Friedrich-Alexander-Universität
Erlangen-Nürnberg

The KM3NeT Neutrino Telescope

Status and outlook

Jutta Schnabel

IPA 2022

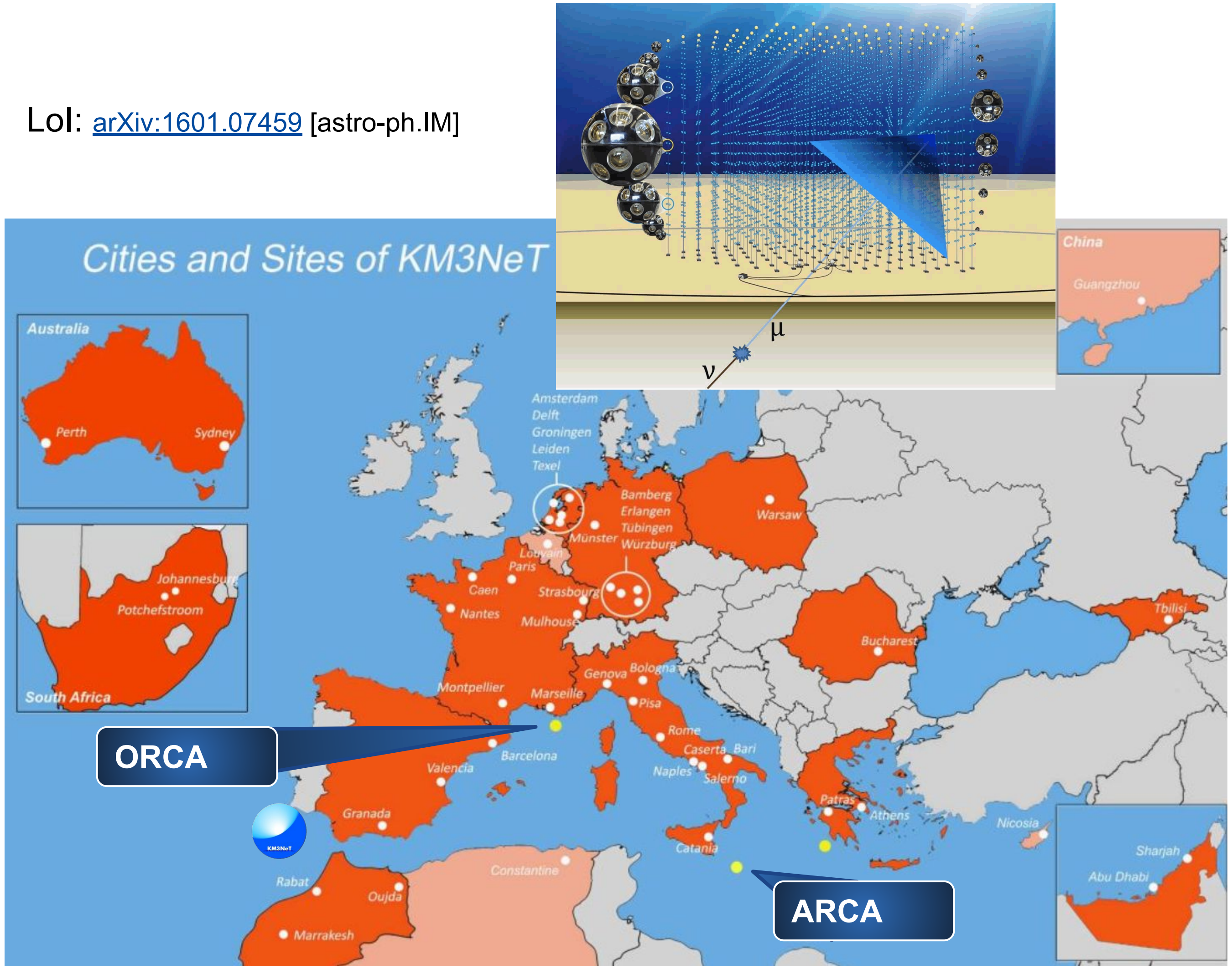
Vienna, 5 - 9th September 2022

Introducing KM3NeT

The detectors and collaboration

- Scientific motivation
- Building the detector
- First results
- Open Science

LoI: arXiv:1601.07459 [astro-ph.IM]



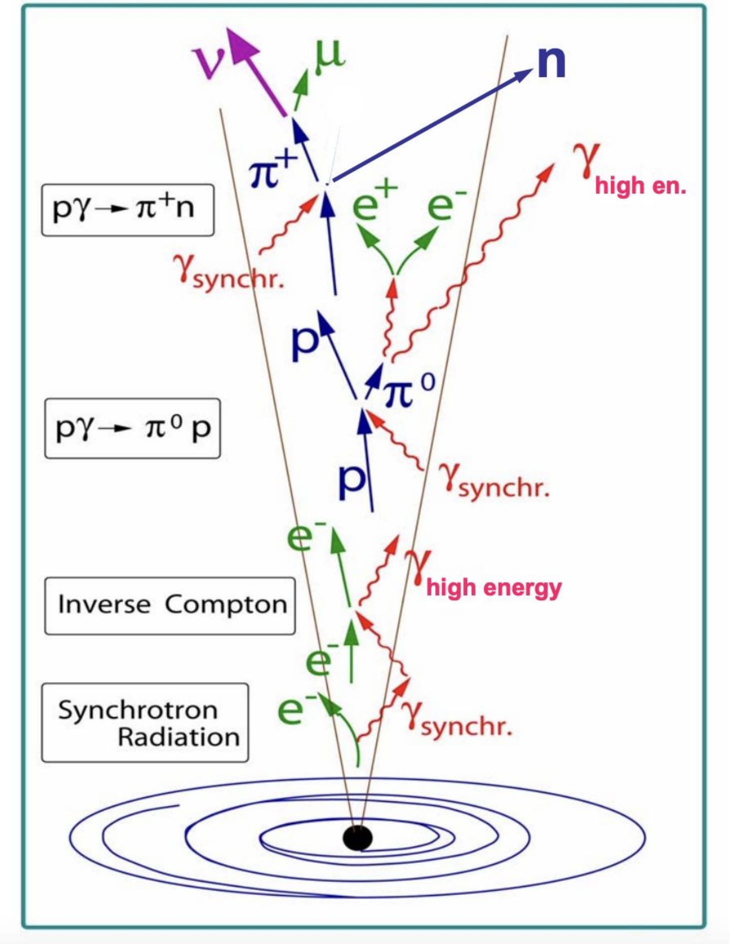
KM3NeT
are Water Cherenkov detectors for high-energy neutrinos in the Mediterranean Sea, under construction

- ORCA
  - data taking with 10 lines
  - ~10 more lines ready for deployment
  - construction in progress (~50 lines)
- ARCA
  - data taking with 19 lines
  - funded for ~150 lines

Scientific motivation

Neutrino generation and sources

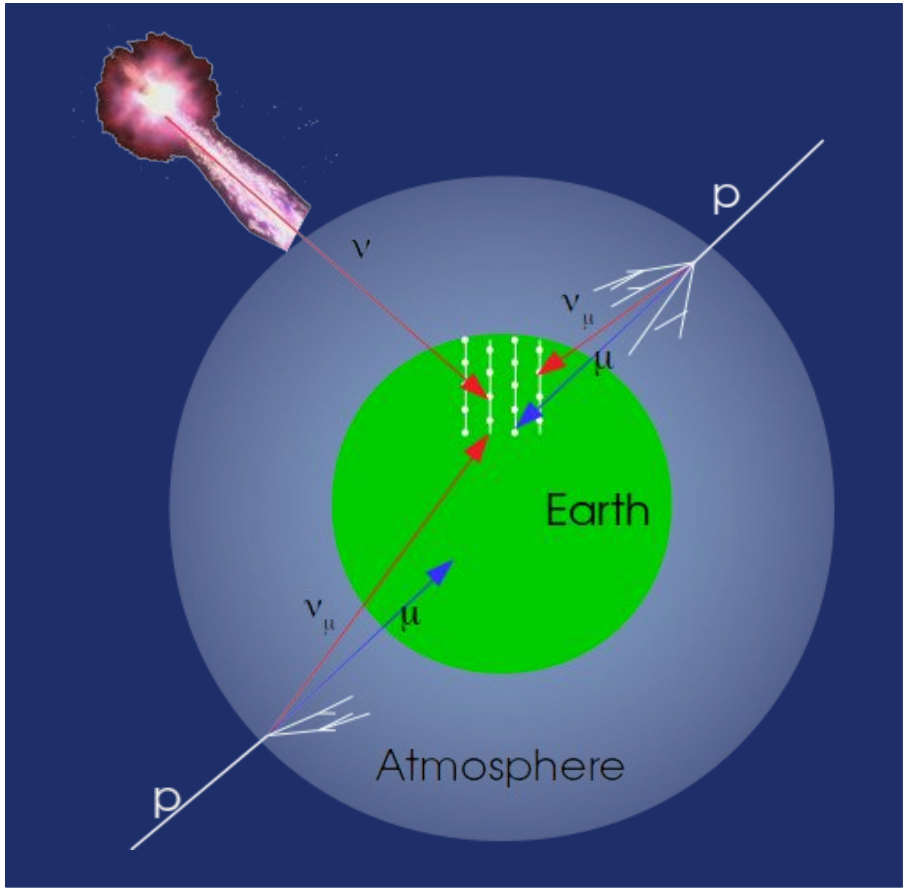
Cosmic, atmospheric or anything else



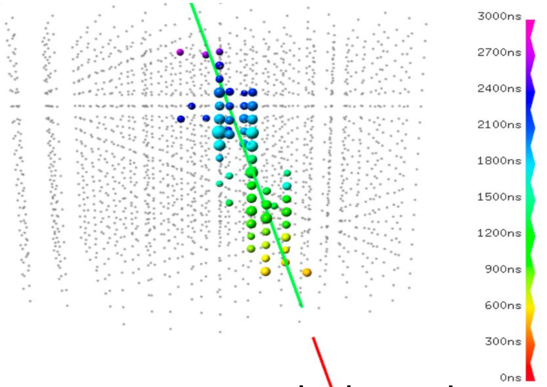
- in cosmic sources
  - classical $\pi^{+/-} \rightarrow e^{+/-} + \nu_e \nu_\mu \bar{\nu}_\mu$
  - acceleration mechanisms for high energies
  - flavour composition 1:1:1 at detection
- in atmosphere
  - from cosmic ray interaction
  - background for cosmic search, signal for neutrino property study
- other interactions, e.g.
  - dark matter: WIMP annihilation
  - …

Detection principle

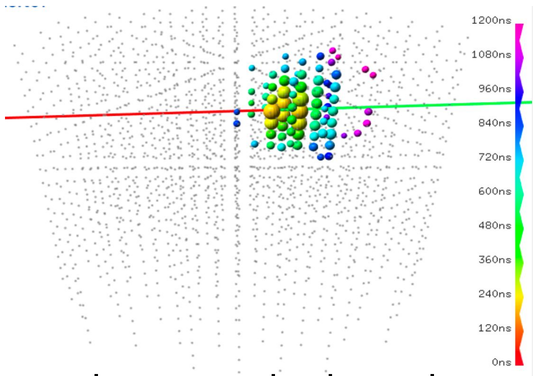
Cherenkov radiation from neutrino interaction secondaries



- neutrino interaction producing high-energy charged leptons
  - Cherenkov radiation allows directional reconstruction
  - radiative processes allows energy reco
- Earth used for shielding of atmospheric muons
- resolution
  - track channel: better than 0.1º for E>100TeV
  - cascade channel: better than 2º



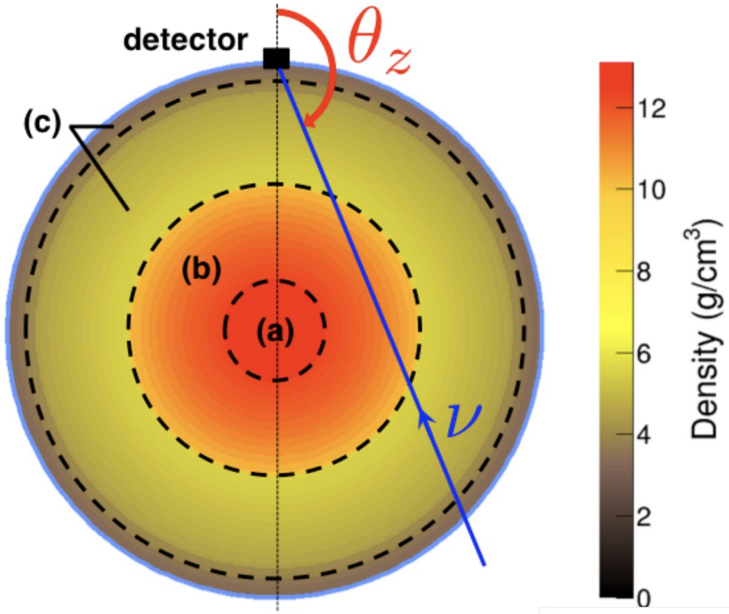
$\nu_\mu \rightarrow$ μ track channel

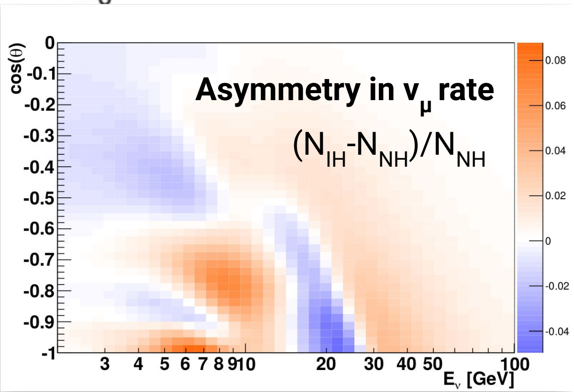


else: cascade channel

Particle physics with ORCA

Oscillation studies using “background”





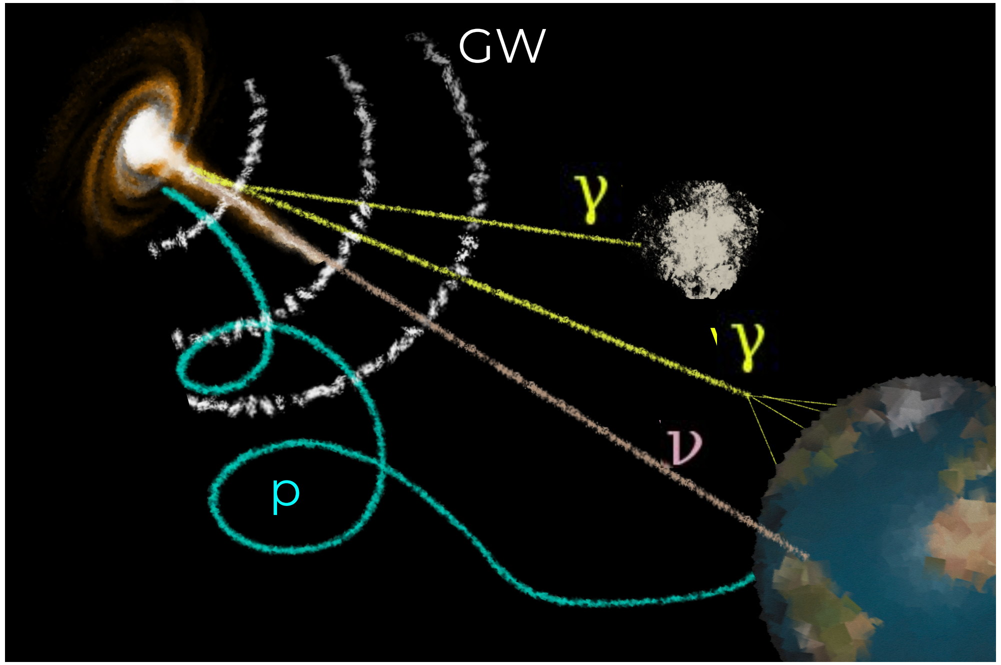
Oscillation **R**esearch with **C**osmics in the **A**byss

- **signal**: neutrinos produced by cosmic rays in atmosphere
- few-GeV energy range
- neutrino properties through oscillation studies
  - mass hierarchy
  - sterile neutrinos & other

- characteristic patterns of neutrino appearance/disappearance at different energies/pathlength

Astroparticle physics with ARCA

Searching all sky for high-energy cosmic neutrinos

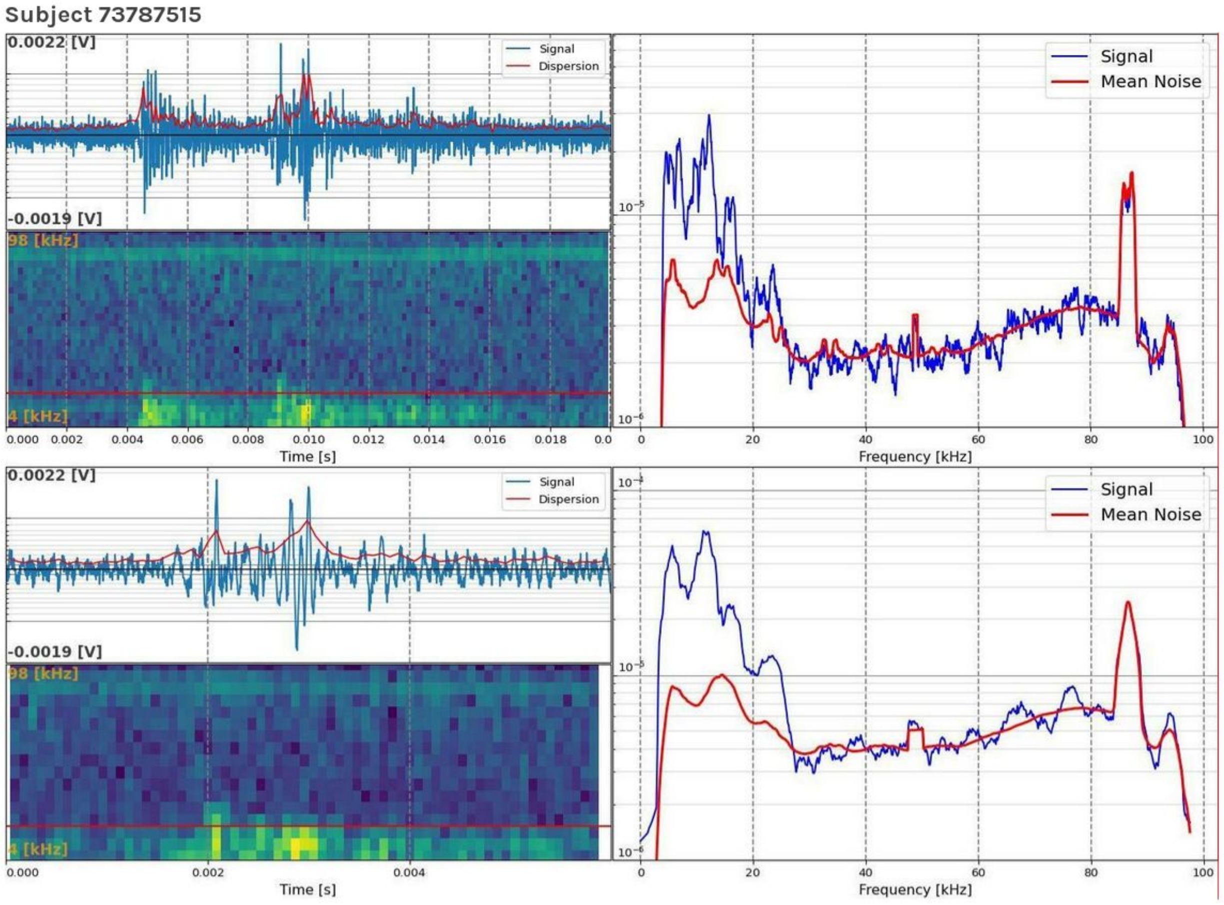


Astroparticle **R**esearch with **C**osmics in the **A**byss

- superior angular resolution
- decides origin, energy spectrum, flavour composition
- 87% of the sky mapped including the Galactic Center
- energies between O(10 GeV) - O(PeV)

Extra: Earth and sea science

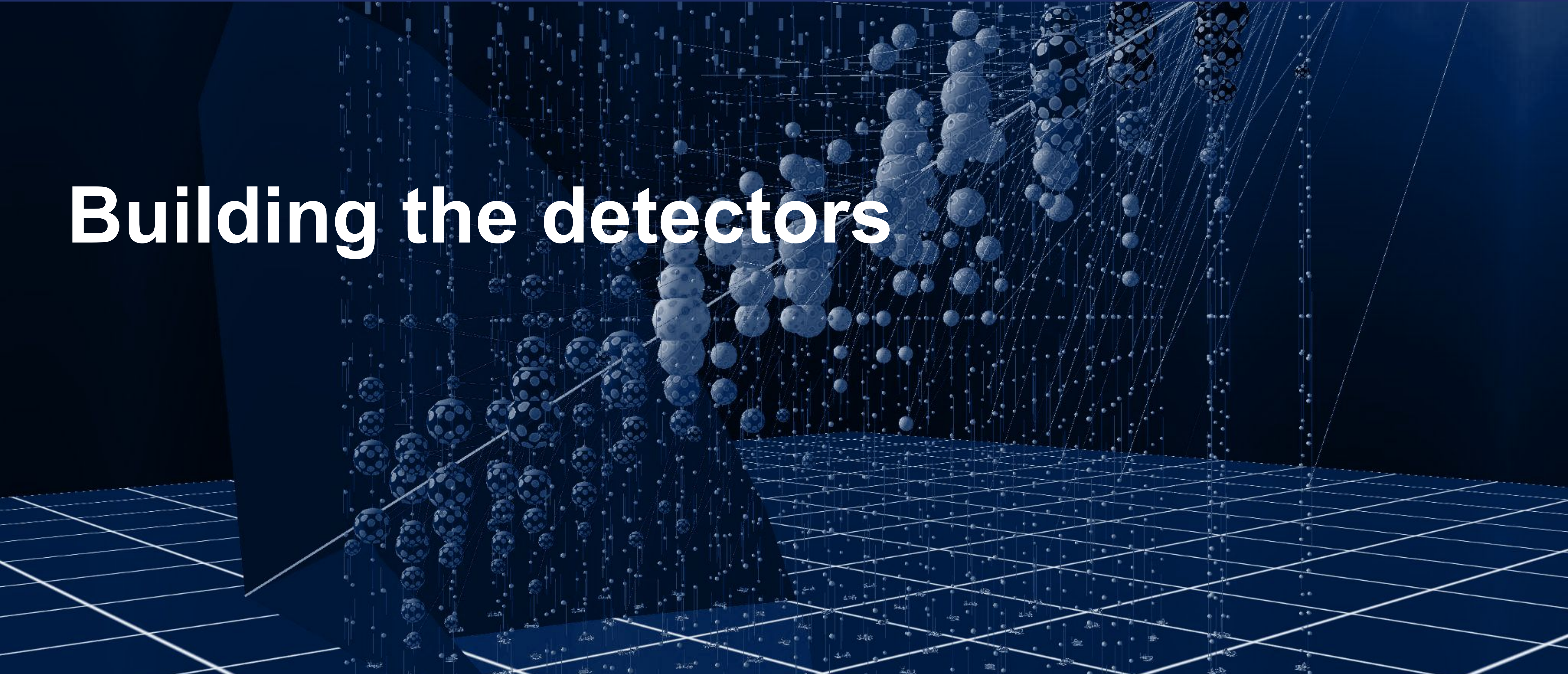
Using the infrastructure for a wide science program



zooniverse project

- access for Earth and Sea science community
  - dedicated instrumentation installable on Detection Units
  - or use of standard equipment of detectors
- standard equipment
  - water optical and oceanographic properties
  - behaviour of bioluminescent organisms
  - measurement of sea currents
  - identification of acoustic noise sources
- collaboration with the European Multidisciplinary Seafloor Observatory (EMSO)

Building the detectors



The sensors

High-precision photon detection

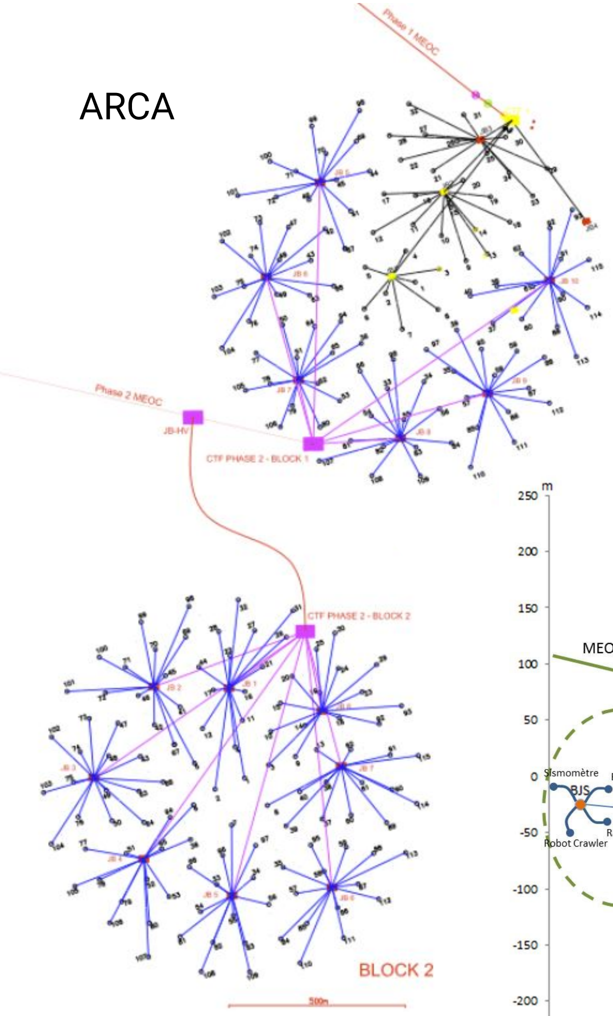
arXiv:2203.10048 [astro-ph.IM]

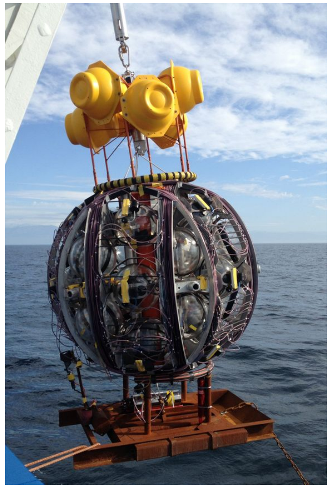
- Digital Optical Modules (DOMs) with 31 PMTs each
  - 3inch diameter
  - PMT base for digitization of signal
- 1 Gb/s bandwidth per sensor module
  - typical bandwidth of ~20 Mb/s
  - mainly light emission of K^{40} decay (5-8 kHz/PMT)
- similar approaches in different detectors of the Global Neutrino Network (GNN)
  10.5281/zenodo.6781203

Deployment and installation

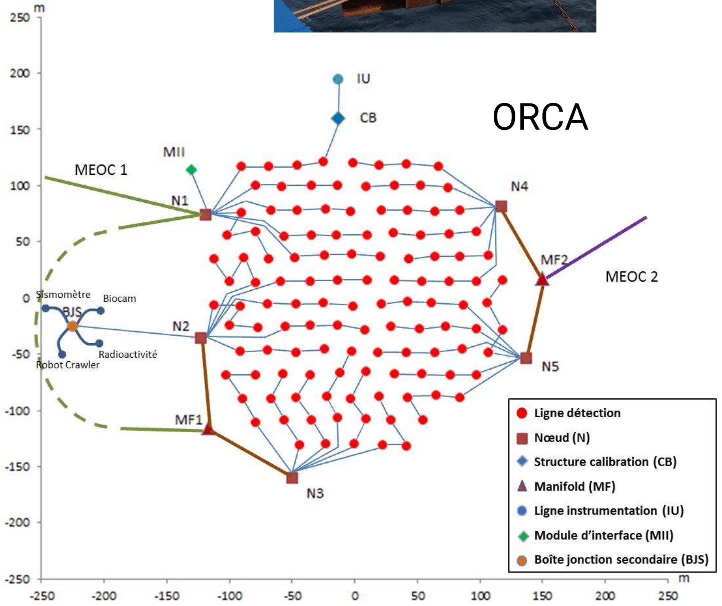
Same implementation, different detectors

ARCA





ORCA

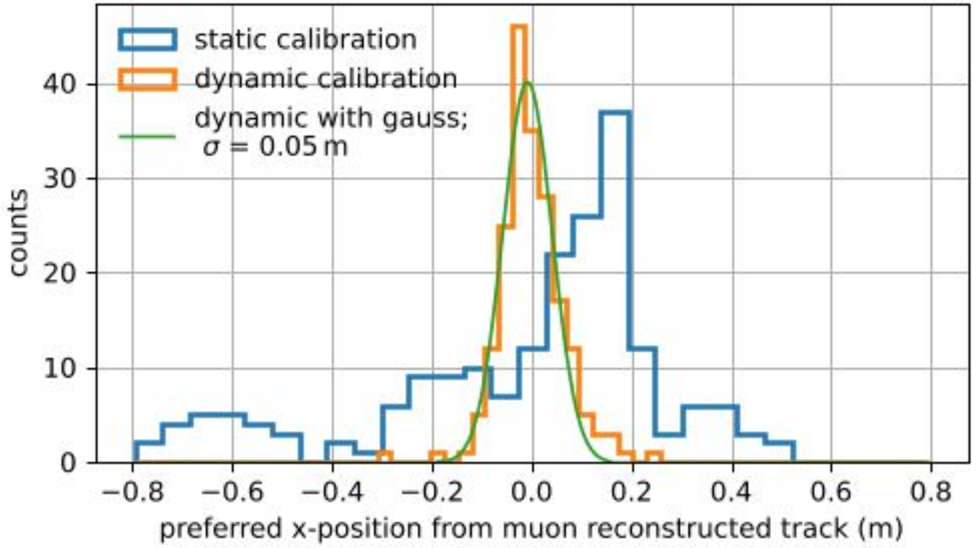


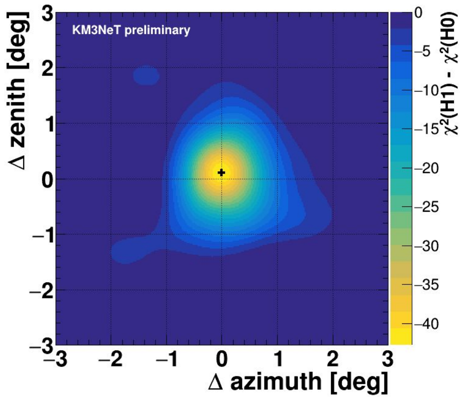
- Detection Units (DUs) containing multiple DOMs
- anchored to the sea bed, uncoiled using a launcher vehicle to place DU within 1m accuracy on floor S. Aiello *et al* 2020 *JINST* **15** P11027
- several DU deployments achievable during a sea operation
- connection to floor network using ROV
- readout of all data to shore

	String Spacing (m)	DOM Spacing (m)	Depth (m)	Instrumented mass (Mton)
ORCA	20-23	9	2470	5-8
ARCA	90	36	3400	500*2

Detector control and calibration

High precision in a varying environment



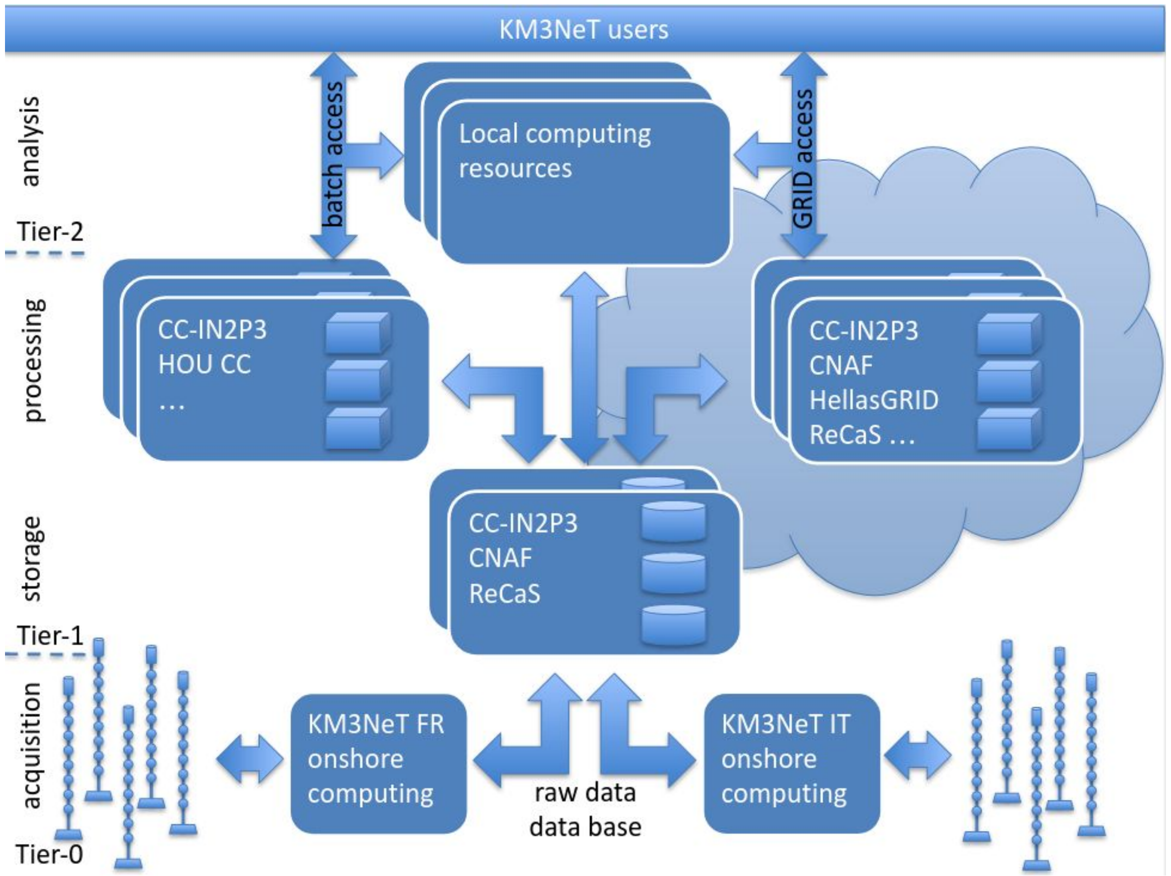


sun shadow for precision measurement

- timing calibration
  - LED pulsers (nanobeacon) for inter-DOM calibration arXiv:2111.00223 [astro-ph.IM]
  - < 1ns precision for relative timing between DOMs
  - individual control for each DOM, each DU base and slow control for the junction boxes at the seabed
- position calibration
  - Tilt and heading in each DOM
  - acoustic positioning system
  - precision down to around 10 cm
- results in < 0.1° precision for neutrino direction

Data acquisition and computing

Big data: high volume, parallelized, distributed



- all digital data from the PMTs sent to shore
  - processing on computing cluster in real time
  - full MC simulation of data processing starting from neutrino generation
- physics events filtered through triggering software
  - different filters can be applied to the data
  - for full building block about 25 Gb/s reduced to 1/100
  - storage for further processing
- model based on the LHC computing model
  - hierarchical data processing system
  - distributed & parallel computing

KM3NeT-InfraDev-WP4-D4.1

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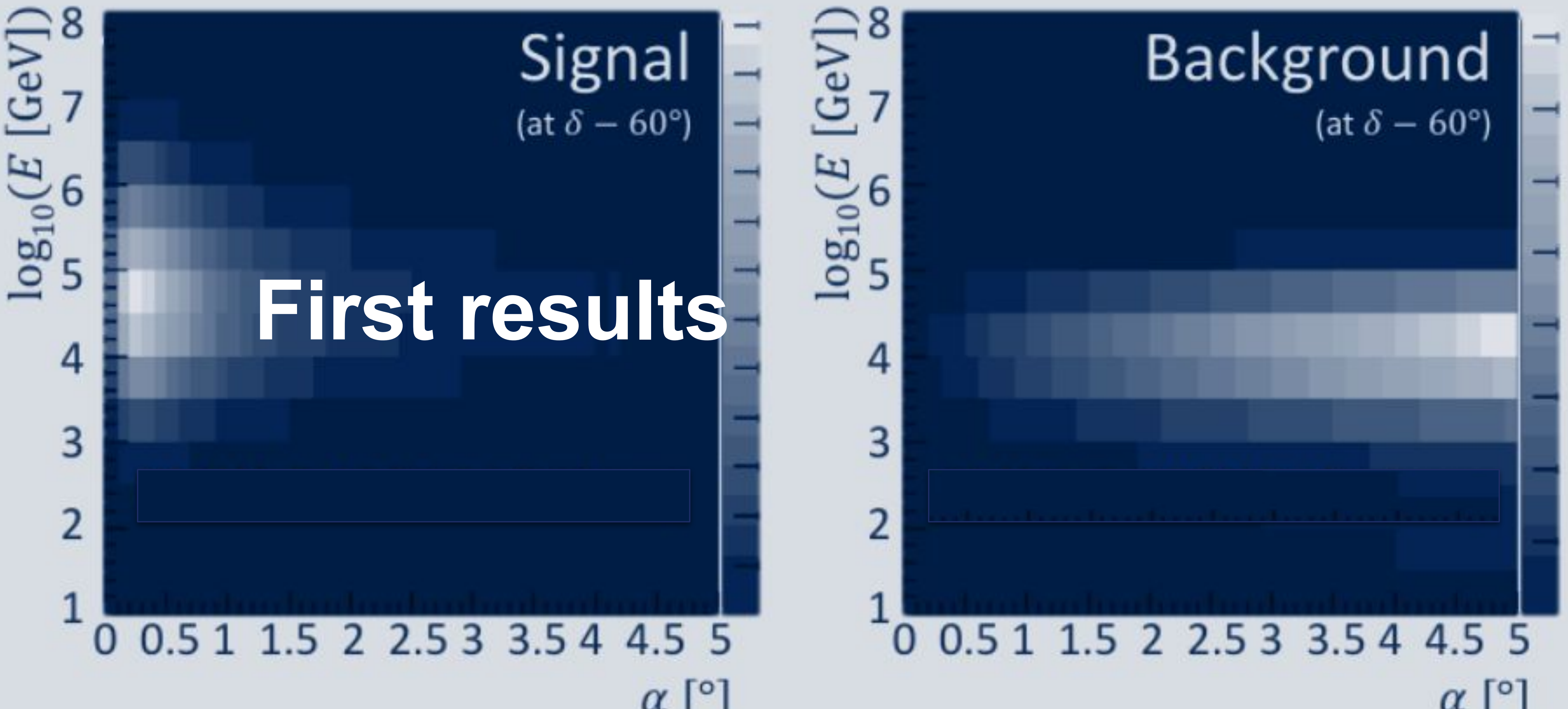
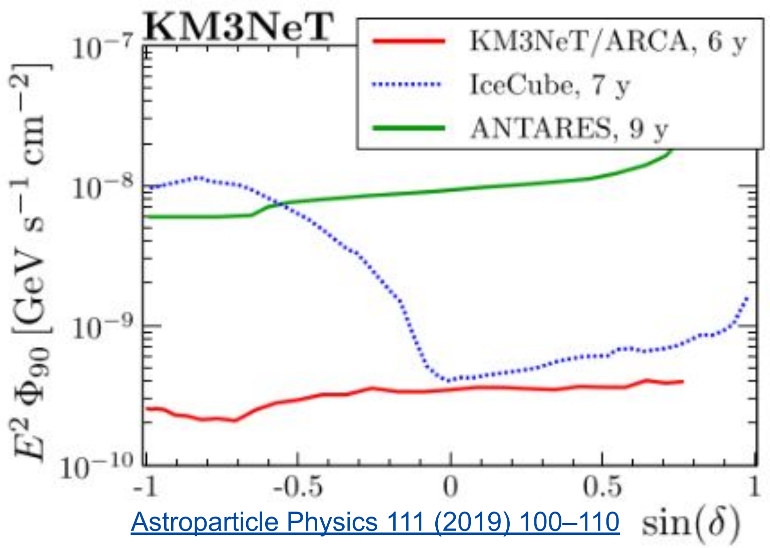


First results

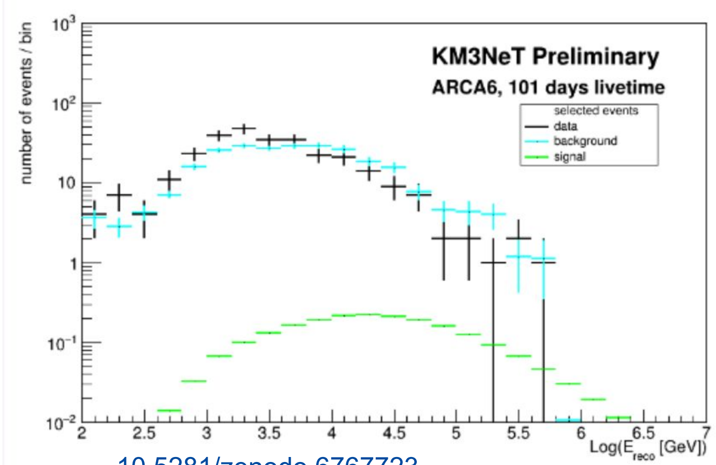
All-sky neutrino flux and point sources

Cosmic neutrino searches from point-like to very extended sources



Astroparticle Physics 111 (2019) 100–110

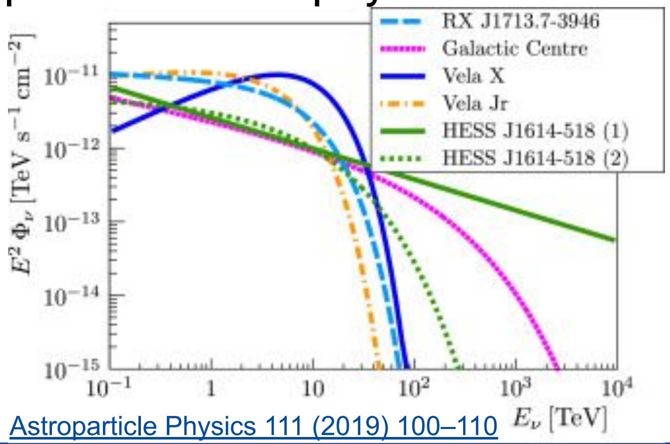
energy spectrum of all-sky cosmic neutrino event selection



10.5281/zenodo.6767723

energy spectrum of all-sky cosmic neutrino event selection

- all-sky neutrino flux (ARCA 101 days)
  - $\Phi_{90\%CL}$ = 17.3 x 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
    - Φ_{test} = 1.44 x 10^{-18} (E/100TeV)$^{-2.28}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}
  - observation with 3σ significance possible in about six years of operation for most intense sources
- extended source, e.g. galactic center
  - on/off-zone analysis 10.5281/zenodo.6767723
- neutrino flux from potential astrophysical neutrino sources



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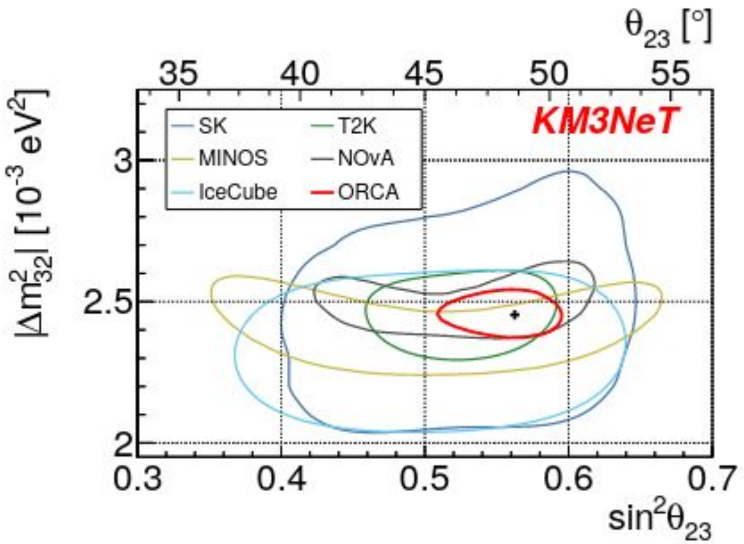
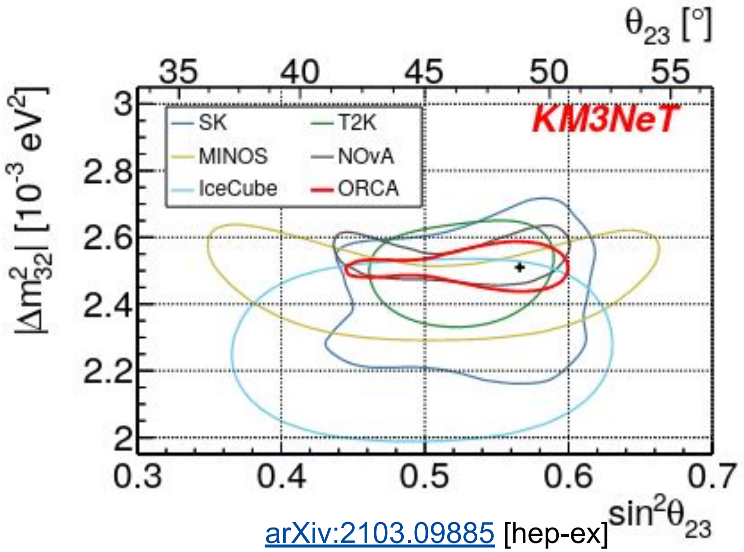
Neutrino oscillations

Determine basic neutrino properties



normal hierarchy



inverted hierarchy

arXiv:2103.09885 [hep-ex]

- after 3 years of data taking
  - sensitivity for neutrino mass ordering at 4.4σ (normal) and 2.3σ (inverted)
  - precision to measure $\Delta m_{32}{}^2$ and θ_{23}: 85 · 10^{-6} eV^2 (normal), 75 · 10^{-6} eV^2 (inverted) ordering
  - unitarity test of the leptonic mixing matrix: exclude ν_τ event rate variations larger than 20% at 3σ level

→ see talk be Lukas Maderer (Thursday)

Further neutrino research

ORCA research extended

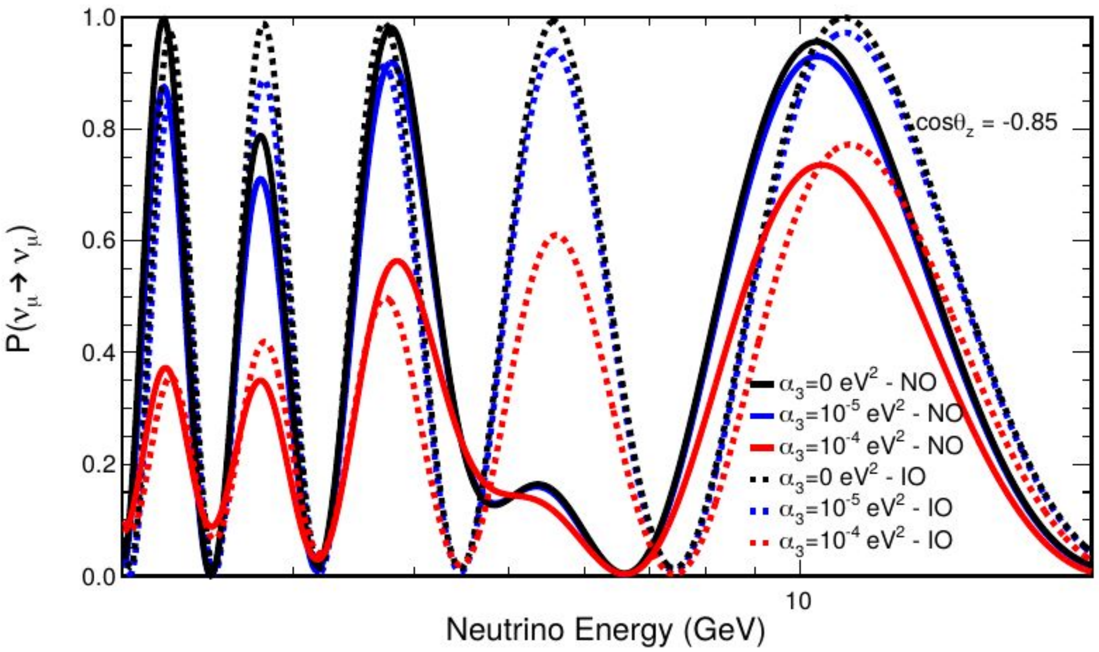
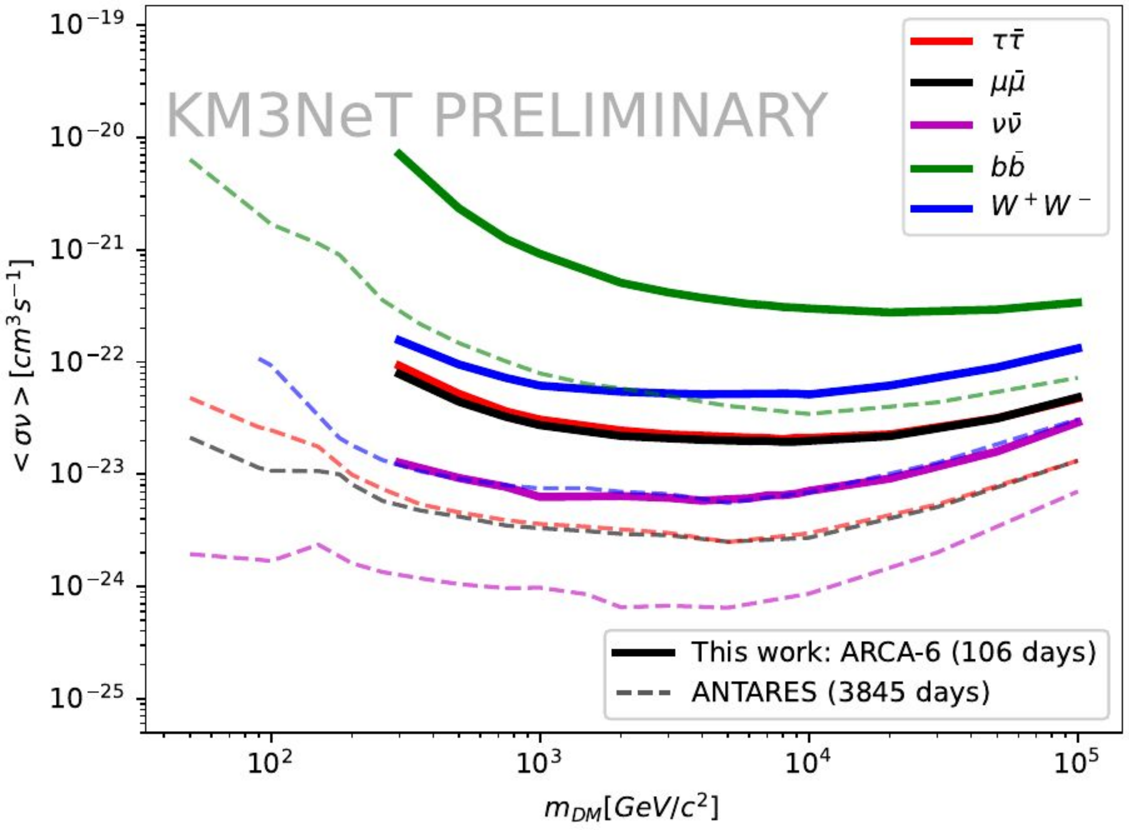


Fig. 1: Muon neutrino survival probabilities in the presence of decay

- probing neutrino invisible decay (neutrino mass state $\nu_3$decays into a sterile neutrino) (zenodo.org/record/6758959)
- sterile neutrino searches: active-sterile mixing with mass squared differences $\Delta m_{41}{}^2$ between 10^{-5} and 10 eV^2 (zenodo.org/record/6804567)
- non-standard interactions: sub-dominant effects in the oscillation patterns (zenodo.org/record/6785232)
- quantum decoherence from quantum gravity (zenodo.org/record/6781033)

Dark matter

Neutrinos from WIMPs



WIMP from the galactic center

WIMPs decaying

- with masses from 300 GeV/c^2 to 100 TeV/c^2,
- five annihilation channels: $\mu^+\mu^-$, $\tau^+\tau^-$, $\bar{\nu}_\mu\nu_\mu$, $b\bar{b}$, W^+W^-

sources with WIMP accumulation

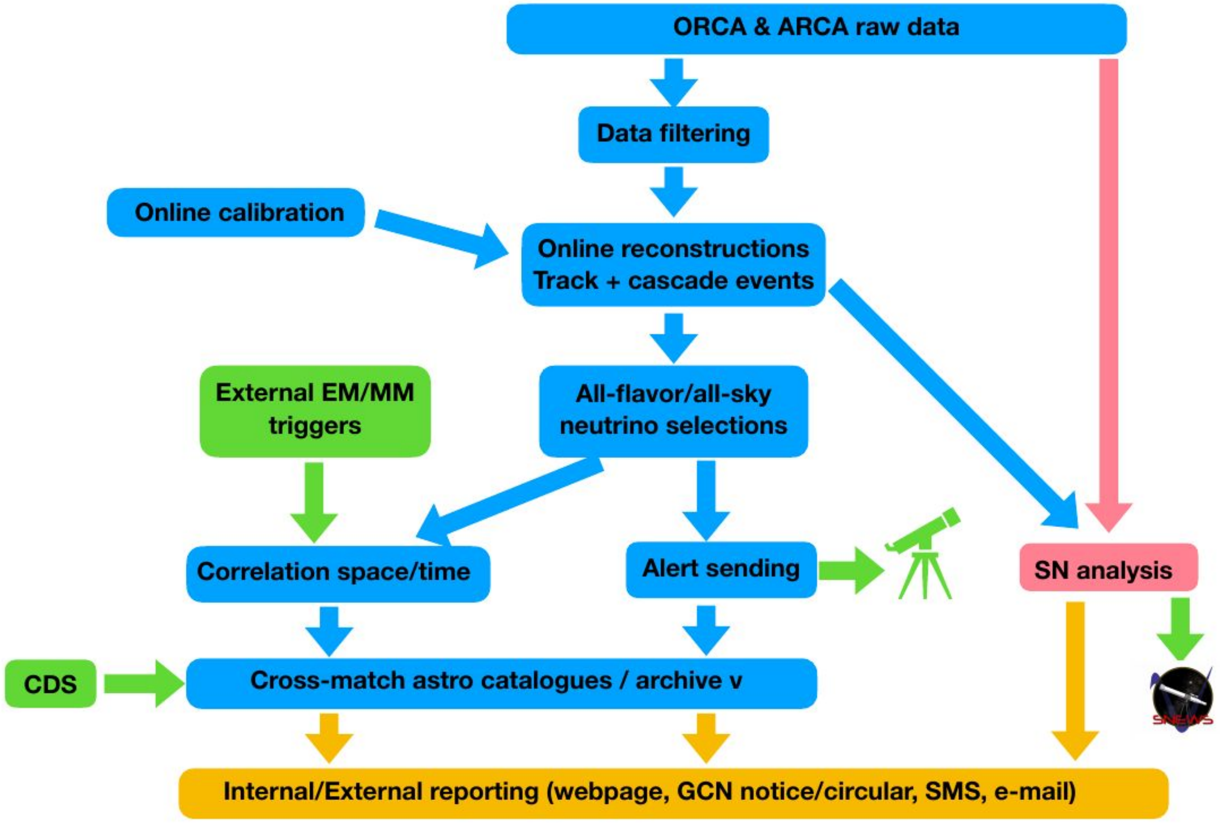
- galactic center (zenodo.org/record/6785348)
- solar core (zenodo.org/record/6775092)

106 days of ARCA data available

- expecting competitive limits with increased data taking

Multimessenger alerts

Sending out alerts on neutrino events

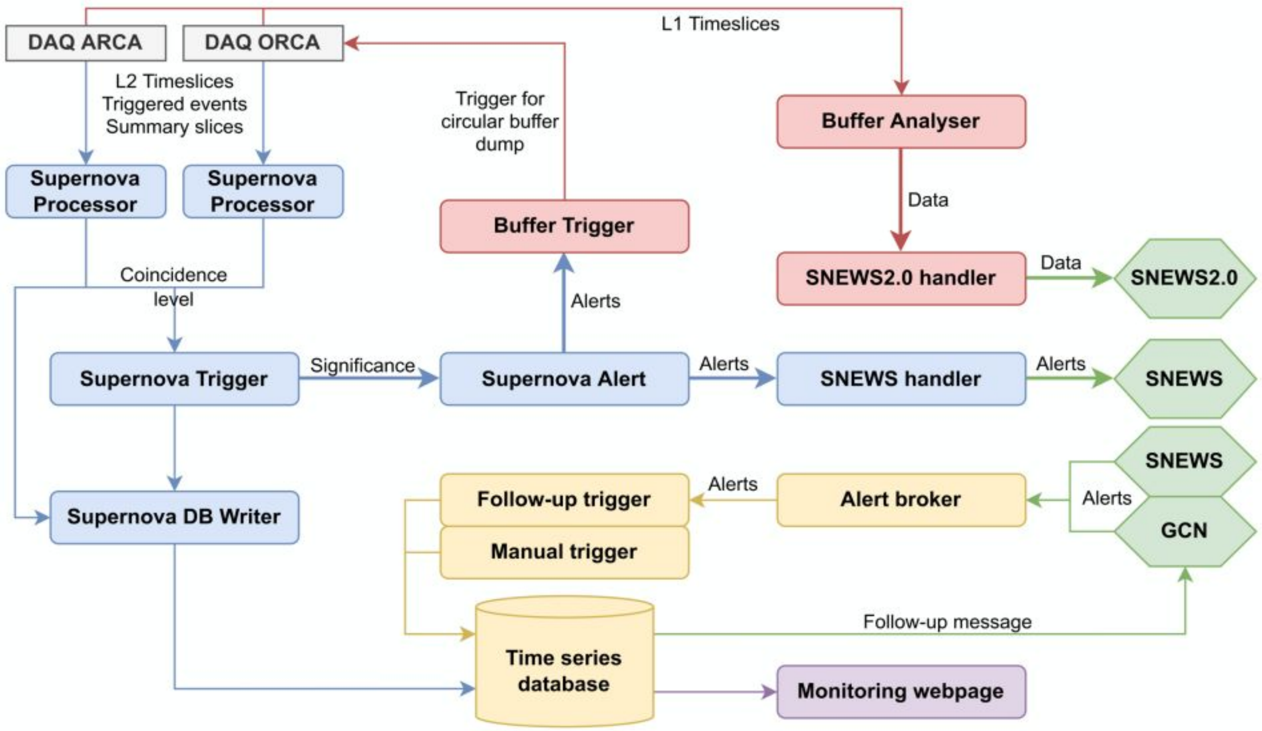


zenodo.org/record/6805417

- various alert types
  - supernova monitoring for prompt alerts, generation latency < 20 s
  - receive external EM/GW/ν alerts
  - send all flavor, all-sky ν alerts, multiplets & HE (GeV - PeV) neutrino alerts
- two pipelines
  - MeV supernova: alert
- planned alert types
  - neutrino triggers (~1/month): high energy and Multiplet neutrino alerts
  - physics triggers (~1-2/month): correlated neutrinos based on astrophysical properties (AGN/TDE/CCSN/GRB/Sun...)

Supernova monitoring

Different observation mode: high

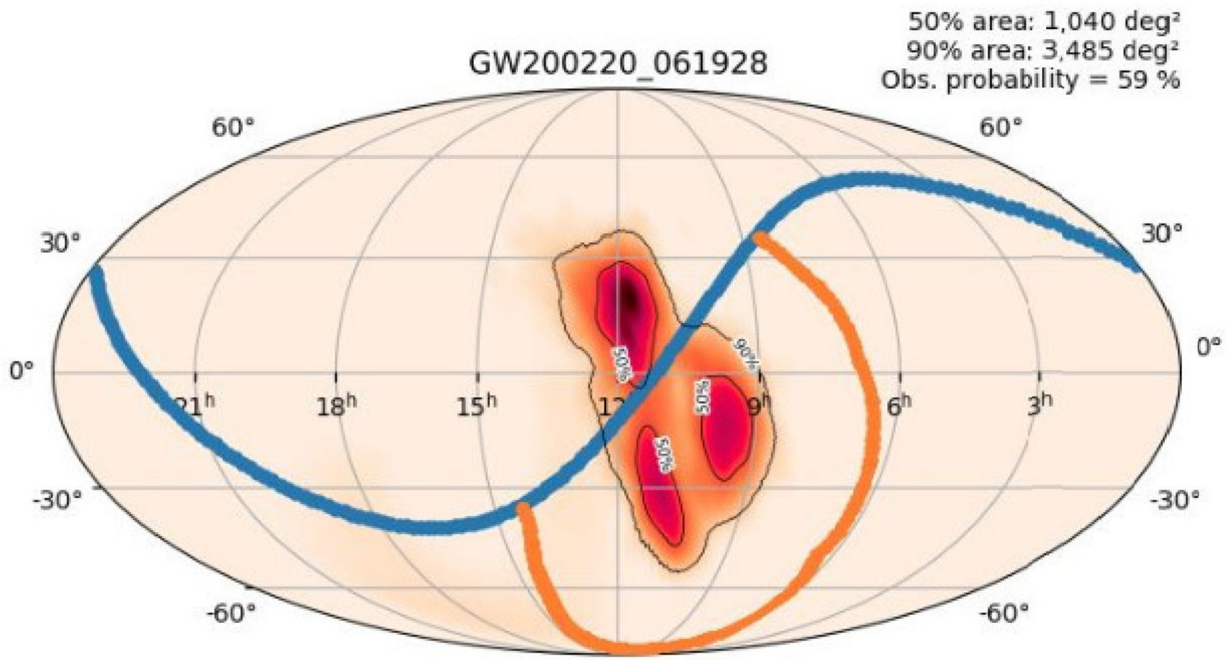


https://zenodo.org/record/6785410

- high flux of low-energy neutrinos, generating positrons producing increase in photon rate
- CCSN detectable as excess of coincidences above the optical background KM3NeT
- building on both detectors for event identification
- injected to Supernova Early Warning System (SNEWS)
- 5σ discovery potential for Galactic and near-Galactic events

Multimessenger analyses: Gravitational waves

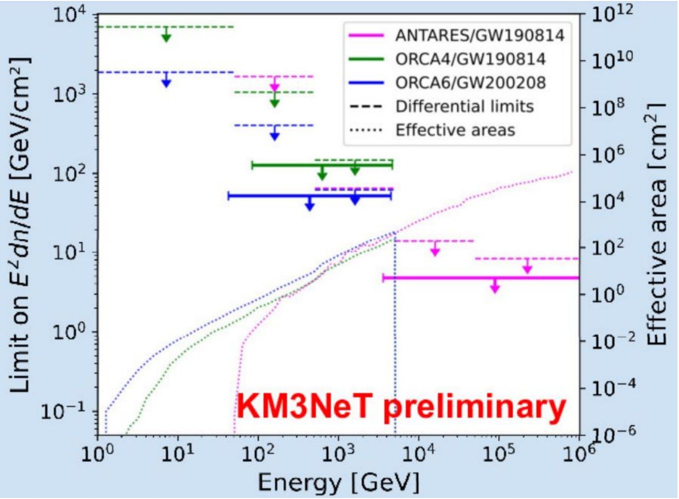
Timing coincidences with GW alerts



zenodo.org/record/6805229

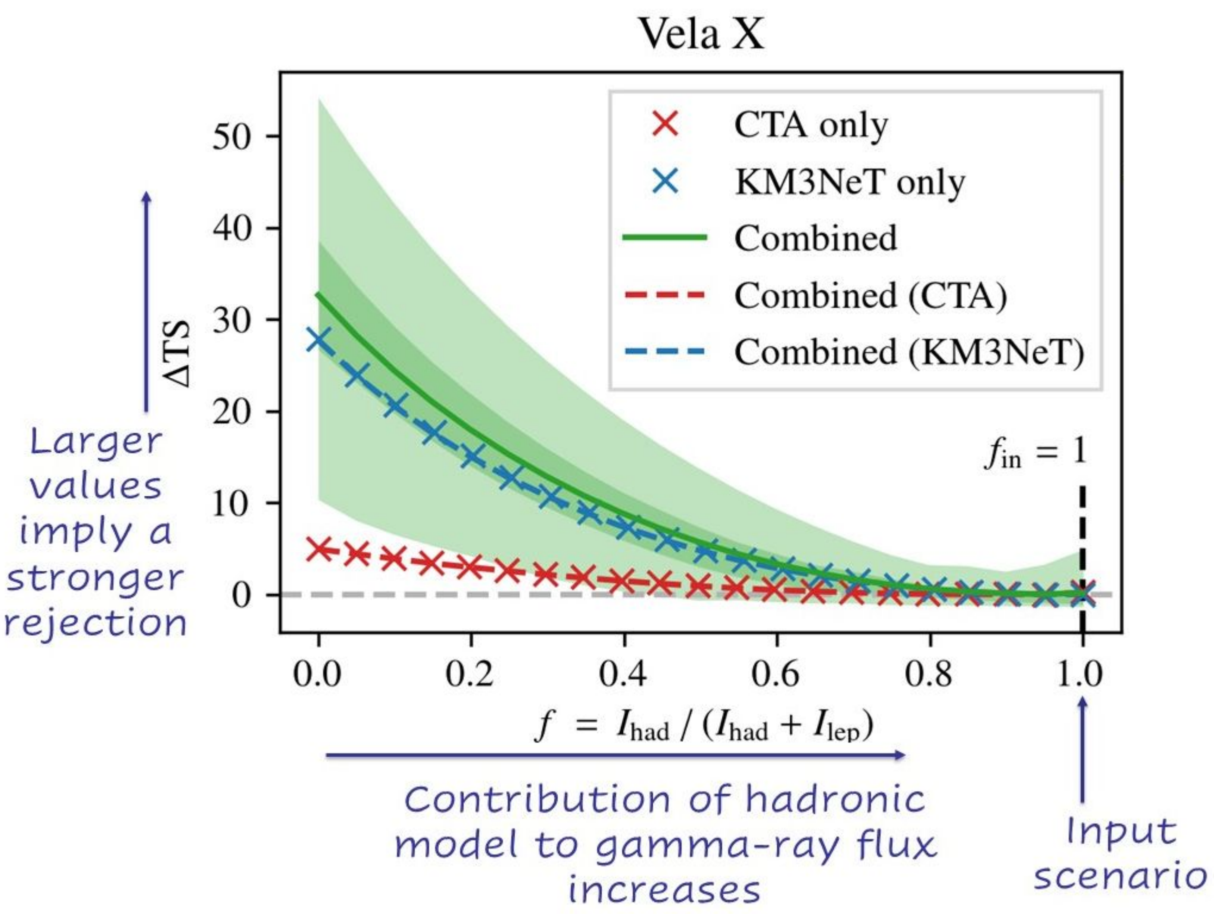
- search for MeV-TeV neutrinos from compact binary mergers (LIGO and Virgo, 3rd observation period)
  - independent search focusing on the MeV and GeV-TeV ranges
  - stacking analysis for neutrino emission in different populations of mergers
- ORCA already surpassing ANTARES in GeV range

Limits on $\phi = E^2 dn/dE$		
(all-flavour, *E^{-2} spectrum)*	**ORCA4**	**ORCA6**
Limits [GeV/cm²]	100-500	50-200
5-95% neutrino energy range	70 GeV - 5 TeV	40 GeV - 5 TeV



Multimessenger analyses: Gamma rays

Coincidences with other neutrino detections & gamma rays

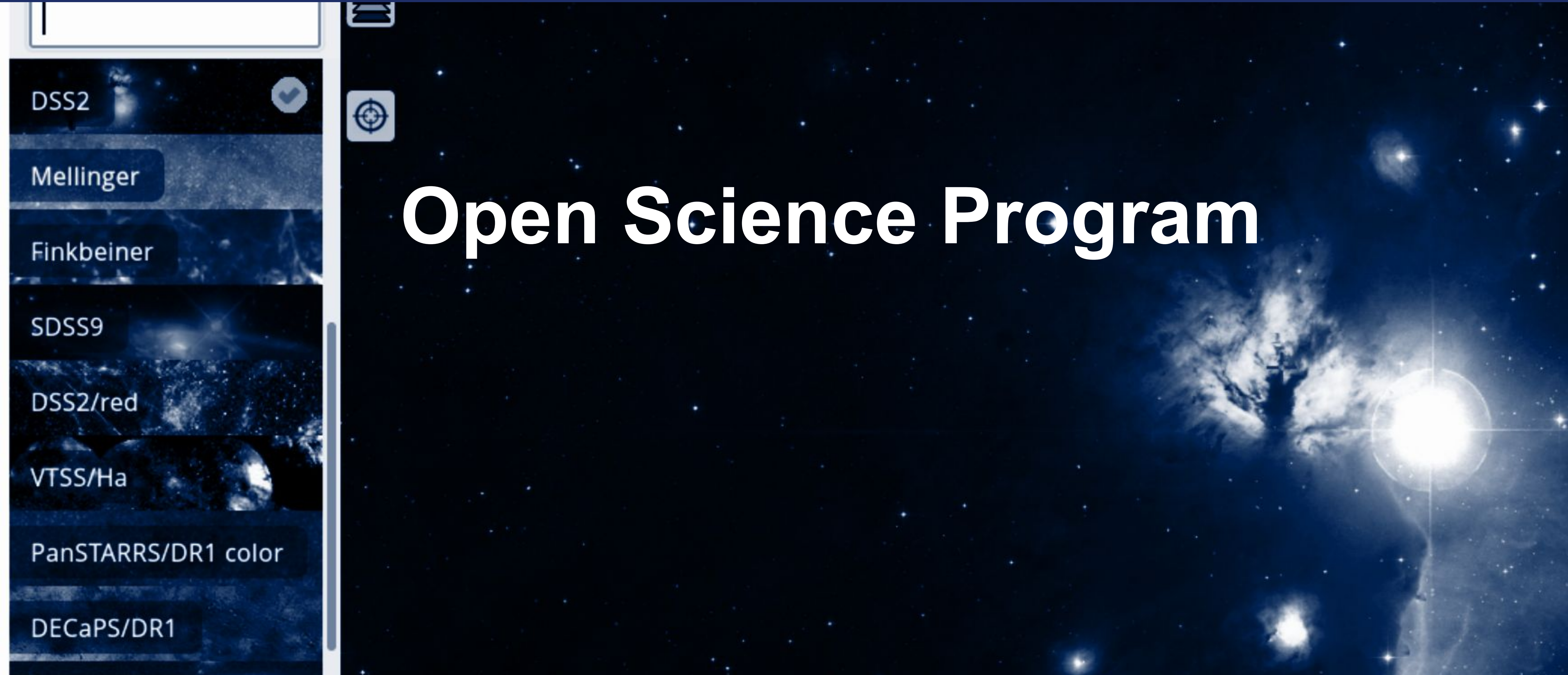


zenodo.org/record/6785224

- combine with gamma ray observations
  - joint binned likelihood analysis
  - for 4 different sources (VelaX et al)
  - pure leptonic / hadronic scenarios
  - gain from combined CTA/KM3NeT analysis
- follow-up IceCube neutrino alerts
  - looking for a signal excess around the best Active Galactic Nuclei (AGN) counterpart (4 alerts in 2021/22)
  - estimating background from off region
  - time window of ±1 day
  - extended search time window: 1 month

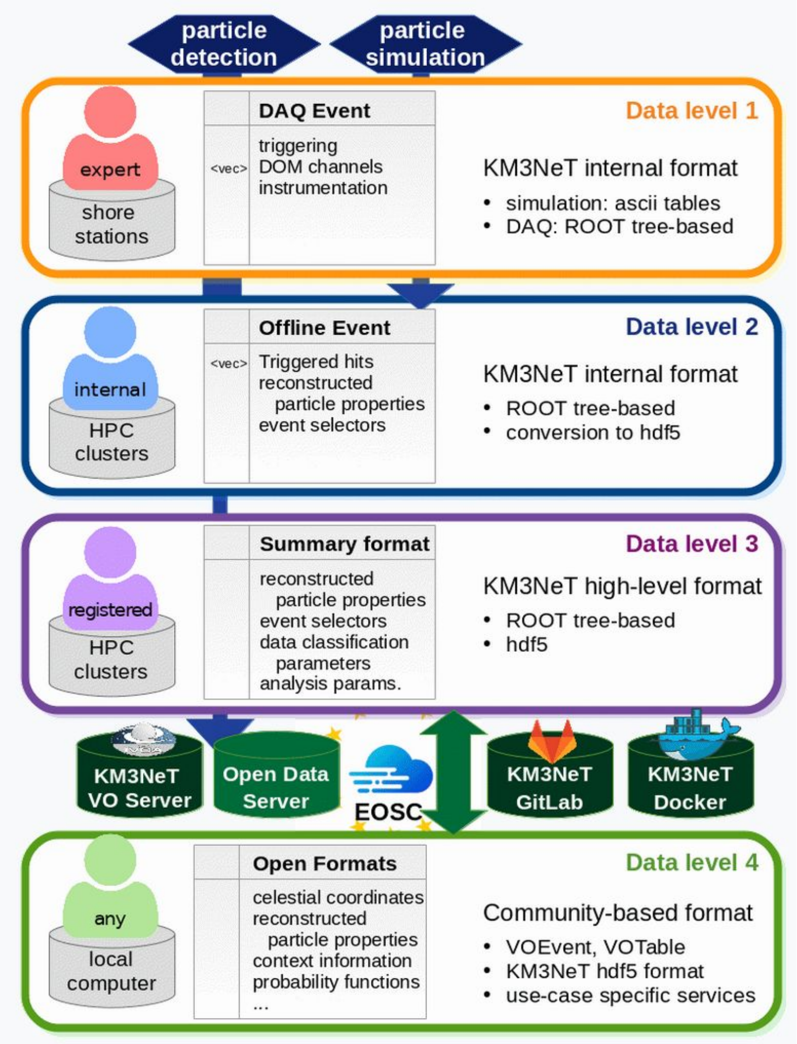
zenodo.org/record/6805372

Open Science Program



Offering data and cooperation

Developing with Open Science

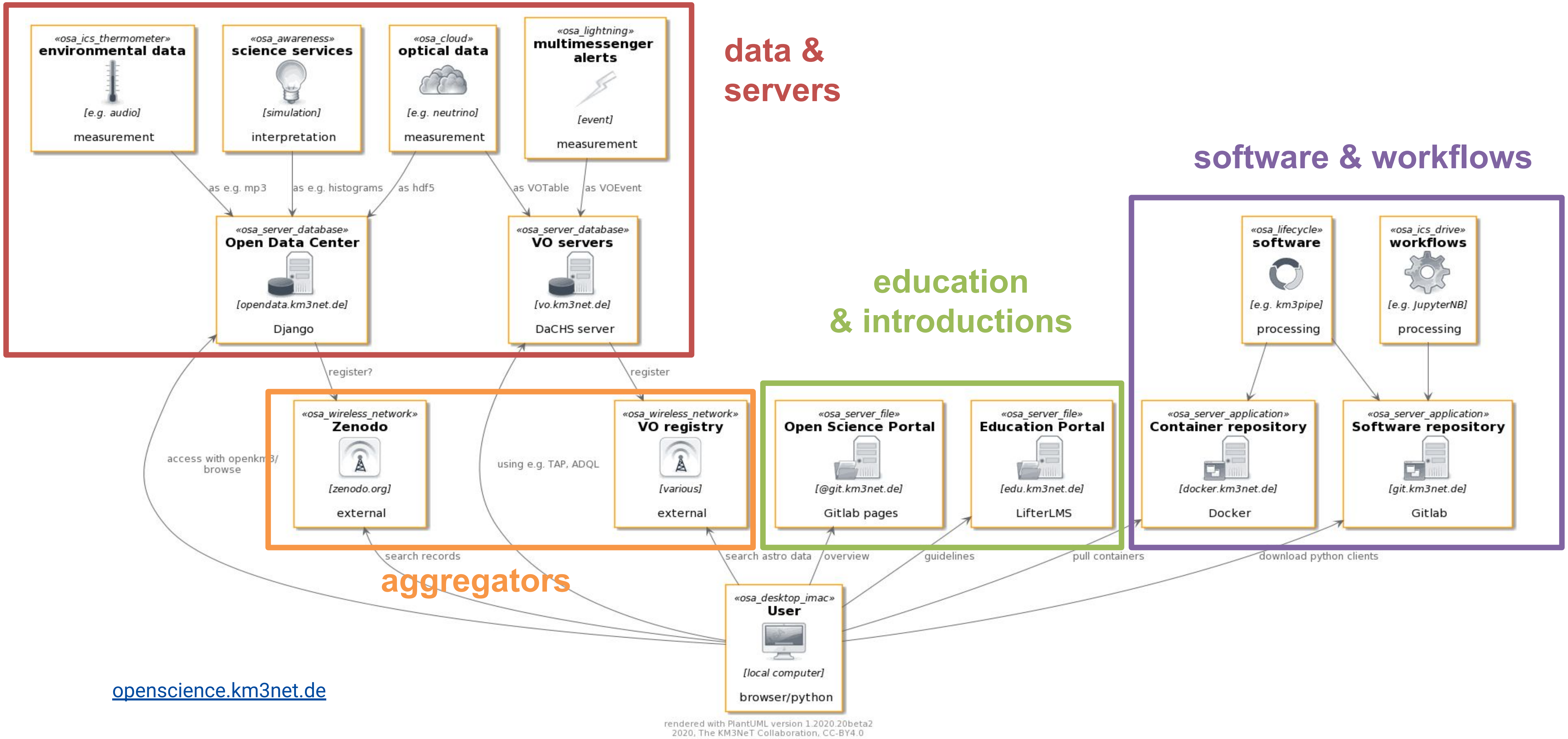


- open science policy
  KM3NeT supports the aims of open data and open science and commits to implement the necessary steps wherever possible. This includes open data access data supporting publications, open source software and open data in general including the information needed to appropriately use the data.

- open data
  - event data in full releases (after embargo)
  - single neutrino events (alerts)
  - services for background estimates/simulations

Open Science Environment

Only publishing data is not enough



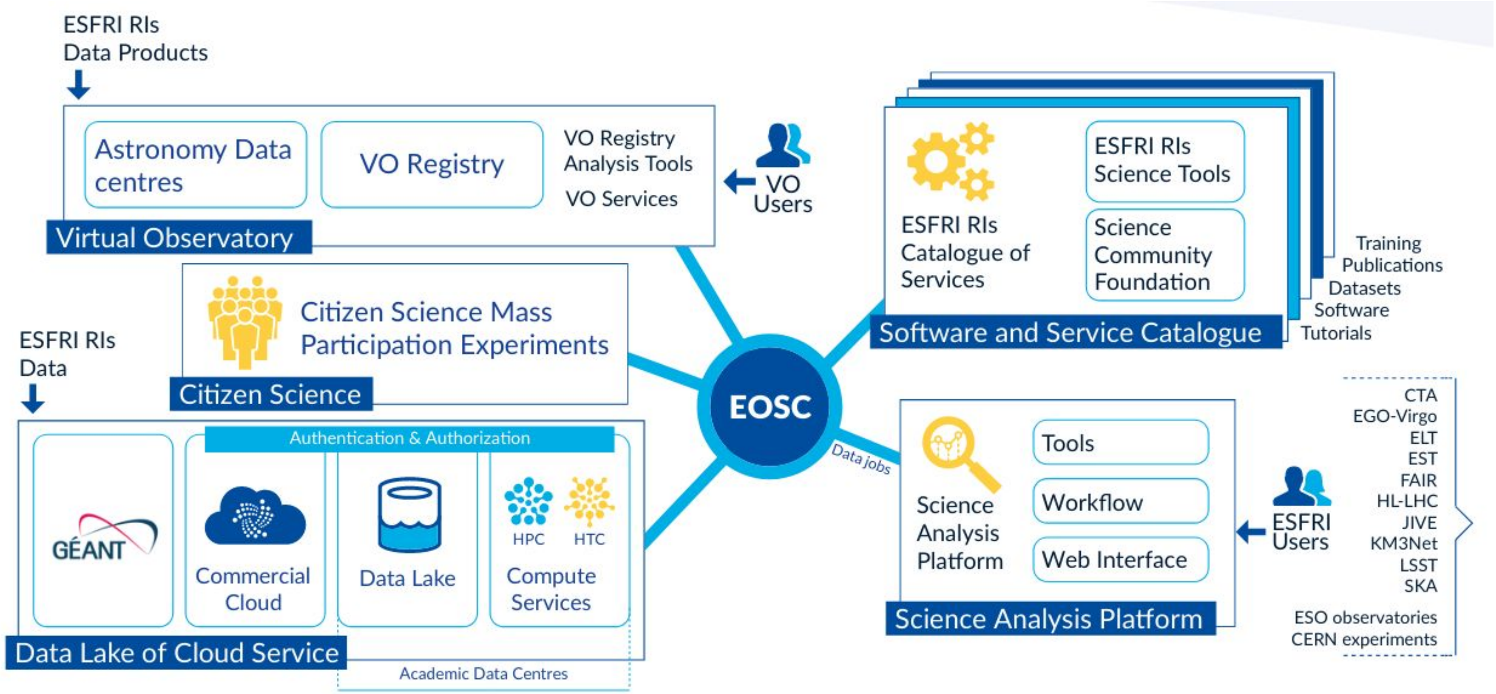
openscience.km3net.de

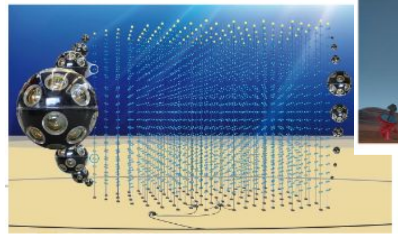
Developing with common initiatives

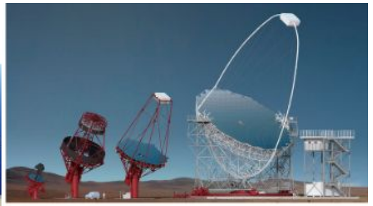
From institute initiatives to large-scale cooperation

Development happens in the community

- in ESCAPE/EOSC future
  - data lake infrastructure
  - common analysis platform
  - software sharing
  - common formats
- in various multi-messenger initiatives

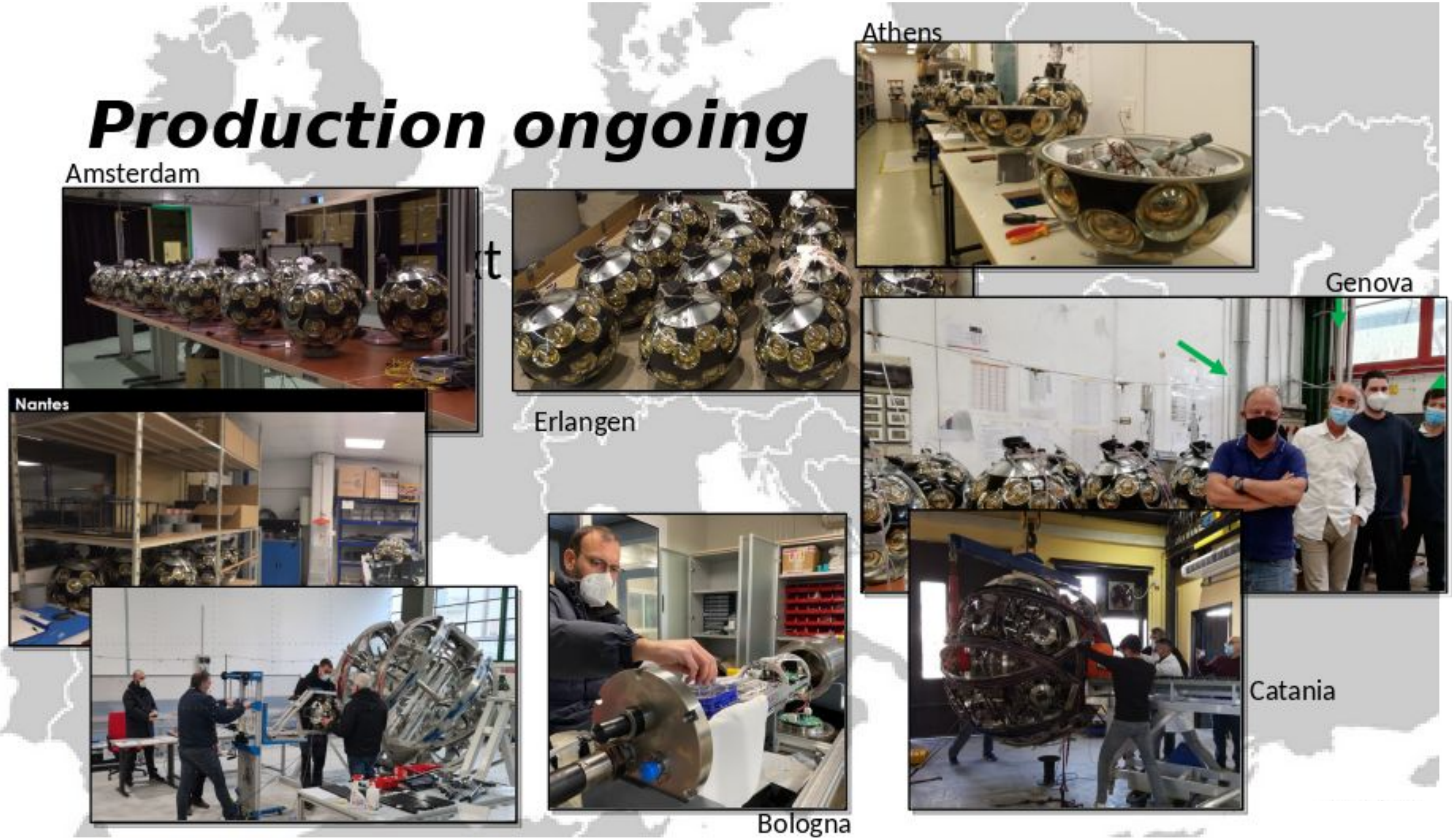






Where are we going

Continuing building - and expanding the physics program



Thank you for your attention!