KM3NeT: UHE neutrinos & more

Piotr Kalaczyński

Work supported by:

Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences

AstroCeNT
Particle Astrophysics Science and Technology Centre
International Research Agenda

AGH University of Krakow

WFiIS AGH

CEAI
Center of Excellence in Artificial Intelligence

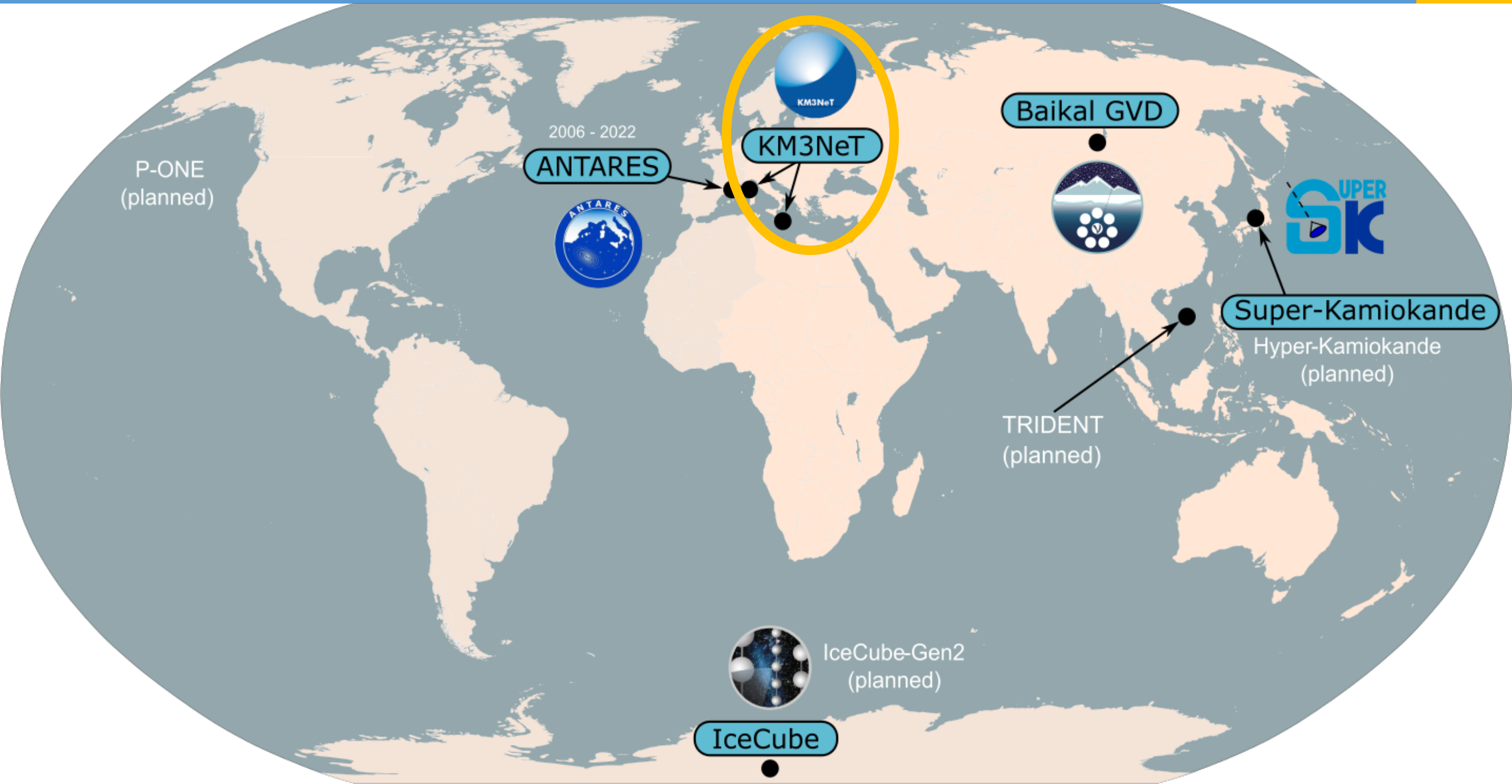
European Funds
Smart Growth

Republic of Poland

FNP
Foundation for Polish Science

European Union
European Regional Development Fund

Water Cherenkov ν telescope landscape



Who we are

France

- CNRS Nucléaire et Particules
- Astroparticle and Cosmology Laboratory, Université Paris Cité, CNRS
- Centre for Particle Physics of Marseille, Aix-Marseille Université, CNRS
- Laboratoire d'Astrophysique de Marseille
- Mediterranean Institute of Oceanography, CNRS Terre et Univers, Marseille
- Université de Toulon
- Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, CNRS
- Subatech, IMT Atlantique, Nantes Université
- Laboratoire Univers et Particules de Montpellier
- Laboratoire de Physique Corpusculaire de Caen, Université de Caen, CNRS

United Kingdom

- University of Hull

Belgium

- UCLouvain, Louvain-La-Neuve
- Université Libre de Bruxelles

The Netherlands

- NWO-I, Nikhef, Amsterdam
- Universiteit van Amsterdam
- Universiteit Leiden
- NIOZ, Texel
- TNO, Technical Sciences, Delft

Germany

- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Max-Planck-Institut für Radioastronomie, Bonn
- Universität Würzburg
- Universität Erlangen, Remeis Sternwarte, Bamberg
- Universität Münster

Italy

- INFN Laboratori Nazionali del Sud, Sezione di Catania
- INFN Sezione di Firenze, Università di Firenze
- INFN Sezione di Genova, Università di Genova
- INFN Sezione di Napoli, Università della Campania, Università di Napoli
- INFN Sezione di Roma, Sapienza Università di Roma
- INFN Sezione di Bari, Politecnico di Bari
- INFN Sezione di Bologna, Università di Bologna
- INFN Sezione di Padova, Università di Padova
- Università degli Studi di Salerno, INFN Gruppo Collegato di Salerno

Slovakia

- Univerzita Komenského v Bratislave
- Slovenská akadémia vied, Kosice

Czech Republic

- Czech Technical University in Prague, Institute of Experimental and Applied Physics

Poland

- AGH University of Krakow
- NCBJ - National Centre for Nuclear Research, Warsaw
- Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw

Romania

- Institute of Space Science - INFLPR Subsidiary, Magurele

Greece

- Institute of Nuclear and Particle Physics, NCSR Demokritos, Athens
- National and Kapodistrian University of Athens

Cyprus

- University of Cyprus, Nicosia

Spain

- Consejo Superior de Investigaciones Científicas (CSIC)
- Instituto de Física Corpuscular, Universitat de València, CSIC
- Universitat Politècnica de València, IGIC, Gandia, València
- Universidad de Granada
- Centro Oceanográfico de Murcia (IEO-CSIC)
- Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
- Instituto de Ciencias del Mar, CSIC, Barcelona

United States of America

- Harvard University, Cambridge
- Drexel University, Philadelphia

Algeria

- Center of Research in Astronomy, Astrophysics, and Geophysics, Bouzaréah
- Université Badji Mokhtar, Annaba
- University of Constantine
- Mohamed Boudiaf University, M'sila

Morocco

- University Mohammed V, Rabat
- National Center of Energy of Sciences and Nuclear Techniques, Rabat
- University Mohammed Ier, Oujda
- Cadi Ayyad University, Marrakesh
- Mohammed VI Polytechnic University, Ben Guerir

KM3NeT Collaboration

5 continents, 21 countries, 68 institutes

KM3NeT

Full members

Observer members

China

- Sun Yat-Sen University, Zhuhai

Georgia

- Tbilisi State University
- University of Georgia, Tbilisi

South Africa

- University of Johannesburg
- University of the Witwatersrand, Johannesburg
- North-West University, Potchefstroom

United Arab Emirates

- University of Sharjah
- Khalifa University of Science and Technology, Abu Dhabi

Australia

- Western Sydney University

Polish KM3NeT team: current status

Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences

AGH University of Krakow

AstroCeNT
Particle Astrophysics Science and Technology Centre
International Research Agenda

- me ☺
- Mariusz Suchenek

WFiIS AGH

WFiIS:

- Artur Ukleja
- Tomasz Szumlak
- Agnieszka Obłąkowska-Mucha
- Kalyani Mehta (PhD student)
- Amine Meskar (PhD student)
- Wiktoria Szewczyk (MSc student)

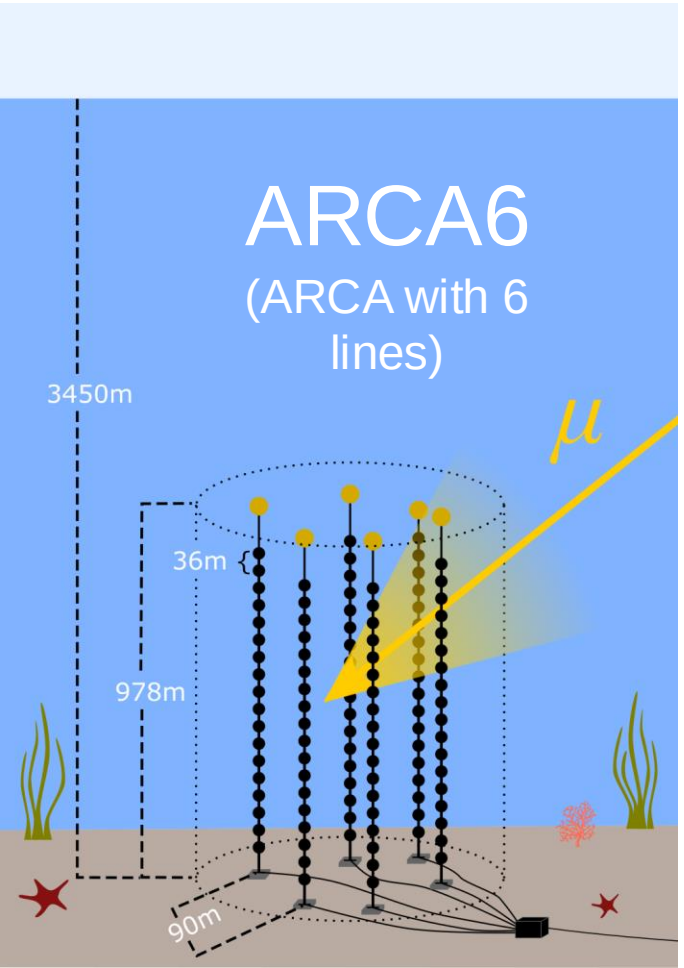
CEAI
Center of Excellence in Artificial Intelligence

- me ☺

Grants:

Under evaluation: OPUS (NCN)
In preparation: MNiSW grant

KM3NeT detectors: brief summary



Detector	ARCA	ORCA
Depth	3.5 km	2.45 km
Volume	$1\ \mathrm{km}^3$ (1Gton)	$0.007\ \mathrm{km}^3$ (7Mton)
# lines	28 / 2x115	24 / 115
Topic	Astroparticle RCA*	Oscillation RCA*
Goal	ν_{astro}	m_ν hierarchy

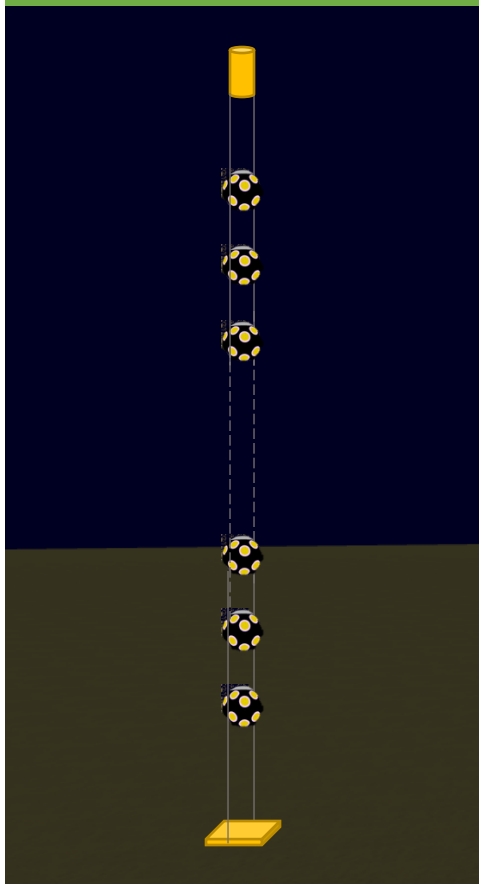
*RCA : Research with Cosmics in the Abyss

Detector design summary

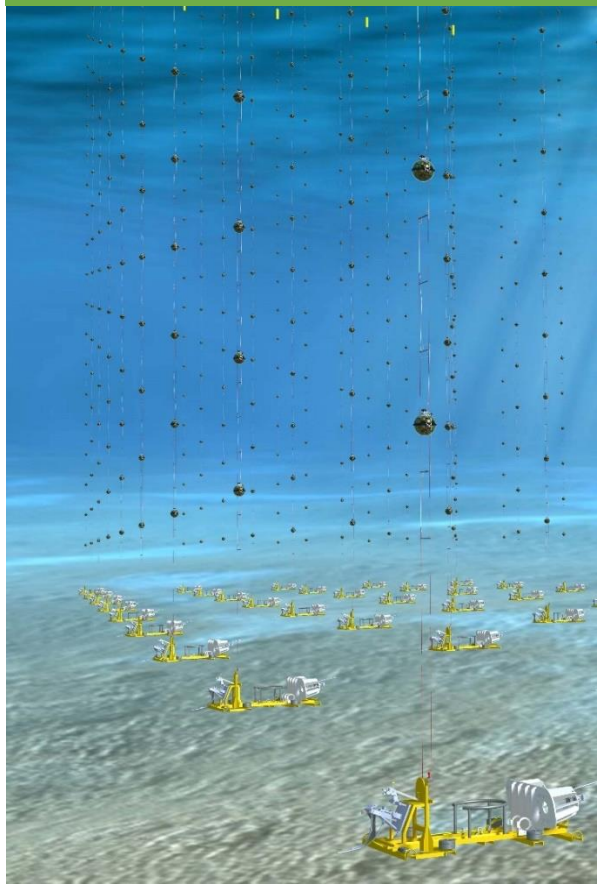
DOM:
71 unique components

1 DOM:
31 PMTs

1 string (DU):
18 DOMs



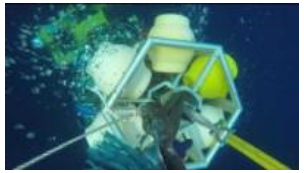
1 building block:
115 DUs



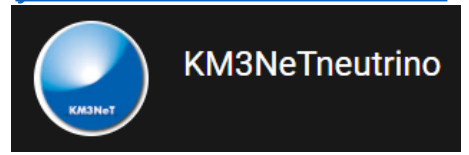
[DOM production:(@Nikhef)]

[Preparation for deployment:]

[String deployment:]



More at:
youtube.com/KM3NeTneutrino

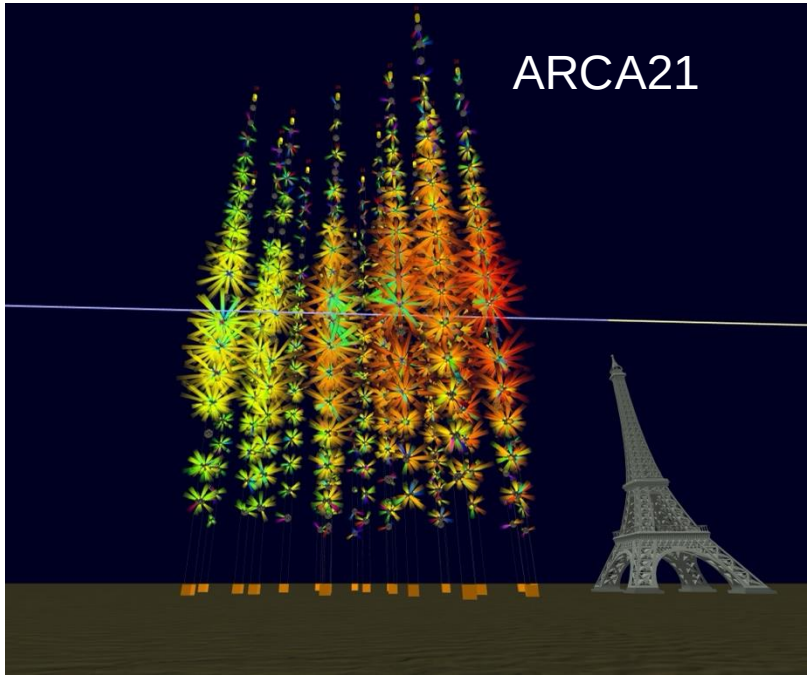


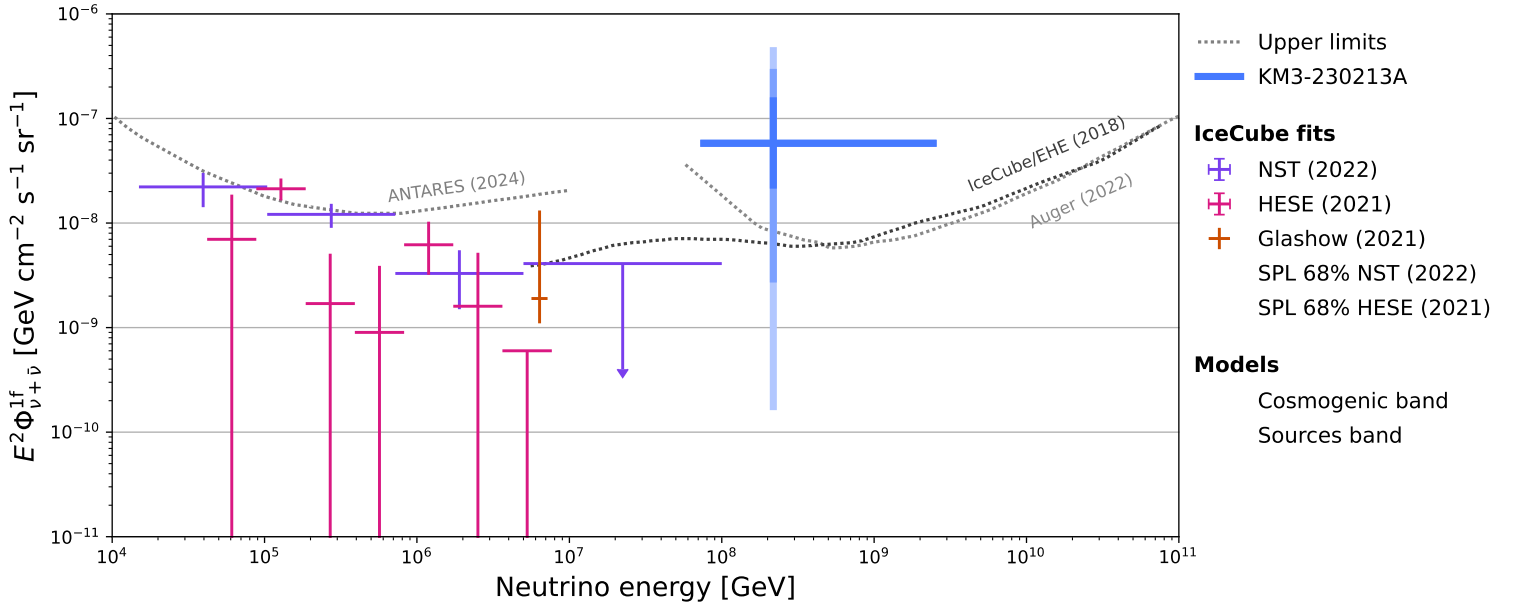

FUGRO
FUGRO
FUGRO

Our latest result: KM3-230213A

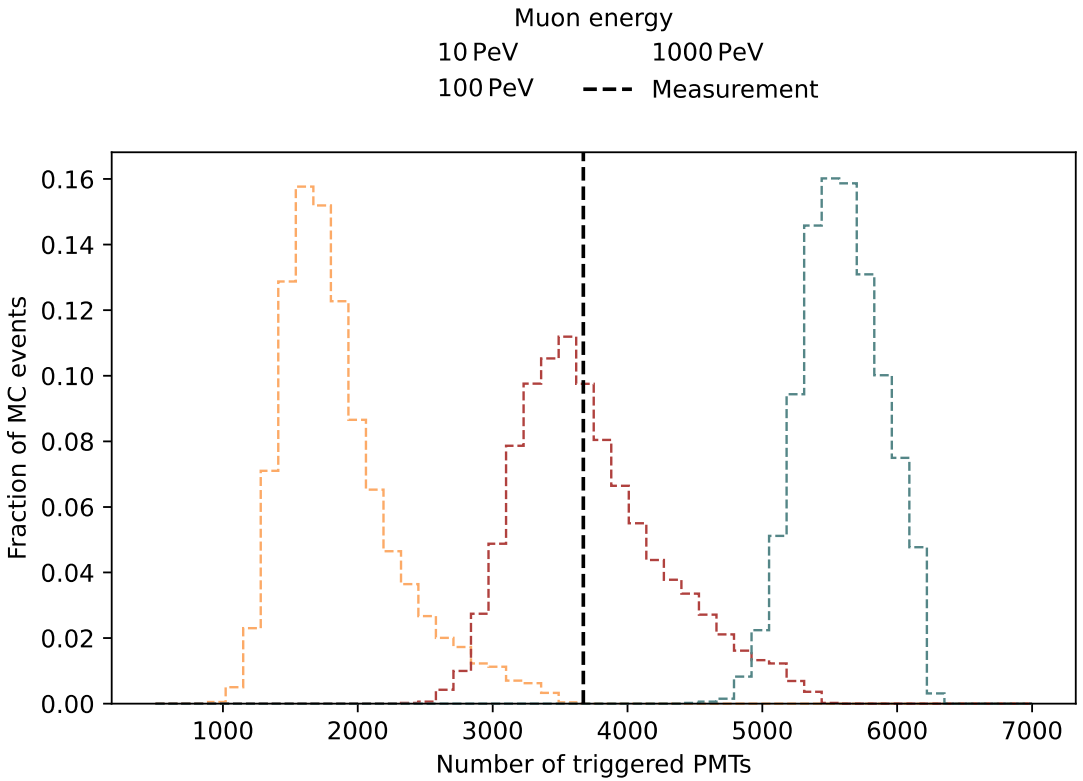
In case you did not follow the news last week …

We've observed quite a beast of a neutrino





KM3-230213A briefly summarized



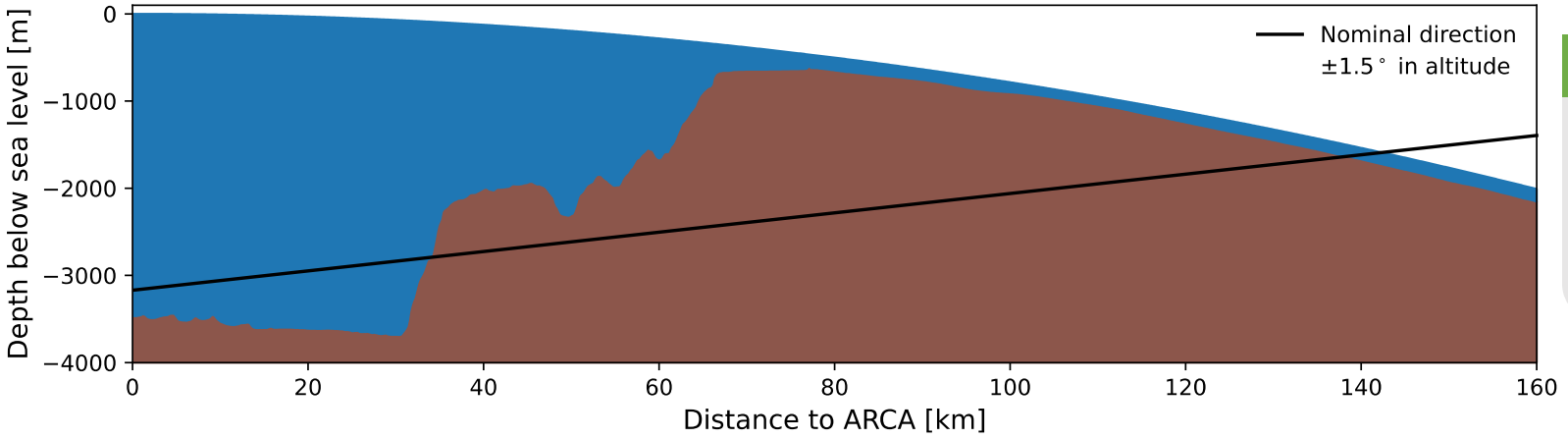
Reco energies:

$$E_\mu = \left(120\ ^{+110}_{-60}\right)\ \text{PeV}$$
$$\mathrm{E}_\nu = \left(220\ ^{+570}_{-110}\right)\ \text{PeV}$$

Origin:

- galactic x
- blazar ?
- cosmogenic ?

Companion papers:
[1] other exp
[2] cosmogenic
[3] blazar
[4] galactic
…
(more coming!)



Geometry:

104 km of rock
38 km of water

309 km w. e. in total

link to the paper
link to the data

How do we increase the statistics?

We need more datapoints at UHE → **Instrument even bigger volume**

… but how?

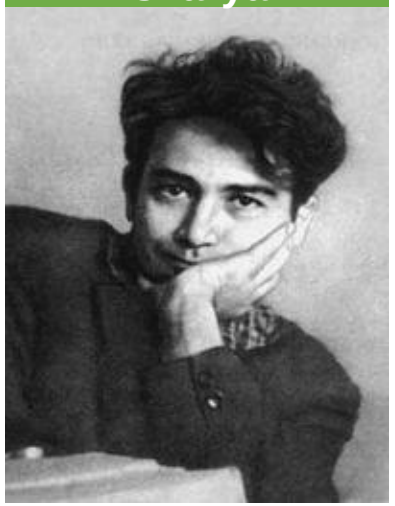
multi-km^3 water Cherenkov telescopes very expensive, biggest planned: $7.5\ \mathrm{km}^3$ (TRIDENT)

The problem: light range ~ few 100m

The solution: sound range ~ few km

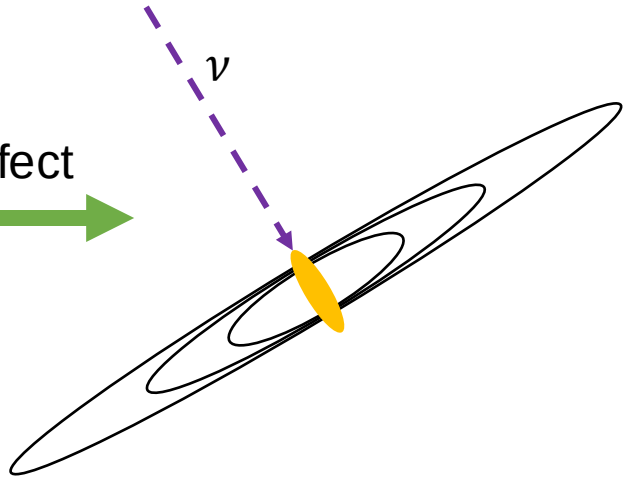
But how do we „hear" a neutrino? →

Gurgen A. Askaryan



source: https://en.wikipedia.org/wiki/Gurgen_Askaryan#/media/File:G_Askaryan.jpg

→ thermoacoustic effect →



~ kHz audio signal

Towards an acoustic neutrino telescope

Hardware

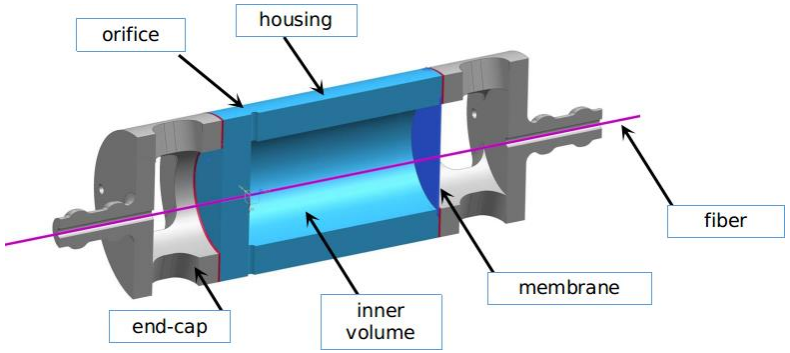
Hydrophones:

- Piezoelectric (already installed)
- Membrane (already installed)
- Optic fibre + membrane (under development)

…?

oceansonics.com

doi.org/10.1051/epjconf/201921602007

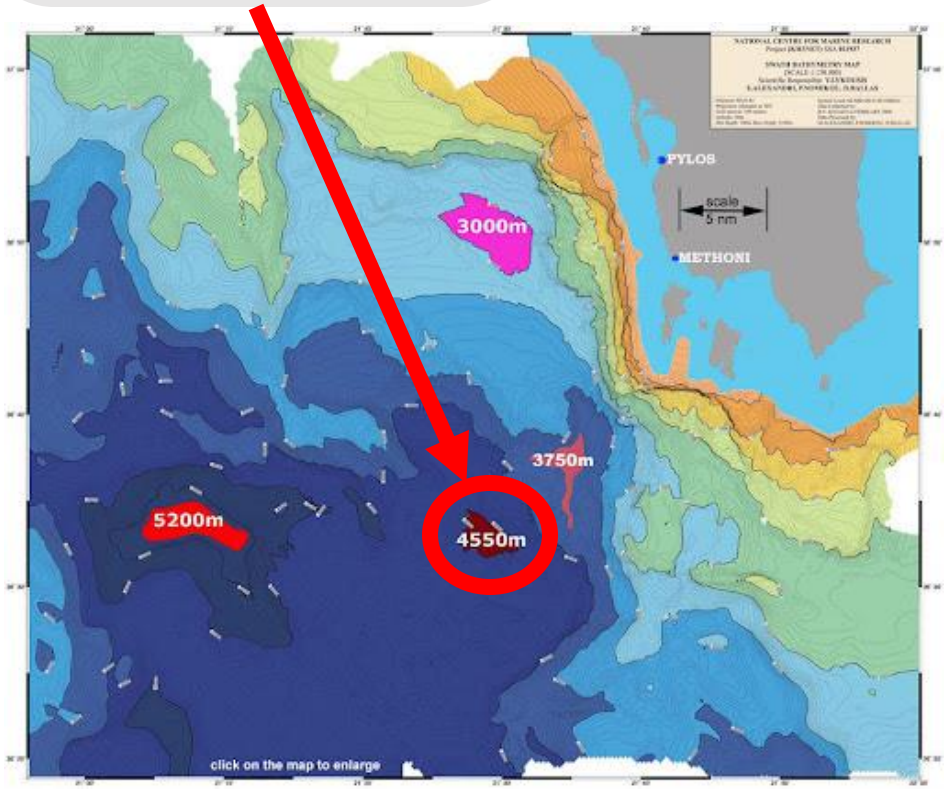


arXiv:2501.12999

Site

KM3NeT-Gr:

- near Pylos
- depth: 4550m
- noise lvl measured
- seabed mapped:
  - sub-m precision
  - quite flat



Software

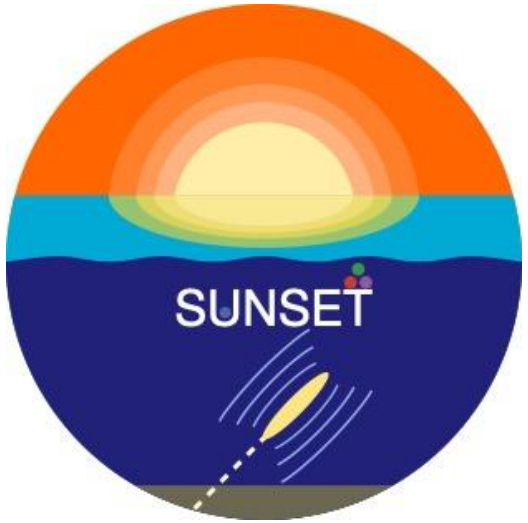
- There once was a MATLAB code from The ACoRNE Collaboration (and it is not available anymore …)
- well … and there's nothing else
- that's where we step in!

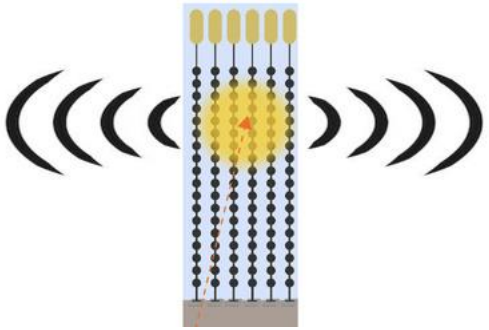
Simulation studies

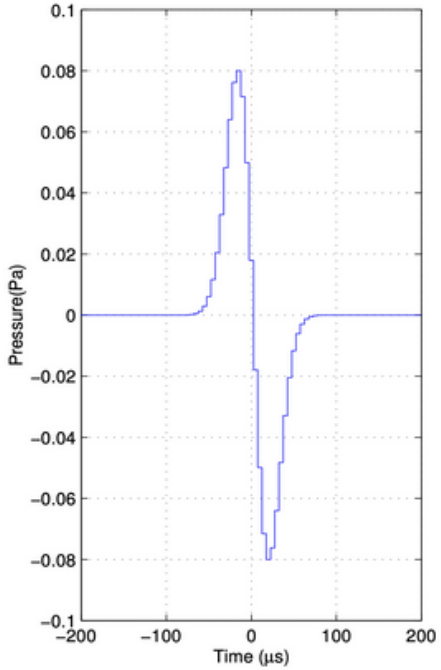
Funding …

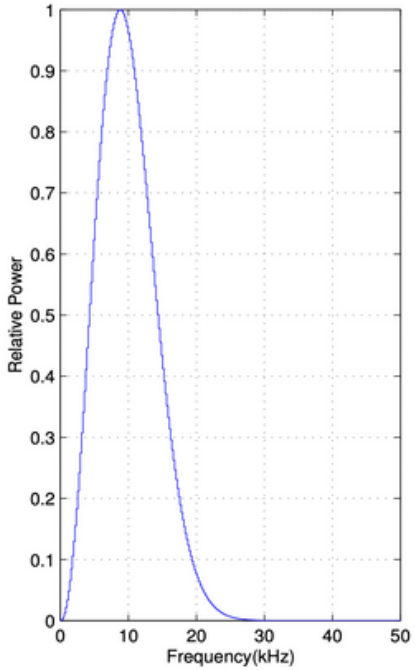
Our focus:

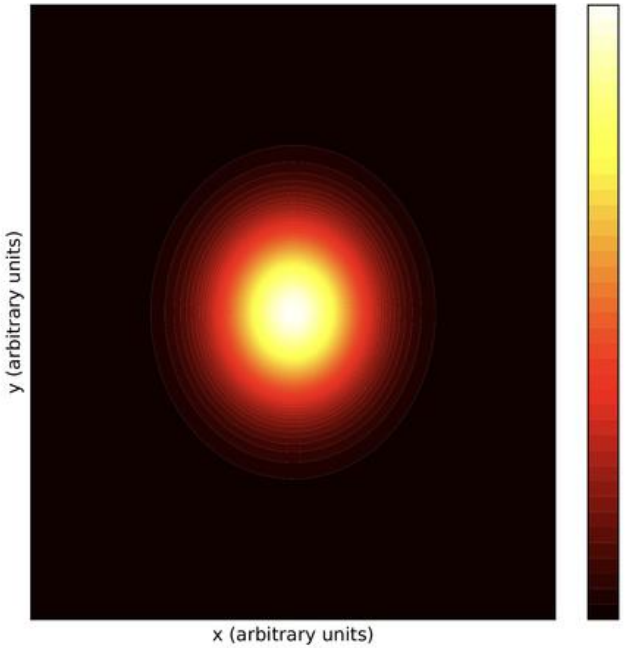
- ❖ Software development & maintenance:
  - new acoustic simulation code: SUNSET [Julia]
    - Acoustic calibration
    - Sound emission by UHE neutrino events

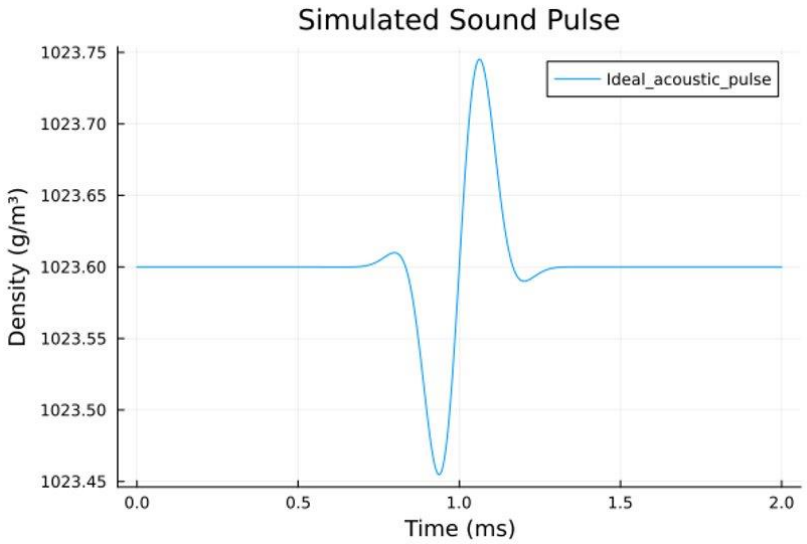












Research plans in a nutshell

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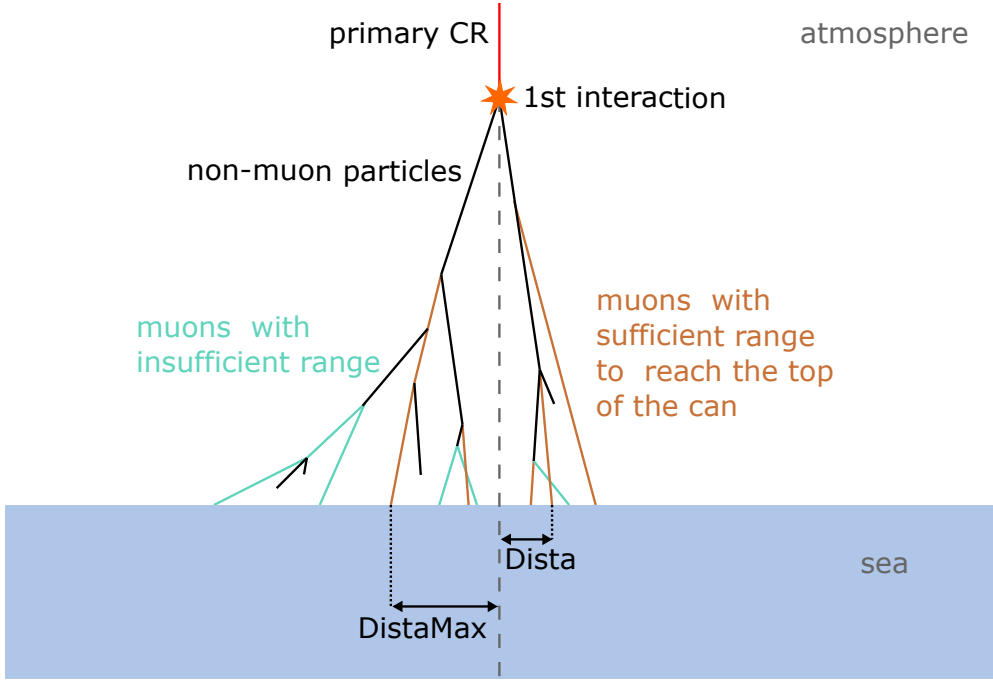
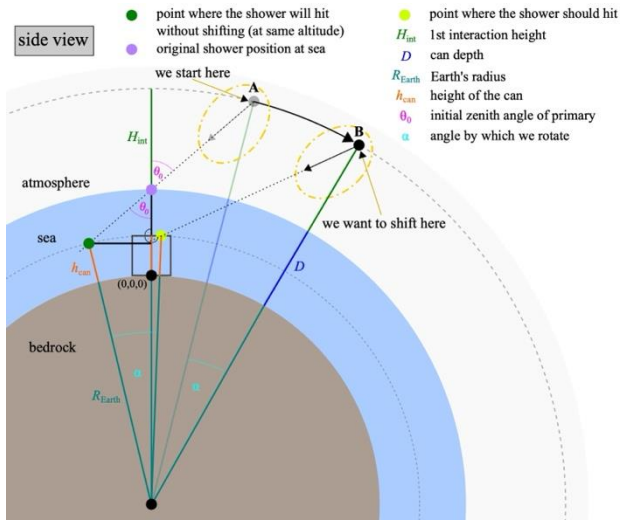
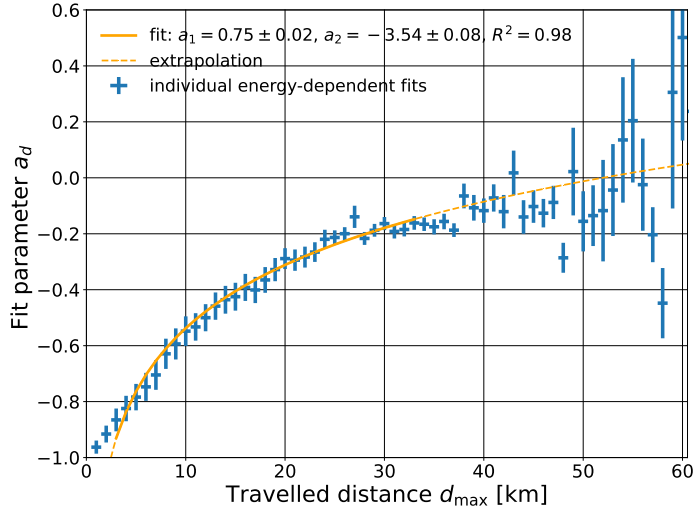
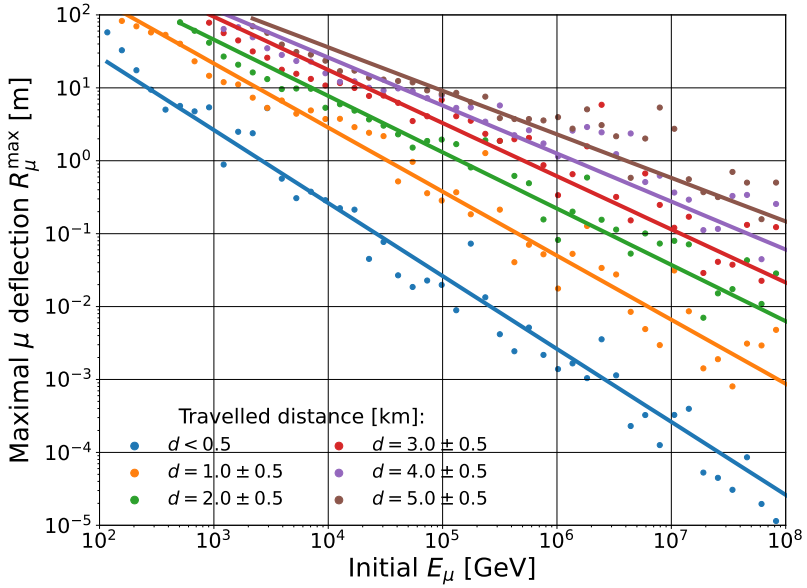
    - Sound emission by UHE neutrino events
  - gSeaGen [C++]
    - GENIE-based neutrino events generator
    - Processing of muons simulated with CORSIKA → Paper submitted to Comp. Phys. Comm.









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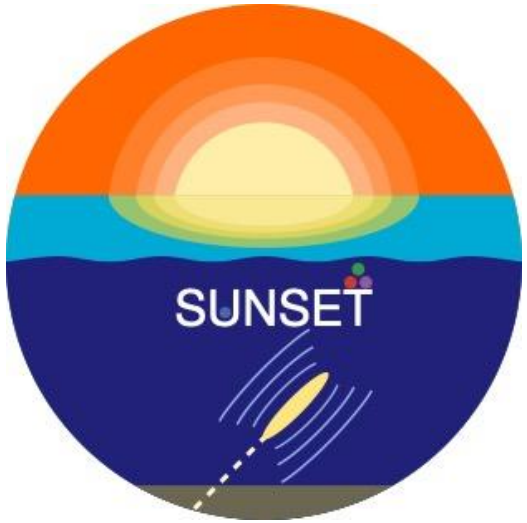
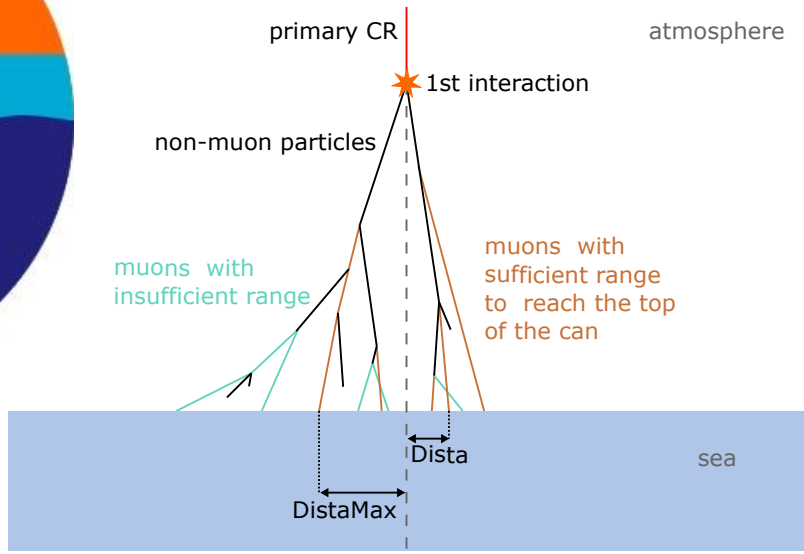
  - Using optical and/or acoustic data
  - Using ML & DL





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- ❖ Neutrino energy & direction reconstruction
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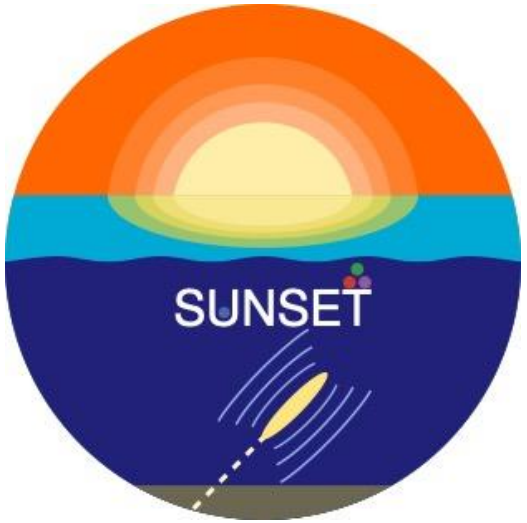
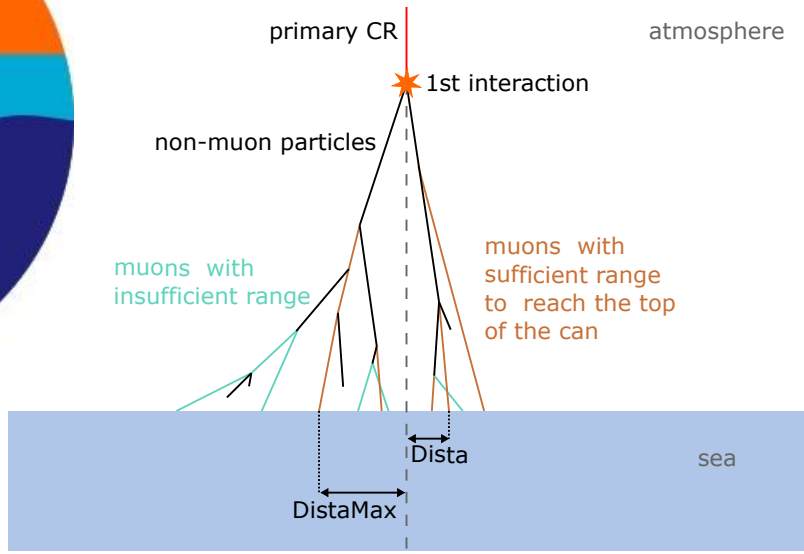
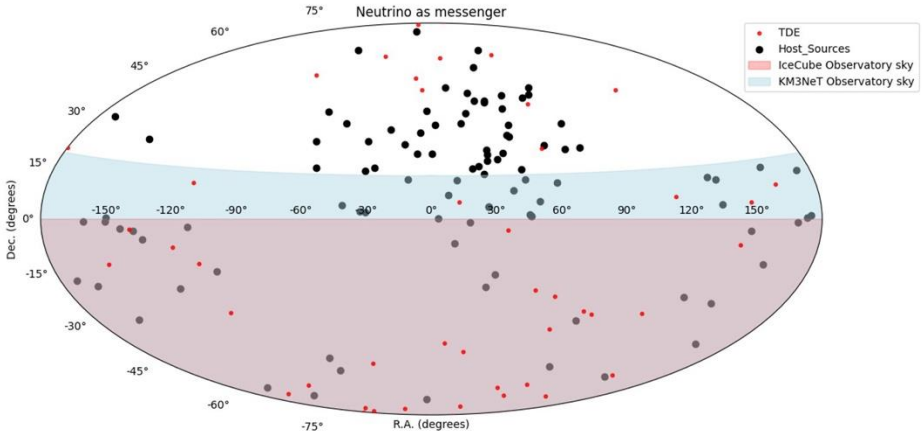
- ❖ Study of TDEs with neutrinos







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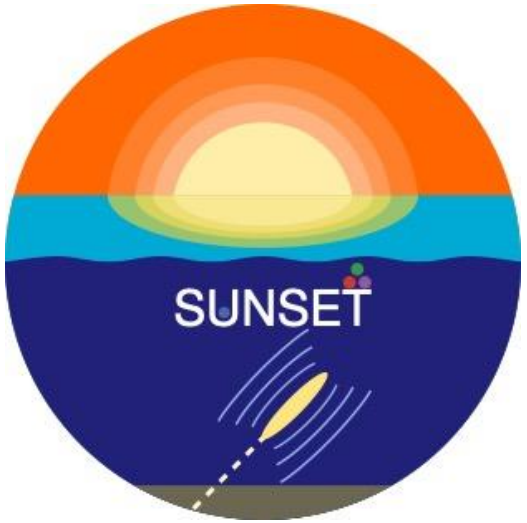
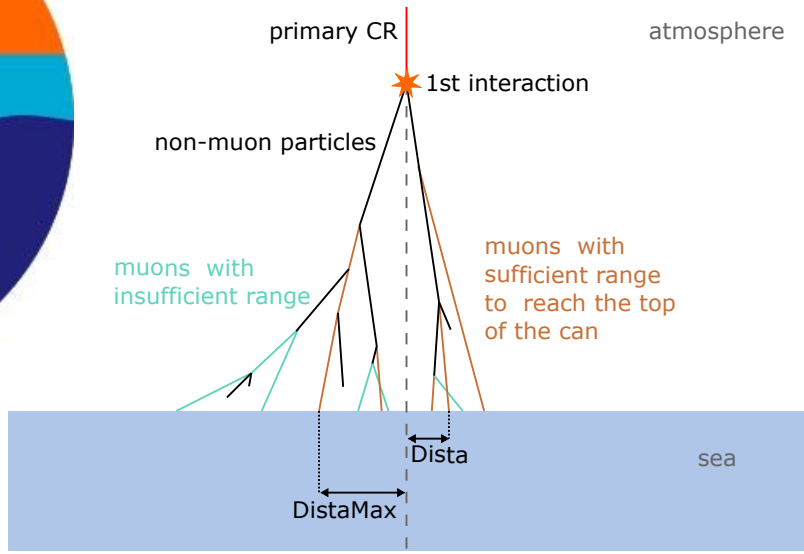
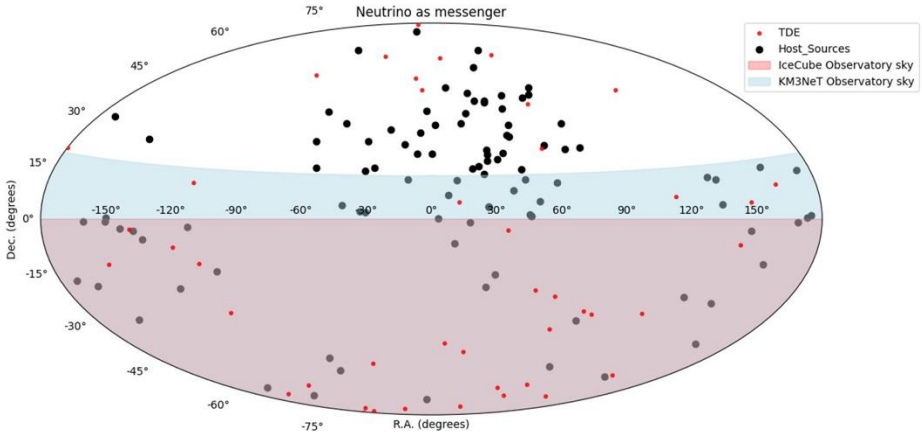
- ❖ Neutrino energy & direction reconstruction
  - Using optical and/or acoustic data
  - Using ML & DL
- ❖ Study of TDEs with neutrinos
- ❖ Muon bundle reconstruction
- ❖ Prompt muon sensitivity study
- ❖ …



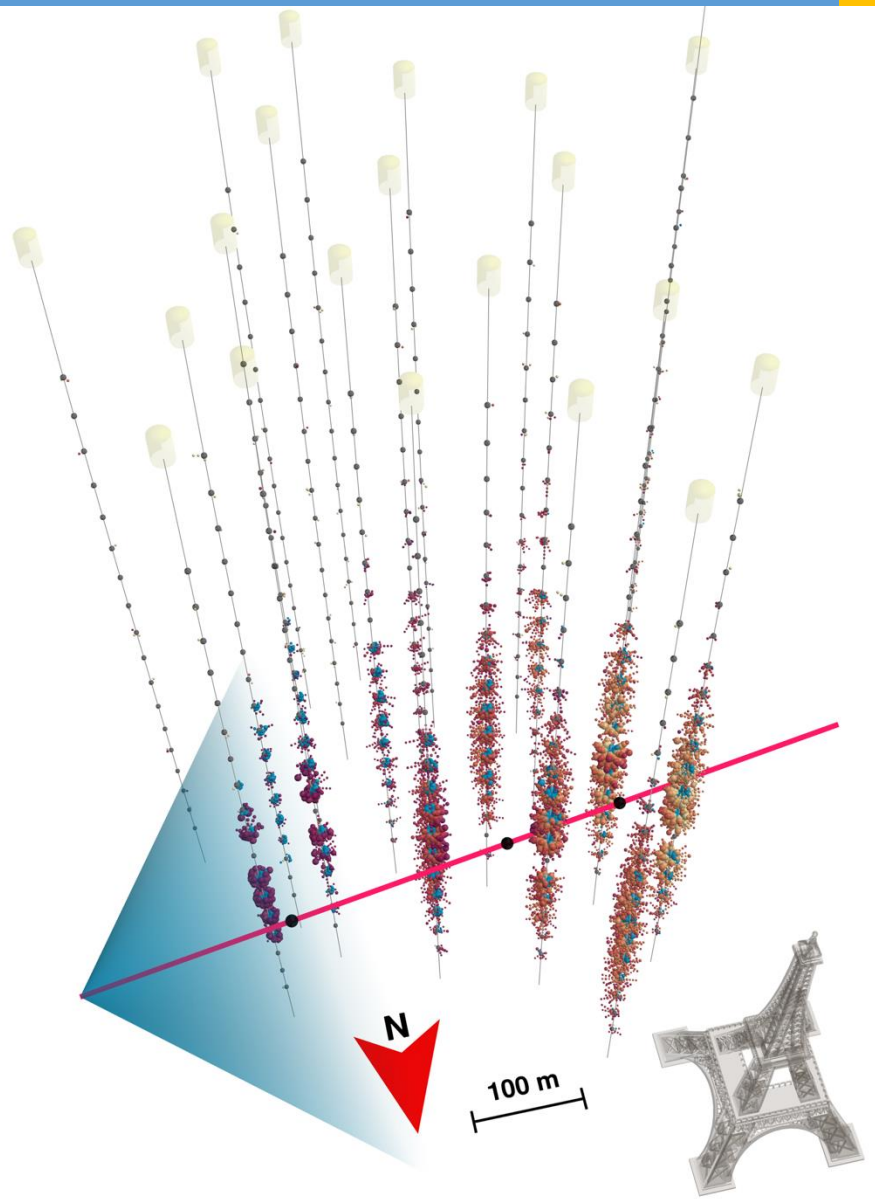




Summary:

- KM3NeT keeps growing & collecting data
- Already competitive in astronomy (and beyond)
- Polish group active in:
  - simulation software development
  - neutrino astronomy
  - cosmic ray physics
  - machine learning
- Stay tuned for more exciting results! ☺

Thank you for your attention!

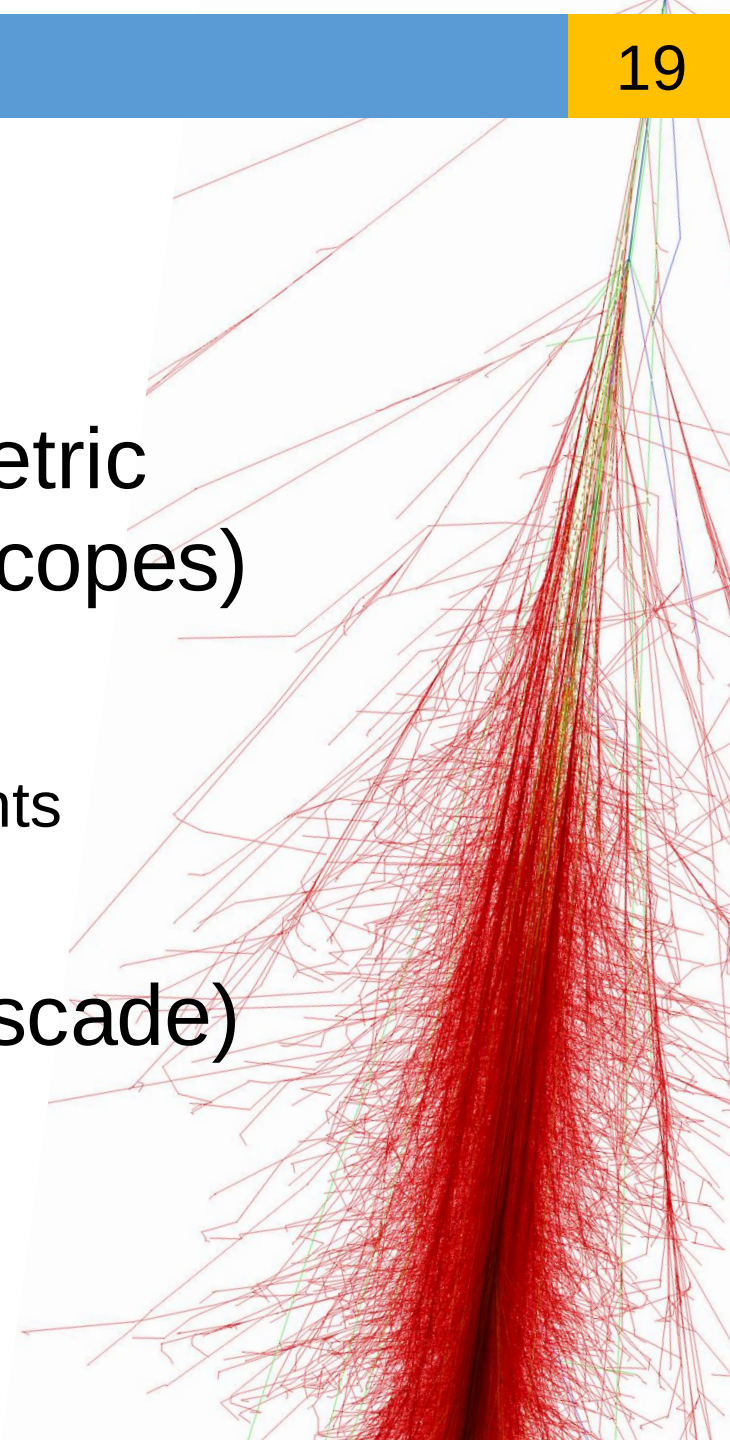


European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

Backup

We have 2 options:

1. MUPAGE (atmospheric **MU**ons from **PA**rametric formulas: a fast **GE**nerator for neutrino telescopes)
   - developed for ANTARES
   - fast muon MC generator
   - based on parametric formulas and MACRO measurements
   - parameters can be freely tuned
2. CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade)
   - developed for KASCADE
   - full simulation of air showers
   - customizable (models, primaries, etc.)



Digital Optical Module (DOM)

acrylic glass sphere with:

- 31 3” PMTs,
- readout electronics,
- pressure gauge,
- acoustic sensonrs,
- ...

2022 JINST 17 P0703

JATIS 7(1), 016001 (2021)

Photomultiplier Tube (PMT)

converts light into electric signal

JINST13 (2018) P05035

DOM arrangement

Detection Unit (DU):

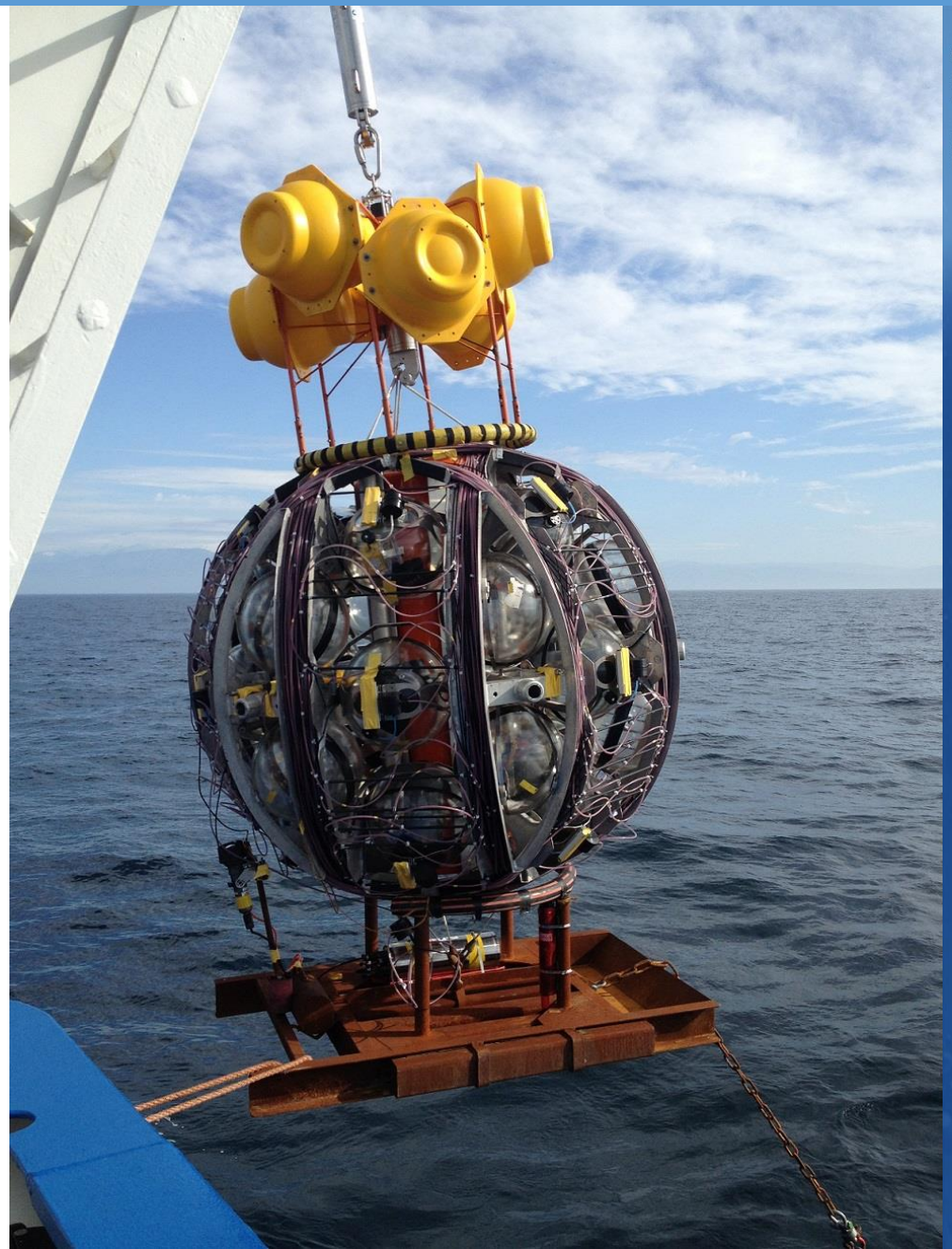
vertical **string** with 18 DOMs

Eur. Phys. J. C 76 (2016) 76:54

Naming:

ORCA6 ↔ ORCA with 6 strings
ARCA2 ↔ ARCA with 2 strings
etc.

2020 JINST 15 P11027



DOM arrangement

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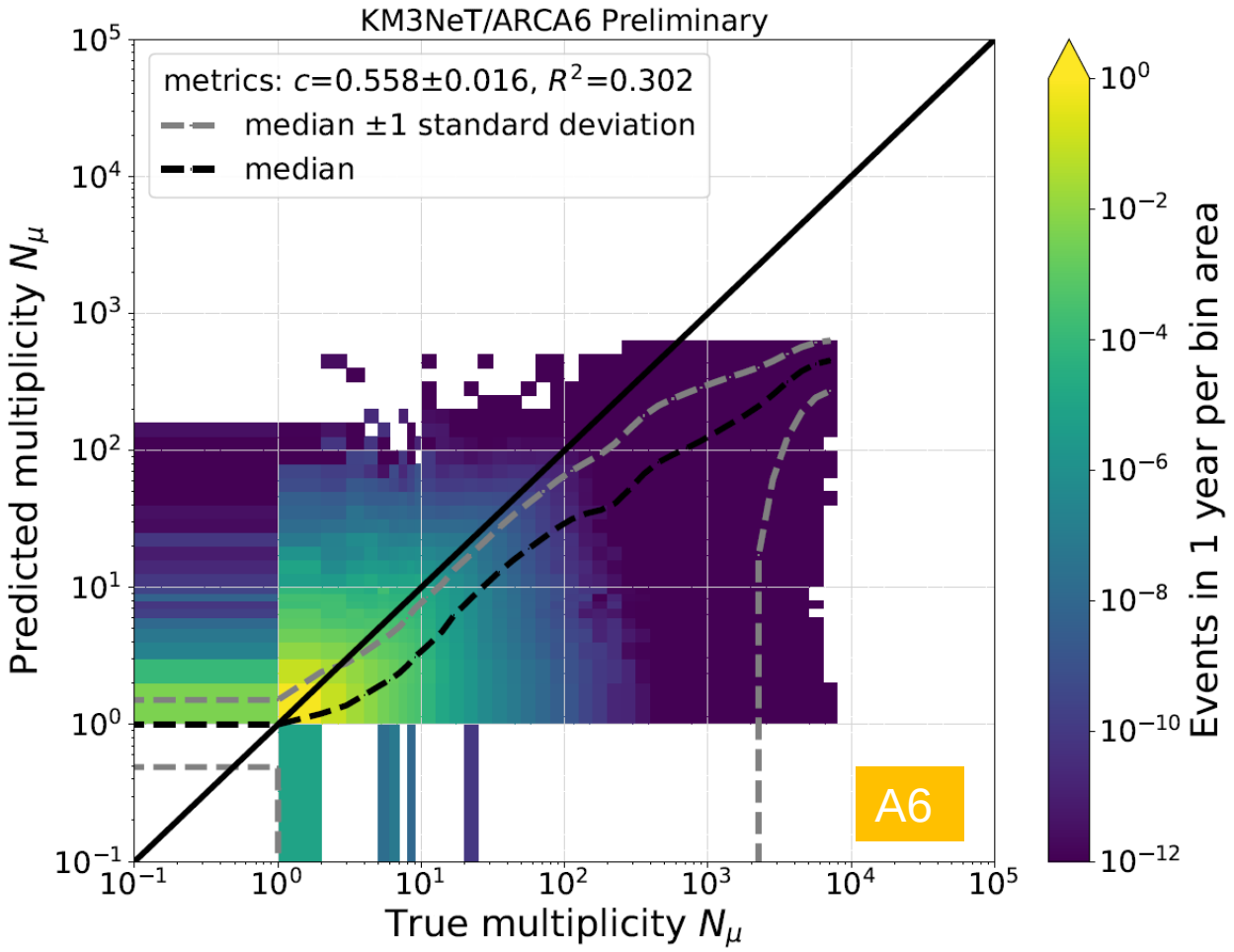
2020 JINST 15 P11027

Multiplicity reco: final results

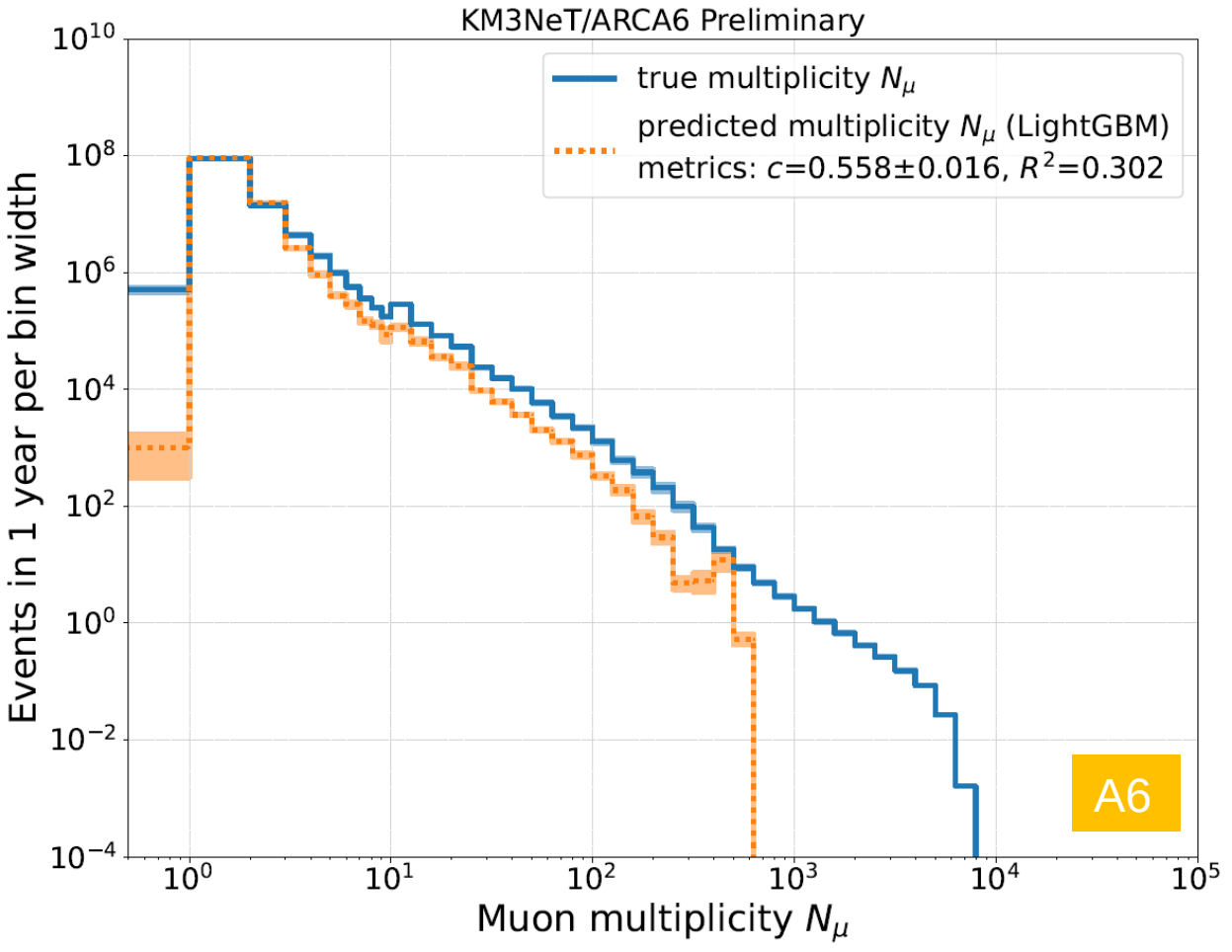
Analogical results obtained for ARCA115, ORCA115 and ORCA6

Example of the results for ARCA6:

2D: pred vs true



1D histograms

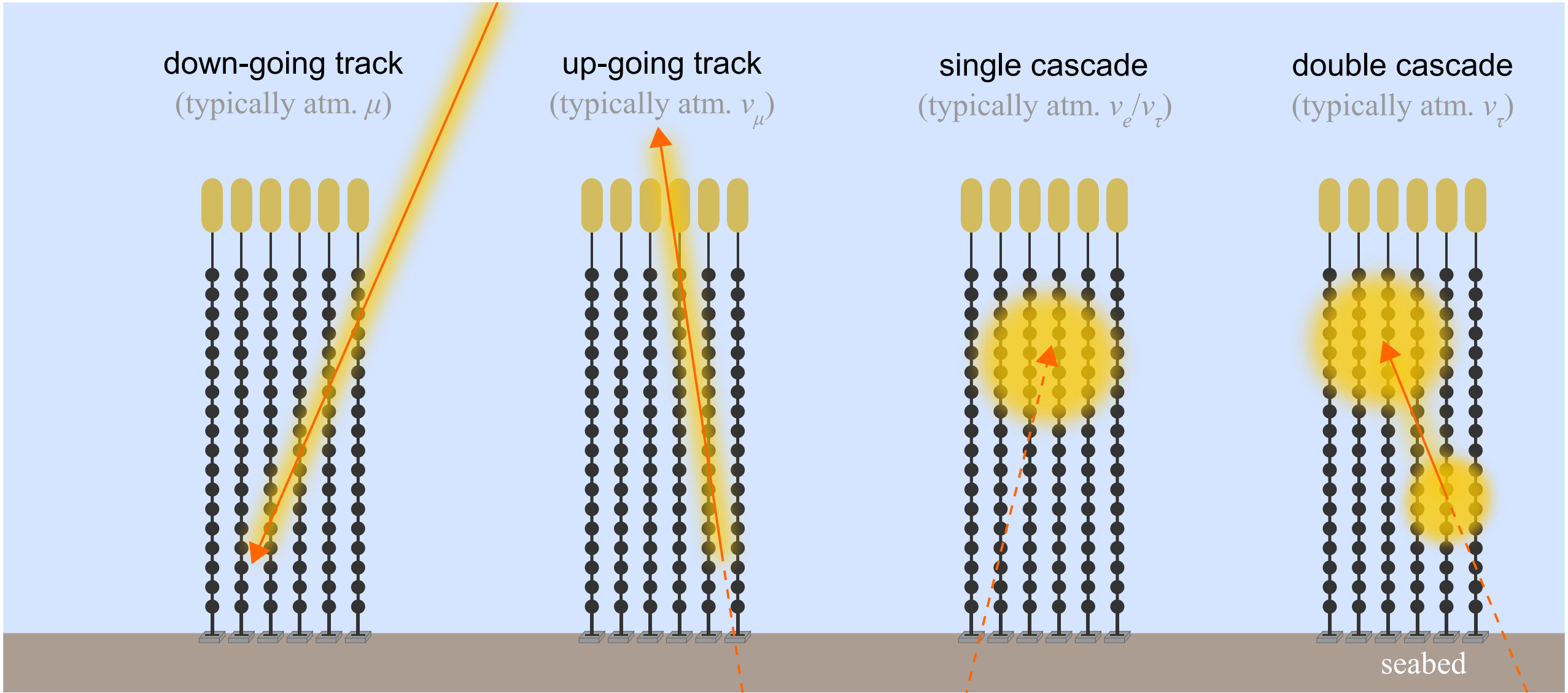


Event topologies

Examples of basic event topologies:

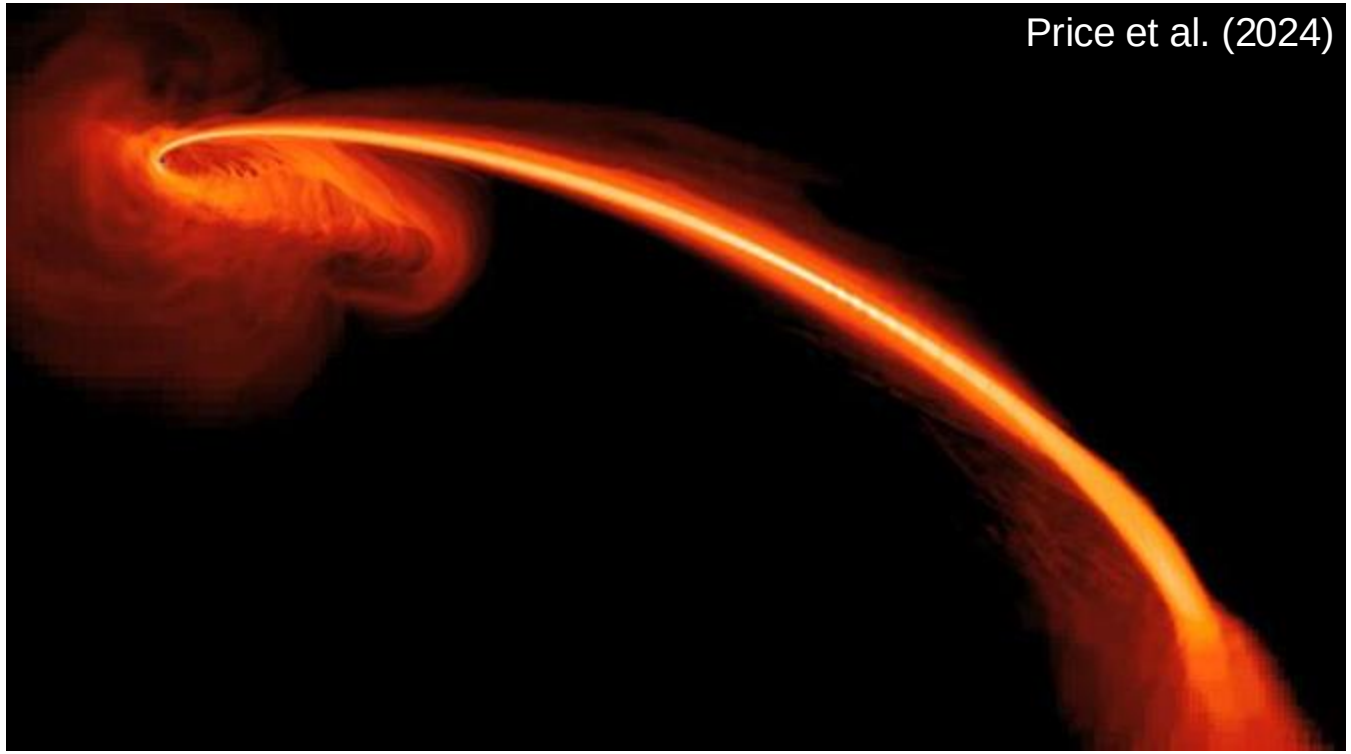
Classes based on combinations of:

- Direction
- Shape

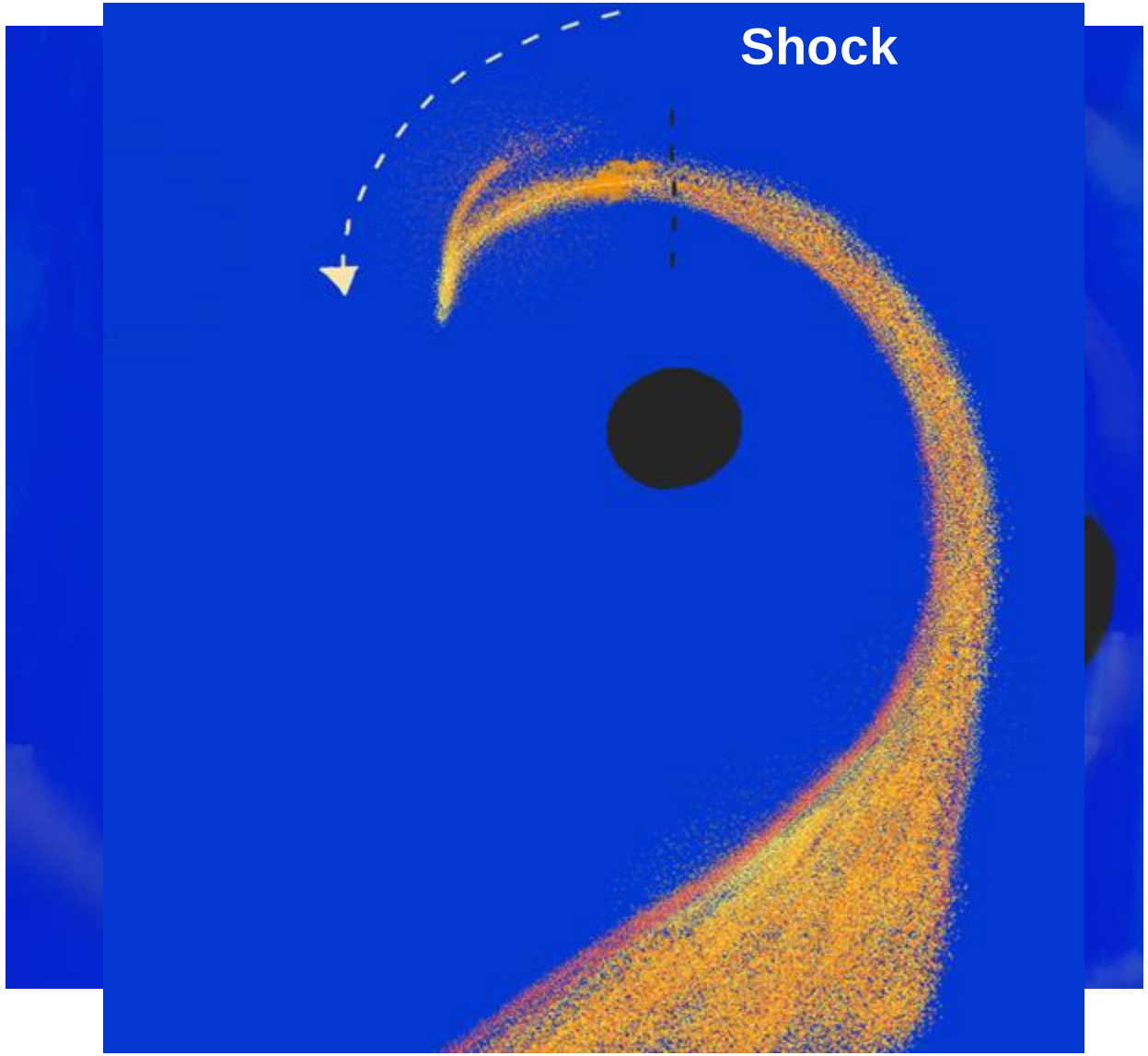


- High-energy neutrino emission is correlated with temporal and spatial emissions across all the multi-messenger

- Tidally disrupted events are one of the potential candidates of high energy neutrinos



- Tidally disrupted events (TDE): Theoretical concept of massive black holes and star system reaching Roche limit
- Main sequence stars of mass 1 - 10 $M_{\odot}$ and black hole mass 10^{6} - $10^{12} M_{\odot}$
- TDE comprises of jet and fallback accretion system



- Multi-messenger properties:
  - Spectral classification by UV - optical color diagram into TDE-H, TDE-H+He, and TDE-He
  - At X-ray and radio energies non-thermal emissions
  - Very high-energy neutrinos of TeV and PeV
  - Gravitational waves candidate up to 10 Hz