Piotr Kalaczyński, pkalaczynski@camk.edu.pl

The 6th Young Astronomers Meeting at CAMK-PAN
08.03.2024

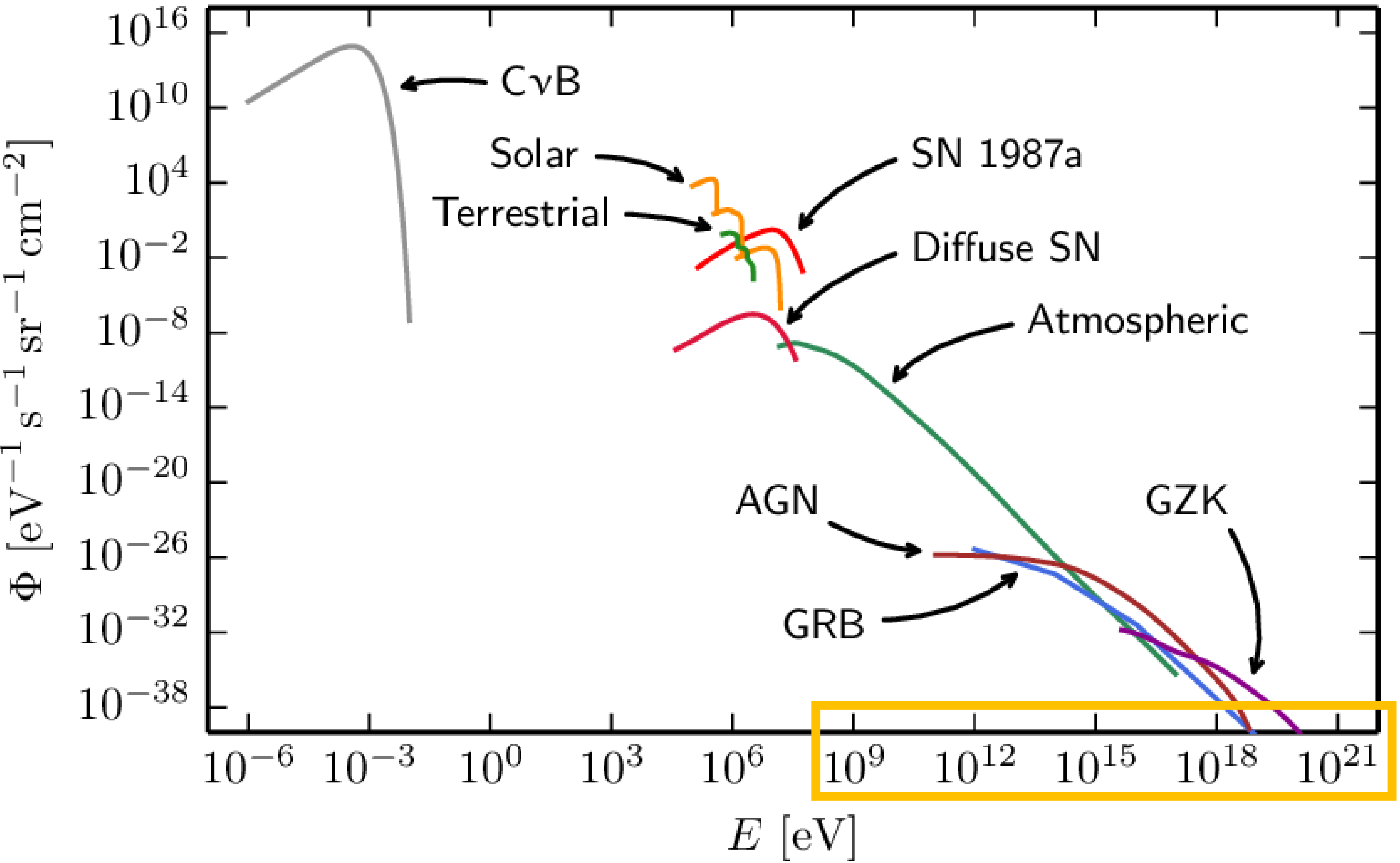
KM3NeT: neutrino astronomy and more

CEAI
Center of Excellence in Artificial Intelligence

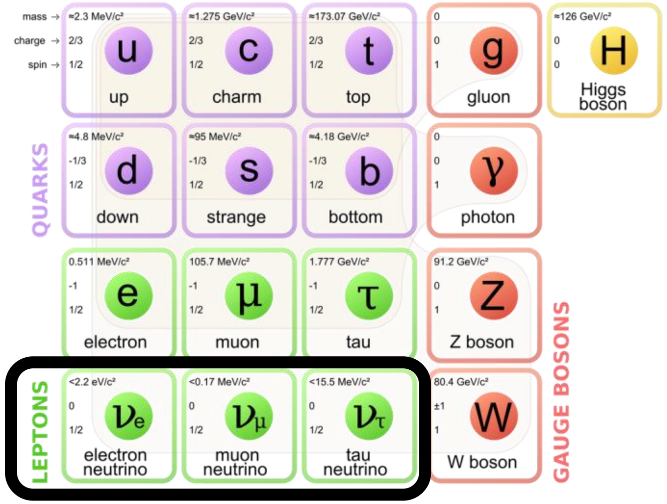
CAMK PAN

Outline

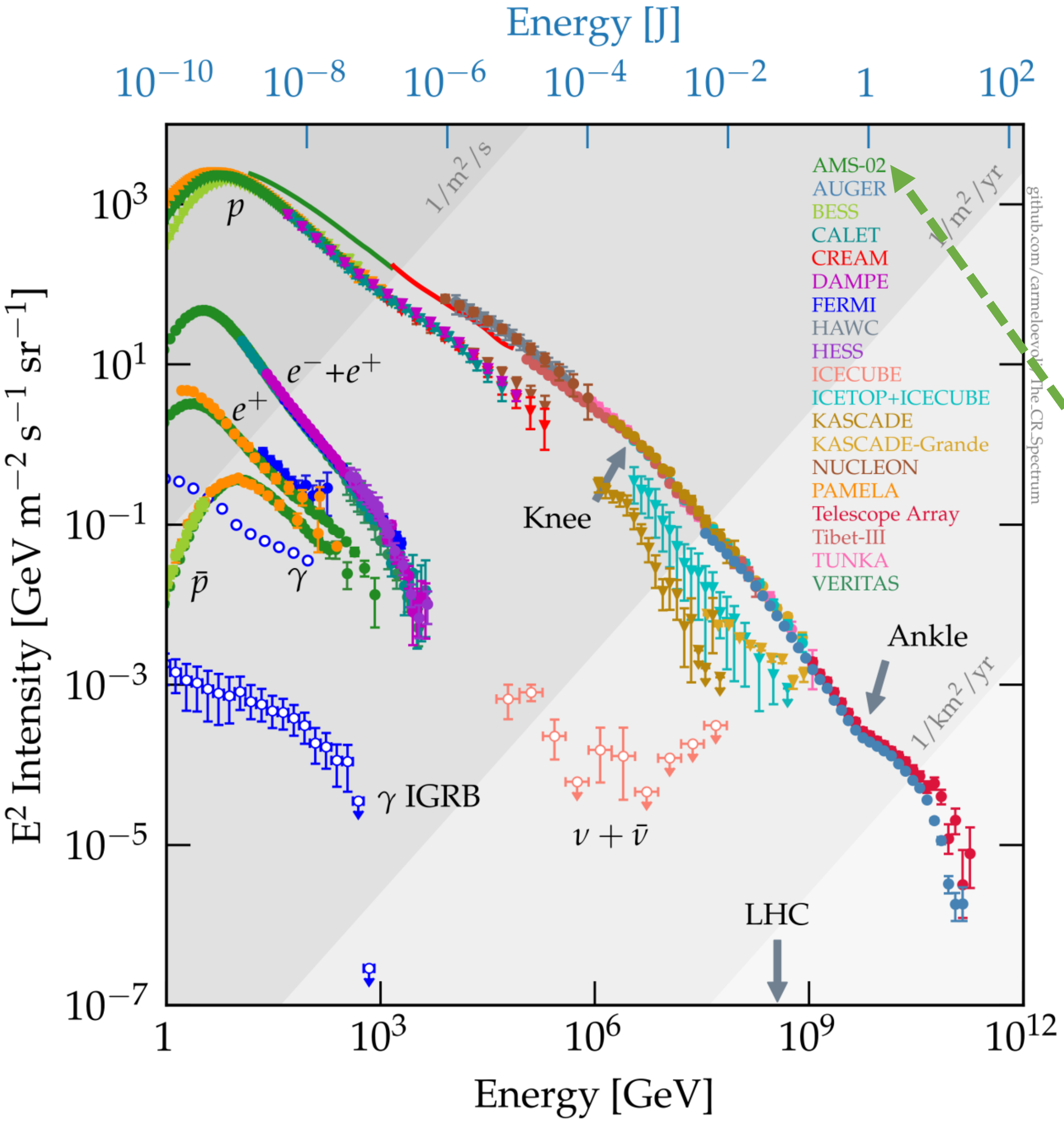
- Introduction
- KM3NeT
- Analyses
- Summary



KM3NeT E scale



Cosmic rays



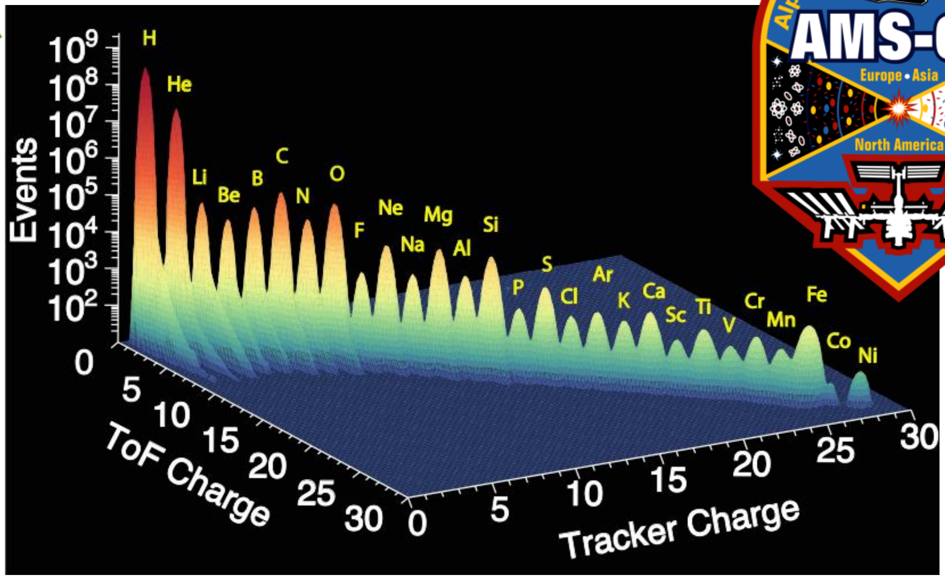
Cosmic Rays (CR):

High-Energy particles & nuclei arriving at Earth from outer space

First discovered by Victor Hess in 1912
(Nobel prize in 1936)

Quite a few measurements since then, e.g.:

https://doi.org/10.1016/j.physrep.2020.09.003



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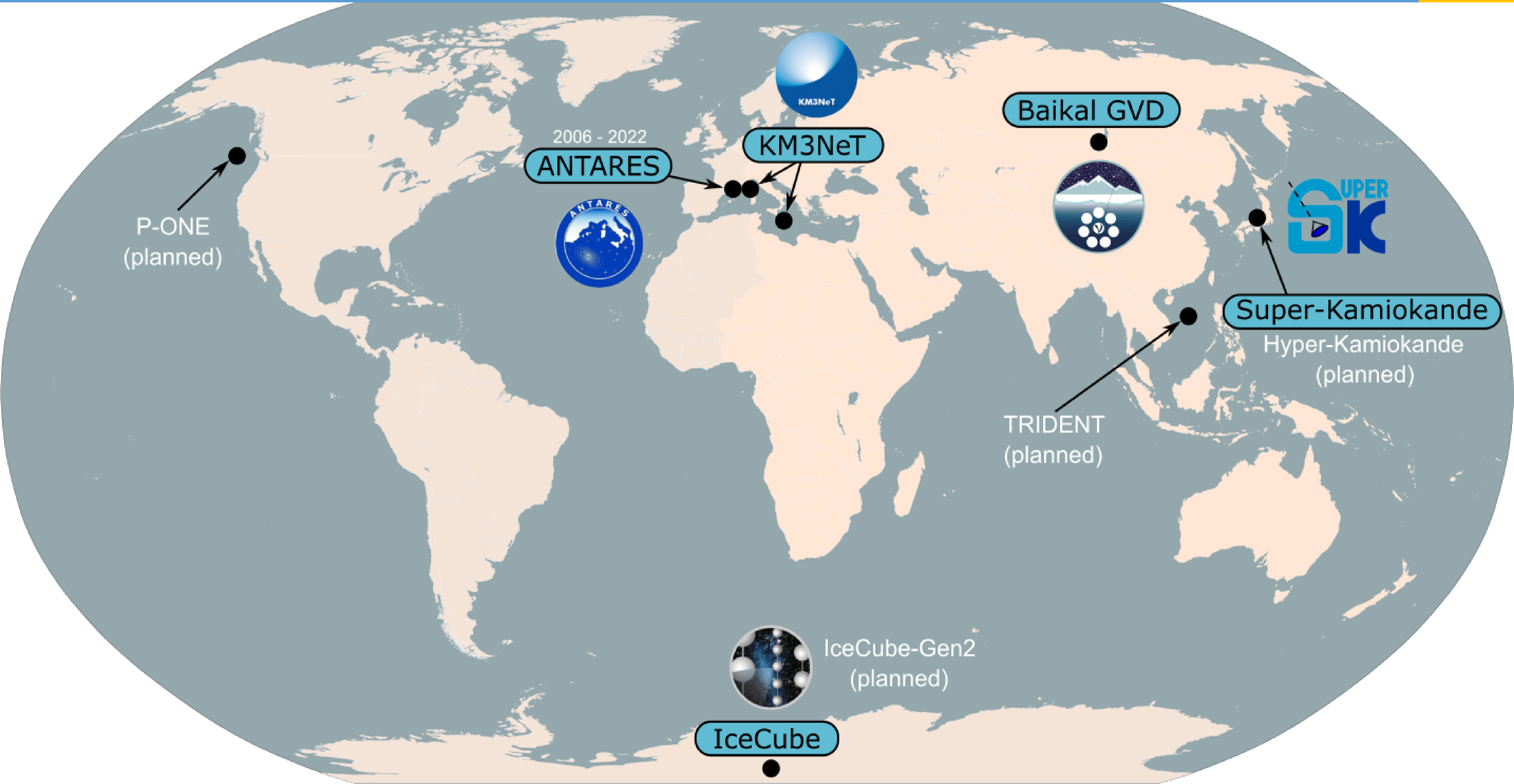
Water Cherenkov ν telescopes

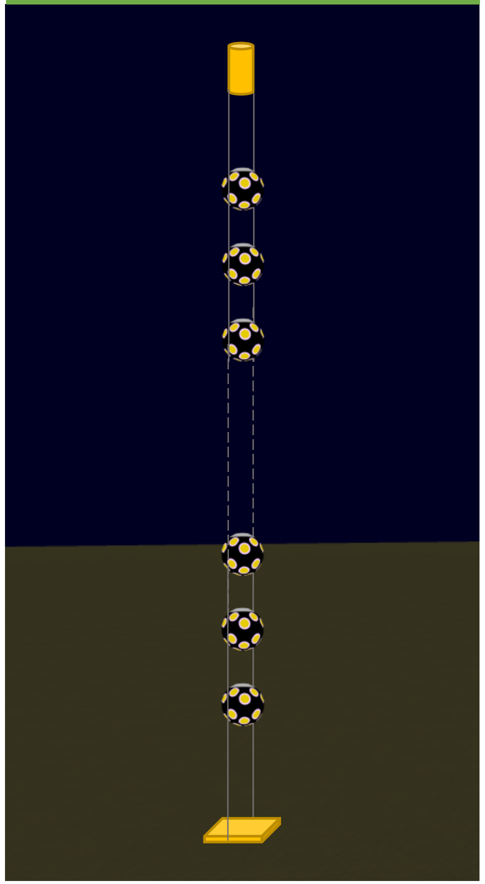


Detector design summary

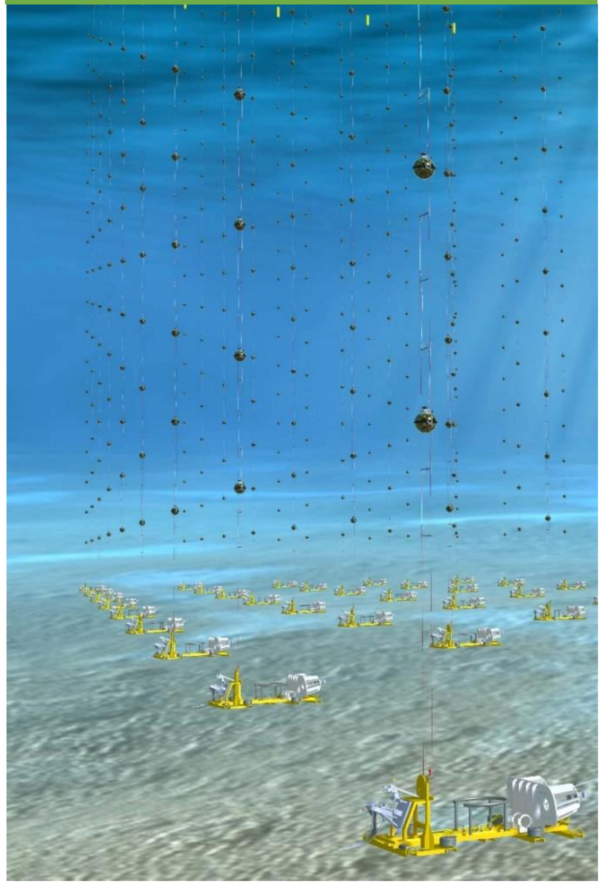
DOM:
71 unique components

1 DOM:
31 PMTs

1 string (DU):
18 DOMs



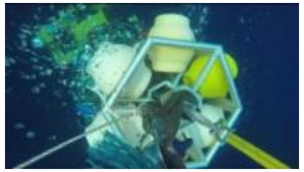
1 building block:
115 DUs



DOM production:(@Nikhef)

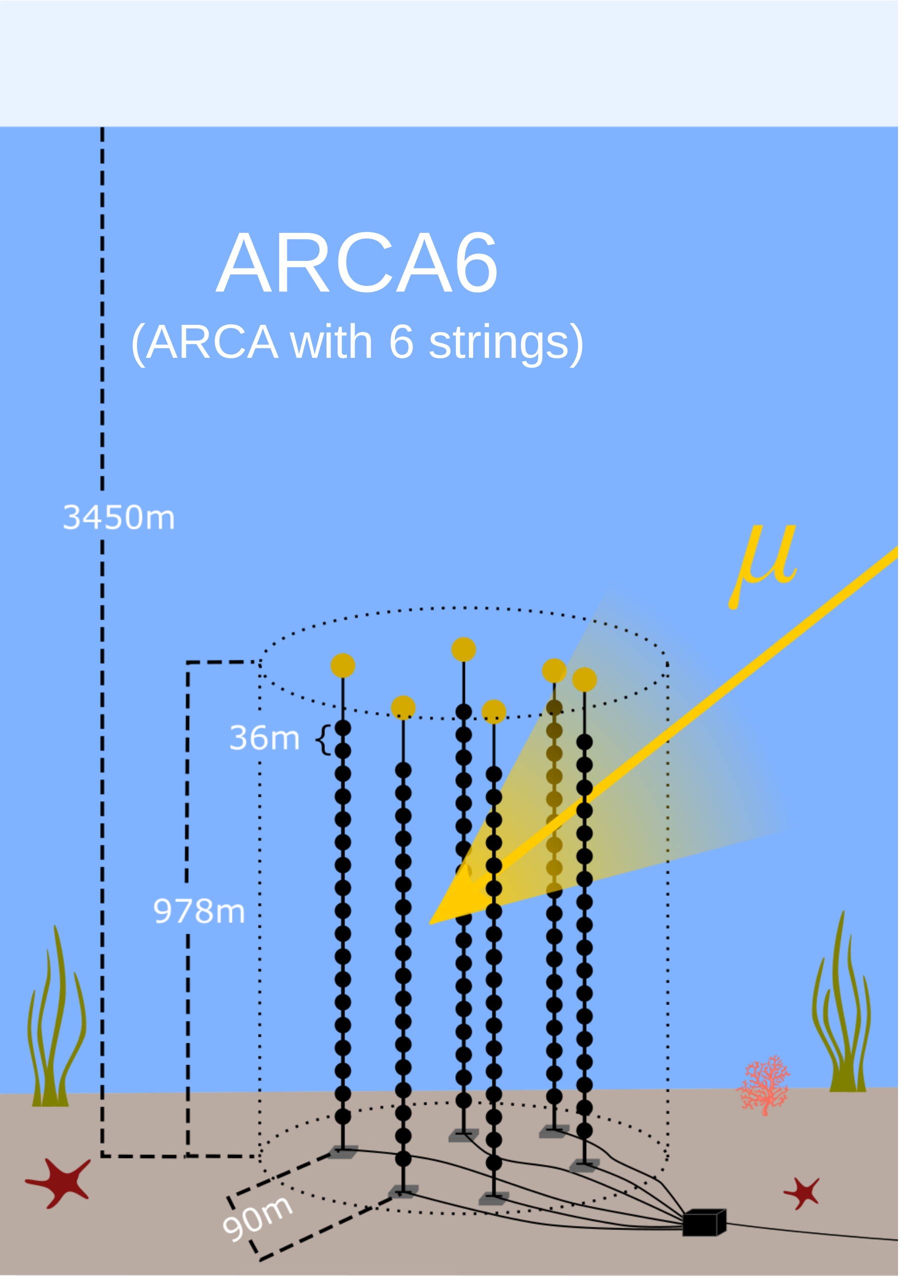
Preparation for deployment:

String deployment:



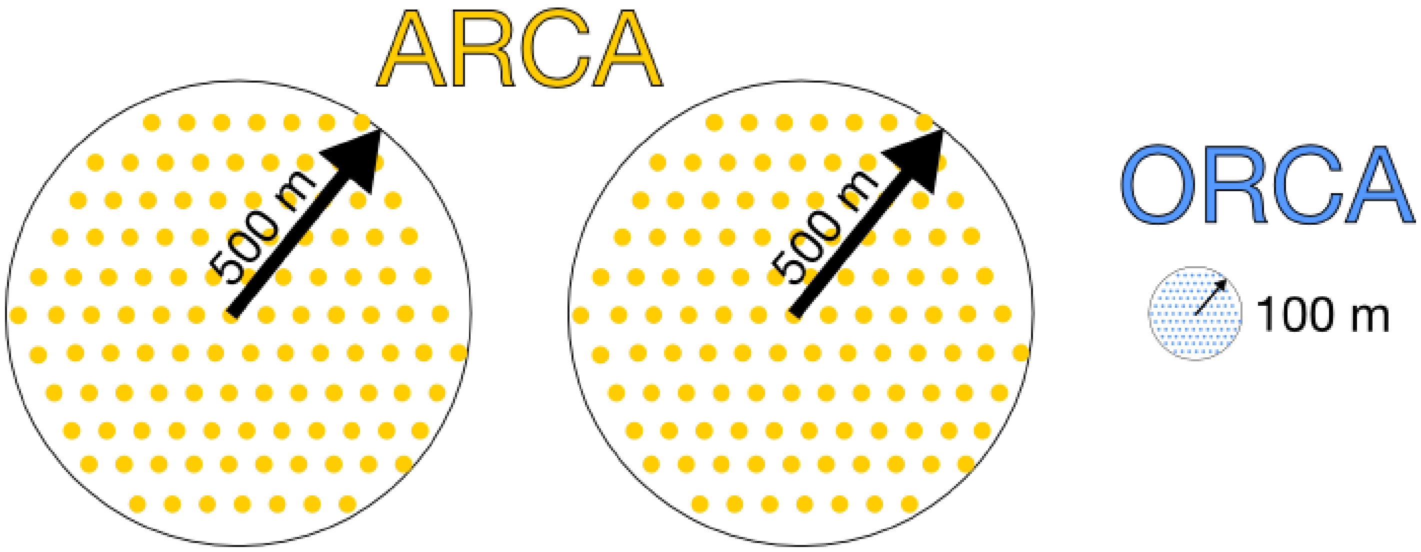
More at:
youtube.com/KM3NeTneutrino

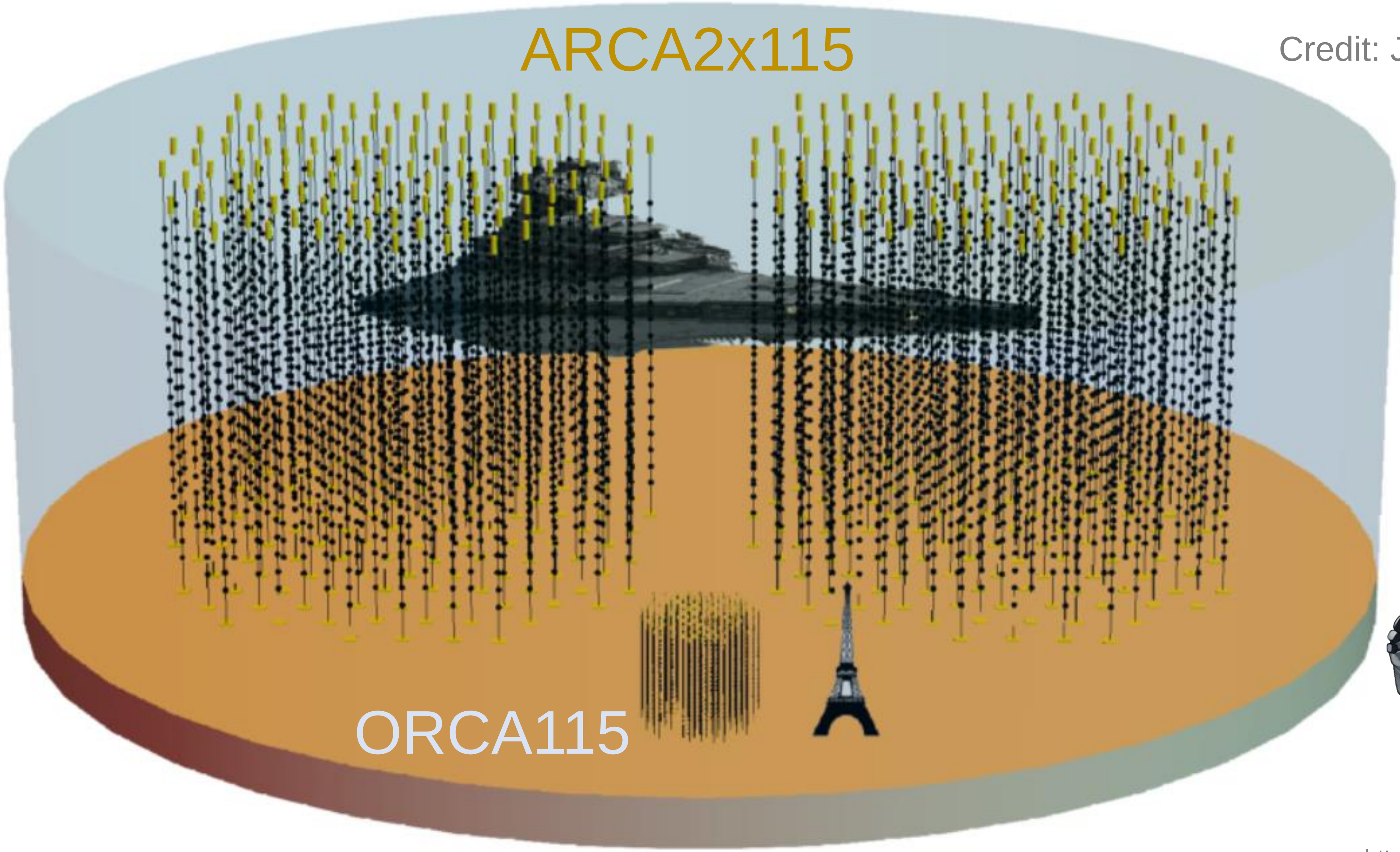
Detectors: details



Detector	ARCA	ORCA
Depth	3.5 km	2.45 km
Volume	1 km^3 (1Gton)	0.007 km^3 (7Mton)
# strings	28 / 2x115	16 / 115
Topic	Astroparticle RCA*	Oscillation RCA*
Goal	ν_{astro}	m_ν hierarchy

*RCA : Research with Cosmics in the Abyss





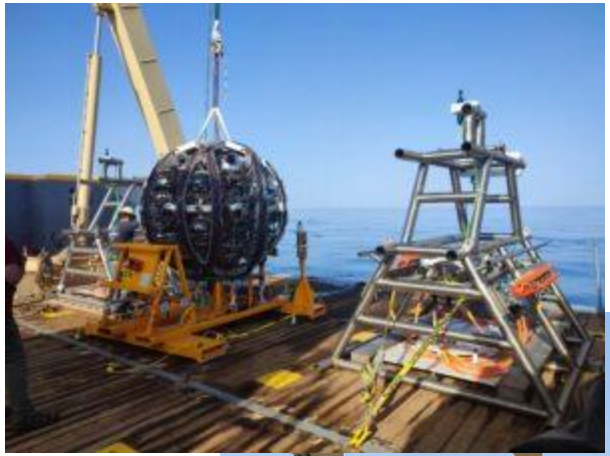
Credit: Joao Coelho

YES, the imperial star destroyer IS up to scale!

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

ARCA timeline

- Dec 2015: first strings
- … [more details](#)
- Sep 2023: +10 **strings**
- Currently: **ARCA28!**
- …
- Summer 2024: next deployment
- …
- 2032(?): ARCA2x115



ORCA timeline

- Dec 2017: first strings
- … [more details](#)
- Apr 2023: +3 **strings**
- Currently: **ORCA16!**
- …
- Dec 2023: next deployment
- …
- 2030(?): ORCA115

For more follow us at:
https://www.km3net.org

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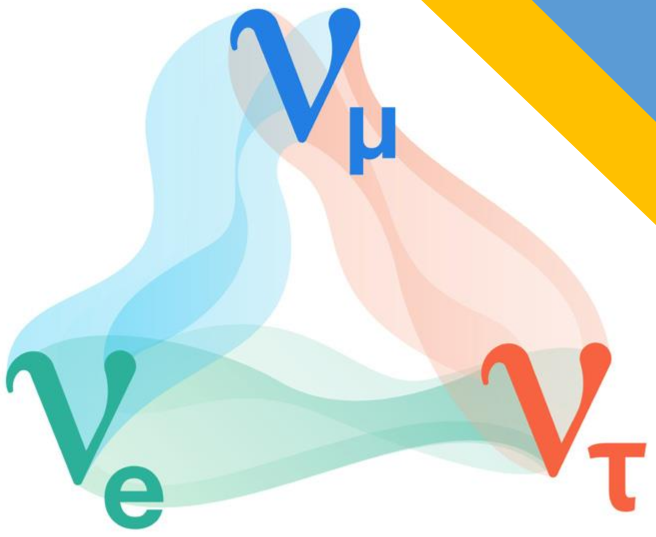
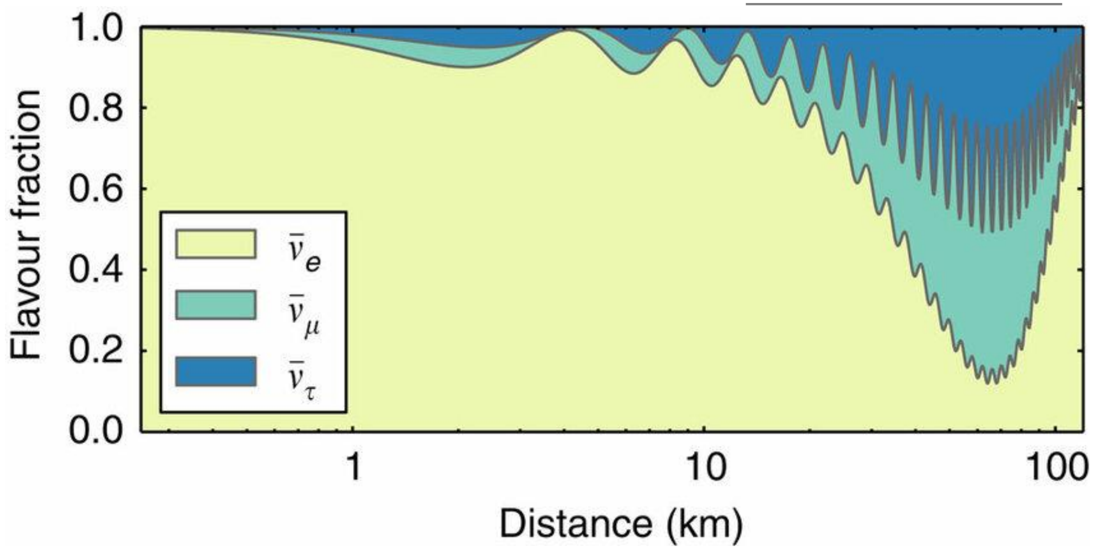


https://sanfordlab.org/article/why-dune-searching-origin-matter

Interactions of neutrinos:

- gravitational
- weak
- <u>ν oscillations</u>

DOI: 10.1038/ncomms7935

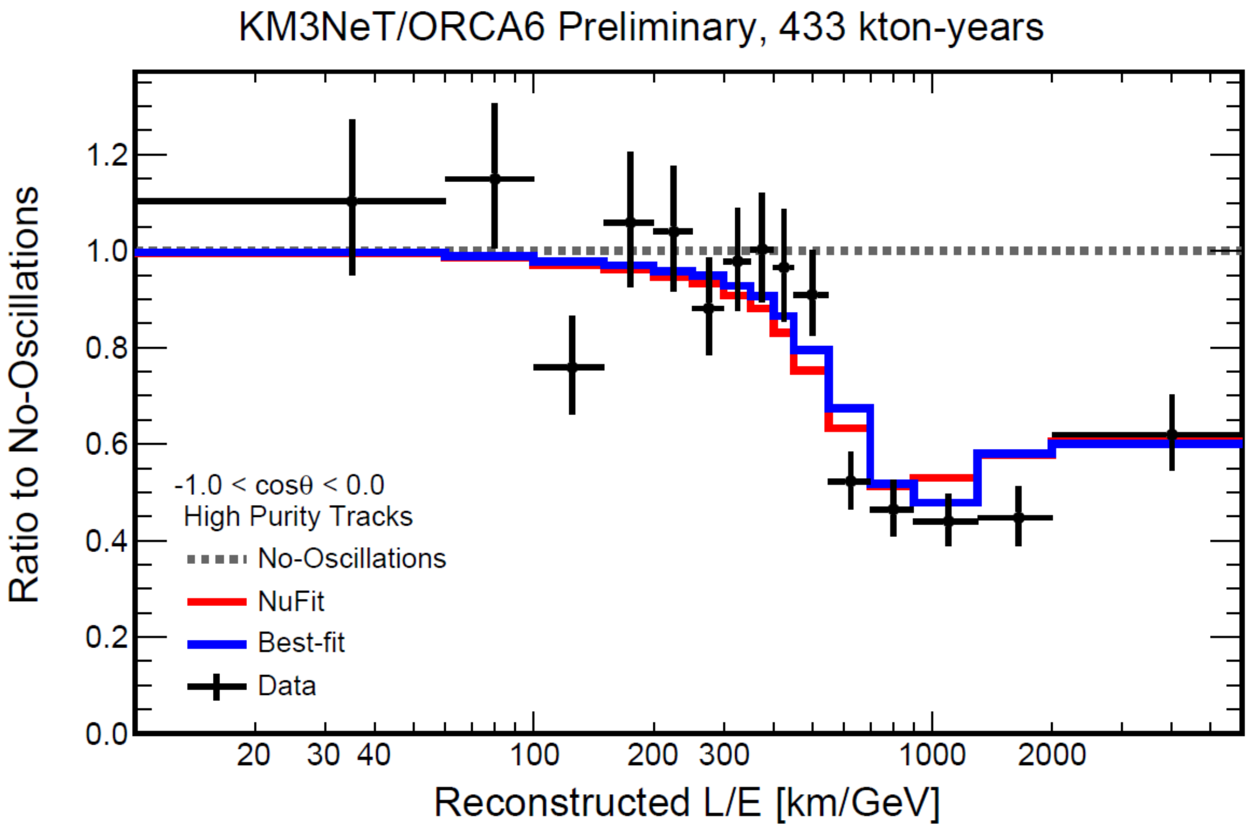


Best fit

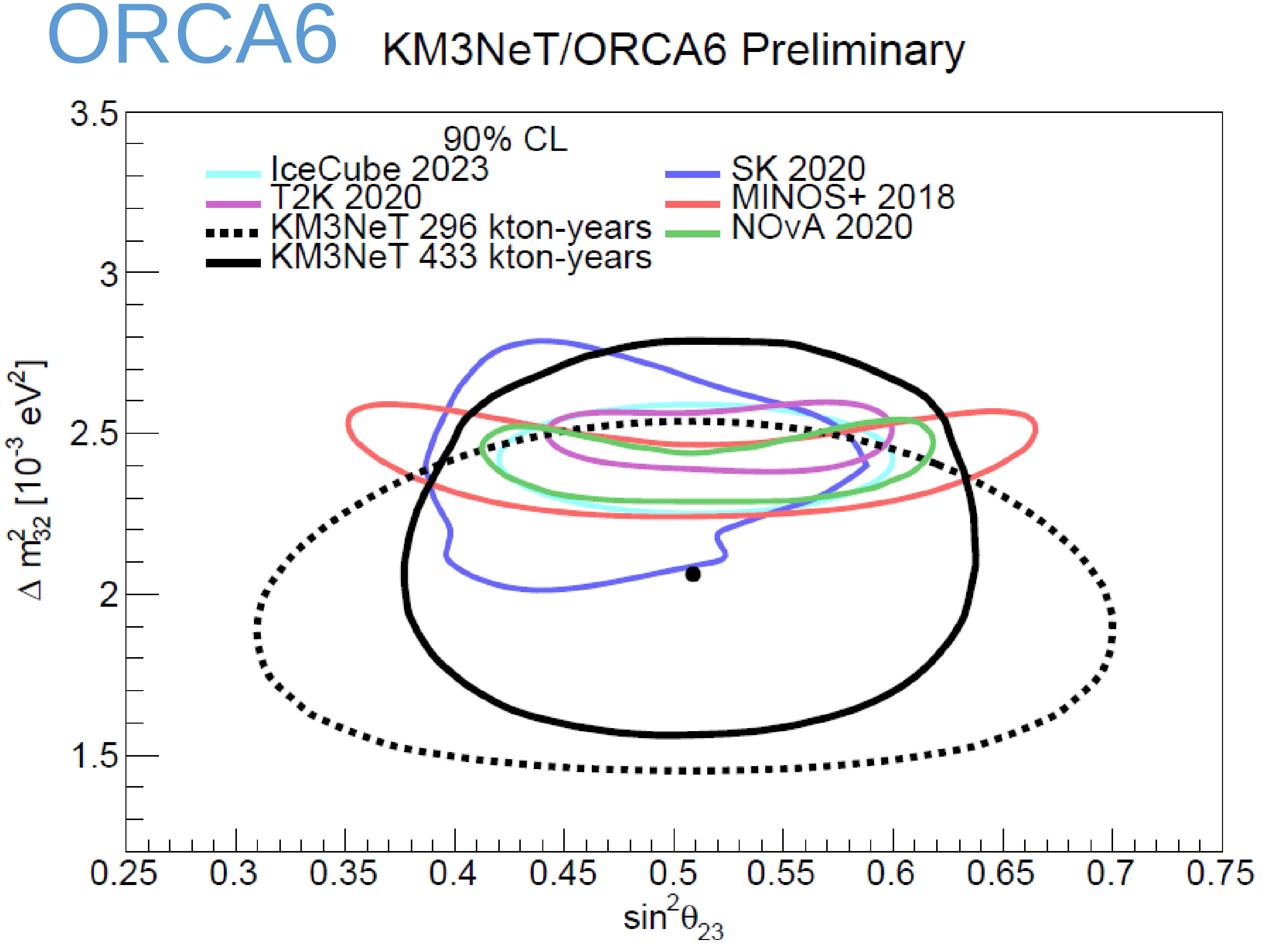
$$\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$$

$$\Delta m^2_{31} = \left(2.14^{+0.36}_{-0.25}\right)\cdot 10^{-3}\ \mathrm{eV}^2$$

Preference for normal ordering (NO): $-2\log\left(\frac{L_{NO}}{L_{IO}}\right) = 0.9$



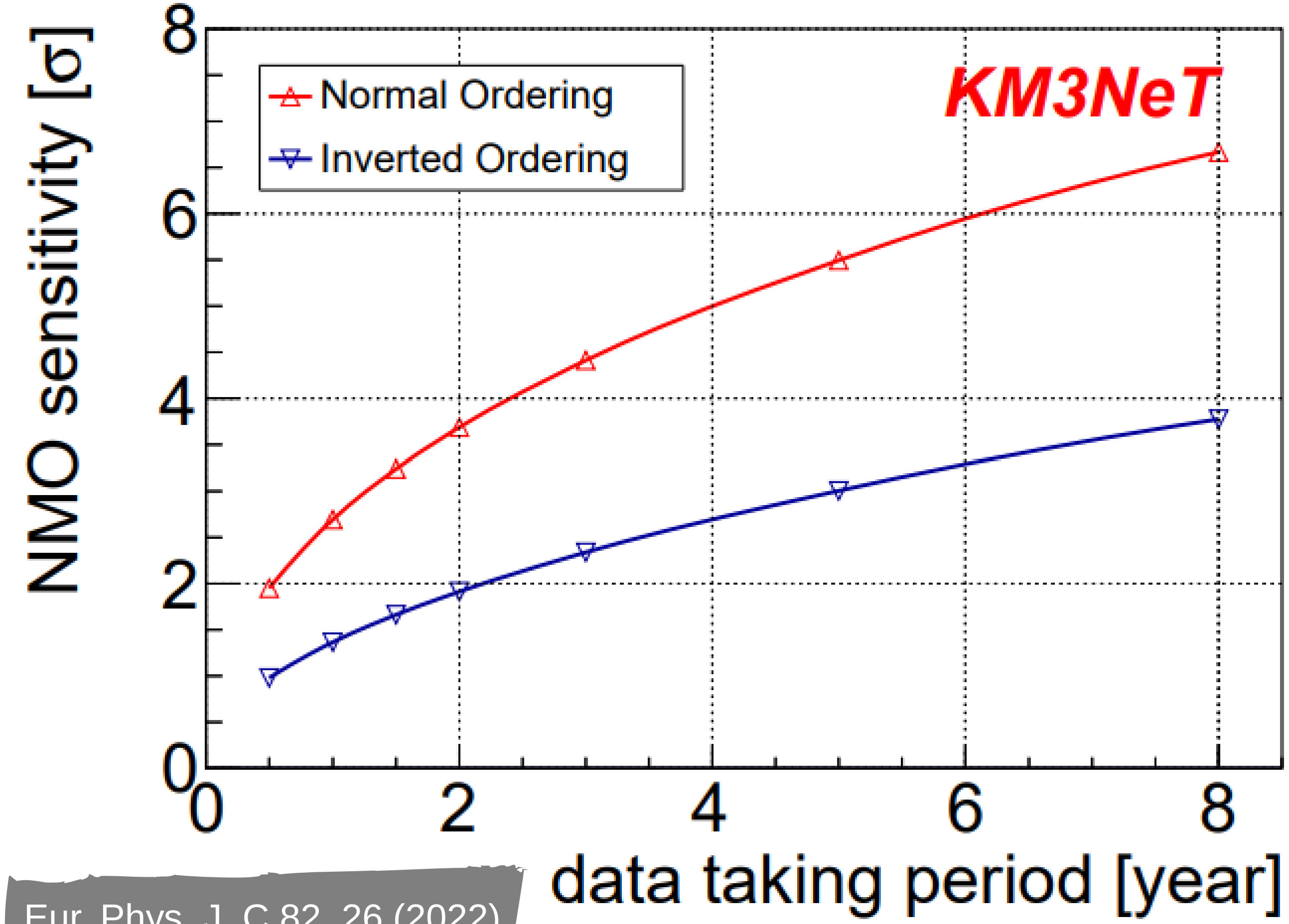
ORCA6



PoS(ICRC2023)996

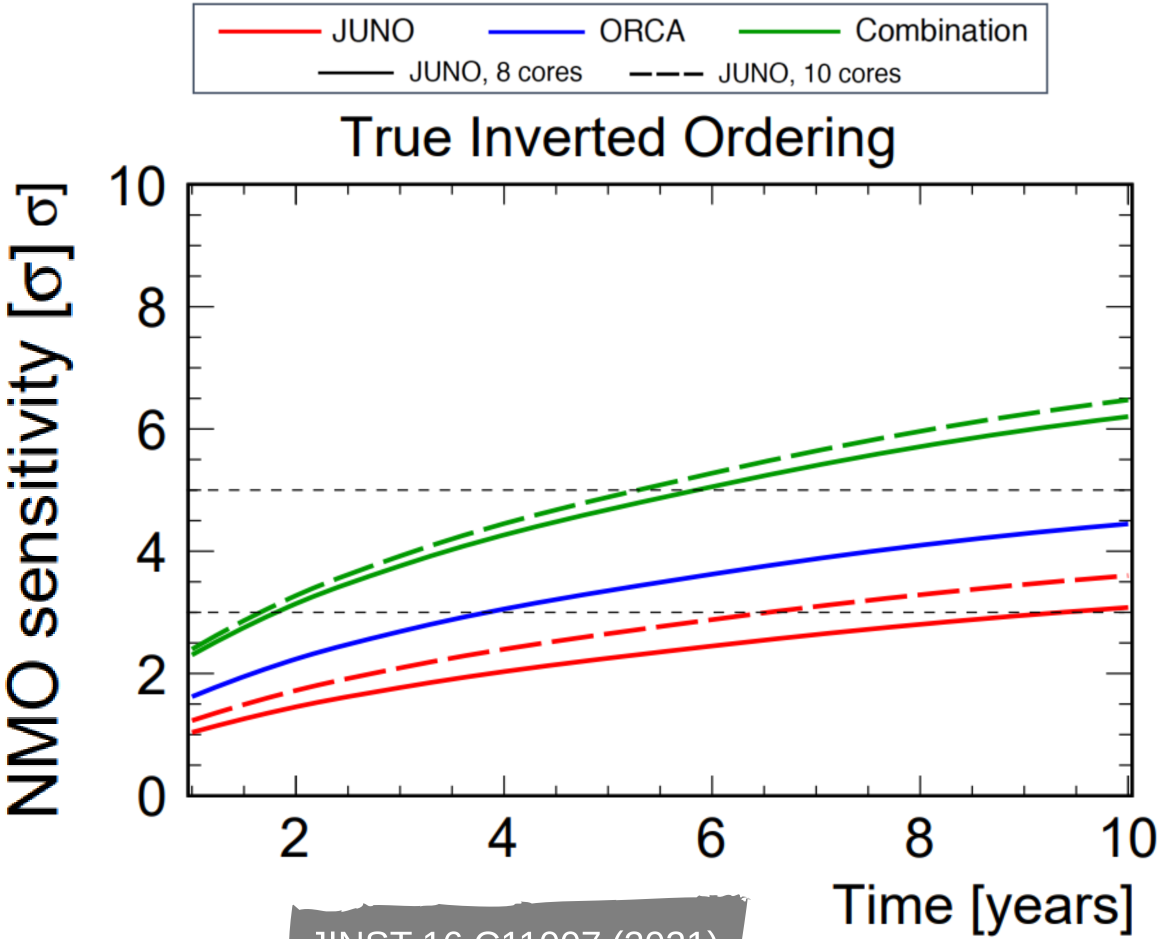
Neutrino Mass Ordering (NMO) sensitivity

ORCA115



Eur. Phys. J. C 82, 26 (2022)

ORCA115 + JUNO

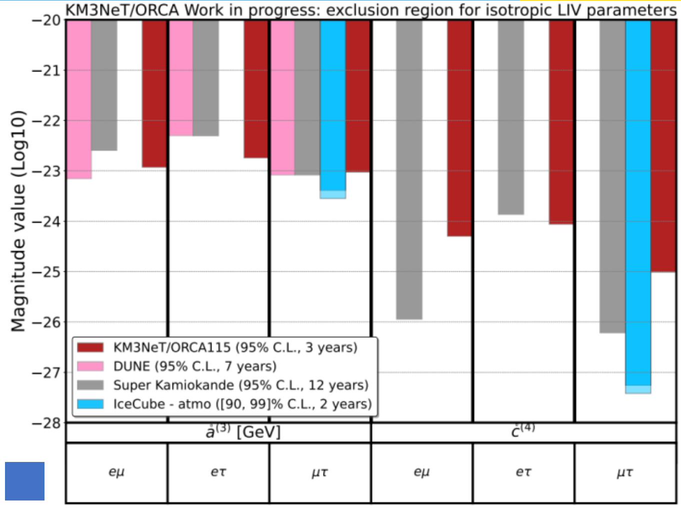


JINST 16 C11007 (2021)

Possibly world-first to determine NMO!

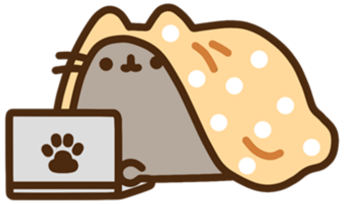
Only selected analyses covered.

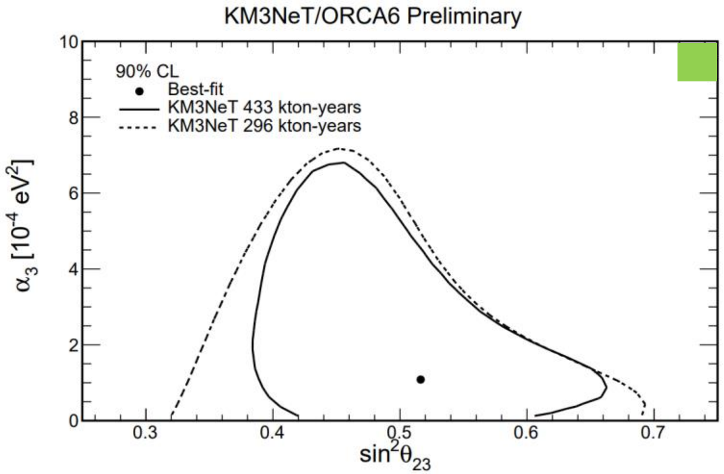
See backup and [arXiv:2309.05016](https://arxiv.org/abs/2309.05016) for more!

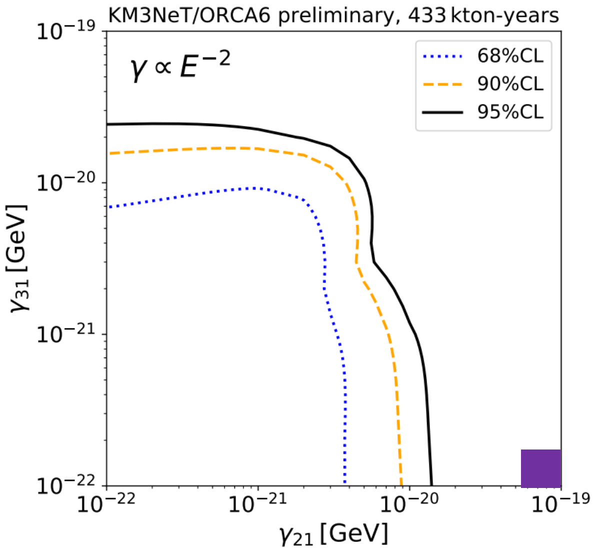


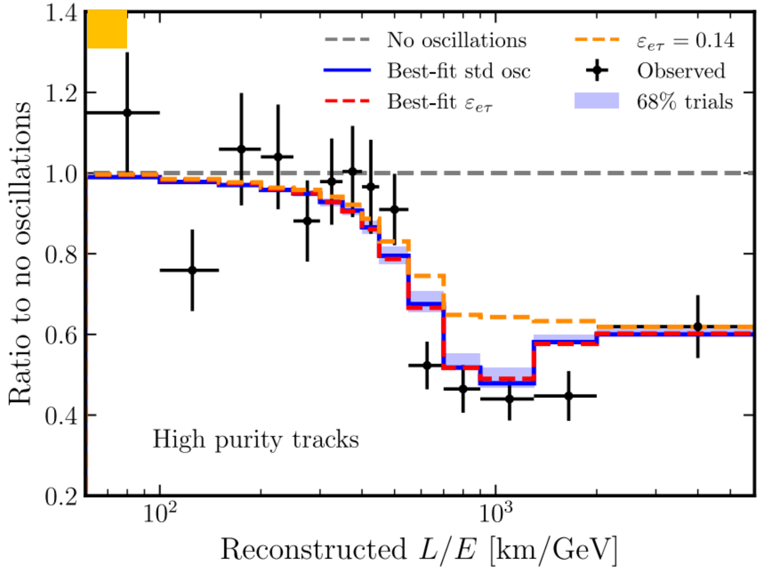
Other osci topics include:

- ❖ Lorentz Invariance Violation [PoS(ICRC2023)1086]
- ❖ Quantum decoherence [PoS(ICRC2023)1025]
- ❖ Non-Standard Interactions [PoS(ICRC2023)998]
- ❖ Invisible neutrino decay [PoS(ICRC2023)997]
- ❖ …



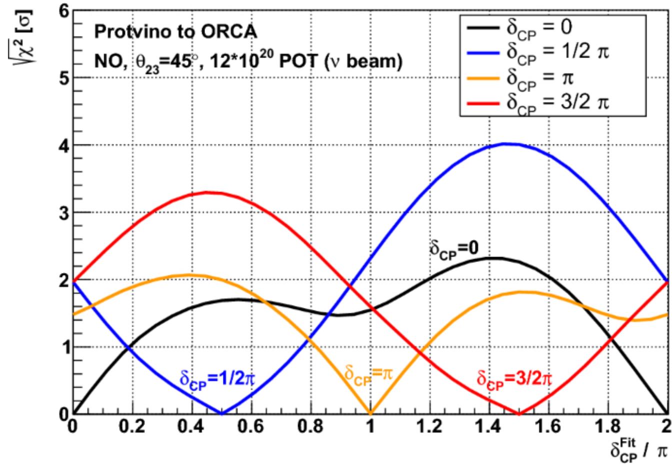






Current Osci open tasks (aka potential theses):

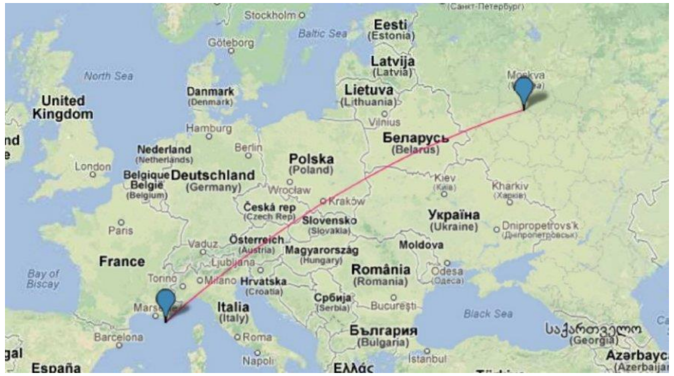
- ❖ Impact of High QE PMT performance on NMO sensitivity
- ❖ Systematic uncertainty study for ORCA6 (and larger configs)
- ❖ Study of systematic correlations
- ❖ Reconstruction of Bjorken-y
- ❖ Identification of neutral current (NC) events



https://doi.org/10.1140/epjc/s10052-019-7259-5

Some more ideas:

- ❖ Neutrino beam to ARCA/ORCA?
  (proposed Protvino to ORCA (P2O) obviously not happening any time soon …)
- ❖ Sensitivity to δ_{CP}
- ❖ …
- ❖ your ideas?



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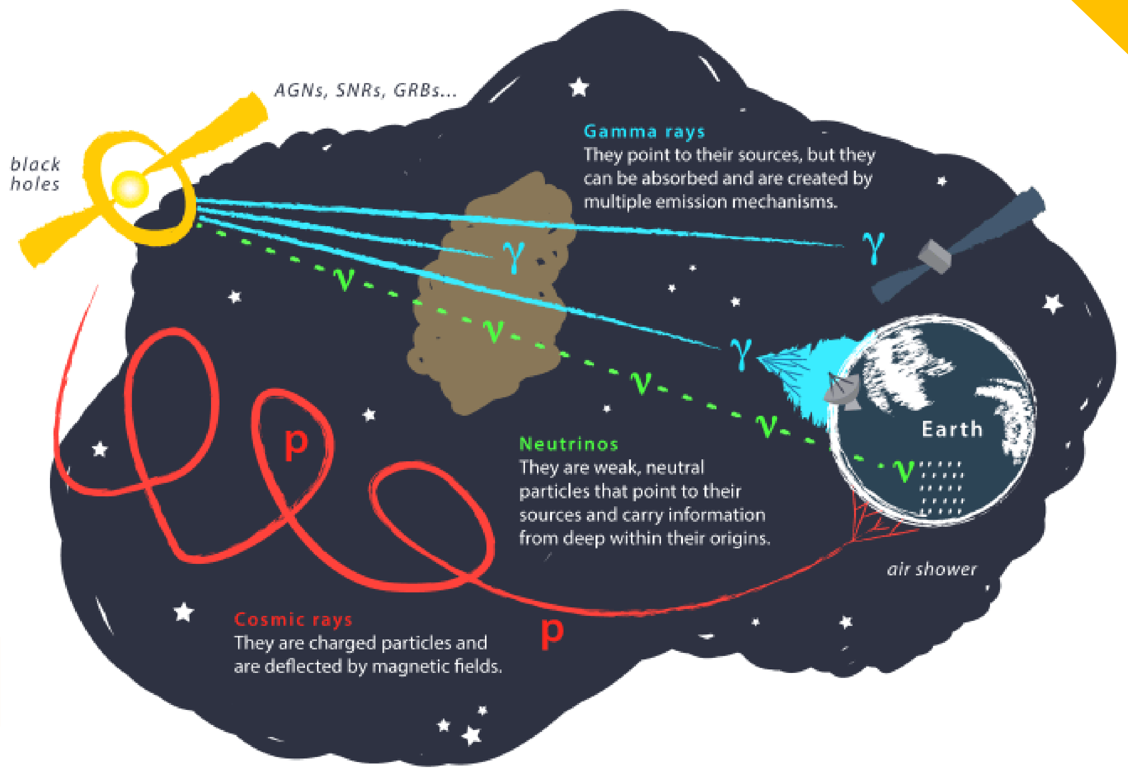


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Point source sensitivity

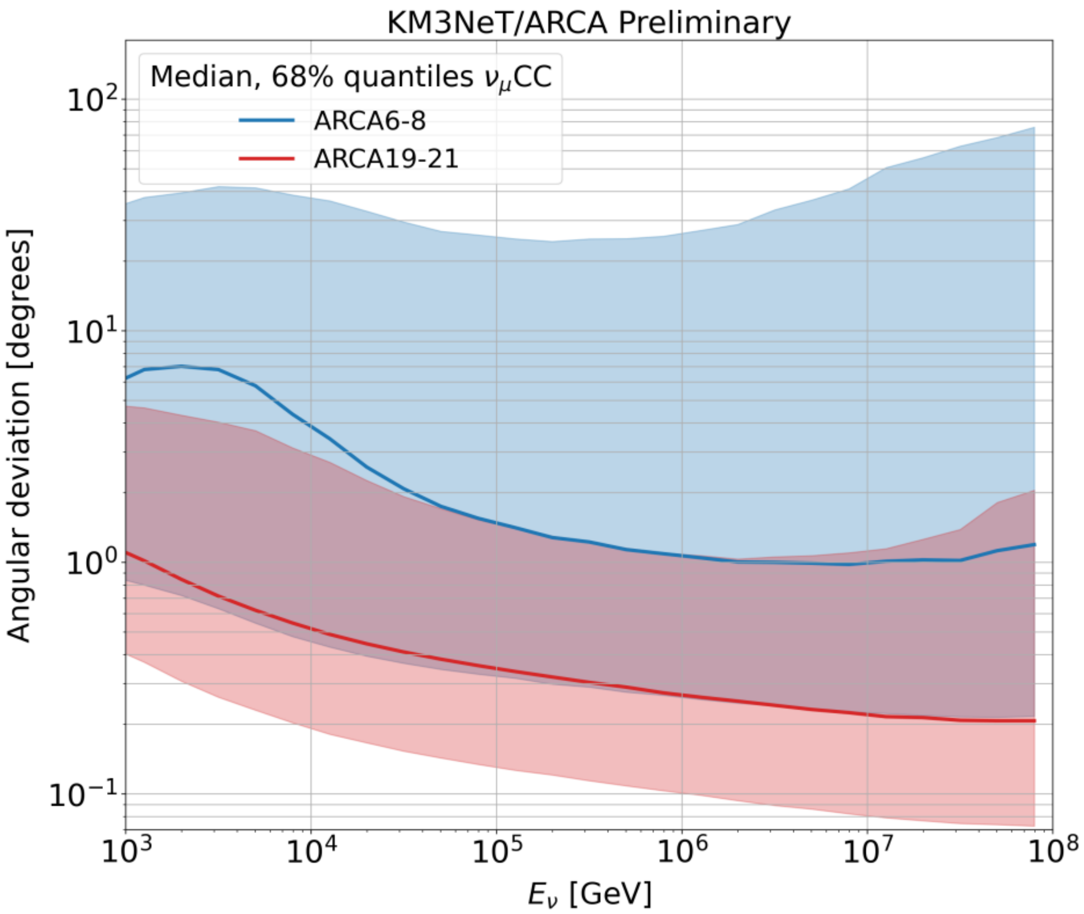
Some details:

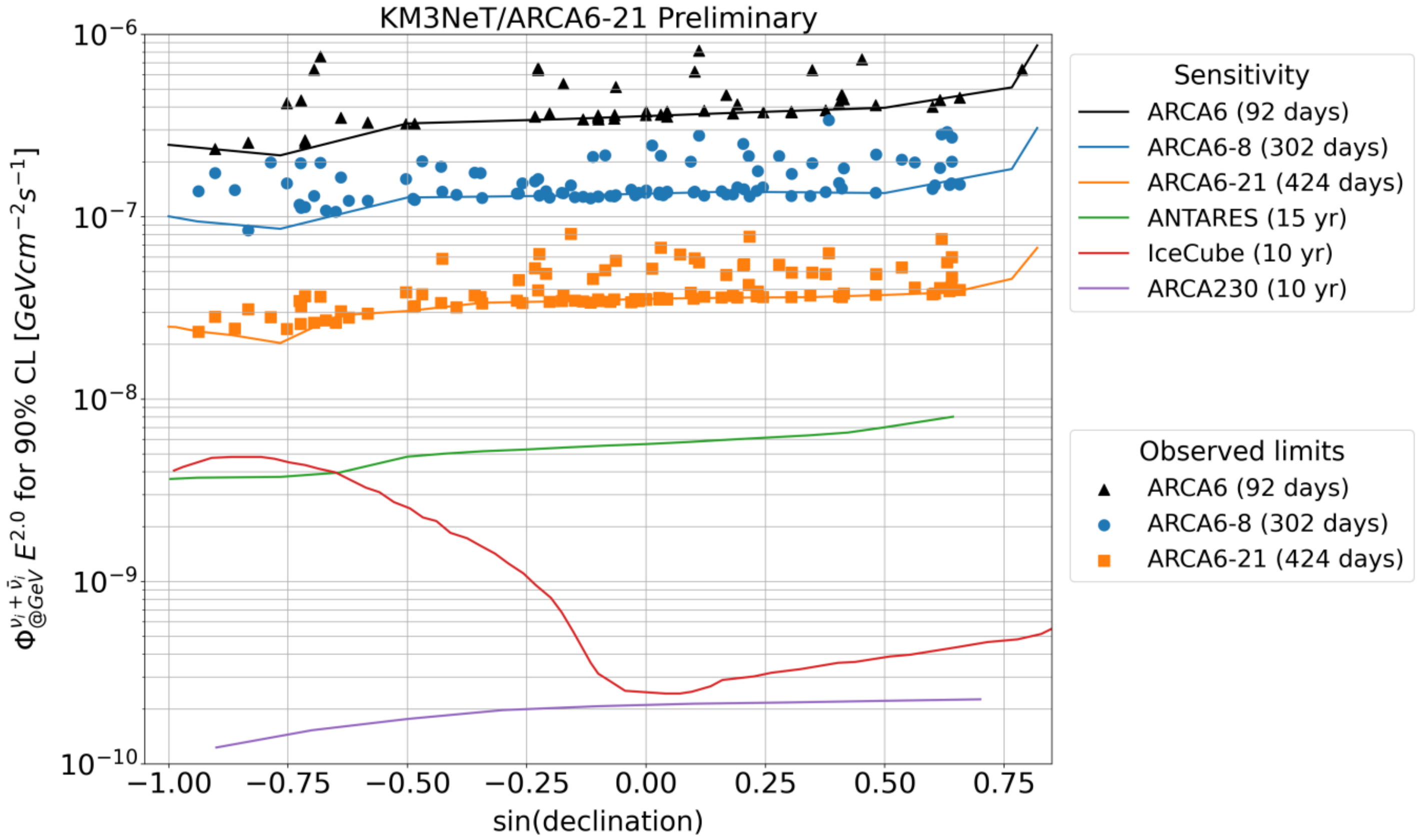
- t-integrated PS search
- 101 candidate sources
- Detector: ARCA6-21
- Livetime: 424d (May-Sep 2021)
- $\Delta\psi \sim 1°$ (for E^{-2})

Results:

- No significant excess [expected]
- Limits not (yet) competitive [expected]
- Best source: Centaurus A ($p = 0.02$) (radio galaxy; yellow arrow)

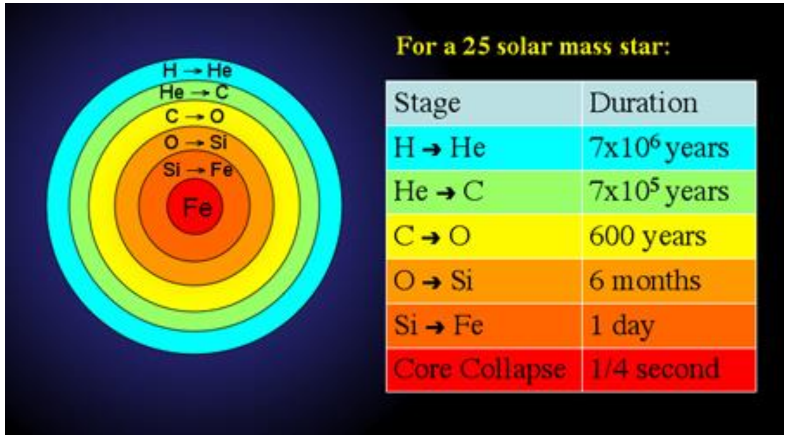
PoS(ICRC2023)1018



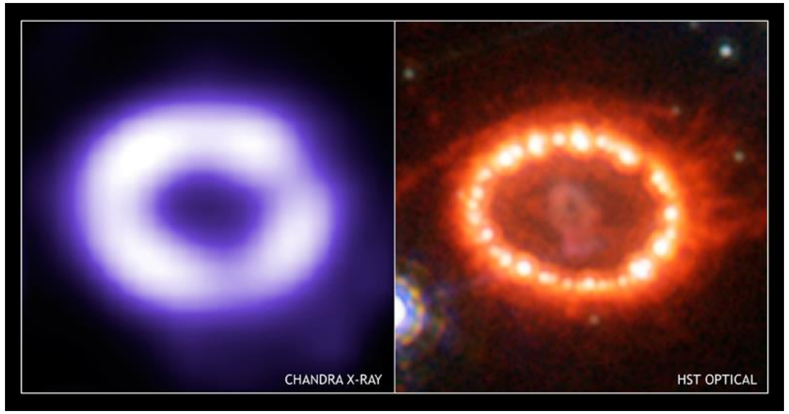


Explosion mechanism not fully understood but we know:

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



Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 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

*core-collapse supernova (type II)

Sensitivity to supernovae

Explosion mechanism not fully understood but we know:

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

2 ways to detect a SN:

- measure the ν's
- background rate

KM3NeT E_ν threshold few GeV → background rate

*core-collapse supernova (type II)

Explosion mechanism not fully understood but we know:

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

2 ways to detect a SN:

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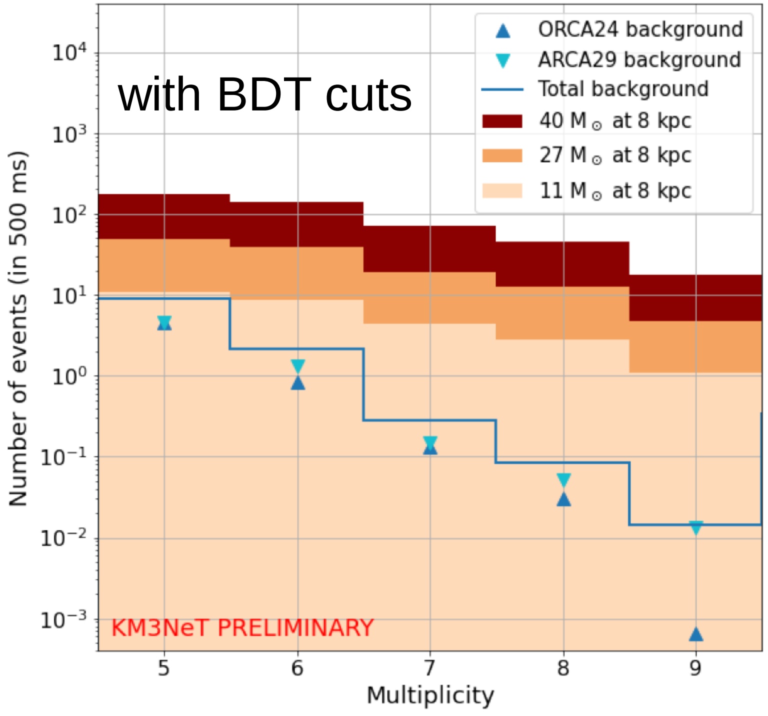


(number of hit PMTs on a DOM)

PoS(ICRC2023)1160

*core-collapse supernova (type II)

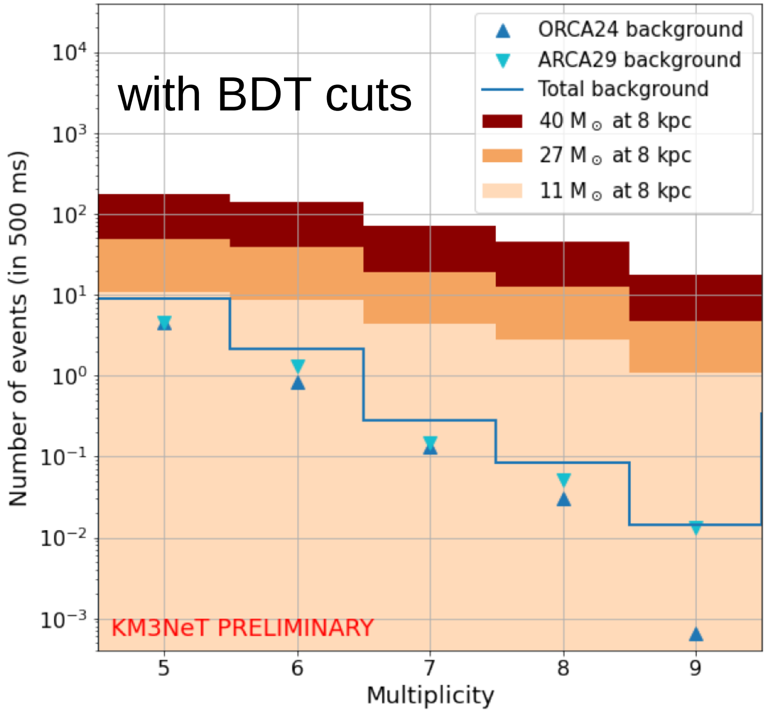
Sensitivity to supernovae

Explosion mechanism not fully understood but we know:

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

2 ways to detect a SN:

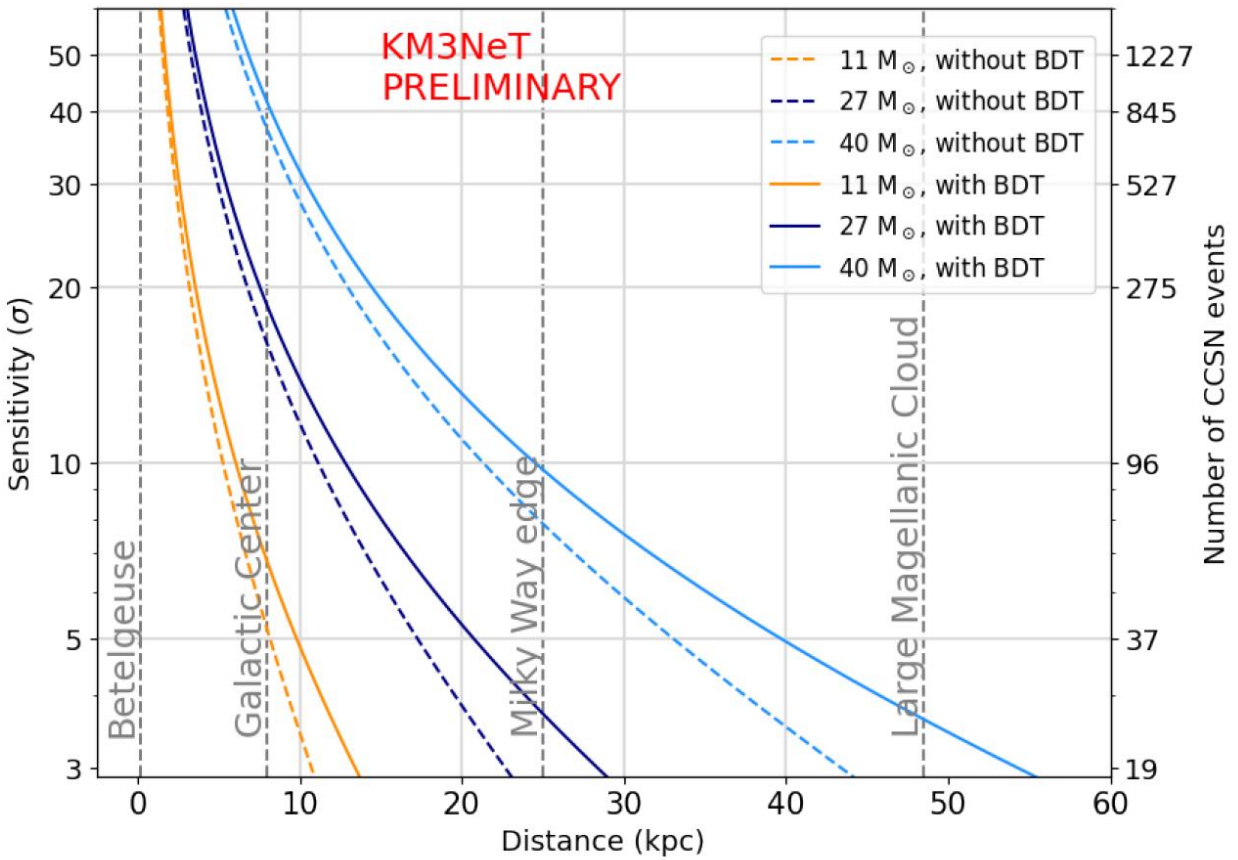
- measure the ν's
- background rate



(number of hit PMTs on a DOM)

PoS(ICRC2023)1160

ARCA115 + ORCA115



Status:

- SN alert system in place
- Part of the SNEWS network
- So far no SN detection

*core-collapse supernova (type II)

Sources in the galactic centre → high-energy CRs

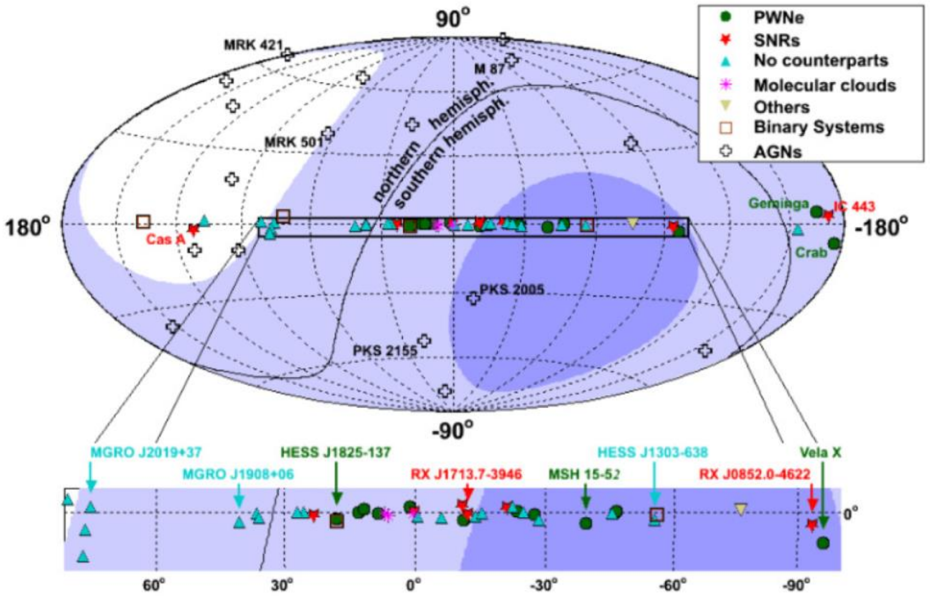
CR + interstellar medium → ν's!

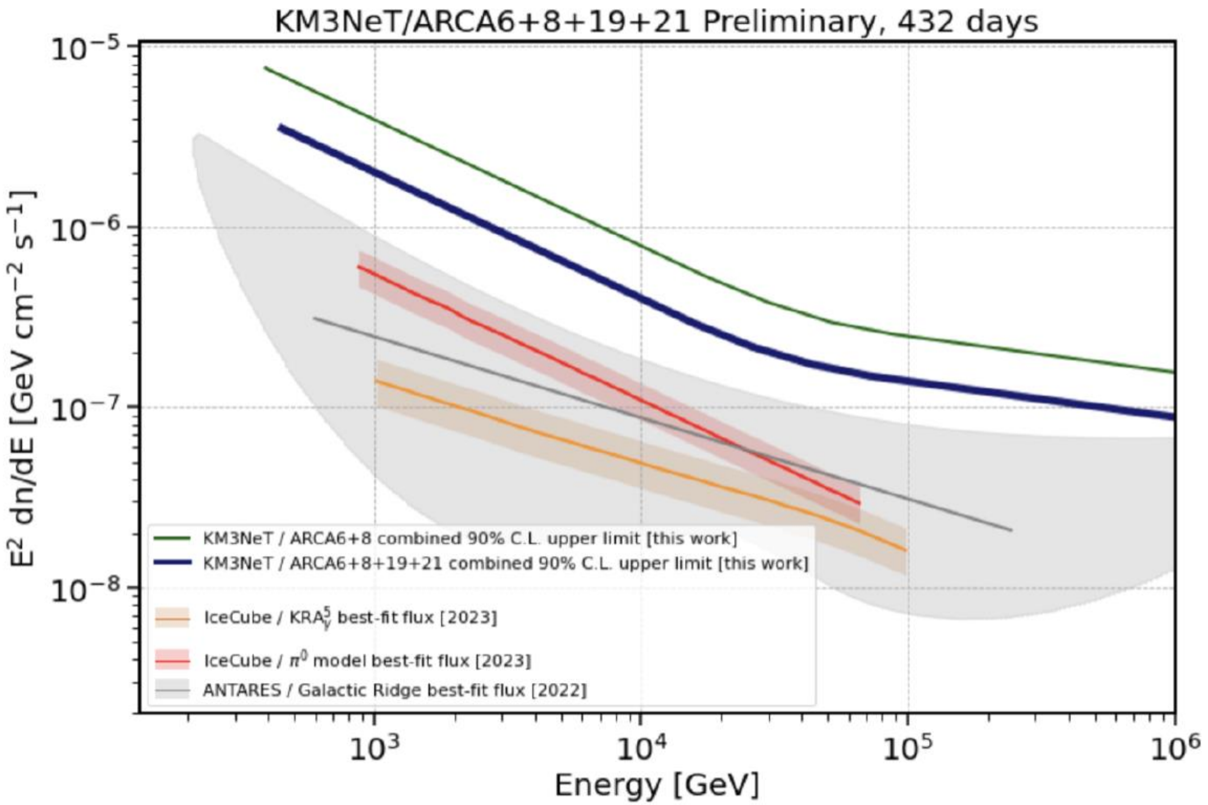
PoS(ICRC2023)1190

detector: ARCA6-21
livetime: 432d
assumed spectrum: $\phi = \phi_0 \cdot E^{-\Gamma_\nu}$, Γ_ν: 2.2 – 2.8
method: ON/OFF technique:

- ON region: galactic ridge ($|L_{\mathrm{gal}}| < 30°$, $|B_{\mathrm{gal}}| < 2°$)
- 12 OFF regions: time-shifting the ON region (avoiding the Fermi Bubbles)

90% C.L. upper limits						
Γ_ν	ARCA6	ARCA8	ARCA6+8	ARCA19	ARCA21	ARCA6+8+19+21
2.2	8.6×10^{-5}	4.5×10^{-5}	3.4×10^{-5}	4.9×10^{-5}	3.4×10^{-5}	1.9×10^{-5}
2.3	2.7×10^{-4}	1.3×10^{-4}	1.1×10^{-4}	1.5×10^{-5}	1.0×10^{-4}	5.8×10^{-5}
2.4	8.2×10^{-4}	3.9×10^{-4}	3.0×10^{-4}	4.1×10^{-4}	2.8×10^{-4}	1.7×10^{-4}
2.5	2.3×10^{-3}	1.1×10^{-3}	9.0×10^{-4}	1.1×10^{-3}	7.8×10^{-4}	4.8×10^{-4}
2.6	6.5×10^{-3}	2.9×10^{-3}	2.5×10^{-3}	2.8×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
2.7	1.7×10^{-2}	7.4×10^{-3}	6.8×10^{-3}	7.1×10^{-3}	5.5×10^{-3}	3.5×10^{-3}

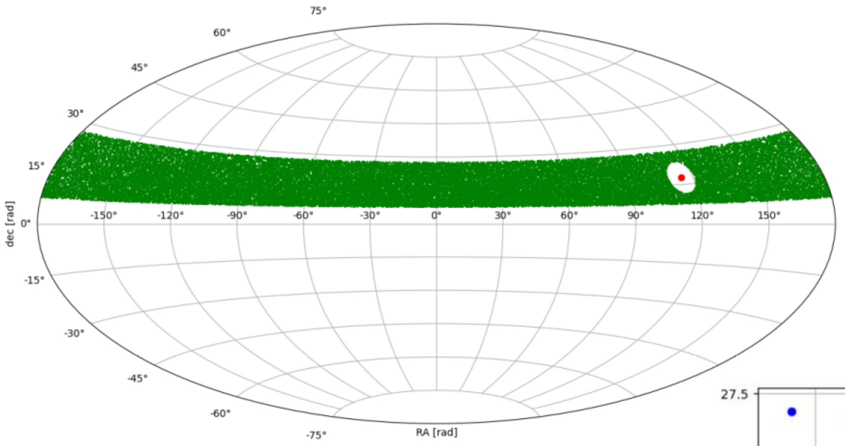




Follow-up observations

Method: ON/OFF technique

- ON region: cone centered on the source position
- OFF region: declination band centered at the source's position (but with ON region subtracted). The solid angle is rescaled to be able to compare with the ON region.
- Example for PKS 0735+17 blazar:

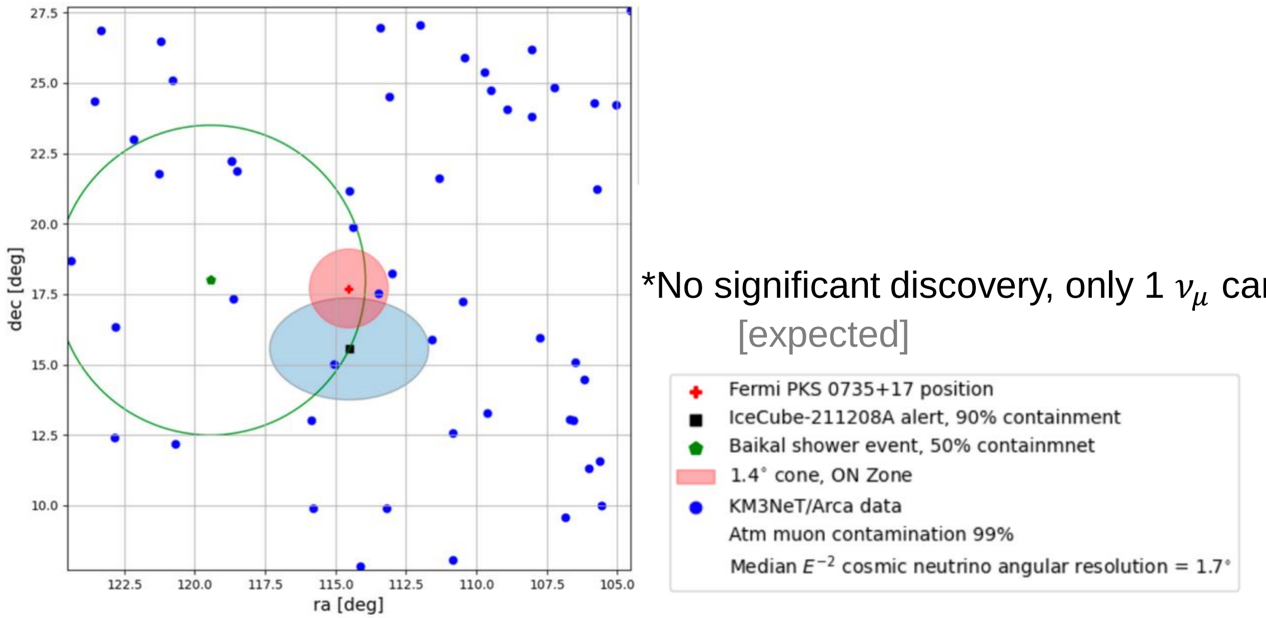


Original detection	Alert(s)	Object name	Events in ON region
Fermi	-	GRB 221009A	0
LIGO/Virgo	-	O3 run (55 events)	0
IceCube	IC211208A	PKS 0735+17	1*
IceCube	IC220205B	PKS 1741-03	0
IceCube	IC220225A	PKS 0215+15	0
IceCube	IC220304A	TXS 0310+022	0

PoS(ICRC2023)1521

detector: ARCA8, ORCA10
assumed spectrum:
$\phi = \phi_0 \cdot E^{-2}$ (all alerts)
selection:
upgoing track-like events

Poster P0739 @Neutrino2022



*No significant discovery, only 1 ν_μ candidate with $E \sim 18\text{TeV}$ ($p = 0.14$) [expected]

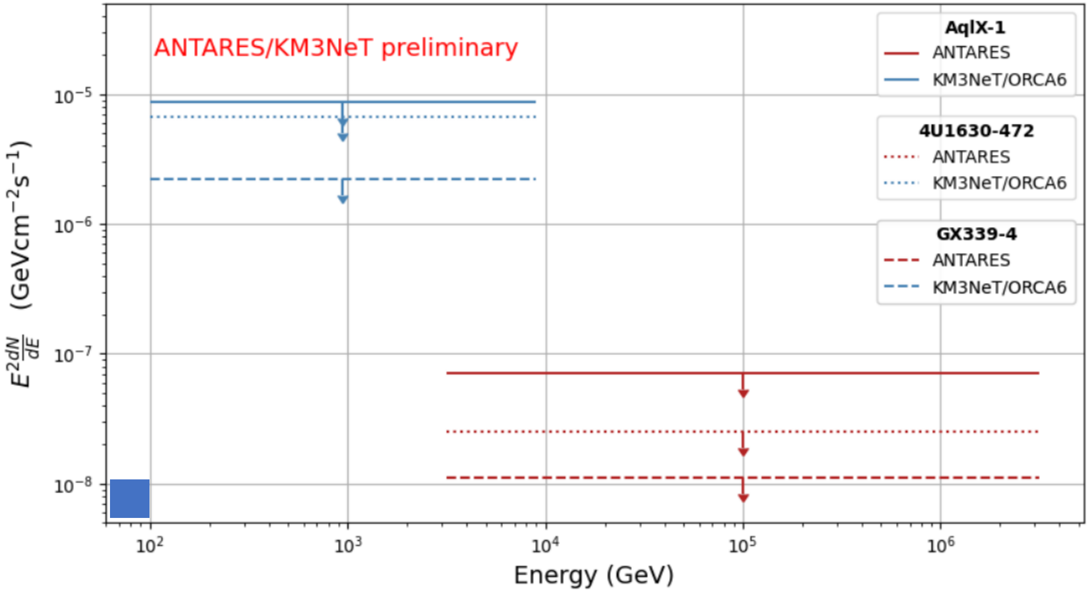
Again, there's even more …

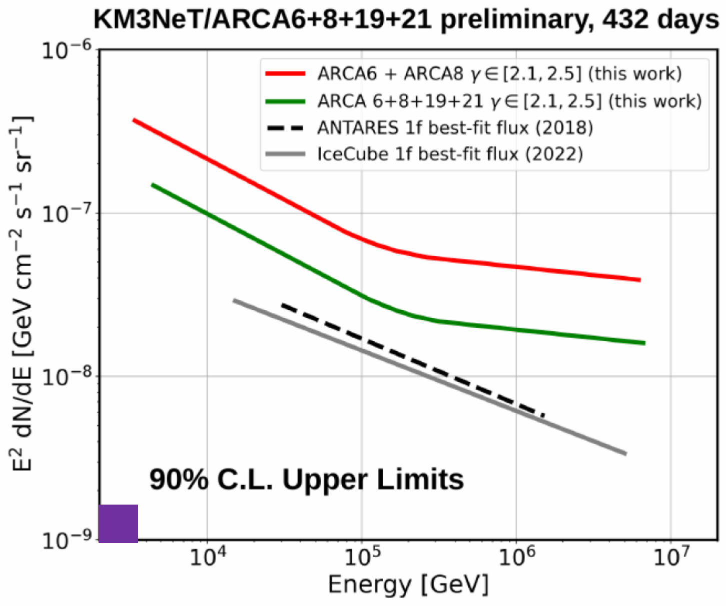
Only selected analyses were covered.

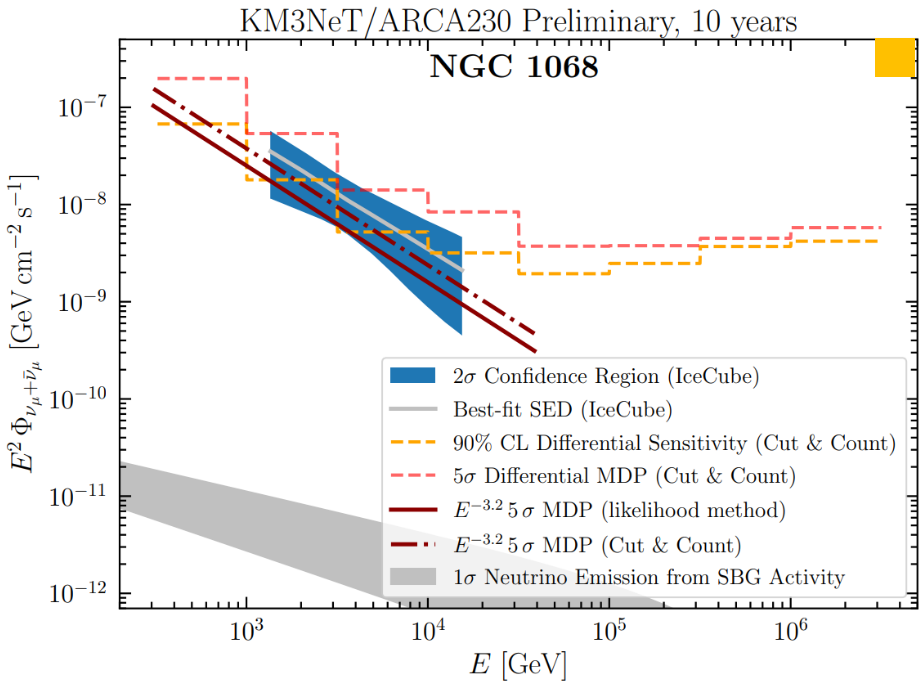
See backup and arXiv:2309.05016 for more!

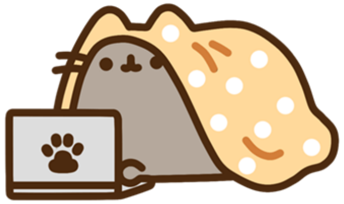
Other astro topics include:

- Microquasar flares [PoS(ICRC2023)1505]
- Diffuse neutrino flux [PoS(ICRC2023)1195]
- Starburst galaxies [PoS(ICRC2023)1150]
- …









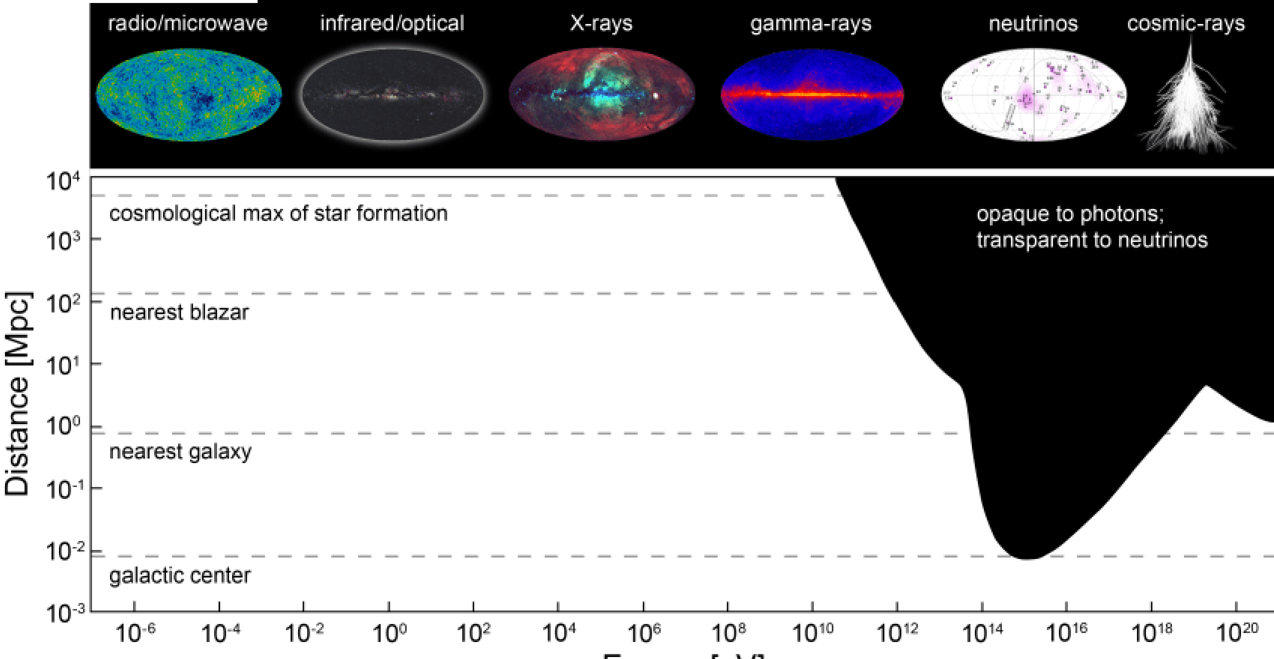
Neutrino Astronomy

Current Astro open tasks (aka potential theses):

- Online monitoring, transient events, alert follow-ups
- Cosmic tau neutrino search
- ARCA 6-21 stacking analysis

Some more ideas:

- Search for point sources:
  angular auto- and/or cross-correlation analysis
- Neutrino emission from UHE catalogs, e.g. LHAASO
- Blazar Flares
- Fermi Bubbles
- …
- your ideas?



https://icecube.wisc.edu/science/research/

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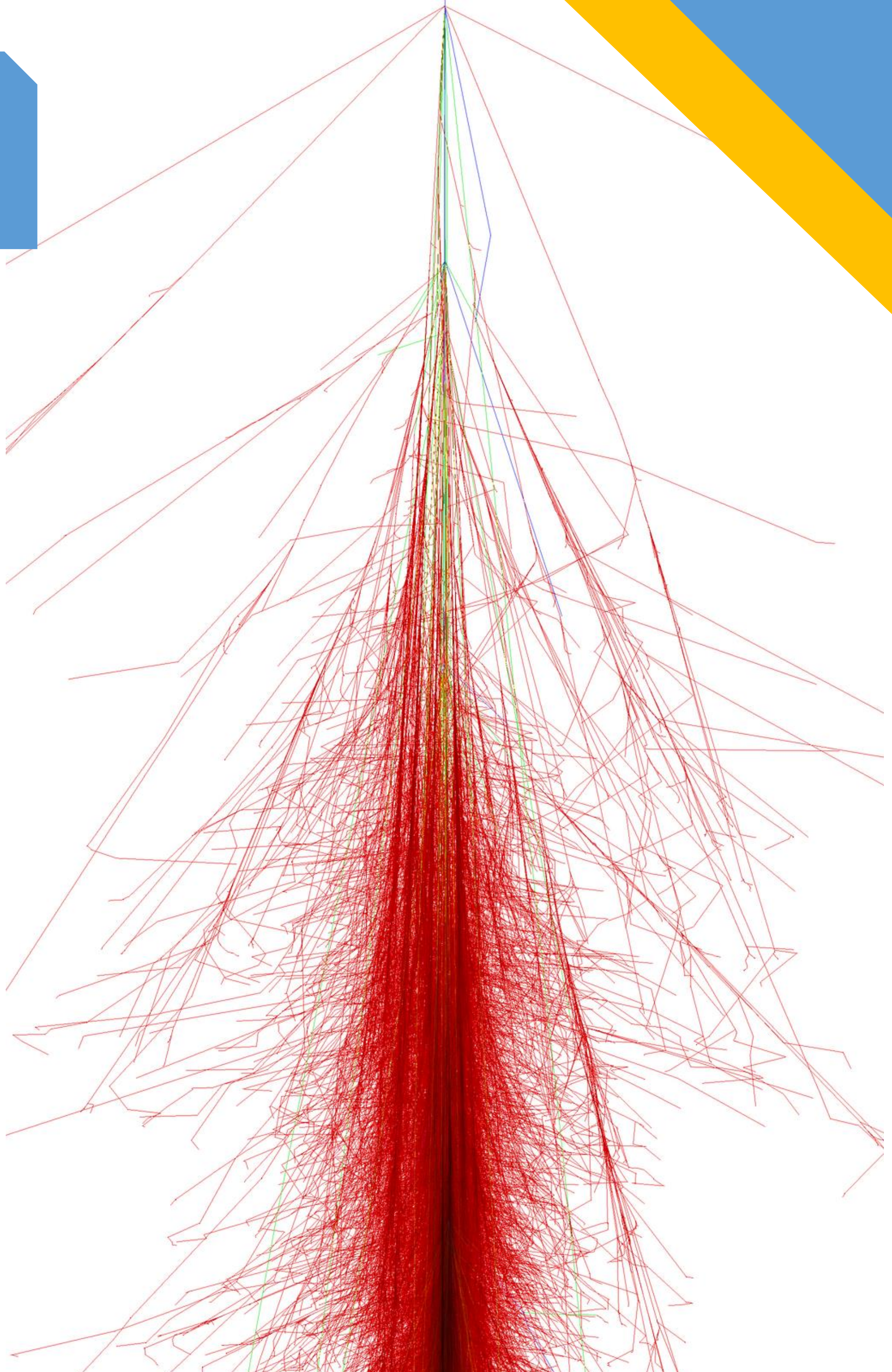
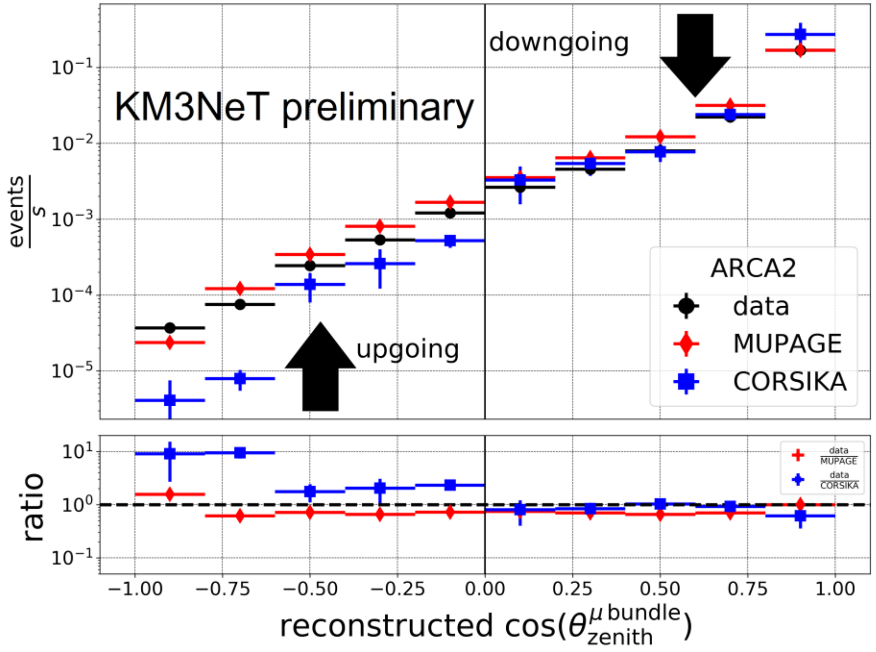
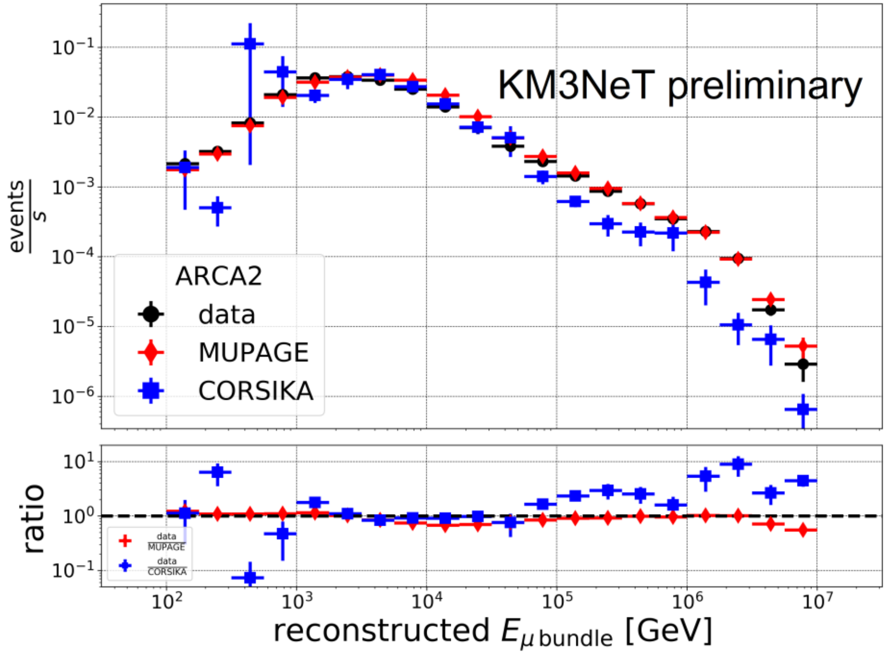


Cosmic Ray muon flux

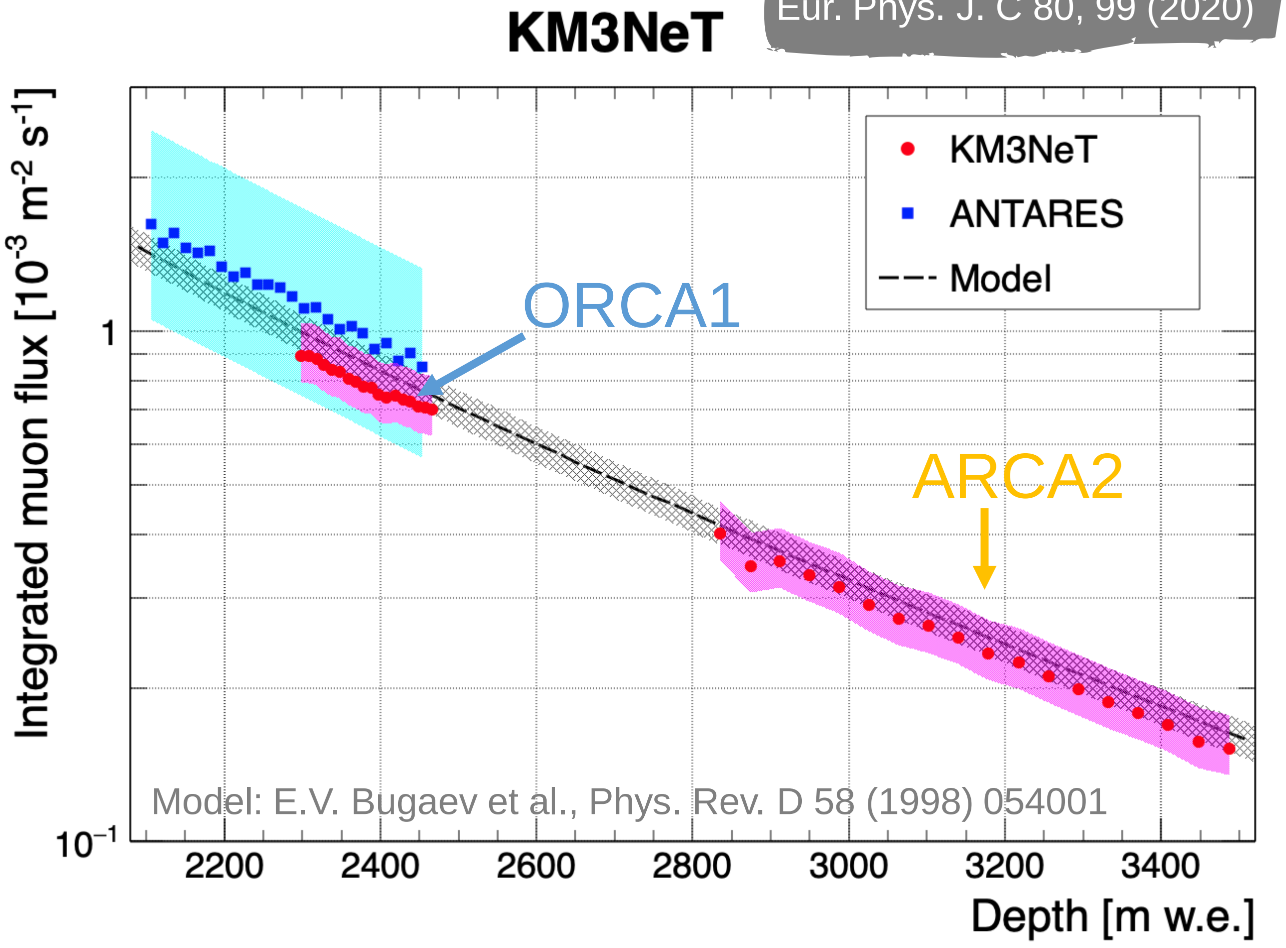




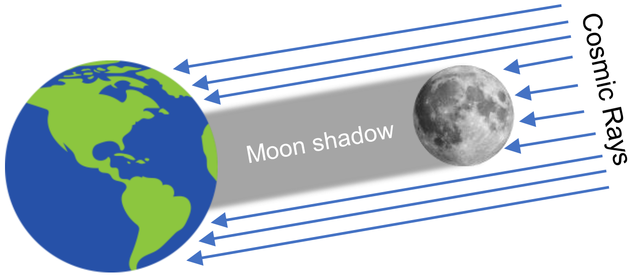
PoS(ICRC2021)1112

Results based on the very first data!

Eur. Phys. J. C 80, 99 (2020)



Cosmic Ray muons: Moon & Sun shadow



https://www.amnh.org/explore/ology/earth/what-is-earth
https://toppng.com/show_download/170855/moon-transparent-png-full-moon/large

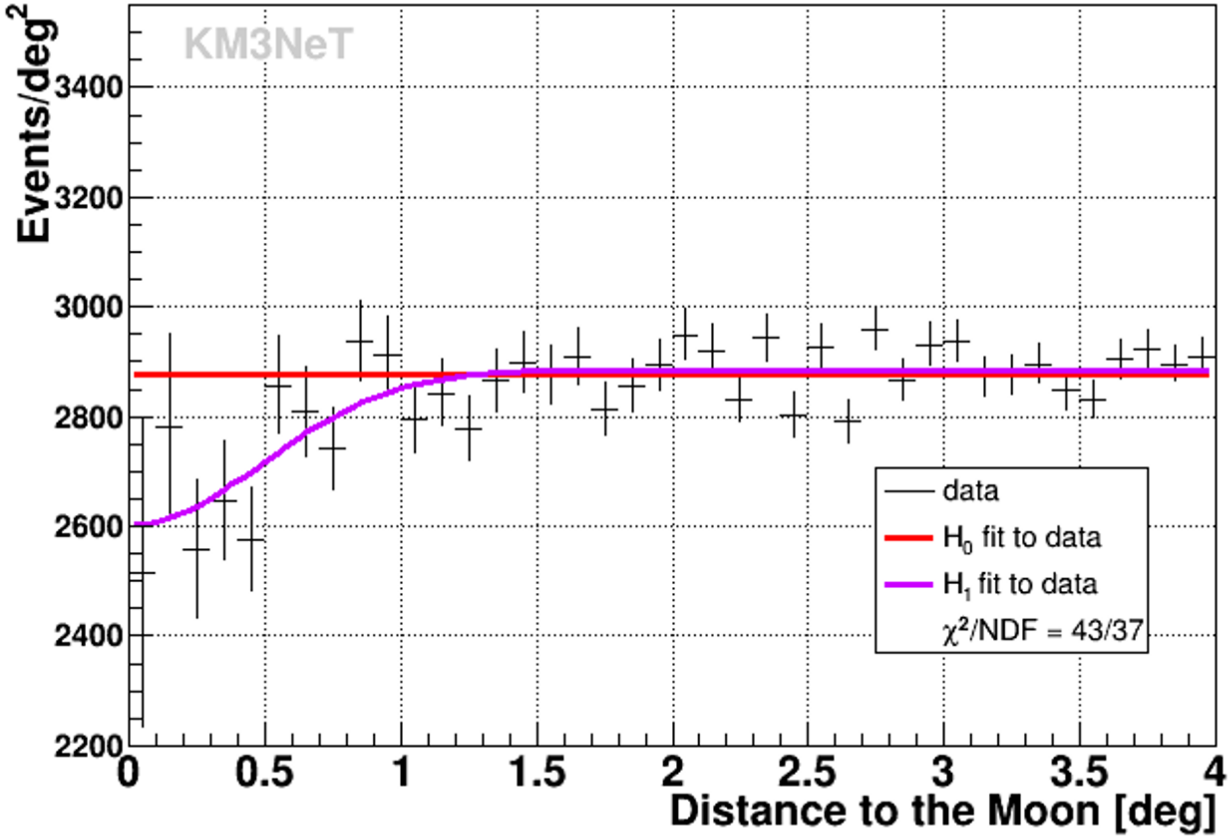
ORCA6

Livetime: 499.3d (11/02/2020 - 18/11/2021)

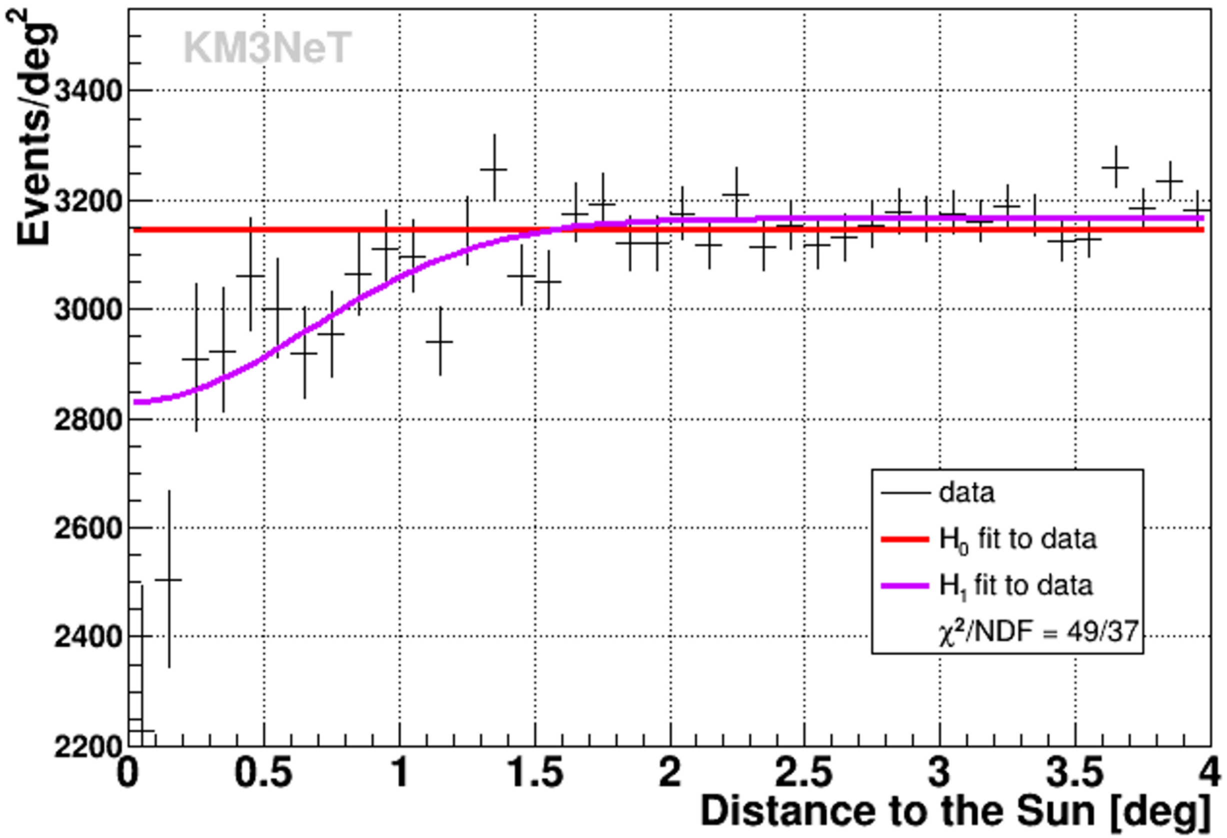
Eur.Phys.J.C 83 (2023) 4, 344

analysis for ARCA underway

Moon



Sun



Cosmic Ray muons: Moon & Sun shadow

https://www.amnh.org/explore/ology/earth/what-is-earth
https://toppng.com/show_download/170855/moon-transparent-png-full-moon/large

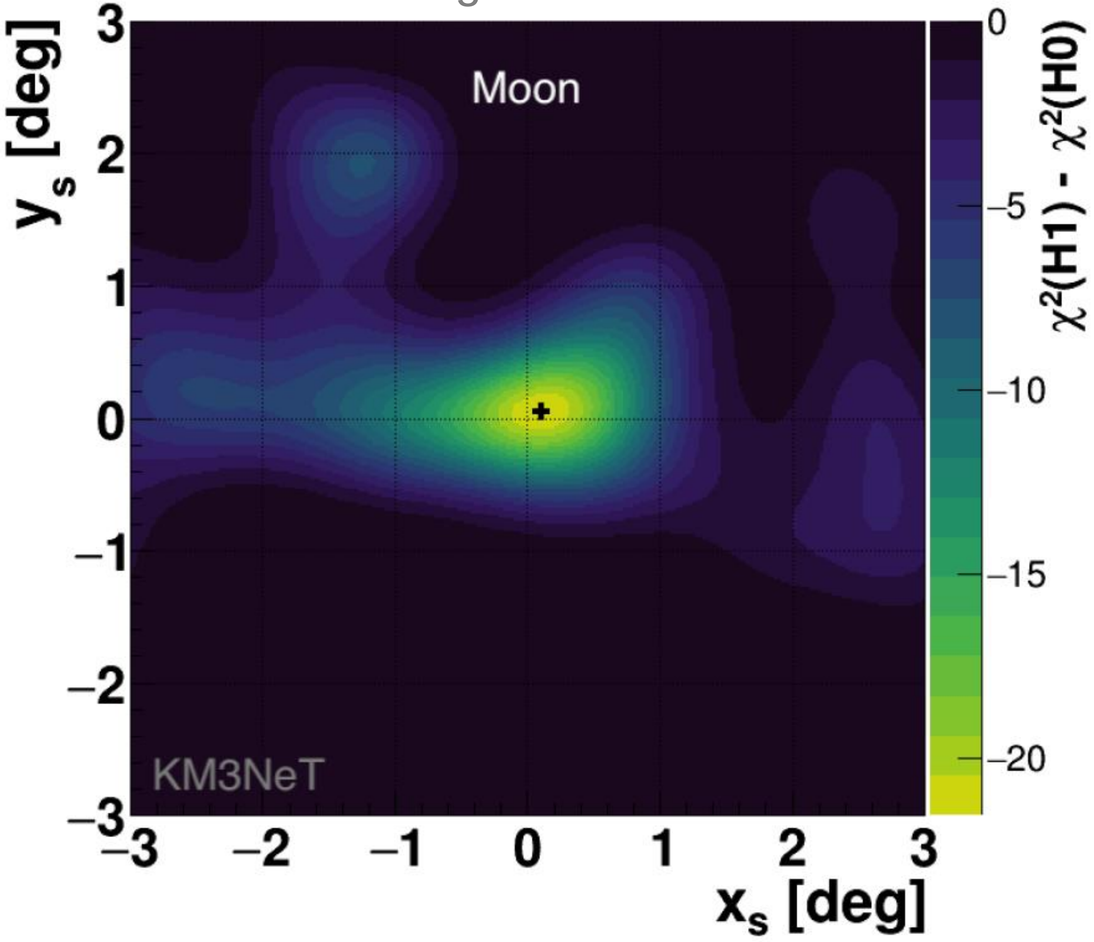
ORCA6

Livetime: 499.3d (11/02/2020 - 18/11/2021)

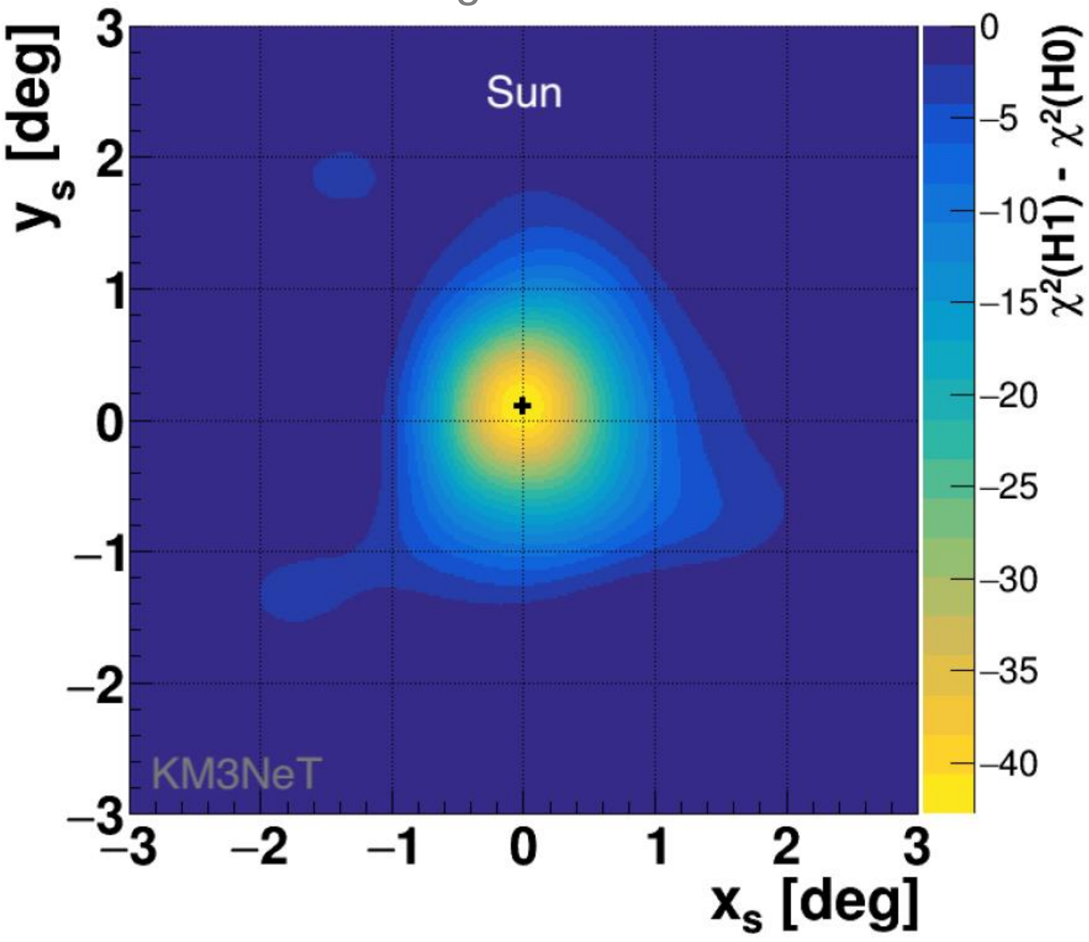
Eur.Phys.J.C 83 (2023) 4, 344

analysis for ARCA underway

Signif.: 4.2σ



Signif.: 6.2σ



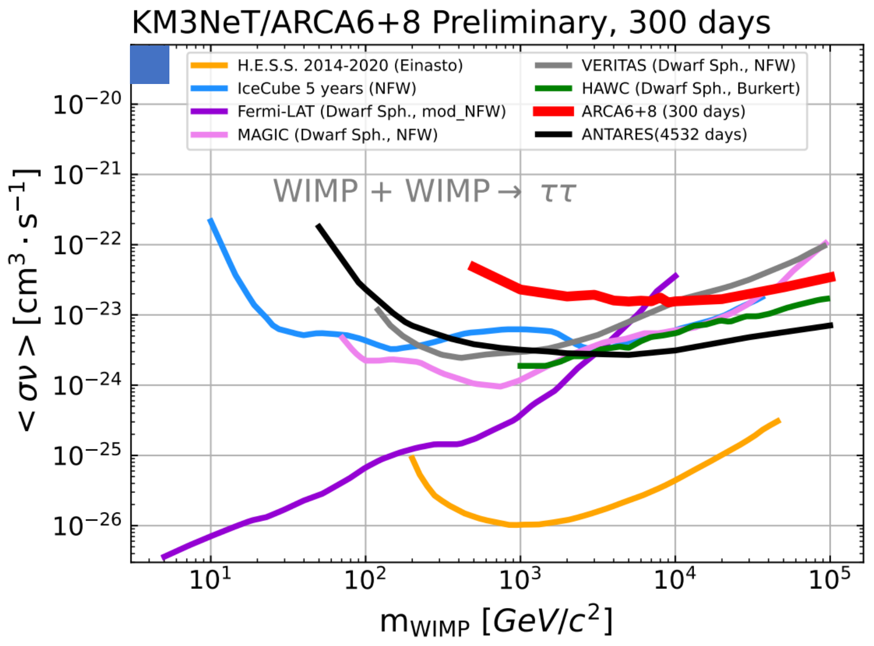
Obviously we again have more …

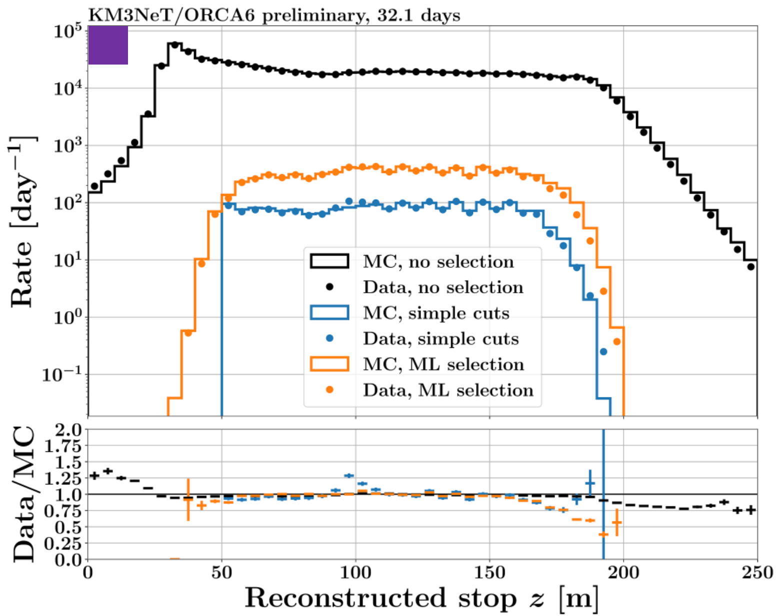
Only selected analyses were covered.

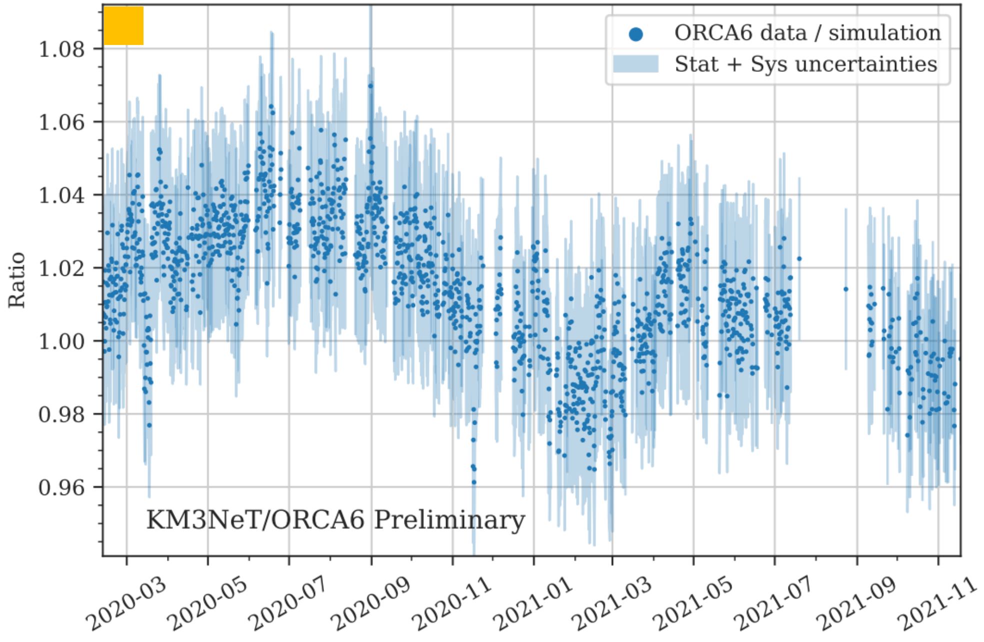
See backup and arXiv:2309.05016 for more!

Other topics include:

- Dark matter [PoS(ICRC2023)1377, 1382, 1406]
- Stopping muons [PoS(ICRC2023)203]
- Seasonal dependence of muon flux [PoS(ICRC2023)355]
- …

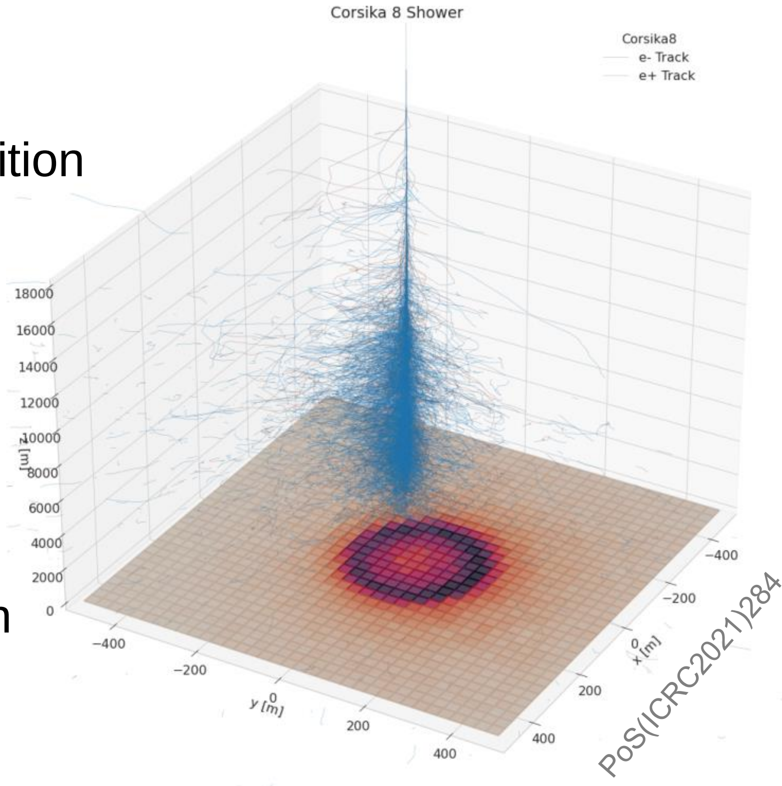






Current CR open tasks (aka potential theses):

- Development of framework to fit primary cosmic ray spectrum and composition
- Self-veto: coincident atmospheric muon and atmospheric neutrino events
- Combined fit of CR observables with other experiments
- CORSIKA 8
- Multi-muon reconstruction (events with >1 muon)
- Time-coincident events (overlapping air showers)
- Study of the detector response with stopping muons
- Investigation of the MUPAGE (fast muon simulation code) parameterization

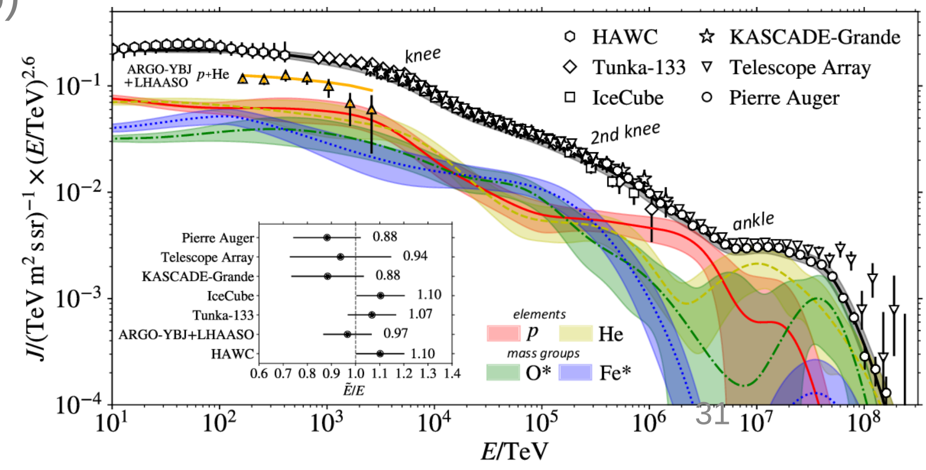


PoS(ICRC2021)284

Some more:

- sea surface detectors for KM3NeT? (analogous to IceCube's IceTop)
- correlation between KM3NeT data & earthquakes
- measurement of the Earth's radius with cosmic ray muons (probably not the most precise, but nobody tried that so far)
- …
- your ideas?

Bull.Am.Astron.Soc. 51 131



Outline

Introduction

KM3NeT

Analyses

Summary

To sum up:

- KM3NeT currently under construction: ARCA28 & ORCA16 (completion around 2032 and 2030)
- Rich physics programme
- Valuable results already with intermediate configurations
- Plenty of possibilities to get involved (I did not even mention DM & Exotics, acoustics etc.)

Thank you for your attention!

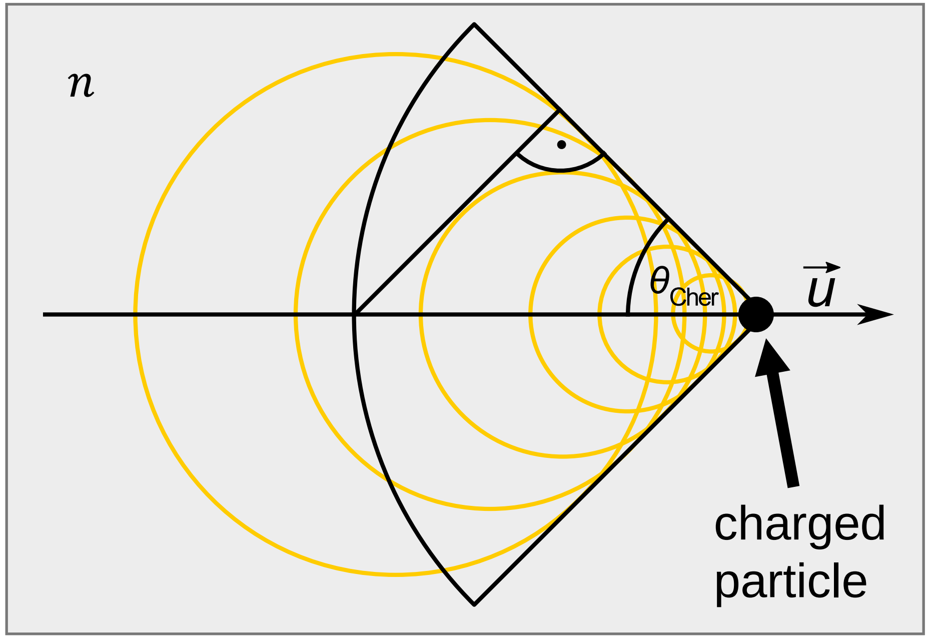
Any Questions?

Interested in a thesis in KM3NeT? Write to us at:
pkalaczynski@camk.edu.pl
gawron@camk.edu.pl
artur.ukleja@ncbj.gov.pl

Backup

In a nutshell:

EM equivalent of a sonic boom shockwave



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

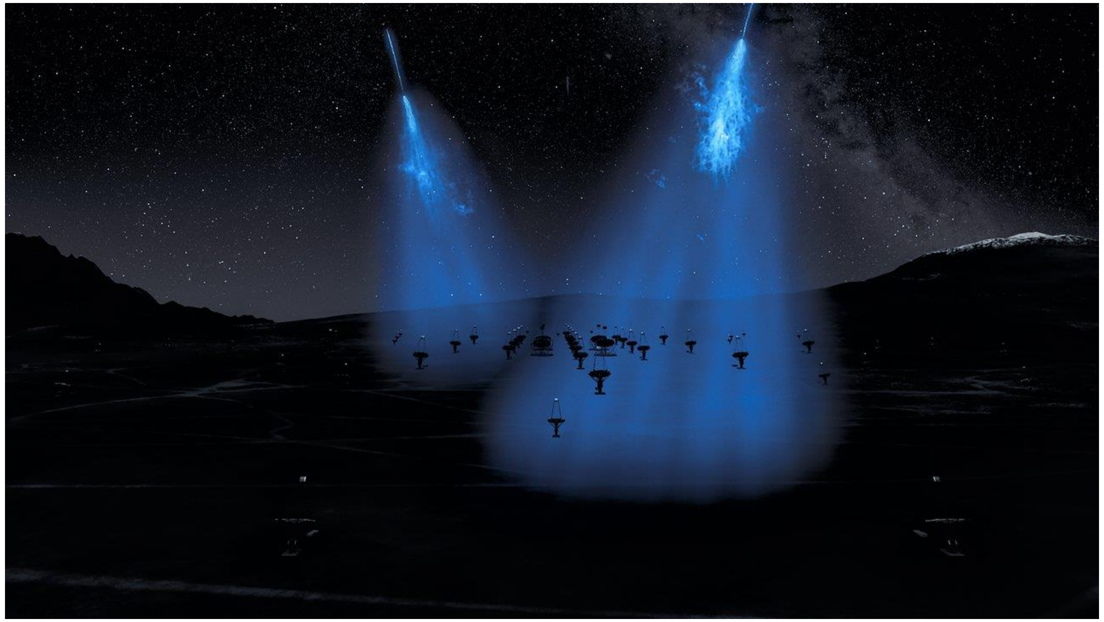
e.g. in water, $\theta_{\text{Cher}} \approx 41°$

Supersonic jetplane:

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

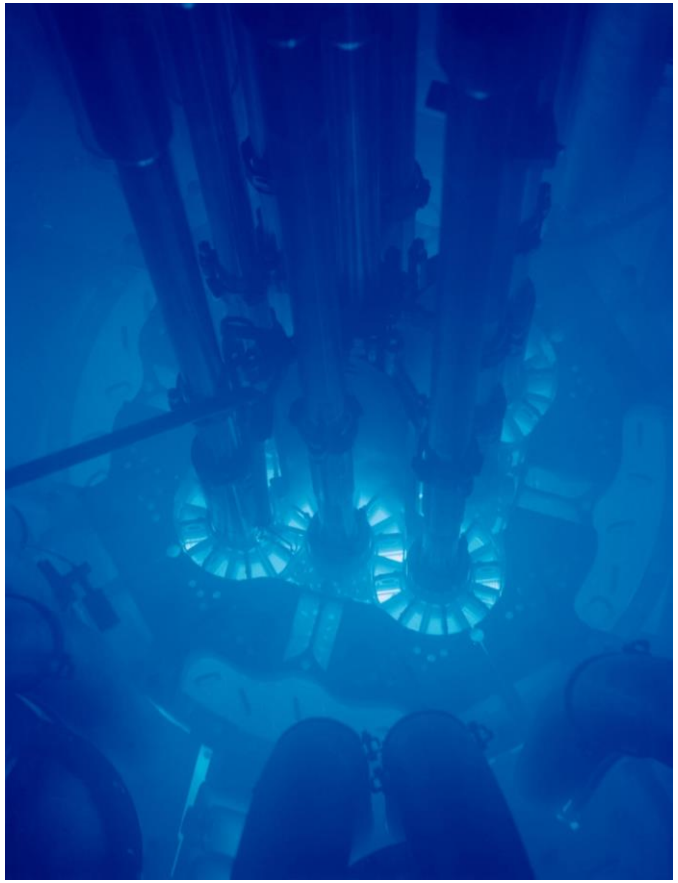
Cherenkov source examples

Extensive Air Showers



eso.org

Nuclear reactors



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

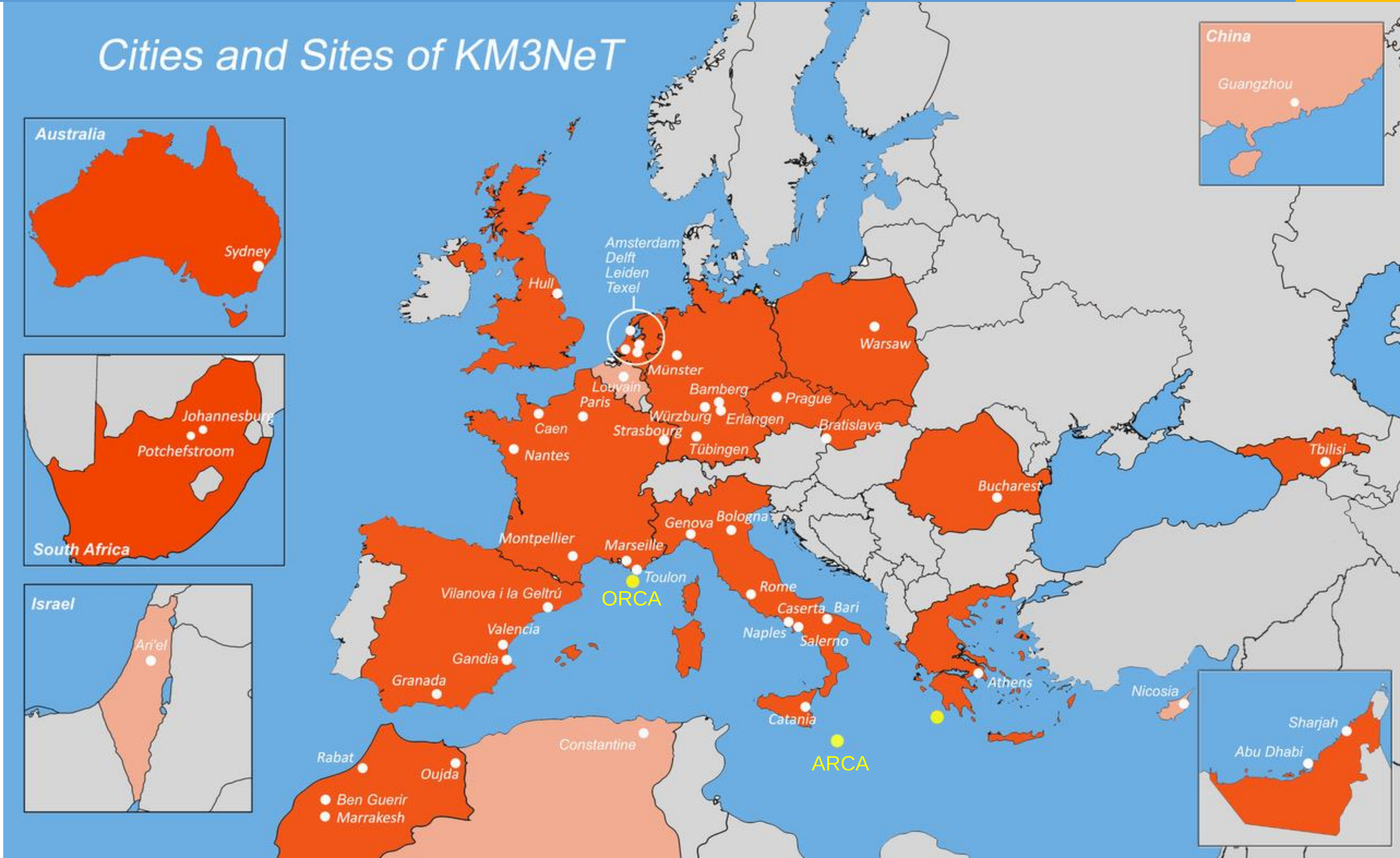
and neutrino interactions!

KM3NeT

KM3NeT

Numbers:

- 47 groups
- 20 countries
- 4 continents
- 2 detectors



Legend:

- group
- observer
- member

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

Detection Unit (DU):

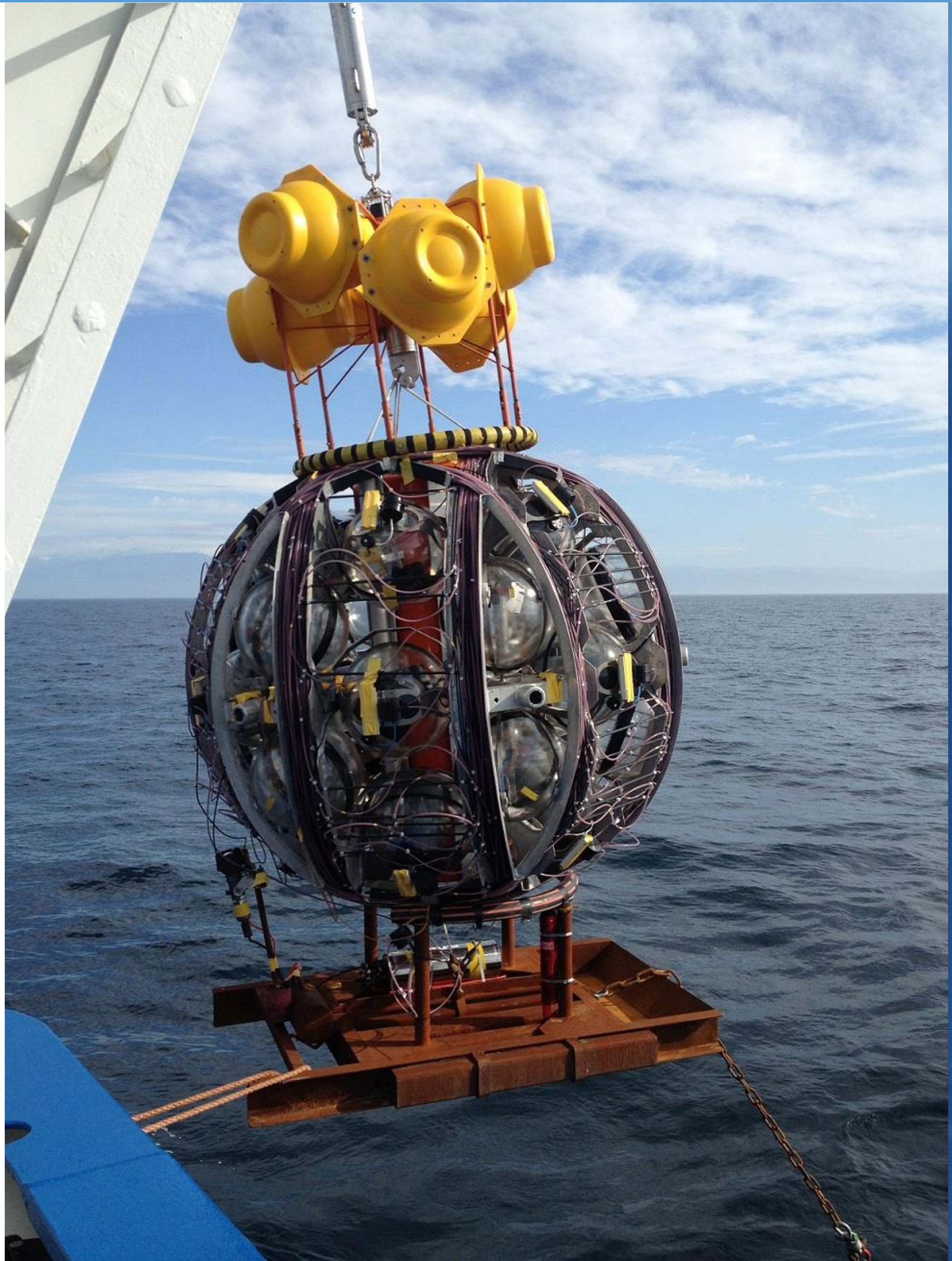
vertical **string** with 18 DOMs

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

Naming:

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

2020 JINST 15 P11027



Detection Unit (DU):

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

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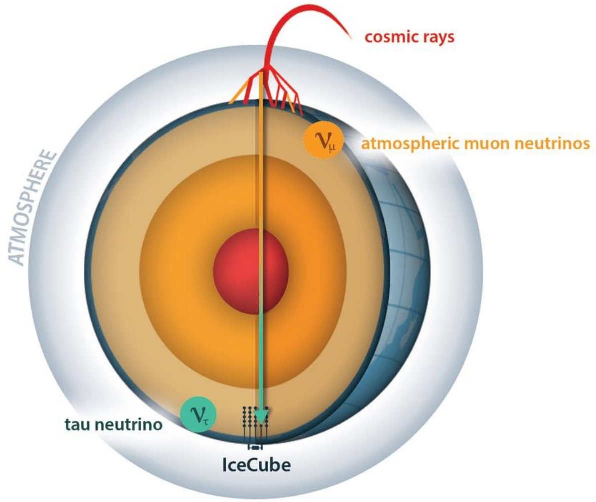
ORCA6 ↔ ORCA with 6 strings
ARCA2 ↔ ARCA with 2 strings
etc.

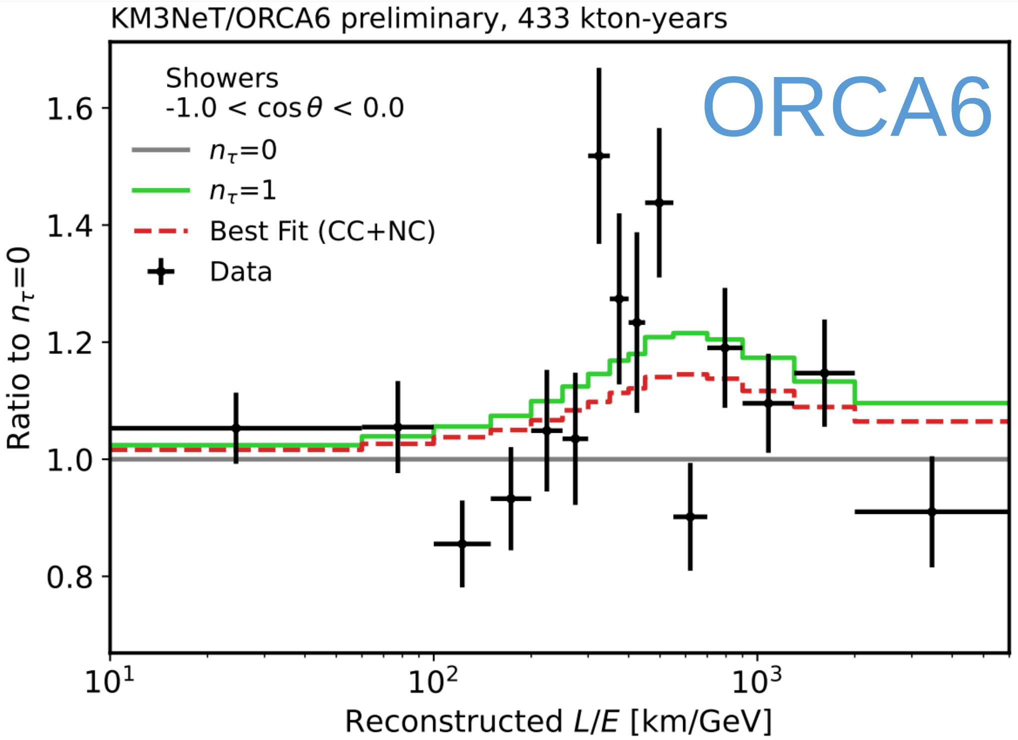
2020 JINST 15 P11027

Tau appearance

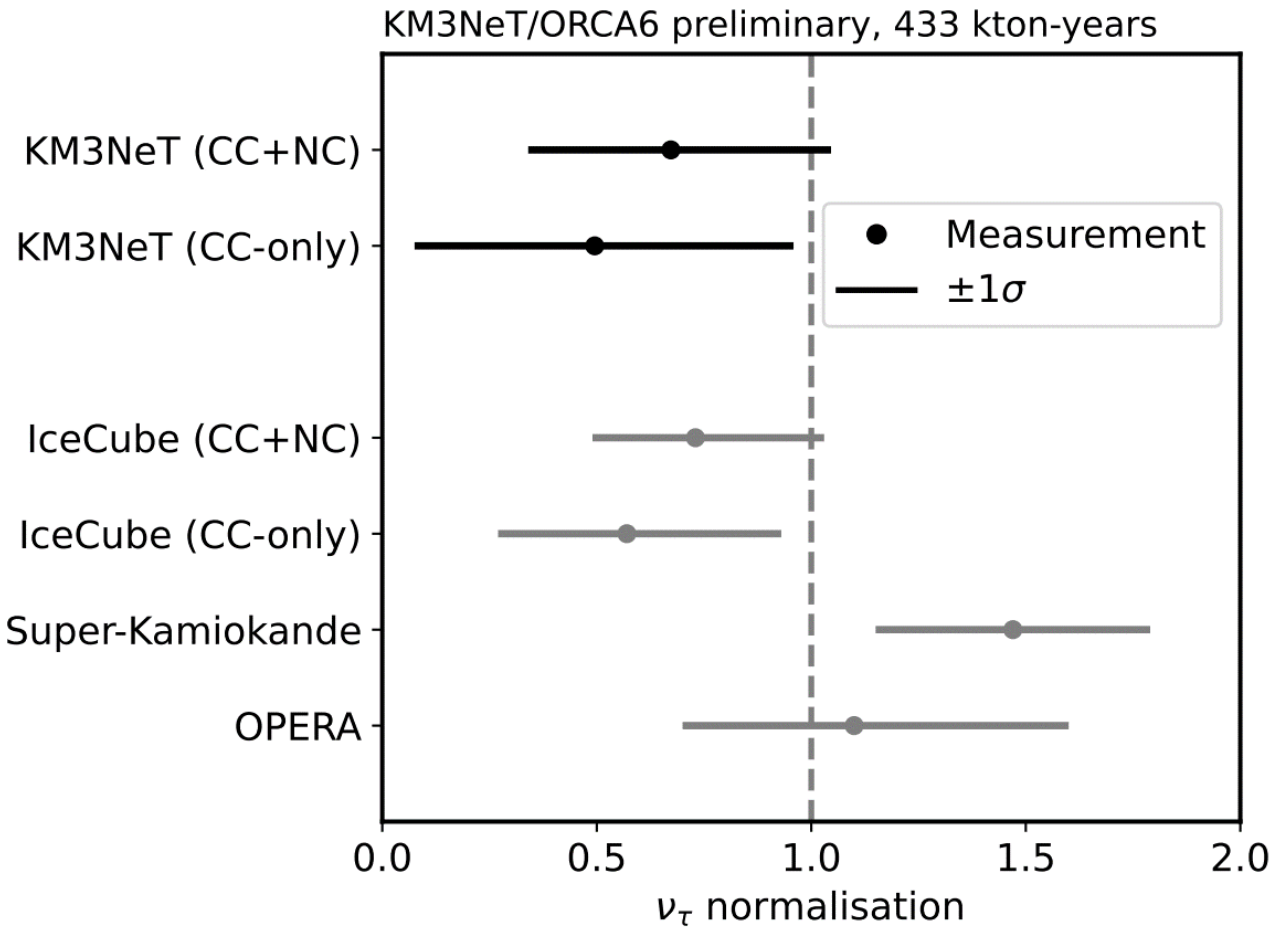
https://icecube.wisc.edu/news/research/2019/01/atmospheric-tau-neutrino-appearance-in-icecube/



PoS(ICRC2023)1107



ORCA6 vs others



Follow-up observations

Method: ON/OFF technique

detector: ORCA4, ORCA6

assumed spectrum:

$\phi = \phi_0 \cdot E^{-2}$

selection:

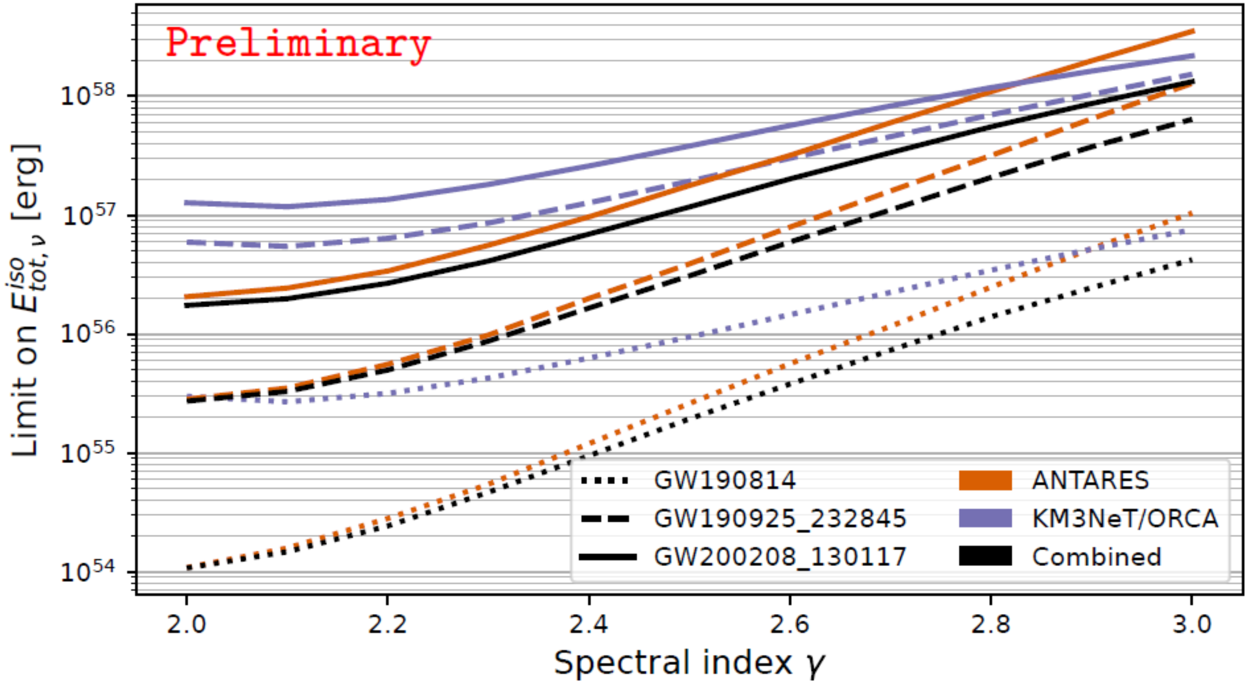
upgoing track-like events

PoS(ICRC2023)1506

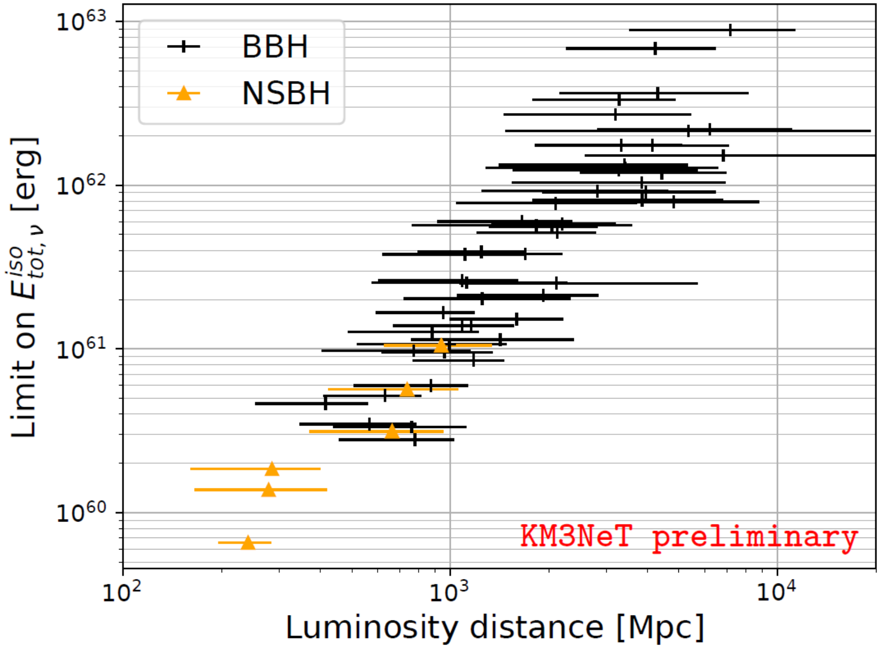
Original detection	Alert(s)	Object name	Events in ON region
Fermi	-	GRB 221009A	0
LIGO/Virgo	-	O3 run (55 events)	0
IceCube	IC211208A	PKS 0735+17	1*
IceCube	IC220205B	PKS 1741-03	0
IceCube	IC220225A	PKS 0215+15	0
IceCube	IC220304A	TXS 0310+022	0

ORCA +ANTARES

(only events fully above the detector horizons at the time of the alert)



90% UL on total E emitted in ν's:



Follow-up observations

Method: ON/OFF technique

detector: ARCA21, ORCA10

assumed spectrum:

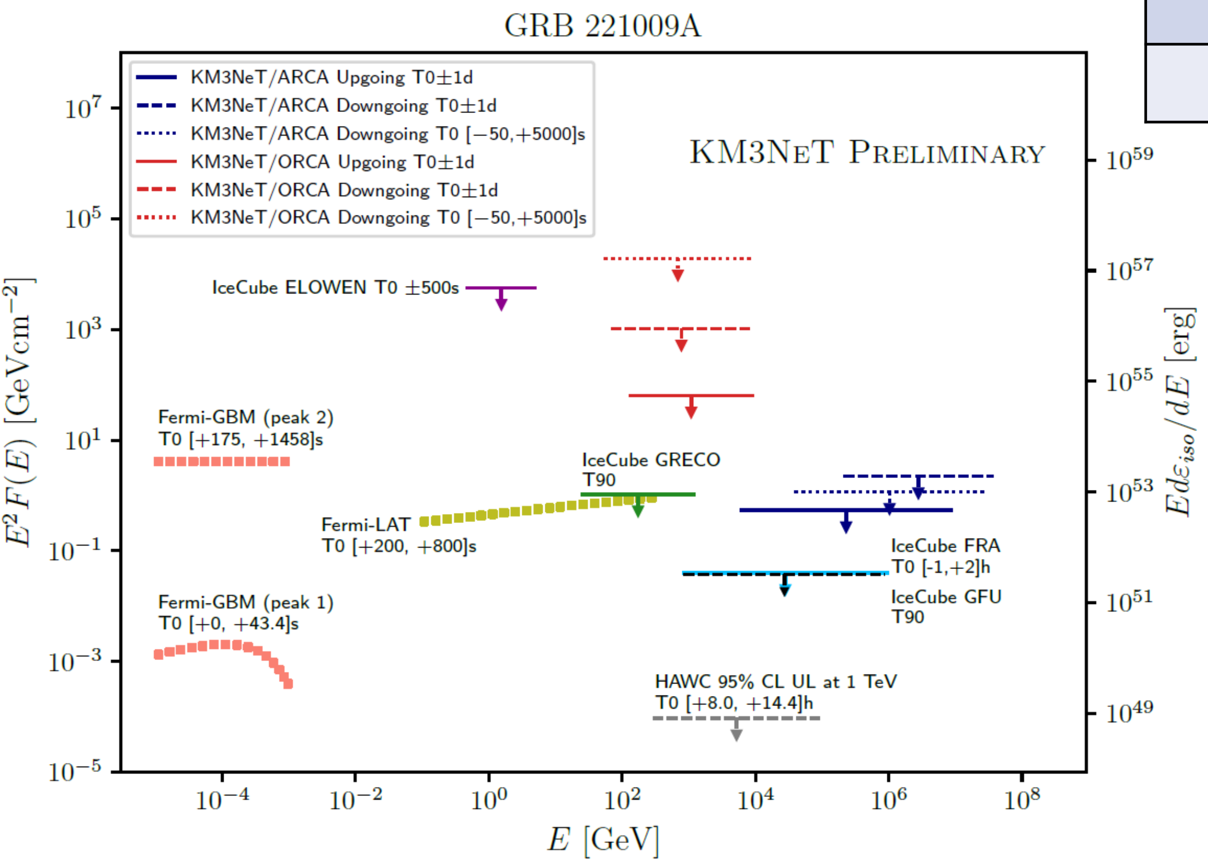
$\phi = \phi_0 \cdot E^{-2}$

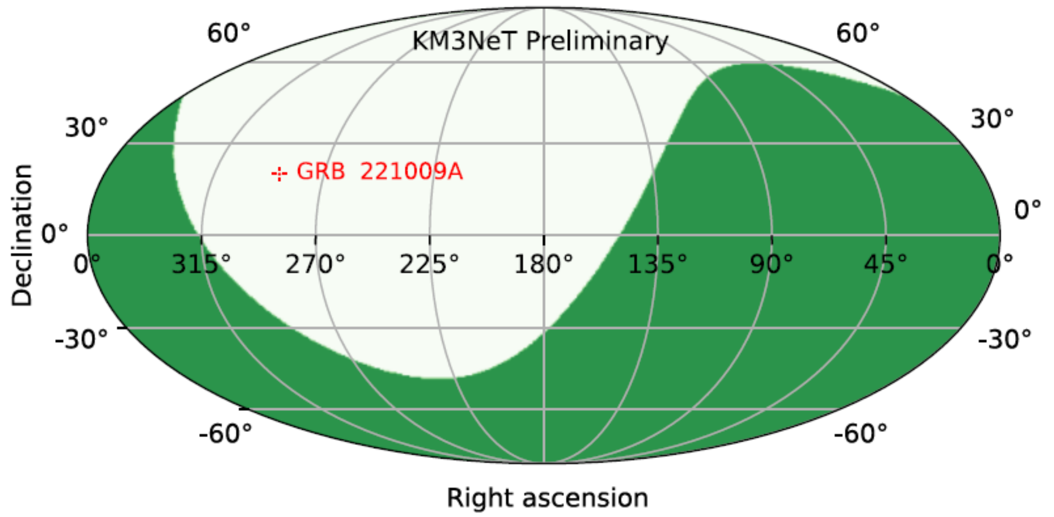
selection:

upgoing track-like events

PoS(ICRC2023)1503

Original detection	Alert(s)	Object name	Events in ON region
Fermi	-	GRB 221009A	0
LIGO/Virgo	-	O3 run (55 events)	0
IceCube	IC211208A	PKS 0735+17	1*
IceCube	IC220205B	PKS 1741-03	0
IceCube	IC220225A	PKS 0215+15	0
IceCube	IC220304A	TXS 0310+022	0

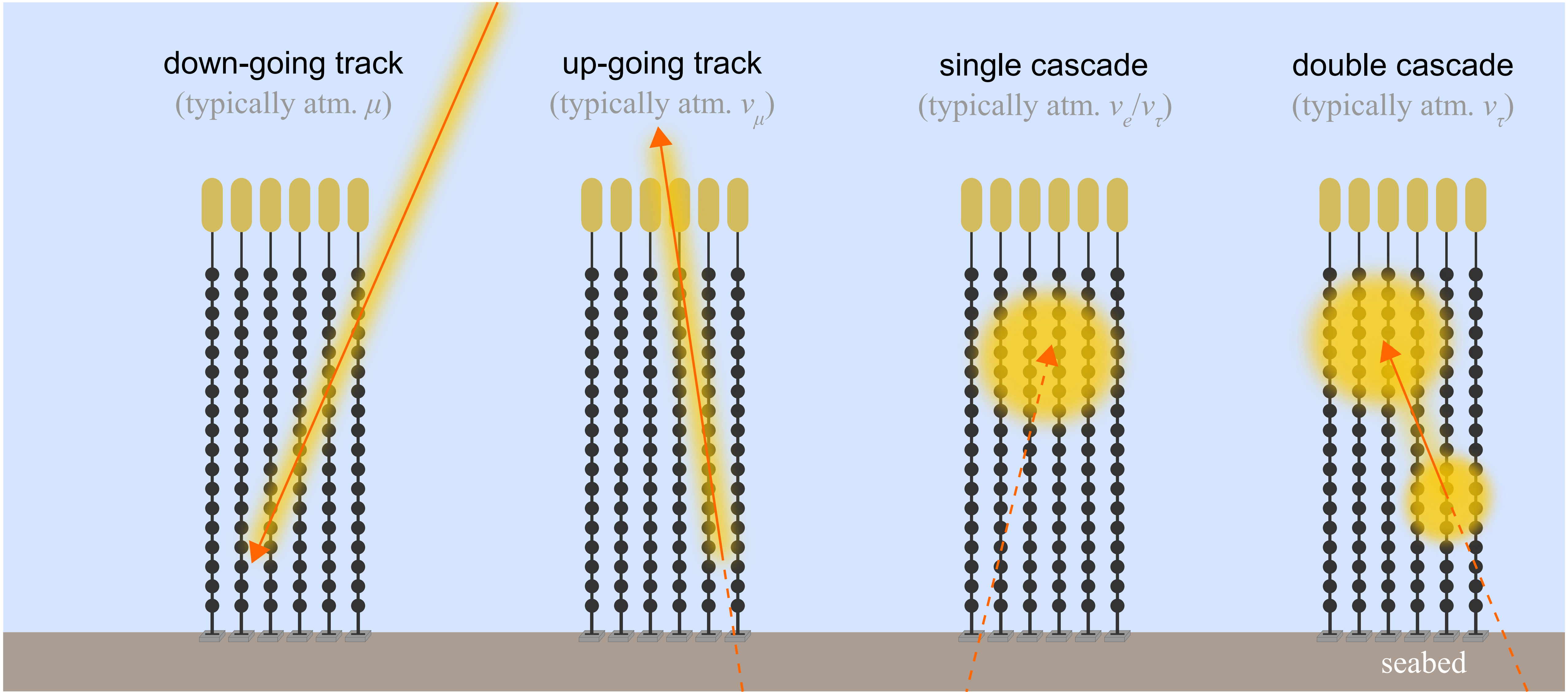




Examples of basic event topologies:

Classes based on combinations of:

- Direction
- Shape



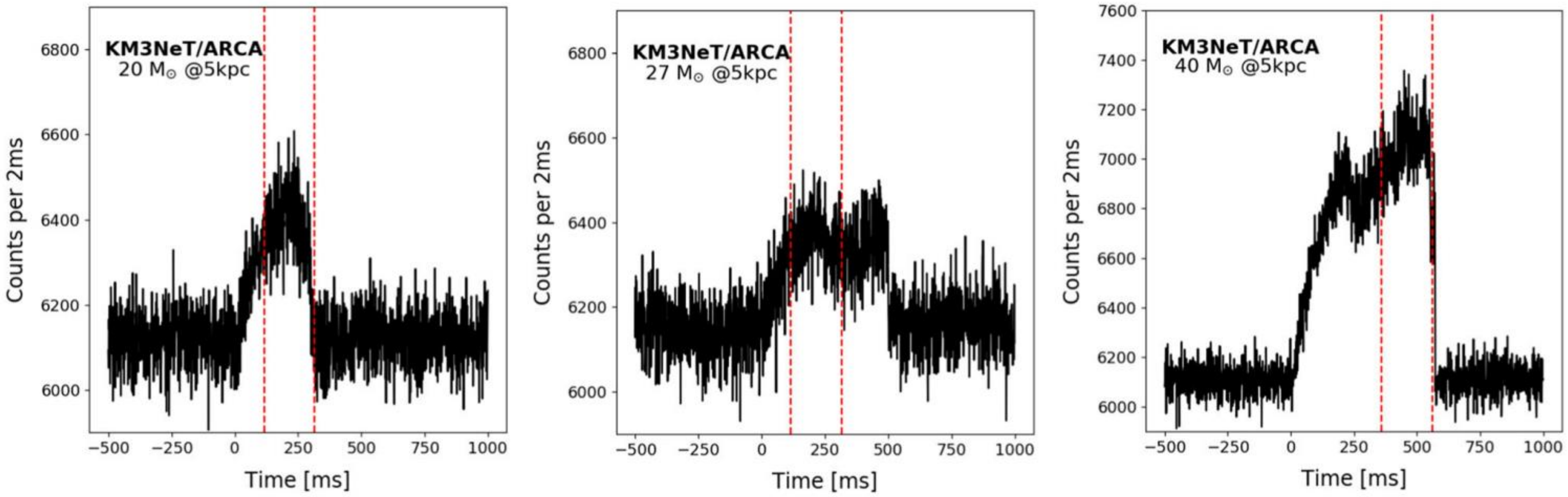
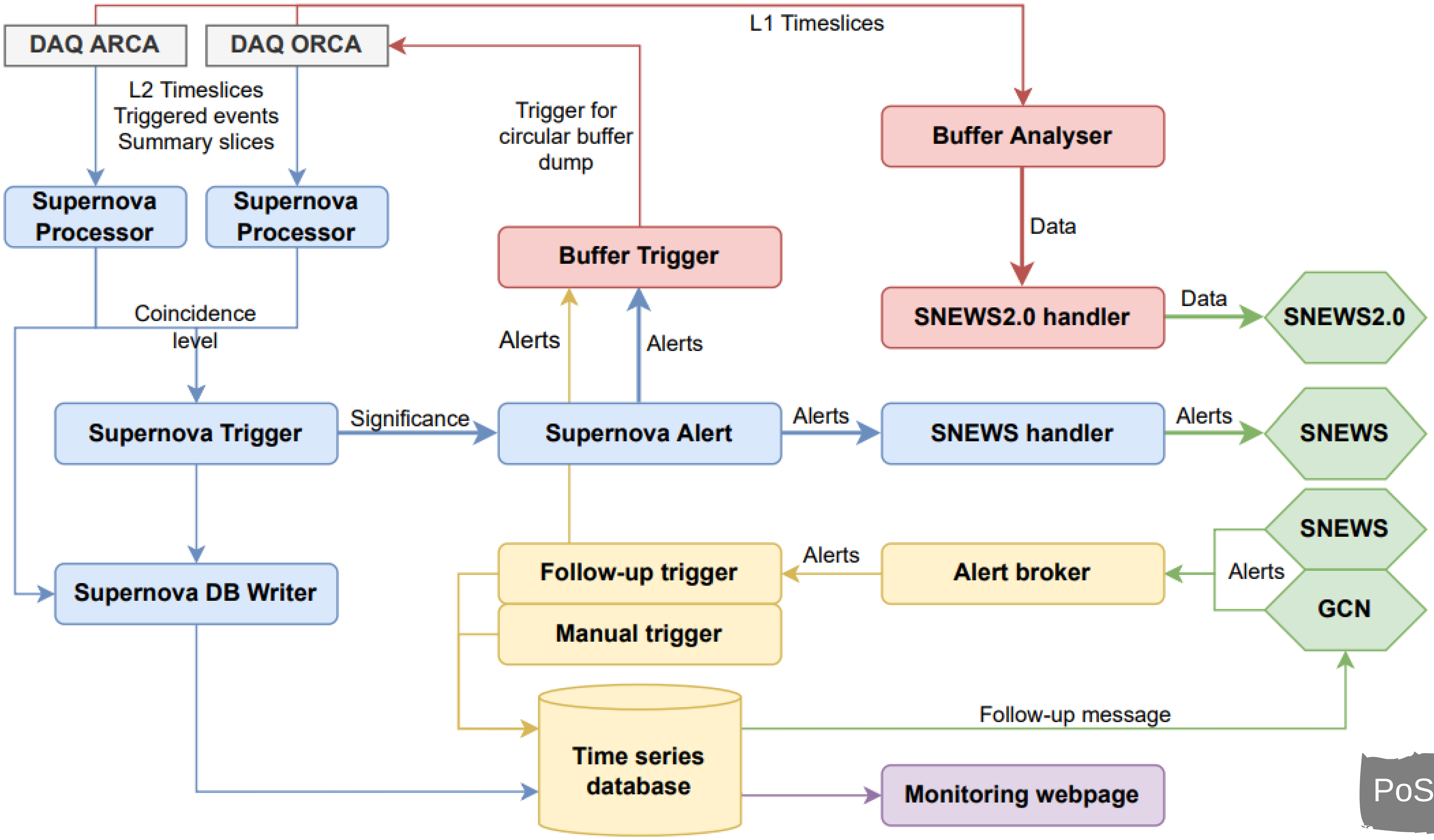


Fig. 12 Pseudo-experiments of the detected neutrino light curves in the full ARCA detector, considering a source at 5 kpc, and the three CCSN progenitors: the 20 $M_\odot$ (left), 27 $M_\odot$ (center), and 40 $M_\odot$ (right). The dashed red lines indicate the interval to which the Fourier transform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

JINST 16 C09034 (2021)

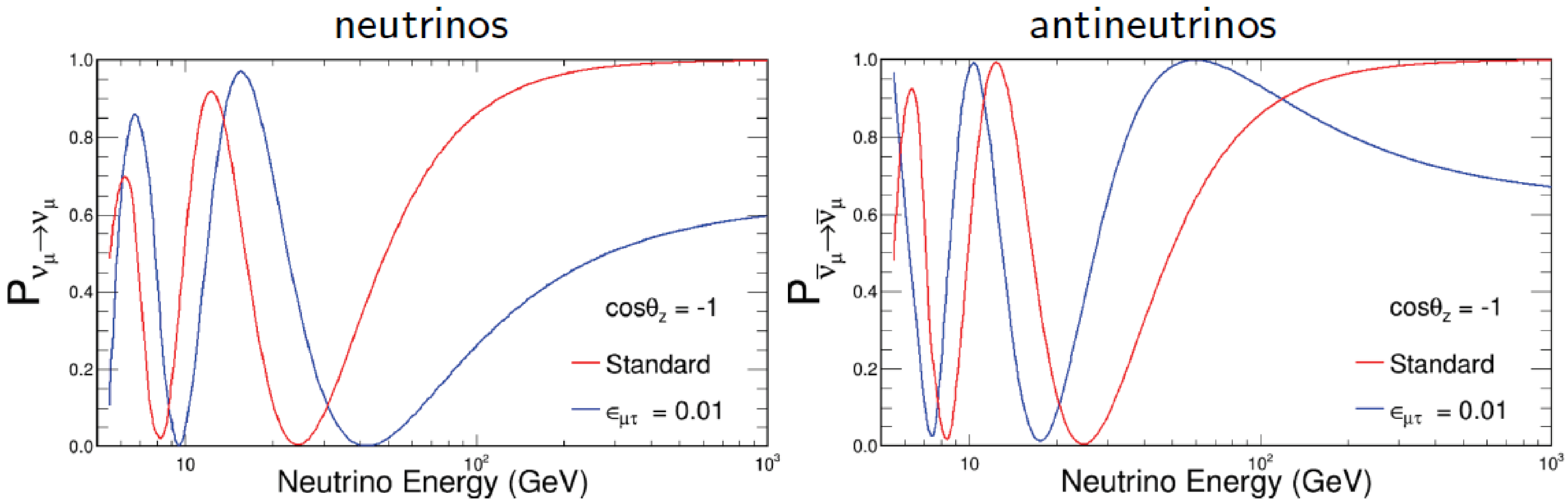
SN alert system



PoS(ICRC2023)1223

NC NSI of ν_α with matter fermions (e, u, d) distort the standard ($\varepsilon_{\alpha\beta} = 0$) MSW effect:
(arXiv:1907.00991v2)

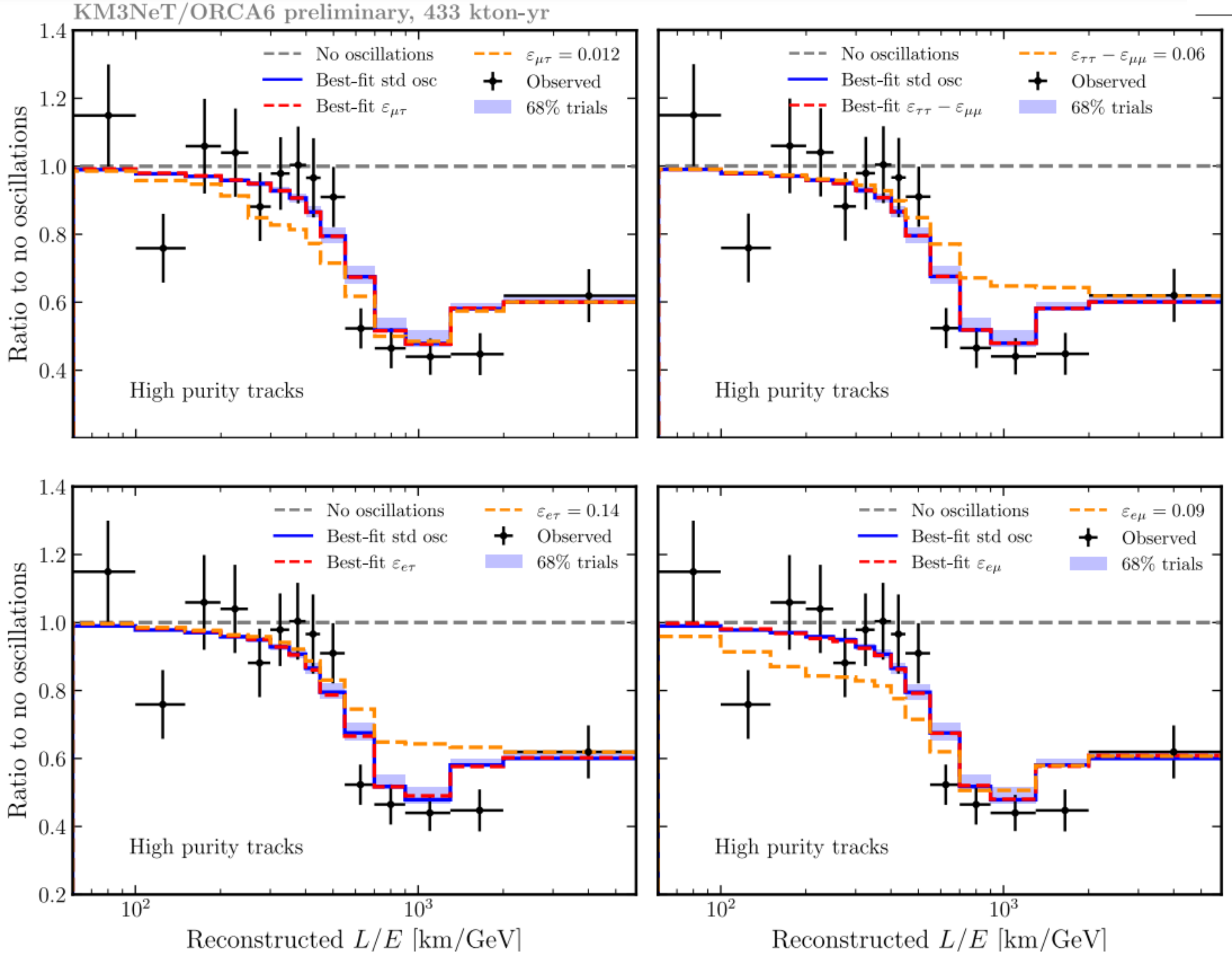
$$H_{\text{eff}} = \frac{1}{2E} U_{\text{PMNS}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix} U_{\text{PMNS}}^\dagger + \sqrt{2} G_{\text{F}} N_e \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{bmatrix}$$

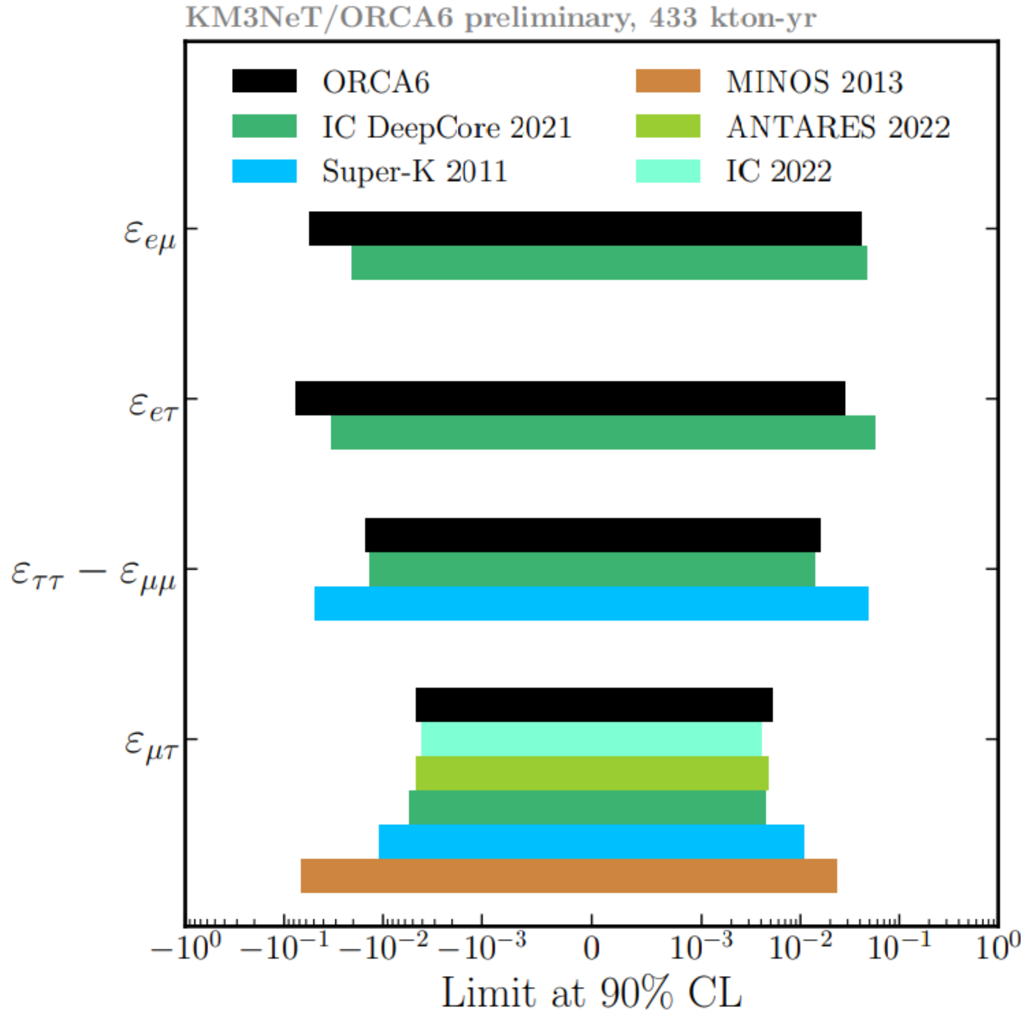


PoS(ICRC2023)998

ORCA6

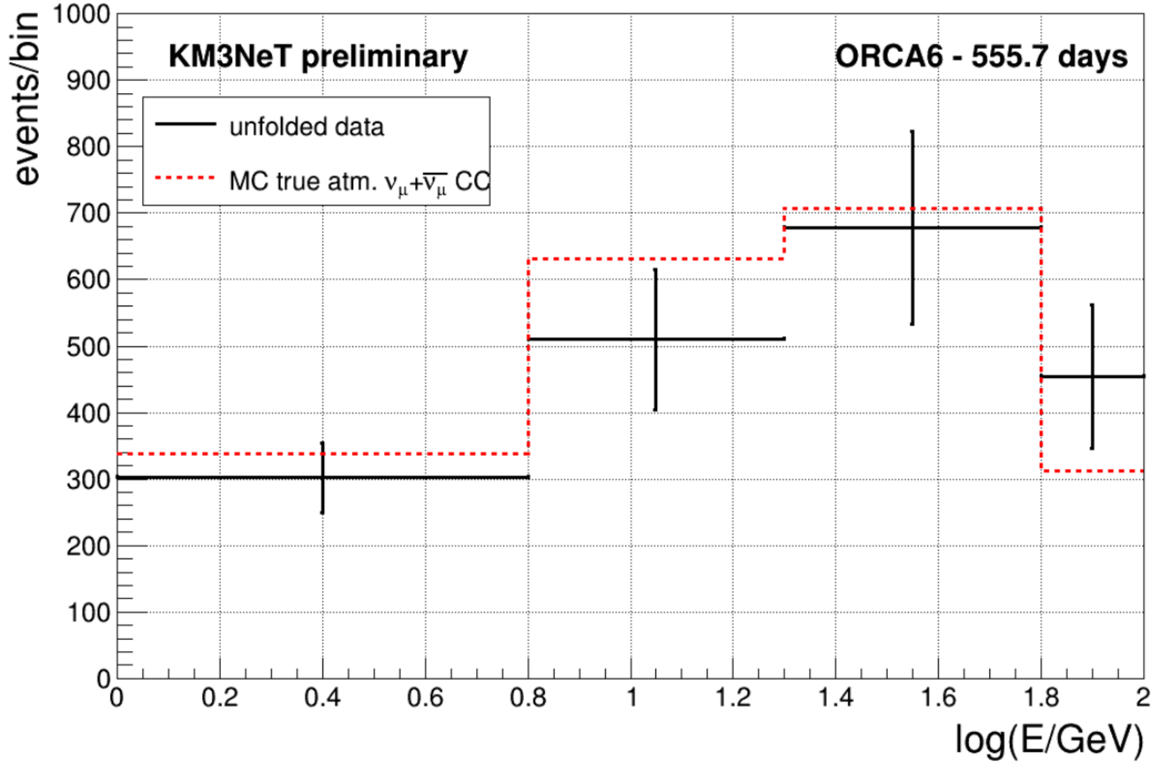
Hypothesis	Best fit $\lvert\varepsilon_{ij}\rvert,\ \delta_{ij}$	p-value	Real-valued 90% CL limit	Complex 90% CL limit
$\varepsilon_{\mu\tau}$	$0.001^{+0.003}_{-0.001},\ 0^{+360°}_{-0}$	0.66	$[-0.0047, 0.0052]$	$\leq 0.0055,\ \delta_{\mu\tau} \in [0°, 360°]$
$\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$	0.00 ± 0.01	0.90	$[-0.015, 0.016]$	—
$\varepsilon_{e\tau}$	$0.04 \pm 0.03,\ 190 \pm 70°$	0.23	$[-0.077, 0.028]$	$\leq 0.078,\ \delta_{e\tau} \in [0°, 360°]$
$\varepsilon_{e\mu}$	$0.03 \pm 0.02,\ 140 \pm 70°$	0.25	$[-0.056, 0.043]$	$\leq 0.058,\ \delta_{e\mu} \in [0°, 360°]$

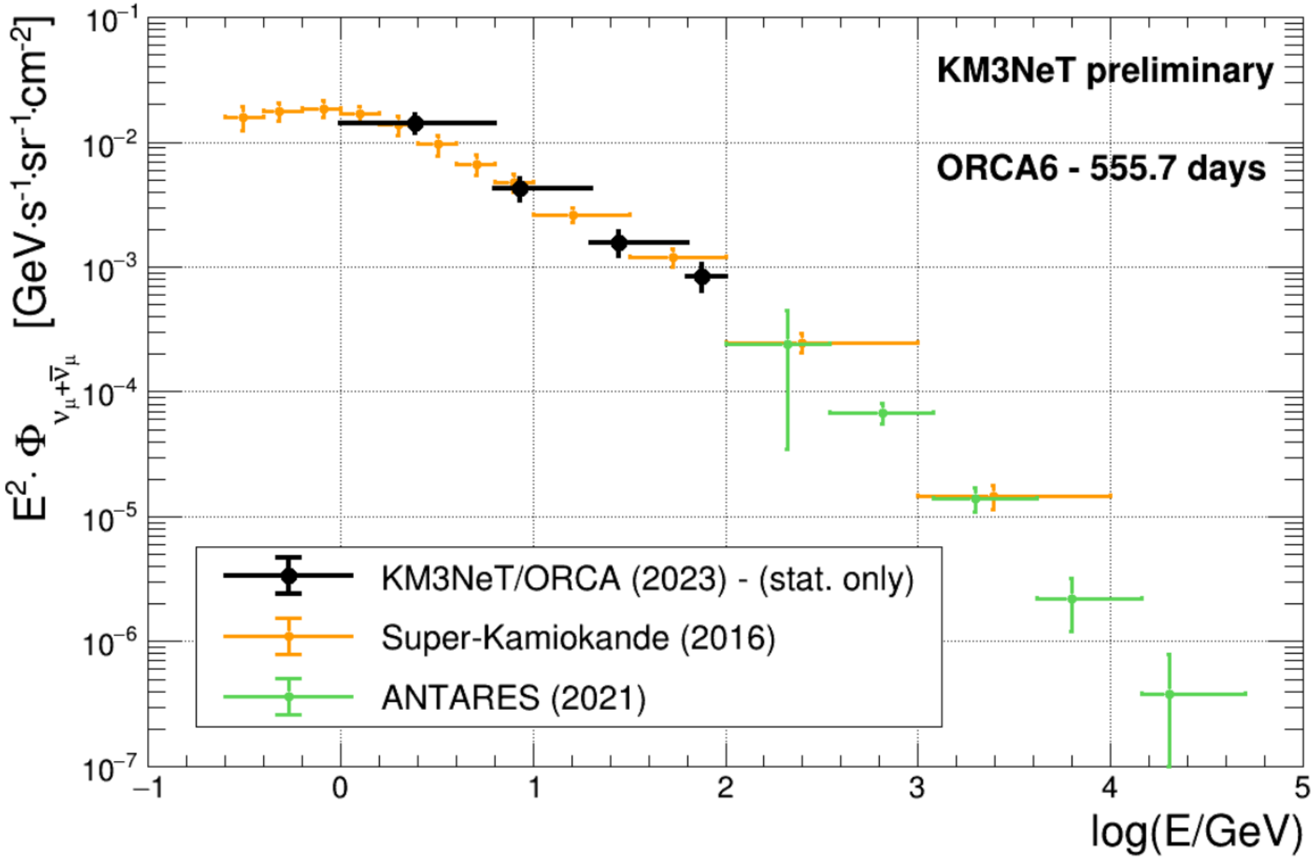




detector: ORCA6
livetime: 555.7d
method: spectrum unfolding

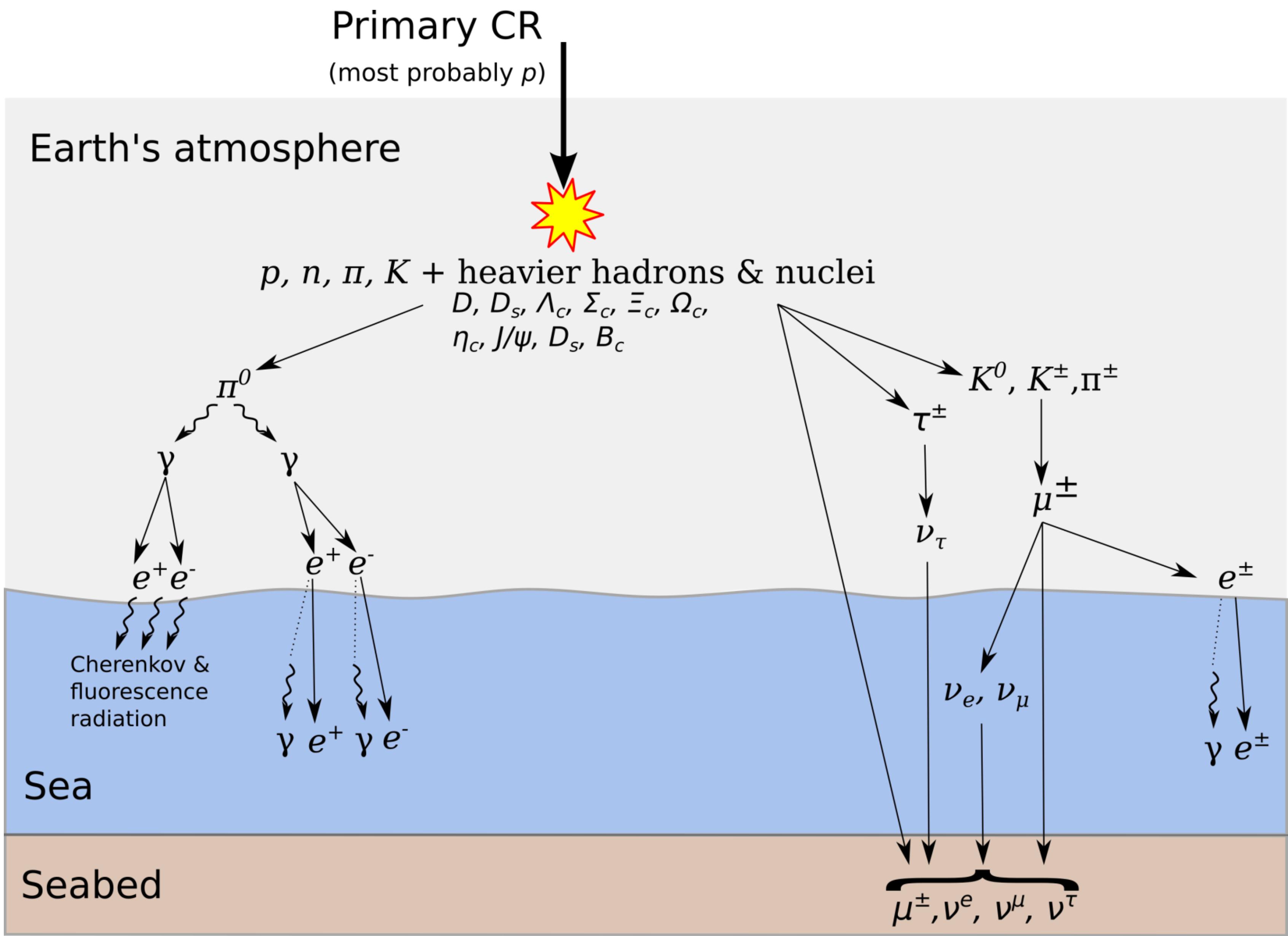
PoS(ICRC2023)1093





EAS:

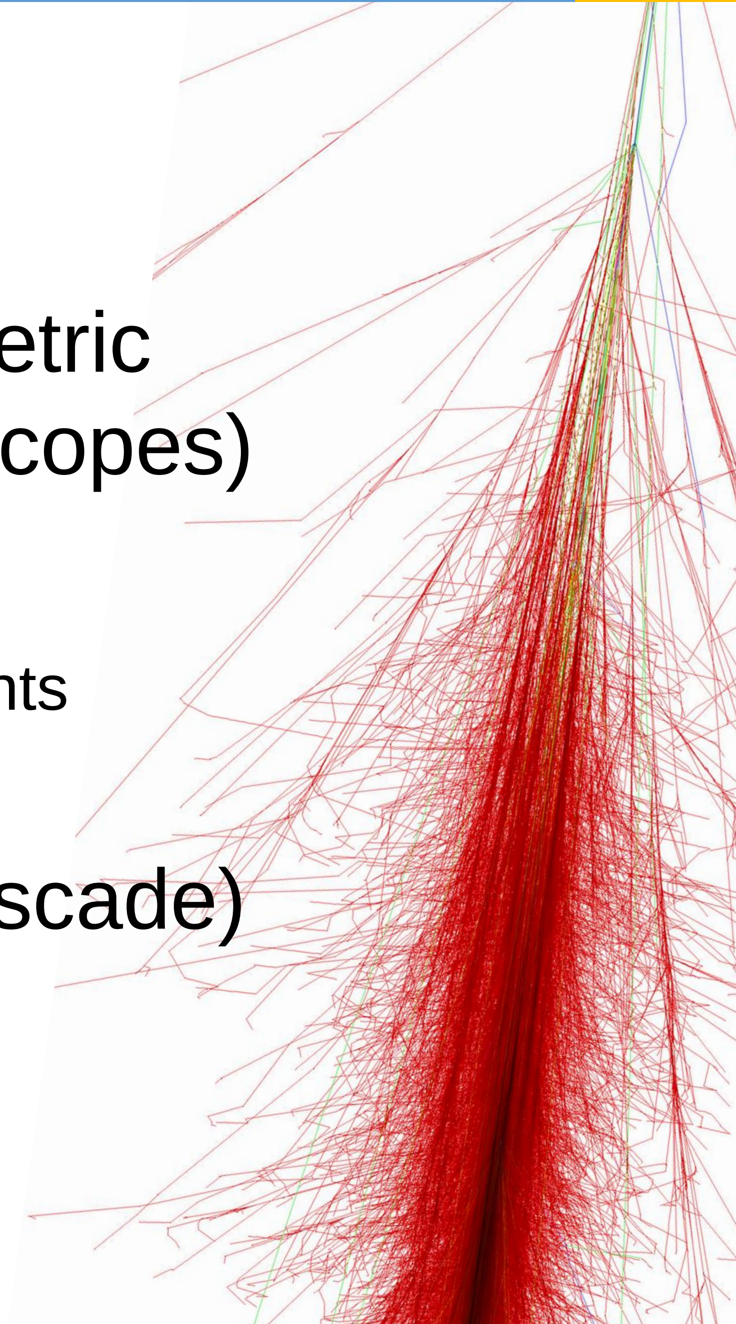
- Caused by primary CR
- Typically start at $h \sim 30 - 40\mathrm{km}$
- 3 main components:
  - electromagnetic (EM)
  - hadronic
  - muonic



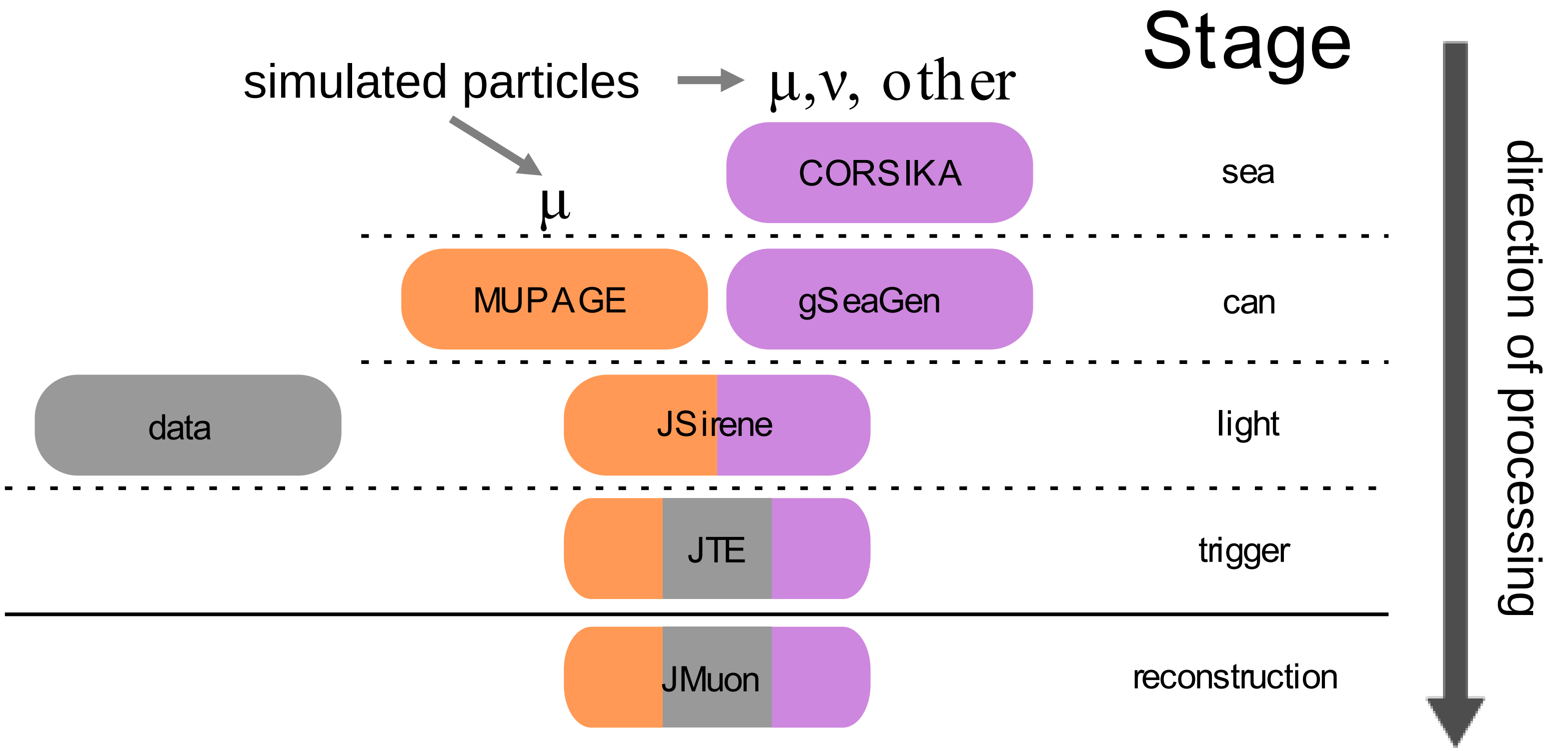
EAS simulations in KM3NeT

We have 2 options:

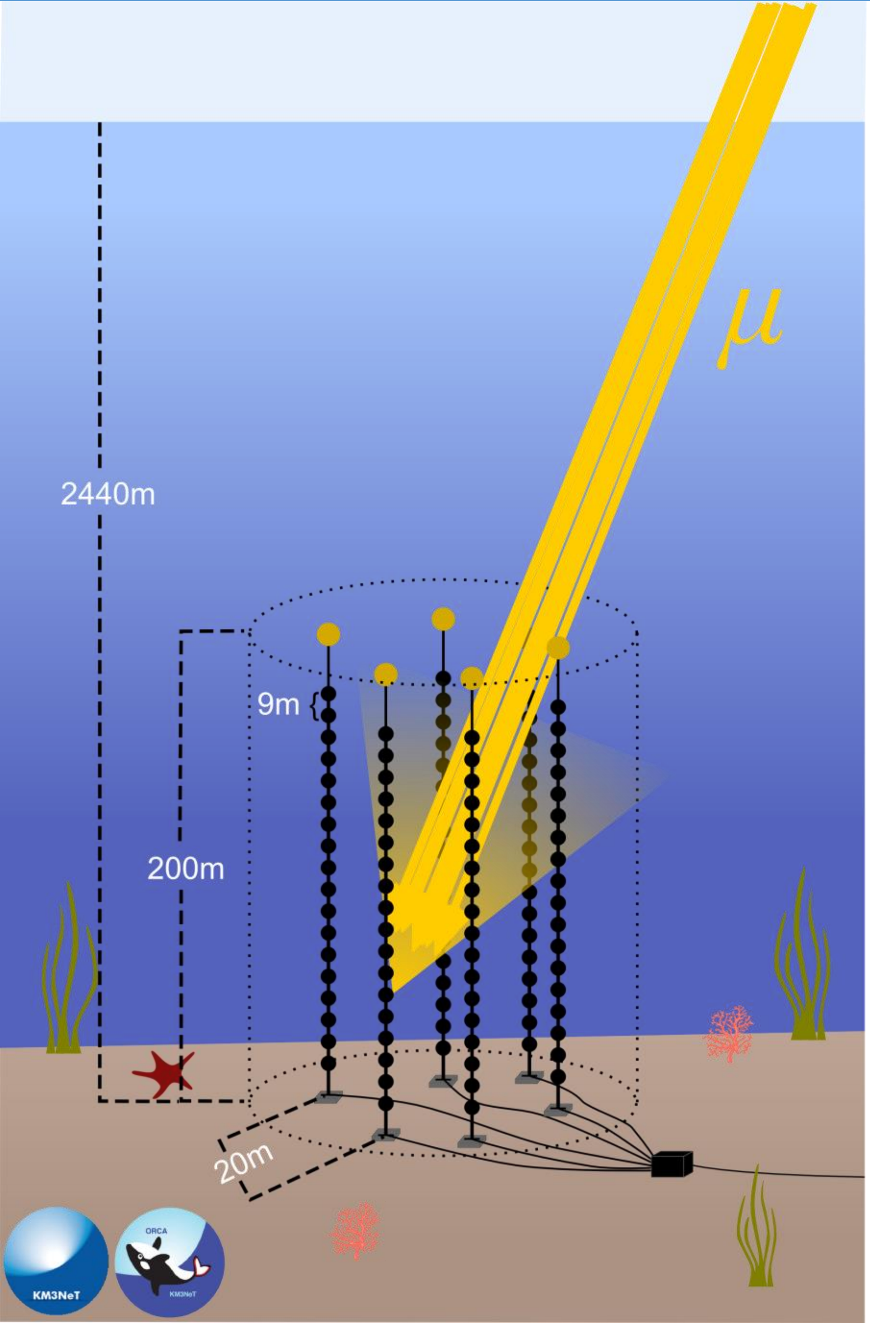
1. MUPAGE (atmospheric **MU**ons from **PA**rametric formulas: a fast **GE**nerator for neutrino telescopes)
    - developed for ANTARES
    - fast muon MC generator
    - based on parametric formulas and MACRO measurements
    - parameters can be freely tuned
2. CORSIKA (**CO**smic **R**ay **SI**mulations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



Workflow of KM3NeT muon simulations:



Here:
sea – sea surface above the km3net detectors
can – cyllindrical volume around the detector
light – simulation of the photon emission inside the can (including the environmental background)
trigger – applying a set of trigger conditions to events, e.g. 3DMuon, tailored to select primarily muon tracks
reconstruction – applying reconstruction algorithms to obtain distributions of observables, e.g. energy, direction



Muon bundle:

bunch of muons coming from a single EAS

Important characteristics:

- $E_{\text{bundle}} = \sum E_\mu$ — rather bad standard reco (designed for single muon events)
- $\cos\theta_{\text{zenith}} = \frac{\sum \cos\theta_{\text{zenith}}}{N_\mu}$ — good standard reco
- multiplicity: N_μ — no standard reco

git.km3net.de/opensource/gseagen

gSeaGen

Code for propagating muons and/or neutrinos to neutrino telescopes. Developed for KM3NeT, but applicable to other experiments.

My involvement in this project:

- Implementation of CORSIKA shower processing
- Speed, memory & storage optimization
- Rework of the geometry: no more flat Earth!
- Code maintenance

Tech stack:

- C++
- ROOT
- PERL
- PROPOSAL (github.com/tudo-astroparticlephysics/PROPOSAL)

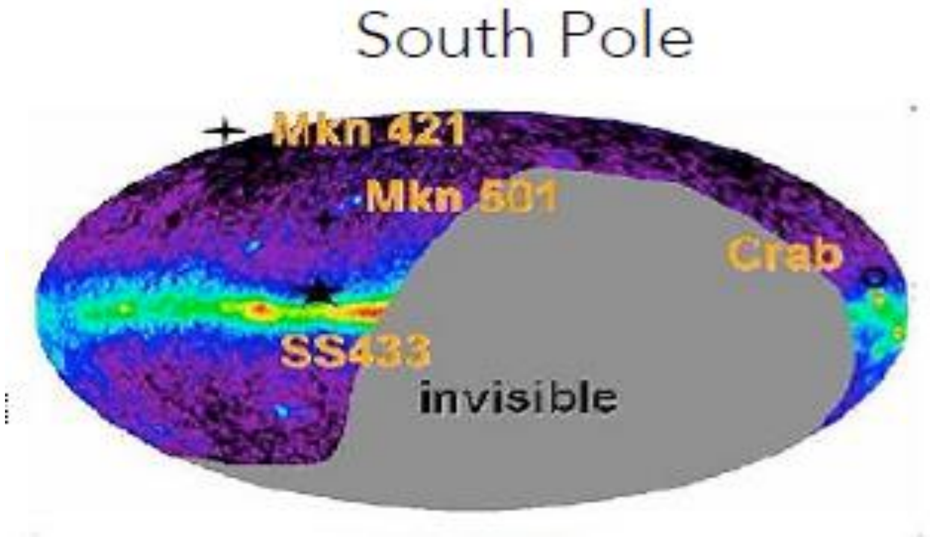
Current devs:

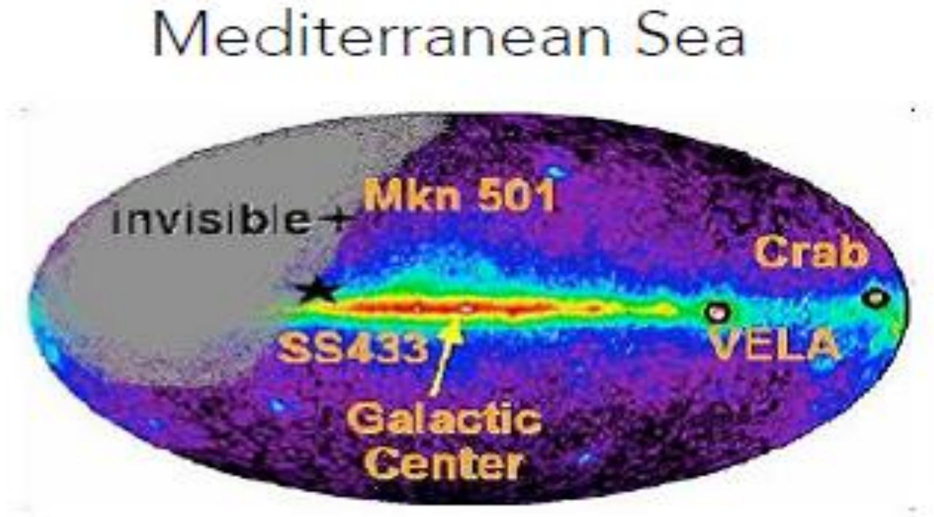
- Carla Distefano
- Alfonso Andres Garcia Soto
- Piotr Kalaczyński
- Johannes Schumann
- Rodrigo Garcia
- Andrey Romanov

paper on this work under collaboration review …

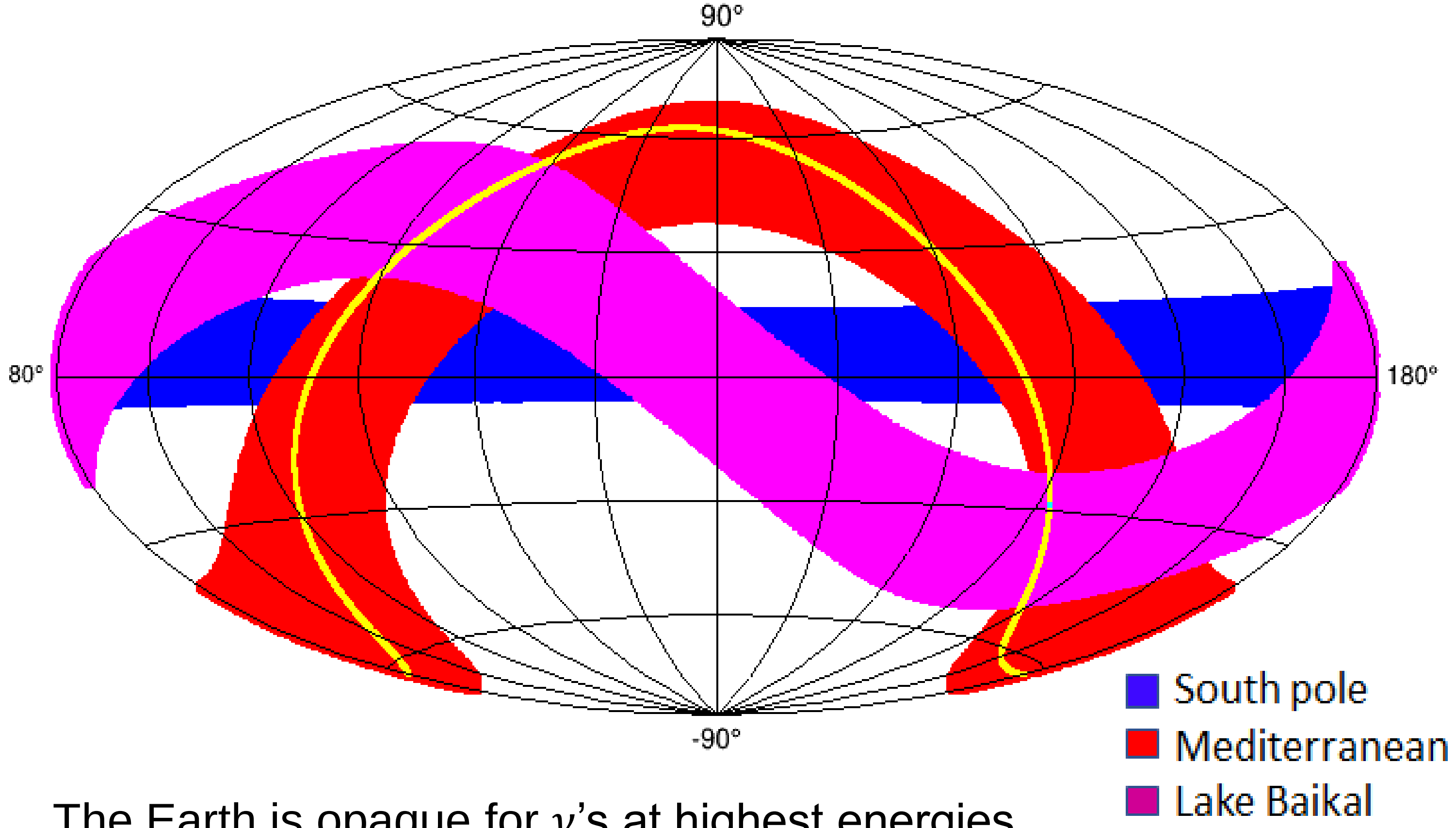
Sky coverage

Galactic sources expected at 1-10 TeV:





Field of view with horizontal tracks



The Earth is opaque for ν's at highest energies

↓

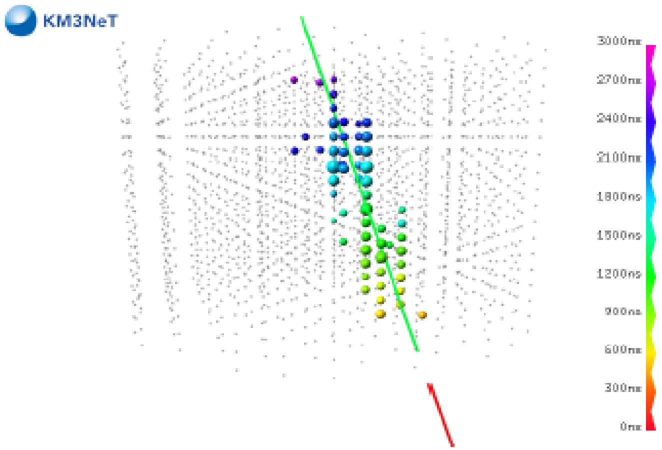
golden channel: horizontal tracks
(atm. μ's are suppressed, but the ν's make it)

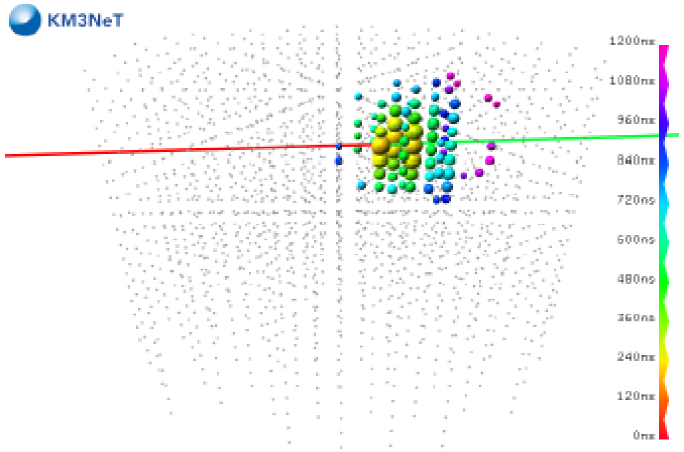
Angular resolution

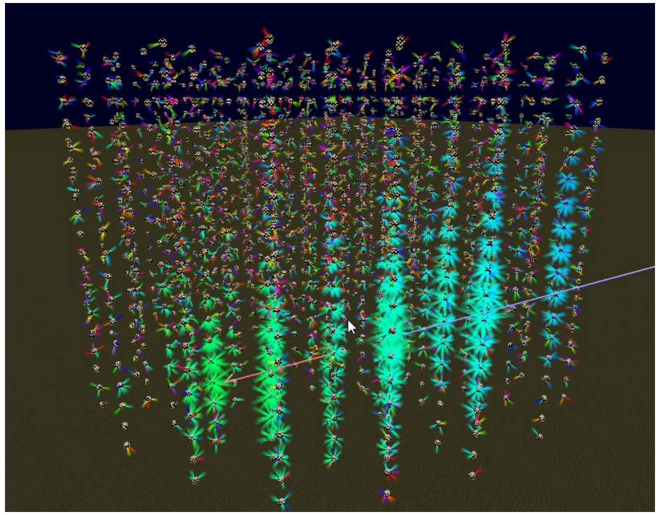
Tracks
(CC: ν_μ, ν_τ ($\tau \rightarrow \mu$))

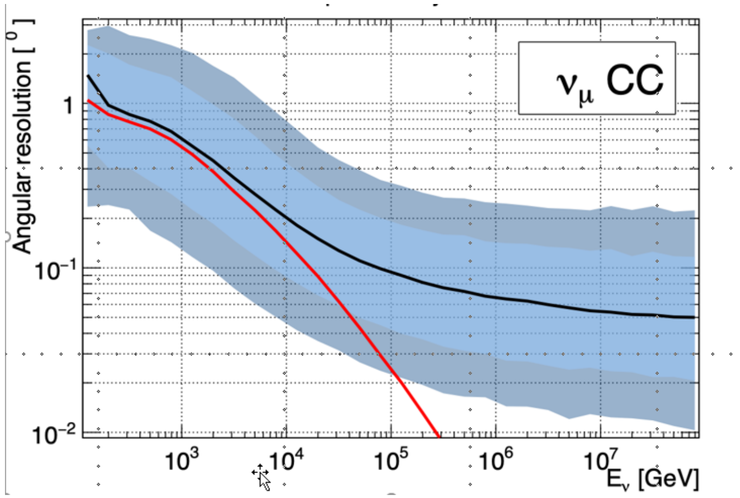
Cascades
(NC: $\nu_{e,\mu,\tau}$, CC: ν_e, ν_τ ($\tau \nrightarrow \mu$))

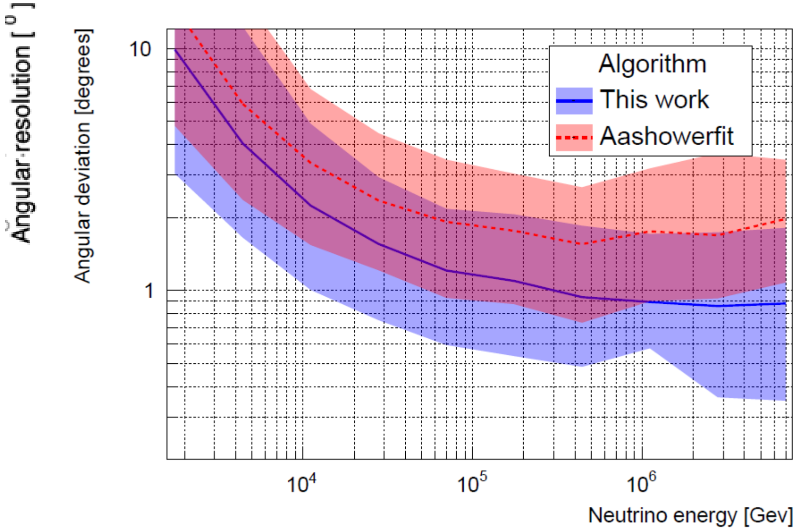
Double Cascades
(ν_τ - only)

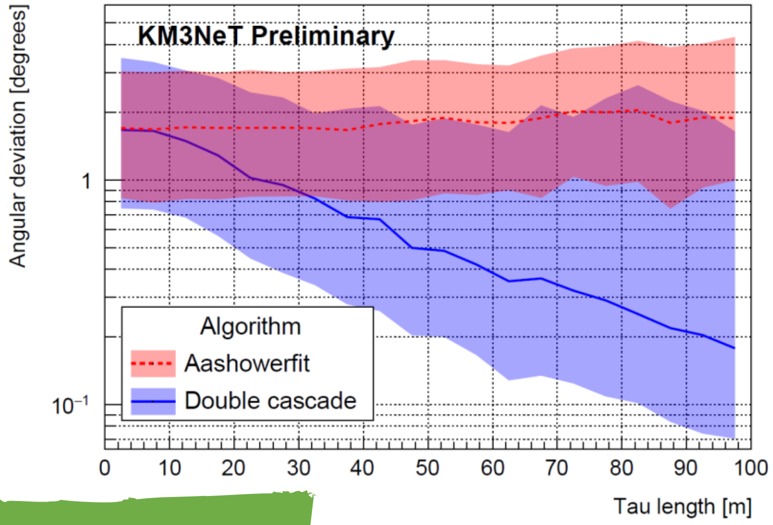








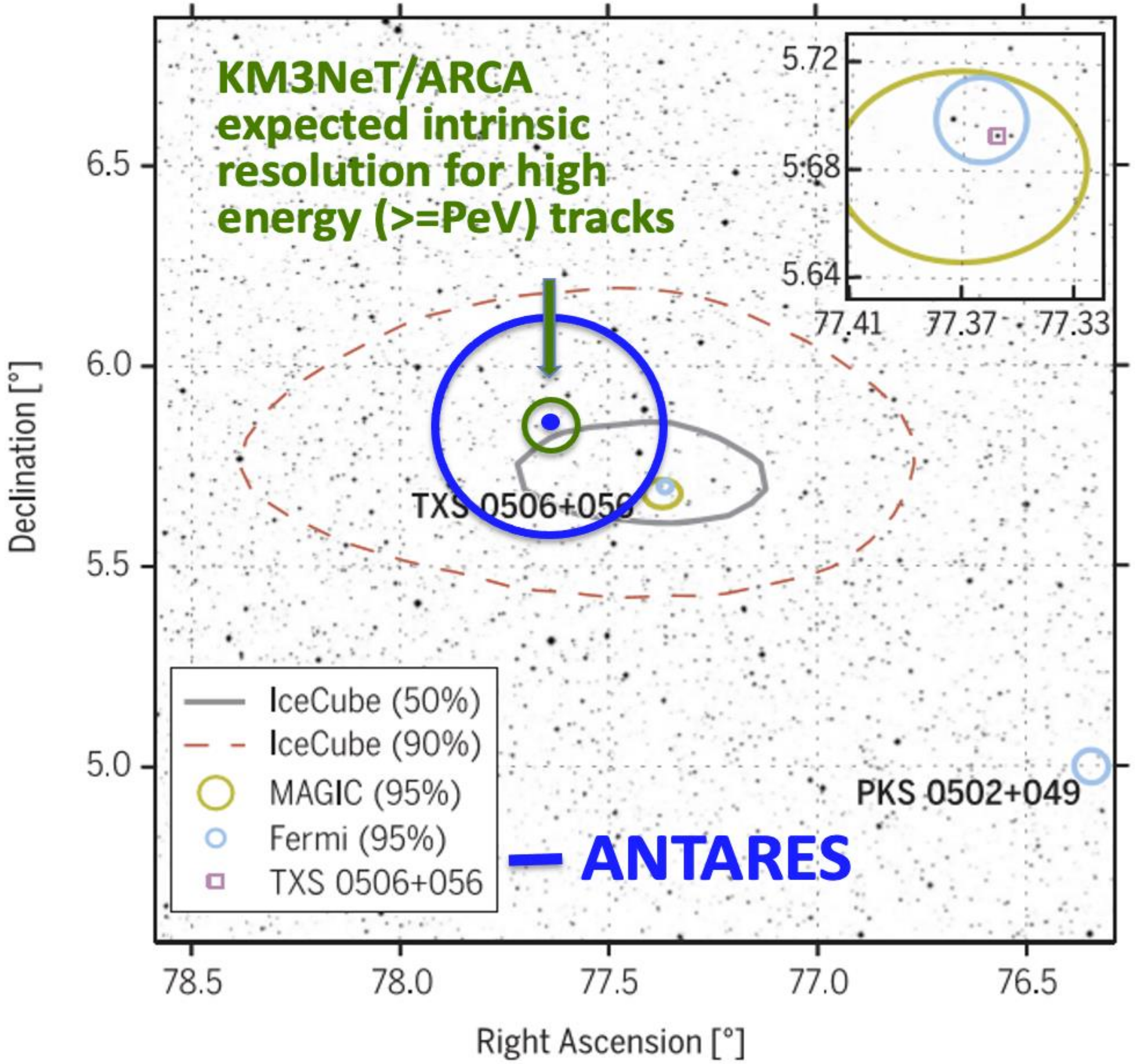




JINST 16 C09021

PoS(ICRC2021)1089

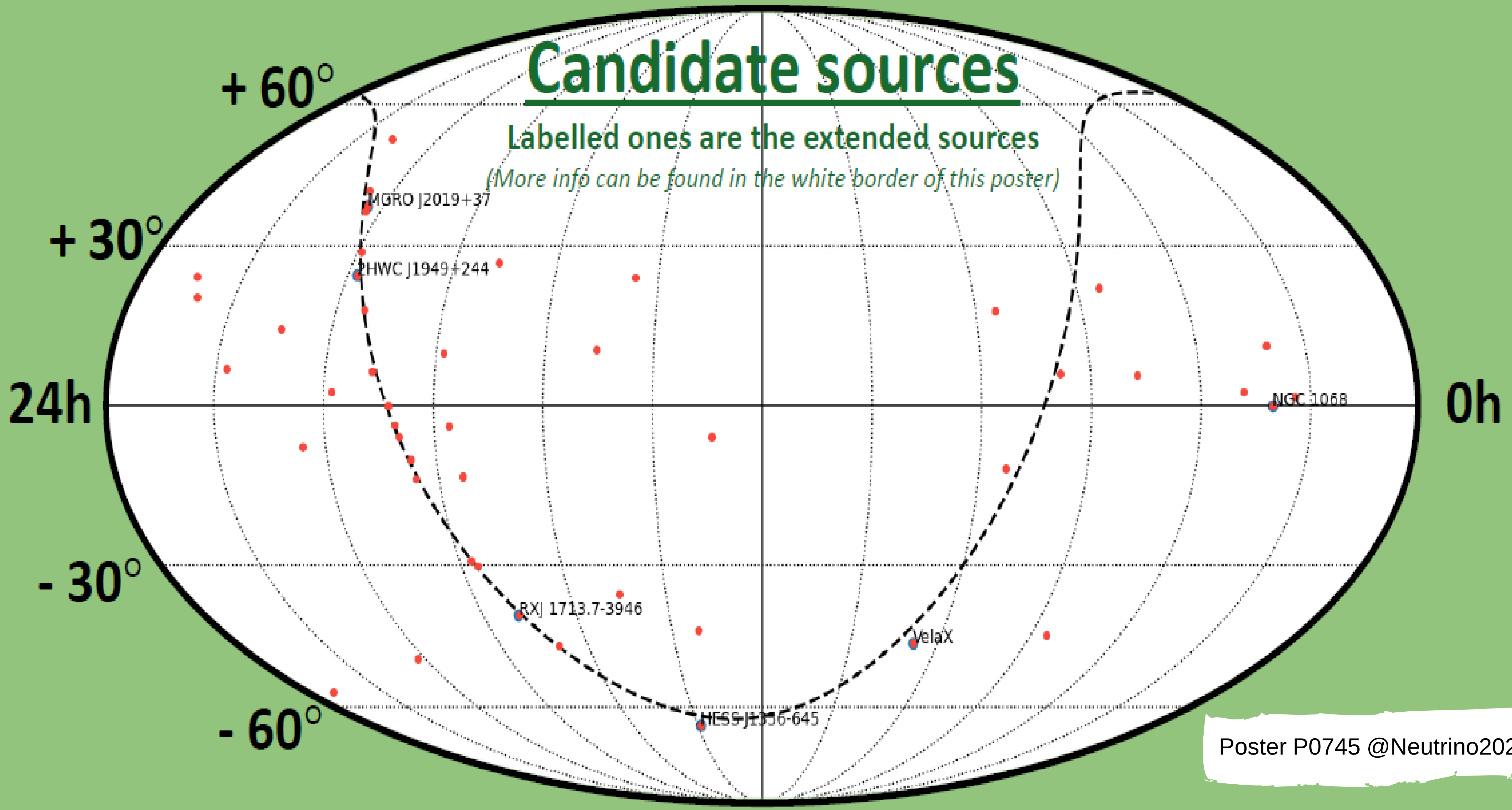
Expected KM3NeT/ARCA resolution drawn on optical skymap around blazar TXS 0506+056:
(first identified HE ν_{cosmic} source by IceCube)



ARCA & ANTARES resolutions are added to the original plot from

SCIENCE 13 Jul 2018 Vol 361, Issue 6398

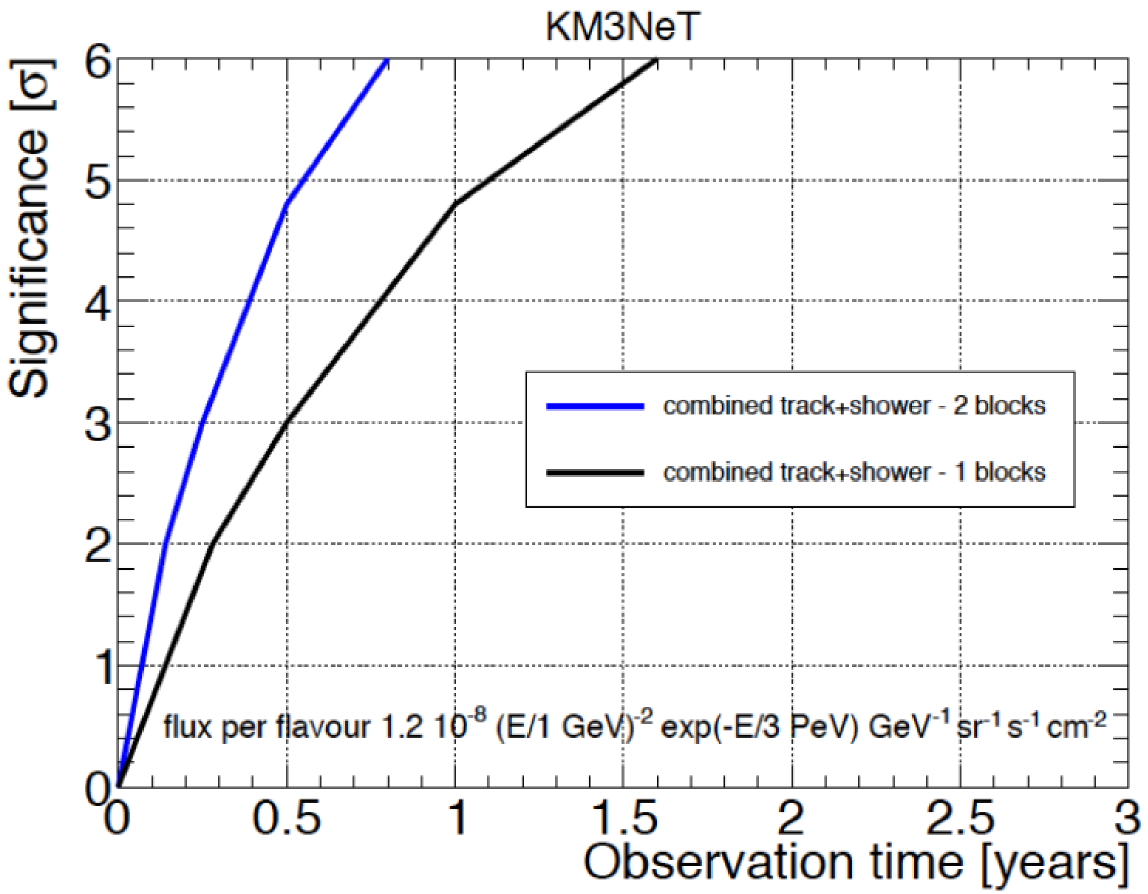
Point & extended source sensitivity

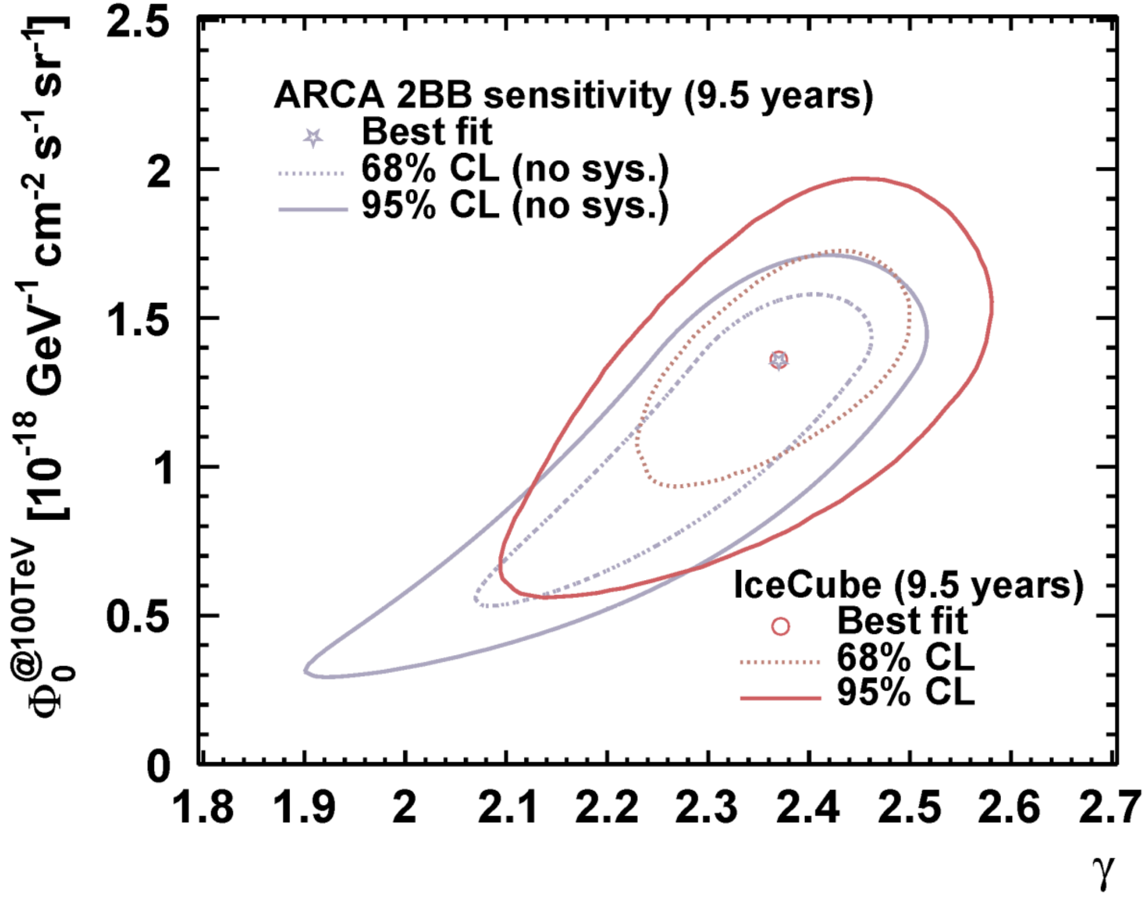


Poster P0745 @Neutrino2022

PoS(ICRC2021)1077

With assumption of ν flux parameters as measured by IceCube:

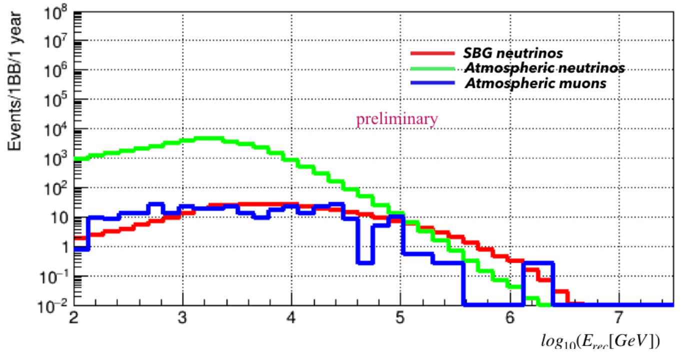




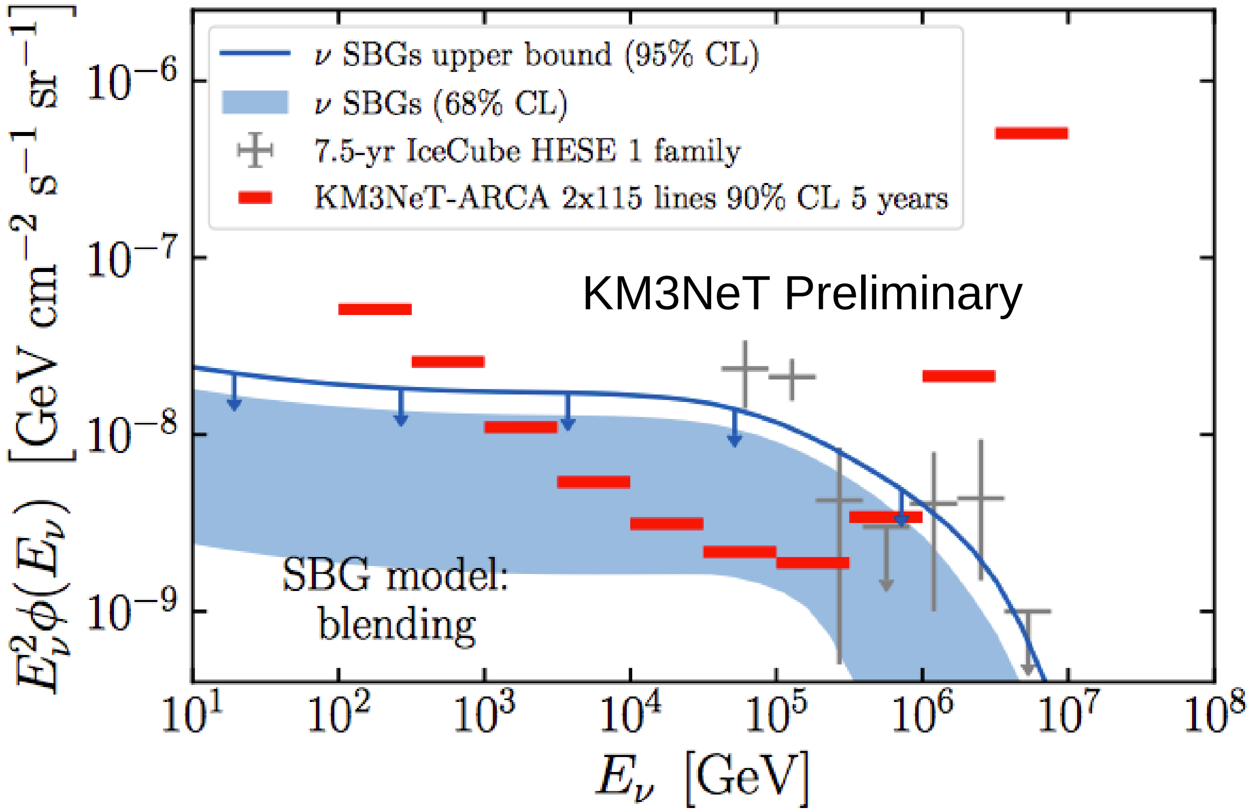
Result for complete ARCA (2x115=230 strings)

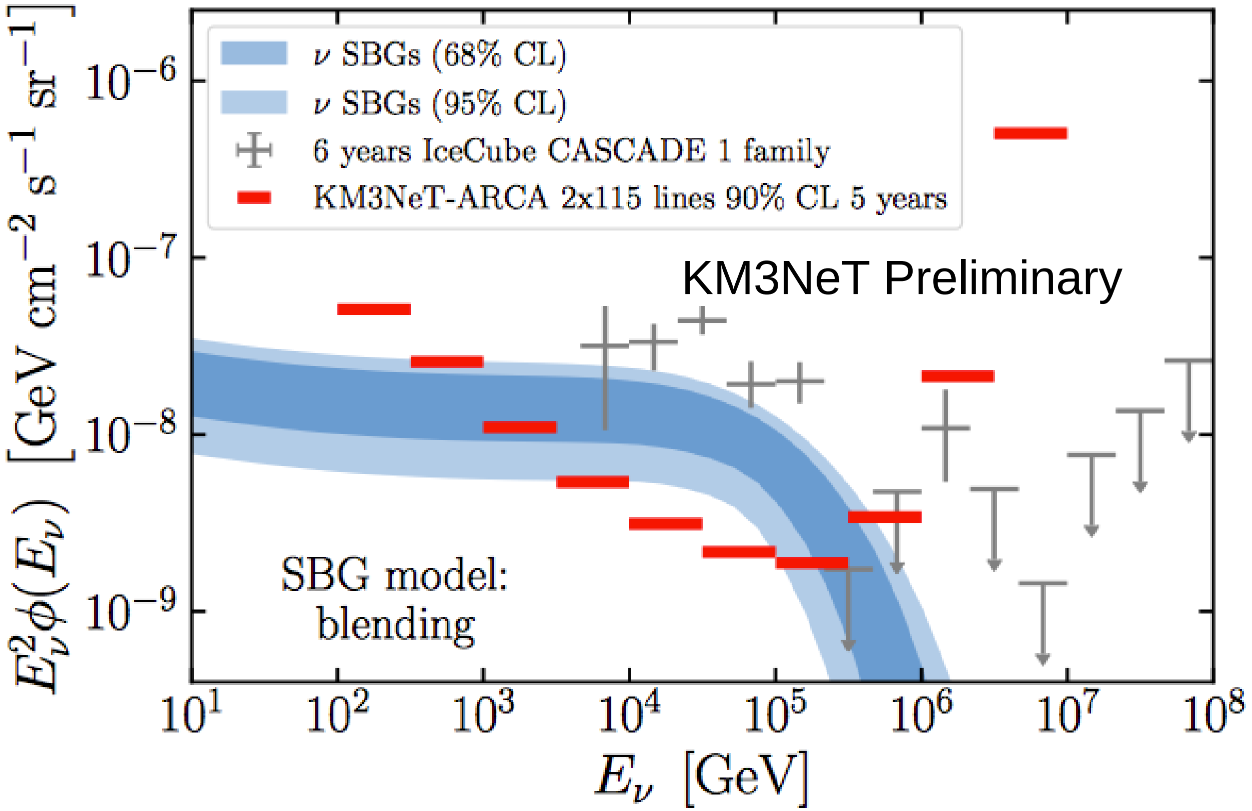
JINST 16 C12016

event distributions after selection:

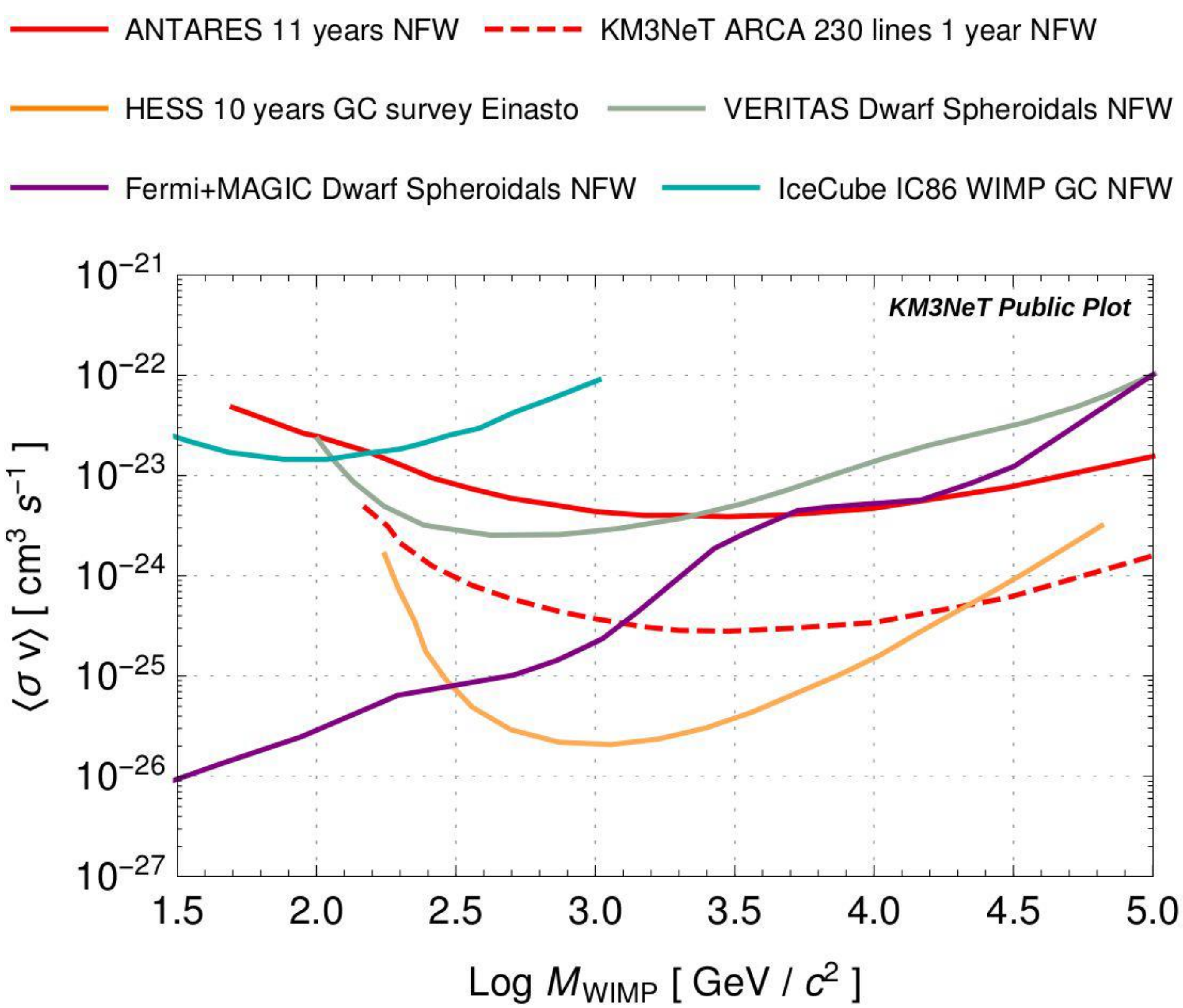


Differential sensitivity to diffuse ν flux coming from Starburst Galaxies (SBGs):





Dark Matter from Galactic Centre



$$\langle \sigma v \rangle = \frac{4\pi}{J_{\text{int}}} \cdot \frac{n_{\text{sig}}}{A \cdot t_{\text{live}}} \cdot M_\chi^2$$

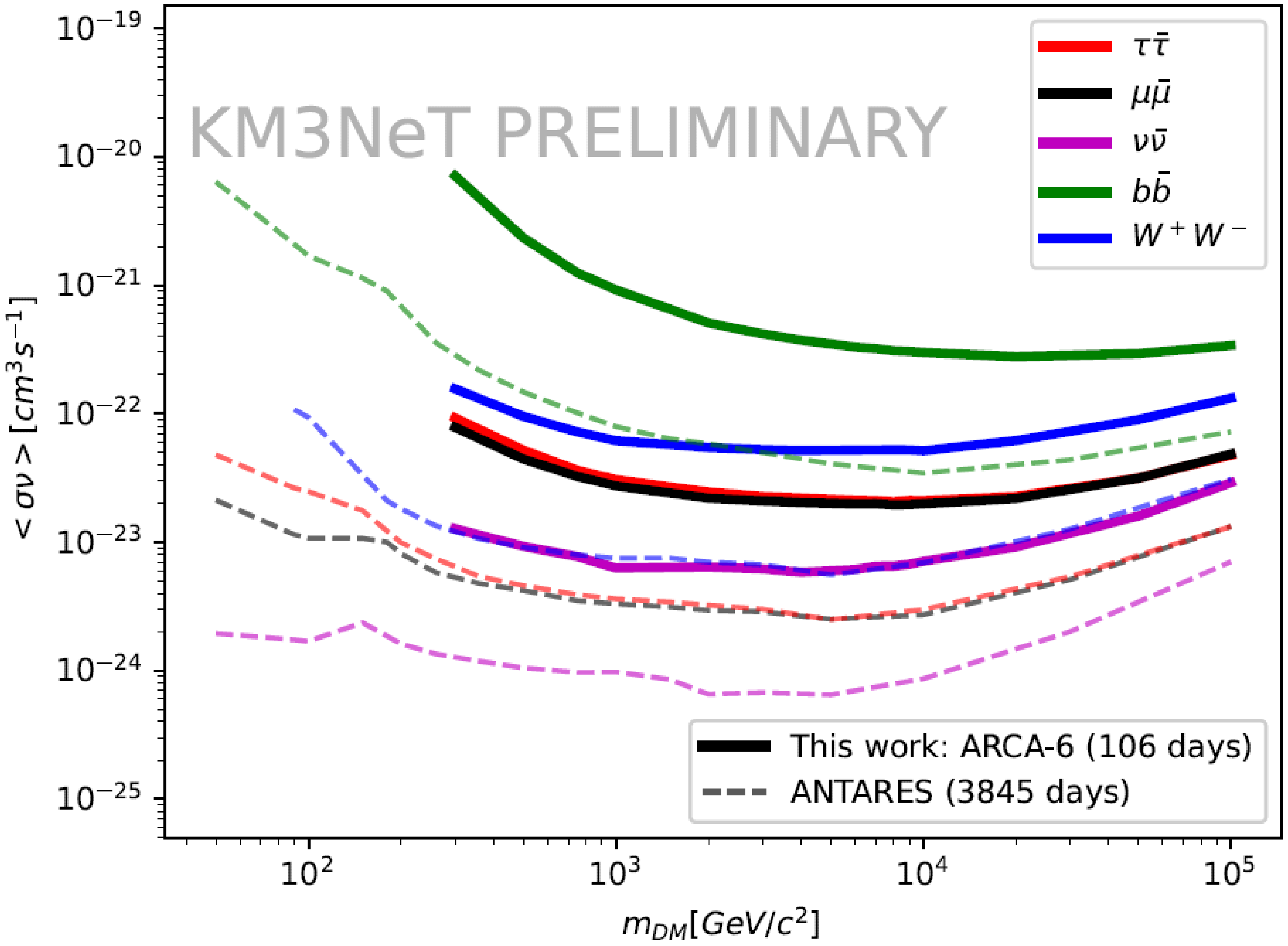
A – acceptance
t_{live} – livetime
J_{int} – geometry factor depending on the source shape
M_χ – mass of the DM particle
n_{sig} – number of distinguishable signal events

Sensitivity for ARCA2x115 (230 strings)

Sensitivity to ν coming from DM annihilation in the Galactic Centre computed by performing pseudo-experiments
(injecting different signals into background skymaps)

JINST 16 C09006

Dark Matter from Galactic Centre



$$\langle \sigma v \rangle = \frac{4\pi}{J_{\rm int}} \cdot \frac{n_{\rm sig}}{A \cdot t_{\rm live}} \cdot M_\chi^2$$

A – acceptance
$t_{\rm live}$ – livetime
$J_{\rm int}$ – geometry factor depending on the source shape
M_χ – mass of the DM particle
$n_{\rm sig}$ – number of distinguishable signal events

Result for ARCA6
Sensitivity to ν coming from DM annihilation in the Galactic Centre computed by performing pseudo-experiments
(injecting different signals into background skymaps)

Poster P0549 @Neutrino2022

KM3NeT: ν data (10y)

CTA:

- Imaging-Air-Cherenkov telescope (IACT)
- γ-ray data (200h)
- $20\text{TeV} < E <$ few 100TeV

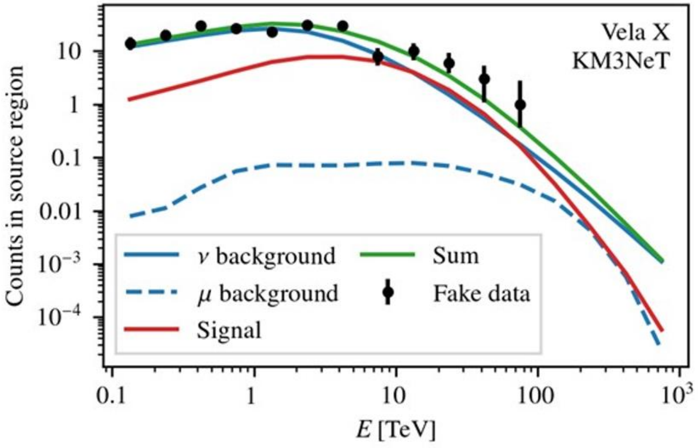
We compare **2 emission scenarios**

- Hadronic: $\gamma + \nu$ (inverse compton model)
- Leptonic: only γ (pion decay model)

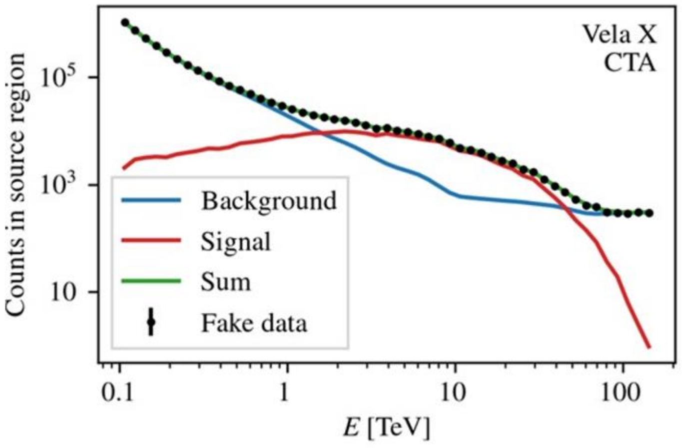
Tested on **4 sources**:

- Vela X (shown in plots)
- RX J1713.7-3946
- HESS J1908+063
- Westerlund1

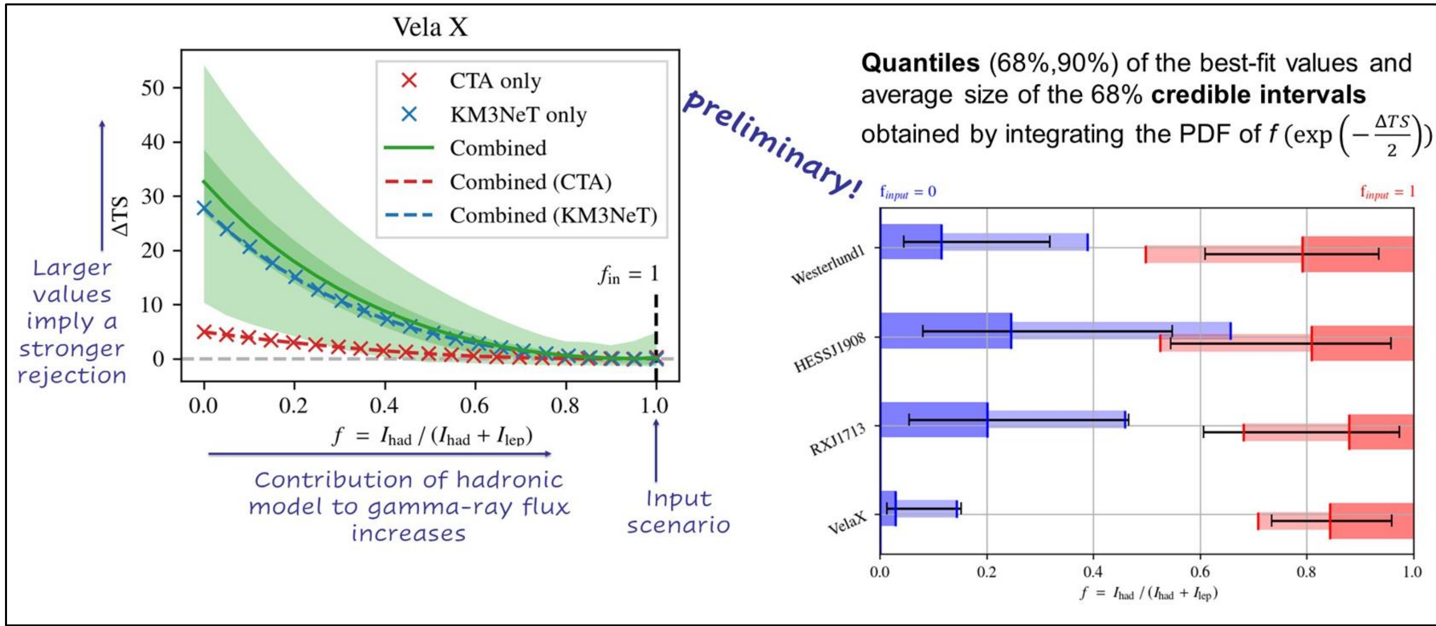
Hadronic emission from VelaX as seen in **neutrinos**



Hadronic emission from VelaX as seen in **gamma rays**



Results:

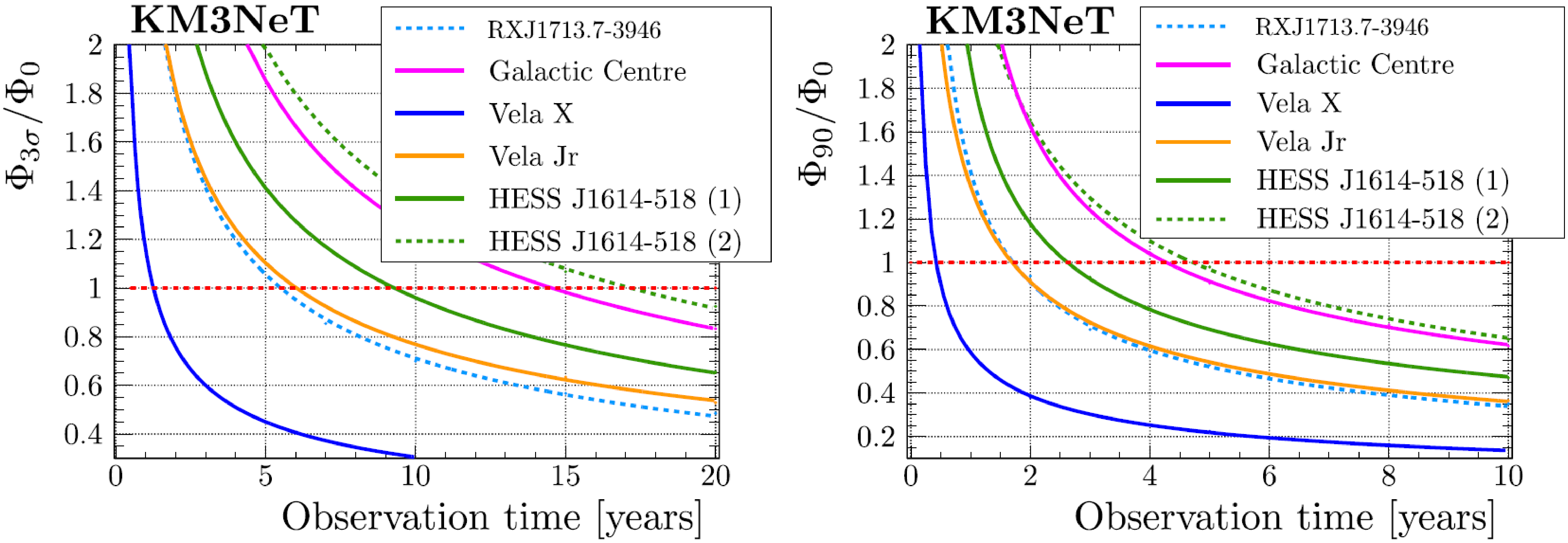


Poster P0519 @Neutrino2022

Astropar. Phys. 111, 100–110 (2019)

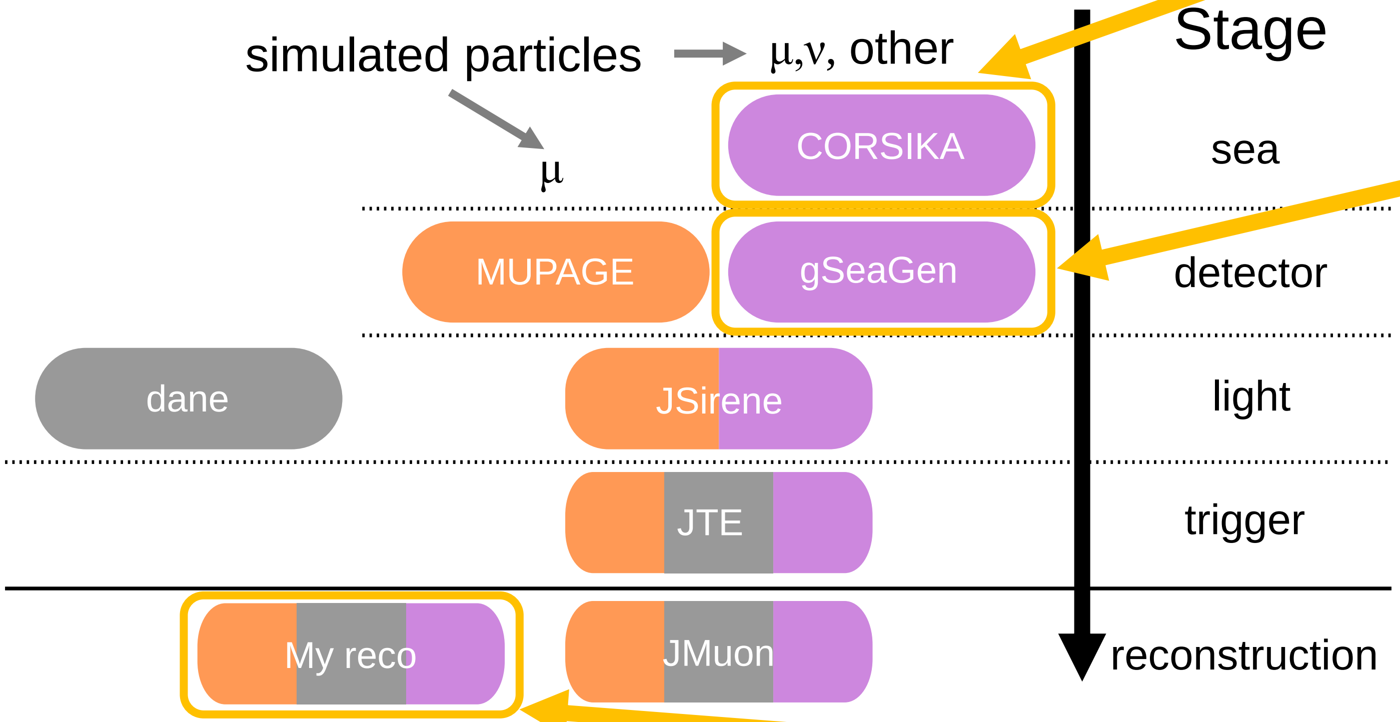
Source	δ	radius	k_0	Γ	E_{cut}	β	γ-ray data	type
RX J1713.7-3946	−39.77°	0.6°	0.89	2.06	8.04	1	[11]	SNR
Vela X	−45.6°	0.8°	0.72	1.36	7	1	[23]	PWN
Vela Jr	−46.36°	1°	1.30	1.87	4.5	1	[12]	SNR
HESS J1614-518 (1)	−51.82°	0.42°	0.26	2.42	–	–	[24]	SNR
HESS J1614-518 (2)	−51.82°	0.42°	0.51	2	3.71	0.5	[24]	SNR
Galactic Centre	−28.87°	0.45°	0.25	2.3	85.53	0.5	[25]	UNID

Φ_0 - expected neutrino flux



KM3NeT muon simulation chain

KM3NeT CR muon simulation chain:



My work:

- ❖ Running CORSIKA:
  - Test productions
  - Mini-prods for systematic studies
  - First mass prod
- ❖ gSeaGen development: git.km3net.de/opensource/gseagen
  - Implementation of CORSIKA processing
  - Improvements in the propagation routine:
    - Speed-up: for EeV 1w -> 40min
    - Earth's curvature
    - Statistics optimization: muon range tolerance margin, possibility to retry propagation etc.
    - More in the publication [under review]: "gSeaGen code by KM3NeT: an efficient tool to propagate muons simulated with CORSIKA" (to be submitted to: Comp. Phys. Comm.)
- ❖ Reconstruction of new observables

Here:

sea – sea surface above the KM3NeT detectors

can – cyllindrical volume around the detector

light – simulation of the γ emission inside the can (including the environmental bgd)

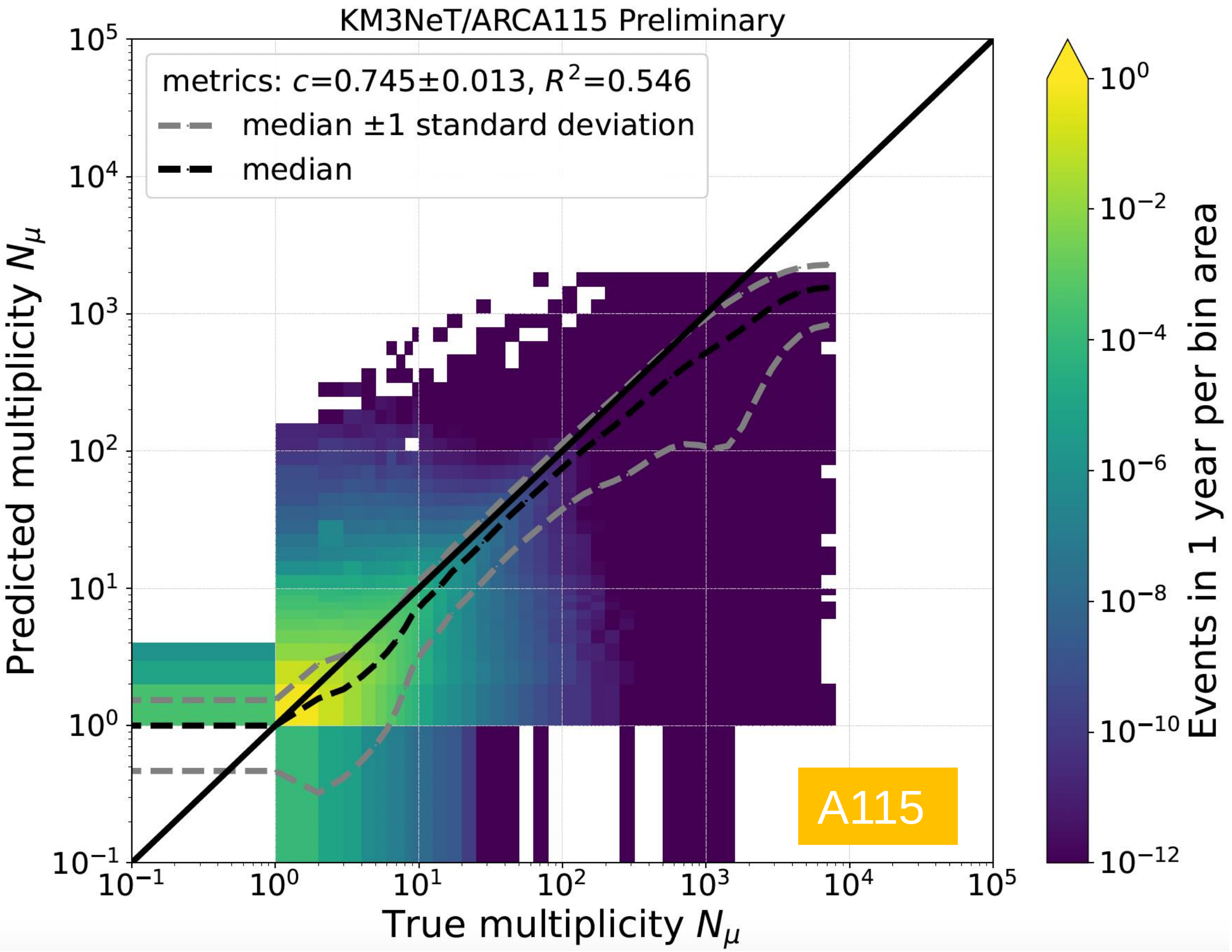
trigger – preselection of interesting events by applying trigger conditions

reconstruction – reconstruction of observables, like energy, direction etc.

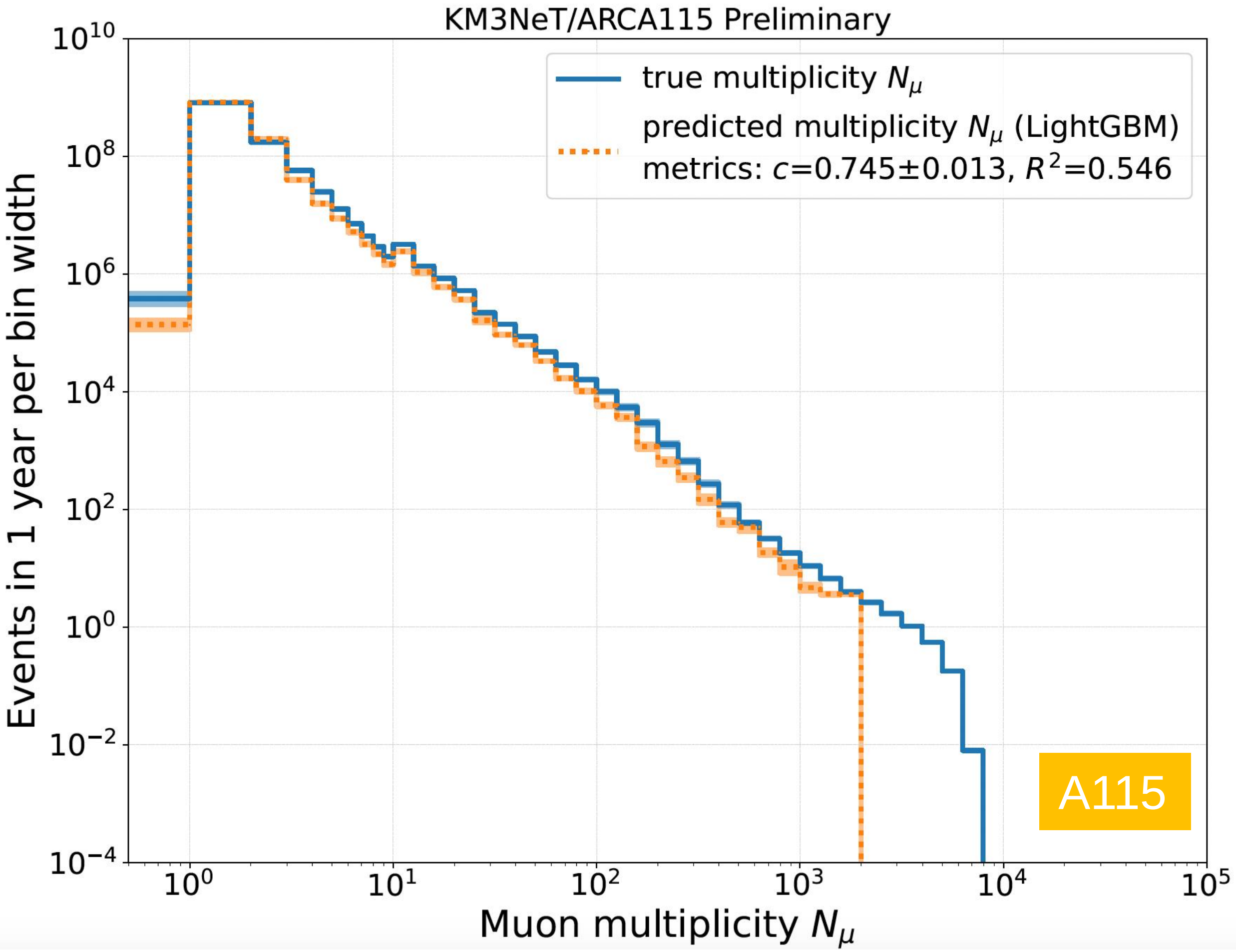
Example of reco results:
muon multiplicity for ARCA115

Analogical results for ARCA6, ORCA115 i ORCA6
(and for 2 other observables)

2D: reco vs true



1D histograms

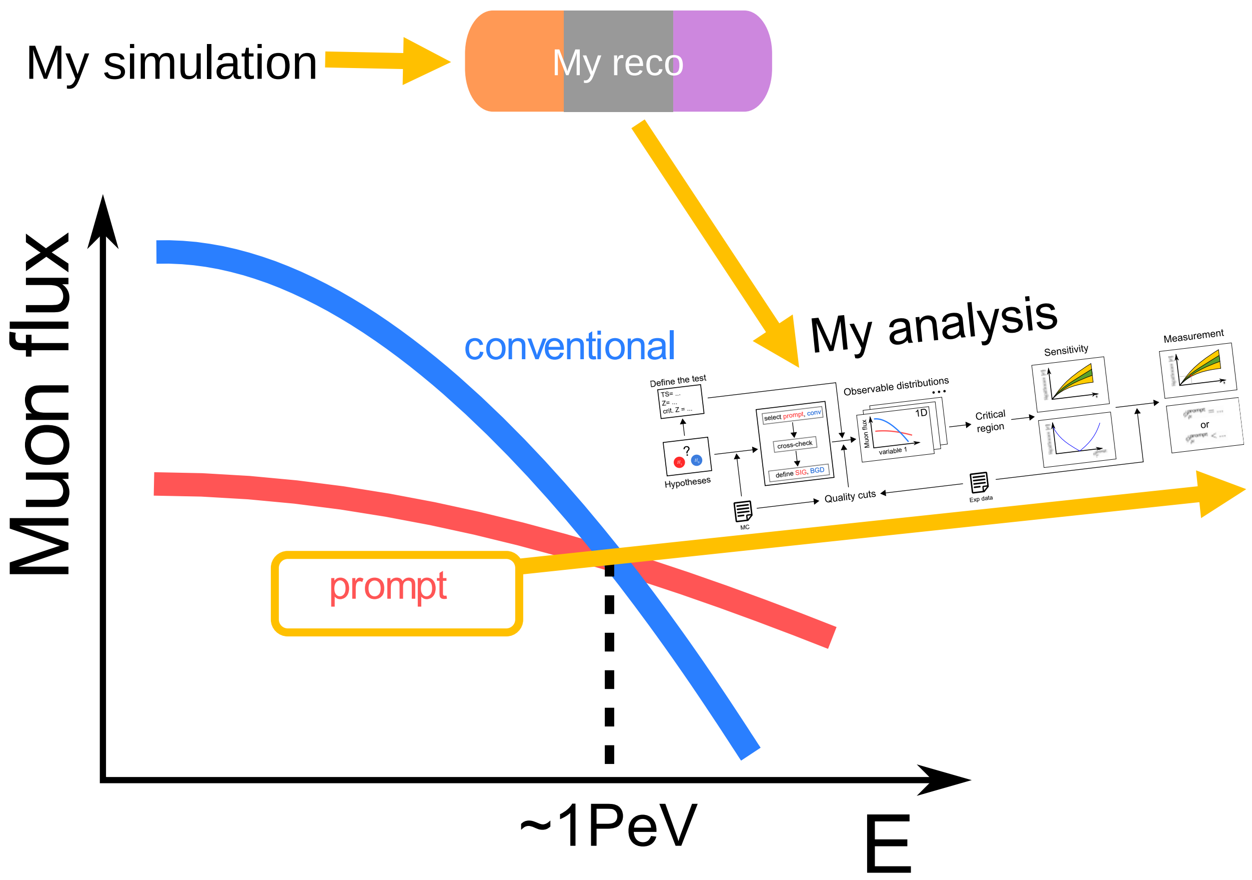


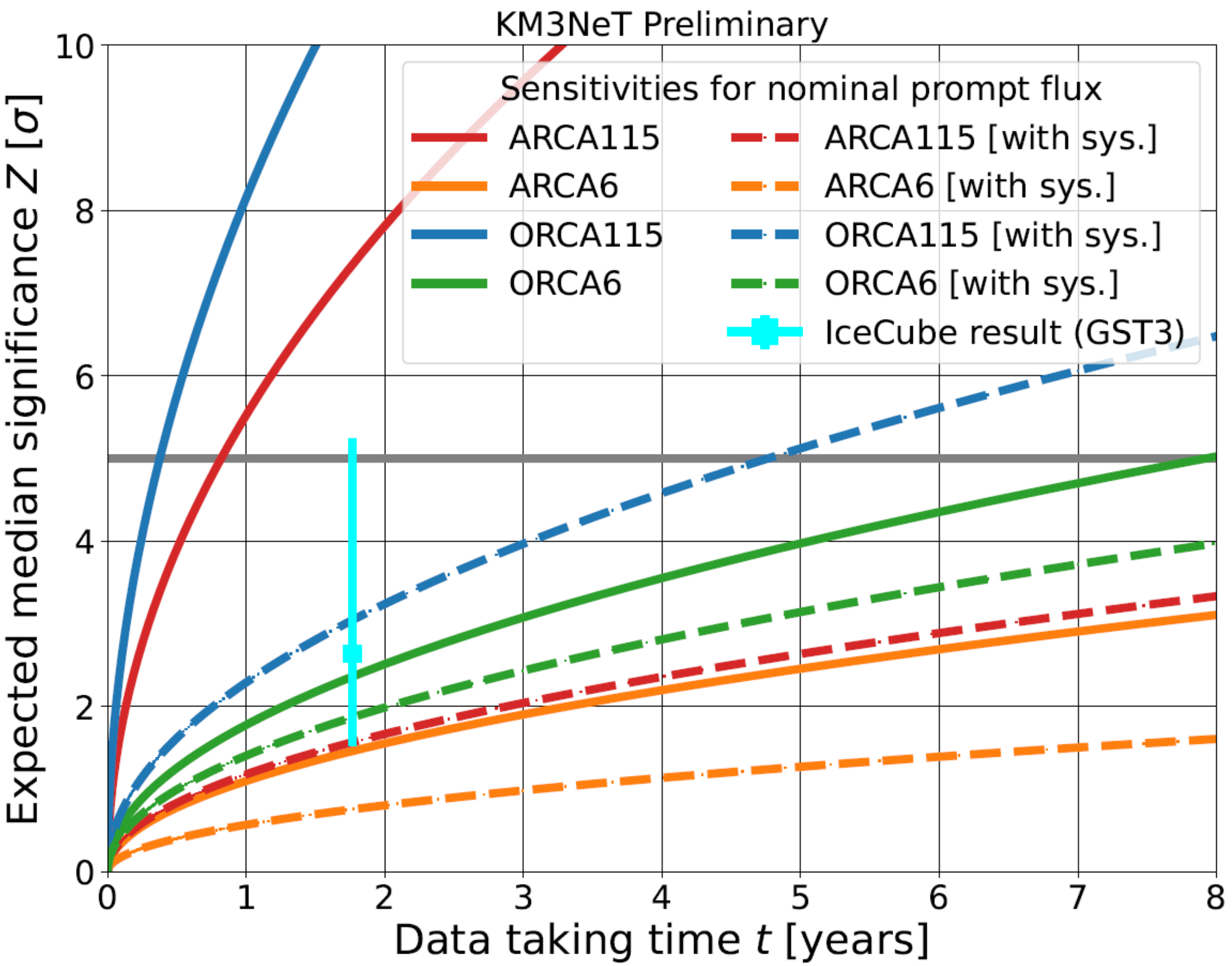
Sensitivities vs time

full analysis covered in my PhD thesis: https://bip.ncbj.gov.pl/attachments/download/258

Comments:

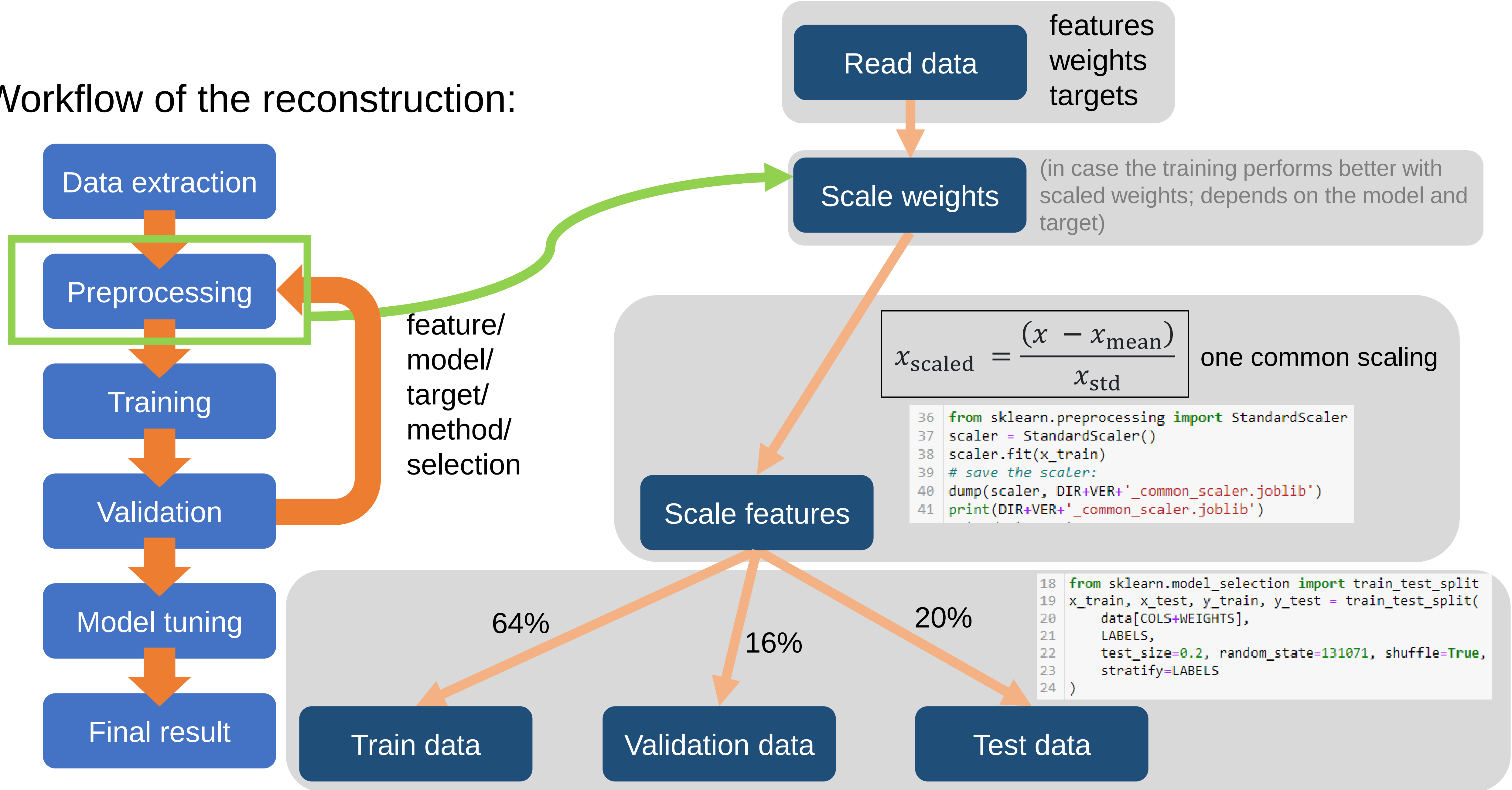
- Sensitivity limited by systematics
- Should improve by the time we complete the construction
- IceCube uncertainty: various CR models





ML reco: general overview

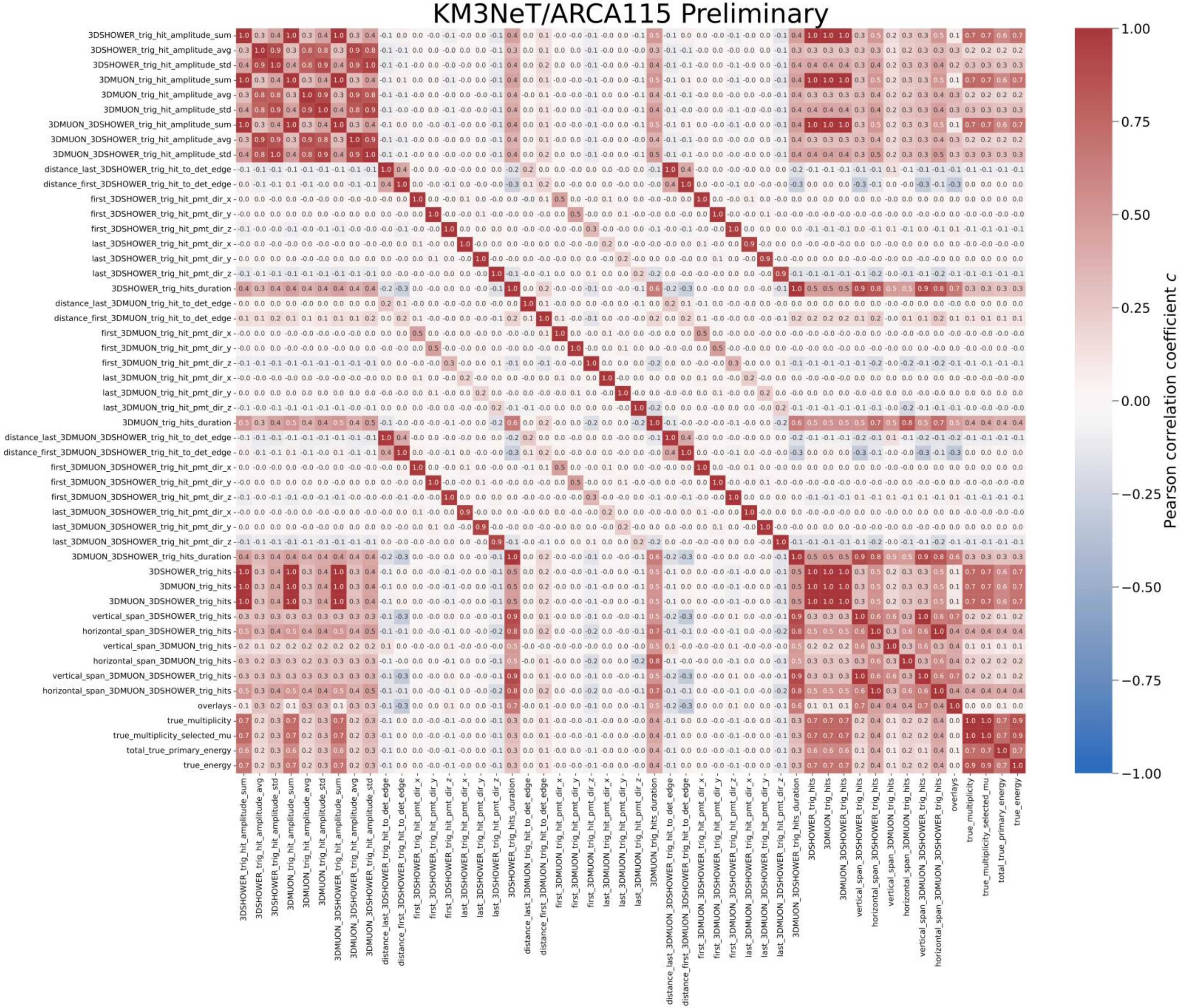
Workflow of the reconstruction:



$$x_{\text{scaled}} = \frac{(x - x_{\text{mean}})}{x_{\text{std}}}$$

```python
from sklearn.preprocessing import StandardScaler
scaler = StandardScaler()
scaler.fit(x_train)
# save the scaler:
dump(scaler, DIR+VER+'_common_scaler.joblib')
print(DIR+VER+'_common_scaler.joblib')
```

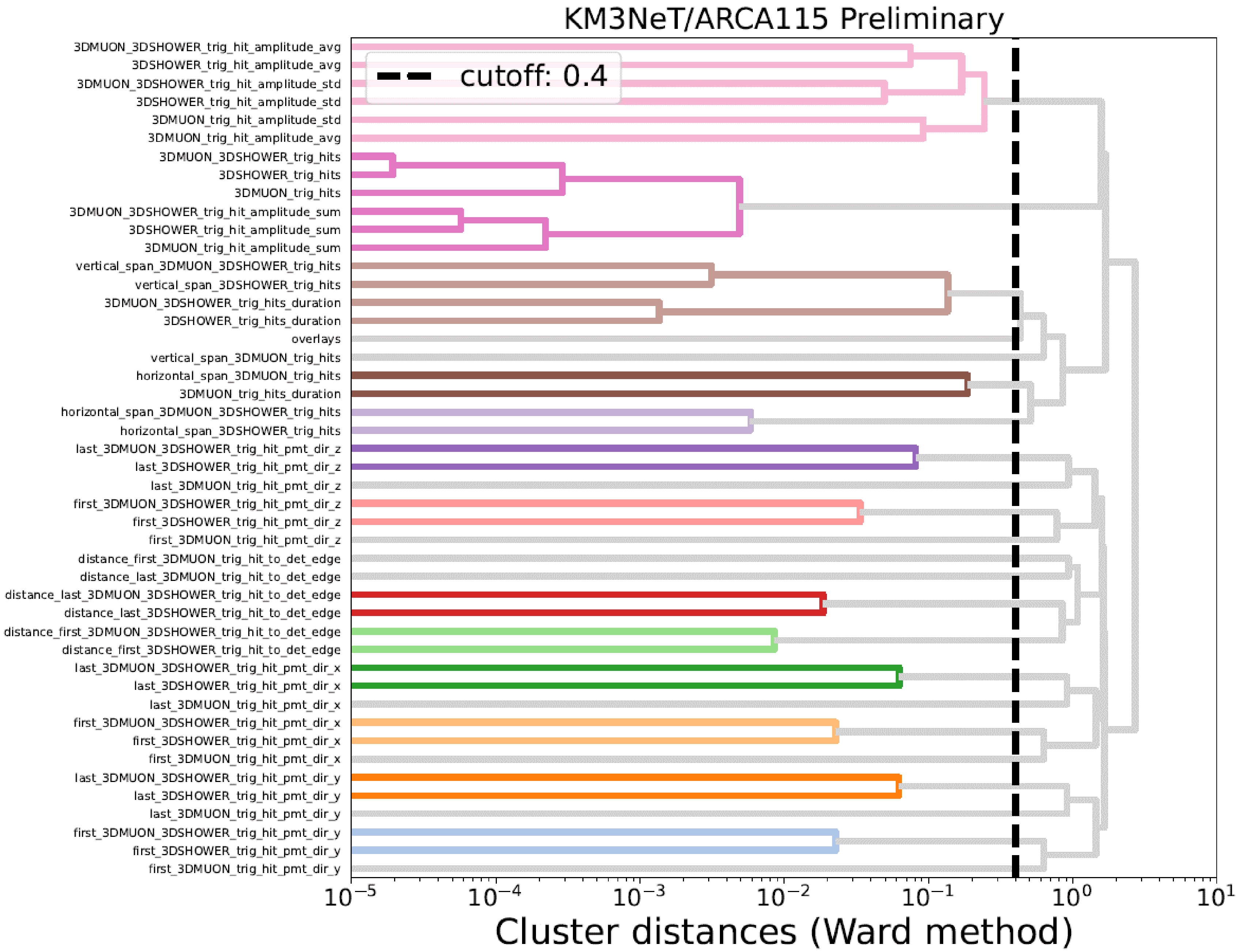
```python
from sklearn.model_selection import train_test_split
x_train, x_test, y_train, y_test = train_test_split(
    data[COLS+WEIGHTS],
    LABELS,
    test_size=0.2, random_state=131071, shuffle=True,
    stratify=LABELS
)
```



In total: 46 features (+4 targets)

Example for ARCA115
(the same was done for ARCA6, ORCA115 and ORCA6)

ML reco: feature clustering



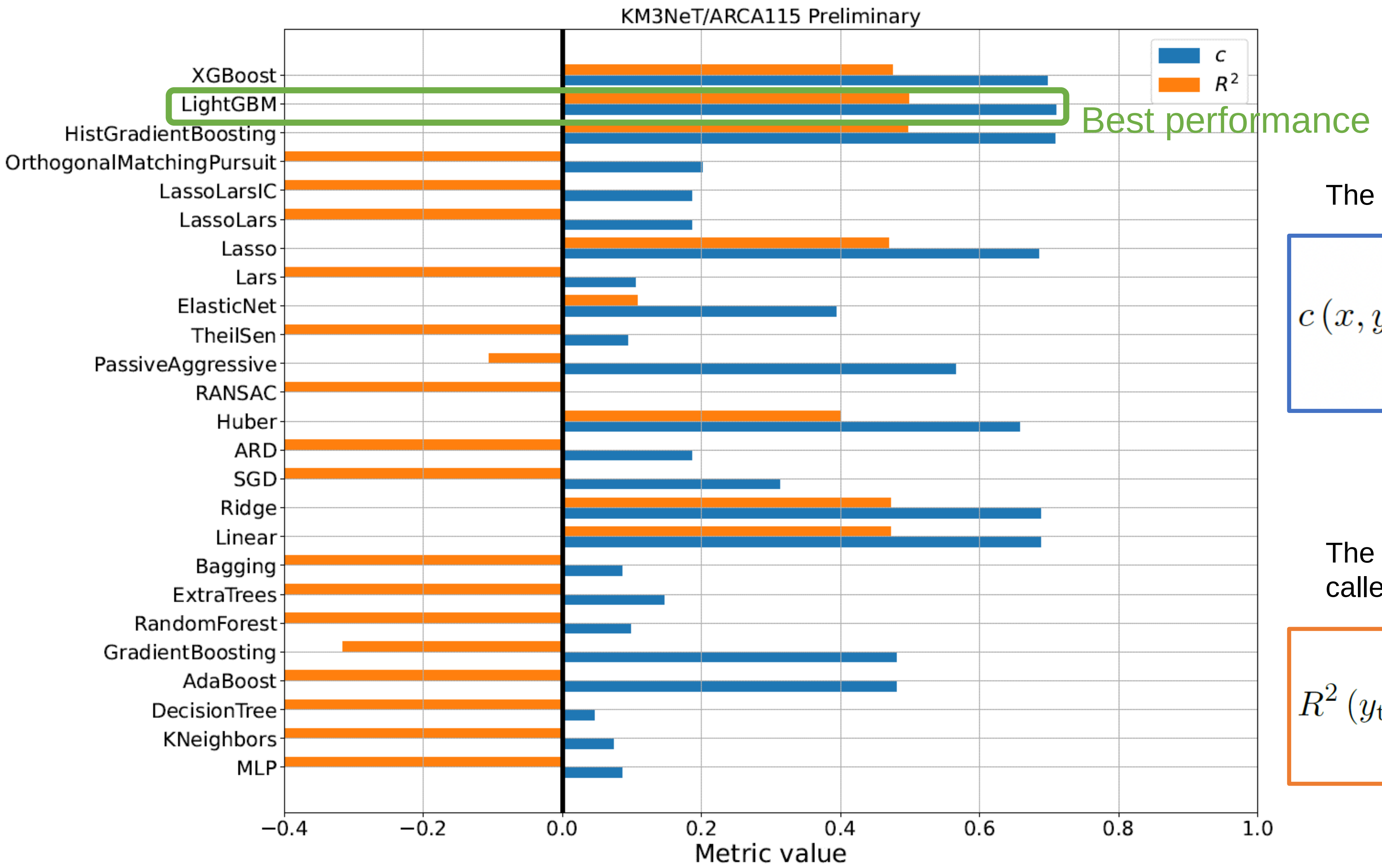
Cluster distance cutoff is arbitrary

Clusters are marked by different colors

Example for ARCA115
(the same was done for ARCA6, ORCA115 and ORCA6)

Bundle energy reco: best ML model selection

Performance comparison on a fraction (50k events) of the training dataset:



The (weighted) Pearson correlation coefficient:

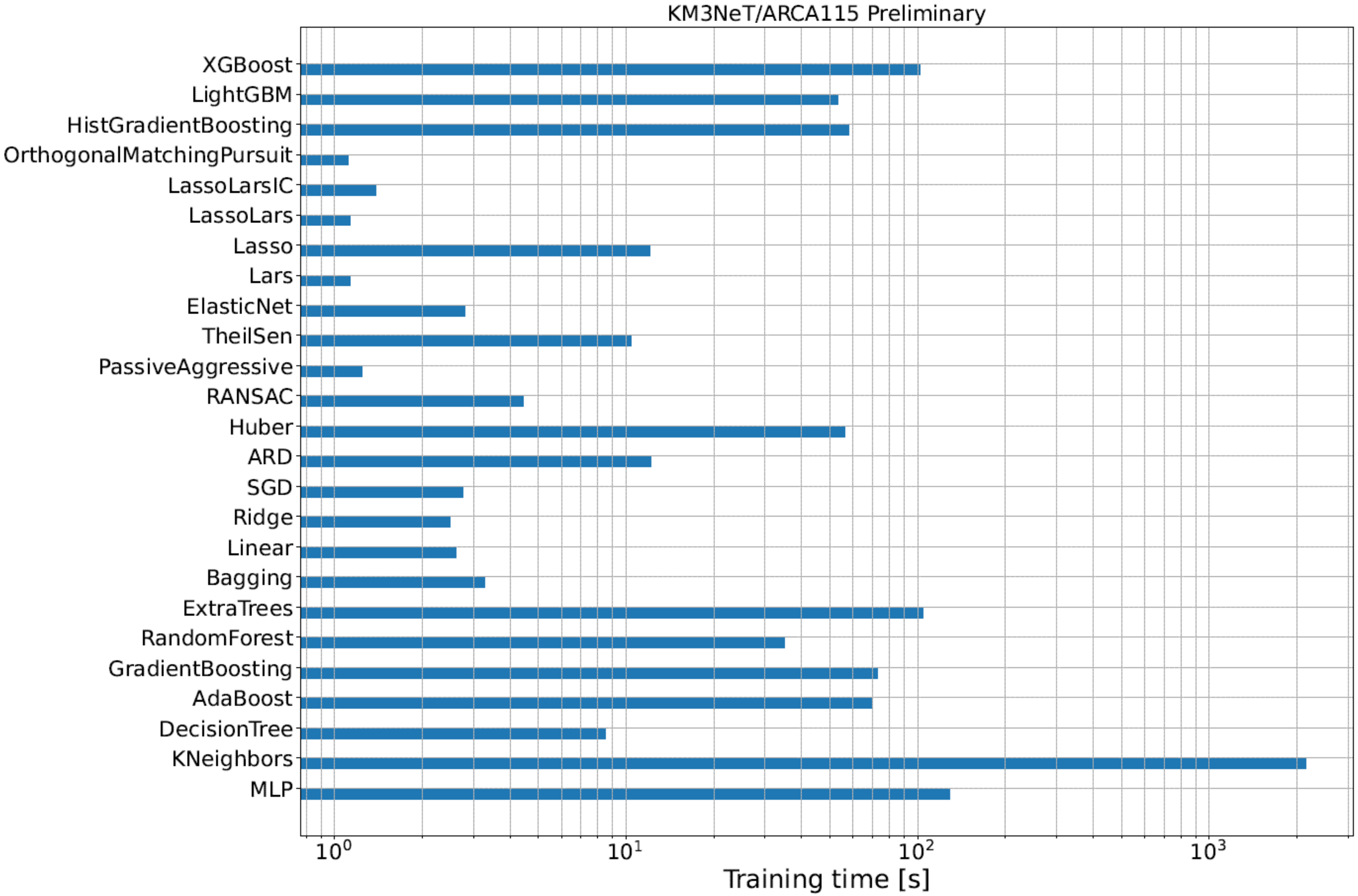
$$c\left(x,y\right)=\frac{\sum_i w_i\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{\sqrt{\sum_i w_i\left(x_i-\bar{x}\right)^2\sum_i w_i\left(y_i-\bar{y}\right)^2}}$$

The (weighted) R2-score,
called the coefficient of determination:

$$R^2\left(y_{\text{true}},y_{\text{pred}}\right)=1-\frac{\sum_i w_i\left(y_{\text{true}}-y_{\text{pred}}\right)^2}{\sum_i w_i\left(y_{\text{true}}-\bar{y}\right)^2}$$

Bundle energy reco: best ML model selection

Speed comparison on a fraction (50k events) of the training dataset:

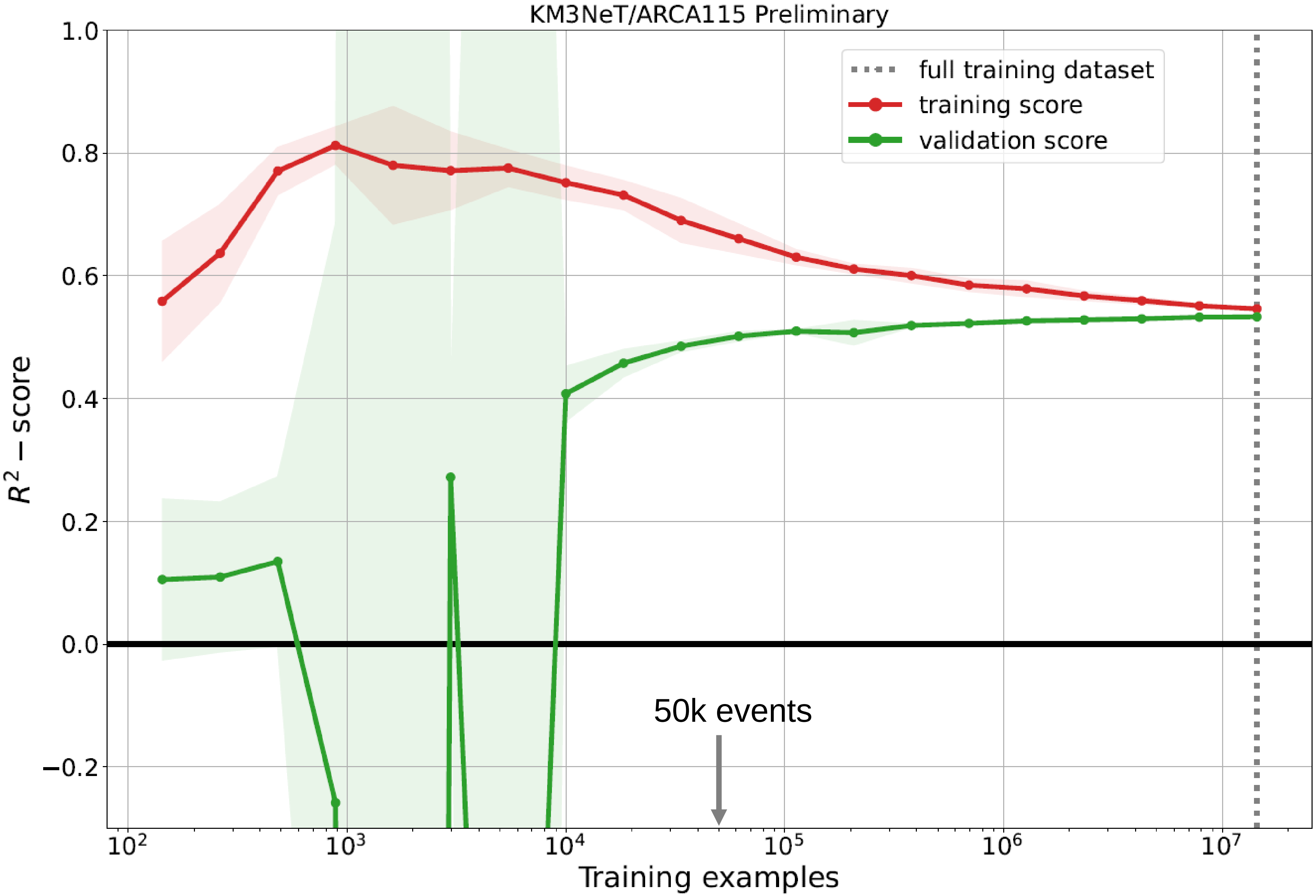


LightGBM:

- ❖ not the fastest, but still very decent
- ❖ + it turned out to scale up very well (entire dataset is orders of magnitude larger)

These times were obtained running with 20 CPU cores in parallel

Bundle energy reco: learning inspection

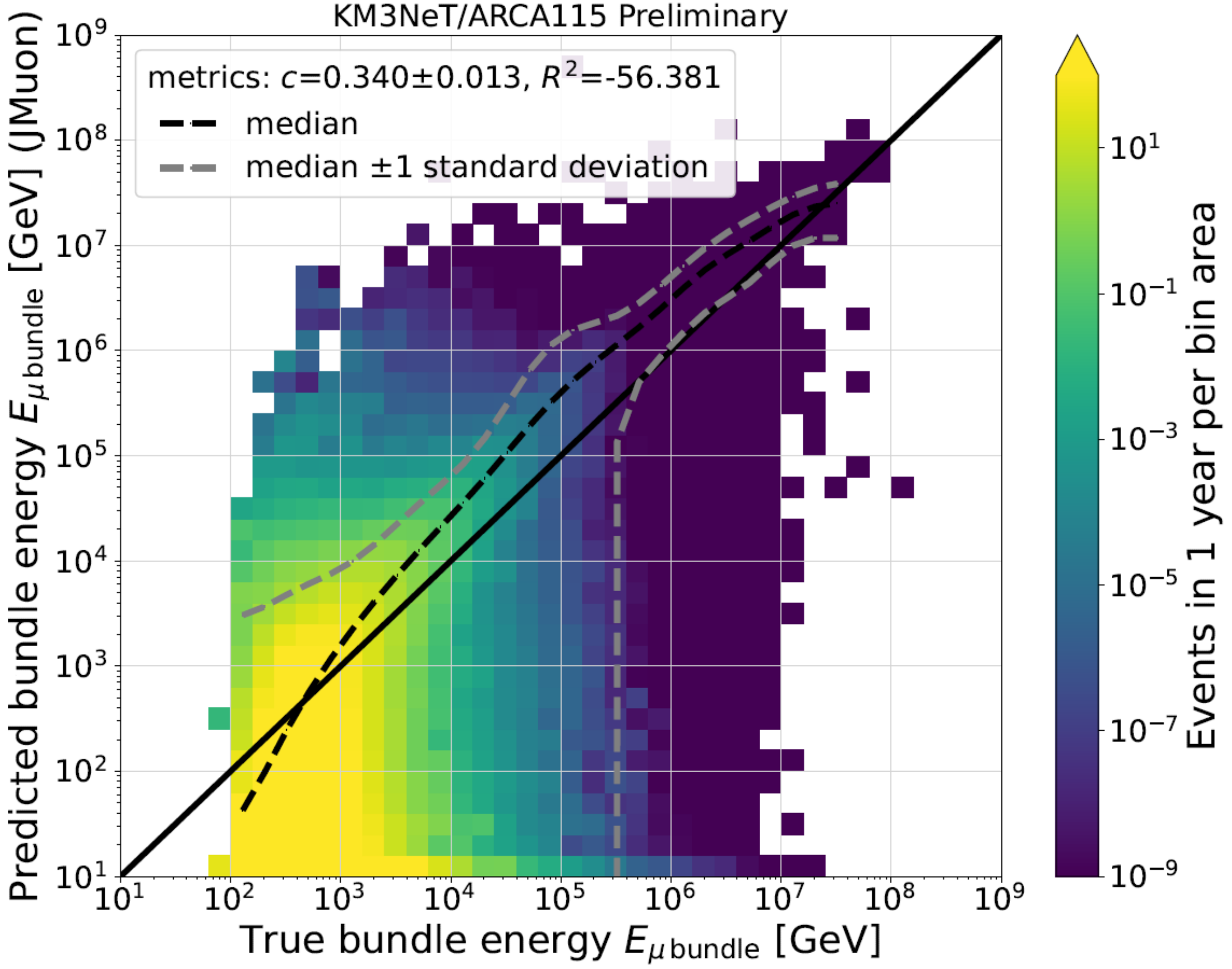


Here we see why 50k events were fine for testing (but e.g. 5k would not be)

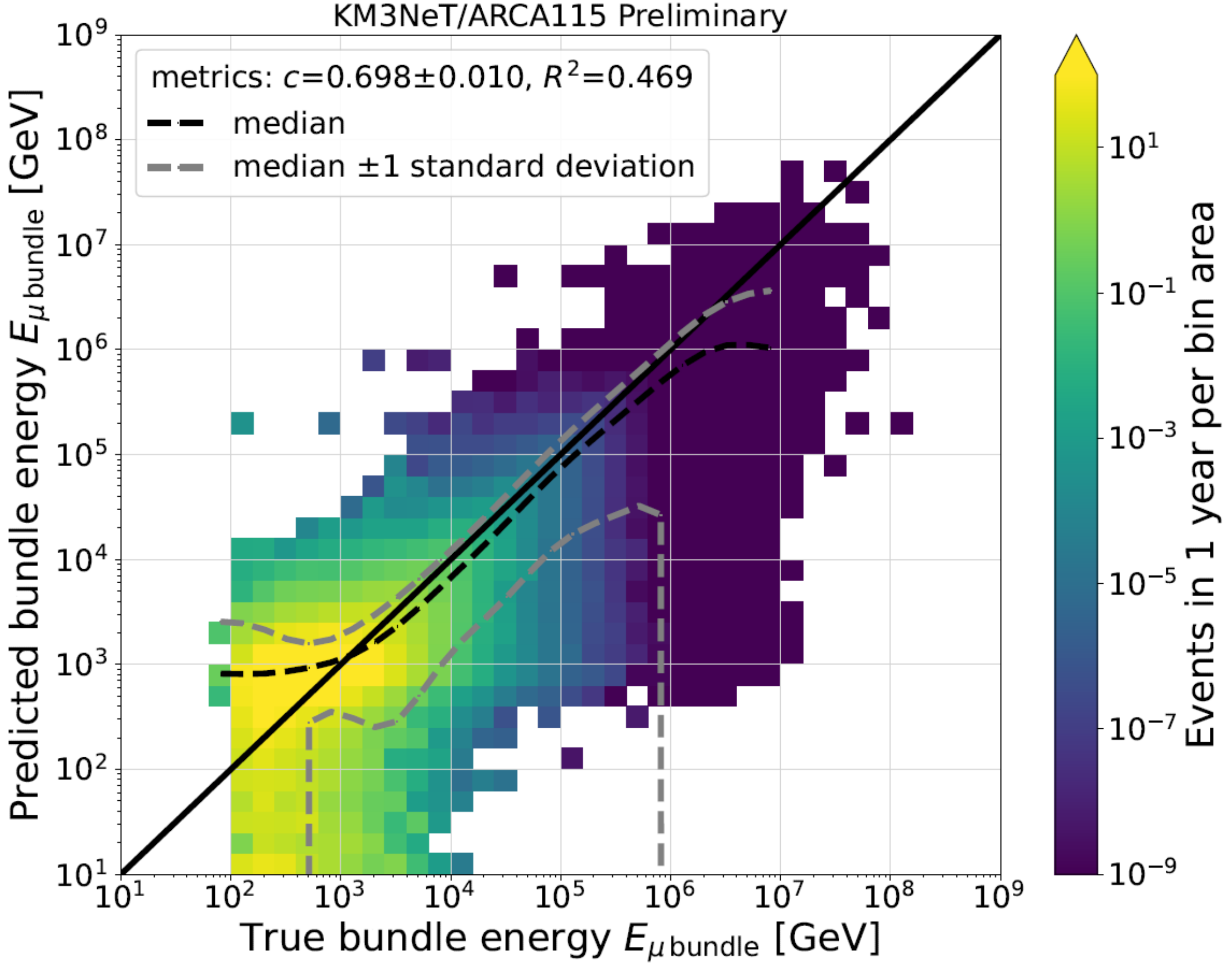
Bundle energy reco: basic comparison with JMuon

Here I just compare LightGBM (no tuning whatsoever) and JMuon reco (non-ML reco)

JMuon

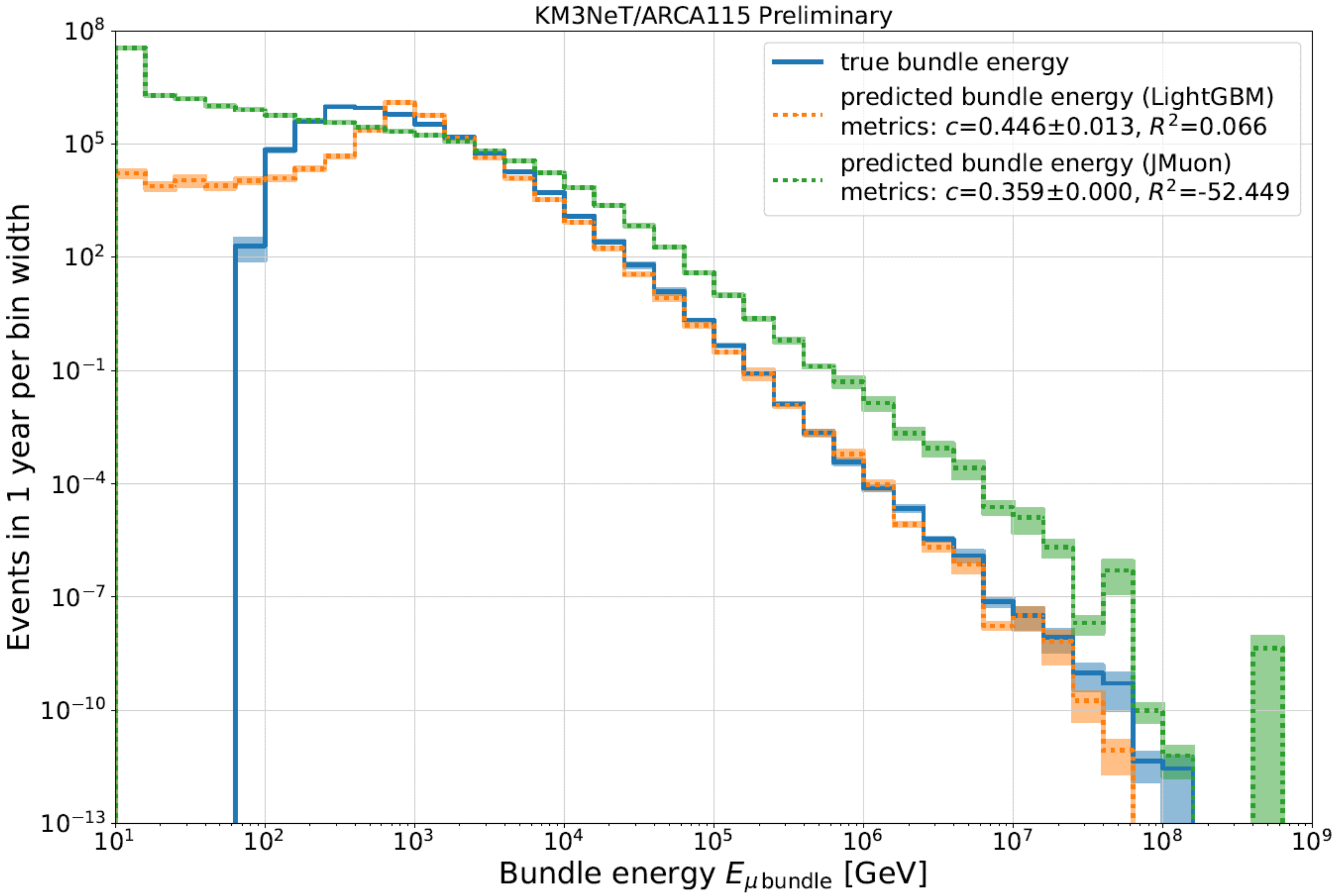


LightGBM



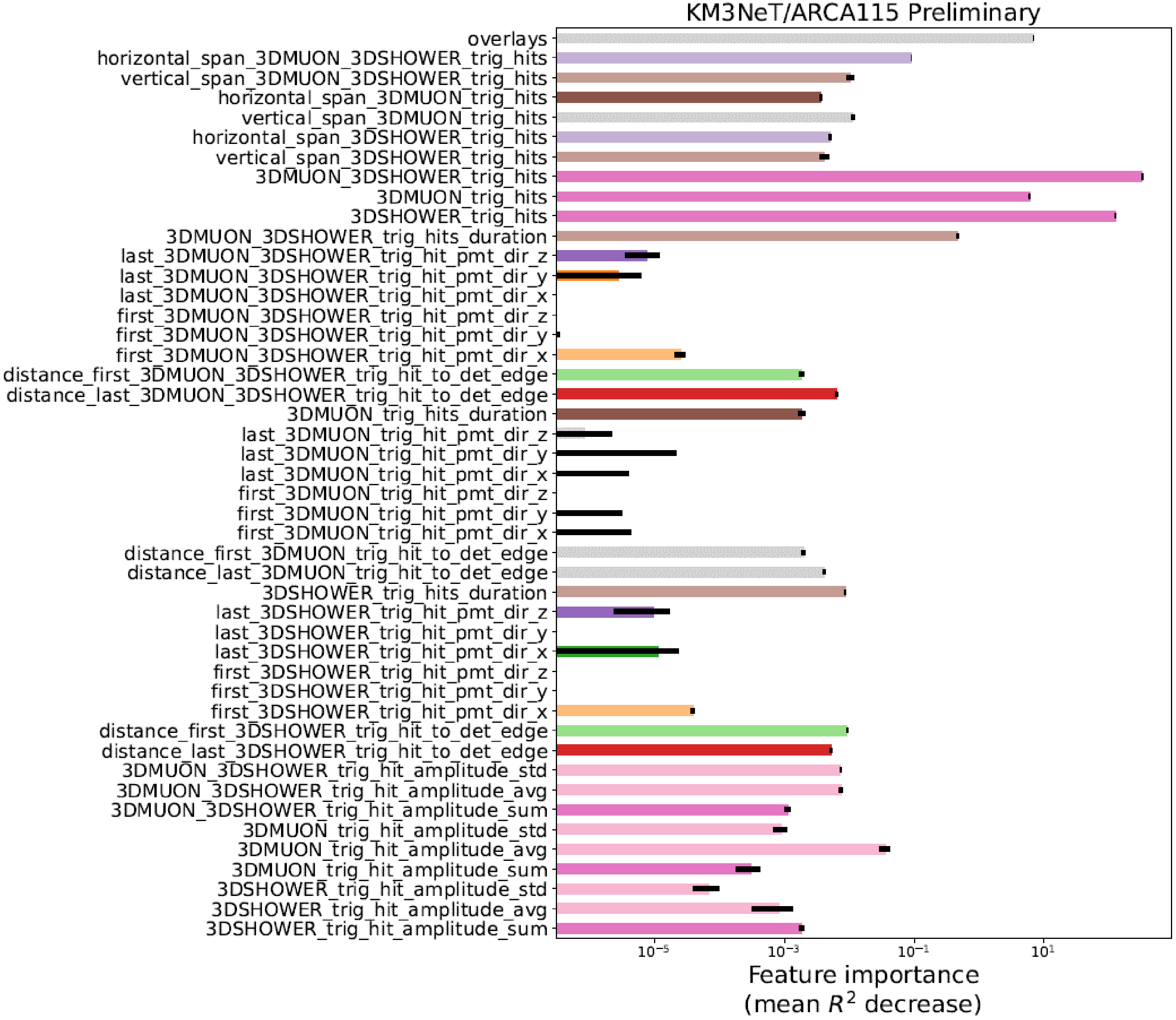
Bundle energy reco: basic result in 1D

Comparison in 1D:



Clearly even untuned ML approach reproduces the distribution much closer

Bundle energy reco: feature importance



Colors here are not random!

They match the feature clustering

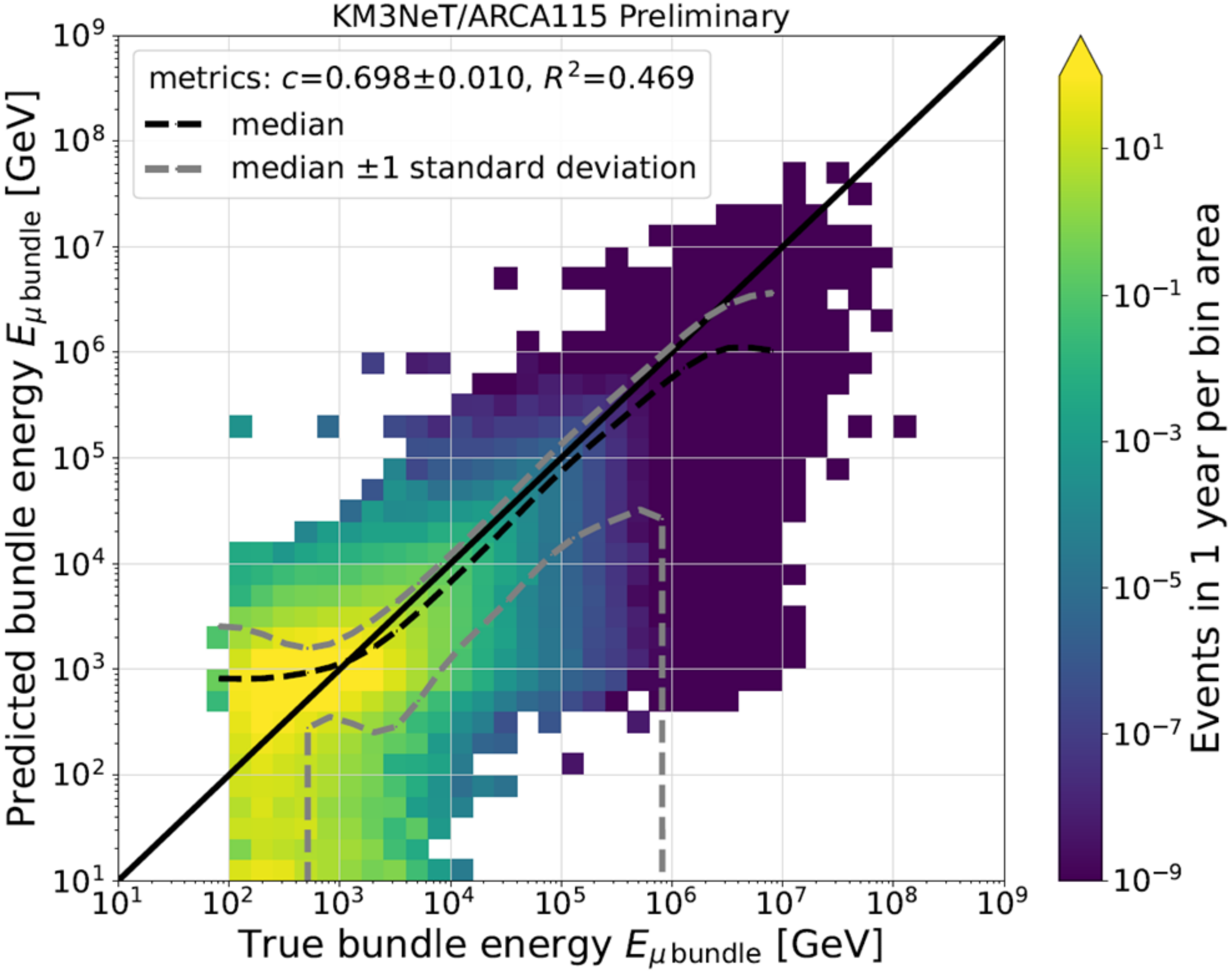
The idea:
Try to select only the most important feature in each cluster

Bundle energy reco: feature selection

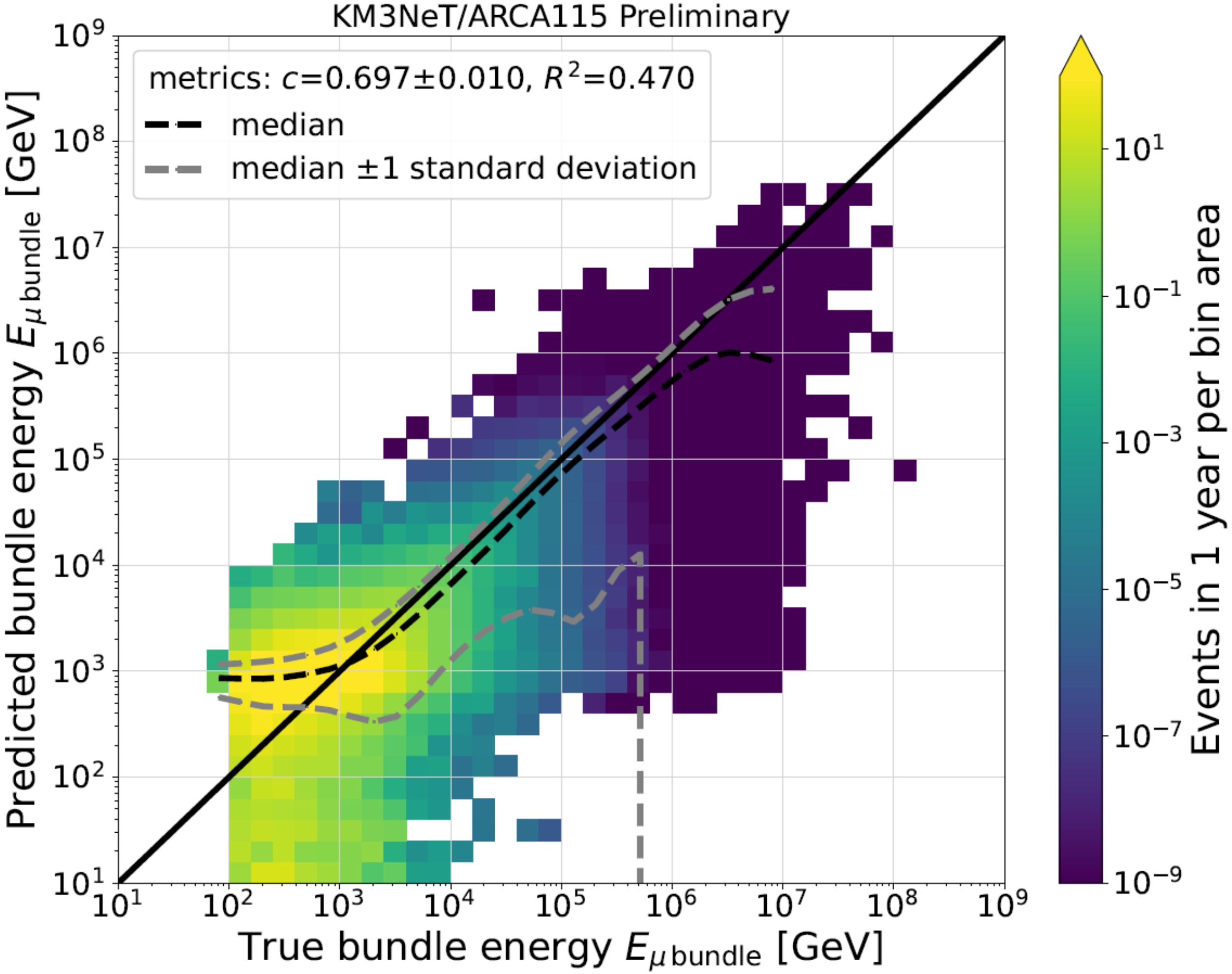
I considered 4 options:

1. All features
2. Features with importance>0 & only the most important one from each cluster
3. The most important feature only
4. Features with importance>0

1. All features



2. importance>0 & clustering

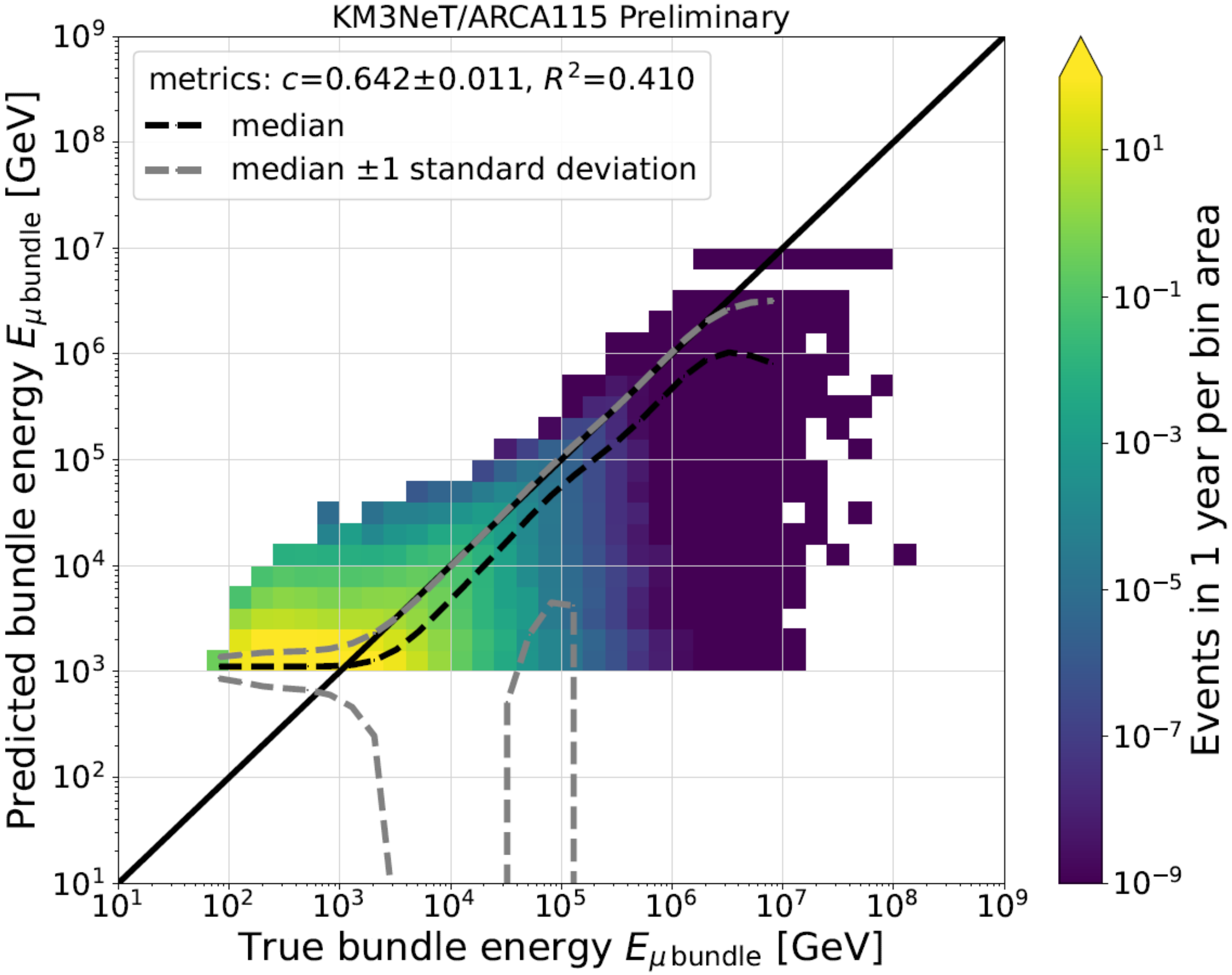


Bundle energy reco: feature selection

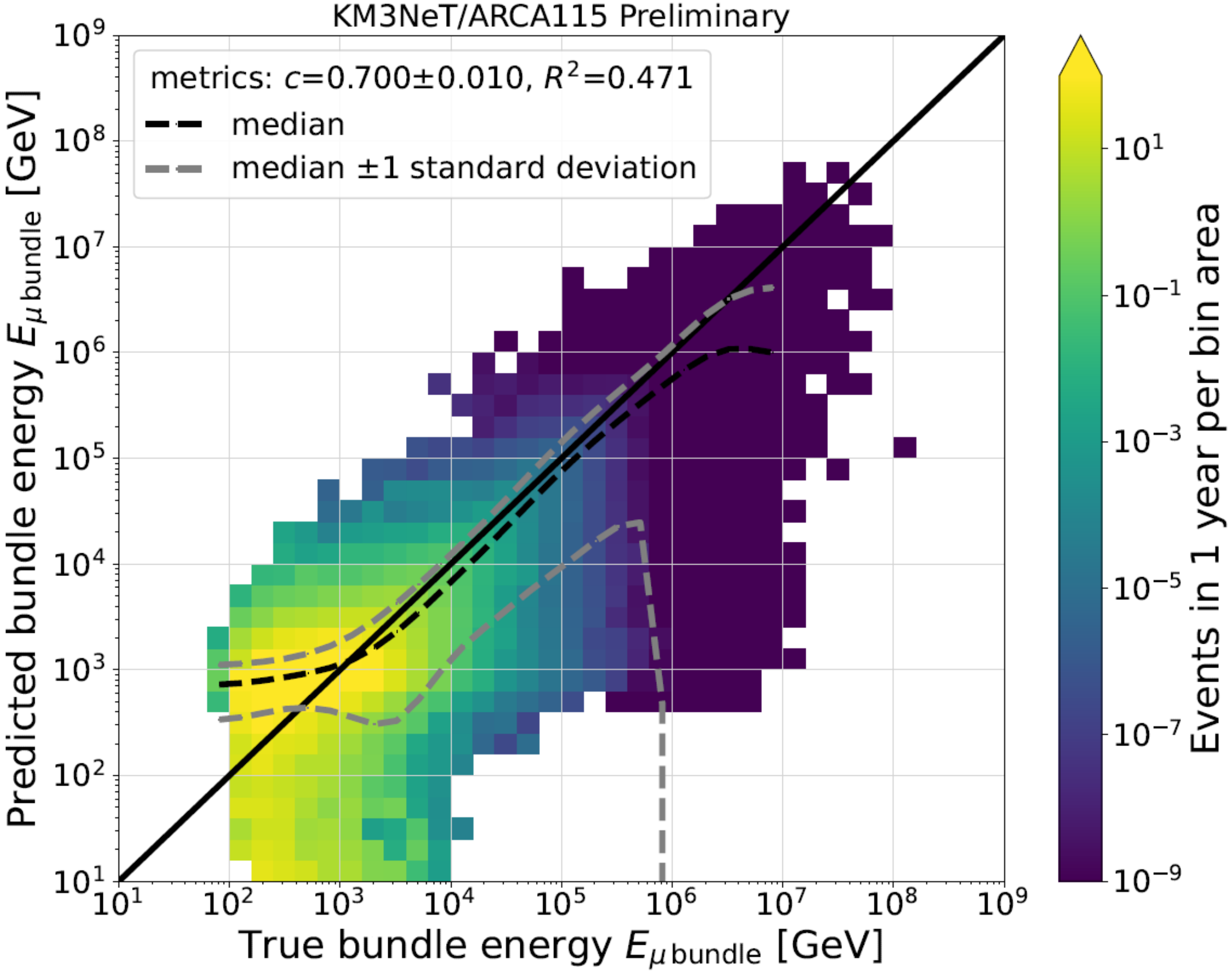
I considered 4 options:

1. All features
2. Features with importance>0 & only the most important one from each cluster
3. The most important feature only
4. Features with importance>0

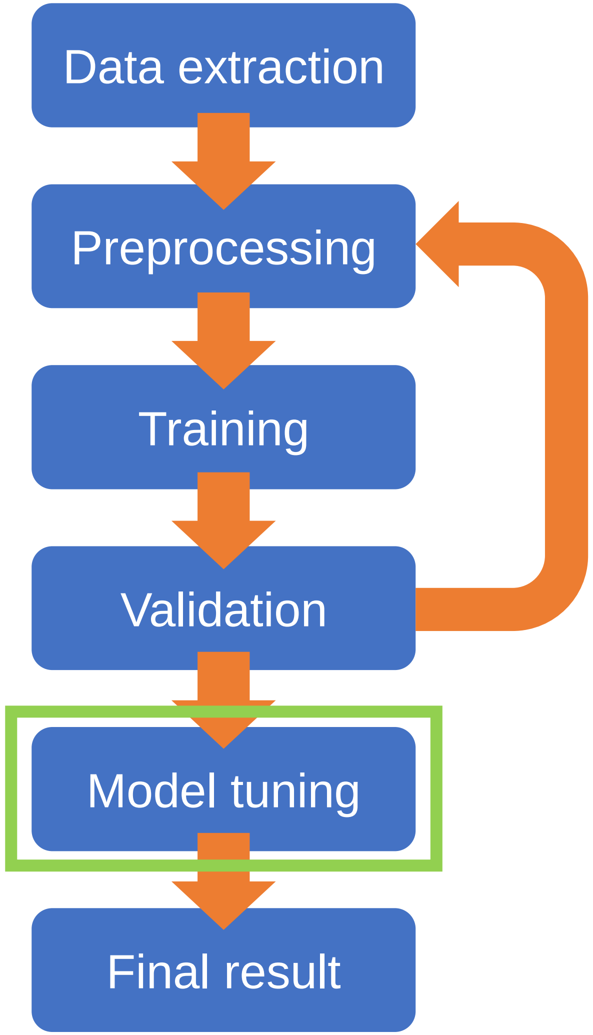
3. 3DMUON_3DSHOWER_trig_hits only



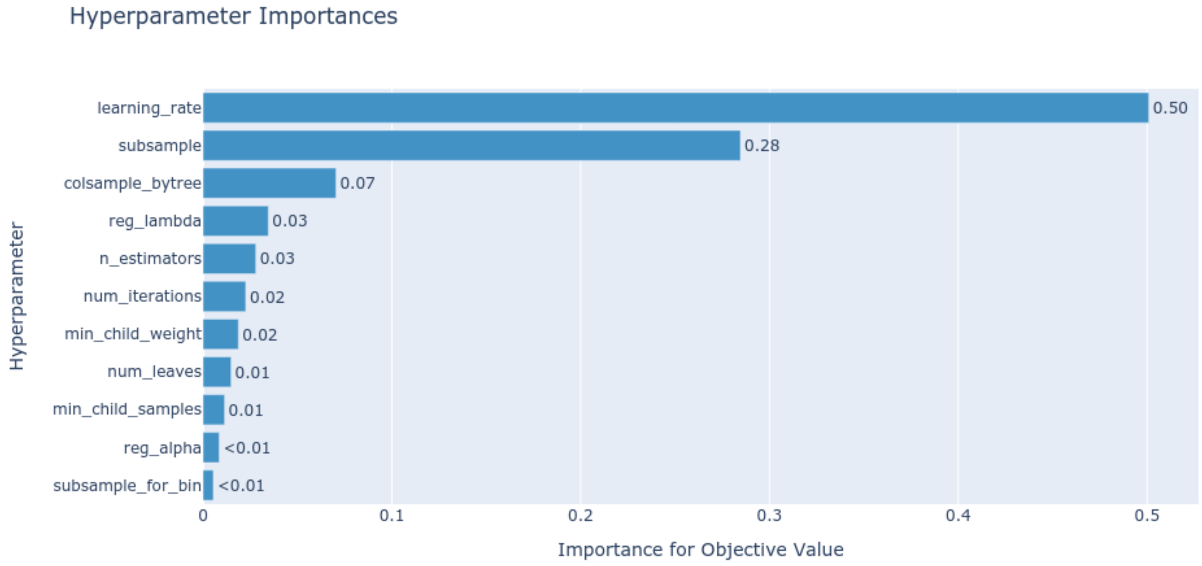
4. importance>0

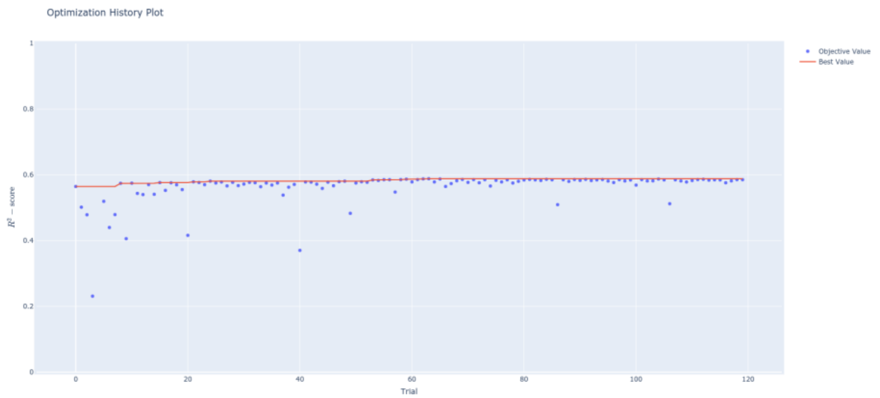


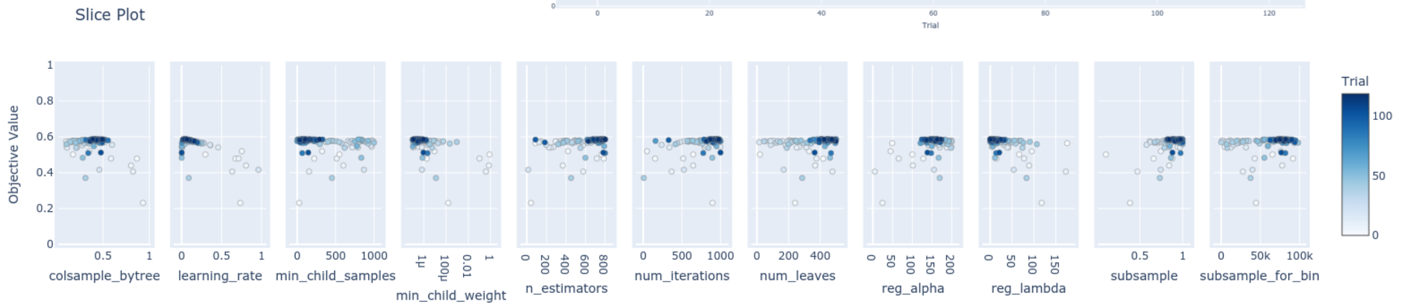
Workflow of the reconstruction:



feature/
model/
target/
method/
selection

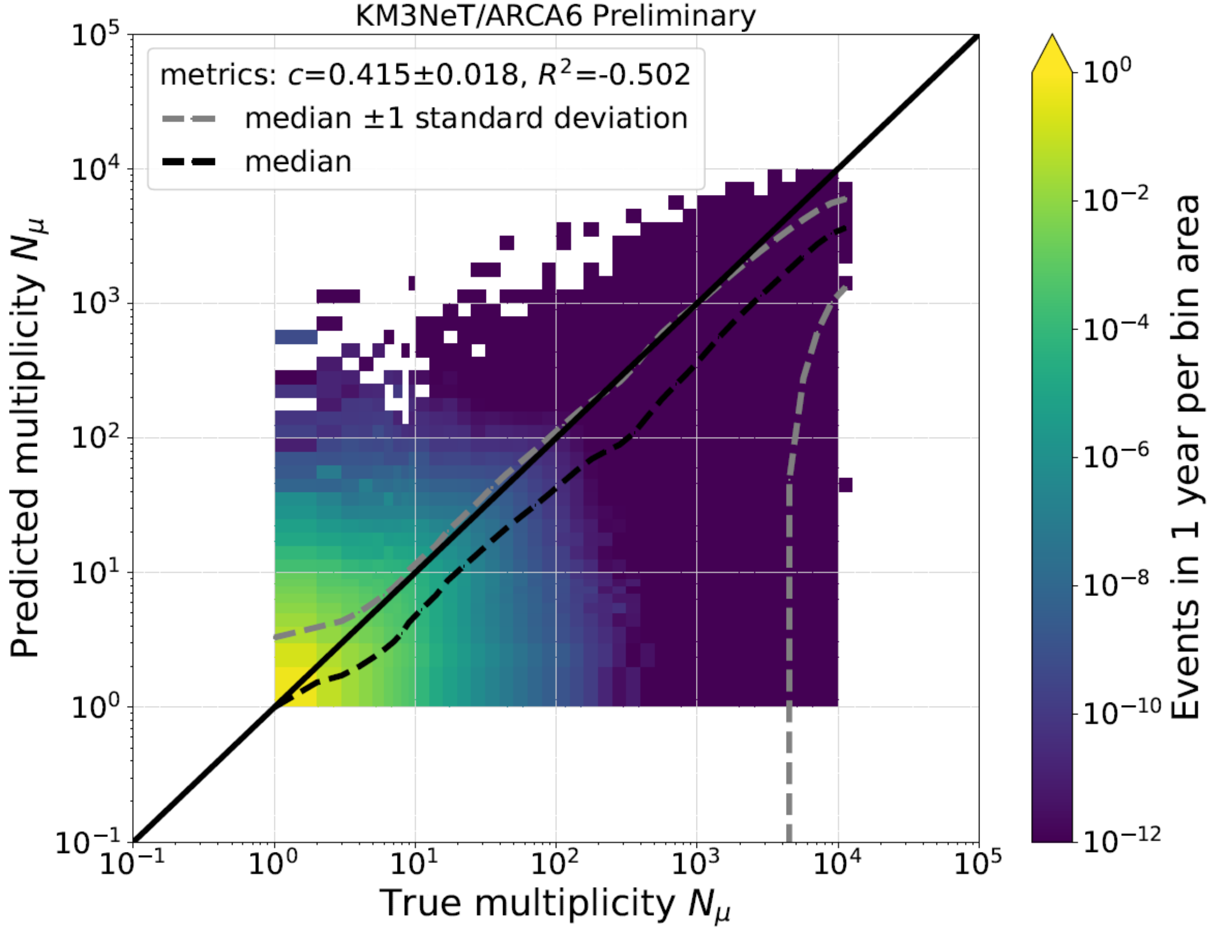




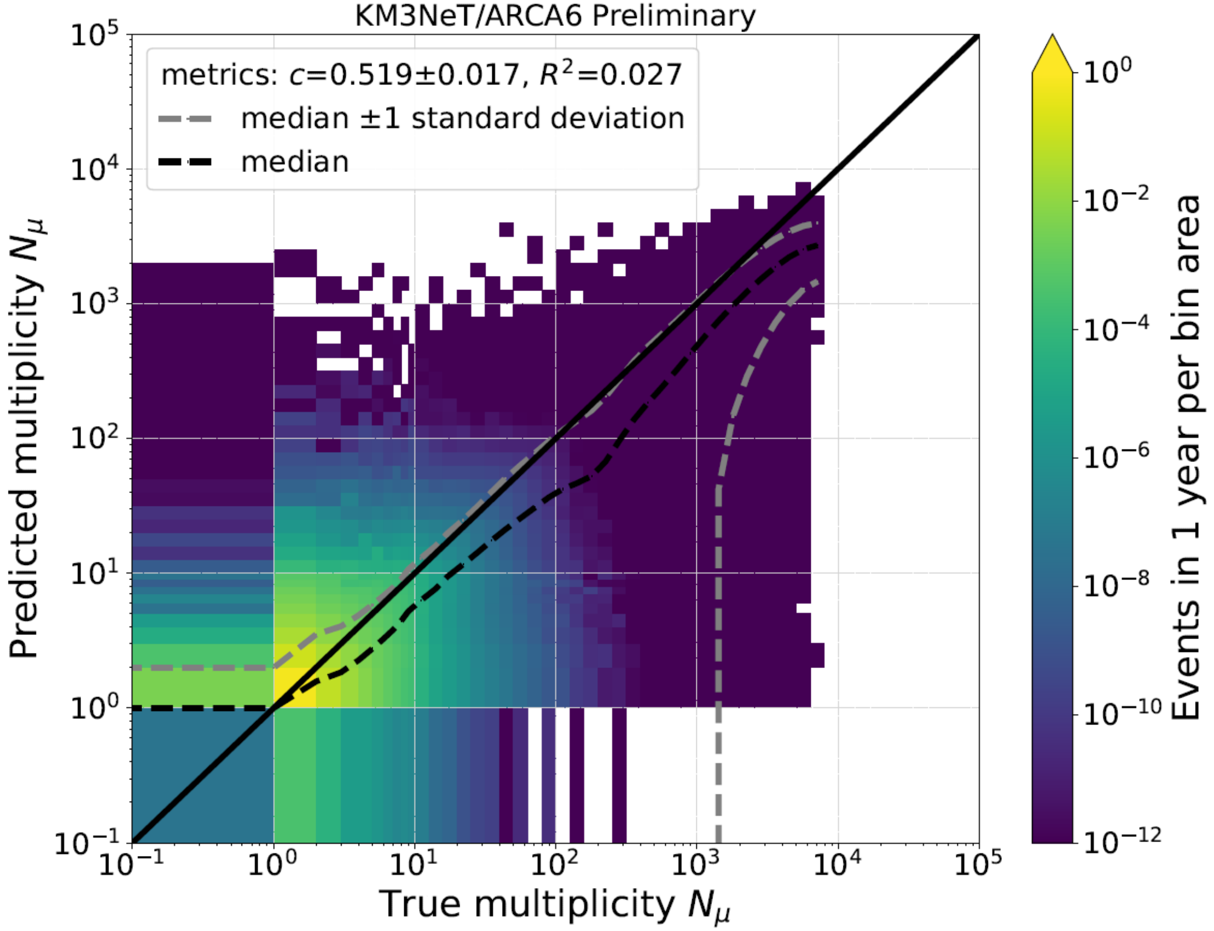


Example of ARCA6, for which the effect is the most pronounced

All muons



Selected muons

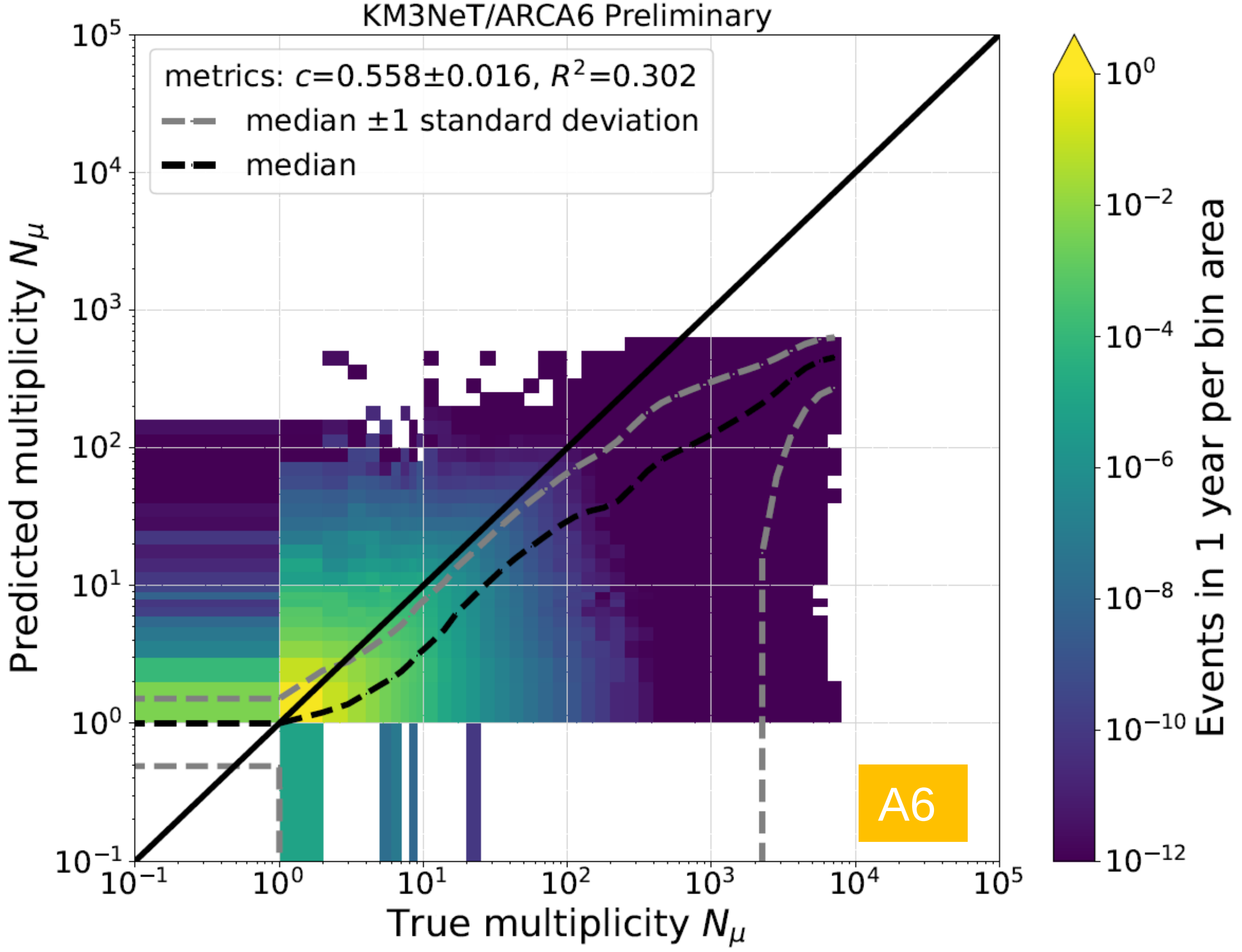


Multiplicity reco: final results

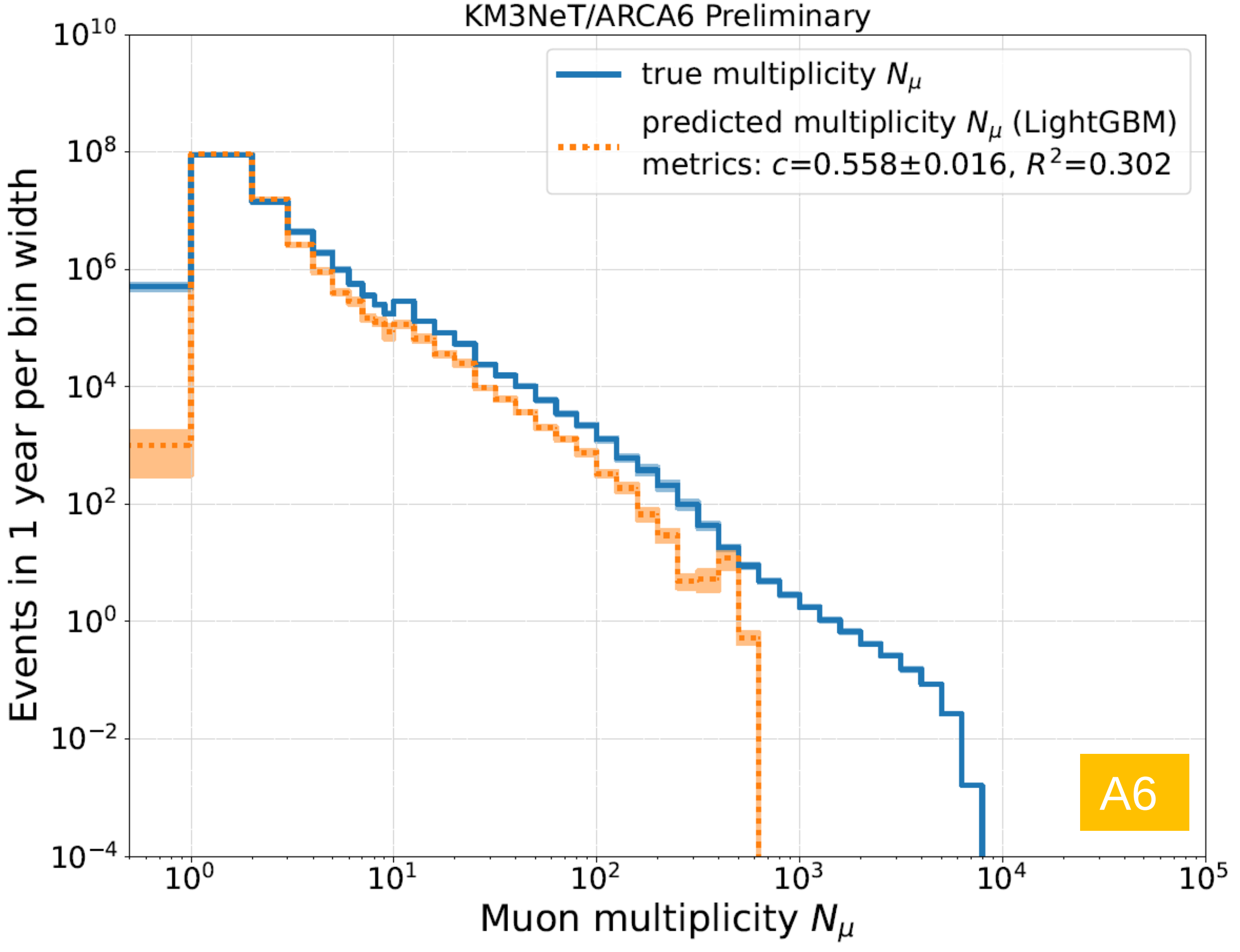
Analogical results obtained for ARCA115, ORCA115 and ORCA6

Example of the results for ARCA6:

2D: pred vs true



1D histograms



Poisson formula for BGD with non-negligible uncertainty: ref1 ref2 ref3

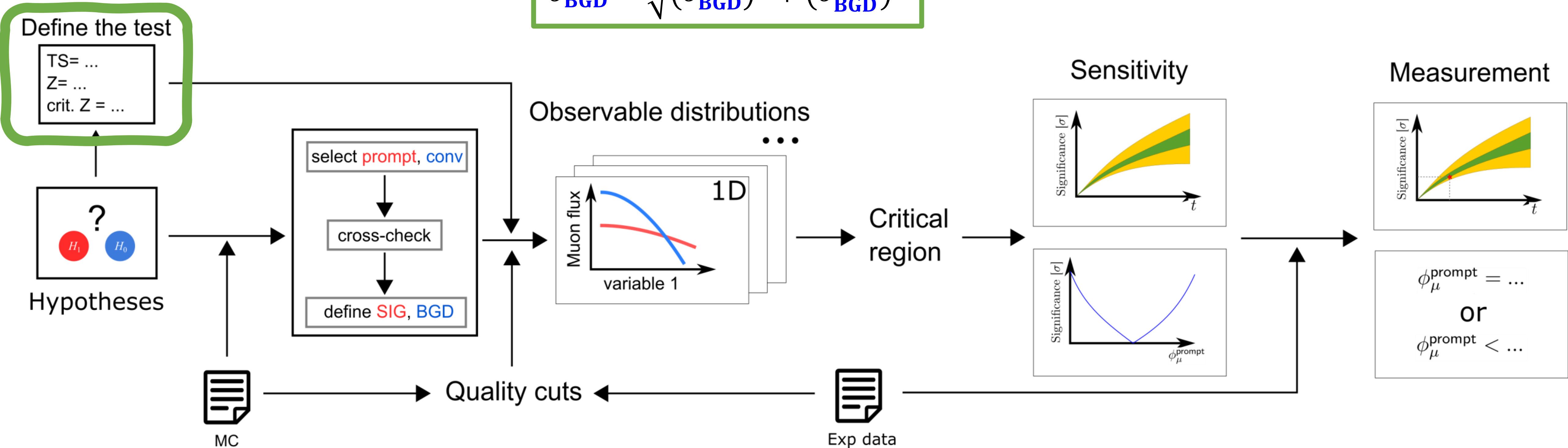
$$\text{TS: } q_0 = \begin{cases} 2 \cdot \left[N_{\mathbf{TOTAL}} \cdot \ln\left(\frac{N_{\mathbf{TOTAL}} \cdot (N_{\mathbf{BGD}} + \sigma^2_{\mathbf{BGD}})}{N^2_{\mathbf{BGD}} + N_{\mathbf{TOTAL}} \cdot \sigma^2_{\mathbf{BGD}}}\right) - \frac{N^2_{\mathbf{TOTAL}}}{\sigma^2_{\mathbf{BGD}}} \cdot \ln\left(1 + \frac{\sigma^2_{\mathbf{BGD}} \cdot (N_{\mathbf{TOTAL}} - N_{\mathbf{BGD}})}{N_{\mathbf{BGD}} \cdot (N_{\mathbf{BGD}} + \sigma^2_{\mathbf{BGD}})}\right)\right] & \text{for } N_{\mathbf{TOTAL}} \geq N_{\mathbf{BGD}} \\ 0 & \text{for } N_{\mathbf{TOTAL}} < N_{\mathbf{BGD}} \end{cases}$$

Significance: $Z = \sqrt{q_0}$

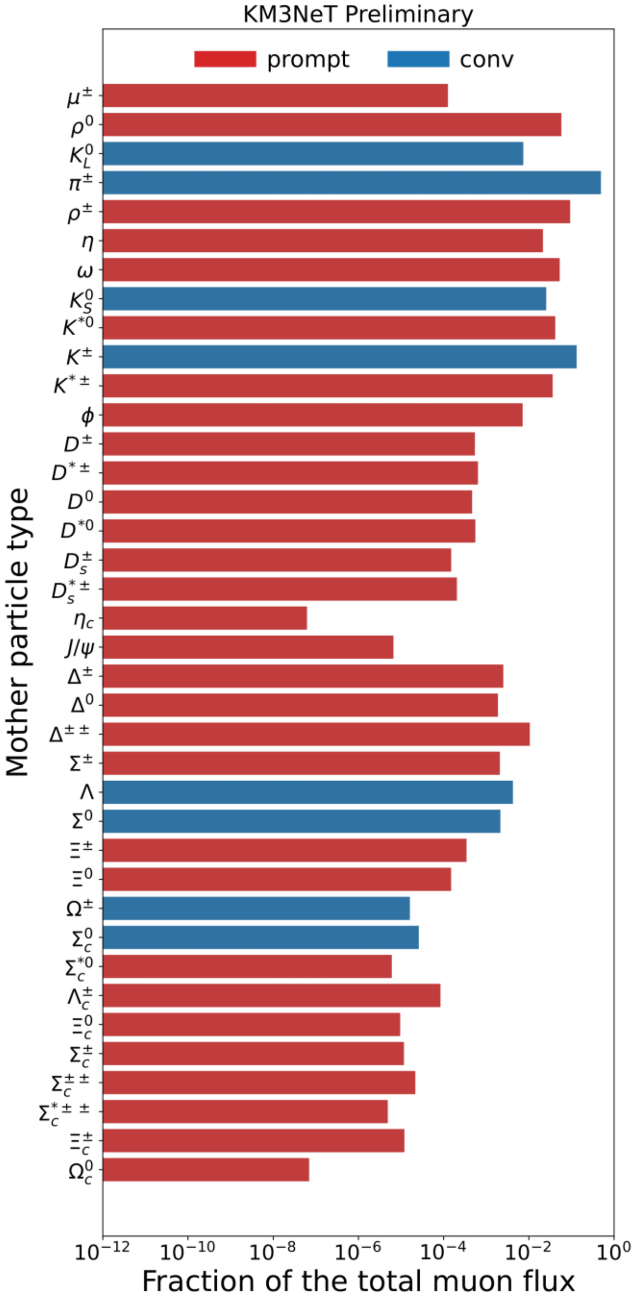
Critical Z: 5σ

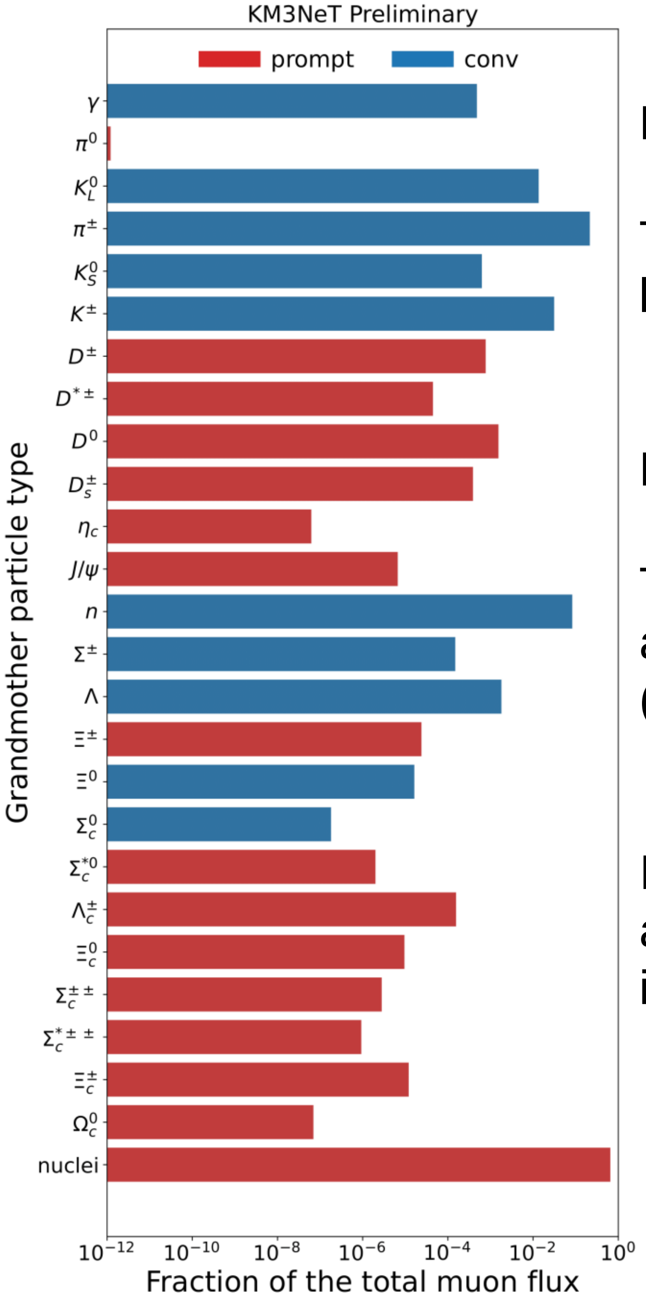
systematic uncertainties are included:

$$\sigma_{\mathbf{BGD}} = \sqrt{(\sigma^{\text{stat}}_{\mathbf{BGD}})^2 + (\sigma^{\text{syst}}_{\mathbf{BGD}})^2}$$



Prompt and conv parent particles





Note: 1 parent conventional → the muon is conventional.

The colours here only tell you if particles have short or long livetimes (if applicable).

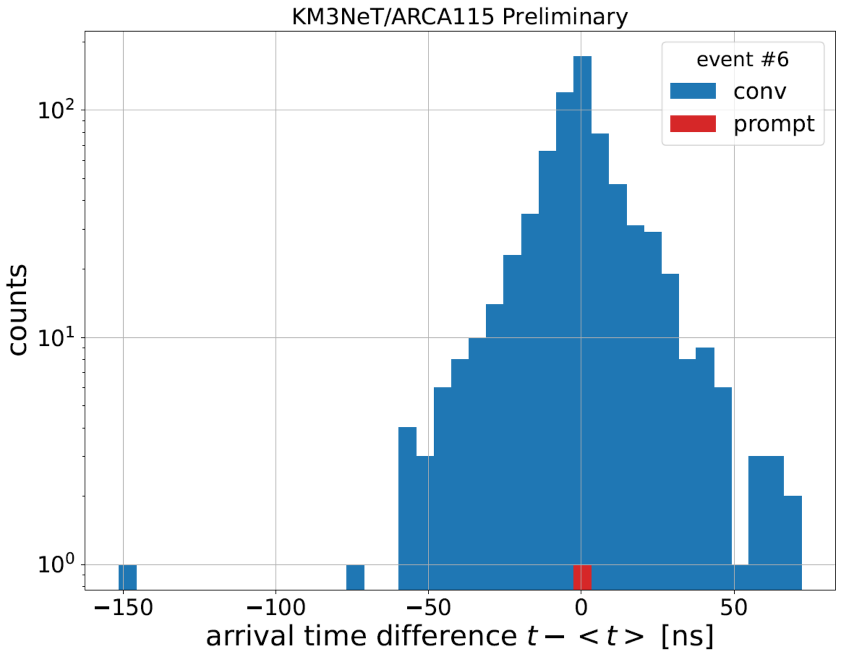
Most muons originate from $\pi^\pm$ and $K^\pm$, as expected.

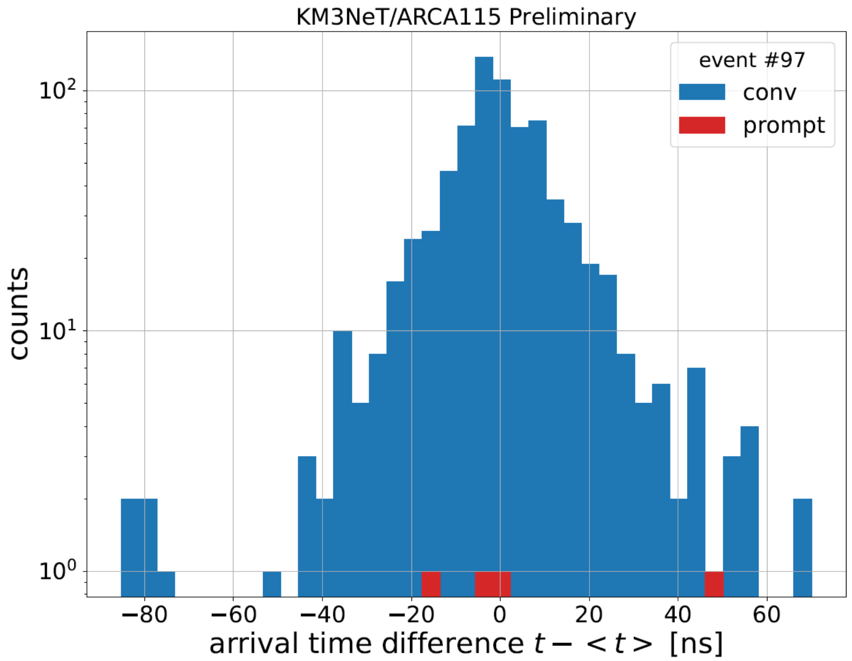
The most important prompt mother particles for muons are light vector mesons (η, ρ, ω), not D mesons (also expected).

If mother is a muon or grandmother is the same nucleus as the primary, it means that there were just less interactions between shower start and muon creation.

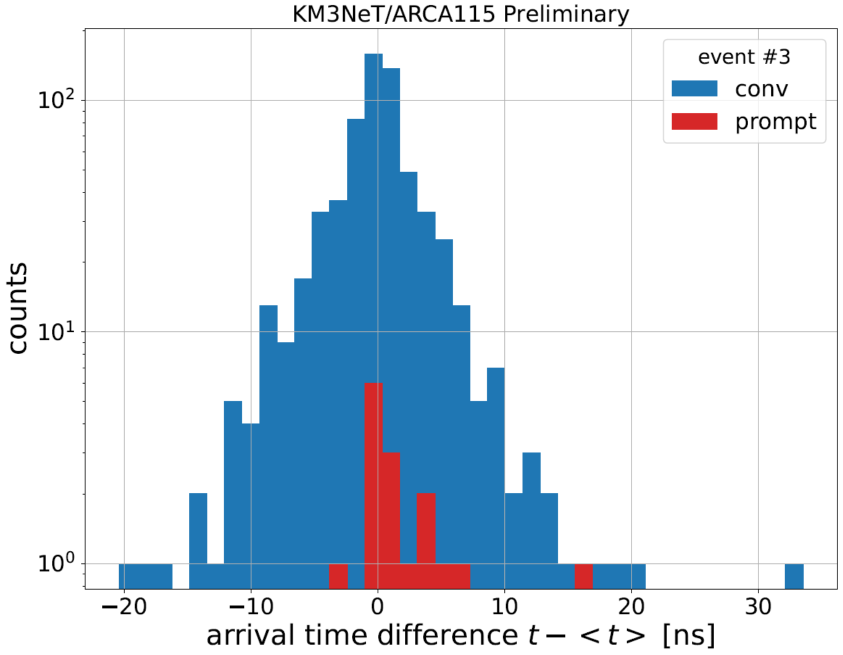
NB: particles & antiparticles are counted together!
(and so are all nuclei, including hydrogen)

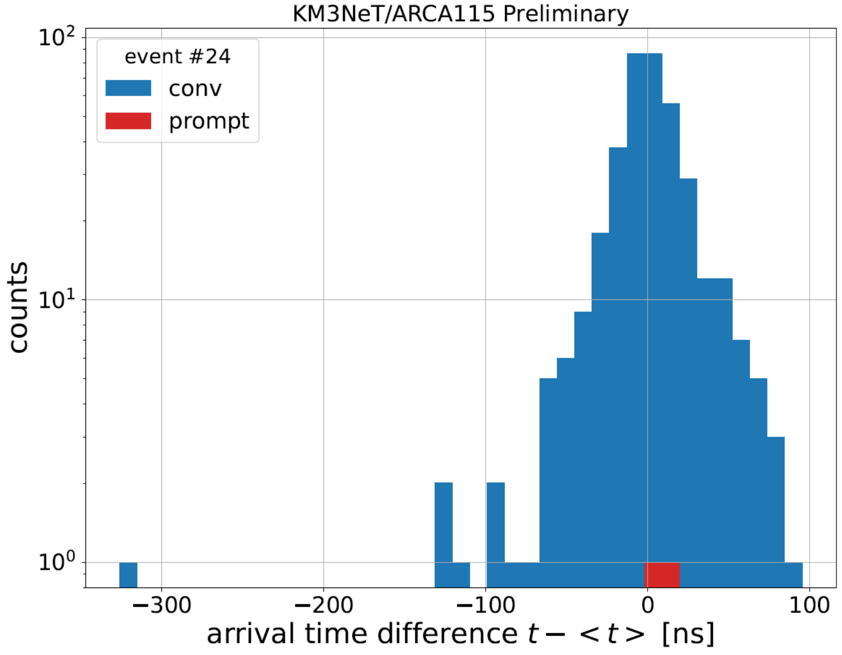
Muon arrival time





Proton events



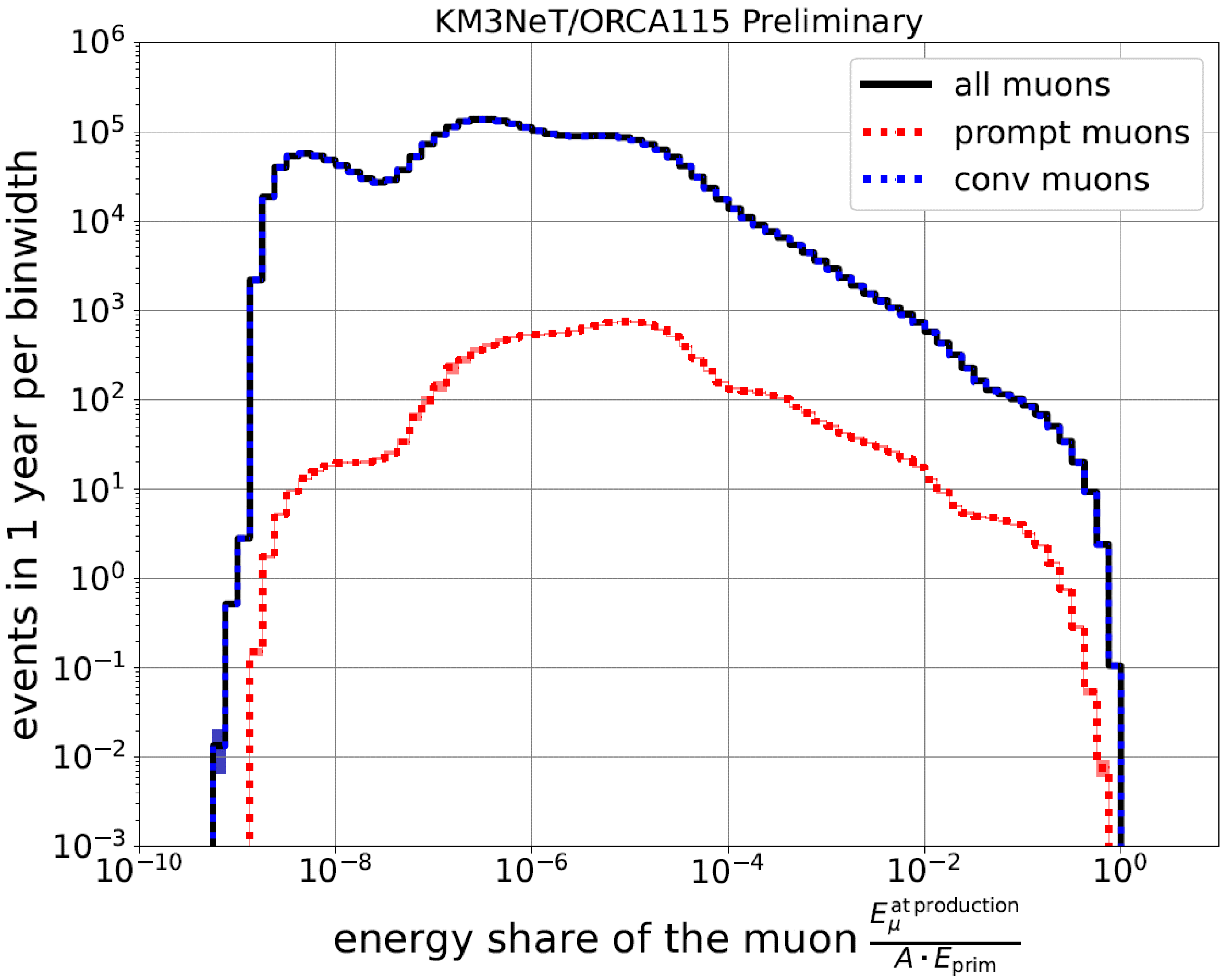


Iron events

arrival time: time between the first interaction of the primary and the muon crossing the can boundary

Conclusion here is that prompt is <u>not really evident from arrival times</u> on event-by-event basis
(which is a bummer, because this could have been measurable)

Muon energy share

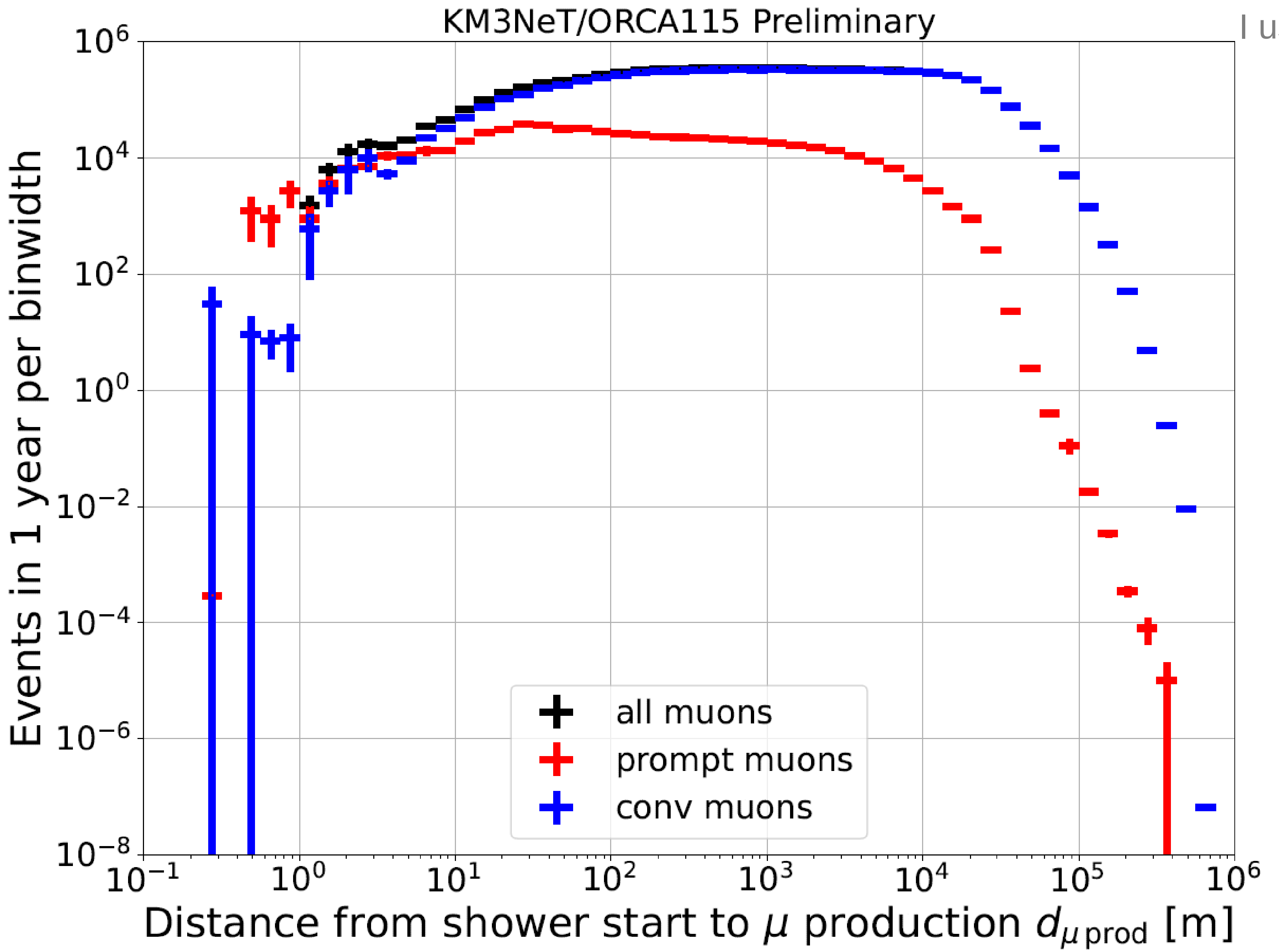


I use ORCA115 to boost the statistics

Prompt muons indeed tend to carry a larger portion of the total primary energy

The wiggles are coming from the contributions of different primaries

Muon production point



I use ORCA115 to boost the statistics

Prompt muons indeed are more often produced close to the 1st interaction