ESSνSB Project for Leptonic CP Violation Discovery based on the European Spallation Source Linac

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Outline

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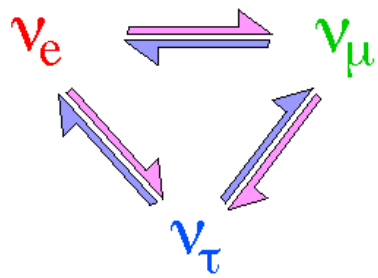
- Neutrino Oscillation formalism
- Past and Present Neutrino Oscillation Experiments
- Neutrino Beams
- Optimizations and θ_{13} measurement
- Future projects and CP Violation
- The ESSνSB project

Neutrino Oscillations



Lepton Mixing and Quantum Mechanics

- The "known" neutrinos are combinations of mass eigen state neutrinos, for example, for electron neutrinos:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- For all neutrinos, we can write:

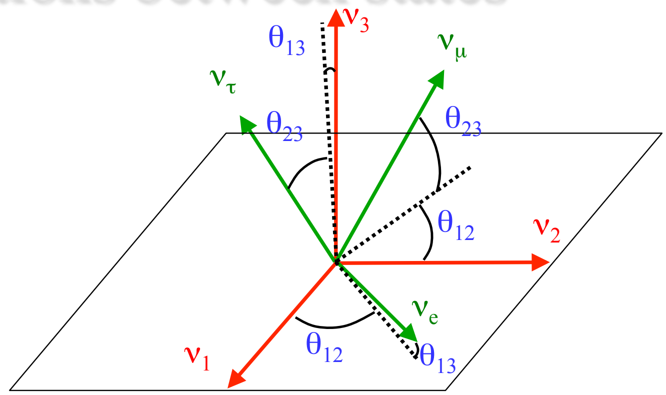
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{unitary mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- U is the transformation operator (matrix),
- the hypothetical states ν_1, ν_2, ν_3 have unique masses and are neutrino fundamental eigen states.
- Unitarity $UU^+=I$ ($U^+=(U^*)^t$)

Pontecorvo-Maki-Nakagawa-Sakata matrix

Rotations between states

3 mixing angles, θ_{12}, θ_{23}, θ_{13}, and one phase, δ_{CP}



$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta ij$

Usual parametrization

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

solar, reactors — atmospheric, accelerators — reactors, accelerators, CP violation — Majorana phases

- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

How neutrinos propagate through vacuum?

For 3 neutrinos with a well defined mass and energy:

Schrödinger equation: (H: Hamiltonian)

$$i\frac{d}{dt}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = H \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

for the mass eigen states

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H_f \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

for the flavour eigen states

with: $H_f = UHU^\dagger$

$$|\nu_j(t)\rangle = e^{-iHt/\hbar} |\nu_j(0)\rangle$$

Solutions of Schrödinger equation

Probability as a function of mixing angles

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Phi_{ij} + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin 2\Phi_{ij}$$

if this term ≠0 → CP violation

$$\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E} = 1.27 \Delta m^2_{ij} \left(\frac{L}{E}\right)$$ (L in km, E in GeV, Δm in eV and $\hbar c$=197 MeV fm)

$\Delta m^2_{ij} = m^2_j - m^2_i$ (3 mass differences but one 2 are independent)

To obtain: $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ CP transformation

replace: $U \to U^*$

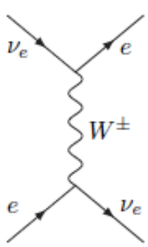
or: $\Phi_{ij} \to -\Phi_{ij}$

if: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ → CP violation (never observed up to now)

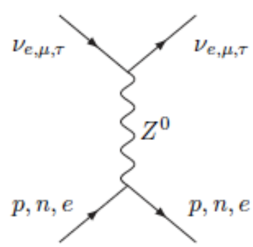
How neutrinos propagate through matter?

(Mikheyev-Smirnov-Wolfenstein effect)

only for electron neutrinos



CC



NC

in "ordinary" matter

$$H_f = UHU^\dagger = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger \to \frac{1}{2E}\left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} A_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right]$$

with: $A_{CC} = 2EV_{CC} = 2\sqrt{2} E G_F N_e \approx 7.56 \times 10^{-5} eV^2 \left(\frac{\rho}{g/cm^3}\right)\left(\frac{E}{GeV}\right)$ (ρ~3 g/cm^3 for earth crust)

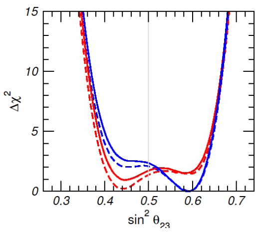
Present measurements

$\theta_{23} = 40.0^{+2.1}_{-1.5}$ or $50.4^{+1.2}_{-1.3}$ deg.

$|\Delta m^2_{31}| = (2.47 \pm^{+0.07}_{-0.07}) \times 10^{-3}$ eV^2

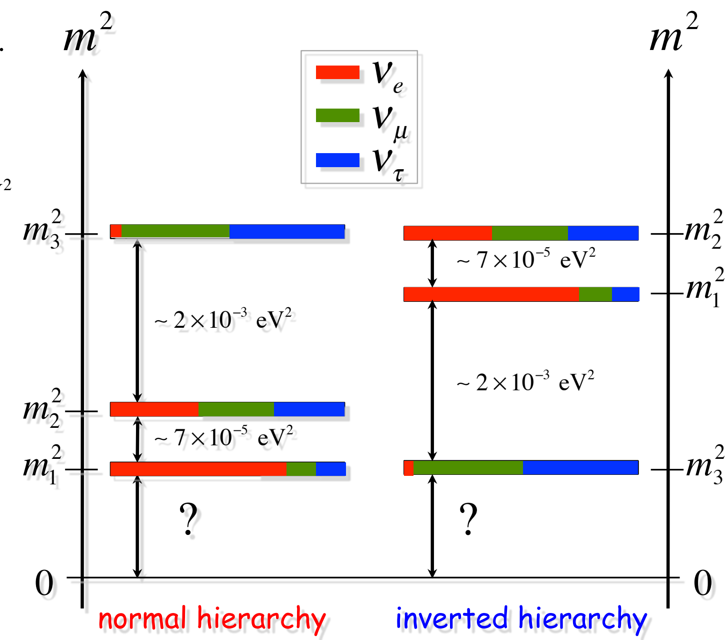
$\theta_{12} = 33.3 \pm 0.8°$

$\Delta m^2_{21} = (7.50 \pm 0.19) \times 10^{-5}$ eV^2



$\theta_{13} < 12.4°$, 90% CL
up to recently

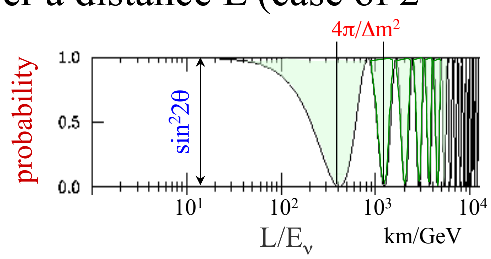
no information on δ_{CP}



Appearance/disappearance experiments

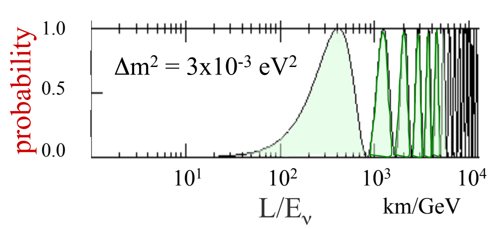
In disappearance experiments we count how many initial neutrinos ν_α survive after traveling over a distance L (case of 2 flavours):

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \ \sin^2\left(\frac{1.27 \Delta m^2 L}{E_\nu}\right)$$

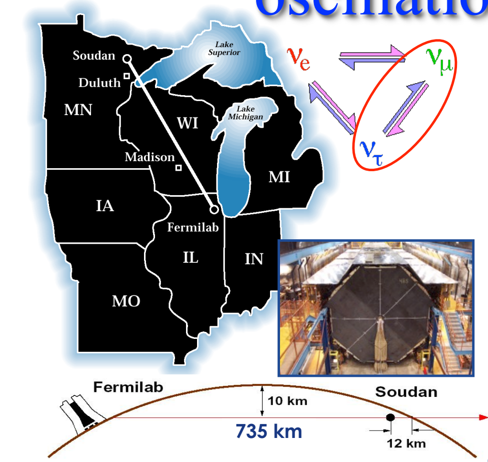


In appearance experiments we look for neutrinos ν_β in a ν_α neutrino beam:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \ \sin^2\left(\frac{1.27 \Delta m^2 L}{E_\nu}\right)$$



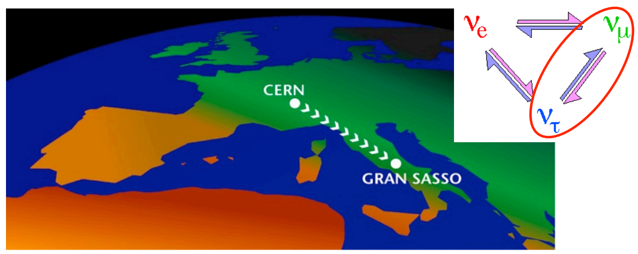
Present accelerator neutrino oscillation facilities in the world



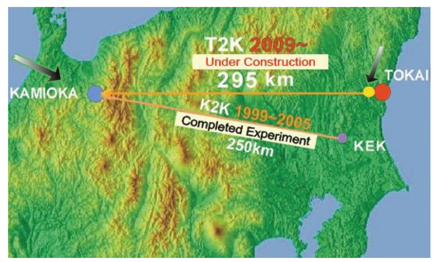
NUMI beam and MINOS experiment
(disappearance experiment)

MINOS Best Fit Parameters

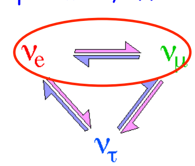
$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$
$$\sin^2(2\theta) > 0.890\ (90\%\ \mathrm{C.L.})$$



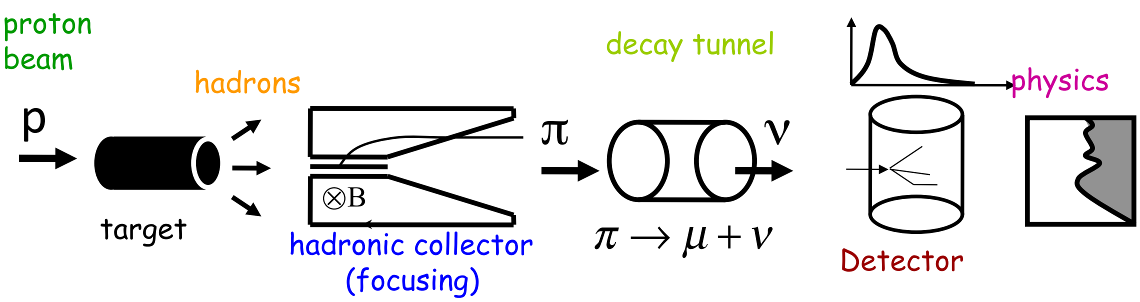
CNGS beam and OPERA (ICARUS) experiment
($\nu_\mu \rightarrow \nu_\tau$ appearance experiment)



JPARC beam and T2K experiment (appearance/ disappearance experiment, off-axis)

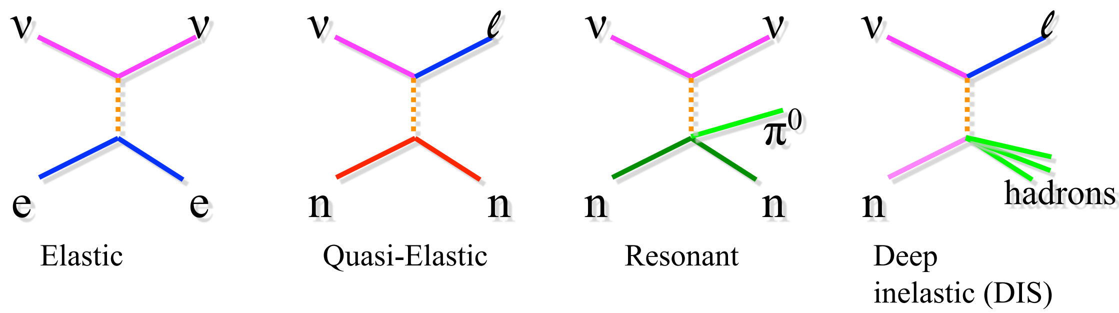


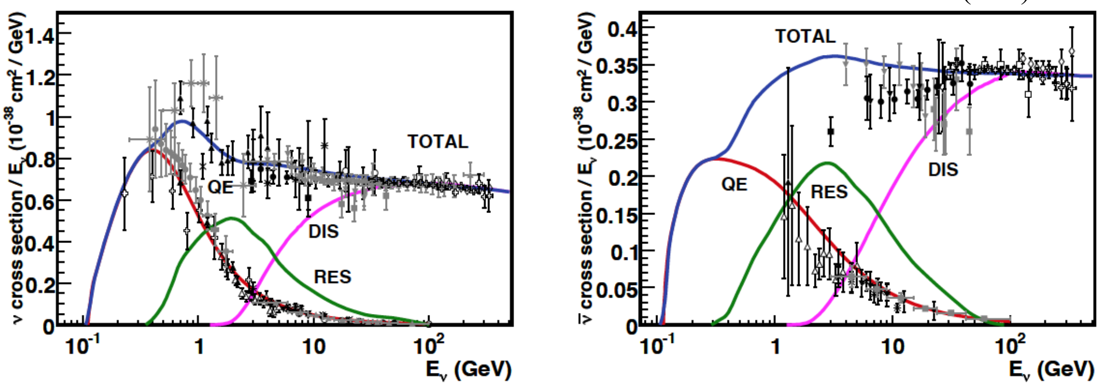
How can we produce a neutrino beam?



- adjustable proton energy,
- adjustable distance between the production point and the detector,
- neutrino type choice (neutrinos or anti-neutrinos),
- but as usual, the neutrino energy is not well defined...

Neutrino Interactions



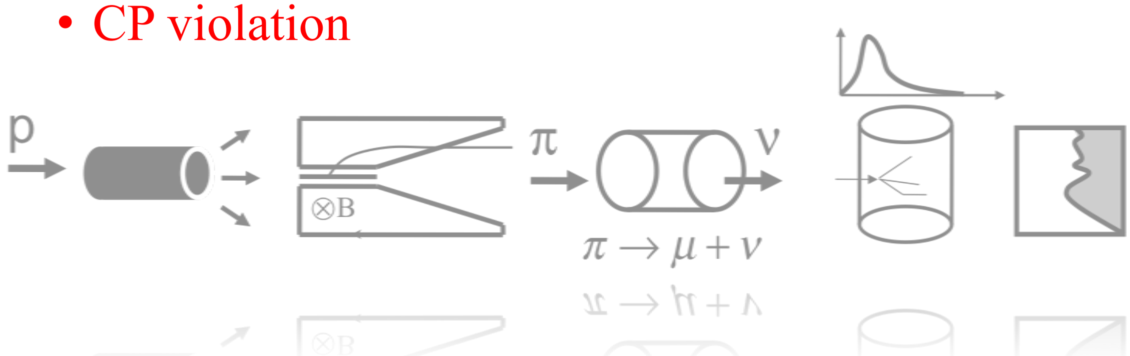


According to neutrinos to be detected their interaction cross-section has to be taken into account.

Meanwhile…

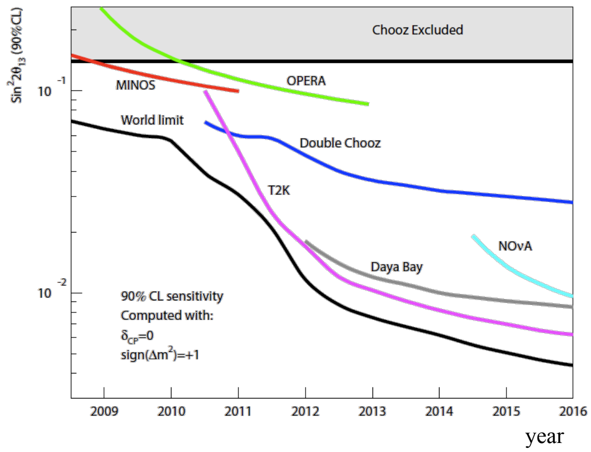
New proposals for neutrino beams to measure:

- θ_{13} as low as possible
- neutrino mass hierarchy (sign of Δm_{13})
- CP violation



θ_{13} hunting…

~short term expectations

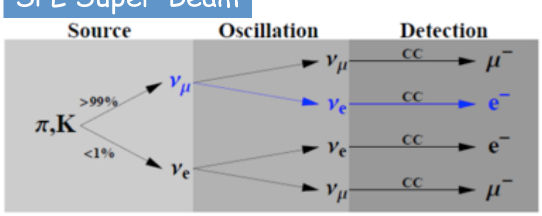


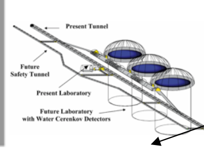
optimization in order to go as low as possible in θ_{13}

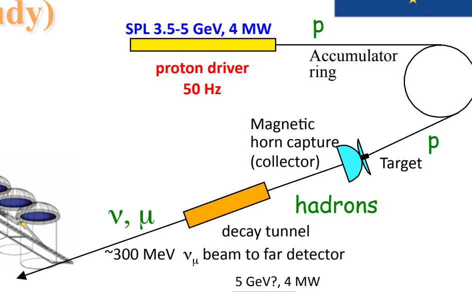
EUROnu Projects

(FP7 design study)

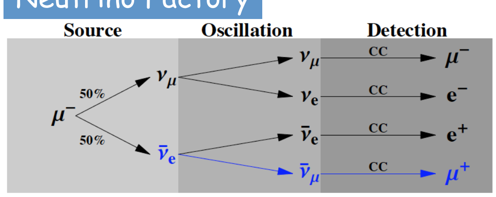
SPL Super-Beam

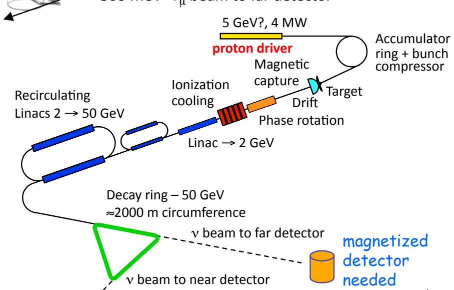




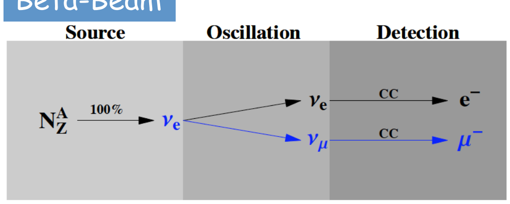


Neutrino Factory

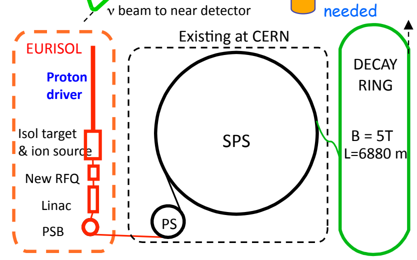




Beta-Beam



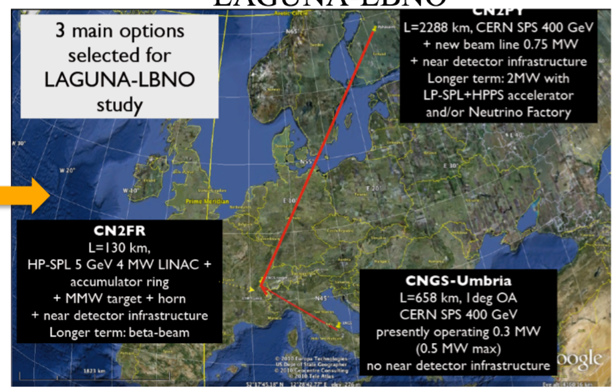
^{6}He for ν_e and
^{18}Ne for ν_e
γ~100



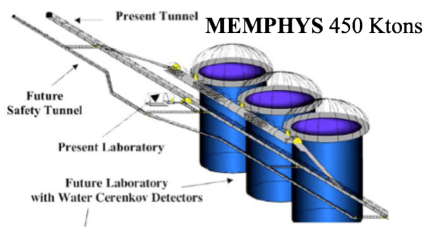
All sites and detection techniques studied by LAGUNA and possible neutrino beams from CERN

LAGUNA

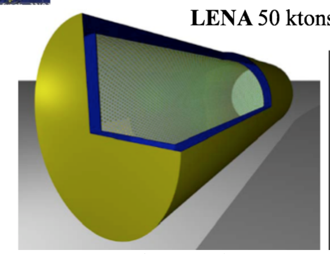
LAGUNA-LBNO



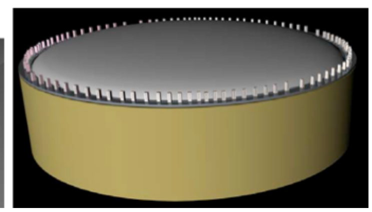
MEMPHYS 450 Ktons



LENA 50 ktons



GLACIER 100 ktons



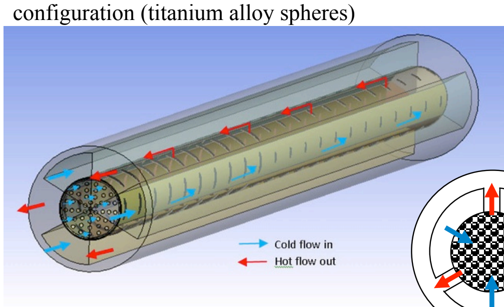
Technological Challenges for next high intensity neutrino beams

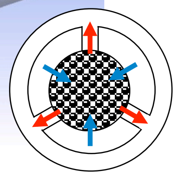
- Very high proton beam power is needed:
  - several MW
  - maximum achieved up to now for neutrino beams ~450 kW
- High repetition rate:
  - up to 50 Hz
  - maximum rate up to now 5 Hz
- Severe radiation conditions
  - remote manipulation systems
  - tritium production
  - …

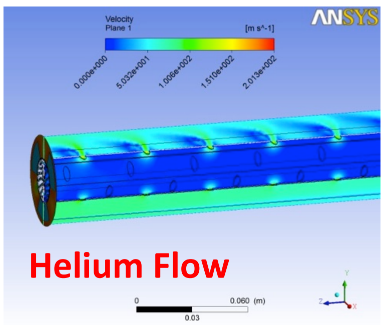
Mitigation of high power effects

(4-Target/Horn system for EUROnu Super Beam)

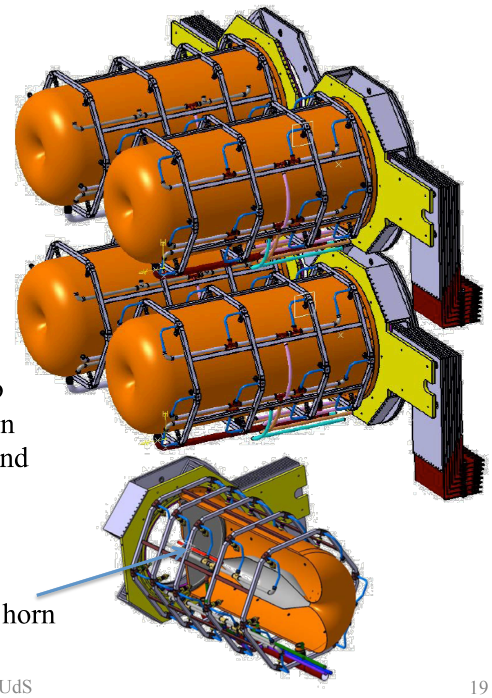
Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)





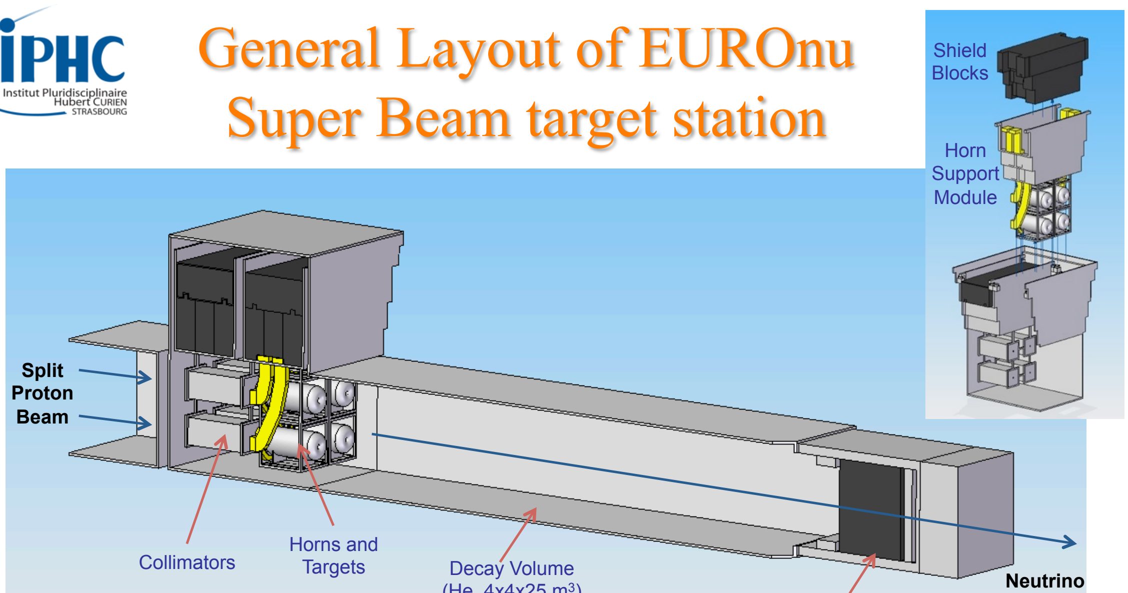


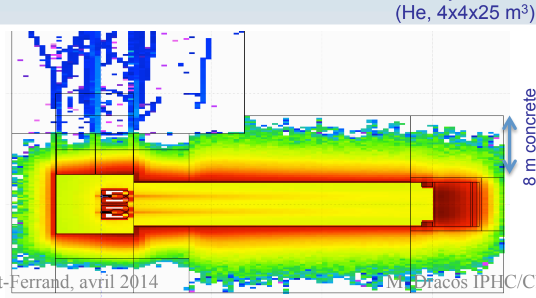
4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)

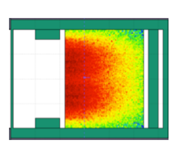


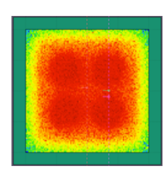
target inside the horn

General Layout of EUROnu Super Beam target station

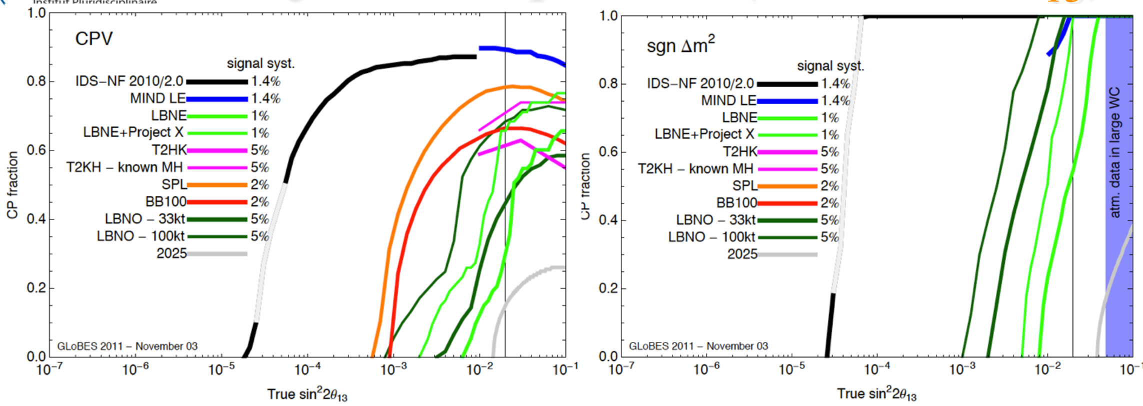








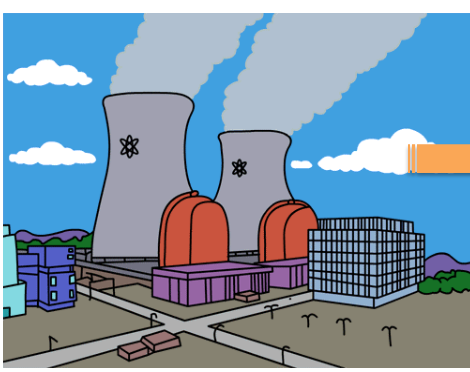
Project Comparison (unknown θ_{13})

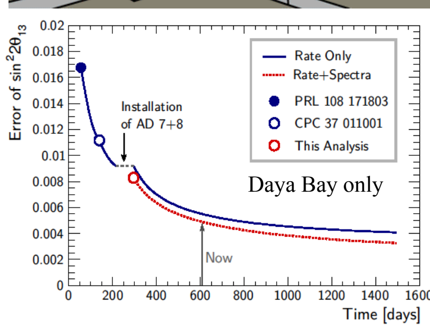


name	baseline	type	mass	power	sec. in year	years	sig. syst.
LBNE	1300	WC/LAr	200/33	0.7MW	2×10^7	5+5	1%
LBNE+ Pro. X	1300	WC/LAr	200/33	2.3MW	2×10^7	5+5	1%
LBNO 33kt	2300	LAr	33	1.7MW	1.7×10^7	5+5	5%
LBNO 100kt	2300	LAr	100	1.7MW	1.7×10^7	5+5	5%
T2HK	295	WC	560	1.66MW	1×10^7	2.1+2.9	5%
SPL	130	WC	440	4MW	1×10^7	2+8	2%
BB100	130	WC	440	1.1×10^{18} Ne 2.9×10^{18} He	1×10^7	5+5	2%
IDS-NF 2.0	4000+7500	MIND	100+50	4MW	1×10^7	5+5	1.4%
MIND LE	2000	MIND	100	4MW	1×10^7	5+5	1.4%

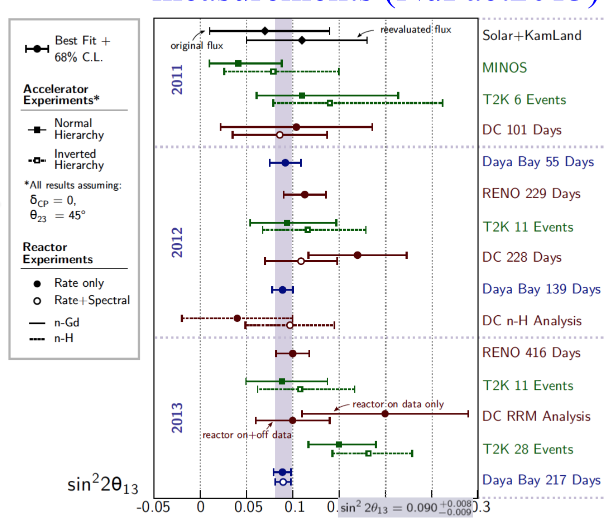
θ_{13} is large!!!

reactor experiments discovered the $1\to3$ oscillation





measurements (NuFact2013)



proposed facilities have to be readjusted…
now, the name of the game is CPV

Upgrades of Present accelerator neutrino oscillation facilities in the world
(CPV, MH)

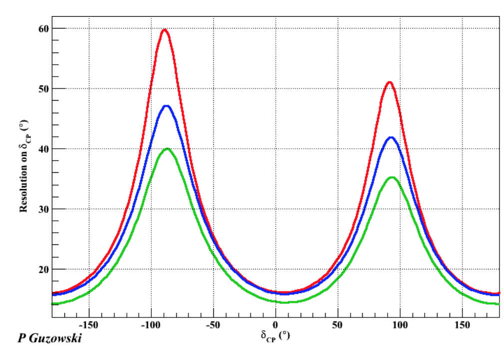
- CNGS ⇒ finished without any possibility of upgrade
- NUMI ⇒ increase the proton beam power
  - MINOS+
  - NOνA
- JPARC
  - go to the designed power of 0.75 MW
  - increase the power at 1.66 MW

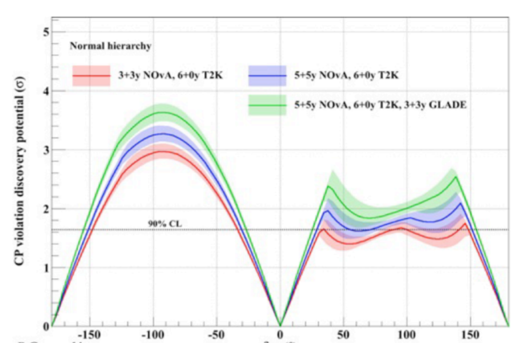
Getting the Most Out of NuMI Beam

CPV

- **CPV and resolution on δ_{CP}:**

3 possibilities:
- NOνA+T2K
- NOνA+T2K+MINOS (significant improvement by adding MINOS)
- NOνA+T2K+GLADE (LAr 5 kt) (significant improvement by adding GLADE)





CP Violating Observables (and MH)

$$P_{\nu_\mu\to\nu_e(\bar\nu_\mu\to\bar\nu_e)} = s_{23}^2\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde B_\mp}\right)^2\sin^2\left(\frac{\tilde B_\mp L}{2}\right)$$ atmospheric

$$+c_{23}^2\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right)$$ solar

Non-CP terms

$$+\tilde J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde B_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde B_\mp L}{2}\right)\cos\left(\pm\delta_{CP}-\frac{\Delta_{13}L}{2}\right)$$ interference

CP violating

$$\tilde J \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij}\equiv\frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde B_\mp \equiv |A\mp\Delta_{13}|,\ A=\sqrt{2}G_F N_e$$

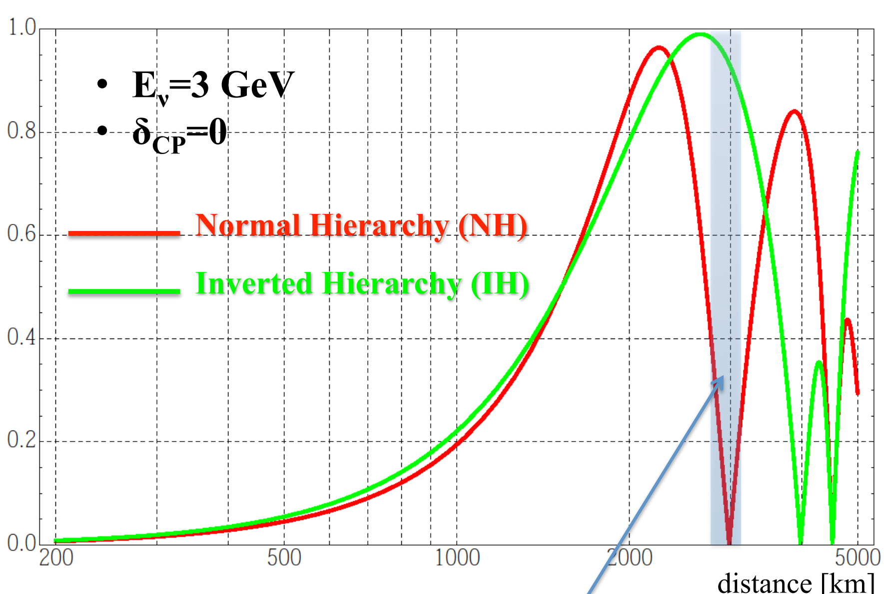
matter effect
⇒ accessibility to mass hierarchy
⇒ long baseline

$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar\nu_\mu\to\bar\nu_e}}$$

≠0 ⇒ CP Violation
be careful, matter effects also create asymmetry

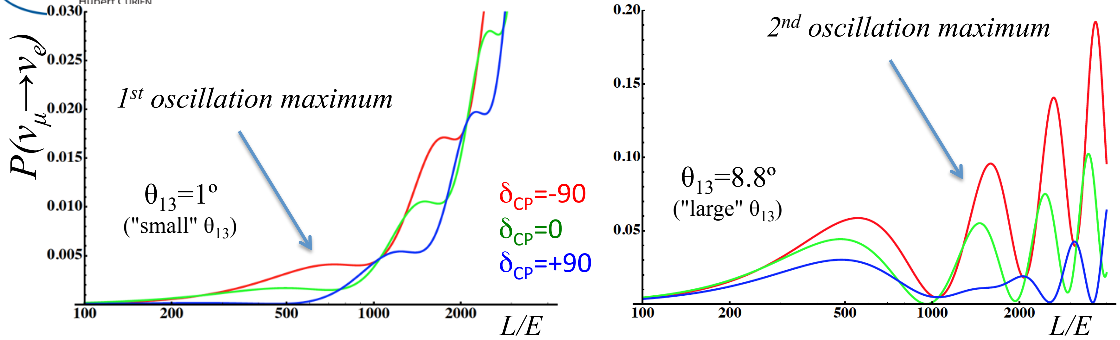
Asymmetry due to matter effects

$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar\nu_\mu\to\bar\nu_e}}$$

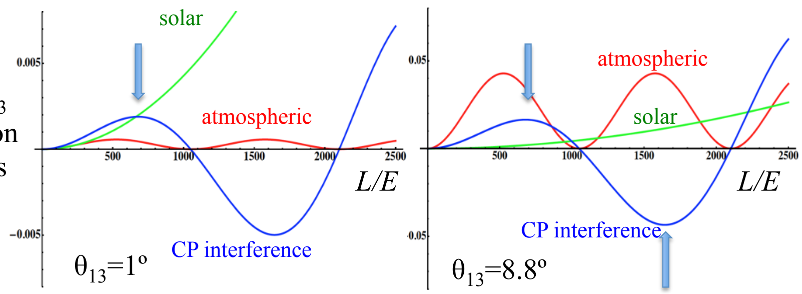


good position to measure MH

Neutrino Oscillations with "large" θ_{13}



for small θ_{13} 1st oscillation maximum is better

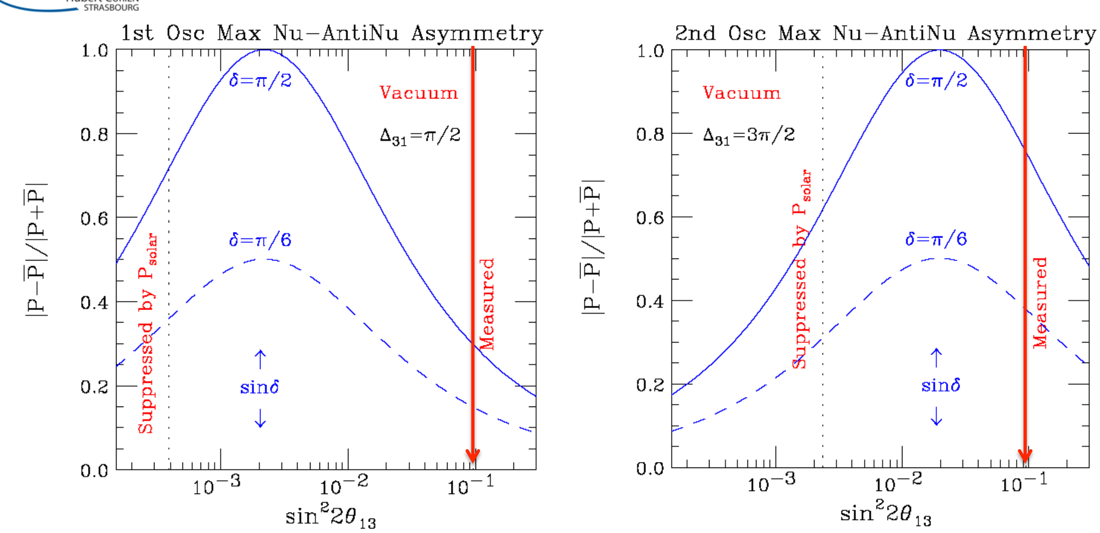


for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term,

→ 2nd oscillation maximum is better

(arXiv:1110.4583)

Neutrino Oscillations with "large" θ_{13}

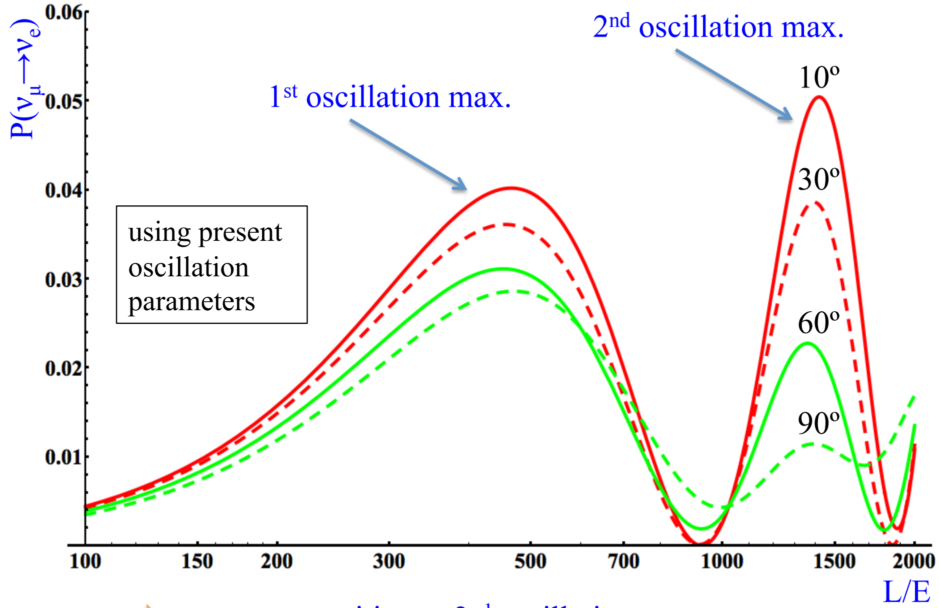


- at the 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- at the 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

→ 2nd oscillation maximum is better

(see arXiv:1310.5992 and arXiv:0710.0554)

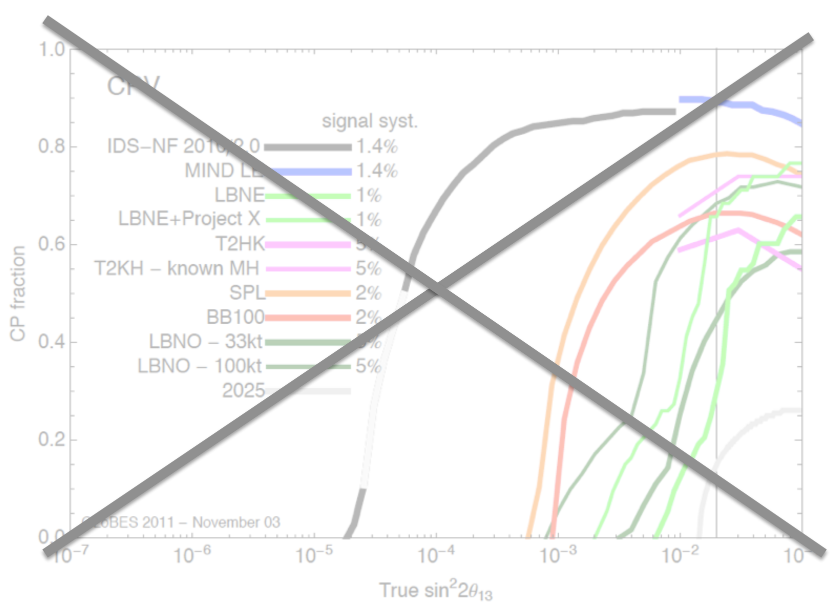
Neutrino Oscillations with "large" θ_{13}



more sensitive to 2nd oscillation max.

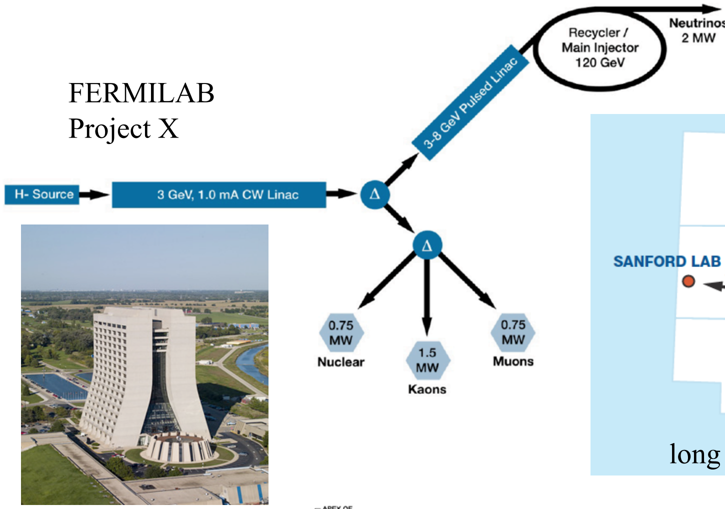
But, to go to the 2nd oscillation max. we must be very rich in protons…

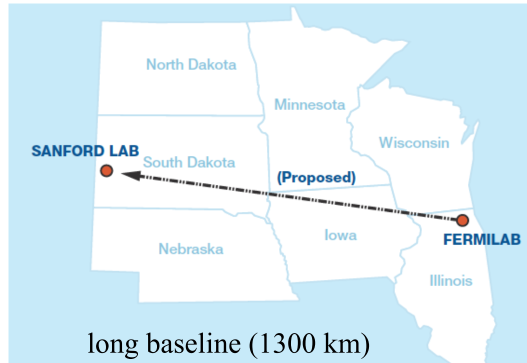
Future accelerator neutrino projects after θ_{13} measurement

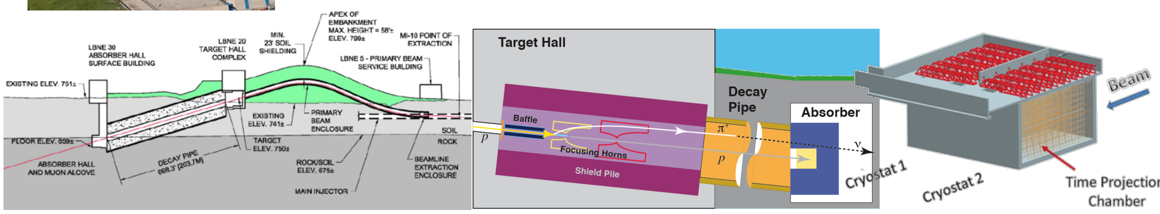


Opportunities for Precision Tests of Three-Neutrino Mixing and Beyond with LBNE

FERMILAB
Project X



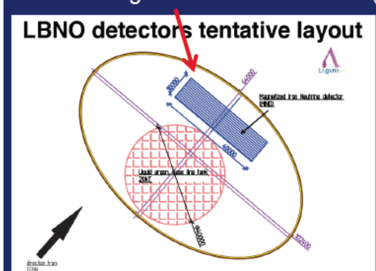


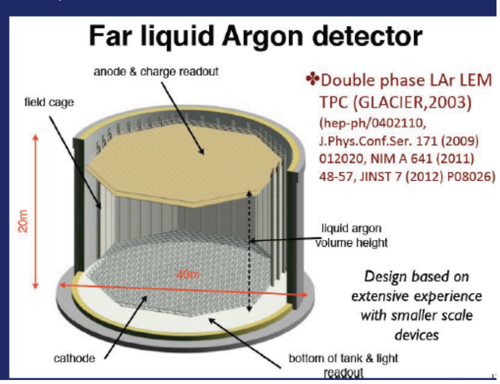


LAGUNA-LBNO

20 Kton double phase LAr TPC
LNG tank technology

35 kton magnetized muon detector (MIND)

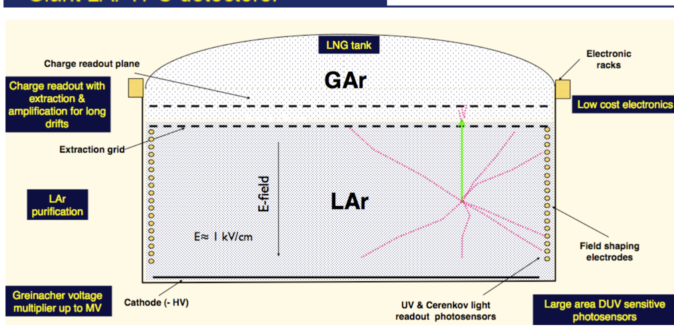


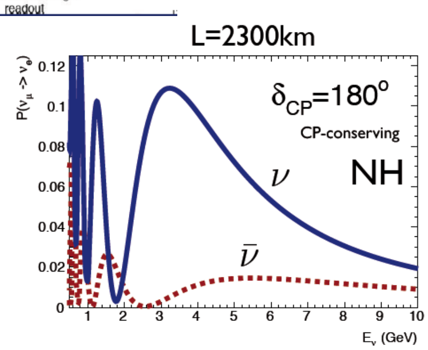


+ near detector at CERN

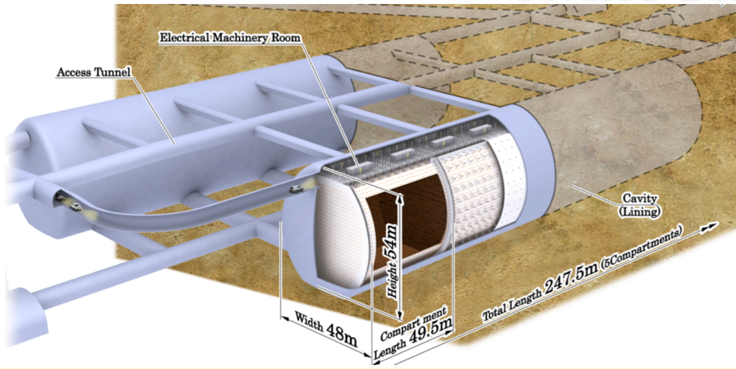
Giant LAr TPC detectors:

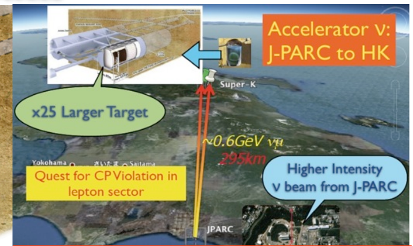
good mass hierarchy sensitivity, thanks to the crossed matter (2300 km)





Hyper-Kamiokande Physics Opportunities: Exploring CP Violation with the Upgraded JPARC Beam



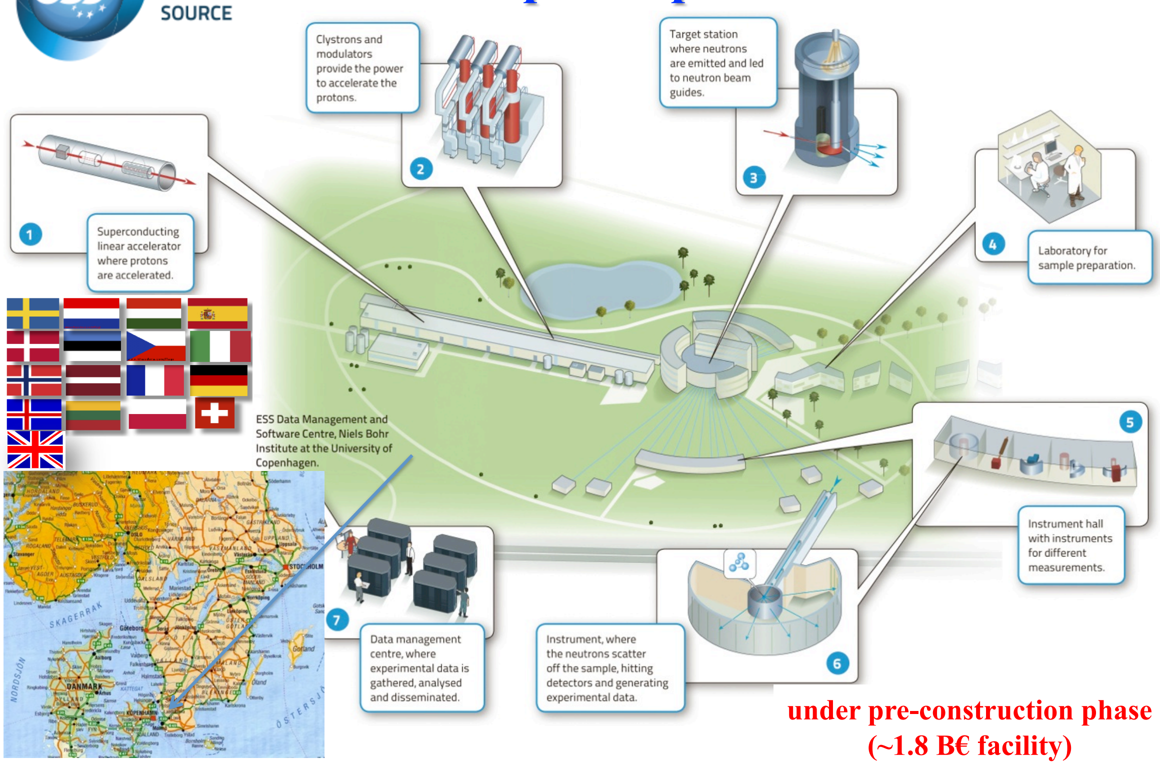


Total mass: 1Mton
Fiducial mass: 560 kton
(2.5º off-axis)
30 GeV protons

- Exploring the full picture of neutrino oscillations
  - Neutrino beam from J-PARC (≥1MW expected)
    - CP asymmetry in lepton sector
  - Atmospheric neutrinos
    - Determination of mass hierarchy and θ_{23} octant
- Search for proton decay
- Measurements of solar and astrophysical neutrinos

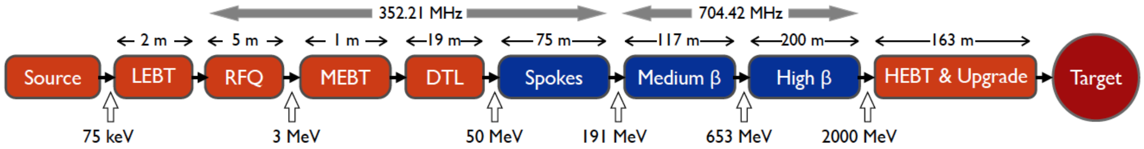
European Spallation Source

EUROPEAN SPALLATION SOURCE

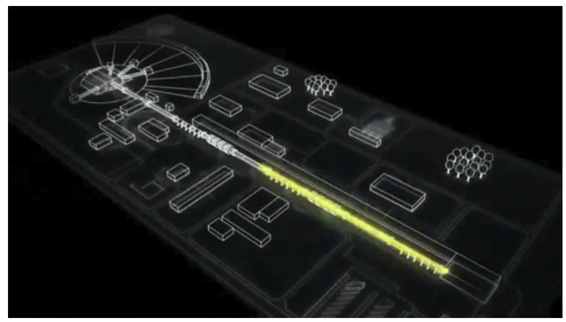


under pre-construction phase
(~1.8 B€ facility)

ESS proton linac



- The ESS will be a copious source of spallation neutrons
- 5 MW average beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **>2.7x10^{23} p.o.t/year**



ESS Schedule

2010 - **ESS Company set up**

2010 - 2012 **Technical Design Review**
2010 - 2012 **Pre-Construction & Site Planning**
2009 - 2012 **Licensing and Planning**
2010 - 2012 **Finalisation of international negotiations**

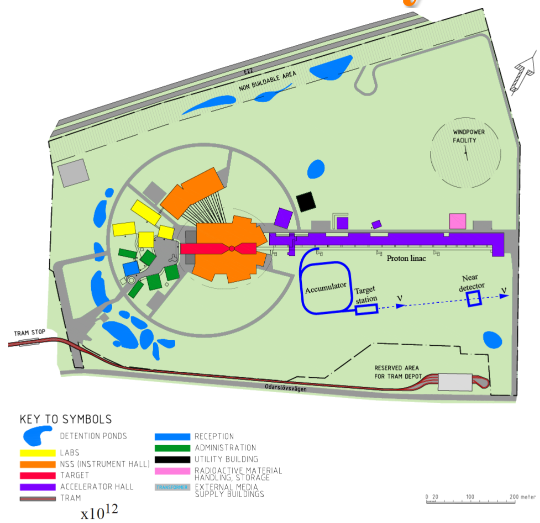
2013 - 2019 **Construction Phase - 7 instruments**
2019 - 2025 **Completion Phase - all 22-33 instruments in place**

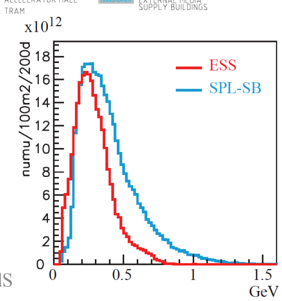
2026 - 2066 **Operations Phase**
2066 – 2071 **Decommissioning Phase**

- 1st beam before the end of the decade
- 5 MW by 2023

How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (ø 143 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons)
  - space charge problems to be solved
- ~300 MeV neutrinos
- Target station (studied in EUROnu)
- Underground detector (studied in LAGUNA)
- Short pulses (~μs) will also allow DAR experiments
- Linac and accumulator could be the first step towards the Neutrino Factory





neutrino flux at 100 km (similar spectrum than for EUROnu SPL SB)

ESS Neutrino Super Beam (ESSνSB)

A Very Intense Neutrino Super Beam Experiment for Leptonic CP Violation Discovery based on the European Spallation Source Linac: A Snowmass 2013 White Paper

arXiv:1212.5048
arXiv:1309.7022

arXiv:submit/0845470 [hep-ex] 12 Nov 2013

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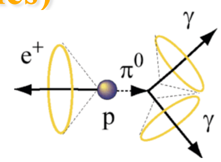
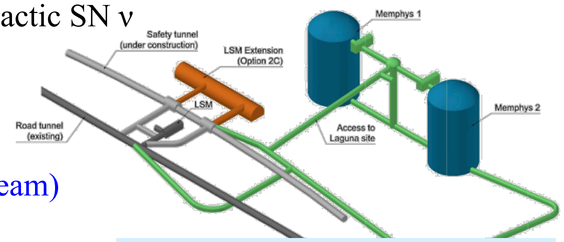
14 participating institutes form 10 different countries, among them ESS and CERN

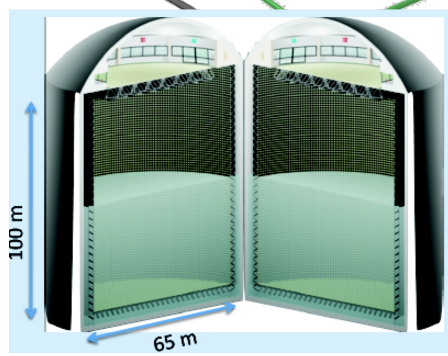
The MEMPHYS WC Detector
(MEgaton Mass PHYSics)

- Proton decay
- Astroparticles
- Understand the gravitational collapsing: galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Neutrino Oscillations (Super Beam, Beta Beam)
- Atmospheric Neutrinos



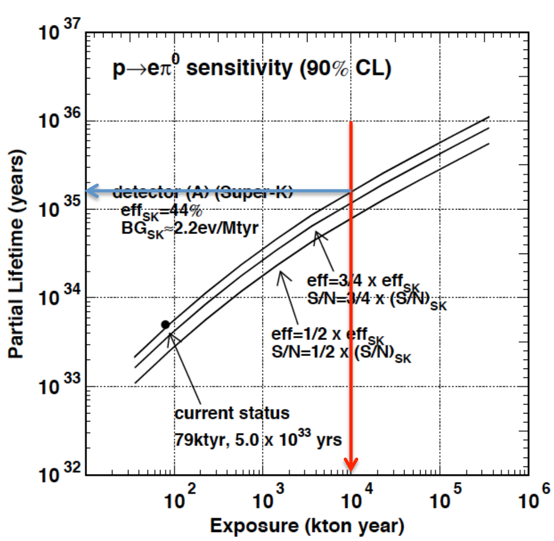


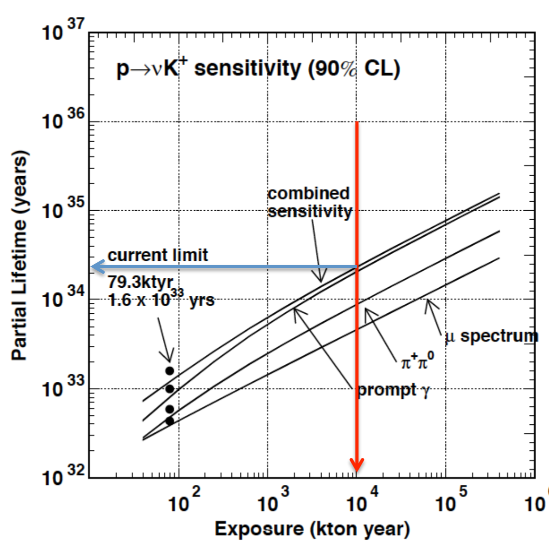
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage



(arXiv: hep-ex/0607026)

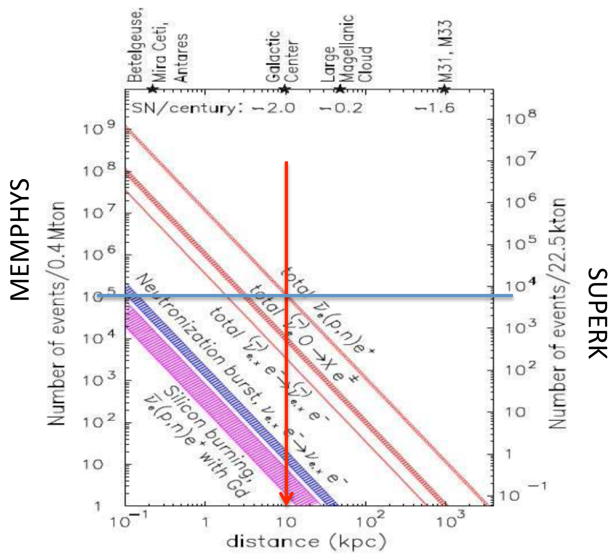
The MEMPHYS Detector
(Proton decay)

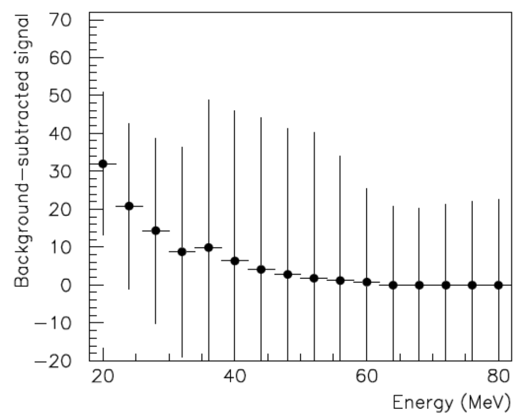




(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)

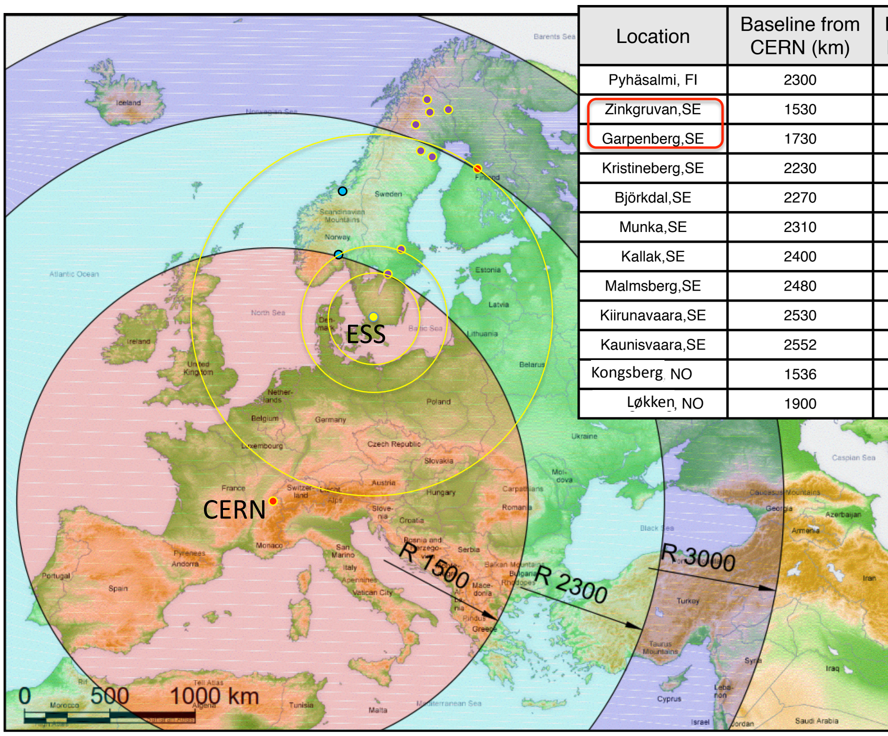




For 10 kpc: ~10^5 events

Diffuse Supernova Neutrinos
(10 years, 440 kt)

WC detector possible locations

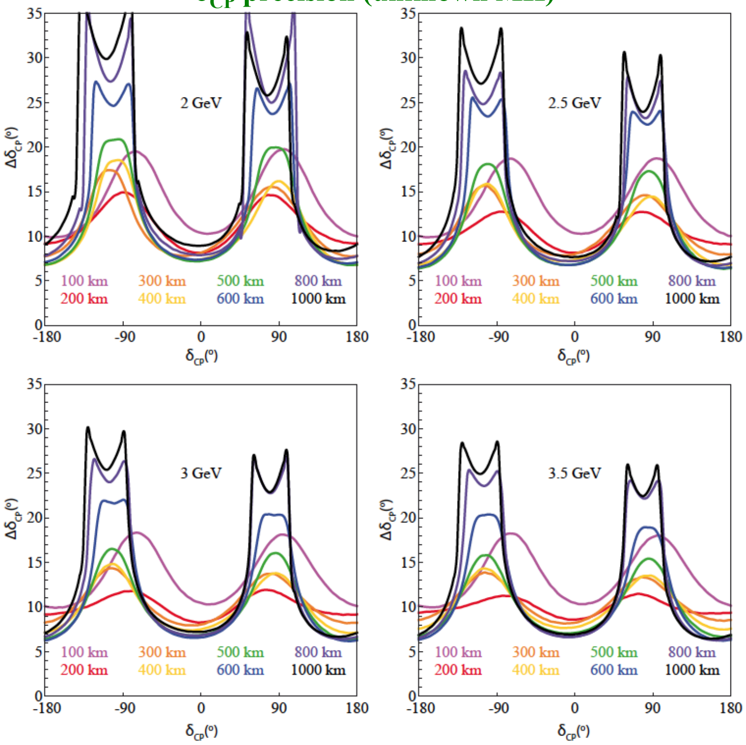


Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320
Kiirunavaara,SE	2530	1700	1380
Kaunisvaara,SE	2552	1580	1390
Kongsberg, NO	1536	1740	500
Løkken, NO	1900	1800	840

Physics Performance for ESSνSB

(Enrique Fernantez, Pilar Coloma)

δ_{CP} precision (unknown MH)

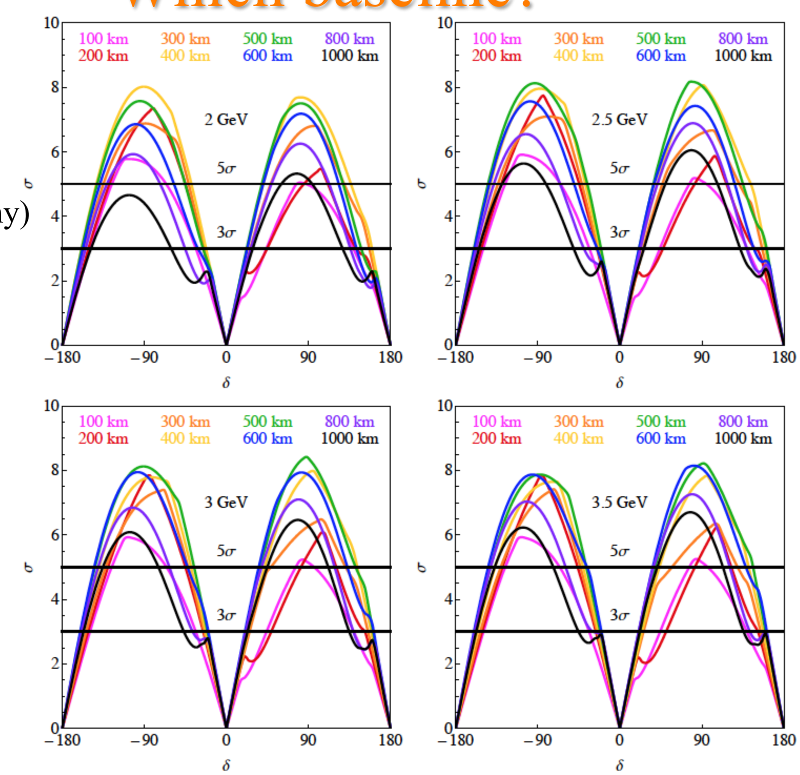


- for 2 GeV
  - optimum 300-400 km
- for 3.5 GeV
  - optimum 500-600 km
- but the variation is small

- CPV discovery implies exclusion at 5 σ of 0° and 180°
- high δ_{CP} resolution around these values is needed
- 1° gain around these values increase the discovery δ_{CP} range by ~4x5x1° (1st approx.)

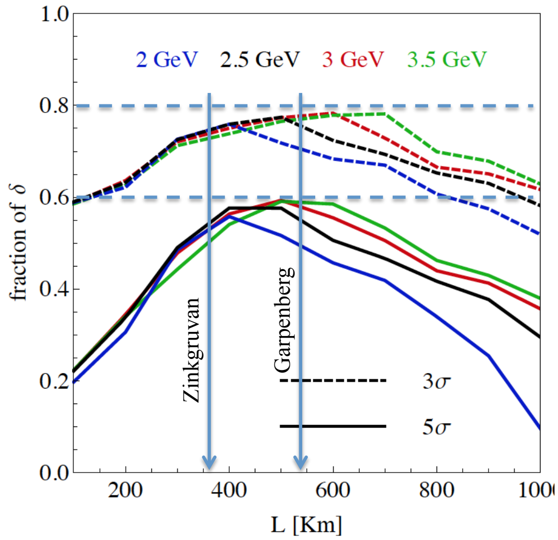
Which baseline?

discovery potential
(unknown mass hierarchy)

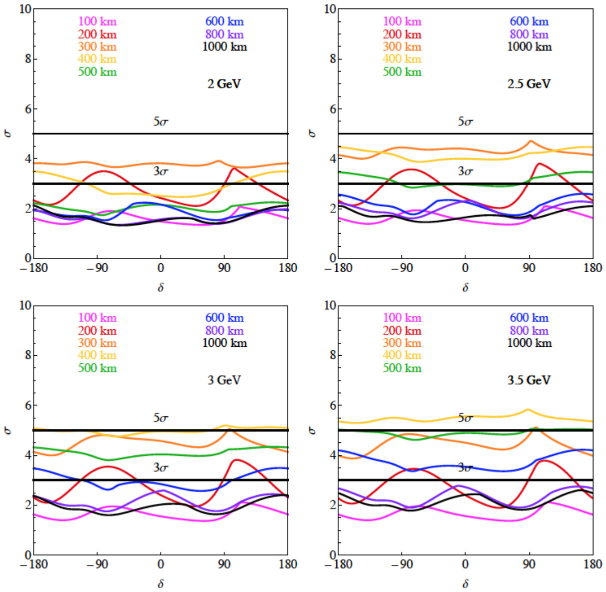


Which baseline?

CPV



MH



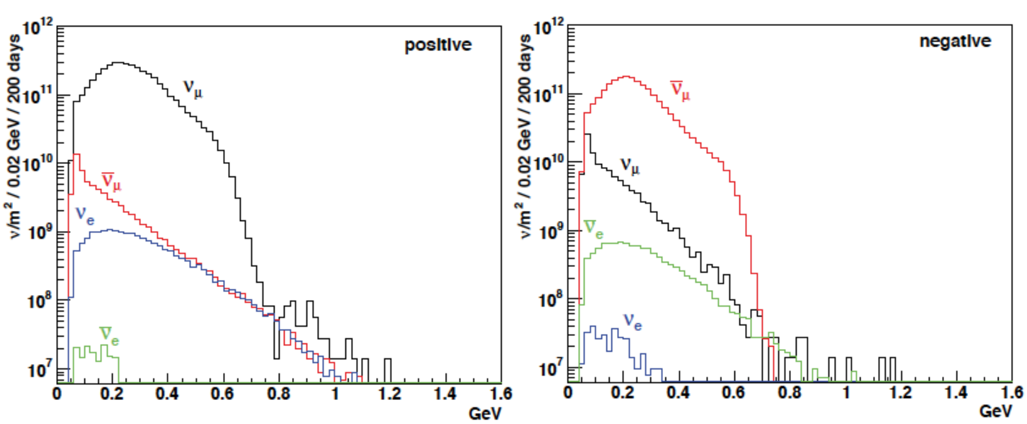
- Zinkgruvan is better for 2 GeV
- Garpenberg is better for > 2.5 GeV
- **systematic errors: 5%/10% (signal/backg.)**

- Zinkgruvan is better
- **atmospheric neutrinos are needed (at least at low energy)**

ESS neutrino energy distribution

	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

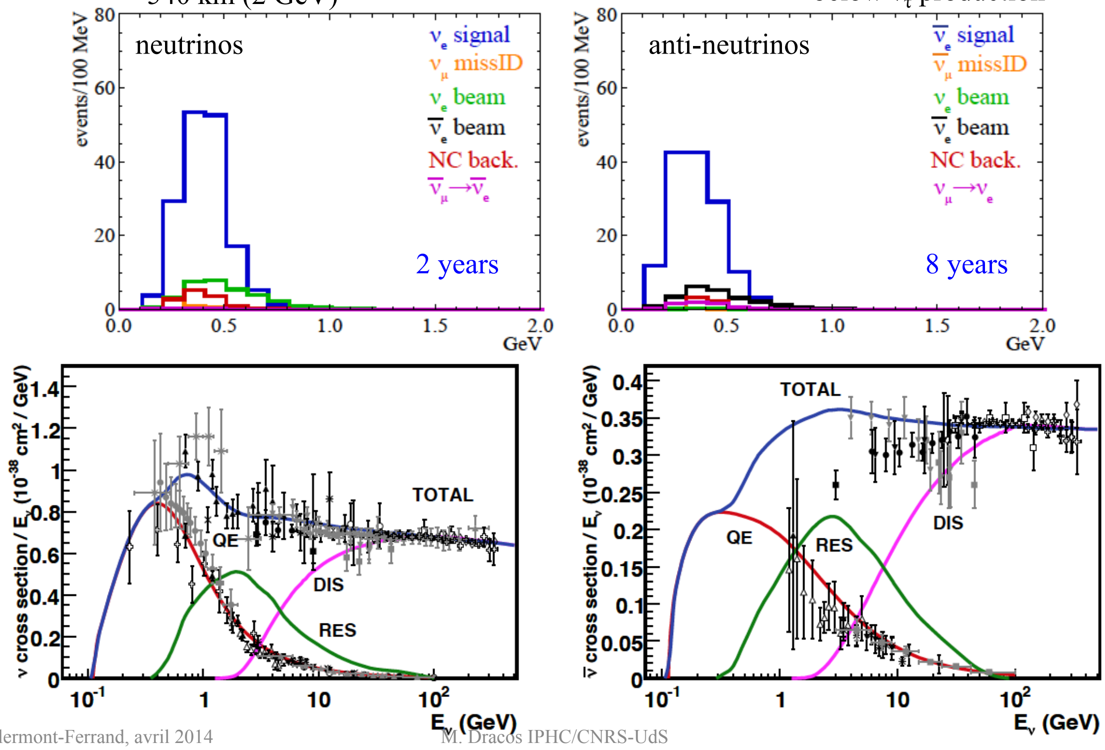
at 100 km from the target and per year



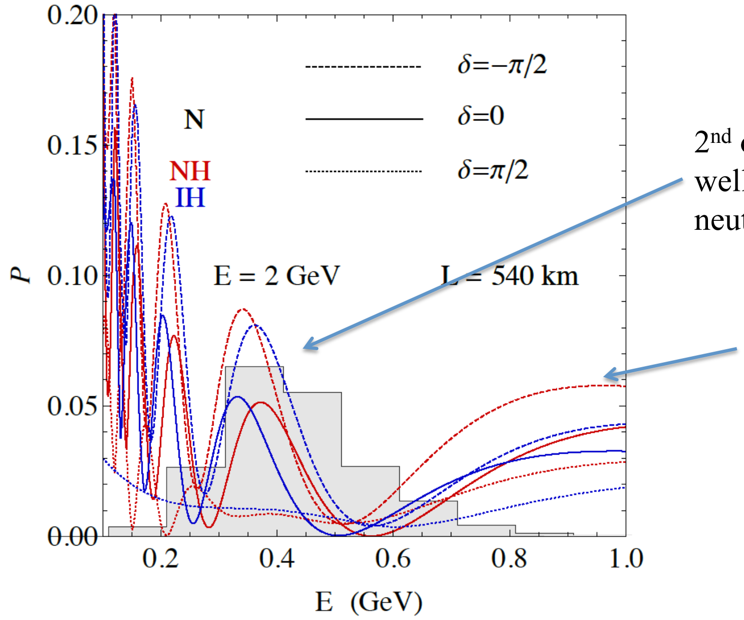
Neutrino spectra

540 km (2 GeV)

below ν_τ production



2nd Oscillation max. coverage

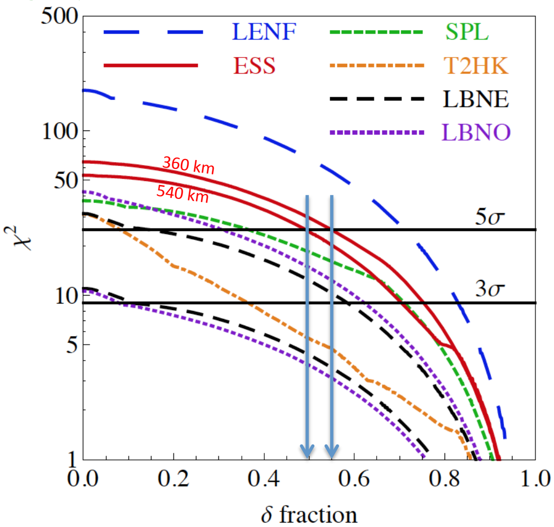


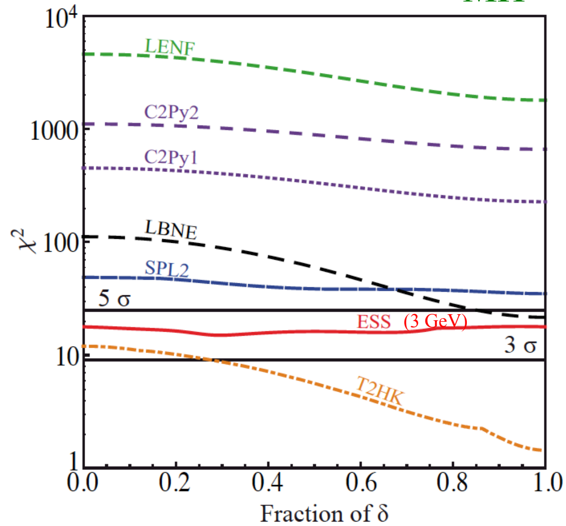
2[nd] oscillation max. well covered by the ESS neutrino spectrum

1[st] oscillation max.

Physics Performance for Future SB projects

CPV (unknown MH) MH

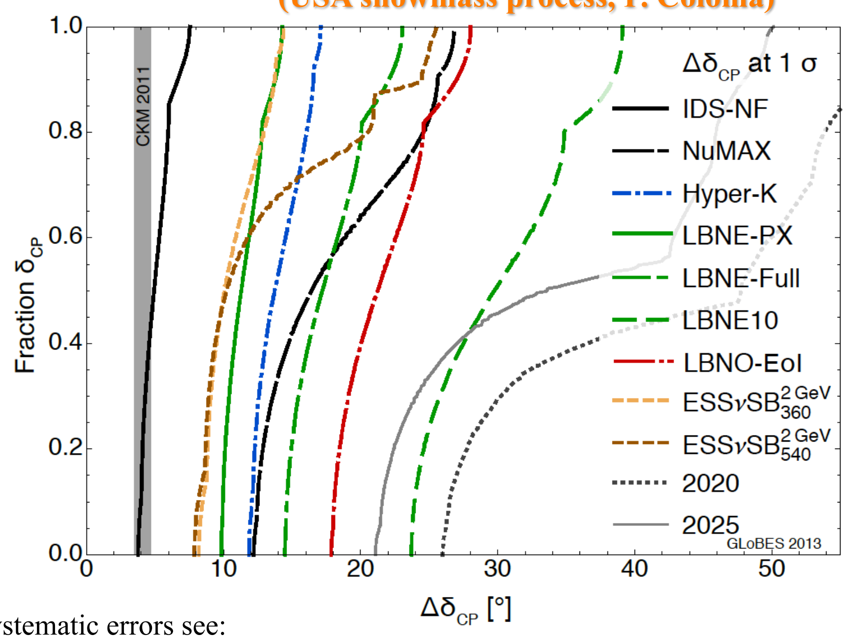




- LBNE: 5+5 years, 0.7 MW, 10/35 kt LAr
- T2HK: 3+7 years, 0.75 MW, 500 kt WC (5%/10% syst. errors)
- SPL: 2+8 years, 4 MW, 500 kt WC (130 km, 5%/10% syst. errors)
- ESS: 2+8 years, 5 MW, 500 kt WC (2 GeV, 360/540 km, 5%/10% syst. errors)
- C2Py: 20/100 kt LAr, 0.8 MW, 2300 km

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)



for systematic errors see:

- Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]
- **arXiv:1310.4340 [hep-ex] Neutrino "snowmass" group conclusions**

Next Steps
(near future)

- Design Study to be submitted to EU (HORIZON2020) before September 2014.
- second preparatory open meeting at CERN 26-27 May to:
    - finalize the content of the EU Design Study
    - prepare the resource requests
    - you are invited to join

Conclusions

- Present neutrino accelerator experiments
    - confirmation of θ_{13} value measured by reactor experiments
    - cannot discover CPV
    - cannot determine mass hierarchy
- Under preparation neutrino accelerator experiments
    - cannot discover CPV but could give some indications
    - hopefully they will determine mass hierarchy
- Very intense neutrino beams are needed
    - Neutrino Super Beam based on ESS linac is very promising
    - ESS will have enough protons to go to the 2^{nd} oscillation maximum and increase its CPV sensitivity
    - CPV: 5 σ could be reached over 60% of δ_{CP} range (ESSνSB)
    - large associated detectors have a rich astroparticle physics program

Collaborators are welcome…

(just email tord.ekelof@physics.uu.se, marcos.dracos@in2p3.fr)