Proton Decay projects in Europe

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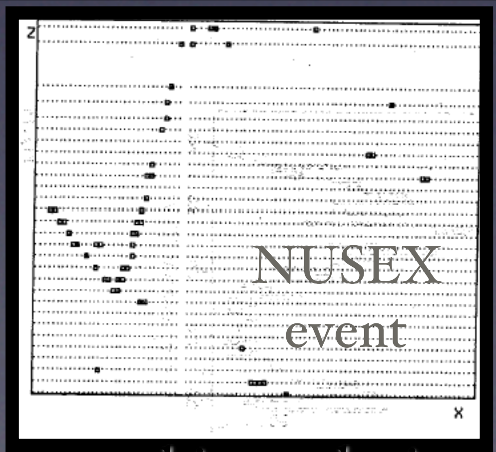
Acknowledgments to FP7 Research Infrastructure "Design Studies" LAGUNA(Grant Agreement No. 212343 FP7-INFRA-2007-1)

The next generation projects in Deep Underground Laboratories, Zaragossa, June 2011

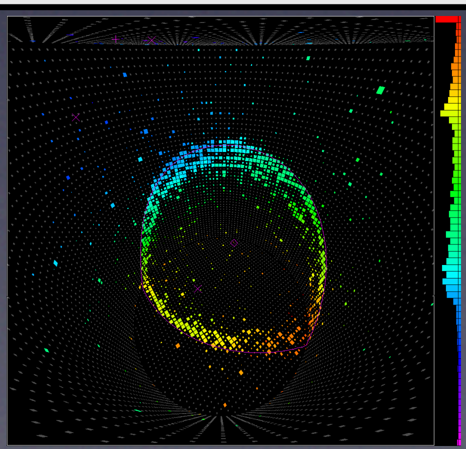
Introduction

Several large underground detectors for proton decay searches and neutrino physics have been built and operated in the last 30 years, including three located in Europe.

Detector	Date	Technology	Location	Fiducial Mass
Irvine-Michigan-BNL	1982	Water Cerenkov	USA	3.3 kton
NUSEX	1982	Tracking calorimeter	Europe	0.13 kton
Fréjus	1985	Tracking calorimeter	Europe	0.7 kton
Soudan-2	1989	Tracking calorimeter	USA	0.96 kton
Kamiokande	1983	Water Cerenkov	Japan	0.88 kton
SuperKamiokande	1996	Water Cerenkov	Japan	22.5 kton
MINOS	2005	Magnetized Fe calorimeter	USA	5 kton
ICARUS T600	2010	Liquid Argon TPC	Europe	0.48 kton

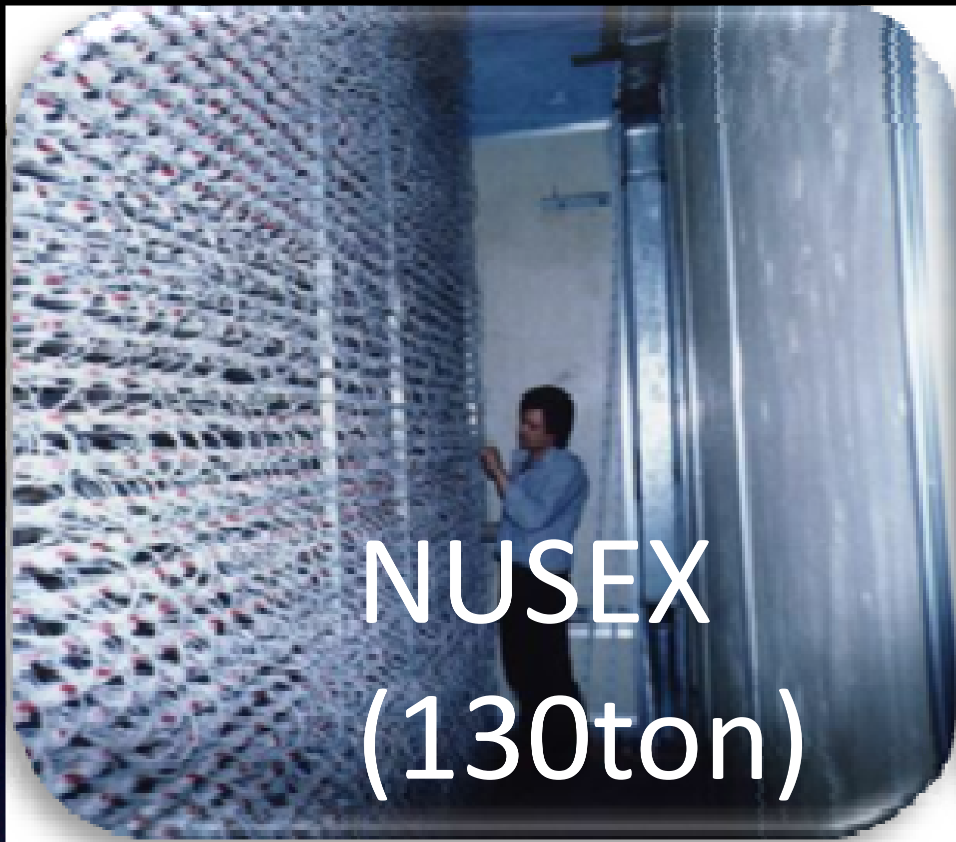


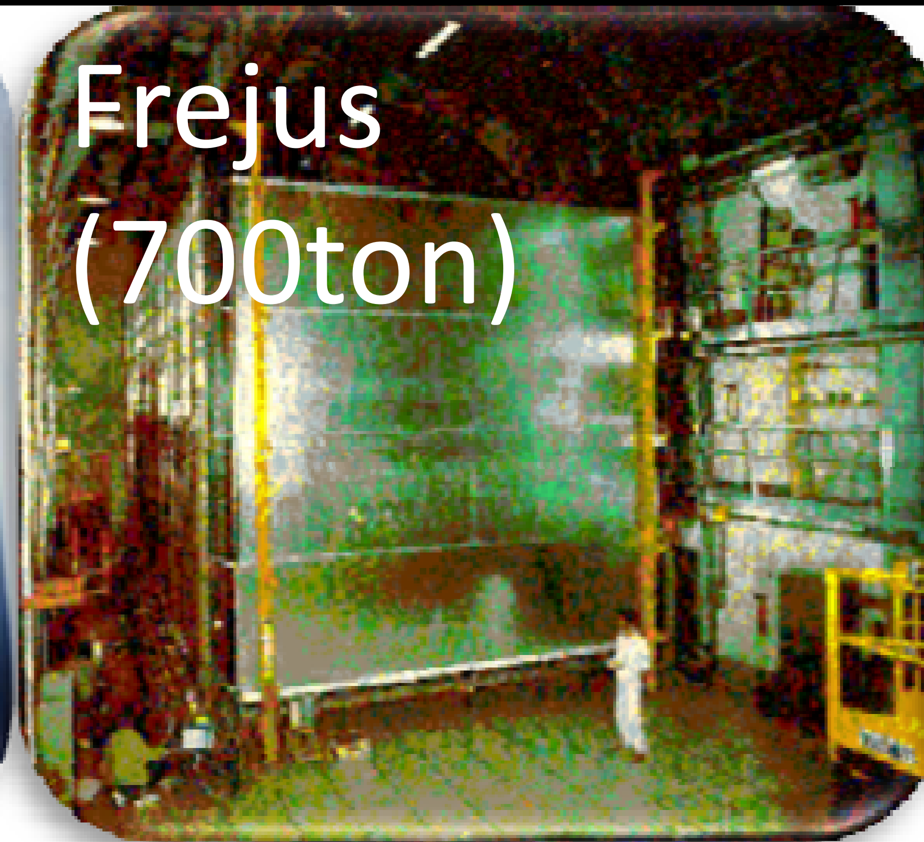
Fine tracking calorimeter



Water Cerenkov (WC) imaging

Liquid Argon TPC





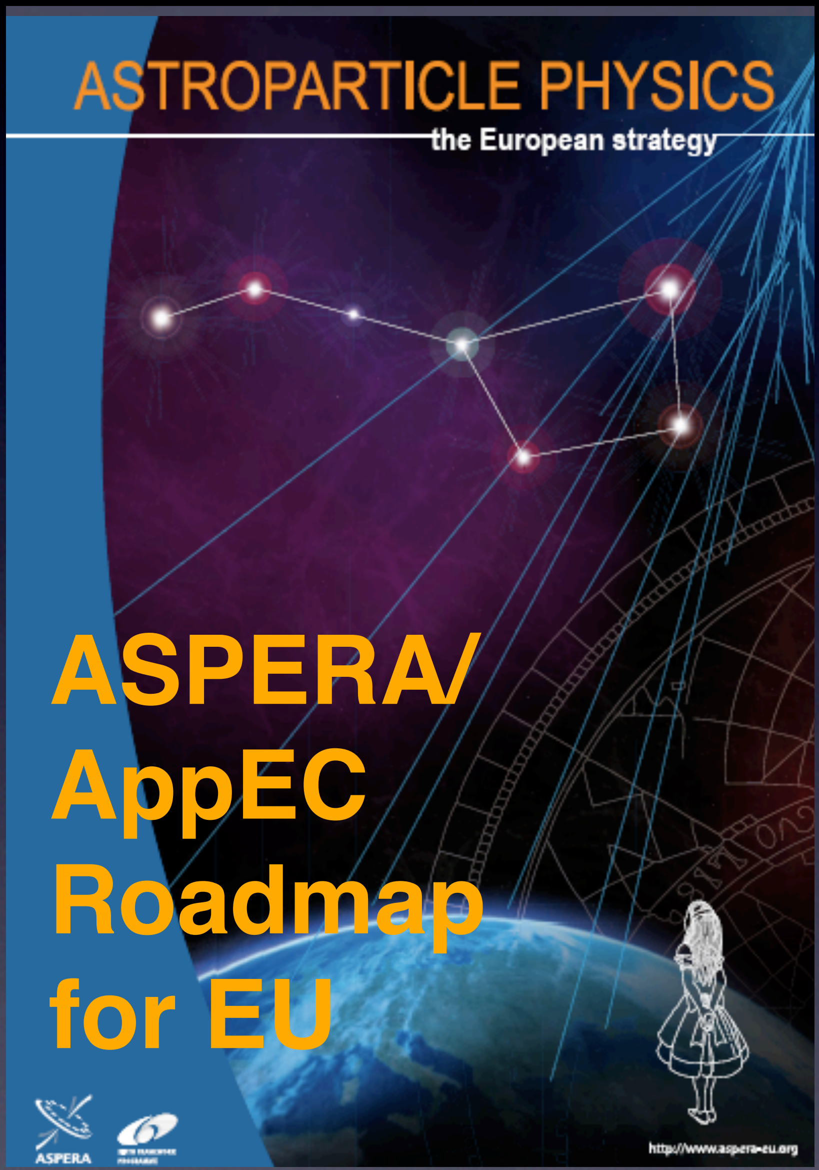
- No longer operating
- Results

τp /Br (90 C.L.) $\approx 10^{31}$-10^{32} yr

- Operating underground at LNGS (Hall B) since 2010
- Collecting CERN CNGS events and cosmic ray induced events
- Results expected soon
- Move to CERN in 2014 ?

Future in Europe ➠ LAGUNA

European Strategy for Astroparticle Physics (2008)



"We recommend that a new large European infrastructure is put forward as a future international multi-purpose facility on the 100-1000 ktons scale for improved studies of proton decay..."

" The three detection techniques being studied for such large detectors in Europe,

- ***Water Cherenkov,***
- ***Liquid Scintillator***
  and
- ***Liquid Argon,***

should be evaluated in the context of a common design study which should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams."

➠ LAGUNA/LAGUNA-LBNO "design studies" funded by the European Commission via FP7 (project duration 2008-2014)

Feasibility Studies (CD-0)

Two design studies of a pan-European Infrastructure for Large Apparatus studying Grand Unification, Neutrino Astrophysics and Long Baseline Neutrino Oscillations

LAGUNA (2008-2011) [FP7 funded]

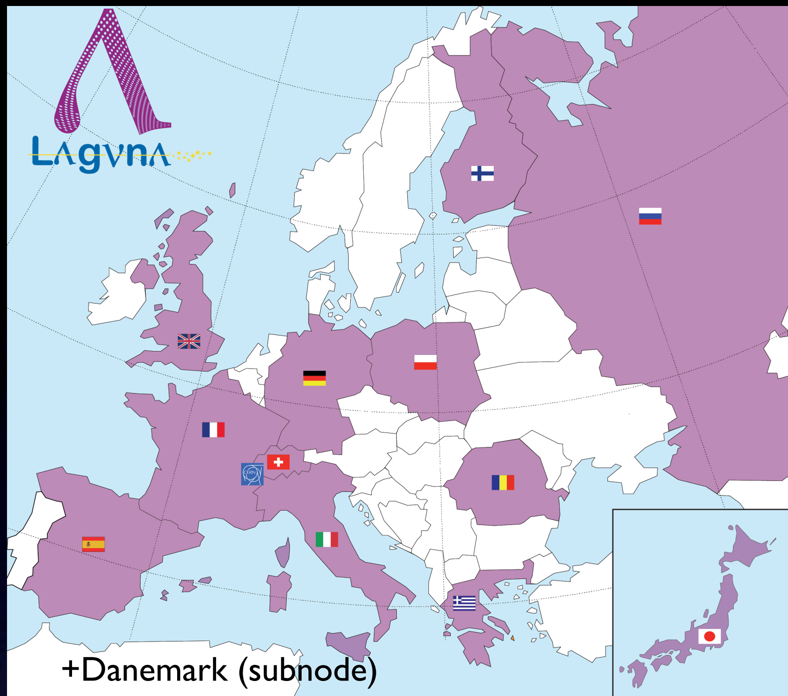
(a) feasibility of huge underground caverns, identify show-stoppers
(b) infrastructure layout and cost estimates
(c) comparison of seven EU sites (mines & road tunnels)
(d) down selection for further more detailed design/studies
(e) created a strong multi-disciplinary collaboration, links with industrial partners

LAGUNA-LBNO (2011-2014) [FP7 funded]

(a) underground construction planning and risks
(b) detector construction and cost estimates, including instrumentation
(c) liquid handling
(d) conceptual studies of new CERN beamlines to Fréjus and Pyhäsalmi
(e) create links with funding agencies and develop implementation plan

LAGUNA-LBNO consortium

13 countries, 45 institutions, ~300 members



Switzerland
University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen(**)
University Tübingen(**)

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus(**)

Italy
AGT*

Russia
INR
PNPI

Japan
KEK

(=industrial partners*
***=associated)*

LAGUNA physics goals

Giant underground detectors provide a comprehensive physics program

☑ *Non-accelerator based*

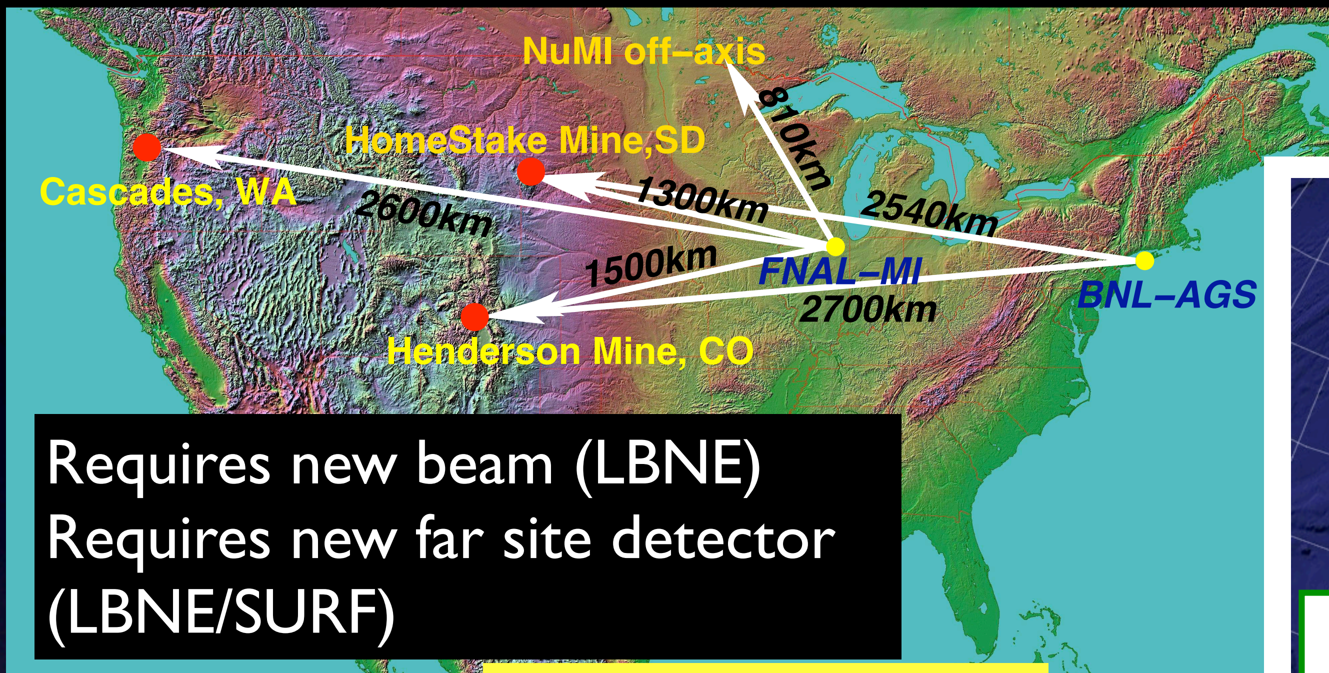
- ★ **Proton decay hunt**
- ★ Precise measurement of supernova neutrinos
- ★ Precise determination of solar and (subleading) atmospheric neutrino oscillation parameters
- ★ Supernovae remnants neutrinos
- ★ Determination of geo-neutrino flux

☑ *Accelerator-based*

- ★ Long baseline neutrino oscillation experiment for θ_{13}, CP-violation and neutrino mass hierarchy discovery and precise parameters determination

Very rich physics recognized by "roadmaps" worldwide

Worldwide challenges



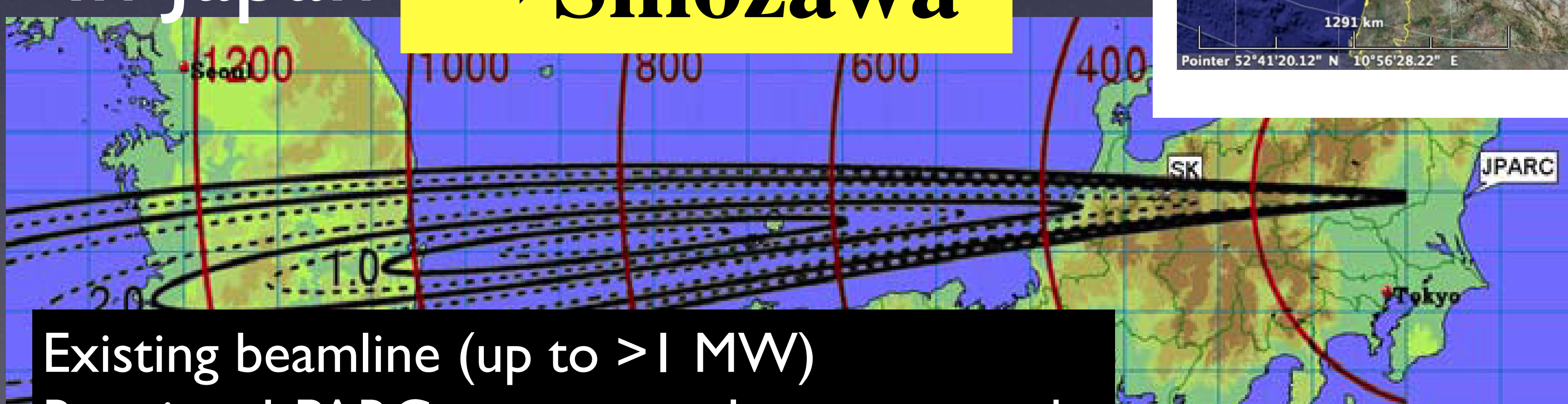
Requires new beam (LBNE)
Requires new far site detector (LBNE/SURF)

In USA →Svoboda

In Europe

Requires new far site detector (LAGUNA + LAGUNA-LBNO)
Requires new beam (LAGUNA-LBNO)

In Japan →Shiozawa



Existing beamline (up to >1 MW)
Requires J-PARC proton accelerator upgrade
Requires new far detector

Conventional facilities
Key experimental factors

- **Giant detectors**
  - Water Cerenkov ≈300-500 kton
  - Liquid Argon TPC ≈100 kton
  - Liquid Scintillator ≈50 kton

at least x10 statistics compared to present generation LBL

- **High proton beam intensities**
  - FNAL: 300-750 kW → 2 MW, 120 GeV MI protons ?
  - CERN: 400-700 kW, 400 GeV SPS → 2 MW 30-50 GeV HP-PS ?
  - J-PARC: 140-750 kW, 30 GeV MR → 1.66 MW ?
  - CERN : 4MW @ 5 GeV SPL ?
- **Long Neutrino Flight Paths**
- **Being Pursued**
  - LBNE (USA), LAGUNA (EU), Future @ J-PARC (Japan)
  - Where will it be realized ? one or two sites / technologies ?

Staged approach to intensity frontier

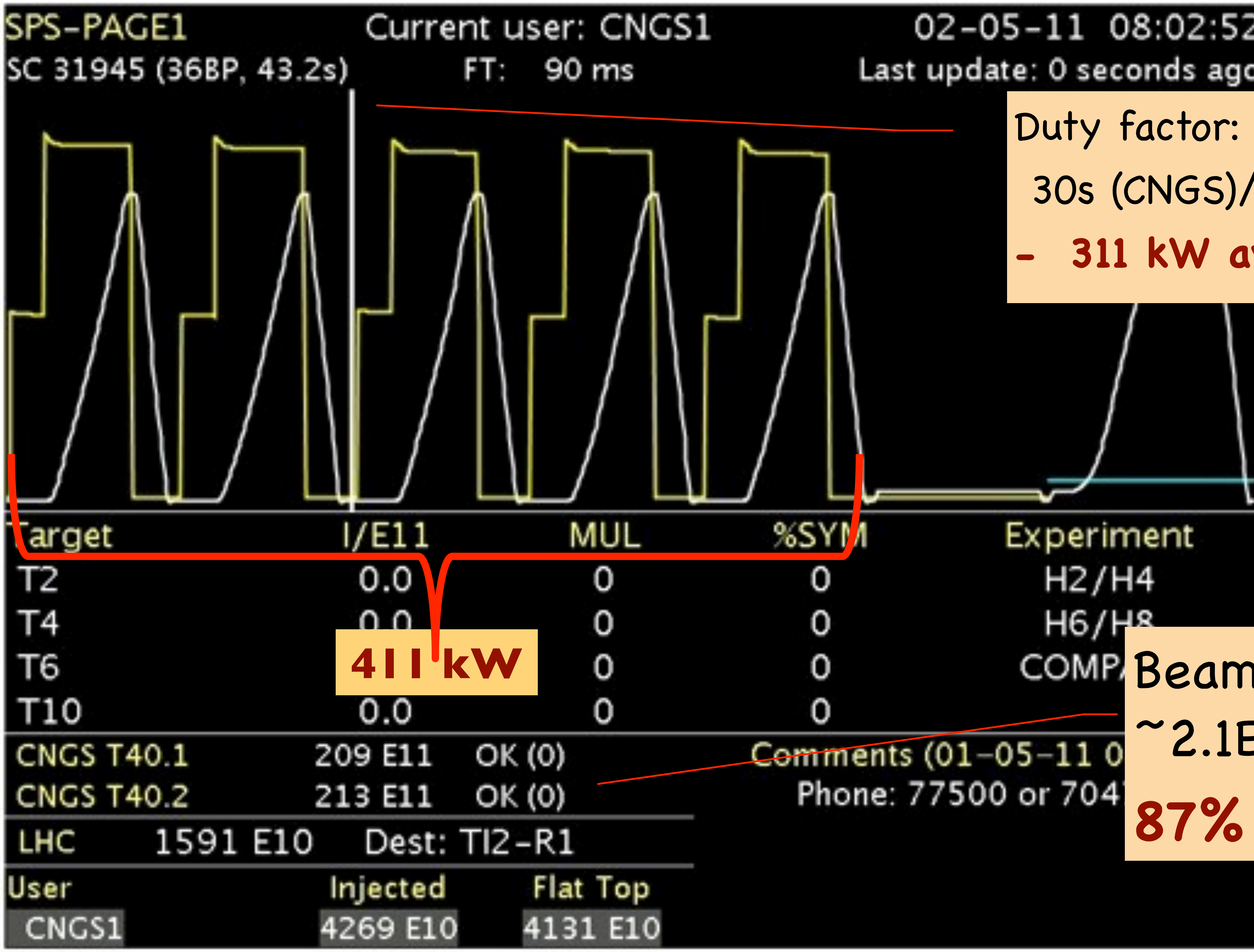
Now

Courtesy: ***Ilias Efthymiopoulos*** *- CERN*

	Now		
JPARC	**T2K (295km)** – **0.15MW** operation in 2011	**T2K (295km)** – expected **0.75MW** gradually ~2014 ?	**T2K (295km) T2O(658km)** – expected **1.66MW** operation, by >2014
FNAL	**NUMI/MINOS (732km)** – **0.3MW** sustained operation	**NUMI/NOVA (732km off-axis)** – **0.75MW** upgrade (~2014)	**LBNE/DUSEL (1300 km)** – **2MW** operation requires Project-X
CERN	**CNGS (732km)** – **0.3MW** sustained operation, **0.45MW** if no beam sharing	**CNGS+ (732km) or CN2PY (2300km)** - **0.75MW** "ultimate", requires SPS and injector upgrade	**CN2PY(2300km) CN2FR(130km)** - **2MW** operation requires LP-SPL+HPPS, or HP-SPL+Accumulator (4MW)

LAGUNA-LBNO, EUROν FP7 Design Studies

CNGS ν-beam performance



Duty factor:

30s (CNGS)/43.2s (total) = **69%**

- **311 kW average power**

Beam Intensity:

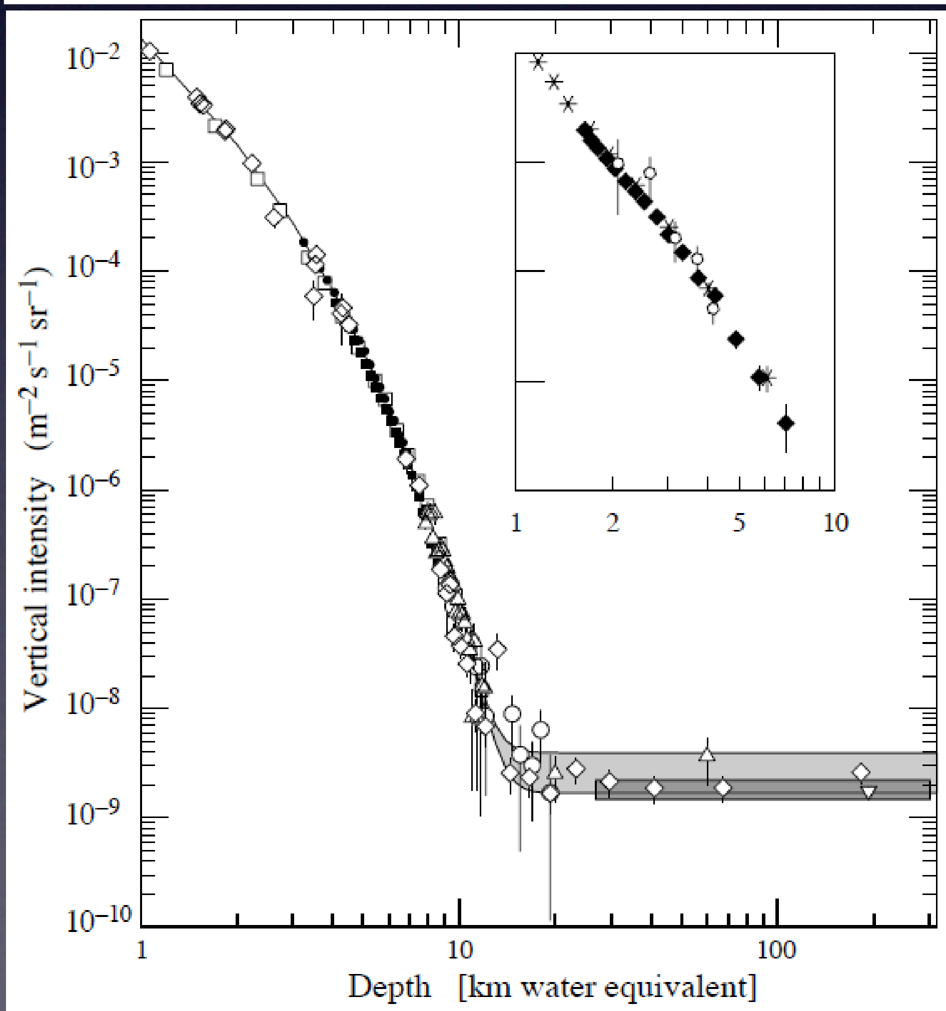
~2.1E19 pot/extr

87% nominal

LAGUNA Underground Labs

Basic characteristics of the studied underground sites:

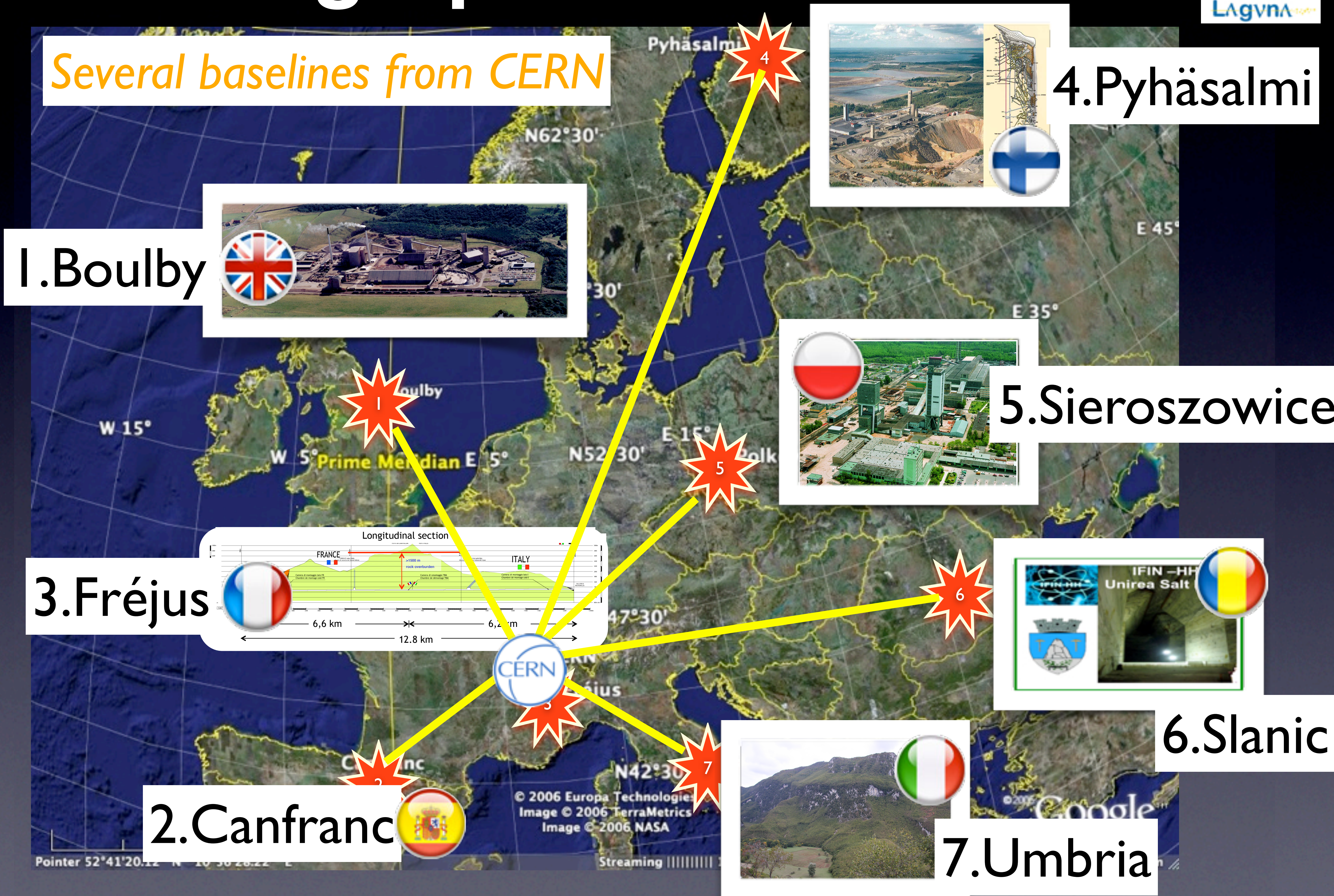
From existing road tunnels:	**Canfranc (1500-2700mwe),**
	Fréjus (4800mwe)
From existing deep mines:	**Boulby (3400-4000mwe),**
	Pyhäsalmi (2500-4000mwe),
	Sieroszowice (1400mwe)
Existing large salt-mine:	**Slanic (840mwe)**
Greenfield site(off-axis CNGS):	**Umbria (1500-2300mwe)**



Guidelines for detector overburden:

GLACIER ≥ 2500 m.w.e (900 m of rock)
LENA ≥ 4000 m.w.e (1400 m of rock)
MEMPHYS ≥ 3000 m.w.e (1100 m of rock)

Geographic locations



LAGUNA at work (2008-2011)

Typical questions addressed

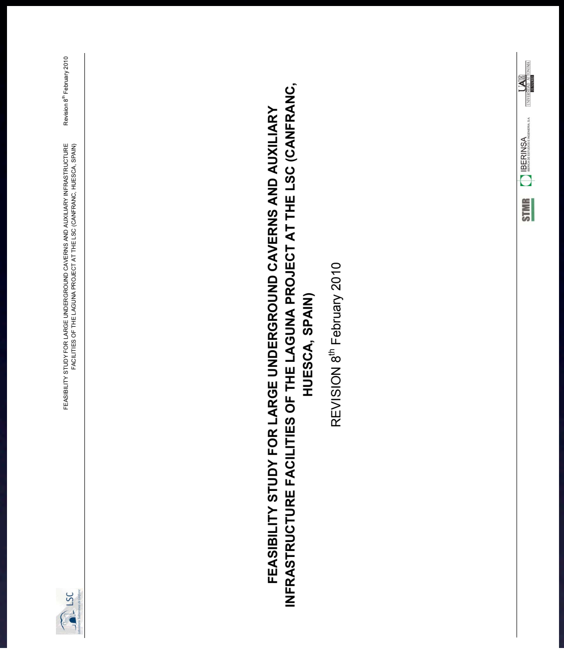
- assessment of strengths and weaknesses
- rock mechanics of caverns
- design of tanks in relation to sites
- overburden vs. detector options
- transport, access, delivery of liquids
- safety e.g. tunnel vs. mine
- environment e.g. rock removal
- relative costs

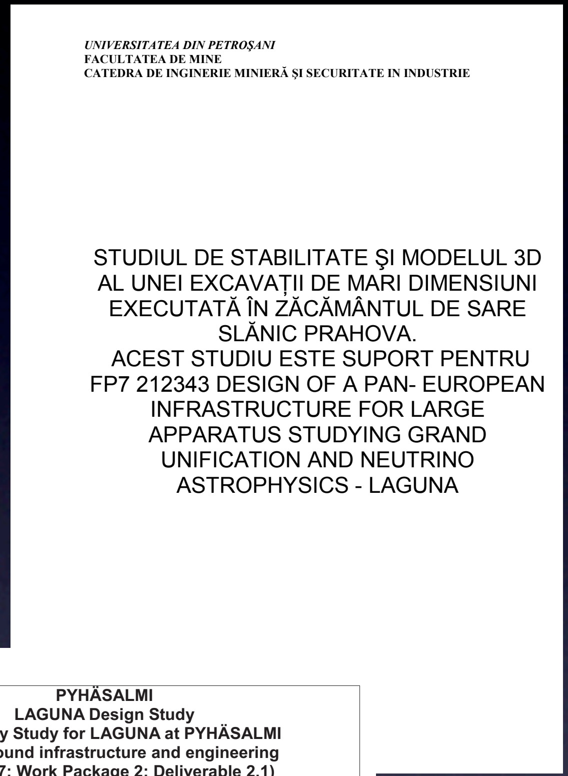
Site visits and meeting

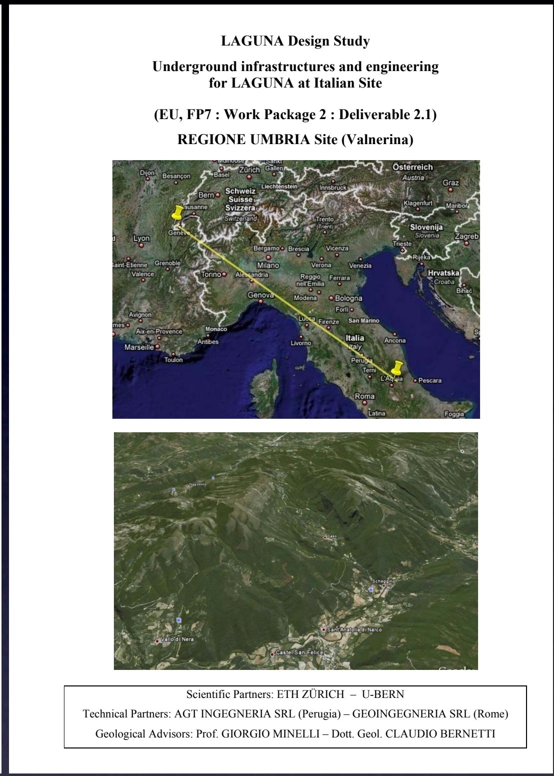
- sites work together on common areas

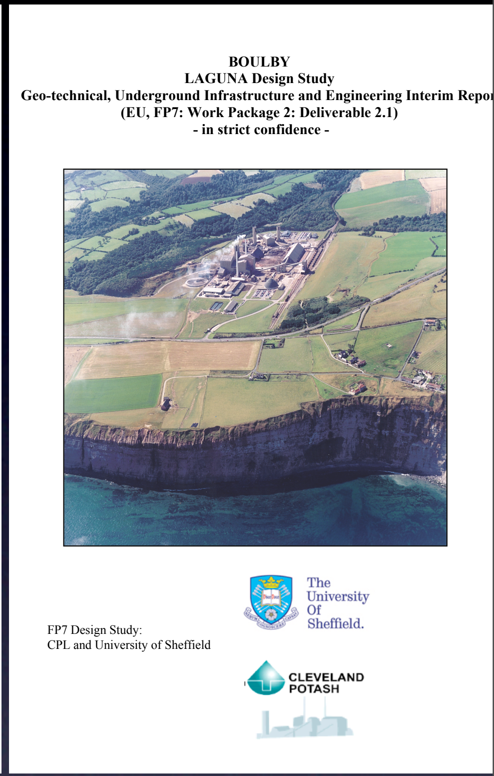
Seven technical reports

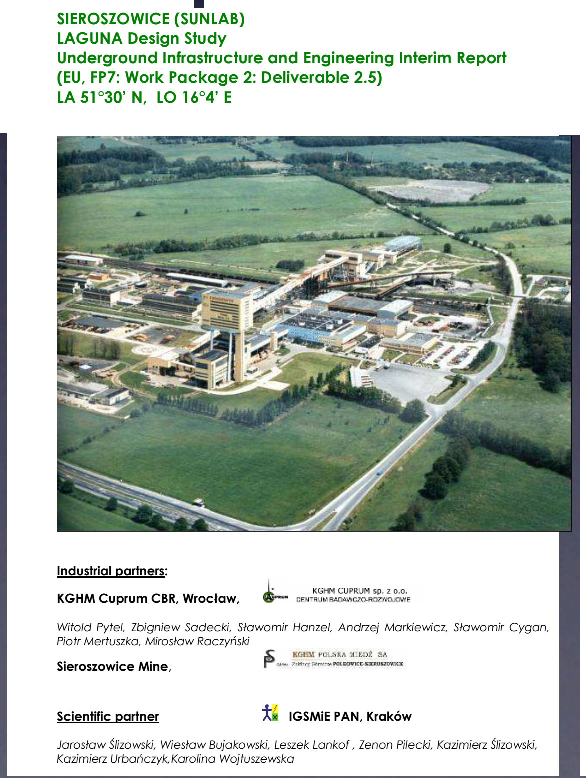
Interim site-dependent geotechnical reports: published
Final joint report on potential European sites: finalized









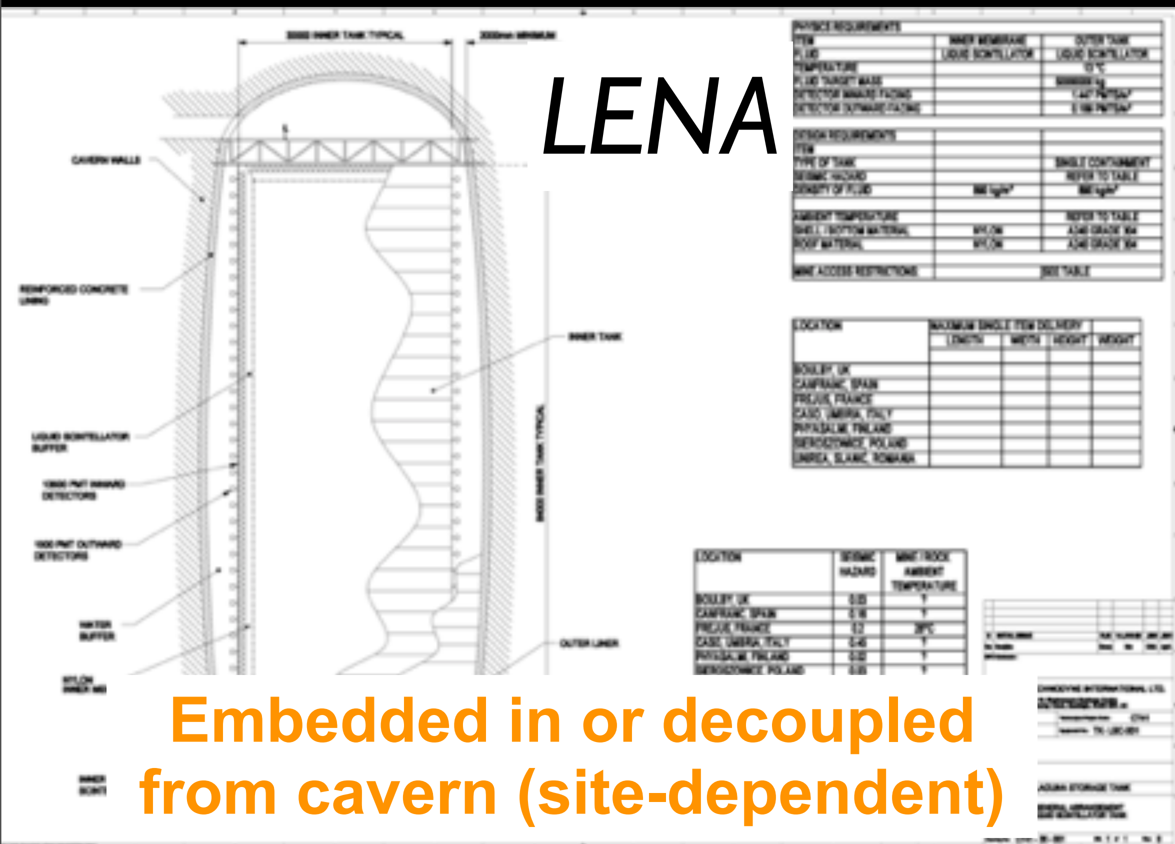


- more than 1200 pages
- large amount of information and details
- healthy competition among sites
- technical basis for site selection

Tank concepts

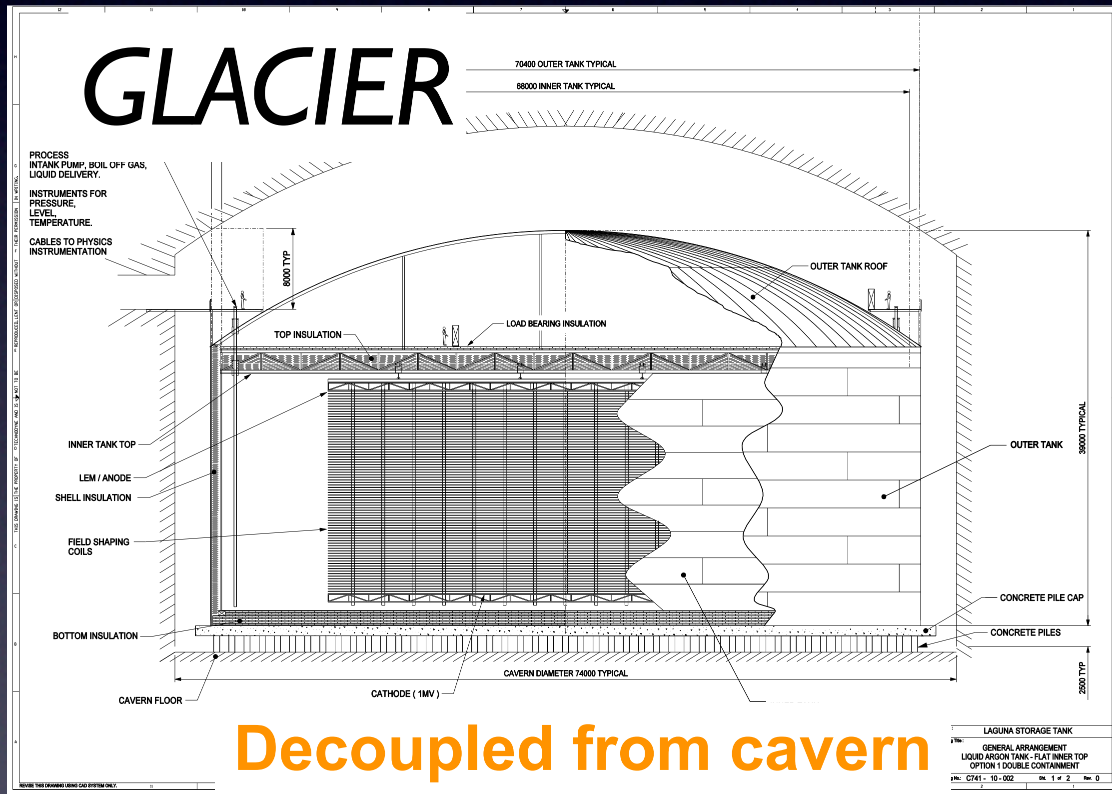
80 pages report by Technodyne Ltd

Item	MEMPHYS	Lena	Glacier
Type	Single Containment	Single Containment	Single or Double Containment
Inner Membrane	Plastic	Nylon	-
Liquid Holding Tank	Stainless Steel	Stainless Steel	Stainless Steel
Cavern Liner	Stainless Steel	Stainless Steel	9% Nickle Steel or Carbon Steel



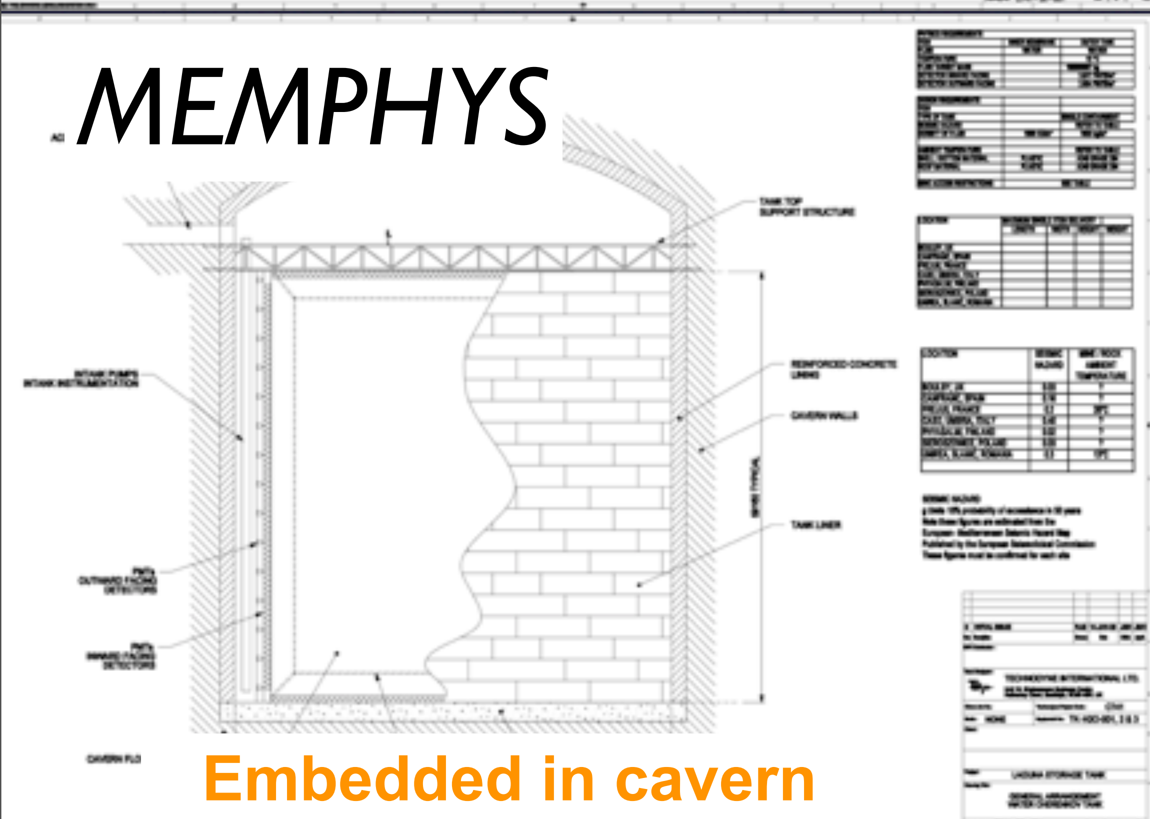
LENA

Embedded in or decoupled from cavern (site-dependent)



GLACIER

Decoupled from cavern



MEMPHYS

Embedded in cavern

Preliminary tank cost estimates have been established as follows:

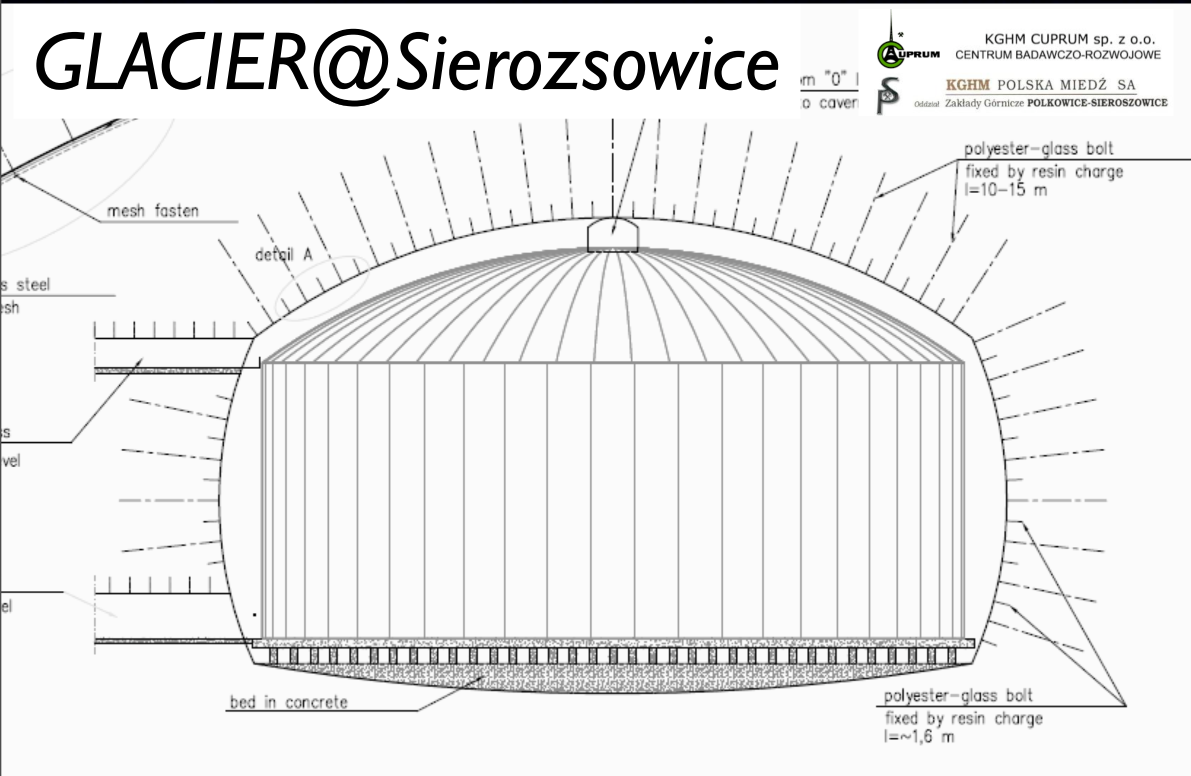
GLACIER tank (Low Seismic Site)	M€
GLACIER tank (High Seismic Site)	M€
LENA tank	M€
MEMPHYS tanks (total for 3 off)	M€

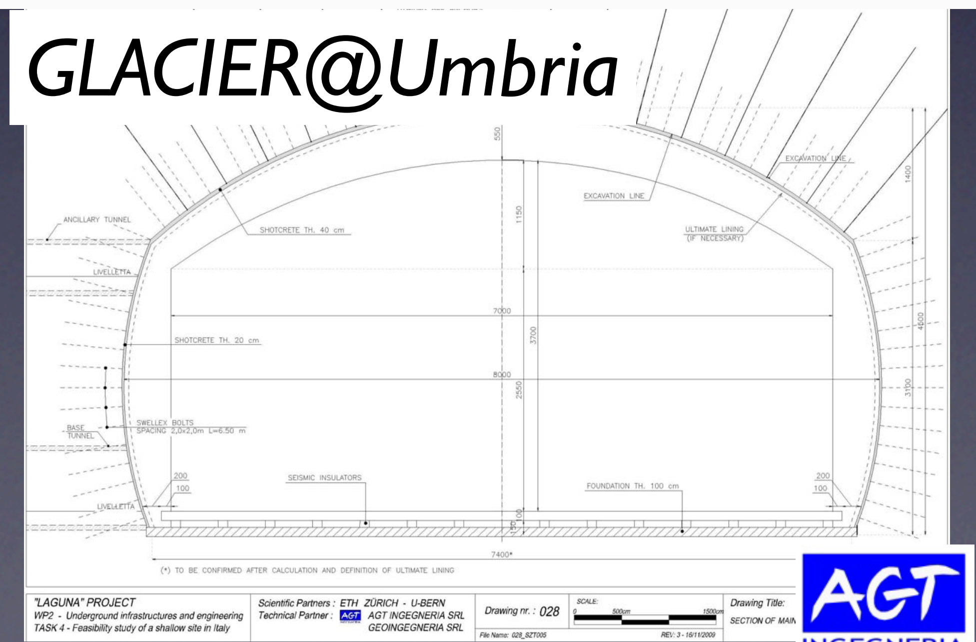
Main cavern engineering

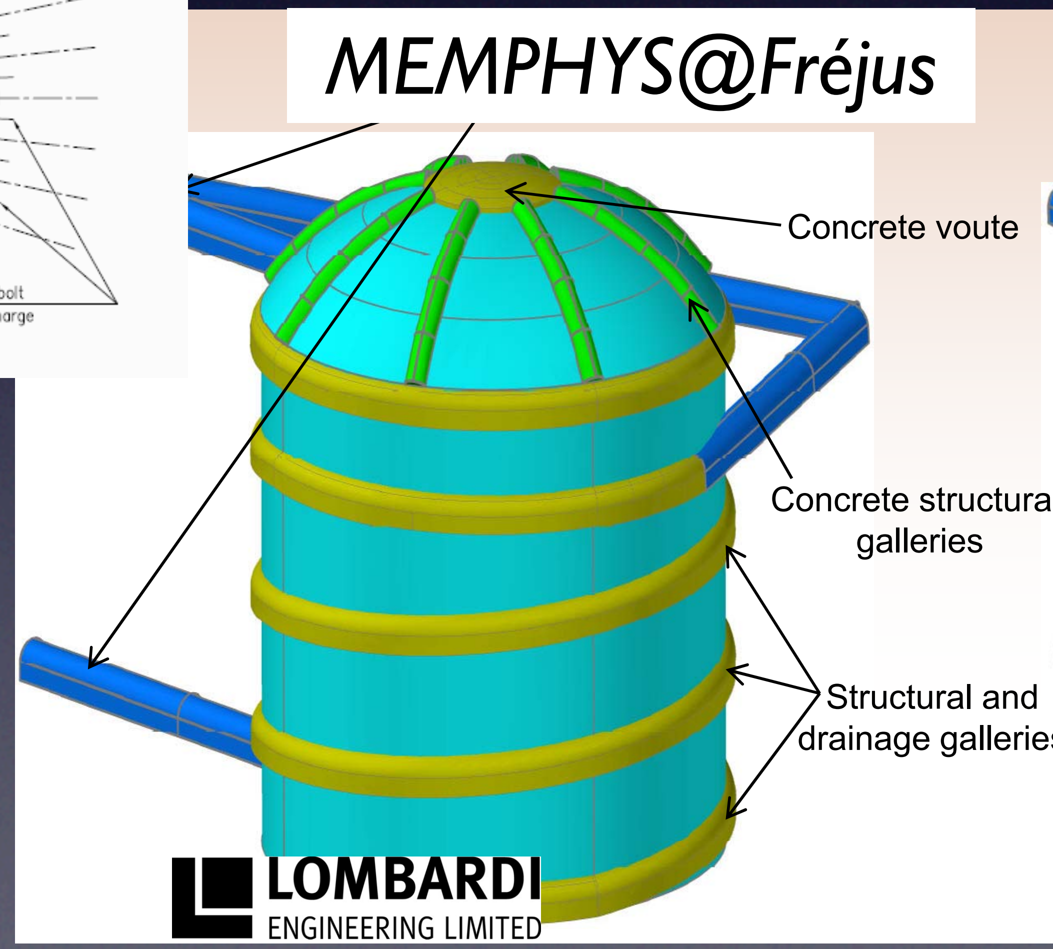
Relationship between tank design and main cavern excavation

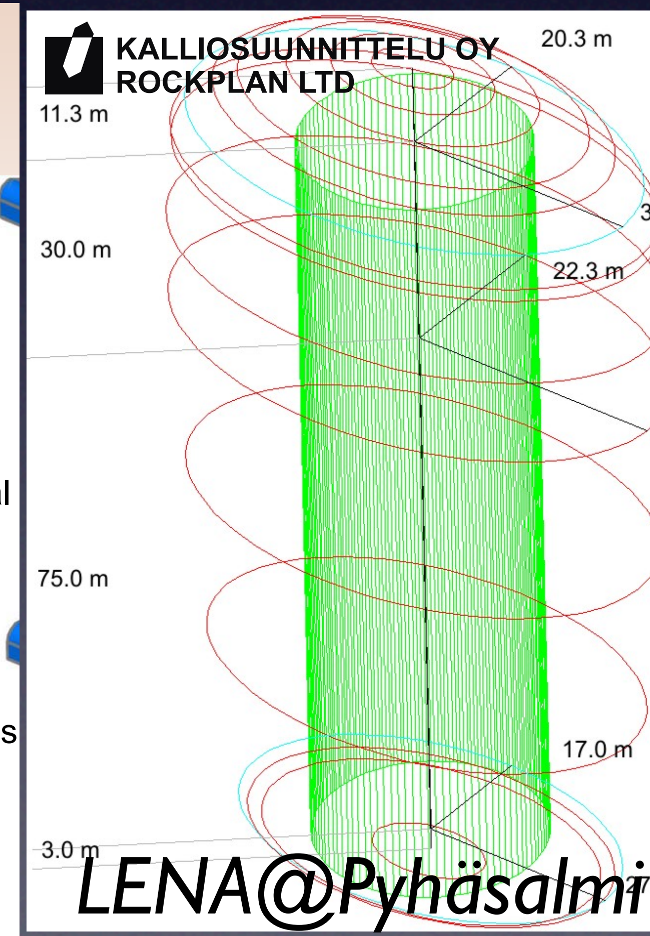
- **Interaction between scientists, Technodyne Ltd. with Rockplan, Cuprum, CPL, AGT, ...**

	MEMPHYS	LENA	GLACIER
Overburden	>2000 mwe	>4000 mwe	>600 mwe
#tanks	3 to 5	1	1 preferred
Dimensions of tank	cylinder 65m Ø x 65m height	SS cylinder of 30m Ø x105 m height, inside a external tank of ~ cylindrical shape, of at least 34m Ø for water-buffer.	cylinder: 72,4m Ø x 26,5m height dome: 12,7m height x 144,8m Ø
Cavern	65m Ø x 70m height + dome	Egg-shaped to house external tank	cylinder: 75,1m Ø x 26,5m height + dome





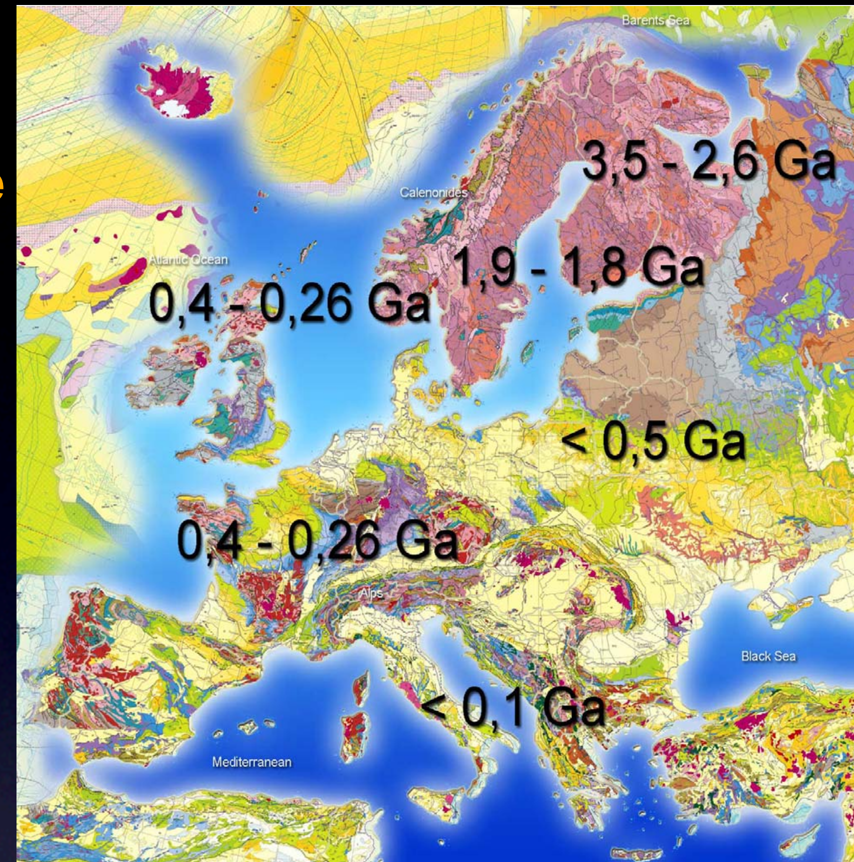


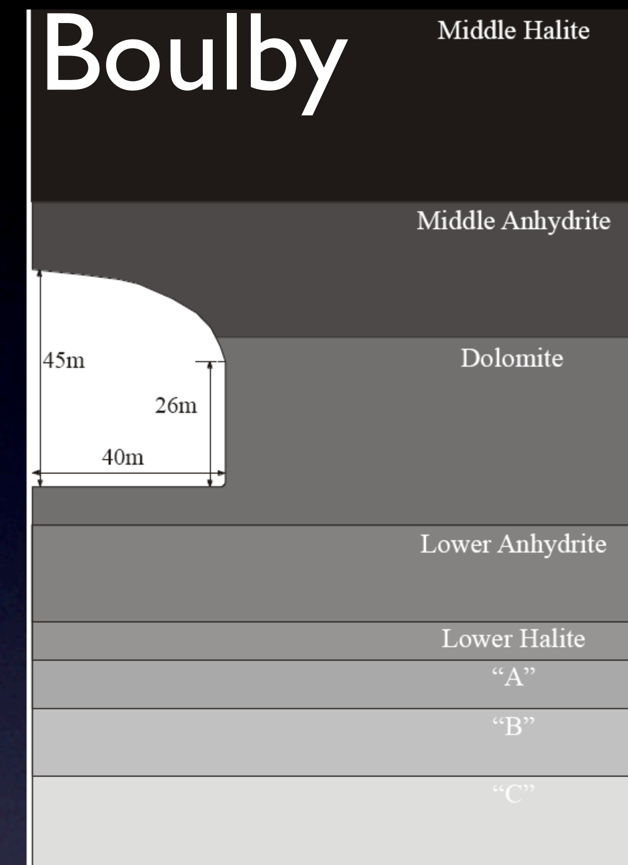


Geomechanical studies

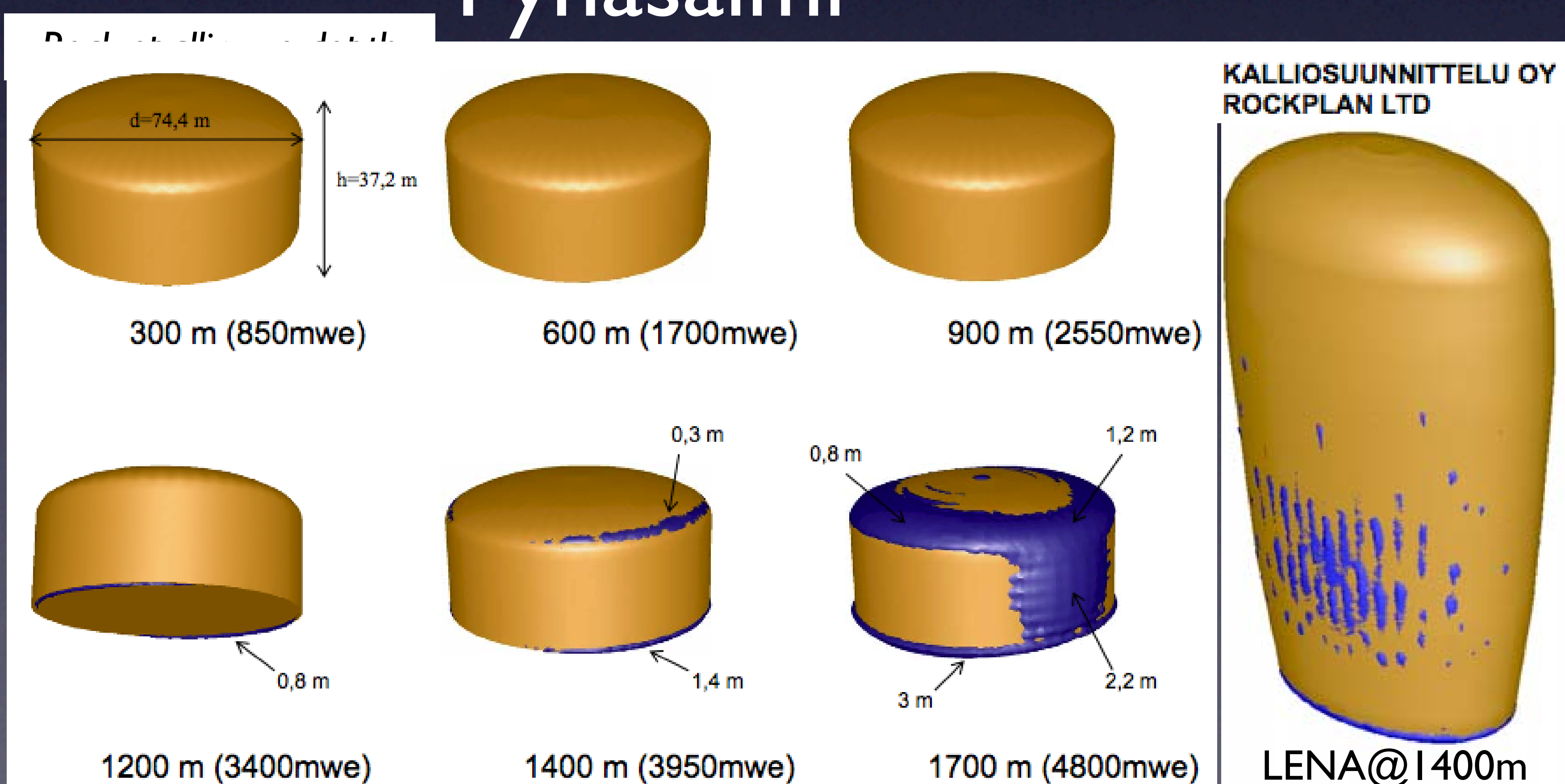
Rock data gathered for all sites
Numerical modeling based on these parameters:

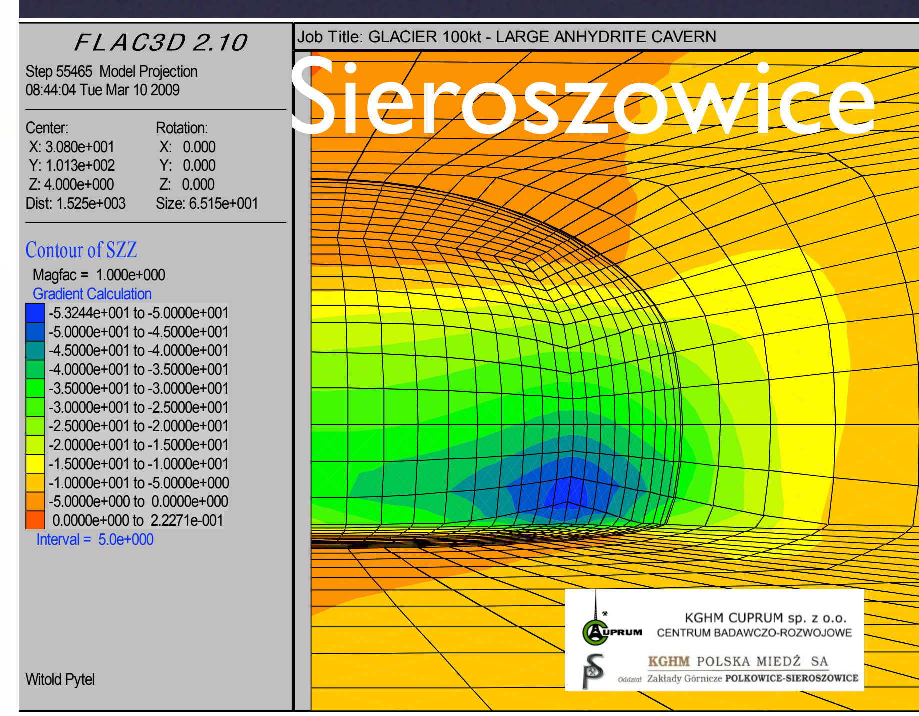
- Convergence
- Spalling
- Rock-bolting
- Mucking
- Multi-strata rock issues
- Cavern shapes





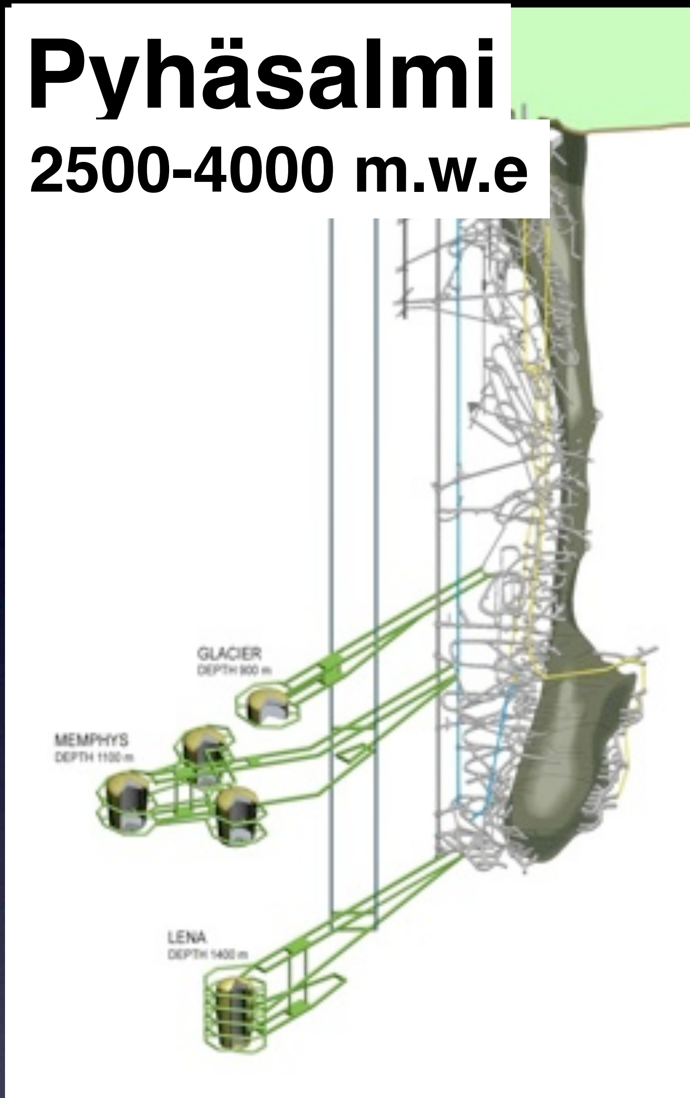
Pyhäsalmi

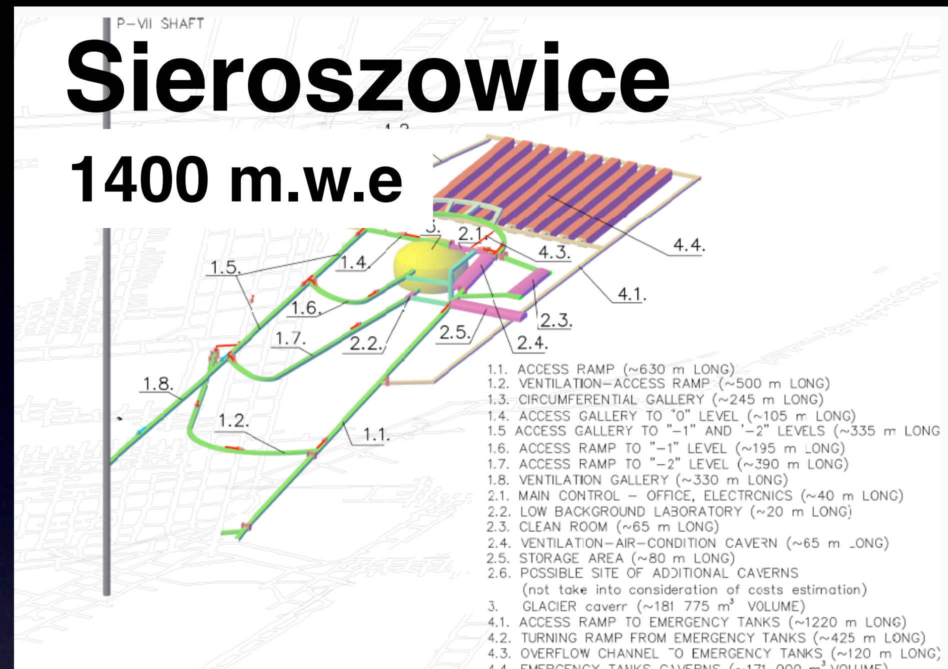


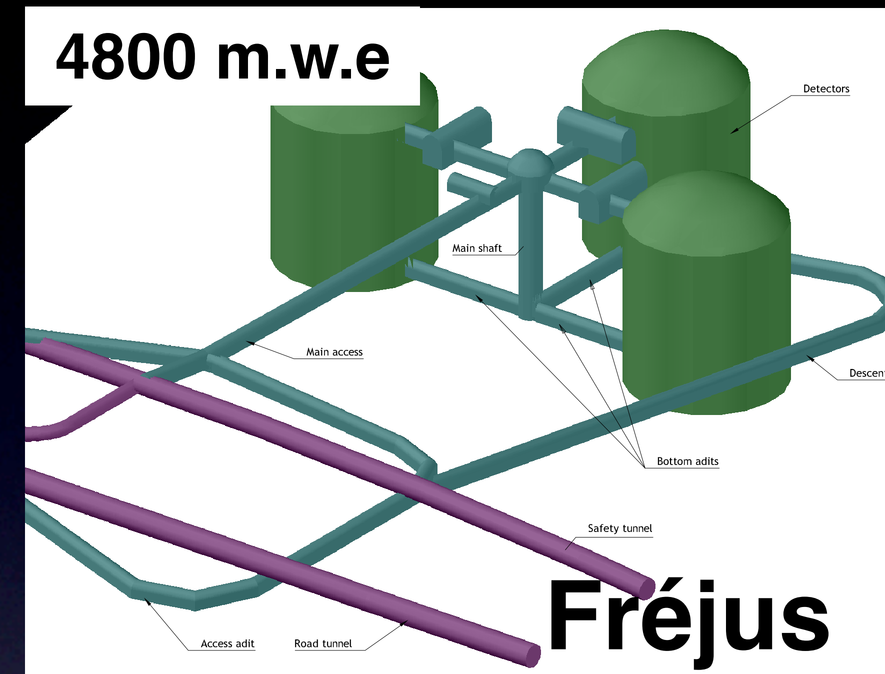


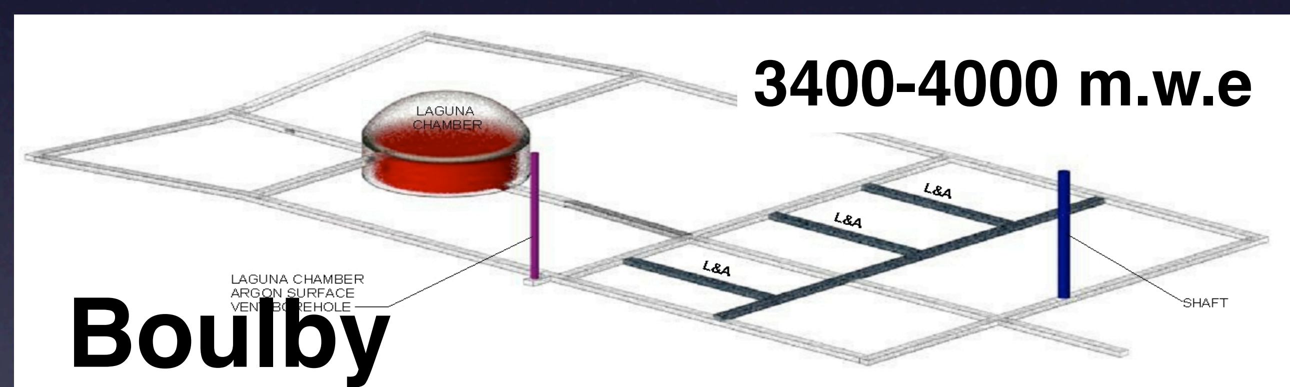
Underground Layouts

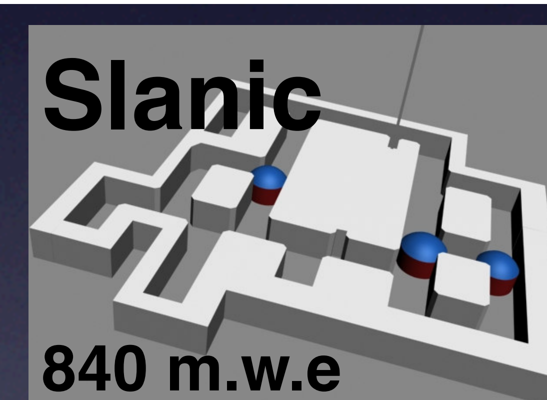
Details of layout including MDC, auxilliary caverns, access, escape routes, etc...

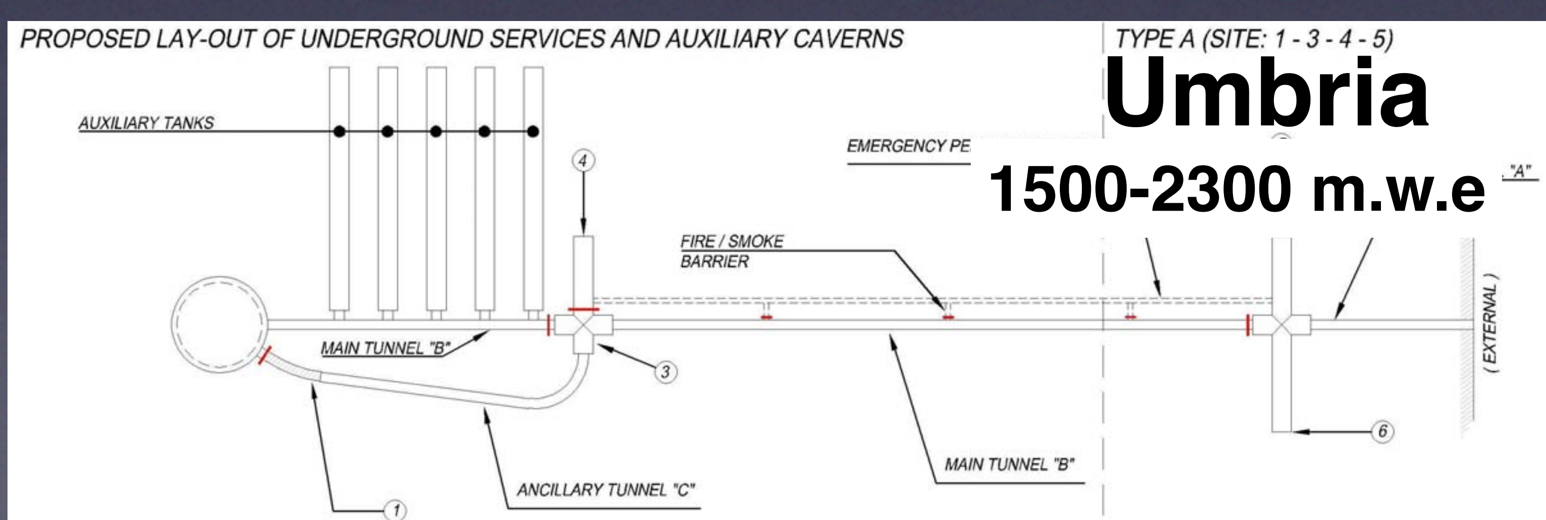


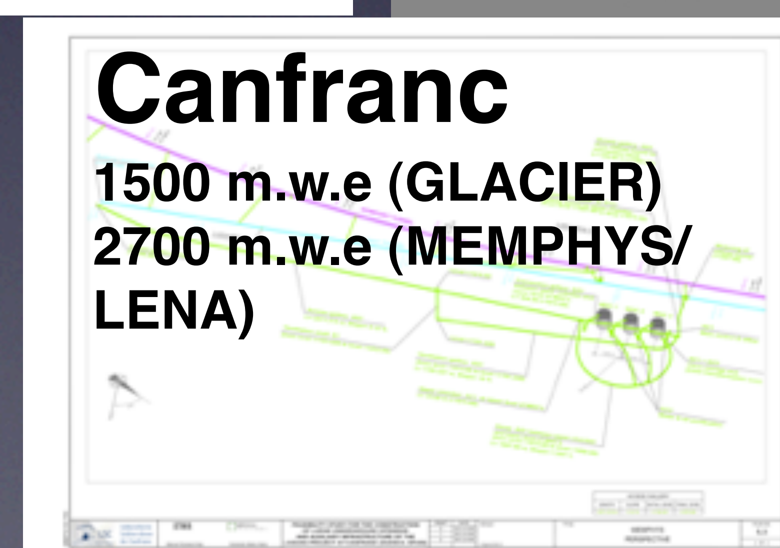










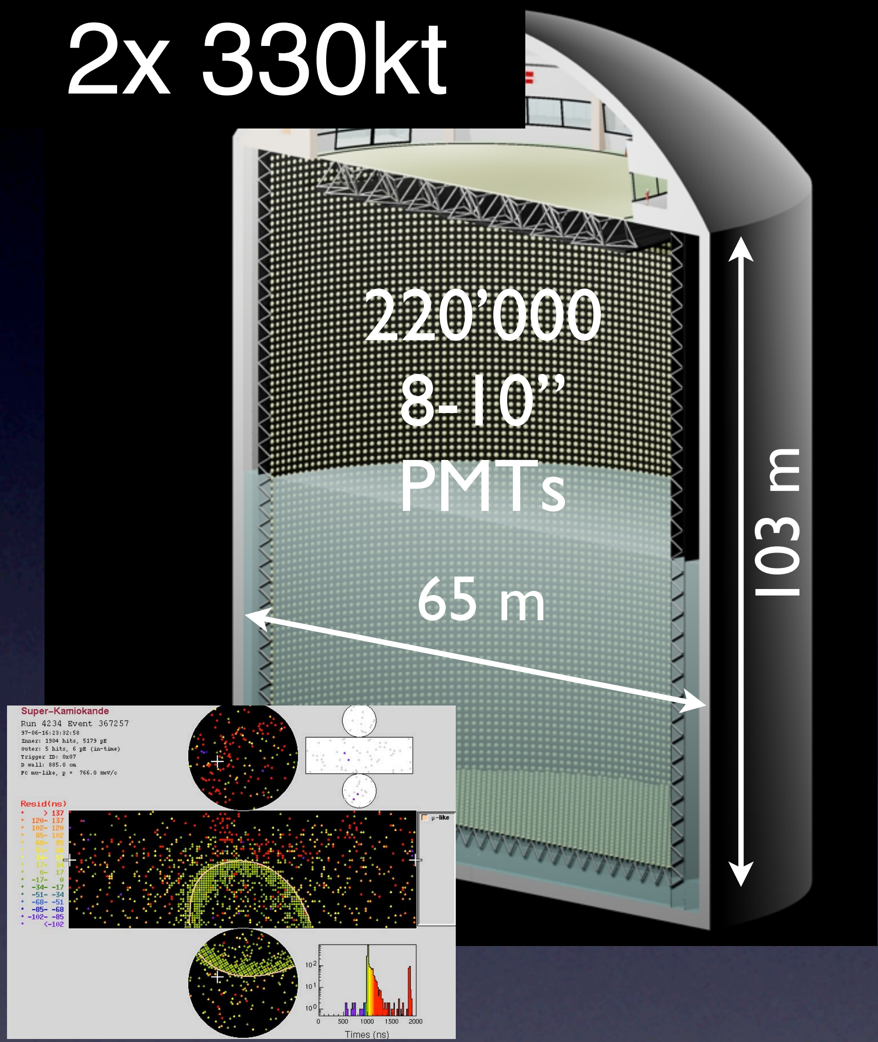


LAGUNA detector options

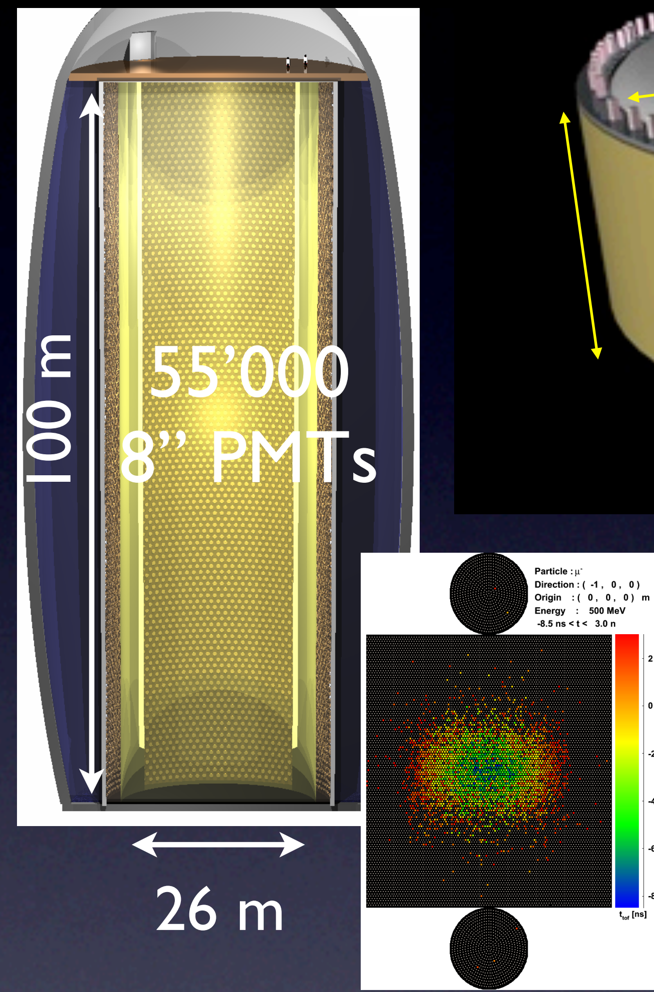
Water Cerenkov *Liquid Scintillator* *Liquid Argon TPC*

MEMPHYS

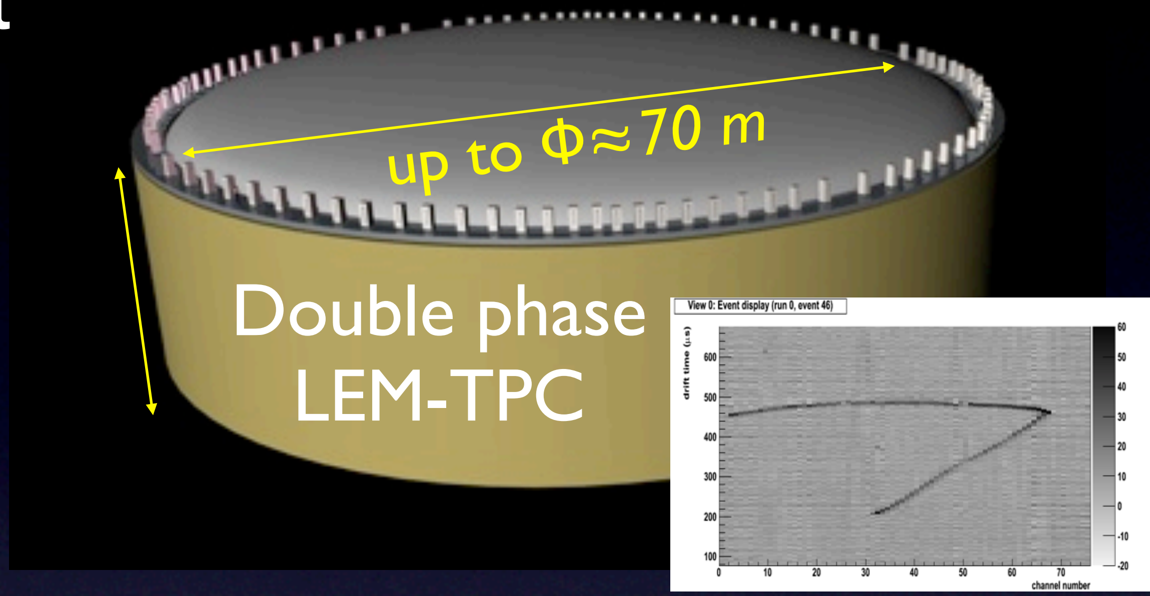
2x 330kt



LENA 50kt

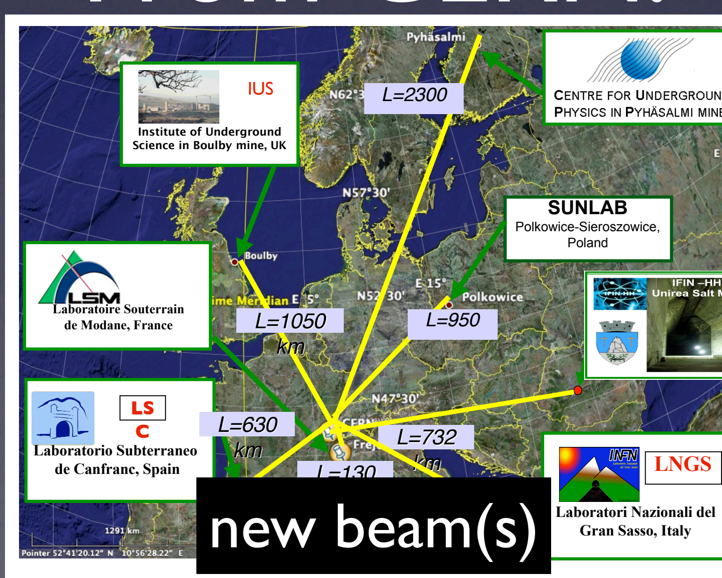


new detectors



GLACIER 100kt

From CERN:



new beam(s)

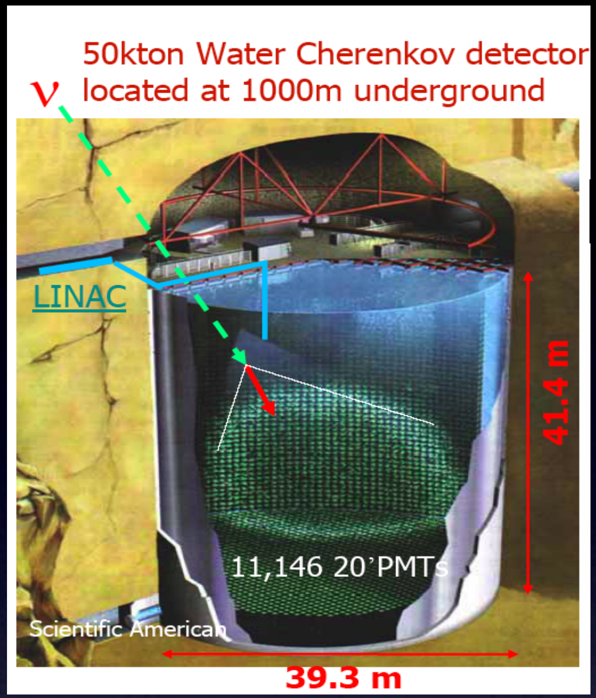
Consider new next generation giant underground ν detectors and new beam line facilities

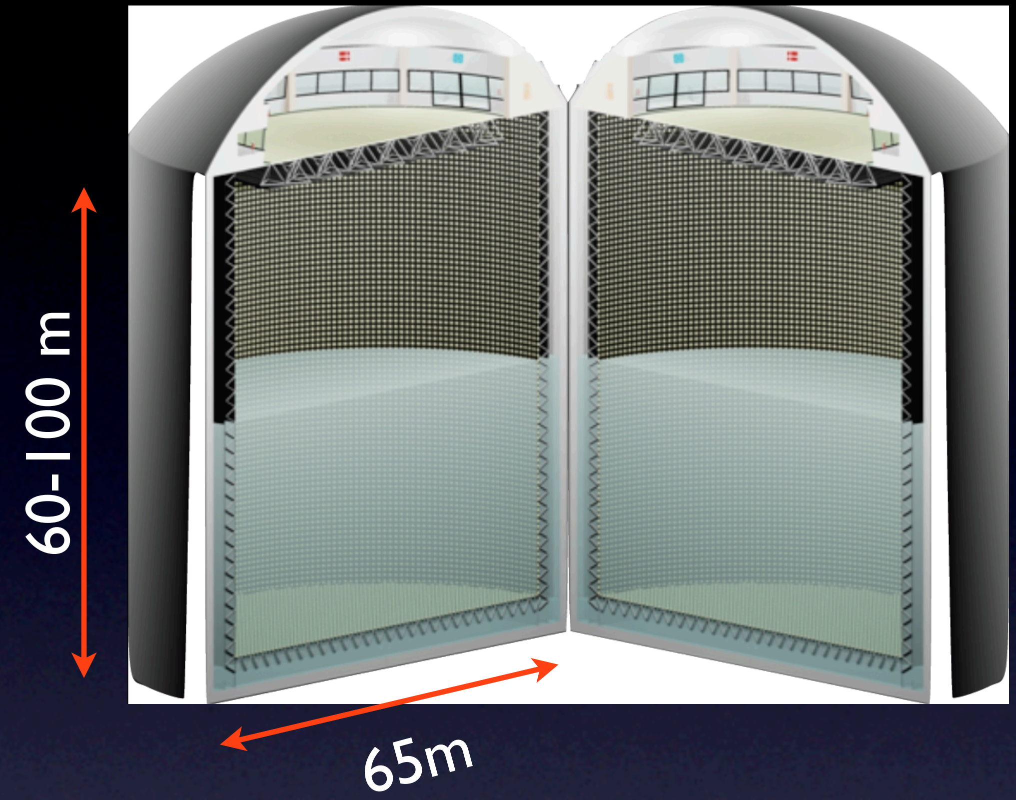
LAGUNA detector selection

- The formal detector selection process will be part of the LAGUNA program in the coming years.
- Up to now, the three "liquid" detectors are studied in parallel, exploiting synergies and common issues.
  - ★ Physics programs are complementary;
  - ★ Technologies, and associated risks, are significantly different;
  - ★ The chosen baseline from CERN (i.e. the site) plays an important role in selecting the appropriate detector technology (since L/E is chosen by nature)
- Converge towards "natural configurations"

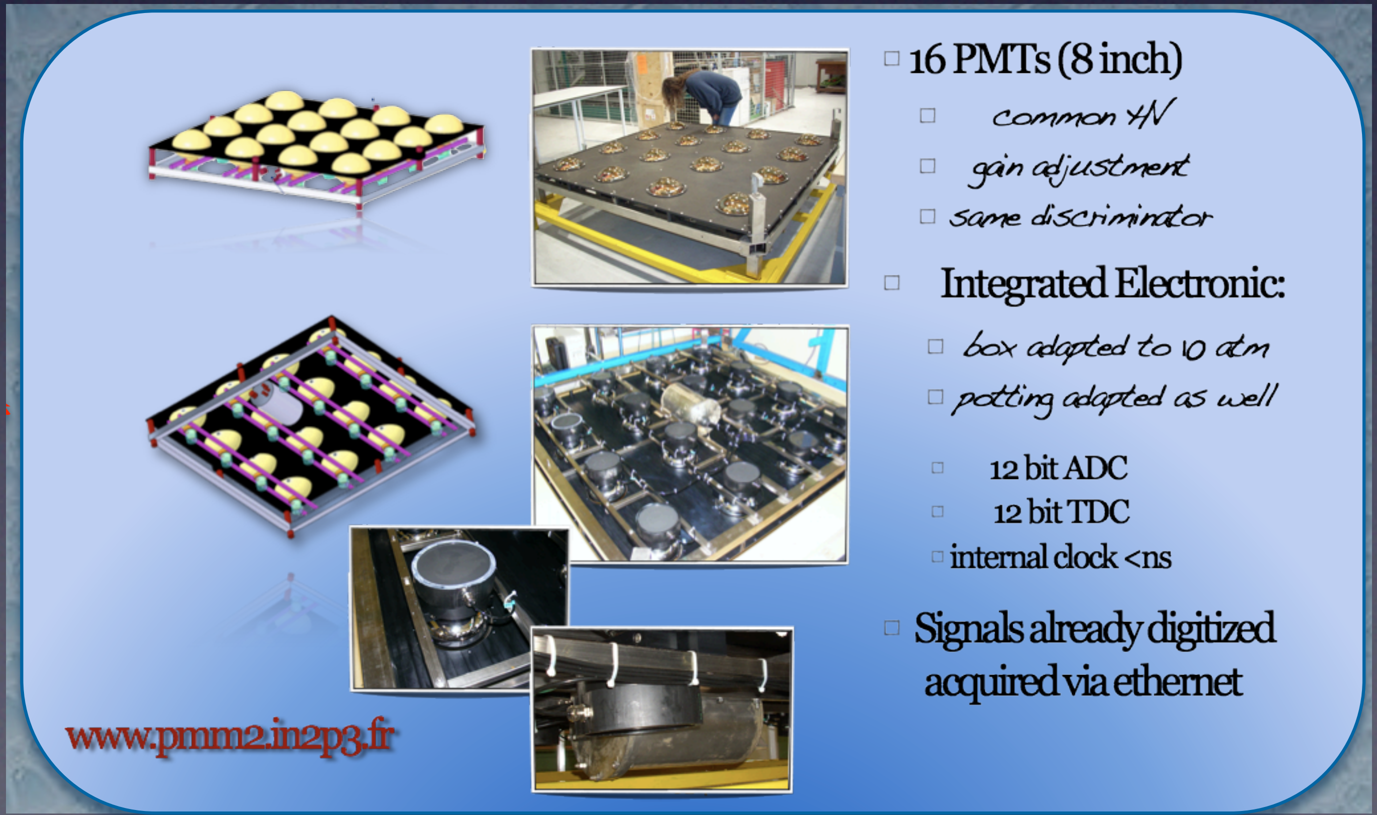
- Detector option A in site A
- Detector option B in site B
- Hybrid: Detector option A+C in site A
- Hybrid: Detection option B+C in site B

MEMPHYS (550 kton)
(Large Water Cerenkov Detector in Europe)





22 kton fiducial mass



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

PMm2 R&D programme:
"intelligent detector"
cost reduction

LENA (50 kton)
(Low Energy Neutrino Astronomy)

Very high purity liquid scintillator with high light yield, optimized for lowest energy range

Liquid scintillator

50 kt LAB/PPO+ bisMSB

Inner vessel (nylon)

Radius r = 13m

Buffer

15kt LAB, Δr =2m

Cylindrical steel tank, e.g. 55000 PMTs (8") with Winston Cones (2x area)

r = 15m, height = 100m,

optical coverage: 30%

Water cherenkov muon veto

5,000 PMTs, Δr > 2m to shield fast neutrons

Cavern egg-shaped for increased stability

Rock overburden: 4000 mwe

Pyhäsalmi design

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

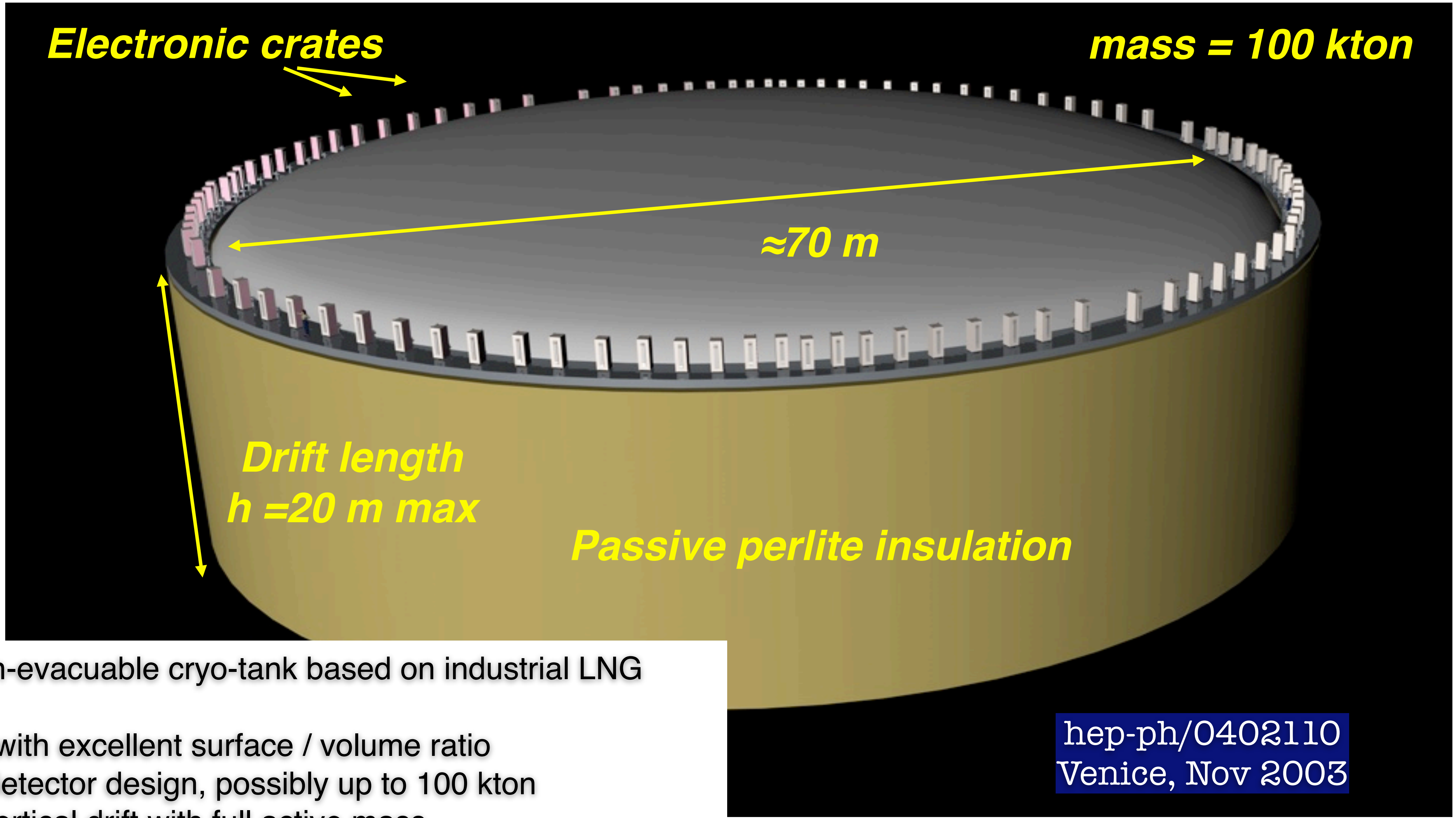
Light yield ≥ 200 pe/MeV

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

LS purity as achieved in Borexino

GLACIER (100 kton)

A scalable detector with a non-evacuable dewar and ionization charge detection with amplification



- Single module non-evacuable cryo-tank based on industrial LNG technology
- Cylindrical shape with excellent surface / volume ratio
- Simple, scalable detector design, possibly up to 100 kton
- Single very long vertical drift with full active mass
- Double phase, large area LAr LEM-TPC for long drift paths
- Possibly immersed visible light readout for Cerenkov imaging
- Possibly immersed (high Tc) superconducting solenoid to obtain magnetized detector
- Reasonable excavation requirements (<250‘000 m^3)

Ongoing R&D roadmap to address this design

How to build a Giant Liquid Argon detector ?

- The realization of a 100 kton LAr TPC demands concrete R&D in several areas. Although correctly relying on the pioneering efforts, it cannot be simply "linearly" extrapolated from the current state-of-art.
- To address this point, a series of workshops dedicated to these issues was initiated to bring together researchers having common interest in realizing a giant neutrino observatory based on the liquid Argon time projection chamber technology combining next-generation searches for proton decay and neutrino physics with natural and artificial sources.

➪ GLA2010: The 1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (Tsukuba, Japan, March 28-31, 2010).

Recently: GLA2011 (Jyväskylä, Finland, June 2011)

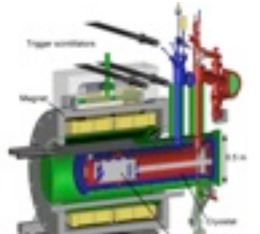
Next year: GLA2012 (Brookhaven, USA)

GLACIER R&D roadmap *(EU-Japan effort)*

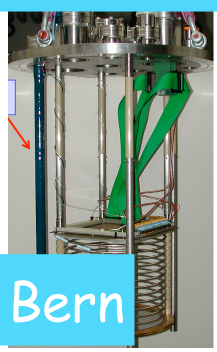
A systematic, comprehensive and staged programme has been implemented

Single phase LArTPC

KEK

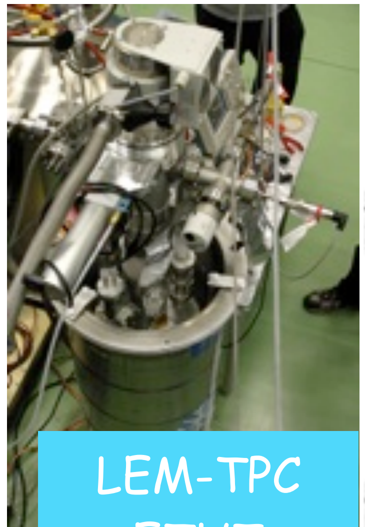


B-field test

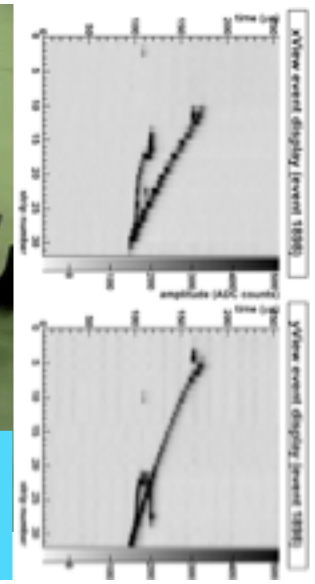


Bern

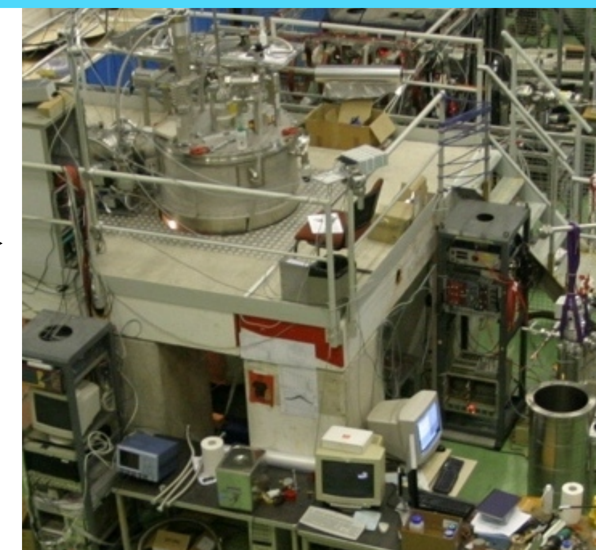
Double phase LAr-LEM TPC



LEM-TPC ETHZ



ArDM-1t(RE18), presently operating@CERN

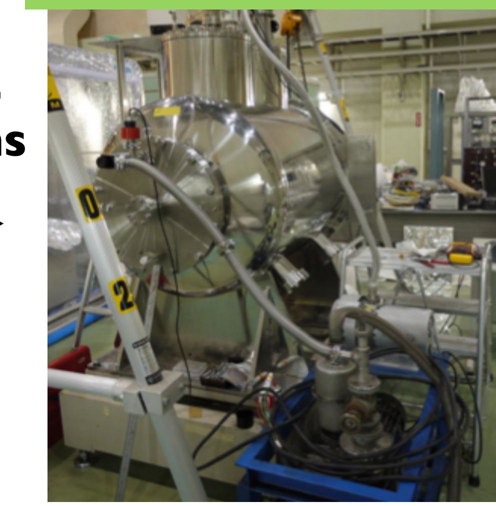


Move underground at LSC in 2011

Test beams

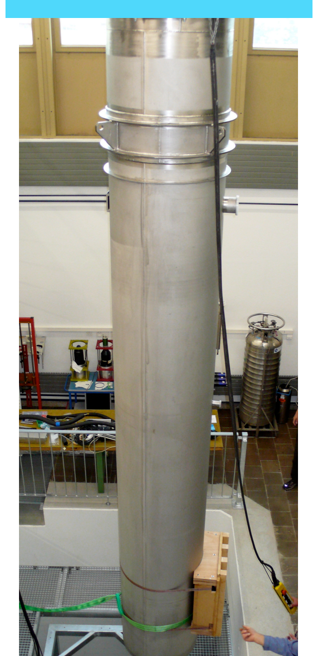
250L@JPARC

Beam exposed in 2010 (and 2012)



direct proof of long drift path up to 5 m

ArgonTube @Bern



first run in 2011

Test beams

6m3 @ CERN

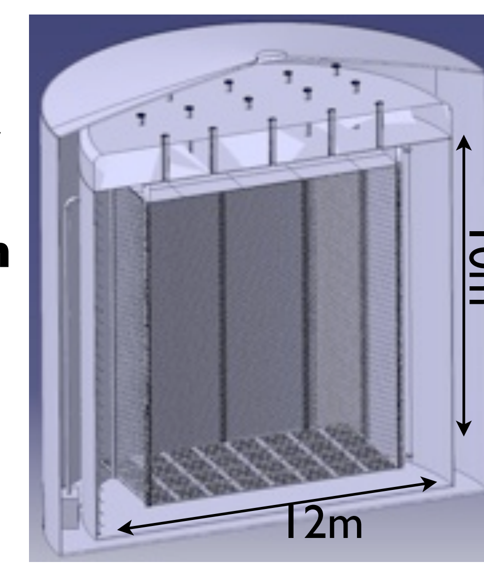
gas flushing: done

LAr: 2012, NA 2013 ?

Charged particles test beam, calorimetry, non-evacuated vessels, LAr purity

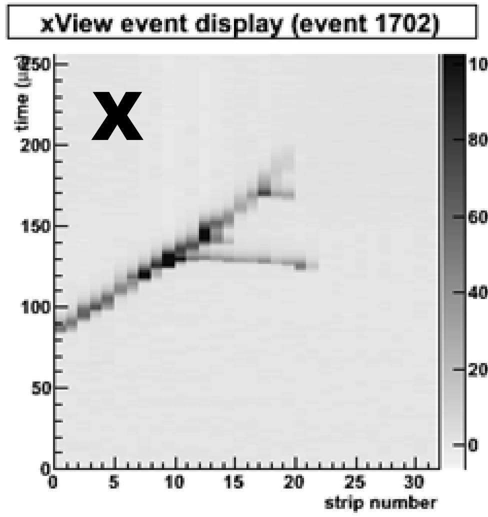
Full engineering demonstrator for larger detectors, with a stand-alone short baseline physics programme or underground ?

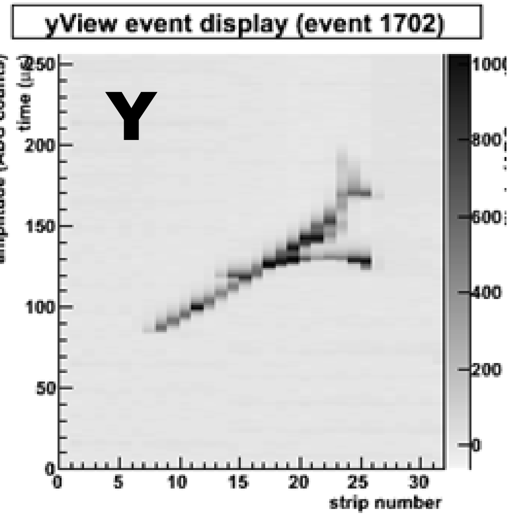
kton-scale



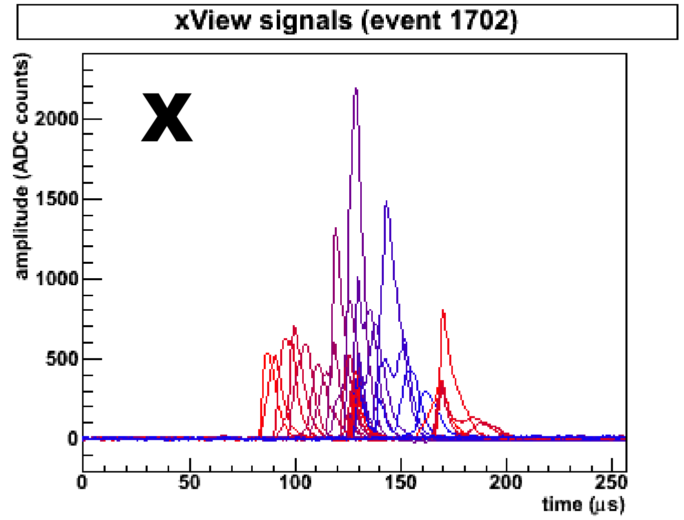
Observation of cosmic rays with a LEM-TPC

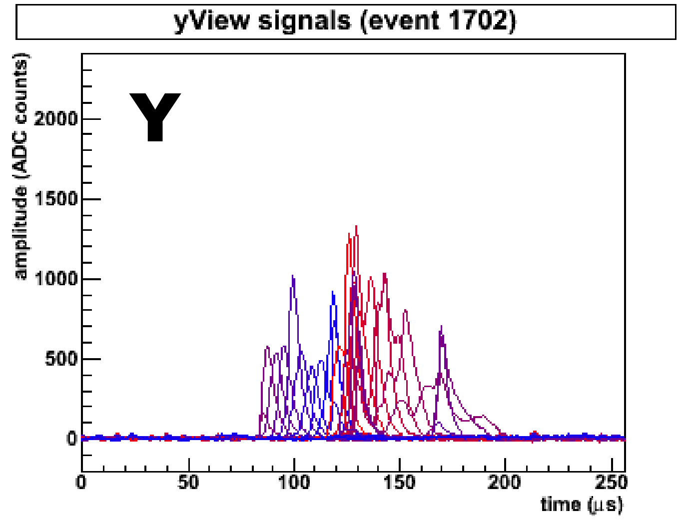
Event display: drift time vs position

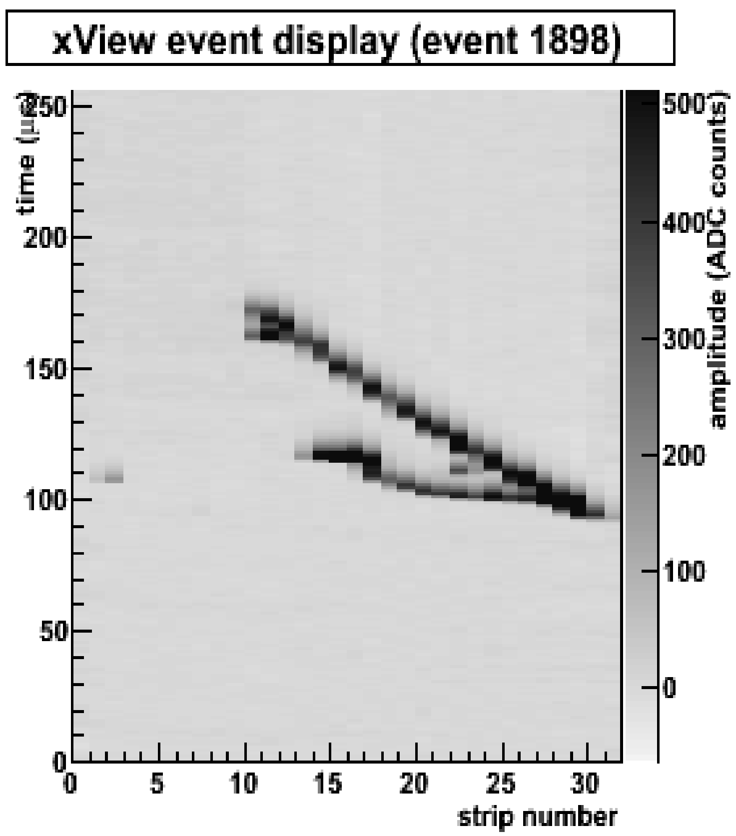


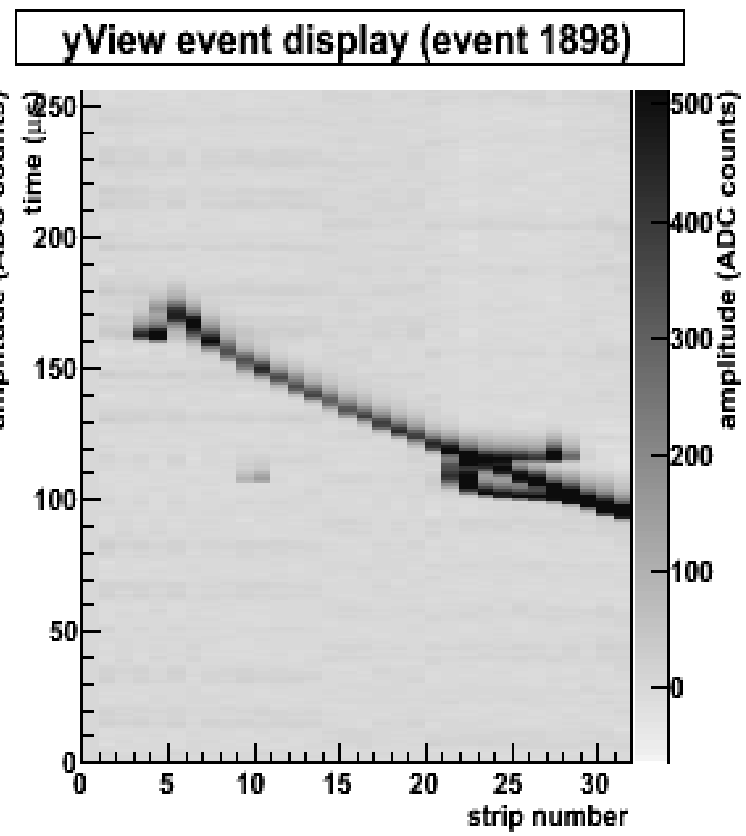


Corresponding digitized signals

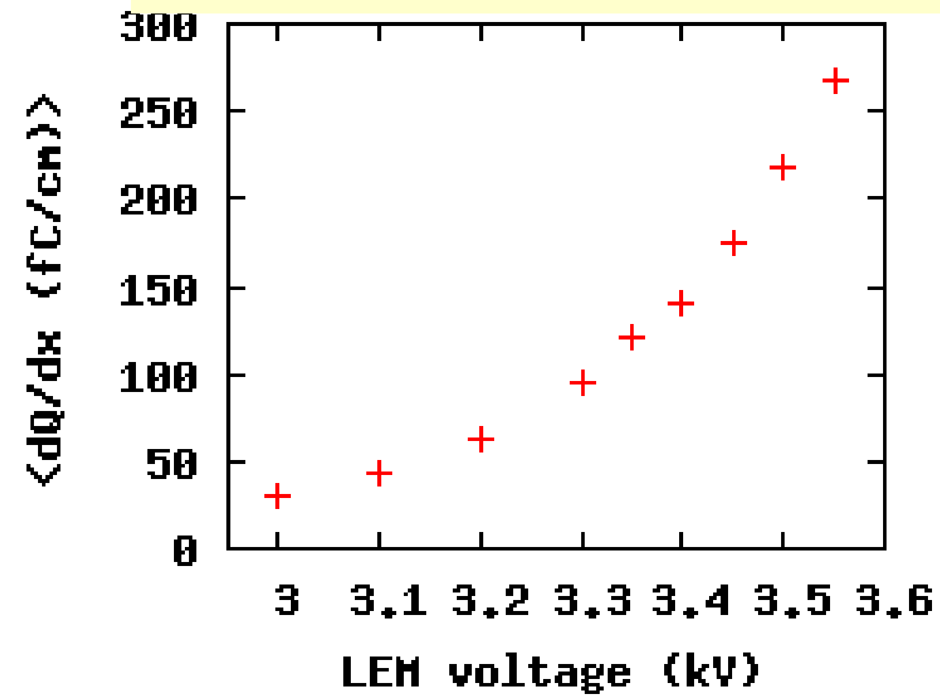








Sum of collected charge in X and Y views



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

Reached an effective charge gain of ≈27

A. Badertscher *et al.*, NIM A 641 (2011) 48

LAGUNA physics reach (astroparticle)

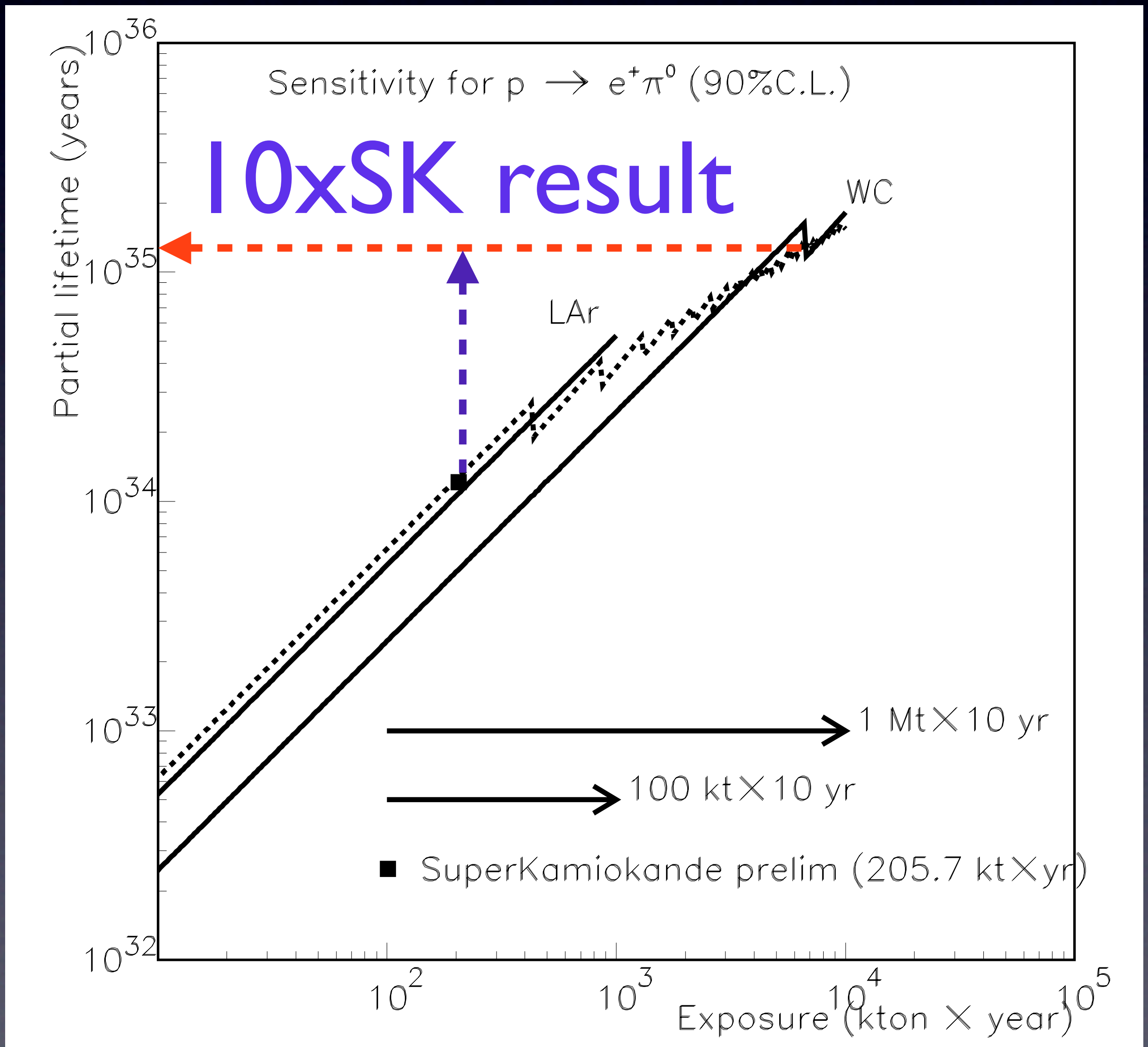
	Water Cerenkov	Liquid Argon TPC	Liquid Scintillator
Total mass	500 kton	100 kton	50 kton
$p \to e\,\pi^0$ in 10 years	1.2×10^{35} years ε = 17%, ≈ 1 BG event	0.5×10^{35} years ε = 45%, <1 BG event	?
$p \to \nu K$ in 10 years	0.15×10^{35} years ε = 8.6%, ≈ 30 BG events	1.1×10^{35} years ε = 97%, <1 BG event	0.4×10^{35} years ε = 65%, <1 BG event
SN cool off $8 \times M_{Sun}$@ 10 kpc	194000 (mostly $\bar{\nu}_e p \to e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)	15000 (all flavors)
SN in Andromeda	40 events	7 (12 if NH-L mixing)	4 events
SN burst @ 10 kpc	≈250 ν-e elastic scattering	380 ν_e CC (flavor sensitive)	≈30 events
SN relic	250(2500 when Gd-loaded)/year	50/year	20-40/year
Atmospheric neutrinos	56000 events/year	≈11000 events/year ≈100 ντ CC/year	5600/year
Solar neutrinos	91250000/year	324000 events/year	≈5400 ^{7}Be events/day
Geoneutrinos	–	–	≈1500 events/year

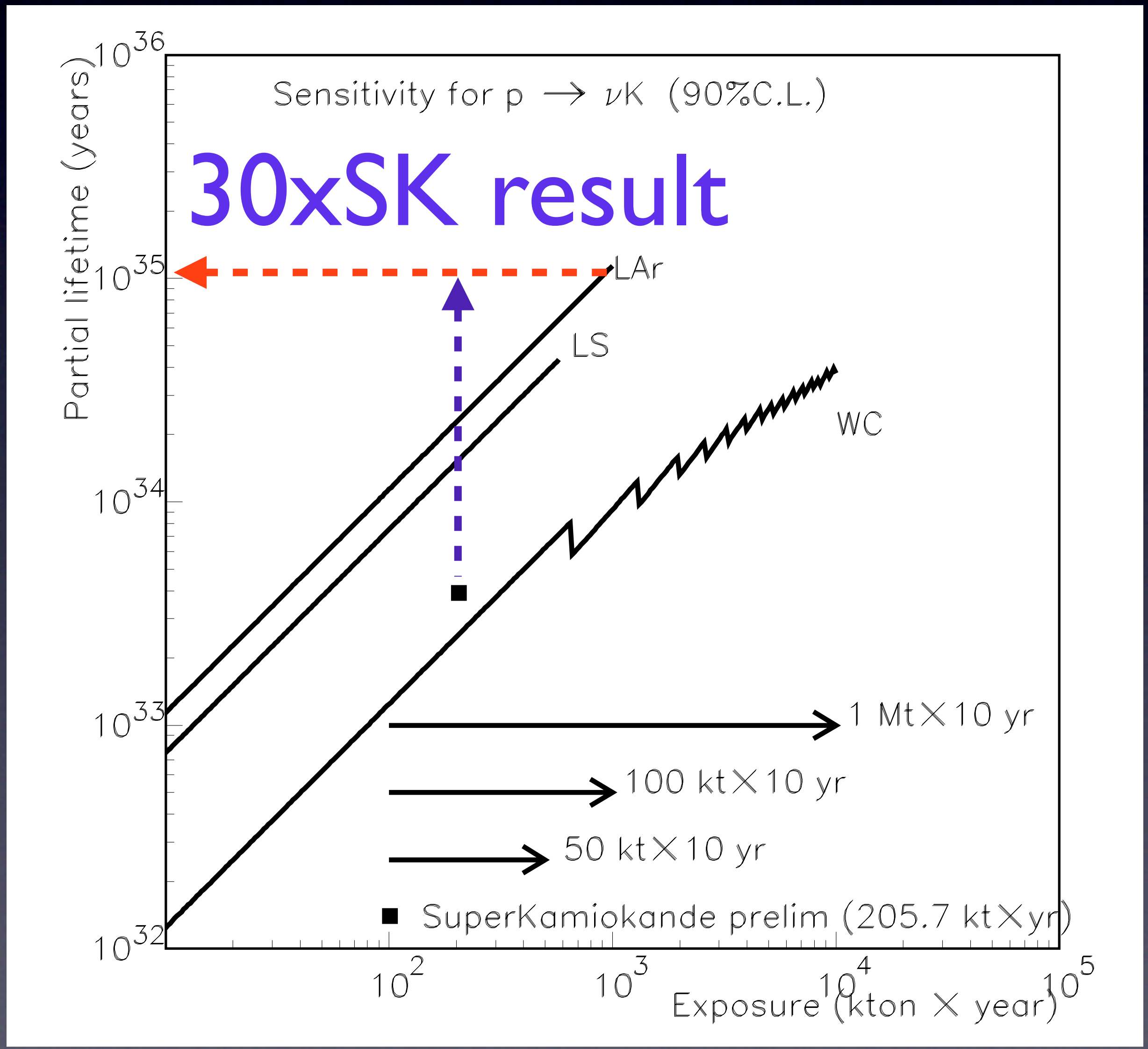
Complementarity between detector techniques

Proton decay sensitivity

In order to achieve an order of magnitude better sensitivities than those of SuperK, truly large detectors, possibly of complementary technologies, are mandatory

Expected sensitivity as a function of exposure (kton x year) for assumed efficiency and background





Present best limits SuperK preliminary (90%CL)

$\tau/B(e\pi^0) = 1.2 \times 10^{34}$ yr and $\tau/B(\nu K) = 0.39 \times 10^{34}$ yr

LAGUNA LBL neutrino oscillations

- θ_{13} - if only limits until then
- τ appearance - if not conclusive until then
- Precision measurements $\Delta m_{23}^2 \pm \delta\Delta m_{23}^2$, $\theta_{23} \pm ??$ (maximal?), $\theta_{13} \pm ??$
- Mass hierarchy $\Delta m_{23}^2 > 0$?, $\Delta m_{23}^2 < 0$?
- CP-violation $\delta \neq 0$? $\delta \pm ??$
- Unitarity of PMNS matrix
- Understand the ν-mixing parameters: tri-bimaximal ?
- Understand differences between the quark and lepton sectors
- Even more physics beyond the SM ?

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

~7500 km magic bln

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

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

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

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

CPV term approximate dependence ~L/E

~2540 km magic bln

solar term

linear dep. on θ_{13}

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

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

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

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

CP asymmetry grows as θ_{13} becomes smaller !

Phenomenological input - global fits

Well-defined phenomenology from 3x3 PMNS matrix formalism ➠ oscillation probability calculable as sum of atmospheric, solar and interference terms

Δm^2_{21}	$(7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$	$\approx \pm 3\%$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	$\approx \pm 7\%$
$\lvert\Delta m^2_{31}\rvert$	$(2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$	$\approx \pm 5\%$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$\approx \pm 14\%$

$\sin^2\theta_{13} < 0.056$ @ 3σ

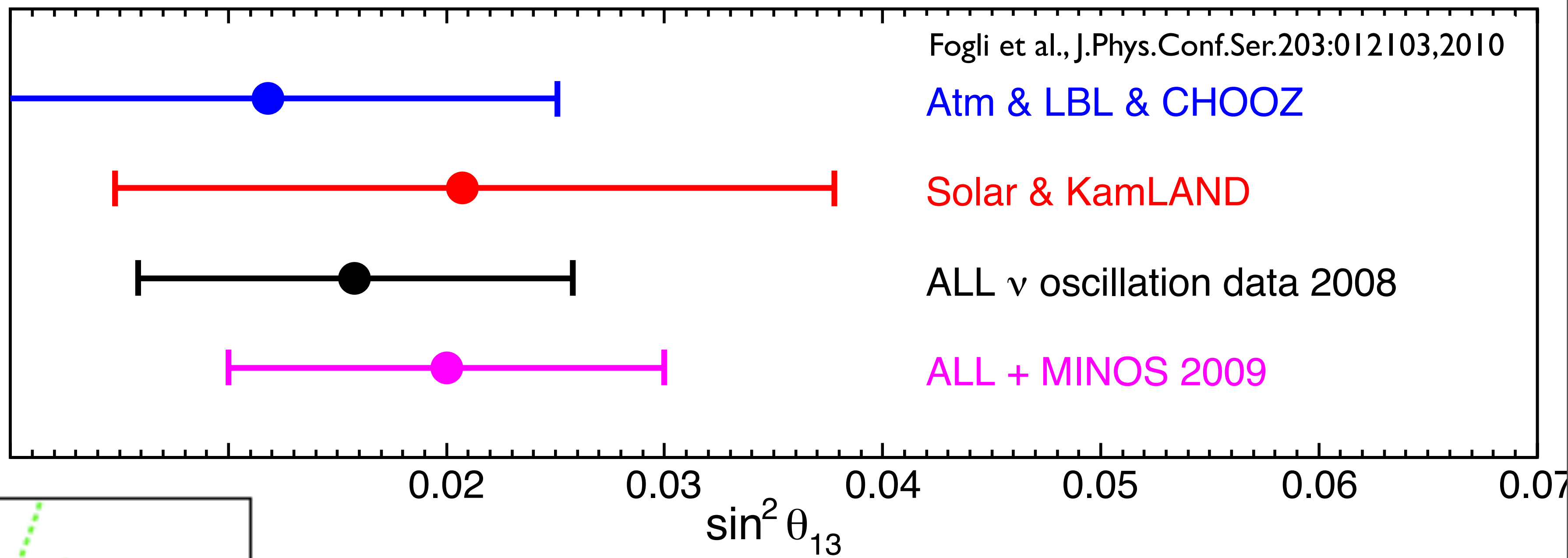
Schwetz, Tortola, Valle, New J.Phys.10:113011,2008

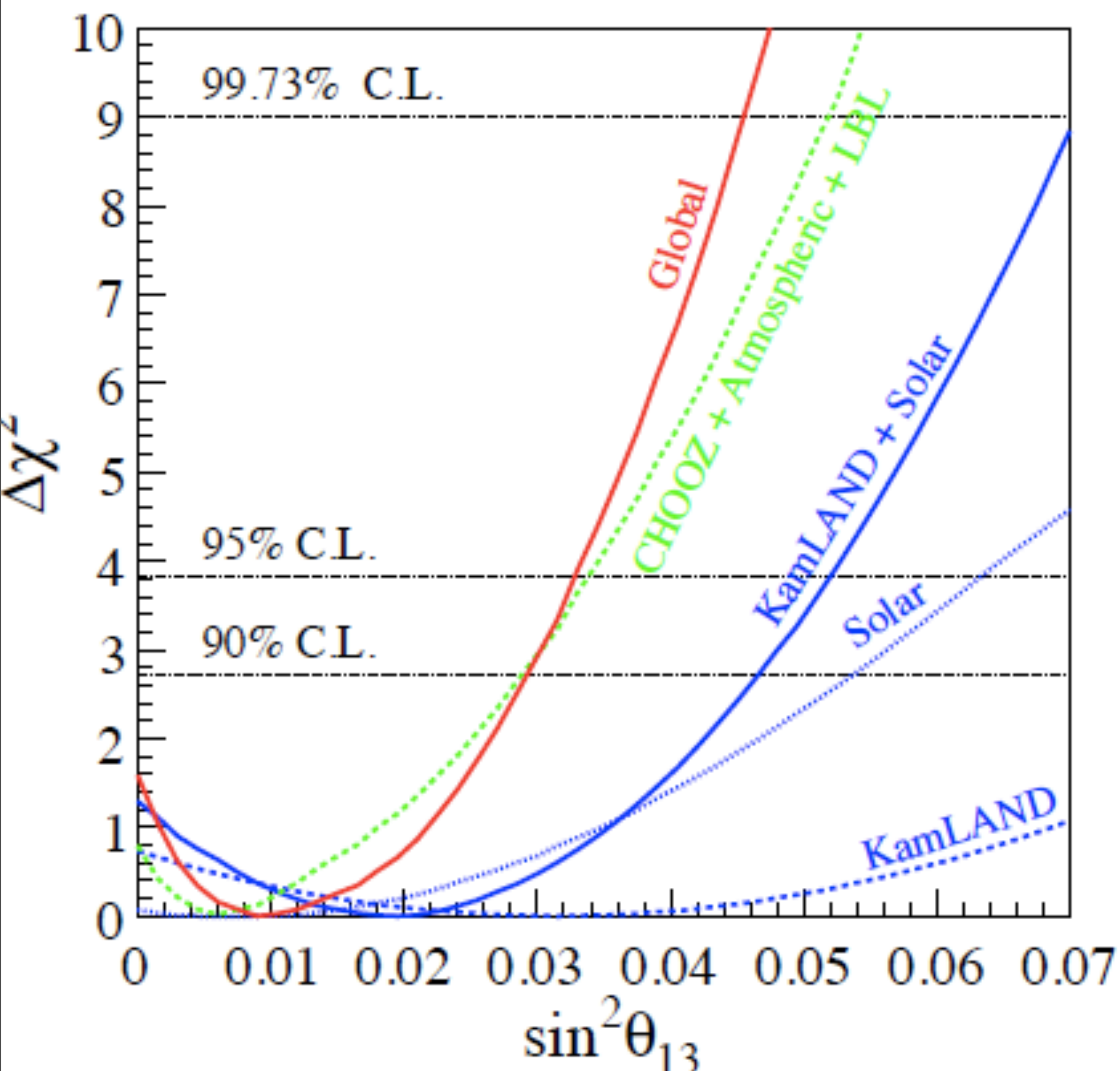
We haven't reached 1%-level...

What about δ ?

Global fits - indirect determination of θ_{13}

Hints !





$\theta_{13} \equiv 0$ hypothesis seems disfavored by combining all data

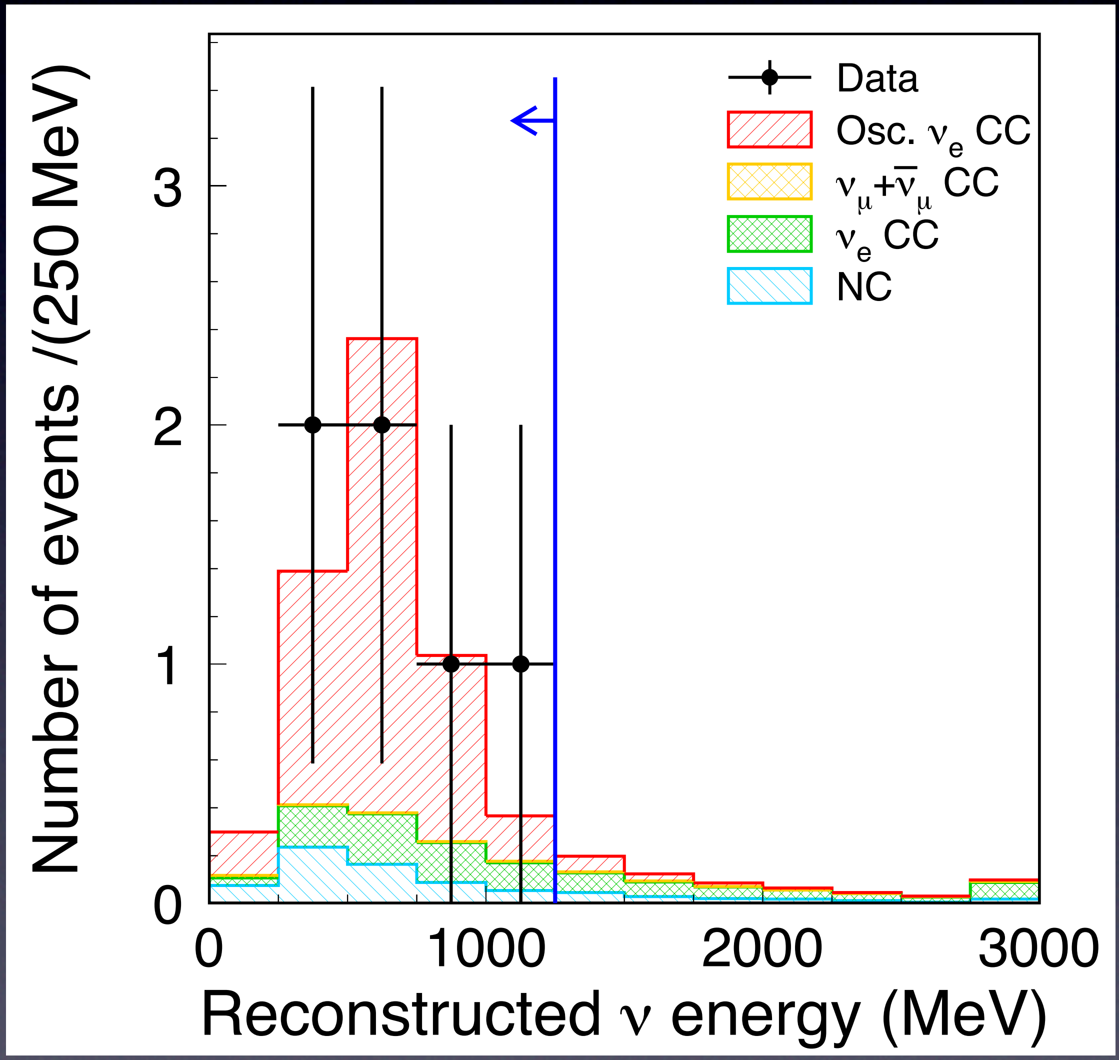
$$\sin^2\theta_{13} \approx 0.01 \div 0.02 \quad ?$$

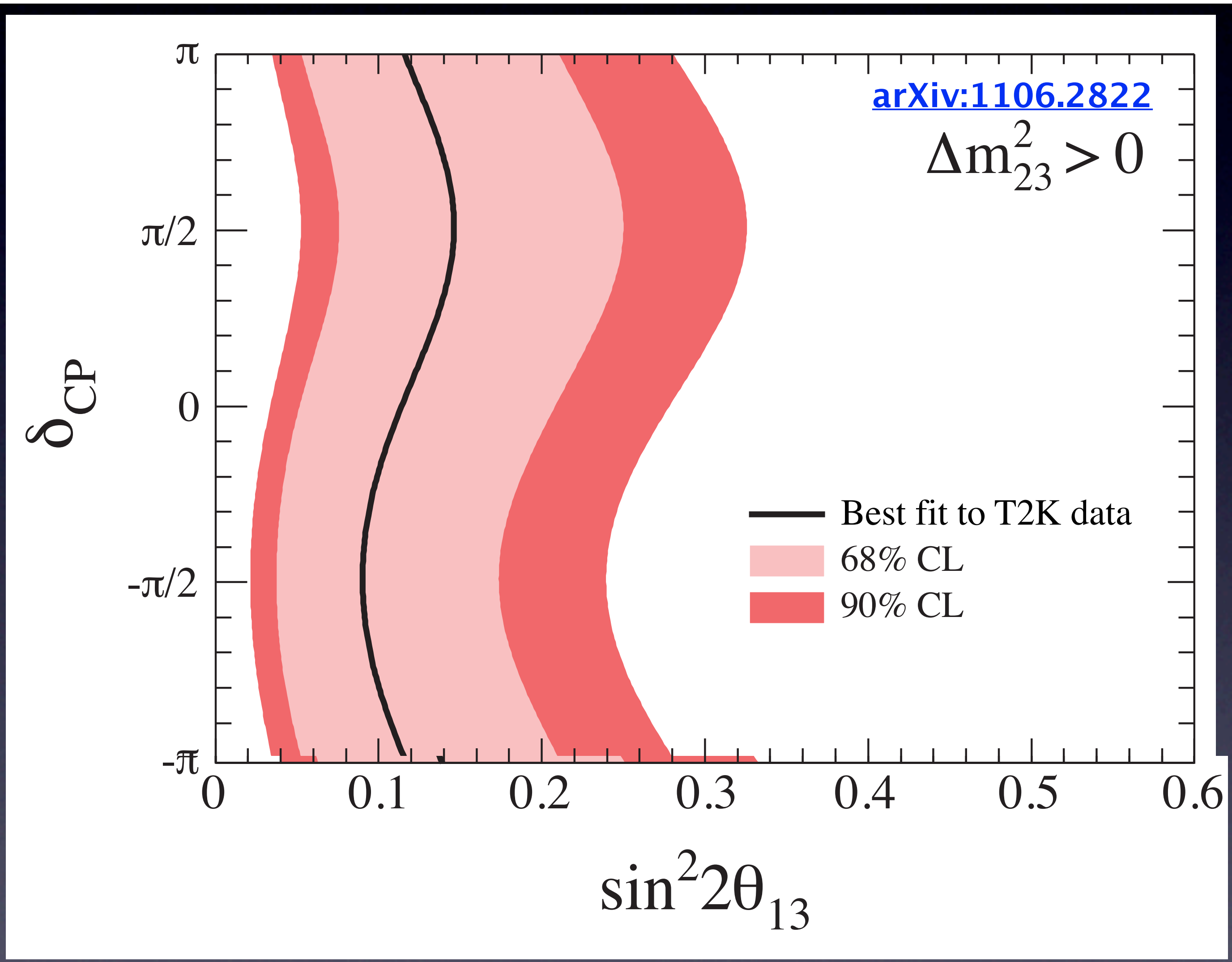
$$\sin^2 2\theta_{13} \approx 0.04 \div 0.08 \quad ?$$

Recent direct results on θ_{13}

T2K

- Expected number of candidates **1.5±0.3(syst.)**
- Observe: **6** events in the FD, a 2.5σ significance





Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)
0.8	0.6	0.1

For $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$: *90%C.L.*

$0.03 < \sin^2 2\theta_{13} < 0.28$ (best fit 0.11) normal

$0.04 < \sin^2 2\theta_{13} < 0.34$ (best fit 0.14) inverted

Implication for beam strategy

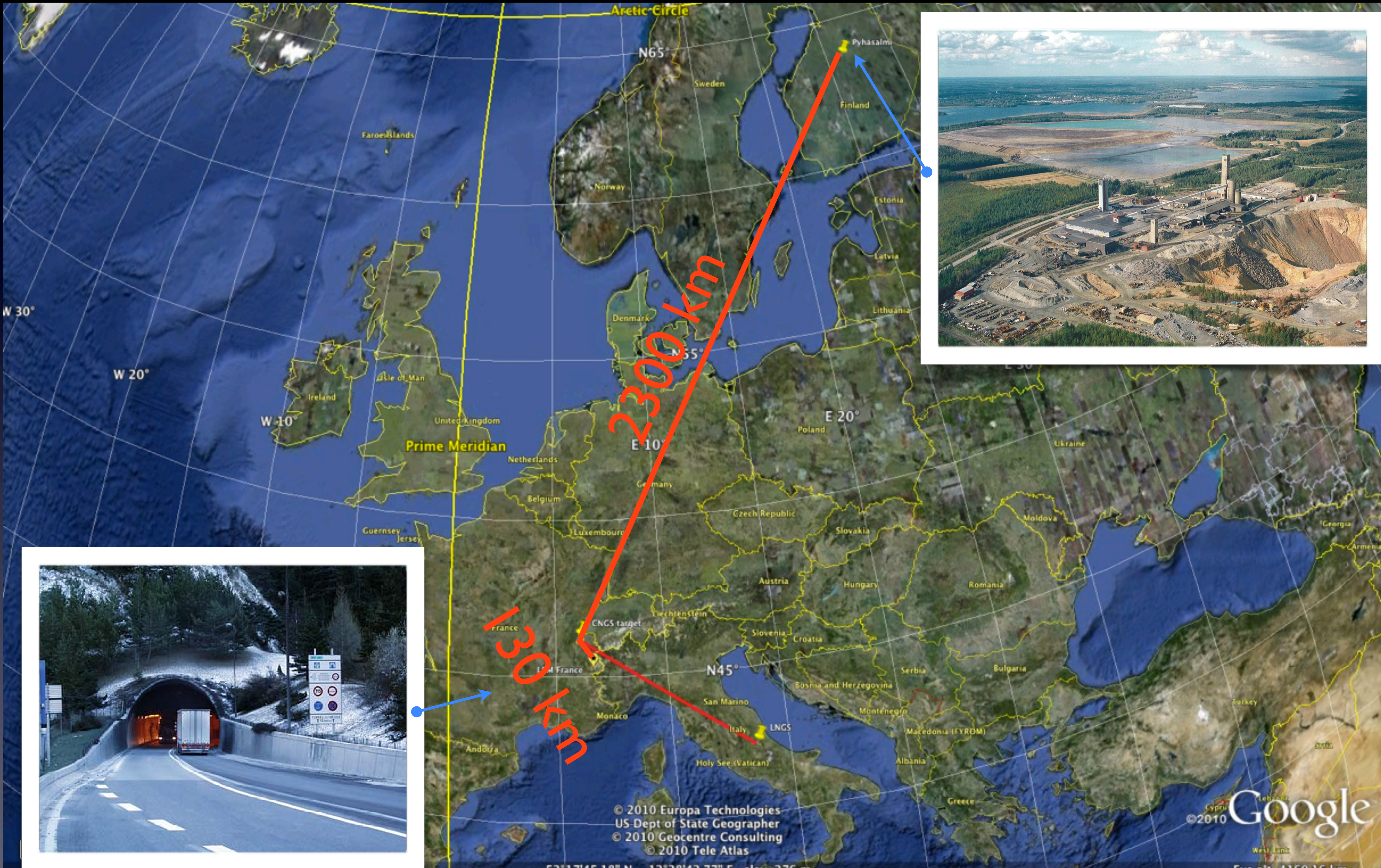
- **Use a conventional high energy beam**
  - Horn produced beam provides high intensity and flexibility in spectrum and energy.
  - Well understood technology (Van Der Meer 1963).
  - A small intrinsic contamination ν_e neutrinos O(≈1%).
  - Adequate performance if $\sin^2 2\theta_{13} > 0.01$

→LAGUNA-LBNO

- **Try to produce a very pure beam**
  - Important requirement if $\sin^2 2\theta_{13} << 0.01$
  - Make beam from decays of muons (neutrino factory)
  - Make beam from decays of accelerated unstable isotopes (betabeam)
  - These technologies are in infancy. How well are they understood ? do we need a "demonstrator" ?
  - [Must find $$$.]

→EuroNU

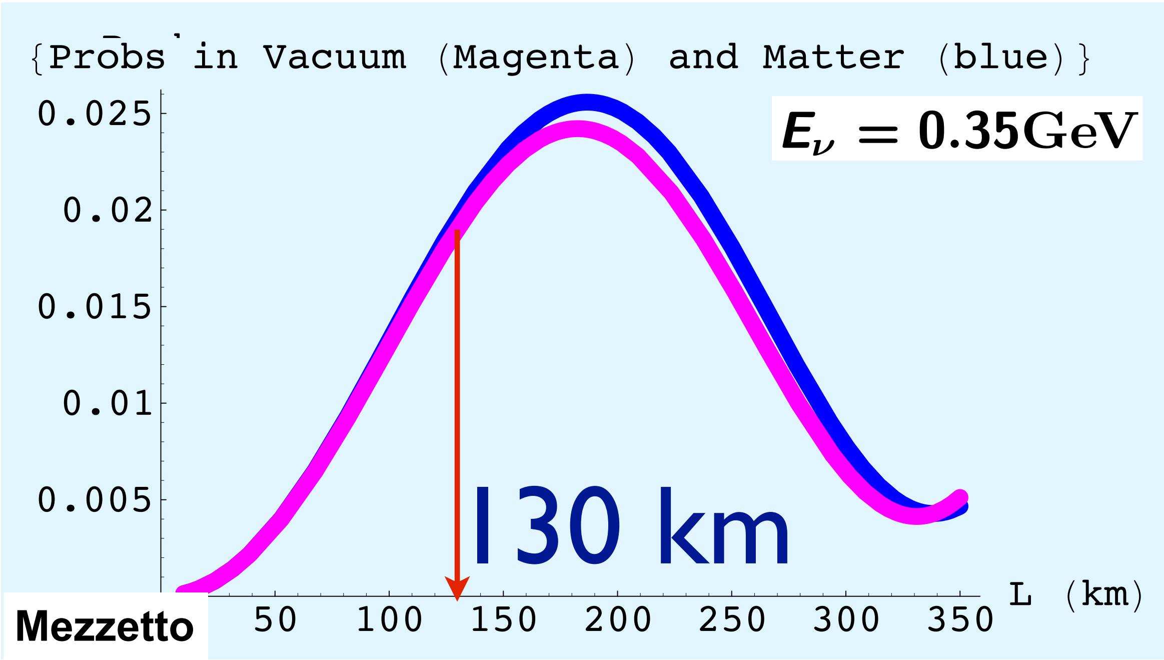
Very short/long baseline concept

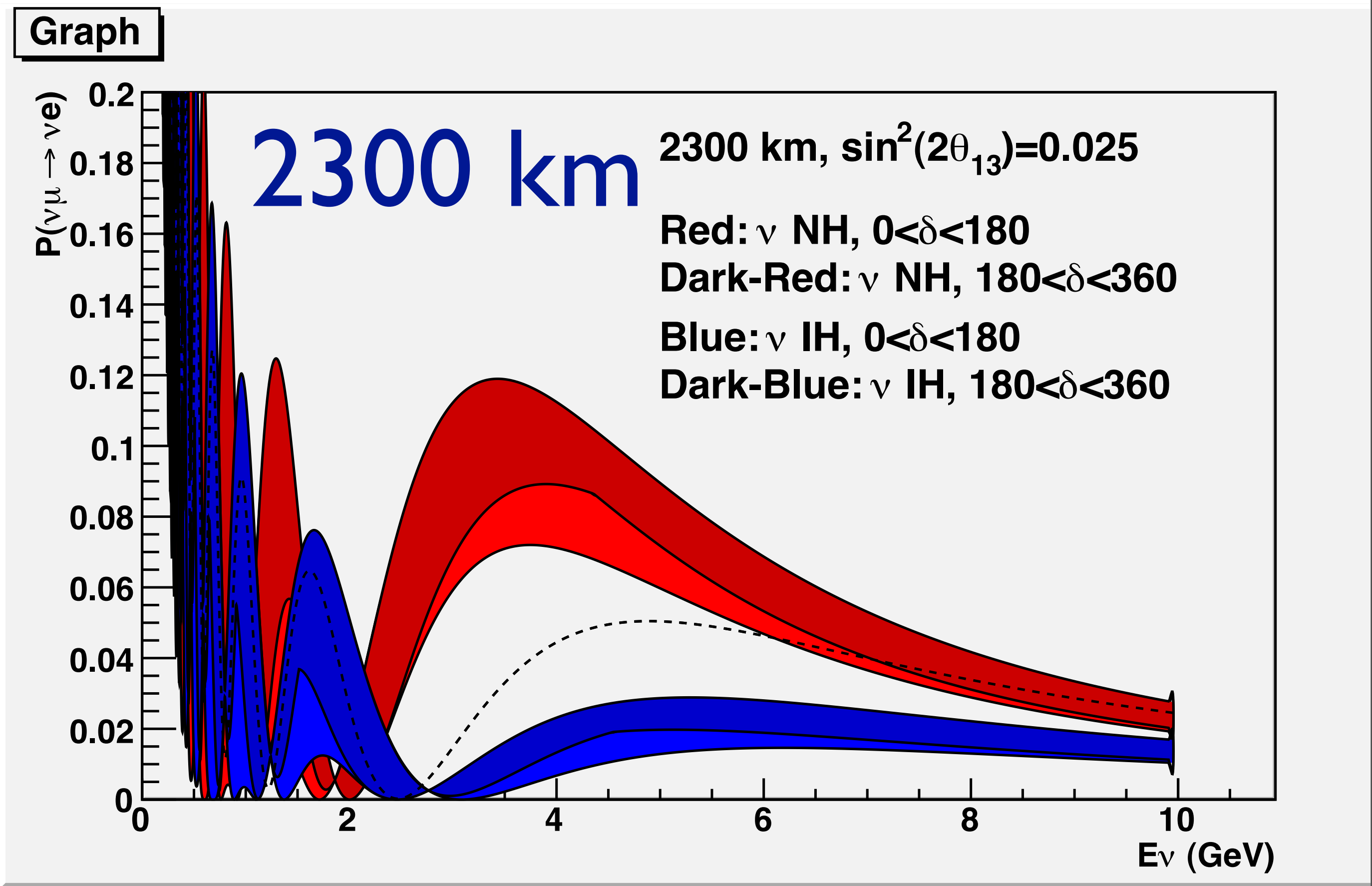


Very short/long baseline concept

CERN-Fréjus offers a very short baseline not considered elsewhere in the world ➠ unique physics opportunities in Europe

CERN-Pyhäsalmi offers a very long baseline not considered elsewhere in the world ➠ unique physics opportunities in Europe





Determine CPV by comparison of neutrinos/ antineutrinos in absence of competing matter effects

need very low energy beam and huge detector

Adequate baseline/energy for betabeam

Determine CPV and mass hierarchy by spectrum measurement and resolve degeneracies and so-called "π-transit" effect

arXiv:0908.3741v1 for "Magic distance"

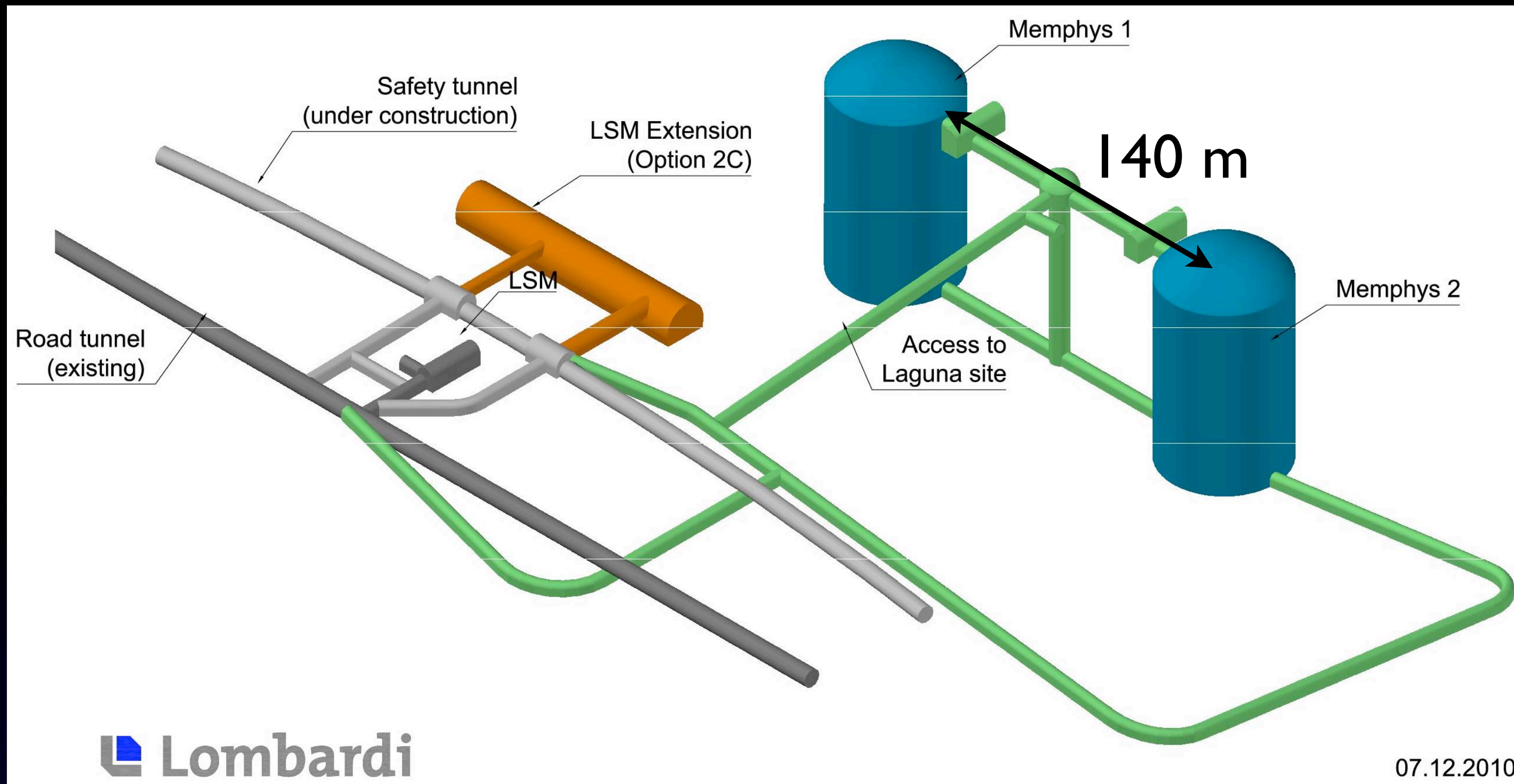
Adequate baseline for neutrino factory

Fréjus - Large extension Modane

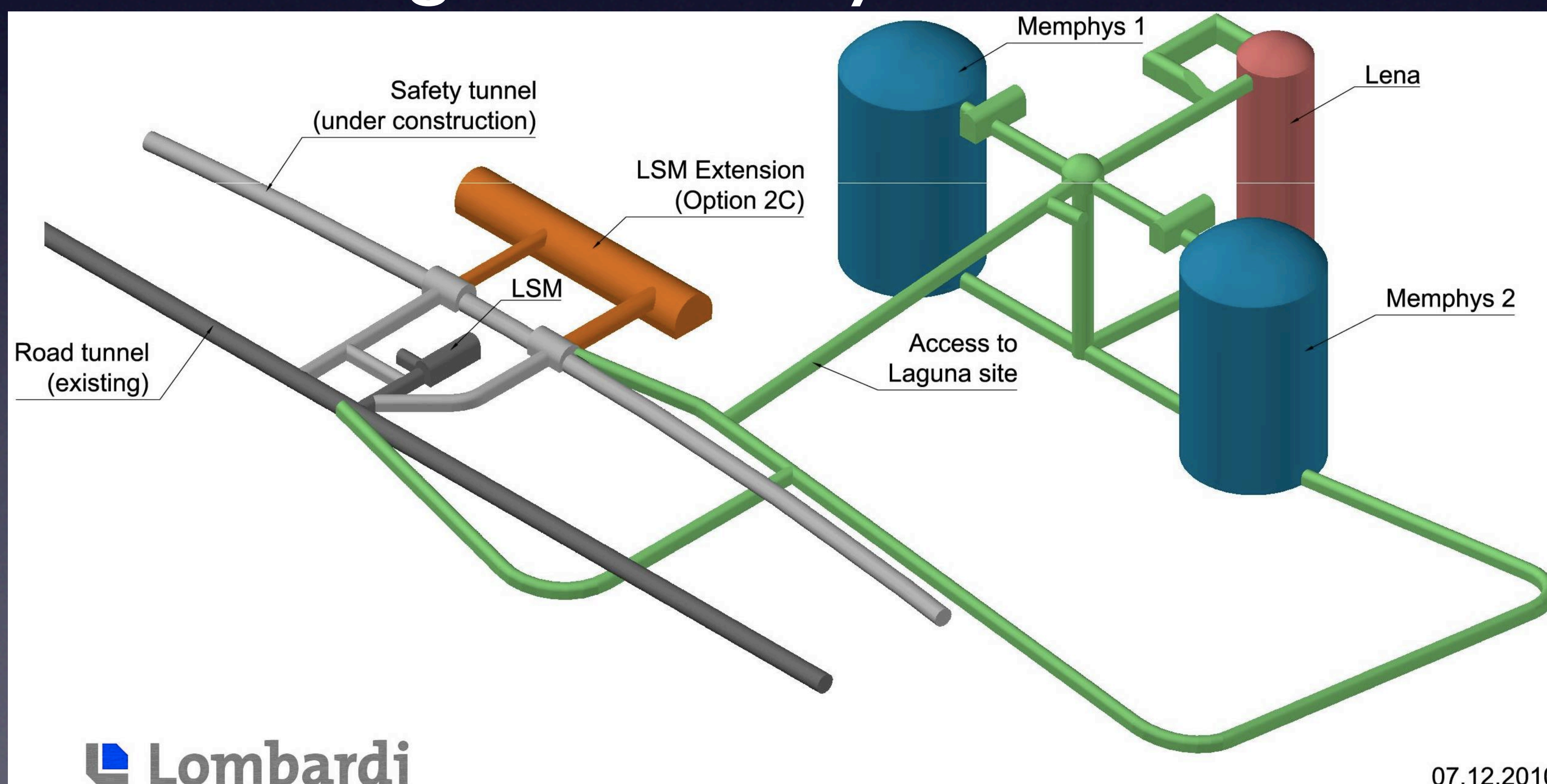
Road tunnel located at 45°08' N, 6°41' E

(from LAGUNA deliverables 2.2&2.8)

1. **The deepest location considered in LAGUNA, thanks to the excellent quality of the rock, with the appropriate amount of plasticity, it allows the excavation of very large cavities at a depth of 4800 mwe.**
2. **The most viable location for the MEMPHYS detector, although the other two proposed options GLACIER and LENA can also be considered, pending safety approval.**
3. **Known rock conditions thanks to the existence of the highway and railway tunnel excavations. Rock temperature: warm, about 28ºC.**
4. **Dedicated, horizontal access: The Fréjus safety tunnel, presently under construction (8 meters in diameter), will provide a dedicated and optimal access to the LAGUNA site.**
5. **Lifetime access and tunnel infrastructure maintenance: expected with the roadway tunnel operation for at least several decades.**
6. **Laboratoire Souterain de Modane** (LSM) has a thirty years of experience in conducting underground scientific experiments.

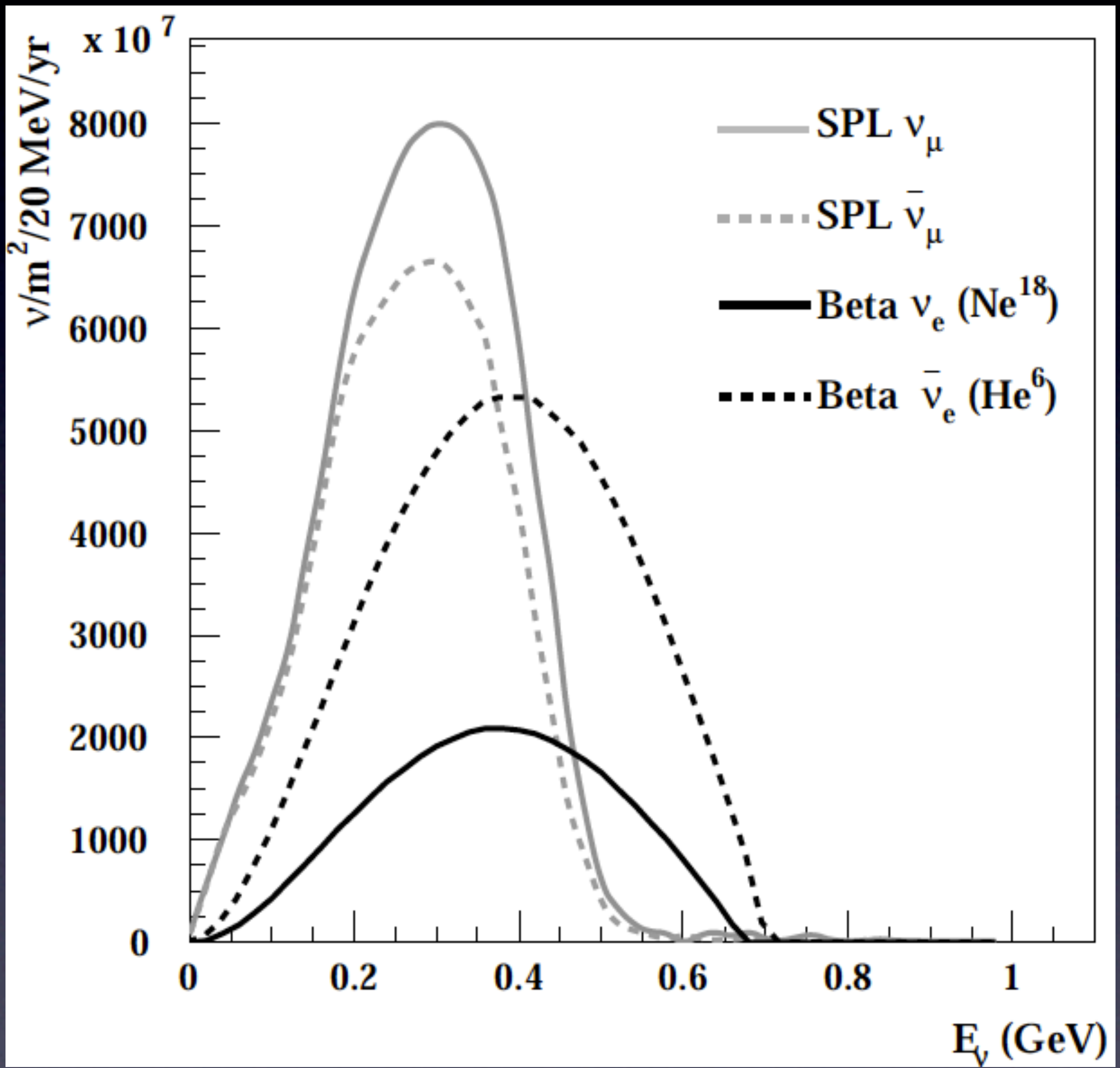


Investigation of a hybrid detector:

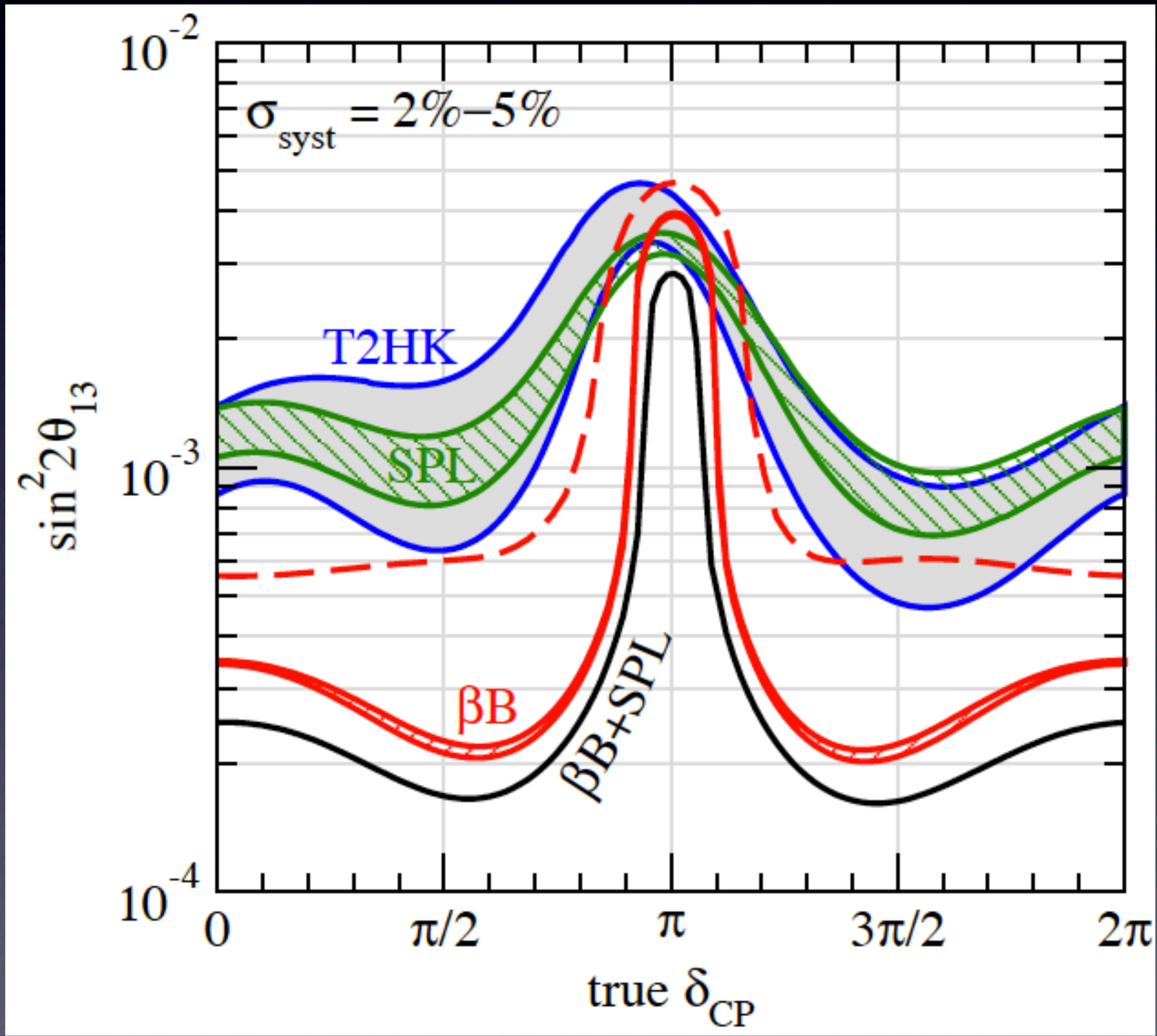


Very high power low energy beams

SUPER-BEAMS BETA-BEAMS



Optimal approach if $\sin^2 2\theta_{13} < 0.01$



Based on CERN HP-SPL (>2025)

Pyhäsalmi Mine - Pyhäjärvi town

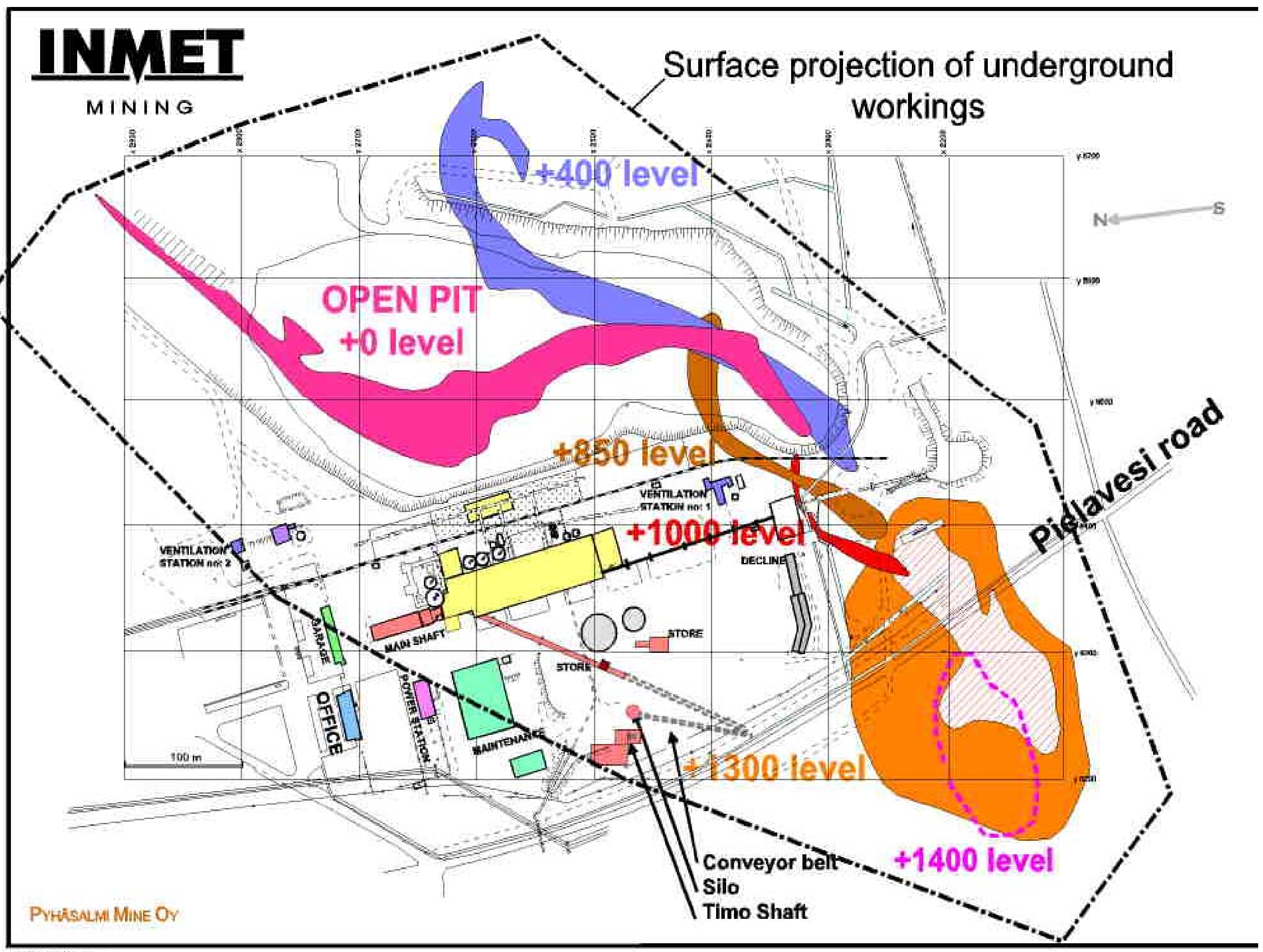
Operating mine located at 63º 39' N, 26º 02' E

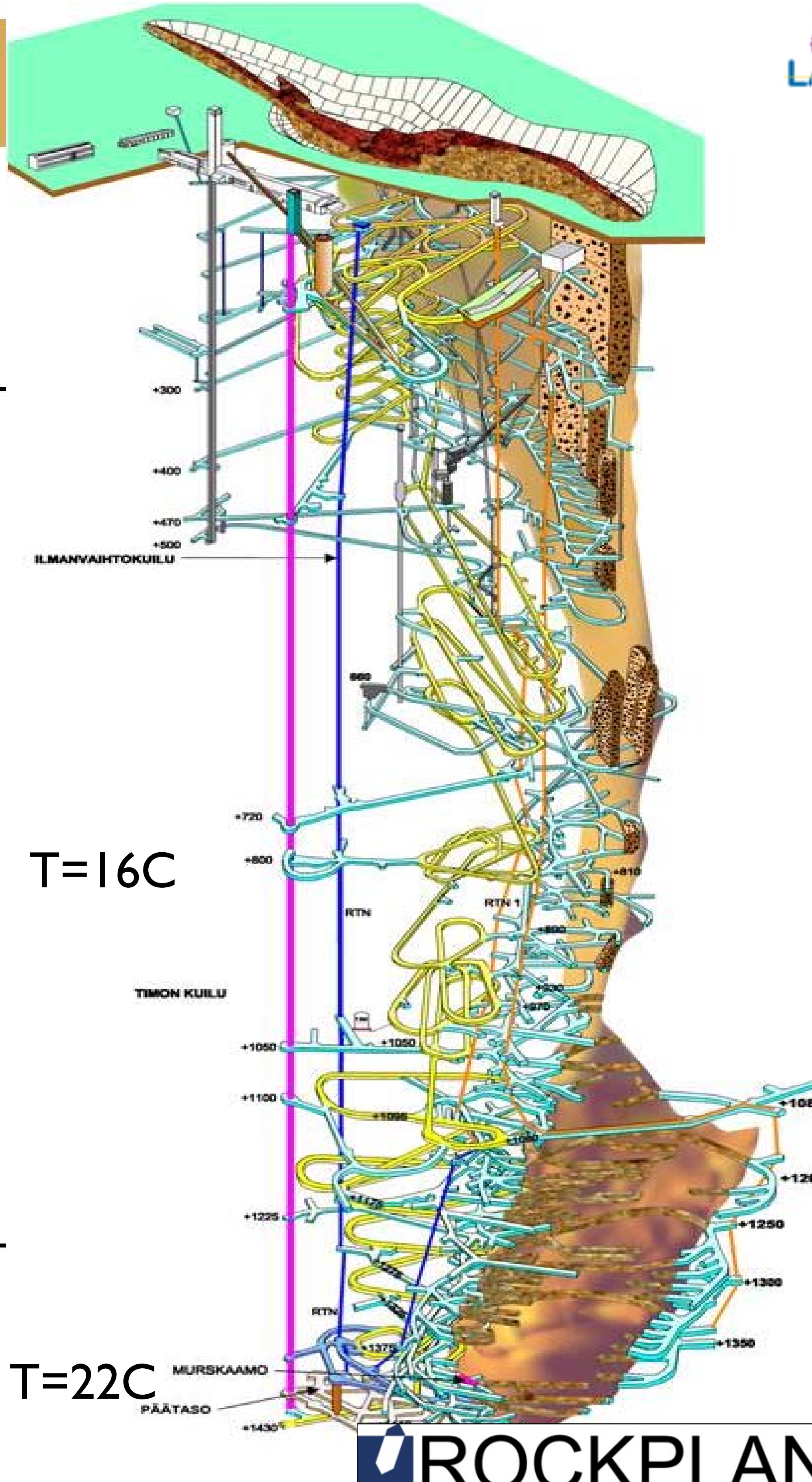
(from LAGUNA deliverables 2.1&2.8)

1. **Excellent rock and dry conditions allow hosting of all LAGUNA detector options** (GLACIER, MEMPHYS, LENA), possibly at once, each at the required depth. Rock temperature: cool, less than 22º C.
2. **The most modern and efficient mine of its type** with uniquely small footprint of the excavation area. The fact that the ore is surrounded by high quality rock **eliminates the need for extended network of tunnels**.
3. **Offers two modes of access:** via a vertical shaft leading directly from the loading zone to the detector, and via a decline access tunnel. No other site offers this feature.
4. **Has excellent safety record**.
5. **The mine owner has signed the memorandum of understanding** concerning LAGUNA.
6. **Centre for Underground Physics in Pyhäsalmi** (CUPP) has a decade of experience in conducting scientific experiments in the mine.

KALLIOSUUNNITTELU OY
ROCKPLAN LTD

3-D impression of Pyhäsalmi mine





Nuijten 03-03-2011

Pyhälsalmi layout

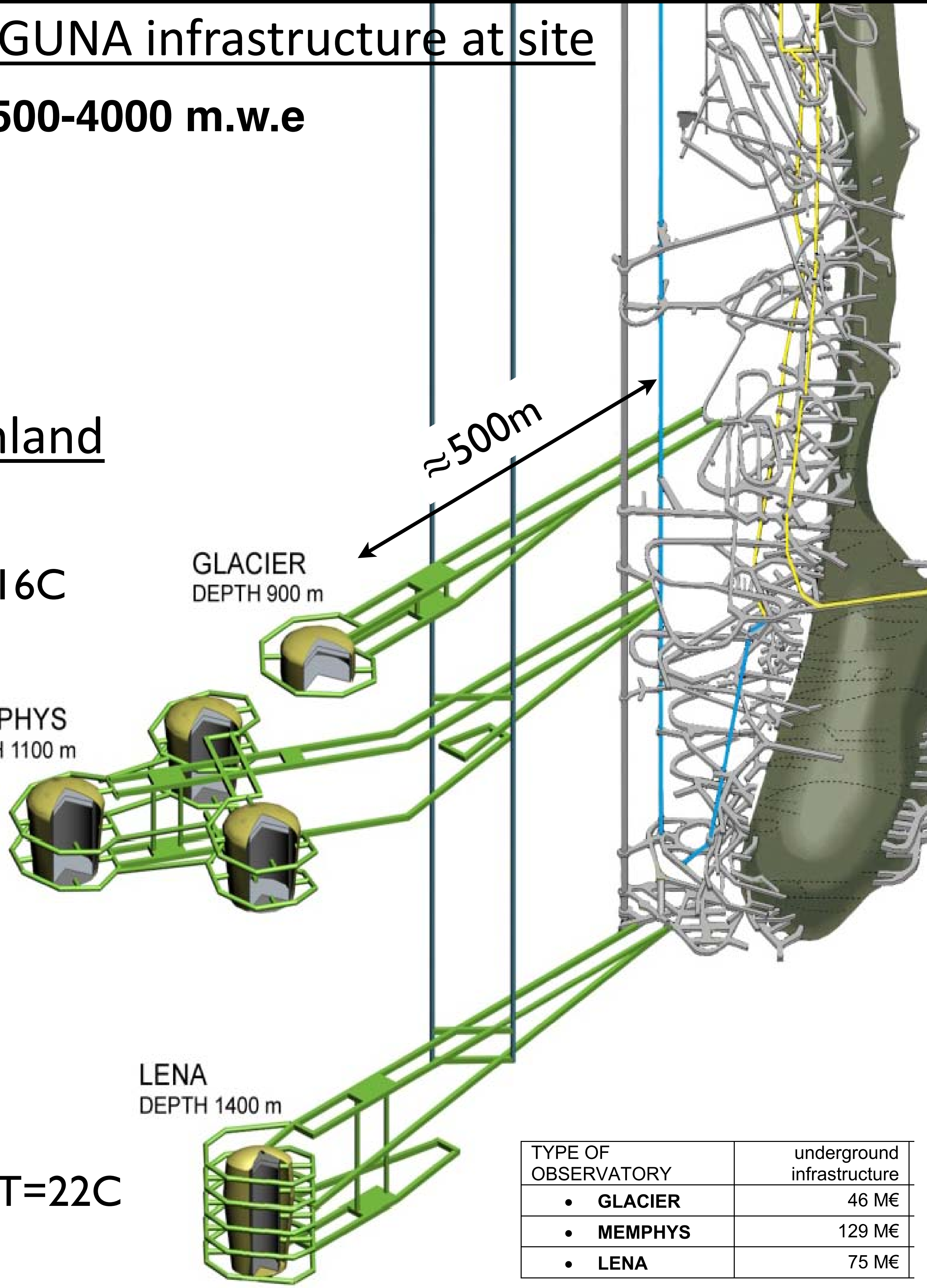
LAGUNA infrastructure at site

2500-4000 m.w.e

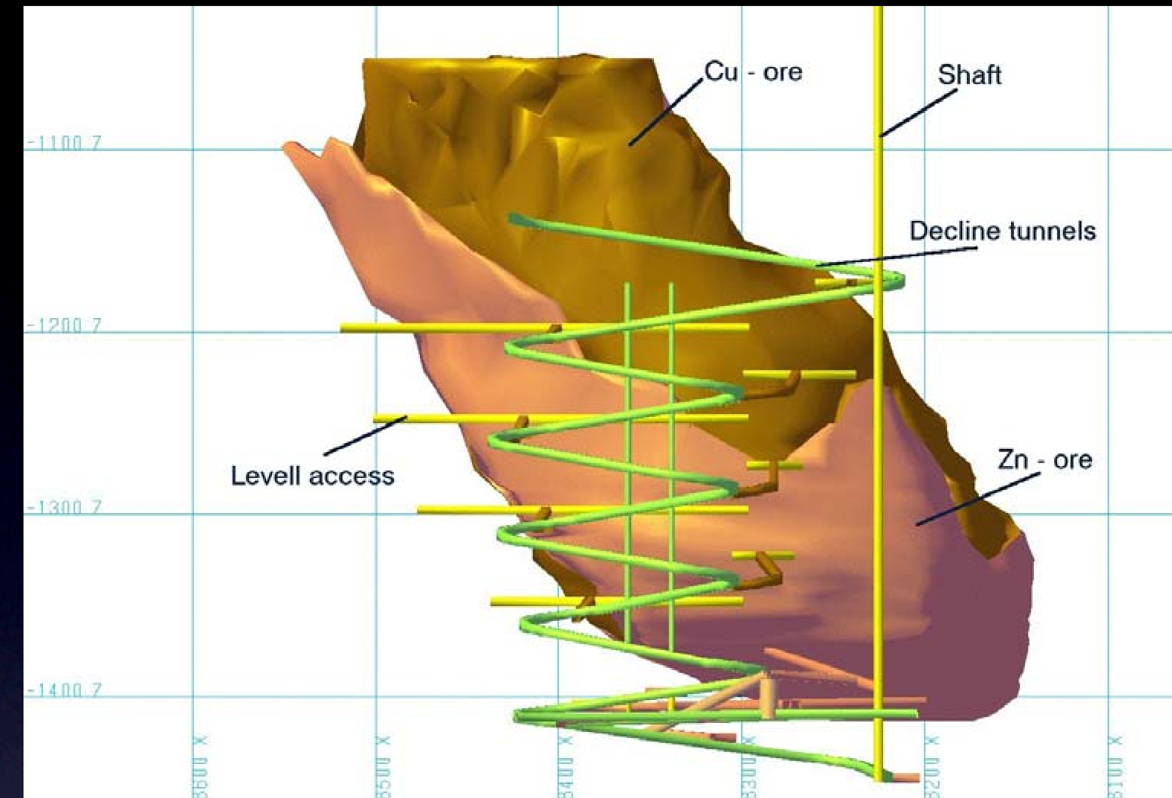
Finland

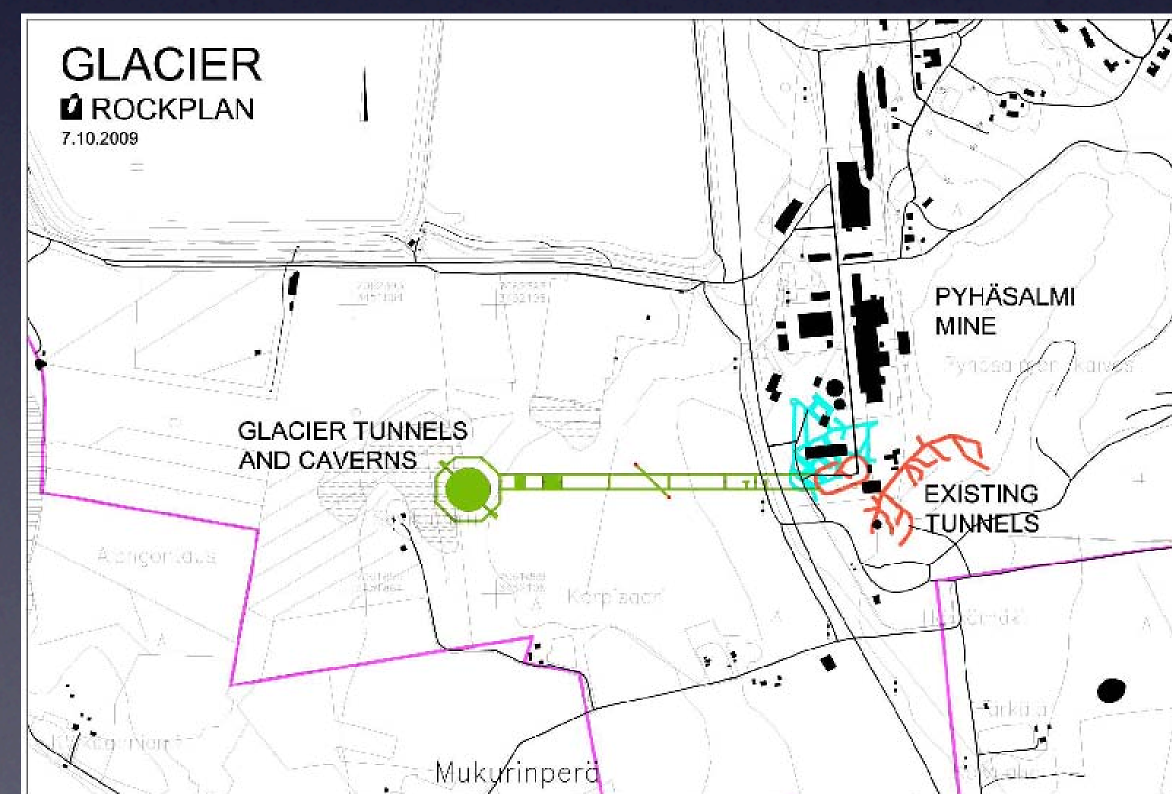
T=16C

T=22C



TYPE OF OBSERVATORY	underground infrastructure
• **GLACIER**	46 M€
• **MEMPHYS**	129 M€
• **LENA**	75 M€





Cosmic Ray experiment EMMA at shallow depth

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

Cafeteria, meeting room and sauna at 1400 m below ground

Mobile phones work and internet available also at 1400 m

Unique features of Pyhäsalmi

Distance from HEP labs

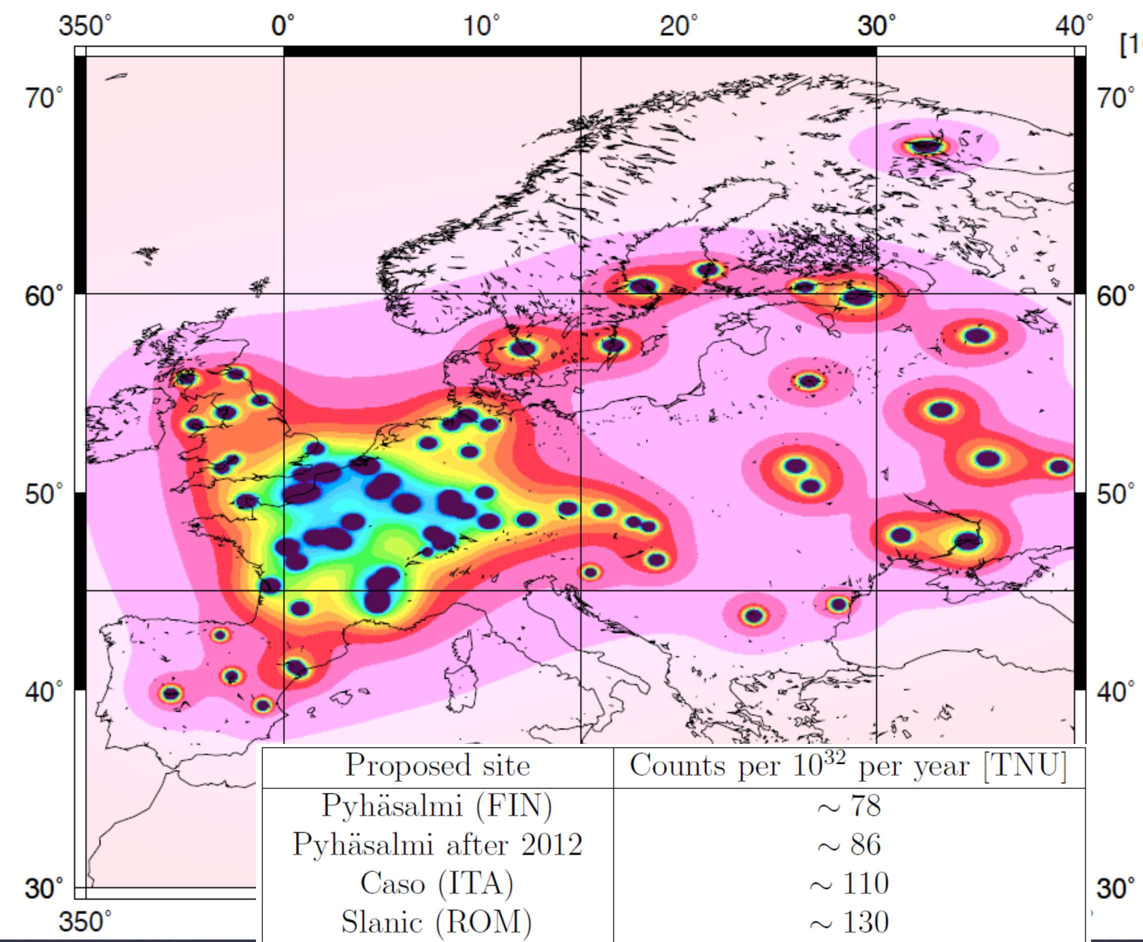
2540 km – bimagic value (feasible)
7250 km – magic value (not yet)

Location Baseline (km)	CERN 2540	J-PARC 7250	Fermilab 7250
Pyhäsalmi	2290 (90%)	7090 (98%)	6630 (91%)
Boulby	1050 (41%)	8480 (117%)	5980 (82%)
Canfranc	650 (26%)	9280 (128%)	6550 (90%)
Frejus	130 (5%)	8900 (123%)	6840 (94%)
Sieroszowice	940 (37%)	8180 (113%)	6960 (96%)
Slanic	1540 (61%)	8150 (112%)	7780 (107%)
Umbria	670 (26%)	8850 (122%)	7300 (101%)

•CERN-Pyhäsalmi offers a very long baseline of 2300km, very close to the bimagic value, not considered elsewhere in the world ➠ unique physics opportunity in Europe

•With distances of 2300 km from CERN and approximately 7000 km from both KEK/JPARC and FNAL, the Pyhäsalmi site offers a potential far detector location for an eventual neutrino factory based programme.

Reactors flux

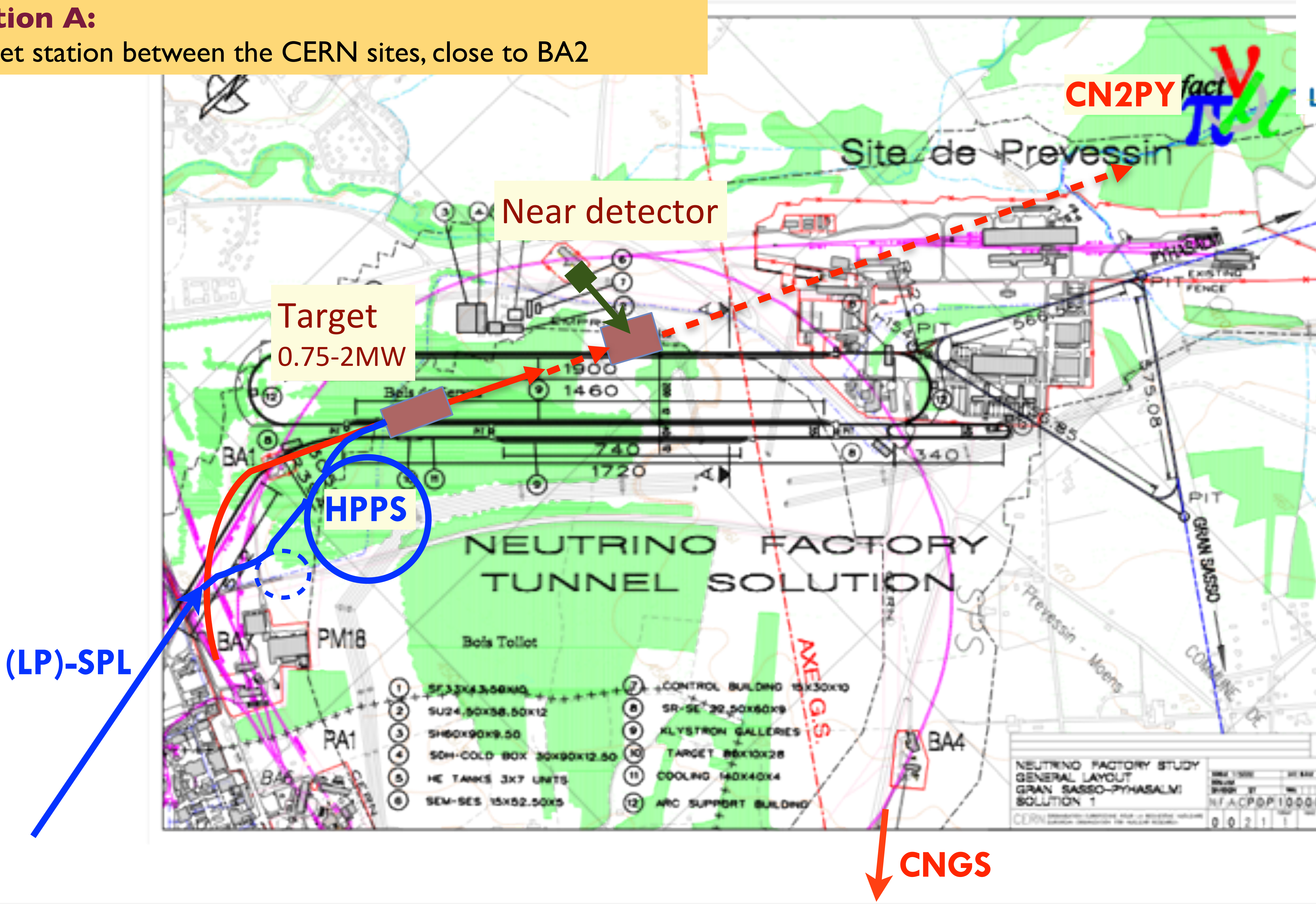


Proposed site	Counts per 10^{32} per year [TNU]
Pyhäsalmi (FIN)	~ 78
Pyhäsalmi after 2012	~ 86
Caso (ITA)	~ 110
Slanic (ROM)	~ 130
Sieroszowice (POL)	~ 200
Canfranc (ESP)	~ 300
Frejus (FRA)	~ 700
Boulby (GBR)	~ 1600
Boulby w/o Hartlepool	~ 280

•Pyhäsalmi offers the lowest reactor neutrino background in Europe, important for the observation of geo-neutrinos

CERN ν-beam to Pyhasalmi - CN2PY

Option A:
Target station between the CERN sites, close to BA2



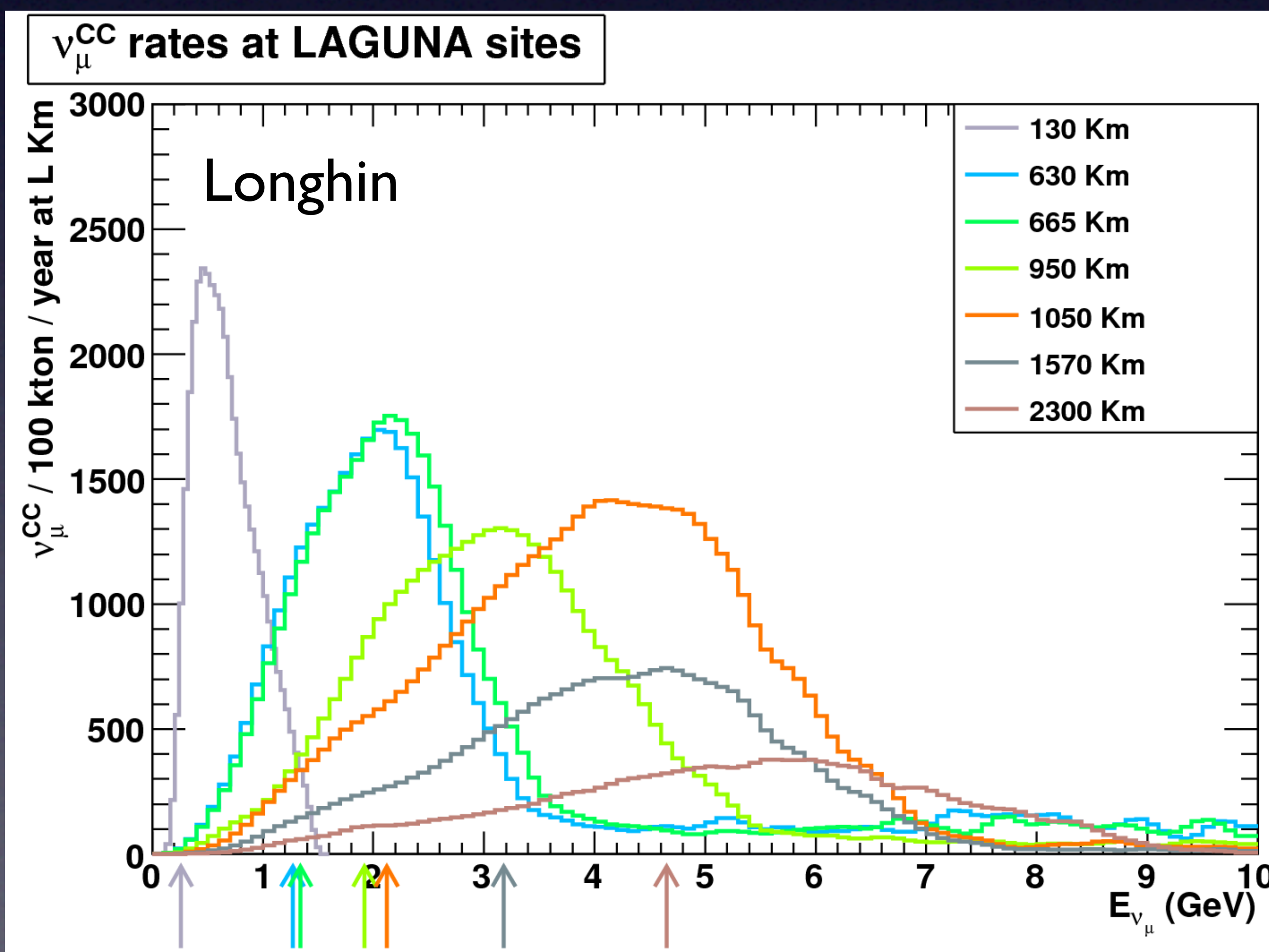
Electron appearance signal

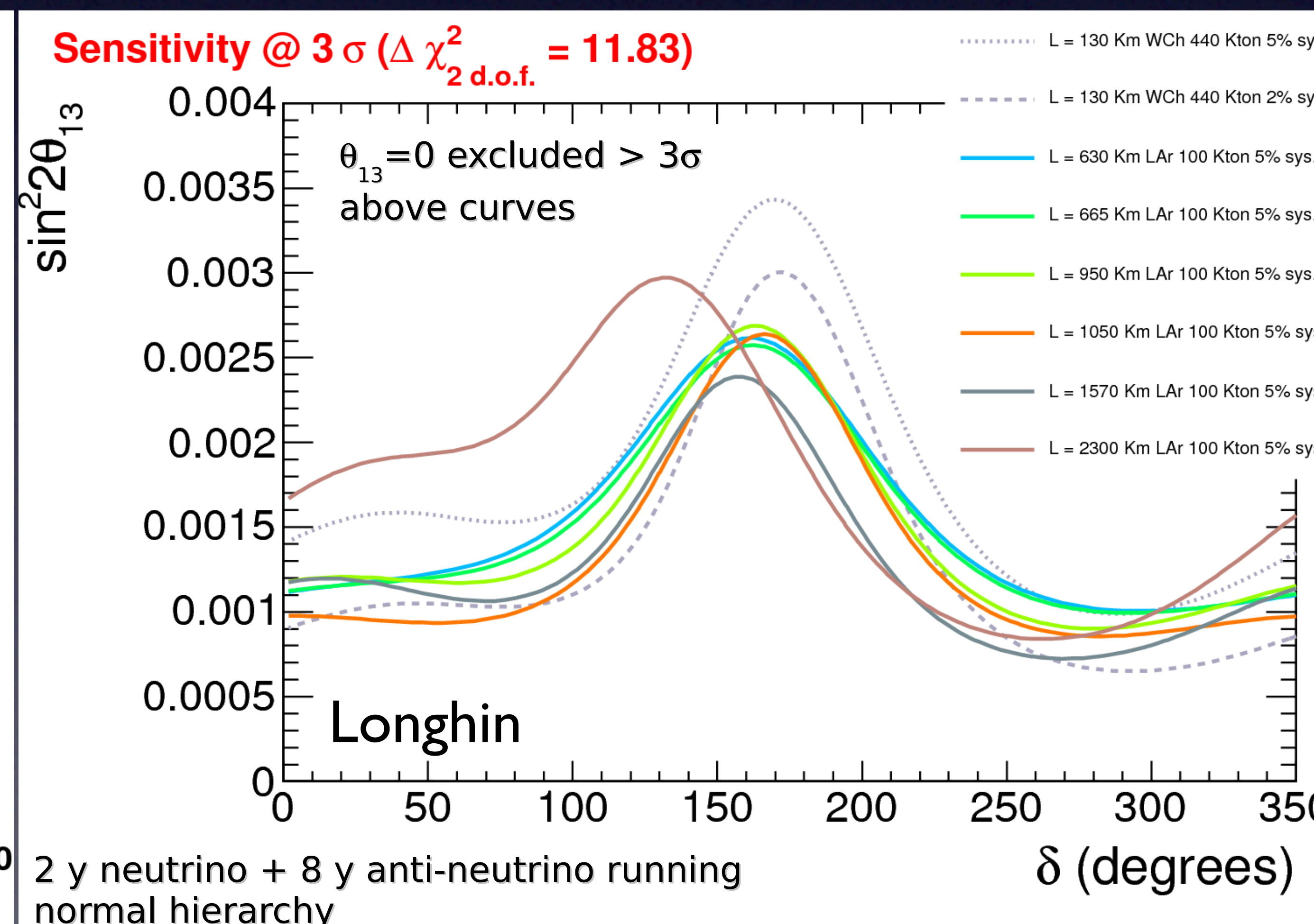
Horn focusing optimized for each LAGUNA baseline in order to maximize sensitivity to θ_{13}

Event rate per year:
100 kton LAr
50 GeV protons
3×10^{21} pots/yr
1.6 MW

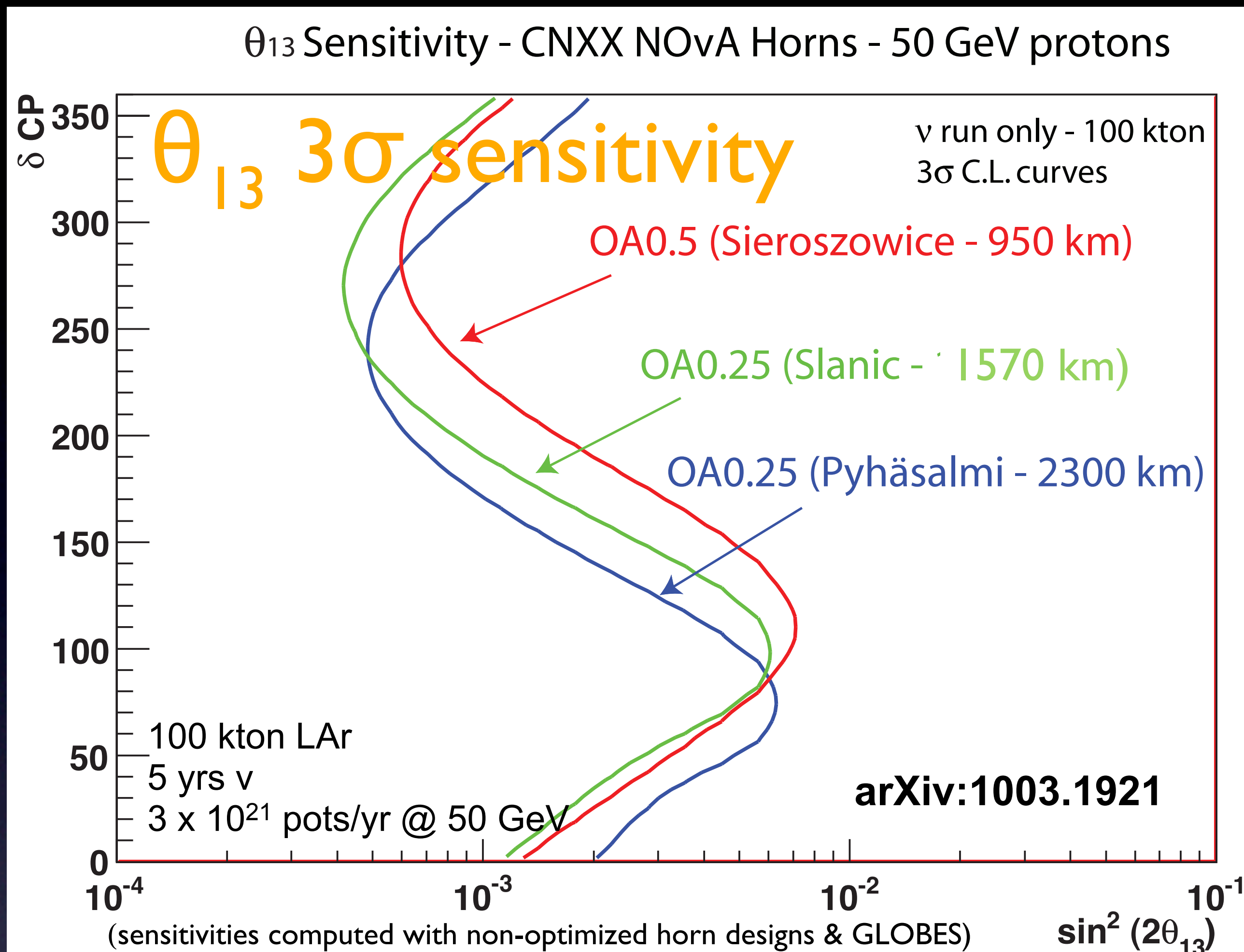
	ν run			$\bar{\nu}$ run		
L (km)	$\nu_\mu^{CC}(\bar{\nu}_\mu^{CC})$	$\nu_e^{CC}(\bar{\nu}_e^{CC})$	$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$ (%)	$\nu_\mu^{CC}(\bar{\nu}_\mu^{CC})$	$\nu_e^{CC}(\bar{\nu}_e^{CC})$	$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$ (%)
130	41316 (94)	174 (2)	0.42	527 (5915)	12 (15)	0.42
630	36844 (2903)	486 (95)	1.5	7930 (13652)	270 (157)	2.0
665	38815 (2967)	516 (96)	1.5	7516 (14287)	280 (158)	2.0
950	37844 (1363)	349 (48)	1.0	3504 (14700)	110 (107)	1.3
1050	51787 (761)	314 (23)	0.64	1964 (21728)	54 (88)	0.60
1570	26785 (385)	174 (10)	0.67	945 (11184)	22 (47)	0.57
2300	17257 (203)	110 (7)	0.67	471 (7577)	16 (32)	0.60

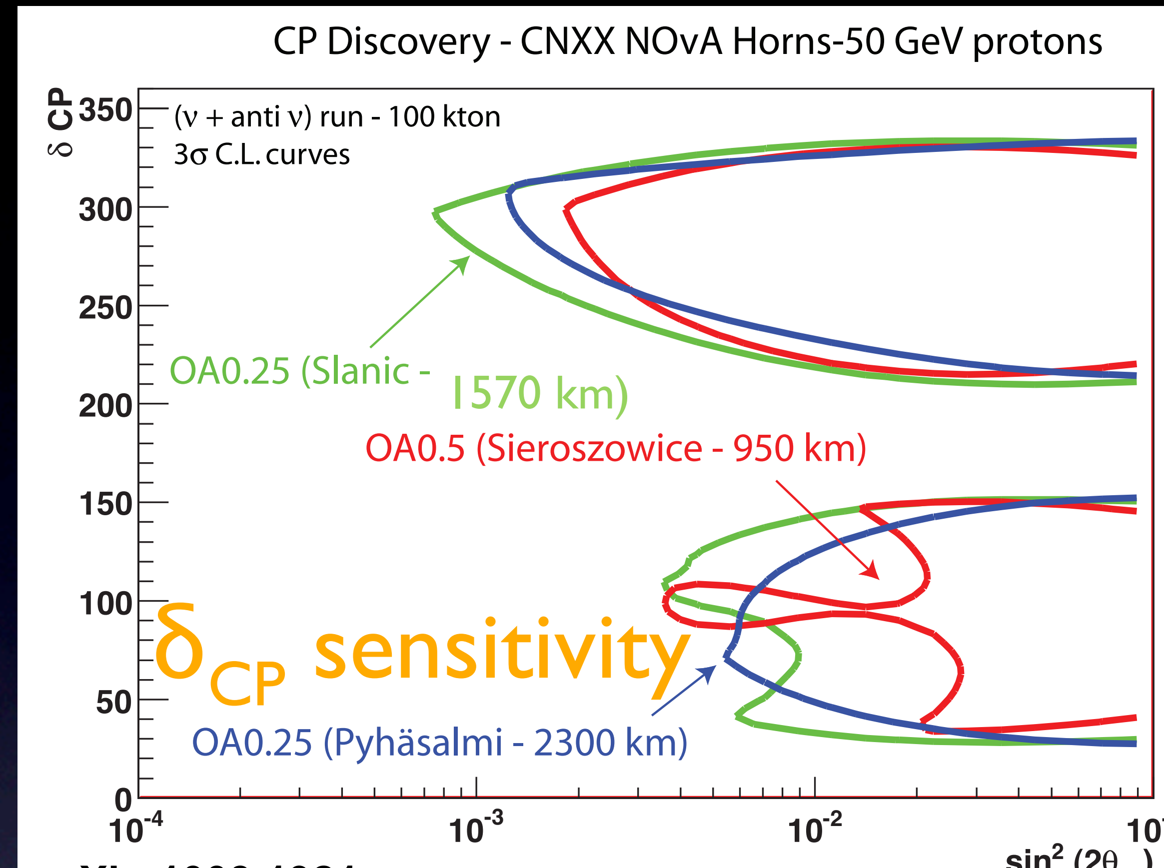
$\Phi \sim 1/L^2$
$\sigma \sim E$
$S \sim \Phi\ \sigma \sim 1/L$
$B \sim 1/L^2$
$S/\sqrt{B} \sim (1/L)/\sqrt{(1/L^2)} \sim O(1)$



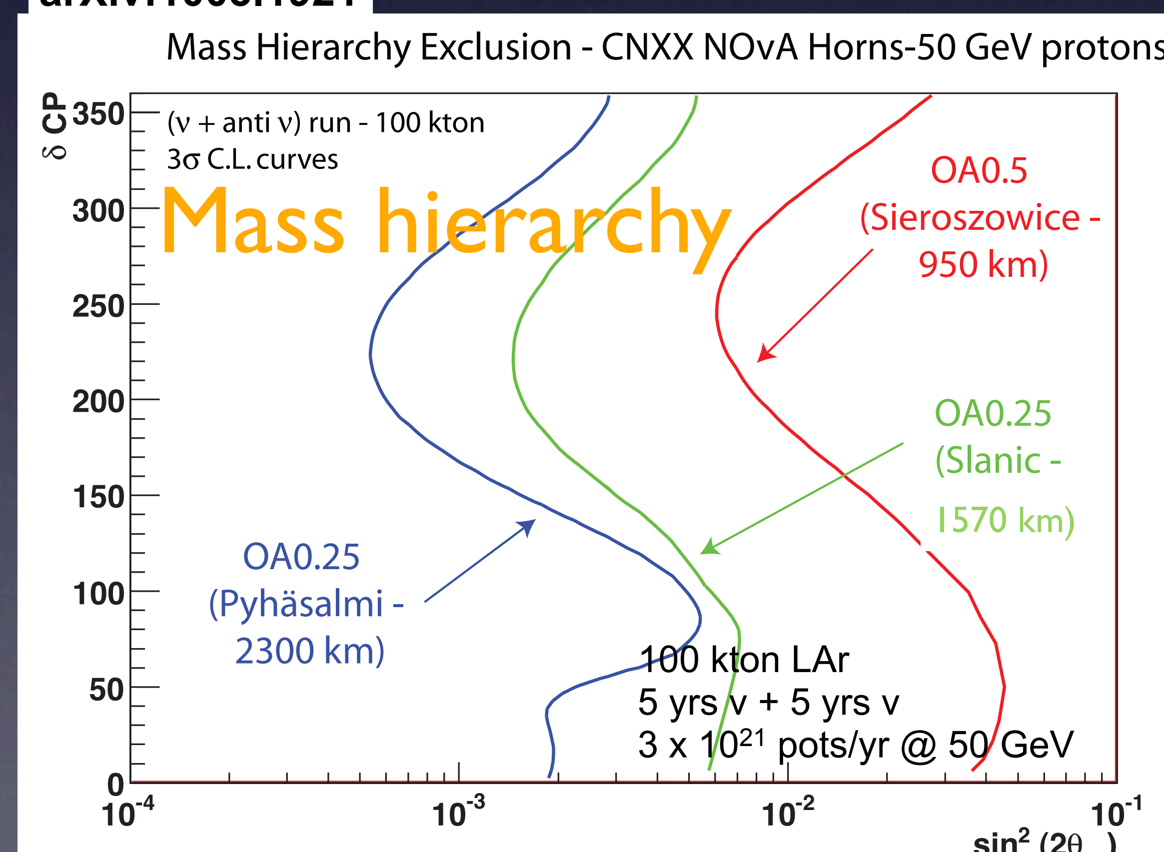


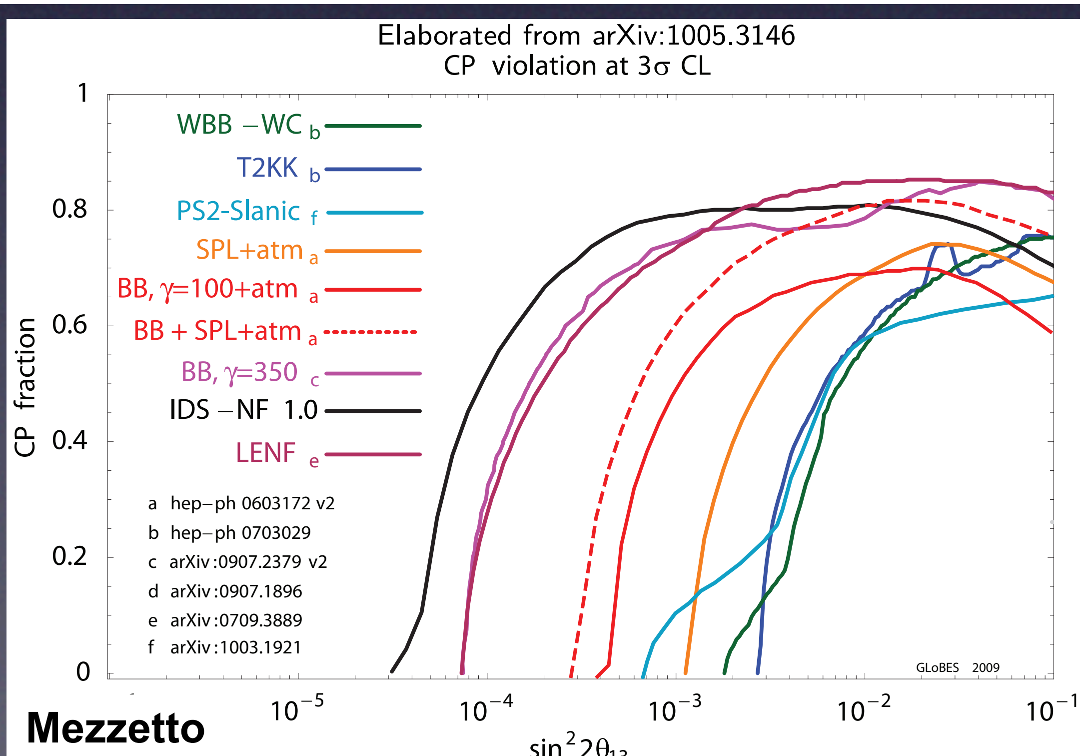
Ultimate oscillation sensitivities





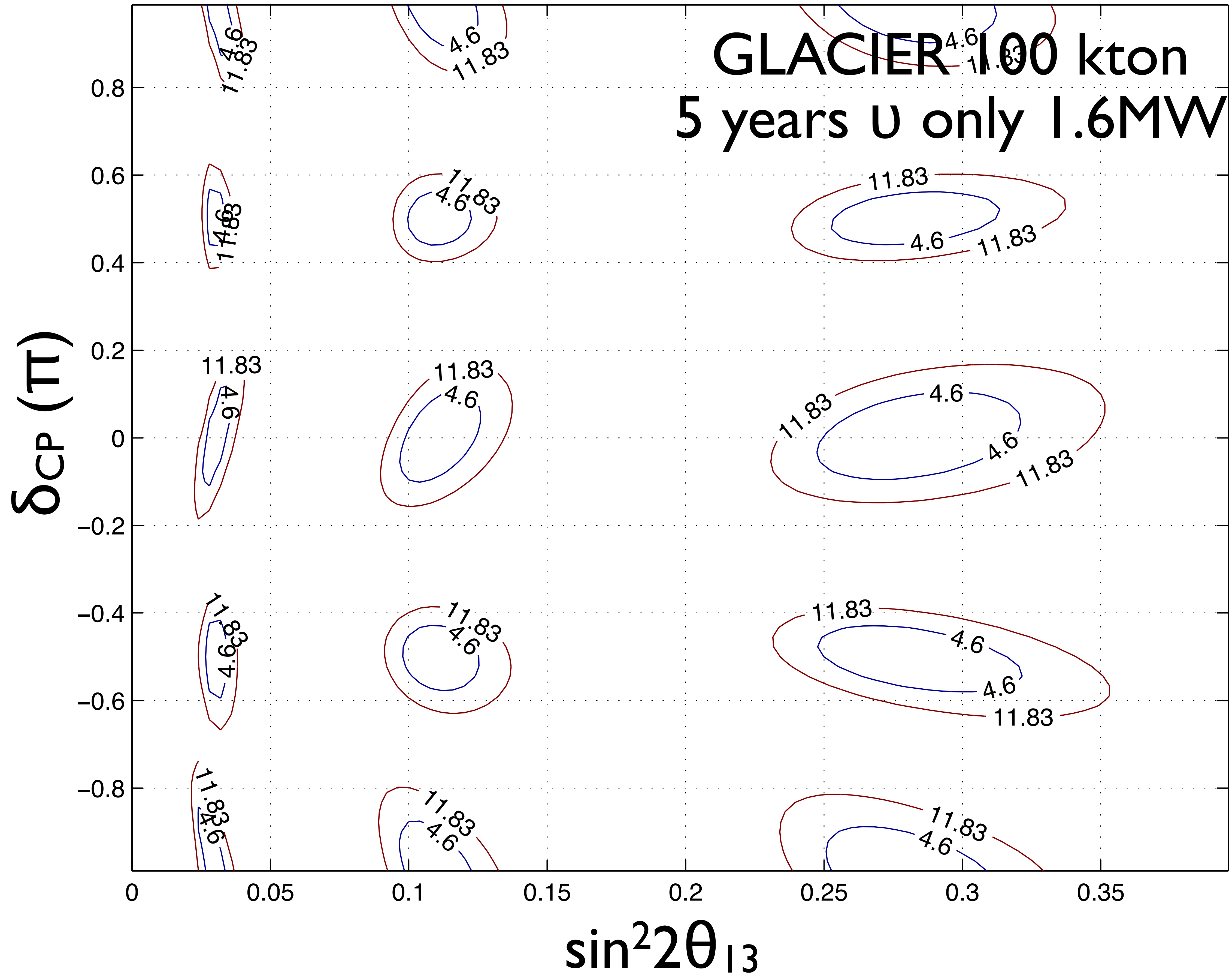
arXiv:1003.1921



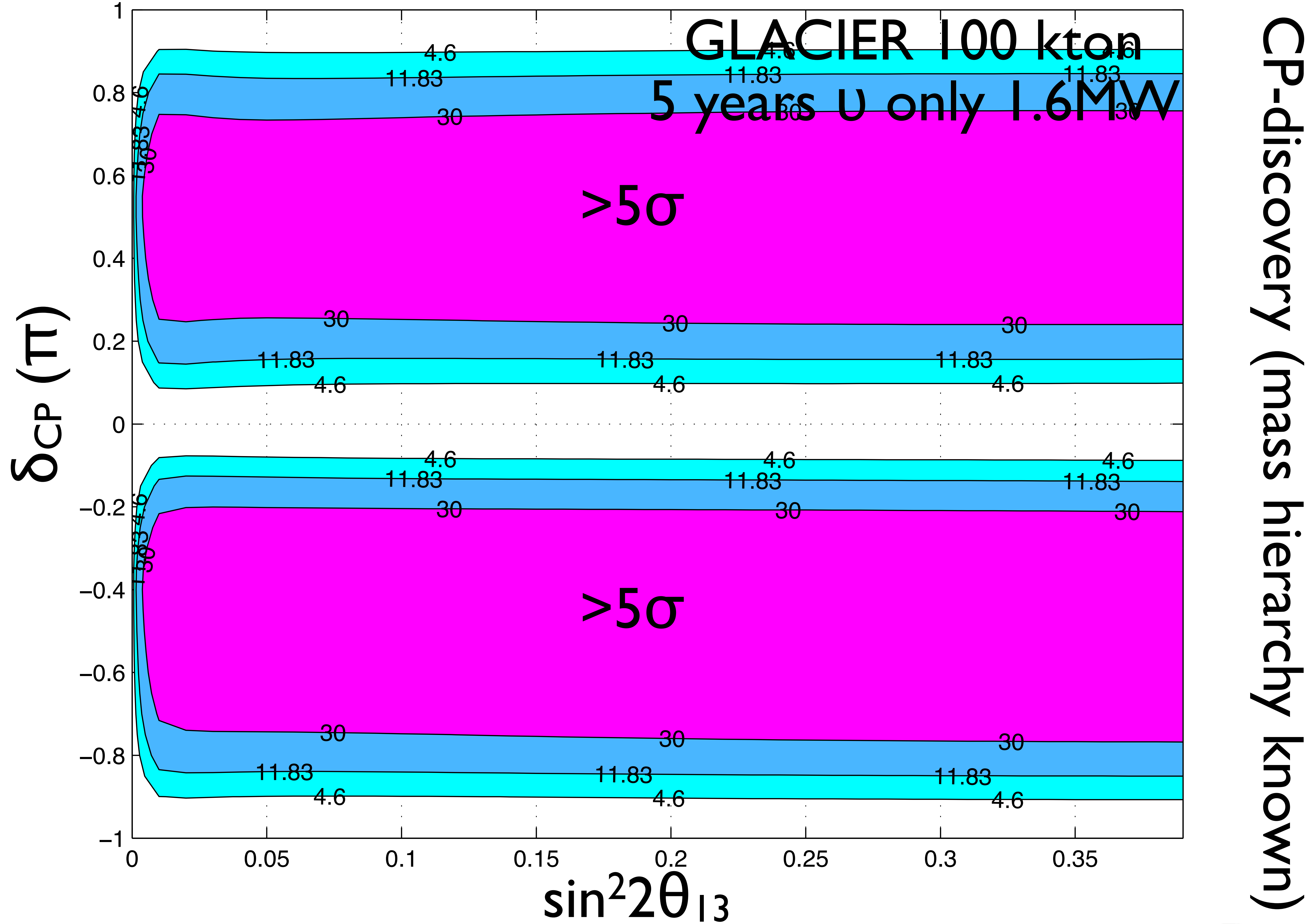


Mezzetto

CP discovery potential (I)

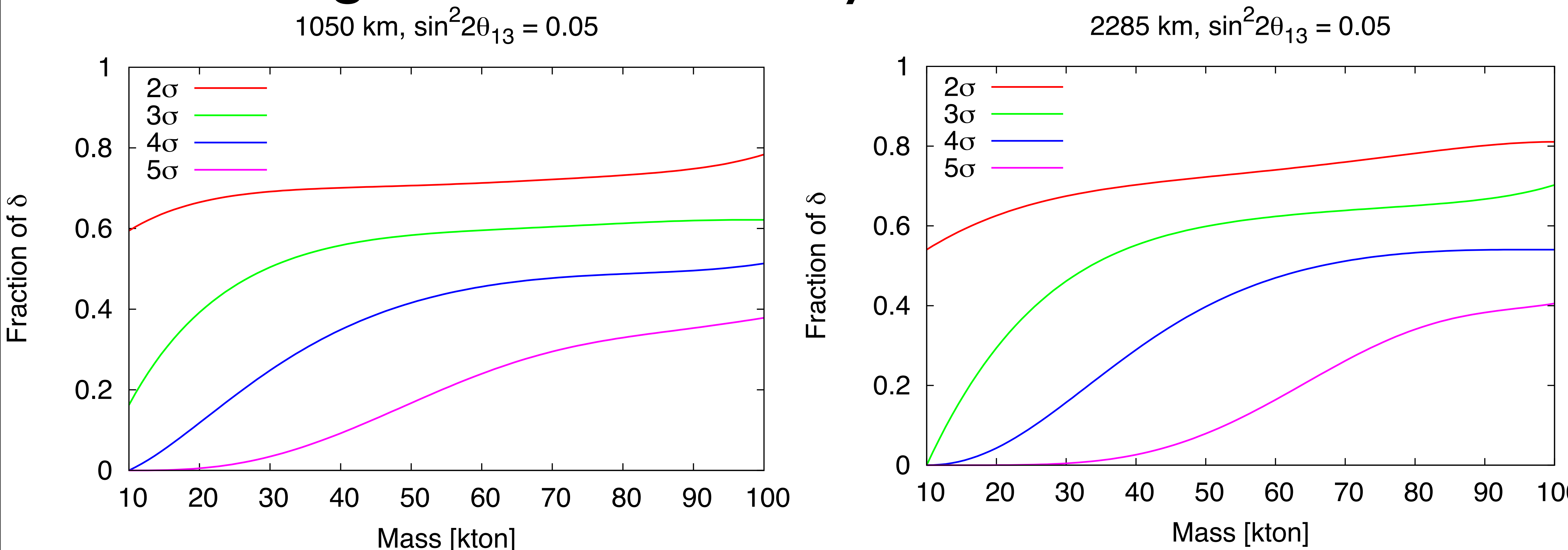


CP discovery potential (II)



CP discovery potential (III)

Staged GLACIER, 5+5 years υ+antiυ 1.6MW



Mass hierarchy unknown

Very preliminary

Agarwalla, Li and AR

Basis for a staged approach : explore phase space by adding detector mass and/or beam power

LAGUNA - Milestones

LAGUNA Design Study funded for site studies: 2008-2011

Categorize the sites and down-select: Sept. 2010

LAGUNA-LBNO: detector design, costing and LBL beam options ➠ fully funded ! 2011-2014

Critical decision (>3σ evidence for $\theta_{13} \neq 0$) 2014 ?

Phase 1 excavation-construction (pilot): 2015-2020 ?

Phase 2 excavation-construction: >2020 ?

Opportunity of "pilot" projects discussed within the LAGUNA-LBNO consortium

Conclusions (I)

(1) Growing worldwide interest and activities on next-generation underground large neutrino and proton decay detectors, both new sites and detector technologies → *the ultimate goal is to discover CP violation in the leptonic sector and proton decay search*

- In Europe a large amount of technical expertise has been gathered to reach the conclusions and a strong collaboration has developed since 2008 thanks to the LAGUNA design study

(2) The Pyhäsalmi site has been identified by the LAGUNA consortium as a high-priority potential site together with the Fréjus site, to be further investigated in the context of the LAGUNA-LBNO study (2011-2014)

(3) LAGUNA-LBNO to focus on detector feasibility and costs, and study of beams for long baseline neutrino from CERN

- Detector magnetization to be addressed
- Conceptual design from CERN to Pyhäsalmi (CN2PY) beam based on SPS
- Concept of 30-50 GeV HPPS
- Physics and detector option optimization

Conclusions (II)

(4) Thanks to the support of CERN to the LAGUNA-LBNO, the feasibility and cost of a new high-energy beam line to Finland, based on the expertise gained at the CNGS, will be studied in details. A second, more challenging option of a very high-intensity, low-energy superbeam directed towards Fréjus based on the potential HP-SPL will also be considered for comparison.

- In the study of the beam towards Finland, we will address the design of a near detector complex which could be conveniently located in the present Prévessin area, around the North Area.

- Near detector complex offers possibly of more than one detector and at different "short" distances (the Prévessin site offers within the CERN "patrimoine" distances of 300m, 1100m, and even 1700m from the NA target).

(5) The discovery of CP violation in the leptonic is admittedly very challenging, as it requires very high intensity beams and huge detectors, with both technical and financial risks.

- Therefore, it is unlikely that such a programme can be accomplished in "one step"

- The LAGUNA programme can be staged

- Therefore we will propose a neutrino programme to CERN that, similarly to LHC, can evolve according to the technological and the physics developments.

Acknowledgements

- FP7 Research Infrastructure “Design Studies” LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1)

Backup slide

Conclusions (III)

(6) European Strategy for Particle Physics ⇒ endorsement ??

- The European LBL programme CNGS will end towards 2013: a European LBL vision post-CNGS must emerge very soon.

- CN2PY will allow exploring unique physics LBL opportunities provided by the bi-magic baseline from CERN (2300km) - unique to Europe, not available elsewhere in the world !

- The CERN-Pyhäsalmi distance is also adequate for a future neutrino factory. And Pyhäsalmi also offers magic distances (7000km) from JPARC/KEK and FNAL

- Hence, CN2PY offers a natural succession, a promptly technically achievable solution, a potential answer to CNGS dismantling, and greatly enhanced physics opportunities, with long term options to evolve towards (1) power upgrades (2) new beam technologies (e.g. neutrino factory) capitalizing on the far detectors infrastructures investments

- The possibility to refurbish and develop the North Area target region into a source for short and long baseline neutrinos is an interesting option for CERN to move towards a balanced neutrino programme, with real chances to develop into an ultimate facility for CP violation discovery.

- With the planned transport of ICARUS T600 to CERN, there will be (soon) no more large LAr TPC doing underground physics.

If neutrinos have mass; the massive states need not be the same as the Weak interaction states.

This will lead to interference effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

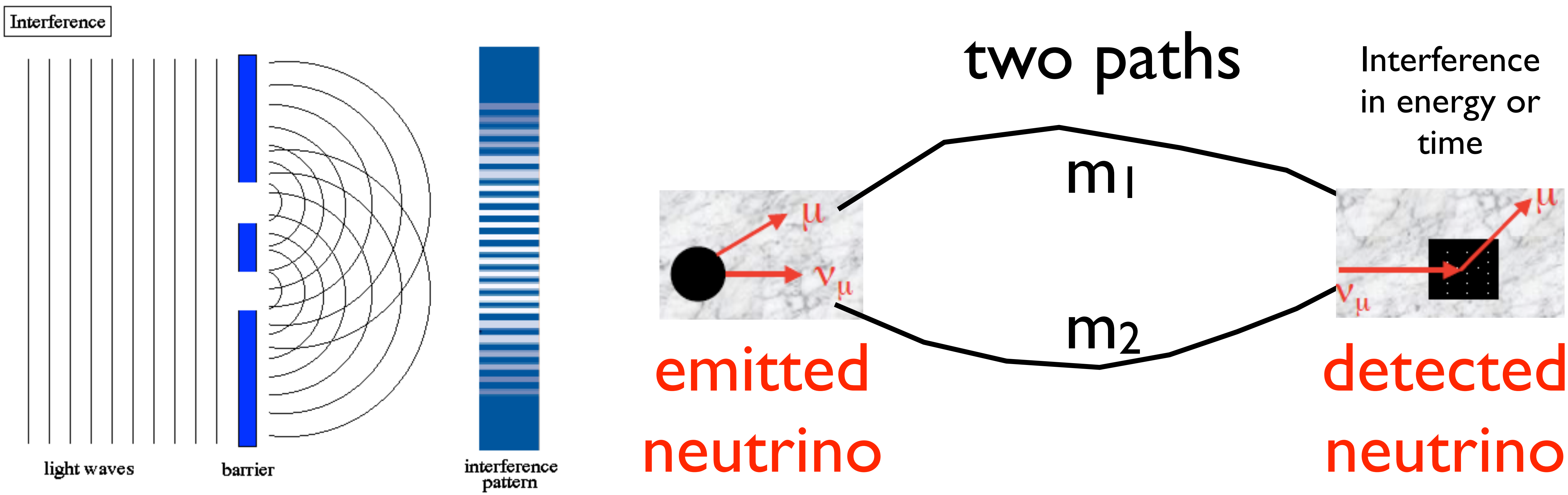
Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

Oscillations is a new interferometry.



- Just as classic optical interferometry has led to new precision, neutrino interferometry has potential to be sensitive to new scales.
- e.g. Measure extremely small masses or interactions.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix} m_2^2-m_1^2 & 0\\ 0 & m_1^2-m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & -\sqrt{2}G_F N_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad (3)$$

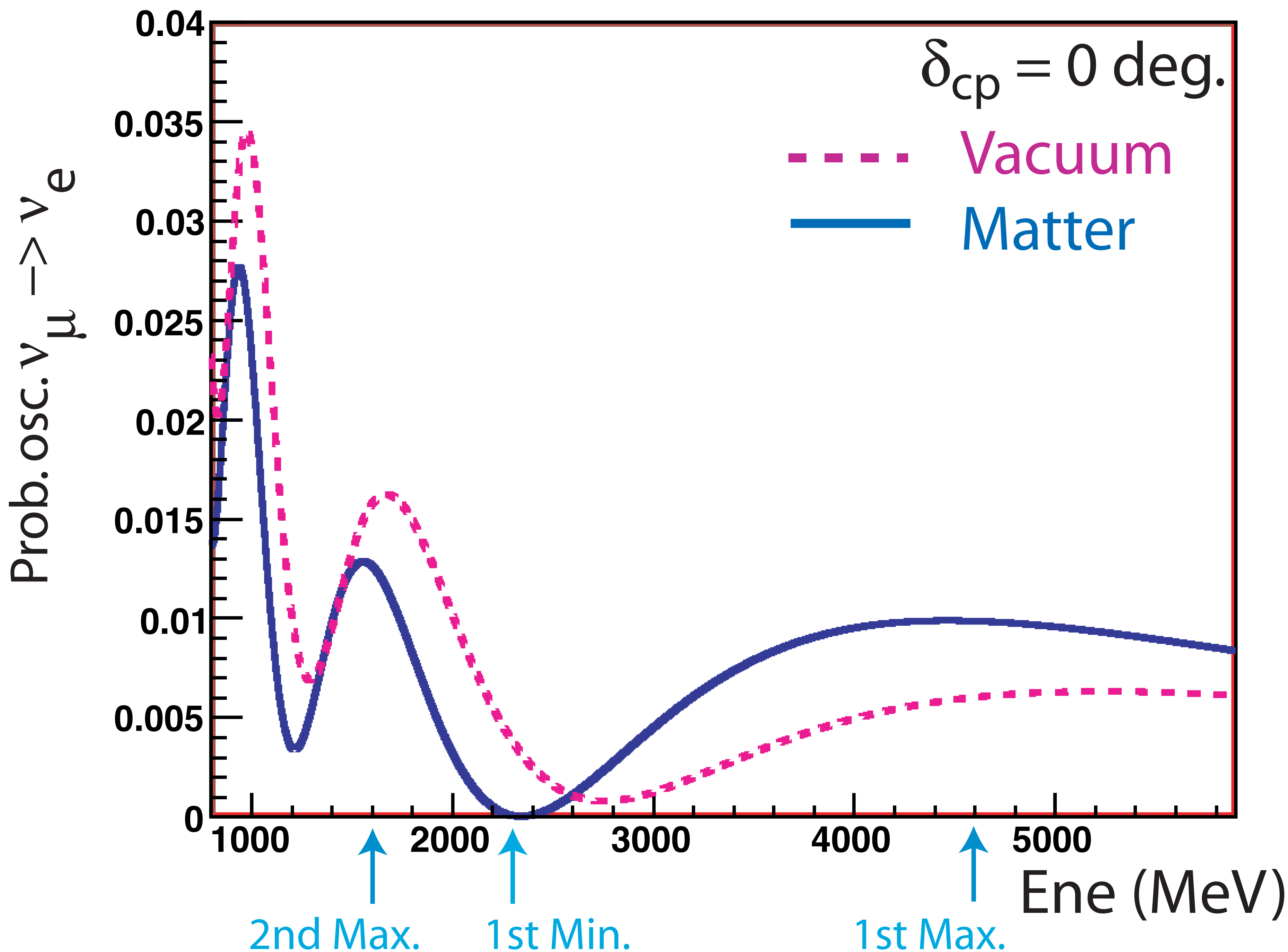
Looking at conversions of muon to electron neutrinos.

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2+\sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

This effect present if electron neutrinos are in the mix

Baseline L = 2300 km



$\Delta m^2 = 0.0025\ eV^2,\ \sin^2 2\theta_{13} = 0.01$

Three-neutrino flavor mixing

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ — Atmos. L/E $\mu \leftrightarrow e$ — Solar L/E $e \to \mu, \tau$ — $0\nu\beta\beta$ decay

500km/GeV — 15km/MeV

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\not{CP}$

Since there are 3 neutrinos, there must be a 3X3 matrix with 3 angles and 1 phase (observable) and 2 Δm^2

How precisely do we know them ?

Theoretical input

Tri-bimaximal mixing

Harrison, Perkins, Scott, PLB 2002, hep-ph/0202074

$$\sin^2\theta_{12} = 1/3\,, \quad \sin^2\theta_{23} = 1/2\,, \quad \sin^2\theta_{13} = 0$$

$$U = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Parameterize deviations

King **arXiv:0710.0530**

$$s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1+s), \quad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

$$0.07 < r < 0.21, \quad -0.05 < s < 0.003, \quad -0.09 < a < 0.04$$

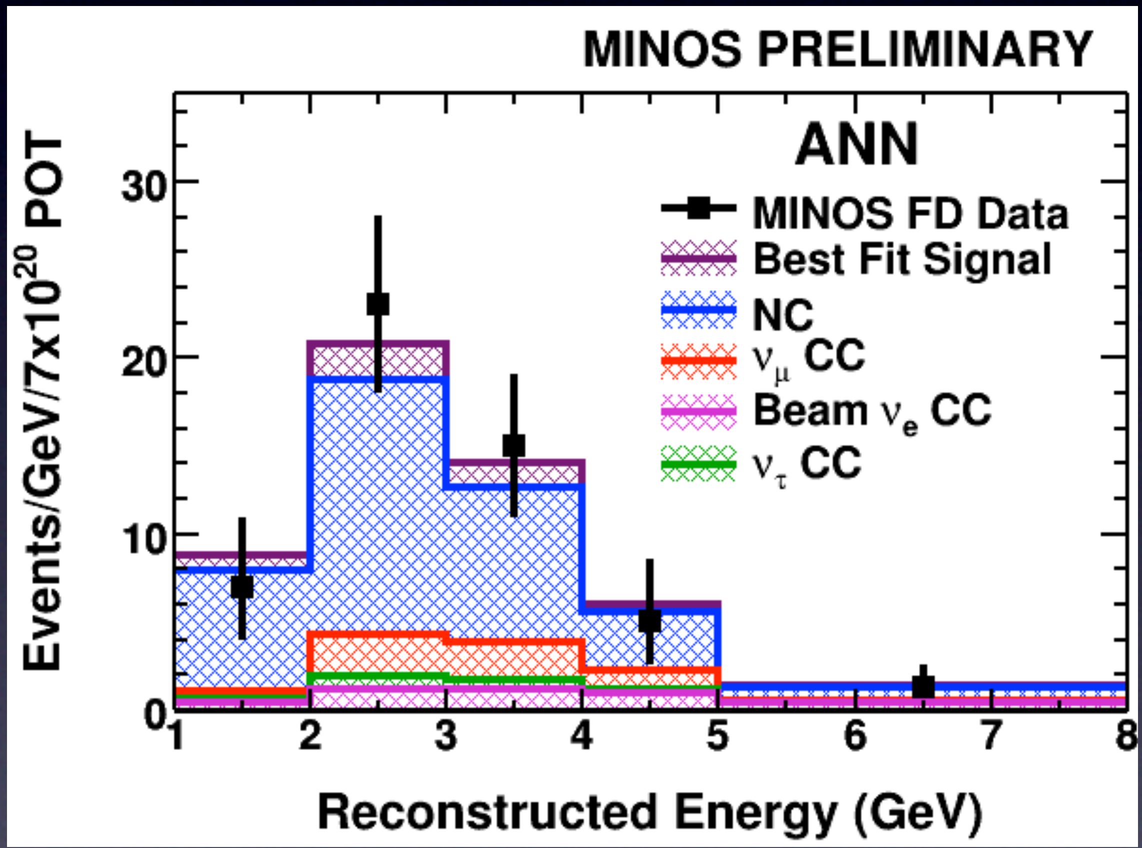
r = reactor s = solar a = atmospheric

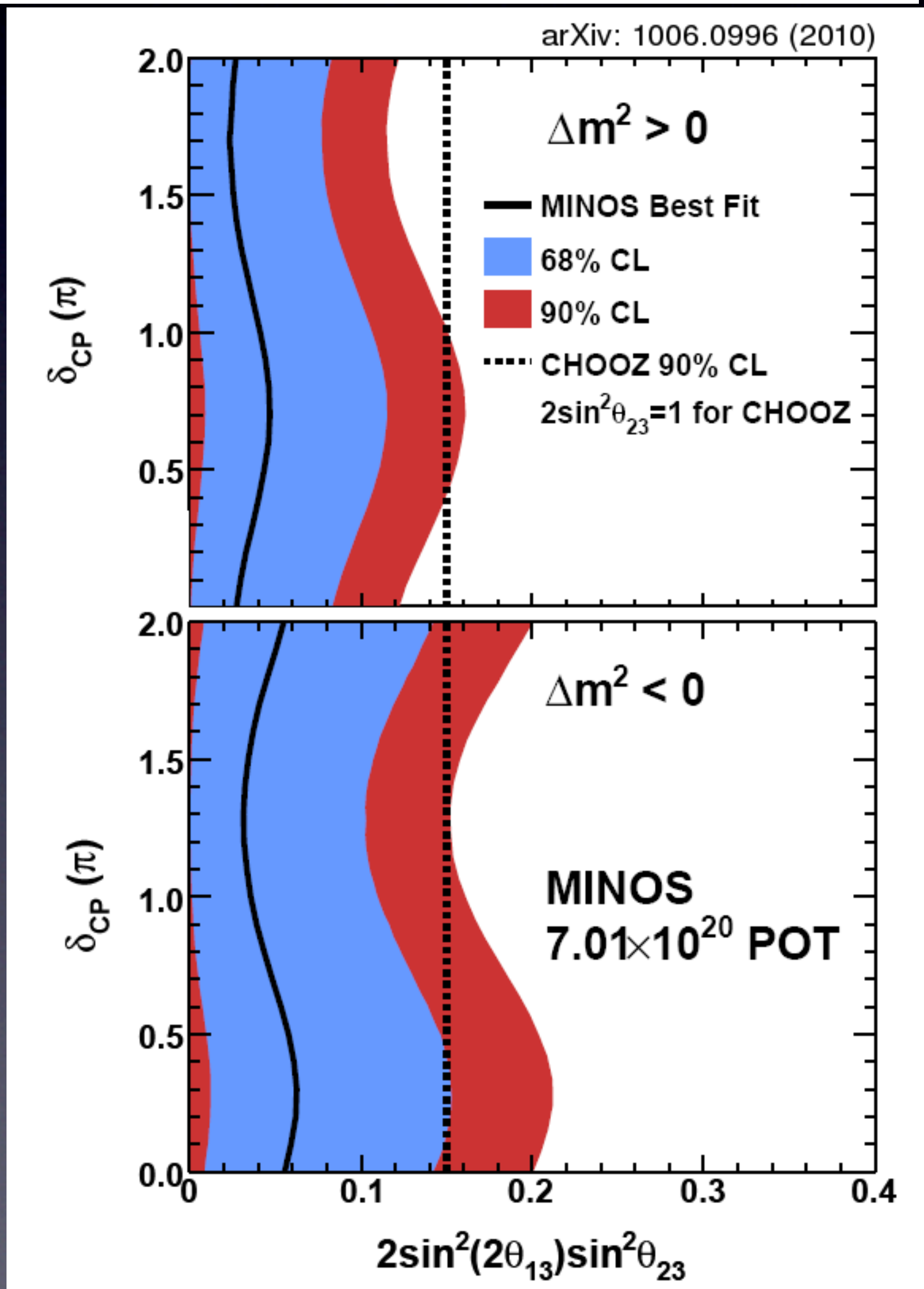
Present data is essentially consistent with r,s,a=0
→ tri-bimaximal so need to measure r,s,a !!

Some recent results on θ_{13}

- Based on ND data, expect: **49.1±7.0(stat.)±2.7(syst.)**
- Observe: **54** events in the FD, a 0.7σ excess

MINOS





For Δm^2_{23} =2.43x10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0

90%C.L.

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

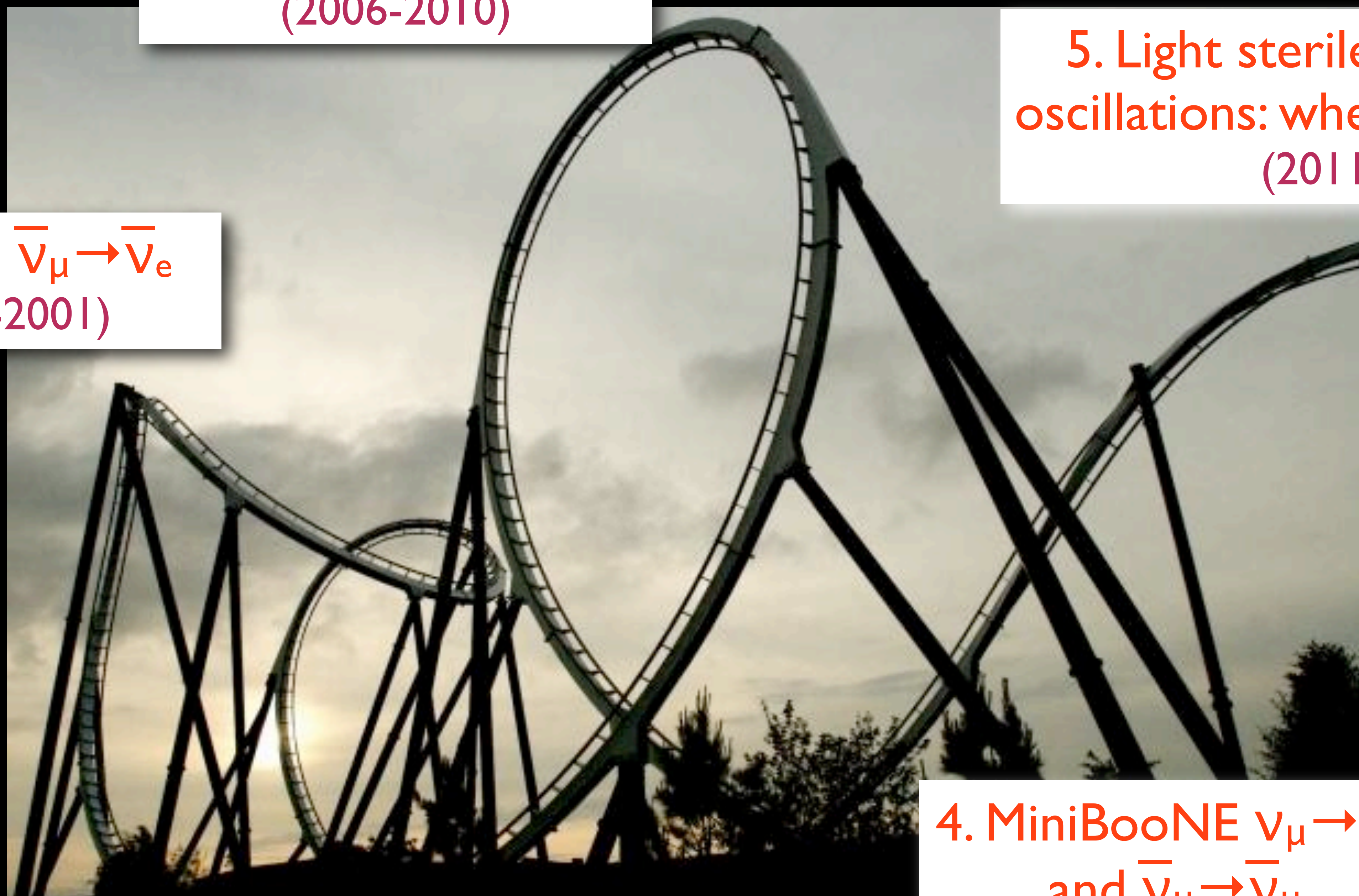
Some unresolved mysteries

M. Sorel

3. MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
(2006-2010)

5. Light sterile neutrino oscillations: where we stand
(2011)

1. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
(1993-2001)



4. MiniBooNE $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
(2001-2011)

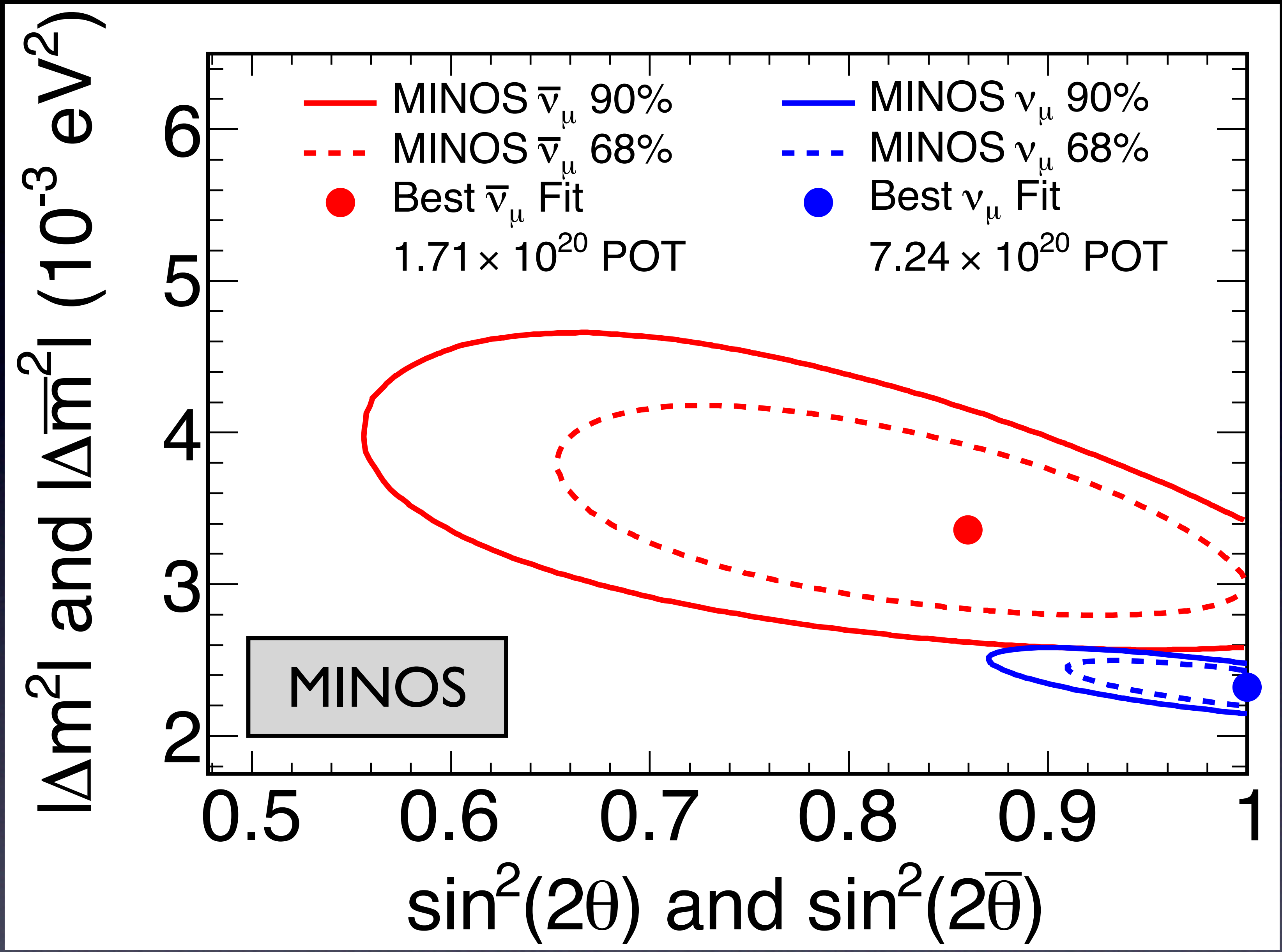
2. MiniBooNE $\nu_\mu \rightarrow \nu_e$
(2001-2007)

Some even more puzzling effects

MINOS may have observed a small difference between neutrino and antineutrino parameters

CPT ?
Additional interaction with matter ?

Waiting for confirmation with more data
Need an independent check at long baselines ?



$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2q) > 0.91\ (90\%\ \mathrm{C.L.})$$

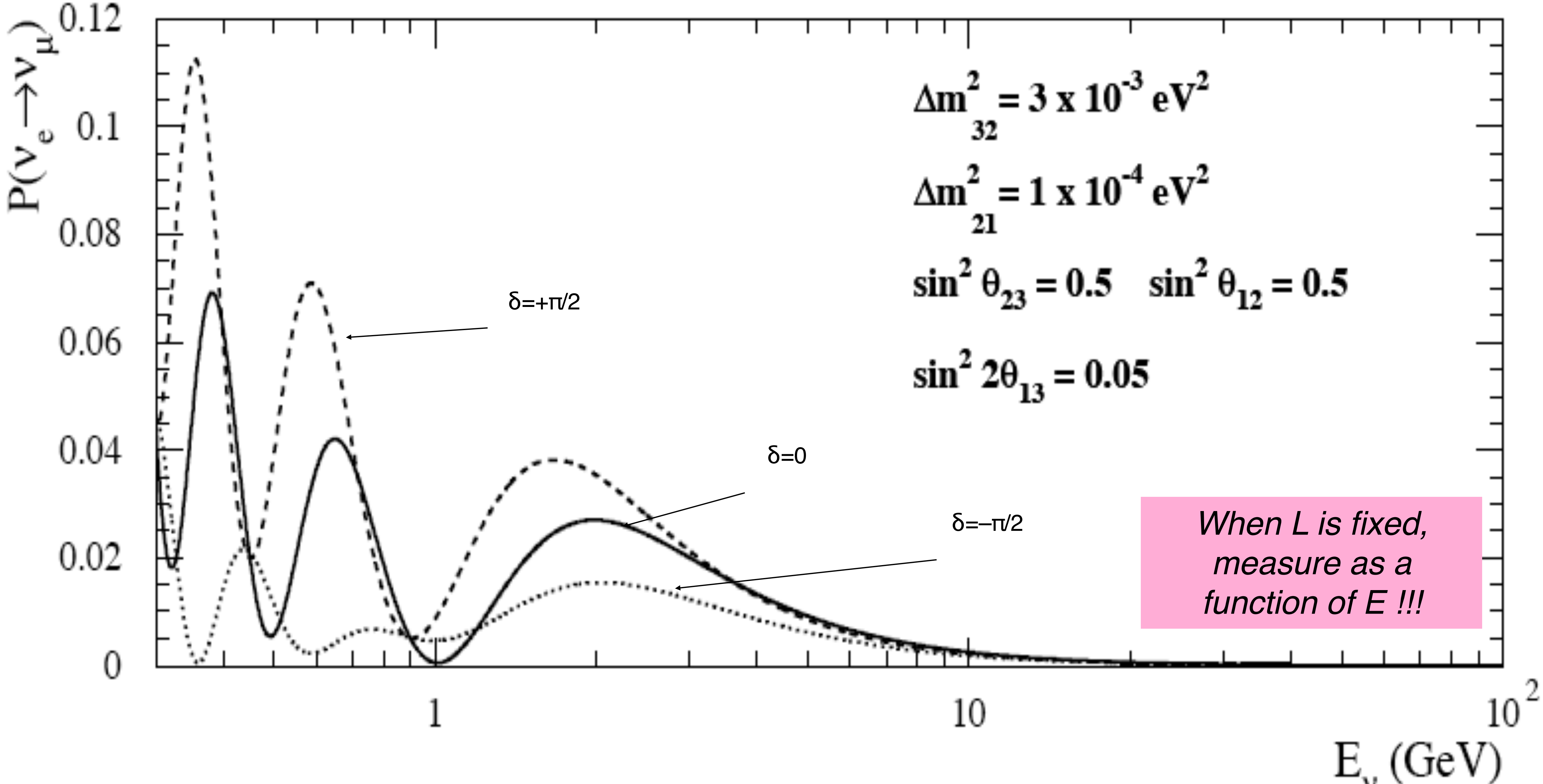
~2% probability of common parameters

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\overline{q}) = 0.86 \pm 0.11$$

Implications

AR, Venice (NOVE) 2003
arXiv:hep-ph/0402110v1

- The CP-phase can only be observed in appearance mode.
- The probability function should have the expected L/E dependence.
- The effect for antineutrinos should be opposite to neutrinos (δ→–δ).



When L is fixed, measure as a function of E !!!


Salt layer - Polkowice-Sieroszowice (Poland)

In quest of the optimal site

Consider deep new underground labs with different characteristics

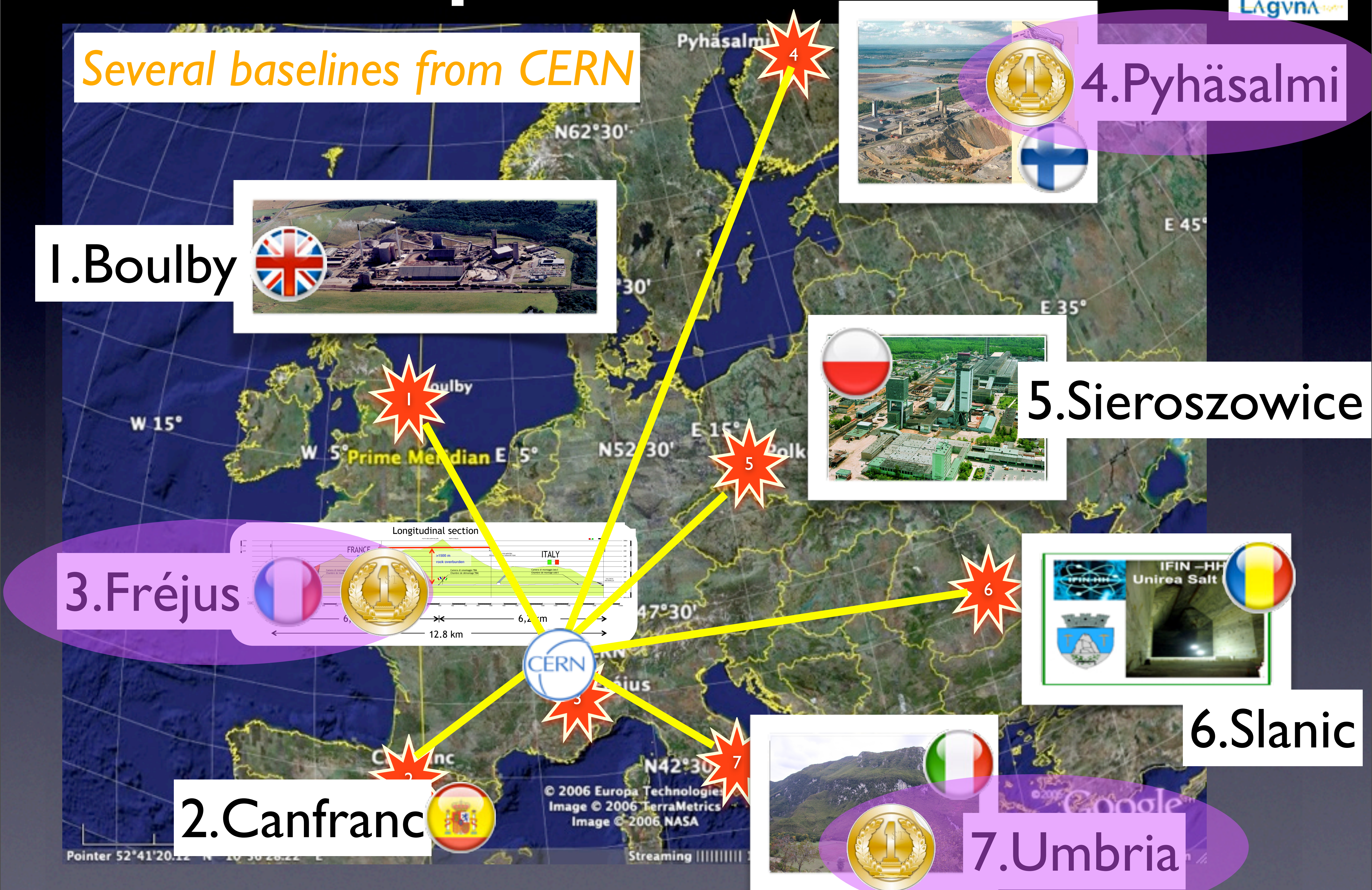
Extension of existing labs and/or new infrastructure

Mines, road tunnels, and green field

Vertical or horizontal access

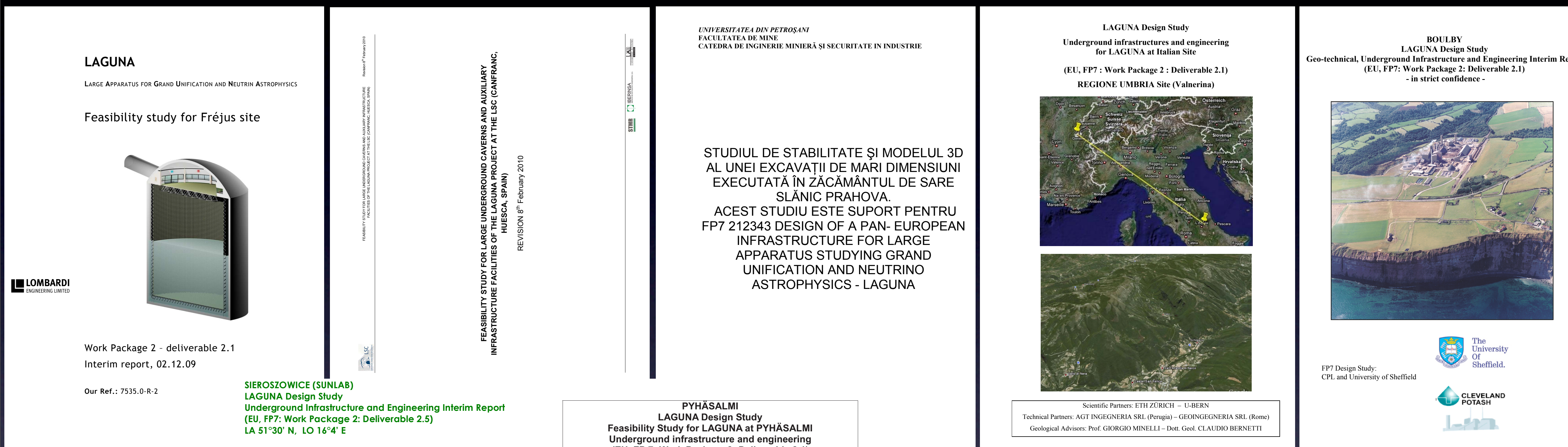
Several baselines from CERN, reactor fluxes, etc...

LAGUNA pre-selected sites



Seven technical reports

Interim site-dependent geotechnical reports: delivered!
Final joint report on potential European sites: soon



- more than 1200 pages
- large amount of information and details
- healthy competition among sites
- publicly available

Underground storage tank and LAr process

Cooperation with industrial partners after many years of investigations (started in 2004)

Several specialized companies in the LNG field

- Initial Concept - 2004
- Use existing technology from industry experience
- Above ground tank, placed below ground
- De-couple the tank from the cavern
  - Several sites
  - Several seismic levels
  - Rock or Salt

Sofregaz

RHYAL ENGINEERING

Also: Linde Kryotechnik AG (Zurich) and AirLiquide (Grenoble)

Underground infrastructure

Rockplan, Pentaocean, ...

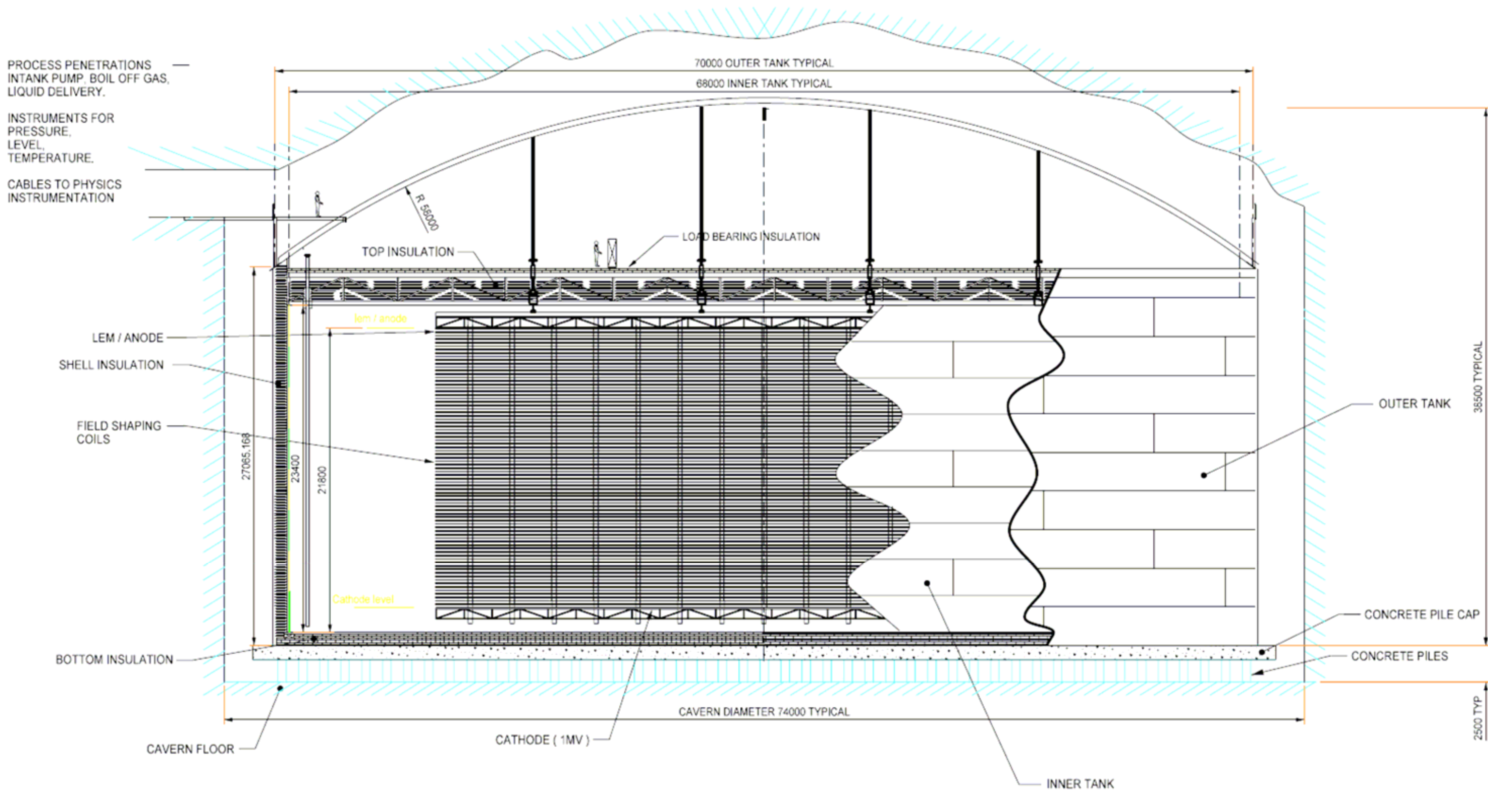
Consulting in underground construction / risk analysis

Alan Auld GROUP LTD

+ CERN LHC/ATLAS/CMS cryogenic experience

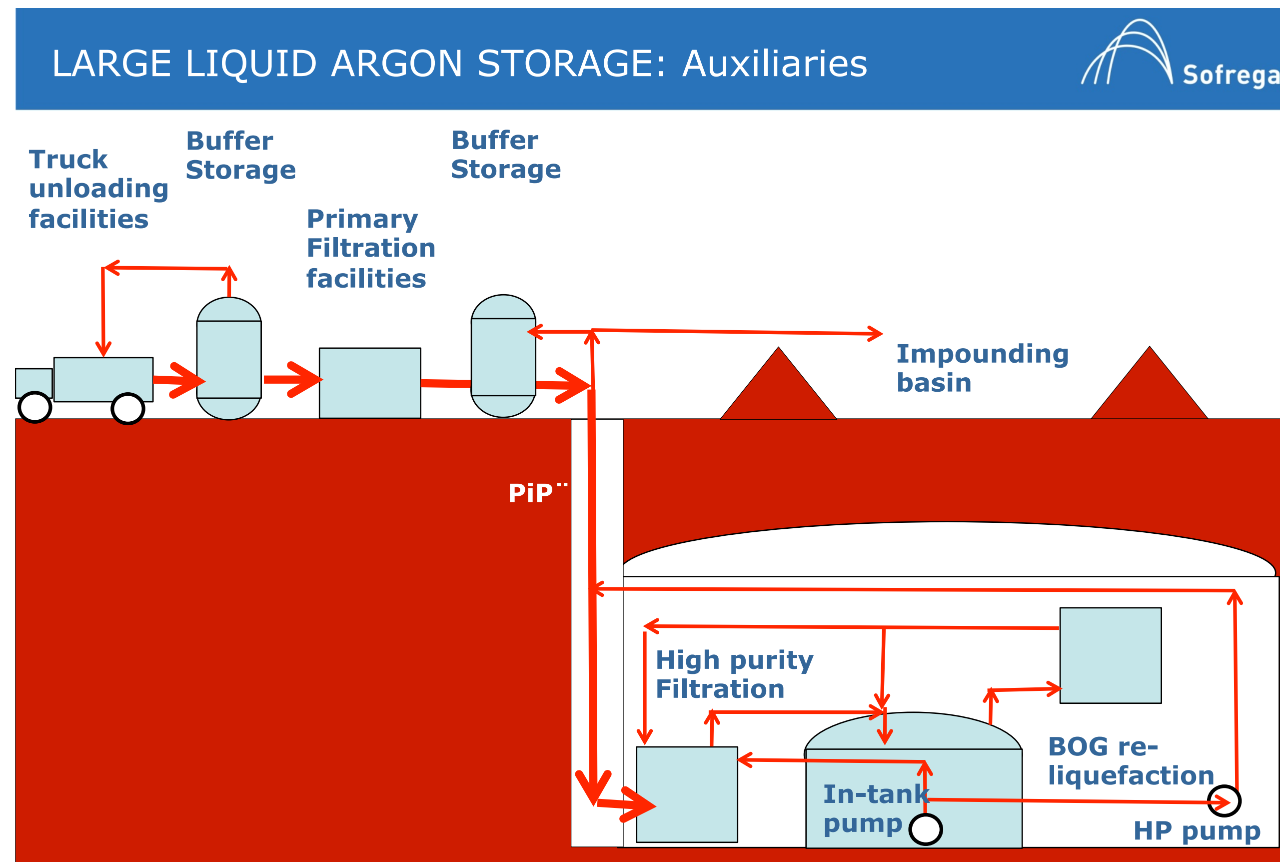
Technodyne

General Arrangement



- Single containment is suitable
  - Full containment not warranted
  - Cavern will contain spill
- Steel / Steel
  - Steel concrete not necessary
  - Membrane not current practice

- Modify design for deck access
- Modify design for sealing of inner tank
- Support for payload



Sofregaz

Astroparticle ν physics and proton decay search

Complementarity between detector techniques

	Water Cerenkov	Liquid Argon TPC	Liquid Scintillator
Total mass	500 kton	100 kton	50 kton
$p \rightarrow e\,\pi^0$ in 10 years	1.2×10^{35} years ε = 17%, ≈ 1 BG event	0.5×10^{35} years ε = 45%, <1 BG event	?
$p \rightarrow \nu\,K$ in 10 years	0.15×10^{35} years ε = 8.6%, ≈ 30 BG events	1.1×10^{35} years ε = 97%, <1 BG event	0.4×10^{35} years ε = 65%, <1 BG event
SN cool off $8 \times M_{Sun}$@ 10 kpc	194000 (mostly $\nu_e p \rightarrow e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)	15000 (all flavors)
SN in Andromeda	40 events	7 (12 if NH-L mixing)	4 events
SN burst @ 10 kpc	≈250 ν-e elastic scattering	380 ν_e CC (flavor sensitive)	≈30 events
SN relic	250(2500 when Gd-loaded)/year	50/year	20-40/year
Atmospheric neutrinos	56000 events/year	≈11000 events/year ≈100 ντ CC/year	5600/year
Solar neutrinos	91250000/year	324000 events/year	≈5400 ^{7}Be events/day
Geoneutrinos	–	–	≈1500 events/year

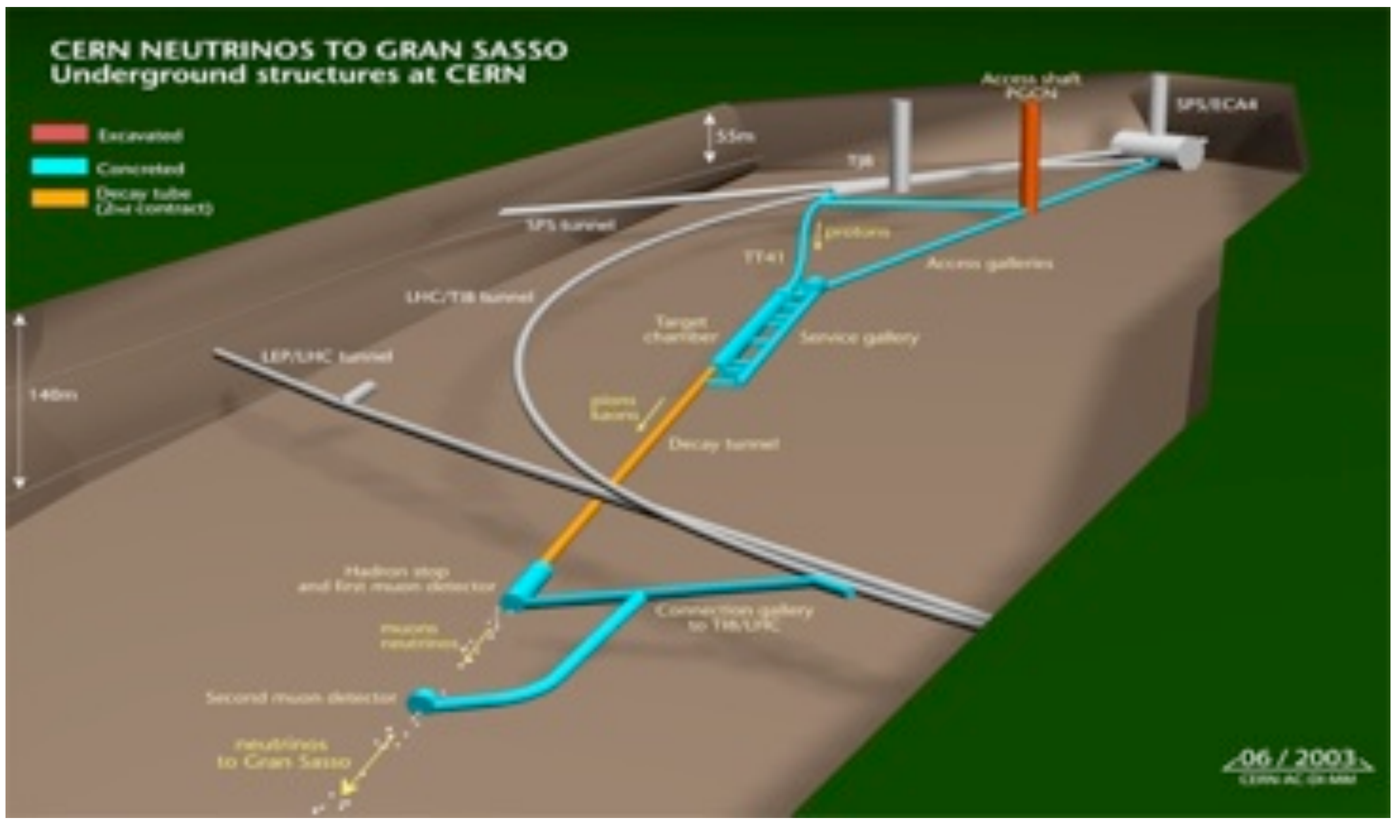
CERN as a beneficiary of LAGUNA-LBNO

WP4 – Long Base Line Neutrino Beams Prospects and Scenarios for Detector Magnetization

- **Task 4.1** Study of impact of CERN SPS accelerator intensity upgrade to neutrino beams
- **Task 4.2** Feasibility of intensity upgrade of CNGS facility
- **Task 4.3** Conceptual design of the CN2PY neutrino beam
- **Task 4.4** Feasibility study of a 30-50 GeV high power PS
- **Task 4.5** Definition of the accelerators and beamlines layout at CERN
- **Task 4.6** Study of the Magnetic Configuration for the LAGUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

ν beams at CERN – The present

- **CNGS** is THE neutrino oscillation facility in Europe
- **ν_τ appearance** optimized detectors: **OPERA**(1.2kt) **ICARUS** (0.6kt)



Proton beam parameters	
Energy	400 GeV/c
Cycle length	• 6 seconds • 2 extractions/cycle, 50ms apart
Extraction	• 2.4 x 10^{13} protons • 10.5 μs long pulse
Beam power	• **500 kW**

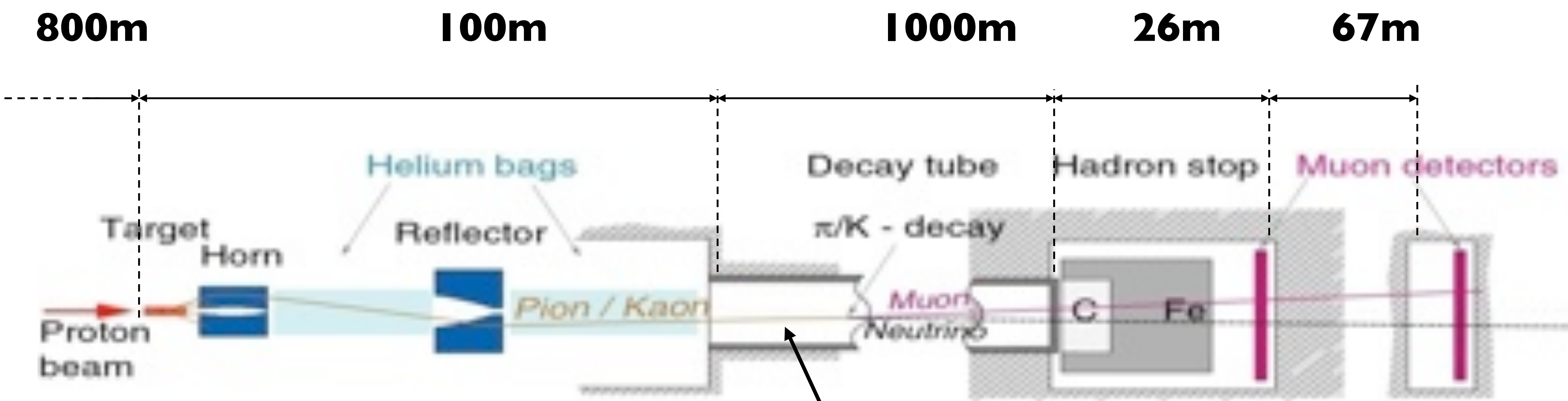
- Installation completed in **June 2006**
- In physics operation since **2007**

Approved program:

- **4.5 × 10^{19} protons/year** – 5 year program
- ~3.5 × 10^{11} ν_μ/year at Grand Sasso
- ~3000 CC ν_μ interactions/kt/year at the experiment
- **~2÷3 ν_τ interactions detected/year** (OPERA)

CNGS - Conventional ν beam

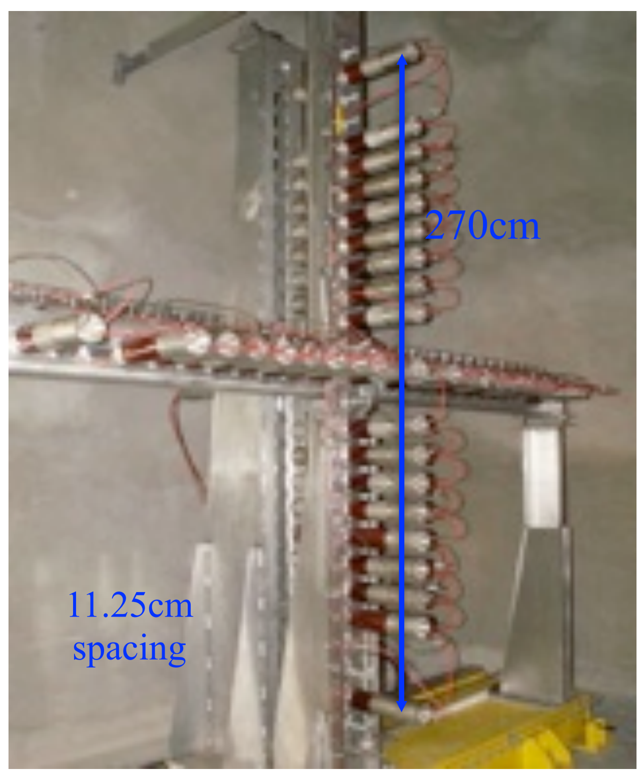
p + C → (interactions) → π^+, K^+ → (decay) → $\mu^+ + \nu_\mu$



TARGET UNIT

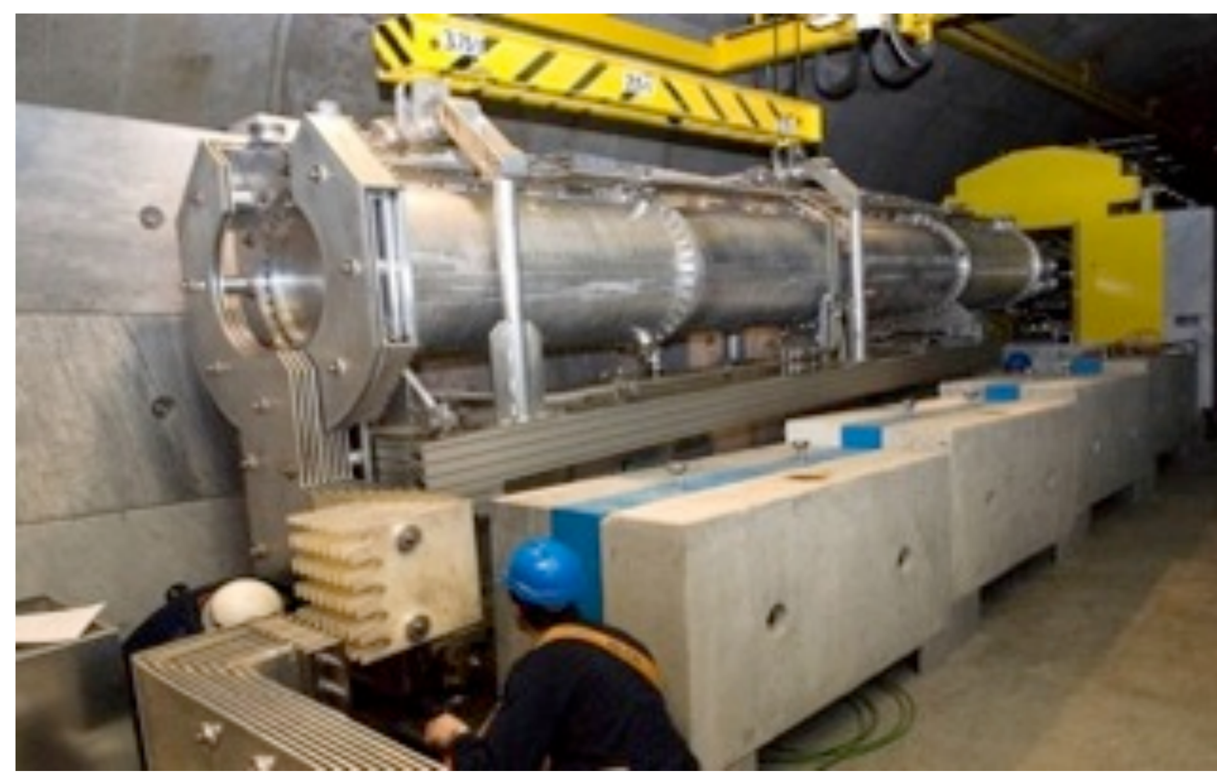
- C rods
- 5(4) mm Ø
- 5 in-situ spares

MUON DETECTORS



- 2 × 41 fixed monitors
- 2 × 1 motorized monitor

MAGNETIC HORNS



Bi-magic distance condition

$$P(\nu_e \to \nu_\mu) \sim \sin^2 2\theta_{13} \cdot T_1 + \alpha \cdot \sin\theta_{13} \cdot (T_2 + T_3) + \alpha^2 \cdot T_4.$$

$$T_1 = \sin^2\theta_{23} \cdot \frac{\sin^2[(1-A)\cdot\Delta]}{(1-A)^2}$$

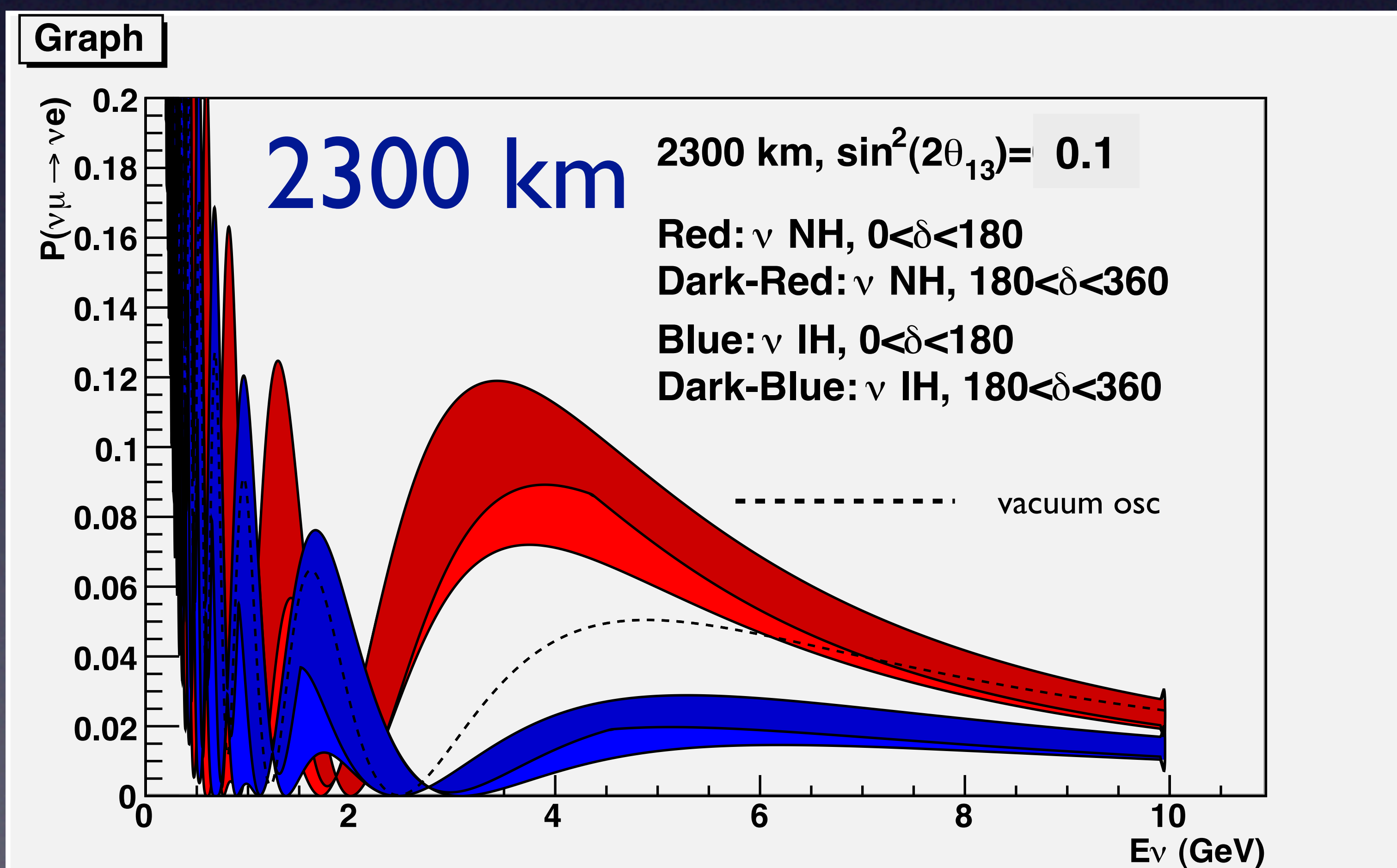
$$T_2 = \sin\delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin\Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$$T_3 = \cos\delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \cos\Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$$T_4 = \cos^2\theta_{23} \cdot \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}.$$

$$A \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$$

Determine CPV and mass hierarchy by spectrum measurement and resolve degeneracies and so-called “π-transit” effect



Apply magic condition by
(1) removing dependence on δ_{CP}
(2) maximizing difference between NH & IH

Solve for E & L

E = 3.3 GeV && L=2540 km

see Phys.Lett.B696:227-231,2011

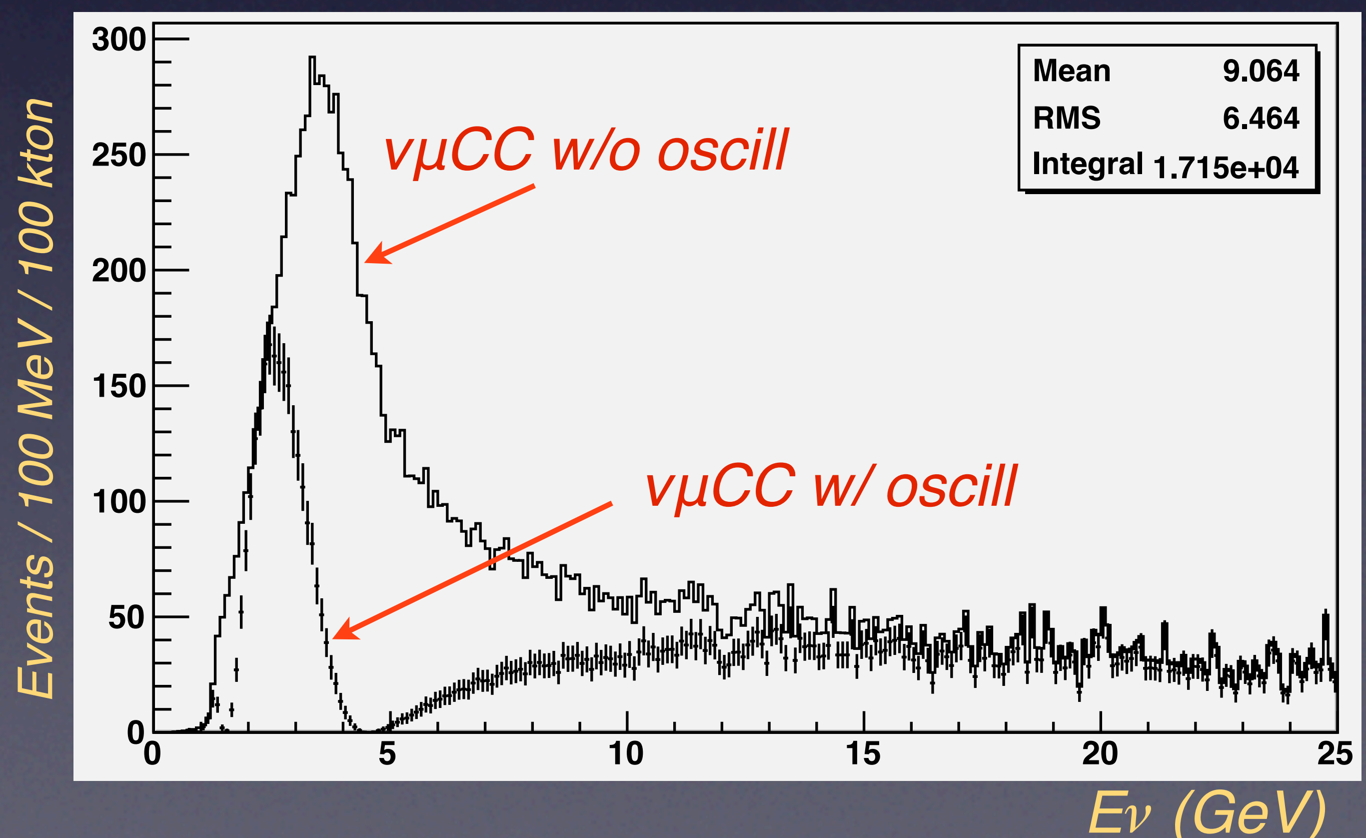
Tau appearance studies

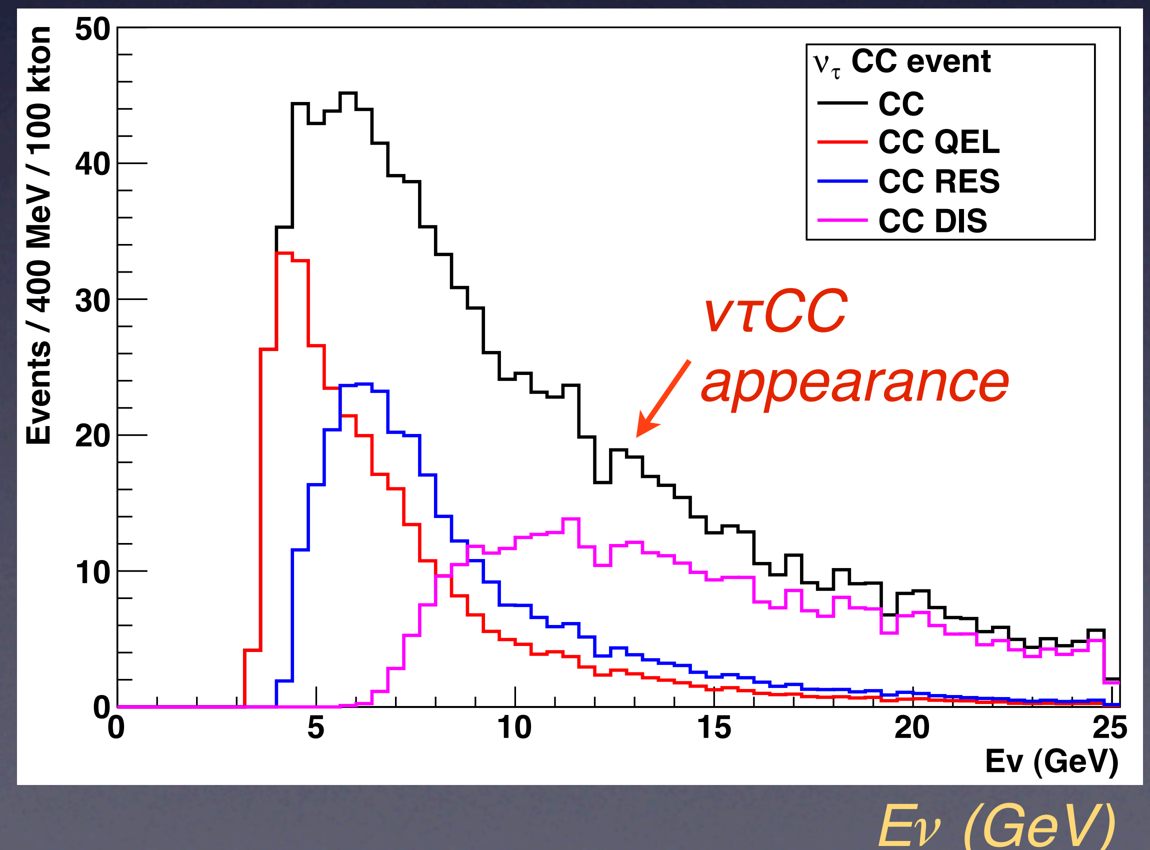
At the CERN-Pyhäsalmi baseline, the energy of the 1st oscillation maximum is above the tau production threshold of 3.47 GeV

	Neutrino horn polarity			
Distance/OA	ν_μCC	ν_eCC	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Pyhäsalmi **2300 km** 0.25 deg	17152 (860)	250 (13)	880 (44)	1018 (51)

5 years @ 9.4x10¹⁹ pots/year
100(5) kton detector mass
$\sin^2 2\theta_{23}$=1.0, $\sin^2 2\theta_{13}$=0.1

≈1000(50) υτ CC
58% with neutrino energy < 10 GeV, where most events are very clean
(study in progress)





Near detector Complex

Mishra/LBNE

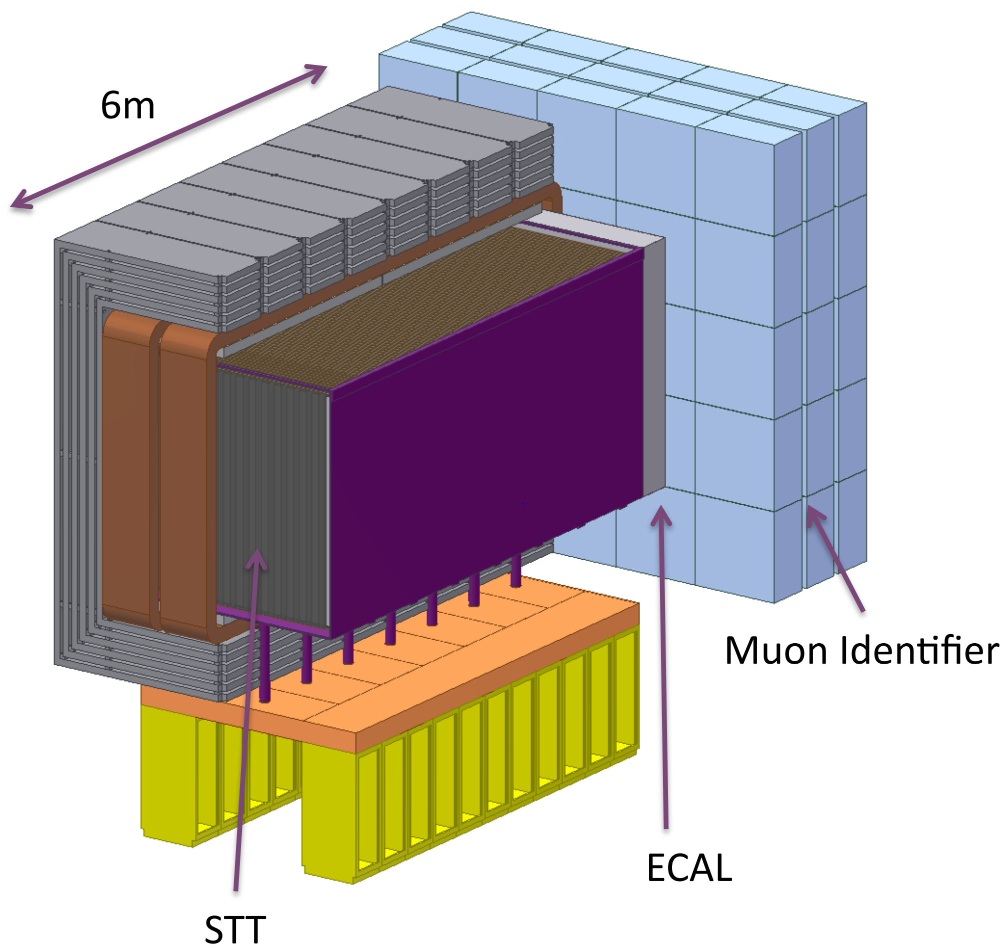
✦ *Need a high resolution detector at the Near-Site to measure systematics affecting the Far-detector:*

- $\nu_\mu, \bar{\nu}, \boxed{\nu_e}, \boxed{\bar{\nu}_e}$ *content vs.* E_ν *and* θ_ν;
- ν*-induced* $\pi^\pm/K^\pm/p/\pi^0$ *in CC and NC interactions;*
- *Quantitative determination of* E_ν *absolute energy scale;*
- *Measurement of detailed event topologies in CC & NC.*

$\Longrightarrow$ *Provide an 'Event-Generator' measurement for* $\mathcal{LBL}\nu$

- Measure over the full range of FD
- Background to the ν(Bar)e/μ-Appearance
- ν -vs0 ν(Bar) Interactions

Straw Tube Tracker (STT)



- Best performance of the 4-options
- 3.5m x 3.5m x 7m STT (7 tons; ρ≃0.1gm/cm^3)

4π-ECAL
Dipole-Field (0.4T)
μ-Detector (RPC) in Dipole and Downstream

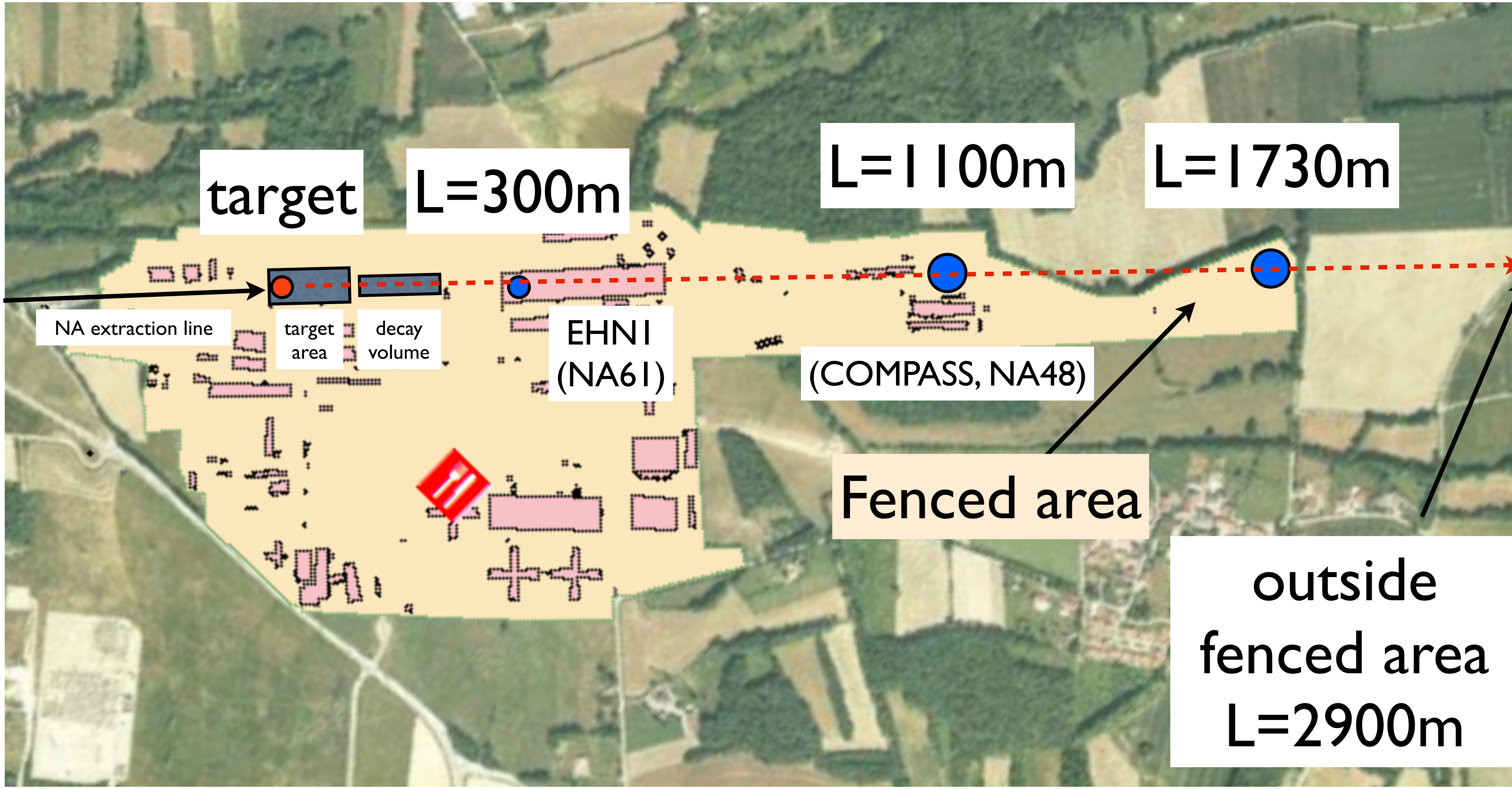
Transition Radiation ↠ e-/e+ ID ⇒ γ
dE/dx ↠ Proton, π+/-, K+/-
Magnet/Muon Detector ↠ μ+/-

- H2O & D2O Targets (≃x5 FD-Stat) ⇛ *WC-FD*

{QE-Proton ID ⇛ Absolute Flux measurement}

- Pressurized Ar-target (≃x5 FD-Stat) ⇛ *LAr-FD*

Short baseline concept in North Area



<u>Present</u>: 400 GeV protons, slow extraction, 3e13 / extraction, 3 targets (T2/T4/T6)