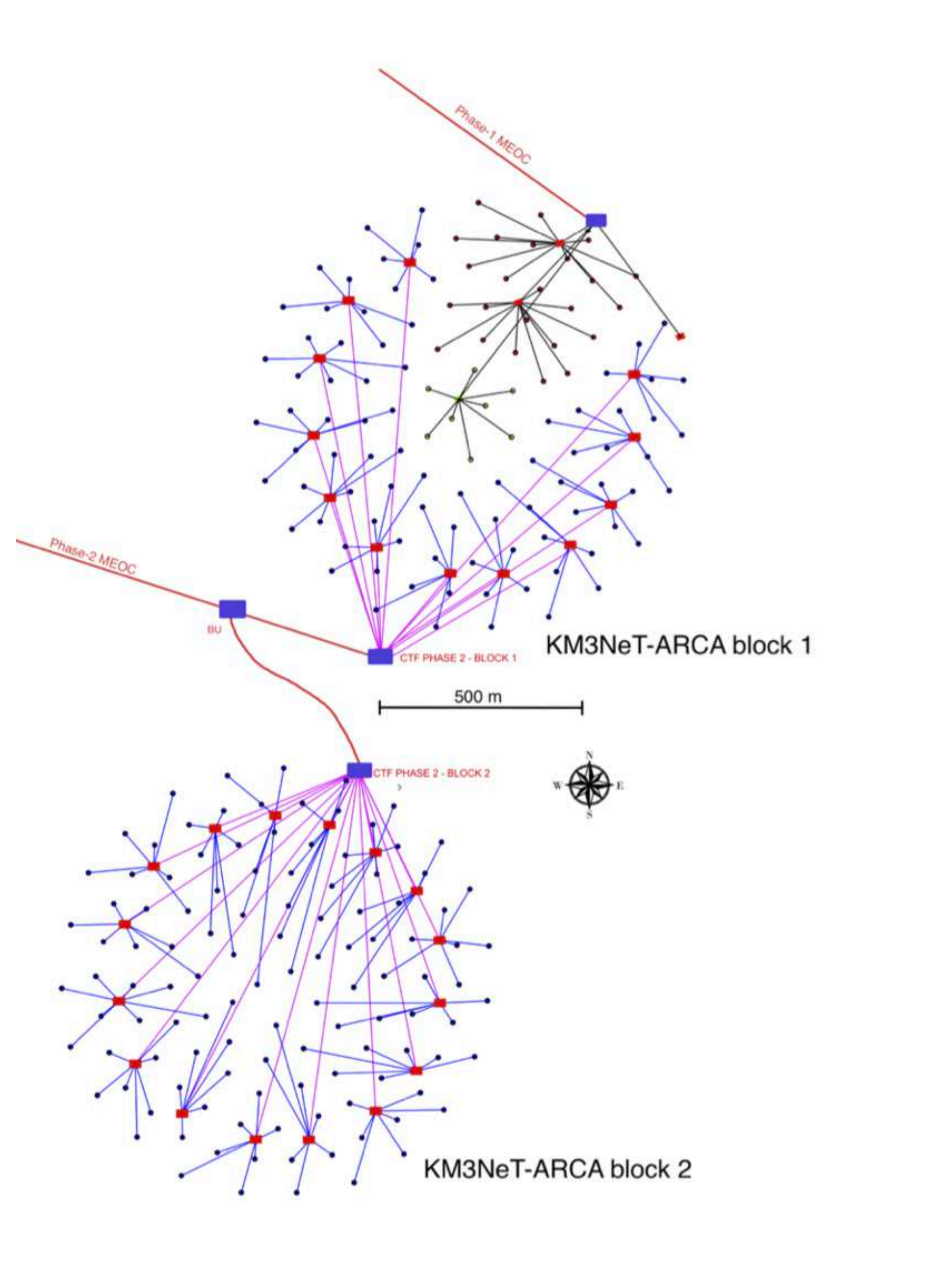
The sky seen from **IceCube**

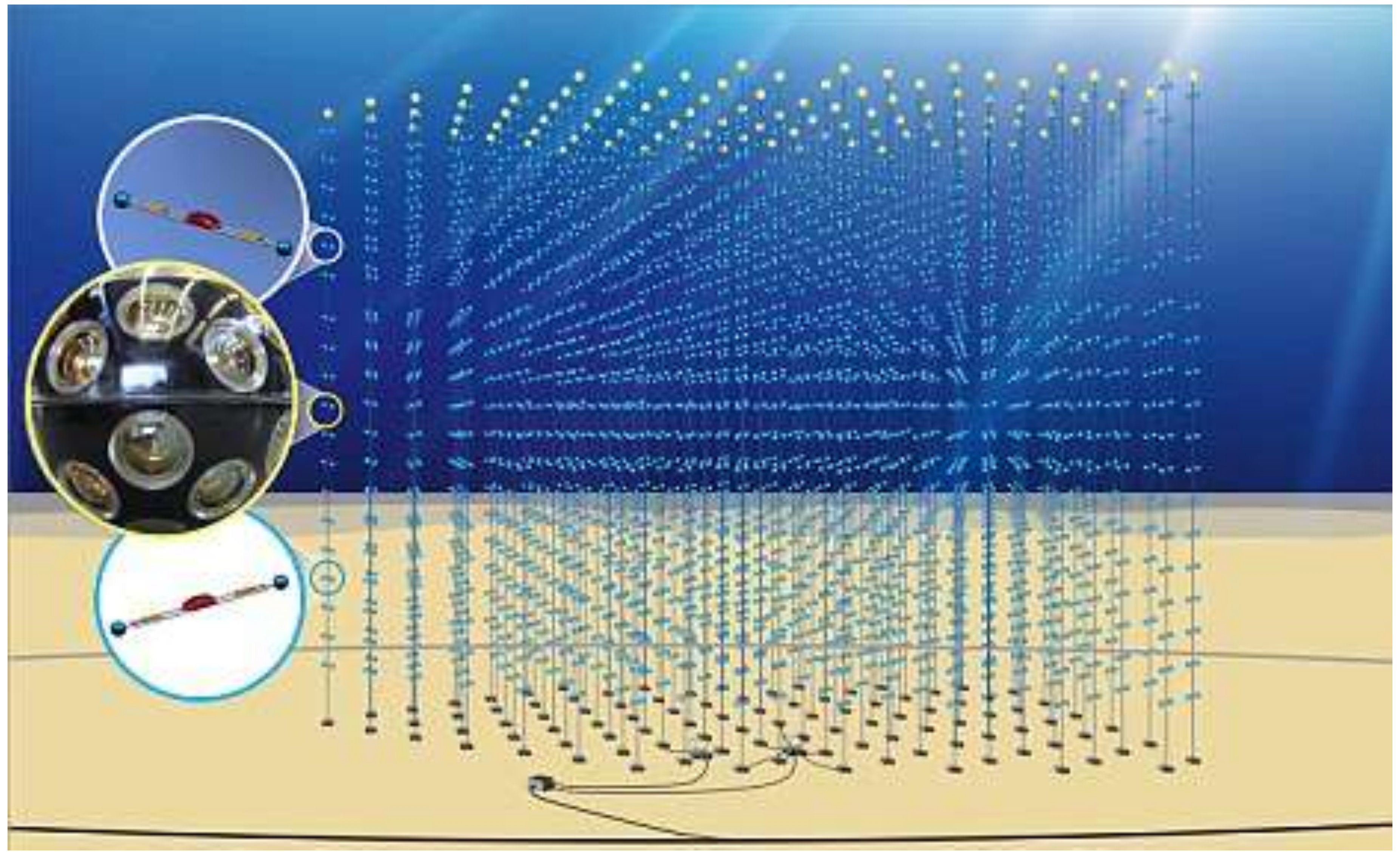


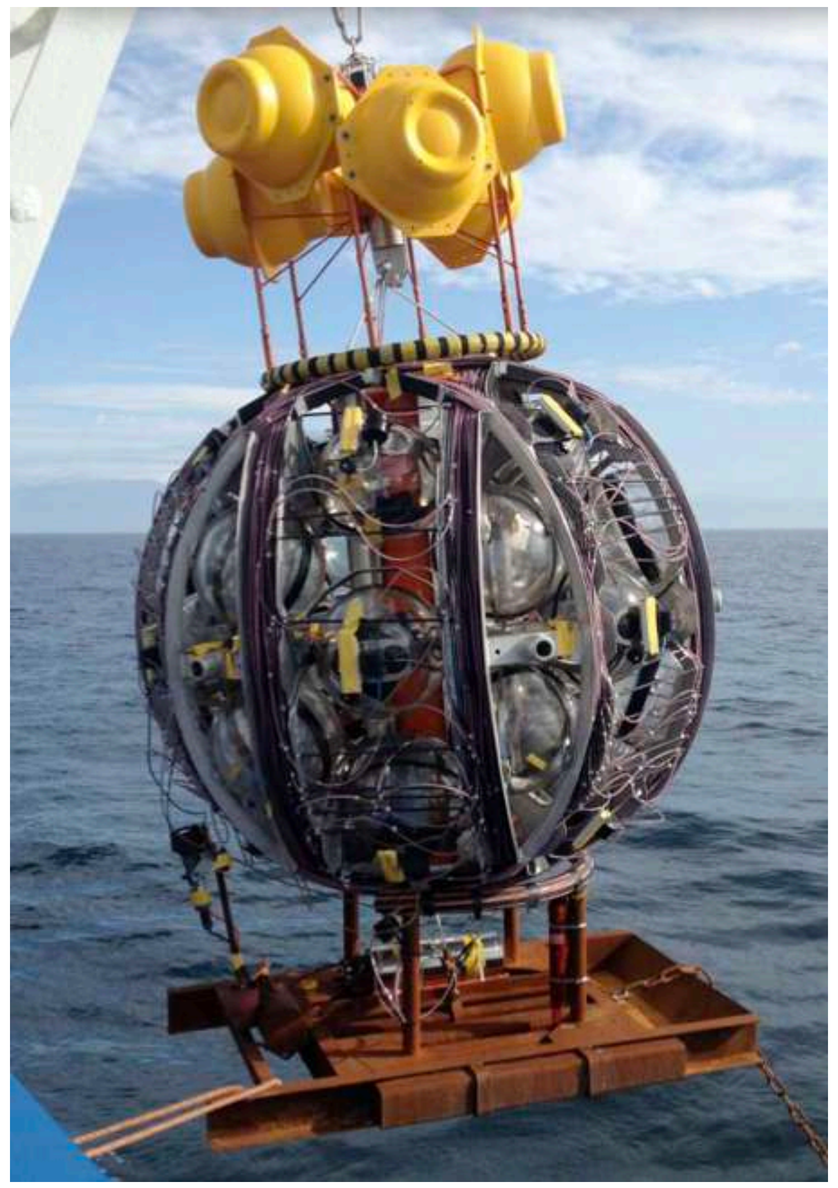
The sky seen from **KM3NeT**



KM3NeT ARCA: the Neutrino Telescope







ARCA:
- 2 building blocks of 115 DUs
- 90 m DU interspacing
- 36 m inter DOM spacing
- 0.5 km3 = 500Mton/block

The basic elements:
- DOM (Digital Optical Module)
- DU (Detection Unit)
- Electro-optical cables and JBs

From "The KM3NeT underwater neutrino telescope: status and future perspective", G. Ferrara, TIPP2023

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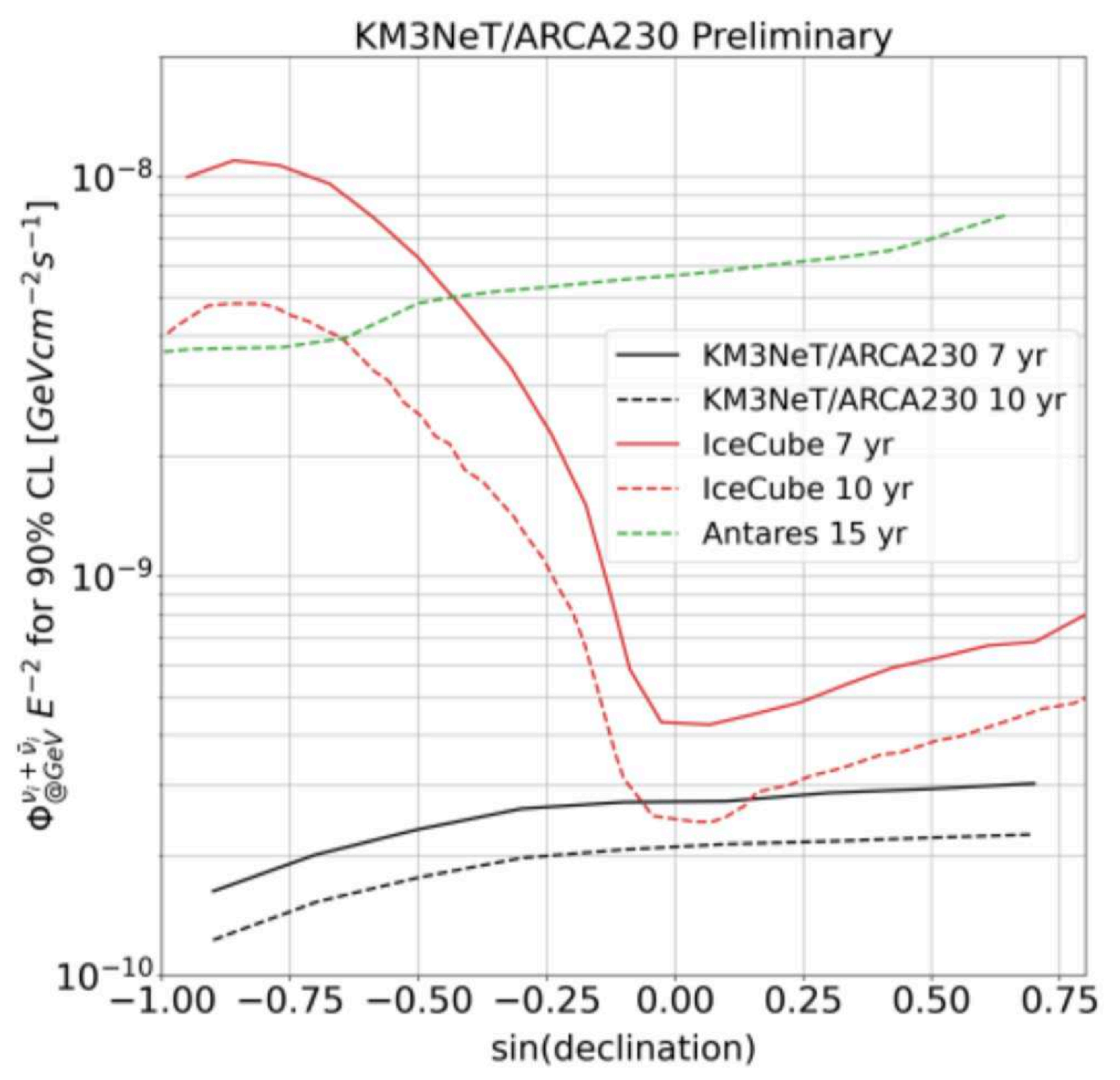
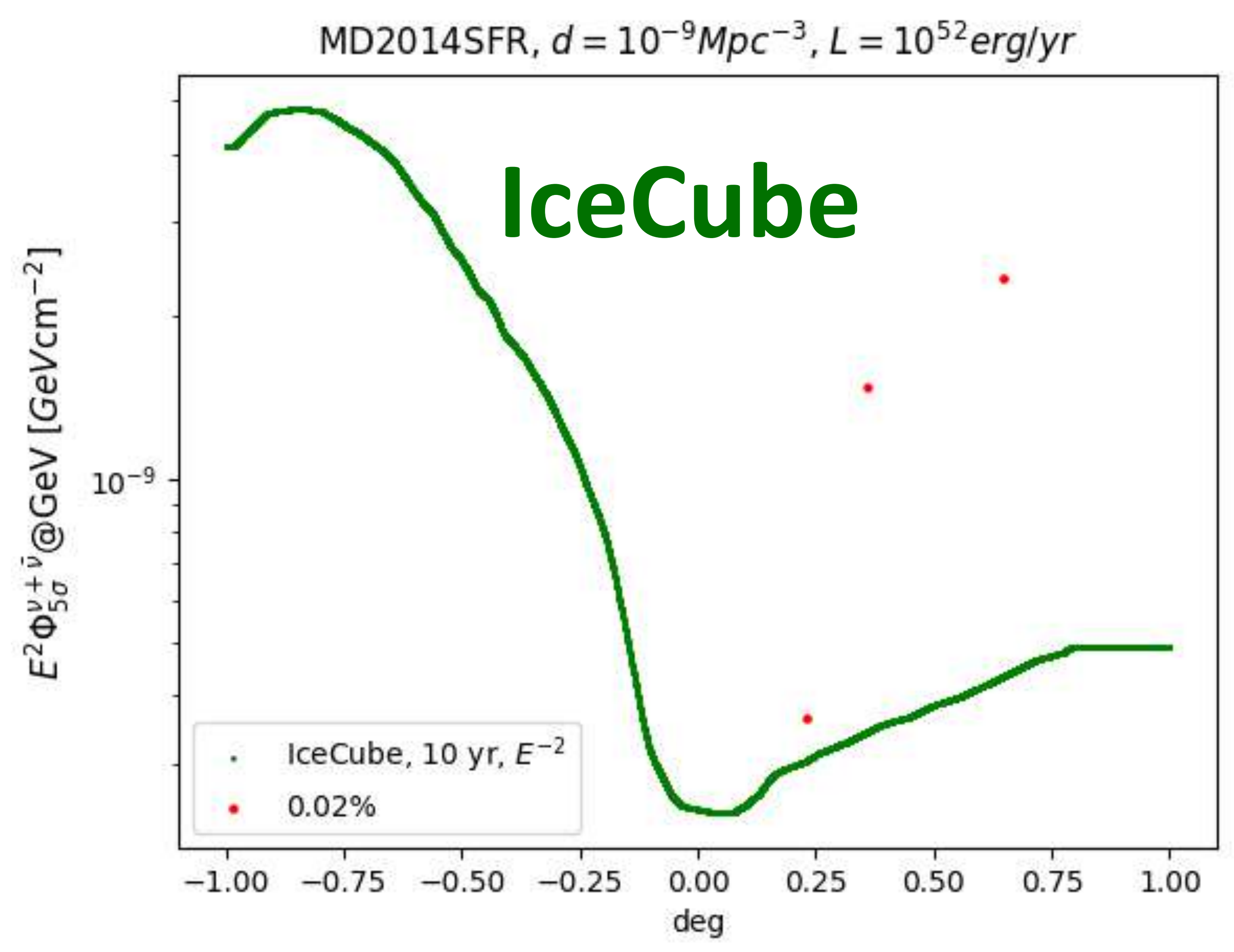
Neutrino Telescope Filter

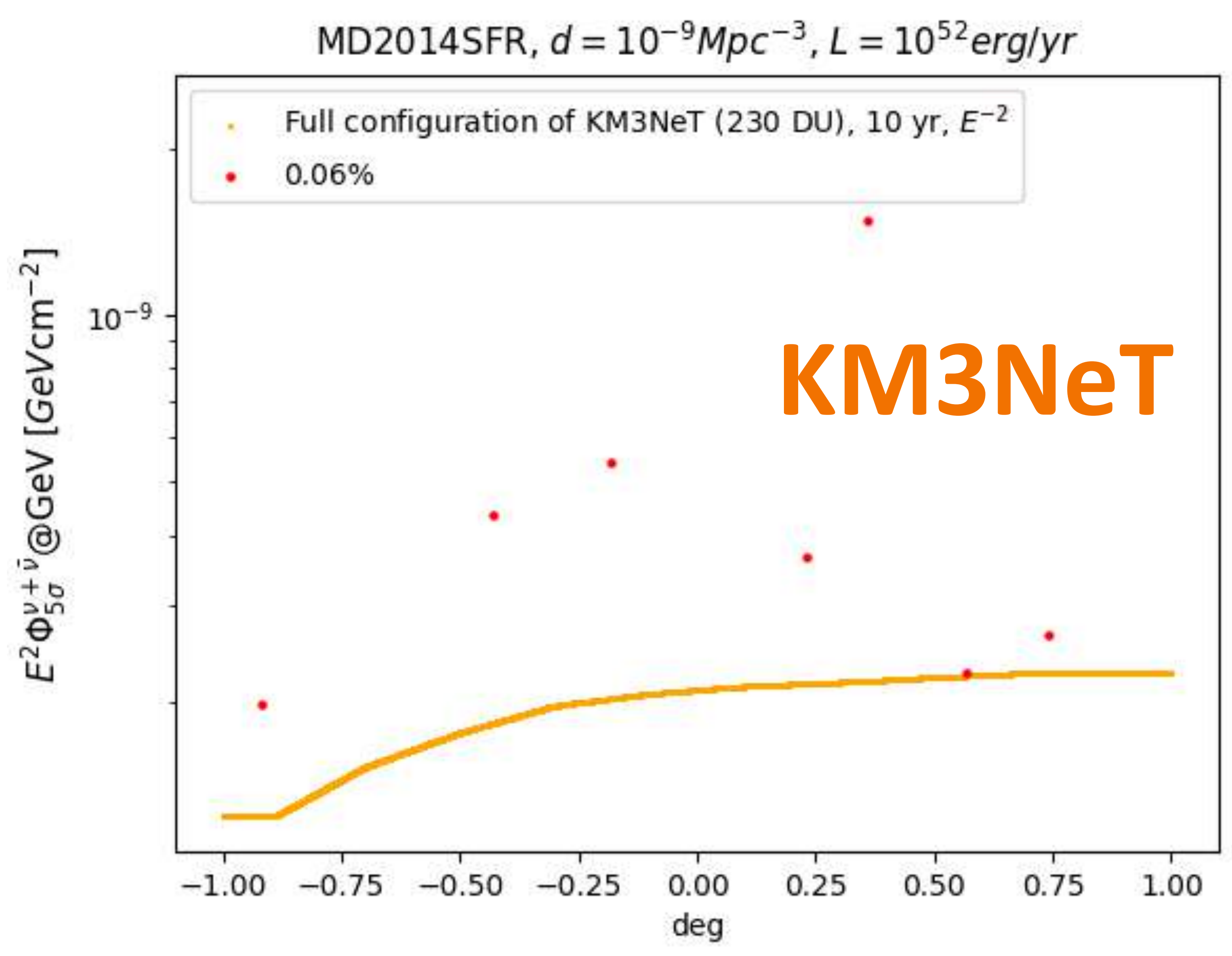
Discovery potential of KM3NeT

Neutrino Telescope Filter



KM3NeT Collaboration, PoS ICRC2023 1075





The red dots represent the neutrinos sources that exceed (with a confidence level of 5σ) the discovery potential of the two neutrino telescopes, which correspond to 0.02% and 0.06% of the sources detected by IceCube and KM3NeT, respectively.

4

CTA performance

CTAO detection probability

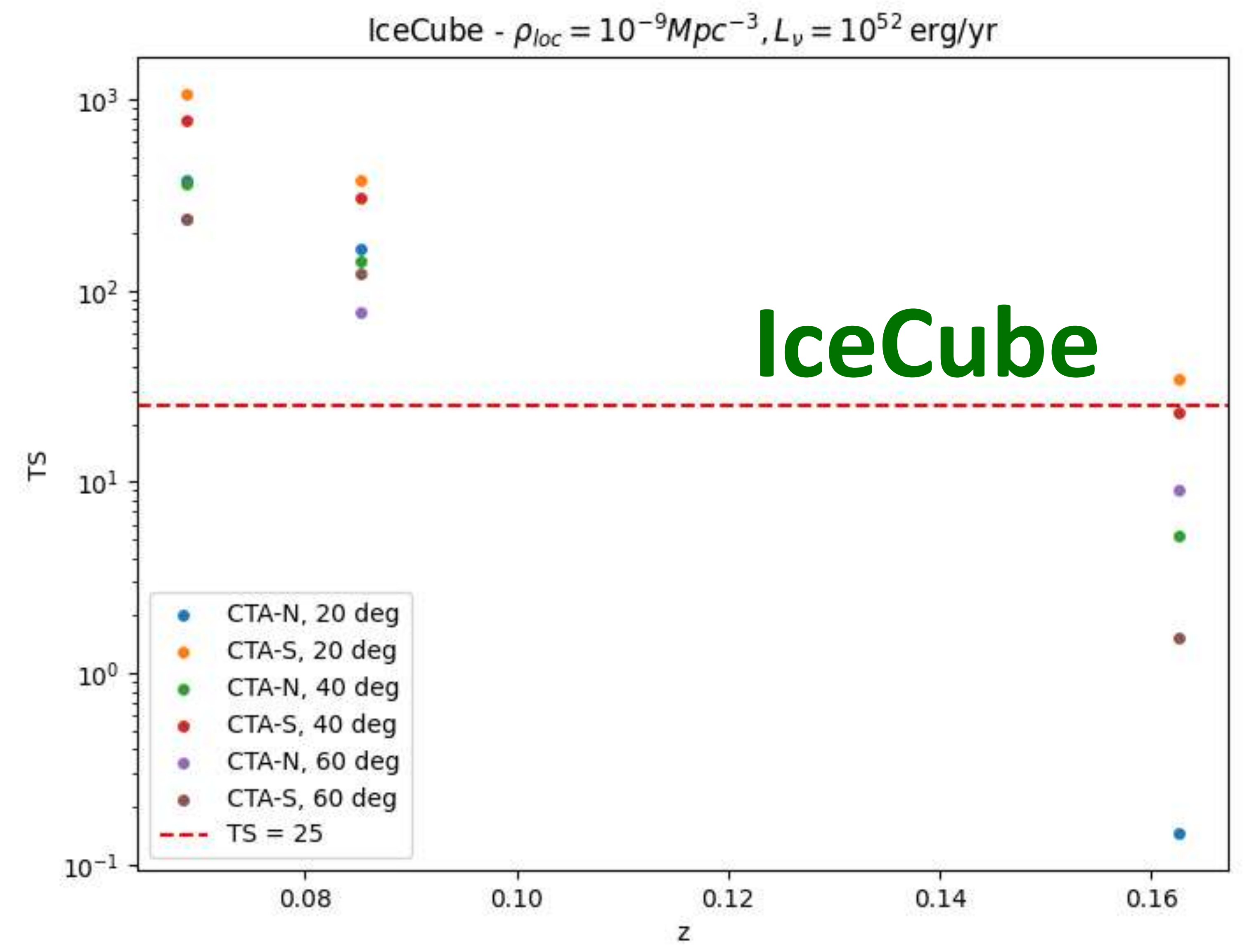
Detection rates and significances of KM3NeT an IceCube

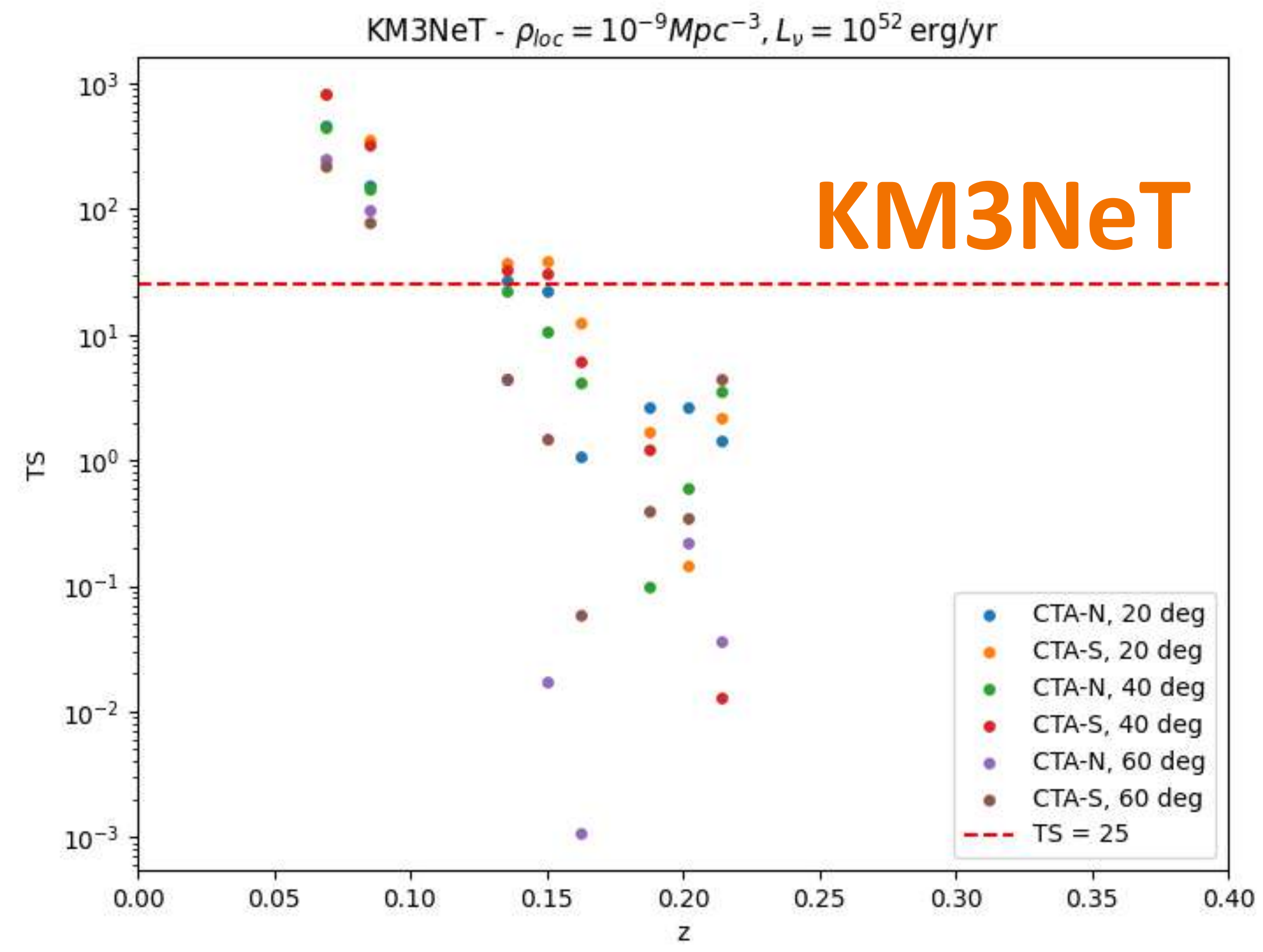
IceCube

Z	N	S
20°	67%	100%
40°	67%	67%
60°	67%	67%

KM3NeT

Z	N	S
20°	37.5%	50%
40°	37.5%	50%
60°	37.5%	25%





Detection rates of simulated neutrino sources observed by IceCube and KM3NeT respectively, whose gamma-ray emission is detected with CTAO (for TS>25), assuming $d = 10^{-9}\ Mpc^{-3}$ and $L = 10^{52}\ erg/yr$.

4

CTA performance

CTAO detection probability

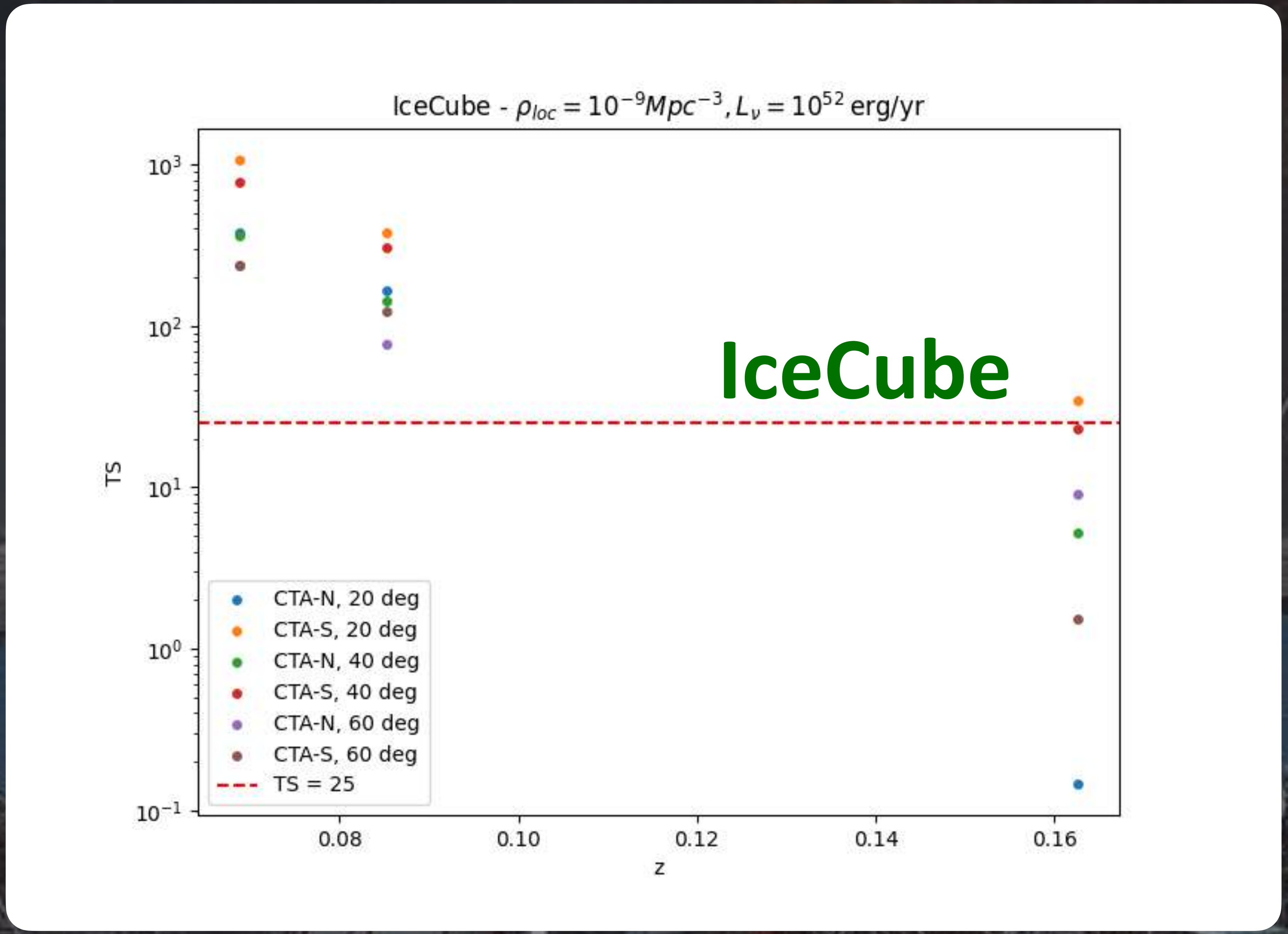
Detected sources - KM3NeT vs IceCube

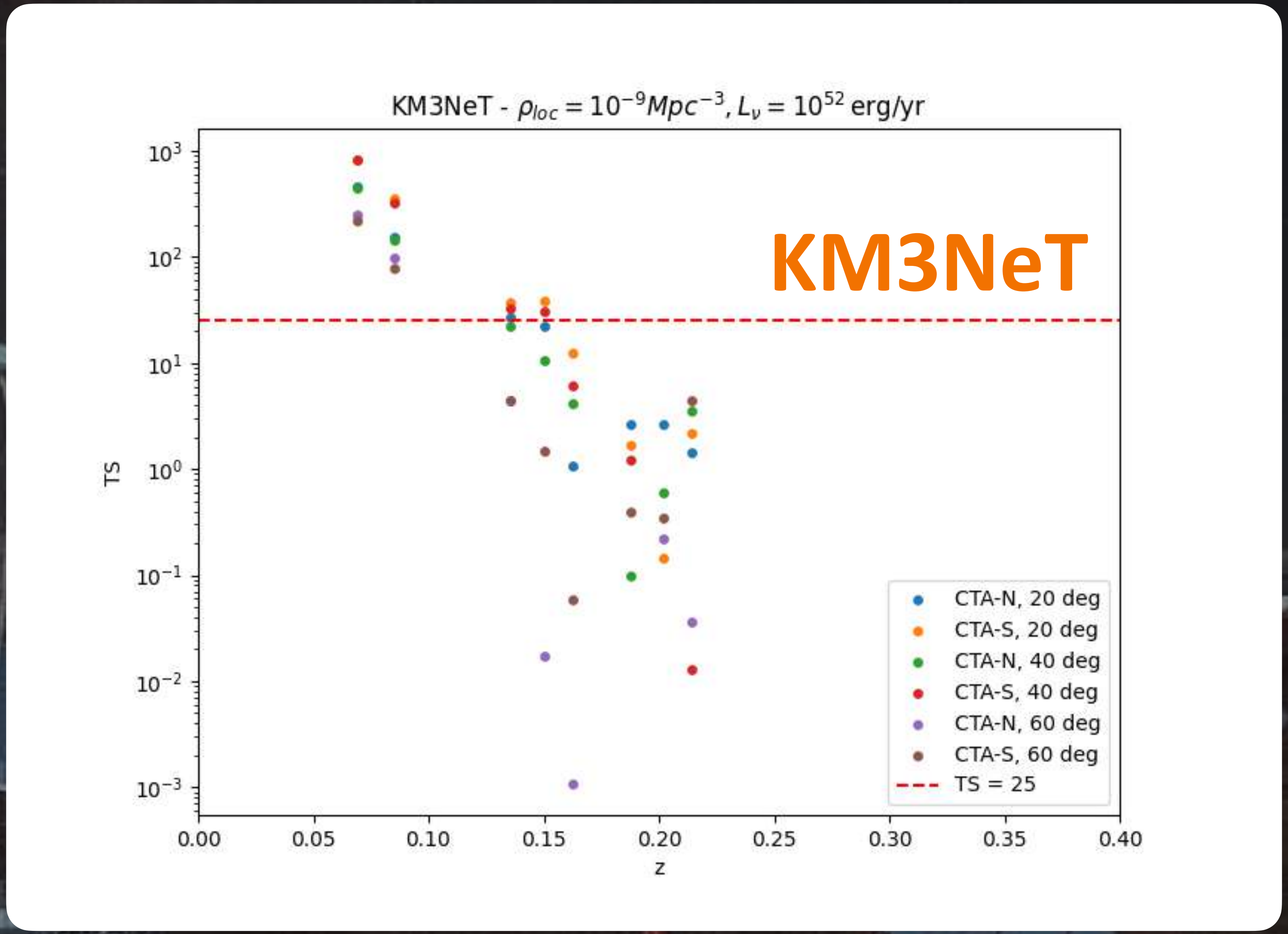
IceCube

Z	N	S
20°	67%	100%
40°	67%	67%
60°	67%	67%

KM3NeT

Z	N	S
20°	37.5%	50%
40°	37.5%	50%
60°	37.5%	25%





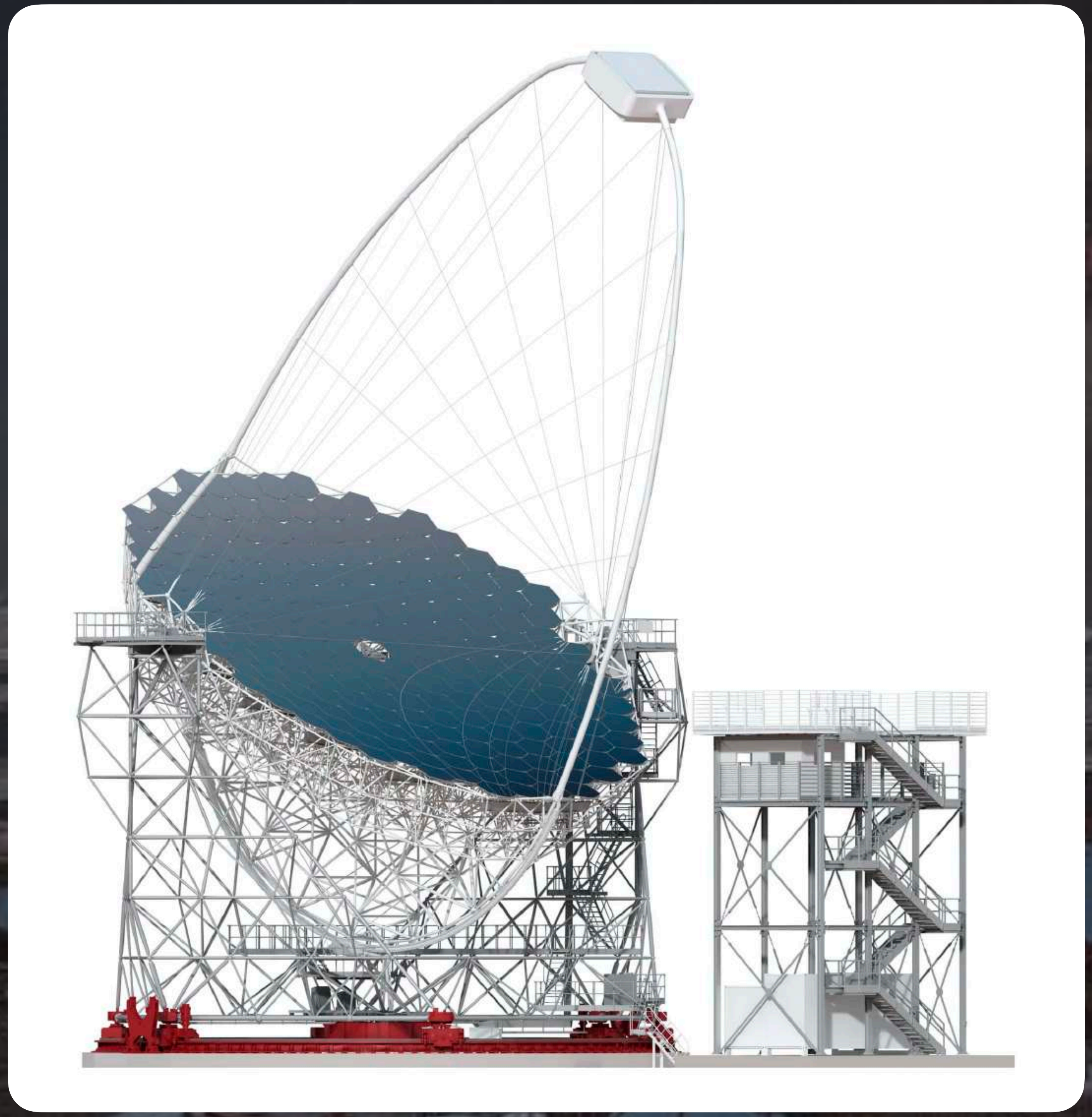
The detection rates for KM3NeT are lower, but it is capable of observing more sources than IceCube, including more distant and fainter sources.

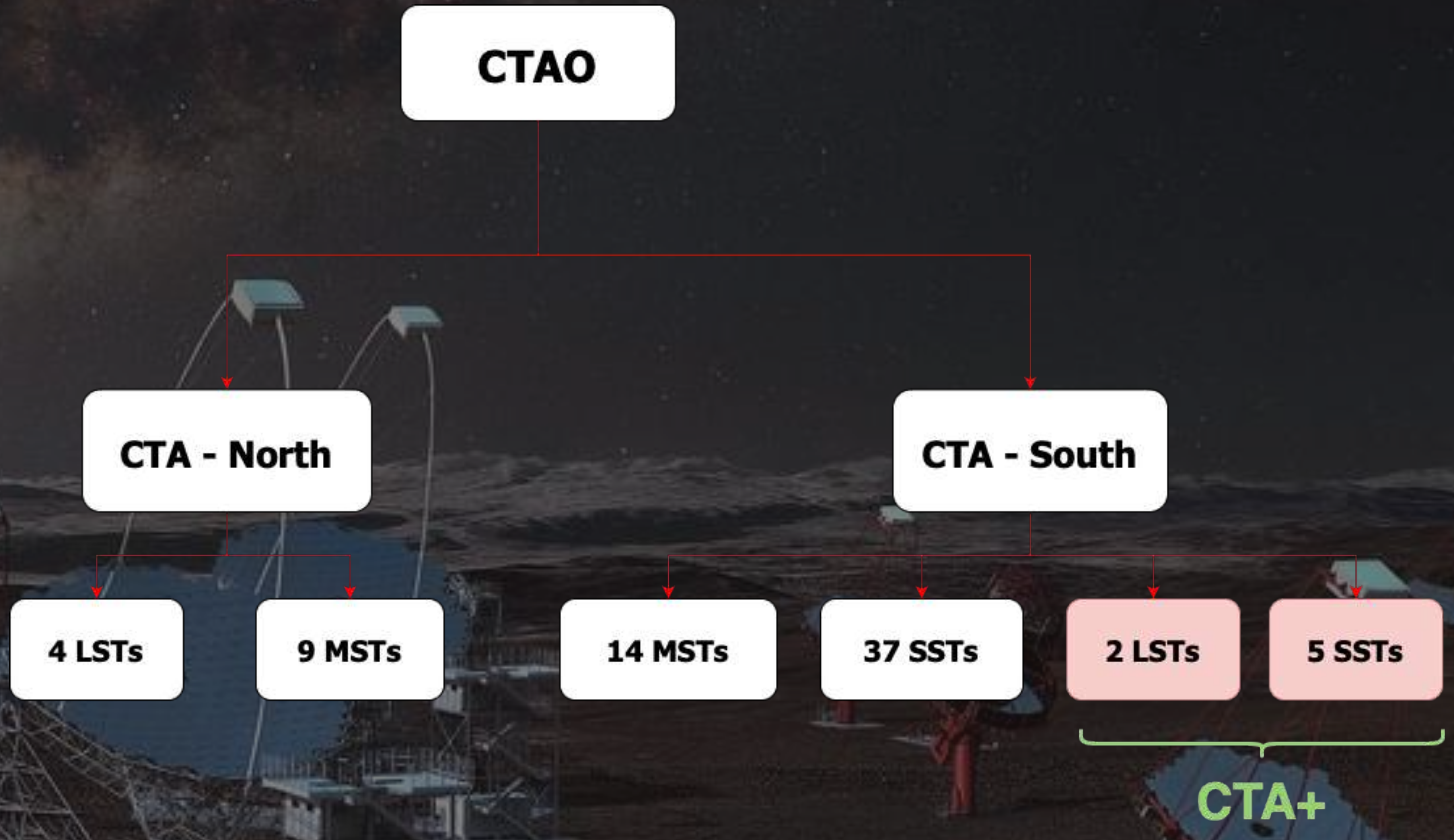
4

CTA performance

CTAO detection probability

The CTA+ project for CTAO





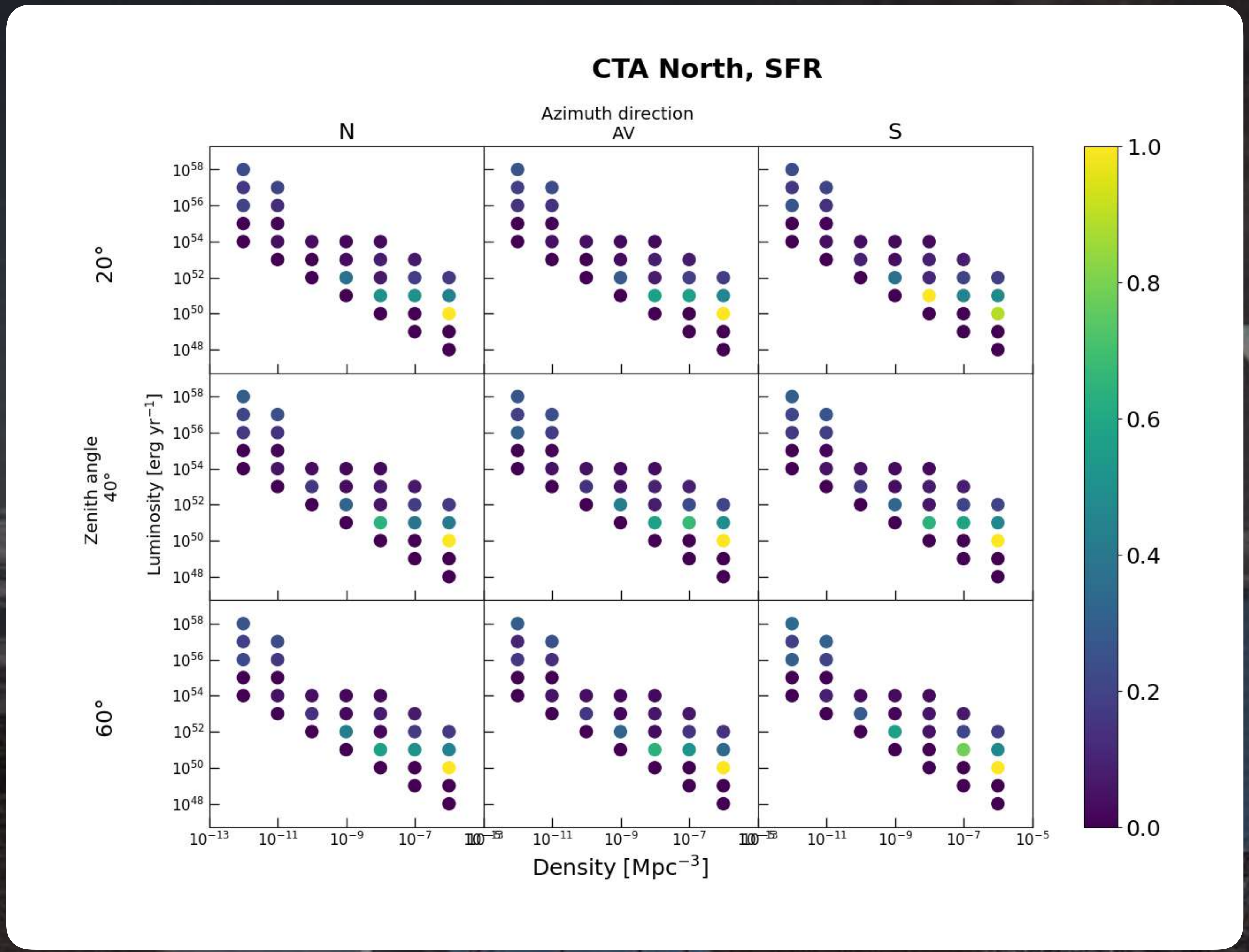
The detection probability for CTAO is lower for KM3NeT than for IceCube due to their different capabilities, although it is expected to improve once the **new configuration** —including two southern LSTs planned by the Italian CTA+ project— is implemented.

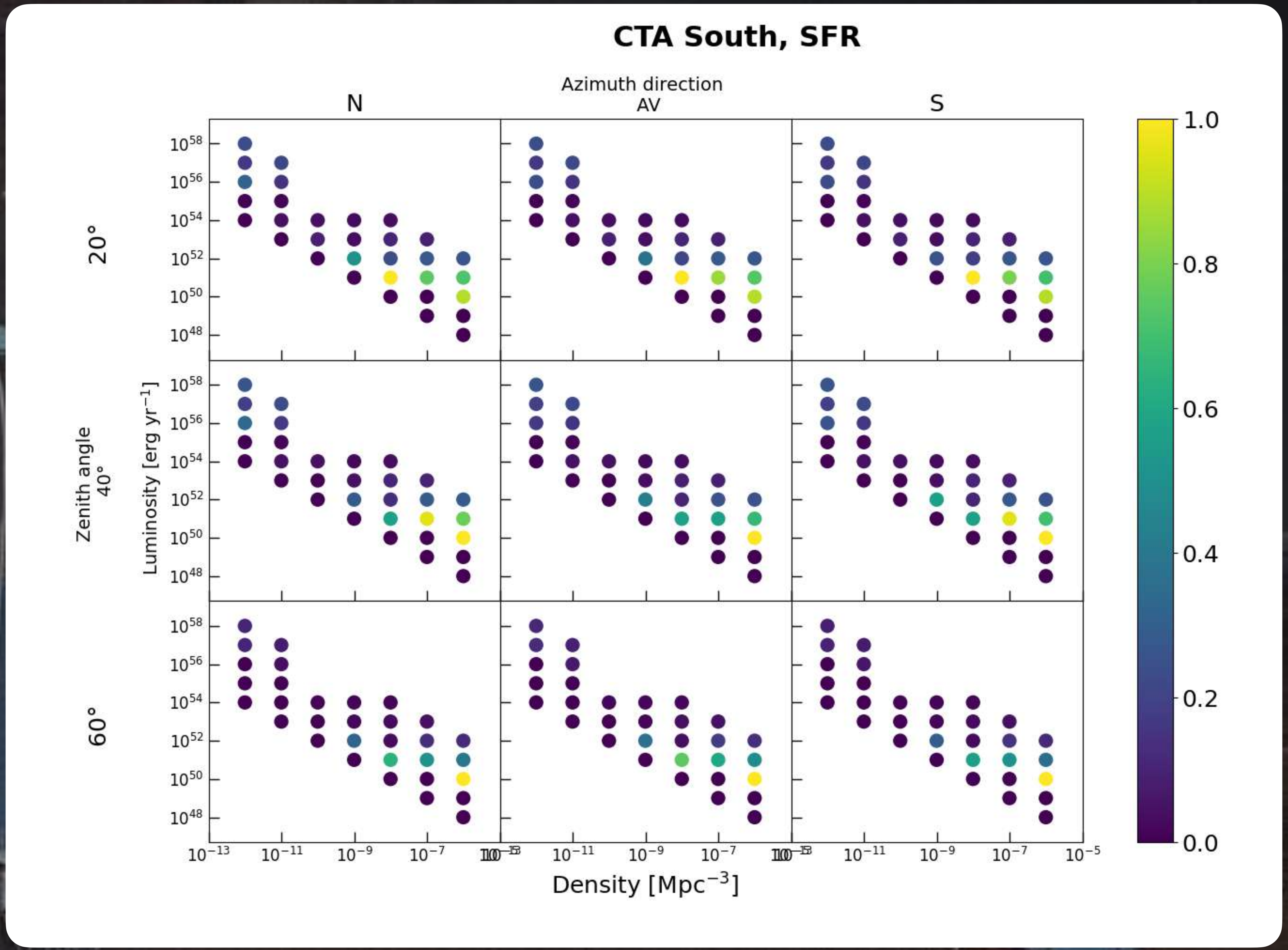
4

CTA performance

CTAO detection probability

CTAO performance





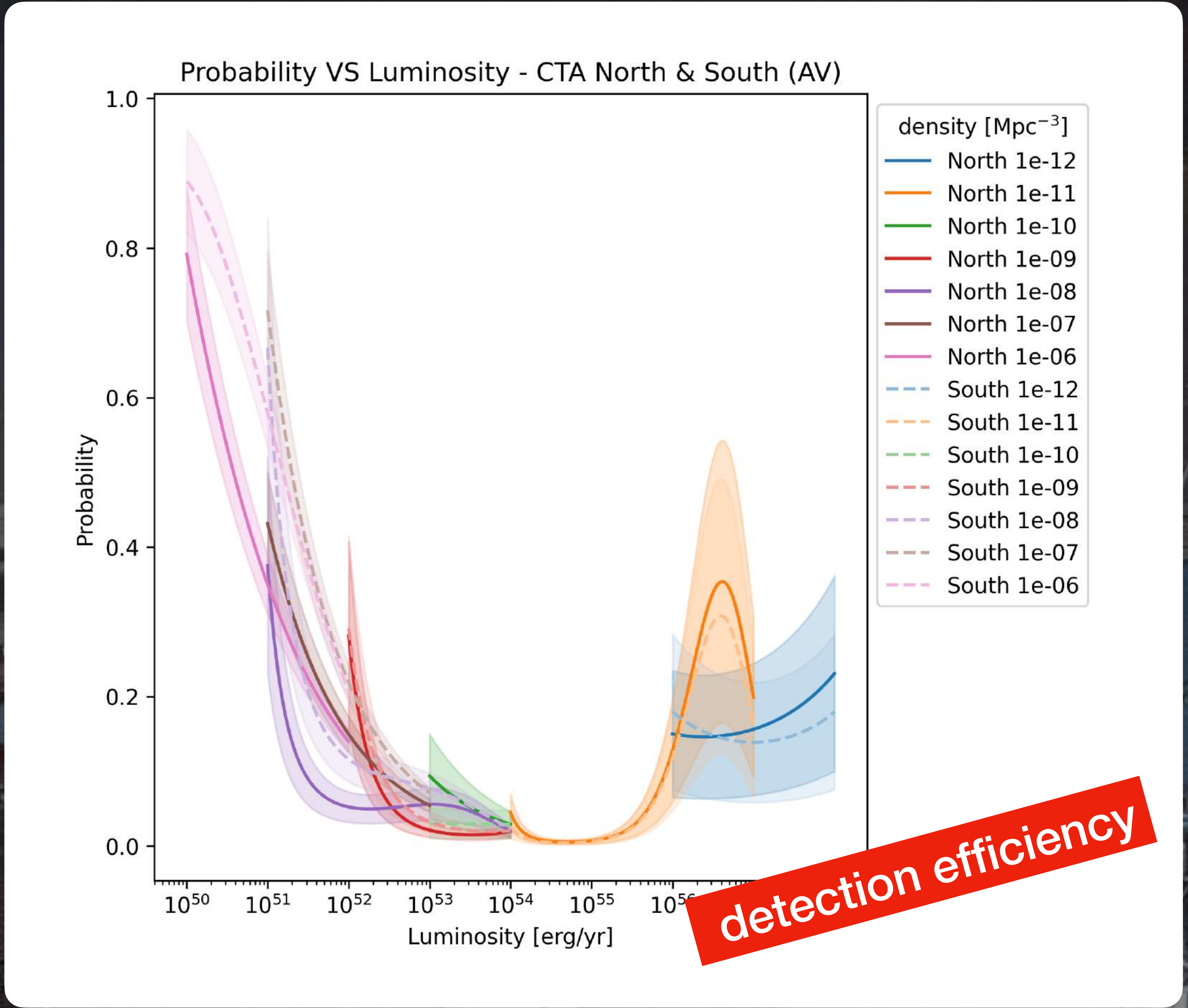
Detection probability maps for CTAO-South (left) and CTAO-North (right), for sources with luminosities below 10^{52} erg/yr and source densities ranging from 10^{-11} to 10^{-6} Mpc^{-3}.

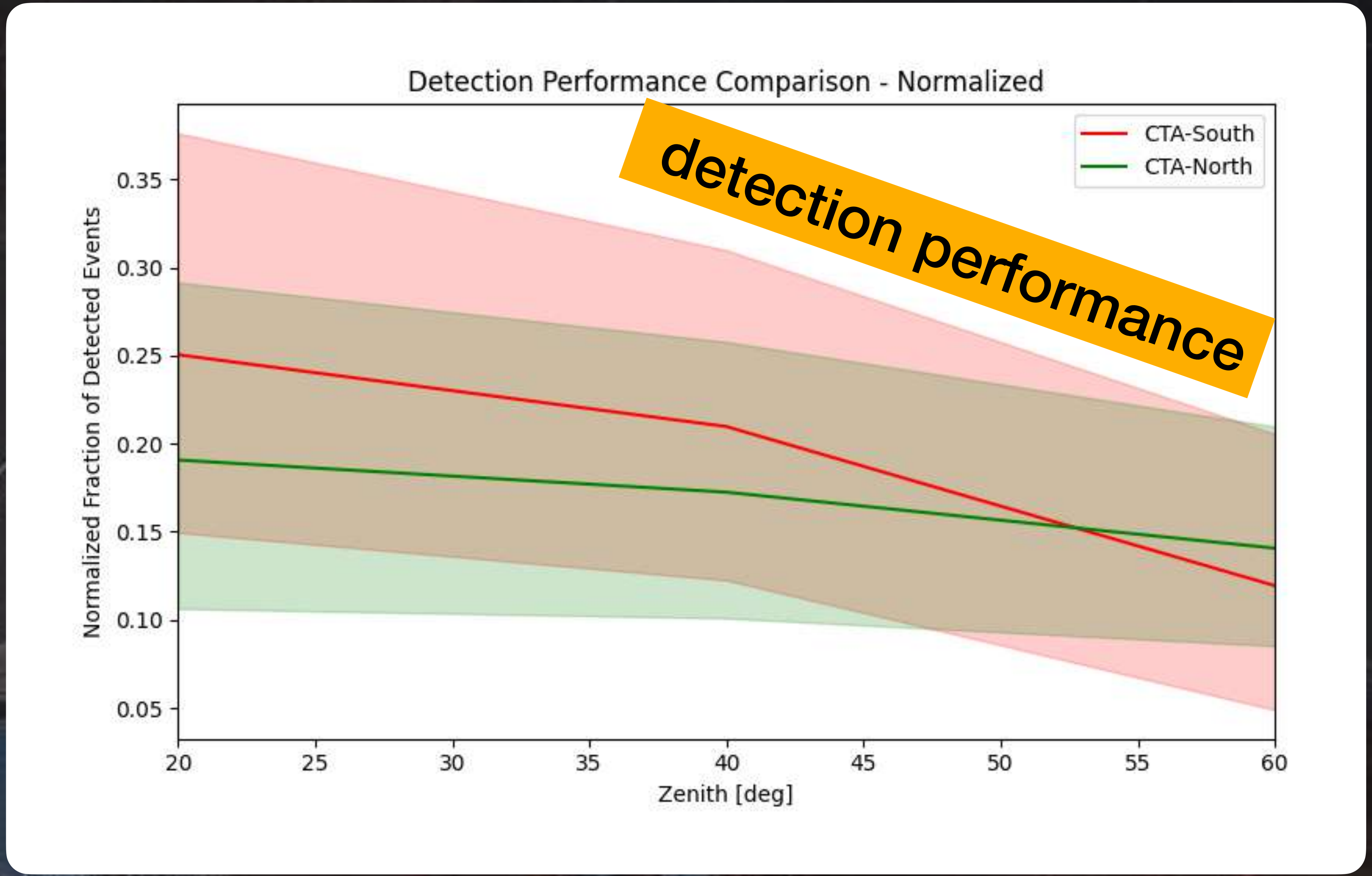
Detection efficiency and performance

4

CTA performance

CTAO detection probability





The plot shows the **detection efficiency** as a function of luminosity. The y-axis represents the detection probability, while the x-axis corresponds to the source luminosity. Each curve corresponds to a different density.

The upper panel shows the **detection performance** of the North (green) and South (red) arrays. The y-axis indicates the fraction of detected and undetected events, while the x-axis represents the zenith angle (i.e., the angle between the zenith and the observed point in the sky).

Conclusions and Future perspectives

IceCube

- **Detection prospects:** up to **37%** chance for flaring blazars in **30 min** observations.
- **Flare duration: ~82 days** (source frame) → it allows observation **within 1 month** after neutrino alert.
- **Expected detections:** ~2.4 – 3.4 flaring sources/year, mainly near the celestial equator (IceCube sensitivity peak).
- **Steady sources:** high CTAO detection probability in specific parameter regions.

KM3NeT

- **CTAO–KM3NeT performance:** current detection probability **lower** than for IceCube, due to array differences (north vs south).
- **Future improvement:** expected with **two new LSTs** in the south (Italian **CTA+** project).
- KM3NeT advantage: can observe more **numerous**, **distant** and **faint sources** than IceCube.
- **Software development:** new Gammapy code with better performance and faster processing → it allows transient observations.

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Thanks for your attention!