Experimental Neutrino Physics

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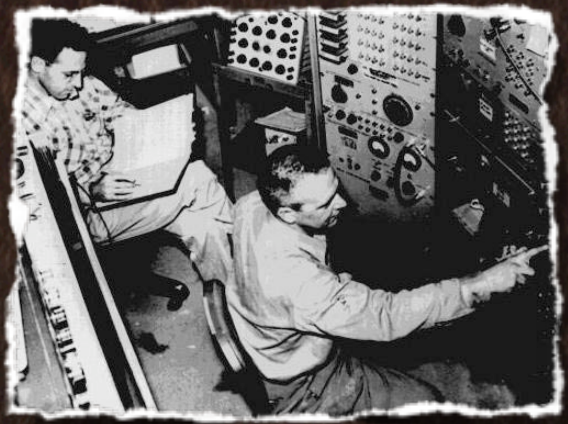


Benasque,10-11 Febrero 2009

The neutrino

The most curious elementary particle
and the one that gave us more surprises

is still a perfect unknown

...because it only interacts weakly

three active neutrinos only

+ the possibility of sterile neutrinos

Flavour mixing
(oscillations)

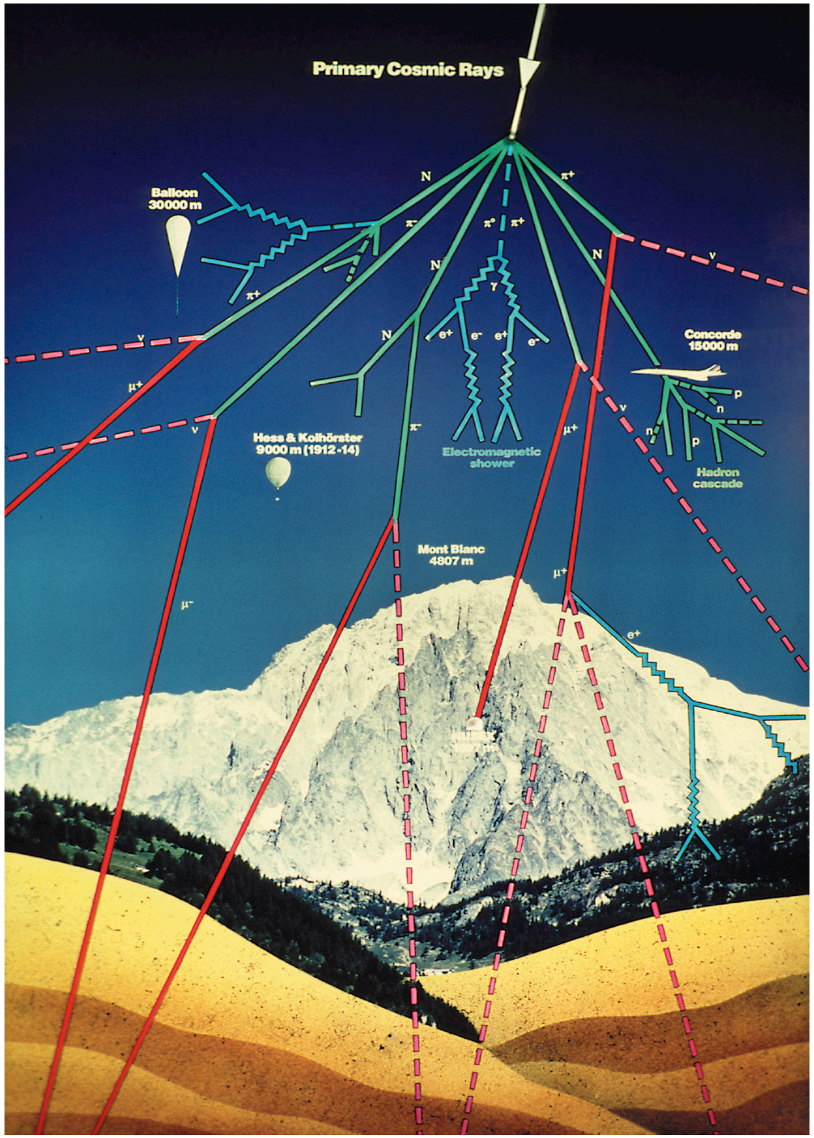
→

Massive Neutrinos

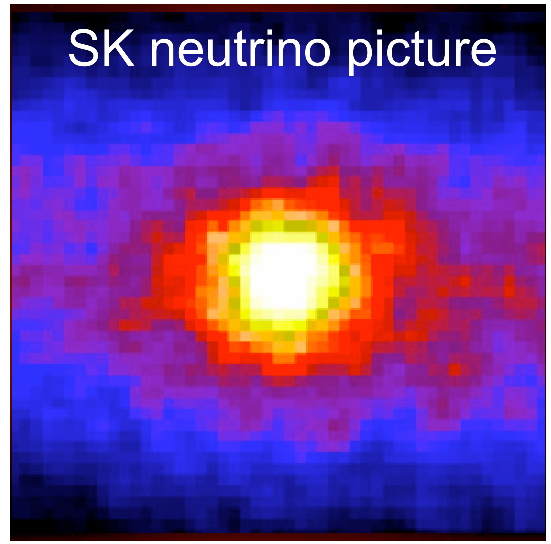
First evidence of Physics beyond
the Standard Model

Neutrino sources

Atmosphere



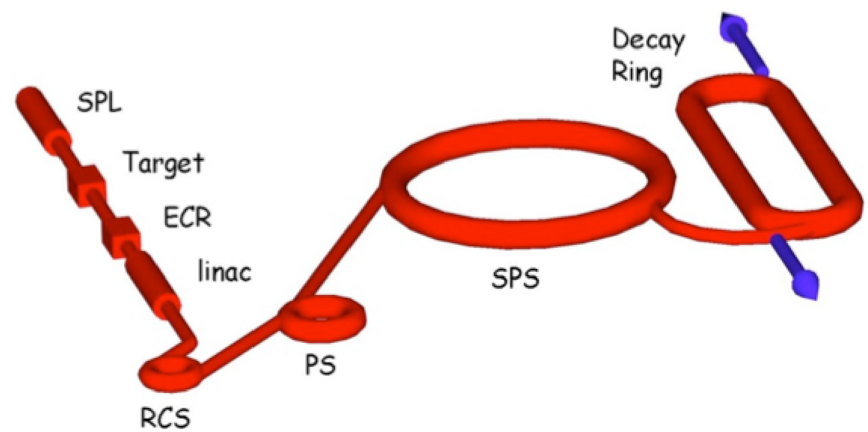
Sun



Supernovae

Reactors

Accelerators



Flavour Mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

m_1

m_2

m_3

mass eigenstates

θ_{23} | θ_{13}, δ_{CP} | θ_{12} | α_1, α_2

PMNS mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

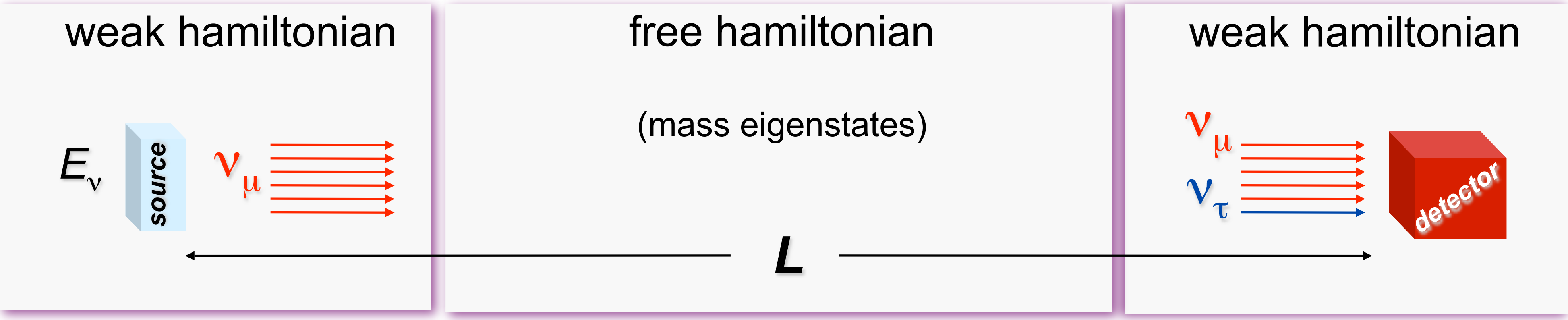
atmospheric sector | connection between solar and atmospheric | solar sector

Majorana

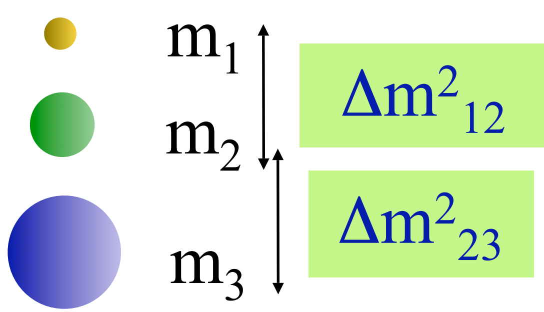
Dirac

Neutrino oscillations

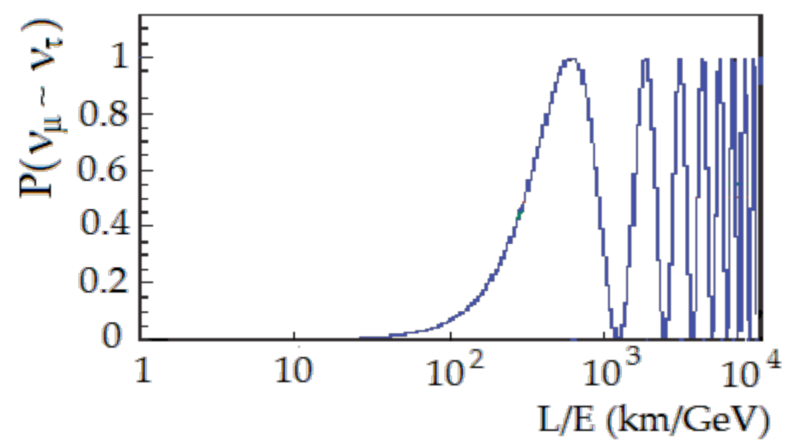
Requirements: Massive neutrinos & different masses



$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$



mass eigenstates



Experimental results

Errors from 10 to 30%

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2\,,$$

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\,\left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}\,, \\ +2.46 \pm 0.15\,\left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}\,, \end{cases}$$

$$\theta_{12} = 34.5 \pm 1.4\,\left(^{+4.8}_{-4.0}\right)\,,$$

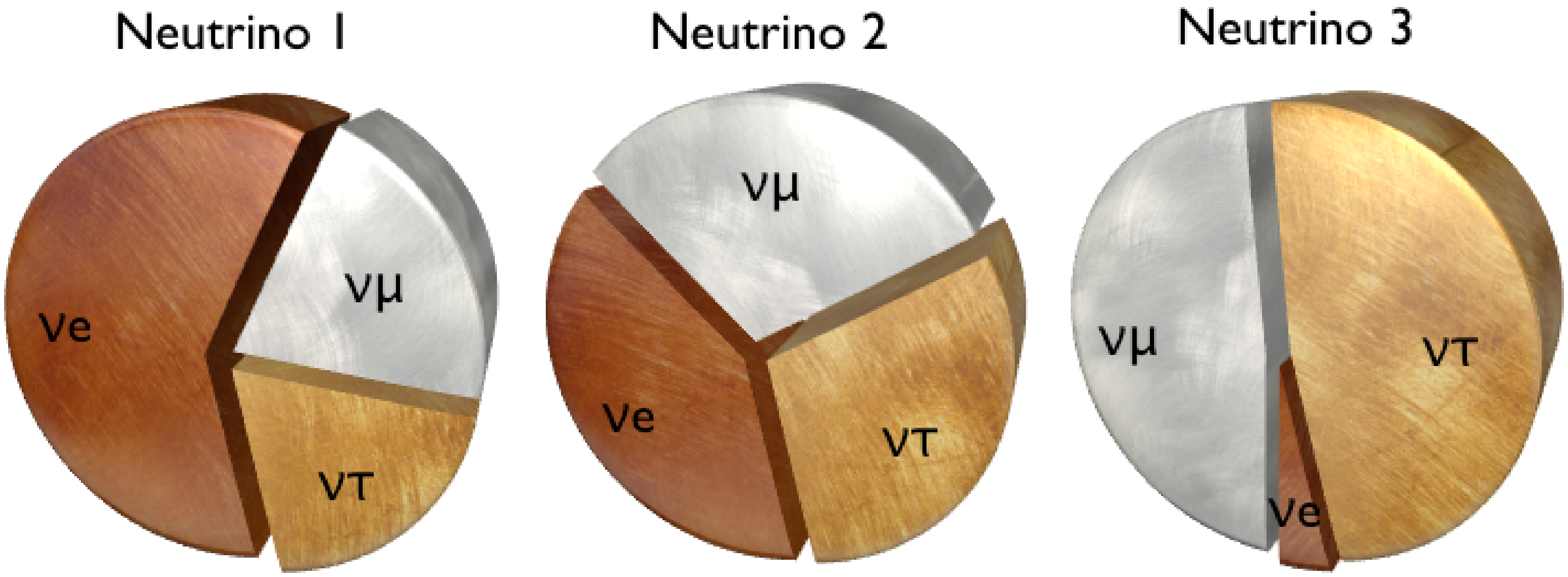
$$\theta_{23} = 42.3\,^{+5.1}_{-3.3}\,\left(^{+11.3}_{-7.7}\right)\,,$$

$$\theta_{13} = 0.0^{+3.9}\,\left(^{+9.0}\right)$$

Still missing

θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^o$?

Mixing angles

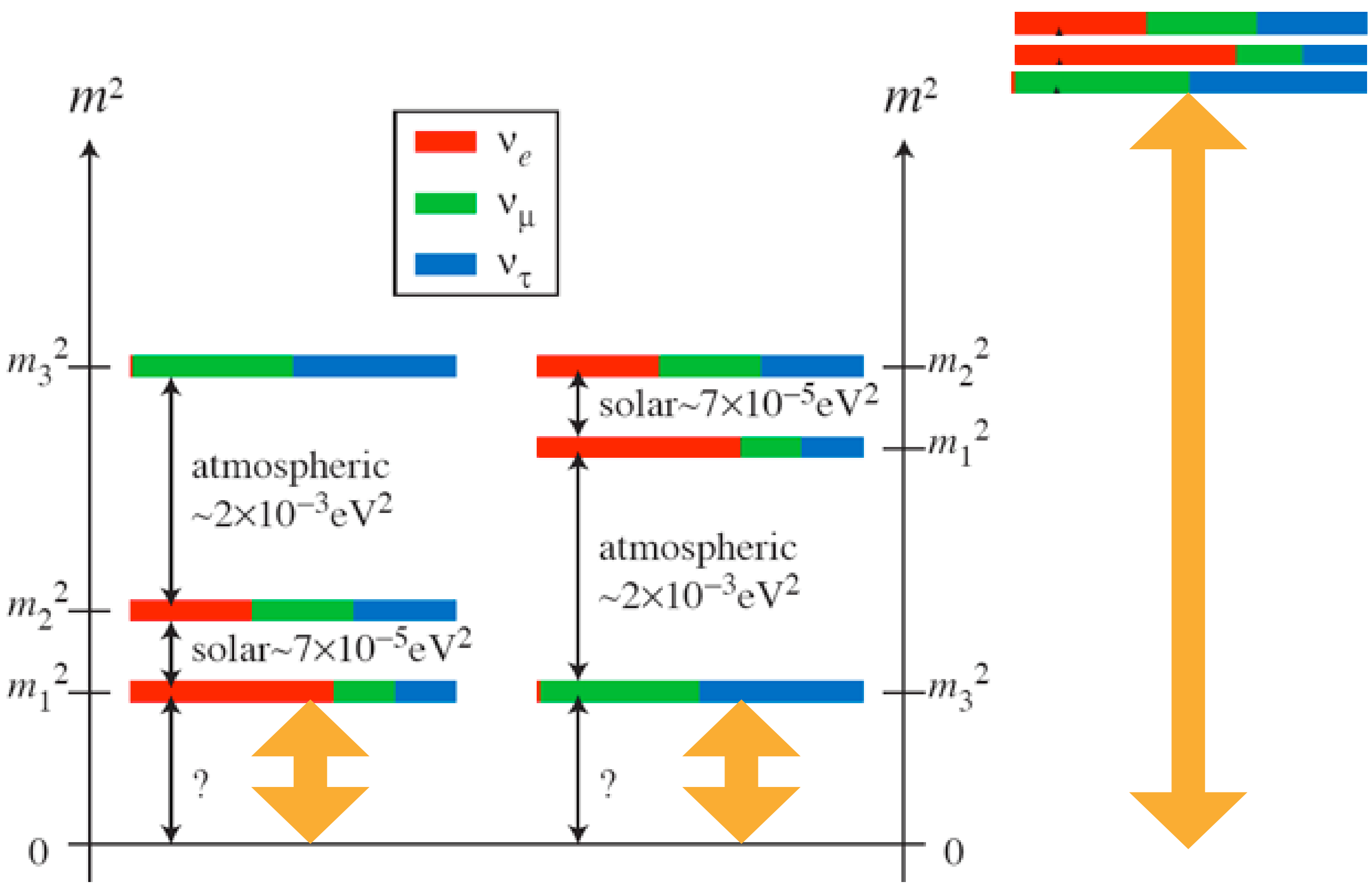


Mass square differences

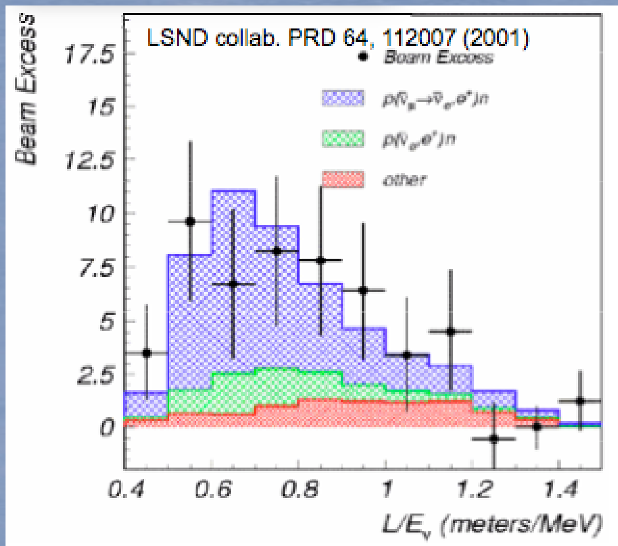
Normal
$\Delta m^2_{23}>0$

Inverted
$\Delta m^2_{23}<0$

Degenerate
$m_i >> \Delta m^2_{23}$



Sterile neutrinos



LSND

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

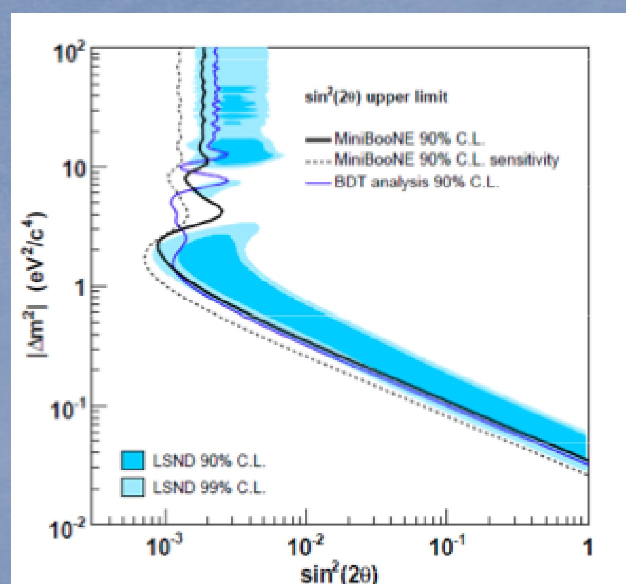
L/E ~ 1

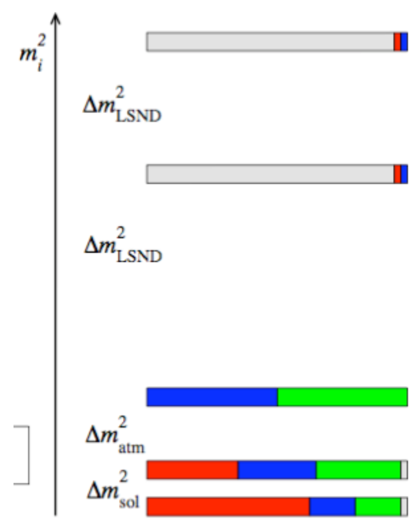
$\Delta m^2 \sim 1$ eV

Incompatible
with all other experiments
for 3 neutrinos only

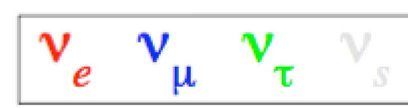
MiniBooNE

Excludes the LSND result as two family oscillations





two sterile neutrinos



Three active light neutrinos

Absolute mass

Cosmology

$\sum m_\nu < 0.3\text{-}0.9$ eV

Neutrinoless doble β decay

$\langle m_{\beta\beta} \rangle < 0.3\text{-}0.9$ eV

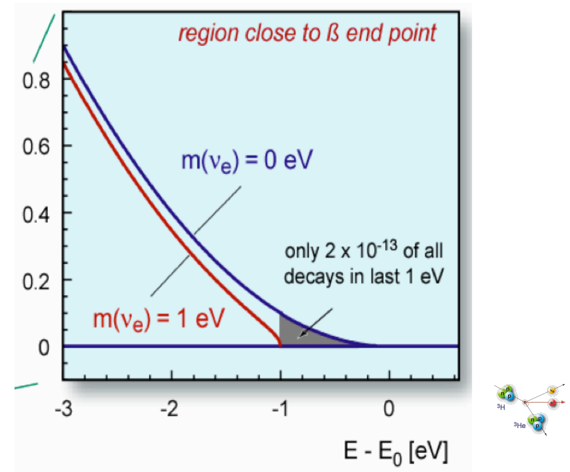
Tritium β decay

Mainz (2000)

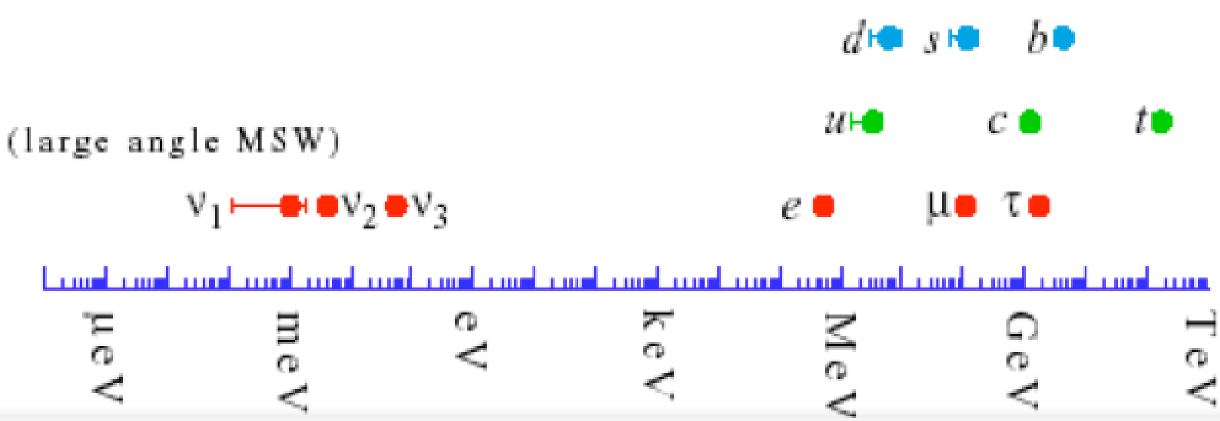
$m_{\nu e} < 2.2$ eV

Katrin (2009)

$m_{\nu e} < 0.2$ eV



Theoretical problem: Why neutrino masses are that small ?

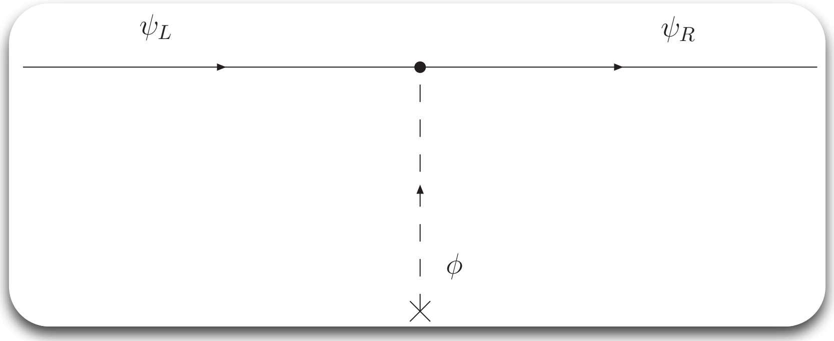


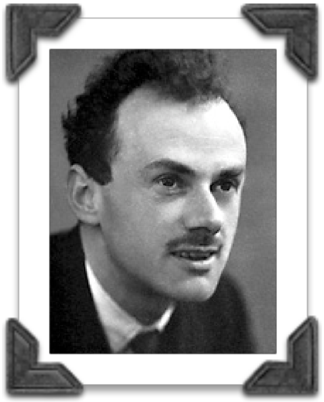
Dirac or Majorana

Dirac

$$\lambda \bar{\psi}_R \phi \psi_L \xrightarrow{\text{SSB}} \lambda v \bar{\psi}_R \psi_L$$

$$m_\nu \equiv \lambda v$$





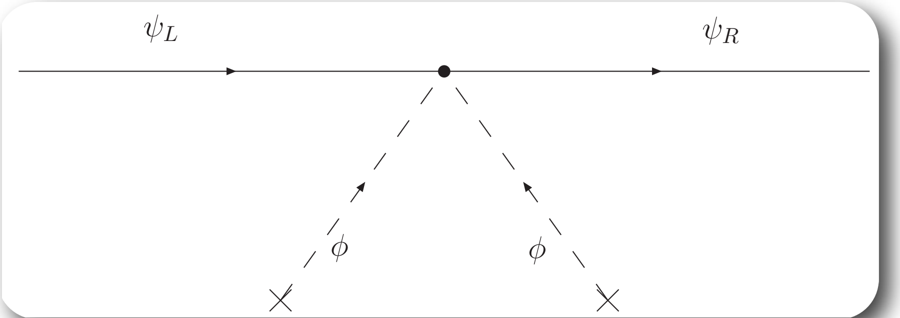
Hierarchy problem

Why λ is much smaller for neutrinos than for the other fermions?

Majorana

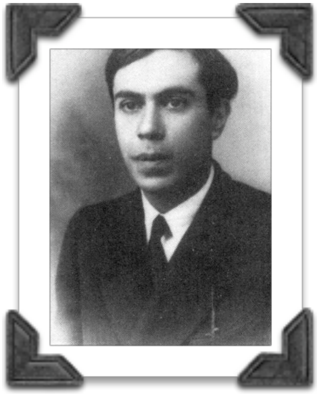
$$\frac{1}{\Lambda}(\bar{\psi}_L \phi)(\phi^T \psi_L^c) \xrightarrow{\text{SSB}} \frac{\lambda v^2}{\Lambda} \bar{\psi}_L \psi_L^c$$

$$m_\nu \equiv \lambda \frac{v^2}{\Lambda}$$

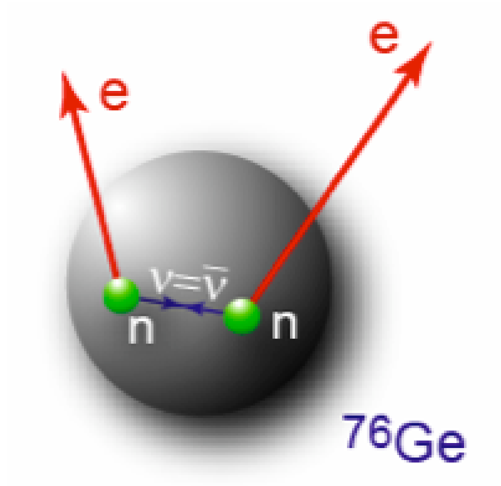


Λ →Scale of new Physics

Λ very large→neutrino mass very small

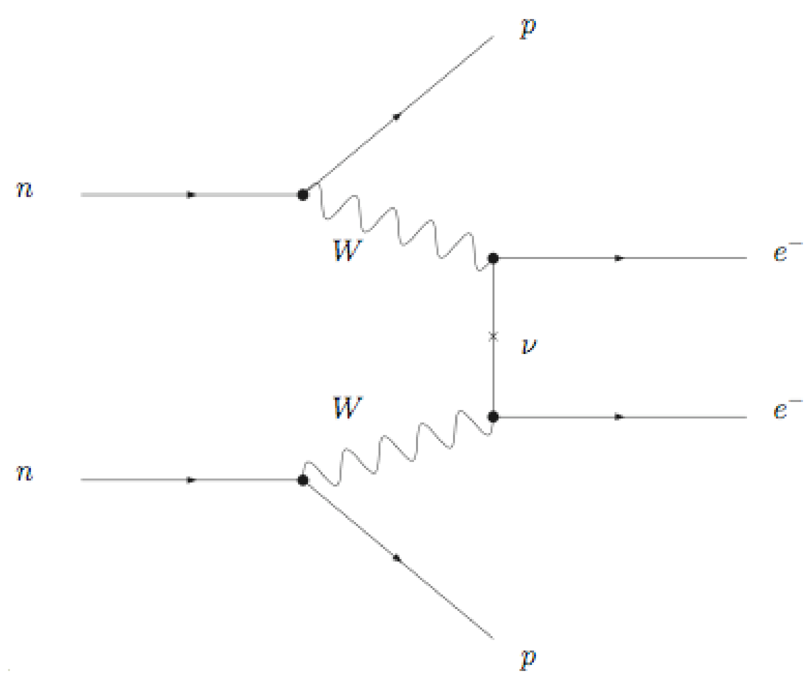


Neutrinoless double beta decay



A very rare process
$T_{1/2} > 10^{26}$ years

Intercambio de neutrinos ligeros de Majorana

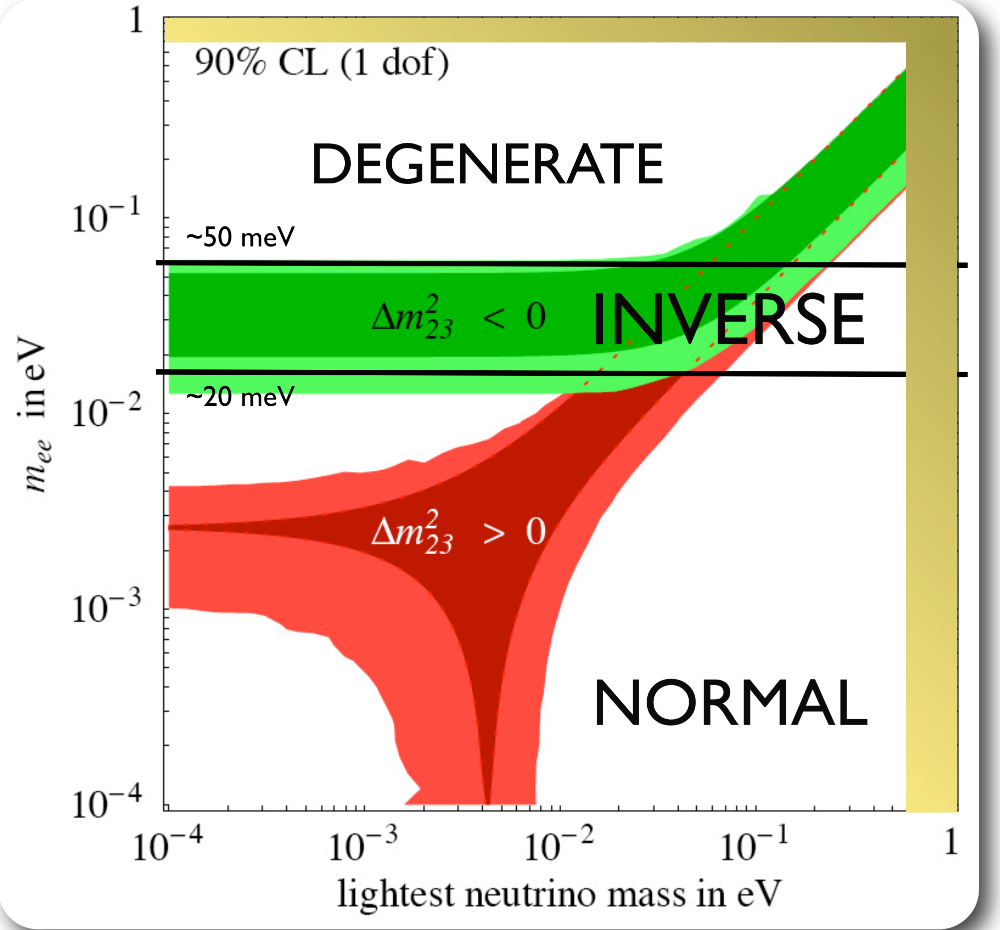


Talk by Igor Arastorza on Thursday

Other mechanisms are possible
But all imply Majoranna neutrinos

… y its connection with mass

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$



Effective Majorana mass:
- mixing angles
- neutrino masses
- Majorana phases

$$\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U^2_{ej}\right|$$

$$= \left|\cos^2\theta_{13}(|m_1|\cos^2\theta_{12} + |m_2|e^{2i\alpha_1}\sin^2\theta_{12}) + |m_3|e^{2i(\alpha_2-\delta)}\sin^2\theta_{13}\right|$$

The big questions

Nature: Majorana or Dirac?

Majorana phases

Absolute mass

Mass hierarchy

Is there CP viaolation in the leptonic sector?

Mixing angles:

θ_{13}

Is θ_{23} maximal?

Are there more than 3 light neutrinos (sterile)?

Why θ_{13} is that small?

If θ_{23} is maximal, why?

Why neutrinos are much lighter than the other fermions?

Is baryon asymmetry produced via leptogenesis ?

cosmology

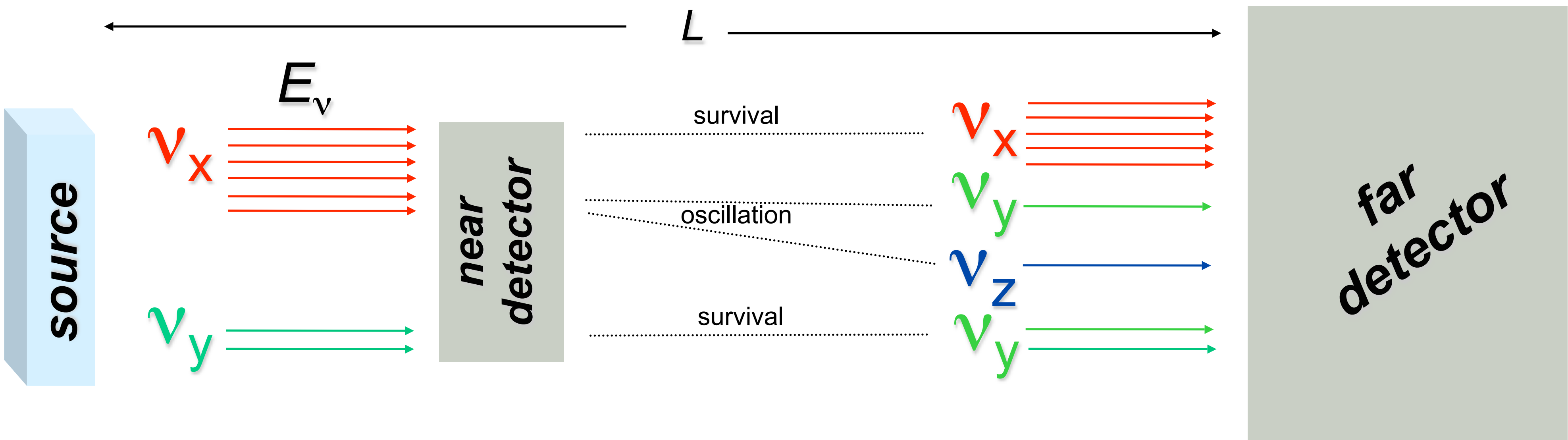
end point of beta decay spectrum

$0\nu\beta\beta$

oscillations

Detecting neutrino oscillations

Ingredients

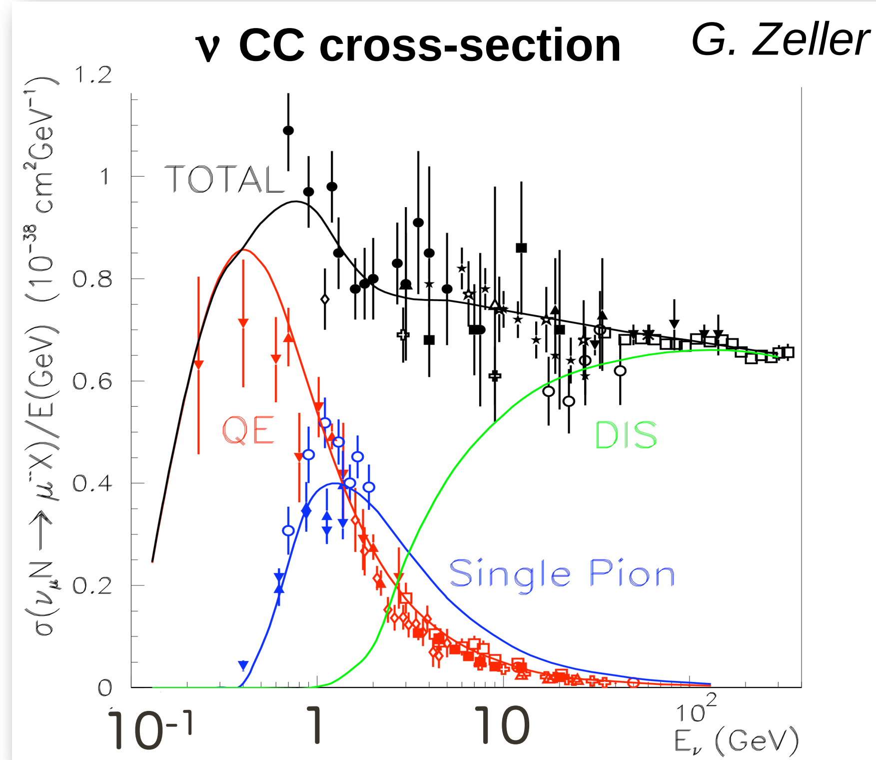


- Neutrino flux and spectra before osc. ?
  - Theoretical models
  - near detector(s): fine grain
  - Hadron production
- Neutrino x-sections at E_ν ?
  - measure x-sections at near detectors or dedicated experiments

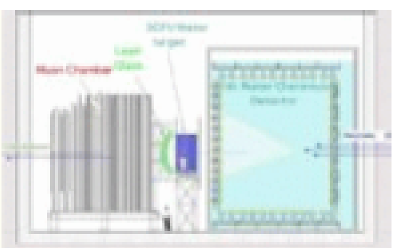
- Measure neutrino type and energy in very massive detector
- Compare prediction with observation

Neutrino x-sections

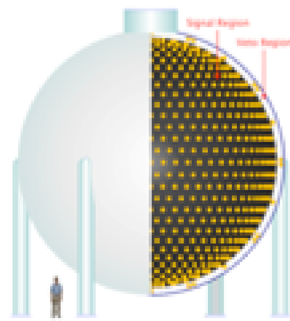
Neutrino x-sections
are poorly know at ~ 1 GeV



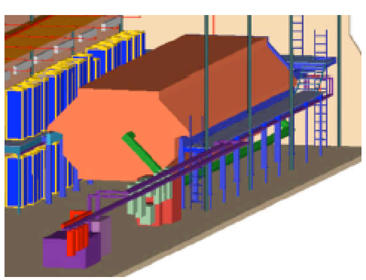
K2K



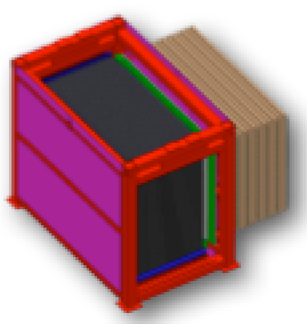
MiniBooNE



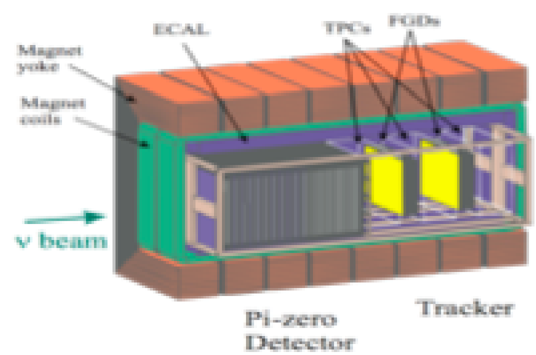
MINOS



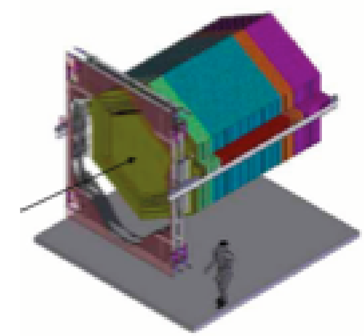
SciBooNE



T2K-ND280



Minerva



Oscillation length

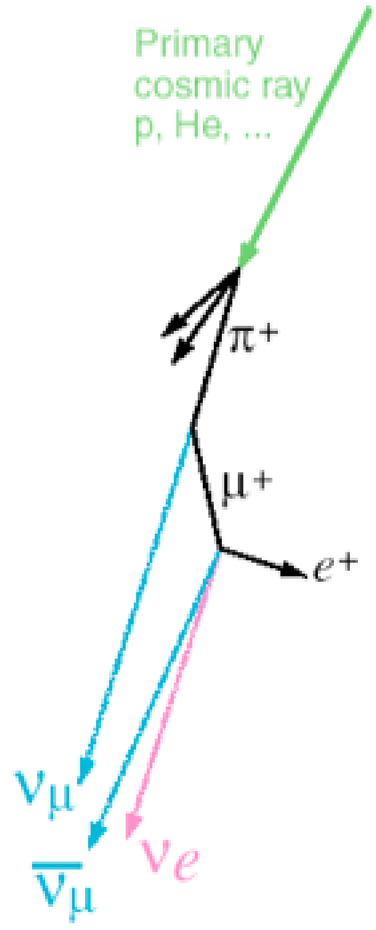
$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

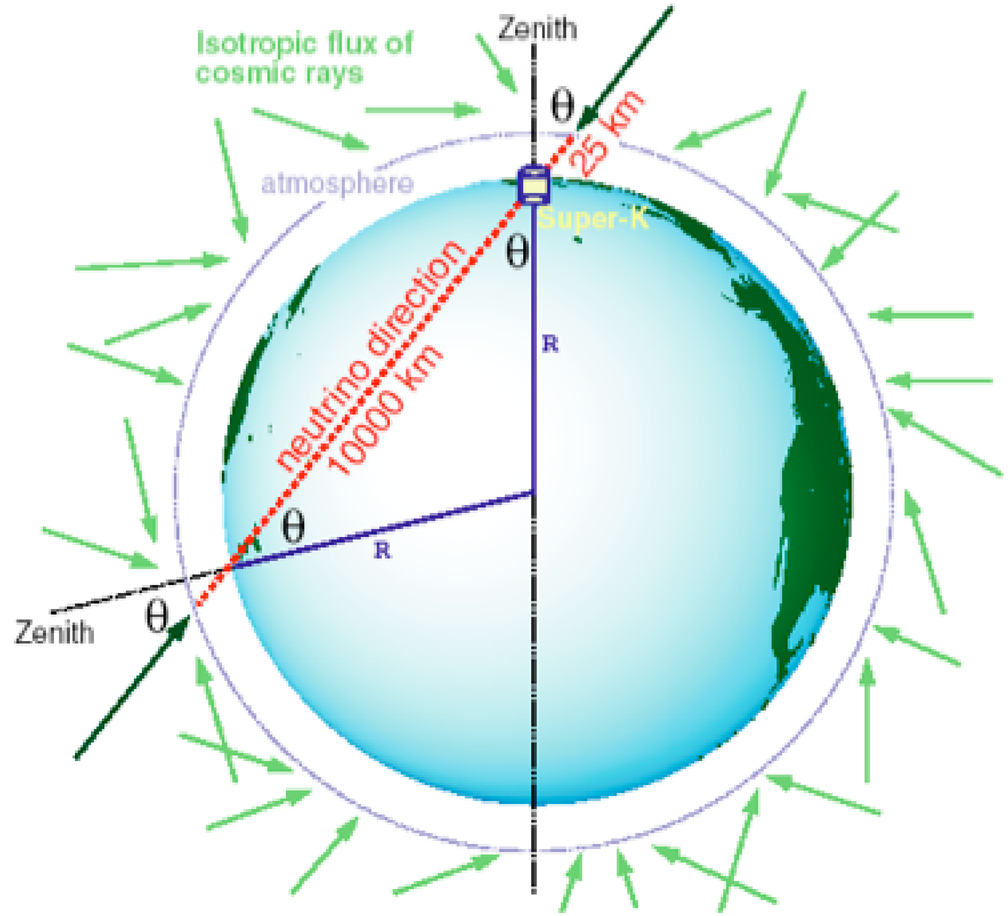
$$\frac{\Delta m^2 \cdot L}{4E_\nu} = \frac{\pi}{2} \xrightarrow{E_\nu = 1 GeV} L_{osc} = \frac{2\pi}{\Delta m^2}$$

$$L_{osc}^{23} = \frac{2\pi}{\Delta m_{23}^2} \simeq 500\, Km$$ atmospheric

$$L_{osc}^{12} = \frac{2\pi}{\Delta m_{12}^2} \simeq 15000\, Km$$ solar

Atmospheric neutrinos





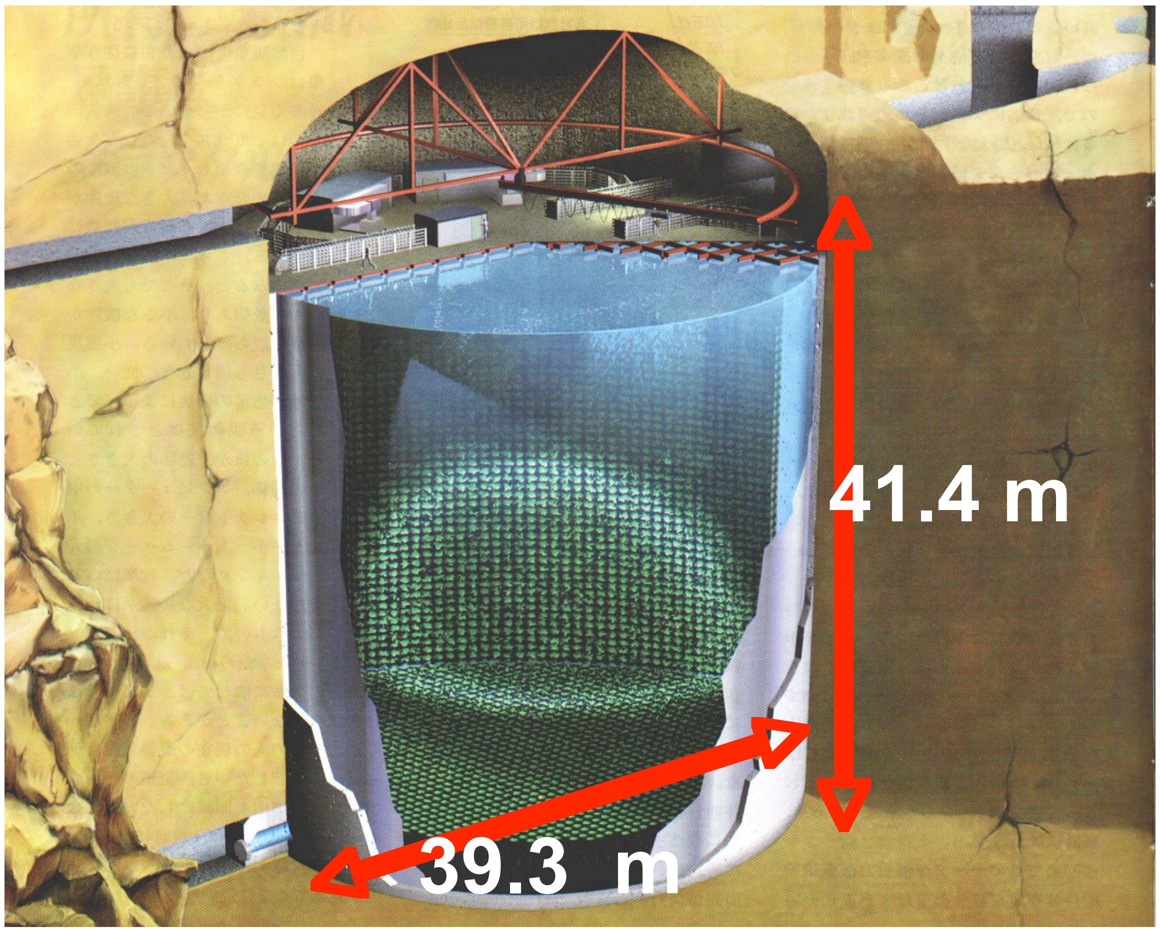
Ratio of $\nu_\mu/\nu_e \sim 2$

L=f(θ)

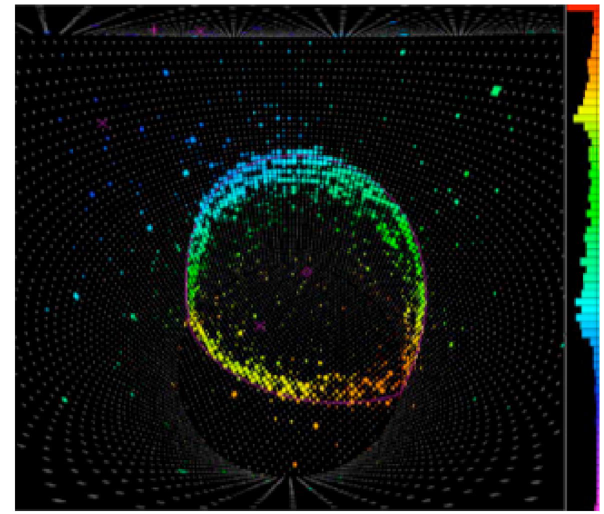
$$L/E \sim 1 - 10^4 \text{ km/GeV}$$

Exp. example I: Super-Kamiokande

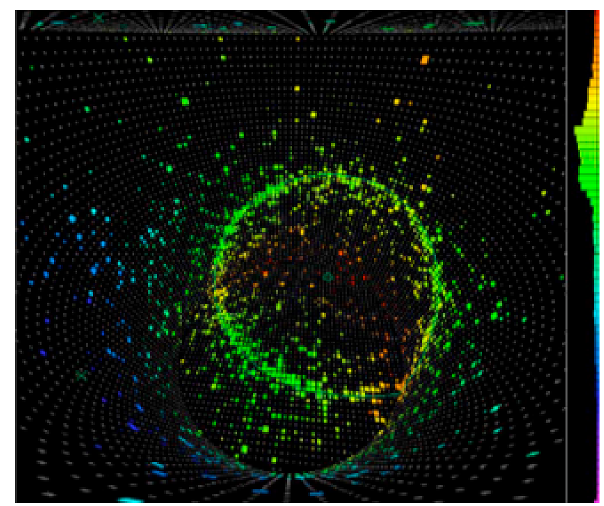
The power of large water cerenkov detectors



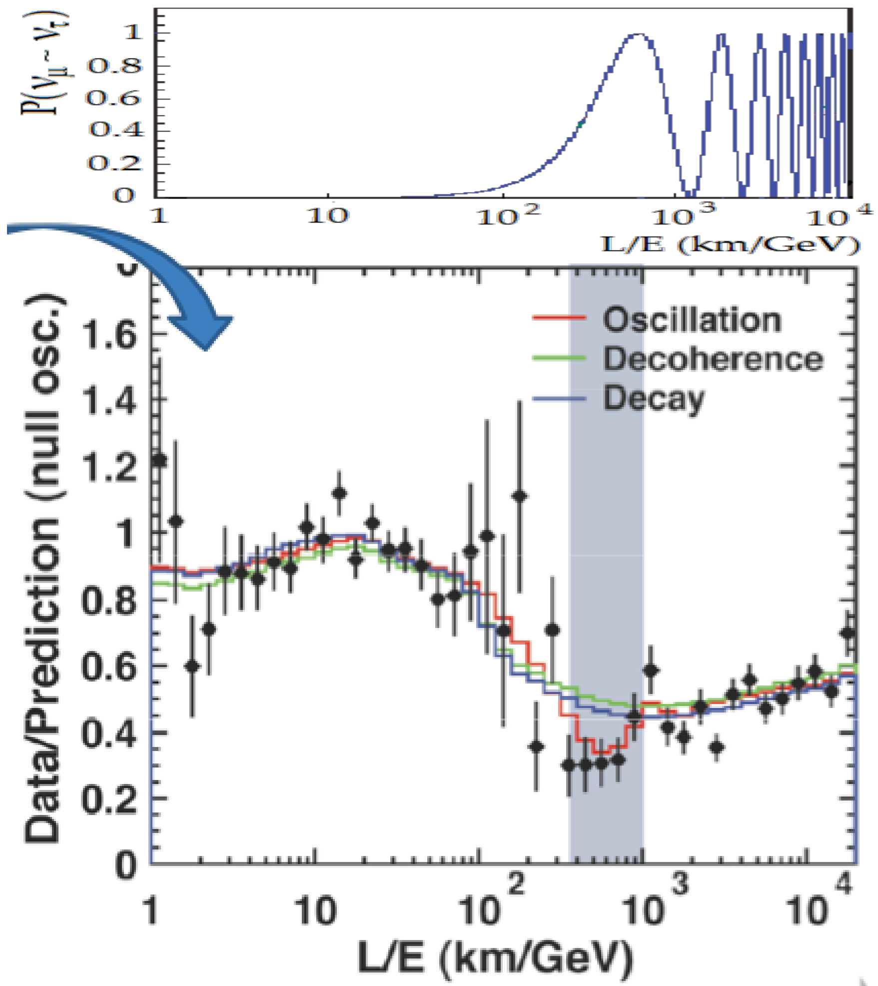
μ-like ring



e-like ring

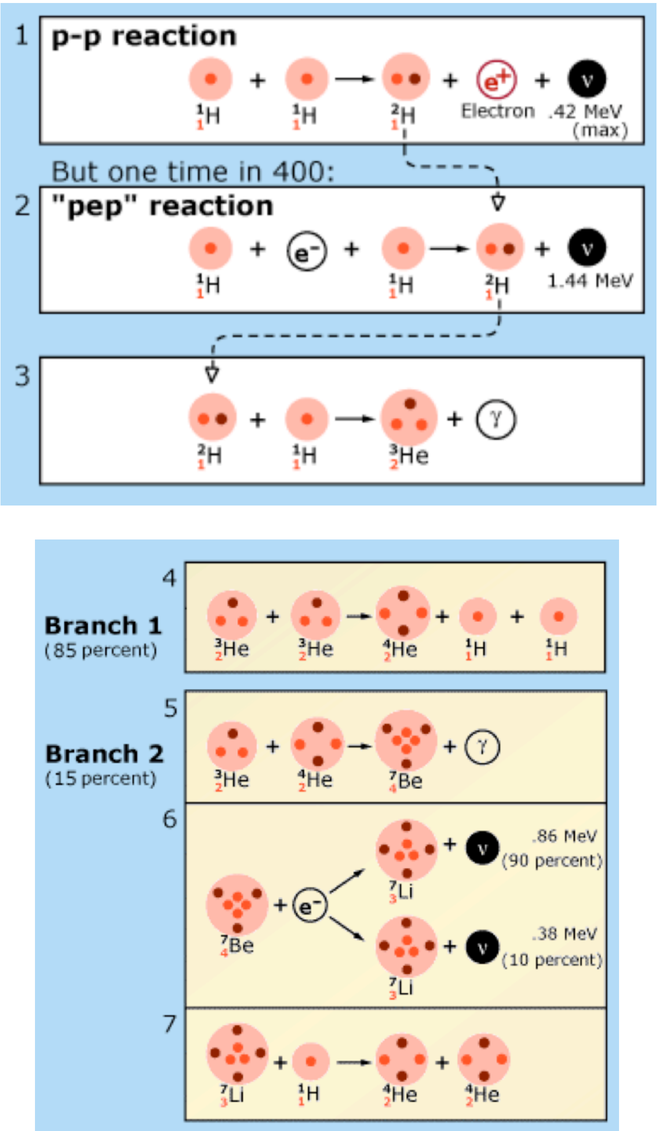


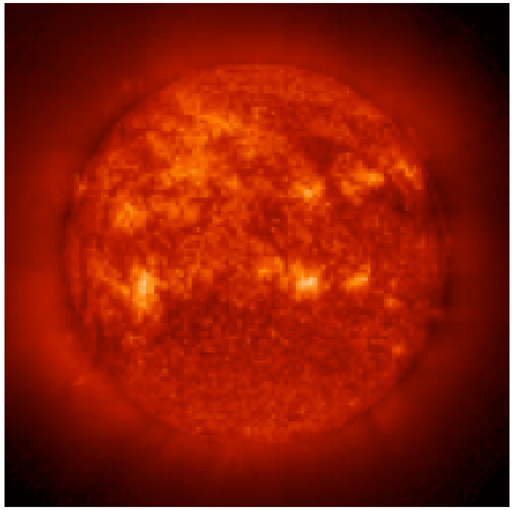
θ_{23} $|\Delta m^2_{23}|$

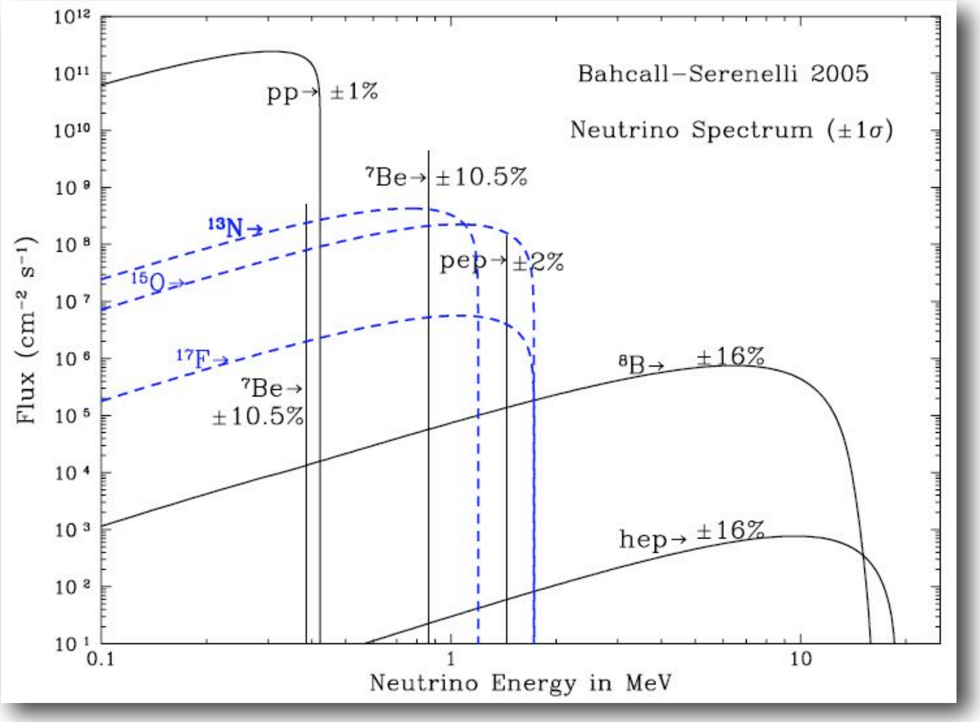


Solar neutrinos

Standard Solar Model



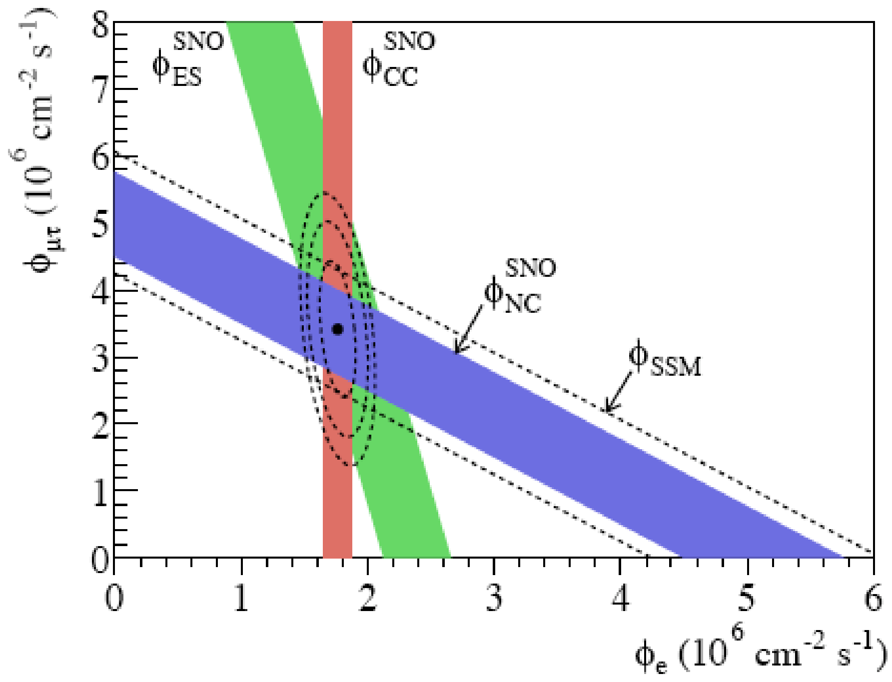




Experimental example II: SNO

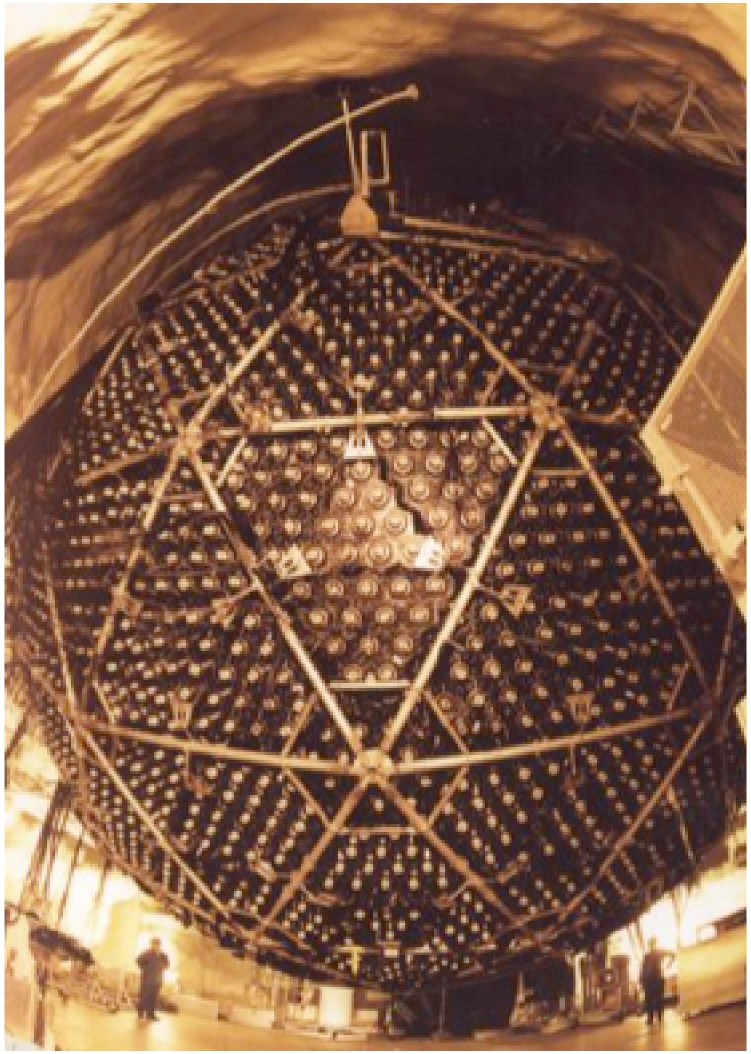
θ_{12} Δm^2_{12}

$$\begin{aligned} \nu_e + \mathrm{d} &\rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^- && \text{(CC)}, \\ \nu_x + \mathrm{d} &\rightarrow \mathrm{p} + \mathrm{n} + \nu_x && \text{(NC)}, \\ \nu_x + \mathrm{e}^- &\rightarrow \nu_x + e^- && \text{(ES)}. \end{aligned}$$

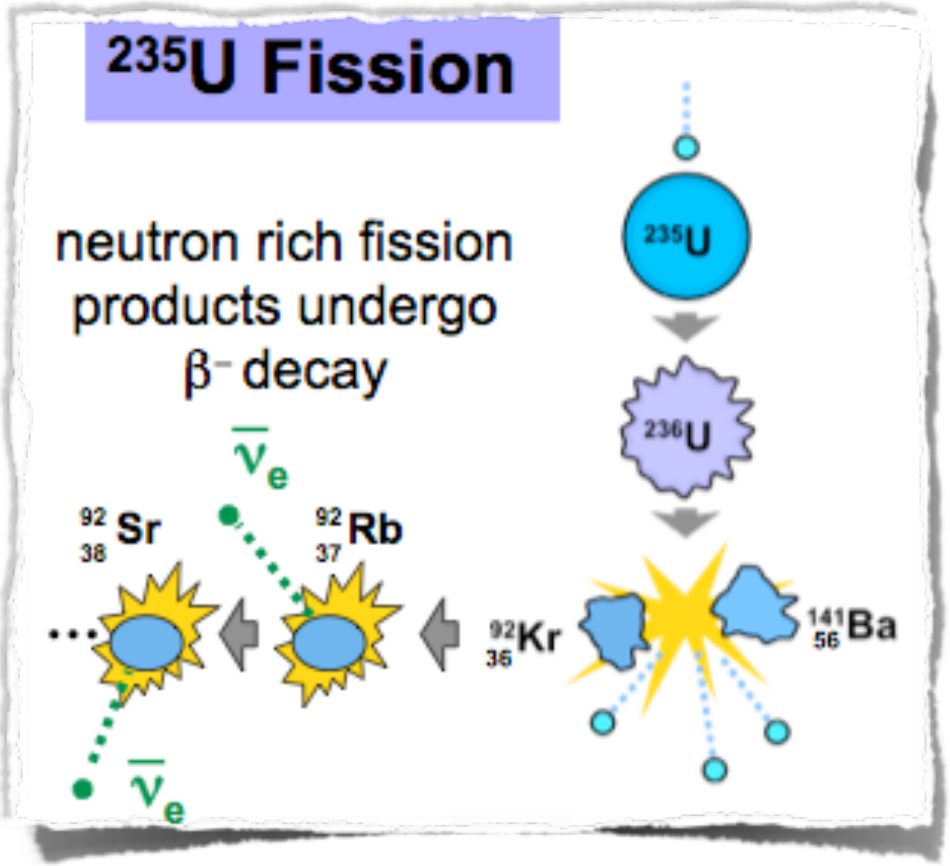


$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$



Reactor neutrinos



$\langle E \rangle$ / fission = 201.7 MeV

$\langle N_\nu \rangle$ / fission ≈ 6

1 $GW_{th} \Rightarrow \sim 2 \cdot 10^{20}$ ν/s

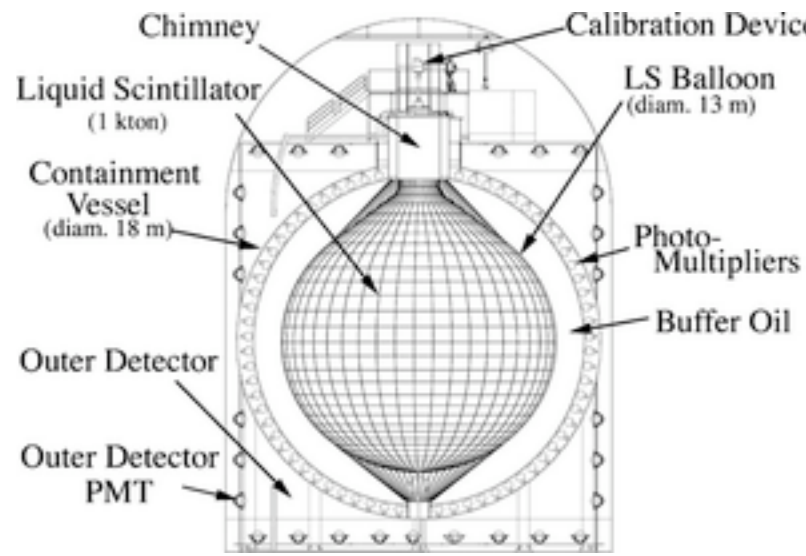
E_ν ~ few MeV

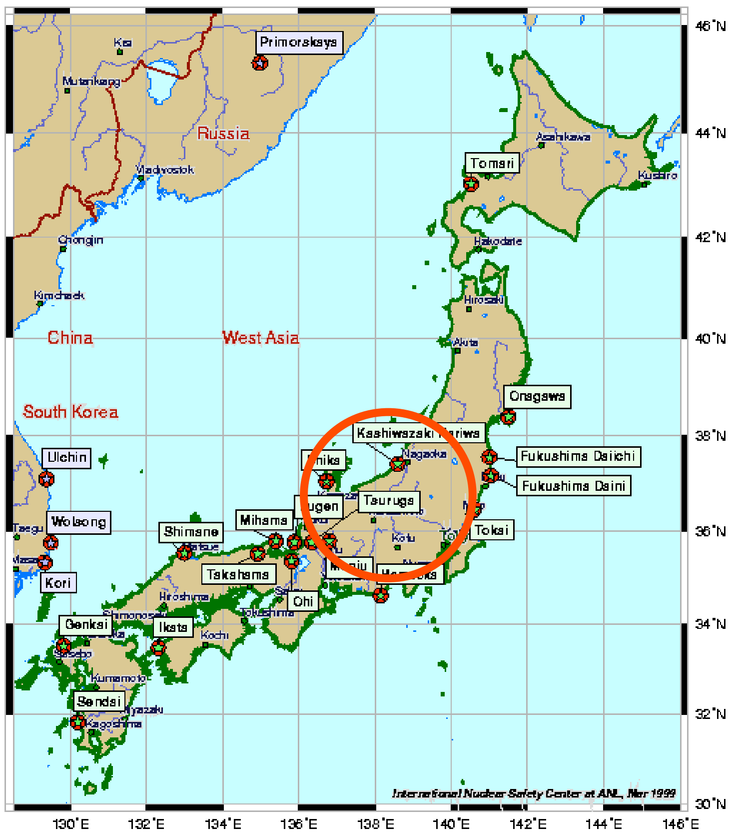
Pure $\bar{\nu}_e$

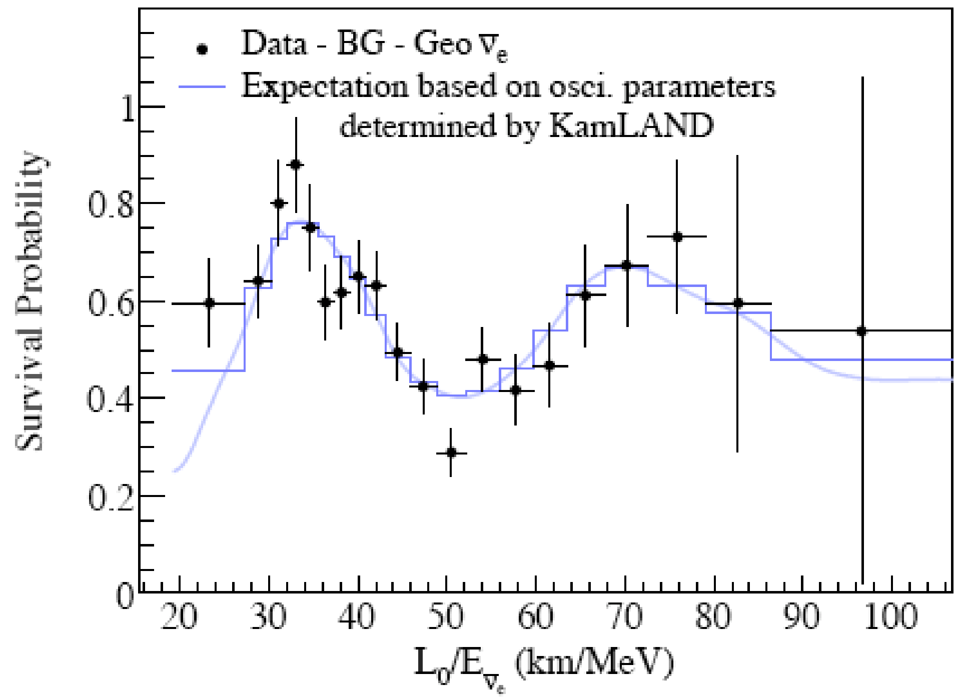
Experimental example III: Kamland

θ_{12} Δm^2_{12}

L/E~180/0.003 = 60000 Km/GeV

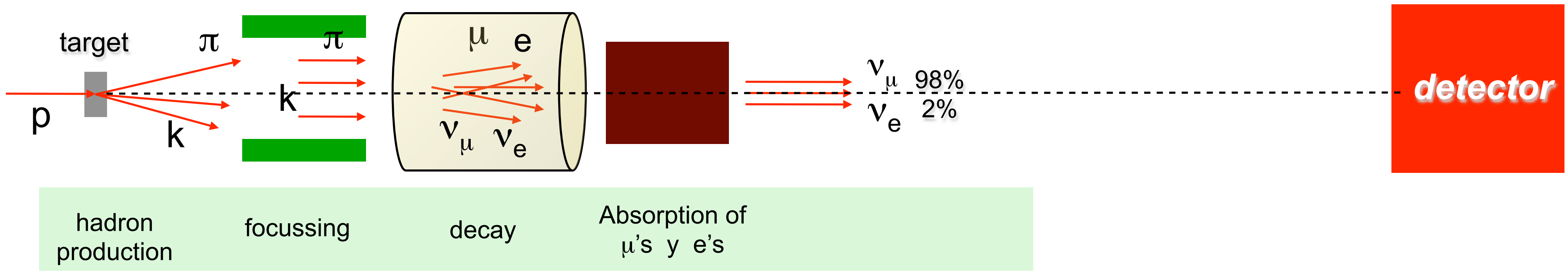




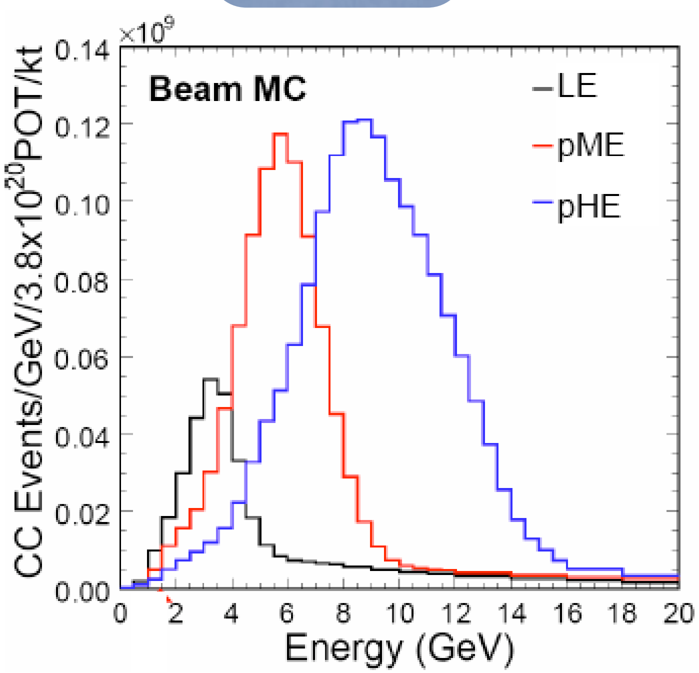


Neutrino beams

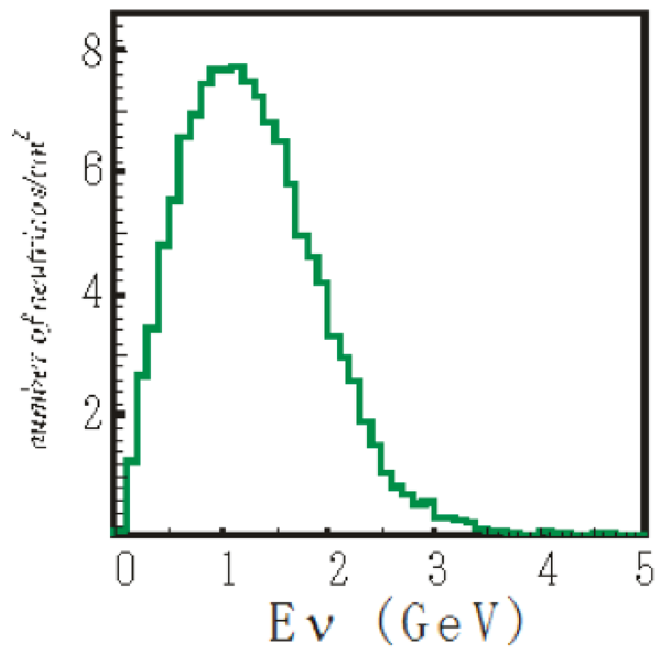
conventional neutrino beam



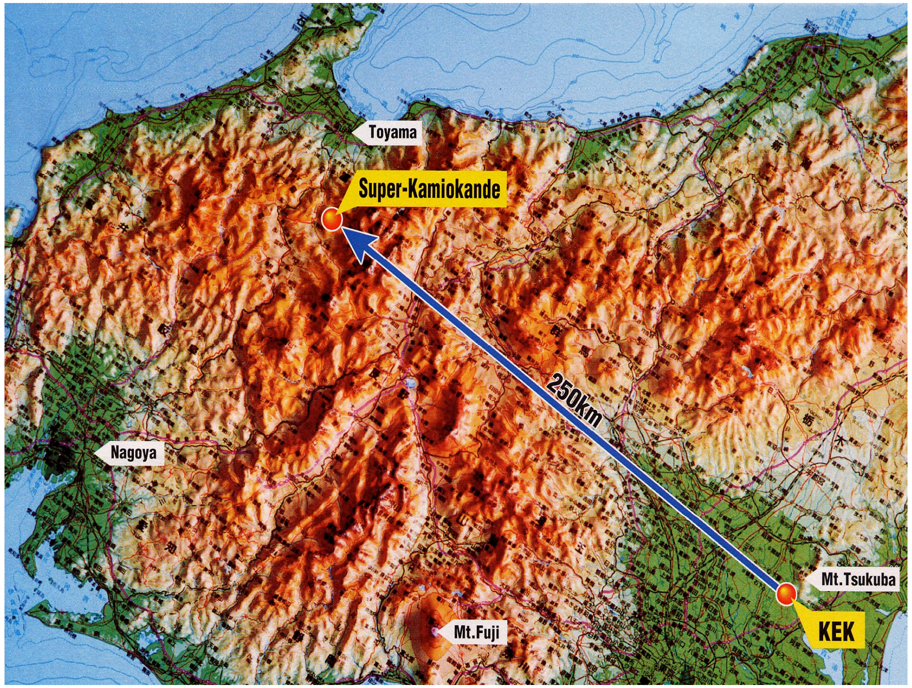
MINOS

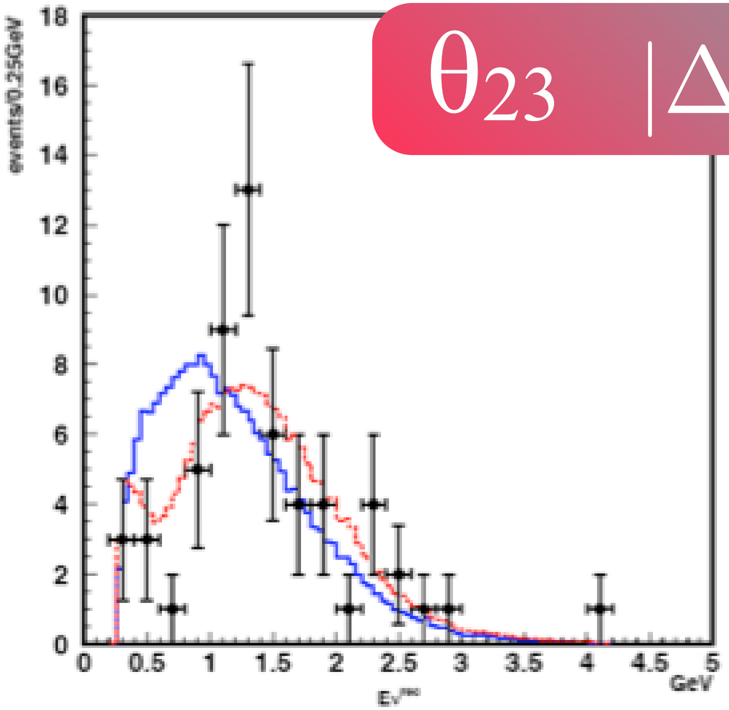


K2K

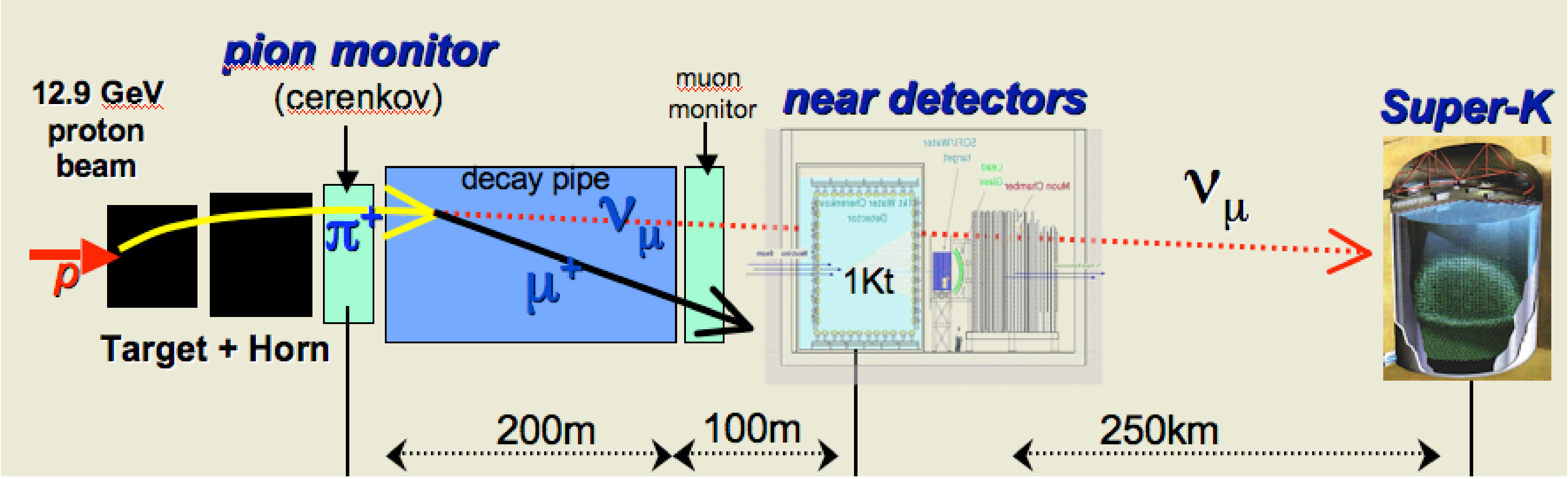


Experimental example IV: K2K

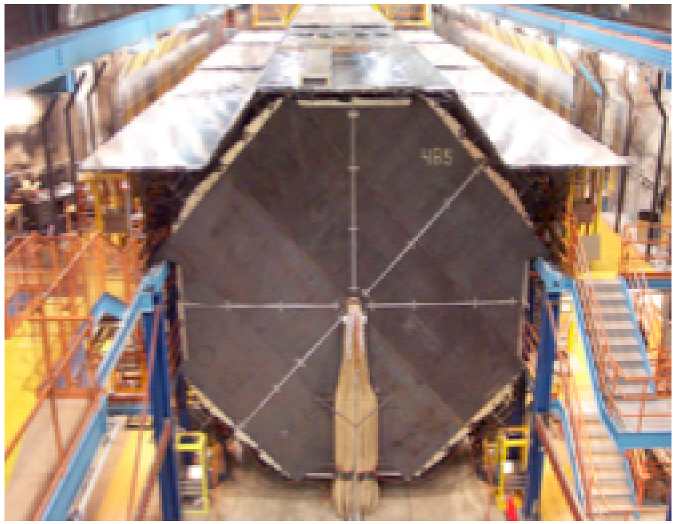




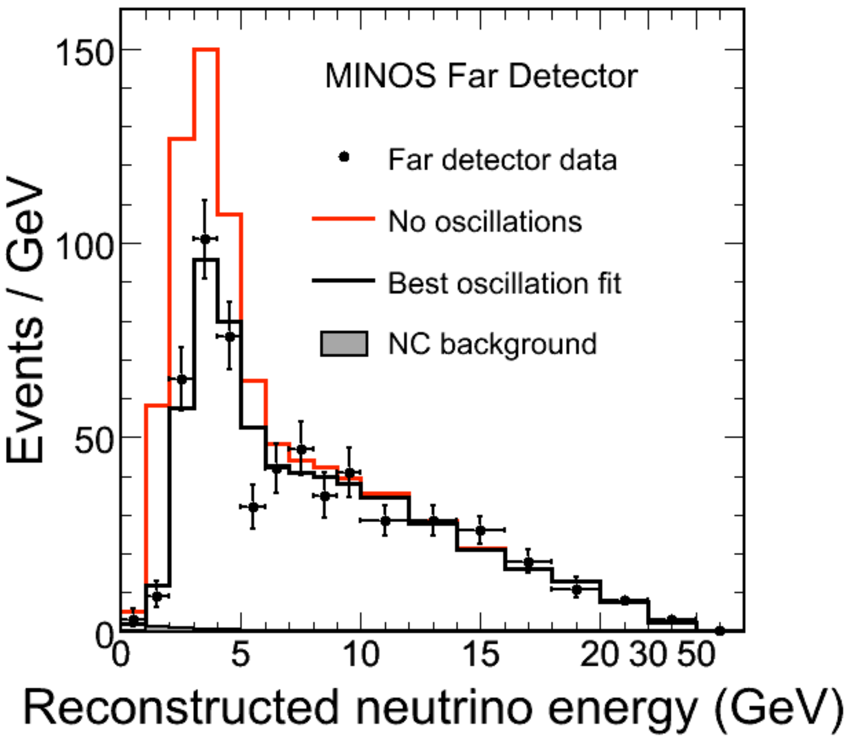
θ_{23} $|\Delta m^2_{23}|$

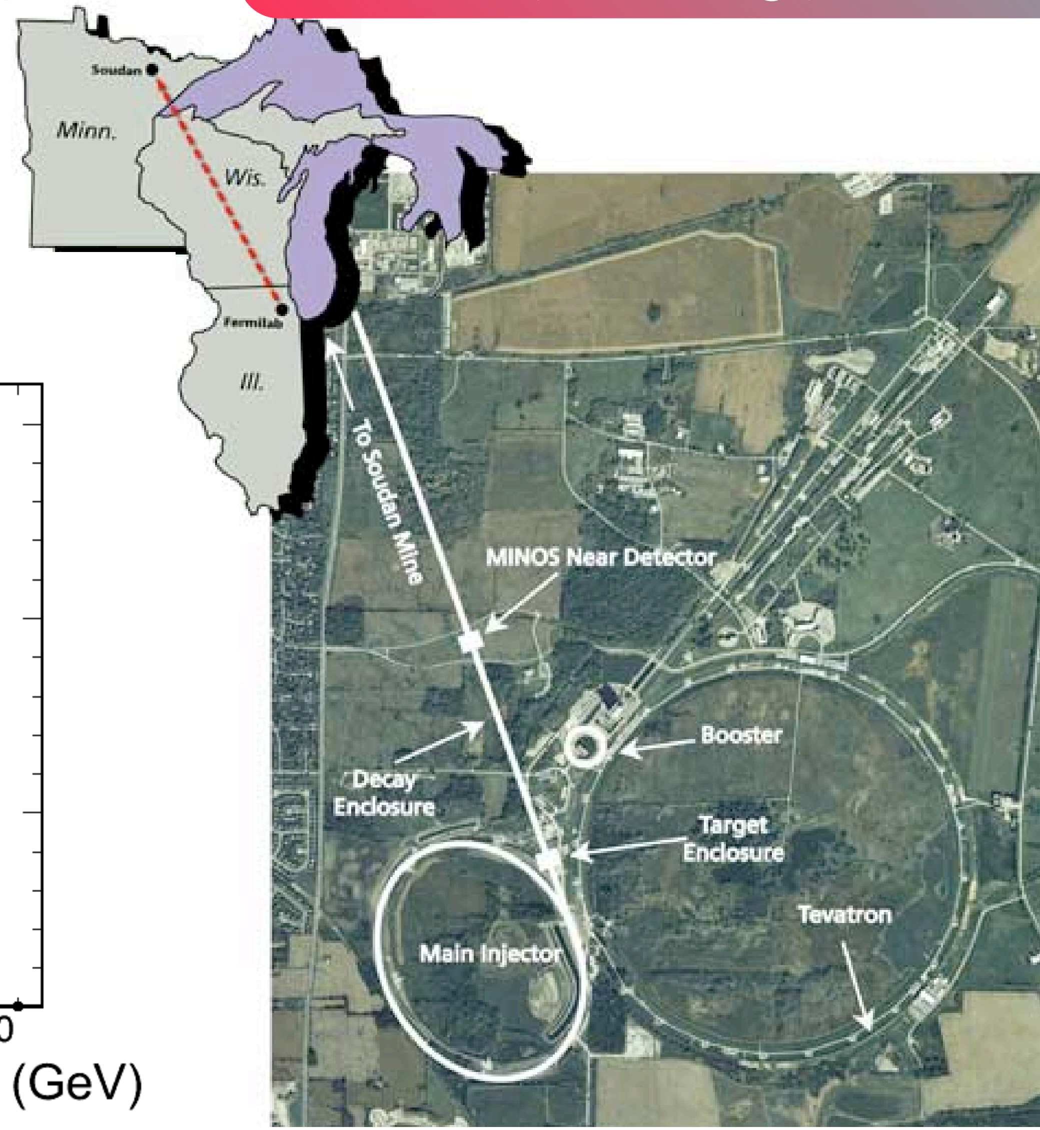


Experimental example V: MINOS

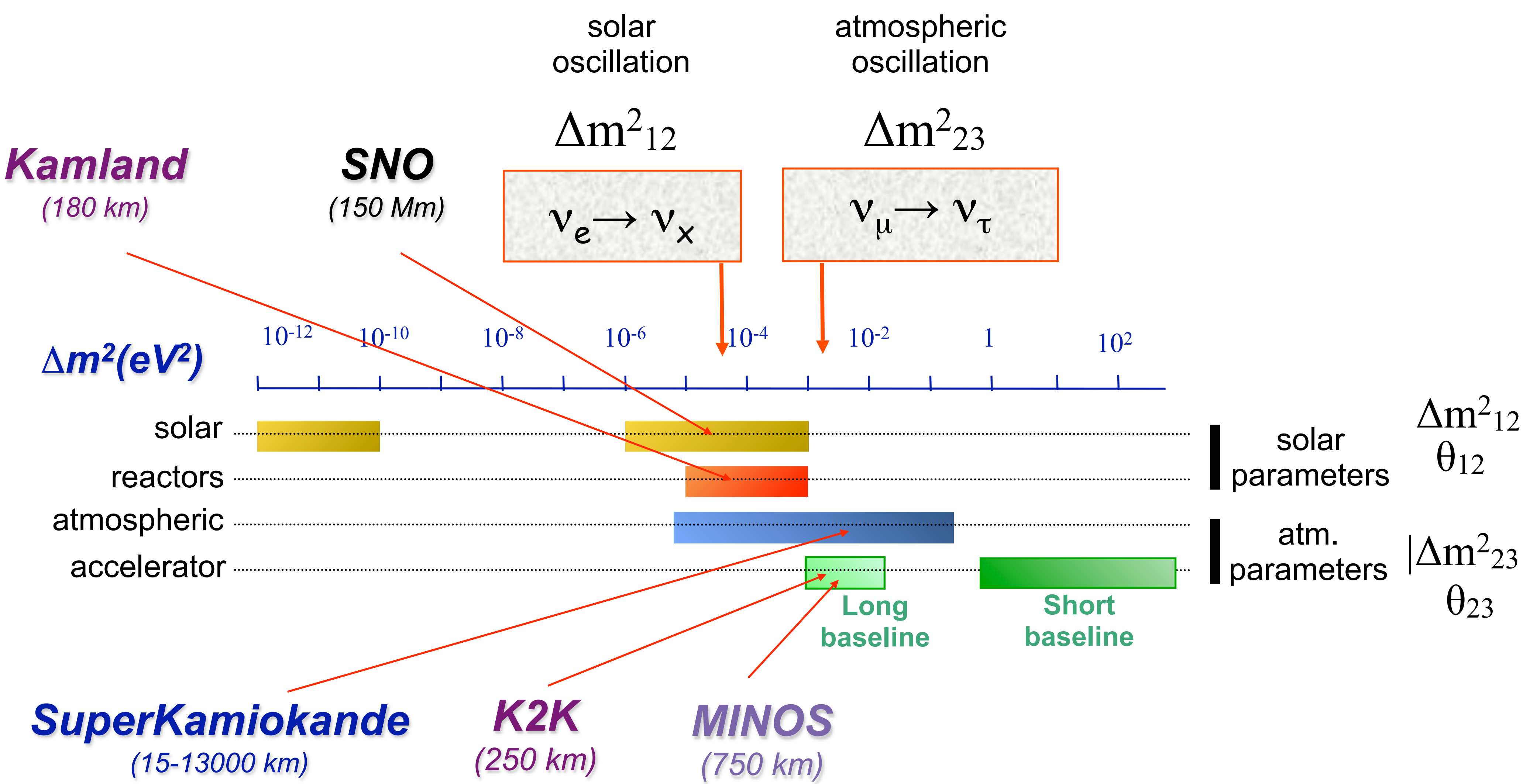


θ_{23} $|\Delta m^2_{23}|$ θ_{13}





All together



Missing parameters

θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^o$?

The θ_{13} quest

From 2 to 3 families

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector | connection between solar and atmospheric | solar sector

~ identity

$\theta_{13} < 10^{o}$ (Chooz)

atmospheric | **solar** | **interference**

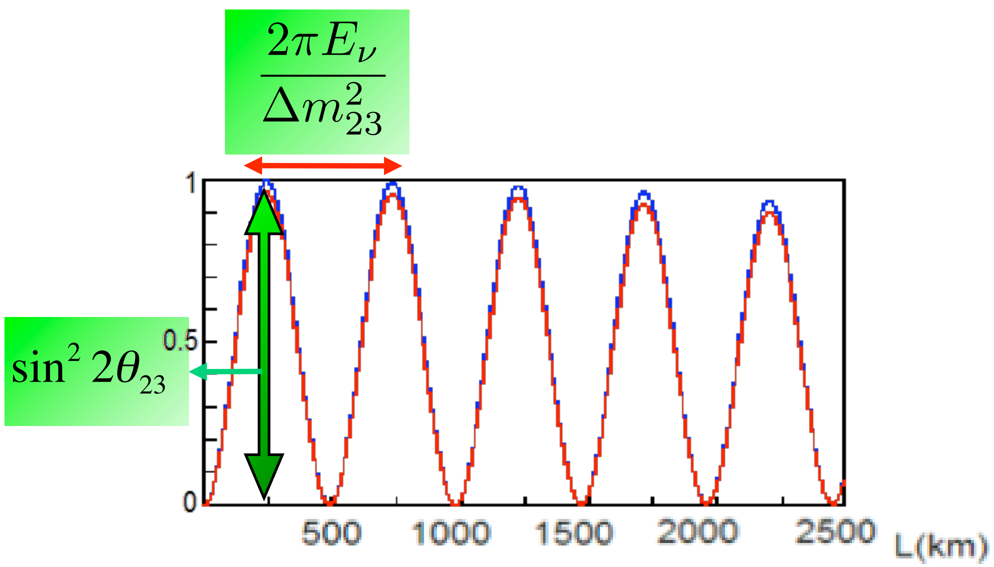
$$P(\text{no } \nu_e) \simeq cos^2 2\theta_{13} \cdot P_{atm}(\theta_{23}, |\Delta m^2_{23}|)$$

$$P(\nu_e) \simeq \frac{sin^2 2\theta_{13}}{2} \cdot P_{atm}(\theta_{23}, |\Delta m^2_{23}|) + P_{sol}(\theta_{12}, \Delta m^2_{12}) \pm sin2\theta_{13} \cdot F_{solar} \cdot F_{atm}(sin2\theta_{23}, |\Delta m^2_{23}|) \cdot F(\delta_{cp}, \Delta m^2_{23})$$

Subdominant oscillation

	atmospheric	solar	interference
$P(\text{no } \nu_e) \simeq$	$P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$		
$P(\nu_e) \simeq$	$\frac{sin^2 2\theta_{13}}{2} \cdot P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$	$+ P_{sol}(\theta_{12}, \Delta m^2_{12})$	$\pm sin2\theta_{13} \cdot F_{solar} \cdot F_{atm}(sin2\theta_{23}, \lvert\Delta m^2_{23}\rvert) \cdot F(\delta_{cp}, \Delta m^2_{23})$

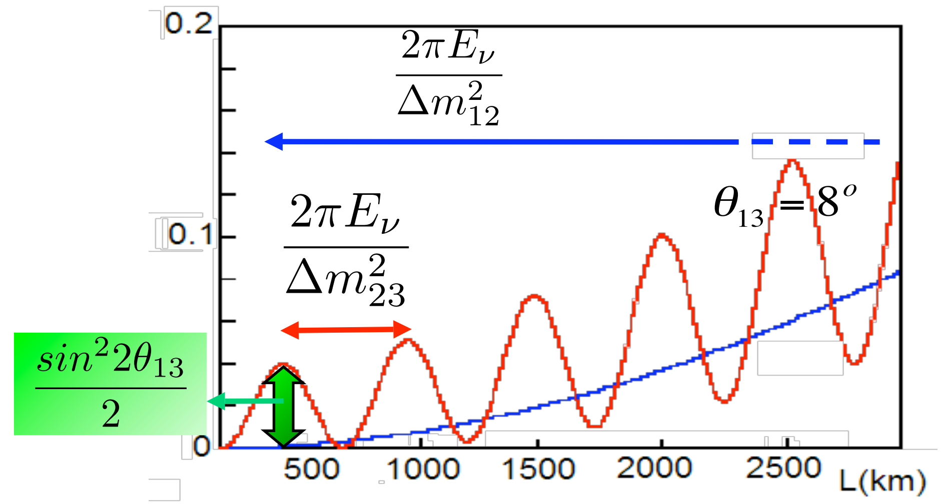
Dominant (no ν_e)



$\nu_\mu \rightarrow \nu_\tau$ OPERA

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

Subdominant (ν_e)



$\nu_e \rightarrow \nu_\mu$

$\nu_e \rightarrow \nu_\tau$

D-Chooz $\nu_e \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_e$ T2K NOvA

Reactor neutrinos

$n \rightarrow p + e^- + \overline{\nu}_e$ $E_\nu \sim$ few MeV $L_{osc\ peak} \sim$ Km

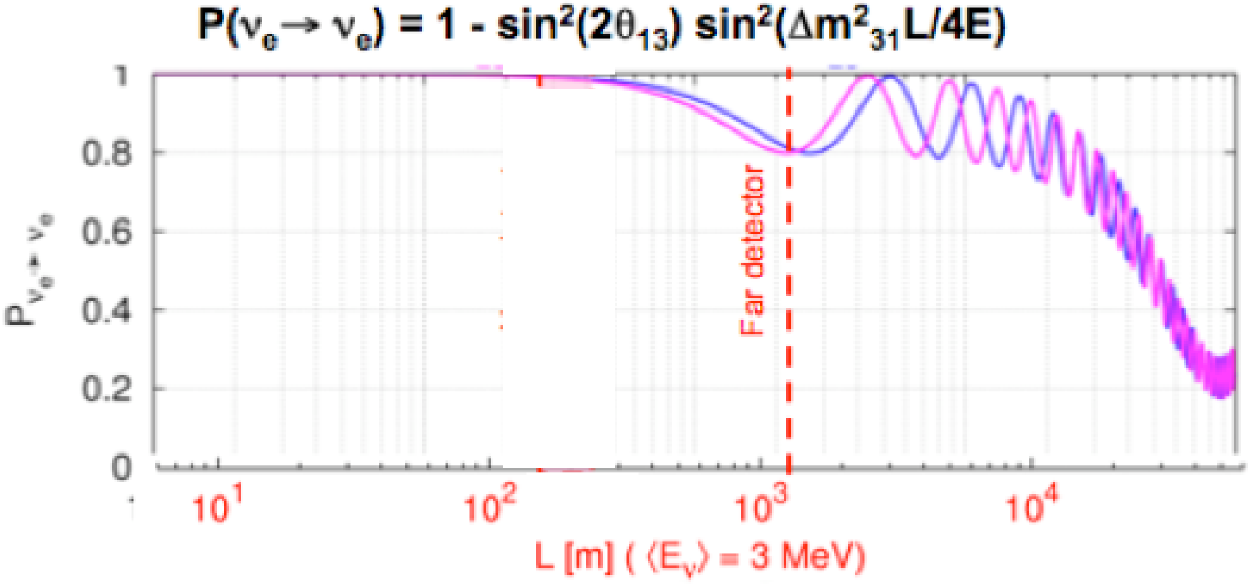
Below muon and tau production thresholds → dissapearence

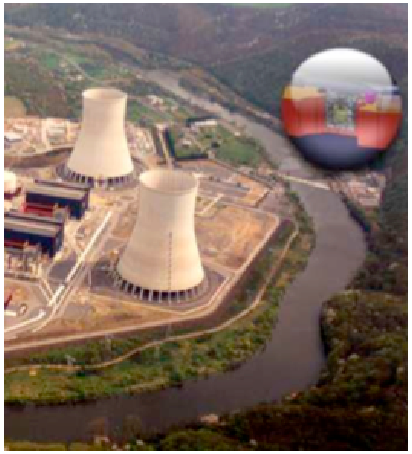
$$P_{\nu_e\nu_e} = 1 - P_{\nu_e\nu_\mu} - P_{\nu_e\nu_\tau} \simeq 1 - sin^2 2\theta_{13} \cdot sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

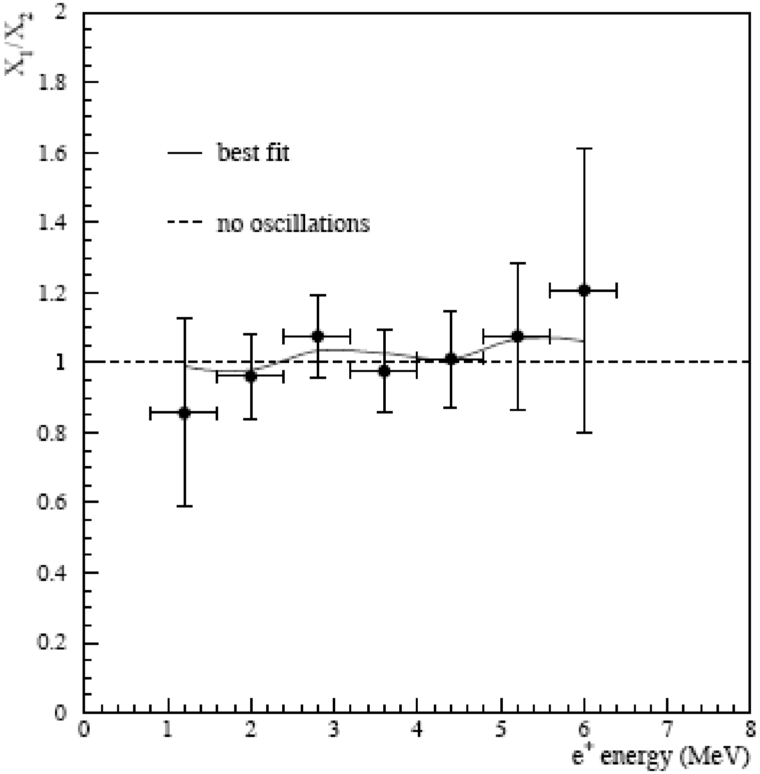
A clean probe of θ_{13}

- Interference term cancels out: **no dependency on δ_{cp}**
- Short baseline: **no dependency on mass hierarchy**
- The solar term is very small: **small dependency on solar params**

Chooz



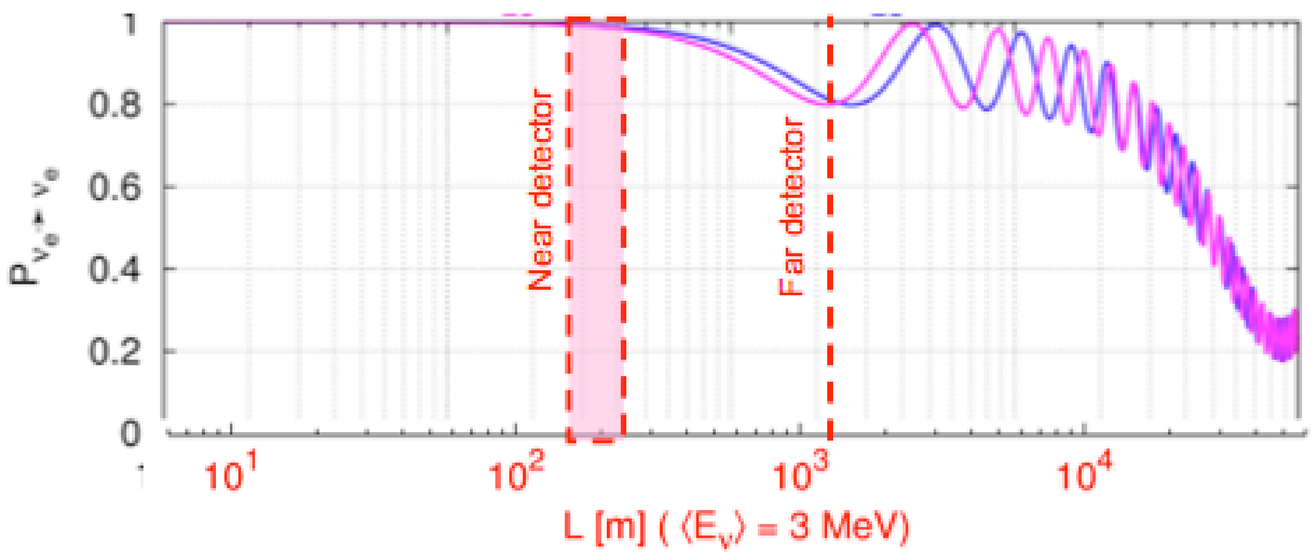


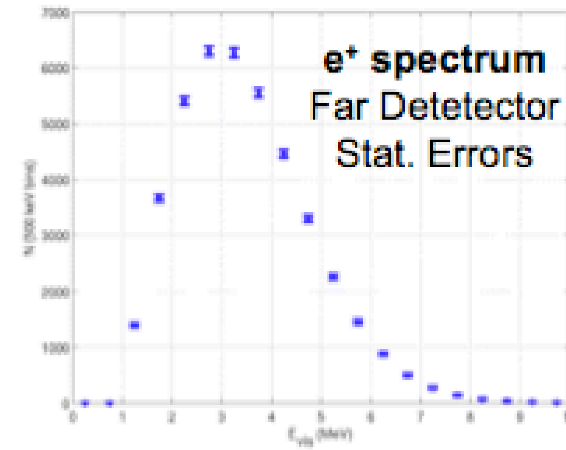


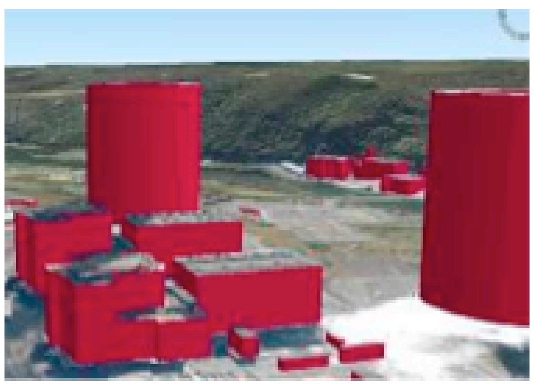
$\theta_{13} < 10^{o}$

Double-Chooz

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\,\sin^2(\Delta m^2_{31} L/4E)$$

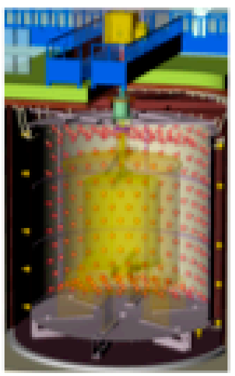






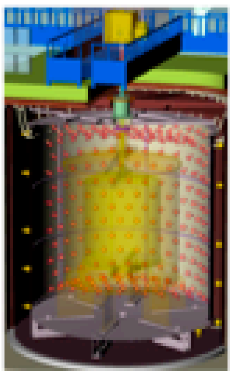
Nuclear Power Station

$\overline{\nu}_e$



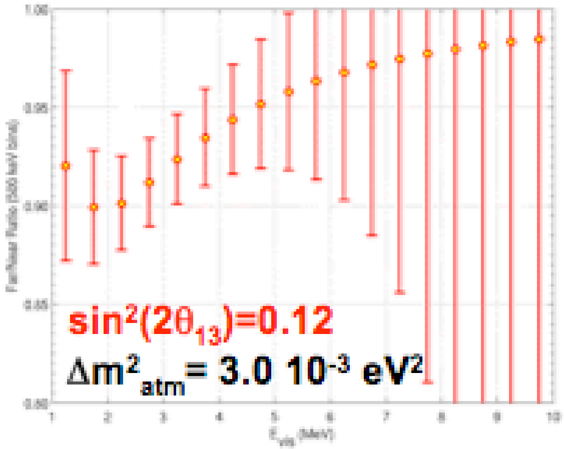
Near detector
400 m

$\overline{\nu}_{e,\mu,\tau}$

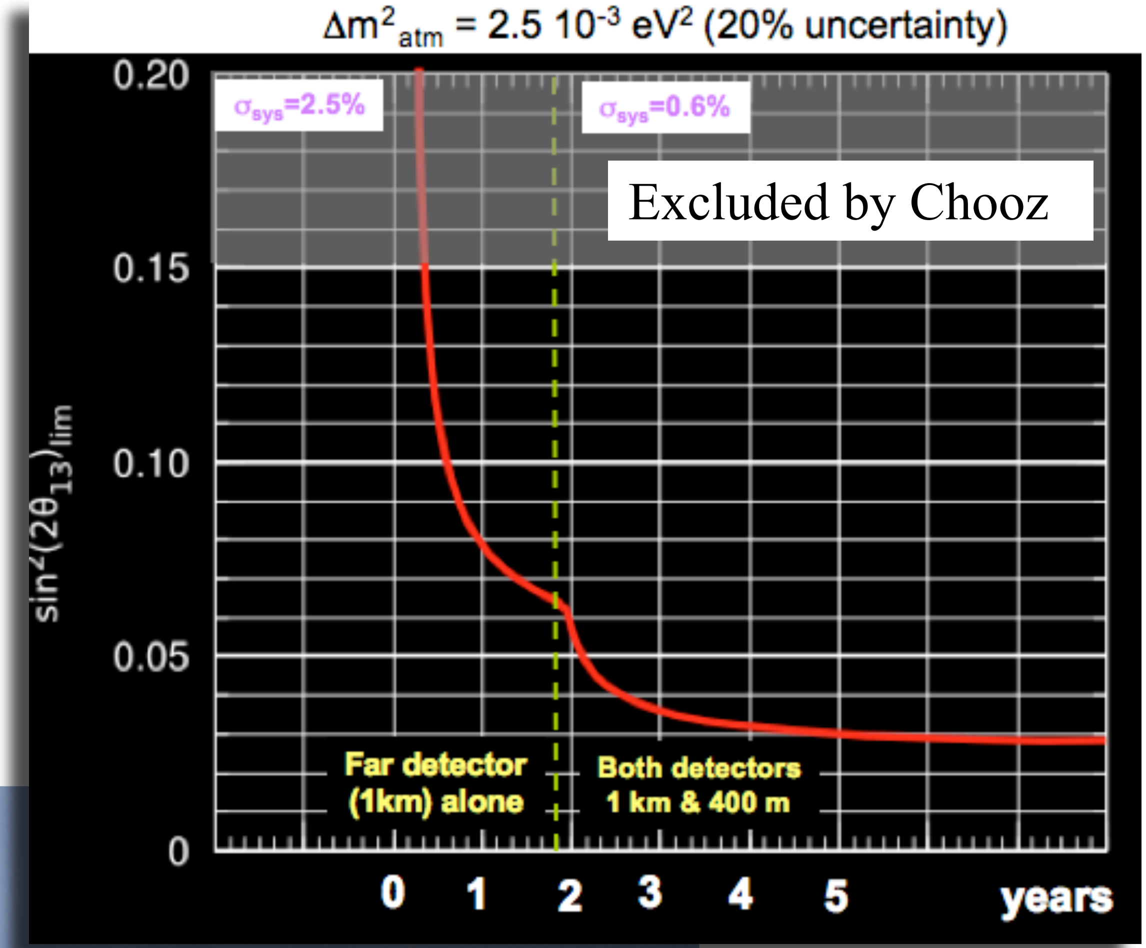


Far detector
1050 m

Far/Near ratio

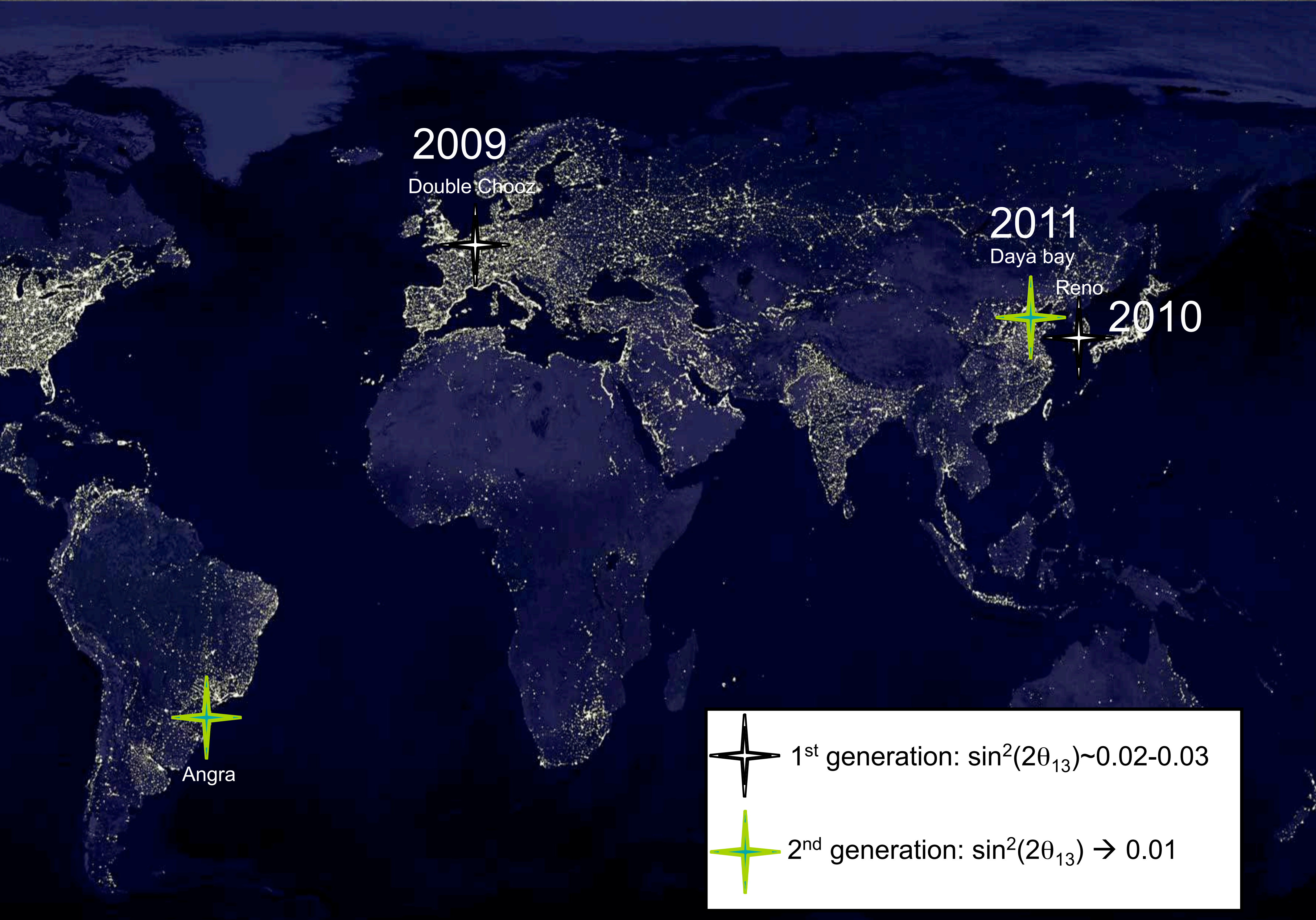


Expected sensitivity

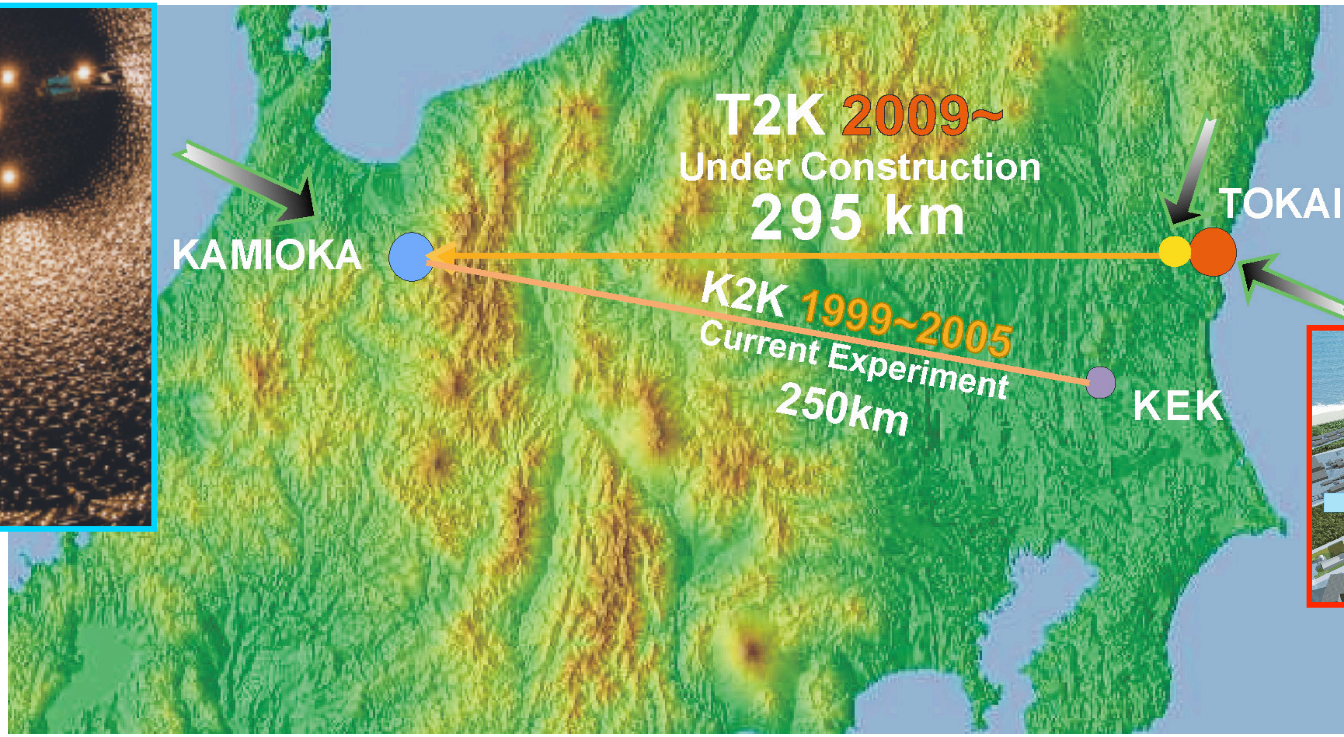


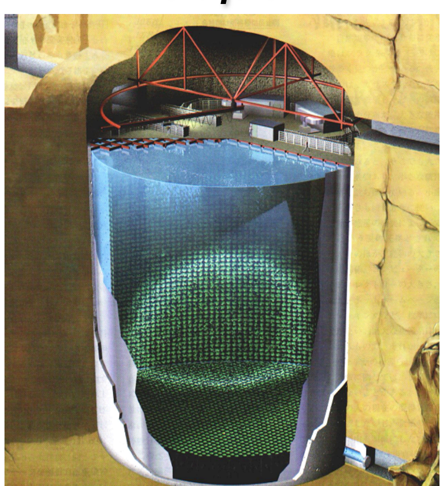
Timeline

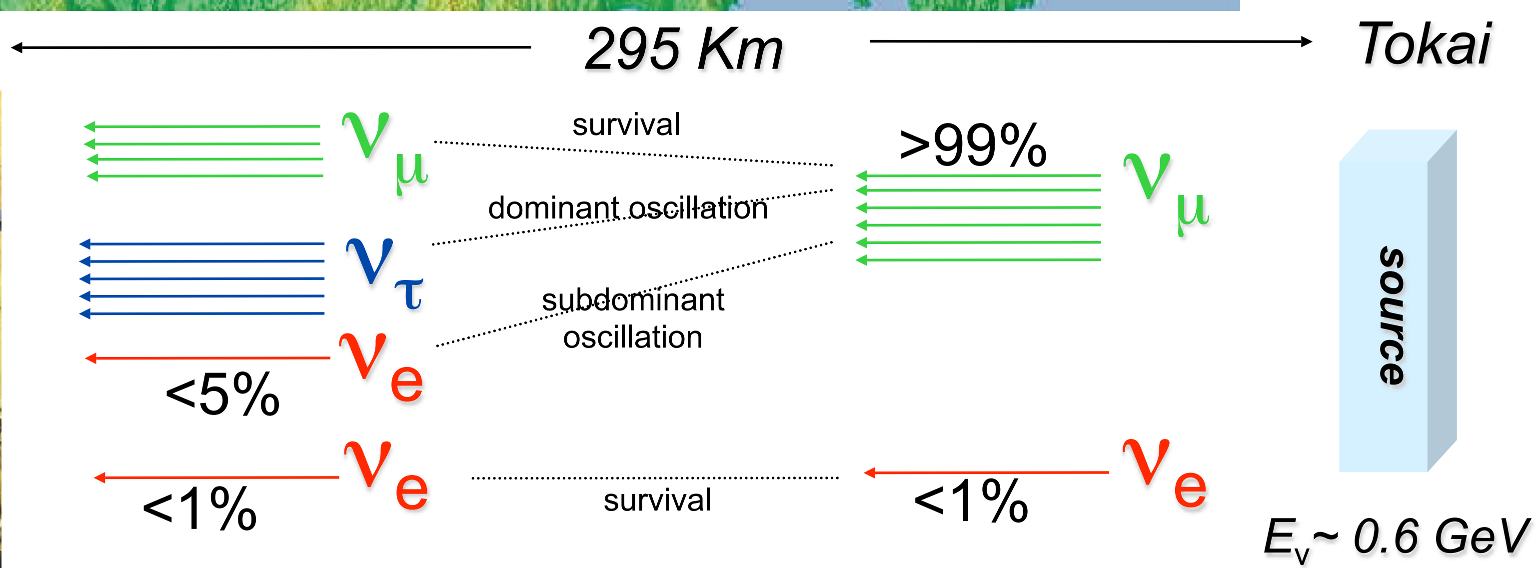
- **2008-09:** Far detector construction and integration
- **Mid-2009:** Phase I data taking
- **2008-10:** near site and detector
- **2011:** Start of phase II data taking


2009
Double Chooz
2011
Daya bay
Reno
2010
Angra
1^{st} generation: $\sin^2(2\theta_{13})$~0.02-0.03
2^{nd} generation: $\sin^2(2\theta_{13}) \rightarrow 0.01$

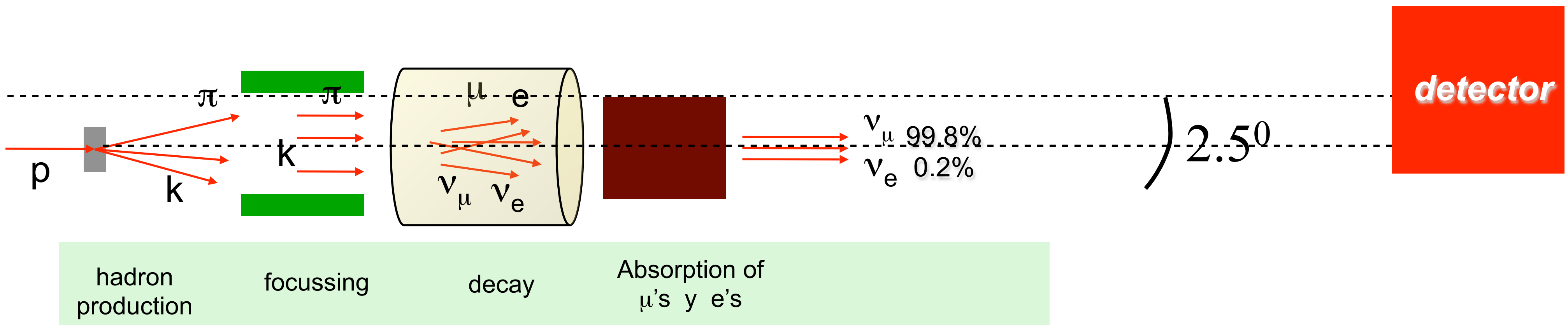
Super-beams I: T2K



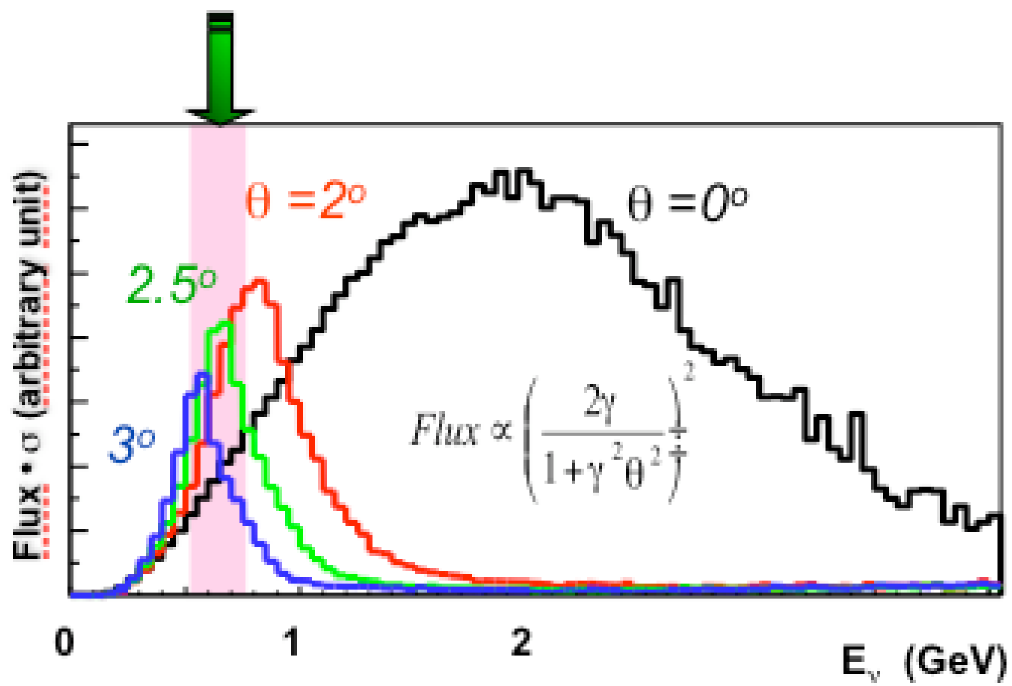




Off-axis beam



oscillation peak at 295 Km



ν_e contamination

2% ➠ 0.2 %

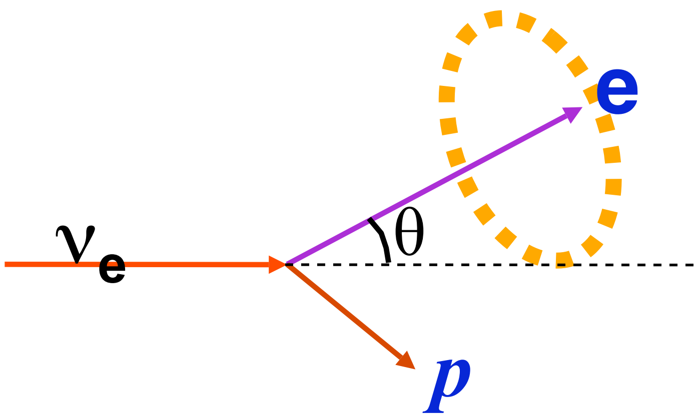
Experimental technique

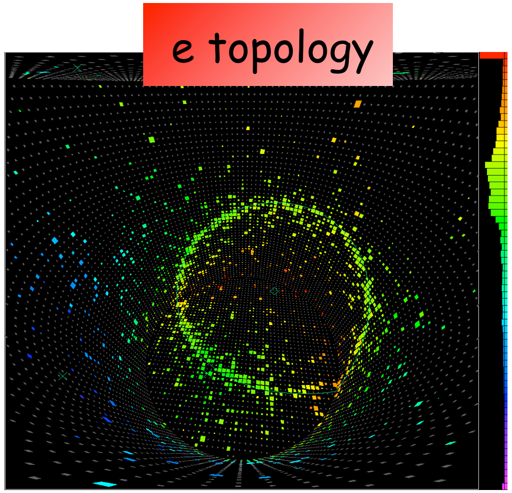
Signal

Quasi-elastic events with an electron-like ring

$E_\nu^{rec} = f(E_e, \theta)$

$\nu_e + n \rightarrow e + p$

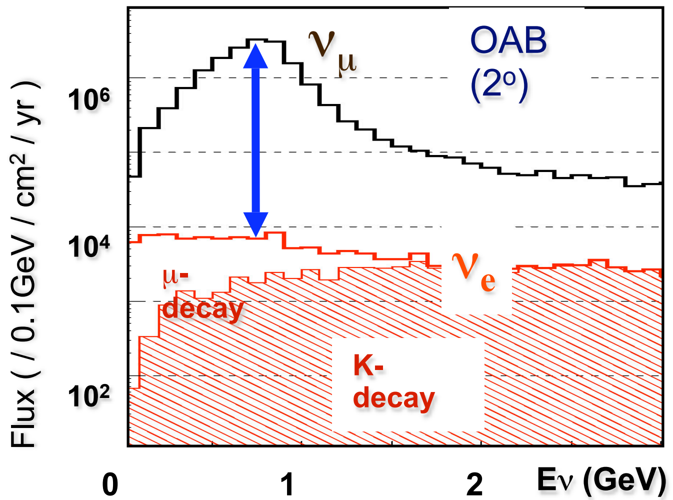




Backgrounds

ν_e contamination in the beam

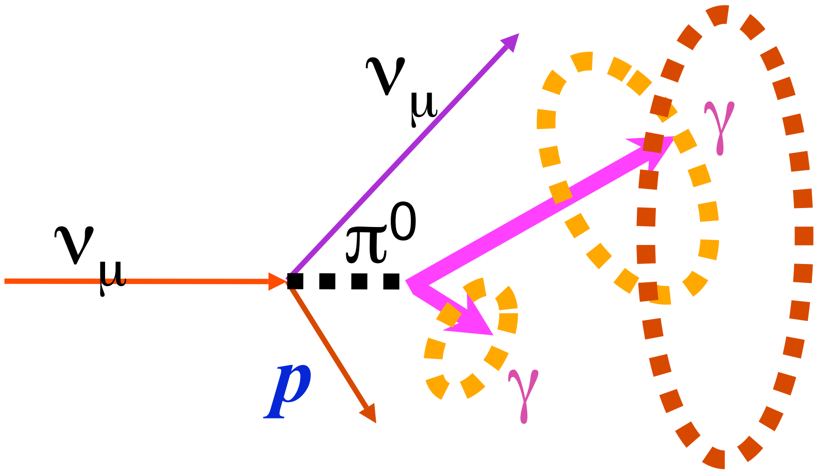
~ 0.2% at the oscillation peak



irreducible
→substract

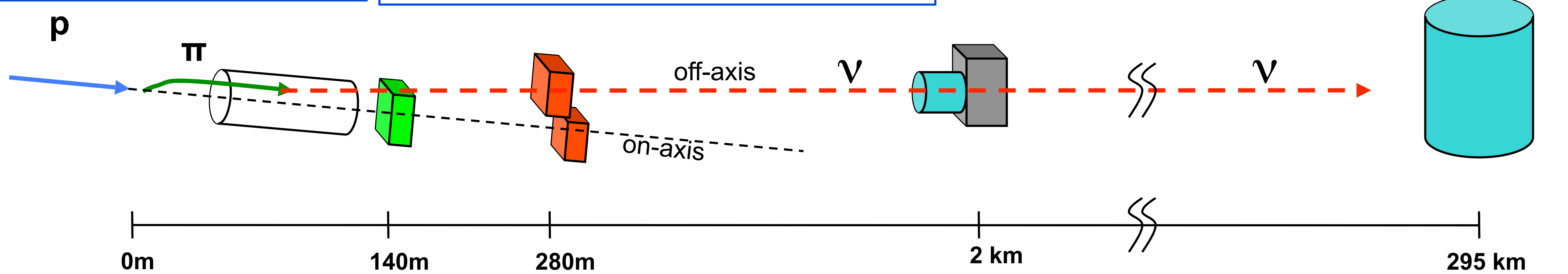
π_0 production in neutral currents

2-rings appearing as 1



The need of near detectors

Beam production | **near detectors** | **Super-K**



Muon monitor
beam direction & intensity
using muons from
pion decay

"Off-axis":
- Neutrino flux
- Neutrino x-sections

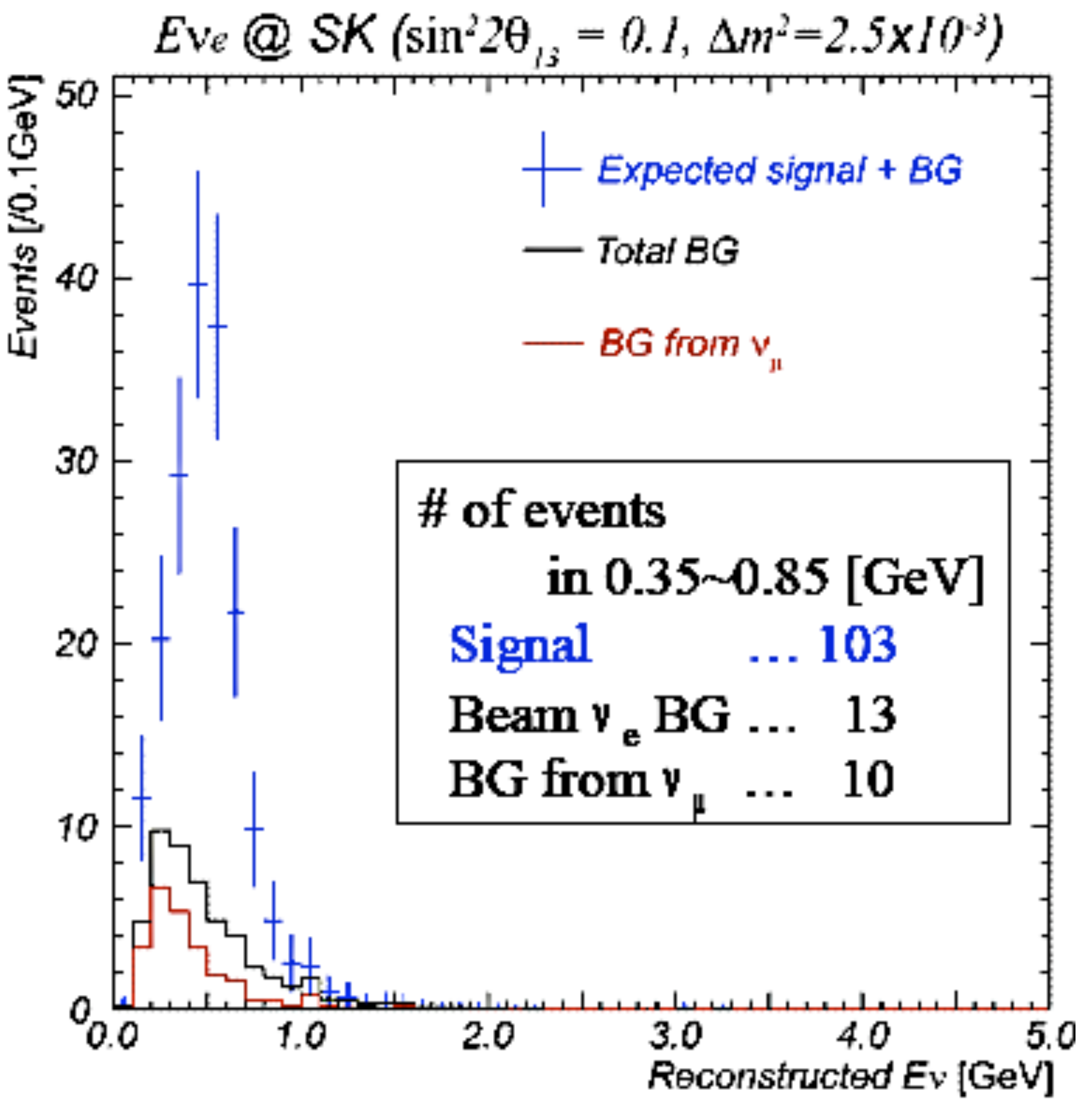
"On-axis":beam direction

reduce
systematics

Super-
Kamioande
(50kt)

T2K expected sensitivity

$\theta_{13} = 9^o$

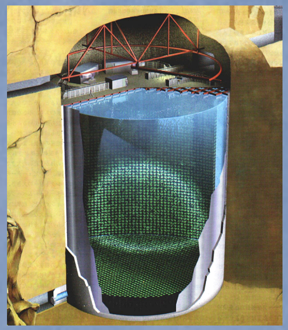


Current status $\theta_{13} < 10^o$

$\sin^2 2\theta_{13} < 0.15$

T2K 1st phase $\theta_{13} \sim 2.5^o$

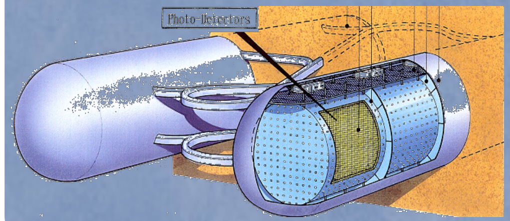
$\sin^2 2\theta_{13} \sim 10^{-2}$



Super-K (50 Kton)

T2K 2nd phase $\theta_{13} \sim 1^o$

$\sin^2 2\theta_{13} \sim 10^{-3}$

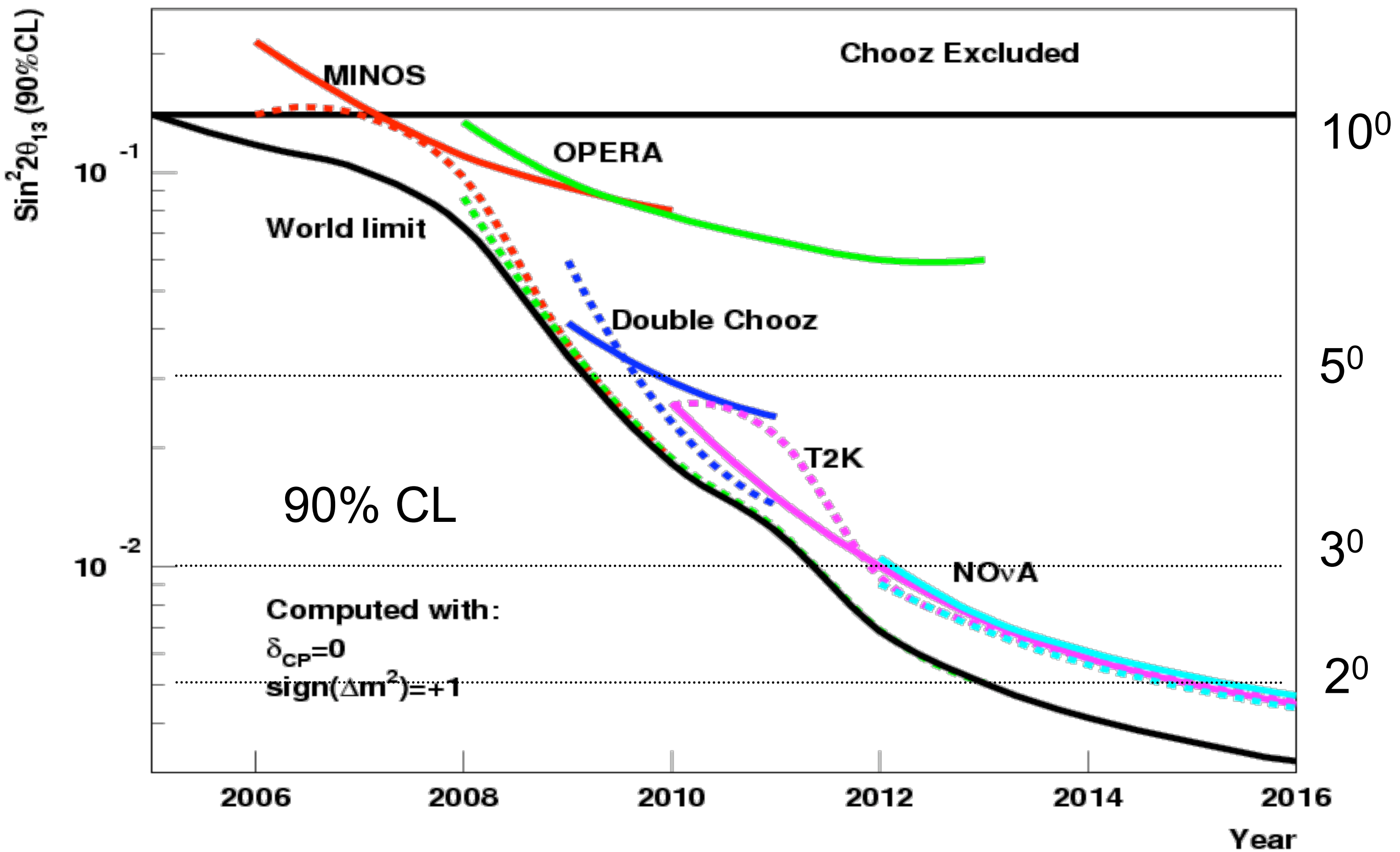


Hyper-K (500 Kton)

The θ_{13} quest

Subdominant oscillation:

Accelerators	Reactors
$\nu_\mu \longrightarrow \nu_e$	$\overline{\nu_e} \longrightarrow \overline{\nu_e}$



Outlook

ν ... the most curios elementary particle
and the one that gave us more surprises ν

has revealed part of his mystery in the last decade

If Nature is generous T2K, D-Chooz, ... will observe the subdominant oscillation $\nu_\mu \to \nu_e$ $(\nu_e \to \nu_e)$ and measure θ_{13}

atmospheric sector (23) ⟷ solar sector (12)

↓ interference

mass hierarchy	$\mathrm{sign}(\Delta m^2_{23})$
CP violation	δ_{cp}