Neutrino Experiments at Kamioka

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36km south from here
Contents

- What experiments are at Kamioka now
- History of neutrino experiments at Kamioka
- Recent highlights from Kamioka
- Future
Kamioka underground (NOW)

Super-K dome

KamLAND (Tohoku Univ.)
- 1000ton liquid scintillator detector
- Reactor, geo neutrinos
- $^{136}$Xe double beta decay

Super-Kamiokande
- 50,000 ton water Cherenkov detector
- Atmospheric, solar, supernova neutrinos
- Proton decay, indirect dark matter search
- Far detector for T2K

CANDLES
- CaF$_2$ scintillation detector for $^{48}$Ca double beta decay

KamLAND (old Kamiokande site)

Gravitational-wave
- CLIO 100m x 100m prototype
- Geo-physics 100m x 100m
- Laser strainmeter

NEWAGE
- Direction dark matter experiment

XMASS
- Direct dark matter search experiment

EGADS
- 200t Gd test tank

Mt. Ikeno-yama
Kamioka underground experiments (NOW)

Mt. Ikeno-yama

KAGRA

Gravitational-wave Telescope

Laser strainmeter

1.5km Geophysics interferometer
Kamioka underground (NOW)

Super-Kamiokande
50,000 ton water Cherenkov detector
Atmospheric, solar, supernova neutrinos
Proton decay, indirect dark matter search
Far detector for T2K

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KamLAND (Tohoku Univ.)
1000 ton liquid scintillator detector
Reactor, geo neutrinos
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KamLAND was here

Gravitational-wave
CLIO
100m x 100m prototype
Geo-physics
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CANDLES
CaF\(_2\) scintillation detector
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Direct dark matter search experiment

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NEWAGE
Direction dark matter experiment

Mt. Ikeno-yama
1000m

Kamiokande was here

IMPDU
Lab.1
Lab.2
Lab.E/IMPU

Lab.A
clean room
water system

Atotsu entrance

Kamiokande was here

Original purpose:
Search for proton decay

Inner detector only.
Readout of charge information only
(i.e. no timing information).

But, proton decay was not observed....

Fiducial volume: 880 ton
(2m from the wall)

1000 20-inch PMTs were used

Photo-coverage: 20%
Upgrade to Kamiokande-II (1984-1985)

Thanks to large photo-coverage, it was found that the detector is sensitive to low energy events. So, the detector was upgraded for solar neutrinos in 1984-1985.

- Made outer detector to shield external gamma rays
- Upgrade electronics for readout of timing information. It improved vertex reconstruction.
SN1987A: a supernova at LMC (Feb.23rd, 1987)

It happened when the Kamiokande detector was almost ready for solar neutrino measurement.

11 events in 13 sec.

Total energy released by $\bar{\nu}_e$ was measured to be $\sim 5 \times 10^{52}$ erg.

It was consistent with core-collapse scenario of supernova.
1988: First observation of solar neutrinos
Based on 450 days’ Kamiokande data taken from Jan. 1987 to May 1988

Observed number of solar neutrinos was about 50. It was almost half of the expectation from the Standard Solar Model (SSM) and confirmed the solar neutrino problem.

Electron-like data is consistent with prediction. But, muon-like data is $59\pm 7\%$ of prediction.

The first hint of neutrino oscillations.
Super-Kamiokande detector (1996 – )

In order to solve the problems of solar and atmospheric $\nu$ and detect more supernova $\nu$.

- 50,000 t water tank (42m high, 40m diameter)
- 32,000 t photo-sensitive volume
- 22,000 t fiducial volume
- 11,146 20-inch PMTs
- Photo-coverage: 40% (x2 of Kamiokande in order to lower energy threshold)
- 1000m underground in Kamioka mine

X 25 fiducial volume than Kamiokande
Cosmic rays produce neutrinos.
\[ \text{P} + \text{A} \rightarrow \text{N} + \pi^\pm + \text{X} \]
\[ \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e + \nu_\mu \]

Super-Kamiokande

Kajita’s presentation in Neutrino 1998 conference.

\( \nu_\mu \) disappearance
2001: Evidence for solar neutrino oscillation

SK ES vs. SNO CC

Interactions
(ES) $\nu + e^- \rightarrow \nu + e^-$  ($\sigma$ of $\nu_{\mu/\tau}$ is 1/7 of $\nu_e$)
(CC) $\nu_e + d \rightarrow p + p + e^-$
(NC) $\nu_X + d \rightarrow \nu_X + p + n$  ($X=e,\mu,\tau$)

$\nu_e$ to $\nu_{\mu/\tau}$ conversion
2002: Reactor neutrino oscillation by KamLAND

Built at old Kamiokande site
1000 ton liquid scintillator.
Run by Tohoku University.

KamLAND

70GWatt power (7% of world total) was generated by reactors in 140 - 210 km from Kamioka.

$\bar{\nu}_e$ disappearance
1999-2004: K2K (KEK to Kamioka)

The first artificial neutrino beam experiment in the world.
Results from K2K experiment

<table>
<thead>
<tr>
<th></th>
<th>$N_{sk}$ obs</th>
<th>$N_{sk}$ pred</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All</strong></td>
<td>112</td>
<td>155.9</td>
</tr>
<tr>
<td><strong>1 ring</strong></td>
<td>67</td>
<td>99.0</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>58</td>
<td>90.8</td>
</tr>
<tr>
<td>$e$-like</td>
<td>9</td>
<td>8.2</td>
</tr>
<tr>
<td><strong>multi-ring</strong></td>
<td>45</td>
<td>56.8</td>
</tr>
</tbody>
</table>

**Oscillation**

Confirmed atmospheric oscillation ($\nu_\mu$ disappearance due to $\Delta m_{23}^2/\theta_{23}$) using an artificial beam.
• J-PARC produces high intensity neutrino beam.
• SK detects neutrinos at 295km.
• Off-axis beam technique was adopted to make narrow band neutrino beam.
2011: Discovery of $\theta_{13}$ by T2K

Search for $\nu_e$ appearance from $\nu_\mu$ beam

6 events were observed.

Number of background was $1.5 \pm 0.3$ (syst.) for $\sin^2(2\theta_{13}) = 0$

Allowed region of $\sin^22\theta_{13}$ and $\delta_{CP}$

$\theta_{13} = 0$ was excluded with $2.5\sigma$

$$0.03 < \sin^22\theta_{13} < 0.28$$

$$\sin^22\theta_{13} = 0.11$$
Maki-Nakagawa-Sakata-Pontecorvo (MNSP) Matrix

$$\begin{align*}
\text{Weak interaction eigenstate} & \begin{pmatrix} 
\nu_e \\
\nu_\mu \\
\nu_\tau 
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \\
\text{Mass eigenstate} & \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\end{align*}$$

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

$$\begin{align*}
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\
s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}c_{23}
\end{pmatrix}
\end{align*}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \ ; \Delta m_{12}^2, \Delta m_{23}^2, \Delta m_{31}^2$$

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

$$\delta : \text{Dirac CP phase}$$

Majorana CP phase is not shown here because it does not affect neutrino oscillations.
Summary of discoveries of neutrino oscillations

Solar \( \nu \): SK vs. SNO (2001)

Solar \( \nu \): SNO (2002)

Reactor neutrino by KamLAND (2002)

Atmospheric neutrino (1998)


T2K (2011)

Short baseline reactor \( \nu \) (2012)

Experiments at Kamioka revealed all oscillation modes for the first time and further.
Neutrino mass and mixing (what we know now)

Normal Hierarchy

\[ \Delta m_{31}^2 = 2.524^{+0.039}_{-0.040} \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{21}^2 = 7.50^{+0.19}_{-0.17} \times 10^{-5} \text{ eV}^2 \]

Inverted Hierarchy

\[ \Delta m_{32}^2 = -2.514^{+0.038}_{-0.041} \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{21}^2 = 7.50^{+0.19}_{-0.17} \times 10^{-5} \text{ eV}^2 \]

Numbers from I. Esteban et al., JHEP 01 (2017) 087
Neutrino mixing vs. quark mixing

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

(3σ C.L. range)

\[
\begin{pmatrix}
0.800-0.844 & 0.515-0.581 & 0.139-0.155 \\
0.229-0.516 & 0.438-0.699 & 0.614-0.790 \\
0.249-0.528 & 0.462-0.715 & 0.595-0.776 \\
\end{pmatrix}
\]

I. Esteban et al., JHEP 01 (2017) 087

Quark mixing (CKM matrix)

\[
\begin{pmatrix}
0.97434 & 0.22506 & 0.00357 \\
0.22492 & 0.97351 & 0.0414 \\
0.00875 & 0.0403 & 0.99915 \\
\end{pmatrix}
\]

They are so much different!

Particle Data Group (2016)
What are unknowns?

- Which mass hierarchy?
- Is CP phase $\delta$ finite?
- Is $\theta_{23} = 45^\circ$ $>$ $45^\circ$ or $<$ $45^\circ$?
- Absolute mass of neutrinos? (→ direct mass experiments)
- Majorana or Dirac mass? (→ double beta decay experiments)
- Sterile neutrino (LSND anomaly)? (→ short baseline accelerator/source experiments)

Those are interesting future subjects.
Recent Highlights from Kamioka (SK, T2K, KamLAND)
Search for events consistent with hadronic decay of $\tau$ lepton
- Multi-ring e-like events with visible energy above 1.3GeV.
- Negligible primary $\nu_\tau$ flux so $\nu_\tau$ must be oscillation-induced: **upward-going**

\[
\begin{align*}
\text{Observed \# / Expected \#} &= 1.47 \pm 0.32 \\
(4.6\sigma \text{ from 0}) \quad \text{assuming NH}
\end{align*}
\]
SK atmospheric $\nu$ analysis (with T2K constraint)

- **SK+T2K ($\theta_{13}$ fixed):** $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -5.2$
  
  
  (-3.8 (-3.1) expected for SK best(combined) oscillation parameters)

- Under IH hypothesis, the confidence level of this $\Delta \chi^2$ is 5.4%, i.e. “IH disfavored at 94.6%”.

| Fit (585 dof)          | $\chi^2$ | $\sin^2 \theta_{13}$ | $\delta_{\text{CP}}$ | $\sin^2 \theta_{23}$ | $|\Delta m^2_{32}| \text{eV}^2$ |
|------------------------|----------|-----------------------|------------------------|------------------------|---------------------------------|
| SK+T2K (IH)            | 644.82   | 0.0219 (fix)          | 4.538                  | 0.55                   | $2.5 \times 10^{-3}$             |
| SK+T2K (NH)            | 639.61   | 0.0219 (fix)          | 4.887                  | 0.55                   | $2.4 \times 10^{-3}$             |

Not a joint analysis, fit external data using publicly available T2K info.
SK solar $\nu$: day/night effect

Day $\rightarrow$ Night

$V_e$: Electron neutrino  
$V_{\mu/\tau}$: Muon/Tau neutrino

$A_{DN} = \frac{(Day - Night)}{(Day + Night) / 2}$

<table>
<thead>
<tr>
<th>D/N asymmetry ($A_{DN}$)</th>
<th>$\Delta m_{21}^2 = 4.84 \times 10^{-5}$ eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>$-2.0 \pm 1.8 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-II</td>
<td>$-4.4 \pm 3.8 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-III</td>
<td>$-4.2 \pm 2.7 \pm 0.7%$</td>
</tr>
<tr>
<td>SK-IV</td>
<td>$-3.6 \pm 1.6 \pm 0.6%$</td>
</tr>
<tr>
<td>combined</td>
<td>$-3.3 \pm 1.0 \pm 0.5%$</td>
</tr>
</tbody>
</table>

Non-zero significance: 3.0$\sigma$

Direct indication of matter effect.

Solar global analysis

~2$\sigma$ diff. in $\Delta m_{12}^2$

Green: Solar global dashed only SK+SNO
Blue: KamLAND
Red: Solar+KamLAND

SK solar $\nu$: spectrum

(tot. # of bins 83) $\chi^2$

Solar+KamLAND: 76.60
Solar: 73.86
Flat Prob.: 72.72

~2$\sigma$ worse
Results from T2K

- $\nu_e$ appearance for the study of $\theta_{13}$ and $\delta CP$
- $\nu_\mu$ disappearance for the study of $\theta_{23}$ & $\Delta m^2_{23}$

Until May 2016
- $15 \times 10^{20}$ POT
  (~20% of the planned total)
Neutrino mode
- $7.57 \times 10^{20}$ POT
Anti-Neutrino mode
- $7.53 \times 10^{20}$ POT
  (POT: Proton On Target)
T2K: $\nu_\mu$ disappearance and $\nu_e$ appearance data

$\nu_\mu$ 7.57x10^{20}$ POT, $\bar{\nu}_\mu$ 7.53x10^{20}$ POT data

$\nu_\mu$ events 135

$\bar{\nu}_\mu$ events 66

$\nu_e$ events 32

$\bar{\nu}_e$ events 4
T2K: results from $\nu_\mu + \bar{\nu}_\mu$ disappearance

$\nu_\mu$ 7.57x10$^{20}$ POT, $\bar{\nu}_\mu$ 7.53x10$^{20}$ POT data

Oscillation parameters of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ compared with others

Best fit values:

$$(\sin^2(\theta_{23}), |\Delta m^2_{32}|) = (0.532, 2.545 \times 10^{-3} (\text{eV}^2))$$

T2K has given the most precise measurement. T2K favors maximal mixing ($\sin^2 \theta_{23} = 0.5$) but NOvA disfavors. Need more data to conclude.
\( \theta_{13} \) and \( \delta_{\text{CP}} \) measurements

- Short baseline reactor: \( \bar{\nu}_e \) disappearance

\[
P(\nu_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27\Delta m^2_{31}L(m)}{E_\nu(\text{MeV})}\right)
\]

- Long baseline accelerator: \( \nu_e \) appearance

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2 \theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31}L(\text{km})}{E_\nu(\text{GeV})}\right)
\]

Sub-leading

\[
\begin{align*}
\delta \rightarrow -\delta \\
a \rightarrow -a
\end{align*}
\]

for \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

\[
\begin{align*}
&+ 8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
&- 8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
&+ 4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2 + S_{12}^2S_{23}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \sin^2\Delta_{21} \\
&- 8C_{13}^2S_{13}^2S_{23}^2 aL \frac{4E_\nu}{(1 - 2S_{13}^2)\cos\Delta_{32} \sin\Delta_{31}} \\
&+ 8C_{13}^2S_{13}^2S_{23}^2 a \frac{\Delta m^2_{31}}{(1 - 2S_{13}^2)\sin^2\Delta_{31}}
\end{align*}
\]

\( \nu_e \) appearance: depends on \( \delta \) and mass hierarchy

\( \Delta_{ij} \equiv \Delta m^2_{ij}L/E_\nu \)

\( a = 2\sqrt{2}G_F n_e E_\nu \)
The best fit points lie near the maximally CP violating value $\delta_{CP} = -0.5\pi$. The CP conserving values ($\delta_{CP} = 0$ and $\delta_{CP} = \pi$) lying outside of the T2K 90% confidence level interval.
KamLAND-Zen

Zero Neutrino double beta decay search

enrXe loaded LS in a mini-balloon

380kg 90% enriched $^{136}$Xe for phase-II

World best $0\nu\beta\beta$ experiment at present

270.7 days
fit region 263.8 days

No significant excess of $0\nu\beta\beta$

$T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr
KamLAND-Zen result on $<m_{\beta\beta}>$

$<m_{\beta\beta}> < (61 - 165) \text{meV}$

It also provides upper limit of $m_{\text{lightest}}$ at 180-480 meV.

A. Gando et al., PRL 117, 082503 (2016)
Future
How to measure CP phase $\delta$

Long baseline accelerator: $\nu_e$ appearance

$$ P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2 \theta_{23} \sin^2 \left( \frac{1.27 \Delta m^2_{31} L(km)}{E_\nu(GeV)} \right) $$

Leading term

Sub-leading

$$ + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} $$

$$ - 8C_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} $$

$$ + 4S_{12}^2 C_{13}^2 (C_{12} C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13}^2 \cos \delta) \sin^2 \Delta_{21} $$

$$ - 8C_{13}^2 S_{13}^2 S_{23} \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cos \Delta_{32} \sin \Delta_{31} $$

$$ + 8C_{13}^2 S_{13}^2 S_{23} \frac{a}{\Delta m^2_{31}} (1 - 2S_{13}^2) \sin^2 \Delta_{31} $$

for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ $\delta \to -\delta$ and $a \to -a$

Compare $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ for CP phase measurement

$S_{ij} \equiv \sin \theta_{ij}, C_{ij} \equiv \cos \theta_{ij}$

$\Delta_{ij} \equiv \Delta m^2_{ij} L/E_\nu$

$a = 2\sqrt{2}G_F n_e E_\nu$
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- As large as $\sim 25\%$ from nominal
- It is sensitive also to exotic (non-PMNS) CP violation cases.
Neutrino oscillation vs. anti-neutrino oscillation

Evidence and precise measurement by Hyper-Kamiokande

Hint of CP violation by T2K

High intensity neutrino beam produced at J-PARC

~0.6GeV $\nu_\mu$

295km long baseline
Upgrade of Super-K in terms of detector size and photon sensitivity.

- **Total Volume**
  - 260 kton x 2 (SK: 50 kton)
- **Fiducial Volume**
  - 190 kton x 2 (SK: 22.5 kton)
- **Single p.e. efficiency**
  - 24% @ 400 nm (SK 12%)
  - $\Delta T$ 1 nsec (SK 2.3 nsec)
Towards leptonic CP asymmetry

Strategy of Japan-based program

- ~3σ indication with T2K→T2K-II,
- >5σ discovery and measurement with HK
A Multi-purpose Experiment

Comprehensive study of $\nu$ oscillation
- CPV
- Mass hierarchy with beam+atmosph. $\nu$
- $\theta_{23}$ octant
- Test of exotic scenarios

Nucleon decay discovery potential
- All visible modes including $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu}K^+$ can be advanced beyond SK.
- Reaching $10^{35}$ yrs sensitivity

Unique Astrophysics
- Precision measurement of solar $\nu$
- High statistics Supernova $\nu$ with pointing capability and energy info.
- Supernova relic $\nu$ (non-burst $\bar{\nu}$) observation is also possible

Earth core's chemical composition Etc.
SK-Gd project

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

0.1% Gd gives ~90% efficiency for n capture
In Super-K this means ~100 tons of water soluble Gd$_2$(SO$_4$)$_3$
Physics with SK-Gd

Supernova Relic Neutrinos (SRN)
- Open window for SRN at 10-30MeV
- Expected event rate 1.3 - 6.7 events/year/22.5kt(10-30MeV)
- Study supernova rate from the beginning of universe.
- Averaged energy spectrum.

• Discriminate proton decay (essentially no neutron) and atmospheric neutrino background (with neutrons).
• Neutrino/anti-neutrino identification.
• Precise measurement of $\theta_{12}$ and $\Delta m^2_{21}$ by reactor neutrinos.

Improve pointing accuracy for supernova bursts, e.g. 4~5° $\rightarrow$ 3° (90%C.L.) for 10kpc

Simulation of a 10kpc supernova
Conclusions

• More than 30 years have passed since we started experiments at Kamioka.
• Neutrino oscillations have been established in the last 30 years.
• There are still many important unknowns in neutrino physics.
• Future developments are expected.

Let’s enjoy neutrino physics!