Long baseline neutrino oscillation experiments: present and future

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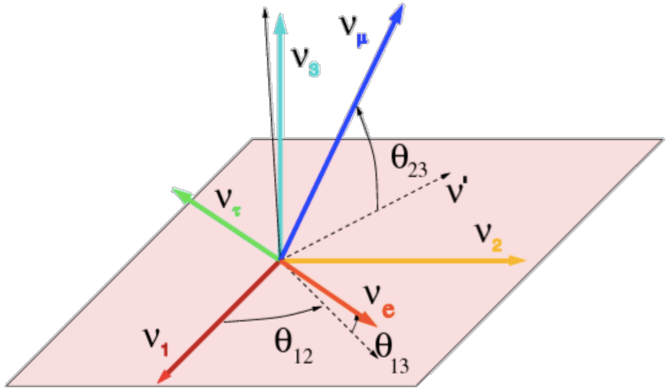
ν mixing: quick reminder

Flavour eigenstates (interaction) ≠ Mass eigenstates (propagation)

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U\,(\nu_1, \nu_2, \nu_3)^T$$



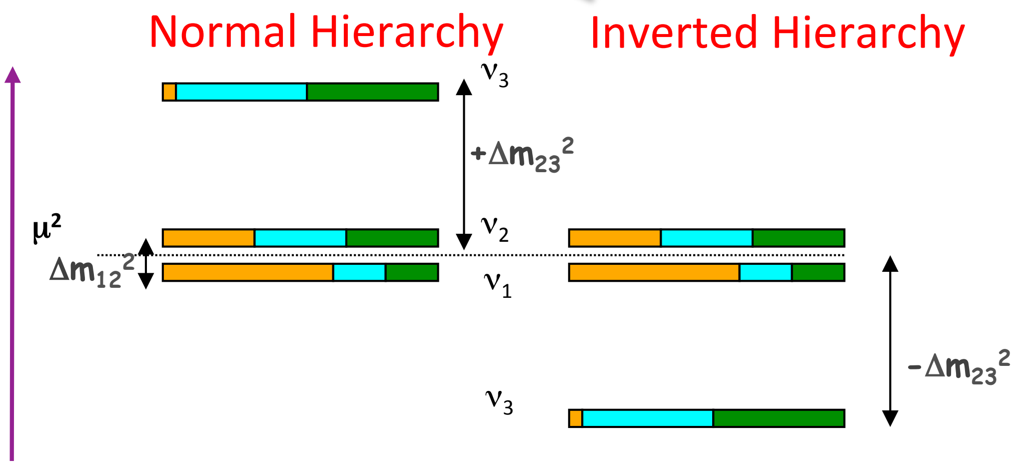
U: mixing matrix

- 3 angles: θ_{12} θ_{23} θ_{13}
- 1 complex phase : δ_{CP}

(CP violation in the leptonic sector !)

OPEN QUESTIONS

+ 2 mass differences

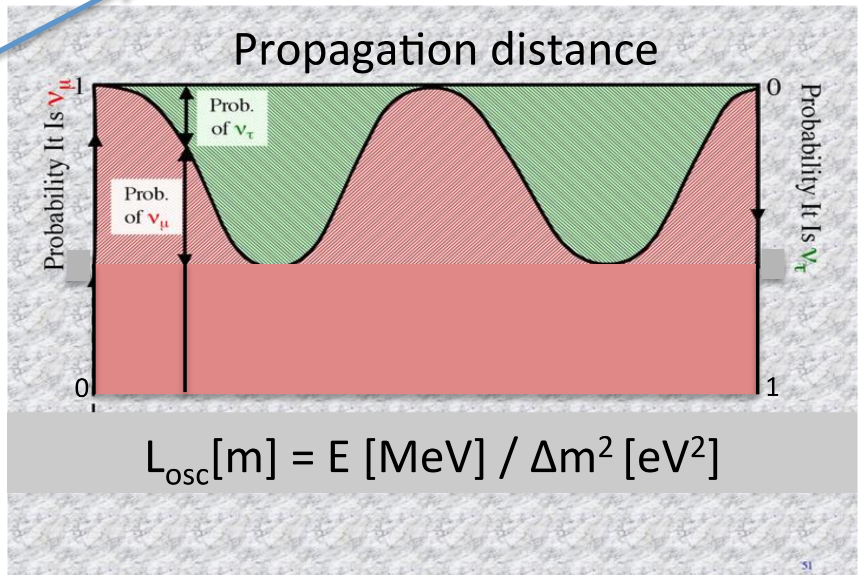


ν oscillations

SOURCE
ν_α

DETECTOR
ν_β

NEAR DETECTOR
Measure ν_α



Max. amplitude => mixing parameters

Modulation => mass difference

In this talk : regime dominated by $\Delta m^2_{13} = \Delta m^2_{atm} \sim 2.5 \times 10^{-3}\ eV^2 \sim E/L$

SOURCE : Reactors : E ~ MeV => L ~ 1 km
Beams : E ~ GeV => L ~ 100-1000 km

"Long Baseline"

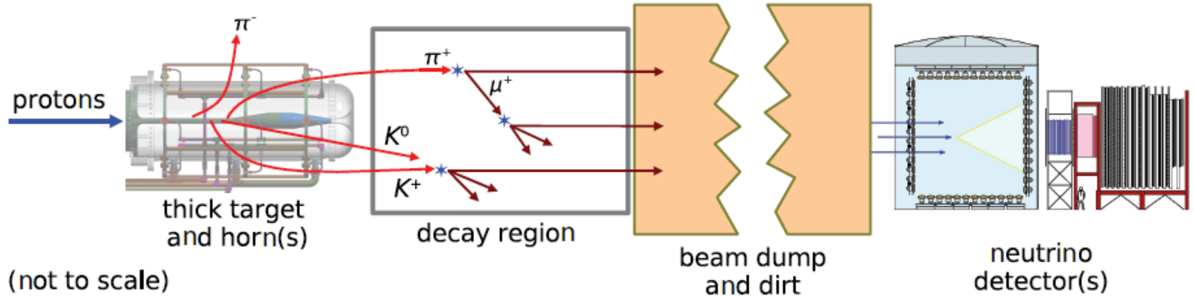
Outline of this talk

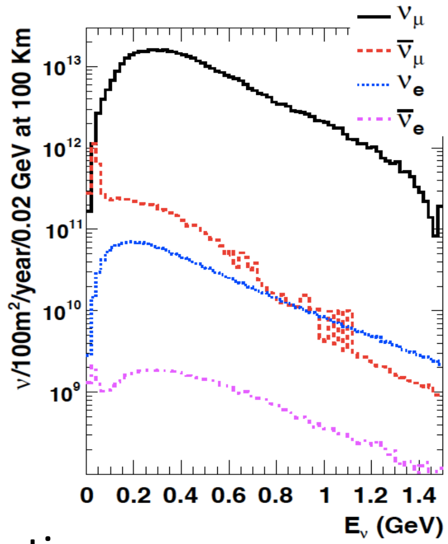
- Neutrino sources : reactors and beams
- LBL oscillations and measurements
- Detectors

- Present : Reactor exp., MINOS, T2K, CNGS
- Future : LAGUNA-LBNO (Europe), LBNE (US), T2HK (Japan)… and beyond…

Neutrino sources

Beams :

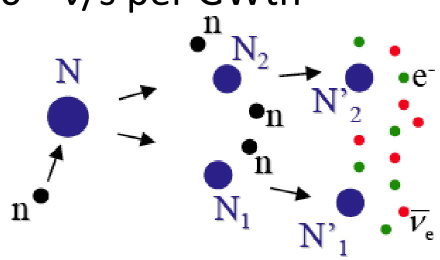




- "Wide band spectrum"
- Mainly ν_μ + few percent of ν_e and anti-ν

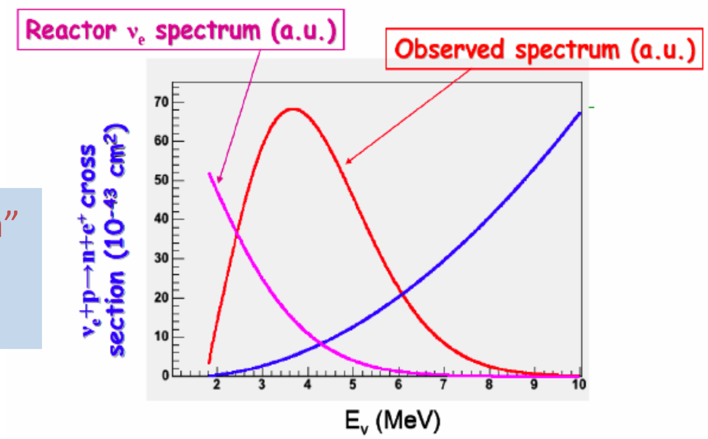
Reactors :

decay of fission products =>
1.9×10^{20} ν/s per GWth



- Purely anti-ν_e

Detection by "inverse beta"
$\nu_e + p \rightarrow e^+ + n$
in scintillator



Long-baseline oscillations

Reactors

$\nu_e \to \nu_e$ ("disappearance")

$\Rightarrow$ measure θ_{13}

Accelerators

Leading : $\nu_\mu \to \nu_\mu$ ("disappearance")

=> cross-check of atmospheric ν "anomaly"

=> measure Δm^2_{23}, θ_{23}

Sub-leading: $\nu_\mu \to \nu_e$ ("appearance")

$\Rightarrow$ measure θ_{13}

Then, since is θ_{13} is "large"

$\Rightarrow$ access to Mass Hierarchy

via Earth matter effects

$\Rightarrow$ access to CP-violation

via ν/anti-ν comparison

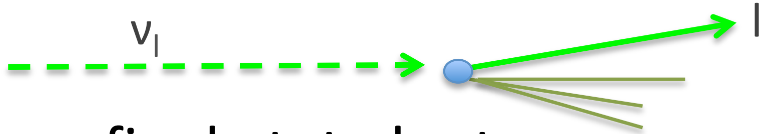
Present

Near future

Far future

Detectors

- CC interactions

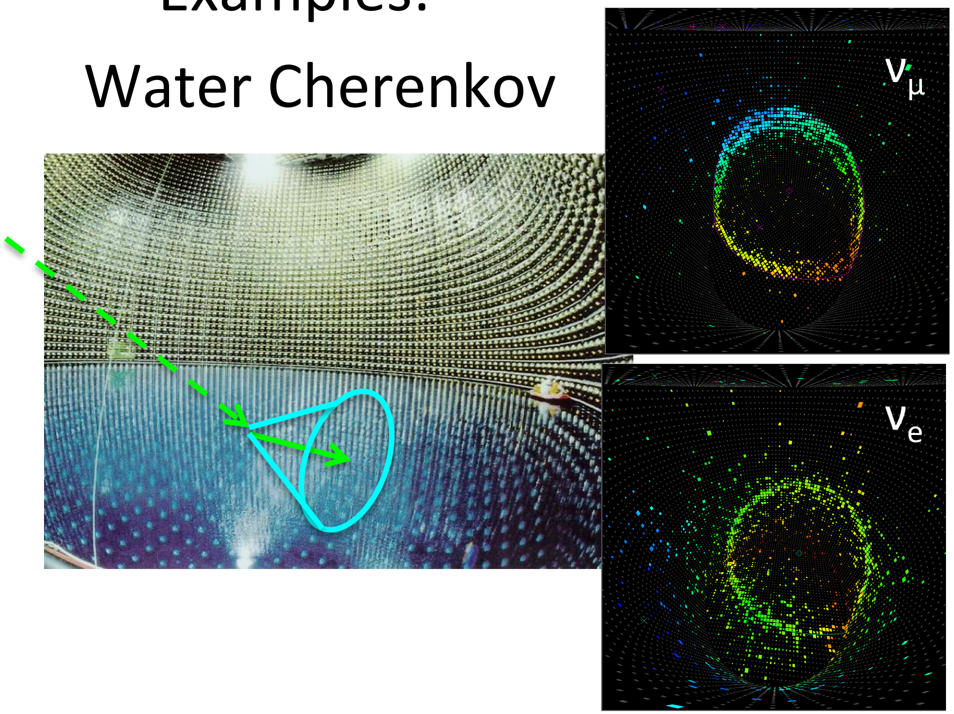


=> identify and measure final-state lepton

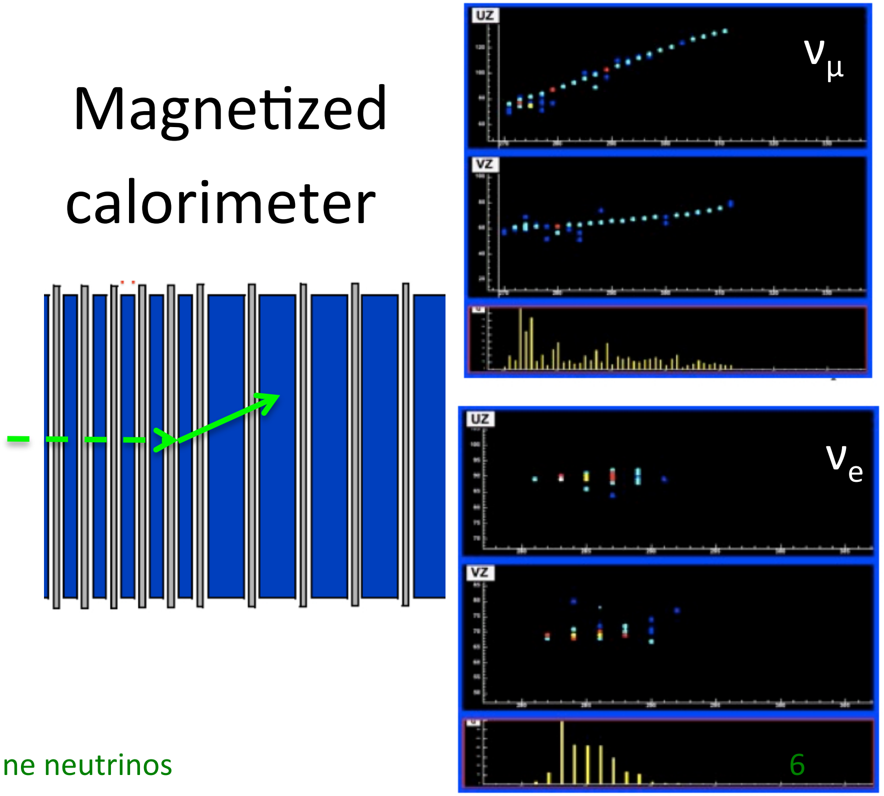
- Backgrounds : NC interactions (no leading lepton), other ν flavours

- Examples:

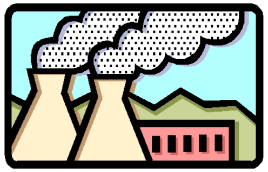
Water Cherenkov

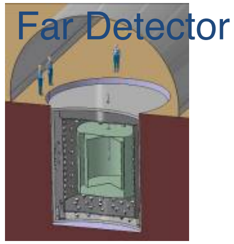


Magnetized calorimeter



Reactor experiments





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \propto \sin^2 2\theta_{13}$$

Double Chooz
(France)

leading role of
French institutes

1st measurement
@2.3σ in 2011

2012: $\sin^2 2\theta_{13}$ [Gd]= 0.086
±0.041 (stat)
± 0.030 (sys)
$\sin^2 2\theta_{13}$ [H] = 0.086
±0.041 (stat)
± 0.030 (syst)

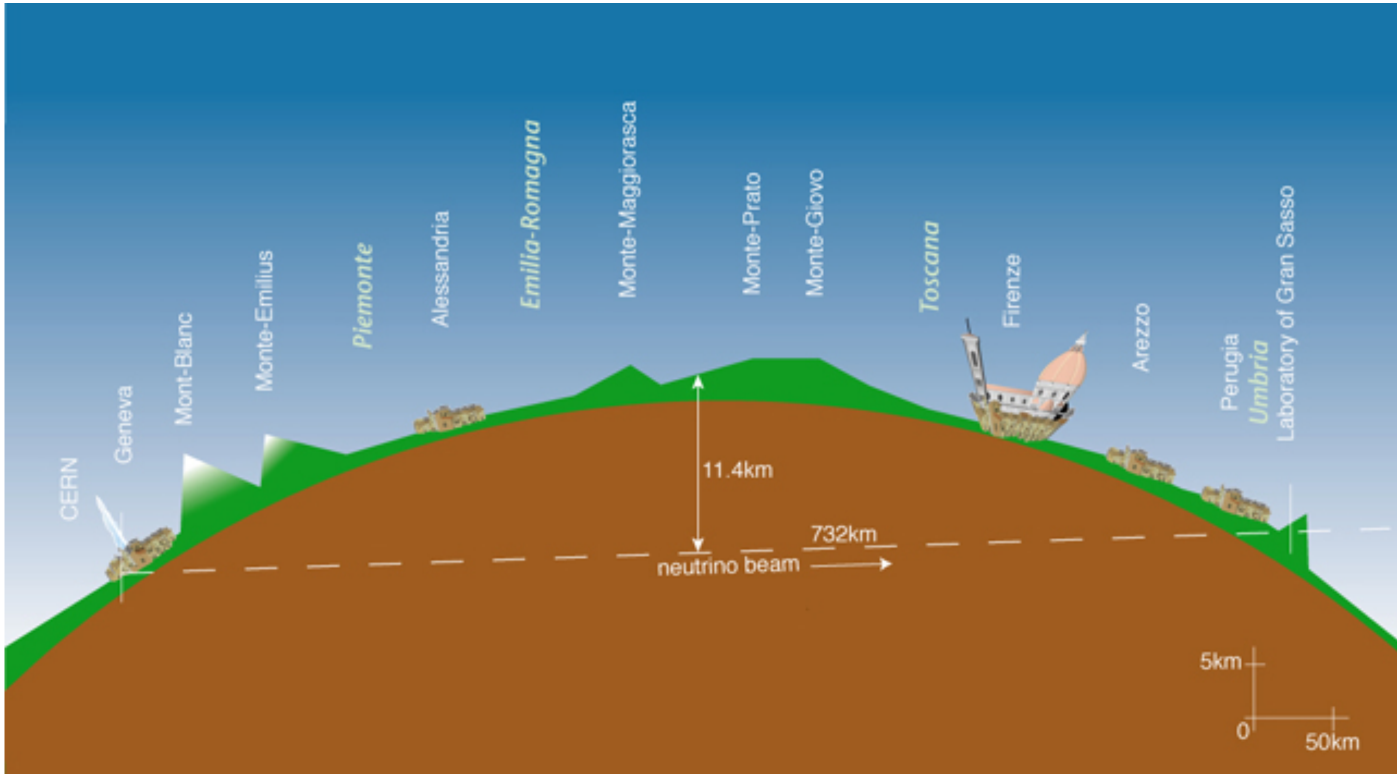
Near detector being installed

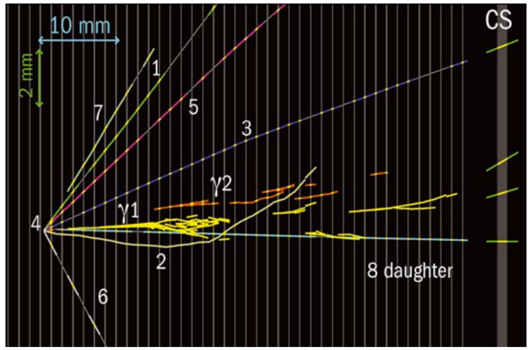
Daya Bay (China) $\sin^2 2\theta_{13}$= 0.089 ± 0.010 (stat) ± 0.005 (syst)

RENO (North Korea) $\sin^2 2\theta_{13}$= 0.113 ± 0.013 (stat) ± 0.019 (syst)

CNGS

CERN Neutrino beam to Gran Sasso

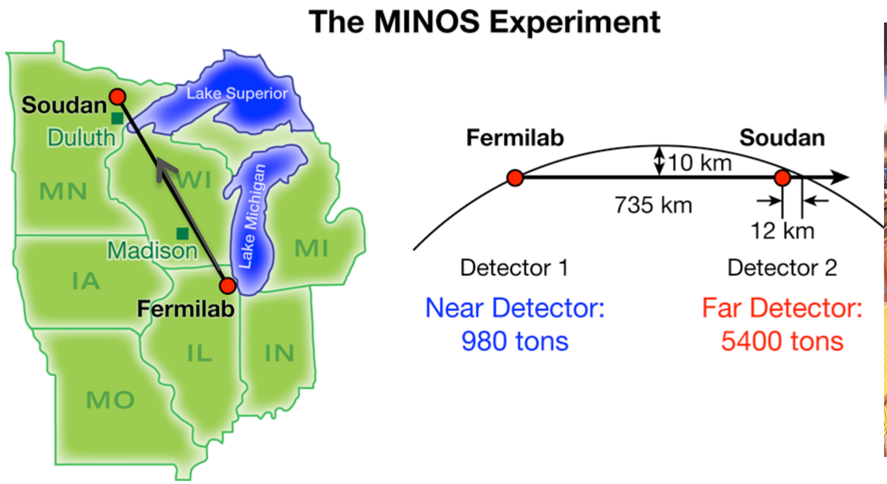


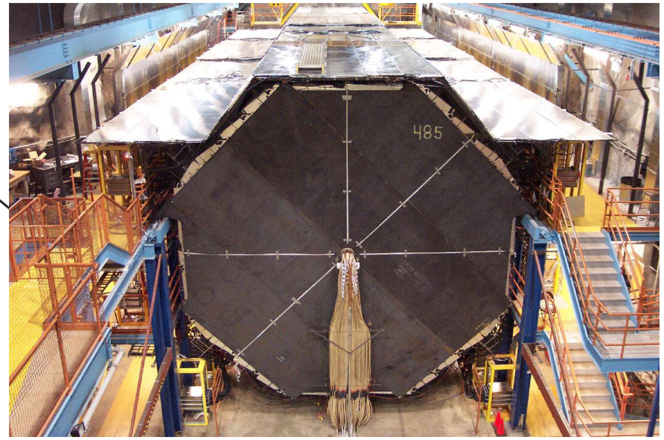


(mainly) ν_μ → OPERA: 3 ν_τ detected

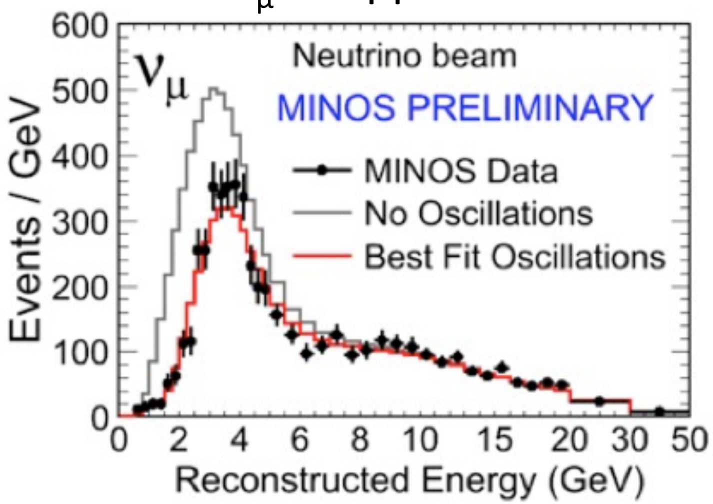
First direct evidence of “appearance”

MINOS





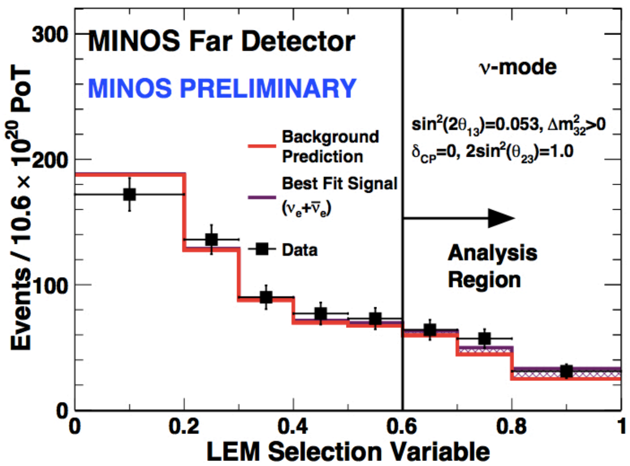
ν_μ disappearance



$\Delta m^2 = 2.39^{+0.09}_{-0.10}$ x10-3 eV^2

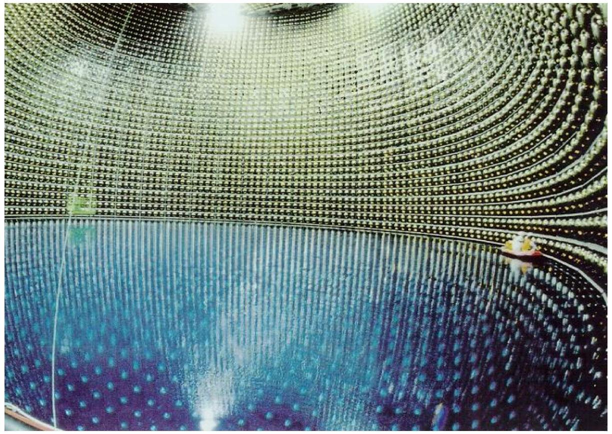
$\sin^2 2\theta_{23} = 0.96 \pm 0.04$

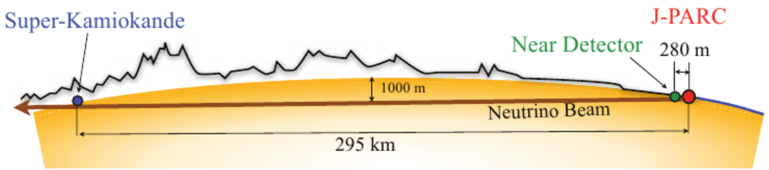
ν_e appearance



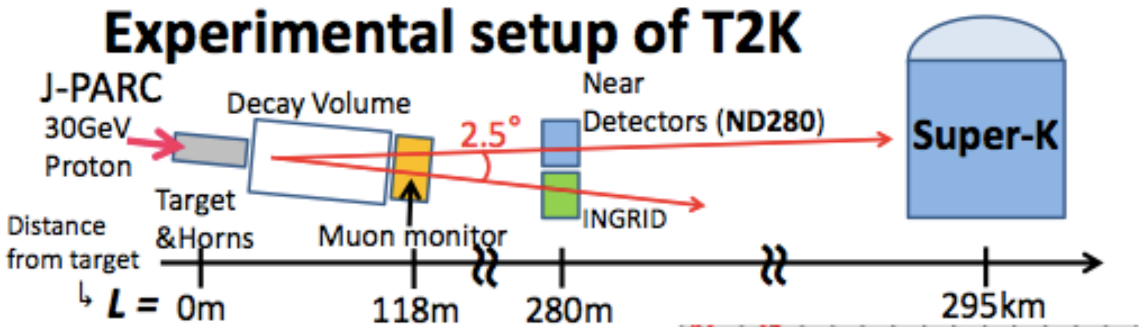
Disfavour $\theta_{13}=0$ at 96%CL (NH, $\delta_{CP}=0$)

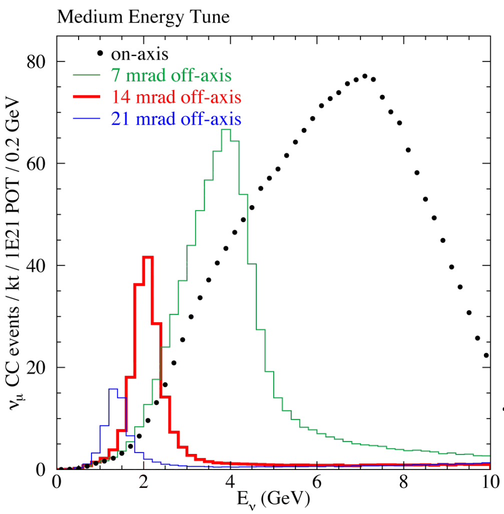
T2K





2.5° off-axis

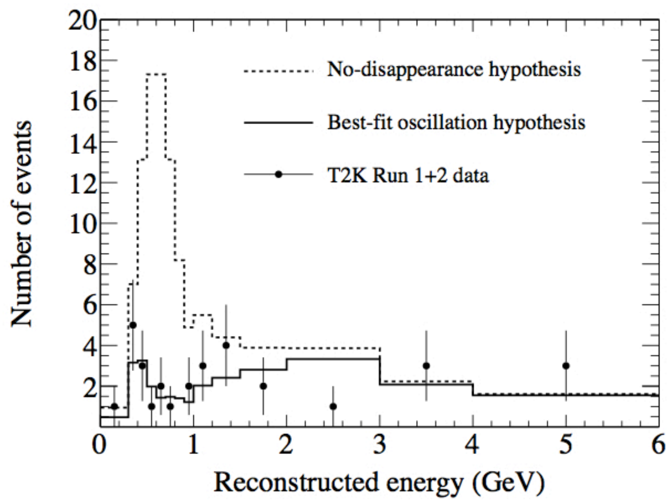




"off-axis" =>
nearly monochromatic
tuned to osc. maximum

T2K

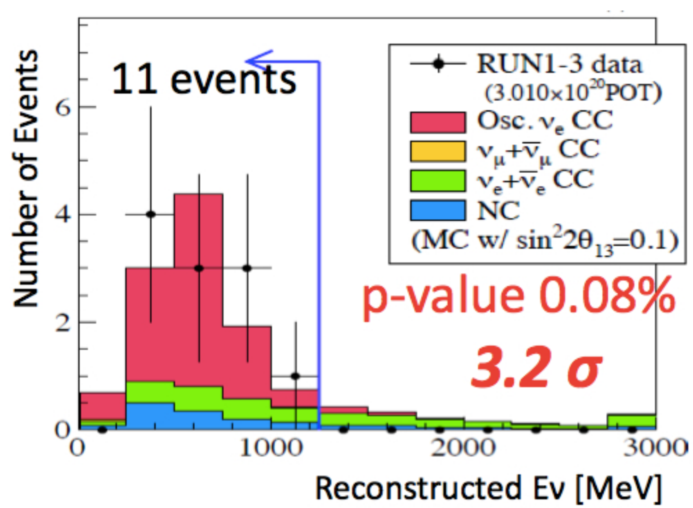
ν_μ disappearance



$(\sin^2 2\theta_{23}, \Delta m^2_{23})$ =
$(1.00_{-0.068}, 2.45 \pm 0.30 \times 10^{-3}\ eV^2)$ 90%CL

ν_e appearance

2011 : 1st indication(6 ev.)
2013:



$\sin^2 2\theta_{13} = 0.094\ ^{+0.053}_{-0.040}\ (0.116^{+0.063}_{-0.049})$
for N.H. (I.H)

3.2σ : evidence !

The future

- ✔ θ_{13} will be measured at ~10% by T2K (in 5 years) and reactor experiments
- ✔ Δm_{32} θ_{23} precision

Since θ_{13} is "large", LBL neutrino experiments can also investigate the two open questions in neutrino oscillations:

- ? • Mass Hierarchy (via matter effects)
- ? • CP violation (via ν-antiν comparison)

T2K and NOvA (US) will access at most (@90%CL) in 3-5 years

- MH for <50% of δ_{CP} values
- ~20% of δ_{CP} values.

Need for future experiments to go further:
→ new detectors and possibly new beams

The future of neutrino LBL in EU

Consensus on a realistic **“incremental approach”**

<u>The LBNO experiment</u> (LAGUNA-LBNO FP7 Design Study)

- phase 1. : establish **Mass Hierarchy**, extend δ_{CP} coverage
  ➔ detector of 10-20kt, beam based on existing accelerators

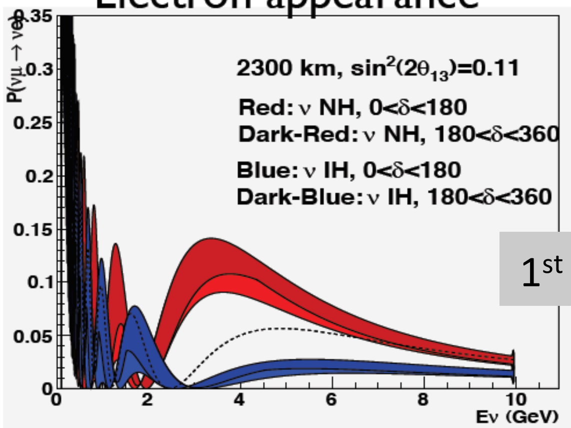
- phase 2. : if **CP** not discovered, extend coverage as much as possible
  ➔ larger detector and new beam

Expression of Interest to CERN/SPSC + input to EU roadmap

LBNO: phase 1

- 10-20 kton Liquid-Argon TPC
  (+ magnetised iron det.)
- located in Pyhäsalmi mine, Finland
- wide-band-beam from CERN,
  based on existing accelerators
- baseline = 2290 km, close to “magic” where
  matter effects for MH disentangle from CPv

Electron appearance

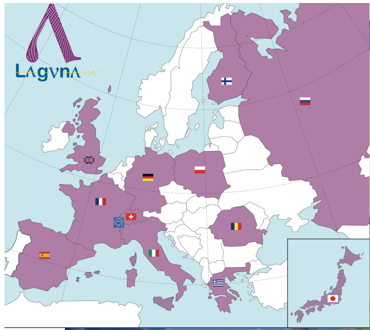


Physics reach :

1) measure Mass Hierarchy
2) cover 20-30% of δ_{CP} values @3σ

LBNO: phase 2

EU FP7 Design Studies



LAGUNA (2008-11)

studied 7 underground sites in Europe

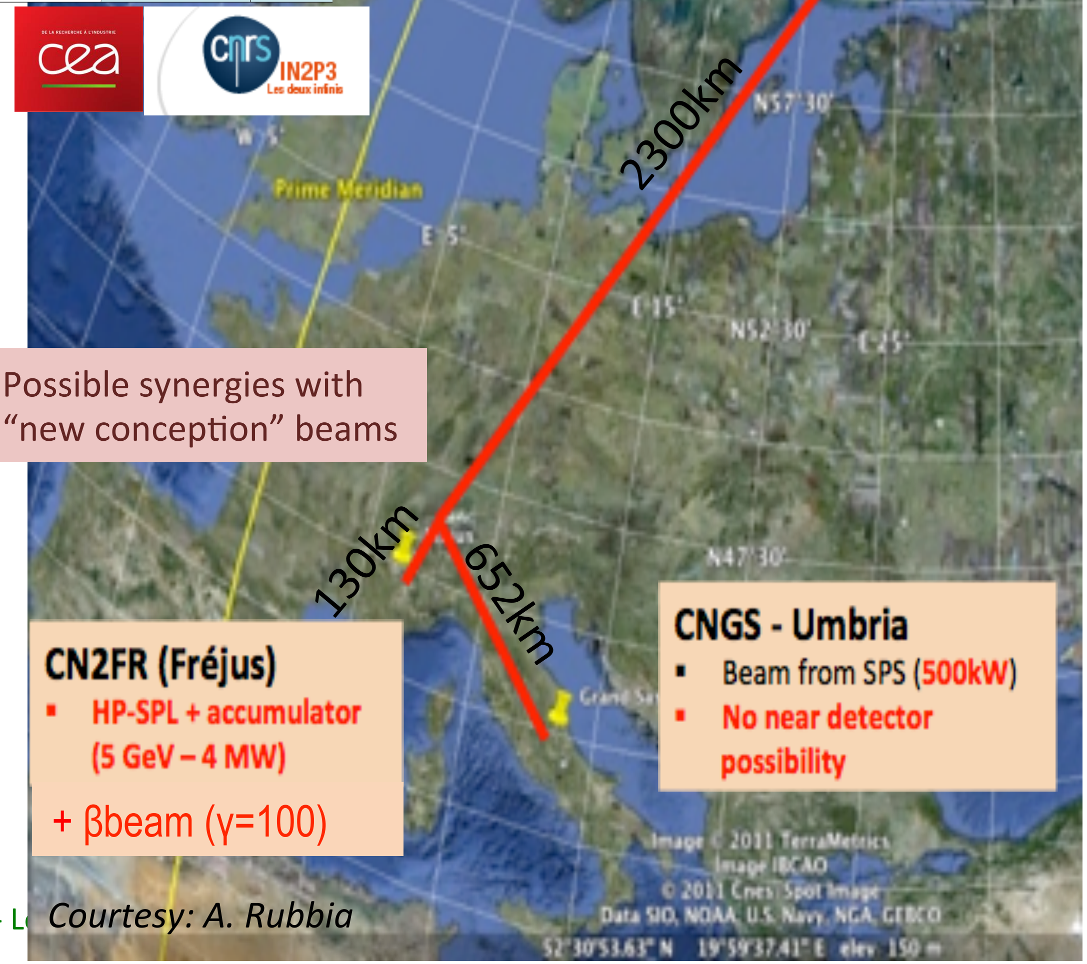
<u>LAGUNA-LBNO </u>(2011-14)

- New conventional ν_μ beams to be considered, based on CNGS experience
- Focus on the 2 baselines specific to Europe:

Possible synergies with "new conception" beams

- **CERN-Fréjus** short baseline.
  - No Matter effects, pure CP-violation
- **CERN-Pyhäsalmi** longest baseline.
  - Close to "magic baseline"

[+CERN-Umbria, with lower priority]



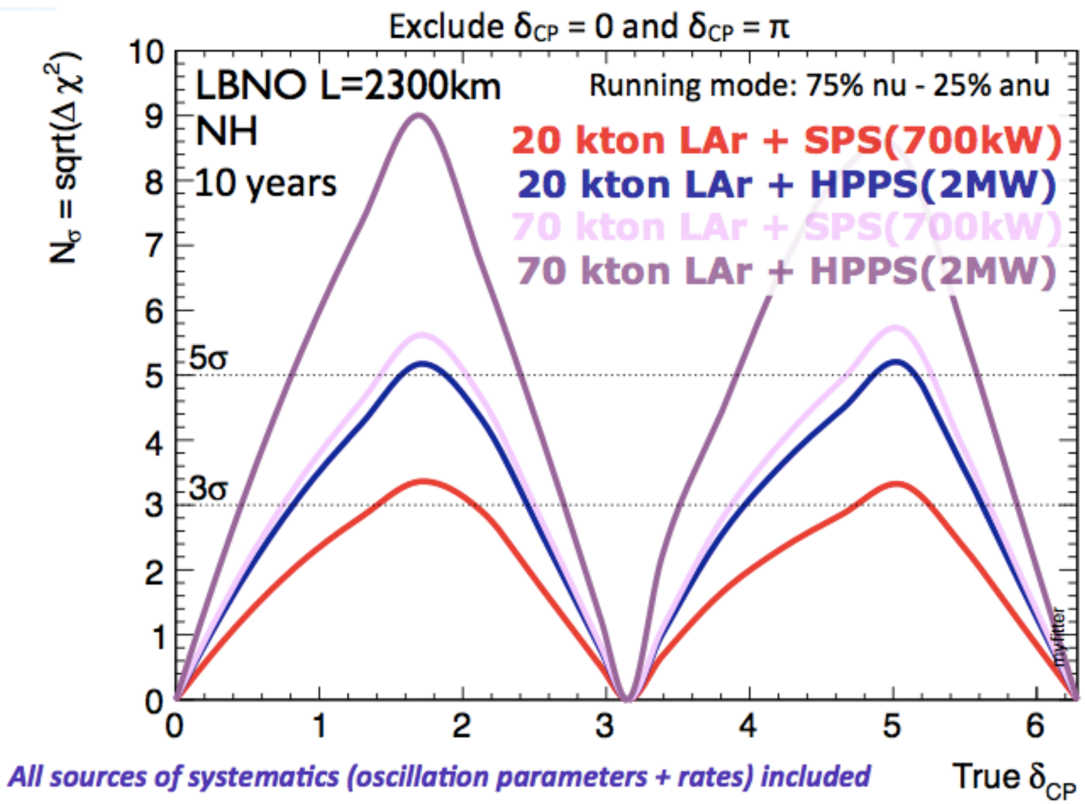
Courtesy: A. Rubbia

Physics reach – ν oscillations

1) Conclusive assessment of Mass Hierarchy in 2 years

2) Cover ~70% of δ_{CP} values in 10 years

Control of systematic uncertainties is crucial

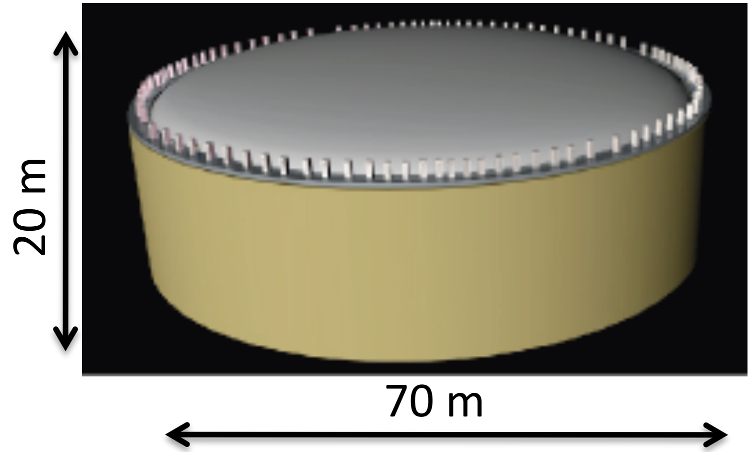


More studies ongoing in LAGUNA-LBNO

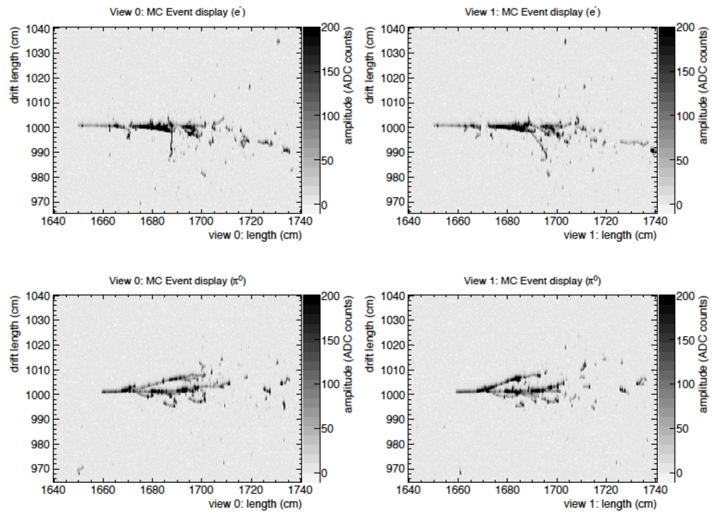
Start data taking : 2025 ?

LAGUNA-LBNO detector(s)

GLACIER

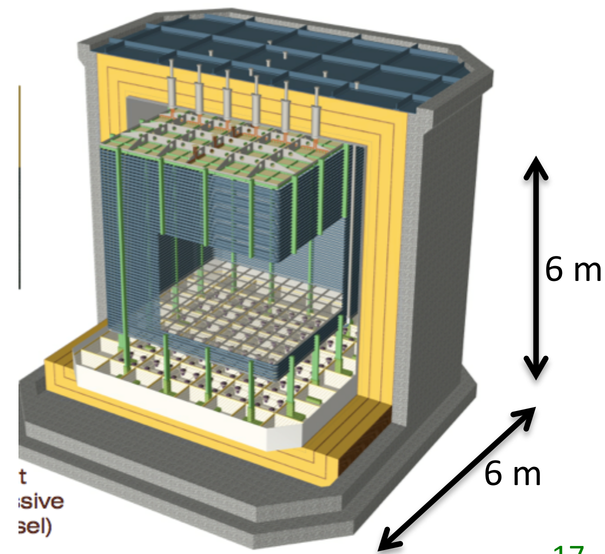


Liquid Argon TPC
Excellent background rejection
Good efficiency at high energy
Excellent energy resolution

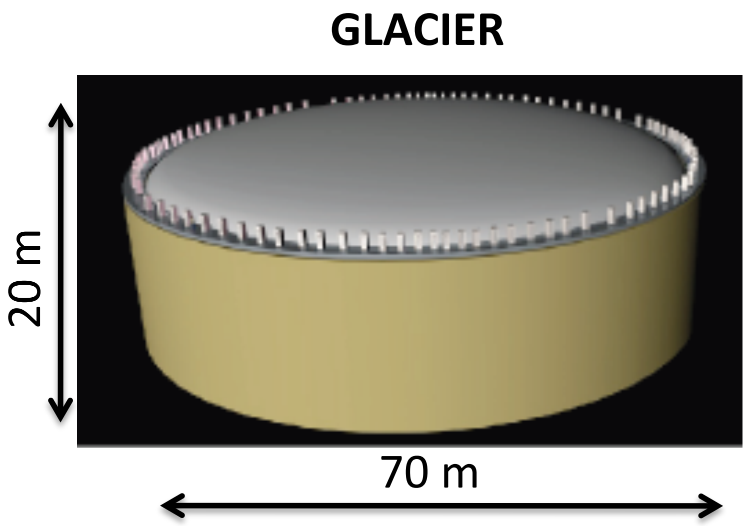


Complete 3D reconstruction of events

Proposal for full small-scale prototype @CERN (2015)

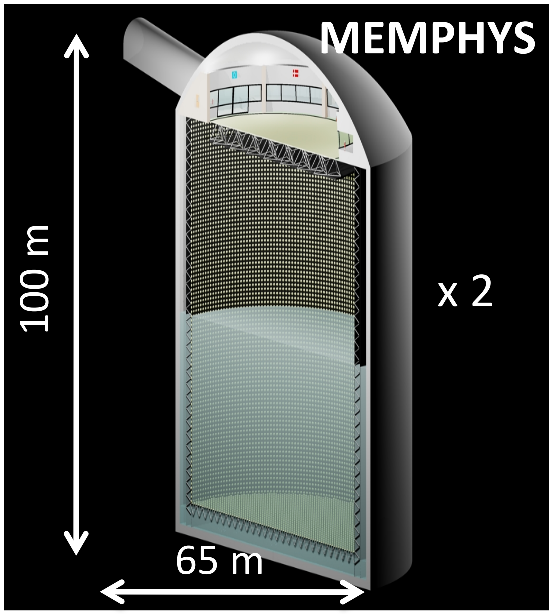


LAGUNA-LBNO detector(s)

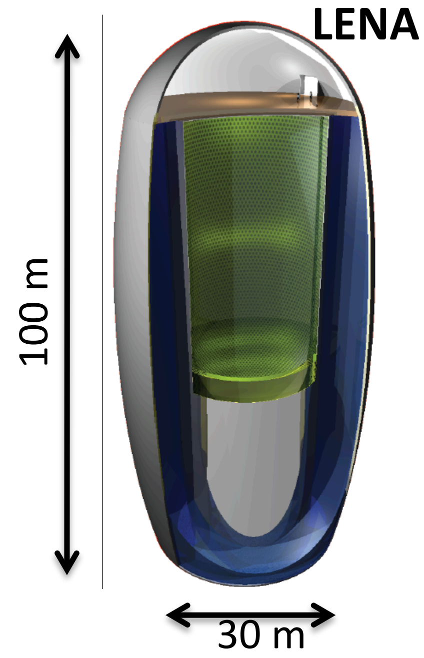


Liquid Argon TPC 70 kt
Excellent background rejection
Good efficiency at high energy
Excellent energy resolution

+ Magnetised Iron Detector
MIND



Water-Cherenkov 2 x 330 kt
Excellent particle-ID and momentum measurement



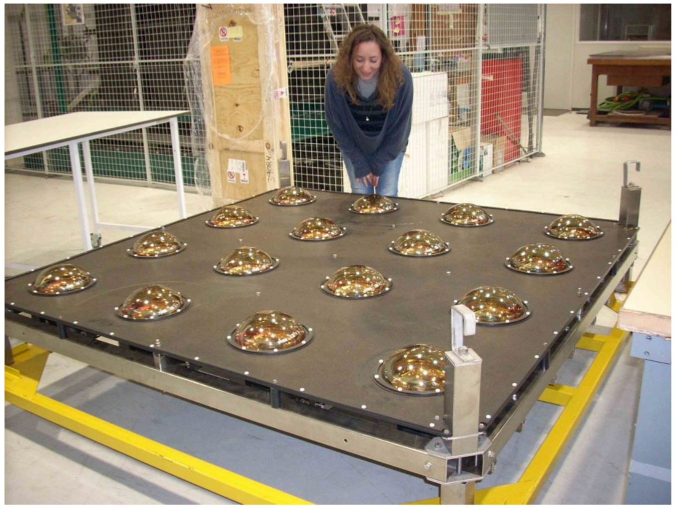
Liquid scintillator 50 kt
Very low energy threshold
Potential for use with beam under development

Underground >4000 m.w.e => Excellent physics reach also for proton decay and for ν's as messengers (SuperNovae, Sun, Earth, atmosphere):
UNDERGROUND NEUTRINO OBSERVATORY

Activities in France : R&D

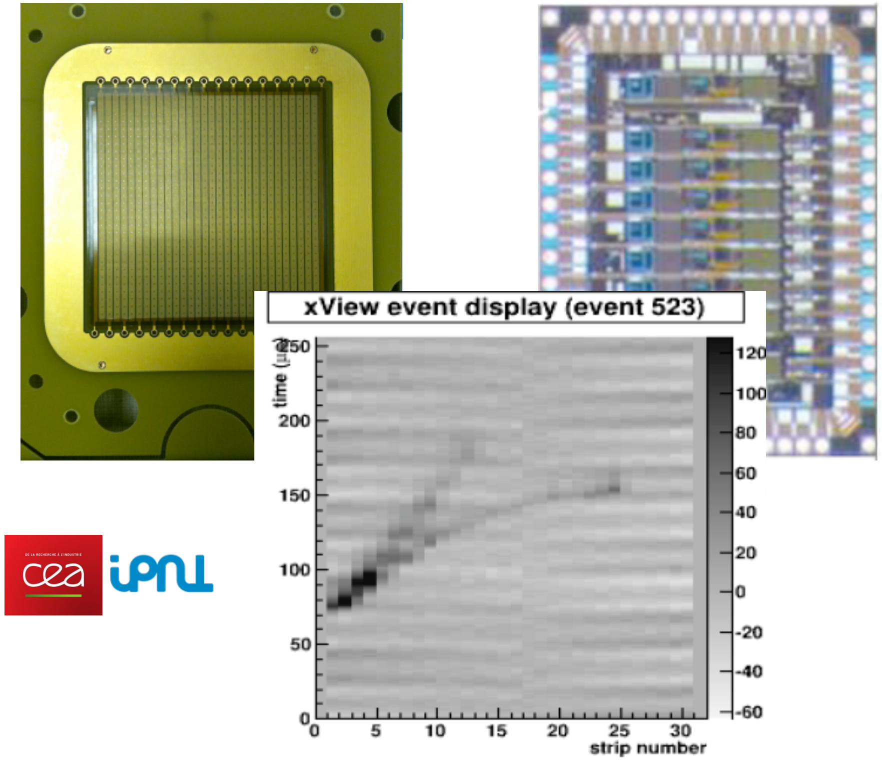
Grouped readout and electronics for PMTs

All LAGUNA detectors have a very large number of PMTs (45000-220000):
need to reduce costs and complexity
→ParisROC card
→MEMPHYNO test bench



MicroMegas + readout electronics for double-phase LAr TPC

(expertise from T2K ND280)
→ Operation in cryogenic environment



PARTICIPATION TO CERN PROTOTYPE + TEST

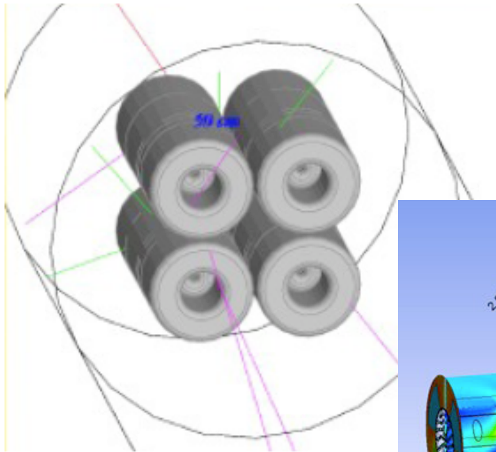
Activities in France : FP7 D.S.

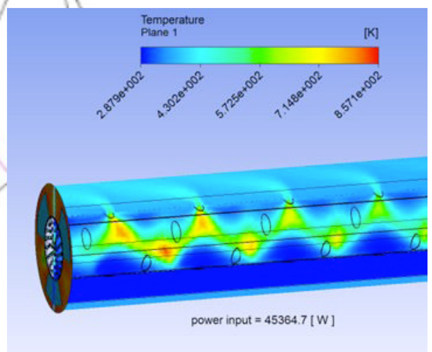
EUROnu (2008-2012)

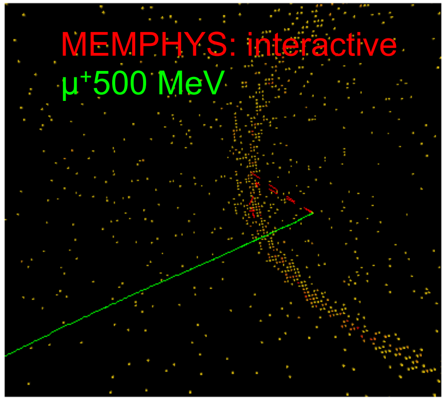
- Design and optimisation of target and horn for super-beam
- Water Cherenkov detector optimisation and simulation
- Study of physics potential

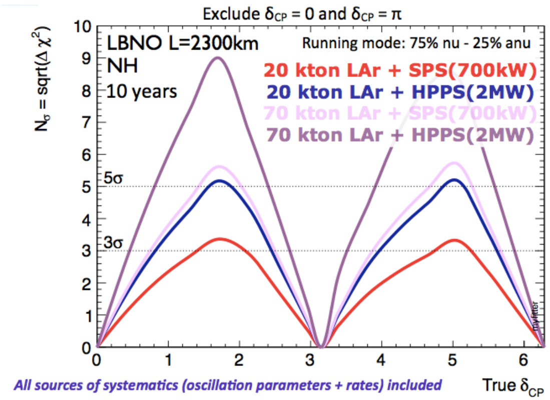
LAGUNA-LBNO (2011-2014)

- Physics coordination
- Detector construction and long-term operation studies
- Underground facilities
- Common simulation and analysis framework
- Detailed physics potential







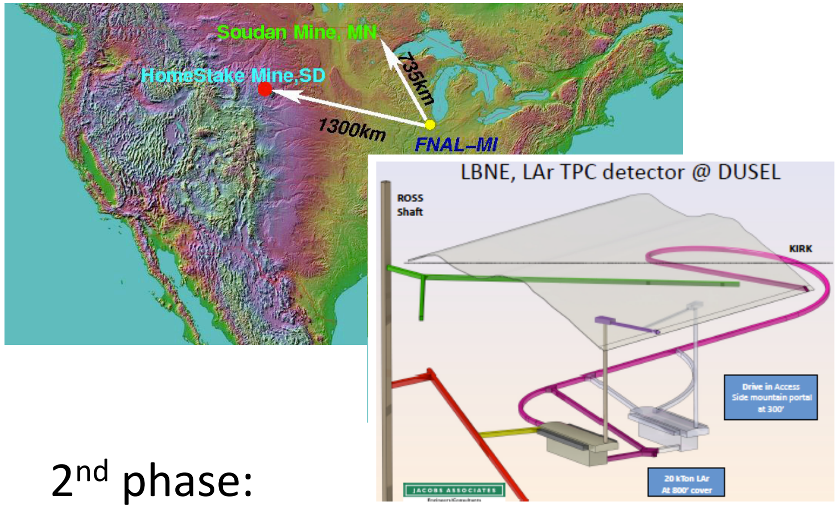


The world context

US : LBNE

Liquid Argon TPC 10 kton on surface
Beam from Fermilab (0.7 MW)

baseline=1300 km <E>~3 GeV

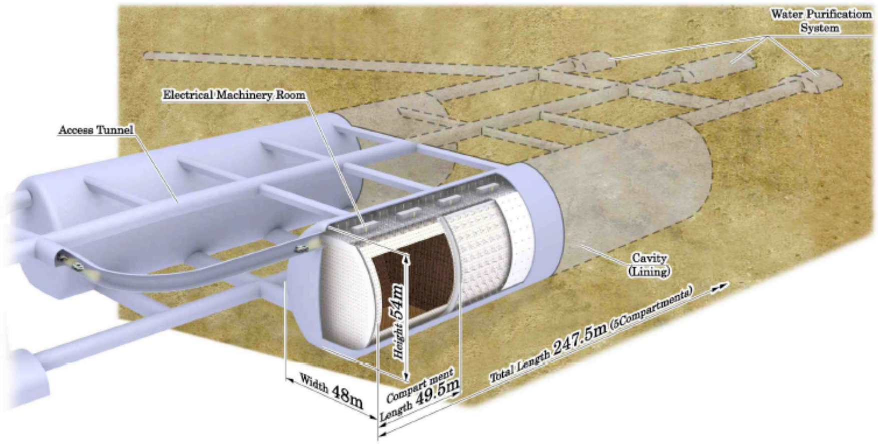


2nd phase:
34 kt Lar + Project-X

Japan : Hyper-K

Water Cherenkov 560 kton
near Kamioka, 1750 mwe
Beam from JPARC (1.66MW)

baseline=,295 km <E>~0.8 GeV



Collaboration/synergies with EU under development

Going even further…

"New-conception" beams:

ν flavour composition and spectrum precisely defined by the decay of primary particles

$$^{18}Li \rightarrow {}^{18}Fe + e^{+} + \nu_{e}$$

$$^{6}He \rightarrow {}^{6}Li + e^{-} + \bar{\nu}_{e}$$

<u>Beta-beams</u> :

decay in-flight of accelerated β-decaying isotopes

<u>Neutrino Factory</u> :

decay in-flight of accelerated μ's

$$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}$$

Summary and outlook

- Long baseline oscillations of beam and reactor neutrinos have provided precise measurement of oscillation parameters θ_{13} θ_{23} Δm^2_{23}, and precision will further improve

- The next generation of projects will explore the remaining open questions :

  Mass Hierarchy and CP violation

- French research groups have a leading role both in ongoing experiments and in paving the way for the future ones