**GDR Neutrinos, Grenoble, June 7th 2016**

Claude Vallée (CPPM-Marseille and DESY-Hamburg)

# FERMILAB NEUTRINOS INTO the PACIFIC

## *Towards a high precision measurement of CP violation in the neutrino sector ?*

1. **An outstanding triangular conjunction**
2. **Semi-quantitative investigation of its potential**
3. **A possible roadmap towards a project**

*Plots and numbers based on:*

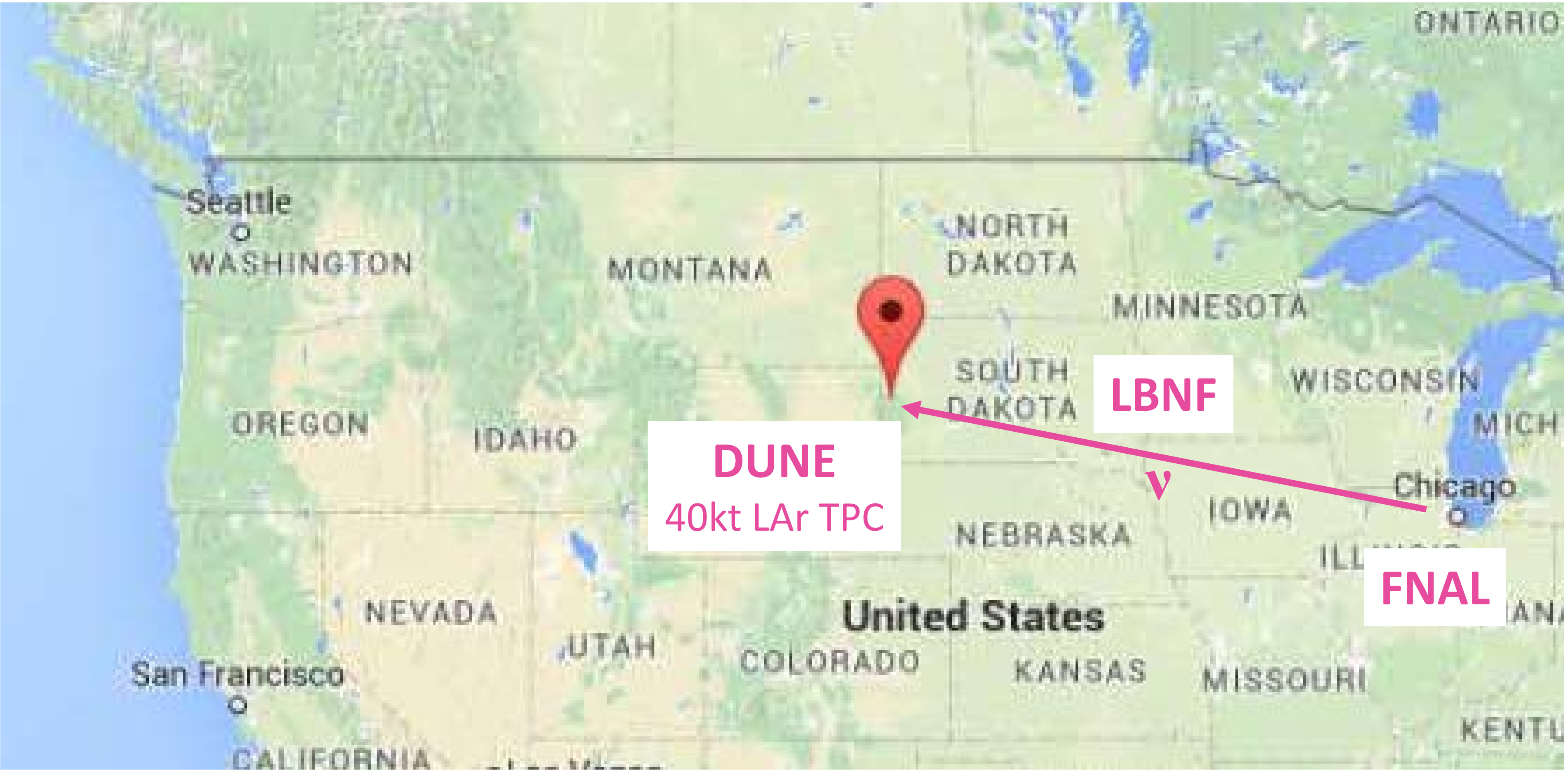
LBNO studies (arXiv:1412.0593 [hep-ph]) and KM3NeT/ORCA LOI (arXiv:1601.0745 [astro-ph.IM])

*(See also pioneering work from Jürgen Brunner: arXiv:1304.6230 [hep-ph])*

**NB: all estimations are orders of magnitudes derived "on the back of the envelope",**
***to be checked with detailed computations and simulations***

# AN OUTSTANDING TRIANGULAR CONJUNCTION : input 1

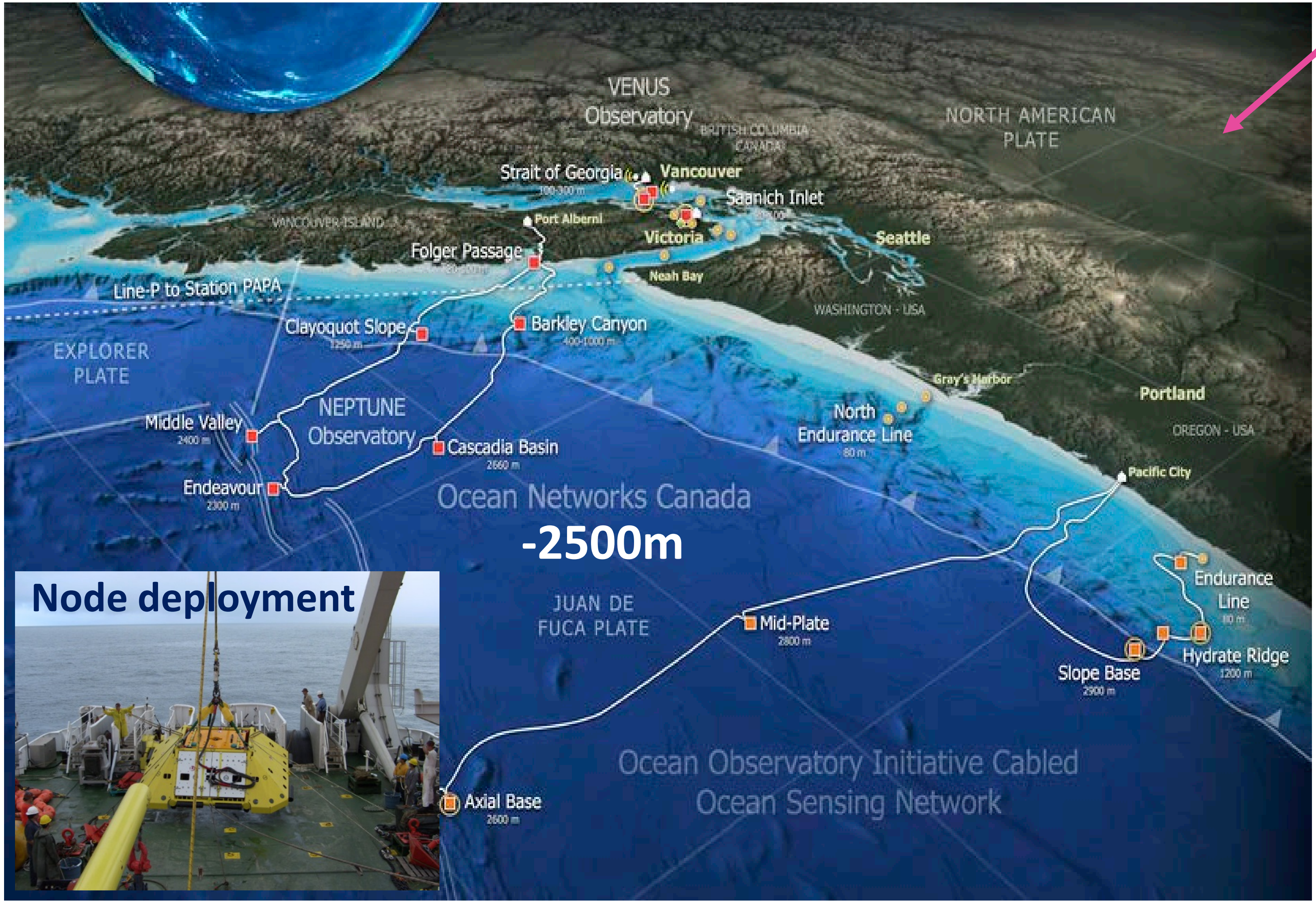
## Establishment of FNAL as a long term worldwide neutrino facility




***A facility to be exploited during decades in regard of the o(1G$) investment***

# AN OUTSTANDING TRIANGULAR CONJUNCTION : input 2

## NEPTUNE (Canada) and OOI (US) deep sea cabled observatories





## Off shore of Vancouver/Seattle

**World-wide unique infrastructure and logistics available to provide :**

- **deep sea operation tools (vessels, ROVs, etc…)**
- **electric power to the deep sea**
- **large data flow to shore**

**within long term environmental observatories, at a depth similar to the ANTARES neutrino telescope**

# AN OUTSTANDING TRIANGULAR CONJUNCTION : input 3

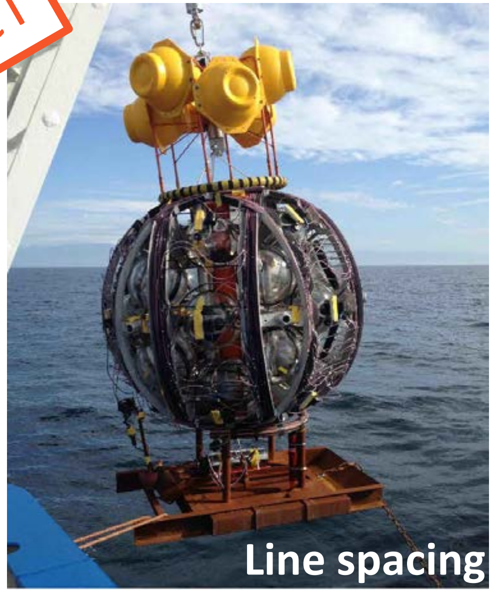
## ANTARES

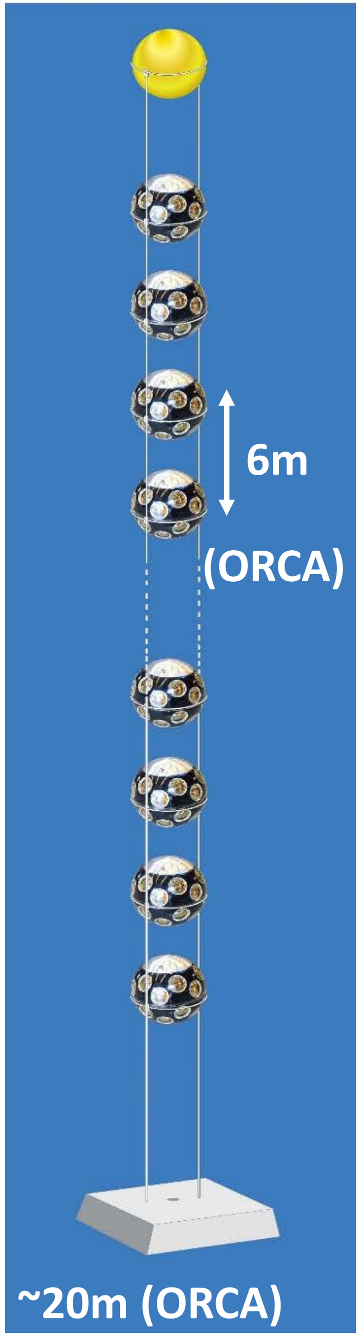
Proof of long term reliability (10 years) of deep sea optical instrumentation for a $\nu$ telescope ($E_{\nu}$ > 20 GeV)

## KM3NeT

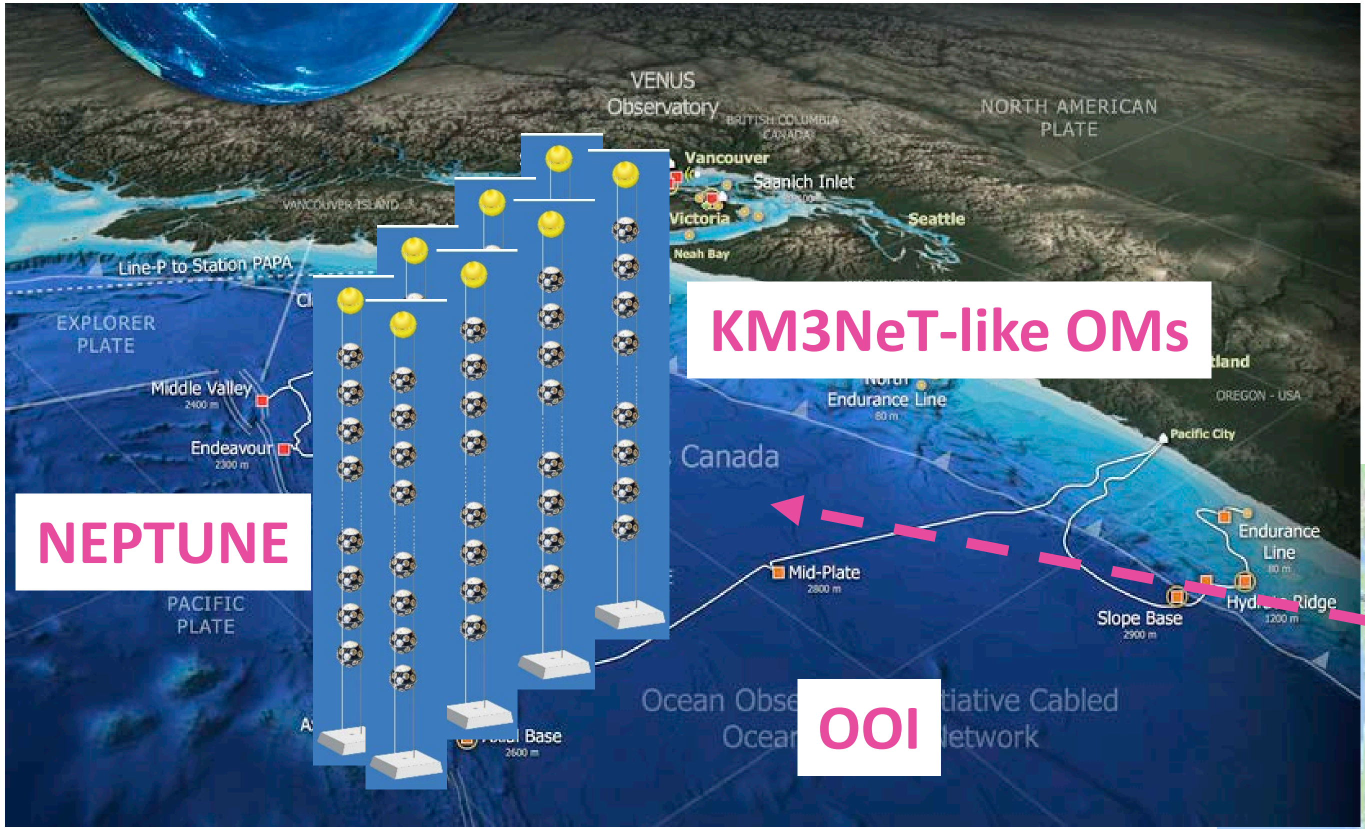
Ongoing final validation of a finer grain deep sea optical instrumentation suitable for few GeV $\nu$'s (ORCA option)

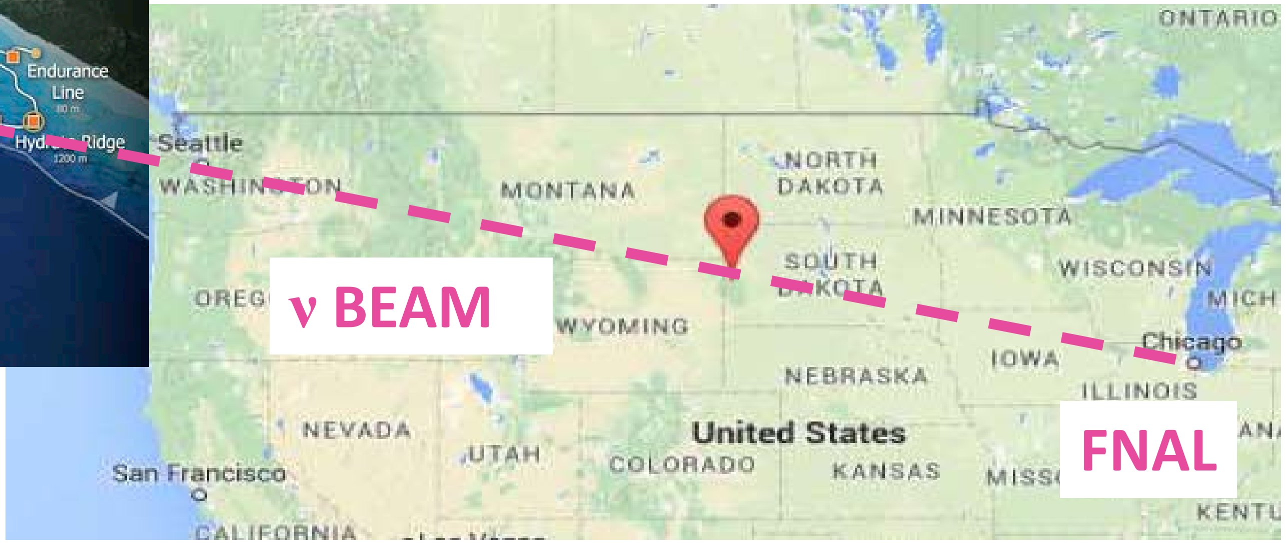
- Multi-PMT Optical Modules with integrated control and R/O electronics
- Fully modular design with each OM acting as independent ethernet hub
- Deep sea infrastructure components similar to NEPTUNE/OOI
- Cost of deployed detector dominated by OMs: ~10k€/OM

# EXPLOITING THE CONJUNCTION (1+2+3): Fermilab Neutrinos Into the Pacific ("FNIP")



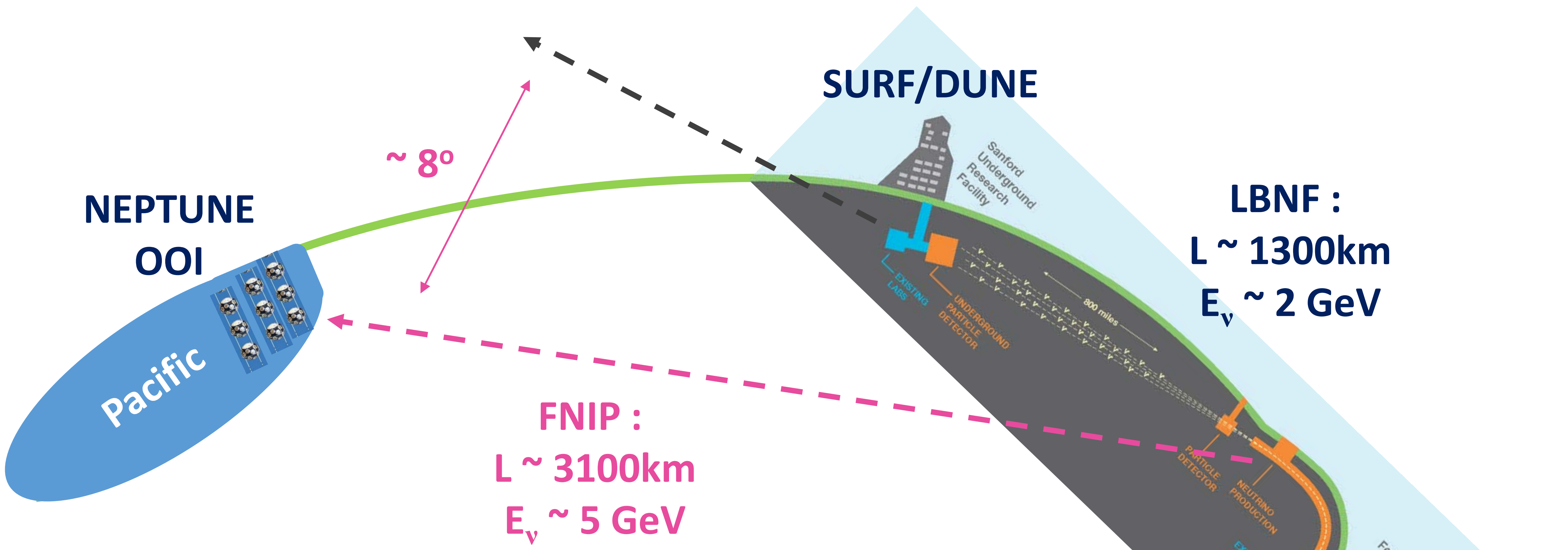

**1 OM/kton water (~ORCA granularity)**

**→ instrumentation of 10 Mton water for a cost of ~ 100 M€**

***NB: Detector volume only limited by sensor funding***

**Mechanical layout may/can be adapted to optimize the detector topology**

**NB: NOT THE SAME BEAM AS LBNF !**




An energy domain:

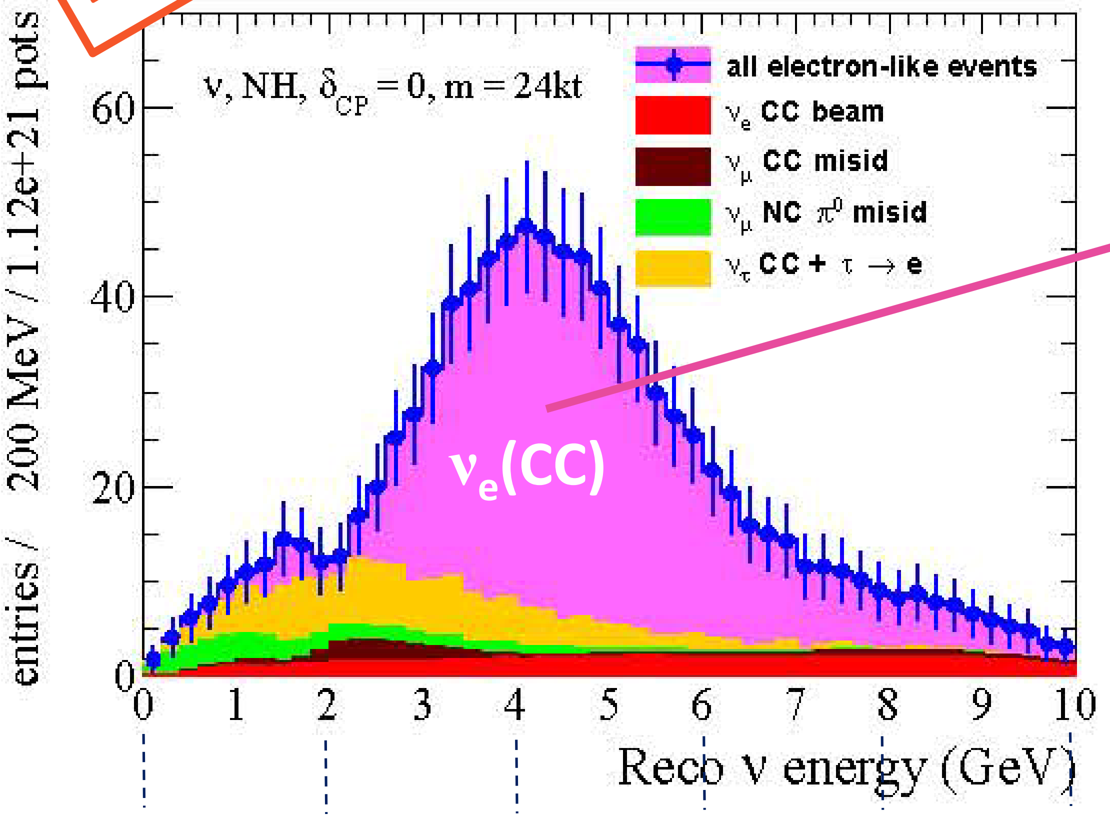
- where ν cross sections and event topologies are under control.
- which makes best use of the unique possibilities (with CERN) of the FNAL high energy complex.

*NB: the large (extensible) size of the detector would not require multi-MW beam operation*

**EXPECTED SIGNAL**
**($\nu_e$ appearance)**

LBNO

24kt LAr TPC, 1.12 $10^{21}$ POT




**FNIP :** 0 3 6 9 12 15

Extrapolated from LBNO study (L = 2300 km)
the studied configuration closest to FNIP
*Show case with neutrinos and Normal Hierarchy only*

$\nu_e$ appearance

| | $\nu_\mu \to \nu_e$ CC | |
|---|---|---|
| $\delta_{CP} = -\pi/2$ | 0 | $\pi/2$ |
| 883 | 693 | 576 |

**LBNO → FNIP**
**#evts x ~ 300 !**

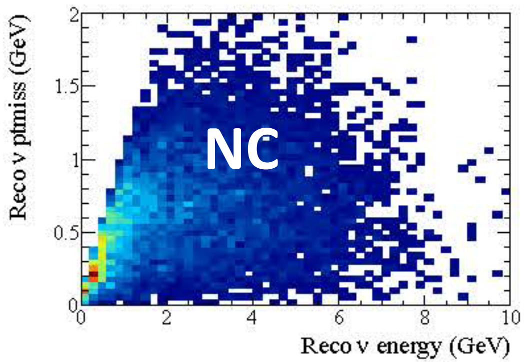
(10000/24) x $(2300/3100)^2$ x (3100/2300)
size angular dispersion $\sigma_\nu$(E)

**Δ(#evts) = o(100 kevts) for $\Delta(\delta_{CP})$= 180°**

**→ statistical precision of o(1°) on $\delta_{CP}$**

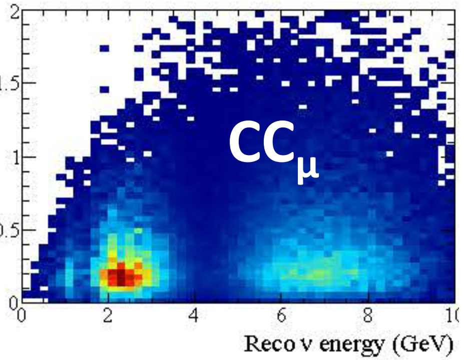
$p_T^{miss}$

# BACKGROUND LEVELS AND TOPOLOGIES

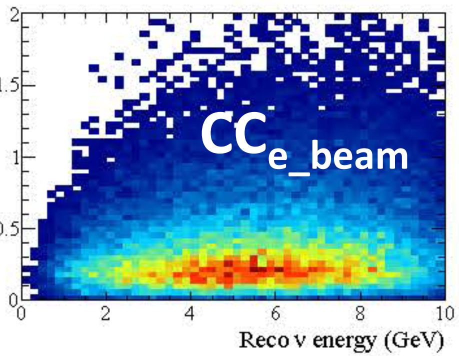


(d) NC$\pi^0$

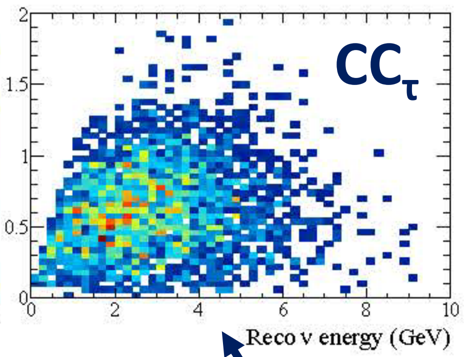
**#NC$_{tot}$ ~ #CC$_\mu$**



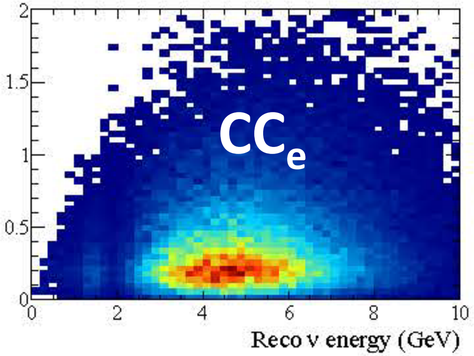
(f) Mis-id $\nu_\mu$



(c) Intrinsic $\nu_e$



(e) $\nu_\tau \to e$ contamination



(b) Signal $\nu_e$

$E_\nu$

LBNO

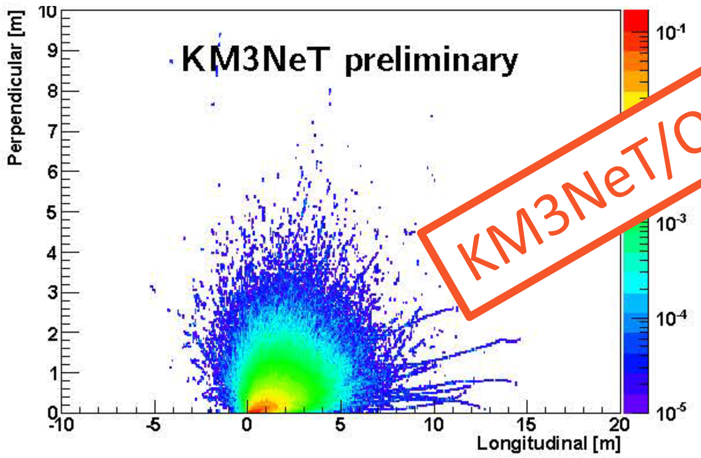
| | $\nu_\mu$ unosc. CC | $\nu_\mu$ osc. CC | $\nu_e$ beam CC | $\nu_\mu \to \nu_\tau$ CC | $\nu_\mu \to \nu_e$ CC 0 |
|---|---|---|---|---|---|
| SPS beam, 24kton, NH $11.25 \times 10^{20}$ POT for $\nu$ | 12492 | 3392 | 77 | 733 | 693 |

| | | | | |
|---|---|---|---|---|
| **Background/Signal :** (before any suppression) | 10 CC$_\mu$ + NC$_{tot}$ | 0.1 CC$_{e_beam}$ | 1 - 0.2 CC$_\tau$ - CC$_{\tau \to e}$ | **Signal** |
| **Suppression criteria :** | μ veto (CC$_\mu$) $P_T^{miss}$ (NC) low E | irreducible high E | H & μ vetos $P_T^{miss}$ low E | |

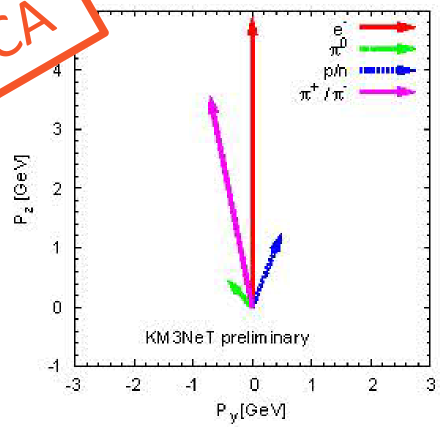
# BACKGROUND SUPPRESSION

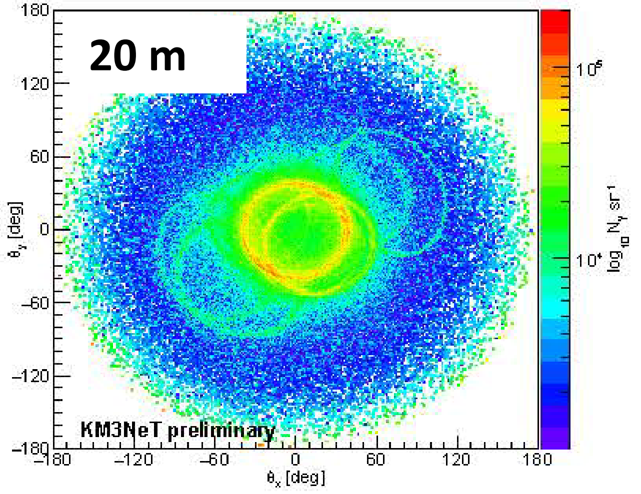
***Key issue: OM granularity needed to achieve the required BG suppression from Cerenkov emission measurement***

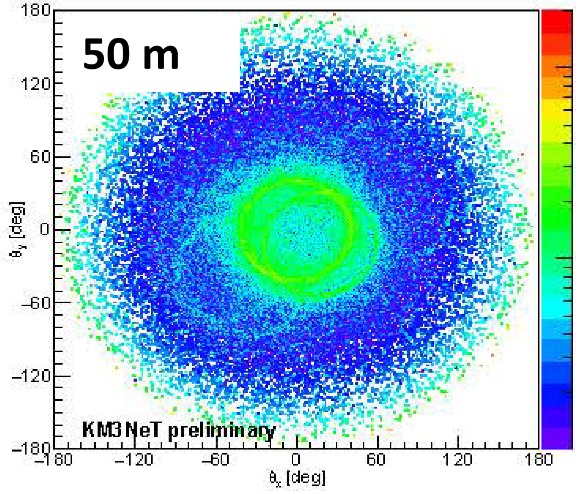
**5 GeV had showers (cumulated)**




**10 GeV $\nu_e$ CC**




**Cerenkov emission from hadronic showers is concentrated on a few meters**

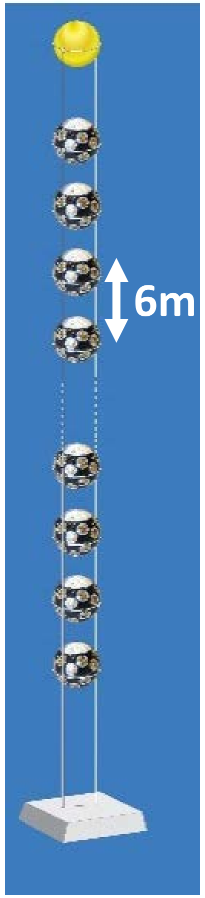
**Cerenkov ring patterns are maintained on the full light absorption range (~60m) thanks to large light scattering length in water**
**→ ORCA-like granularity should allow signal/background separation**

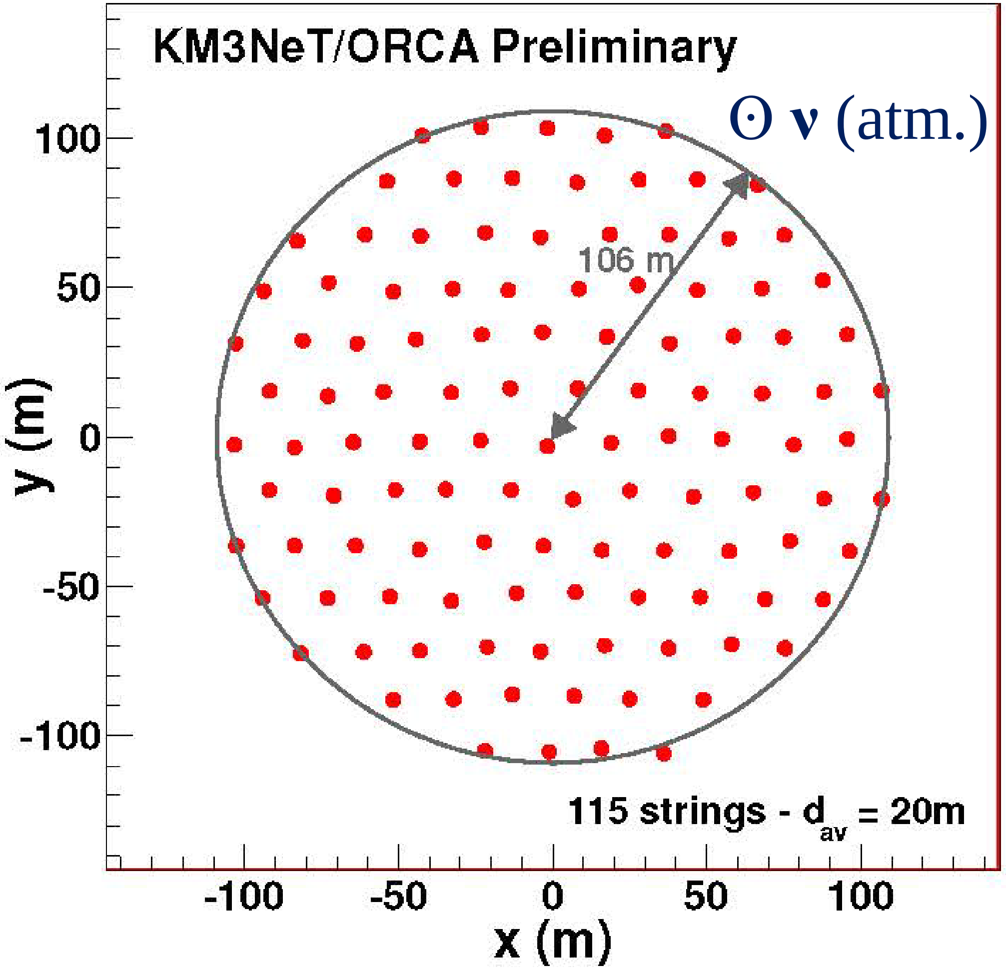
**NB1: Very large event samples allow to rely on statistical suppression methods**

**NB2: Background suppression must be controlled with high precision to benefit from the full statistical precision of the signal sample.**

# ORCA

**$\nu_e$(CC) : $dV_{int}$ ~ 1m, $dE_\nu/E_\nu$ ~ 20%, $d\theta_e$ ~ 5°, $d\theta_{had}$ < 20°**

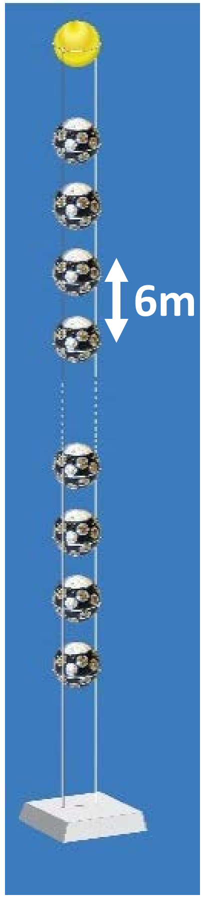


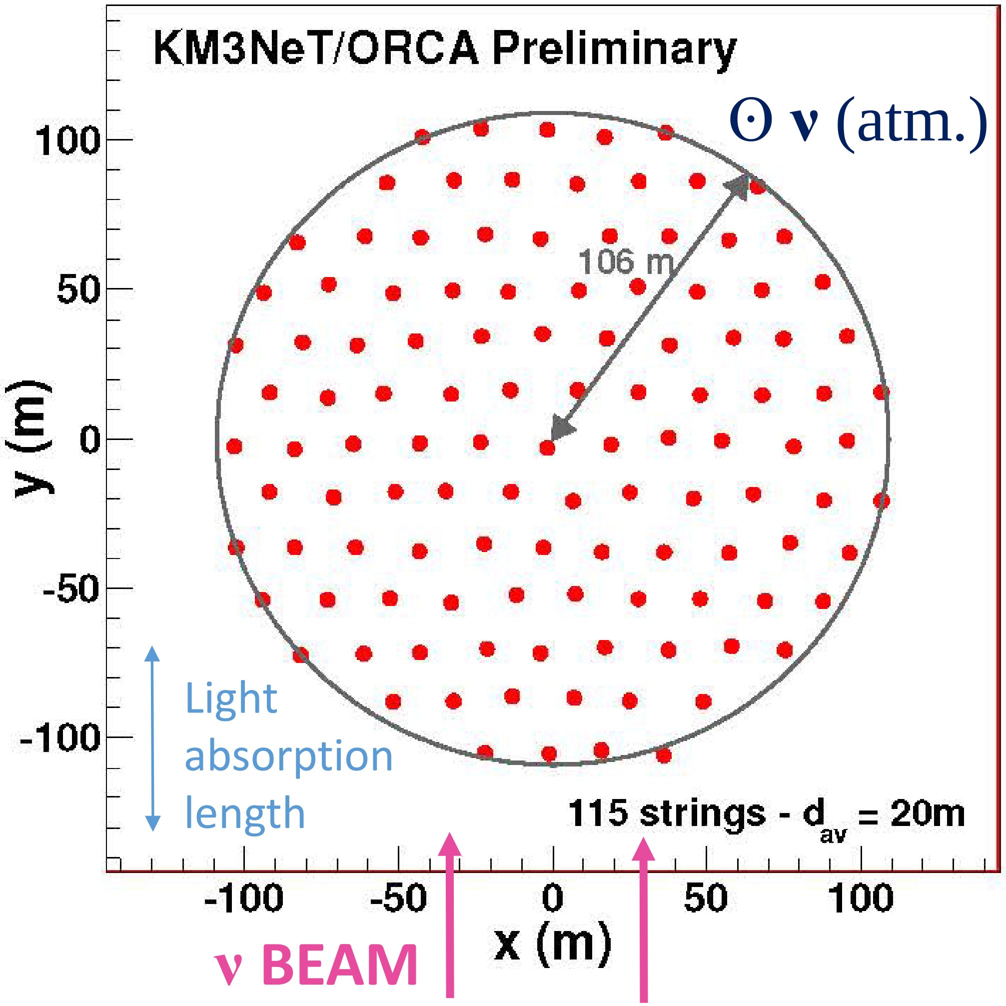



# DETECTOR LAYOUT

## ORCA → FNIP

$\nu_e$(CC) : $dV_{int}$ ~ 1m, $dE_\nu/E_\nu$ ~ 20%, $d\theta_e$ ~ 5°, $d\theta_{had}$ < 20°




- With an horizontal beam, staggered lines would provide an effective instrumentation granularity of ~6m in both transverse directions on a depth corresponding to light absorption. It might be necessary to reduce the OM vertical spacing to ~3m to increase Cerenkov ring pattern efficiency.

- Beam timing fully suppresses atmospheric muon background
  → much relaxed reconstruction cuts
  → improved sensitivity to event patterns

- Beam direction allows more efficient reconstruction algorithms and kinematical constraints (PT balance)

- Optional core with denser instrumentation could allow reaching the 2nd oscillation peak

# POSSIBLE ROADMAP TOWARDS A PROJECT

**Short term :** ~ few months of 1 (good!) physicist already active in the domain

- Confirmation of the potential with detailed simulation of the beam, of the neutrino oscillations and interactions, and of the response of a simple regular matrix of KM3NeT-like OMs, followed by a realistic reconstruction of events.

**Mid term** (if positive outcome of previous step):
parallel activities involving small teams with minor investments

- Design the optimal detector and beam (ν/anti-ν) configuration for CP violation measurement.

- Get acquainted with corresponding technologies within the KM3NeT/ORCA project offshore of Toulon/France (proof of principle of few GeV ν measurement).

- Get in contact with NEPTUNE/OOI to initiate collaboration and site studies.

- In LBNF design, anticipate the possibility to later build a new beam towards a (slightly) different direction without interfering with LBNF operation.

# OUTLOOK

**Deep sea instrumentation with multi-PM optical modules is reaching maturity and may provide the optimal compromise between detector size and instrumentation granularity for the long term future of long baseline neutrino physics**

**North America offers the geographical opportunity and the institutional synergies necessary for a concrete realization of such a project**