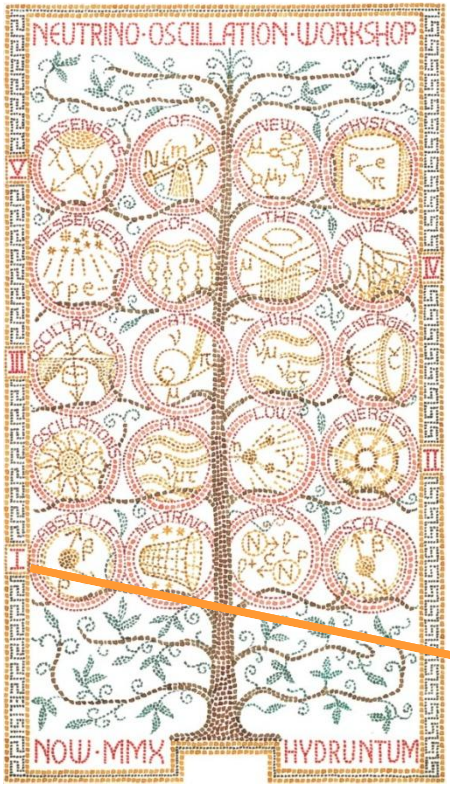
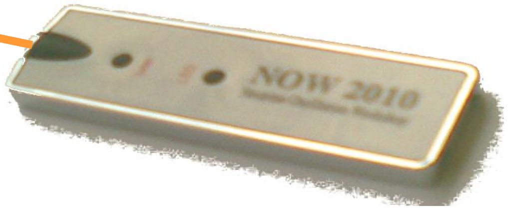


Prospects for large-volume neutrino detectors

Tobias Lachenmaier
Technische Universität München



Neutrino Oscillation Workshop, Otranto, September 2010

Why large neutrino detectors?

With the discovery of neutrino oscillations, there is a clear sign for physics beyond the Standard Model.

GUT

proton decay

baryon/
anti-baryon
asymmetry

leptogenesis

There are still open questions to complete our knowledge on fundamental neutrino properties and to understand neutrino mixing in detail: θ_{13}, CP-violation, mass hierarchy, absolute mass scale, nature of the neutrino.

Strong interest and growing effort for large-volume neutrino detectors in Europe, US, and Asia.

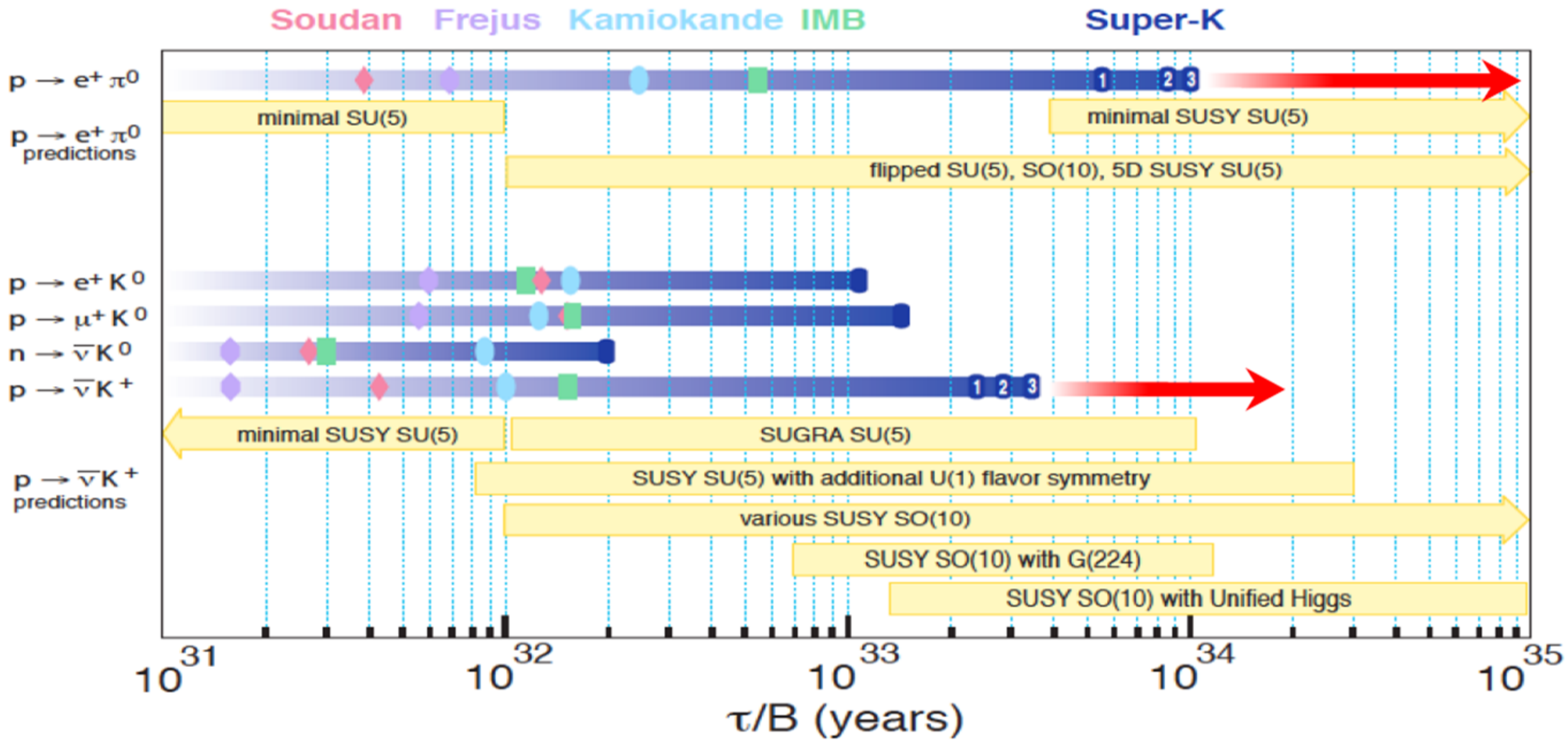
Complementary to **LHC**:

- **LHC**: Higgs mechanism, SUSY, rare decays
- **LAGUNA**: Proton decay, neutrino astronomy, CP violation in leptons

Many thanks to R. Svoboda, T. Kobayashi and M. Shiozawa for contributions.

Search for proton decay

- **current limits in most channels dominated by Super-Kamiokande. Want to improve at least factor of 10.**
- **observation would be de-facto discovery of Grand Unification**



CP violation in the leptonic sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

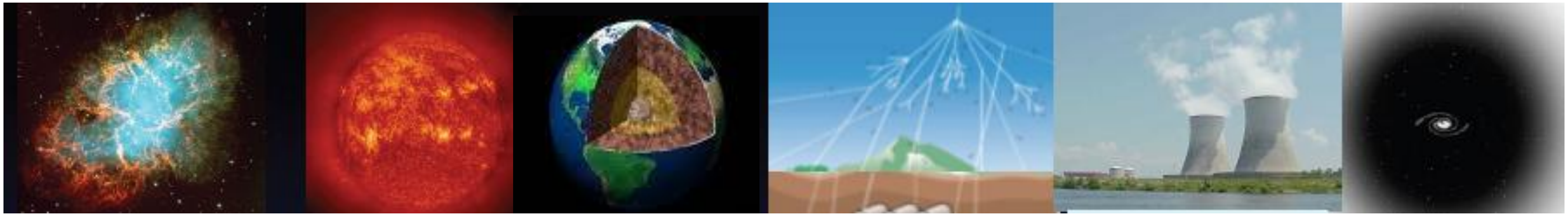
If there ***does*** exist a RH heavy partner for the LH neutrinos, ***and*** if such a partner violates CP in its decay, it could influence the baryon/anti-baryon symmetry of the universe (leptogenesis).
CP violation in the light neutrinos does not *prove* that neutrinos have a heavy CP-violating partner, but it is strong circumstantial evidence.

Search for CP violation with the channels $\nu_\mu \rightarrow \nu_e$ / $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
in long baseline neutrino experiments by looking for a difference between $\nu_e/\overline{\nu}_e$ appearance probability

-> size of observable effect is depending on $\sin\theta_{13}$
-> sensitive to any mechanism that creates nu/anti-nu asymmetry, separation of non-CPV effects needed

Why large neutrino detectors?

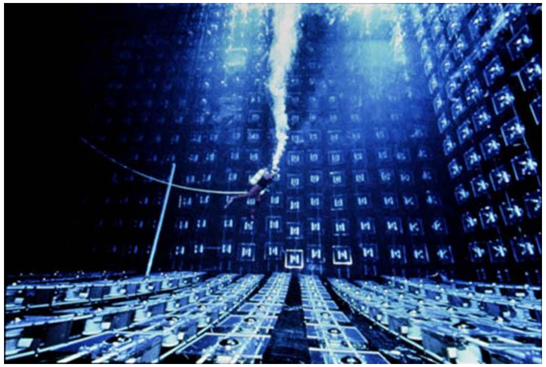
- Galactic Supernova Burst
- Diffuse Supernova Neutrino Background
- Solar Neutrinos
- Geo neutrinos
- Reactor neutrinos
- Neutrino oscillometry
- Atmospheric Neutrinos
- Dark Matter



Detector technologies under discussinon

- Water Cherenkov detector
- Liquid Argon TPC
- Liquid Scintillator detector

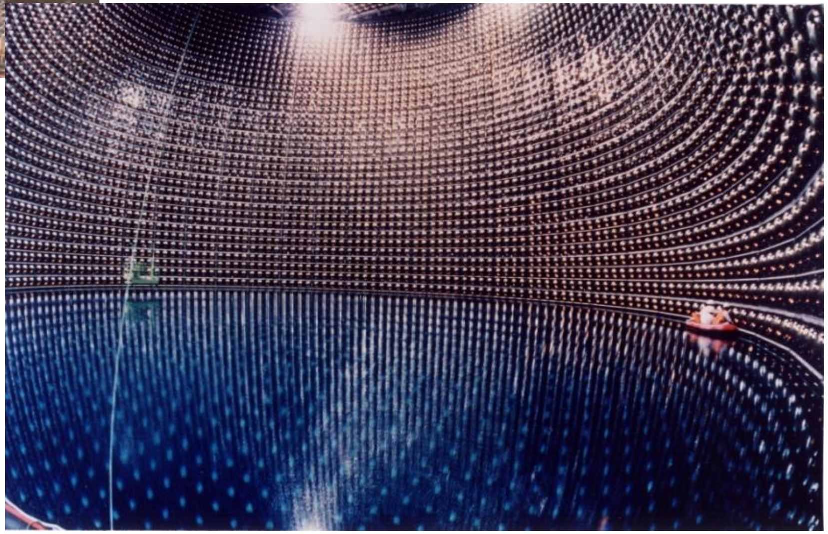
Water Cherenkov detectors



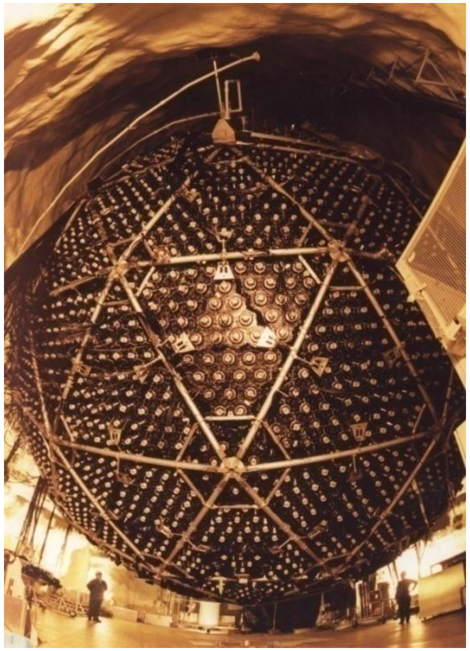
IMB
3 ktons

Kamiokande
1 kton

Large and useful experience: performance, calibration and operation are well established.



Super-Kamiokande
22 ktons



SNO
1 kton

Water Cherenkov technique

- basic techology is well established
- aim is to go to 0.5-1 Megaton

- good tracking especially at 1 GeV or less
- good PID capability at low energy
- energy resolution for e and μ ~3% (SK)
- for long-baseline beam experiment:
  good at low E (< 1GeV) narrow band beam
- technique is still evolving: e.g. better efficiency for muon decay electrons

Challenges:

- huge amount of photosensors needed (~200.000 for 40% coverage as SK). Reduction by a factor of 2 works well for high energy applications (beam and proton decay). To what extent is additional reduction possible?
- very large underground cavities needed
- cost implied by these two points

see T. Kajita

Liquid Argon TPC

- electronic "bubble chamber", detailed event topology
- brilliant energy reconstruction and track resolution of every particle, capable up to higher energies
- PID with dE/dx and separation of tracks possible
- basically background-free for many applications
- aim at O(100kt)

Challenges:

- "complicated" detector technology
- huge number of channels (depending on position resolution)
- limited drift length leads to large span of the cavity
- staged R&D program: prototypes detecting cosmics and beam, ICARUS T600 @ Gran Sasso, ArgoNeuT @Fermilab, KEK 250lt

see P. Sala, O. Palamara

Liquid Scintillator technology

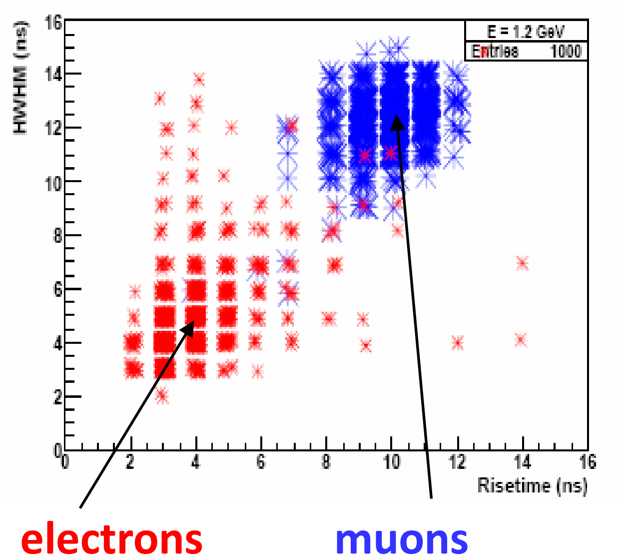
- mature technology (Borexino, KamLAND, SNO+)
- good energy and position resolution, very low energy threshold
- aim at 50kt

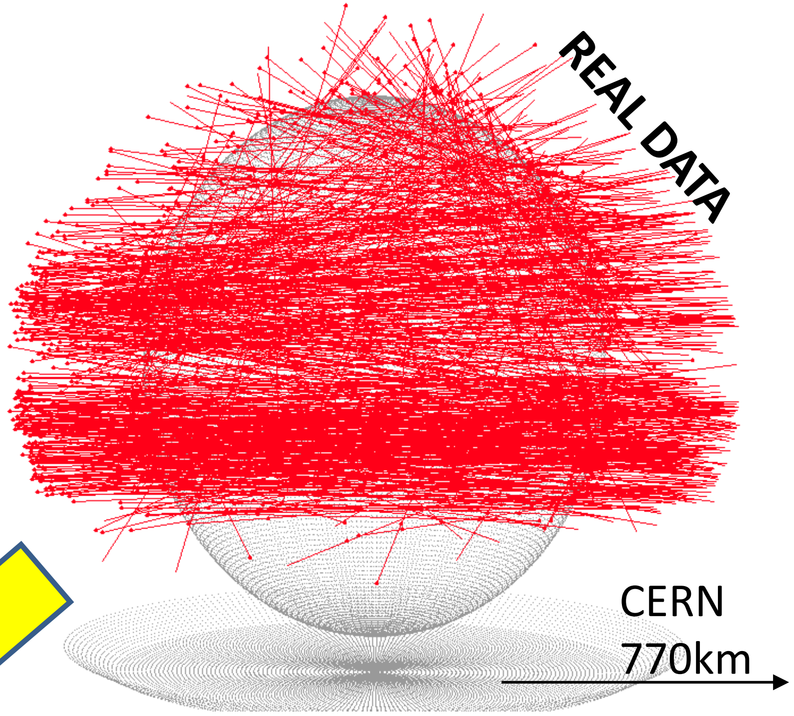
Challenges:

- cavity excavation (size comparable to SuperK)
- improvement for PMs and electronics needed
- keep Borexino purity in larger volume (surface-to-volume ratio is advantageous)
  -> relevant for sub-MeV neutrino detection

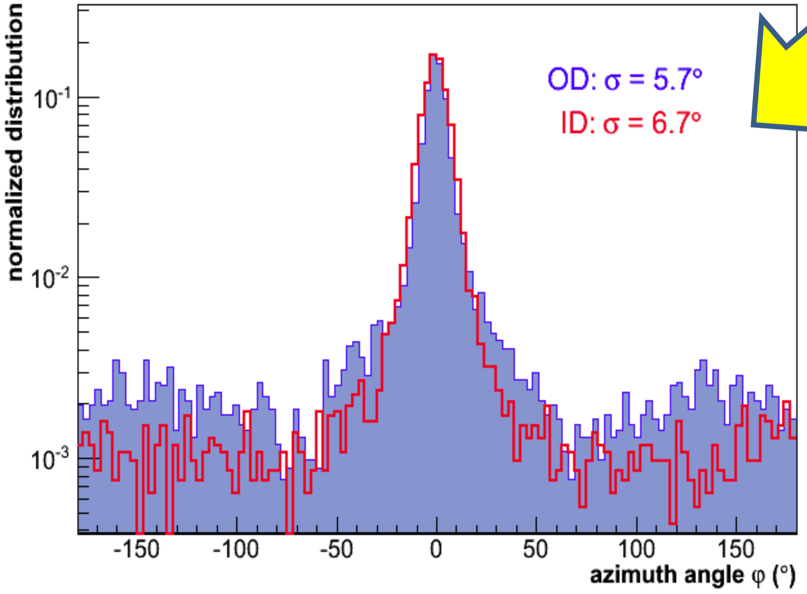
see L. Oberauer

e/μ discrimination and tracking





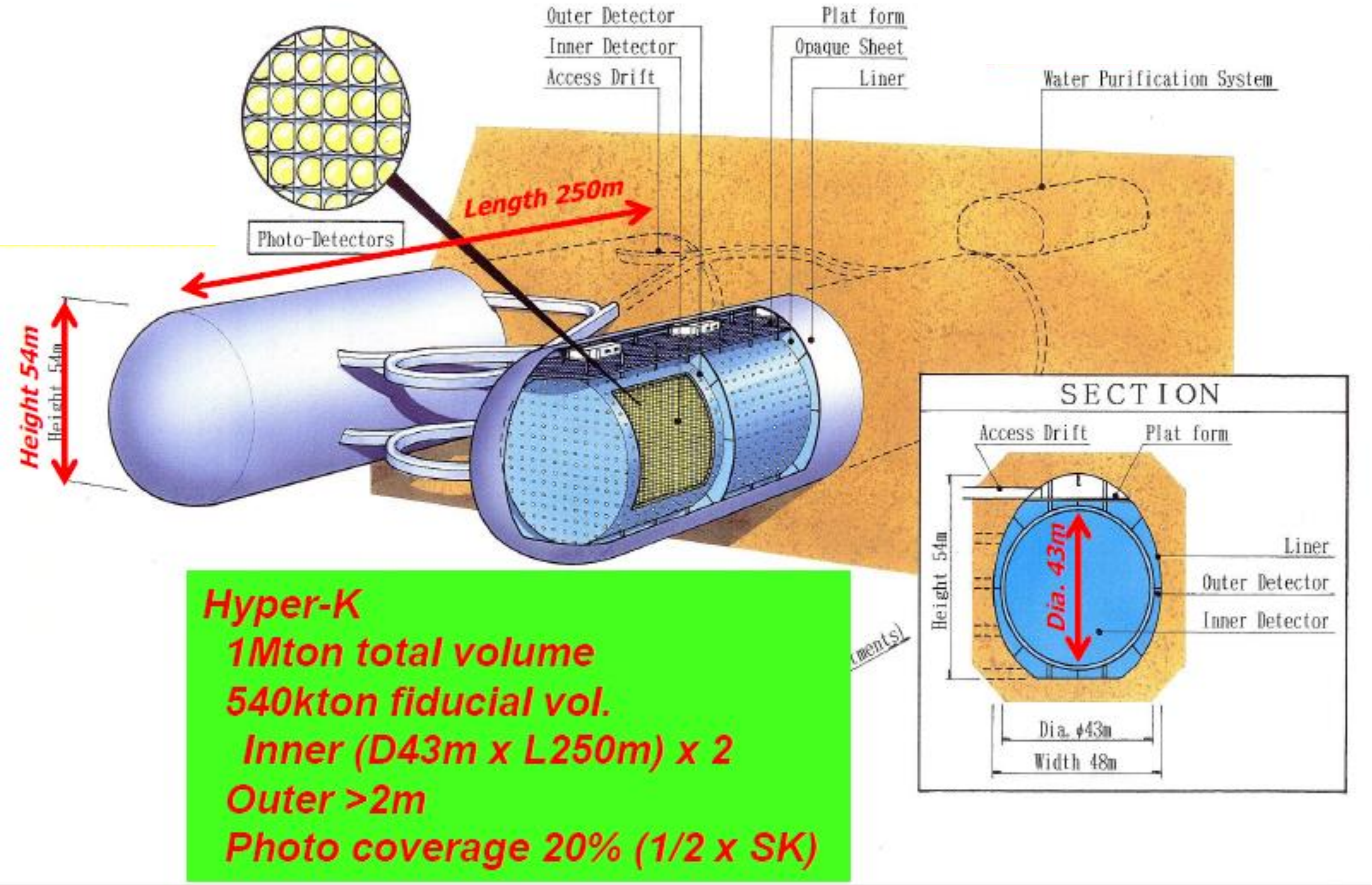
CNGS neutrino induced muons in Borexino.



World-wide efforts to realize a huge detector

- Japan
- U.S.
- Europe

Japan: Hyper-Kamiokande



Hyper-K
- 1Mton total volume
- 540kton fiducial vol.
  - Inner (D43m x L250m) x 2
- Outer >2m
- Photo coverage 20% (1/2 x SK)

Japan: Three possible scenarios under discussion

Korea

Okinoshima

Kamioka

JPARC

1000km
1deg. Off-axis

Hyper-K

658km
0.8deg. Off-axis

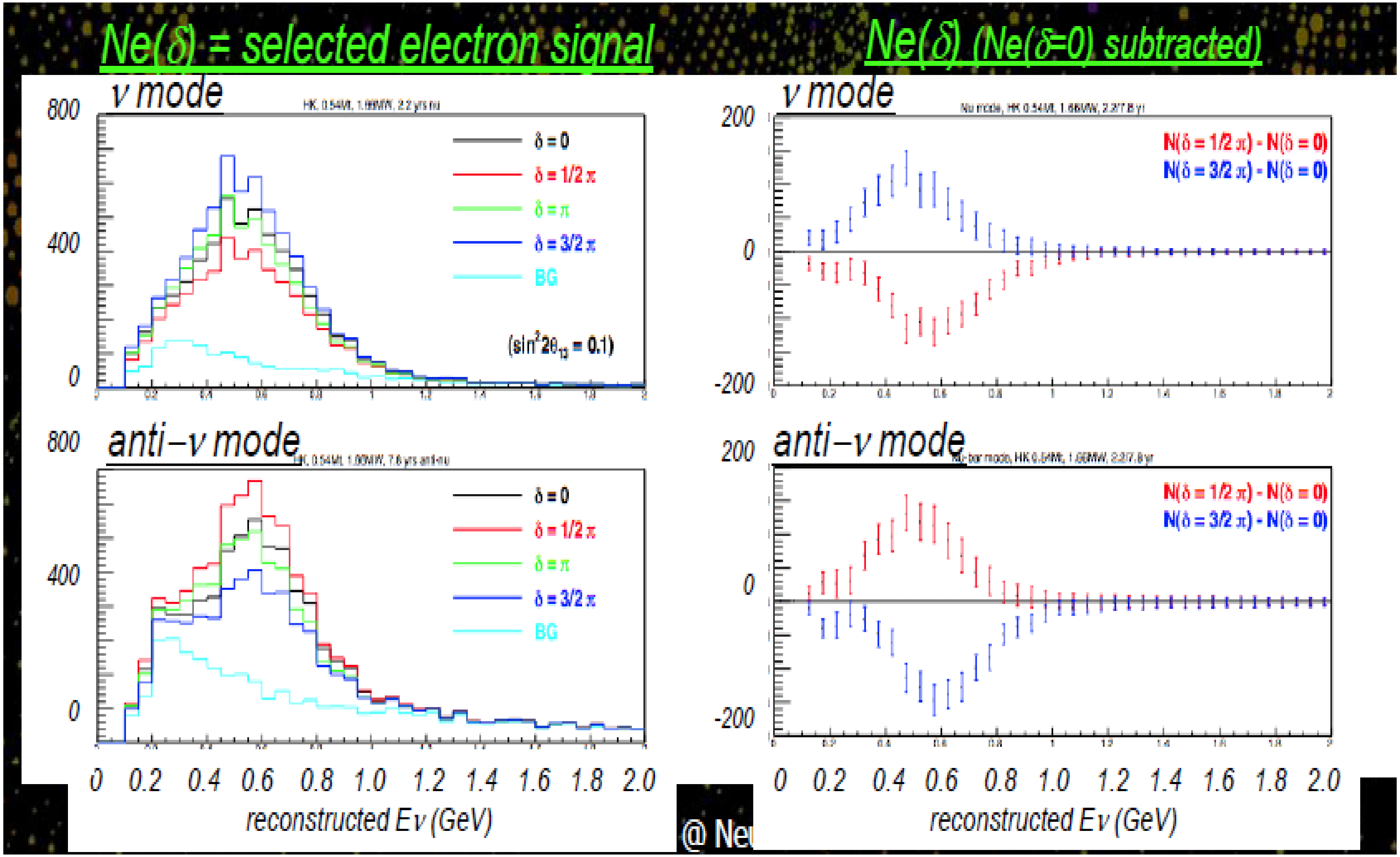
100kt LAr

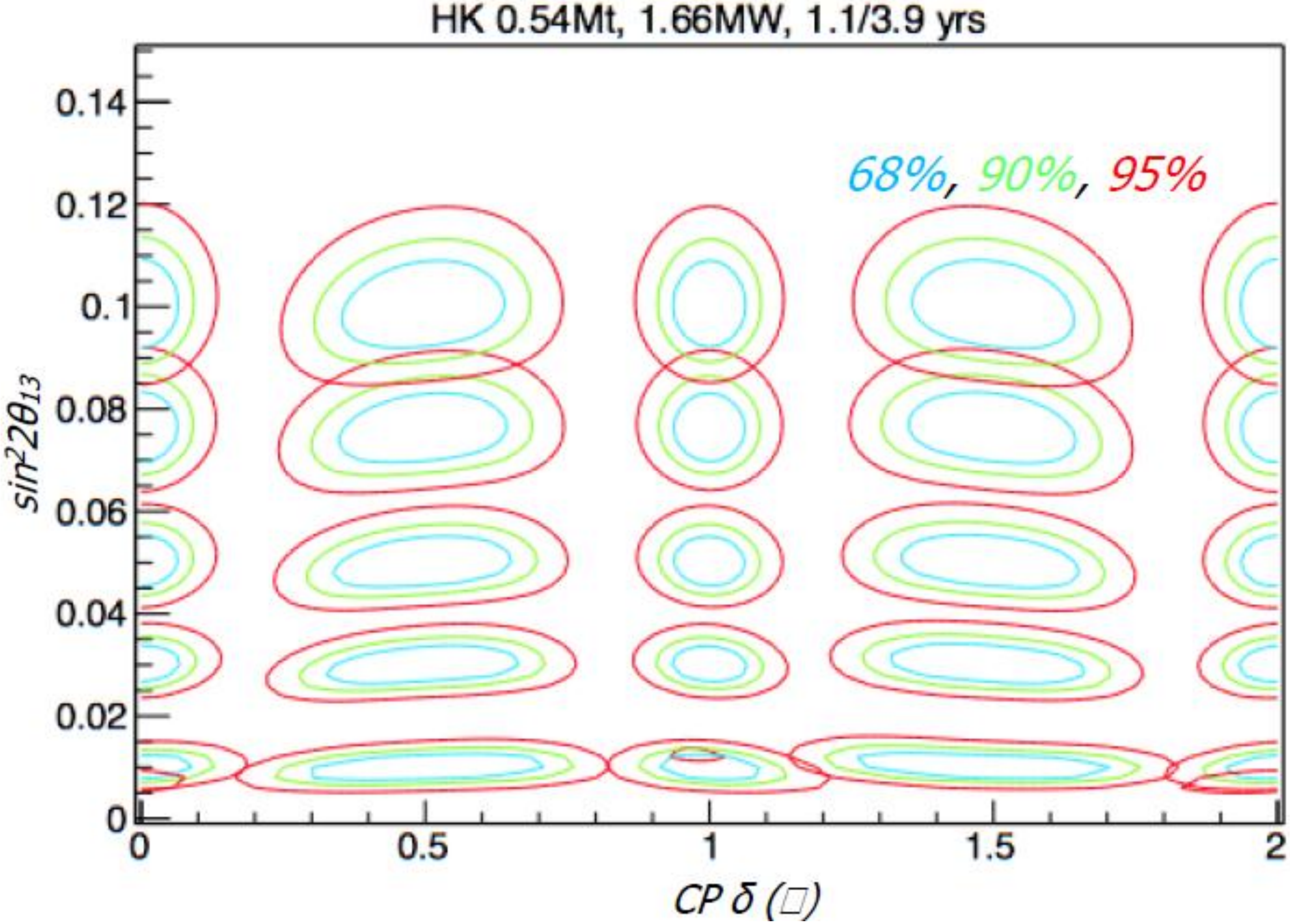
295km
2.5deg. Off-axis

Hyper-K

see T. Kobayashi

Scenario JPARC-HK (540kt, 295 km,1.66 MW) as an example:




HK 0.54Mt, 1.66MW, 1.1/3.9 yrs
68%, 90%, 95%
$sin^2 2\theta_{13}$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
CP δ (□)

Hyper-K near-future plans

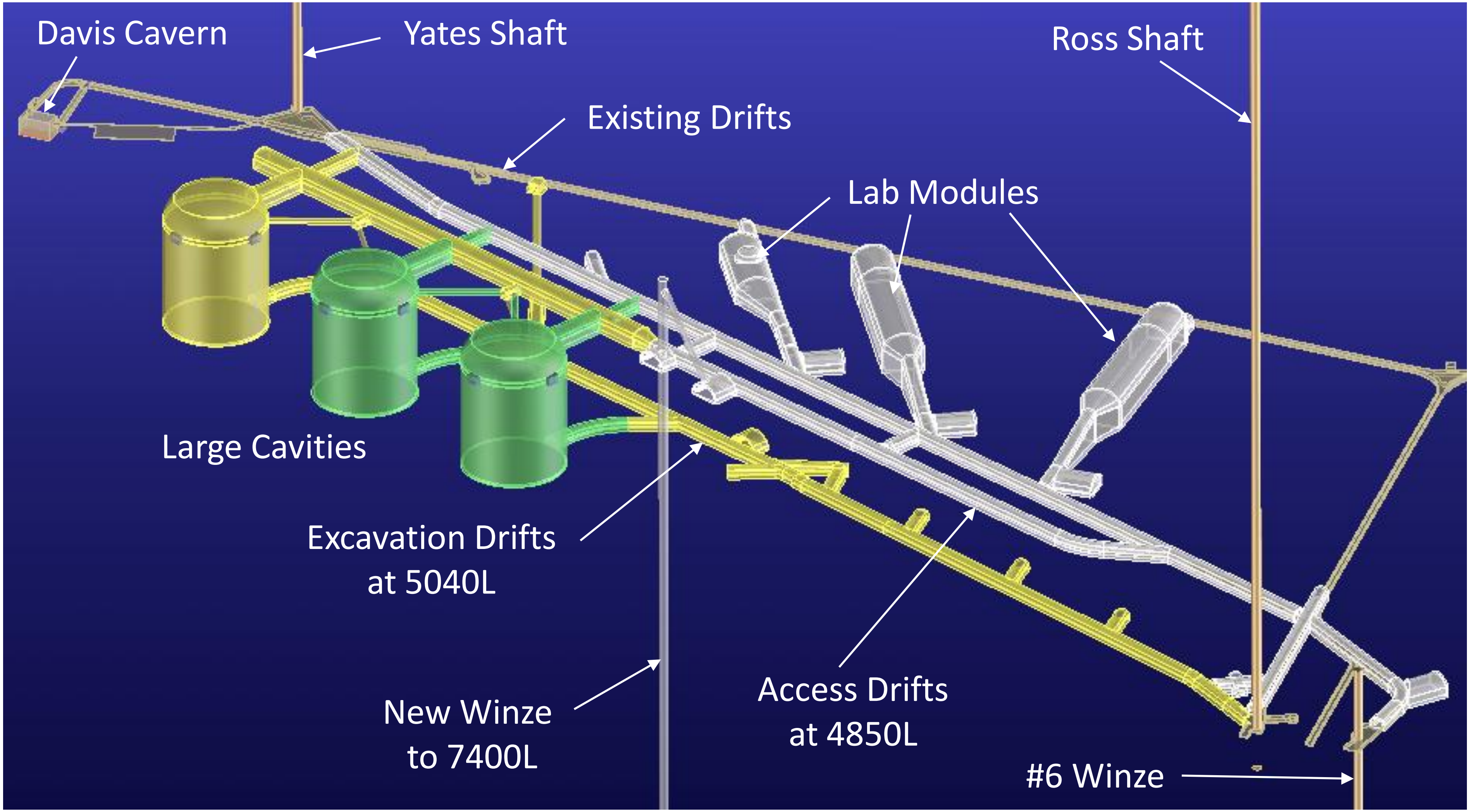
Future plan

- *Global survey of the candidate site in this year*
  (precise location and layout of the cavern)
- *Optimize Water tank design, sensors, electronics*
- *construction scheduling and precise cost estimation*

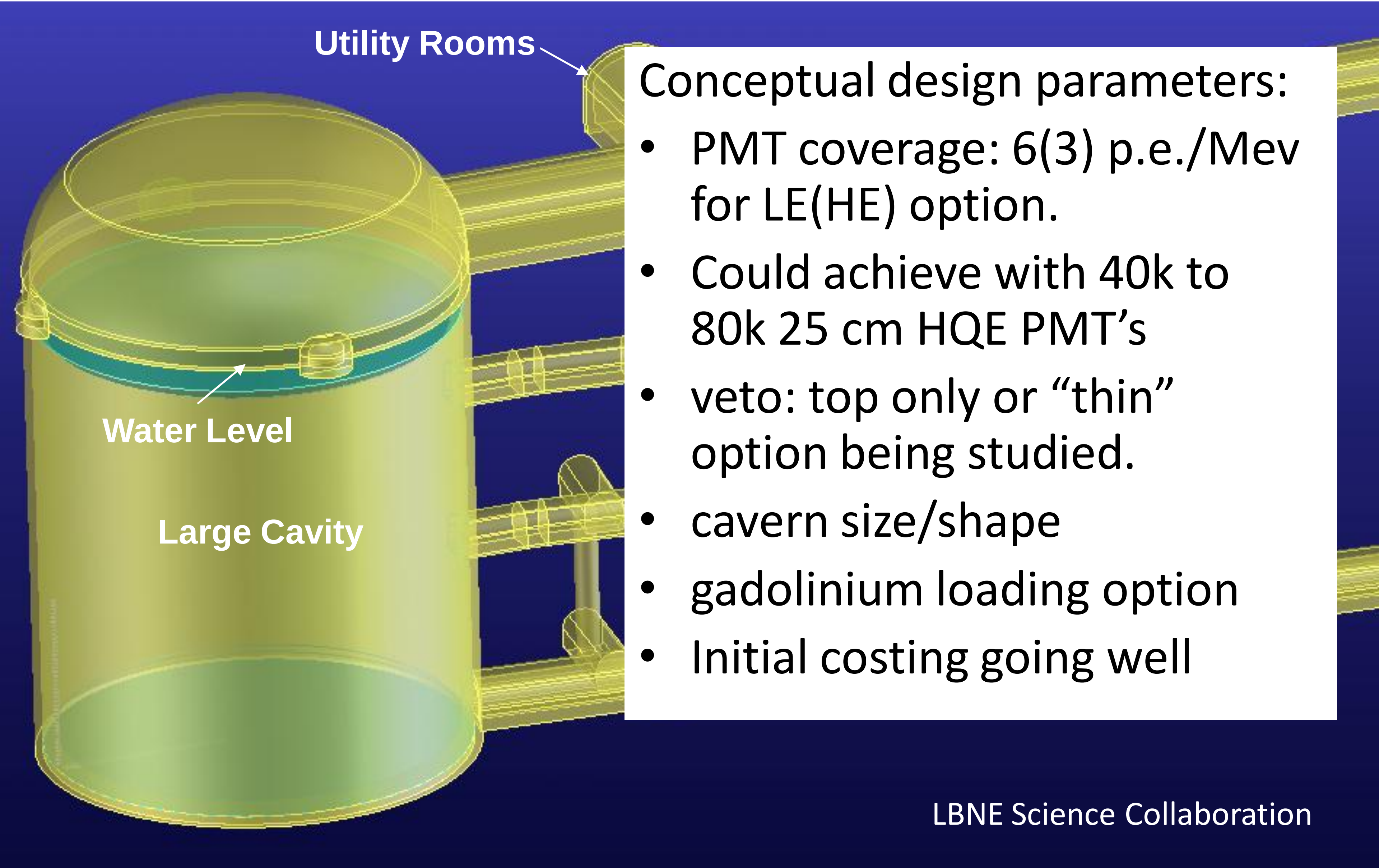
Design report in a year

U.S.

DUSEL Excavation Plan



Large Cavity, Water Cerenkov Detector
Water: 53m Dia. x 54m vertical, Fiducial Volume: 50m Dia. x 51m vertical



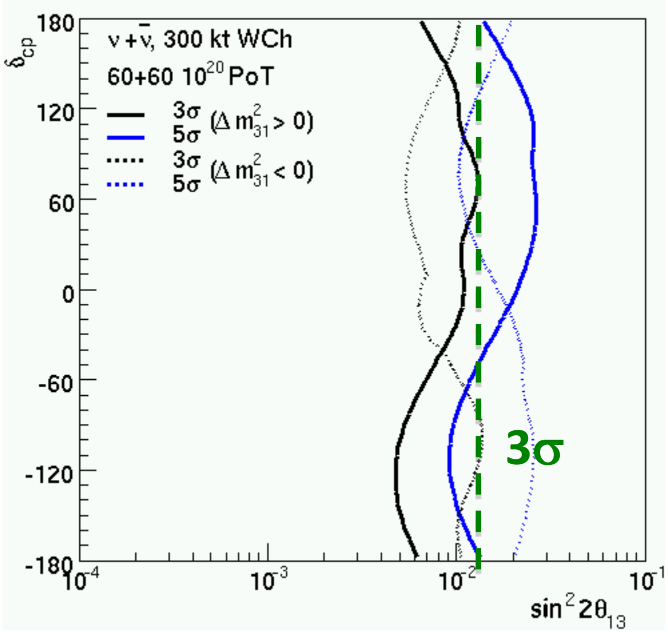
Conceptual design parameters:

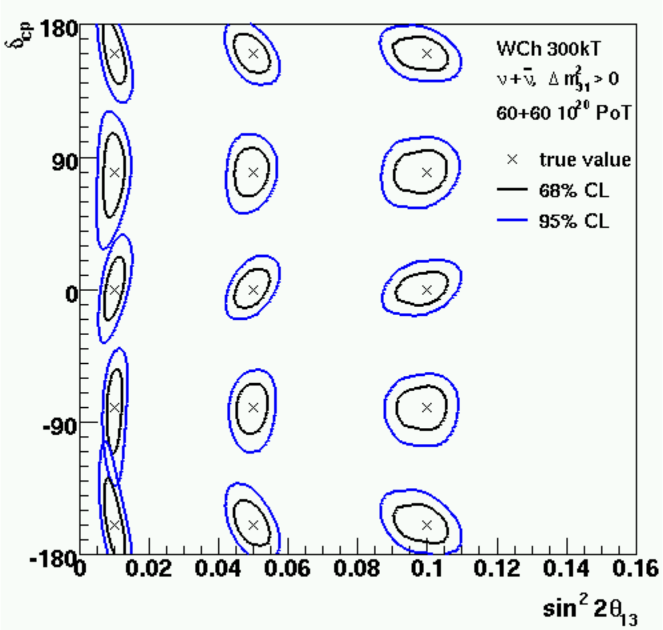
- PMT coverage: 6(3) p.e./Mev for LE(HE) option.
- Could achieve with 40k to 80k 25 cm HQE PMT’s
- veto: top only or “thin” option being studied.
- cavern size/shape
- gadolinium loading option
- Initial costing going well

LBNE Science Collaboration

LBNE Water Cherenkov

Sensitivity to mass hierarchy and CP violation





700 kW, 8+8 years
$2\text{x}10^7$ s/yr, 120 GeV

LBNE Schedule

- Initial design and costing complete by Fall, 2010
- Detector(s) choice for FD/Science Program defined by Science Collaboration: end of 2010
- DOE CD-1, late 2010 or early 2011
- National Science Board, Summer 2011
- Preliminary Design (~CD-2), end of 2012
- DUSEL construction start, end of 2013
- LBNE construction, 2015-2019 (this could be earlier depending on DUSEL lab readiness)

for more on the DUSEL program, see C. Mariani

Europe

Europe: LAGUNA

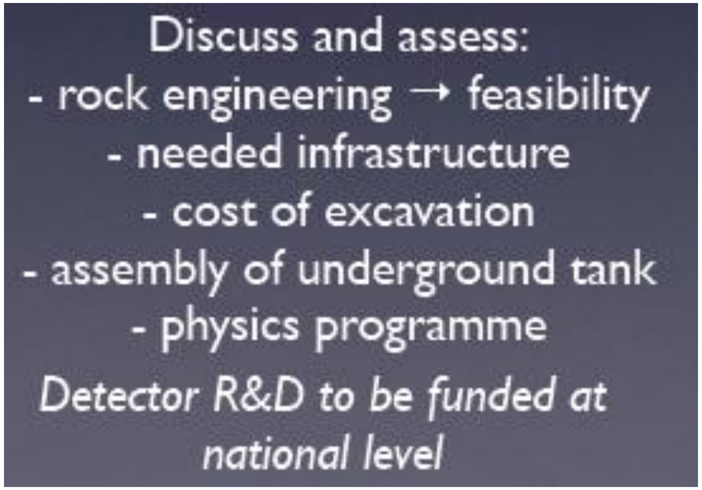
Consortium composed of 21 beneficiaries in 9 countries

9 university entities (ETHZ, Bern, Jyväskylä, OULU, TUM, UAM, UDUR, USFD, UA)

8 research organizations (CEA, IN2P3, MPG, IPJ PAN, KGHM CUPRUM, GSMiE PAN, LSC, IFIN-HH)

4 private companies (Rockplan, Technodyne, AGT, Lombardi)

Additional university participants (IPJ Warsaw, Silesia, Wroclaw, Granada)



Discuss and assess:
- rock engineering → feasibility
- needed infrastructure
- cost of excavation
- assembly of underground tank
- physics programme

Detector R&D to be funded at national level

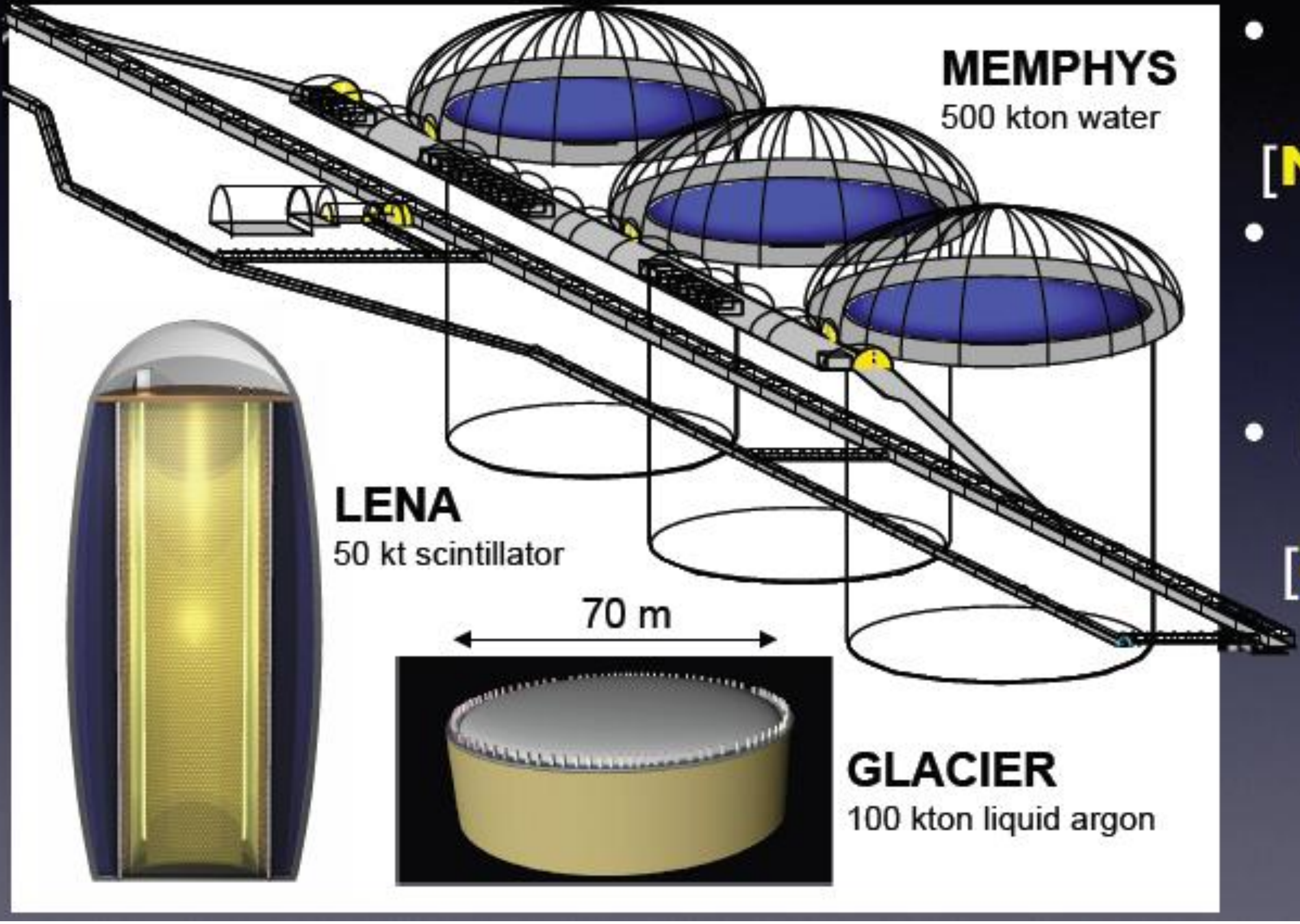
WP2: Underground infrastructures and Engineering

WP3: Safety, environmental and socio-economic issues

WP4: Science Impact and Outreach

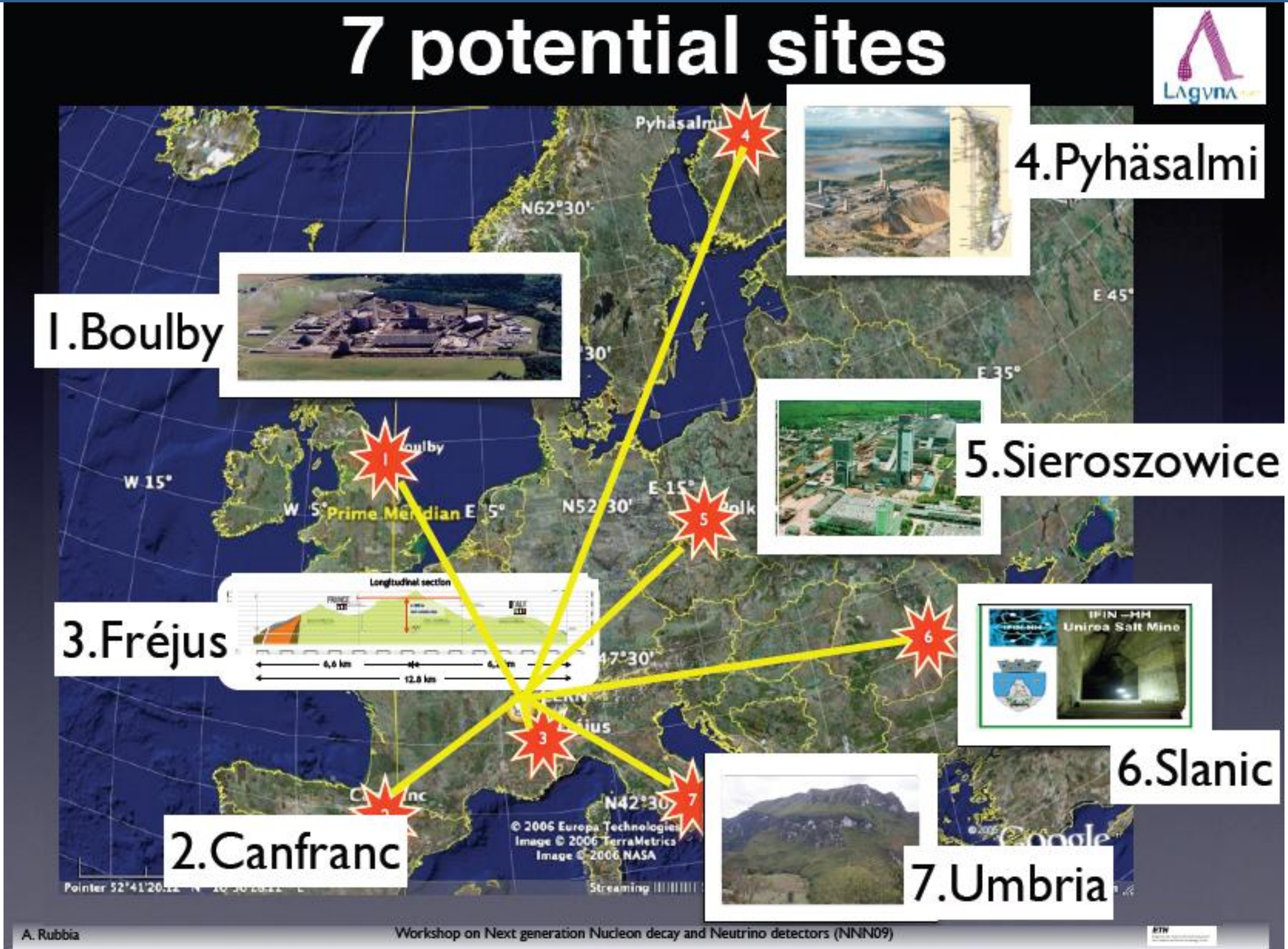
Europe: LAGUNA

- three options considered (MEMPHYS, LENA, GLACIER) with total mass in the range 50-500 kton



- Water Cerenkov [**MEMPHYS**]
- Liquid scintillator [**LENA**]
- Liquid Argon TPC [**GLACIER**]

Europe: LAGUNA



7 potential sites

1.Boulby

2.Canfranc

3.Fréjus

4.Pyhäsalmi

5.Sieroszowice

6.Slanic

7.Umbria

A. Rubbia

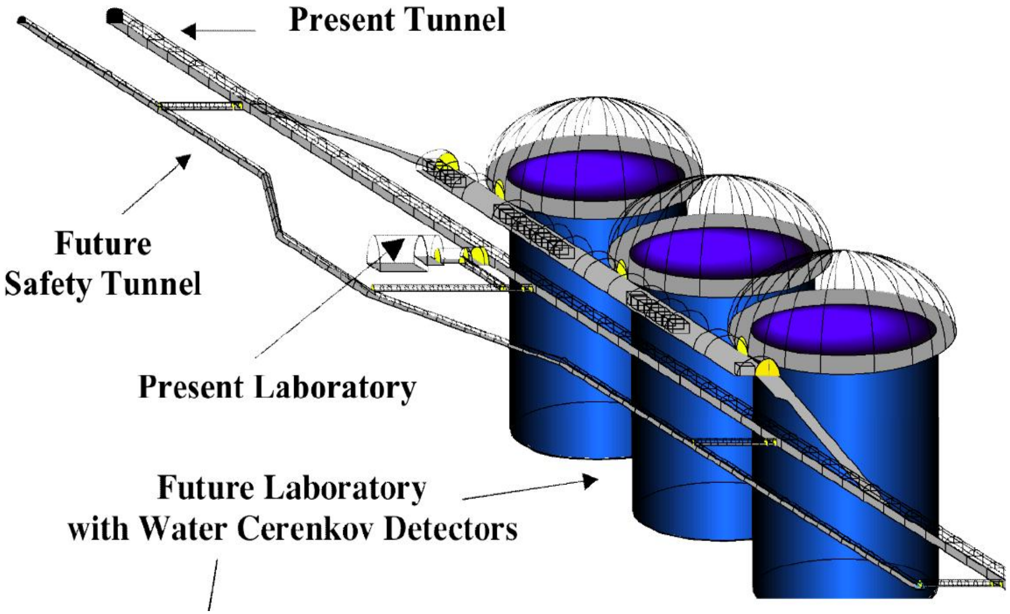
Workshop on Next generation Nucleon decay and Neutrino detectors (NNN09)

Europe: LAGUNA

Design Study (EU FP7 funded):	2008 - 2010
Interim safety, socio-economic, environmental report:	finished
Interim geotechnical reports on the seven sites:	finished
Prioritize the sites and down-select:	2010

Final LAGUNA general meeting in Modane these days!

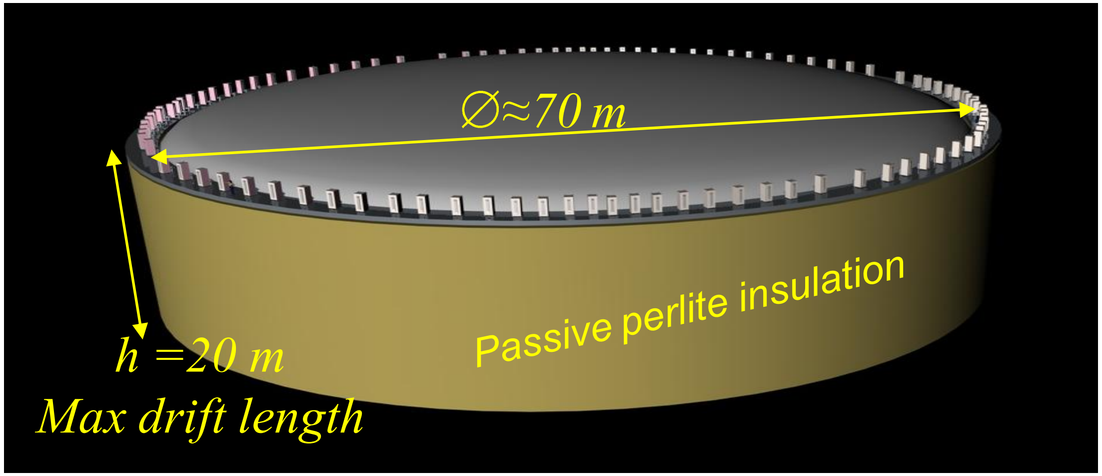
MEMPHYS

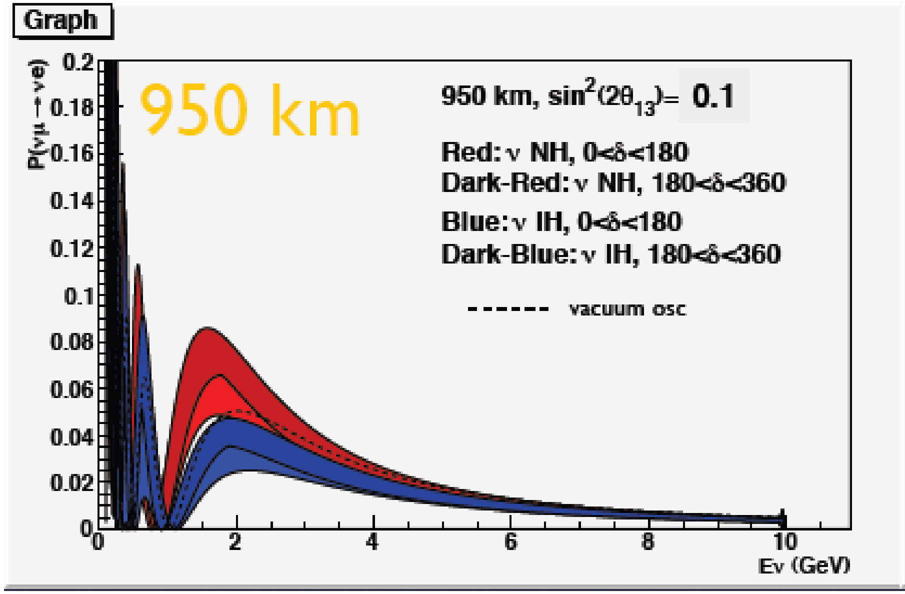


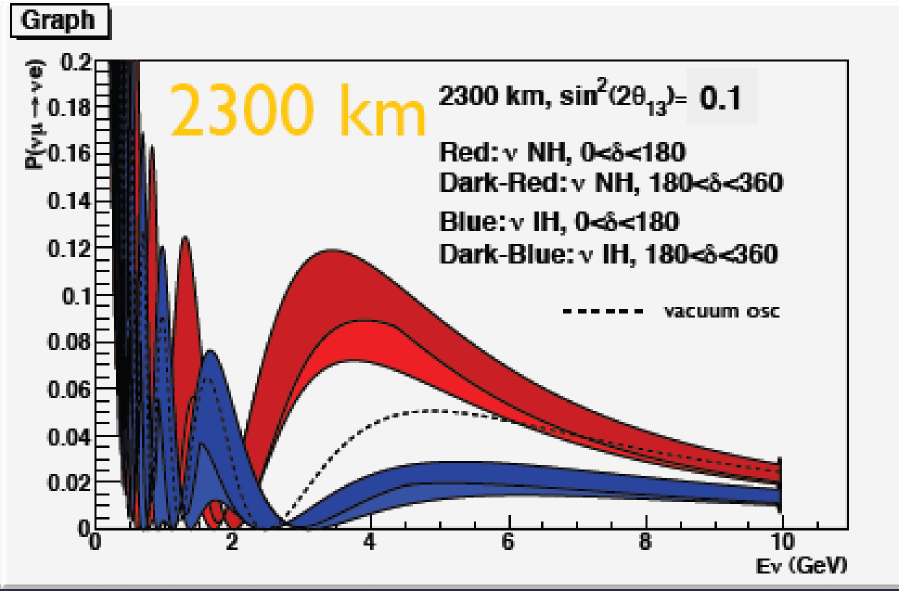
- Fiducial mass: 440 kt
- Baseline:
  -- 3 cylindric modules 60 x 65 m;
  -- Size limited by the attenuation length (λ~80m) and the pressure on the PMTs;
  -- Readout: 12"-10" PMTs, 30% geom. coverage

As a Water Cherenkov detector, suited for low energy (<1 GeV) beam
-> original concept in connection with beta-beam from CERN
-> connects this detector type in Europe presumably to the Fréjus site

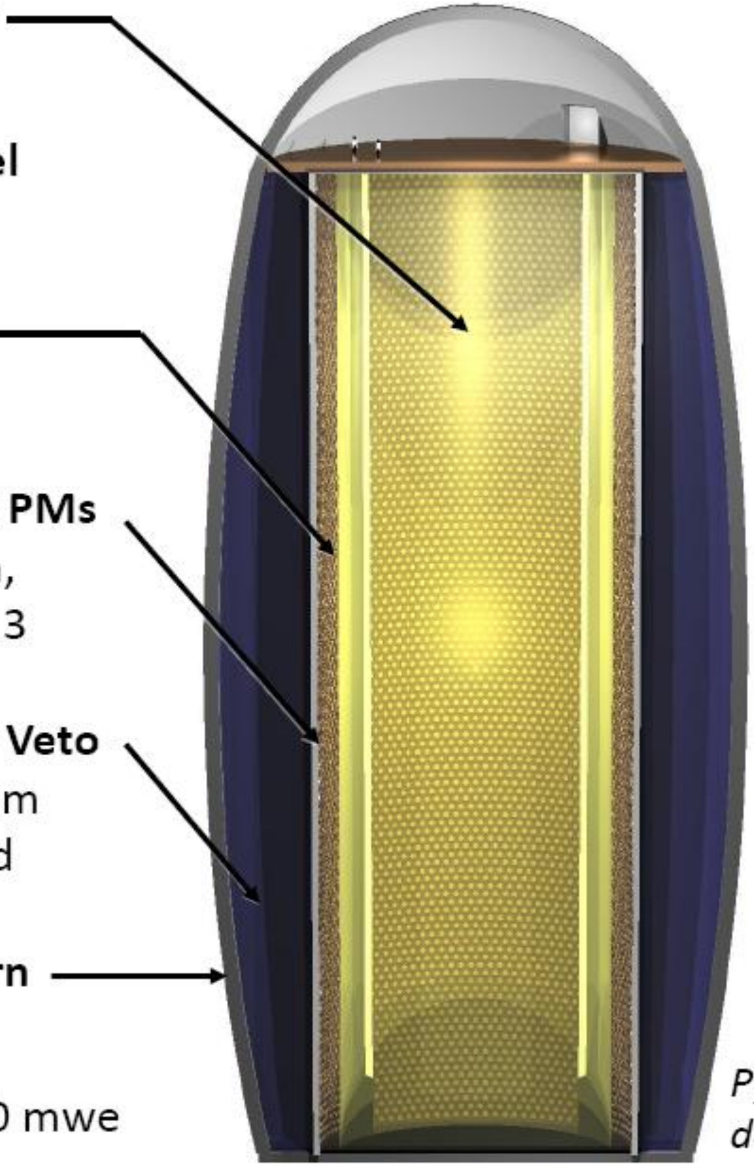
GLACIER


∅≈70 m
h =20 m
Max drift length
Passive perlite insulation


Graph
950 km
950 km, sin²(2θ13)= 0.1
Red: ν NH, 0<δ<180
Dark-Red: ν NH, 180<δ<360
Blue: ν IH, 0<δ<180
Dark-Blue: ν IH, 180<δ<360
vacuum osc
P(νμ → νe)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
Eν (GeV)


Graph
2300 km
2300 km, sin²(2θ13)= 0.1
Red: ν NH, 0<δ<180
Dark-Red: ν NH, 180<δ<360
Blue: ν IH, 0<δ<180
Dark-Blue: ν IH, 180<δ<360
vacuum osc
P(νμ → νe)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
Eν (GeV)

LENA



Liquid Scintillator
ca. 50kt PXE/LAB

Inner Nylon Vessel
radius: 13m

Buffer Region
inactive, $\Delta r = 2$m

Steel Tank, 13500 PMs
r = 15m, h = 100m,
optical coverage: .3

Water Cherenkov Veto
1500 PMTs, $\Delta r > 2$m
fast neutron shield

Egg-Shaped Cavern

Overburden: 4000 mwe

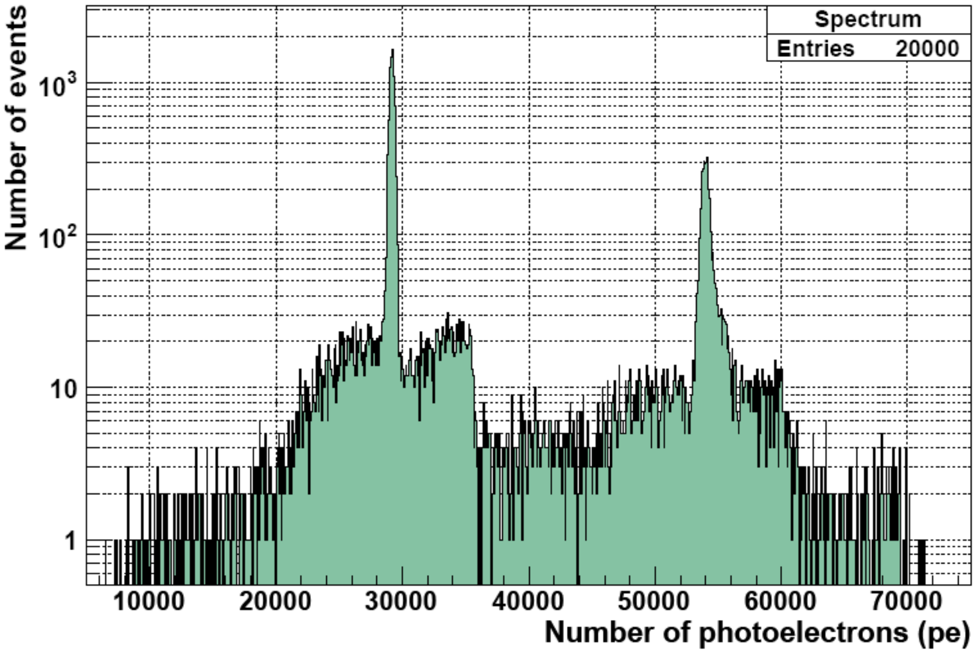
Pyhäsalmi design

LENA

Low-**E**nergy
Neutrino
Astronomy

see L. Oberauer

Sensitivity to proton decay **p → K⁺ν**



Simulated energy spectrum of 20000 proton decay events into Kaon channel (light yield 180 p.e./MeV)

Two peaks:

- Kaon + Muon ~ 257 MeV
- Kaon + Pions ~ 459 MeV

Energy-cut efficiency ε_E=99.5%, bound protons of ^{12}C included.

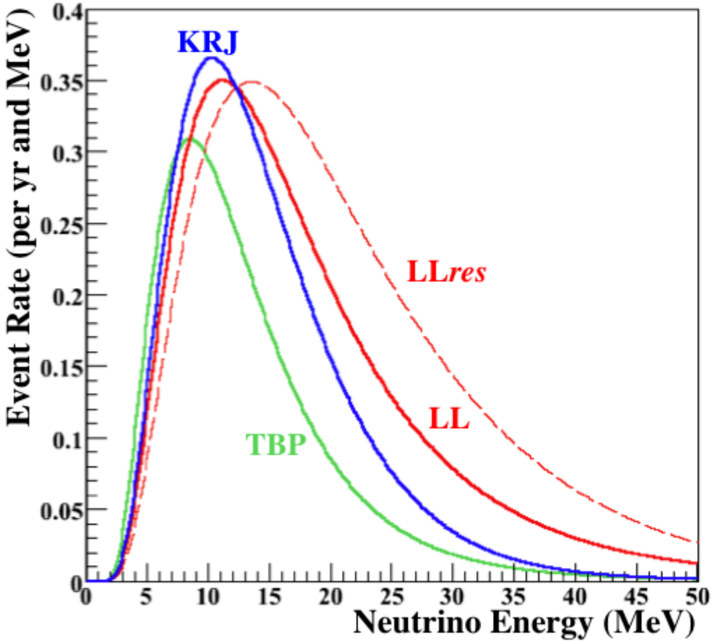
Potential of LENA (10 y measuring time)

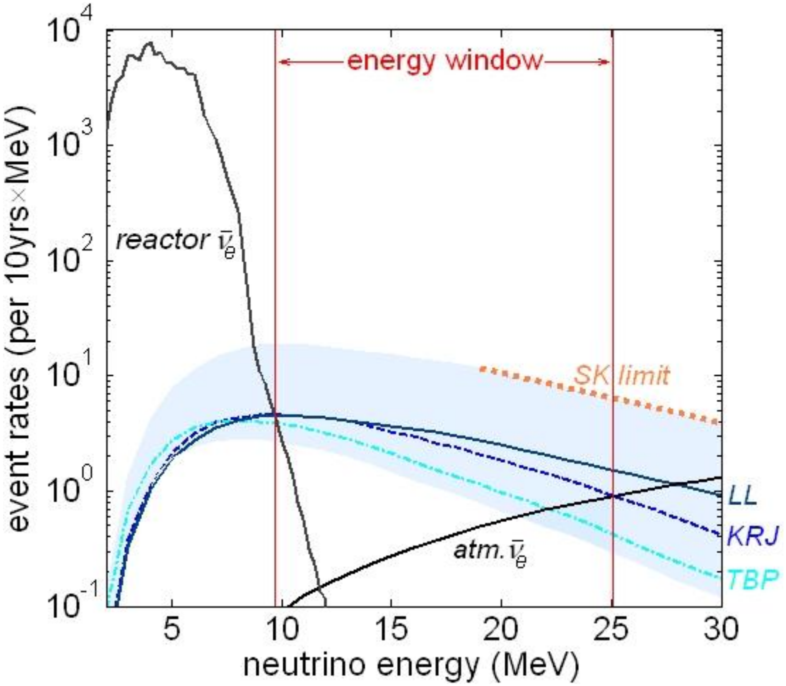
- For Superkamiokande current limit: $\tau = 2.3 \cdot 10^{33}\ \mathrm{y}$
  - About 40 events in LENA and $\lesssim$ 1 background
- Limit at 90% (C.L) for no signal in LENA:
  - $\tau > 4.1 \cdot 10^{34}\ \mathrm{y}$ with $\epsilon = 65\%$

Variety of other channels can be tested.

Diffuse Supernova Neutrino Background

- Excellent background rejection (inverse beta decay)
- Energy window 10 to 30 MeV.
- High efficiency (100% with 50 kt target)
- High discovery potential in LENA
  ~2 to 20 events per year are expected
  (model dependent)





A galactic SN in LENA

Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \rightarrow n + e^+$
- $\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+$
- $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$
- $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$

ca 15.000 events
for a galactic SN

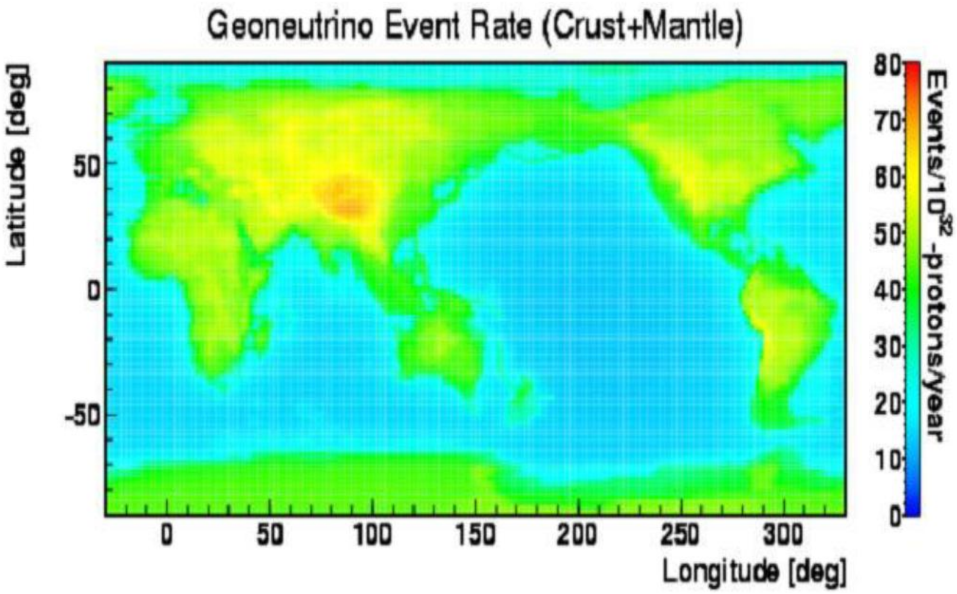
high statistics
energy dispersive
time dispersive
flavour resolving

- Antielectron ν spectrum with high precision
- Electron ν flux with ~ 10 % precision
- Total flux via neutral current reactions
- Separation of SN models
- independent from (collective) oscillations in NC reactions

Geo neutrinos

Detect anti-neutrinos of the U, Th decay chains (inverse β-decay energy threshold on proton is 1.8 MeV).

Within the discussed detector options, only LS is able to determine the geoneutrino flux.



LENA

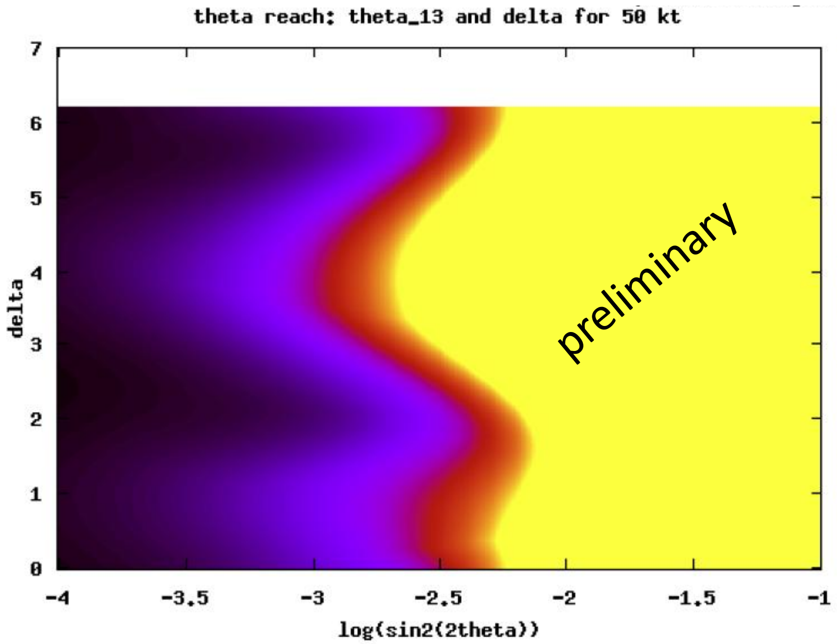
Expected event rate at Pyhäsalmi :
300-3000 events/year in 50 kt
Background from reactors:
240 events/year in 50 kt
in the relevant energy window

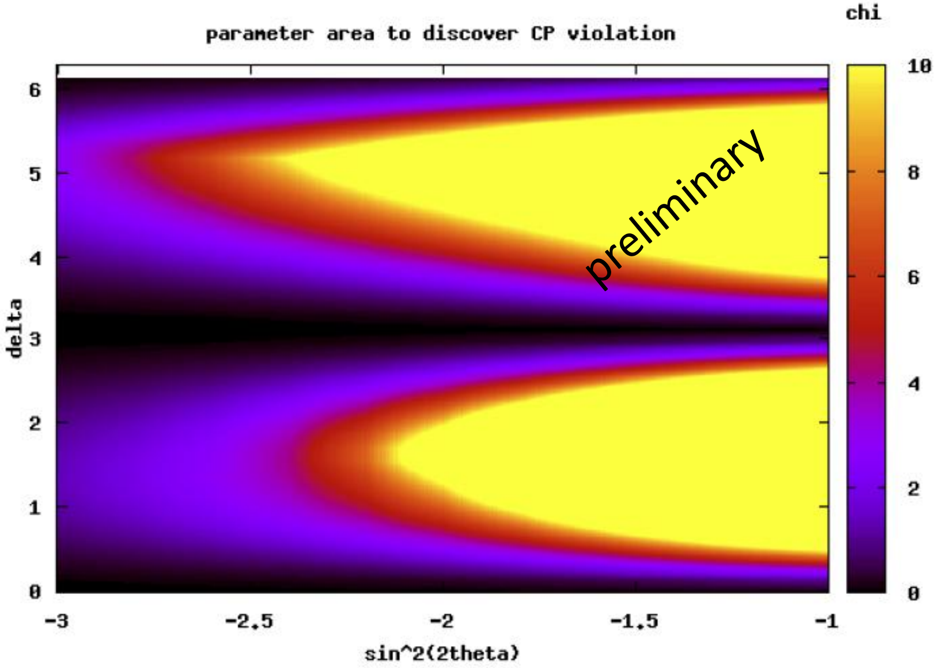
determine U/Th ratio

disentangle continental/oceanic crust with more than one detector location (e.g. HanoHano)

separation of geological models

Study CERN-LENA@Pyhäsalmi

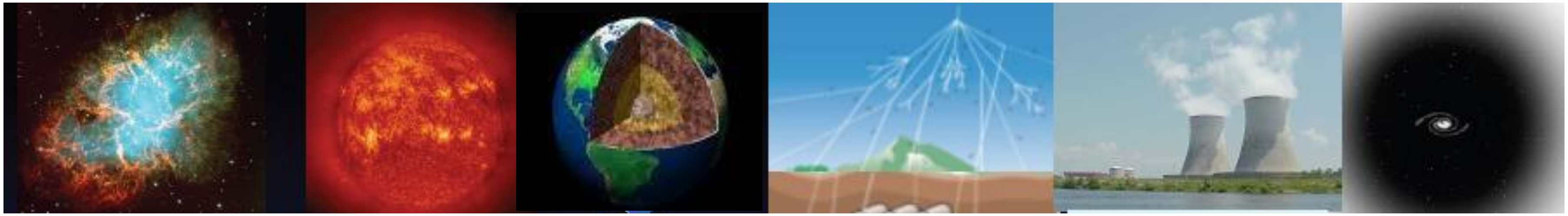

theta reach: theta_13 and delta for 50 kt


parameter area to discover CP violation

CERN - Pyhäsalmi 2288 km
5 years nu + 5 years anti-nu
1st maximum @ 4.2 GeV
Wide band beam 1 – 6 GeV, 1.5 MW

Conclusions

Strong physics case for large-volume neutrino detectors.



Baryon asymmetry
nucleon stability

fundamental neutrino properties
CP violation in the lepton sector

Growing community for the realization of large-volume underground detectors.

New laboratories planned world-wide. Site and excavation studies with encouraging result for the feasibility of such labs. Site selection in US, in Europe with the LAGUNA final report priorization and down-selection of proposed sites, in Japan study scenarios until mid-2011.

3 detector technologies. Broad R&D program on all 3 technologies, progress towards realization.