NCBJ annual seminar, 20.12.2021

Recent results from KM3NeT neutrino telescopes

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BP3

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Introduction

Introduction

KM3NeT

- Detectors
- Status

Results

Summary

ν detection in water (upgoing ν_μ example)

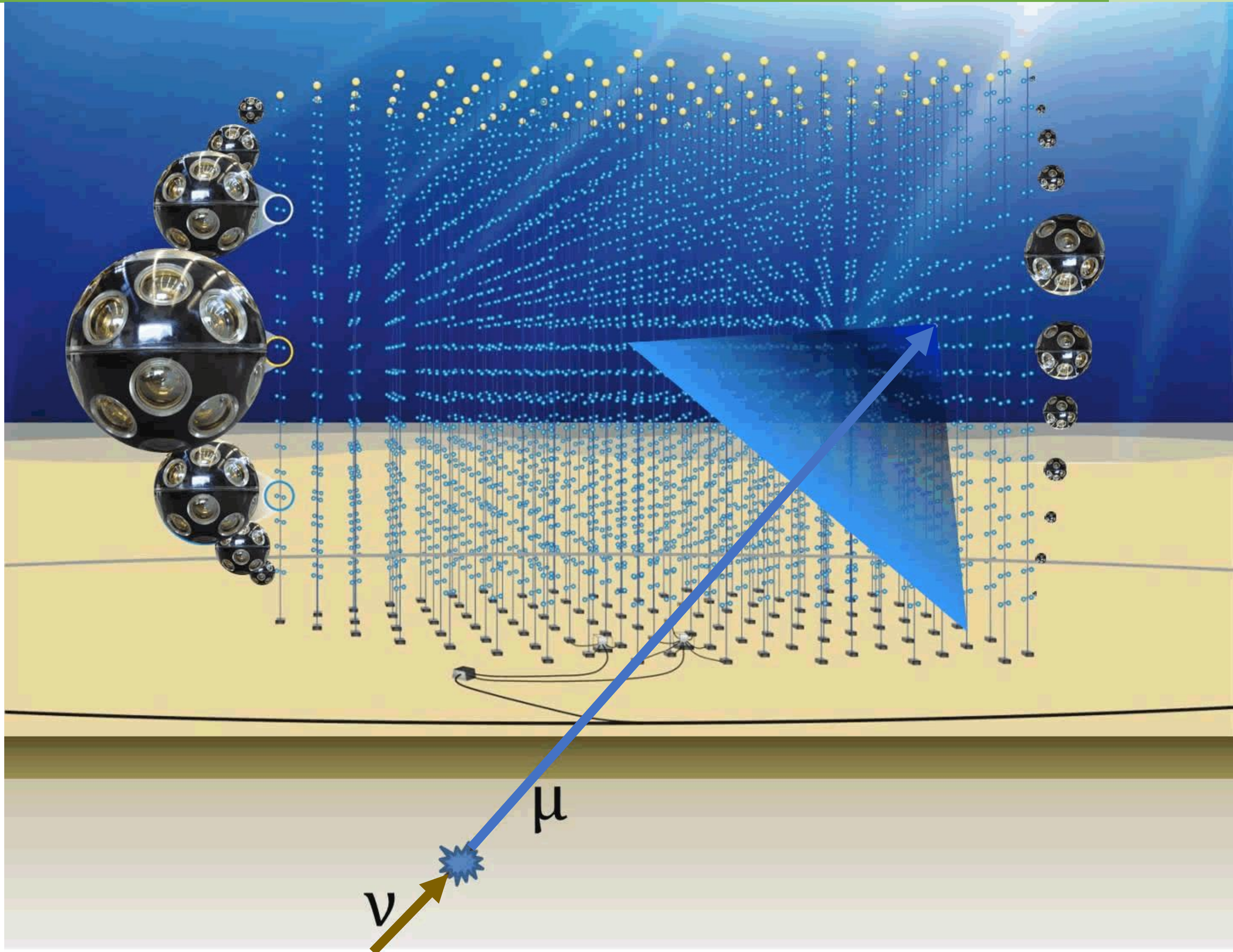
How it works in a nutshell:

1 ν_μ interacts → $\mu^\pm$ is produced (background: atm. μ!)

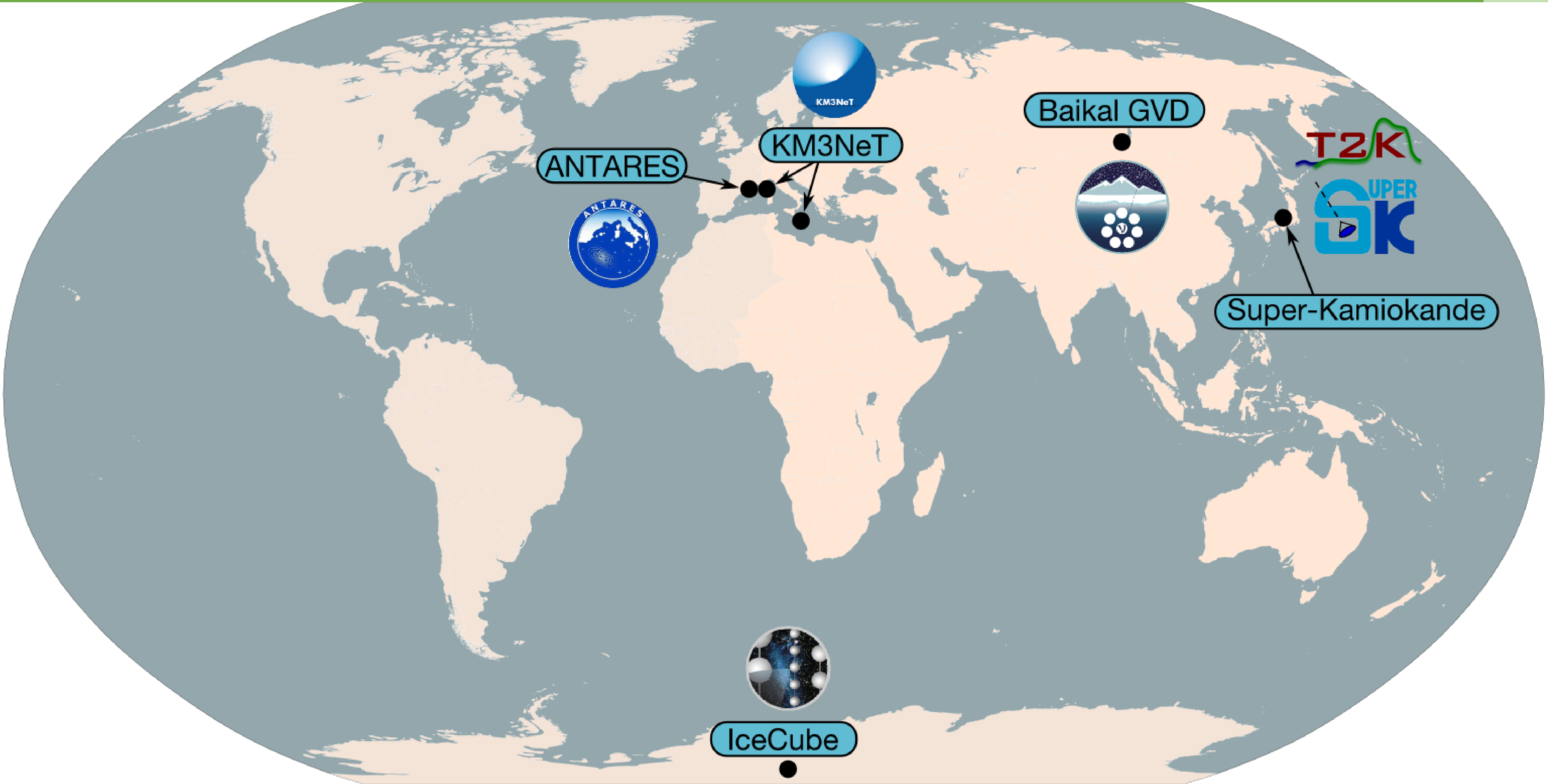
2 $\mu^\pm$ is charged → polarizes water molecules

3 water molecules return to ground state and re-emit light (Cherenkov radiation)

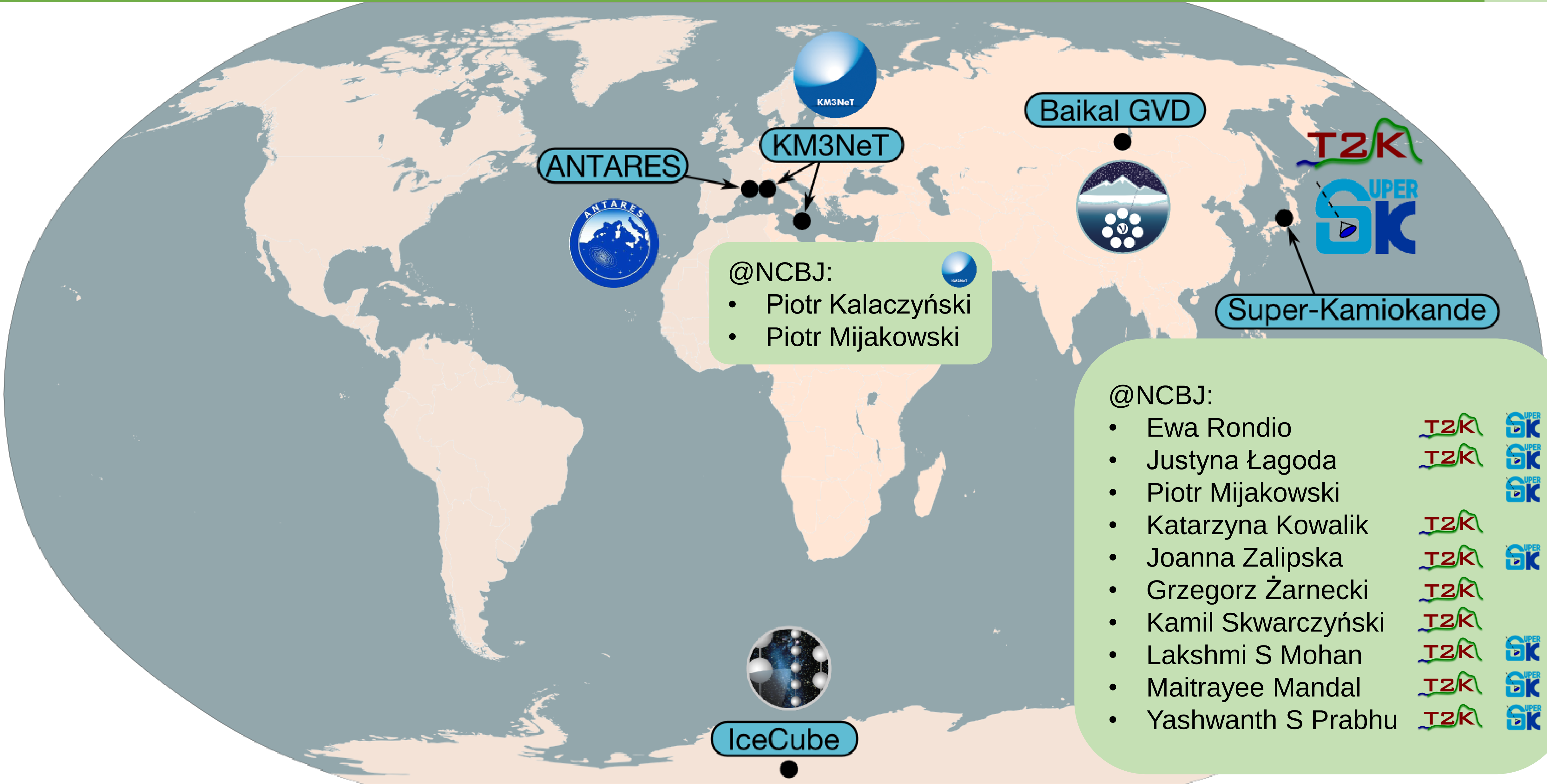
we detect it



Water Cherenkov ν telescopes



Water Cherenkov ν telescopes



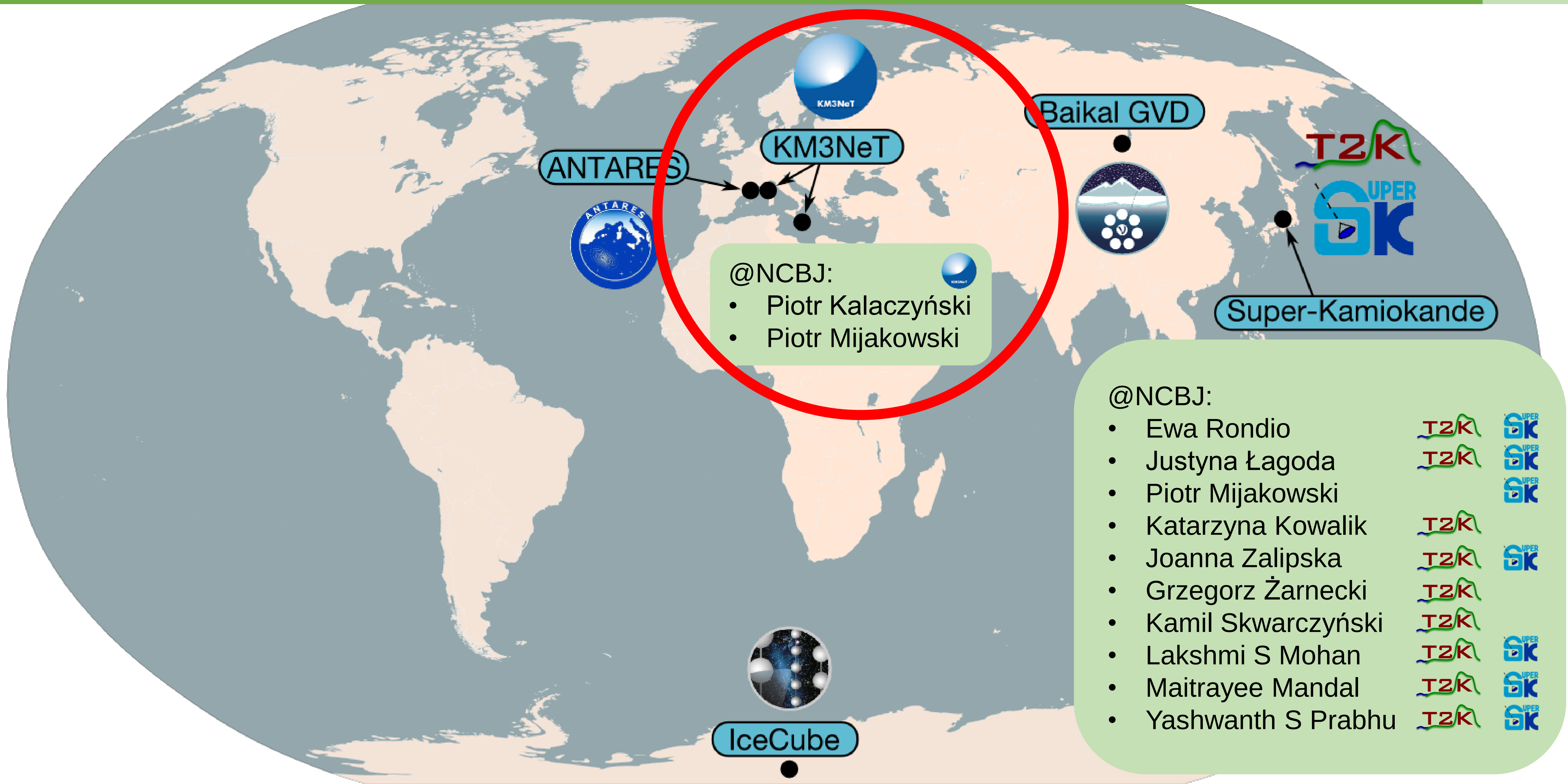
@NCBJ:

- Piotr Kalaczyński
- Piotr Mijakowski

@NCBJ:

- Ewa Rondio (T2K, SK)
- Justyna Łagoda (T2K, SK)
- Piotr Mijakowski (SK)
- Katarzyna Kowalik (T2K)
- Joanna Zalipska (T2K, SK)
- Grzegorz Żarnecki (T2K)
- Kamil Skwarczyński (T2K)
- Lakshmi S Mohan (T2K, SK)
- Maitrayee Mandal (T2K, SK)
- Yashwanth S Prabhu (T2K, SK)

Water Cherenkov ν telescopes



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KM3NeT

Introduction

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The KM3NeT Collaboration

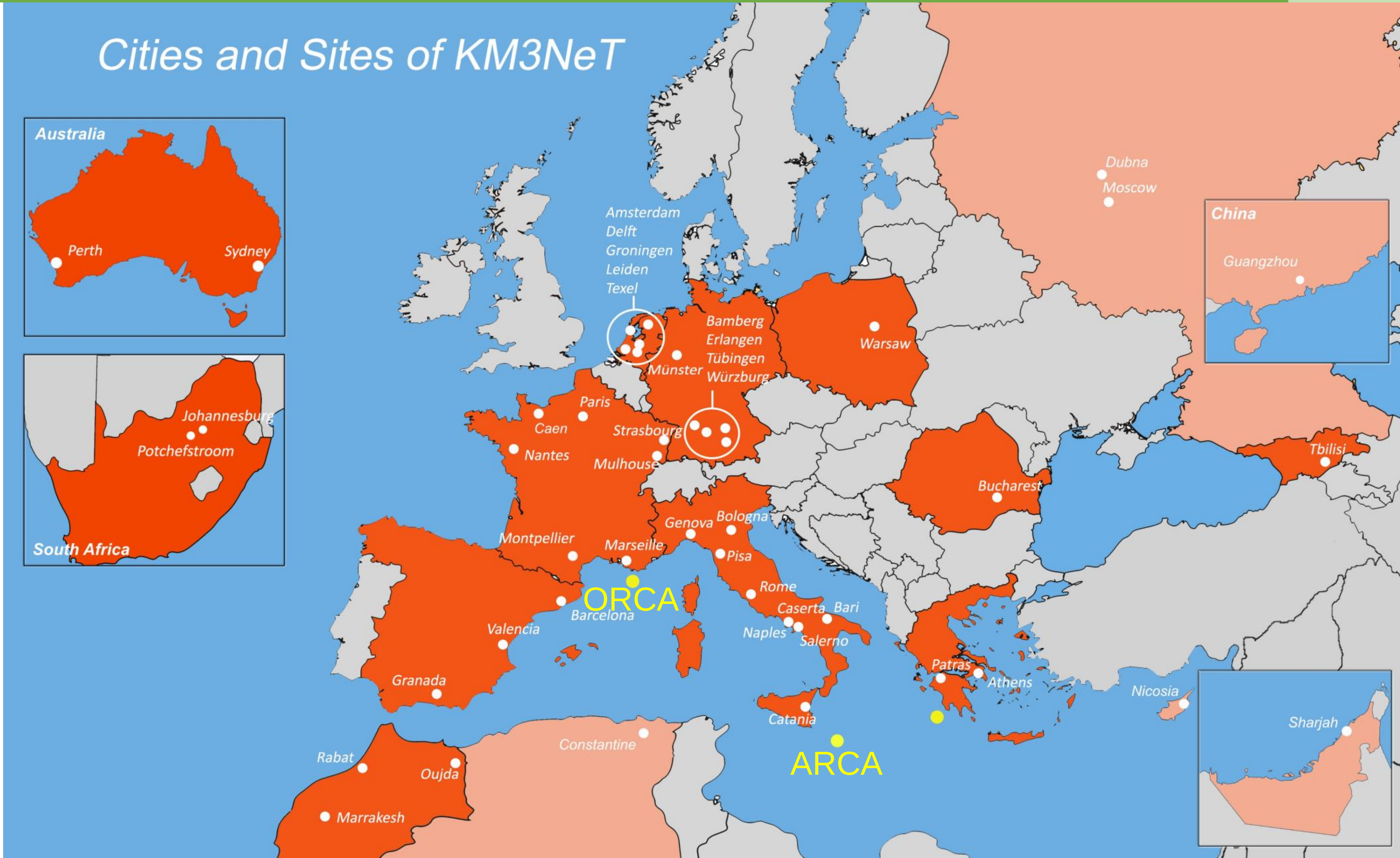
KM3NeT

Numbers:

- 57 groups
- 17 countries
- 4 continents

Legend:

- group
- observer
- member



Detectors

Introduction

KM3NeT
- Detectors
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Summary

Light sensors

Digital Optical Module (DOM)

acrylic glass sphere with:

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

Photomultiplier Tube (PMT):

converts light into electric signal

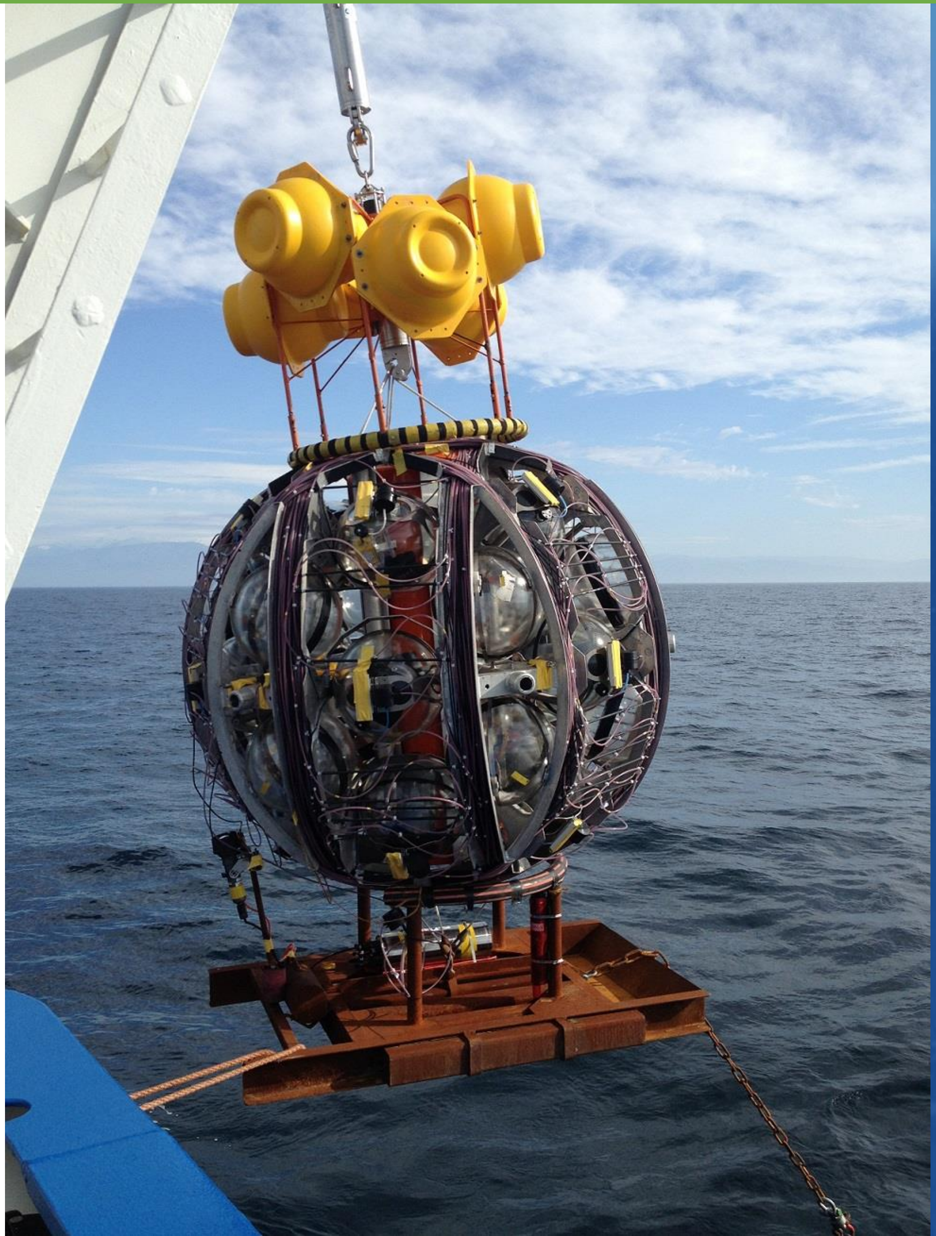
DOM arrangement

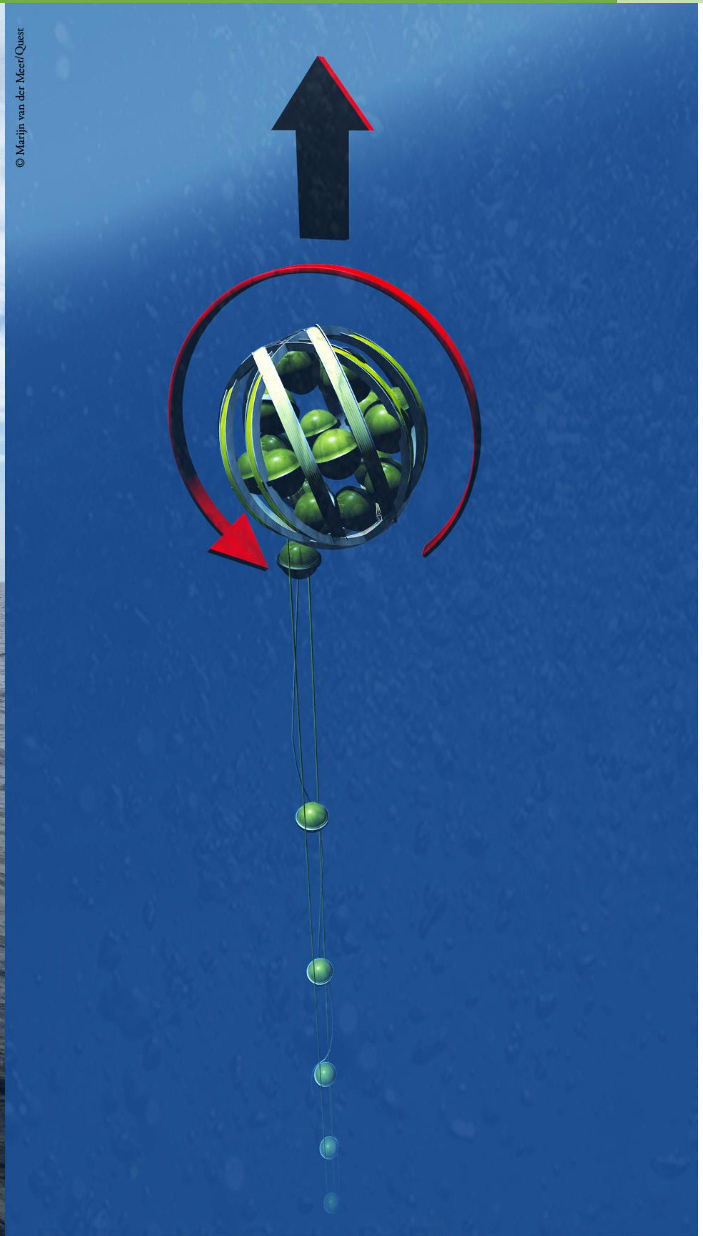
Detection Unit (DU):

vertical string with 18 DOMs

Naming:

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



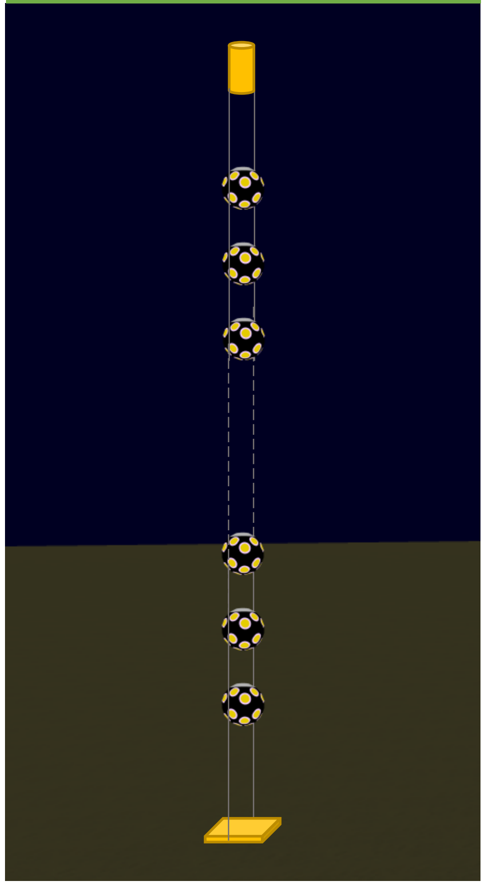


Detector design summary

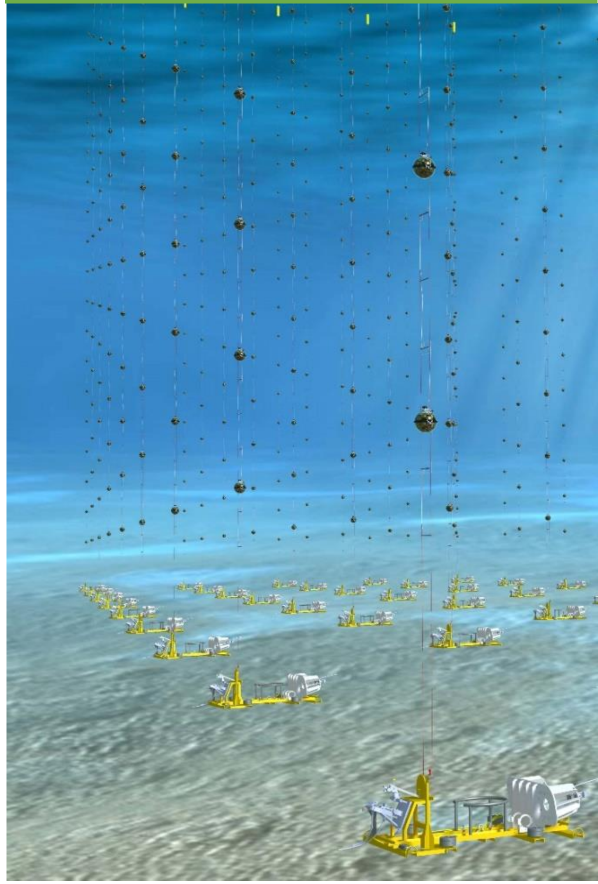
DOM:
71 unique components

1 DOM:
31 PMTs

1 string (DU):
18 DOMs



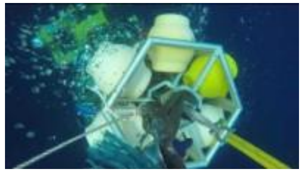
1 building block:
115 DUs



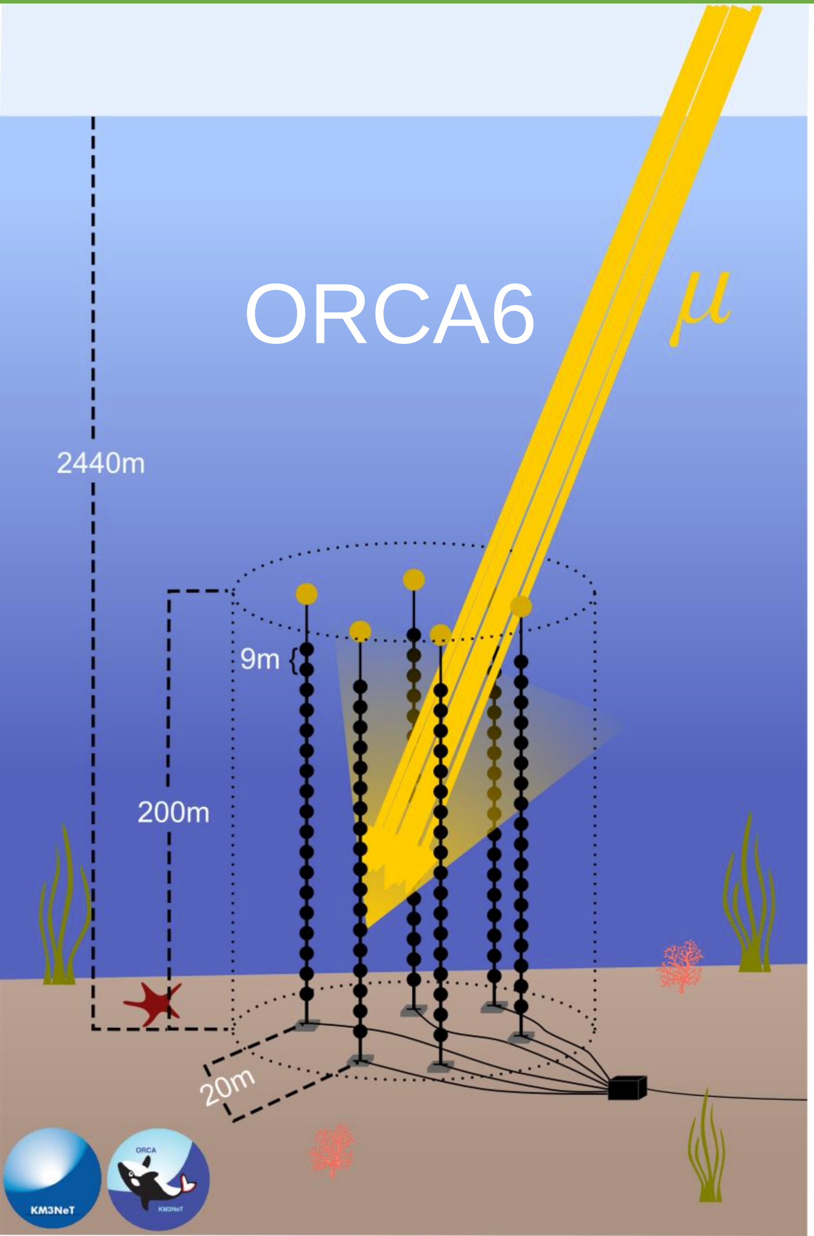
DOM production:
(@Nikhef)

Preparation for
deployment:

ORCA string
deployment:

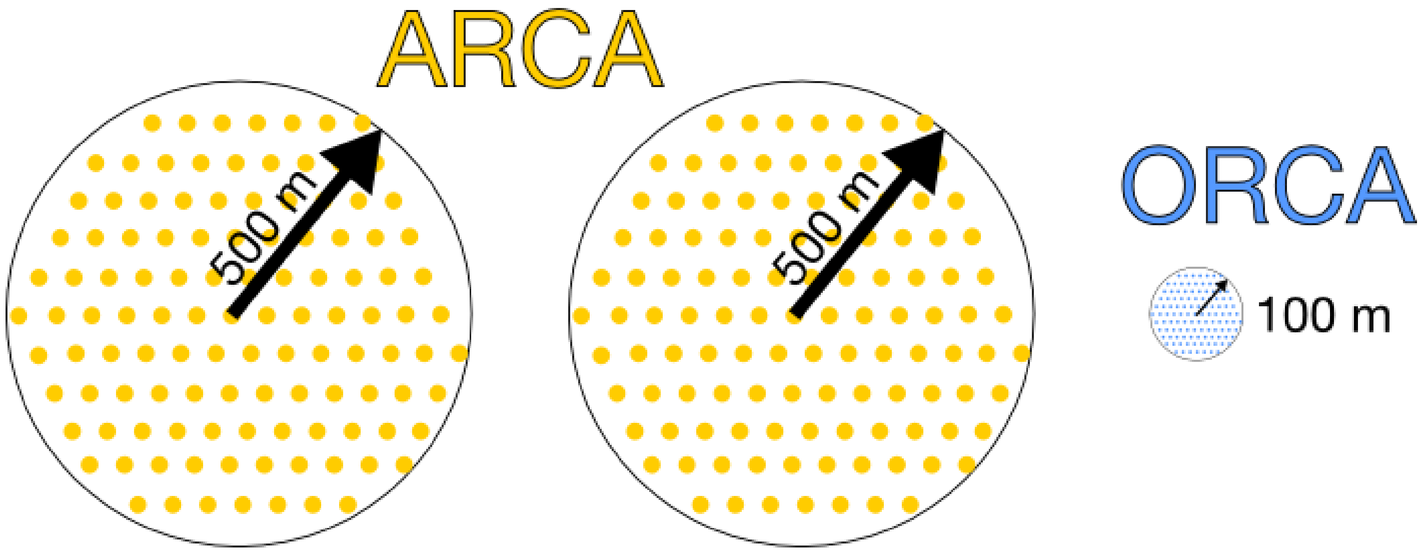


Detectors: details

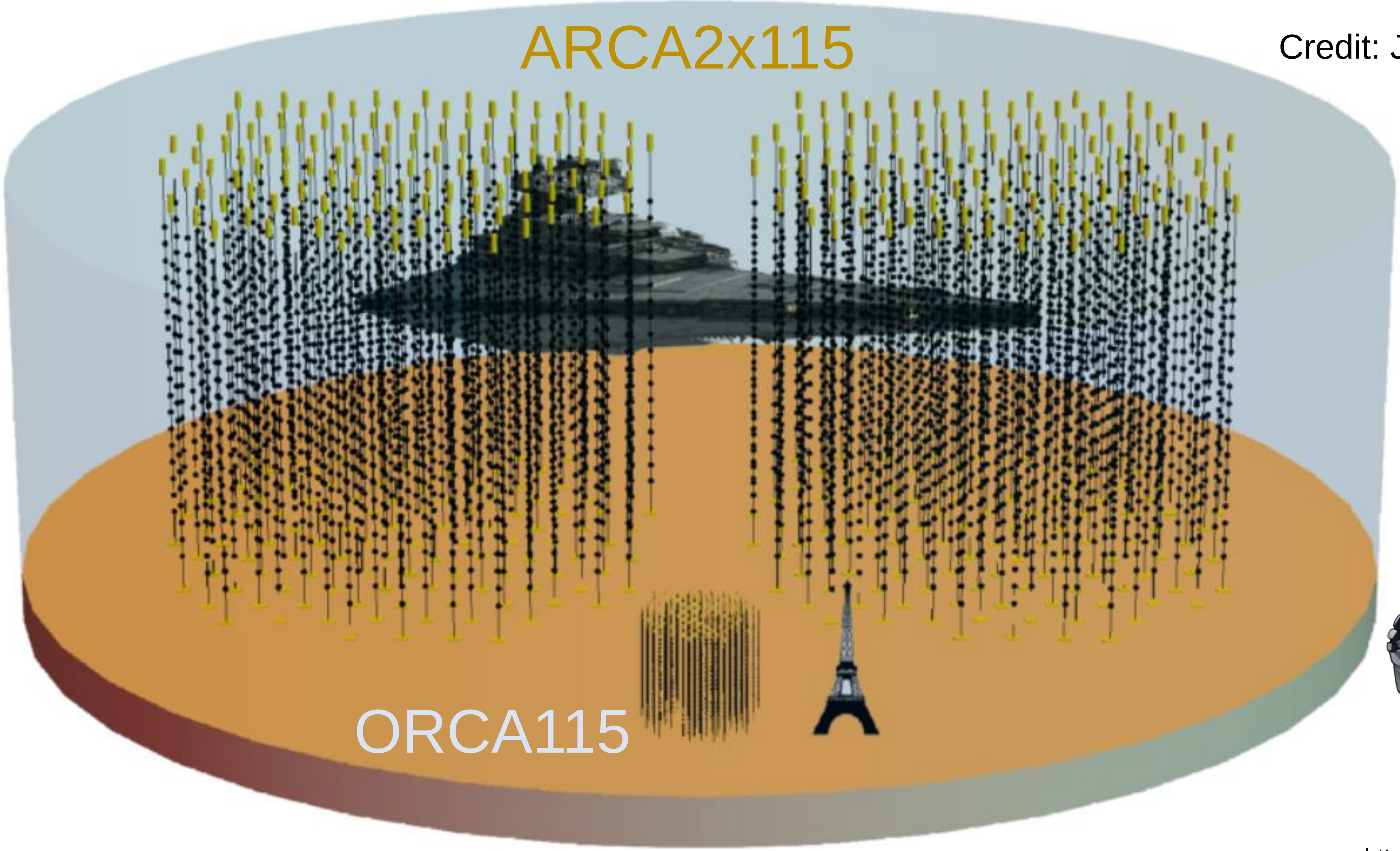


Detector	ARCA	ORCA
Depth	3.5 km	2.5 km
Volume	$1\ km^3$ (1Gton)	$0.007\ km^3$ (7Mton)
# strings	8 / 2x115	10 / 115
Topic	Astroparticle RCA*	Oscillation RCA*
Goal	ν_{astro}	m_ν hierarchy

*RCA : Research with Cosmics in the Abyss



Detector size comparison



Credit: Joao Coelho

YES, the imperial
star destroyer
IS up to scale!

https://www.pngegg.com/en/png-sujmc

Status

Introduction
- Cherenkov radiation
- Neutrinos

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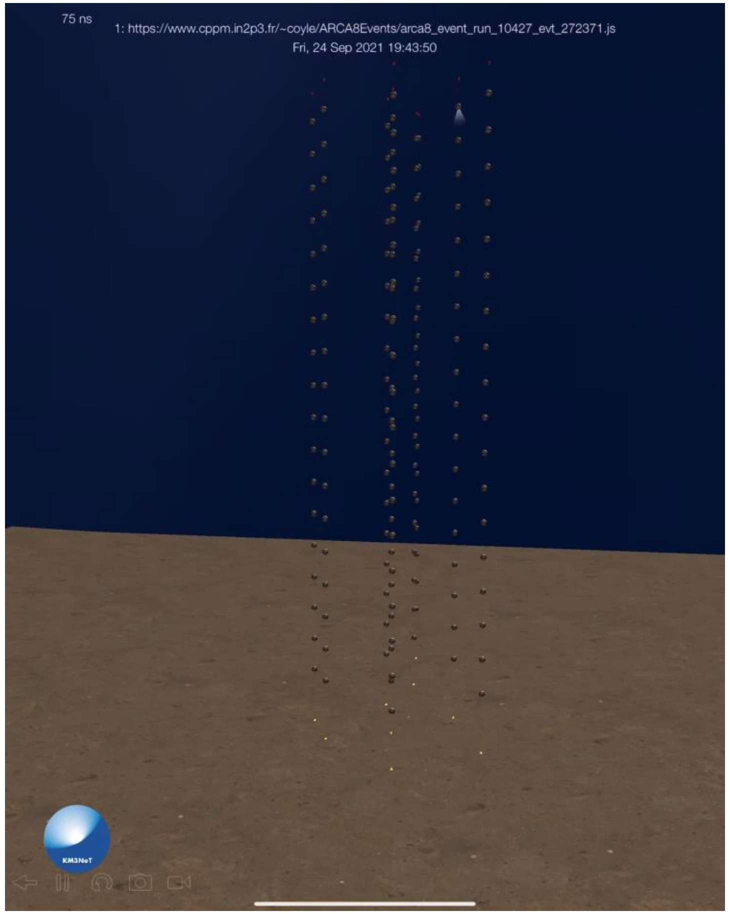
Current status and history

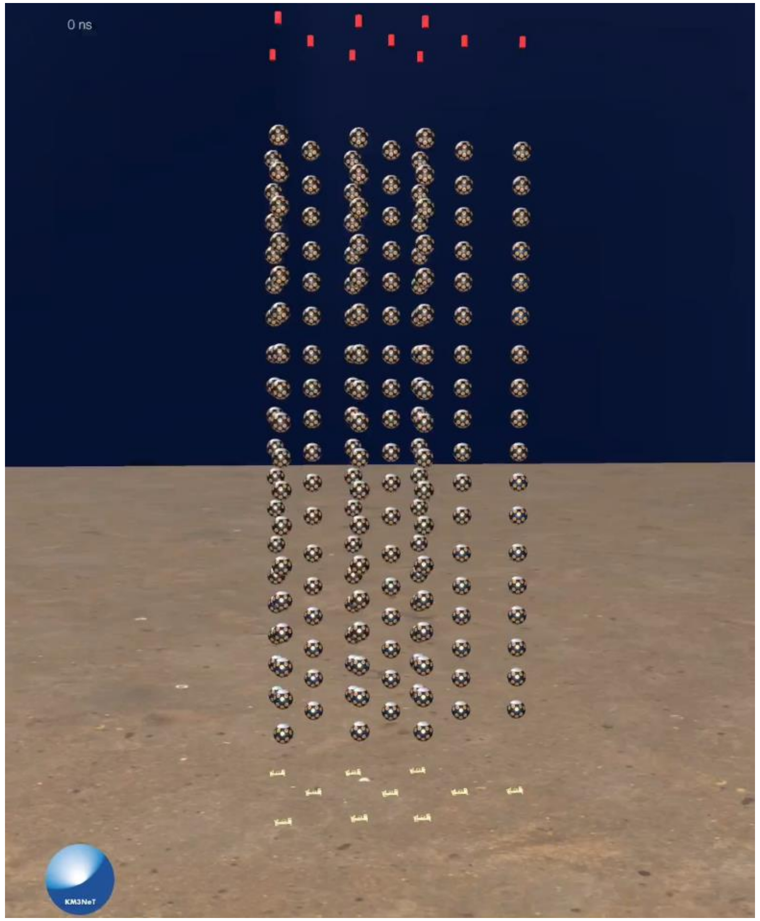
ARCA8

- First strings: 2015
- Sep 2021: +2 $\Longrightarrow$ **8 strings**
- **Next deployment: spring 2022**
- **Complete: summer 2030**



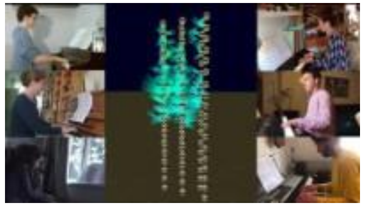
ORCA10

- First string: 2017
- Nov 2021: +4 $\Longrightarrow$ **10 strings**
- **Next deployment: winter 2022**
- **Complete: spring 2028**



Check out our celebration videos:

Route 66



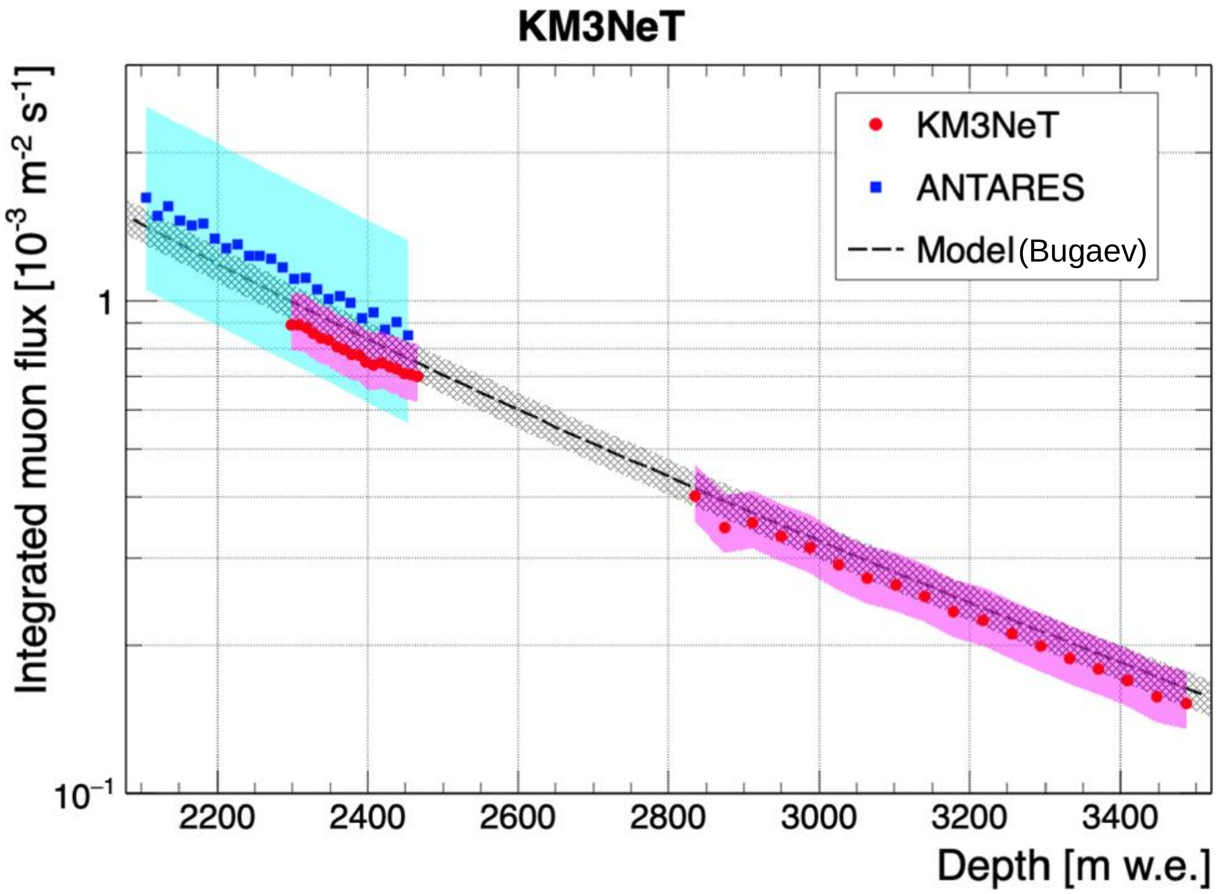
6 strings
6 months

ARCA66

Measurements

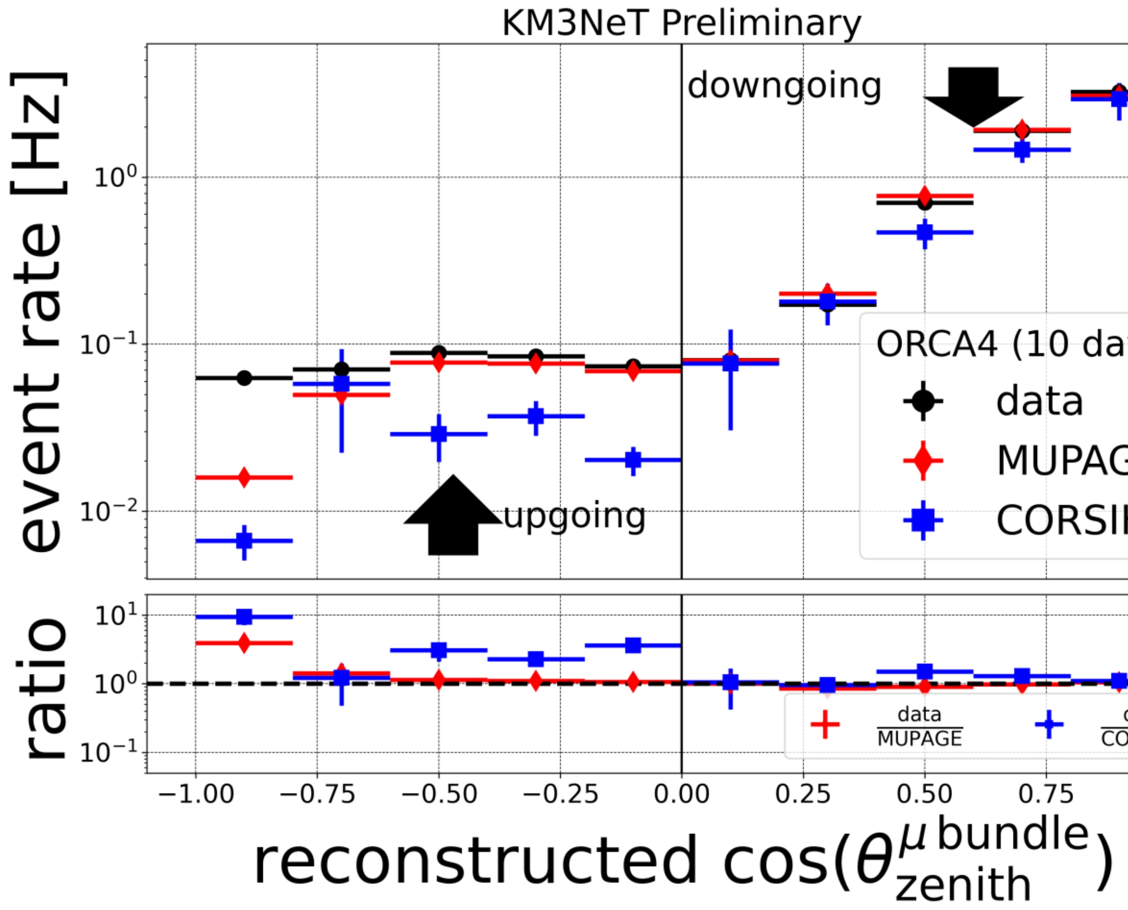
Atmospheric muon flux

ORCA1 & ARCA2



Muon flux vs depth
Eur. Phys. J. C 80, 99 (2020)

ORCA4



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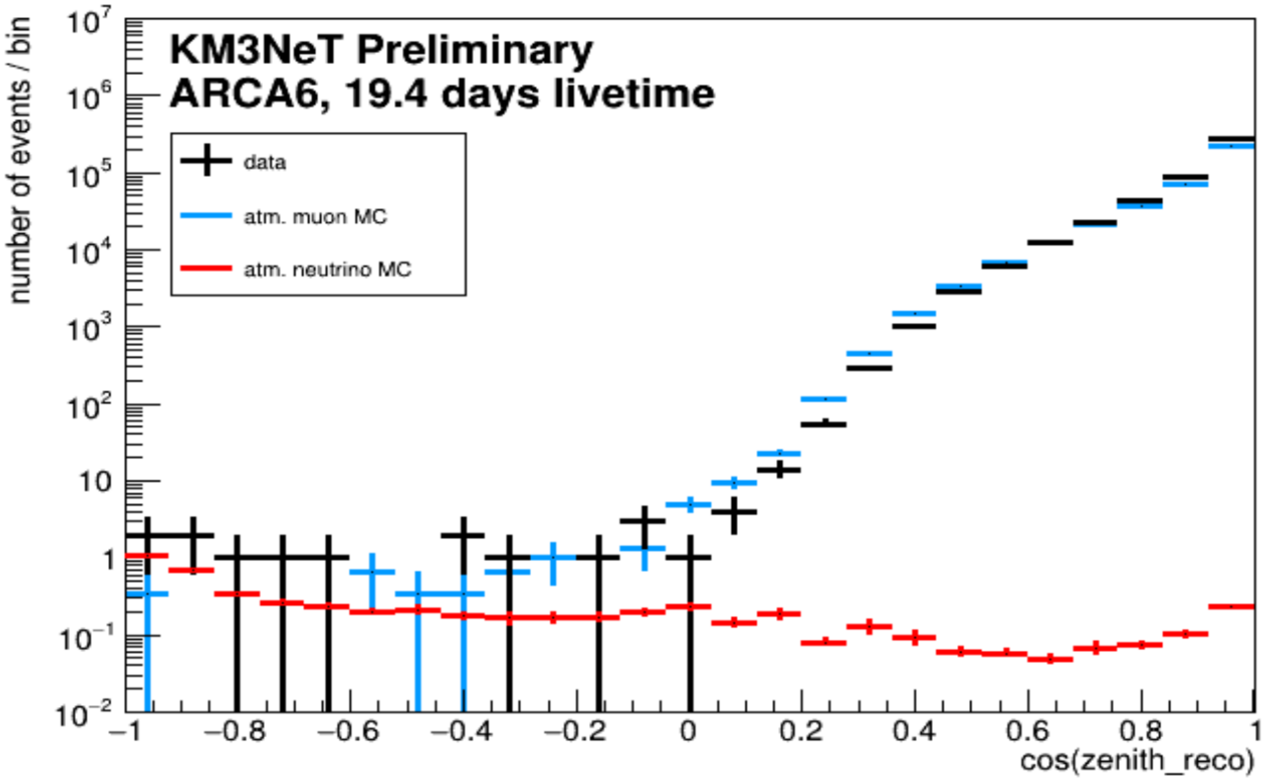
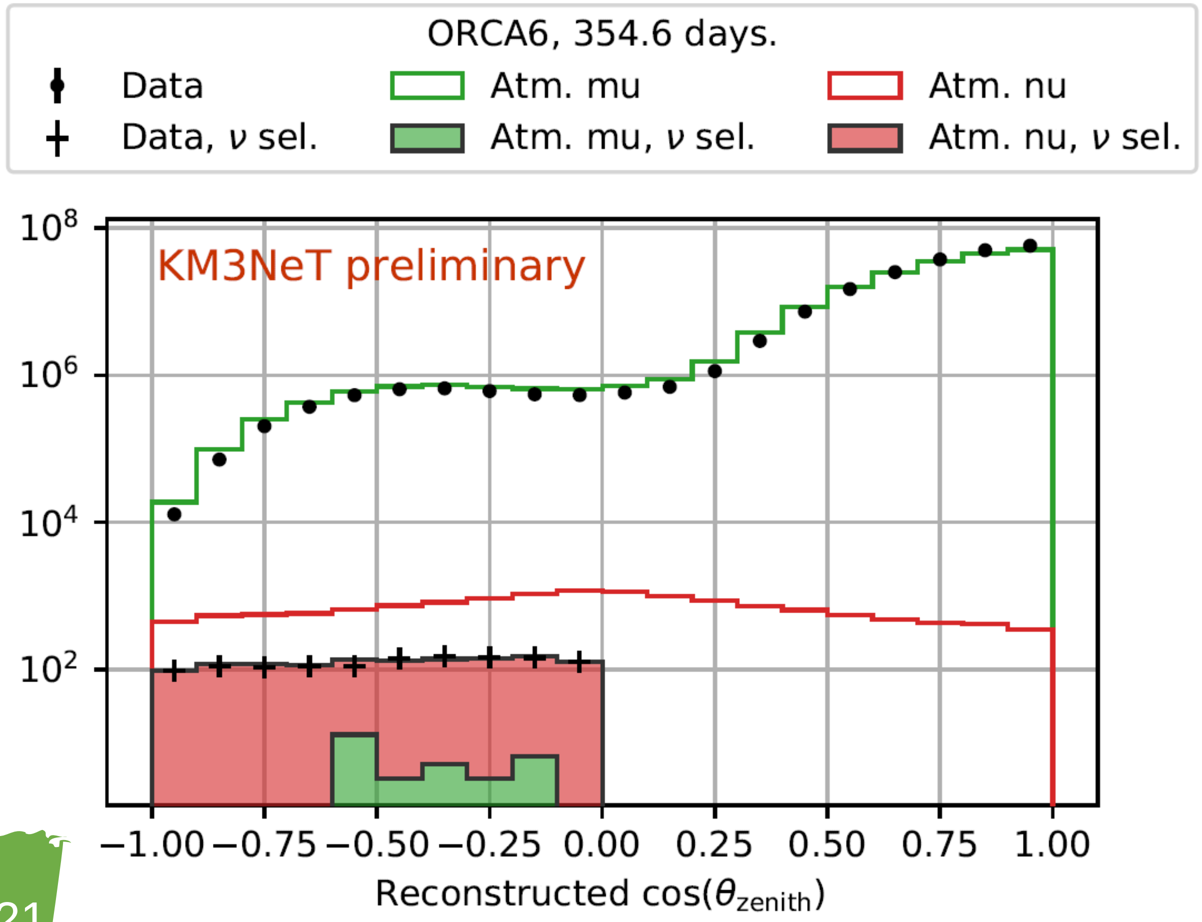
Muon rate vs zenith
PoS(ICRC2021)1112

Atmospheric neutrino flux

ARCA6



ORCA6

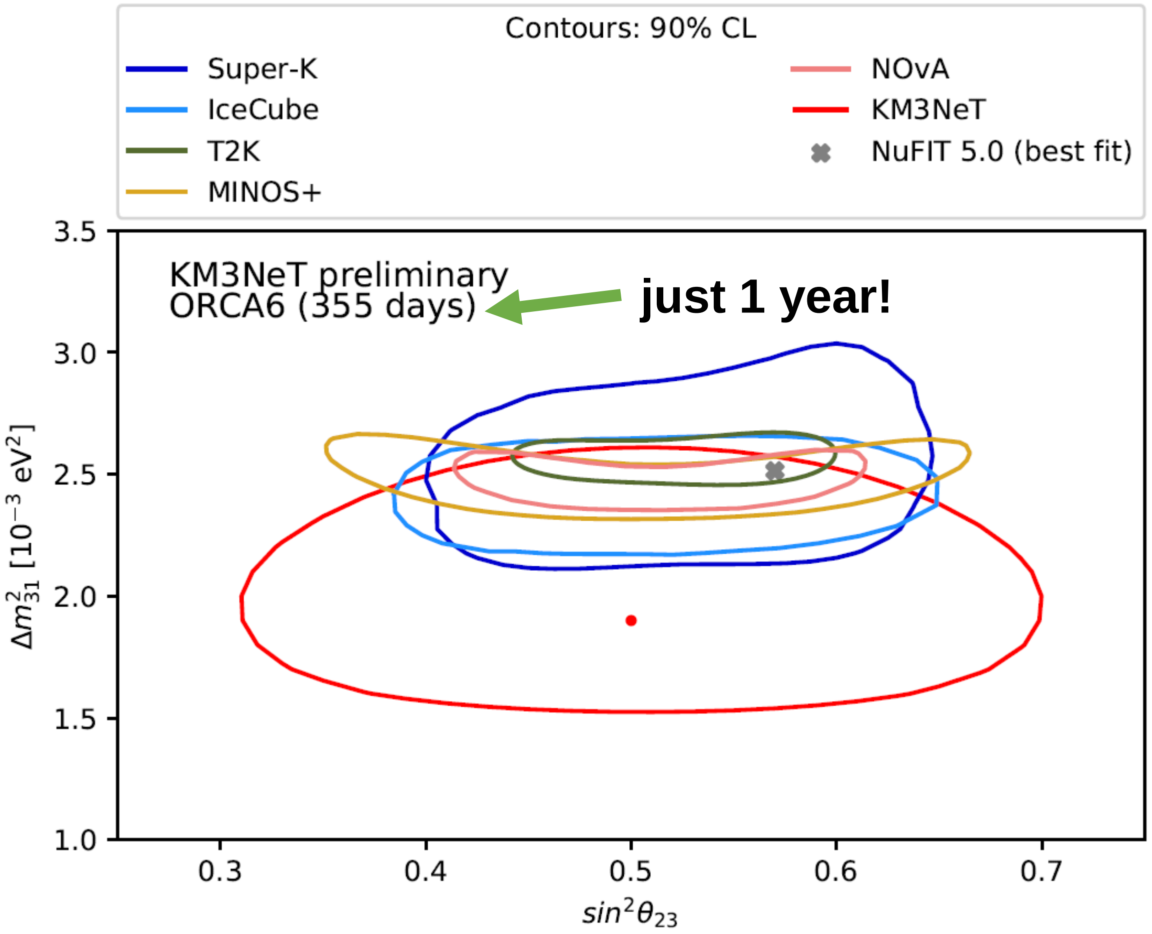


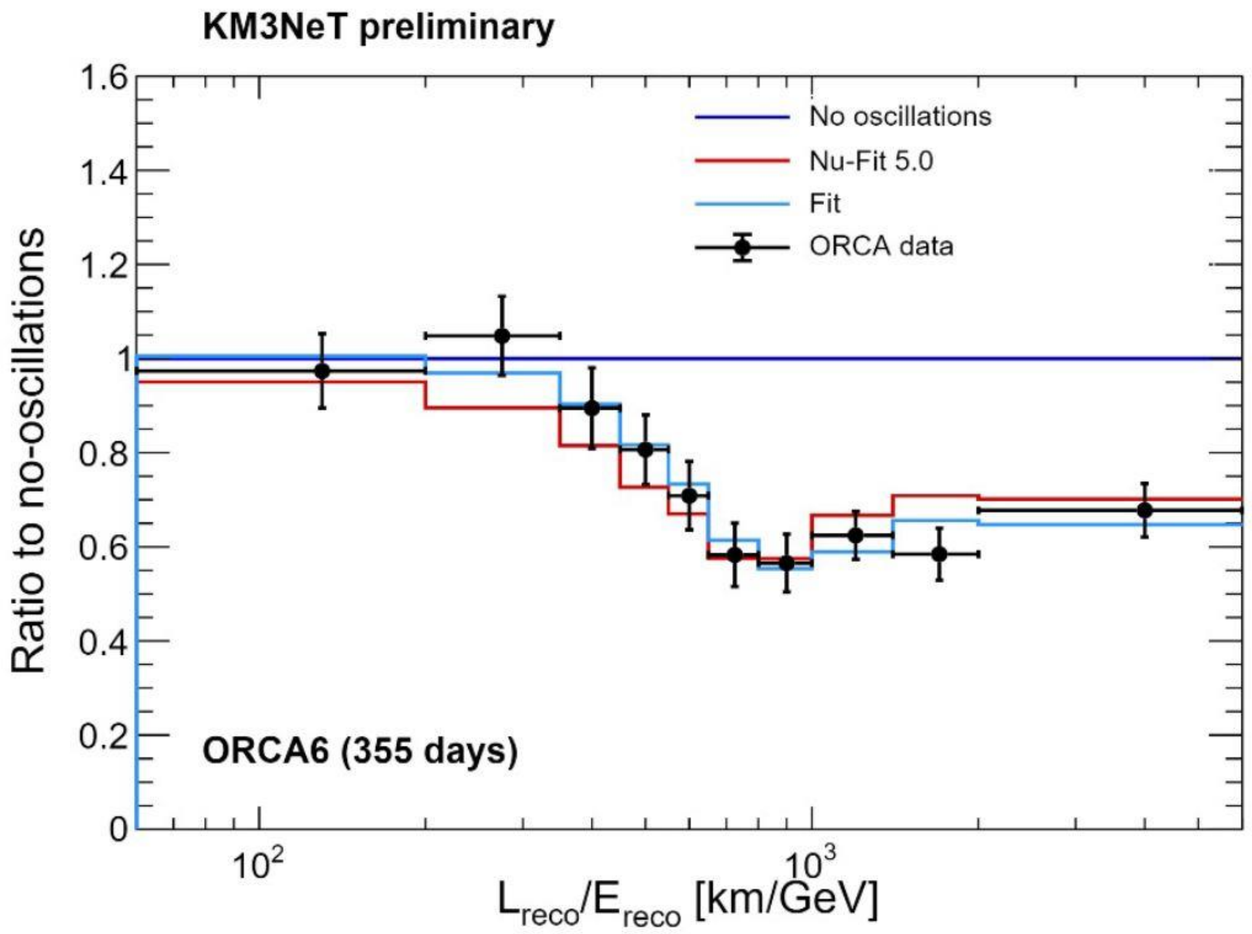
Atmospheric neutrino selections from ICRC2021

PoS(ICRC2021)1134 and PoS(ICRC2021)1123

Neutrino oscillations

ORCA6





Neutrino oscillation measurement from ICRC2021

PoS(ICRC2021)1123

Sensitivities

Introduction
- Cherenkov radiation
- Neutrinos

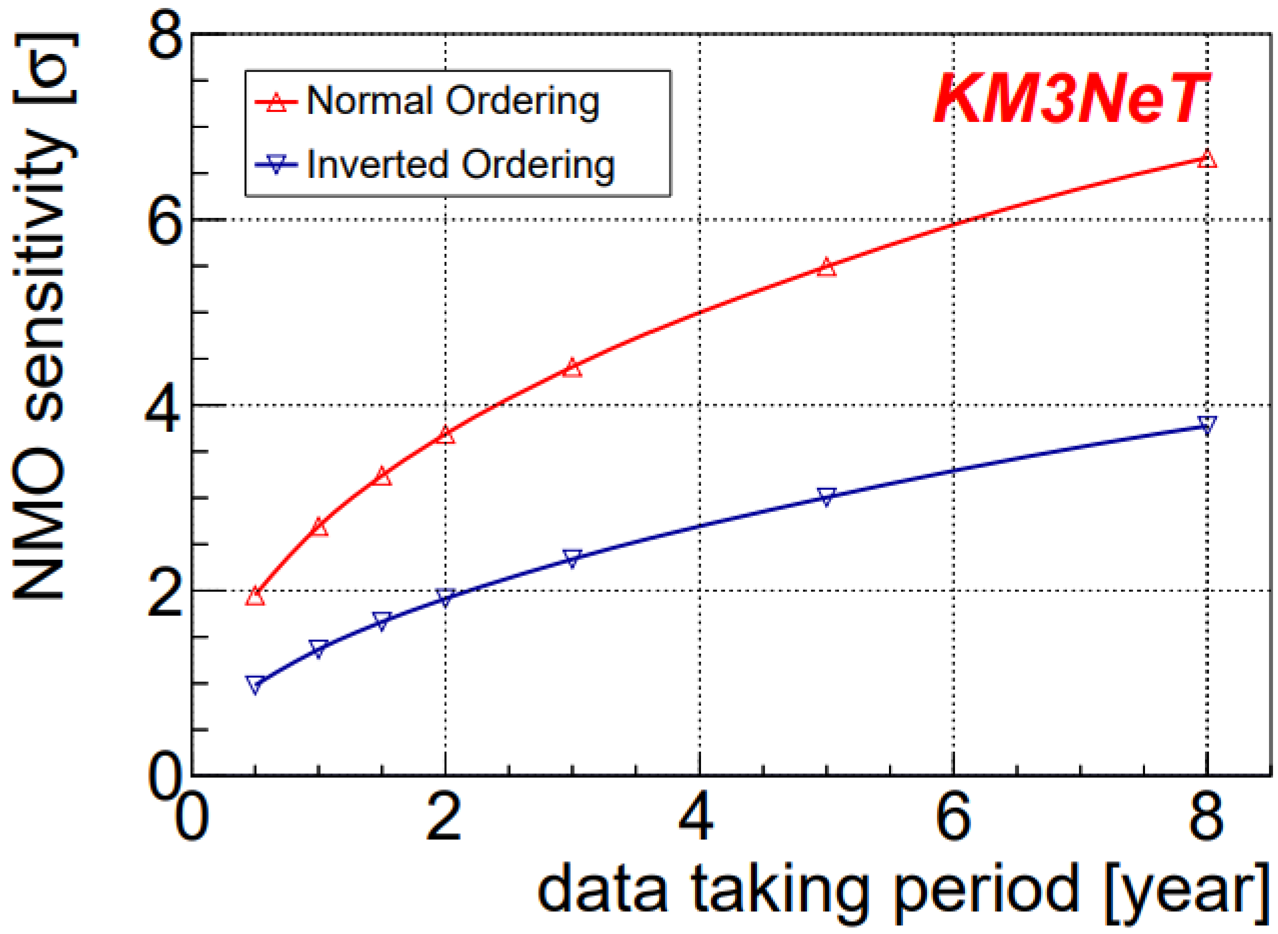
KM3NeT
- Detectors
- Status

Results
- Measurements
- Sensitivities

Summary

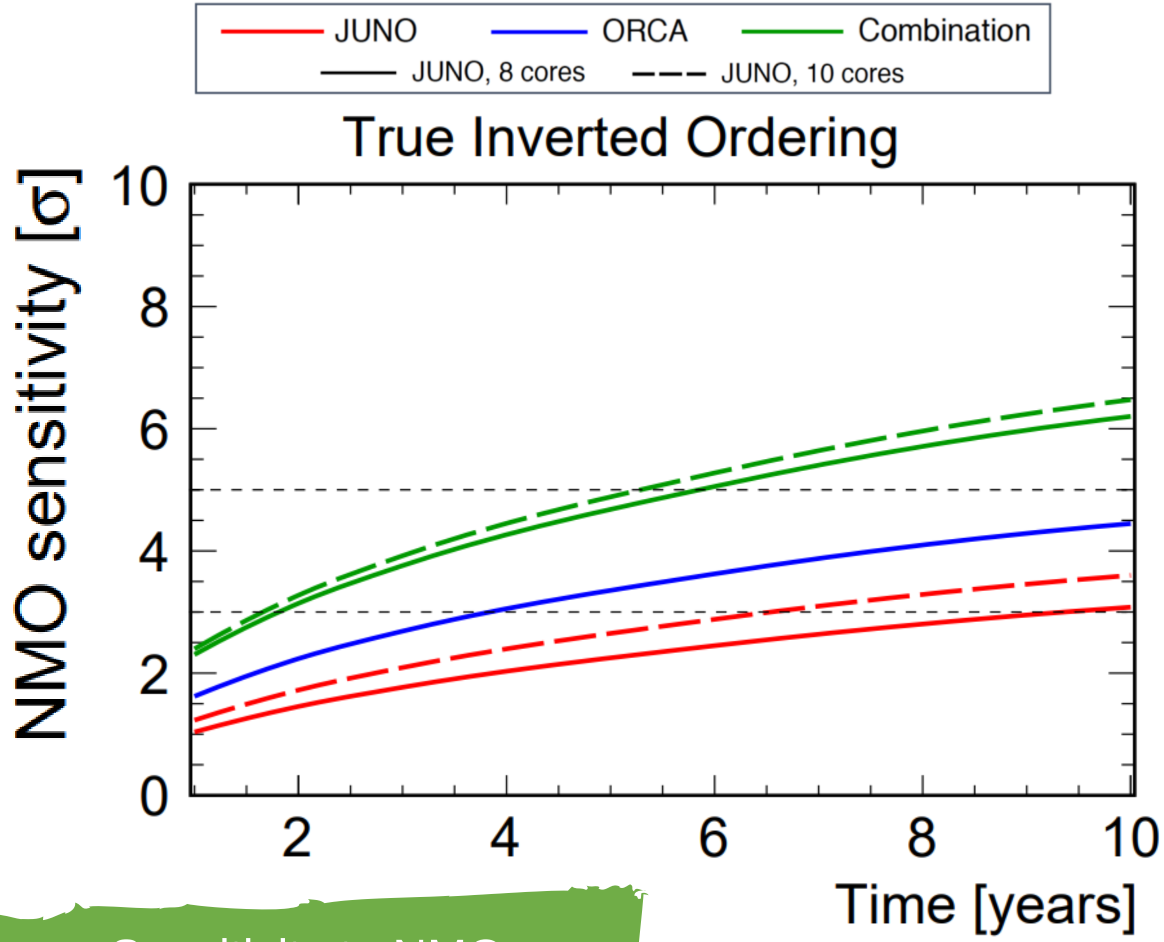
Neutrino Mass Ordering (NMO)

ORCA115



Possibly world-first to determine NMO!

ORCA115 + JUNO

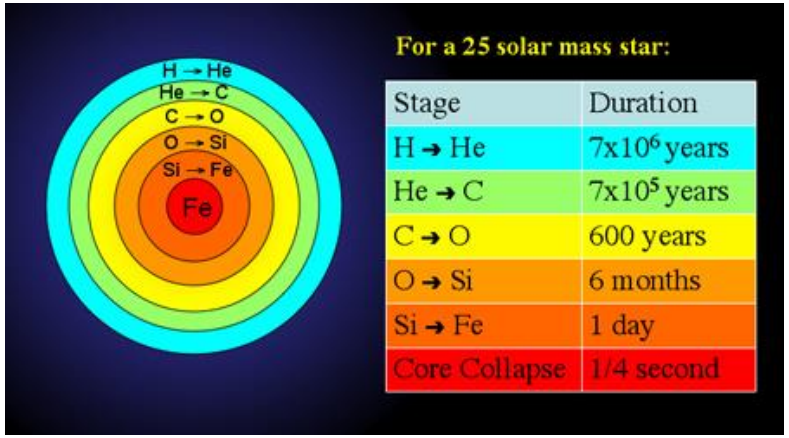


Sensitivity to NMO
arXiv:2103.09885 and JINST 16 C11007 (2021)
(accepted for EPJ-C)

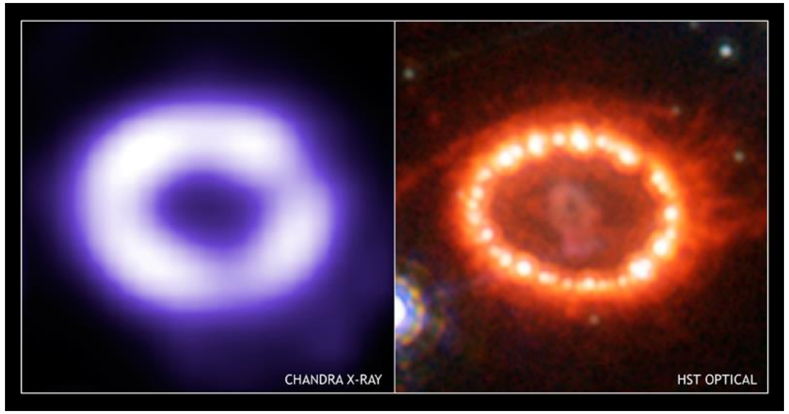
Astrophysics (supernovae)

Explosion mechanism not fully understood but we know:

- 99% of $E_{\text{grav}} \to \nu$ when γ cannot escape
- CCSN* produce MeV ν's



Stage	Duration
H → He	7x10^6 years
He → C	7x10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second



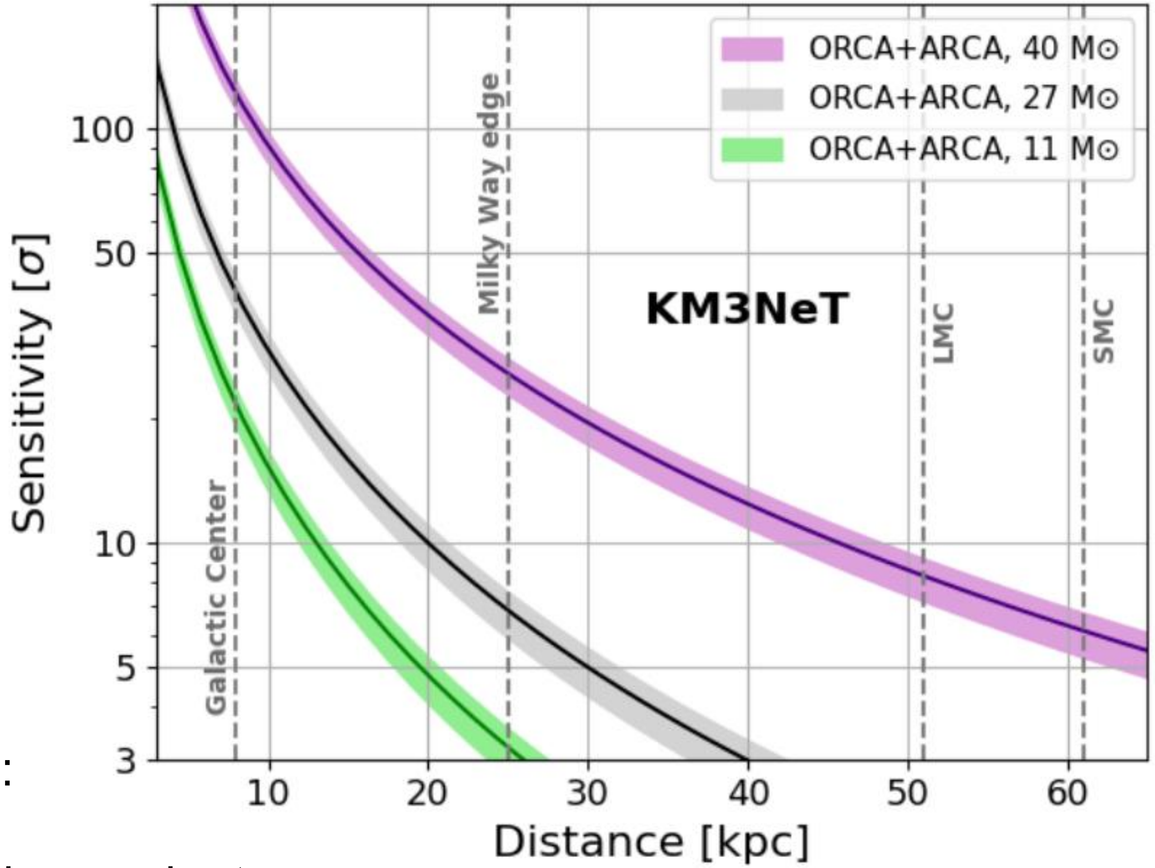
First and only observation: 24ν from SN1987A

KM3NeT threshold: few GeV

2 ways to detect SNe:

- measure the ν's
- look at the PMT background rate

ARCA115 + ORCA115



Sensitivity to CCSN*
JINST 16 C09034 (2021)

*core-collapse supernova

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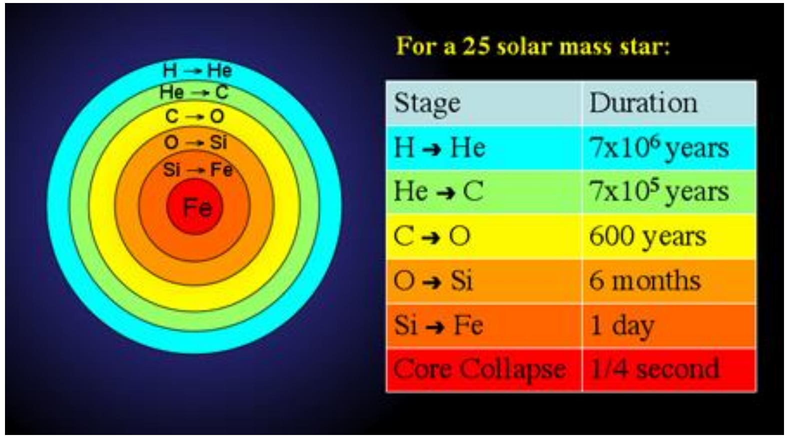

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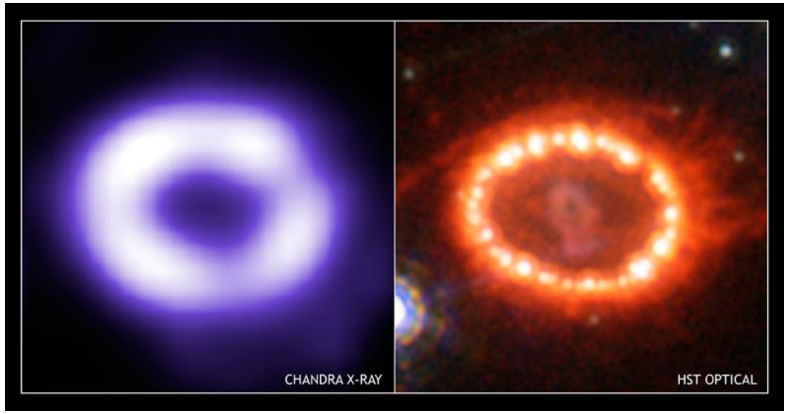

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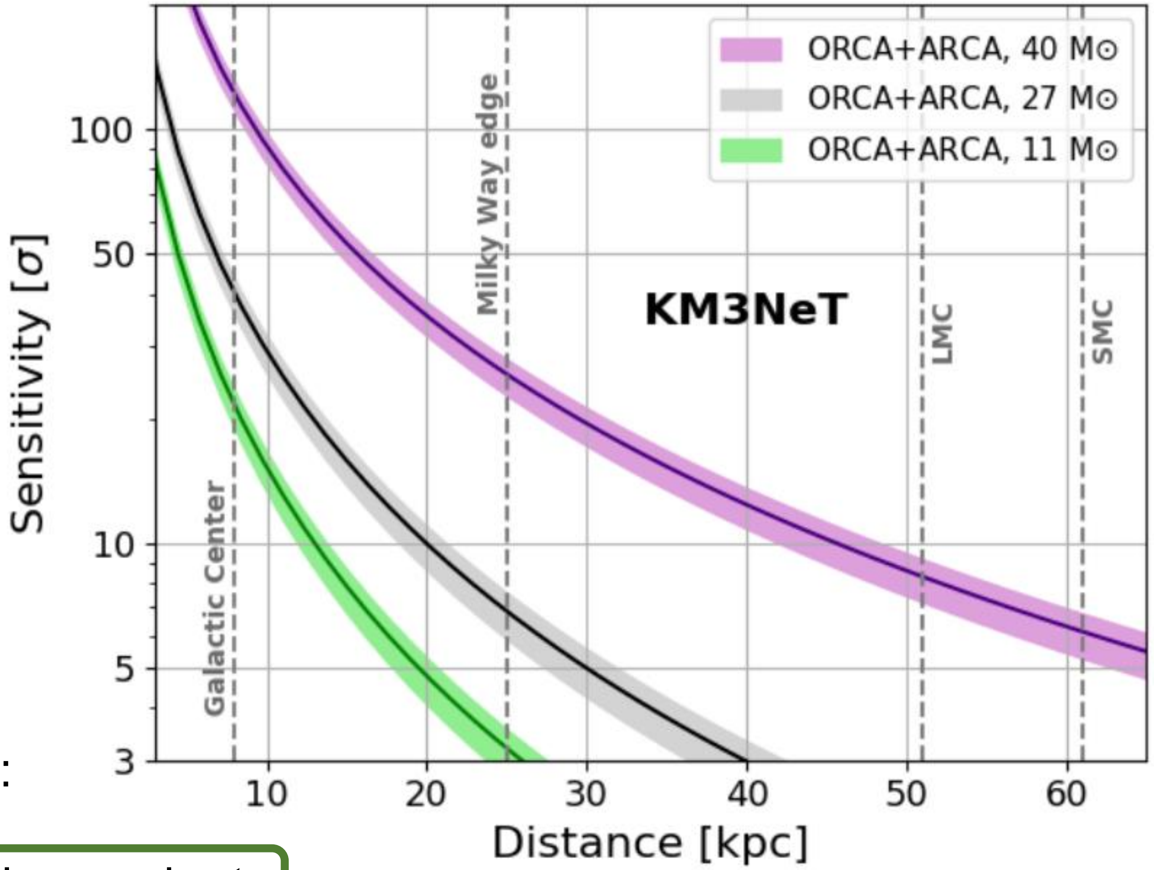
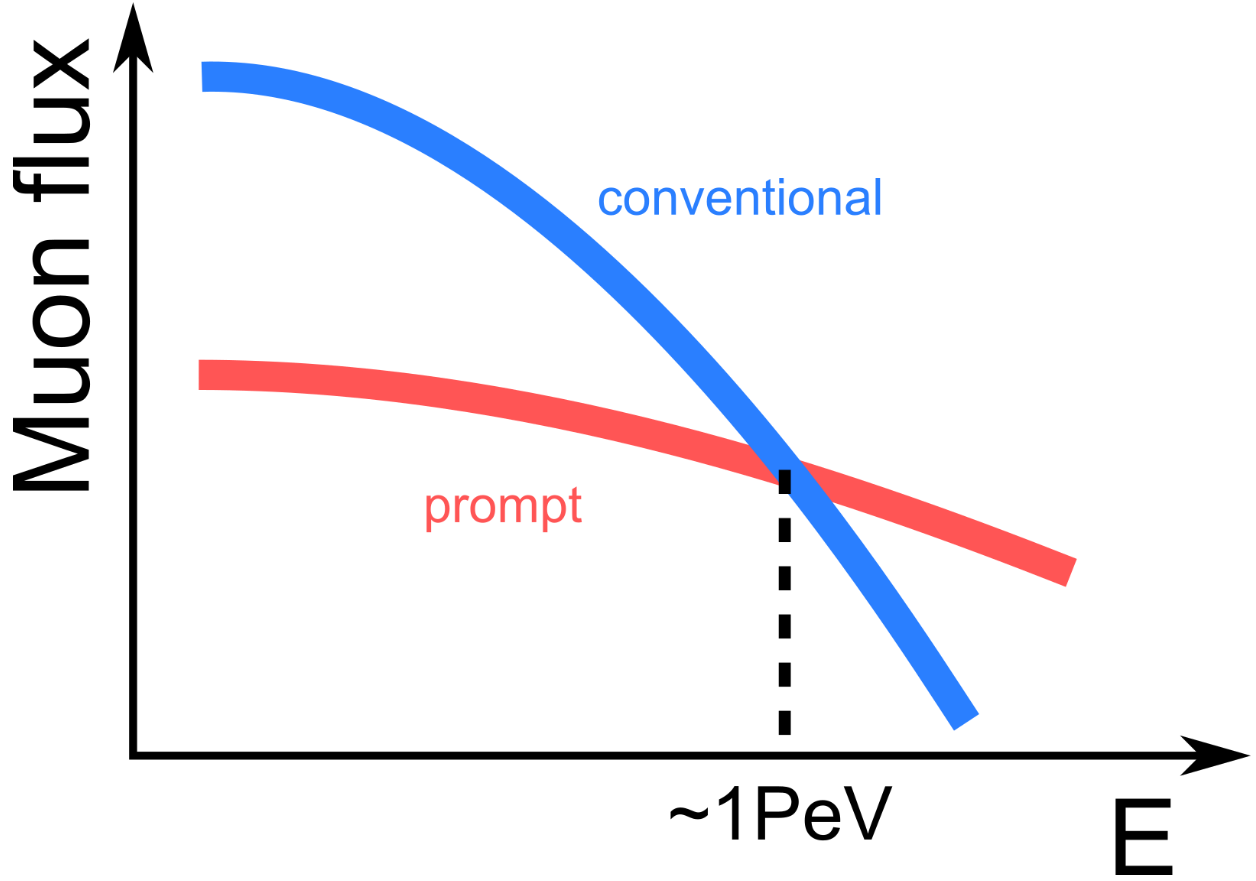


Sensitivity to CCSN*

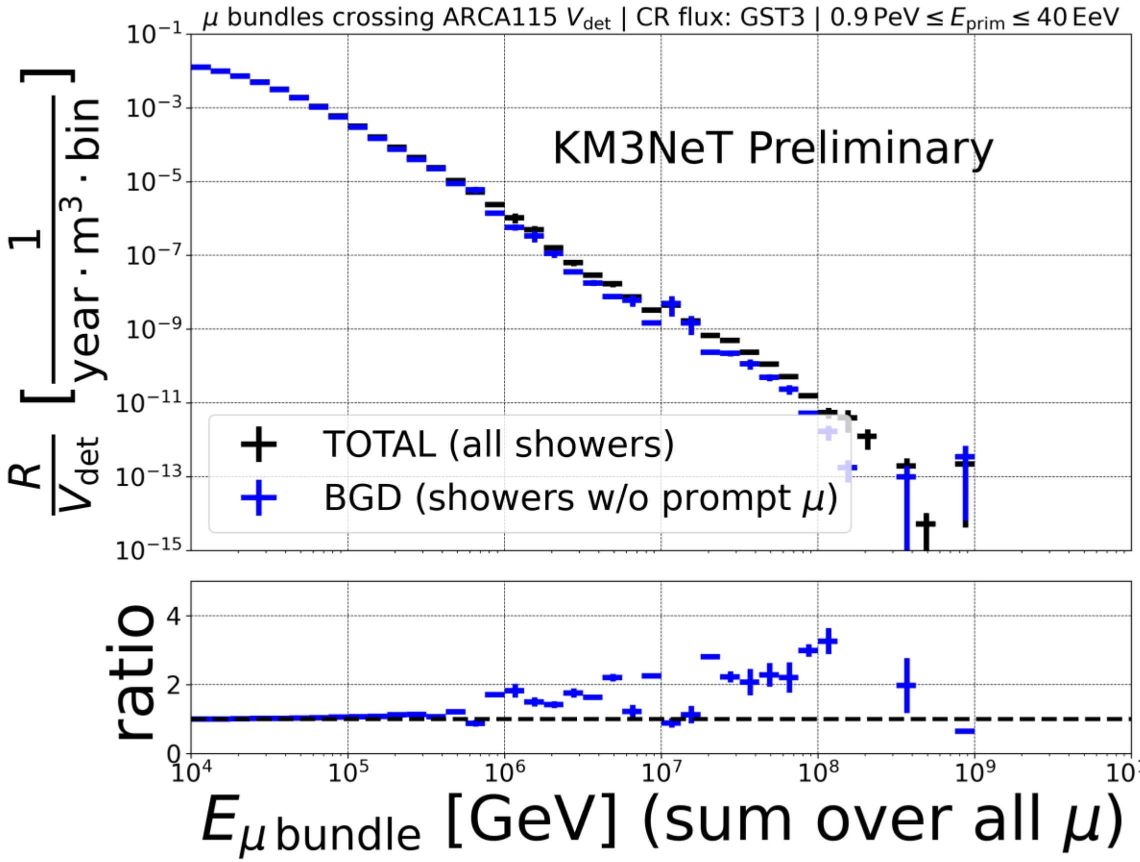
JINST 16 C09034 (2021)

*core-collapse supernova

Prompt muons



ARCA115



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Prompt muon analysis
JINST 16 C09035 (2021)

Summary

Introduction
- Cherenkov radiation
- Neutrinos

KM3NeT
- Detectors
- Status

Atmospheric μ
- First data
- Prompt μ analysis
- Multiplicity reco

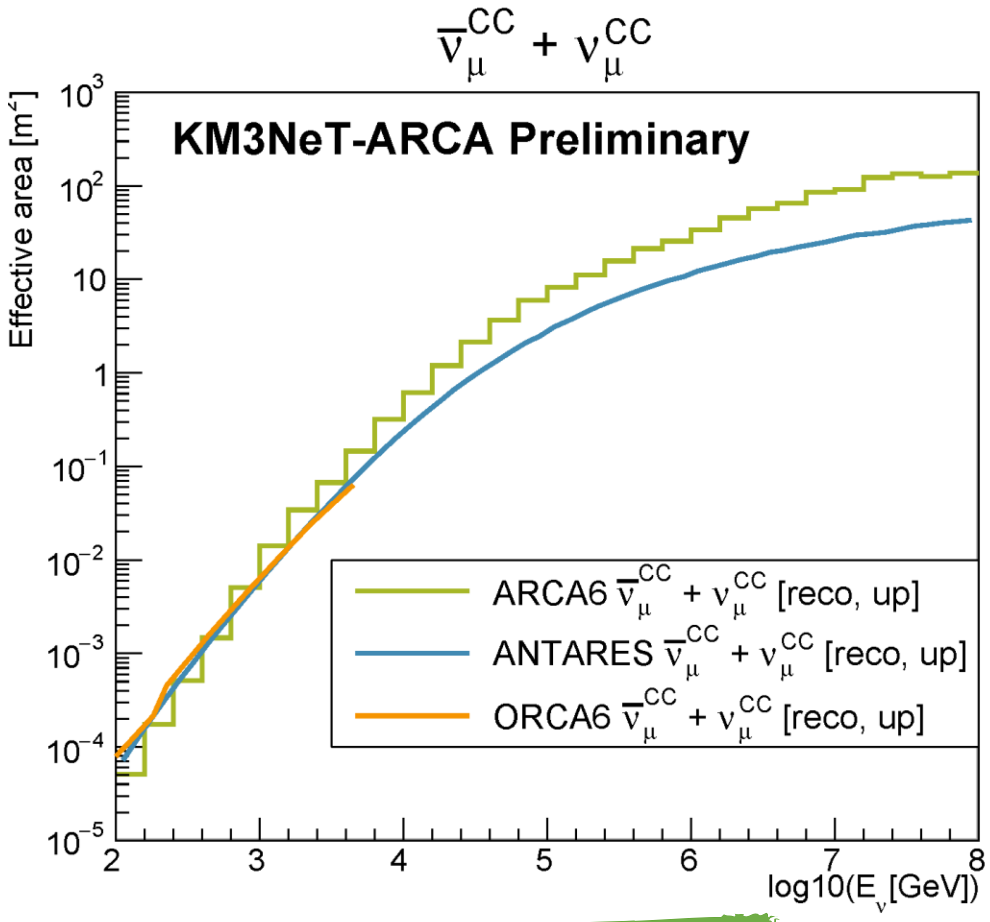
Summary

The end

To sum up:

- ARCA & ORCA under construction
- Already outgrown ANTARES
- Succesful measurements of μ, ν fluxes, ν oscillations
- Very good sensitivity to ν_{astro} & osci
- Many analyses ongoing

ARCA6 + ORCA6



ν effective areas

JINST 16 C09034 (2021)

The end. Thank you for listening!

To sum up:

- ARCA & ORCA under construction
- Already outgrown ANTARES
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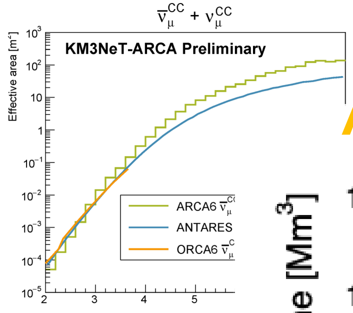
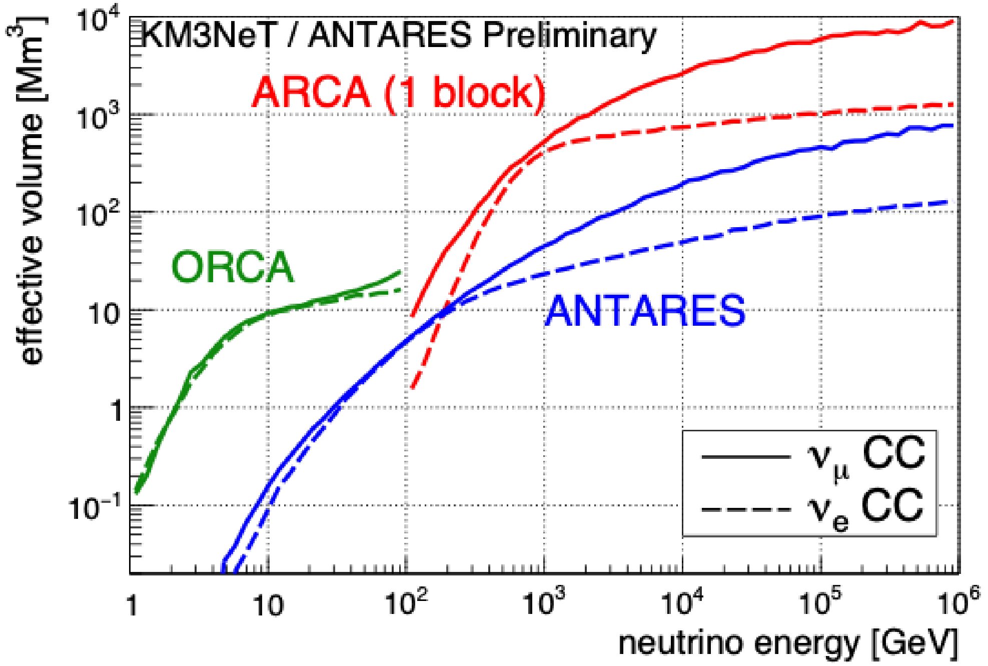


ARCA115 + ORCA115



ν effective areas
JINST 16 C09034 (2021)

Outlook:

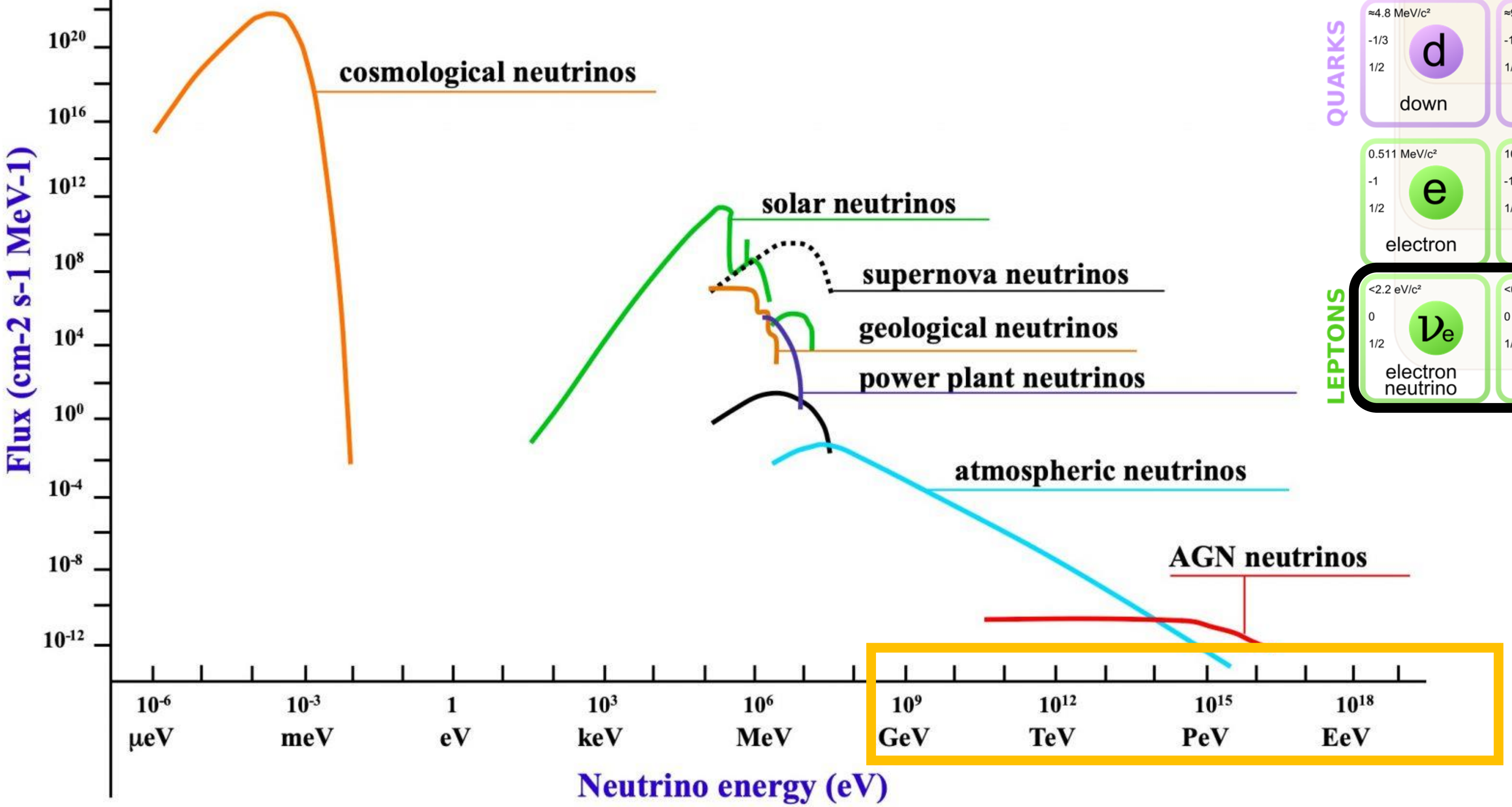
- Detectors will grow further in 2022!
- New results soon!

KM3NeT

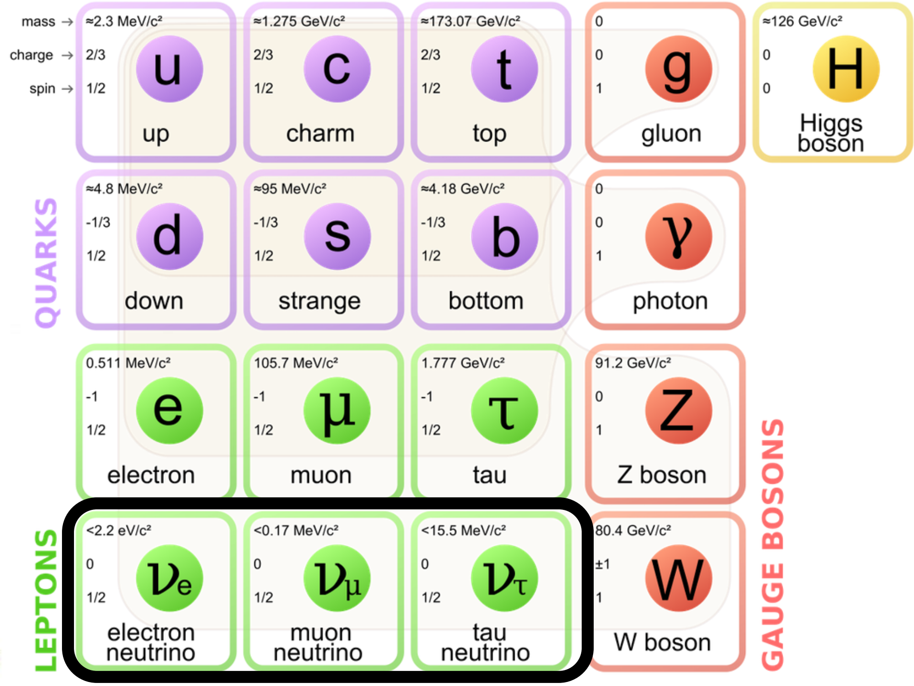
Backup

Neutrino sources

Neutrino sources:



Relevant E scale



Michel Cribier, Michel Spiro, Daniel Vignaud, La lumière des neutrinos, Seuil (1995)

Neutrino interactions

Possible interactions:

- gravitational
- weak:
  - Charged current (CC) : $\nu_l + N \xrightarrow{W^\pm} l + X$
  - Neutral current (NC) : $\nu_l + N \xrightarrow{Z^0} \nu_l + X$
  - Elastic scattering (ES) : $\nu_l + N \xrightarrow{W^\pm/Z^0} \nu_l + l$
- ν oscillations

may cause Cherenkov light emission (if charged)

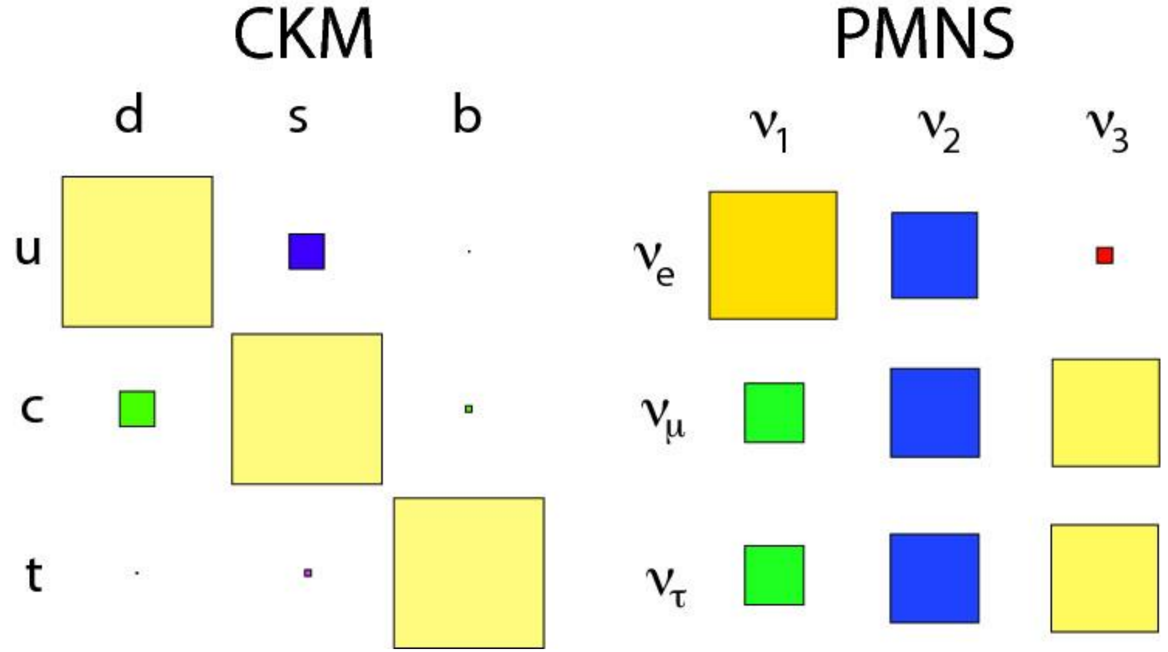
Neutrino oscillations

Mixing of neutrino mass and flavour states:

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U_{\mathrm{PMNS}}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

U_{PMNS} matrix:

- NOT diagonal like CKM for quarks!
- not measured as precisely as CKM



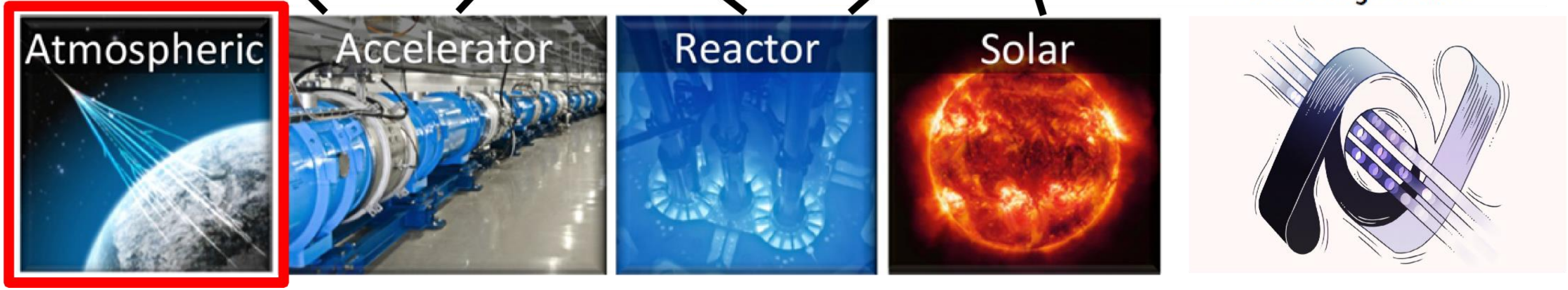
PMNS = Pontecorvo-Maki-Nakagawa-Sakata
CKM = Cabibbo–Kobayashi–Maskawa

U_{PMNS} parametrization

The usual parametrization of U_{PMNS}:

$$U_{\alpha i} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}\underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}\underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}\underbrace{\begin{bmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}} \quad (1)$$

Only if ν's are Majorana



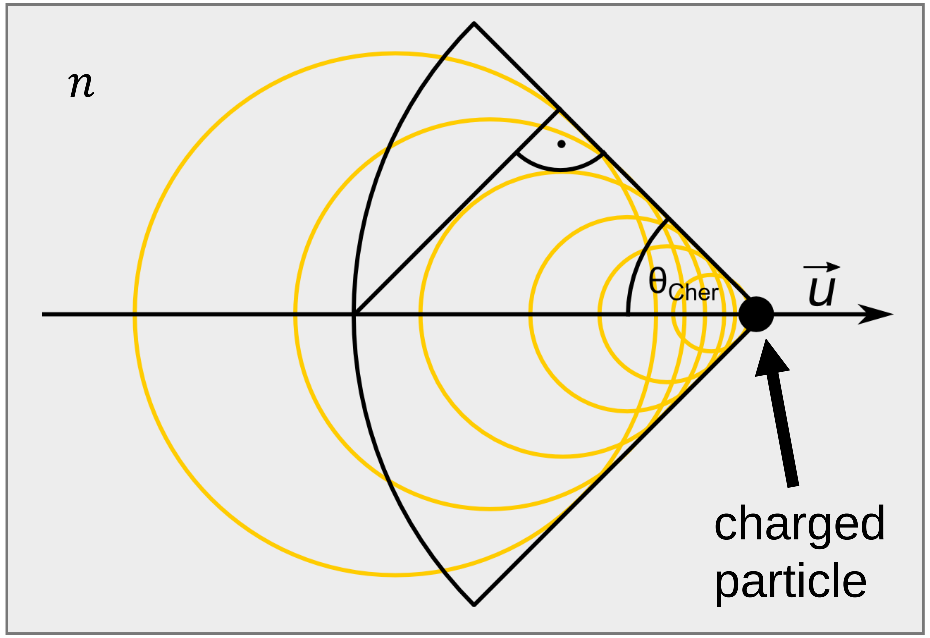
$c_{ij} \equiv \cos\theta_{ij}$ $\quad$ δ – CP-violating phase (charge-parity)

$s_{ij} \equiv \sin\theta_{ij}$ $\quad$ α_1, α_2 – Majorana phases

Cherenkov radiation

In a nutshell:

EM equivalent of a sonic boom shockwave



$$\cos\theta_{\mathrm{Cher}} = \frac{c}{u \cdot n}$$

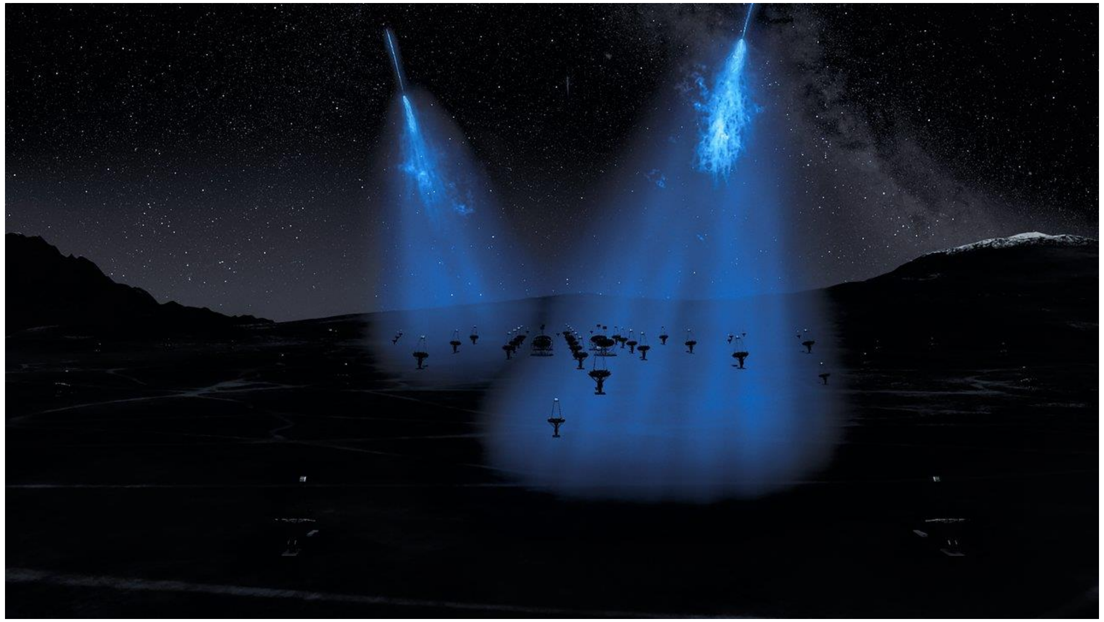
e.g. in water, $\theta_{\mathrm{Cher}} \approx 41°$

Supersonic jetplane:

https://www.quora.com/Can-a-pilot-hear-his-own-sonic-boom-when-he-slows-down-the-plane

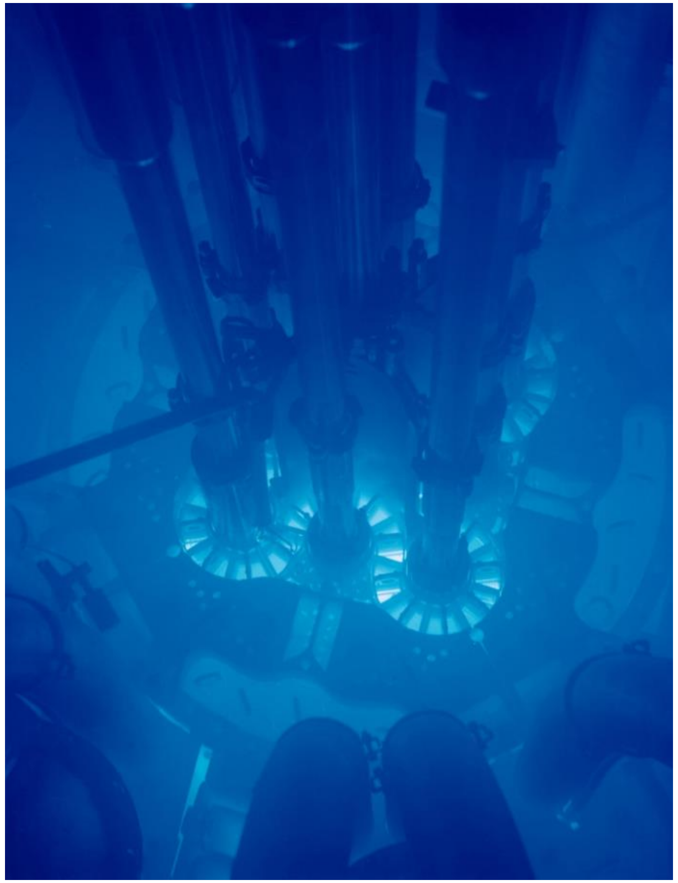
Examples

Extensive Air Showers



eso.org

Nuclear reactors



https://www.flickr.com/photos/35734278@N05/3954062594/

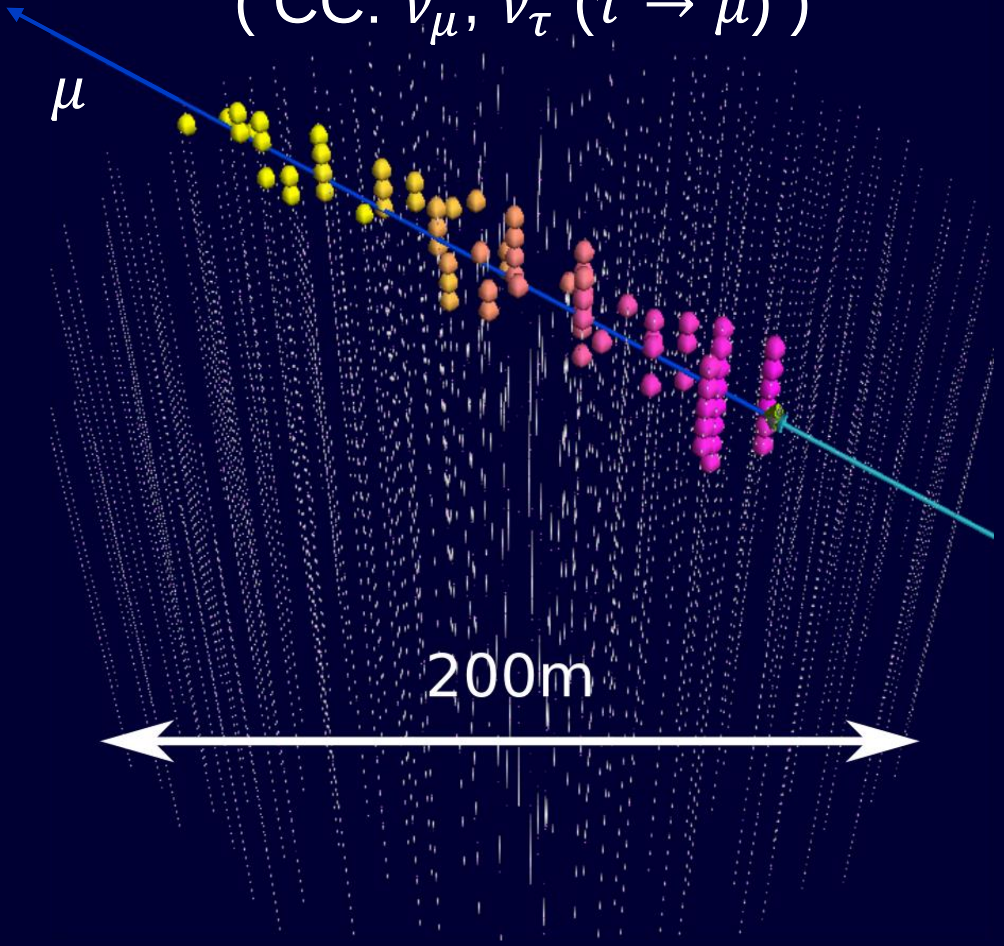
and …

KM3NeT

Event topologies (ORCA115 MC)

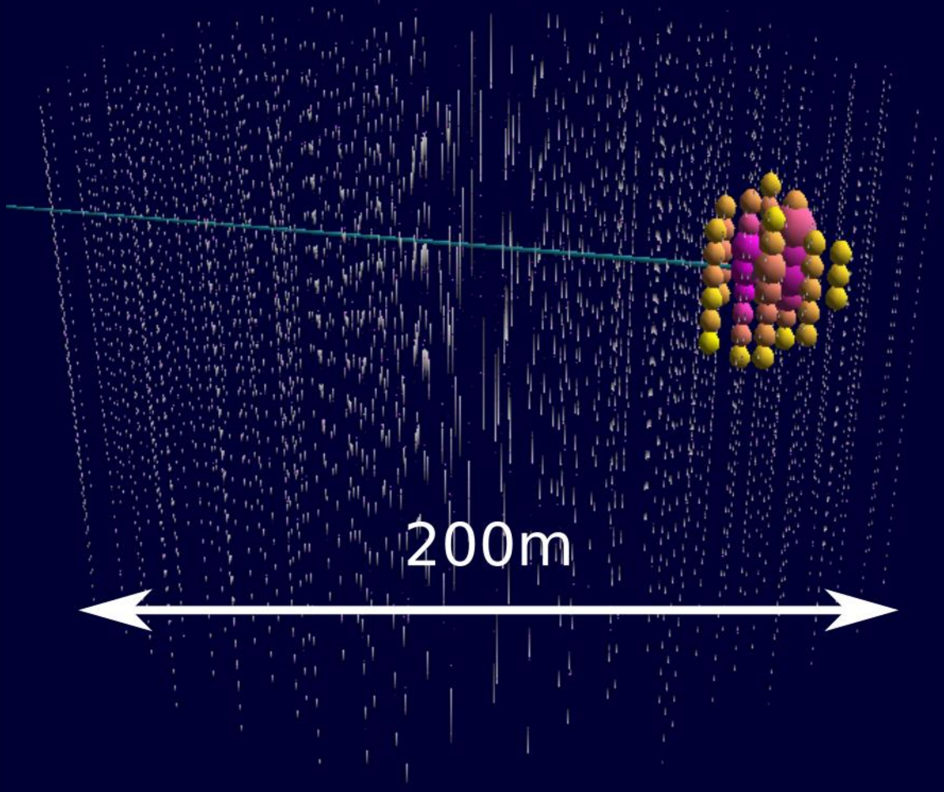
Tracks

(CC: ν_μ, ν_τ $(\tau \rightarrow \mu)$)



Showers

(NC: $\nu_{e,\mu,\tau}$, CC: ν_e, ν_τ $(\tau \nrightarrow \mu)$)



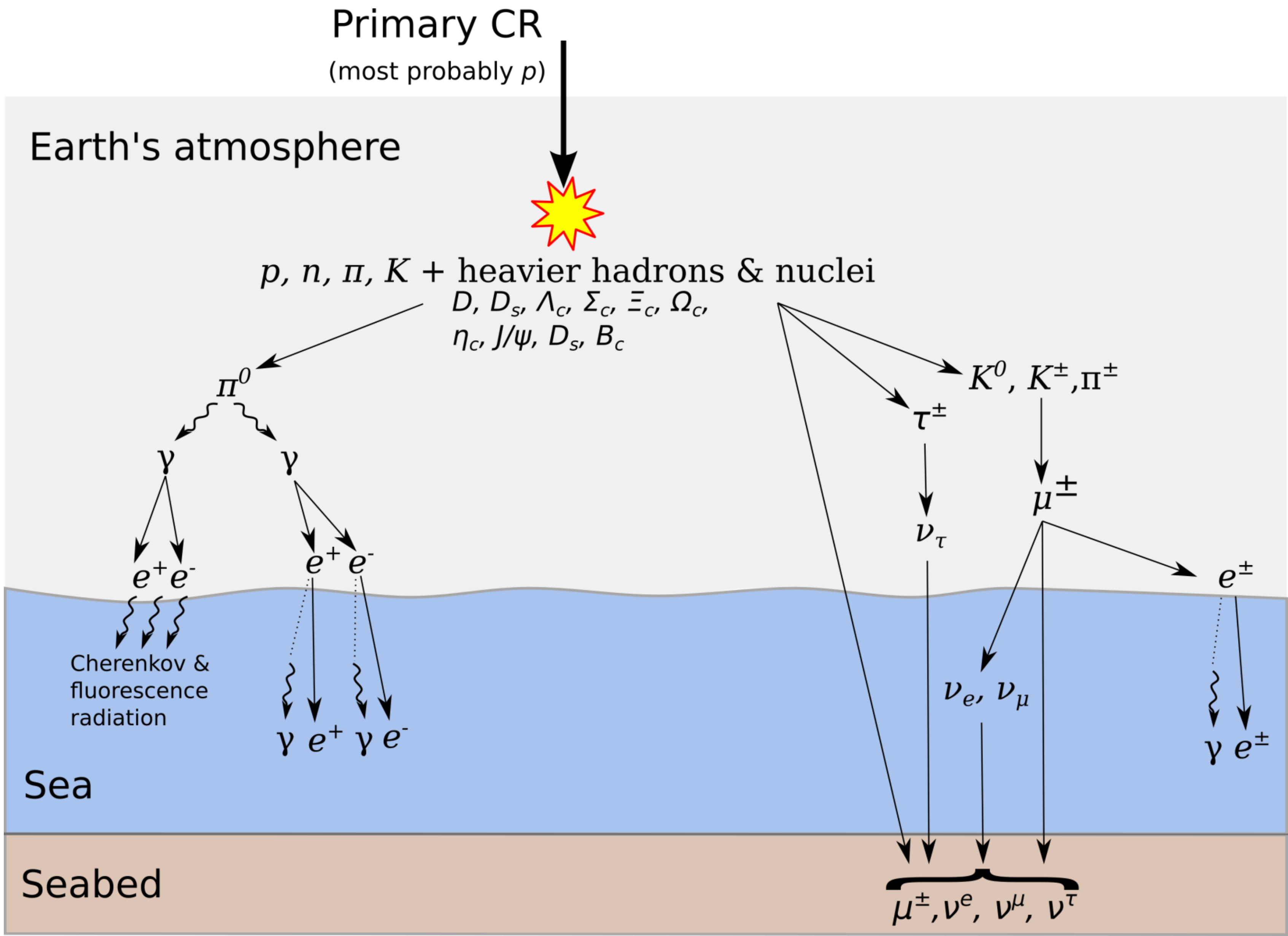
Ball size $\leftrightarrow$ #hit PMTs on a DOM

color $\longrightarrow$ time

Extensive Air Showers (EAS)

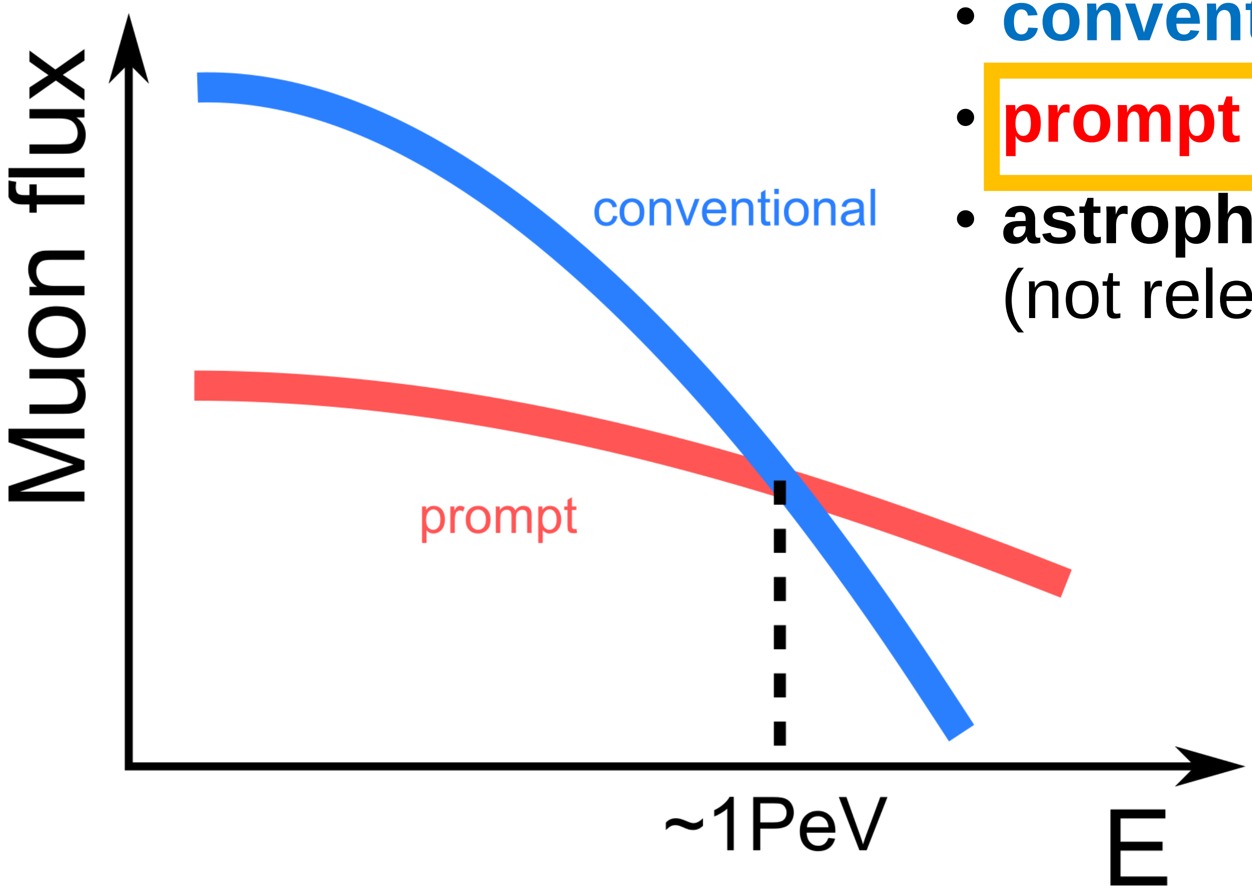
EAS:

- Caused by primary cosmic rays (CR)
- Typically start at $h \in (20{,}100)\mathrm{km}$
- 3 main components:
  - electromagnetic (EM)
  - hadronic
  - muonic



Prompt muons: basic motivation

Flux categories commonly used by ν telescopes:



- **conventional** – μ, ν mostly from π and K decays
- **prompt** – μ, ν mostly from heavy hadron decays
- **astrophysical** – ν from AGNs, SNe, etc. (not relevant for μ)

We want these!

CCSN: time resolution

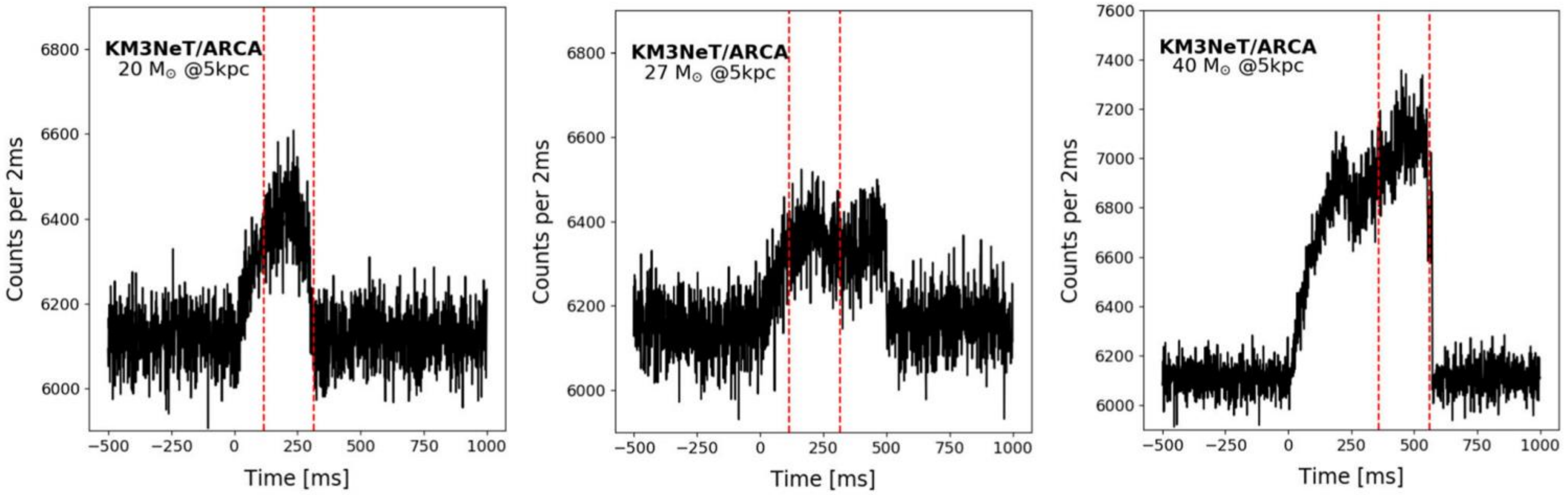


Fig. 12 Pseudo-experiments of the detected neutrino light curves in the full ARCA detector, considering a source at 5 kpc, and the three CCSN progenitors: the 20 $M_\odot$ (left), 27 $M_\odot$ (center), and 40 $M_\odot$ (right). The dashed red lines indicate the interval to which the Fourier transform is applied

Sensitivity to CCSN*
JINST 16 C09034 (2021)