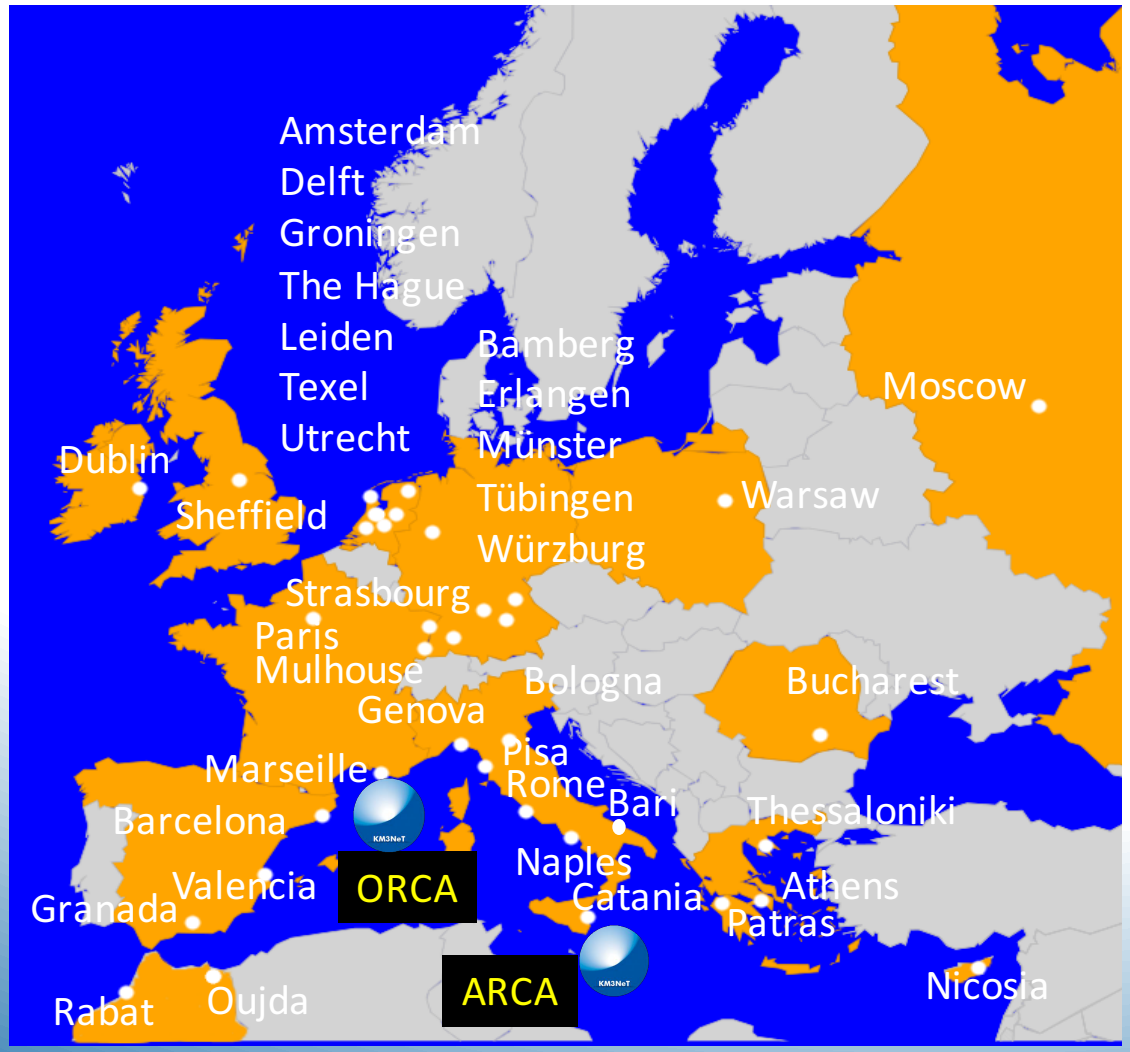
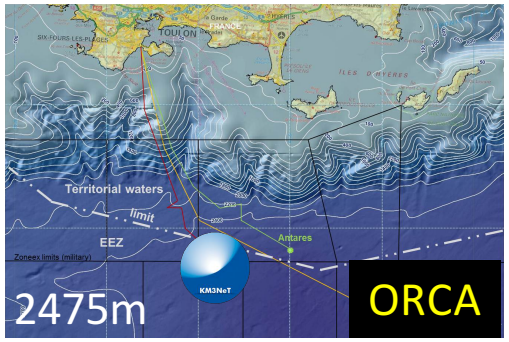
Astroparticle and neutrino oscillation research with KM3NeT

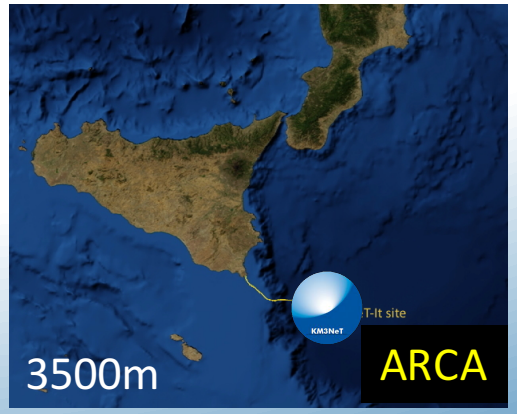
V. Kulikovskiy (CPPM/CNRS)

KM3NeT

Multi-site deep-sea neutrino research infrastructure

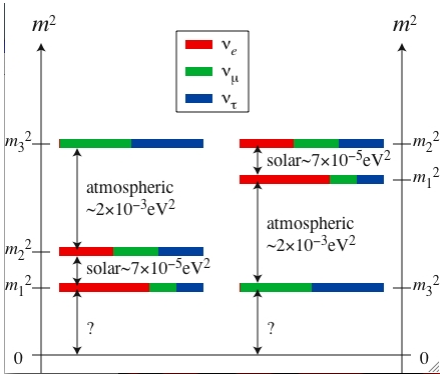


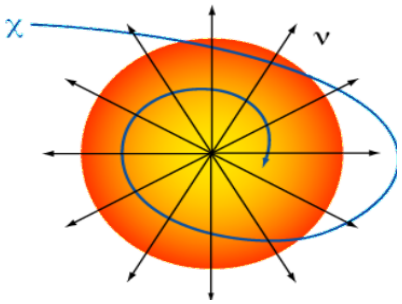


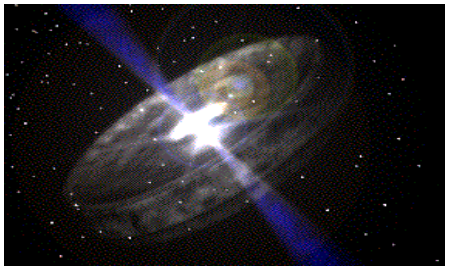


Single Collaboration, Single Technology

Objectives







Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations ν Mass Hierarchy	Dark Matter search + Exotic searches	ν from extra-terrestrial sources Origin and production mechanism of HE CR

KM3NeT-ORCA — ANTARES — KM3NeT-ARCA

Oscillation Research with Cosmics in the Abyss (ORCA)

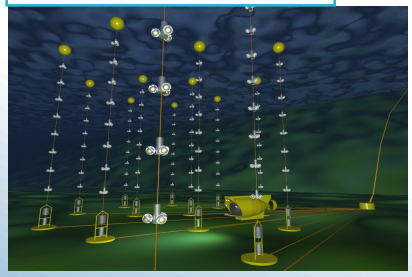
See talk of M. Spurio

Astroparticle Research with Cosmics in the Abyss (ARCA)

Detector sizes

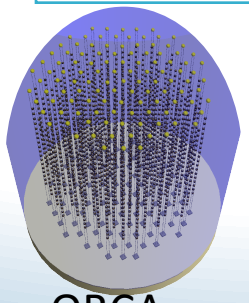
	ANTARES	ORCA (denser)	ARCA (larger)
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Interline dist	70 m	20 m	90 m

12 lines
25 sectors/line

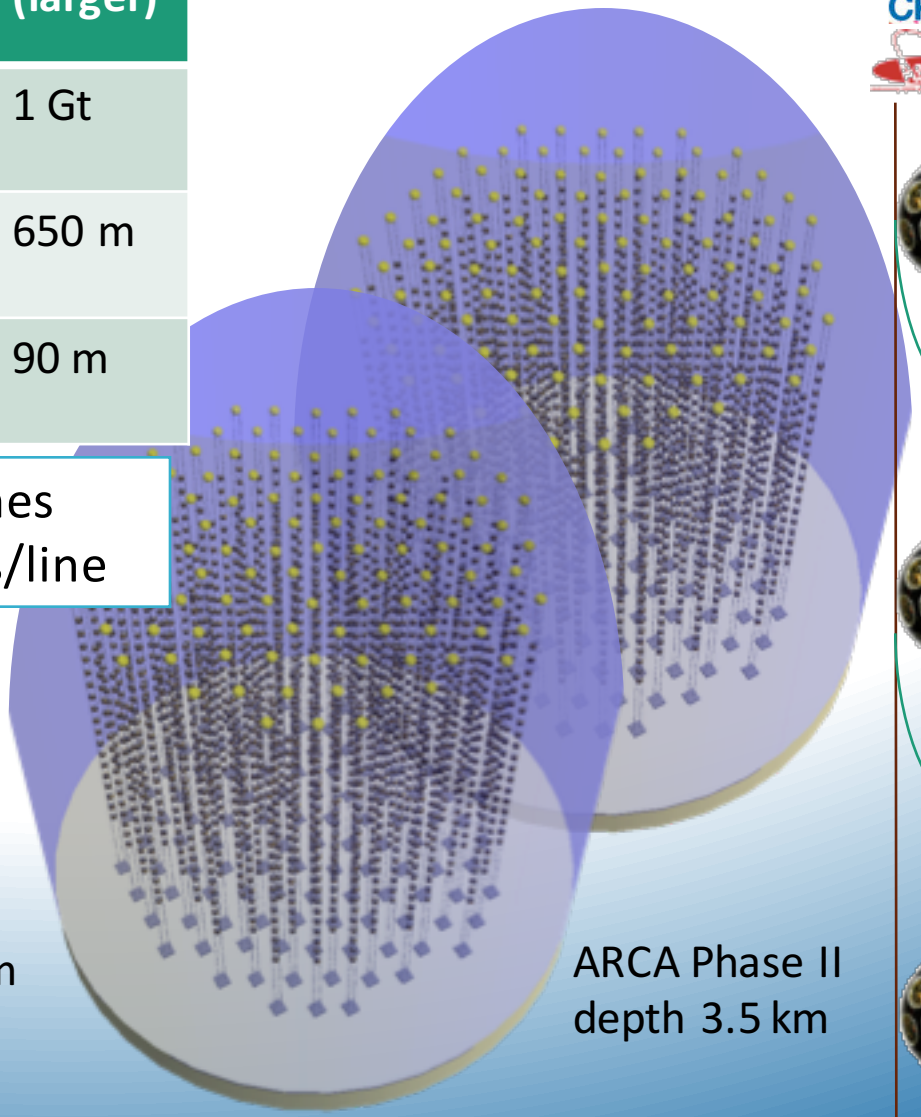


ANTARES
depth 2.5 km

115 lines
18 DOMs/line



ORCA
depth 2.5 km

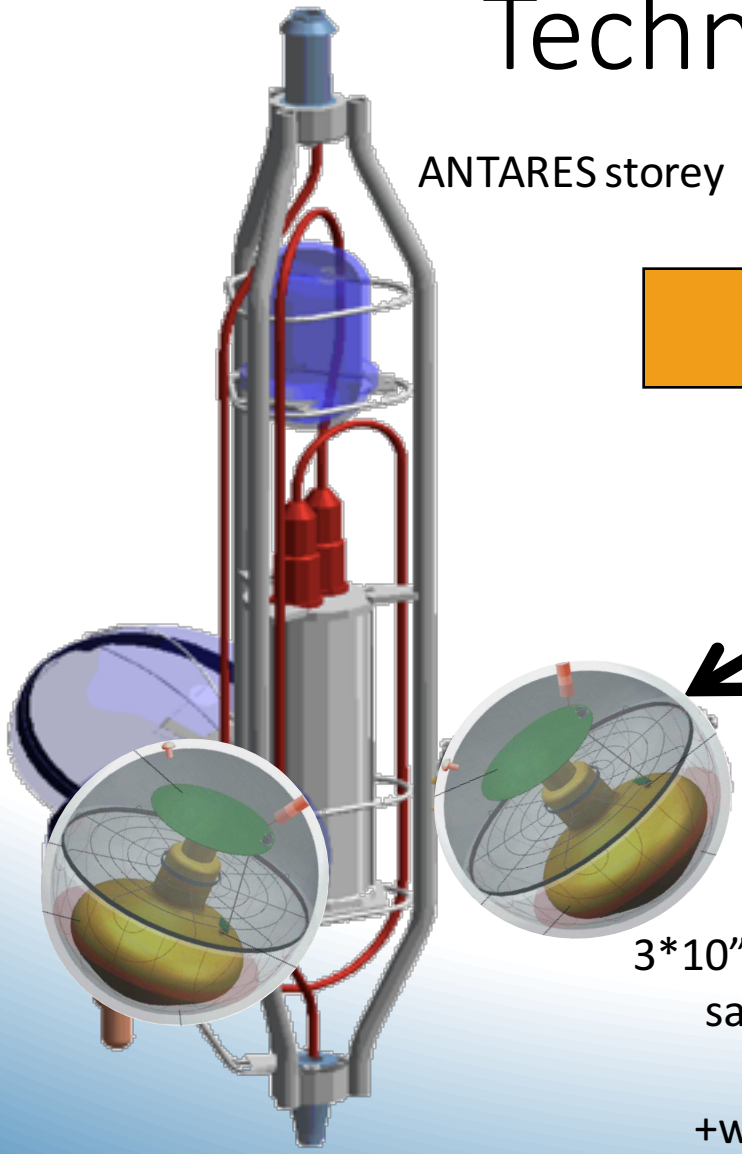


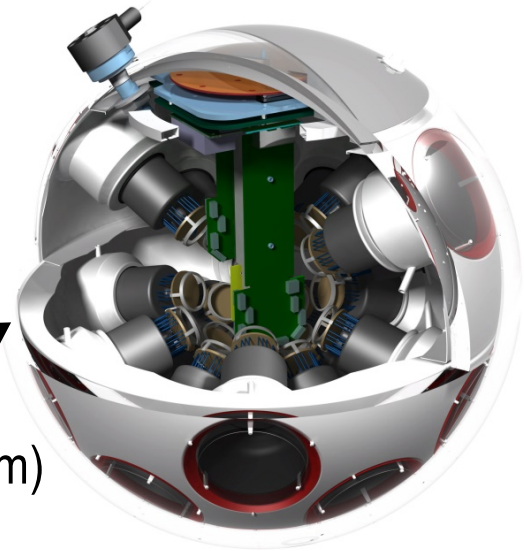
ARCA Phase II
depth 3.5 km

Technologies

ANTARES storey

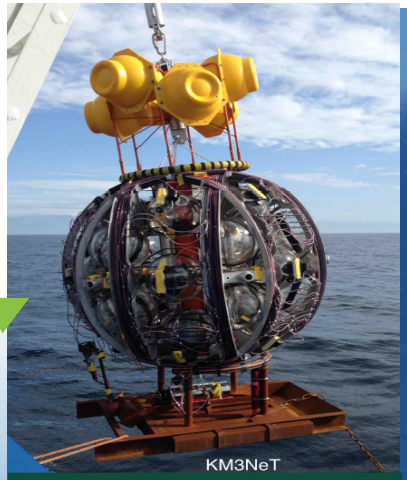
DOM

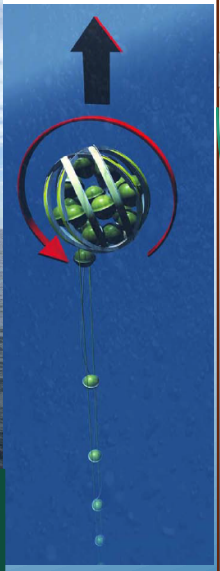




Same size (43cm)

3*10” PMTs -> 31*3” PMTs
same sensitive area
+compactness
+wider angle of view
+directional information
+digital photon counting
+cost reduction

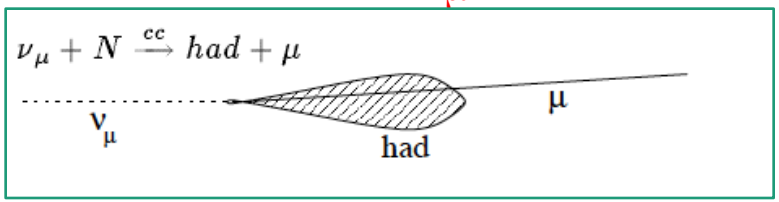




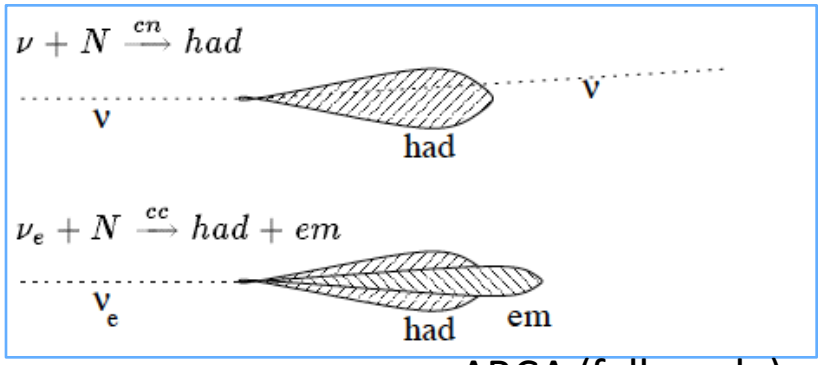
rapid deployment
autonomous unfurling
recoverable

Event topologies

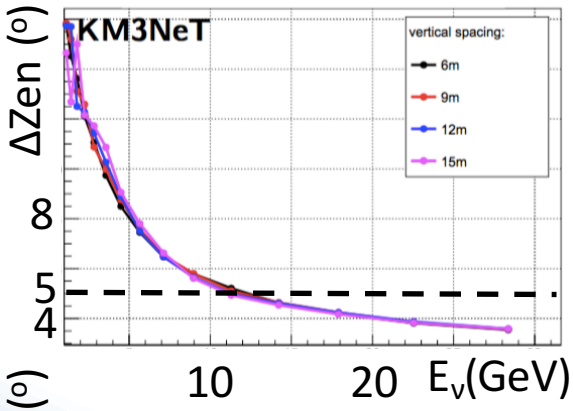
Track-like (ν_μ^{CC})

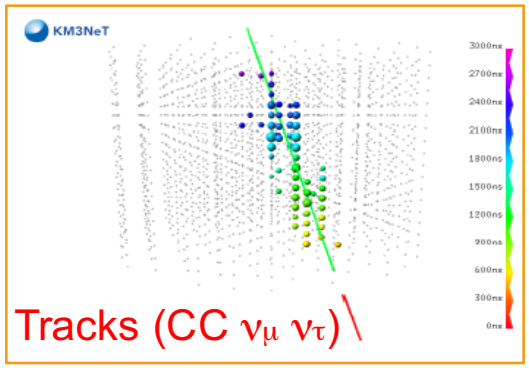


shower-like (ν^{NC}, ν_e^{CC})

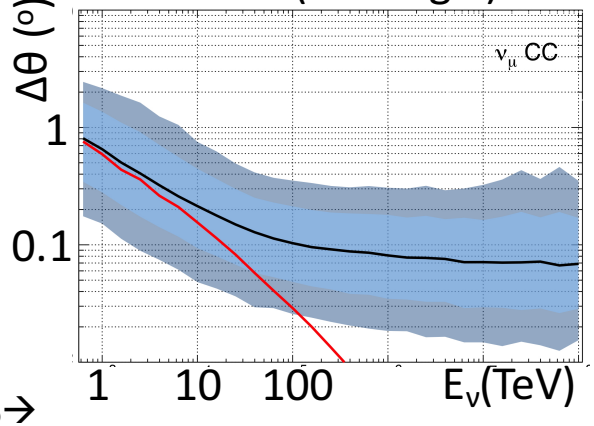


ORCA (zenith)

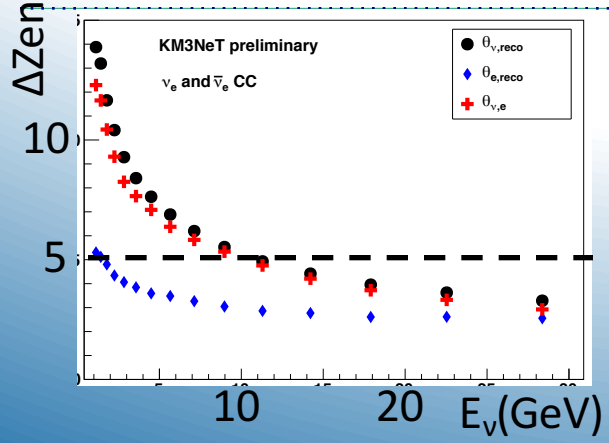


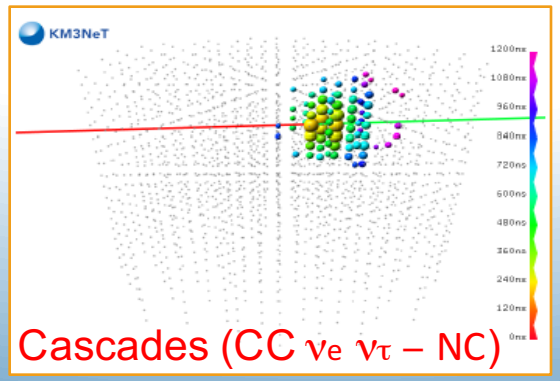


ARCA (full angle)

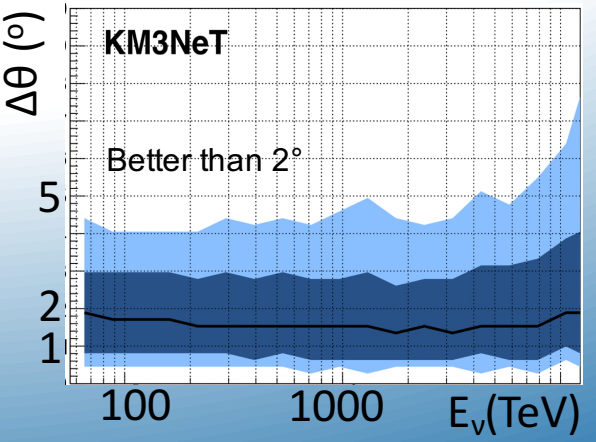


←<30% E_ν Resolution E_μ <27%→





←26% Energy Resolution 5%→

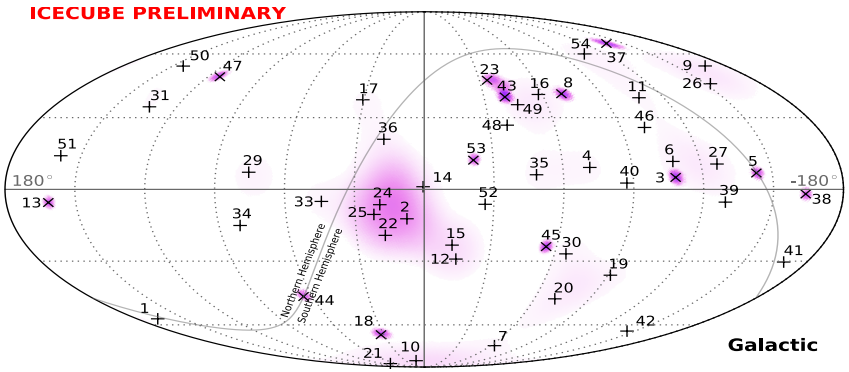


ARCA

Astroparticle Research with Cosmics in the Abyss

Diffuse flux searches

IceCube confirmed existence of cosmic neutrino diffuse flux
The sources are unknown.

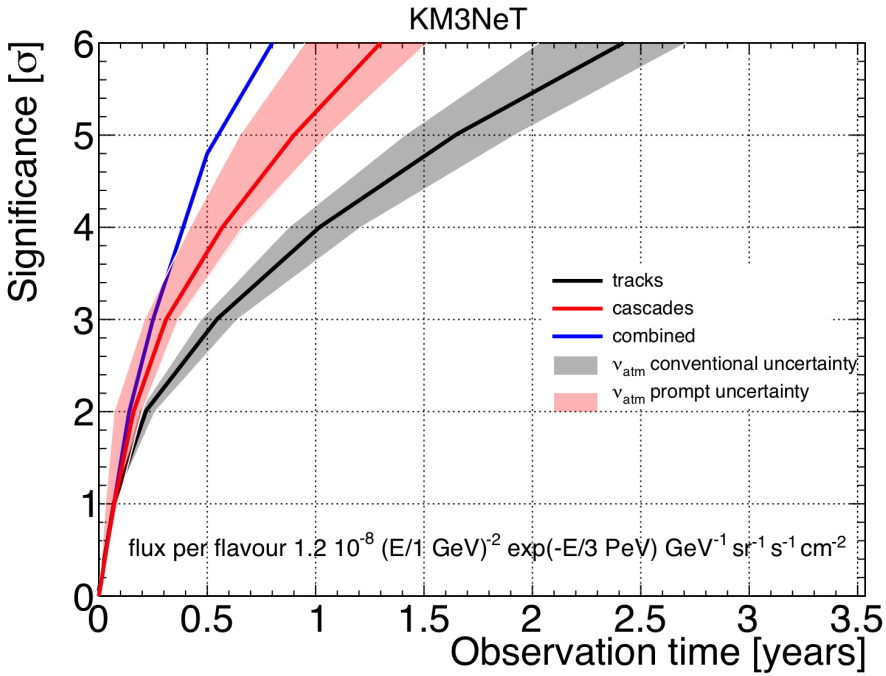


- **Track channel**

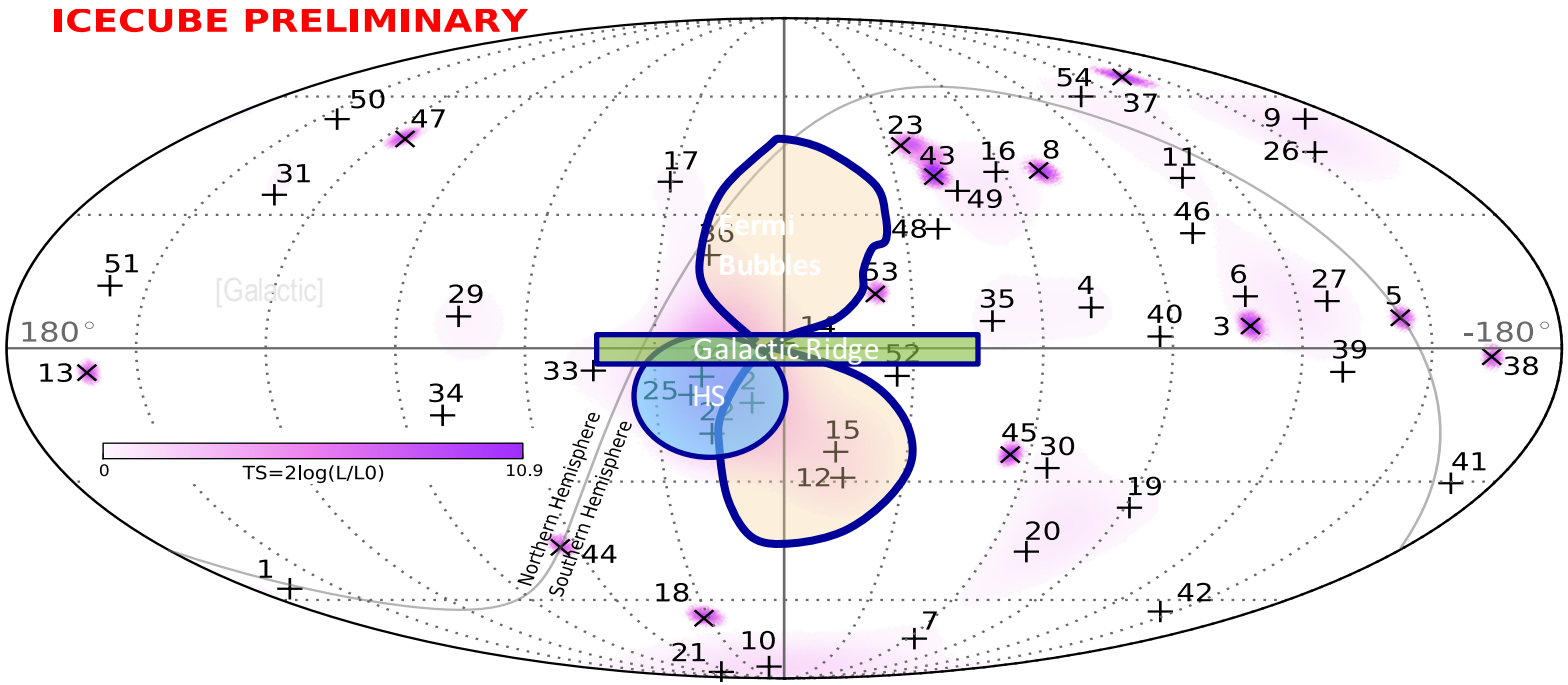
Analysis for up-going events based on maximum likelihood
Pre-cuts on θ_{zen} >80°, reconstruction quality parameter and N_{hit} (proxy for muon energy)

- **Cascade channel**

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



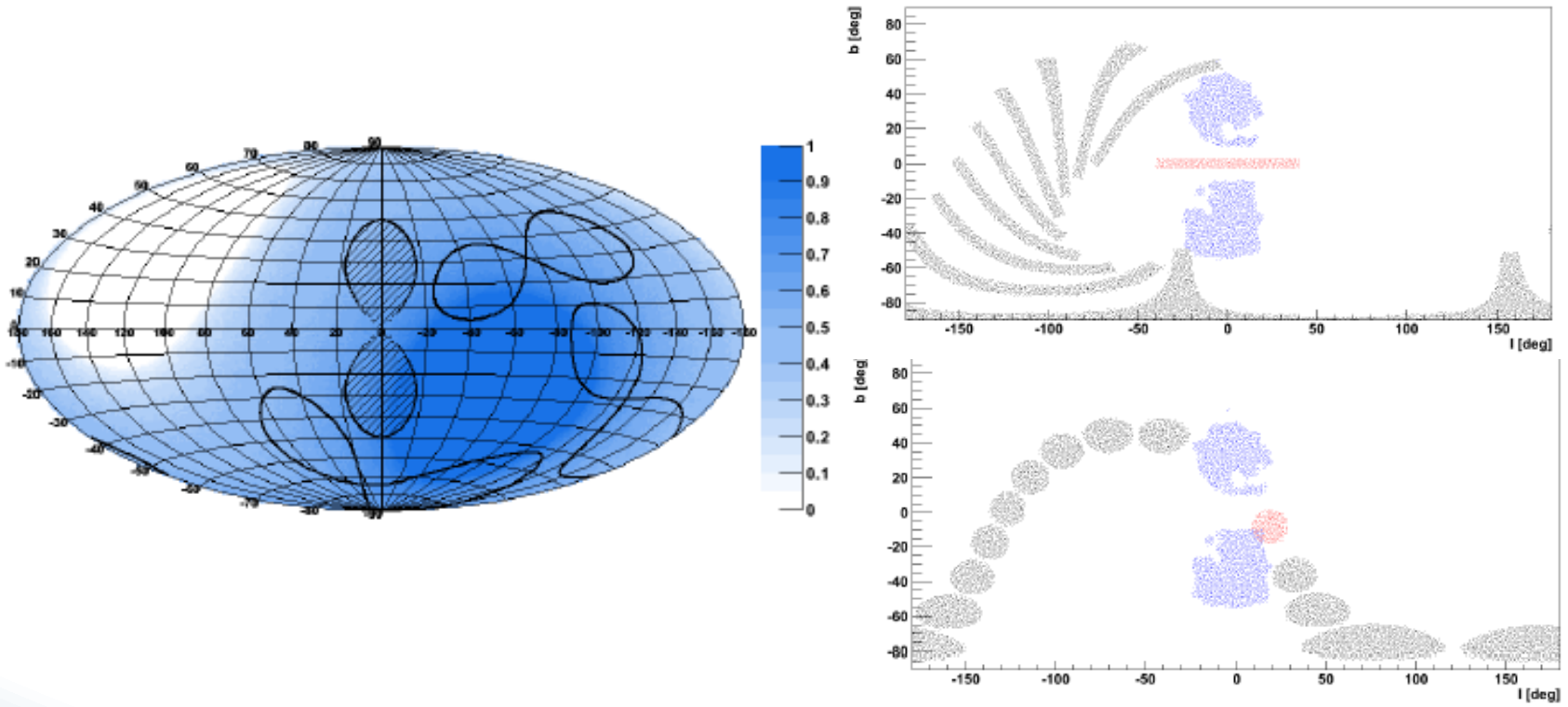
Reduced search windows



Enhanced flux areas are proposed:

- Galactic Ridge
- Fermi bubbles
- IceCube “Hot Spot”
- …

Reduced search windows



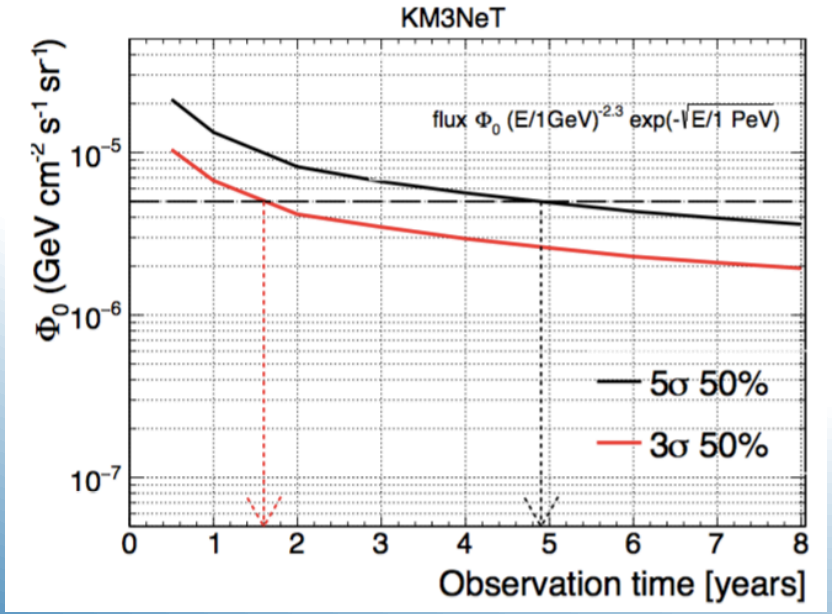
- More robust data analyses will be possible respect to the full sky: background measured from OFF regions of same local acceptance.
- Off-zones definition and analysis are first proposed and approbated for the ANTARES data analysis of FB and after applied for GP and HS. 🕮 V. Kulikovskiy, ISBN 978-3-319-20412

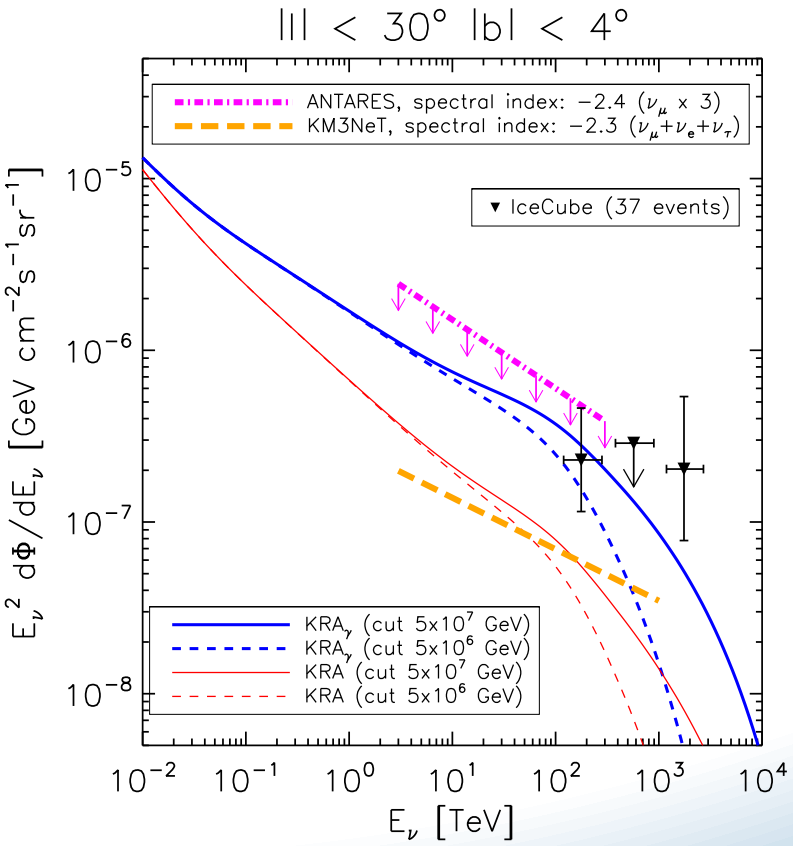
Inner Galactic plane

ANTARES upper limits for 1500 days

Phys lett. B2016.06.0511504.00227

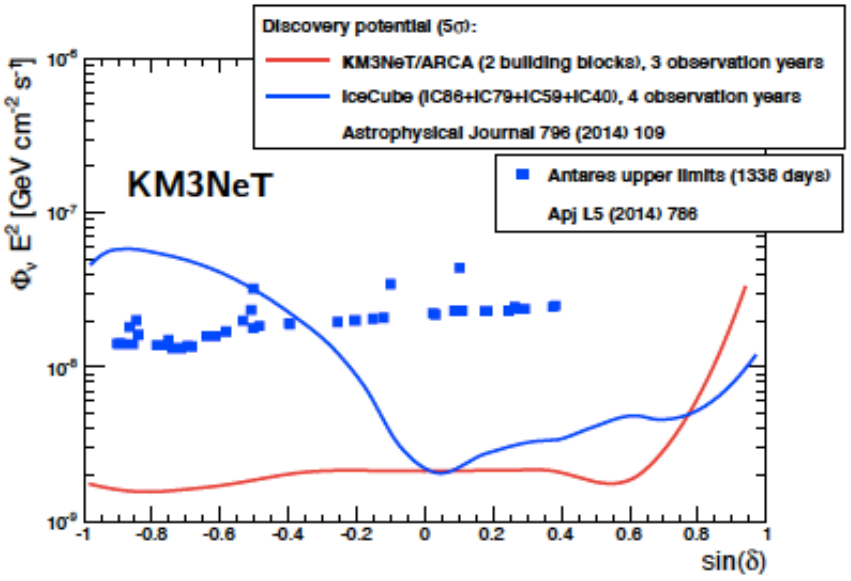
KM3NeT/ARCA 5 discovery potential (track events only) for this region considering 1500 days.
Improved analysis is ongoing.

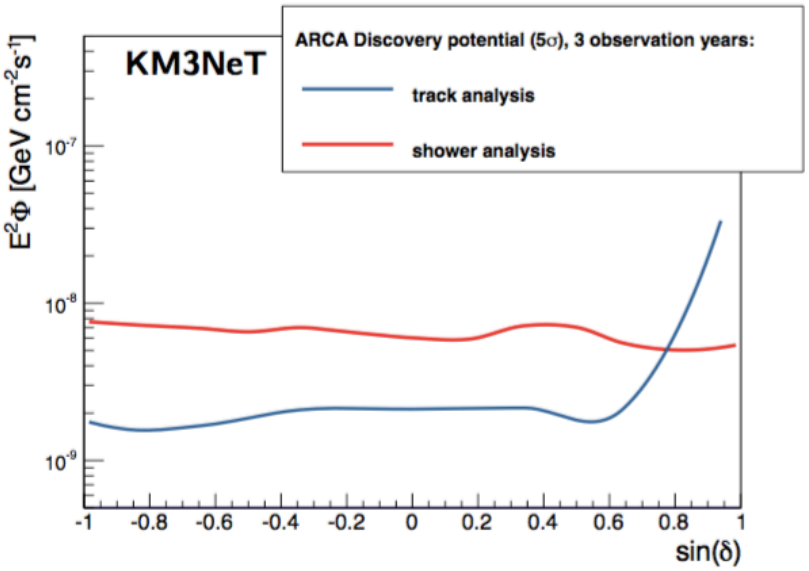




Updated version of the plot from: ICRC2015 Arxiv:1508.03681 (Antonio Marinelli)

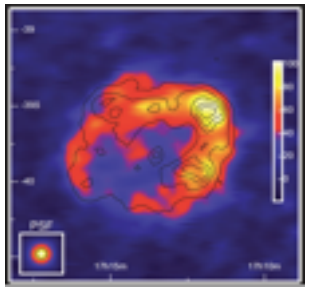
Point-like sources

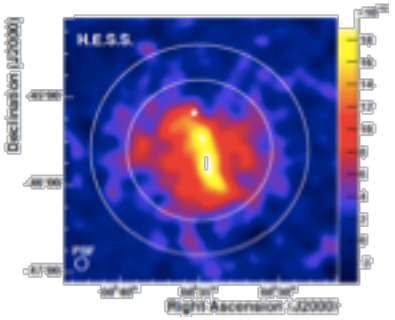


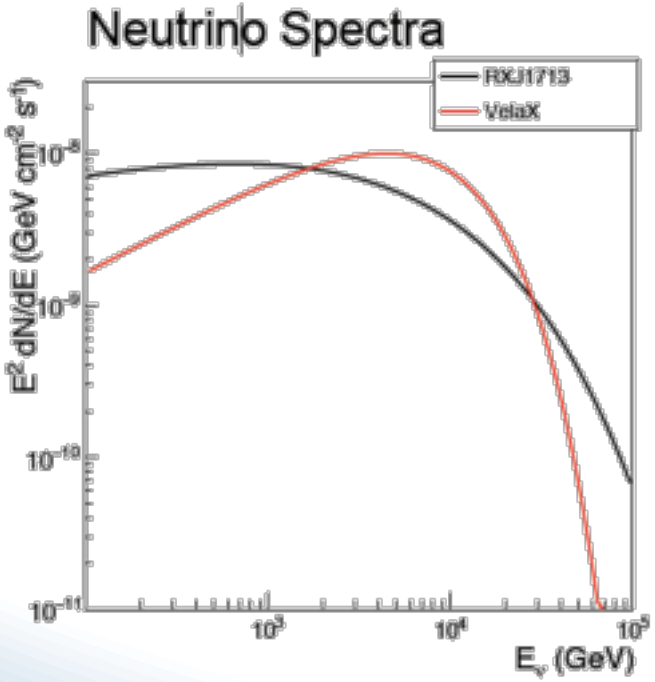


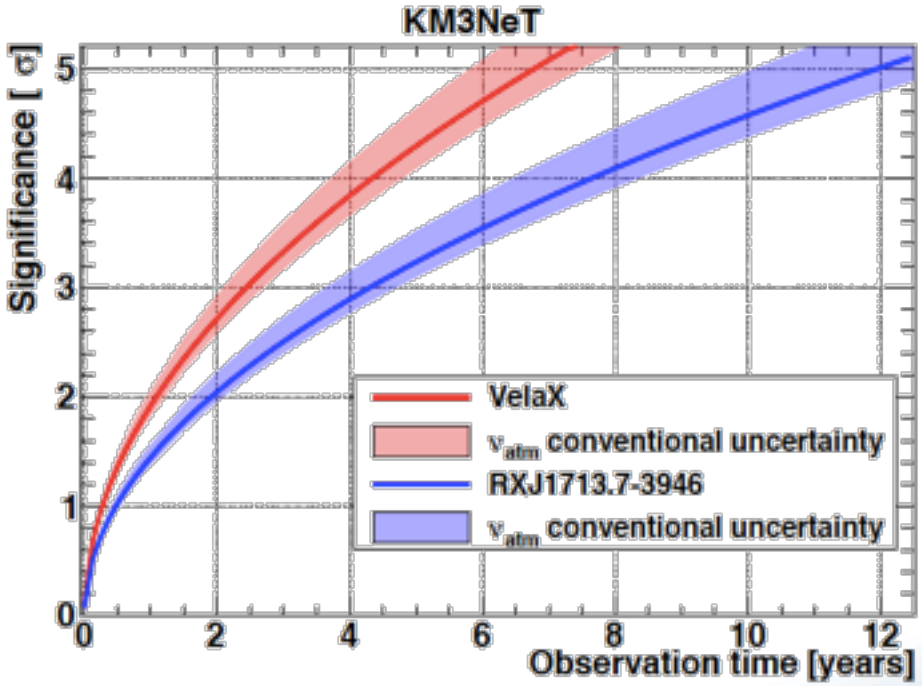
- KM3NeT sensitivity for point-like sources with unbroken E^{-2} spectrum.
- Shower channel is also promising (especially for N.H.).
- The sensitivity may be increased for transient/periodic sources if the time information is provided (from gamma, GW, radio detectors…). Source stacking for the candidate lists.

RXJ1713 & VelaX









Neutrino fluxes estimation from the measured gamma-ray flux (H.E.S.S.) and assuming a pure hadron model.

📖 F. Vissani, Astropart. Phys. 26, 310 (2006).

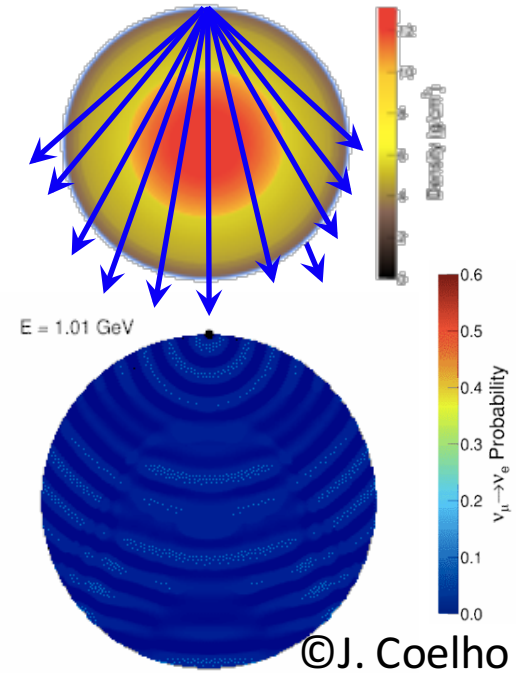
📖 S. R. Kelner et al, Phys. Rev. D 78 039901 (2009)

ORCA

Oscillation Research with Cosmics in the Abyss

Measuring NMH with Atmospheric Neutrinos

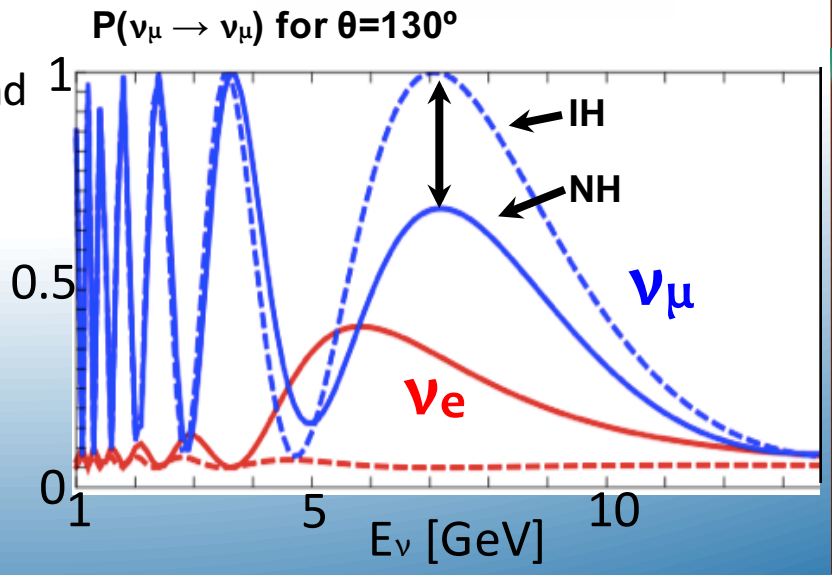
- A free "beam" of known composition (ν_e, ν_μ)
- Wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- Oscillation pattern distorted by Earth matter effects (hierarchy-dependent):
  - maximum difference IH vs NH at
  - $\theta=130^\circ$ (7645 km) and $E\nu$ = 7 GeV
- Opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
- BUT differences in flux and cross-section:
- $\Phi atm(\nu) \approx 1.3 \times \Phi atm(anti\text{-}\nu)$
- $\sigma(\nu) \approx 2\sigma(anti\text{-}\nu)$ at low energies



©J. Coelho

- Measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count muon and electron channel events

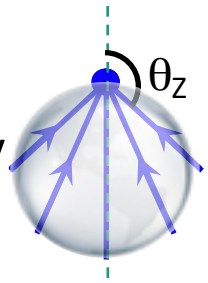
- Careful treatment of systematics mandatory



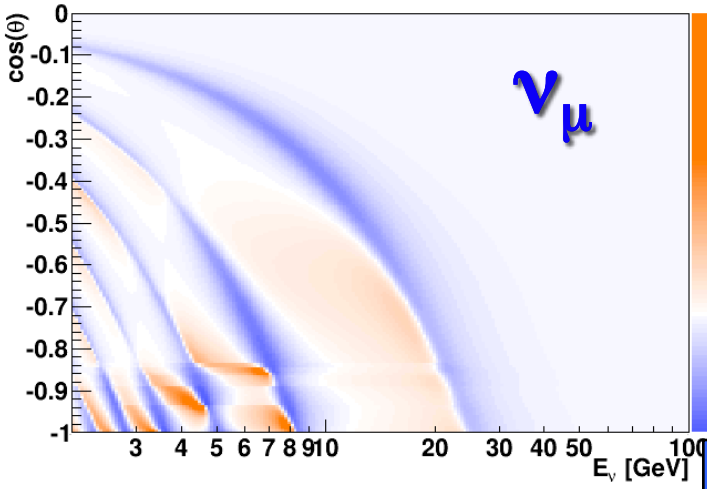
NMH Experimental Signature

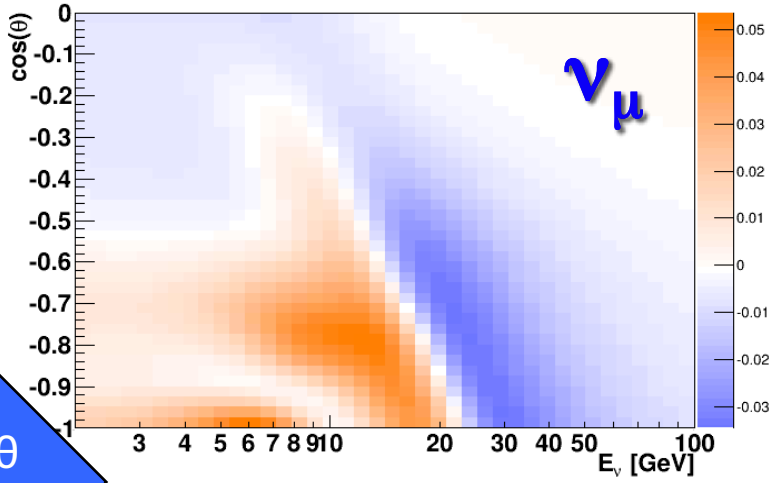
Both muon and electron channels contribute to hierarchy asymmetry

Electron channel more robust against detector resolution effects

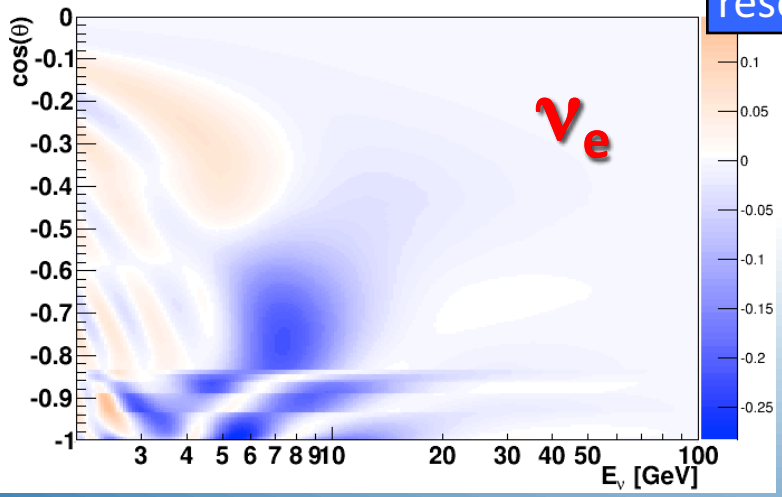


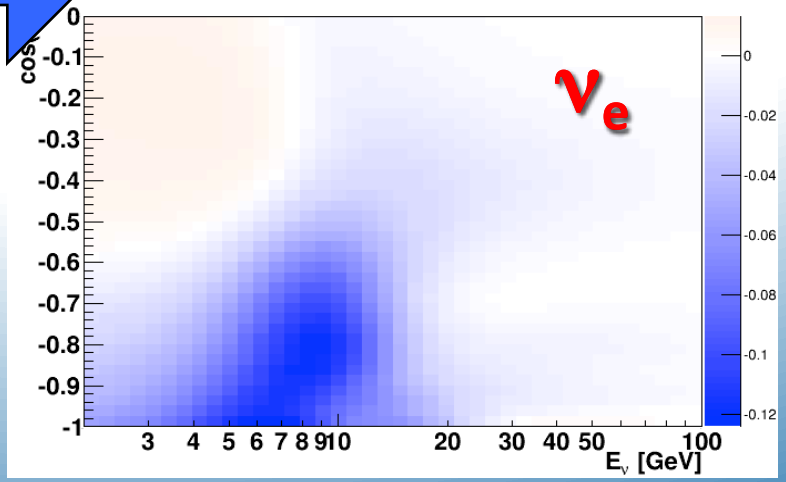
$(N_{IH}-N_{NH})/N_{NH}$





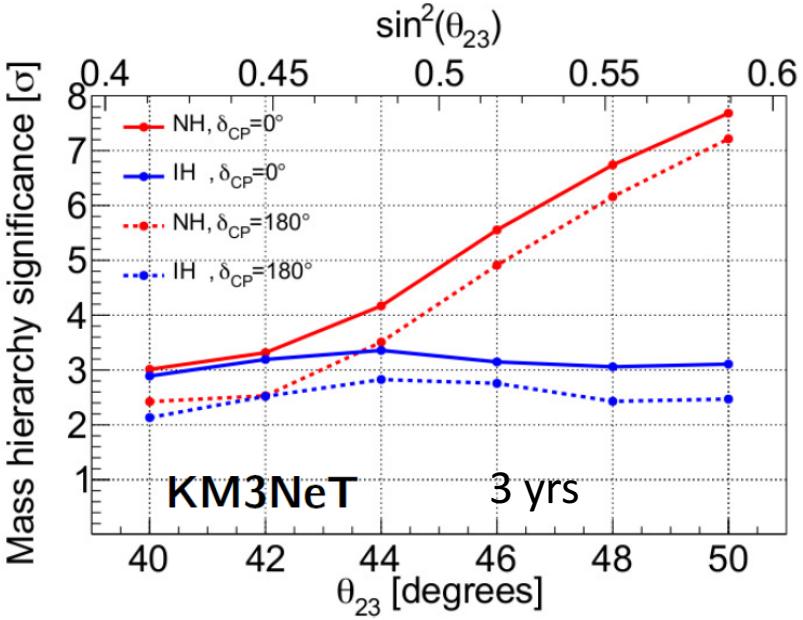
ORCA E,θ resolutions

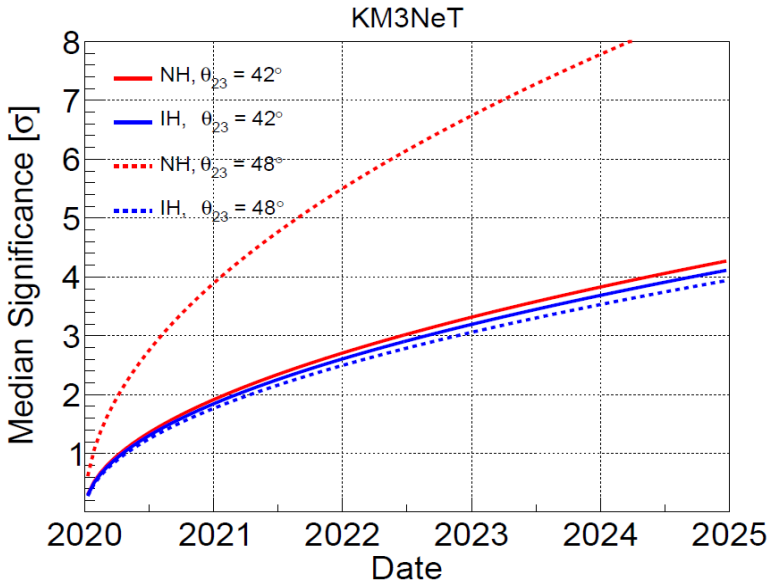




Sensitivity to Mass Hierarchy

- **~3σ** MH sensitivity **in 3 years**
- The combination of **NH and upper octant** of θ_{23} would significantly improve sensitivity (**5σ in 3 years**)
- For IH, sensitivity is essentially independent of θ_{23}
- The value of δ_{cp} has small but non-negligible impact on sensitivity

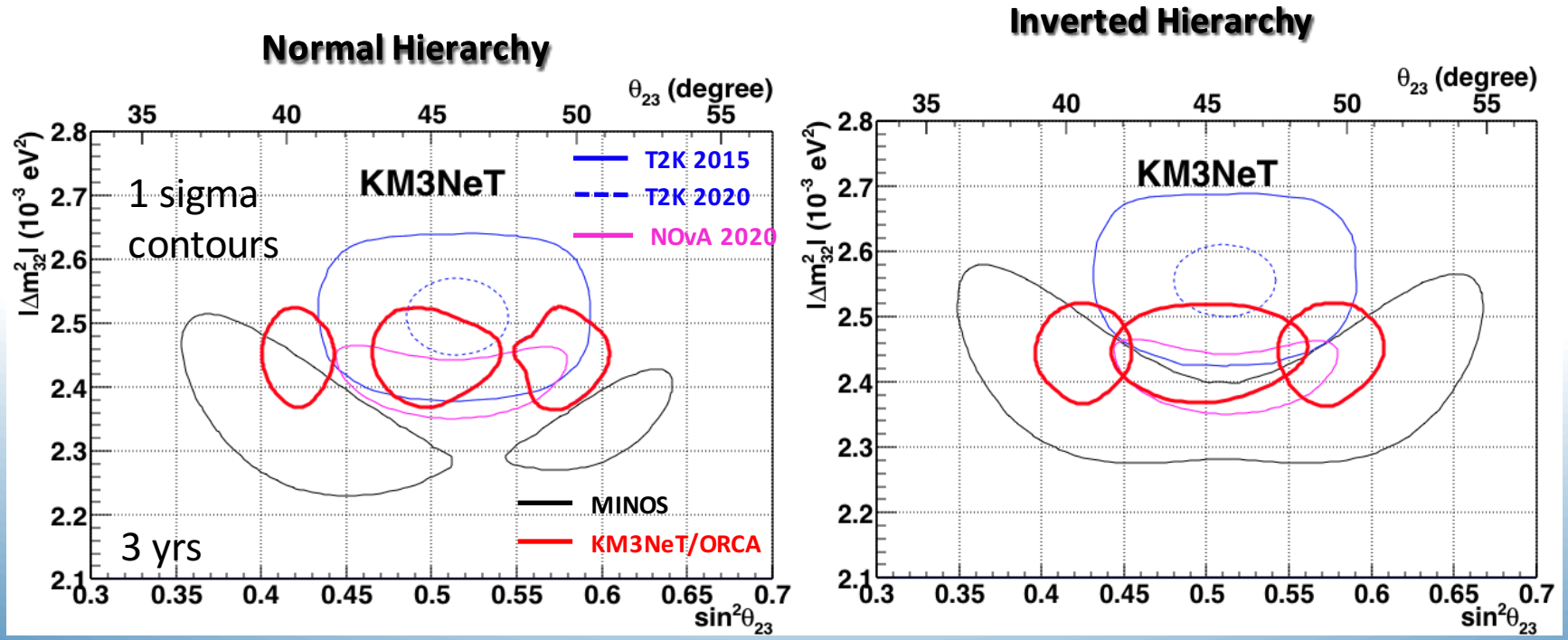




- **Best case** scenario (NH and θ_{23}=48°) could achieve **>5σ by mid 2021** (1.5 years)

Measurement of Δm^2_{32} and $\sin^2\theta_{23}$

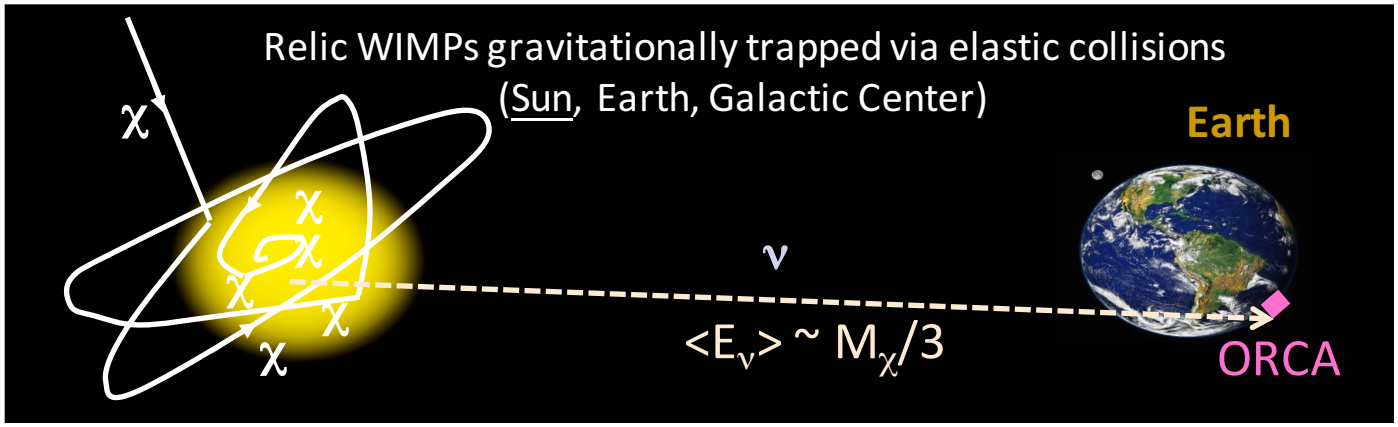
- High statistics and excellent resolution → Measure Δm^2_{32} and $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$



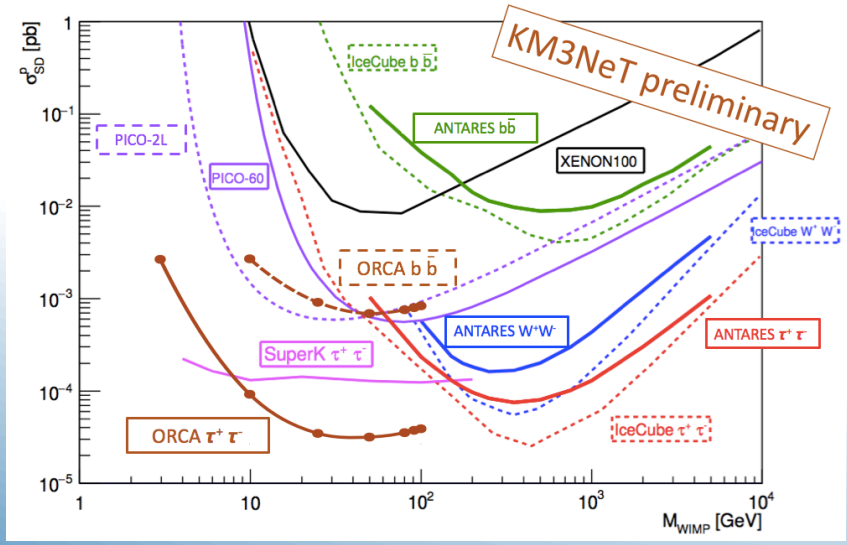
Additional ORCA Physics Topics

- Test NSI, sterile and other exotic physics — 🕮 J. Coelho, P2.026 Neutrino 2016
- **Indirect Search for Dark Matter**
- Earth tomography and composition — 🕮 W. Winter, arXiv:1511.05154
  - Low energy neutrino astrophysics
    - Gamma-ray bursts, Colliding Wind Binaries,.. — 🕮 J. Becker Tjus, arXiv:1405.0471 ...
  - A neutrino beam from Protvino to ORCA — 🕮 J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.
    - NMH and CP phase
  - **Supernovae monitoring**
  - Earth and Sea sciences: oceanography, seismology, bioacoustiques, bioluminescence,..

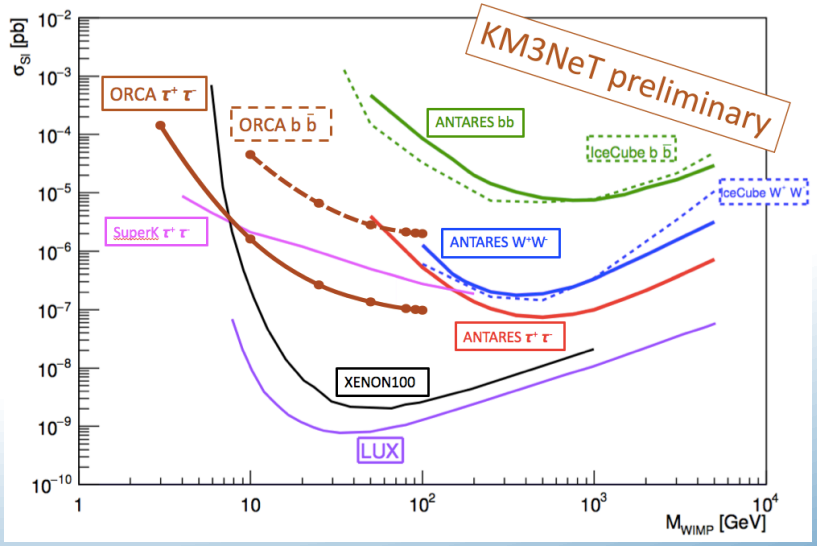
Indirect Detection of Dark Matter



Spin Dependent



Spin Independent



ORCA 3 years - tracks+showers

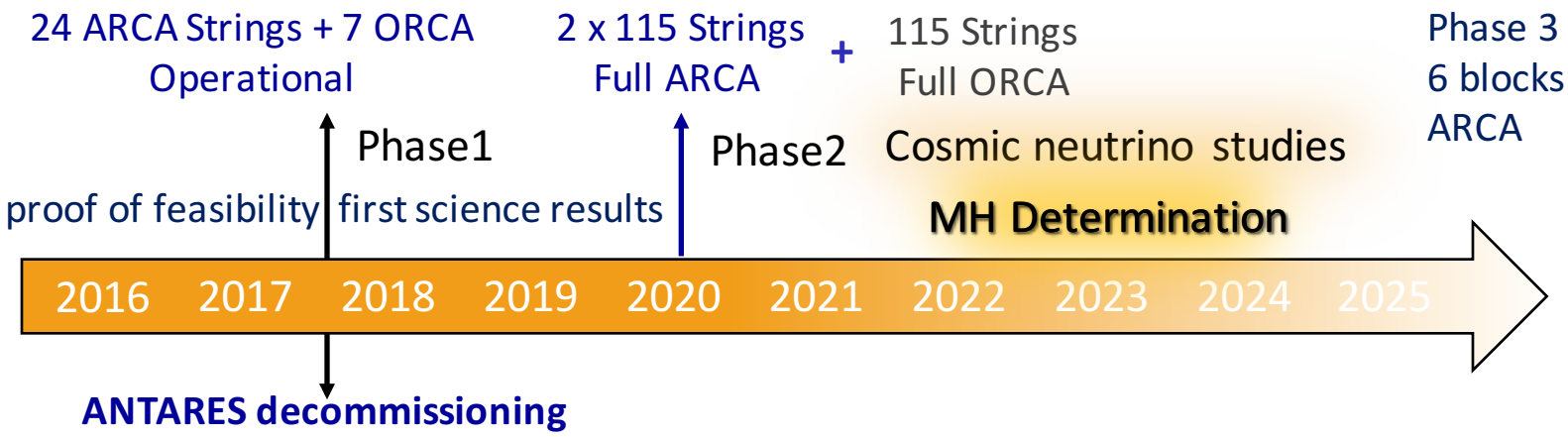
Future multi-messenger programs

following ANTARES

Bringing together the astronomy, astrophysics and particle astrophysics communities.

+SNEWS (low energy neutrinos). Both ORCA and ARCA are promising for the supernovae detection in our Galaxy (optical rate increase in the detector) work is in progress.

Achieved and planned goals



- DOM prototype tested in situ (2500 m) — Eur. Phys. J. C (2014) 74:3056
- DU prototype tested (3 DOMs) in situ (3500 m) — Eur. Phys. J. C (2016) 76: 54
- Detector geometries well defined
- Letter Of Intent is published — J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001
- Data taking at ARCA is ongoing with two DUs already
- ORCA infrastructure is ready to operate the first DUs
- Mass production of the DUs is in preparation (for ORCA and ARCA)
  - Non-critical design changes due to the investigated failure of the ARCA DU3
- KM3NeT 2.0 is in ESFRI Roadmap 2016

Summary and Perspectives

- KM3NeT: phased construction of a next-generation neutrino telescope (ARCA-high energy + ORCA-low energy)
- ORCA
  - Neutrino Telescope optimised for low energy (GeV) atmospheric neutrinos offers prospect of rapid and cost-effective measurement of NMH
  - Worst case scenario (IH, NH/first octant) can determine NMH at 3 sigma level in 3 years. Much quicker if NH/second octant
  - Competitive measurements of Δm^2_{32} and $\sin^2\theta_{23}$ parameters, sterile neutrinos, NSI, low mass dark matter,…
- ARCA
  - Soon provides complementary measurement of IC flux
  - Great capabilities for point-like search (angular resolution <0.2 deg, effective for E>1 TeV) for track events
  - Checks neutrino emission from:
    - Galactic plane (3 sigma in 1.3 years)
    - RXJ1713 (3 sigma in 4 years), Vela X (in 2 years)
    - GC (<4 years to rule out the recent model)
    - Other point and extended candidates from gamma-rays (stacking)
  - New unknown sources (extragalactic/optically thick)
- Multimessenger searches
- Multidisciplinary (bio-, geophysics)
- Developed novel and performant multi-PMT technology
  - interest from Gen2/Pingu, HyperK, NuPrism, …







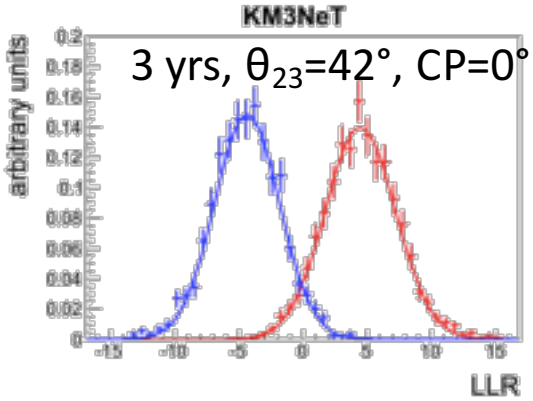
Thank you and stay tuned!

Collaboration meeting in Strasbourg, September 2016

Backup

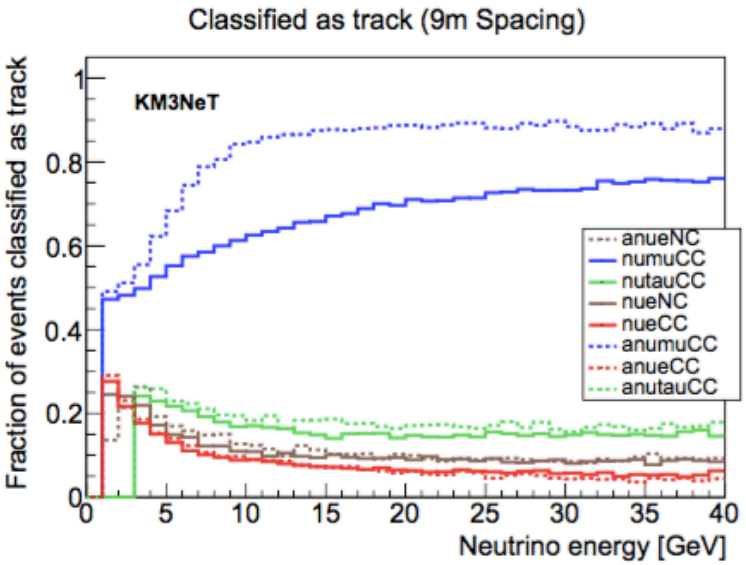
Sensitivity studies

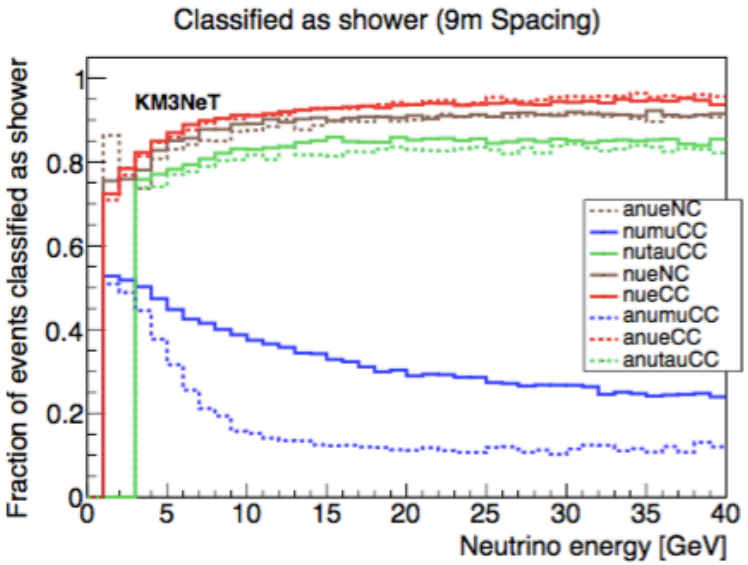
- Pick set of true values for oscillation parameters and other systematics
- Generate pseudo-experiments for NH, IH cases
- Find best-fit likelihoods L_{NH}, L_{IH} for the NH, IH cases (maximising w.r.t. 8/9 free parameters)
- Calculate the log-likelihood ratio log (L_{NH}/L_{IH})



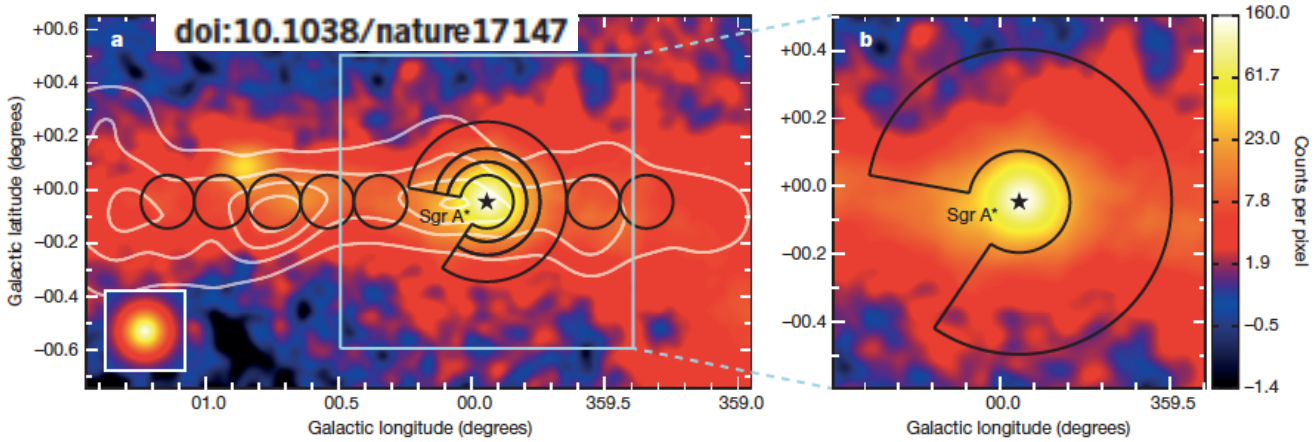
	parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
nu parameters	θ_{23} [°]	$\{40, 42, \ldots, 50\}$	uniform over [35, 55] †	fitted	no
	θ_{13} [°]	8.42	$\mu = 8.42$, $\sigma = 0.26$	fitted	yes
	θ_{12} [°]	34	$\mu = 34$, $\sigma = 1$	nuisance	N/A
	ΔM^2 [10^{-3} eV^2]	$\mu = 2.4$, $\sigma = 0.05$	$\mu = 2.4$, $\sigma = 0.05$	fitted	no
	Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6$, $\sigma = 0.2$	nuisance	N/A
	δ_{CP} [°]	0	uniform over [0, 360]	fitted	no
systematics	overall flux factor	1	$\mu = 1$, $\sigma = 0.1$	fitted	yes
	NC scaling	1	$\mu = 1$, $\sigma = 0.05$	fitted	yes
	$\nu/\bar{\nu}$ skew	0	$\mu = 0$, $\sigma = 0.03$	fitted	yes
	μ/e skew	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes
	energy slope	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes

PID


Classified as track (9m Spacing)
KM3NeT
Fraction of events classified as track
Neutrino energy [GeV]
anueNC
numuCC
nutauCC
nueNC
nueCC
anumuCC
anueCC
anutauCC


Classified as shower (9m Spacing)
KM3NeT
Fraction of events classified as shower
Neutrino energy [GeV]
anueNC
numuCC
nutauCC
nueNC
nueCC
anumuCC
anueCC
anutauCC

Galactic Center & Point sources



Neutrino spectra from Sgr A* estimated from the measured gamma spectra under the hypothesis of pure hadronic mechanism and no absorption for the measured high energy gamma rays.

📖 S. Celli et al., arXiv:1604.08791

Neutrino spectra from the "Pacman" region applying the new (KRA-gamma) scenarios for the galactic CR transport.

📖 Gaggero et al. arXiv:1504.00227

Sensitivity studies are ongoing.