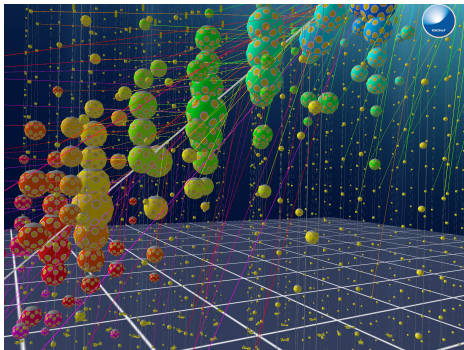


KM3NET AND THE ORCA TELESCOPE

KM3 Neutrino Telescope / Oscillation Research with Cosmics in the Abyss

Contributions of IPHC

Thierry PRADIER



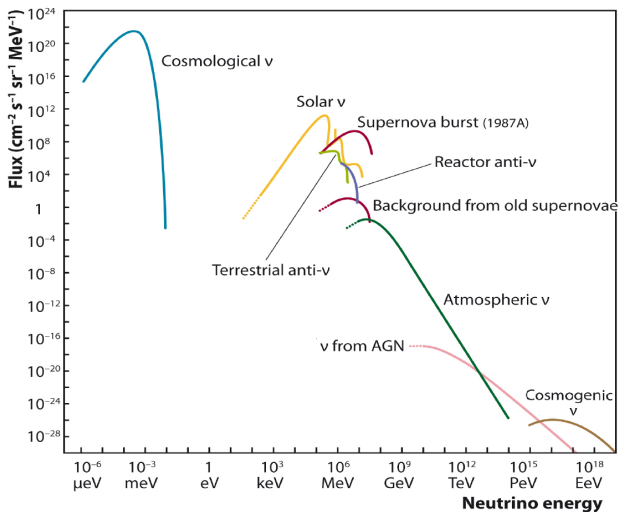
People involved

- Physics :
 - T.P.
 - 2018 : GRPHE - A. Albert - D. Drouhin
 - Post-doc : R. Gracia-Ruiz (ANR)
 - 2017 : Post-doc H2020
 - PhD : M. Organokov
- Technical :
 - S. Kihel (DOM Supervision)
 - C. Weber (DOM Integration)
 - S. Suzanne (Quality)

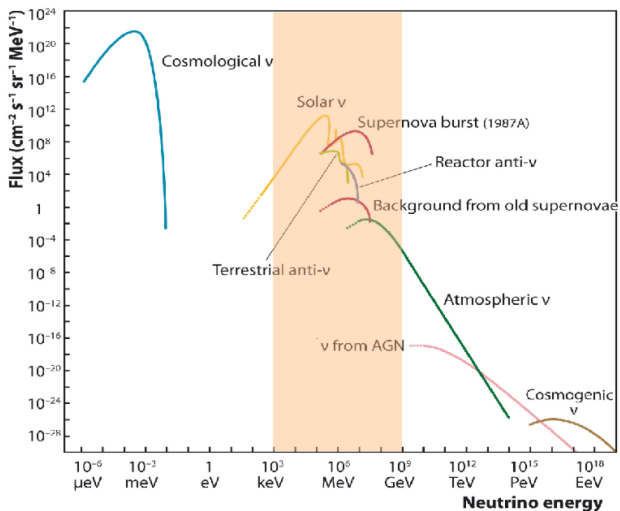
Outline of the Presentation

- 1 Neutrinos & their detection
- 2 Past Contributions to Neutrino Telescopes @ IPHC
- 3 KM3NET/ORCA in a nutshell
- 4 ORCA @ IPHC
- 5 Conclusions

Detecting Neutrinos



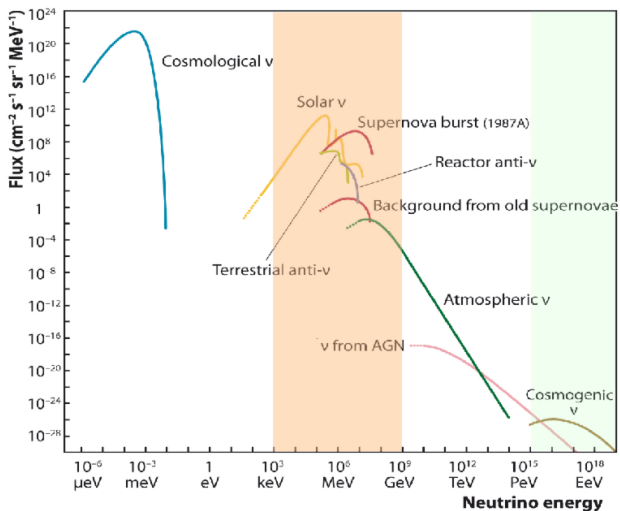
Detecting Neutrinos



Energy $\lesssim 1$ GeV

- Under Rock + Cherenkov techniques : Borexino, Super-Kamiokande,...

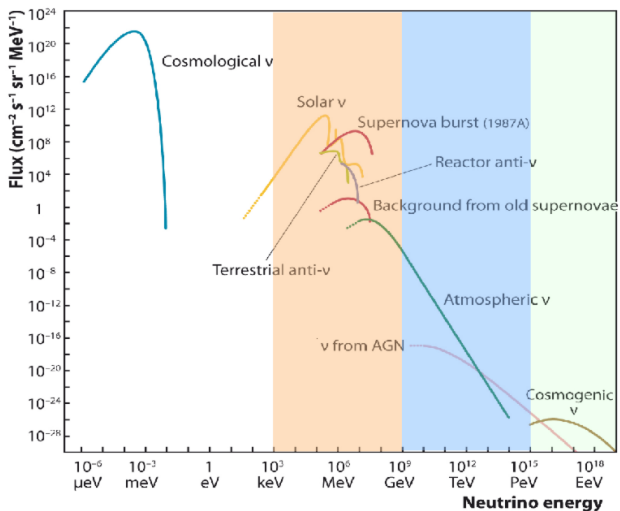
Detecting Neutrinos



Energy $\gtrsim 10^7$ GeV

- Giant Arrays + Acoustics/Radio techniques

Detecting Neutrinos



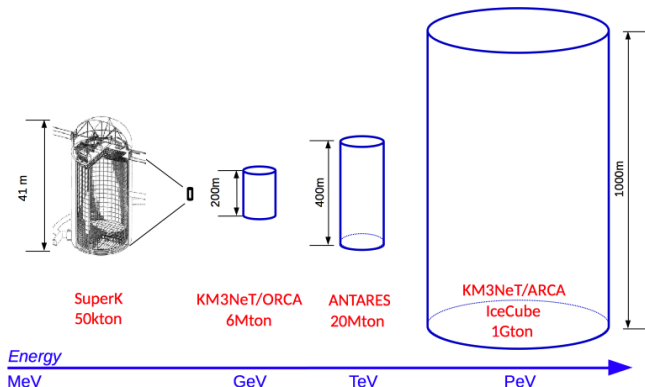
Energy $\in 1 - 10^9$ GeV

- Under Water + Cherenkov techniques

Detecting Neutrinos

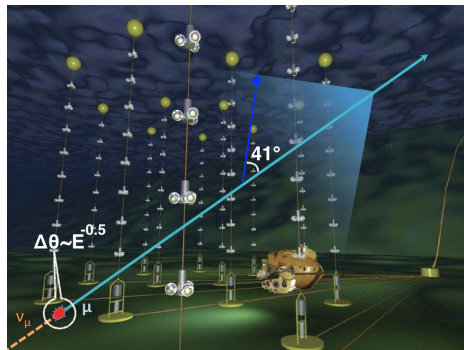
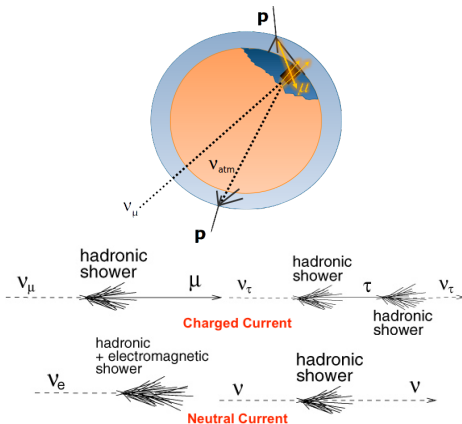
Energy $\in 1 - 10^9$ GeV

- Under Water + Cherenkov techniques



Low Fluxes + Small Cross-Sections \Rightarrow Very large detectors needed

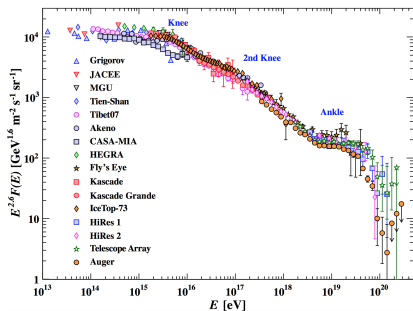
Detecting Neutrinos : Underwater Neutrino Telescopes



Event Topologies

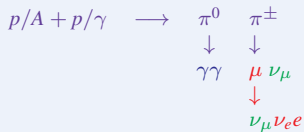
- **Track-like**
 - Cascade + track (ν_μ Charged Currents interactions)
- **Shower-like**
 - 80% of all interactions → Charged Current ν_e, ν_τ + Neutral Currents all flavours

1st Objective : Cosmic Neutrinos TeV-PeV



A Hadronic « radiation »

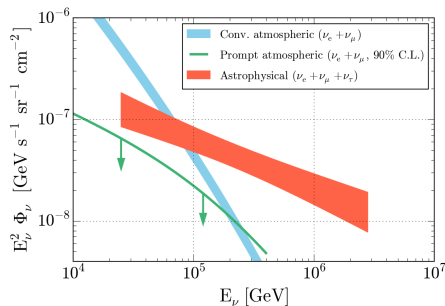
- Neutrinos TeV-PeV are guaranteed



⇒ Neutrinos detected (2013, IceCube)

1st Objective : Cosmic Neutrinos TeV-PeV

Cosmic ν detected, but Sources not identified !



Identify the Sources of Cosmic Rays

⇒ ANTARES : 2006 - 2018

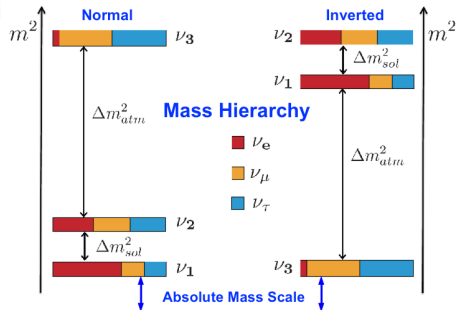
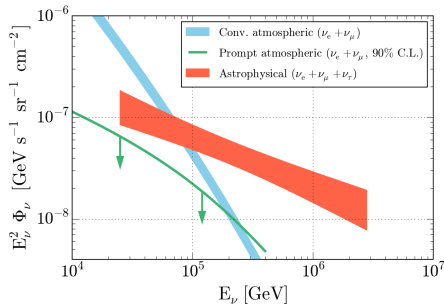
- Astronomy with a Neutrino Telescope and Abyss environmental REsearch

⇒ KM3NeT/ARCA : in Italy, >2016

- Astroparticle Research with Cosmics in the Abyss

2nd Objective : Neutrino Mass Spectrum MeV-GeV

Cosmic ν detected, but Sources not identified !



Identify the Sources of Cosmic Rays

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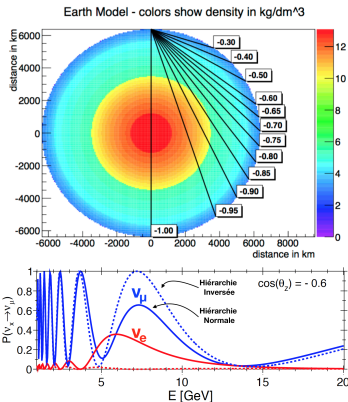
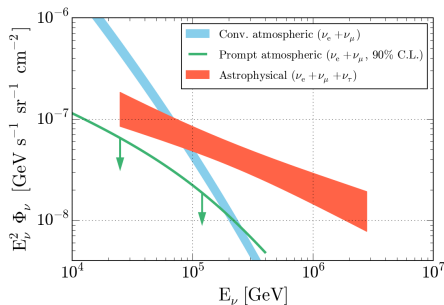
- Astroparticle Research with Cosmics in the Abyss

ν have a mass $\neq 0$

- « Mixing » of neutrinos known
- Neutrino Mass Hierarchy (NMH) unknown
- Absolute Scale unknown

2nd Objective : Neutrino Mass Spectrum MeV-GeV

Cosmic ν detected, but Sources not identified !



Identify the Sources of Cosmic Rays

⇒ ANTARES : 2006 - 2018

- Astronomy with a Neutrino Telescope and Abyss environmental REsearch

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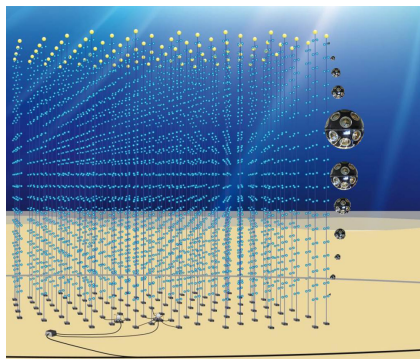
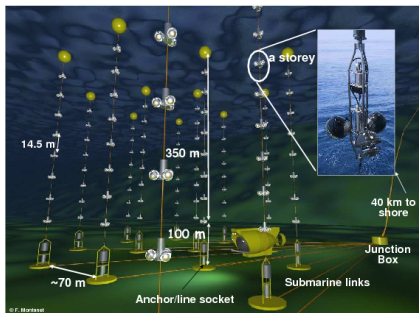
- Astroparticle Research with Cosmics in the Abyss

Atmospheric ν and Mass Hierarchy

⇒ Mass Hierarchy

- ⇒ KM3NET/ORCA : in France, >2017
- Oscillation Research with Cosmics in the Abyss

From ANTARES to KM3NET



ANTARES : TeV-PeV

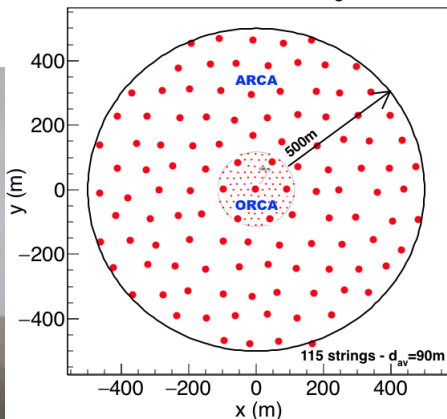
- 40km from Toulon, 2500m underwater
- 12 Lines, 15m between storeys, 70m between lignes
- Operation 2006-2018
- 120 members, 8 countries

At IPHC since 2001

KM3NET : GeV \rightarrow PeV

- Construction (250 members, including IPHC)
- ORCA : Mass Hierarchy GeV
 - \Rightarrow Toulon, 115 Lines
 - \Rightarrow 9m inter-storeys, 20m inter-lines
- ARCA : Cosmics TeV
 - \Rightarrow Sicily, 2 \times 115 lines (36m \times 90m)

From ANTARES to KM3NET



- Elementary Brick : *Digital Optical Module*
- To be produced at IPHC

- Footprint of ARCA/ORCA
- Both part of KM3NET Collaboration

Building on past experiences

1- Understanding the environment : ANTARES [2002-06]

- Data Analysis/Modelling of Excitation of Bioluminescence
 - KM3NeT : Multi-PMTs adapted to study of environment - expertise in Bioluminescence

2- Building the Telescope : ANTARES [2003-08]

- Conception/Production of Front-End Electronics
 - KM3NeT : experience in characterization/mass production/follow-up of production

3- Operating the Telescope : ANTARES [2006-10]

- Time/Charge Calibration
 - KM3NeT : useful expertise in DOMs

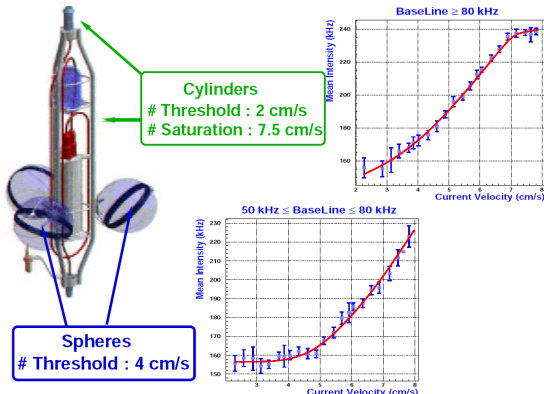
4- Analyzing its data : ANTARES [since 2008]

- Looking for Neutrino Sources : Multi-Messenger Astronomy
 - Gravitational Waves + High Energy Neutrinos (GWHEN) - Supervised by IPHC
 - KM3NeT : Combine ORCA/ARCA data for correlations with Gravitational Waves

Building on past experiences : 1- Understanding the environment

1- Understanding the environment : ANTARES [2002-06]

- Data Analysis/Modelling of Excitation of Bioluminescence with Analysis of Prototype Lines



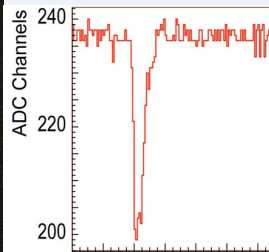
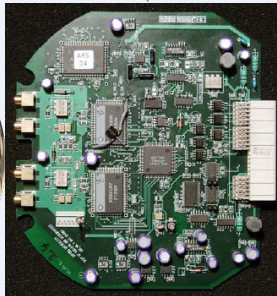
From ANTARES to KM3NeT

- Multi-PMT technology adapted to careful study of bioluminescence

Building on past experiences : 2- Building the Telescope

2- Building the Telescope : ANTARES [2003-08]

- Conception/Production of Front-End Electronics (ARS MotherBoard)



- Characterization, production and follow-up of **900 boards**

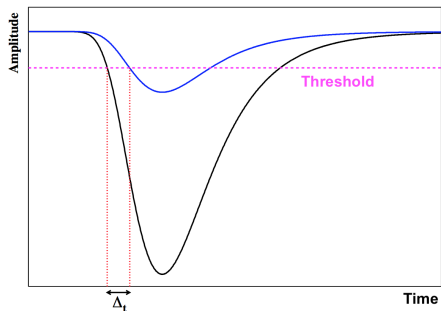
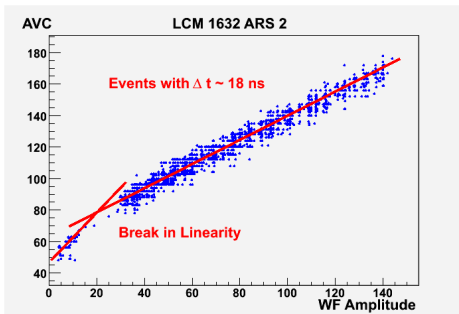
From ANTARES to KM3NeT

- Experience of mass production & follow-up of production

Building on past experiences : 3- Operating the Telescope

3- Operating the Telescope : ANTARES [2006-10]

- Charge Calibration [Linearity of integrator]
- Time Calibration [Walk Effect]



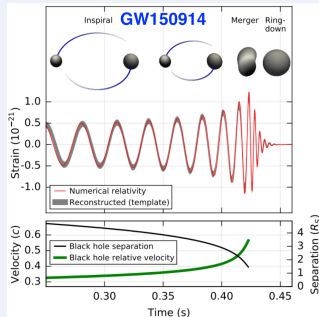
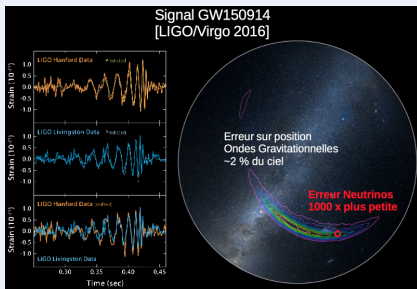
From ANTARES to KM3NeT

- Experience in time/charge calibration \rightarrow useful expertise in DOMs

Building on past experiences : 4- Analyzing the data

4- Analyzing its data : ANTARES [since 2008]

Search for Neutrino "Counterparts" of GW signals with ANTARES



- O1 (09/2015 → 01/2016) : Search for HEN from GW150914, GW151226, LVT151012
- O2 (Since 11/2016) : Search for HEN from GW170104 + Reception of GW Real-Time Alerts

From ANTARES to KM3NeT

- Apply GWHEN analyses to GeV-PeV neutrinos detected with ORCA/ARCA

Vacuum & Matter Oscillations

Mixing Matrix Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{Flavour}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}}_{\text{Atmospherics, } \theta_A \sim 45^\circ} \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}}_{\text{Reactors, } \theta_{13} \sim 10^\circ + \text{CP Phase}} \times \\
 \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, } \theta_\odot \sim 30^\circ} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha}{2} + i\beta} \end{pmatrix}}_{\text{Nature (Majorana/Dirac)}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{Mass}}$$

Oscillations in Vacuum : for ν of energy E_ν travelling a distance L

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right)$$

Not sensitive to the sign of $\Delta m_{31}^2 = m_3^2 - m_1^2$!

Vacuum & Matter Oscillations

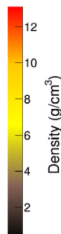
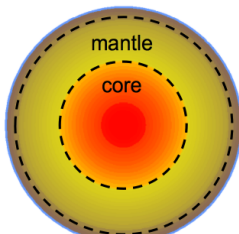
Matter Effects in ORCA modify the Oscillation Probability

$$P^m(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 \left(\frac{\Delta^m m_{31}^2 L}{4E_\nu} \right),$$

$$\sin^2 2\theta_{13}^m \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m_{31}^2}{\Delta^m m_{31}^2} \right)^2, \quad \Delta^m m_{31}^2 \equiv \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - 2E_\nu V_{\text{eff}})^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

- P^m maximal when $\Delta^m m_{31}^2$ minimal for ν in NH/ $\bar{\nu}$ in IH at energy $[V_{\text{eff}} = \pm\sqrt{2}G_F N_e]$:

$$E_{\text{res}} \equiv \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2V_{\text{eff}}} \simeq 7 \text{ GeV} \left(\frac{4.5 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \underbrace{\cos 2\theta_{13}}_{\theta_{13} \text{ Measured in 2012} \approx 10^\circ}.$$



- $E_{\text{mantle}} = 7 \text{ GeV}$
- $E_{\text{core}} = 3 \text{ GeV}$

Vacuum & Matter Oscillations

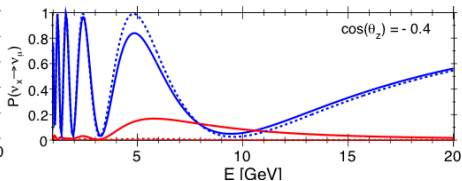
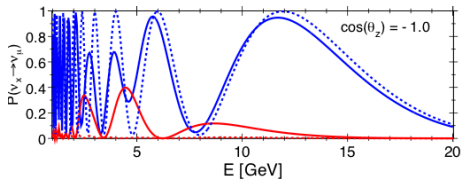
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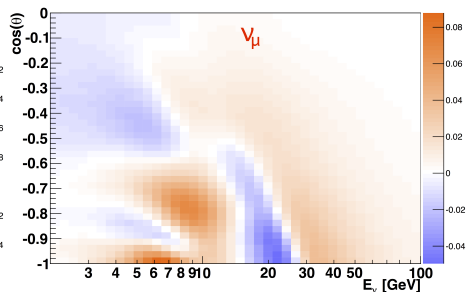
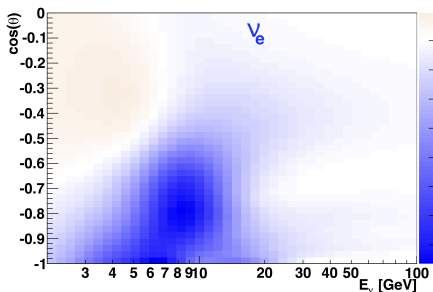
Oscillation Patterns

$$\nu_\mu \rightarrow \nu_e [1 - 15 \text{ GeV}]$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau [5 \text{ GeV} - 5 \text{ TeV}]$$

J. Coelho (APC)

Oscillation Patterns

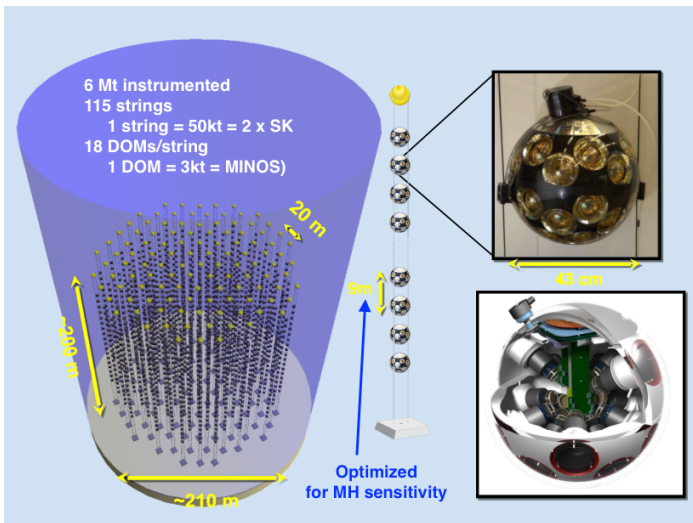


$$\text{Asymmetry } (\nu_e/\nu_\mu) : \mathcal{A} = \frac{N_{IH} - N_{NH}}{\sqrt{N_{NH}}}$$

↪ $\sigma_\nu \approx 2 \times \sigma_{\bar{\nu}}$ + Differences in ν_e, ν_μ in Atmospheric spectrum

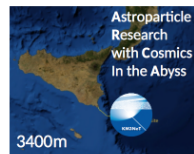
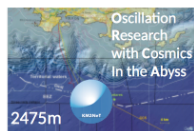
↪ Requires large statistics and good energy/angular resolutions

The KM3NeT Collaboration & Status

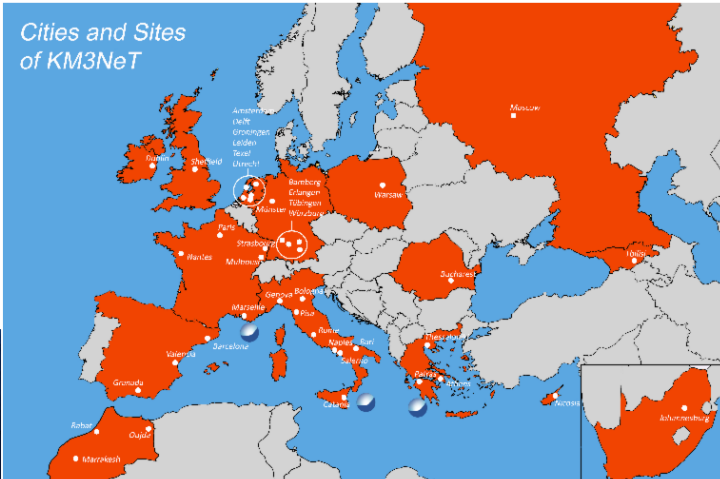


Spacings/Geometry optimized for MH sensitivity

The KM3NeT Collaboration & Status



Cities and Sites of KM3NeT



Already 3 ARCA strings deployed (2015-2016)
 First ORCA string deployed in 2017 → 6 in 2018

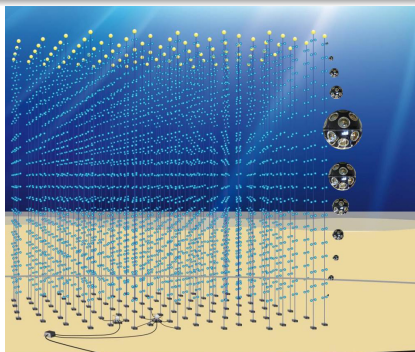
The KM3NeT Collaboration & Status

Phase - 1 = 7+24 strings - 31 M€ -funded

- France : 7M€+ Netherlands : 8M€+ Italy : 16M€

Phase - 2 = 115+230 strings - +95M€

- France : 8.1M€+ 10-20M€PIA-3
- Netherlands : 14M€ + Italy : 28M€+ 40M€
- Germany : 1.2M€ + Canada : 2M€ + Spain, Korea, UK...



The KM3NeT Collaboration & Status

IN2P3 Contributions

- **CPPM - KM3NeT Physics Coordinator + ORCA Site Manager + Equipment Qualification + Detector Operations**

- ↳ Seabed infrastructure, Onshore DU Calibration, Instrumentation Unit
- ↳ Base Container + Anchor, LOM Loading, DU deployment/connection
- ↳ Detector Operations + Anti-Biofouling

- **APC - ORCA Physics Coordinator**

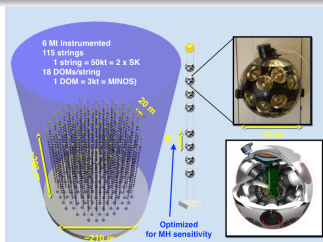
- ↳ Calibration Unit, DOM Characterization + Base Container ?

- **Subatech (since Dec. 2016)**

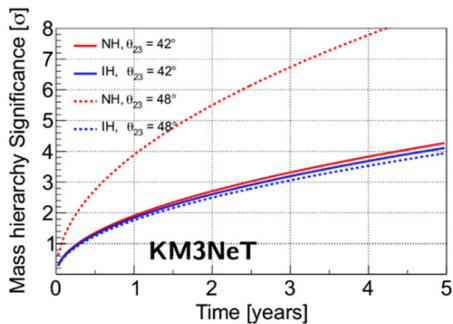
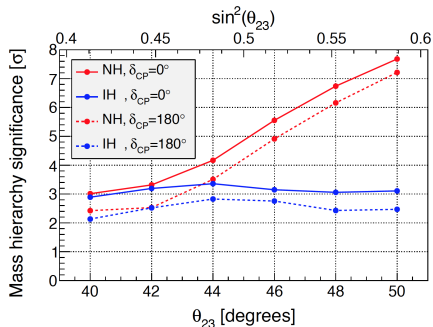
- ↳ Anti-biofouling, Filter-DOM + DOM Integration

- **IPHC**

- ↳ Wavelength-Shifting DOM
- ↳ DOM Integration + VEOC Integration ?



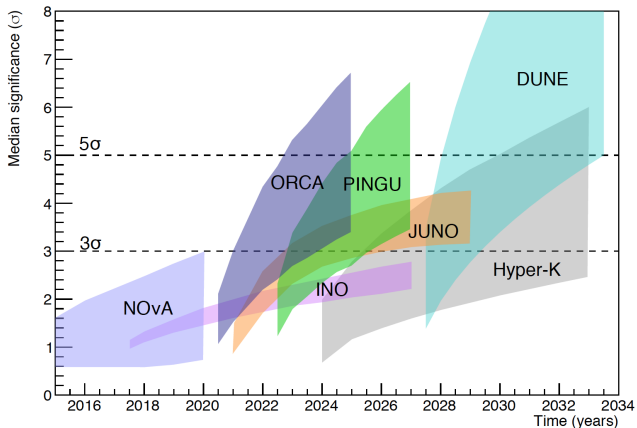
Projected Sensitivity for ORCA



KM3NeT 2.0 : Letter of Intent for ARCA and ORCA, J. Phys. G-Nucl. Part. Phys. 43 (2016) 084001

Projected Sensitivity for ORCA

Expected sensitivities vs. time

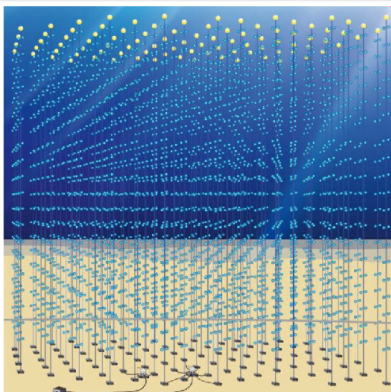


With both JUNO and ORCA, IPHC will play a leading role
in the determination of the Neutrino Mass Hierarchy !

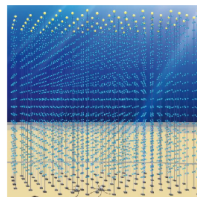
KM3NET/ORCA @ IPHC : Feasibility Study (2012 → 2015)

2012 : $\theta_{13} \approx 9^\circ$ [Reactors : $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$]

- $E_{\text{resonance}}^{\text{matter}} \propto \cos 2\theta_{13} \approx 5 \text{ GeV}$ in Earth
 ⇒ Possible Determination of MH with atmospheric GeV neutrinos, with Neutrino Telescopes
- Birth of "ORCA" concept : denser telescope, for GeV ν



2012



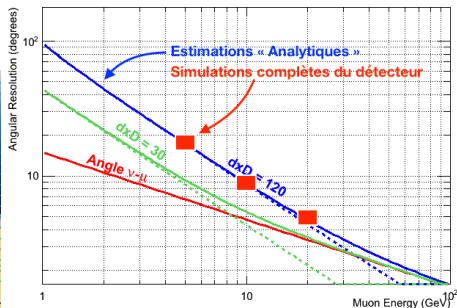
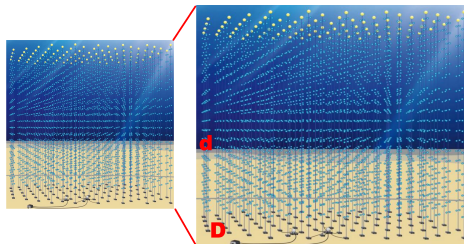
KM3NET/ORCA @ IPHC : Feasibility Study (2012 → 2015)

2012 : $\theta_{13} \approx 9^\circ$ [Reactors : $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$]

- Birth of "ORCA" concept : denser telescope, for GeV ν

2012 - 2013 : 1st estimates of ORCA sensitivity

- Contribution : scaling laws ("first principles") for angular/energy resolutions



- Analytical estimates very close to estimates with complete simulations

KM3NeT/ORCA @ IPHC : Feasibility Study (2012 → 2015)

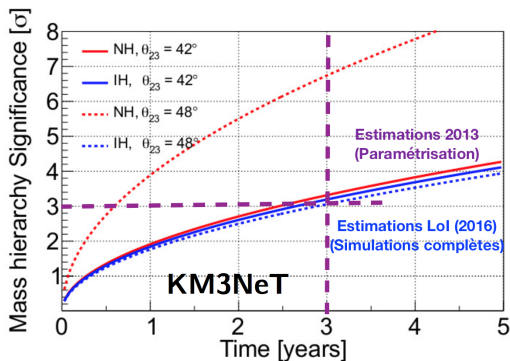
2012 : $\theta_{13} \approx 9^\circ$ [Reactors : $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$]

- Birth of "ORCA" concept : denser telescope, for GeV ν

2012 - 2013 : 1st estimates of ORCA sensitivity

- 2013 - First estimates of ORCA sensitivity at IPHC/APC (A. Meregaglia, C. Jollet)

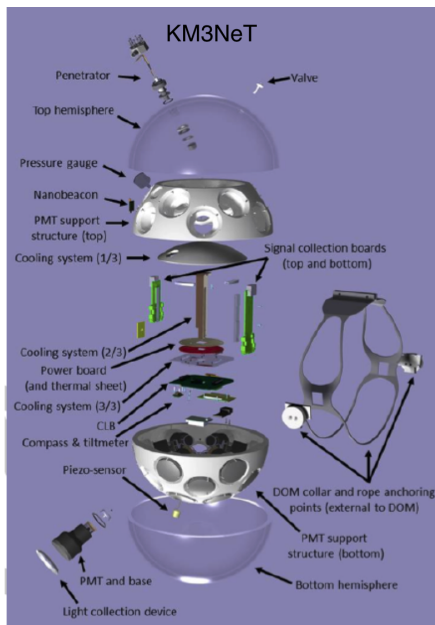
⇒ Mass hierarchy determination with atmospheric neutrinos in large volume ice/water Cherenkov detectors, D. Franco et al. - JHEP 2013, 4 (2013)



The DOM, elementary brick of ORCA



The DOM, elementary brick of ORCA



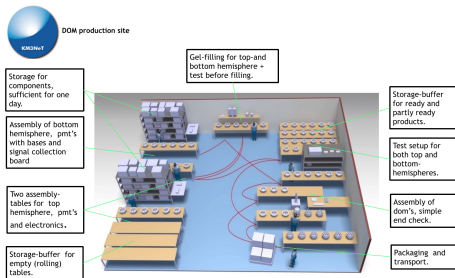
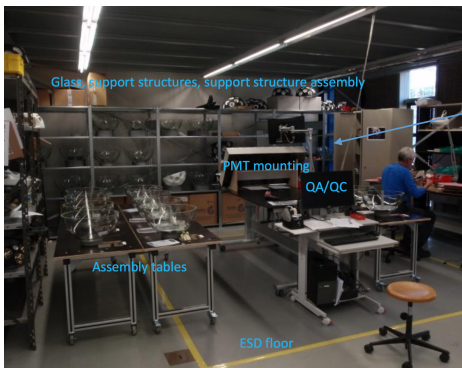
The DOM, elementary brick of ORCA



IPHC proposed as Integration Site in late 2016

- At least 4 others : NIKHEF (NL), Erlangen (DE) + Nantes (in progress) + Rabat (Marocco, in progress)
- 2070 DOMs in 3 years → requested "plateau" production rate = 20 DOM/month
- **Reachable at IPHC with 1 additional Technical Staff**

DOMs @ IPHC



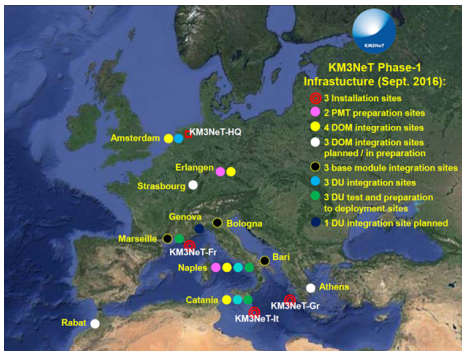
Installation Status - June 2017

- People involved :
 - S. Kihel - involvement in DOM Integration Review (2016-17) - 80%
 - C. Weber - installation & integration - 100% + S. Suzanne - Quality - 30%
- Storage & Integration Facilities : 15k€ (Budget : Lab)
- Tools : ≈ 50k€ (Budget : Regional Funds PACA)
- LED Lighting : 4k€ (Budget : AP IN2P3 to ORCA-IPHC)

DOMs @ IPHC : reinforcing the Technical Team

DOM Integration : Need for reinforcement

- DOM desired production rate **is not reachable** with current staff
 - ⇒ Maximum "plateau" rate 10 DOM/month in a few months
- DOM integration on Vertical Electro-Optical Cable (VEOC) is on **Critical Path**
 - ⇒ **VEOC integration at IPHC requested from IN2P3**

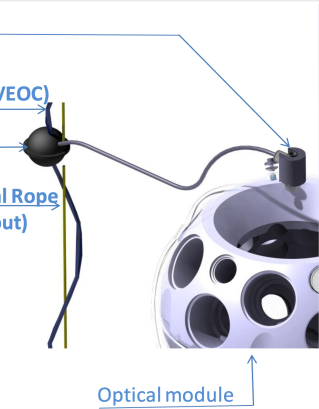


3) Penetrator

2) Backbone (VEOC)

Break out box

1) Mechanical Rope (rope layout)



DOMs @ IPHC : reinforcing the Technical Team

DOM Integration : Need for reinforcement

- DOM desired production rate **is not reachable** with current staff
 - ⇒ Maximum "plateau" rate 10 DOM/month in a few months
- DOM integration on Vertical Electro-Optical Cable (VEOC) is on **Critical Path**
 - ⇒ **VEOC integration at IPHC requested from IN2P3**

		2017												2018																																
Date		Jun 17	Jul 17	Aug 17	Sept 17	Oct 17	Nov 17	Dec 17	Jan 18	Feb 18	Mar 18	Apr 18	May 18	Jun 18	Jul 18	Aug 18	Sept 18	Oct 18	Nov 18	Dec 18	Jan 19																									
Weeks		1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4																									
Room		Equipment			OK																																									
Material		Tools making/ordering			OK																																									
Staff		Documentation			Training			Learning			Improving			Routine																																
NOW	DOM Rate/month				DOM0			1-2			3			10			0			10						10			0			10			0			0								
NOW	VEOC	Equipment, Tools, Training												DU 1									DU 2									DU 3														
NOW	DOM Produced							2						11						41									51						66											
+1	DOM Rate/month				DOM0			1-2			4			20			0			0			20						20			0			20			0			0			20		
+1	VEOC	Equipment, Tools, Training												DU 1			DU 2									DU 3						DU 4			DU 5			DU 6								
+1	DOM Produced							2						14						74												114						124								

With 1 additional Technical Staff

DOMs @ IPHC

DOM Integration : Need for reinforcement

- DOM desired production rate **is not reachable** with current staff
 - ⇒ Maximum "plateau" rate 10 DOM/month in a few months
 - ⇒ **In 2020/2022 : -270/-490 DOMs** if no reinforcement
- DOM integration on Vertical Electro-Optical Cable (VEOC) is on **Critical Path**
 - ⇒ **VEOC integration at IPHC requested from IN2P3**
 - ⇒ **In 2020/2022 : -15/-27 lines** if no reinforcement

		2019	2020	2021	2022
Current Staff	DOM	174	284	394	504
	VEOC	9	15	21	28
	%ORCA	8	13	18	24
Staff+1	DOM	331	551	771	991
	VEOC	18	30	42	55
	%ORCA	16	26	37	48

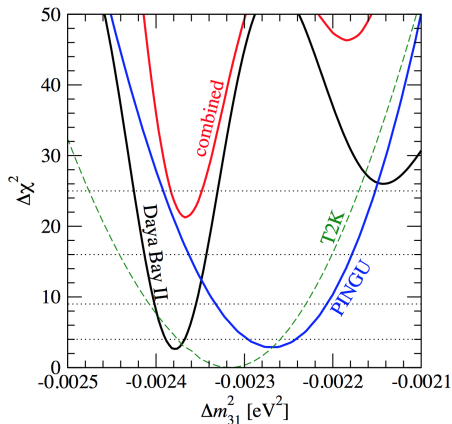
With 1 additional Full-Time Technical Staff

IPHC could produce up to 30% → 50% of ORCA in 3 → 5 years !

Without 1 additional Full-Time Technical Staff

ORCA will miss at least 15/27 lines in 2020/2022

Physics : Improving the sensitivity to the NMH



- When data analyzed with wrong NMH, best fit at \neq values of parameters
- Wrong NMH can be excluded by mismatch of the fitted values
- ↪ excellent accuracy for measurements in both experiments

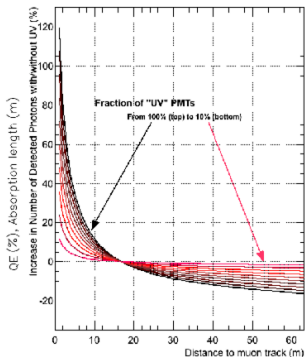
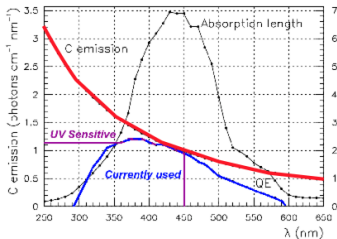
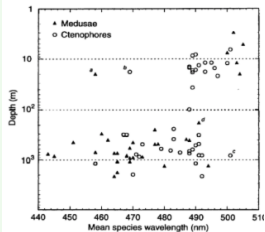
Synergy with JUNO (>2020)

M. Blennow & T. Schwetz, JHEP09(2013)089

⇒ Assess ORCA-JUNO synergy (Post-doc)

ORCA and beyond : towards sub-GeV Physics

UV Cherenkov Photons & Bioluminescence



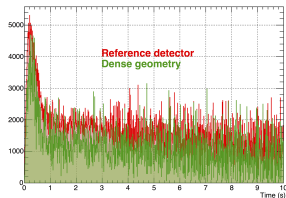
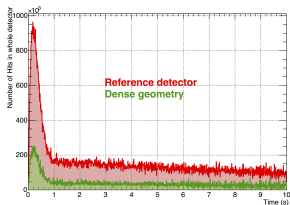
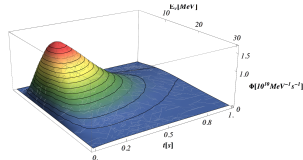
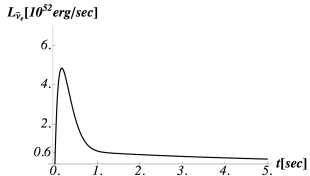
Development of UV DOMs

- Would allow to discard bioluminescent photons \Rightarrow lower Optical Background
- Increase Number of Cherenkov Photons detected/event
 - \Rightarrow Increase in NMH Sensitivity (to be assessed)

ORCA and beyond : towards sub-GeV Physics

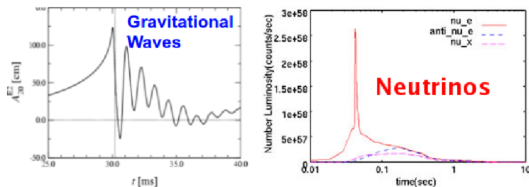
ORCA-UV/Denser Geometry : MeV Neutrinos from Type II Supernovae

- ORCA-UV/Denser Geometry : Increase in Number of Photons/event
 - ⇒ Increased sensitivity to MeV-GeV neutrinos
 - ⇒ To be assessed with 50-MeV Michel Electrons with ORCA



T. Pradier, HDR (2015)

ORCA and beyond : towards sub-GeV Physics



ORCA/Denser Geometry : towards the Neutrino Absolute Mass Scale

- Coincidence with Gravitational Waves during a Type II Supernova

$$\Delta t_{\nu-GW} = \Delta t_{\text{mass}} + \Delta t_{\bar{\nu}_e-\text{bounce}} - \Delta t_{\text{GW-bounce}}$$

$$\Delta t_{\text{mass}} \approx 5.15 \text{ms} \left(\frac{m_{\nu}}{c^2} \right) \left(\frac{10 \text{ MeV}}{E_{\nu}} \right)^2$$

- ⇒ Possible determination of Absolute Mass Scale
- ⇒ Access to full Mass Spectrum of Neutrinos !

N. Arnaud et al., Phys.Rev. D65 (2002) 033010

KM3NET & ORCA : a very rich physics program !

1 - Building & Operating ORCA !

- Objective = **Reach in 2018 the rate 5 DOMs/week**
 - ⇒ **Only possible with 1 additional Technical Staff**
- Integrate the produced DOM on VEOC before sending to CPPM
 - ⇒ **Only possible with 1 additional Technical Staff**
- Deployment of complete Telescope → end 2020
 - ⇒ Time/Charge Calibration - use of DOM expertise

2 - Determining the NMH - Synergy ORCA+JUNO

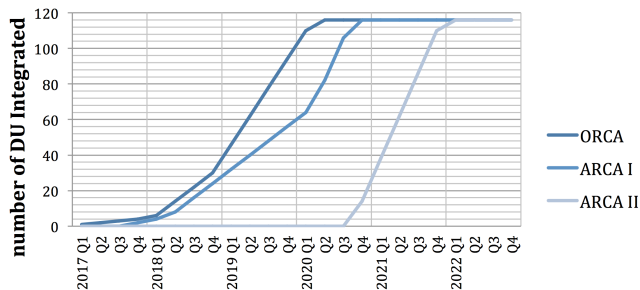
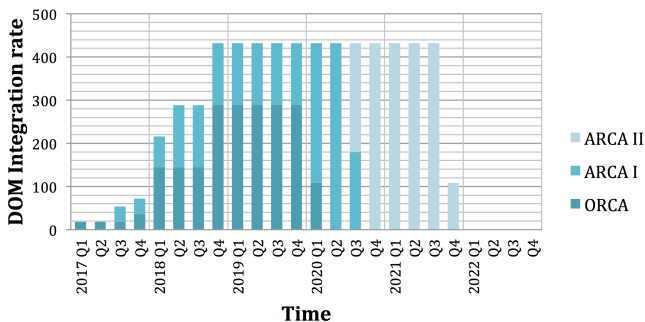
- Different Beams/Detectors, different systematics
- **Collaboration with JUNO members from IPHC** - Double expertise ORCA/JUNO

3 - UV-ORCA+VIRGO/LIGO : Neutrino Absolute Mass Scale

- R&D of *Wavelength-Shifting Materials* deposited on DOMs : $N_{\text{photons}}^{\text{Cherenkov}} \times 4$
- ORCA to access the whole Neutrino Mass Spectrum

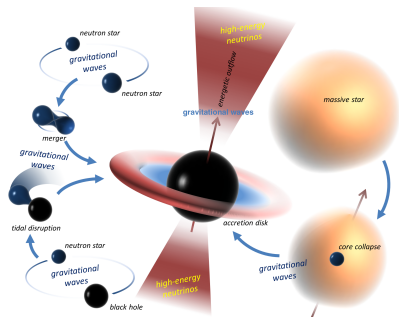
Ambitious Physics Program justifies a reinforcement in Physicists
IPHC can become leader in NMH determination, with ORCA & JUNO

DOM & DU Production Rates [Official]

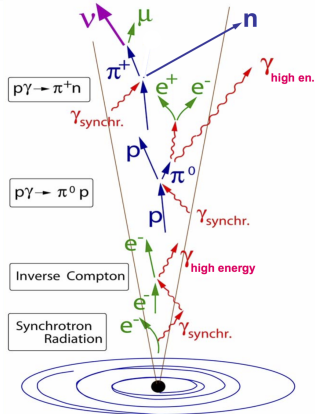


Physics : ORCA, ARCA and VIRGO/LIGO

Combine ORCA/ARCA - from GeV to PeV



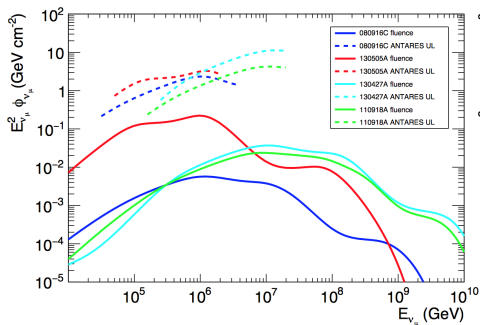
Gravitational Waves



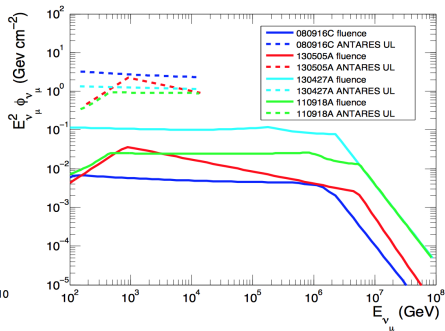
Neutrinos

ORCA/ARCA+VIRGO/LIGO : understanding the connection Collapse \rightarrow Ejection

Physics : Combining ORCA and ARCA - ν Astronomy from GeV to PeV



TeV-PeV with ARCA

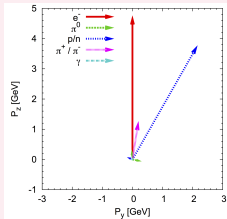
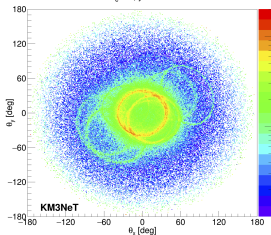
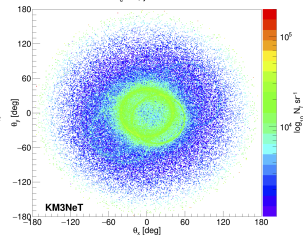


GeV with ORCA

Combine ORCA+ARCA for the identification of Neutrino Cosmic Sources, from GeV to PeV

Physics : Improving the Sensitivity to the NMH

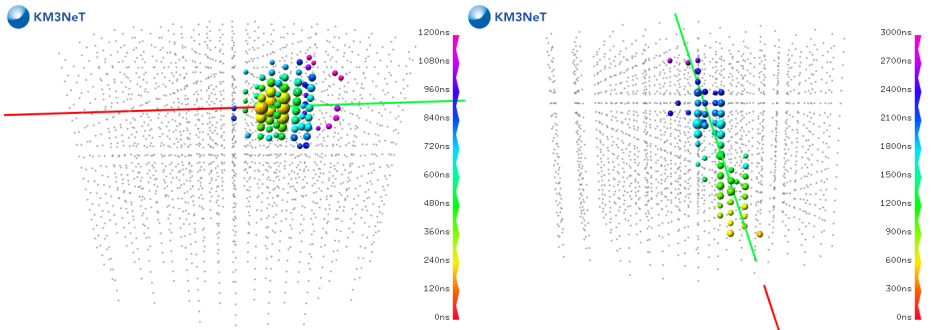
Multi-Particle Reconstruction

10 GeV ν_e CC, $y=0.5$ in water at 20m10 GeV ν_e CC, $y=0.5$ in water at 50m

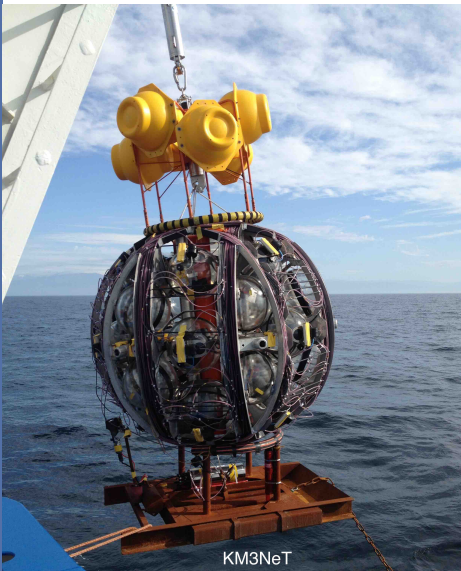
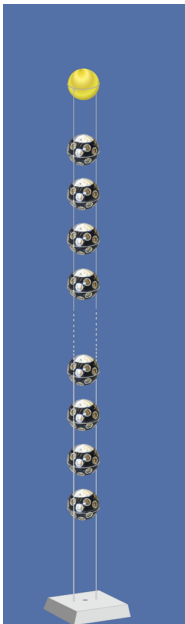
Develop algorithms for multi-particle reconstruction → improvement of sensitivity

KM3NeT 2.0 : Letter of Intent for ARCA and ORCA, J. Phys. G-Nucl. Part. Phys. 43 (2016) 084001

Events

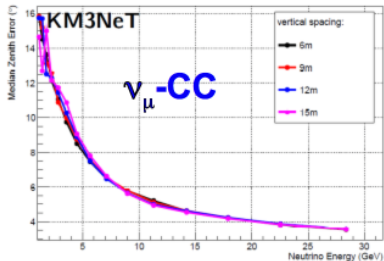


Detection Units

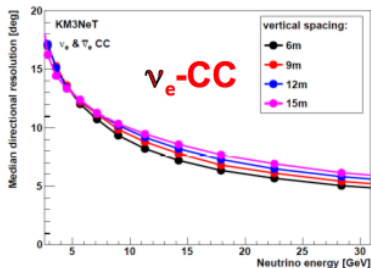


Performances

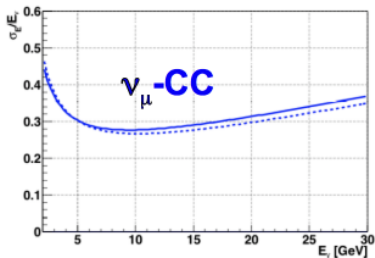
θ Res.



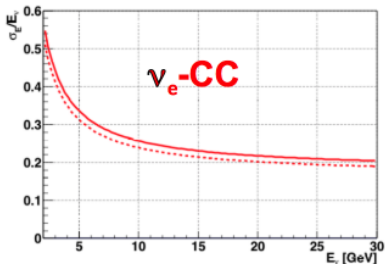
θ Res.



E Res.

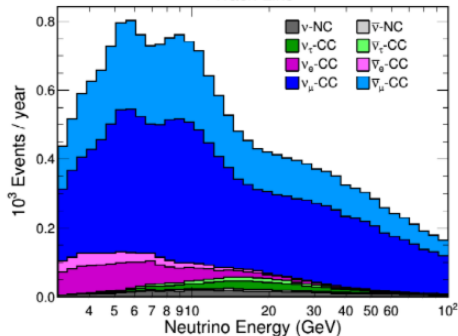


E Res.

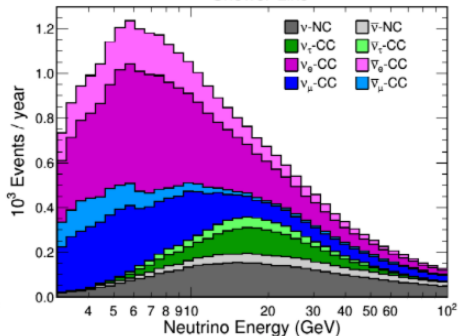


Performances

Track-Like



Shower-Like



Parameters & Systematics

Table 14. Default parameter settings used for the LLR analysis. Where μ and σ are given, they refer to a Gaussian distribution.

Parameter	True value distr.	Initial value distr.	Treatment	Prior
θ_{23} ($^\circ$)	{40, 42, ..., 50}	uniform over [35, 55] †	Fitted	No
θ_{13} ($^\circ$)	8.42	$\mu = 8.42, \sigma = 0.26$	Fitted	Yes
θ_{12} ($^\circ$)	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} ($^\circ$)	0	Uniform over [0, 360]	Fitted	No
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

Note. The † indicates that the initial values for θ_{23} are generated in a special way: a total of seven initial values is tried. They are $x + i \times 5^\circ$, where x is the randomly drawn value and $i \in [-3, -2, \dots, 3]$.