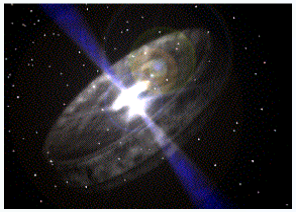
Catching Neutrinos from the Deep Sea

Astroparticle & Oscillations Research with Cosmics in the Abyss

DESY Seminar – June 23rd, 2021

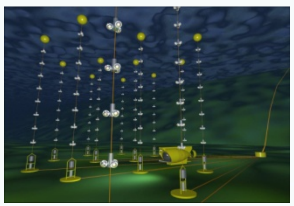
Outline

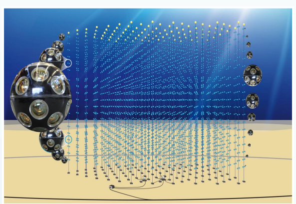


The High-Energy Physics Case – The cosmic endeavour

Historical aspects & Scientific motivations

Detection principles & Performances





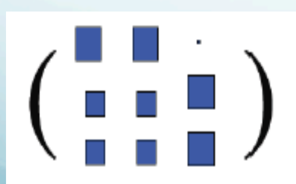
Status of ANTARES and KM3NeT/ARCA

Selected results in today's context

Prospects

The Low-Energy Physics Case – A new endeavour

KM3NeT/ORCA



Proposed detector & performances

Expected Sensitivity & first results

First ideas early 60's…science

Ann.Rev.Nucl.Sci
10 (1960) 1

NEUTRINO INTERACTIONS[1]

BY FREDERICK REINES[2]

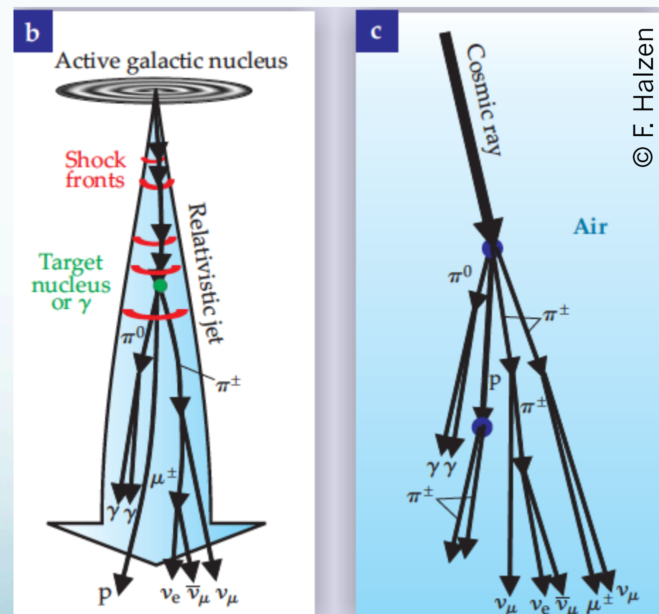
IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves



Courtesy: Ch. Spiering

First ideas early 60's…method

Ann.Rev.Nucl.Sci
10 (1960) 63

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

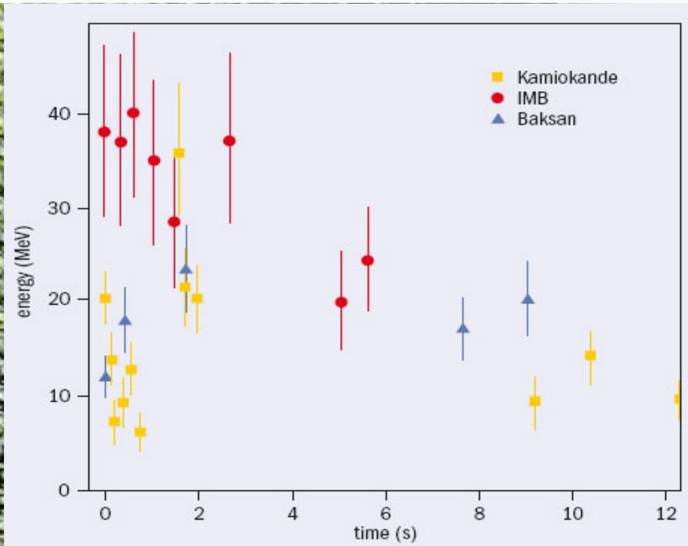
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

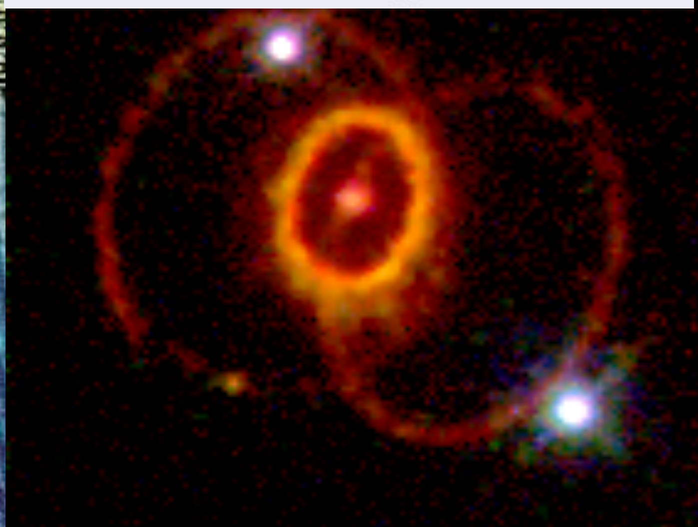
Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

Courtesy: Ch. Spiering

First extraterrestrial neutrinos

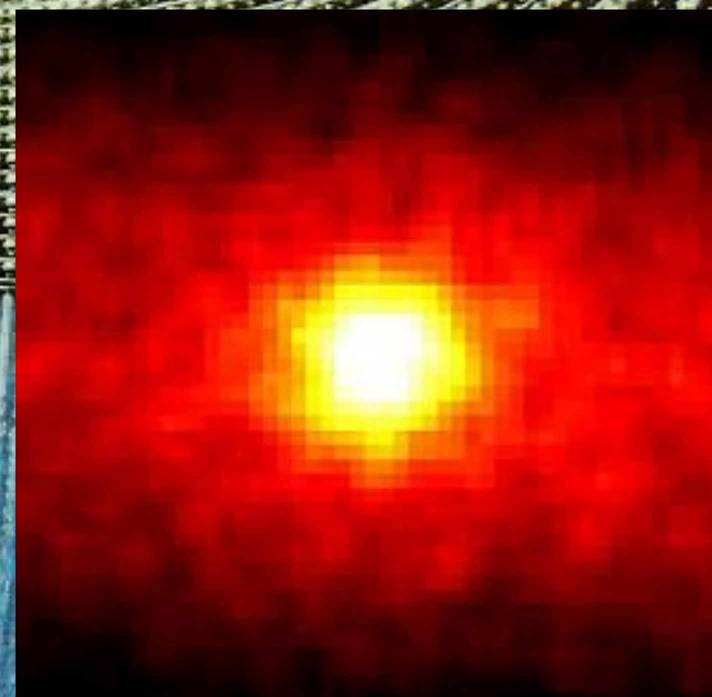


Kamiokande then SuperKamiokande



Neutrinos from SN1987A
25 events in 12 s

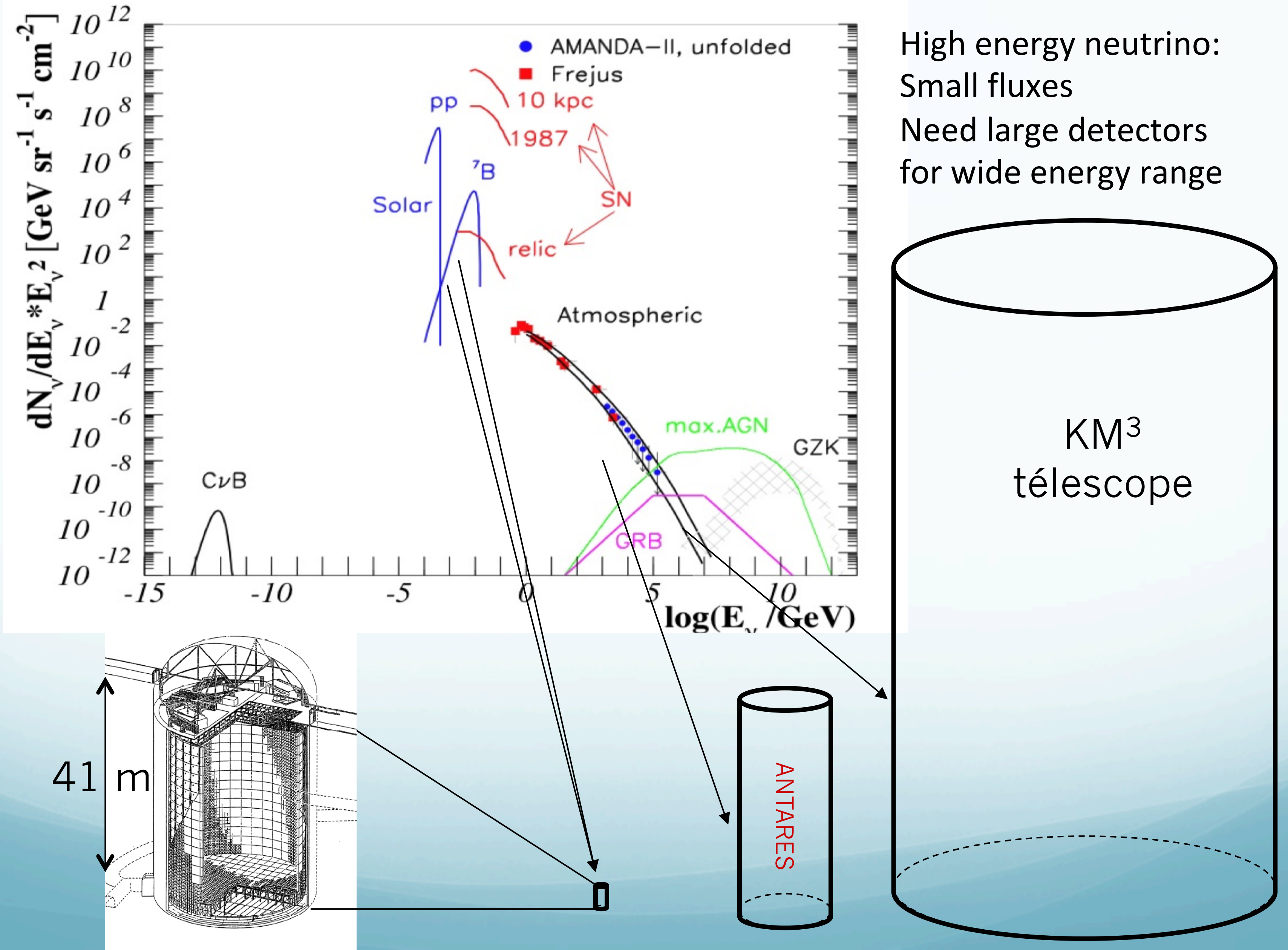
~MeV



The Sun seen by SuperKamiokande

From MeV ν to PeV ν : natural medium

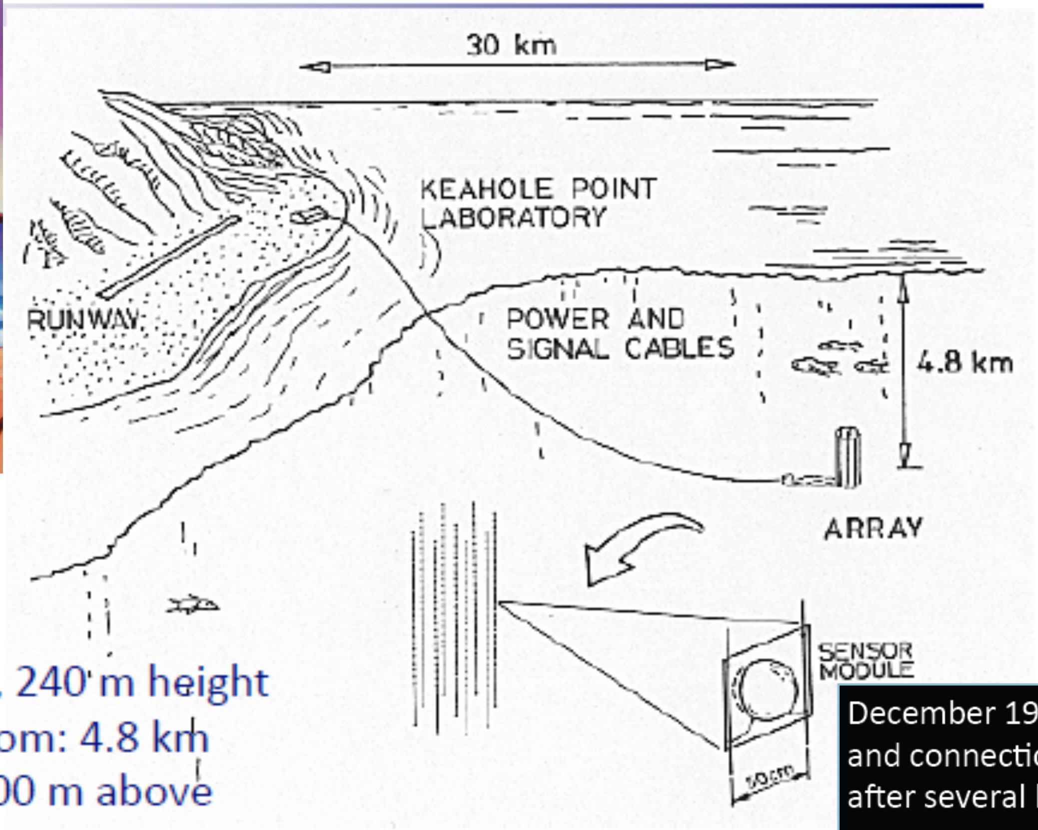
High energy neutrino:
Small fluxes
Need large detectors
for wide energy range



Years 80's : the first project

See also: A.Roberts: The birth of high-energy neutrino astronomy: a personal history of the DUMAND project, Rev. Mod. Phys. 64 (1992) 259.

DUMAND-II (The Octagon)



9 strings
216 OMs
100 diameter, 240 m height
Depth of bottom: 4.8 km
Lowest OM 100 m above bottom

December 1993: deployment of first string and connection to junction box. Failure after several hours

1995: DUMAND project is terminated

First steps in the Ice...

Observation of muons using the polar ice cap as a Cerenkov detector

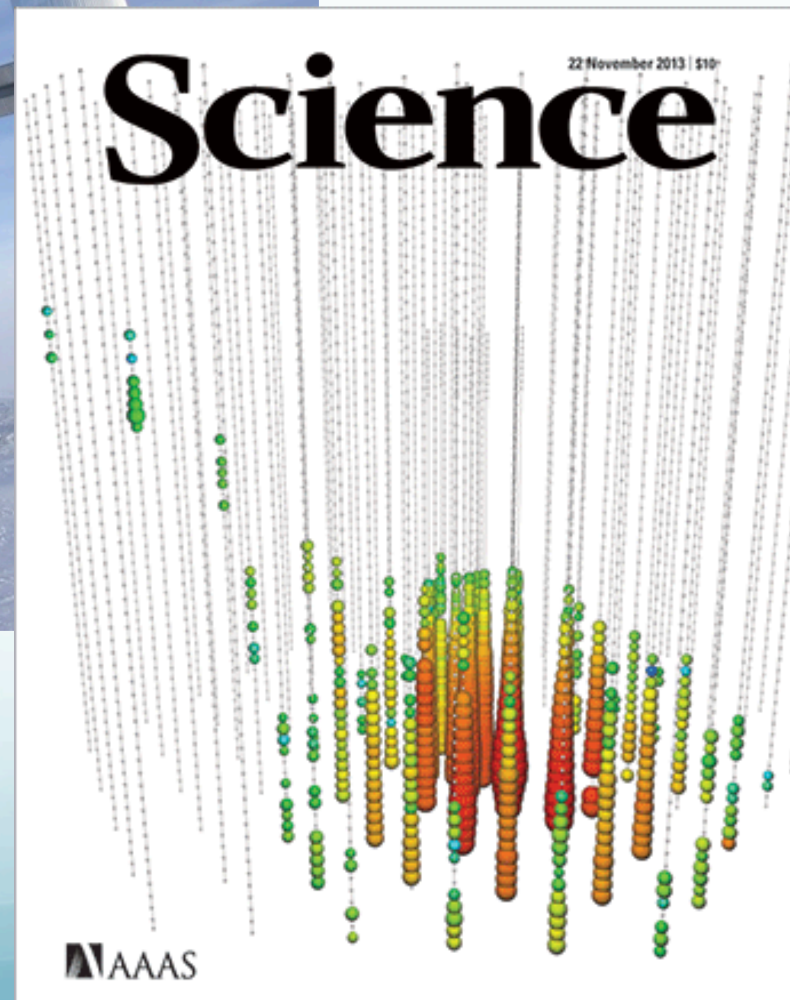
Nature Sept 91

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* Department of Physics, University of California, Berkeley, California 94720, USA
† Department of Physics, University of California, Irvine, California 92717, USA
‡ Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

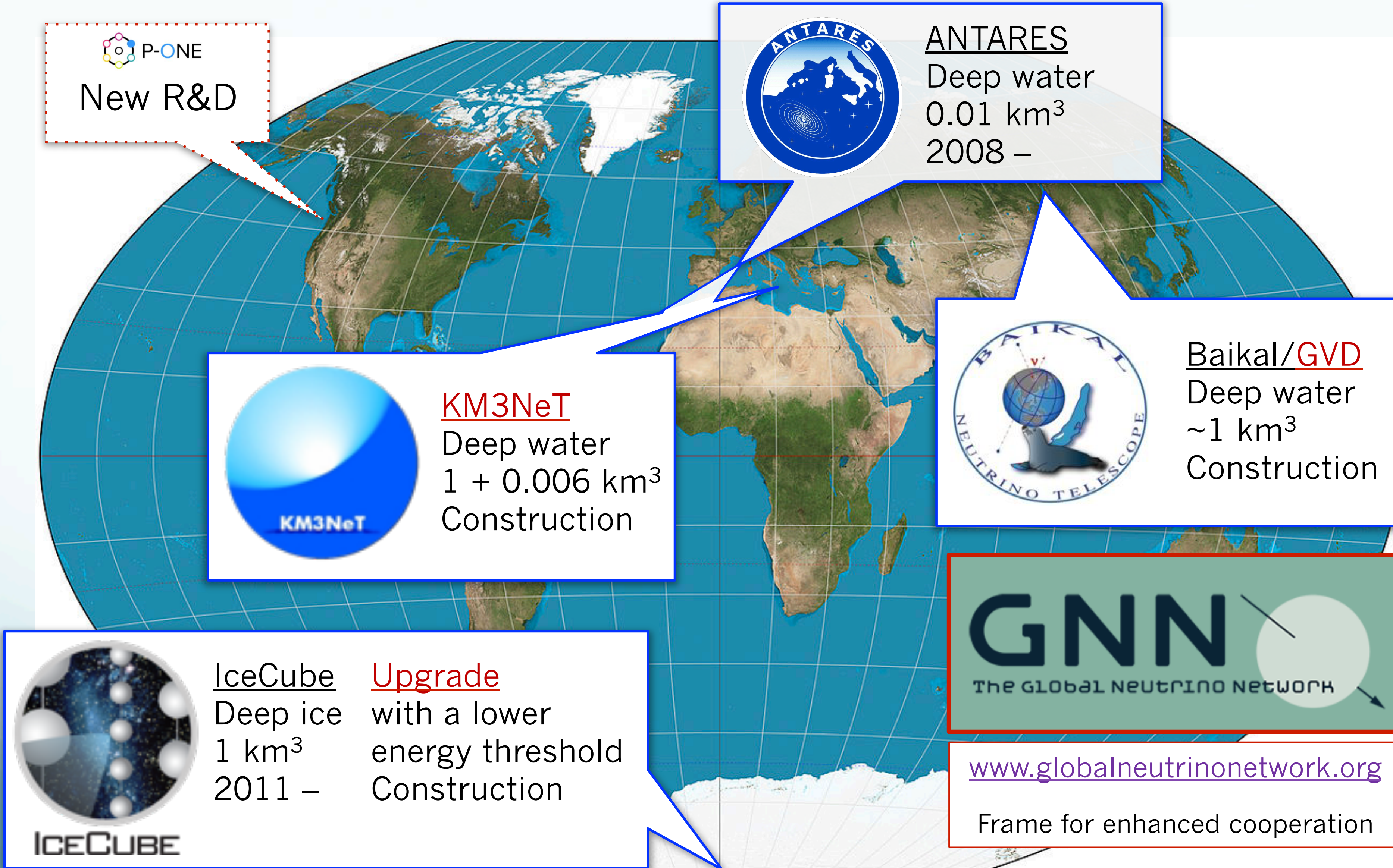
F. Halzen

First HE detection … 2013!

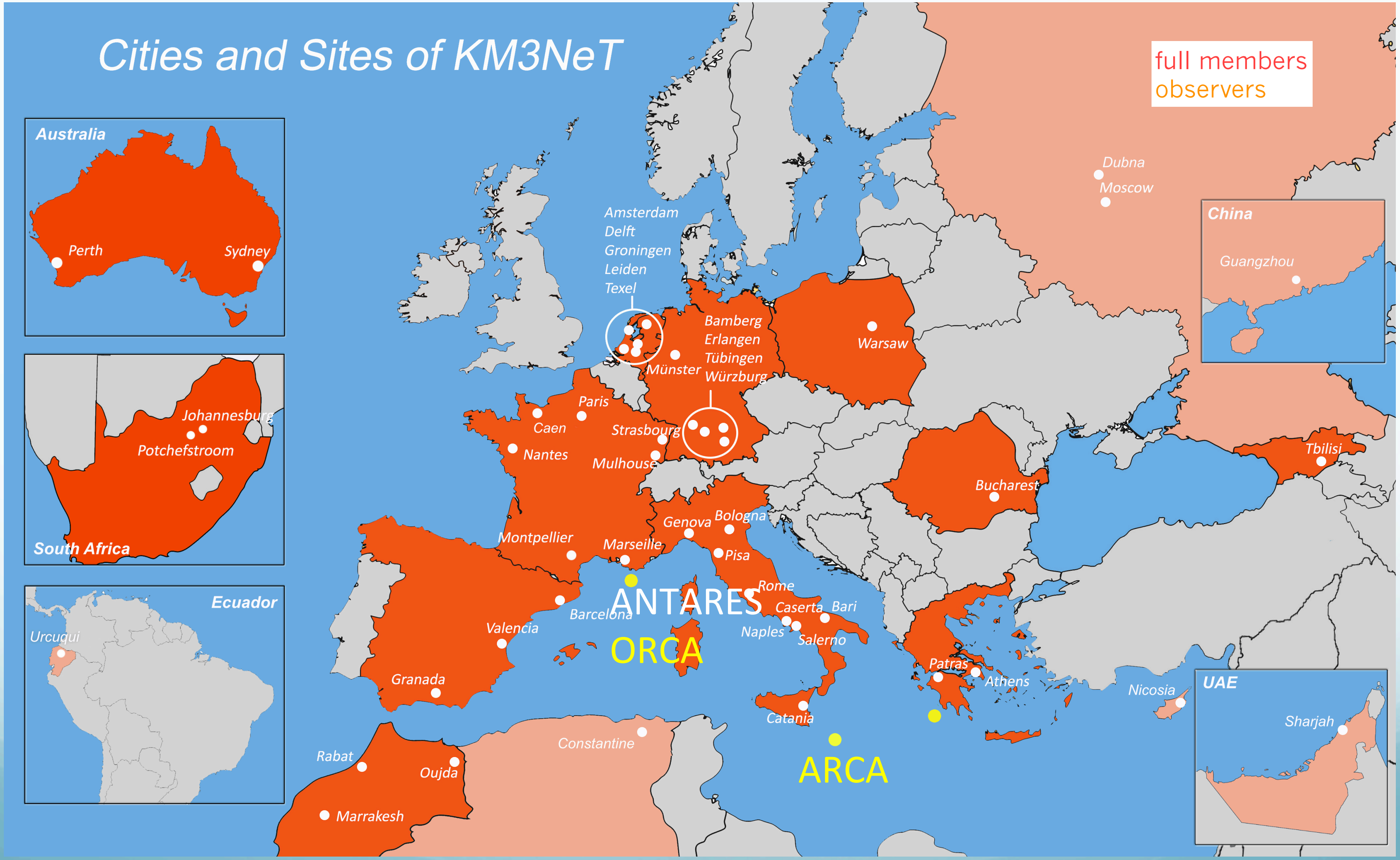


The field now truly opens !

The neutrino telescope world map 2020



ANTARES & KM3NeT



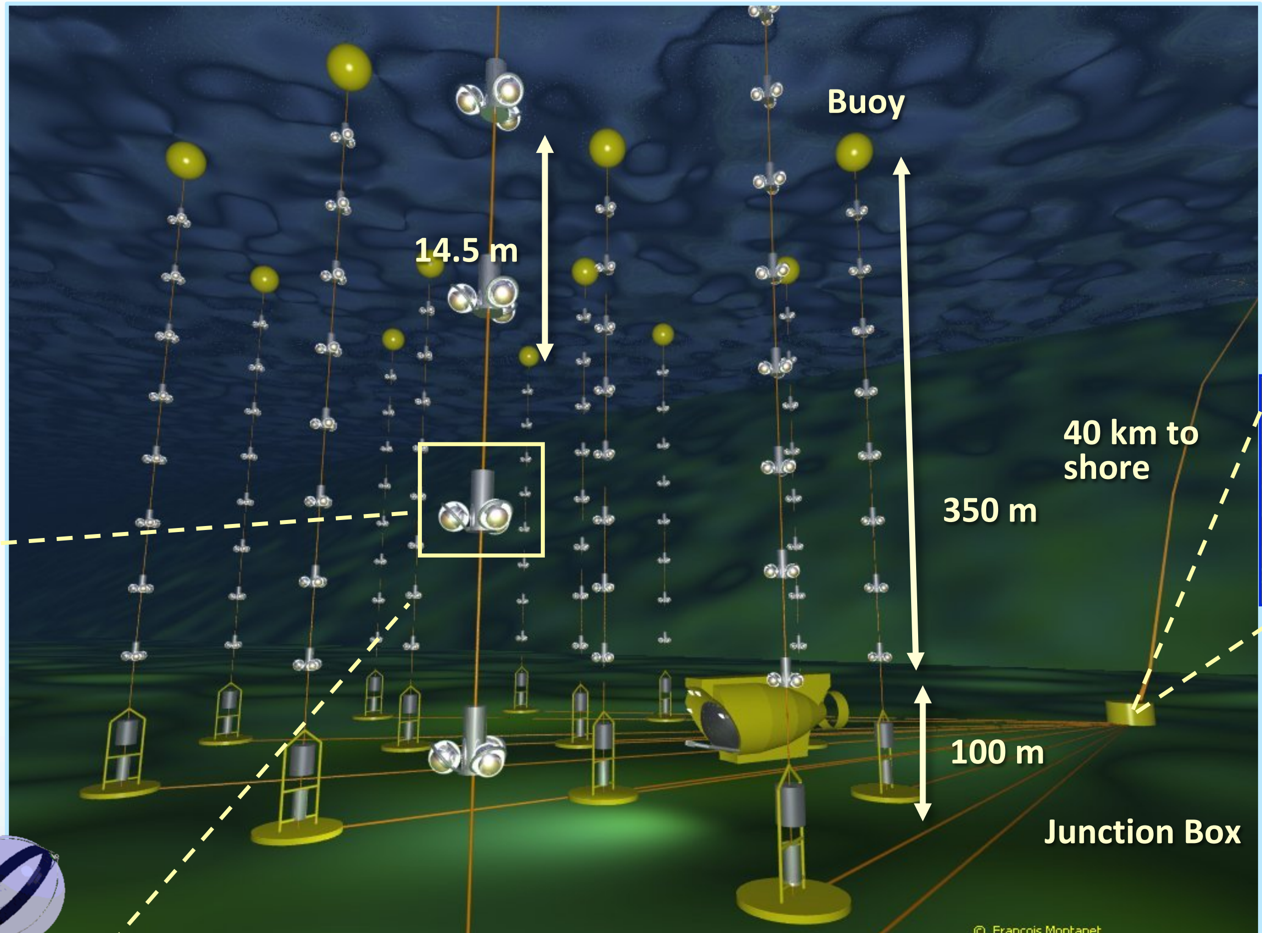
ANTARES

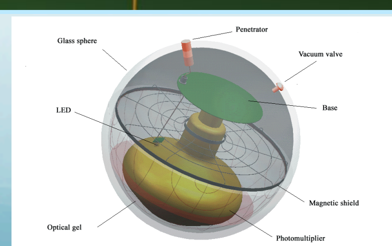
- 12 lines (885 PMTs)
- 25 storeys / line
- 3 PMTs / storey
- 5-line setup in 2007
- Completed in 2008

LED Beacon

Hydrophone

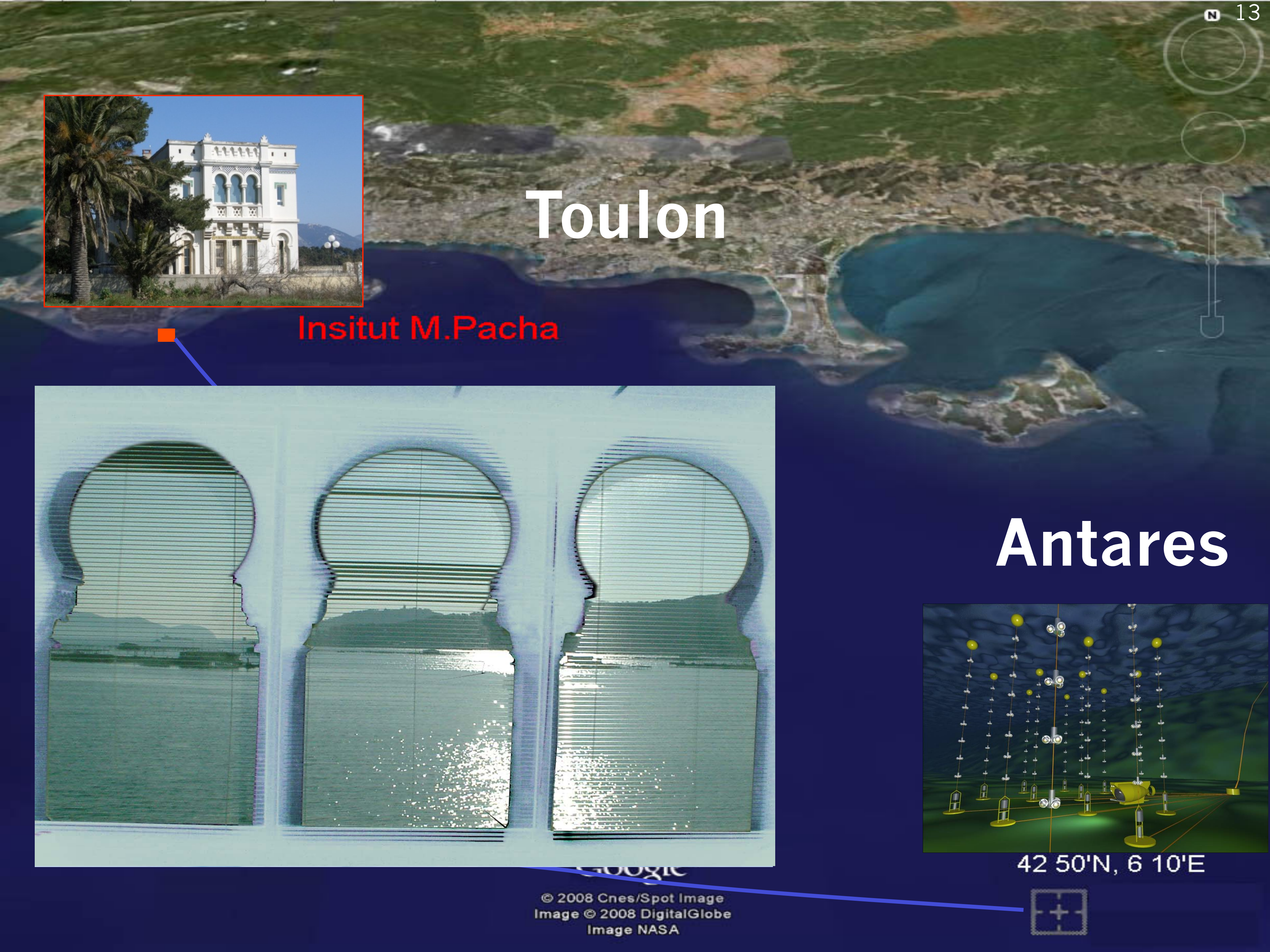
Optical Modules 10" PMT



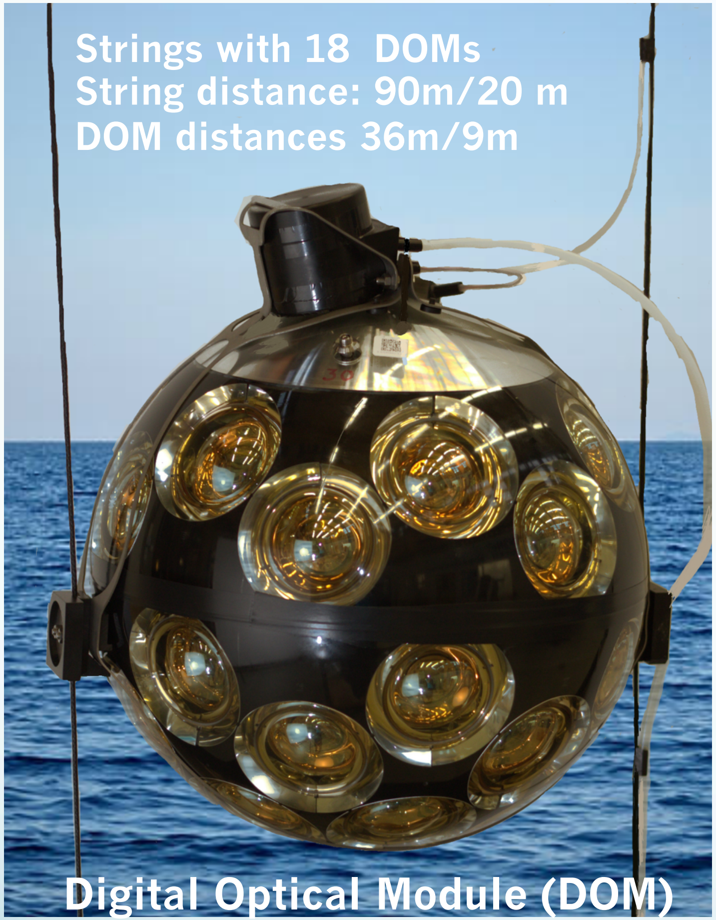


Junction Box

Shore station


Toulon
Insitut M.Pacha
Antares
42 50'N, 6 10'E
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA

KM3NeT



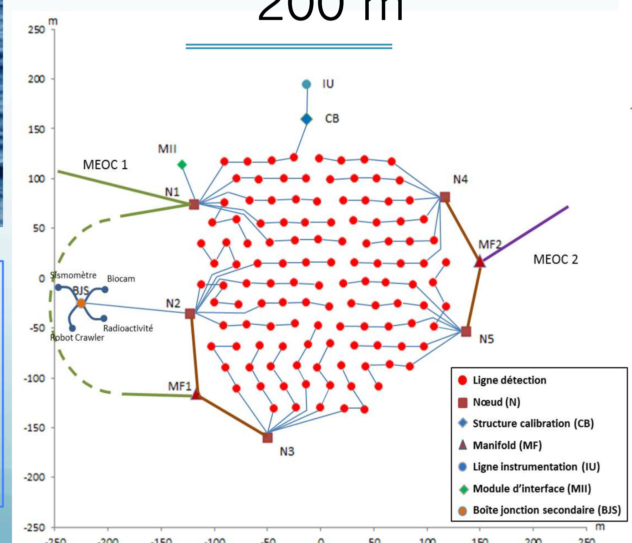
- 31 PMTs in one sphere
- 3 x cathode area wrt ANTARES OM
- Single photon counting
- Directional information
- Inspiring design for IceCube-Gen 2

KM3NeT ARCA/ORCA

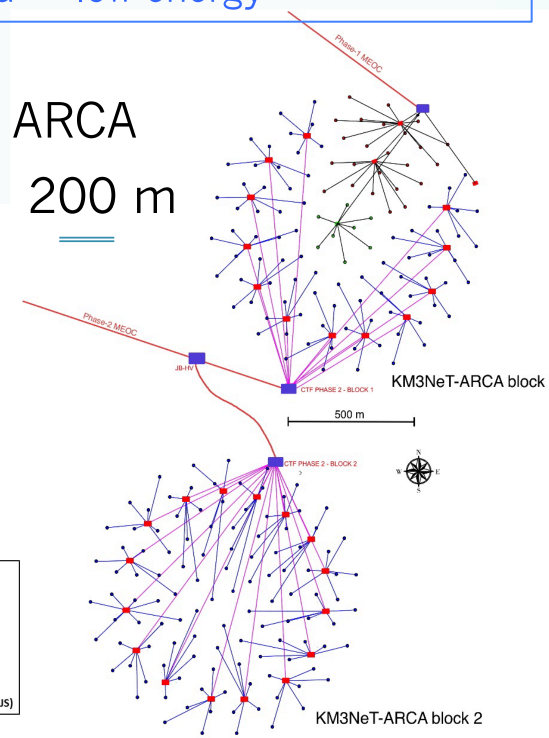
Astrophysics/**O**scillation **R**esearch with **C**osmics in the **A**byss

ARCA: 3.5km depth, 100km from Capo Passero (Sicily)
Focus: Cosmic Neutrino Sources
large, sparse grid -> high energy
ORCA: 2.5 km depth, 40km from Toulon (France)
Focus: Atmospheric neutrino oscillations
small, dense grid -> low energy

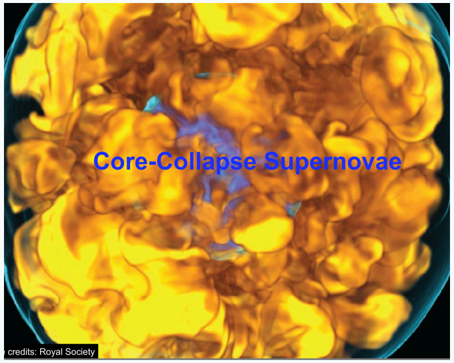
ORCA 200 m

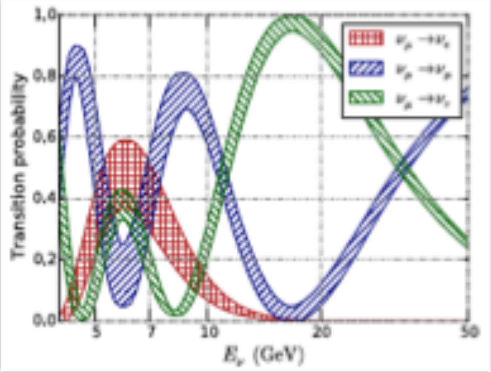


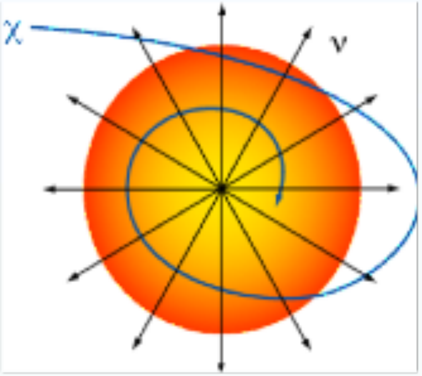
ARCA 200 m

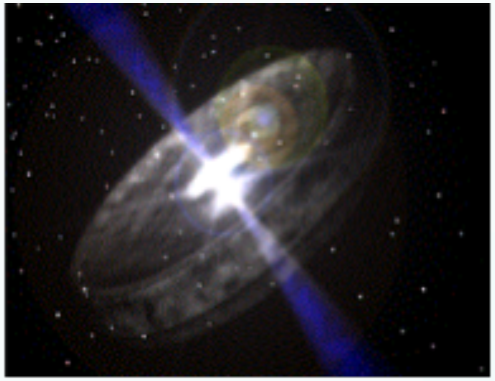


The Physics Scope









MeV Energy No reco. in HE NT	Low Energy GeV < E < 50 GeV	Medium Energy 10GeV < E < 1 TeV	High Energy E > 1 TeV
CCSNe	**Oscillation**	**Dark Matter**	**HE Astrophysics**
Full Galactic coverage All mass progenitors Triangulations ⇩ Localisation Coleiro et al., Eur. Phys. J. C 80, 856 (2020)	Focus of this talk	Not covered here	Focus of this talk

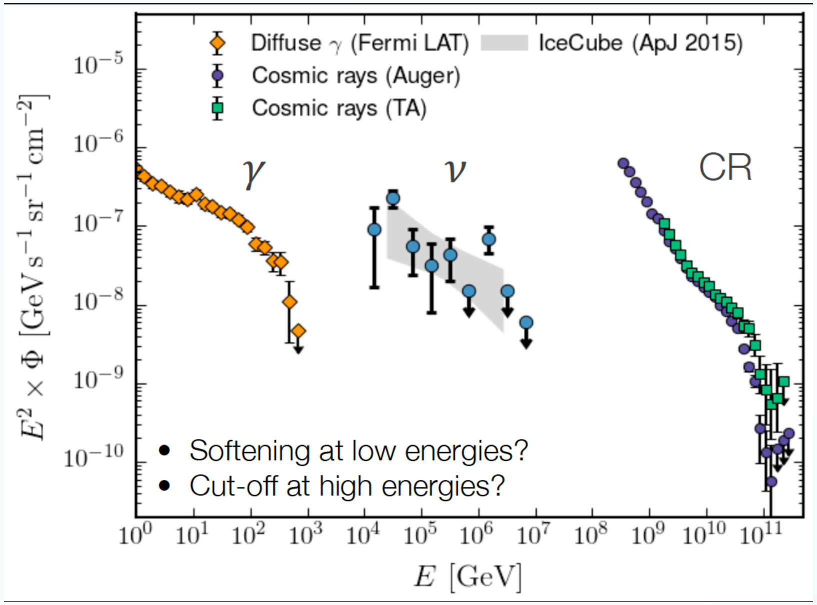
+ Exotics (Monopoles, Nuclearites, etc.)

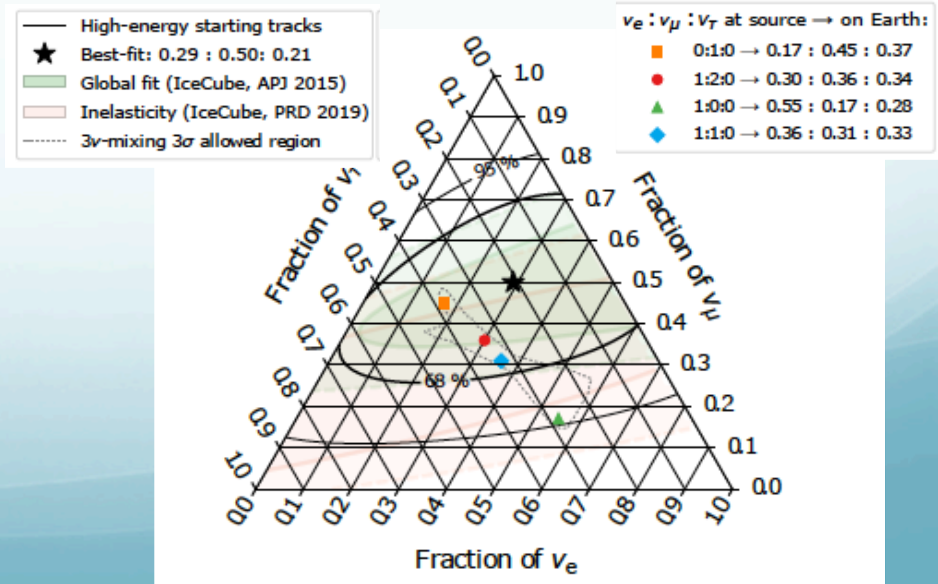
+ Environnemental Sciences

What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
- Sources
- Multi-messengers
- Catalogues
- Flavor ID
- Neutrino Physics
- Supernovae

Spectral break ?
North/South difference ?
Galactic Contribution?





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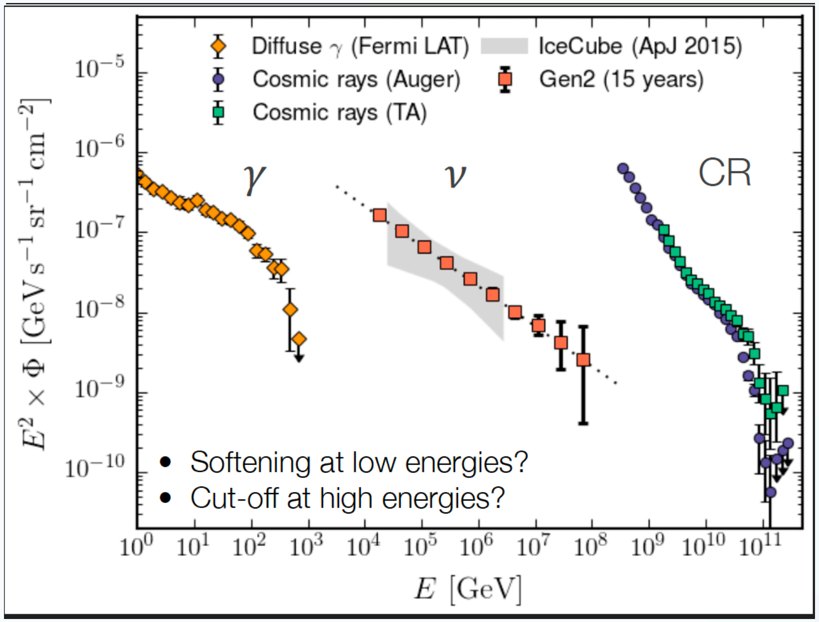
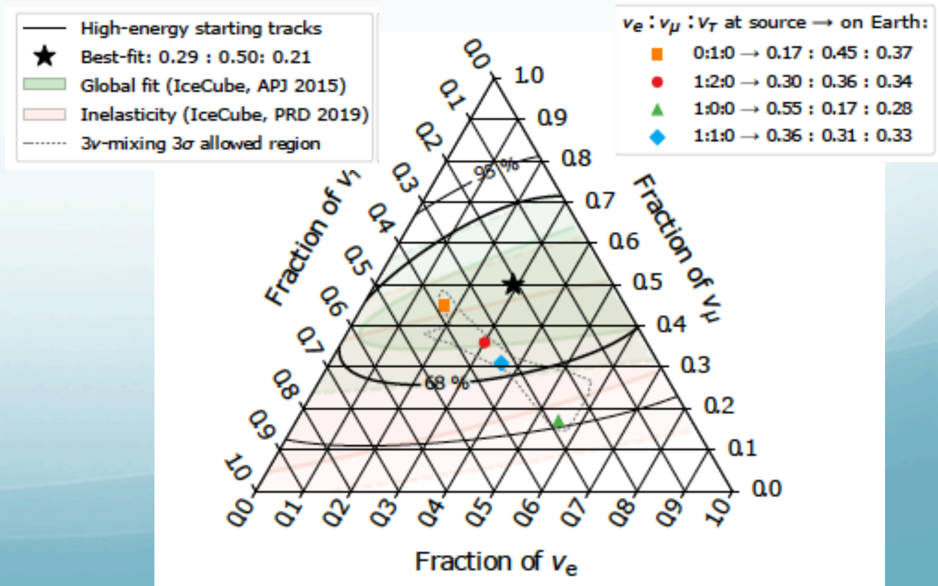
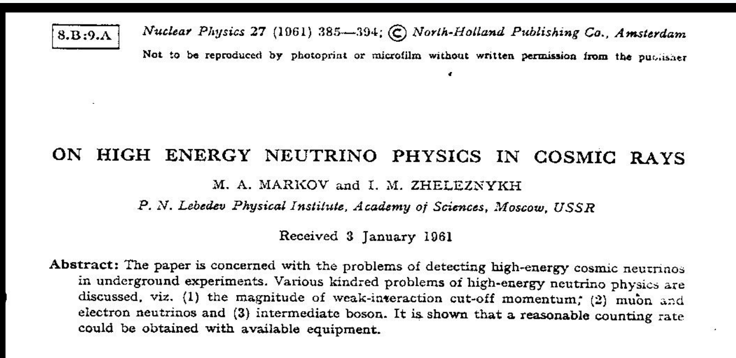




Detection Principles



8.B:9.A Nuclear Physics 27 (1961) 385—394; © North-Holland Publishing Co., Amsterdam

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH
P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

Received 3 January 1961

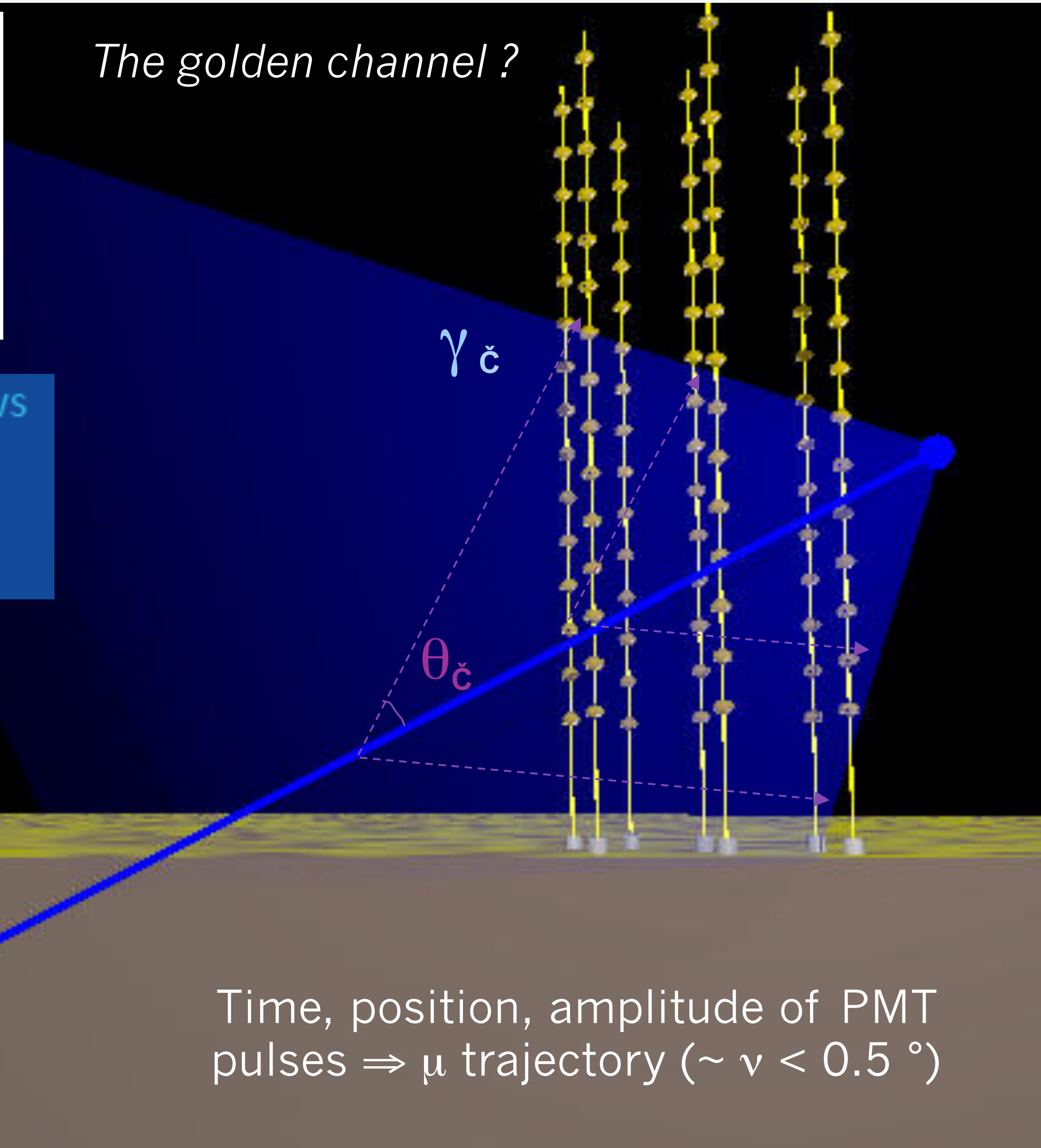
Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum; (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.

The golden channel ?

Natural radiator is low cost and allows huge instrumented regions
→ Deep sea or lake
→ Deep clear Ice

Detection of Cherenkov light emitted by muons with a 3D array of PMTs

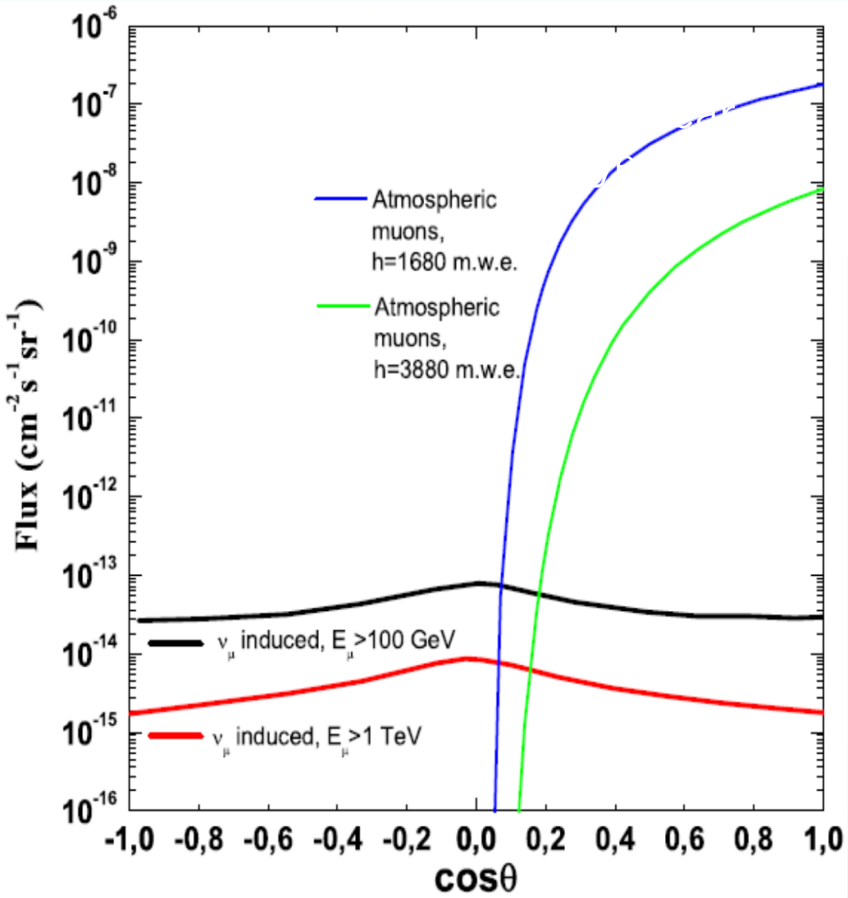
Requires a large (km³) dark transparent detection medium

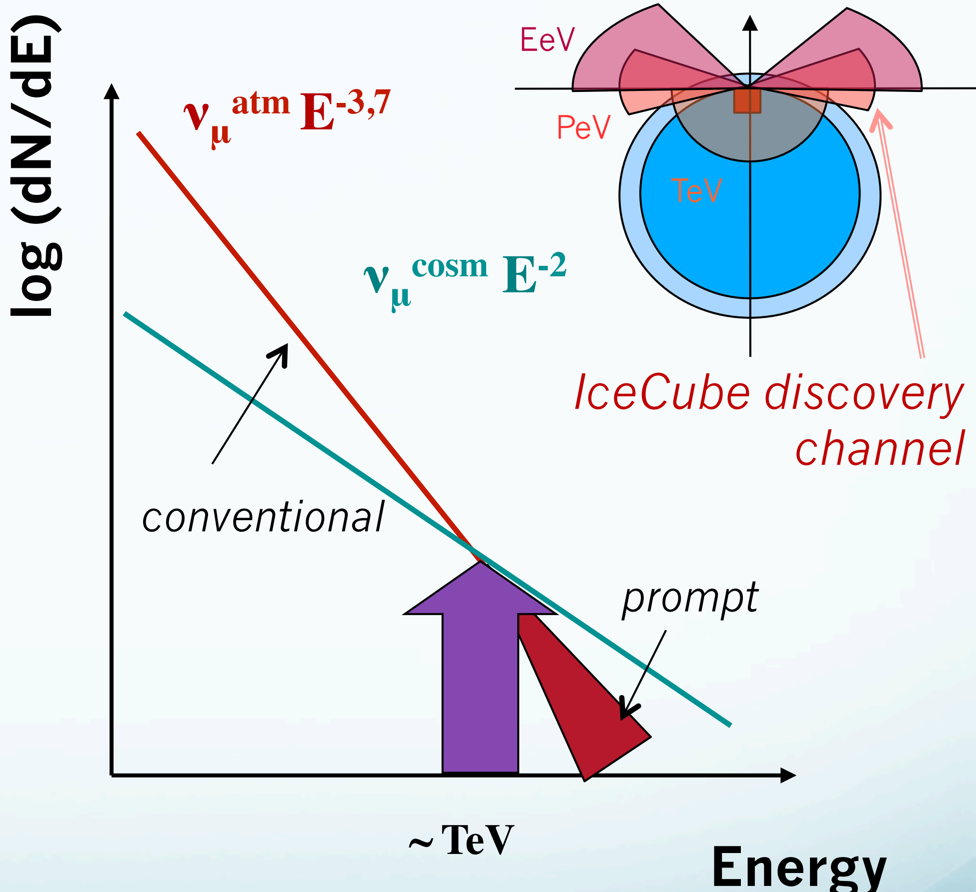


Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Atmospheric background vs cosmic ν's

Atmospheric muons: shield detector, look down, apply veto





Atmospheric neutrinos: search for

- An excess at High Energy
- Anisotropies, spatial clustering
- Time / space coincidence with other cosmic probes

Water versus Ice

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

- Logistically attractive

  Close to shore (deployment / repair)

- Complementarity to IceCube South Pole

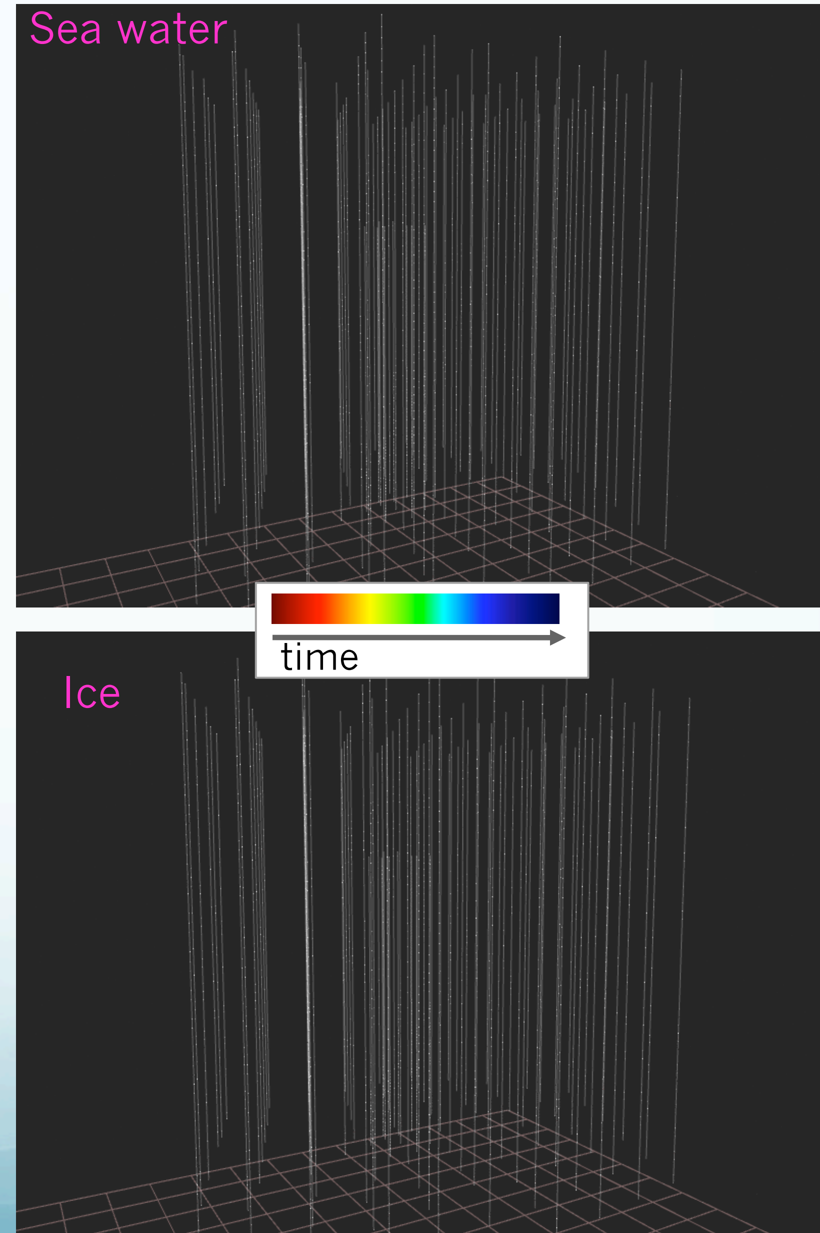
  Excellent view of Galaxy

- Mild Latitude

  On/off studies → Background control

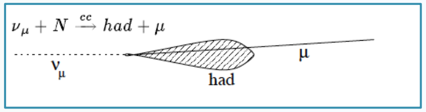
- K40 optical background

  Useful calibration, but requires causality filters



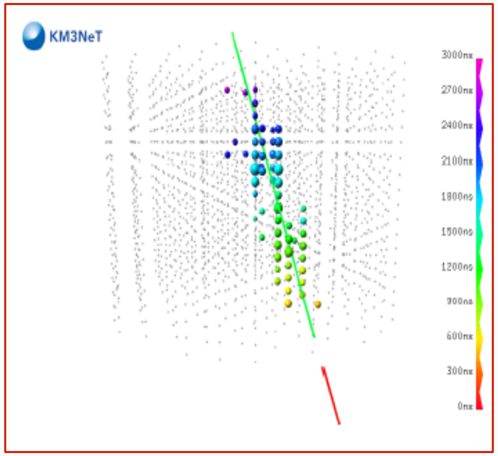
Performance – Track events

CC ν_μ

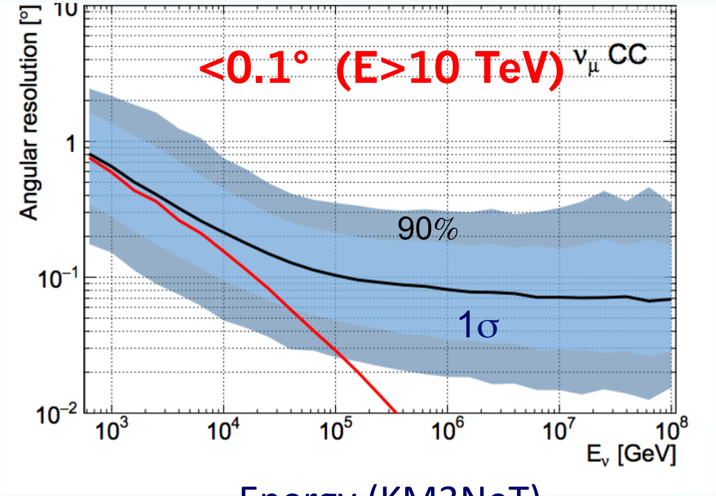


- Golden channel
- High angular accuracy
- Enhanced volume (100's m to a few Km muon range)

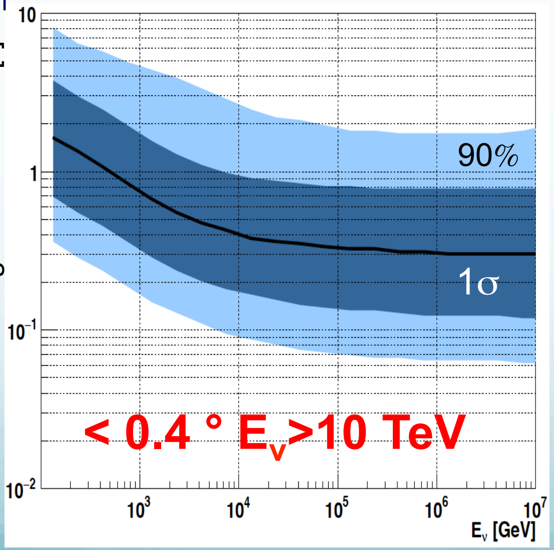
KM3NeT event



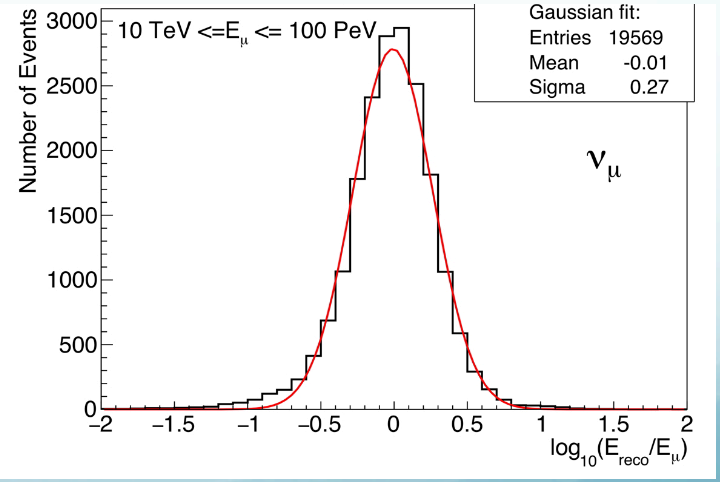
Direction (KM3NeT)



Direction (ANTARES)

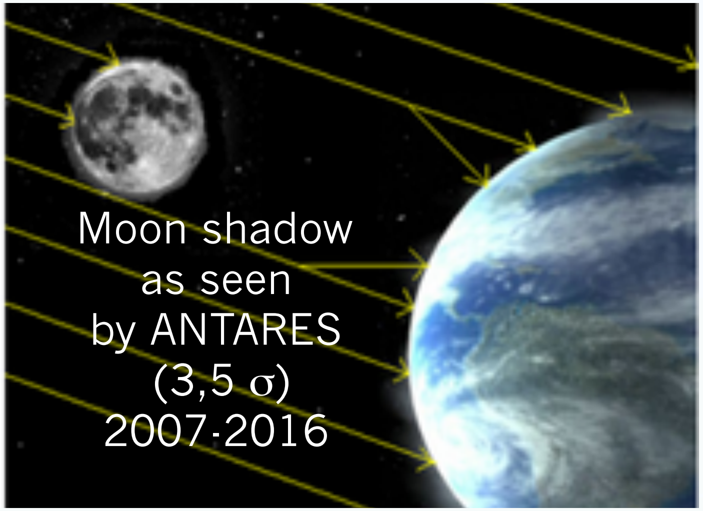


Energy (KM3NeT)

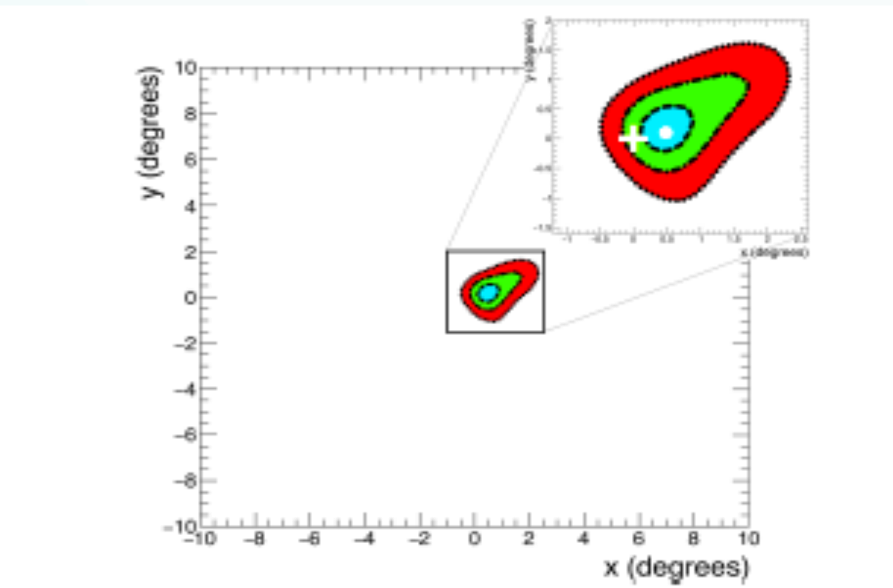


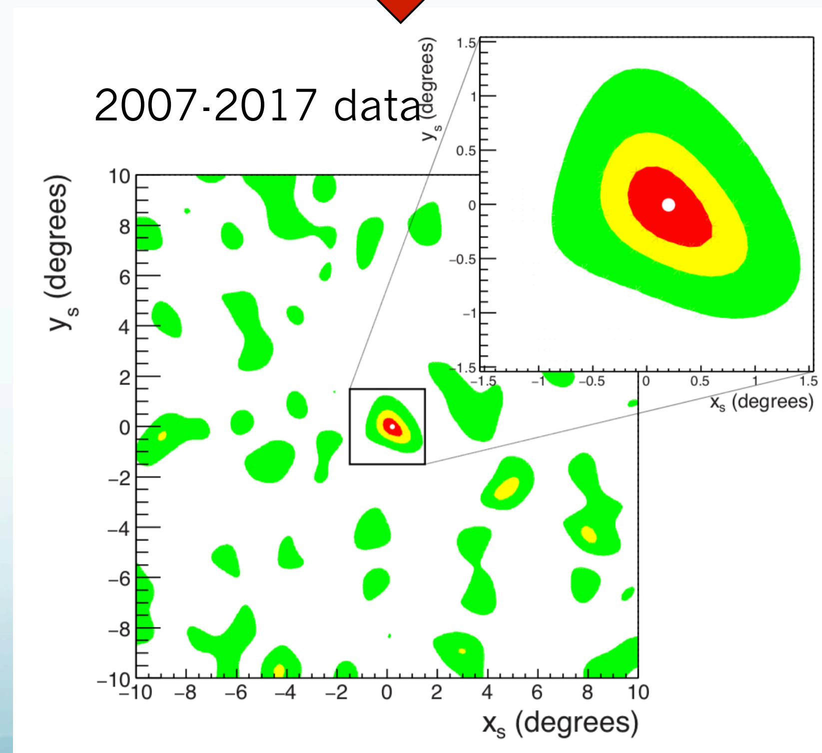
0.3 Log E (E>10 TeV)

Absolute Pointing



The Sun shadow is also observed with a statistical significance of $3.7\,\sigma$, and an angular resolution of $0.59° \pm 0.10°$ for downward-going muons.



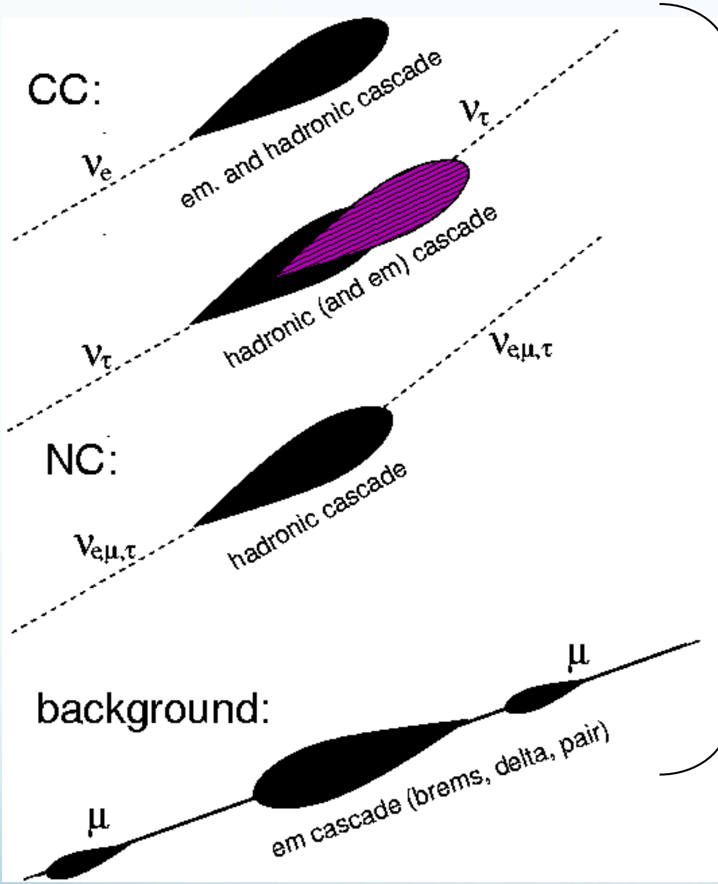


📖 Eur.Phys.J. C78 (2018) no.12, 1006

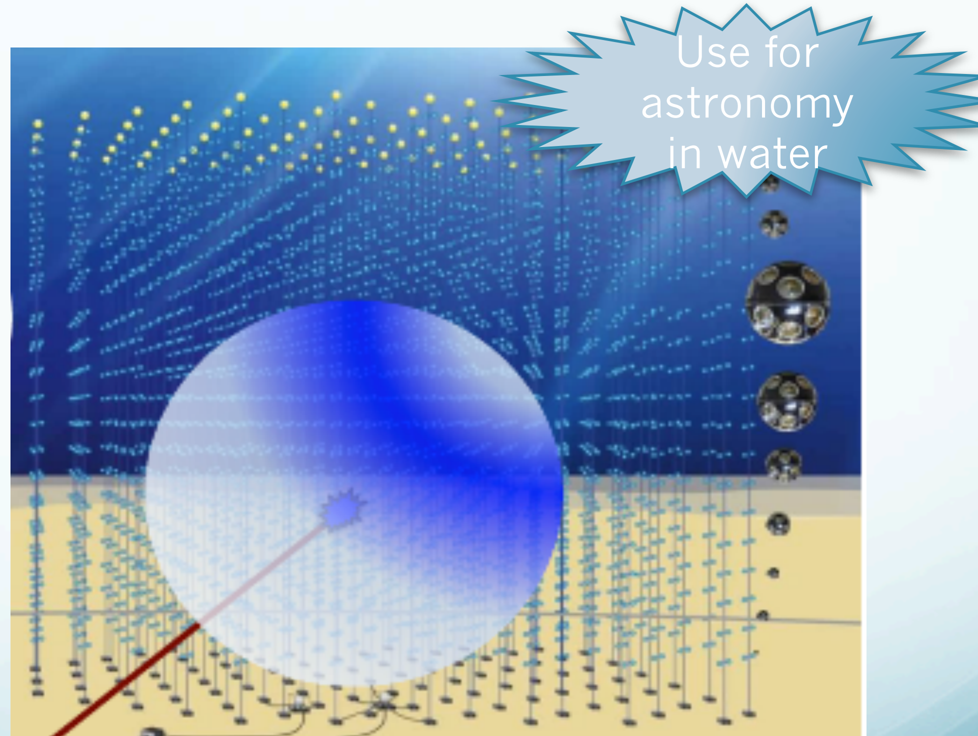
📖 Phys. Rev. D 102, 122007 (2020)

Cascade topology

$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source —*oscillation*→ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !



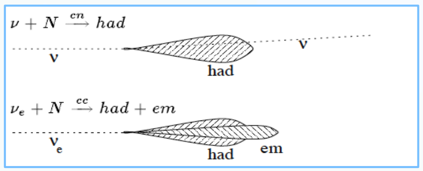
IceCube discovery channel



→ Provides sensitivity to all neutrino flavours – Increases overall sensitivity

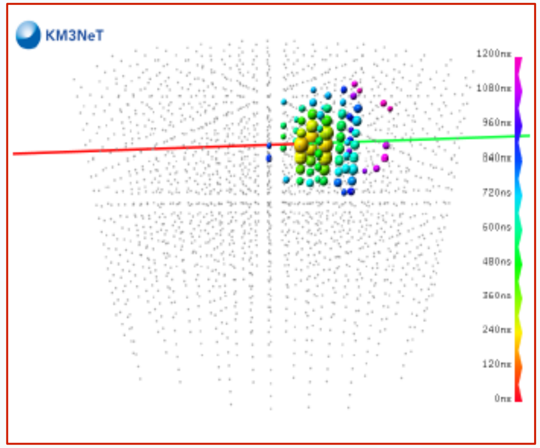
Performance – Shower events

NC ν_{all}
CC ν_e

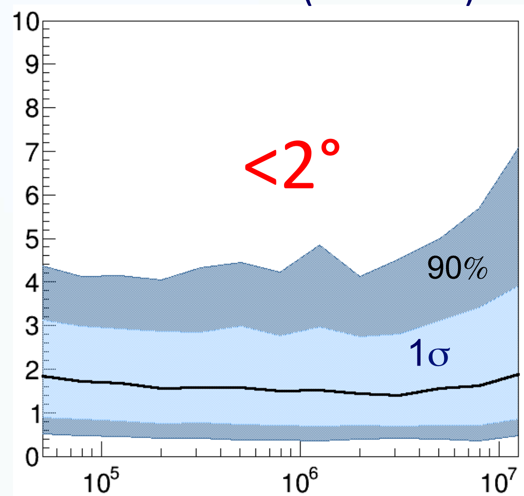


- Good energy reconstruction
- Fair angular resolution (low light scattering in water)

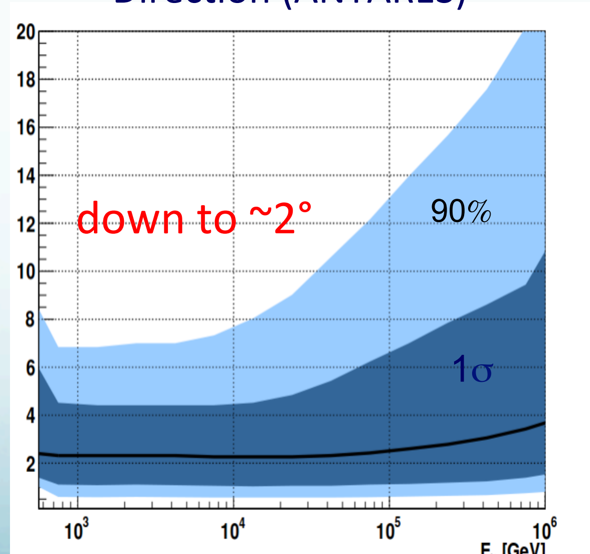
KM3NeT event



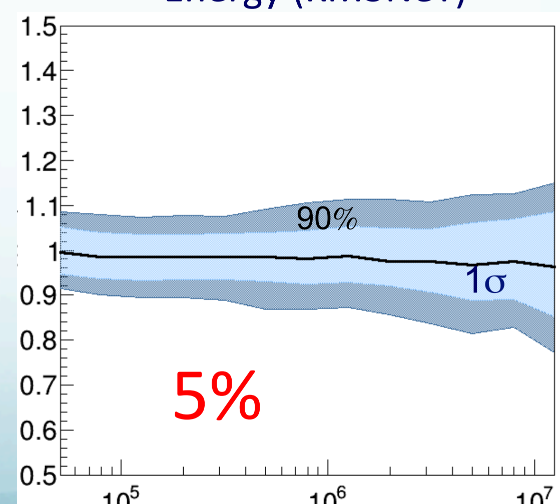
Direction (KM3NeT)



Direction (ANTARES)

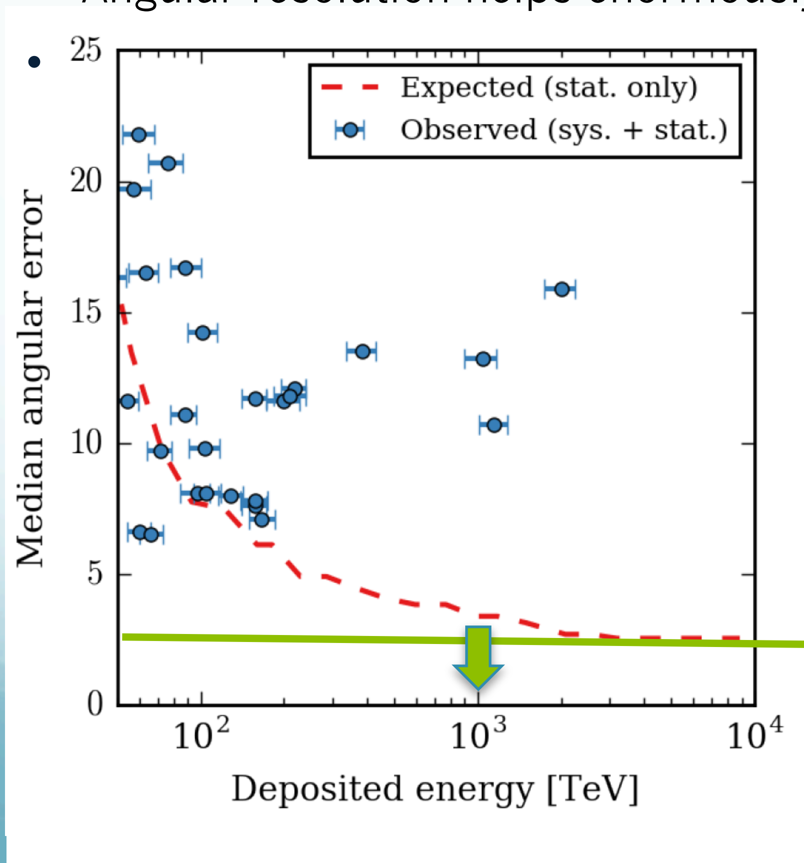


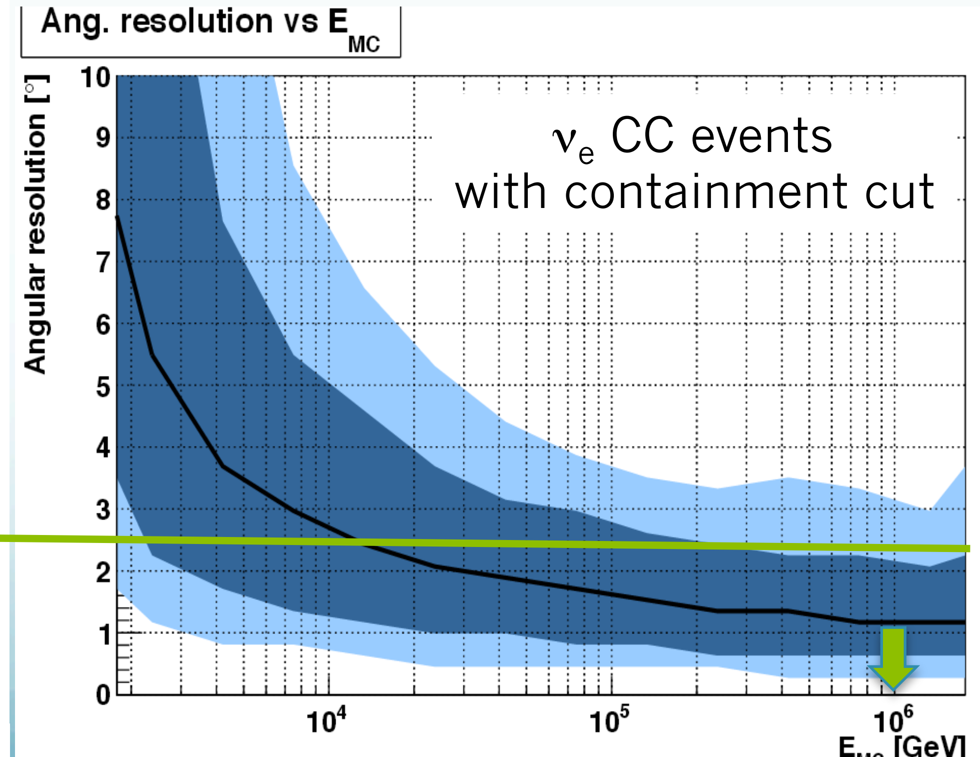
Energy (KM3NeT)



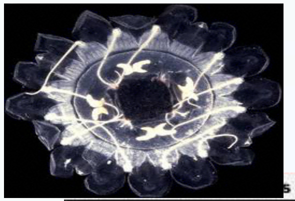
Some Complementarities

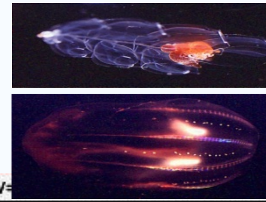
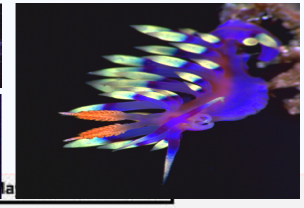
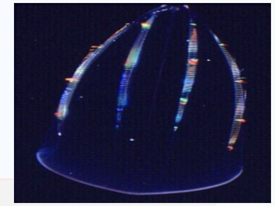
- **Distinct medium, distinct systematics**
  - Ice properties is limiting factor for reconstruction precision and flavour id: Upgrade !
  - Water is a much more homogenous medium than ice with long scattering length.
    - ARCA/Current IC tracks 0.2°/ 0.6* @10 TeV 0.05°/0.25° @10 PeV
  - Angular resolution helps enormously in source association *Bartos et al. PRD* 96 (2017) 2, 023003
  -

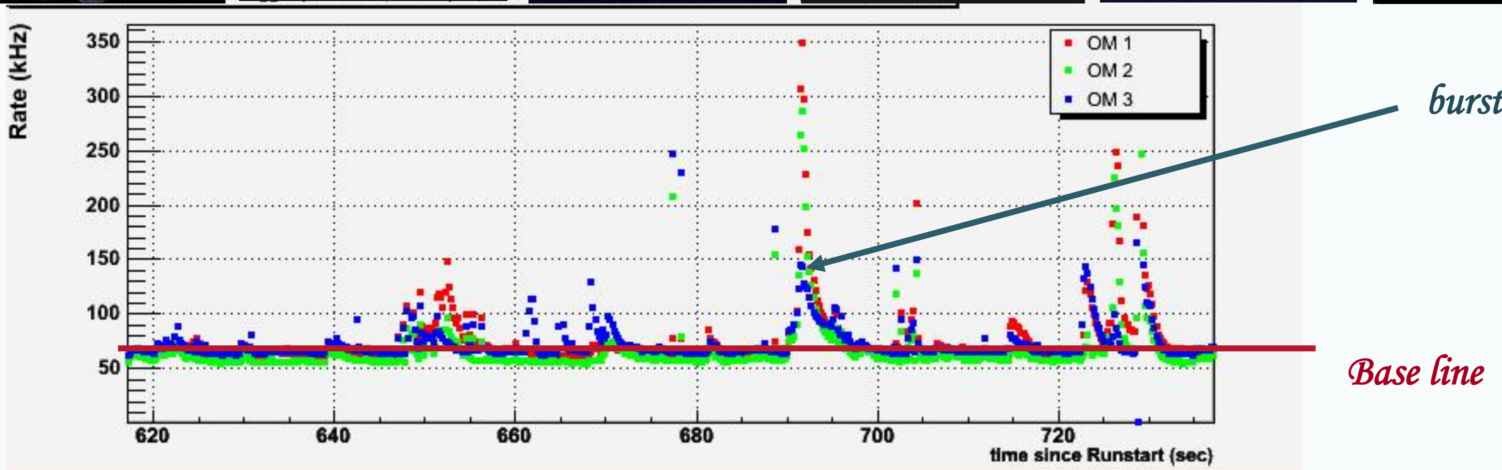




Optical background

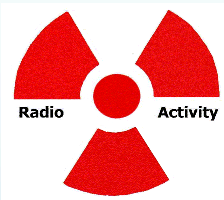


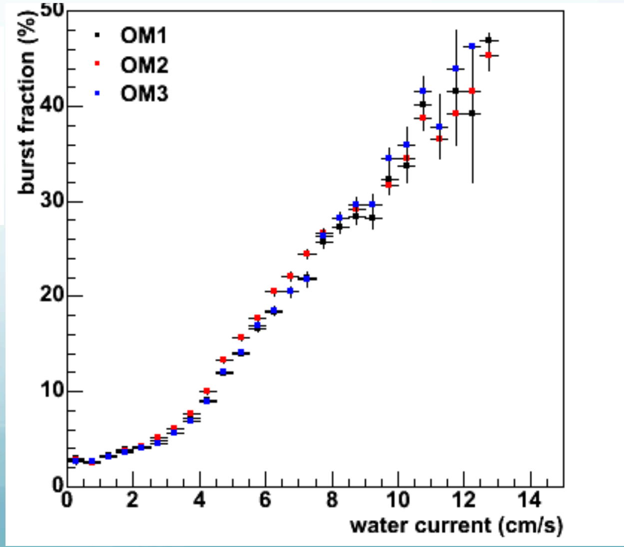




Base line ^{40}K

Bio-luminescence

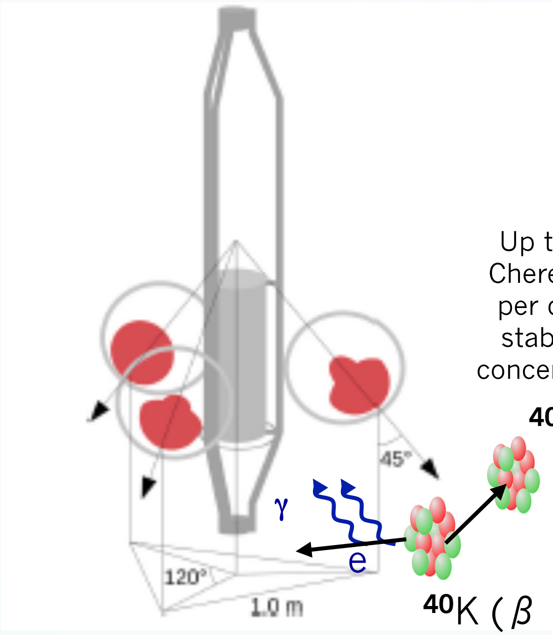




Bio-luminescence burst:

photo-emitter animals

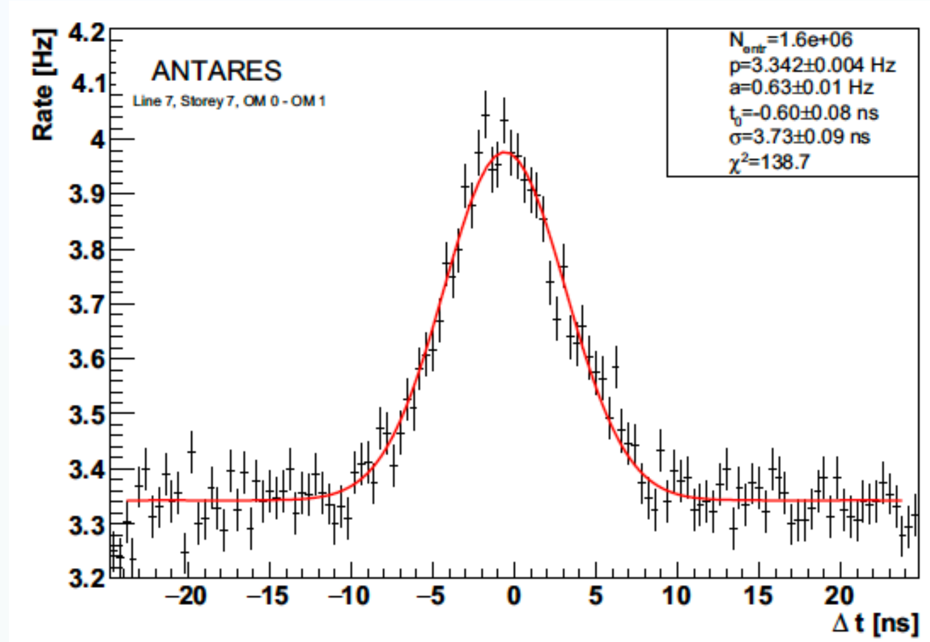
^{40}K as monitoring tool

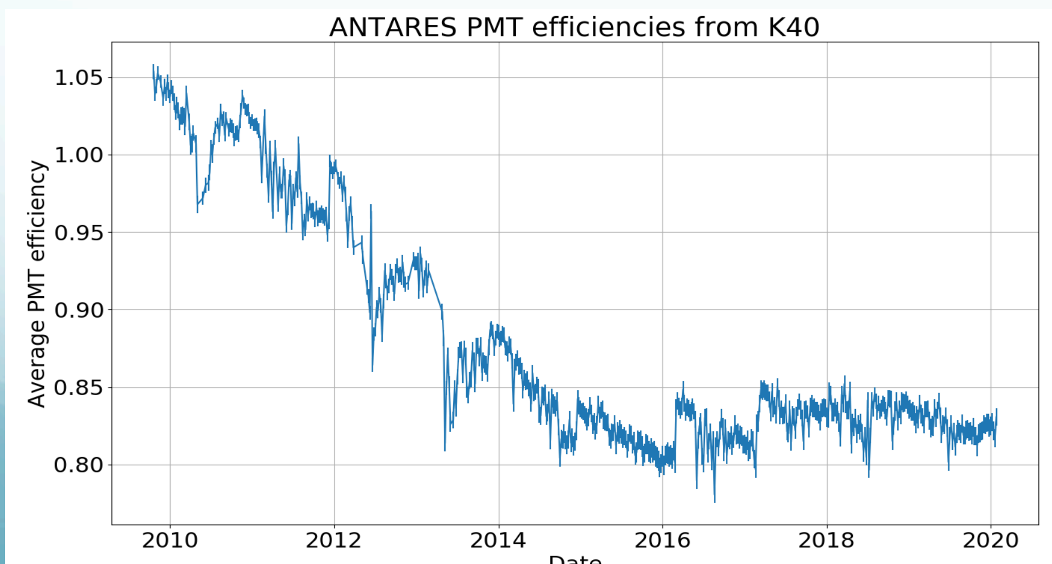


Up to 150 Cherenkov γ per decay; stable ^{40}K concentration

^{40}Ca

^{40}K (β decay)





Regular tunings
Only ~20% efficiency loss

^{40}K powerful calibration tool

Eur. Phys. J. C (2018) 78: 669

Deep-Sea Cabled observatories

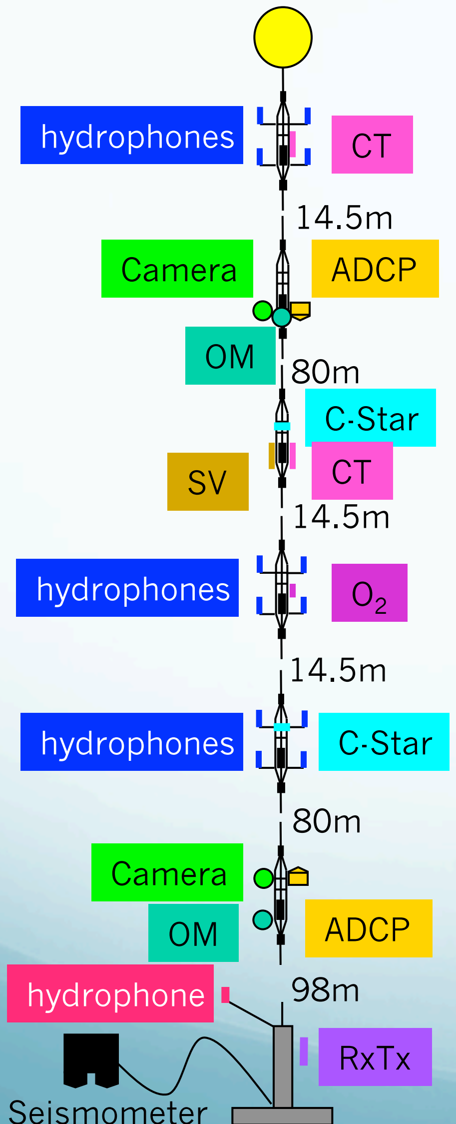
- Real-time
- High power
- High bandwidth, High frequency
- Multiple sensors in same location
- Continuous, Long term
- Trigger for studies with other sensors
- Oceanography (water circulation, climate change):
  - Current intensity and direction, water temperature, water salinity, oxygen, radionuclides…
- Geophysics (geohazard):
  - Seismic phenomena, low frequency passive acoustics, magnetic field variations,…
- Biology (micro-biology, cetaceans,…):
  - Passive acoustics, biofouling, bioluminescence, video, water samples analysis,…

Program extended with KM3NeT (link with EMSO)

More and more important in the context of a rapid climate change

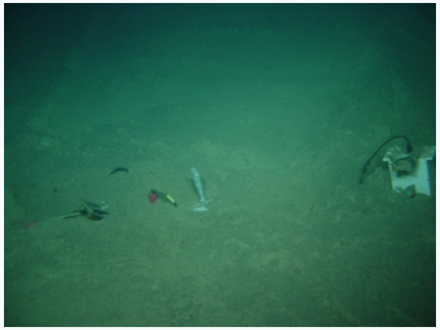
Earth and Sea Sciences

Instrumentation Line

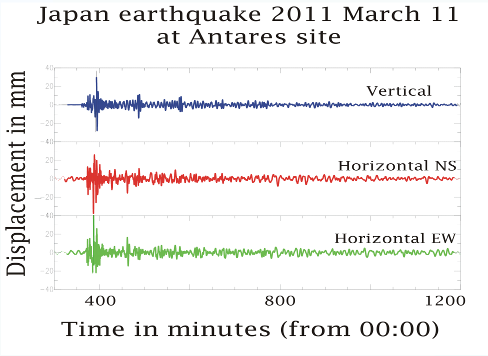


Seismometer

In lab



Burried



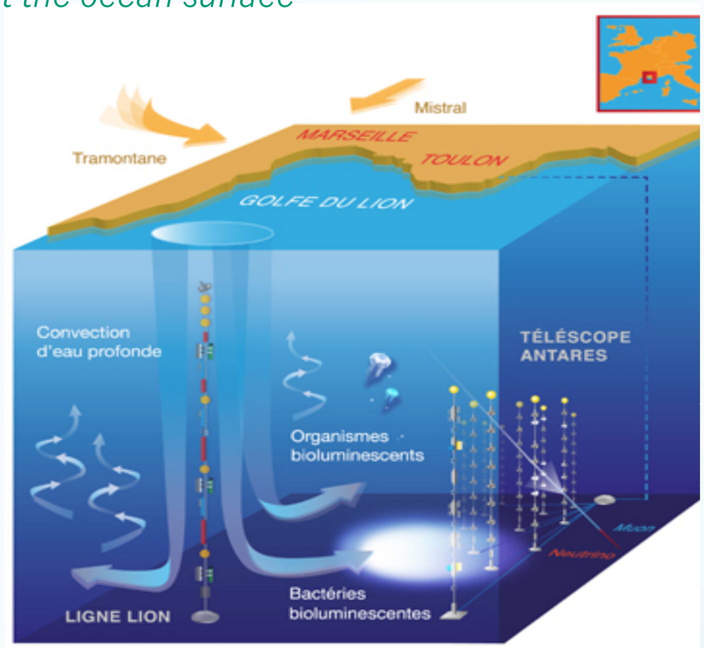
Video-monitoring

Deep-Sea NT are multidisciplinary observatories

Earth and Sea Sciences

📖 PLoS ONE 8 (7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface

📖 *Journal of Geophysical Research: Oceans, Vol 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection



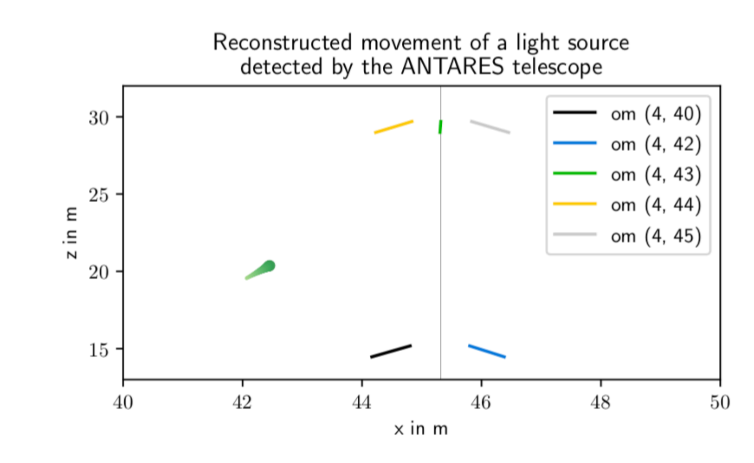
📖 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

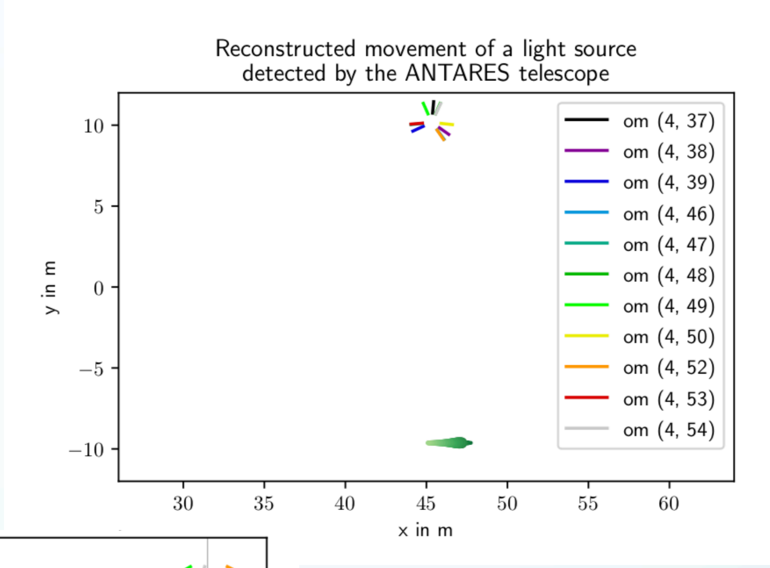
📖 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

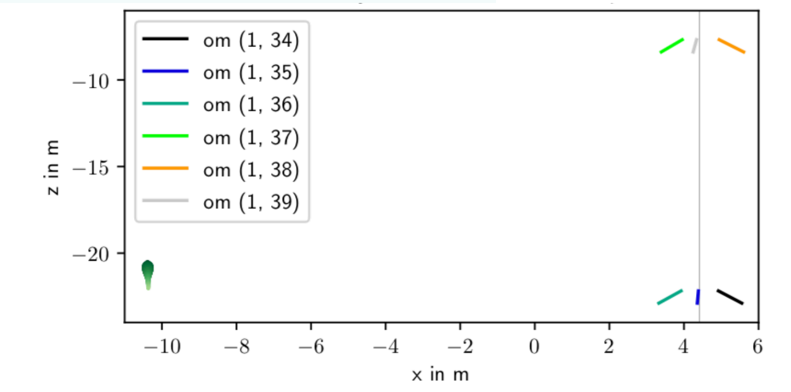
New: bioluminescent flashes

A novel technique to infer information on bioluminescent organisms without actively interfering with them.
→ Reconstruction of the light emission of individual organisms, as well as their location and movement.





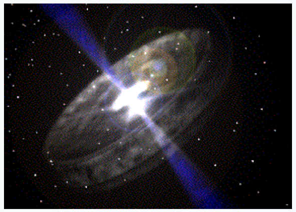
Application to ANTARES data



Led by the AI group of the Max Plack Institute of Garching

Open Science in KM3NeT era

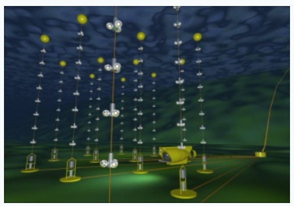
Outline

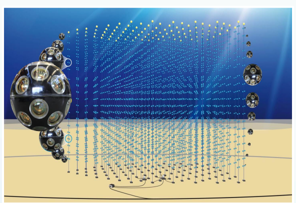


The High-Energy Physics Case – The cosmic endeavour

Historical aspects & Scientific motivations

Detection principles & Performances

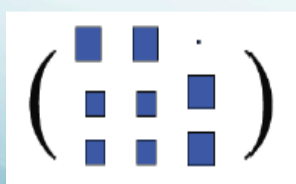




Status of ANTARES and KM3NeT/ARCA

Selected results in today's context

Prospects



The Low-Energy Physics Case – A new endeavour

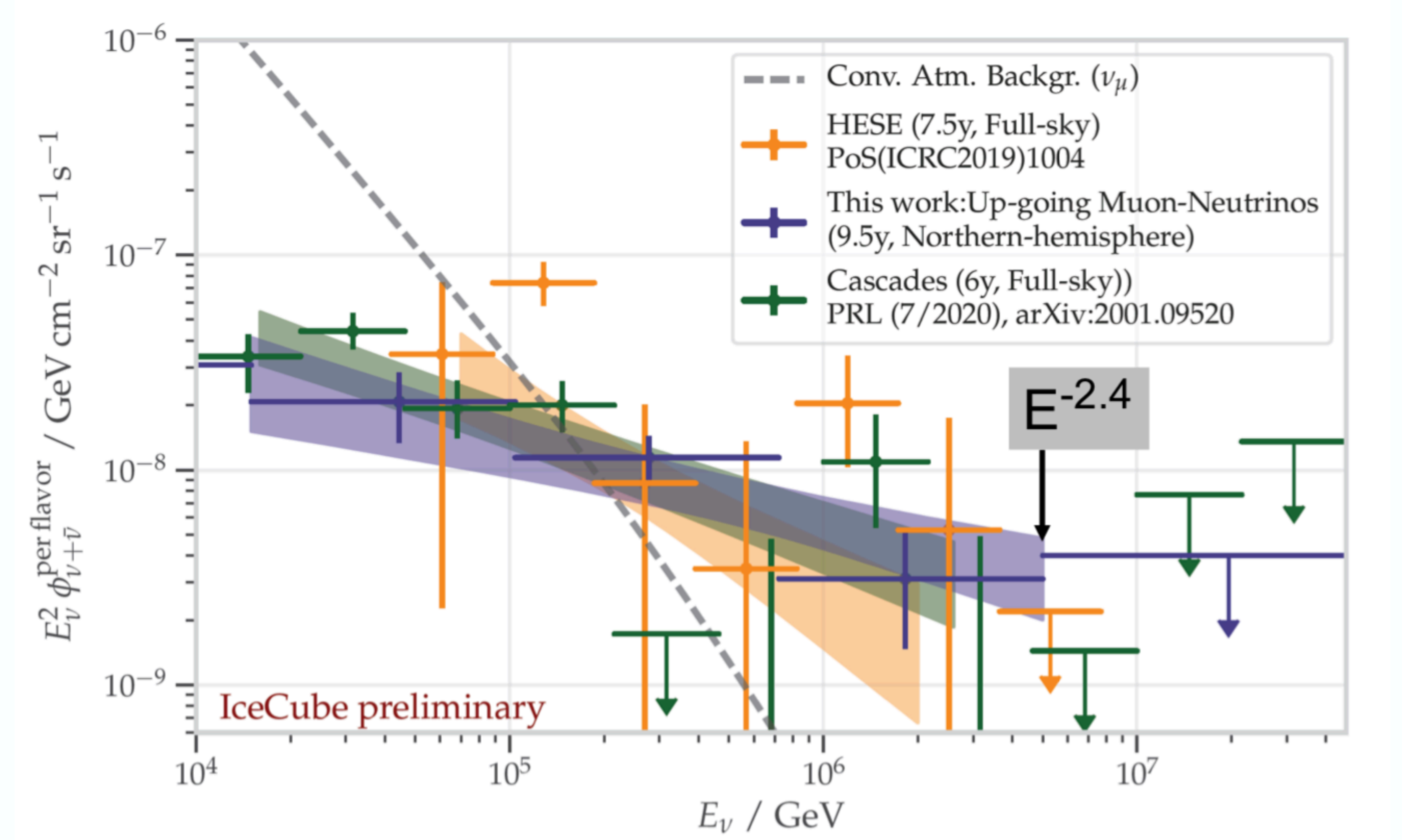
KM3NeT/ORCA

Proposed detector & performances

Expected Sensitivity & first results

Summary of recent IC results

Halzen, NT conference 2021



Indication of spectral break (different energy thresholds) ?

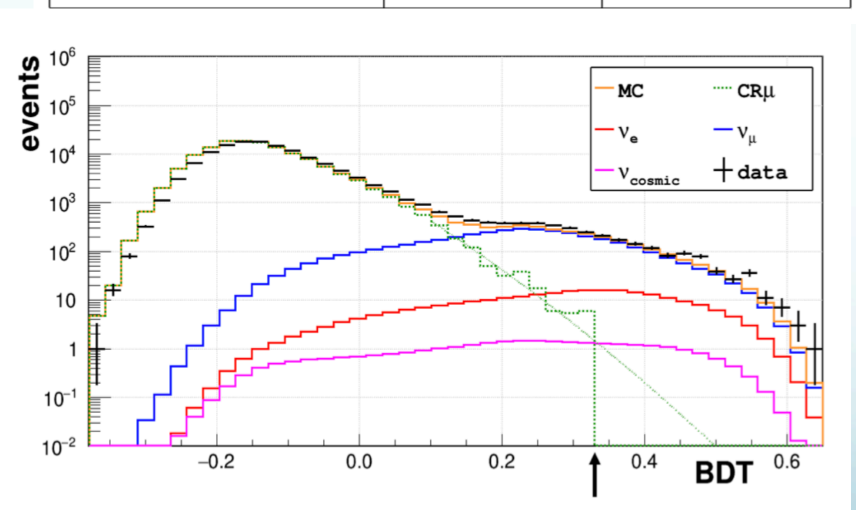
Indication of galactic and extra-galactic contributions (different hemispheres) ?

Atmospheric neutrinos

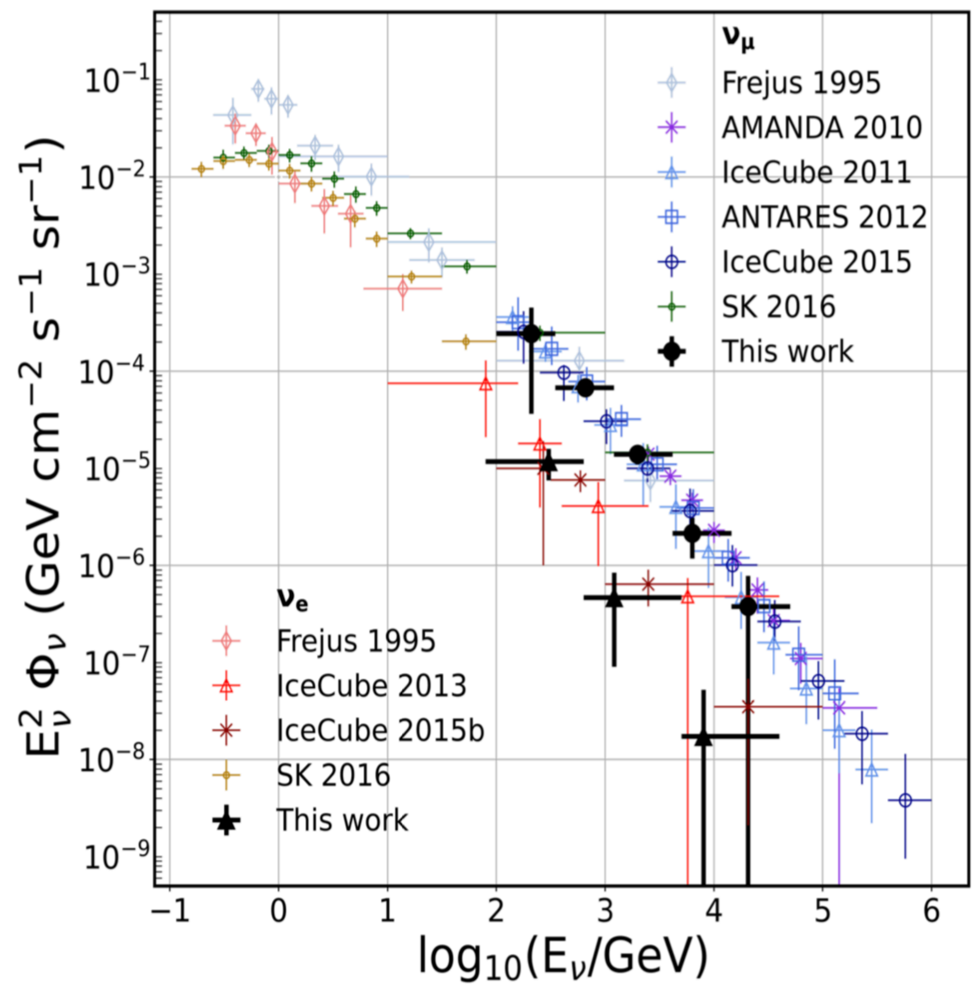
Data collected from 2007 until the end of 2017

BDT selection on 15 parameters

	Preselection $+ \Lambda > -5.7$	$+\mathrm{BDT} > 0.33$
CRμ	136700	$\sim$3
Atmospheric ν_e CC	242	96
Atmospheric ν_e NC	22	9
Atmospheric ν_μ CC	3780	620
Atmospheric ν_μ NC	400	180
Cosmic ν	30.4	9.2
MC sum	141200	917
Data	133676	1016



Unfolded spectrum



📖 Phys. Lett. B 816 (2021) 136228

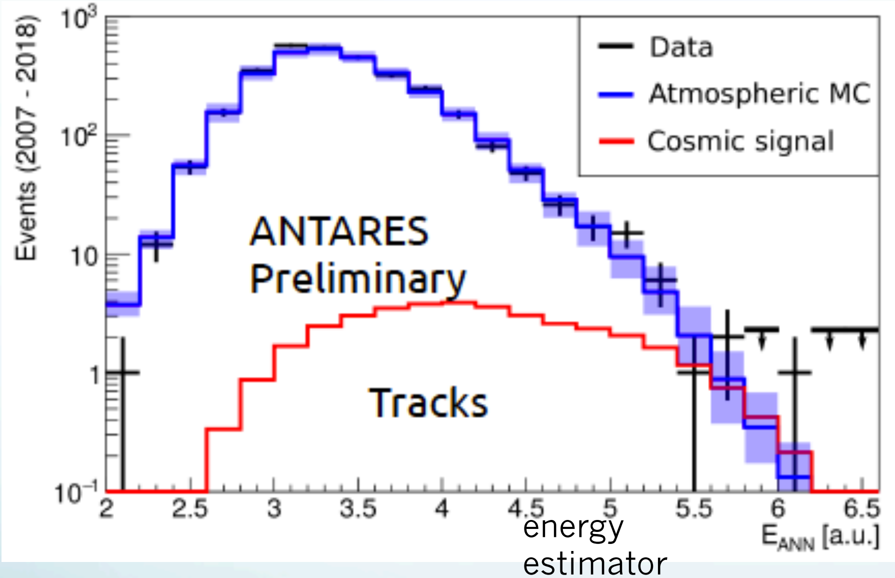
Worldwide consistent results

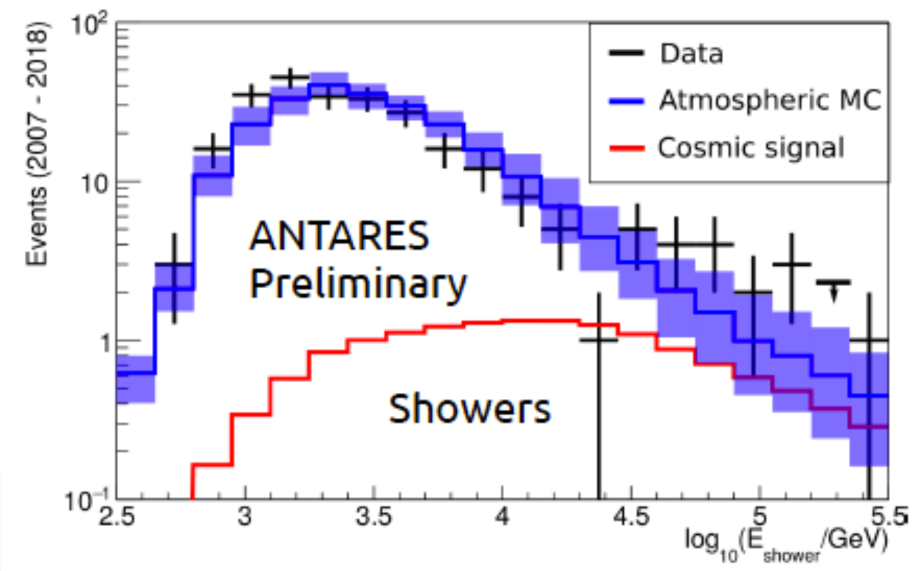
Diffuse flux

Updated data sample @ ICRC2019: 2007-2015 (2450 days) → 2007-2018 (3330 days)

All-sky / All-flavor neutrino search

- Selection cuts optimized with MRF procedure (assumed spectral index $\Gamma = 2.5$)
- Look for excess above a given E_{th}
- Combine track & shower samples





Data: 50 events (27 tracks + 23 showers)

Background expectation (atm. flux, HONDA + Enberg, scaled x ~1.25) :
36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

Results not really constraining… but fully compatible with IceCube

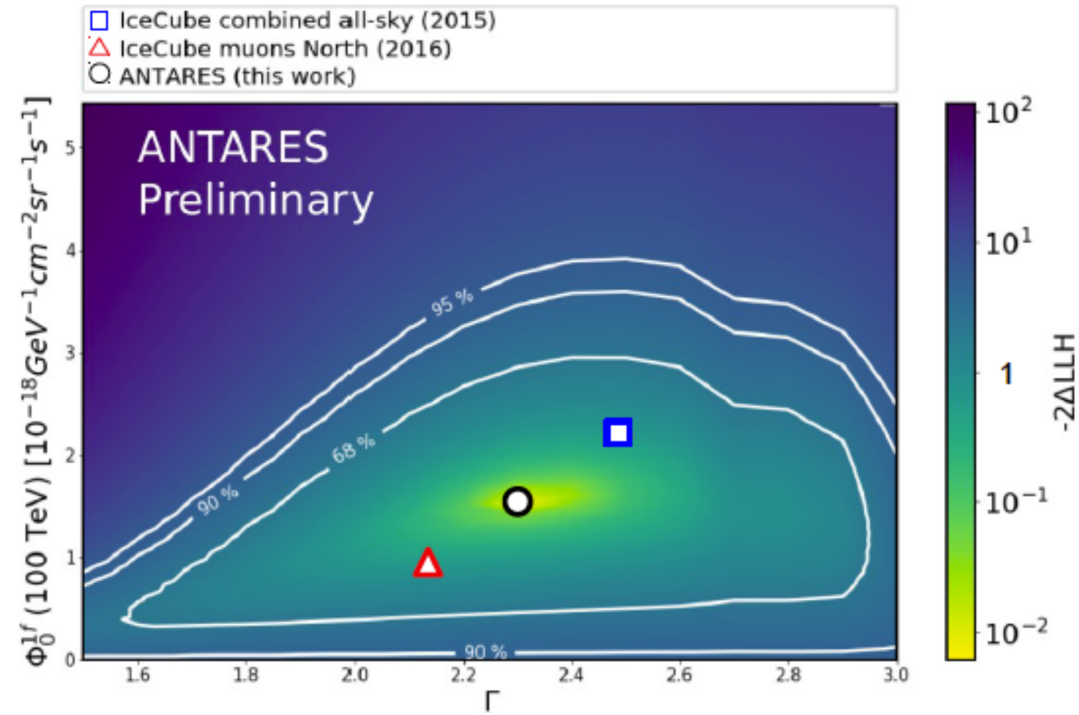
Diffuse flux

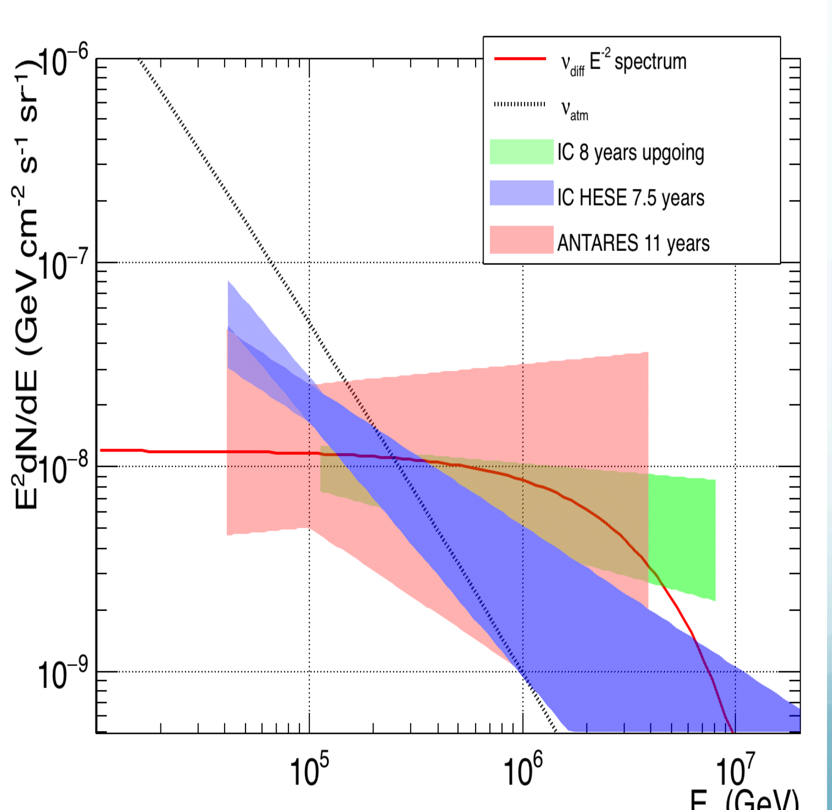
Combined (tracks+showers) likelihood fitting:

Atmospheric: $\Phi_{atm} = 1.25 \times (\mathrm{Honda} + \mathrm{Enberg})$

Cosmic: $\Phi_{100\ \mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$

$\Gamma = 2.3 \pm 0.4$



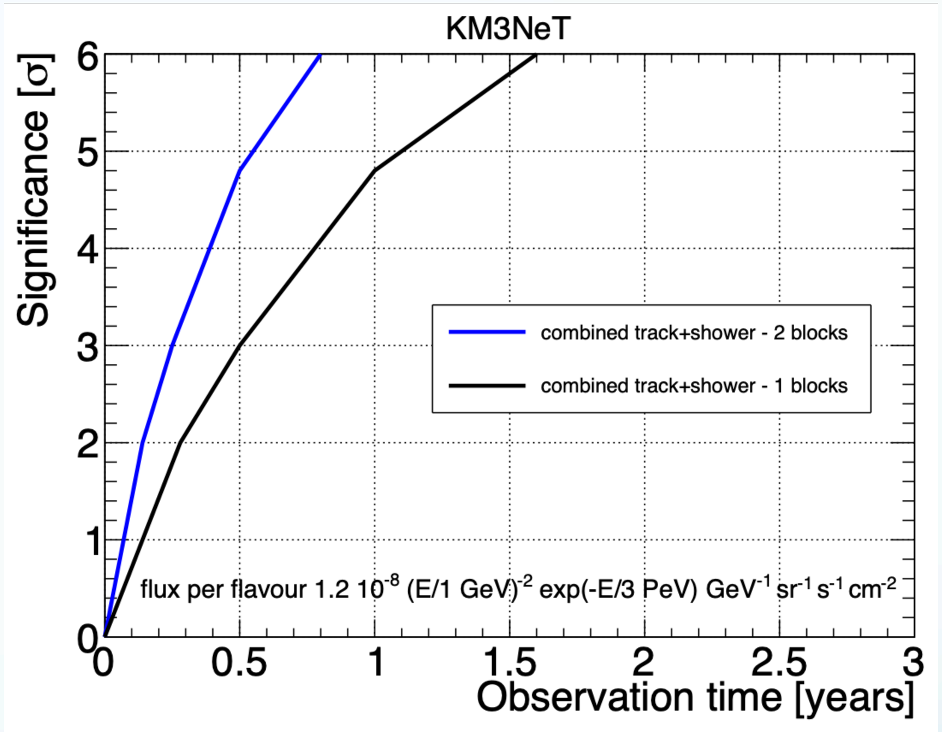


Results not really constraining... but fully compatible with IceCube

KM3NeT-ARCA sensitivity

- **Track channel**
  Analysis for up-going events based on maximum likelihood
  Pre-cuts on q_{zen} >80°, reconstruction quality parameter and N_{hit} (proxy for muon energy)

- **Cascade channel**
  Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)
  All sky analysis based on BDT and maximum likelihood.



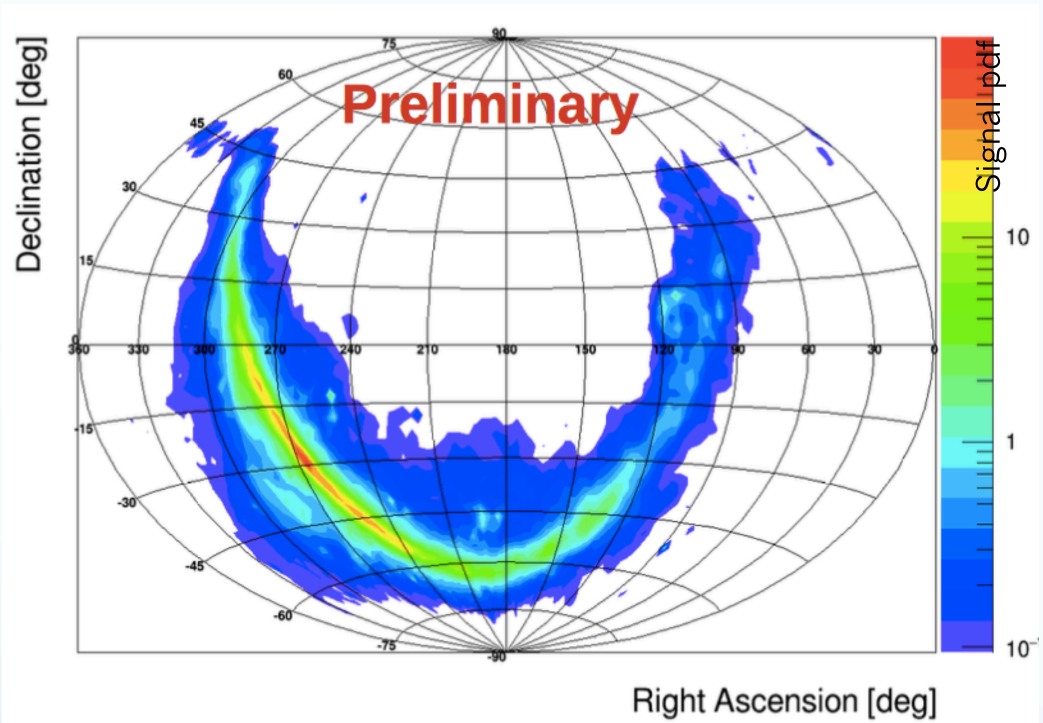
📖 Astrop. Phys. 111 (2019) 100 -110

KM3NeT can observe (3 σ) IceCube signal in 3 months and confirm it (5 σ) in six months

High resolution follow-up and e.g. flavour composition

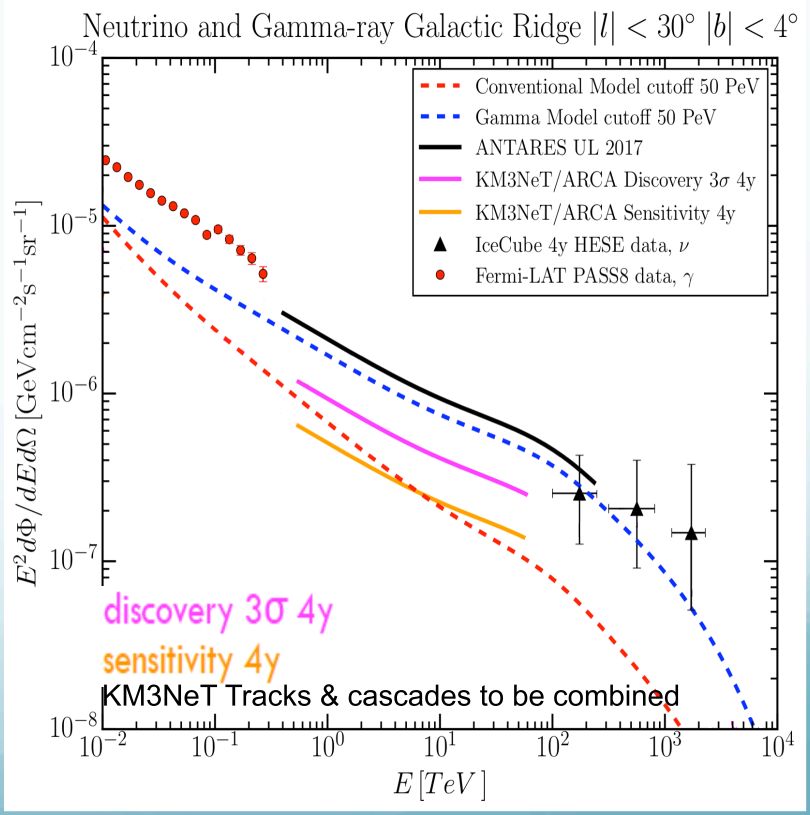
Focus on the Galactic Plane

📖 Phys. Rev. D 96, 062001 (2017)



- ANTARES Limit is a factor 1.2 above the 'KRAγ' model.
- Combination with IC ongoing

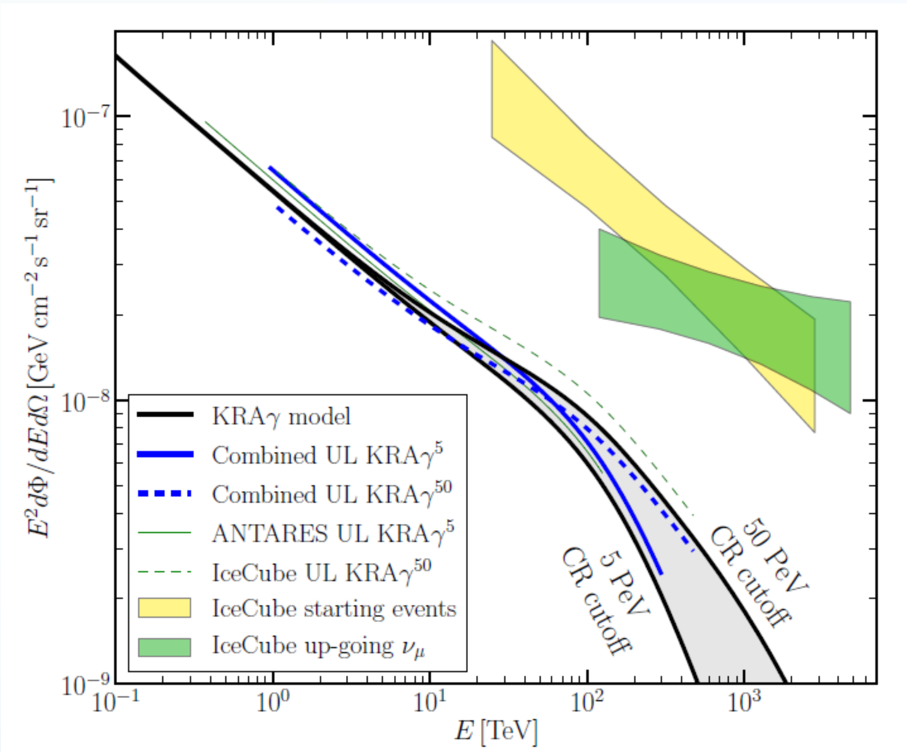
- KMNeT sensitivity promising.



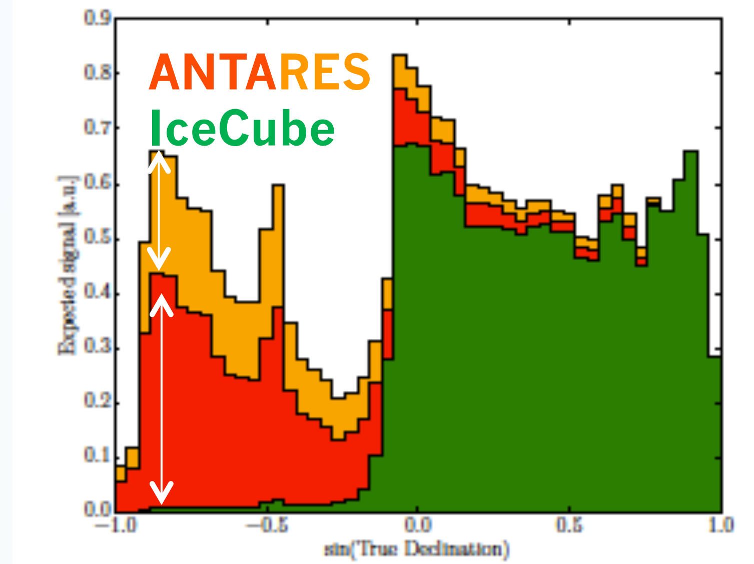
- Guaranteed galactic neutrinos from CR interactions with matter
- Does it contribute to IC flux ?
- Test 'KRAγ' model reproduce Fermi & Milagro data.
- Analysis uses full model morphology & spectrum – tracks and cascades

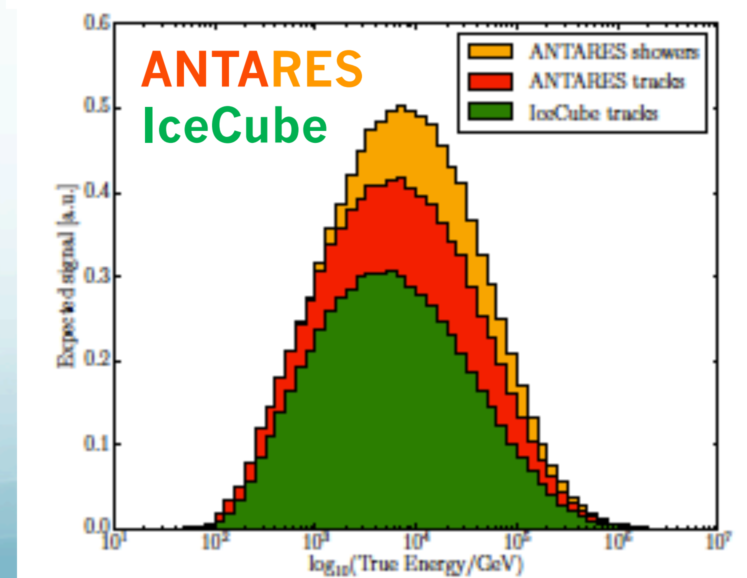
Focus on the Galactic Plane

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5-50 PeV cutoff)



Stacked expected signal vs. δ (top) and energy (bottom). Colors relative contribution to the sensitivity

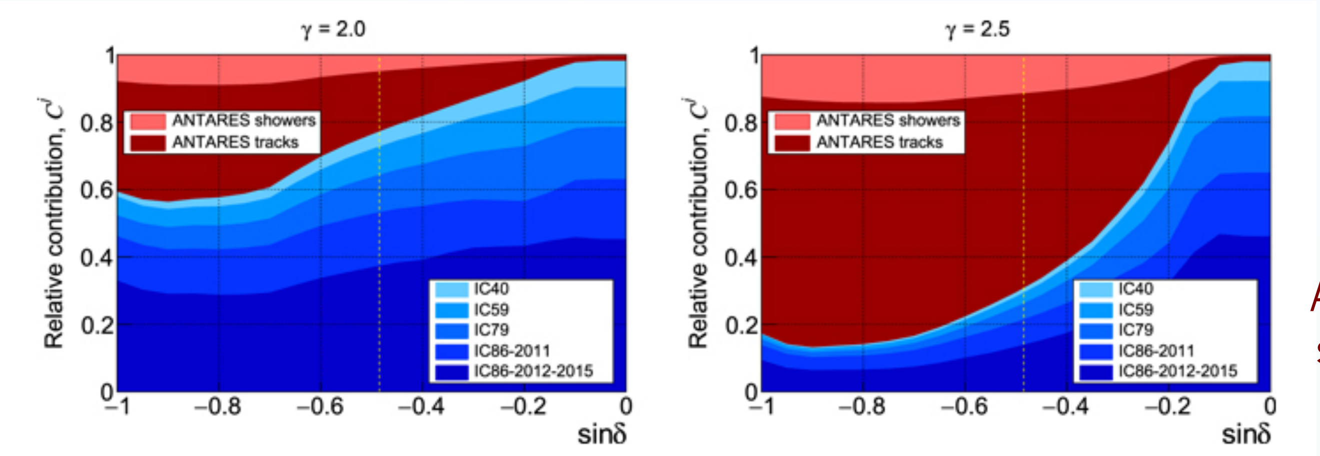




Result: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC astrophysical signal* (E_ν> 30 TeV)
Updates desired...

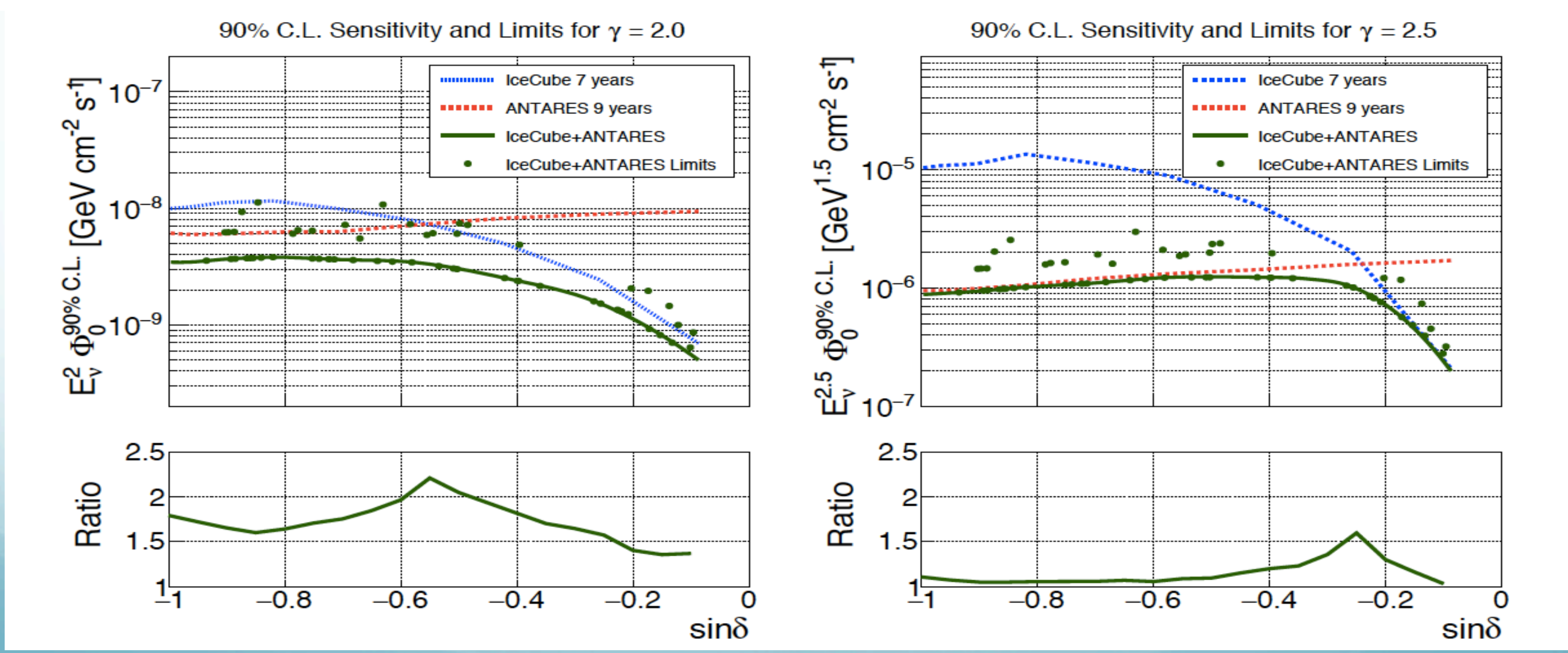
📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018)

Joint ANTARES-IceCube search



Fraction of signal events which would be detected by each sample ($E^{-\gamma}$)

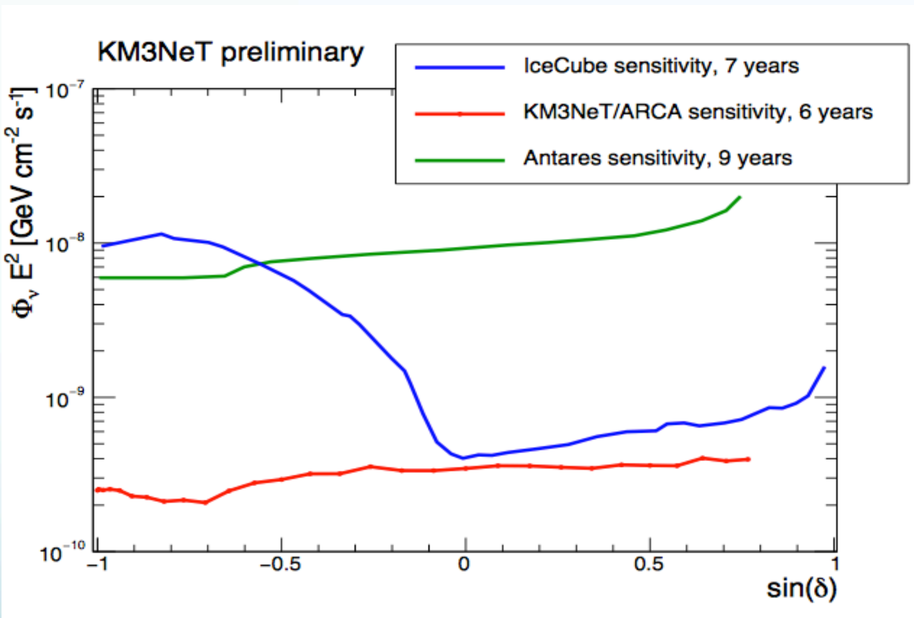
ANTARES data set is public : see https://antares.in2p3.fr

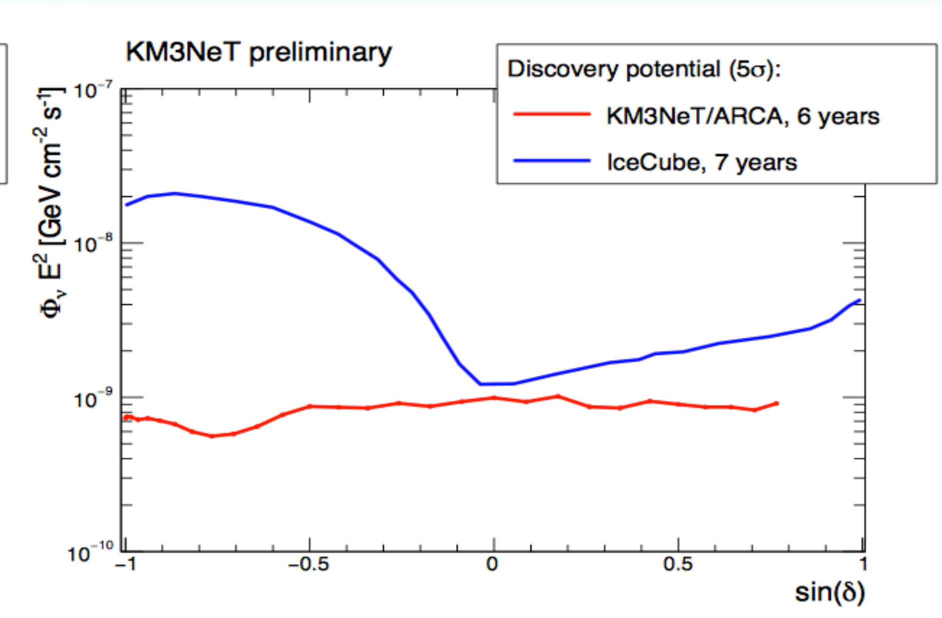


Prospect for KM3NeT-ARCA

Sensitivity | Discovery potential

(E^{-2} Spectrum)





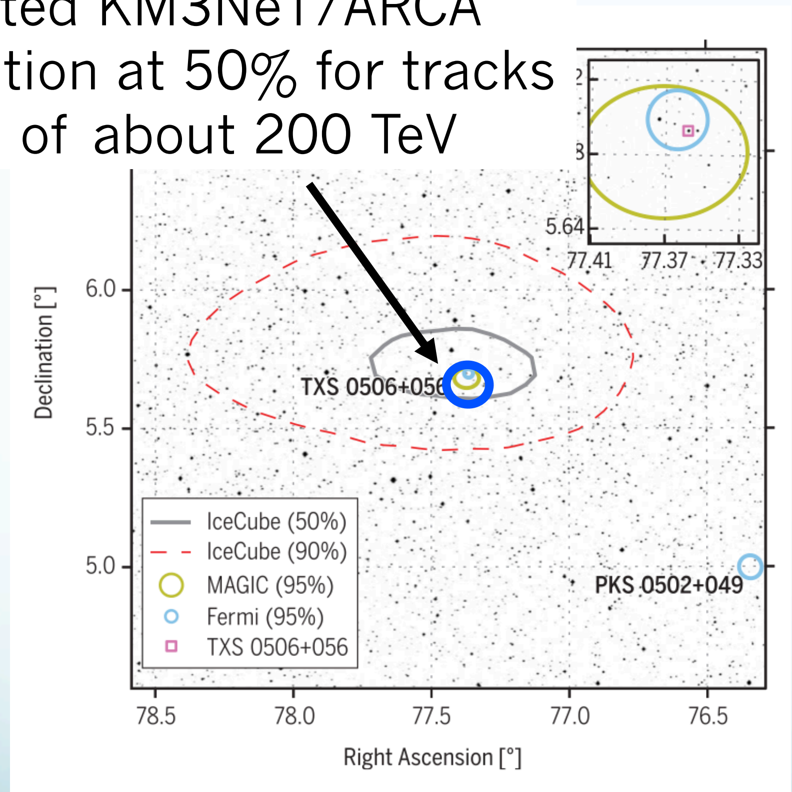
Only up-going track events

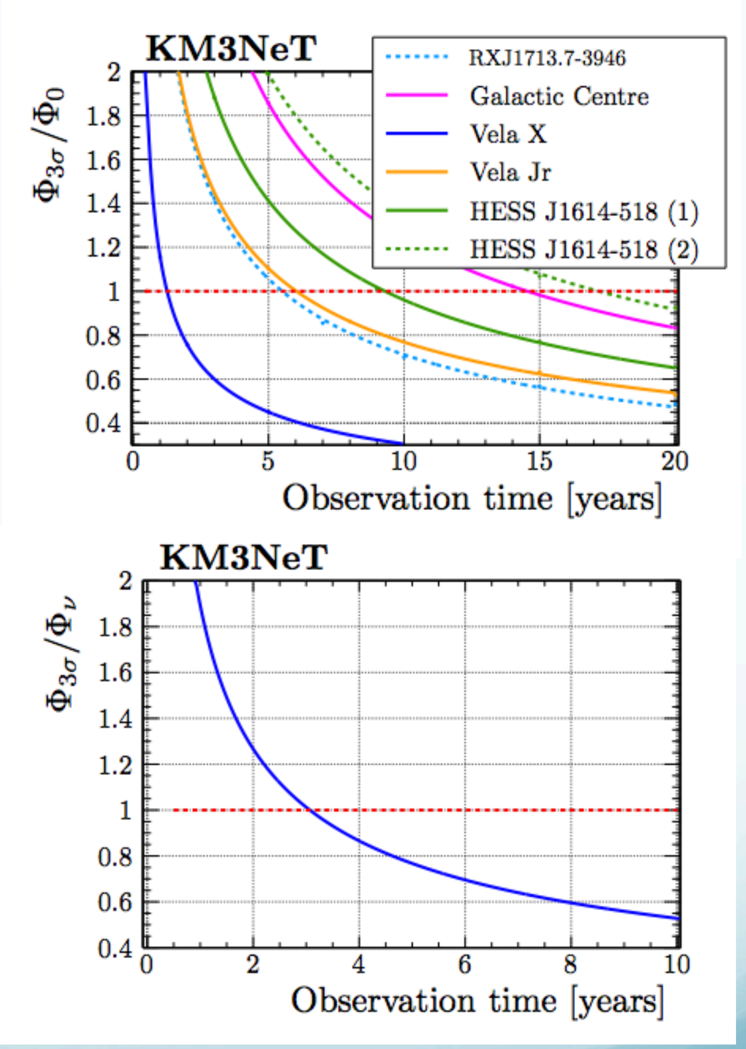
estimated contribution from cascades ~ 20%

More than order of magnitude improvement in Southern Hemisphere

Prospect for KM3NeT-ARCA

Expected KM3NeT/ARCA resolution at 50% for tracks for E_ν of about 200 TeV





Stacking Vela Jr and RX J1713.7-3946

👉 3σ significance within 3 years.

Directly constrain (or discover) hadronic scenario in galactic TeV gamma sources

ANTARES Catalog-based searches

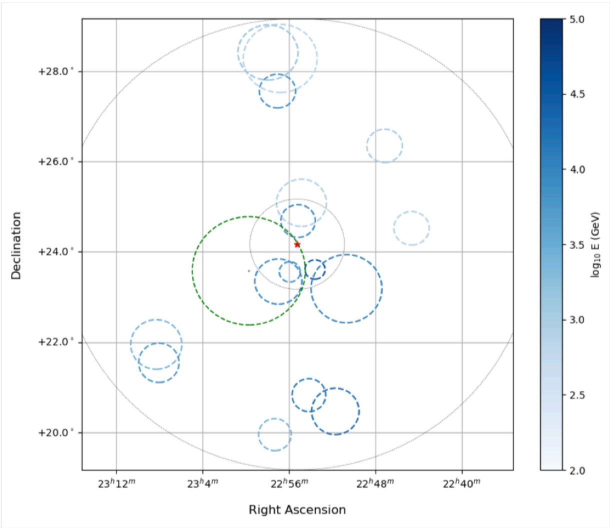
Likelihood based stacking approach

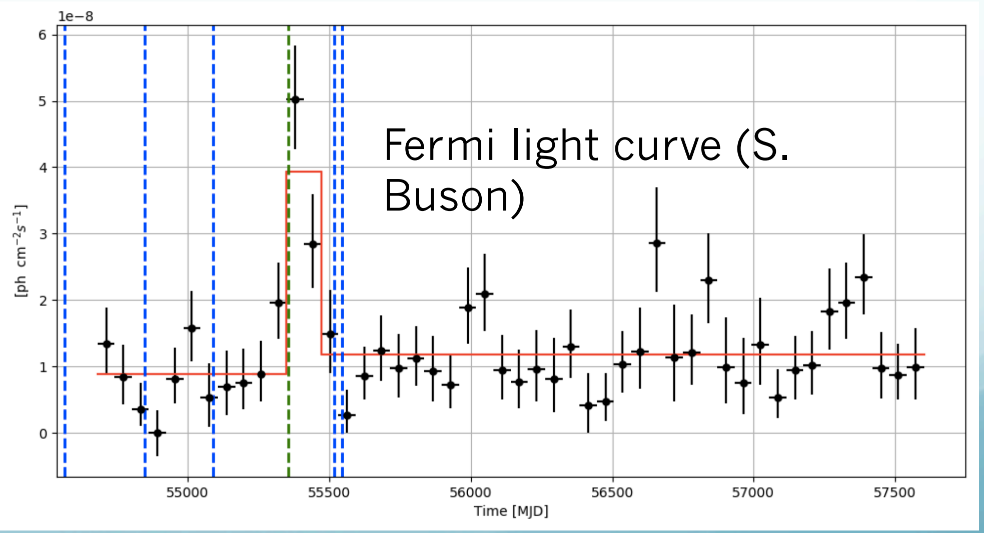
CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	**0.088**	**0.64**	**MG3J225517+2409**
Radio-galaxies	**$4.8\ 10^{-3}$**	**0.10**	**3C403**
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

0.10 → $1.6\ \sigma$

Mild excess seen for radio galaxies

Blazar MG3 J225517+2409
ANTARES & IceCube tracks





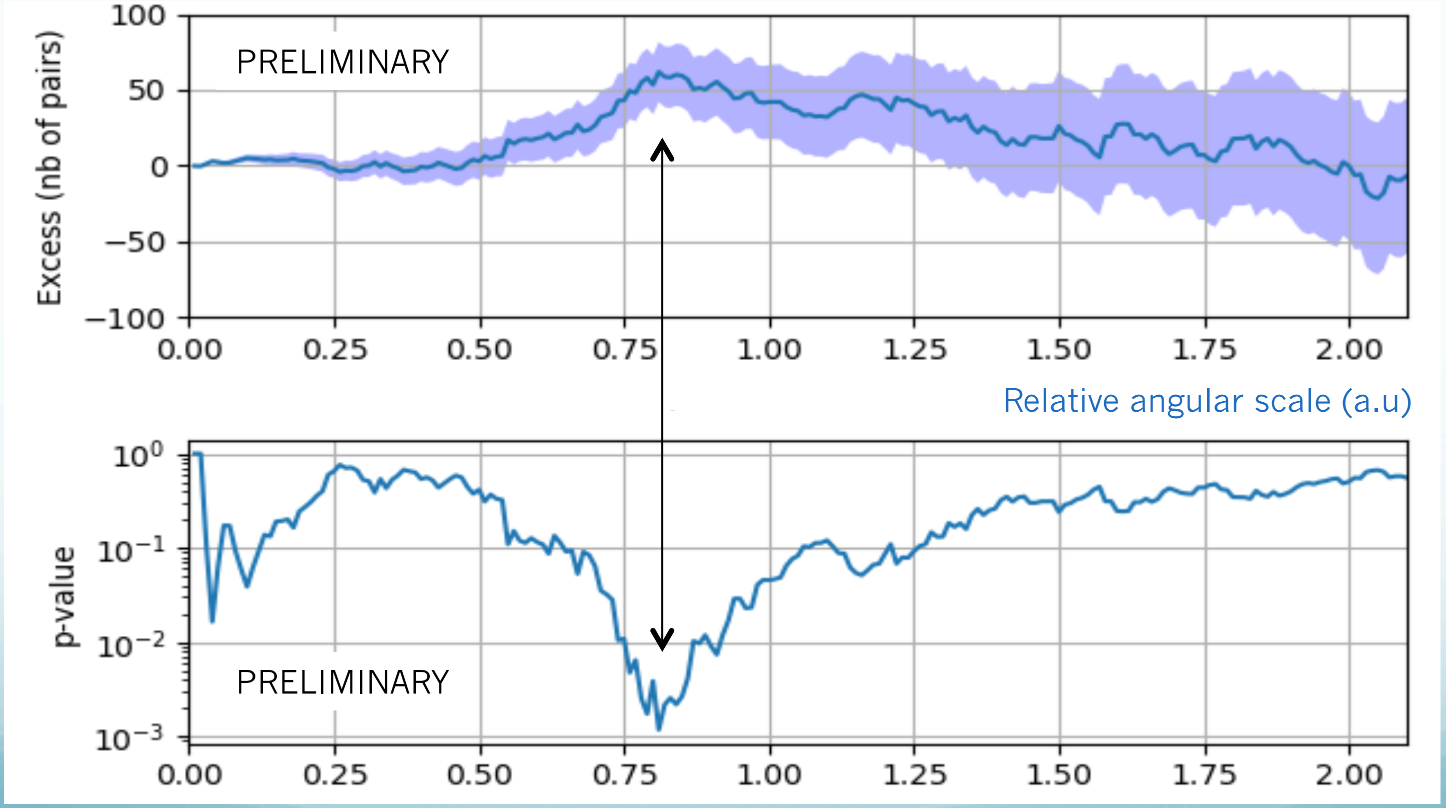
Space-time association: ANTARES -> **2.3σ** & IceCube track -> **2.6σ**

Catalog-based searches

PRELIMINARY !

- Following 📖 A. V. Plavin *et al* 2021 *ApJ* **908** 157, ongoing search for correlation between neutrino candidates and radio blazars seen in VLBI data (3411 objects)
- Use the ANTARES PS sample 2007-2020 (10162 tracks) with same stacking method yields a p-value of $8.3\ 10^{-2}$ (about 1.8 σ)

- Simple pair counting also shows hint of correlation at sub-degree angular scale

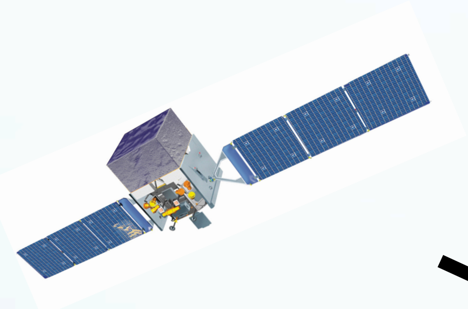


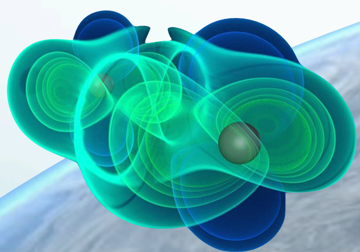
Stay tuned for updated results in summer conferences !

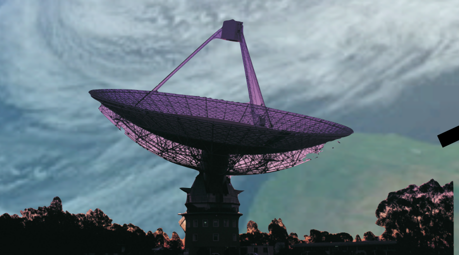
The multi-messenger endeavor

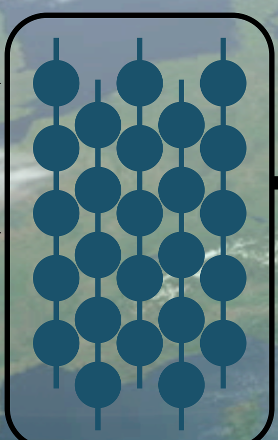
1ST APPROACH:

Time dependent searches









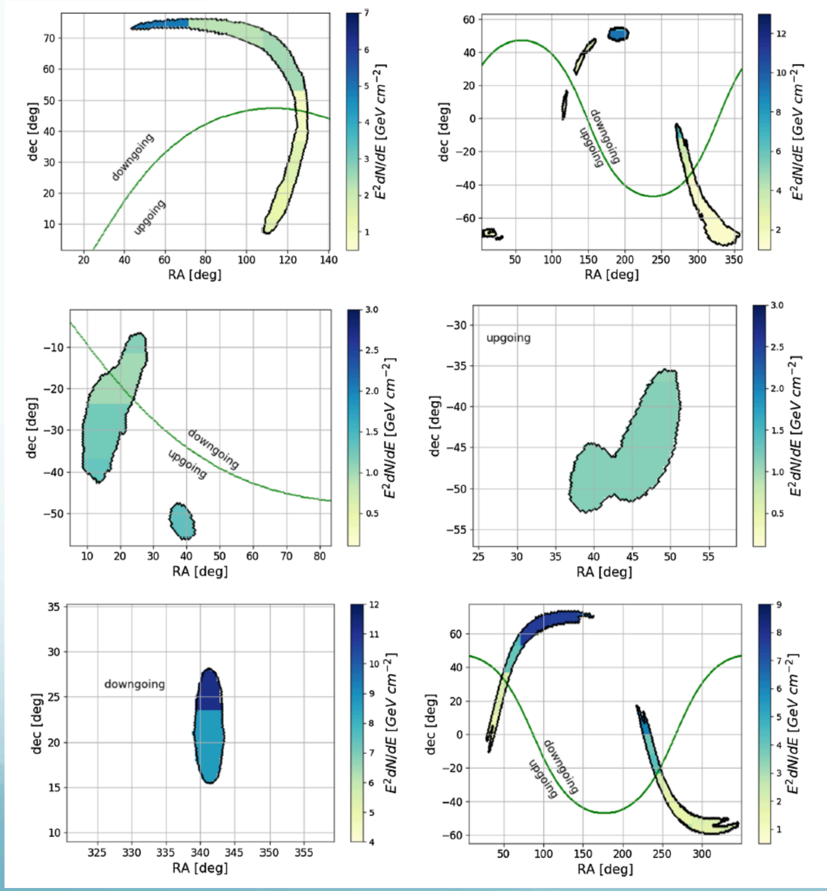
GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts

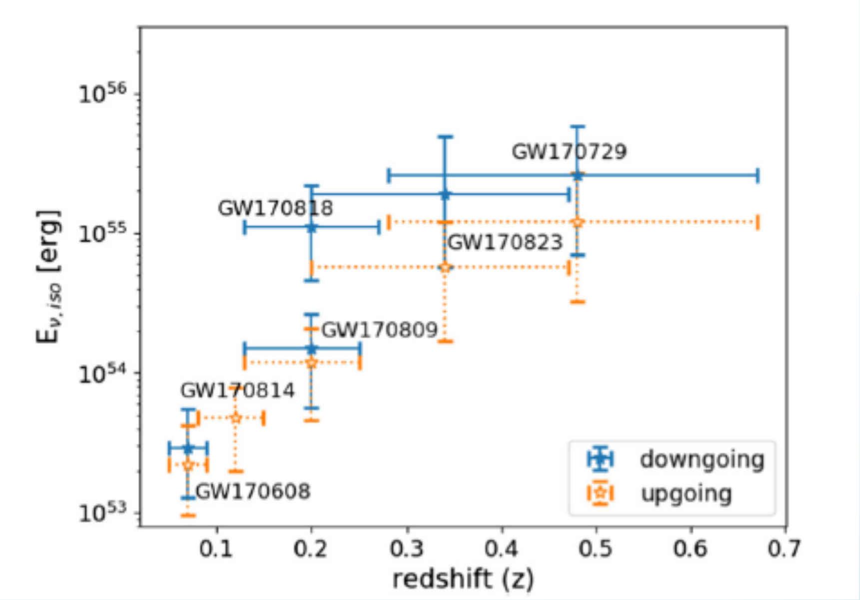
First joint search for neutrinos and GW prior to discoveries (2007 data)

📖 JCAP06 (2013) 008

Follow-up of Gravitational Waves

- Online alerts followed. Results from counterpart searches after 24hr through GCN
- Refined offline searches (fully calibrated sample): No events found → limits set.
- Latest O2 BBH: Constraints on fluence and $E_{\nu,\mathrm{iso}}$ for BBH



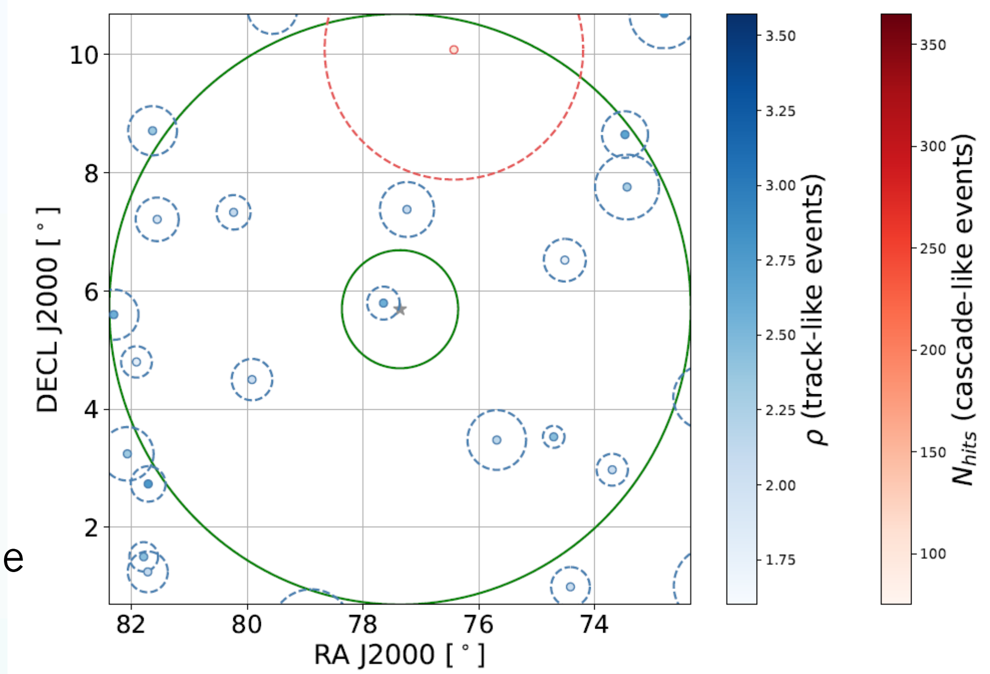


📖 Eur. Phys. J. C 80, 487 (2020)
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 022005
📖 Phys. Rev. D 93 (2016) 122010
📖 JCAP06(2013)008

Search for neutrinos from TXS 0506+056

Time integrated archival search

- Same method as PS searches, +2016/17
- Expected background (3136 days) :
  - 0.23/deg² for track-like
  - 0.005/deg² for shower-like events
- # of events fitting the likelihood signal function for the source: μ_{sig} **= 1.03**
- **Pre-trial p-value of 3.4%** (post-trial 87%)
- 1 track (12/12/2013) 0.3° from the source
- Flux U.L. (@100 TeV) for E^{-2}: 1.6×10^{-18} GeV^{-1} cm^{-2} s^{-1} in the range [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have a smaller p-value

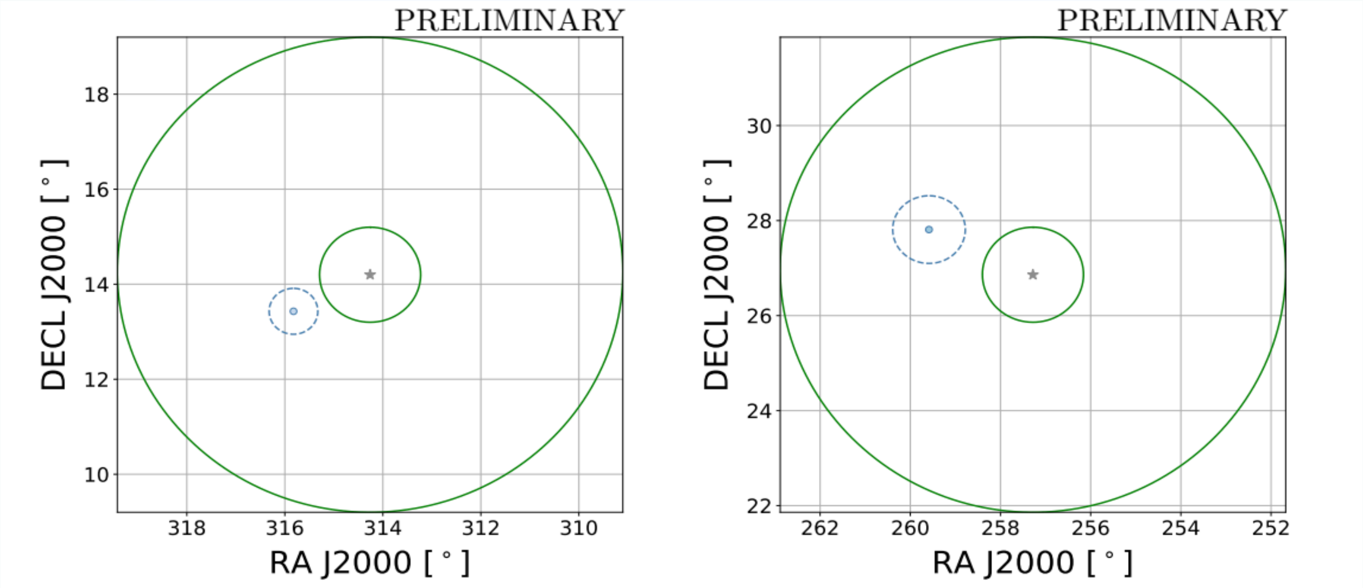


Distribution of the 13 tracks +1 shower events in the (RA,δ) coordinates around (radius=1° and 5°) the position of TXS 0506+056.

ApJL 863, L2 (2018)

Search for ν counterparts to TDE events

IC191001A & AT2019 dsg IC200530A & AT2019 dsg



arxiv:2103.15526

Source		Results						
Name	γ	$\hat{\mu}_{\rm sig}$	p-value	$\Phi_0^{90\%\rm C.L.}$ sensitivity	$\Phi_0^{90\%\rm C.L.}$ limit	$\mathcal{F}^{90\%\rm C.L.}$ sensitivity	$\mathcal{F}^{90\%\rm C.L.}$ limit	$\log(\frac{E_{\rm min}}{\rm GeV})$ - $\log(\frac{E_{\rm max}}{\rm GeV})$
AT2019dsg	2.0	< 0.1	12%	7.3×10^{-8}	1.0×10^{-7}	14	19	3.6 - 6.6
	2.5	0.2	10%	1.5×10^{-5}	2.2×10^{-5}	29	43	2.8 - 5.5
	3.0	0.7	8.9%	1.2×10^{-3}	2.0×10^{-3}	230	380	2.1 - 4.7
AT2019fdr	2.0	0.5	6.7%	8.5×10^{-8}	1.3×10^{-7}	15	23	3.6 - 6.6
	2.5	0.5	7.9%	2.1×10^{-5}	3.0×10^{-5}	39	55	2.8 - 5.5
	3.0	0.6	9.1%	2.0×10^{-3}	3.0×10^{-3}	360	540	2.1 - 4.7

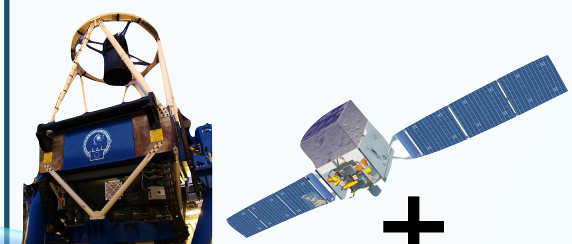
The multi-messenger endeavor

Telescope-Antares Target of Opportunity
(TatoO)

2ND APPROACH:

Alert triggering

Real-time analysis

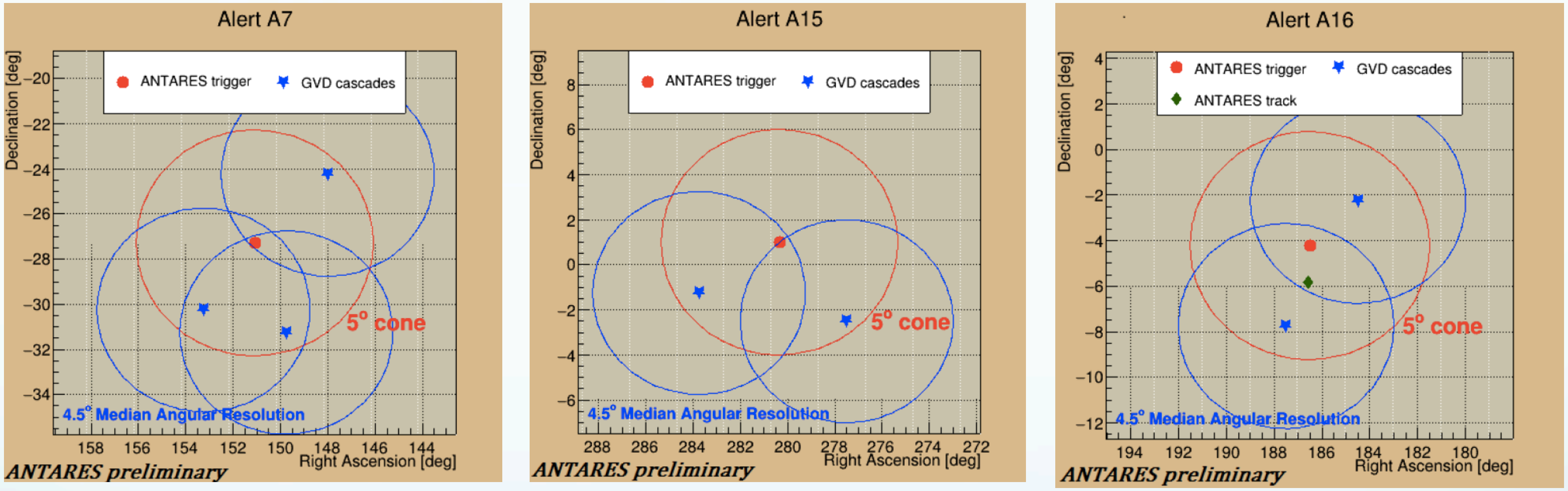


- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction, multiplets

GVD Baikal follow-up of ANTARES alerts

38 ANTARES alerts sent to GVD Baikal, 32 followed up:
Search within ±500s, ±1hour, ±1 day within 5 degree
(cascade median resolution 4.5 degrees)

=> For 3 alerts multiplets of cascades reconstructed within ±1day



5 GVD clusters running during that period
Background events/cluster/day ranging from 0.02-0.05

No additional tracks or showers seen offline in ANTARES for that same direction within ±1 day

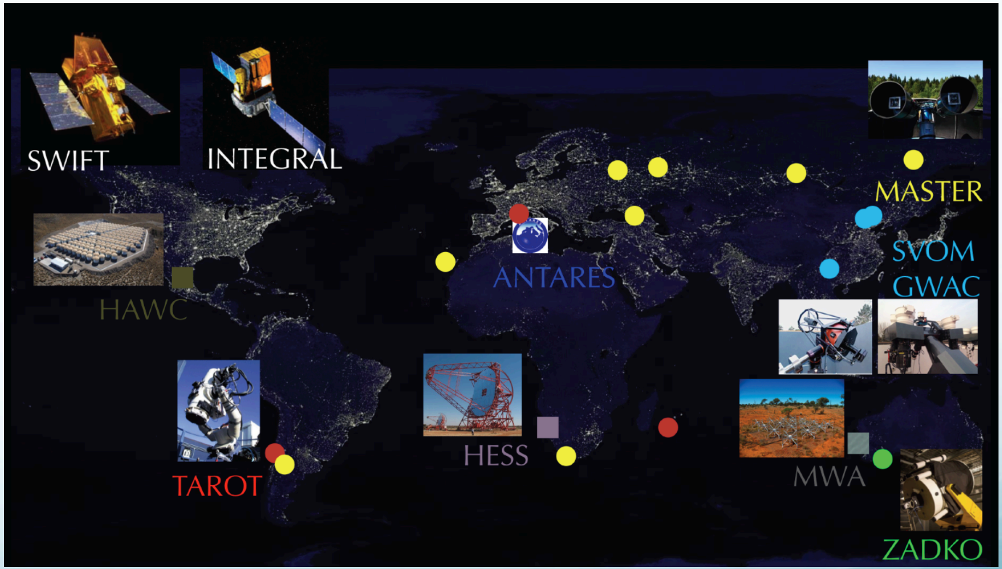
TATOO and the transients

MNRAS, 48 (2019) 1
ApJ, 886:98 (2019)

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA (12/yr)	**TAROT ZADKO MASTER (GWAC) (30/yr)**	**Swift (6/yr) Integral**	**Fermi (offline)**	**HESS (2/yr) HAWC (offline)**

Triggers:

- Doublet of neutrinos (<3°, <15 min): ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 events/ yr
- Single VHE neutrinos: ~30 TeV, ~3-4 events/ yr



Performances:

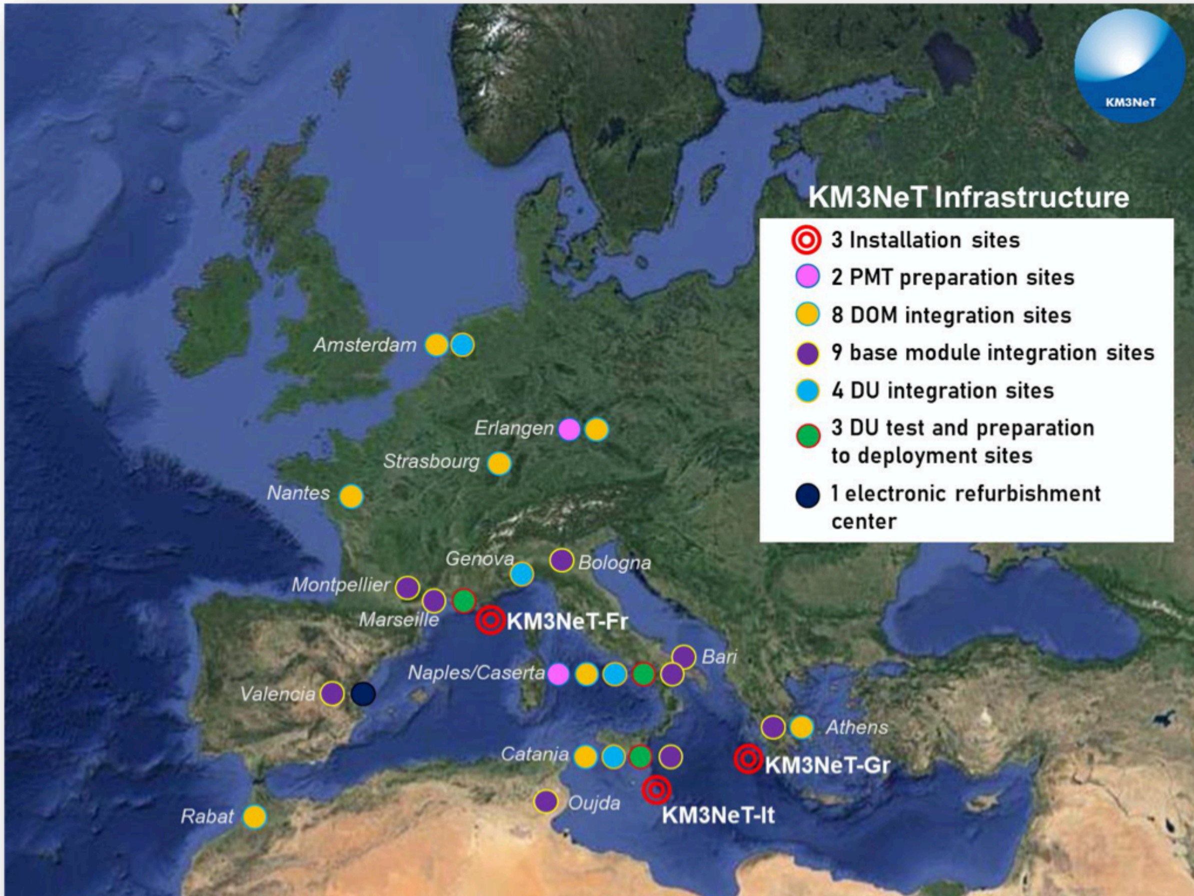
- Time to send an alert: ~5 s
- Median angular resolution: ~ 0.4°

Sent neutrino alerts (2009-2020)

322 to robotic telescopes
+26 to Swift
+12 to INTEGRAL
+~25 to MWA
+2 to HESS

Follow-up efficiencies: ~70% (X-ray / optical) + ~20% (radio)

What's next: KM3NeT



DOMs:

- 8 integration sites
- 640 DOM produced (400 ARCA,240 ORCA)
- 100 currently in progress

BMs:

- 9 integration sites
- 27 BMs produced
- 6 currently in progress

DUs:

- 5 integration sites
- 13 DUs produced
- 8 currently in progress

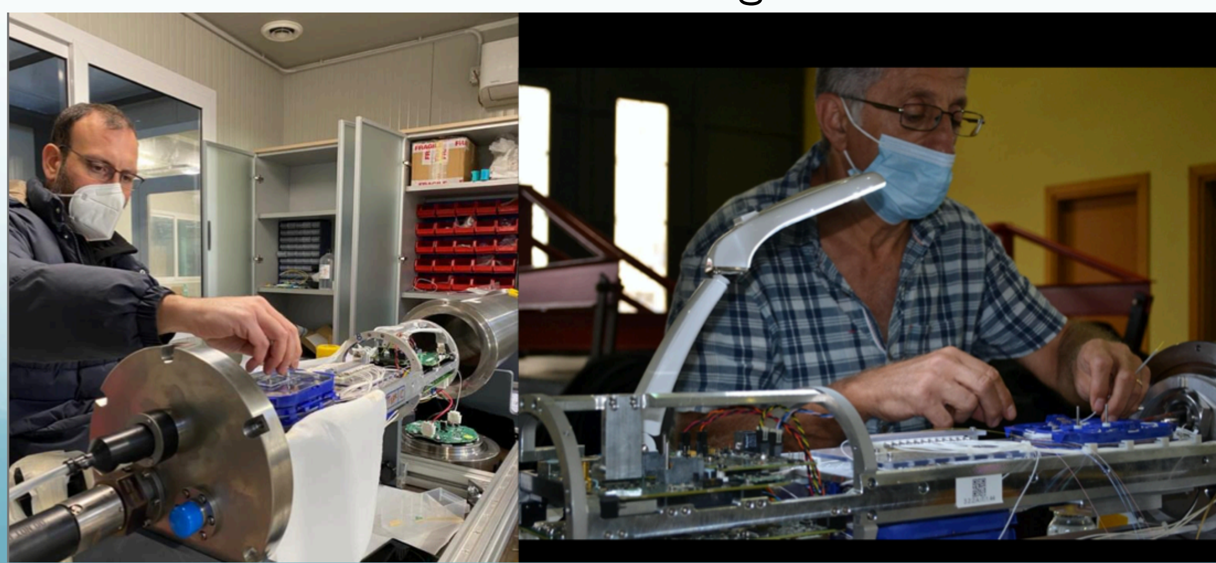
Total:22 integration sites!
(last year:15)

Despite pandemic big efforts are on going in the detector construction

Integration efforts

DOM integration

Base Module integration



Integration efforts

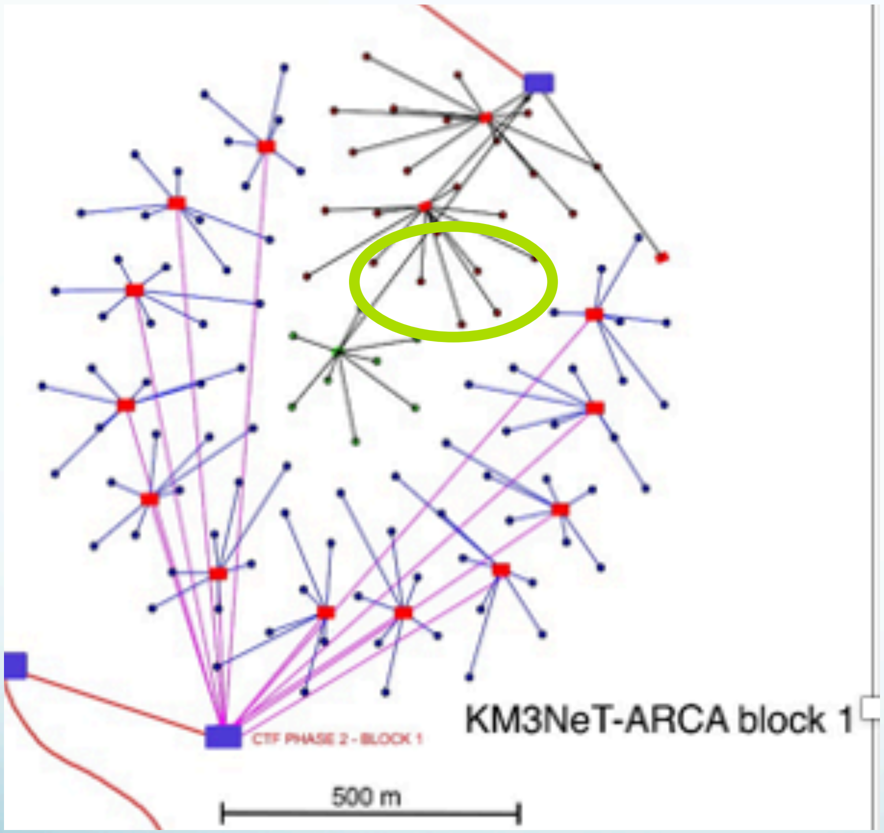
DU integration

Deployment Procedure

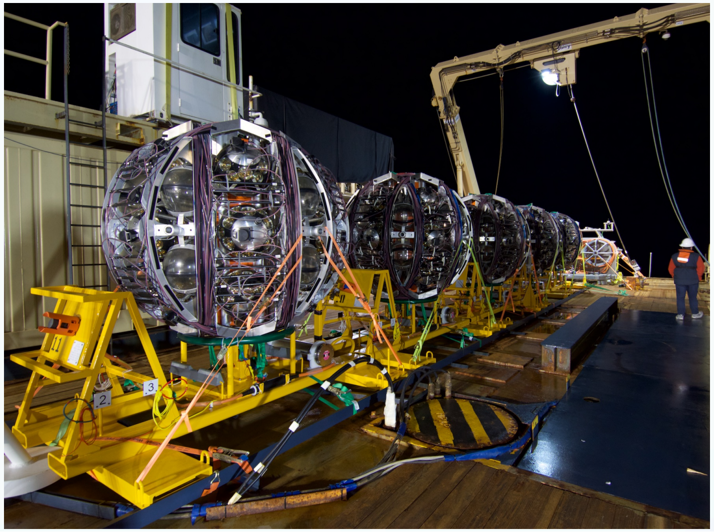
Actually 1st ORCA string here

KM3NeT/ARCA status

8-15 April 2021 👉Successful deployment of 5 DUs and 1 JB
6 DUs now in operation (1 DU deployed in Dec 2015 and still in operation)



5 DUs on deck before deployment

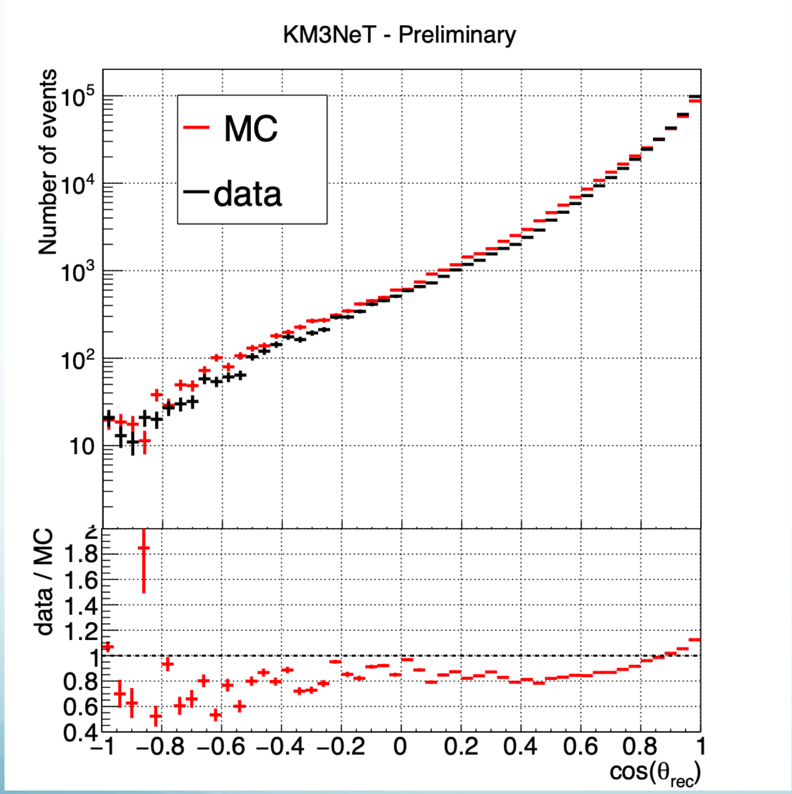


Commissioning phase over
Stable data taking from 13-May

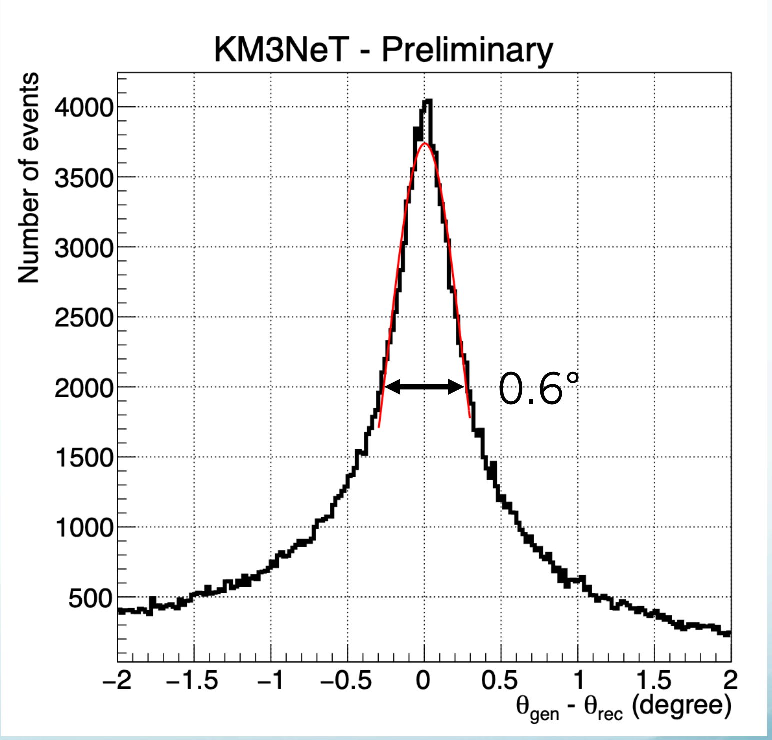
ARCA6: first results

After about 1 month from deployment:

- First time/position calibration already set up
- First run-by-run MC

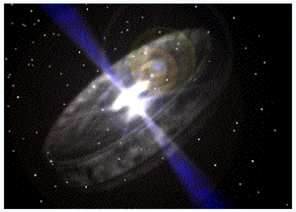


Reasonable agreement data/MC



Zenith angular resolution 0.6° (FWHM)

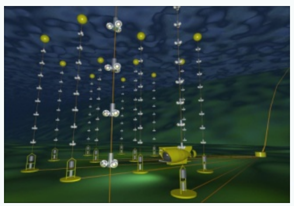
Outline

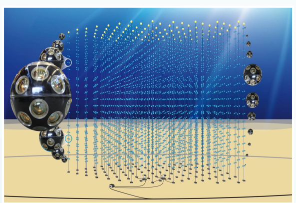


The High-Energy Physics Case – The cosmic endeavour

Historical aspects & Scientific motivations

Detection principles & Performances





Status of ANTARES and KM3NeT/ARCA

Selected results in today's context

Prospects

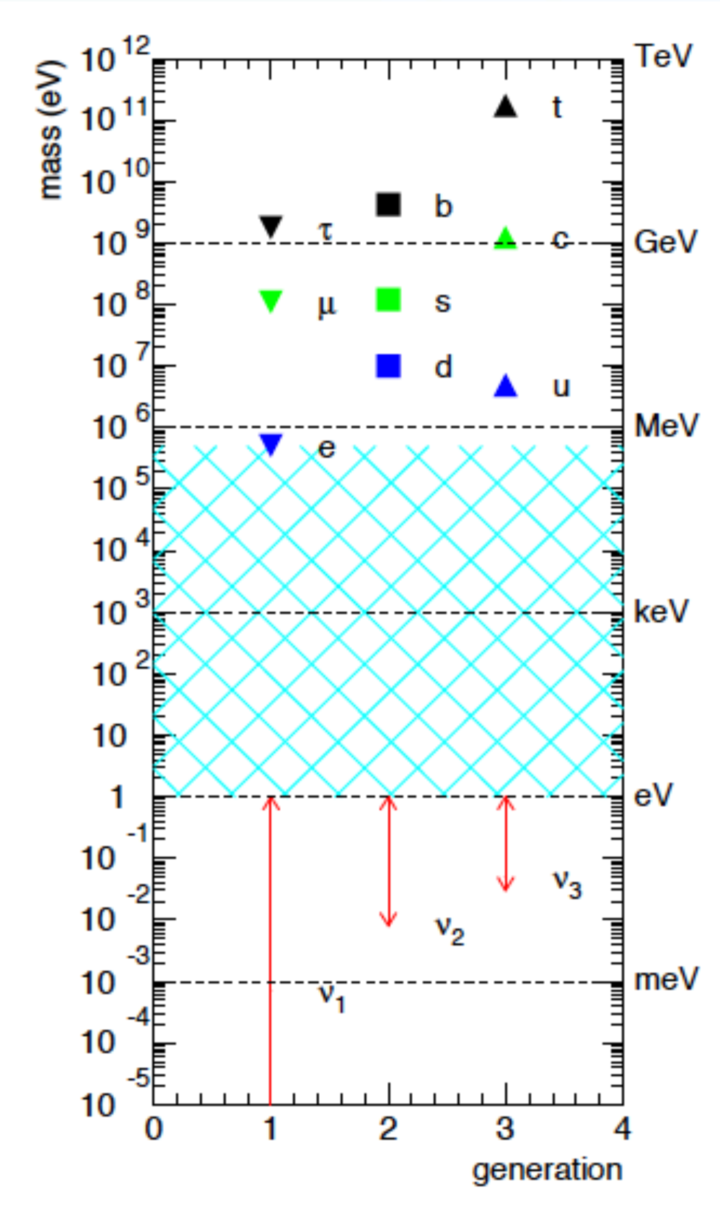
The Low-Energy Physics Case – A new endeavour

KM3NeT/ORCA

Proposed detector & performances

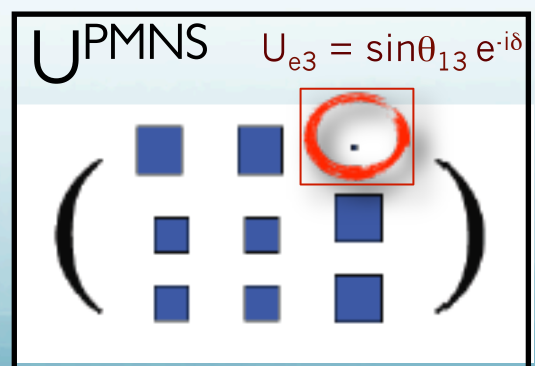
Expected Sensitivity

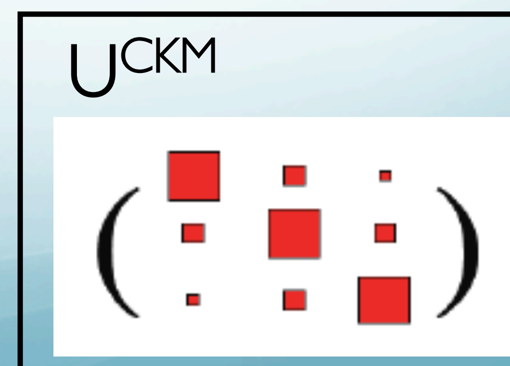
Massive neutrinos



- Neutrinos have distinct masses => why so light?
- Often considered as first evidence of physics beyond the Standard Model. Are neutrinos fundamentally different from other particles?
- Neutrinos mix like quarks ⟹ why so similar/different?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





Oscillations of Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric
θ_A~45°

Reactor
θ_{13}~9°
↓
CP violating phase δ_{CP}

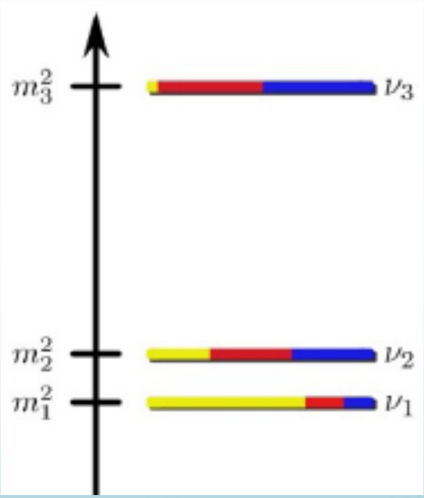
Solar
$\theta_\odot$~30°

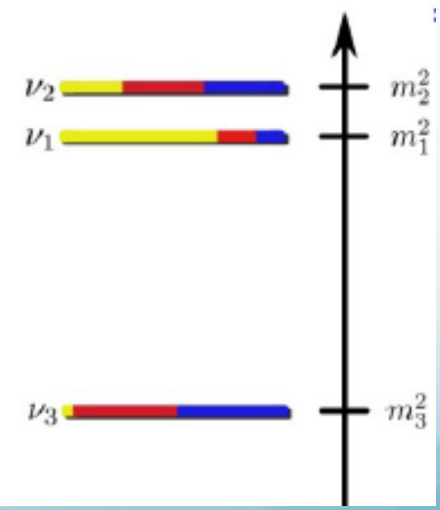
Majorana

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

All parameters measured to fair precision except:
<u>mass hierarchy</u>
octant of θ_{23}
CP phase

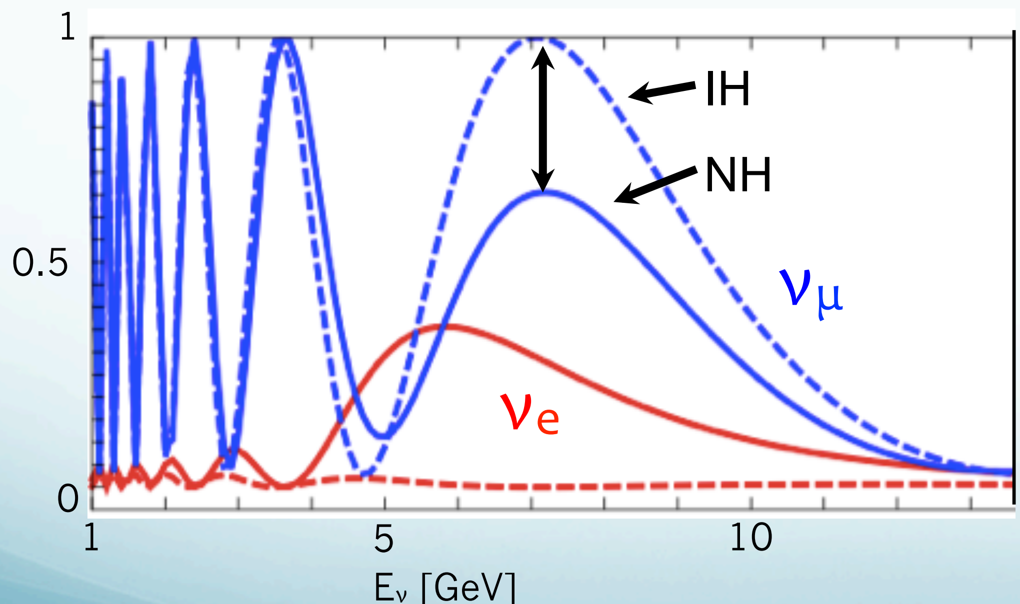


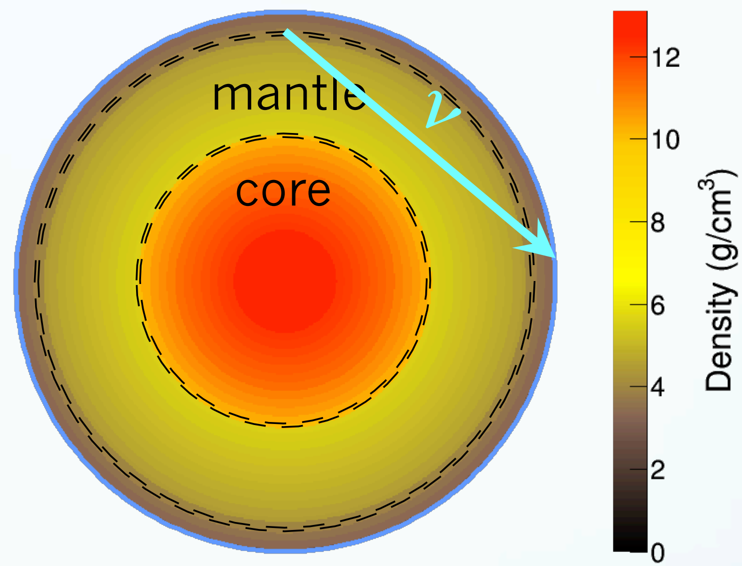


Atmospheric neutrinos

- Resonance occurs for NH only for neutrinos and vice versa for antineutrinos
- **Mantle crossing** neutrinos provide strongest signal for MH measurements

$P(\nu_\mu \to \nu_x)$ for θ=130º





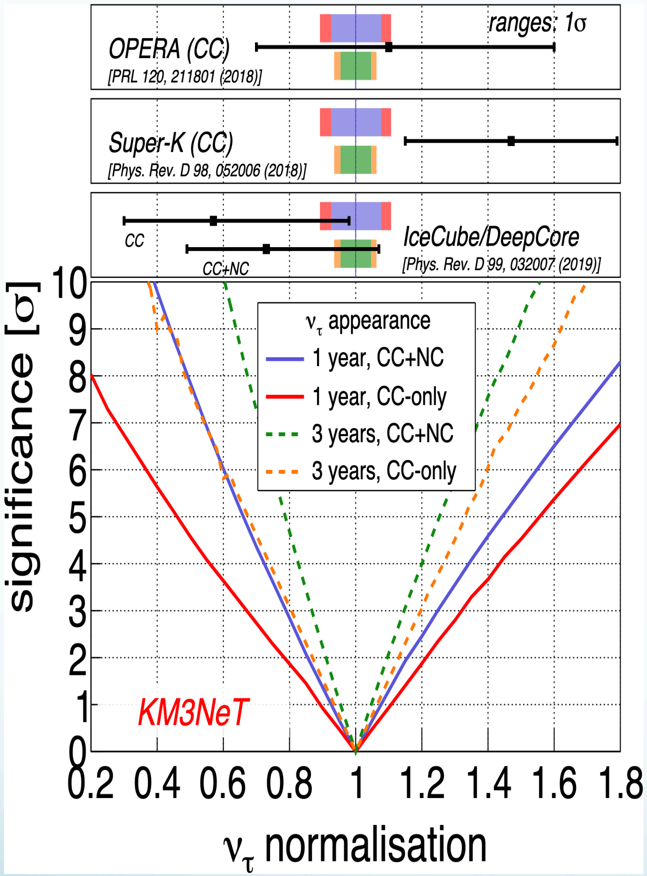
Oscillations are **resonant** at certain energies

E_{res} ~ 7 GeV in Mantle
E_{res} ~ 3 GeV in Core

- Distinction between neutrinos and anti-neutrinos → Flux and cross-sections!

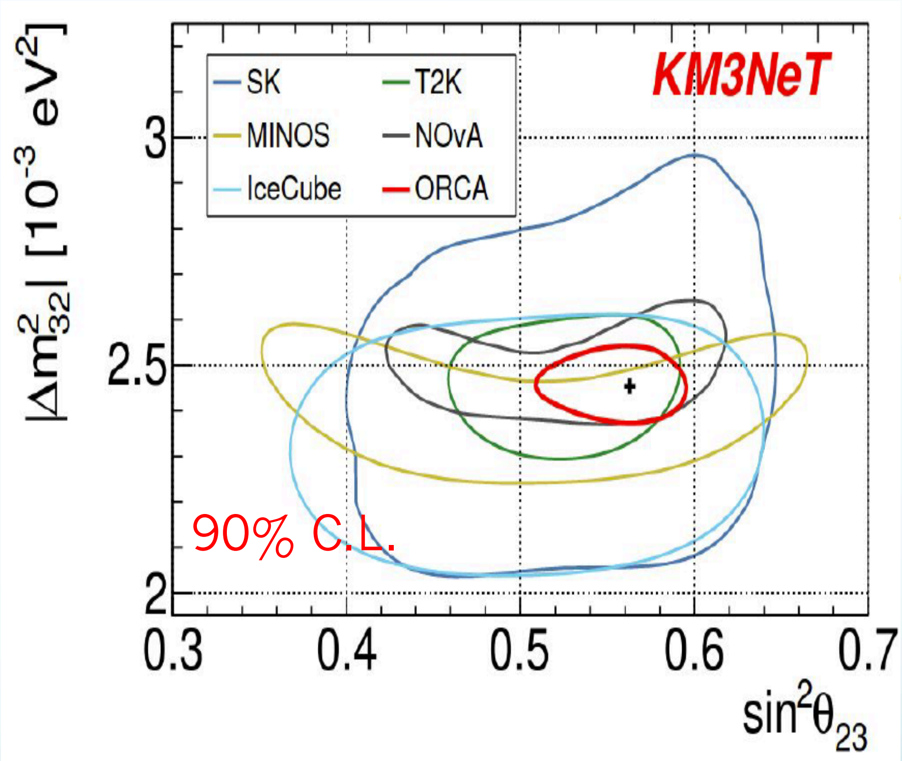
Sensitivity projections

ν_τ appearance



- Confirmation possible after a few months operation with full ORCA
- Fit robust against q_{23} and mass ordering

Oscillation parameters



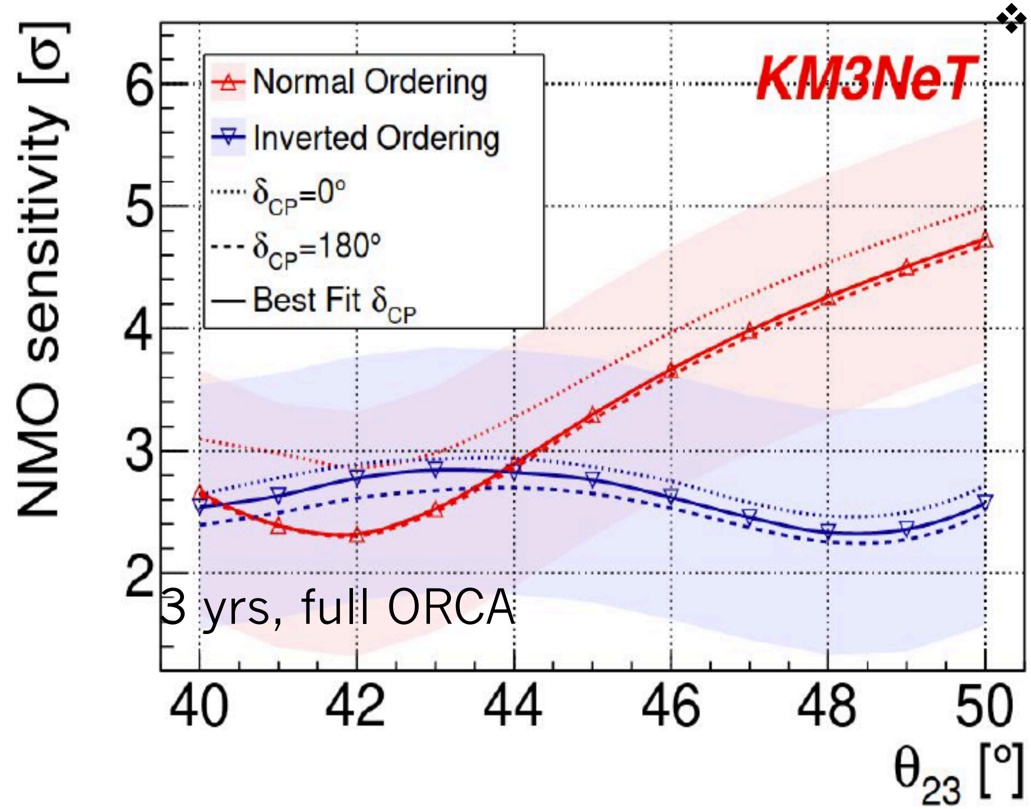
- 3 years of full ORCA
- Normal ordering, q_{23} = 48.6° (NuFit v4.1)

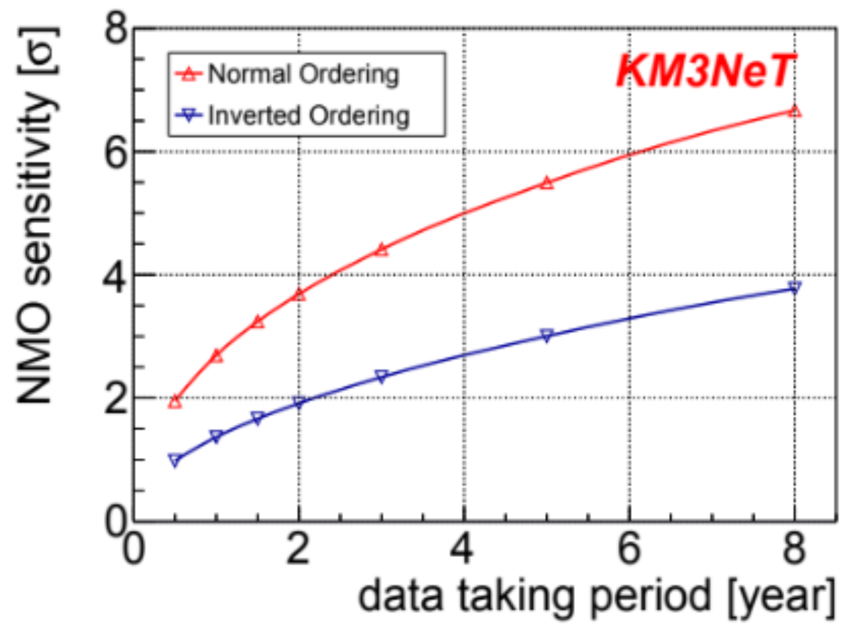
KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C

Sensitivity projections

Neutrino mass ordering

- Favourable scenario: Normal Ordering
→ measurement at 5σ after 4 years
- For Inverted Ordering scenario:
→ measurement at 3σ after 5 years
- moderate impact of δ_{CP} on sensitivity





68% sensitivity bands (Asimov); Oscillation parameters from NuFit 4.1

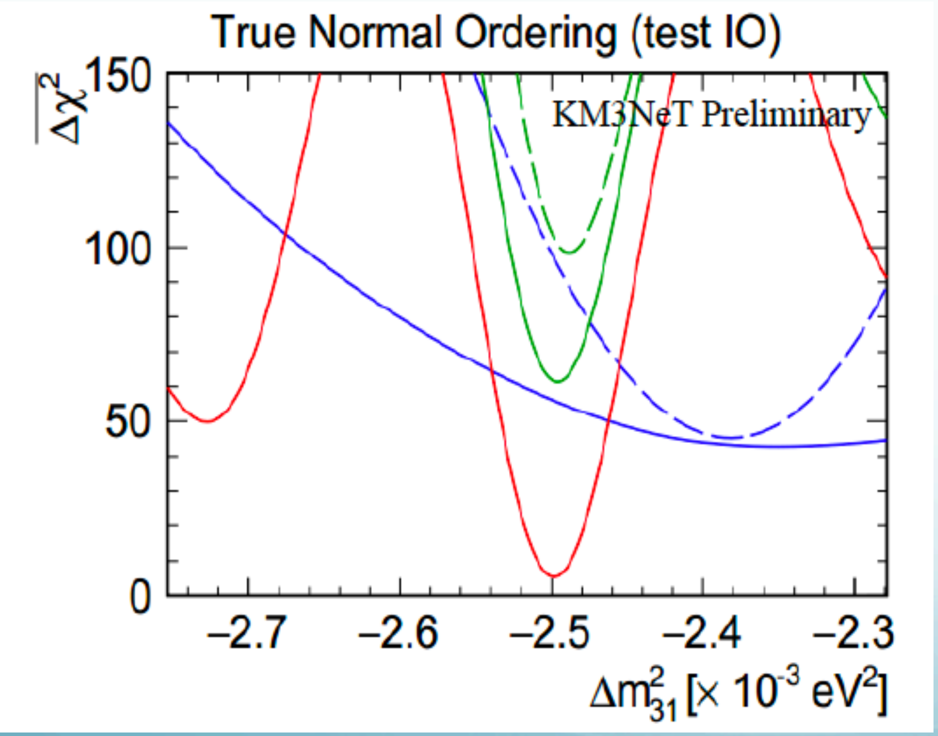
*KM3NeT Coll., arXiv: hep-ex/*2103.09885 , *submitted to EPJ C*

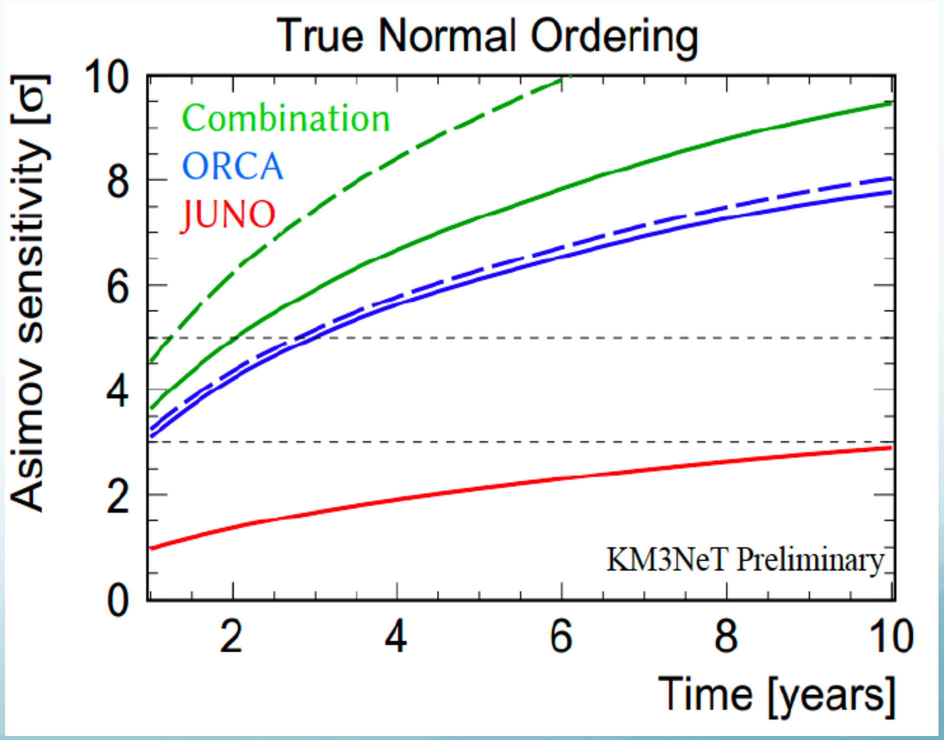
Sensitivity projections

Neutrino mass ordering: combination with JUNO

Tension between the best-fit Δm^2_{31} with a wrong ordering assumption enhances sensitivity when combining ORCA+JUNO

- ❖ 5σ discrimination achievable for all hierarchy/octant scenarios in < 6 yr
- ❖ detail of energy-scale systematic are important

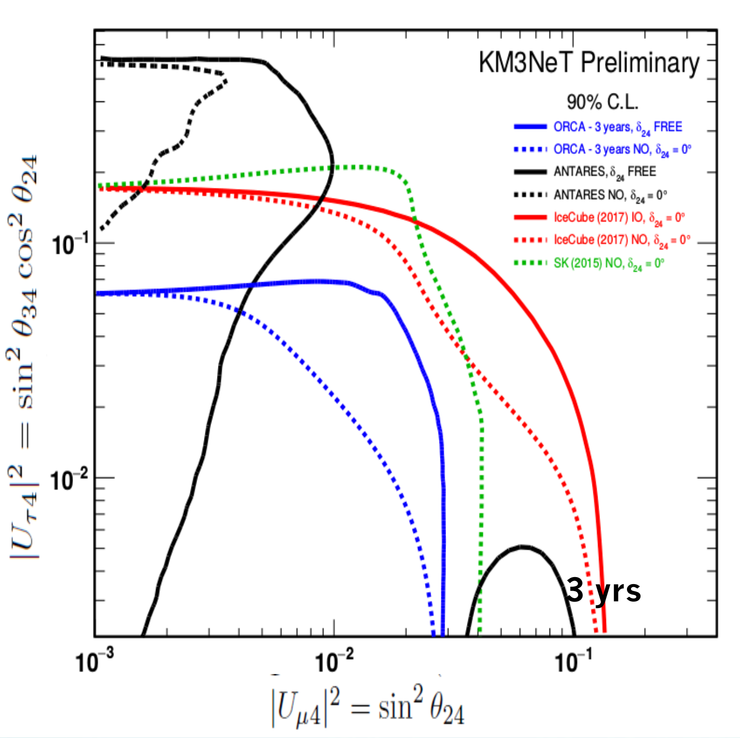




Oscillation parameters from NuFit 4.1

Other neutrino physis: sterile

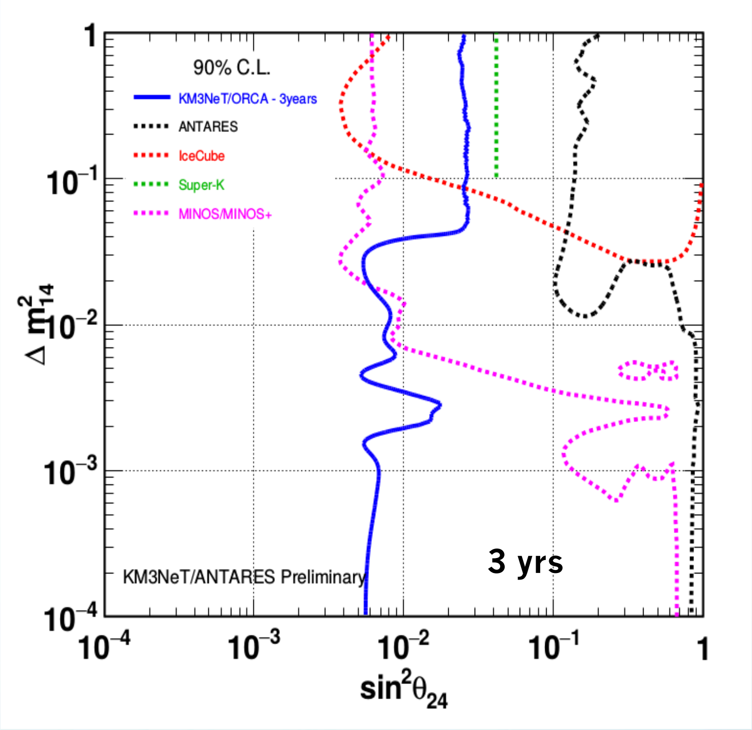
$\Delta m_{41}^2 > 0.1\ eV^2$



Dependence on δ_{24}

Factor of two better sensitivity on $U_{\tau 4}$ than current limits from SK and IC

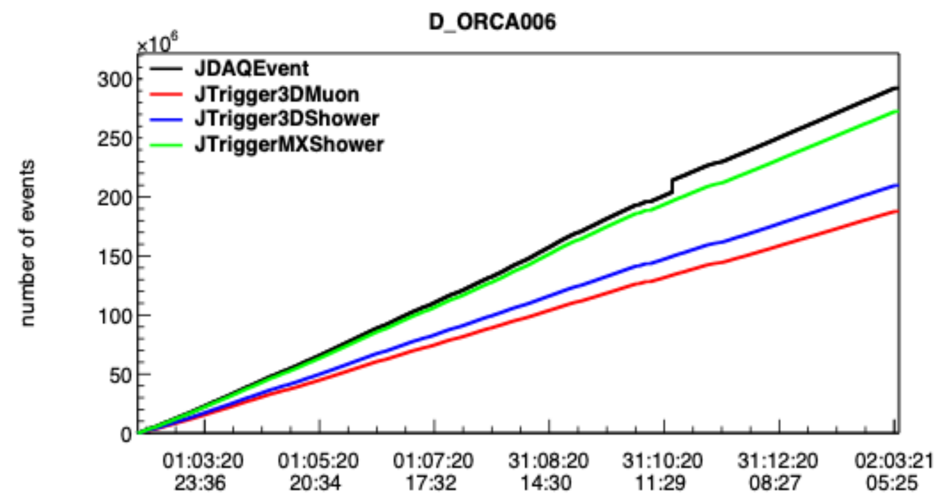
$\Delta m_{41}^2 < 0.1\ eV^2$



Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

ORCA Status

From February 2020 six detection units in operation



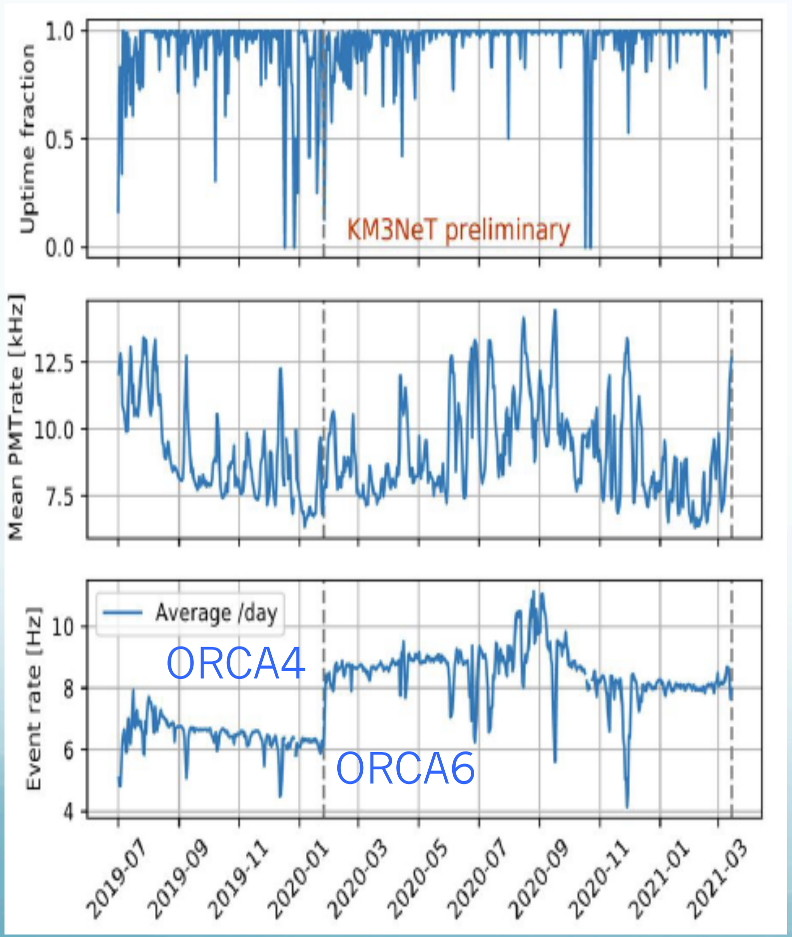
More than one year of data available

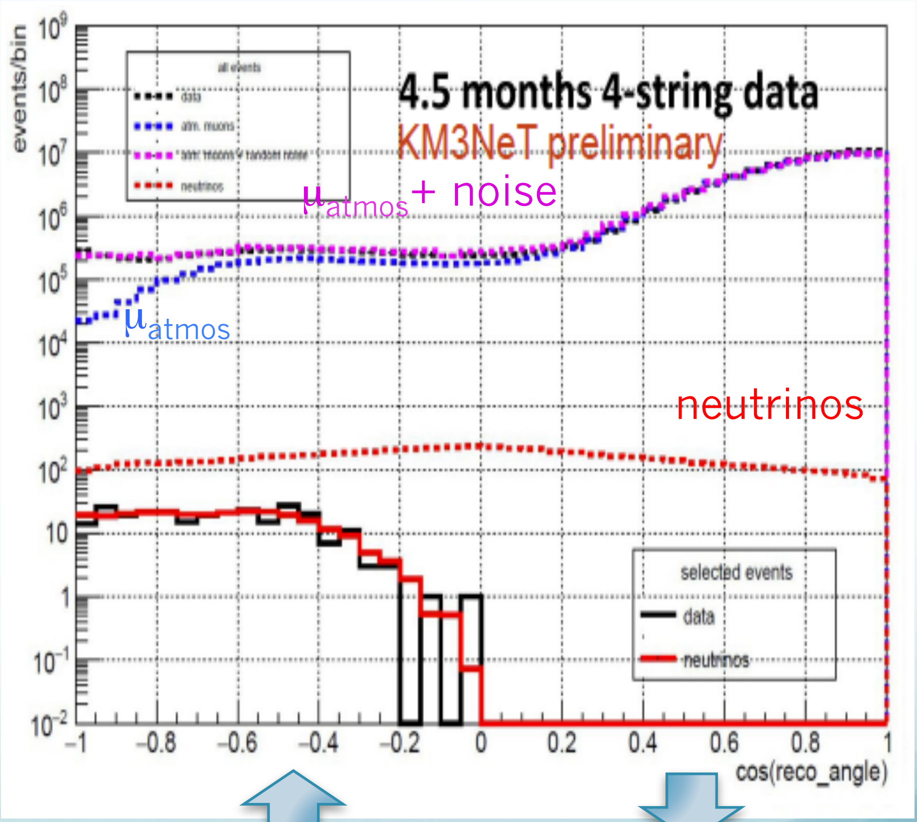
Data Taking efficiency of 98.8%

ORCA4: First Results

- Stable data taking since mid-2019
- Uptime 91% (2019) → 99% (2021)
- Good stability of trigger

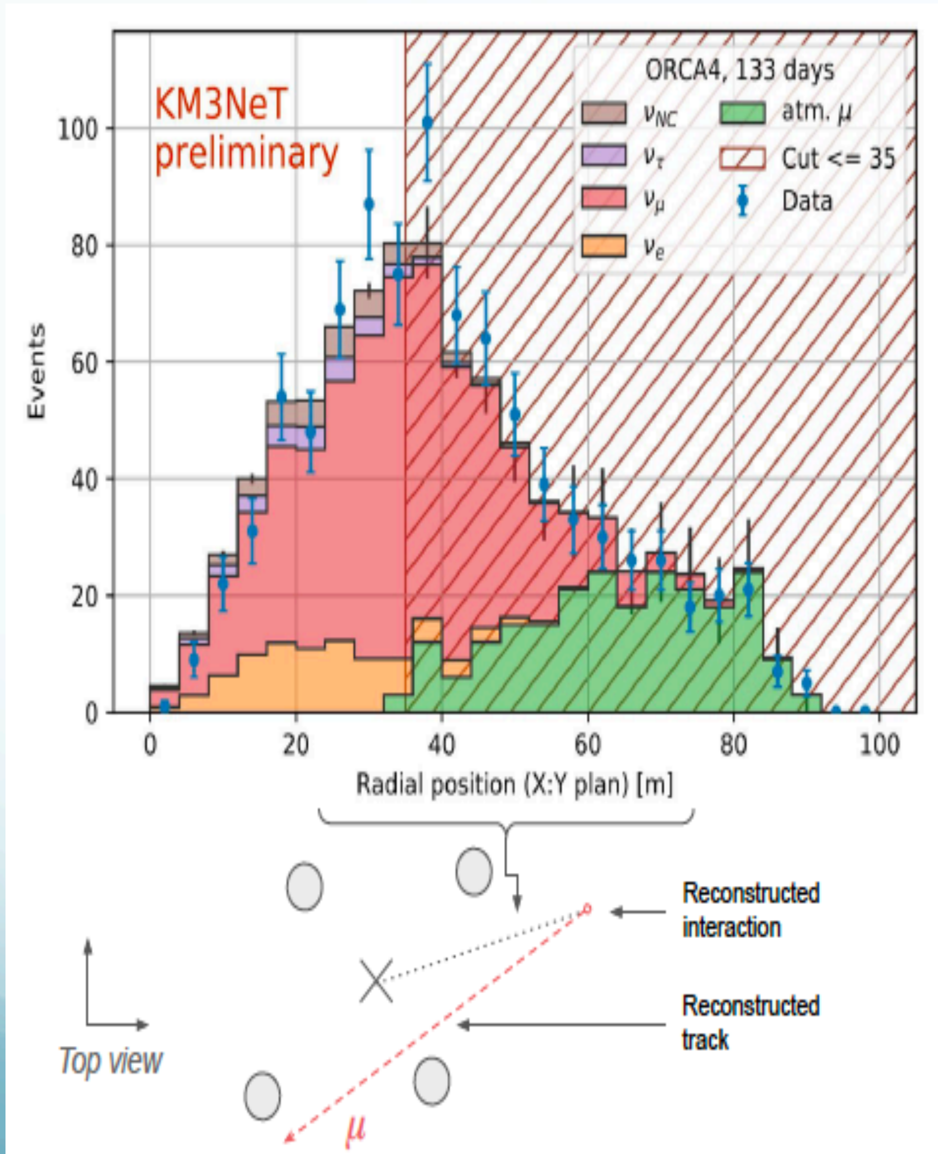
- ORCA4 data sample: 133.1 days
- Good data-MC agreement





~600 000 muons/day
~40 neutrinos/day

ORCA4: First Results



❖ Neutrino selection:

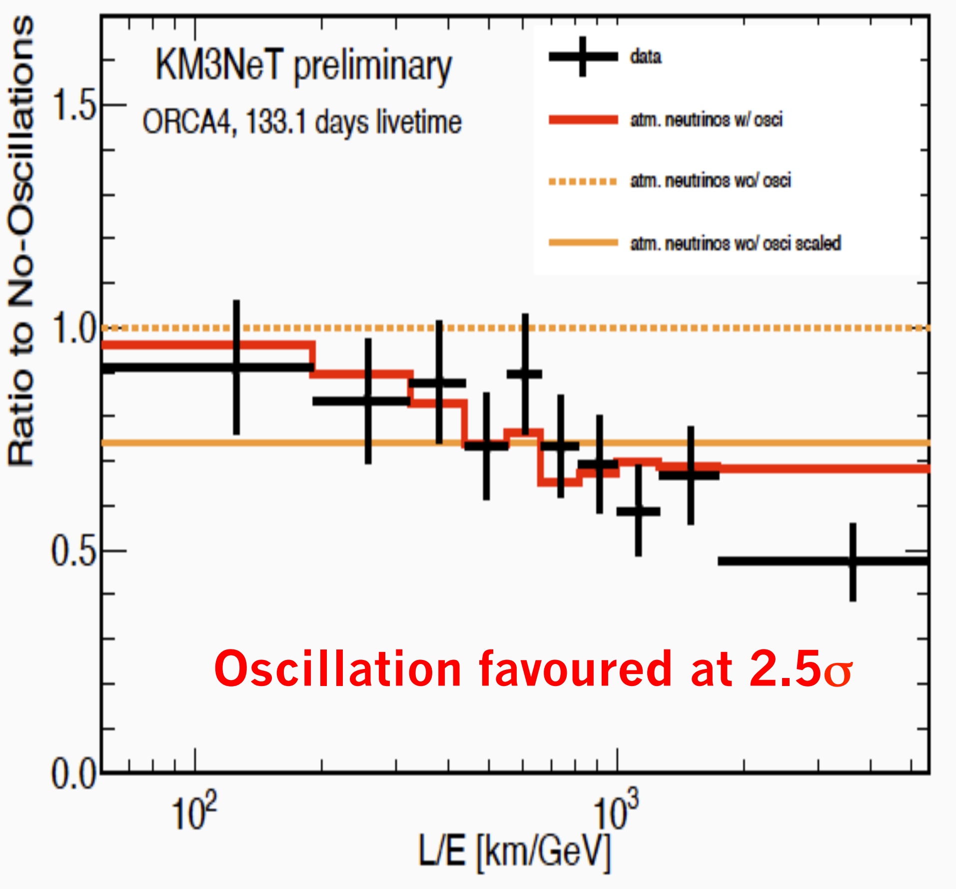
- Upgoing tracks
- Track quality parameter
- « containment » condition on reconstructed vertex

High-purity neutrino sample:

• Data	2.86	± 0.15 /day
• ν_{atm}	2.92	± 0.02 /day
• $\nu_{atm\ (no\text{-}osc)}$	3.94	± 0.03 /day
• μ_{atm}	0.02	± 0.02 /day

Only stat.

ORCA4: First Results



- First preliminary measurement
  Honda atmospheric flux + NuFit 4.0
  Flux normalization free

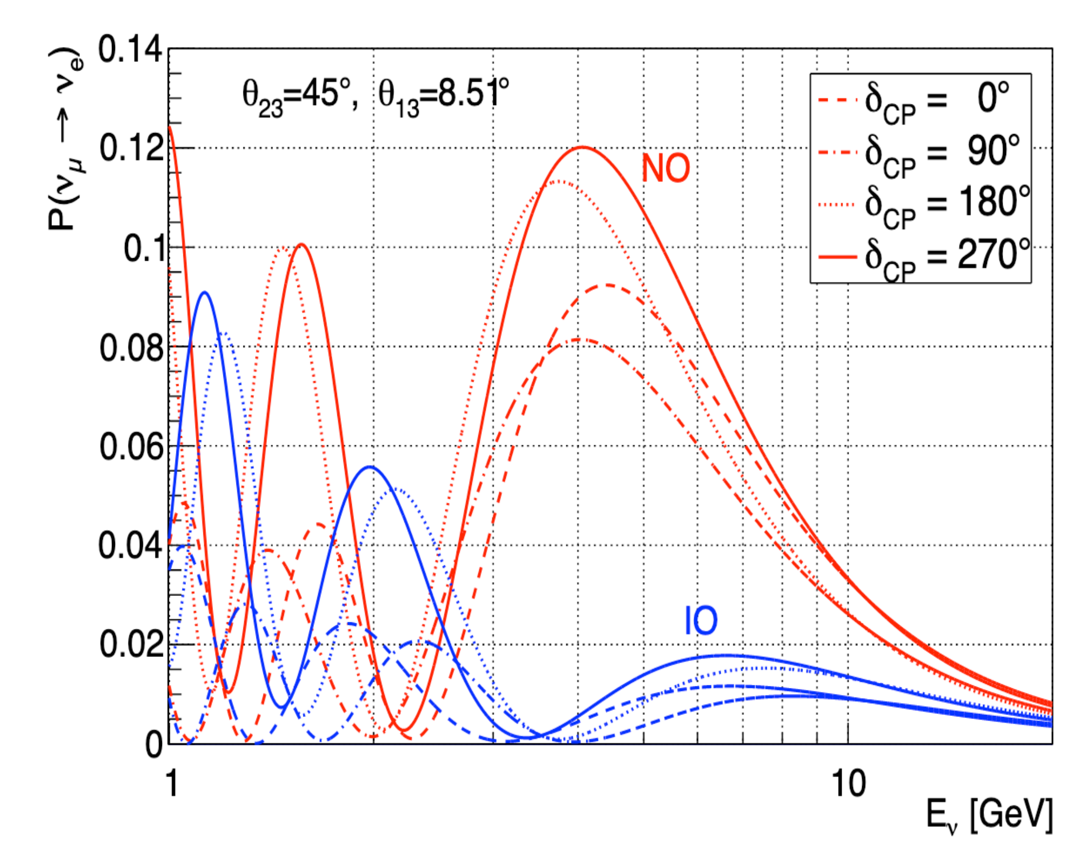
- Good data/MC agreement

- Statistically limited
- No track/shower separation:
  all events reconstructed as tracks
- resolutions (energy/direction) limited
  by small size of detector

P2O : Protvino to ORCA

- From U70-Protvino to ORCA (P2O)
- Up to 450 kW beam power
- Baseline 2595 km

- First oscillation maximum ~5 GeV
- Sensitivity to mass ordering and CP violation

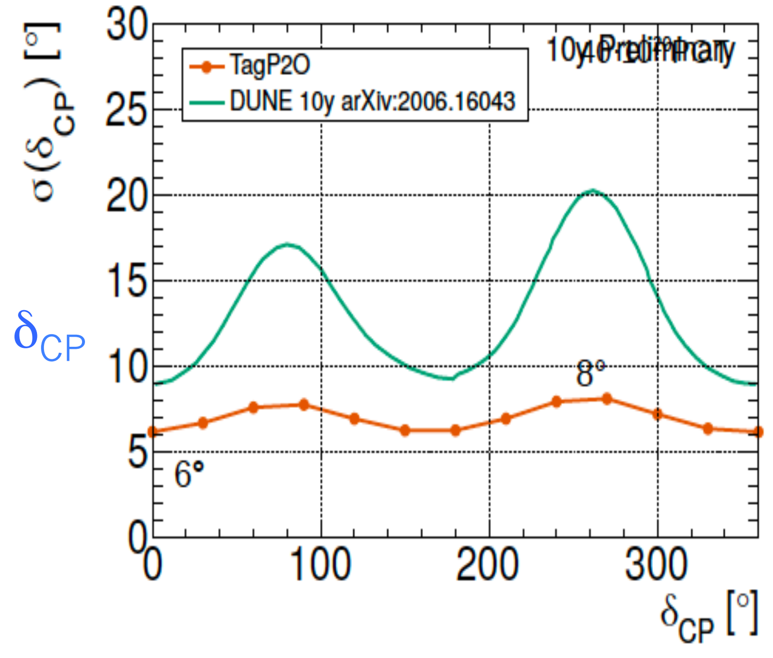


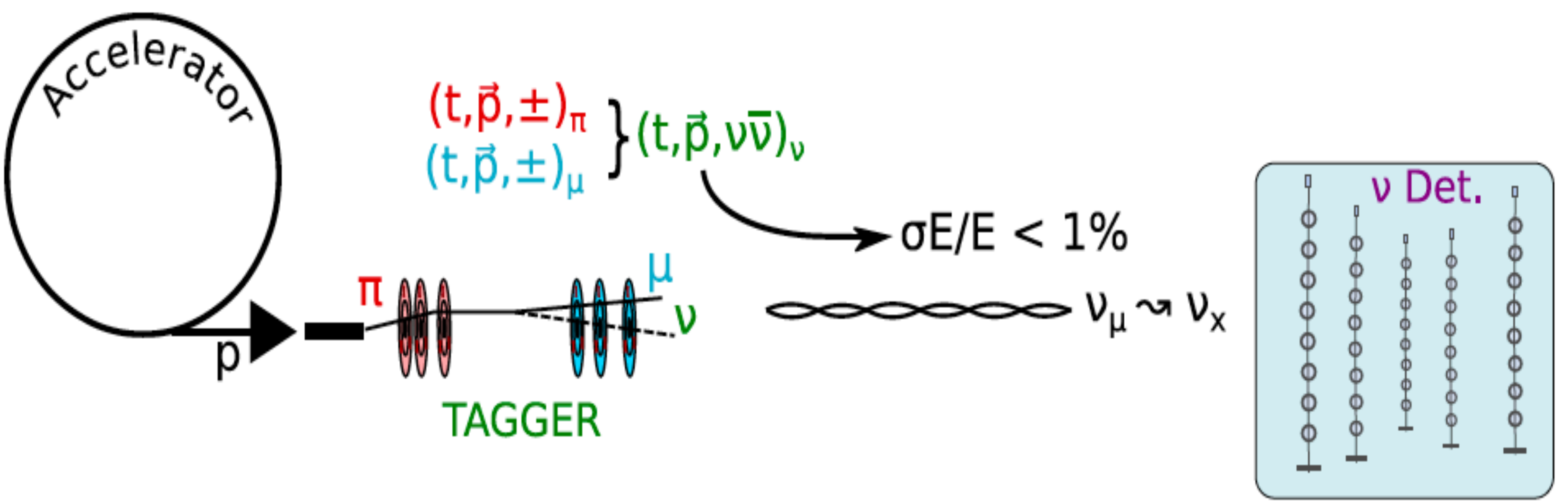
P2O LoI: Eur.Phys.J.C 79 (2019) 9, 758

P2O : Protvino to ORCA

- From U70-Protvino to ORCA (P2O)
- Up to 450 kW beam power
- Baseline 2595 km
- New idea: use a tagged beam

→ Improved & quasi-uniform sensitivity to δ_{CP}

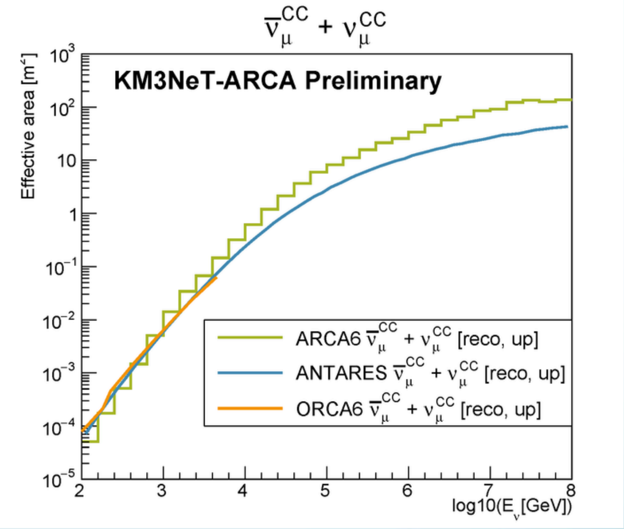




📖 P2O LoI: Eur.Phys.J.C 79 (2019) 9, 758

Summary and perspectives

- IceCube has just opened the field of neutrino astronomy but sources remain to be identified. → Exciting times ahead of us !
- ANTARES: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky
  - Competitive sensitivities (especially for Galactic neutrino component, Dark matter searches)
  - More results to come
  - Taking data until mid ~2022
- KM3NeT: phased approach to next-generation NT
  - Letter of Intent
  - Prototypes performing well
  - Deployment of the first detection units.
  - End of 2021 : 31 DUs in total
    About 1/3rd of what is currently funded -> continue the build!



  - **ARCA → HE neutrino astronomy (tracks & showers)**
  - **ORCA for the measurement of NMH**