Neutrino Physics

1. Neutrino oscillations
2. History of neutrino oscillation
3. T2K neutrino oscillation experiments
4. Current and future neutrino experiments
5. Neutrino astronomy
6. Conclusion

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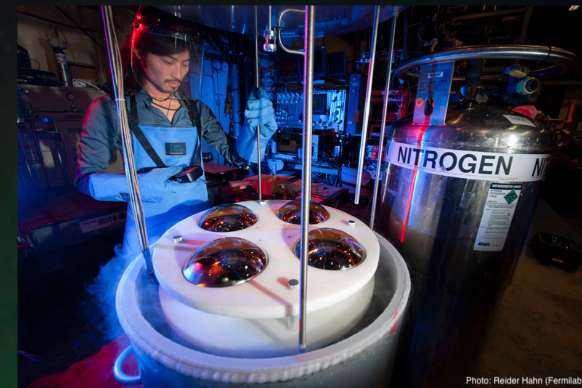
Teppei Katori
King's College London
JENNIFER2 Summer School
July 22-23, 2020

Hi, my name is Teppei!



Experimental particle physicist
- MiniBooNE
- T2K, Super-Kamiokande, Hyper-Kamiokande
- IceCube

Interests
- Neutrino interaction physics
- Effective operator new physics search
- Phenomenology
- Neutron capture application

Lecture slides:
https://nms.kcl.ac.uk/teppei.katori/teach/2020/20_JENNIFER2/

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1. **Neutrino oscillations**
2. History of neutrino oscillation
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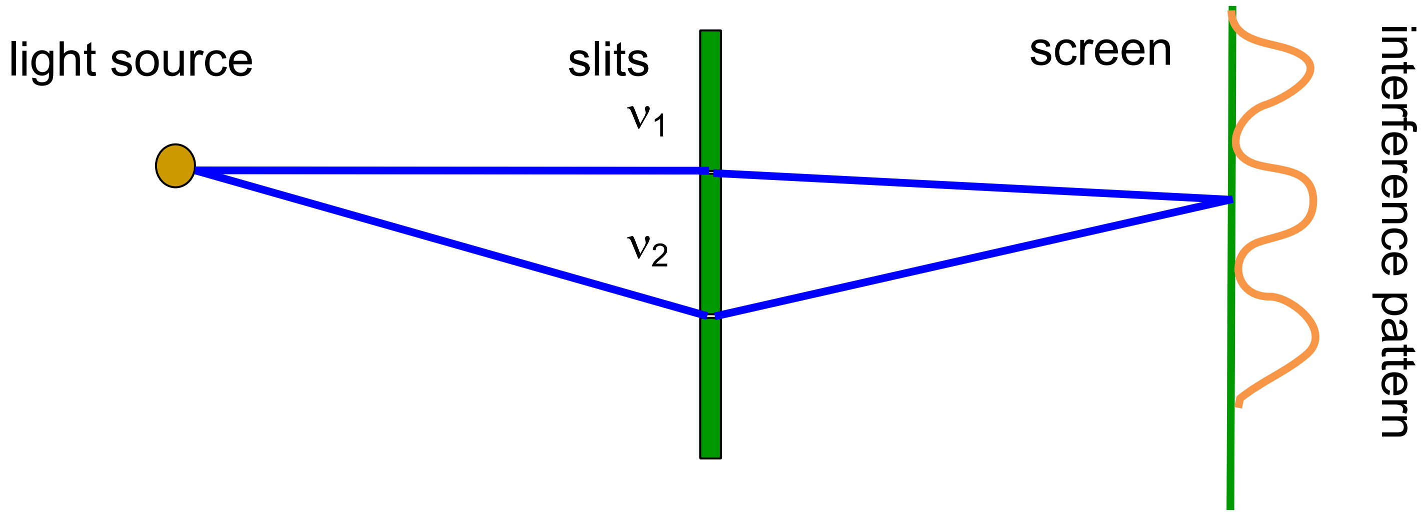
1. Neutrino oscillations

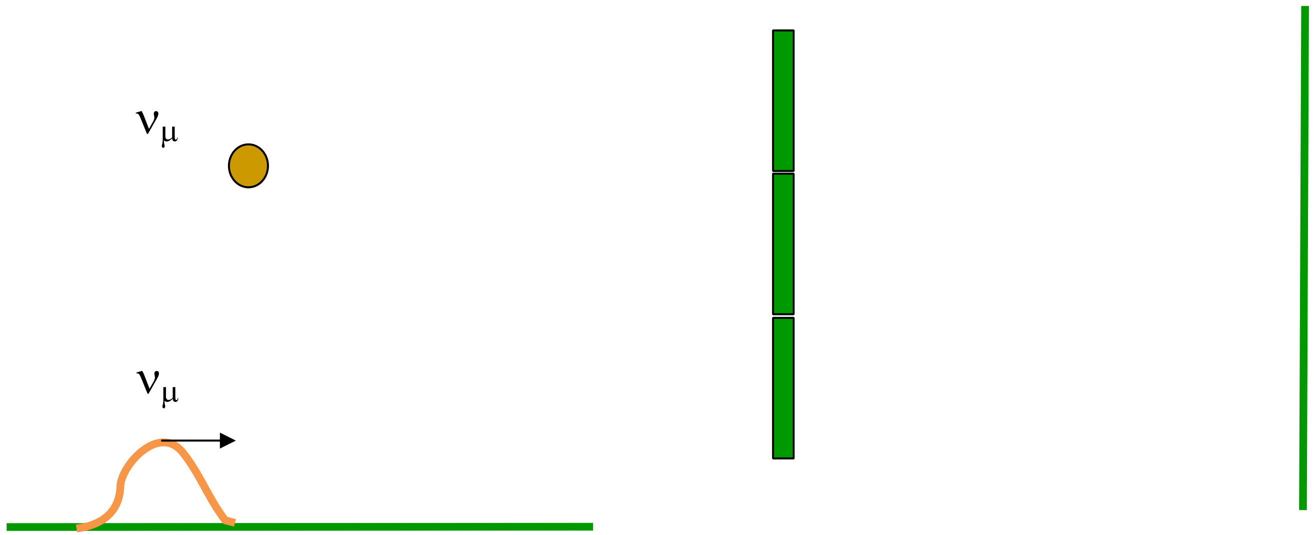
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

1. Neutrino oscillations

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



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

1. Neutrino oscillations

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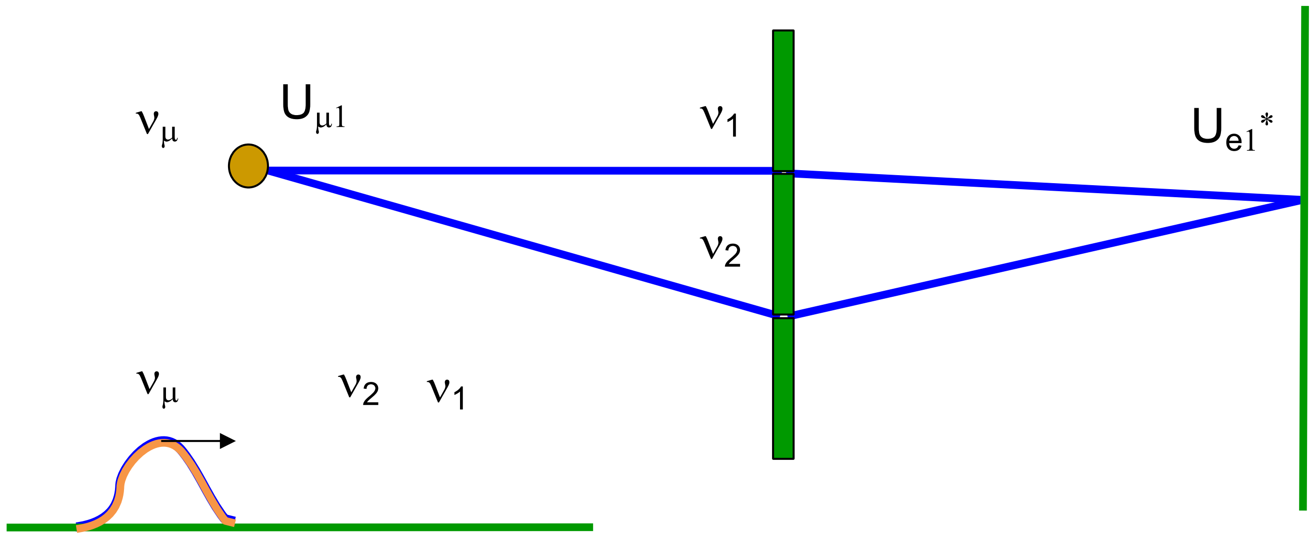

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

1. Neutrino oscillations

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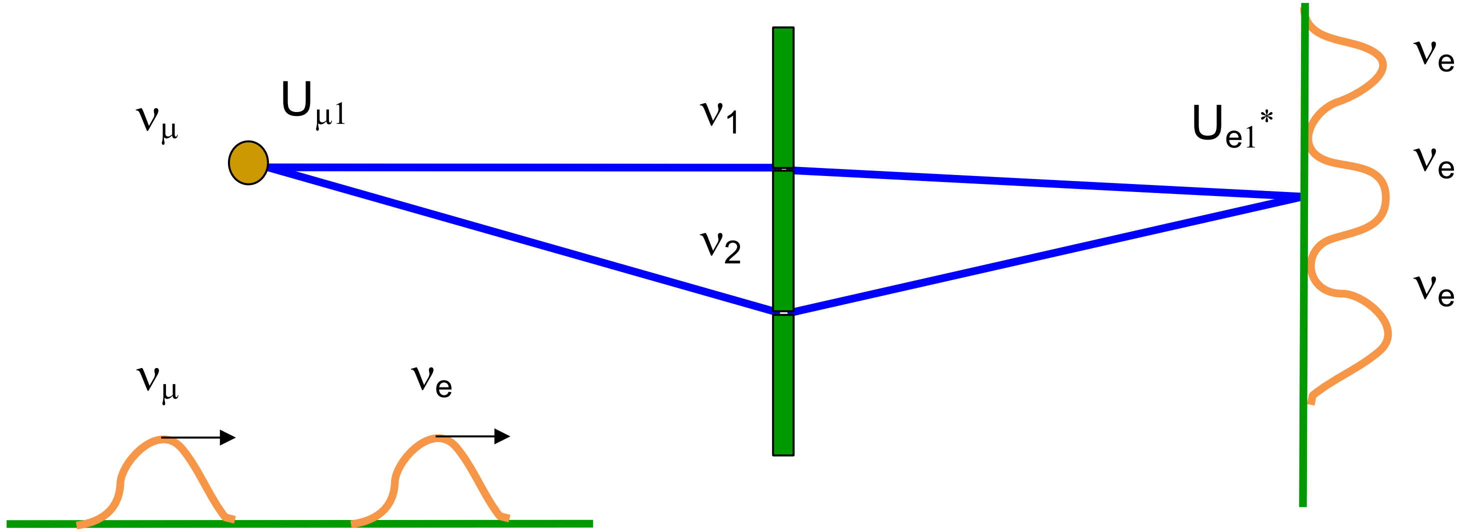

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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The detection may be different flavor (neutrino oscillations).

1. Neutrino oscillations

2 neutrino mixing

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

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

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

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

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

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

1. Neutrino oscillations

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

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

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

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

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

After adjusting the unit

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

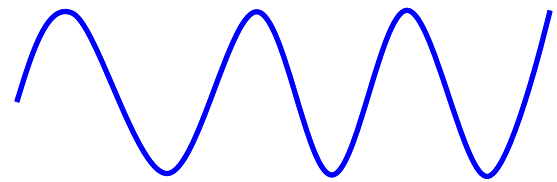
Kayser,PRD24(1981)110

1. Neutrino oscillations

Wave packet formalism

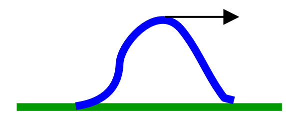
- real formulation of neutrino oscillations

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



$$\downarrow$$

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



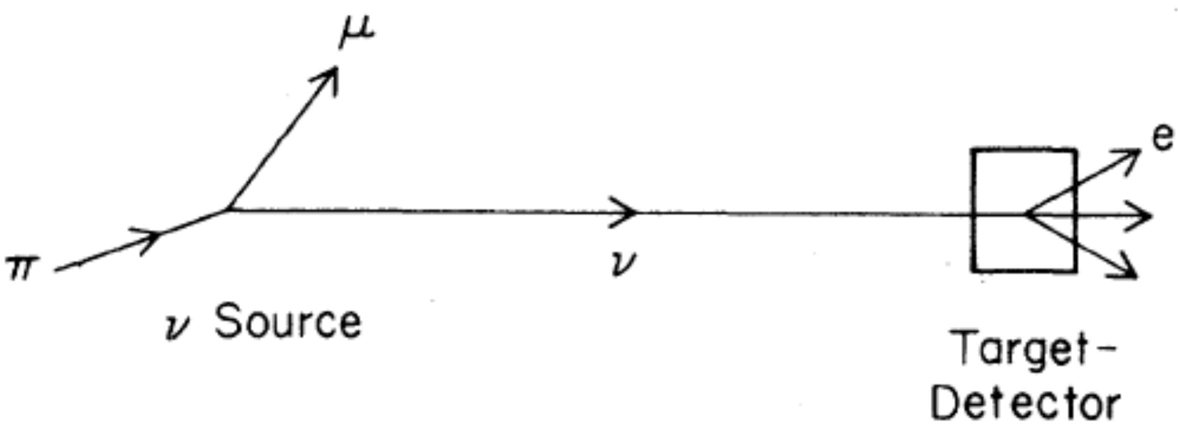


FIG. 1. A typical neutrino-oscillation experiment.

1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{osc}_{ij}} - \left(\frac{L}{L^{coh}_{ij}} \right)^2 - 4\pi^2 \left(\frac{\sigma_x}{L^{osc}_{ij}} \right)^2 \right]$$

Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

Giunti,Kim,Lee,PRD44(1991)3635

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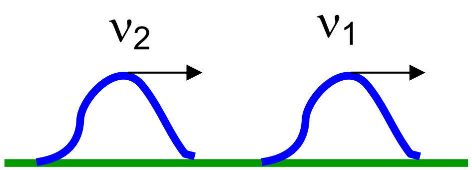
$$\sim \sin^2 2\theta \sin^2 \left(\pi \frac{L}{L^{osc}} \right)$$

1. Neutrino oscillations



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Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

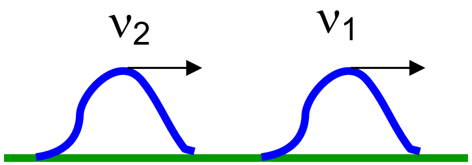
$$P \propto \left[-\left(\frac{L}{L^{coh}}\right)^2\right] \quad , \quad L^{coh} \propto \frac{\sigma_x}{|v_i - v_j|}$$

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

How to estimate σ_x?

Giunti,Kim,Lee,PRD44(1991)3635
de Gauvea et al, arXiv:2005.032022

1. Neutrino oscillations



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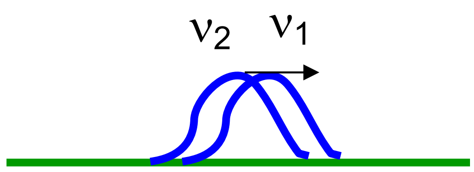
Decoherence happens faster for narrower wave packet (small σ_x) and bigger group velocity difference difference (bigger Δm^2, lower energy)

How to estimate σ_x?
→ controversial subject
Reactor neutrino data interpretation says it is at least bigger than $\sim 10^{-13}$m...

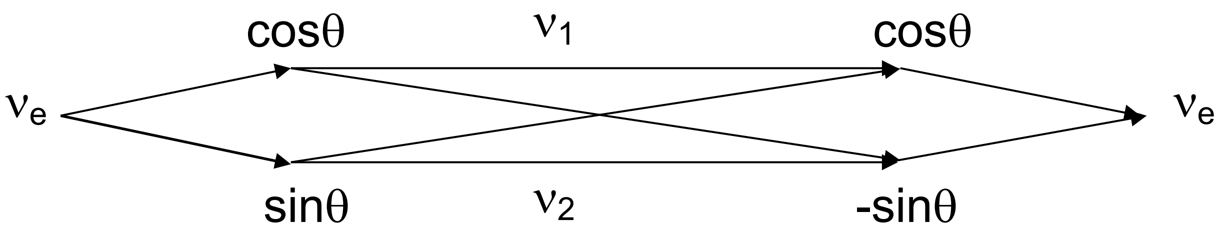
1. Neutrino oscillations



Wave packet formalism

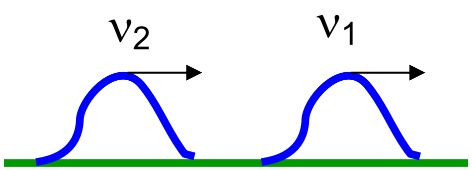
- real formulation of neutrino oscillations

Neutrino oscillation



$P=|A_1+A_2|^2$

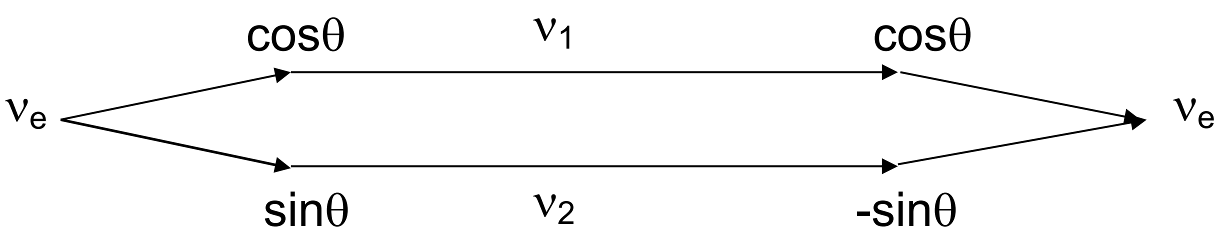
1. Neutrino oscillations



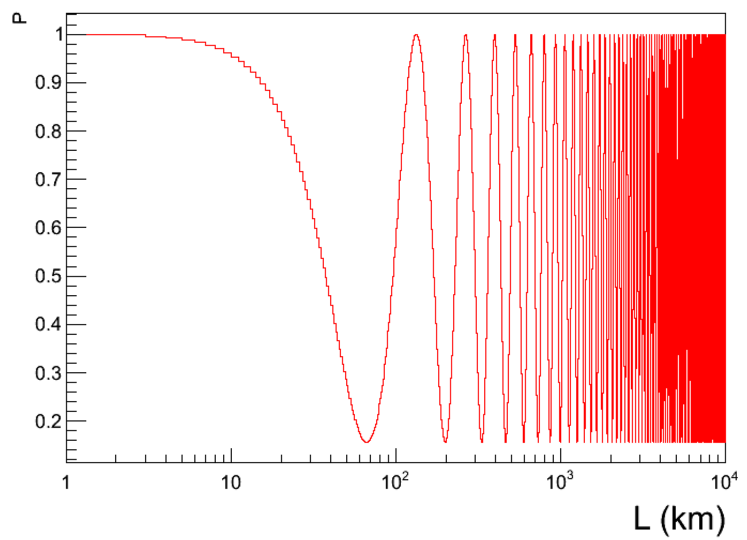
Wave packet formalism

- real formulation of neutrino oscillations

Decoherent neutrino oscillation (time averaged neutrino oscillation)



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



1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

$$P_{\alpha\beta}(L) \propto \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-2\pi i \frac{L}{L^{osc}_{ij}} - \left(\frac{L}{L^{coh}_{ij}} \right)^2 - 4\pi^2 \left(\frac{\sigma_x}{L^{osc}_{ij}} \right)^2 \right]$$

Coherent oscillation

Decoherence during propagation

Decoherence at production and detection

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

If the neutrino production or detection uncertainty is bigger than oscillation length, neutrino oscillation doesn't happen (time averaged oscillation or neutrino mixing). This is the situation of solar neutrinos.

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

1. Neutrino oscillations

Wave packet formalism

- real formulation of neutrino oscillations

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

Beuthe,Phys.Rept.375(2003)105

Five terms:

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

1. Neutrino oscillations with new physics

Neutrino oscillation is interferometer

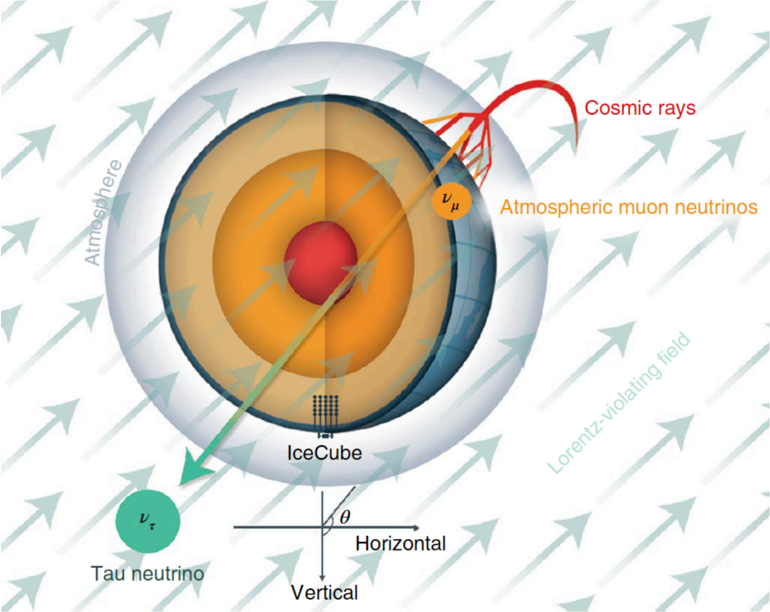
$$H = H_{mass} + H_{matter} + H_{exotic} \rightarrow P_{\alpha\rightarrow\beta} = P_{\alpha\rightarrow\beta}(H_{mass}, H_{matter}, H_{exotic})$$

- tiny effect shifts oscillation (interference pattern) visible amount
- sensitive to new physics search

Search of non-standard interaction with matter
Search of neutrino-light dark matter interaction
Search of neutrino-dark energy interaction
Search of new long-range force
etc

e.g.) Search of violation of Lorentz invariance

- Interferometer arm length ~ 12700km
- Sensitivity goes far beyond Michelson-Morley experiment, or beyond any experiments (optics, atomic physics)



1. Neutrino oscillations

Neutrino oscillation is a natural interferometer

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

Neutrino oscillations are also useful to look for new physics

1. Neutrino oscillations

2. History of neutrino oscillation

3. T2K neutrino oscillation experiments

4. Current and future neutrino experiments

5. Neutrino astronomy

6. Conclusion

2. Before 1998

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

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

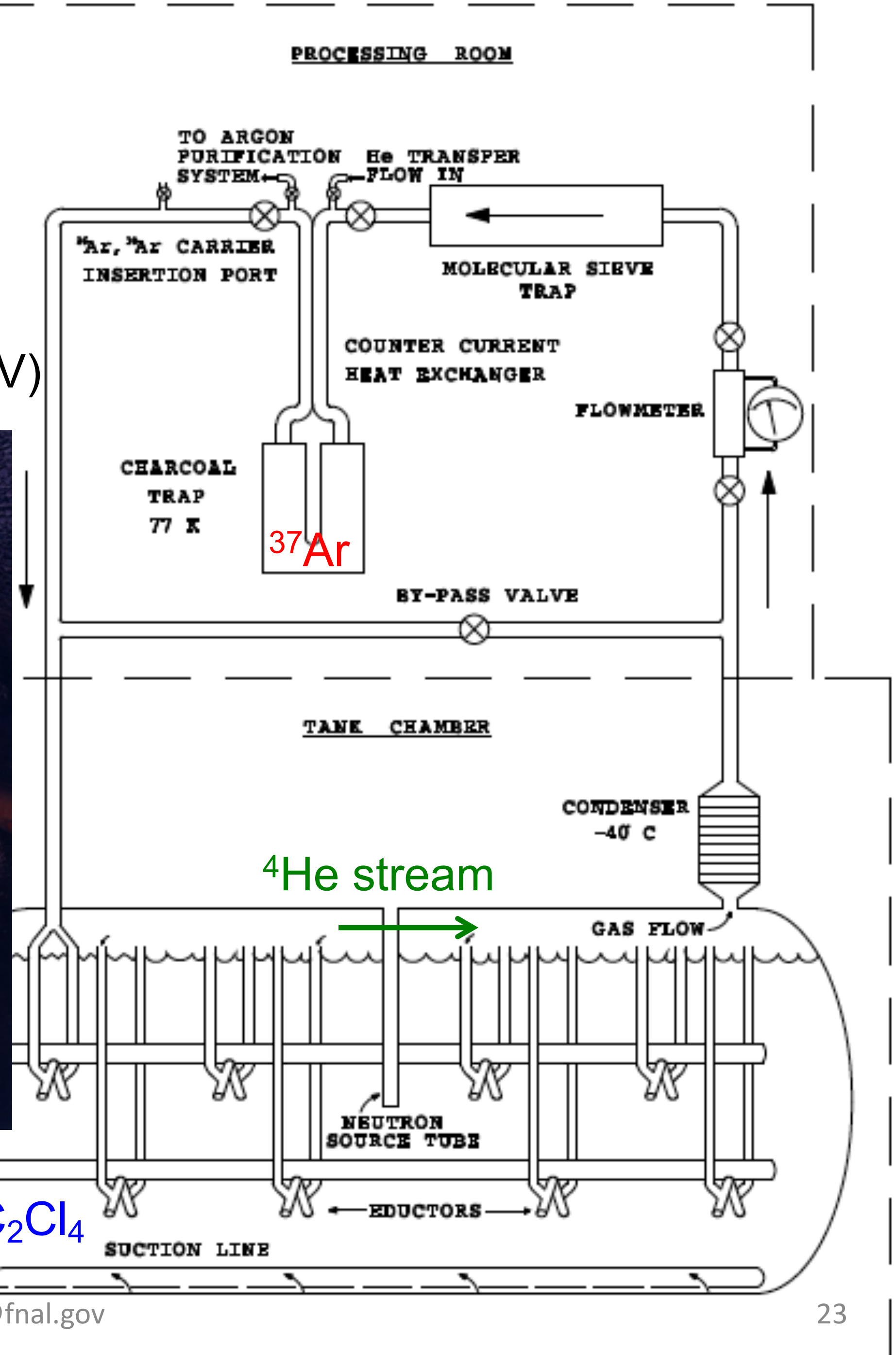
2. Solar neutrino problem

Homestake experiment

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

(proposed by Pontecorvo)

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



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

2. Solar neutrino problem

Homestake experiment

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

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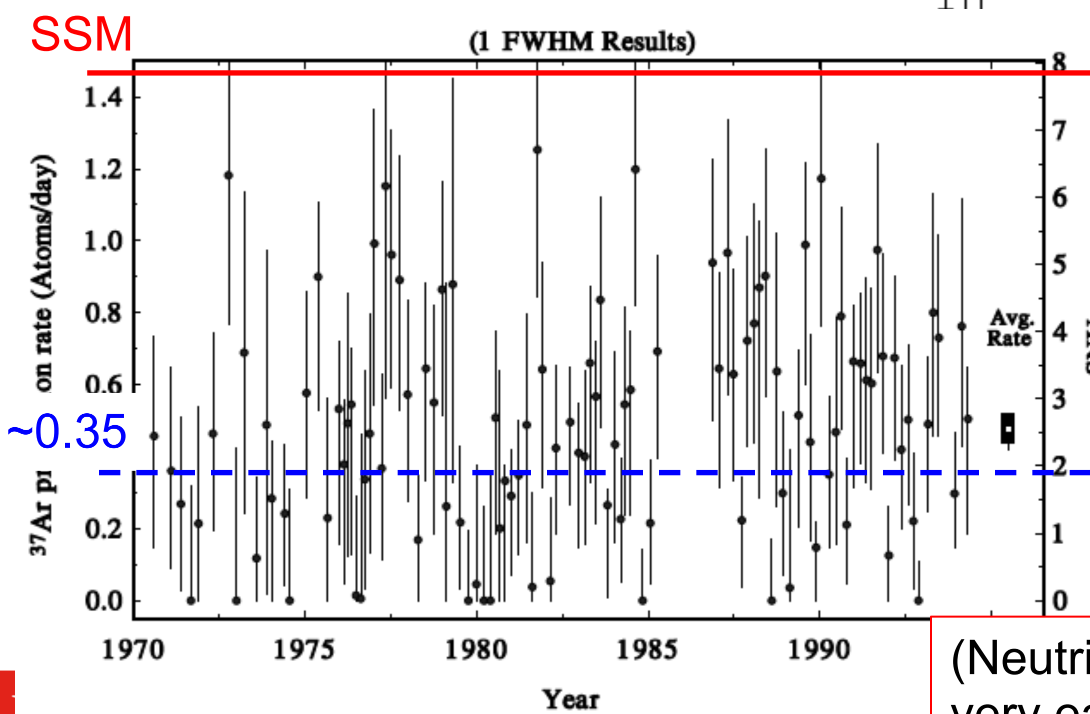
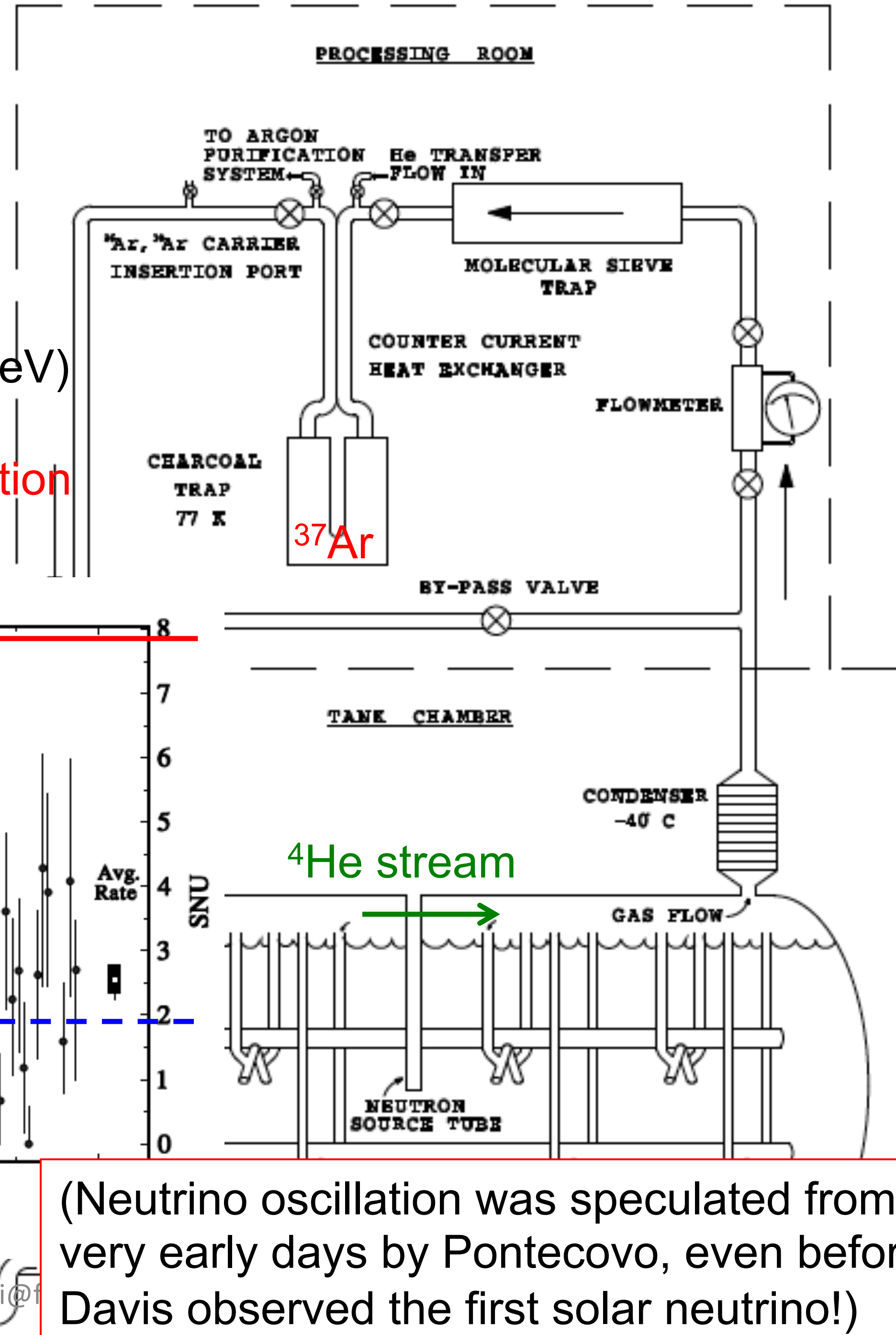
- mainly sensitive to ${}^{8}B$ neutrino (~10 MeV)
- Measured rate was consistently lower than SSM (standard solar model) prediction





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

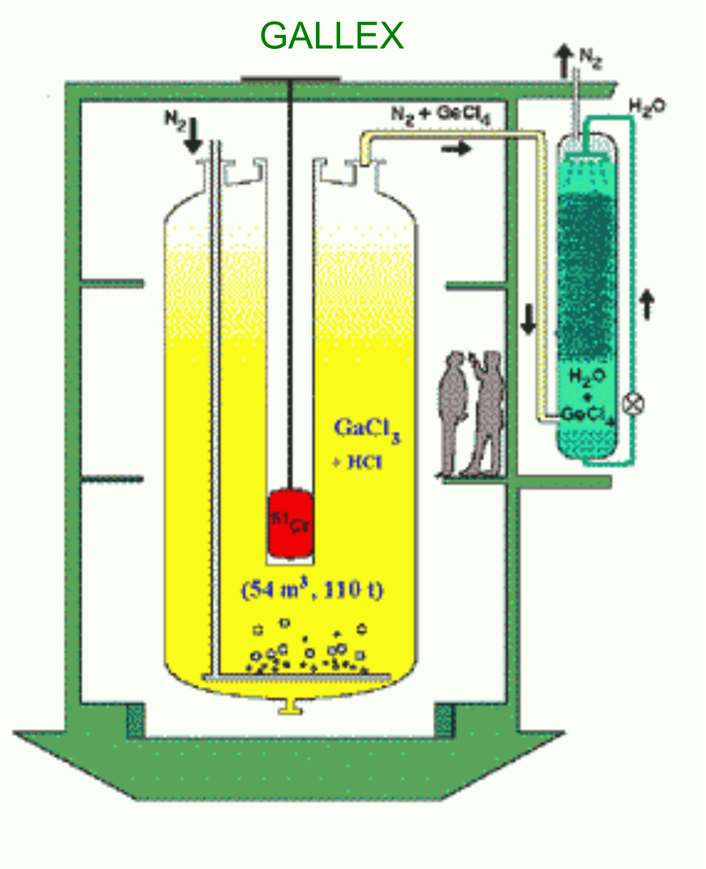
GALLEX, PLB490(2000)16
SAGE, J.Expt.Theor.Phys.95(2002)181

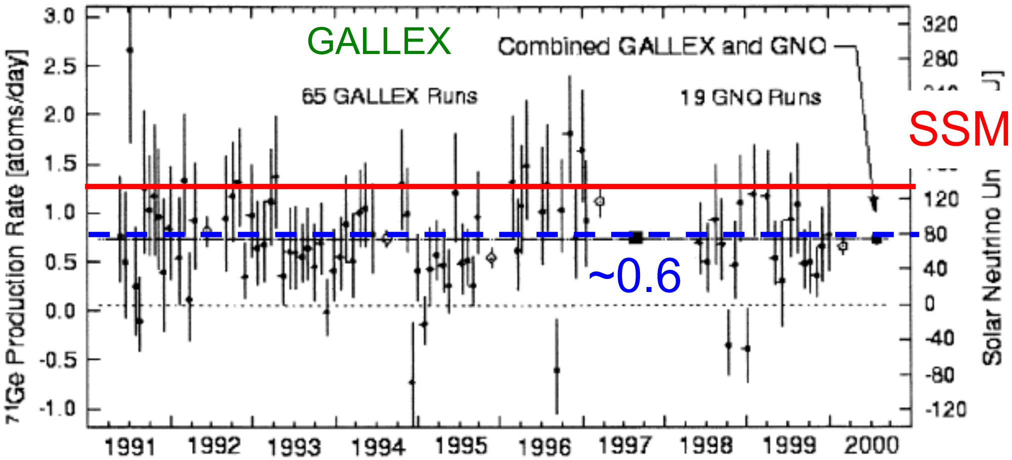
2. Solar neutrino problem

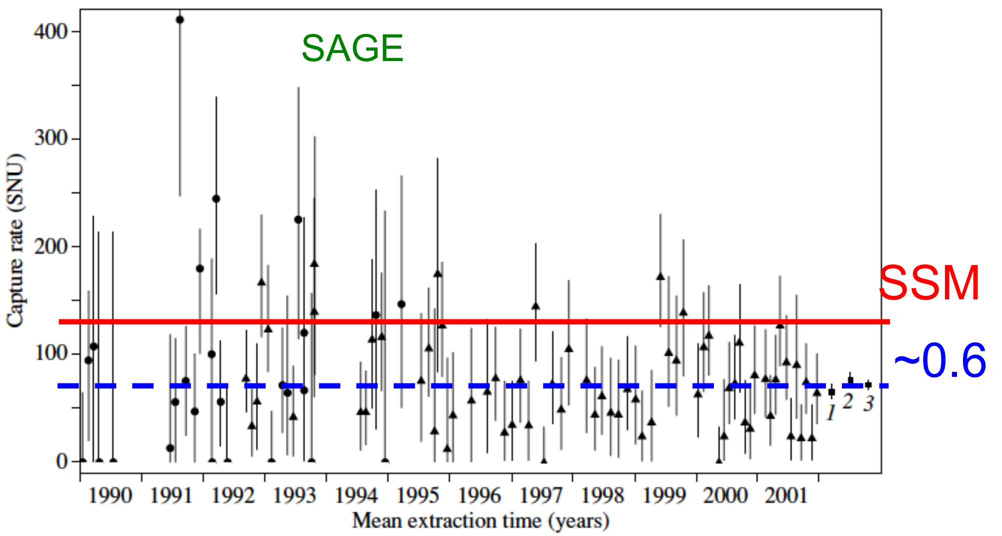
Gallium experiment

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

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







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

2. MSW effect

Neutrino oscillation in vacuum

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

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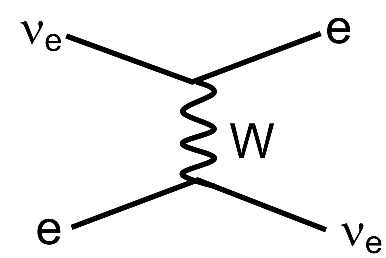

Neutrino oscillation in matter

- Neutrinos interact with media
- Only electron neutrino exchange W

Wolfenstein term

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

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

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

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

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

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

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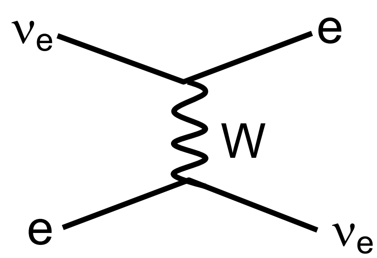

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Both θ_m and $(m^2)'$ are function of n_e and E
- no matter effect If density and/or energy is too low
- the Sun happens to have n_e~150 cm^{-3} and $E(^8B\text{-}\nu)$~10 MeV

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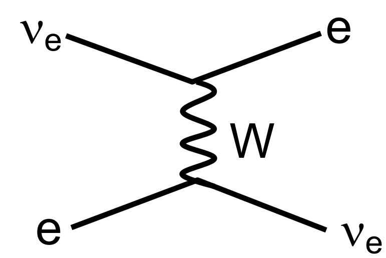
2. MSW effect



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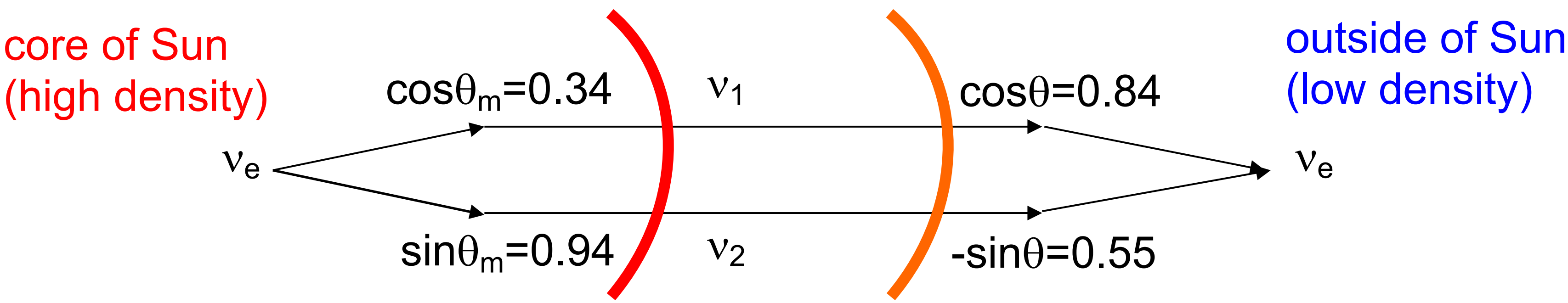


$P=|A_1|^2+|A_2|^2 = \cos^2\theta_m \cdot \cos^2\theta + \sin^2\theta_m \cdot \sin^2\theta < \cos^4\theta + \sin^4\theta$

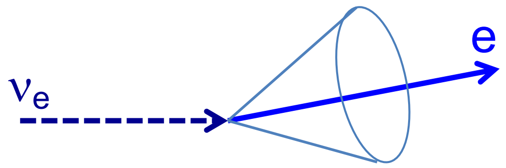
~0.35 (MSW) ~0.6 (no MSW)

2. Kamiokande II experiment

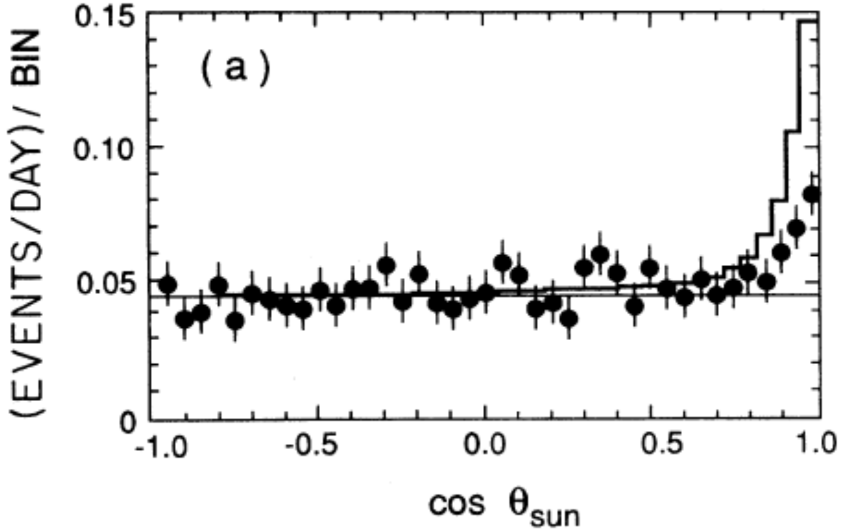
Solar neutrino

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

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



solar-ν angular distribution



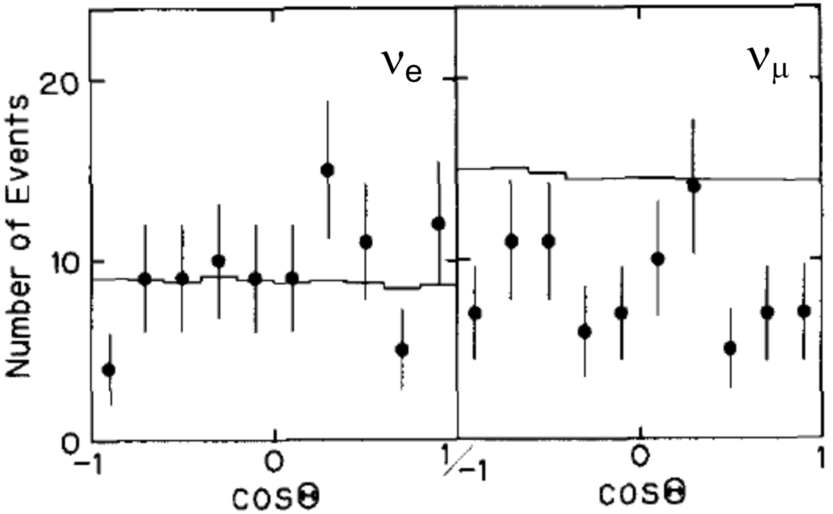
Atmospheric neutrino

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

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

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

atmospheric neutrinos



Supernova neutrino

- 12 events are observed (IMB observed 8 events)

2. Before 1998

There are 3 major discoveries

- Solar neutrino anomaly

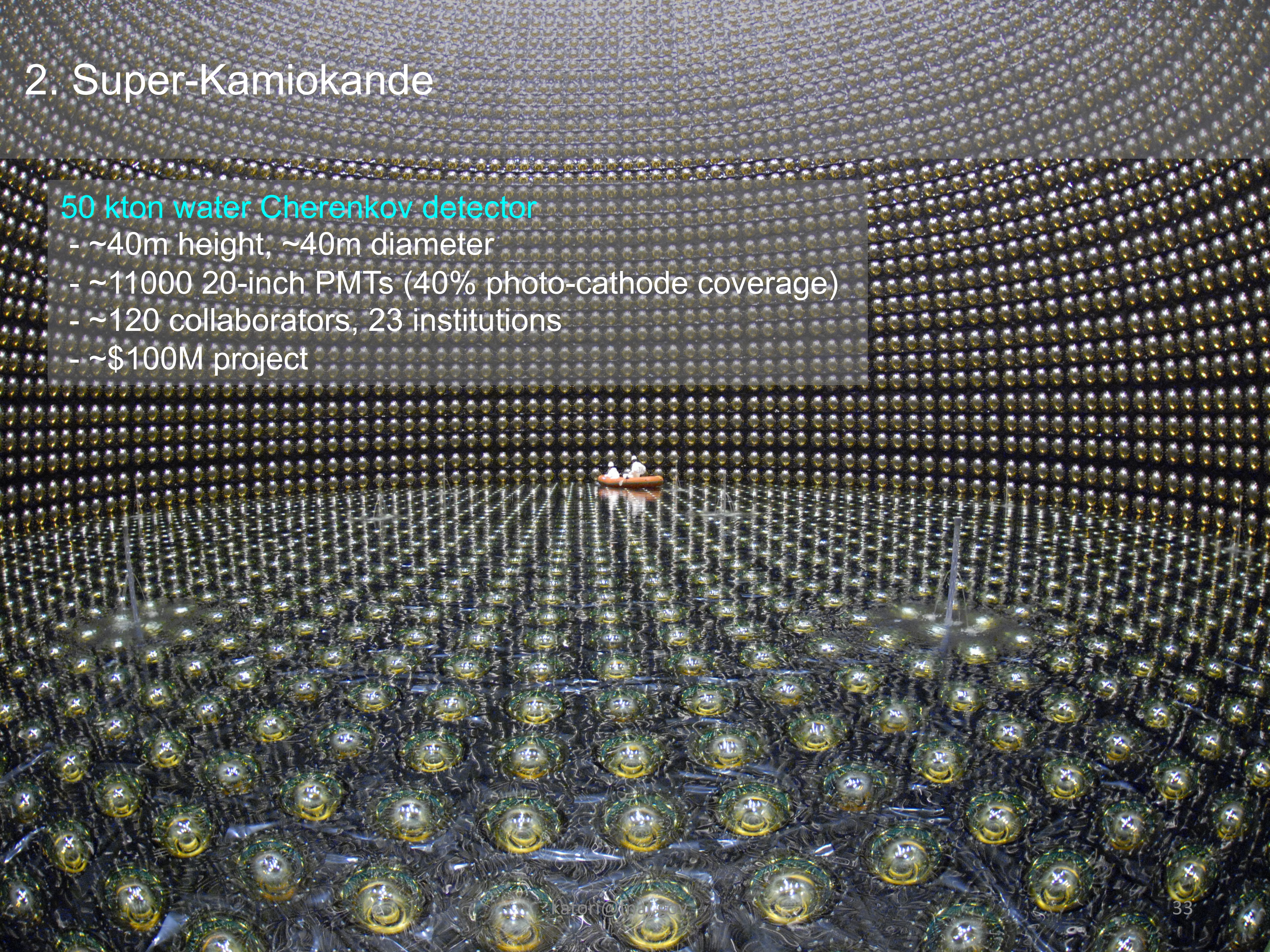
- MSW effect

- Atmospheric neutrino anomaly

2. 1998-2004

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

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

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50 kton water Cherenkov detector
- ~40m height, ~40m diameter
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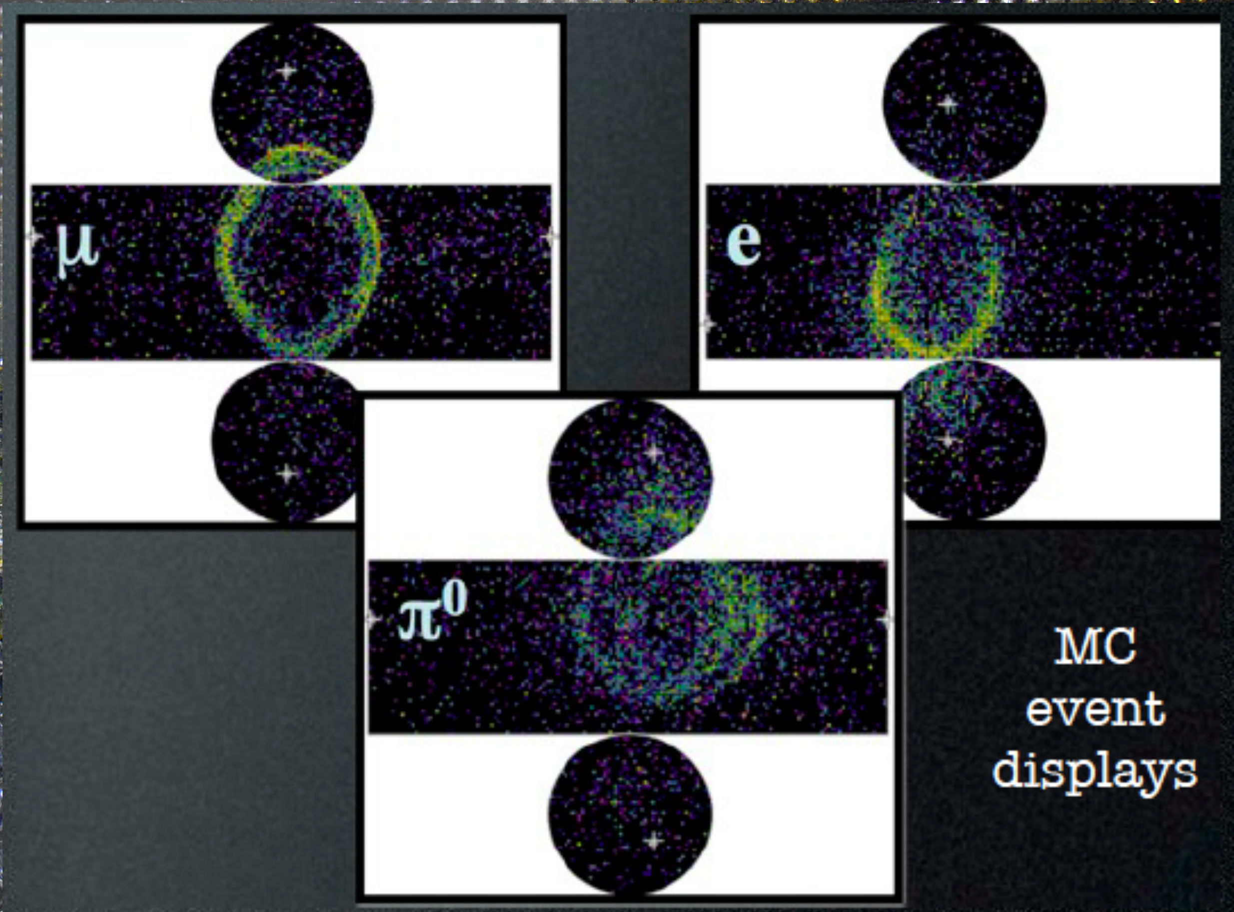
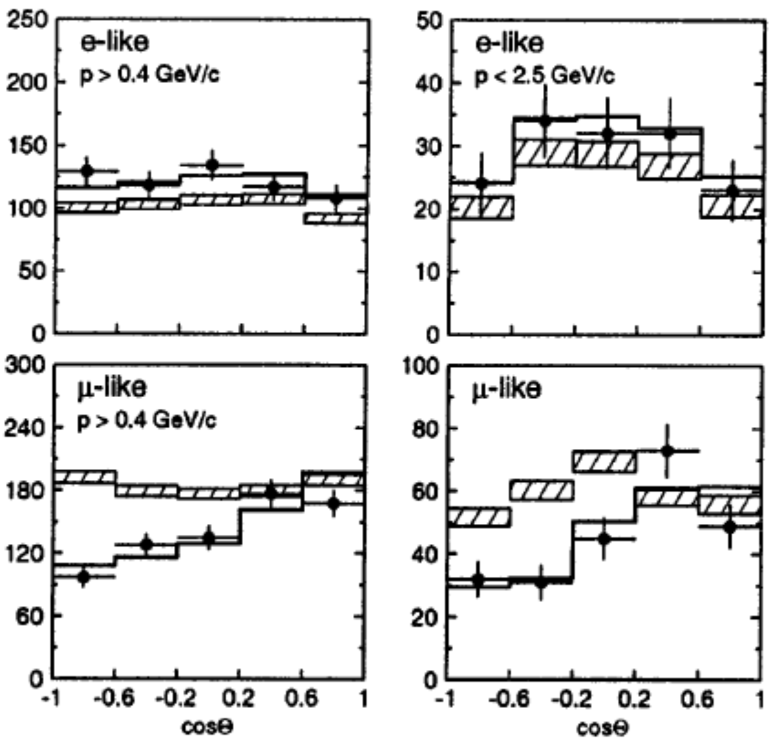
Particle ID
μ : sharp ring
e : fuzzy ring
π^o : 2 fuzzy rings



2. Super-Kamiokande

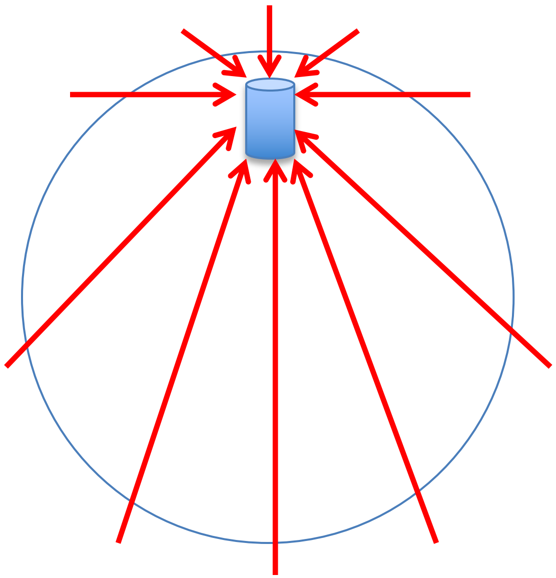
Up-Down asymmetry

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



$$p + X \rightarrow X' + \pi \begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \end{cases}$$

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)$$

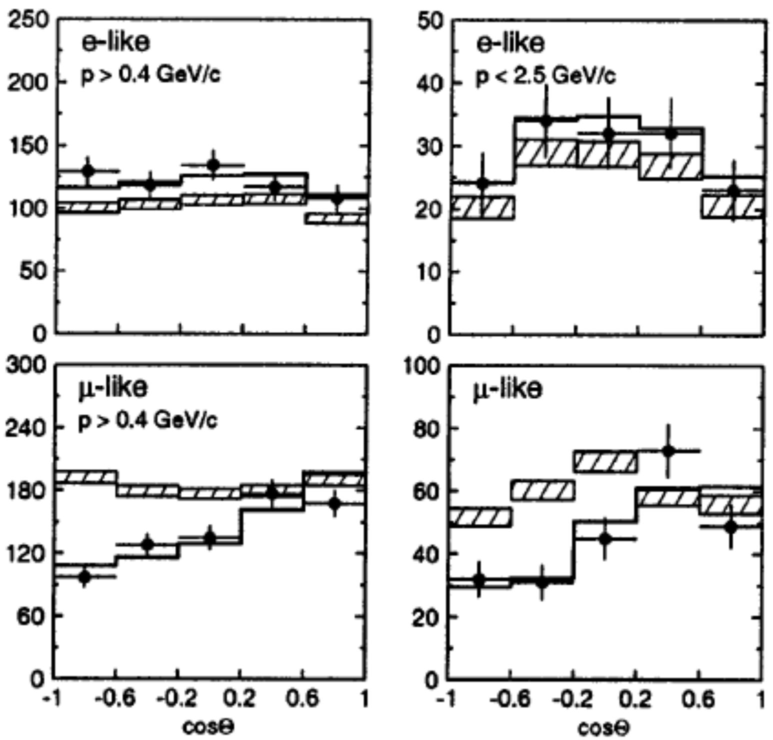


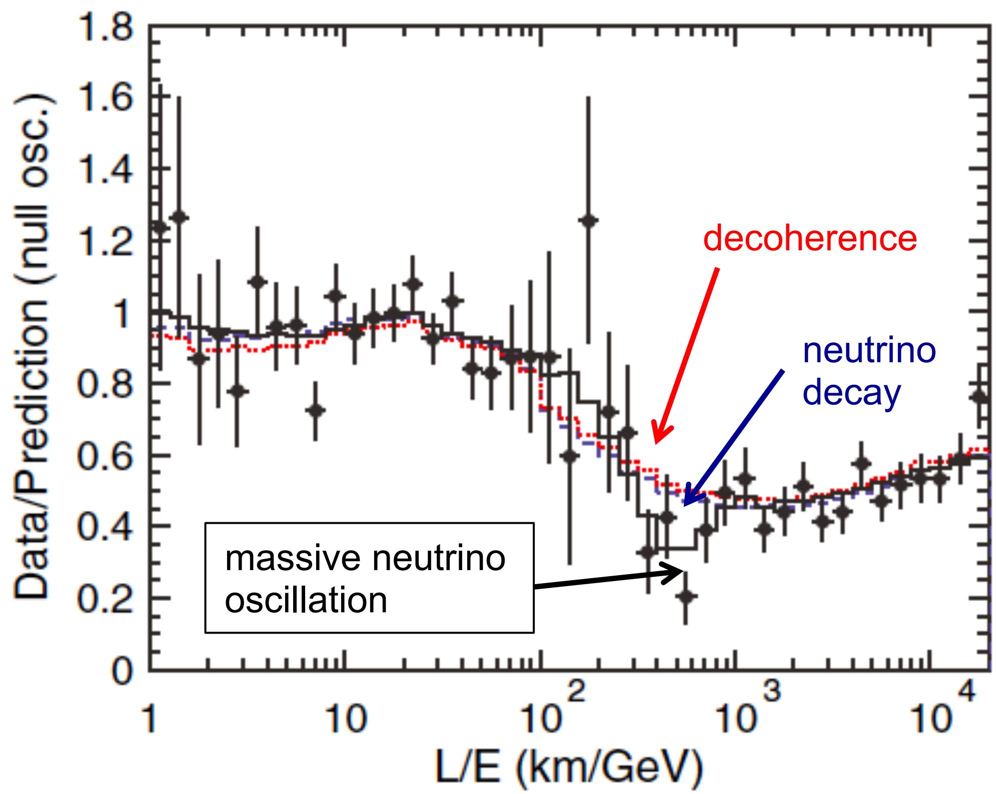
Super-kamiokande, PRL81(1998)1562, PRL93(2004)101801

2. Super-Kamiokande

Up-Down asymmetry

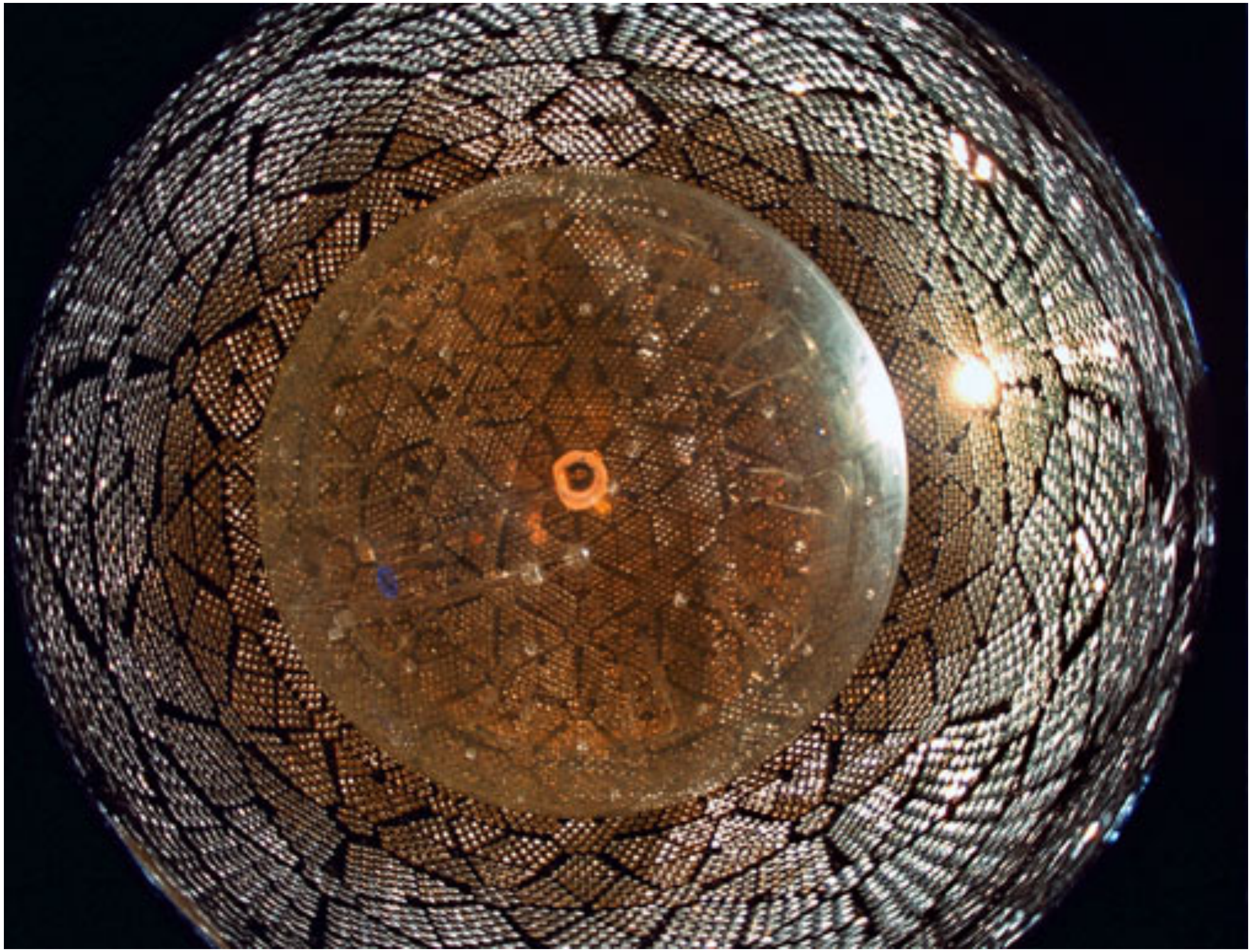
- Atmospheric neutrino anomaly is function of distance
- But neutrinos might just disappear (decayed) or lose coherence (decoherence)
- Later Super-K also shows the first neutrino oscillatory behavior
- Super-K concludes ν-oscillation is the solution of atmospheric neutrino anomaly





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

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2. SNO

D_2O in acrylic vessel
Simultaneously measure 3 channels
- SNO concludes neutrino oscillation is the solution of solar neutrino problem

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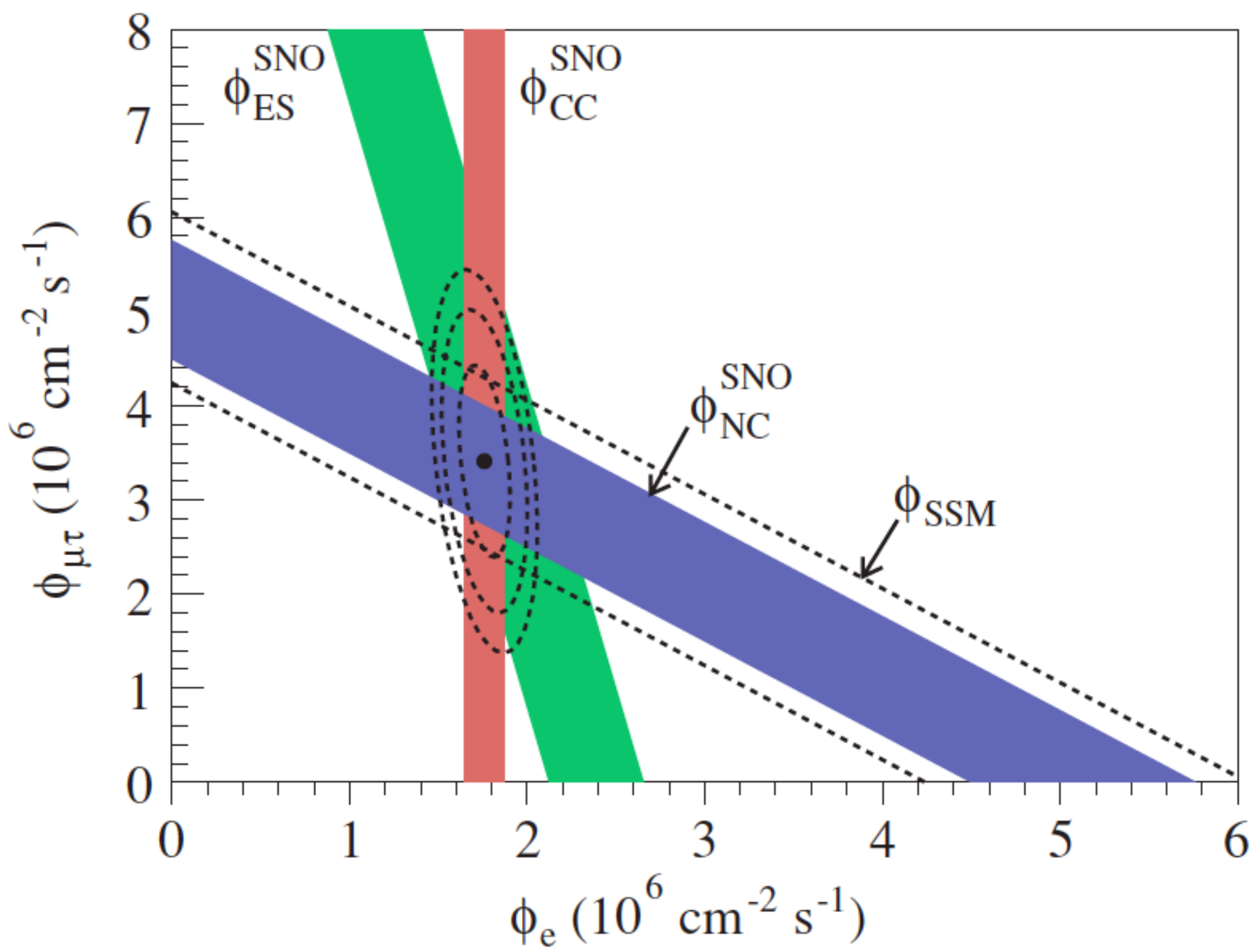
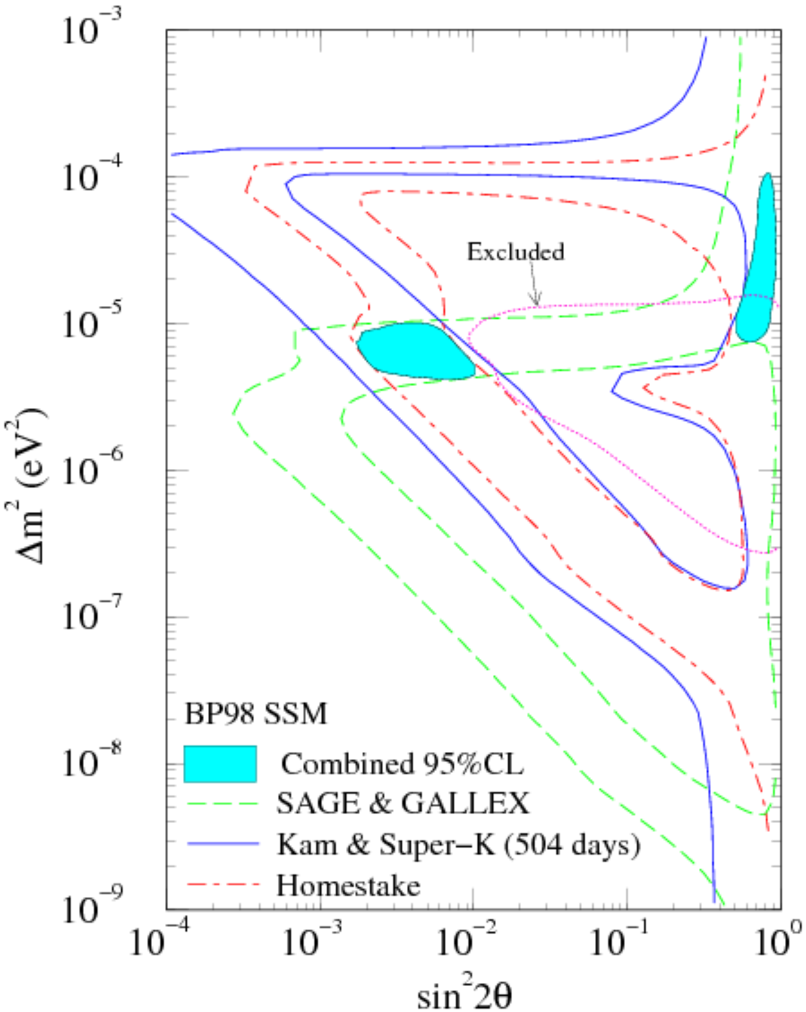


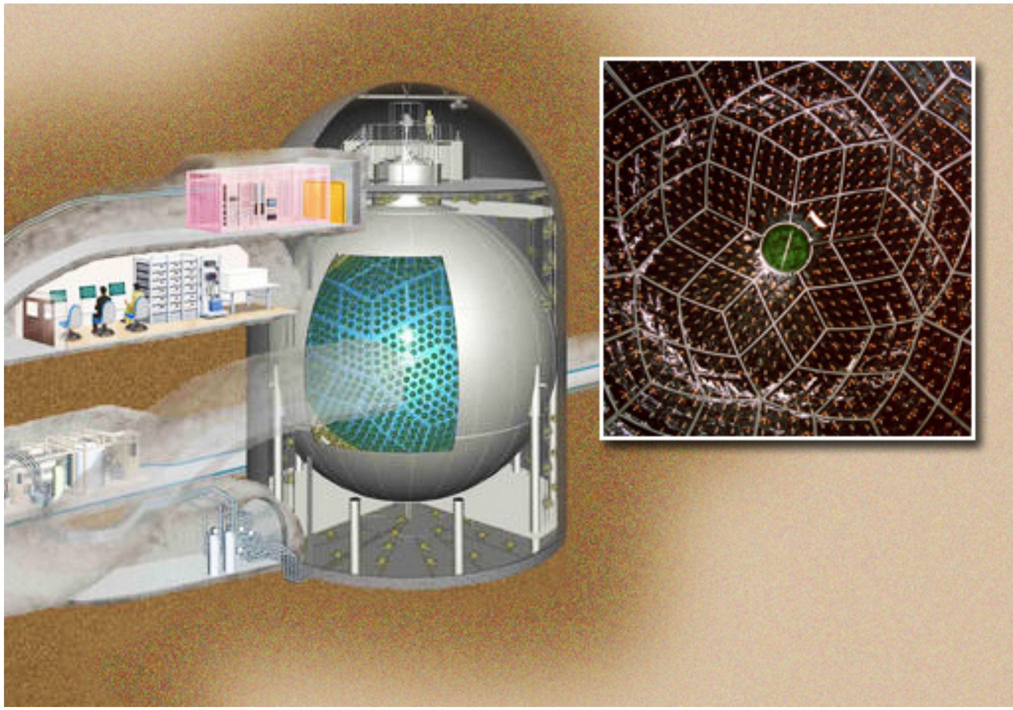
2. KamLAND

Liquid scintillator detector

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

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





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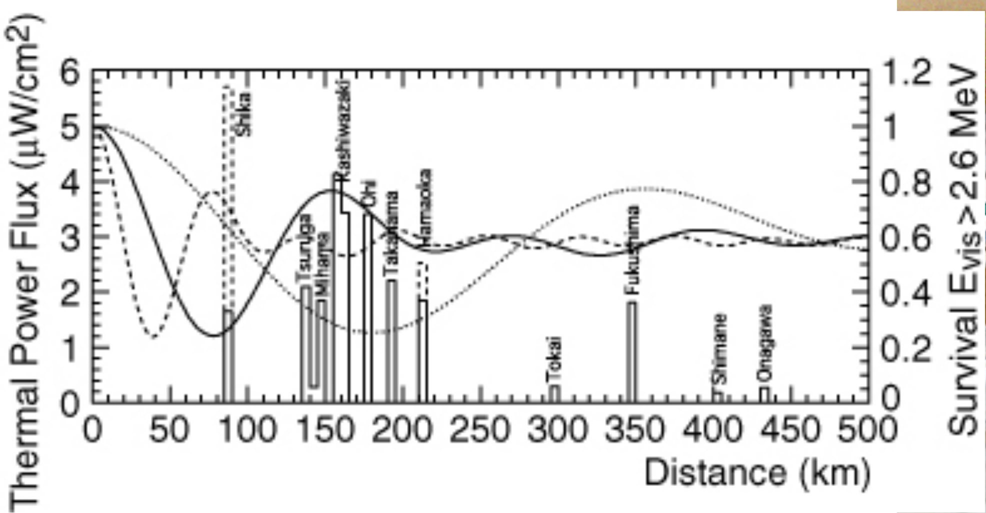

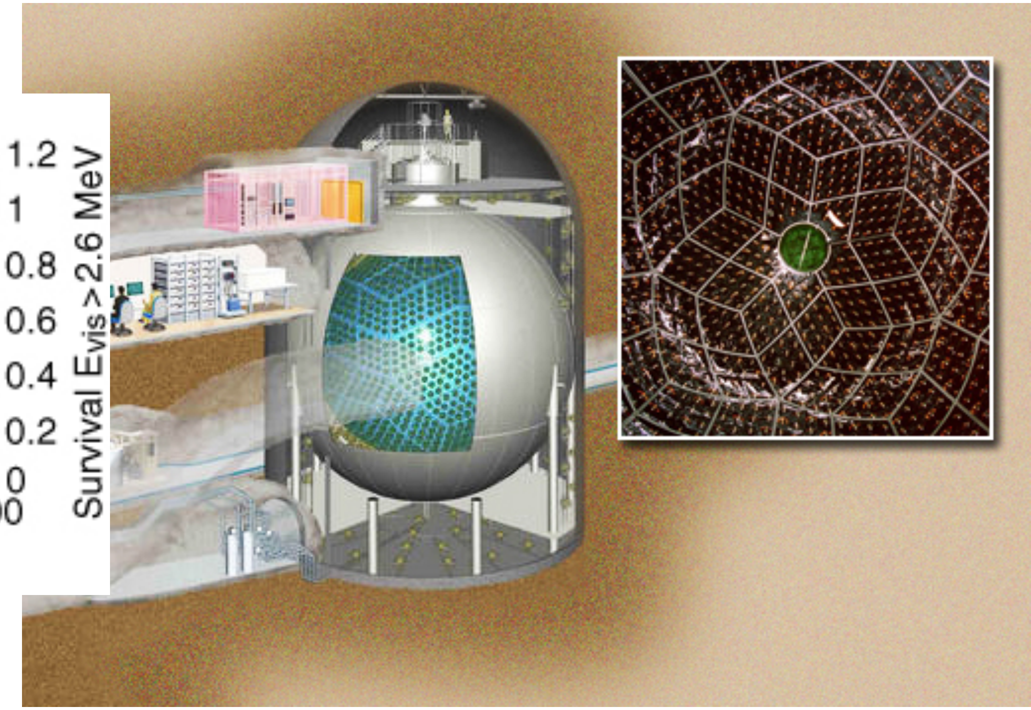

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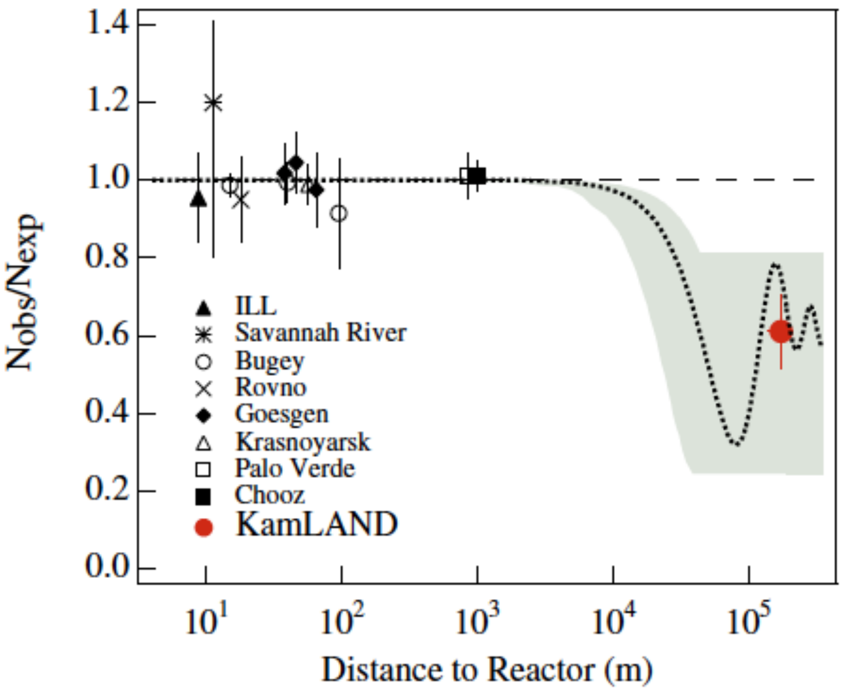
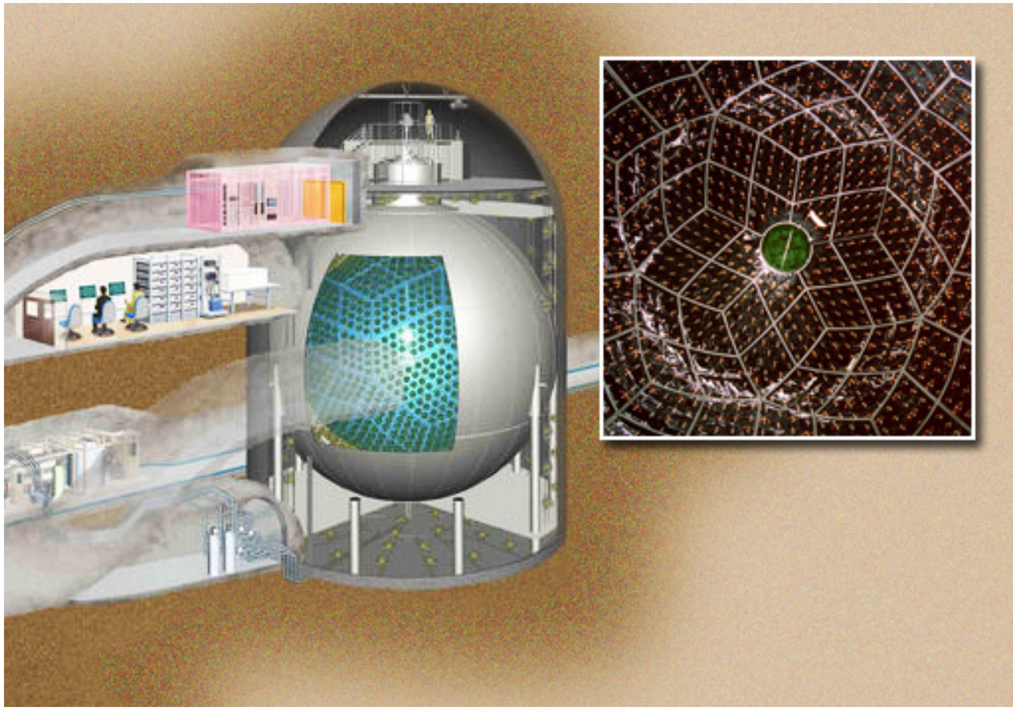
- Solar neutrino parameters are fixed





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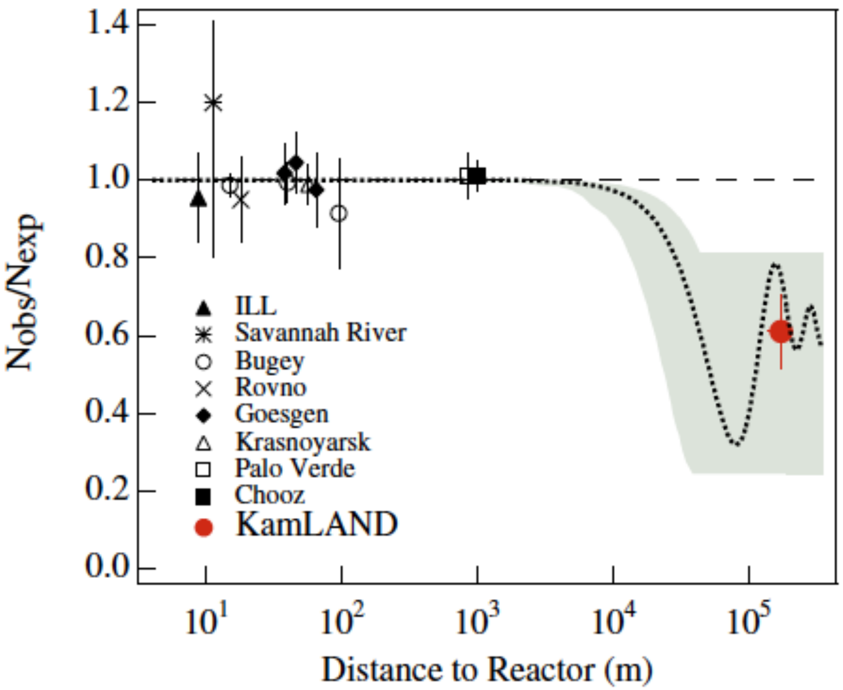

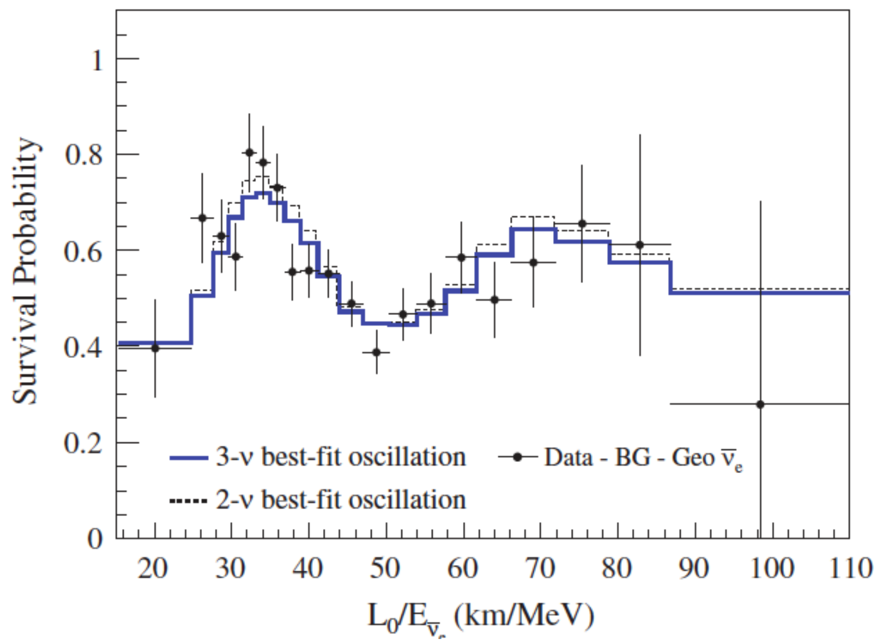

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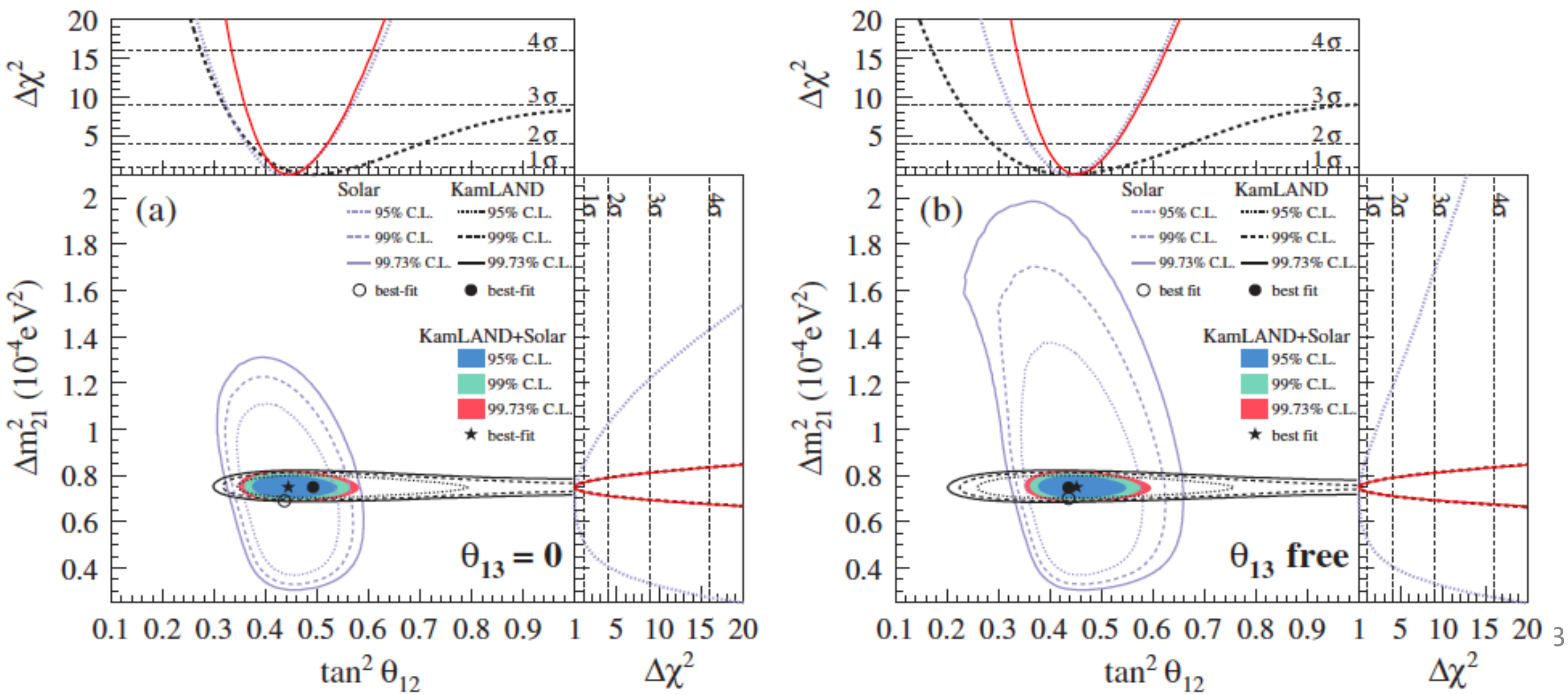
- First evidence of reactor neutrino oscillations
- Solar neutrino parameters are fixed
- Result shows nice oscillatory shape
- Nonzero θ_{13} makes agreement with solar data better...



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
- Models to explain atmospheric neutrino anomaly are mostly dead (neutrino decay, neutrino decoherence, Lorentz violation, etc)
- Models to explain solar neutrino anomaly are mostly dead (large neutrino magnetic moment, etc)
- It was the biggest genocide time for phenomenologists. These days phenomenologists look for second order effects in data

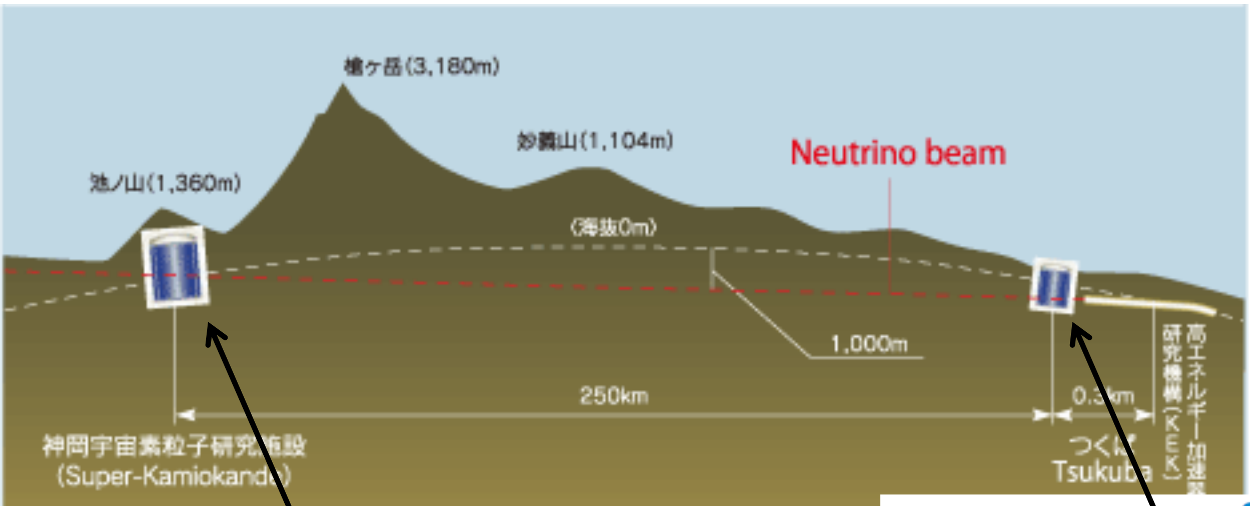
2. 2005-2011

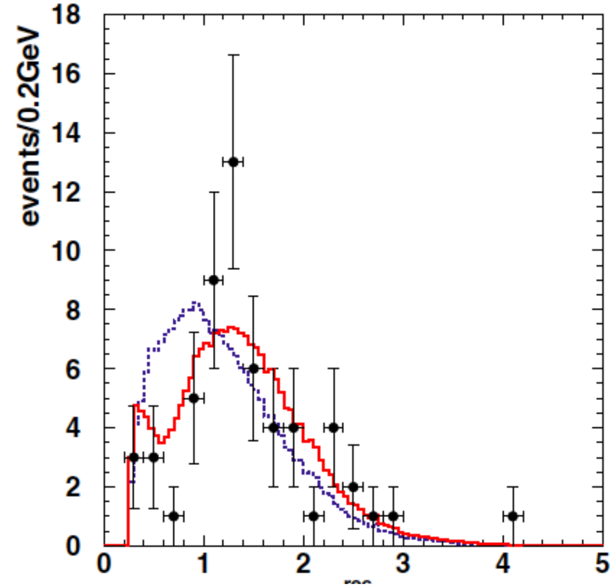
	2005	2006	2007	2008	2009	2010	2011	2012	2013
solar neutrino				Borexino ^{7}Be neutrino agrees with MSW				Borexino pep neutrino agrees with MSW	
reactor neutrino	KamLAND neutrino oscillatory			Hint of $\theta_{13}>0$				θ_{13} is measured - Double Chooz - Daya Bay - Reno	
atmospheric neutrino		MINOS charge separate atmospheric neutrino oscillation							Super-K ν_τ appearance result
accelerator neutrino	K2K neutrino oscillation agrees with atmospheric neutrino oscillation						MINOS charge separate accelerator neutrino oscillation	T2K ν_e appearance result	

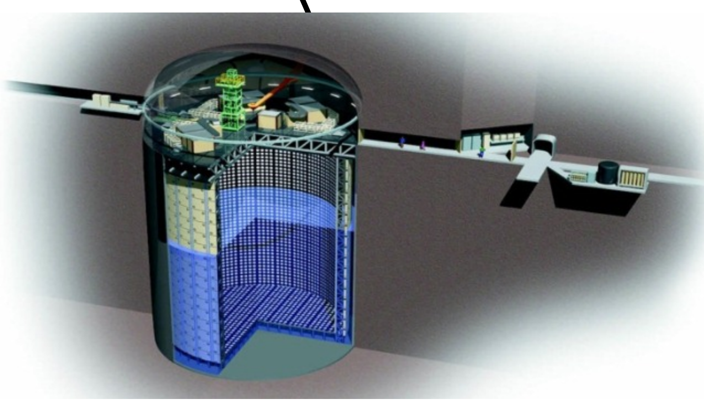
2. K2K experiment

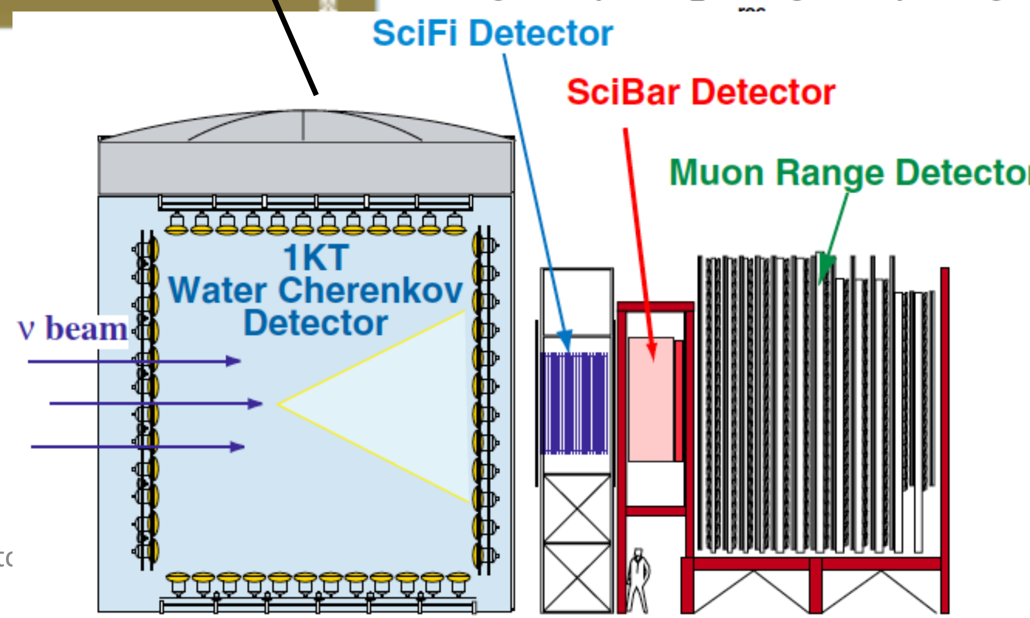
First long baseline neutrino oscillation experiment

- ~1.3GeV muon neutrinos over 250km

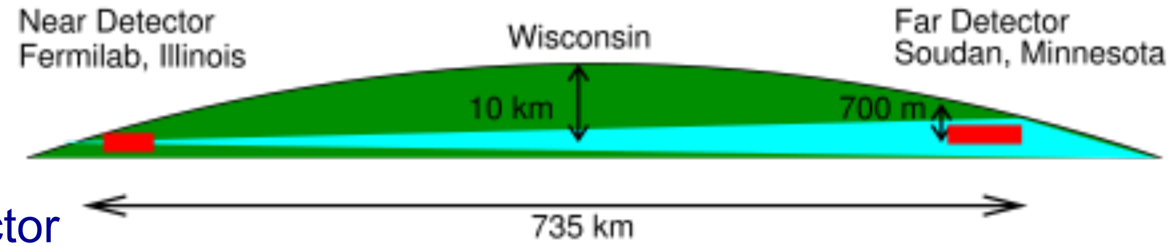








2. MINOS



Magnetized detector

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

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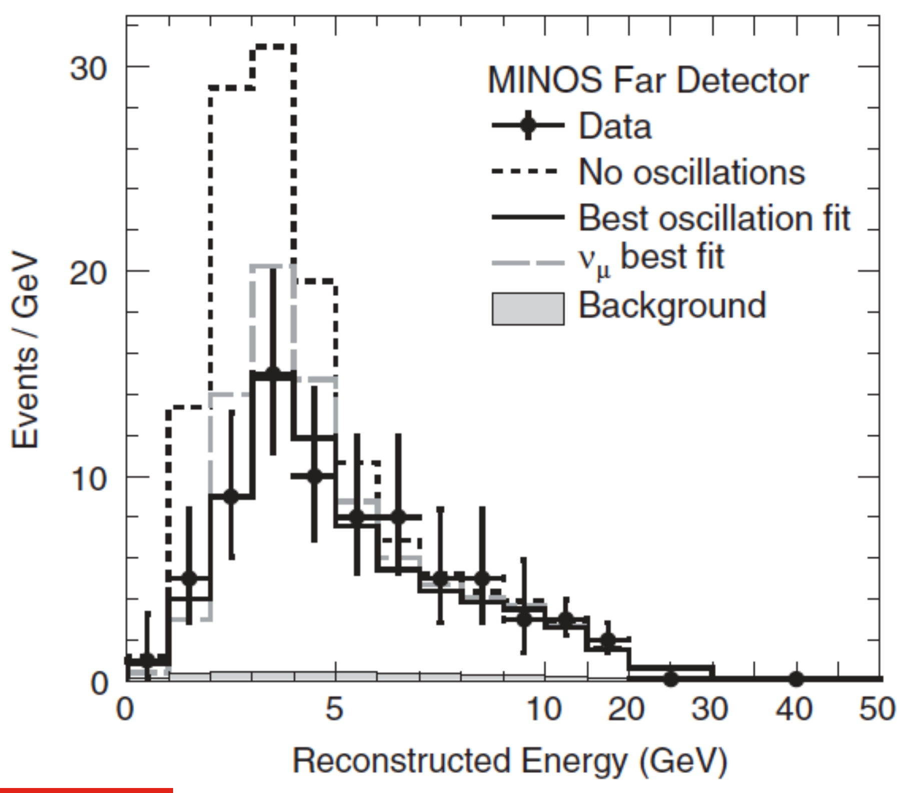
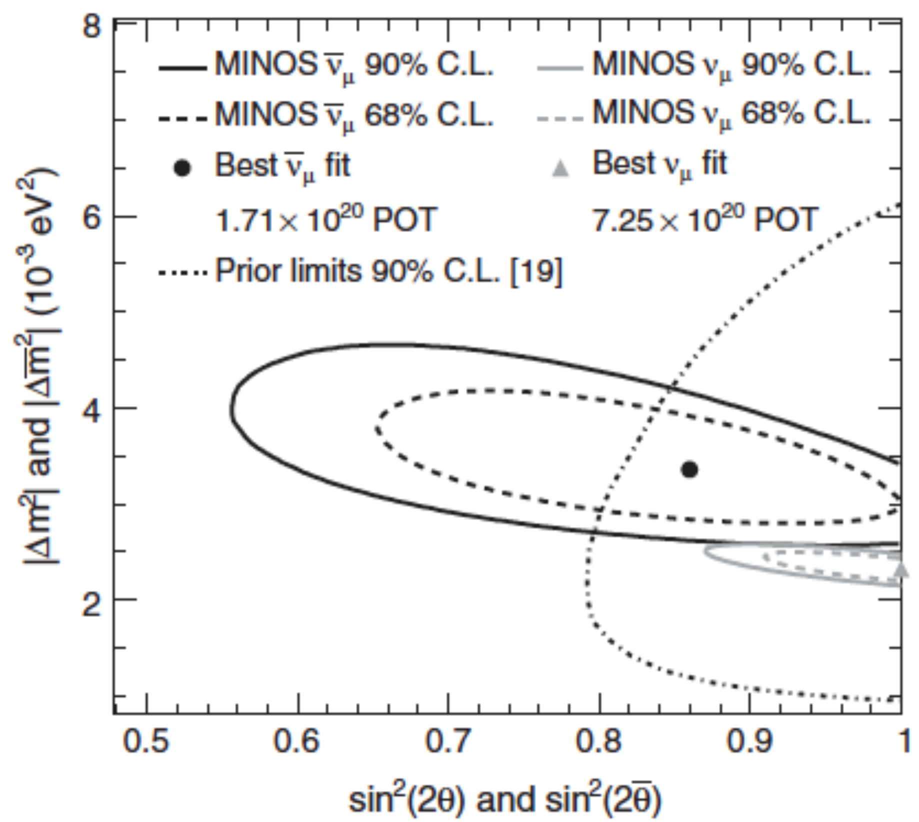
2. MINOS

Magnetized detector

- ~3GeV muon neutrinos and muon anti-neutrinos over 735km
- Due to B-field, neutrino and anti-neutrino interactions are separated
- First direct measurement of anti-neutrino oscillation parameter consistent only 2%



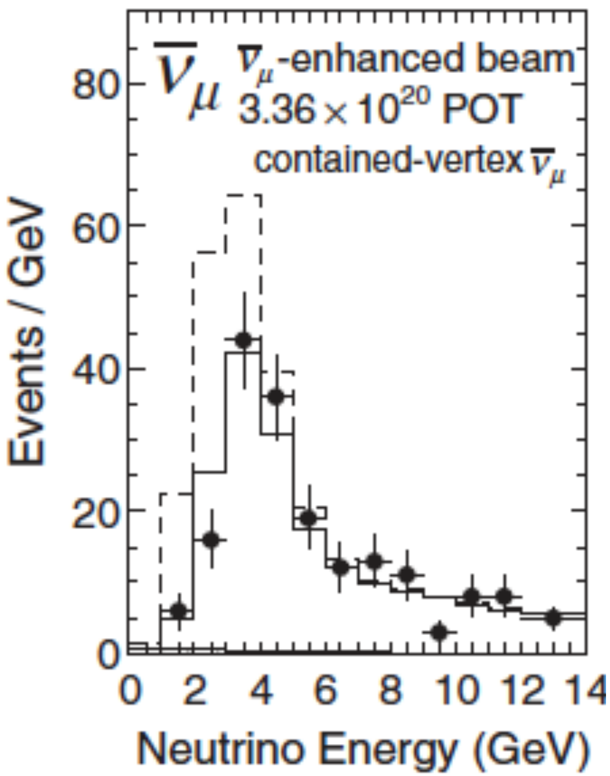


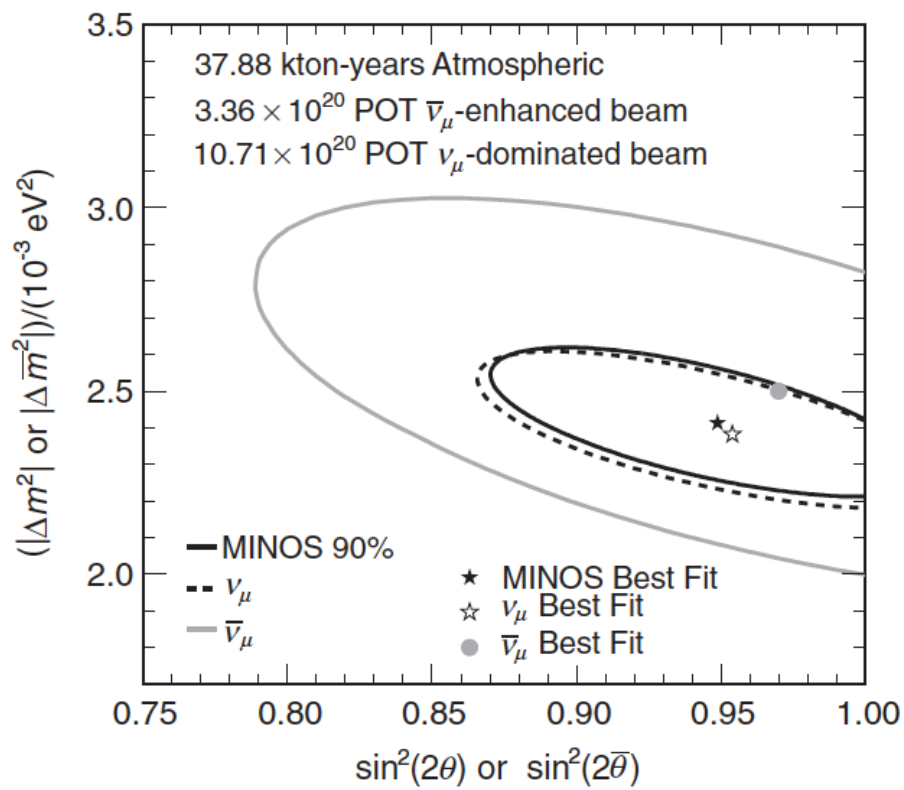
2. MINOS

Magnetized detector

- ~3GeV muon neutrinos and muon anti-neutrinos over 735km
- Due to B-field, neutrino and anti-neutrino interactions are separated
- First direct measurement of anti-neutrino oscillation parameter consistent only 2%
- Final data show no anomalies, neutrino and anti-neutrino data are consistent

(one and only one neutrino oscillation experiment with magnetized far detector)



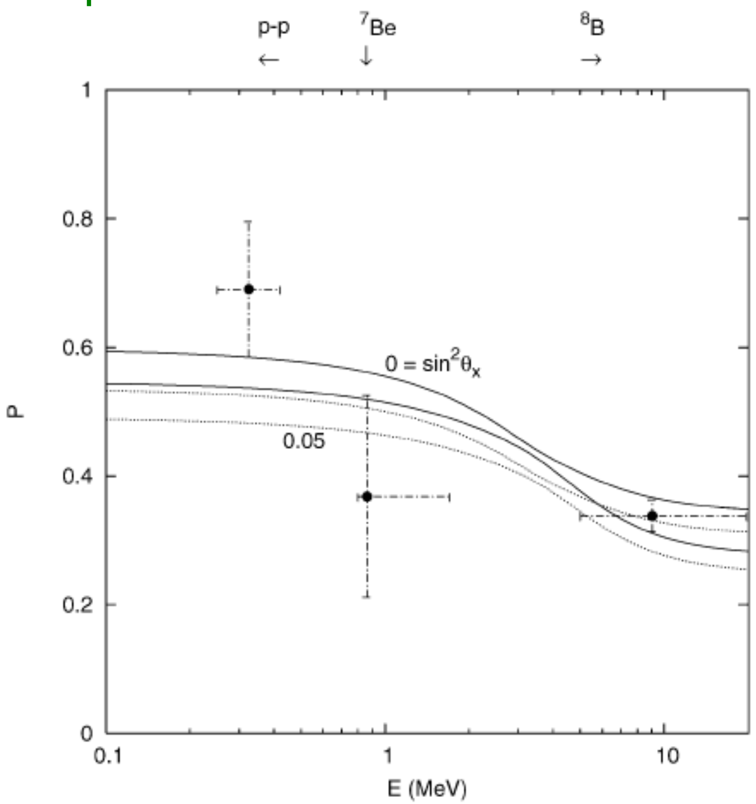


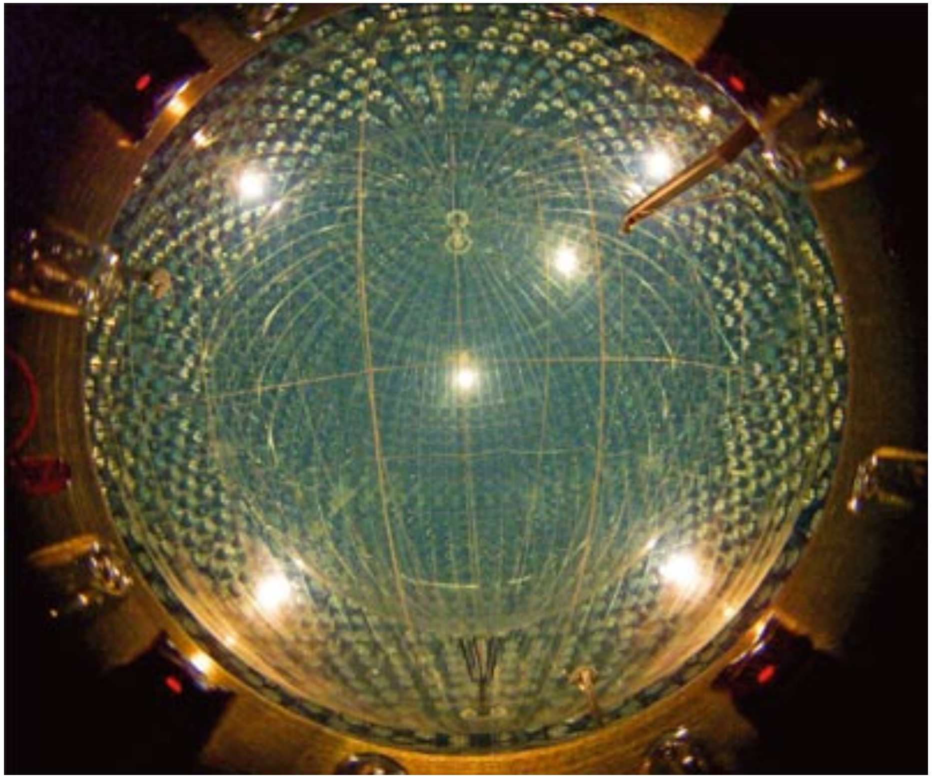
2. Borexino

^{7}Be 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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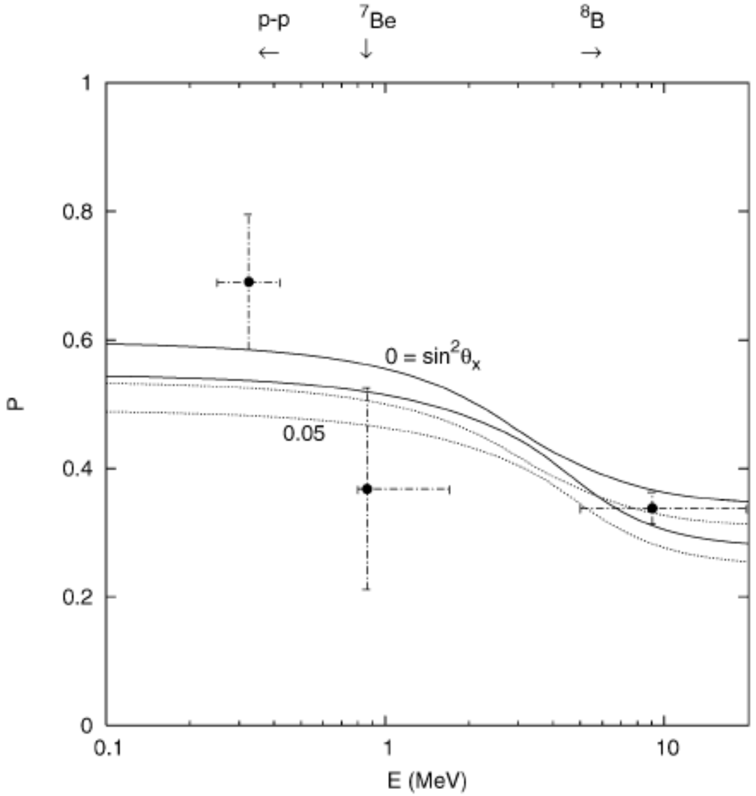
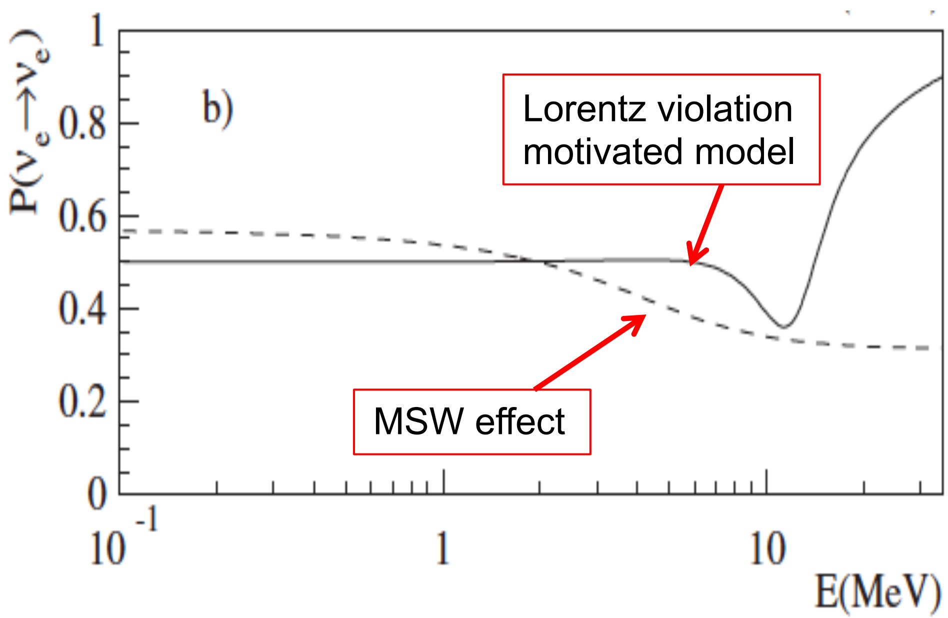
pre-Borexino world solar-ν data





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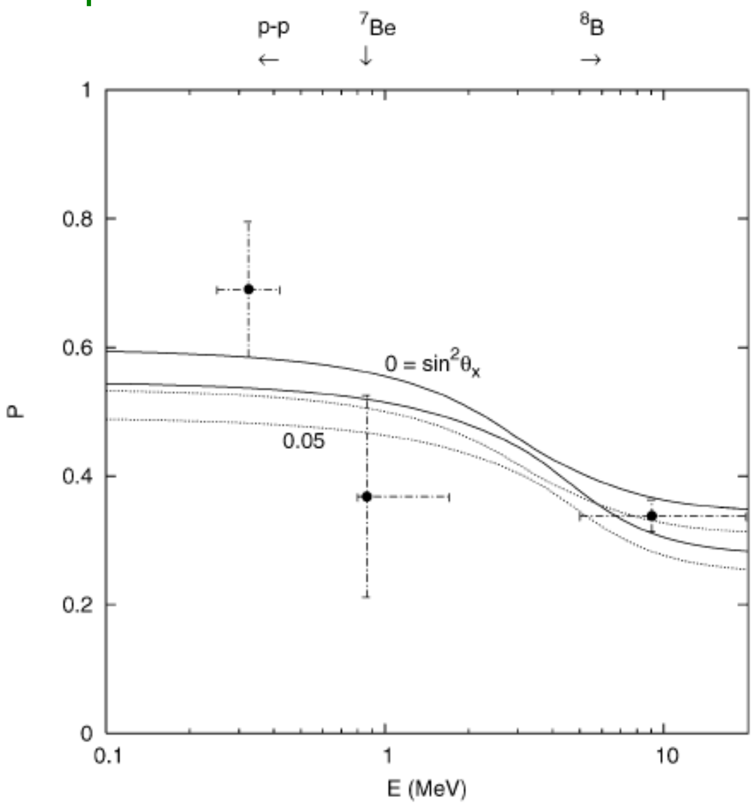
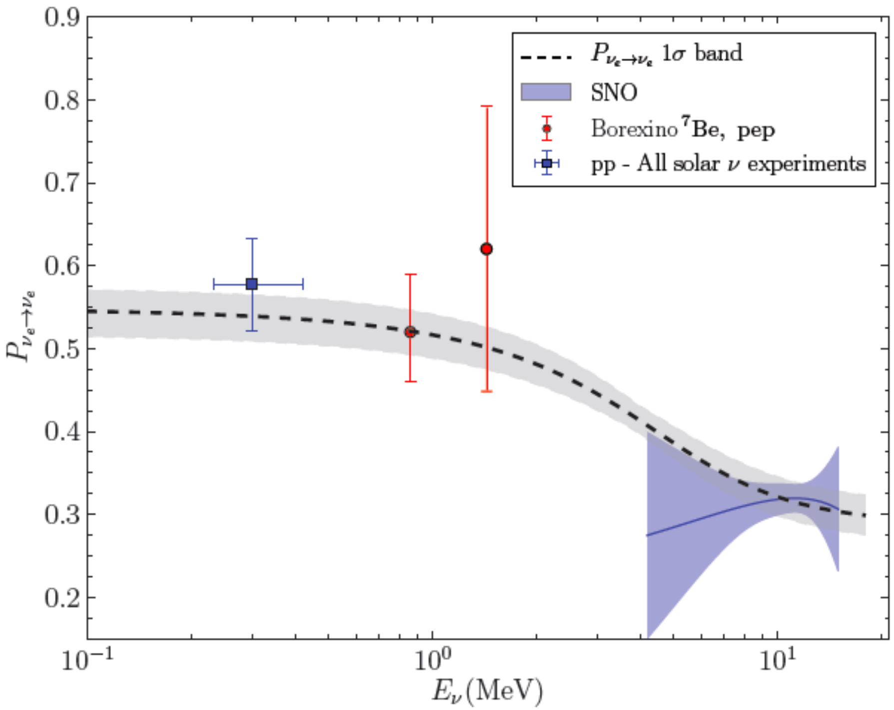
pre-Borexino world solar-ν data → post-Borexino world solar-ν data



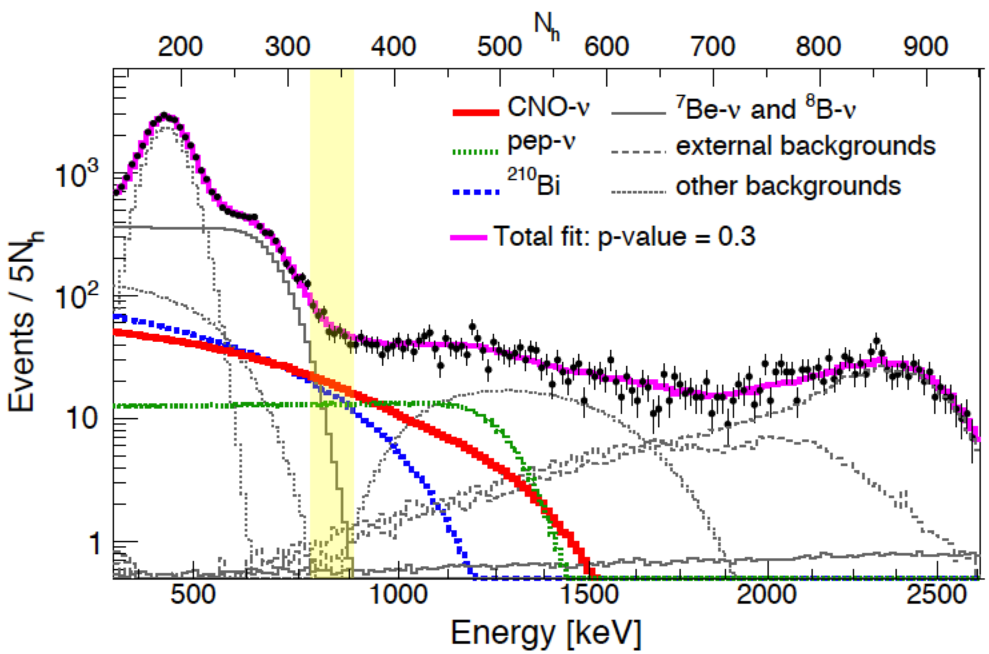


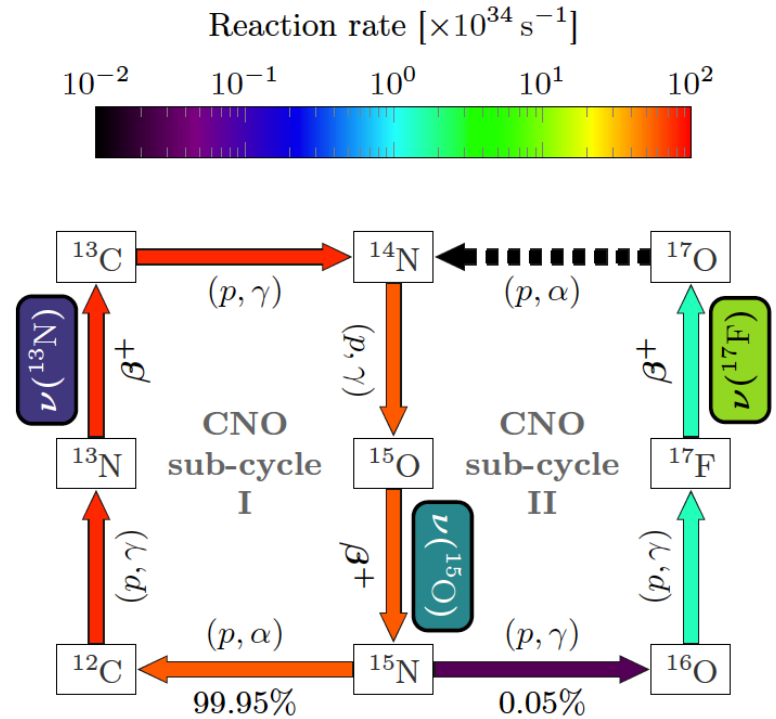
Borexino, ArXiv:2006.15115

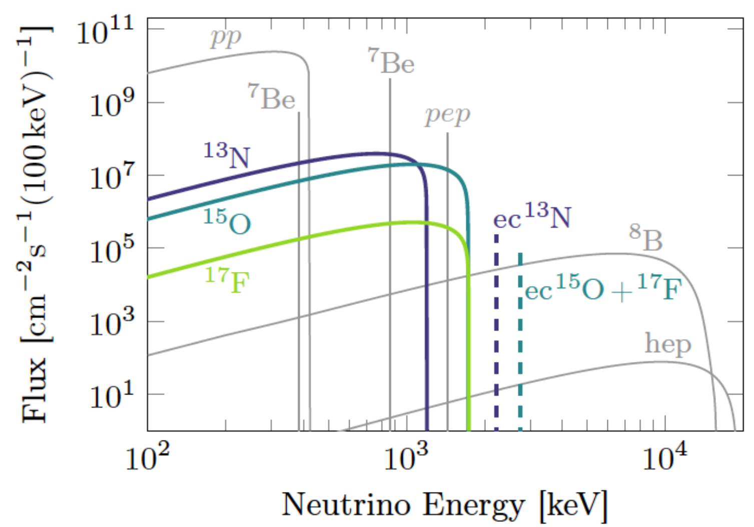
2. Borexino (2020)

CNO neutrino

- Sub-dominant heat production mechanism in the Sun (but the main heat production for all other massive stars)
- Finally, we confirmed why stars are bright!







2. 2005-2011

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

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

2. 2012-2020

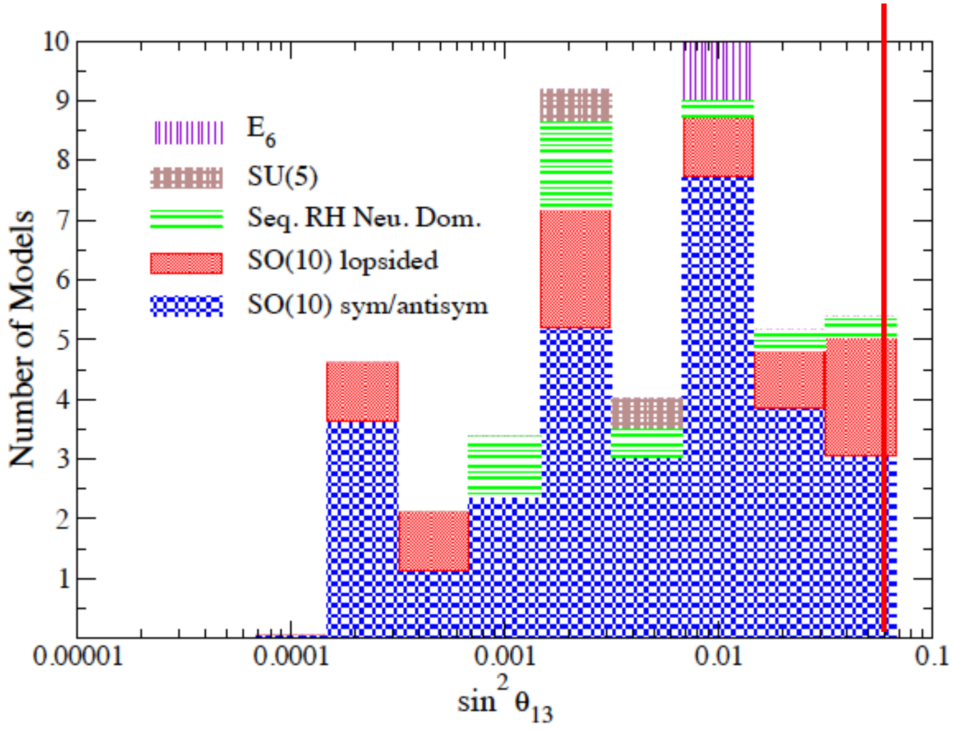
	2012	2013	2014	2015	2016	2017	2018	2019	2020
solar neutrino	Borexino pep neutrino agrees with MSW			McDonald won the Nobel prize					Borexino measures CNO neutrinos
reactor neutrino	θ_{13} is measured - Double Chooz - Daya Bay - Reno								
atmospheric neutrino		Super-K ν_τ appearance result		Kajita won the Nobel prize			Hint of normal mass ordering by SuperK?		
accelerator neutrino	T2K ν_e appearance result	MiniBooNE keeps showing anomalous excess							Hint of large CP violation by T2K?

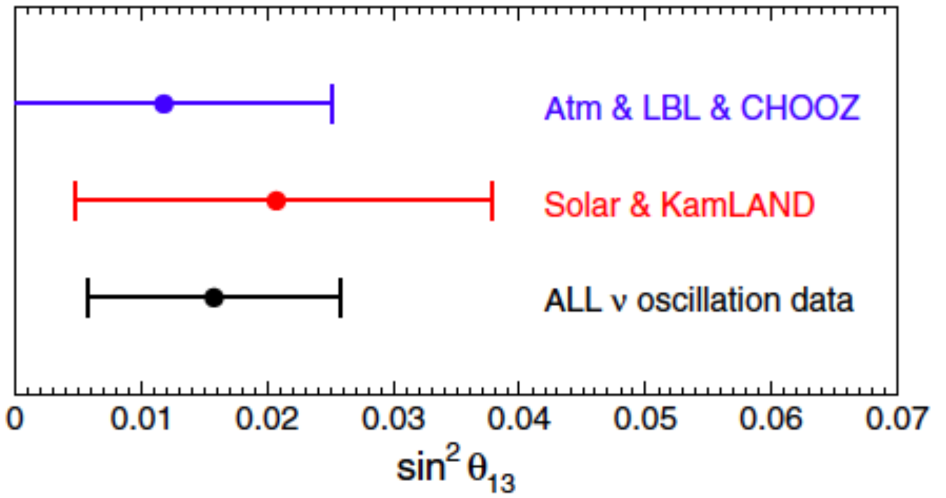
Albright, ArXiv:0905.0146
Fogli et al,PRL101(2008)141801

2. Discovery of nonzero 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)





Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802
Daya Bay, PRL112(2014)061801, T2K, PRL112(2014)061802

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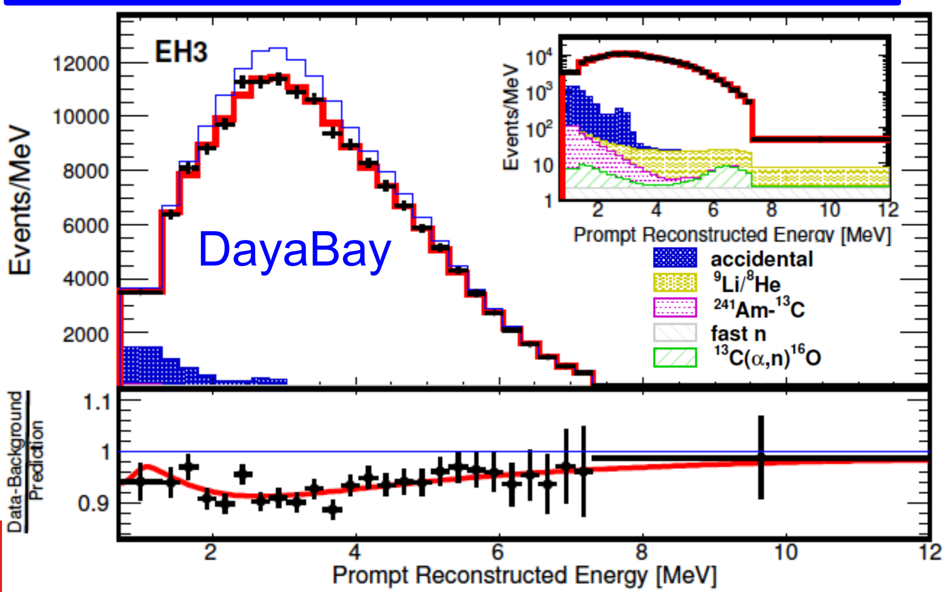
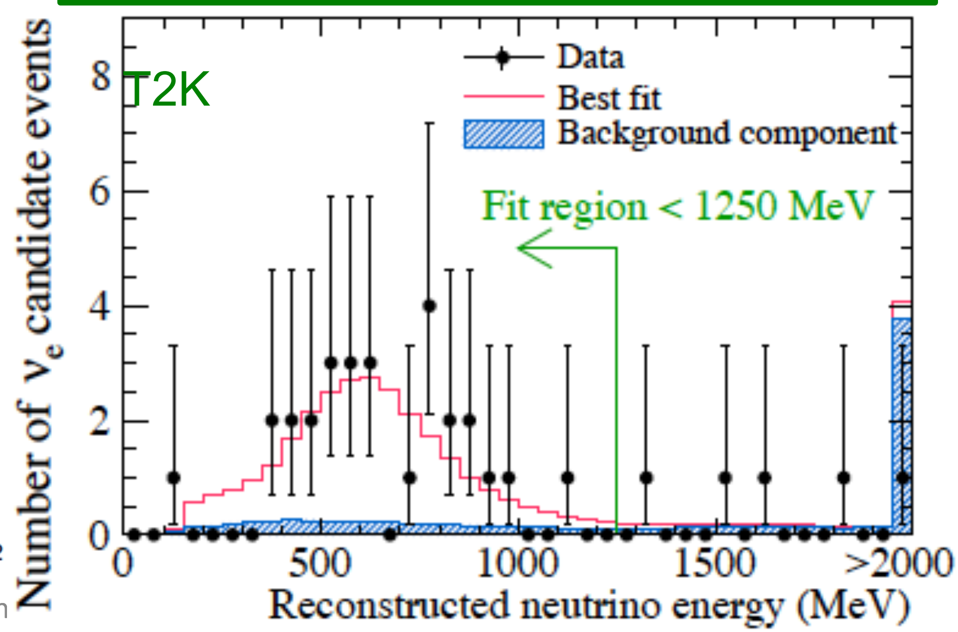
- θ_{13} was truly unknown parameter
- there was a “hint” from Solar-KamLAND tension
- nature was too kind for us!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation

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

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





Double Chooz,PRL108(2012)131801; DayaBay,PRL108(2012)171803; Reno,108(2012)191802
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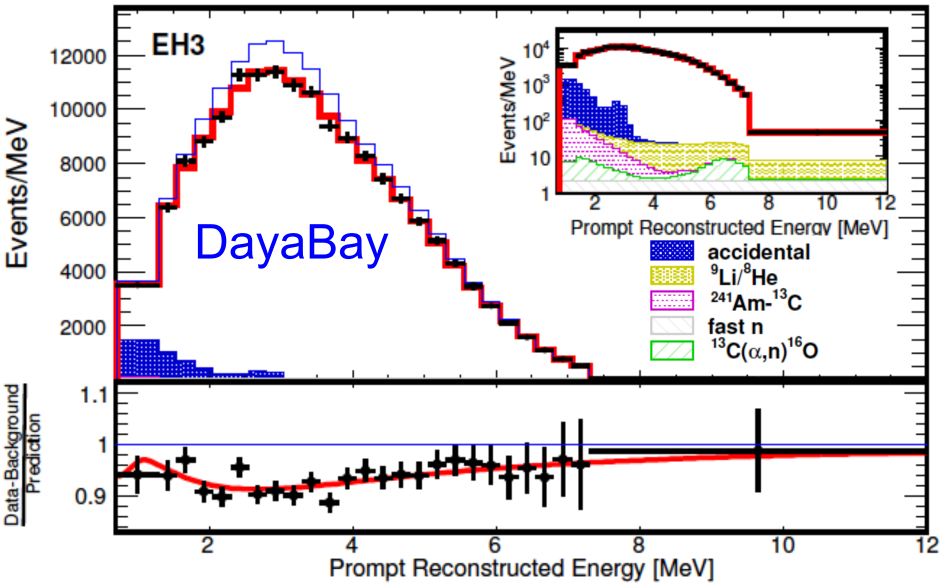
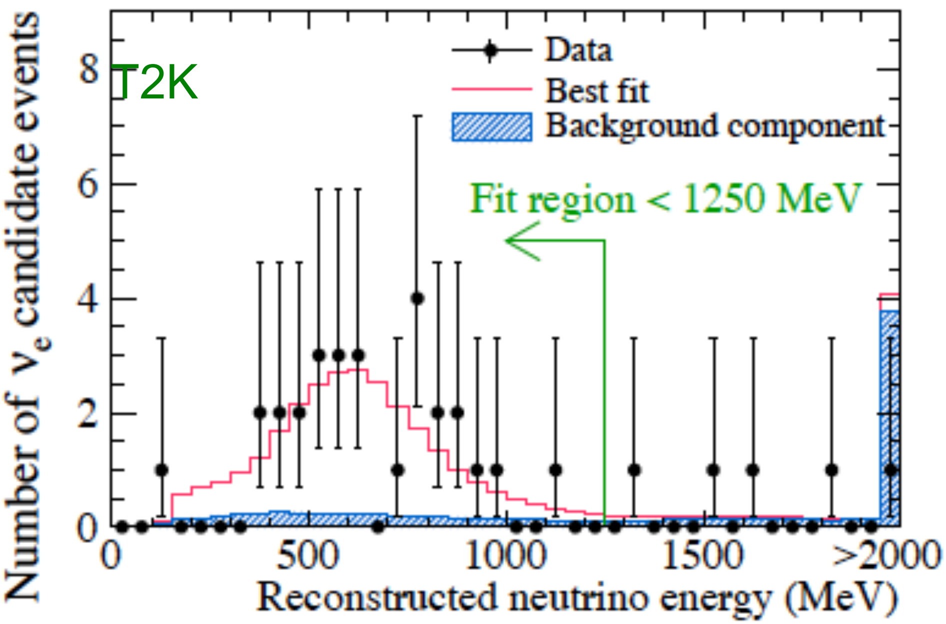
- nature was too kind for us!
  - anti-ν_e reactor disappearance
  - $\nu_\mu \rightarrow \nu_e$ long baseline neutrino oscillation
- nonzero θ_{13} → leptonic CP violation

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

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





Neutrino Physics takes center stage!

BREAKTHROUGH PRIZE

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"*

2. Toward leptonic CP violation search

3-flavor neutrino oscillation

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

Jarlskog invariant

$$J_{CP,l} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} \quad (1)$$

T2K CP violation search

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$
$$\mp \frac{1.27\Delta m_{21}^2 L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) \quad (2)$$

- Neutrino
+ Antineutrino

...including high-order term to look for mass ordering

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e)$$
$$\simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\phi_{31}\left[1 \overset{(-)}{+} \frac{2a}{\Delta m_{31}^2}(1-2s_{13}^2)\right]$$
$$\overset{(+)}{-} 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\phi_{32}\sin\phi_{31}\sin\phi_{21}\sin\delta_{CP}$$
$$\overset{(+)}{-} 8c_{13}^2 s_{13}^2 s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\phi_{32}\sin\phi_{31}$$
$$+ (CP\text{-even, solar terms}), \quad (1)$$

JUNO mass-ordering search

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

$$\Delta_{ij} = 1.27\Delta m_{ij}^2 L/E$$

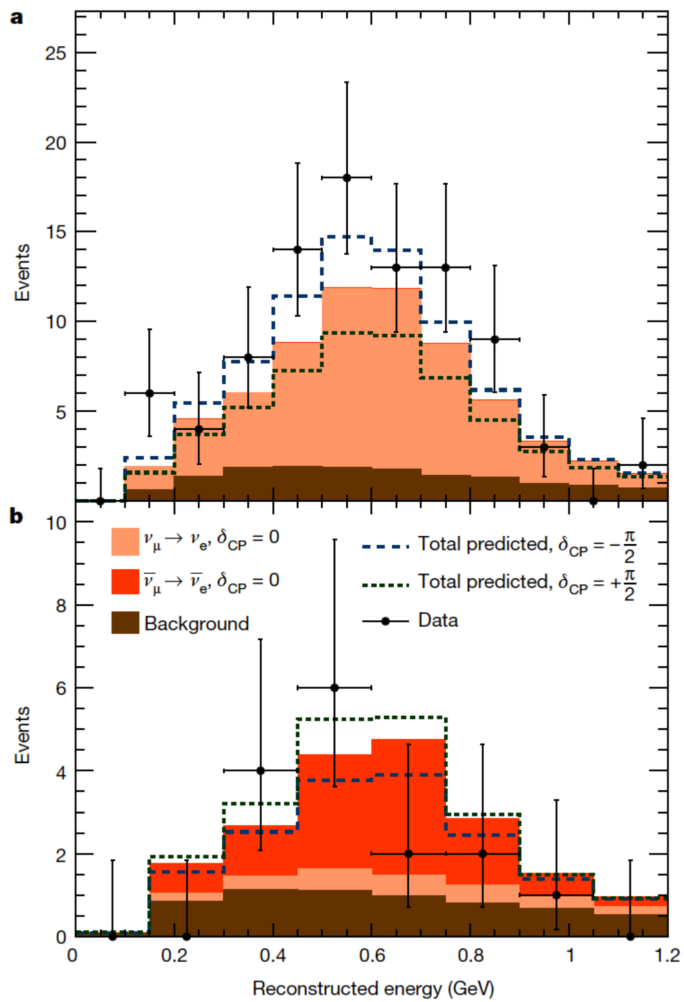
T2K, Nature 580 (2020) 339
T2K, Nature 580 (2020) 339

2. T2K (2020)

Indication of nonzero dCP

- T2K observe too many electron neutrinos

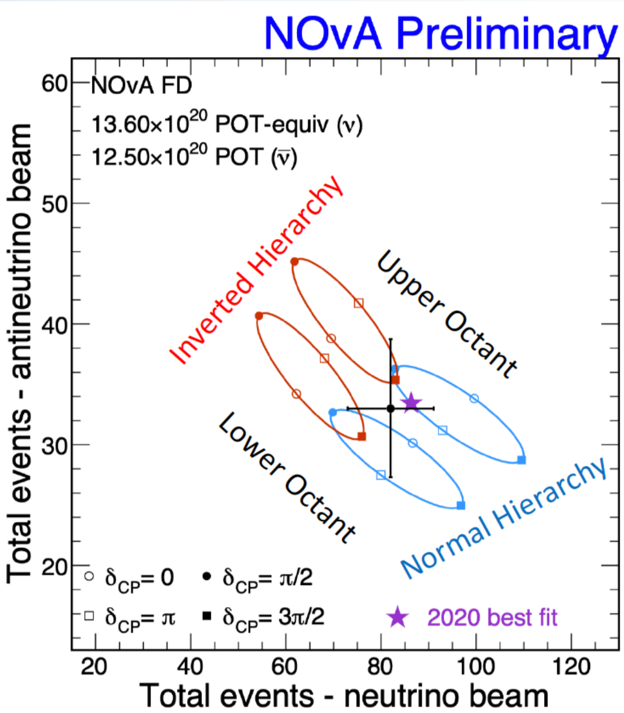
→ upper octant+NMO+large negative dCP



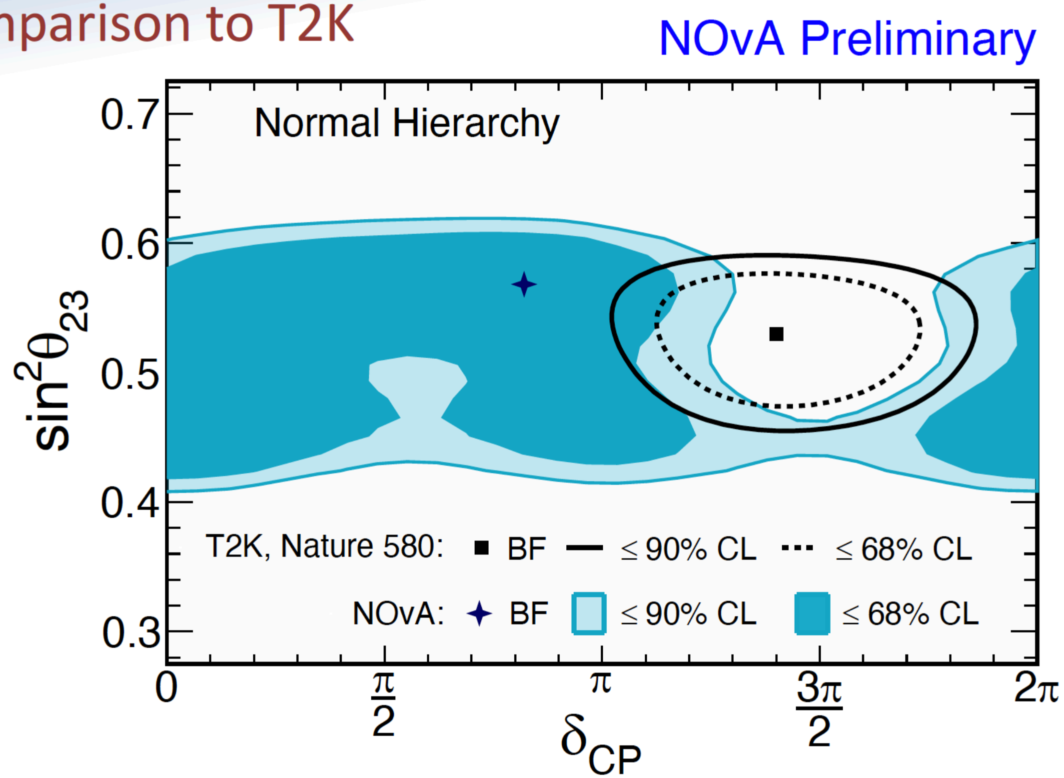
2. NOvA (2020)

Indication of nonzero dCP?

- T2K observe too many electron neutrinos
  → upper octant+NMO+large negative dCP
- NOvA observed moderate signals in both electron neutrinos and antineutrinos

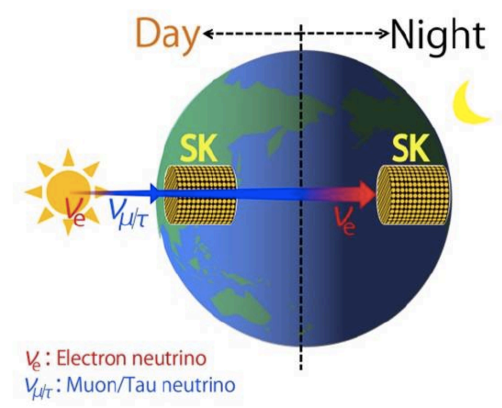


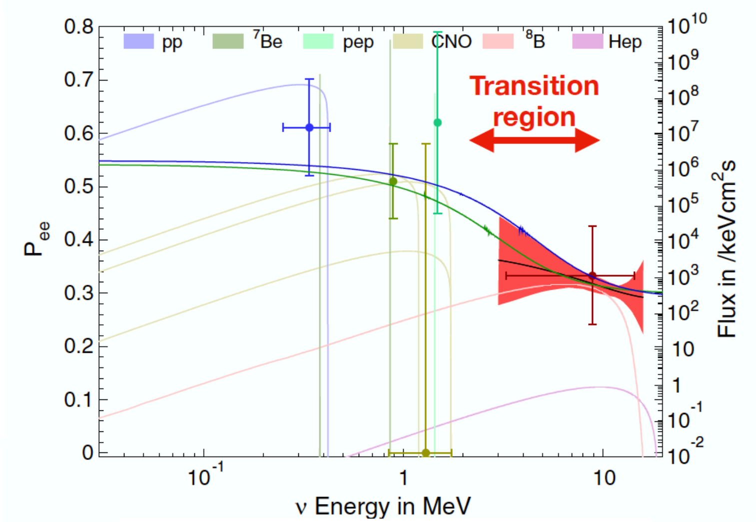
Comparison to T2K

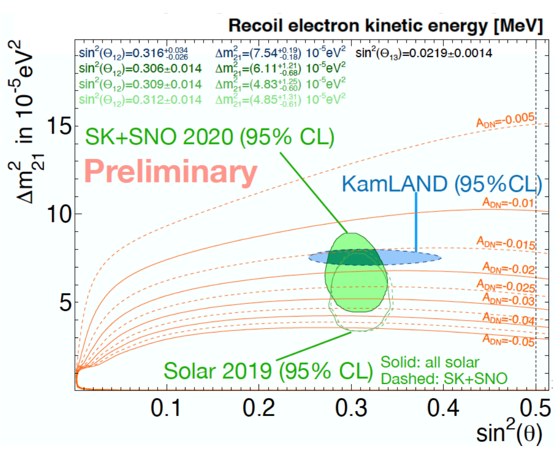


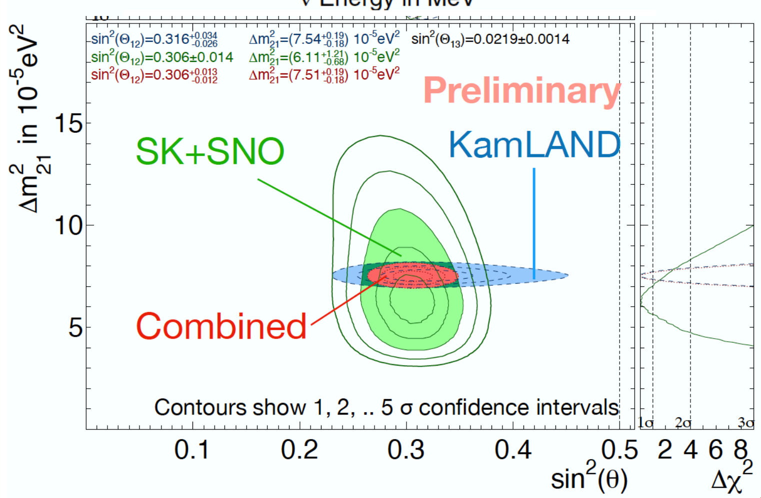
2. Super-Kamiokande (2020)

State-of-the-art solar neutrino physics
- No upturn of ^{8}B solar neutrino (no evidence of MSW transition)
- 1.9σ signal of day-night effect (no definitive earth matter effect)
- Solar-KamLAND tension is reduced (no sign of new physics)





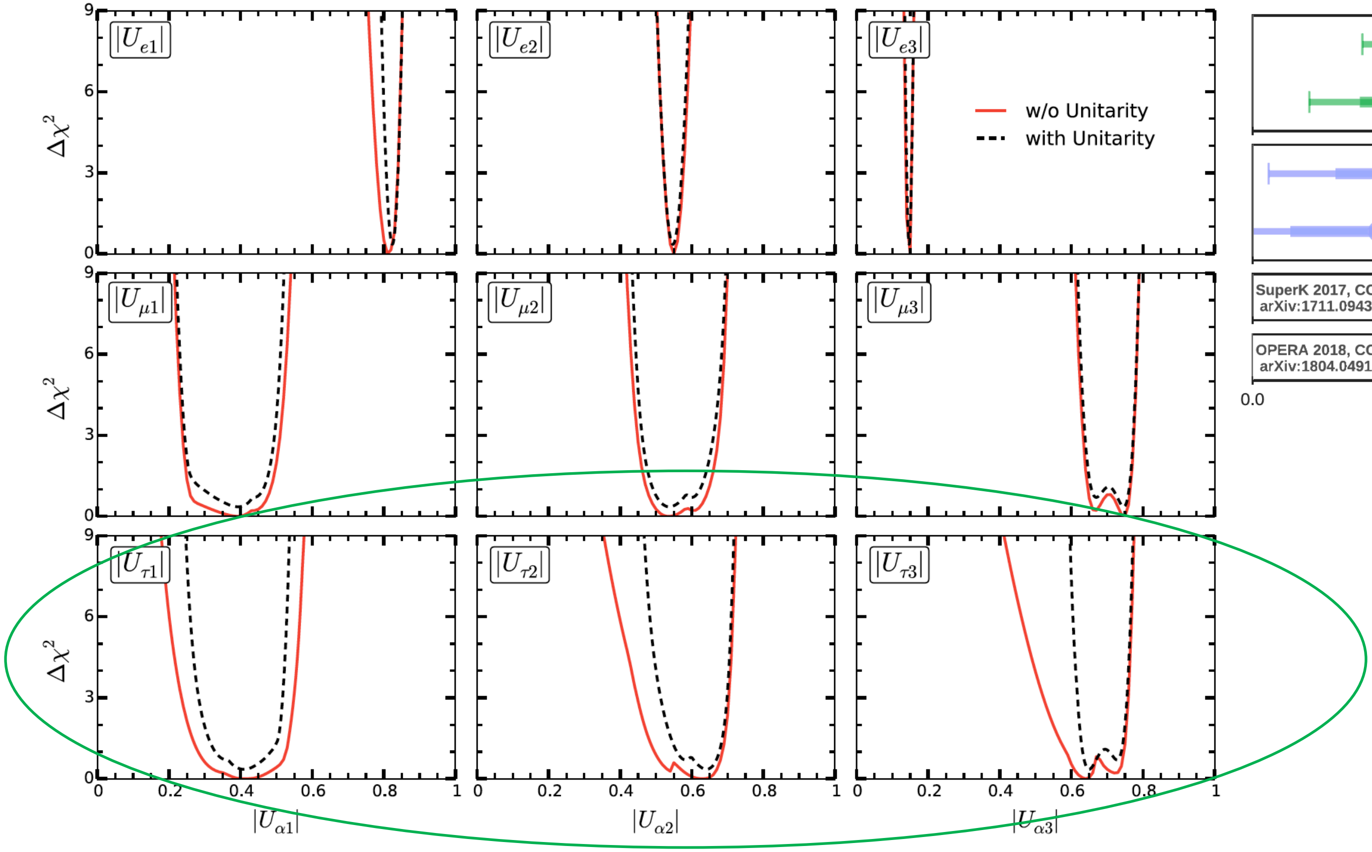


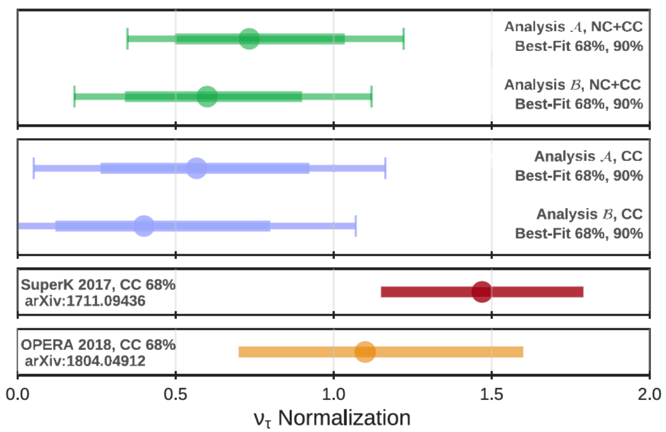


2. Non-unitarity of PMNS matrix (2020)

Precision era of neutrino physics

- Without unitarity, some PMNS elements have large error
- It looks tau neutrino appearance ($\nu_\mu \rightarrow \nu_\tau$) is the most important channel
- tau neutrinos are not easy to measure





2. Neutrino physics 2020

Neutrino Standard Model (νSM)

- SM + 3 active massive neutrinos

Unknown parameters of νSM

- Dirac CP phase
- θ_{23} (θ_{23}=40^o and 50^o are same for sin2θ_{23}, but not for sinθ_{23})
- order of mass (normal ordering $m_1<m_2<m_3$ or inverted ordering $m_3<m_1<m_2$)
- Majorana phases
- Dirac or Majorana
- absolute neutrino mass

} not relevant to neutrino oscillation experiment?

Unmeasured effects

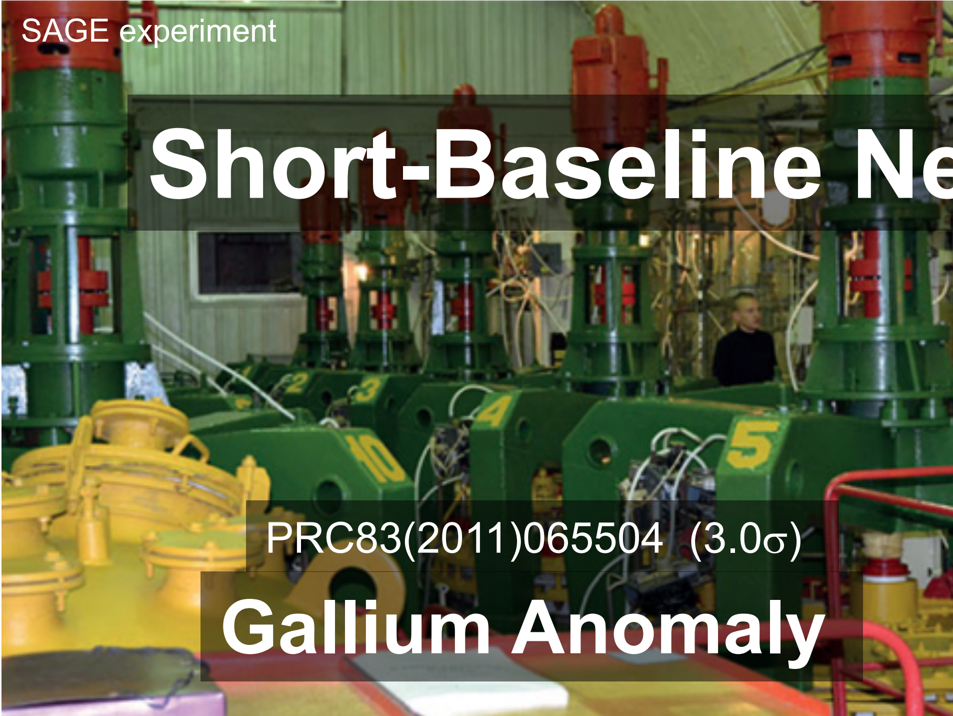
- Upturn of ^{8}B solar neutrino
- Solar neutrino day-night effect
- PMNS matrix unitarity

Very few unsolved anomalies

- Solar-KamLAND tension
- LSND signal
- MiniBooNE signal
- Reactor anomaly
- Gallium anomaly

} motivation of 1eV scale sterile neutrino

Short-Baseline Neutrino Anomalies

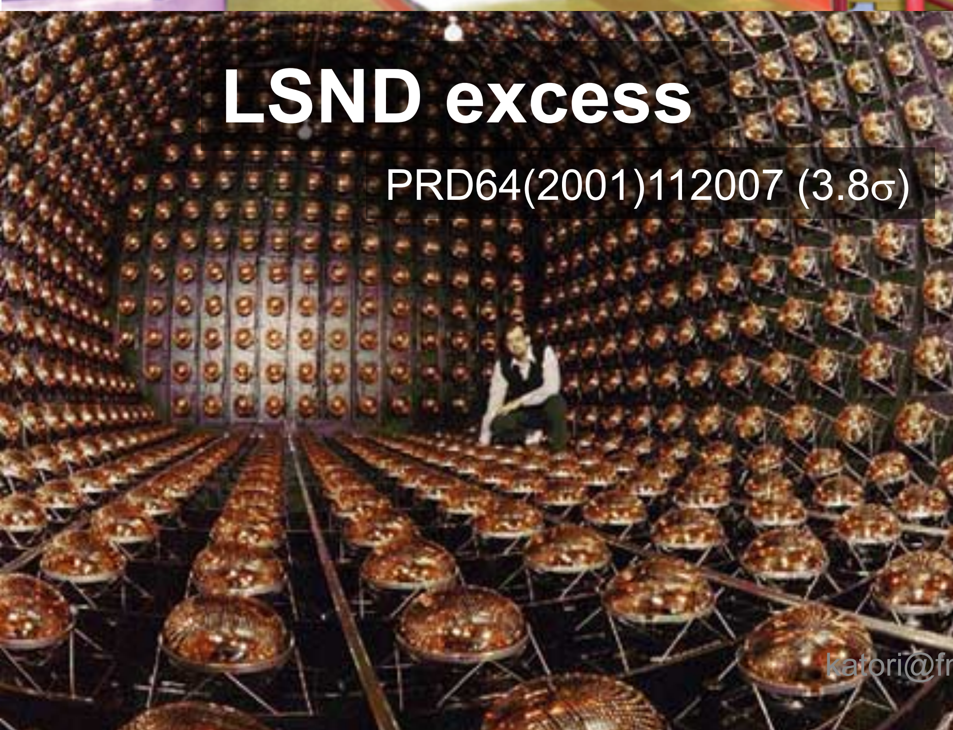


PRC83(2011)065504 (3.0σ)

Gallium Anomaly

PRC83(2011)054615 (2.5σ)

Reactor Anomalies

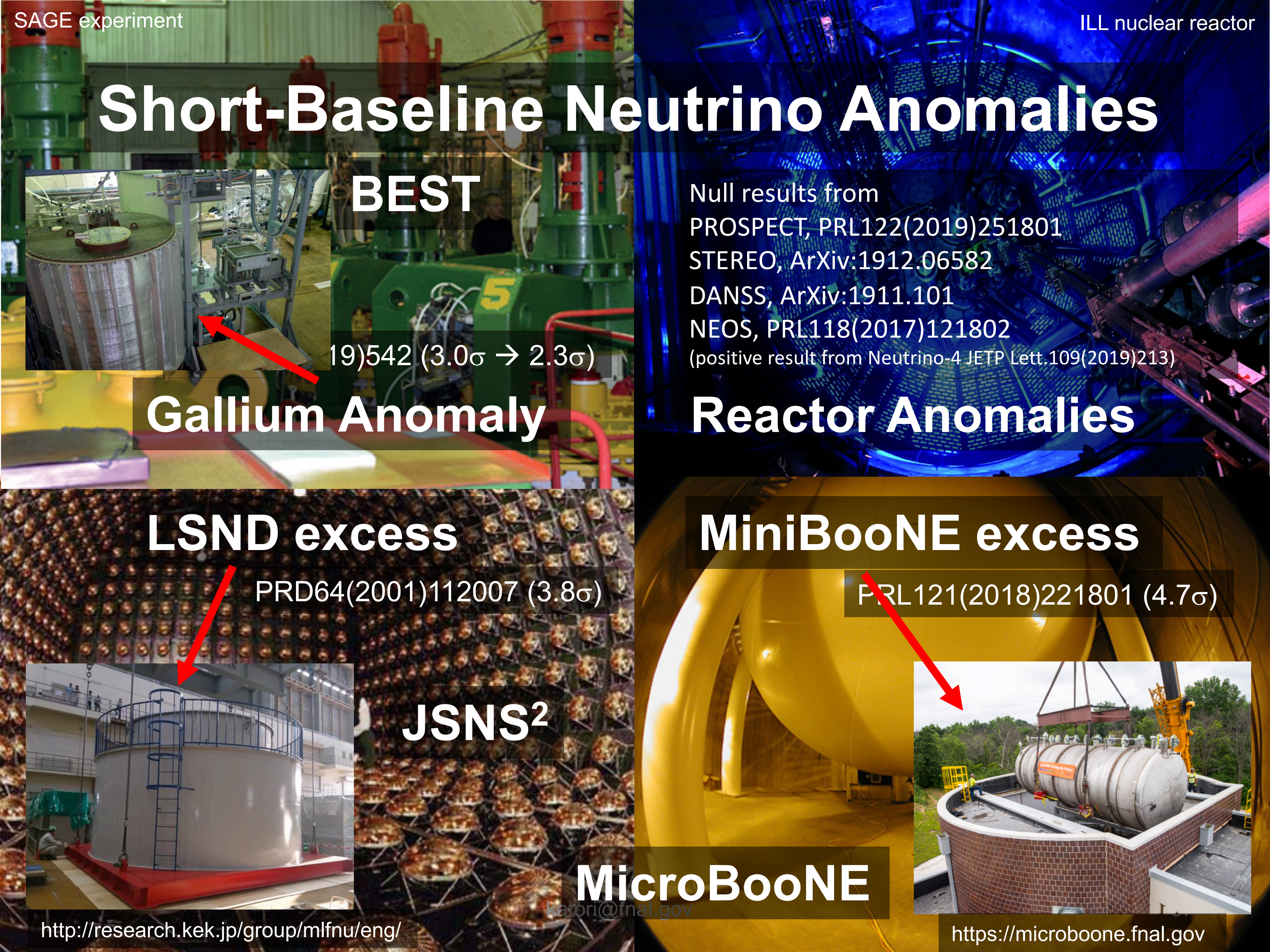


LSND excess

PRD64(2001)112007 (3.8σ)

MiniBooNE excess

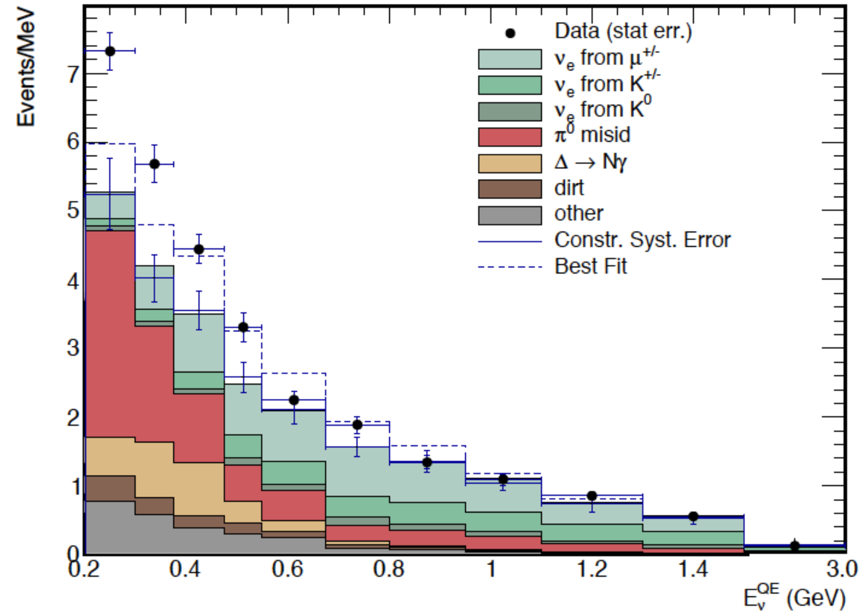
PRL121(2018)221801 (4.7σ)

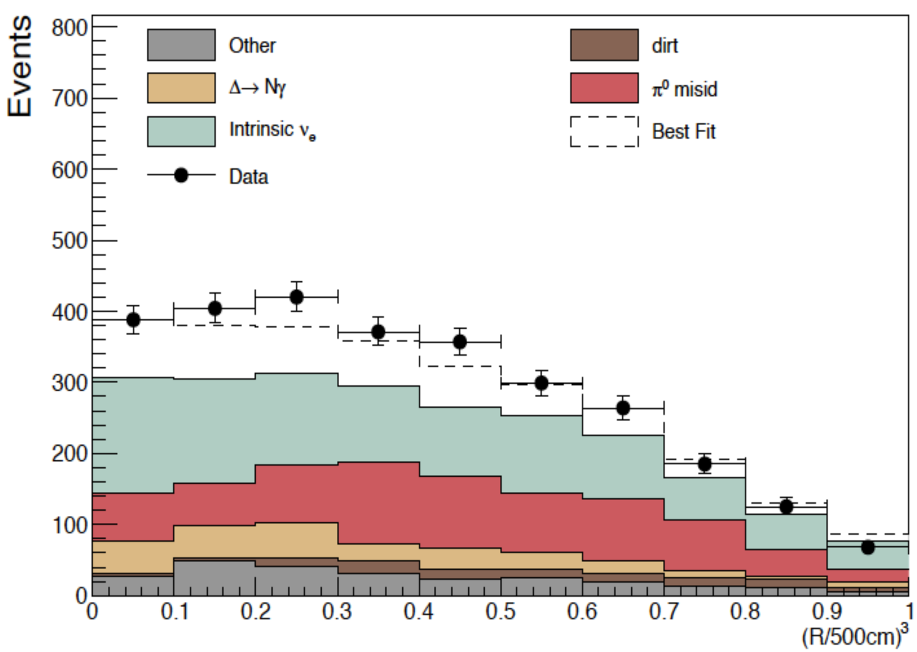


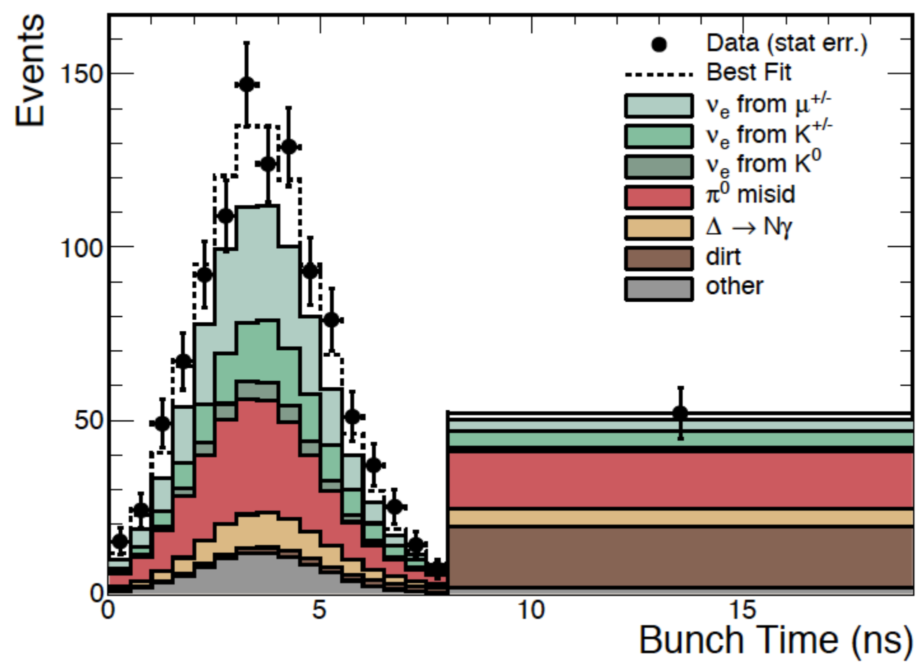
SAGE experiment
ILL nuclear reactor
Short-Baseline Neutrino Anomalies
BEST
19)542 (3.0σ → 2.3σ)
Gallium Anomaly
Null results from
PROSPECT, PRL122(2019)251801
STEREO, ArXiv:1912.06582
DANSS, ArXiv:1911.101
NEOS, PRL118(2017)121802
(positive result from Neutrino-4 JETP Lett.109(2019)213)
Reactor Anomalies
LSND excess
PRD64(2001)112007 (3.8σ)
JSNS²
MiniBooNE excess
PRL121(2018)221801 (4.7σ)
MicroBooNE
katori@fnal.gov
http://research.kek.jp/group/mlfnu/eng/
https://microboone.fnal.gov

2. MiniBooNE (2020)

MiniBooNE final oscillation result
- Full statistics of 17 years data
- More excess at low energy (4.8σ)
- Both timing and coordinate distributions are consistent with $\nu_\mu \rightarrow \nu_e$ oscillation signal...







2. Conclusions

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

Very few anomalies left (sorry for phenomenologists!), and all exotic processes are sub-dominant.

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

Unmeasured effects
- Upturn of ^{8}B solar neutrino
- Solar neutrino day-night effect
- PMNS matrix unitarity

1. Neutrino oscillations

2. History of neutrino oscillation

3. T2K neutrino oscillation experiments

4. Current and future neutrino experiments

5. Neutrino astronomy

6. Conclusion

3. Neutrino oscillations for CP violation measurement

Keep the first order of CP violation for muon neutrino to electron neutrino oscillation

Jarlskog invariant

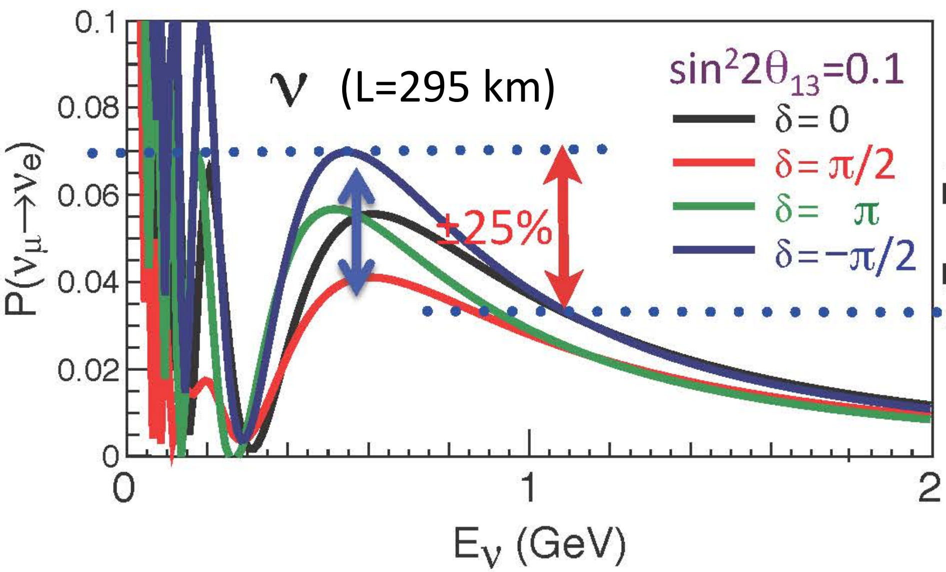
$$J_{CP,1} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} \quad (1)$$

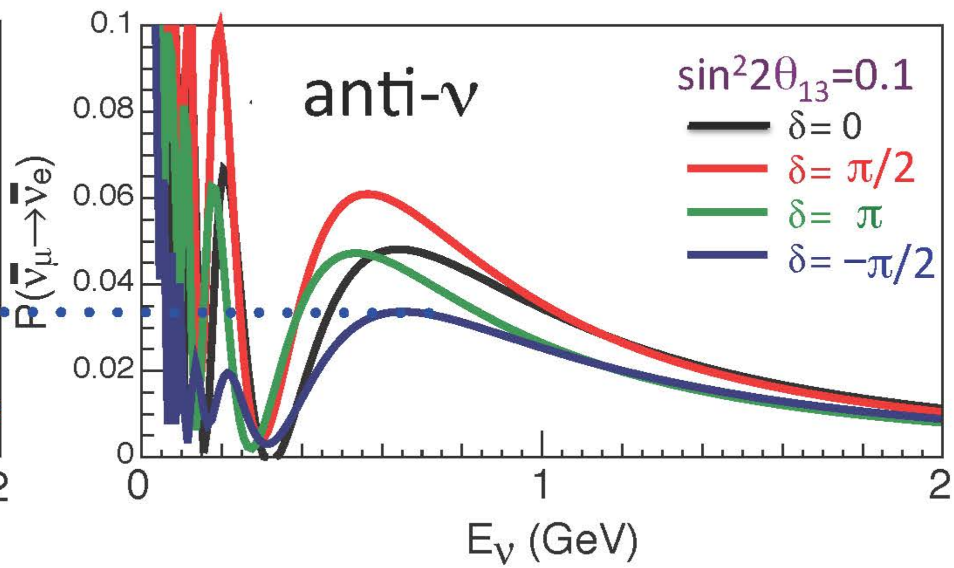
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) \mp \frac{1.27\Delta m_{21}^2 L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) \quad (2)$$

- Neutrino
+ Antineutrino

If there is no CP violation, $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ are the same

Expected oscillation probability to measure δ_{CP} is small





If CP symmetry is violated, neutrino oscillation and anti-neutrino oscillation looks very different

KING'S College LONDON

3. Neutrino oscillation experiment

Data

Create neutrino beam

Measure muon neutrinos at the near detector

Measure electron neutrinos (and muon neutrinos) at the far detector

Simulation

Simulate neutrino flux at the near detector and the far detector

Simulate neutrino interaction at the near detector and the far detector

Simulate detector response at the near detector and far detector

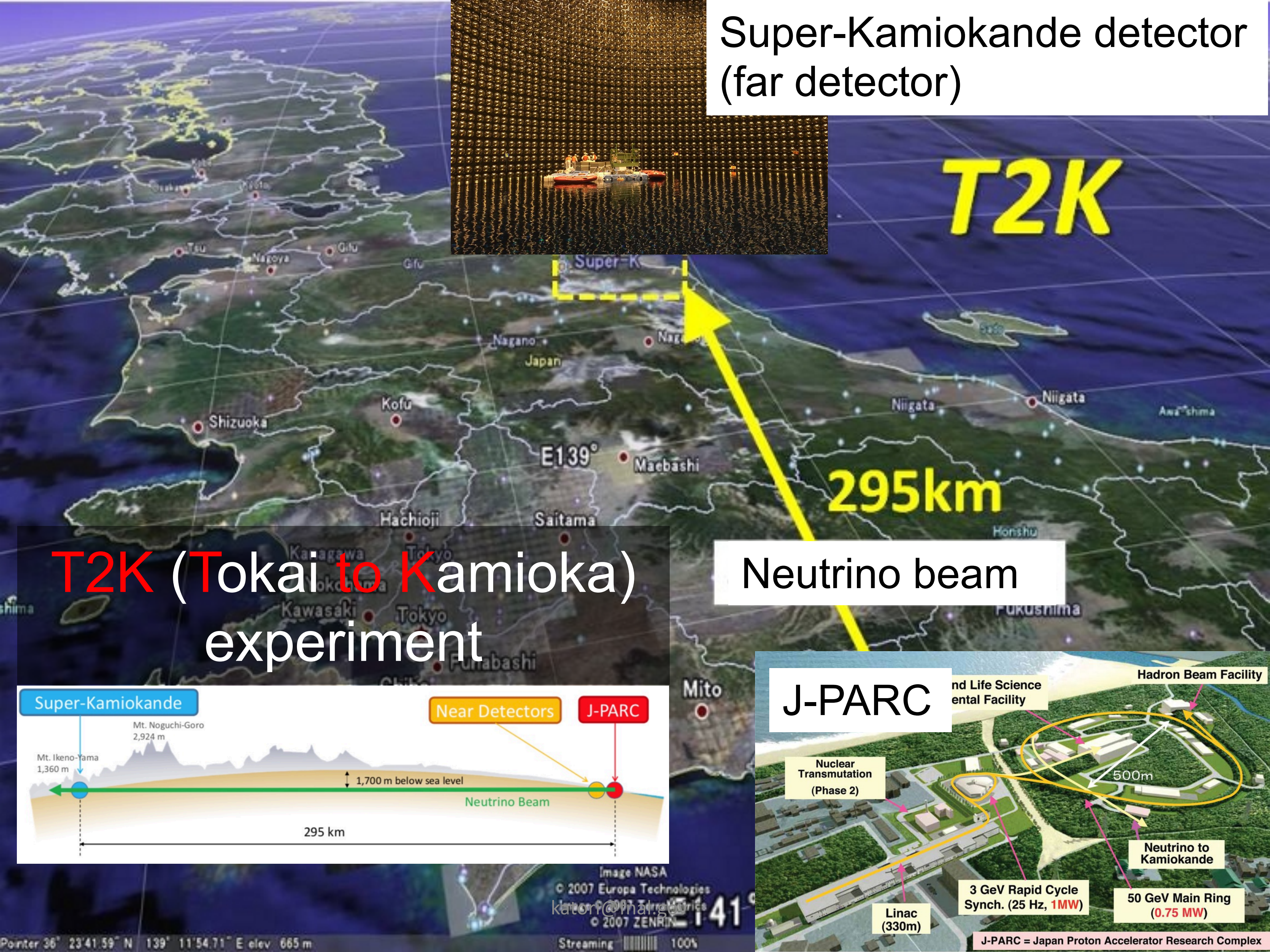
Apply oscillation formula to the far event distribution

Oscillation analysis

Compare data and simulation to find oscillation parameters
(use near detector information to constrain systematic errors)

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

KING'S College LONDON


Super-Kamiokande detector
(far detector)
T2K
Super-K
295km
Neutrino beam
T2K (Tokai to Kamioka)
experiment
Super-Kamiokande
Near Detectors
J-PARC
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
1,700 m below sea level
Neutrino Beam
295 km
J-PARC
nd Life Science
ental Facility
Hadron Beam Facility
Nuclear
Transmutation
(Phase 2)
500m
Neutrino to
Kamiokande
3 GeV Rapid Cycle
Synch. (25 Hz, 1MW)
50 GeV Main Ring
(0.75 MW)
Linac
(330m)
J-PARC = Japan Proton Accelerator Research Complex
Shizuoka
Kofu
Nagano
Japan
Niigata
E139°
Maebashi
Hachioji
Saitama
Tokyo
Kawasaki
Mito
Fukushima
Honshu
Image NASA
© 2007 Europa Technologies
© 2007 ZENRIN
Streaming 100%

3.1. Neutrino beam

3.2. Neutrino detector

3.3. Neutrino interaction physics

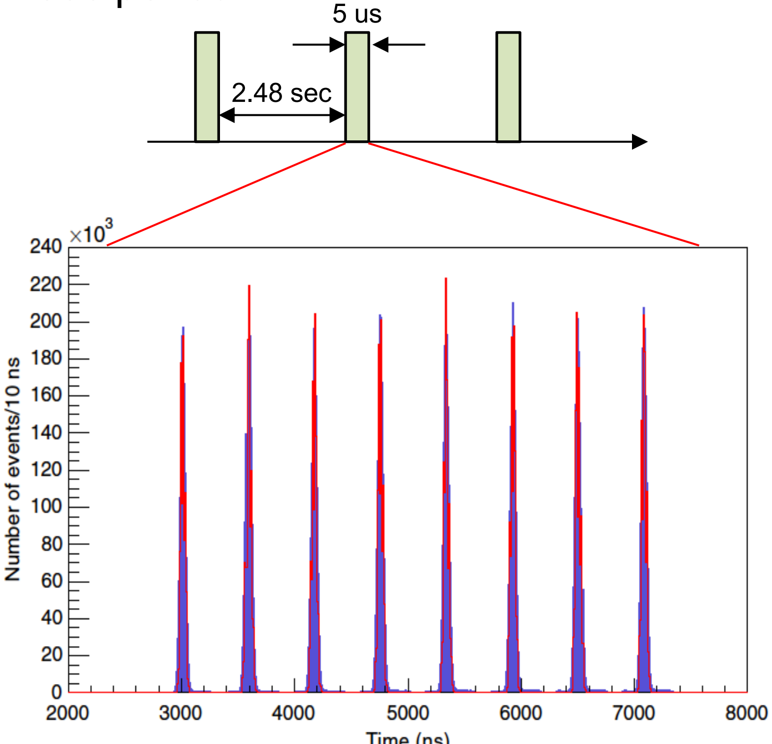
3.4. Oscillation result


LINAC
- 400 MeV
RCS (Rapid Cycling Synchrotron)
- 3 GeV
To Kamioka
Neutrino
Main Ring
- 30 GeV

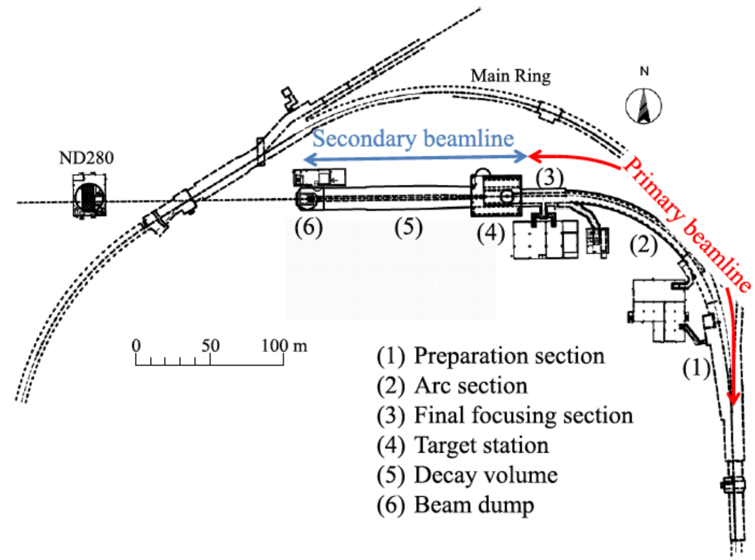
3.1. Neutrino beamline

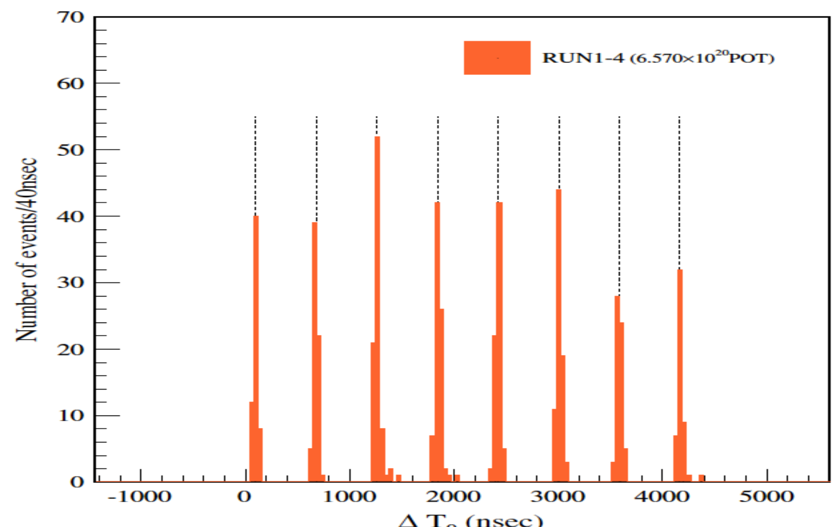
Primary beamline

- 30 GeV protons are extracted from MR by superconducting magnets
- 1 pulse contains 8 bunches in ~5us, about ~2.5E14 ppp (protons per pulse) with 2.48 sec period

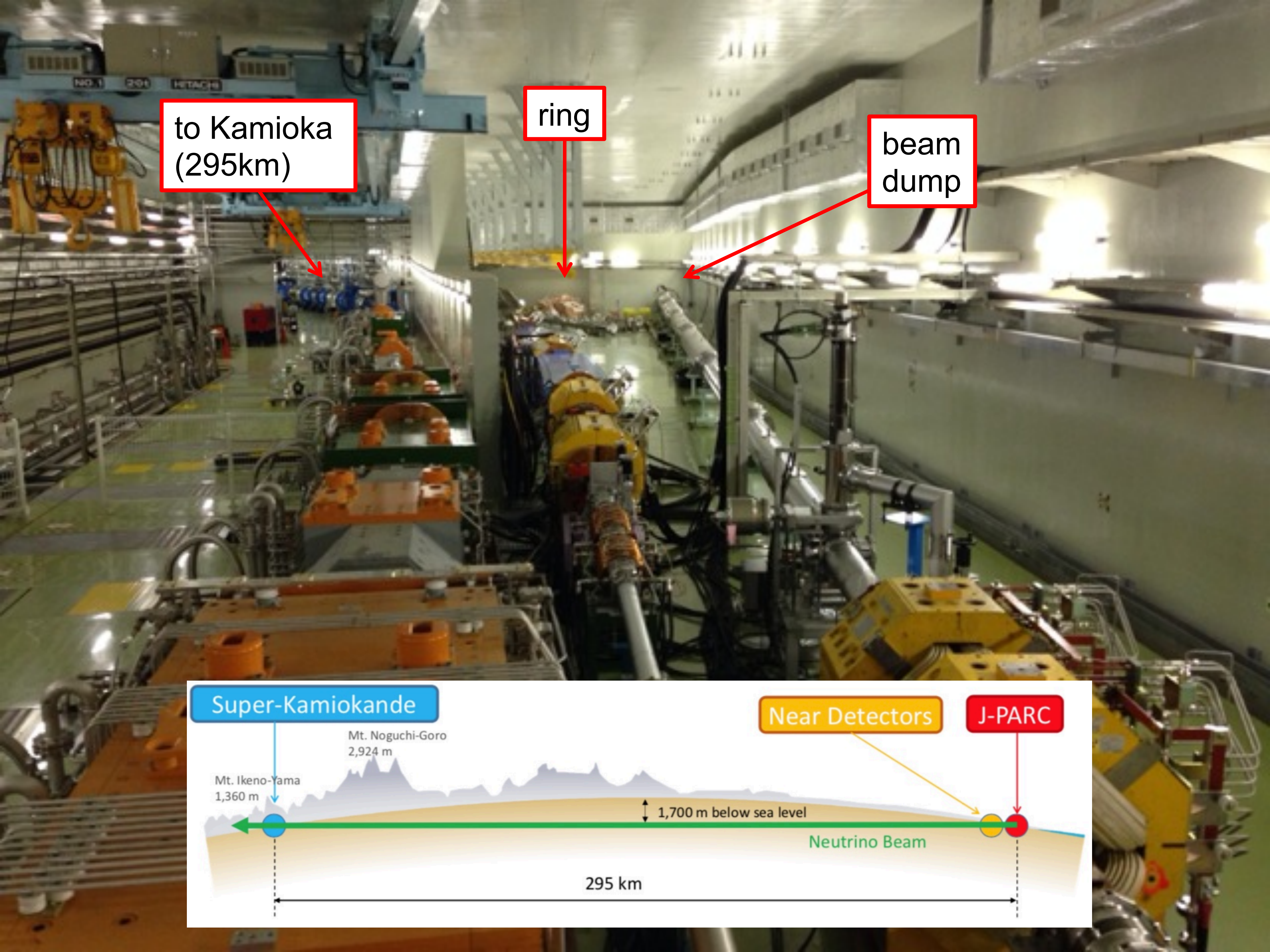


Neutrino events at the near detector





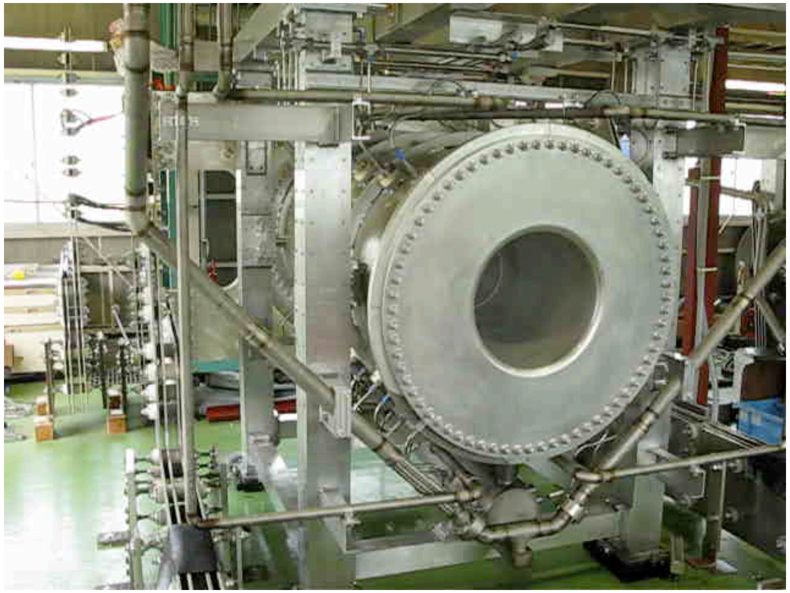
Neutrino events at the far detector


to Kamioka (295km)
ring
beam dump
Super-Kamiokande
Near Detectors
J-PARC
Mt. Noguchi-Goro 2,924 m
Mt. Ikeno-Yama 1,360 m
1,700 m below sea level
Neutrino Beam
295 km

This is the sound of neutrinos!

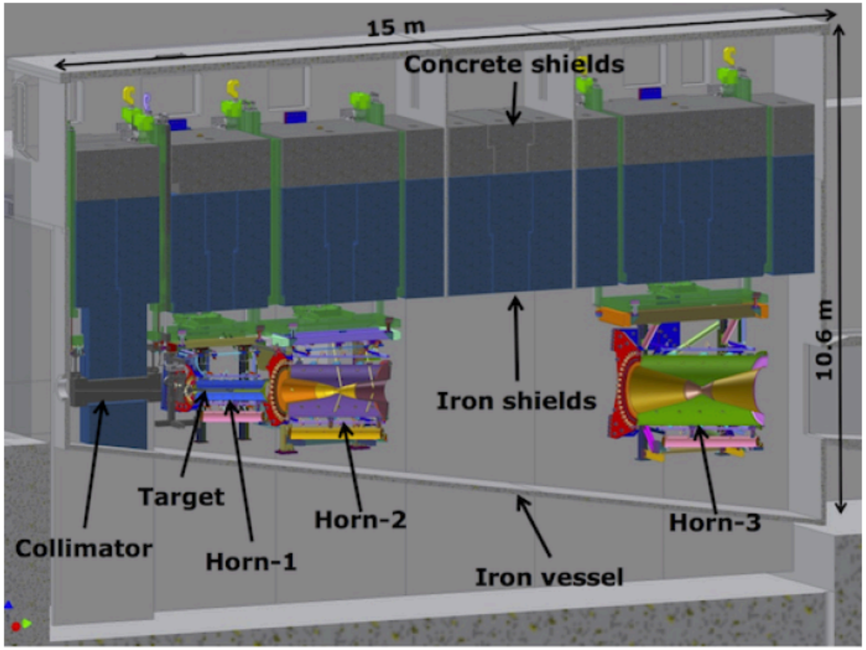
3.1. Neutrino beamline

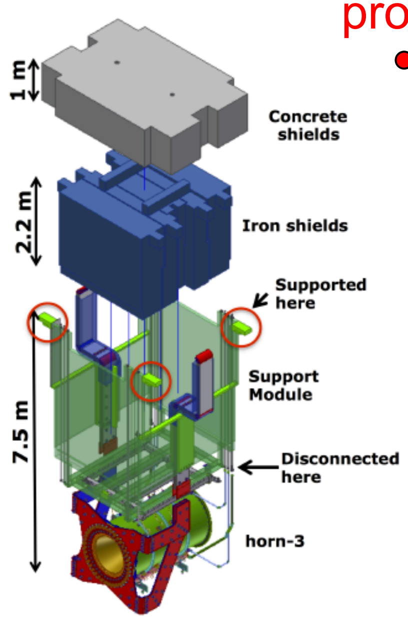
Horn 3 test (250 kA, ~1.7 T)

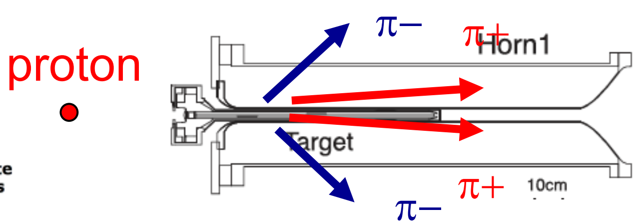


Secondary beamline

- Protons collide the graphite target (in the Horn 1) to produce mesons, and these mesons decay in the decay volume to produce neutrinos (decay-in-flight).
- In neutrino mode, 3 magnetic horns focus positive mesons and defocus negative mesons to produce neutrino beam (flux ~x17). In antineutrino mode, horn current is reversed to focus negative mesons.







T2K, PRD87(2013)012001
NA61/SHINE, EPJC76(2016)84

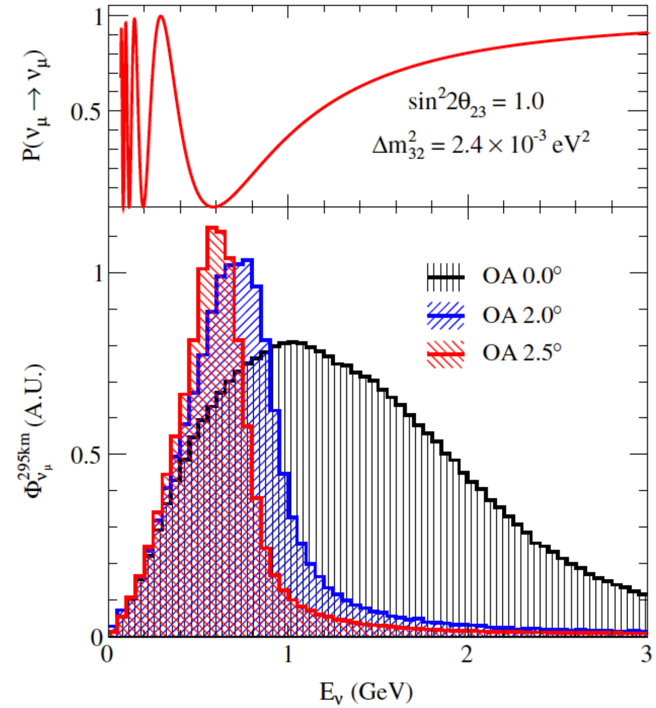
3.1. Neutrino beamline

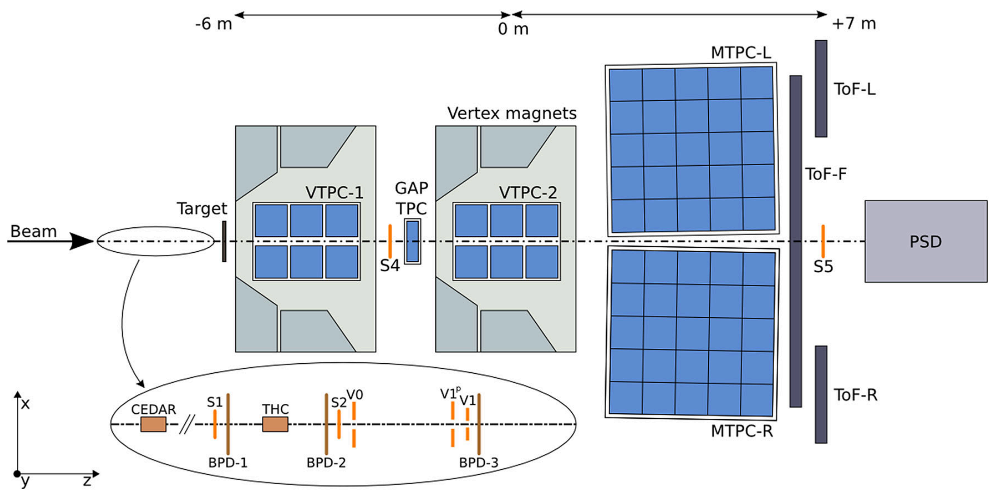
Off-axis beam

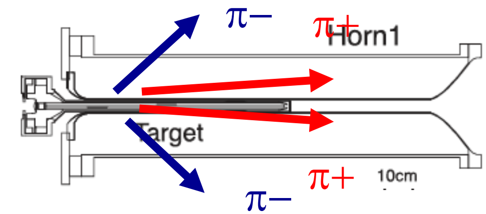
- 2.5º off-axis to make ~0.6 GeV narrow band beam

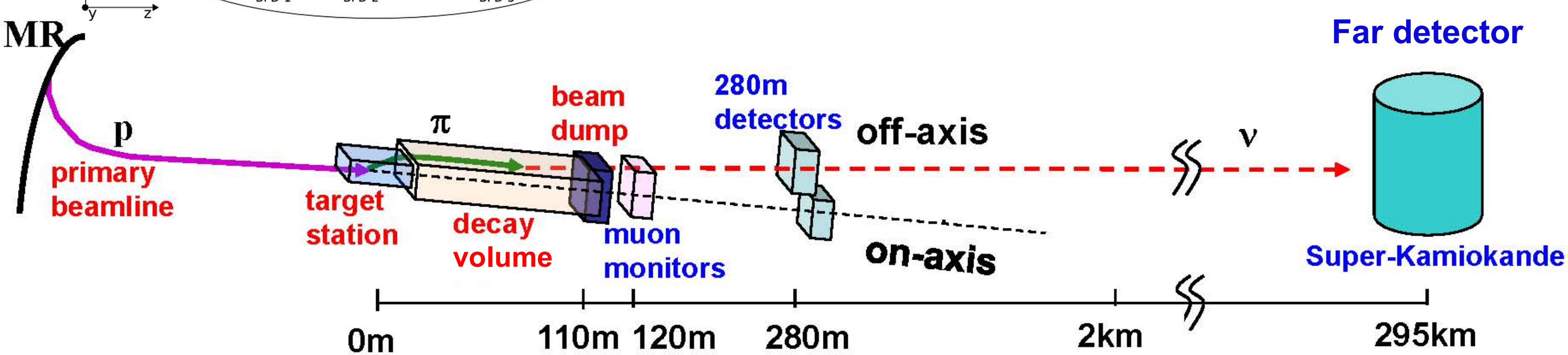
CERN NA61/SHINE

- Hadron production at the target is simulated with the data from the hadron measurement



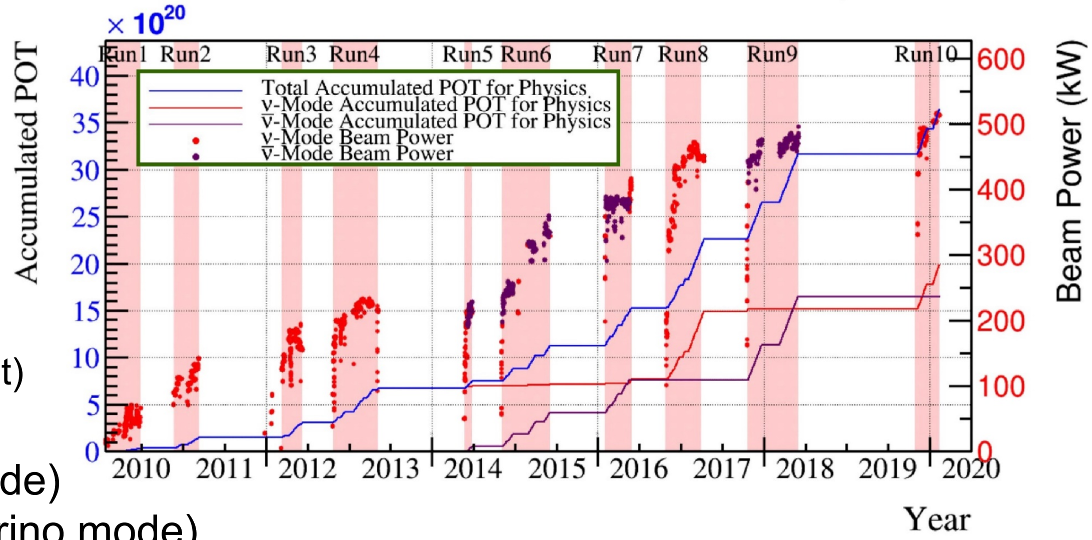






T2K, PRD87(2013)012001
Vladisavljevic (T2K), NuInt18

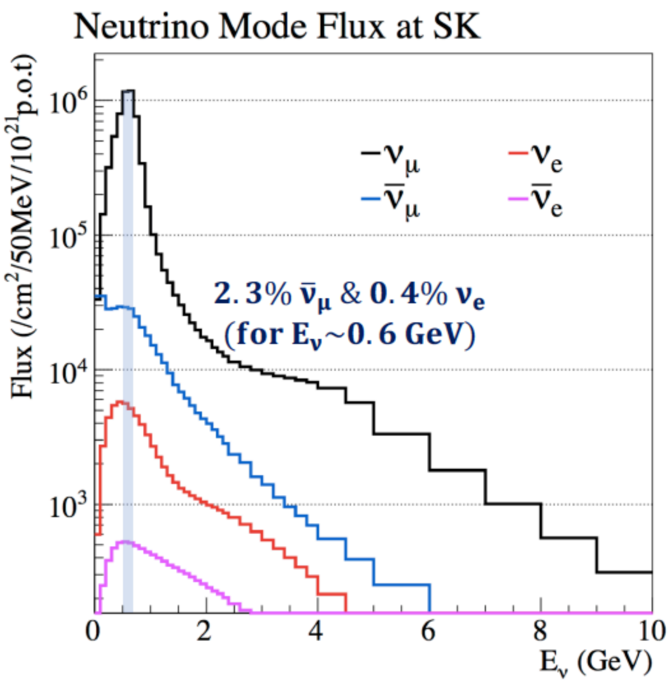
3.1. Neutrino beamline

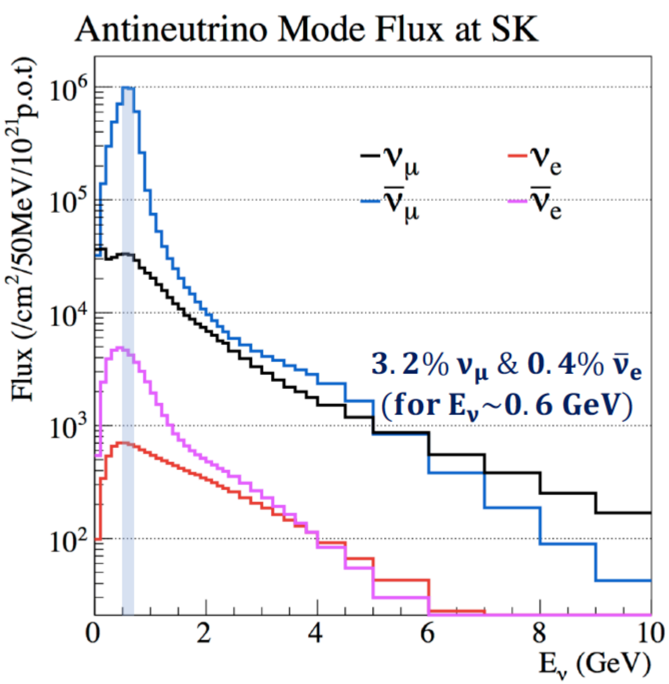


2009 – 2018 data
- Neutrino mode, 1.49E21 POT
- Antineutrino mode, 1.64E21 POT

(POT=protons on target)

Neutrino flux prediction
- muon neutrino dominant (neutrino mode)
- muon antineutrino dominant (antineutrino mode)
- ~9% error at the flux peak
- replica target NA61/SHINE data can reduce error to ~5%





3.1. Neutrino beam

3.2. Neutrino detector

3.3. Neutrino interaction physics

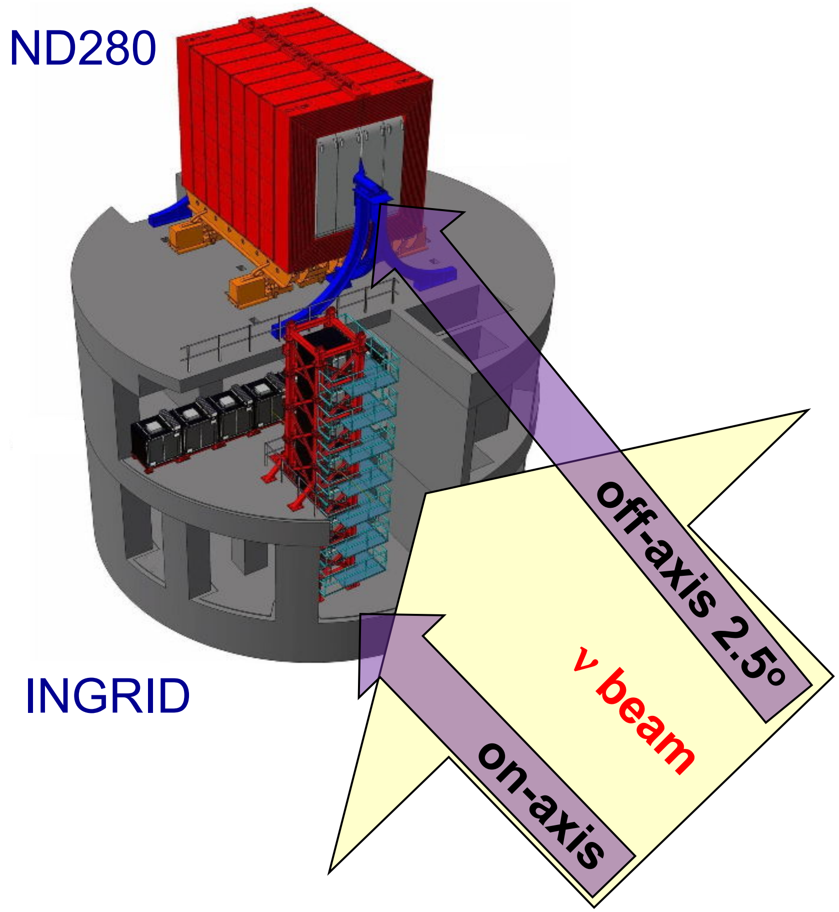
3.4. Oscillation result

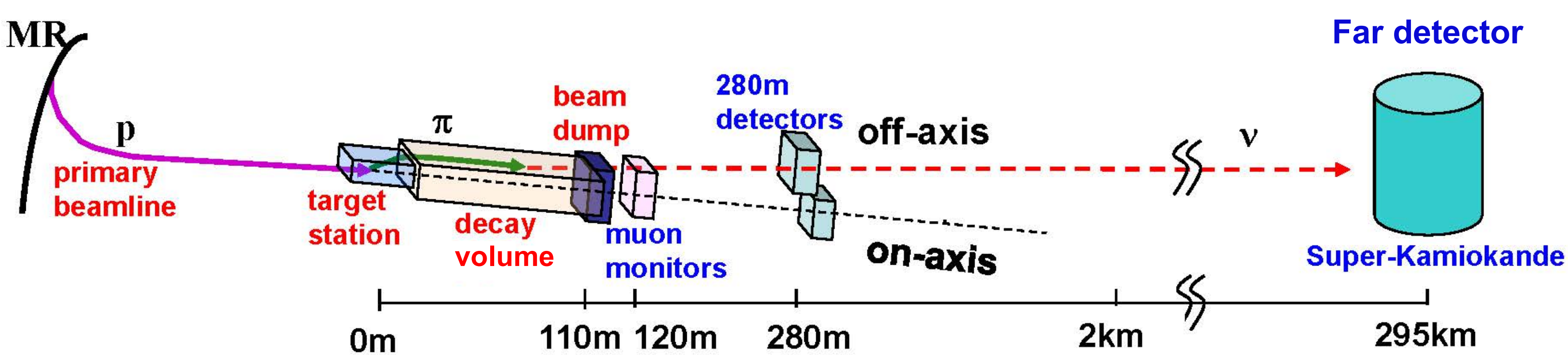
T2K, NIMA659(2011)106
Oyama (T2K), CNNP2020

3.2. Near detectors

INGRID
- on-axis near detector
- Mainly for neutrino flux monitoring

ND280
- off-axis near detector
- Data are used to constrain various systematics

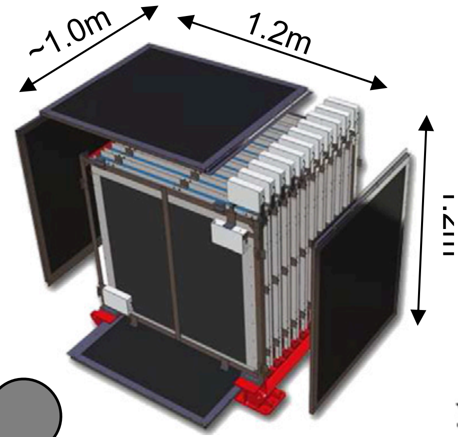


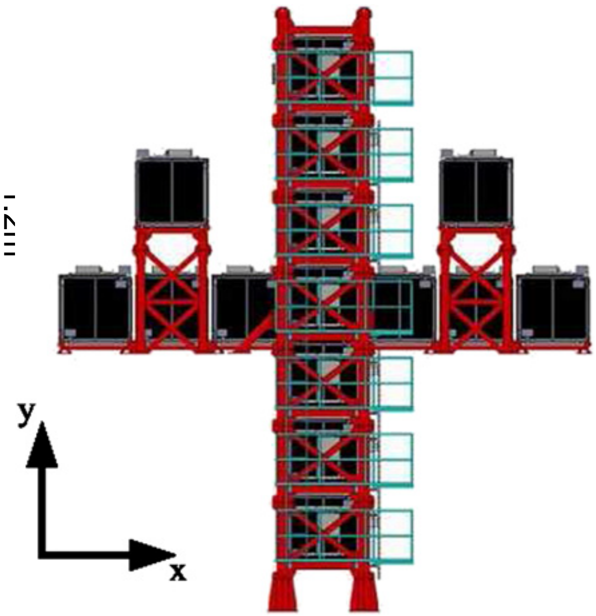


3.2. On-axis detector

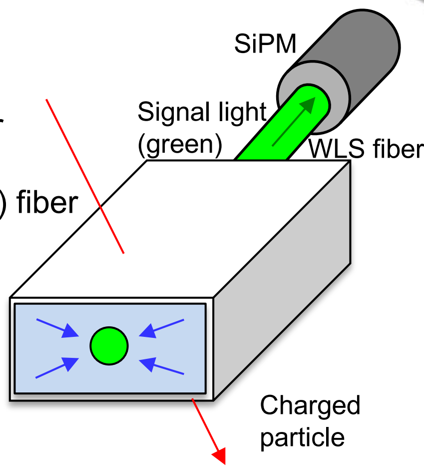
INGRID

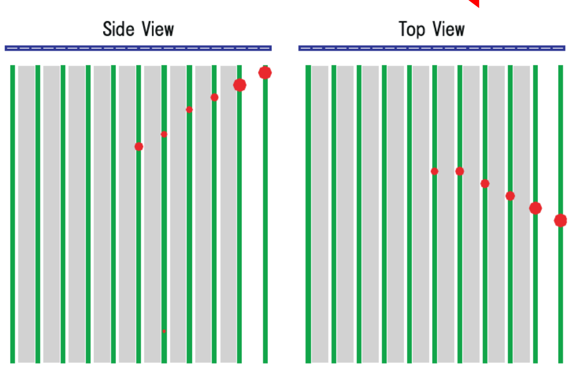
- An array of 16 modules
  - Scintillator-iron tracker
  - nominal accuracy ~ 0.1 mrad

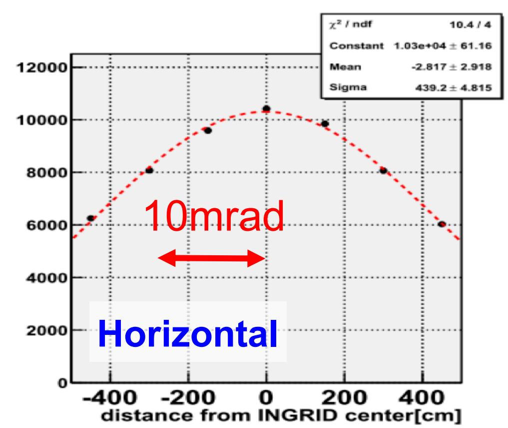


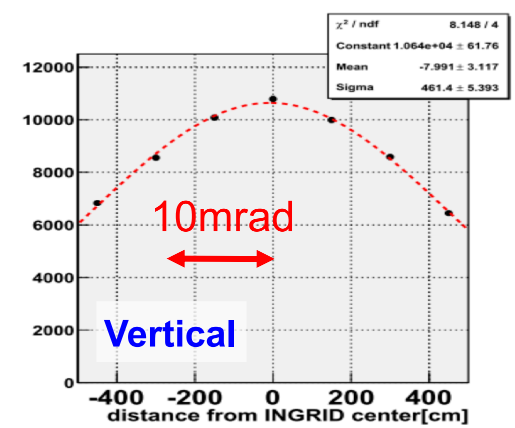


Scintillator
- Organic plastic scintillator
- polystyrene, TiO2 reflector
- PPO, POPOP doping
- Wavelength shifting (WLS) fiber
- SiPM reading





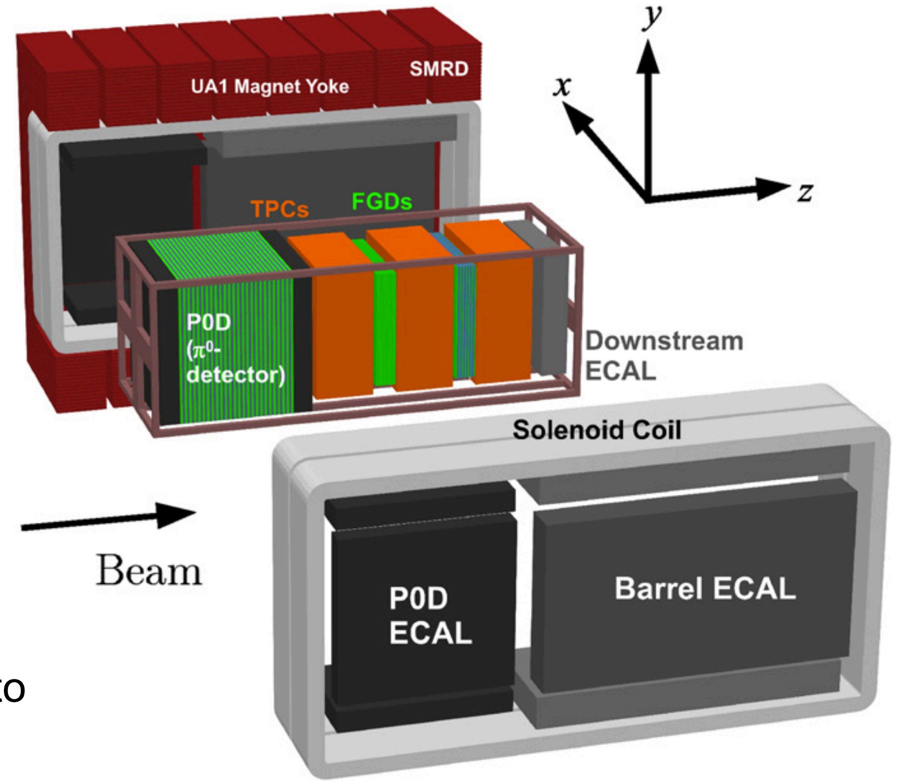




3.2. Off-axis detectors

ND280

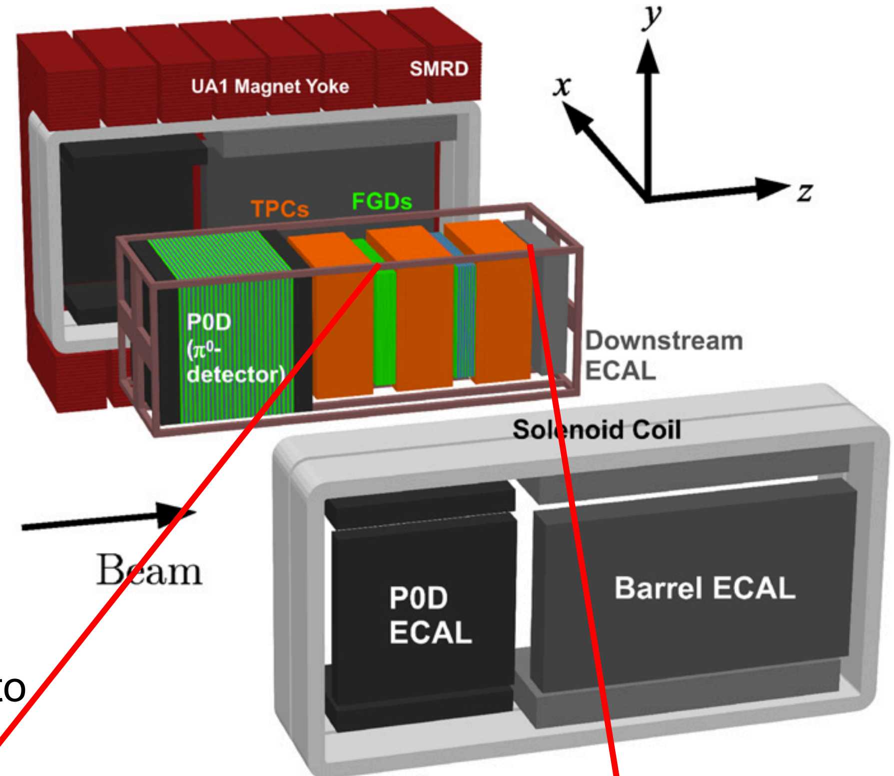
- P0D: Water-scintillator tracker
- FGD: Fully active scintillator tracker
- TPC: Ar gas TPC
- ECal: Lead-scintillator calorimeter
- SMRD: Iron-scintillator tracker
- UA1 magnet



Near detector data

- 14 samples are used for the oscillation analysis to constrain flux and cross-section systematic errors

3.2. Off-axis detectors



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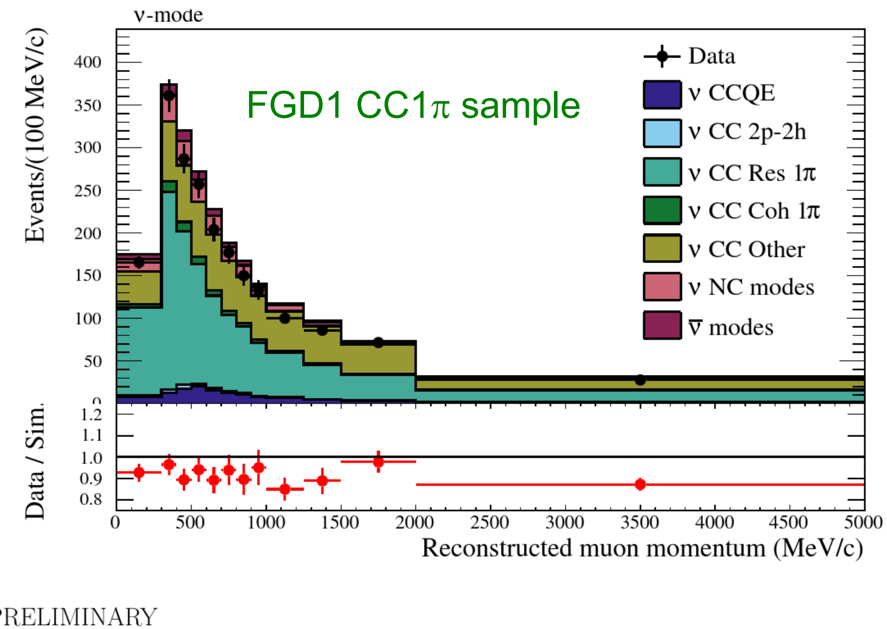
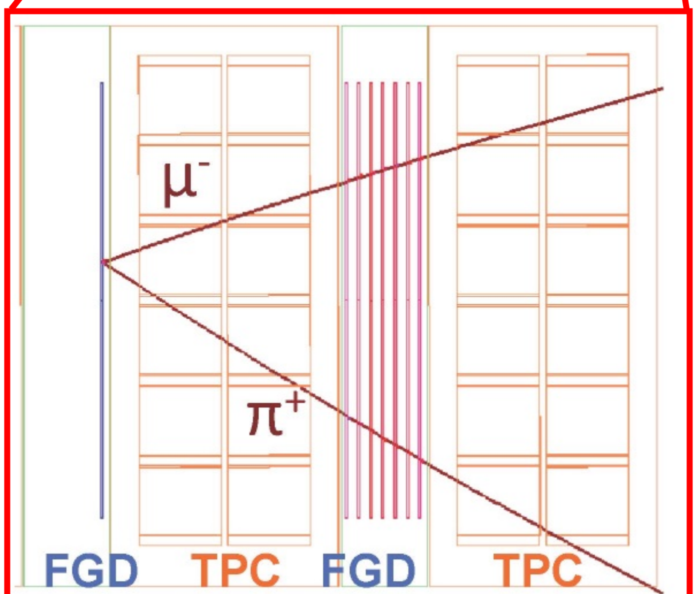
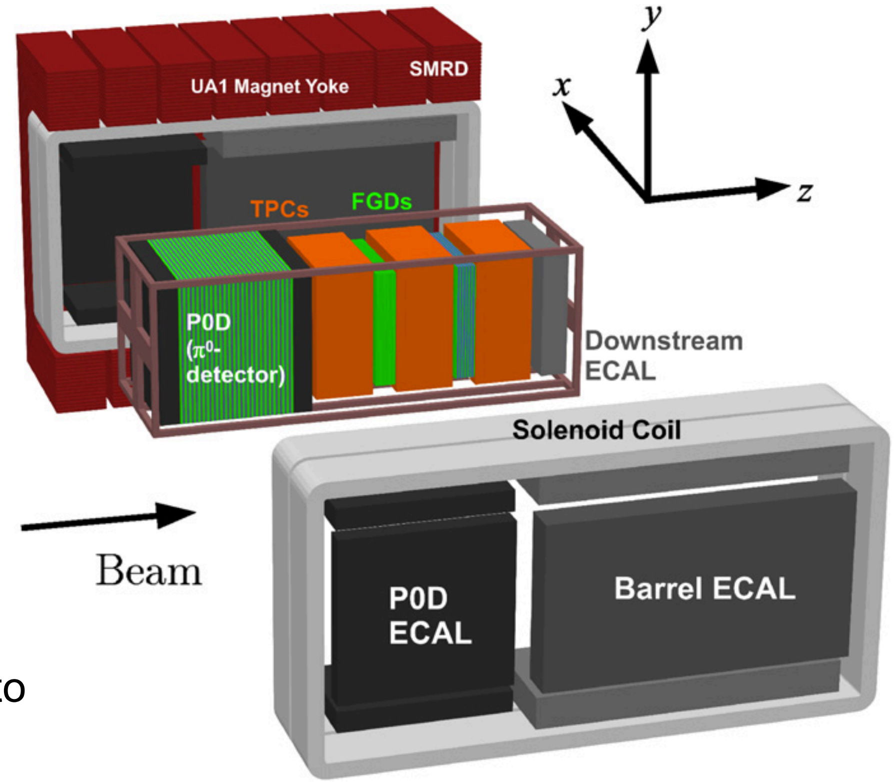
Near detector data

- 14 samples are used for the oscillation analysis to constrain flux and cross-section systematic errors





3.2. Off-axis detectors

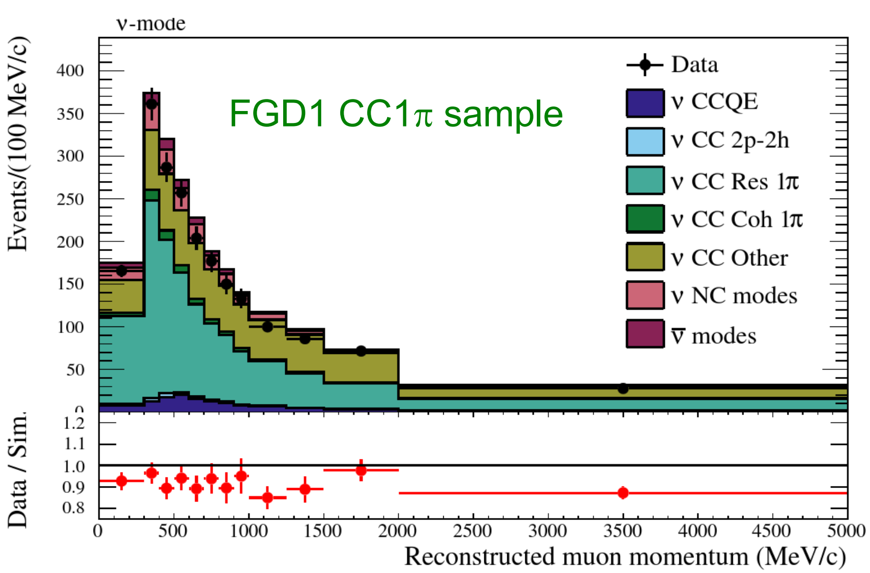


ND280

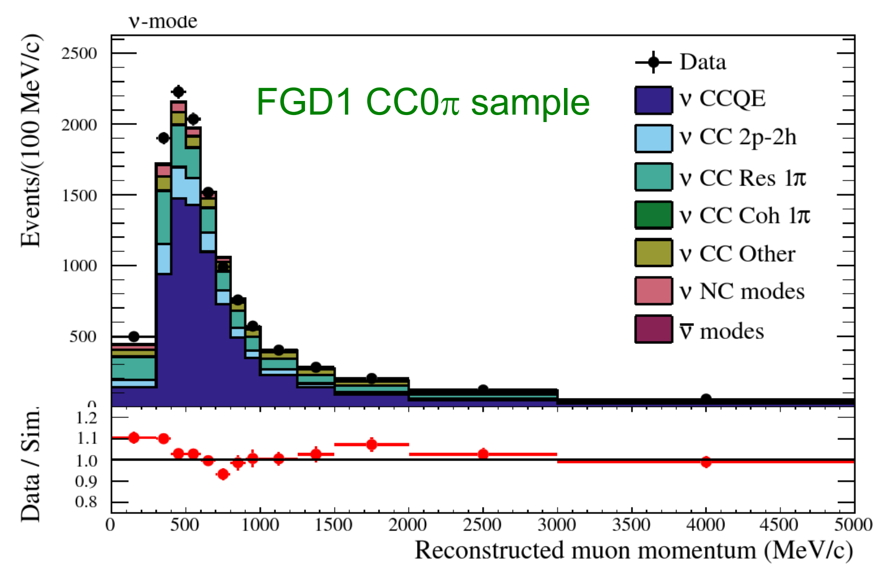
- P0D: Water-scintillator tracker
- FGD: Fully active scintillator tracker
- TPC: Ar gas TPC
- ECal: Lead-scintillator calorimeter
- SMRD: Iron-scintillator tracker
- UA1 magnet

Near detector data

- 14 samples are used for the oscillation analysis to constrain flux and cross-section systematic errors



PRELIMINARY



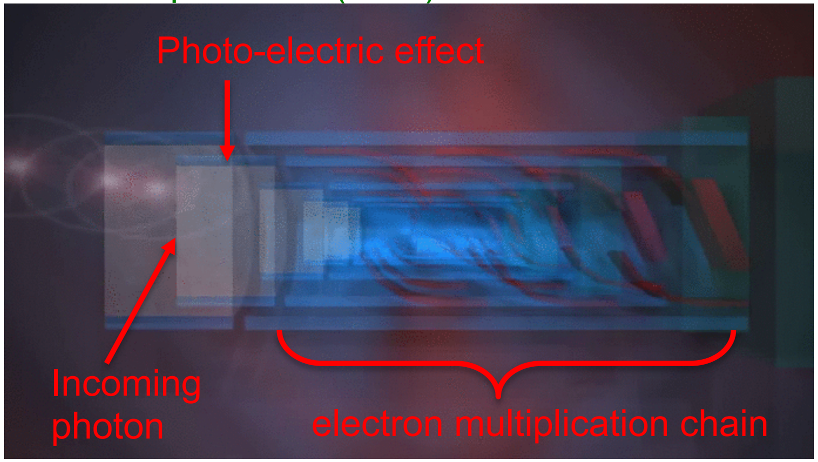
PRELIMINARY

SuperK, NIMA501(2003)418

3.2. Far detector

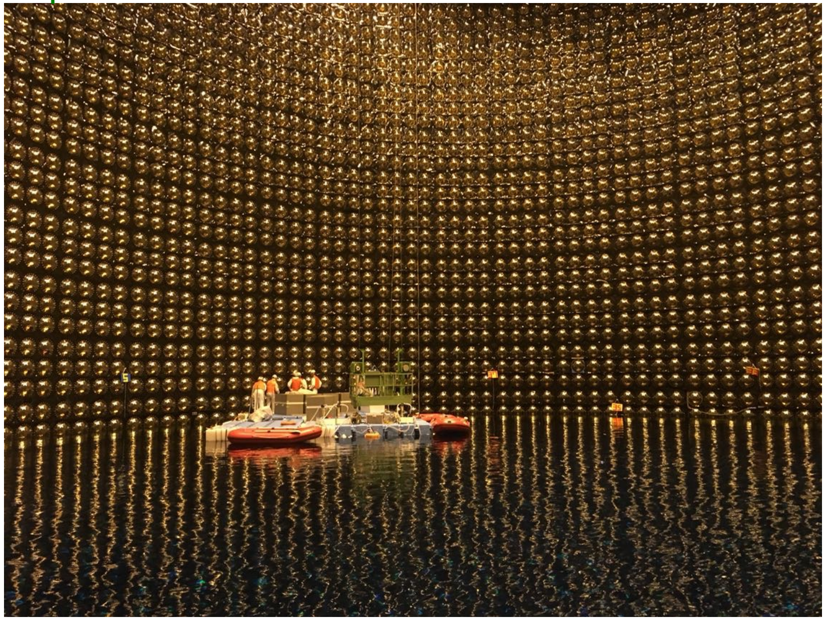
Super-Kamiokande
- 50 kton water Cherenkov detector
- 2015 Nobel prize
- 11,146 20-inch PMTs (inner detector)
- 1,885 8-inch PMTs (outer detector)

Photo-multiplier tube (PMT)



20-inch PMT is quite big...

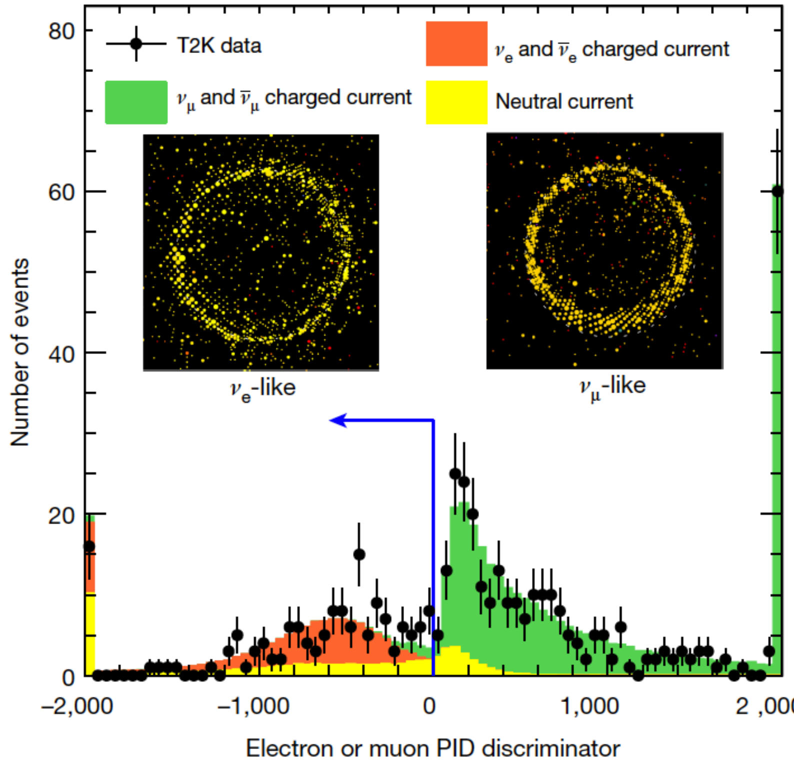
Super-K inner detector



Super-K outer detector

SuperK, NIMA501(2003)418

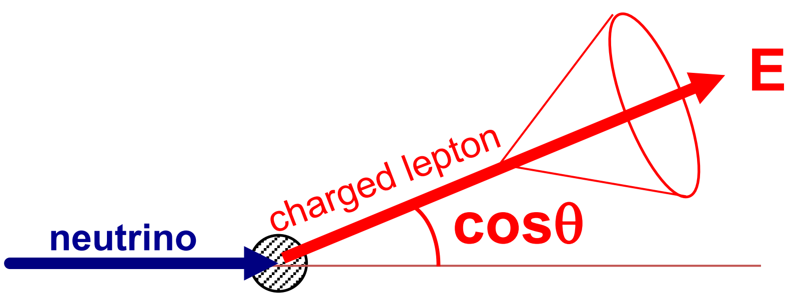
3.2. Far detector



Event reconstruction

- From measured time and charge information from all PMTs, particle identification (PID) and kinematics are reconstructed
- From reconstructed charged lepton kinematics, neutrino energy is reconstructed

$$E_\nu^{QE} = \frac{ME - 0.5m_l^2}{M - E + p\cos\theta}$$



$\nu_e(\bar{\nu}_e)$ measurement has 2 major backgrounds

1. Intrinsic background
$\nu_e(\bar{\nu}_e)$ contamination in the beam (~0.5%)

2. misID background
Gamma rays counted as electron (positron). Majority of them are from neutral current π^o production where one of γ is undetected

$$\nu_\mu + A \rightarrow \nu_\mu + A' + \pi^o, \pi^o \rightarrow \gamma + \not{\gamma}$$

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3.1. Neutrino beam

3.2. Neutrino detector

3.3. Neutrino interaction physics

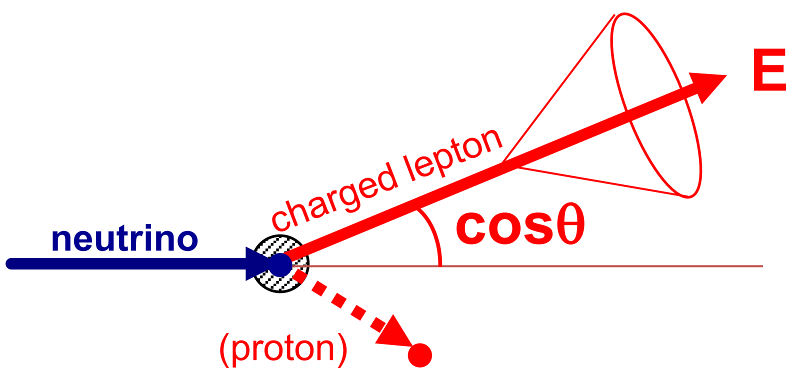
3.4. Oscillation result

3.3. Charged current quasi-elastic (CCQE) scattering

Event reconstruction

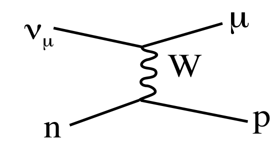
- From measured time and charge information from all PMTs, particle identification (PID) and kinematics are reconstructed
- From reconstructed charged lepton kinematics, neutrino energy is reconstructed

$$E_\nu^{QE} = \frac{ME - 0.5m_l^2}{M - E + p\cos\theta}$$



CCQE is the most abundant interaction at ~1 GeV.

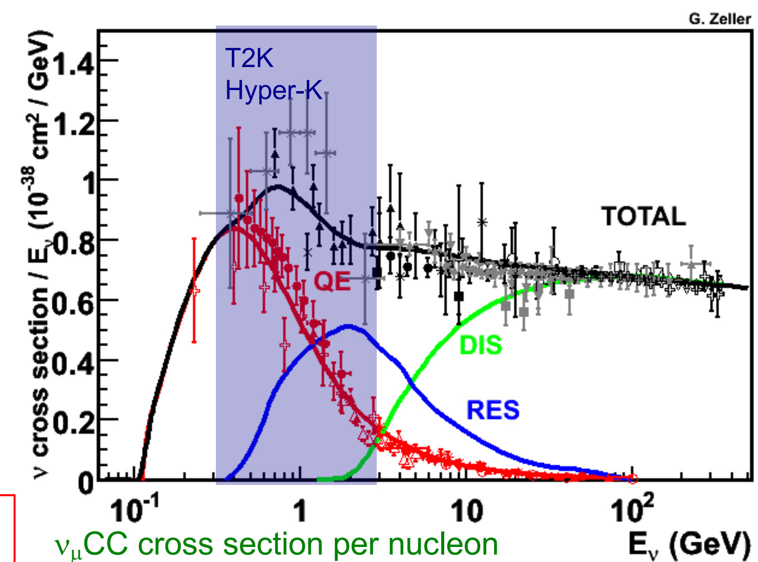
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$(\nu_\mu + X \rightarrow \mu^- + X')$$



Neutrino energy is reconstructed from the observed lepton kinematics

"QE assumption"

1. assuming neutron at rest
2. assuming interaction is CCQE (2-body kinematics)



All neutrino cross-section channels (including CCQE) have large error

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3.3. CCQE puzzle

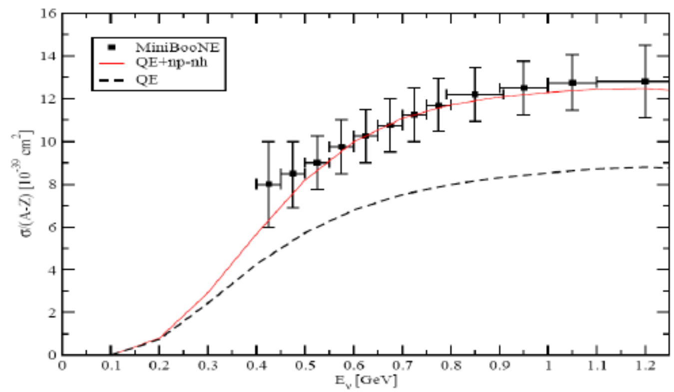
An explanation of this puzzle

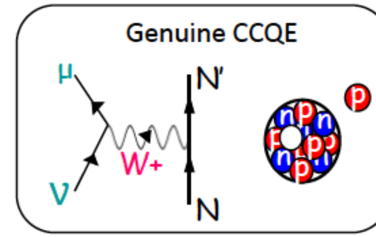
Nuclear correlations

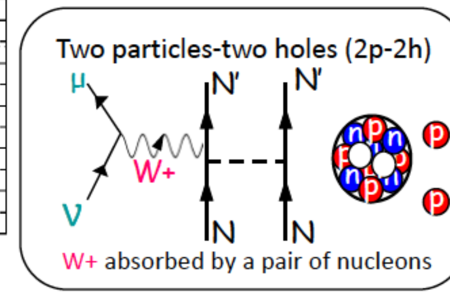
- Martini et al pointed out that neutrino interactions around 1 GeV can be modified ~30% by correlated nucleons (2p2h, 2-body current, meson exchange current, etc)

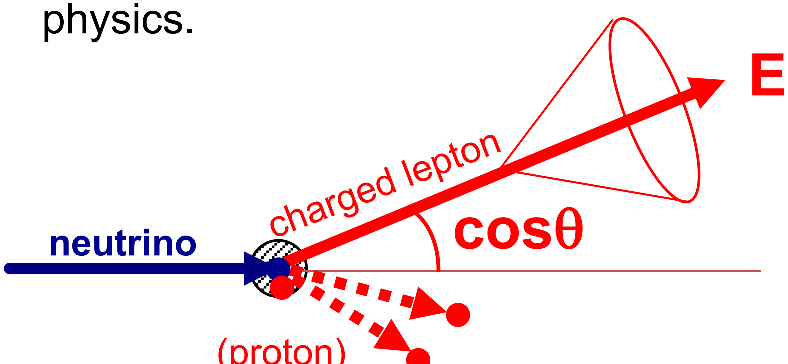
A large community effort (both theorists and experimentalists) to understand the role of nucleon correlations in neutrino interaction physics.

Inclusion of the multinucleon emission channel (np-nh)



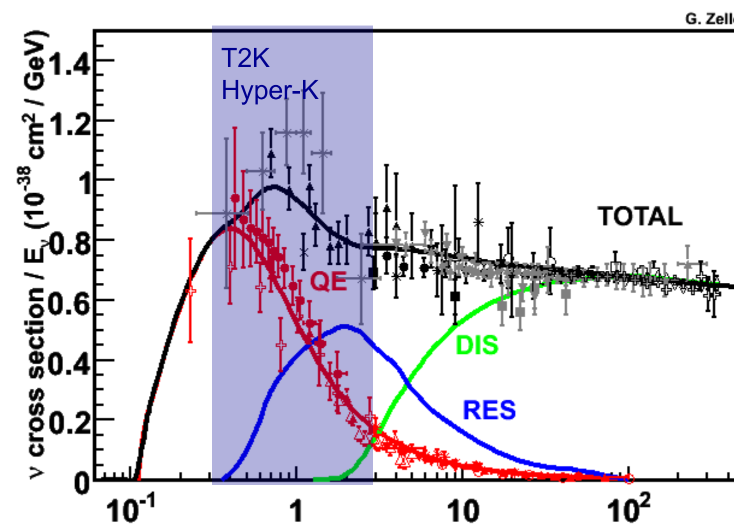






It's not 2-body kinematics

$$E_\nu^{QE} \neq \frac{ME - 0.5m_l^2}{M - E + p\cos\theta}$$



ν_μCC cross section per nucleon

Martini et al,PRC80(2009)065501, TK, Martini, JPhysG45(2017)1

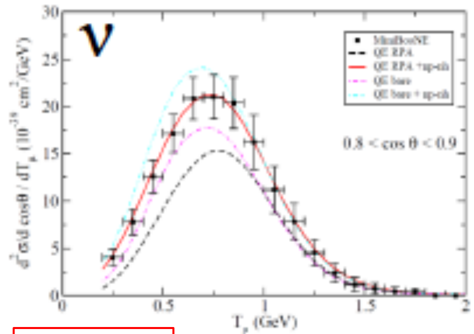
3.3. CCQE puzzle (2020)

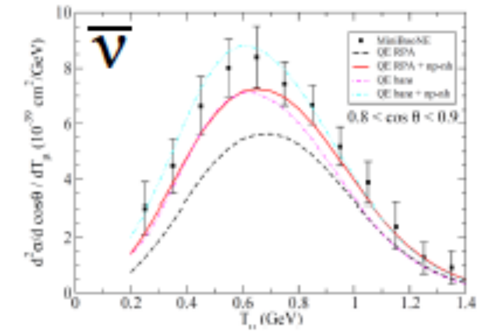
Advanced nuclear models can reproduce MiniBooNE CCQE-like data, but there are large systematics errors on nuclear parameters.

Martini – RPA+2p2h
Nieves – Valencia 2p2h model
SuSA – Superscaling+MEC
Giusti – Relativistic Green's function
Butkevich – RDWIA+MEC

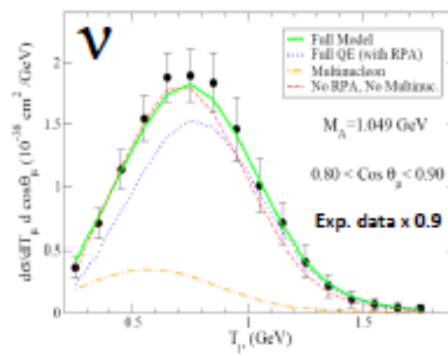
We use Valencia 2p2h model for our simulation

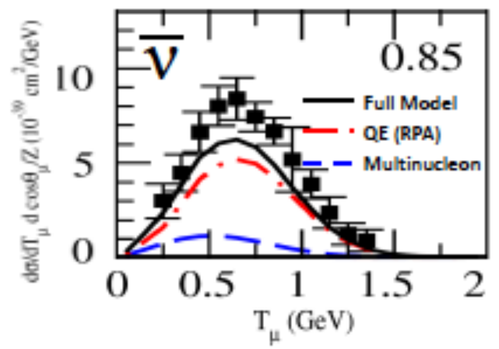
Martini et al



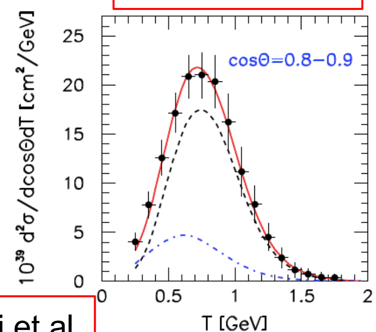


Valencia

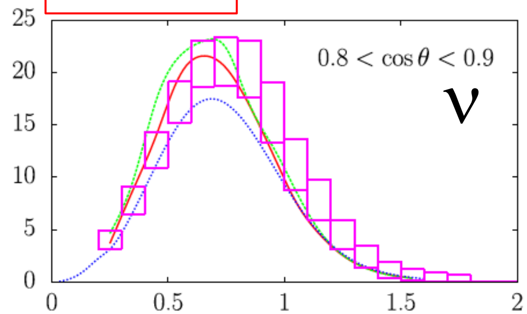




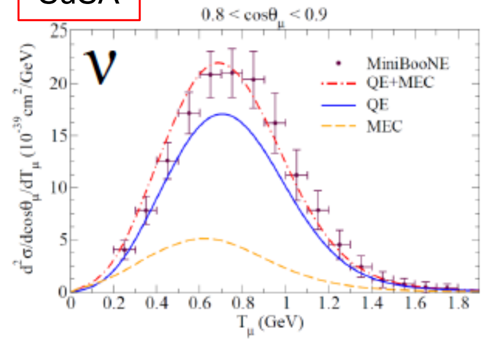
Butkevich et al

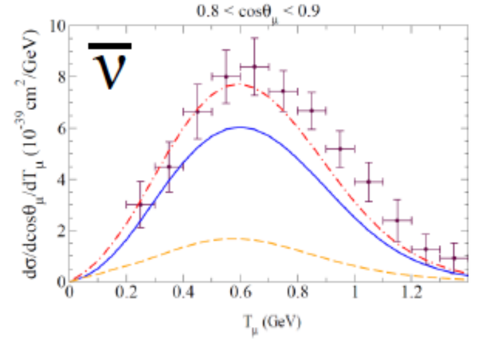


Giusti et al



SuSA





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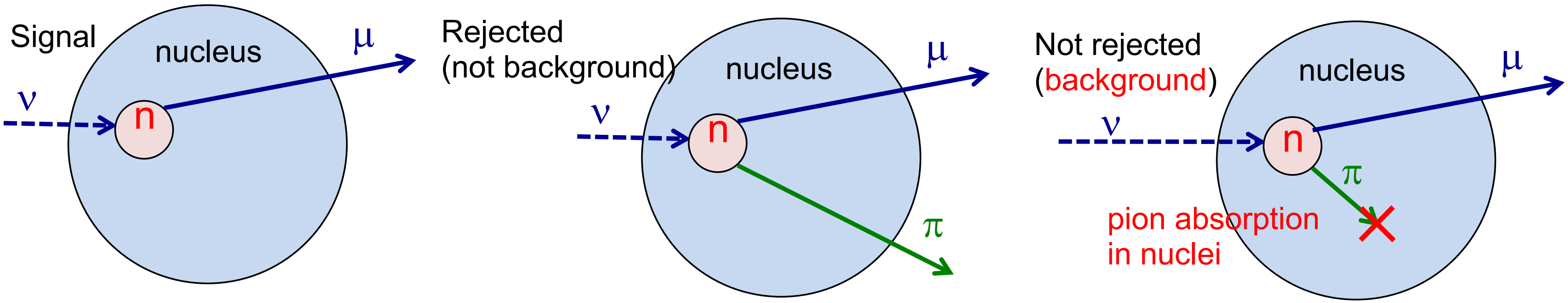
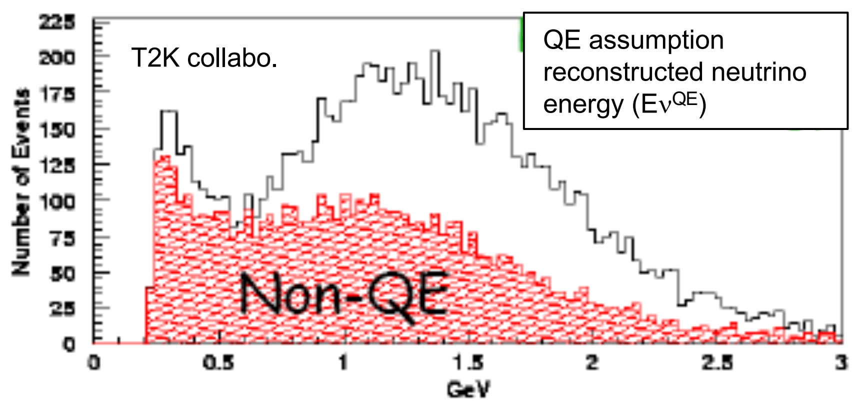
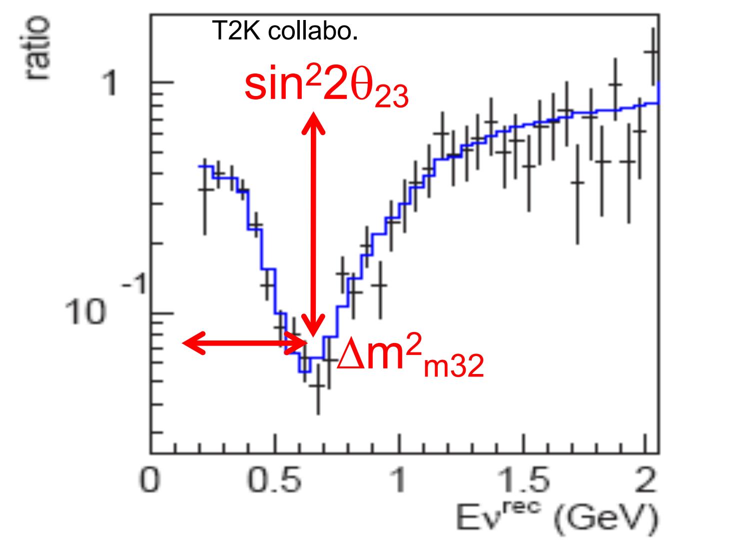
3.3. Neutrino-induced single pion production

Baryon resonant pion production + final state interaction (FSI)
- Neutrino induced pion productions have large errors
- Final state interaction of hadrons have large errors



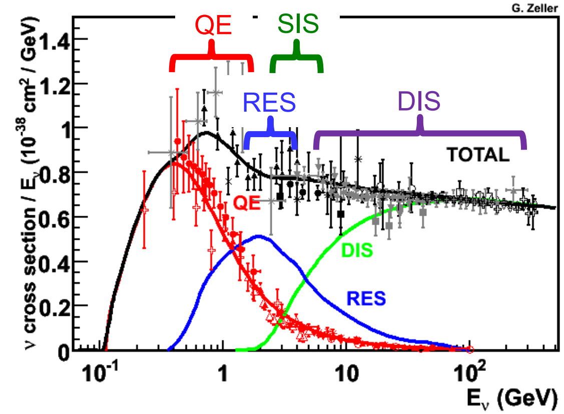
muon neutrino disappearance simulation





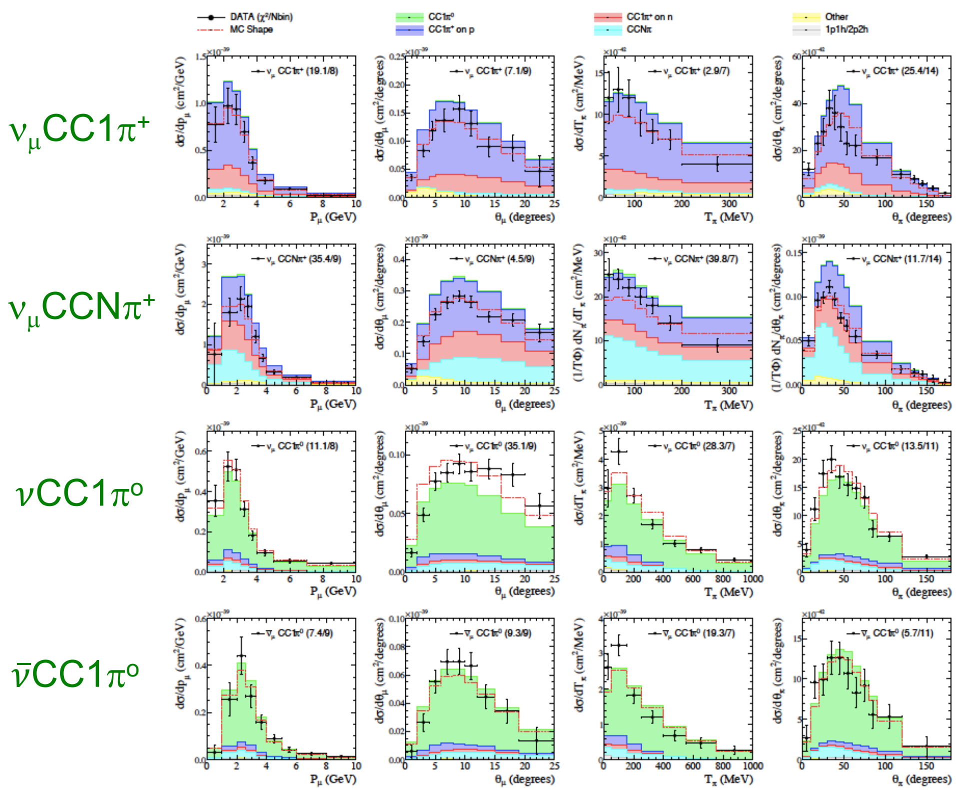
MINERvA,PRD100(2019)072005
MiniBooNE,PRD83(2011)052009, Lalakulich et al,PRC87(2013)014602

3.3. Pion puzzle (2020)



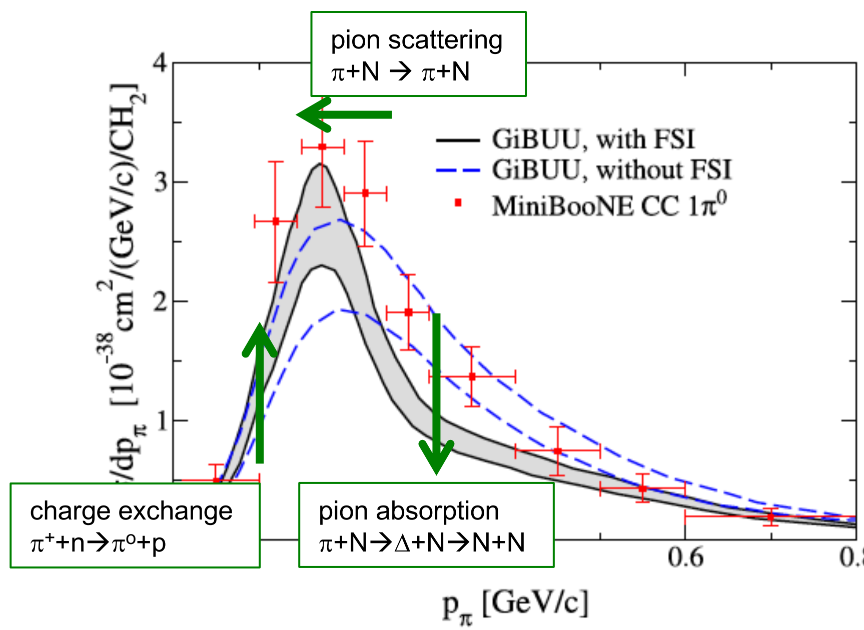
MINERvA simultaneous fit for 4 different data set

- Most advanced study in this community
- Not conclusive on baryon resonance and FSI models



GiBUU vs. MiniBooNE $CC\pi^o$ data

- You need to simulate both $CC\pi^o$ and $CC\pi^\pm$, and FSI including inelastic scattering, charge exchange, pion absorption



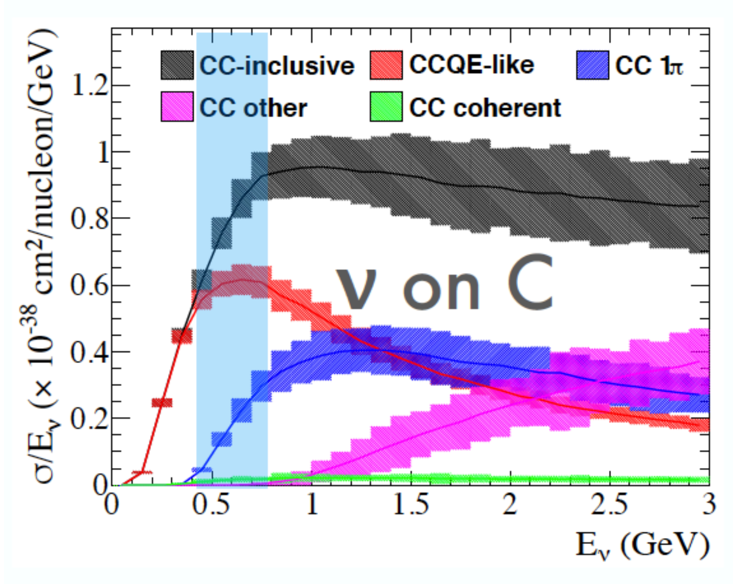
3.3. Neutrino interaction physics, external data constraints

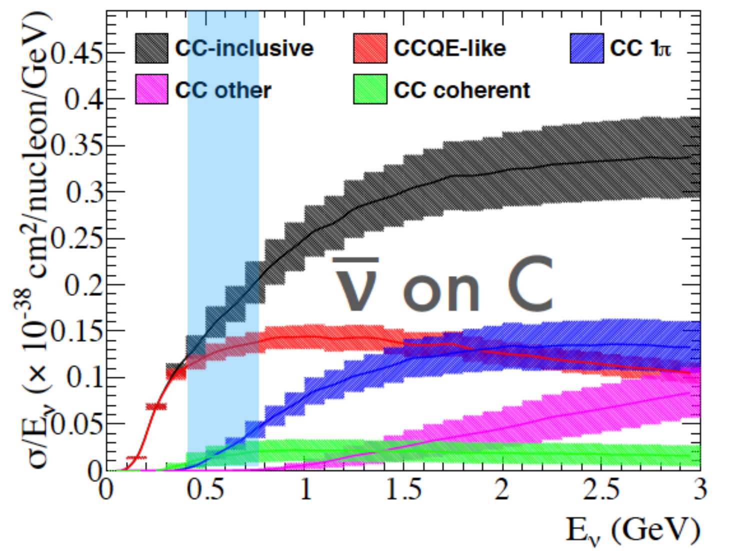
We accept large systematic errors on neutrino interaction models

We need to constrain these errors internally, using the data from the ND280 near detector data

PDG (2020)
Section 43. Monte Carlo Neutrino Generators
Section 51. Neutrino Cross Section Measurements

NuSTEC (https://nustec.fnal.gov/)
New theory-experiment collaboration to promote neutrino interaction physics





3.1. Neutrino beam

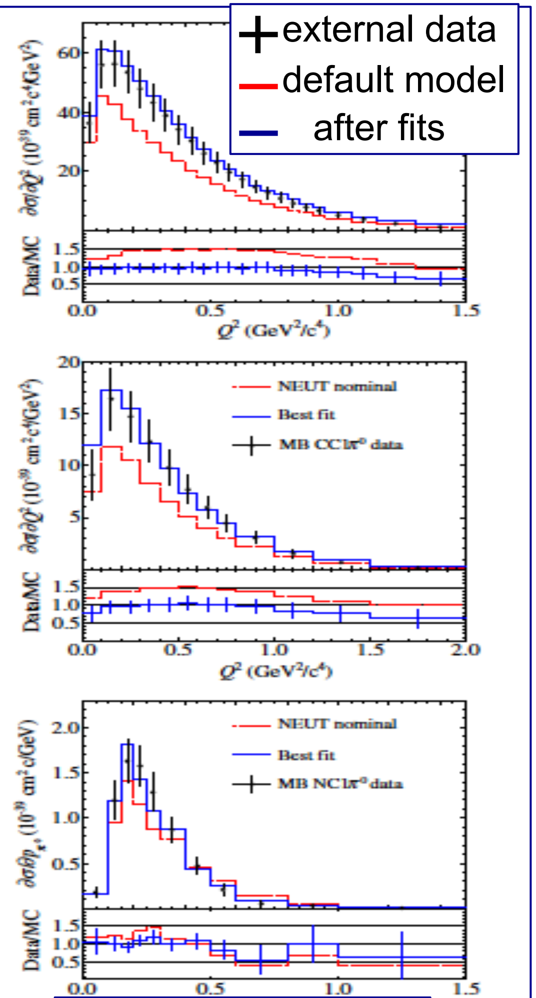
3.2. Neutrino detector

3.3. Neutrino interaction physics

3.4. Oscillation result

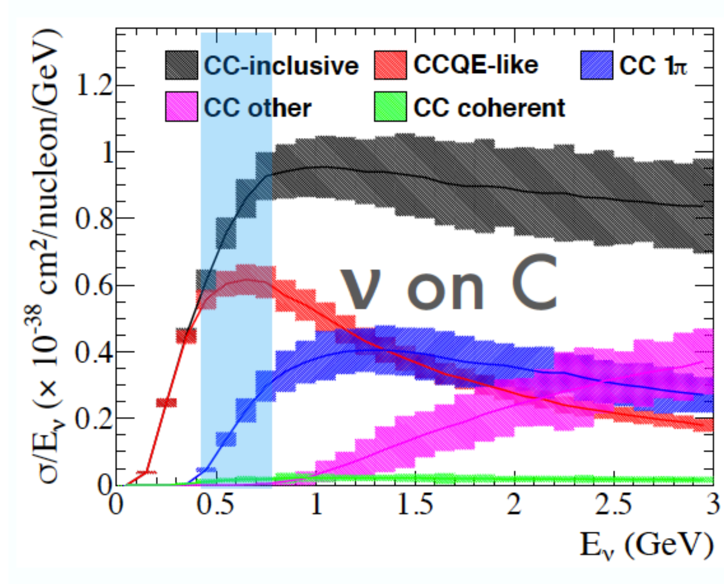
3.4. T2K oscillation results

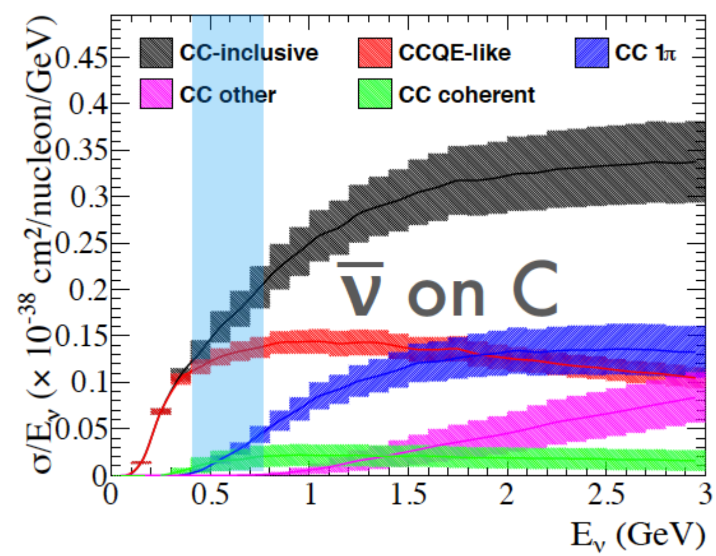
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics





3.4. T2K oscillation results

External constraint

MiniBooNE, MINERvA, SciBooNE

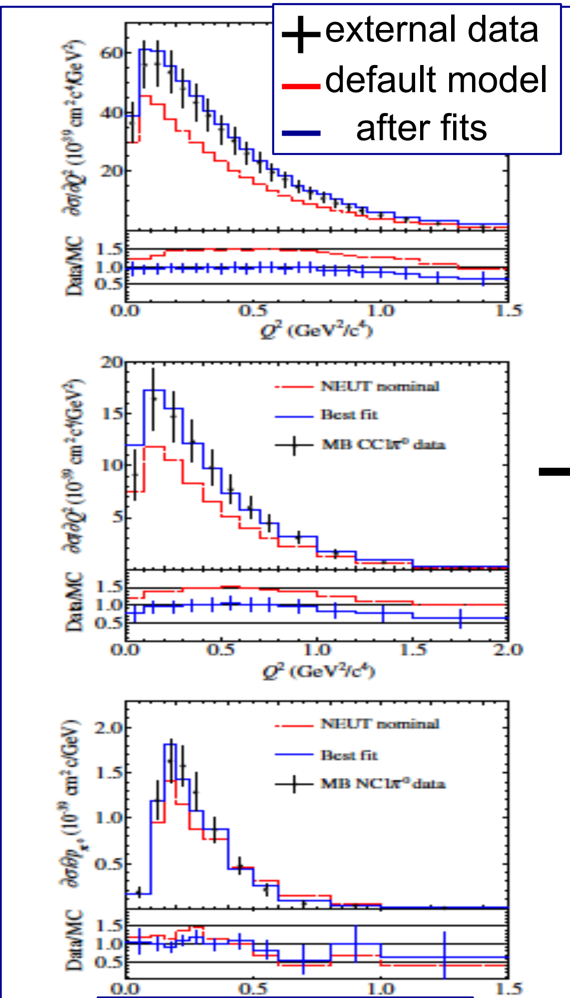
K2K, MINOS, Bubble chambers

Internal constraint

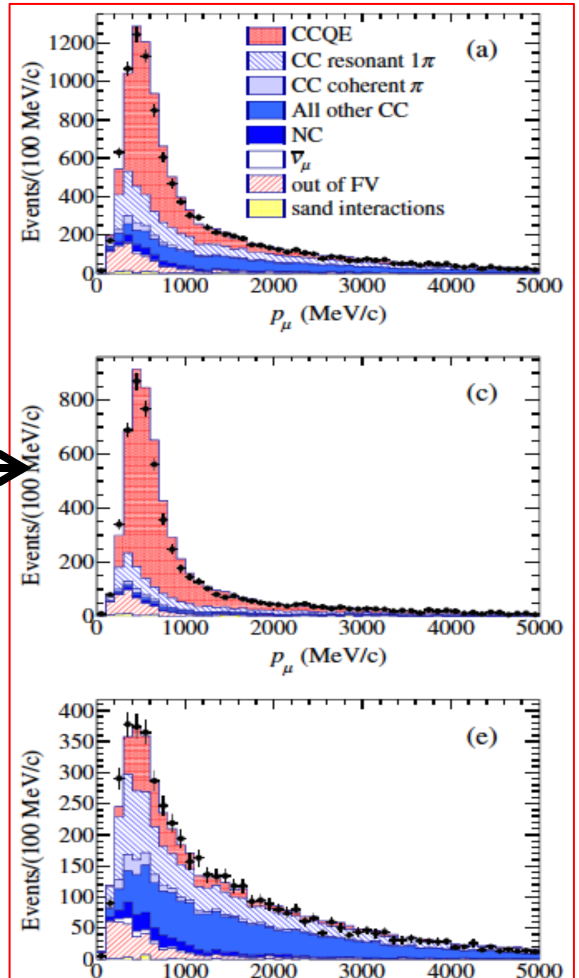
Near detector

oscillation non-sensitive channels

Internal data can constrain systematic errors for the event rate (flux x cross-section)



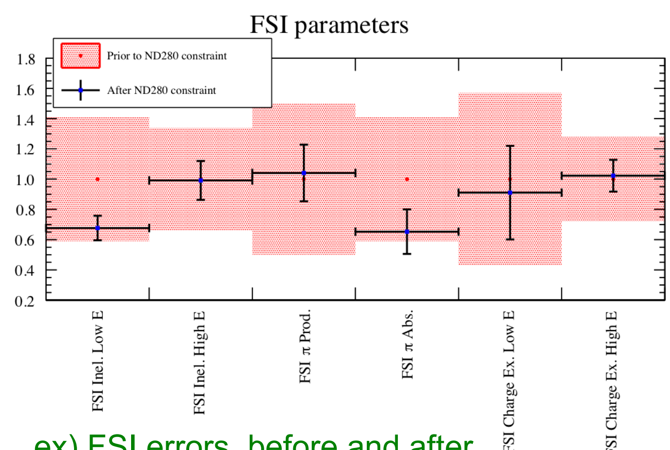
External data fit



T2K ND280 data fit

SuperK sample systematic error

sample	Without ND280	With ND280
ν μ-like ring	14.6%	5.1%
ν e-like ring	16.9%	8.8%
$\bar{\nu}$ μ-like ring	12.5%	4.5%
$\bar{\nu}$ e-like ring	14.4%	7.1%



ex) FSI errors, before and after internal constraints

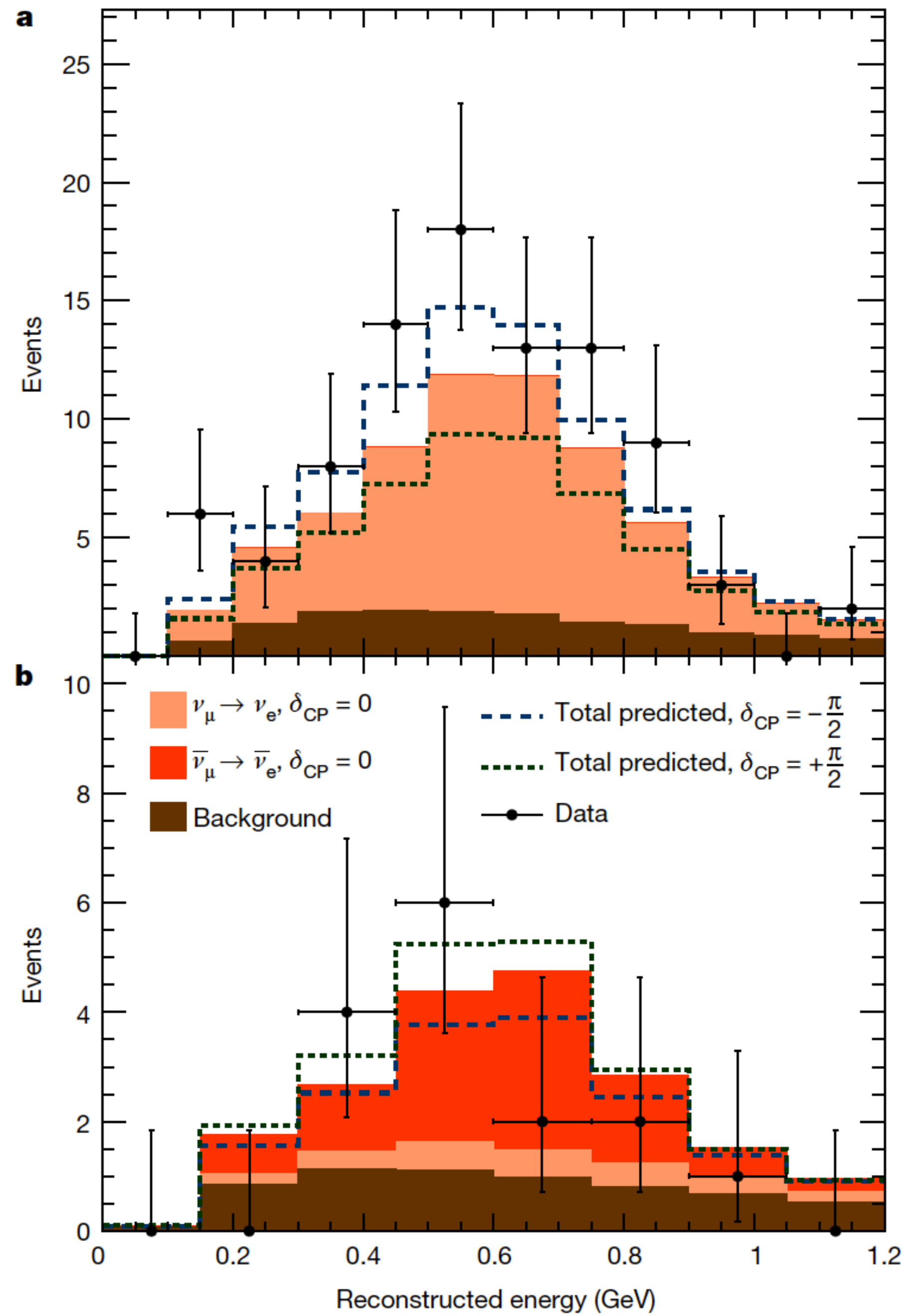
3.4. T2K oscillation results

SuperK data prefer a model with negative CP violation angle (~-π/2)

- Enhancement of $P(\nu_\mu \to \nu_e)$
- Suppression of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15



2009 – 2018 data

- Neutrino mode, 1.49E21 POT
- Antineutrino mode, 1.64E21 POT

T2K, Nature 580 (2020) 339

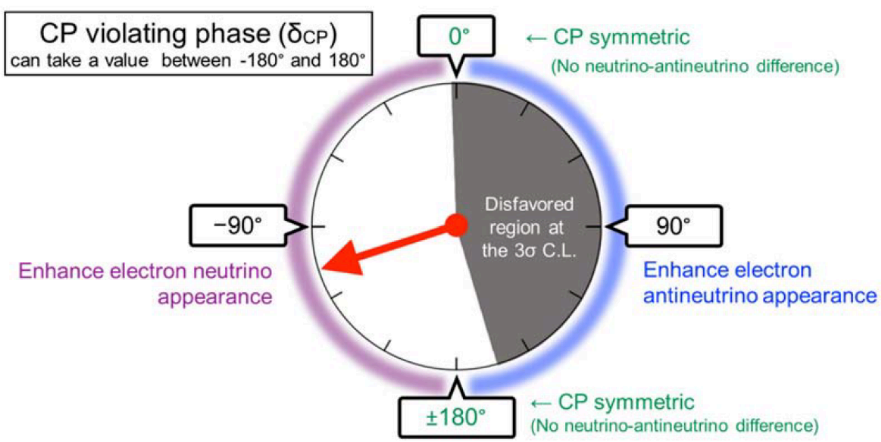
3.4. T2K oscillation results

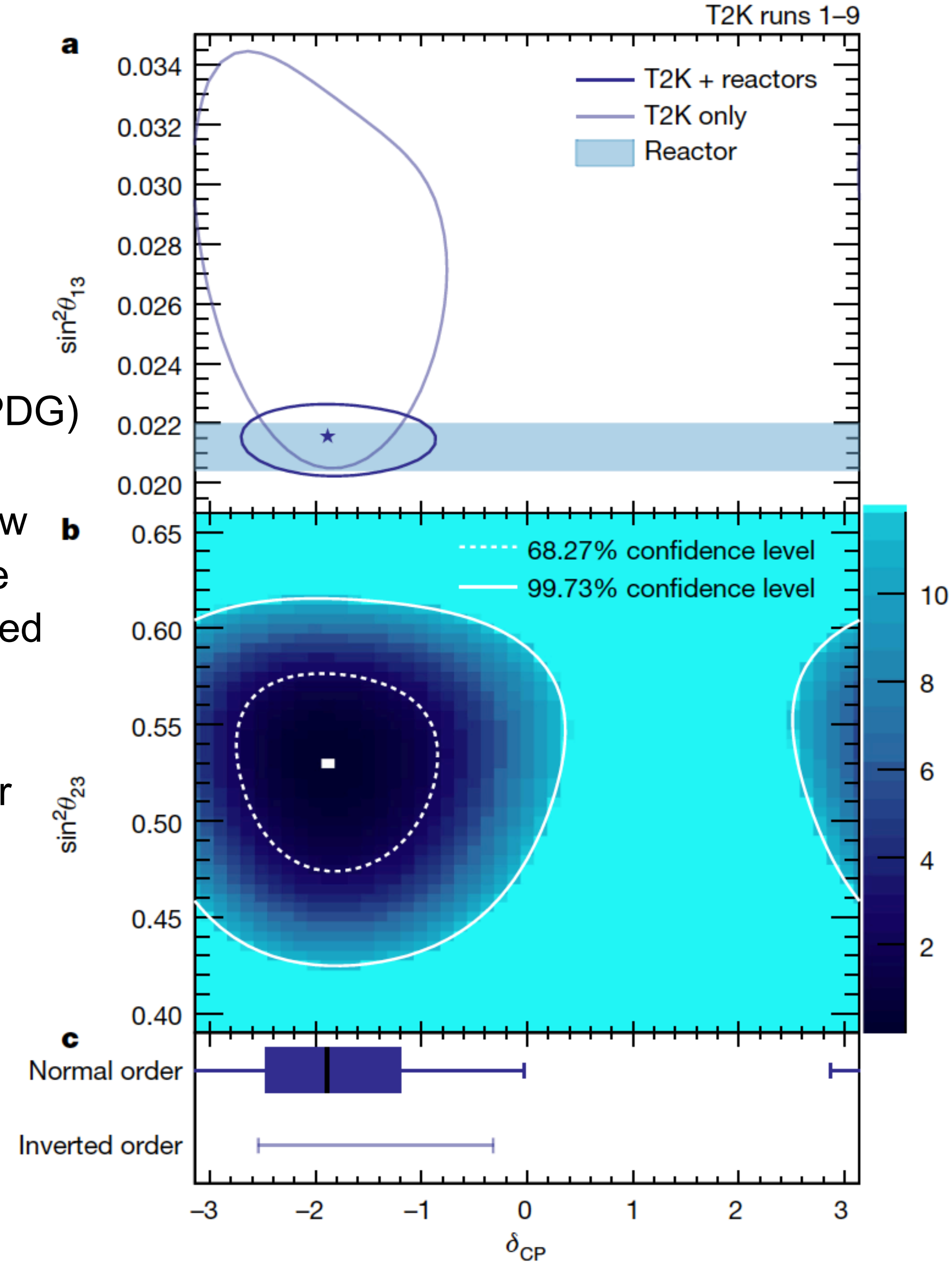
All oscillation parameters are fit by assuming normal or inverted mass ordering.

- δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32} : flat prior
- $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, Δm^2_{21} : external constraint (PDG)

Now the 3σ contour is closed, more data or new generation experiments can find the right value from here (Note, zero CP violation is not rejected with 3σ).

Normal ordering is favoured with 89% posterior probability.





Conclusion

T2K is the second generation long-baseline neutrino oscillation experiment in Japan

Neutrinos from the J-PARC neutrino beam are measured by the Super-Kamiokande detector

2009-2018 data shows asymmetric oscillations, and neutrino oscillation is enhanced, and antineutrino oscillation is suppressed. This can be interpreted as negative CP violation phase.

$\delta CP=0$ is rejected more than 2σ, and 3σ interval is $[-3.41, -0.03]$ (normal ordering), and $[-2.54, -0.32]$ (inverted ordering)