Rencontres IPhT/SPP

Mardi 24 janvier 2012

# Future long baseline neutrino oscillation experiments

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CEA, IRFU, SPP

# Outline

- Motivation.
- Beams
- Detectors.
- Projects around the world.

# Motivation

- flavor oscillation described by PNMS matrix
- parametrized by 3 mixing angles and CP-violating phase $\delta_{CP}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{CP}}\\0&1&0\\-\sin\theta_{13}e^{-i\delta_{CP}}&0&\cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

“atmospheric sector”
**$\theta_{23}$**

| | |
|---|---|
| $\lvert\Delta m^2_{31}\rvert$ | $(2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$ |
| $\sin^2\theta_{23}$ | $0.50^{+0.07}_{-0.06}$ |

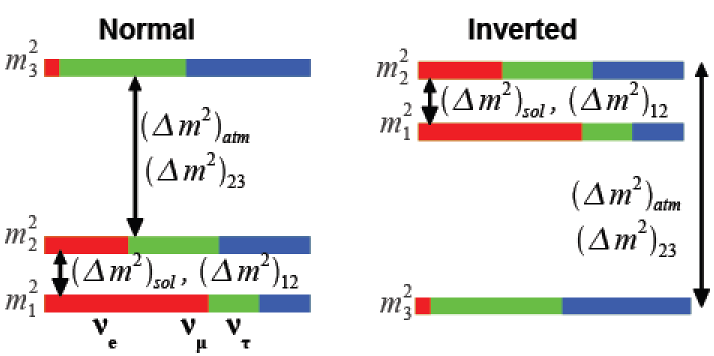
**$\theta_{13}$**

new

| | |
|---|---|
| $\sin^2\theta_{13}$ | $0.013^{+0.007}_{-0.005}$<br>$0.016^{+0.008}_{-0.006}$ |
| $\delta$ | $(-0.61^{+0.75}_{-0.65})\,\pi$<br>$(-0.41^{+0.65}_{-0.70})\,\pi$ |

“solar sector”
**$\theta_{12}$**

| | |
|---|---|
| $\Delta m^2_{21}$ | $(7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$ |
| $\sin^2\theta_{12}$ | $0.304^{+0.022}_{-0.016}$ |




*Most urgent points:*

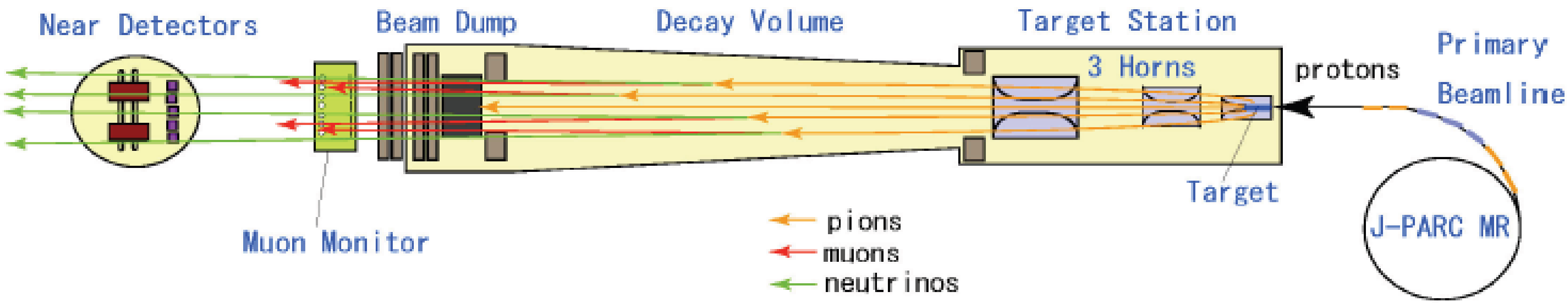
- $\sin^2 2\theta_{13} > 0.01$ at $>5\sigma$ significance ?
- Mass hierarchy $\Delta m_{31}^2>0$ ?, $\Delta m_{31}^2<0$ ?
- CP-phase $\delta \neq 0, \pi$ at $>3\sigma$ significance, $\delta$ true ?
- Unitarity ? tri-bimaximal ? differences between quark and lepton sectors ?

# Future experiment

- To explore further ν oscillations (CP violation, mass hierarchy, test PMNS), need
  - Intense beams of ν.
  - Huge underground detectors.

- Detector has huge physics potential.
  - Proton decay.
  - Astrophysical ν sources.
  - Geo ν.

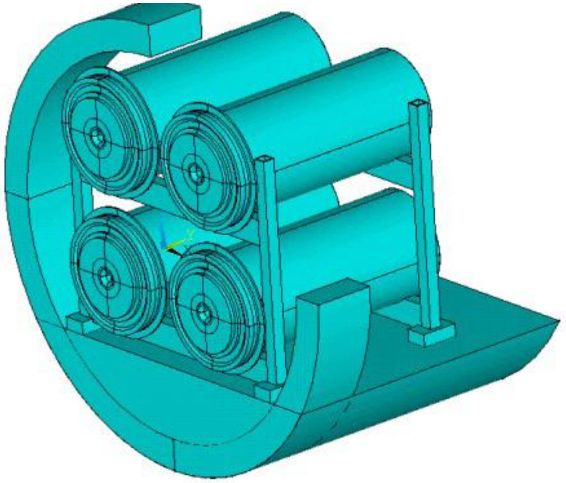
# Current beam




- Produced by decays of an intense π beam.
- Gives ~ 98% of $\nu_\mu$ ($\pi^+ \rightarrow \mu^+ \nu_\mu$).
  - Thus study $\nu_\mu \rightarrow \nu_e$ oscillation.
- J-PARC reached 145 kW (nominal 750 kW).
- Future beam options studied in EURONU.

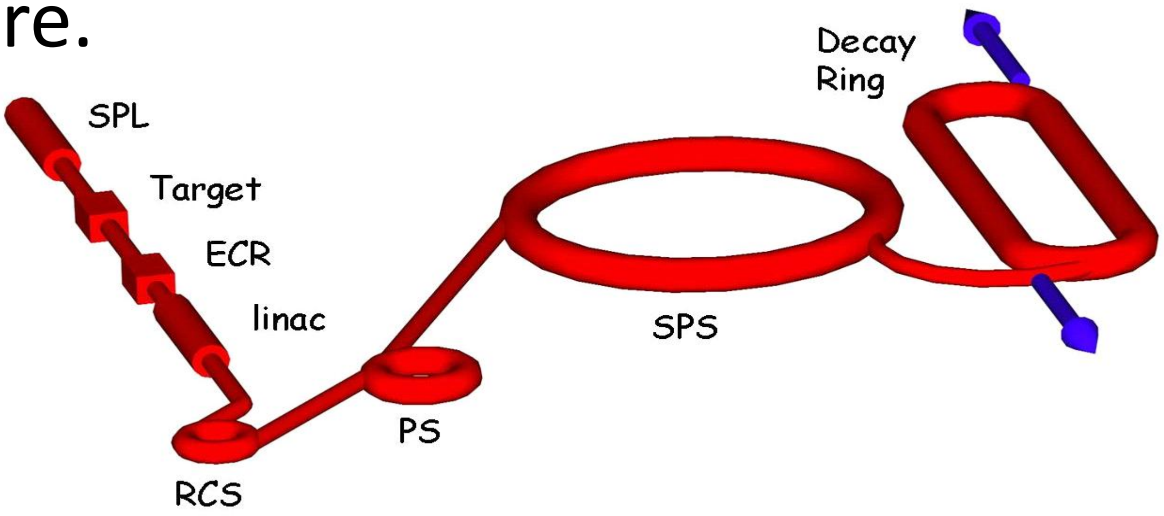
# Super beam

- Higher-power version of current ν beam facility.
- The least expensive.
- Main challenge are target and horn.
  - Should handle ~ 4 MW of protons.
- Multiple target design.
  - 4 x 1 MW.



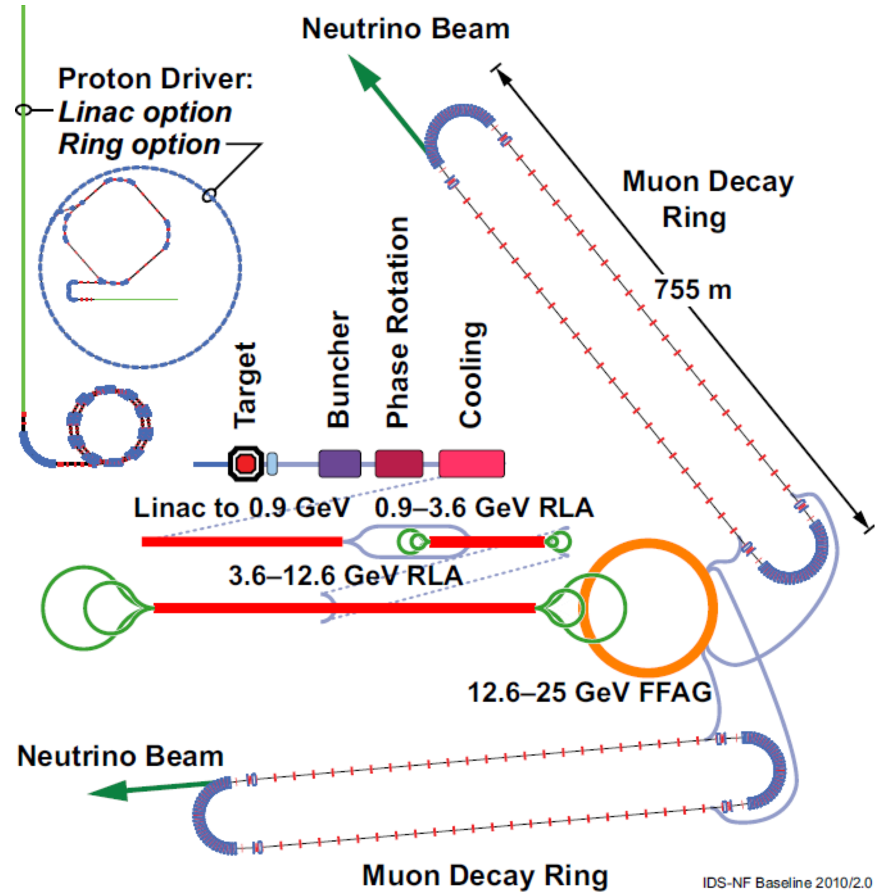
# β beam

- Produced by decays of a stored beam of β unstable ions.
- Gives only $\nu_e$.
- Baseline scenario produces low energy $\nu_e$.
- Long term future.



# Neutrino factory

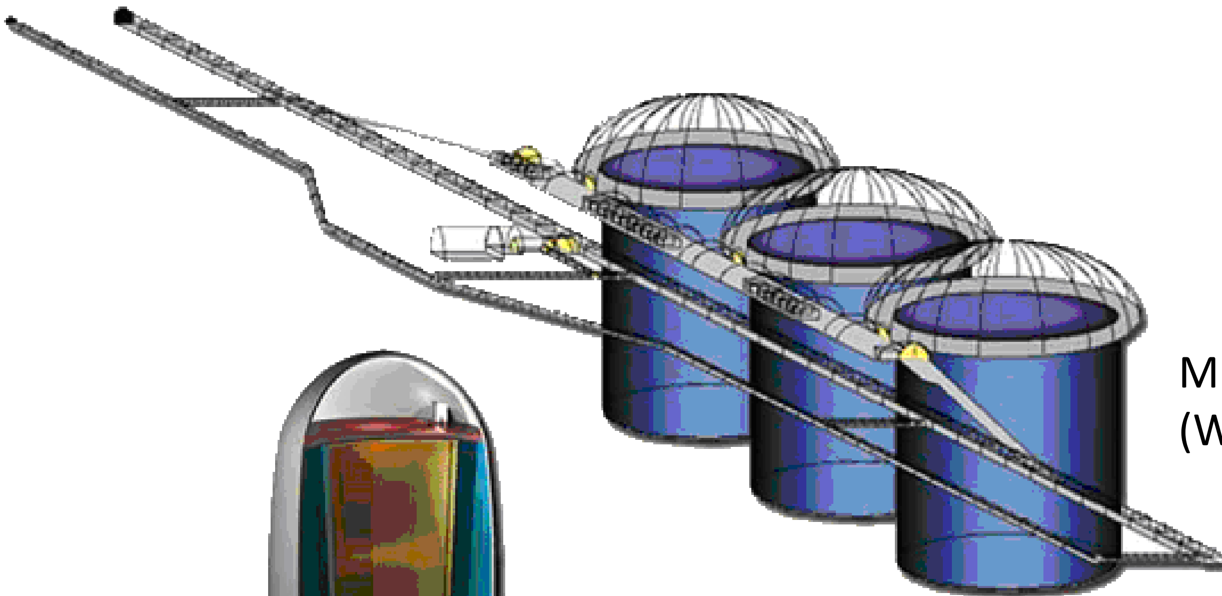
- Produced by decays of a stored μ beam.
  - Precursor of a μ collider.
- Gives both $\nu_e$ and $\nu_\mu$.
- Produces high energy ν (above τ threshold).
- Long term future.



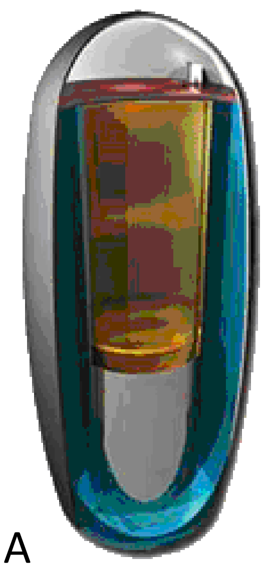
# Shift of paradigm

- Measurement of small $\theta_{13}$.
  - As long as there were no hints for non-zero $\theta_{13}$.
  - Optimize future facilities with sensitivity on $\sin^2(2\theta_{13})$.
  - Ranking was: super-beam ($\rightarrow$0.01), β beam($\rightarrow$0.001), ν factory ($\rightarrow$0.001).
- Measurement of CP violation and mass hierarchy for a given (large) value of $\theta_{13}$.
  - With present evidence that $\theta_{13} > 0$ (at >3σ).
  - Expect $\theta_{13}$ measurement (at >5σ) in the coming years.
  - Optimize future facilities with sensitivity on CP violation and mass hierarchy.
  - Can be done with super-beam.

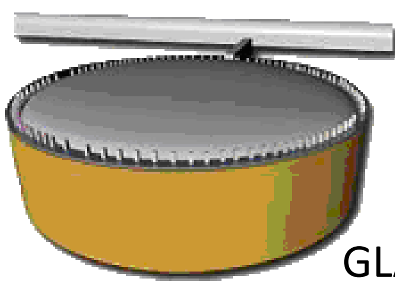
# The detector options



MEMPHYS
(Water Cherenkov)

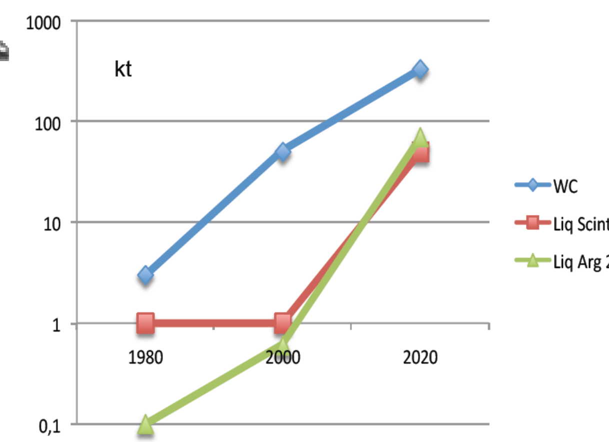


LENA
(Liquid Scintillator)



GLACIER

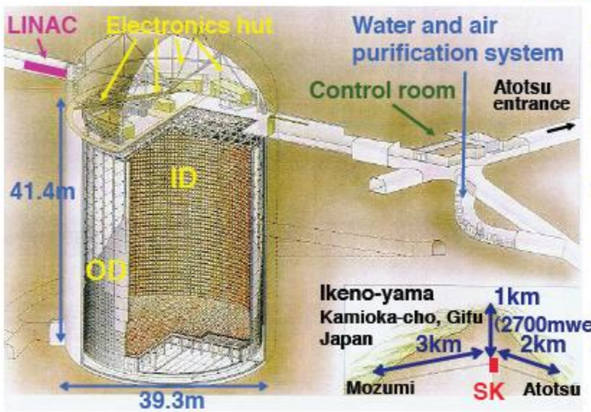
(Liquid Argon)



# Water Cerenkov (current)

## Super-Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/sk/

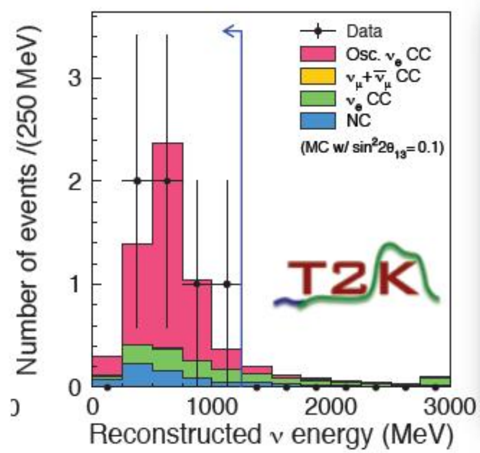


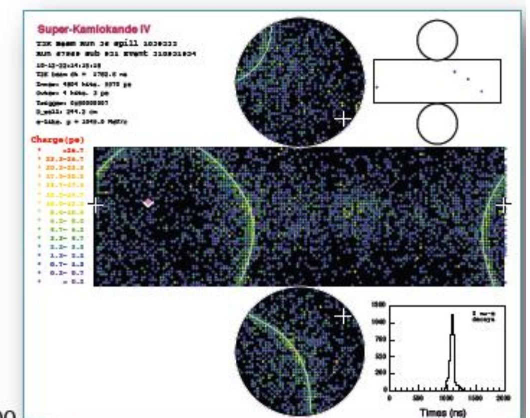

- 50kton water
- 32kt ID viewed by 20-inch PMTs
- ~2m OD viewed by 8-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- $E_{total}$=~4.5MeV energy threshold
- SK-I: April 1996~
- SK-IV is running

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

**Large Size**: for rare events, low fluxes
**Low Threshold**: as low as MeV with high efficiency
**Excellent e/μ**: >98% from single ring pattern
**Low cost/kton**: "affordable" way to megaton mass
**Free protons**
**Mature technology**: short development time
**Safety, Maintenance, Accessibility**

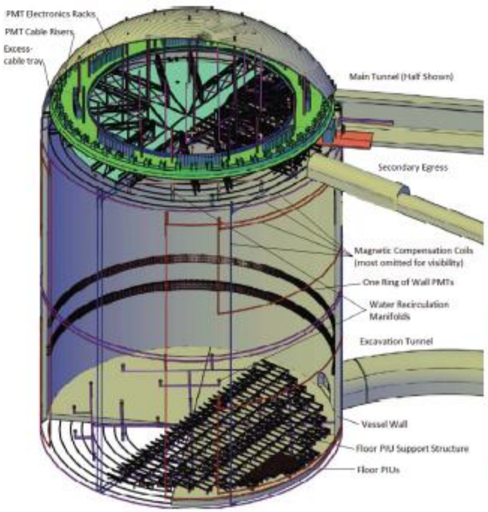
Excellent performance especially for low energy w/ low multiplicity
Cherenkov threshold
Energy reconstruction assuming CCQE
Efficient for low energy
Good PID (μ/e)
Established analysis
**Good at low E (<1GeV)**
**narrow band beam**
Match with low energy off-axis beam



# Water Cerenkov (future)

## LBNE WCD option

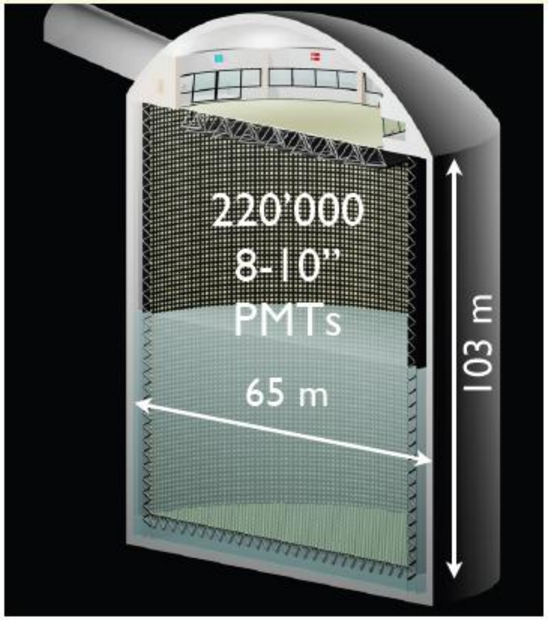



Main Detector Components
- Large Cavern
- Water Vessel
- Ultra-pure water system
- PMTs with Electronics

150-200 kton FD
8-10" PMT to reach
20% photocoverage
4300 mwe depth

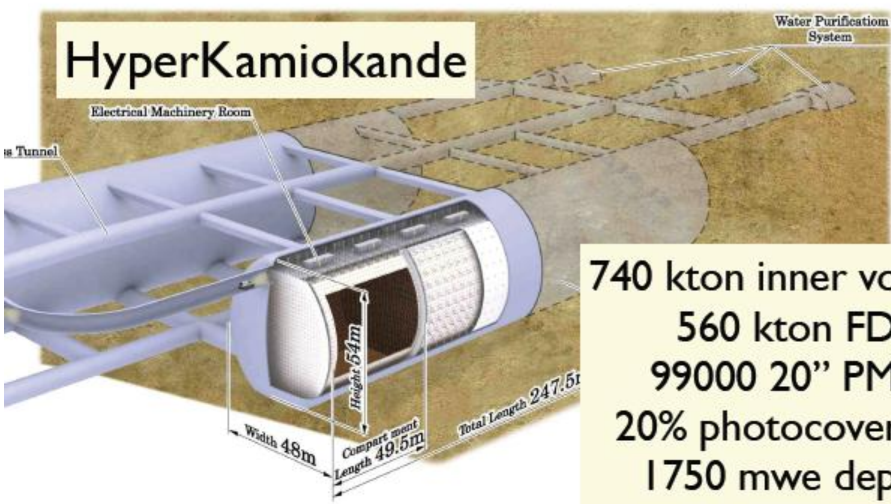
Well-known, "ready to go" technology
Engineering challenges lie in huge excavation and photo-sensors procurement

## MEMPHYS (LAGUNA WCD option)




2x330kt total volume
440 kton FD
220'000 8-10" PMT
4800 mwe depth

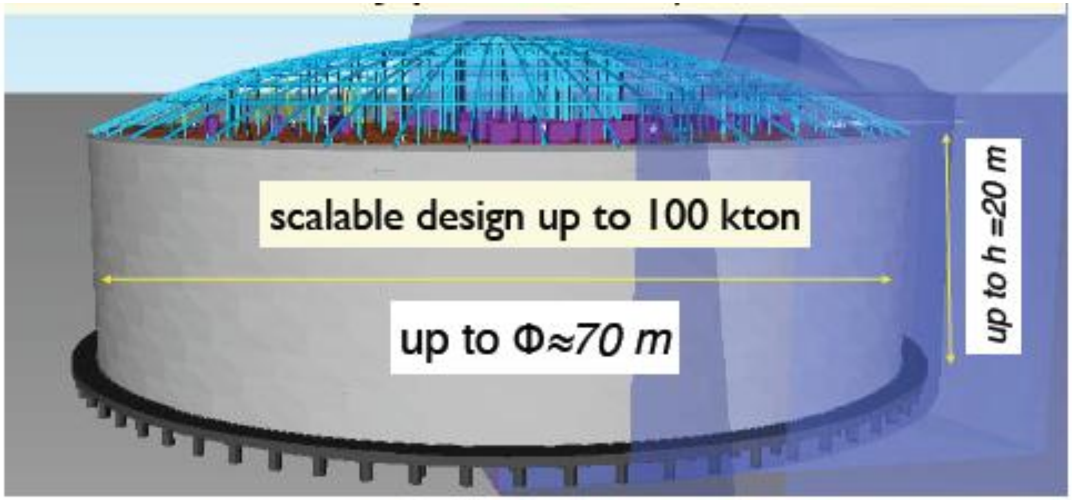
## HyperKamiokande




740 kton inner volume
560 kton FD
99000 20" PMT
20% photocoverage
1750 mwe depth

# Liquid argon detector

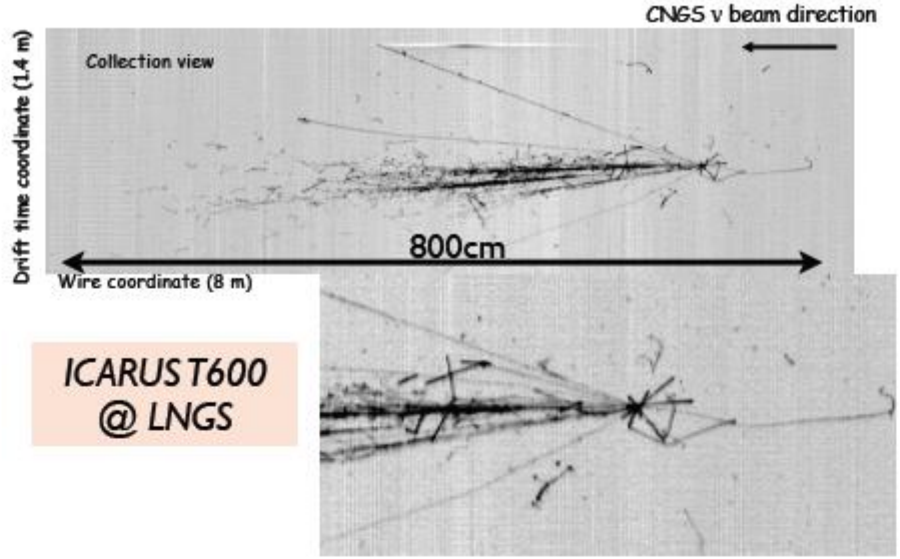
- Exclusive final state reconstruction.
- 3D tracking of charged particles with millimeter space resolution.
- Excellent energy resolution.
- Excellent particle ID.

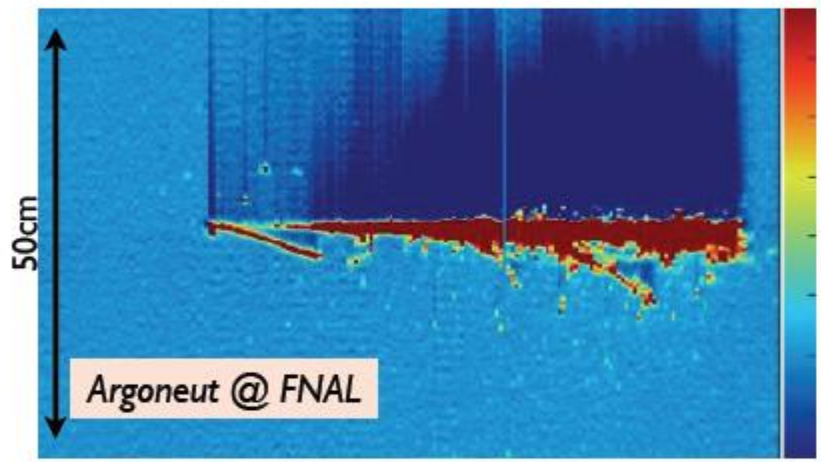



J.Phys.Conf.Ser. 308 (2011) 012030

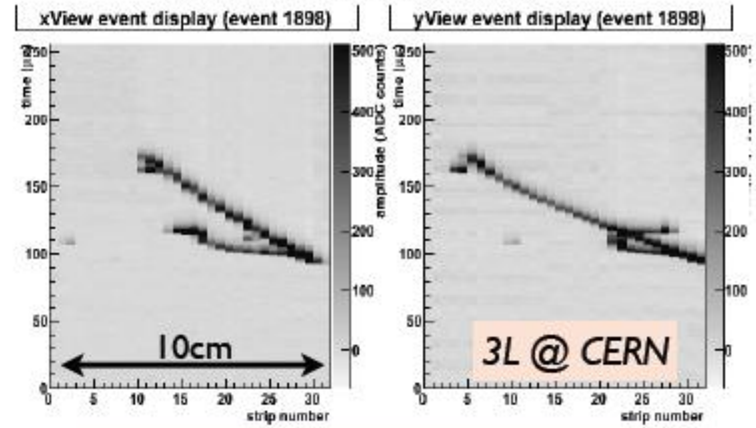
# Liquid argon detector

*"electronic bubble chambers"*



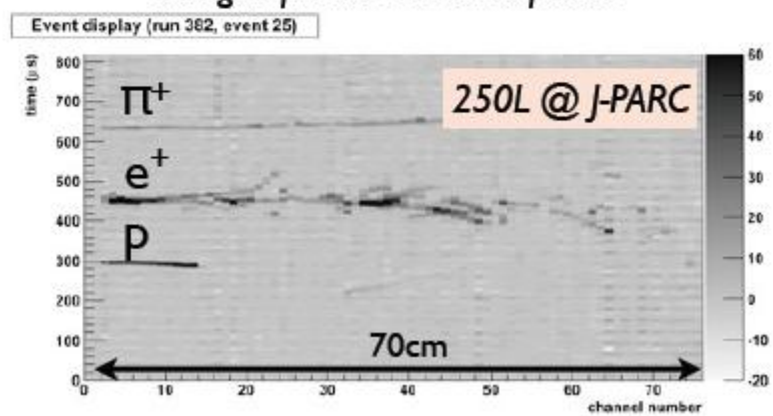




*Cosmic track in double phase 3L LAr-LEM TPC with adjustable gain @ CERN*




**Much improved S/N (>100) compared to single-phase LAr operation (≈15)**

*Charged particle beam exposure*

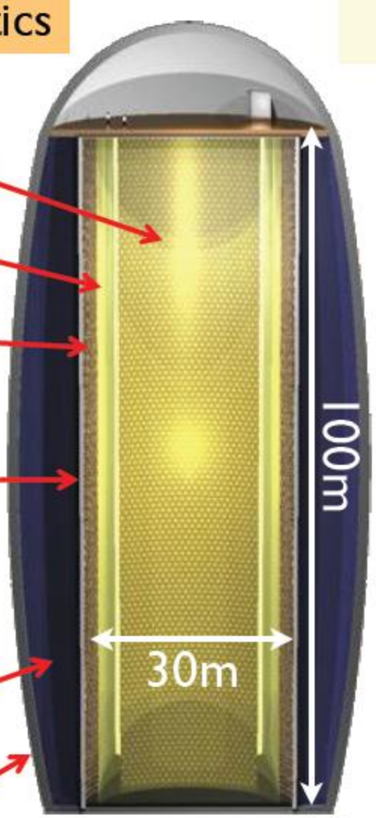


# Liquid scintillator detector

Very high purity liquid scintillator with high light yield, optimized for lowest energy range (large size: KamLAND, Borexino, SNO+, etc.)

ideally matched to study low energy neutrinos (MeV) with high statistics

LENA (LAGUNA LScint option)
4200 mwe




Pyhäsalmi design

Desired **energy resolution**
→ 30% optical coverage
→ 3000m² effective photo-sensitive area

Light yield ≥ 200 pe/MeV

The **tracking option** adds to the requirements of the PMT array and electronics:
- → more, but smaller, faster PMTs
- → full waveform digitizing

response to high energy neutrino beam under study

# Oscillation probability

Approximate formula (M. Freund)

quadratic dep. on $\theta_{13}$

matter effect ~E

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

~7500 km magic bln

CPV term approximate dependence ~L/E

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

~2540 km magic bln

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

solar term

linear dep. on $\theta_{13}$

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

CP asymmetry grows as $\theta_{13}$ becomes smaller !

Correlations !

Going to anti-ν: $\delta \to -\delta$ and $\hat{A} \to -\hat{A}$.

# Main strategies

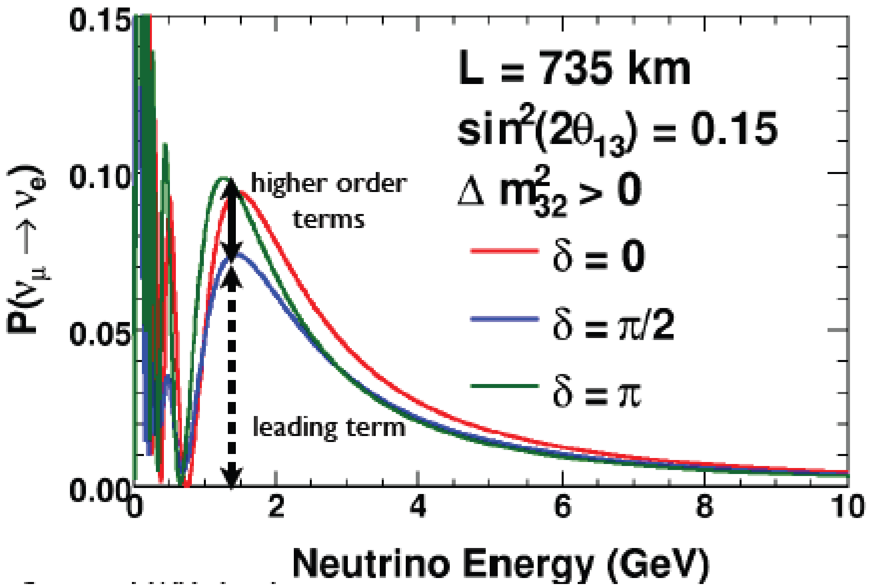
- Differences between ν and anti-ν appearance.
  - Obtained by inverting beam polarity.
  - Can be done in narrow band beam.
  - Systematics between ν and anti-ν runs.
- Appearance spectrum of ν.
  - Peak position and height at maxima and minima.
  - Need wide band beam.
  - Good energy resolution required.

# Appearance spectrum

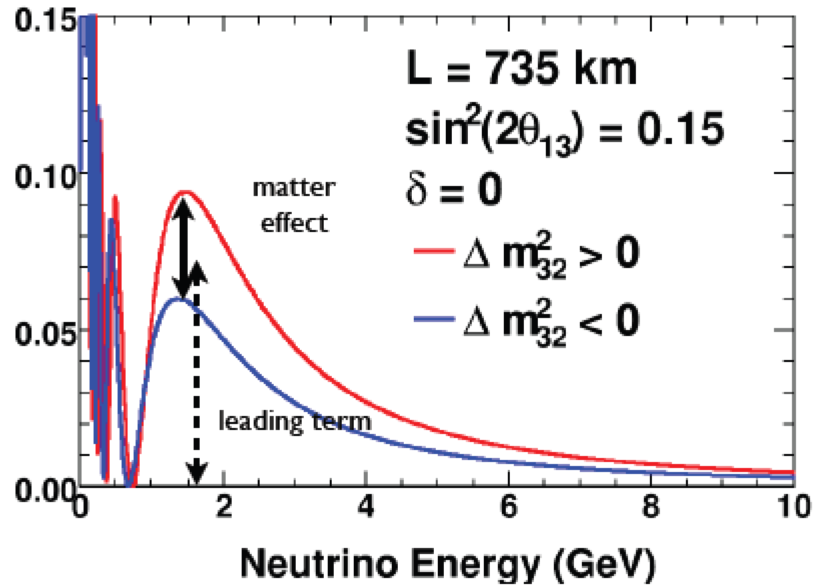
$\nu_e$ appearance in a $\nu_\mu$ beam <u>with high precision</u> to test higher order terms that depend on $\delta_{CP}$ and determine the matter effects

➠ Measure energy-binned probability with rel. error < O(5%)

δ dependence




mass hierarchy dependence

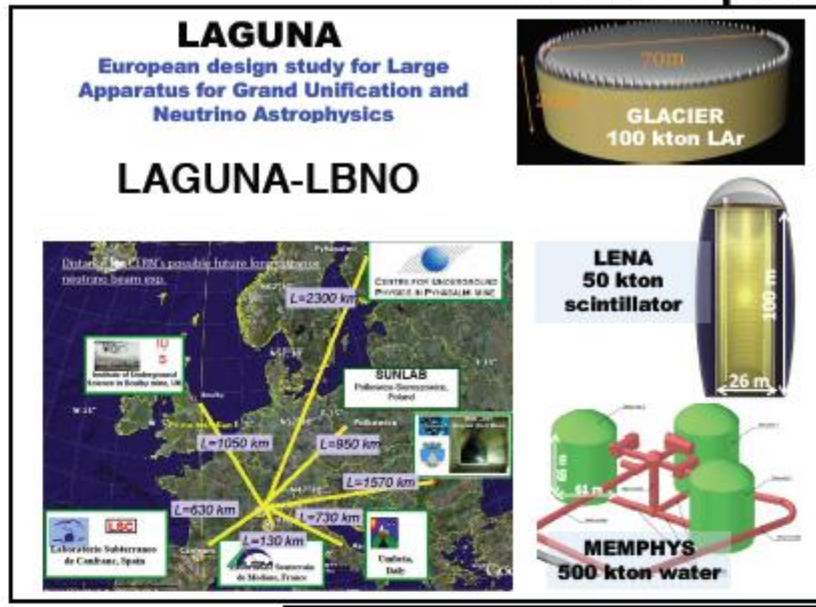


# International context

## In USA

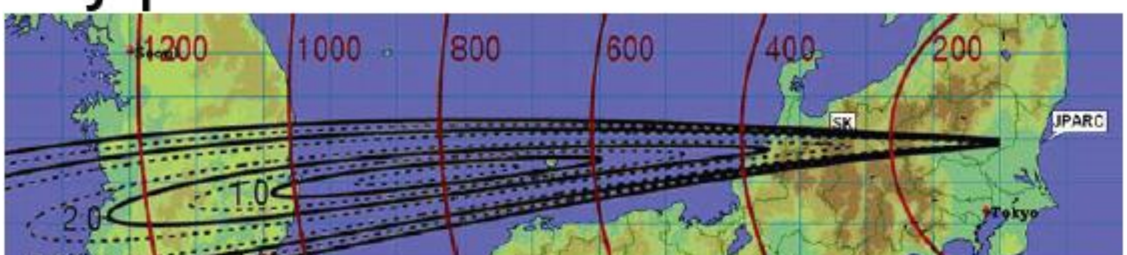

LBNE – a plan to build a new neutrino beam at Fermilab aimed at Homestake, where either a large water Cerenkov detector or a LAr tracking calorimeter would be built

## In Europe




LAGUNA/LAGUNA-LBNO – study considering three detector options for astroparticle physics and new long baseline in Europe

## In Japan




An upgrade of the J-PARC neutrino beam to reach 1.6 MW beam power and new far detector(s) at Kamioka, Okinoshima, or Korea

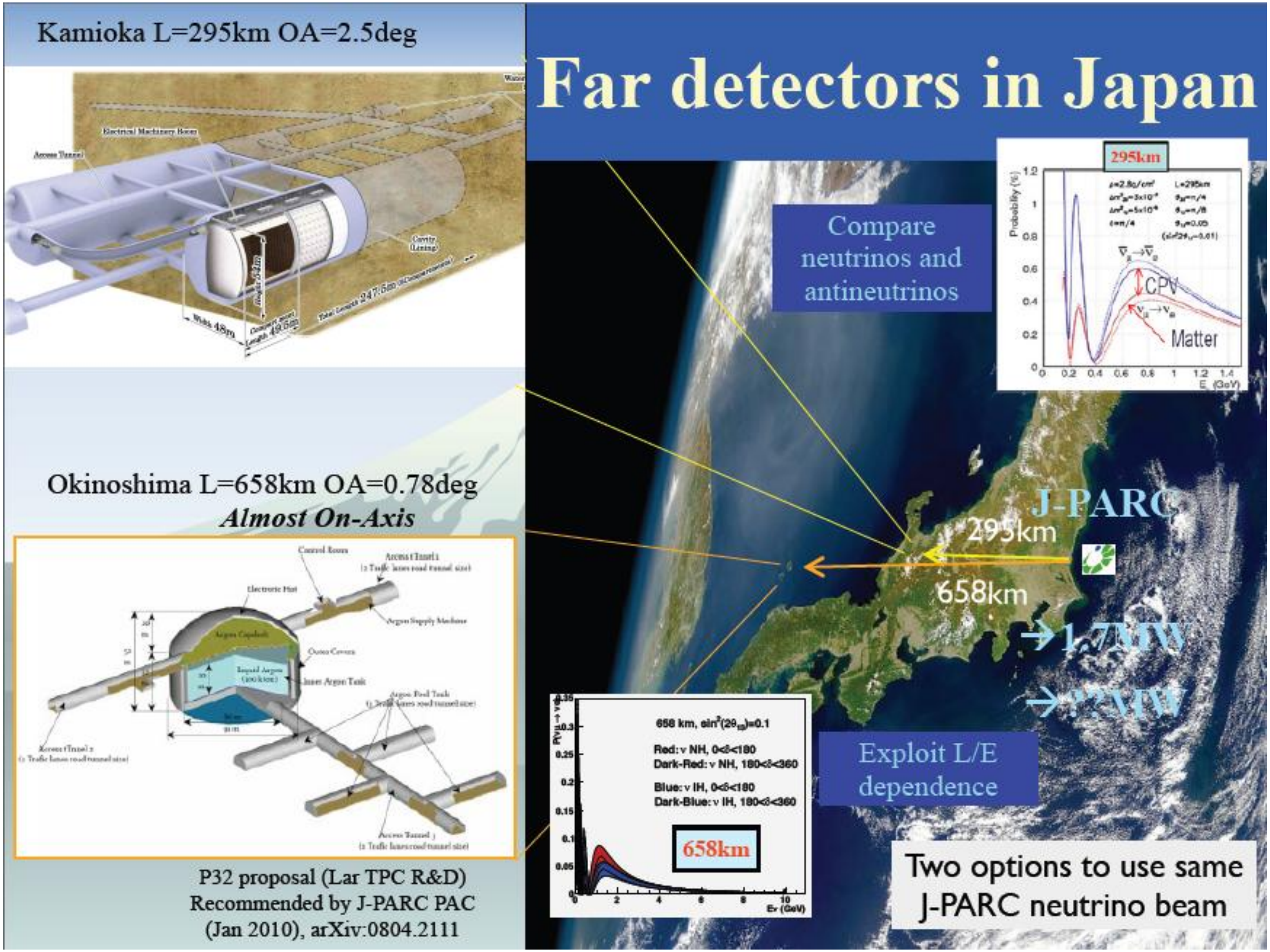
*Each of the three community ≈ same size*

# In the US


Beam: 700 kW, 60-120 GeV, 5 years ν + 5 years $\bar{\nu}$
on-axis, wide band, **upgradable to 2.3 MW**
Baseline: 1300 km FNAL to Homestake
Far Site: Underground location to facilitate broad program
Near Site: on current Fermilab property
Configurations: several options under study for beam,
near, and far detectors

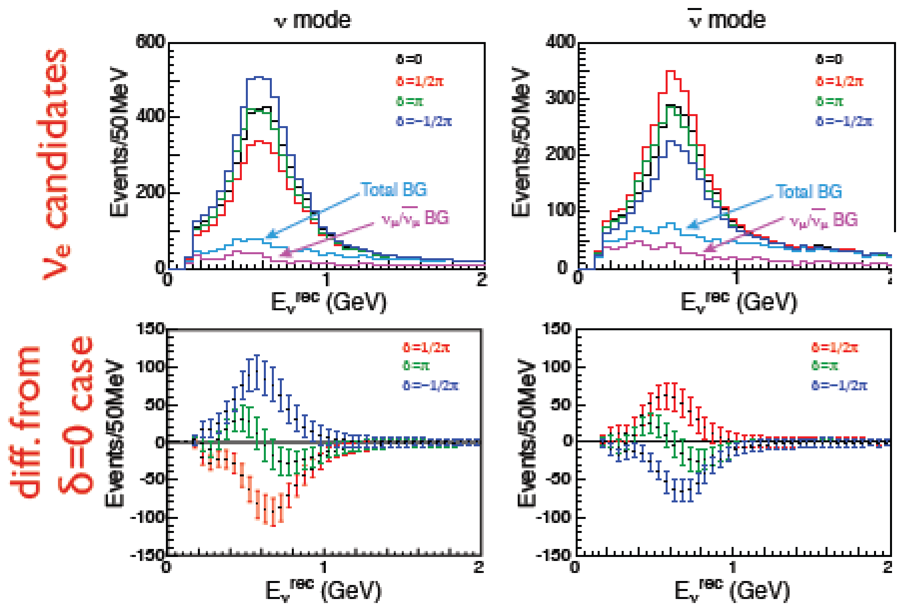
- CD-0 in January 2010 ➠ goal to have CD-1 in FY2012
- Two detector technologies (WCD and LArTPC) to be located at 4850ft and 800ft levels

# In Japan


Kamioka L=295km OA=2.5deg
Okinoshima L=658km OA=0.78deg
*Almost On-Axis*
P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111
Far detectors in Japan
Compare neutrinos and antineutrinos
295km
CPV
Matter
J-PARC
295km
658km
Exploit L/E dependence
658km
Two options to use same J-PARC neutrino beam

# HK physics reach

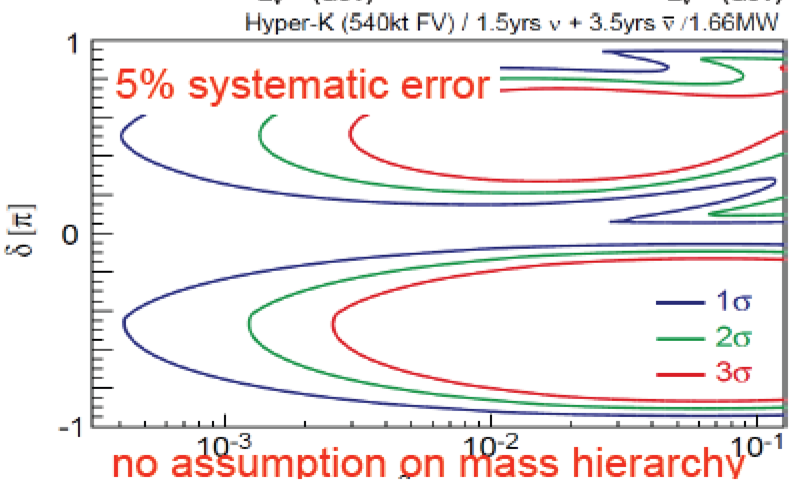
1.5 yr υ + 3.5yrs $\overline{\upsilon}$ @ 1.66 MW

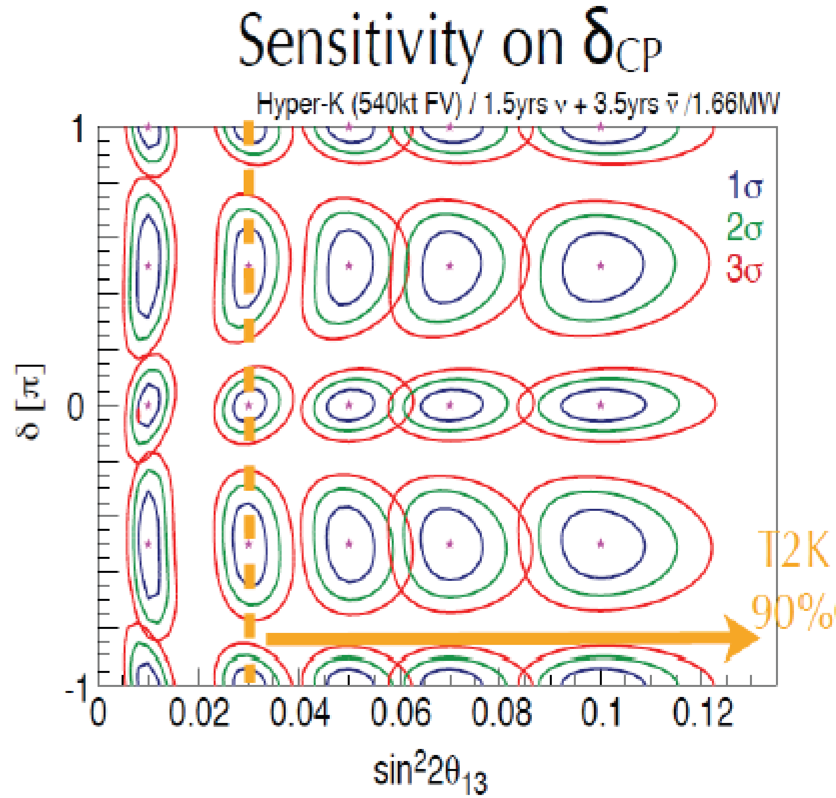



Very good chance to detect CPV & have potential on sign($\Delta m_{23}$) with atm ν

Becomes more difficult for large $\theta_{13}$

Challenge: reach a systematic error <5%

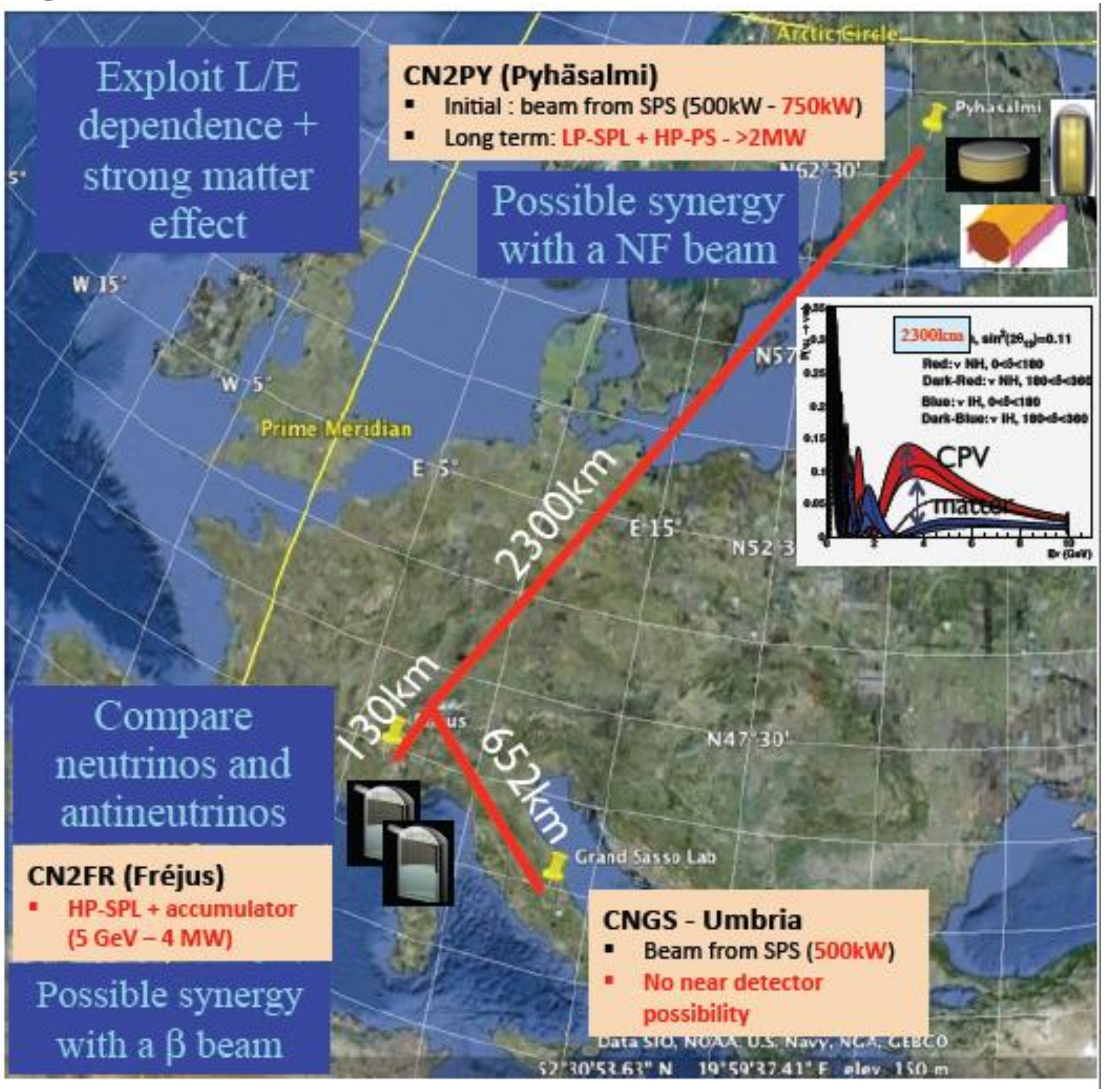



*Courtesy: M. Shiozawa*

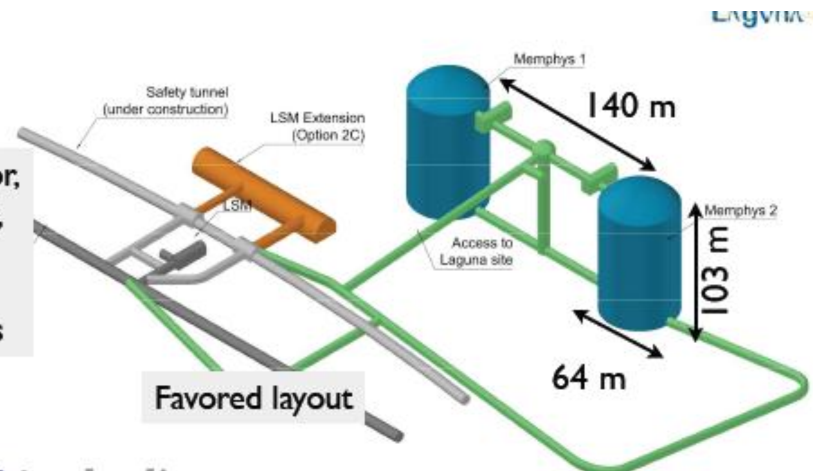
# In Europe: LAGUNA-LBNO

- LAGUNA had converged to two sites.
- Fréjus.
  - Shortest BL.
- Pyhäsalmi.
  - Longest BL.
- (Umbria.
  - Existing beam.)

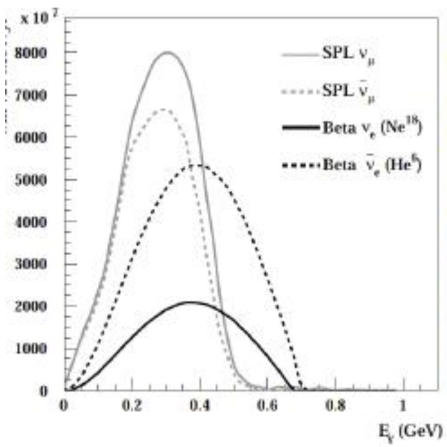


# Option Fréjus / MEMPHYS


Water Cerenkov detector,
2 independent modules,
330'000 $m^3$ each
220'000 8-10" PMTs
≈500 kton fiducial mass



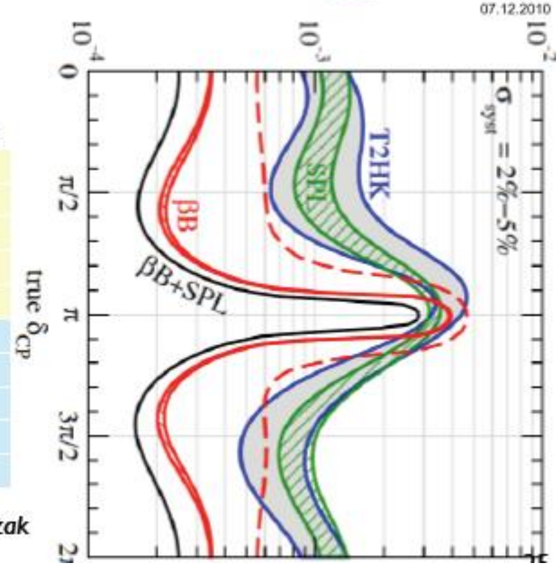

CERN SPL 5 GeV 4MW



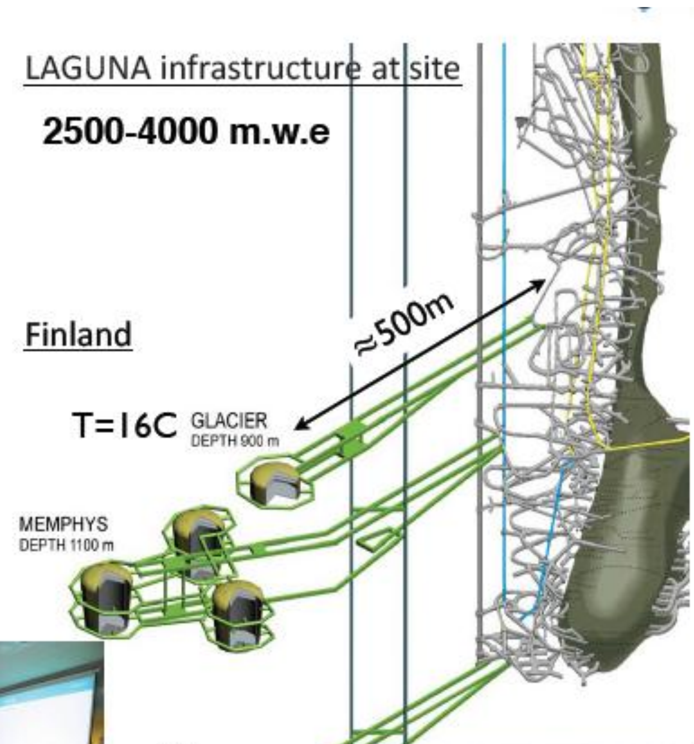

2 yr $\nu$ + 8yrs $\bar{\nu}$ @ 4 MW

| | βB | | SB | |
|---|---|---|---|---|
| | $\delta_{CP}=0$ | $\delta_{CP}=\pi/2$ | $\delta_{CP}=0$ | $\delta_{CP}=\pi/2$ |
| **Appearance $\nu$** | | | | |
| Bkgd | 143 | | 622 | |
| $\sin^2 2\theta_{13} = 0$ | 28 | | 51 | |
| $10^{-3}$ | 76 | 88 | 105 | 14 |
| $10^{-2}$ | 326 | 365 | 423 | 137 |
| **Appearance $\bar{\nu}$** | | | | |
| Bkgd | 157 | | 640 | |
| $\sin^2 2\theta_{13} = 0$ | 31 | | 57 | |
| $10^{-3}$ | 83 | 12 | 102 | 146 |
| $10^{-2}$ | 351 | 126 | 376 | 516 |

Courtesy: T. Patzak



# Option Pyhäsalmi


## Main aspects of the infrastructure

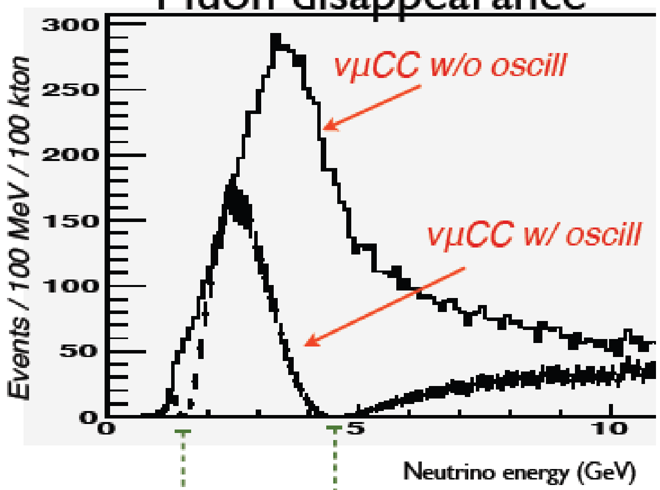
- *existing working mine with very high standards*
- *existing decline tunnel access to deepest level*
- *excellent excavation strategy*
- *efficient rock disposal*
- *no disturbance with hosting site*
- *sufficient fresh air inlet*
- *effective outlet of return air*
- *safety*
- *supply routes for construction*
- *storage of material*
- *quality control of material at the vicinity*
- *supply route (pipe lines) for liquids*


Cafeteria, meeting room and sauna at 1400 m below ground


250 m long tunnel and a cavern at 1400m excavated for LAGUNA R&D

# Option Pyhäsalmi

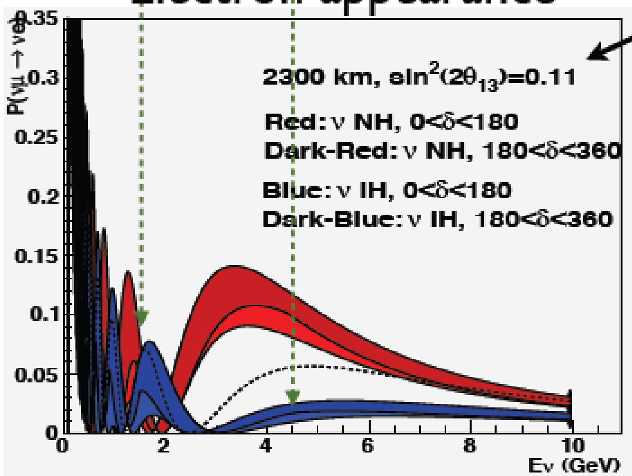
Muon disappearance



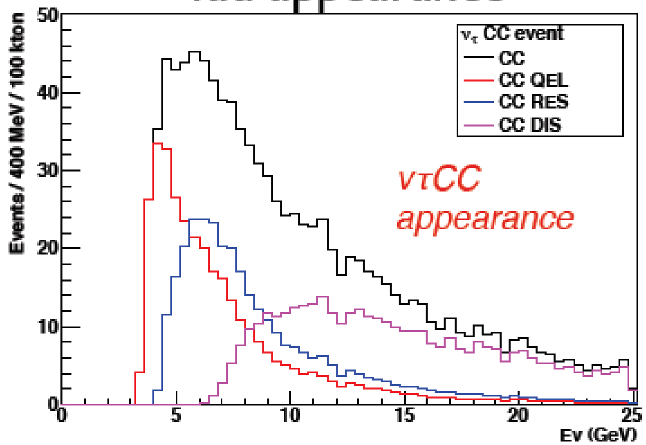

*Event rates: CERN SPS 400 GeV*
*5 years @ 9.4x10$^{19}$ pots/year*

| | Neutrino horn polarity $\sin^2 2\theta_{23}=1.0$, $\sin^2 2\theta_{13}=0.1$ | | | |
|---|---|---|---|---|
| Distance/OA | $\nu_\mu$CC | $\nu_e$CC | $\nu_\mu \rightarrow \nu_e$ | $\nu_\mu \rightarrow \nu_\tau$ |
| Pyhäsalmi 2300 km 0.25 deg | 17152 | 250 | 880 | 1018 |

Electron appearance

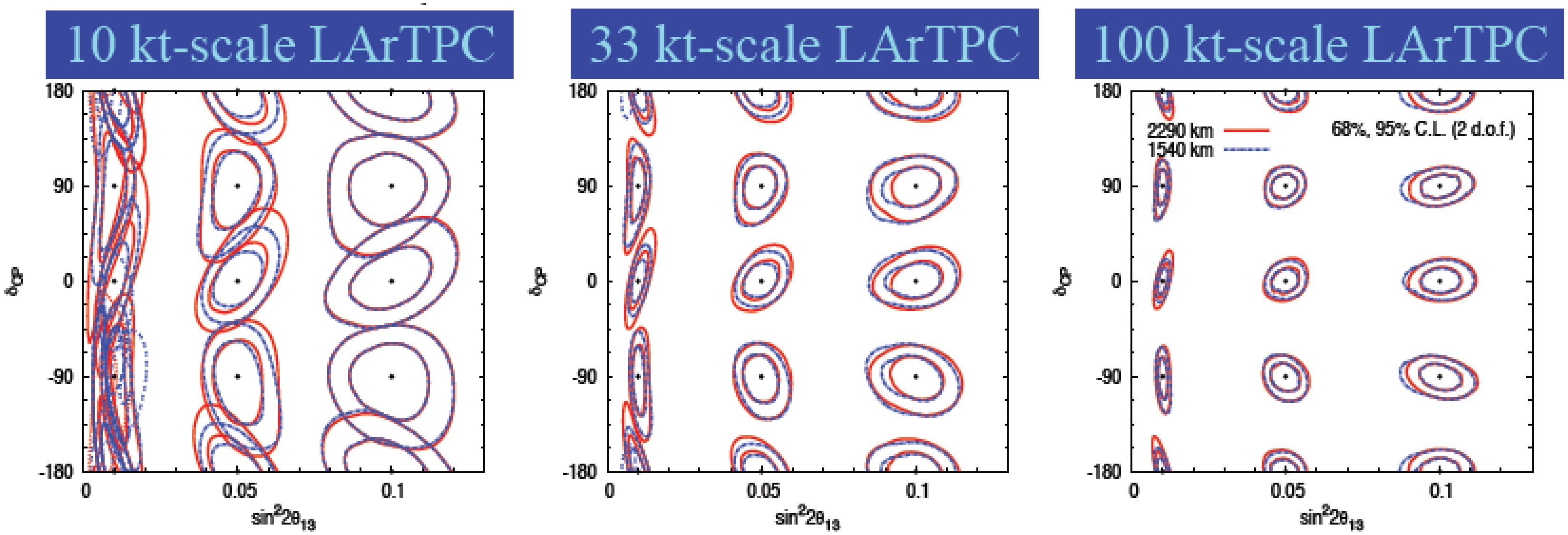



Tau appearance



# Incremental approach

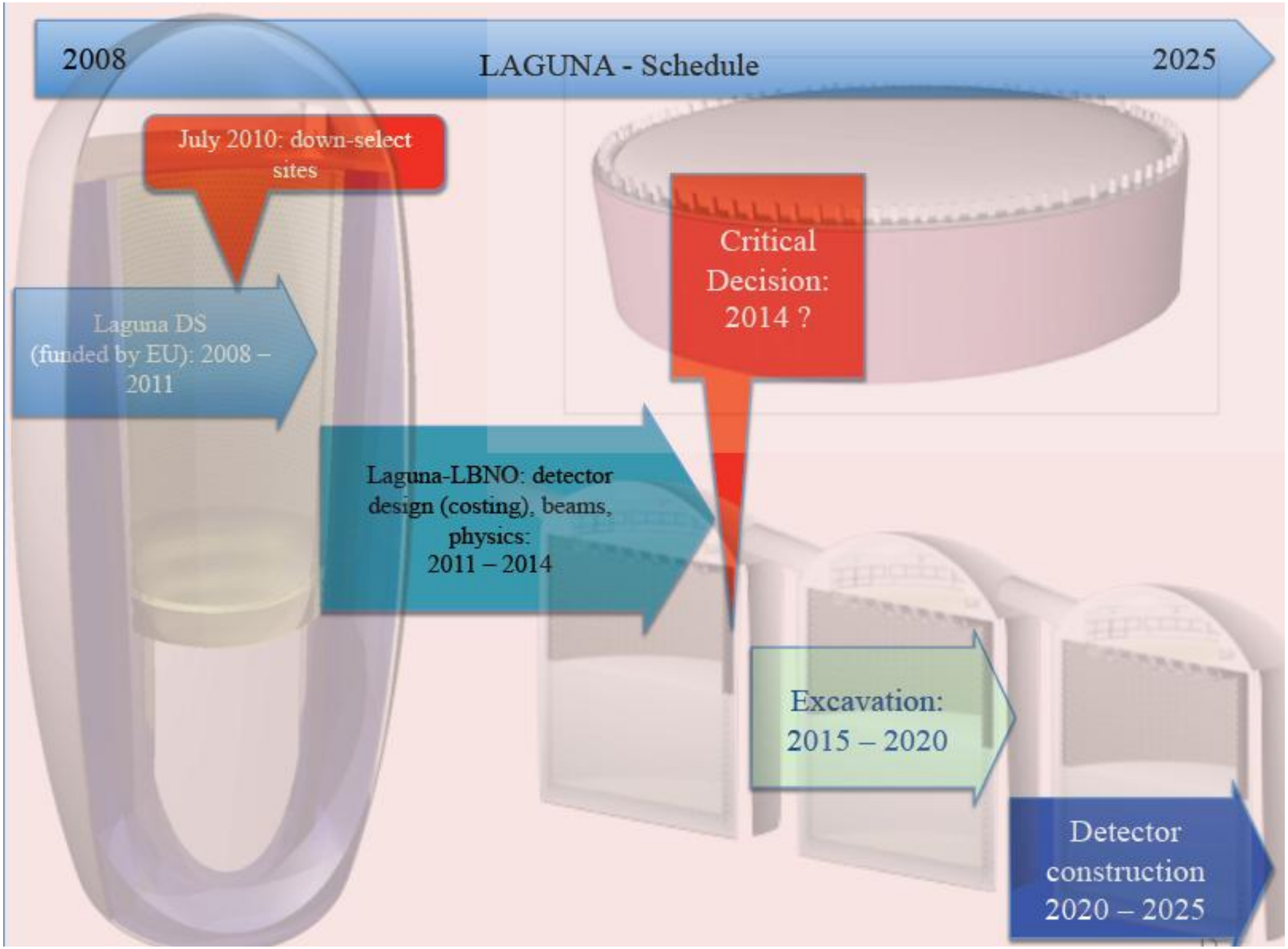
- Produce significant physics results at each phase.
- Reduce risks, ease funding.



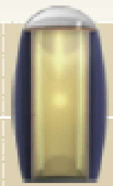

(red) CERN-Pyhäsalmi 2300 km
(blue) CERN-Slanic 1540 km

5 yr $\nu$ + 5 yr $\bar{\nu}$ HP-PS

# Schedule


2008
LAGUNA - Schedule
2025
July 2010: down-select sites
Laguna DS (funded by EU): 2008 – 2011
Critical Decision: 2014 ?
Laguna-LBNO: detector design (costing), beams, physics: 2011 – 2014
Excavation: 2015 – 2020
Detector construction 2020 – 2025

# p decay and astrophysical ν

| |  GLACIER |  LENA |  MEMPHYS |
|---|---|---|---|
| Total mass | 100 Kton | 50 kton | 500 Kton |
| p -> $e\pi^{o}$ in 10 y | $0.5 \times 10^{35}$ y<br>ε = 45%, ~1 BG event | ? | $1.2 \times 10^{35}$ y<br>ε = 17%, ~1 BG event |
| p -> ν K in 10 y | $1.1 \times 10^{35}$ y<br>ε = 97%, ~1 BG event | $0.4 \times 10^{35}$ y<br>ε = 65%, <1 BG event | $0.15 \times 10^{35}$ y<br>ε = 8.6%, ~30 BG events |
| SN cool off at 10 Kpc | 38·500 (all flavors) (64·000 if NH-L mixing) | 20·000 (all flavors) | 194·000 (mostly $\nu_e p \to e^+ n$) |
| Sn in Andromeda | 7 - (12 if NH-L mixing) | 4 events | 40 events |
| SN burst at 10 Kpc | 380 $\nu_e$ CC (flavor sensitive) | ~ 30 events | ~ 250 ν-e elastic scattering |
| DSN | 50 | 20-40 | 250 (2500 with Gd) |
| Atm. neutirnos | ~1·100 events/y | 5600/y | 56·000 events/y |
| Solar neutrinos | 324·000 events/y | ? | 91·250·000/y |
| Geo-neutirnos | 0 | ~ 3·000 events/y | 0 |

# Conclusion

- Current value of $\theta_{13}$ makes a long baseline ν oscillation experiment based on a super beam and a huge underground detector the most attractive next step.
- Lots of efforts in Japan, US, and Europe aiming at this new generation experiment.
- Goal is to measure mass hierarchy and CP violation, and to test PMNS picture.
- Same experiment will study proton decay and astrophysical ν.