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Neutrinos

Natalia Di Marco
Laboratori Nazionali del Gran Sasso – INFN

Outline

- Neutrino History
- Neutrino Oscillation Physics
- Sources of Neutrinos
- Oscillation Experiments
- Known and UnKnown

Neutrino History

- **1930**

In a letter to the attendees of a physics conference in Tübingen, Germany, **Wolfgang Pauli** proposes as a "desperate remedy" the existence of a new neutral particle to explain the apparent energy nonconservation in radioactive decay

- **1933**

Enrico **Fermi** proposes "neutrino" as the name for Pauli's postulated particle

- **1956**

Two American scientists, **Frederick Reines and Clyde Cowan**, report the first evidence for neutrinos. They use a fission reactor as a source of neutrinos and a well-shielded scintillator detector nearby to detect them.

- **1957**

An Italian physicist**, Bruno Pontecorvo**, living in the USSR, formulates a theory of neutrino "oscillations”

- **1958**

Maurice Goldhaber, Lee Grodzins, and Andrew Sunyar at Brookhaven National Laboratory demonstrate that the new neutrino has lefthanded helicity, meaning that it spins along the direction of its motion in the sense of a lefthanded screw.

- **1962**

A group of scientists from Columbia University and Brookhaven National Laboratory perform the first accelerator neutrino experiment and demonstrate the existence of two species of neutrinos, the electron neutrino, , and the muon neutrino, . In 1987, **Jack Steinberger, Leon Lederman, and Mel Schwartz** win the Nobel Prize for this discovery.

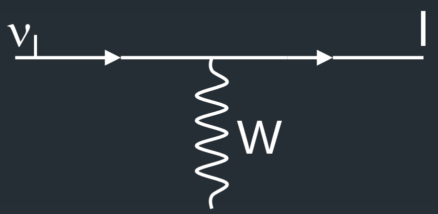
- **1968**

An experiment deep underground in the **Homestake** mine in South Dakota makes the first observation of neutrinos from the sun. But experimenters see far fewer neutrinos than solar models had predicted.

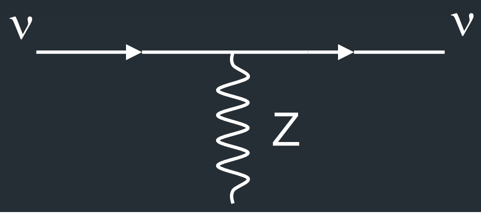
Neutrinos in the SM

- Neutrinos are **neutral, massless** fermions. They interact with quarks and leptons via weak interactions:

Charged currents (CC)



Neutral currents (NC)



$$\mathcal{L}_I^{\mathrm{CC}} = -\frac{g}{2\sqrt{2}}\, j_\rho^{\mathrm{CC}}\, W^\rho + \mathrm{h.c.}$$

$$\mathcal{L}_I^{\mathrm{NC}} = -\frac{g}{2\cos\theta_W}\, j_\rho^{\mathrm{NC}}\, Z^\rho\,.$$

$$j_\rho^{\mathrm{CC}} = 2\sum_{\ell=e,\mu,\tau} \overline{\nu_{\ell L}}\,\gamma_\rho\,\ell_L + \ldots$$

$$j_\rho^{\mathrm{NC}} = \sum_{\ell=e,\mu,\tau} \overline{\nu_{\ell L}}\,\gamma_\rho\,\nu_{\ell L} + \ldots$$

Weak currents are left handed:

$\nu_L = \nu^-$ $\overline{\nu}_R = \overline{\nu}^+$

helicity = -1
L = 1

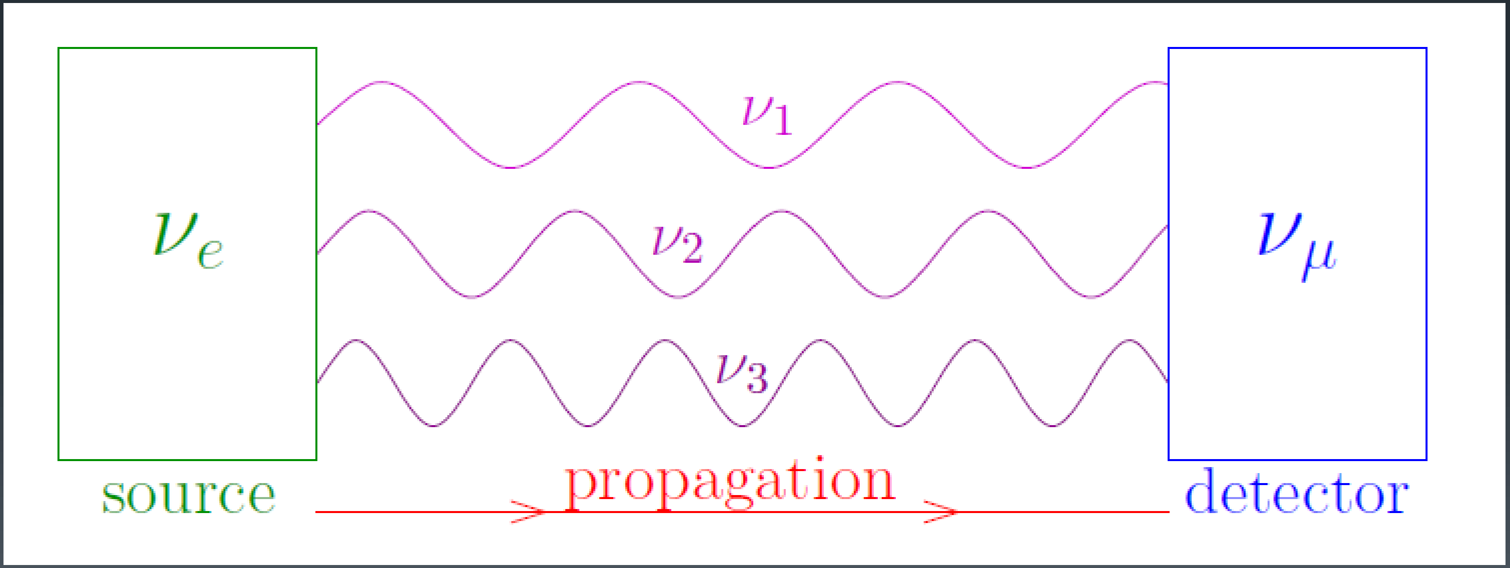
helicity = +1
L = -1

- Lepton Number (L) is conserved.
- Family lepton numbers (L_α) are conserved.

The number of **active** neutrinos can be determined with high accuracy from the decay width of the Z bosons: $N_\nu = 2.994 \pm 0.012$

Neutrino Oscillation Physics

The experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidences for the existence of neutrino oscillations transitions in flight between the different flavour neutrinos ν_e, ν_μ, ν_τ caused by non-zero neutrino masses and neutrino mixing.



Flavor eigenstates (ν_α, α=e,μ,τ) may not coincide with mass eigenstates ($\nu_{j,}$, j=1,2…n)

Neutrino Oscillation Physics

Field

$$\nu_{lL}(x) = \sum_{j} U_{lj} \nu_{jL}(x)$$

$$l = e, \mu, \tau$$

Neutrino Oscillation Physics

Field $\nu_{lL}(x) = \sum_j U_{lj} \nu_{jL}(x)$ $l = e, \mu, \tau$ $|\nu_l\rangle = \sum_j U_{lj}^* |\nu_{jL}\rangle$ State

U → Pontecorvo-Maki-Nakagawa-Sakata matrix

Neutrino Oscillation Physics

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$$\mathcal{H}|\nu_k\rangle = E_k|\nu_k\rangle \quad \Rightarrow \quad |\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle \quad \Rightarrow \quad |\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k}\, e^{-iE_k t}|\nu_k\rangle$$

Neutrino Oscillation Physics

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$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)\right|^2 = \left|\sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}\right|^2$$

Transition Probability

Neutrino Oscillation Physics

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$$\nu_{lL}(x)=\sum_j U_{lj}\,\nu_{jL}(x)$$

$$l=e,\mu,\tau$$

$$|\nu_l\rangle=\sum_j U^*_{lj}\,|\nu_{jL}\rangle$$

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Transition Probability

Ultra-relativistic approssimation and assuming $p_k=p=E$

$$P_{\nu_\alpha\to\nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 \qquad \Leftarrow \ \text{constant term}$$

$$+\ 2\mathrm{Re}\sum_{k>j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right) \qquad \Leftarrow \ \text{oscillating term}$$

Neutrino Oscillation Physics

3ν mixing – no CP violation → U is real → 3 angles (θ_{12} , θ_{13} , θ_{23})

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

Solar ν, LBL reactor ν

SBL reactor ν

Atmo ν, LBL accelator ν

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$\cancel{CP}$, mass-mixing originating from Dirac mass term (1 $\cancel{CP}$ phase - δ)

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

Note that:
if $\theta_{13} = 0$, CP violation not observable

Neutrino Oscillation Physics

3ν mixing – no CP violation → U is real → 3 angles (θ_{12} , θ_{13} , θ_{23})

$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&1&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}=\begin{pmatrix}c_{12}c_{13}&s_{12}c_{13}&s_{13}\\-s_{12}c_{23}-c_{12}s_{23}s_{13}&c_{12}c_{23}-s_{12}s_{23}s_{13}&s_{23}c_{13}\\s_{12}s_{23}-c_{12}c_{23}s_{13}&-c_{12}s_{23}-s_{12}c_{23}s_{13}&c_{23}c_{13}\end{pmatrix}$$

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Note that:
if $\theta_{13}=0$, CP violation not observable

Majorana mass term (2 additional phases – φ_2 , φ_3)

$$U \rightarrow U\bullet V$$

$$V=\begin{pmatrix}1&&\\&e^{\frac{i}{2}\varphi_2}&\\&&e^{\frac{i}{2}(\varphi_3+2\delta)}\end{pmatrix}$$

φ_2 and φ_3 not observable in oscillations. Important for $0\nu\beta\beta$ decay.

Neutrino Oscillation Physics

2 neutrino approximation

$$U = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

$$c_\theta = \cos(\theta)\ ;\ \ s_\theta = \sin(\theta)$$

Neutrino Oscillation Physics

2 neutrino approximation

$$U = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

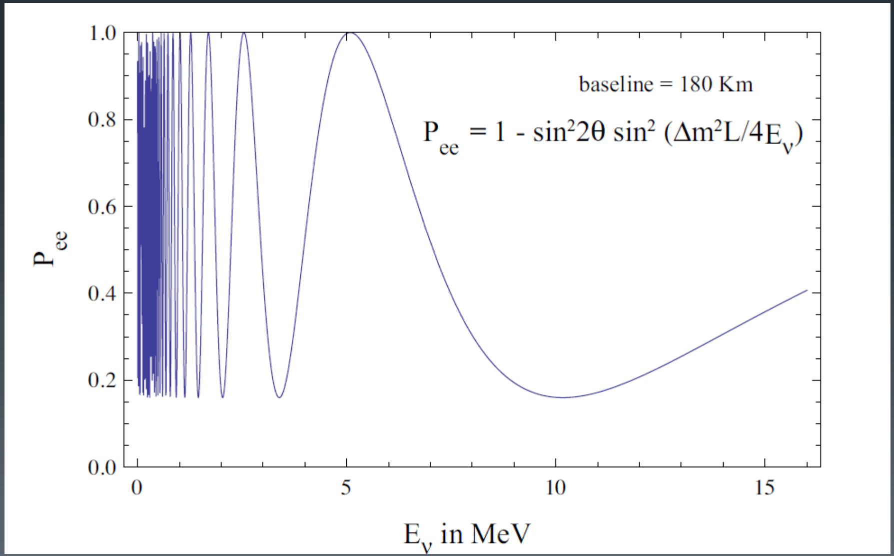
$$c_\theta = \cos(\theta)\,;\ \ s_\theta = \sin(\theta)$$

- In vacuum:

$$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\delta m^2 L}{4E}\right)$$

$$\delta m^2 = m_1^2 - m_2^2$$

L = oscillation baseline

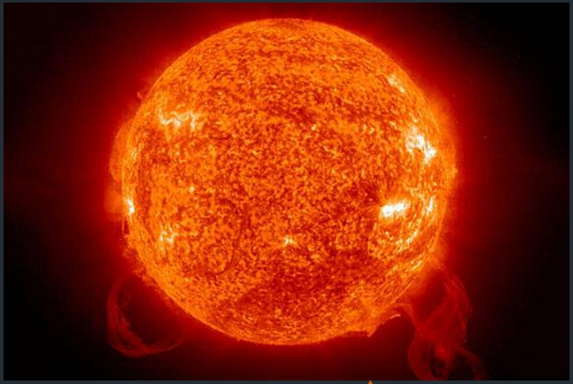


“It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong”

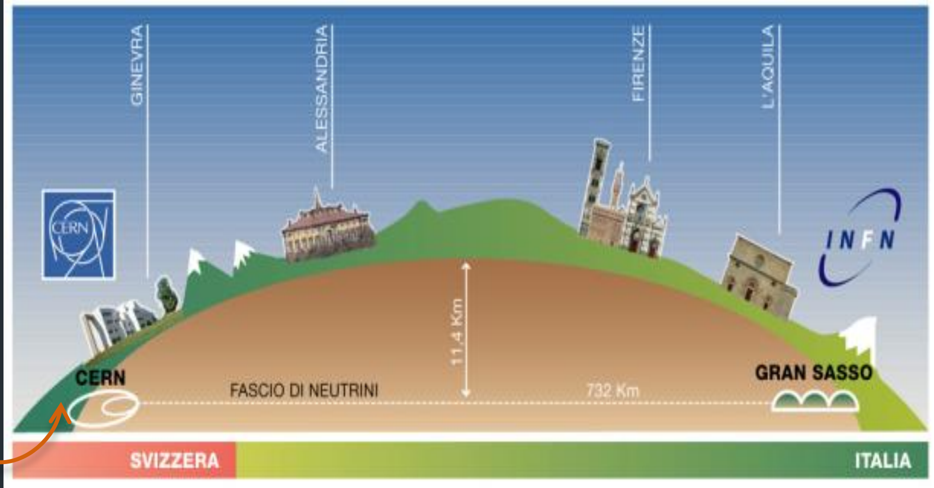
Richard P. Feynman

Neutrino Sources

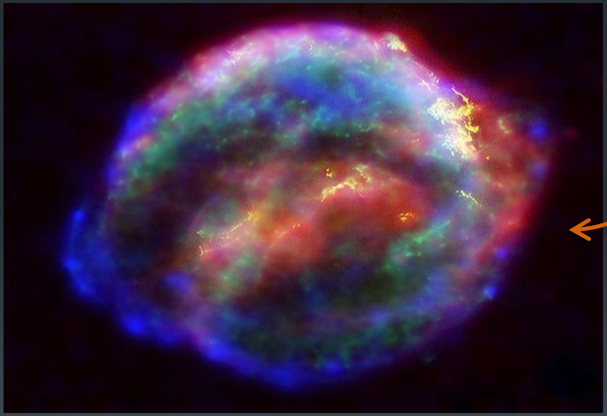
Solar



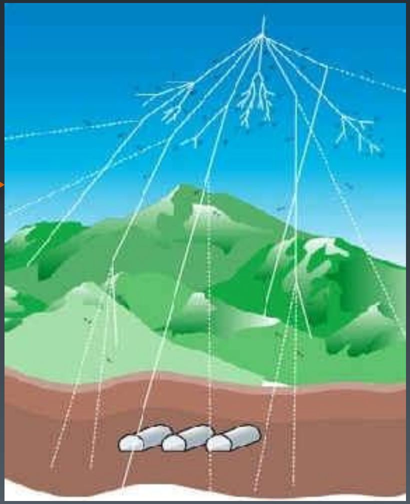
Accelerator



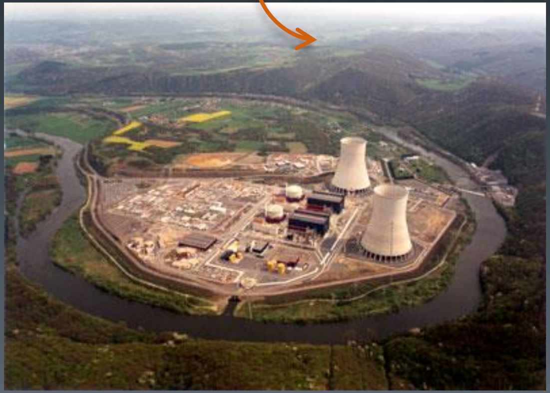
SuperNovae



ν



Atmospheric

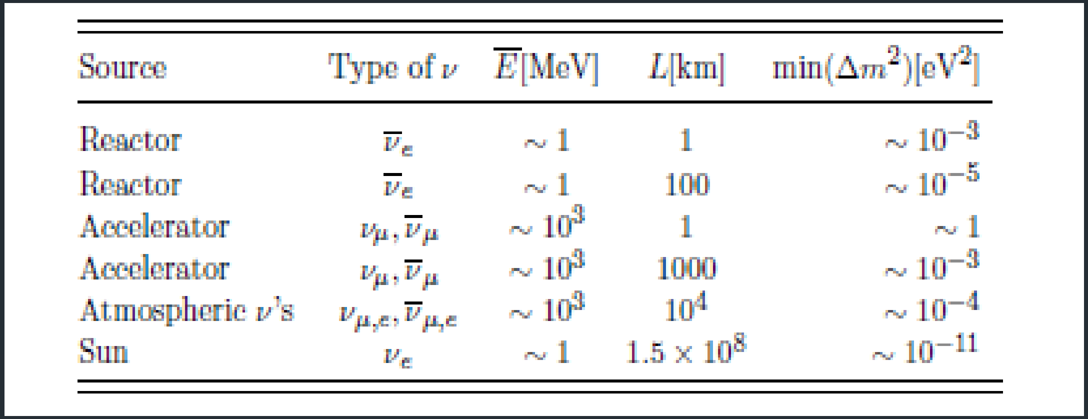


Reactor

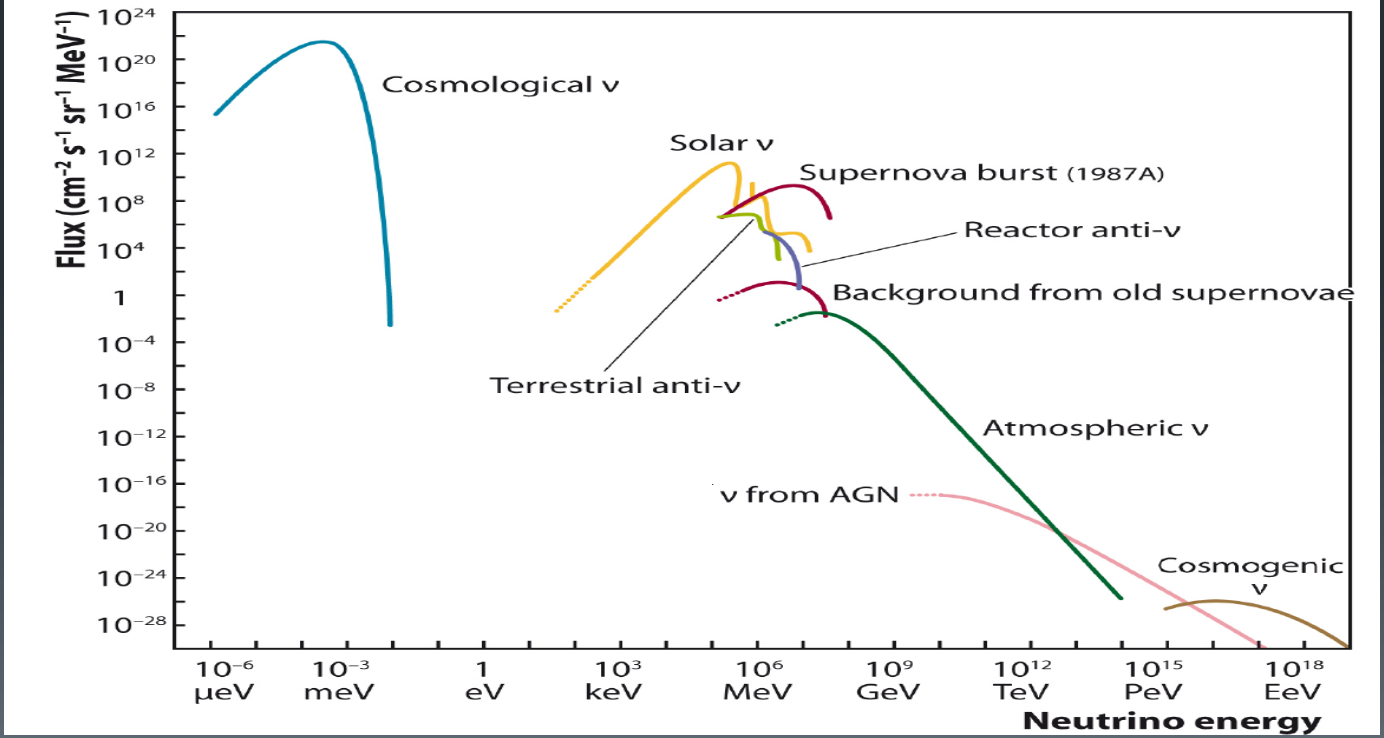
Neutrino Sources

$$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\delta m^2 L}{4E}\right)$$

$$\min(\delta m^2) \approx 2E/L$$



Source	Type of ν	$\overline{E}$[MeV]	L[km]	$\min(\Delta m^2)$[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

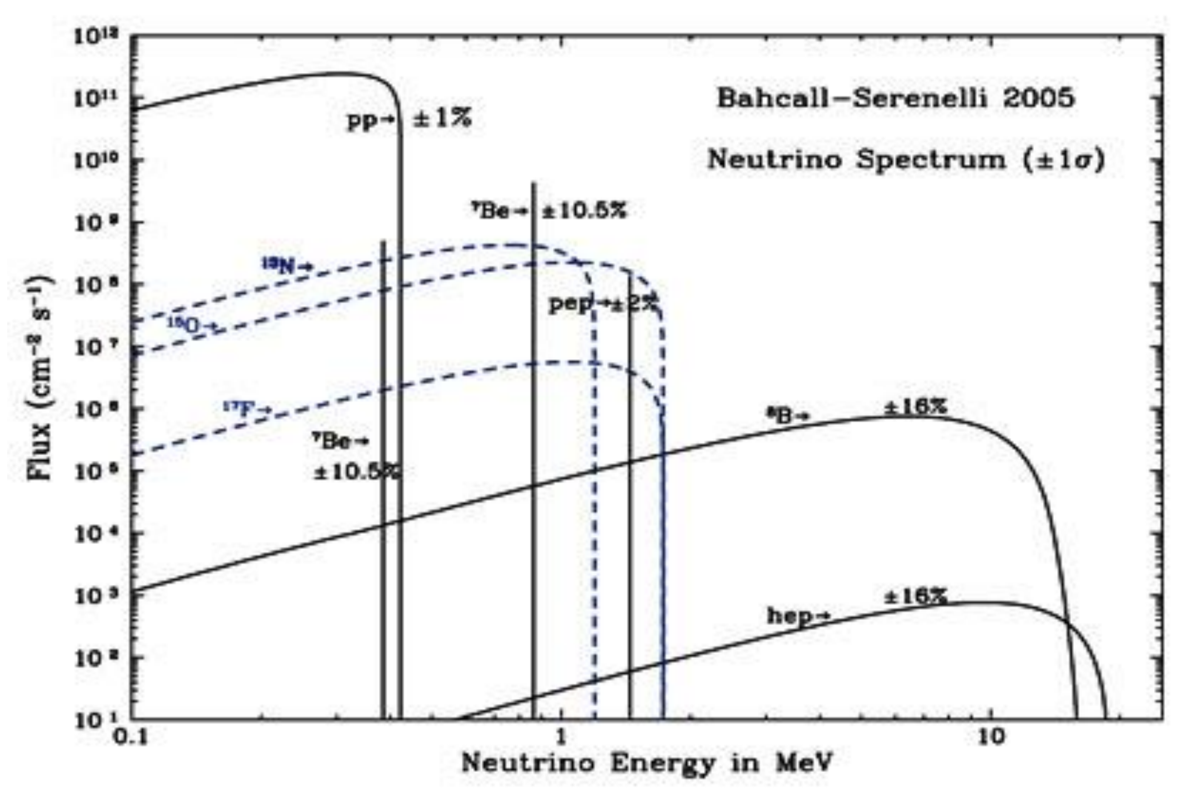


Neutrino Oscillation Experiments

Solar

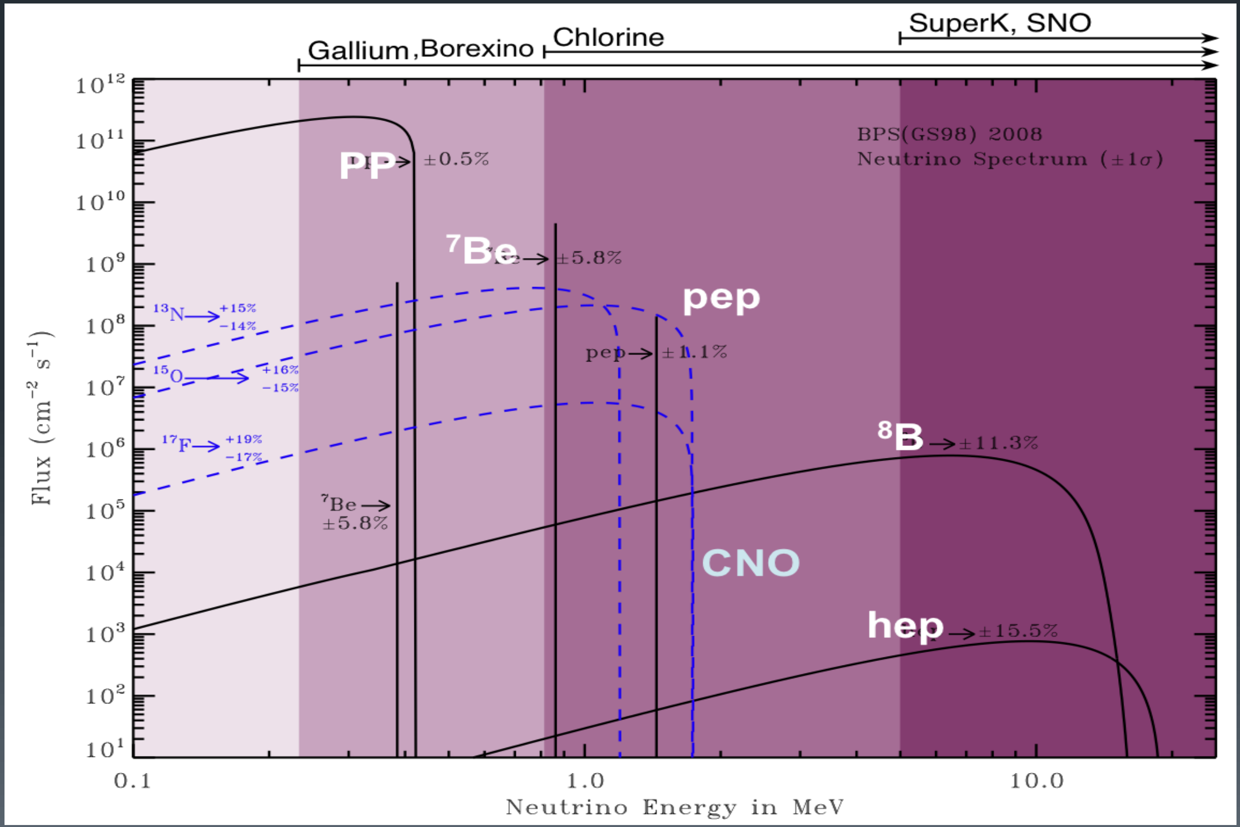
Observation of solar neutrinos directly addresses the theory of stellar structure and evolution, which is the basis of the standard solar model (SSM).

$$4p \longrightarrow {}^{4}He + 2e^{+} + 2v_{e}$$



Neutrino Oscillation Experiments
Solar

ν_e disappearance: sensitive to $(\Delta m^2)_{12} + \theta_{12}$



Neutrino Oscillation Experiments

Solar – radiochemical exp

Pioneering solar neutrino experiment by Davis and collaborators at **Homestake** (US) (1967)

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

(threshold 814 keV) ^{8}B neutrinos
+ (^{7}Be, pep, ^{13}N, ^{15}O)

The observed flux was significantly smaller than the SSM prediction, provided nothing happens to the electron neutrinos after they are created in the solar interior. This deficit has been called "**the solar-neutrino problem**"

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Gallium experiments (**GALLEX** and **GNO** at Gran Sasso in Italy and **SAGE** at Baksan in Russia, 1990-2000) utilize the reaction

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

(threshold 233 keV)
pp solar neutrinos.

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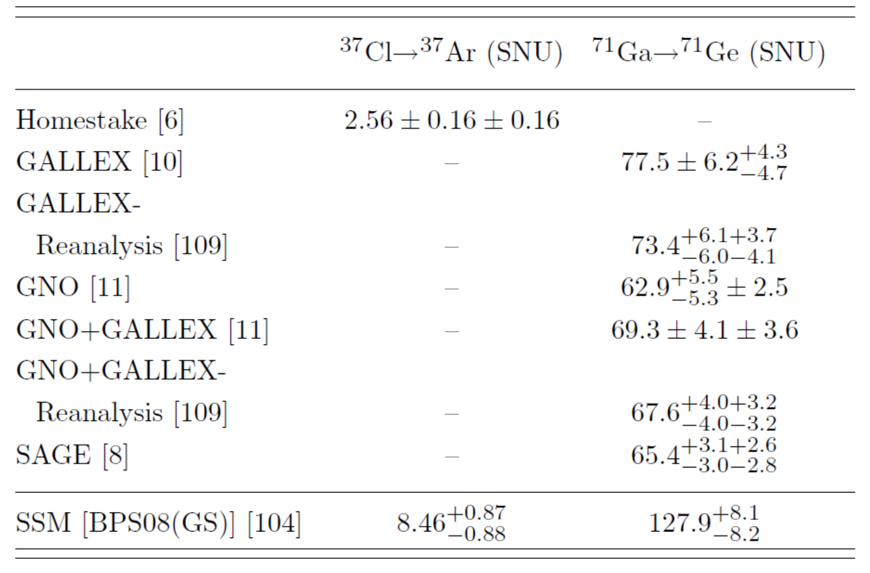

	^{37}Cl→^{37}Ar (SNU)	^{71}Ga→^{71}Ge (SNU)
Homestake [6]	$2.56 \pm 0.16 \pm 0.16$	–
GALLEX [10]	–	$77.5 \pm 6.2^{+4.3}_{-4.7}$
GALLEX- Reanalysis [109]	–	$73.4^{+6.1+3.7}_{-6.0-4.1}$
GNO [11]	–	$62.9^{+5.5}_{-5.3} \pm 2.5$
GNO+GALLEX [11]	–	$69.3 \pm 4.1 \pm 3.6$
GNO+GALLEX- Reanalysis [109]	–	$67.6^{+4.0+3.2}_{-4.0-3.2}$
SAGE [8]	–	$65.4^{+3.1+2.6}_{-3.0-2.8}$
SSM [BPS08(GS)] [104]	$8.46^{+0.87}_{-0.88}$	$127.9^{+8.1}_{-8.2}$

Neutrino Oscillation Experiments
Solar – Cherenkov exp

In 1987, the **Kamiokande** (1 kton H_2O) experiment in Japan succeeded in real-time solar neutrino observation, utilizing ve scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

(7MeV - ^{8}B solar neutrinos)

Directional correlation between the incoming neutrino and the recoil electron → first direct evidence that neutrinos come from the direction of the Sun

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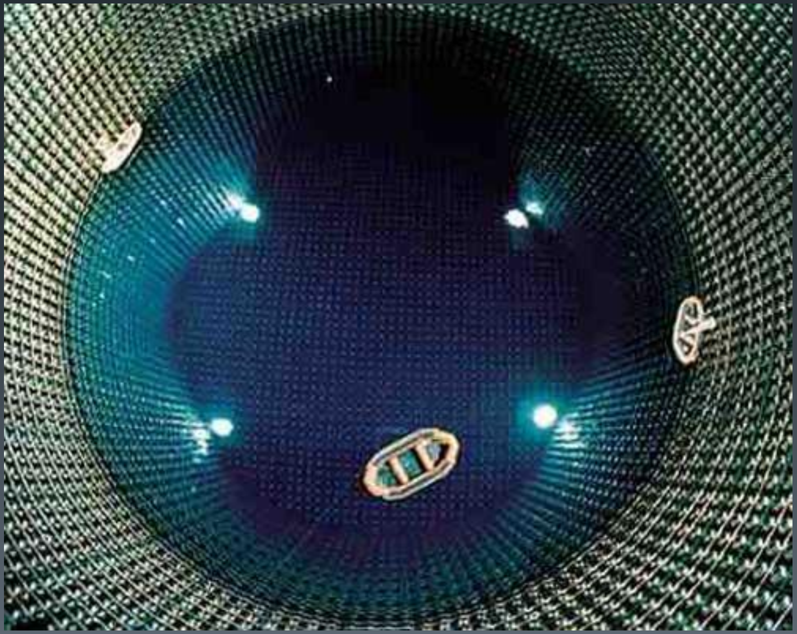


SuperKamiokande:
50 Kton Water Cherenkov

2.7 σ indication of non-zero day-night asymmetry of 8B solar neutrinos

$$A_{DN} = 2(R_D - R_N)/(R_D + R_N) = -0.032 \pm 0.022 \pm 0.005$$

→ Earth matter effects on flavour oscillations of solar neutrinos

Neutrino Oscillation Experiments

Solar – Cherenkov exp

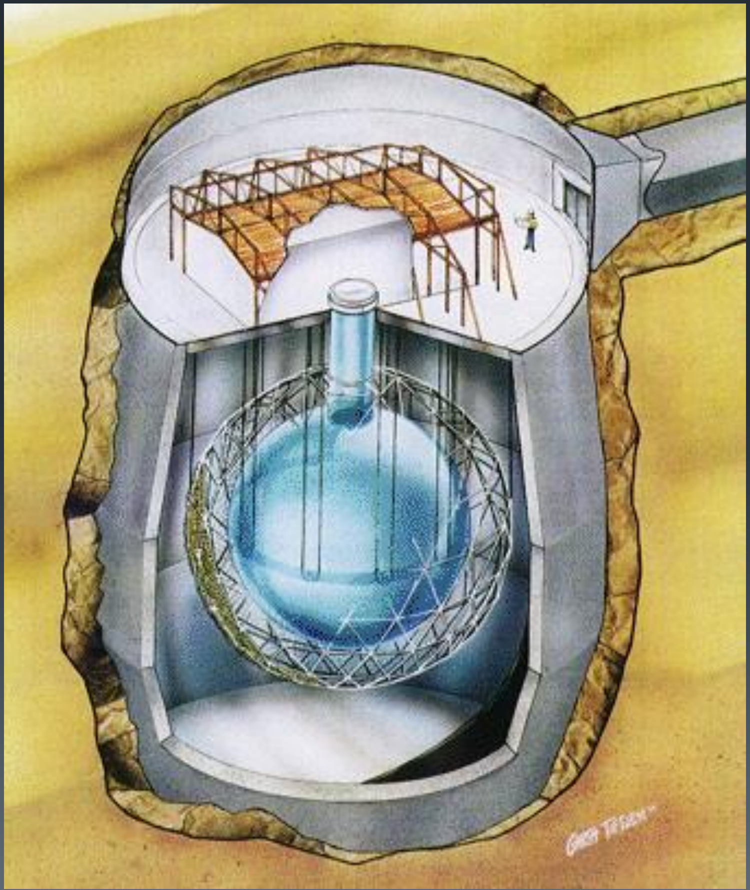
1999: **SNO** (Sudbury Neutrino Observatory), Canada - 1Kton D_2O (heavy water)

$$\nu_e + d \rightarrow e^- + p + p (CC)$$

$$\nu_x + d \rightarrow \nu_x + p + n (NC)$$

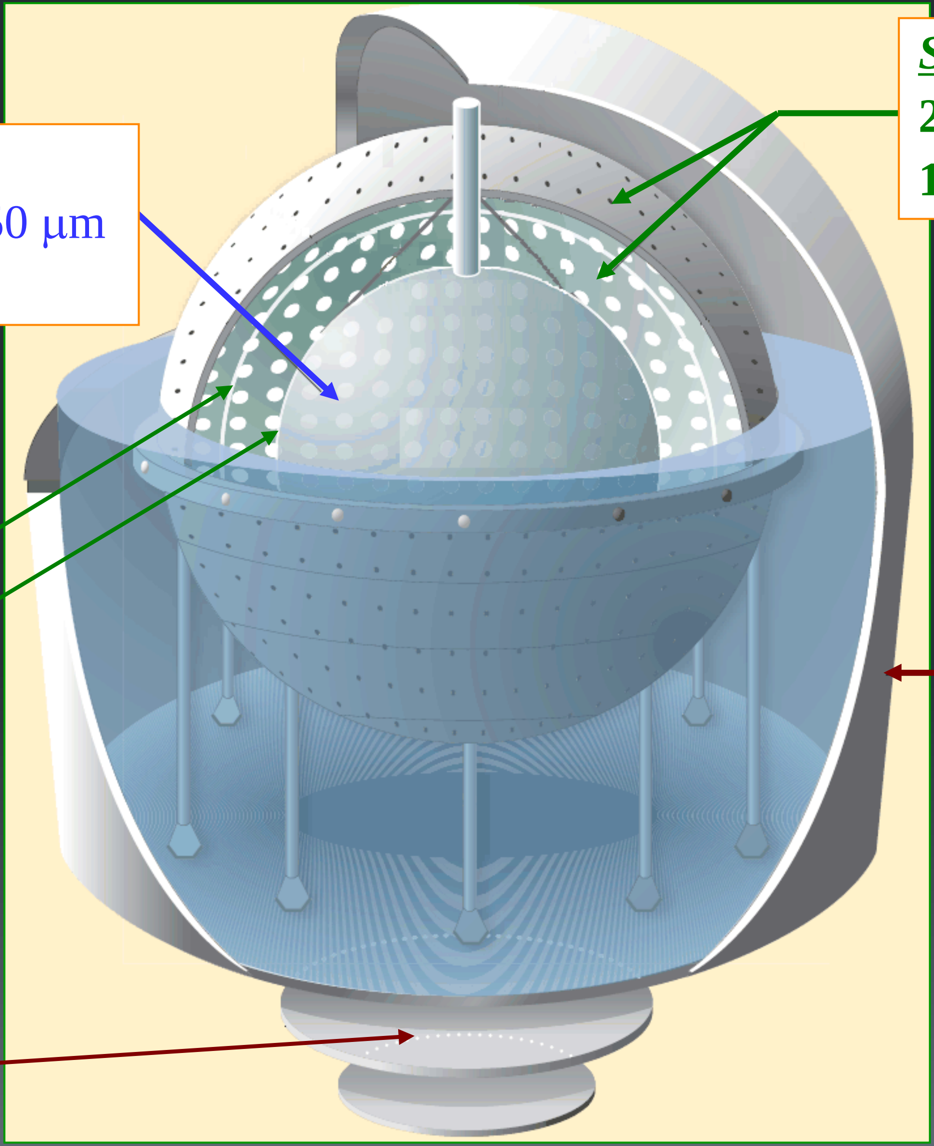
$$\nu_x + e^- \rightarrow \nu_x + e^- (ES)$$

Key feature to solve the solar neutrino problem. If it is caused by flavour transitions such as neutrino oscillations, the solar neutrino fluxes measured by CC and NC reactions would show a significant difference



Neutrino Oscillation Experiments
Solar – Liquid scintillator

Borexino@LNGS



Scintillator:

270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:

2212 PMTs

1350 m^3

Nylon vessels:

Inner: 4.25 m

Outer: 5.50 m

Water Tank:

γ and n shield

μ water Č detector

208 PMTs in water

2100 m^3

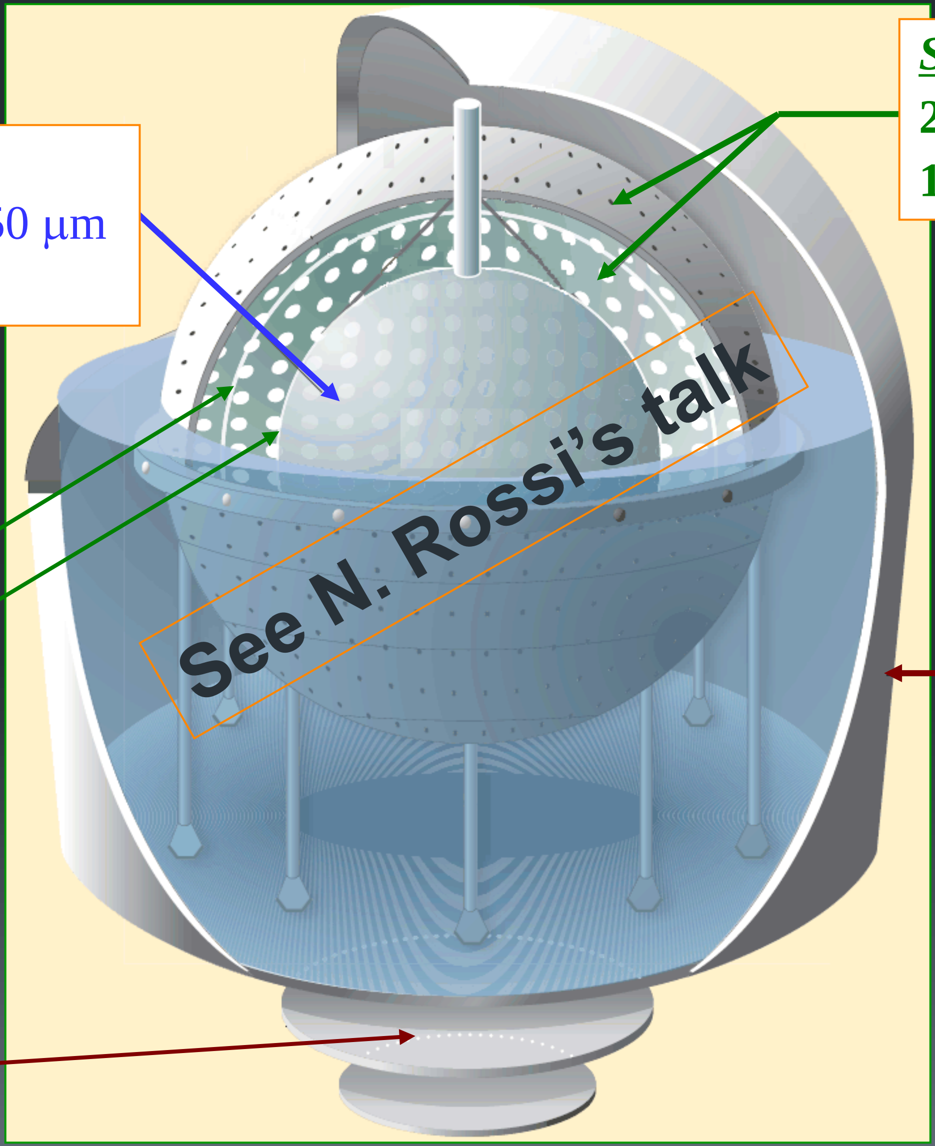
Carbon steel plates

$vx + e^- \rightarrow vx + e^-$ (ES)

Neutrino Oscillation Experiments

Solar – Liquid scintillator

Borexino@LNGS



See N. Rossi's talk

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208 PMTs in water
2100 m^3

Carbon steel plates

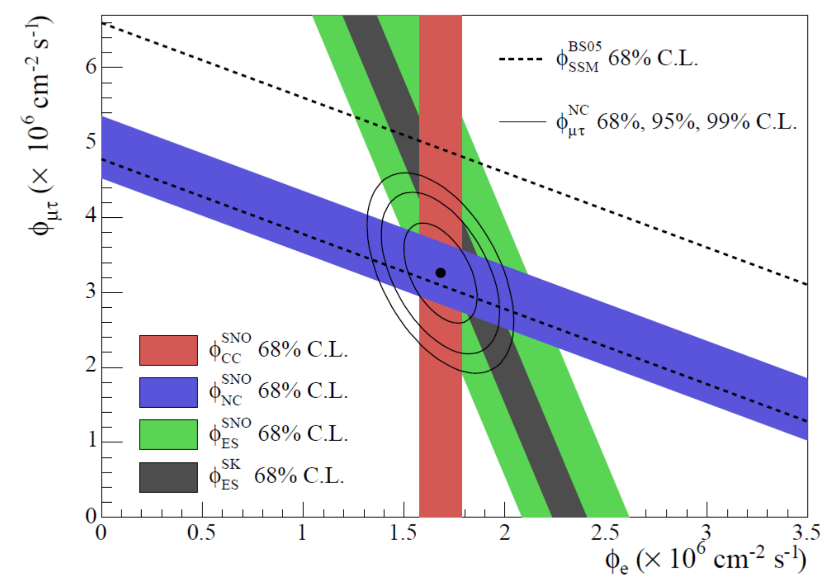
vx + e− → vx + e− (ES)

Neutrino Oscillation Experiments
Solar - Results

$$\phi^{\mathrm{CC}}_{\mathrm{SNO}} = (1.68 \pm 0.06^{+0.08}_{-0.09}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1} ,$$

$$\phi^{\mathrm{ES}}_{\mathrm{SNO}} = (2.35 \pm 0.22 \pm 0.15) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1} ,$$

$$\phi^{\mathrm{NC}}_{\mathrm{SNO}} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1} ,$$



$$\phi(\nu_{\mu \text{ or } \tau}) = \left(3.26 \pm 0.25^{+0.40}_{-0.35}\right) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

The non-zero $\varphi(\nu_{\mu \text{ or } \tau})$ is strong evidence for neutrino flavor conversion. These results are consistent with those expected from the LMA (large mixing angle) solution of solar neutrino oscillation in matter with Δm^2

$\Delta m_\odot \sim 7.5 \times 10^{-5}$ eV^2 and $\tan^2\theta_\odot \sim 0.45$.

Neutrino Oscillation Experiments

Reactor - KamLAND

1-kton ultra-pure liquid scintillator detector @ Kamiokande’s site (Japan).

Long Baseline (LBL) experiment (L ~ 180 km) neutrino oscillation studies using $\overline{\nu}_e$’s emitted from nuclear power reactors.

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

delayed coincidence of the positron with a 2.2 MeV γ-ray from neutron capture

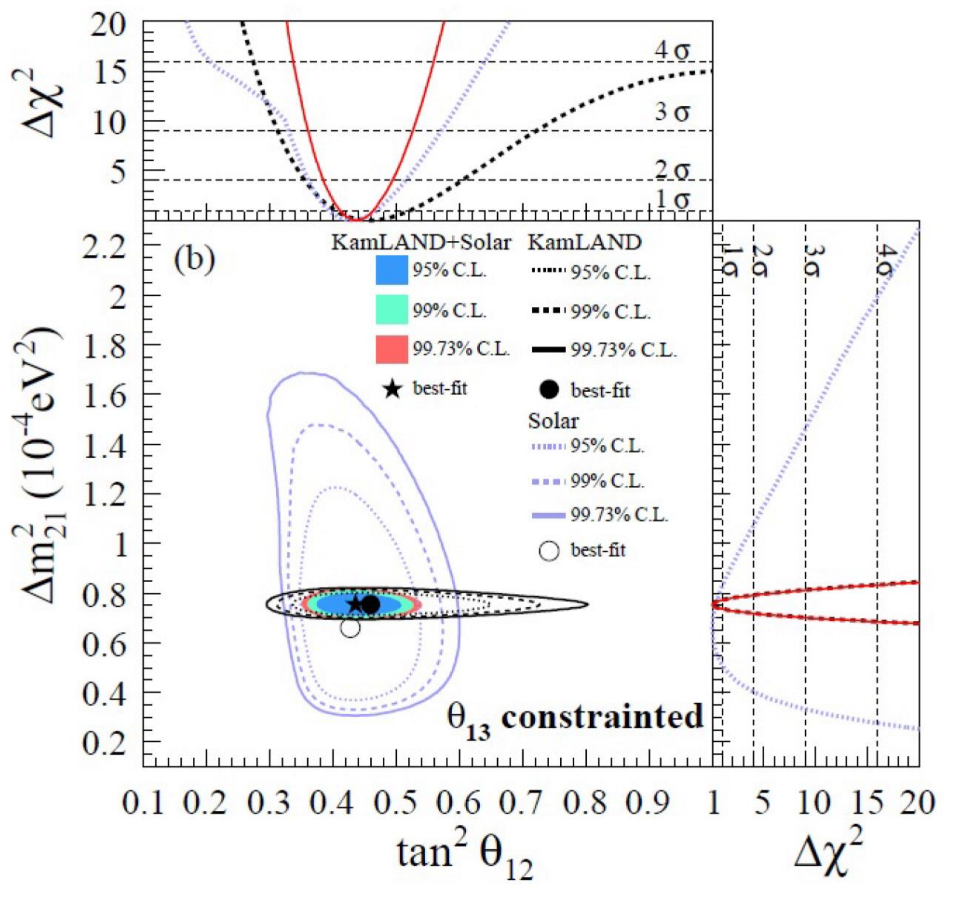
E < 8 MeV, $\Delta m^2 \sim 10^{-5}$ eV^2.

if the LMA solution is the real solution of the solar neutrino problem, KamLAND should observe reactor $\overline{\nu}_e$ disappearance, assuming CPT invariance.

$$\frac{N_{obs} - N_{bg}}{N_{NoOsc}} = 0.611 \pm 0.085 \pm 0.041$$

Solar neutrinos+KamLAND combined results on $(\Delta m^2)_{12}$+ θ_{12}

Taken together, solar and KamLAND select a very narrow region in the $(\Delta m^2)_{12}$- θ_{12} plane;



$$\Delta m^2_{12} = 7.53^{+0.18}_{-0.18} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$

KamLAND+SOLAR
arXiV: 1409.4515

Neutrino Oscillation Experiments

Reactor - intermediate baseline

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

anti-ν_e disappearance: sensitive to $(\Delta m^2)_{13} + \theta_{13}$

EXPERIMENTS
- Daya-Bay, Reno, Double-Chooz

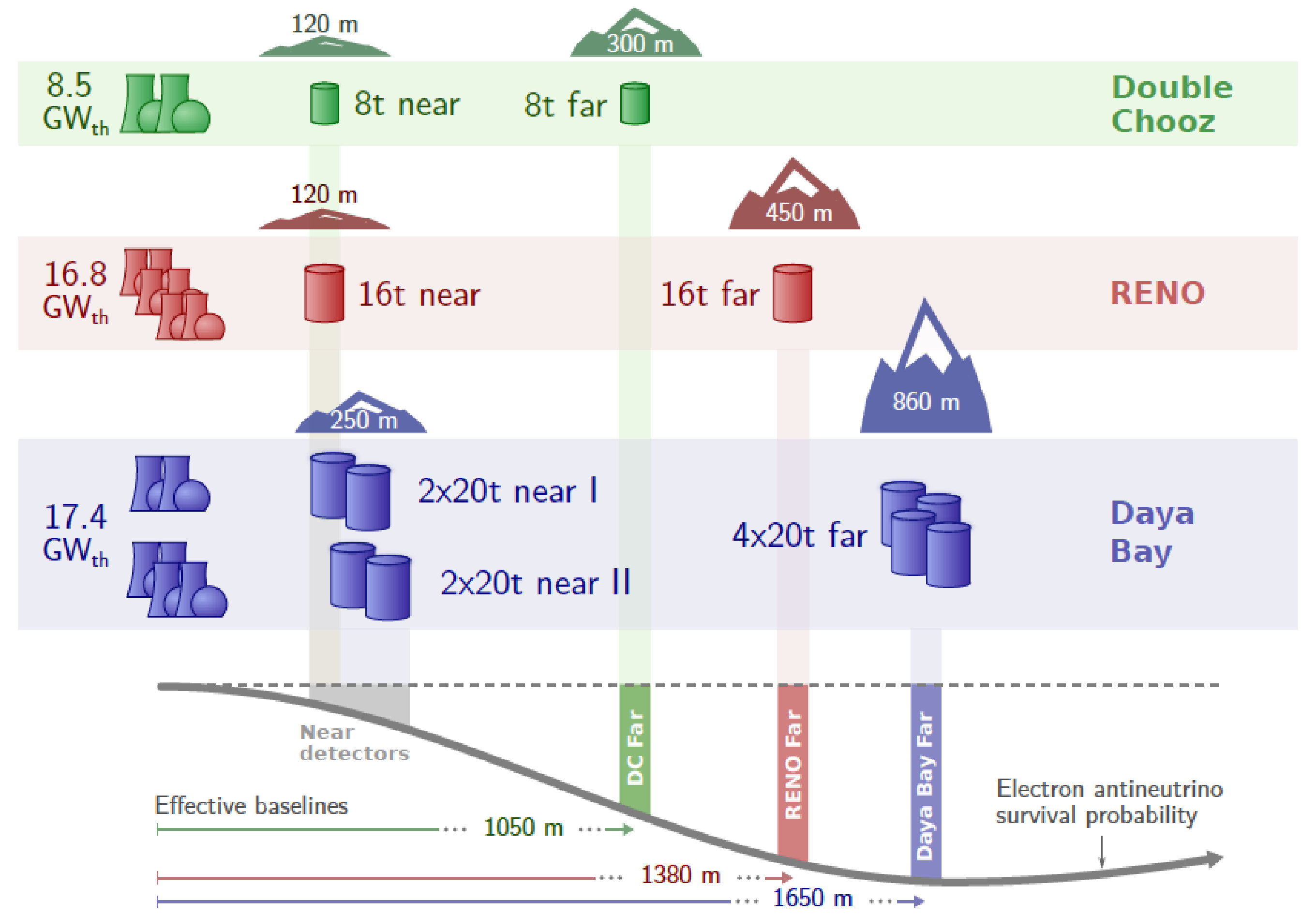
BASELINE
- L=1-2 Km

ENERGY
- E(reactor)~ 5 MeV

E/L ~ 10^{-3} eV^2

B. Caccianiga @ CSN2
13-15 Apr 2015

Neutrino Oscillation Experiments
Reactor - intermediate baseline



Double Chooz:

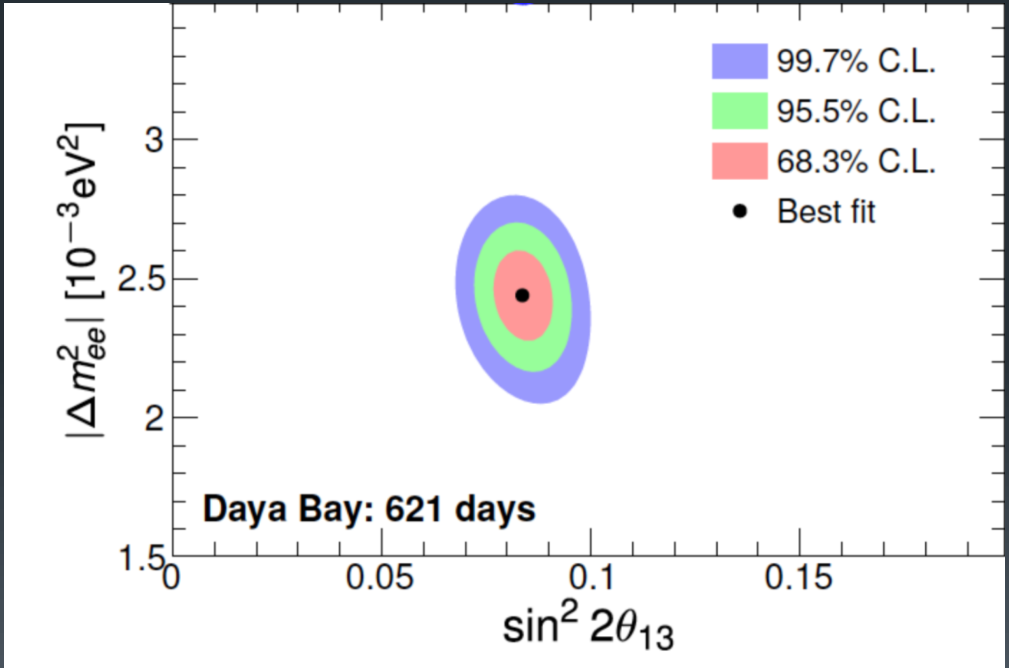
- so far results only with the far detector
- near detector takes data since dec 2014 (first results with both detectors by end of 2015)

Daya-Bay: deeper, higher nuclear plant power, more far/near detectors, more favourable baseline;

Neutrino Oscillation Experiments
Reactor - intermediate baseline

RESULTS FROM DAYA-BAY (Moriond 2015)

- Best precision on θ_{13} measurement (~6%)



$$\sin^2 2\vartheta_{13} = 0.084^{+0.005}_{-0.005}$$

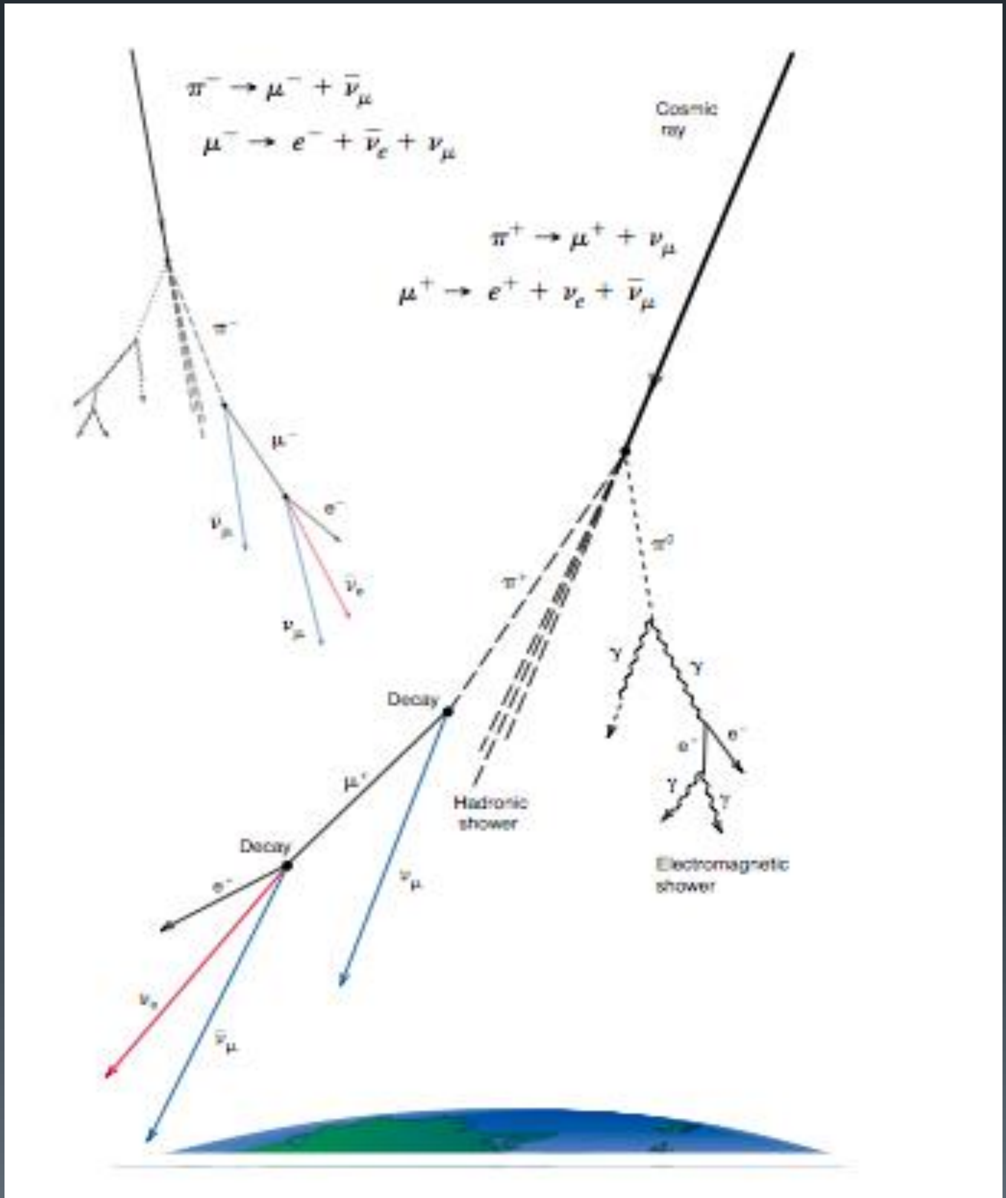
$$\Delta m^2_{ee} = 2.44^{+0.10}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$

$$\chi^2/\mathrm{NDF} = 134.7/146$$

Neutrino Oscillation Experiments

Atmospheric

π,K mesons produced by the nuclear interaction of the primary component of CRs in atmosphere

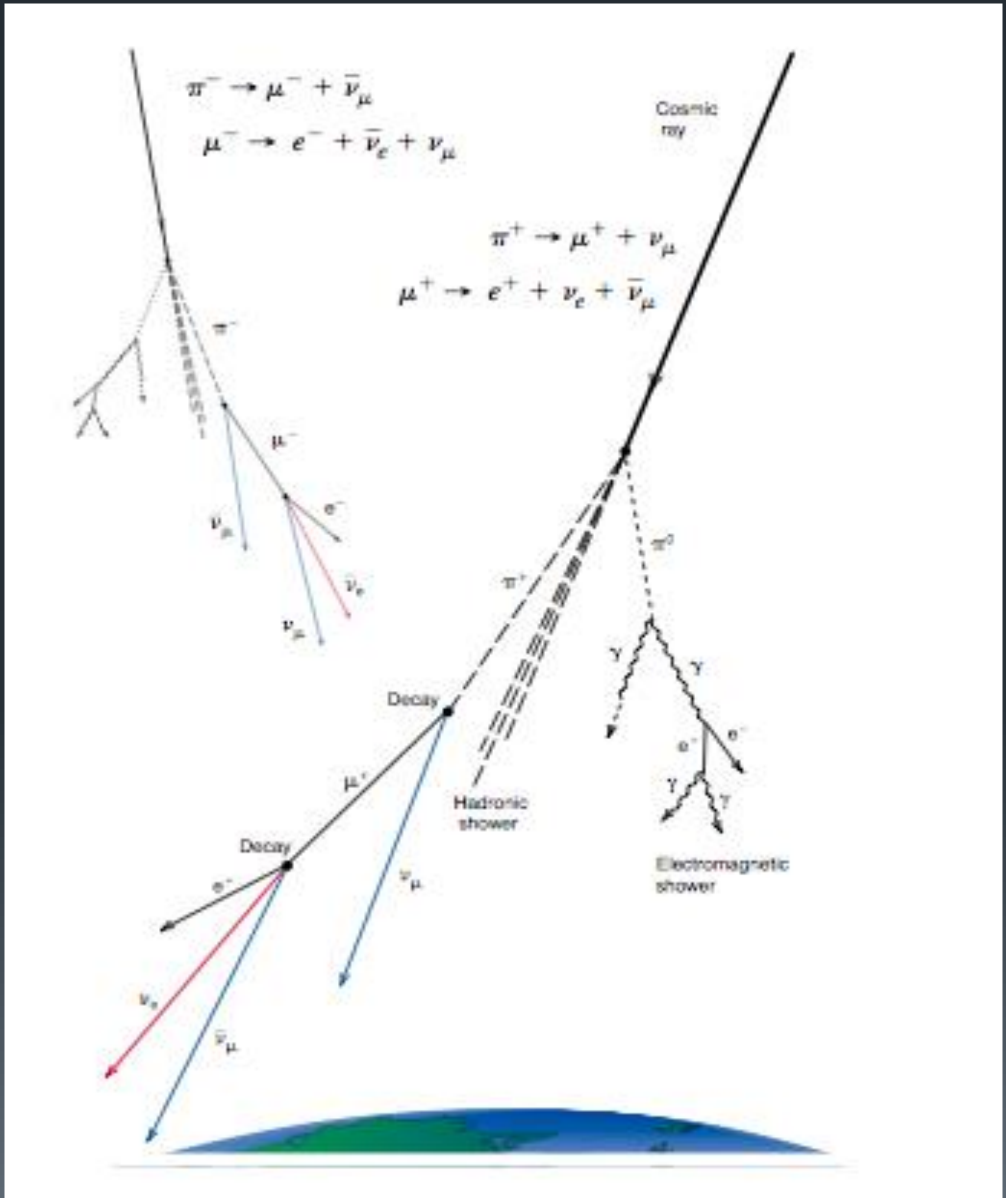


Neutrino Oscillation Experiments

Atmospheric

π,K mesons produced by the nuclear interaction of the primary component of CRs in atmosphere

$$\frac{\Phi\left(\nu_\mu + \overline{\nu_\mu}\right)}{\Phi\left(\nu_e + \overline{\nu_e}\right)} \approx 2$$



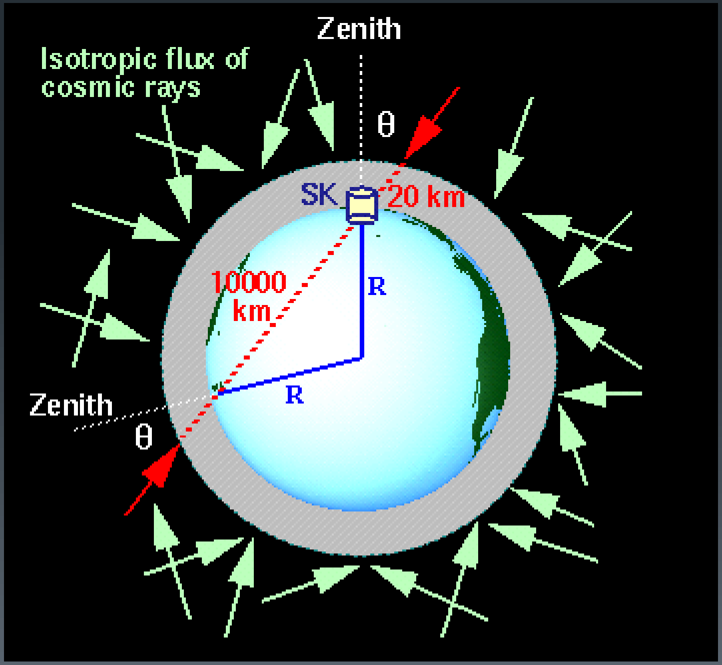
Neutrino Oscillation Experiments

Atmospheric

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance: sensitive to to $(\Delta m^2)_{23} + \theta_{23}$

$E = 1 \sim 10$ GeV.
$L = 10000$ km.
$\Delta m_A \sim 10^{-3}$ eV^2



Neutrino Oscillation Experiments

Atmospheric

The first compelling evidence for the neutrino oscillation was presented by the Super-Kamiokande Collaboration (SK-I) in 1998

Disappeared muon neutrinos may have oscillated into tau neutrinos because there is no indication of electron neutrino appearance

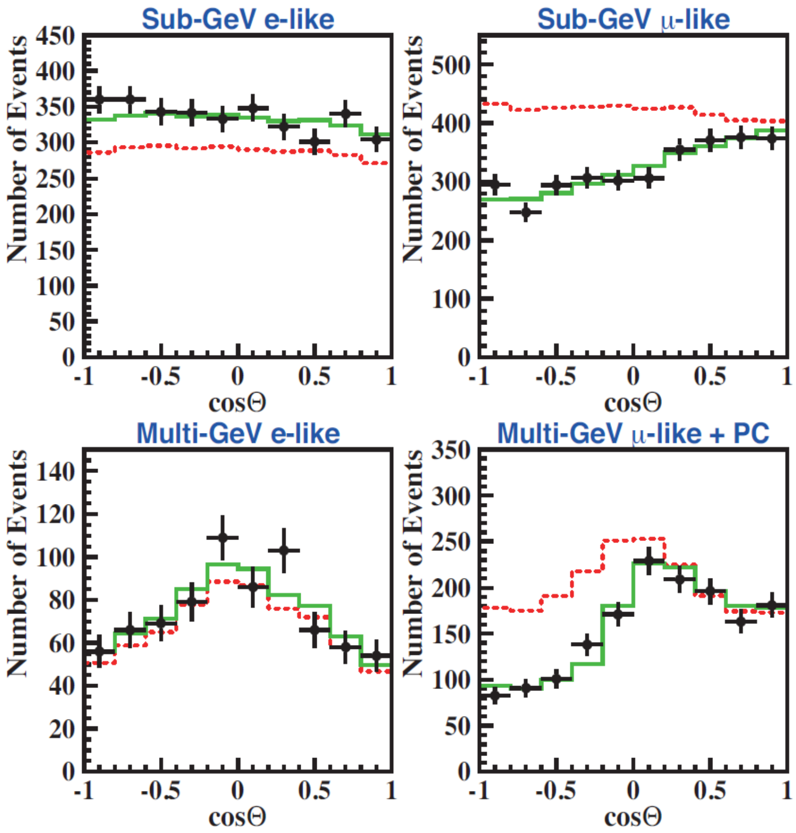
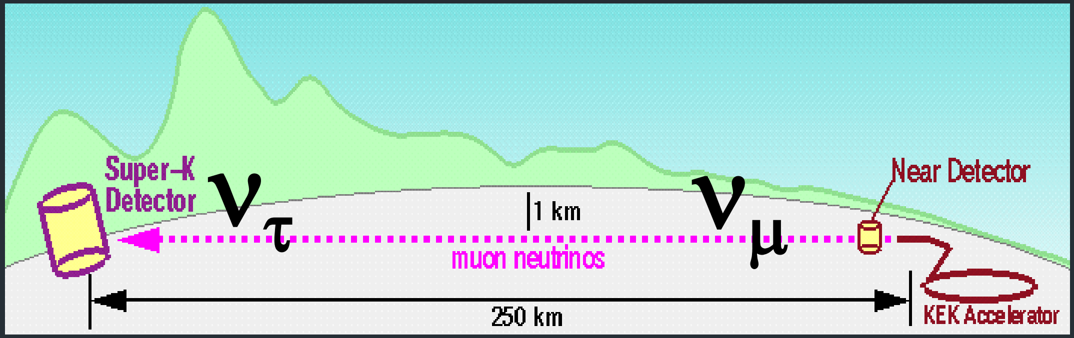


Figure 14.5: The zenith angle distributions for fully contained 1-ring *e*-like and μ-like events with visible energy < 1.33 GeV (sub-GeV) and > 1.33 GeV (multi-GeV). For multi-GeV μ-like events, a combined distribution with partially contained (PC) events is shown. The dotted histograms show the non-oscillated Monte Carlo events, and the solid histograms show the best-fit expectations for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. (This figure is provided by the Super-Kamiokande Collab.)

Neutrino Oscillation Experiments
Accelerator

The $\Delta m^2 \sim 10^{-3}$ eV^2.region can be explored by accelerator-based long-baseline experiments with typically E ~ 1 GeV and L ~ several hundred km

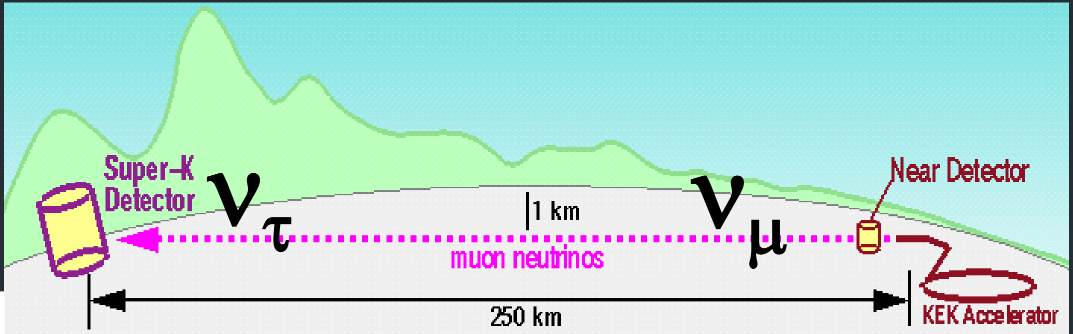
1999-2004 K2K (KeK-to-Kamioka)
: L = 250 km, E~1.3 GeV

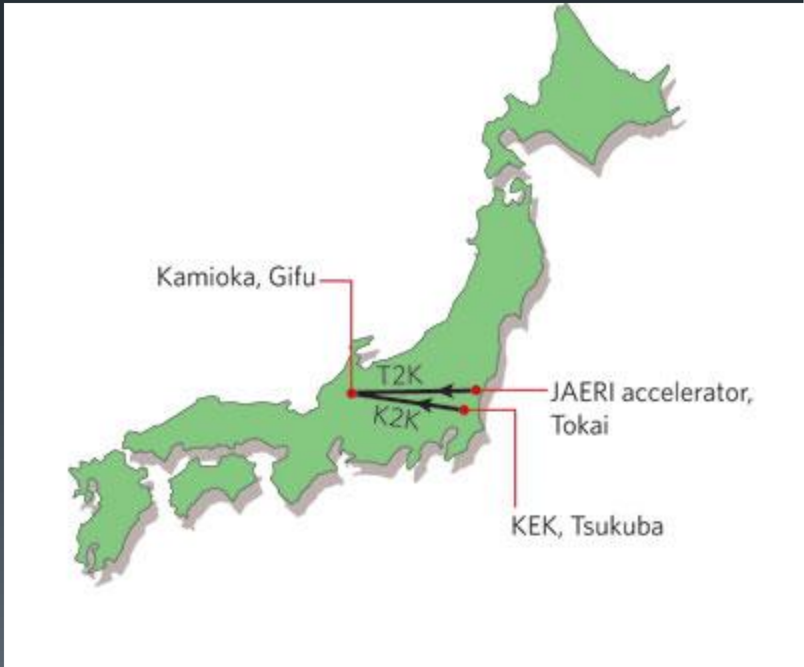


Neutrino Oscillation Experiments
Accelerator

The $\Delta m^2 \sim 10^{-3}$ eV^2.region can be explored by accelerator-based long-baseline experiments with typically $E \sim 1$ GeV and $L \sim$ several hundred km

1999-2004 K2K (KeK-to-Kamioka)
: L = 250 km, E~1.3 GeV

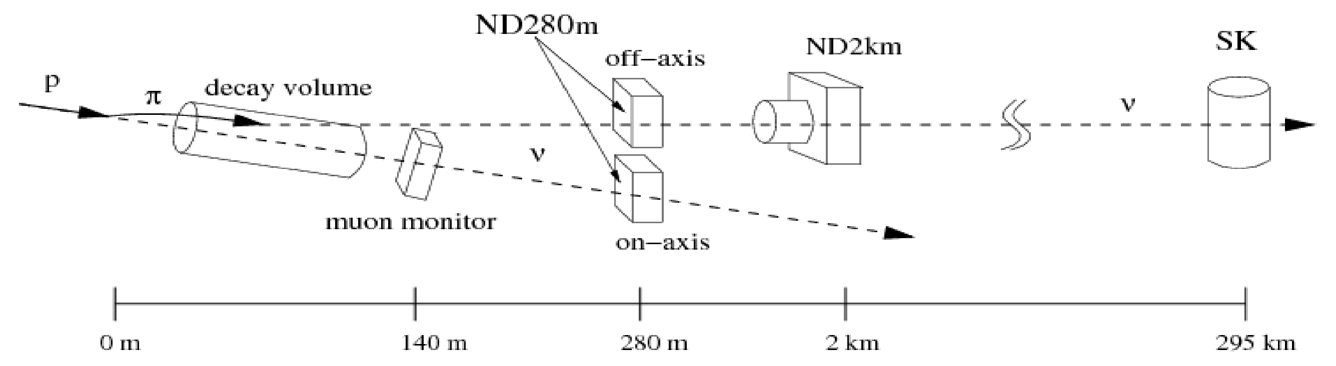


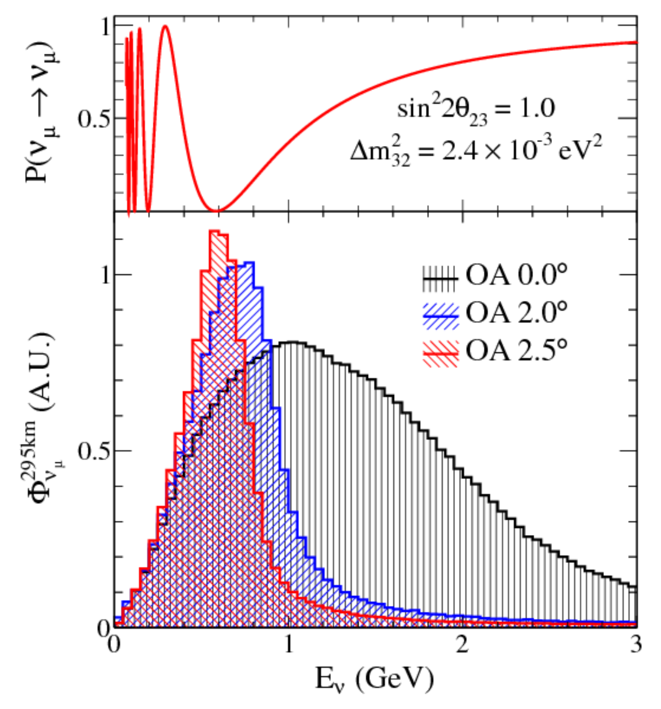


T2K (Tokai-to-Kamioka) :
L = 295 km, E~0.6 GeV
Off-axis

Neutrino Oscillation Experiments

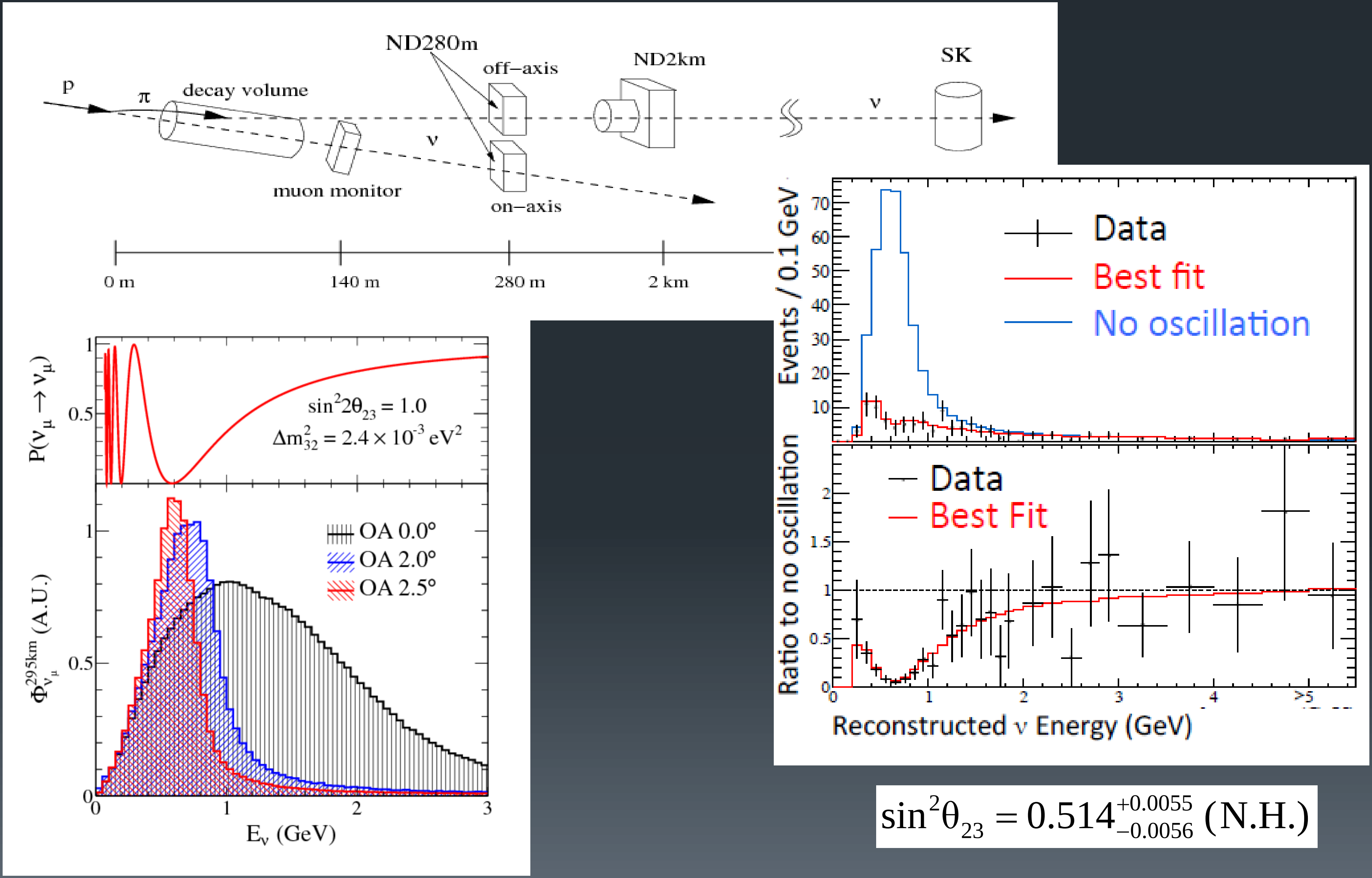
Accelerator





Neutrino Oscillation Experiments

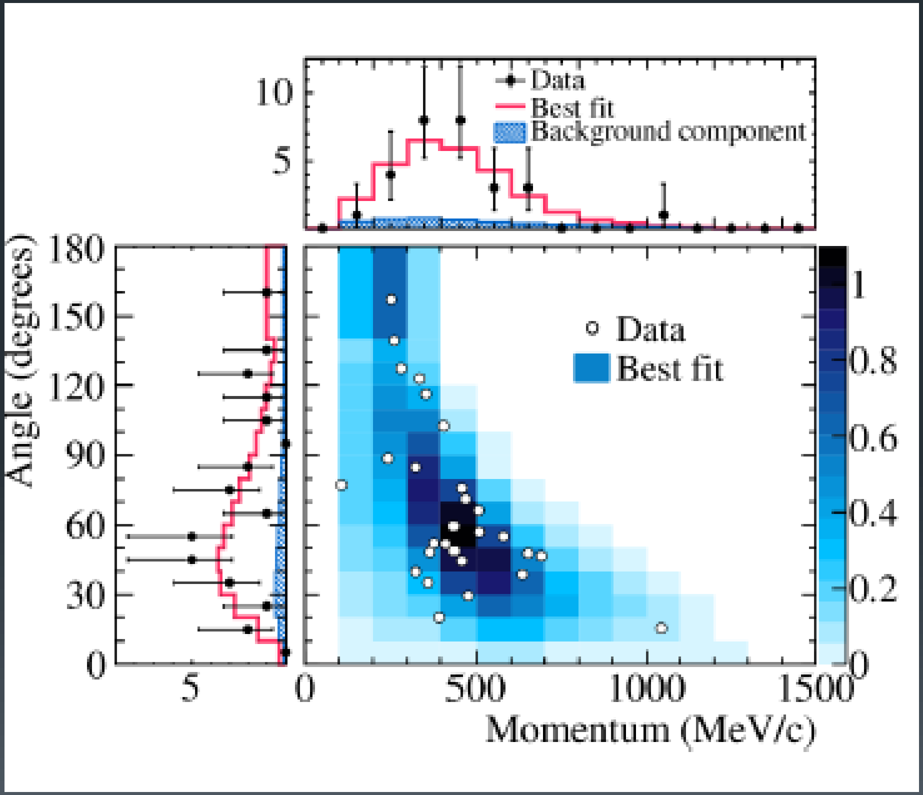
Accelerator



$$\sin^2\theta_{23} = 0.514^{+0.0055}_{-0.0056}\ \text{(N.H.)}$$

Neutrino Oscillation Experiments
Accelerator

$\nu_\mu \rightarrow \nu_e$ appearance: sensitive to $(\Delta m^2)_{23} + \theta_{13} + \theta_{23}$



- Discovery of $\nu_\mu \rightarrow \nu_e$ at 7.3 σ (28 ν_e)
- T2K finds a value of θ_{13} slightly larger than reactors;

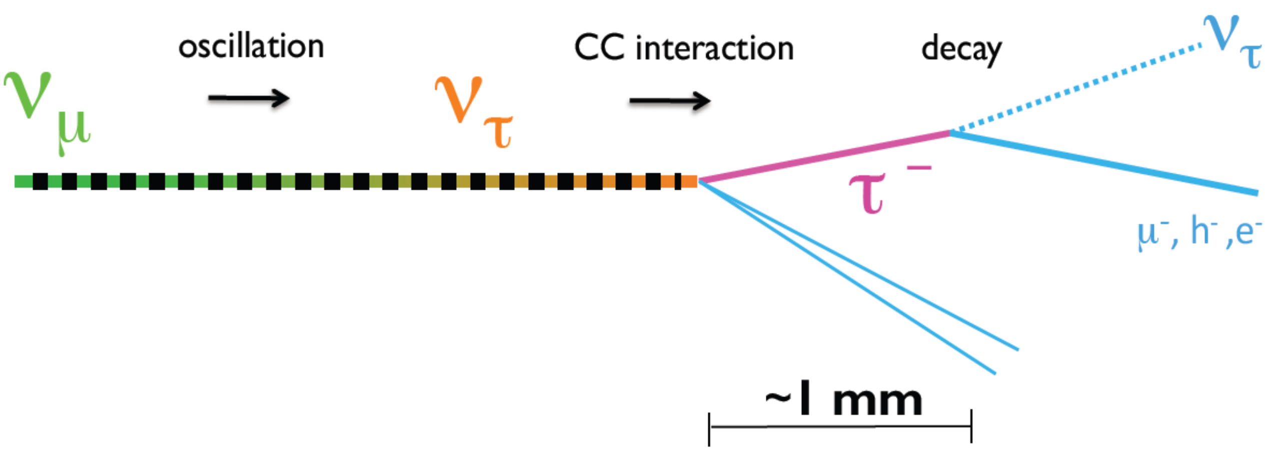
*Phys.Rev.Lett.***112**,061802 (2014)

Neutrino Oscillation Experiments

Accelerator - $\nu_\mu \to \nu_\tau$ **appearance**

OPERA (LNGS)

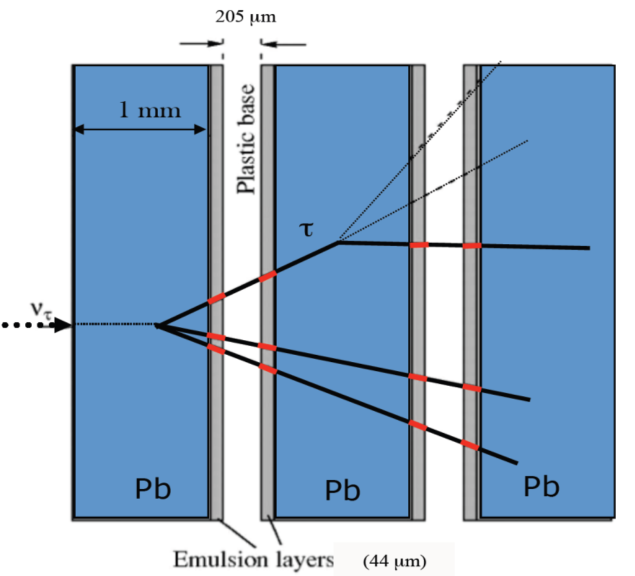
- L ~ 730 Km
- E~17 GeV
- 1.3 Kton emulsion – lead target + magnetic spectrometer

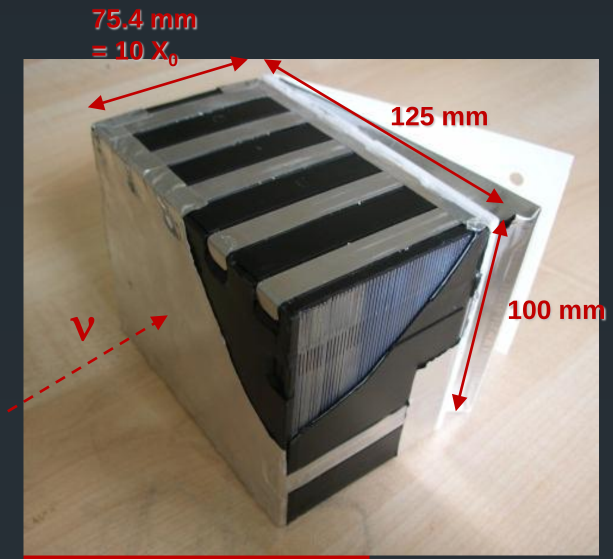


τ decay channel	B.R (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	49.5
$\tau \to 3h$	15.0

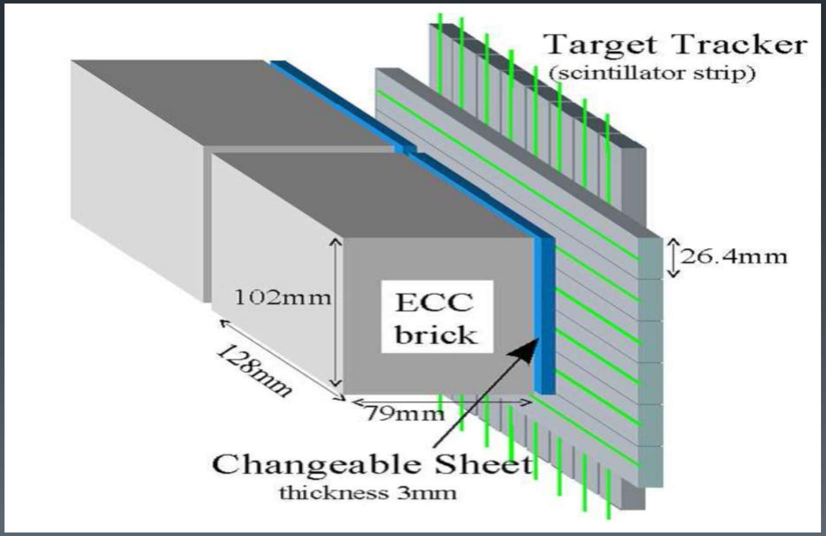
Neutrino Oscillation Experiments

Accelerator - $\nu_\mu \rightarrow \nu_\tau$ appearance



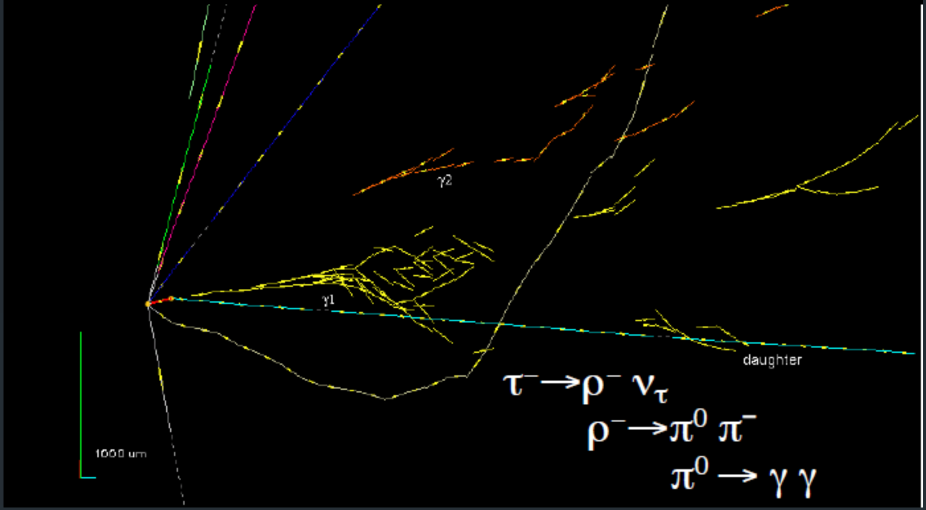


Brick weight = 8.3 kg



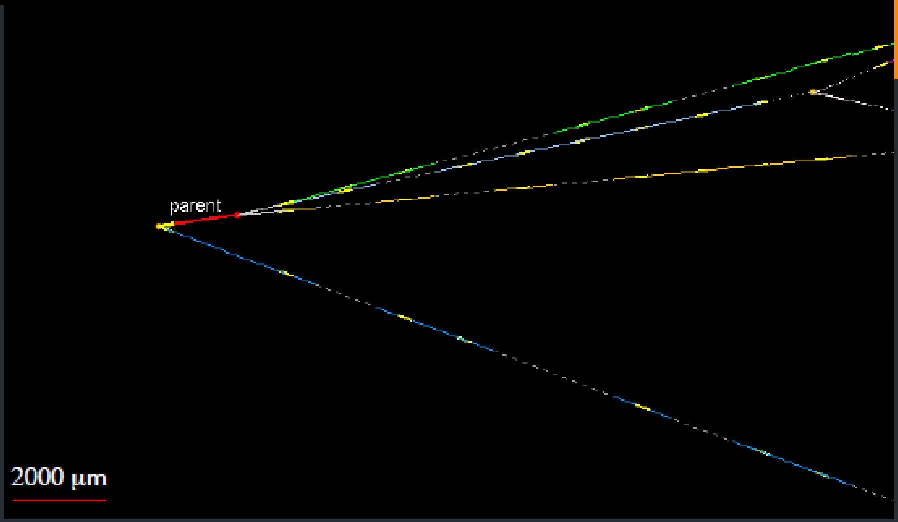
Total OPERA target :
~ 150000 bricks → 1.25 Kton

1-st ν_τ event: taken Aug 2009



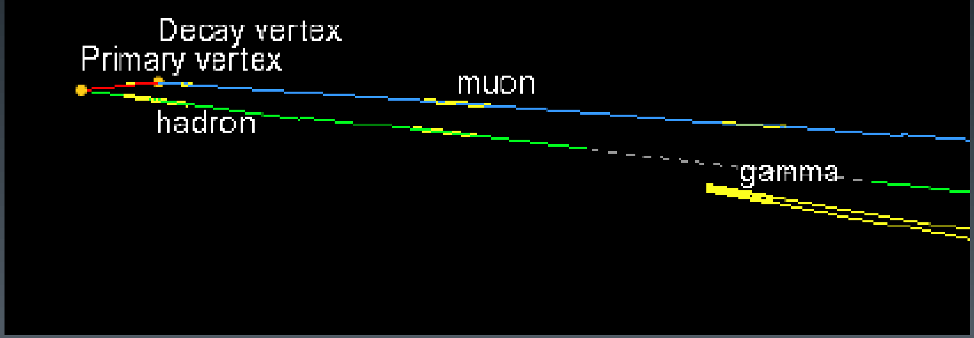
$$\tau^- \rightarrow \rho^- \nu_\tau$$
$$\rho^- \rightarrow \pi^0 \pi^-$$
$$\pi^0 \rightarrow \gamma\gamma$$

2-nd ν_τ event: taken Apr 2011

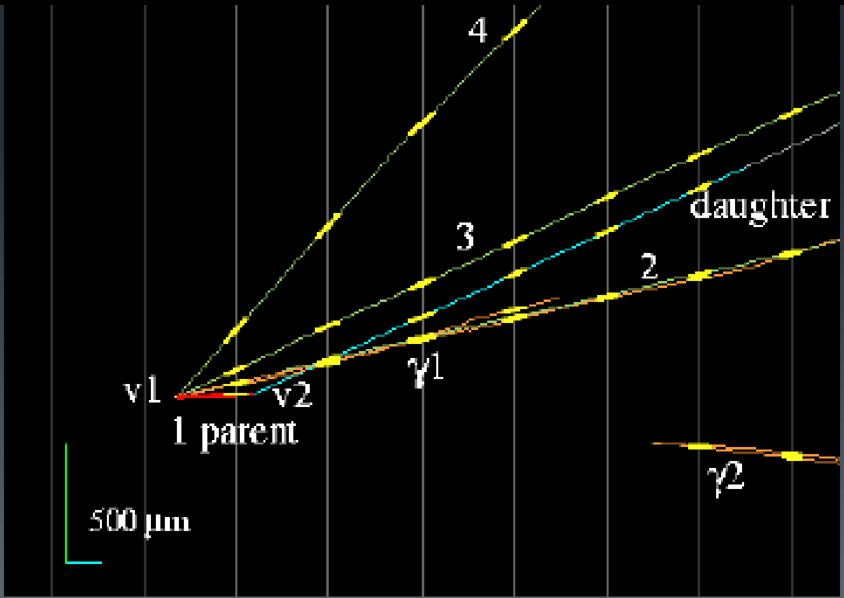


3-rd ν_τ event: taken May 2012

$\tau \rightarrow \mu$

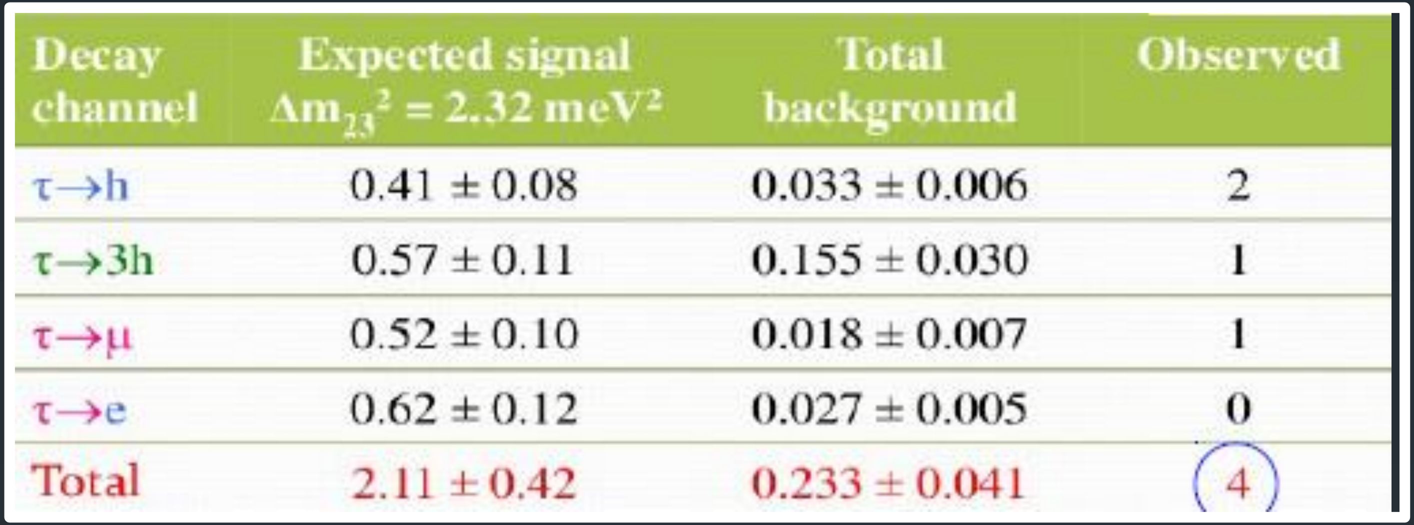


4-th ν_τ event: taken Sep 2012



Neutrino Oscillation Experiments

Accelerator - $\nu_\mu \rightarrow \nu_\tau$ appearance



Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ \mathrm{meV}^2$	Total background	Observed
$\tau \rightarrow h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \rightarrow \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \rightarrow e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

- 4 ν_τ candidates found;
- Exclusion of null hypothesis at 4.2 σ ;
- Still analysing data

Know…

- **Three families of active ν's;**
- **3 angles + 2 Δm^2**

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

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\substack{\text{atmosferic } \nu \\ \text{accelerator } \nu}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\substack{\text{SBL reactor } \nu \\ \text{accelerator } \nu}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\substack{\text{solar } \nu \\ \text{LBL reactor } \nu}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{23} \sim 45°$

$\theta_{13} \sim 9°$

$\theta_{12} \sim 33°$

$$\Delta m_{12}^2 \sim 8\times10^{-5}\,\mathrm{eV}^2 \qquad \Delta m_{23}^2 \sim 3\times10^{-3}\,\mathrm{eV}^2$$

Unknown…

- Absolute mass scale;
- Mass hierarchy;
- CP violation?

- **Three families of active ν's;**
- **3 angles + 2 Δm^2**

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

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\substack{\text{atmosferic } \nu \\ \text{accelerator } \nu}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}\boxed{e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}\boxed{e^{i\delta}} & 0 & c_{13} \end{bmatrix}}_{\substack{\text{SBL reactor } \nu \\ \text{accelerator } \nu}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\substack{\text{solar } \nu \\ \text{LBL reactor } \nu}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{23} \sim 45°$

$\theta_{13} \sim 9°$

$\theta_{12} \sim 33°$

$$\Delta m^2_{12} \sim 8\times10^{-5}\,\mathrm{eV}^2 \qquad \Delta m^2_{23} \sim 3\times10^{-3}\,\mathrm{eV}^2$$

Unknown…

- **Three families of active ν's;**
- **3 angles + 2 Δm²**

- Absolute mass scale;
- Mass hierarchy;
- CP violation?
- ν nature (Majorana or Dirac)?
- 1 or more sterile neutrinos?;

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

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{atmosferic } \nu \text{ accelerator } \nu} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{SBL reactor } \nu \text{ accelerator } \nu} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{solar } \nu \text{ LBL reactor } \nu} \times \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}}_{\text{Neutrinoless Double Beta Decay}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{23} \sim 45°$

$\theta_{13} \sim 9°$

$\theta_{12} \sim 33°$

$$\Delta m^2_{12} \sim 8\times10^{-5}\,\mathrm{eV}^2 \qquad \Delta m^2_{23} \sim 3\times10^{-3}\,\mathrm{eV}^2$$

Thanks for your attention!