Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
CTAO
INFN Istituto Nazionale di Fisica Nucleare

Detecting Gamma-Ray Counterparts of High-Energy Neutrino Events with KM3NeT and CTAO

Gloria Maria Cicciari, University of Palermo and INFN Catania, NToO for CTA

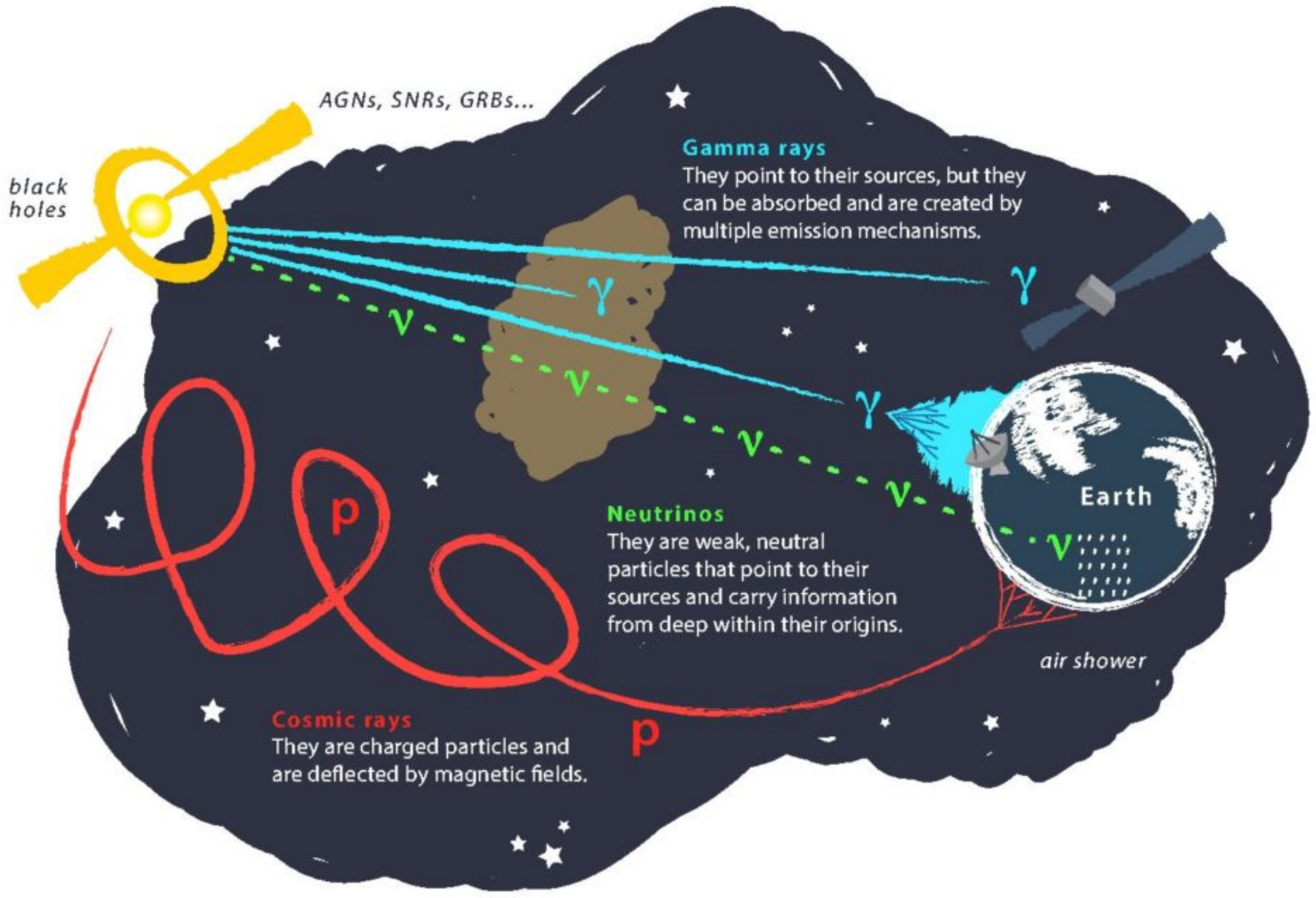
Outline

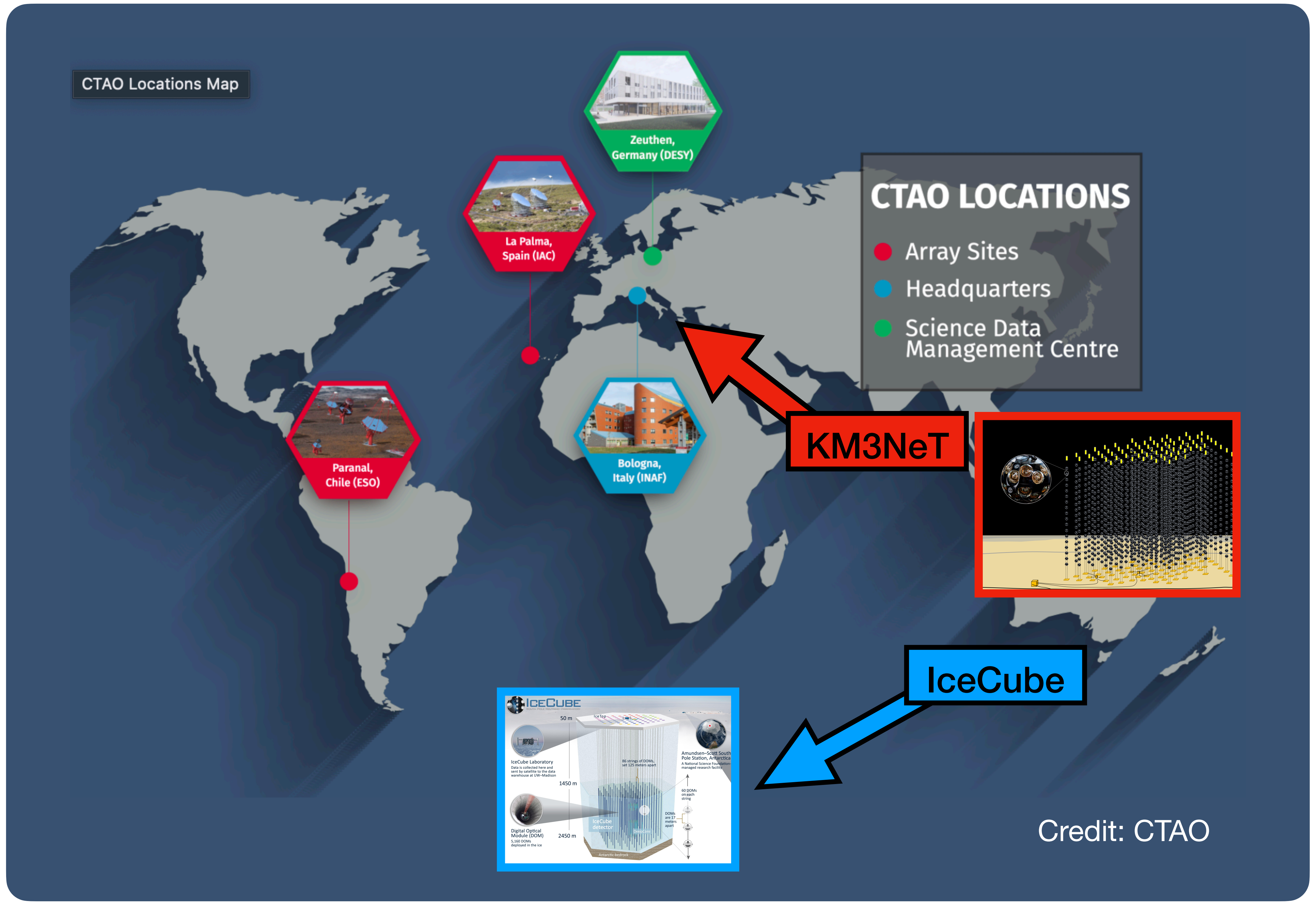
- Multi-messenger astronomy
- Neutrino and gamma-ray telescopes
- Neutrino Target of Opportunity (NToO)
    - Neutrino Simulations
    - Gamma Simulations
    - CTAO Performance
- Next steps

Outline

- Multi-messenger astronomy

Cosmic Messenger Connection





IceCube-170922A & TXS 0506+056

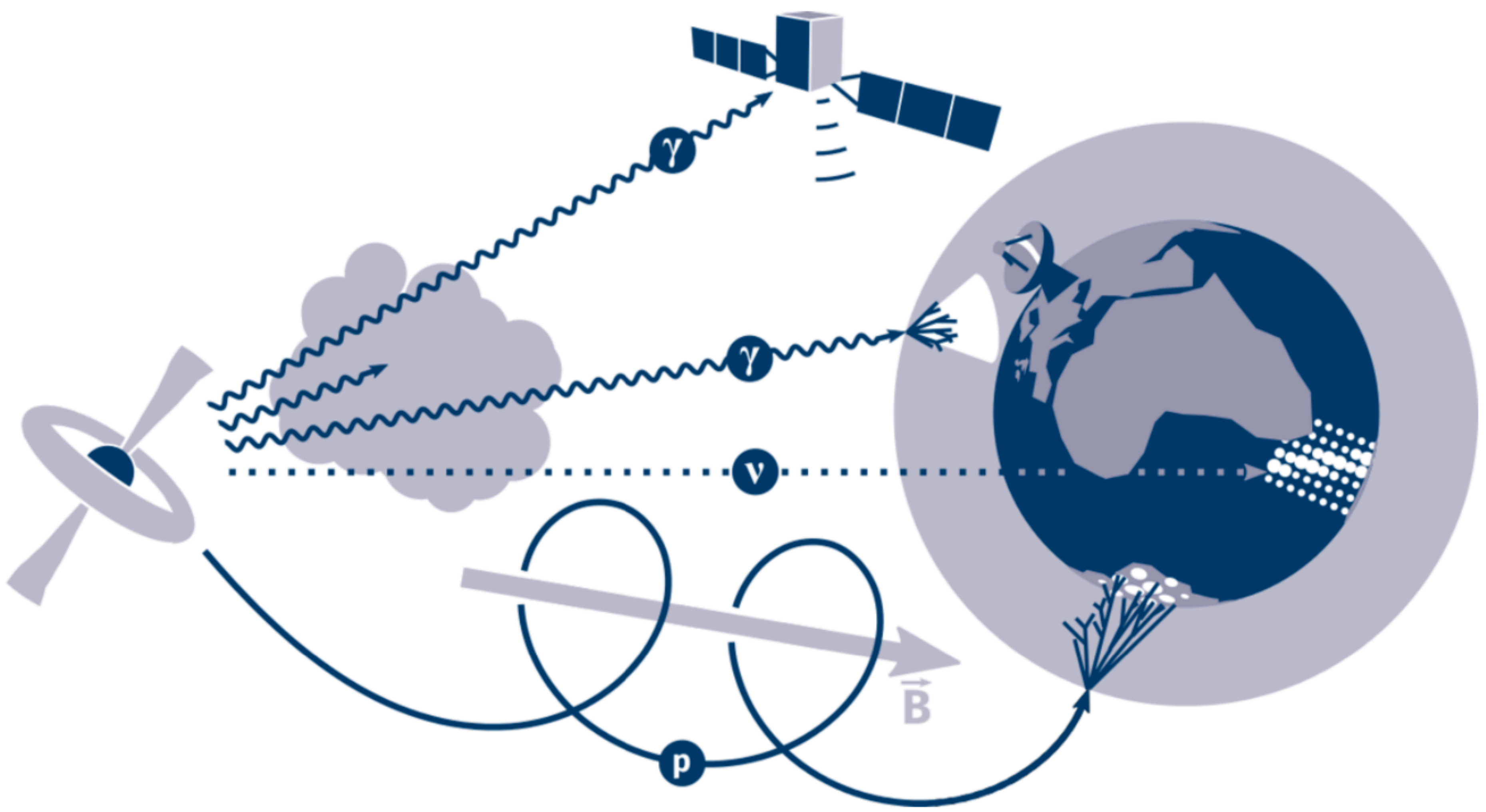


Figure 1.43: Multi-messenger picture of an astrophysical object. Image Credits: Inter-University Institute For High Energies; www.iihe.ac.be/icecube, last accessed on 01/08/22.

Follow-up Observations

23 Sep 2017: H.E.S.S. and VERITAS

24/28 Sep 2017: MAGIC, HAWC, AGILE (Radio, Optical and X-rays)

22 September 2017

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

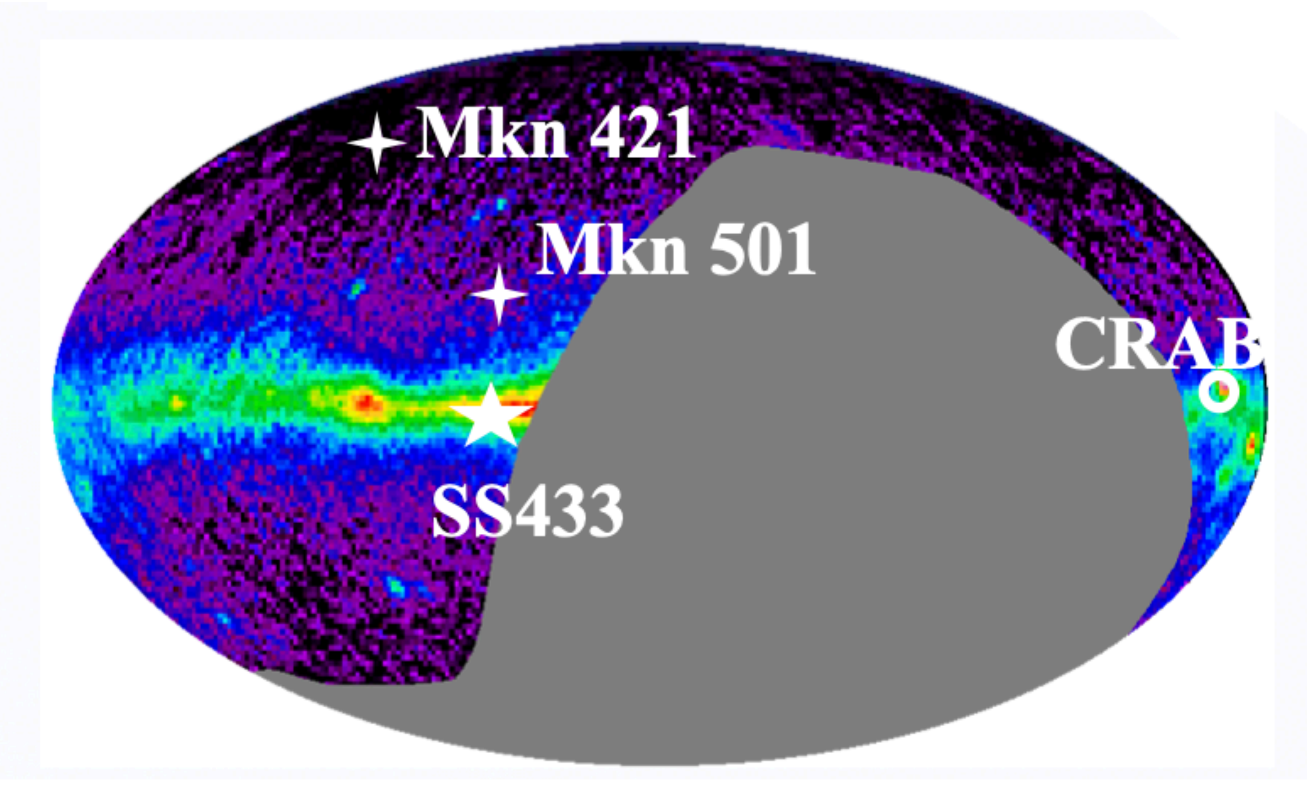
28 September 2017

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

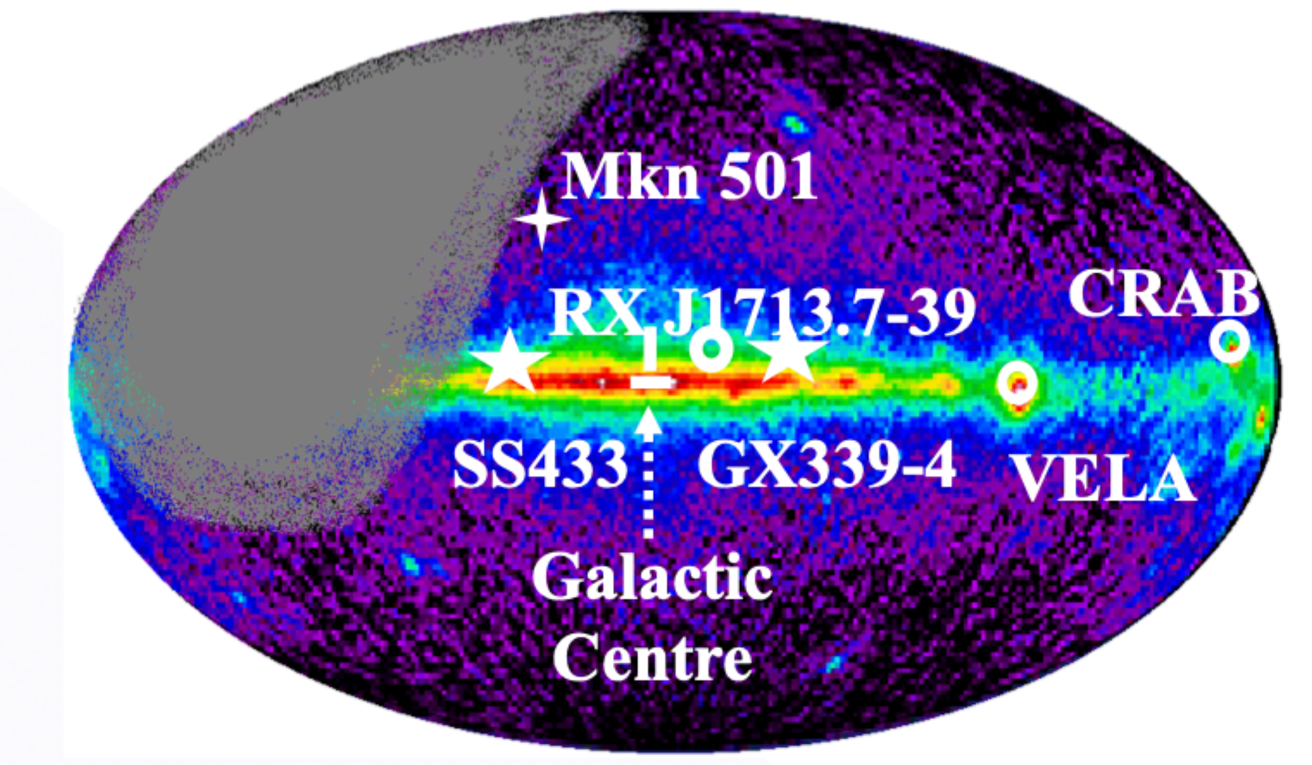
From IceCube to KM3NeT: Expanding the Neutrino Sky

- The 2017 IceCube event marked a turning point in neutrino astronomy.
- It demonstrated the potential of real-time alerts and follow-ups at multiple wavelengths.
- KM3NeT, now under construction in the Mediterranean Sea, will **extend and complement** IceCube's range.
- With improved angular resolution and optimal visibility of the southern sky, KM3NeT aims to **improve the potential for discovering cosmic neutrino sources.**

The sky seen from **IceCube**



The sky seen from **KM3NeT**



Outline

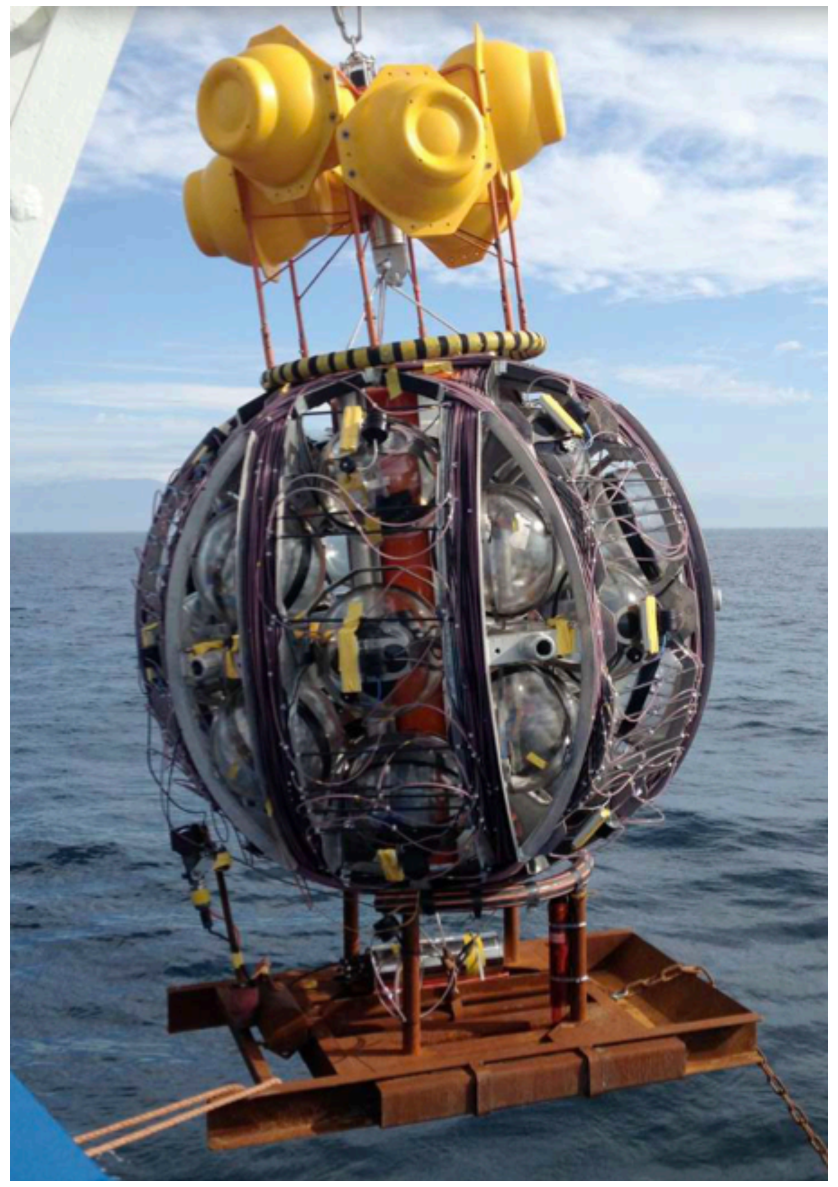
- Neutrino and gamma-ray telescopes

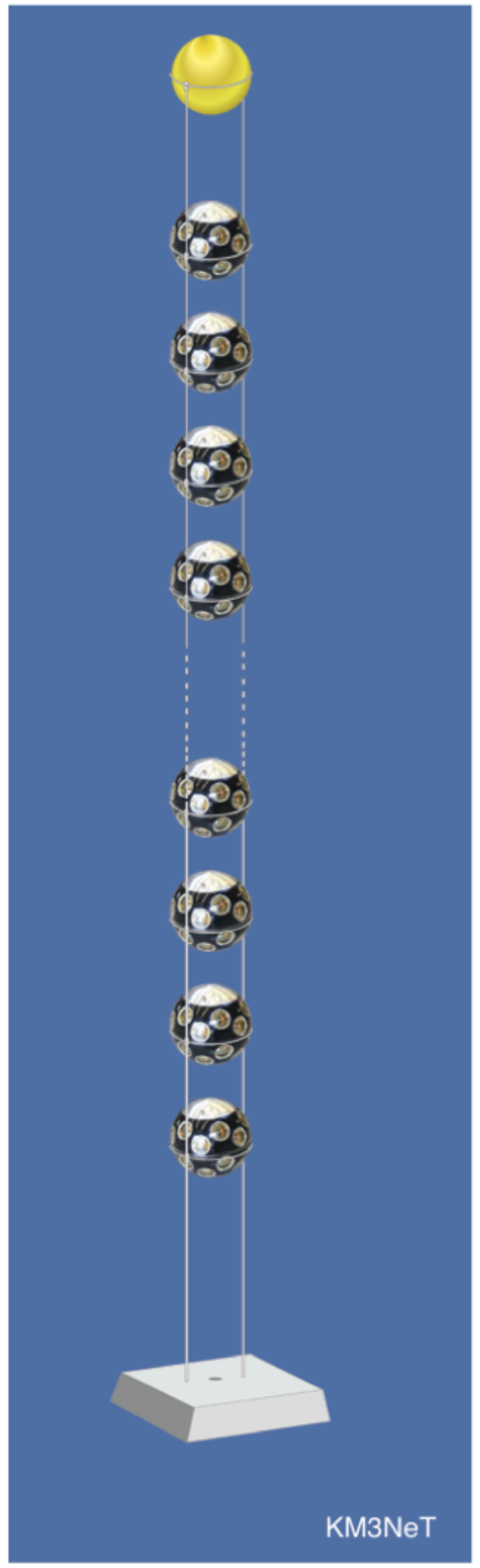
KM3NeT: the Neutrino Telescope

- DU (Detection Unit)
- DOM (Digital Optical Module)
- Seafloor network: electro-optical cables and JBs

DU
- 250/750 m (ORCA/ARCA)
- 18 DOMs (~9/36 m btw DOMs)
- Anchor
- Buoy

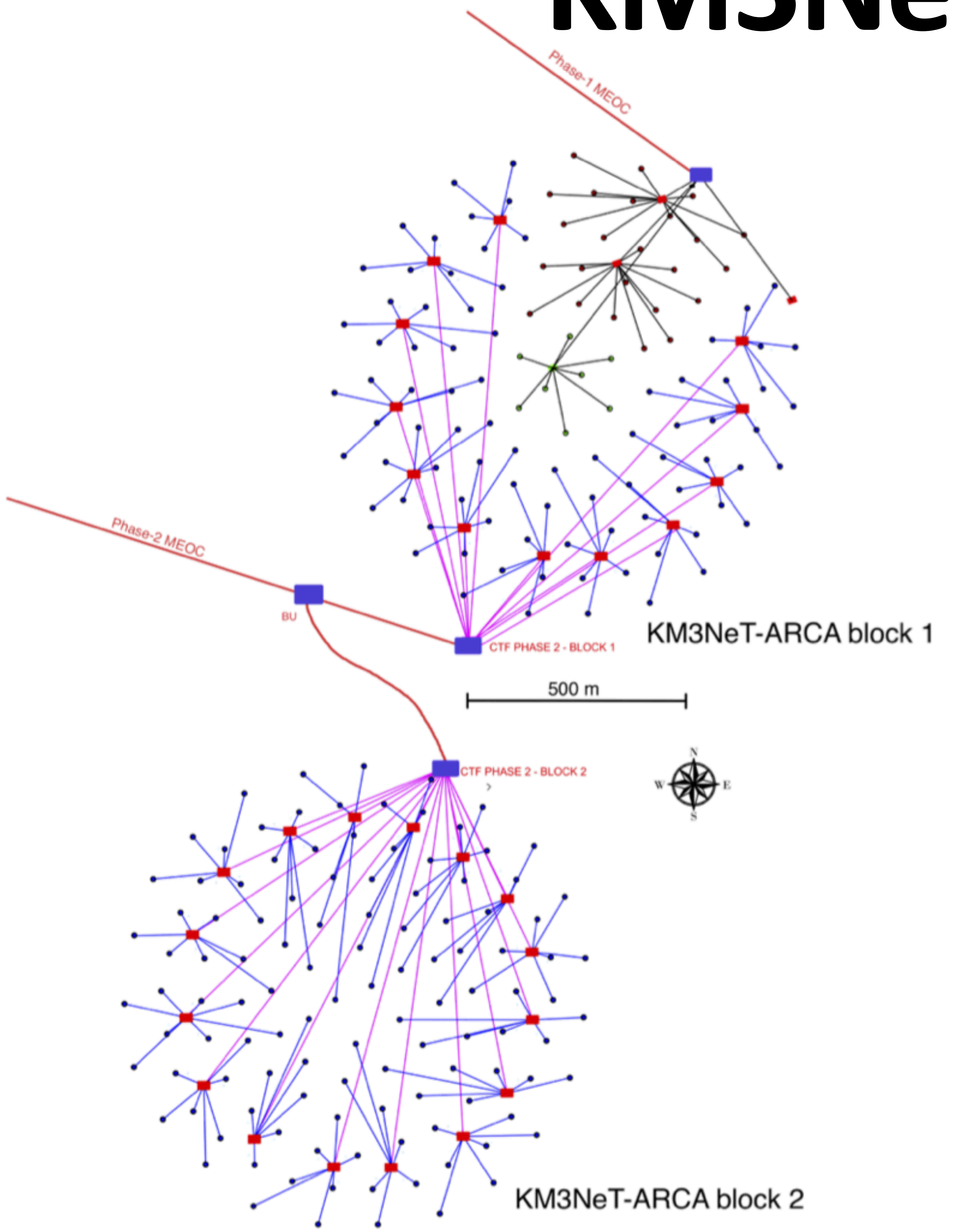
DOM
- 17” glass sphere with 31 3” PMTs
- LED and Piezo
- Front-end electronics

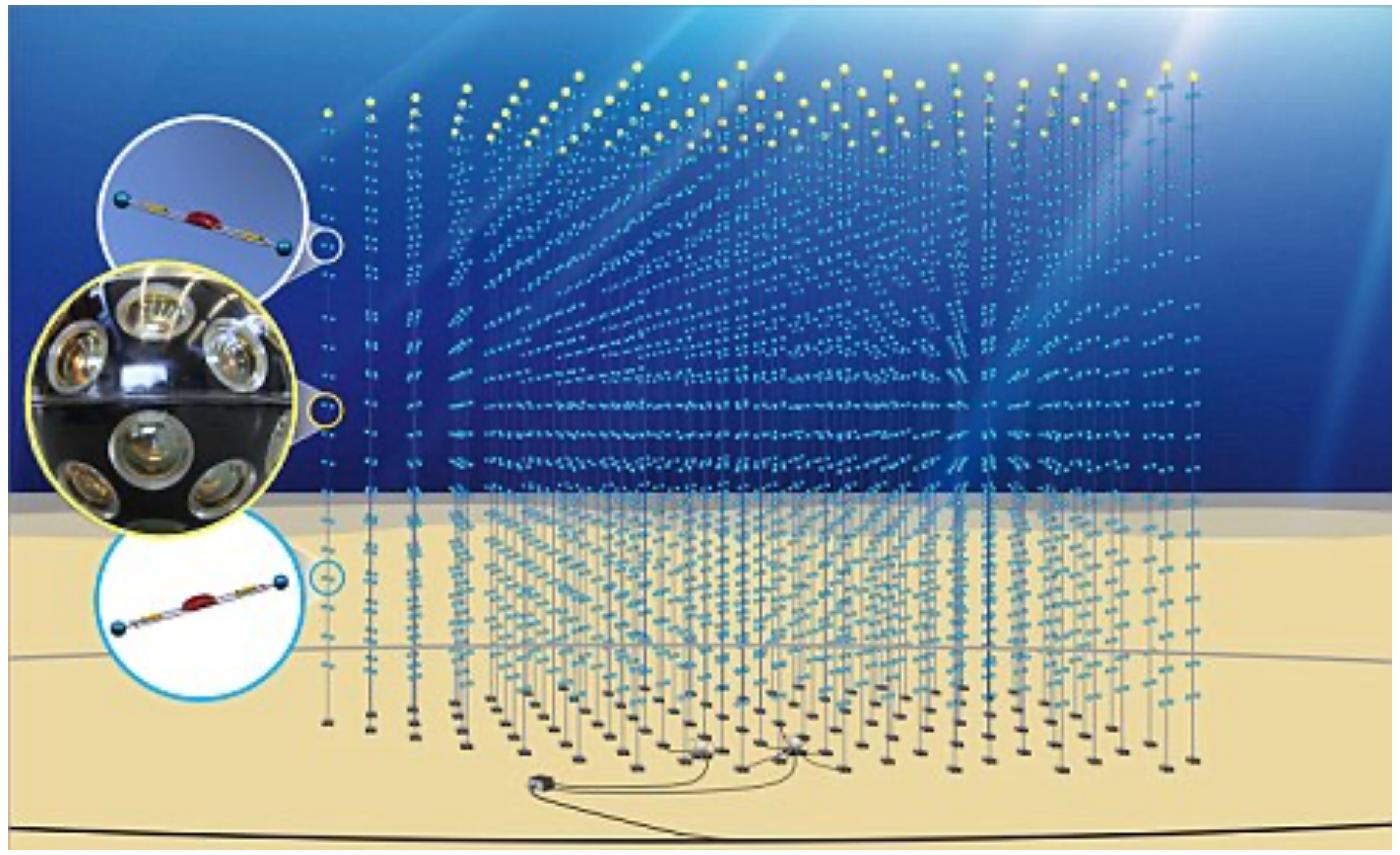




From “The KM3NeT underwater neutrino telescope: status and future perspective”, G. Ferrara, TIPP2023

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

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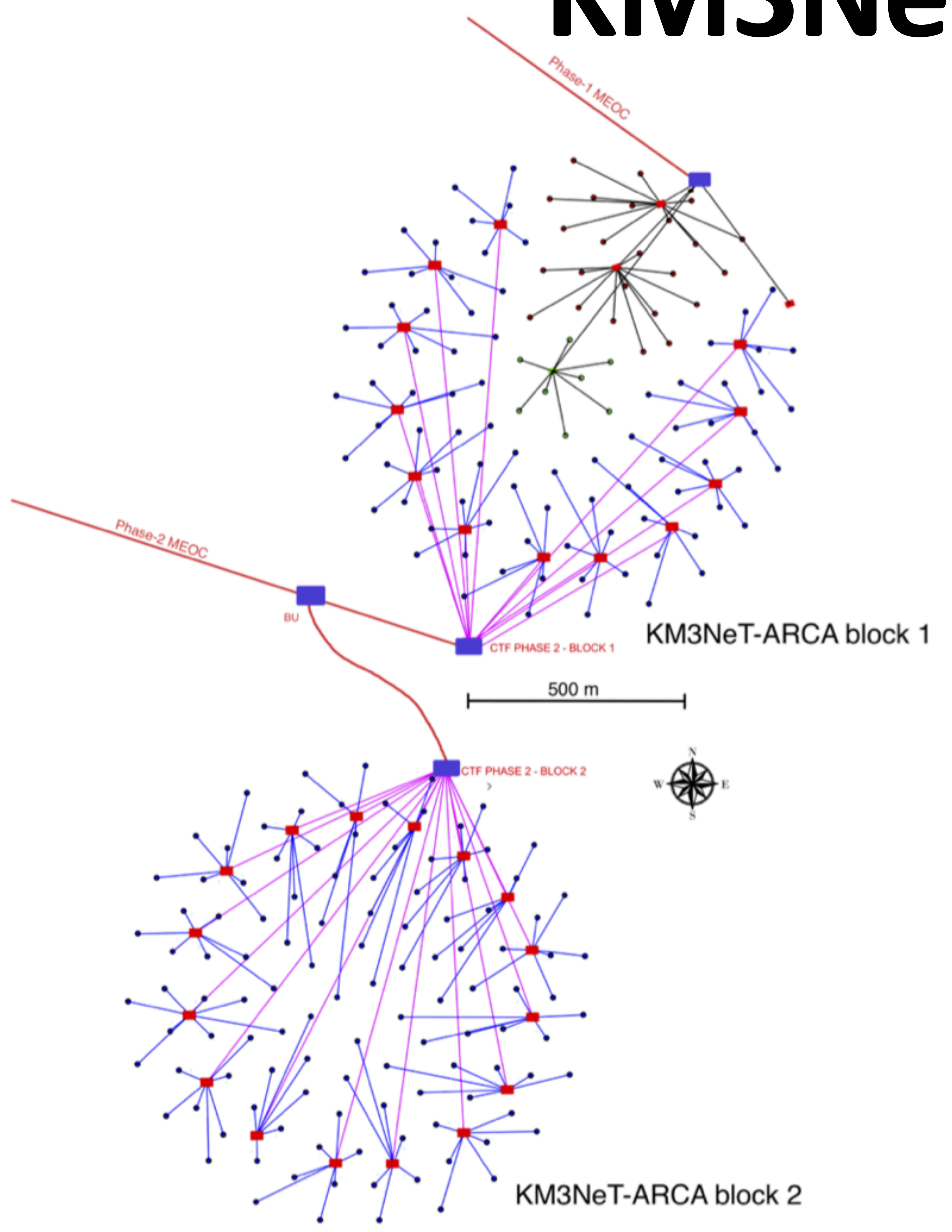

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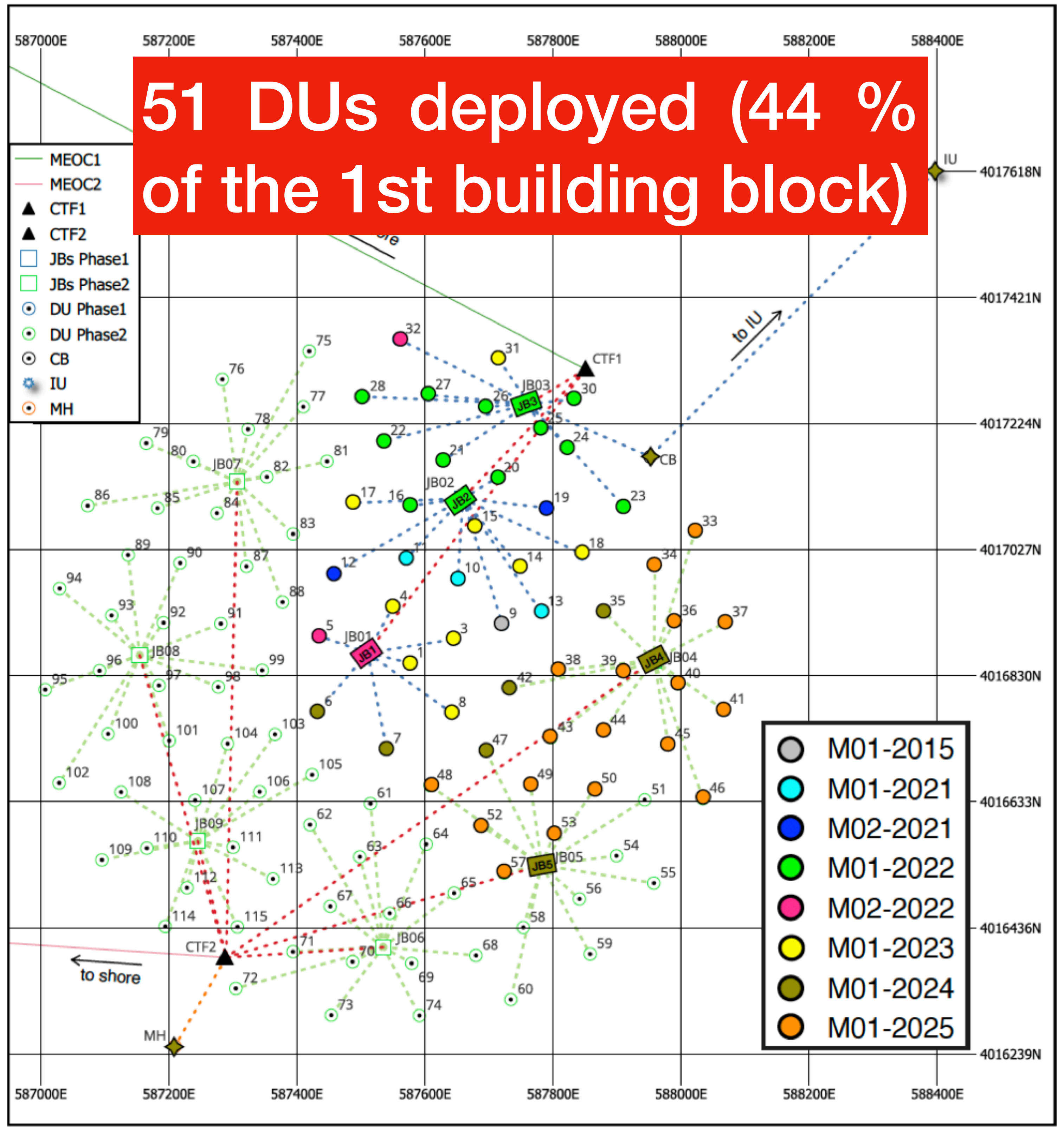

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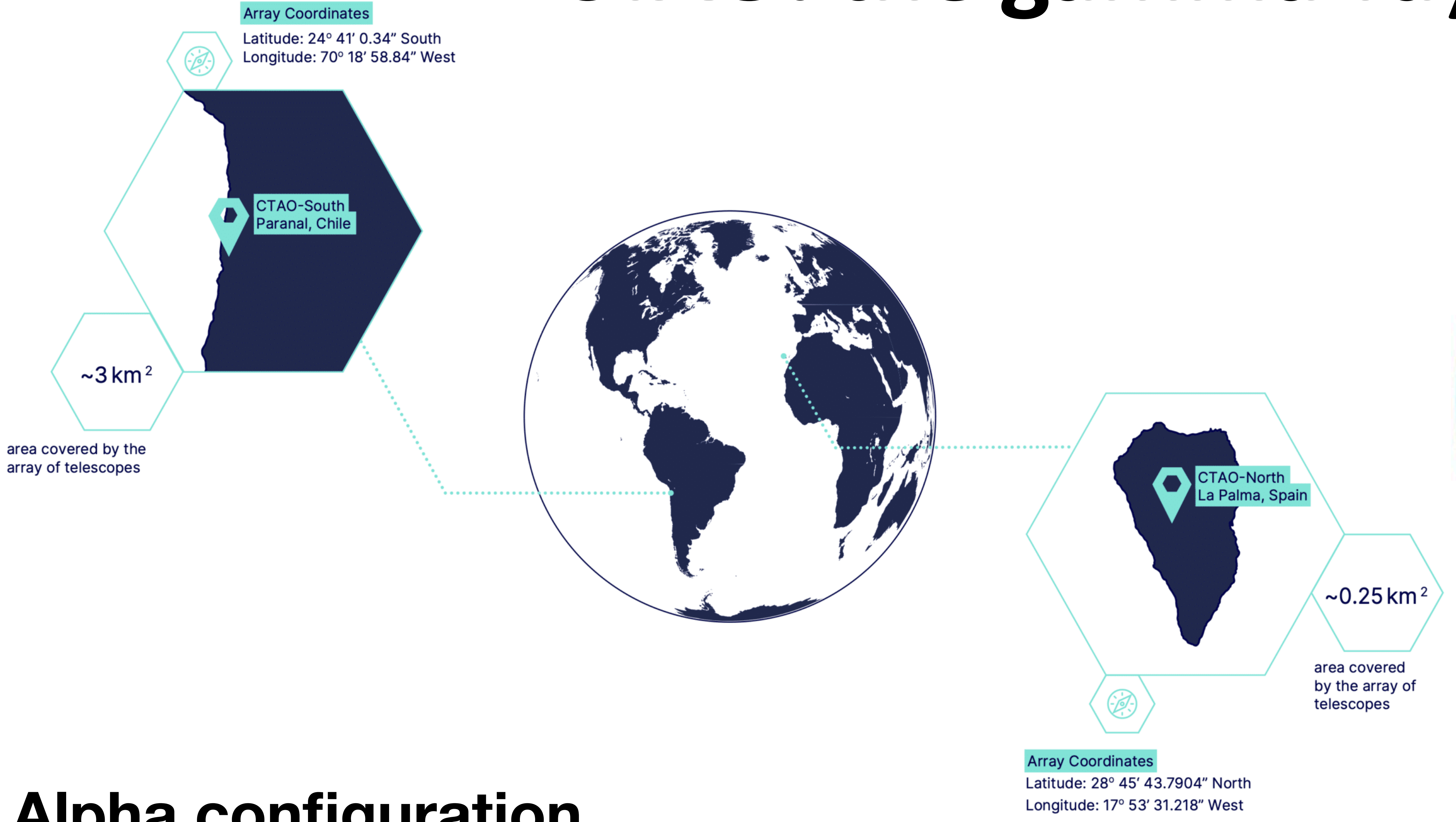
CTAO: the gamma-ray observatory



LST	MST	SST

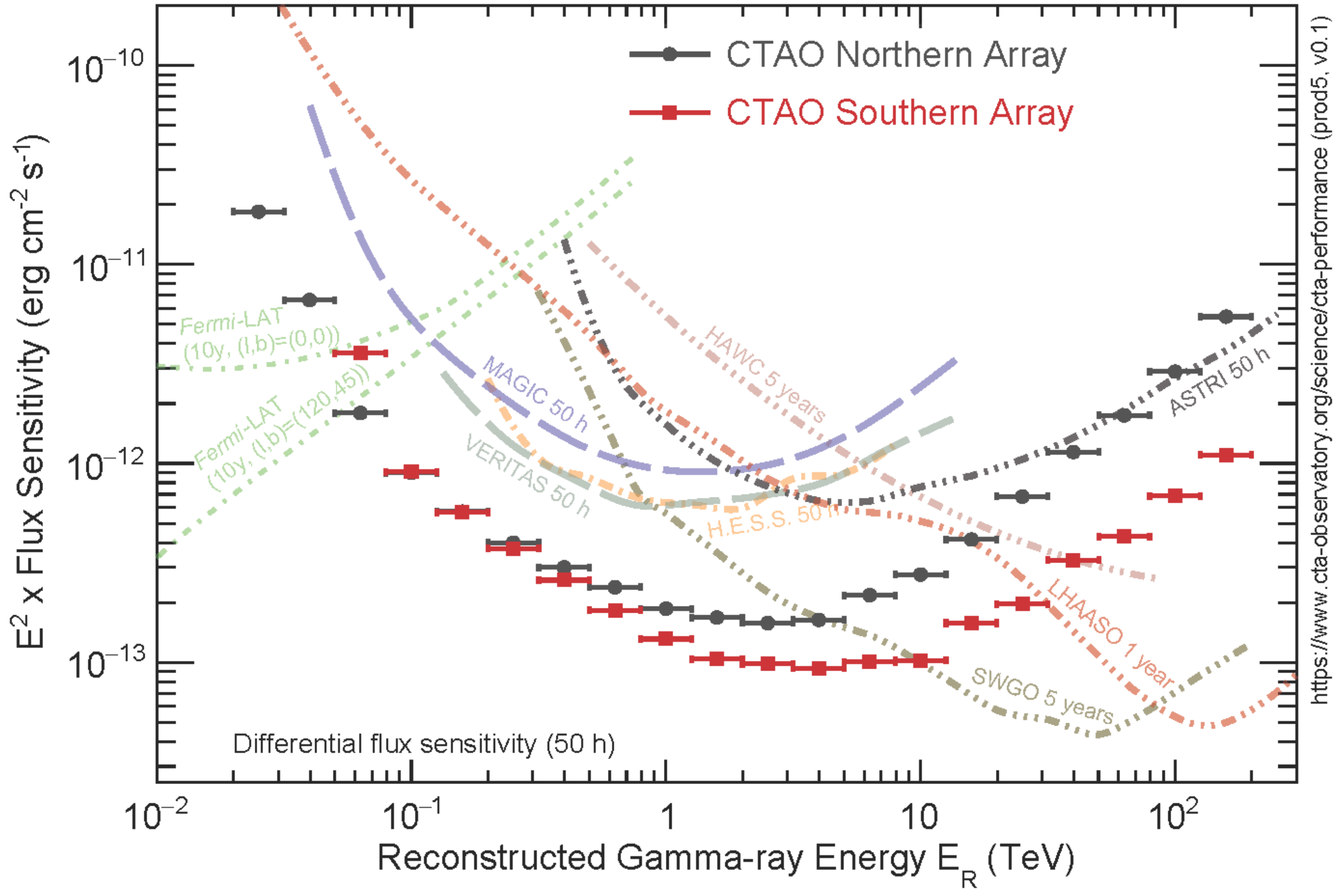
sub-TeV	**TeV**	**multi-TeV**
23 m diameter	12 m diameter	4.3 & 1.8 m diameter
370 m² effective area	90 m² effective area	6 m² effective area
28 m focal length	16 m focal length	2.2 m focal length
4.5° field of view	8° field of view	9.6° field of view

Alpha configuration

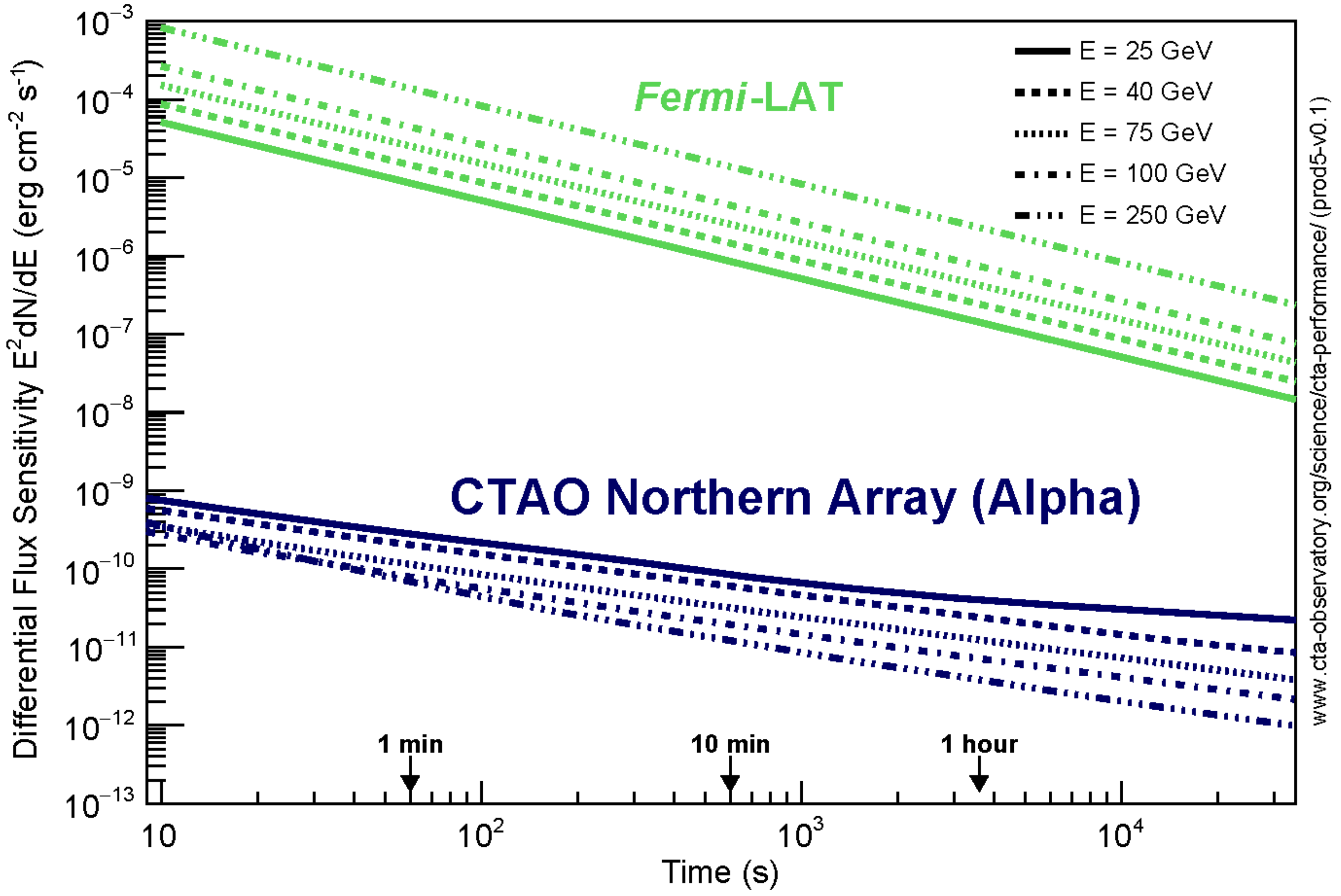
- **CTAO Northern Array:** 4 Large-Sized Telescopes (LSTs) and 9 Medium-Sized Telescopes (MSTs)
- **CTAO Southern Array:** 14 Medium-Sized Telescopes (MSTs) and 37 Small-Sized Telescopes (STSs)

CTAO: the gamma-ray observatory

Sensitivity



Sensitivity vs Observation Time



Outline

- Neutrino Target of Opportunity (NToO)
  - Neutrino Simulations
  - Gamma Simulations
  - CTAO Performance

Neutrino Target of Opportunity

The study of **transient phenomena** has been included in the key science objectives for CTA (CTA Consortium, 2019a), so that CTA will perform **follow-up observations** when public alerts are issued by other observatories.

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1 — 2 — 3 — 4

1. Neutrino Simulations

FIRESONG python code

2. Neutrino Telescope Filter

Discovery potential of KM3NeT

3. Gamma Simulations

EBL model and Alpha configuration of IRFs

4. CTA performance

CTAO detection probability

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   CTAO detection probability

- **Steady Sources** and **Long Transient Sources** - constant neutrino flux
- **Neutrino-flaring Sources** - variable neutrino flux (e.g. neutrino-flaring blazar)

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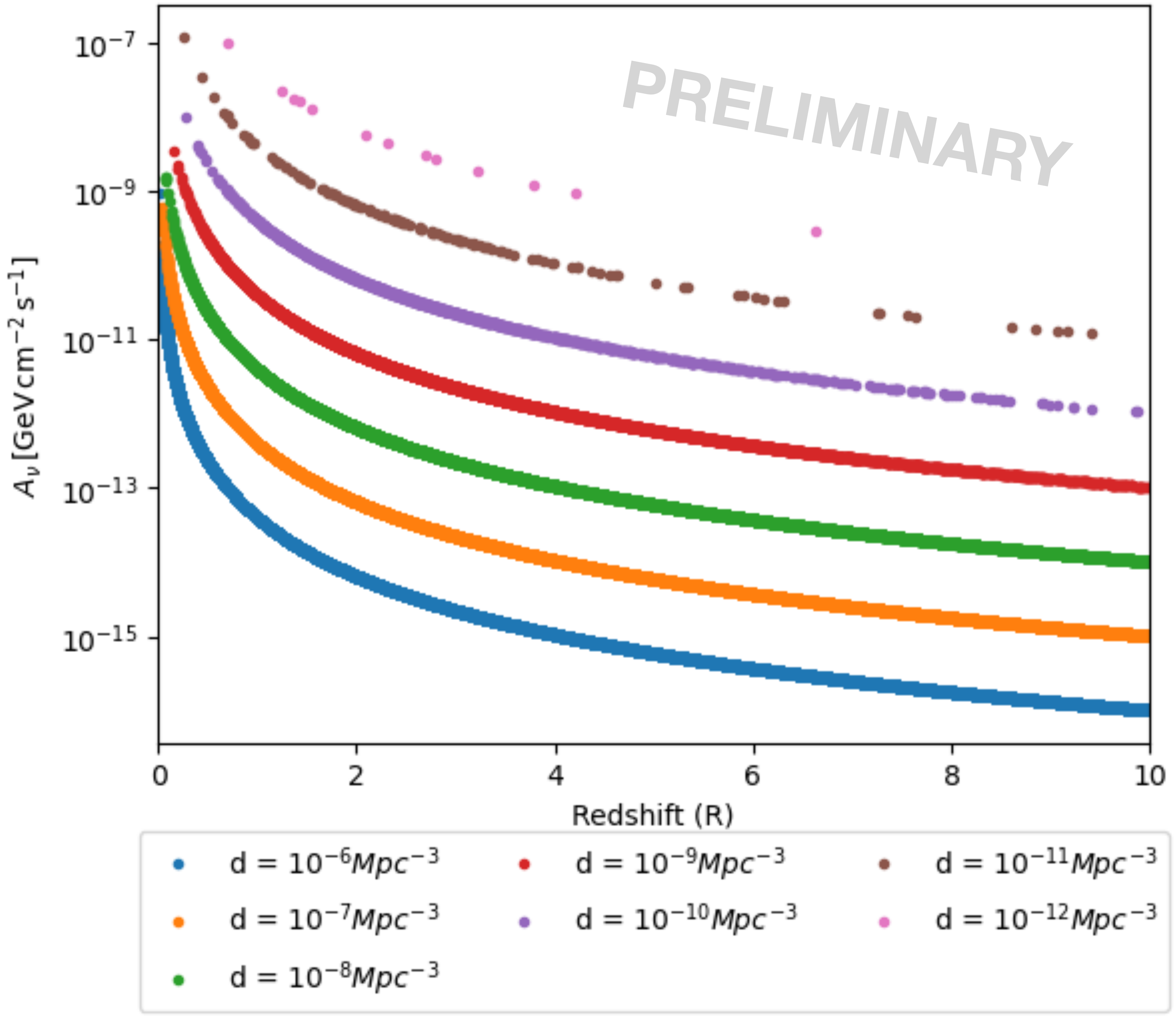
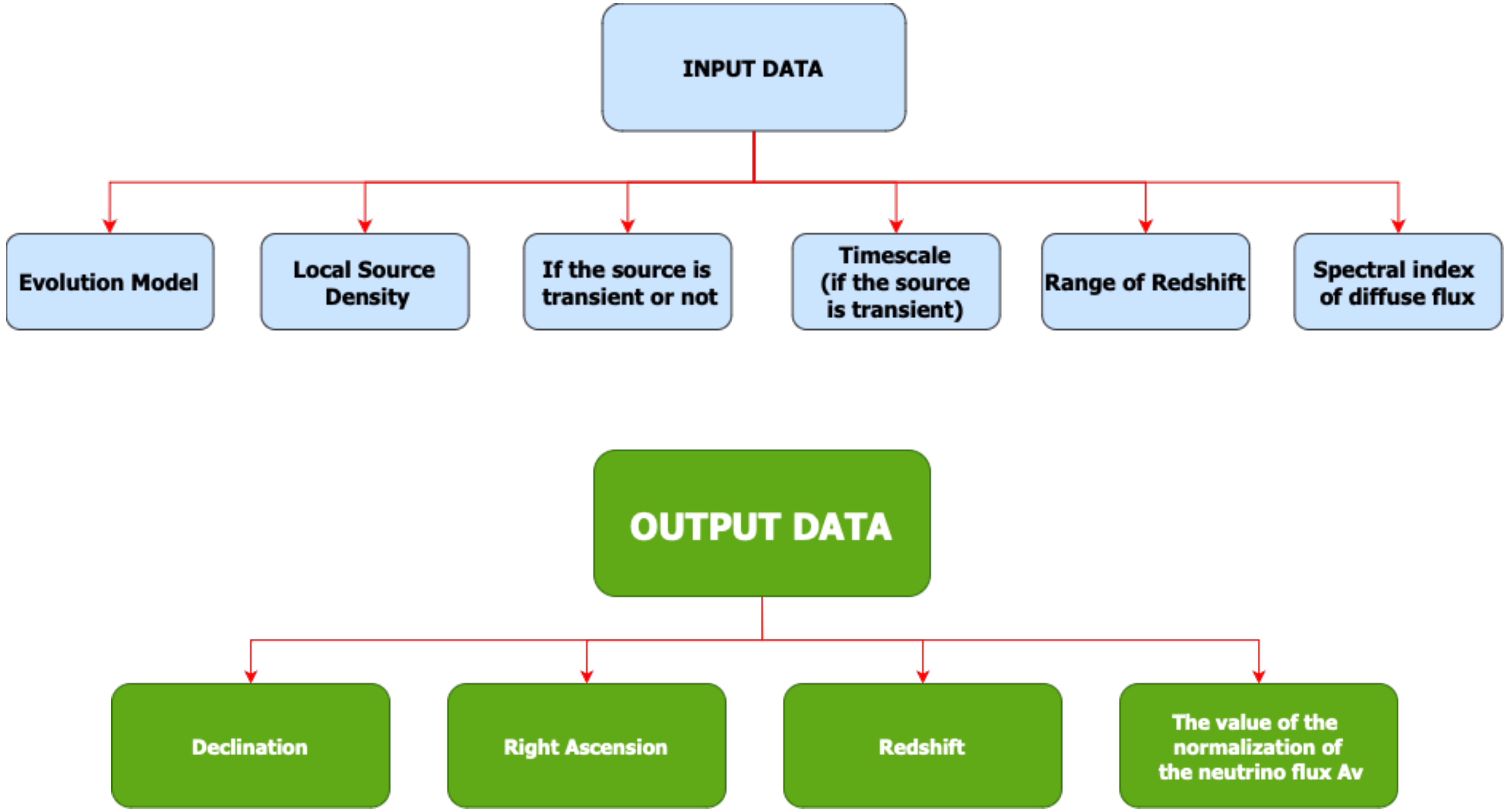
Neutrino Simulations

FIRESONG python code

Neutrino Simulations

FIRESONG is **an open source python code** used to simulate source populations in the L (luminosity) vs ρ (density) plane. *(Tung et al., Journal of Open Source Software, 2021)*





1

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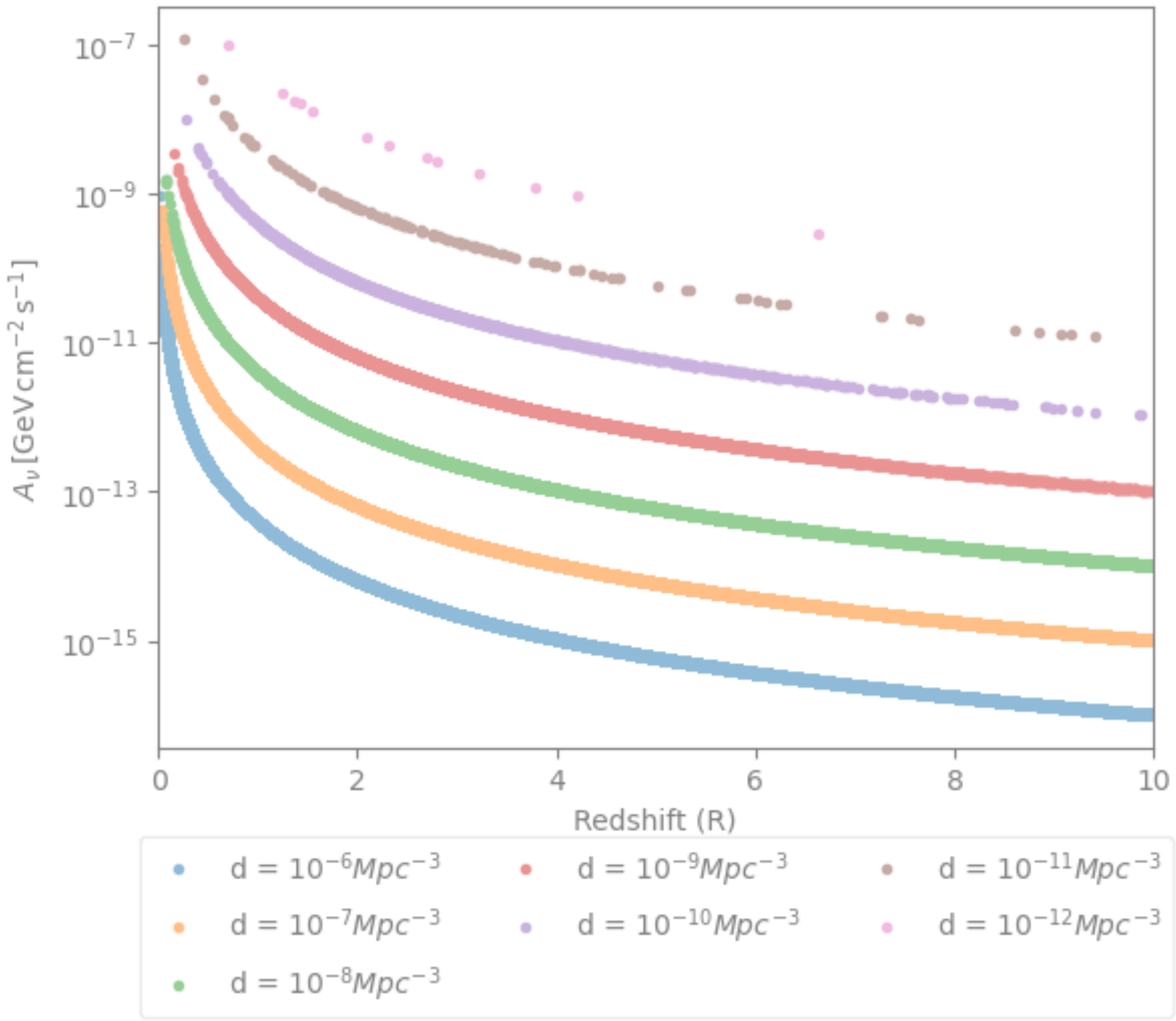


$$E^2 \frac{dN}{dE} = A_\nu \left(\frac{E}{100\ \text{TeV}} \right)^{\Gamma - 2}$$

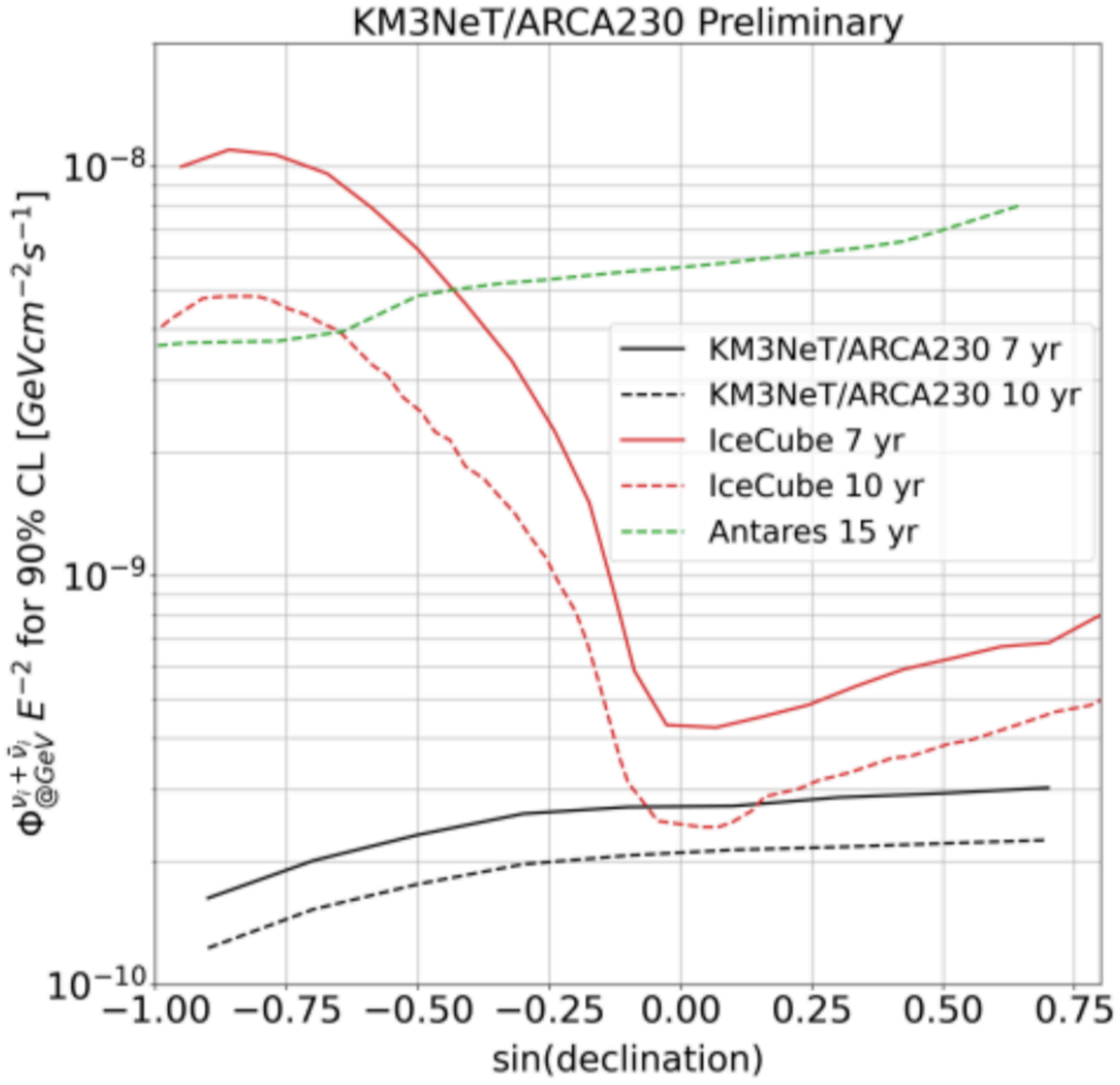
A_ν is the normalization factor of the neutrino flux at 100 TeV and Γ is the spectral index

2

Neutrino Telescope Filter

Discovery potential of KM3NeT

Neutrino Telescope Filter



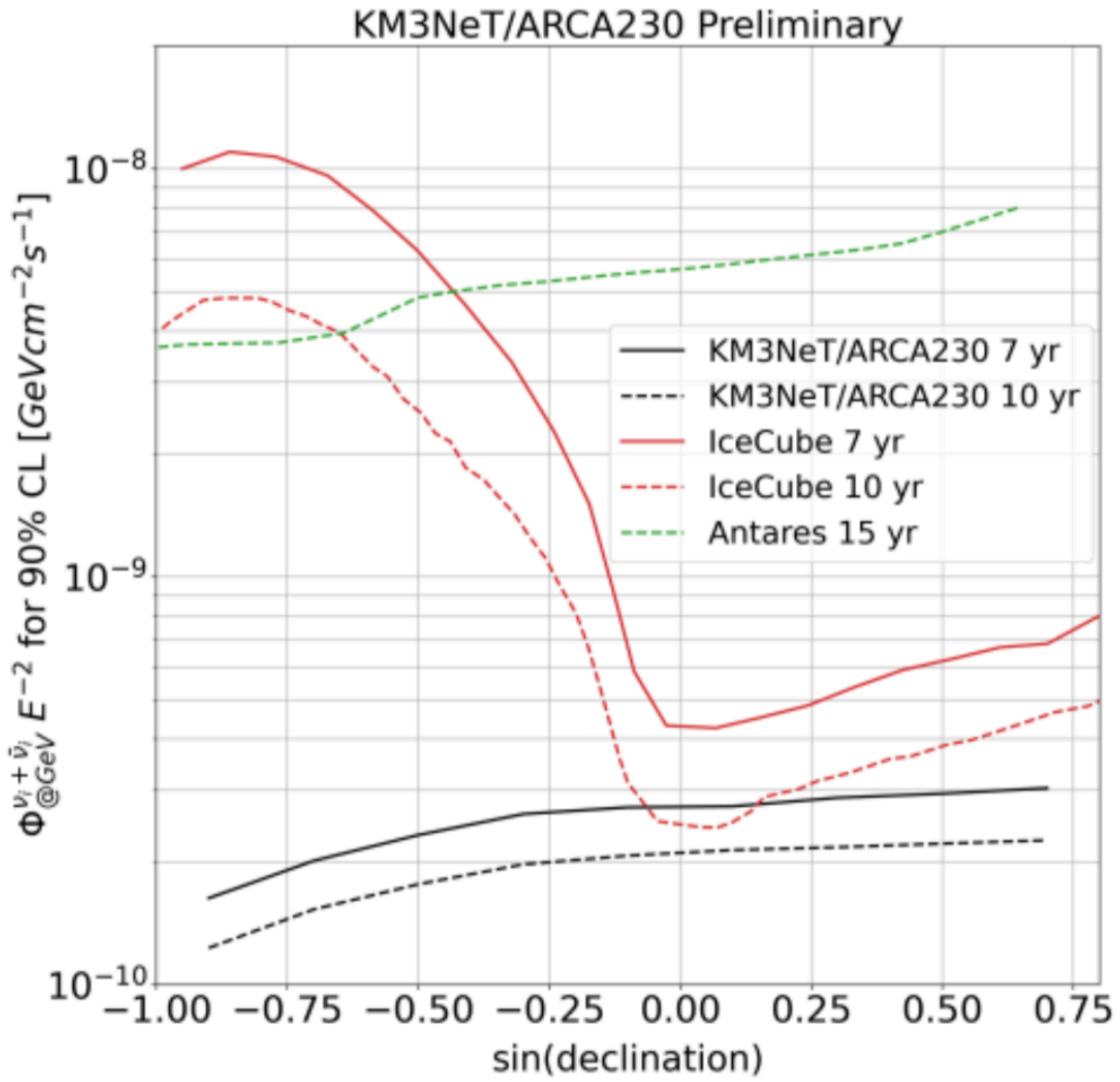
KM3NeT Collaboration, PoS ICRC2023 1075

2

Neutrino Telescope Filter

Neutrino Telescope Filter

Discovery potential of KM3NeT



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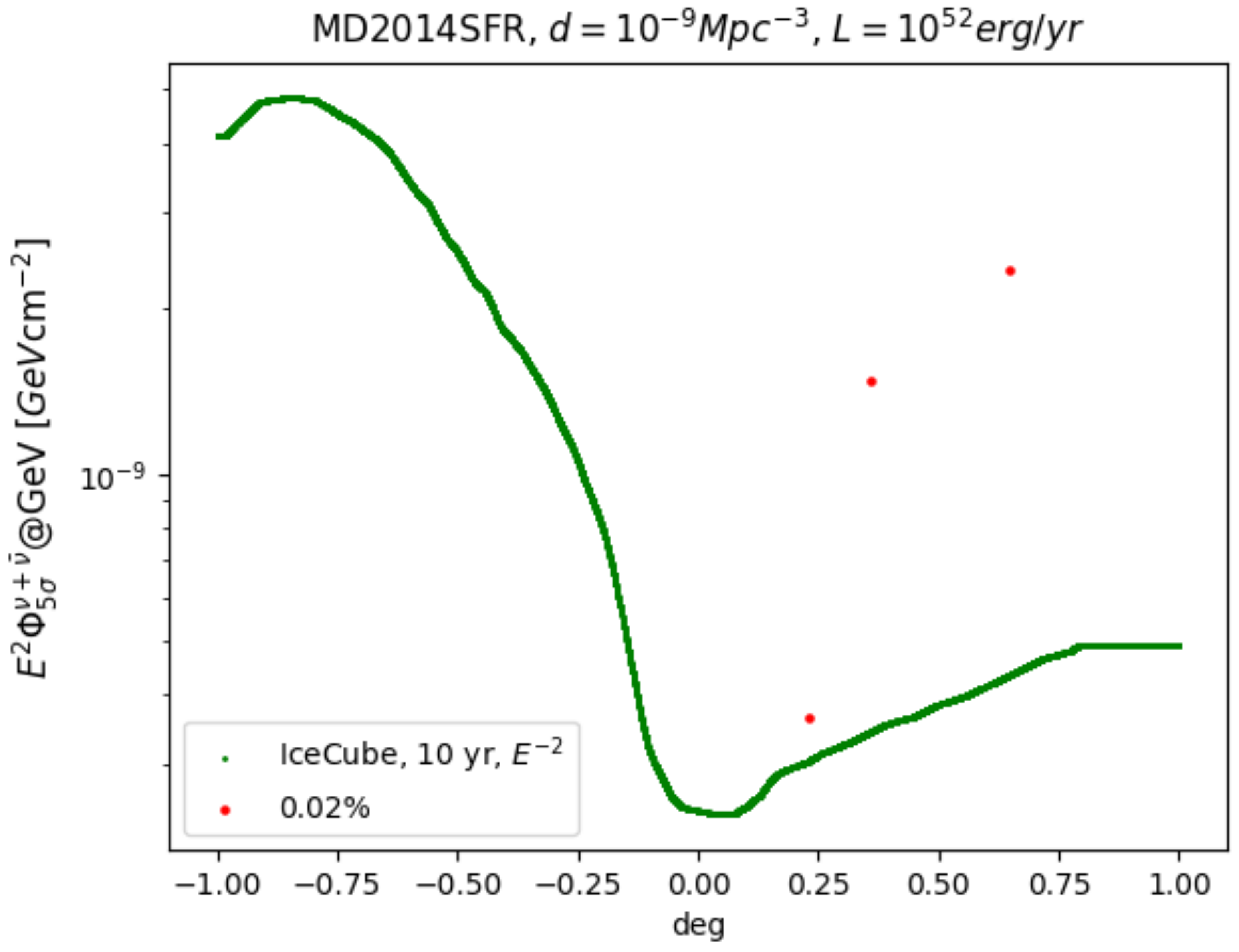
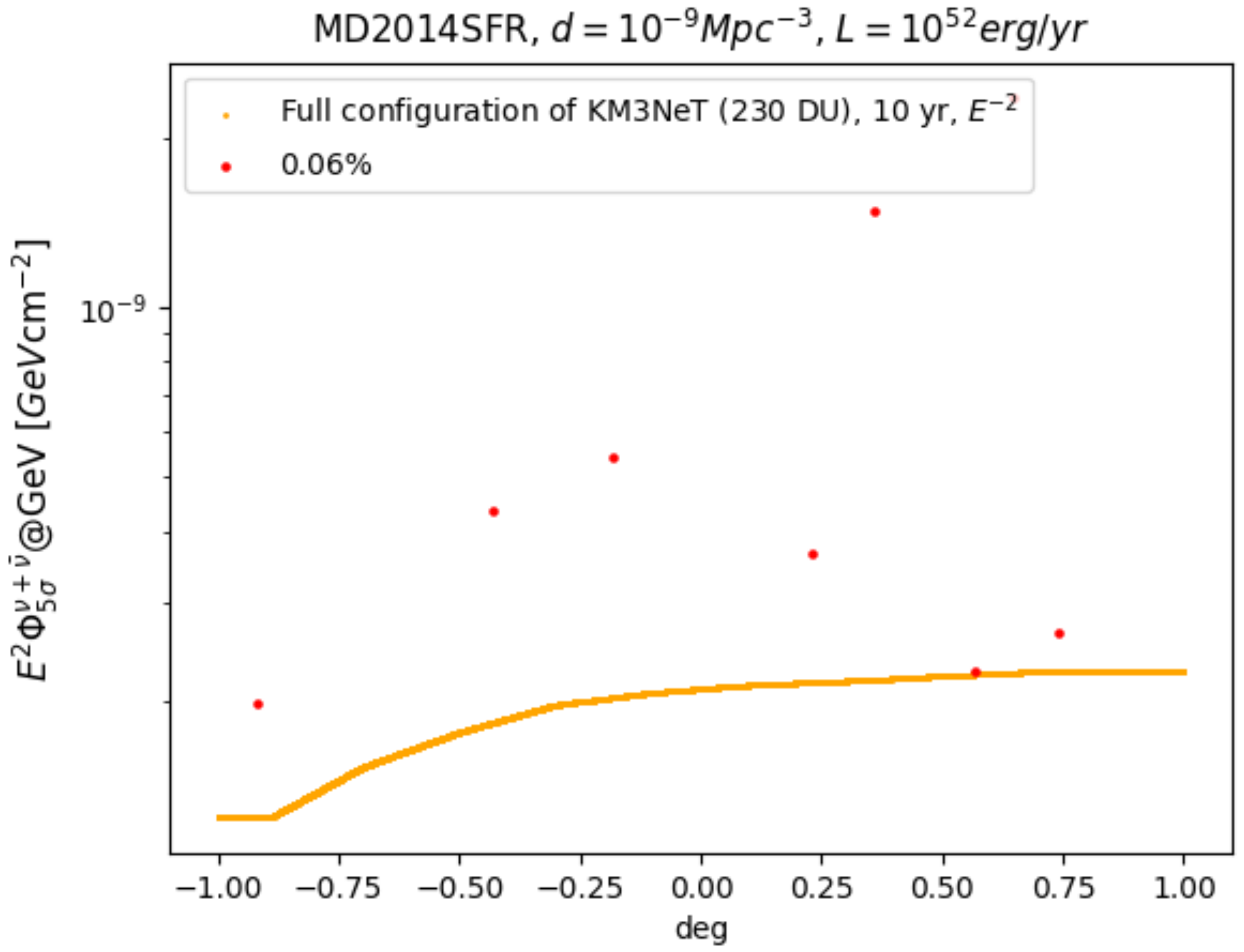


IceCube



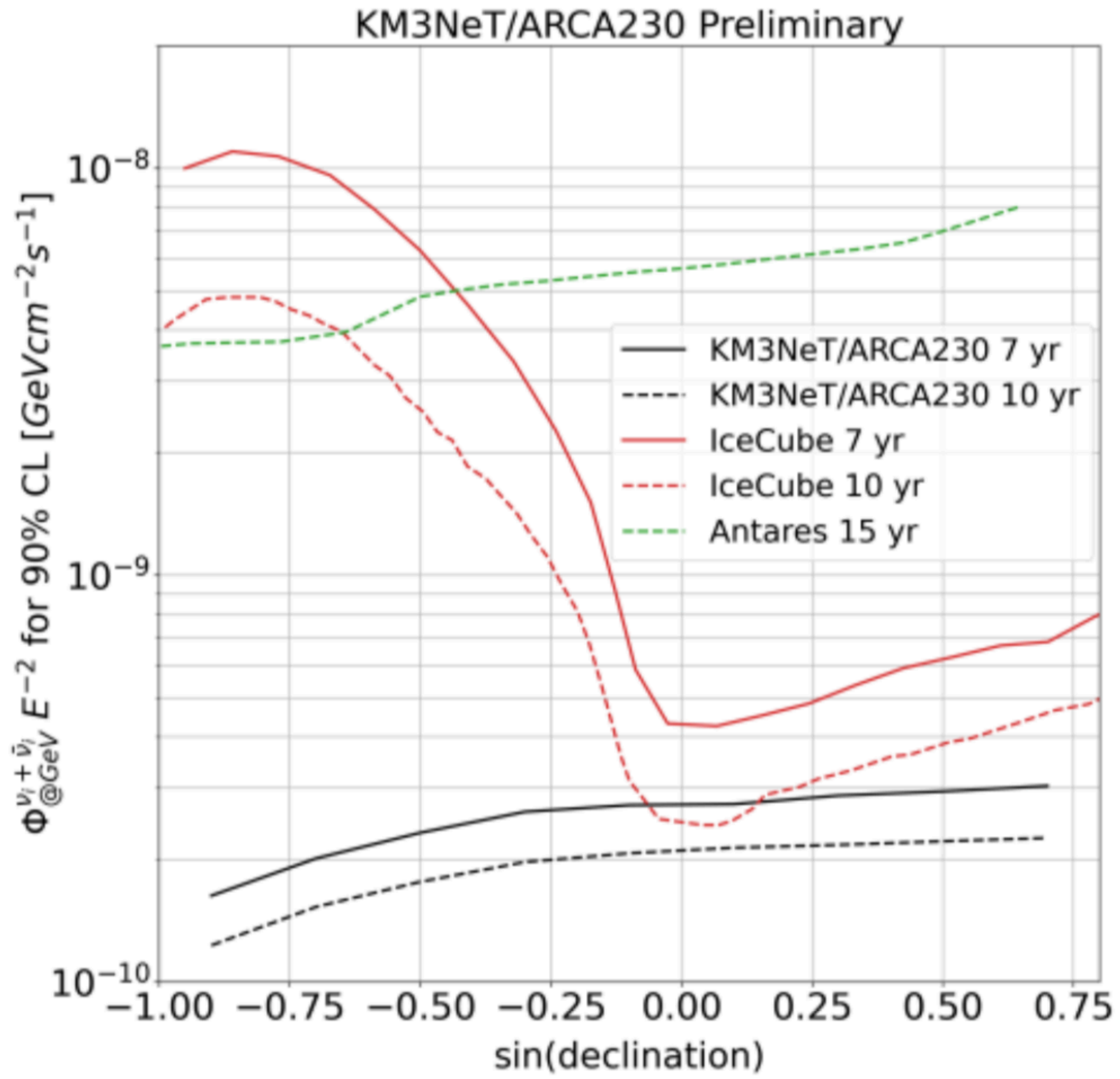
KM3NeT

Neutrino Telescope Filter

2

Neutrino Telescope Filter

Discovery potential of KM3NeT



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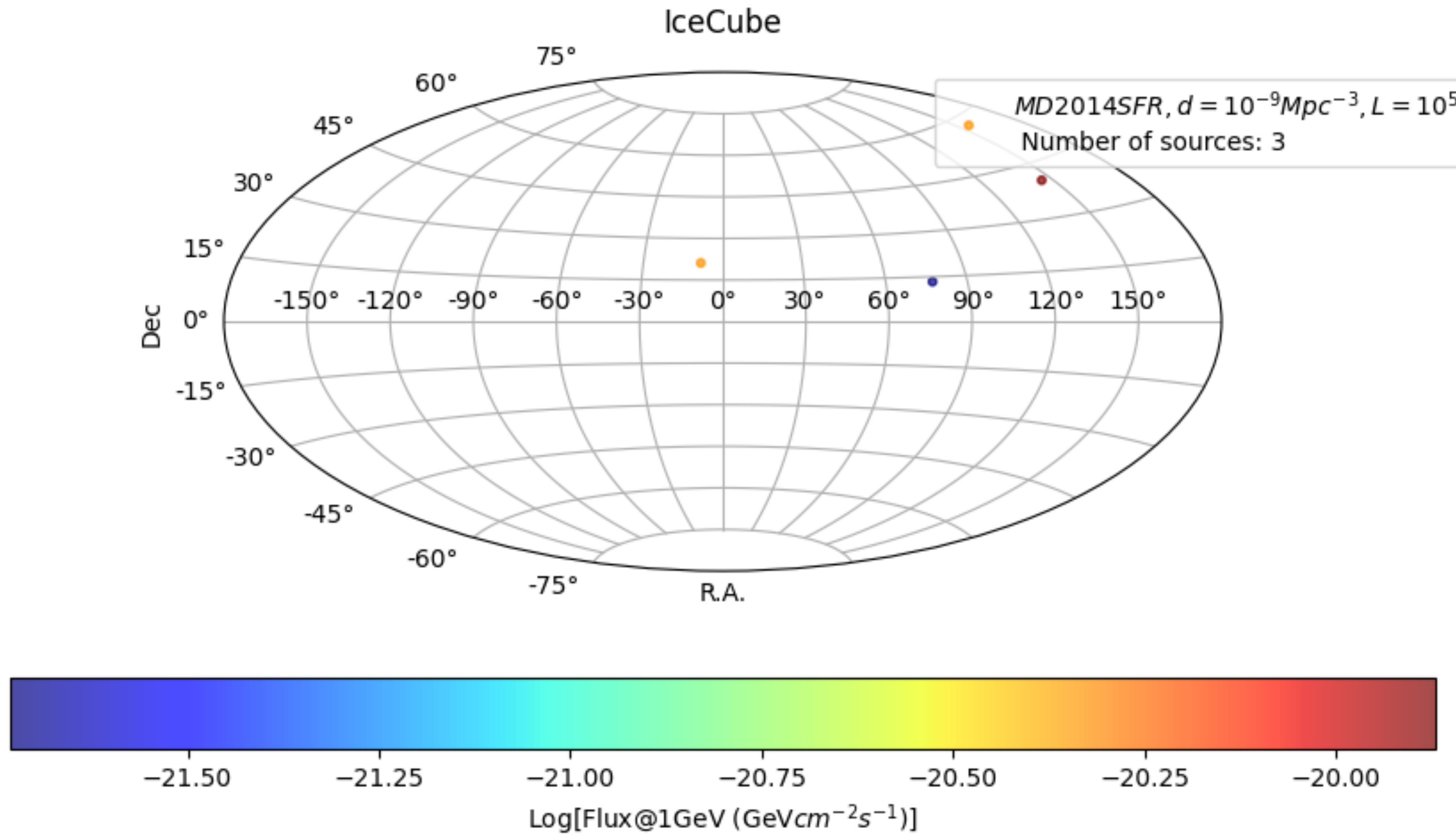

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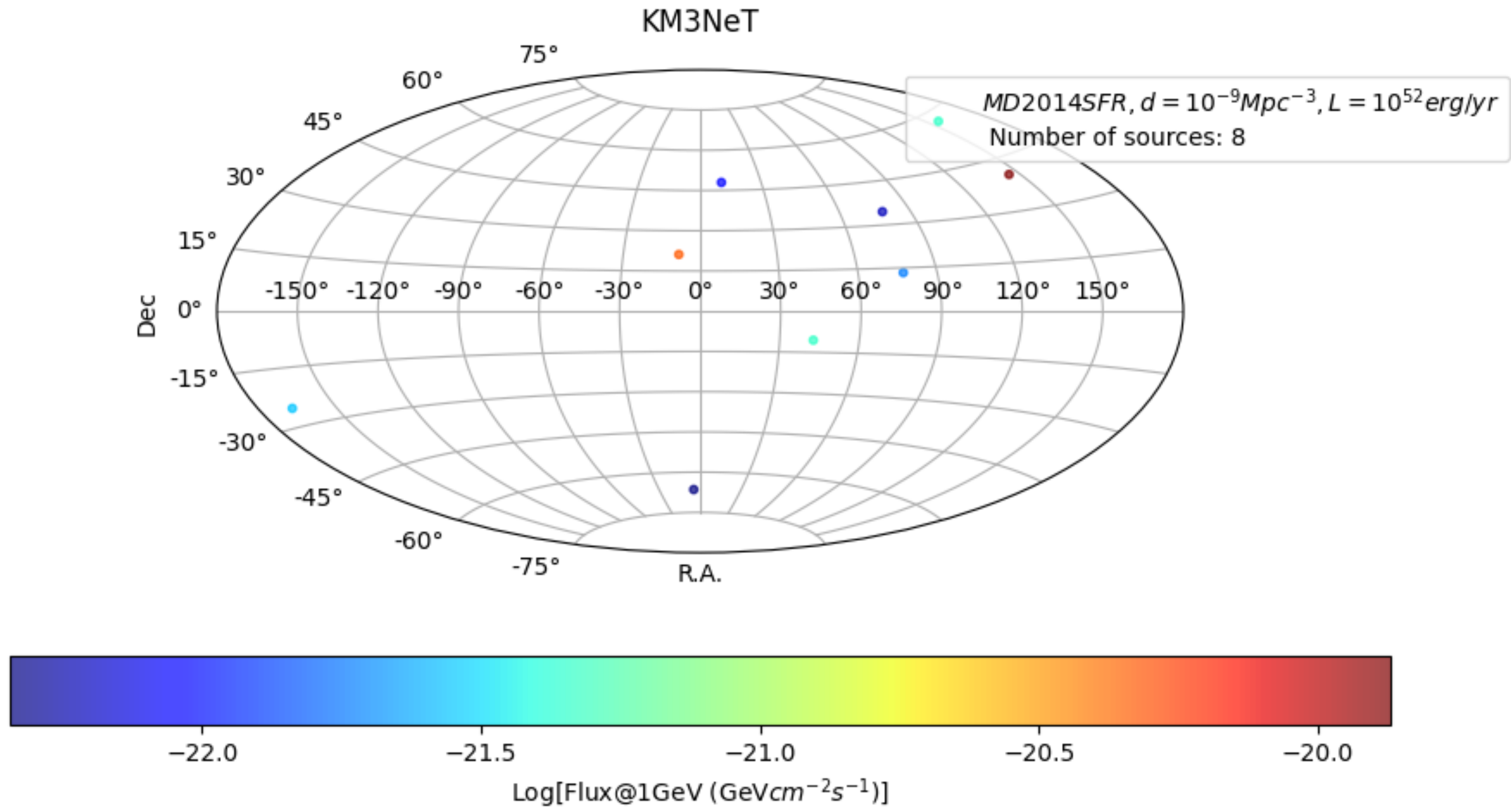


KM3NeT

3

Gamma Simulations

EBL model and Alpha configuration of IRFs

Gamma-ray simulations

Ahlers and Halzen (2018)

$$\frac{1}{3}\sum_{\alpha} E_{\nu}^{2} A_{\nu_{\alpha}}(E_{\nu}) = \frac{K_{\pi}}{4} E_{\gamma}^{2} A_{\gamma}(E_{\gamma})$$

3

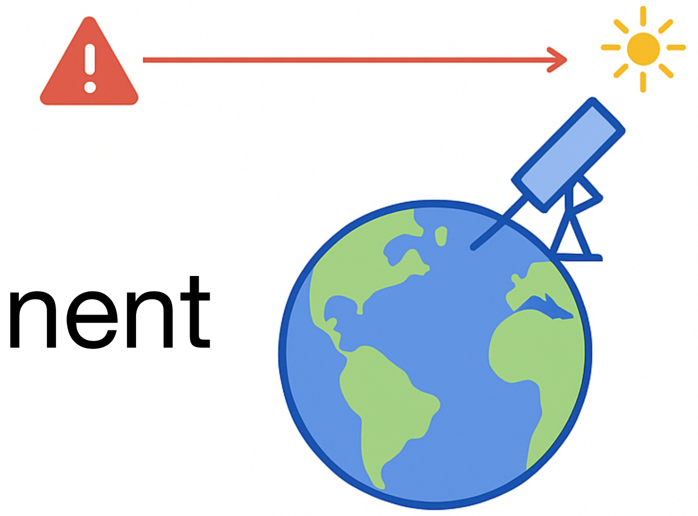
Gamma Simulations

EBL model and Alpha configuration of IRFs

Gamma-ray simulations

Spatial model

a point-source model is used for the spatial component



3

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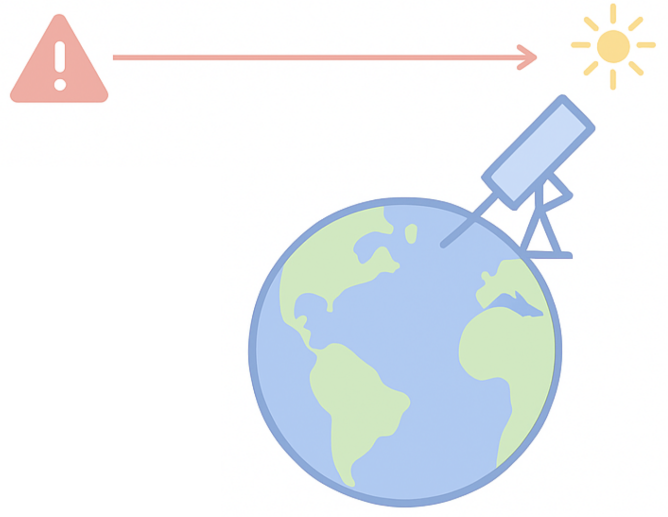


Ahlers and Halzen (2018)

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 A_{\nu_\alpha}(E_\nu) = \frac{K_\pi}{4} E_\gamma^2 A_\gamma(E_\gamma)$$

Spectral model

(Fiorillo et al., 2021) based on (Halzen, 2019)

$$\frac{dN_\gamma}{dE} = A_\nu \left(\frac{E}{100\mathrm{TeV}}\right)^{-\Gamma} \exp\left(-\frac{E'_L}{(1+z)E} - \frac{E(1+z)}{E'_H}\right)$$

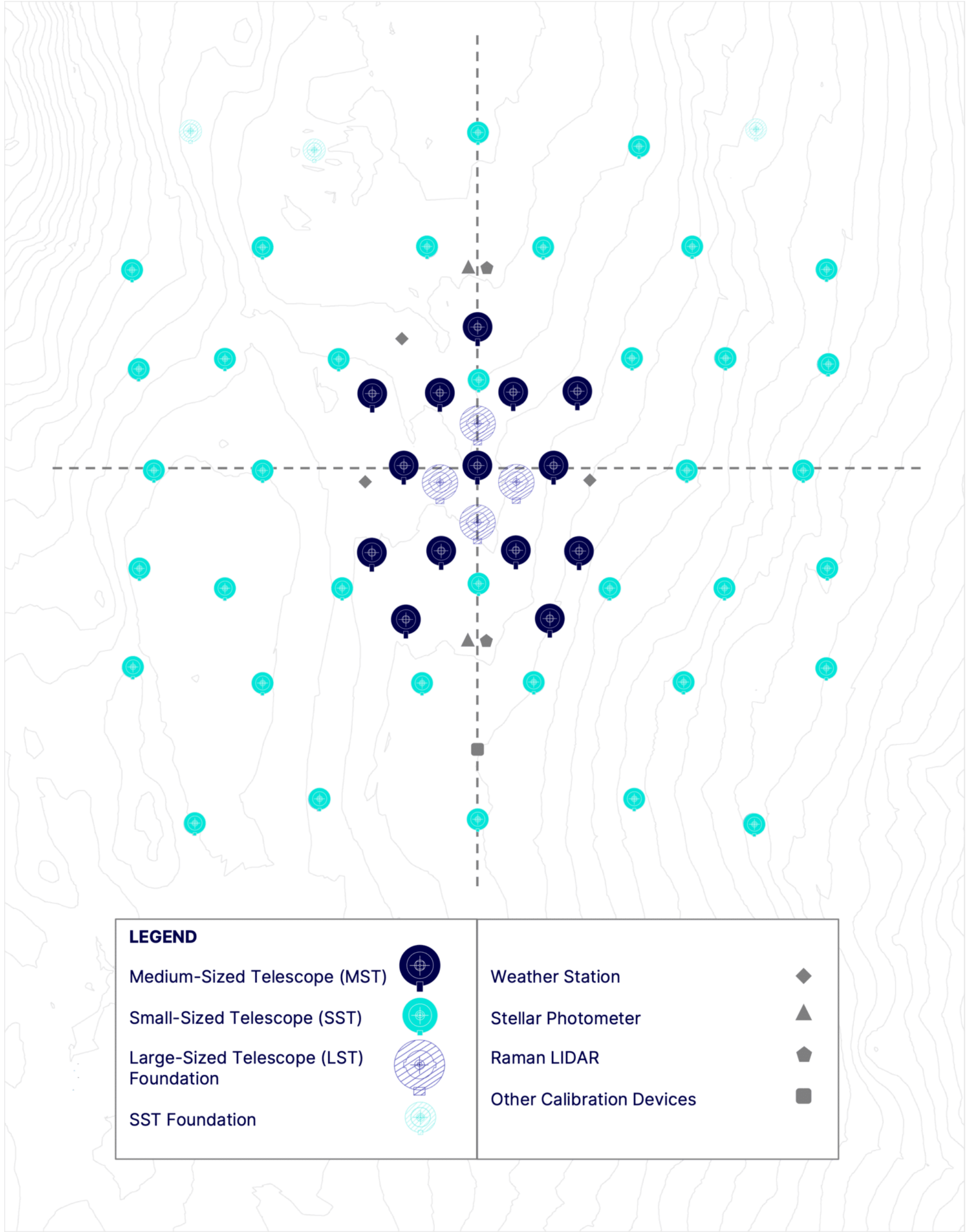
Γ is the spectral index, A_ν is a neutrino flux normalization constant (as above), and E'_L and E'_H are the low and high energy cutoffs in the source rest frame respectively. This approach can also be considered a simplified 'toy' model, as a comprehensive treatment of the reprocessing via $\gamma\gamma$ collisions is complex and highly model dependent.

Gamma
Simulations

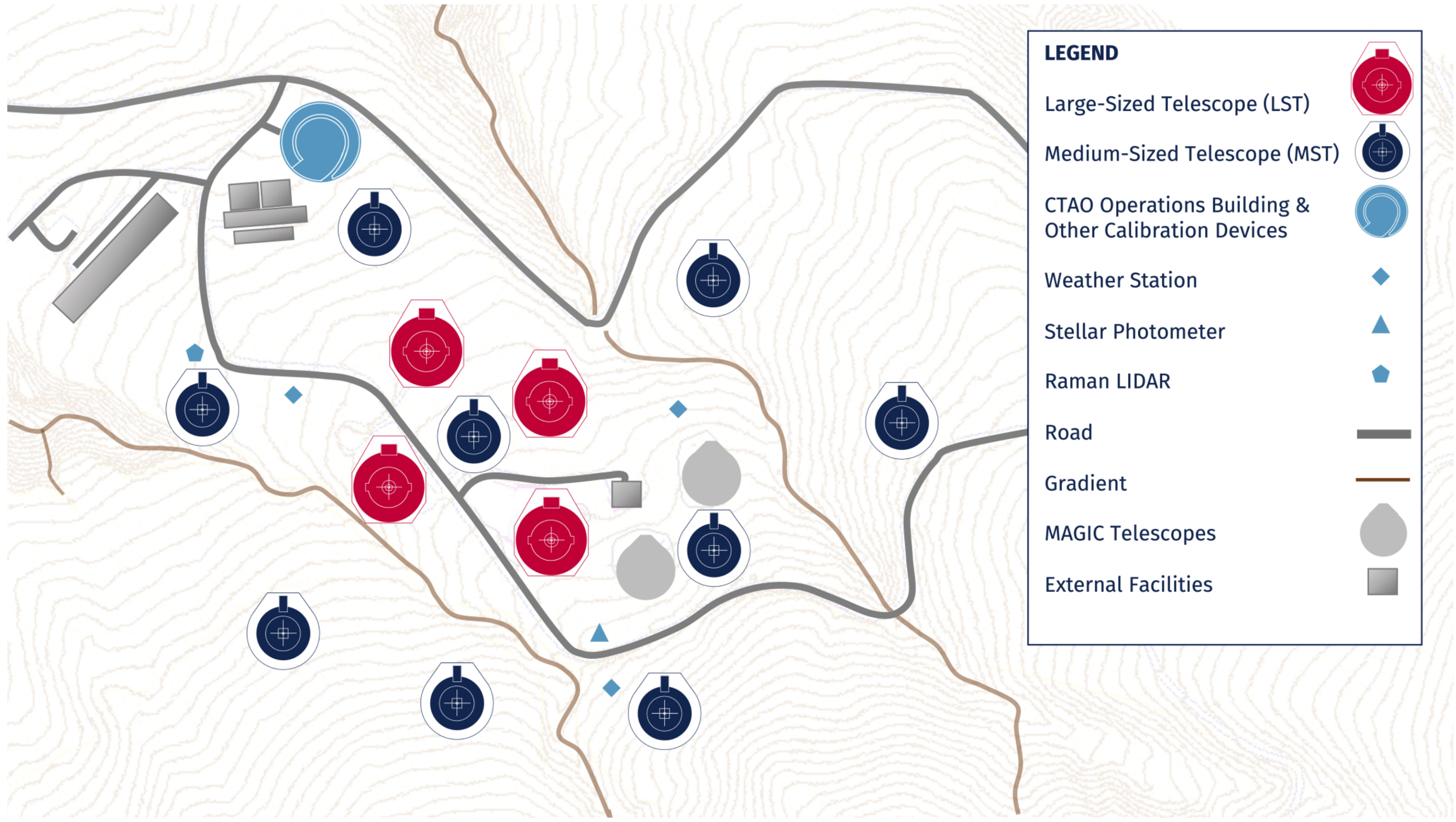
EBL model and Alpha configuration of IRFs

Gamma-ray simulations output

- **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)



Layout of the CTAO southern array on Atacama desert



Layout of the CTAO northern array on La Palma (Spain)

4

CTA performance

CTAO detection probability

Detected sources

The **Test Statistic** is a statistical quantity used to assess the presence of a significant source in the data by comparing the likelihood of the model with and without the source.

The TS value can be converted into the detection significance σ

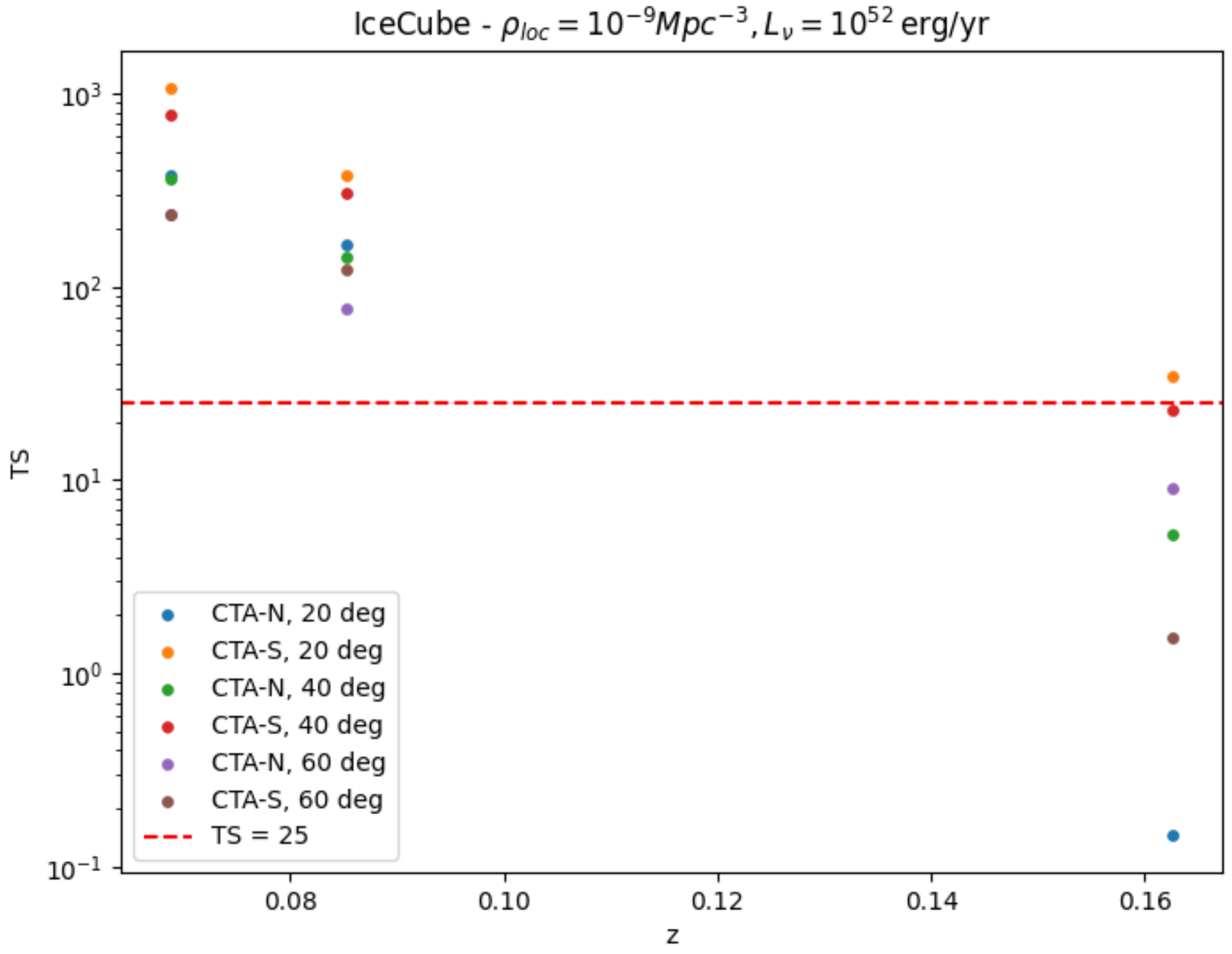
$$\sigma = \sqrt{TS} \quad \Rightarrow \quad TS \geq 25 \quad \Rightarrow \quad \sigma \geq 5$$

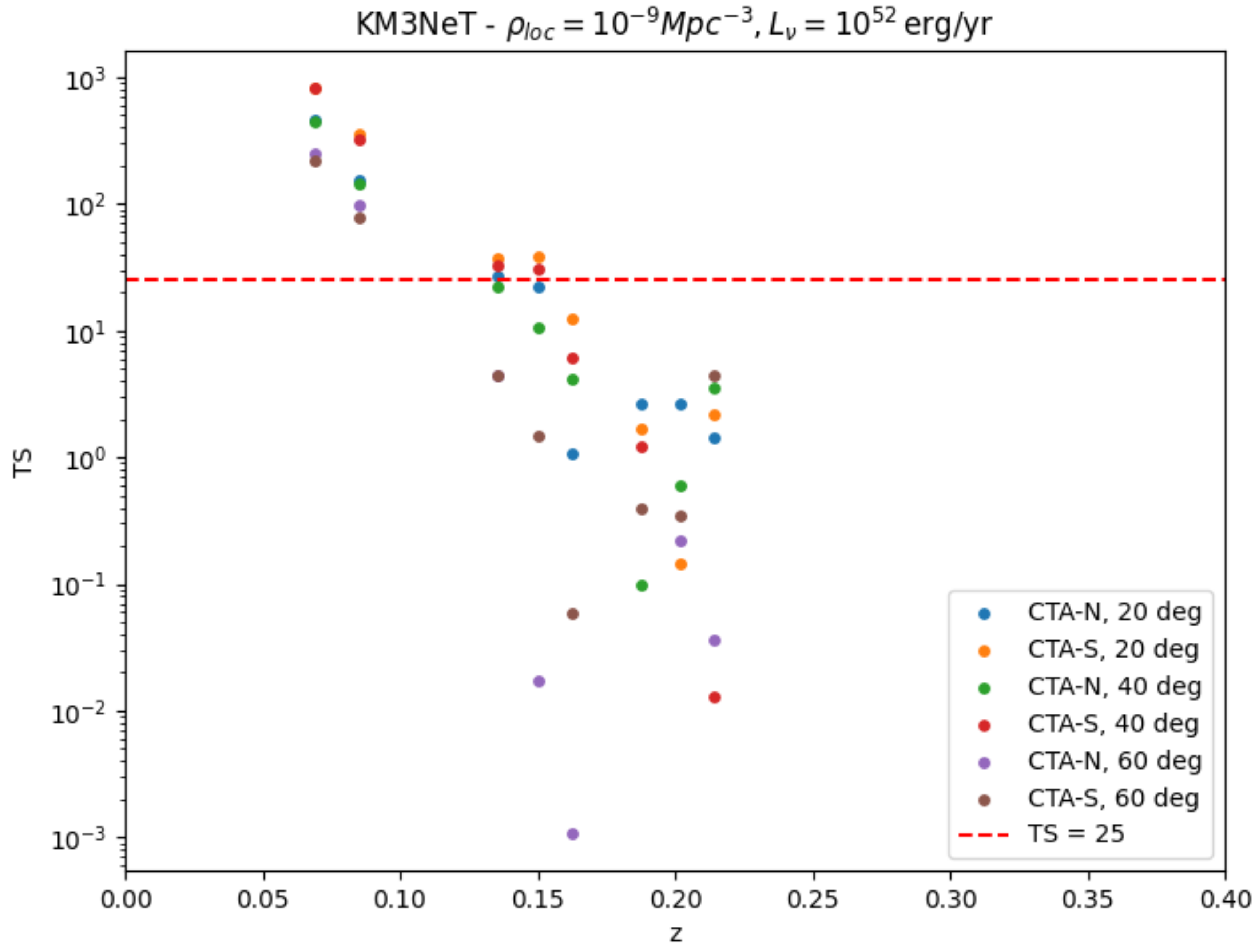
4

CTA performance

CTAO detection probability

Detected sources - KM3NeT vs IceCube





The figures, IceCube and KM3NeT respectively, show TS as a function of redshift for $d = 10^{-9}\ Mpc^{-3}$ and $L = 10^{52}\ erg/yr$.

Detected sources - KM3NeT vs IceCube

4

CTA performance

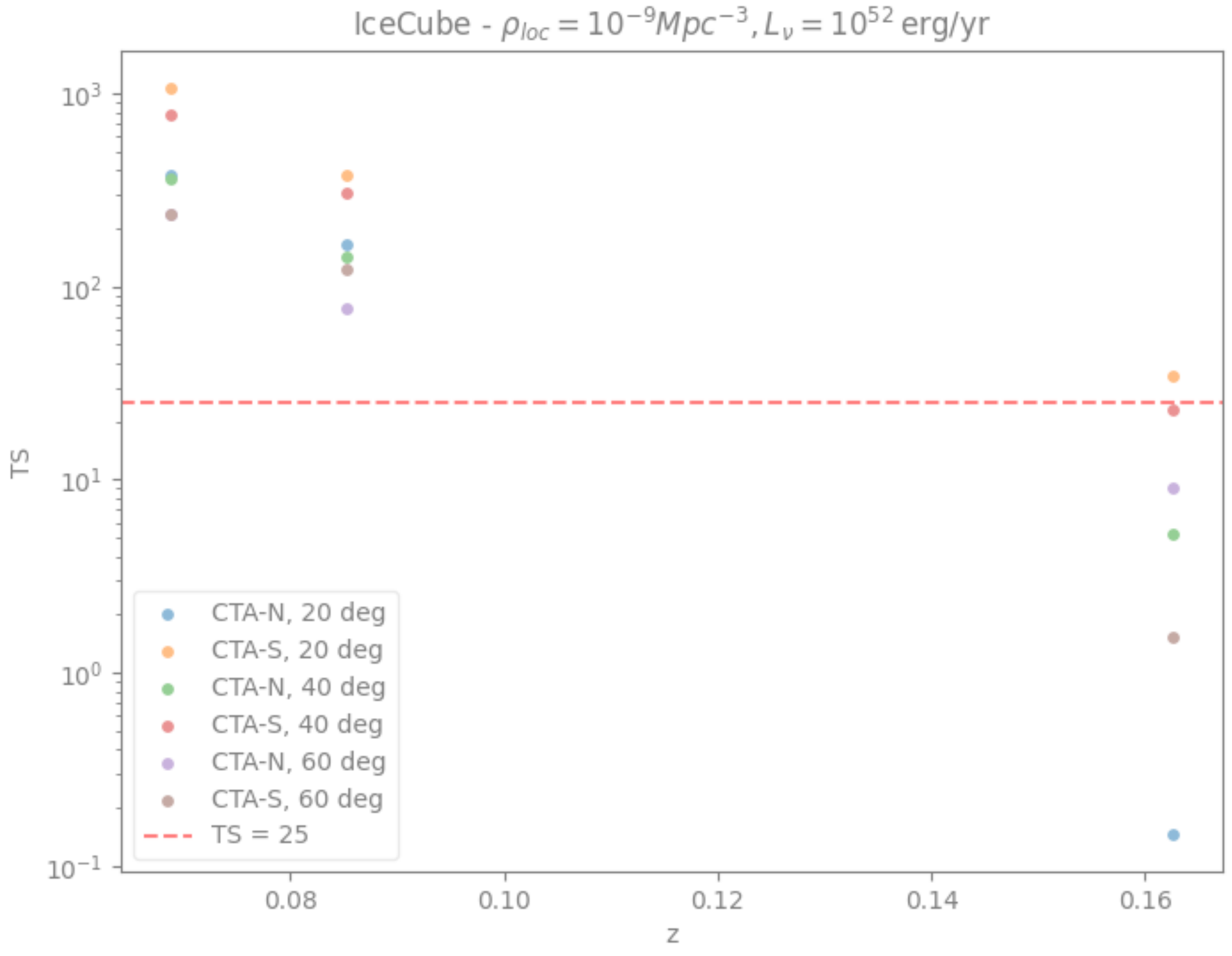
CTAO detection probability

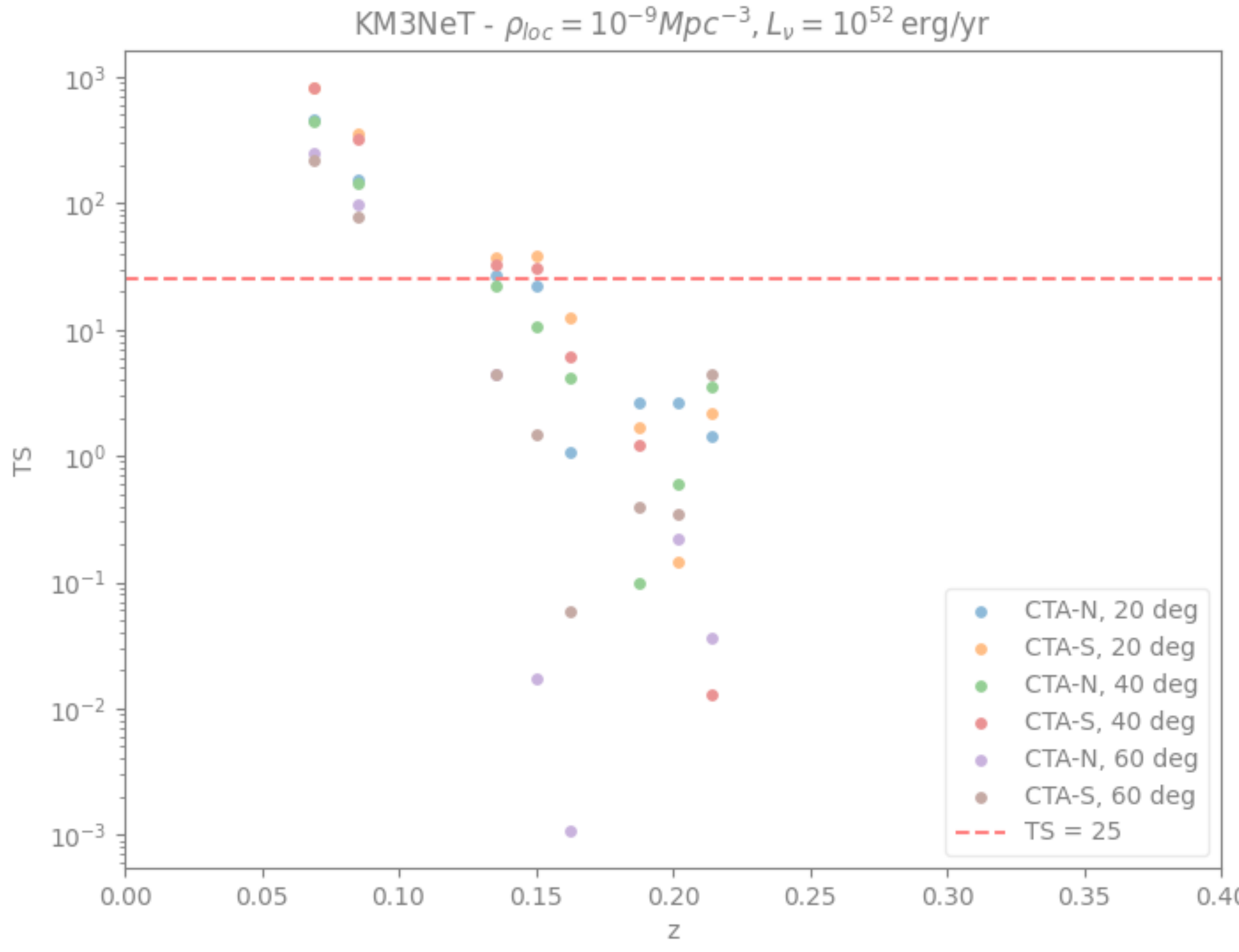
IceCube

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

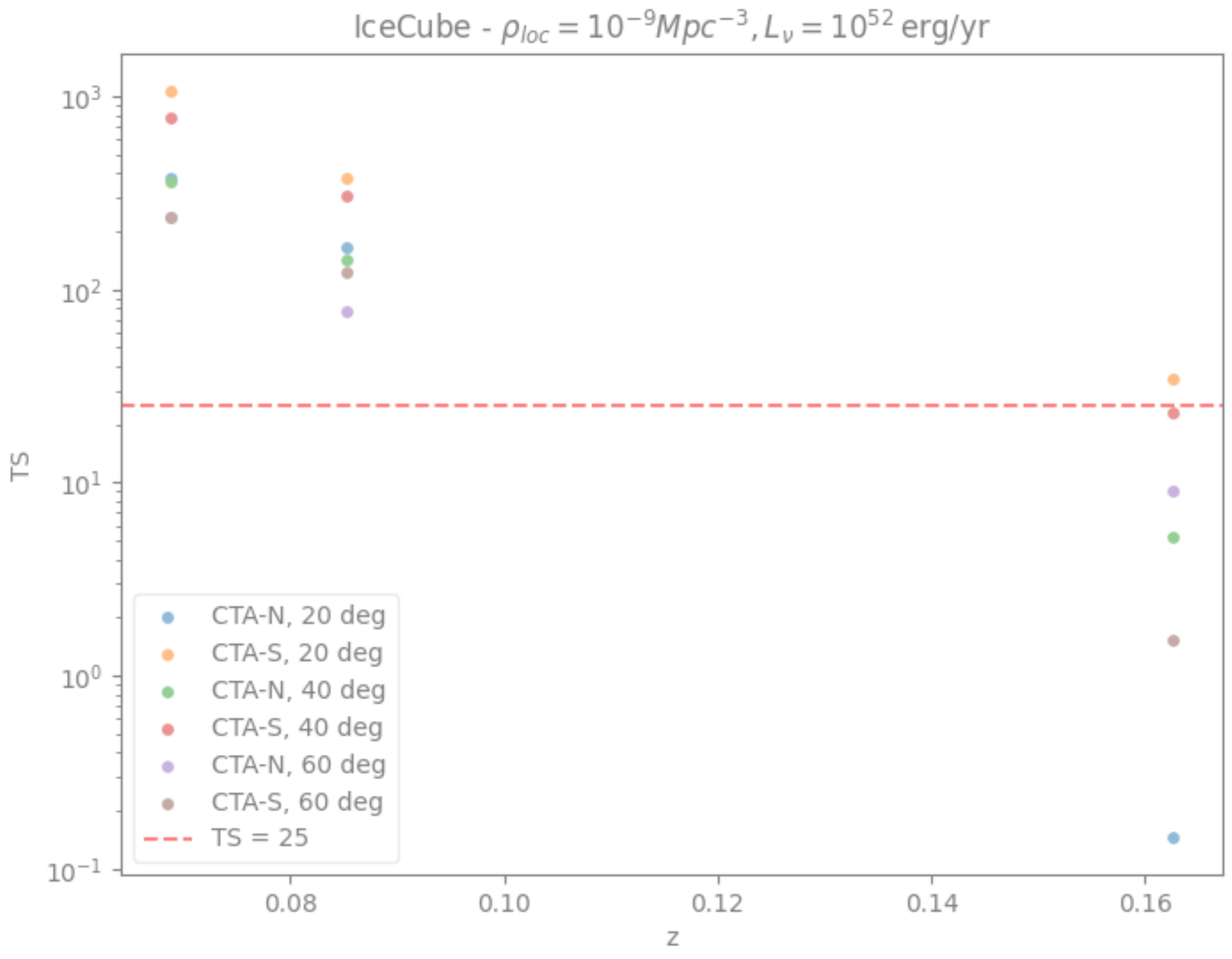
Detected sources - KM3NeT vs IceCube

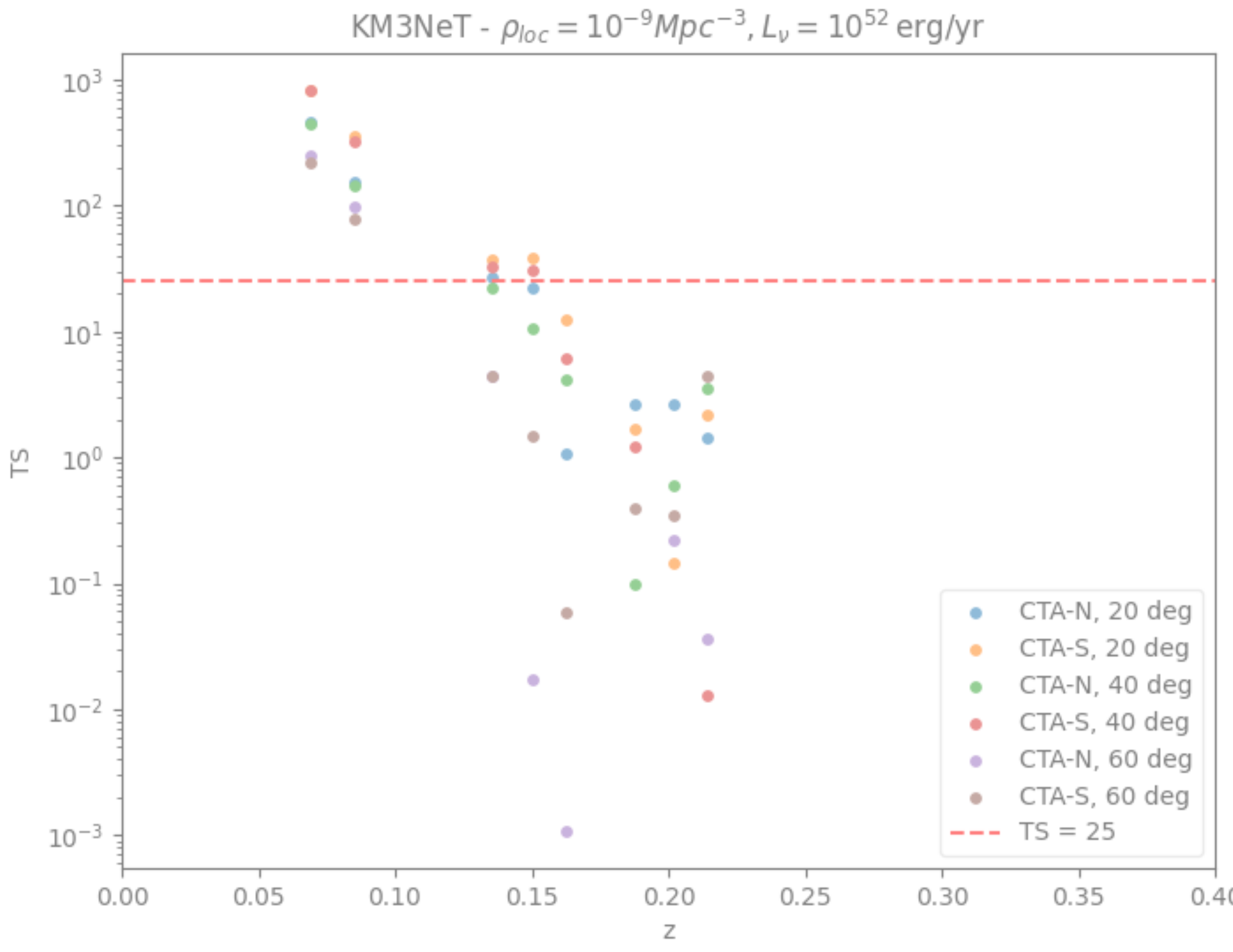
IceCube

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%





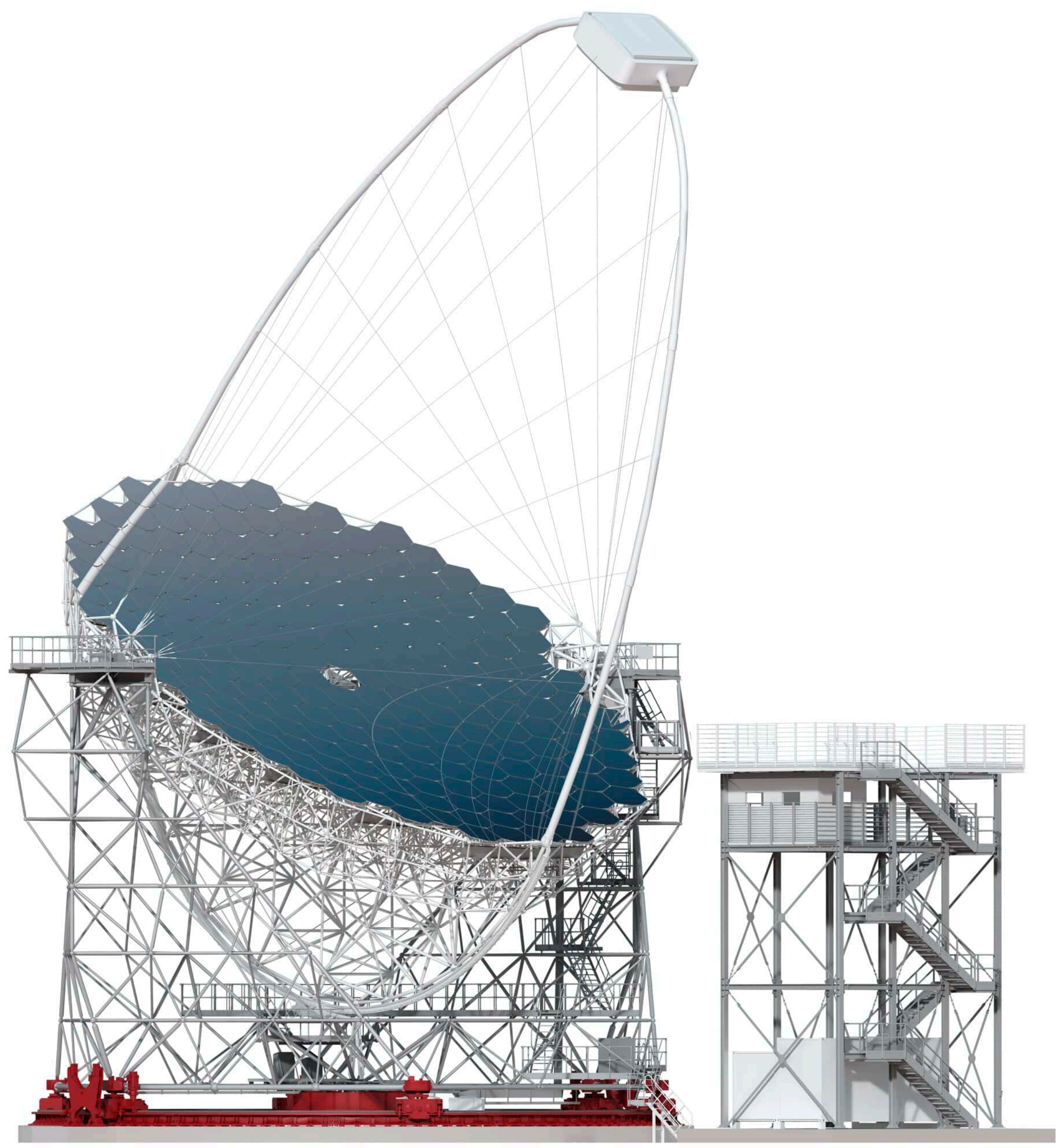
The detection rates for KM3NeT are lower, but it is capable of observing more sources than IceCube, including more distant and fainter sources.

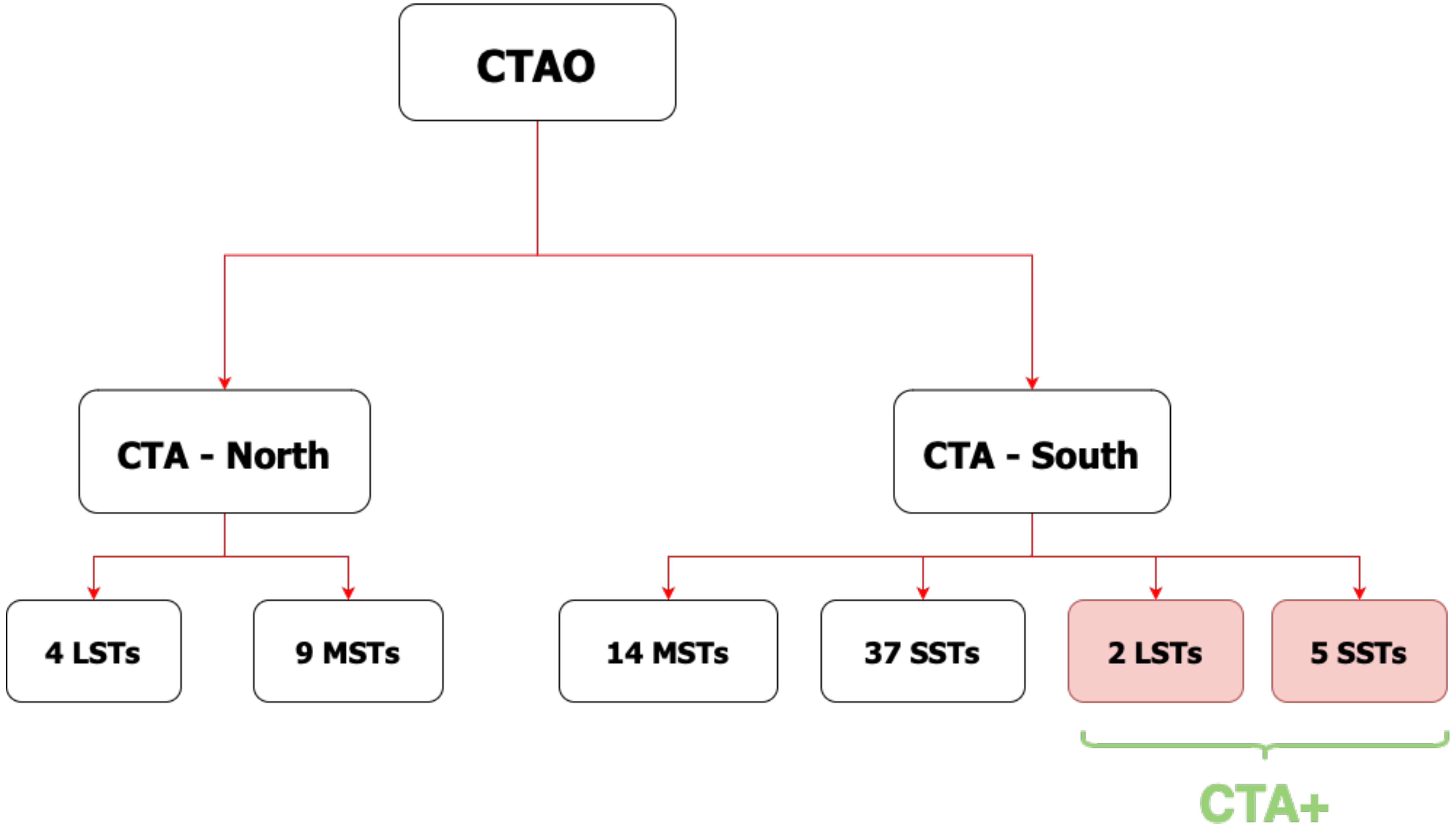
4

CTA performance

CTAO detection probability

The CTA+ project for CTAO





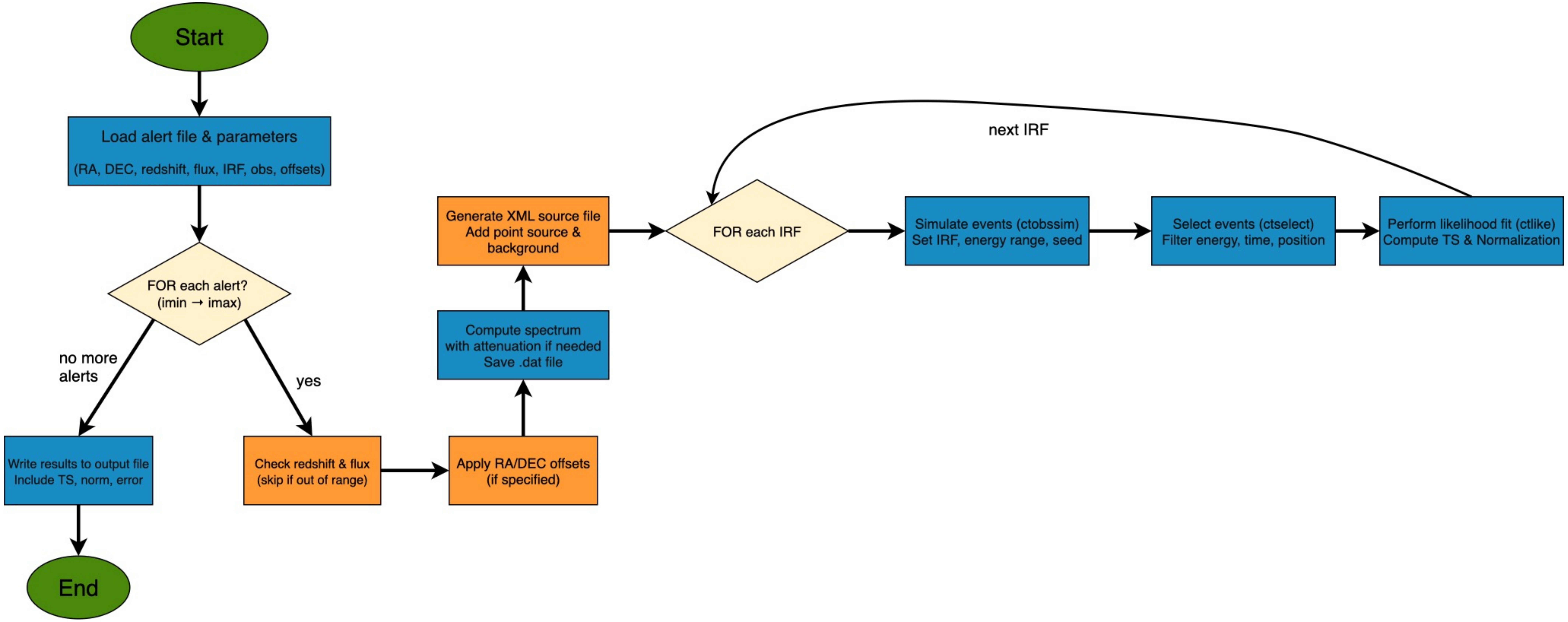
The detection probability for CTAO is lower for KM3NeT than for IceCube due to their different capabilities, although it is expected to improve once the **new configuration** —including two southern LSTs planned by the Italian CTA+ project— is implemented.

3

Gamma Simulations

EBL model and Alpha configuration of IRFs

Gamma-ray simulations



4

CTA performance

CTAO detection probability

CTAO performance

$$P_{CTA} = \frac{N_{detected}}{N_{filtered}}$$

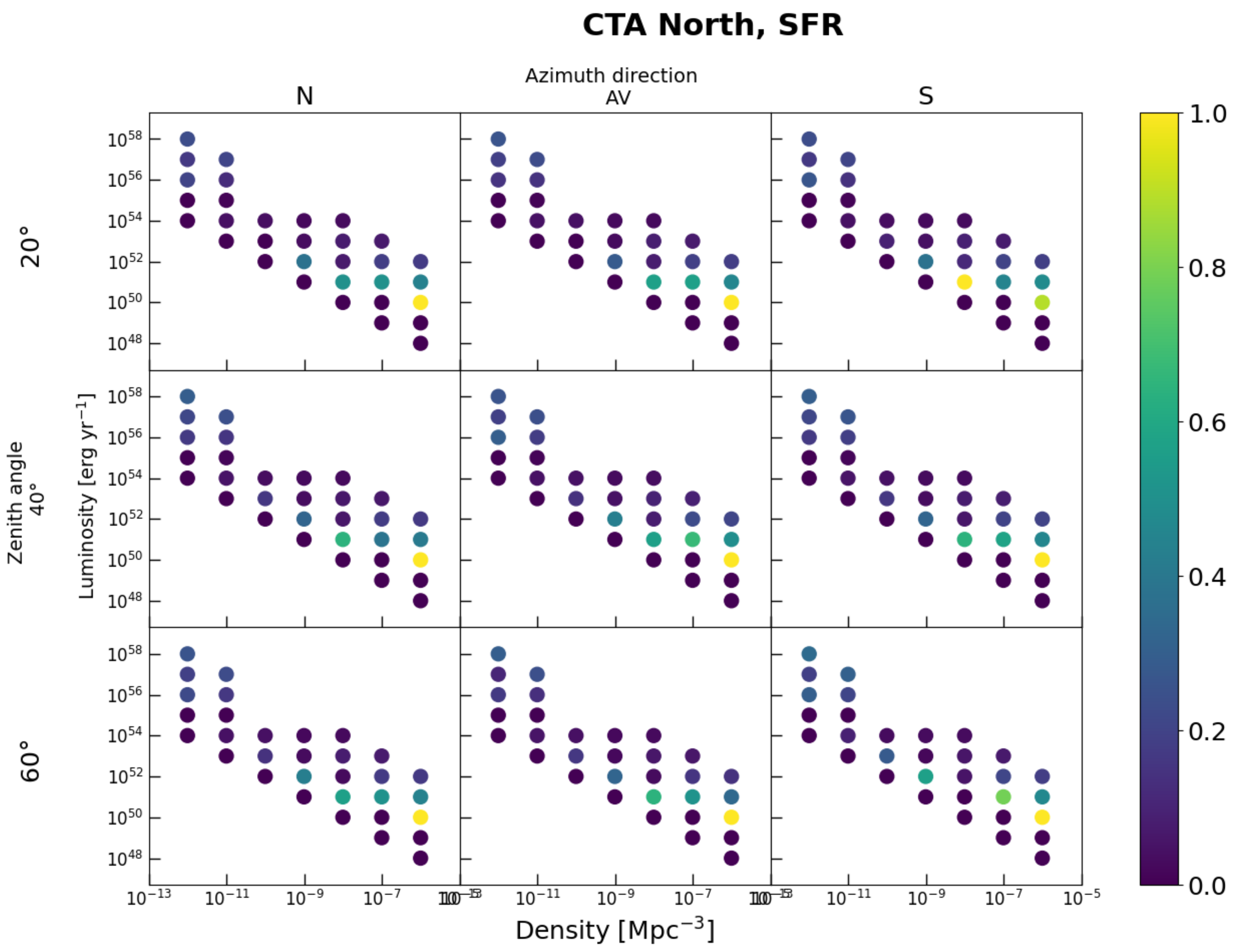
where $N_{detected}$ is the number of sources detected by CTA from the gamma-ray simulations, and $N_{filtered}$ is the total number of neutrino sources simulated with FIRESONG that exceed the discovery potential of the neutrino telescope.

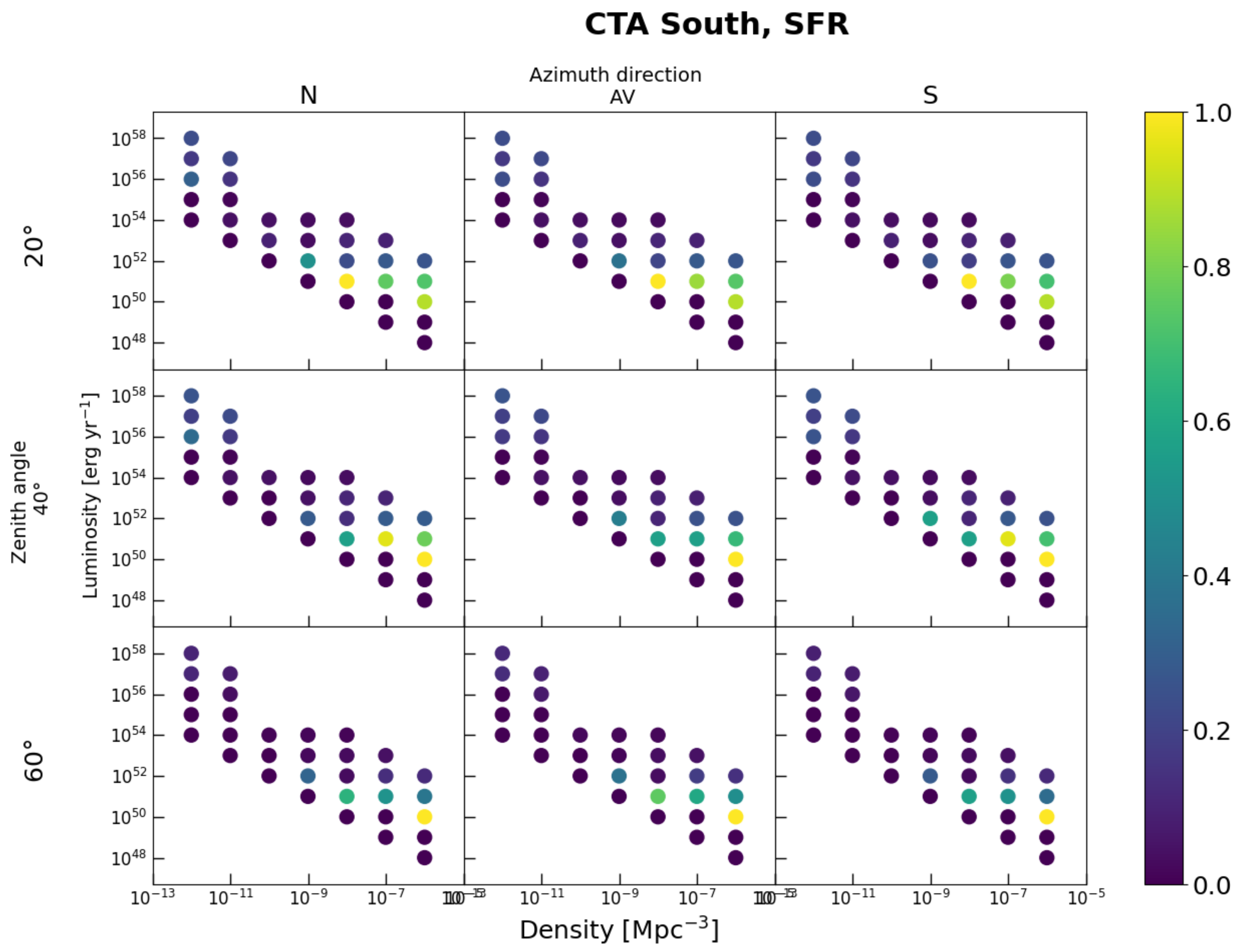
CTAO performance

4

CTA performance

CTAO detection probability





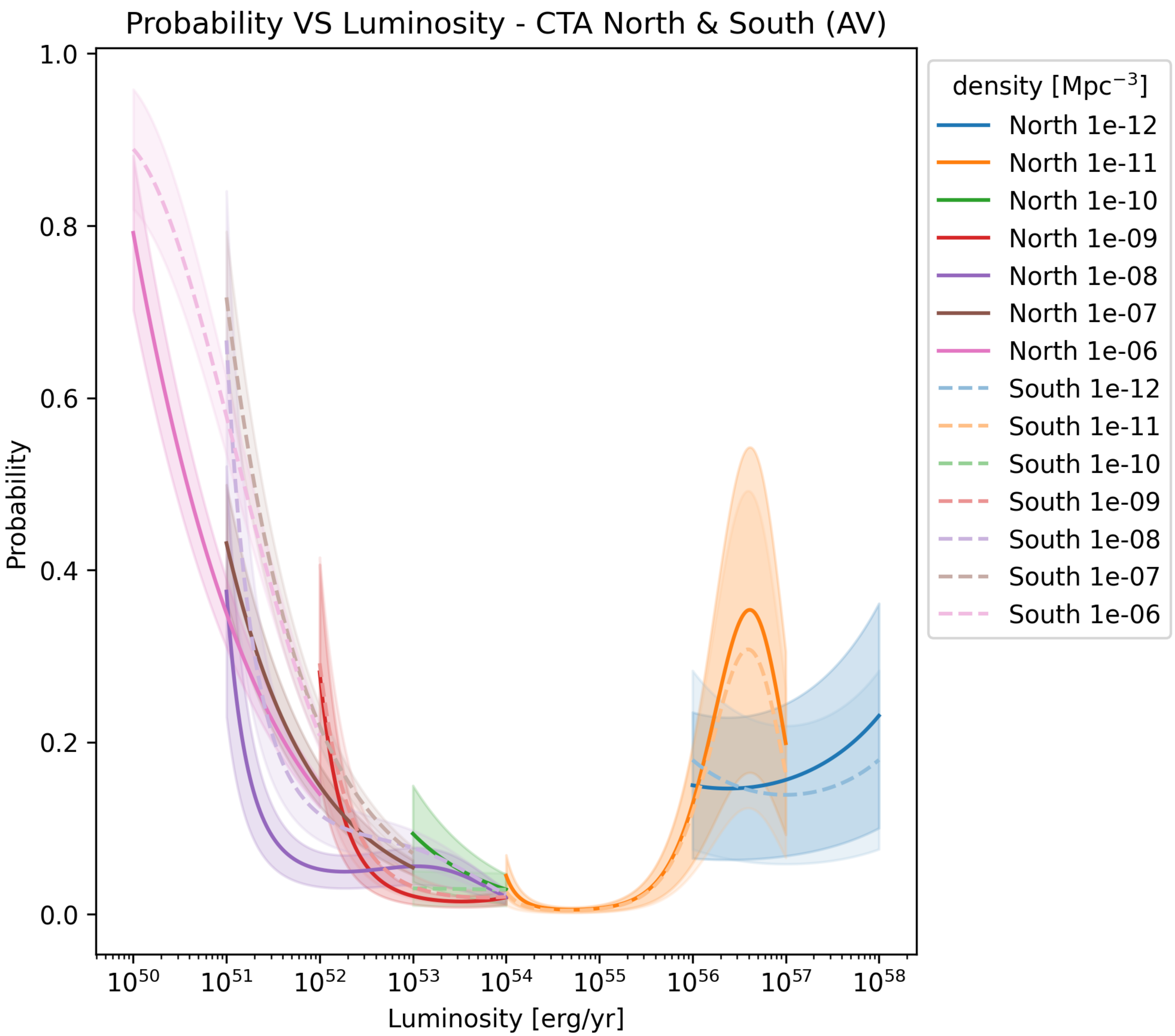
Detection probability maps for CTAO-South (left) and CTAO-North (right), for sources with luminosities below 10^{52} erg/yr and source densities ranging from 10^{-11} to 10^{-6} Mpc^{-3}.

4

CTA performance

CTAO detection probability

Detection efficiency



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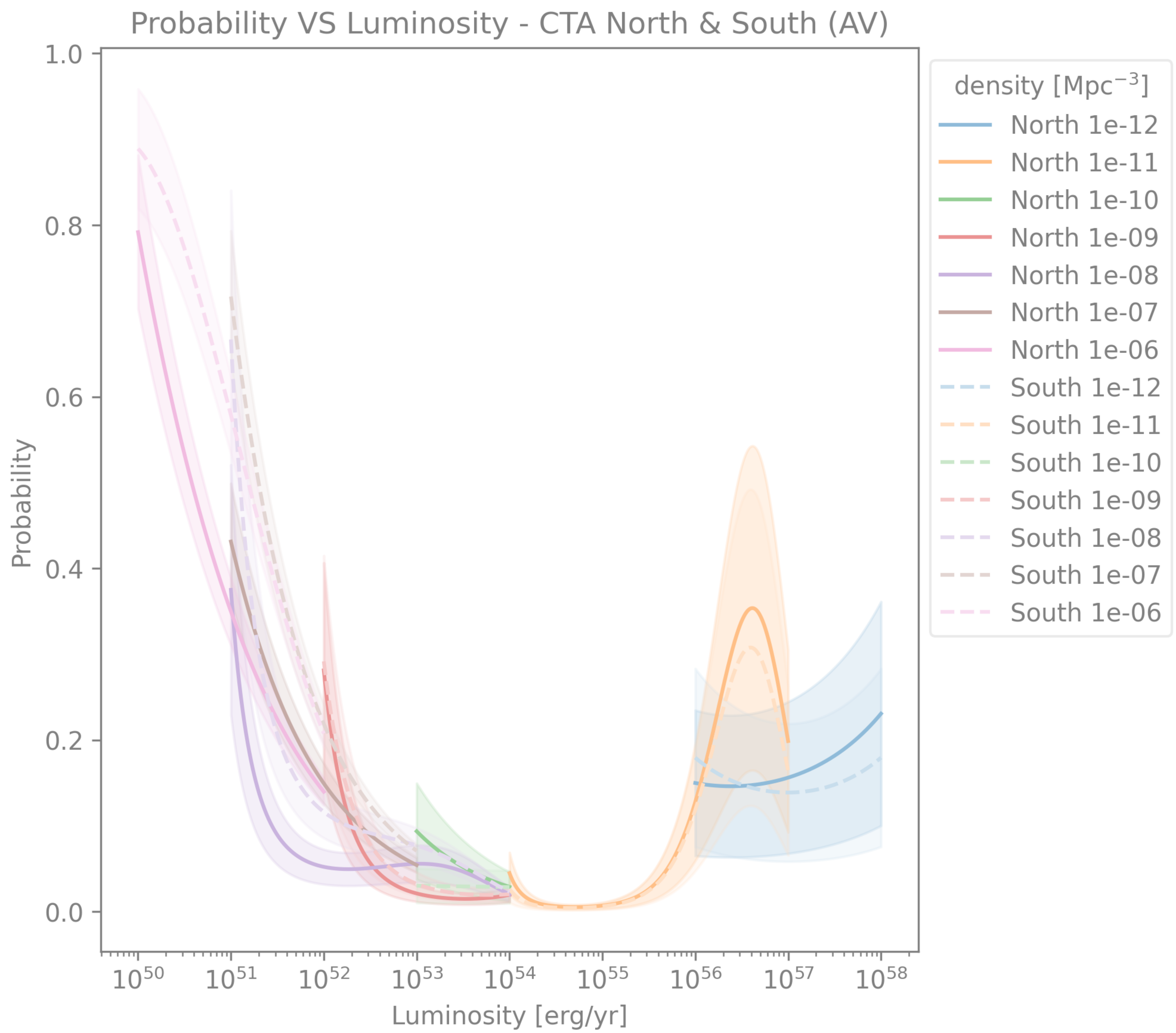
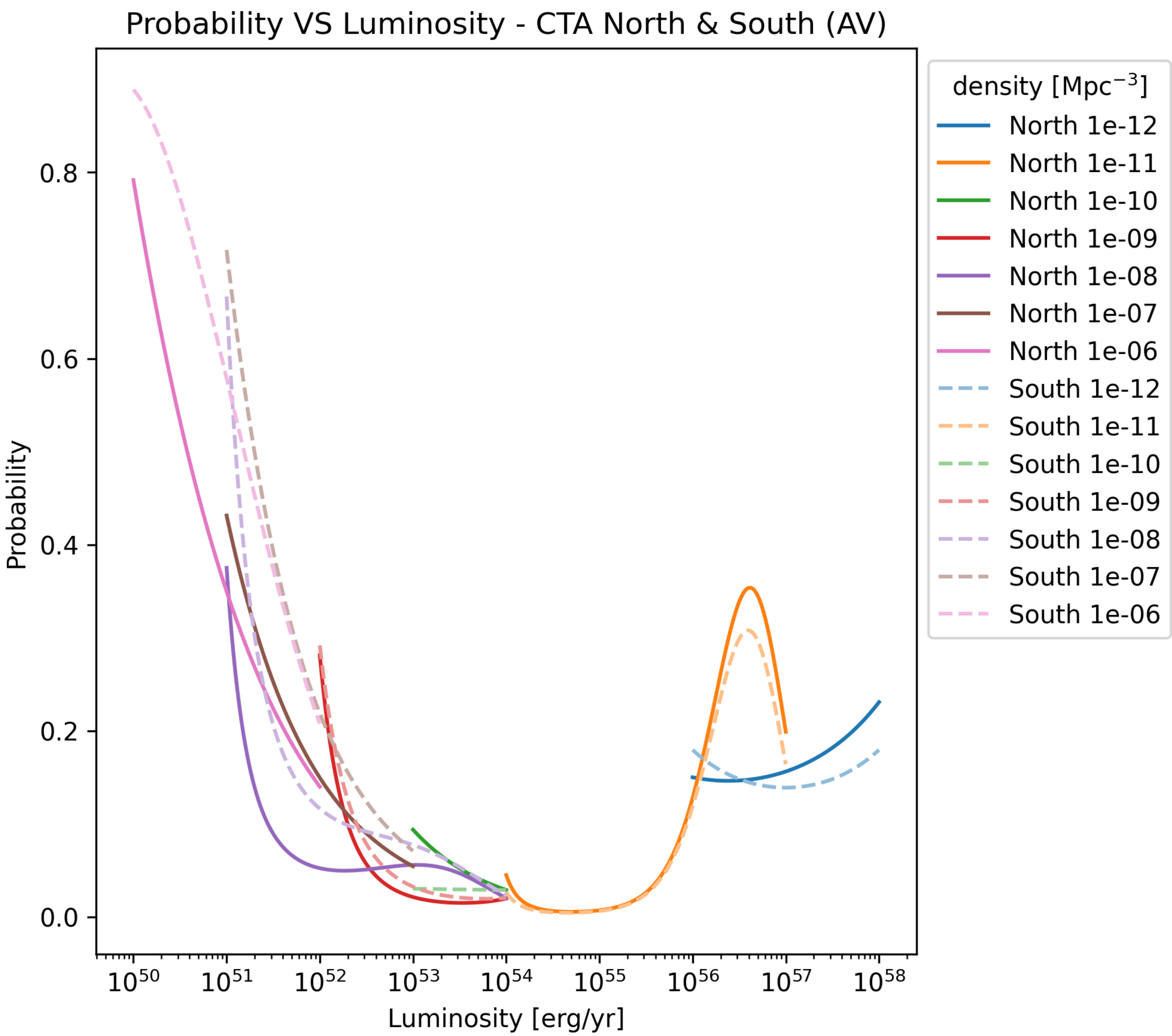
CTA performance

CTAO detection probability

Detection efficiency



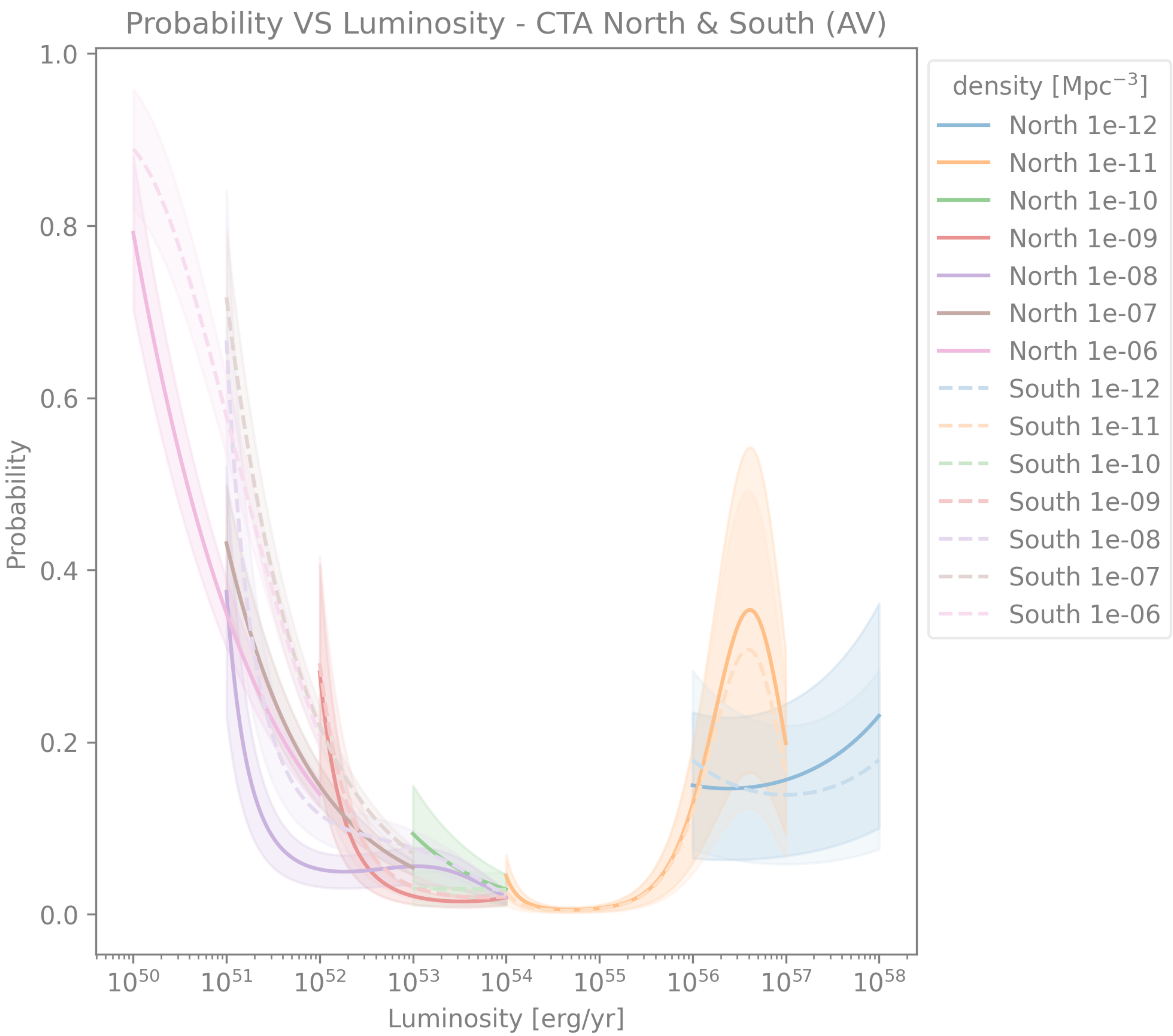


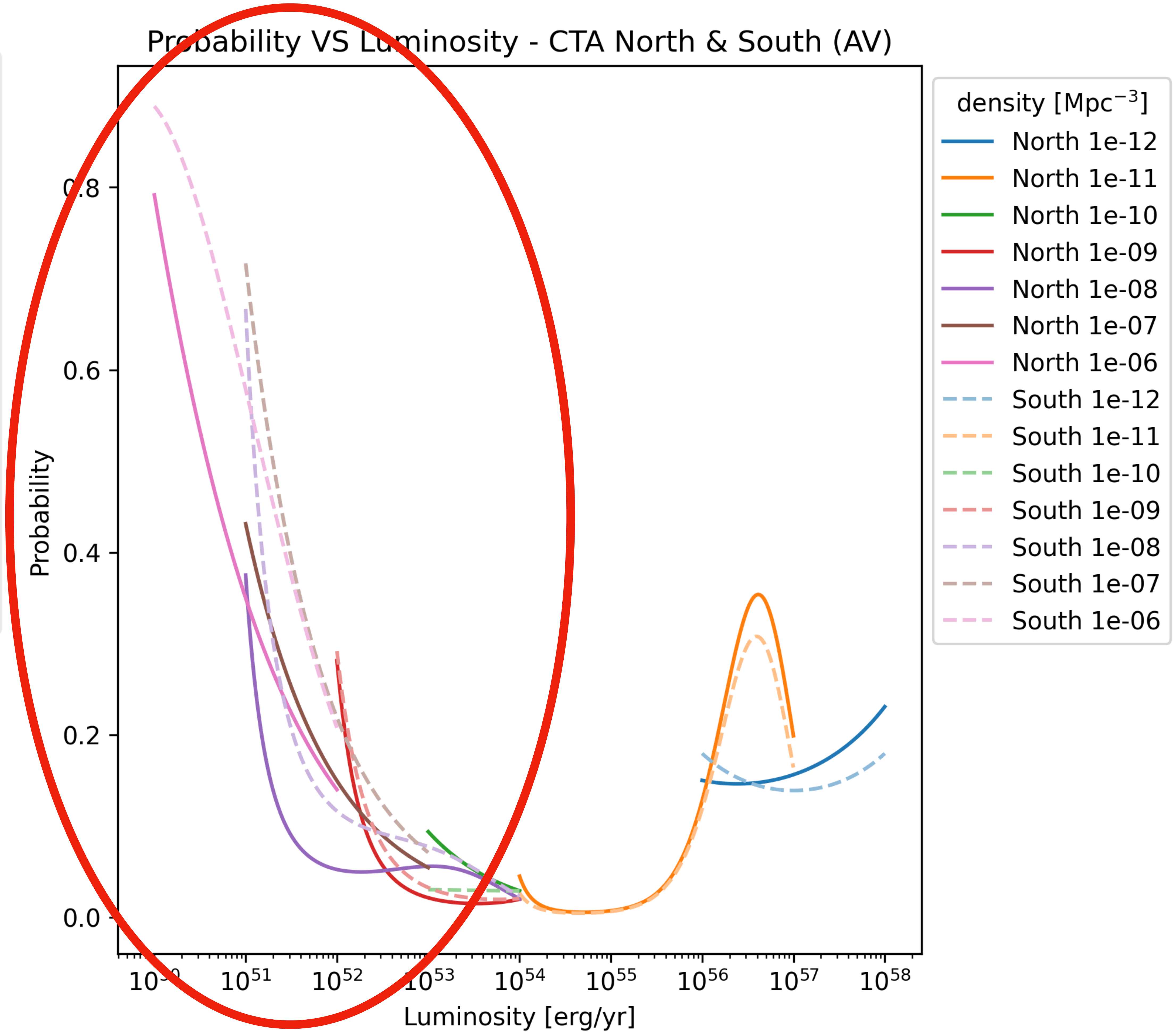
4

CTA performance

CTAO detection probability

Detection efficiency



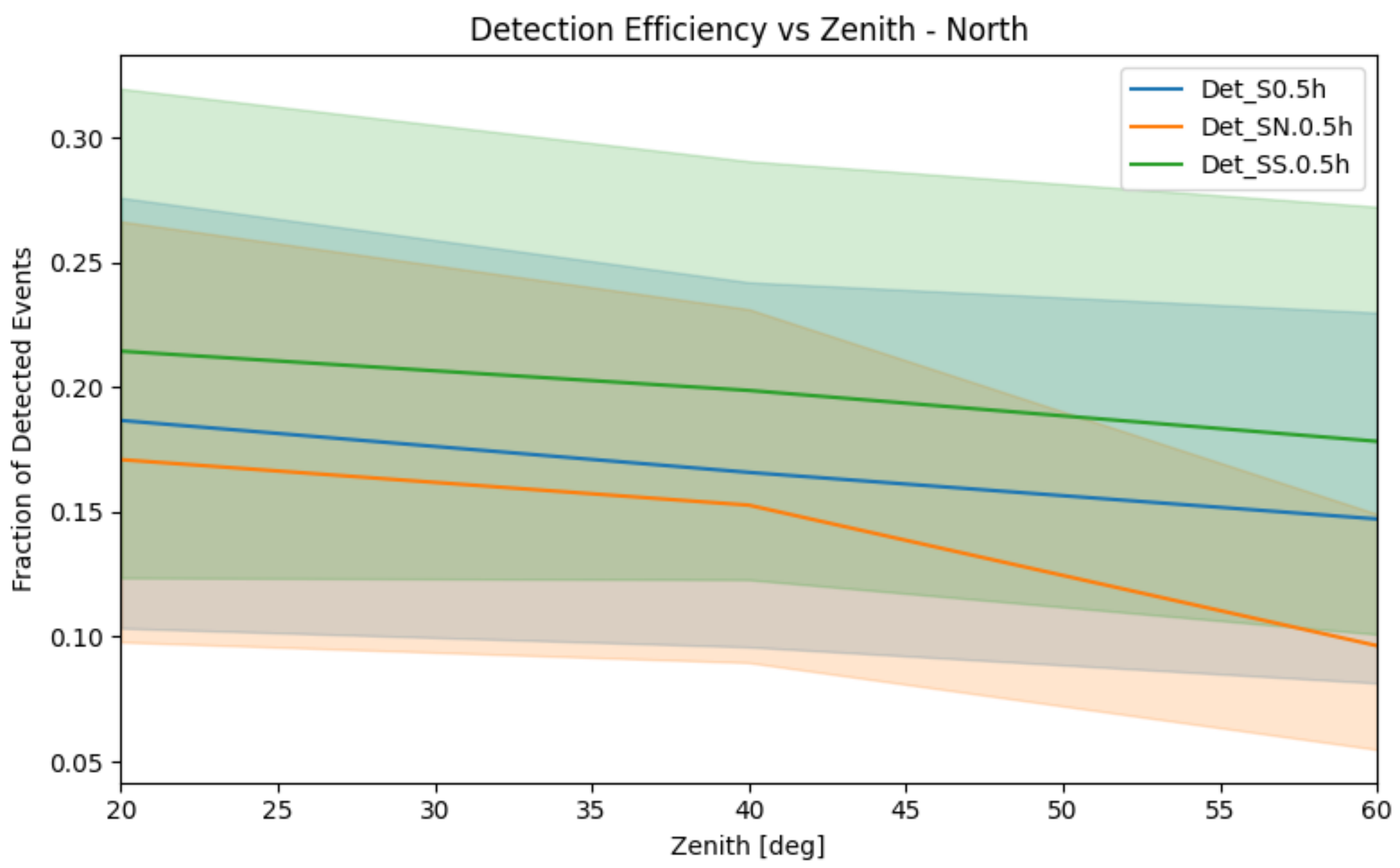


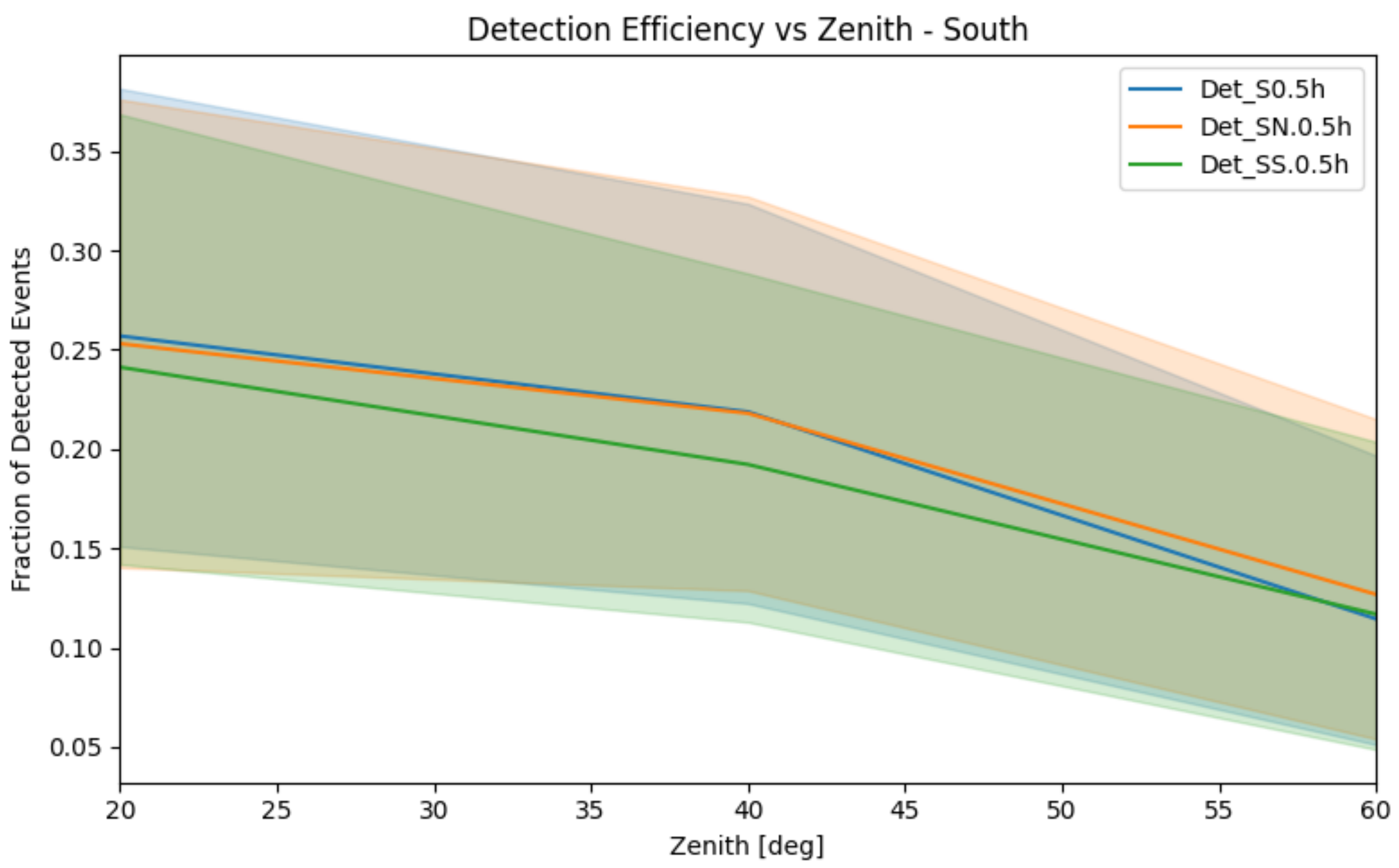
4

CTA performance

CTAO detection probability

Detection Performance



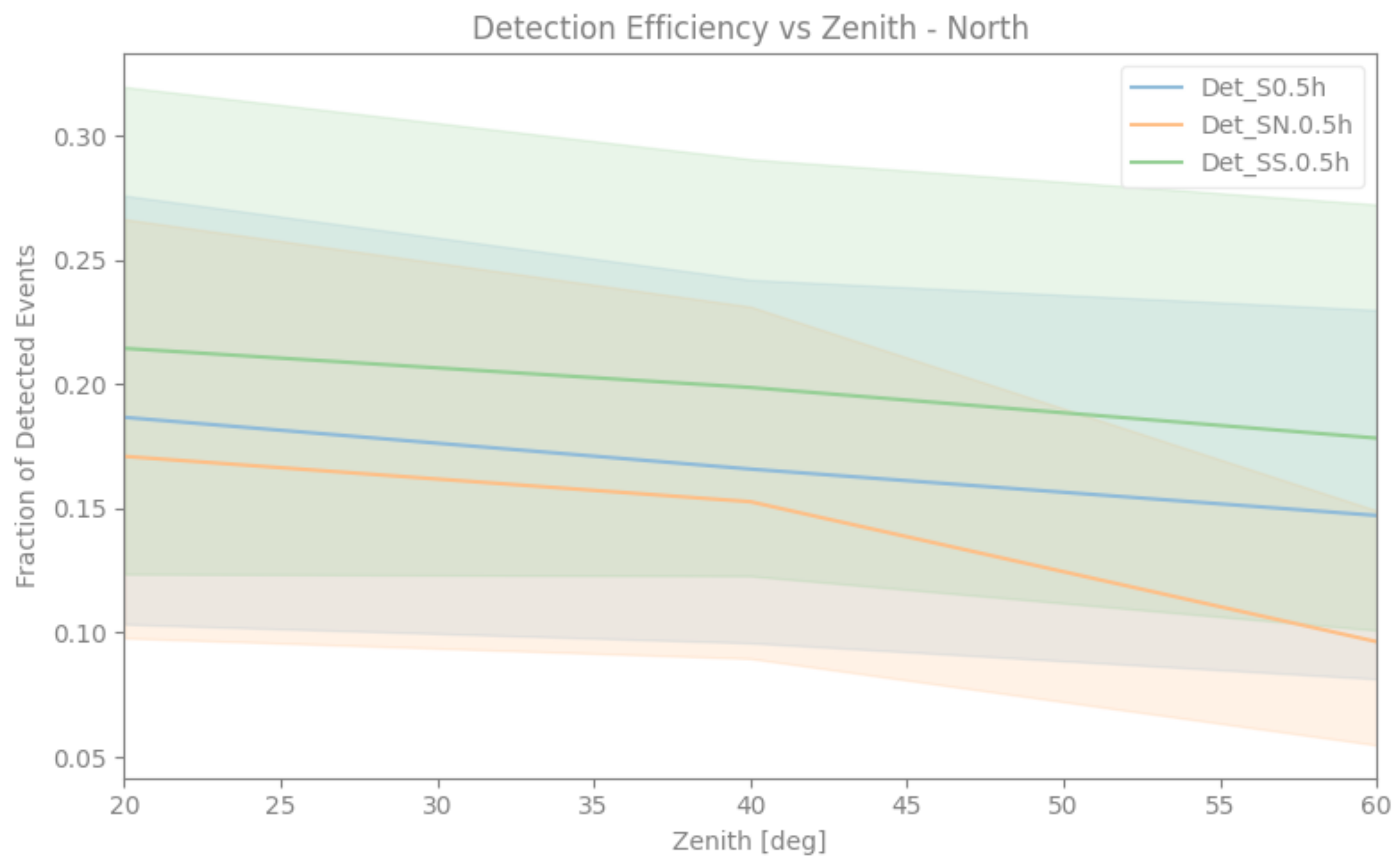


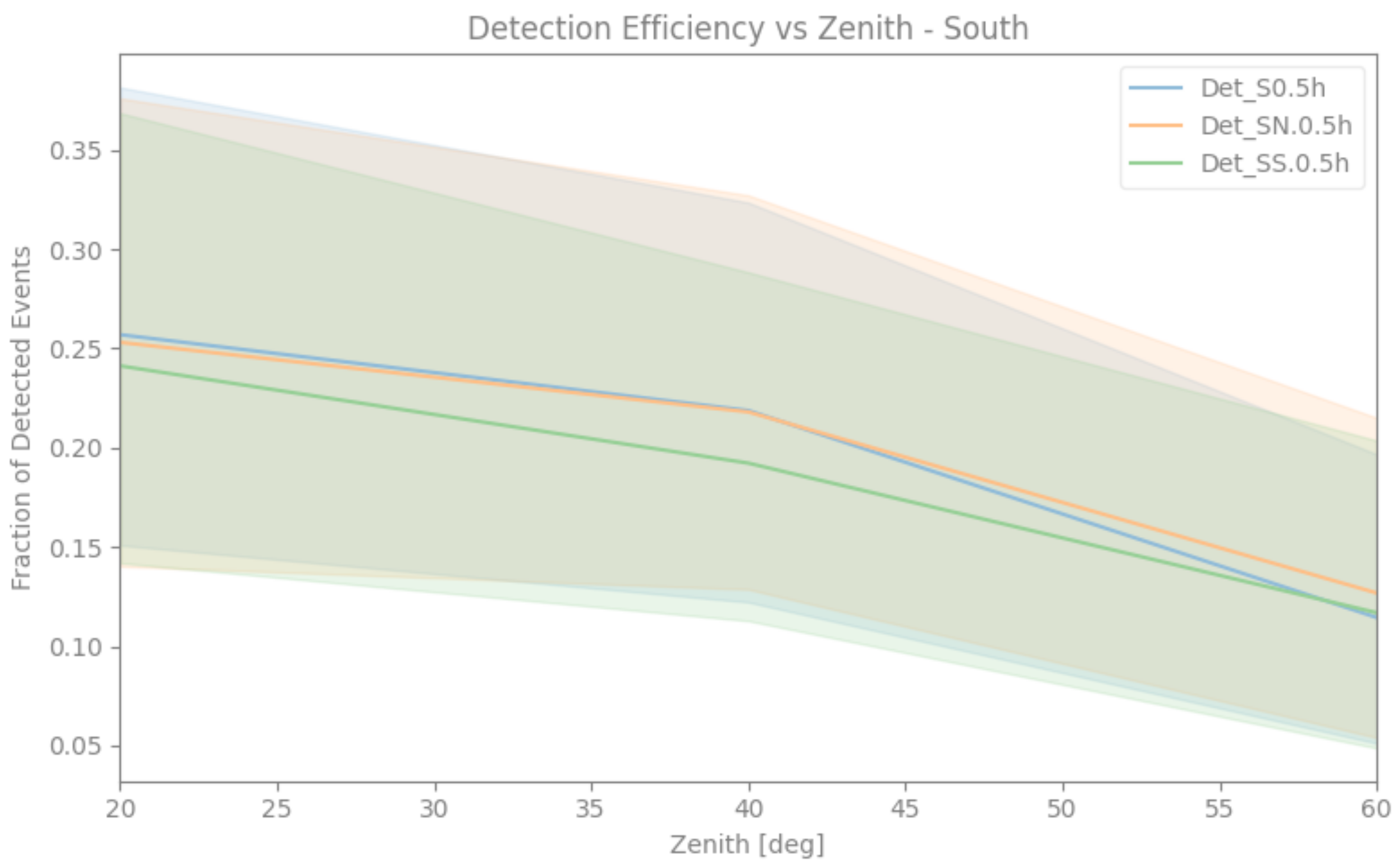
4

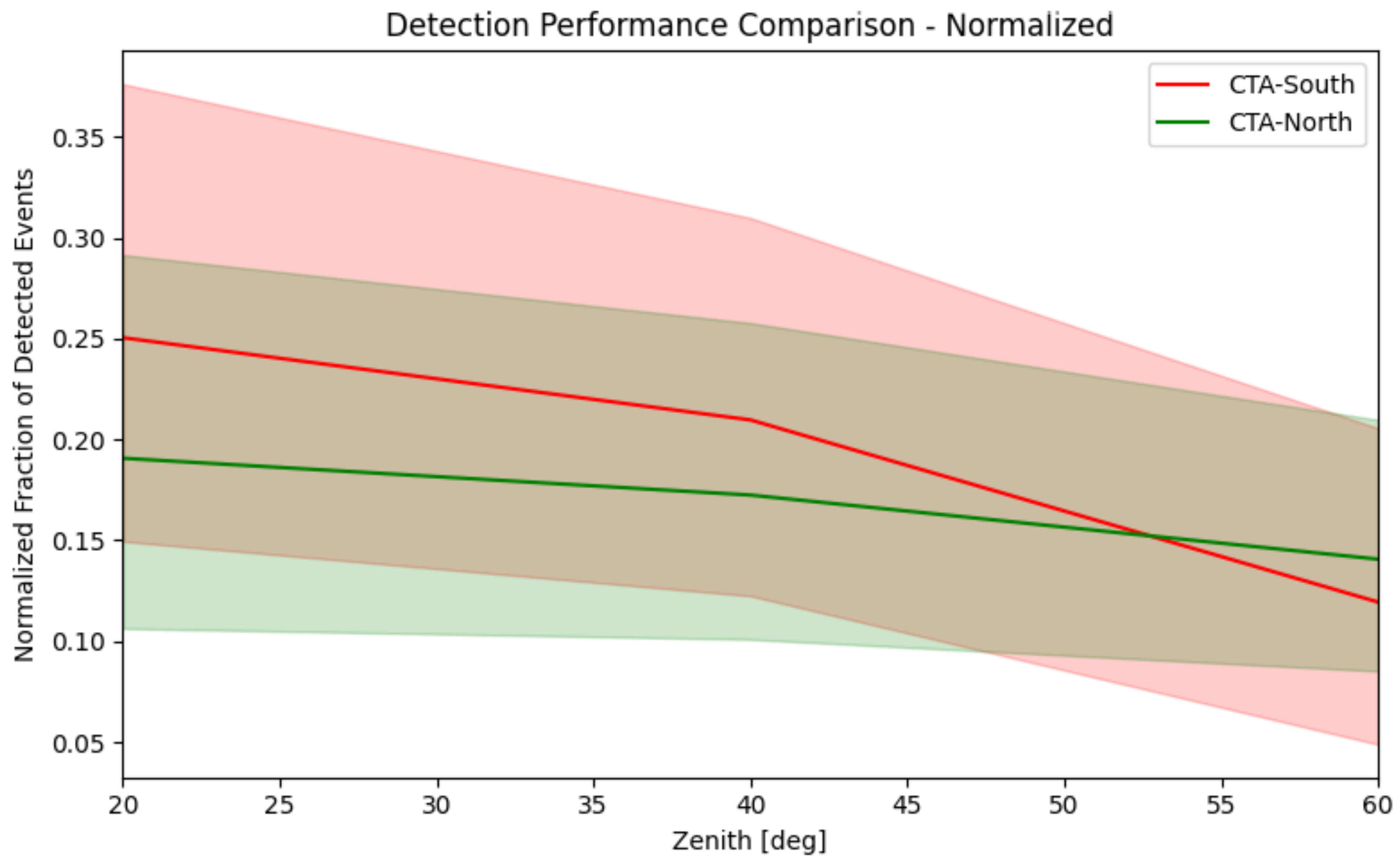
CTA performance

CTAO detection probability

Detection Performance





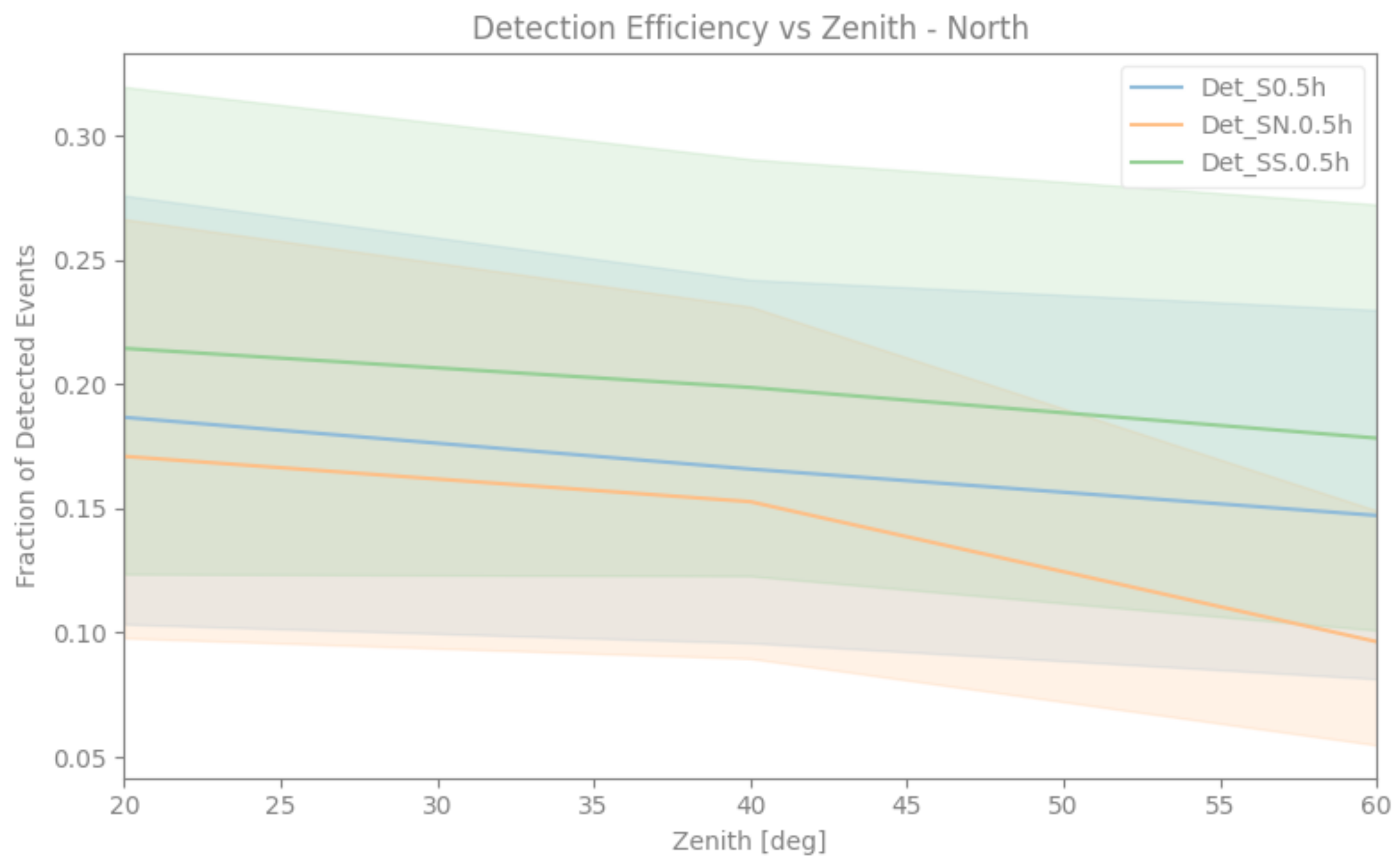


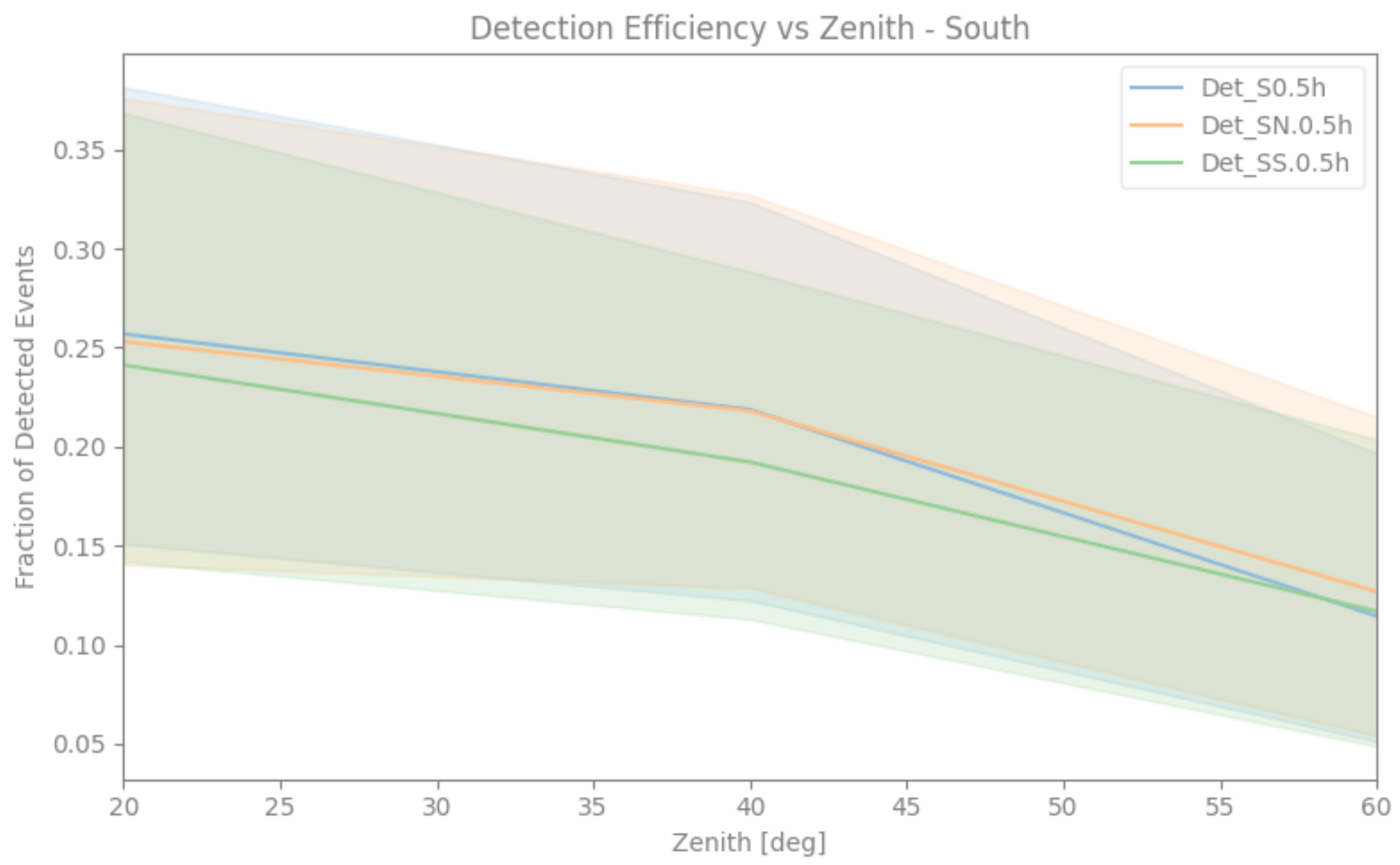
4

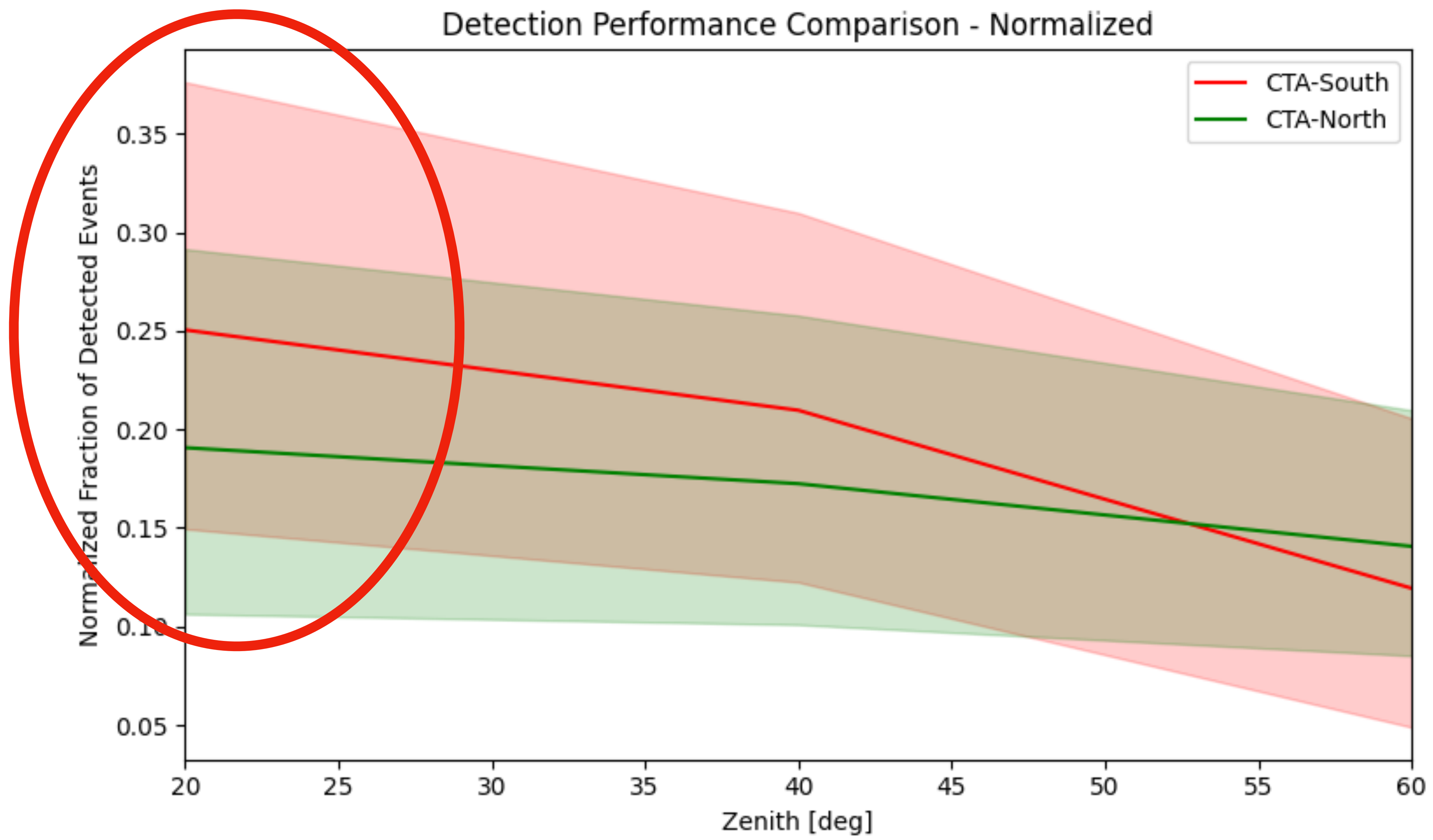
CTA performance

CTAO detection probability

Detection Performance







Outline

- **Next steps**

Next steps: neutrino-flaring sources

1

Neutrino Simulations

FIRESONG python code

Timescale emission in second

2

Neutrino Telescope Filter

Effective Area of KM3NeT neutrino

3

Gamma Simulations

EBL model and Alpha configuration of IRFs

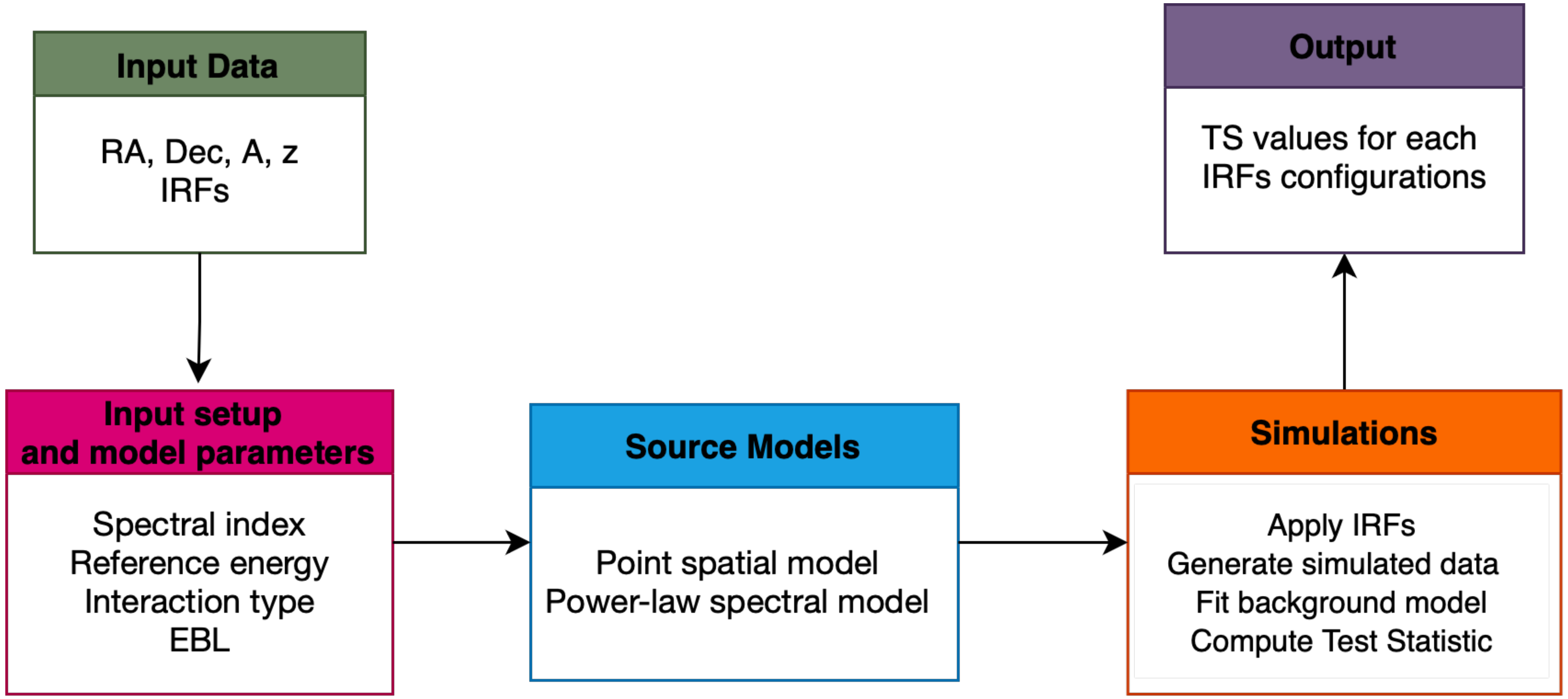
4

CTA performance

CTAO detection probability

Next steps: Testing New Gammapy Code

- We're currently testing a new NToO analysis pipeline in Gammapy
- Preliminary results expected by **November**



Conclusions and Future perspectives

- The probability of CTAO detection is **currently lower for KM3NeT** alerts than for IceCube, mainly due to the different characteristics of the northern and southern arrays.
- However, an improvement is expected with the new CTA configuration, which includes **two additional large telescopes (LSTs) in the south**, planned as part of the Italian **CTA+ project**.
- Although KM3NeT shows lower detection rates, it is capable of observing a **higher number of sources** than IceCube, including **more distant** and **fainter** ones.
- Analysis focusing on different types of neutrino sources is about to begin, i**ncluding neutrino sources that show variable activity over time**, as well as constant and periodic emitters. This next step will contribute to a better understanding of how variability and different emission patterns affect detection probabilities and will extend the study beyond constant sources.
- In addition, we are developing a new code in **Gammapy**, which offers **improved performance** and **faster processing**. This will allow us to explore a wider range of scenarios and optimize detection strategies, particularly for variable and weak sources that are difficult to analyze.

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Thanks for your attention!