Neutrino oscillation

Outline

1. Neutrino oscillations
2. before 1998
3. 1998-2004
4. 2005-2011
5. 2012-2013
6. Current issues
7. Conclusion

Teppei Katori
Queen Mary University of London
YETI2014, IPPP, Durham, UK, Jan. 14, 2014

1. Neutrino oscillations

2. Before 1998

3. 1998-2004

4. 2005-2011

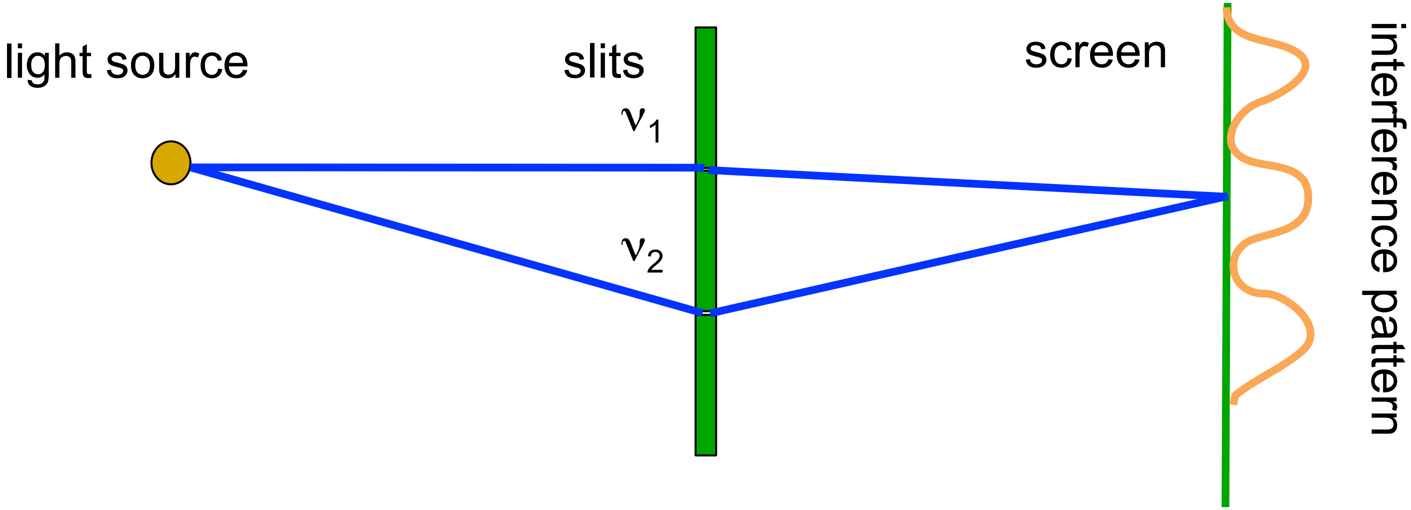
5. 2012-2013

6. Current issues

7. Conclusion

1. Neutrino oscillations

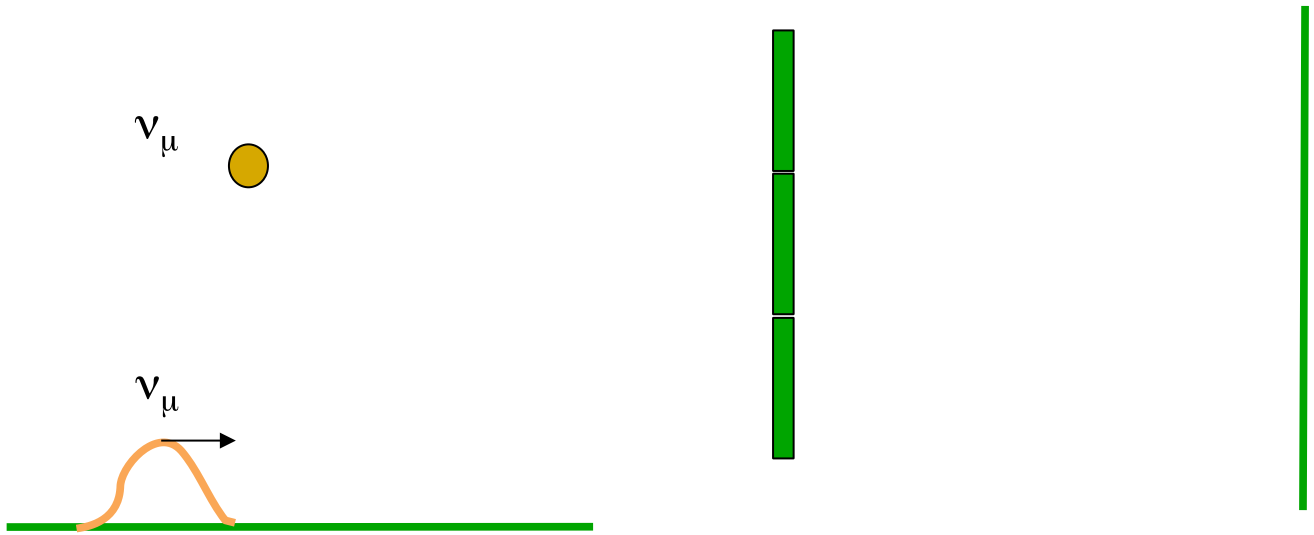
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

1. Neutrino oscillations

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

1. Neutrino oscillations

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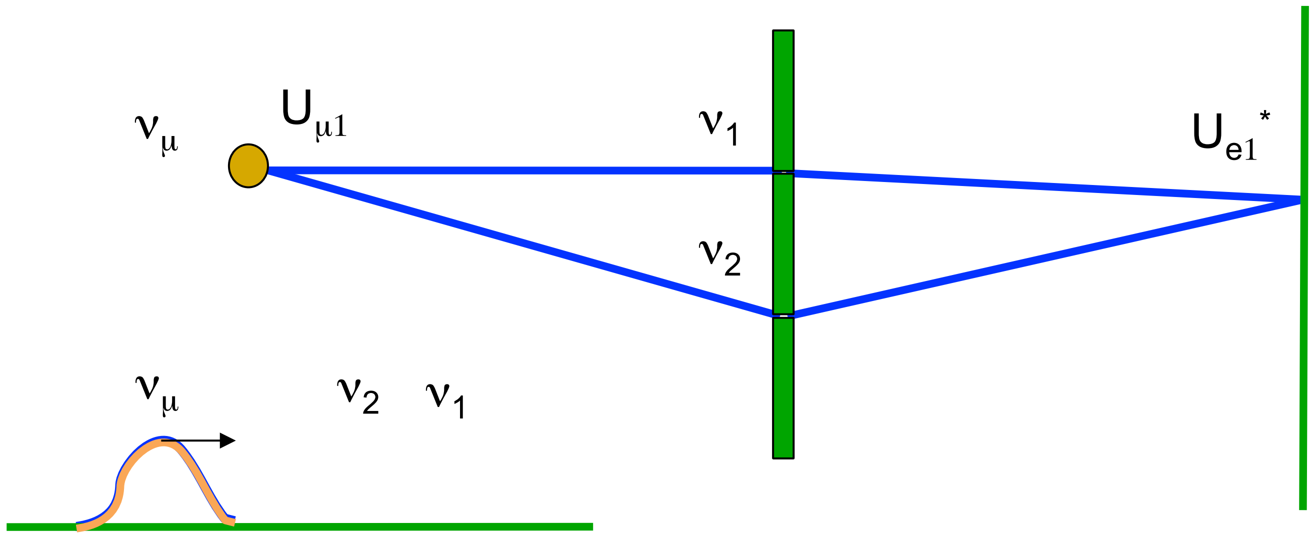

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

1. Neutrino oscillations

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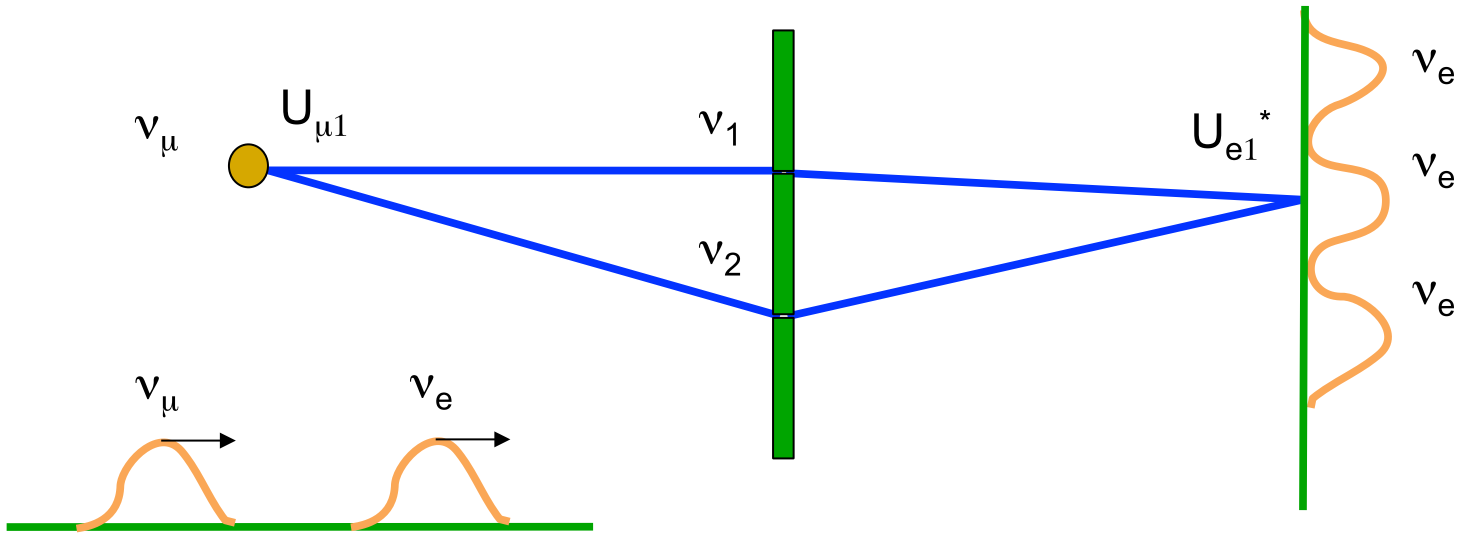

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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The detection may be different flavor (neutrino oscillations).

1. Neutrino oscillations

2 neutrino mixing

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1 and ν_2, and their mixing matrix elements.

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1 and ν_2 .

$$|\nu_\mu(t)\rangle = U_{\mu 1}e^{-i\lambda_1 t}|\nu_1\rangle + U_{\mu 2}e^{-i\lambda_2 t}|\nu_2\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is,

$$P_{\mu\to e}(t) = \left|\langle \nu_e | \nu_\mu(t)\rangle\right|^2 = -4U_{e1}U_{e2}U_{\mu 1}U_{\mu 2}\sin^2\left(\frac{\lambda_1-\lambda_2}{2}t\right)$$

1. Neutrino oscillations

In the vacuum, 2 neutrino effective Hamiltonian has a mass term,

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is ($\Delta m^2 = |m_1^2 - m_2^2|$)

$$L^{osc} \equiv \frac{4\pi E}{\Delta m^2}$$

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2 2\theta \sin^2\left(\pi \frac{L}{L^{osc}}\right)$$

After adjusting the unit

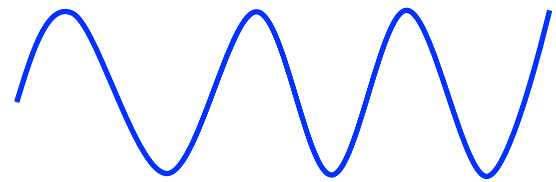
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 (eV^2) \frac{L(m)}{E(MeV)}\right)$$

1. Neutrino oscillations

Wave packet formalism

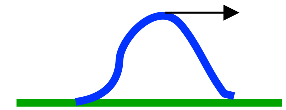
- real formulation of neutrino oscillations

$$|\nu_\alpha\rangle = \sum U_{\alpha a} |\nu_a\rangle$$



↓

$$|\nu_\alpha\rangle \propto \sum U_{\alpha a} \exp\left(i\bar{p}_a x - \bar{E}_a t - \frac{(x - v_a t)^2}{4\sigma_x^2} \right) |\nu_a\rangle$$



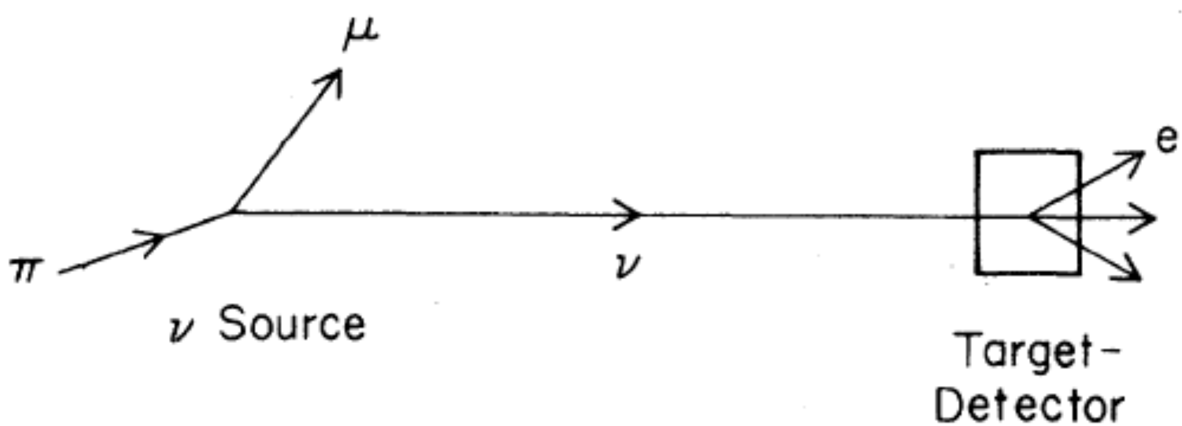


FIG. 1. A typical neutrino-oscillation experiment.

1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{osc}_{ij}} - \left(\frac{L}{L^{coh}_{ij}} \right)^2 - 2\pi^2 \left(\frac{\sigma_x}{L^{osc}_{ij}} \right)^2 \right]$$

Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

Giunti,Kim,Lee,PRD44(1991)3635

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$$\sim \sin^2 2\theta \sin^2\left(\pi \frac{L}{L^{osc}}\right)$$

Giunti,Kim,Lee,PRD44(1991)3635

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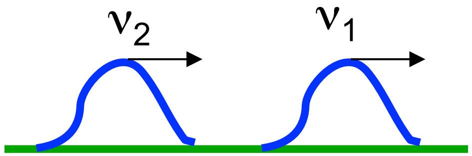

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$$P \propto \left[-\left(\frac{L}{L^{coh}}\right)^2\right] \quad , \quad L^{coh} \propto \frac{\sigma_x}{|v_i - v_j|}$$

Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference difference (bigger Δm^2, lower energy)

How to estimate σ_x?

Giunti,Kim,Lee,PRD44(1991)3635

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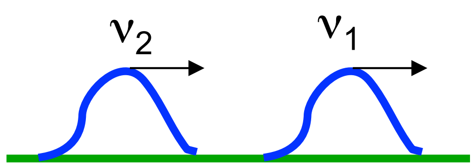

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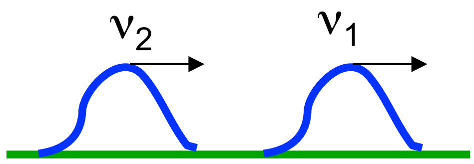
How to estimate σ_x?

e.g.) NuMI beam (from Joachim Kopp's Fermilab theory seminar)
10^{-9}cm << σ_x < 10cm (probably bigger than atomic distance, but smaller than detector resolution)

1. Neutrino oscillations



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How to estimate σ_x?

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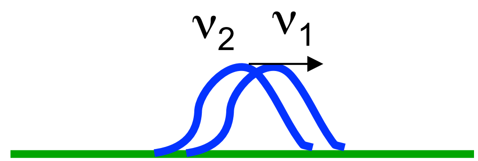
10^{-9}cm << σ_x < 10cm (probably bigger than atomic distance, but smaller than detector resolution) → L^{coh} > 6×10^5 light year

1. Neutrino oscillations



Wave packet formalism

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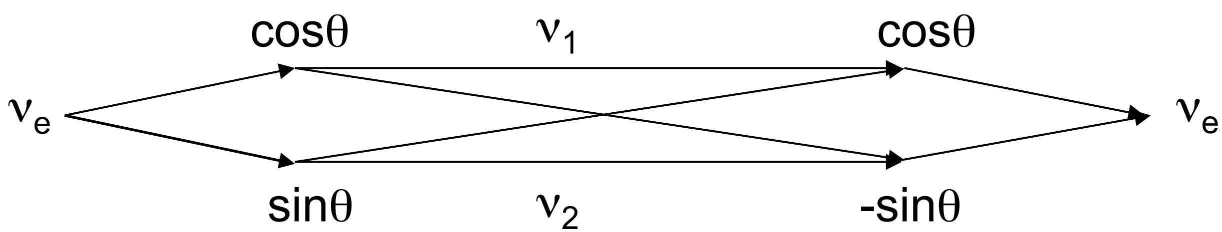
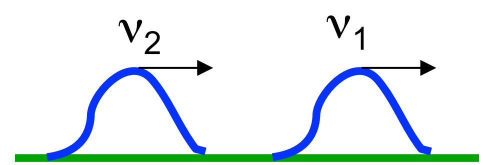
Neutrino oscillation



$P=|A_1+A_2|^2$

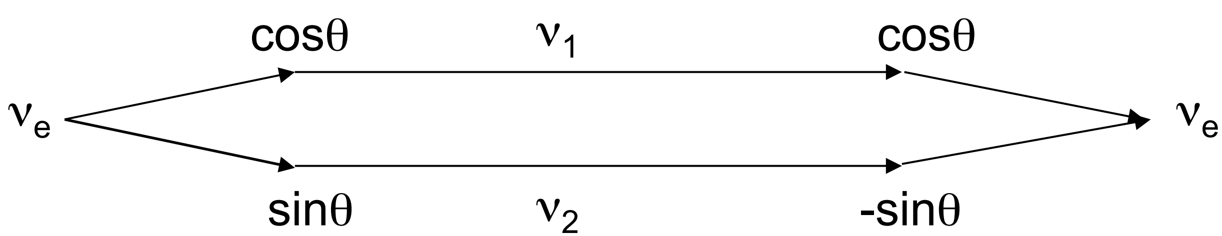
1. Neutrino oscillations



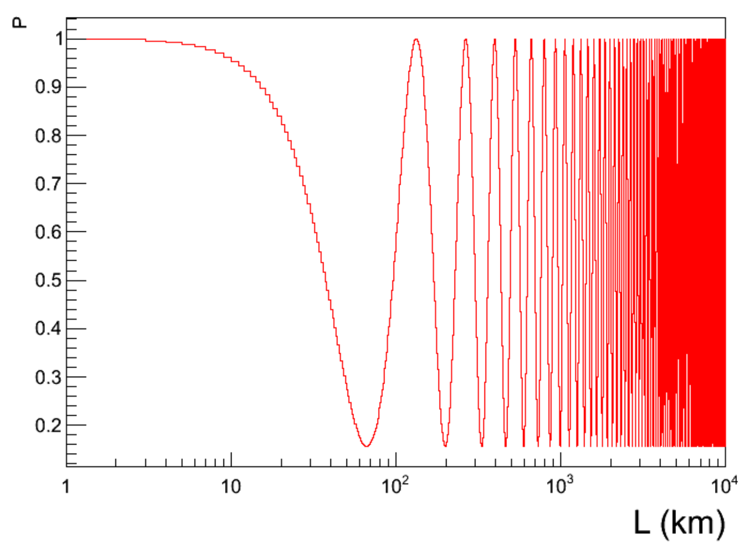
Wave packet formalism

- real formulation of neutrino oscillations

Decoherent neutrino oscillation (time averaged neutrino oscillation)



$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta = 1-\sin^2 2\theta\cdot\frac{1}{2} = 1-\sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)\Bigg|_{L\to\infty}$$



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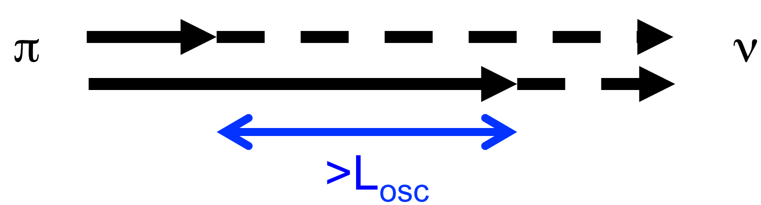
Coherent oscillation
Decoherence during propagation
Decoherence at production and detection

$$P \propto \exp\left[-4\pi^2 \left(\frac{\sigma_x}{L^{osc}} \right)^2 \right]$$

If the production uncertainty is bigger than oscillation length, oscillation doesn't happen (time averaged oscillation)

neutrino production uncertainty

cf. solar neutrino



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Coherent oscillation

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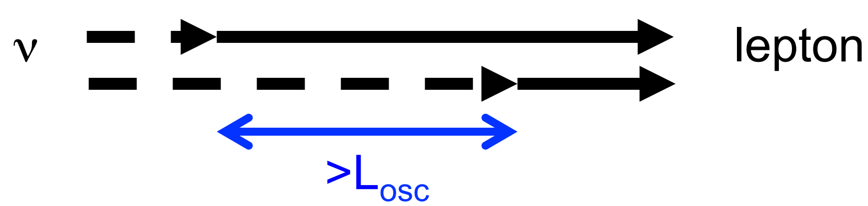
$$P \propto \exp\left[-4\pi^2 \left(\frac{\sigma_x}{L^{osc}} \right)^2 \right]$$

If the detection uncertainty is bigger than oscillation length, oscillation doesn't happen (time averaged oscillation)

neutrino detection uncertainty



1. Neutrino oscillations

Wave packet formalism

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$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2\xi^2 \left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2}\right],$$

Beuthe,Phys.Rept.375(2003)105

Five terms:

- Oscillation ($L^{\rm osc}_{jk} = 4\pi E/\Delta m^2_{jk}$)
- Decoherence during propagation
- Decoherence at production/detection
- Localization: Typically requires size of neutrino wave packet σ_x smaller than oscillation length (ξ = process-dependent parameter, can also be ~ 0)
- Approximate conservation of average energies/momenta

1. Neutrino oscillations

Neutrino oscillation is a natural interferometer

Formal description of neutrino oscillation is not easy, just because quantum mechanics is not easy

1. Neutrino oscillations

2. Before 1998

3. 1998-2004

4. 2005-2011

5. 2012-2013

6. Current issues

7. Conclusion

2. Before 1998

	before	1998	1999	2000	2001	2002	2003	2004
solar neutrino	solar neutrino problem - Homestake - Kamiokande II - SAGE - GALLEX				SNO solved solar neutrino problem	Davis (Homestake) and Koshiba (Kamiokande II) won Nobel prizes		
reactor neutrino	null reactor neutrino oscillation - many						KamLAND reactor neutrino oscillation (LMA)	
atmospheric neutrino	atmospheric neutrino anomaly - Kamiokande II - IMB - Frejus	Super-K up-down asymmetry agrees with neutrino oscillation						Super-K neutrino oscillatory
accelerator neutrino	null accel. neutrino oscillation - many							

Cleveland et al.,Astrophys.J.496(1998)505
Pontecorvo,Phys.Lett.28B(1969)493

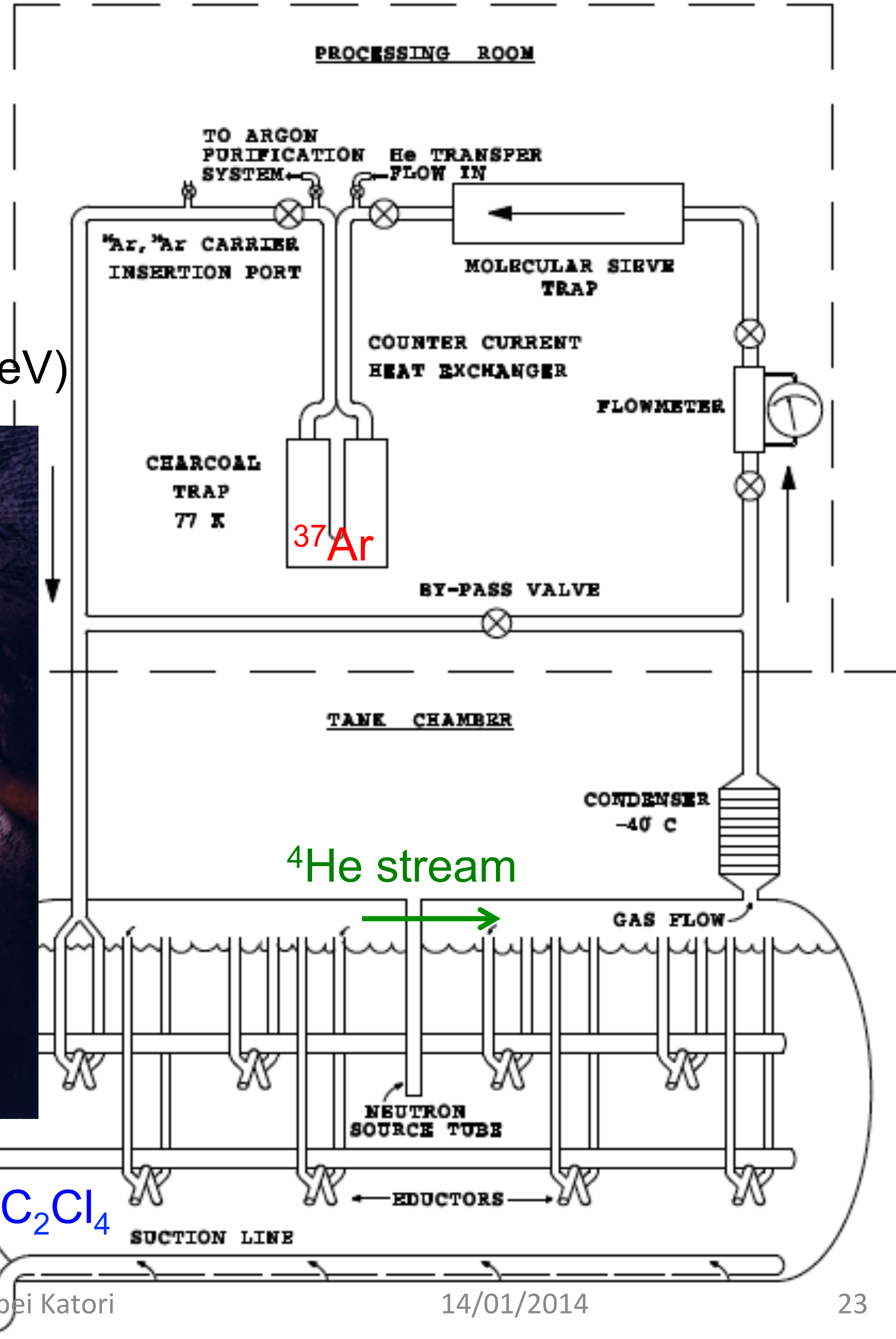
2. Solar neutrino problem

Homestake experiment

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

(proposed by Pontecorvo)

- mainly sensitive to ^8B neutrino (~10 MeV)



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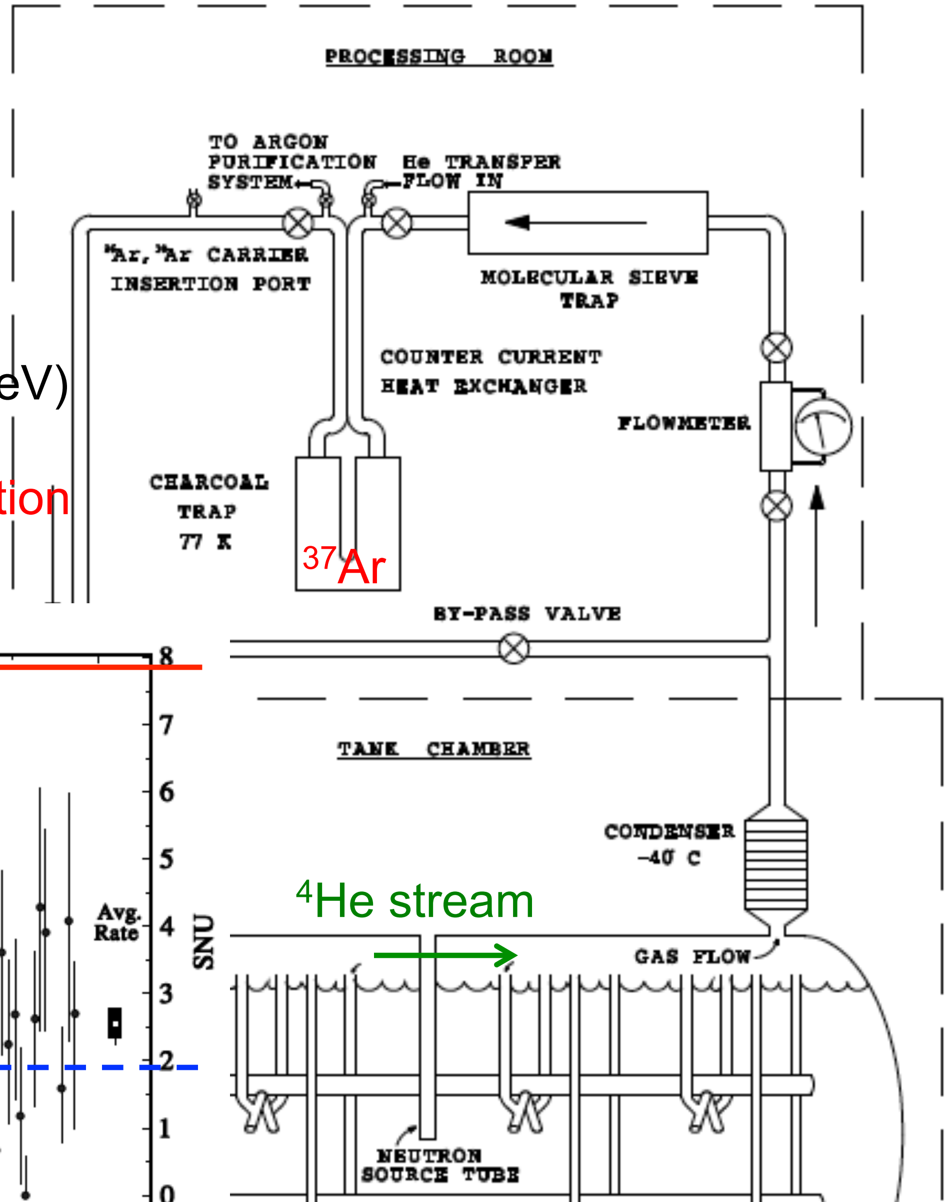
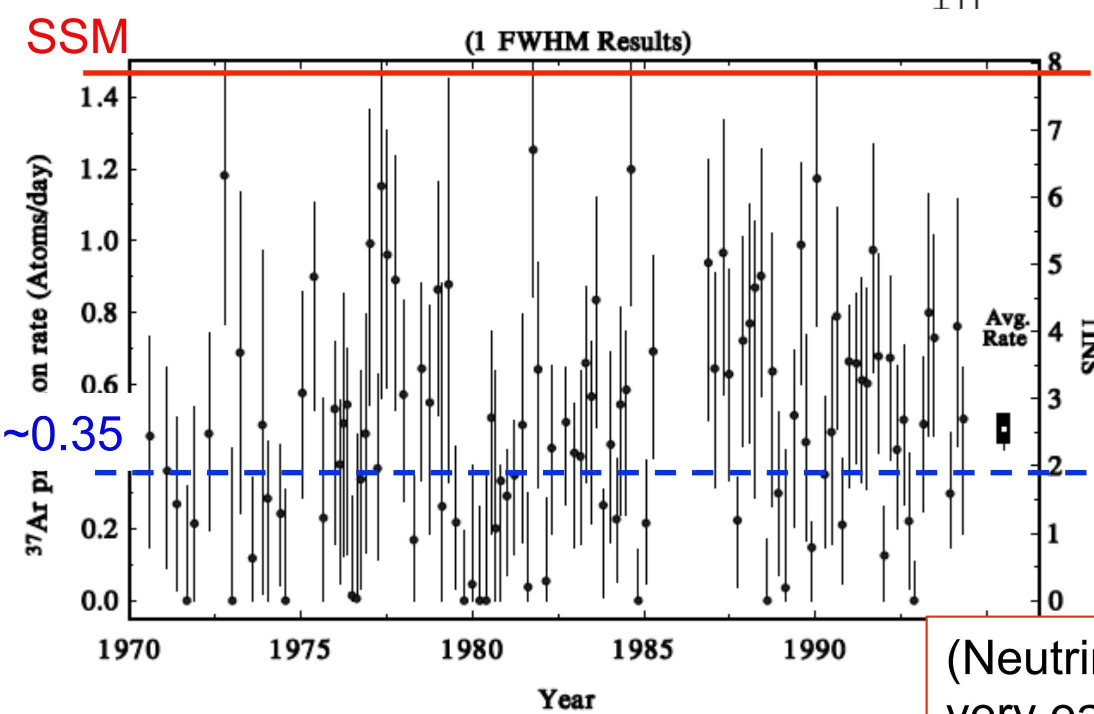
Homestake experiment

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

(proposed by Pontecorvo)

- mainly sensitive to ^{8}B neutrino (~10 MeV)
- Measured rate was consistently lower than SSM (standard solar model) prediction





(Neutrino oscillation was speculated from very early days by Pontecovo, even before Davis observed the first solar neutrino!)

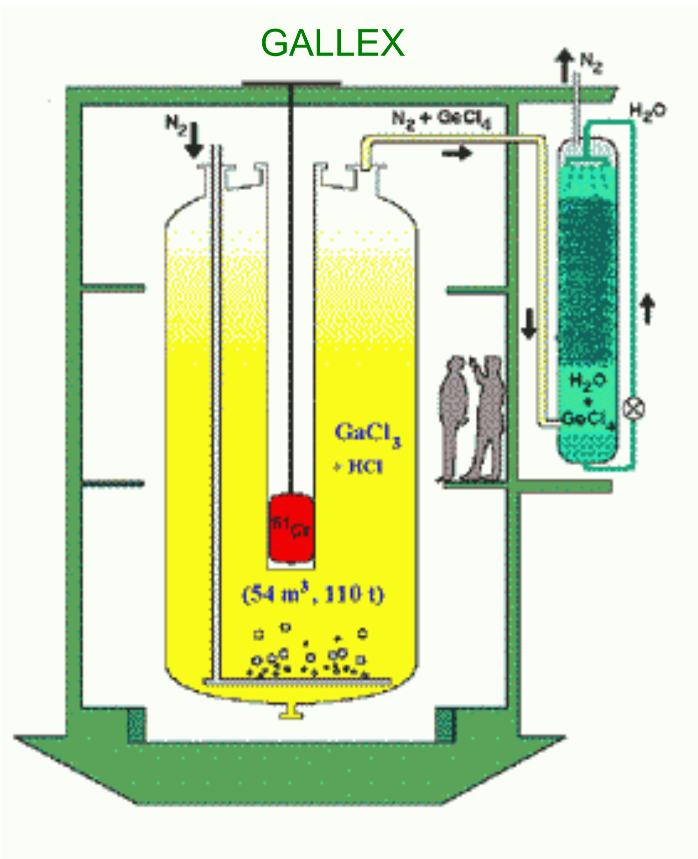
GALLEX, PLB490(2000)16
SAGE, J.Expt.Theor.Phys.95(2002)181

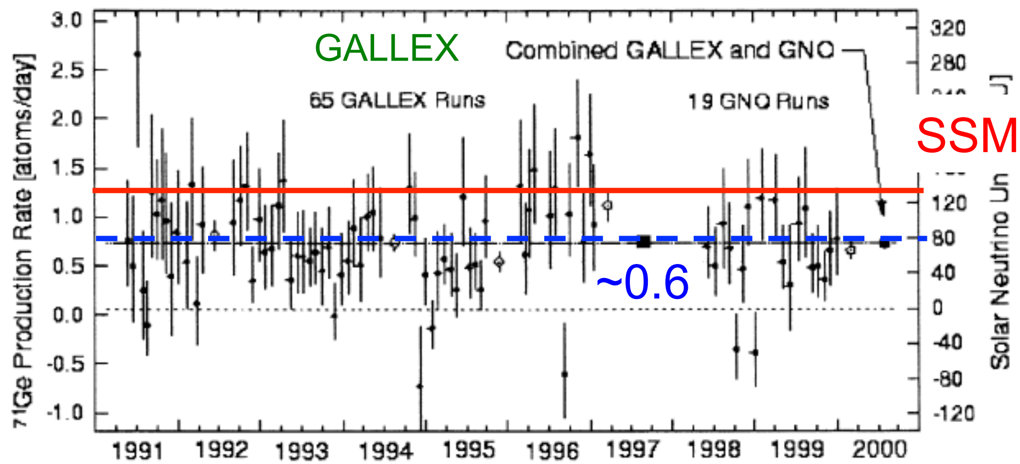
2. Solar neutrino problem

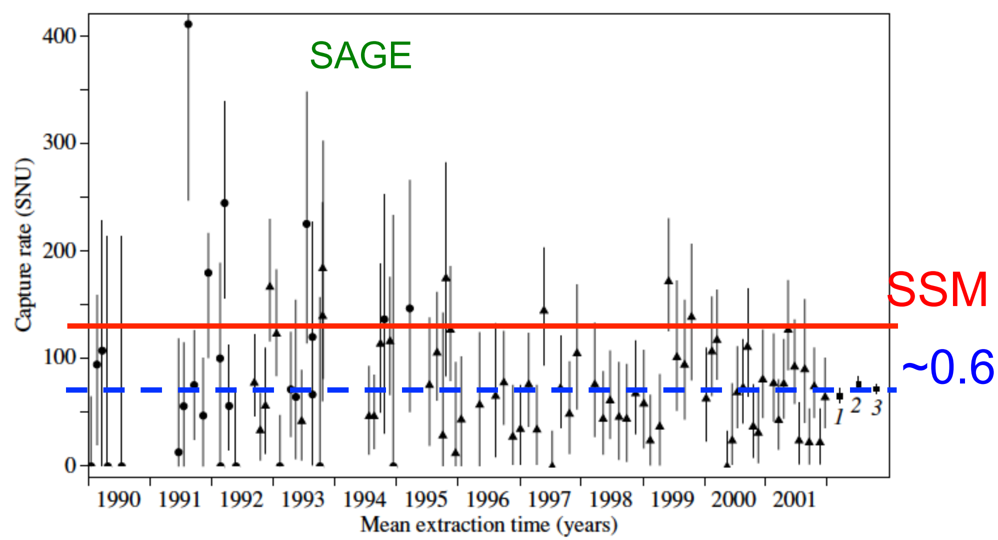
Gallium experiment

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

- Sensitive to pp-neutrino (0.42 MeV), 90% of total solar neutrino flux.
- Both experiments observed deficit, but weaker than Homostake







Wolfenstein,PRD17(1978)2369
Mikheyev and Smirnov,Sov.J.Ncl.Phys,42(1986)913

2. MSW effect

Neutrino oscillation in vacuum

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

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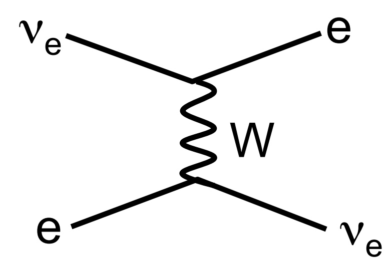

Neutrino oscillation in matter

- Neutrinos interact with media
- Only electron neutrino exchange W

Wolfenstein term

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m^2_{ee}}{2E} + \sqrt{2}G_F n_e & \frac{m^2_{e\mu}}{2E} \\ \frac{m^2_{e\mu}}{2E} & \frac{m^2_{\mu\mu}}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta_m & -\sin\theta_m \\ \sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \frac{(m_1^2)'}{2E} & 0 \\ 0 & \frac{(m_2^2)'}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix}$$

Both θ_m and $(m^2)'$ are function of n_e and E

- no matter effect If density and/or energy is too low

$$\cos 2\theta_m = \frac{-AEn_e + \cos 2\theta}{\sqrt{\left(AEn_e - \cos 2\theta\right)^2 + \sin^2 2\theta}}$$

$$A \equiv \frac{2\sqrt{2}G_F}{\Delta m^2}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(AEn_e - \cos 2\theta\right)^2 + \sin^2 2\theta}}$$

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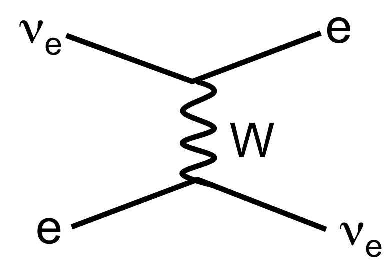

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Both θ_m and $(m^2)'$ are function of n_e and E

- no matter effect If density and/or energy is too low
- the Sun happens to have n_e~150 cm^{-3} and E(^{8}B-ν)~10 MeV

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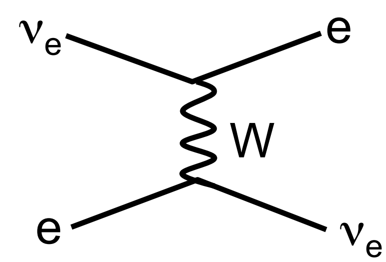

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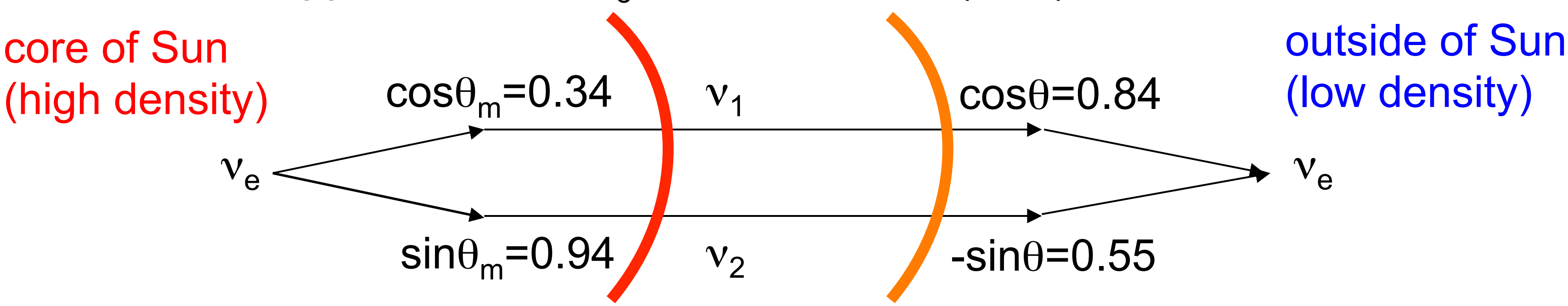
Both θ_m and $(m^2)'$ are function of n_e and E
- no matter effect If density and/or energy is too low
- the Sun happens to have $n_e \sim 150\ cm^{-3}$ and $E(^8B\text{-}\nu) \sim 10$ MeV



$$P=|A_1|^2+|A_2|^2 = \cos^2\theta_m \cdot \cos^2\theta + \sin^2\theta_m \cdot \sin^2\theta < \cos^4\theta + \sin^4\theta$$

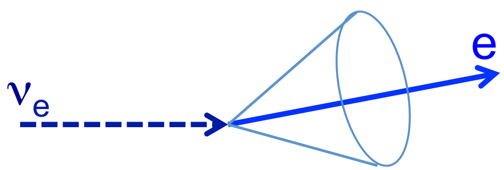
~0.35 (MSW) ~0.6 (no MSW)

2. Kamiokande II experiment

Solar neutrino

$\nu_e + e \rightarrow \nu_e + e$

- Direction of recoil electron (~direction of neutrino) is consistent from the Sun.



Atmospheric neutrino

$\nu_e + X \rightarrow e + X'$

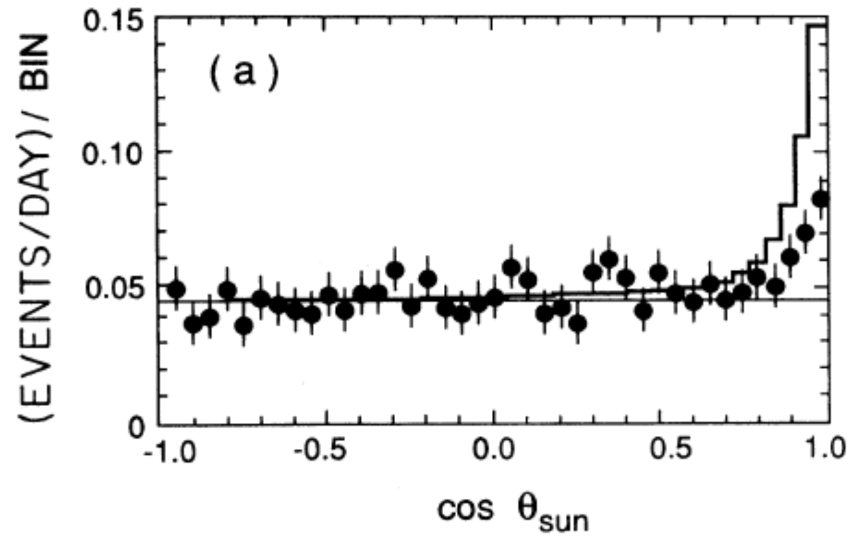
$\nu_\mu + X \rightarrow \mu + X'$

- electron neutrino is consistent with MC, but muon neutrino shows deficit

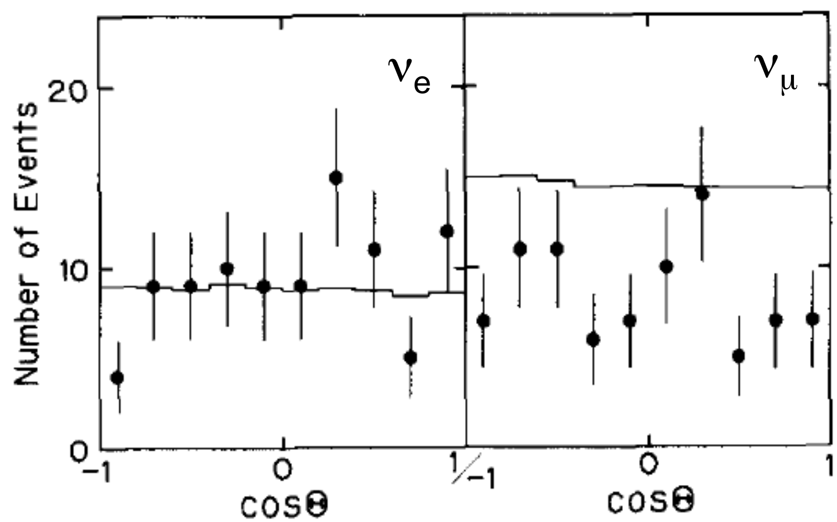
Supernova neutrino

- 12 events are observed (IMB observed 8 events)

solar-ν angular distribution



atmospheric neutrinos



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2. Before 1998

There are 3 major discoveries

- Solar neutrino problem

- MSW effect

- Atmospheric neutrino anomaly

1. Neutrino oscillations

2. Before 1998

3. 1998-2004

4. 2005-2011

5. 2012-2013

6. Current issues

7. Conclusion

3. 1998-2004

	before	1998	1999	2000	2001	2002	2003	2004
solar neutrino	solar neutrino problem - Homestake - Kamiokande II - SAGE - GALLEX				SNO solved solar neutrino problem	Davis (Homestake) and Koshiba (Kamiokande II) won Nobel prizes		
reactor neutrino	null reactor neutrino oscillation - many						KamLAND reactor neutrino oscillation (LMA)	
atmospheric neutrino	atmospheric neutrino anomaly - Kamiokande II - IMB - Frejus	Super-K up-down asymmetry agrees with neutrino oscillation						Super-K neutrino oscillatory
accelerator neutrino	null accel. neutrino oscillation - many							

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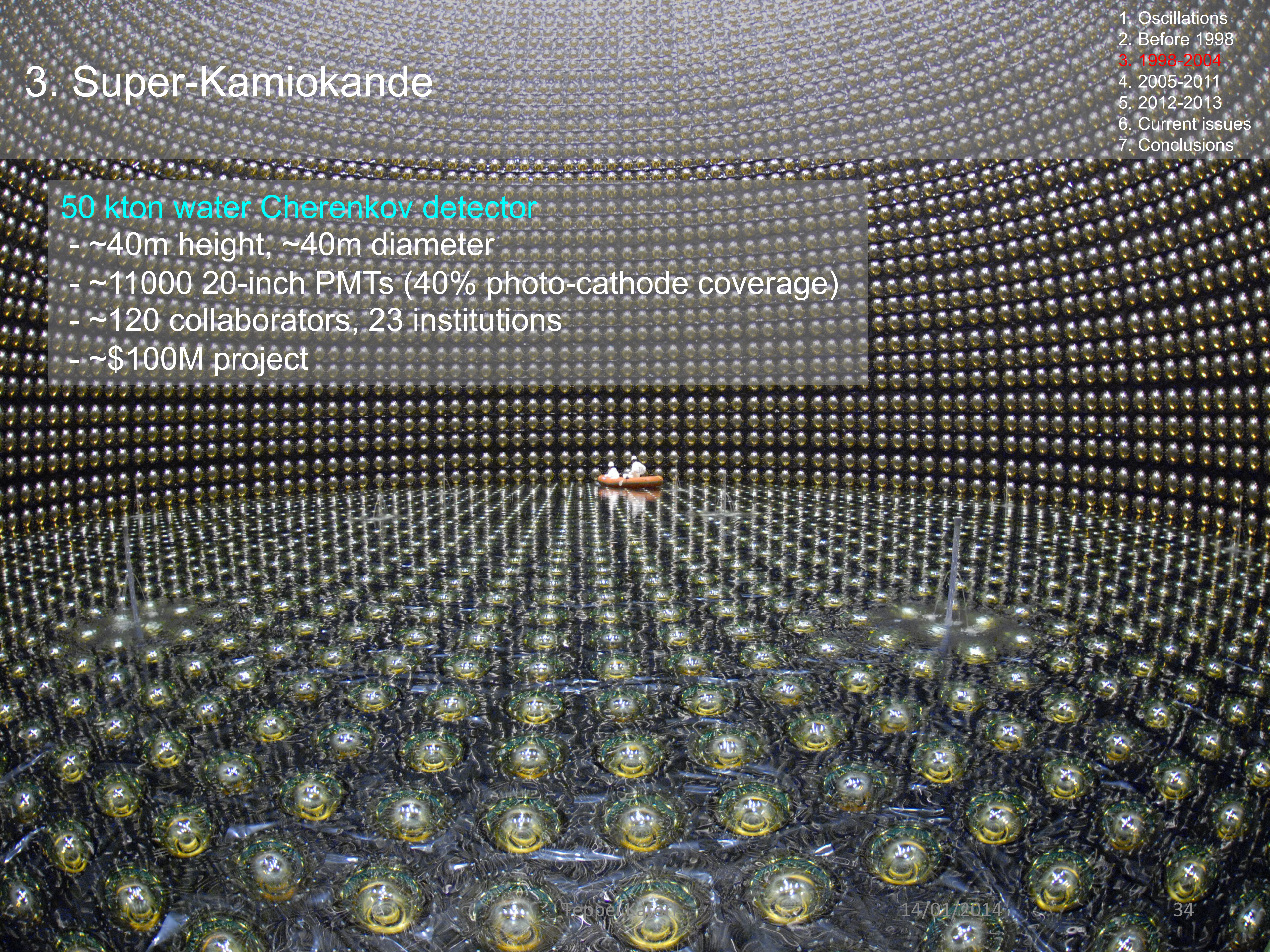
3. Super-Kamiokande



50 kton water Cherenkov detector
- ~40m height, ~40m diameter
- ~11000 20-inch PMTs (40% photo-cathode coverage)
- ~120 collaborators, 23 institutions
- ~$100M project

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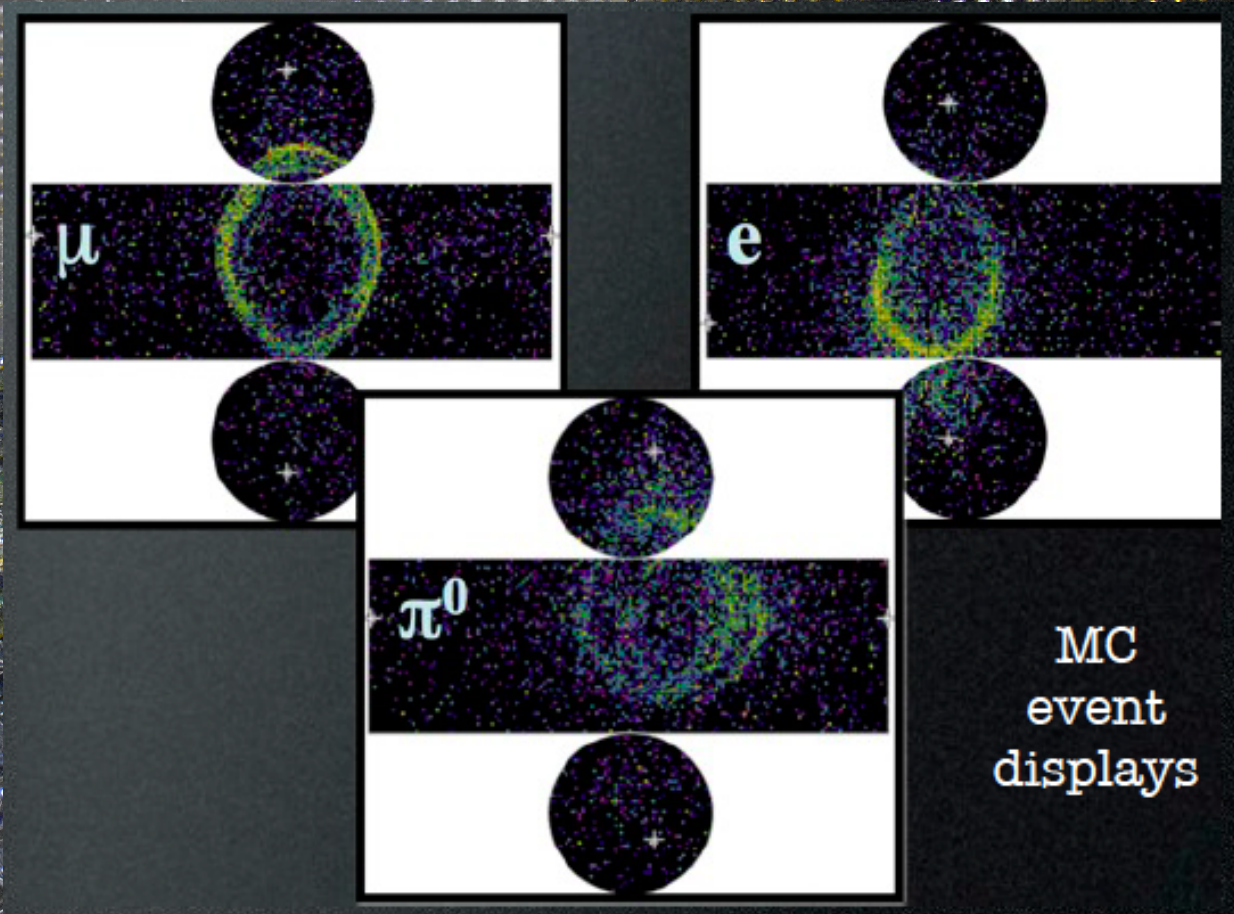
Particle ID

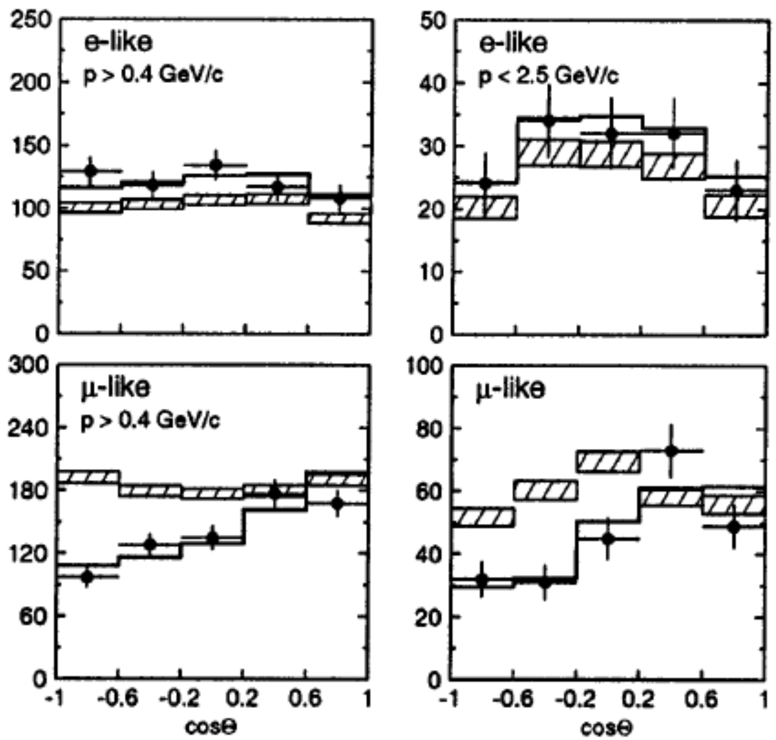
μ : sharp ring
e : fuzzy ring
π^0 : 2 fuzzy rings

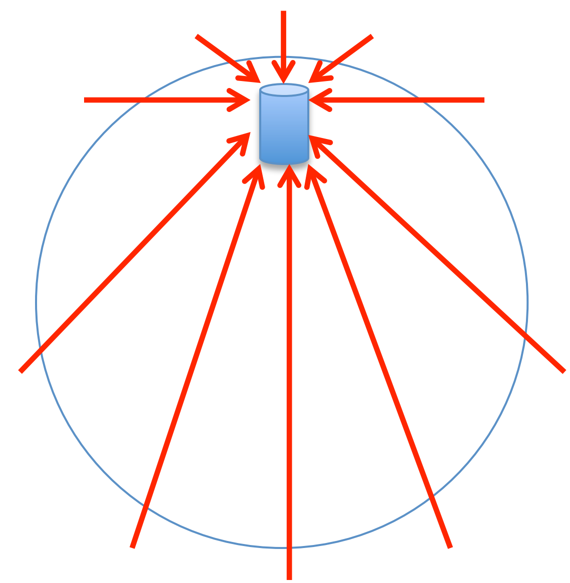


3. Super-Kamiokande

Up-Down asymmetry

- Atmospheric neutrino anomaly is function of distance
- But neutrinos might just disappear (decayed) or lose coherence (decoherence)



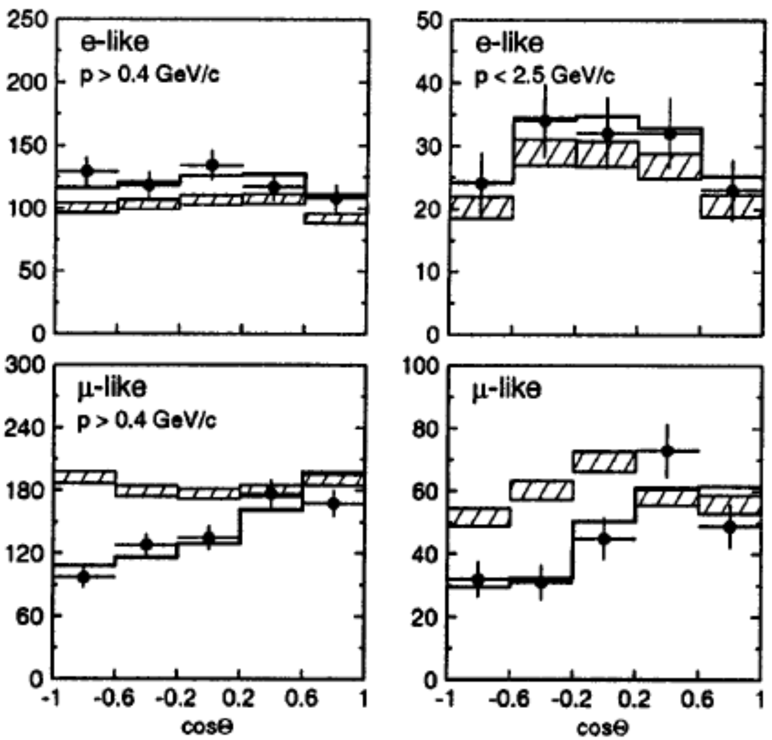


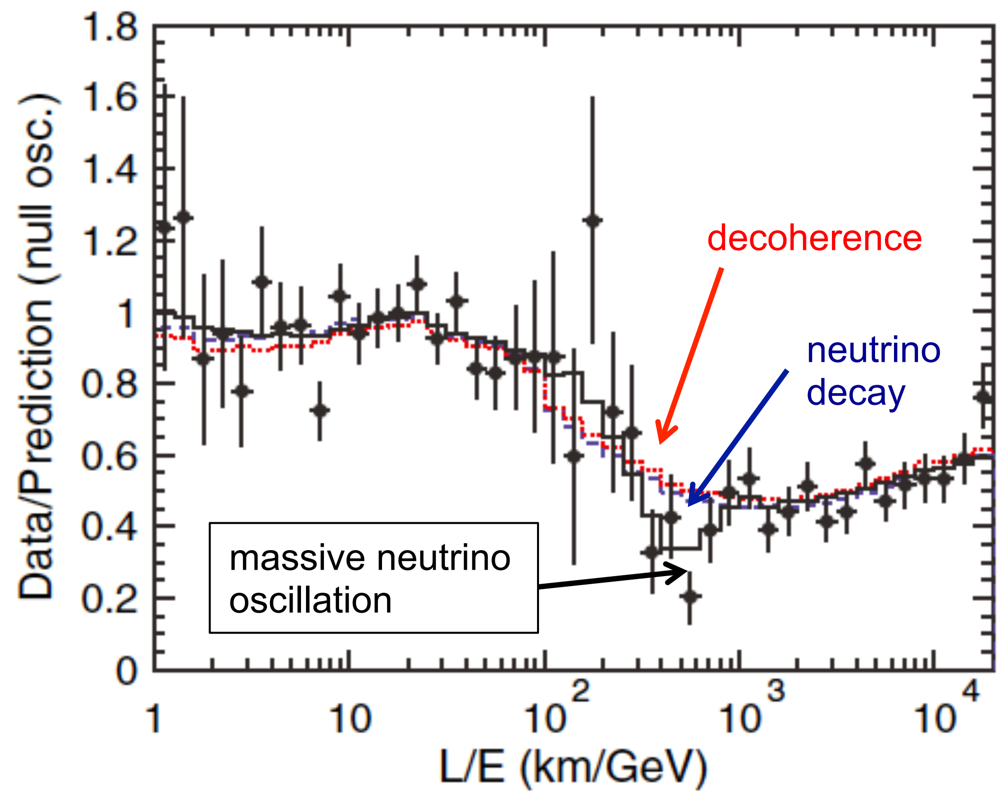
Super-kamiokande, PRL81(1998)1562, PRL93(2004)101801

3. Super-Kamiokande

Up-Down asymmetry

- Atmospheric neutrino anomaly is function of distance
- But neutrinos might just disappear (decayed) or lose coherence (decoherence)
- Later Super-K also shows the first neutrino oscillatory behavior
- Super-K concludes ν-oscillation is the solution of atmospheric neutrino anomaly





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3. SNO

D_2O in acrylic vessel
Simultaneously measure 3 channels

$\nu_e + d \rightarrow p + p + e$
- charged current (CC)
- only sensitive to ν_e

$\nu_x + d \rightarrow p + n + \nu_x$
- neutral current (NC)
- sensitive to all flavors

$\nu_e + e \rightarrow \nu_e + e$
- elastic scattering (ES)
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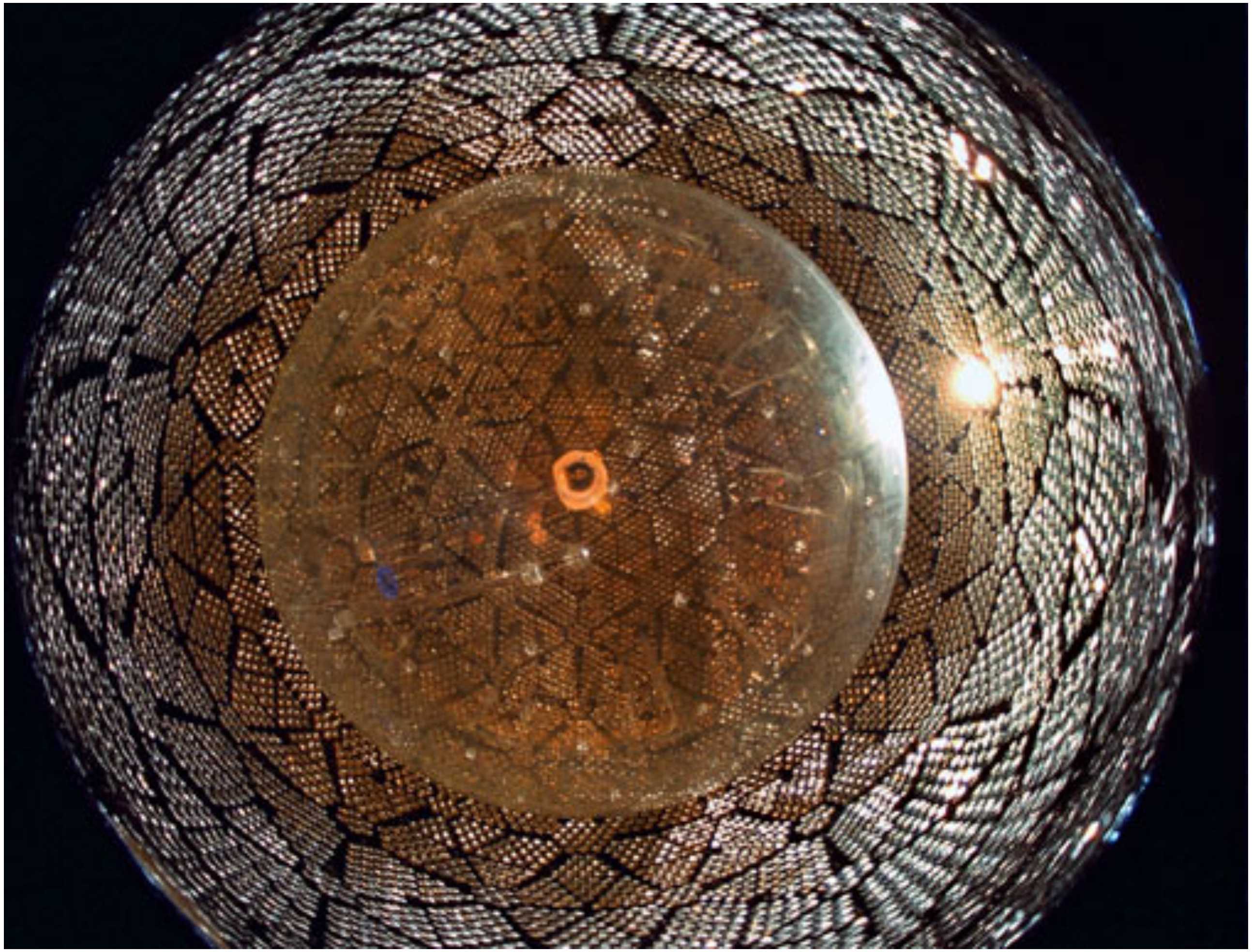

3. SNO

D_2O in acrylic vessel

Simultaneously measure 3 channels

- SNO concludes neutrino oscillation is the solution of solar neutrino problem

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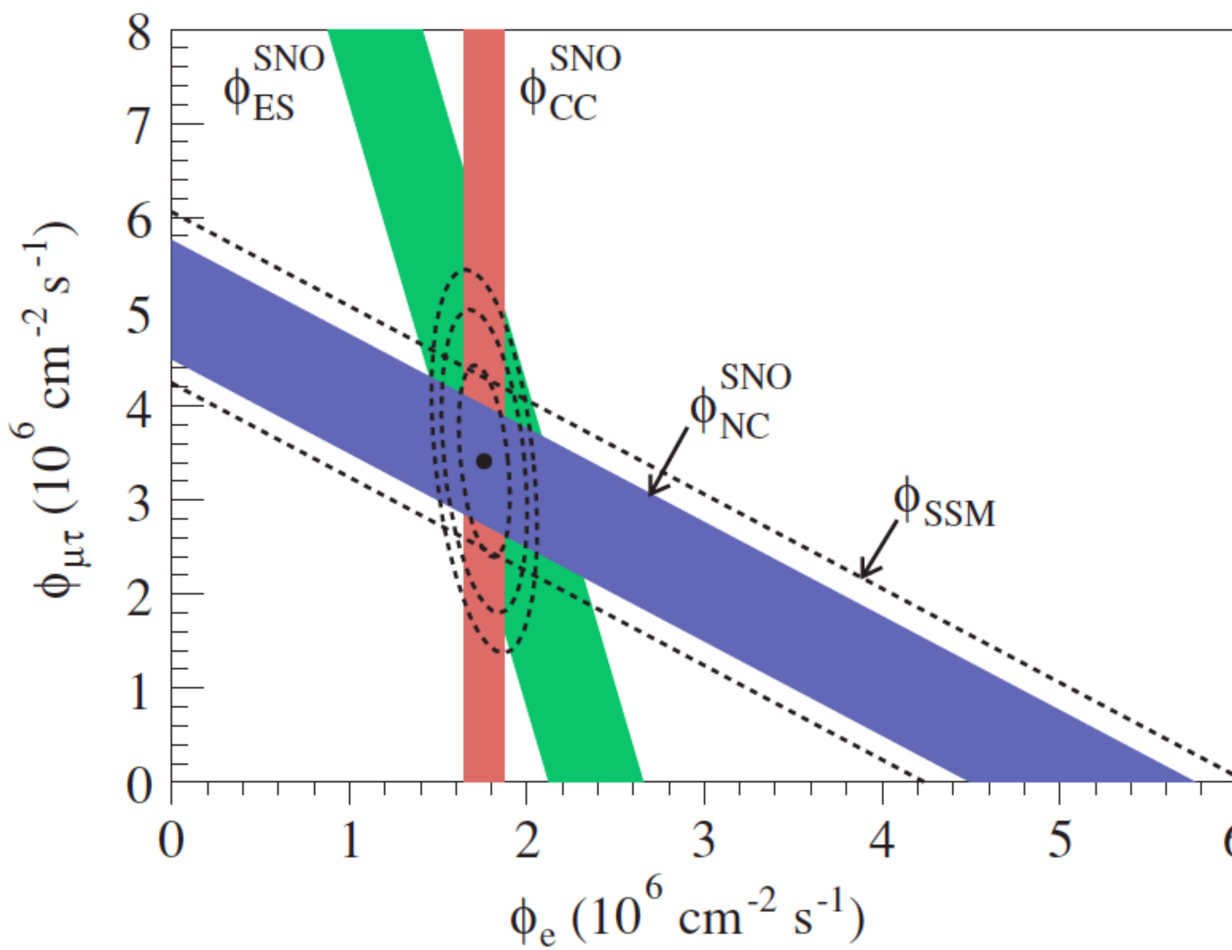

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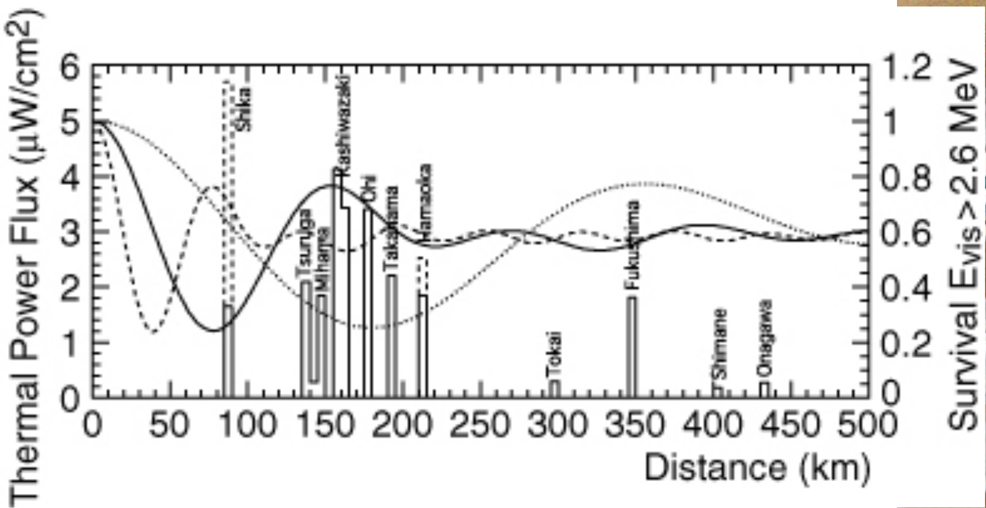
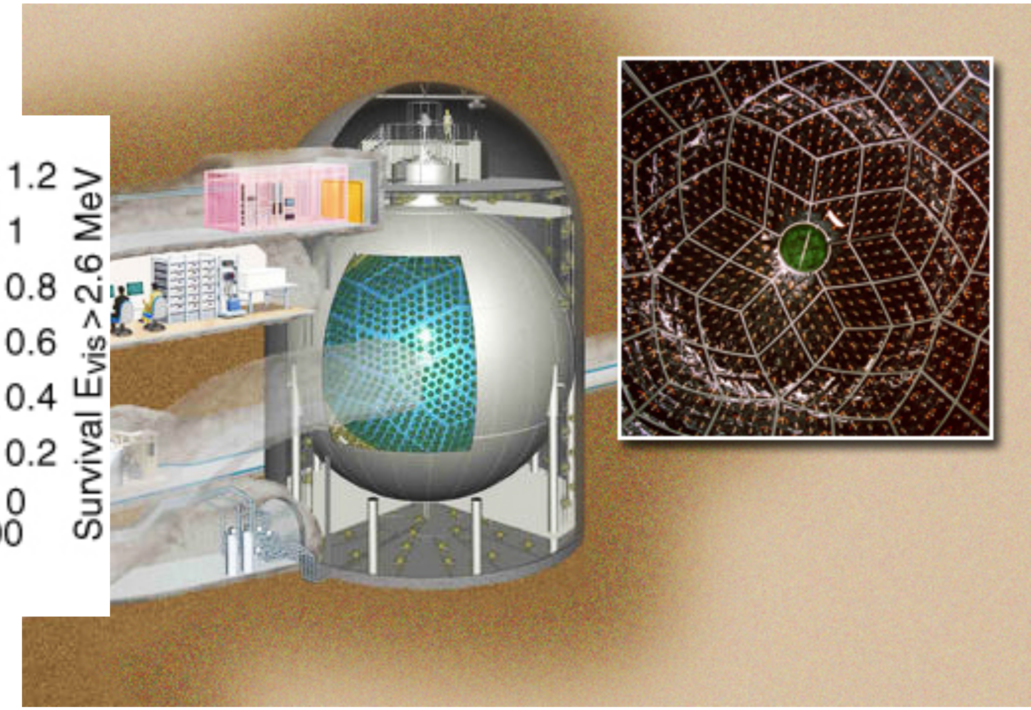
3. KamLAND

Liquid scintillator detector

- Measure reactor electron anti-neutrinos from reactors from all over Japan

$$\text{anti-}\nu_e + p \rightarrow e^+ + n \ , \ n + p \rightarrow d + \gamma \ (2.2 \text{ MeV})$$





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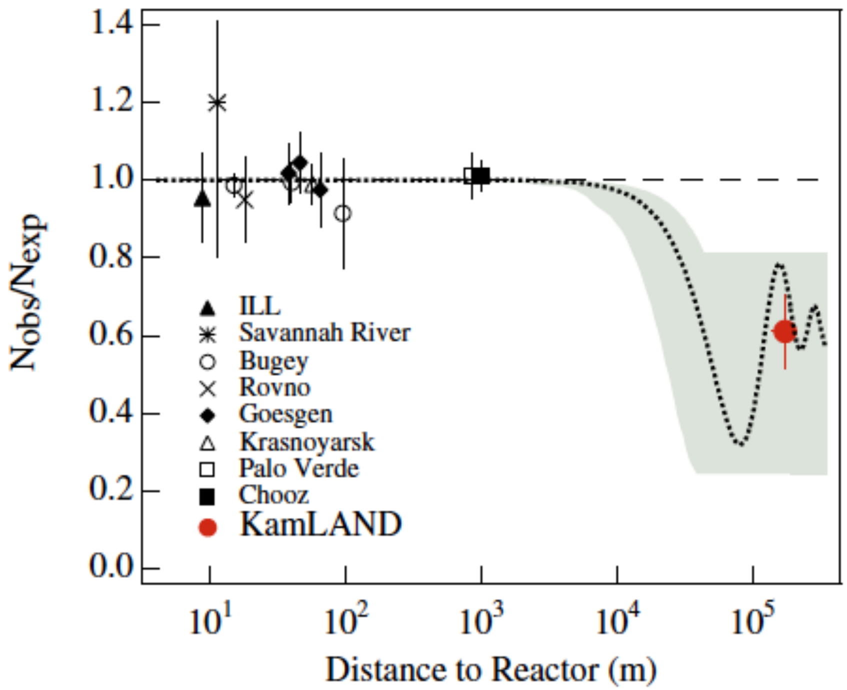
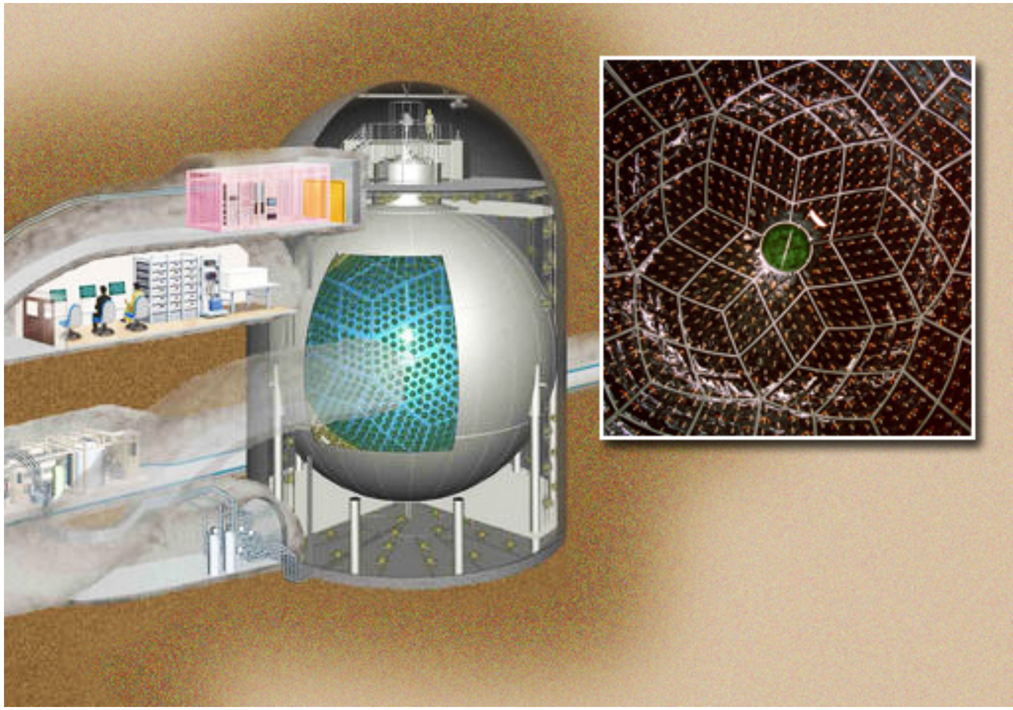
- Solar neutrino parameters are fixed





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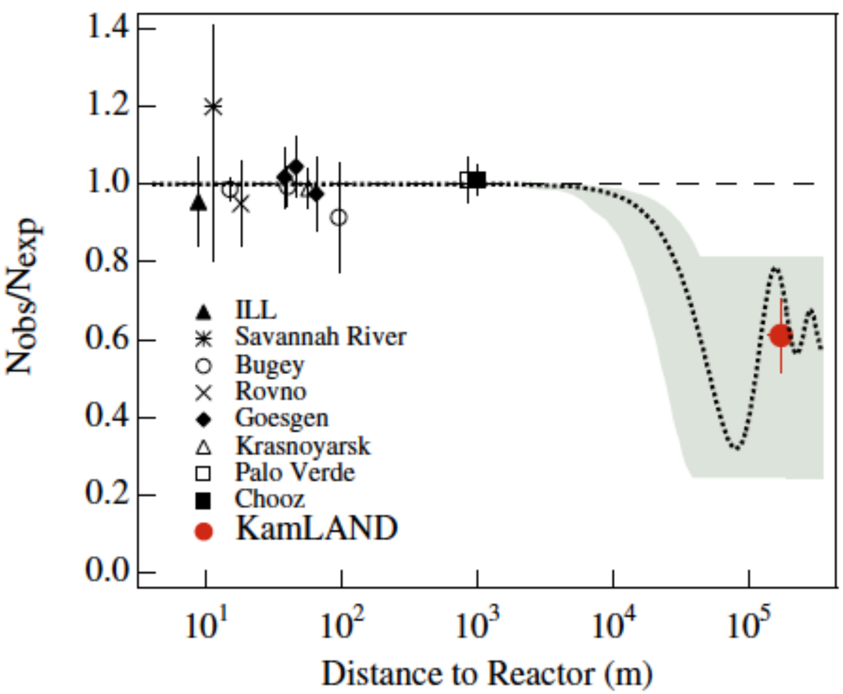

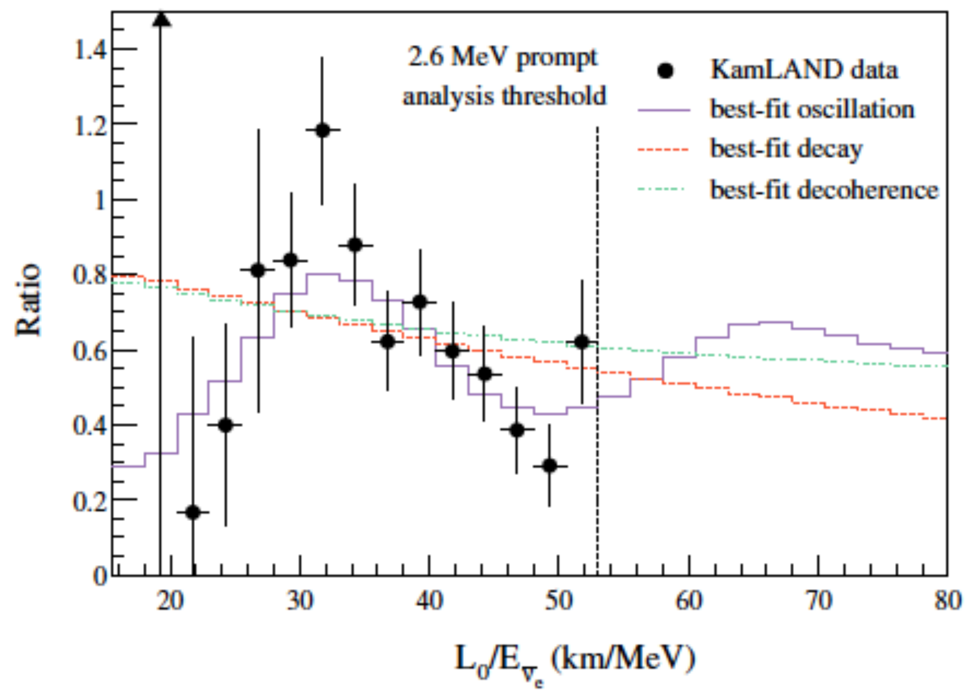

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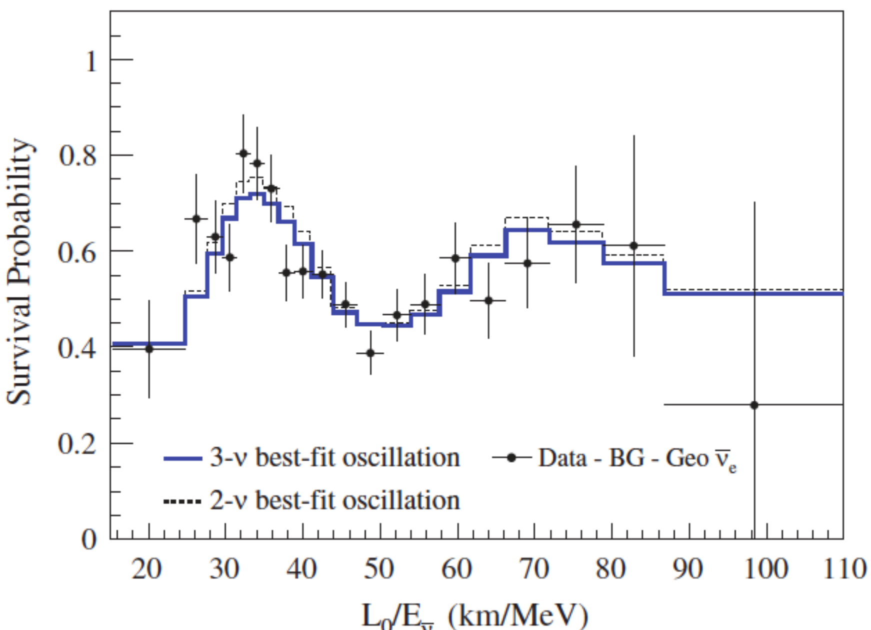
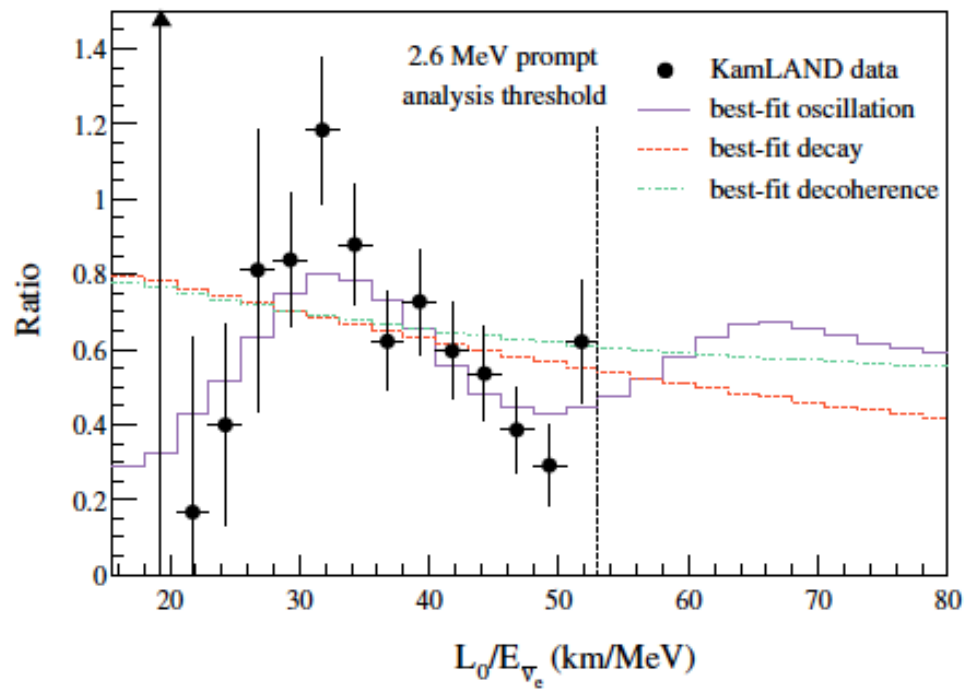
- Final result shows nicer oscillatory shape (and probability < 1)





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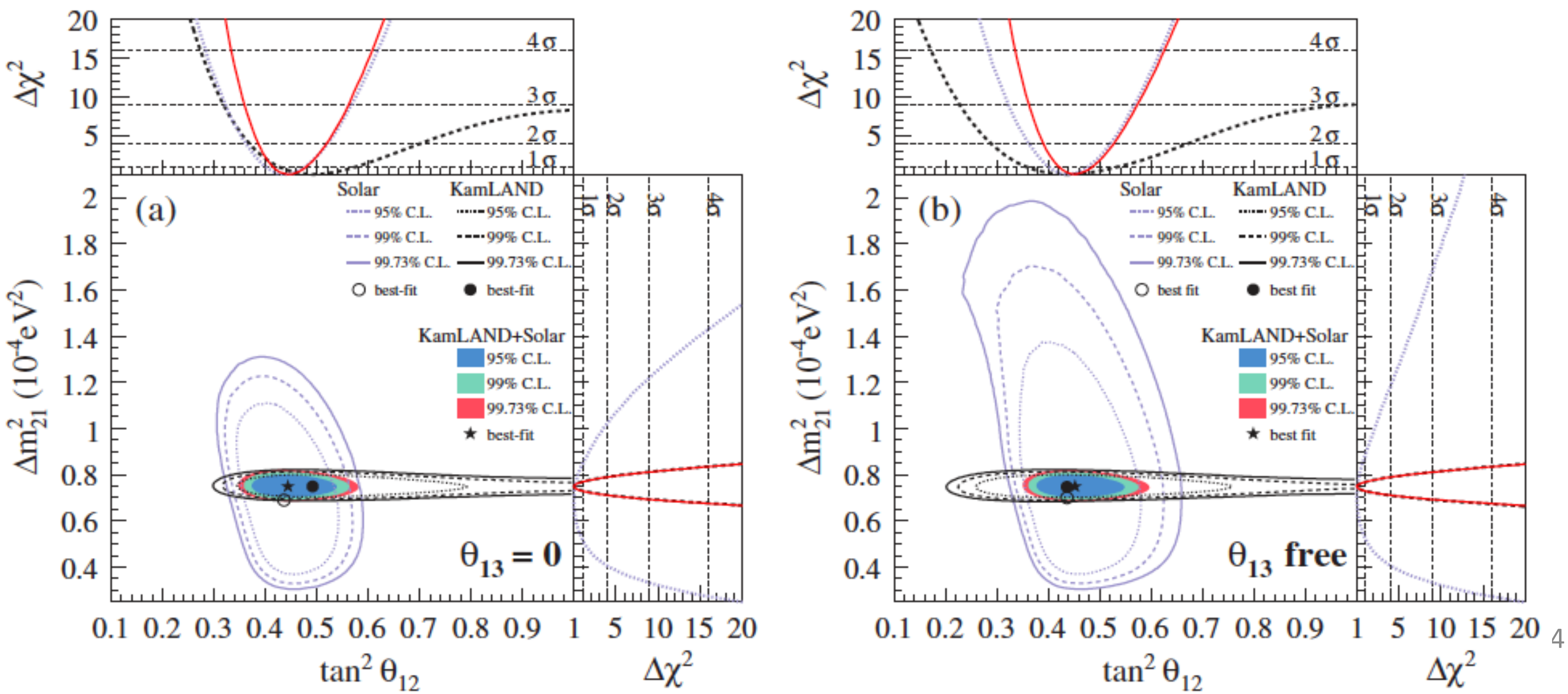
- Second result shows oscillatory, but probability is >1(?!)
- Final result shows nicer oscillatory shape (and probability < 1)
- Nonzero θ_{13} makes agreement with solar data better...



3. 1998-2004

2 major problems are solved
- Super-Kamiokande solved atmospheric neutrino anomaly
- SNO solved solar neutrino problem

KamLAND nailed down there was only 1 oscillation parameter set to explain solar neutrino oscillation in 2 massive neutrino oscillation model

A lot of exotic models are killed
- atmospheric neutrino based modes (neutrino decay, neutrino decoherence, etc)
- solar neutrino based models (large neutrino magnetic moment, etc)

1. Neutrino oscillations

2. Before 1998

3. 1998-2004

4. 2005-2011

5. 2012-2013

6. Current issues

7. Conclusion

4. 2005-2011

	2005	2006	2007	2008	2009	2010	2011	2012	2013
solar neutrino				Borexino ^{7}Be neutrino agrees with MSW				Borexino pep neutrino agrees with MSW	Super-K earth matter effect
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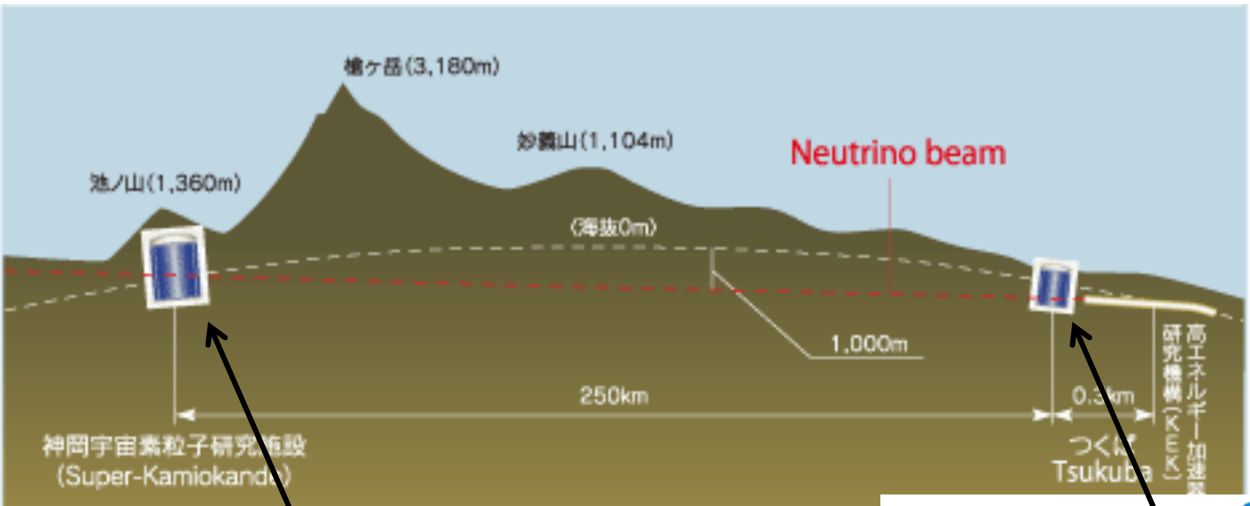
accelerator neutrino	K2K neutrino oscillation agrees with atmospheric neutrino oscillation						MINOS charge separate accelerator neutrino oscillation	T2K ν_e appearance result	

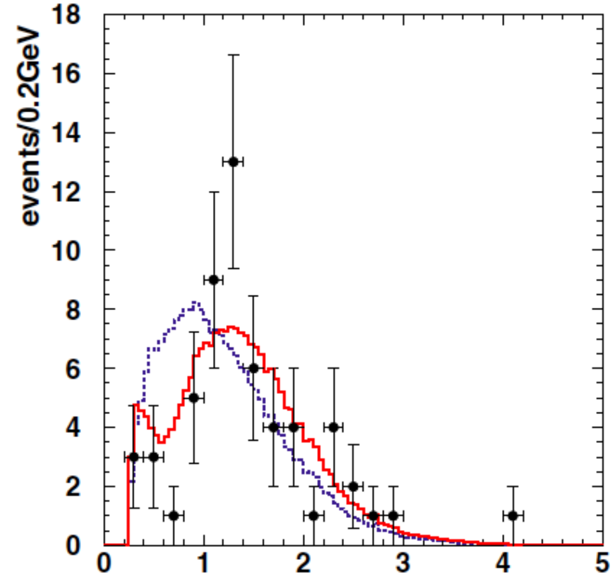
K2K, PRD74(2006)072003

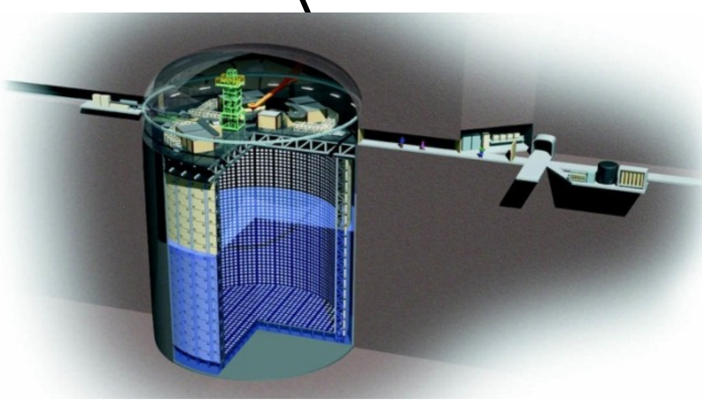
4. K2K experiment

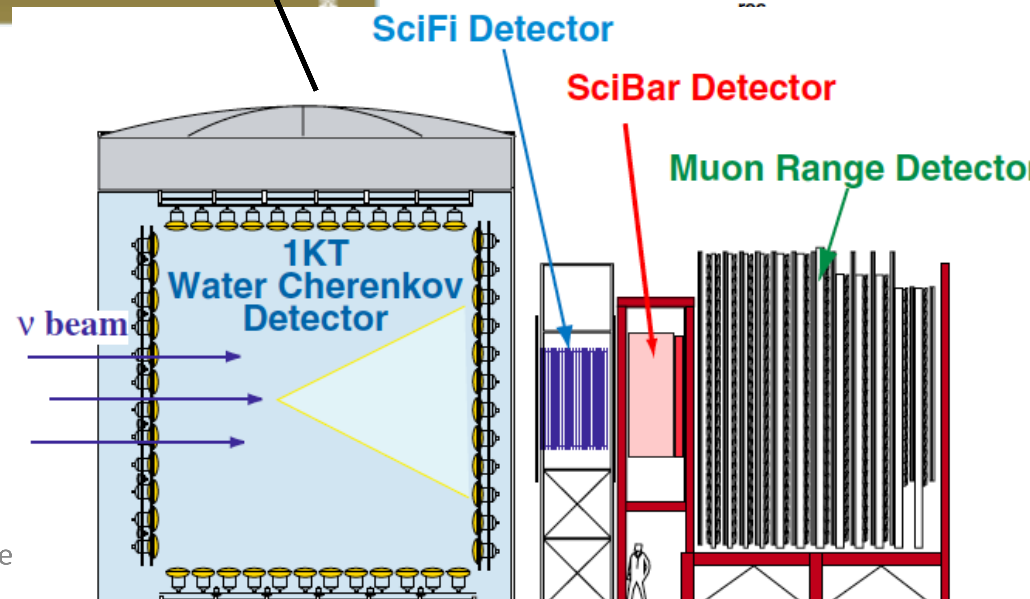
First long baseline neutrino oscillation experiment

- ~1.3GeV muon neutrinos over 250km









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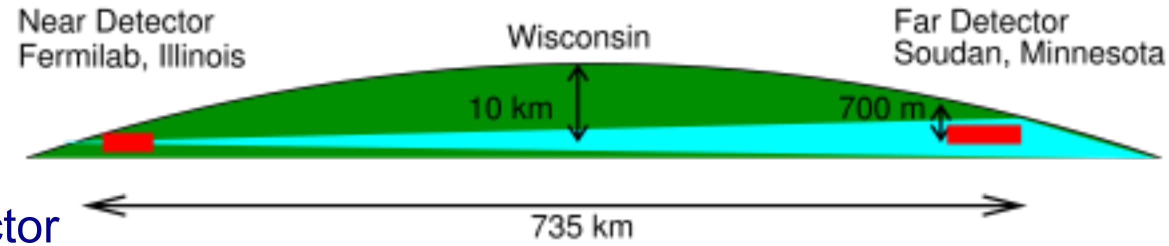
4. MINOS



Magnetized detector

- ~3GeV muon neutrinos and muon anti-neutrinos over 735km
- Due to B-field, neutrino and anti-neutrino interactions are separated

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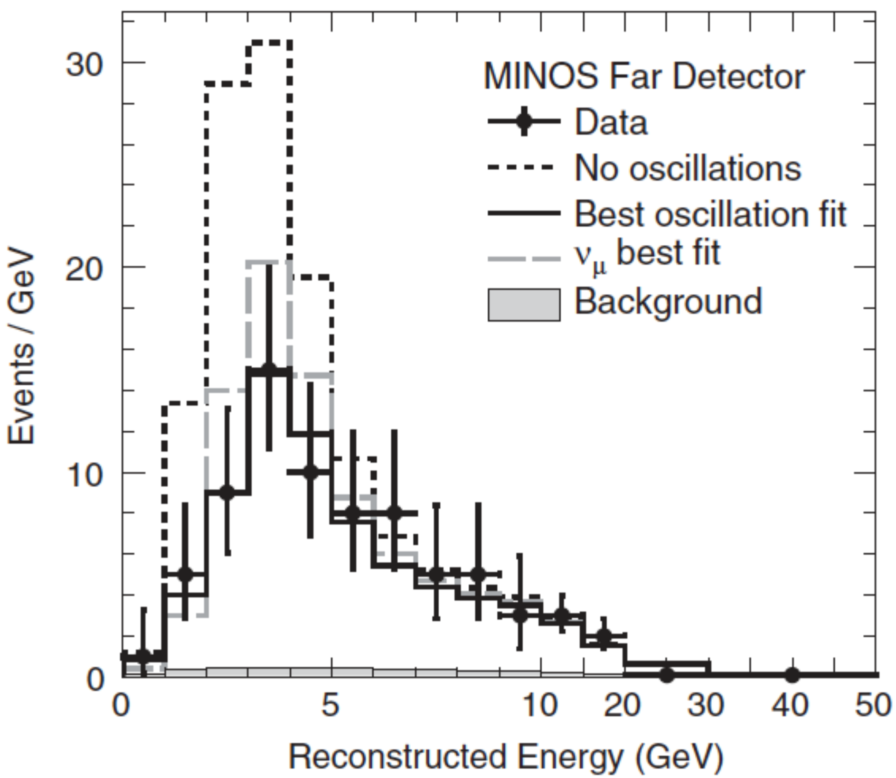
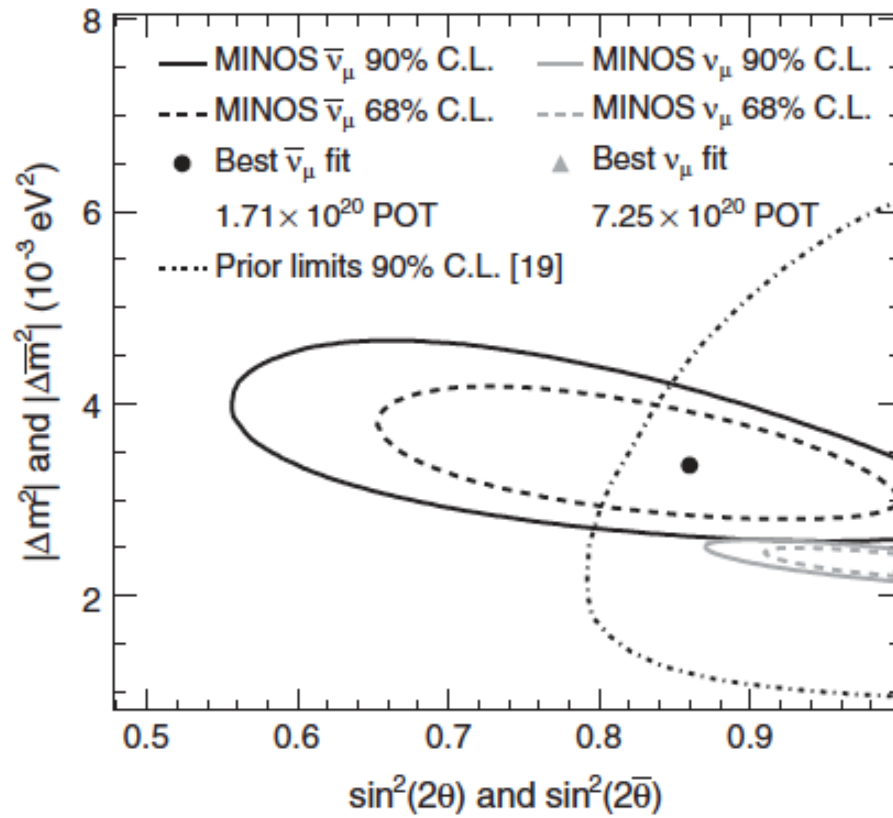
- First direct measurement of anti-neutrino oscillation parameter consistent only 2%





4. MINOS

Magnetized detector

- ~3GeV muon neutrinos and muon anti-neutrinos over 735km
- Due to B-field, neutrino and anti-neutrino interactions are separated
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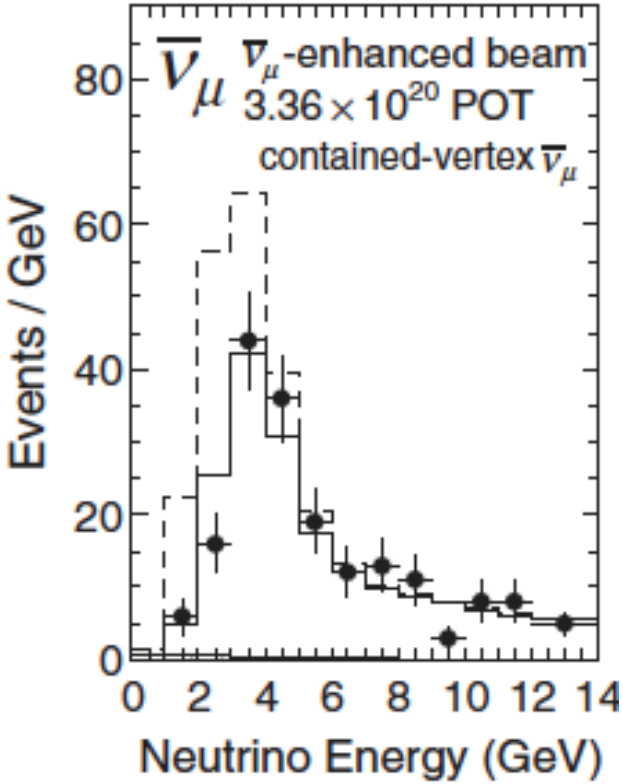
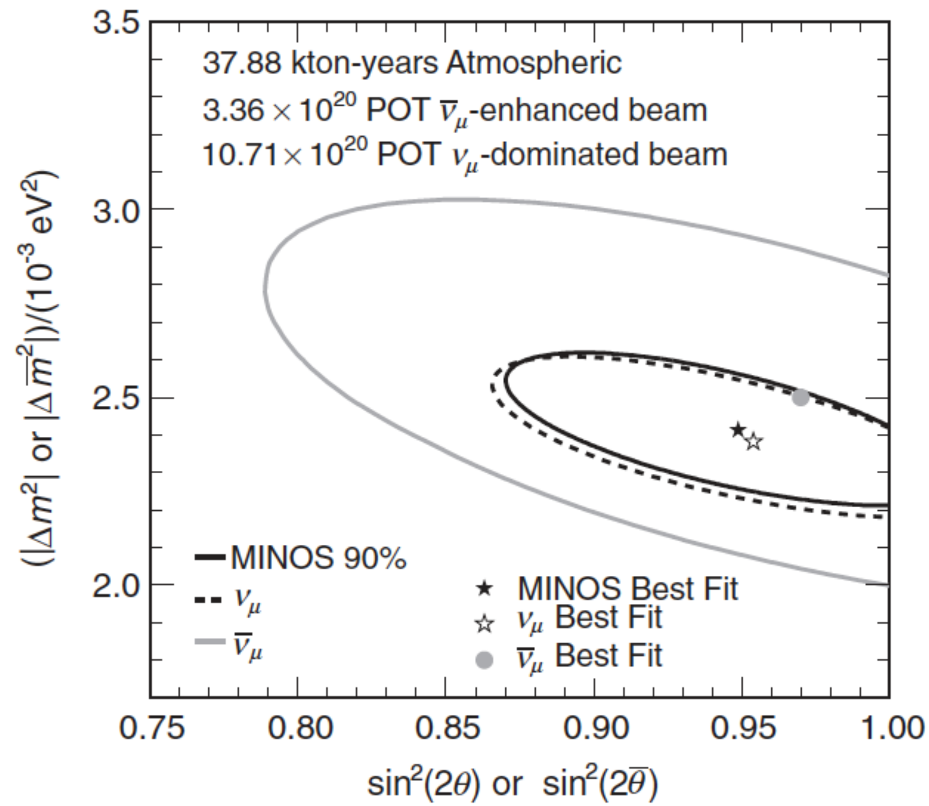
- Final data show no anomalies, neutrino and anti-neutrino data are consistent



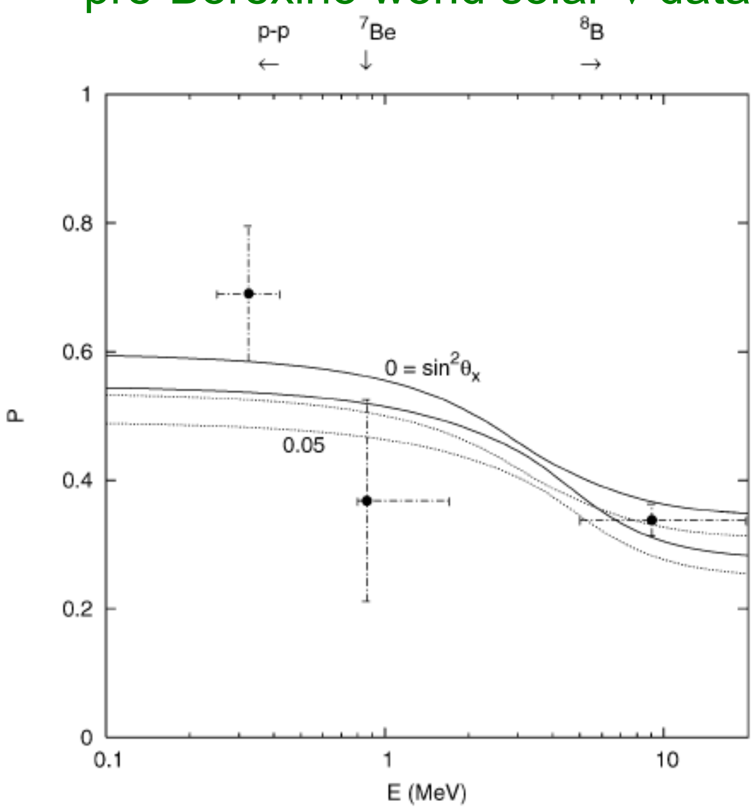


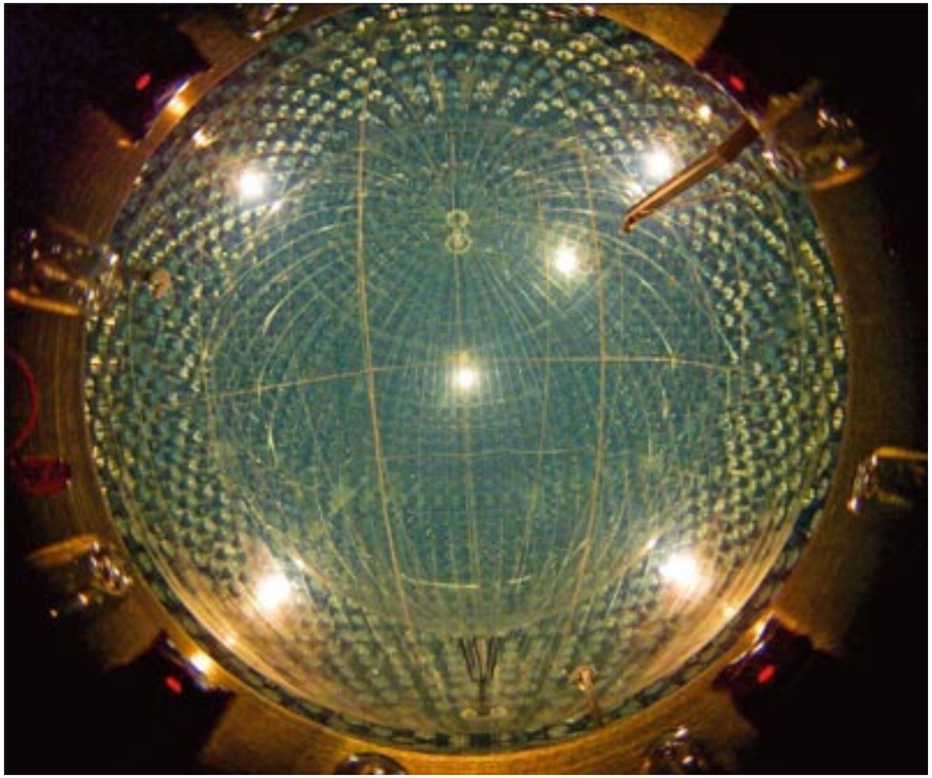
4. Borexino

7Be solar neutrino

- high pure liquid scintillator detector to detector low energy (=^{7}Be solar neutrino)
- Pre-borexino → MSW was about right, but not quite right

pre-Borexino world solar-ν data





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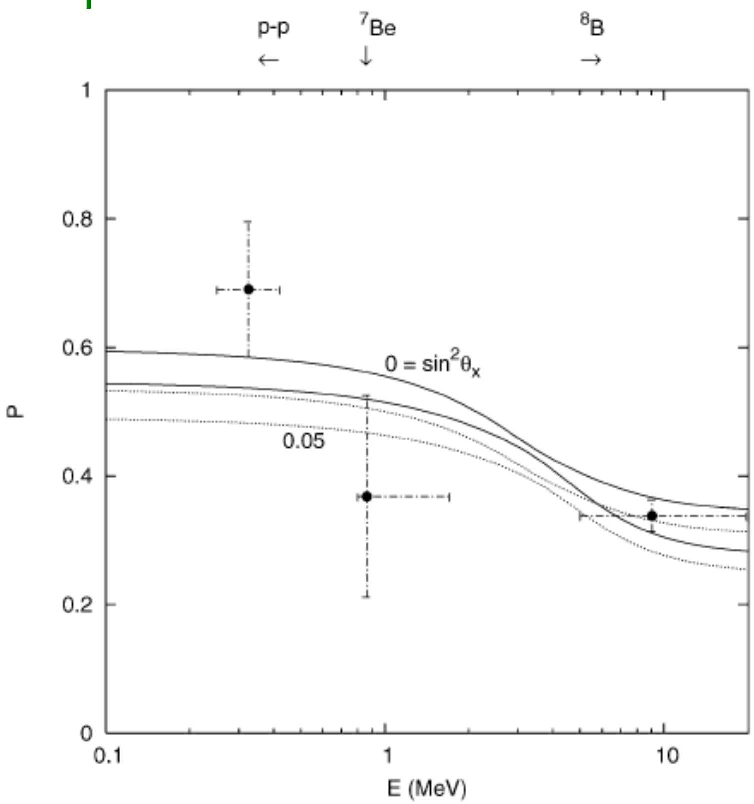

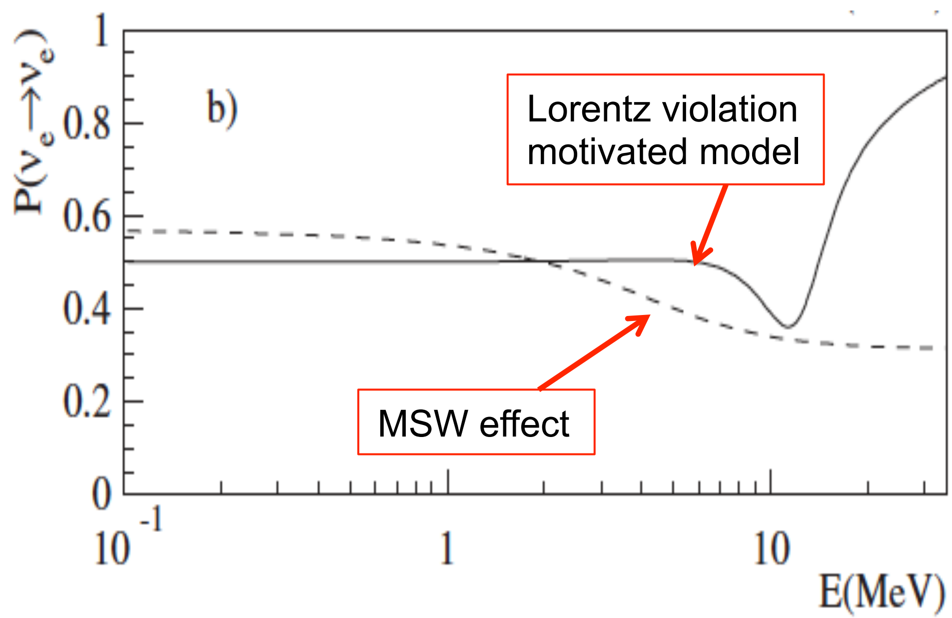

Borexino, PRL101(2008)091302;108(2012)051302
Haxton et al, ArXiv:1303.1681

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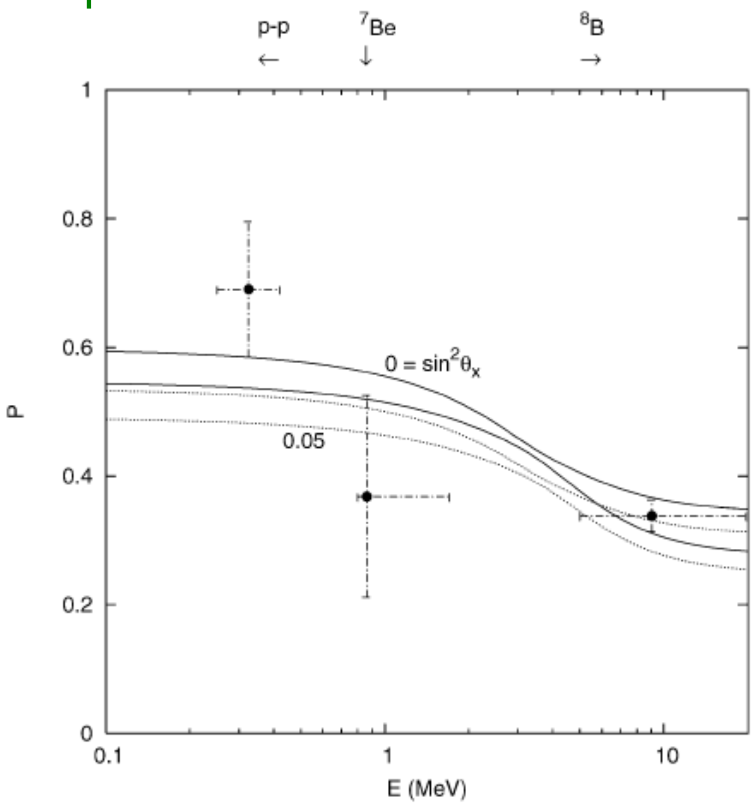
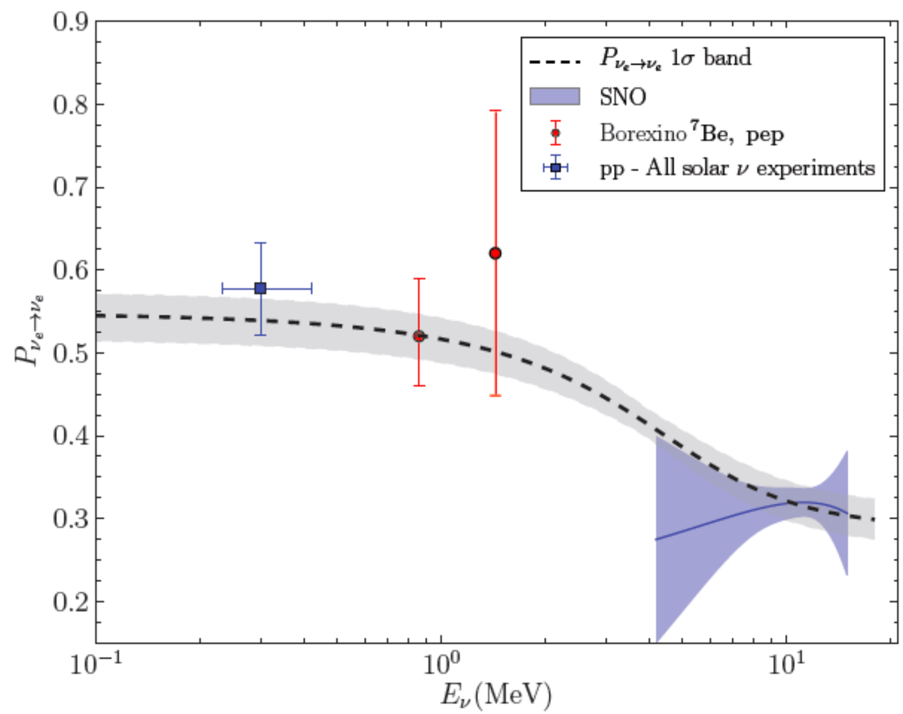
pre-Borexino world solar-ν data → post-Borexino world solar-ν data





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4. 2005-2011

Neutrino oscillation physics is getting into precision era
- neutrino and anti-neutrino oscillation parameters are tested
- 2 massive neutrino oscillation models are established (θ_{solar}, Δm^2_{solar}, θ_{atm}, Δm^2_{atm})

Almost all alternative exotic models are killed, neutrino oscillations are due to neutrino masses, and all exotic effects are secondary
- non-standard interaction
- sterile neutrino mixing
- Lorentz violation
- decay, decoherence, extra-dimension, etc

1. Neutrino oscillations

2. Before 1998

3. 1998-2004

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5. 2012-2013

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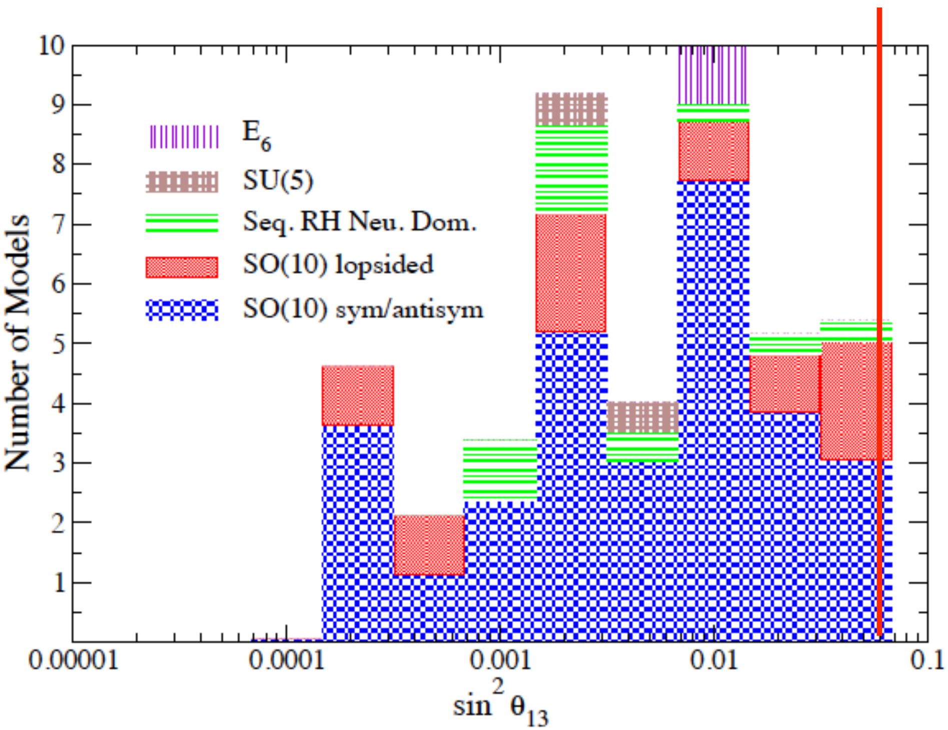
Albright, ArXiv:0905.0146
Fogli et al,PRL101(2008)141801

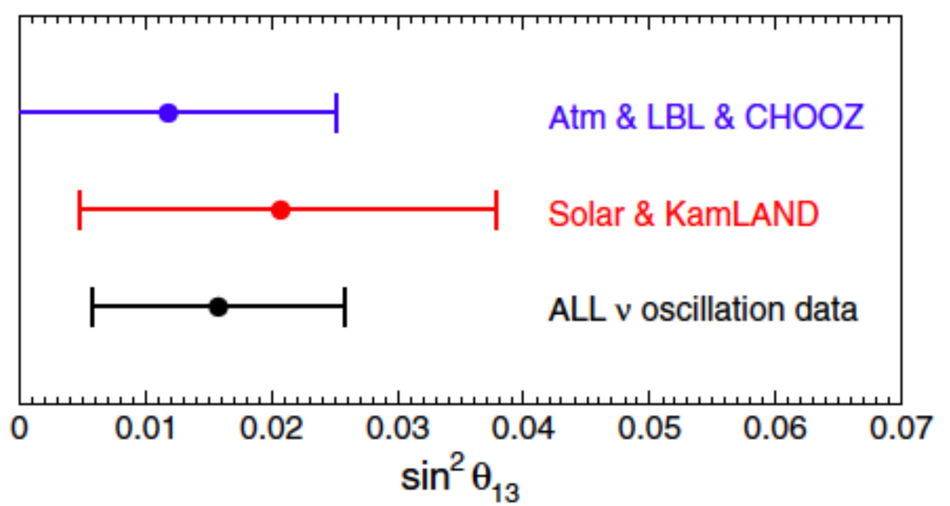
5. Boom of θ_{13}

T2K, Double Chooz, Daya Bay, Reno

- θ_{13} was truly unknown parameter
- there was a "hint" from Solar-KamLAND tension

Limit of θ_{13} (2009)





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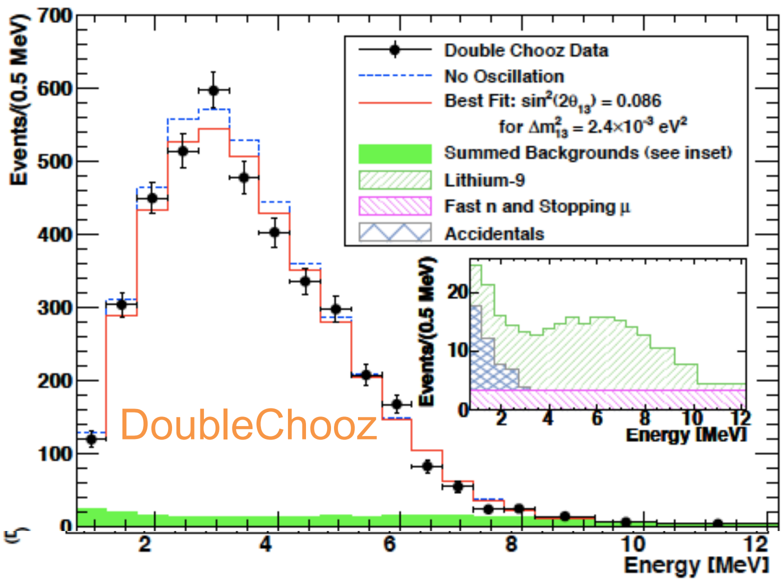
  - anti-ν_e reactor disappearance

$$P_{\rm sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$



Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802

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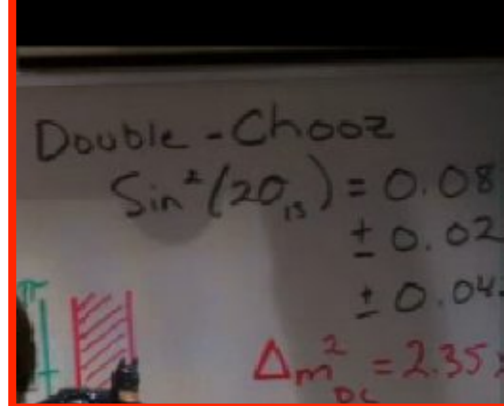

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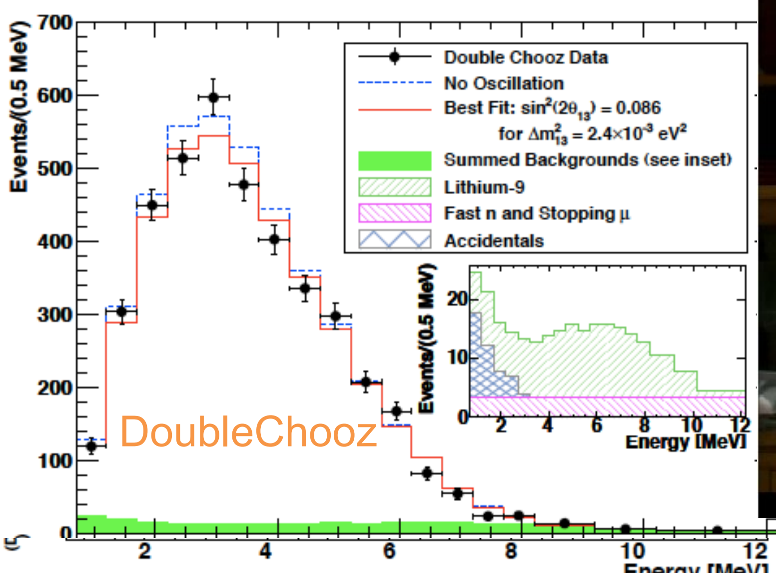

The Big Bang Theory (CBS)

Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802
Daya Bay, ArXiv:1310.6732

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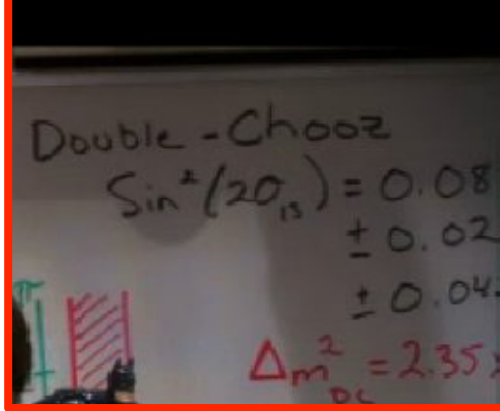

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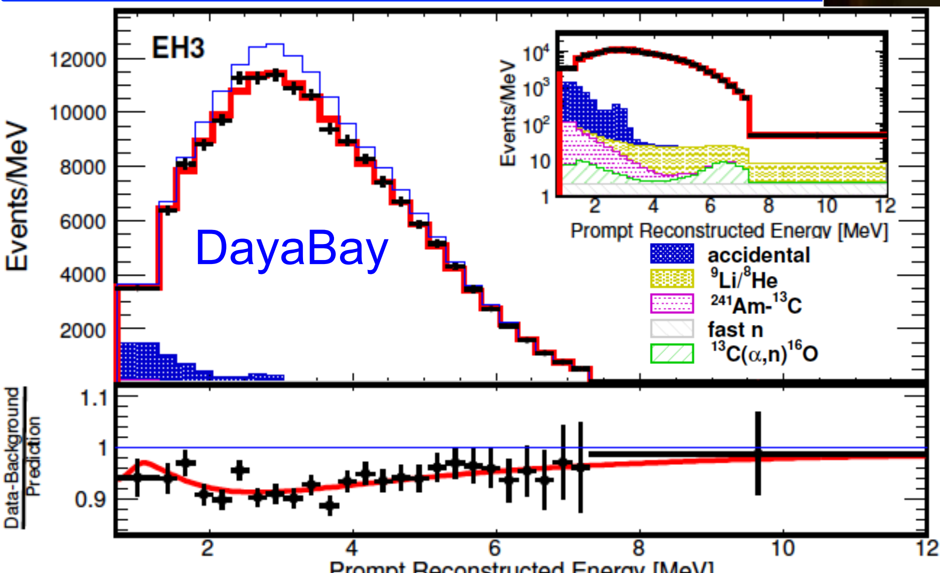

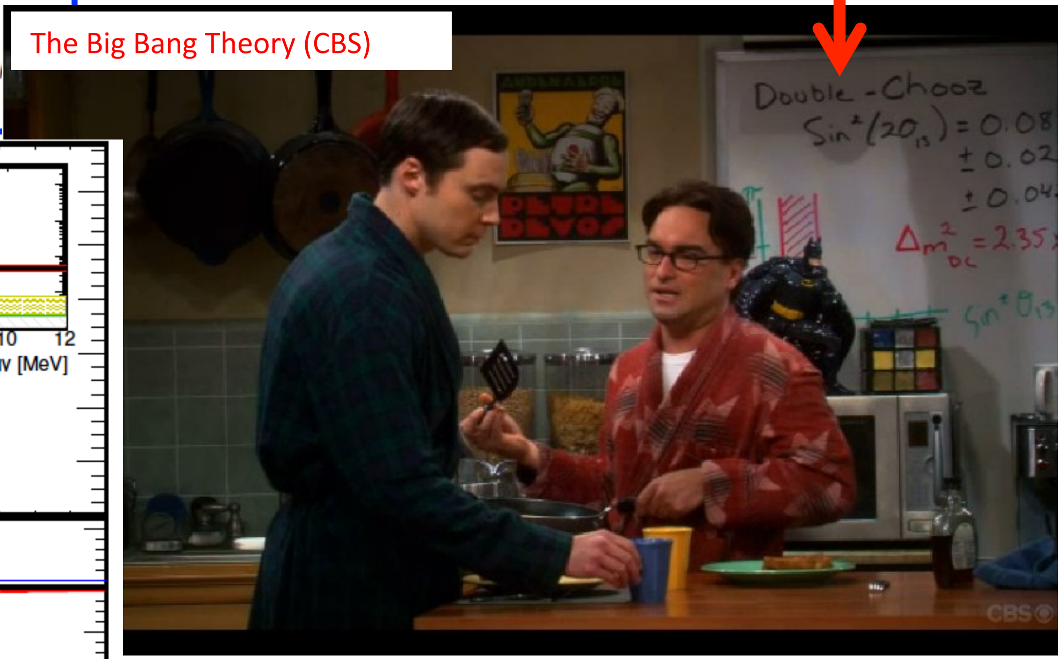

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Daya Bay, ArXiv:1310.6732, T2K, ArXiv:1311.4750

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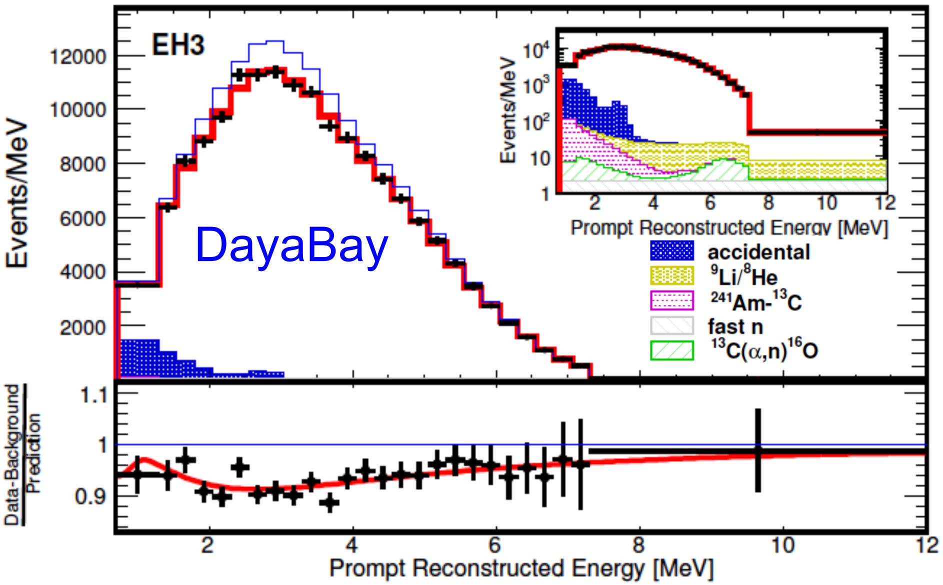
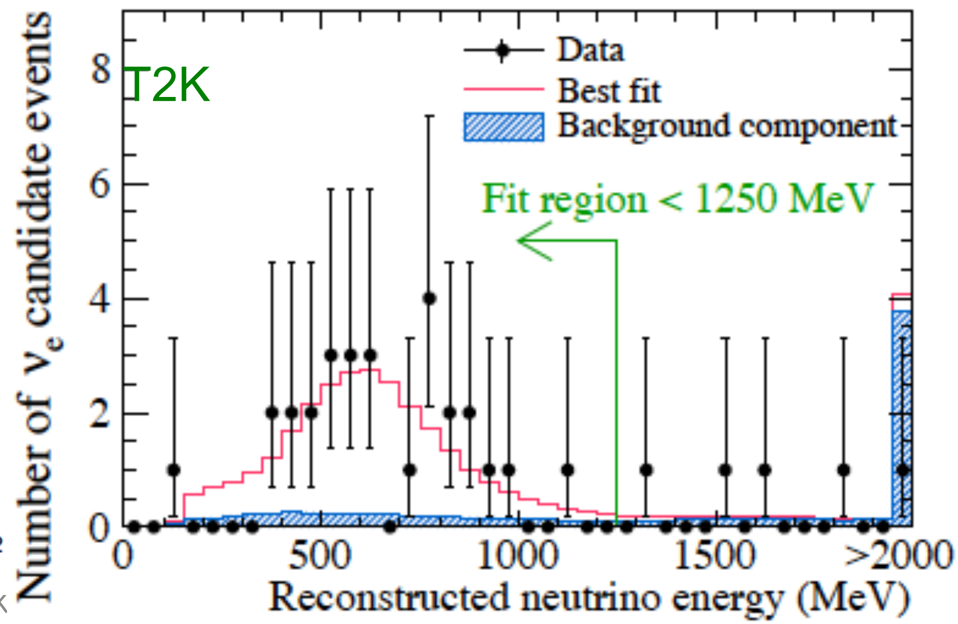
- nature was too kind for us!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$

$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$





Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802
Daya Bay, ArXiv:1310.6732, T2K, ArXiv:1311.4750

5. Boom of θ_{13}

T2K, Double Chooz, Daya Bay, Reno

- θ_{13} was truly unknown parameter
- there was a "hint" from Solar-KamLAND tension
- nature was too kind for us!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation
- nonzero θ_{13} → leptonic CP violation

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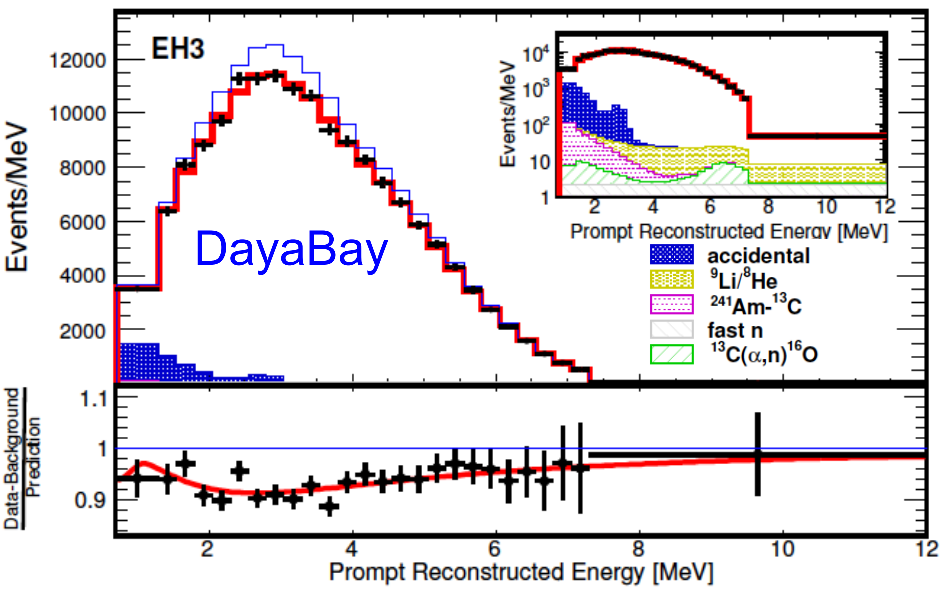

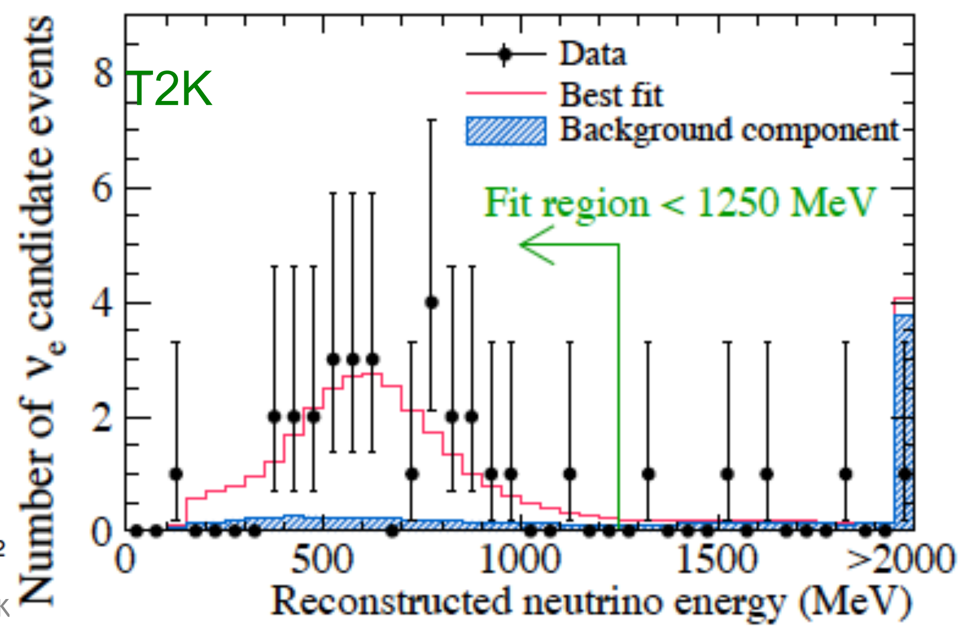

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  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation
- nonzero θ_{13} → leptonic CP violation

It is no longer adequate to use 2 neutrino oscillation model, it must be 3 neutrinos

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= | \, U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} \, |^2 \\ &= |2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21}|^2 \\ &\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2 \end{aligned}$$

$$\Delta_{ij} = \frac{\delta m_{ij}^2 L}{4E}$$

where $\sqrt{P_{atm}} = 2|U_{\mu 3}||U_{e3}| \sin\Delta_{31} = \sin\theta_{23} \sin 2\theta_{13} \sin\Delta_{31}$

and $\sqrt{P_{sol}} \approx \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21}$.

5. 2012-2013

Neutrino Standard Model (νSM)

- SM + 3 active massive neutirnos

Unknown parameters of νSM

- Dirac CP phase
- θ_{23} (θ_{23}=40° and 50° are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
- order of mass (normal hierarchy $m_1<m_2<m_3$ or inverted hierarchy $m_3<m_1<m_2$)
- Majorana phases
- Dirac or Majorana
- absolute neutrino mass

(Majorana phases, Dirac or Majorana, absolute neutrino mass:) not relevant to neutrino oscillation experiment?

$$P(\nu_\mu \to \nu_e) = | \, U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} \, |^2$$
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$$\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

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- Majorana phases
- Dirac or Majorana
- absolute neutrino mass

} not relevant to neutrino oscillation experiment?

Very few remained anomalies

- Upturn of ^{8}B solar neutrino
- Reactor anomaly
- Gallium anomaly
- LSND and MiniBooNE signals

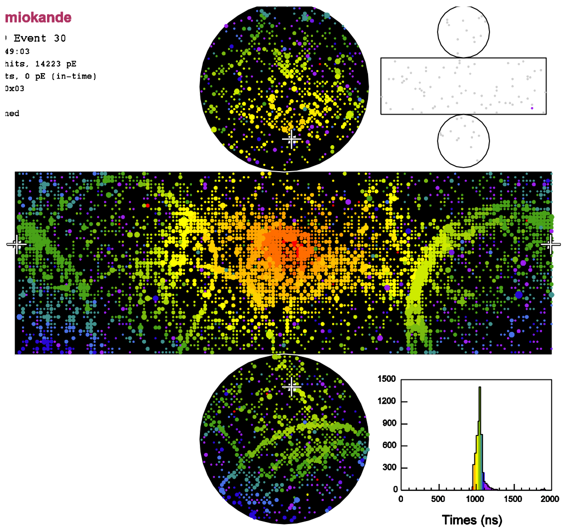
} motivation of 1eV scale sterile neutrino

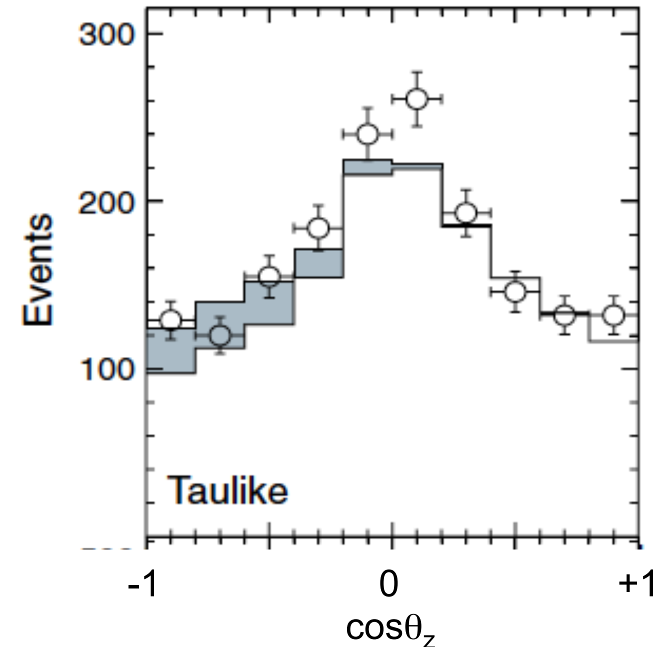
Super-kamiokande, PRL110(2013)181802; ArXiv:1312.5176
OPERA, ArXiv:1401.2079

5. 2012-2013, final remarks

ν_t appearance measurement by Super-K

- τ-decay to multi hadrons
- 3.8σ excess of up-going τ-like events



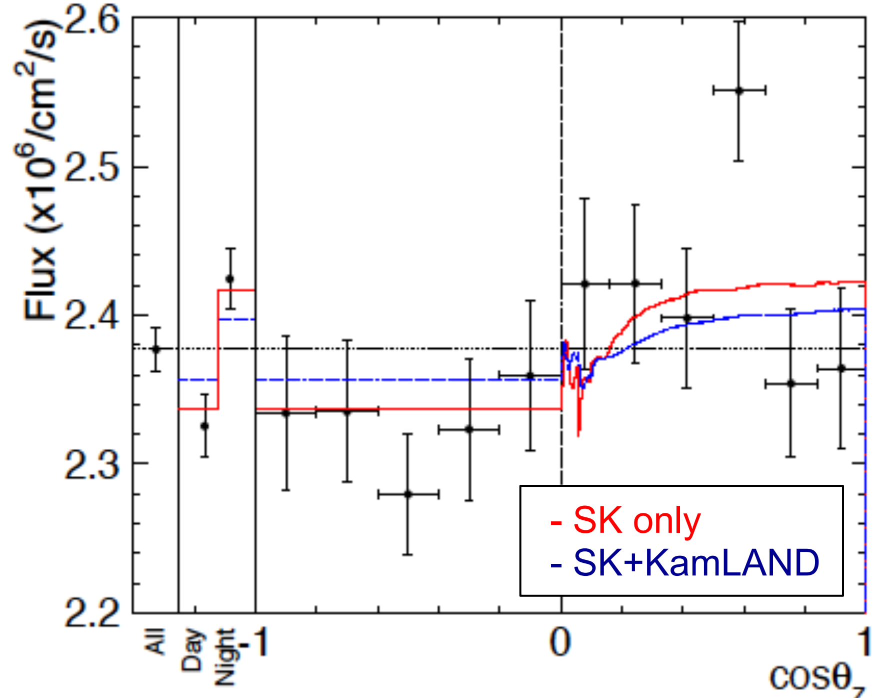


OPERA ν_τ appearance (last week)

-3 events observation corresponds to 3.4σ

Solar-ν day-night asymmetry by Super-K

- day-night asymmetry → Earth matter effect
- 2.7σ (statistically limited)



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6. Current issues

Unknown parameters of νSM

δ_{CP}: Dirac CP phase

θ_{23}: θ_{23}=40^o and 60^o are same how sin2θ_{23}, but not for sinθ_{23}

MH: mass hierarchy, normal hierarchy $m_1<m_2<m_3$ or inverted hierarchy $m_3<m_1<m_2$

Long baseline neutrino oscillations

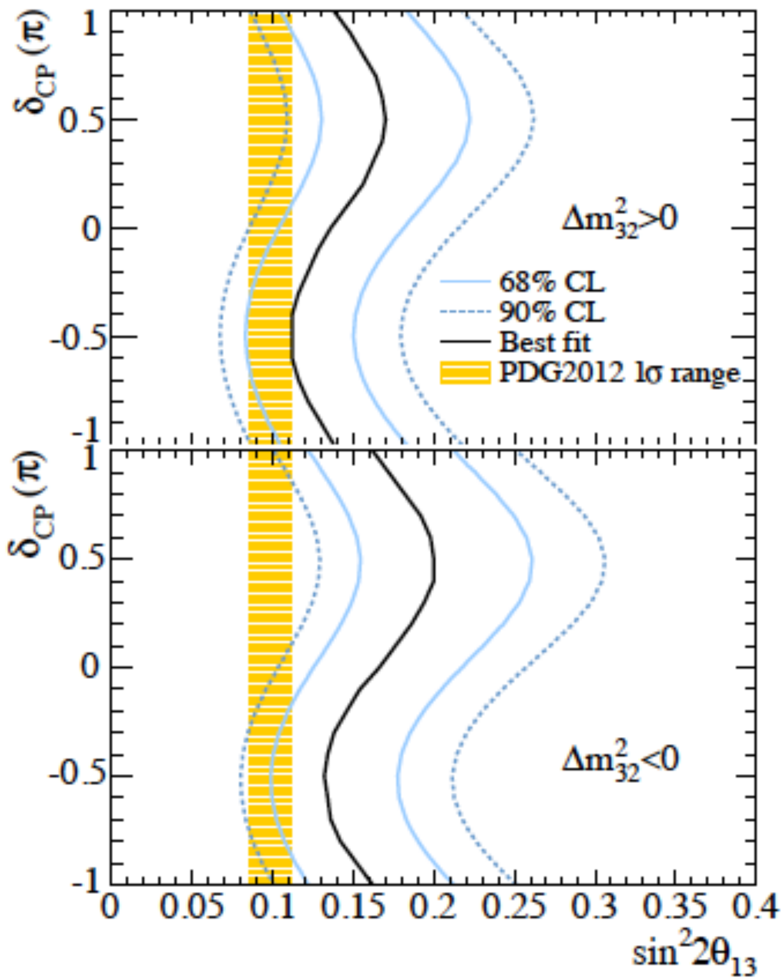
- T2K (running)
- NOvA (about running)
- PINGU (planned)
- JUNO (planned)
- LBNE (planned)
- Hyper-K (planned)

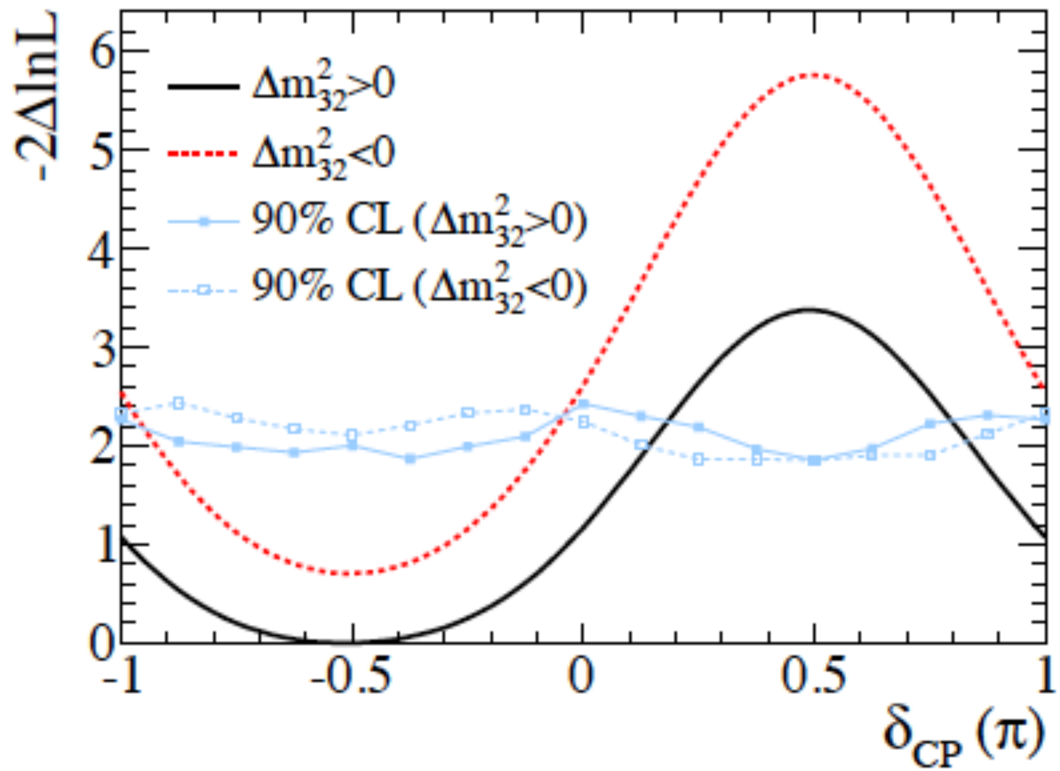
6. T2K experiment

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

δ_{CP} limit

- oscillation fit including θ_{13} constraint from reactor experiments
- data prefer δ_{CP}~ $-\pi/2$.





Muether, NNN'13
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=17

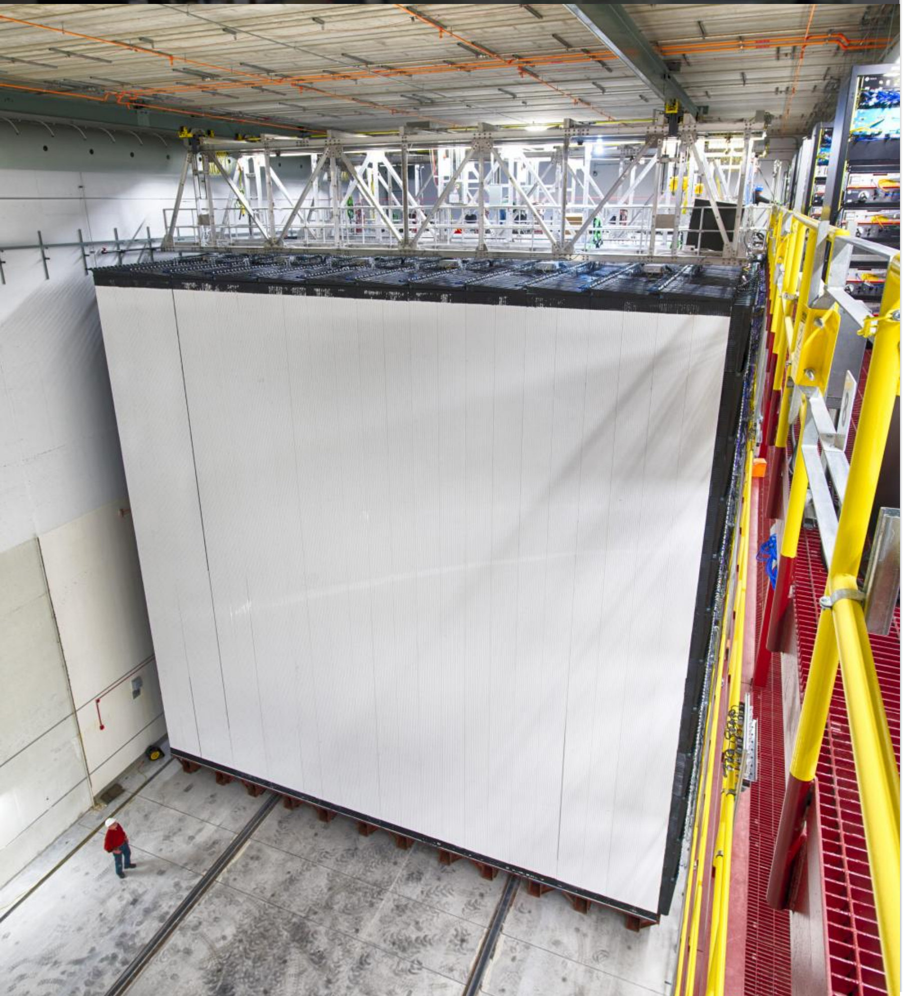
6. NOvA

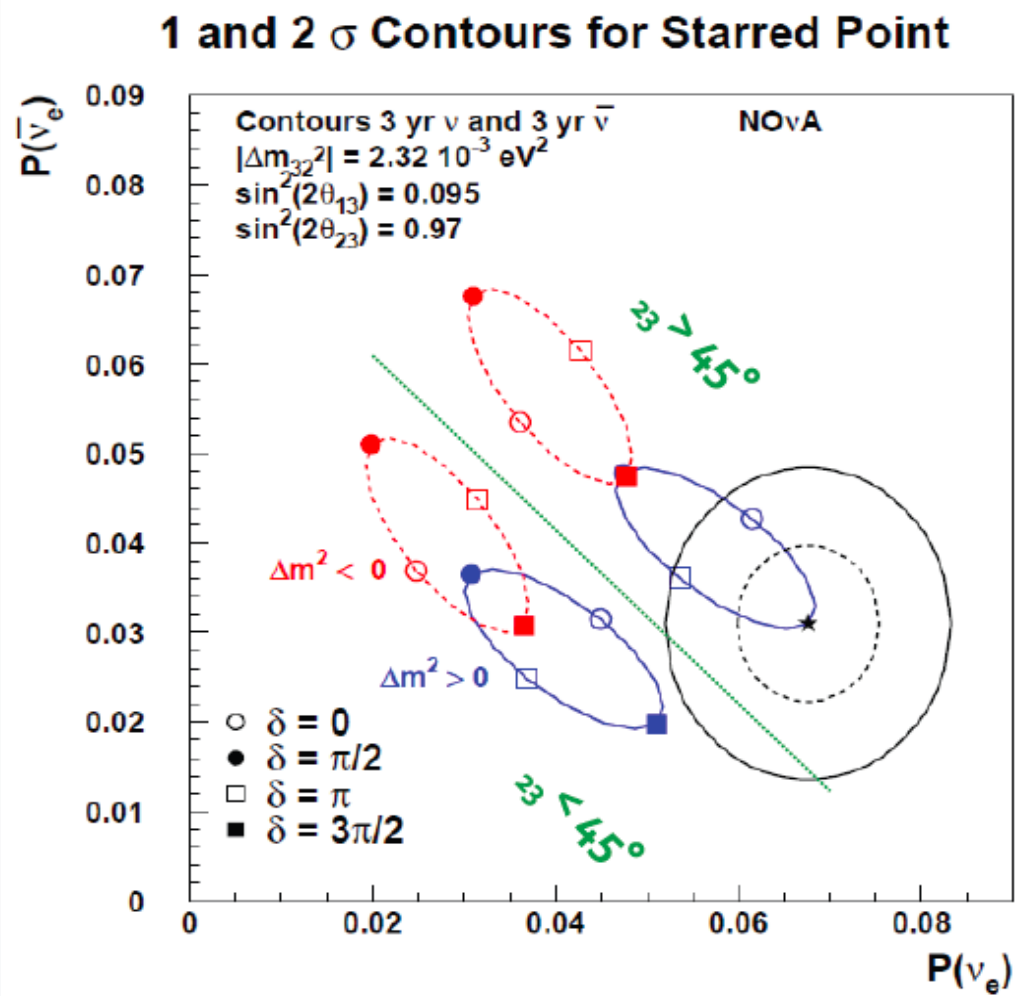
$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

Massive plastic tubes with liquid scintillator

- 14 kton total, 810 km from Fermilab (E~2GeV)
- NOvA has a chance to solve degeneracy and find all (δ_{CP}, θ_{23}, MH)

→ If NOvA knows mass hierarchy a priori, it helps to solve degeneracy even better





PINGU, ArXiv:1306.5846
Akhmedov,Razzaque,Smirnov,JHEP02(2013)082

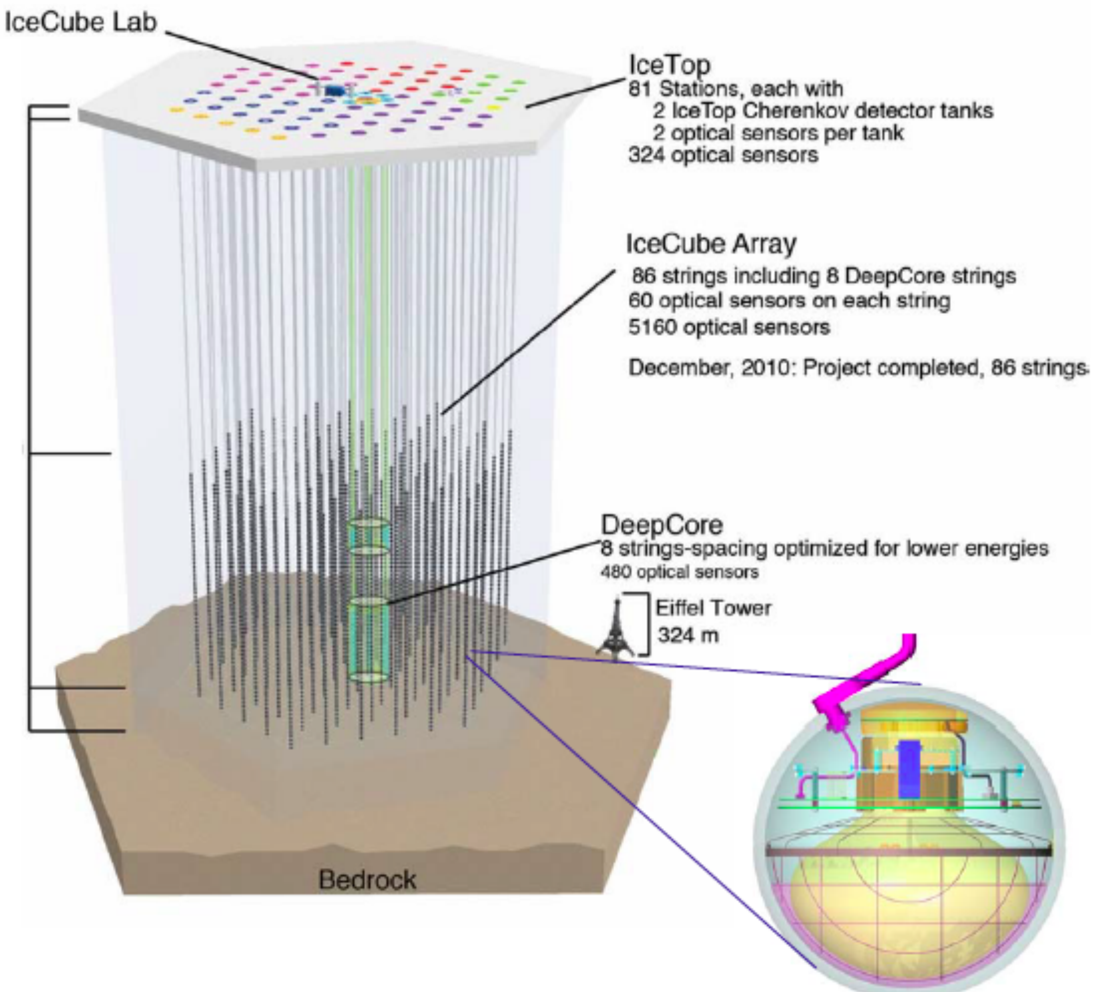
6. PINGU

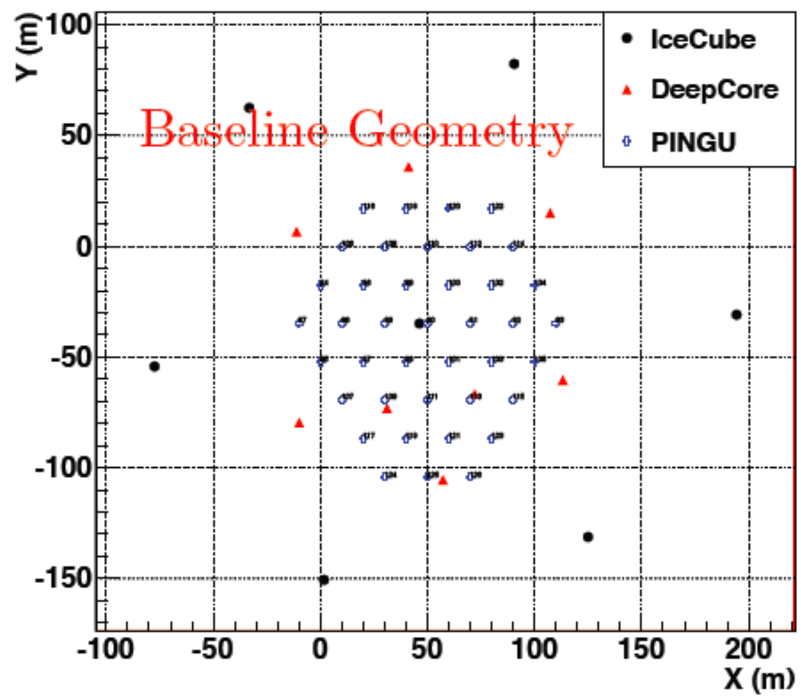
effective 2-ν matter oscillation — interference of propagation states

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23} - s_{23}^4 P_A + \frac{1}{2}\sin^2 2\theta_{23}\sqrt{1-P_A}\cos\phi_X$$

More strings in IceCube

- They know how to do it (no R&D), also they know how to estimate cost
- more strings in central area of IceCube → reduce threshold down to ~few GeV
- It can find mass hierarchy in few years from ν_μ disappearance





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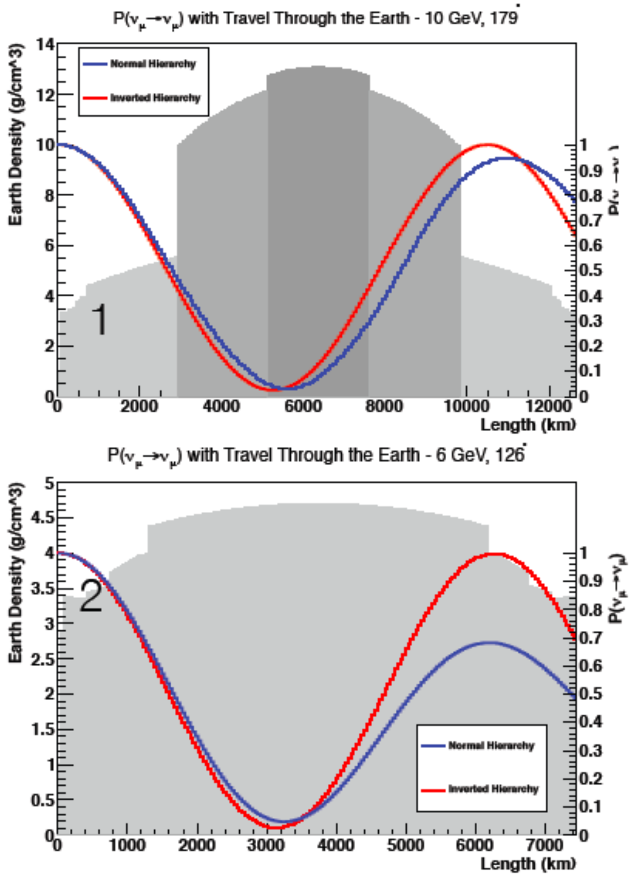

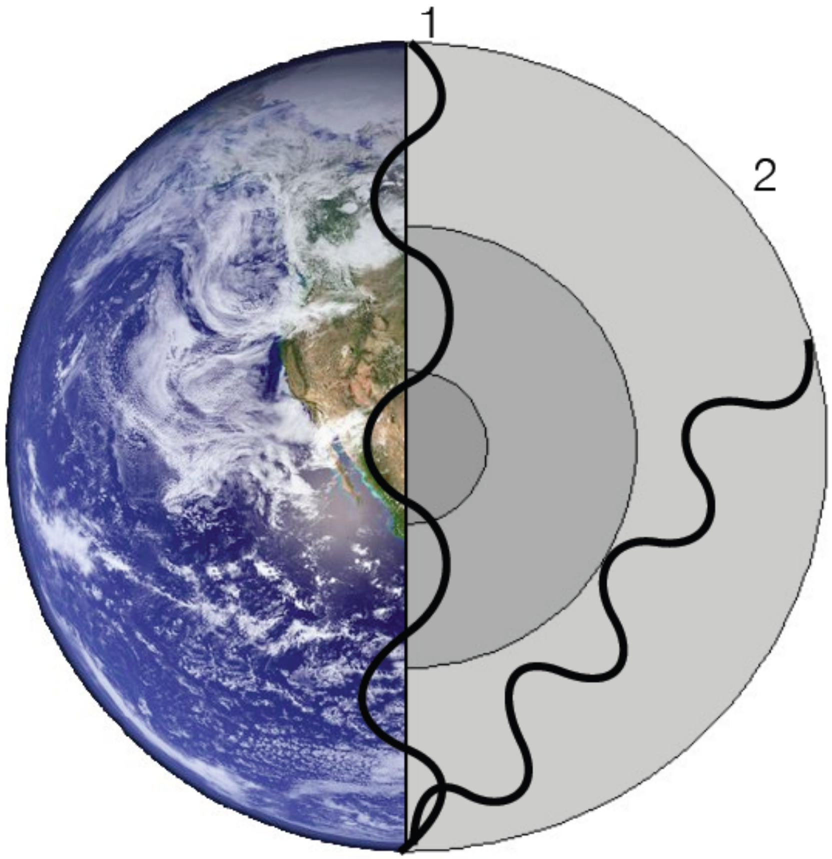

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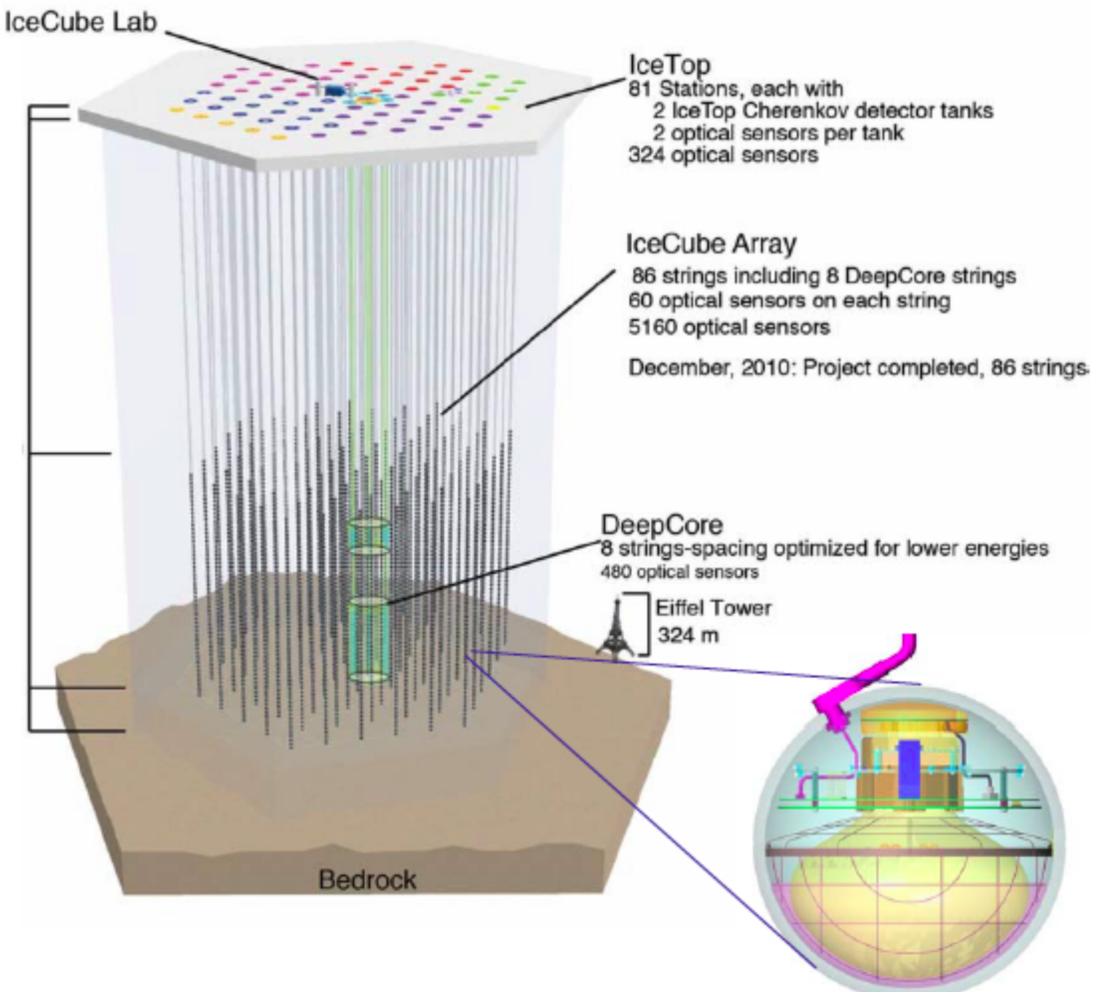
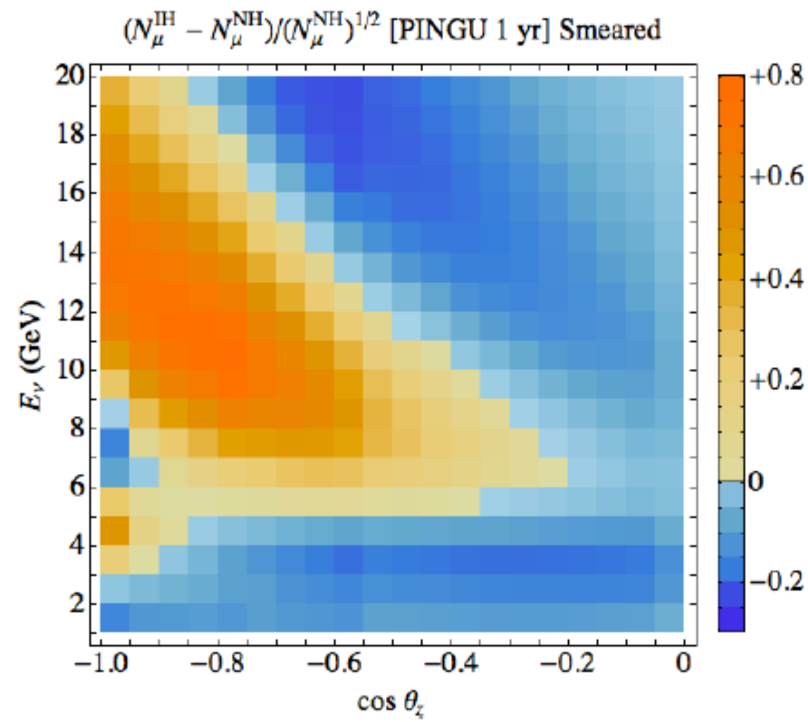


hierarchy asymmetry of PINGU ν_μ-like event (with systematic error)

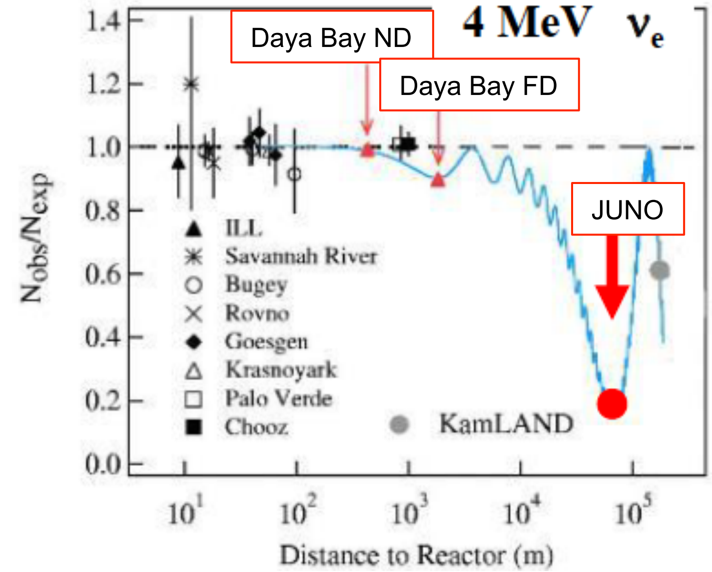


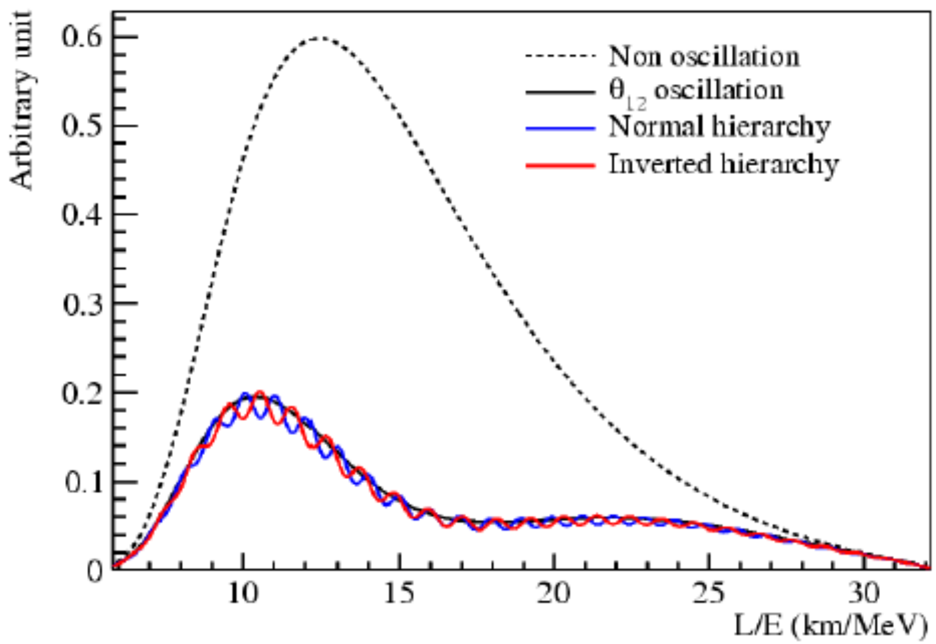
Cao, NNN'13
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=17

6. JUNO

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\underline{\sin^2(\Delta_{31})}$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\underline{\sin^2(\Delta_{32})}$$

Better detector at further location at Daya Bay
- Significant sensitivity improvement is required (bigger detector with better resolution)
- It can find mass hierarchy in few years
- Similar proposal in Korea (RENO-50)





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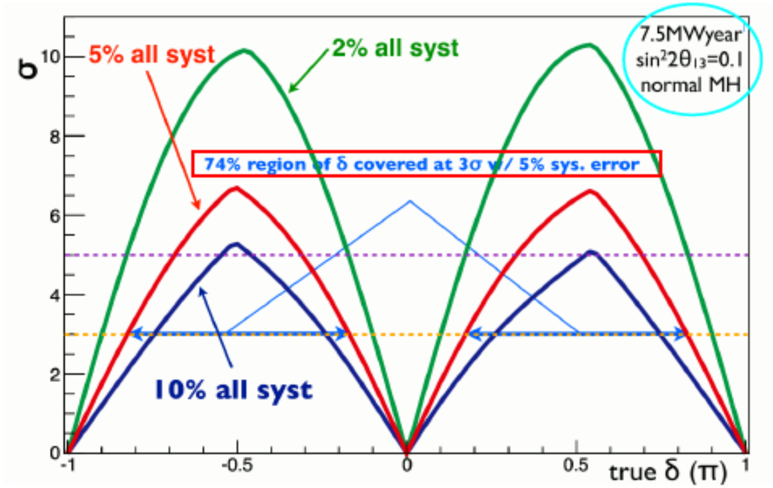
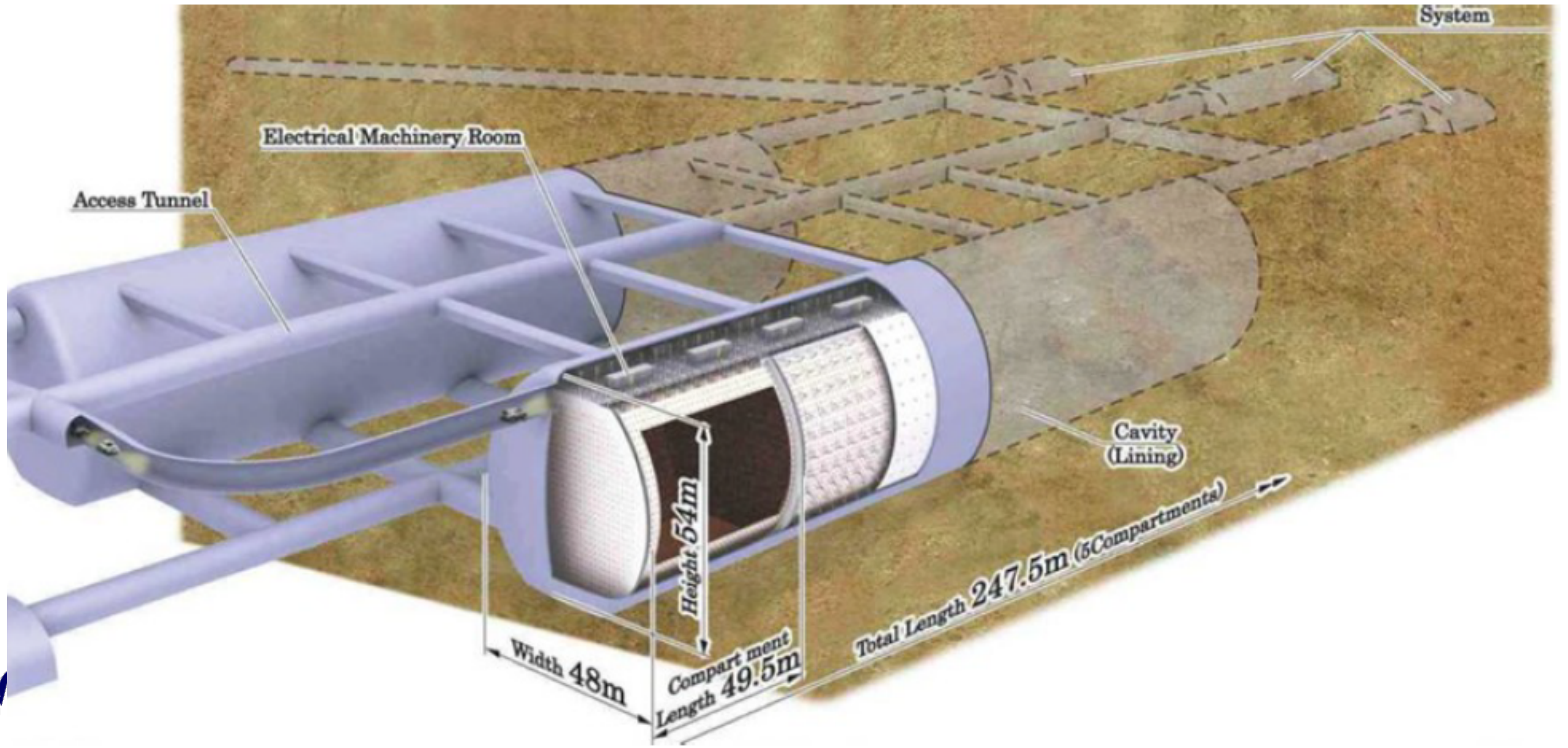
Di Lodovico, NNN'13
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=17

6. T2HK



T2K with Hyper-Kamiokande

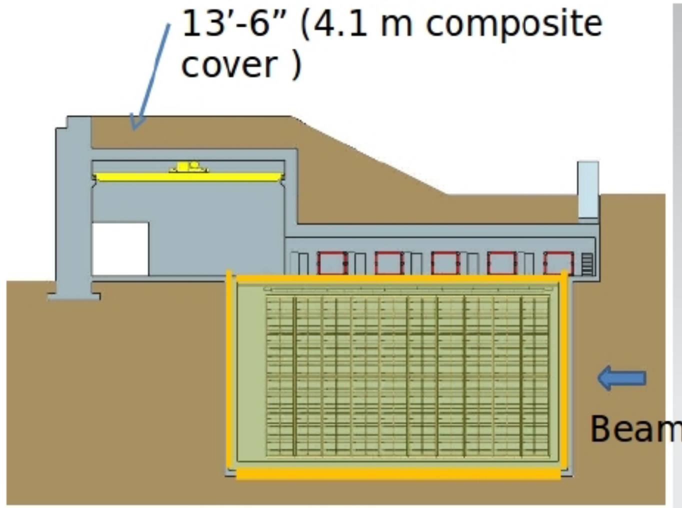
- Known technology
- δ_{CP} from ν_e appearance
- θ_{23} from ν_μ disappearance
- MH from atmospheric neutrinos
- All kind of other physics (p-decay, solar/atmospheric/supernova neutrinos, etc)

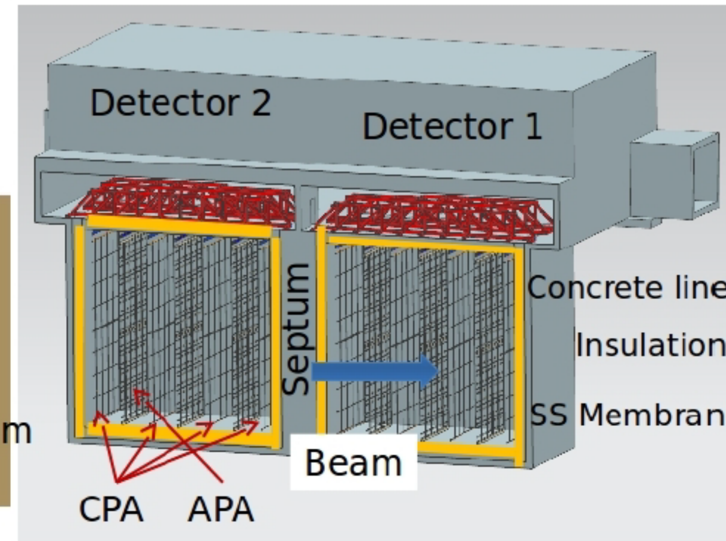


6. LBNE

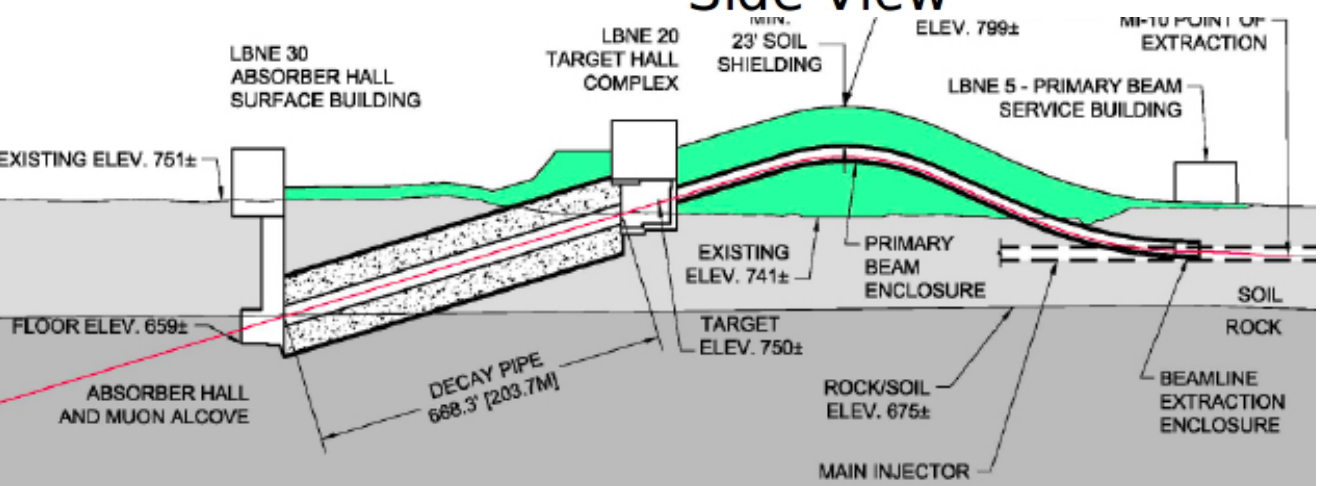
New beamline and new detector

- 10 kton Liquid argon time projection chamber (LArTPC)
- New beamline to South Dakota





Side View



7. Mother nature is kind to us

Solar density, solar density gradient, solar neutrino energy are all right value so that we can detect solar neutrino oscillation through MSW effect

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But θ_{13} is big enough so that we can measure it and we can find leptonic CP violation

7. Conclusions

Neutrino oscillation physics show series of discoveries in the last 20 years.

There are very few anomalies (sorry for phenomenologist), and all exotic processes are sub-dominant (unfortunately).

Current unknown parameters of νSM are
- δ_{CP}
- θ_{23}
- mass hierarchy
- Majorana phase
- Dirac or Majorana
- Absolute neutrino mass

And current and future oscillation experiments are good position to find first three

Thank you for your attention!

Backup

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But θ_{13} is big enough so that we can measure it and we can find leptonic CP violation

Mass hierarchy is inverted so that we can find Majorana or Dirac through neutrinoless double beta decay

1. Neutrino oscillations

Formal description of neutrino oscillation is not easy, just because quantum mechanics is not easy

e.g.) Can GSI anomaly be explained by neutrino oscillation?

$$^{142}Pm^{60+} \rightarrow {}^{142}Nd^{60+} + \nu_e$$

Measured electron capture (EC) decay rate shows modulation. Ivanov et al proposed to explain this using neutrino oscillations.

But this is quickly refuted by many.

Initial state is measured, but not final state (neutrinos will not oscillate))

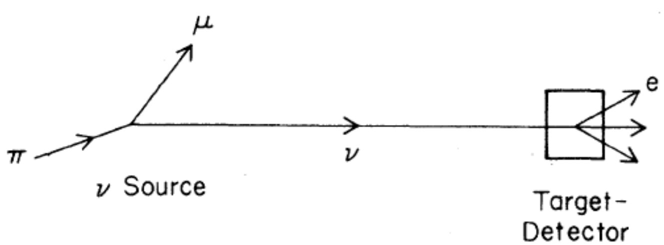
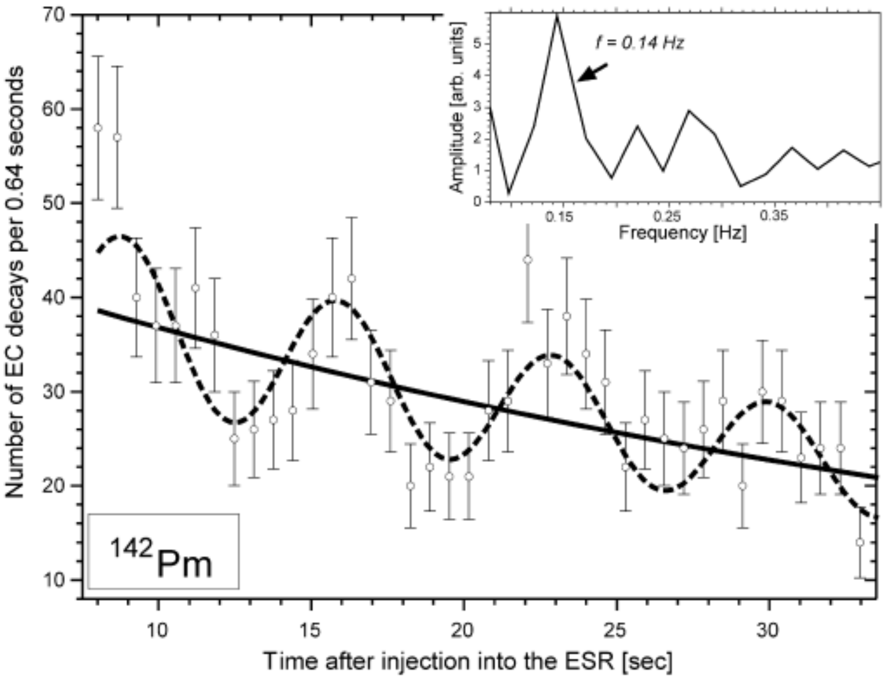


FIG. 1. A typical neutrino-oscillation experiment.



Bilenky,von Feilitzsch,Potzel,J.Phys.G.35(2008)095003
Akhemedov,Kopp,Lindner, J.Phys.G.36(2009)078001

1. Neutrino oscillations

Formal description of neutrino oscillation is not easy, just because quantum mechanics is not easy

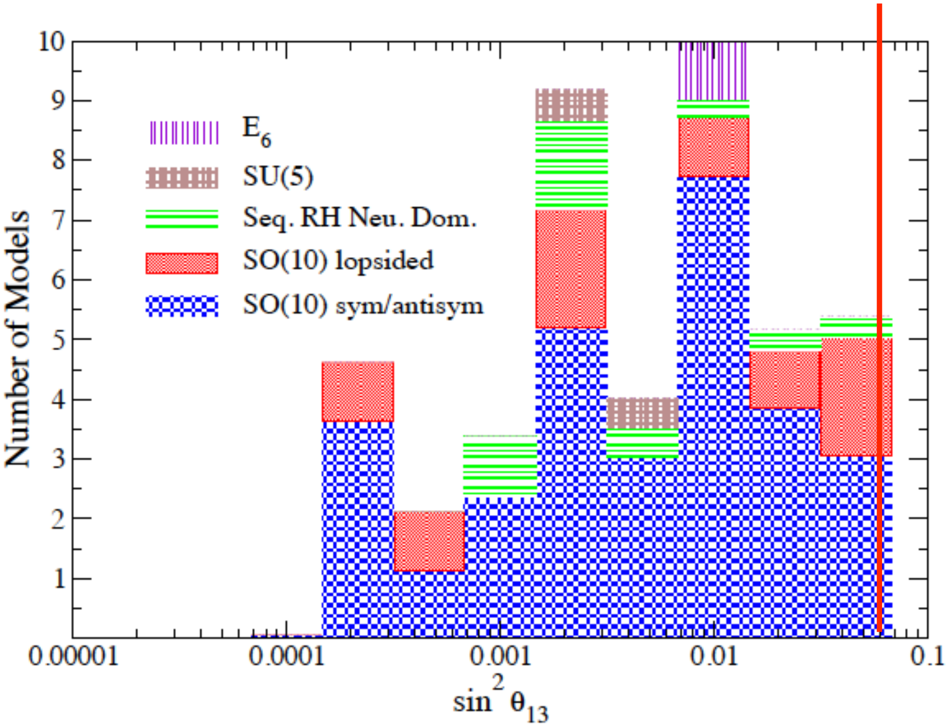
e.g.) Unsettled issues: Can experiment tell neutrinos oscillate in space or in time?
- Yes: Bilenky, von Felitzsch, Potzel
- No: Akhmedov, Kopp, Lindner

What do you think?

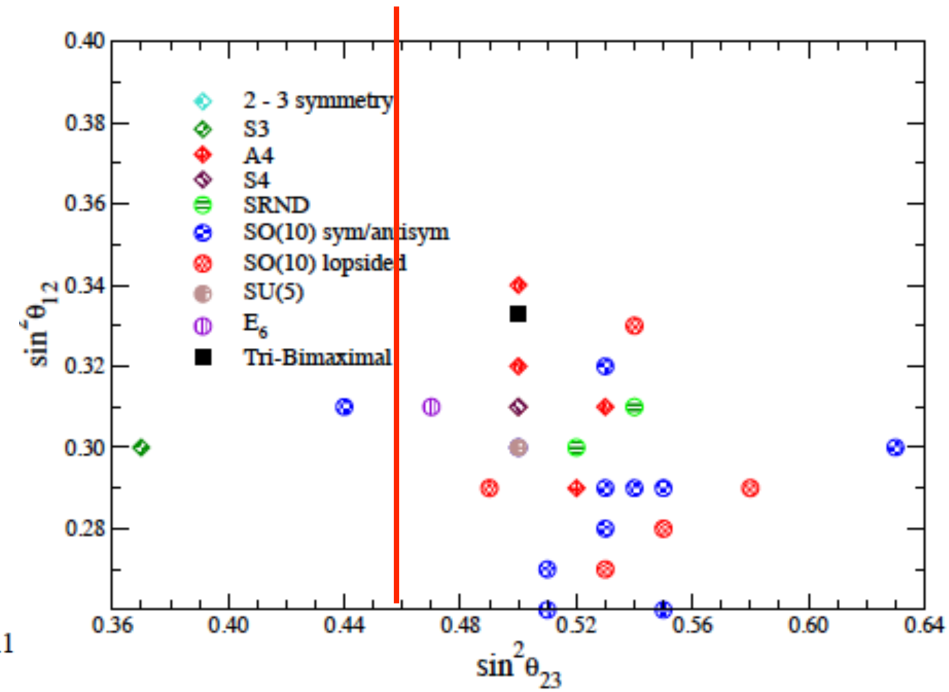
5. Path to θ_{13}

T2K, Double Chooz, Daya Bay, Reno
- θ_{13} was truly unknown parameter

Limit of θ_{13} (2009)



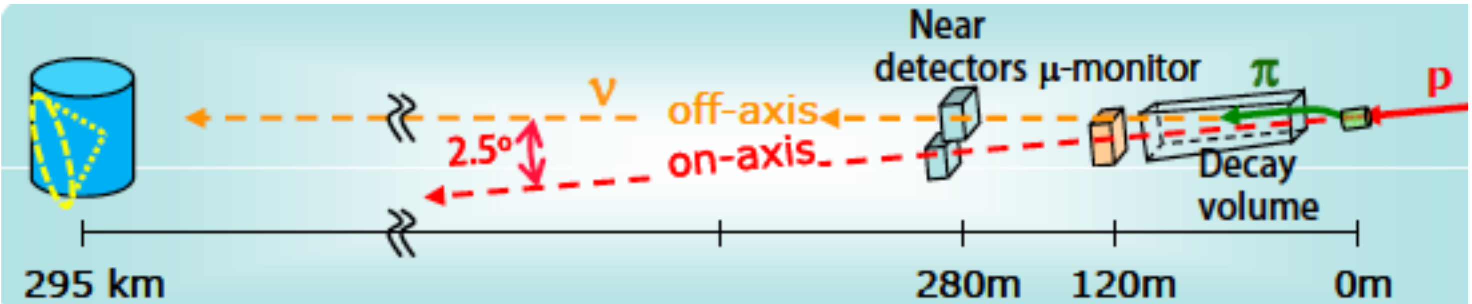
Best fit $\sin^2\theta_{23}$ (2009)

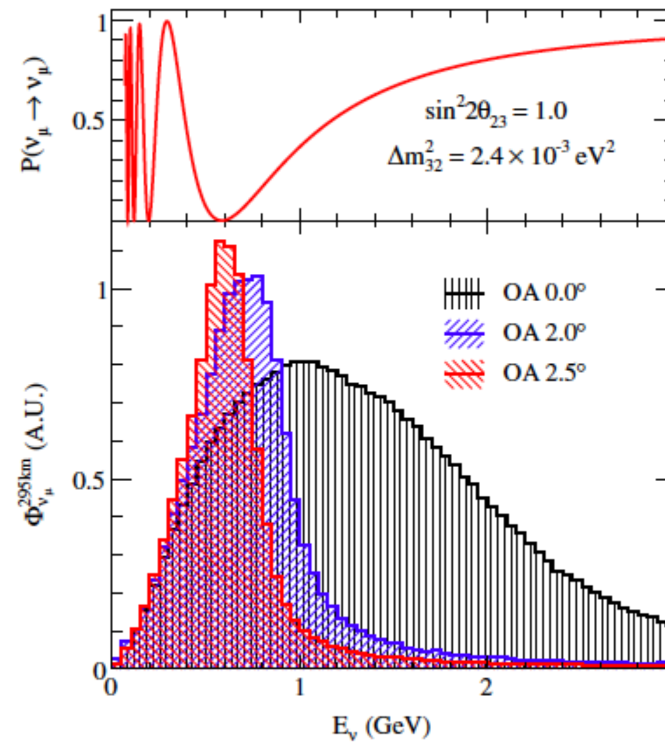


T2K, PRD87(2013)012001

6. T2K experiment

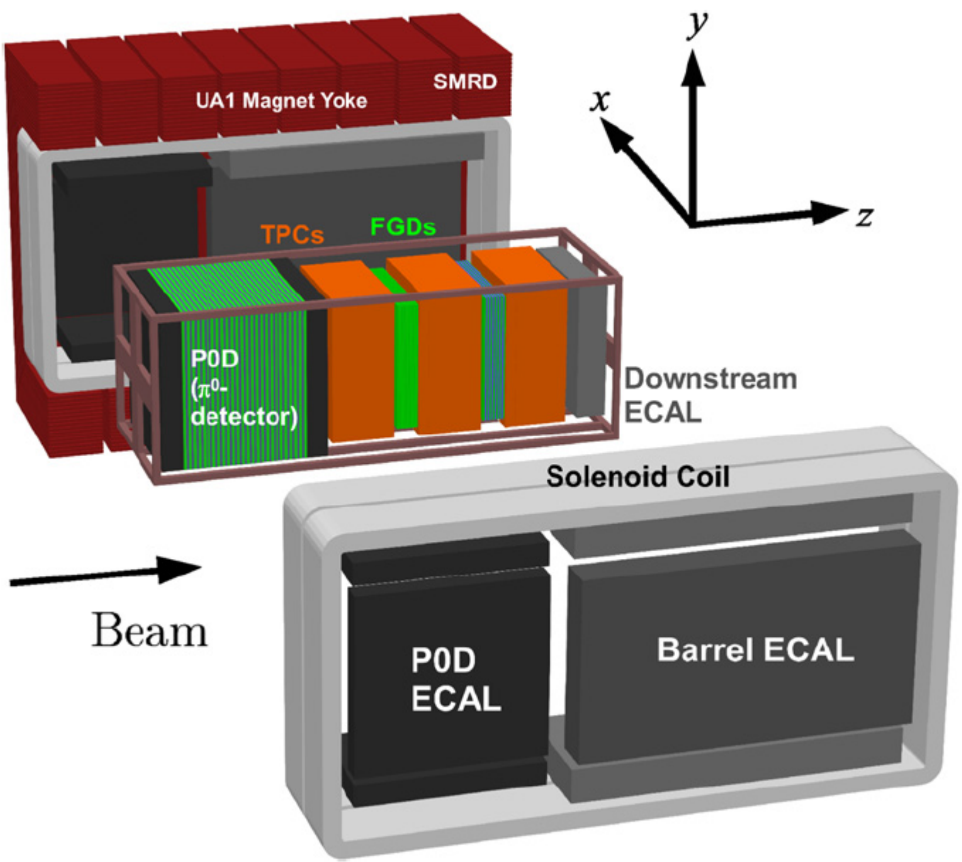
Second generation long baseline experiment
- Off axis beam to narrower the beam





6. T2K experiment

Second generation long baseline experiment
- Off axis beam to narrower the beam
- Complex near detector to maximize scientific capability



P0D (pi 0 detector)
- water target
- organic scintillator + WLS fiber
- MPPC readout

TPC (time projection chamber)
- argon gas TPC

FGD (fine grained detector)
- organic scintillator + WLS fiber
- MPPC readout

ECAL (electromagnetic calorimeter)
- lead foil
- organic scintillator + WLS fiber
- MPPC readout

SMRD (side muon range detector)
- metal york
- organic scintillator + WLS fiber
- MPPC readout

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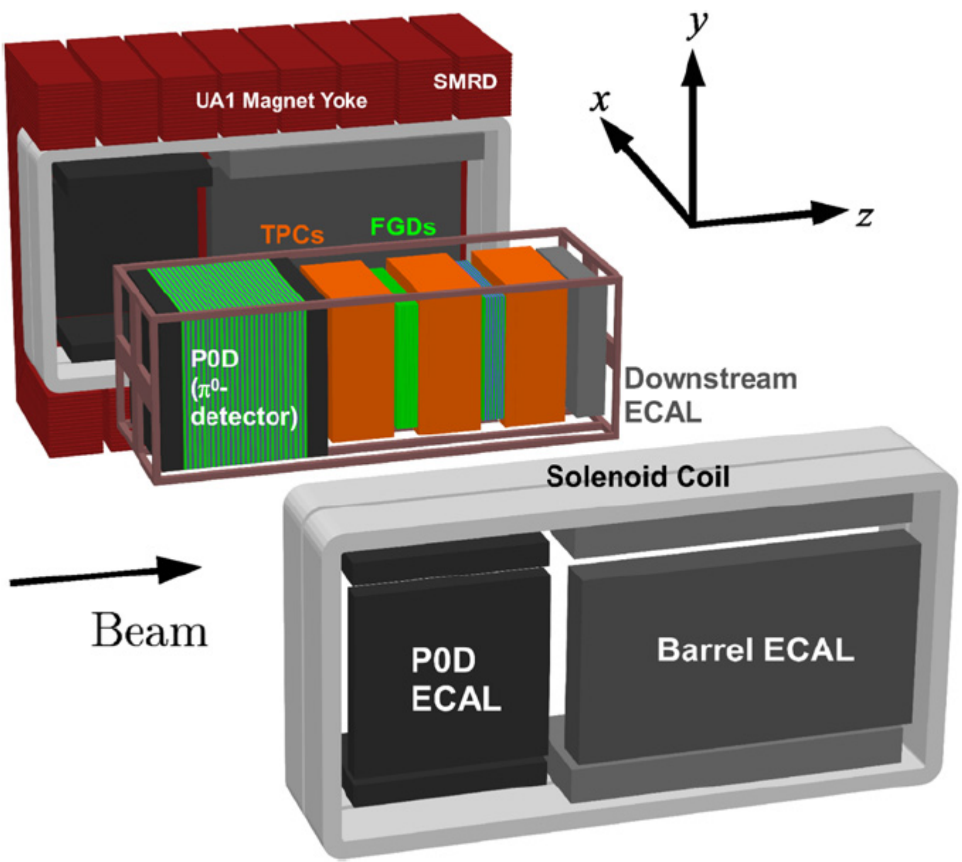

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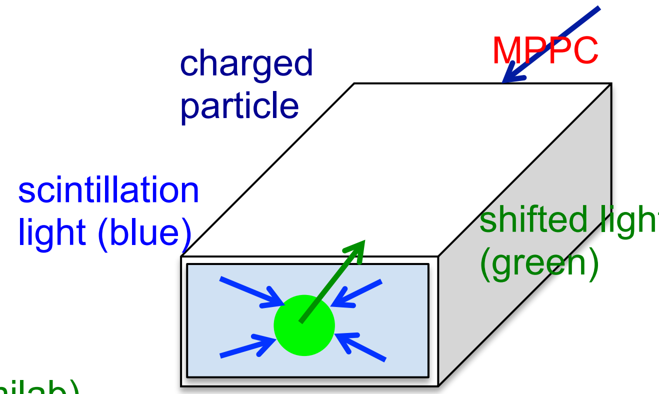
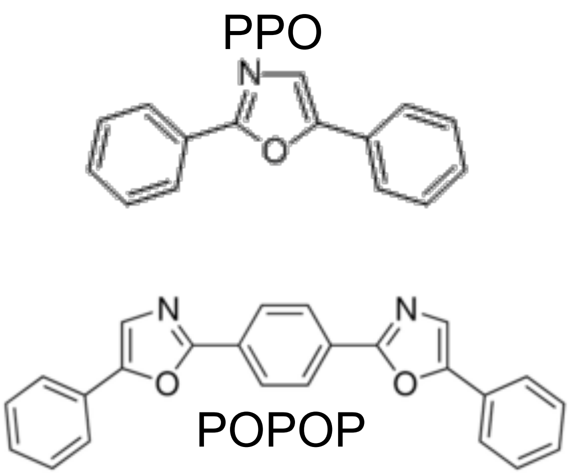
6. T2K experiment

Organic scintillator
- polystyrene base
- 1% PPO and 0.03% POPOP
- TiO2 reflector is merged
- ~20PE for MIP particle
- K2K, MINOS, SciBooNE, MINERvA, T2K,...

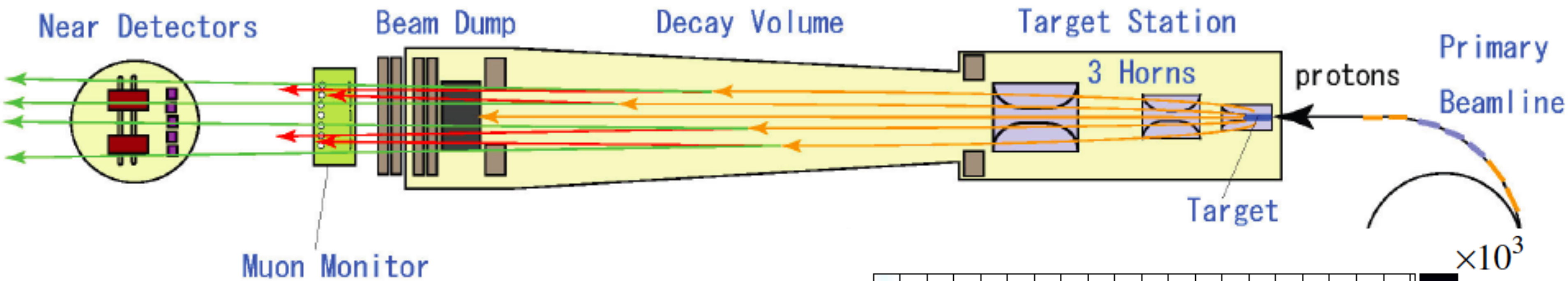


Extruded scintillator production machine (Fermilab)

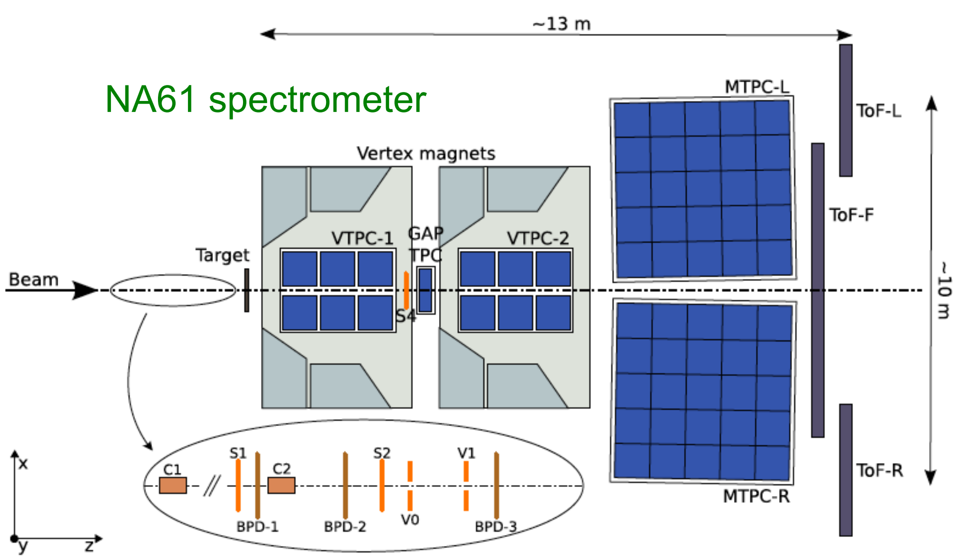


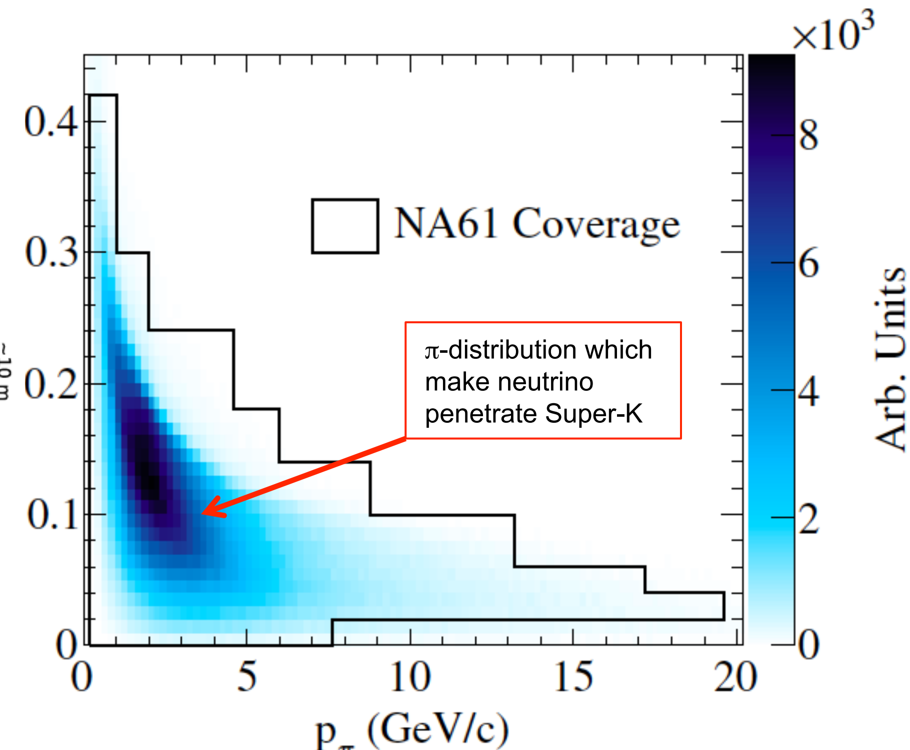
6. T2K experiment

Second generation long baseline experiment
- Off axis beam to narrower the beam
- Complex near detector to maximize scientific capability
- Precise beam prediction based on high precision hadron measurement



NA61 spectrometer





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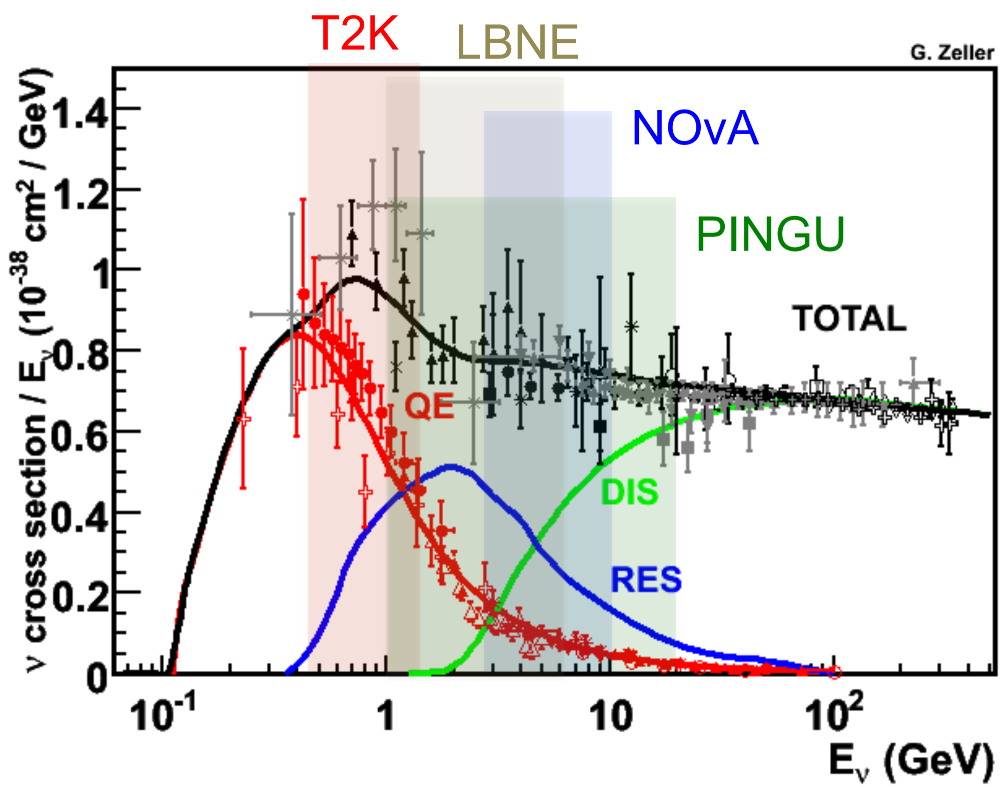
Tepp

T2K, PRD87(2013)012001, NIMA659(2011)106
NA61, PRD87(2013)012001

6. T2K experiment

Second generation long baseline experiment
- Off axis beam to narrower the beam
- Complex near detector to maximize scientific capability
- Precise beam prediction based on high precision hadron measurement
- Maximize external cross section data to constrain cross section systematic errors

Neutrino cross section around 1-10 GeV is very important for T2K, NOvA, LBNE, PINGU, all of them!
- nuclear effect is significant
- many different process contribute
- hadronic predictions are important



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T2K, PRD87(2013)012001, NIMA659(2011)106
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6. T2K experiment

Second generation long baseline experiment

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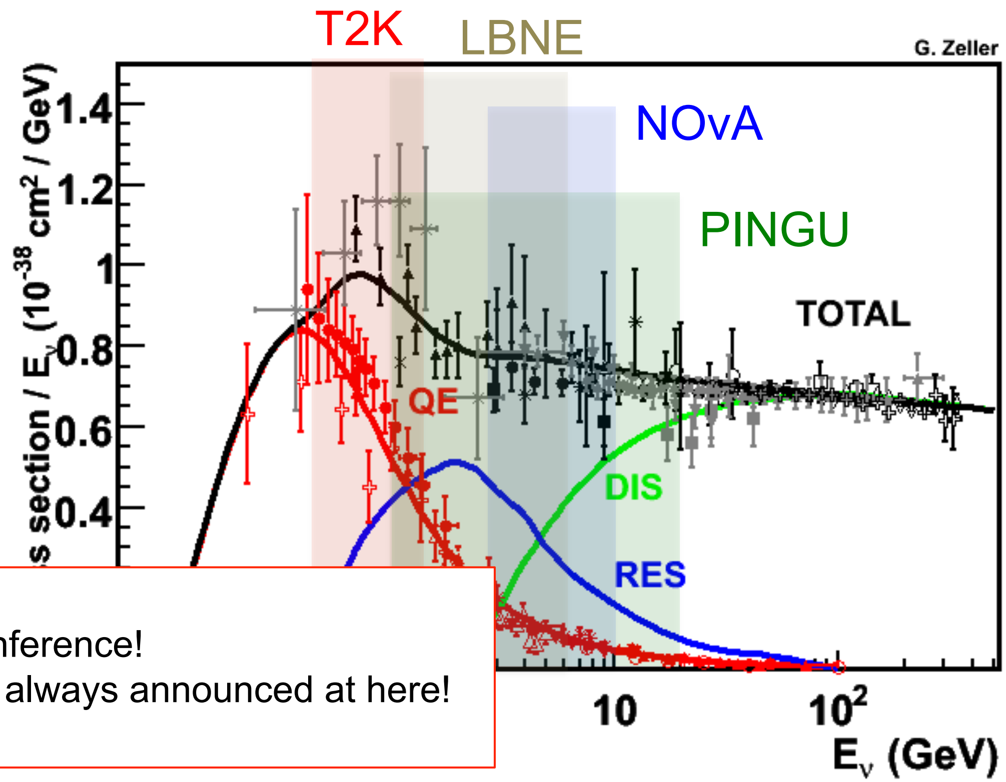

NuInt 14, in London (May 19-24)
- most exciting neutrino cross section conference!
- latest neutrino cross section results are always announced at here!
- please mark your calendar!

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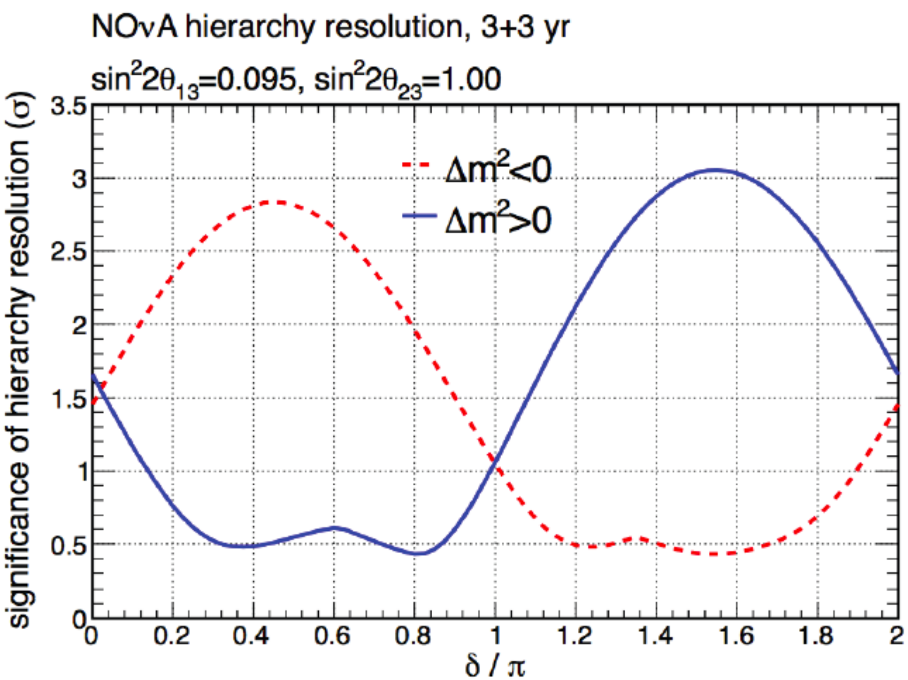
Muether, NNN'13
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=17

6. NOvA sensitivity

Massive plastic tubes with liquid scintillator

- Due to longer baseline (=stronger matter effect), NOvA has better sensitivity for mass hierarchy.



Muether, NNN'13
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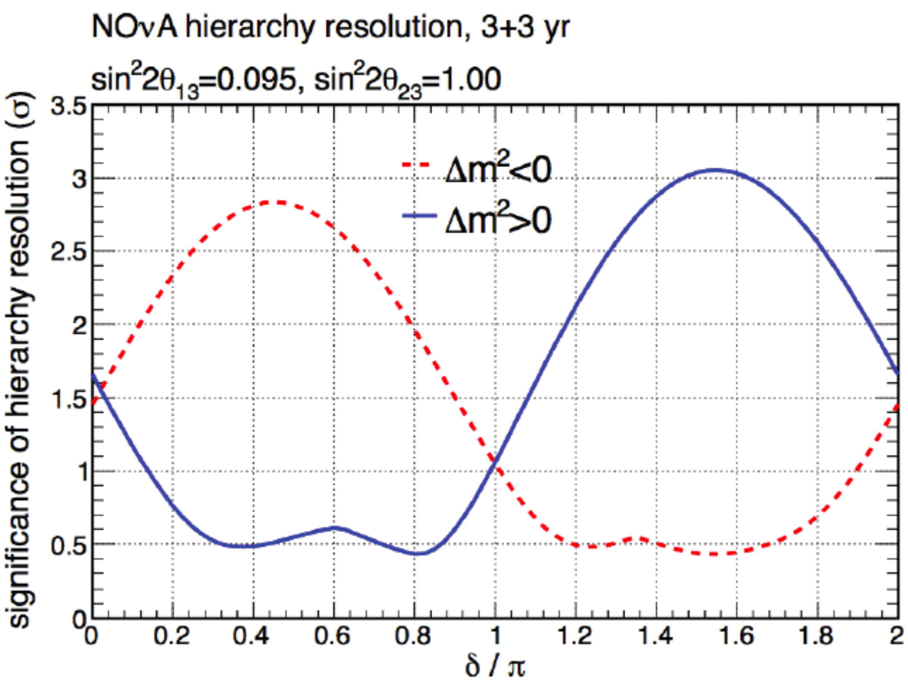
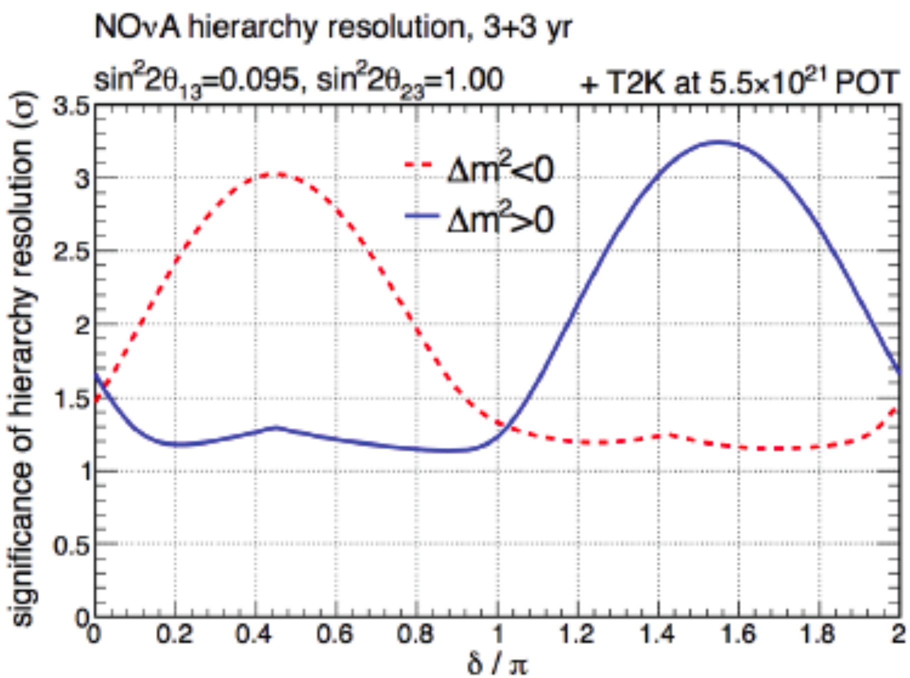
6. NOvA sensitivity

Massive plastic tubes with liquid scintillator

- Due to longer baseline (=stronger matter effect), NOvA has better sensitivity for mass hierarchy.
- Combining with T2K improves sensitivity.





6. Theorists are always wrong

(Murayama, Neutrino 2006)

Solution of solar neutrino problem is SMA, because it's pretty
→ wrong, LMA is the solution

Natural scale of neutrino mass is 10-100 eV^2, because it's cosmologically interesting
→ wrong, much smaller

Atmospheric neutrino anomaly is not neutrino oscillation, because it requires large mixing angle even though CKM matrix V_{cb} ~ 0.04
→ wrong, PMNS matrix has big off-diagonals

Bet your money to the other side from what theorists say!

Kopp,Fermilab theory seminar (2012)
http://theory.fnal.gov/seminars/seminars.html

1. Neutrino oscillations

Wave packet formalism
- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2 \xi^2 \left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2}\right],$$

Beuthe,Phys.Rept.375(2003)105

Five terms:

- Oscillation ($L^{\rm osc}_{jk} = 4\pi E/\Delta m^2_{jk}$)
- Decoherence during propagation
- Decoherence at production/detection
- Localization: Typically requires size of neutrino wave packet σ_x smaller than oscillation length (ξ = process-dependent parameter, can also be ~ 0)
- Approximate conservation of average energies/momenta

1. Neutrino oscillations

Wave packet formalism
- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{j,k} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{\rm osc}_{jk}} - \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 - \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2} - 2\pi^2 \xi^2 \left(\frac{\sigma_x}{L^{\rm osc}_{jk}}\right)^2 - \frac{(m_j^2 + m_k^2)^2}{32\sigma_m^2 E^2}\right],$$

Five terms: oscillation term

Beuthe,Phys.Rept.375(2003)105

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i(E_j - E_k)t + i(\vec{p}_j - \vec{p}_k)\vec{x}}$$

$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-2\pi i \frac{L}{L^{\rm osc}_{jk}}\right]$$

$$\simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

Kopp,Fermilab theory seminar (2012)
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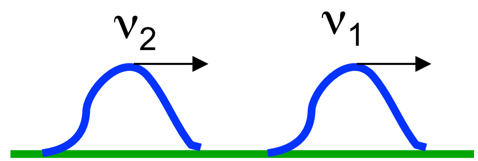
1. Neutrino oscillations

Wave packet formalism
- real formulation of neutrino oscillations



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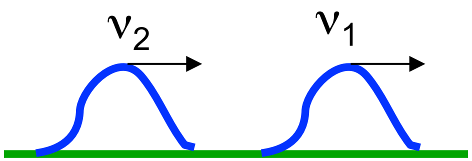
Five terms: decoherence during propagation

Beuthe,Phys.Rept.375(2003)105

$$P_{\alpha\beta}(L) \propto \exp\left[- \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2 \right] = \exp\left[- \left(\frac{L\,\Delta m^2_{jk}}{4\sqrt{2}\sigma_x E^2}\right)^2 \right]$$

Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference (larger Δm^2)
Problem: nobody knows how to estimate σ_x

1. Neutrino oscillations



Wave packet formalism
- real formulation of neutrino oscillations

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Beuthe,Phys.Rept.375(2003)105

$$P_{\alpha\beta}(L) \propto \exp\left[-\left(\frac{L}{L^{\rm coh}_{jk}}\right)^2\right] = \exp\left[-\left(\frac{L\,\Delta m^2_{jk}}{4\sqrt{2}\sigma_x E^2}\right)^2\right]$$

Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference (larger Δm^2)
Problem: nobody knows how to estimate σ_x

e.g.) NuMI beam
10^{-9}cm << σ_x < 10cm (probably bigger than atomic distance, but smaller than detector resolution)

Kopp,Fermilab theory seminar (2012)
http://theory.fnal.gov/seminars/seminars.html

1. Neutrino oscillations

Wave packet formalism
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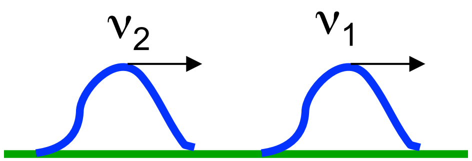

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Beuthe,Phys.Rept.375(2003)105

Coherence length

$$L^{\rm coh}_{jk} = 4\sqrt{2}\sigma_x E^2/\Delta m^2_{jk}$$

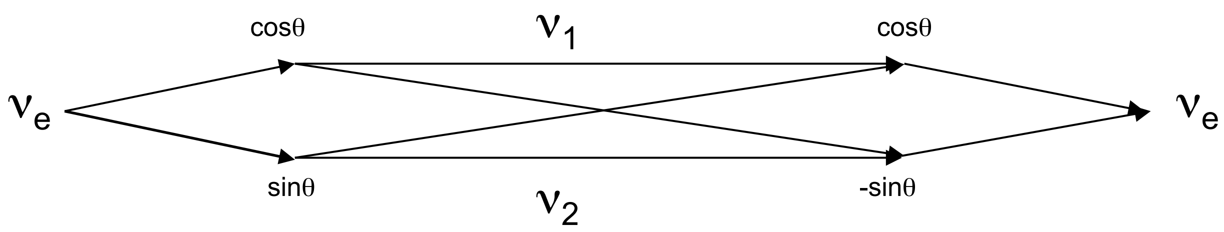
$$\simeq 6 \times 10^5 \text{ light years} \left(\frac{\sigma_x}{10\text{ cm}}\right)\left(\frac{E}{5\text{ GeV}}\right)^2 \left(\frac{2.4\times 10^{-3}\text{ eV}^2}{\Delta m^2_{jk}}\right)$$

1. Neutrino oscillations

Wave packet formalism

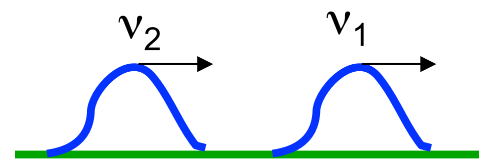
- real formulation of neutrino oscillations

Neutrino oscillation



$P=|A_1+A_2|^2$

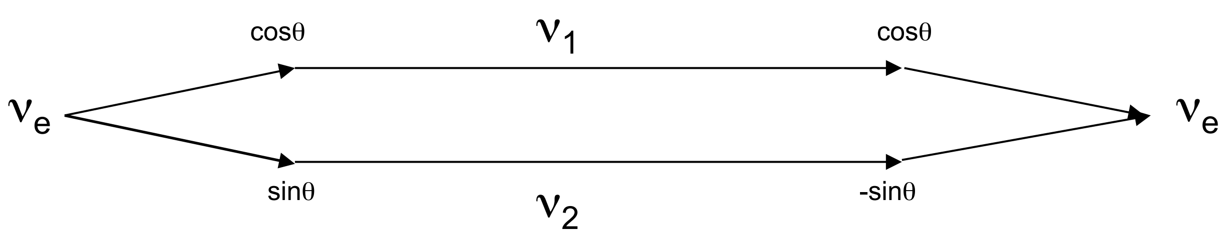
1. Neutrino oscillations



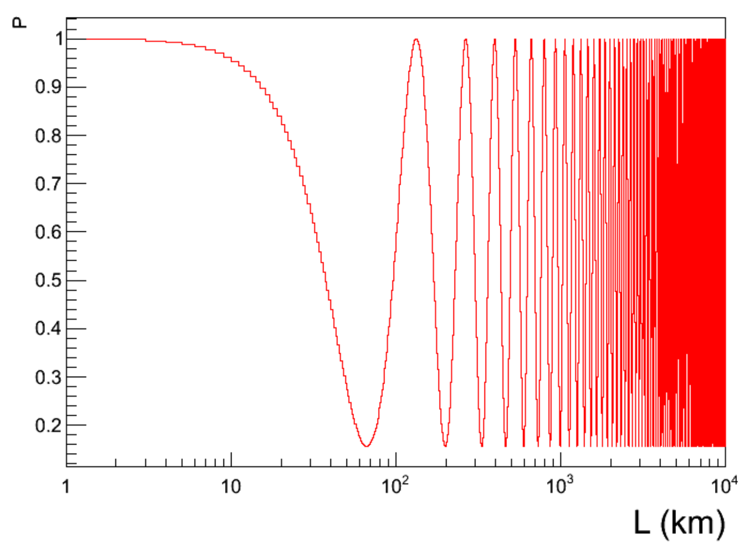
Wave packet formalism

- real formulation of neutrino oscillations

Decoherent neutrino oscillation (time averaged neutrino oscillation)



$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta = 1-\sin^2 2\theta\cdot\frac{1}{2} = 1-\sin^2 2\theta\sin^2\left(\frac{\Delta m^2}{4E}L\right)\Bigg|_{L\to\infty}$$



1. Neutrino oscillations

Wave packet formalism
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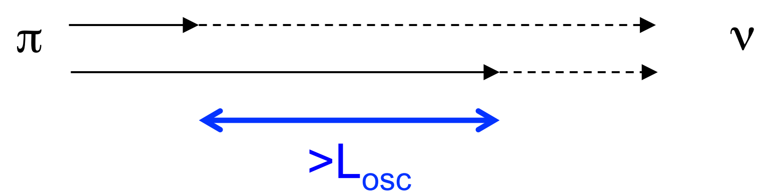
neutrino production uncertainty



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Five terms: decoherence at production/detection

Beuthe,Phys.Rept.375(2003)105

$$P_{\alpha\beta}(L) \propto \exp\left[- \frac{(\Delta m^2_{jk})^2}{32\sigma_m^2 E^2}\right]$$

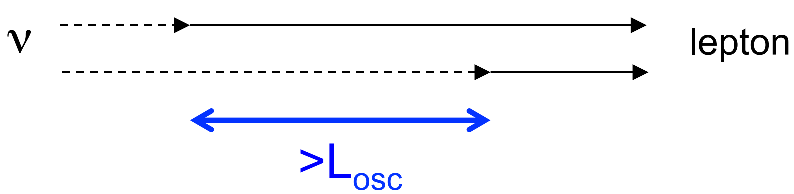
If the production uncertainty is bigger than oscillation length, oscillation doesn't happen (time averaged oscillation)

cf. solar neutrino

1. Neutrino oscillations

Wave packet formalism
- real formulation of neutrino oscillations

neutrino detection uncertainty



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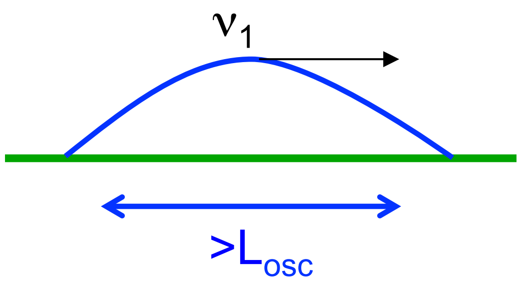

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3. SNO

D_2O target in acrylic vessel
Simultaneously measure 3 channels

$\nu_e + d \rightarrow p + p + e$
- charged current (CC)
- only sensitive to ν_e

$\nu_x + d \rightarrow p + n + \nu_x$
- neutral current (NC)
- sensitive to all flavors

$\nu_e + e \rightarrow \nu_e + e$
- elastic scattering (ES)
- sensitive to all flavors