Queen Mary
University of London

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 – 2013
    - 3.5 Current issues
4. Beyond νSM
5. Conclusions

NEUTRINO2014
XXVI International Conference on Neutrino Physics and Astrophysics
June 2-7, 2014, Boston, U.S.A.

IOP Institute of Physics
NuInt14
9th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region
19–24 May 2014, Selsdon Park Hotel, Surrey, UK

Teppei Katori
Queen Mary University of London

HEP seminar, Univ. Gent, Gent, Belgium, June 23, 2014

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 – 2013

3.5 Current issues

4. Beyond νSM

5. Conclusions

1. Neutrino physics, the future of particle physics

2014 May 22, there was a major news
in high energy physics community...

1. Neutrino physics, the future of particle physics

2014 May 22, there was a major news in high energy physics community...

NBC NEWS HOME LATEST SEARCH

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

BY ALAN BOYLE

NewScientist Physics & Math

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Neutrinos top list of targets for US particle physics

15:00 22 May 2014 by Jessica Orwig
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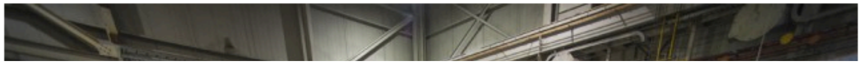
US particle physics roadmap: Build facilities for neutrinos and muons

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



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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.

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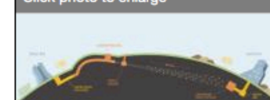

This undated handout graphic provided by Fermilab in Chicago shows a proposed particle... (AP)

1. Neutrino

2014 May 22, th
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Neutrinos top list of t

15:00 22 May 2014 by Jessica C
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**US particle physi
for neutrinos an**

But goals face a budget crunch be

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

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

DRAFT FOR APPROVAL

Report of the Particle Physics Project Prioritization Panel — May 2014

SEARCH

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: Beam us up

COMMENTS

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

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

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

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

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3.4: Understand Cosmic Acceleratio
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- 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.

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

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HL (high luminosity) LHC

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- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

Long-baseline neutrino oscillation
Neutrinoless double beta-decay
Direct neutrino mass measurement

dark matter
warm dark matter

cosmology
neutrino mass
neutrino flavors

new physics search
1eV sterile neutrino

Table 1
Summa

			Senario C	Higgs	Neutrinos	Dark Matt	Cosm. Acc	The Unkno	Technique (Frontier)
DM G3	Y, reduced								C
PINGU	Further developm								C
ORKA	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. Neutrino physics, the future of particle physics

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3. Neutrino Standard Model (νSM)

3.1 Before 1998

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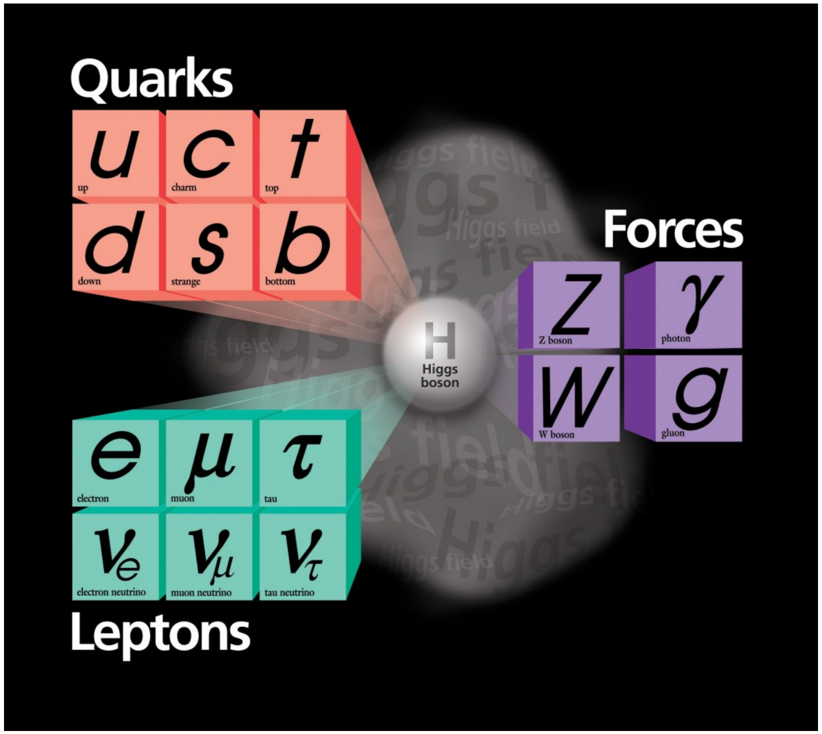
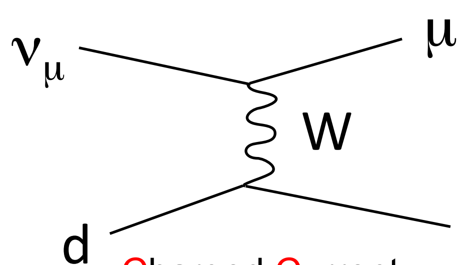
2. Neutrinos in Standard Model (SM)

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

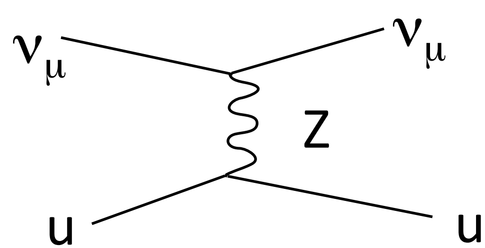


Neutrinos are special because,

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.

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

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

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3.1 Before 1998

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3.5 Current issues

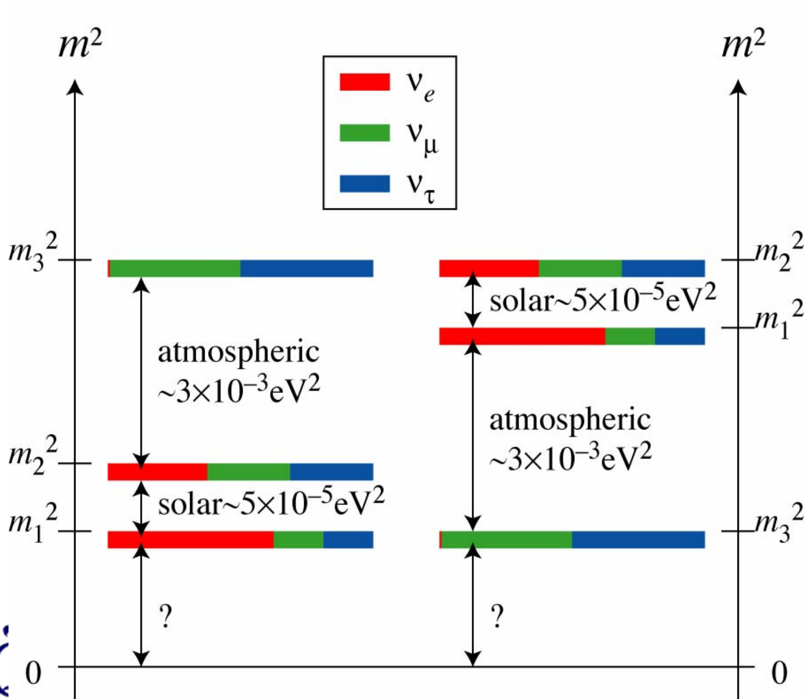
4. Beyond νSM

5. Conclusions

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 hierarchy
3. absolute neutrino mass

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

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

3.3 2005 – 2011

3.4 2012 – 2013

3.5 Current issues

4. Beyond νSM

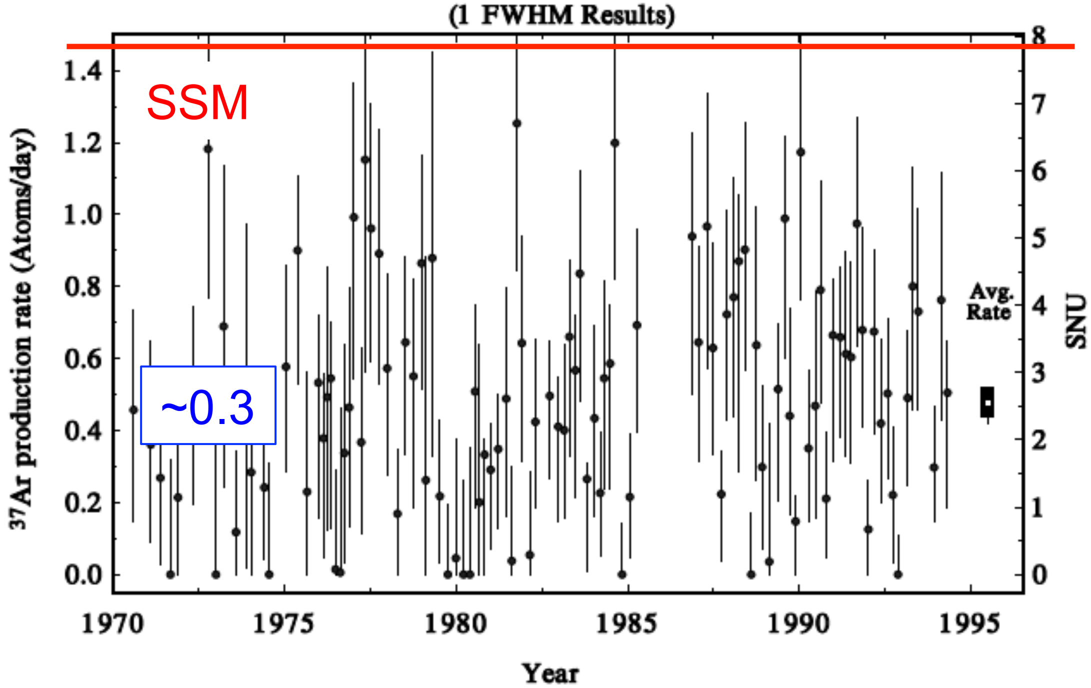
5. Conclusions

3.1 Homestake experiment

1. Neutrinos
2. Oscillations
3. νSM
4. Beyond νSM
5. Current issues
6. Conclusions

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

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
(proposed by Pontecorvo)
- sensitive to ^8B 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!)

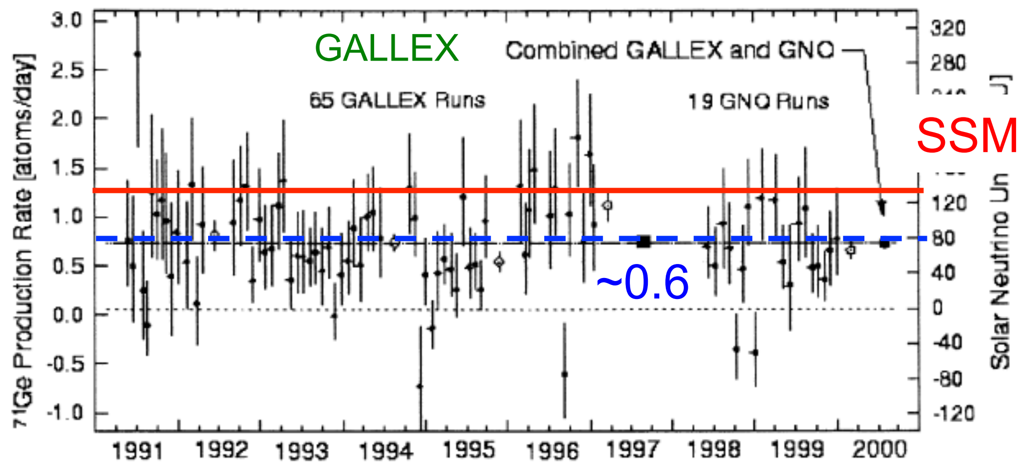
GALLEX, PLB490(2000)16
SAGE, J.Expt.Theor.Phys.95(2002)181

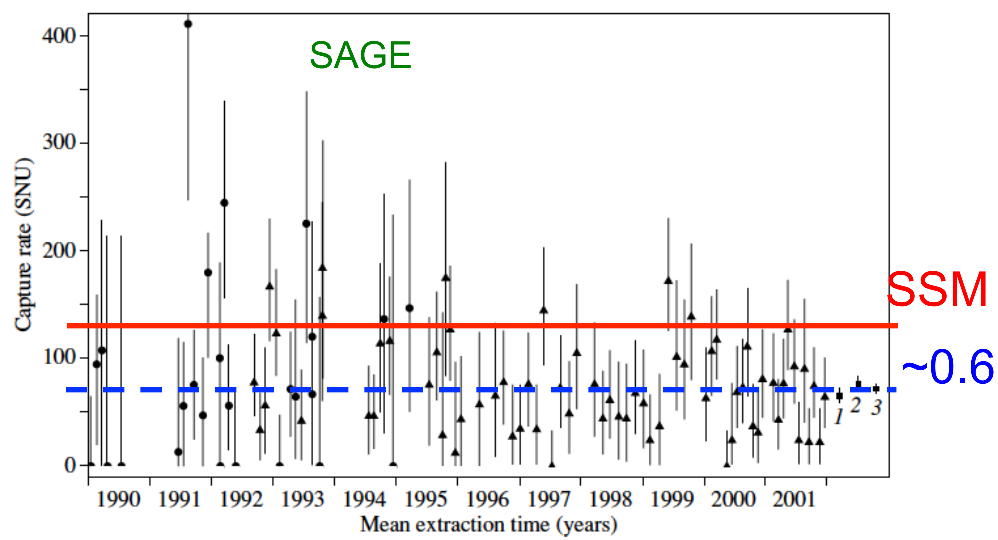
3.1 Gallium experiments

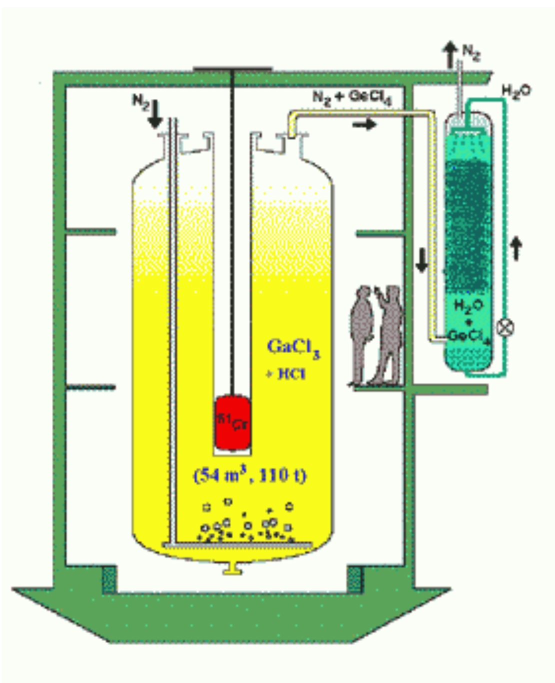
3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

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

- 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

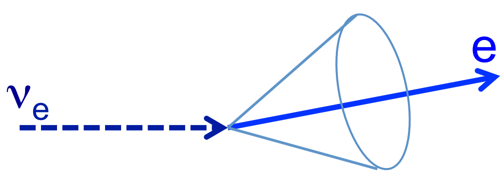
$$\nu_e + X \rightarrow e + X'$$
$$\nu_\mu + X \rightarrow \mu + X'$$

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

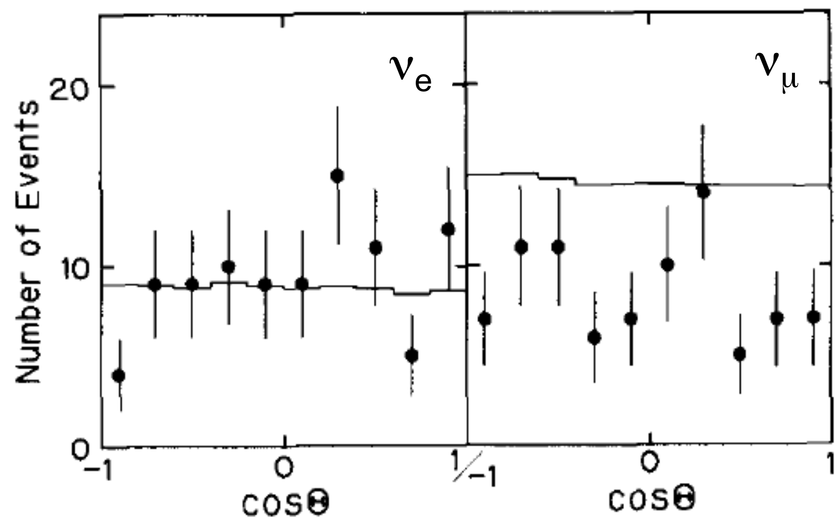
Solar neutrino

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

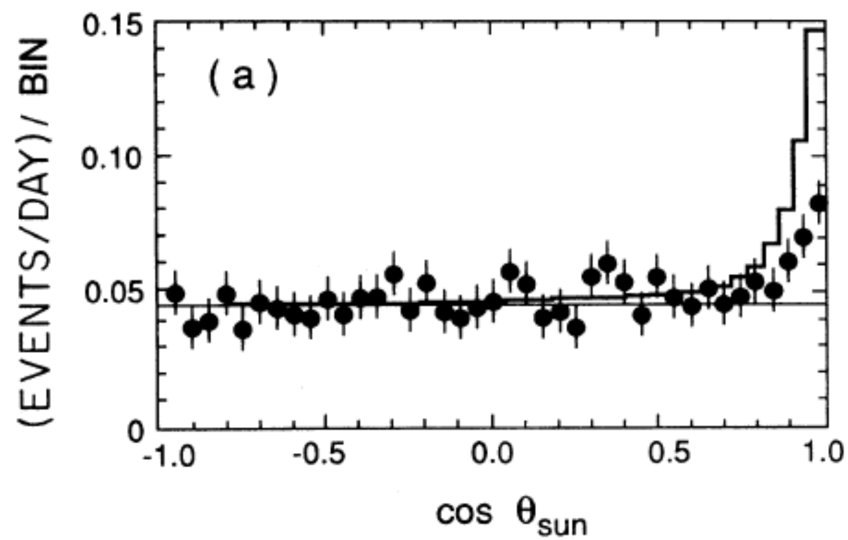
- Direction of recoil electron (~direction of neutrino) is consistent from the Sun.



atmospheric neutrinos



solar-ν angular distribution



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

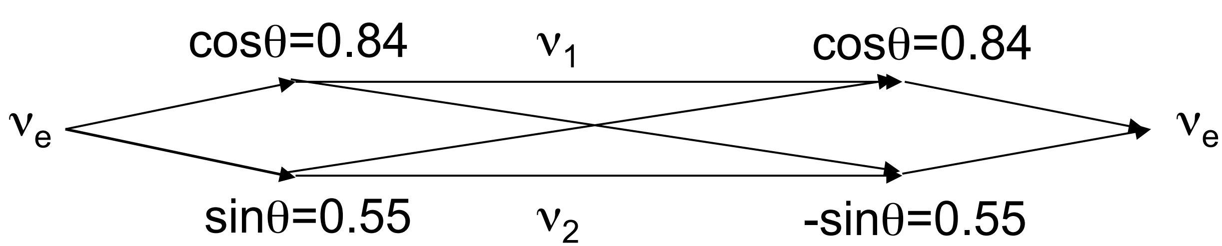
Wolfenstein,PRD17(1978)2369
Mikheyev and Smirnov,Sov.J.Ncl.Phys,42(1986)913

3.1 Neutrino oscillation in matter

3 major discoveries

- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

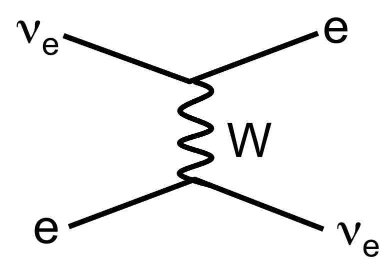
$$H_{eff} \rightarrow \begin{pmatrix} \frac{m^2_{ee}}{2E} & \frac{m^2_{e\mu}}{2E} \\ \frac{m^2_{e\mu}}{2E} & \frac{m^2_{\mu\mu}}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m^2_1}{2E} & 0 \\ 0 & \frac{m^2_2}{2E} \end{pmatrix}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



$P=|A_1+A_2|^2$

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

3.1 Neutrino oscillation in matter

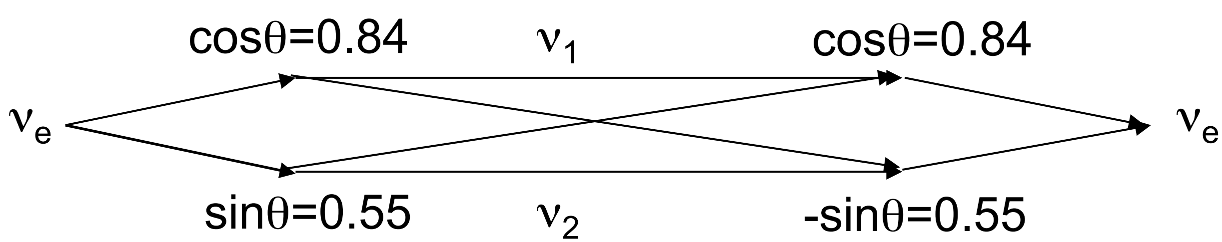


3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

Wolfenstein term

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

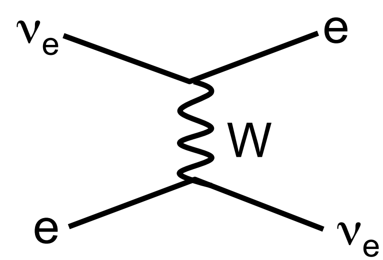
No matter effect If density and/or energy is too low



$P=|A_1+A_2|^2$

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

3.1 Neutrino oscillation in matter

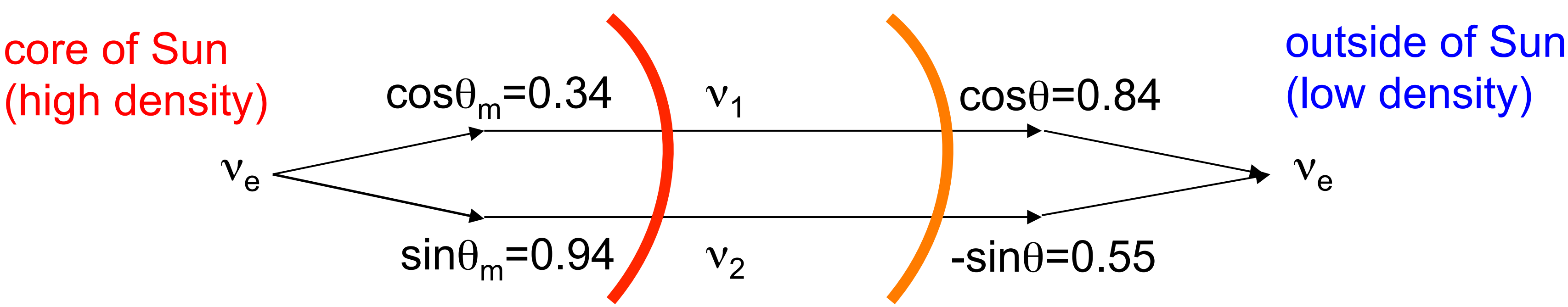


3 major discoveries
- Solar neutrino problem
- Atmospheric neutrino anomaly
- MSW effect

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
- the Sun happens to have right density n_e~150 cm^{-3} and E(^{8}B-ν)~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)

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Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

Queen Mary University of London

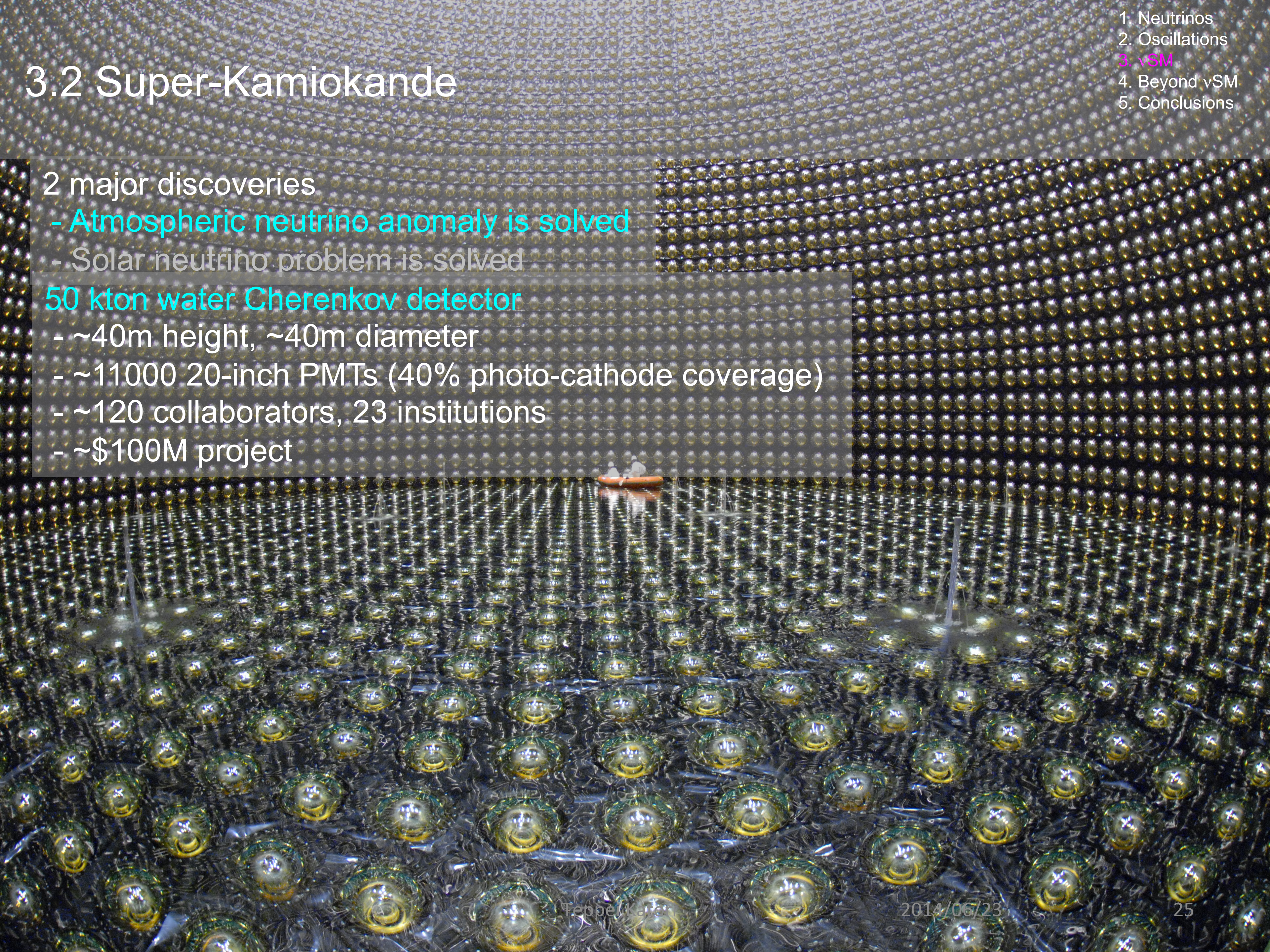
3.2 1998 to 2004

2 major discoveries
- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

3.2 Super-Kamiokande

2 major discoveries
- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

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

2 major discoveries
- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

50 kton water Cherenkov detector
- ~40m height, ~40m diameter
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1. Neutrinos
2. Oscillations
3. νSM
4. Beyond νSM
5. Conclusions

3.2 Super-Kamiokande

2 major discoveries
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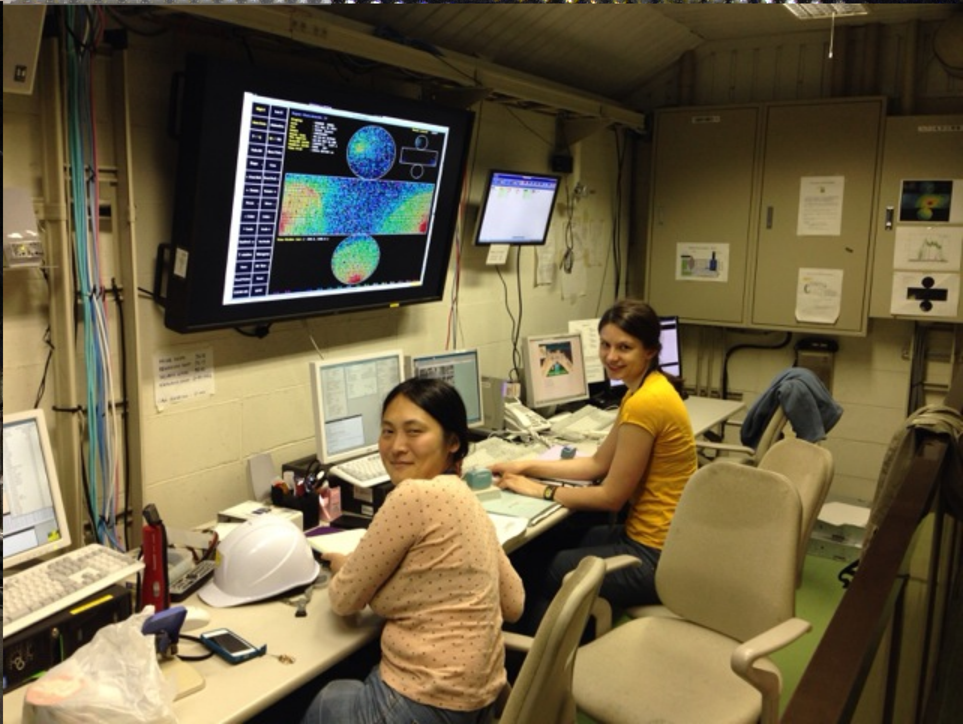
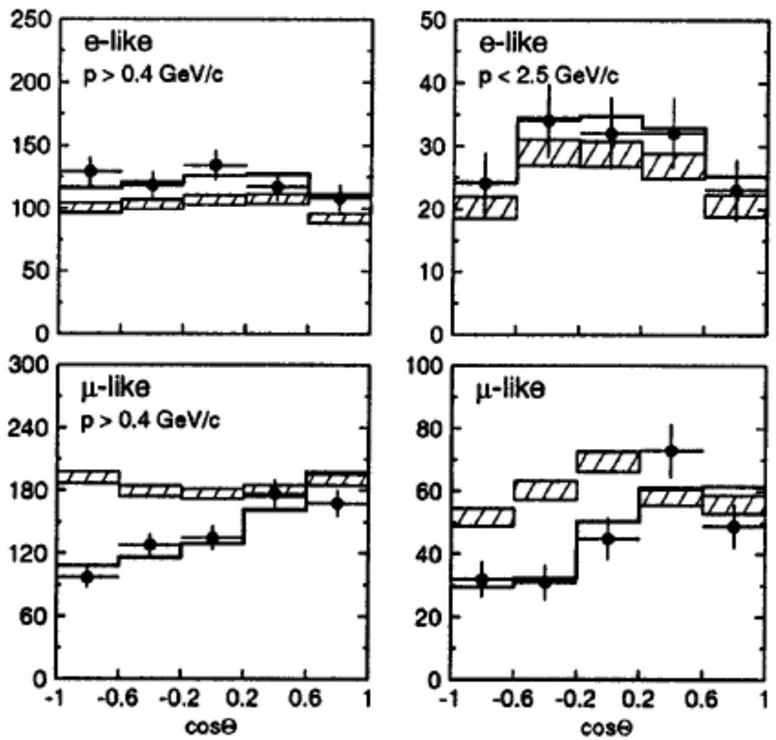
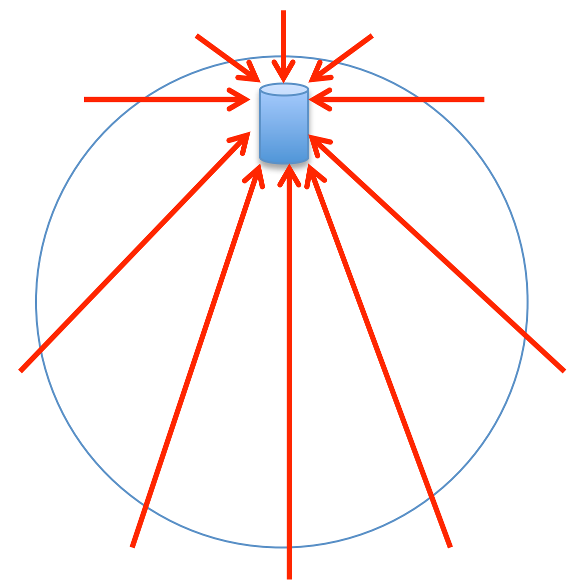


3.2 Super-Kamiokande

2 major discoveries
- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

Up-Down asymmetry
Atmospheric neutrino anomaly is function of distance





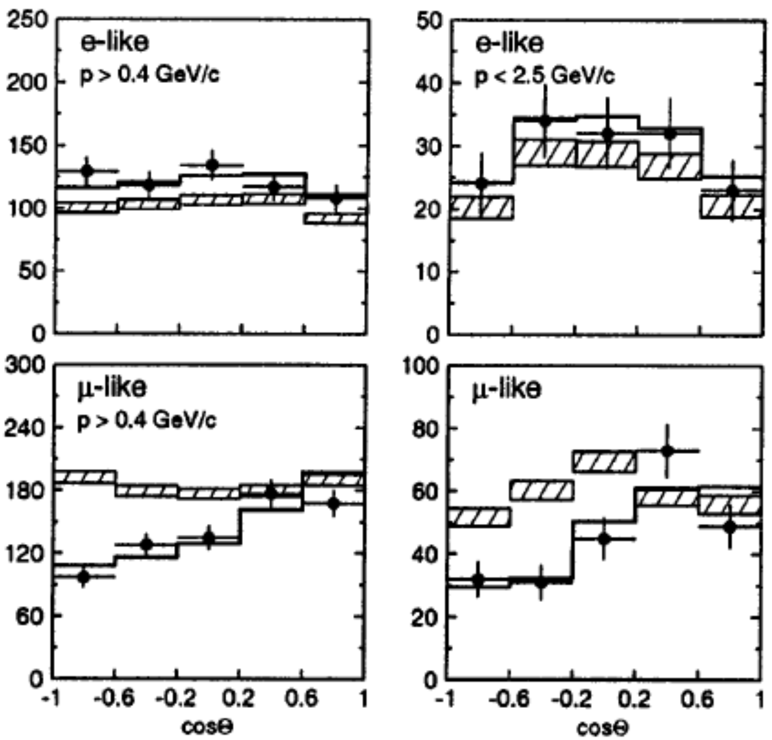
3.2 Super-Kamiokande

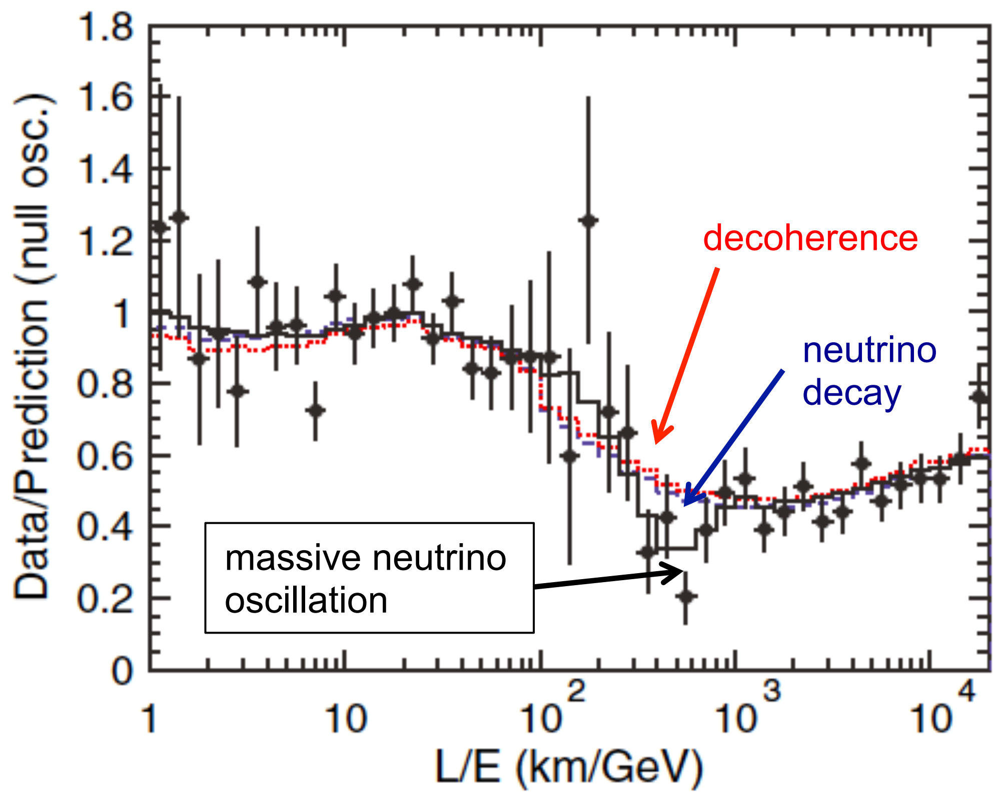
2 major discoveries

- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

L/E dependence

Strong evidence of neutrino oscillation by mass term





SNO, PRC75(2007)045502

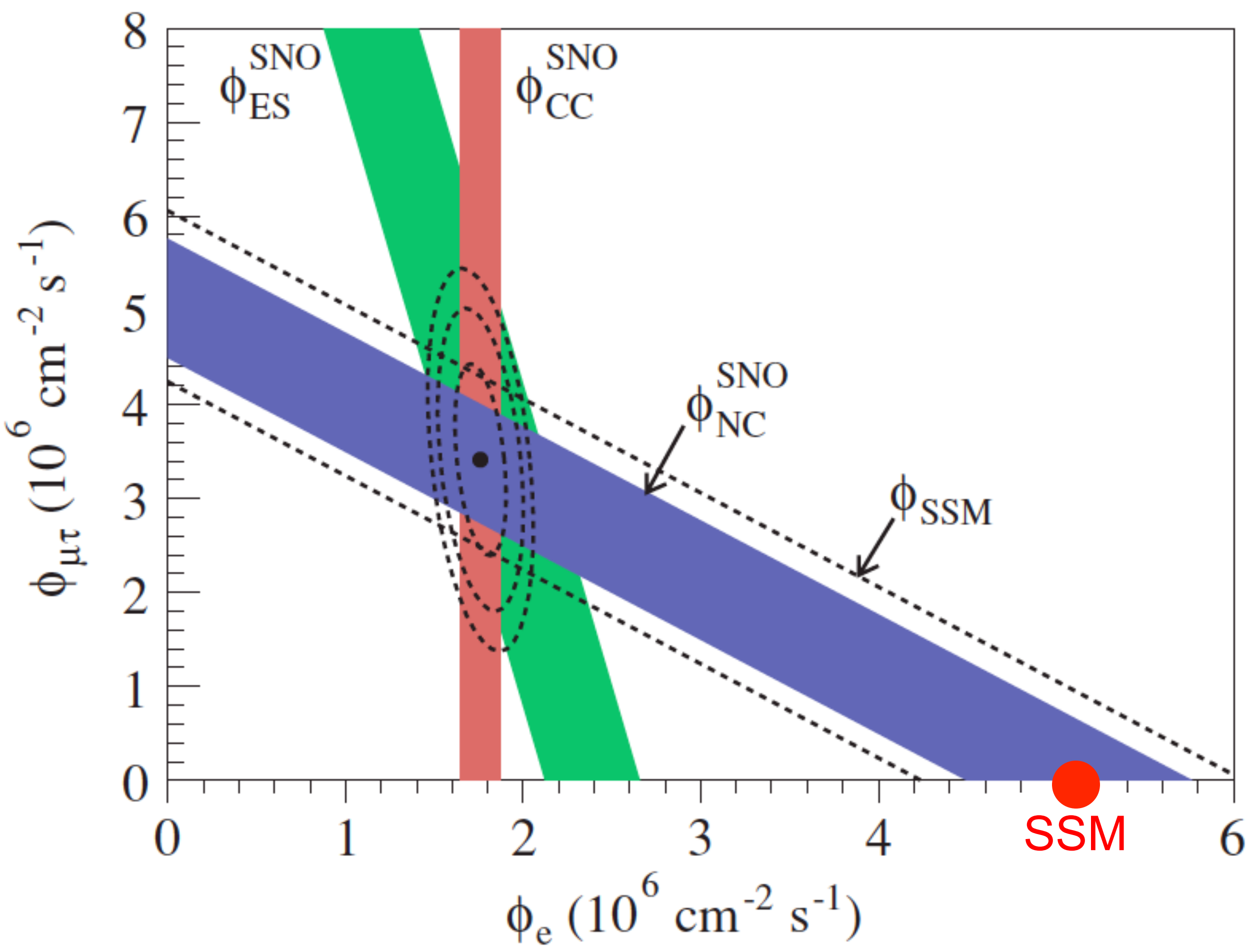
3.2 SNO

2 major discoveries
- Atmospheric neutrino anomaly is solved
- Solar neutrino problem is solved

$\nu_e + d \rightarrow p + p + e$
- 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



Queen Mary
University of London

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 – 2013

3.5 Current issues

4. Beyond νSM

5. Conclusions

Solar neutrino problem
Atmospheric neutrino anomaly
MSW effect

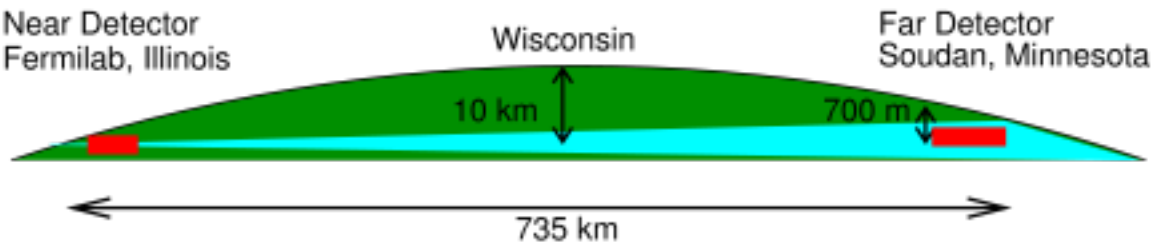
Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

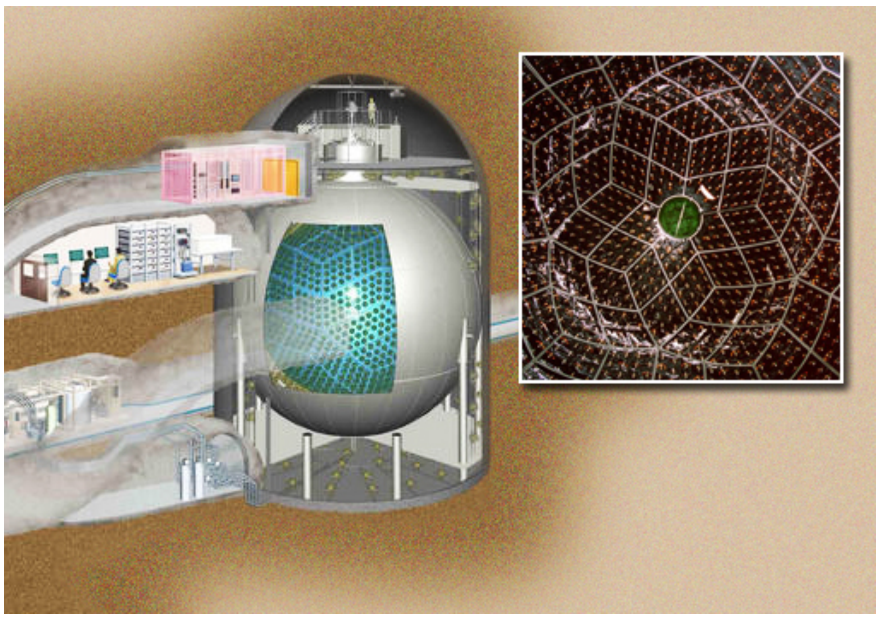
Precision measurement era

3.3 2005 to 2011

Precision neutrino oscillation measurement era

- K2K
- KamLAND
- MINOS
- Borexino
- ...





3.3 2005 to 2011

Precision neutrino oscillation measurement era
- K2K
- KamLAND
- MINOS
- Borexino
- ...

2 massive neutrino oscillation models are established (θ_{12}, Δm^2_{sol}, θ_{23}, Δm^2_{atm})

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

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)

1. Neutrino physics, the future of particle physics

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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 – 2013 ← Boom of θ_{13}

3.5 Current issues ← Future long-baseline neutrino oscillation experiments

4. Beyond νSM

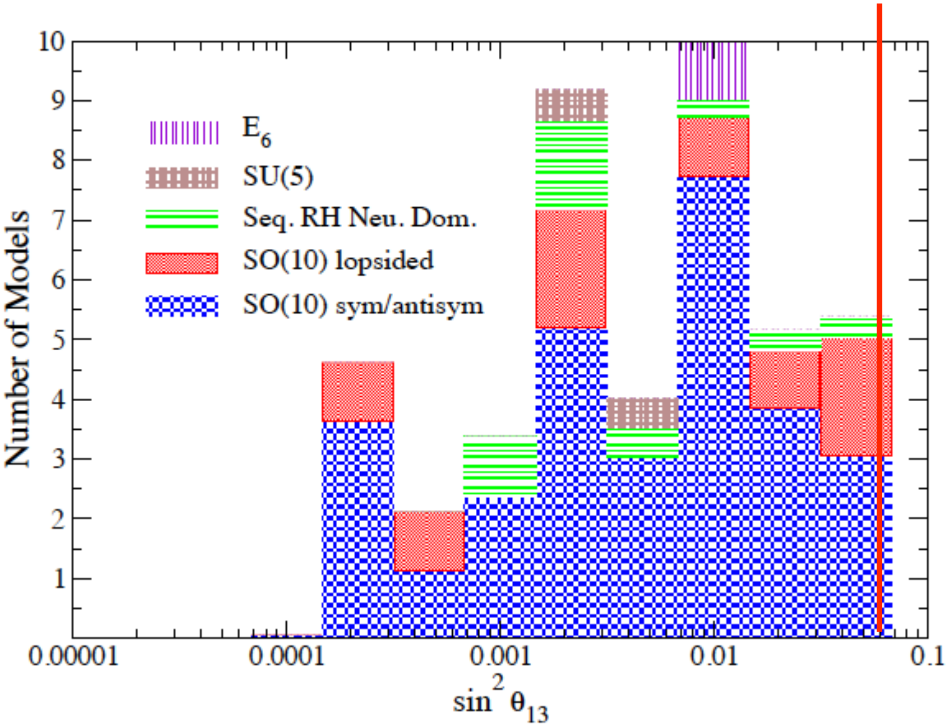
5. Conclusions

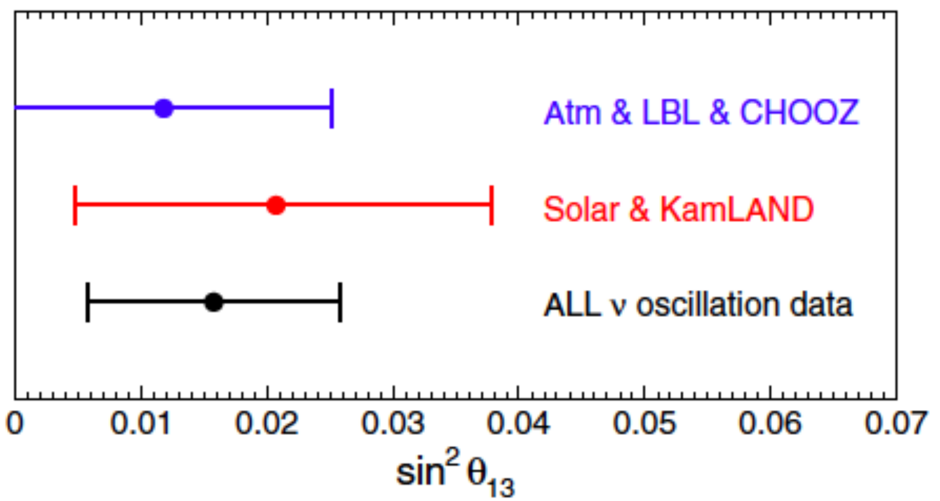
Albright, ArXiv:0905.0146
Fogli et al,PRL101(2008)141801

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)





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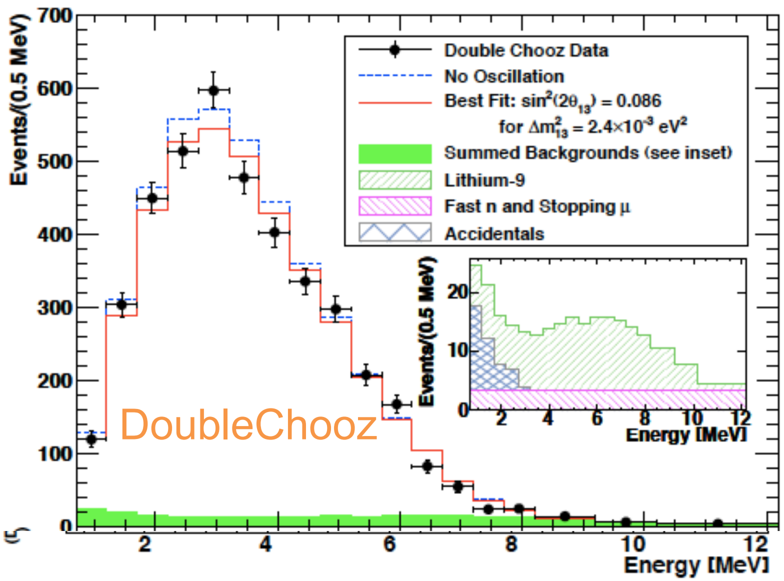
- Mother Nature was kind again!
  - anti-ν_e reactor disappearance

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



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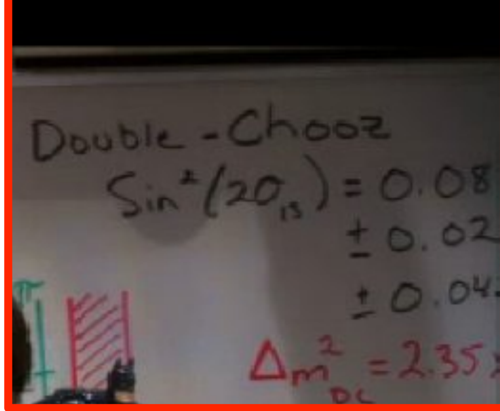

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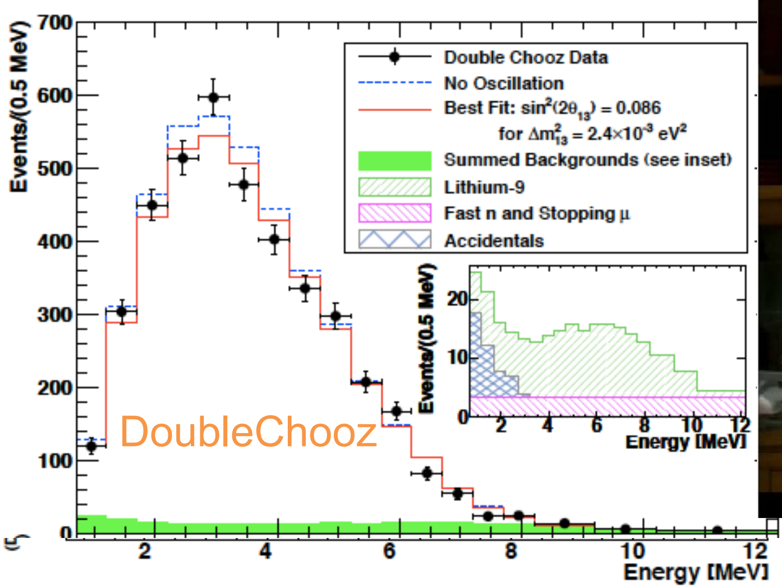
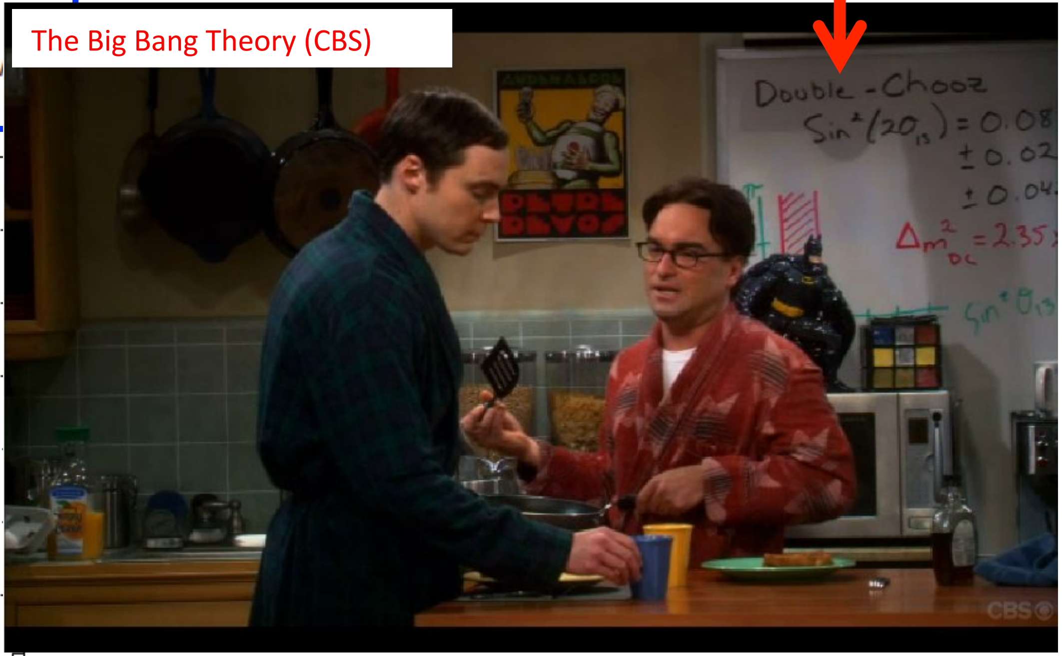
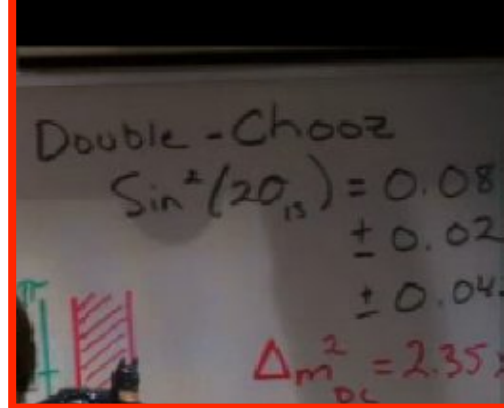




Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802
Daya Bay, PRL112(2014)061801

3.4 Boom of θ_{13}



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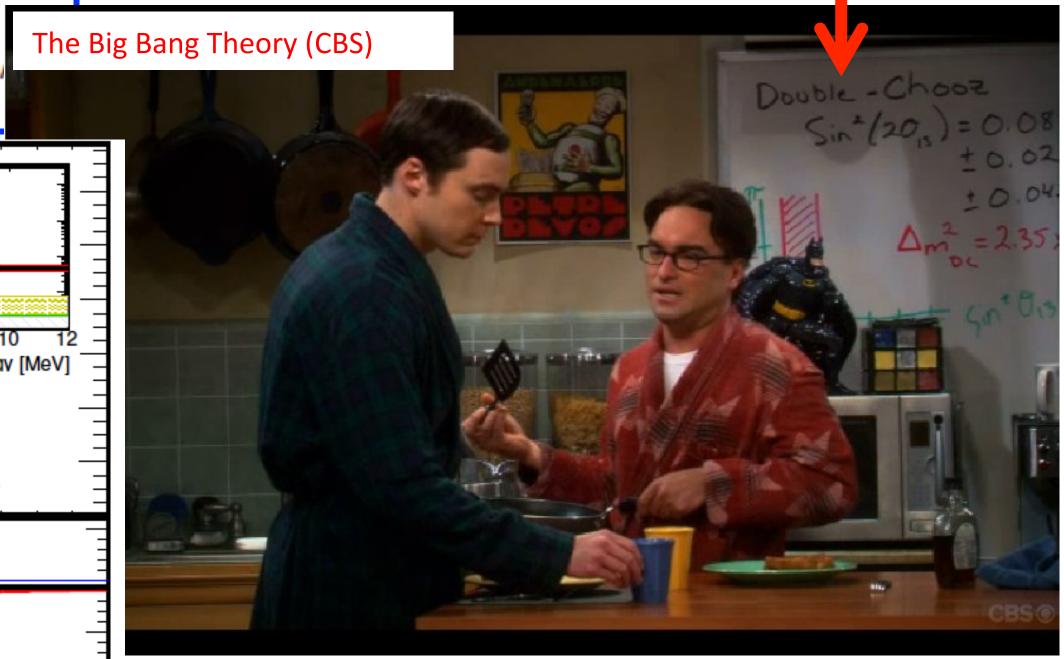

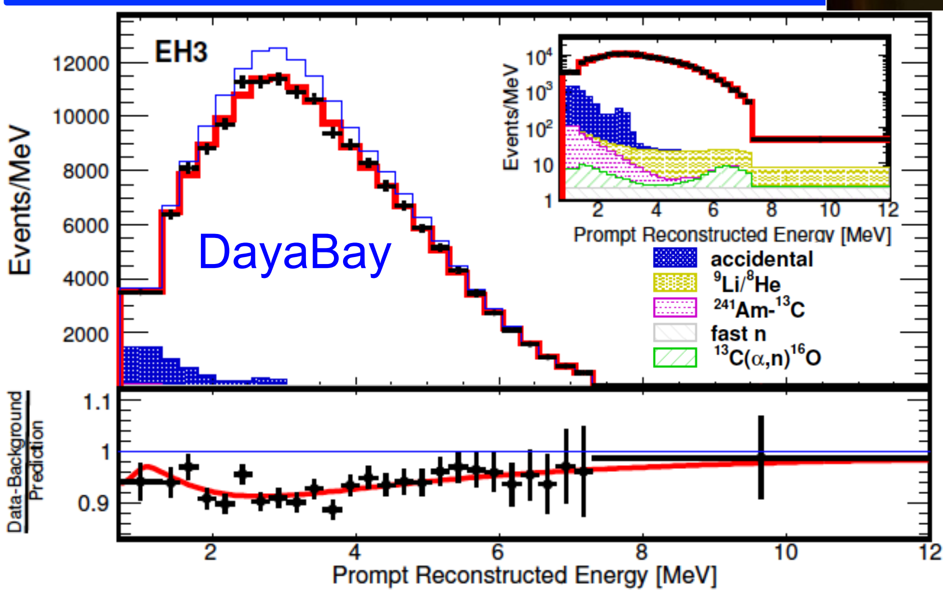

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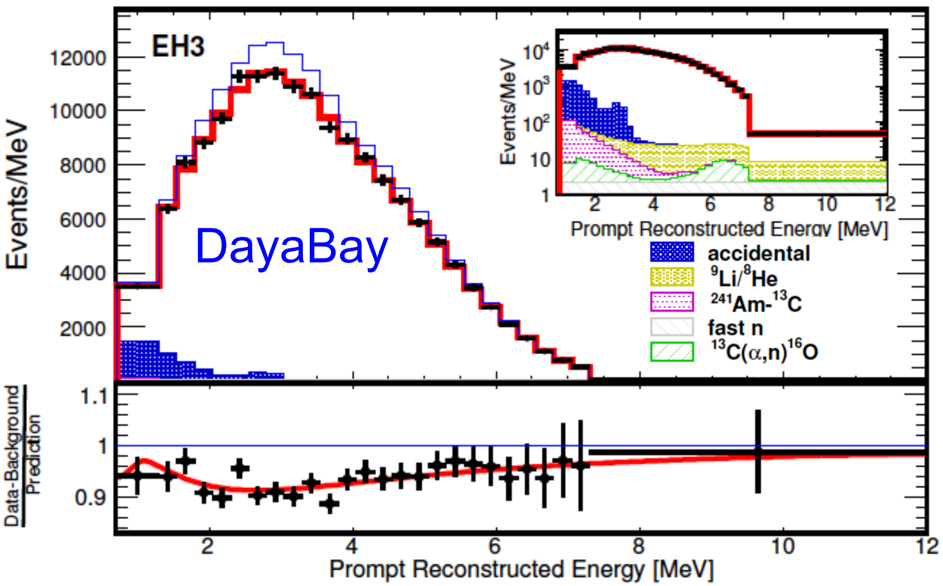
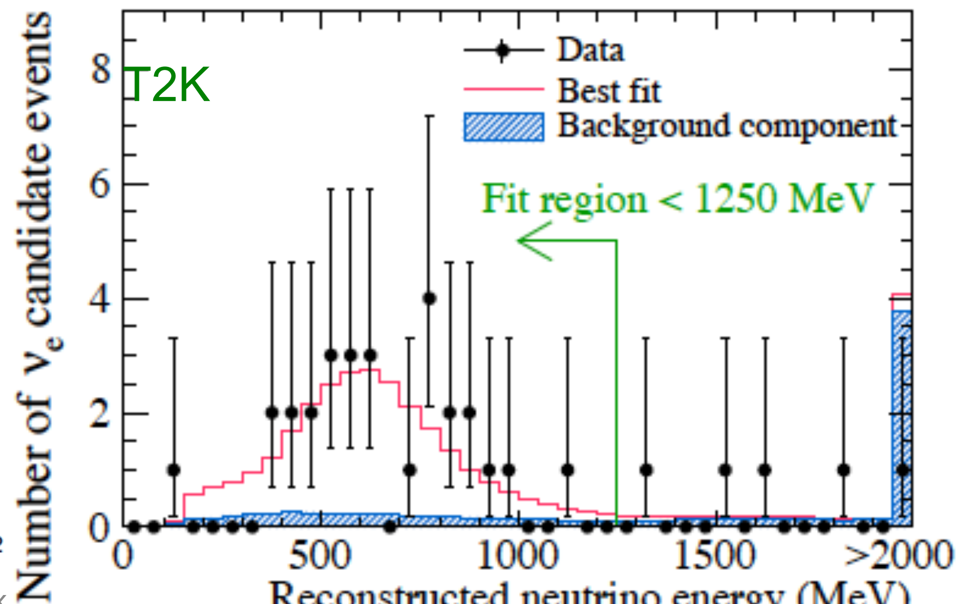
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation

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

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





Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,PRL108(2012)191802
Daya Bay, PRL112(2014)061801, T2K, PRL112(2014)061802

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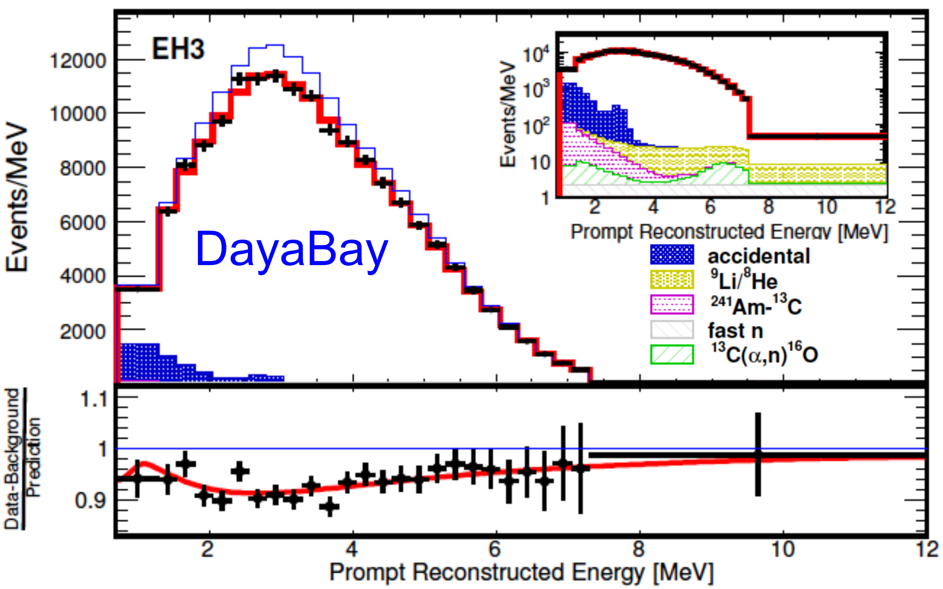

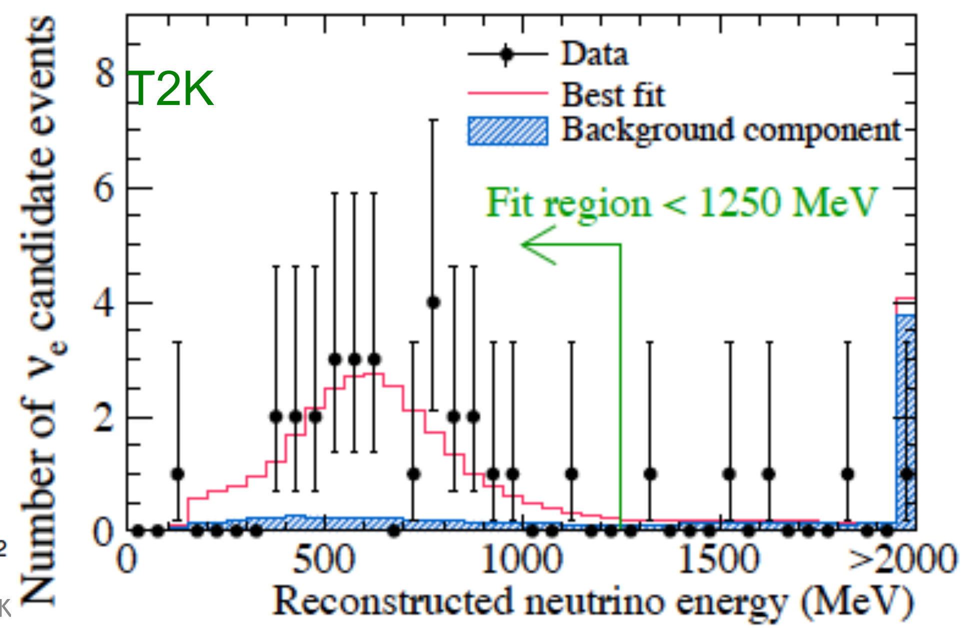

3.4 2012 to 2013

T2K, Double Chooz, Daya Bay, Reno

- θ_{13} was truly unknown parameter
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- 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

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

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

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

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

3.4 2012 to 2013

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 $\sin2\theta_{23}$, 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

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

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MSW effect

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Atmospheric neutrino anomaly is solved
Solar neutrino problem is solved

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Precision measurement era

3.4 2012 – 2013

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

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

Long baseline neutrino oscillations

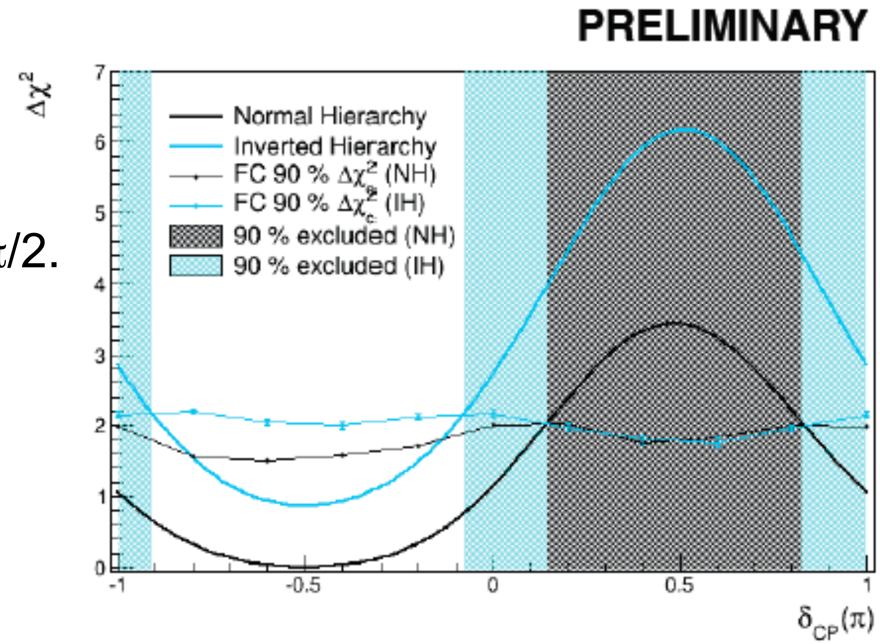
- T2K (running)
- NOvA (about running)
- PINGU (planned)
- JUNO (planned)
- INO (planned)
- LBNE (planned)
- Hyper-K (planned)

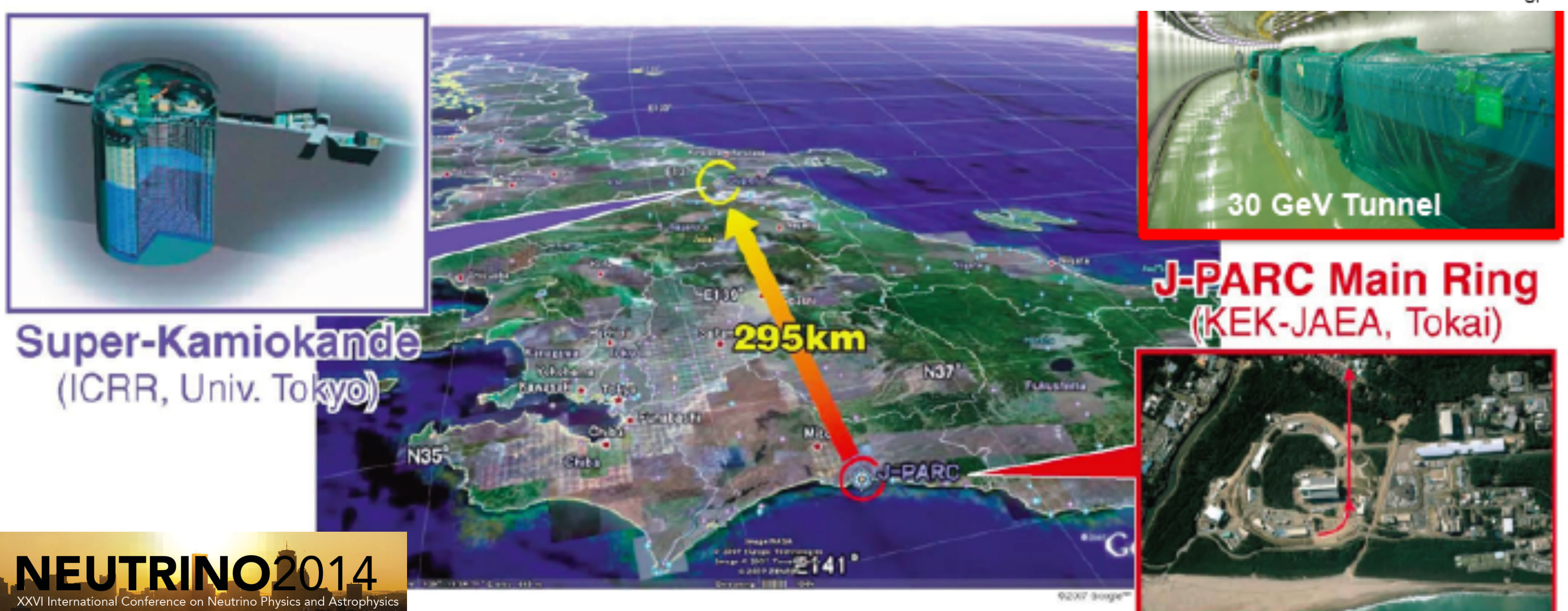
3.5 T2K

δ_{CP} limit Joint ν_μ+ν_e fit

- data prefer normal hierarchy with δ_{CP}~ -π/2.

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



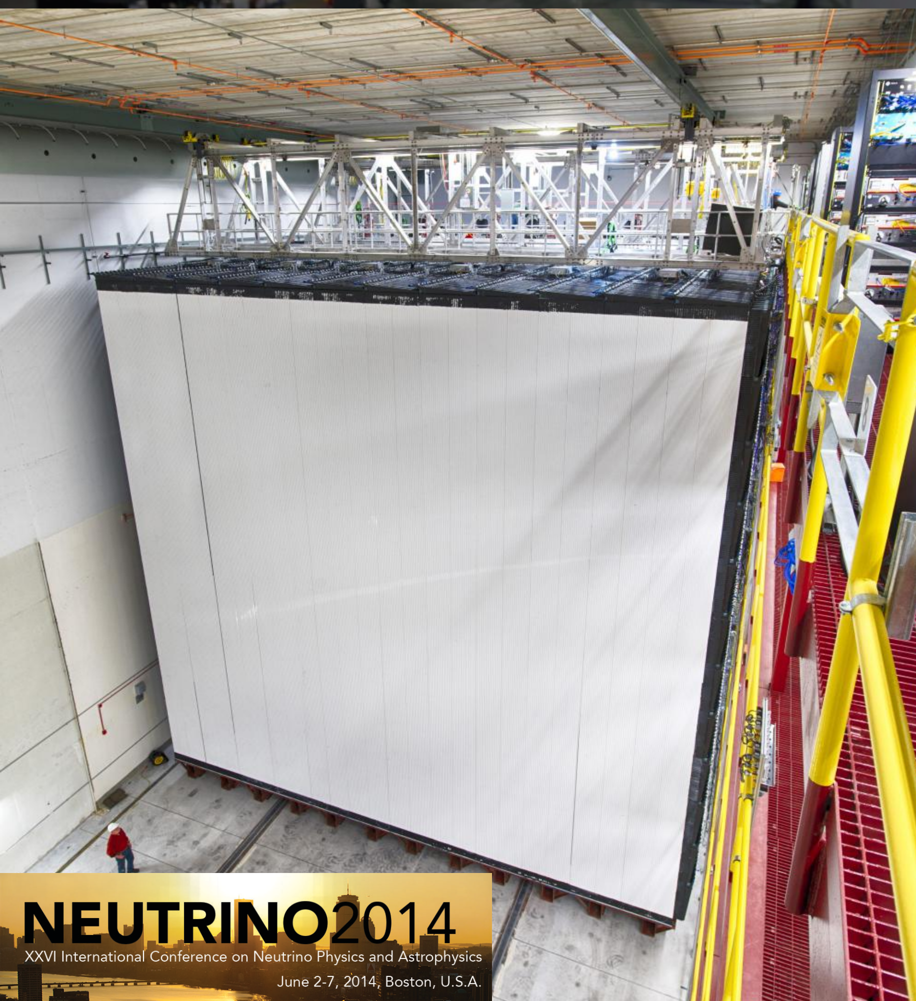


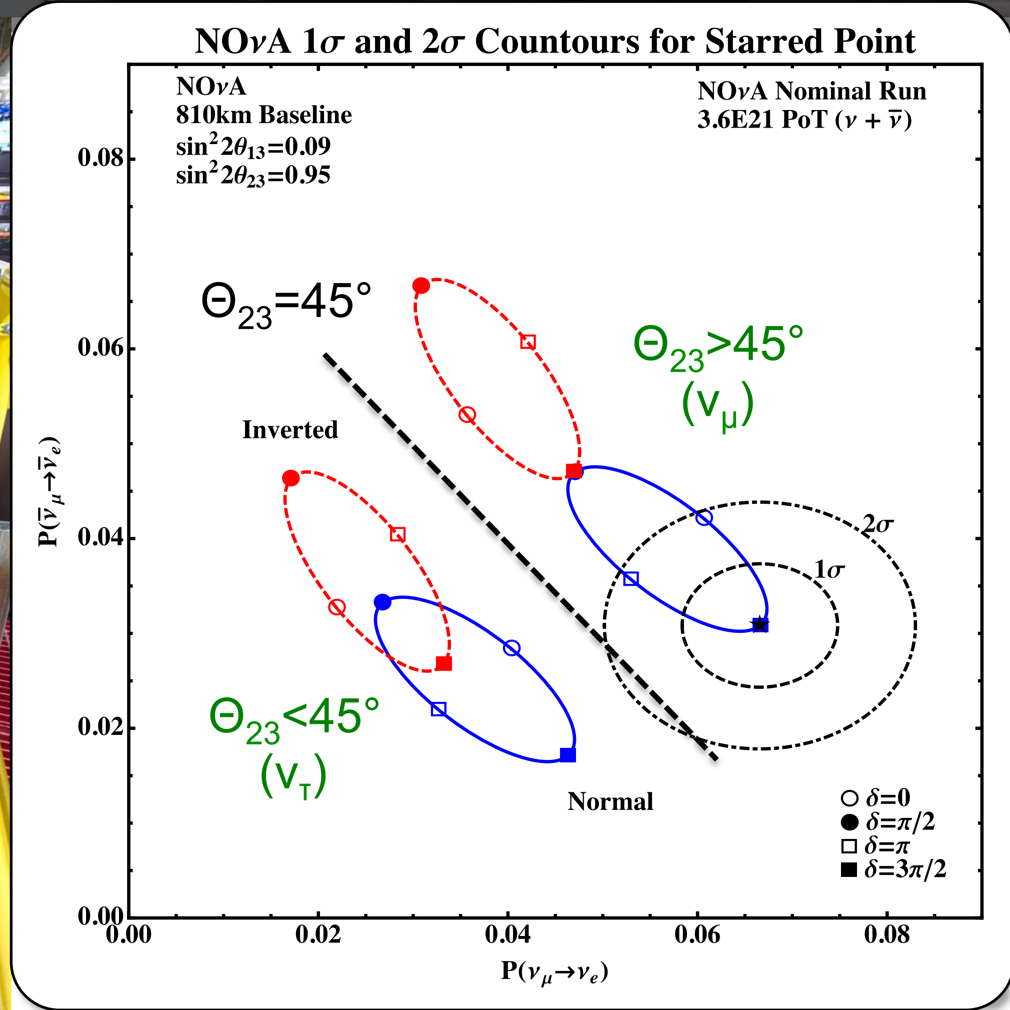
3.5 NOvA

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

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 PINGU

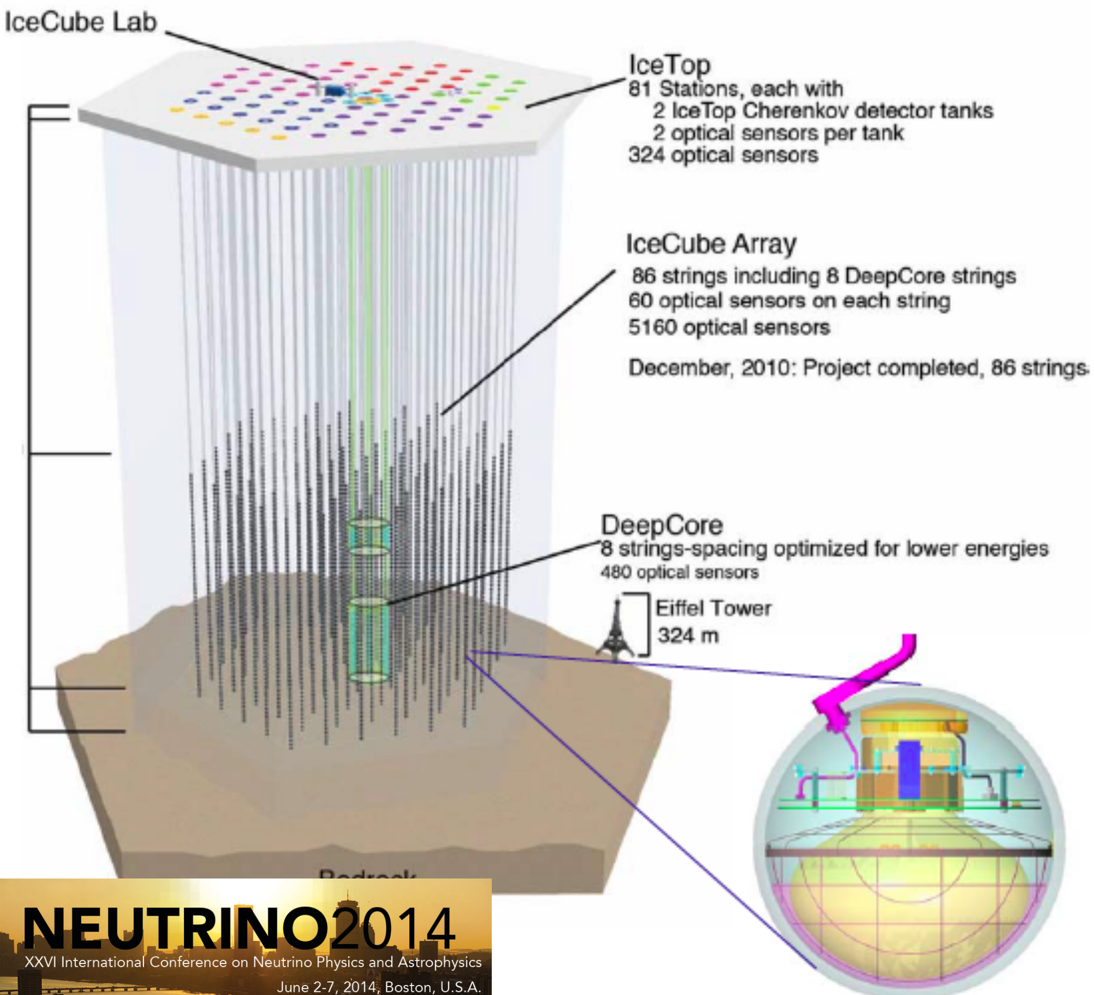
effective 2-ν matter oscillation

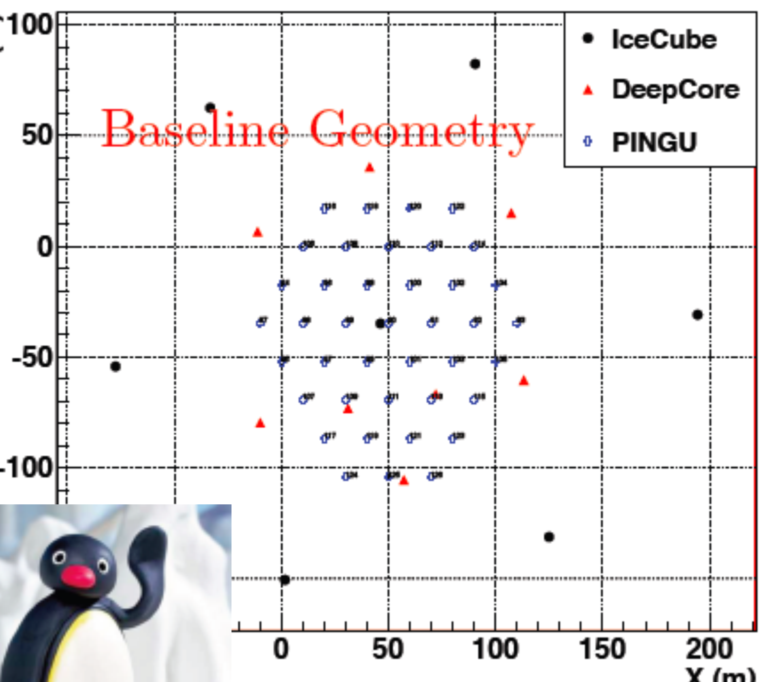
interference of propagation states

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

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



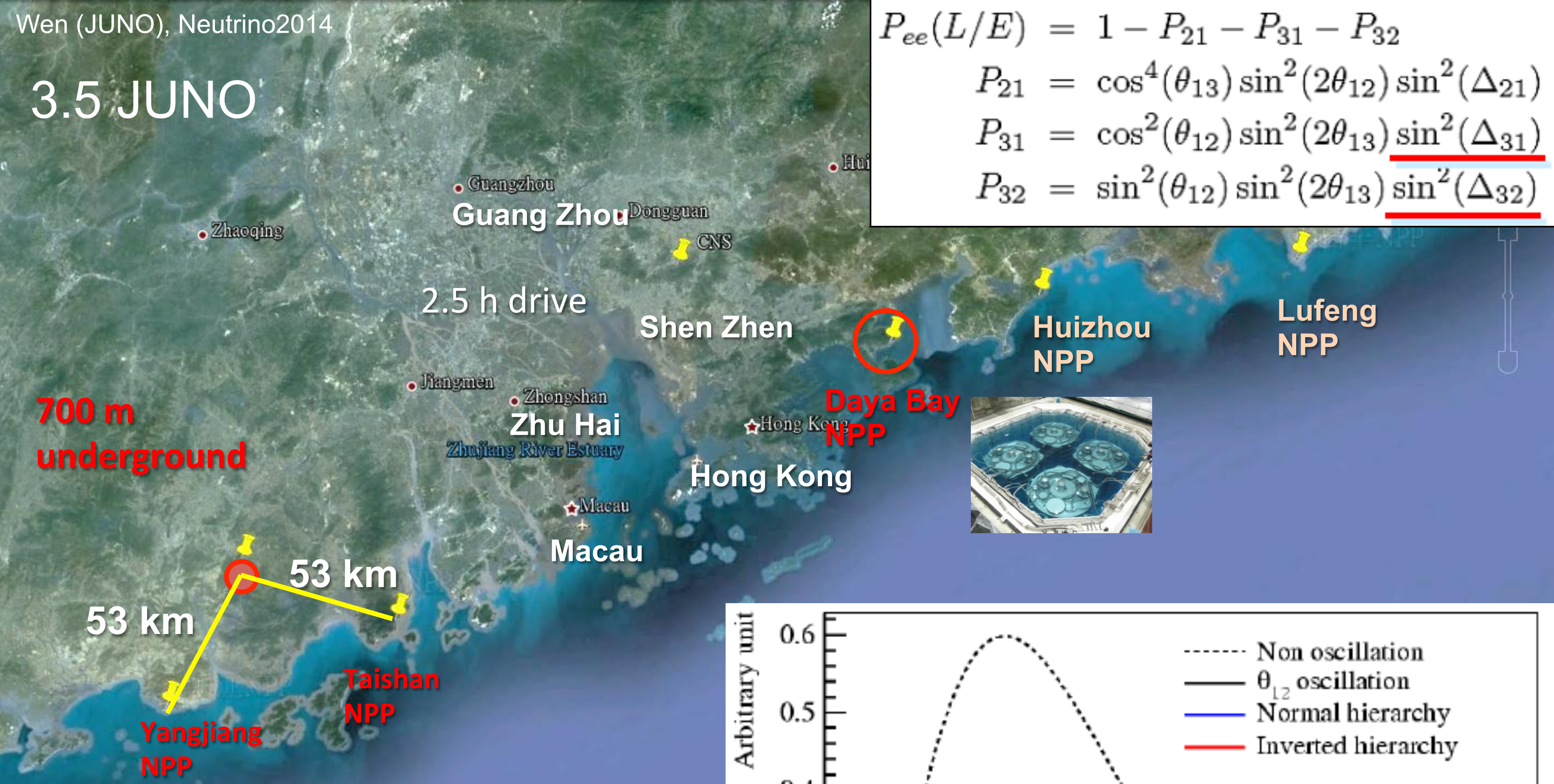


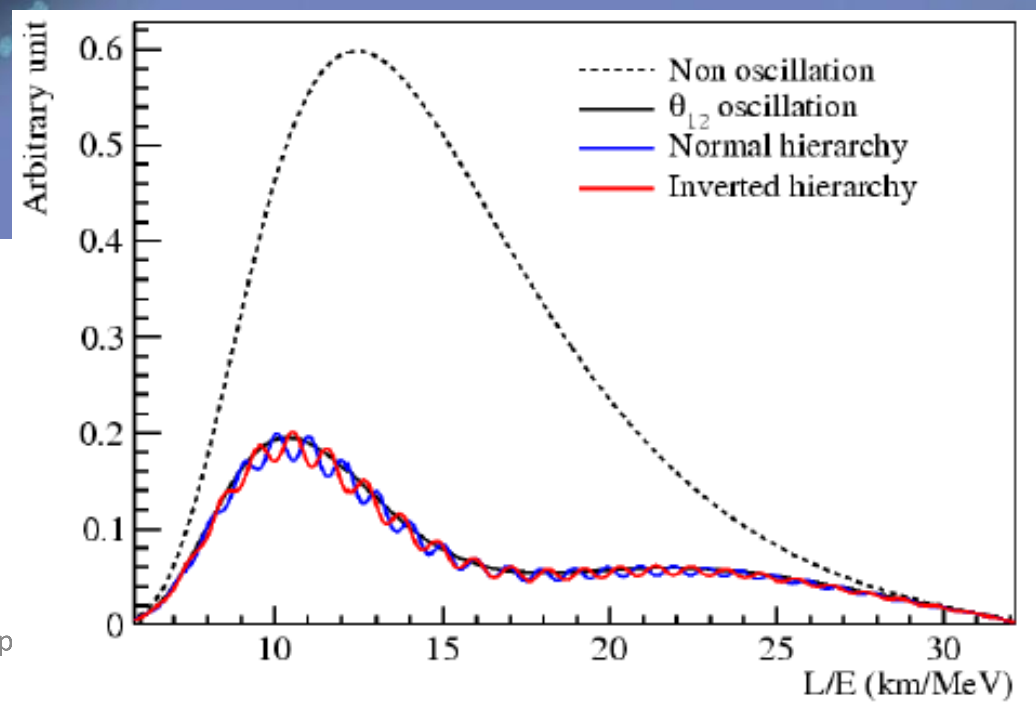
NEUTRINO2014
XXVI International Conference on Neutrino Physics and Astrophysics
June 2-7, 2014, Boston, U.S.A.

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

NEUTRINO2014
XXVI International Conference on Neutrino Physics and Astrophysics
June 2-7, 2014, Boston, U.S.A.

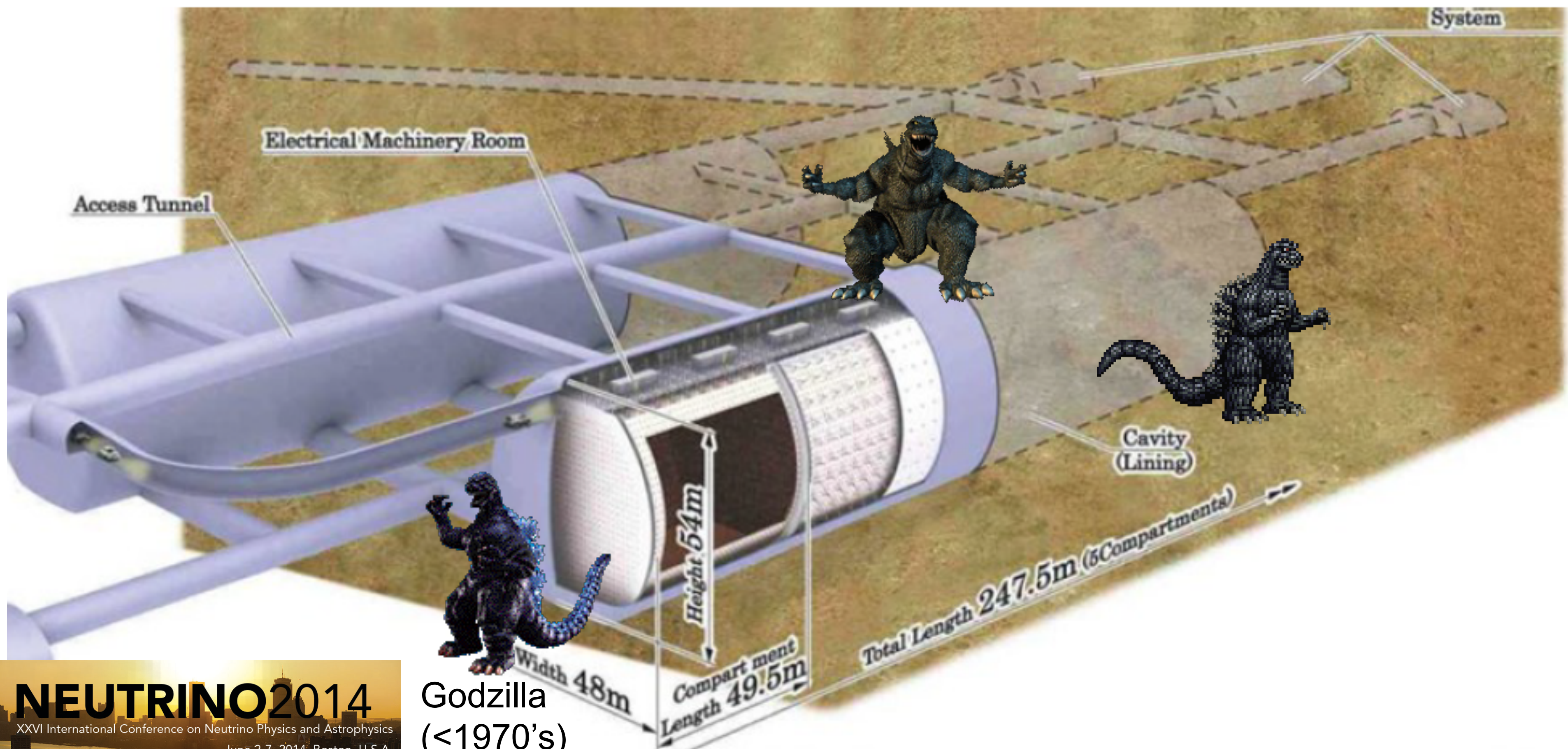
Tep

Hayato (HyperKamiokande), Neutrino2014

3.5 Hyper-Kamiokande

Hyper-Kamiokande with upgraded J-PARC beam

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



3.5 LBNE

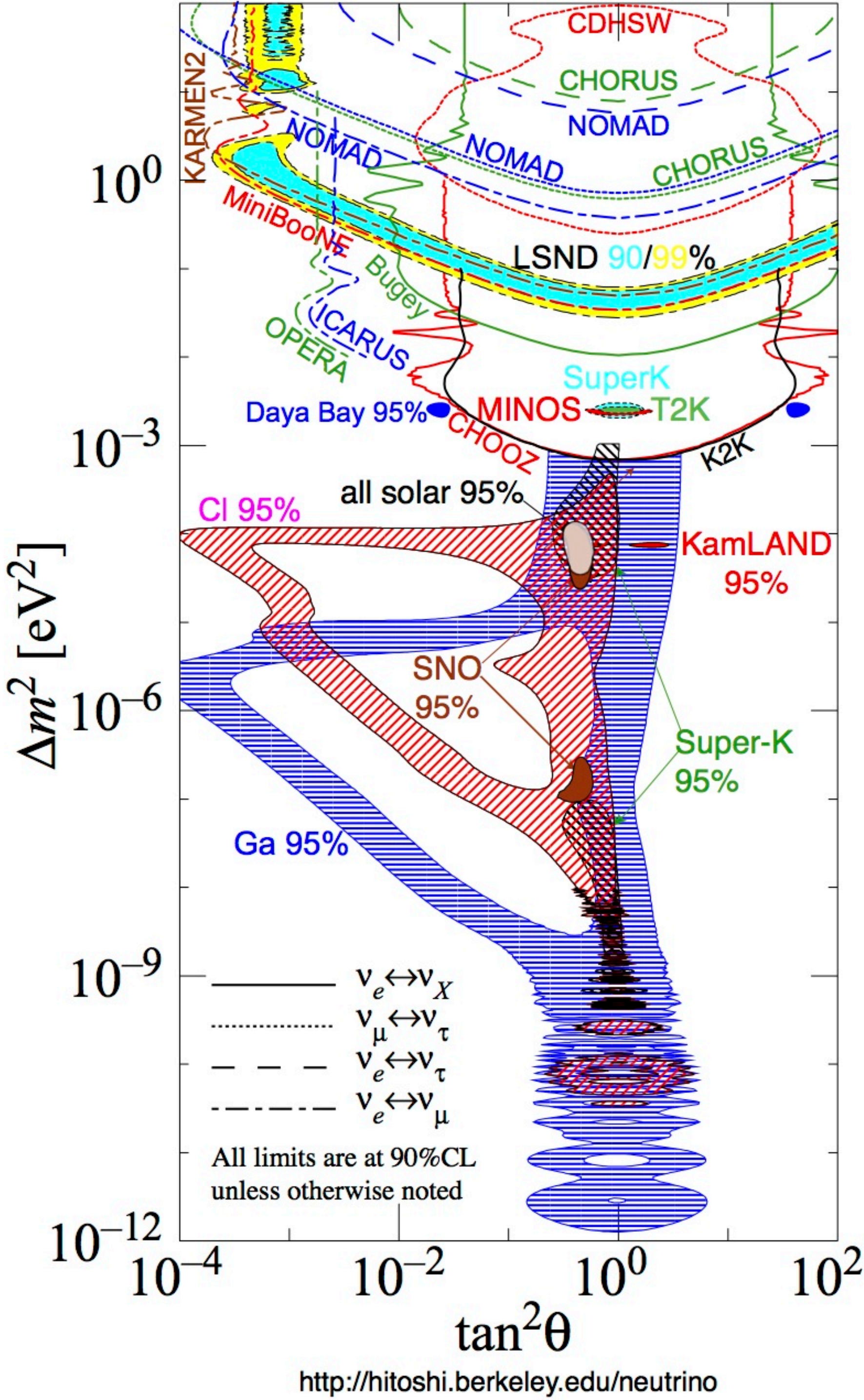
New beamline and new detector

- 34 kton Liquid argon time projection chamber
- New beamline to South Dakota
- “Reformation” is recommended in P5 report

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

3. Summary of νSM

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



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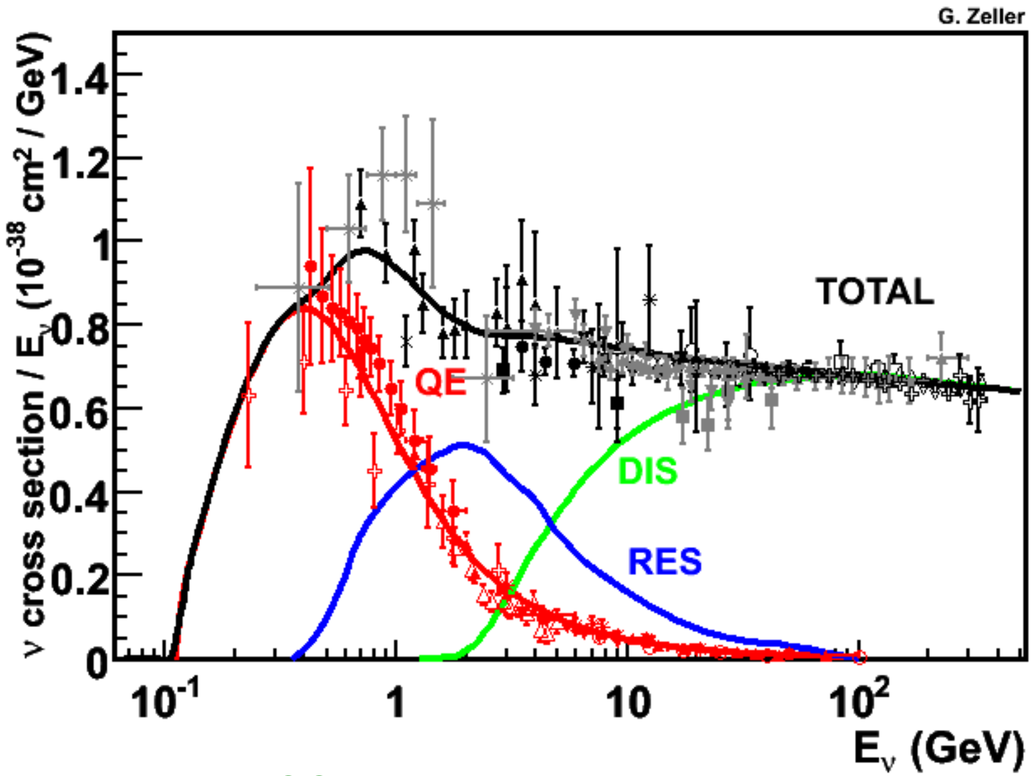
4. Neutrinos, as probes of new physics

Neutrino cross-section measurements

- Neutrino oscillation experiment ~1-10 GeV (T2K, HyperK, NOvA, LBNE, PINGU)
- Nuclear effects are significant
- Urgent programs both theories and experiments



ν_μCC cross section per nucleon

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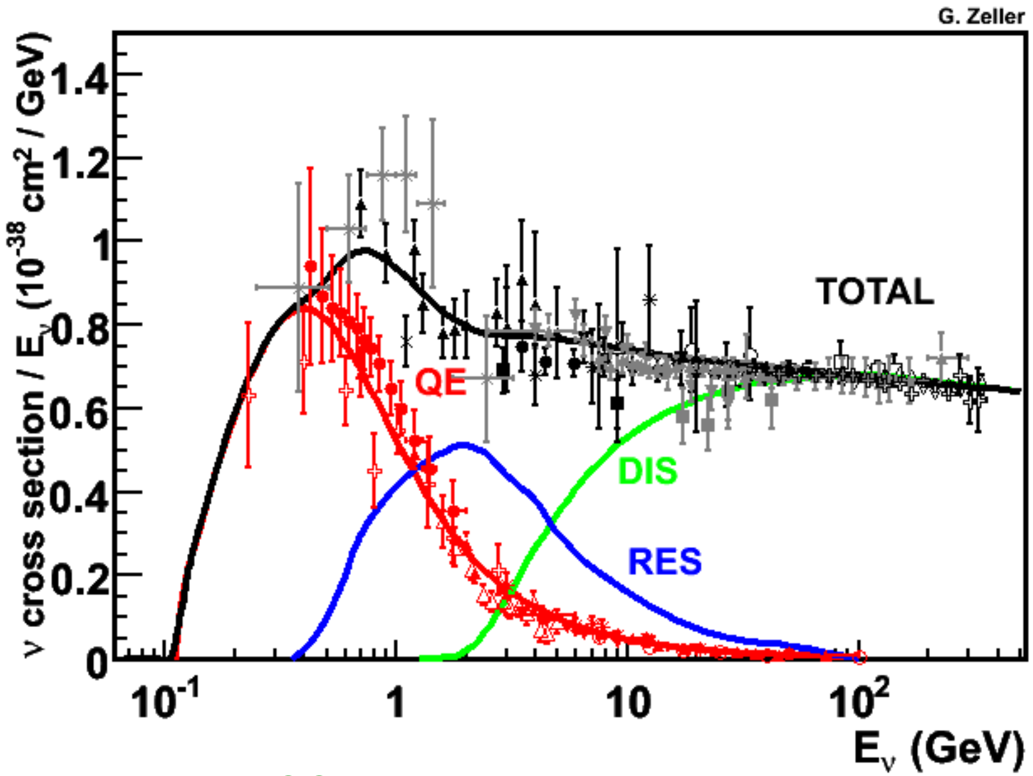

ν_μCC cross section per nucleon

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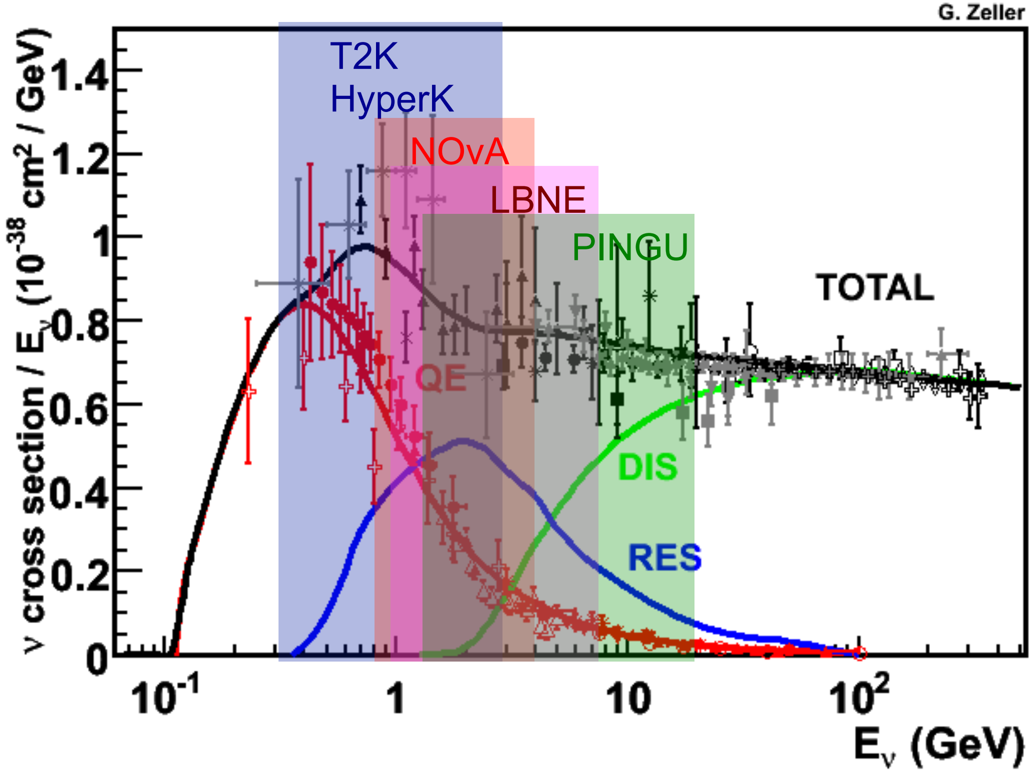
- Nuclear effects are significant
- Urgent programs both theories and experiments



Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
3. Coherent pion production puzzle
4. CCQE puzzle

1. Neutrinos
2. Oscillations
3. νSM
4. Beyond νSM
5. Conclusions

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
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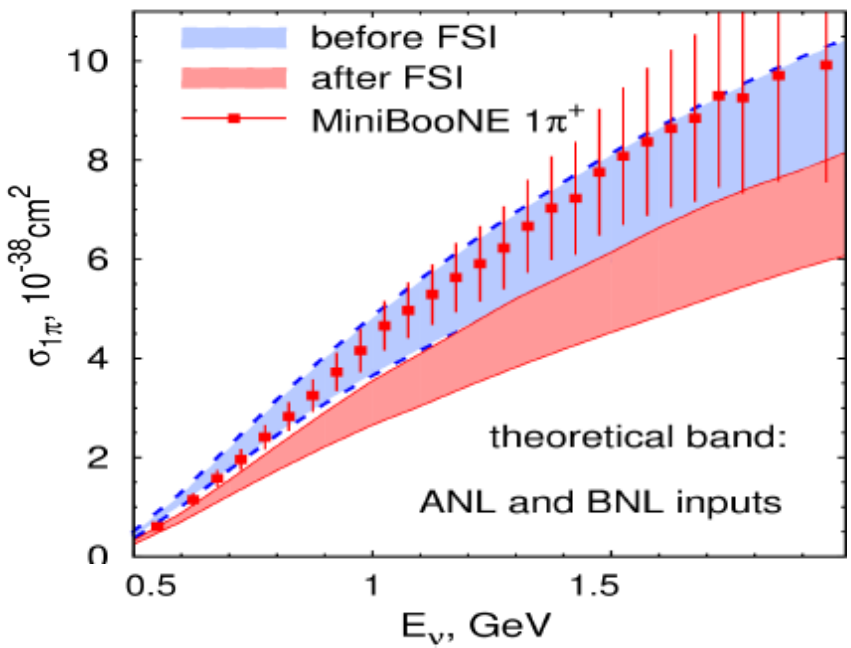

All phenomenological models use deuteron data as input → all pion production models end up with ~30% normalization errors (>30 years old problem)

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
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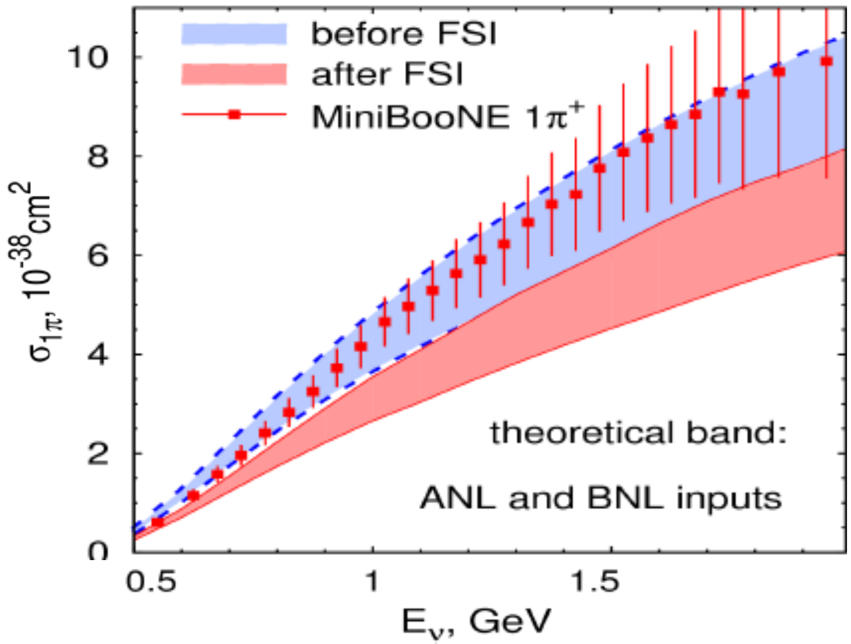
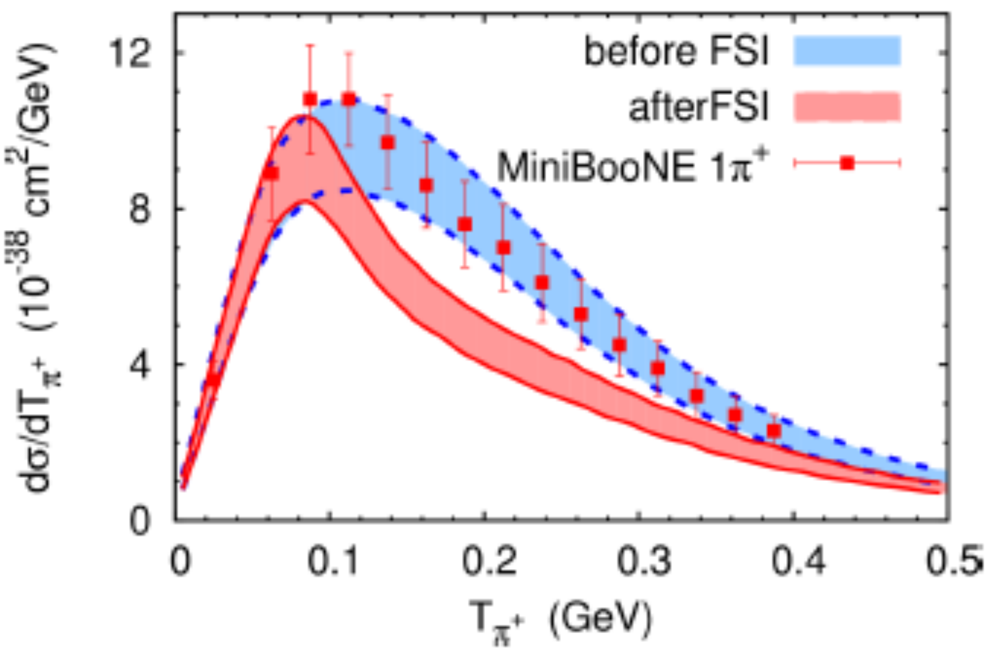
4. CCQE puzzle

MiniBooNE data also disagree with shape





4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

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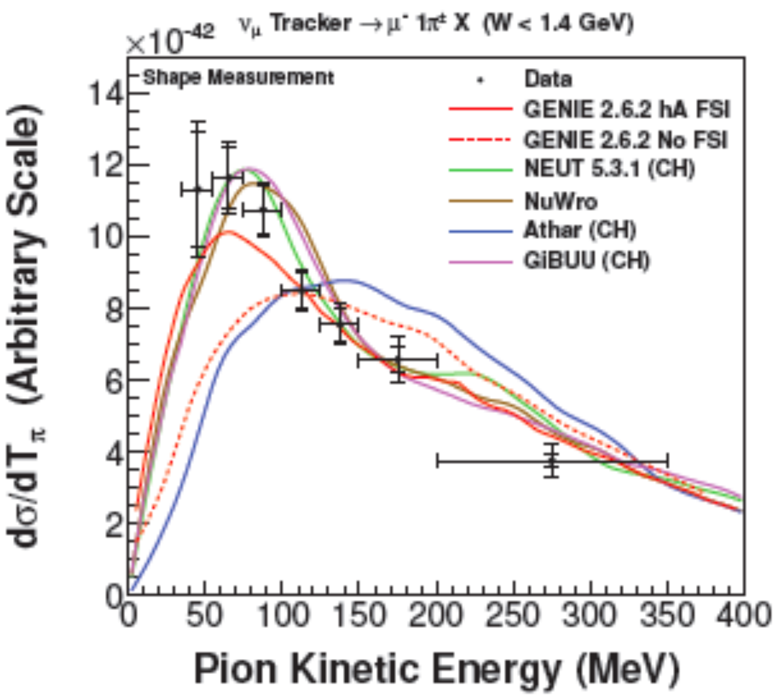
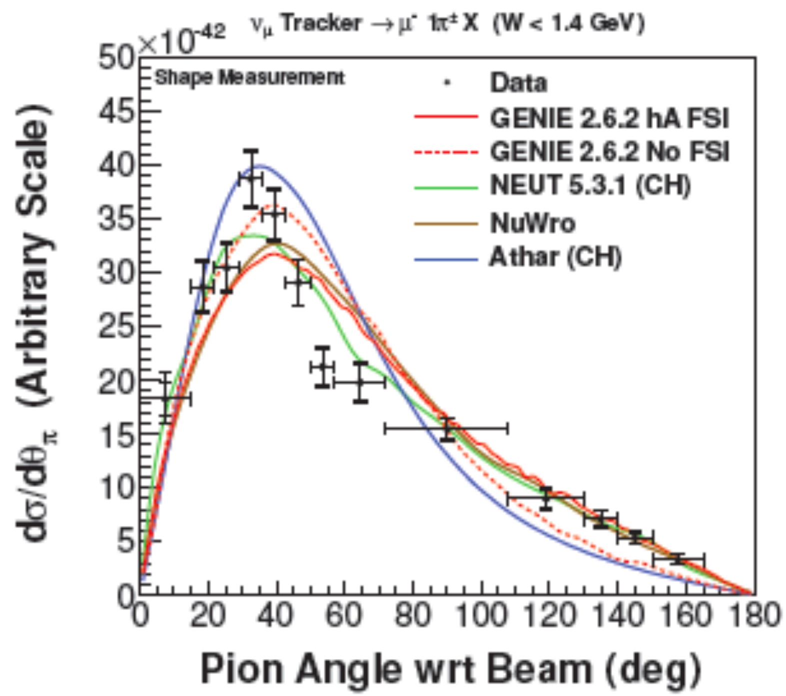
Recent MINERvA data leave some tensions with state-of-the-art models





pion kinematics: pion production model and pion propagation model

4. Neutrinos, as probes of new physics

1. Neutrinos
2. Oscillations
3. νSM
4. Beyond νSM
5. Conclusions

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
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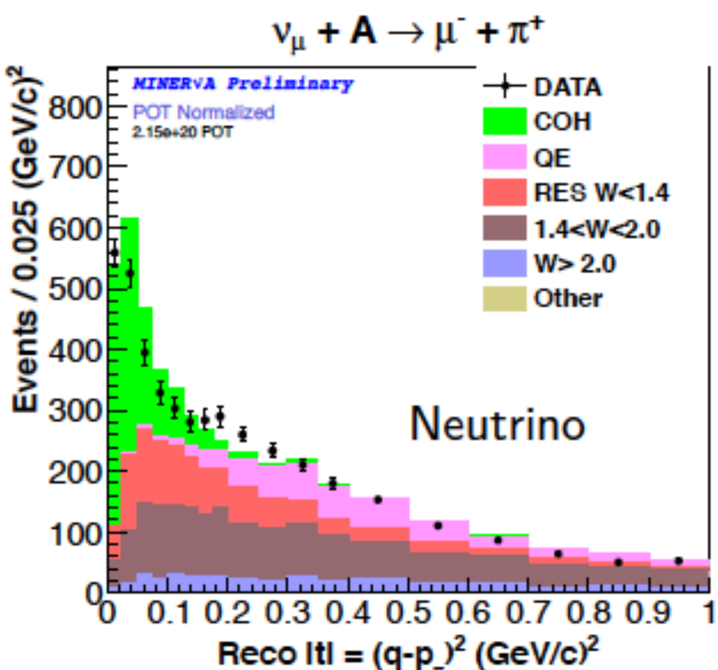
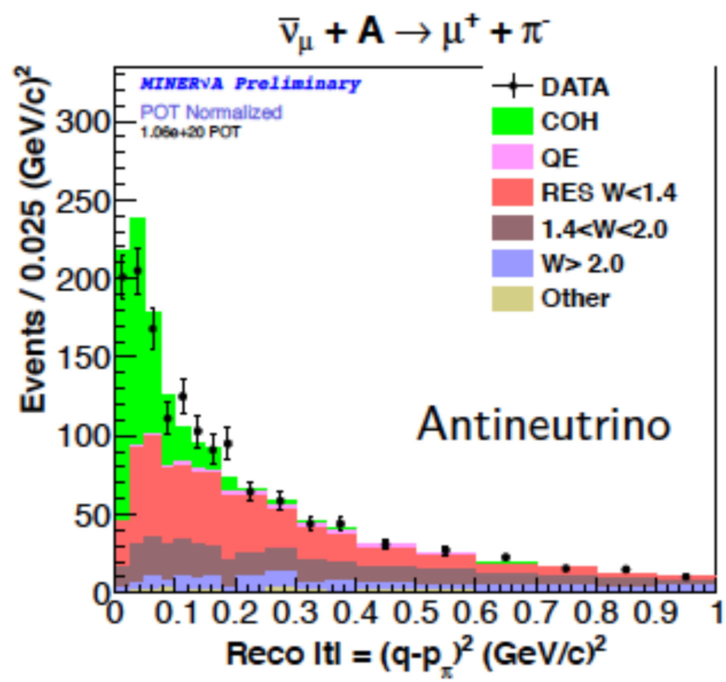
4. CCQE puzzle

NCcohπ: Yes: MiniBooNE, SciBooNE
CCcohπ: Yes: MINERvA, T2K
No: K2K, SciBooNE





Naively, NCcohπ:CCcohπ=1:2, but data are far from that

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
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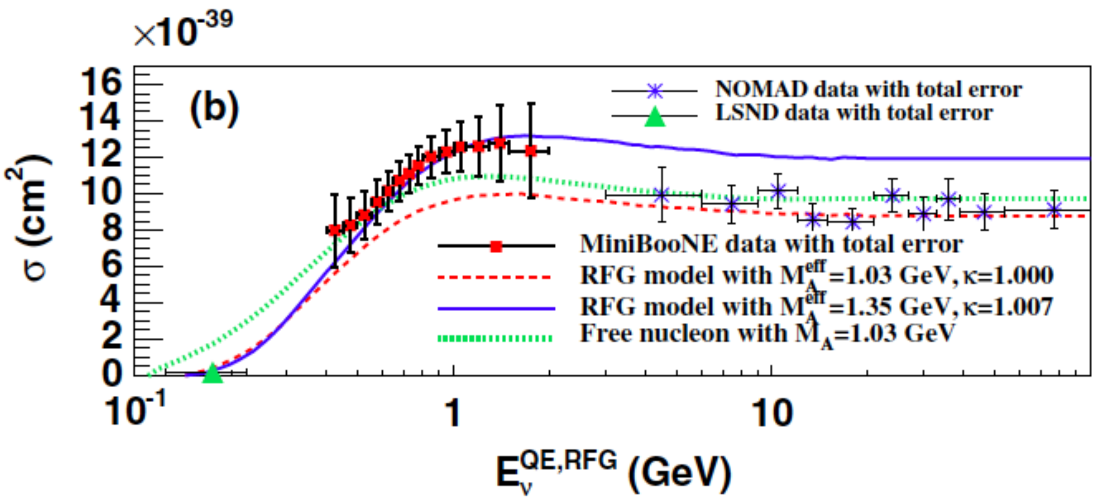
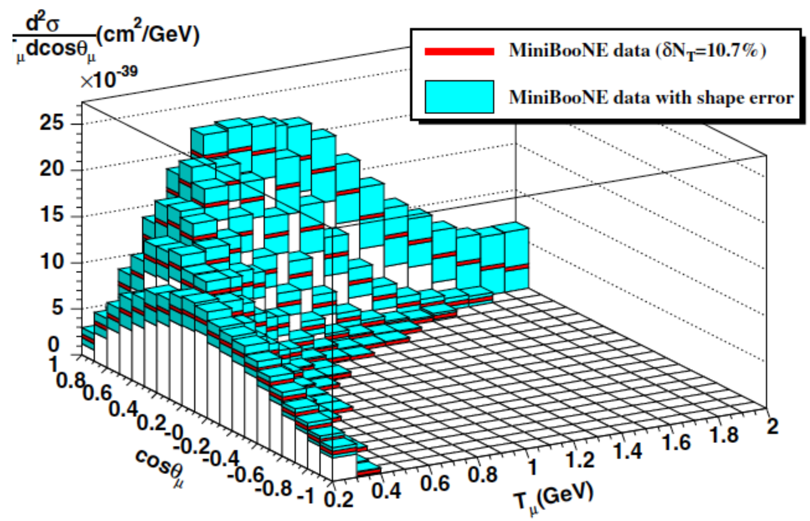
4. CCQE puzzle

MiniBooNE CCQE cross section
1. high normalization
2. hard spectrum

→ axial mass (M_A) = 1.35 GeV
(photo-pion production data, M_A~1)





MiniBooNE,PRD81(2010)092005

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

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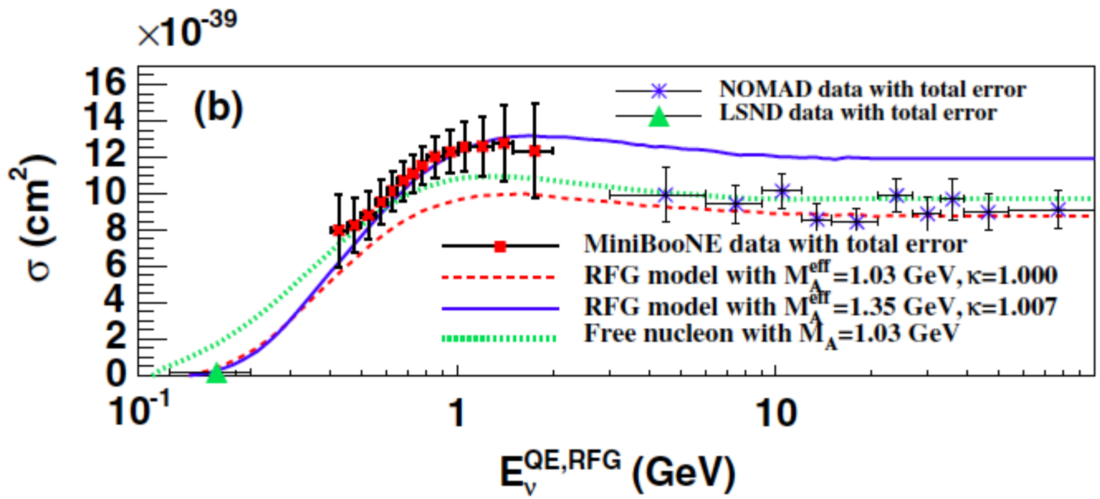
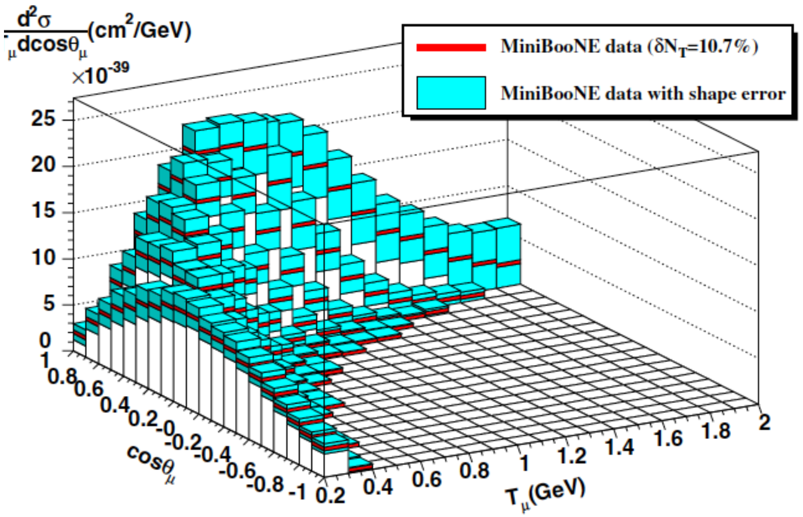




MiniBooNE,PRD81(2010)092005
Martini et al,PRC80(2009)065501

4. Neutrinos, as probes of new physics

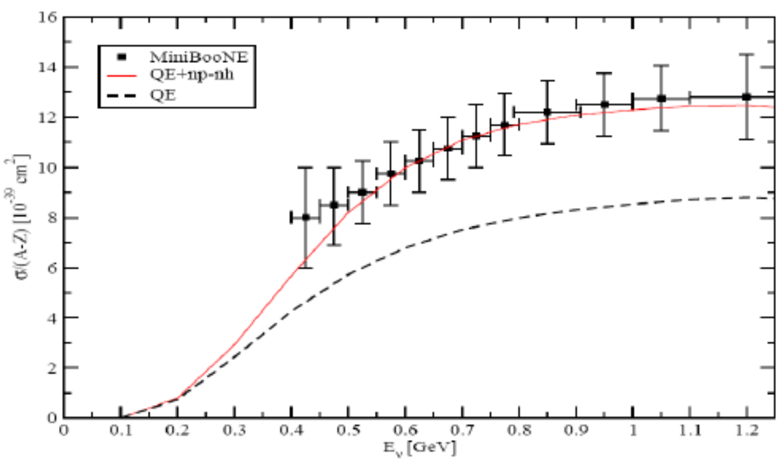
Marco Martini

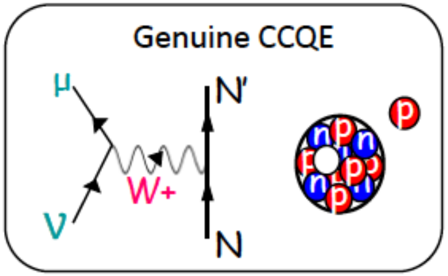
Open questions of neutrino cross-section community

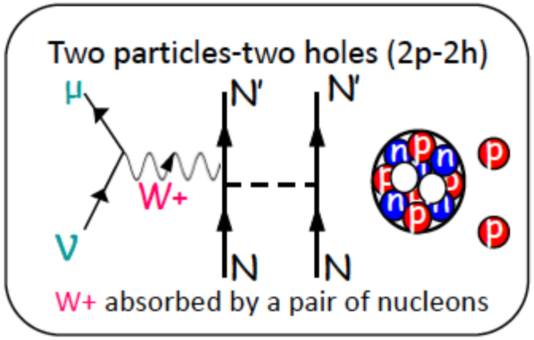
1. ANL-BNL puzzle
2. CC1π puzzle
3. Coherent pion production puzzle
4. CCQE puzzle

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

T2K,PRD87(2013)092003
Martini et al,ArXiv:1404.1490

4. Neutrinos, as probes of new physics

Marco Martini

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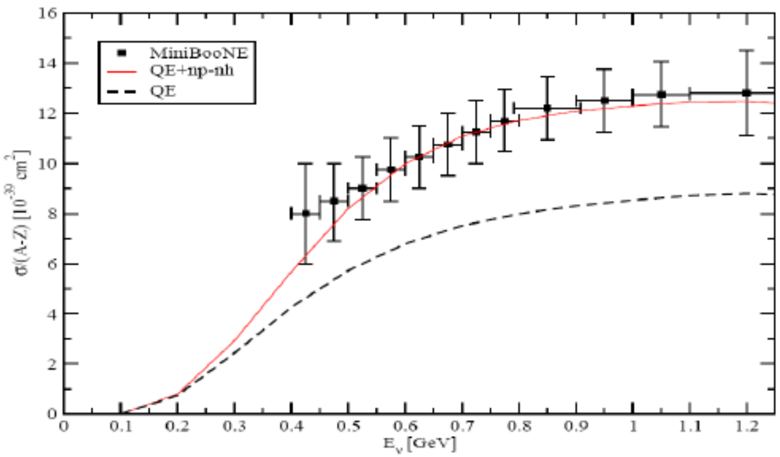

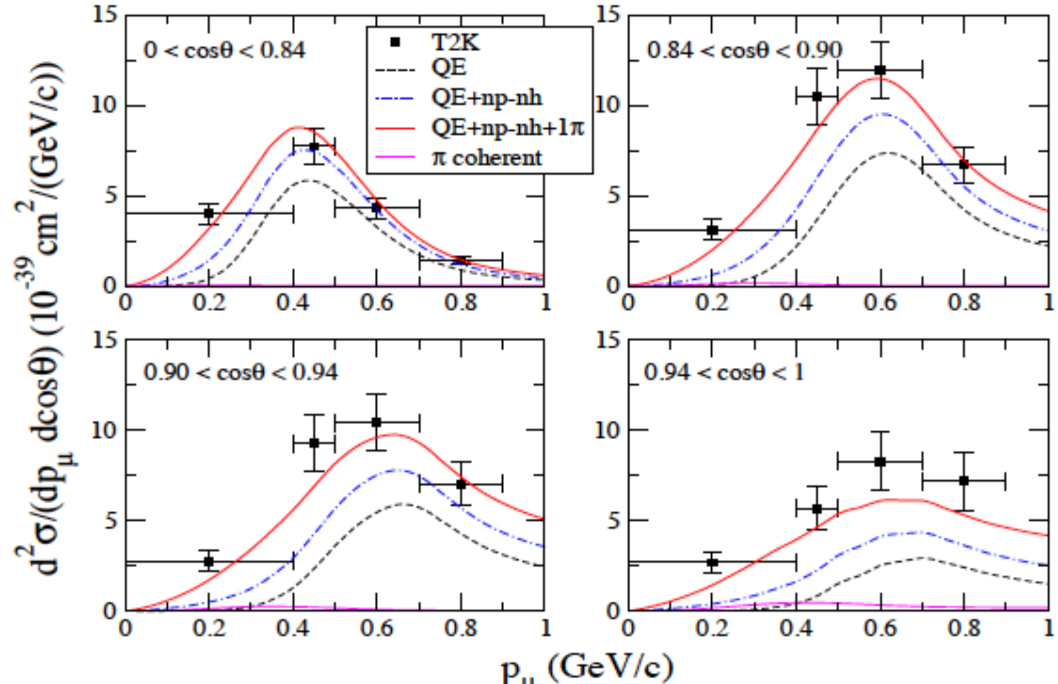

M. Martini, M. Ericson, G. Chanfray, J. Marteau Phy

Agreement with MiniBooNE without increasing M

Solution: presence of 2-body current

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
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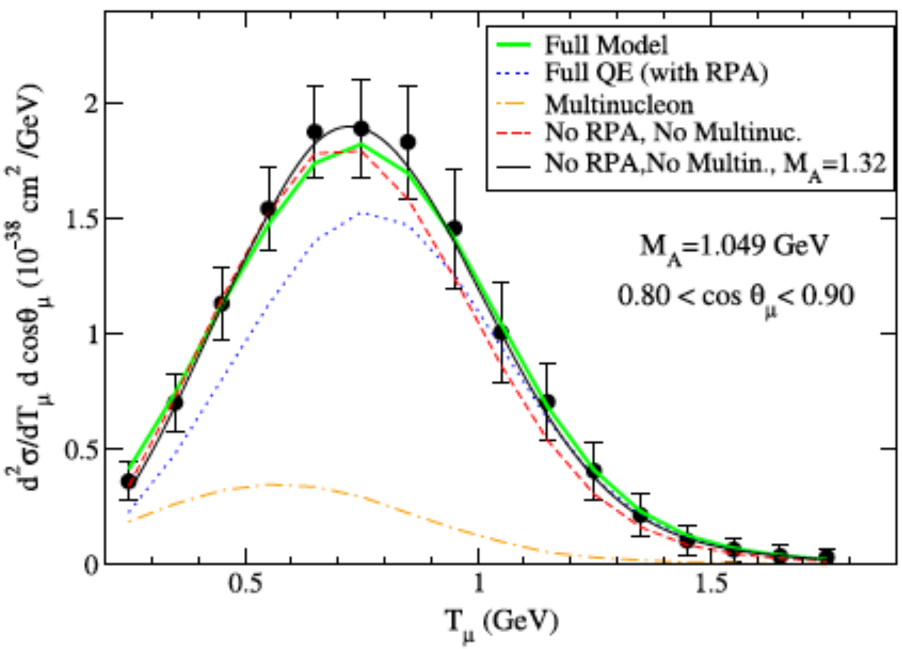
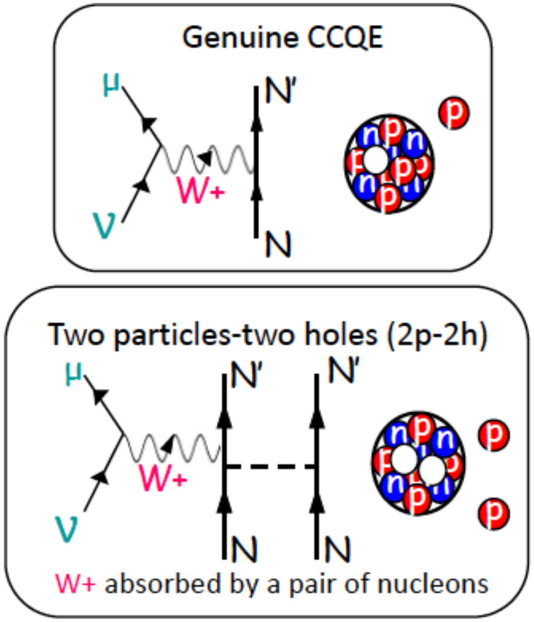
4. CCQE puzzle

There is a growing consensus (role of 2-body current in ν-A scattering)





Solution: presence of 2-body current

4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
3. Coherent pion production puzzle
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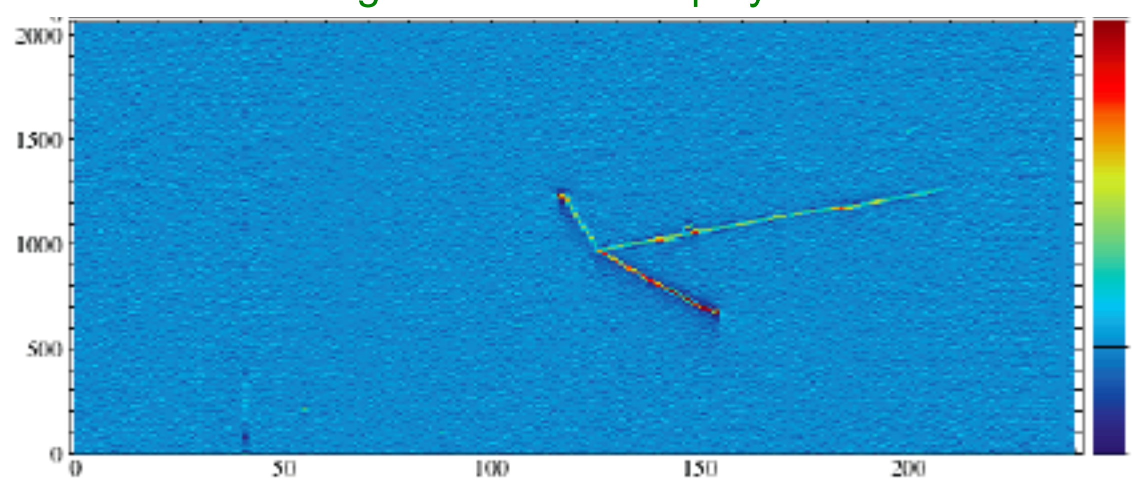
2-body current
→ 2 nucleon emission?

There is world-wide effort to understand hadronic system (both theoretically and experimentally)

ArgoNeuT event display



4. Neutrinos, as probes of new physics

Open questions of neutrino cross-section community

1. ANL-BNL puzzle
2. CC1π puzzle
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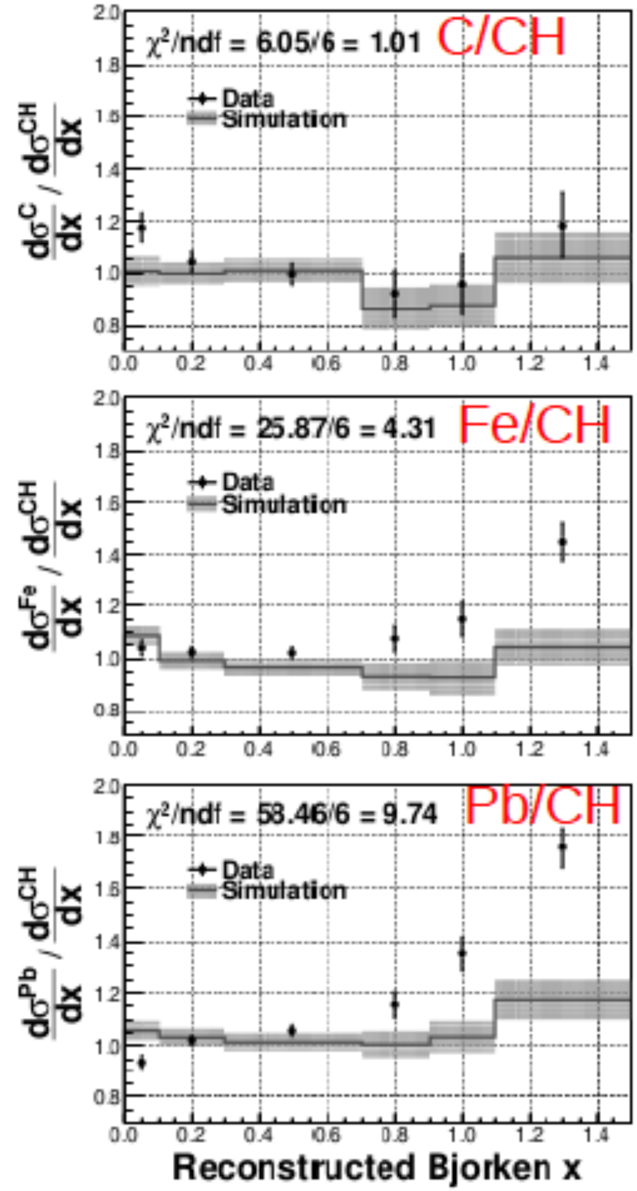
4. CCQE puzzle
5. MINERvA target ratio

A dependent behaviour for low x and high x.
(somewhat similar with electron scattering shadowing effect)



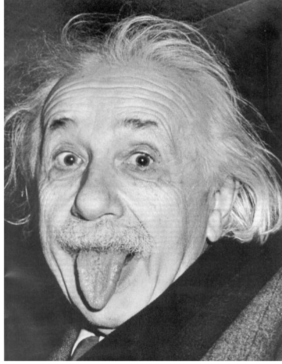
4. Neutrinos, as probes of new physics

Marco

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

Kostelecký and Samuel,PRD39(1989)683

4. Neutrinos, as probes of new physics



Albert

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

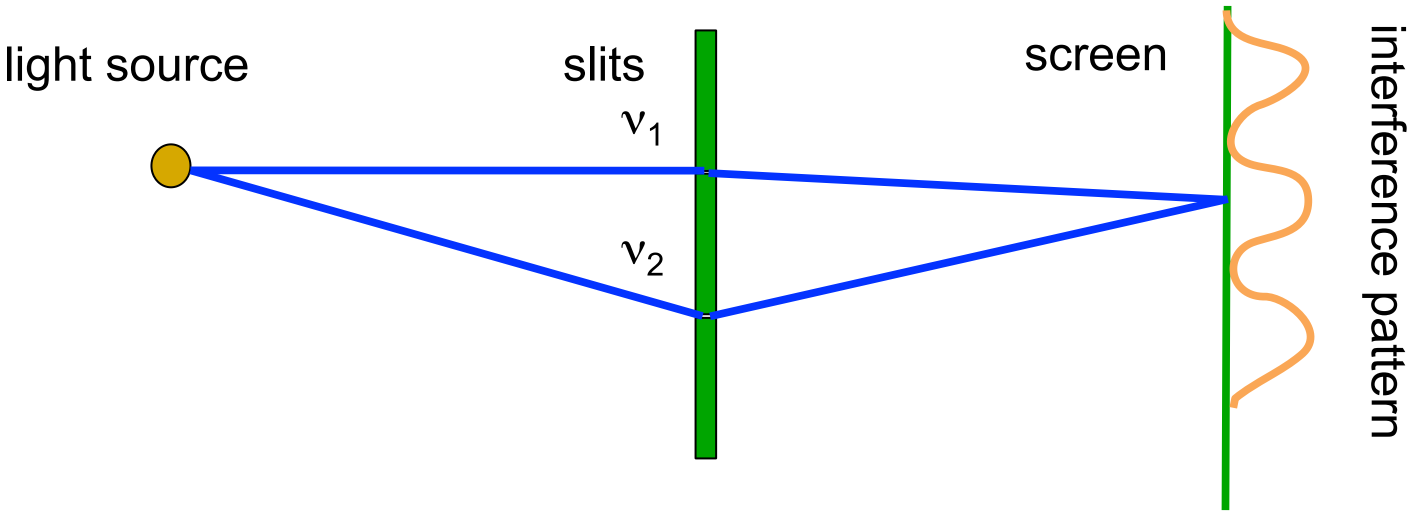
$$\Gamma^{\nu}_{AB} = \gamma^{\nu} \delta_{AB} + c^{\mu\nu}_{AB} \gamma_{\mu} + d^{\mu\nu}_{AB} \gamma_{\mu} \gamma_5 + e^{\nu}_{AB} + i f^{\nu}_{AB} \gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB} \sigma_{\lambda\mu} \cdots$$

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

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

4. Neutrino oscillations

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

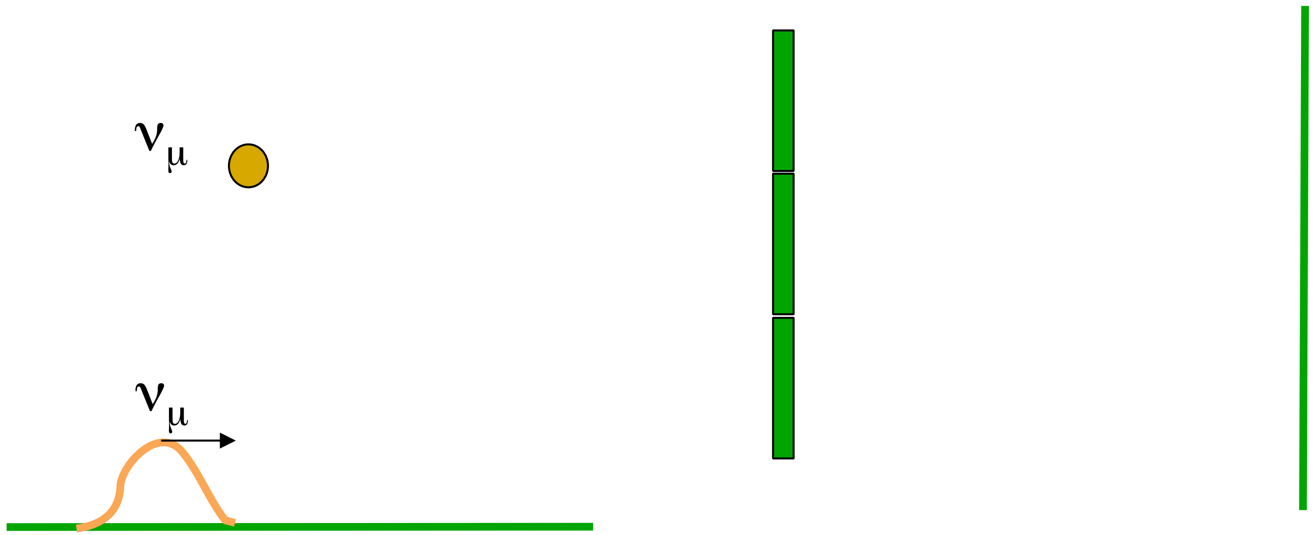


For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

Kostelecký and Mewes, PRD69(2004)016005
Diaz, Kostelecký and Mewes, PRD80(2009)076007

4. Lorentz violating neutrino oscillation

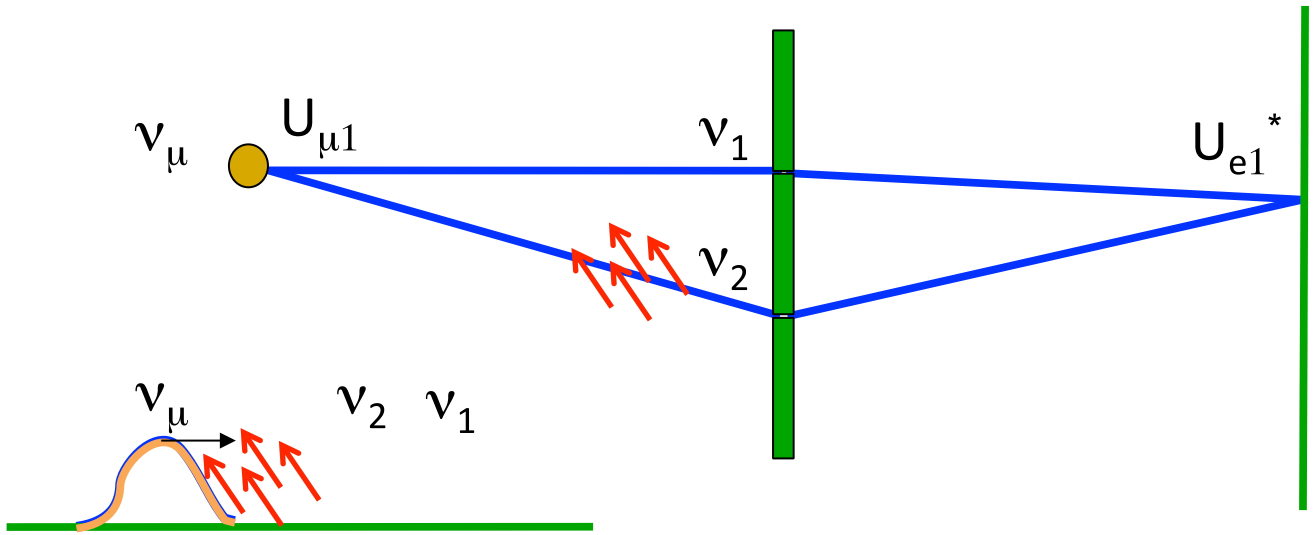
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

4. Lorentz violating neutrino oscillation

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 Lorentz violating field, neutrinos also oscillate. The sensitivity of neutrino oscillation is comparable the target scale of Lorentz violation ($<10^{-19}$GeV).

Kostelecký and Mewes, PRD69(2004)016005
Diaz, Kostelecký and Mewes, PRD80(2009)076007

4. Lorentz violating neutrino oscillation

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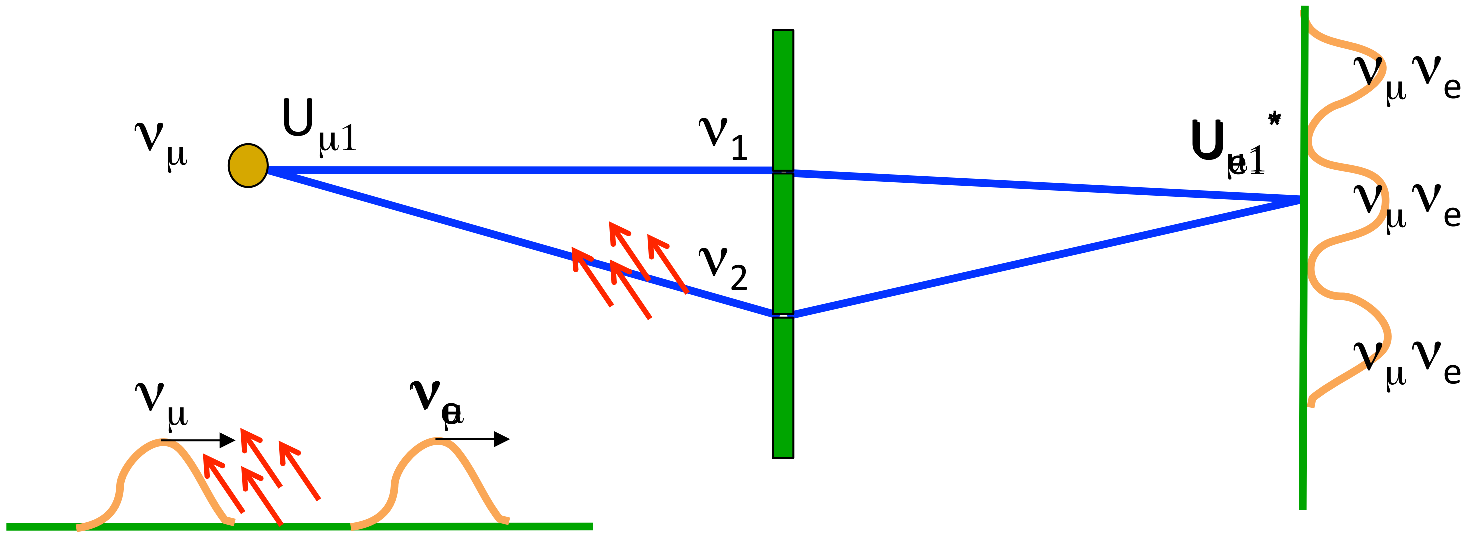

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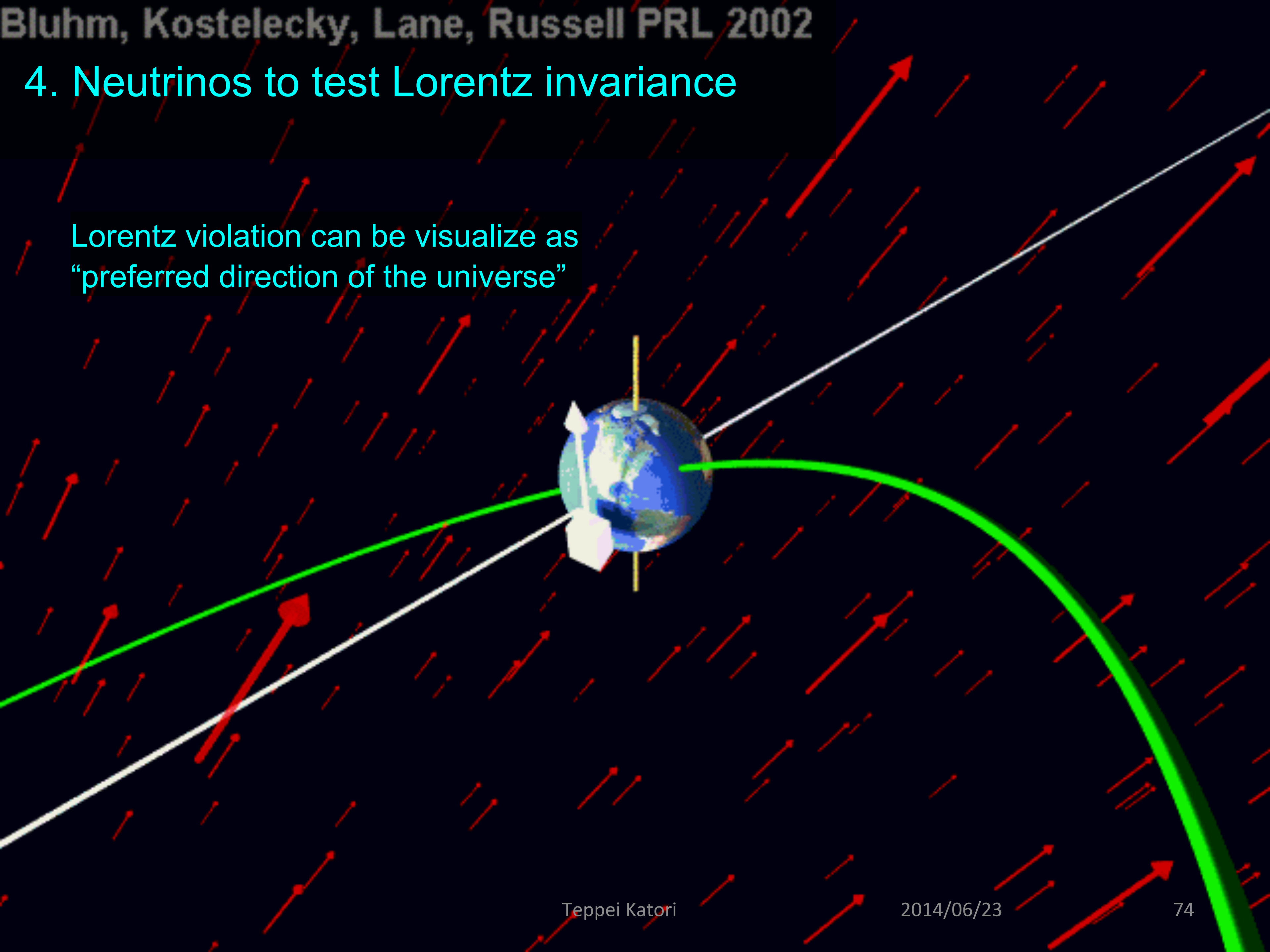
If neutrino oscillation is caused by Lorentz violation, interference pattern (oscillation probability) may have sidereal time dependence.

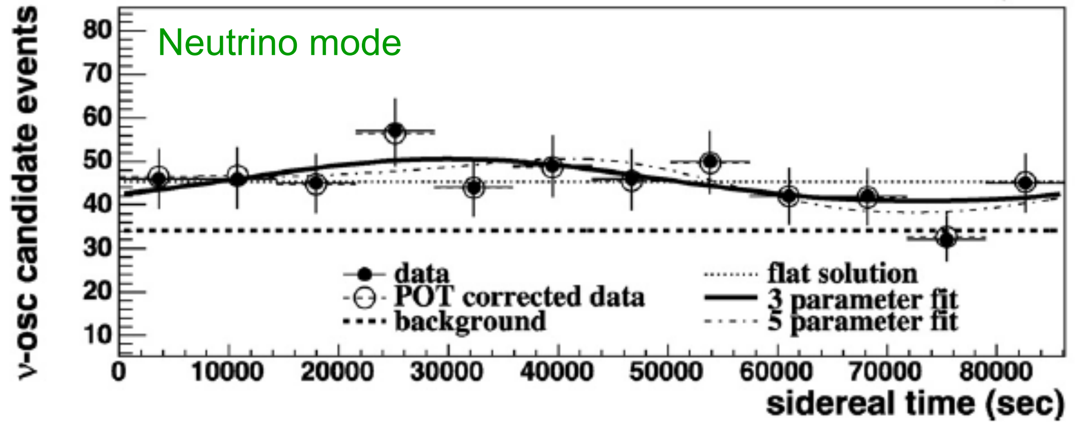
4. Neutrinos to test Lorentz invariance

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

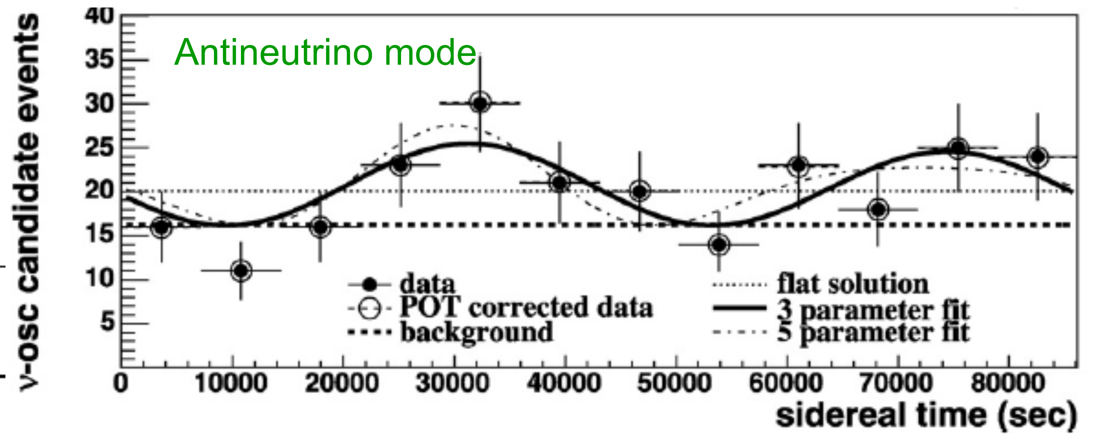


4. Lorentz violating neutrino oscillation

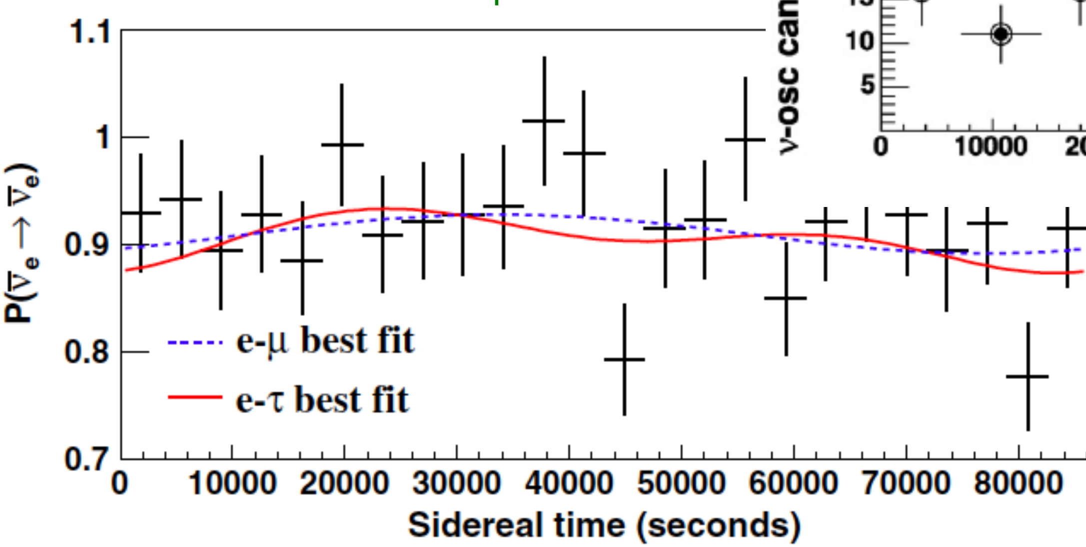
MiniBooNE electron neutrino candidate data prefer sidereal time independent solution (flat)



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

1. Neutrinos
2. Oscillations
3. νSM
4. Beyond νSM
5. Conclusions

Lorentz violation is tested with all neutrino channels

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

Limits of Lorentz violation coefficient from neutrino oscillation experiments

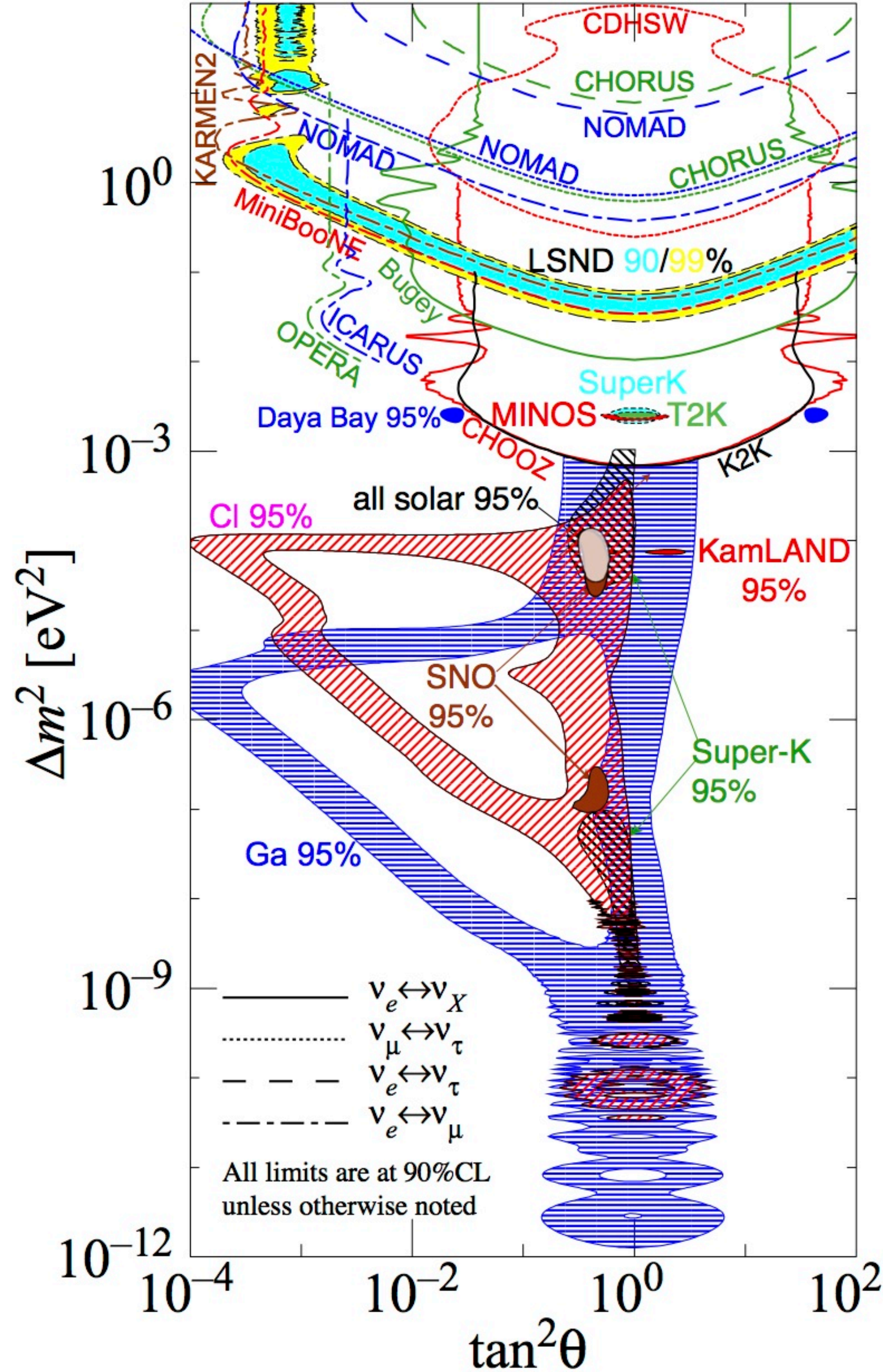
		MiniBooNE, MINOS ND	Double Chooz	IceCube, MINOS FD
$d=3$	**Coefficient**	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Z$	10^{-19} 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}	–

4. νSM in Δm^2-$\tan^2\theta$ plane

Majority of phase space are explored, and world data are nailed down in tiny regions.

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 model independent diagram look like?



http://hitoshi.berkeley.edu/neutrino

1. Neutrinos
2. Oscillations
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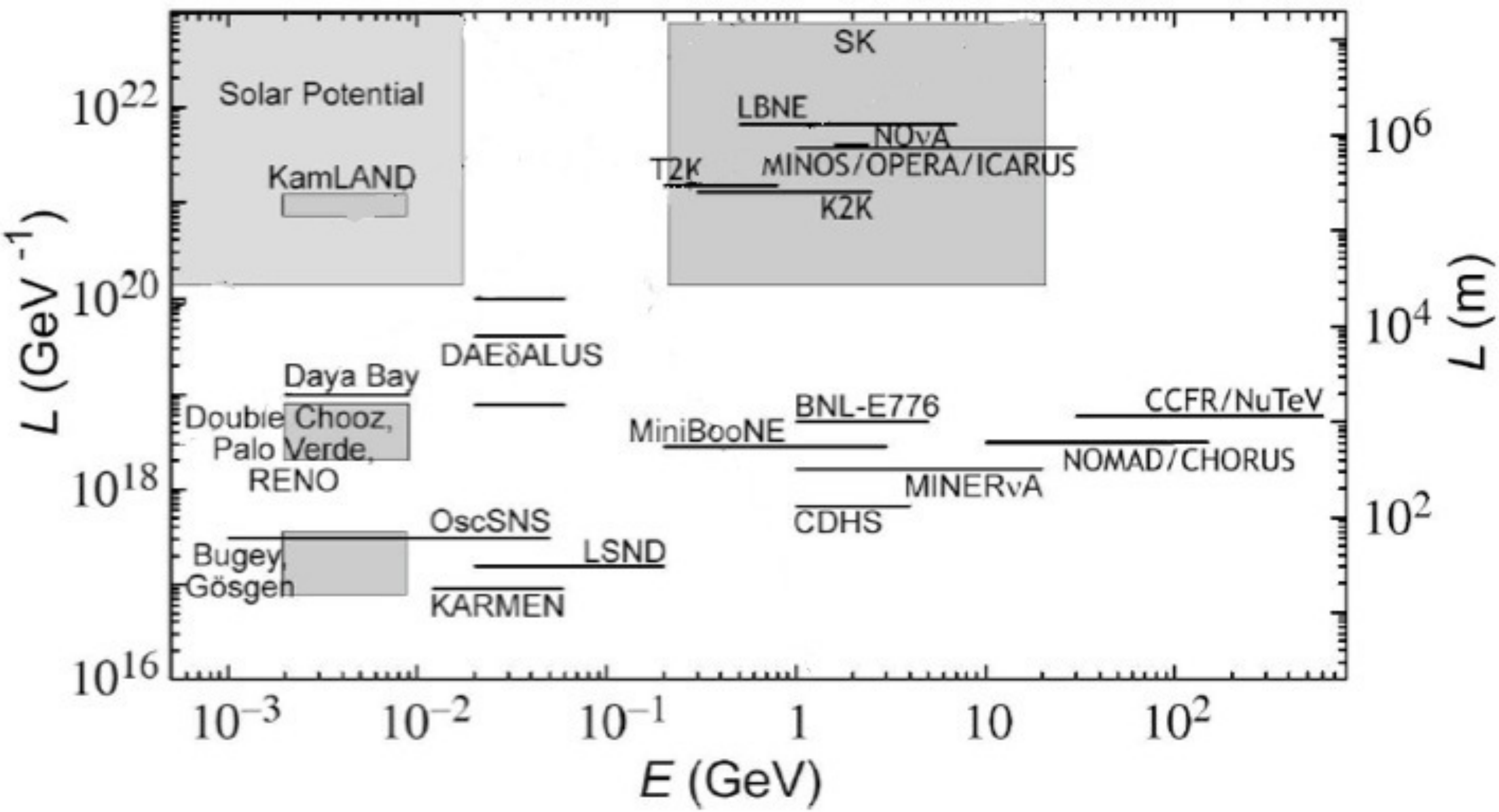
5. Conclusions

4. Lorentz violating neutrino oscillation

Model independent neutrino oscillation data is the function of neutrino energy and baseline.



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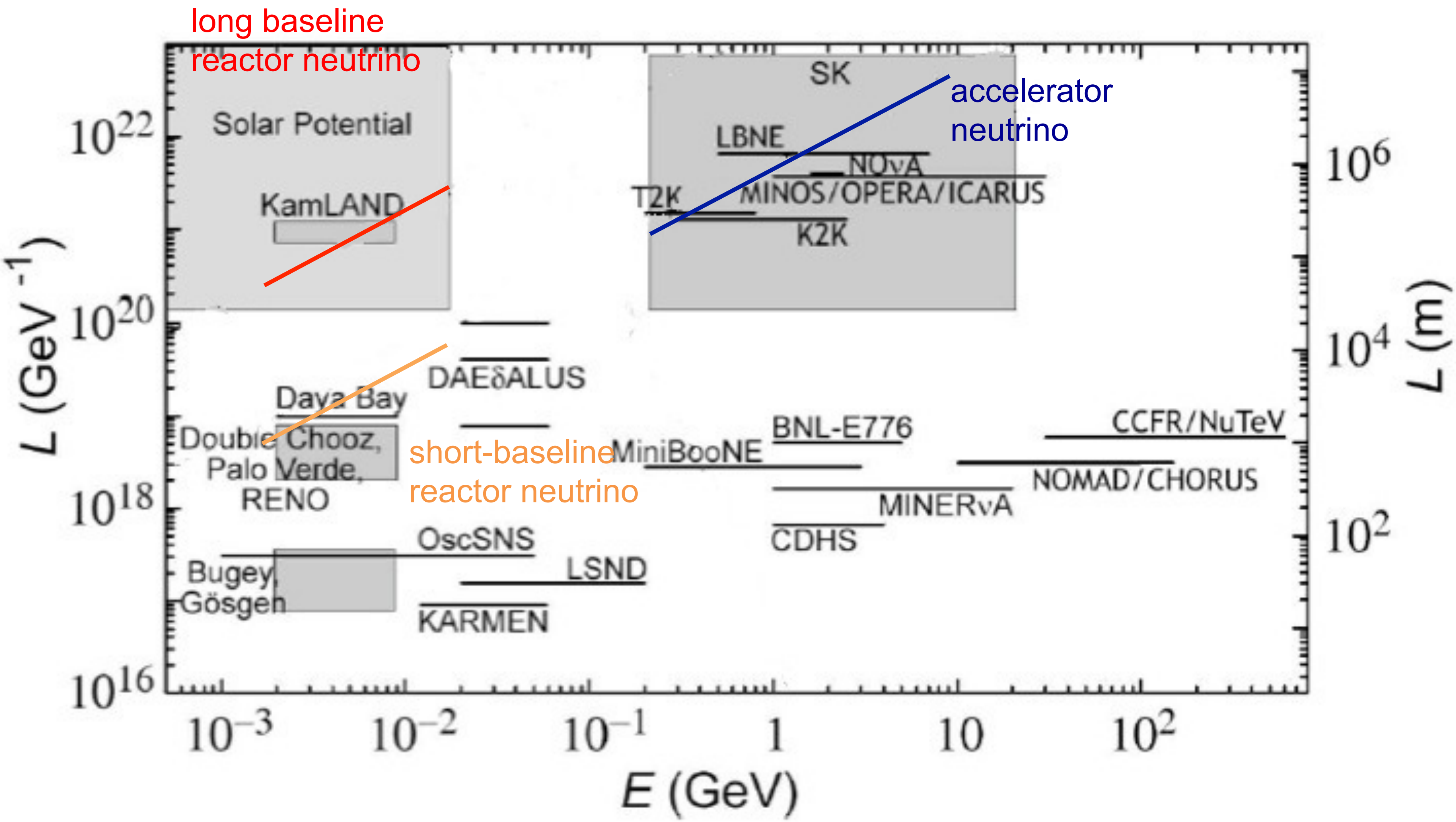

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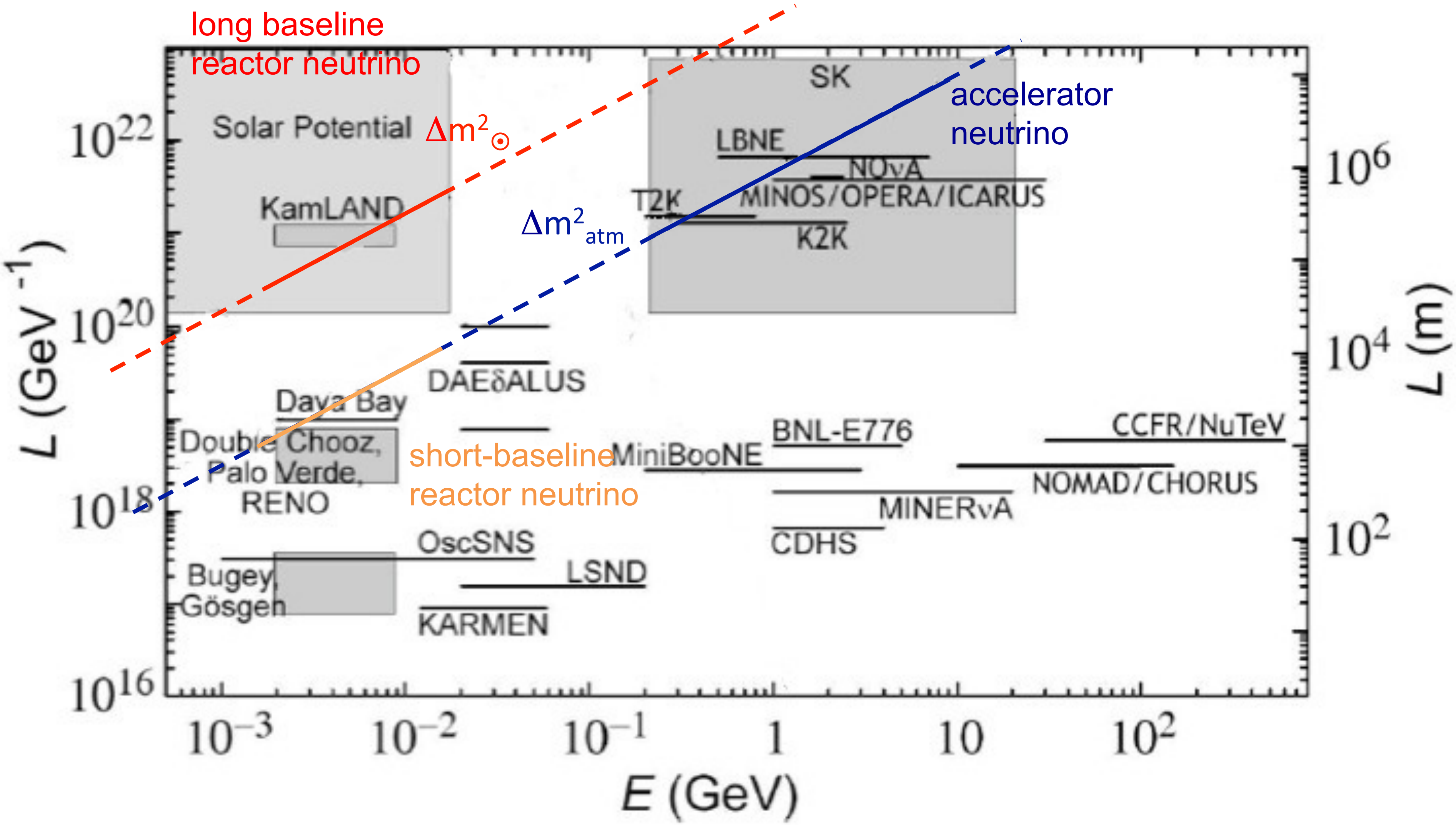

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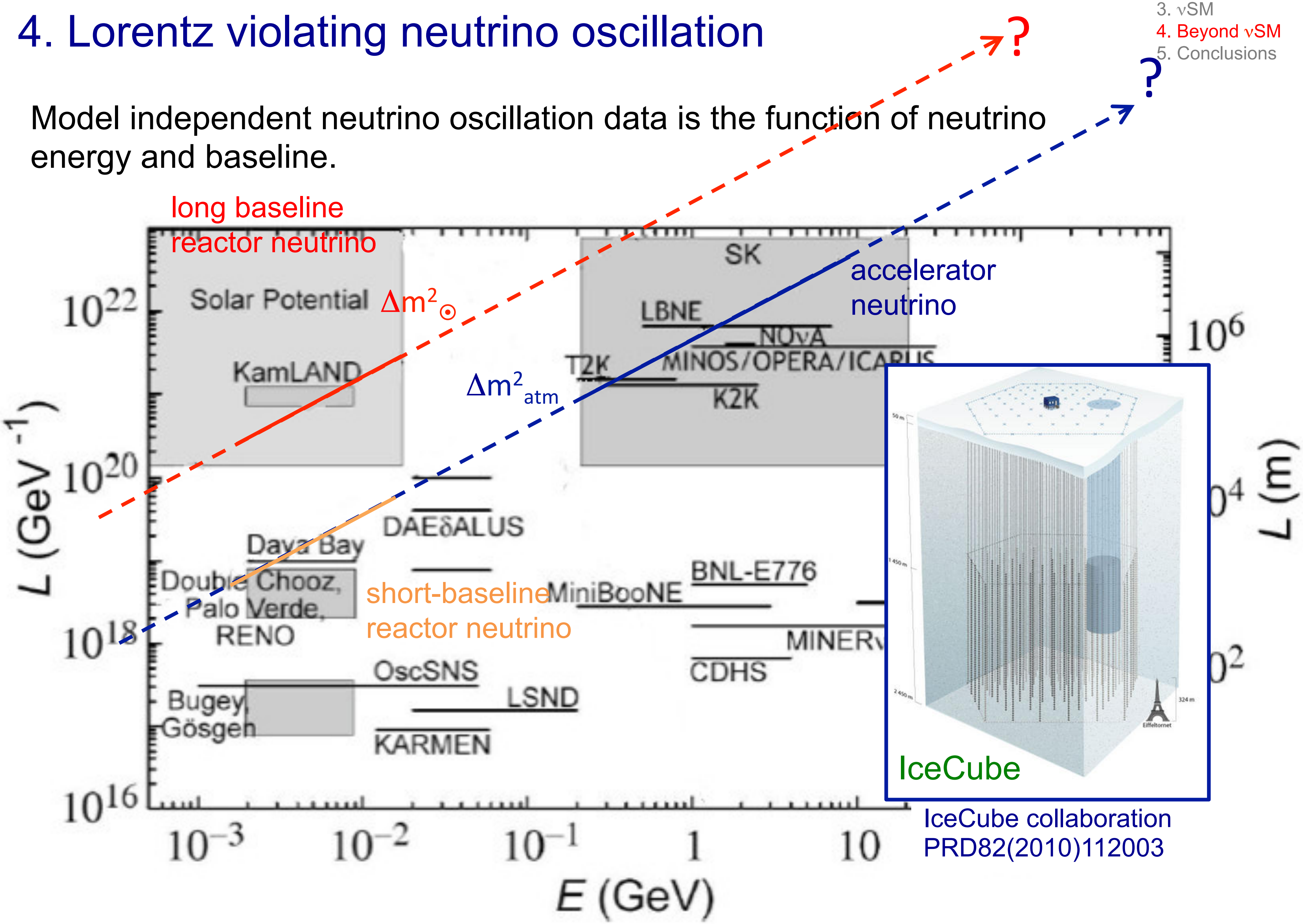


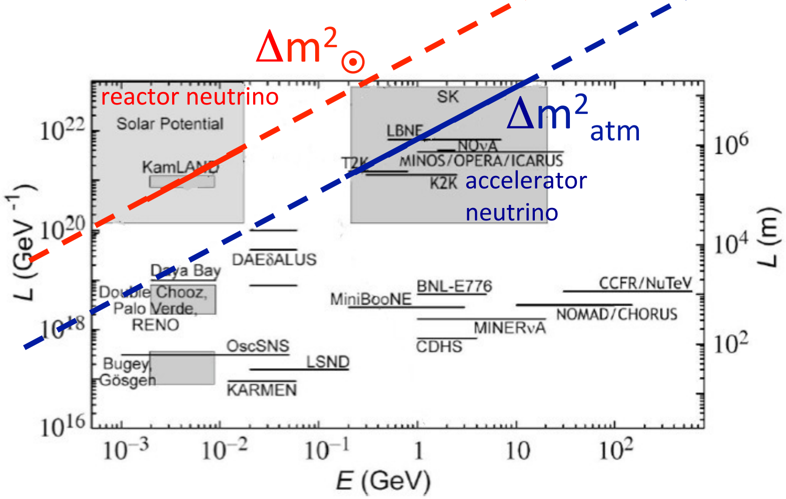
IceCube collaboration
PRD82(2010)112003

Kostelecký and Mewes, PRD69(2004)016005

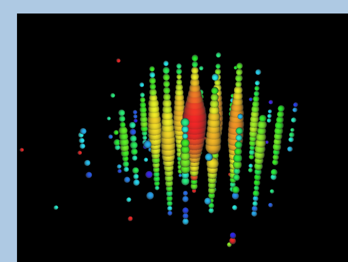
4. Lorentz violating neutrino oscillation

Extra galactic neutrino
IceCube potential

1Mpc



UHE neutrino
IceCube potential



1PeV

Potential of extragalactic neutrinos are enormous!

Queen Mary
University of London

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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Supernova 1987A happens right time when Kamiokande II is online
(6 galactic supernovae in the last 1000 years)

5. Mother Nature is kind to us

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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The earth is right size so that we can detect atmospheric neutrino oscillation through up-down asymmetry

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θ_{13} is small so that 2 massive neutrino approximation work well to study solar and atmospheric neutrino oscillation

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But θ_{13} is big enough so that we can measure it

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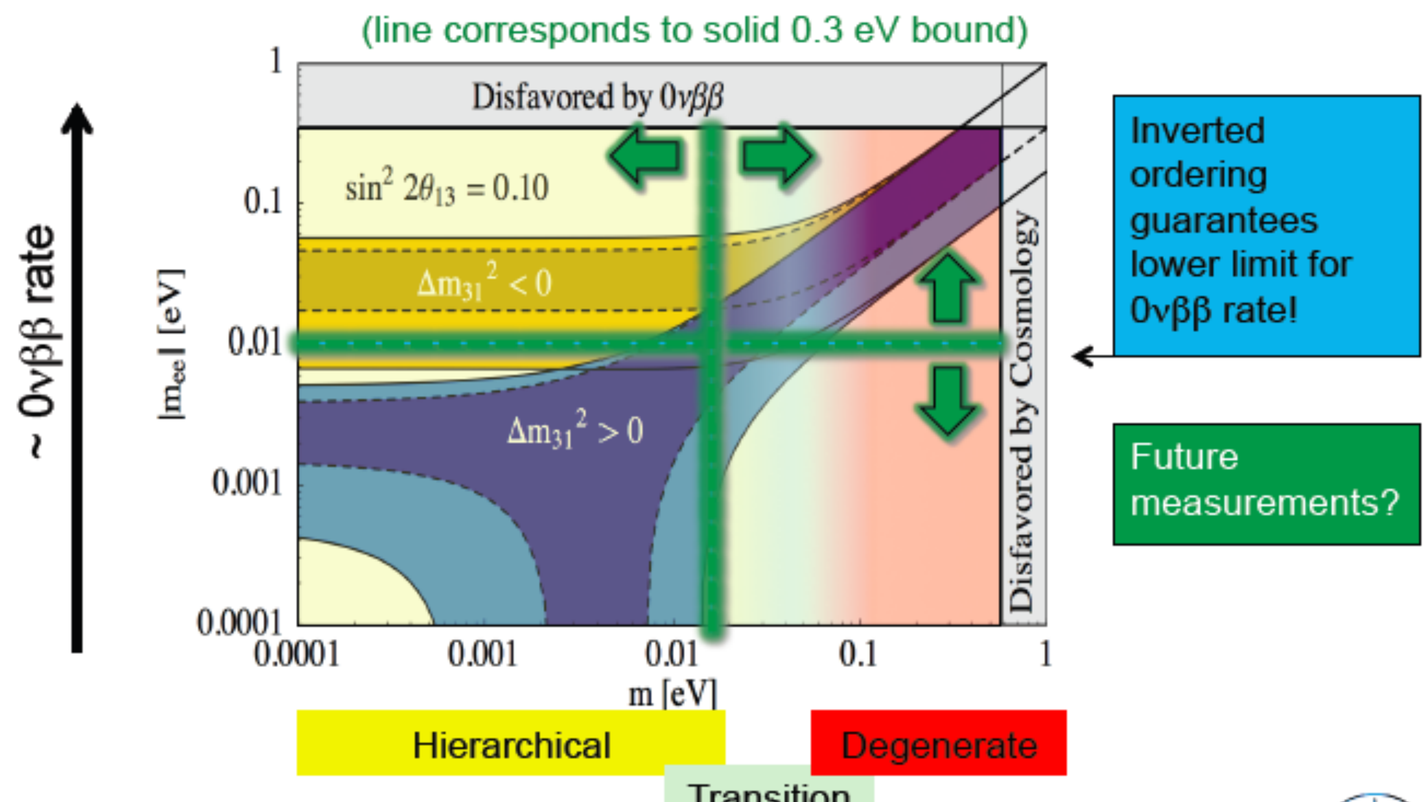
Mass hierarchy must be inverted so that we can find Dirac or Majorana?????

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:



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

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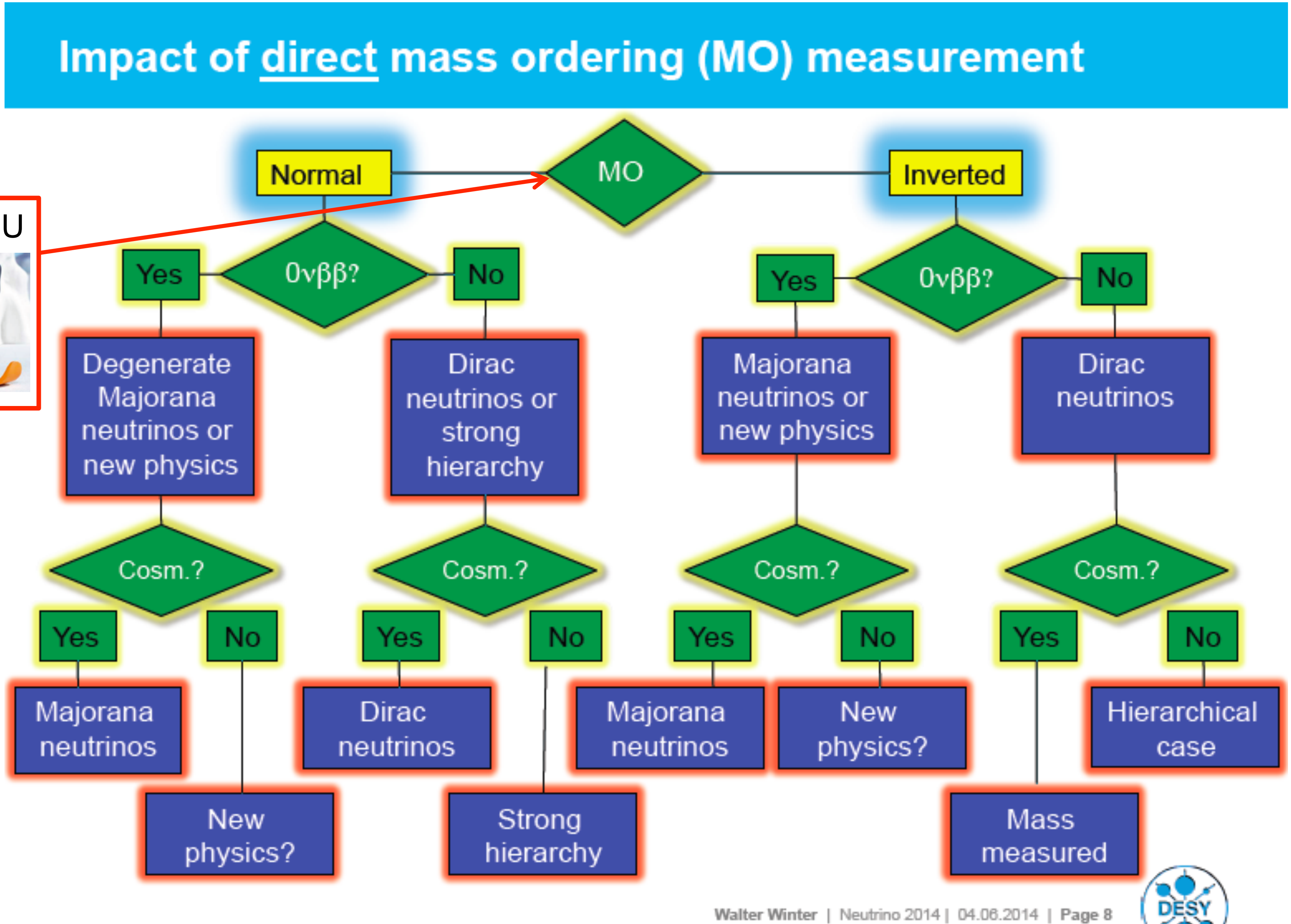
If mass hierarchy is normal, there is a chance we cannot find Dirac or Majorana from $0\nu\beta\beta$

PINGU



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

Neutrinos are interesting probes for Beyond SM physics, such as Lorentz violation

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

Thank you for your attention!

Backup

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

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

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. Neutrino physics for...

4. Neutrino physics for Peace

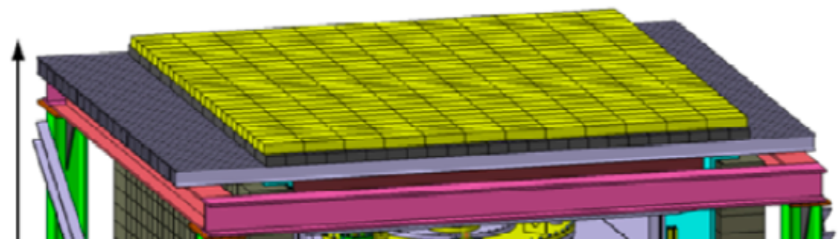
Paper Number: IAEA-CN-184/27

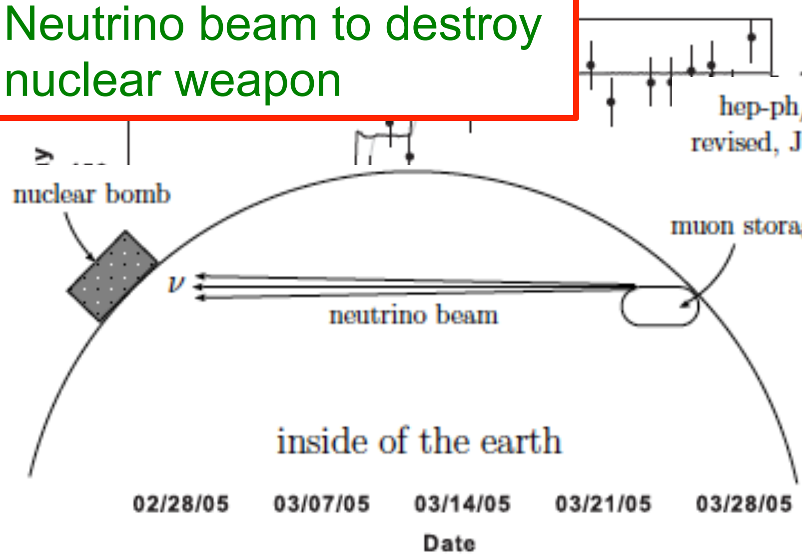
Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

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

Neutrino beam to destroy nuclear weapon





hep-ph/0305062
revised, June 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡

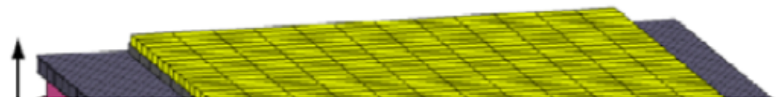
3 m

4. Neutrino physics to become Rich

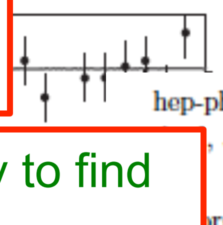
Paper Number: IAEA-CN-184/27

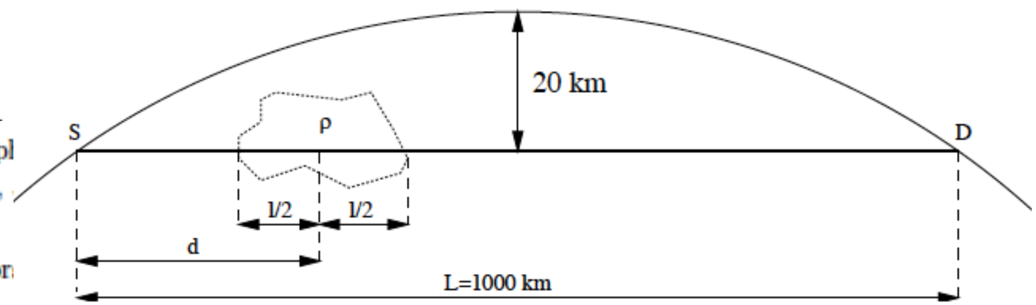
Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

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
- 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(**)

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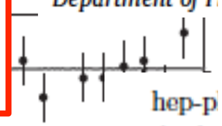
4. Neutrino Communications

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?

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Patrick Huber

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Galactic neutrino communication

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

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Finally, MINERvA experiment sent Morse code signal through neutrino beam

DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

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4. Neutrino Communications

The Future Of Stock Trading: Neutrino Beams

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

TECH | 4/30/2012 @ 4:44AM | 26,551 views

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.

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

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

Tomorrow's stocks could be traded via neutrino beam

Robert T. Gonzalez
Filed to: FUTURISM 5/01/12 2:59pm
3,958

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

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