BREAKTHROUGH PRIZE

2015 was "Year of Neutrinos"

2016 Fundamental Physics Breakthrough Prize
- Koichiro Nishikawa (K2K and T2K)
- Atsuto Suzuki (KamLAND)
- Kam-Biu Luk (Daya Bay)
- Yifang Wang (Daya Bay)
- Art McDonald (SNO)
- Yoichiro Suzuki (Super-Kamiokande)
- Takaaki Kajita (Super-Kamiokande)

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Neutrino physics – Past, Present, and Future

Outline

1. Neutrino physics, the future of particle physics
2. Neutrinos in Standard Model (SM)
3. Neutrino Standard Model (νSM)
    3.1 Before 1998
    3.2 1998 – 2004
    3.3 2005 – 2011
    3.4 2012
    3.5 Current issues
4. Beyond νSM
5. Conclusions

Teppei Katori
Queen Mary University of London
Univ. Catholique de Louvain, Louvain-la-Neuve, Belgium, January 20, 2016

1. Neutrino physics, the future of particle physics

2. Neutrino in Standard Model (SM)

3. Neutrino Standard Model (νSM)

3.1 Before 1998

3.2 1998 – 2004

3.3 2005 – 2011

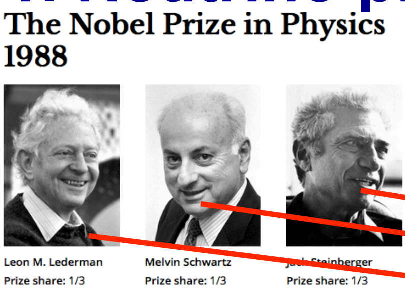
3.4 2012

3.5 Current issues

4. Beyond νSM

5. Conclusions

1. Neutrino physics, the ...



Standard M...

...andard Mo...

3.1 Before 1998

3.2 1998 – 2004

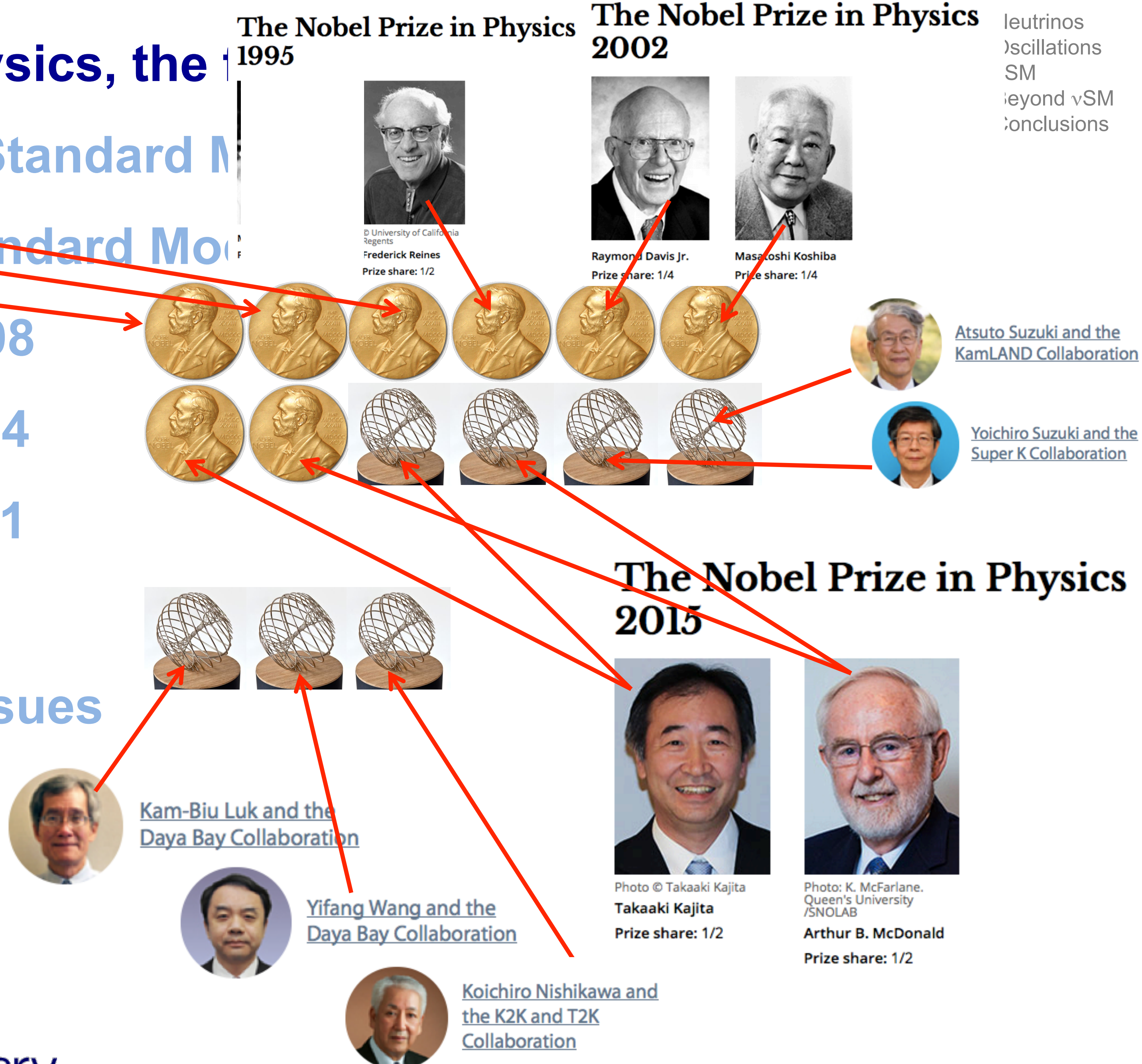
3.3 2005 – 2011

3.4 2012

3.5 Current issues

4. Beyond νSM

5. Conclusions



...leutrinos
...scillations
...SM
...eyond νSM
...onclusions

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discovery of muon neutrino (not covered today)

The Nobel Prize in Physics 1988

Leon M. Lederman
Prize share: 1/3

Melvin Schwartz
Prize share: 1/3

Prize share: 1/3

first detection of neutrino (not covered today)

The Nobel Prize in Physics 1995

Frederick Reines
Prize share: 1/2

The Nobel Prize in Physics 2002

Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

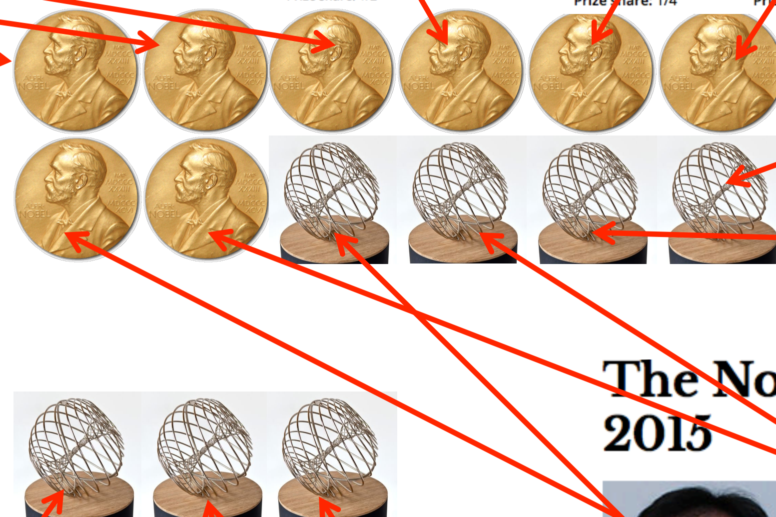
discovery of solar neutrino problem

KamLAND

Atsuto Suzuki and the KamLAND Collaboration

Yoichiro Suzuki and the Super K Collaboration

Super-Kamiokande



3.1 Before 1998

3.2 1998 – 2004

3.3 2005 – 2011

3.4 2012

3.5 Current issues

4. Beyond νSM

5. Conclusions

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

discovery of neutrino oscillations

Kam-Biu Luk and the Daya Bay Collaboration

Yifang Wang and the Daya Bay Collaboration

Daya Bay

Koichiro Nishikawa and the K2K and T2K Collaboration

K2K and T2K

Queen Mary
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1. Neutrino physics, the future of particle physics

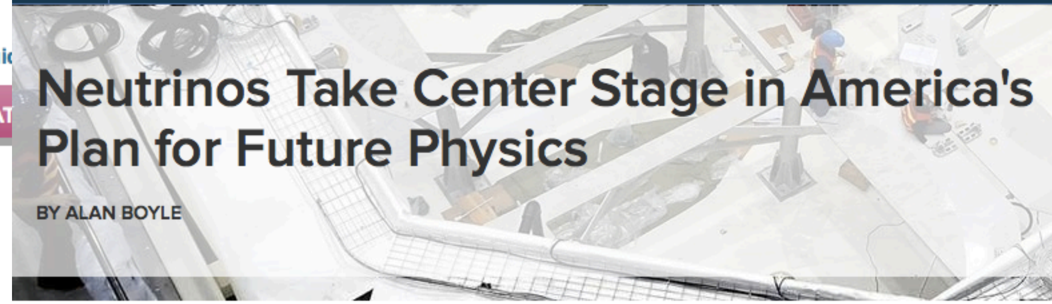
1. Neutrino physics, the future of particle physics

Neutrinos top list of targets for US particle physics

› 15:00 22 May 2014 by Jessica Orwig
› For similar stories, visit the US national issues and Quantum World Topic Guides

Neutrino physics in the US should receive a budget boost, according to recommendations by the Particle Physics Project Prioritization Panel (P5) – but dark matter detectors may be delayed.

P5, an international group of distinguished experts, has issued its long-awaited



Neutrinos Take Center Stage in America's Plan for Future Physics

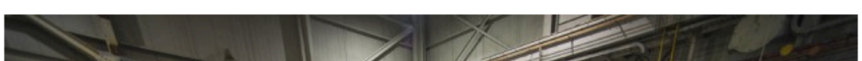
BY ALAN BOYLE

US particle physics roadmap: Build facilities for neutrinos and muons

But goals face a budget crunch before they leave the starting line.

by John Timmer - May 24 2014, 5:10am JST

PHYSICAL SCIENCES SCIENCE POLICY AND EDUCATION 45



Physics panel to feds: Beam us up some neutrinos

Seth Borenstein AP Science Writer

UPDATED: 05/22/2014 02:16:04 PM EDT

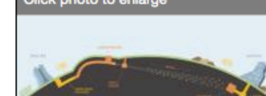
COMMENTS

WASHINGTON (AP) — The U.S. should build a billion-dollar project to beam ghostlike subatomic particles 800 miles underground from Chicago to South Dakota, a committee of experts told the federal government Thursday.

That would help scientists learn about these puzzling particles, called neutrinos, which zip right through us.

The proposed invisible neutrino beam would be the biggest U.S.

Click photo to enlarge



This undated handout graphic provided by Fermilab in Chicago shows a proposed particle... (AP)

1. P5 report (Particle Physics Project Prioritization Panel)

25 of prominent physicists made a list of recommendations for the future directionality of US particle physics

Contents

Table 1
Summary of Scenarios

	Scenarios			Science Drivers					
Project/Activity	Scenario A	Scenario B	Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

1. P5 report (Particle Physics Project Prioritization Panel)

25 of prominent physicists made a list of recommendations for the future directionality of US particle physics

Contents

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

CERN → LHC
Fermilab → Neutrinos

Table 1
Summary of Scenarios

	Scenarios			Science Drivers					
			Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
			Y					✓	I
			Y	✓		✓		✓	E
			Y, enhanced		✓			✓	I,C
			Y	✓		✓		✓	E
			N		✓				I
			N		✓				I
			Y		✓		✓		C
			Y			✓			C
			Y		✓	✓	✓	✓	All
			Y, enhanced	✓	✓	✓		✓	E,I
			Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

1. CERN-USA, KEK-ICRR…

Political pacts are made to strengthen large collaborations…

CERN - USA

KEK - ICRR

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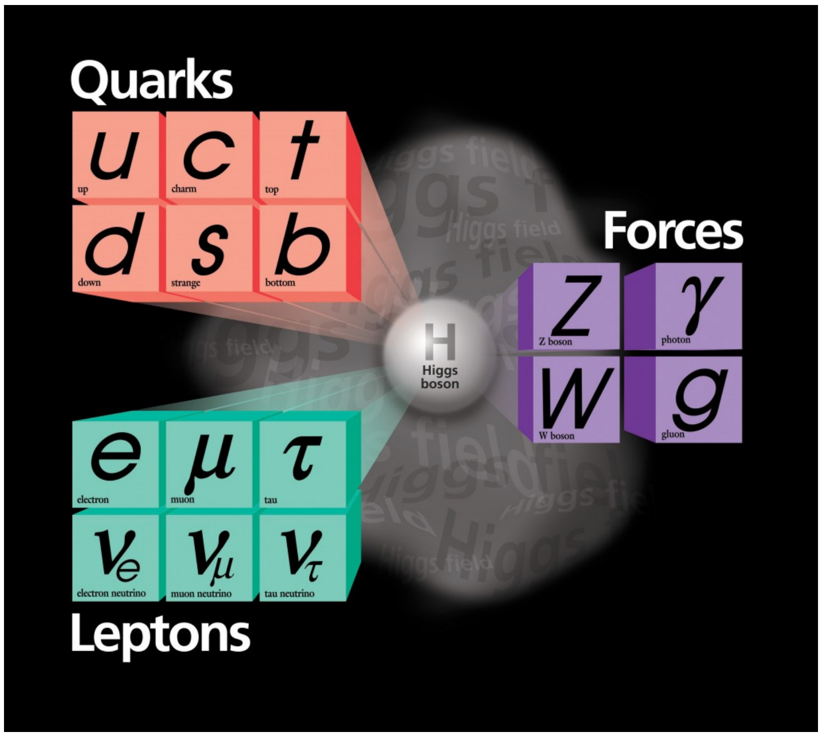
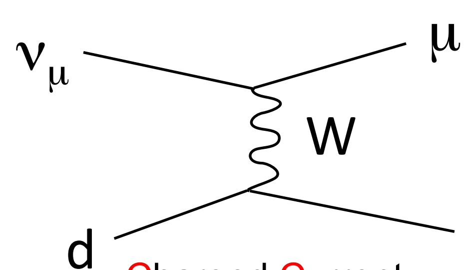
2. Neutrinos in Standard Model (SM)

SM describes 6 quarks and 6 leptons and 3 forces and Higgs boson.

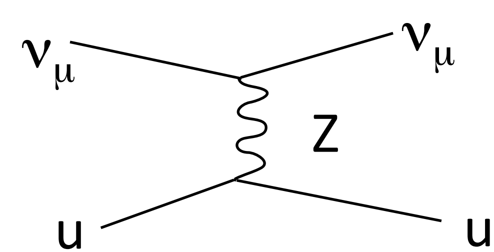


Neutrinos are special because,

1. they only interact with weak nuclear force.



Charged Current (CC) interaction
"W-boson exchange"



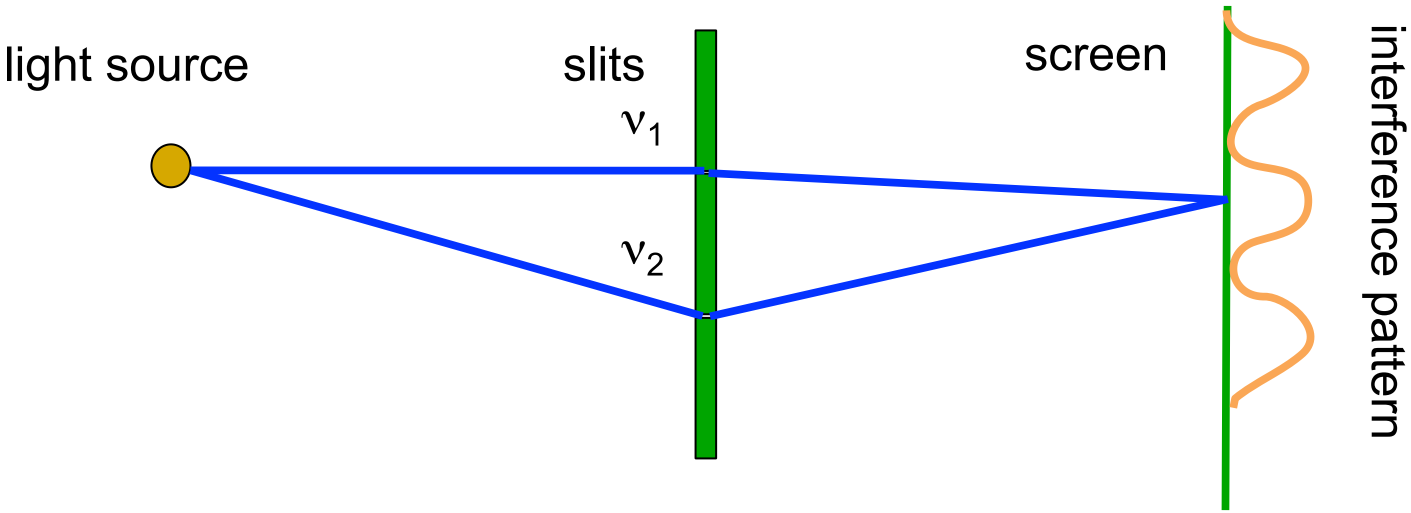
Neutral Current (NC) interaction
"Z-boson exchange"

2. interaction eigenstate is not Hamiltonian eigenstate (propagation eigenstate). Thus propagation of neutrinos changes their species, called neutrino oscillation.

Queen Mary University of London

1. Neutrino oscillations

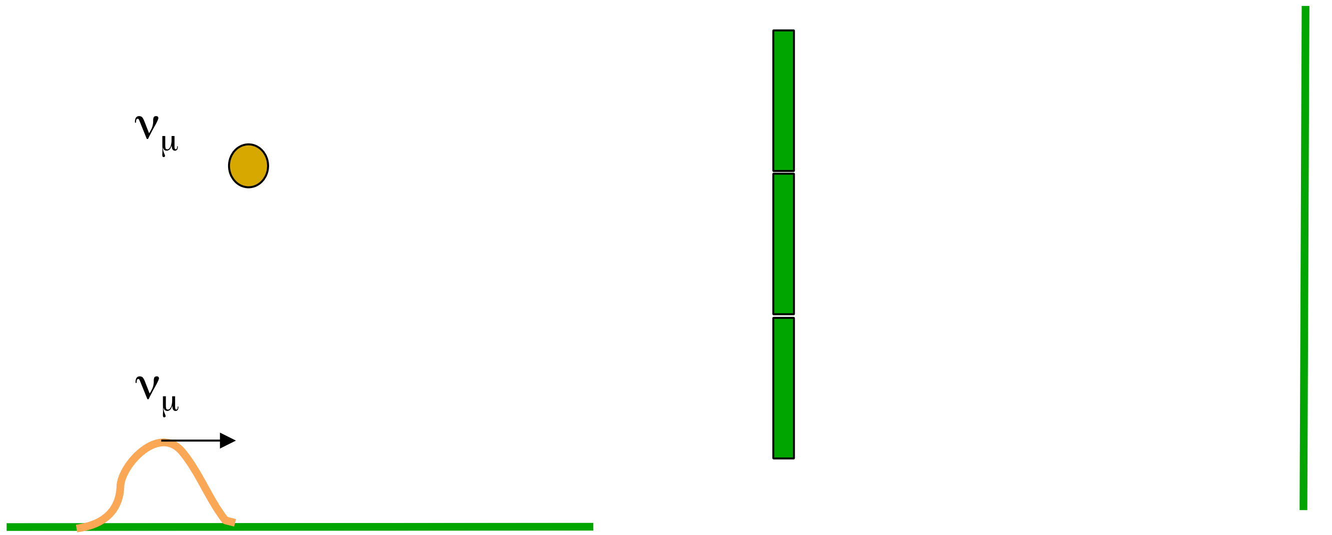
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

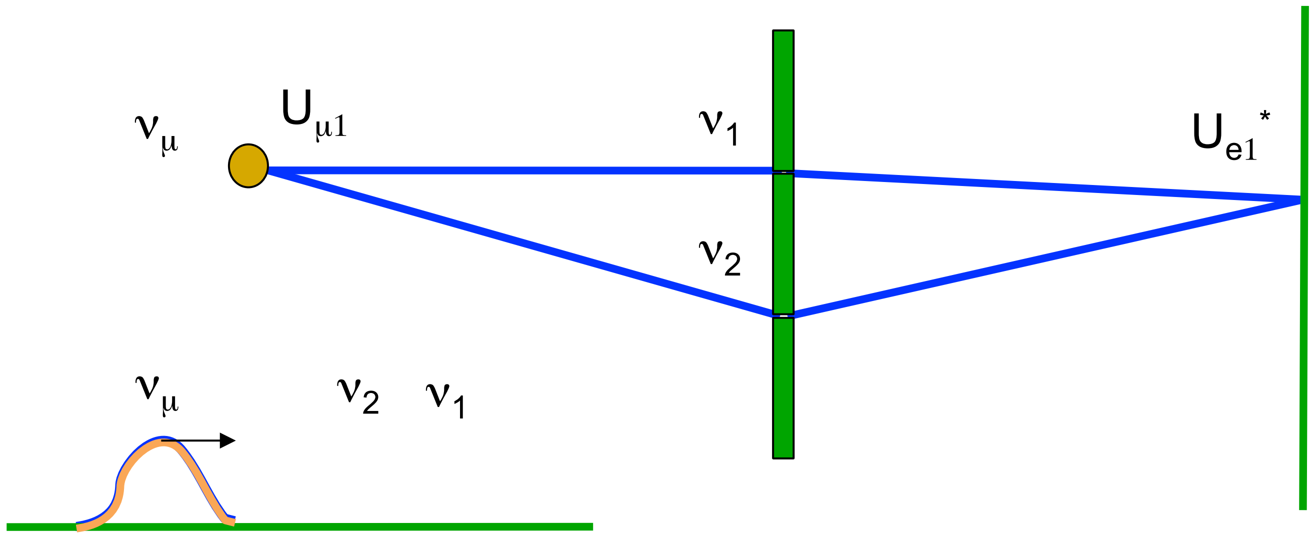
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

1. Neutrino oscillations

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.

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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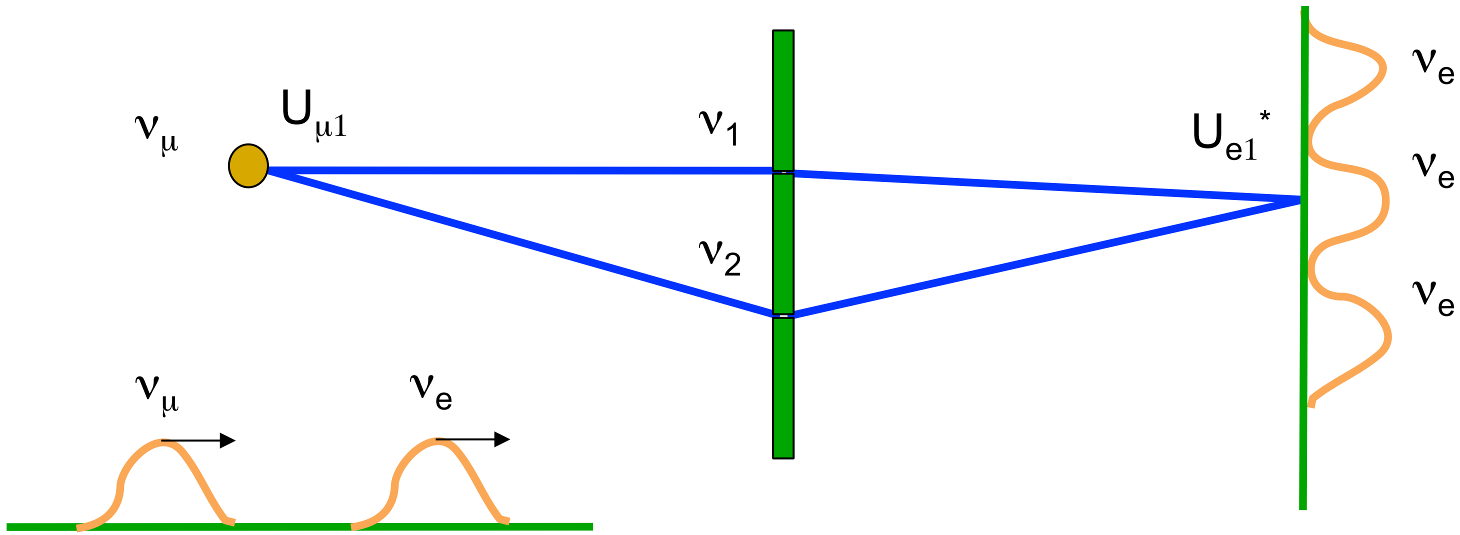


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

The detection may be different flavor (neutrino oscillations).

2. 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,

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

2. Neutrino oscillations

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

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

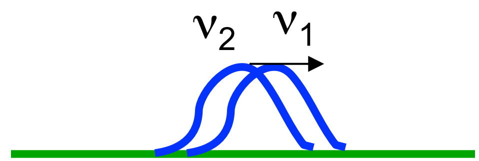
Therefore, 2 massive neutrino oscillation model is ($\Delta m^2=|m_1^2-m_2^2|$)

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

After adjusting the unit, 2 neutrino oscillation formula

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

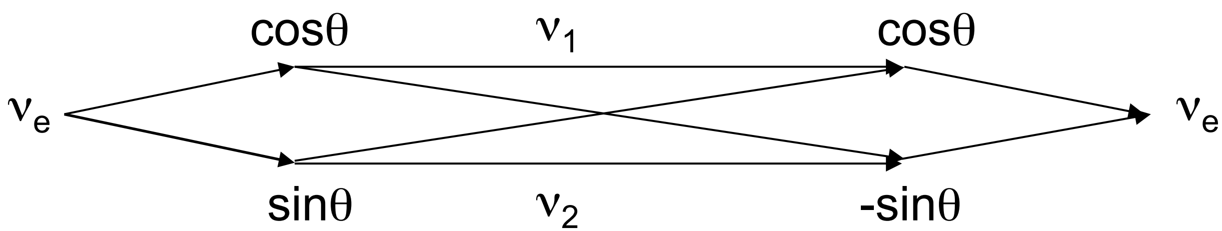
2. Neutrino oscillations



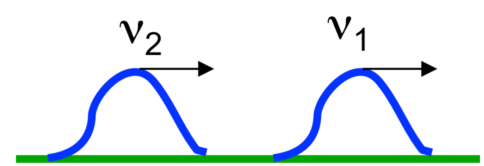
Wave packet formalism

- real formulation of neutrino oscillations

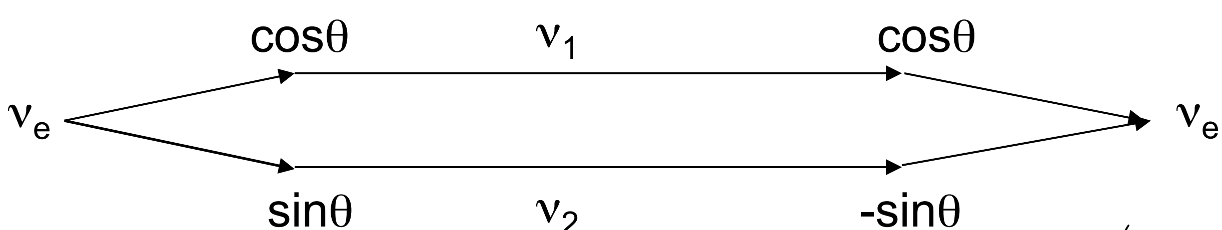
Neutrino oscillation

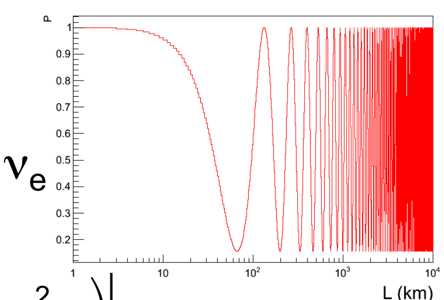


$$P=|A_1+A_2|^2 = 1-\sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$



Neutrino mixing (time averaged neutrino oscillation)



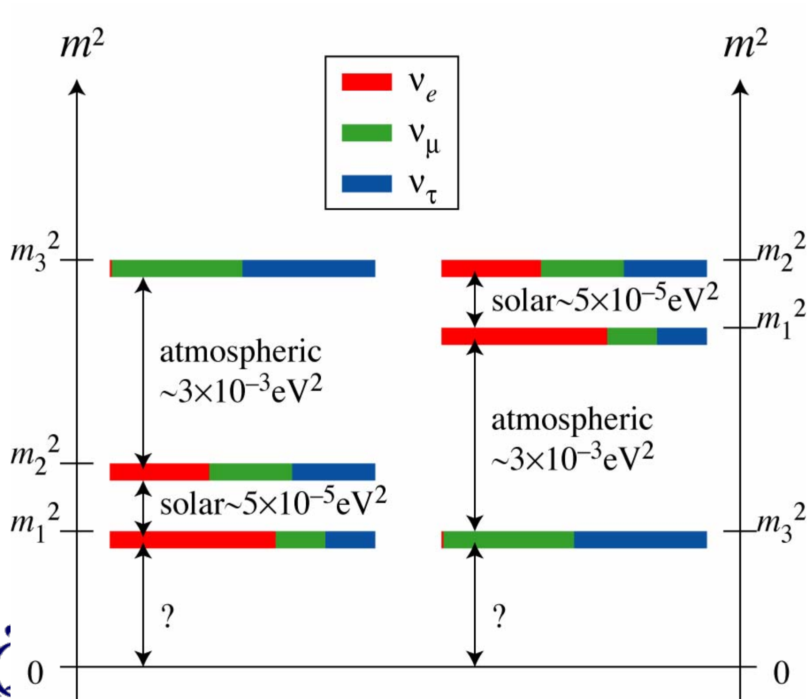


$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta = 1-\sin^2 2\theta\cdot\frac{1}{2} = 1-\sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)\Big|_{L\to\infty}$$

2. Neutrino Standard Model (νSM)

Through series of neutrino oscillation results, 3 massive neutrinos with the Standard Model (νSM) is well established.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$



1. Δm^2_{atm} and Δm^2_{sol}
2. mass ordering of them
3. absolute neutrino mass

Free parameters
- 3 neutrino masses
- 3 mixing angles
- 1 Dirac phase (δ_{CP})
- Dirac or Majorana
- 2 Majorana phases

Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

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

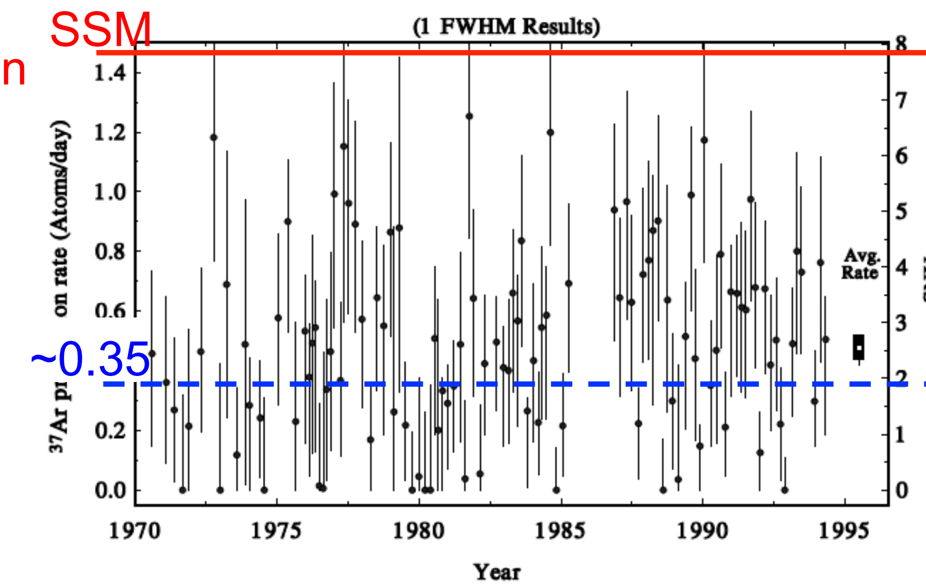
3.1 Solar neutrino problem

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!)

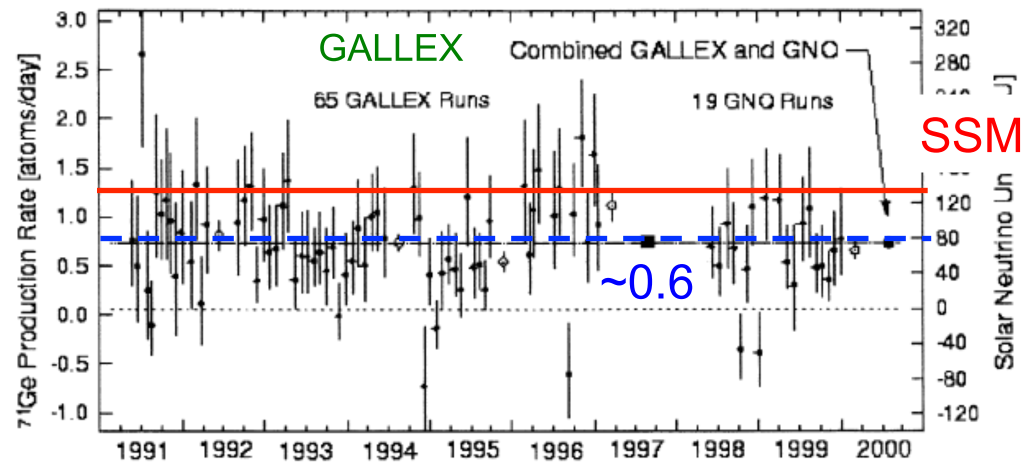
GALLEX, PLB490(2000)16
SAGE, J.Expt.Theor.Phys.95(2002)181

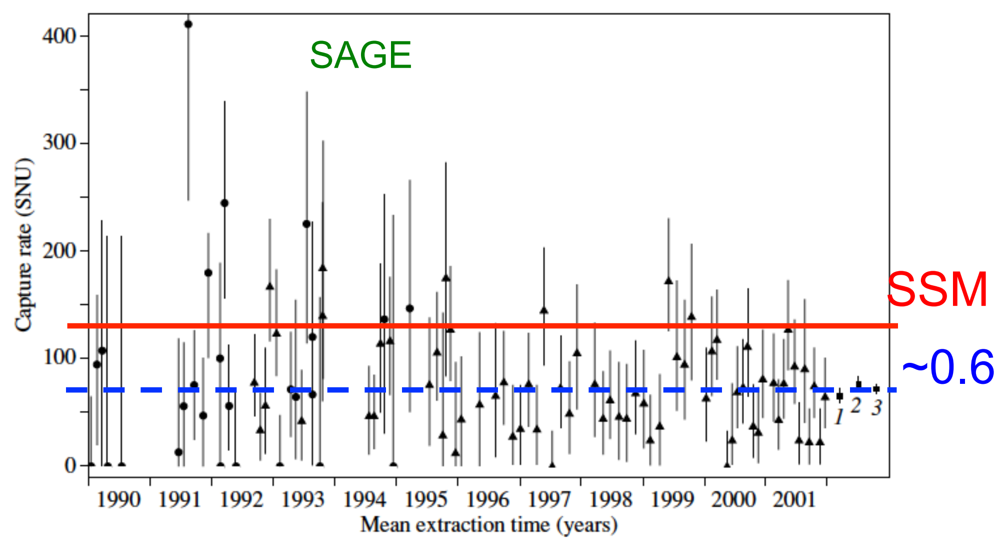
3.1 Gallium experiments

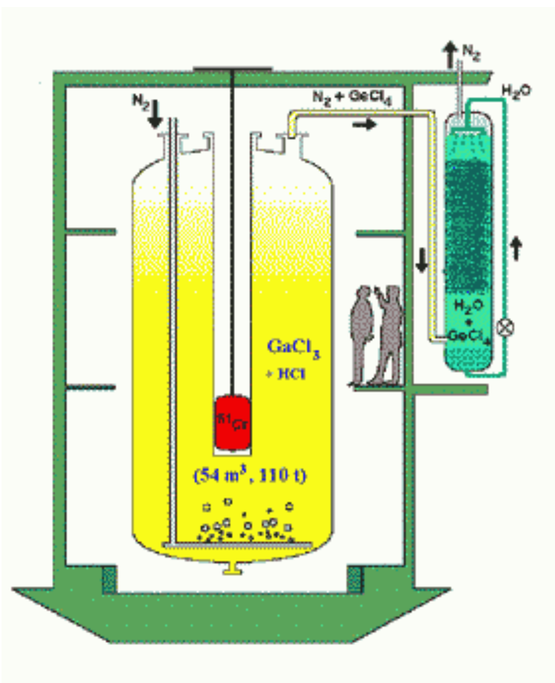
3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

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

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







3.1 Kamiokande II

3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

Atmospheric neutrino

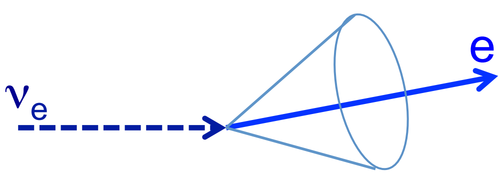
$$\nu_e + X \rightarrow e + X'$$
$$\nu_\mu + X \rightarrow \mu + X'$$

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

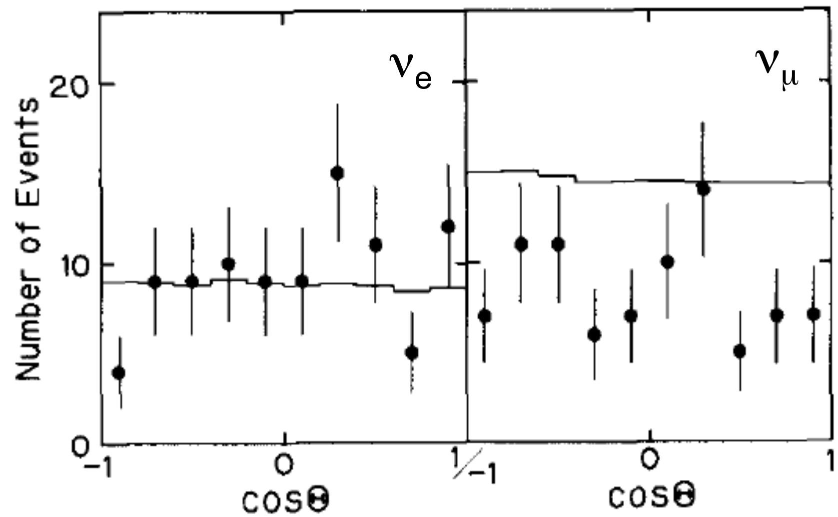
Solar neutrino

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

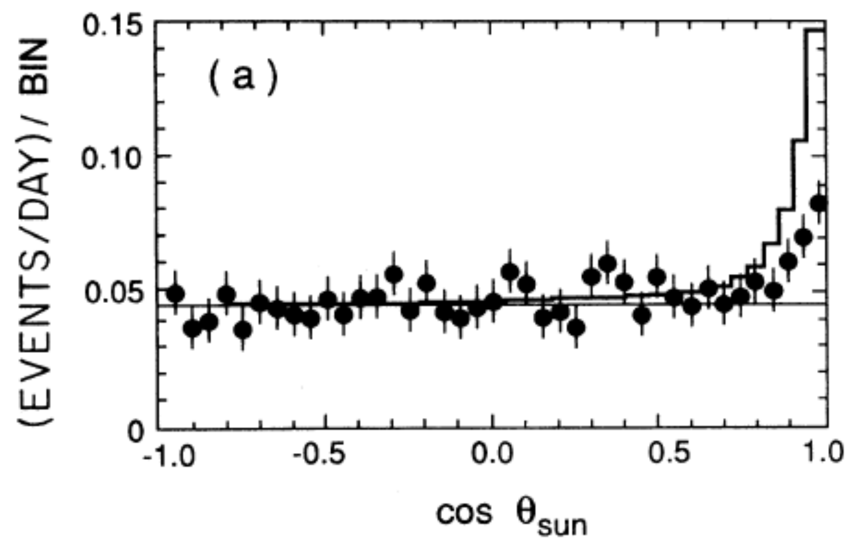
- Direction of recoil electron (~direction of neutrino) is consistent from the Sun.



atmospheric neutrinos



solar-ν angular distribution



By the way they also observed 12 events from Type II Supernova (and got Nobel prize)

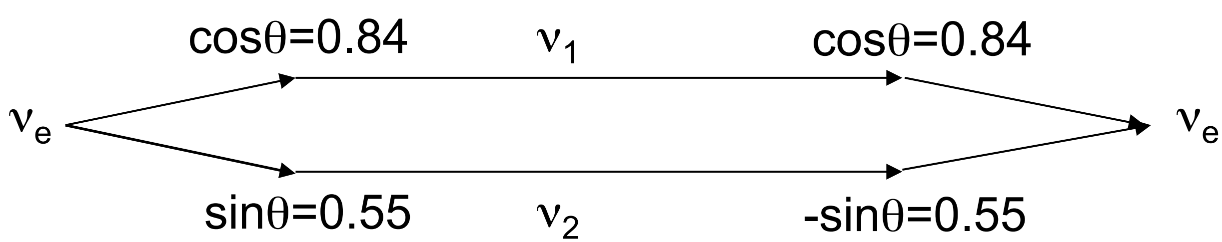
Queen Mary University of London

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

3.1 Neutrino oscillation in matter

3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

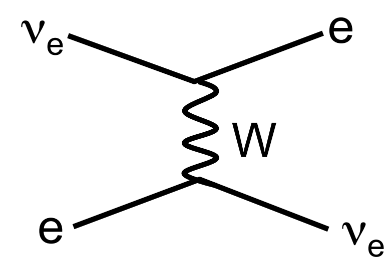
$$H_{eff} \rightarrow \begin{pmatrix} \frac{m^2_{ee}}{2E} & \frac{m^2_{e\mu}}{2E} \\ \frac{m^2_{e\mu}}{2E} & \frac{m^2_{\mu\mu}}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m^2_1}{2E} & 0 \\ 0 & \frac{m^2_2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$



$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta \sim 0.6$$

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

3.1 Neutrino oscillation in matter

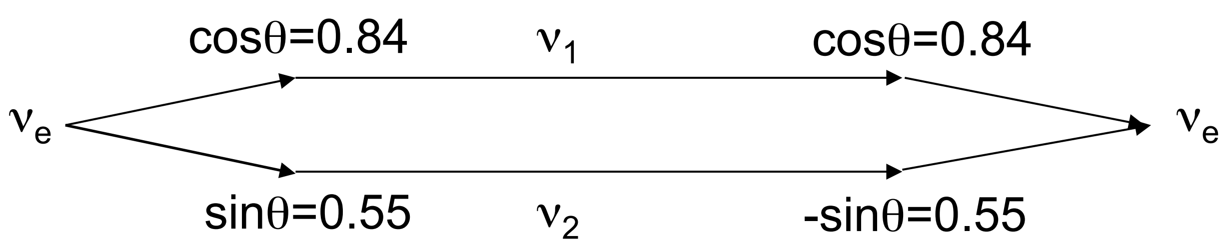


3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

Wolfenstein term

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

No matter effect If density and/or energy is too low

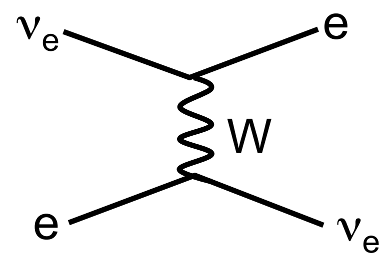


$$P=|A_1|^2+|A_2|^2 = \cos^4\theta+\sin^4\theta \sim 0.6$$

Queen Mary
University of London

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

3.1 Neutrino oscillation in matter



3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

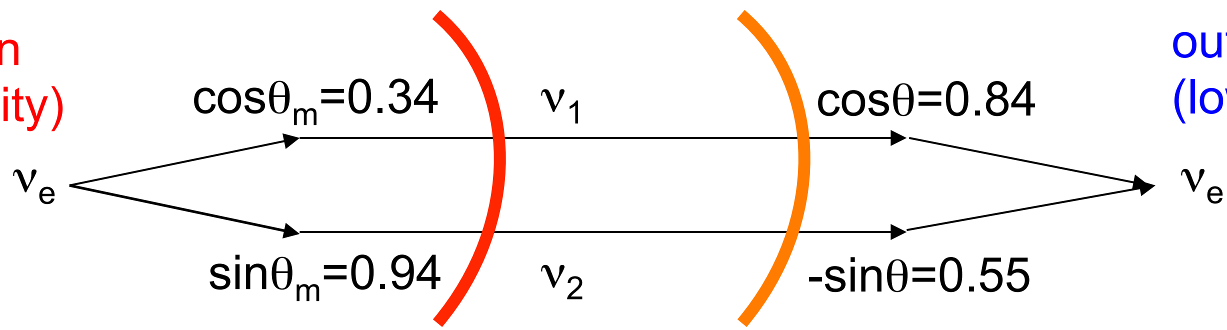
Wolfenstein term

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

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

core of Sun
(high density)

outside of Sun
(low density)



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

~0.35 (MSW) ~0.6 (no MSW)

3.1 Before 1998

There are 3 major discoveries

- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

3.2 1998-2004

2 major problems are solved

- Super-Kamiokande solved atmospheric neutrino anomaly

- SNO solved solar neutrino problem

3.2 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

3.2 Super-Kamiokande

50 kton water Cherenkov detector
- ~40m height, ~40m diameter
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Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

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Photo © Takaaki Kajita

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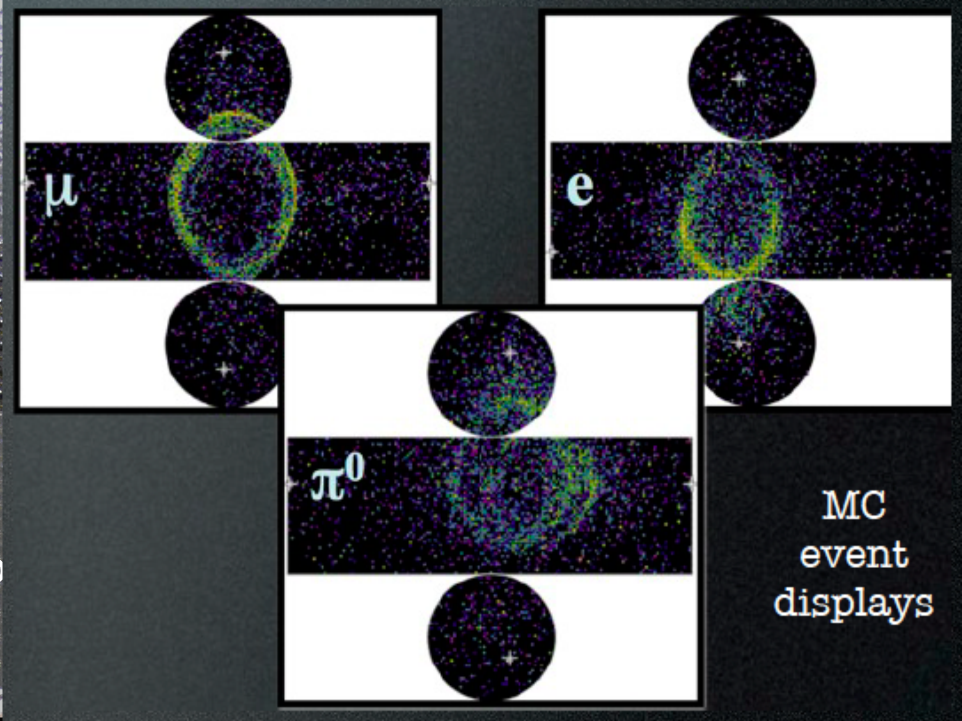
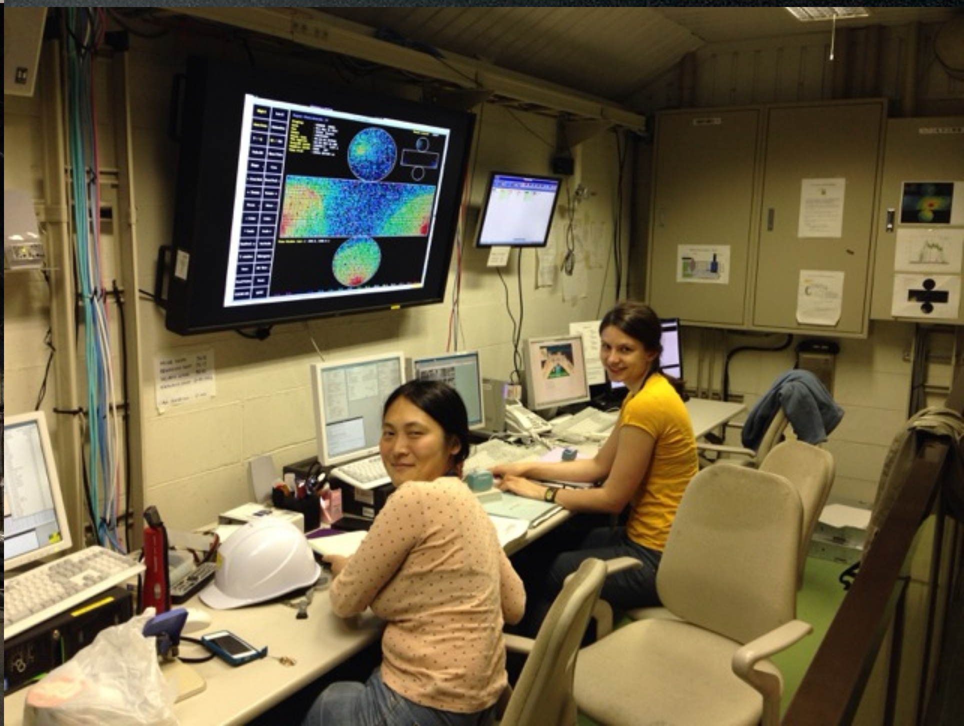
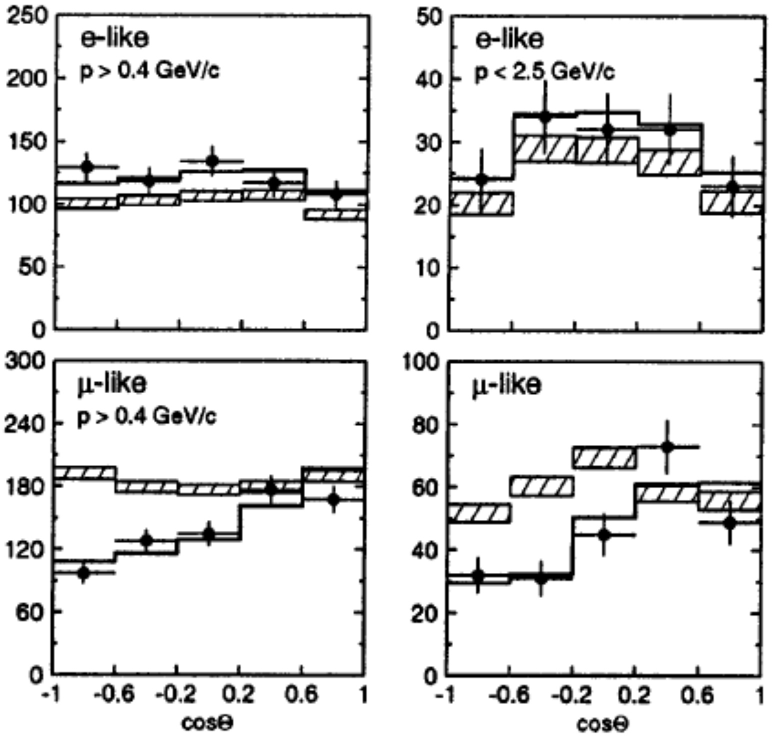


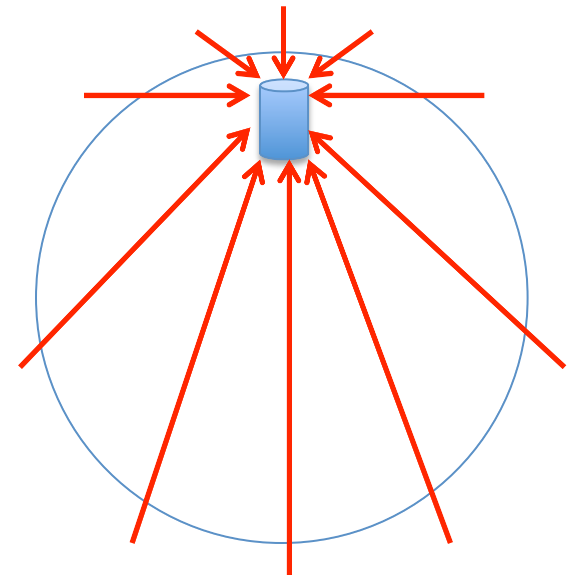


3.2 Super-Kamiokande

Atmospheric neutrino anomaly is solved

Up-Down asymmetry
Atmospheric neutrino anomaly is function of distance

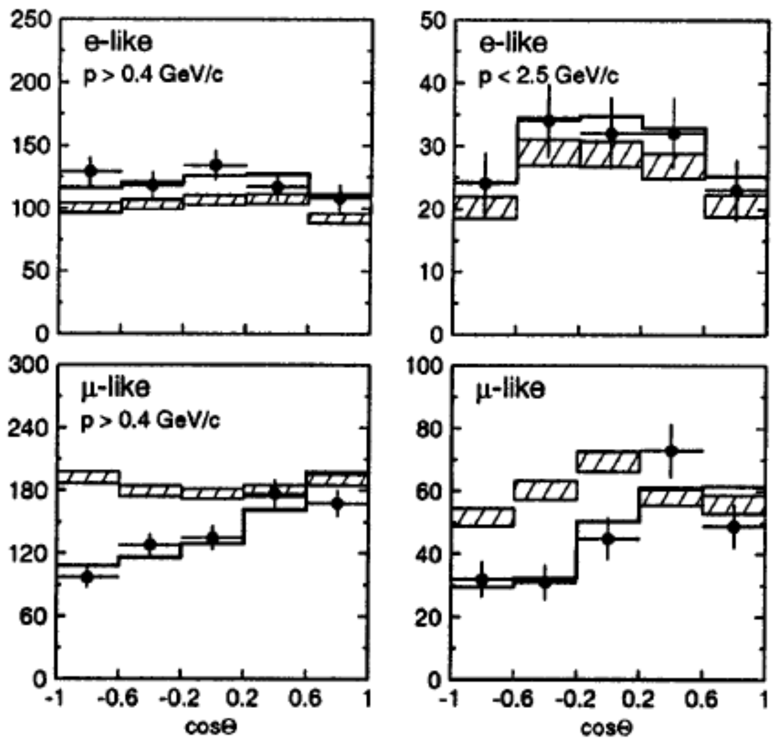


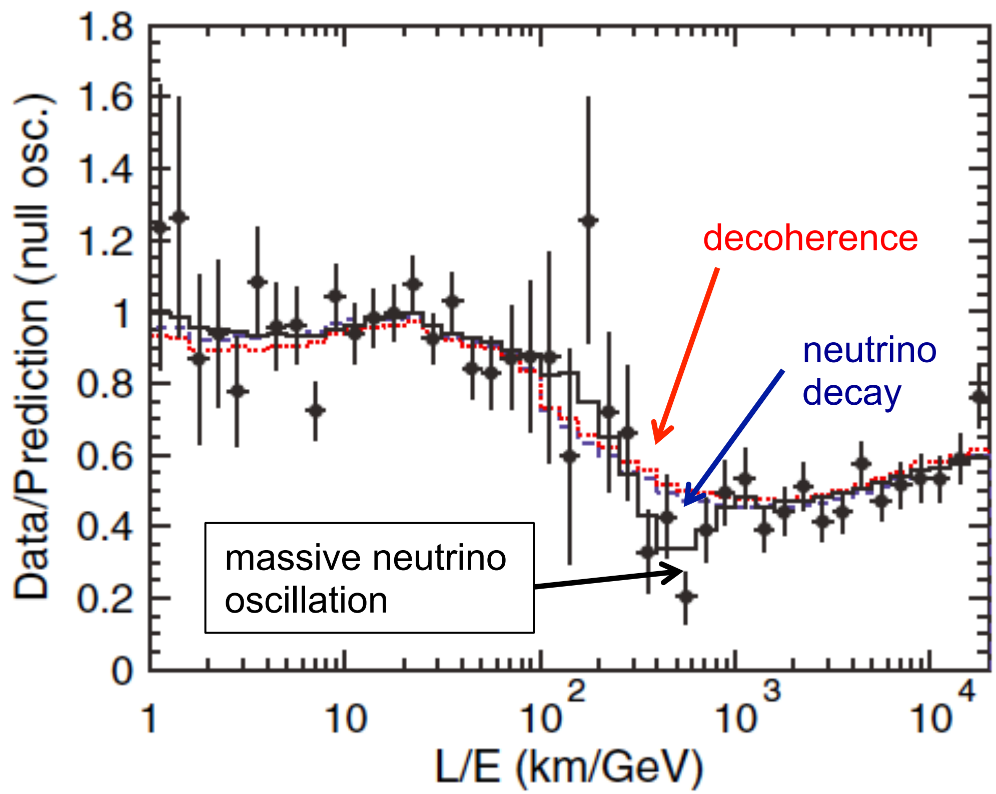


3.2 Super-Kamiokande

Atmospheric neutrino anomaly is solved

L/E dependence
Strong evidence of neutrino oscillation by mass term





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3.2 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)
- sensitive to all flavors

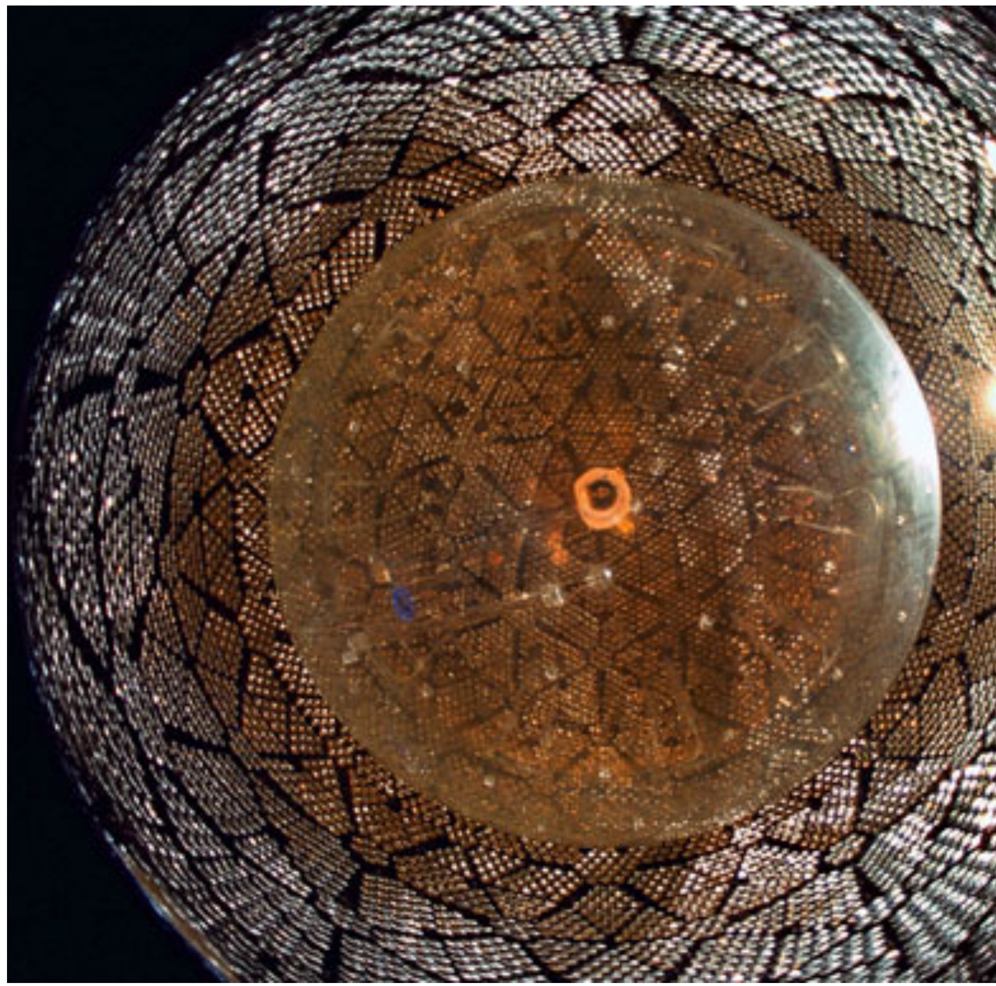

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

Queen Mary University of London

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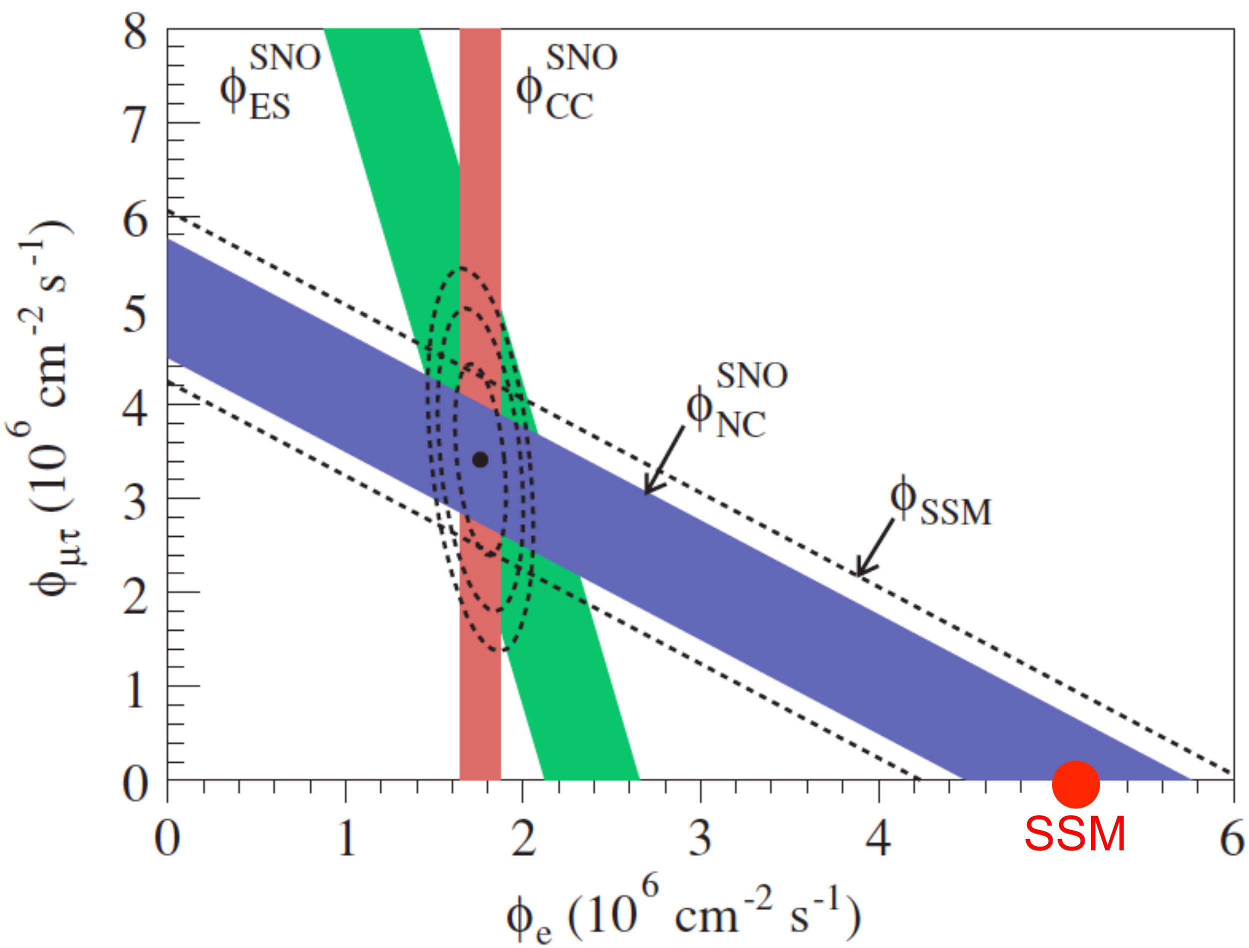

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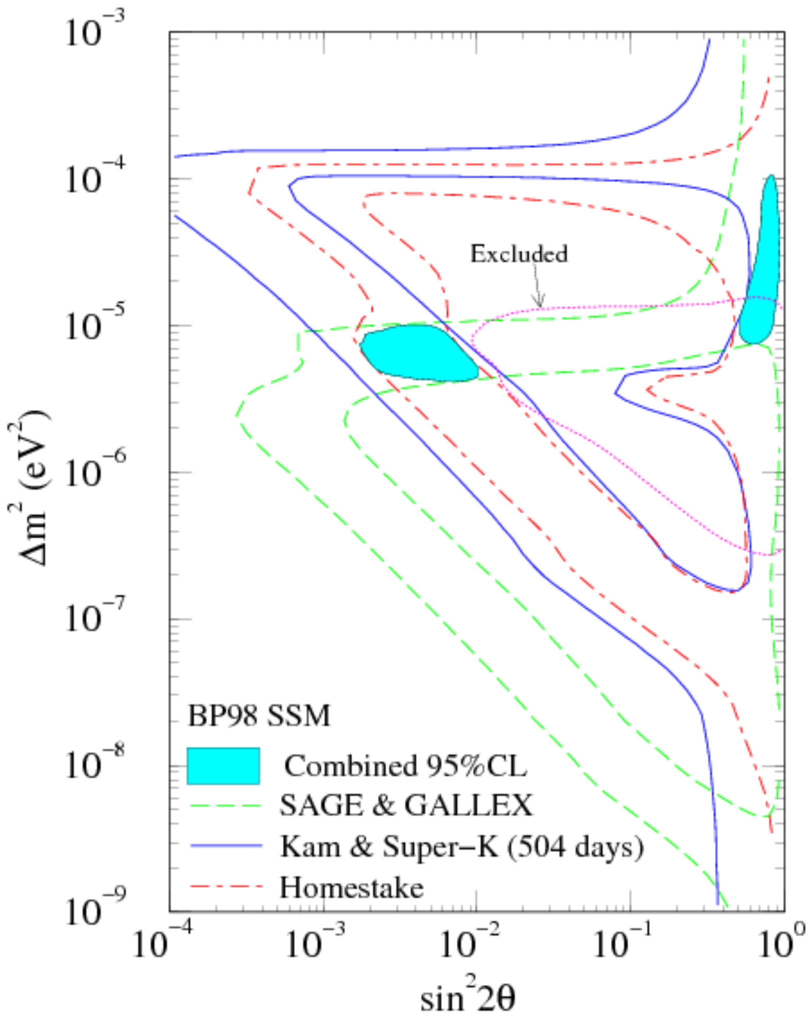
3.2 KamLAND

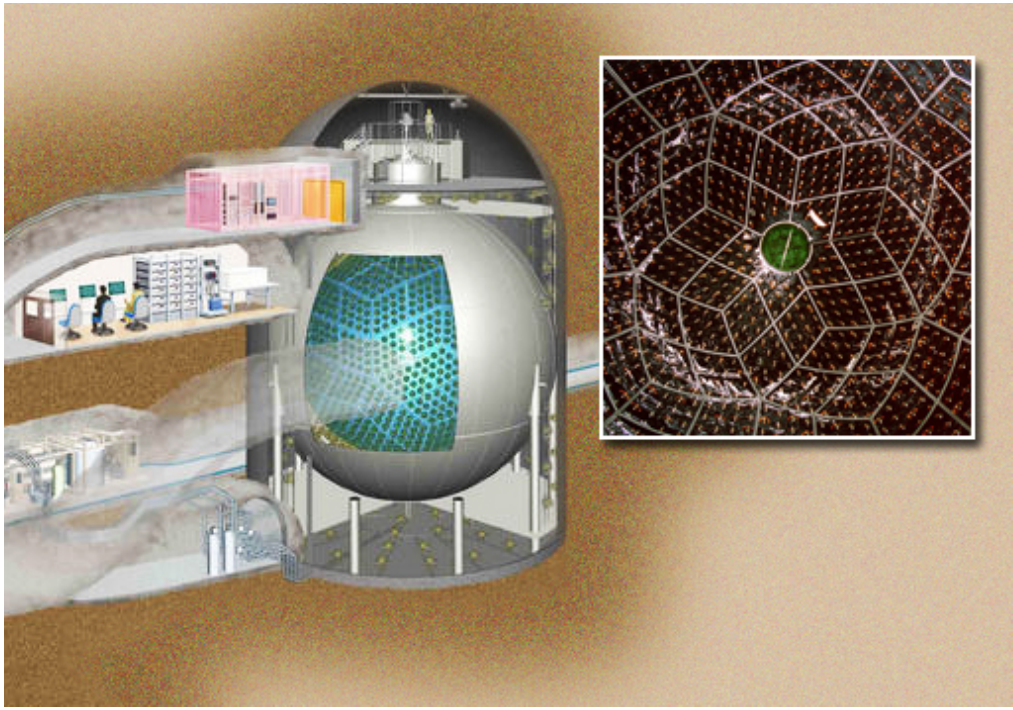
Atsuto Suzuki and the KamLAND Collaboration

Liquid scintillator detector

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

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





3.2 KamLAND

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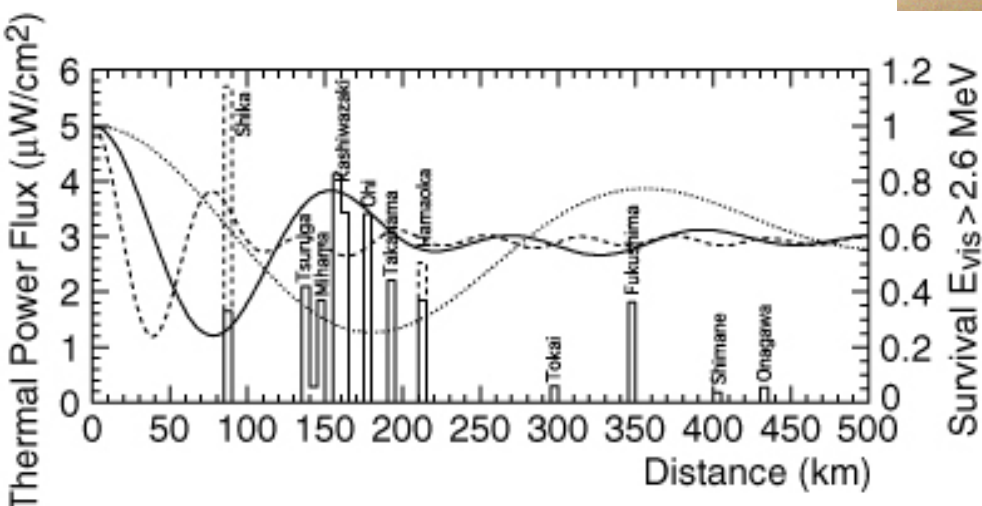
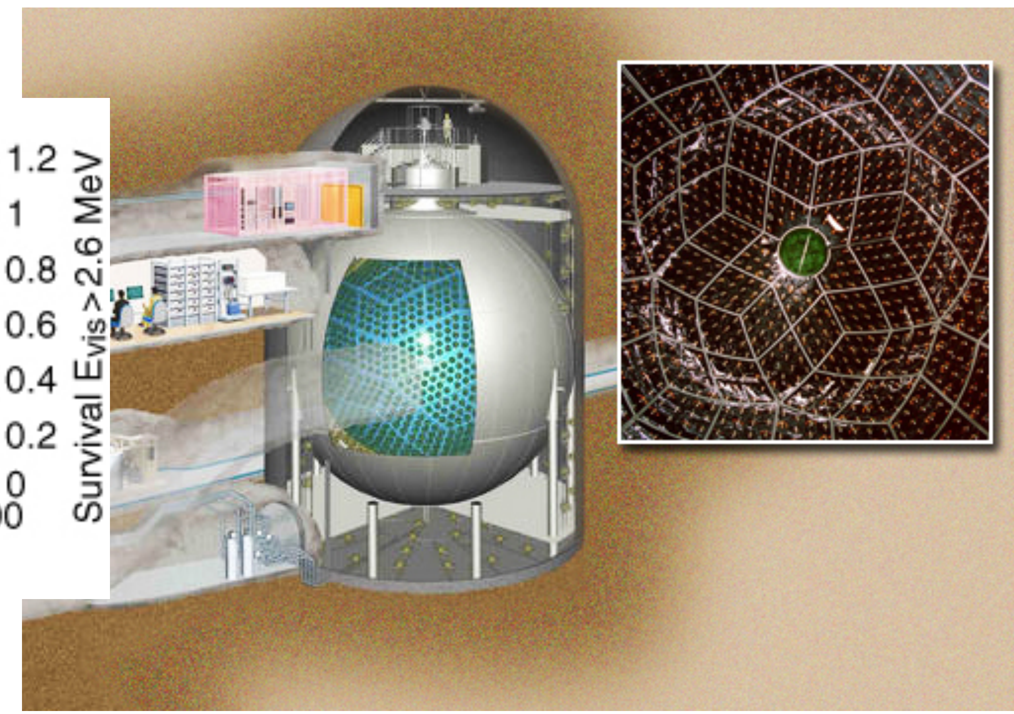




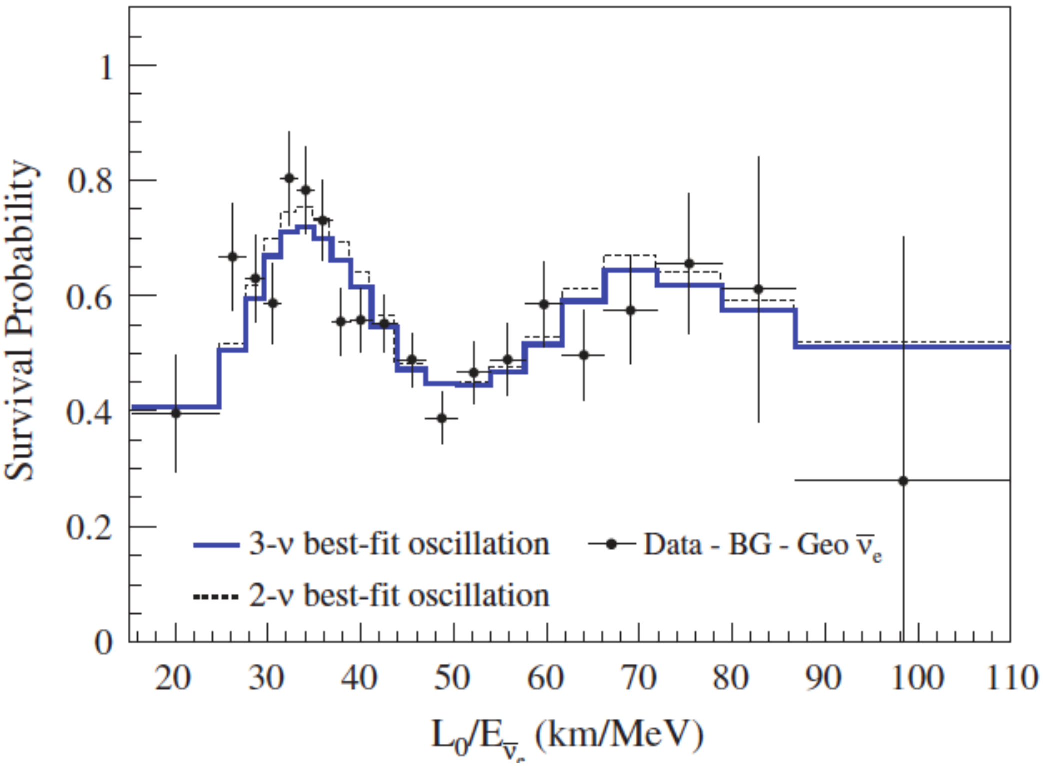
3.2 KamLAND

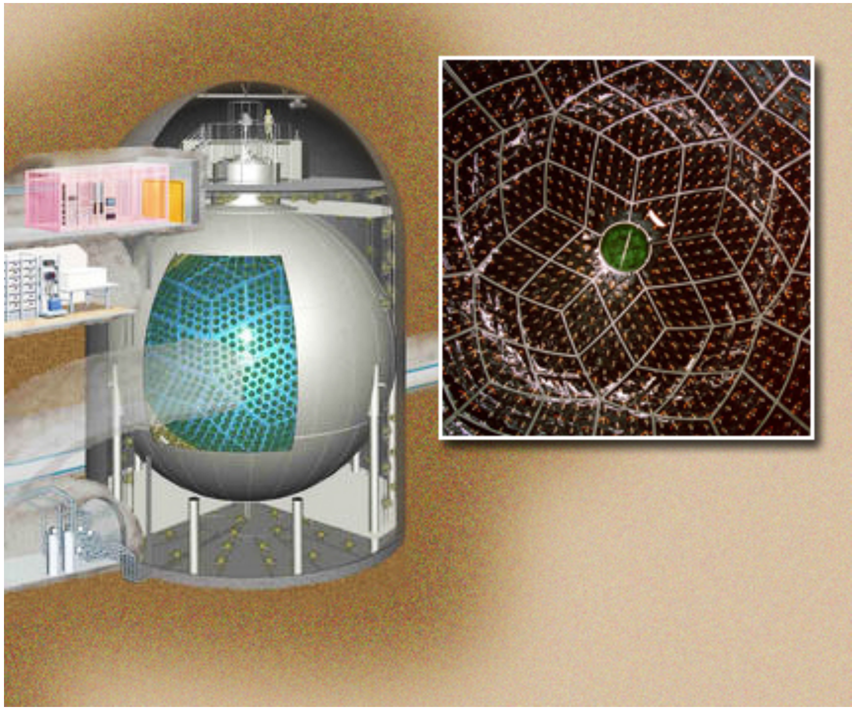
Liquid scintillator detector

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

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

- Solar neutrino parameters are fixed





KamLAND, PRL90(2003)021802;94(2005)081801; PRD83(2011)052002
Fogli et al,PRL101(2008)141801

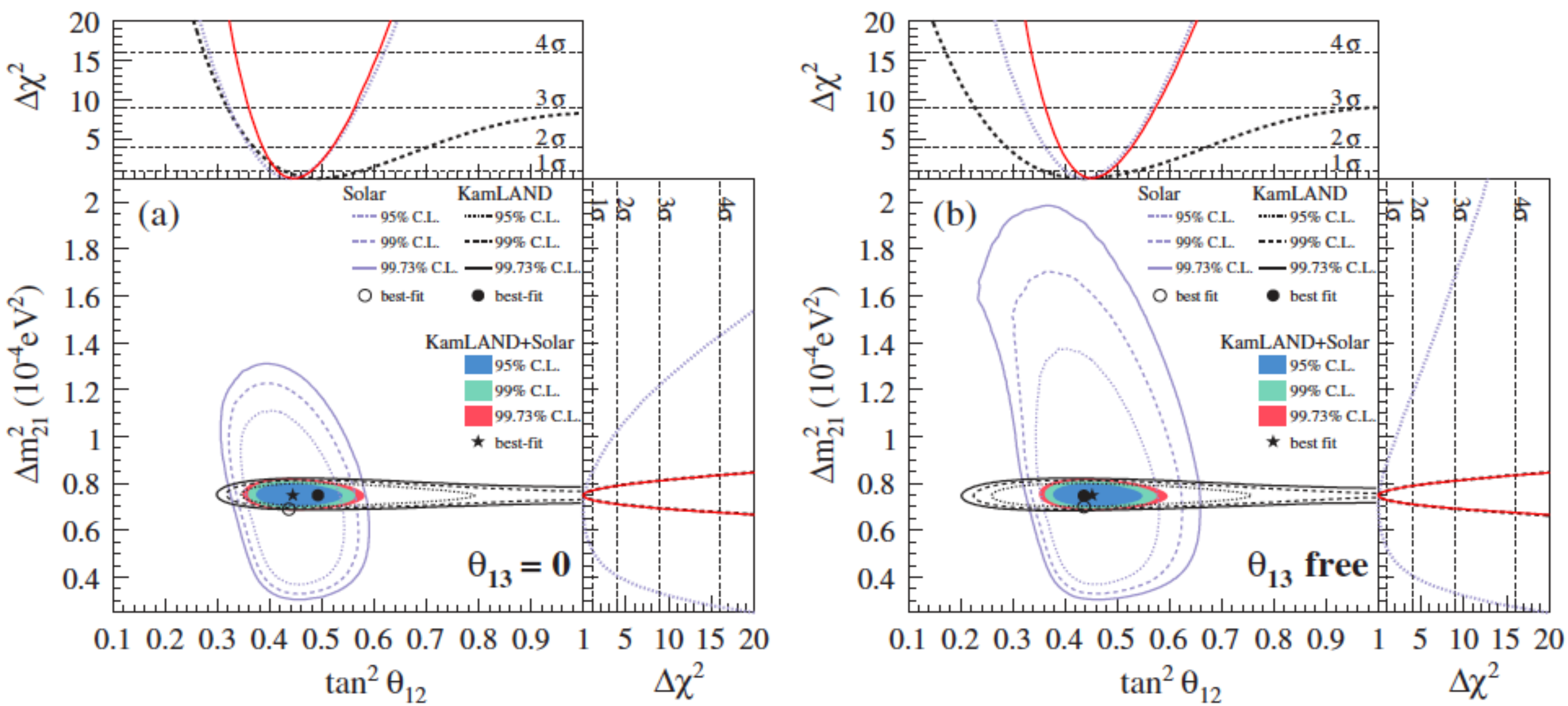
3.2 KamLAND

Liquid scintillator detector

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

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

- Solar neutrino parameters are fixed
- Nonzero θ_{13} makes agreement with solar data better...



3.2 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
- exotic models for atmospheric neutrino anomaly (neutrino decay, neutrino decoherence, etc)
- exotic models for solar neutrino problem (large neutrino magnetic moment, etc)

1. Neutrino physics, the future of particle physics

2. Neutrino in Standard Model (SM)

3. Neutrino Standard Model (νSM)

3.1 Before 1998

Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

3.2 1998 – 2004

Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

3.3 2005 – 2011

Precision measurement era

3.4 2012

3.5 Current issues

4. Beyond νSM

5. Conclusions

3.3 2005-2011

Precision neutrino oscillation measurement era

- K2K
- MINOS
- Borexino
- ...

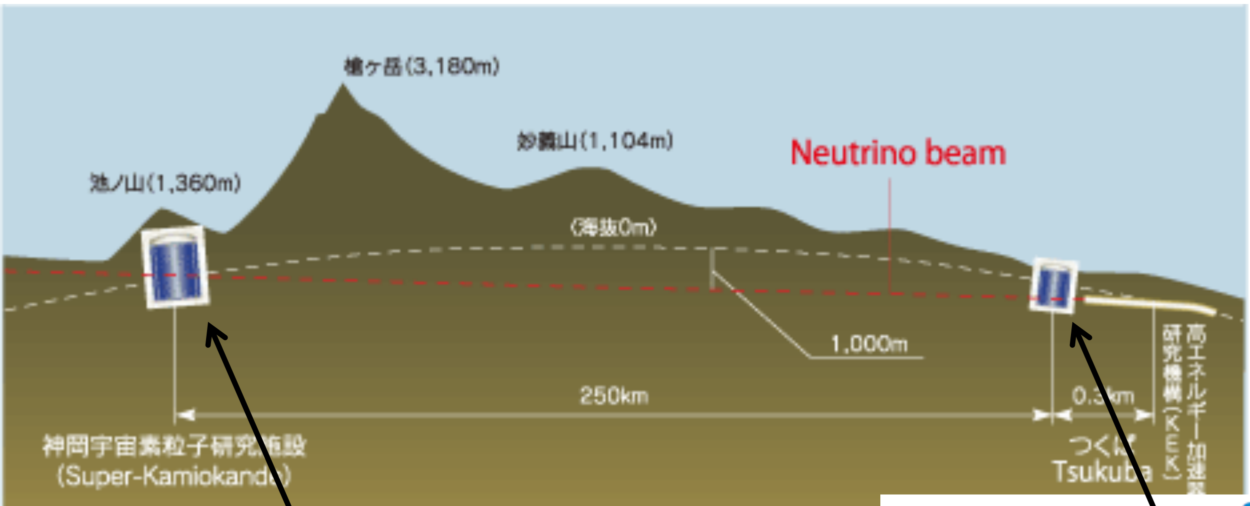
K2K, PRD74(2006)072003

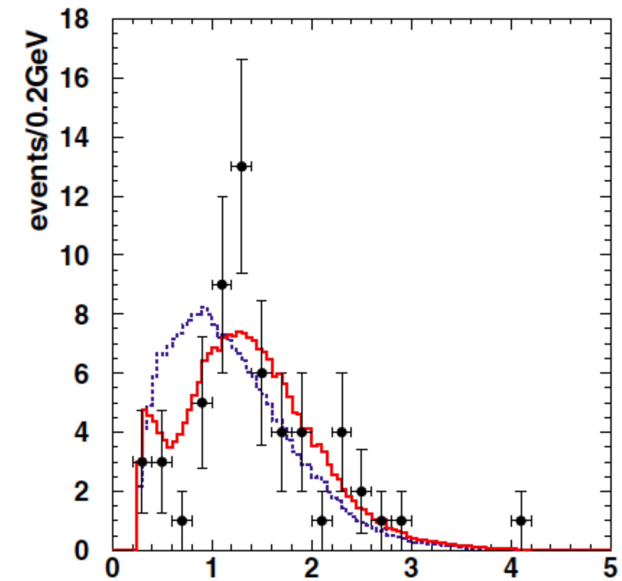
3.3 K2K experiment

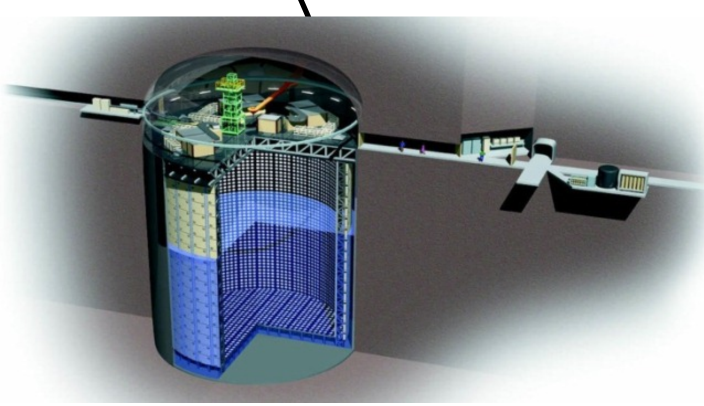
Koichiro Nishikawa and the K2K and T2K Collaboration

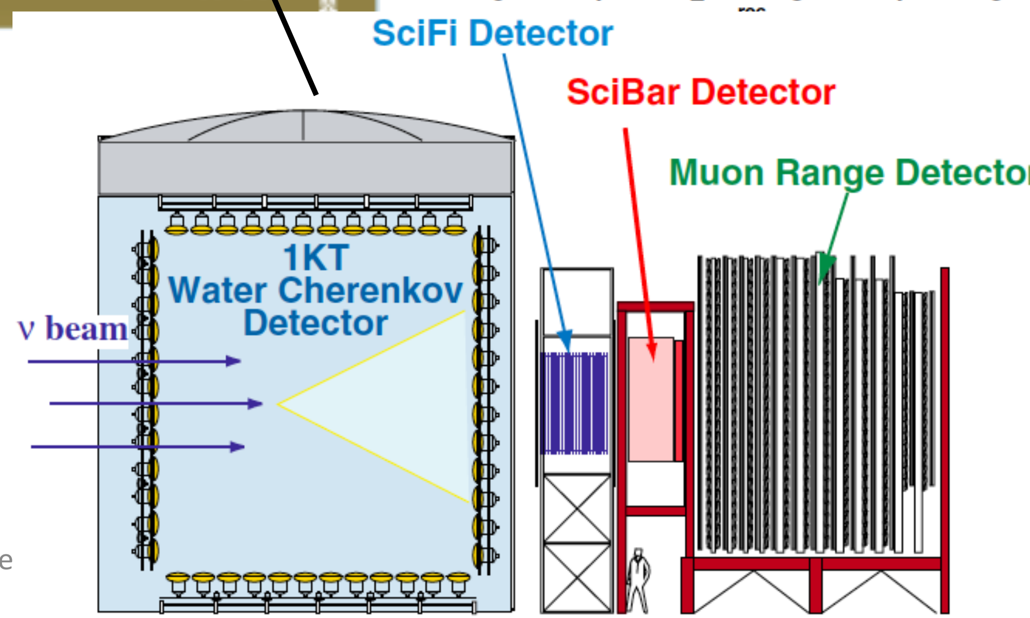
First long baseline neutrino oscillation experiment

- ~1.3GeV muon neutrinos over 250km









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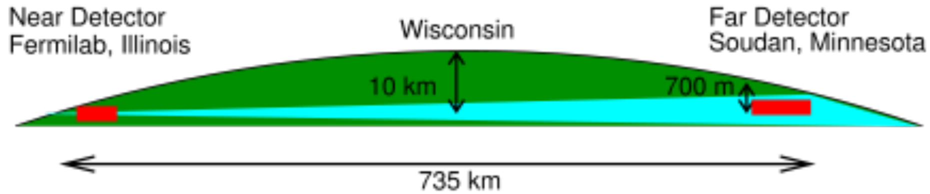
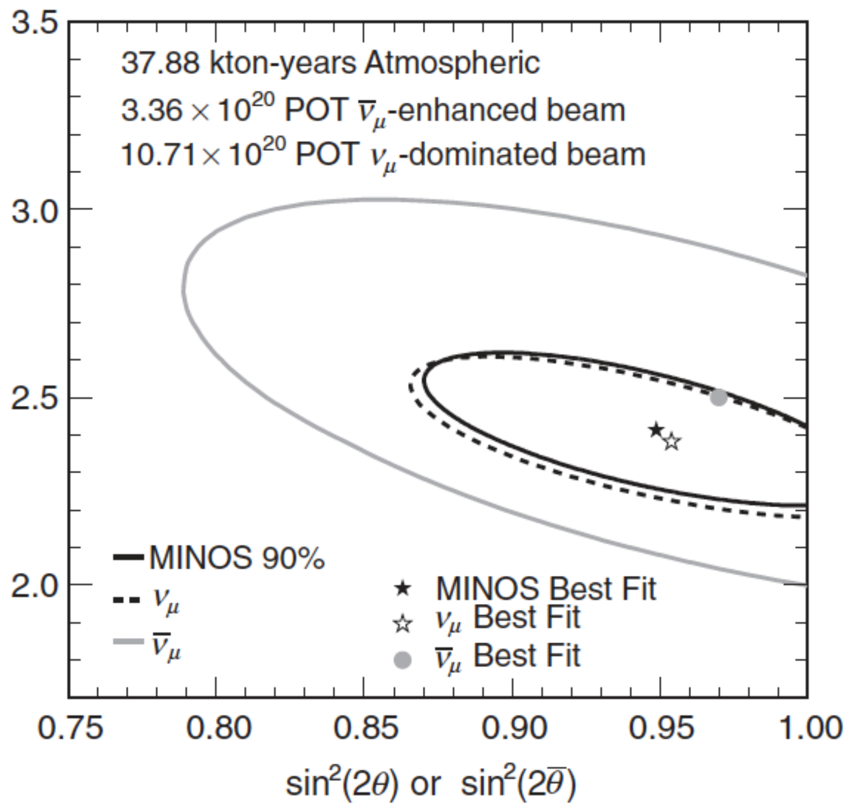
3.3 MINOS



Magnetized detector

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

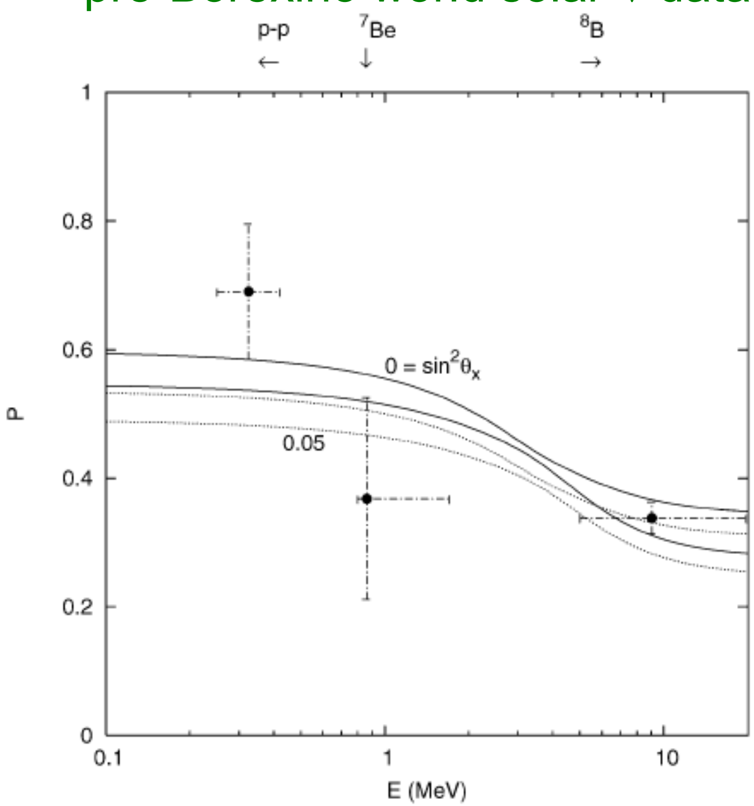


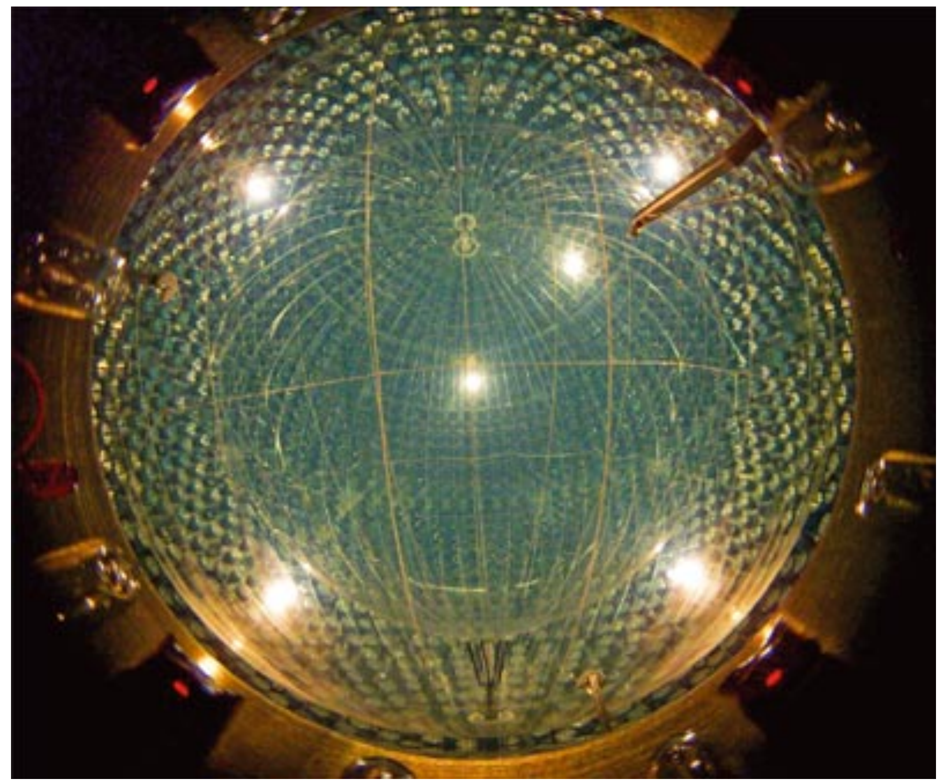
3.3 Borexino

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





Barger et al, PLB617(2008)78
TK,Kostelecky,Tayloe,PRD74(2006)105009

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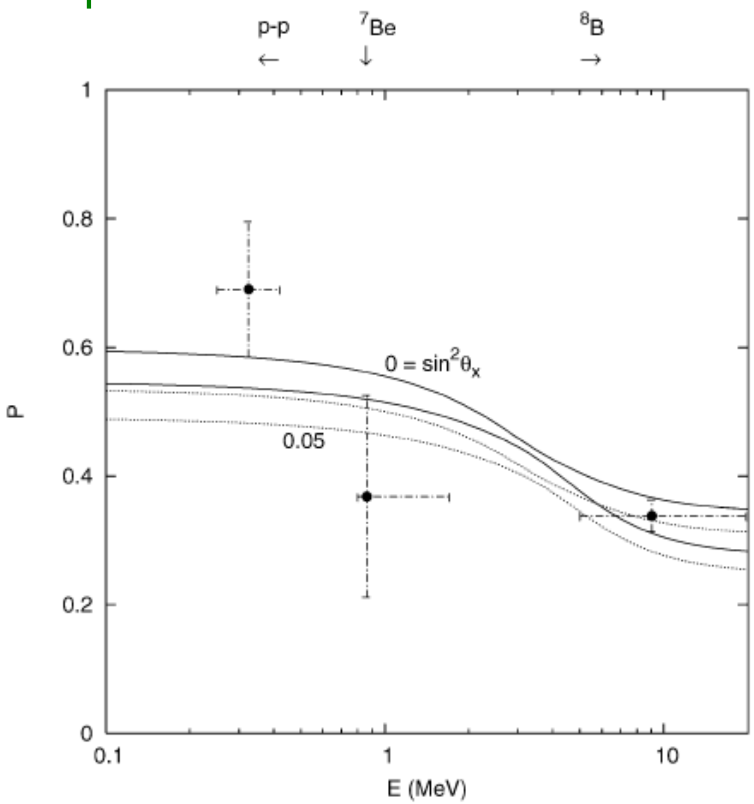

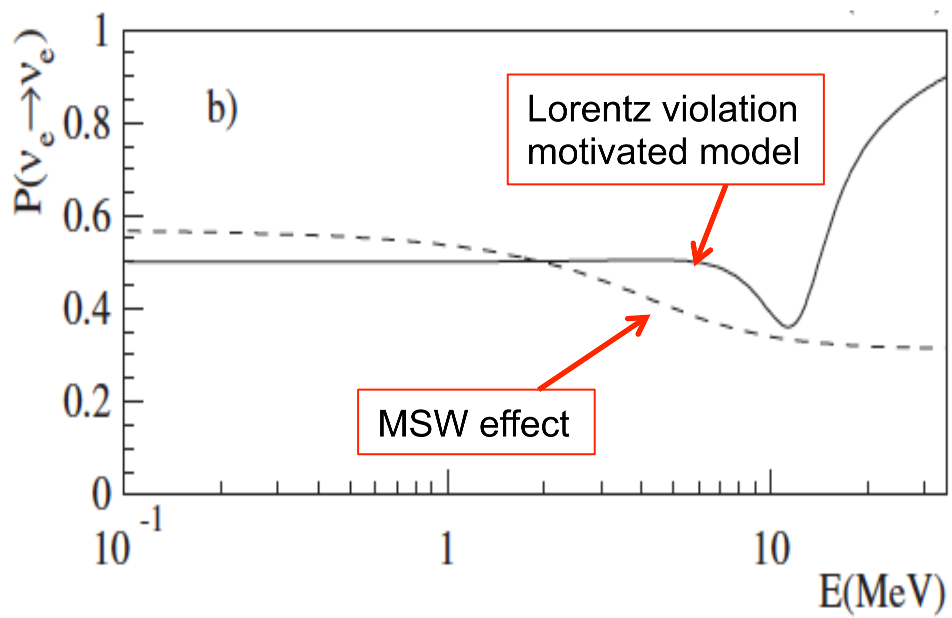

Borexino, PRL101(2008)091302;108(2012)051302
Haxton et al, ArXiv:1303.1681

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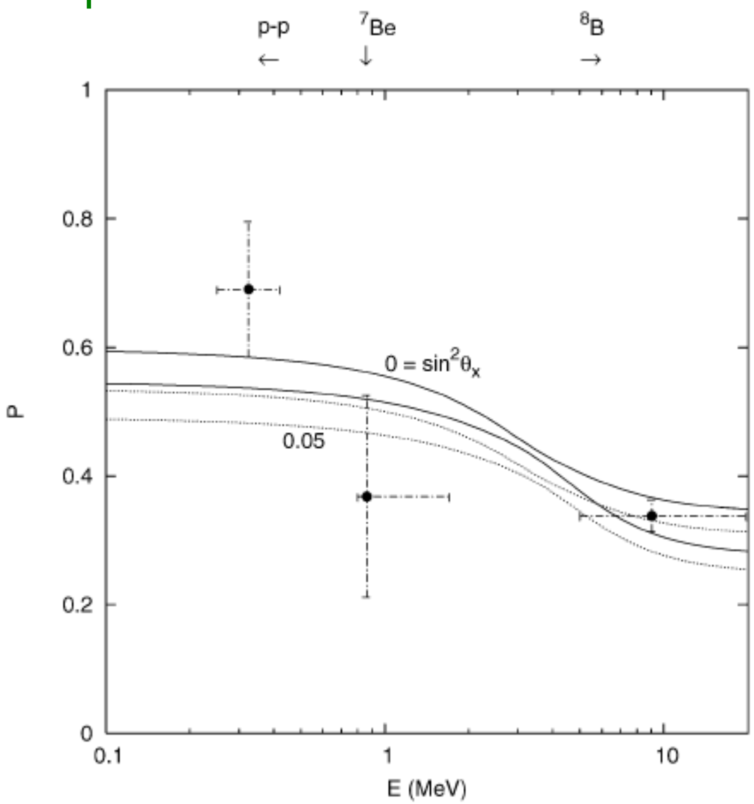
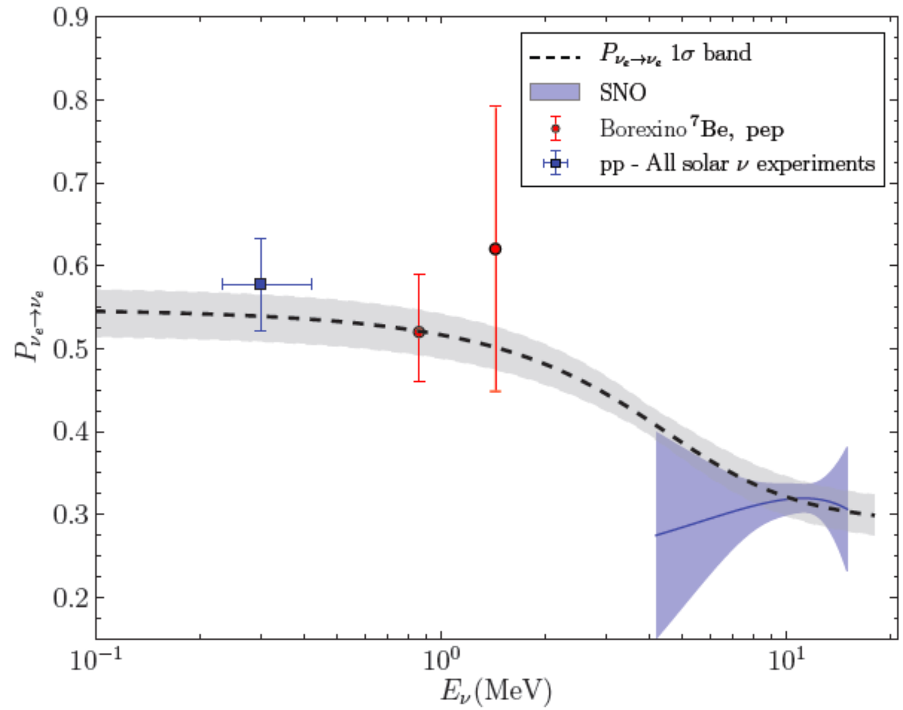
pre-Borexino world solar-ν data → post-Borexino world solar-ν data





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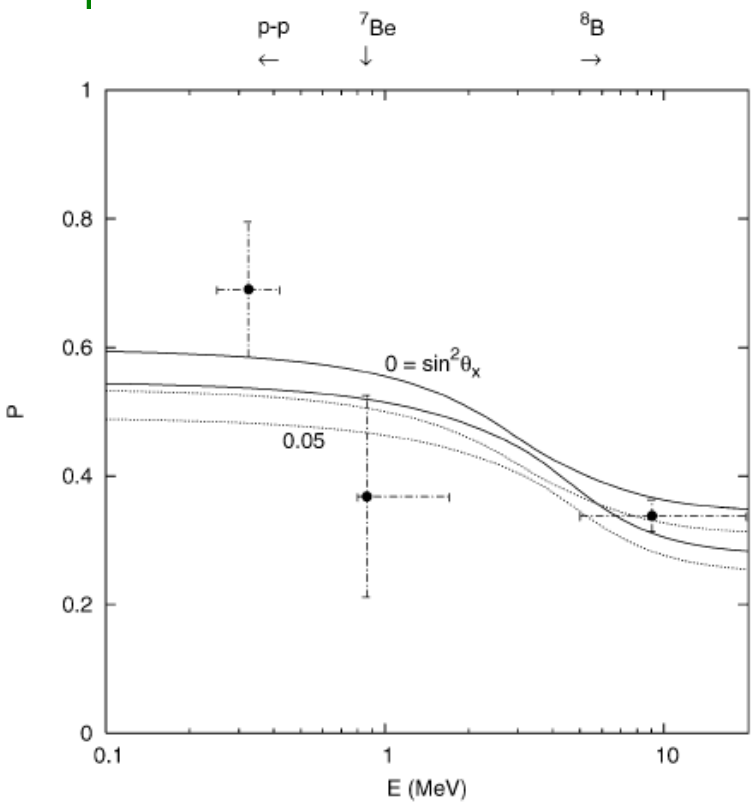
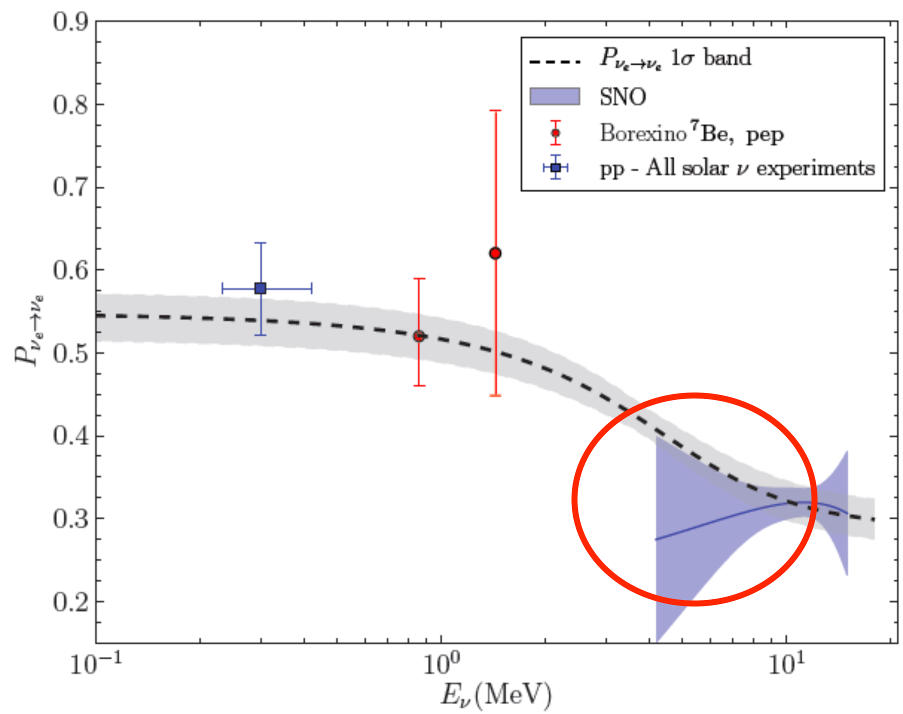
7Be solar neutrino

- high pure liquid scintillator detector to detector low energy (=^{7}Be solar neutrino)
- Pre-Borexino → MSW was about right, but not quite right
- Borexino 7Be, and pep measurement agree with MSW prediction
- one remained problem, no experiments measure 8B neutrino "upturn"

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





3.3 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})

$$P_{\alpha\to\beta}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Unknown parameter, θ_{13}

θ_{13} is interesting because nonzero θ_{13} implies leptonic CP violation
(cf., 3 generations are required to have CP violation in quark sector)

Almost all exotic models are killed, neutrino oscillations are due to neutrino masses, and all exotic effects are sub-dominant (even if exists)
- non-standard interaction
- sterile neutrino mixing
- Lorentz violation
- neutrino decay, decoherence, extra-dimension, etc

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Precision measurement era

3.4 2012

Boom of θ_{13}

3.5 Current issues

Future long-baseline neutrino oscillation experiments

4. Beyond νSM

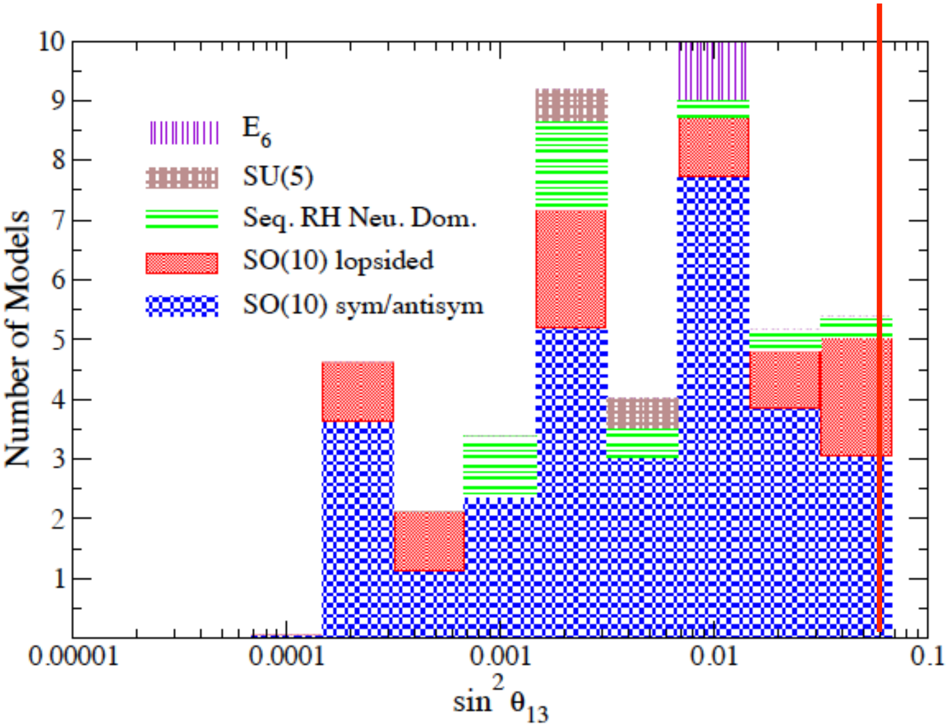
5. Conclusions

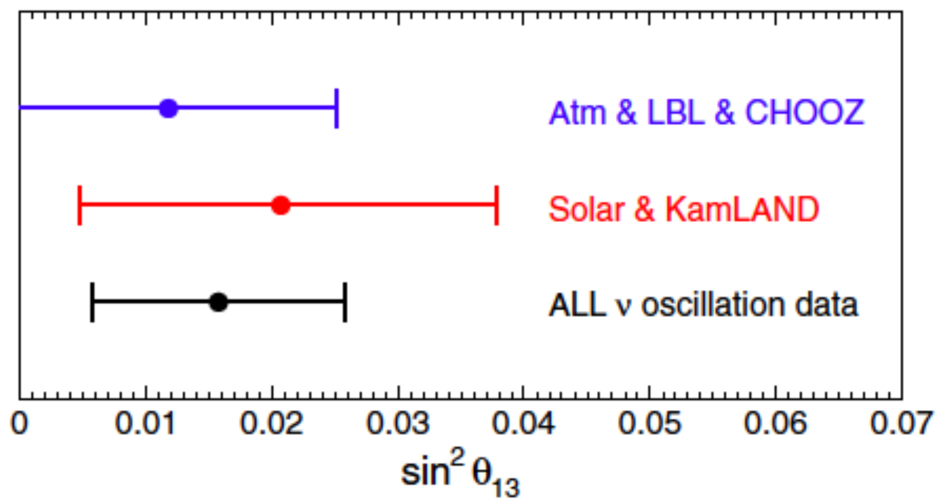
Albright, ArXiv:0905.0146
Fogli et al,PRL101(2008)141801

3.4 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)





3.4 Boom of θ_{13}

T2K, Double Chooz, Daya Bay, Reno

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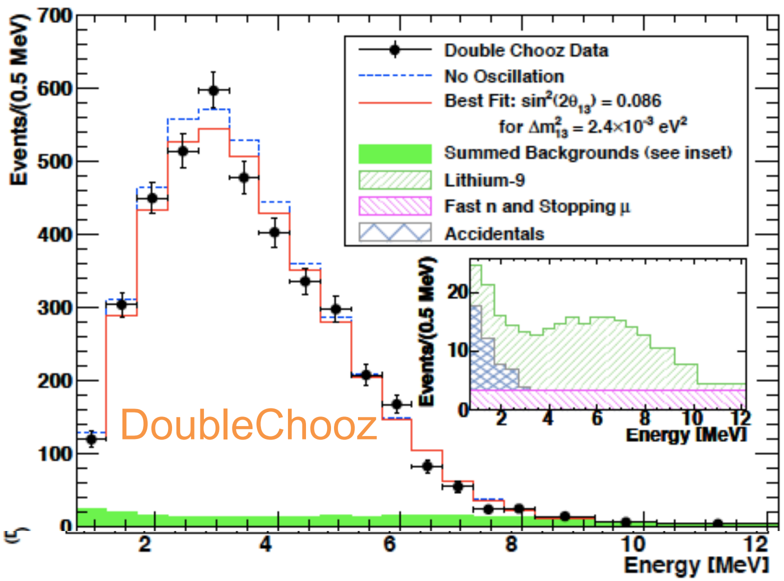
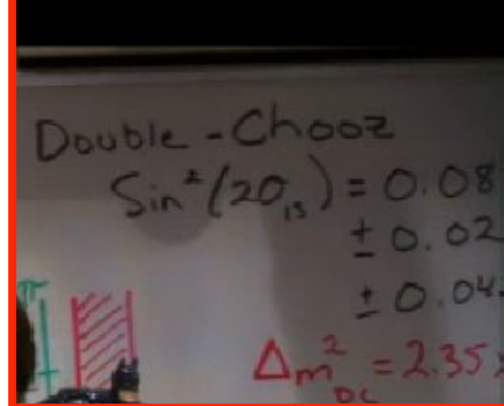
- Mother Nature was kind again!
  - anti-ν_e reactor disappearance

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



Double Chooz,PRL108(2012)131801

3.4 Boom of θ_{13}



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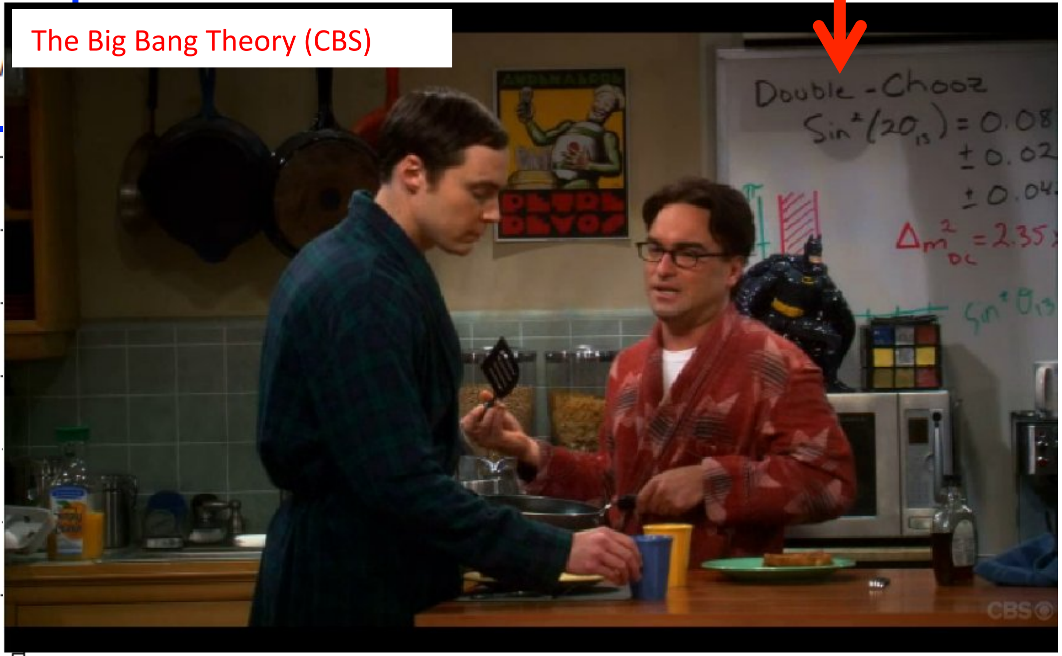
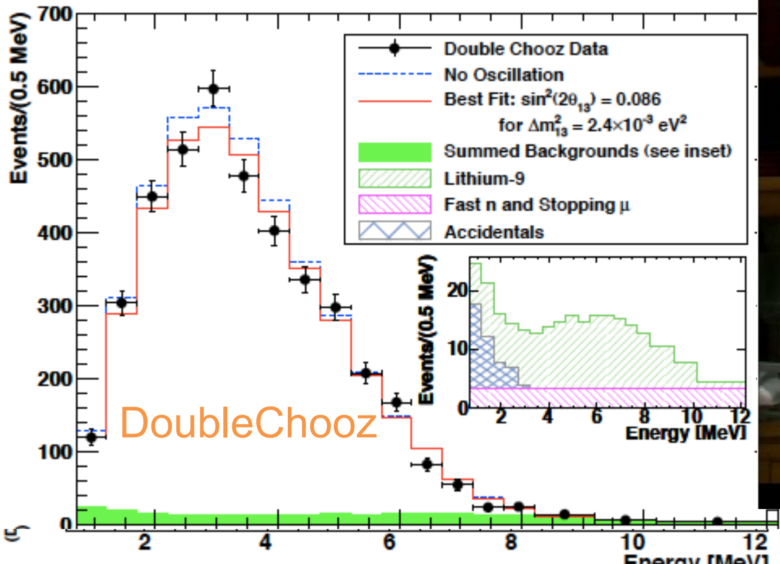
The Big Bang Theory (CBS)





University of London

3.4 Boom of θ_{13}

Yifang Wang and the Daya Bay Collaboration

Kam-Biu Luk and the Daya Bay Collaboration

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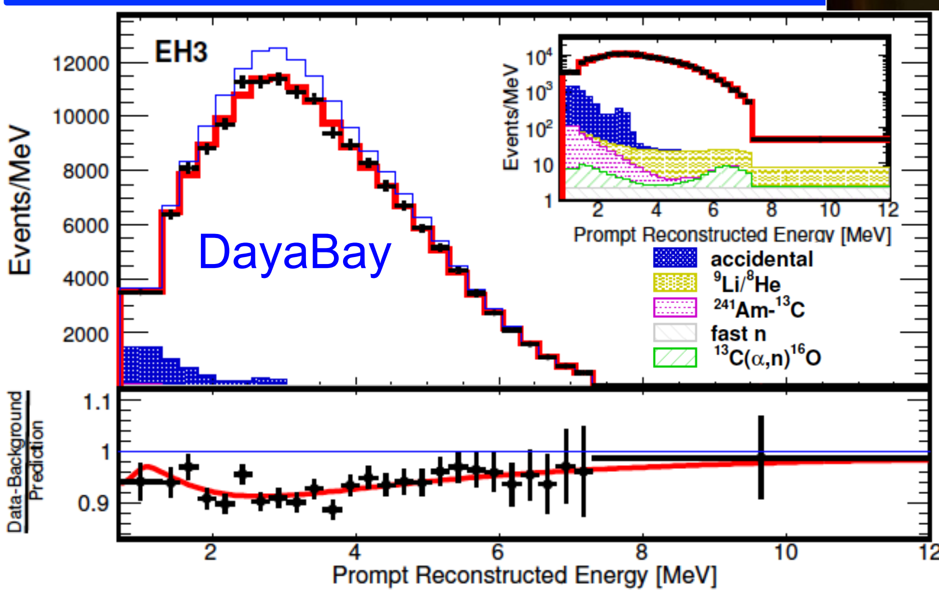
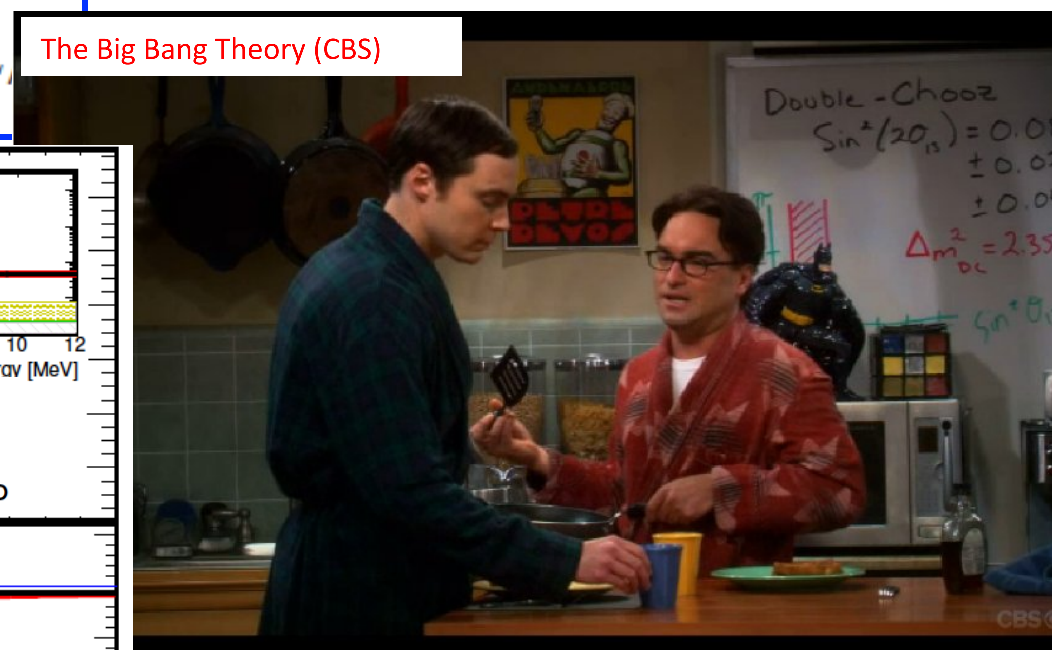




The Big Bang Theory (CBS)

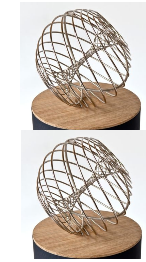
Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802
T2K, PRL112(2014)061802

3.4 Boom of θ_{13}

Yifang Wang and the Daya Bay Collaboration

Kam-Biu Luk and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

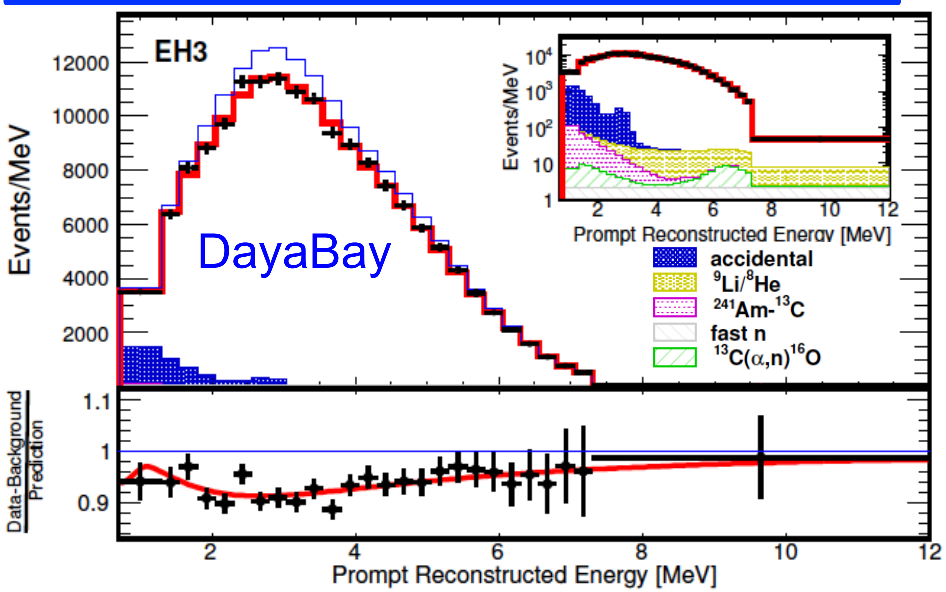


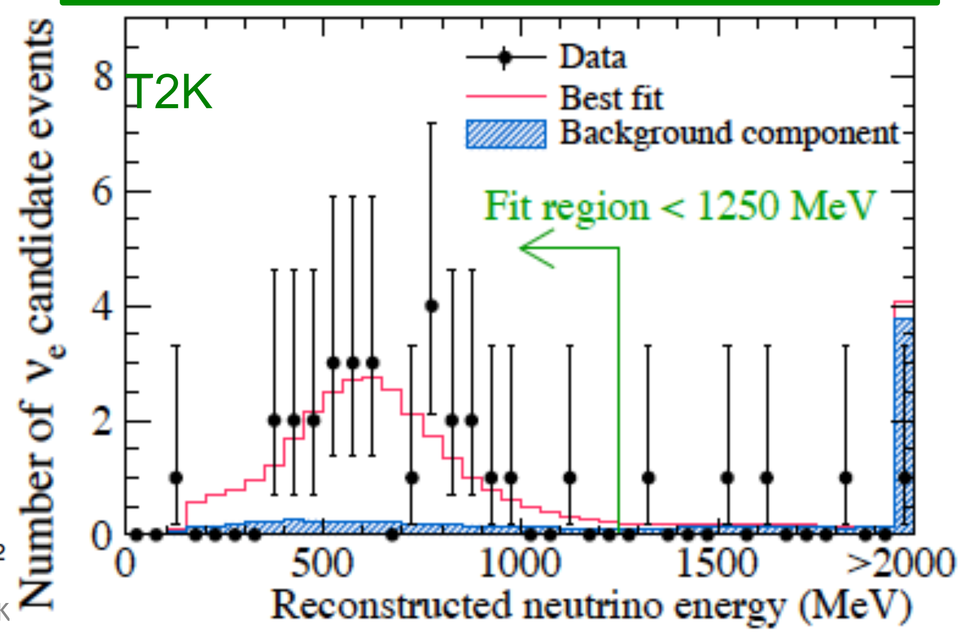
T2K, Double Chooz, Daya Bay, Reno

- θ_{13} was truly unknown parameter
- there was a "hint" from Solar-KamLAND tension
- Mother Nature was kind again!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation

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

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





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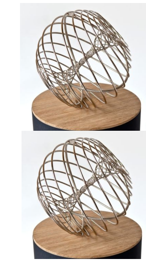
Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802
T2K, PRL112(2014)061802

3.4 Boom of θ_{13}

Yifang Wang and the Daya Bay Collaboration

Kam-Biu Luk and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

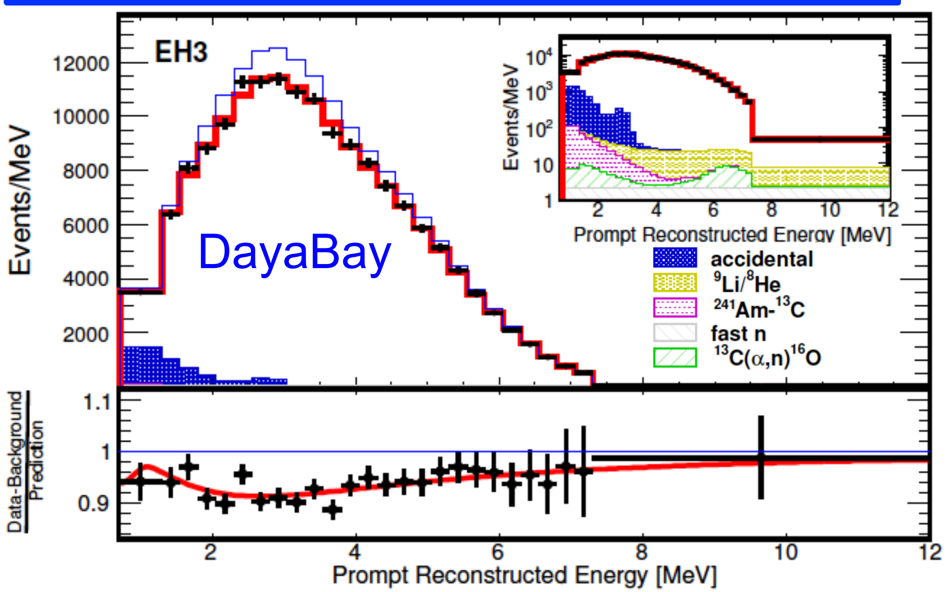


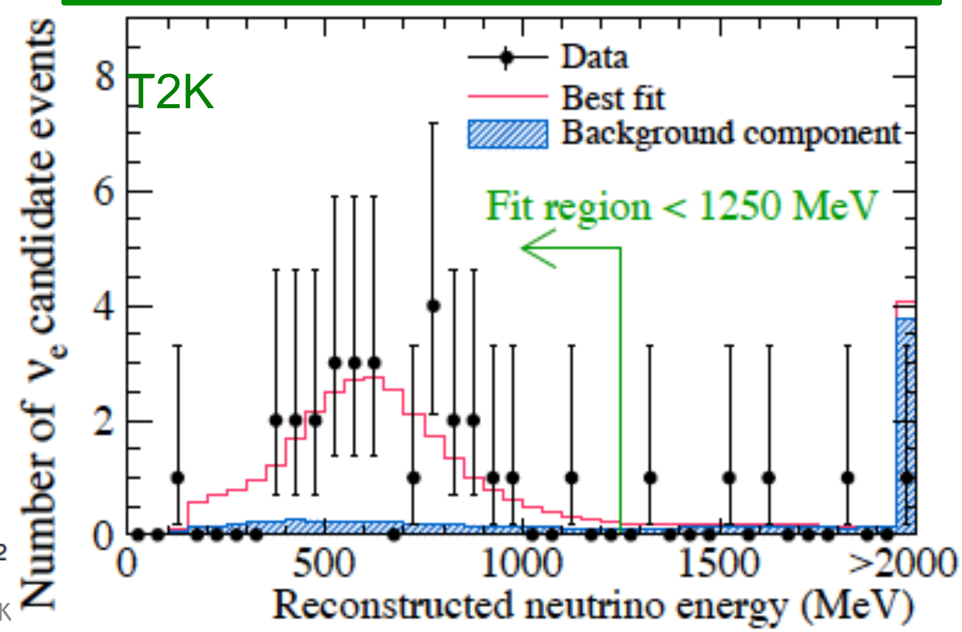
T2K, Double Chooz, Daya Bay, Reno

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

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

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





3.4 2012

T2K, Double Chooz, Daya Bay, Reno
- θ_{13} was truly unknown parameter
- there was a "hint" from Solar-KamLAND tension
- Mother Nature was kind again!
  - 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

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

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

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

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

3.4 2012

Neutrino Standard Model (νSM)

- SM + 3 active massive neutrino is established

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 $m_3<m_1<m_2$)
- Dirac or Majorana
- Majorana phase
- absolute neutrino mass

} not relevant to neutrino oscillation experiment?

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

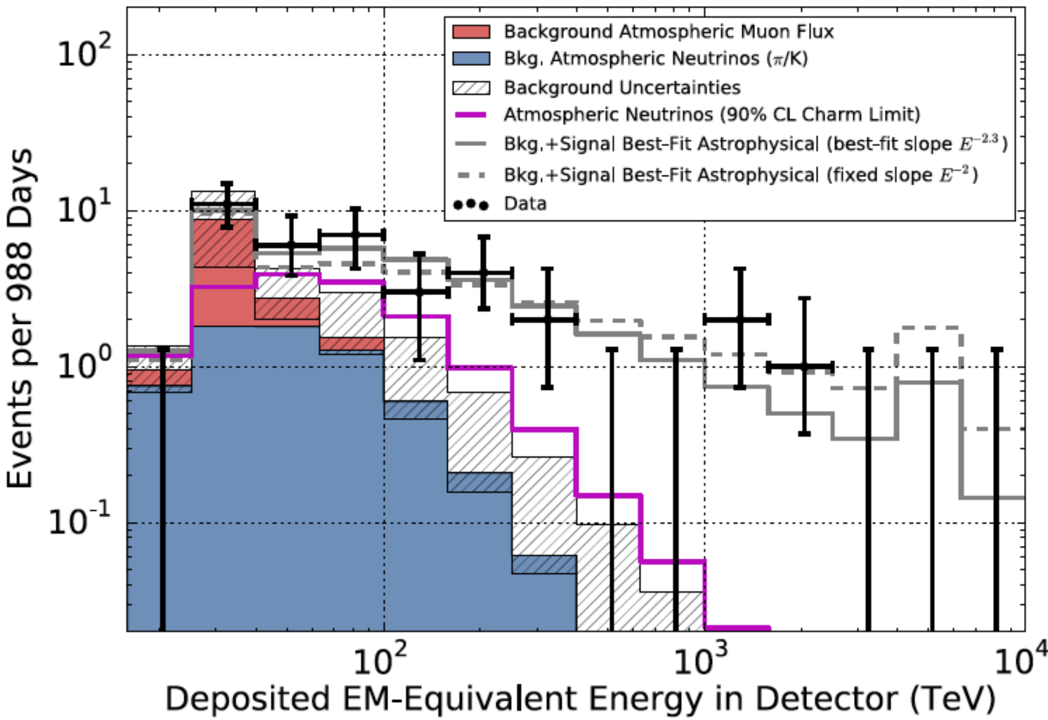
$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$$

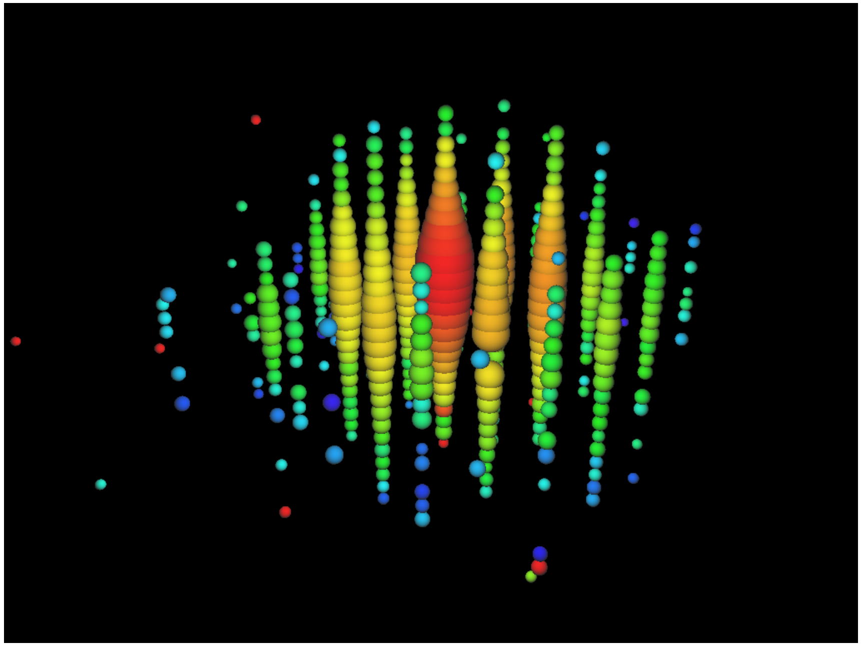
where $\sqrt{P_{atm}} = 2|U_{\mu 3}||U_{e3}| \sin \Delta_{31} = \sin\theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$

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

3.4 Astrophysical very high energy (VHE) neutrinos

IceCube observed the first astrophysical PeV neutrinos
- Inconsistent with atmospheric neutrino
- Inconsistent with GZK ultra high energy (UHE) neutrinos
- Inconsistent (so far) with Glashow resonance UHE neutrinos (6.3 PeV)





1. Neutrino physics, the future of particle physics

2. Neutrino in Standard Model (SM)

3. Neutrino Standard Model (νSM)

3.1 Before 1998

Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

3.2 1998 – 2004

Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

3.3 2005 – 2011

Precision measurement era

3.4 2012

Boom of θ_{13}

3.5 Current issues

Future long-baseline
neutrino oscillation experiments

4. Beyond νSM

5. Conclusions

3.5 Current issues

Unknown parameters of νSM

δ_{CP}: Dirac CP phase

θ_{23}: θ_{23}=40° and 50° are same how $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$

MO: mass ordering, normal $m_1<m_2<m_3$ or inverted $m_3<m_1<m_2$

Long baseline neutrino oscillations

- T2K (running)
- NOvA (running)
- PINGU/ORCA/INO (planned)
- JUNO/RENO50 (planned)
- Hyper-Kamiokande (planned)
- DUNE (planned)

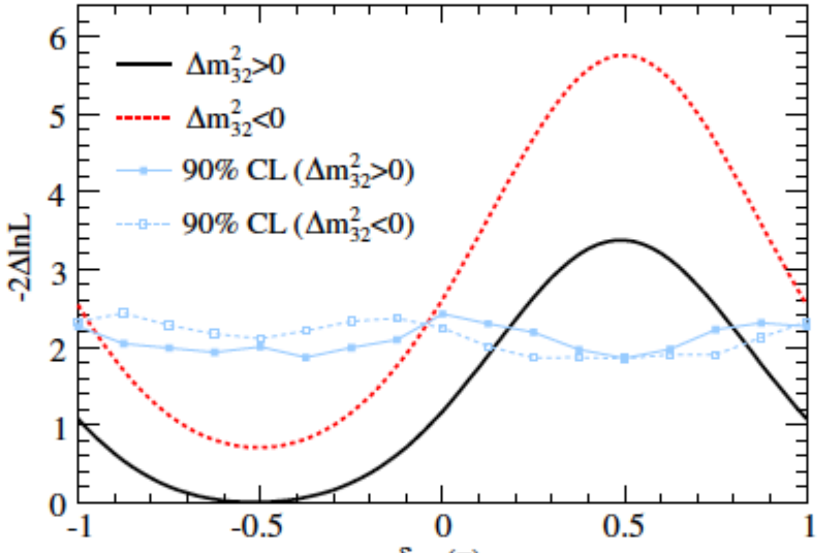
T2K,PRL112(2014)061802

3.5 T2K

The first δ_{CP} limit Joint ν_μ+ν_e fit

- data prefer normal hierarchy with δ_{CP}~ -π/2.
- first time some region of δ_{CP} is excluded.

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

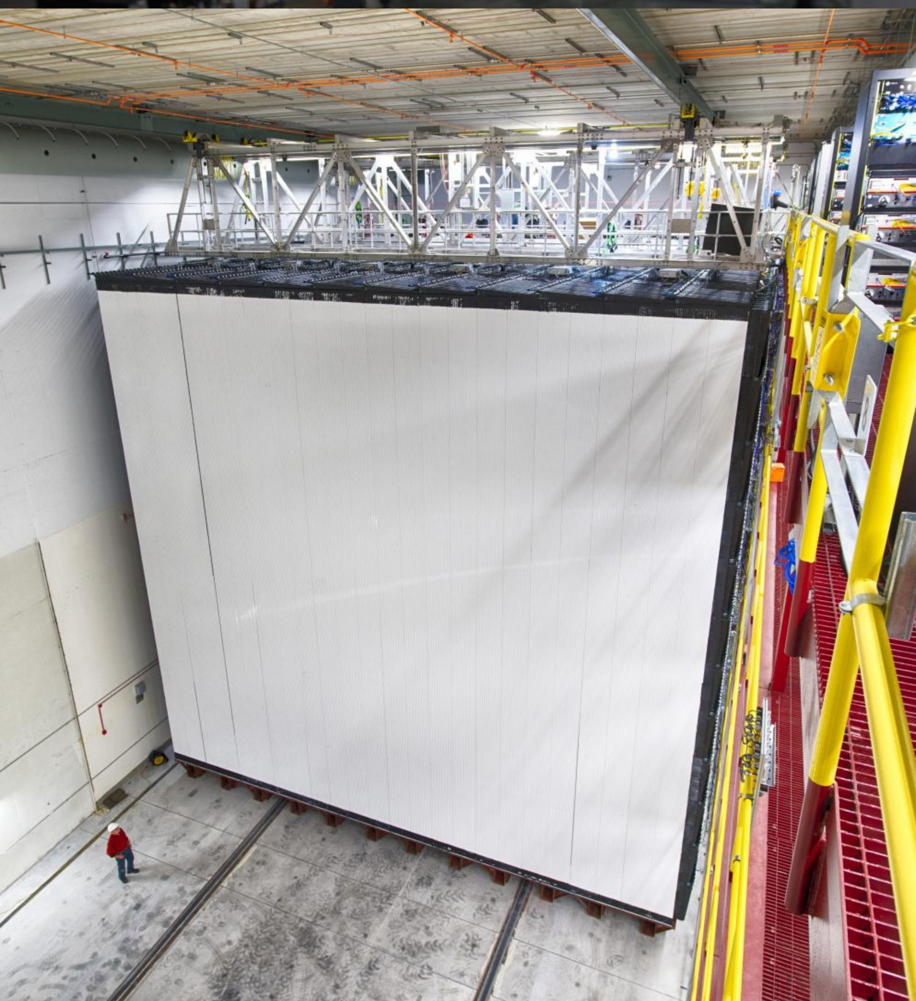


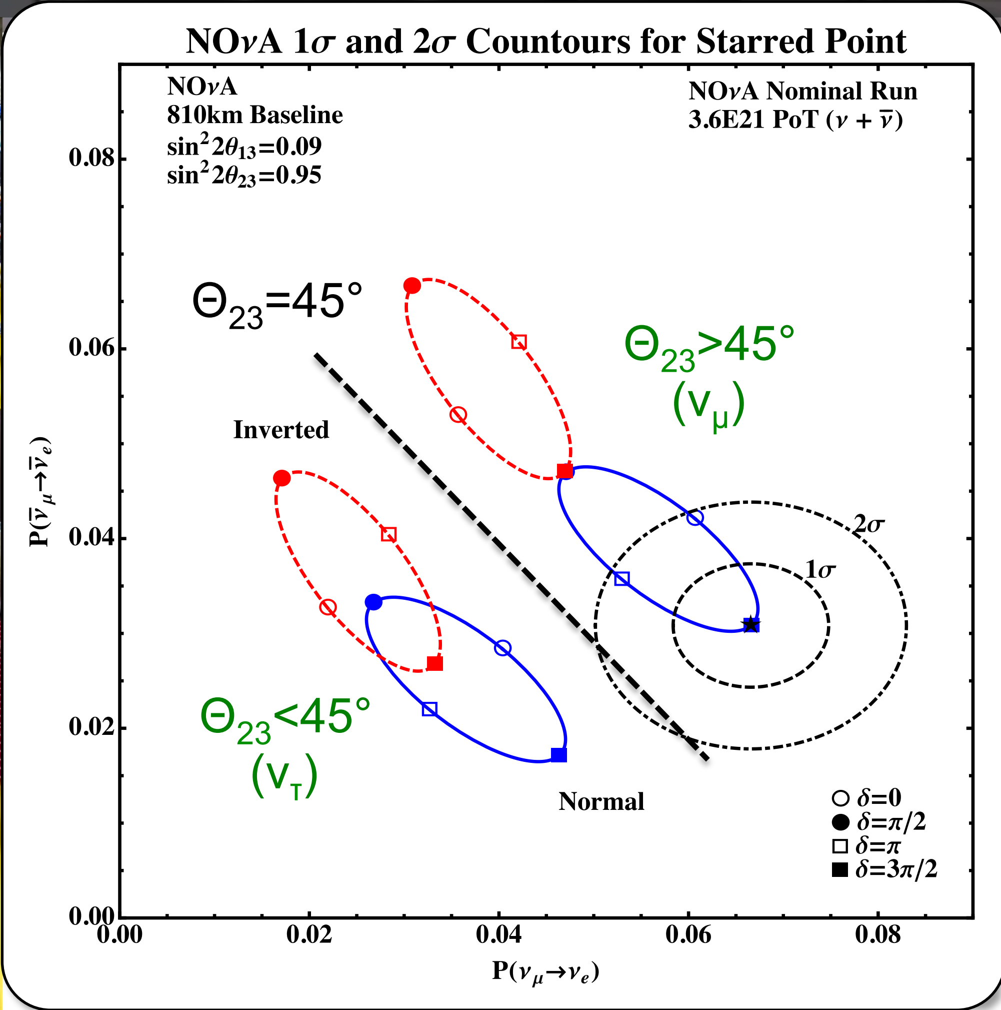
3.5 NOvA

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

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)





3.5 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)

...egeneracy and find all (δ_{CP}, θ_{23}, MH)

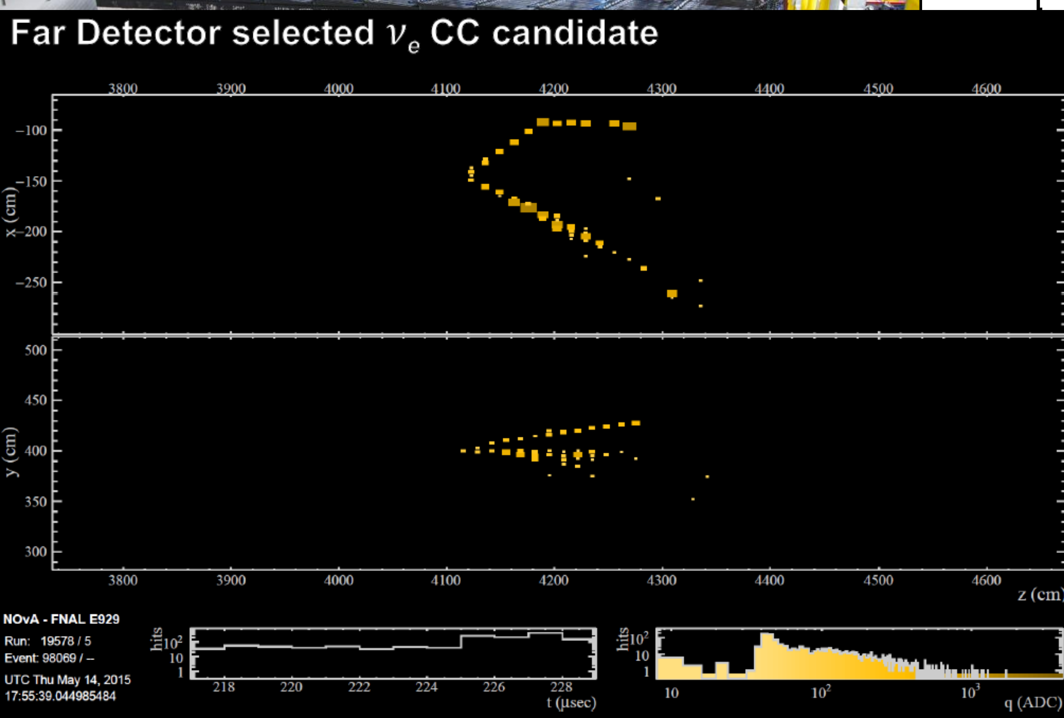
The first result (2015)

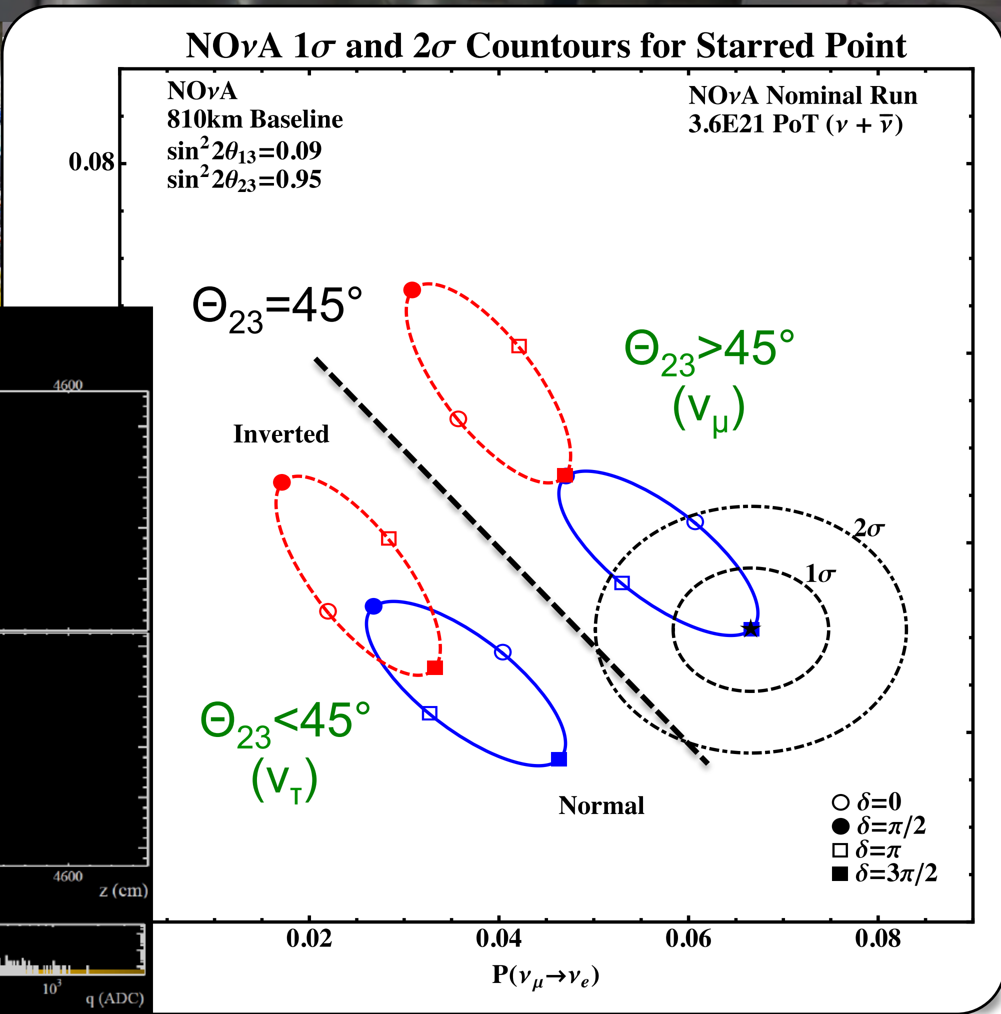
- Analysis I, 6 ν_eCC candidates
- Analysis II, 11ν_eCC candidates

(background ~1 event)

Prediction at $\delta=-\pi/2$, $\theta_{23}=\pi/4$

- Normal, 5.91 ± 0.65
- Inverted, 2.34 ± 0.26





3.5. PINGU

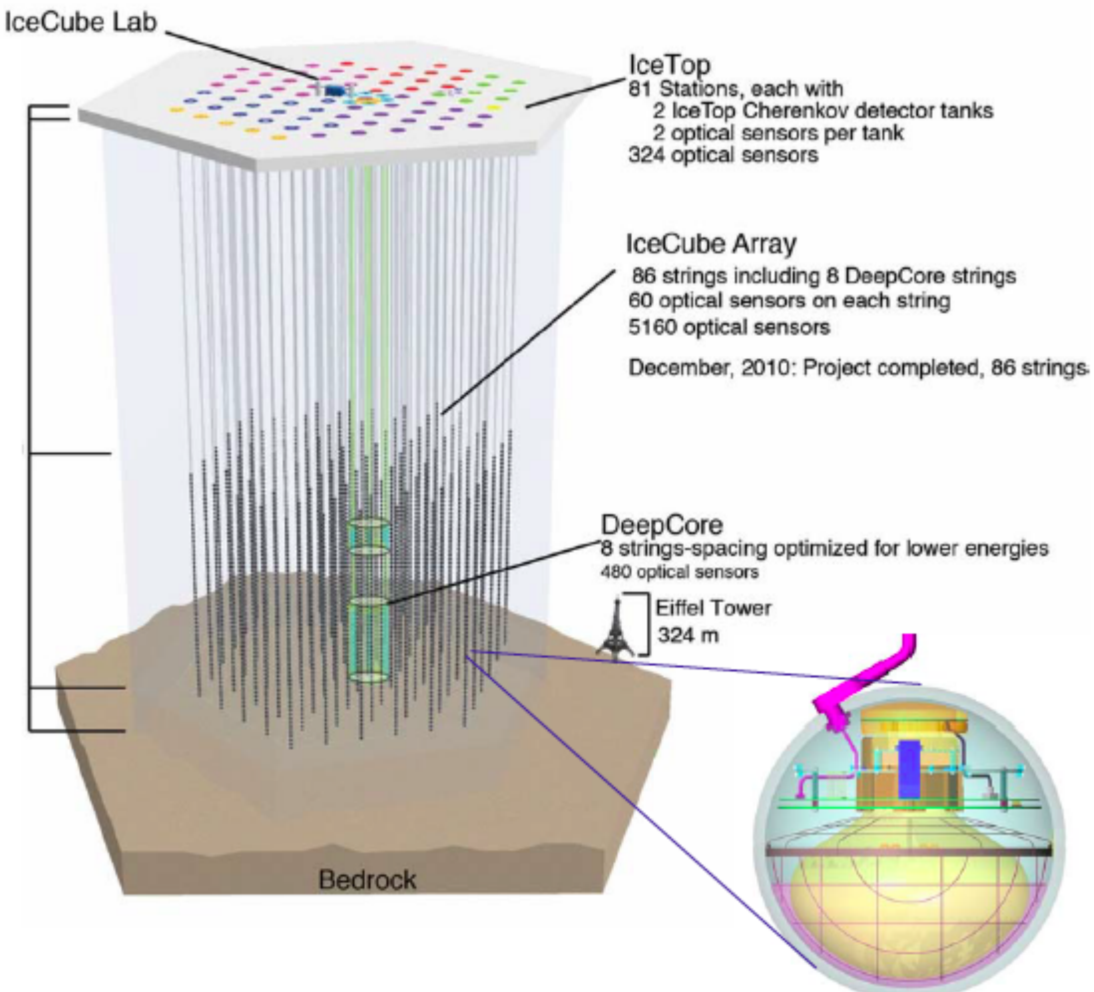
effective 2-ν matter oscillation

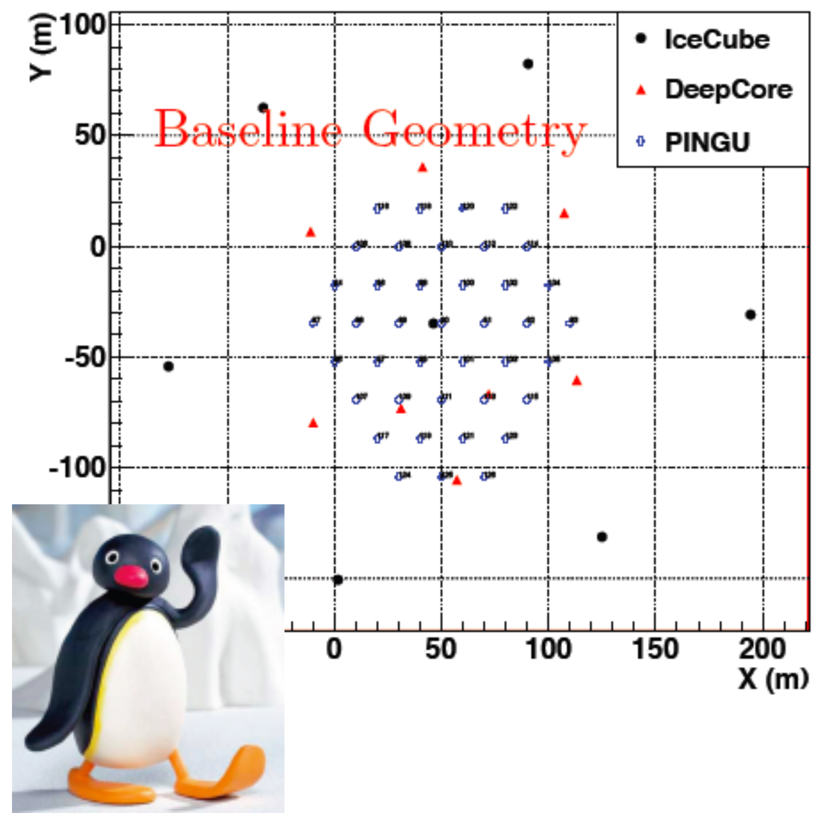
interference of propagation states

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

More strings in IceCube

- Known technology
- more strings in central area of IceCube → reduce threshold down to ~few GeV
- It can find mass ordering from ν_μ matter oscillation

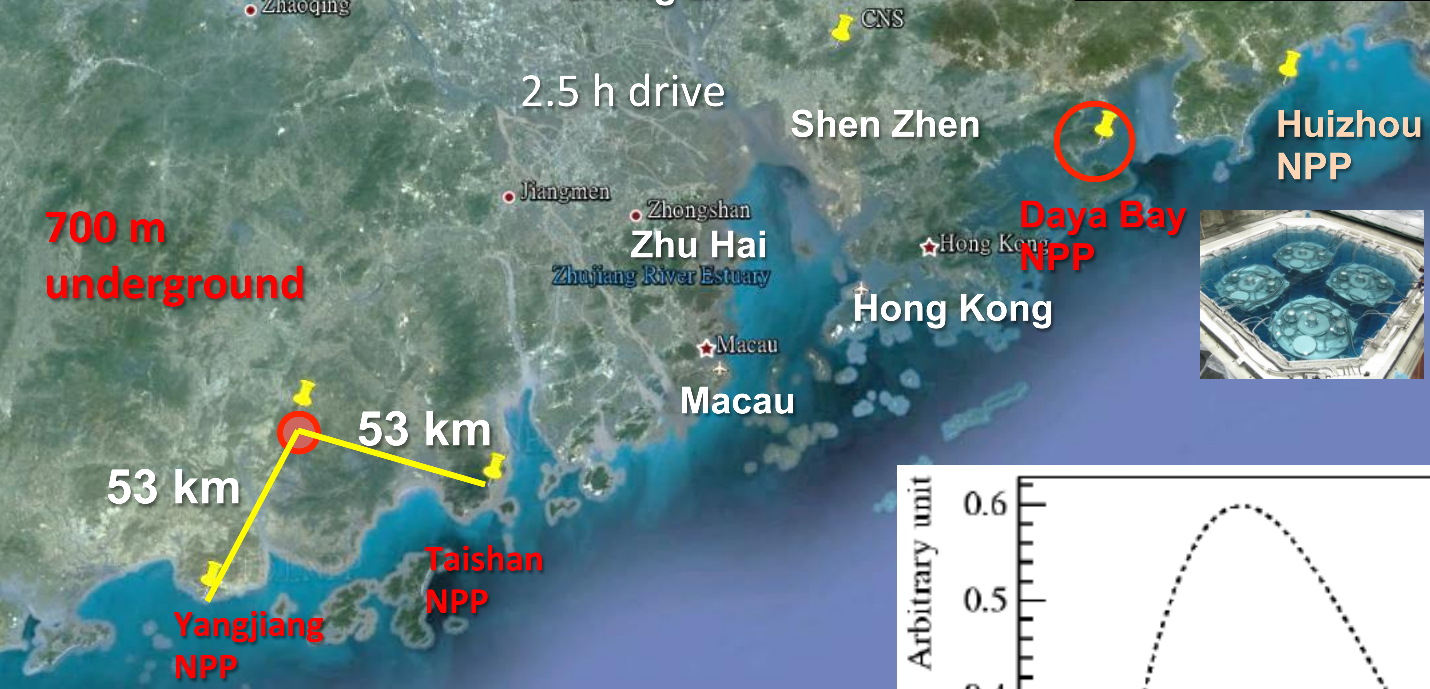


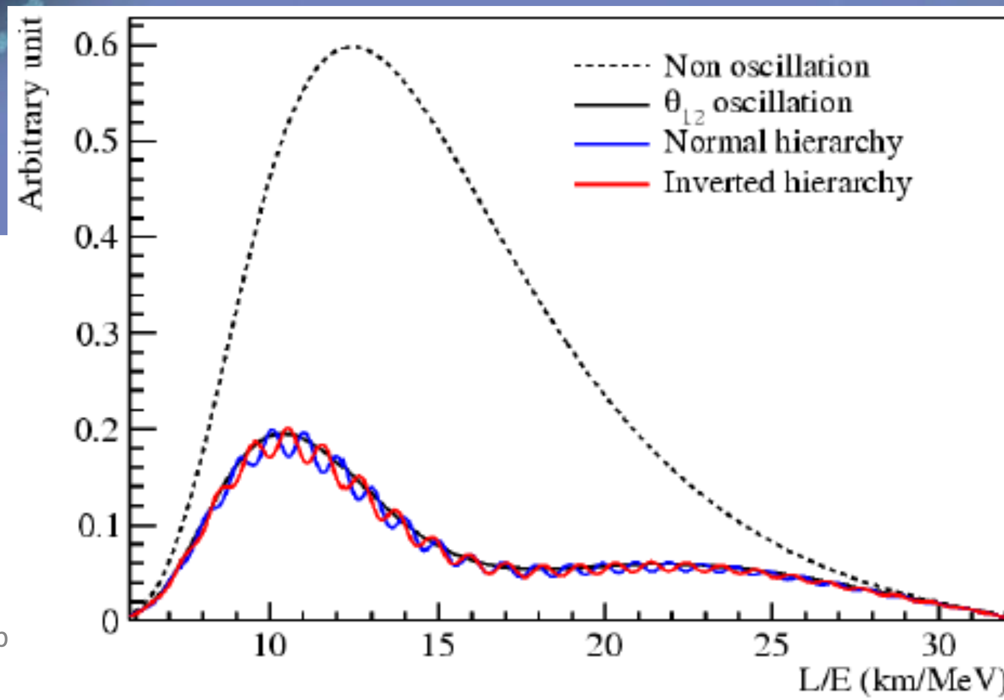


Wen (JUNO), Neutrino2014

3.5. JUNO

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





Significant sensitivity improvement is required, It can find mass hierarchy in few years

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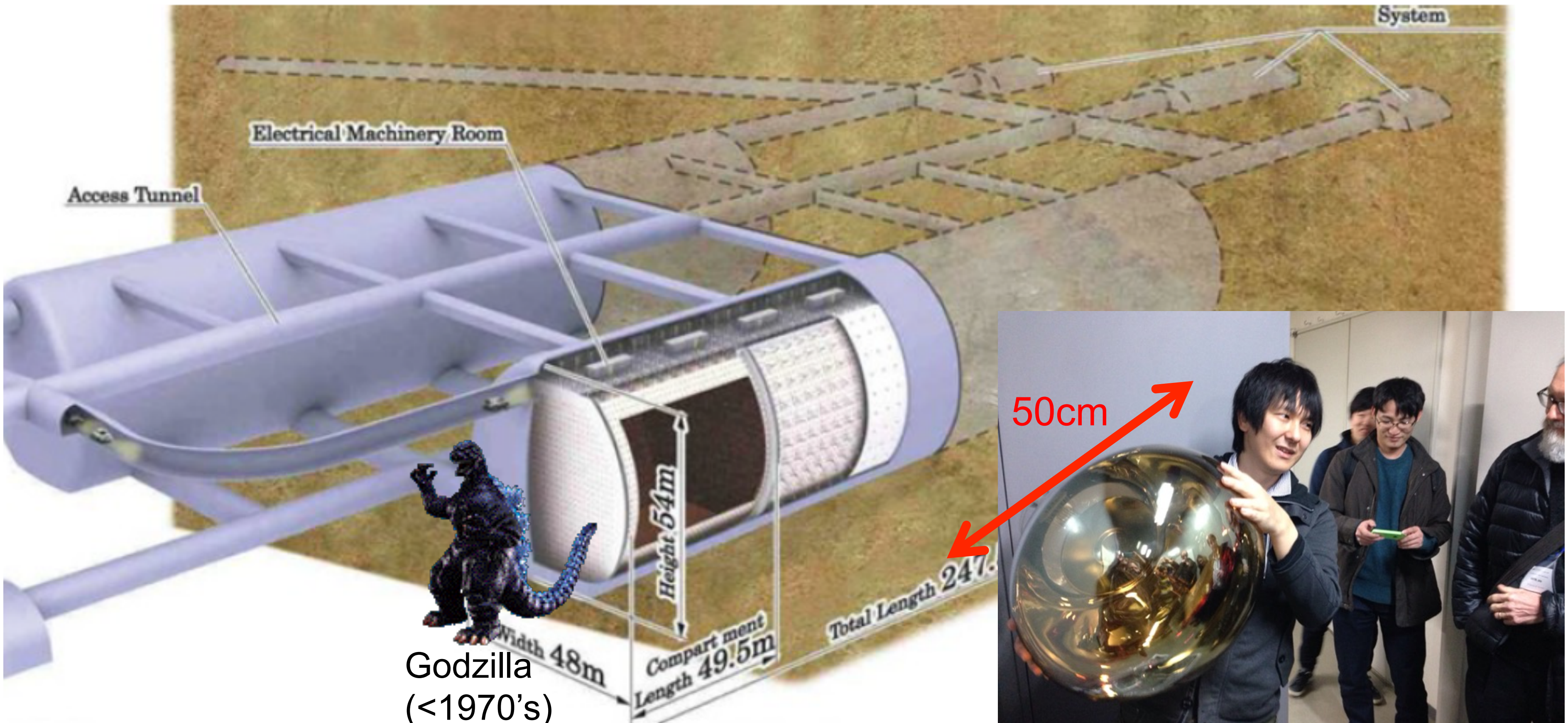
Tep

Yokoyama (HyperKamiokande), NuPhys2015

3.5. Hyper-Kamiokande

Hyper-Kamiokande with upgraded J-PARC beam

- known technology
- 560 kton water Cherenkov x 2 (each tank can contain more than 10 Godzillas!)
- δ_{CP} from ν_e appearance, θ_{23} from ν_μ disappearance, MO from atmospheric ν
- All kind of other physics (p-decay, solar/atmospheric/supernova neutrinos, etc)
- Expected to operate from ~2025

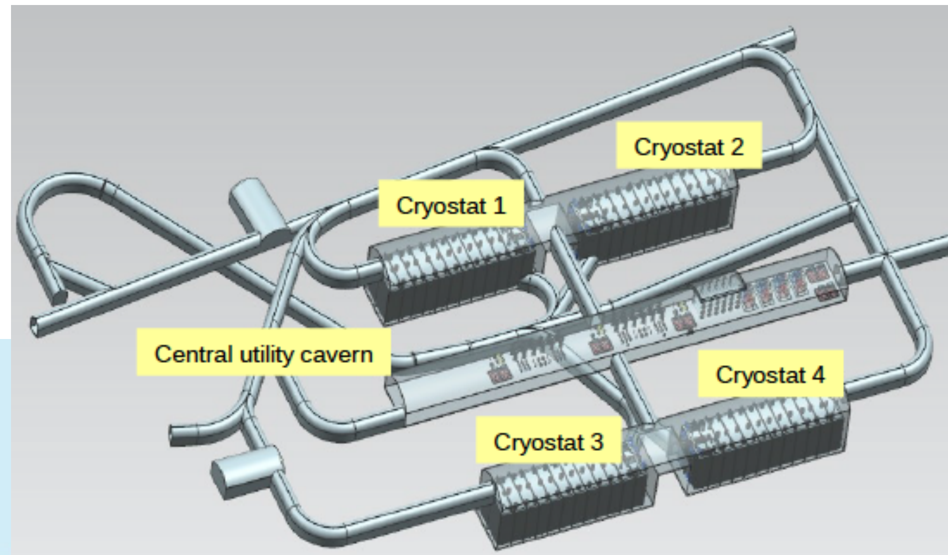


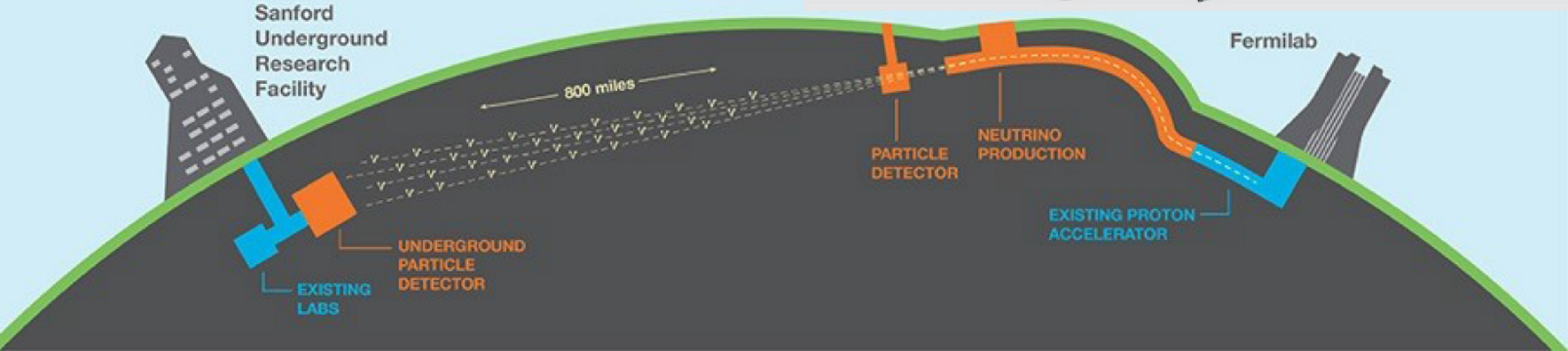
3.5. DUNE

New beamline and new detector

- There are intensive R&D at every levels (Fermilab, CERN, universities)
- 10 kton Liquid argon time projection chamber x 4
- New beamline to South Dakota
- Measure all of 3 (δ_{CP}, θ_{23}, MO)

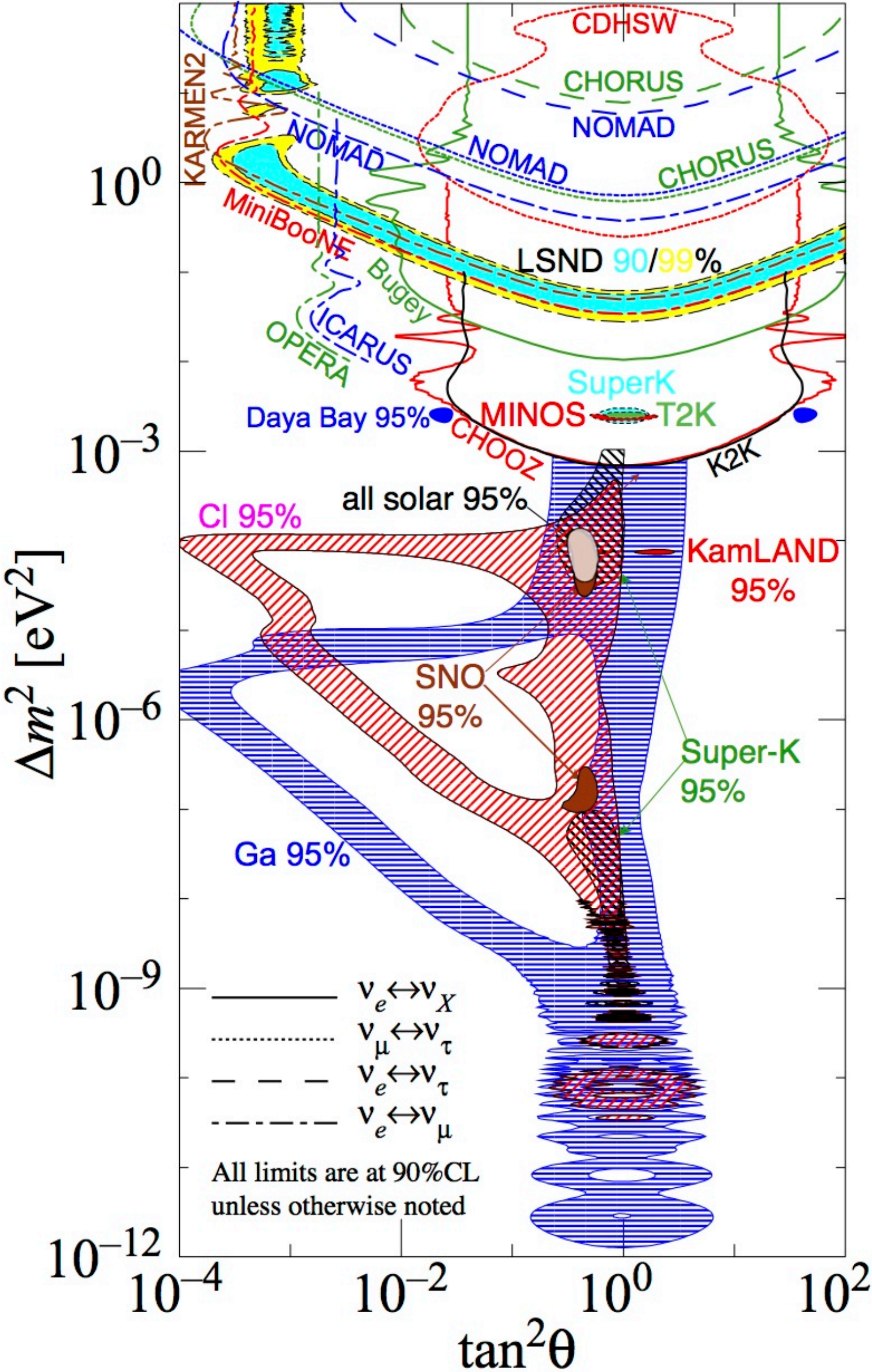
The first cryostat will be ready ~2024





3.5. Summary of νSM

Land scape of νSM in Δm^2-$\tan^2\theta$ space
- World data are nailed down all parameters in tiny regions, and all others are "excluded".



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1. Neutrino physics, the future of particle physics

2. Neutrino in Standard Model

3. Neutrino Standard Model (νSM)

3.1 Before 1998

3.2 1998 – 2004

3.3 2005 – 2011

3.4 2012 – 2013

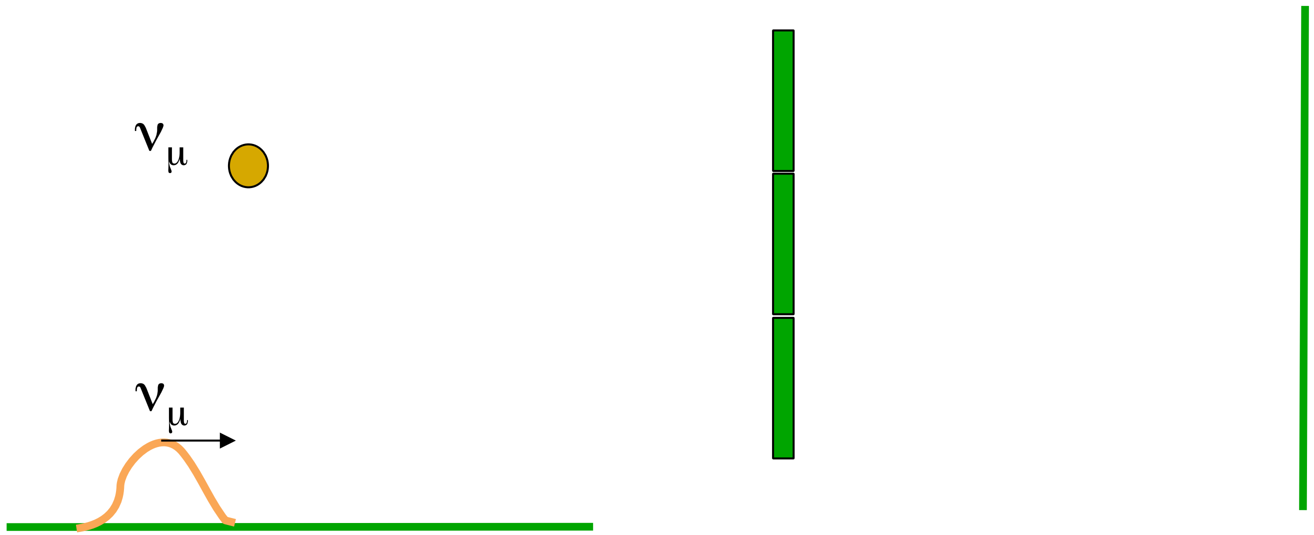
3.5 Current issues

4. Beyond νSM

5. Conclusions

4. Neutrino oscillation as a probe of new physics

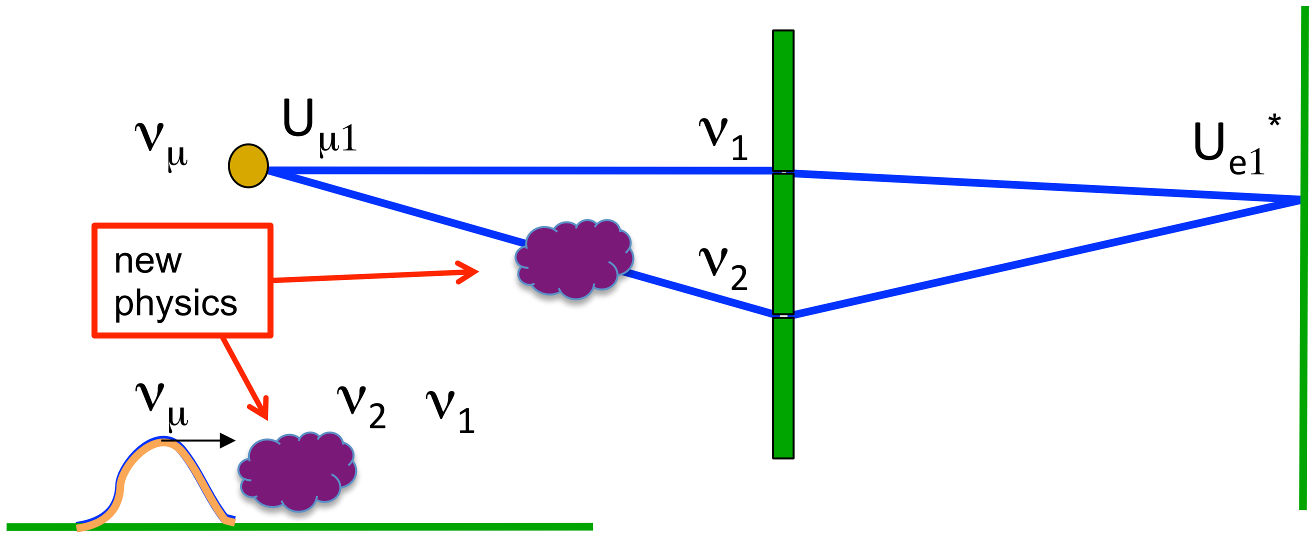
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

4. Neutrino oscillation as a probe of new physics

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.

If ν_1 and ν_2, have different coupling with new physics field, neutrinos also oscillate. The sensitivity of "neutrino interferometer" is comparable with precise atomic/optical interferometers.

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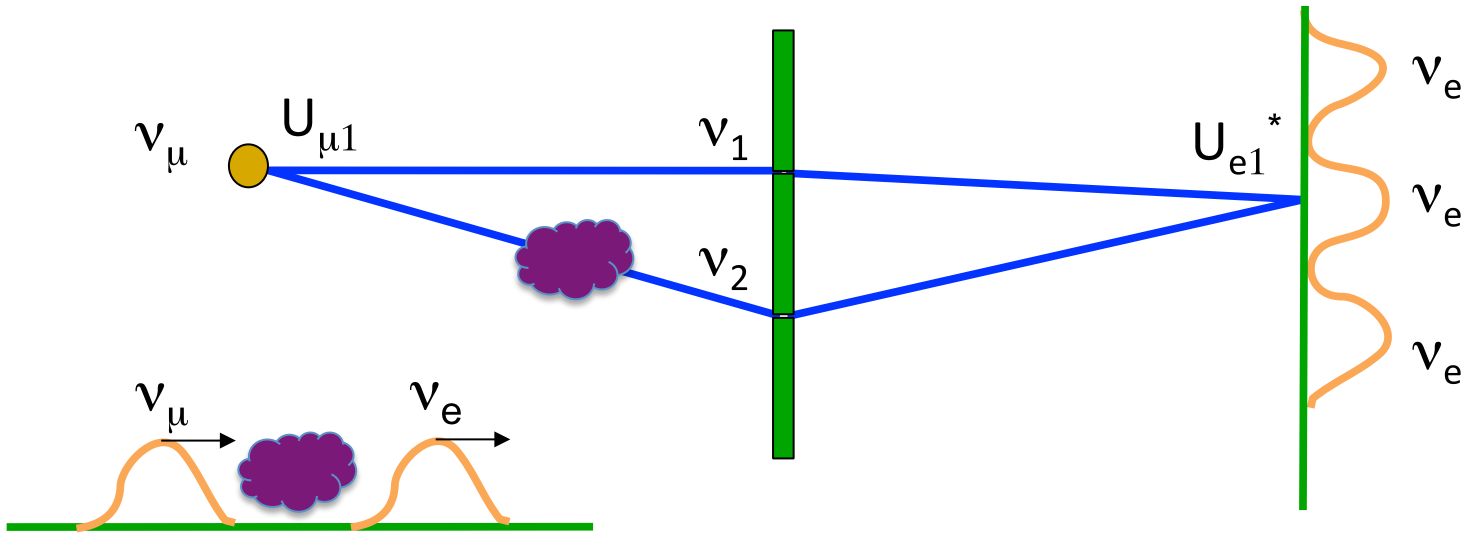


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different coupling with new physics field, neutrinos also oscillate. The sensitivity of "neutrino interferometer" is comparable with precise atomic/optical interferometers.

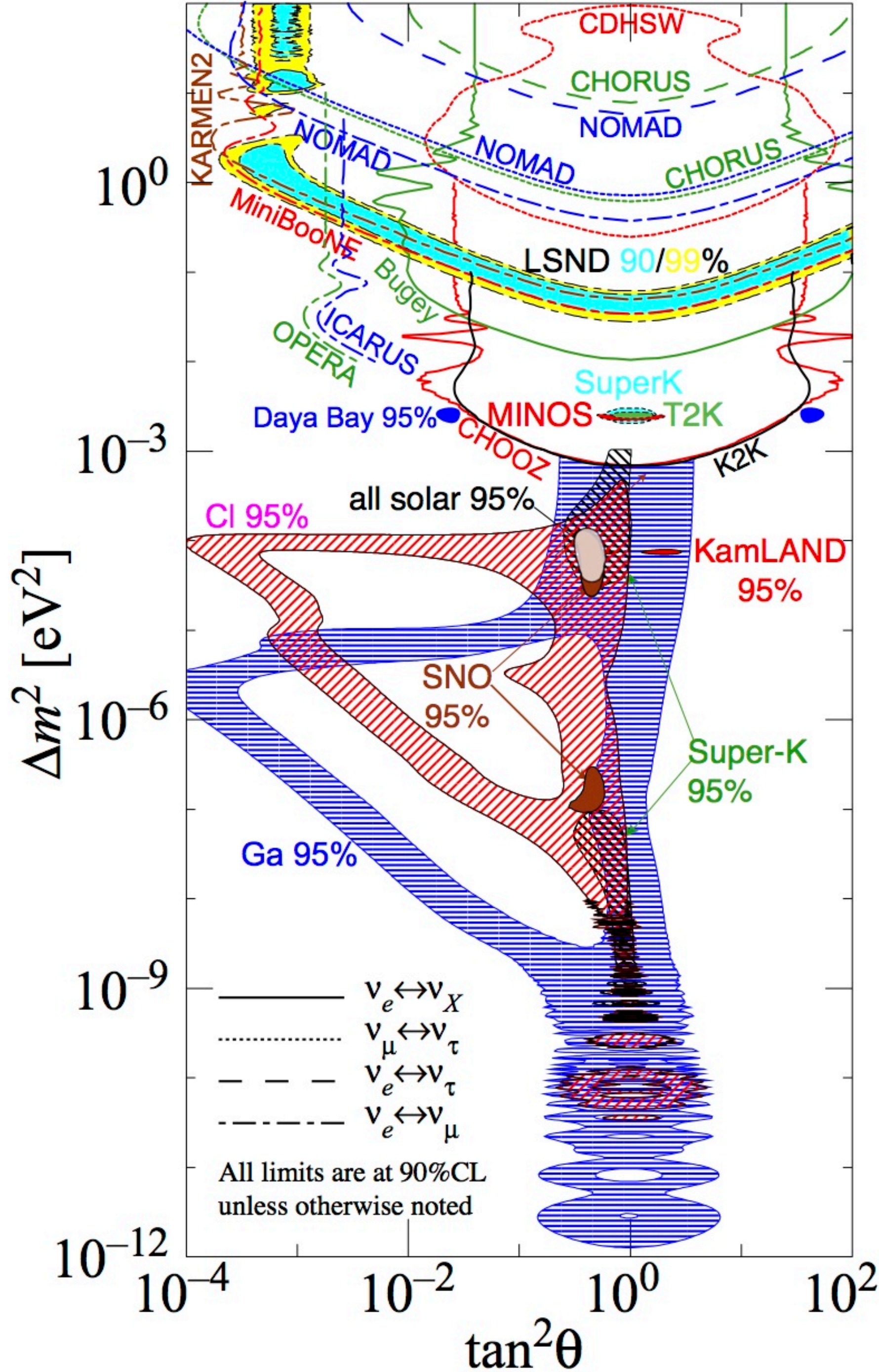
4. Beyond νSM

Land scape of νSM in Δm^2-$\tan^2\theta$ space

- World data are nailed down all parameters in tiny regions, and all others are "excluded".

But this is model dependent diagram, because it assumes neutrino mass as phase, and mass mixing matrix elements as amplitude of neutrino oscillations

What is the model-independent diagram?



http://hitoshi.berkeley.edu/neutrino

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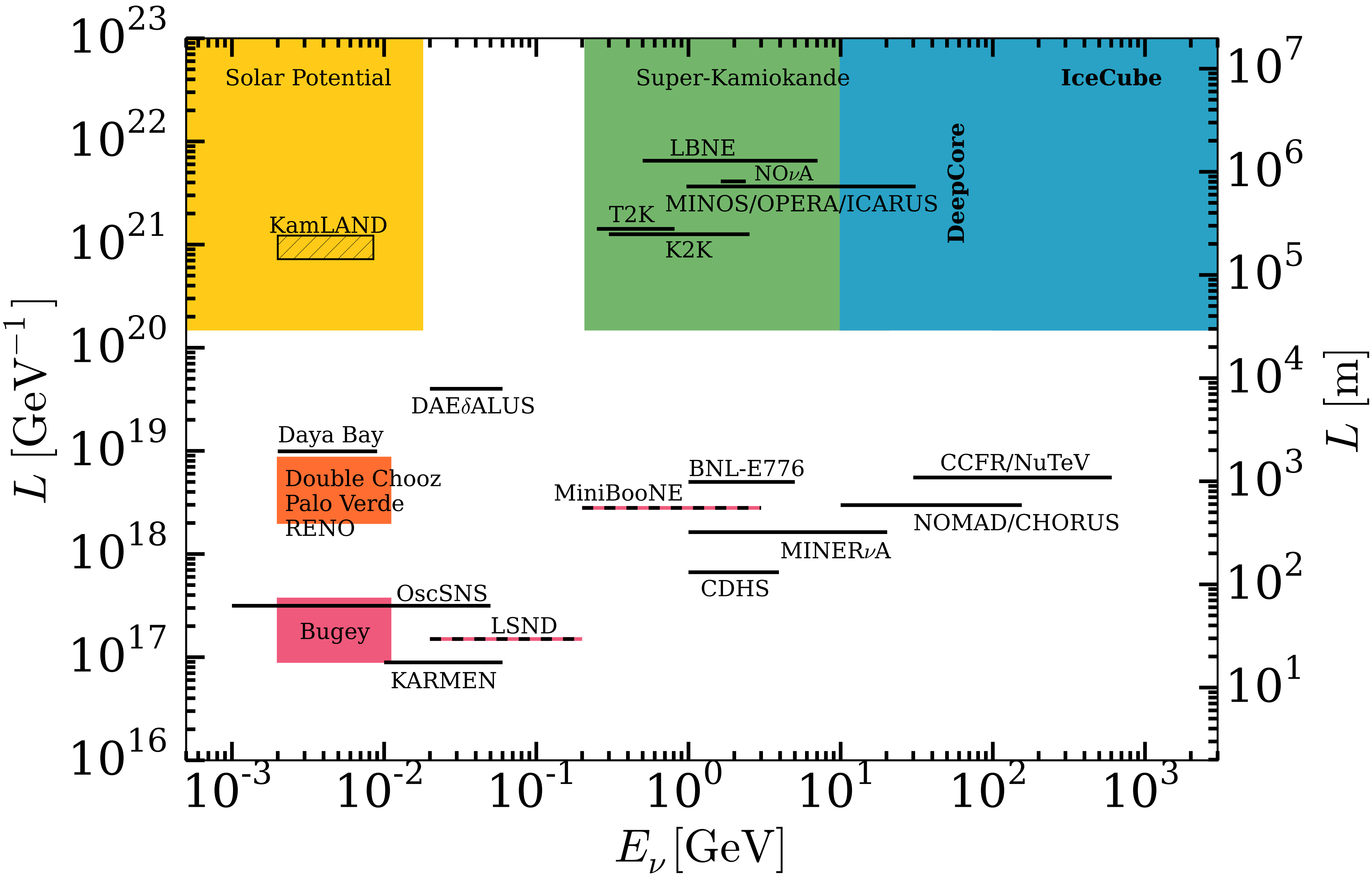
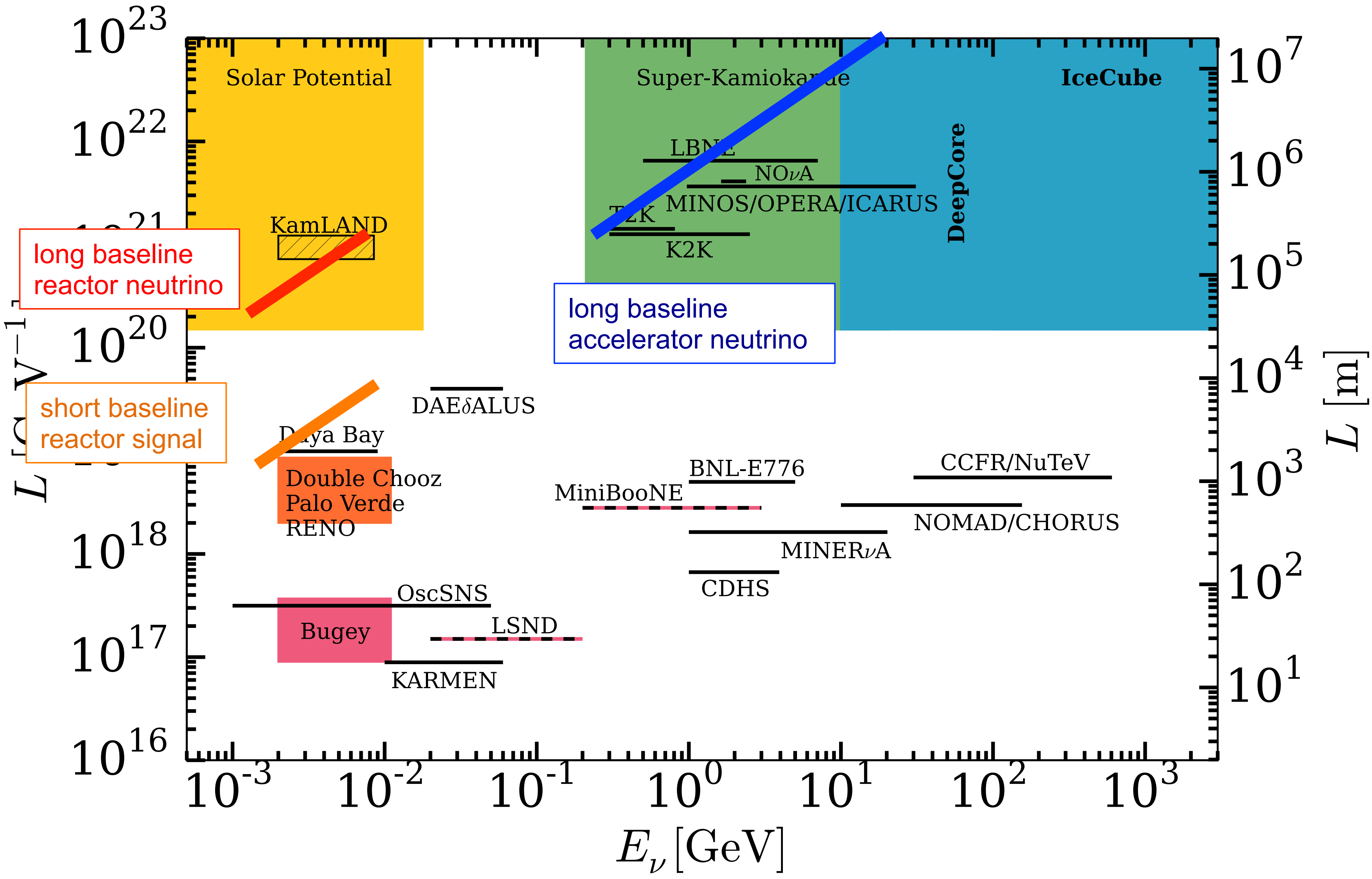
4. Beyond νSM, L-E plane



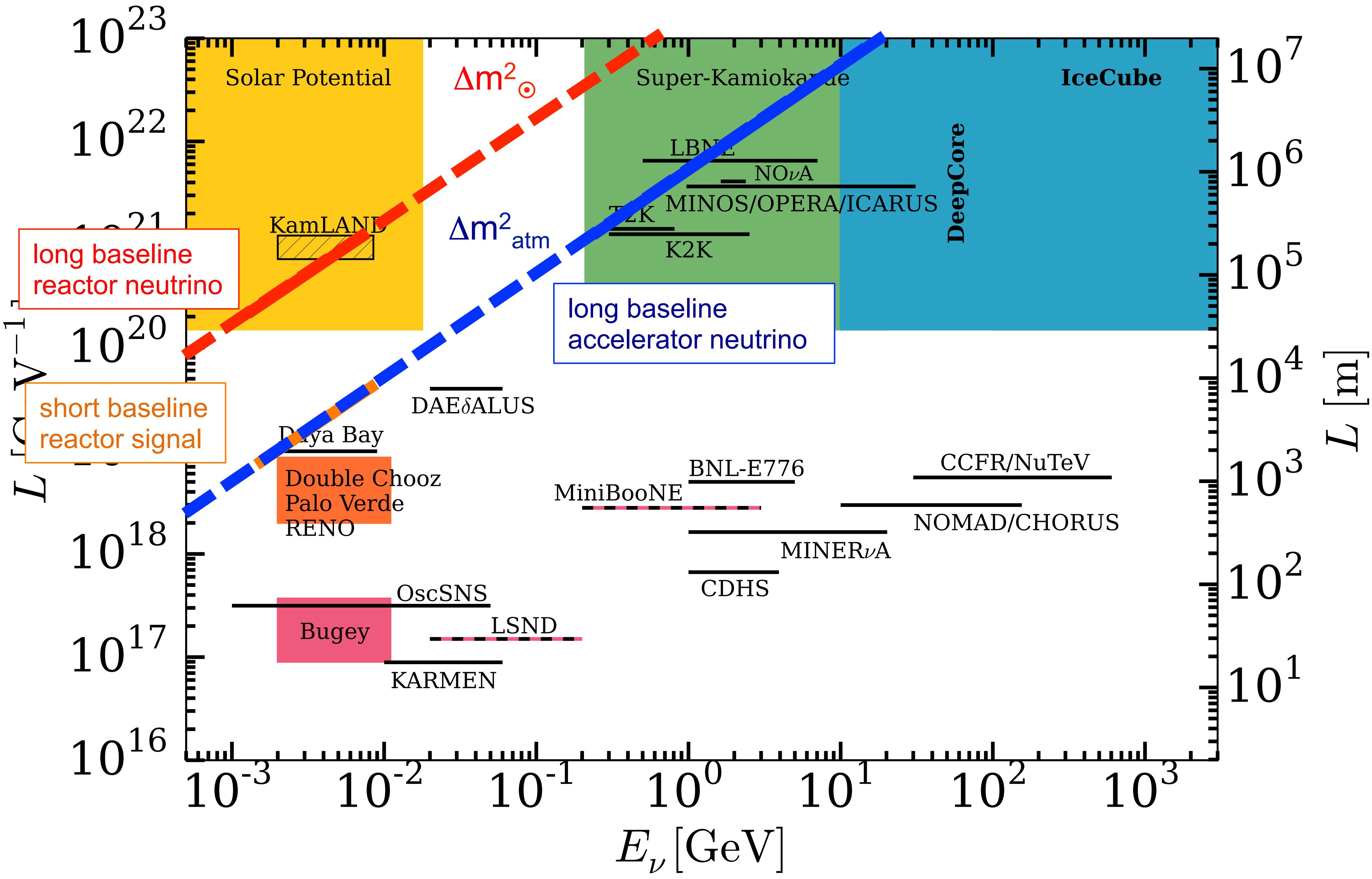
Kostelecký and Mewes, PRD69(2004)016005

4. Beyond νSM, L-E plane



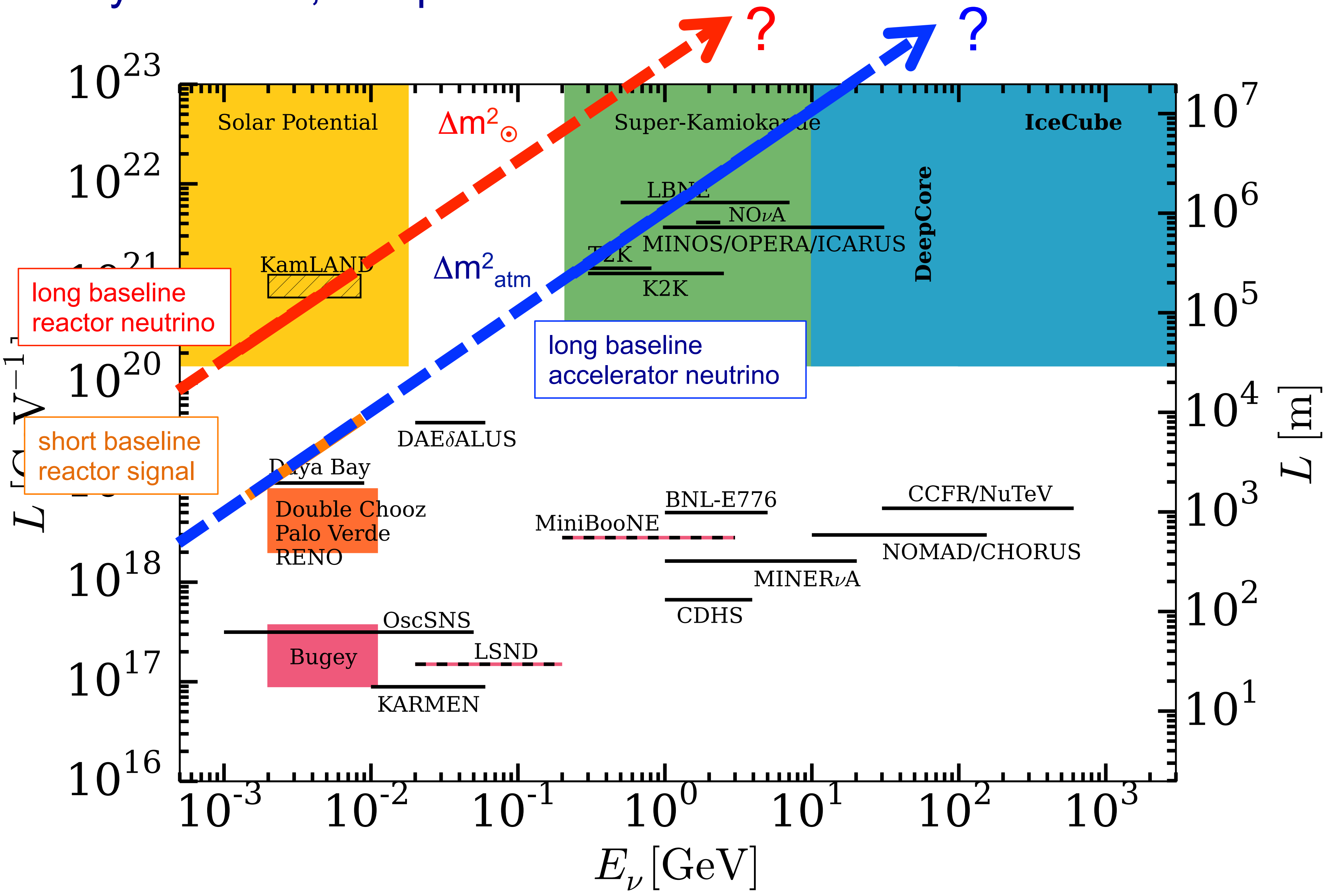
Kostelecký and Mewes, PRD69(2004)016005

4. Beyond νSM, L-E plane



Kostelecký and Mewes, PRD69(2004)016005

4. Beyond νSM, L-E plane



Kostelecký and Mewes, PRD69(2004)016005

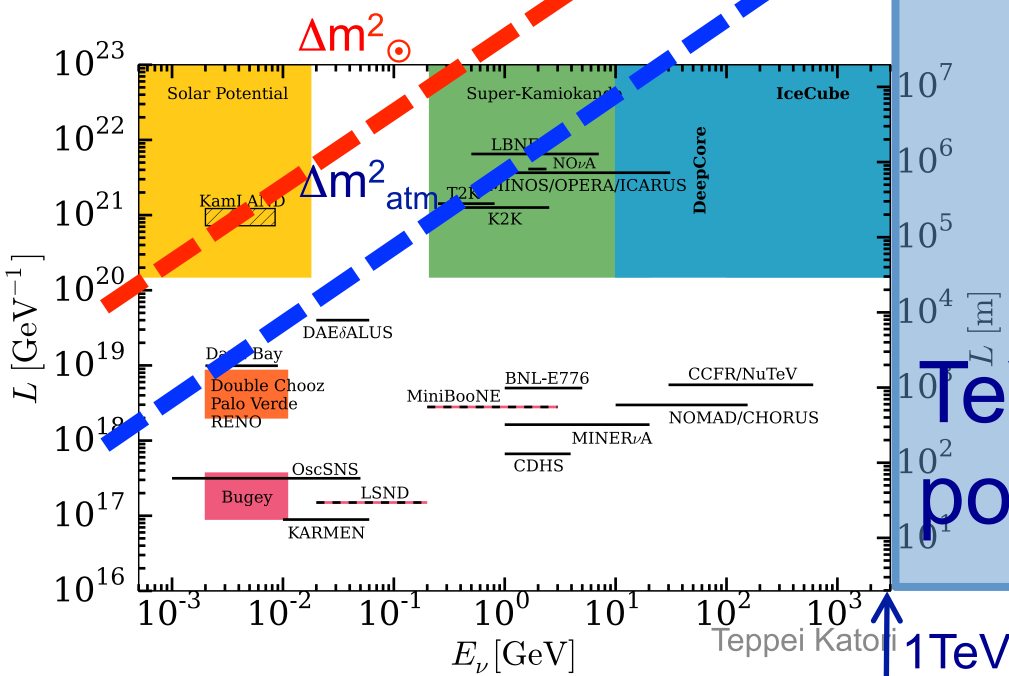
4. Beyond νSM, L-E plane

extra galactic neutrino potential

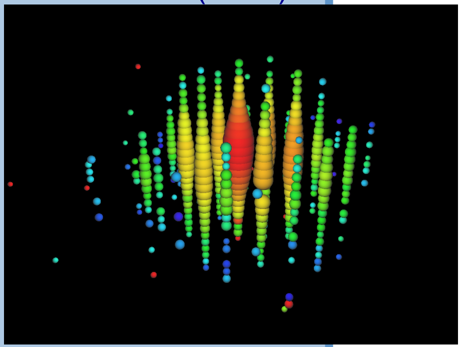
1Mpc(~Andromeda)

?

?



IceCube collaboration PRL111(2013)021103



TeV neutrino potential

1TeV

University of London

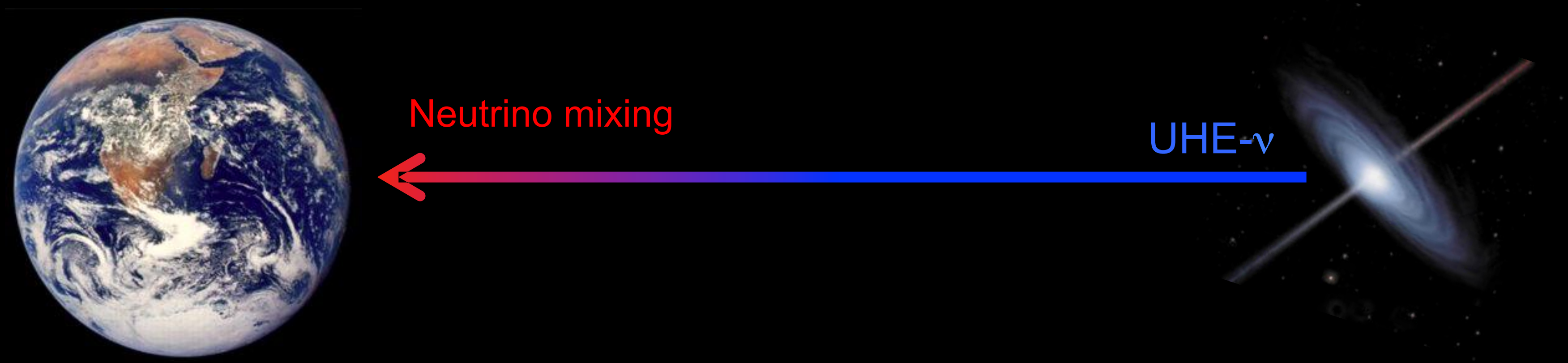
Diaz, Kostelecký, Mewes, PRD85(2013)096005;89(2014)043005
Aruguelles, TK, Salvado,PRL115(2015)161303

4. New physics with extra-terrestrial neutrinos

Combination of longer baseline and higher energy makes extra-terrestrial UHE neutrino to be extremely sensitive to new fundamental physics (such as Lorentz violation).

Tiny contamination of new physics would shows up as an anomalous flavour content

$$h_{eff} = \frac{1}{2E} U^\dagger M^2 U + \sum_n \left(\frac{E}{\Lambda_n} \right)^n \tilde{U}_n^\dagger O_n \tilde{U}_n$$



Aruguelles, TK, Salvado, PRL115(2015)161303

4. Standard flavour triangle diagram

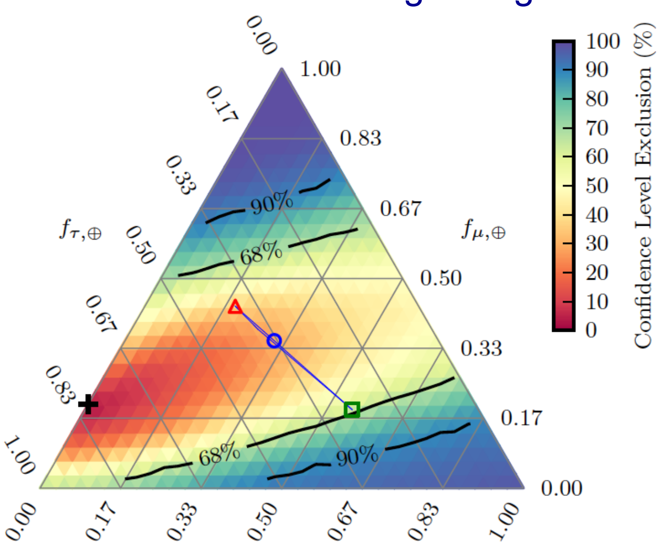
There are 3 UHE neutrino production models

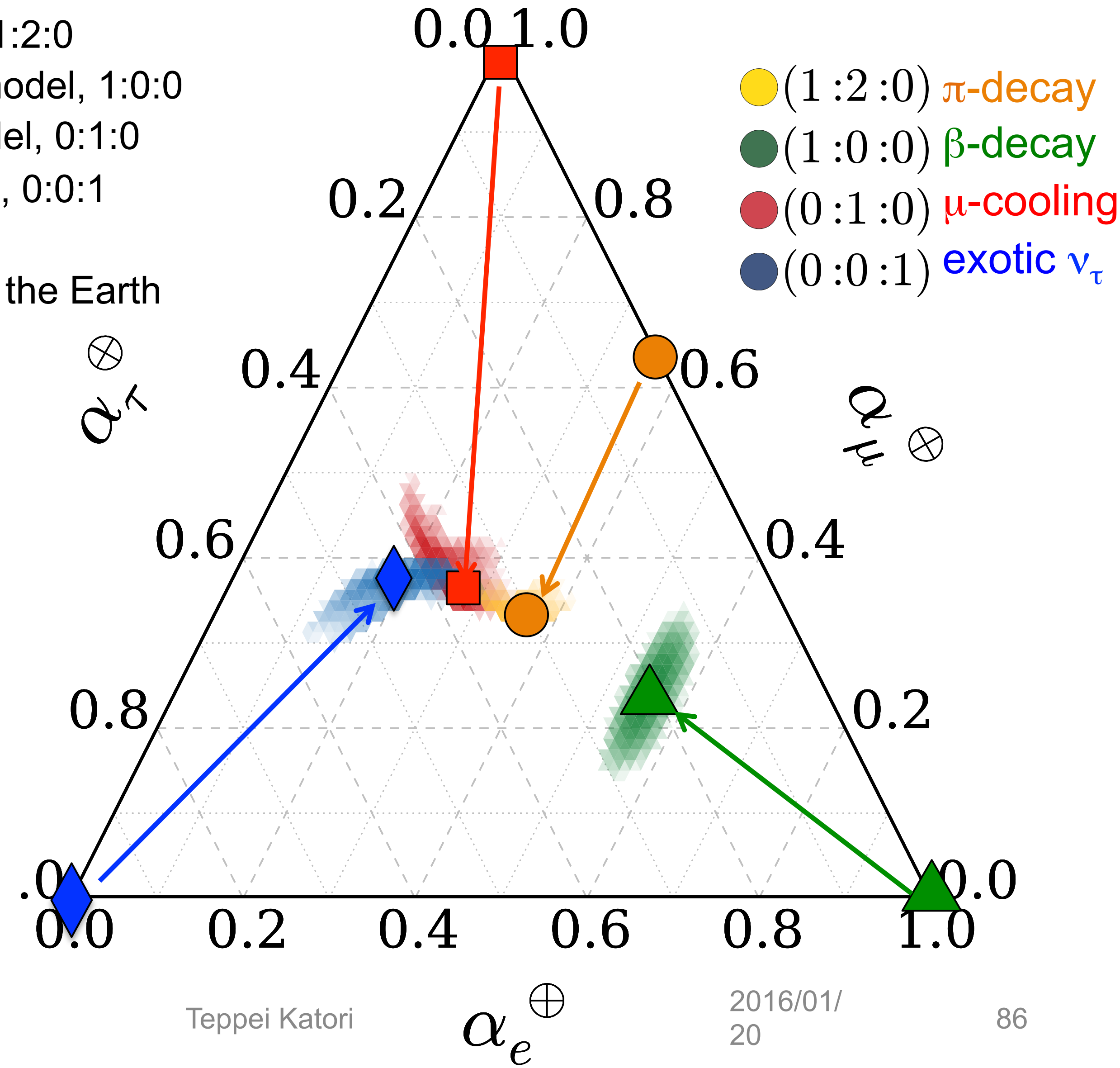
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1

Initial flavour ratio is modified on the Earth due to neutrino mixing

IceCube collaboration
PRL114(2015)171102

IceCube flavour triangle diagram



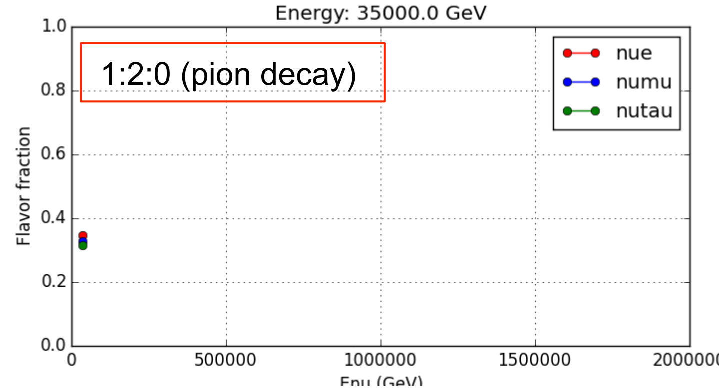


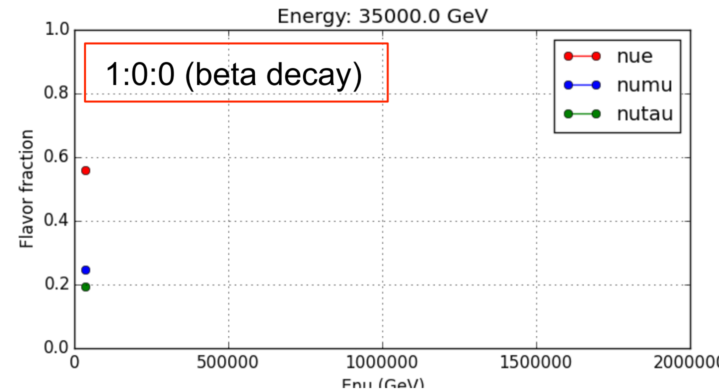
4. Neutrino flavour ratio with new physics

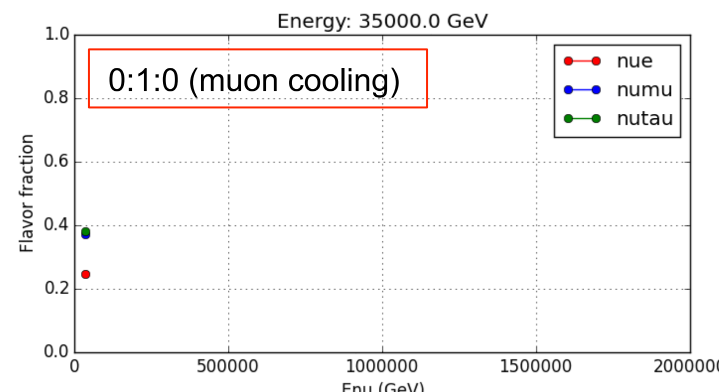
Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

An example Hamiltonian with new physics term
(~10^{-26} GeV CPT odd Lorentz violation)

$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + E\cdot\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c_{\mu\tau} \\ 0 & c_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$







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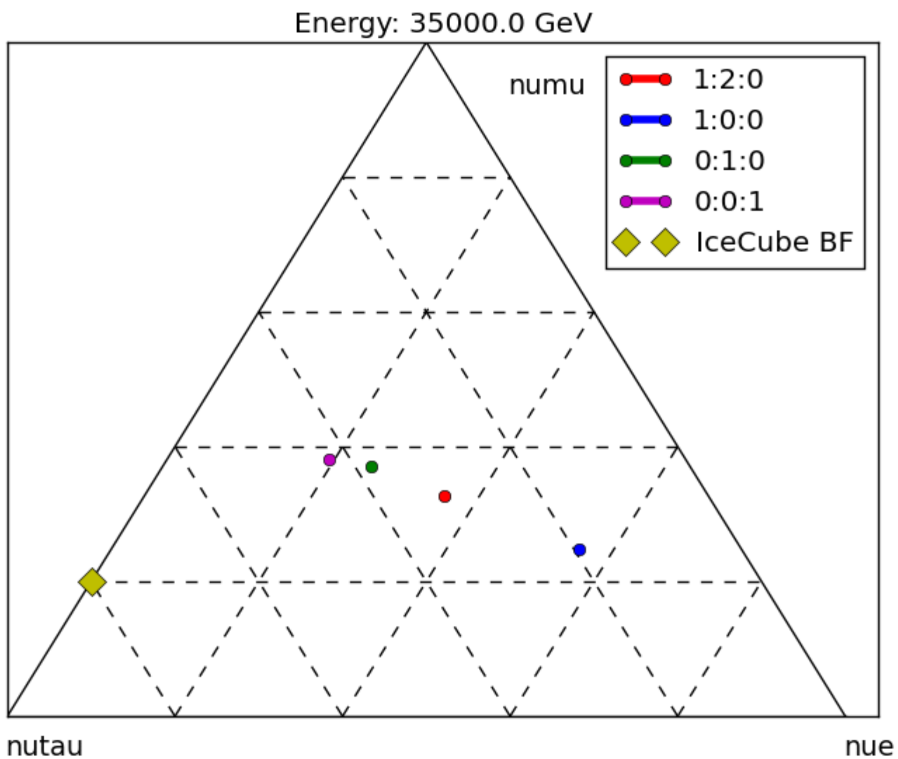
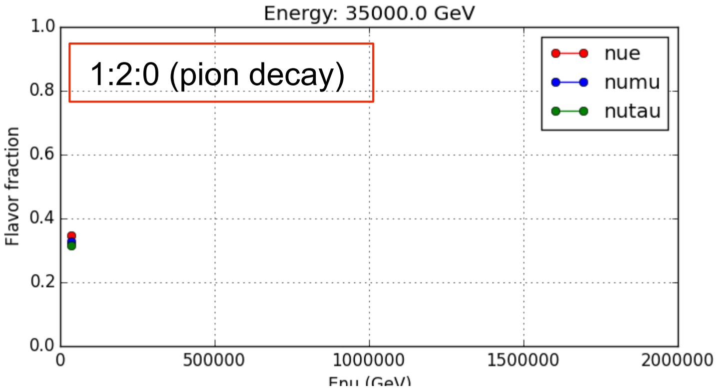
Aruguelles, TK, Salvado, PRL115(2015)161303

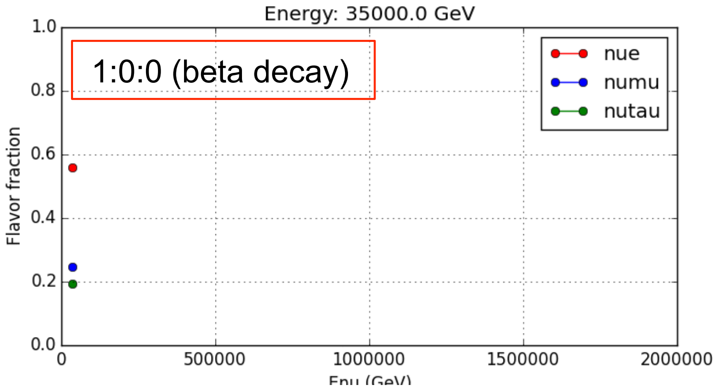
4. Neutrino flavour ratio with new physics

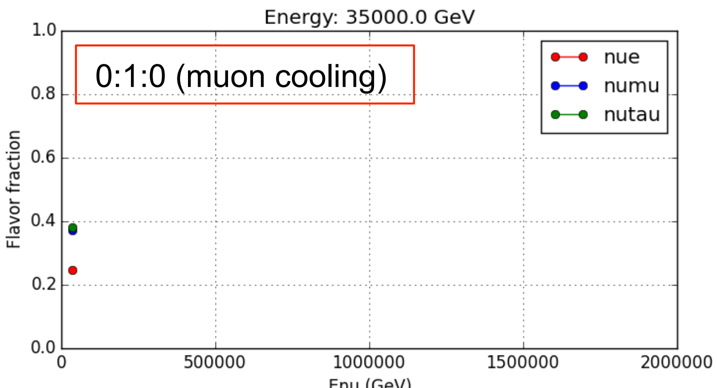
Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

Flavor triangle diagram is a convenient way to show these models.









Aruguelles, TK, Salvado, PRL115(2015)161303

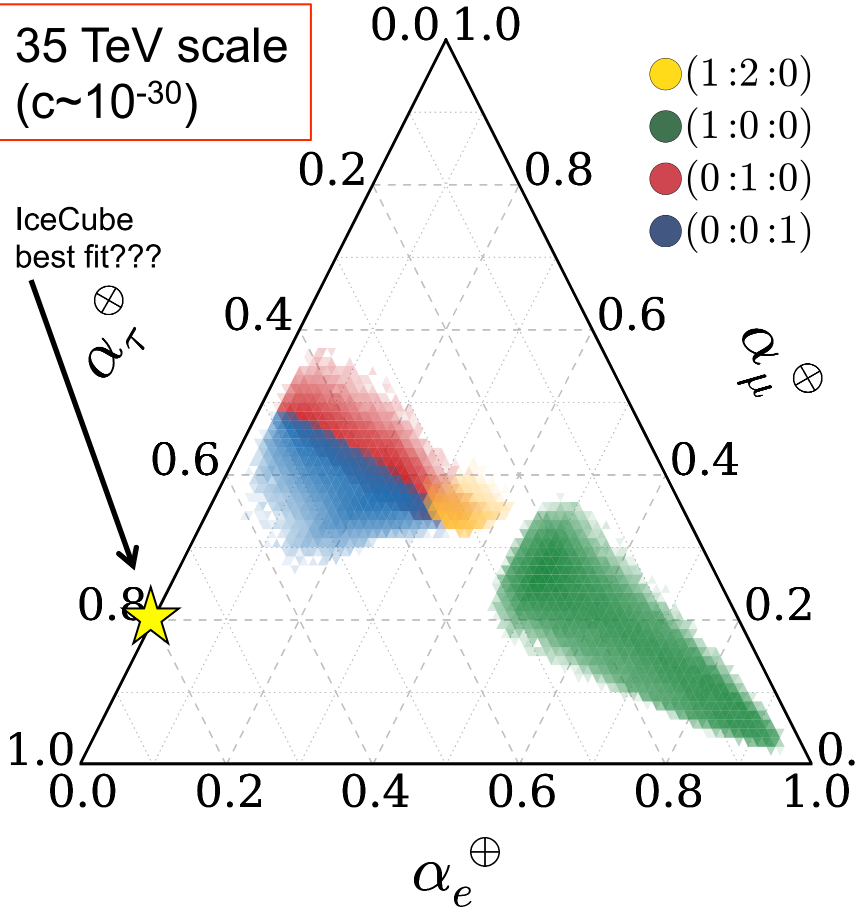
4. Flavour triangle histogram

Exotic models can make variety of flavour ratios, but not every flavour ratio is possible.

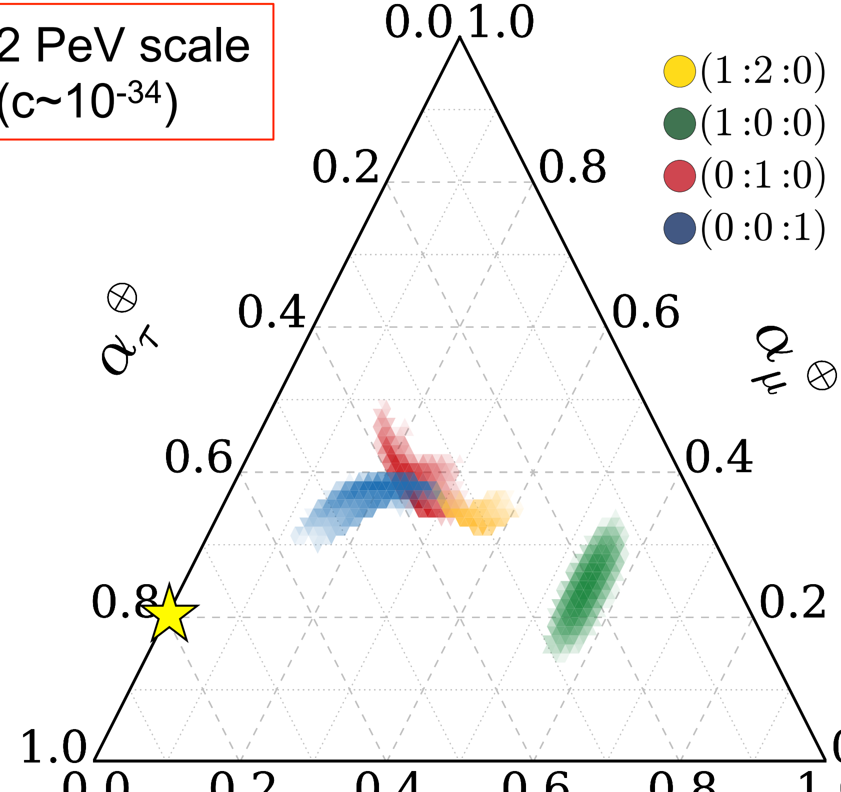
$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + E\cdot\begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & c_{\mu\mu} & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & c_{\tau\tau} \end{pmatrix}$$

Dimension-4 operator new physics

35 TeV scale ($c \sim 10^{-30}$)



2 PeV scale ($c \sim 10^{-34}$)



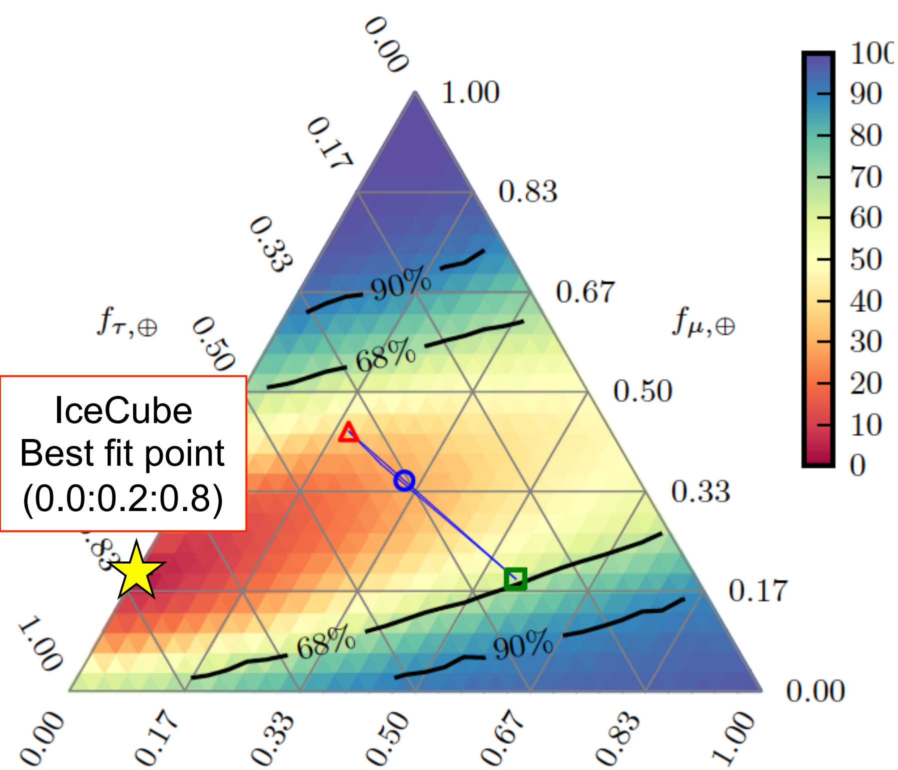
The flavour ratio is the most powerful tool to explore any new physics within particle physics

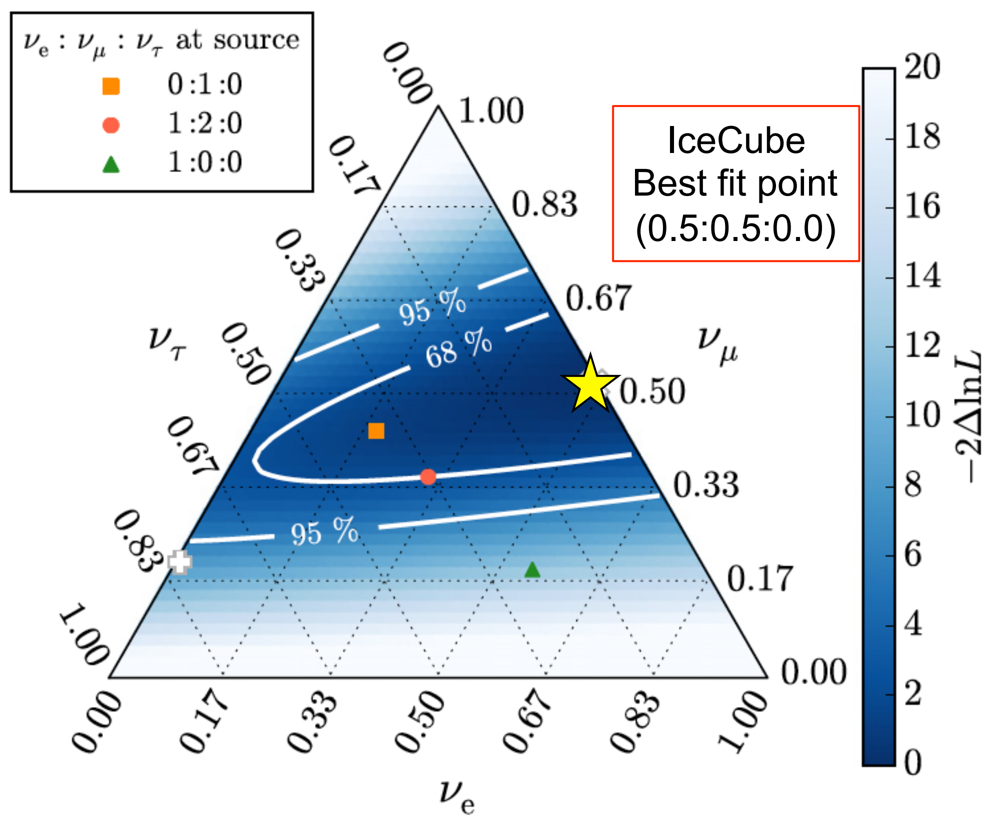
IceCube collaboration, PRL114(2015)171102, Astro.J.809:98(2015)
Palomares-Ruiz et al,PRD91(2015)103008

4. Flavour triangle by IceCube

Flavor ratio is sensitive with analysis method…

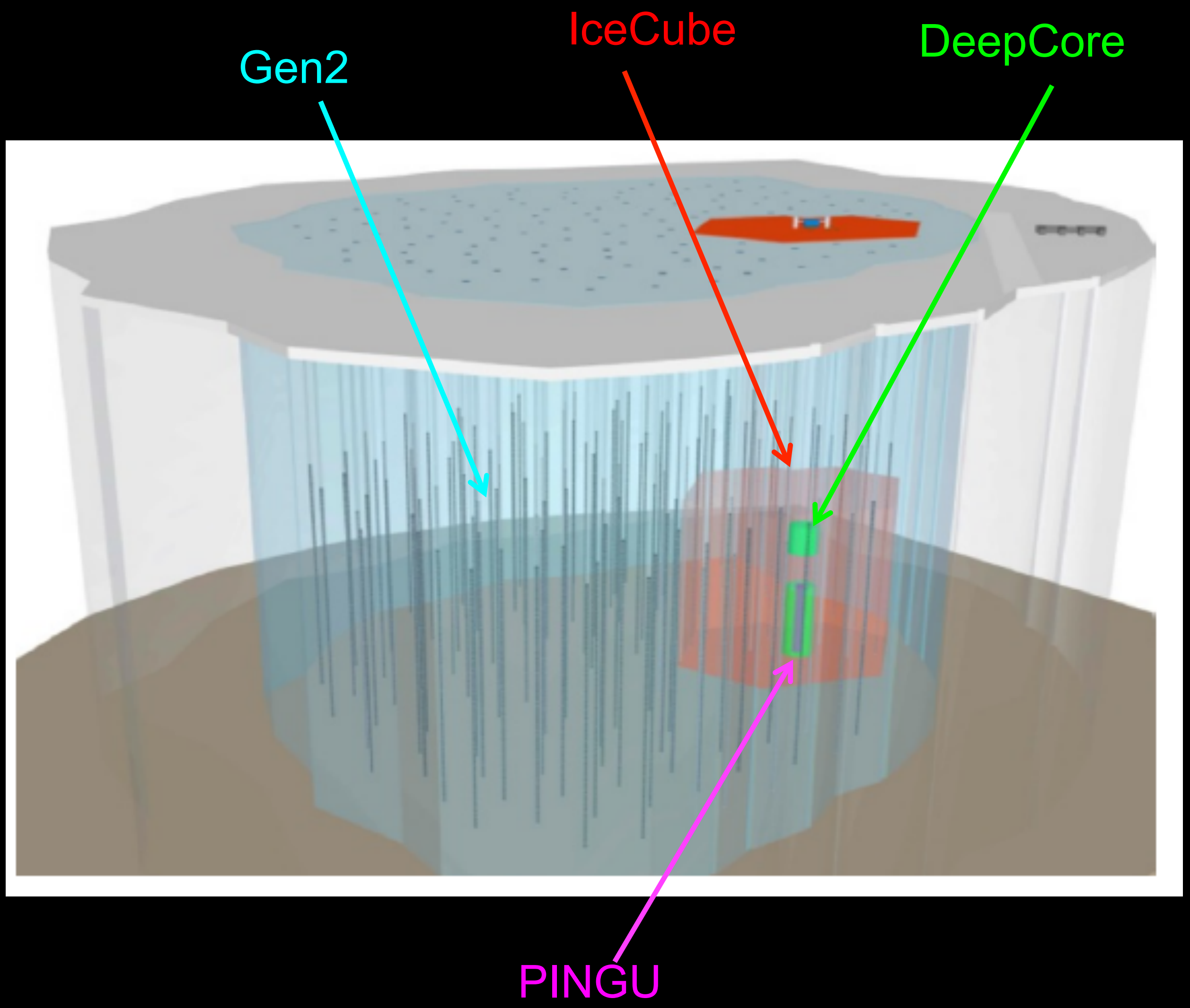
There is very shallow x2 min from ν_e-dominant to ν_τ-dominant solutions. Assumption of primary flux change the interpretation of data (absence of “Glashow resonance” events → cascade events are dominated by ν_τ? etc)





IceCube-Gen2 collaboration
arXiv:1412.5106

4. IceCube-Gen2



Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

IceCube-Gen2 collaboration
arXiv:1412.5106

4. IceCube-Gen2

IceCube-Gen2 collaboration meeting (May 1, 2015)

Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

The proposal will be submitted to NSF

1. Neutrino physics, the future of particle physics

2. Neutrino oscillations

3. Neutrino Standard Model (νSM)

3.1 Before 1998

3.2 1998 – 2004

3.3 2005 – 2011

3.4 2012 – 2013

3.5 Current issues

4. Beyond νSM

5. Conclusions

5. Mother Nature is kind to us

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

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(6 galactic supernovae in the last 1000 years)

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Mass hierarchy must be inverted so that we can find Dirac or Majorana?????

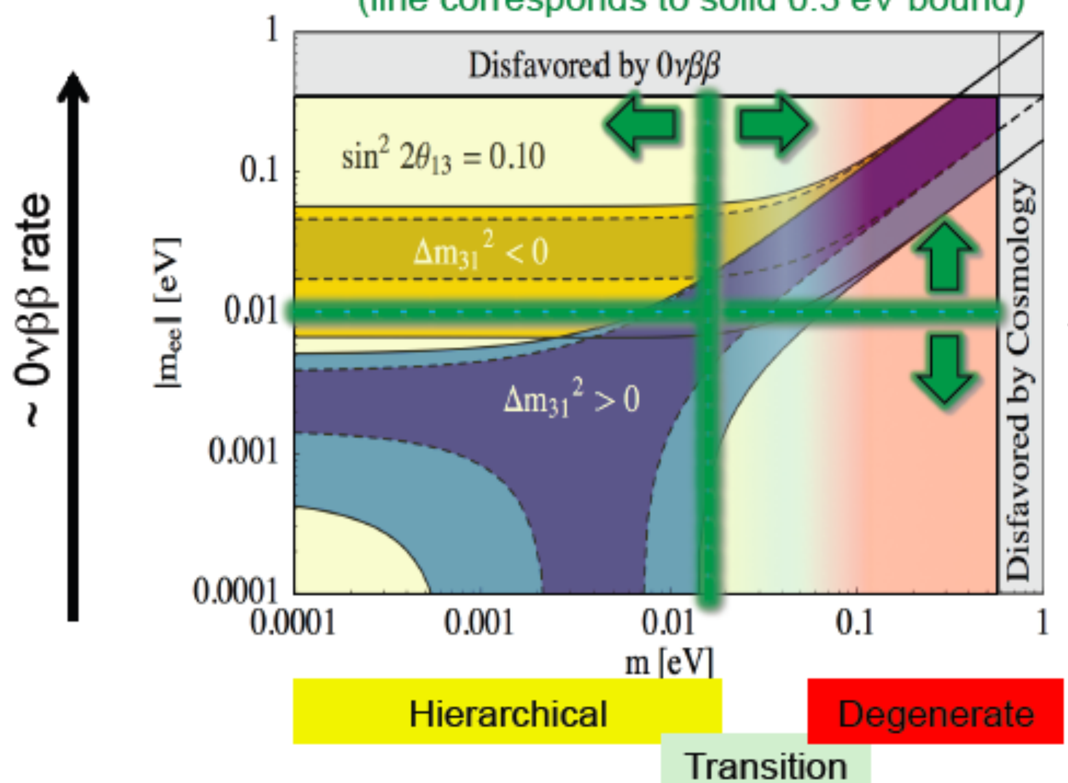
5. Mother Nature is kind to us

If mass hierarchy is normal, there is a chance we cannot find Dirac or Majorana from 0νββ

Neutrinoless double beta decay

- If neutrinos are Majorana neutrinos, they will mediate 0νββ.
- The 0νββ rate depends on the hierarchy in degenerate regime:

(line corresponds to solid 0.3 eV bound)



Inverted ordering guarantees lower limit for 0νββ rate!

Future measurements?

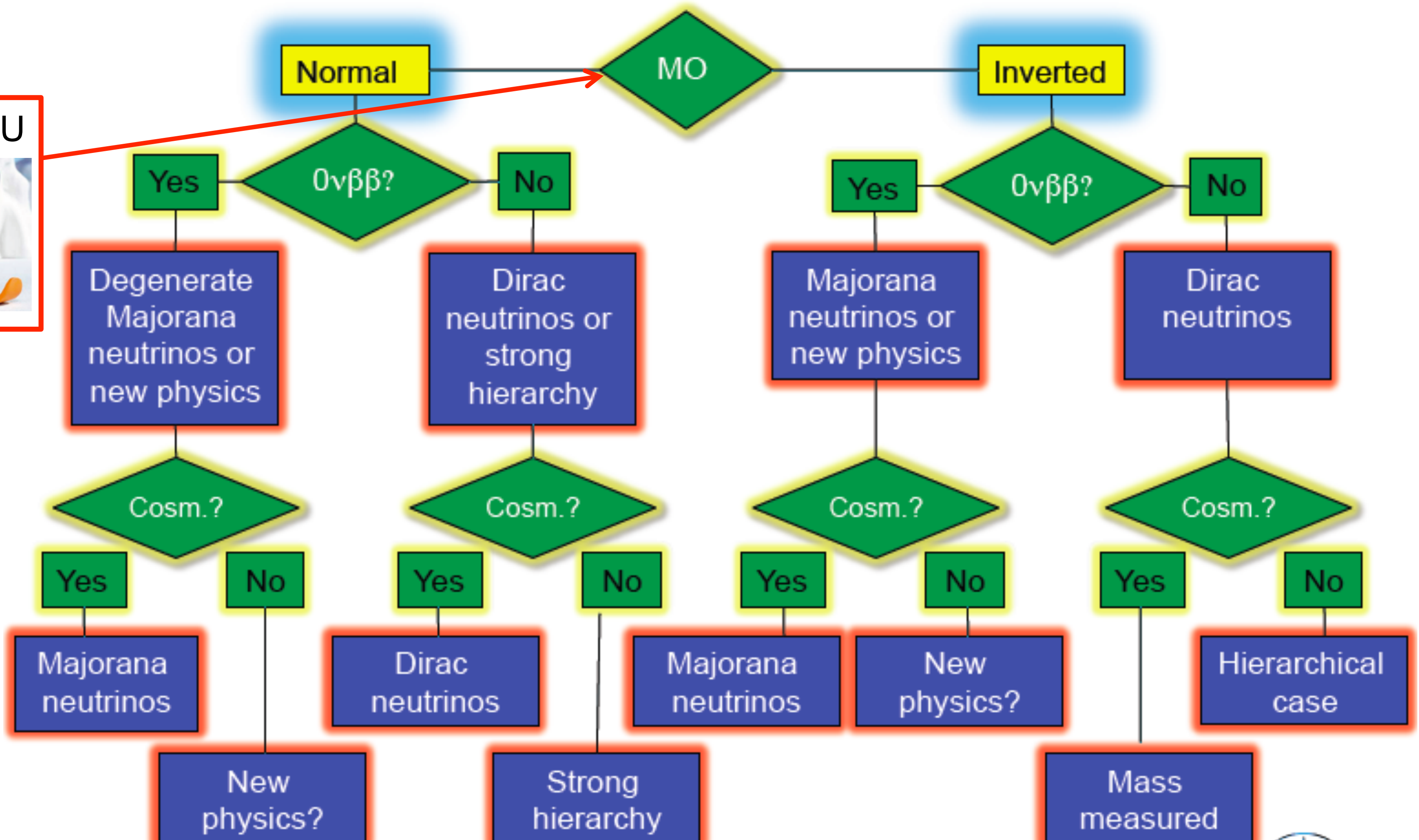
(from: Lindner, Merle, Rodejohann, hep-ph/0512143; see talk by Martin Hirsch)

5. Mother Nature is kind to us

If mass ordering is normal, there is a chance we cannot find Dirac or Majorana from $0\nu\beta\beta$

Impact of direct mass ordering (MO) measurement

PINGU



5. Mother Nature is not kind to Theorists

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 $V_{cb} \sim 0.04$
→ wrong, PMNS matrix has big off-diagonals

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

Conclusions

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

νSM is established, current unknown parameters of νSM are

- δ_{CP}
- θ_{23}
- mass hierarchy
- Majorana phase
- Dirac or Majorana
- Absolute neutrino mass

Neutrino oscillations are interesting probes for Beyond SM physics

Current and future oscillation experiments are good position to find δ_{CP}, θ_{23}, and mass hierarchy

Thank you for your attention!

Backup

3.5 Hyper-Kamiokande

Project Status

- **Strong support from Japanese communities**
  - "the core of future high energy physics research in Japan" (the Subcommittee on Future Projects of High Energy Physics)
  - "one of the top priority projects" (the Subcommittee on Cosmic Ray Community Future Projects)
  - Workshop/symposium with astrophysics commnunity.
- **Master Plan 2014 by Science Council of Japan (Mar. 2014)**
  - Hyper-K was selected as one of 27 high priority projects among 207 large-scale projects in all fields
- **Not listed on the MEXT roadmap 2014 (Aug. 2014)**
  - We are preparing for the next revision of roadmap foreseen in 2016-17.
  - Organization, international participation, cost estimation

3.5 DUNE

Timeline

- July 2015 "CD-1 Refresh" review. Conceptual design review. - **Completed!**
- Oct 2015: protoDUNE **approved** at CERN
- Dec 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting. - **Completed!**
- 2017 Ongoing shaft renovation at SURF complete
- 2017 Start of far site conventional facilities.
- 2018 Testing of "full-scale" far detector elements at CERN
- 2019 Technical Design review
- 2021 Ready for start of installation of the first far detector module
- 2024 start of physics with one detector module
  - Additional far detector modules every ~2 years.
- 2026 Beam available
- 2026 Near detector available
- 2028 DUNE construction finished

3.5 JUNO/RENO50

Overview of JUNO / RENO-50

- **JUNO/RENO-50** : An underground (~700 m) detector consisting of 20/18 kton ultra- low-radioactivity liquid scintillator & 18,000/15,000 20" PMTs, at ~50 km

- **Goals** : - Determination of neutrino mass hierarchy sensitivity: 3~4 σ w/ 6 yr data (JUNO), 3 σ w/ 10 yr (RENO-50)
  - High-precision measurement of θ_{12} and Δm^2_{21}
  - Study neutrinos from the Sun, the Earth, supernova, atmosphere. sterile ν search etc.

- **Budget** : $ 300M for JUNO; $ 100M for RENO-50

- **Schedule** : 2013 ~ 2021 : Facility and detector construction
(JUNO) 2020 ~ : Operation and experiment

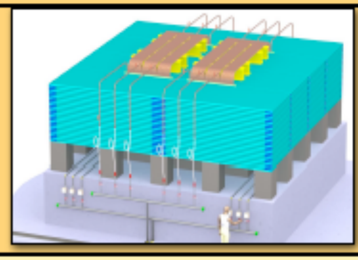
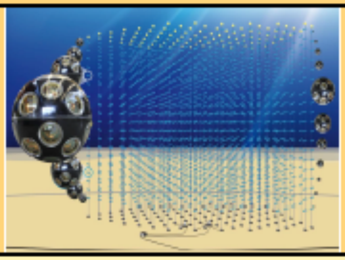
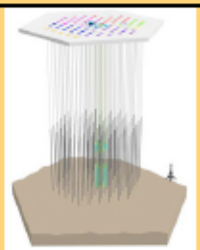
- **Schedule** : 2016 ~ 2021 : Facility and detector construction
(RENO-50) 2022 ~ : Operation and experiment

3.5 PINGU/ORCA/INO

PINGU: awaiting funding, initial MO measurement in ongoing with DeepCore
ORCA: deploy 6 strings in 2016, awaiting full funding for 115 strings
INO: awaiting funding

→~3σ NMO by early 2020s

The Detectors

	INO India-based Neutrino Observatory	ORCA Oscillation Research with Cosmics in the Abyss	PINGU Precision IceCube Next-Generation Upgrade
Location	South India	French coast	South Pole
Type	Magnetized Tracking Calorimeter	Water Cherenkov	Ice Cherenkov
Fiducial Mass	50-100 KT	~4 MT	~5 MT
arXiv	1505.07380v1	(in progress)	1401.2046v1
Cartoon			

1. P5 report

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Senario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

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University of London

1. P5 report

Figure 1
Construction and Physics Timeline

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4. Neutrinos, as probes of new physics

SM physics with neutrinos
- PDF measurement (unpolarized, polarized)
- Nuclear structure measurement

BSM physics with neutrinos
- Neutrino oscillation is an interference experiment
- Neutrinos are naturally sensitive to small space-time properties, such as Lorentz invariance.

SME Lagrangian in neutrino sector

$$L = \frac{1}{2} i \bar{\psi}_A \Gamma^{\nu}_{AB} \partial_{\nu} \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.$$

SME coefficients

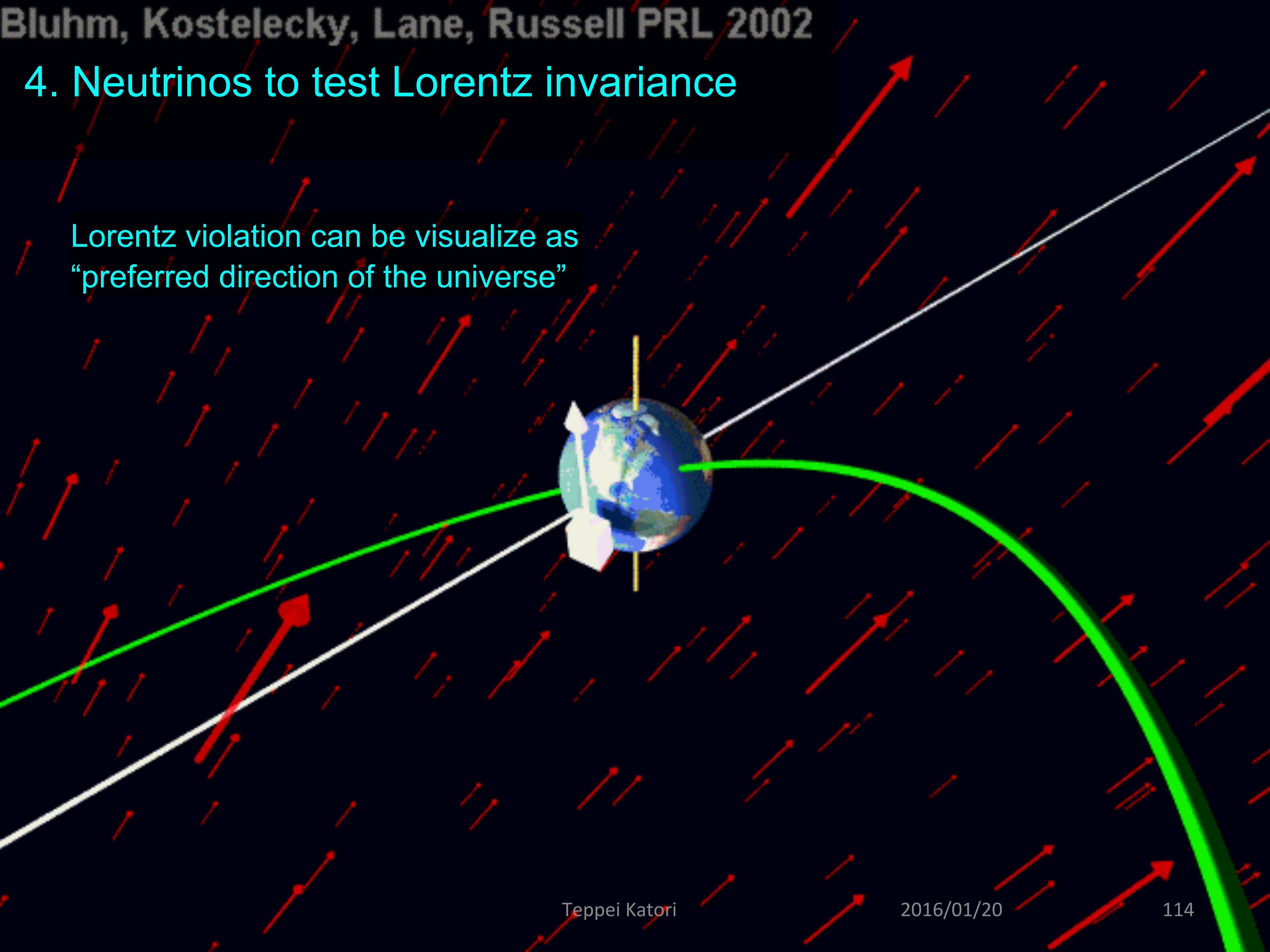
$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_{\mu} + d^{\mu\nu}_{AB}\gamma_{\mu}\gamma_5 + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu} \cdots$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_5 + a^{\mu}_{AB}\gamma_{\mu} + b^{\mu}_{AB}\gamma_5\gamma_{\mu} + \frac{1}{2} H^{\mu\nu}_{AB}\sigma_{\mu\nu} \cdots$$

Standard Model Extension (SME) is the standard formalism for the general search for Lorentz violation.

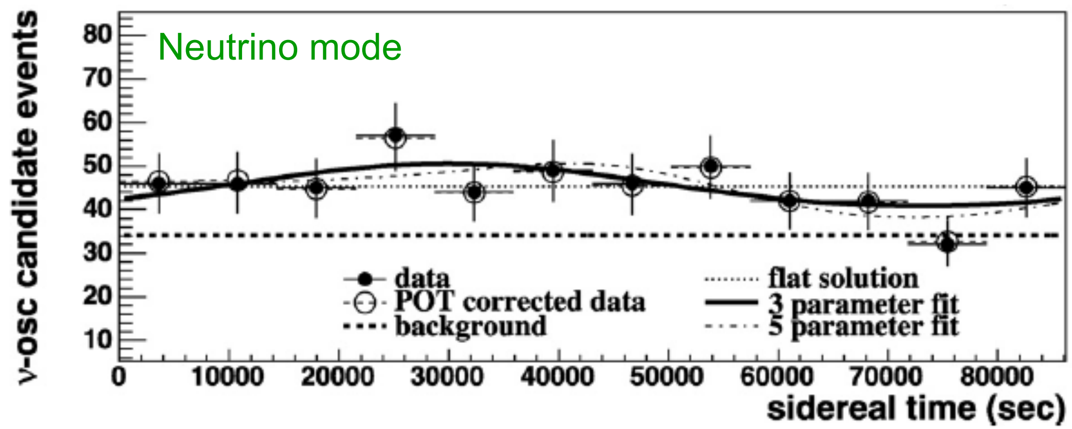
4. Neutrinos to test Lorentz invariance

Lorentz violation can be visualize as "preferred direction of the universe"

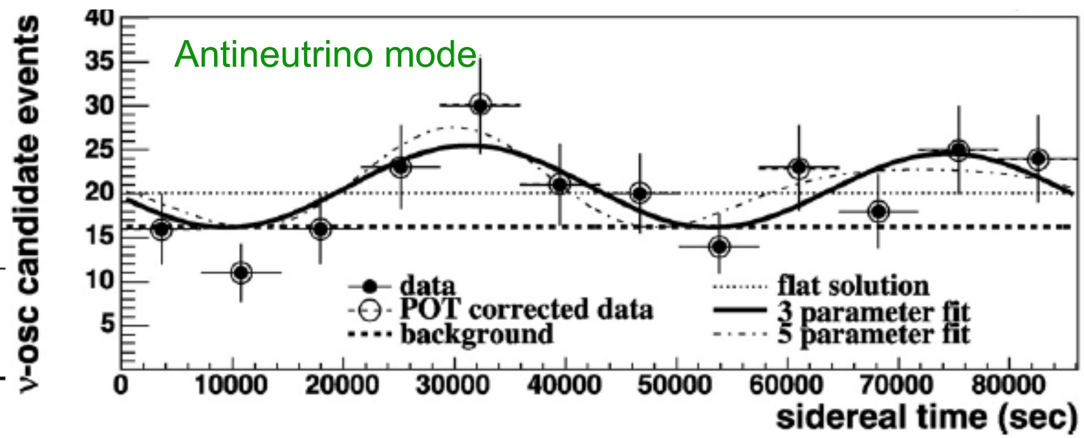


4. Lorentz violating neutrino oscillation

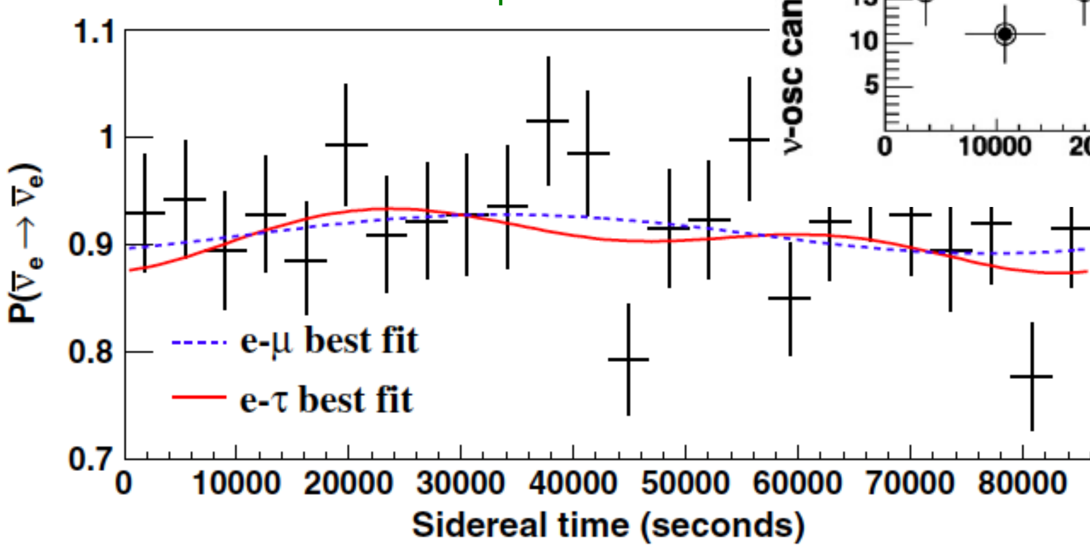
MiniBooNE electron neutrino candidate data prefer sidereal time independent solution (flat)



MiniBooNE electron antineutrino candidate data prefer sidereal time dependent solution, however statistical significance is marginal



Double Chooz neutrino data/prediction ratio



Double Chooz disappearance signal prefers sidereal time independent solution (flat)

4. Lorentz violating neutrino oscillation

Lorentz violation is tested with all neutrino channels

Chance to see the Lorentz violation in terrestrial neutrino experiments will be very small

MiniBooNE MINOS ND → $e\mu$
Double Chooz → $e\tau$
IceCube MINOS FD → $\mu\tau$

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	–
$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{ZZ}$	10^{-19}	10^{-16}	–
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–
	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	10^{-16}	–

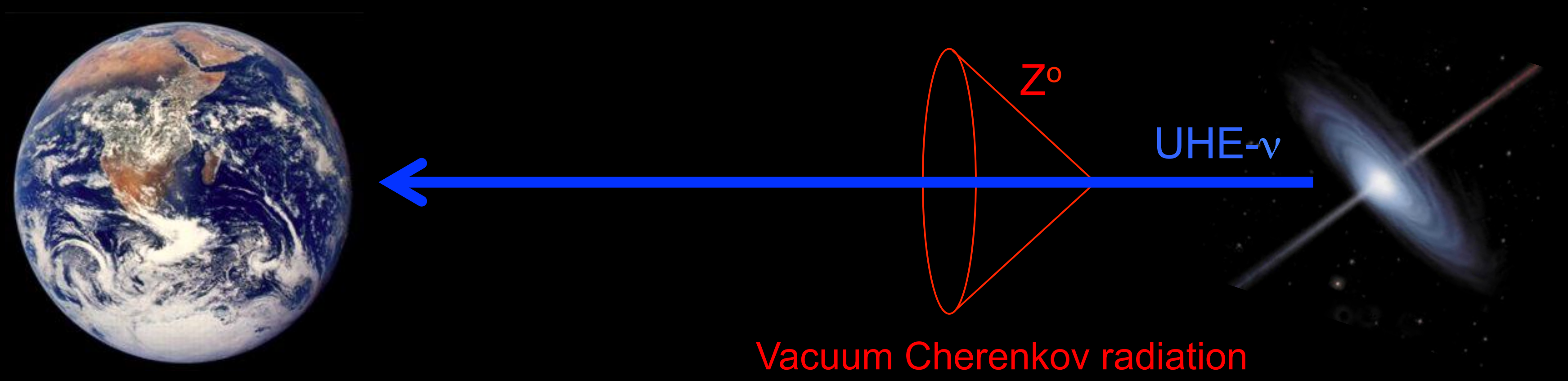
Limits of Lorentz violation coefficient from neutrino oscillation experiments

Queen Mary
University of London

4. New physics with extra-terrestrial neutrinos

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Vacuum Cherenkov radiation can limit new physics of neutrino up to 10^{-20}



4. Neutrino flavour with new physics

Any new physics can end up in the effective Hamiltonian

$$h_{eff} = \frac{1}{2E}U^{\dagger}M^{2}U + \sum_{n}\left(\frac{E}{\Lambda_{n}}\right)^{n}\tilde{U}_{n}^{\dagger}O_{n}\tilde{U}_{n} = V^{\dagger}\Delta V$$

neutrino oscillation formula

$$P_{\alpha\to\beta}(L) = 1 - 4\sum_{i>j}\mathrm{Re}(V_{\alpha i}^{*}V_{\beta i}^{*}V_{\alpha j}V_{\beta j})\sin^{2}\left(\frac{\Delta_{ij}}{2}L\right) + 2\sum_{i>j}\mathrm{Im}(V_{\alpha i}^{*}V_{\beta i}^{*}V_{\alpha j}V_{\beta j})\sin\left(\Delta_{ij}L\right)$$

neutrino mixing formula

$$P_{\alpha\to\beta}(L\to\infty) \sim 1 - 2\sum_{i>j}\mathrm{Re}(V_{\alpha i}^{*}V_{\beta i}^{*}V_{\alpha j}V_{\beta j}) = \sum_{i}\left|V_{\alpha i}\right|^{2}\left|V_{\beta i}\right|^{2}$$

Information of small contamination of new physics appears on neutrino flavours

At high energy, neutrino mass term is suppressed
→ (probably) mixing properties of the UHE neutrinos are the most sensitive method to look for new physics within particle physics

4. Flavour triangle histogram

However, we don't observe flavour ratio with function of energy
→ neutrino flux model (~E^{-2}) is convoluted

Also, there are many possible models
→ flavour triangle histogram

We follow the anarchic sampling scheme to choose the new physics model, and the model density is shown as a histogram on the triangle diagram.

$$d\tilde{U} = ds_{12}^2 \wedge dc_{13}^4 \wedge ds_{23}^2 \wedge d\delta$$

Large Lorentz violation → observed flavour ratio can be many option
Small Lorentz violation → only tiny deviation from the standard value is possible

4. Neutrino physics for...

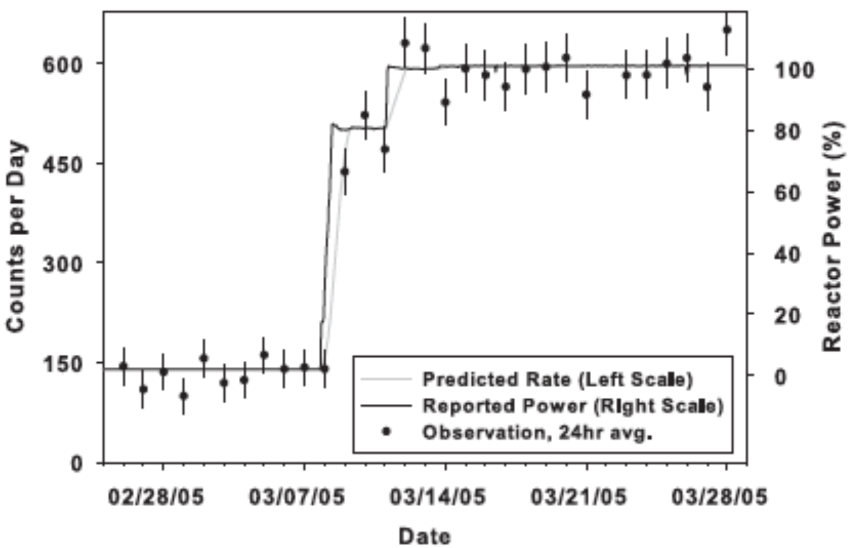
4. Neutrino physics for Peace

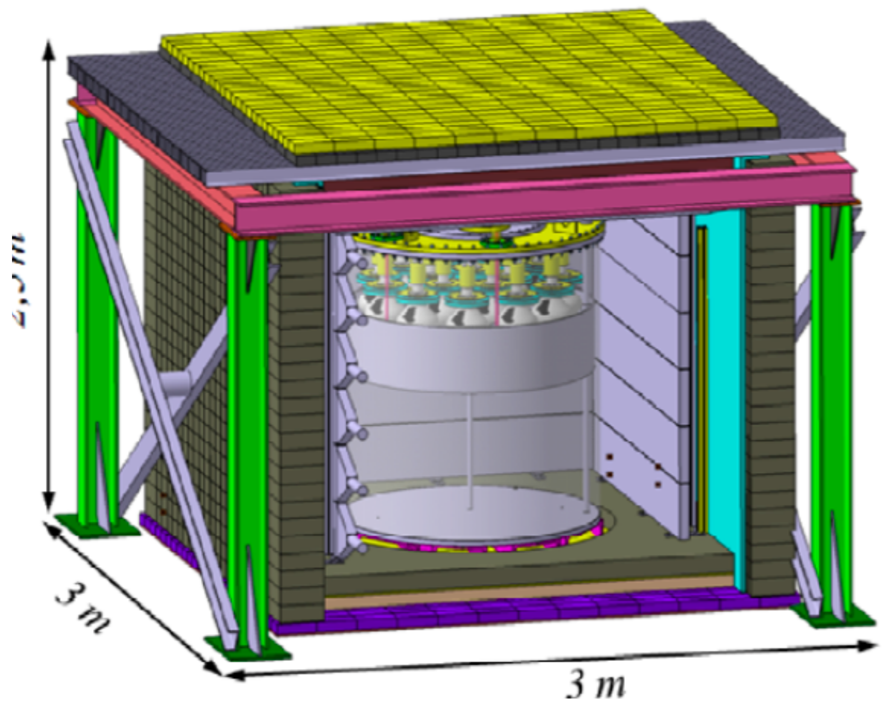
Paper Number: IAEA-CN-184/27

Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

Th. Lasserre, V.M. Bui, M. Cribier, A. Cucoanes, M. Fallot, M. Fechner, J. Gaffiot, L. Giot, R. Granelli, A. Letourneau, D. Lhuillier, J. Martino, G. Mention, D. Motta, Th.A. Mueller, A. Porta, R. Queval, J. L. Sida, C. Varignon, F. Yermia

Neutrino nuclear reactor monitoring





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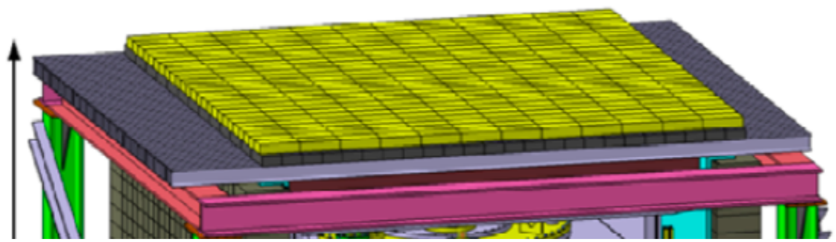
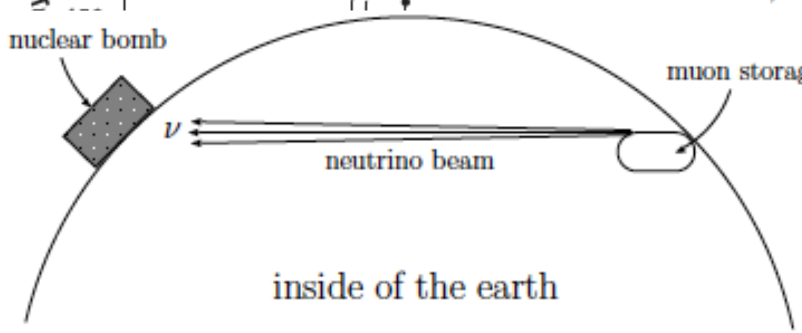
Neutrino nuclear reactor monitoring

Neutrino beam to destroy nuclear weapon





02/28/05 03/07/05 03/14/05 03/21/05 03/28/05
Date

hep-ph/0305062
revised, June 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Iirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡

3 m

4. Neutrino physics to become Rich

Paper Number: IAEA-CN-184/27

Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

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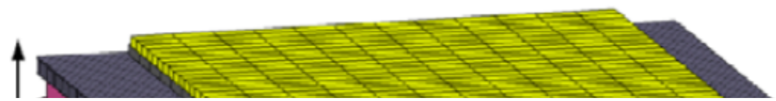
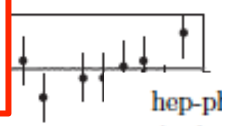
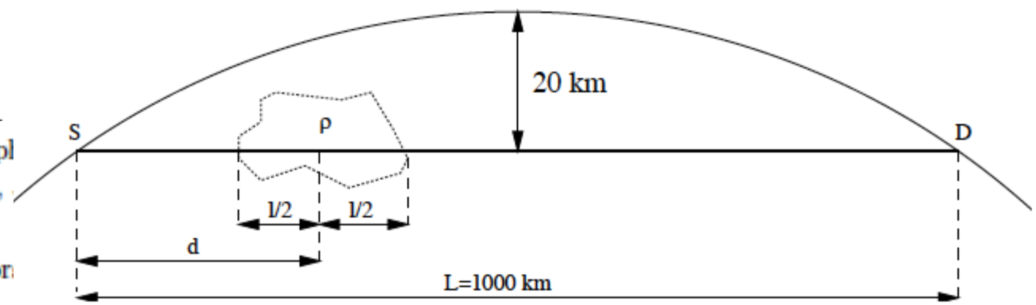
Neutrino nuclear reactor monitoring



Neutrino beam to destroy nuclear weapon



Neutrino earth tomography to find oil reservoir



Could one find petroleum using neutrino oscillations in matter?

T. Ohlsson(*) and W. Winter(**)

Institut für Theoretische Physik, Physik-Department, Technische Universität München James-Franck-Straße, 85748 Garching bei München, Germany

4. Neutrino Communications

Reactor Neutrino Detecti

Th. Lasserre, V.M. Bui, M. Cribier,
Letourneau, D. Lhuillier, J. Martino
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Neutrino nuclear reactor monitoring

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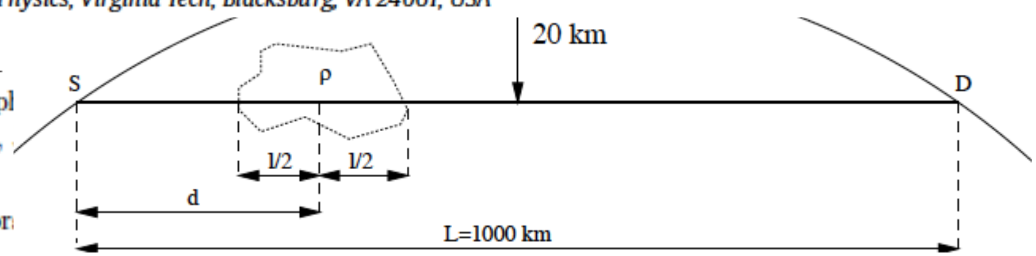
Using neutrino to communicate submarines under the deep water

Submarine neutrino communication

Patrick Huber

Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA



hep-pl

Could one find petroleum using neutrino oscillations in matter?

T. Ohlsson(*) and W. Winter(**)

Institut für Theoretische Physik, Physik-Department, Technische Universität München James-Franck-Straße, 85748 Garching bei München, Germany

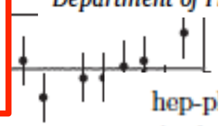
4. Neutrino Communications

Reactor Neutrino Detecti

Th. Lasserre, V.M. Bui, M. Cribier,
Letourneau, D. Lhuillier, J. Martino
C. Varignon, F. Yermia

Neutrino nuclear reactor monitoring

Neutrino beam to destroy nuclear weapon



Neutrino earth tomography to find oil reservoir

Could one find petroleun
in matter?

T. Ohlsson(*) and W. Winter(

Institut für Theoretische Physik, Physik-Department, Technische Universität München
James-Franck-Straße, 85748 Garching bei München, Germany

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Using neutrino to communicate submarines under the deep water

Submarine neutrino communication

Patrick Huber

Department of P

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High power neutrino beam to communicate with Aliens(?)

Galactic neutrino communication

John G. Learned [a], Sandip Pakvasa [a,*], A. Zee [b]

[a] *Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA*
[b] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*

4. Neutrino Communications

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Finally, MINERvA experiment sent Morse code signal through neutrino beam

DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

D. D. STANCIL[1,*], P. ADAMSON[2], M. ALANIA[3], L. ALIAGA[4], M. ANDREWS[2], C. ARAUJO DEL CASTILLO[4], L. BAGBY[2], J. L. BAZO ALBA[4], A. BODEK[5], D. BOEHNLEIN[2], R. BRADFORD[5], W. K. BROOKS[6], H. BUDD[5], A. BUTKEVICH[7], D. A. M. CAICEDO[8], D. P. CAPISTA[2], C. M. CASTROMONTE[8], A. CHAMORRO[3], E. CHARLTON[9], M. E. CHRISTY[10], J. CHVOJKA[5], P. D. CONROW[5], I. DANKO[11], M. DAY[5], J. DEVAN[9], J. M. DOWNEY[12], S. A. DYTMAN[11], B. EBERLY[11], J. R. FEIN[11], J. FELIX[13], L. FIELDS[14], G. A. FIORENTINI[8], A. M. GAGO[4], H. GALLAGHER[15], R. GRAN[16], J. GRANGE[17], J. GRIFFIN[5], T. GRIFFIN[2], E. HAHN[2], D. A. HARRIS[2,†], A. HIGUERA[13], J. A. HOBBS[14], C. M. HOFFMAN[5], B. L. HUGHES[1], K. HURTADO[3], A. JUDD[5], T. KAFKA[15], K. KEPHART[2], J. KILMER[2], M. KORDOSKY[9], S. A. KULAGIN[7], V. A. KUZNETSOV[14], M. LANARI[16], T. LE[18], H. LEE[5], L. LOIACONO[5,19], G. MAGGI[6], E. MAHER[20], S. MANLY[5], W. A. MANN[15], C. M. MARSHALL[5], K. S. MCFARLAND[5,2], A. MISLIVEC[5], A. M. MCGOWAN[5], J. G. MORFÍN[2], H. DA MOTTA[8], J. MOUSSEAU[17], J. K. NELSON[9], J. A. NIEMIEC-GIELATA[5], N. OCHOA[4], B. OSMANOV[17], J. OSTA[2], J. L. PALOMINO[8], J. S. PARADIS[5], V. PAOLONE[11], J. PARK[5], C. PEÑA[6], G. PERDUE[5], C. E. PÉREZ LARA[4], A. M. PETERMAN[14], A. PLA-DALMAU[2], B. POLLOCK[9], F. PROKOSHIN[6], R. D. RANSOME[18], H. RAY[17], M. REYHAN[18], P. RUBINOV[2], D. RUGGIERO[5], O. S. SANDS[12], H. SCHELLMAN[14], D. W. SCHMITZ[2], E. C. SCHULTE[18], C. SIMON[21], C. J. SOLANO SALINAS[3], R. STEFANSKI[2], R. G. STEVENS[19], N. TAGG[22], V. TAKHISTOV[18], B. G. TICE[18], R. N. TILDEN[14], J. P. VELÁSQUEZ[4], I. VERGALOSOVA[18], J. VOIRIN[2], J. WALDING[9], B. J. WALKER[14], T. WALTON[10], J. WOLCOTT[5], T. P. WYTOCK[14], G. ZAVALA[13], D. ZHANG[9], L. Y. ZHU[10] and B. P. ZIEMER[21]

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Institut für Theoretische Physik, Physik-Department, Technische Universität München
James-Franck-Straße, 85748 Garching bei München, Germany

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4. Neutrino Communications

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The Future Of Stock Trading: Neutrino Beams

INVESTOPEDIA.com By James Kerin July 7, 2012 9:36

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Tomorrow's stocks could be traded via neutrino beam

Robert T. Gonzalez
Filed to: FUTURISM 5/01/12 2:59pm

3,958

EXPAND

Neutrinos may not travel faster than light, but that doesn't mean they can't be put to good use.

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Neutrinos to Give High-Frequency Traders the Millisecond Edge

13 comments, 5 called-out + Comment Now + Follow Comments

Eighty some years after Wolfgang Pauli first postulated its existence, the lowly neutrino is now on the cusp of being harnessed to facilitate automated high-frequency trading through earth itself. That is, if this weakly-interacting, electrically-neutral subatomic particle can be successfully time-encoded and pointed from one financial center to another.

The idea is that by sending neutrino-based buy-and-sell messages via a 10,000 km shortcut through earth; high-velocity traders could handily beat their competitors.

Most neutrinos are leftover relics of thermal reactions that took place during the Big Bang, some 13.7 billion years ago. Today, however, they're artificially generated inside

Trading floor of the New York Stock Exchange a few years before the arrival of computer-driven

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