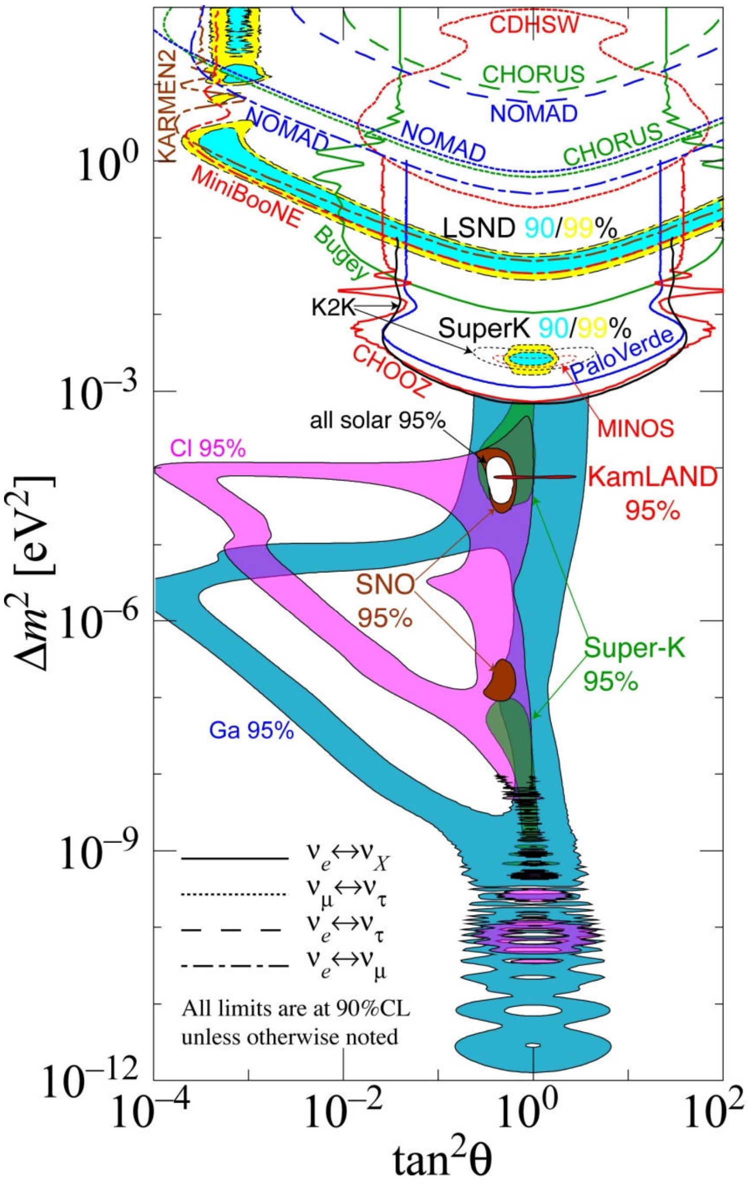
# The oscillation industry

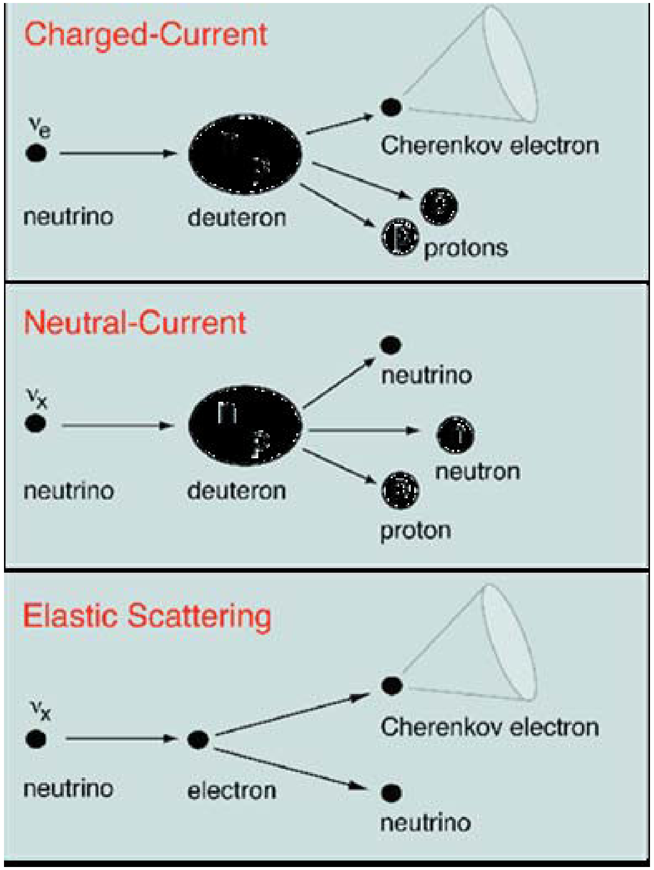
*25 years of negative results (almost)*

Only serious hints (2002): solar and atmospheric disappearances



http://hitoshi.berkeley.edu/neutrino

# The SNO experiment



Target made of 1000 tons of heavy water $D_2O$

$\nu_e + d \Rightarrow p + p + e^-$ 1,4 MeV

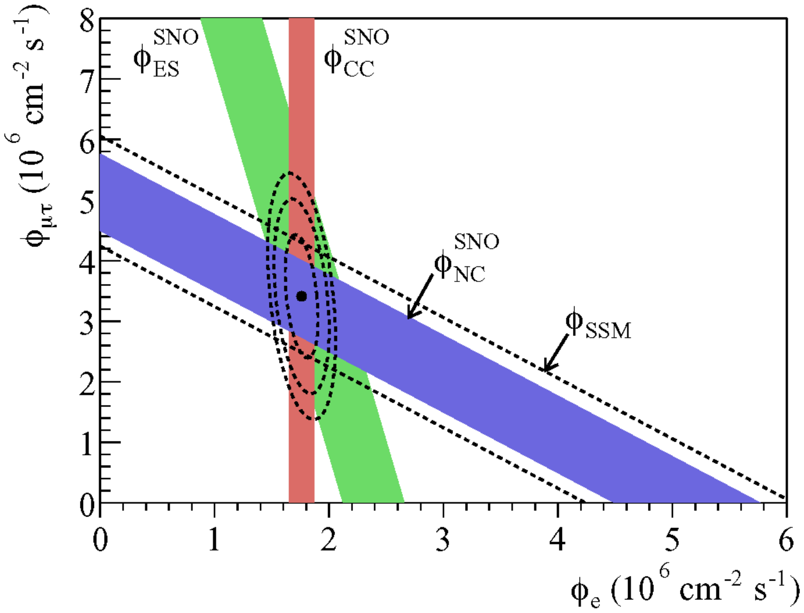
$\nu_x + d \Rightarrow p + n + \nu_x$ 2,2 MeV

$\nu_x + e^- \Rightarrow \nu_x + e^-$

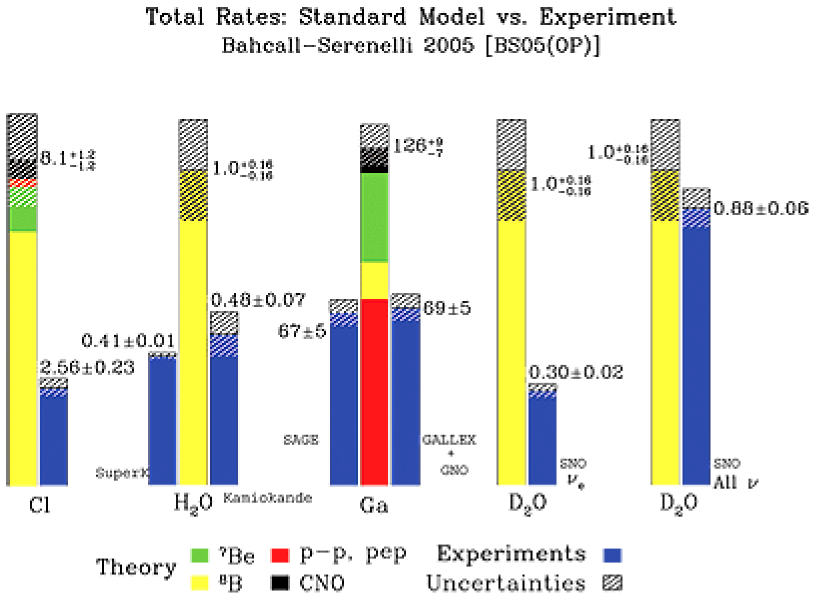
# The SNO result (2002)

SNO measures separately the flux of $\nu_e$, and the total flux of all three types.

*Agreement with the theory, $\nu_e$ flux represents 1/3 of the total flux.*



# The puzzle explained



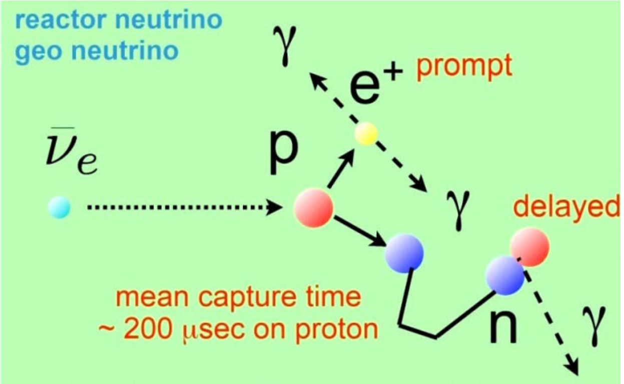
Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(OP)]

# Confirmation by Kamland

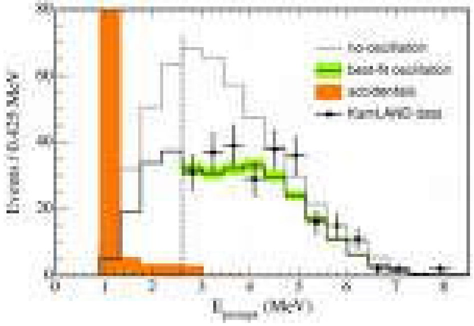
Neutrinos from Japanese (and Korean) reactors

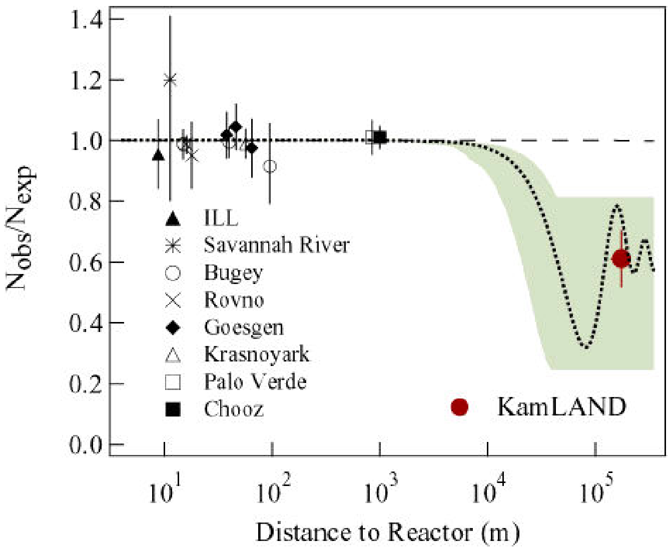
Liquid scintillator in Kamiokande

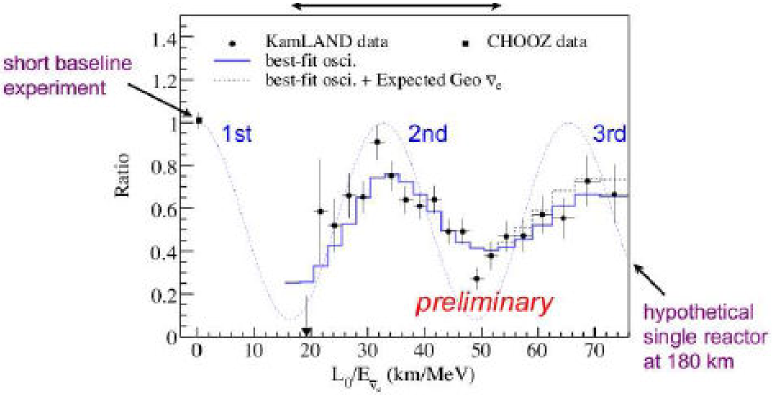
*Average distance 180 km*



# Kamland results

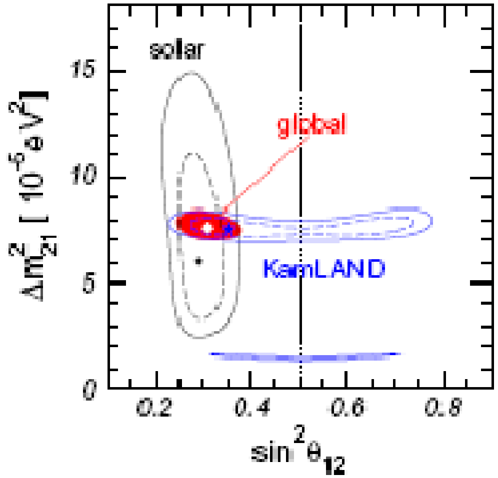






short baseline experiment

hypothetical single reactor at 180 km

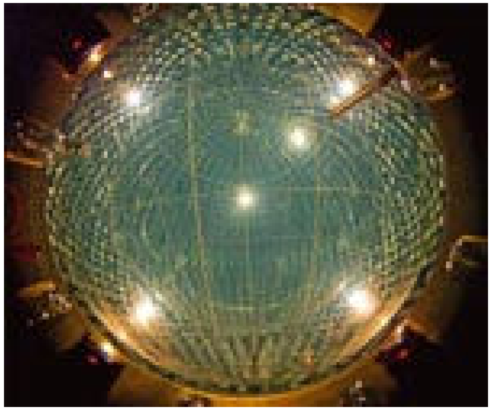


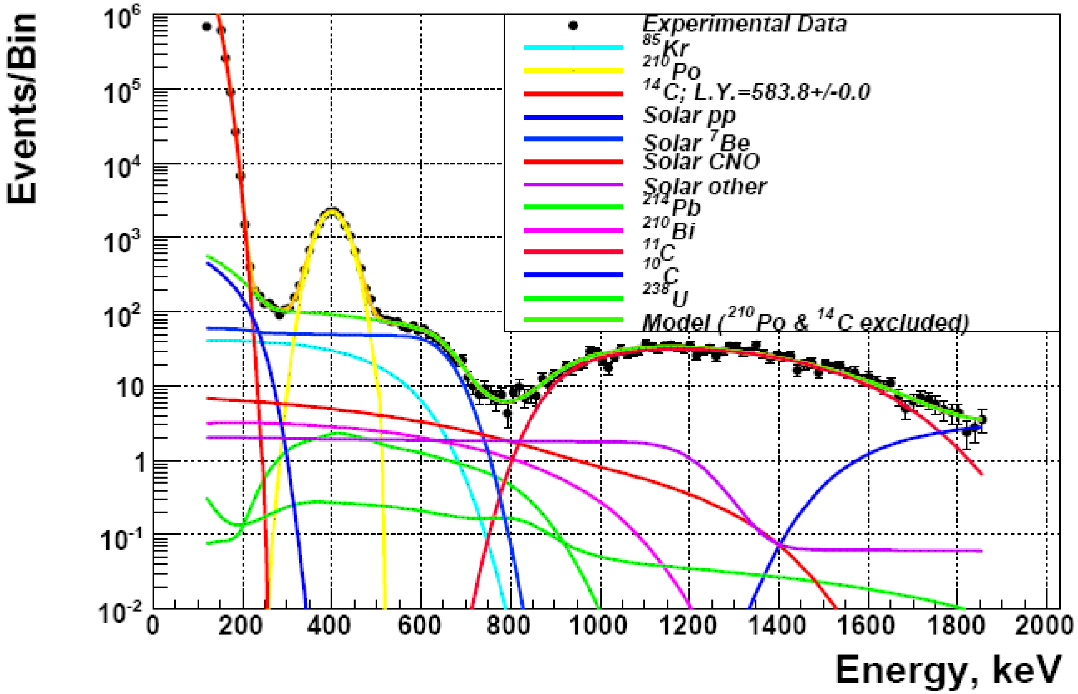
*Terrestrial neutrinos oscillate*

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}\,, \qquad \Delta m^2_{21} = 7.65^{+0.23}_{-0.20}\times 10^{-5}\,\mathrm{eV}^2$$

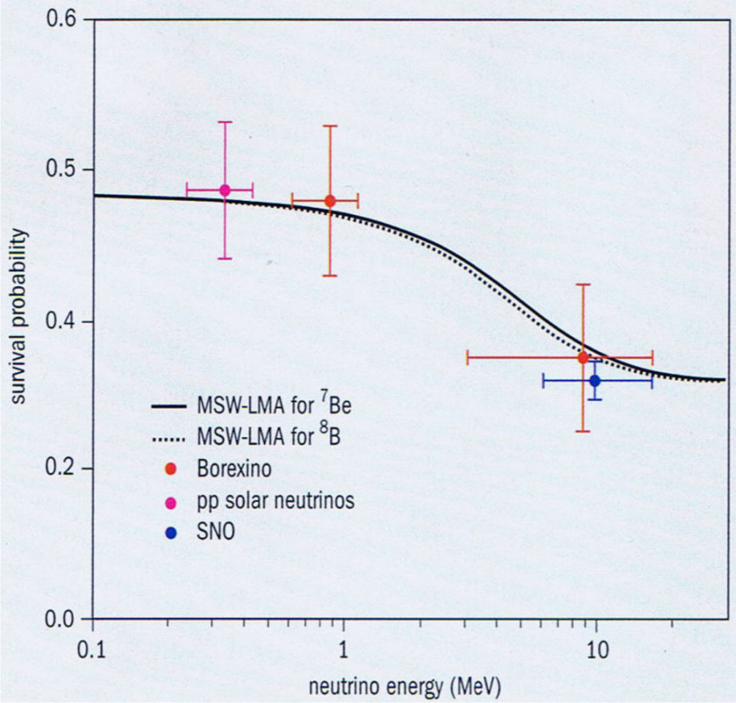
# Confirmation by Borexino

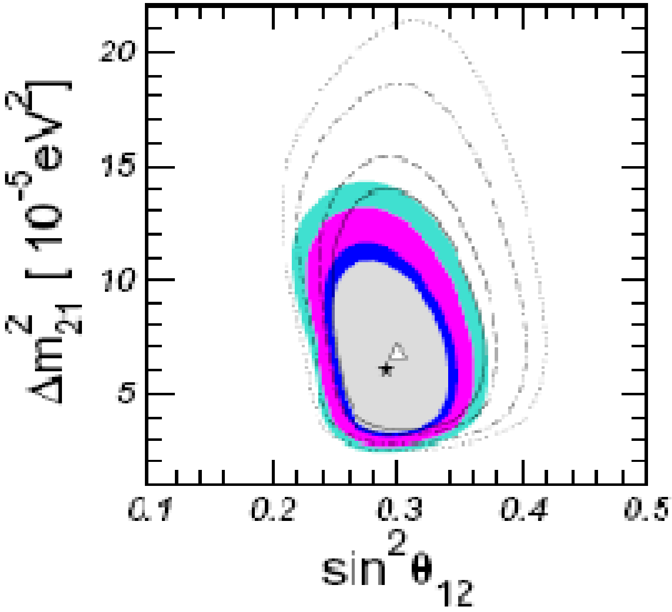
- Optimized for $^{7}$Be neutrinos
- *Extremely low radioactive background*





# Results





49 ± 3 ± 4 events/(d 100t)

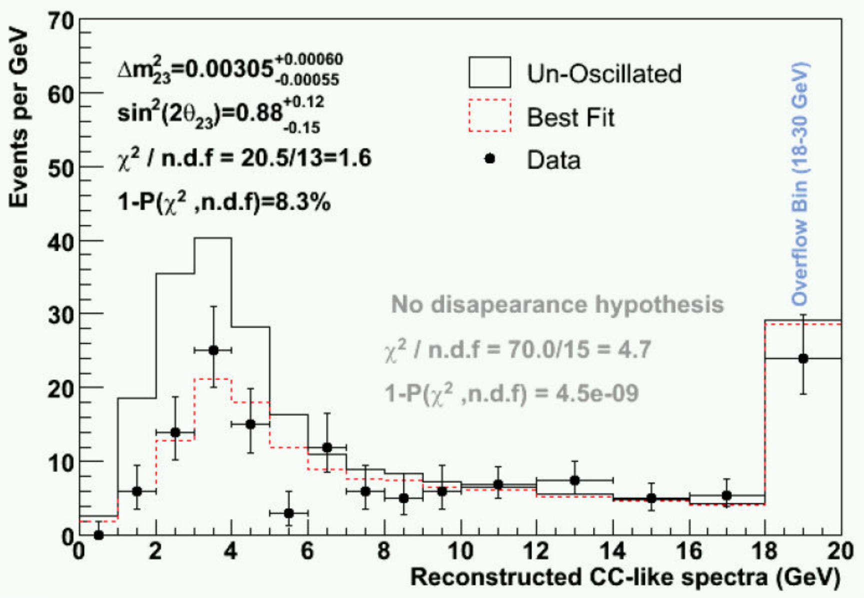
*Expectations without mixing 74 ± 4*

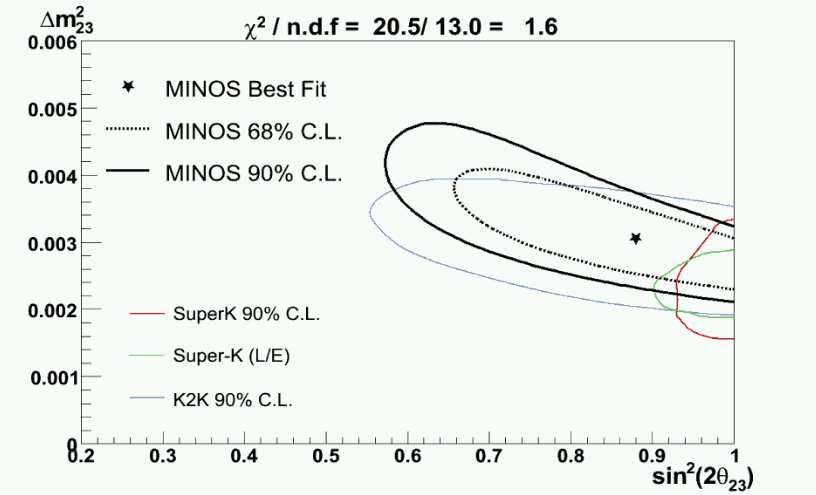
# Confirmation by MINOS

*Accelerator neutrinos, over 730 km distance*

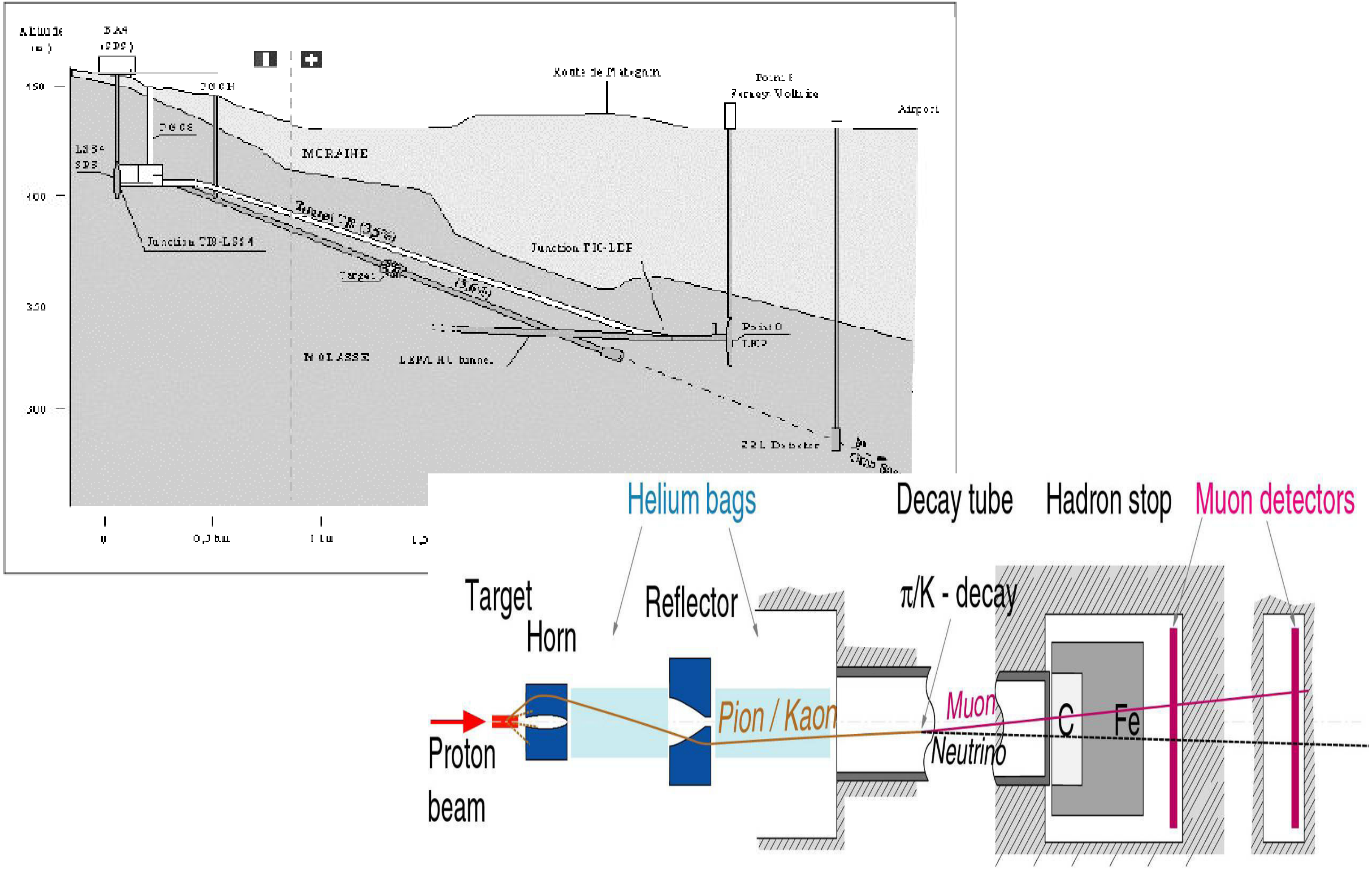
Data taking since ~ September 2001

Installation fully completed in July 2003.





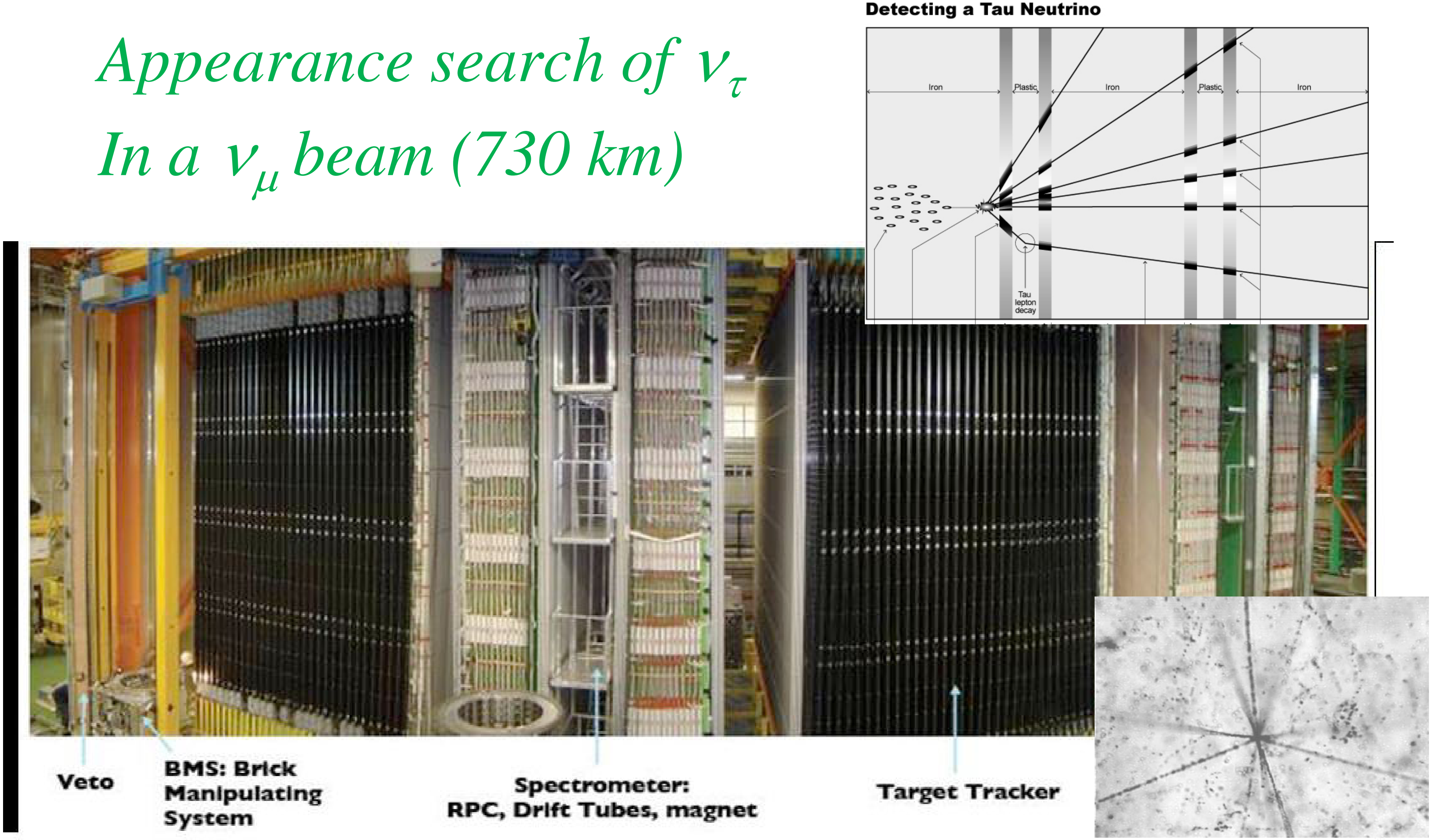
# CNGS beam


ALTITUDE (m)
BA4 (SPS)
450
400
350
300
PGCN
PGC8
LSS4 SPS
MORAINE
Junction TI8-LSS4
Tunnel TI8 (3,5%)
Target
(5,6%)
MOLASSE
LEP/LHC tunnel
Route de Mategnin
Junction TI8-LEP
Point 8 Ferney Voltaire
Point 8 LEP
Airport
Detector
0
0,5 km
1 km
1,5
Helium bags
Decay tube
Hadron stop
Muon detectors
Target
Horn
Reflector
π/K - decay
Proton beam
Pion / Kaon
Muon
Neutrino
C
Fe

# OPERA in CNGS

*Appearance search of $\nu_\tau$*

*In a $\nu_\mu$ beam (730 km)*

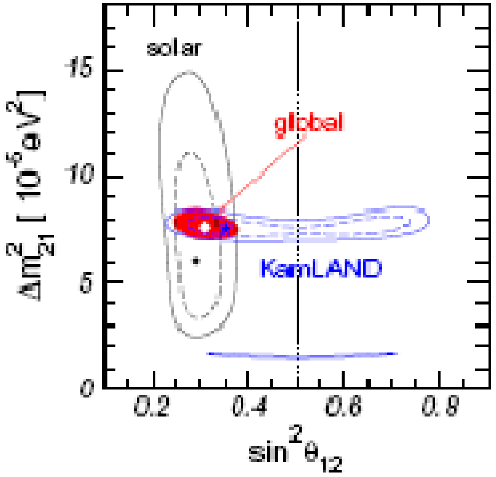


Detecting a Tau Neutrino

# Summary of oscillations

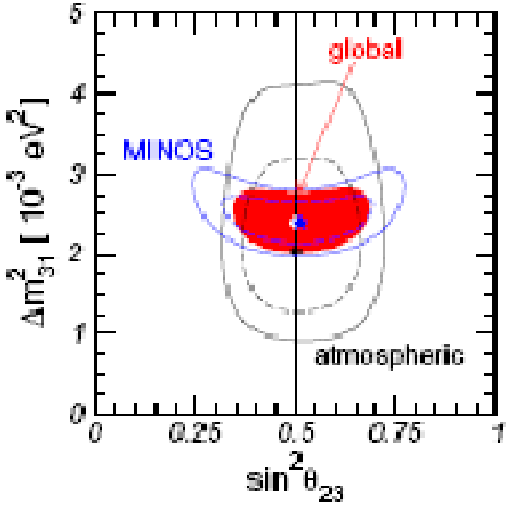
## Solar + Kamland

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}, \qquad \Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$



## Atmospheric + Minos

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}, \qquad |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$



# Mixing matrix

$$\begin{array}{cccc} & \Delta m^2_{31} & & \Delta m^2_{21} \\ U = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ & \text{atmospheric+LBL} & \text{Chooz} & \text{solar+KamLAND} \end{array}$$

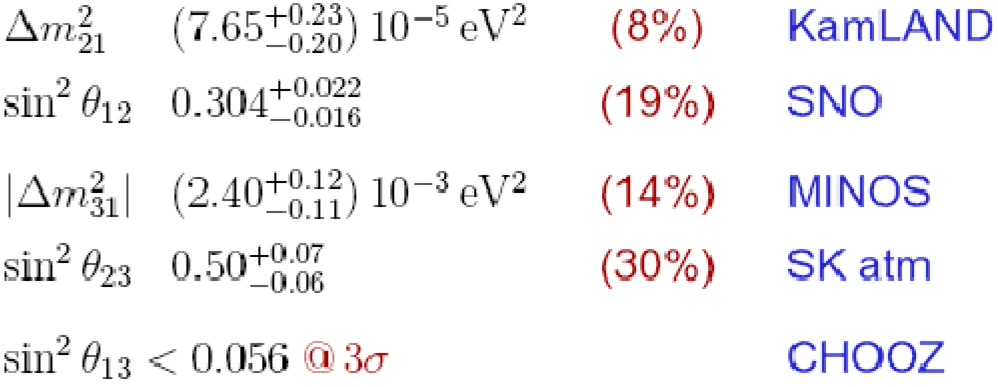
It remains to measure: $\theta_{13}$, $\delta$ and the absolute mass scale

# Importance of oscillations

- *Oscillations require massive neutrinos.*
- (But they only fix a difference between squared masses)

- *The minimum standard model of particles assumed neutrinos with no mass. The discovery of oscillations demands to go beyond.*

- Solar neutrinos (confirmed by KamLand) give: $\delta m^2 = 7.6\ 10^{-5}\ eV^2$
- Atmospheric neutrinos (confirmed by Minos) give: $\delta m^2 = 2{,}4\ 10^{-3} eV^2$



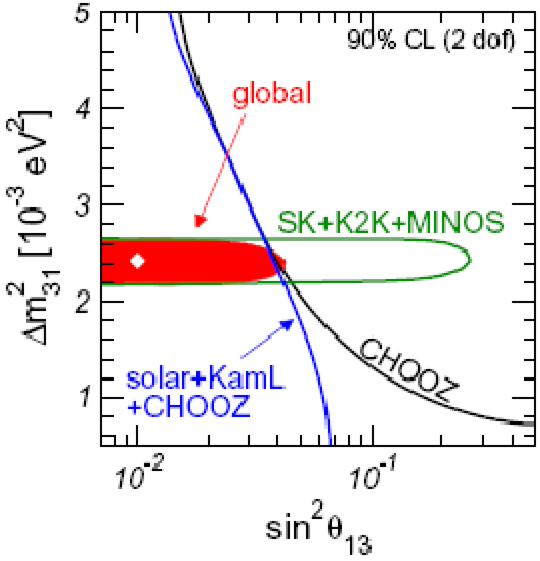
| | | | |
|---|---|---|---|
| $\Delta m^2_{21}$ | $(7.65^{+0.23}_{-0.20})\ 10^{-5}\ \mathrm{eV}^2$ | (8%) | KamLAND |
| $\sin^2\theta_{12}$ | $0.304^{+0.022}_{-0.016}$ | (19%) | SNO |
| $\lvert\Delta m^2_{31}\rvert$ | $(2.40^{+0.12}_{-0.11})\ 10^{-3}\ \mathrm{eV}^2$ | (14%) | MINOS |
| $\sin^2\theta_{23}$ | $0.50^{+0.07}_{-0.06}$ | (30%) | SK atm |
| $\sin^2\theta_{13} < 0.056$ @ $3\sigma$ | | | CHOOZ |

# First priority: $\theta_{13}$

$\delta m_{13}^2 \sim \delta m_{23}^2$

- Disappearance of reactor $\nu_e$ over L/E atmospheric (Chooz)
- Appearance of $\nu_e$ in $\nu_\mu$ accelerator beam

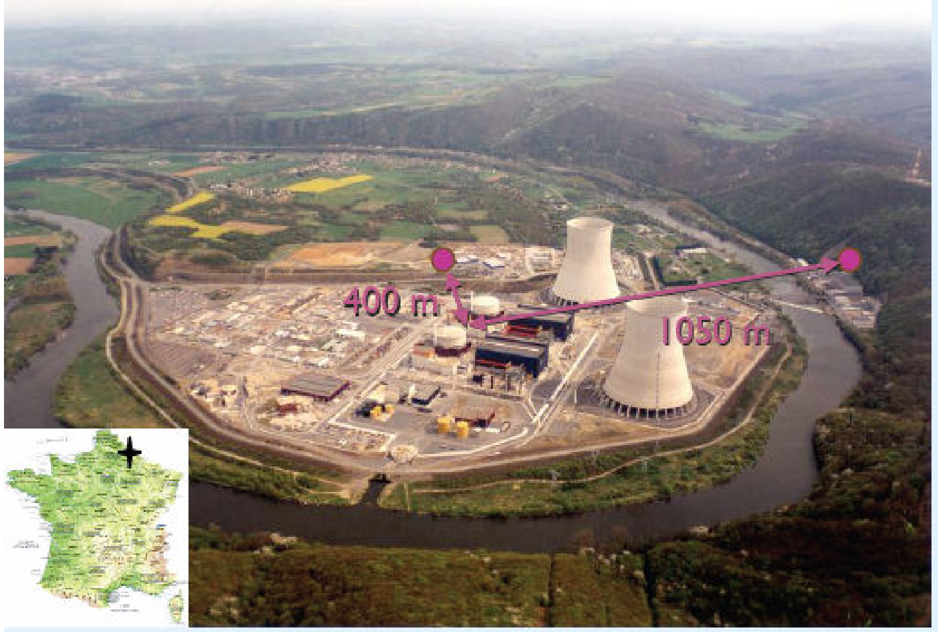
global data: $\sin^2\theta_{13} < 0.035\ (0.056)$ at 90% CL $(3\sigma)$

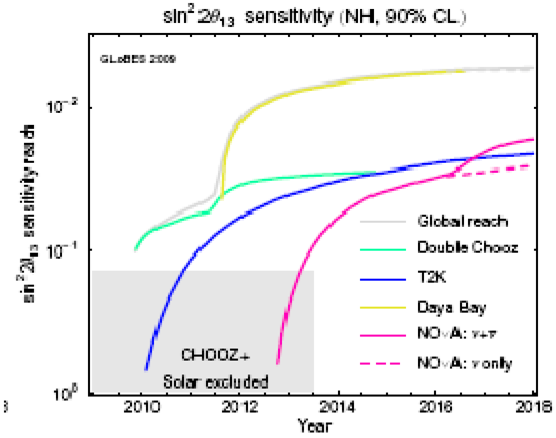


# Near future

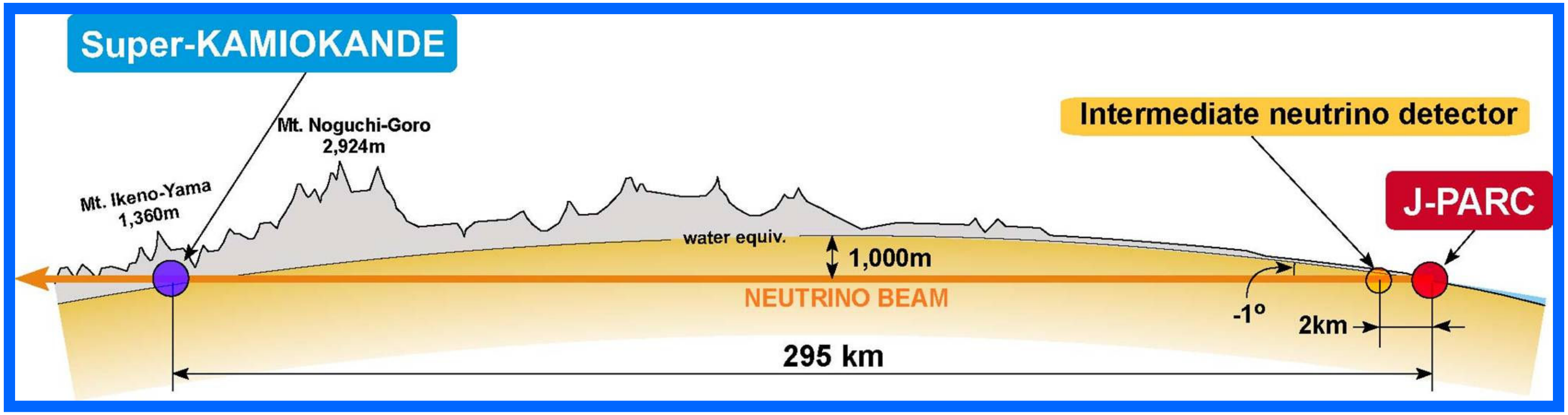
- Measurement of the last mixing angle

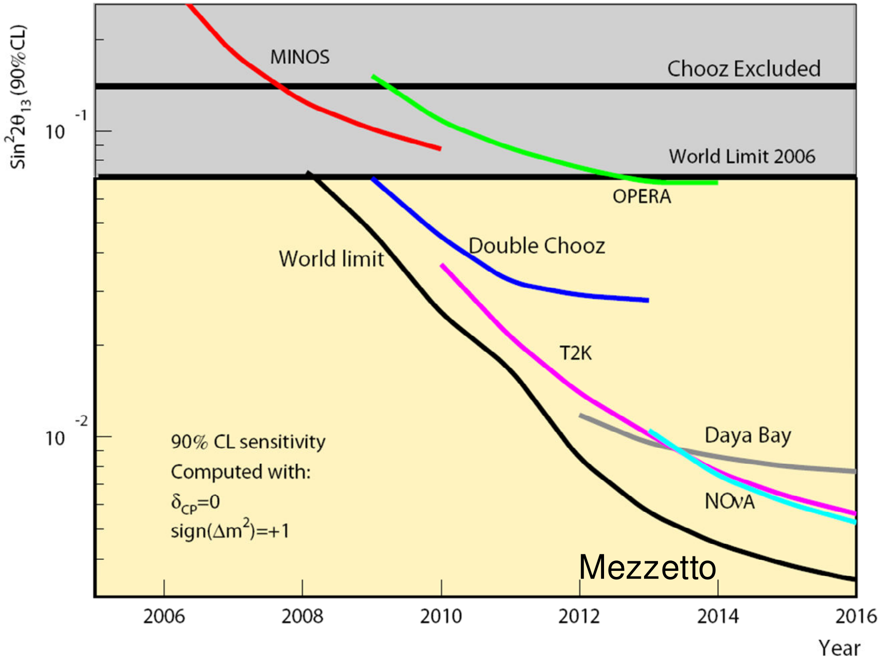
| | baseline | power | FD mass | channel |
|---|---|---|---|---|
| **Reactor experiments with near and far detectors:** | | | | |
| **D-Chooz** | $1.05\,\mathrm{km}$ | $8.6\,\mathrm{GW_{th}}$ | $\sim 10\,\mathrm{t}$ | $\bar{\nu}_e \to \bar{\nu}_e$ |
| **Daya Bay** | $2./1.6\,\mathrm{km}$ | $17.4\,\mathrm{GW_{th}}$ | $\sim 80\,\mathrm{t}$ | $\bar{\nu}_e \to \bar{\nu}_e$ |
| **Off-axis superbeams:** | | | | |
| **T2K** | $295\,\mathrm{km}$ | $0.75\,\mathrm{MW}$ | $22.5\,\mathrm{kt}$ | $\nu_\mu \to \nu_e, \nu_\mu$ |
| **NO$\nu$A** | $812\,\mathrm{km}$ | $0.7\,\mathrm{MW}$ | $15\,\mathrm{kt}$ | $\nu_\mu \to \nu_e, \nu_\mu$ |





# T2K

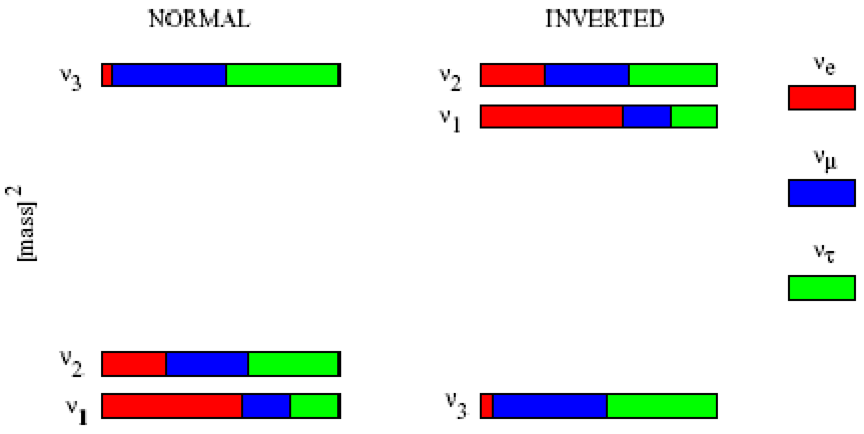




Mezzetto

# Mass hierarchy

two possibilities for the neutrino mass spectrum

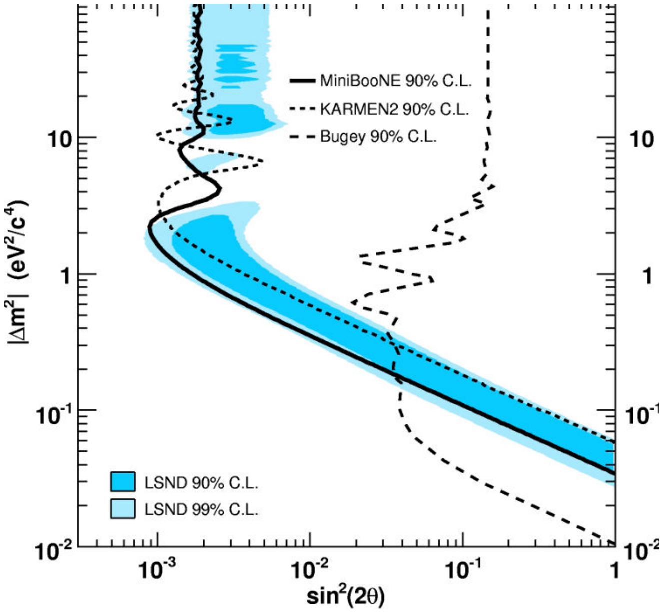


$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

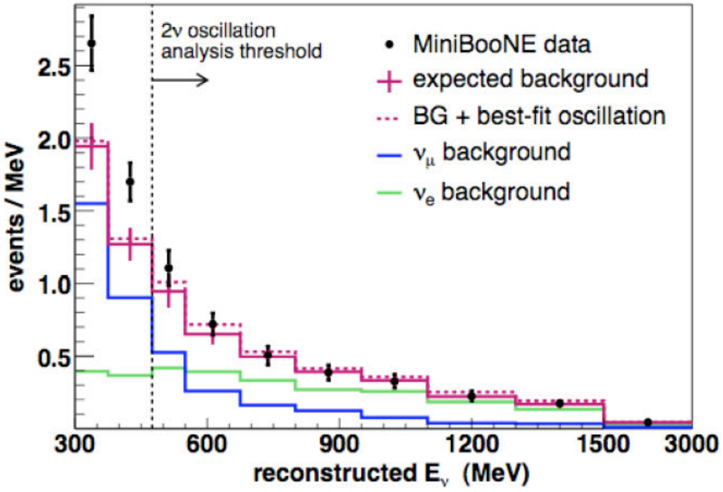
*To solve the degeneracy problem matter effects must be seen, INO, Nova*

# LSND and MiniBoone puzzles

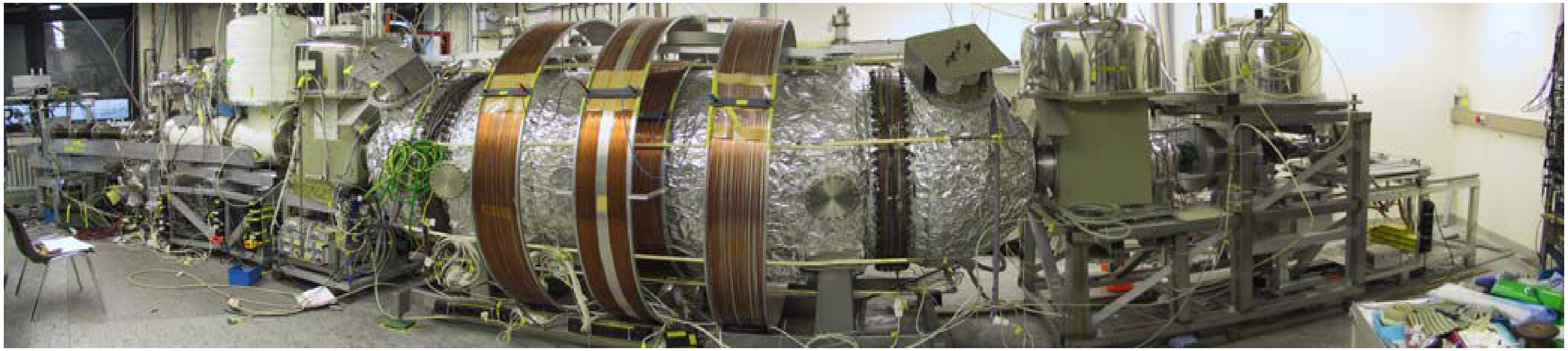
*150 ton detector in beam-stop at Los Alamos(1993-1998)*
*Intense anti-$\nu_\mu$ beam*
*$88 \pm 22 \pm 6$ events compatible with anti-$\nu_e$ interactions*
*« Evidence » for oscillations at level 0.2%*



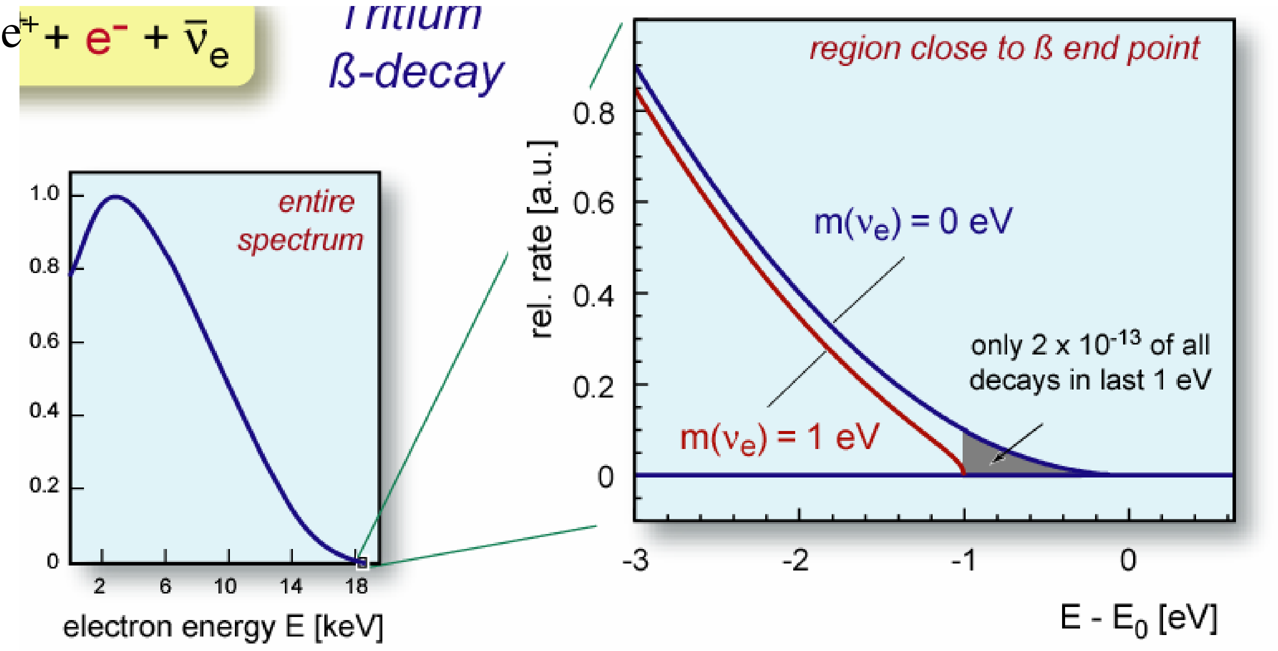
Repeat at Fermilab
From 30 m/30 MeV to
800 m/800 MeV



# Direct mass measurement of $\nu_e$



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



# Direct mass measurements, cont.

- 1) $\nu_e$ end-point in tritium decays
- Mainz/Troitzk, $m(\nu_e) < 2.2$ eV/$c^2$
- *Crucial measurement to tell if neutrinos are mass degenerated or non degenerated.*

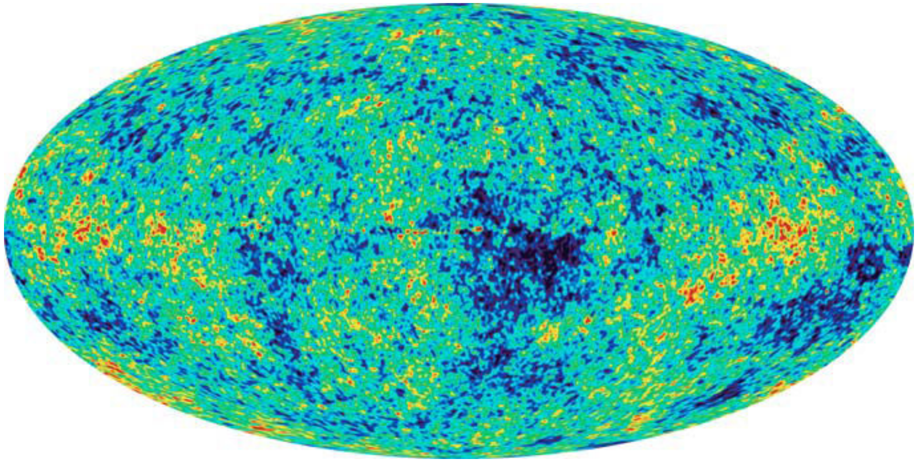
- 2) $\nu_\mu$ in $\pi$ decays
- PSI, $\pi$ at rest or in flight (1990), $m(\nu_\mu) < 200$ keV/$c^2$

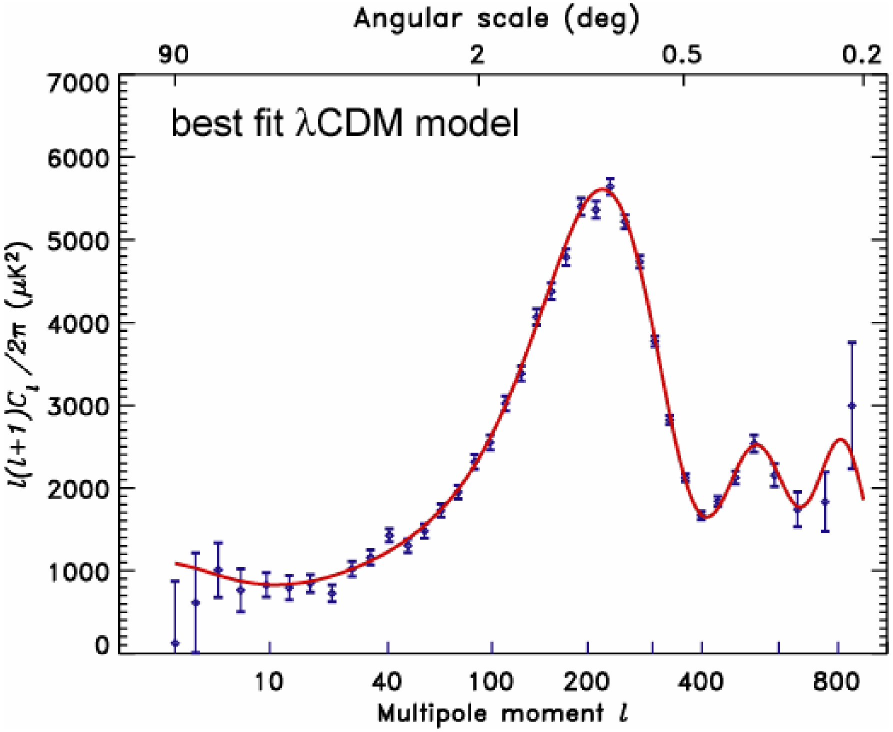
- 3) $\nu_\tau$ in $\tau$ decays
- Aleph at LEP (1995), $m(\nu_\tau) < 18$ MeV/$c^2$

# Next: KATRIN

- *Tritium decay again,towards 0.2 eV mass sensitivity for* $\nu_e$

# New competition from the sky





$\Sigma$ (m) < 0.7 eV

*Level of interest 0.05 eV*

# Neutrino masses

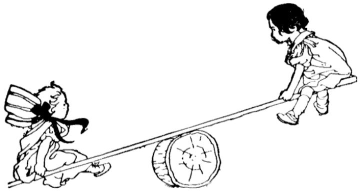
- In the simplest scenario (normal hierarchy, non degenerated neutrinos), one obtains:
- $m(\nu_\tau) \sim 50$ meV/$c^2$
- $m(\nu_\mu) \sim 9$ meV/$c^2$
- With $m(\nu_e)$ much smaller

- *The heaviest neutrino would have a mass 2 billion times smaller than the proton. The Big Bang model predicts about 3 billion times more neutrinos than hadrons.*
- Amazing conclusion: as much mass exists in neutrinos as in all the stars!

# Neutrinos and the SM

- In the MSM neutrinos have no mass, they do not oscillate
- *Physics beyond the SM? Yes and no.*

The most popular solution is the *seesaw mechanism*, where right-handed neutrinos with very large Majorana masses are added. If the right-handed neutrinos are very heavy, they induce a very small mass for the left-handed neutrinos.



$$m_\nu = M^D (1/M_M)(M^D)^T$$

If it is assumed that the neutrinos interact with the Higgs field with approximately the same strength as the charged fermions do, the heavy mass should be close to the GUT scale. There are other varieties of seesaw models and it is not clear which, if any, Nature has chosen.

The apparently innocent addition of right-handed neutrinos has the effect of adding new mass scales, completely unrelated to the mass scale of the Standard Model. Heavy right-handed neutrinos look to be the first real glimpse of physics beyond the Standard Model.