Experimental overview of current and future neutrino experiments

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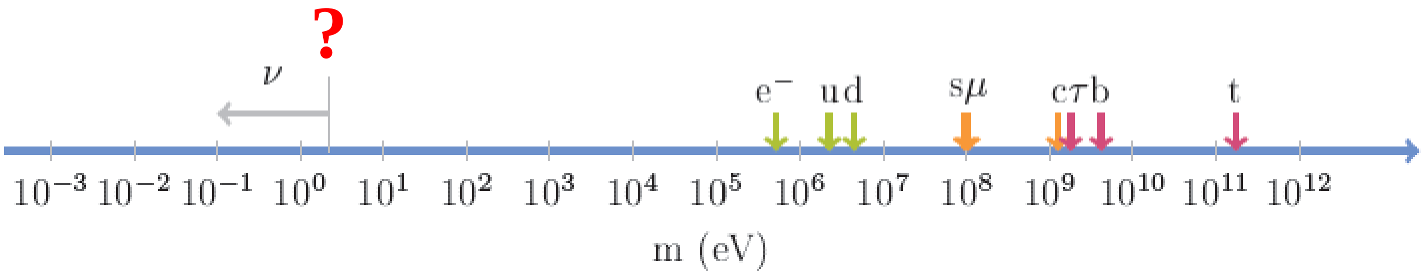
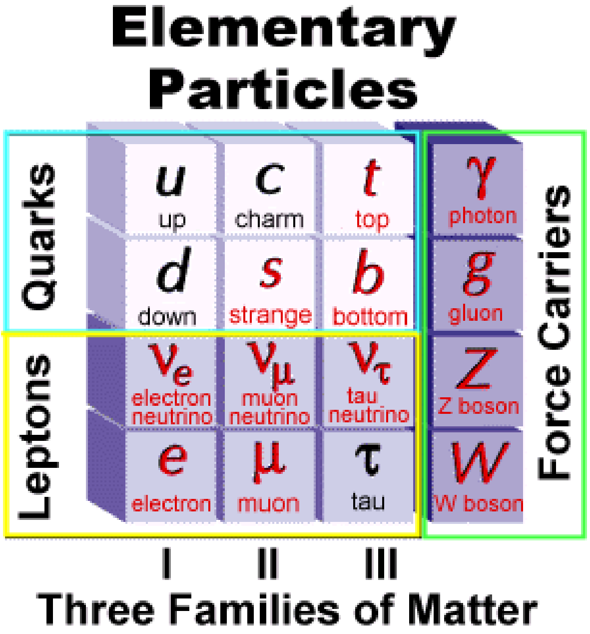
LAPP, Annecy

- Introduction
- Neutrino mass and nature
- Oscillation physics: towards CP violation and Mass hierarchy
- Anomalies and sterile neutrino search
- Conclusions



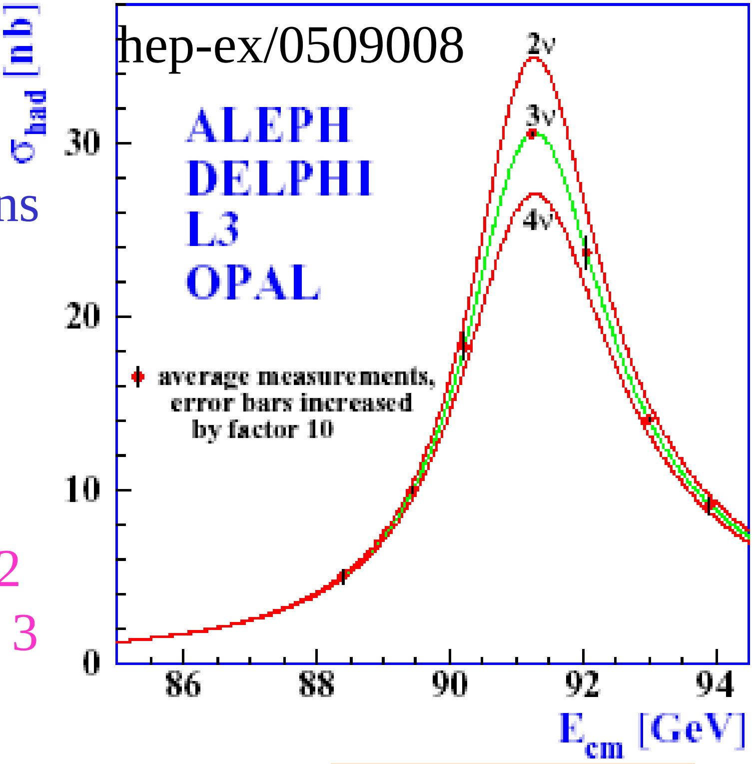
ENIGMASS Kick-off meeting
LAPP, October 12th 2012

The neutrinos and the Standard Model :

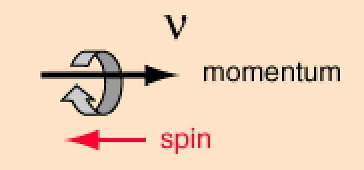


- Neutral spin ½ fermions
- Subject to Weak interactions only.

LEP
→ N_ν= 2.9840+- 0.0082
No room for more than 3 light ν species



Standard Model: ν are always Left Handed and $m_\nu = 0$



Flavour changing process observed (oscillation):

→ ν are massive => hints for physics beyond the standard model

→SM should be extended to reconcile with massive ν and the Higgs

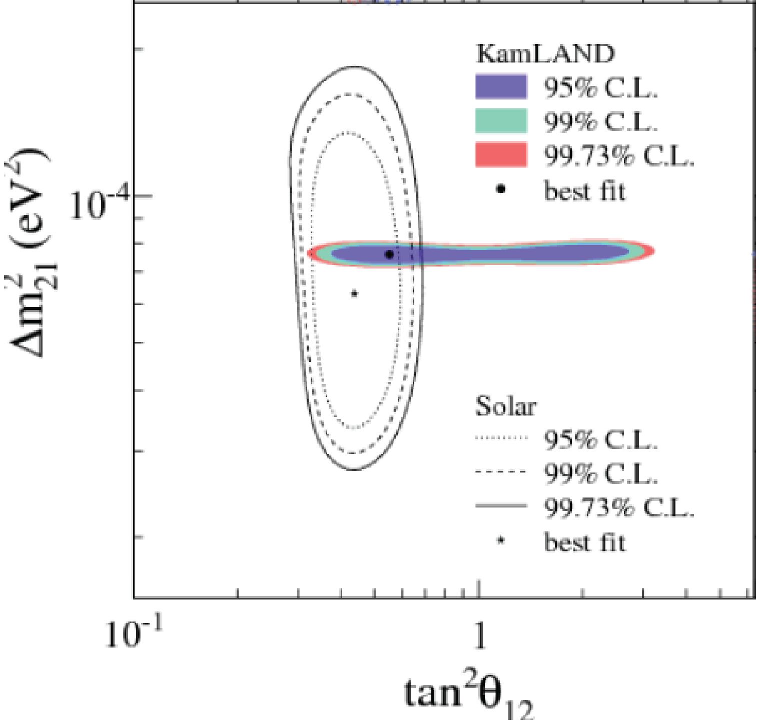
-Dirac ν: minimal extension with Dirac mass term but RH ν interacts with Higgs too weakly (10^{12} times weaker than that of the top) to acquire mass

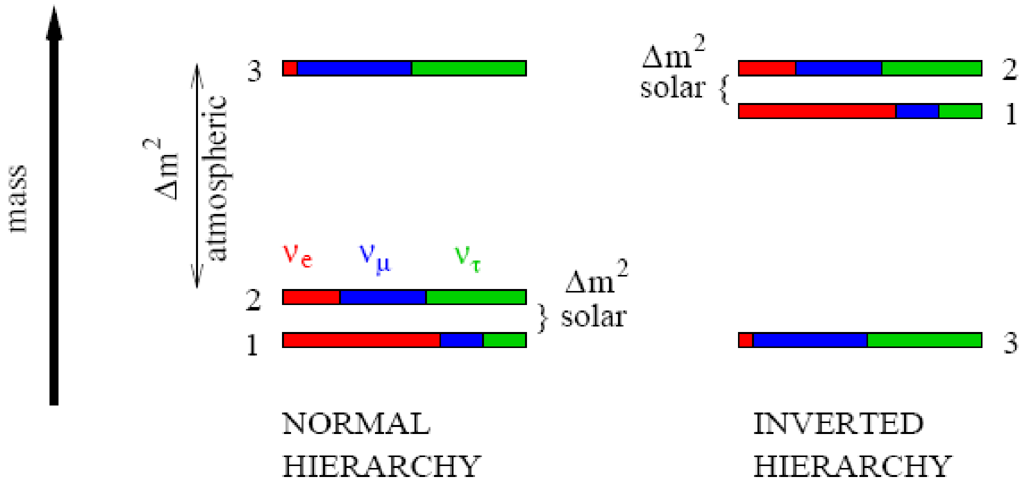
- Majorana ν: Heavy RH neutrinos are created for a brief moment (See-Saw mechanism) from LH ν interaction with Higgs ; no fundamental distinction between matter and anti-matter

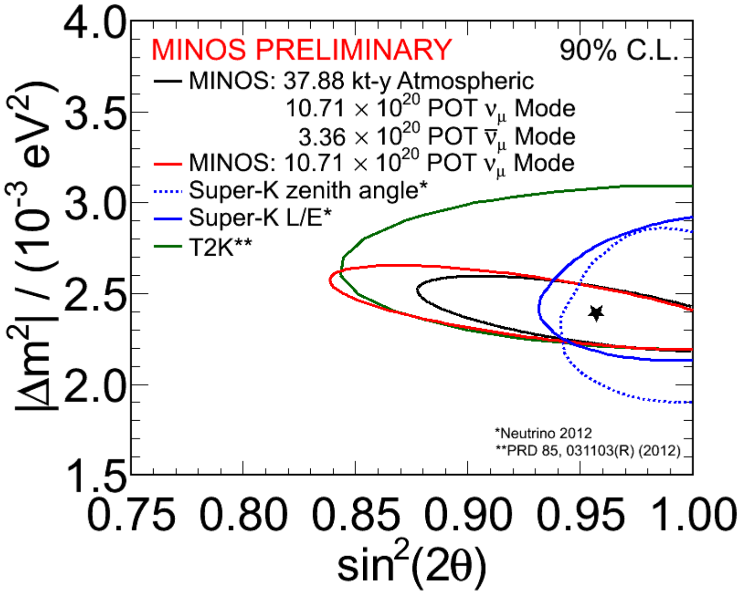
Neutrino mixing status in 2012

6 parameters		Precision 2σ
Δm^2_{12}	7.54 10^{-5} eV²	5%
$\|\Delta m^2_{23}\|$	2.43 10^{-3} eV²	7%
$\sin^2\theta_{12}$	0.307	11%
$\sin^2\theta_{23}$	0.386	12%
$\sin^2\theta_{13}$	0.024	21%
δ	?	

Ref: G.L. Fogli et al. arXiv:1205.5254v3







Some neutrino open fundamental questions and how to answer experimentally

- absolute mass scale?

-> fundamental for cosmology and unification scheme of interactions

time of flight: Supernova 1987A m< 20 eV

end of electron beta spectrum : Tritium m< 2.5 eV

Fluctuations of Cosmological Microwave Background: WMAP m<0.23 eV

- are neutrinos their own antiparticle (Majorana neutrinos) or not (Dirac neutrinos)

search for neutrinoless double beta decay (possible clue to absolute mass scale)

- relation between neutrino flavor eigenstates and mass eigenstates (mixing matrix) under investigation => key result has been obtained this year with θ_{13}

- Is there CP violation in the neutrino sector? (LEPTOGENESIS)

- Are there "sterile" neutrinos? Are there more than 3 mass eigenstates?

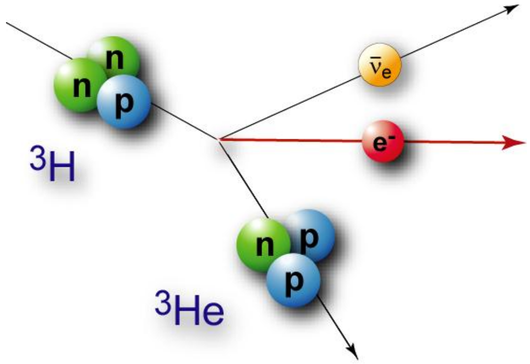
flavour oscillations

Use all possible neutrino sources: Sun, nuclear reactors, atmospheric showers, beam accelerators of various energies……

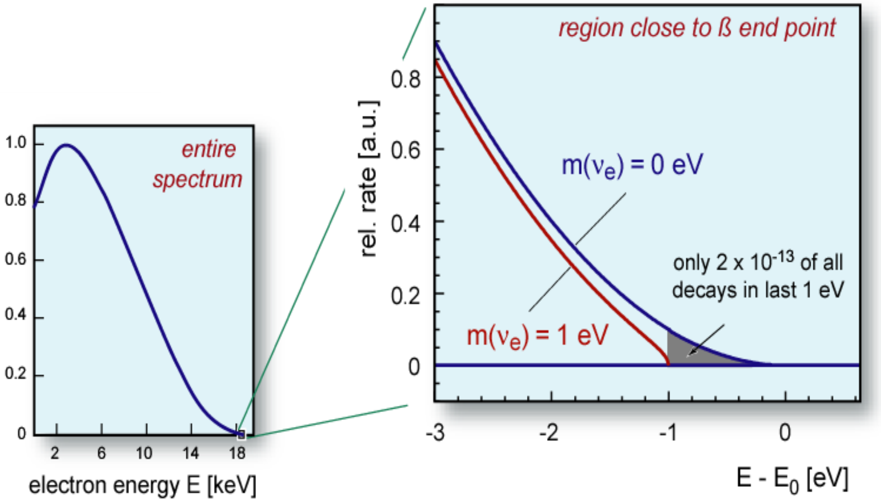
Neutrino mass:

Cosmological limit: in the future with galaxy and CMB lensing (Planck, LSST), may improve by a factor 7 the current limit if theoretical predictions of the matter power spectrum are accurate to ~ 1%.

Direct determination using β decay spectrum endpoint



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$



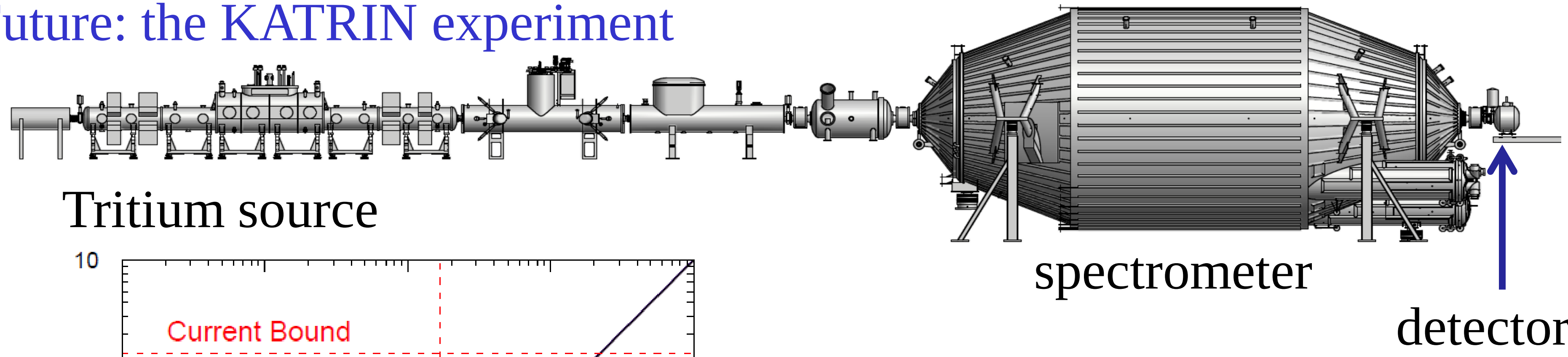
$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$

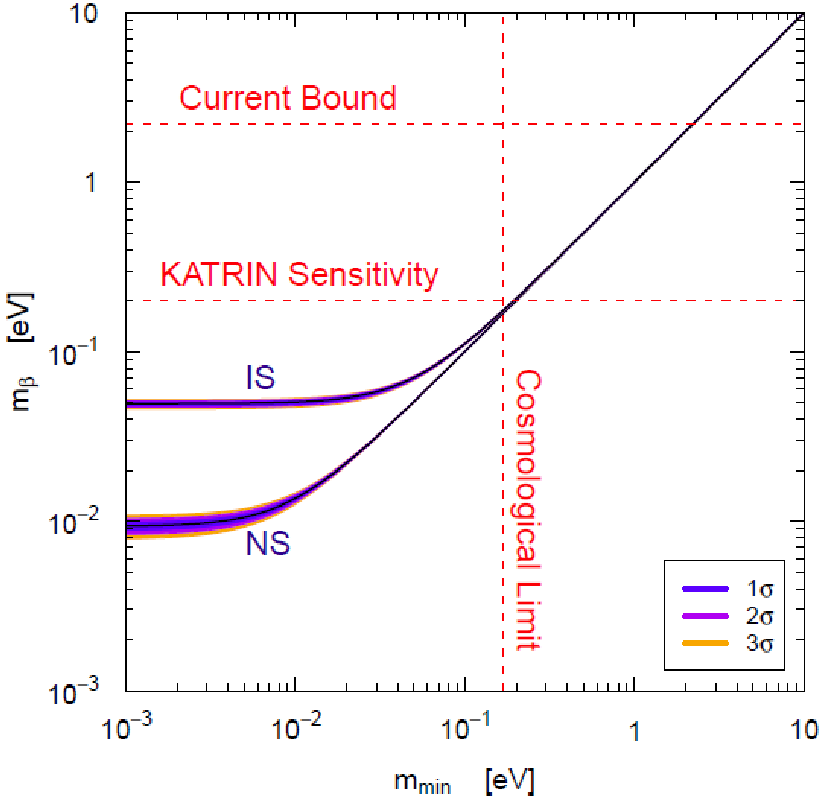
Previous results from Troitzk and Mainz experiments: $m_{\nu e} < 2$ eV

C. Kraus et al., Eur. Phys. J. C40, 447 (2005)

V. Aseev et al., PRD in press (2011)

Future: the KATRIN experiment





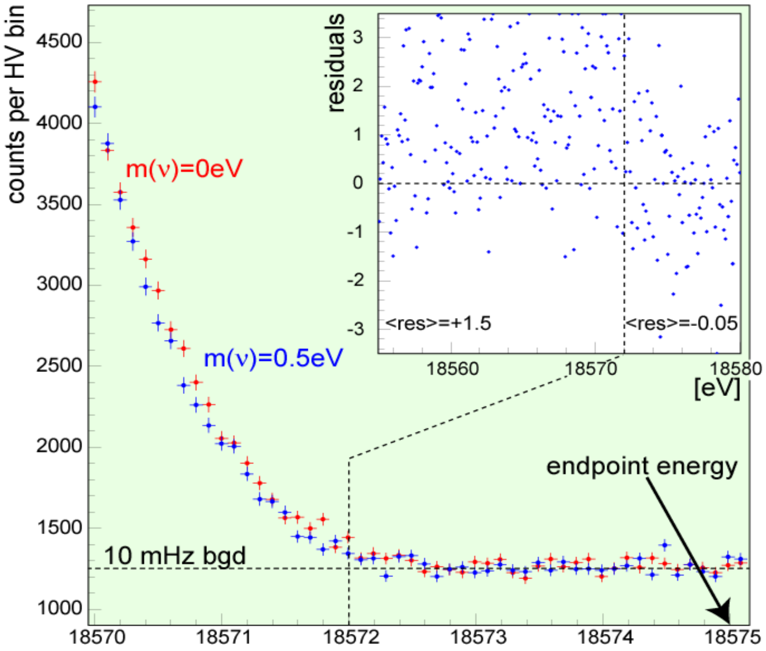
► If $m_\beta \lesssim 4 \times 10^{-2}$ eV

$\Downarrow$

Normal Spectrum

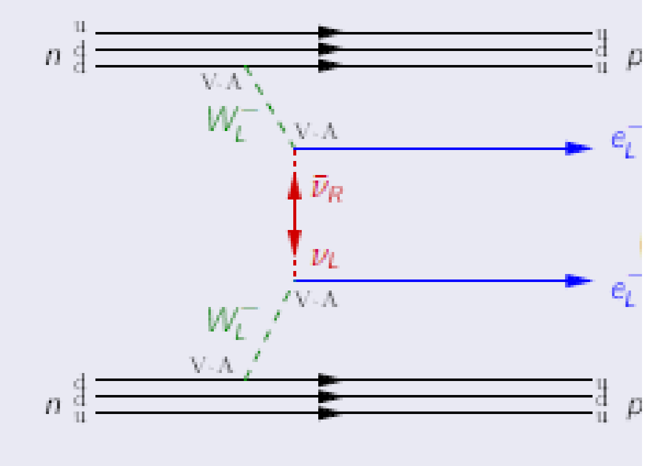
Goal: Direct neutrino mass measurement

Sensitivity = 200 meV [90% C.L.]



Data taking will start in 2015

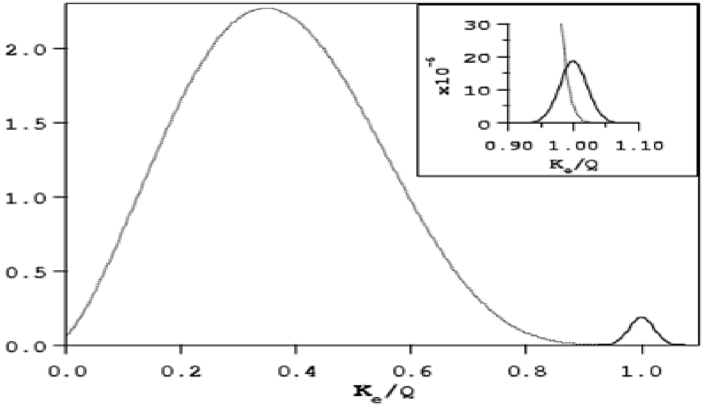
Nature of the neutrino: Double beta decay experiments

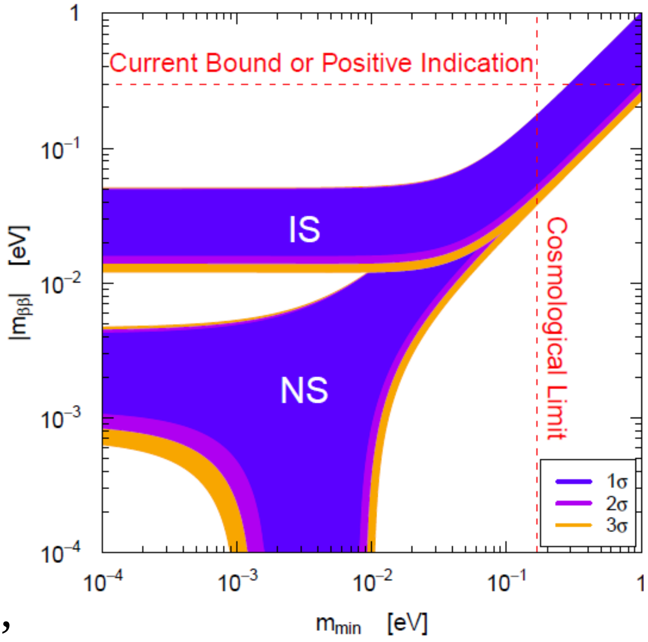


If $0\nu\beta\beta$ decay is observed ⇒ neutrinos are Majorana particles and lepton number is violated

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_2}\, m_2 + |U_{e3}|^2\, e^{i\alpha_3}\, m_3$$

$(A,Z) \rightarrow (A,Z+2) + 2\, e^-$





Several observables: electron energy, angular distribution, excited states, daughter nucleus id.
=> Several experimental approaches

- If $|m_{\beta\beta}| \lesssim 10^{-2}\,\mathrm{eV}$

$$\Downarrow$$

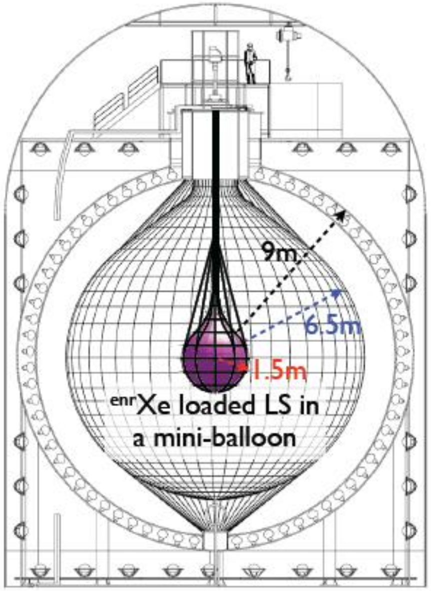
Normal Spectrum

Current limits are around 0.3 eV

Recent results with new generation 2β0ν experiment with Xenon

KAMLAND-ZEN

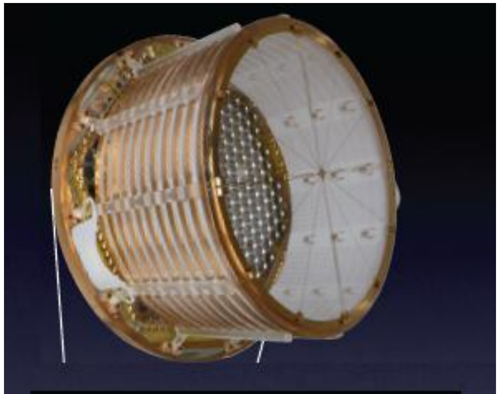
Zero Neutrino
double beta decay search



$\langle m_{\beta\beta}\rangle$ <0.26~0.54 eV @90% C.L.

EXO-200

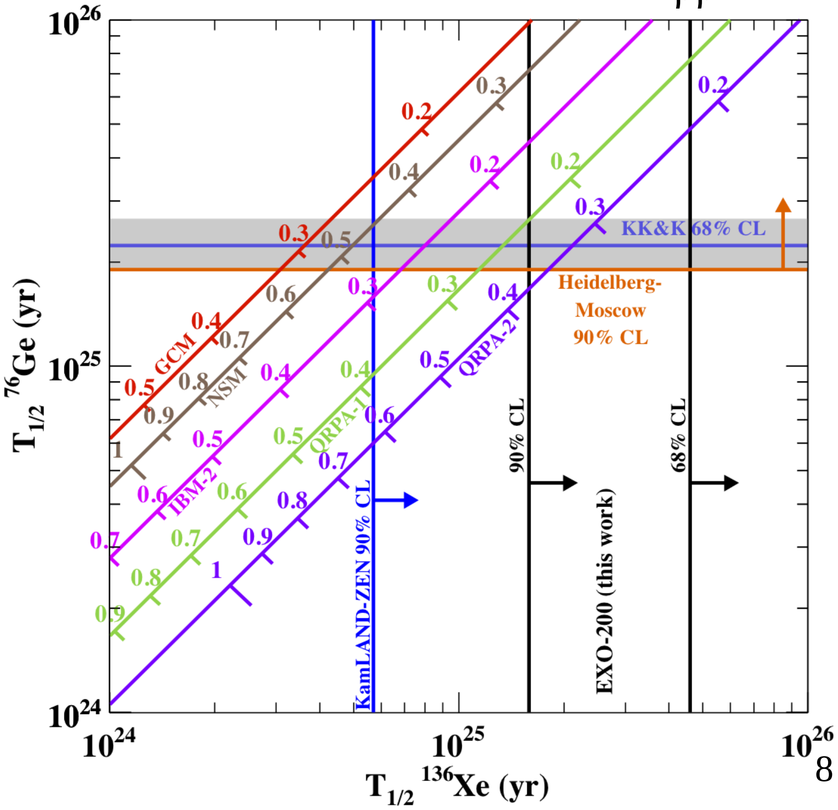
Best limit on 0νββ decay in Xenon
Limit on $m_{\beta\beta}$ < 140-380 meV



Two almost identical halves reading
ionization and 178 nm scintillation,

Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXe

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta}\rangle$



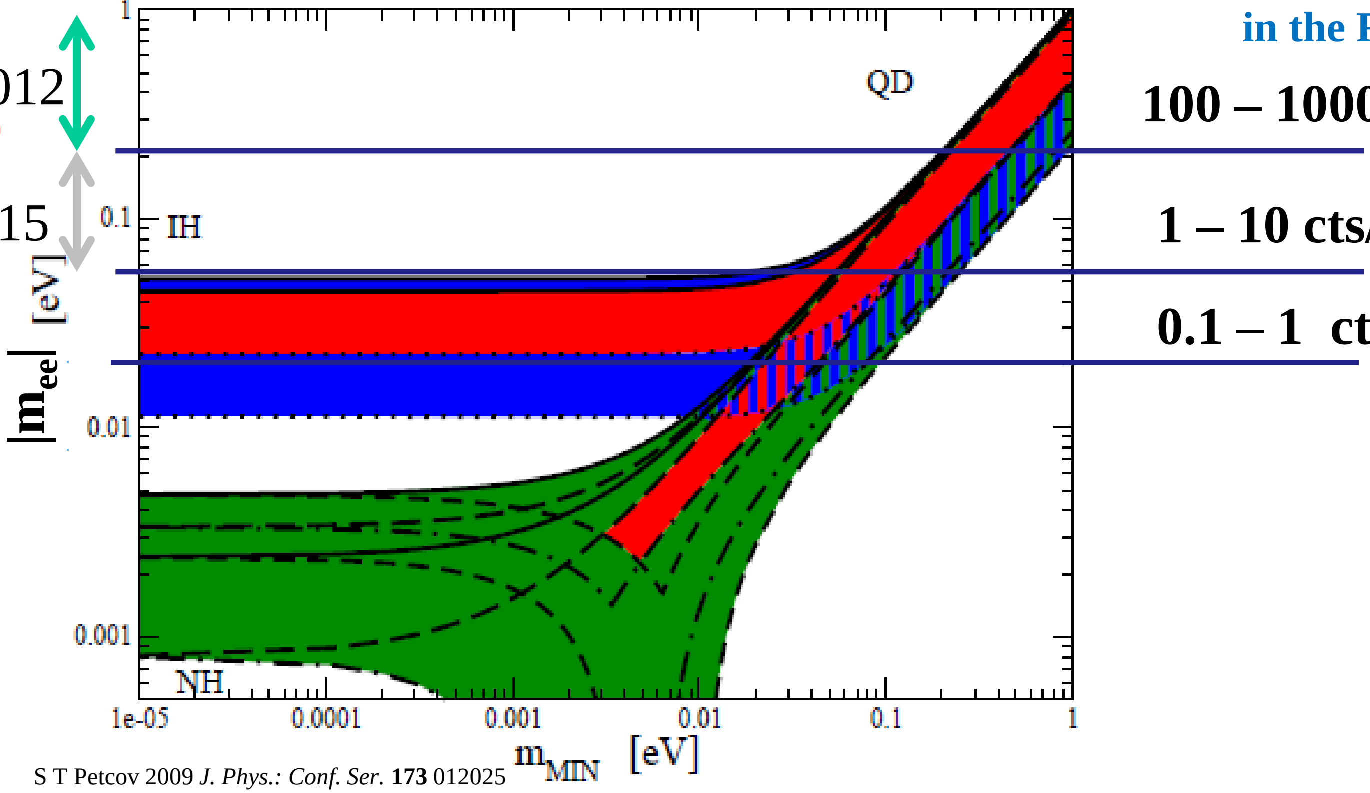
Double beta decay experiments

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Goal of the next generation

Isotope mass

Required background level in the ROI



~ 10 kg 2012 **(200 – 400kg ^{136}Xe)** — **100 – 1000 cts/yr/ton**

~ 100 kg 2015 — **1 – 10 cts/yr/ton**

~ 1000 kg — **0.1 – 1 cts/yr/ton**

S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

Next generation will use ≥ 100 kg (started with Xe experiments)

Improvements of background needed

Next generation of 2β0ν experiments

Calorimeter

Ge diode
ε, ΔE
^{76}Ge
→ GERDA, MAJORANA

Bolometers
ε, ΔE
^{130}Te, ^{82}Se, ^{100}Mo
→ CUORE, LUCIFER, ZnMo4

Liquid Xe
ε, M, (N_{bckd})
^{136}Xe
→ EXO

Scintillator
ε, M
^{136}Xe, , ^{48}Ca, ^{150}Nd, ^{100}Mo
→ KamLAND-Zen, CANDLES, SNO+, Borexino, CdWO4, AMoRE

Tracker

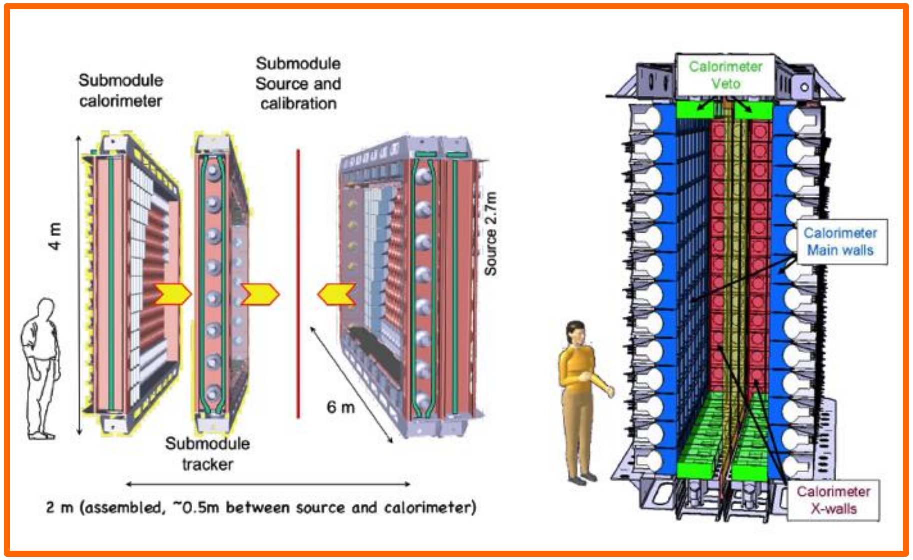
Tracko-calo
N_{Bckg} , isotopes
^{82}Se (^{150}Nd, ^{48}Ca)
→ SuperNEMO

Pixellized CdZnTe
ε, N_{Bckd}
^{116}Cd
→ COBRA

TPC
ε, N_{Bckd}
^{136}Xe, ^{150}Nd
→ MTD, EXO-gas, NEXT

SuperNEMO

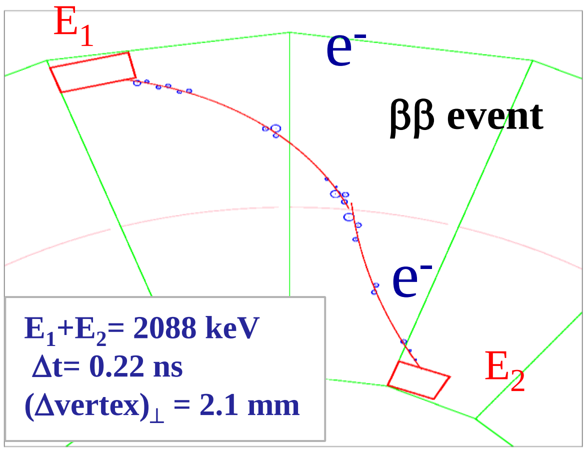
A module



20 modules

Located in LSM extension

Similar tracking approach as Nemo3



$E_1+E_2= 2088$ keV
$\Delta t= 0.22$ ns
$(\Delta\text{vertex})_\perp = 2.1$ mm

	Demonstrator module	**20 Modules**
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	$6.6\ 10^{24}$ y (No background)	$1.\ 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	200 – 400 meV	40 – 100 meV

Oscillation physics: towards CP violation and Mass hierarchy

Goals of the next oscillation experiments: :

Go deeper in the understanding of the MNSP mixing matrix and mechanism :

- More precise measurements of θ_{23} and Δm^2_{23}
- Mass hierarchy studies and the sign of Δm^2_{23} (matter effect studies)
- Study possible CP violation (δ) looking at $(P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta))$

Lengthy experimental and theoretical program with several challenging steps

MNSP Matrix and 3 ν oscillation

(MNSP: Maki-Nakagawa-Sakata-Pontecorvo)

$$\nu_\alpha = \sum_{j=1}^{3} U_{\alpha j}\,\nu_j$$

$U_{\alpha j}$ matrix element

Formalism

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathrm{U} = \underbrace{\overset{\Delta m^2_{31}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}}_{\text{atmos+LBL(dis)}} \underbrace{\overset{\Delta m^2_{31}}{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}}_{\text{Chooz+LBL(app)}} \underbrace{\overset{\Delta m^2_{21}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}_{\text{solar+KamLAND}}$$

Oscillation probability

$$\boxed{P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i}\, e^{-i\frac{\Delta m^2_{ij} L}{2E}} \approx \sin^2 2\theta_{ij} \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)}$$

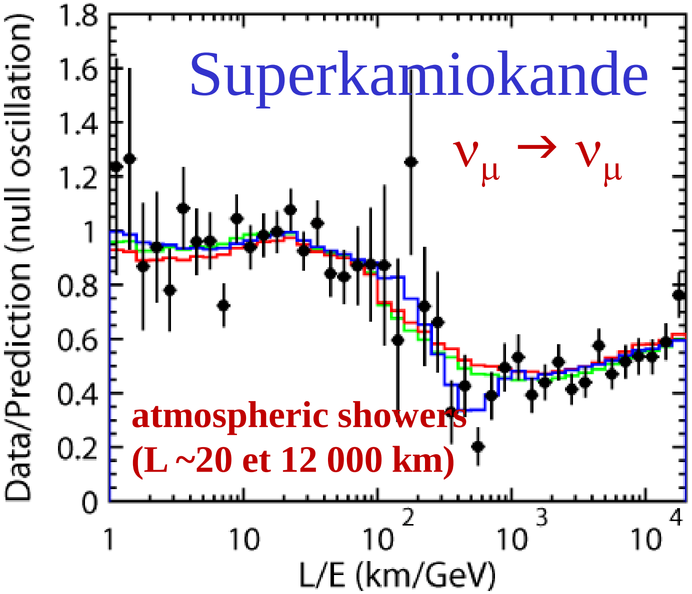
6 parameters to determine:

- 3 angles, 2 mass differences,
- 1 CP violation phase

Experimental evidence of ν oscillation in disappearance mode

All possible sources and baselines

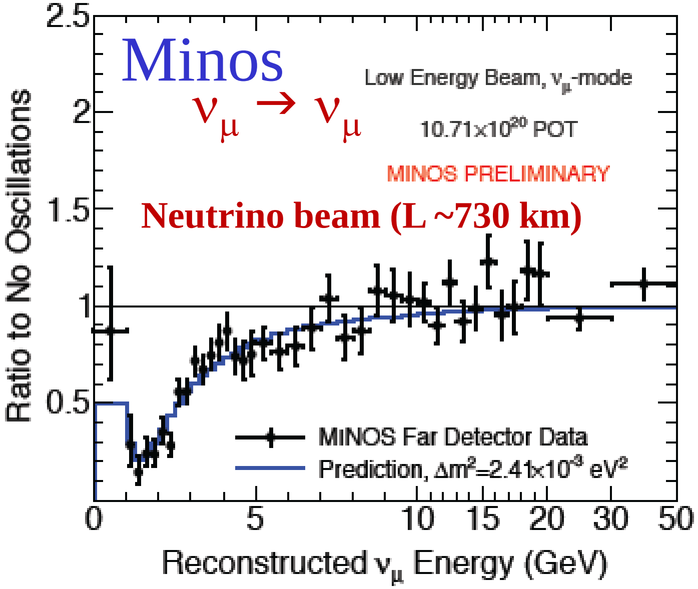
$|\Delta m^2_{31}|$ et θ_{23}



Superkamiokande

$\nu_\mu \rightarrow \nu_\mu$

atmospheric showers (L ~20 et 12 000 km)

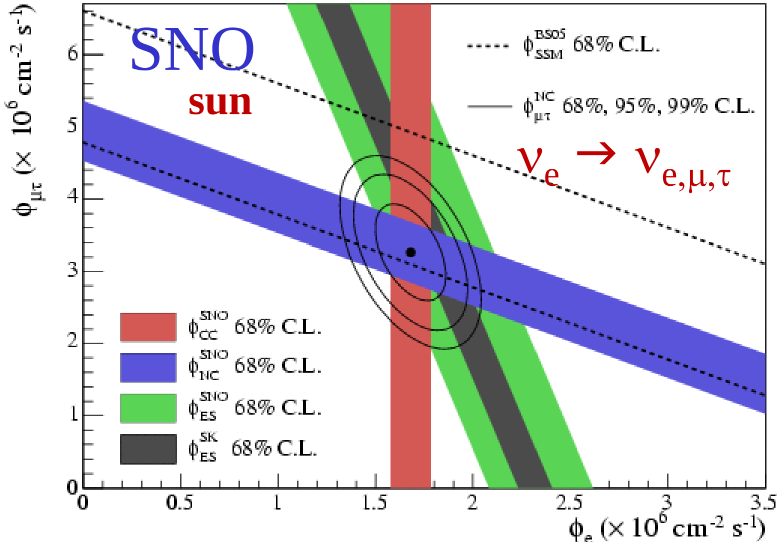


Minos

$\nu_\mu \rightarrow \nu_\mu$

Neutrino beam (L ~730 km)

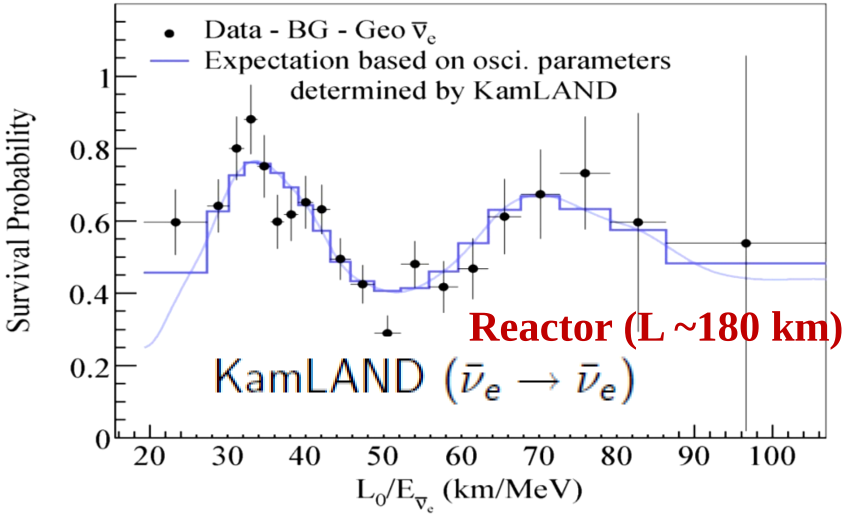
Δm^2_{12} et θ_{12}



SNO

sun

$\nu_e \rightarrow \nu_{e,\mu,\tau}$

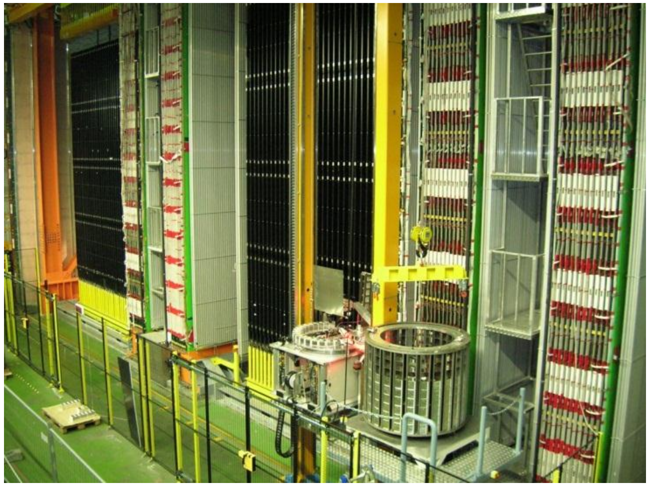


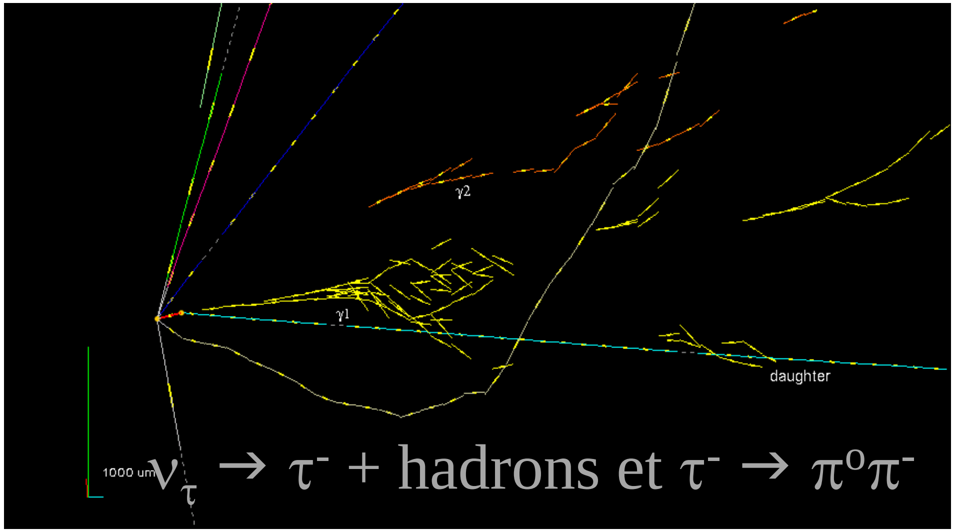
Reactor (L ~180 km)

KamLAND ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)

Experimental evidence of ν oscillation in appearance mode

OPERA in CNGS beam $\nu_\mu \rightarrow \nu_\tau$



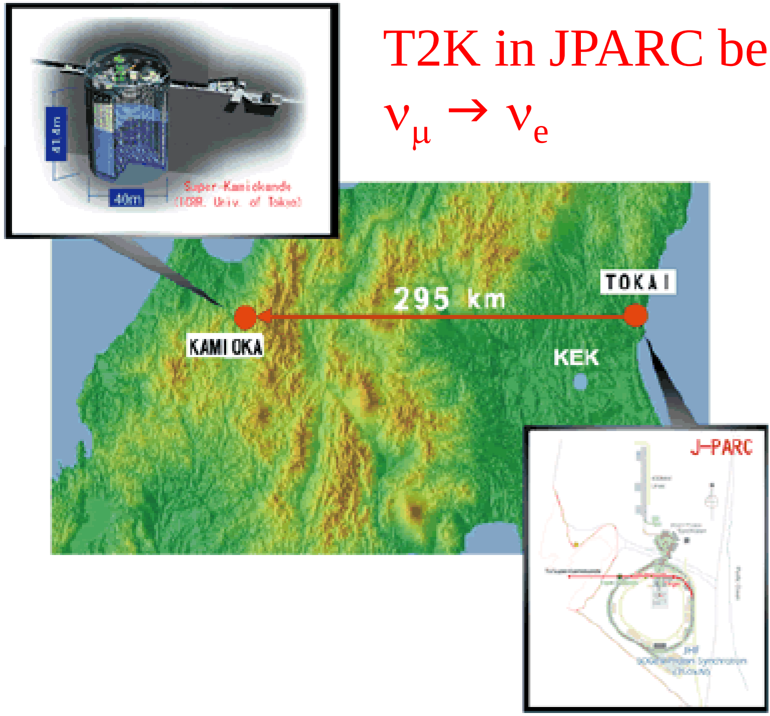


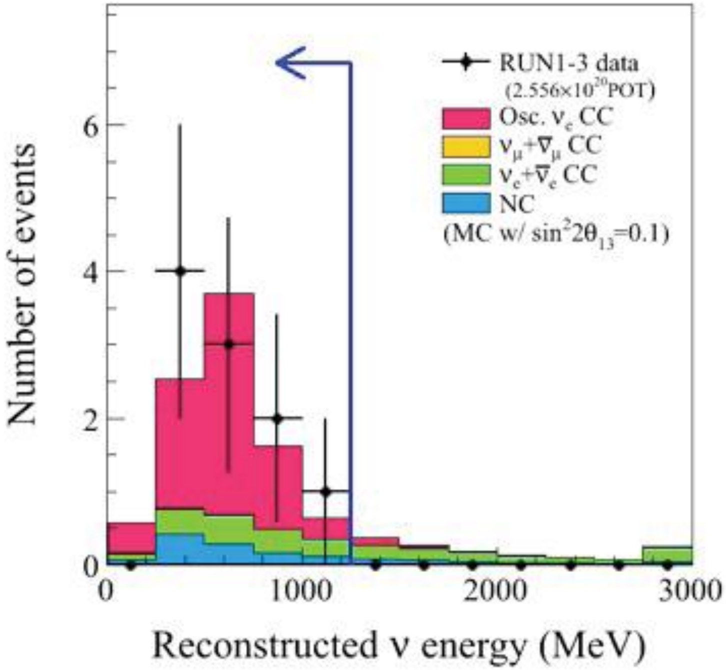
$\nu_\tau \rightarrow \tau^- + \text{hadrons et } \tau^- \rightarrow \pi^0\pi^-$

A second τ event observed in 2012

T2K in JPARC beam

$\nu_\mu \rightarrow \nu_e$





θ_{13} at reactors from the survival rate of ν_e

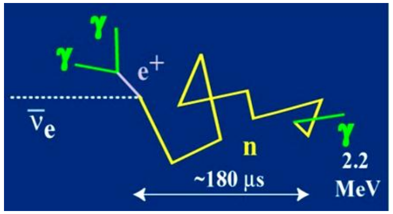
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \underbrace{\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}}$$

Negligible term if L/E chosen near the atmospheric maximum and $\sin^2 2\theta_{13} > 10^{-3}$

Advantages:

- No dependence on δ
- Negligible matter effect
- Only sensitive to θ_{13}

Signature: Inverse β decay process.

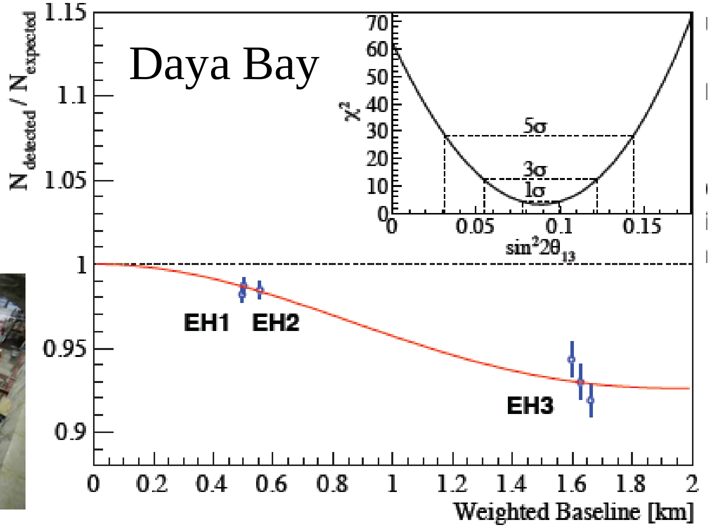


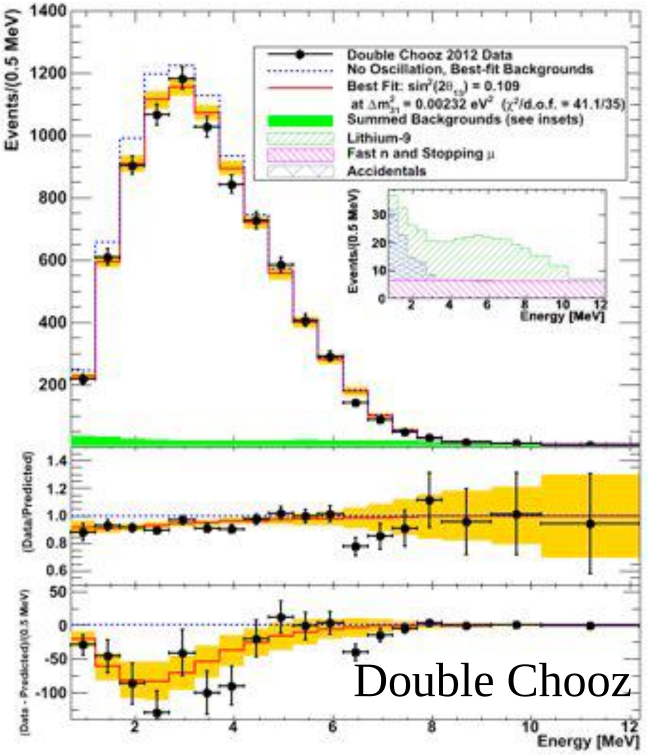
3 reactor experiments;

- Double Chooz (France)
- Daya Bay (China)
- Reno (Korea)

Near/Far ratio to cancel reactor and detector systematics

Gd loaded liquid scintillators

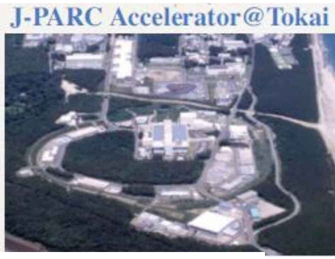




Double Chooz

$\boxed{\theta_{13}}$ at accelerators from the ν_e appearance

T2K in Japan: $\nu_\mu \rightarrow \nu_e$



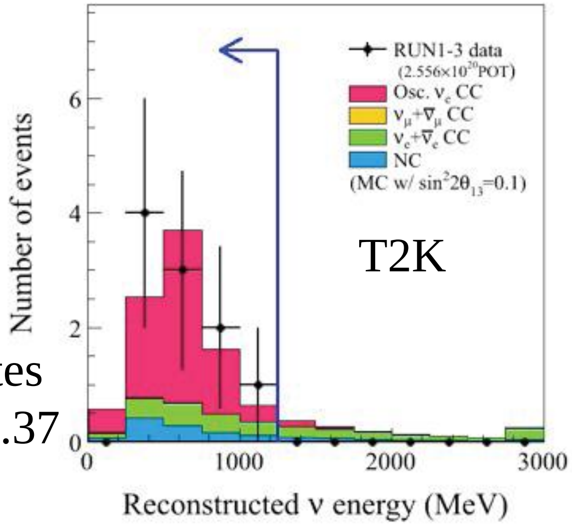
$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

- $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{13}^2\, L/E)$
- $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m_{12}^2\, L/E)$
- $P_3 = \mp J \sin(\delta) \sin(1.27\, \Delta m_{13}^2\, L/E)$
- $P_4 = J \cos(\delta) \cos(1.27\, \Delta m_{13}^2\, L/E)$

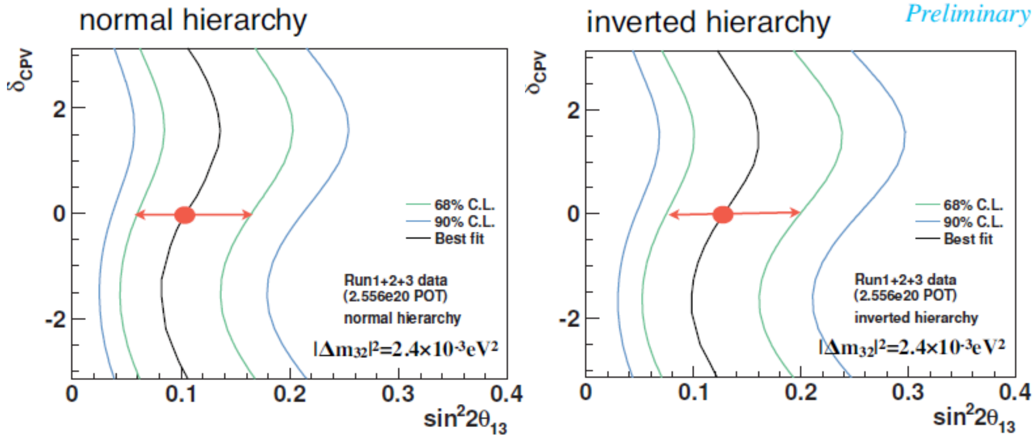
where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

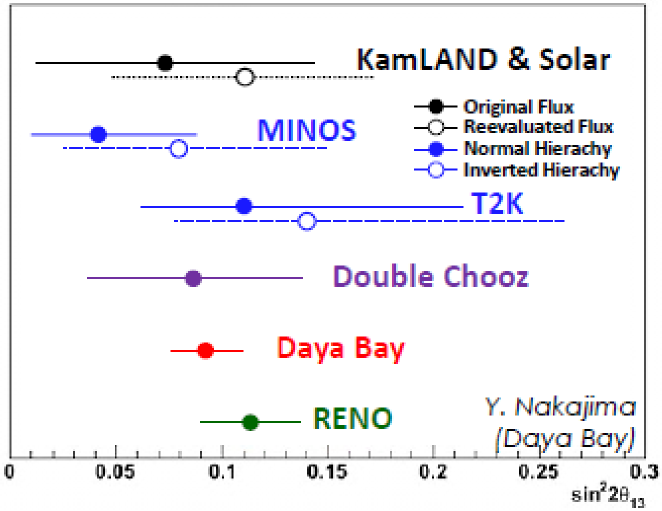
$\sin(1.27\, \Delta m_{13}^2\, L/E) \sin(1.27\, \Delta m_{12}^2\, L/E)$

Negligible with LBL for L/E< max. atm.



10 candidates
back exp. 2.37

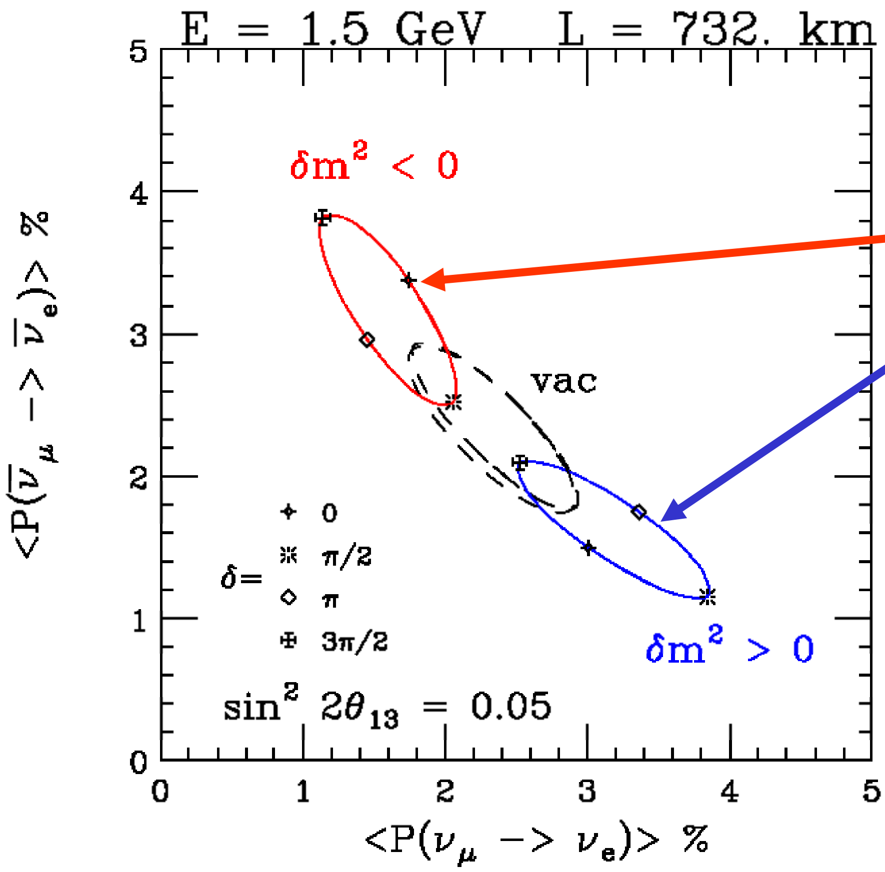




$\sin^2 2\theta_{13} = 0.094$ (+-10%)

δ and sign(Δm^2_{31})

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$
$$-16 s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta \sin\left(\frac{\Delta m^2_{12}}{4E}L\right)\sin\left(\frac{\Delta m^2_{13}}{4E}L\right)\sin\left(\frac{\Delta m^2_{23}}{4E}L\right)$$



Minakata and Nunokawa, hep-ph/0108085

Matter effects

No other way to access the mass hierarchy

Be careful: the effects from θ_{13} and δ are not separable with a simple measurement of $P(\nu_\mu \to \nu_e) \to$ parameters are correlated

- ➢2nd generation of neutrino beams coupled to large volume detectors like Megatonne Water cerenkov, Liquid Argon etc…
- ➢ Neutrino factory

Future Long Baseline Projects

LAGUNA –LBNO
New EU FP7 design study 2011-2014

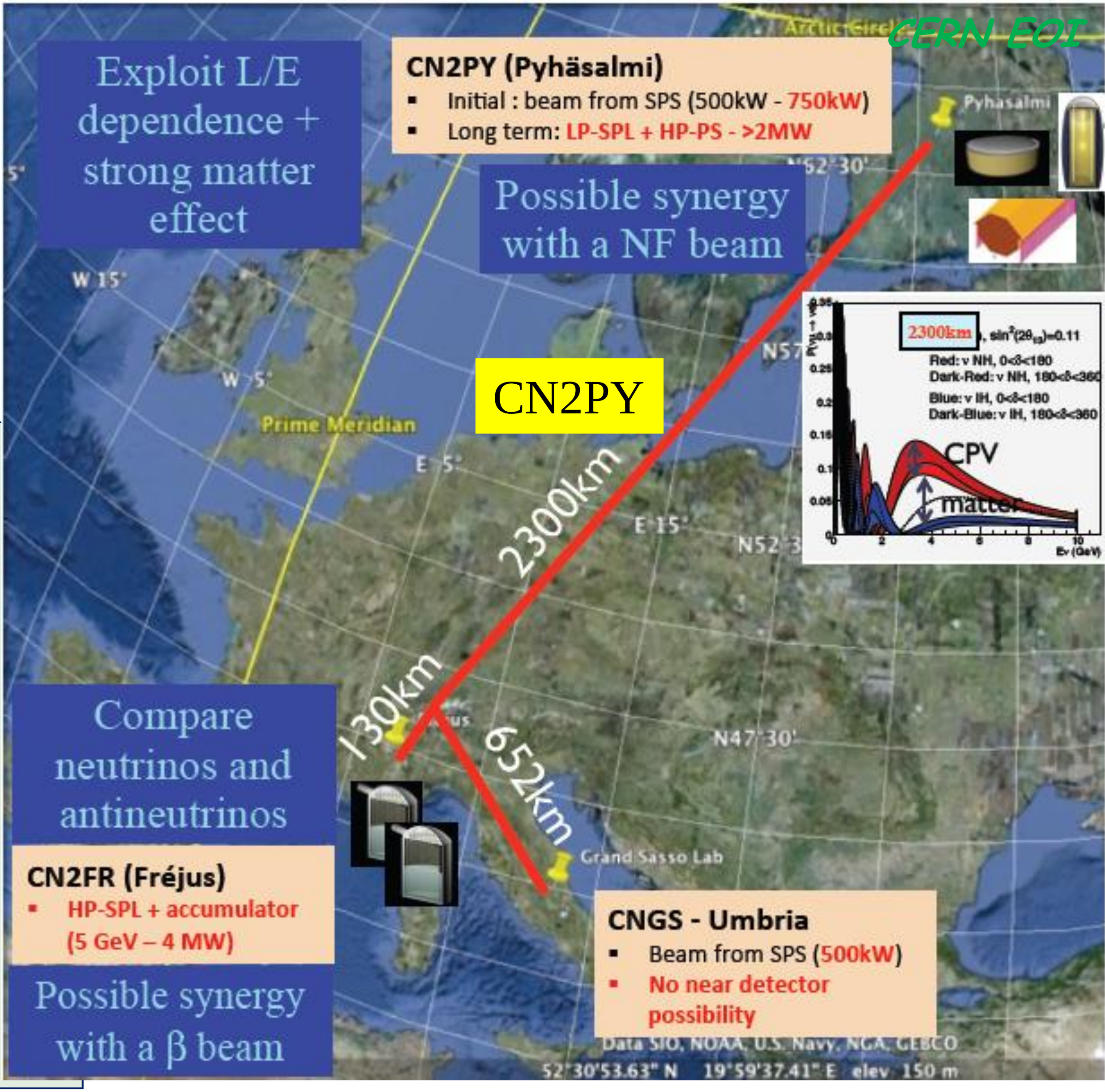
New conventional ν_μ beams to be considered, based on CNGS experience

2 main options

Short distance: 130km
Memphys at Frejus
SPL+beta beam
CP and T violation

Long distance: 2300km
Pyhasalmi
Fine grain detector
e.g. 20kton fid. Larg
+ Magnetized detector
Long distance allows rapid sensitivity to
sign(Δm^2_{13})

1st step easier: SPS C2PY
➔ consortium 1st priority
Nextsteps: HP 50 GeV PS …
…or neutrino factory



CERN EOI

Exploit L/E dependence + strong matter effect

CN2PY (Pyhäsalmi)
- Initial : beam from SPS (500kW - 750kW)
- Long term: LP-SPL + HP-PS - >2MW

Possible synergy with a NF beam

CN2PY

Compare neutrinos and antineutrinos

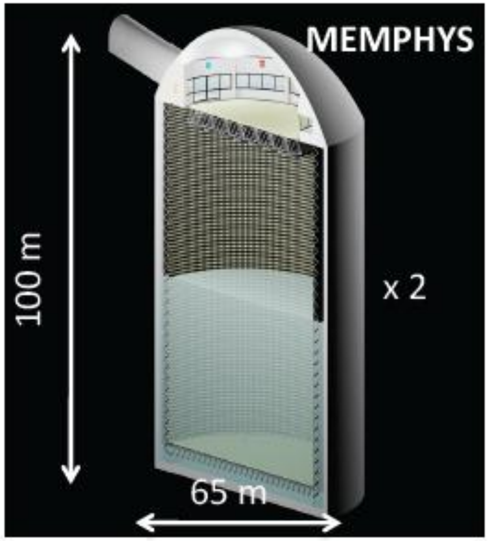
CN2FR (Fréjus)
- HP-SPL + accumulator (5 GeV – 4 MW)

Possible synergy with a β beam

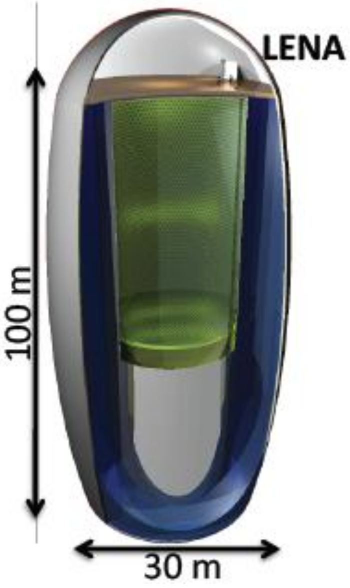
CNGS - Umbria
- Beam from SPS (500kW)
- No near detector possibility

Rich physics program

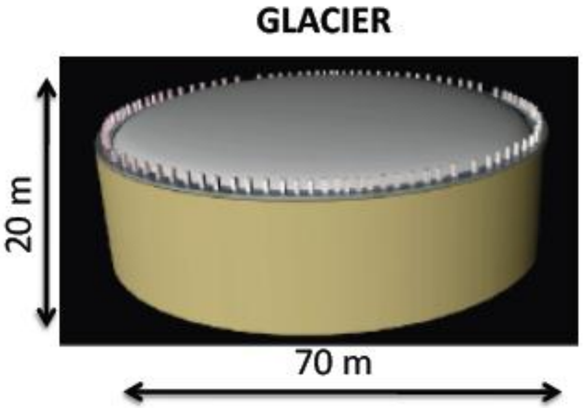
- ν properties(oscillation, mass hierarchy leptonic CP violation: beams, ν atm..)
- Study of astrophysical phenomena linked to ν:
  - Gravitational star collapse (ν from Supernovae)
  - Star formation at the beginning of the universe (SN ν diffuse background)
  - Study of thermonuclear fusion process (solar ν)
- Test of geophysical mode of the earth (Geo - ν , U, Th - ν)
- Nucleon decay



Water Čerenkov 2x 300kT



Liq. Scintillator →50kT



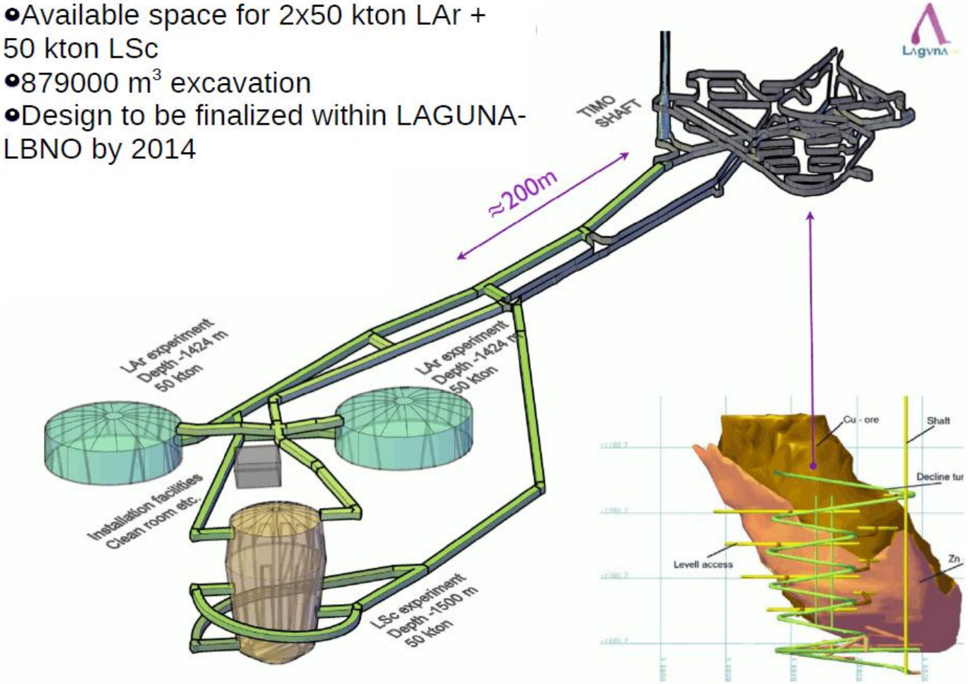
Liq. Argon →100kT

Future Long Baseline Projects

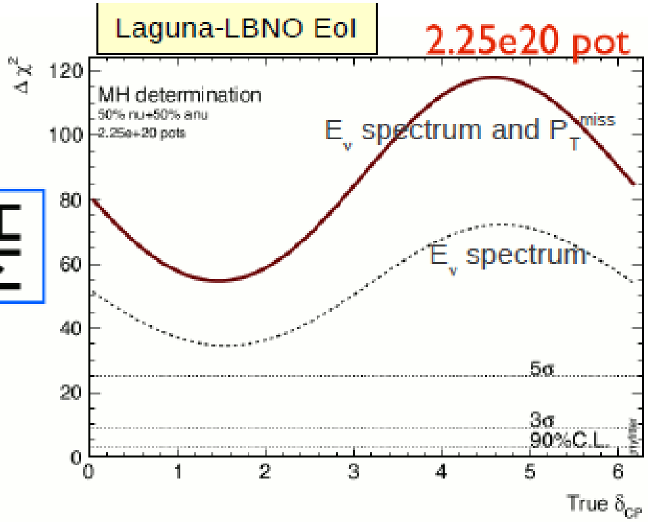
CERN beam to Pyhäsalmi in Finland (2300 km)

high energy wide band beam (neutrinos >1 GeV) => 1st and 2nd maxima

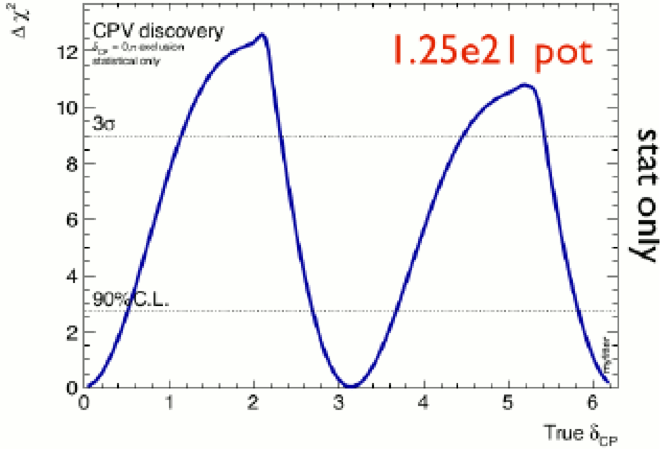
- Available space for 2x50 kton LAr + 50 kton LSc
- 879000 m³ excavation
- Design to be finalized within LAGUNA-LBNO by 2014



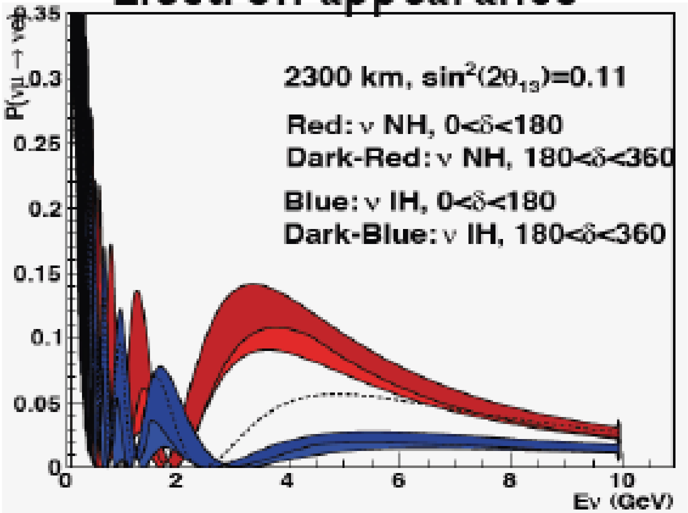
MH



CPV



Electron appearance



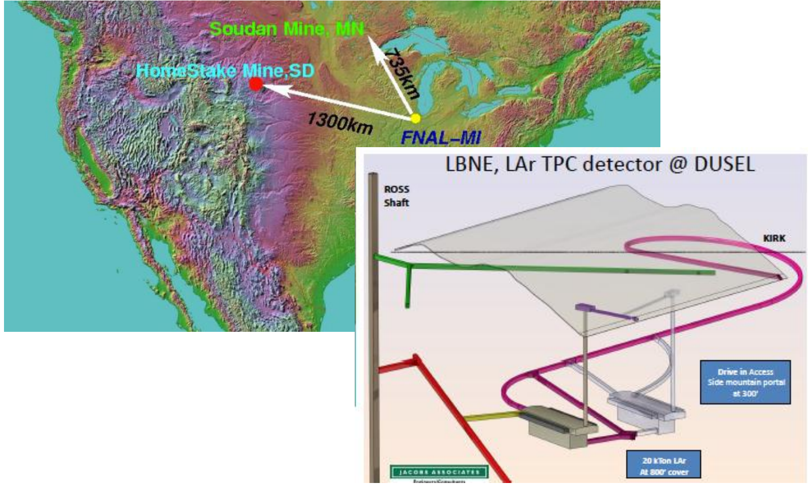
MH: 100% coverage at >5σ in a few years

CPV: ≈60% coverage and evidence for maximal CP (π/2, 3π/2) at ~3σ in 10y

Future Long Baseline Projects in the World

US : LBNE

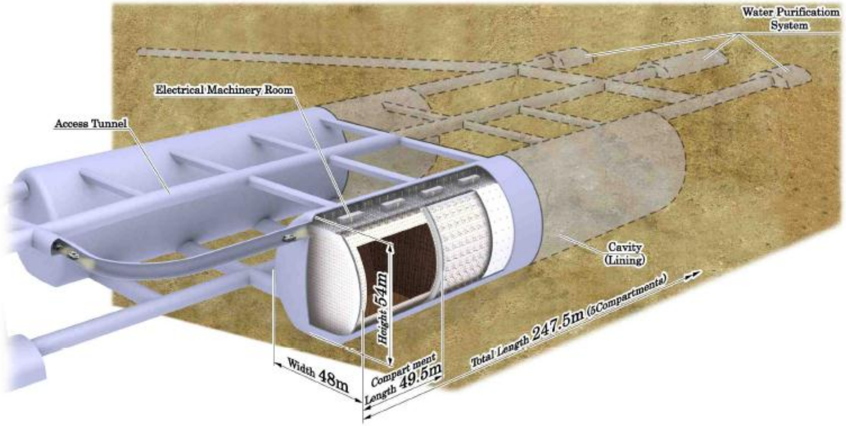
Liquid Argon TPC 25 kton
at DUSEL (Homestake Mine) ~2400mwe
Beam from Fermilab (0.7-2.5MW)
baseline=1300 km <E>~3 GeV



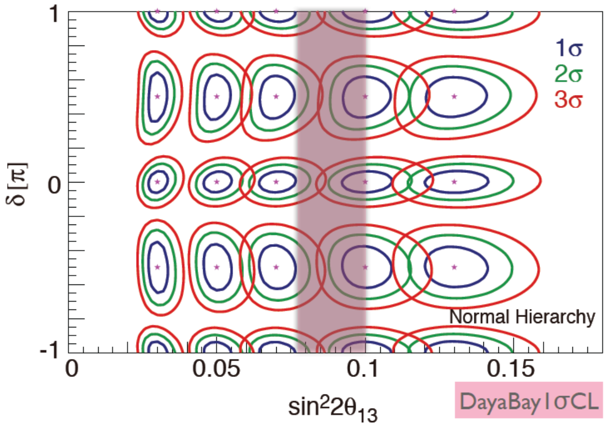
Recently “downscoped” by DOE

Japan : Hyper-K

Water Cherenkov 560 kton
near Kamioka, 1750 mwe
Beam from JPARC (1.66MW)
baseline=,295 km <E>~0.8 GeV

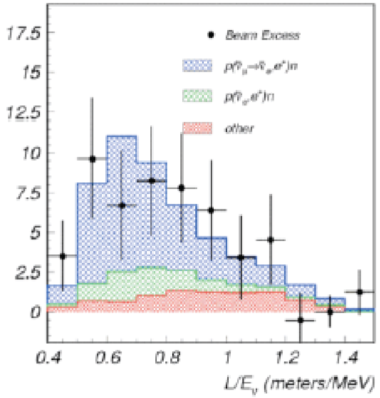


Letter of Intent ArXiv 1109.3262

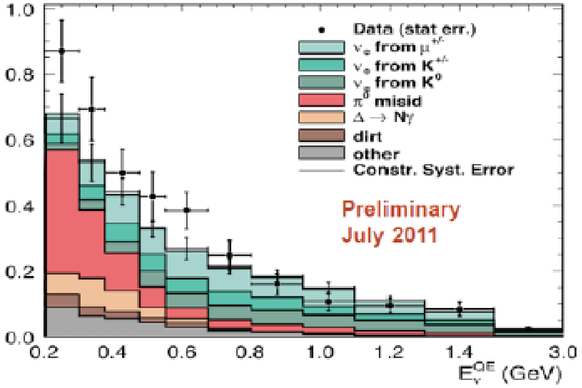


Anomalies in 3-ν interpretation of global neutrino oscillation data

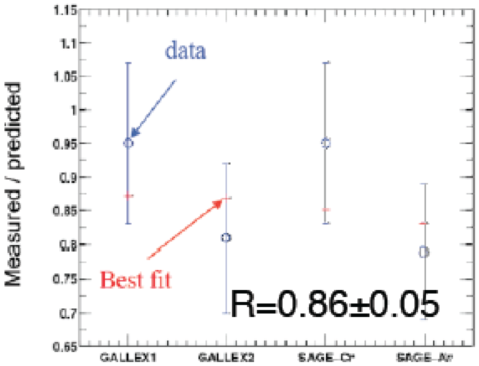
LSND



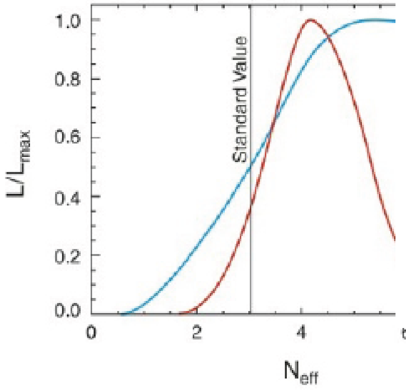
MiniBoone



Ga Anomaly

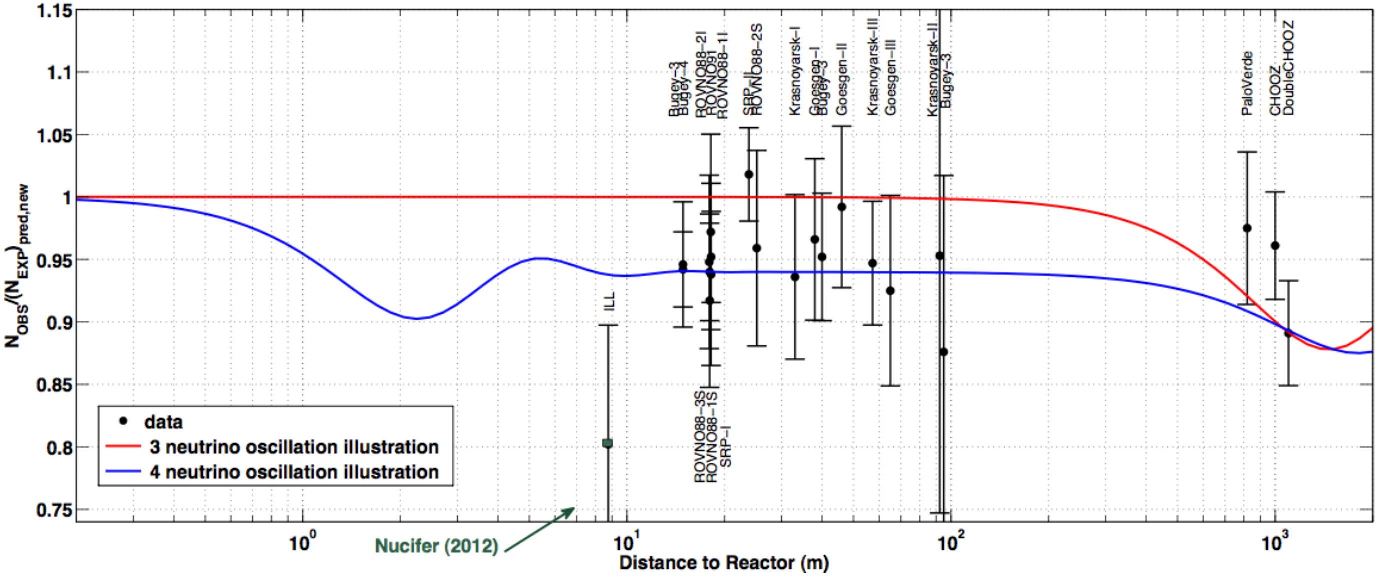


Cosmology (WMAP)



Short-baseline reactor anomaly (νe disappearance)

Improved reactor neutrino spectra +3.5%



if new oscillation signal, requires $\Delta m^2 \sim O(1\text{eV}^2)$ and $\sin^2 2\theta > 10^{-3}$

➔ very short baseline oscillation for reactor ν, **$L_{osc} \sim$ 2-10m**

Anomaly investigation and search for sterile neutrino

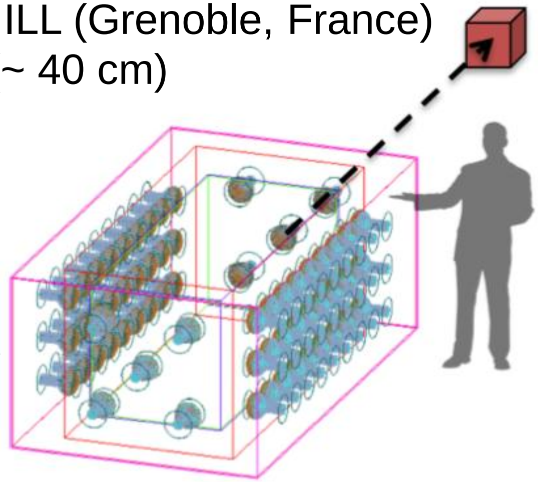
STEREO Experiment Concept: under study

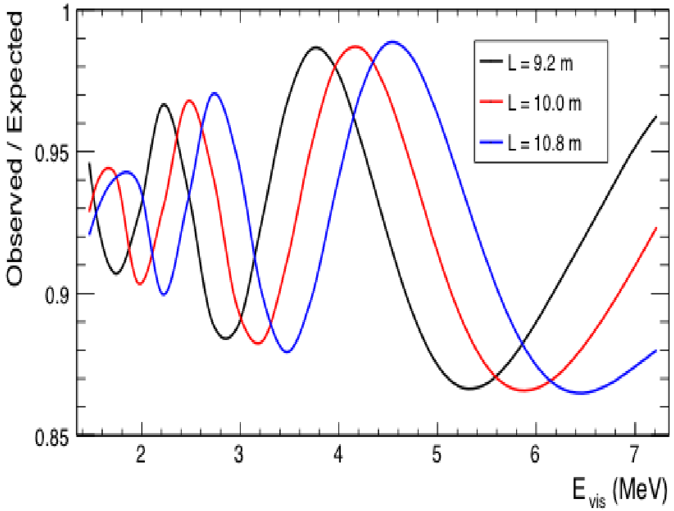
Proposal under study

Reactor experiment @ ILL (Grenoble, France)
Compact reactor core (~ 40 cm)

Detector Liq. Scint.
1m x 1m x 2m
64 PMTs

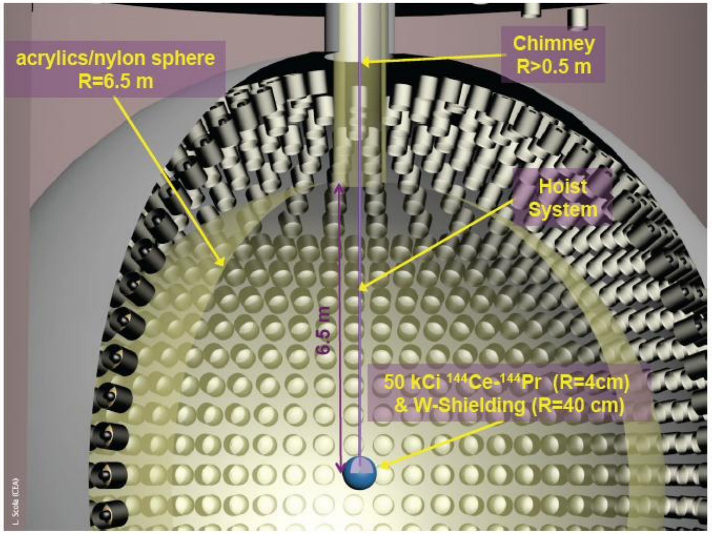
Goal: focus on shape distorsion





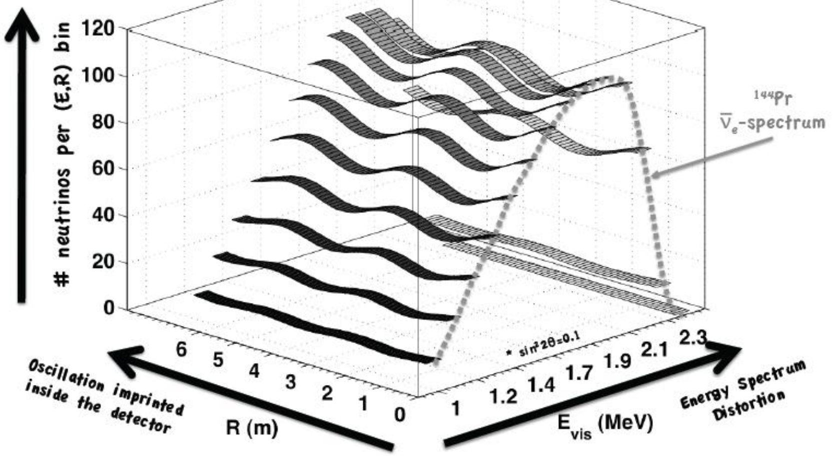
CeLAND (joint Study by Saclay, RCNS Tohoku, ITEP, IPC)

PRL 107, 201801, 2011



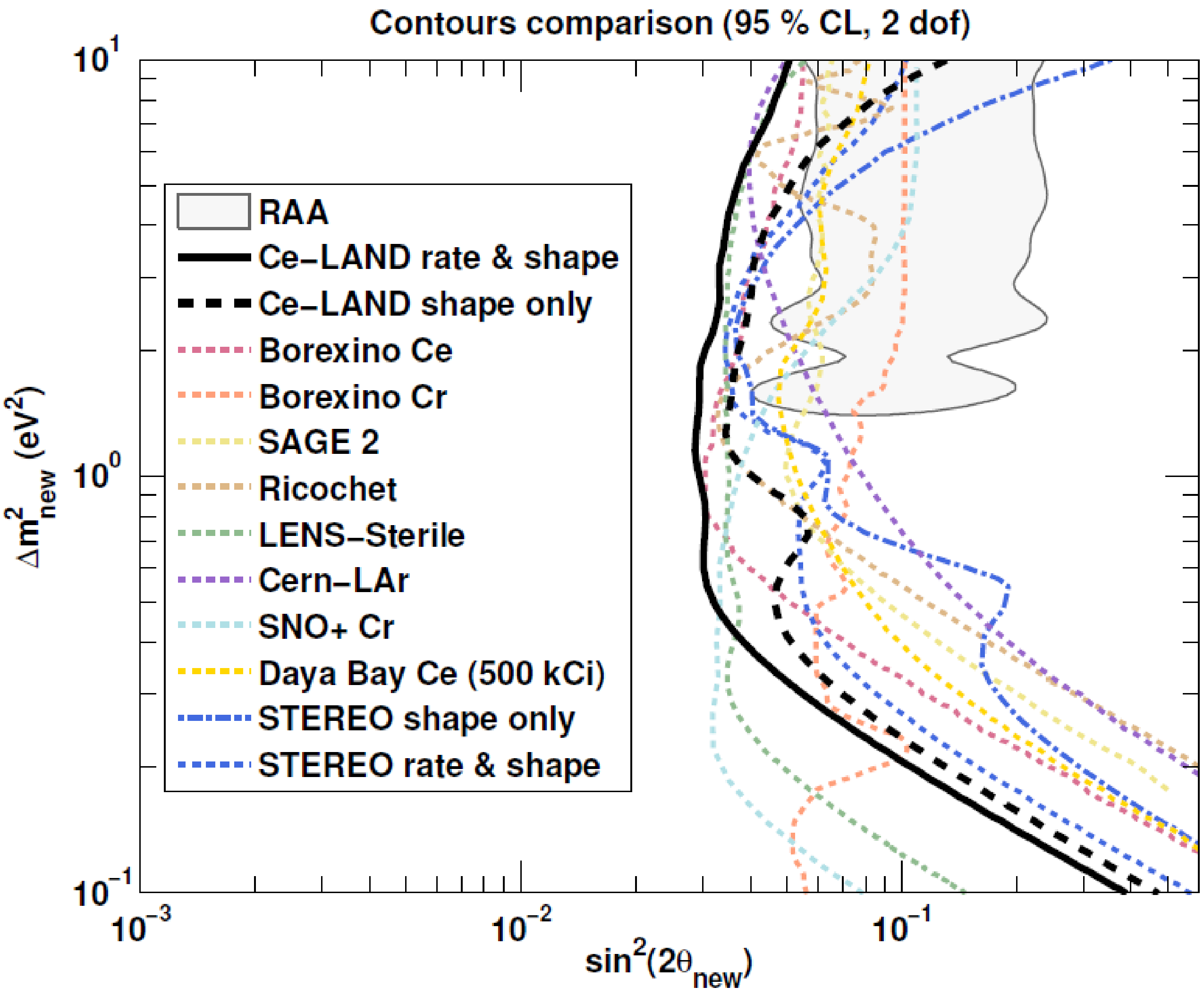
CeLAND Expected Signal (Oscillation)

$$\frac{d^2N(R,E_\nu)}{dRdE_\nu} = A_0\cdot n\cdot\sigma(E_\nu)\cdot\mathcal{S}(E_\nu)\cdot\mathcal{P}(R,E_\nu)\int_0^{t_e} e^{-t/\tau}dt,$$



Anomaly investigation and search for sterile neutrino

In addition to source and reactor experiments,
SBL beam projects exist. Ex: Icarus T600 at CERN (project submitted to SPSC)



Conclusions and perspectives:

- Neutrino physics is a very active field

- Since 15 years several new results changed our view of the field and comforted us to revise our current knowledge within the Standard Model

- A lot of experimental and theoretical challenges are in front of us and worth to be pursued.

Neutrino Pole in ENIGMASS is a Collaboration: LAPP, LPSC, LSM, and LAPTh

The scientific program axes cover most of the present fundamental research on the neutrino physics

- Mass hierarchy and CP violation
- Neutrino nature
- Sterile neutrinos
- Supernovae neutrinos

This program is in adequation with the national and international raodmaps. It will be performed using close infrastructures : CERN, LSM, ILL

Short term(2012 -2015): oscillation CNGS/OPERA
sterile neutrinos and anomalies (ILL reactor, SEDINE, STEREO)

Middle term (2012 – 2020) : Double beta decay (SuperNEMO)
Long Baseline studies (LSM is candidate for the site)

Long term (2020 and beyond): Long Baseline

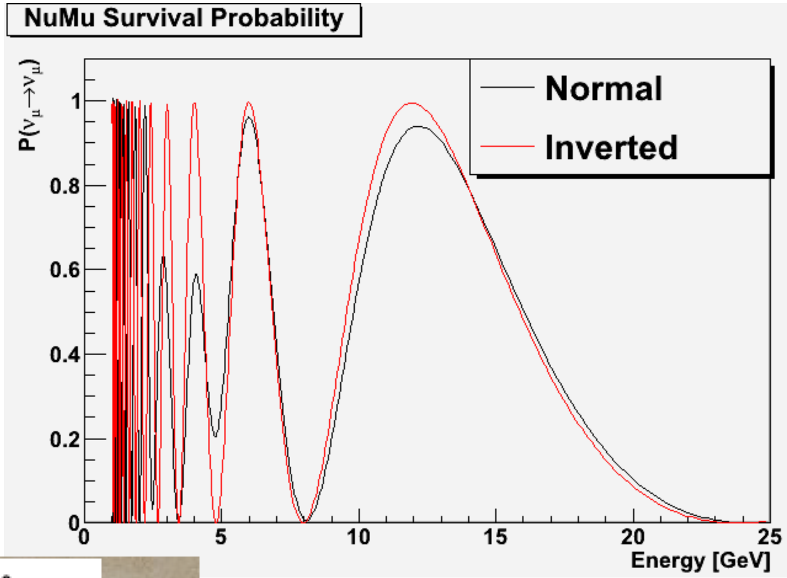
Support from theoretical groups of LaPTh and LPSC

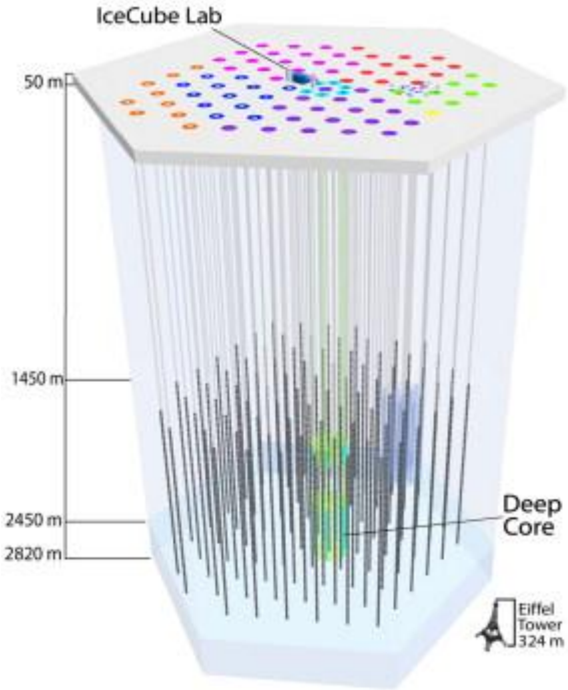
The End

Mass hierarchy:

Other investigation techniques:

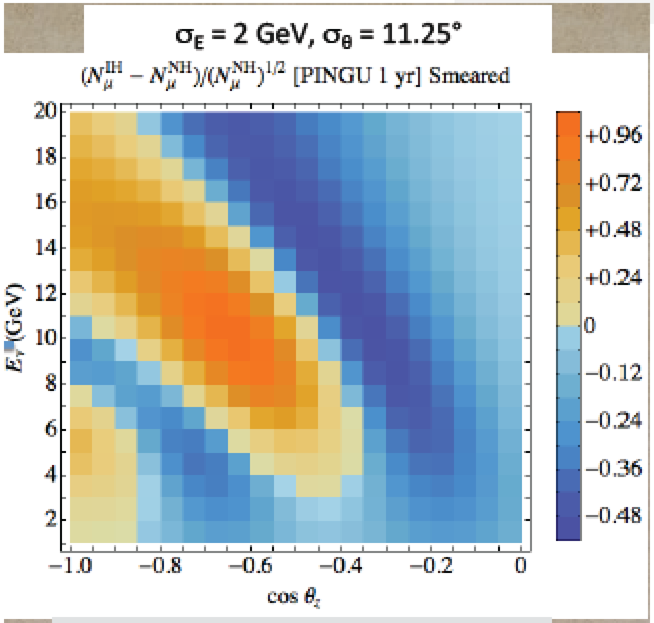
Atmospheric neutrinos: looking at the effect of matter effect in the νμ rate





<10% effect

PINGU



Also

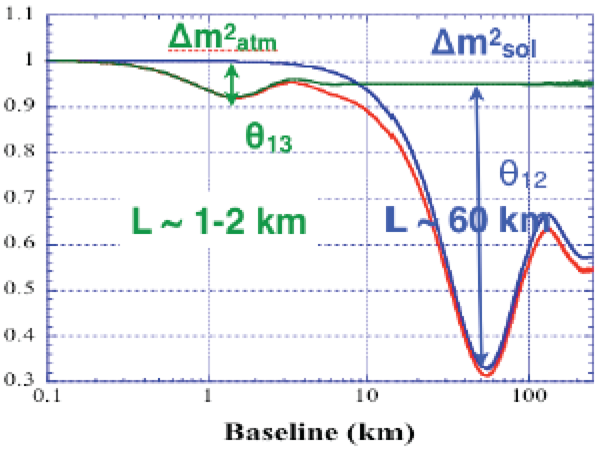
INO: 50 kton iron-RPC calorimeter

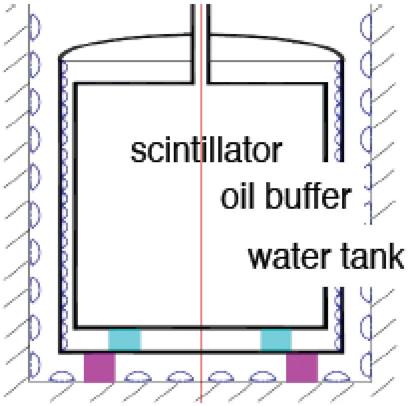
HyperK in Japan

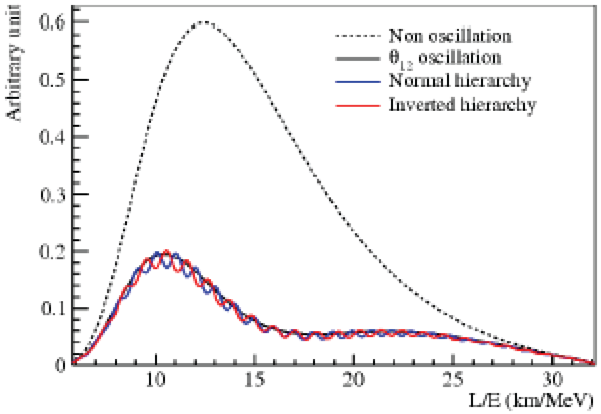
Mass hierarchy:

Daya Bay II

Long Baseline reactor with large detector

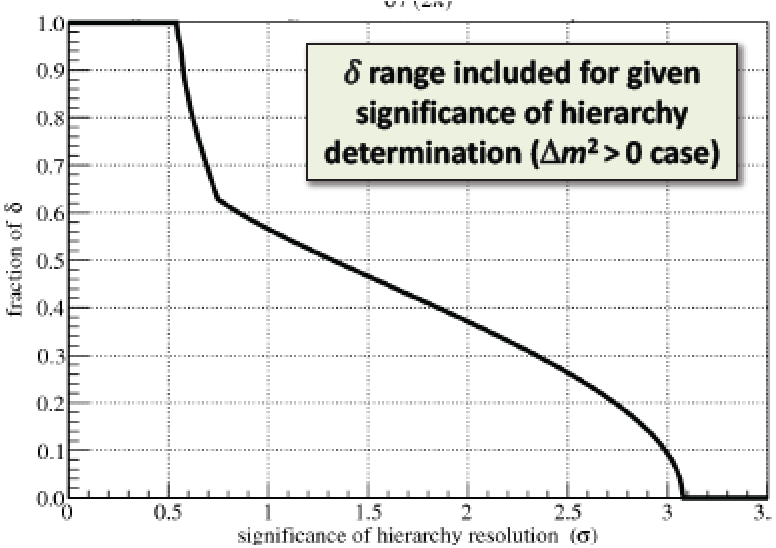




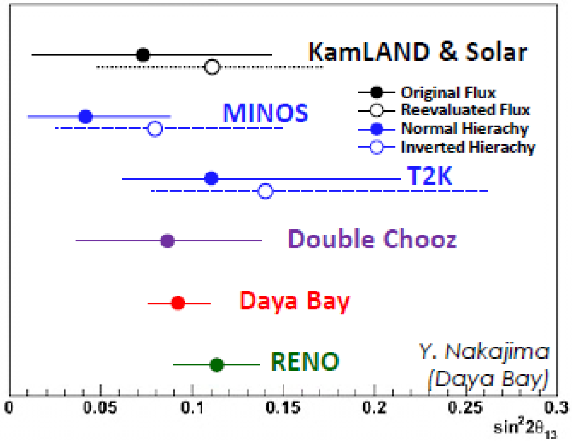


- 20-50 kton LS detector
- 2-3 % energy resolution
- Rich physics possibilities
  - ⇨Mass hierarchy
  - ⇨Precision measurement of 4 mixing parameters
  - ⇨Supernovae neutrino
  - ⇨Geoneutrino
  - ⇨Sterile neutrino
  - ⇨Atmospheric neutrinos
  - ⇨Exotic searches

Accelerator: Nova, T2K



What is the impact of the new oscillation results for the Design Studies:



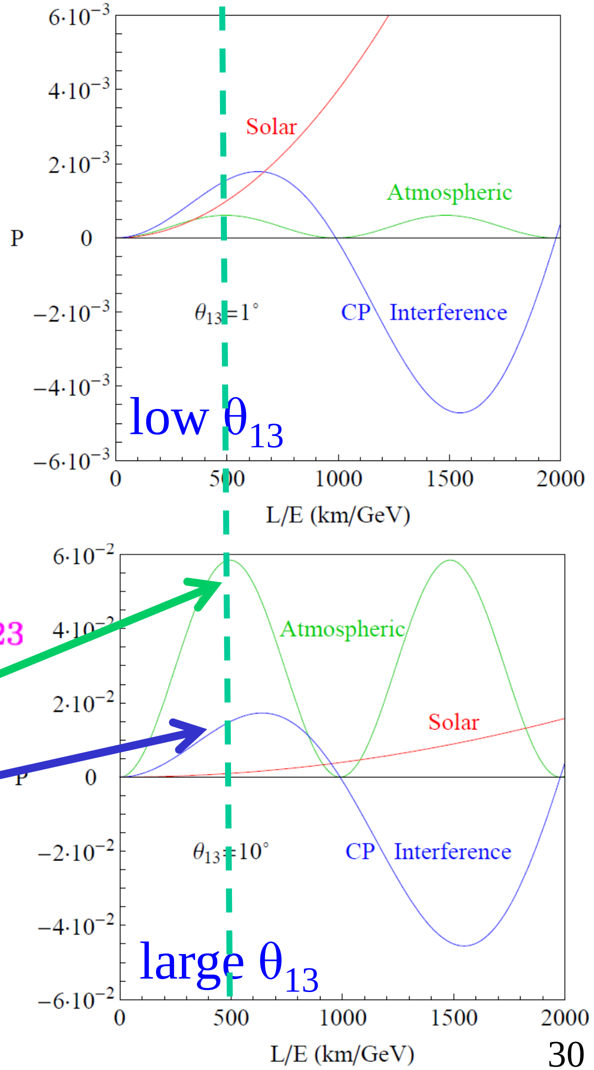
Previous analyses have been optimised for $0.001<\sin^2(2\theta_{13})<0.01$

$\sin^2 2\theta_{13} = 0.1 \Leftrightarrow \theta_{13}$ large

Next goals:

- δ_{CP}
- Mass Hierarchy

P. Coloma and E. Fernandez-Martinez
hep-ph/1110.4583v3



Observable: $\nu_\mu \leftrightarrow \nu_e$ transition probabilty

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{atmos} \\
&+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\,L}{2}\right) && \equiv P^{solar} \\
+\tilde J \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right) \frac{\Delta_{12}\,L}{2} \sin\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{inter}
\end{aligned}
$$

In vacuum

$$\tilde J \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}$$

θ_{13} large: at first maximum atm. term tends to dominate => can hide subdominant CP interference term, syst. can wash out => Systematics and statistical error control is crucial

Re-estimate the performance and do a full simulation work to assess properly the statistical and systematic uncertainties for the different beam and detector options.