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Evaluation of the CTA performance to the gamma-ray emission from neutrino sources detectable by the IceCube and KM3NeT

A.M.Brown, **G.M.Cicciari,** G.Ferrara, M.Mallamaci, G.Marsella, A.Rosales de Leon, O.Sergijenko

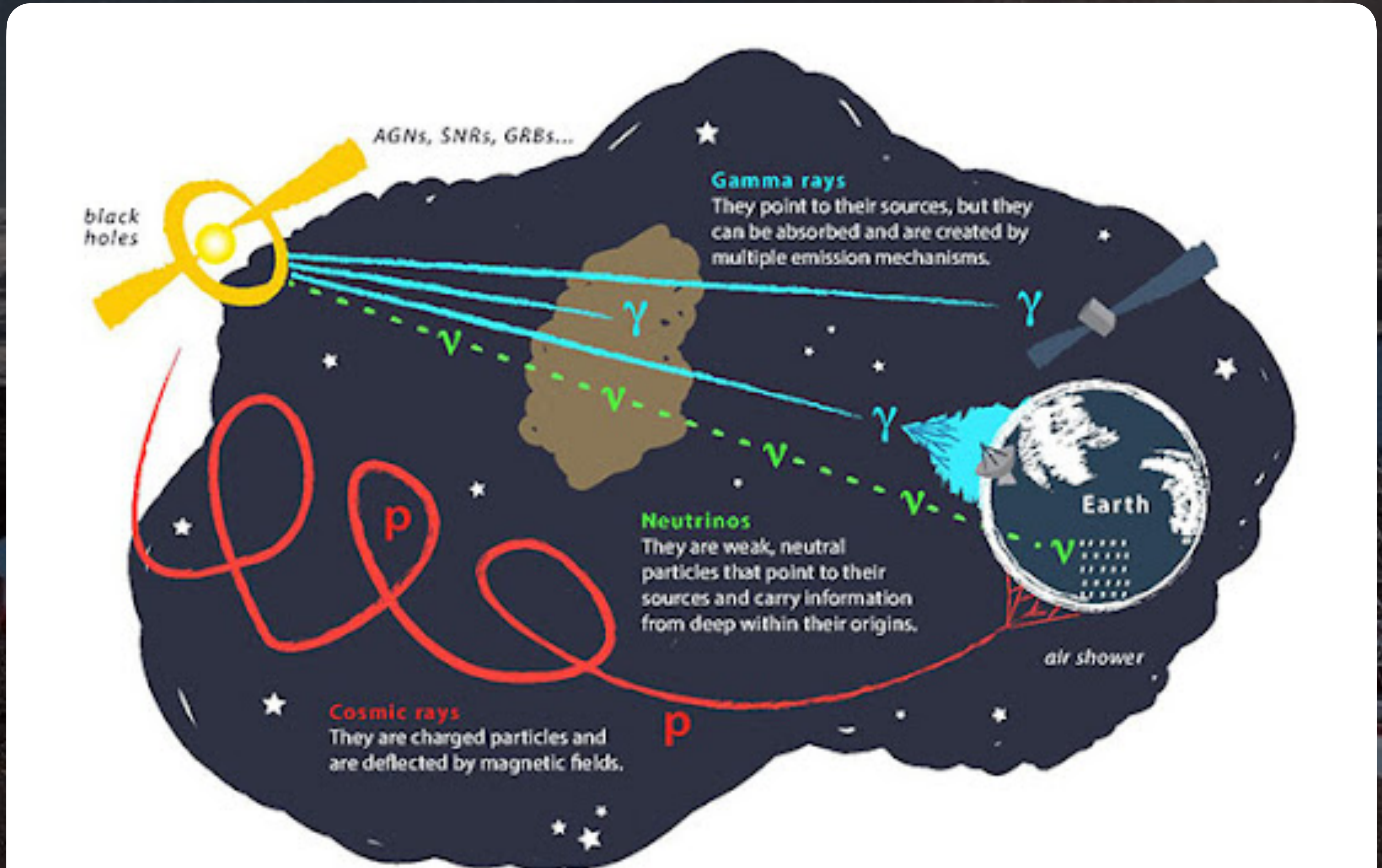
CTAO Science Symposium - 2nd edition - 17 April 2024, Bologna

Outline

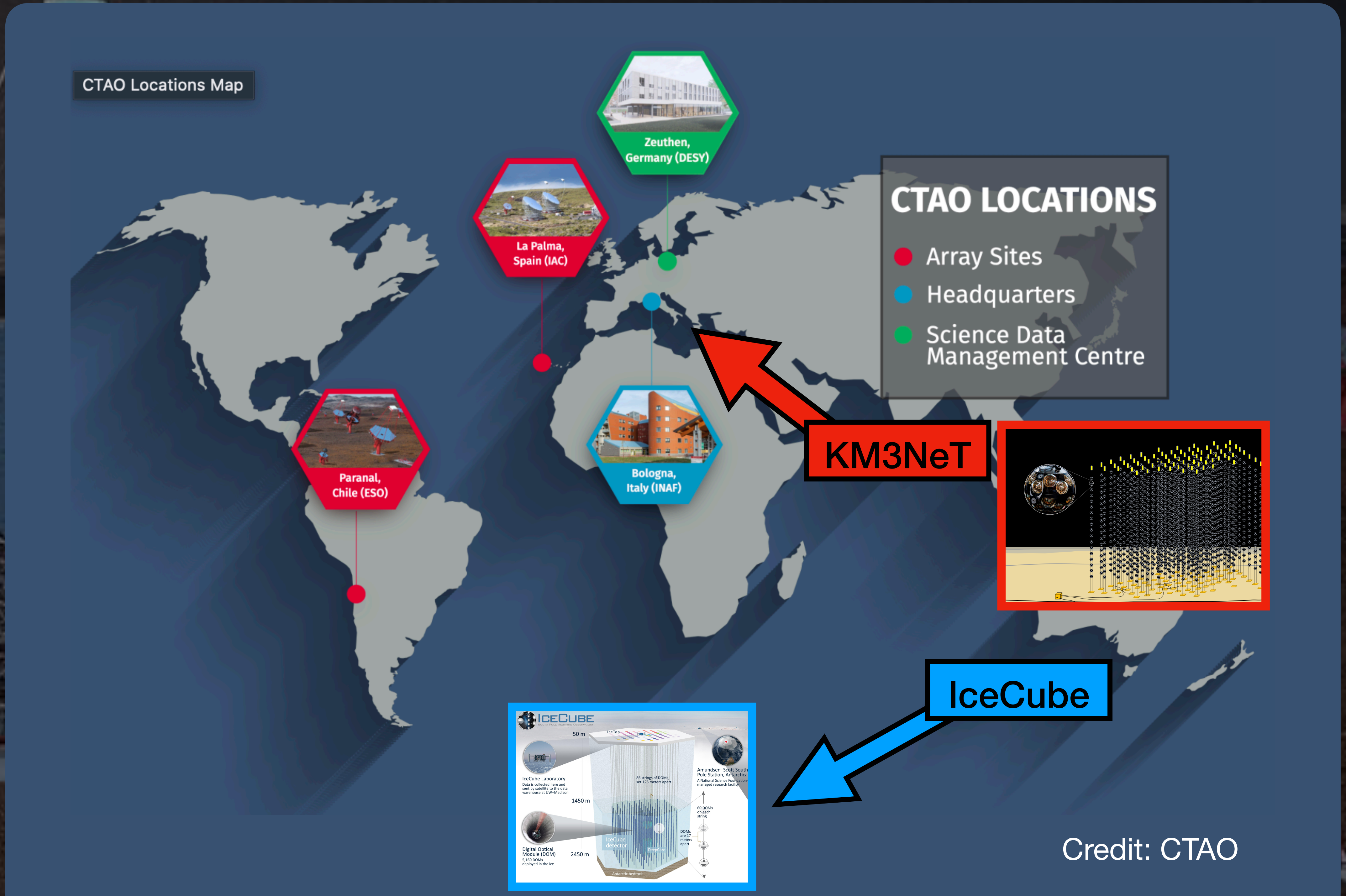
- Multi-messenger astronomy
- The Cherenkov Telescope Array Observatory (CTAO)
- Neutrino Target of Opportunity (NToO)
- Neutrino simulations with FIRESONG
- The implementation of the discovery potential of neutrino telescopes
- Simulations of gamma rays and CTA performance
- The CTA+ program for CTAO
- Conclusion and Next Steps

The multi-messenger astronomy

The exploration of the Universe through **combined information** from **cosmic messengers: gamma rays** and **neutrino**



Credit: IceCube collaboration



Credit: CTAO

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cherenkov telescope array

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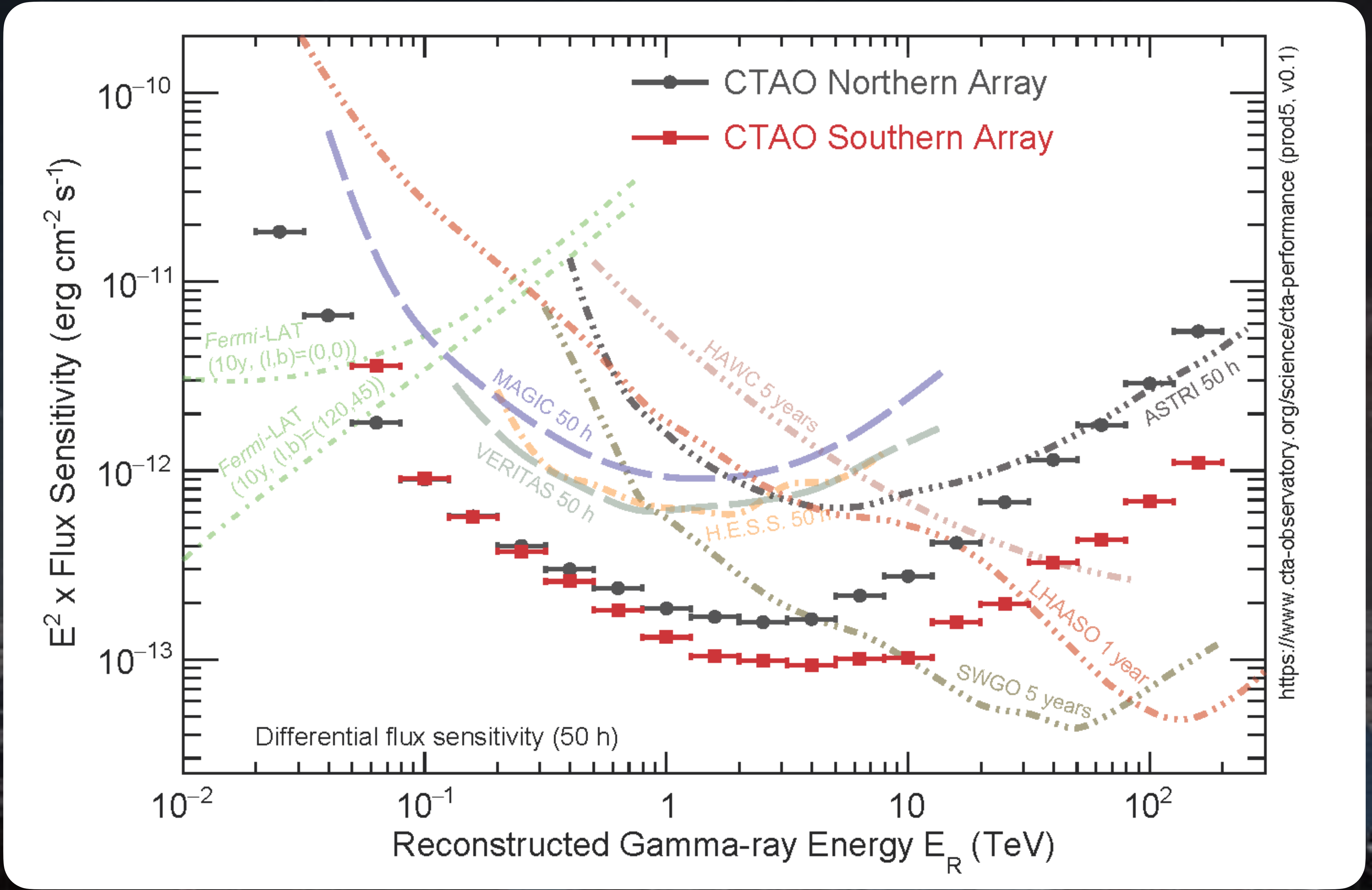
The Cherenkov Telescope Array Observatory (CTAO)



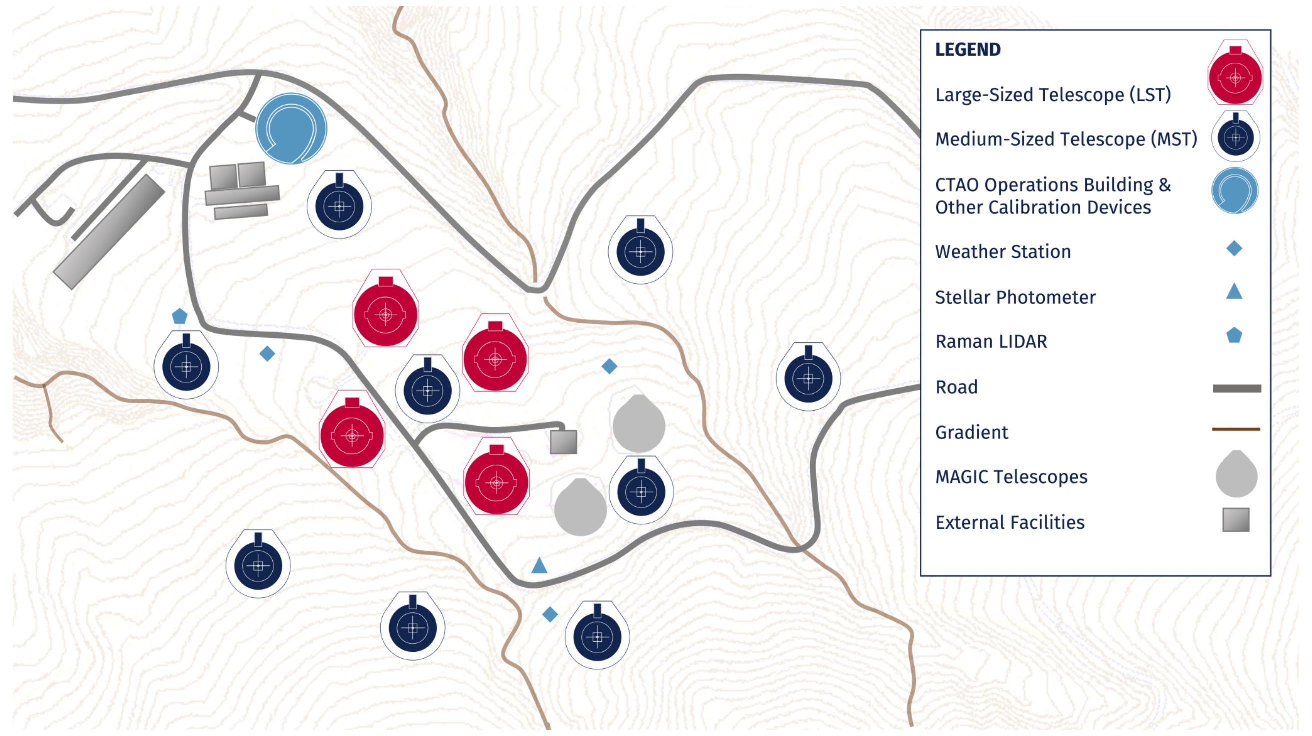
CTA flux sensitivity for the Northern and Southern arrays, on axis, for 50 h observation time, including the sensitivity of other gamma-ray instruments, credit: CTAO

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

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
SST	4 m
MST	12 m
LST	23 m



Layout of the CTAO northern array on La Palma

credit: Tomohiro Inada

Neutrino Target of Opportunity (NToO) - Current Status

CTA will be able to look for **a gamma-ray counterpart** from **a neutrino source alert** and also monitor “hot-spots” that exceeds IceCube (IC) sensitivity

What are we simulating?

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

Neutrino Telescope + **Cherenkov Telescope**

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Neutrino Sinulations (FIRESONG) → **Neutrino Telescope "Filter"** → **IceCube** → **Gamma Simulations** → **The Alpha configuration of the array** → **CTA performance**

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see Olga's poster

Neutrino Target of Opportunity (NToO) - Innovations

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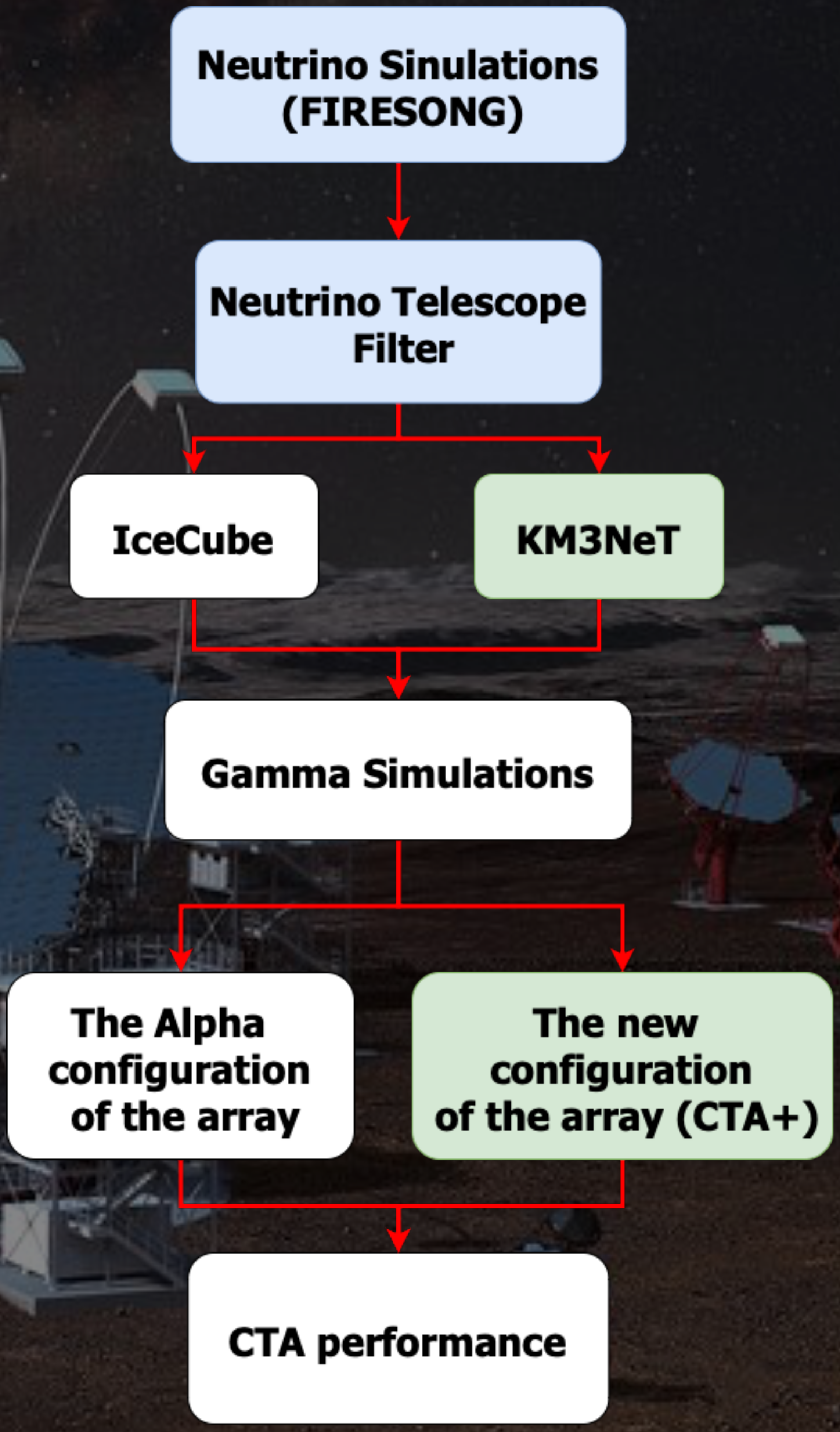

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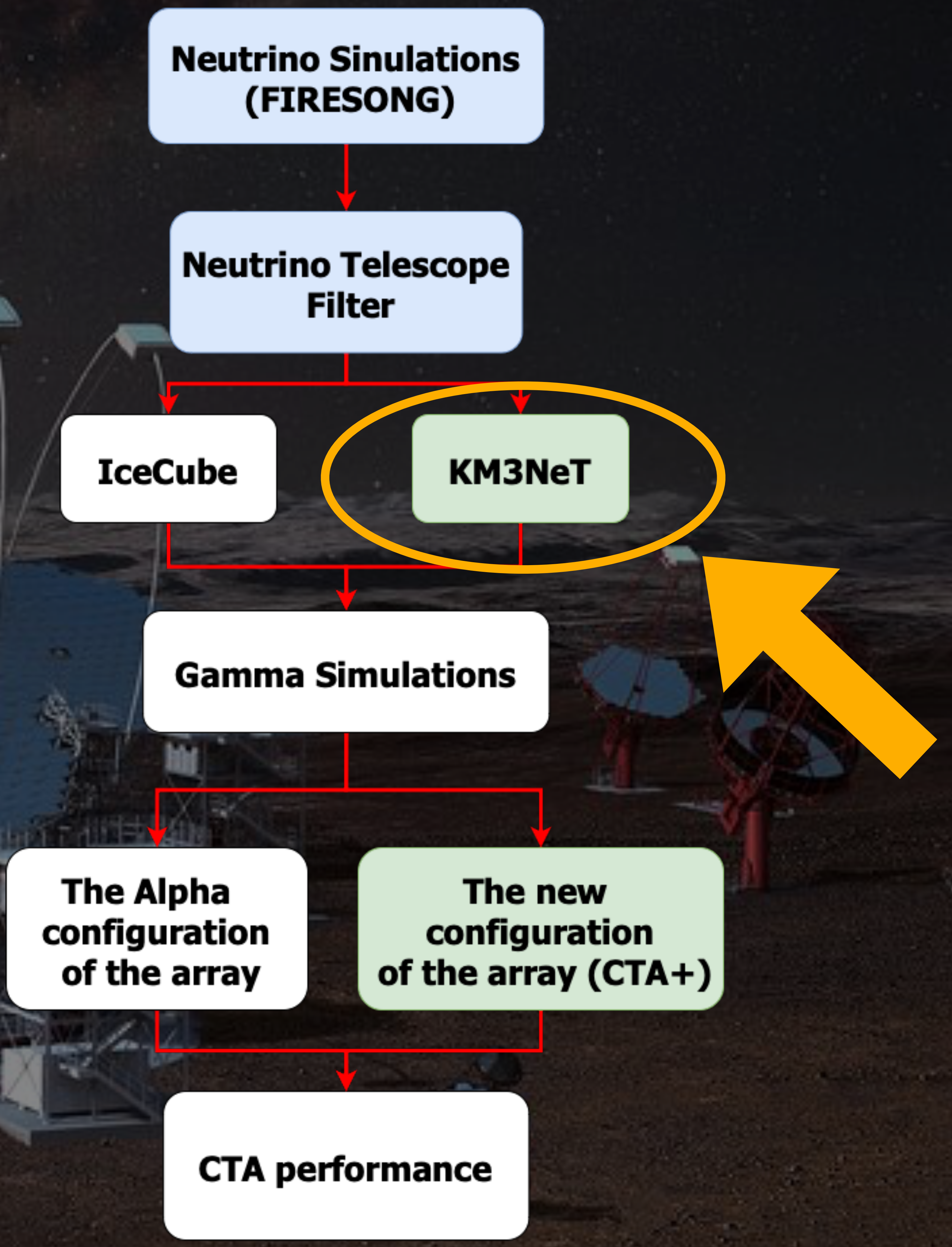


Neutrino Simulations

FIRst Extragalactic Simulation Of Neutrino and Gamma-ray (FIRESONG)

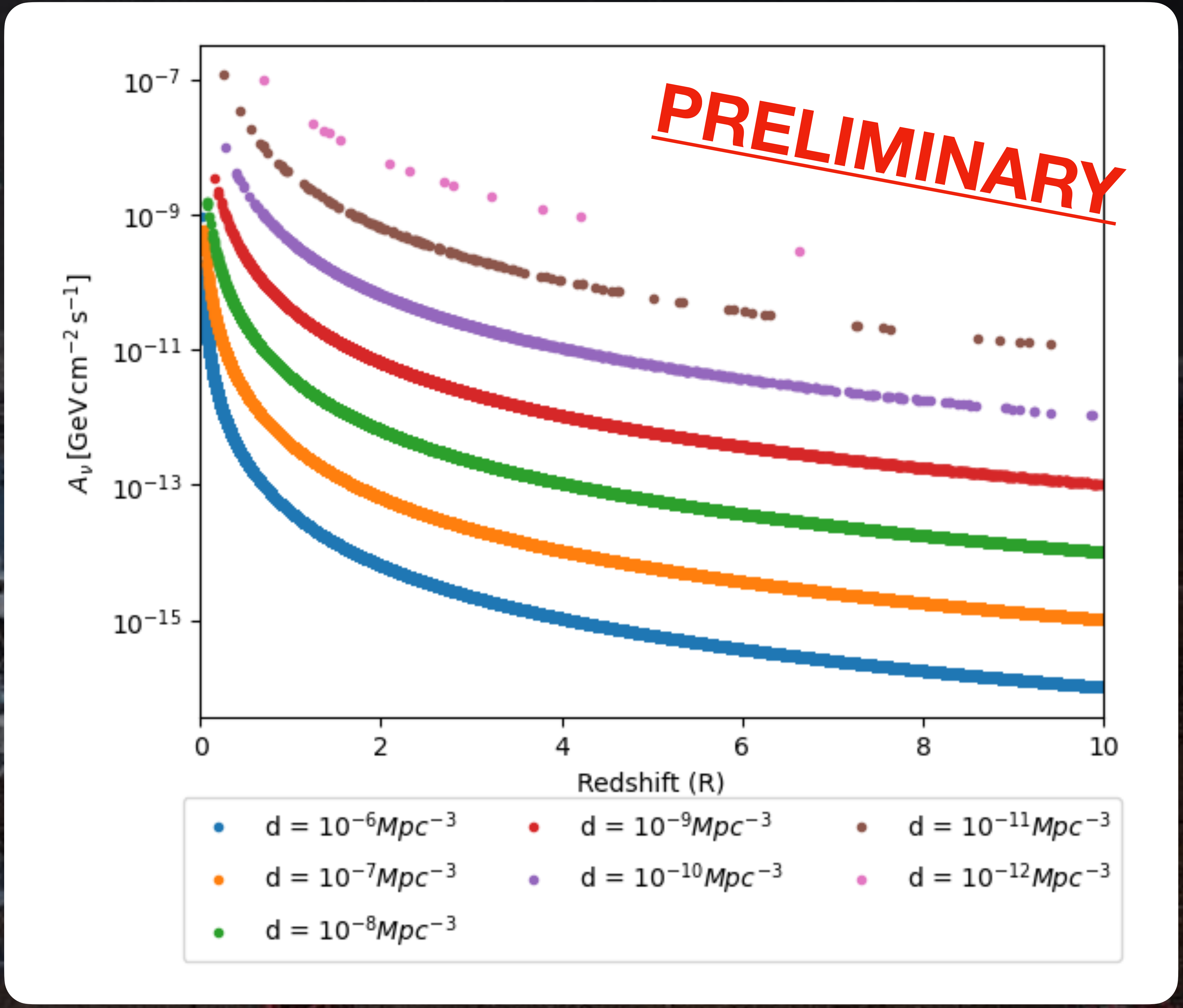
FIRESONG is **an open source python code** used to simulate source populations in the L (luminosity) vs ρ (density) plane. *(Tung et al., Journal of Open Source Software, 2021)*

INPUT DATA

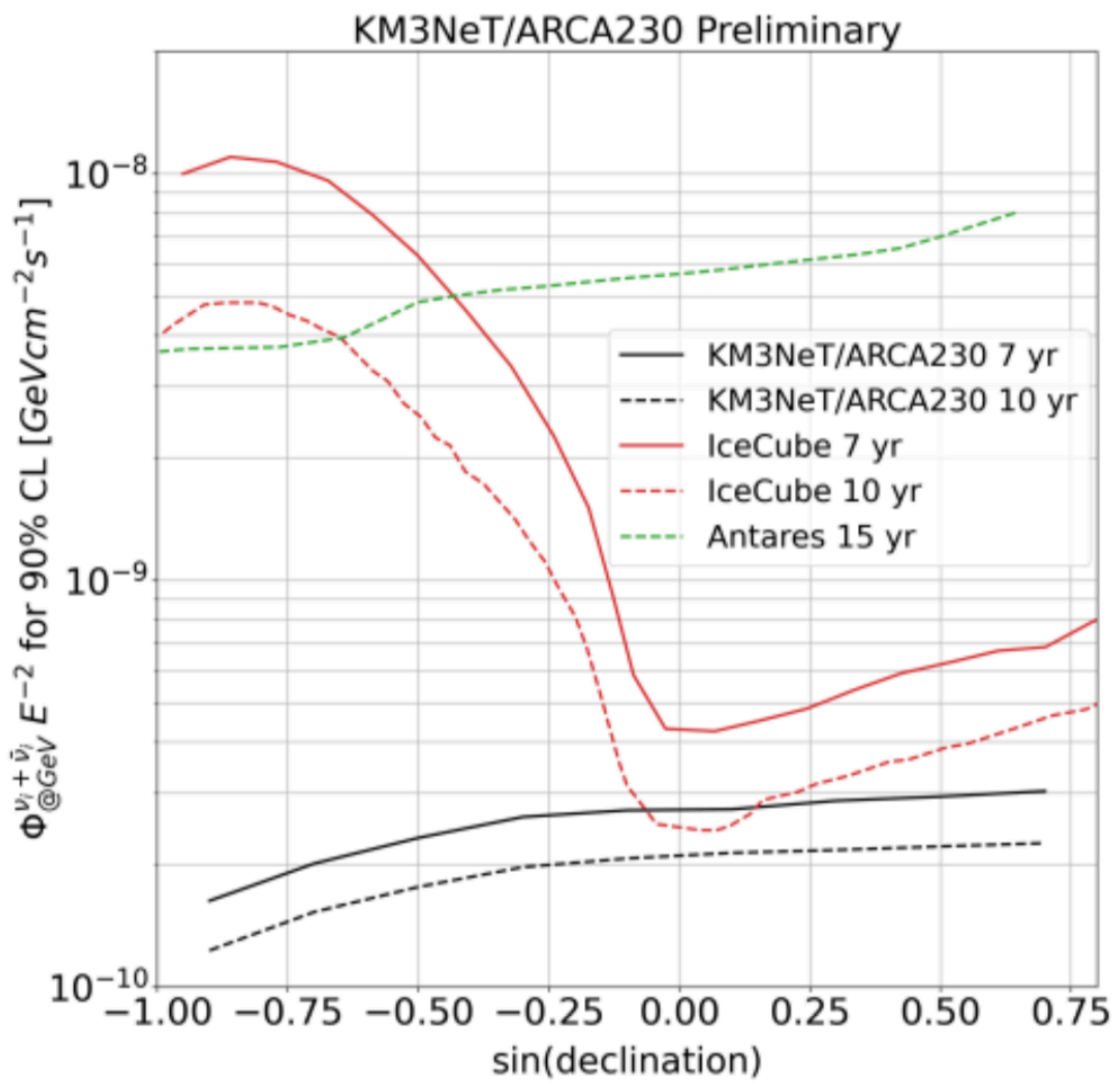
- **Evolution Model**
- **Local Source Density**
- **If the source is transient or not**
- **Timescale (if the source is transient)**
- **Range of Redshift**
- **Spectral index of diffuse flux**

OUTPUT DATA

- **Declination**
- **Right Ascension**
- **Redshift**
- **The value of the normalization of the neutrino flux Av**

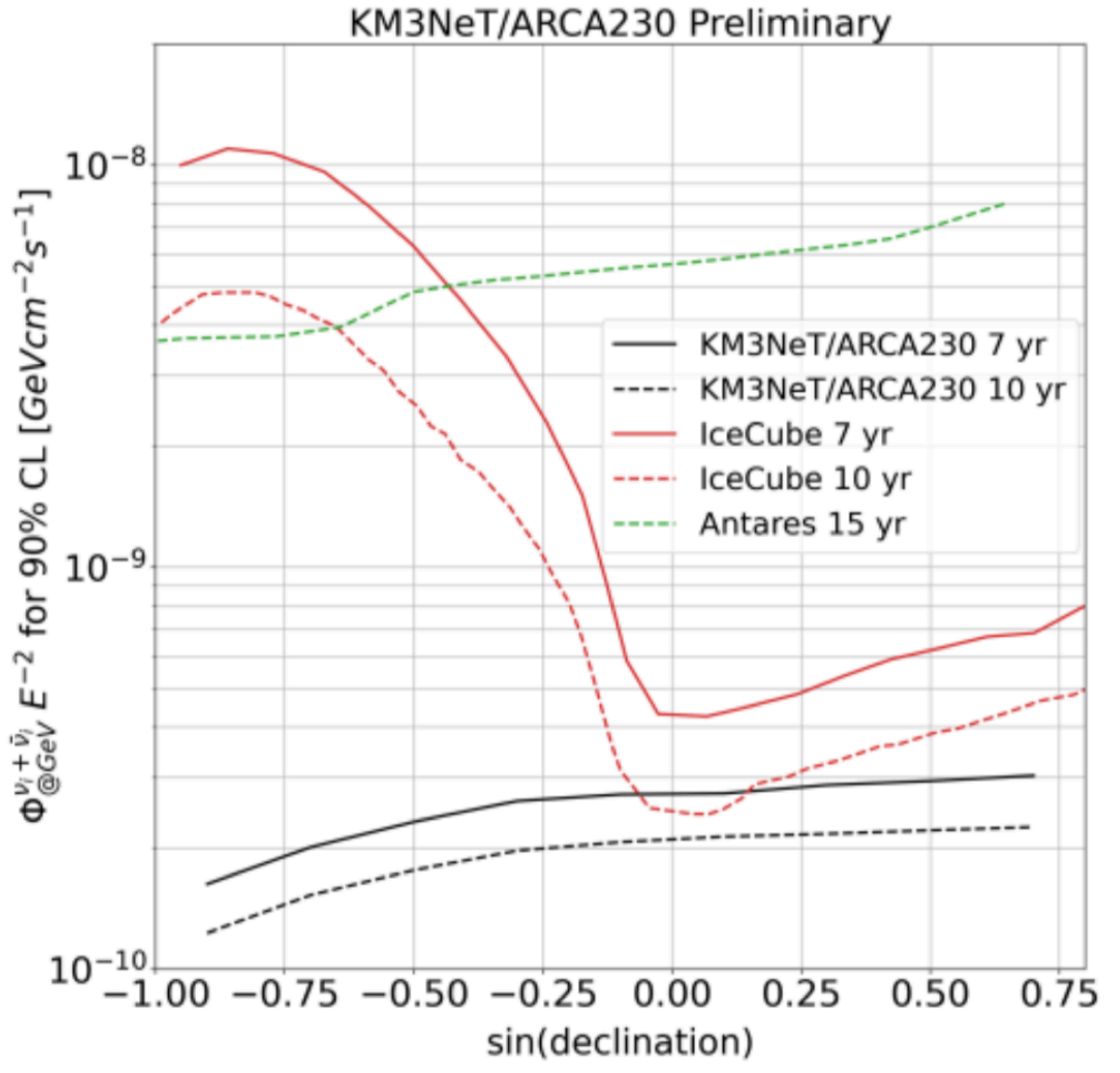


The implementation of the Discovery Potential

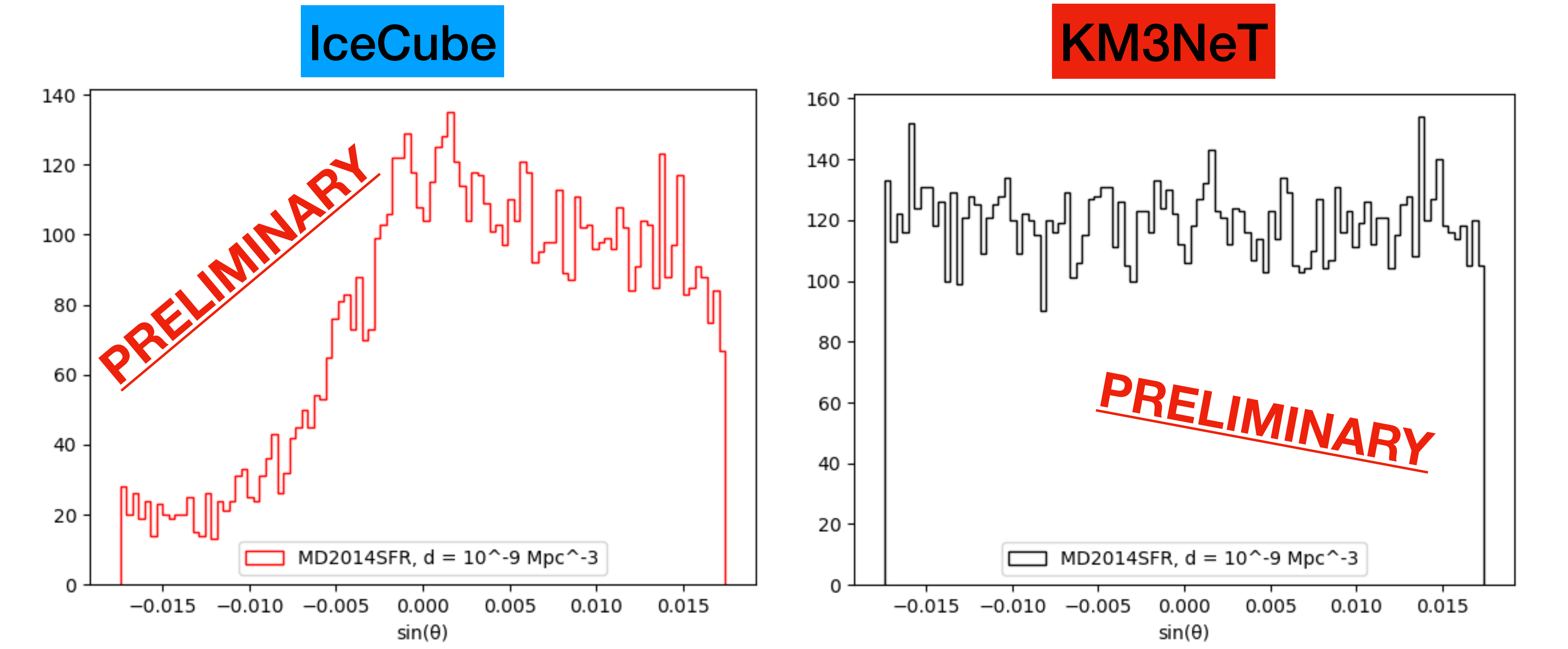


KM3NeT Collaboration, PoS ICRC2023 1075

The implementation of the Discovery Potential

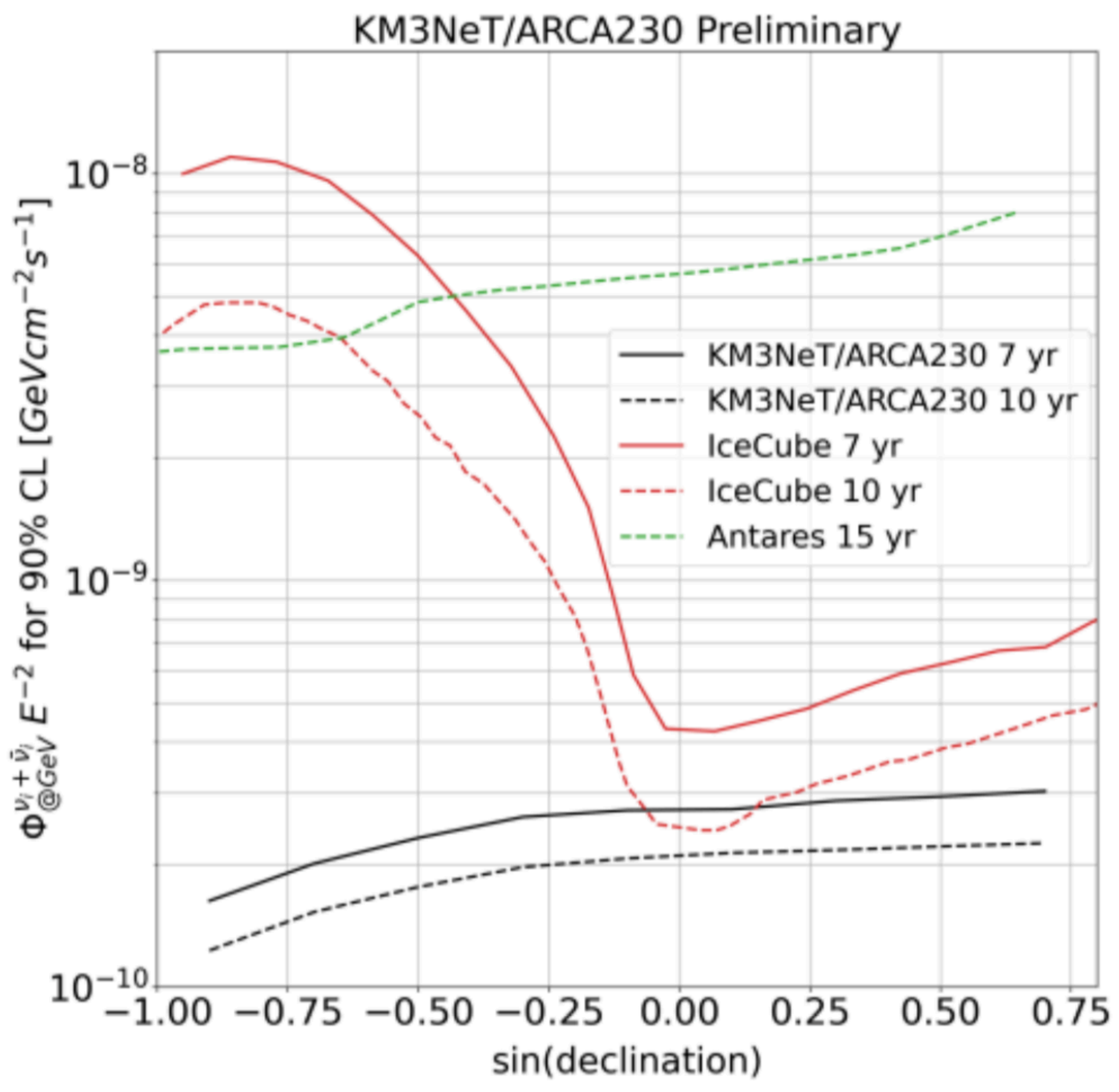


KM3NeT Collaboration, PoS ICRC2023 1075



The distributions of sin zenith of the simulated neutrino sources passing the discovery potential of IceCube (left) and KM3NeT (right)

The implementation of the Discovery Potential



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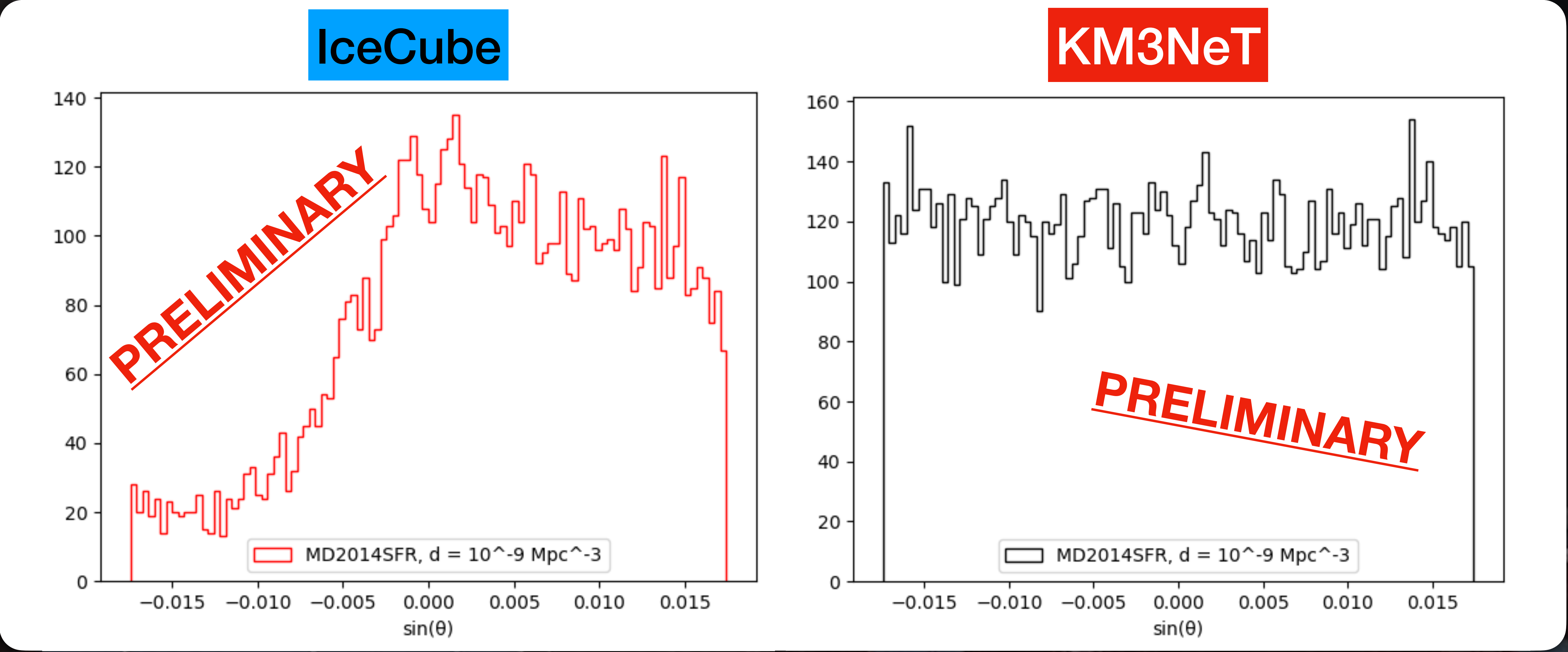
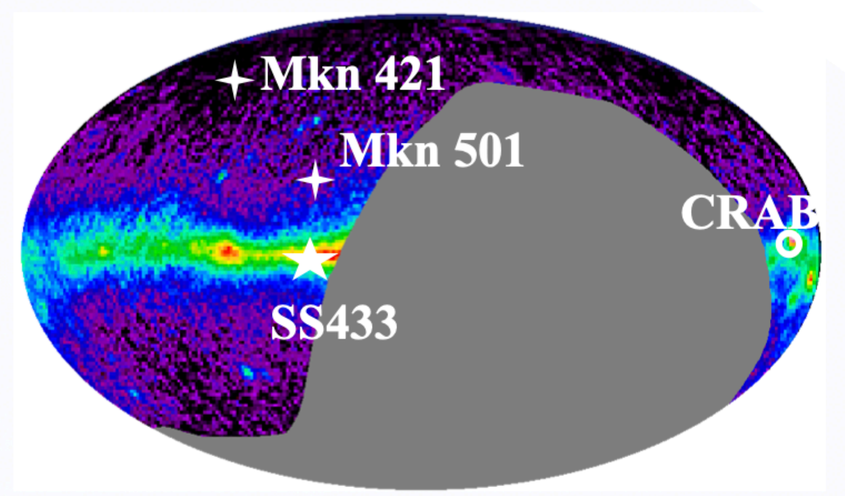
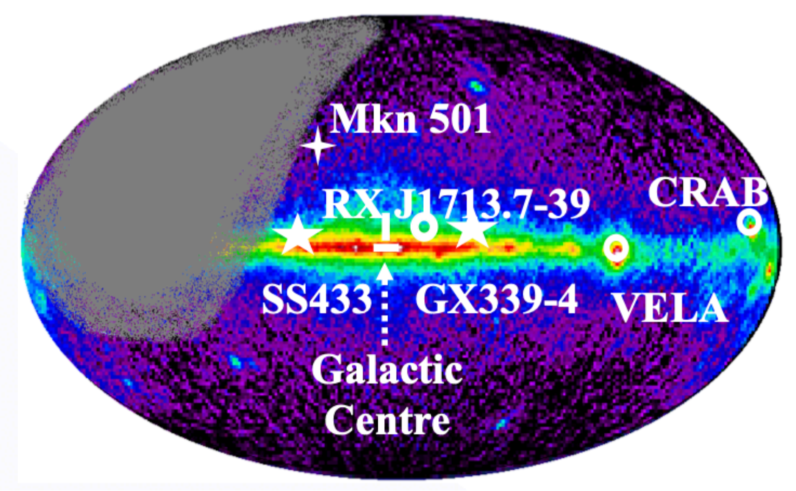


The distributions of sin zenith of the simulated neutrino sources passing the discovery potential of IceCube (left) and KM3NeT (right)

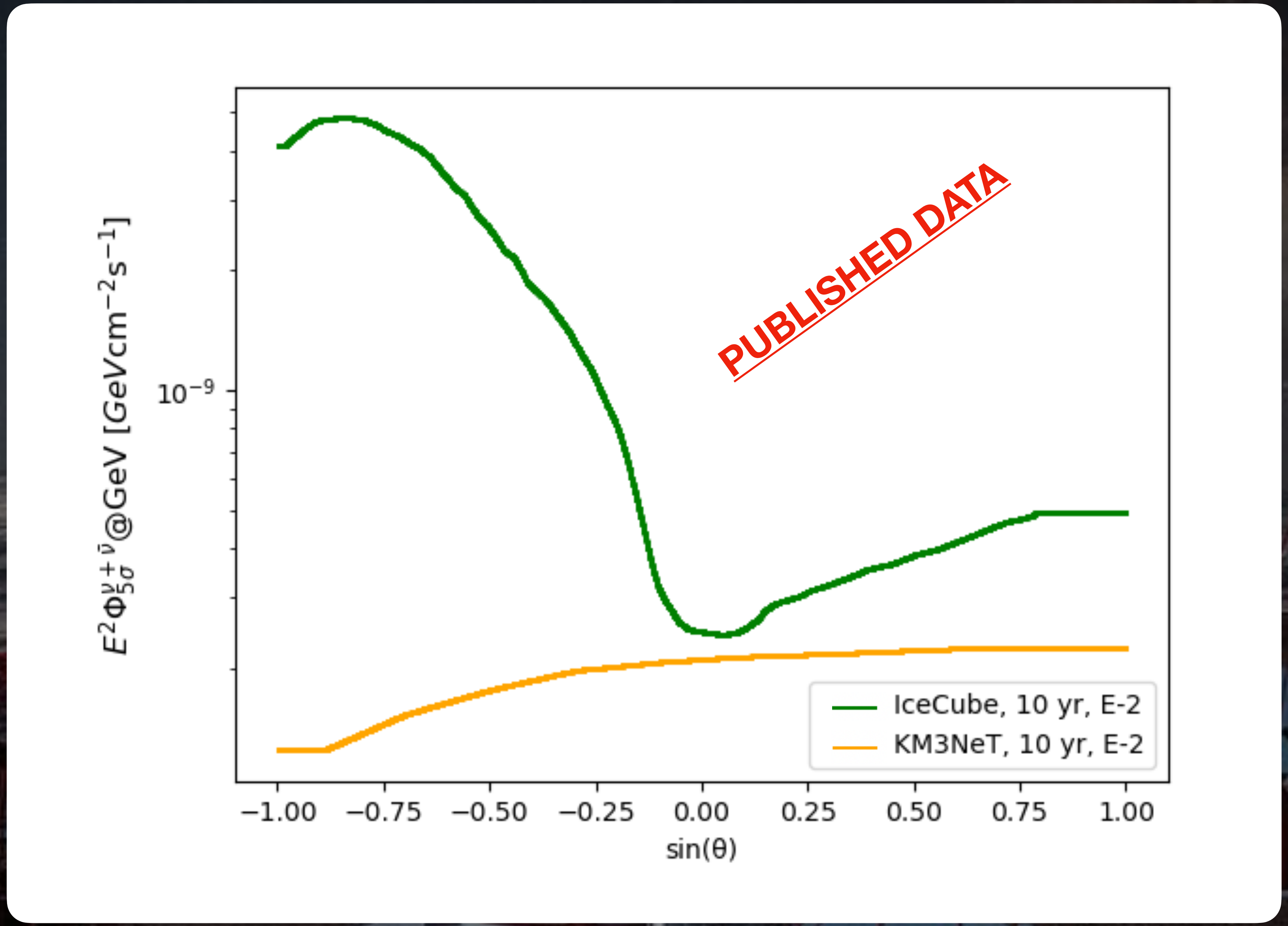
The sky seen from **IceCube**



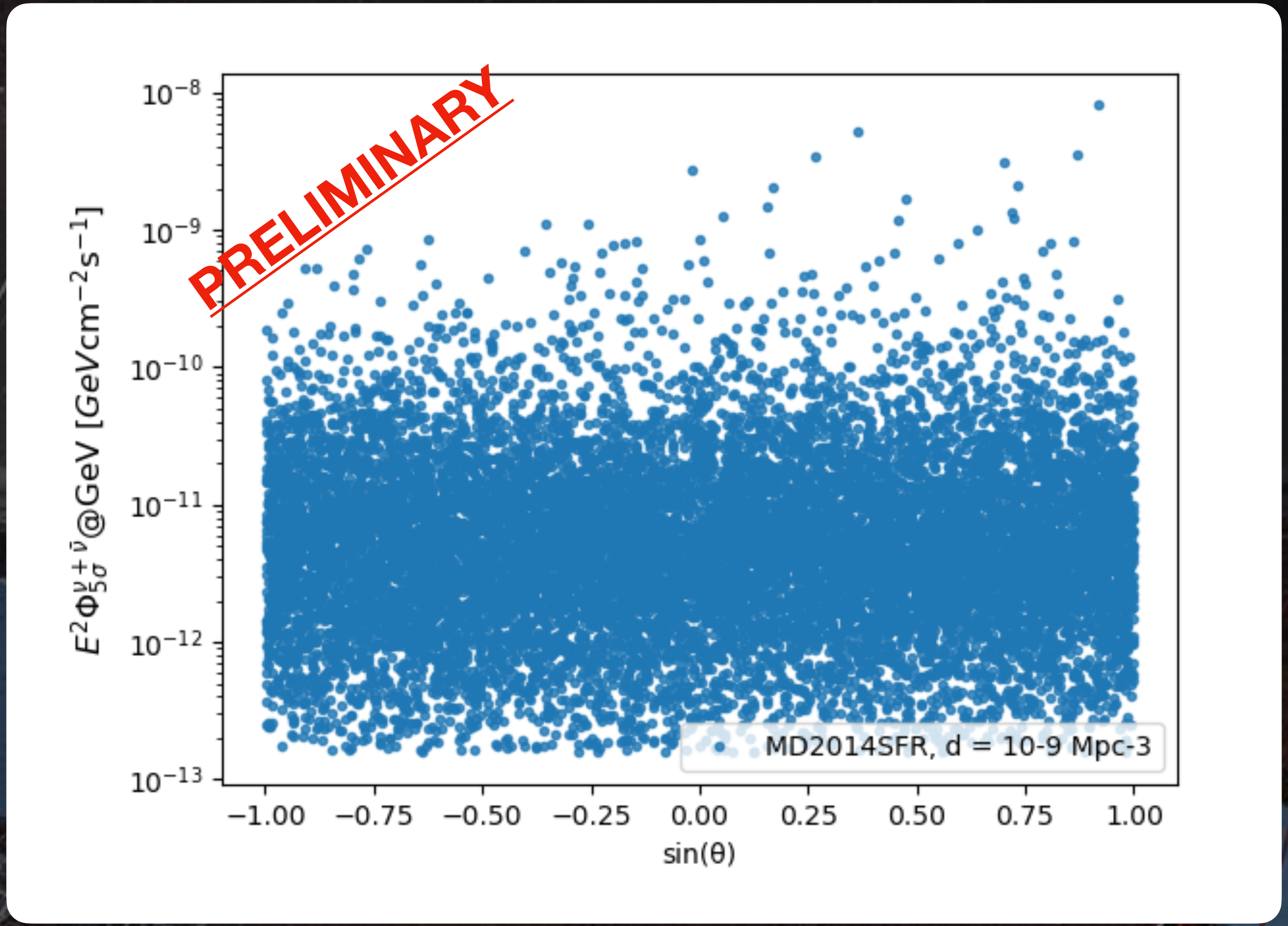
The sky seen from **KM3NeT**



The implementation of the Discovery Potential



The discovery potentials of the two neutrino telescopes, IceCube (green line) and KM3NeT (yellow line) obtained from published data

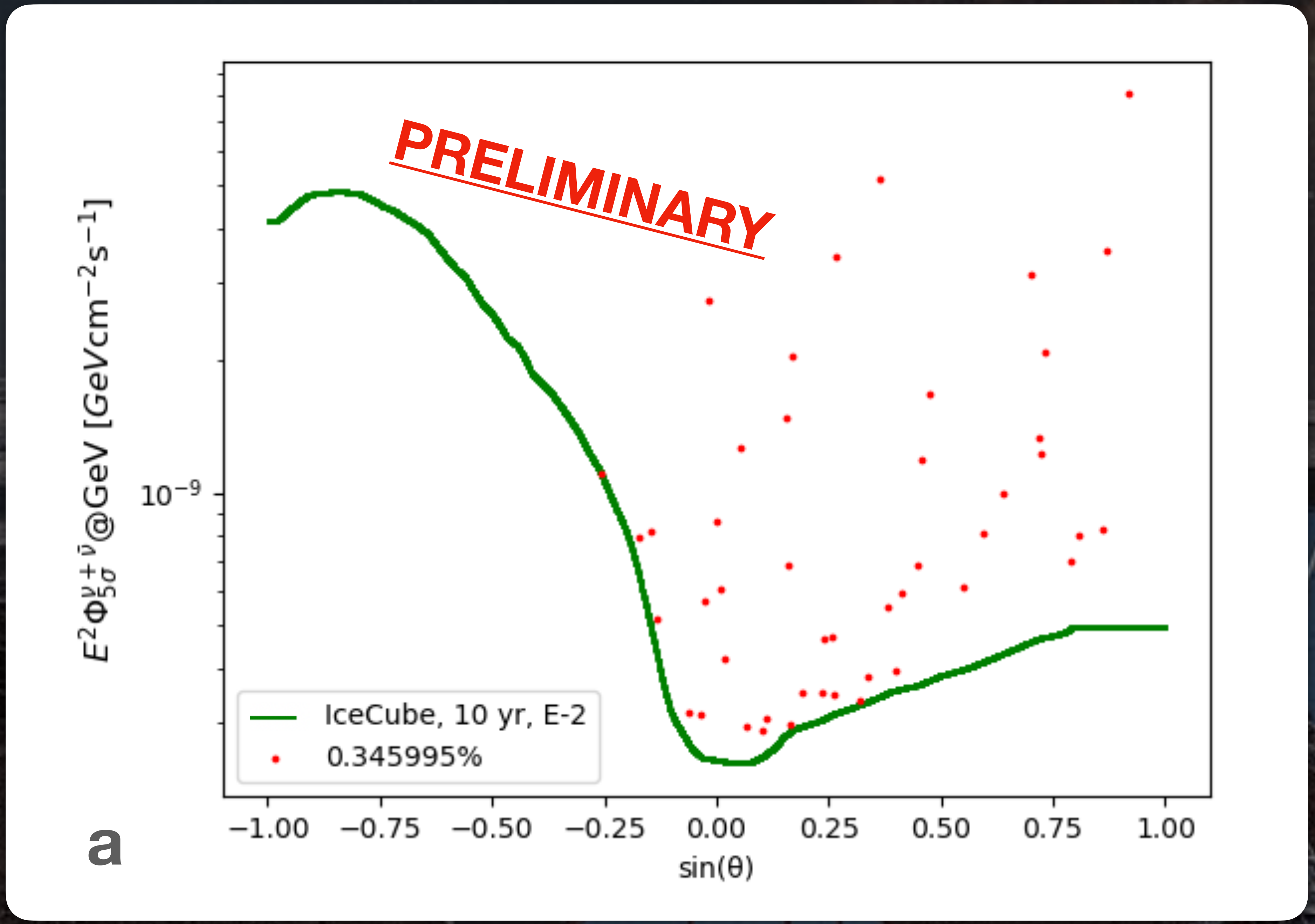


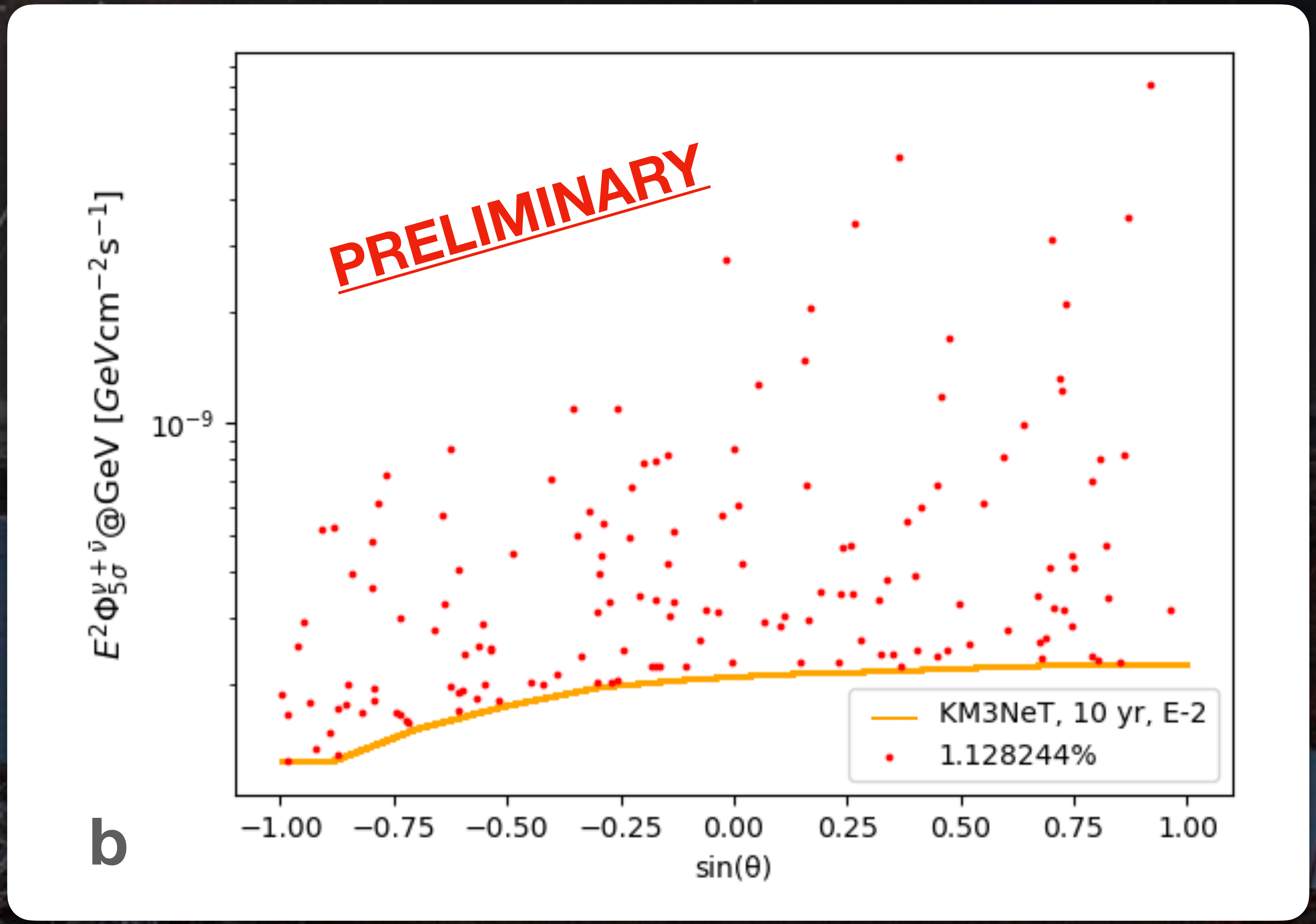
Simulated neutrino sources obtained by FIRESONG

The implementation of the Discovery Potential

IceCube

KM3NeT

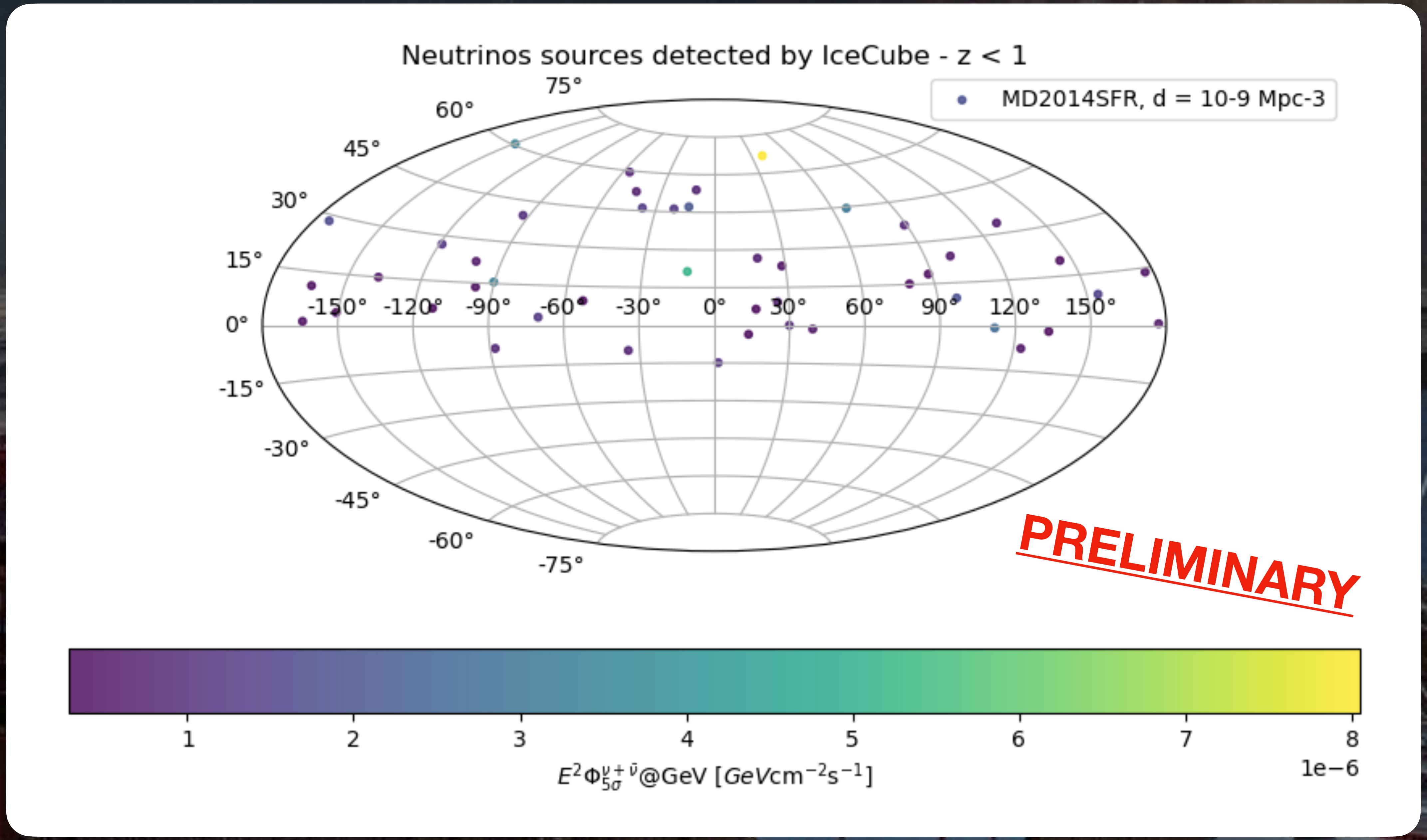




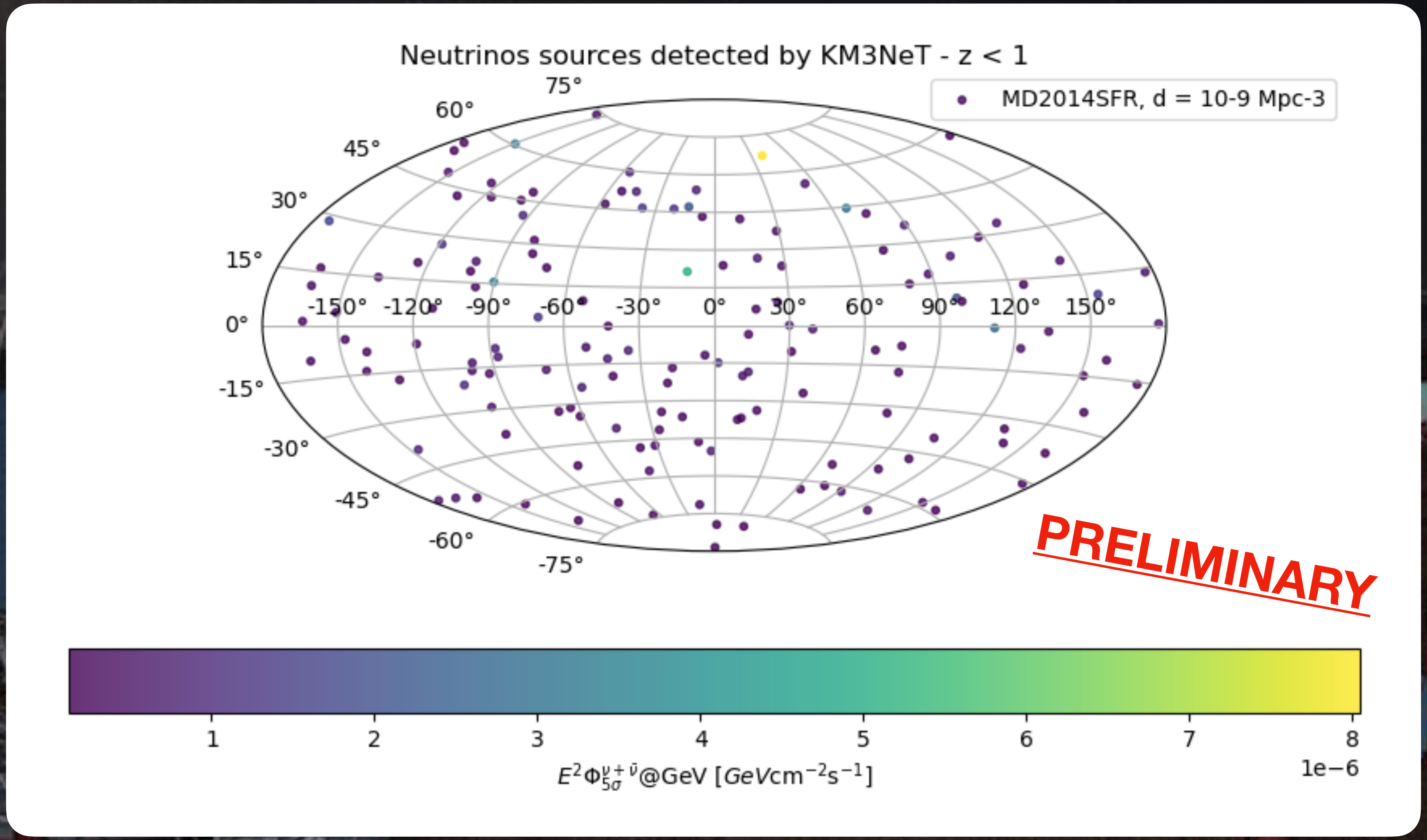
The red dots represent the neutrinos sources that exceed (with a confidence level of 5σ) the discovery potential of the two neutrino telescopes, **46** for IceCube and **115** for KM3NeT respectively

Skymaps of the distribution of the simulated neutrino sources

IceCube



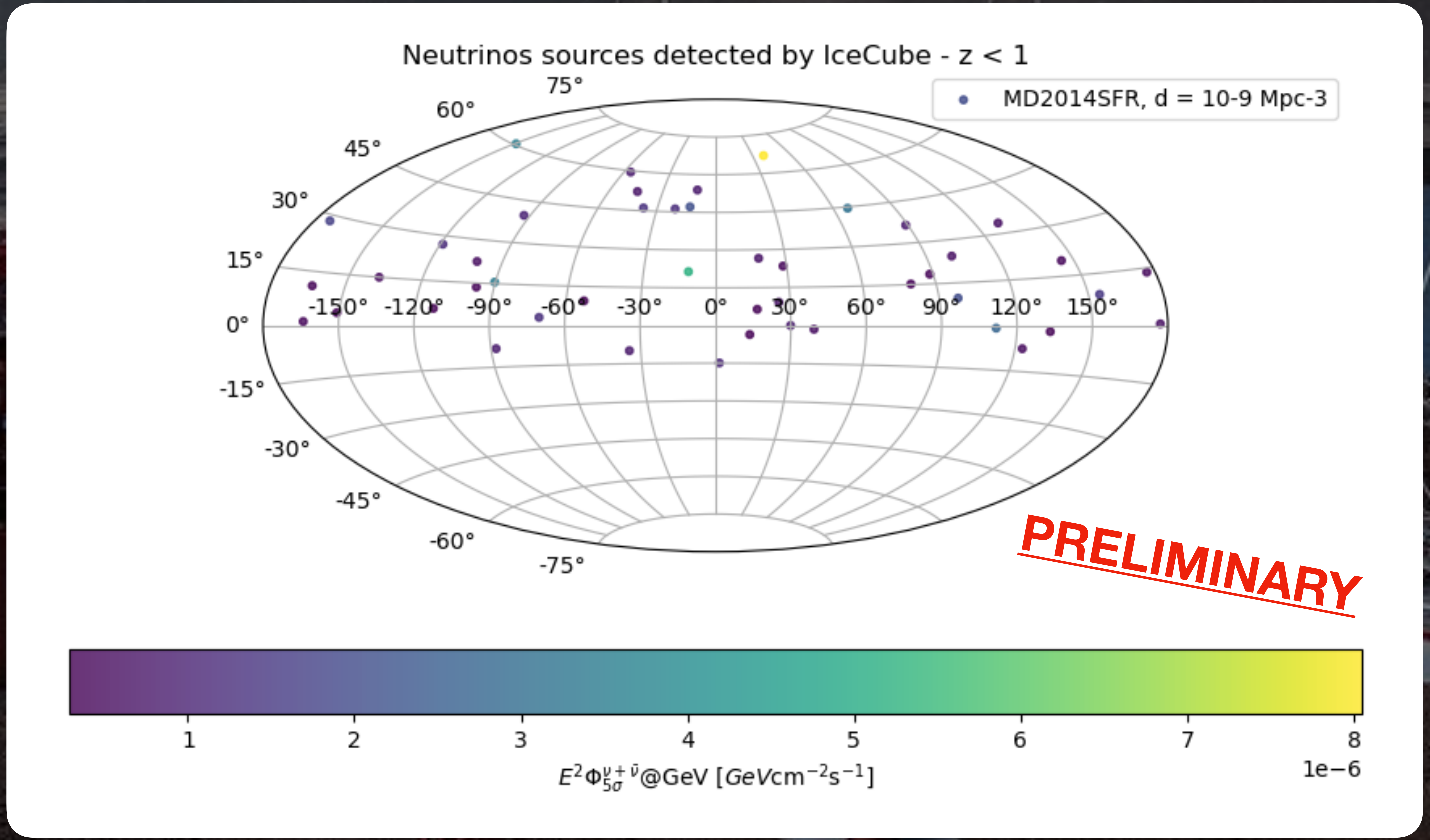
KM3NeT



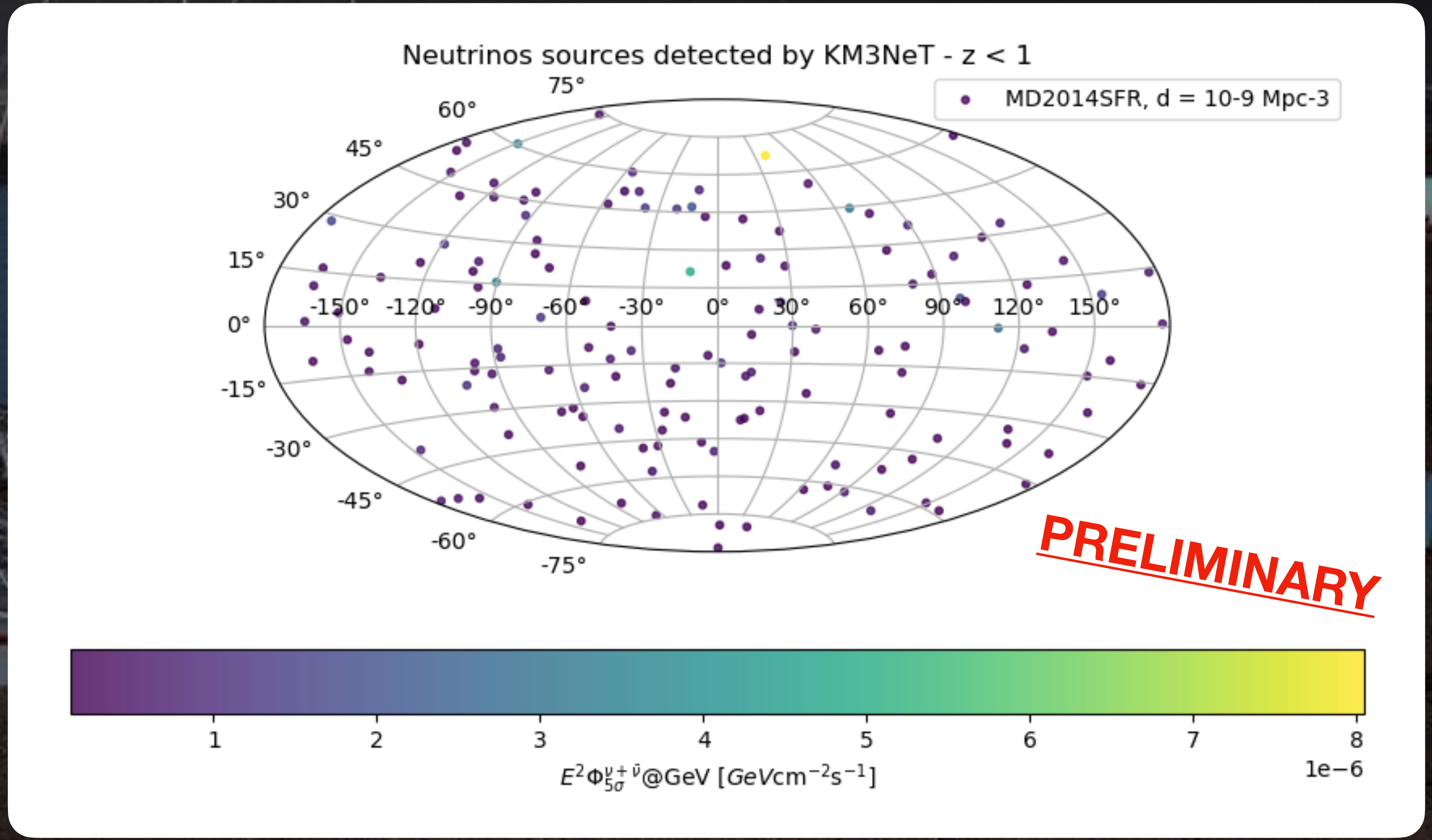
Skymaps of the distribution of the simulated neutrino sources

KM3NeT would make possible to detect sources located in the **southern hemisphere**

IceCube



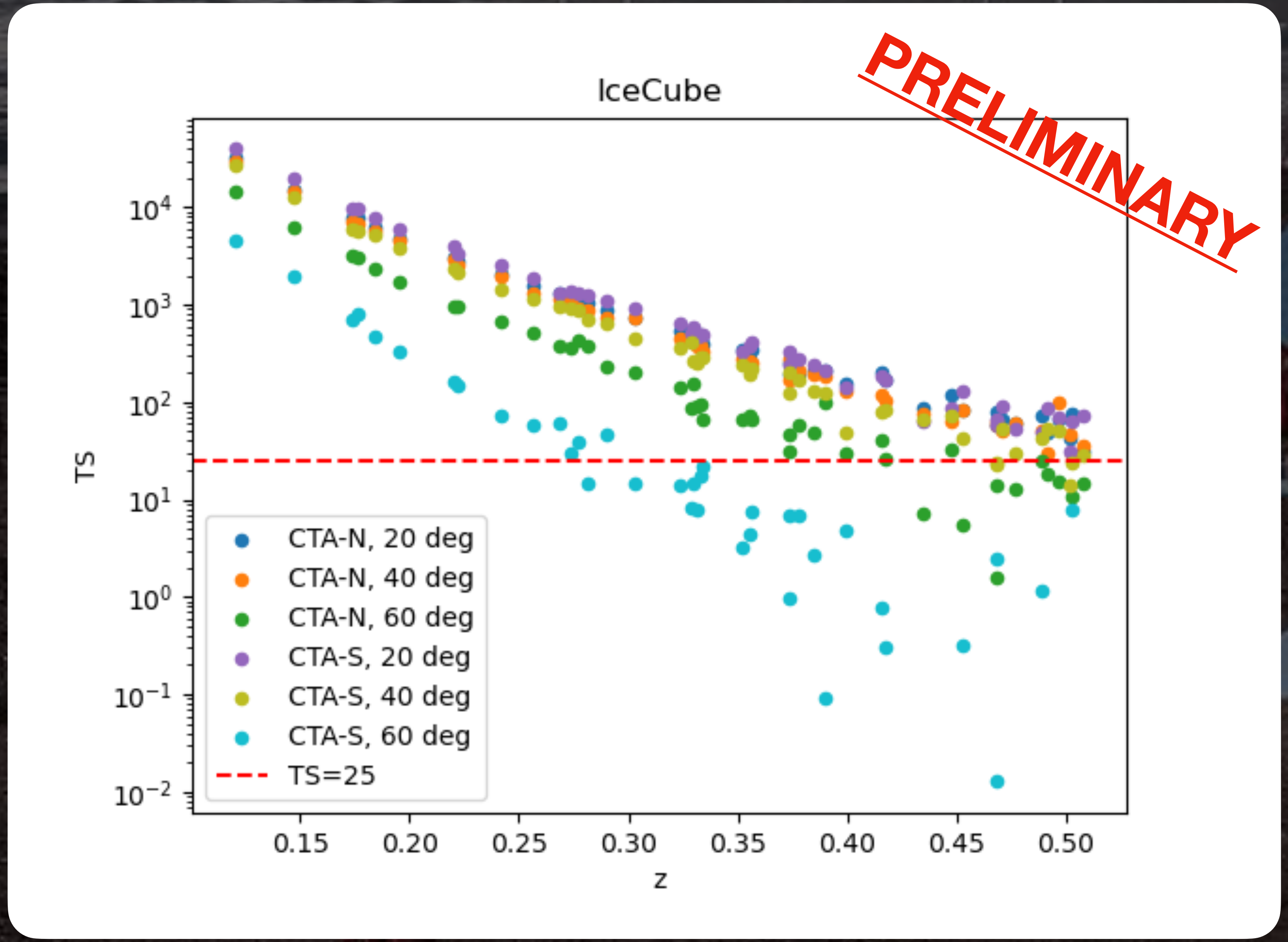
KM3NeT



Simulations of gamma rays and CTA performance

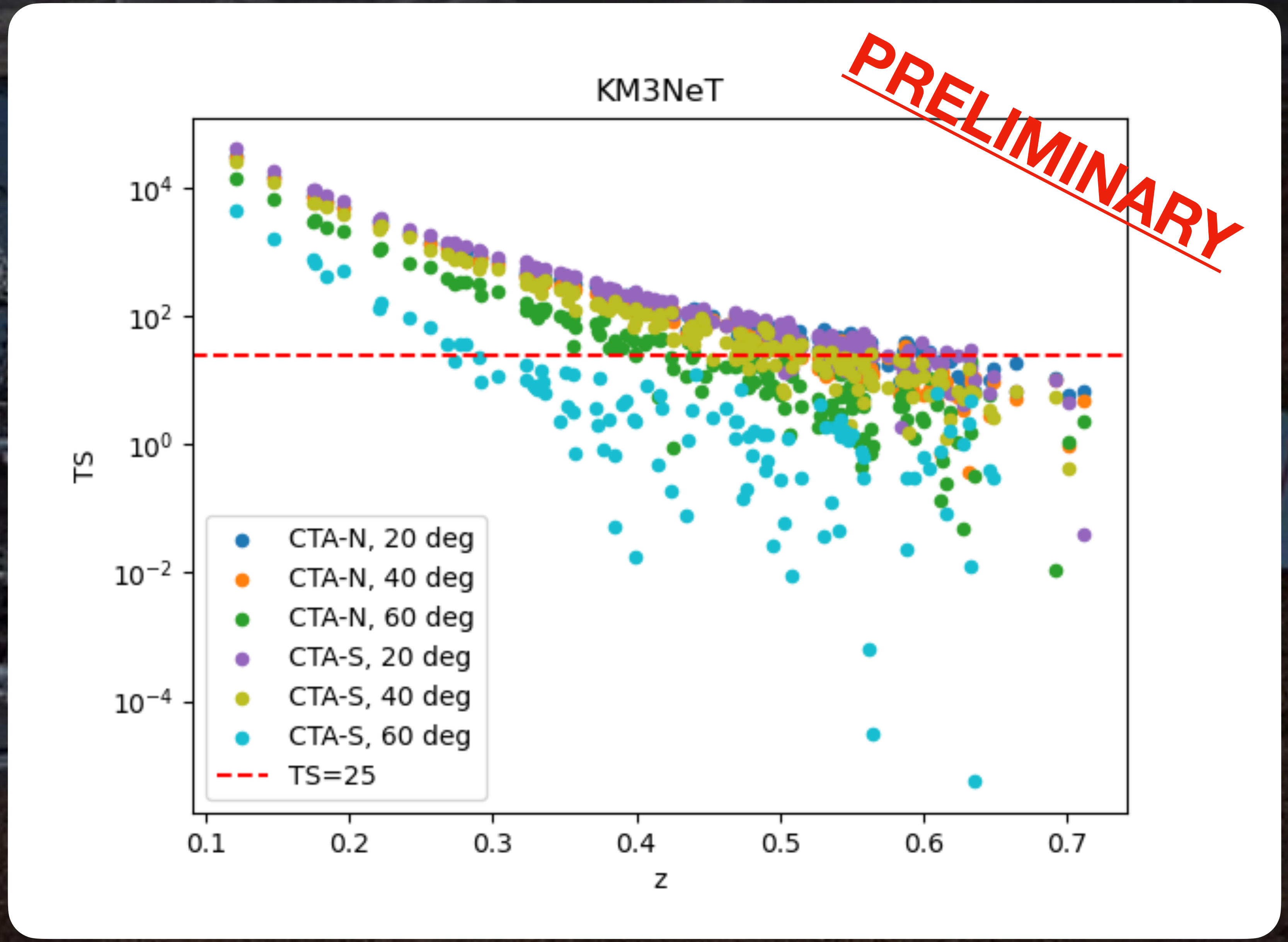
Percentage of simulated Icecube sources detected with CTA (TS>25)

Z	N	S
20°	100%	100%
40°	100%	91%
60°	76%	30%



Percentage of simulated KM3NeT sources detected with CTA (TS>25)

Z	N	S
20°	79%	79%
40°	65%	56%
60°	33%	9%

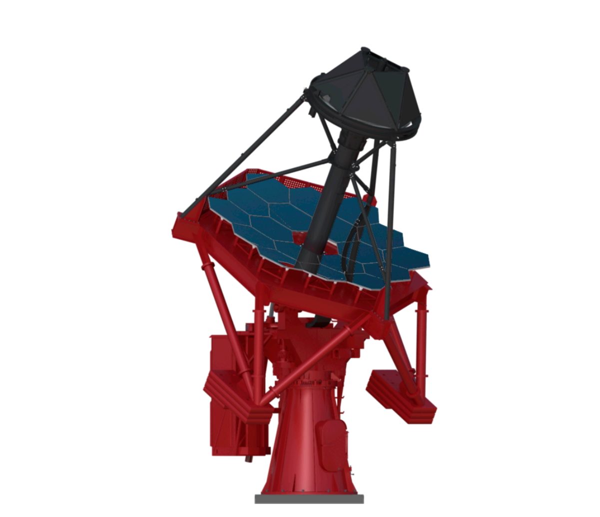


The CTA+ program for the CTAO

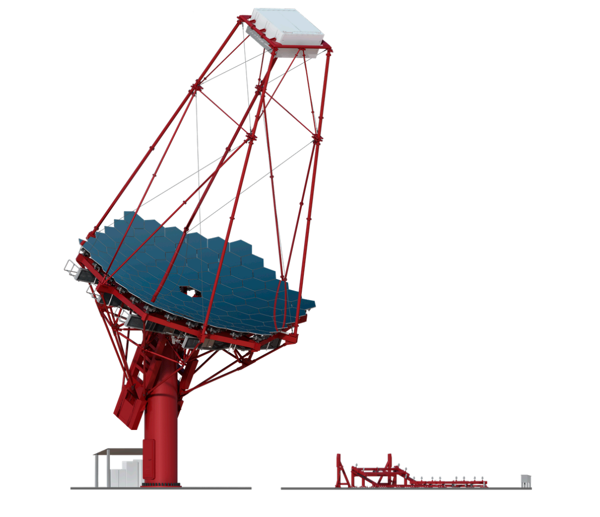
Neutrino Simulations (FIRESONG)
→ Neutrino Telescope Filter
→ IceCube | KM3NeT
→ Gamma Simulations
→ The Alpha configuration of the array | The new configuration of the array (CTA+)
→ CTA performance

CTAO
- CTA - North
  - 4 LSTs
  - 9 MSTs
- CTA - South
  - 14 MSTs
  - 37 SSTs
  - 2 LSTs
  - 5 SSTs

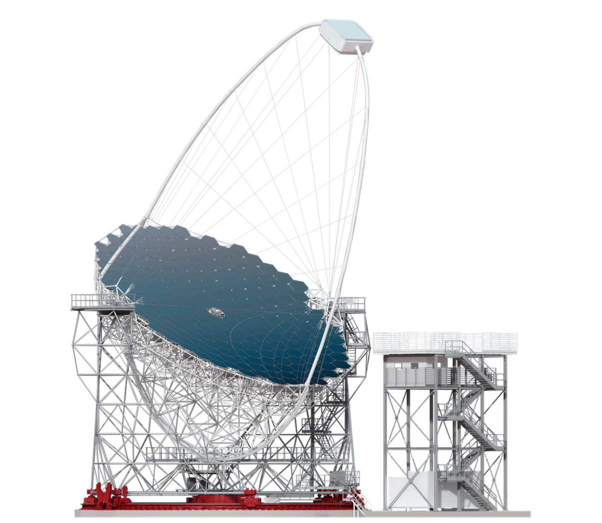
$\underbrace{\text{2 LSTs} \quad \text{5 SSTs}}_{\text{CTA+}}$



SST. credit: G. Pérez. IAC. SMM



MST. credit: G. Pérez. IAC. SMM



LST. credit: G. Pérez. IAC. SMM

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The CTA+ program for the CTAO

Neutrino Simulations (FIRESONG)

Neutrino Telescope Filter

IceCube

KM3NeT

Gamma Simulations

The Alpha configuration of the array

The new configuration of the array (CTA+)

CTA performance

CTAO

CTA - North

CTA - South

4 LSTs

9 MSTs

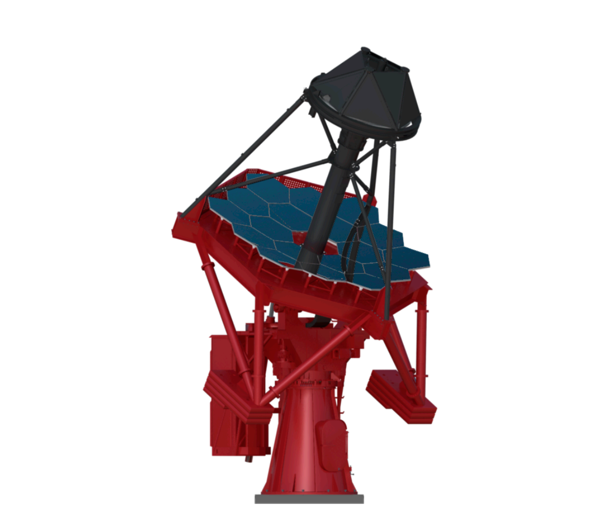
14 MSTs

37 SSTs

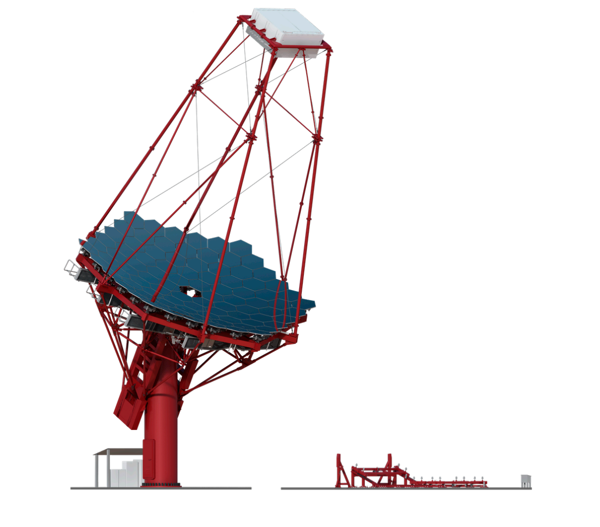
2 LSTs

5 SSTs

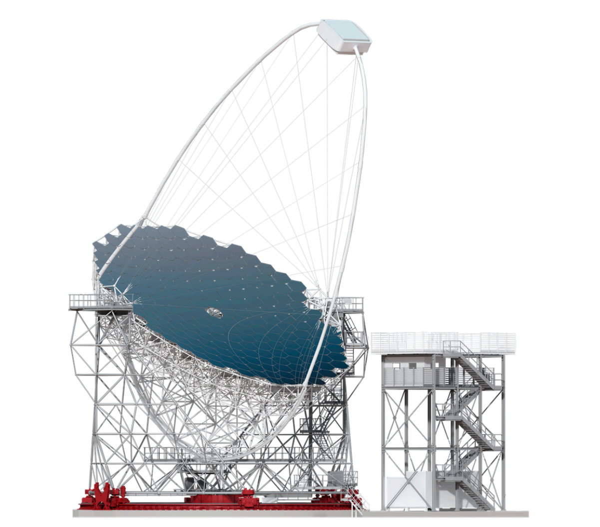
CTA+



SST. credit: G. Pérez. IAC. SMM



MST. credit: G. Pérez. IAC. SMM



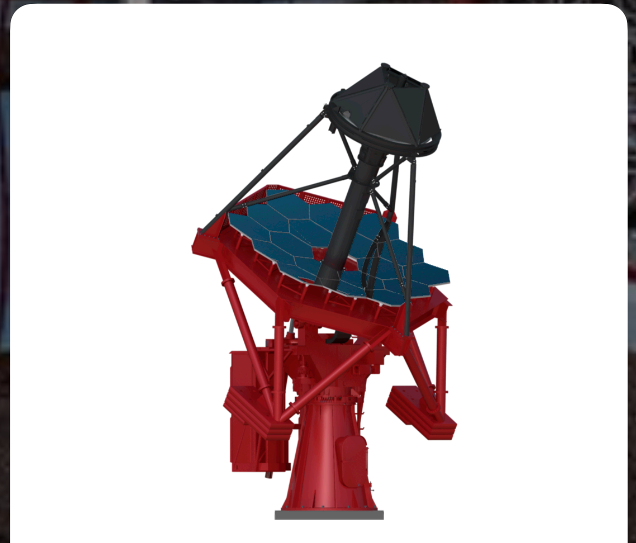
LST. credit: G. Pérez. IAC. SMM

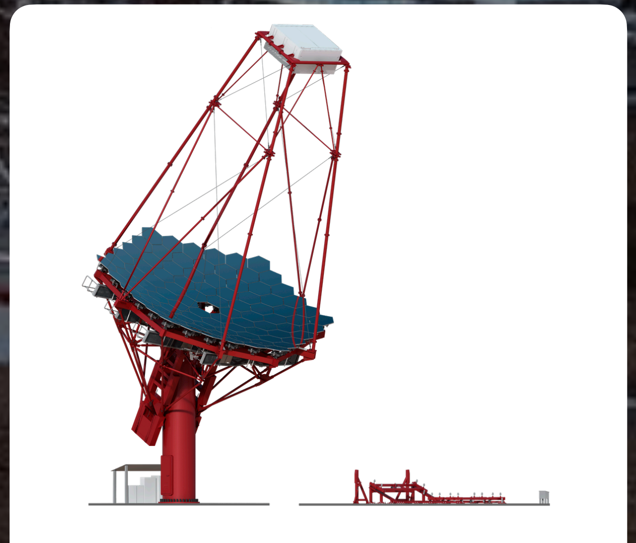
The CTA+ program for the CTAO

- Neutrino Simulations (FIRESONG)
  - Neutrino Telescope Filter
    - IceCube
    - KM3NeT
      - Gamma Simulations
        - The Alpha configuration of the array
        - The new configuration of the array (CTA+)
          - CTA performance

- CTAO
  - CTA - North
    - 4 LSTs
    - 9 MSTs
  - CTA - South
    - 14 MSTs
    - 37 SSTs
    - 2 LSTs
    - 5 SSTs

2 LSTs + 5 SSTs: CTA+


SST. credit: G. Pérez. IAC. SMM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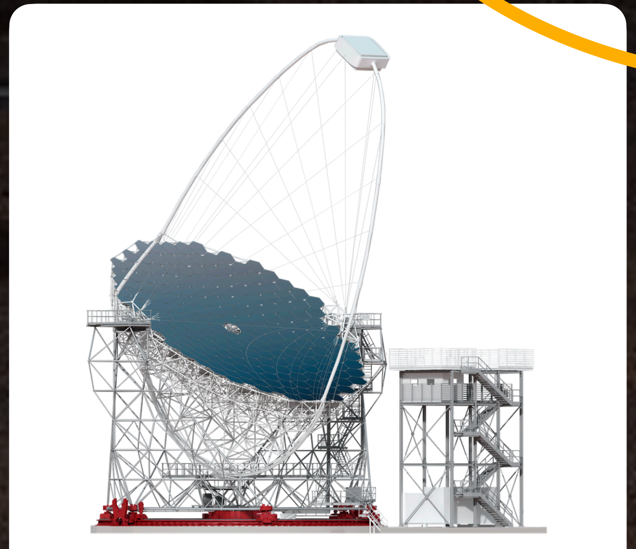
LST. credit: G. Pérez. IAC. SMM

Conclusion and Next Steps

KM3NeT will be able to explore sources with **lower neutrino fluxes** and which are at **larger redshift** with respect to IceCube.

According to our preliminary simulations, the percentage of sources which could be detected by Km3NeT spans from 80% with CTA-N and events at low zenith angles, down to around 10% with CTA-S and events at large zenith angles.

- the **short-term goal:** to simulate the CTA performance considering the CTA+ array;
- the **long-term goal:** to investigate and to simulate new classes of neutrino and transient sources.

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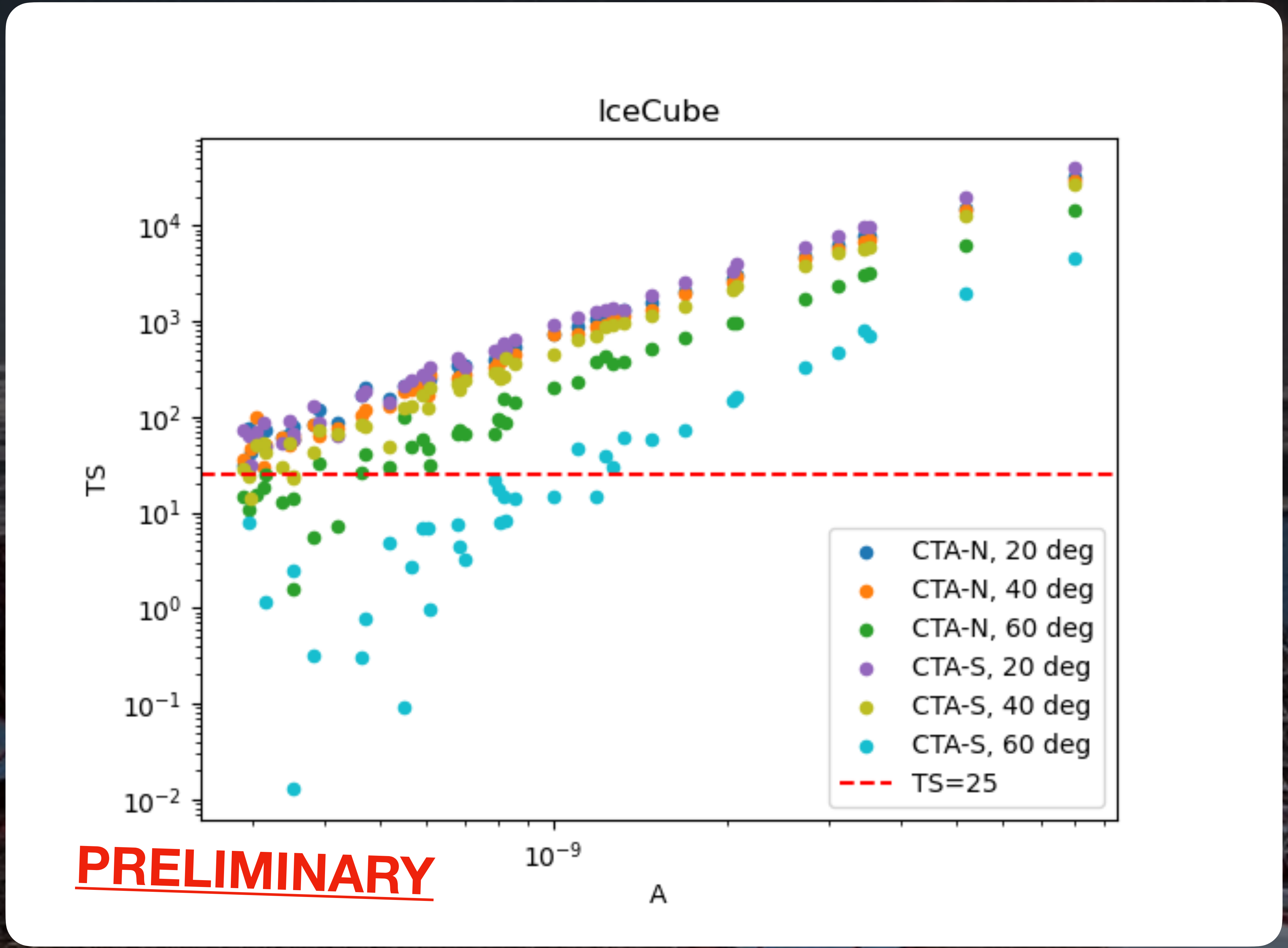
Thank you for your attention!

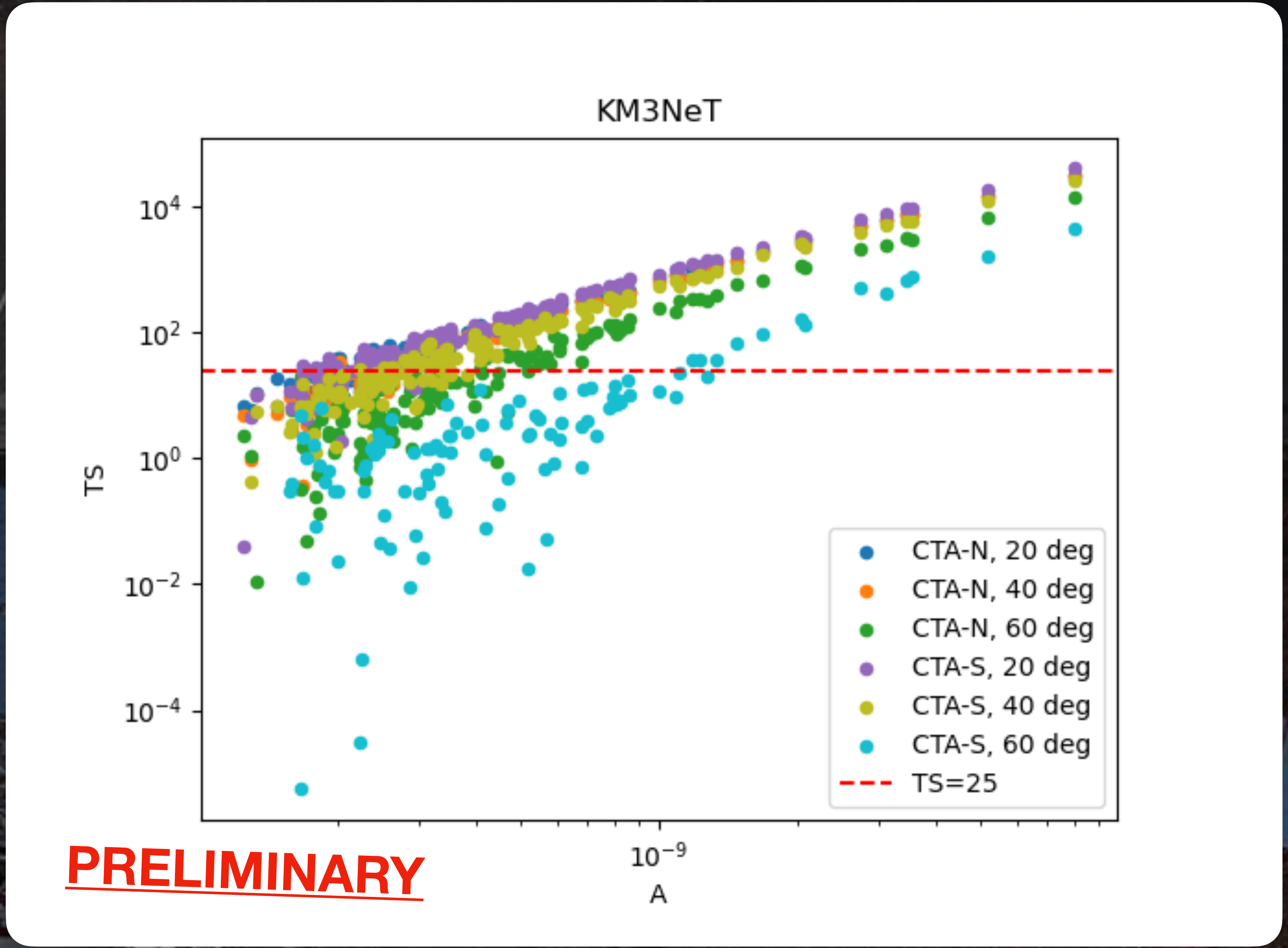
BACKUP SLIDES

FIRESONG INPUT DATA

- **Density:** local density of neutrino sources. Units of Mpc^-3 (Mpc^-3 yr^-1 if Transient=True)
- **Various cosmic evolution models:** "NoEvolution", "HB2006SFR", "YMKBH2008SFR", "CC2015SNR", "MD2014SFR"
- **Transient:** If true, simulate transient neutrino sources instead of steady sources
- **Timescale** in seconds for transient sources
- **zmax:** farthest redshift to consider
- **bins:** number of bins used when creating the redshift PDF
- **Fluxnorm:** normalization on the total astrophysical diffuse flux, E^2dPhi/dE. Units of GeV s^-1 sr^-1
- **index:** spectral index of diffuse flux
- **Luminosity function** (LF): choose between standard candle (SC) or LogNormal (LG)
- **sigma:** width of lognormal distribution if LF="LG"
- **Luminosity:** manually fix the luminosity of sources if not equal to 0. (overrides fluxnorm) Units of erg/yr
- **emin:** minimum neutrino energy in GeV
- **emax:** maximum neutrino energy in GeV

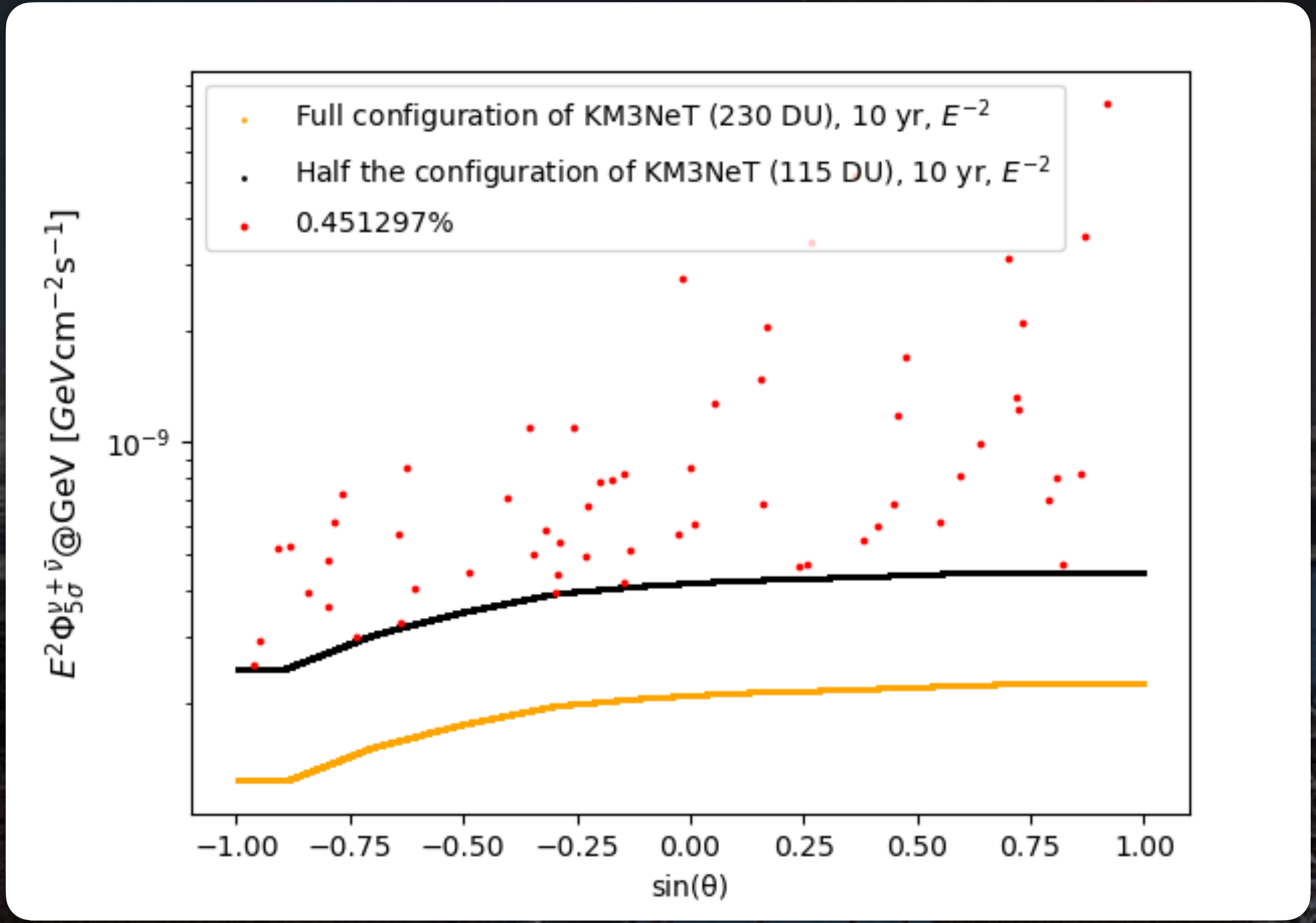
Simulations of gamma rays and CTA performance

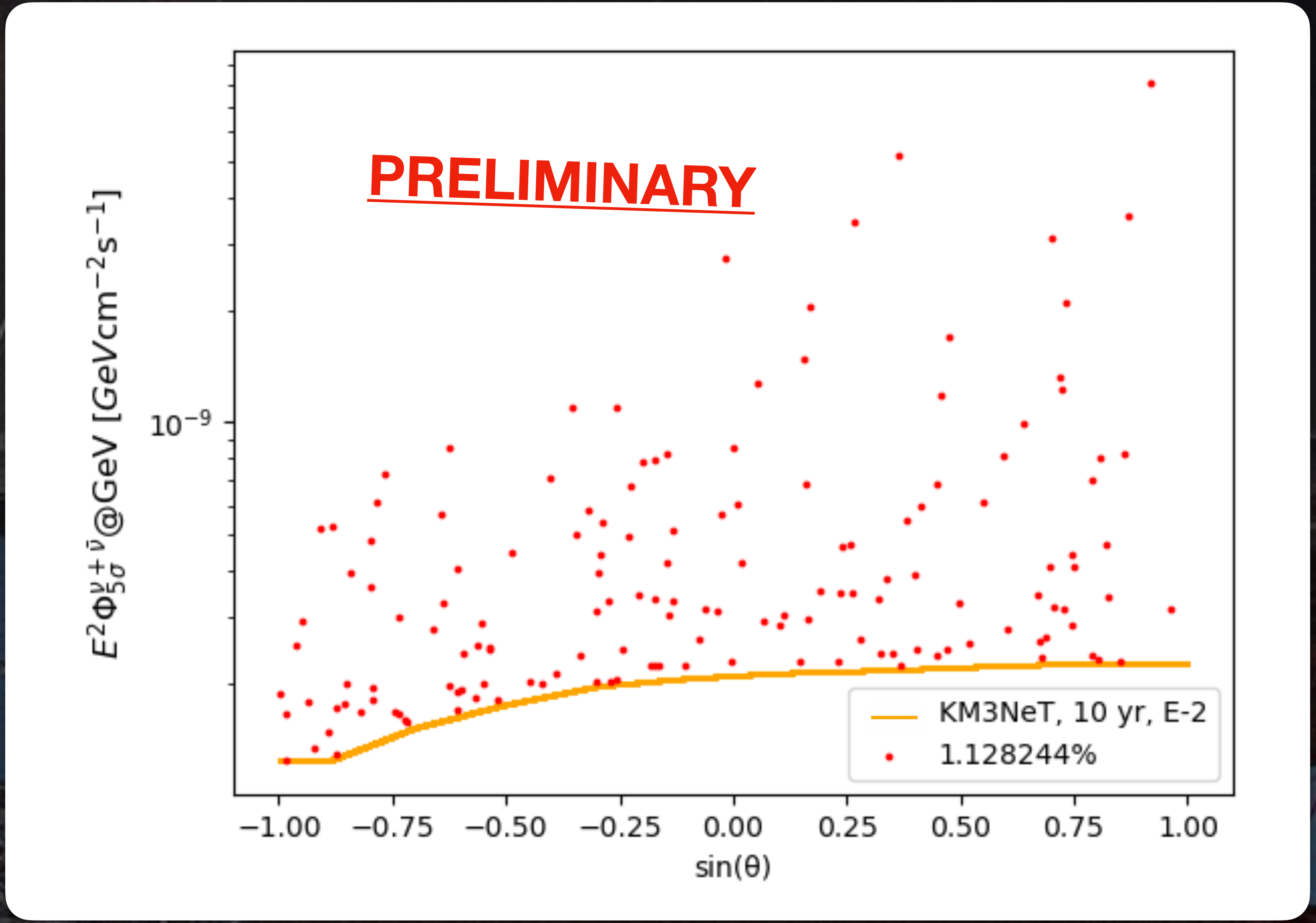




In which A is the value of the normalization of the neutrino flux

The comparison between the full and the half configuration of KM3NeT





This is the configuration of KM3NeT ARCA230, in which ARCA stands for Astroparticle Research with Cosmics in the Abyss

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The KM3NeT technology and infrastructure

The basic elements:

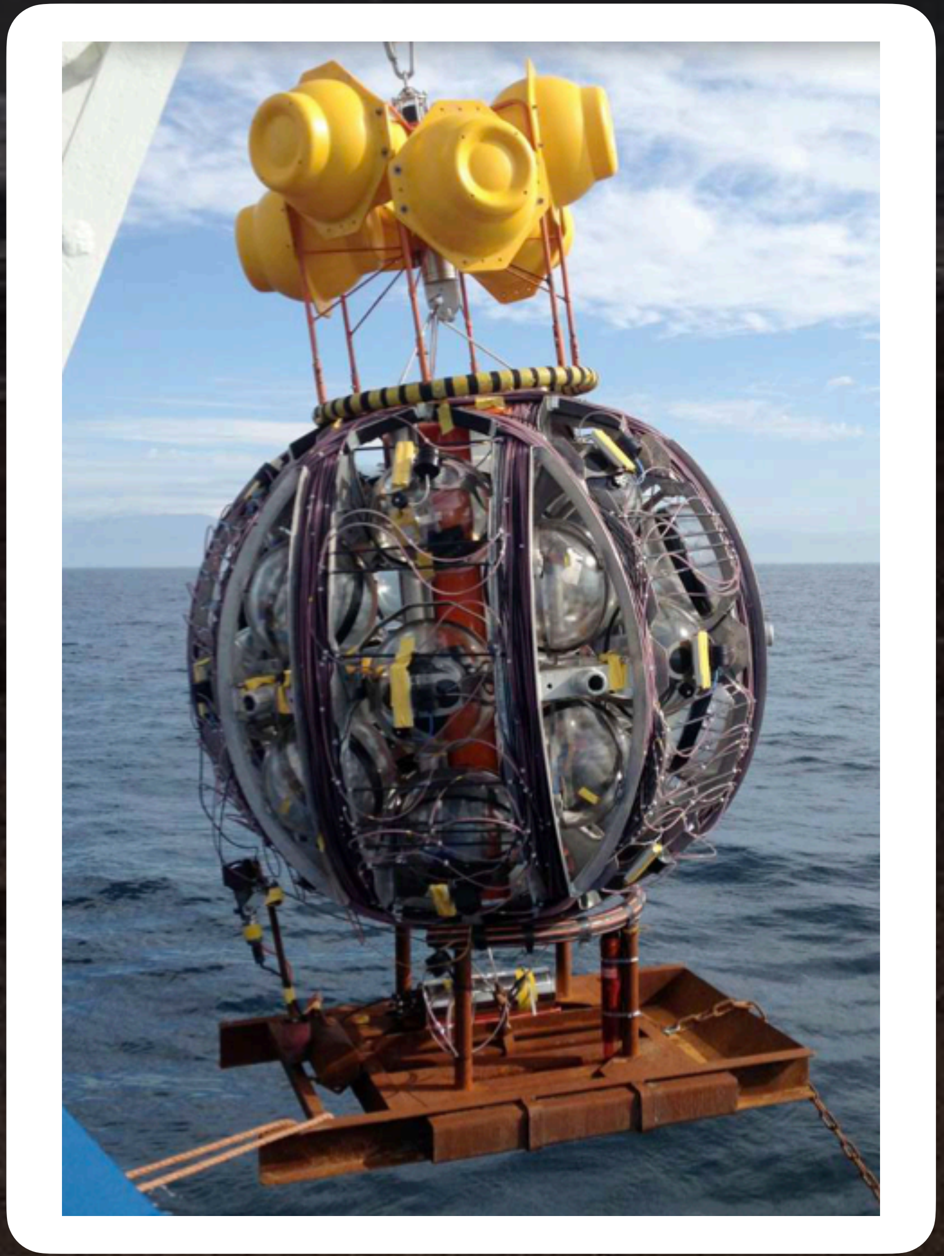
- DOM (Digital Optical Module)
- DU (Detection Unit)
- Seafloor network: electro-optical cables and JBs

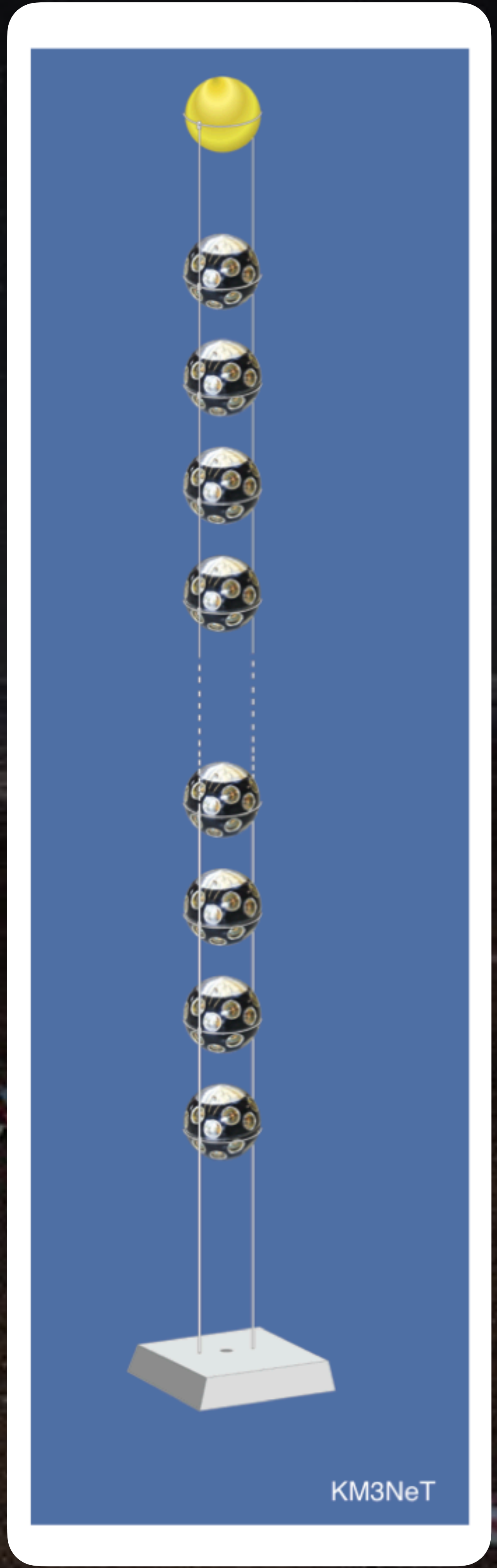
DOM

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

DU

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

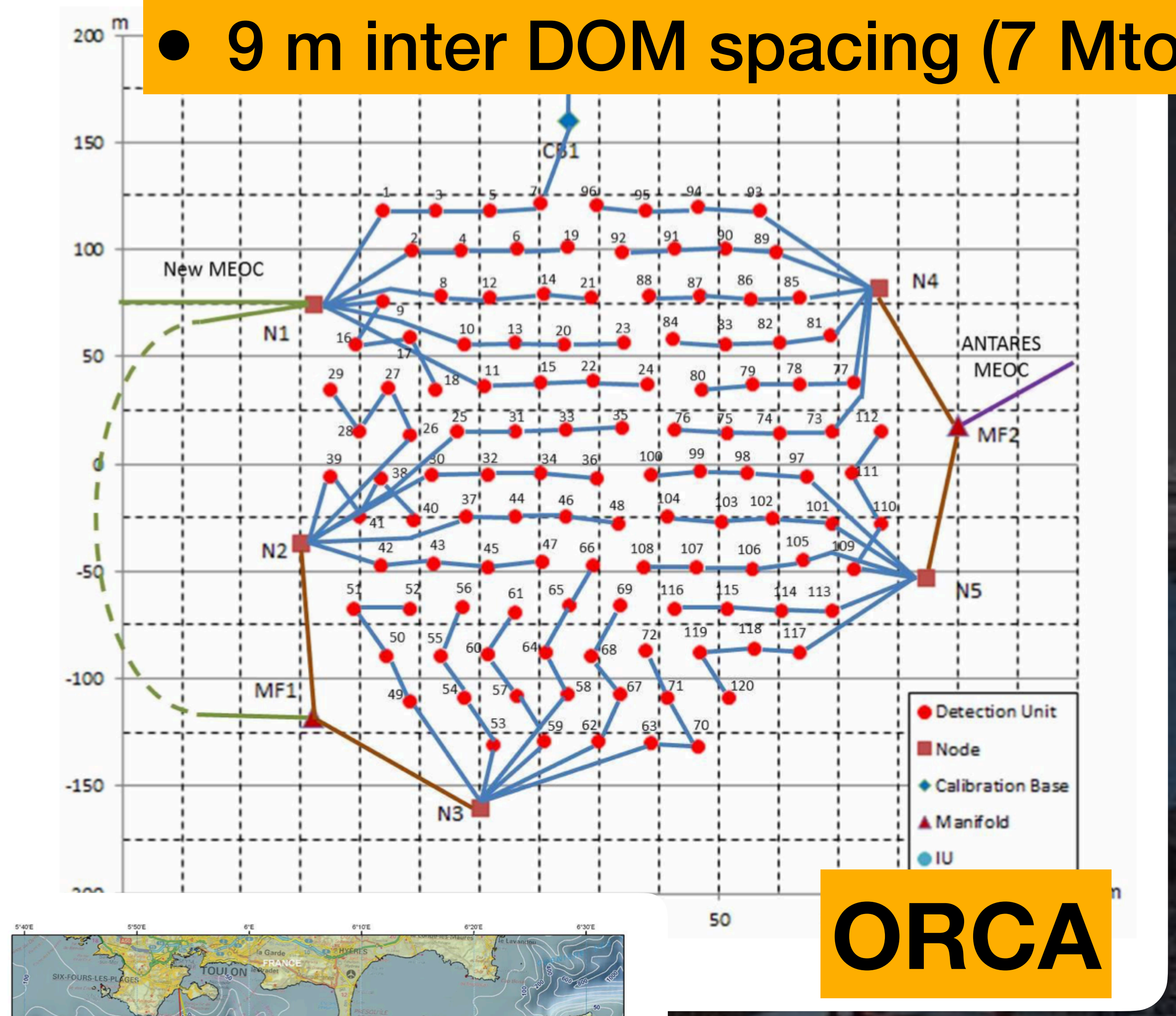


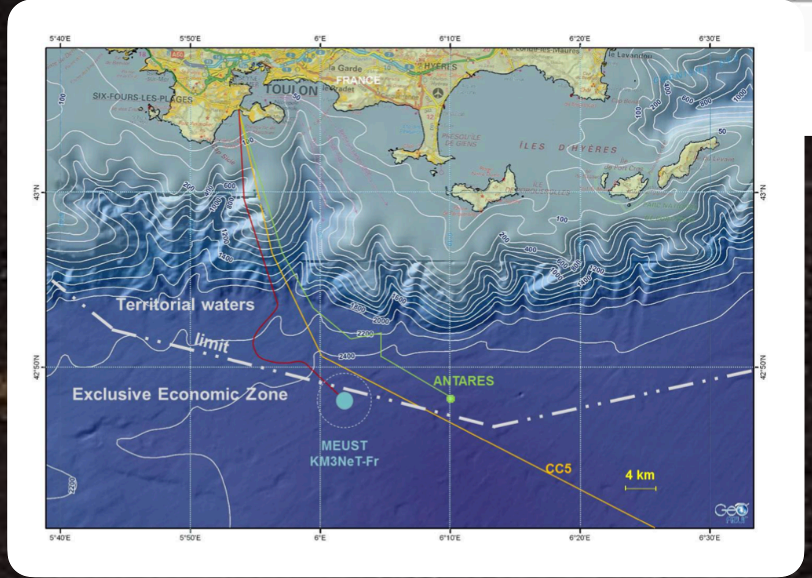


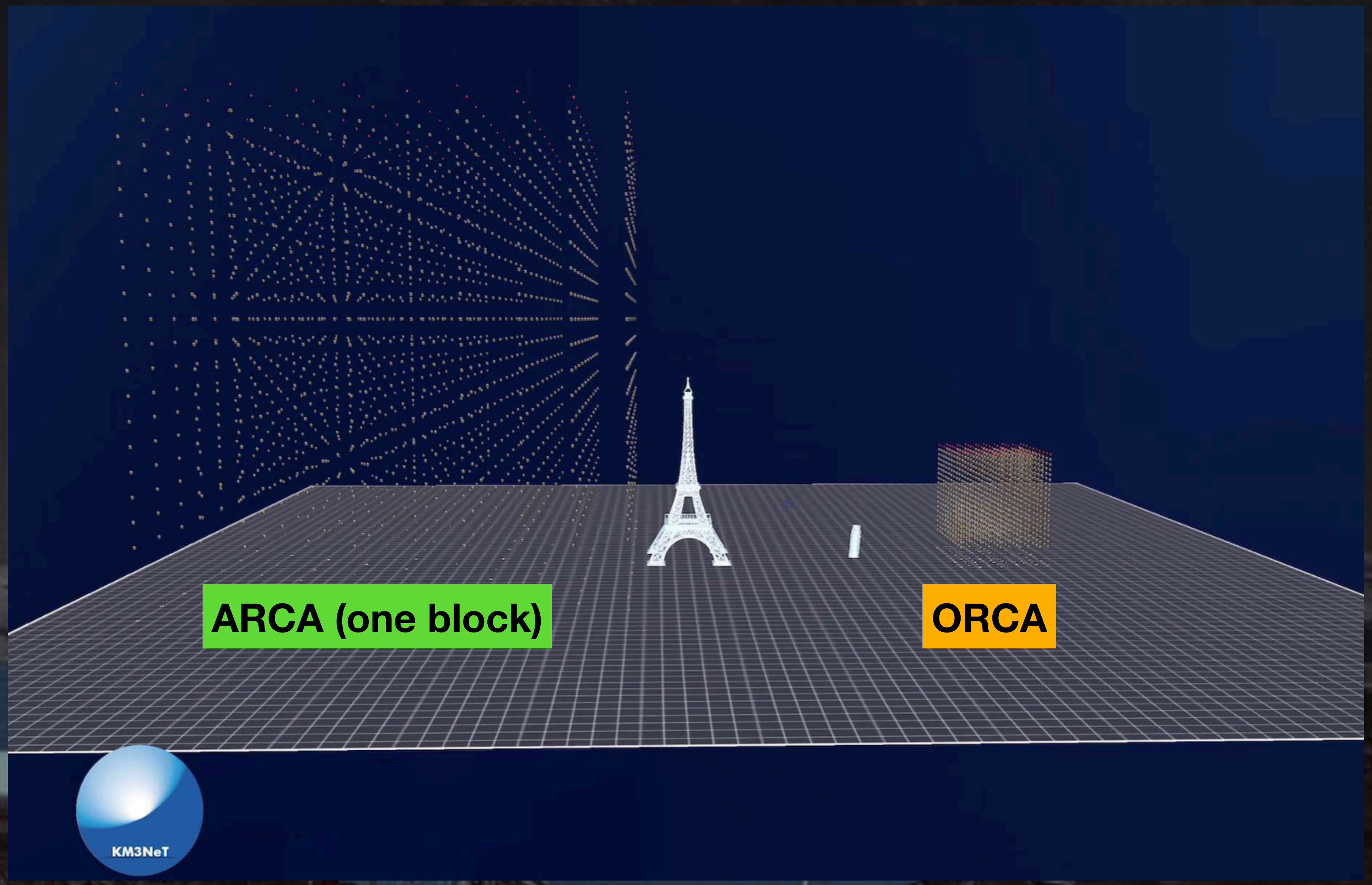
From “The KM3NeT underwater neutrino telescope: status and future perspective”, G. Ferrara, TIPP2023

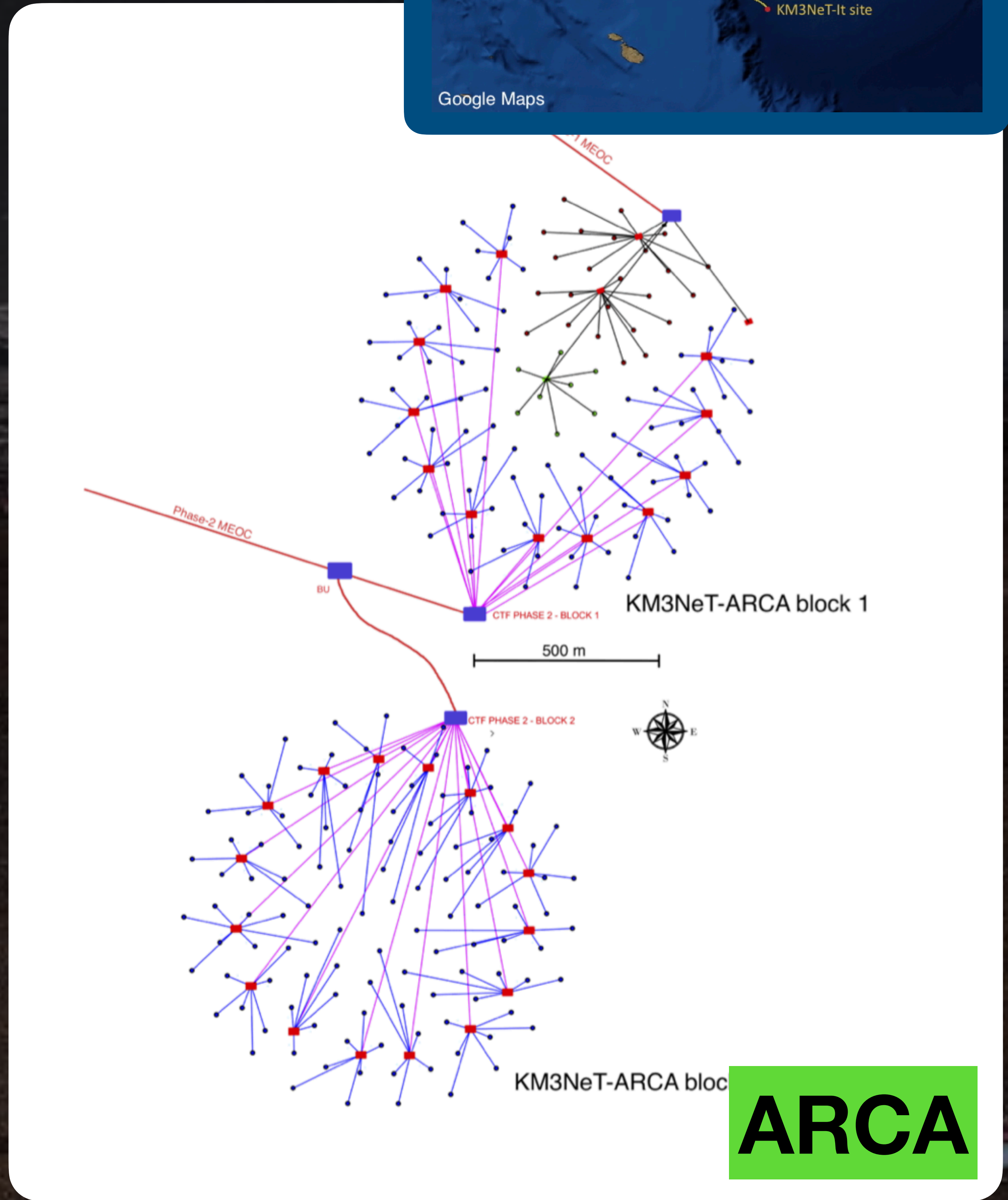
The KM3NeT technology and infrastructure

ORCA:
- 1 building block (BB) of 115 DUs
- 20 m DU interspacing
- 9 m inter DOM spacing (7 Mton)









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

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

Finanziato dall'Unione europea NextGenerationEU
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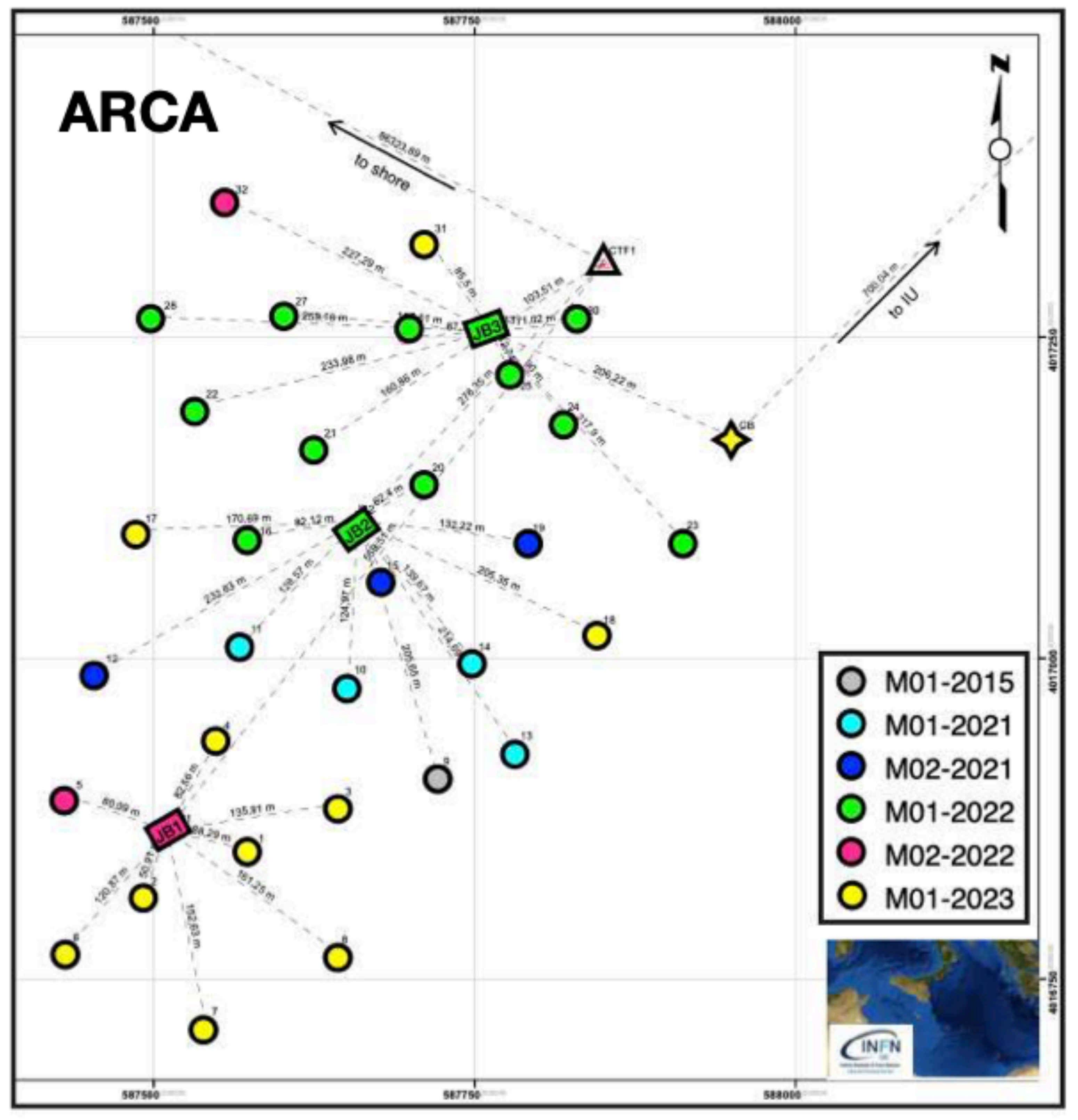
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
cta cherenkov telescope array
INFN Istituto Nazionale di Fisica Nucleare

Current Status of KM3NeT-ARCA

Current Staus: 28 ARCA DUs

KM3NeT infrastructure procurement and construction in progress

Funding assured for ~125 ARCA DUS **(one full block)**



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