Experimental Neutrino Physics

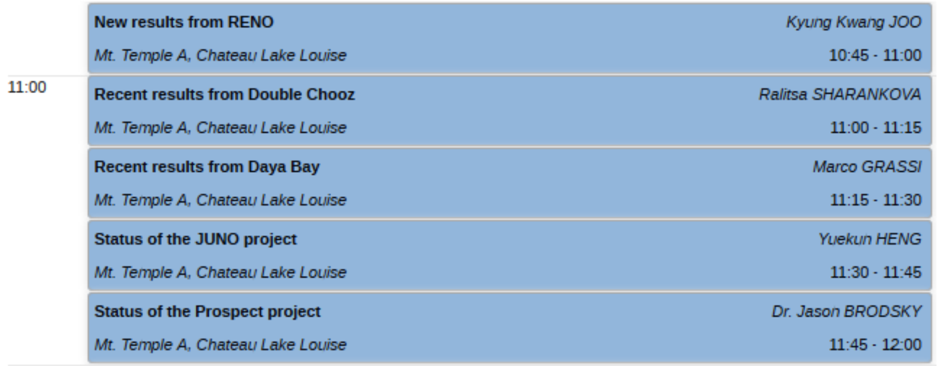
Jonathan Link

Center for Neutrino Physics, Virginia Tech

Lake Louise Winter Institute

February 11, 2016

Talks in the Neutrino Sessions



	Talk	Speaker	Room	Time
	New results from RENO	*Kyung Kwang JOO*	*Mt. Temple A, Chateau Lake Louise*	10:45 - 11:00
11:00	**Recent results from Double Chooz**	*Ralitsa SHARANKOVA*	*Mt. Temple A, Chateau Lake Louise*	11:00 - 11:15
	Recent results from Daya Bay	*Marco GRASSI*	*Mt. Temple A, Chateau Lake Louise*	11:15 - 11:30
	Status of the JUNO project	*Yuekun HENG*	*Mt. Temple A, Chateau Lake Louise*	11:30 - 11:45
	Status of the Prospect project	*Dr. Jason BRODSKY*	*Mt. Temple A, Chateau Lake Louise*	11:45 - 12:00

12:00
13:00
14:00
15:00
16:00
17:00

Nota bene:
Galactic Supernova
will occur here!

	Talk	Speaker	Room	Time
	New results from MINERvA	*Vittorio PAOLONE*	*Mt. Temple A, Chateau Lake Louise*	17:30 - 17:50
18:00	**Recent results from MicroBoone**	*Roxanne GUENETTE*	*Mt. Temple A, Chateau Lake Louise*	17:50 - 18:05
	Latest results from MINOS+	*Will FLANAGAN*	*Mt. Temple A, Chateau Lake Louise*	18:05 - 18:20
	Latest results from NOvA	*Evan NINER*	*Mt. Temple A, Chateau Lake Louise*	18:20 - 18:35
	Recent oscillation results from T2K	*Georgios CHRISTODOULOU*	*Mt. Temple A, Chateau Lake Louise*	18:35 - 18:50
19:00	**The Charged-Current Cross Section on Water in the T2K Near Detector**	*Enrico SCANTAMBURLO*	*Mt. Temple A, Chateau Lake Louise*	18:50 - 19:05
	Status of the DUNE project	*Norm BUCHANAN*	*Mt. Temple A, Chateau Lake Louise*	19:05 - 19:20
	Status of the Hyper-Kamiokande project	*Hirohisa A. TANAKA*	*Mt. Temple A, Chateau Lake Louise*	19:20 - 19:35

Today

Tomorrow

	Talk	Speaker	Room	Time
	status of the KM3NeT project	*Alexis COLEIRO*	*Mt. Temple A, Chateau Lake Louise*	08:30 - 08:45
	Status of the ARA project	*Ming-Yuan LU*	*Mt. Temple A, Chateau Lake Louise*	08:45 - 09:00
09:00	**Latest results from Opera**	*Andrea LONGHIN*	*Mt. Temple A, Chateau Lake Louise*	09:00 - 09:15
	Latest results from IceCube point source searches	*Stefan COENDERS*	*Mt. Temple A, Chateau Lake Louise*	09:15 - 09:30
	Latest results from CUORE-0 and status of CUORE	*Brian ZHU*	*Mt. Temple A, Chateau Lake Louise*	09:30 - 09:45
	EXO-200 results and current status	*Fabrice RETIERE*	*Mt. Temple A, Chateau Lake Louise*	09:45 - 10:00
10:00	**Tea break**		*Mt. Temple A, Chateau Lake Louise*	10:00 - 10:15
	Status of the Majorana experiment	*Benjamin SHANKS*	*Mt. Temple A, Chateau Lake Louise*	10:15 - 10:30
	Status of the SNO+ project	*David AUTY*	*Mt. Temple A, Chateau Lake Louise*	10:30 - 10:45
	Status of the Katrin project	*Florian FRAENKLE*	*Mt. Temple A, Chateau Lake Louise*	10:45 - 11:00

Open Questions in Neutrino Physics

Types of Neutrino Experiments

Neutrino mass hierarchy: normal or inverted?

Is there CP violation in neutrino mixing?

Are neutrinos their own antiparticle? (Dirac vs. Majorana)

How many neutrinos are there? (Sterile neutrinos?)

What is the absolute neutrino mass scale?

Astrophysical neutrinos?

Related Talks in the Neutrino Sessions

RENO (Joo)
Double Chooz (Sharankova)
Daya Bay (Grassi)
MINOS+ (Flanagan)
NOvA (Niner)
T2K (Christodoulou)
Opera (Longhin)

JUNO (Heng)
DUNE (Buchanan)
Hyper-K (Tanaka)
Prospect (Brodsky)
MicroBooNE (Guenette)

CUORE (Zhu)
EXO/nEXO (Retiere)
Majorana (Shanks)
SNO+ (Auty)

Katrin (Fraenkle)

Neutrino Telescopes

KM3NeT (Coleiro)
ARA (Lu)
IceCube (Coenders)

JUNO (Heng)
DUNE (Buchanan)
Hyper-K (Tanaka)

Neutrino Cross Sections

MINERvA (Paolone)
T2K (Scantamburlo)

But Let’s Start With What We Already Know

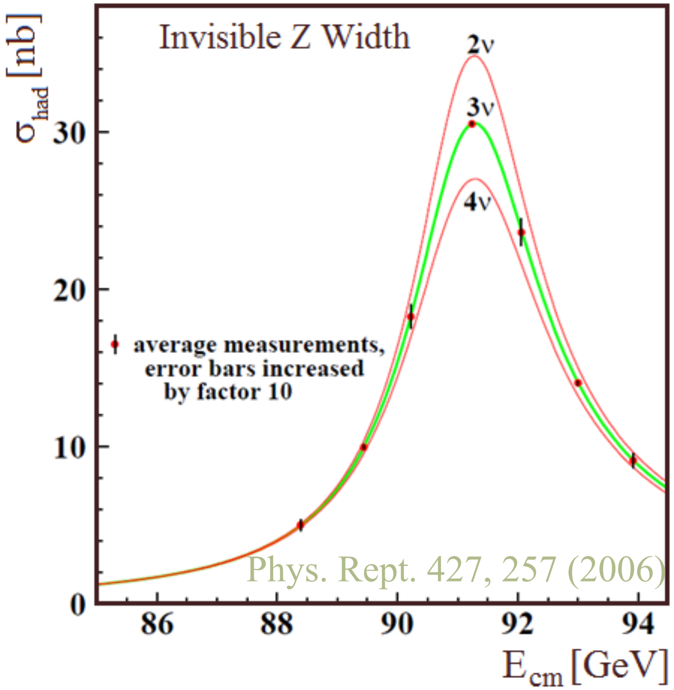
There are three neutrino flavors:

ν_e

ν_μ

ν_τ

LEP tells us that there are exactly three that couple to the Z boson



Phys. Rept. 427, 257 (2006)

Neutrinos Have Mass and They Mix

2015 Nobel Prize in Physics:
Takaaki Kajita of Super-K and Arthur McDonald of SNO

2016 Breakthrough Prize in Fundamental Physics:
To the members of the Super-K, SNO KamLAND, Daya Bay, K2K and T2K Collaborations.

Neutrinos Have Mass and They Mix

Neutrino mixing is governed by the PMNS mixing matrix which relates the mass eigenstates to the flavor eigenstates:

Flavor Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Eigenstates

PMNS Mixing Matrix

In the simplest approximation, the probability that a neutrino, which started out as a ν_α, is detected as a ν_β is given by:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\Delta m_{ij}^2 L/4E_\nu\right)^*$$

where $\Delta m_{ij}^2 = m_i^2 - m_j^2$

* This two neutrino approximation gives a serviceable representation of the data that we have so far, but going forward it will no longer be a sufficient.

The Neutrino Mixing Matrix

The PMNS mixing matrix is constructed as the product of three independent rotations (a unitary matrix with three mixing angles and one phase)

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

Such that:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & e^{i\delta}s_{13} \\ -s_{12}c_{23} - e^{i\delta}s_{13}c_{12}s_{23} & c_{12}c_{23} - e^{i\delta}s_{13}s_{12}s_{23} & s_{23}c_{13} \\ s_{12}s_{23} - e^{i\delta}s_{13}c_{12}c_{23} & -c_{12}s_{23} - e^{i\delta}s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}$$

The three mixing angles have all been measured,

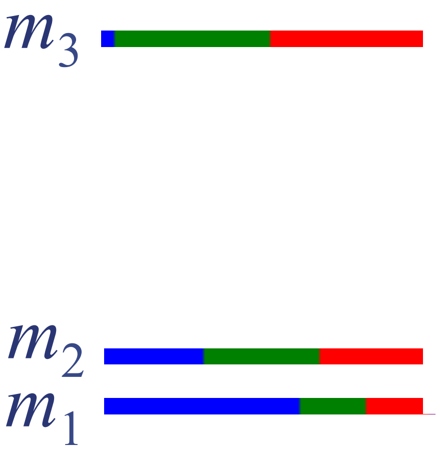
but the CP violating phase, δ, is still unknown.

The Neutrino Mass Scale and Hierarchies

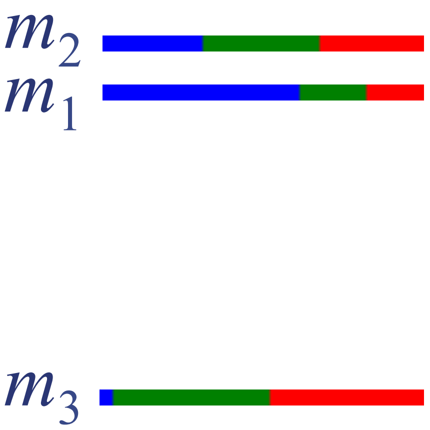
In addition to the four mixing matrix parameters, there are two independent Δm^2 scales (Δm_{21}^2 and Δm_{32}^2)

$$\Delta m_{31}^2 = m_{32}^2 + m_{21}^2$$

$$\Delta m_{31}^2 = m_{32}^2 - m_{21}^2$$



Or

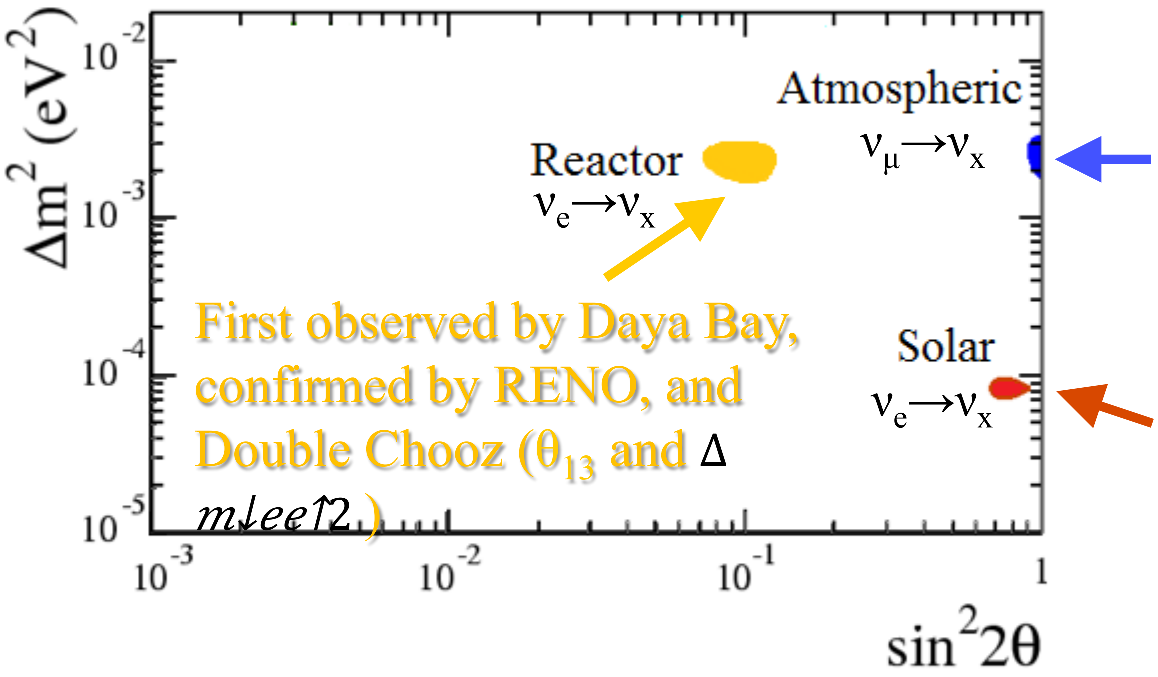


Normal Hierarchy

Inverted Hierarchy

In the Inverted Hierarchy both Δm_{31}^2 and Δm_{32}^2 are negative.

Neutrino Oscillation Data



First observed by Daya Bay, confirmed by RENO, and Double Chooz (θ_{13} and Δm_{ee}^2)

Seen by Super-K, confirmed by K2K, Minos, T2K and NOvA (θ_{23} and $\Delta m_{\mu\mu}^2$)

First observed by Ray Davis. Nailed down by Super-K, SNO and KamLAND. Dominated by mixing of mass states 1 and 2 (θ_{12} and Δm_{21}^2)

The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent.

Specifically, Δm_{ee}^2 and $\Delta m_{\mu\mu}^2$, which are different linear combinations of Δm_{31}^2 and Δm_{32}^2, agree to within Δm_{21}^2.

The Nuances of $\nu_\mu \rightarrow \nu_e$ Appearance

Recall, the ν_e Disappearance Probability:

$$P(\nu_e \nrightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2(\Delta m_{ee}^2 \; L/4E)$$

Appearance Probability (in vacuum):

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m_{\mu\mu}^2 \; L/4E)$$

Atmospheric

$$+ \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(\Delta m_{21}^2 \; L/4E)$$

Solar

$$\mp J \sin\delta \sin(\Delta m_{\mu\mu}^2 \; L/4E)$$

CP Violating

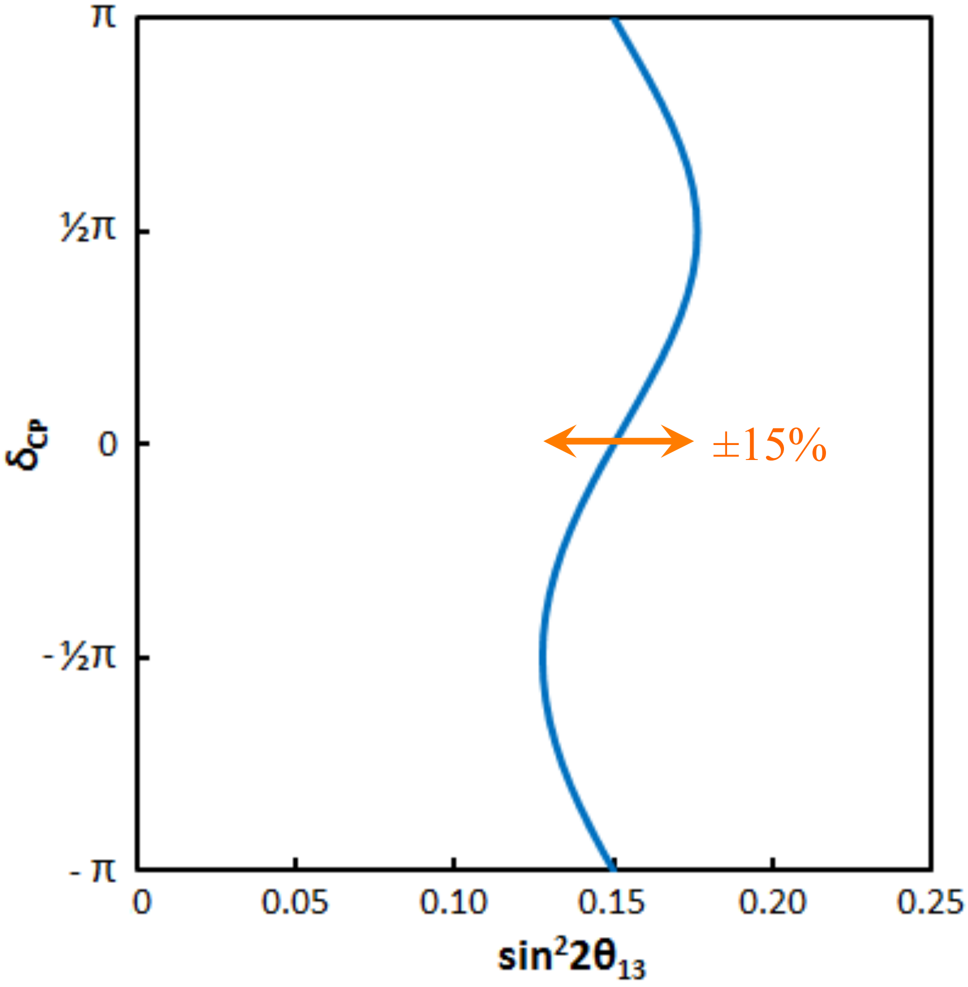
$$+ J \cos\delta \cos(\Delta m_{\mu\mu}^2 \; L/4E)$$

Interference Terms

with $J = \cos\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin(\Delta m_{\mu\mu}^2 \; L/4E) \sin(\Delta m_{21}^2 \; L/4E)$

Impact of CP Phase on the Parameters

With a measured appearance rate in a long-baseline experiment, the value of $\sin^2 2\theta_{13}$ is dependent on the CP phase, δ…



See LBL talks on
NOvA by Niner
T2K by Christodoulou
MINOS+ by Flanagan
DUNE by Buchanan
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$+ \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(\Delta m{\downarrow}21{\uparrow}2\ \ L/4E)$ Solar

ν

ν

$\mp J \sin\delta \sin(\Delta m{\downarrow}\mu\mu{\uparrow}2\ \ L/4E)$ CP Violating

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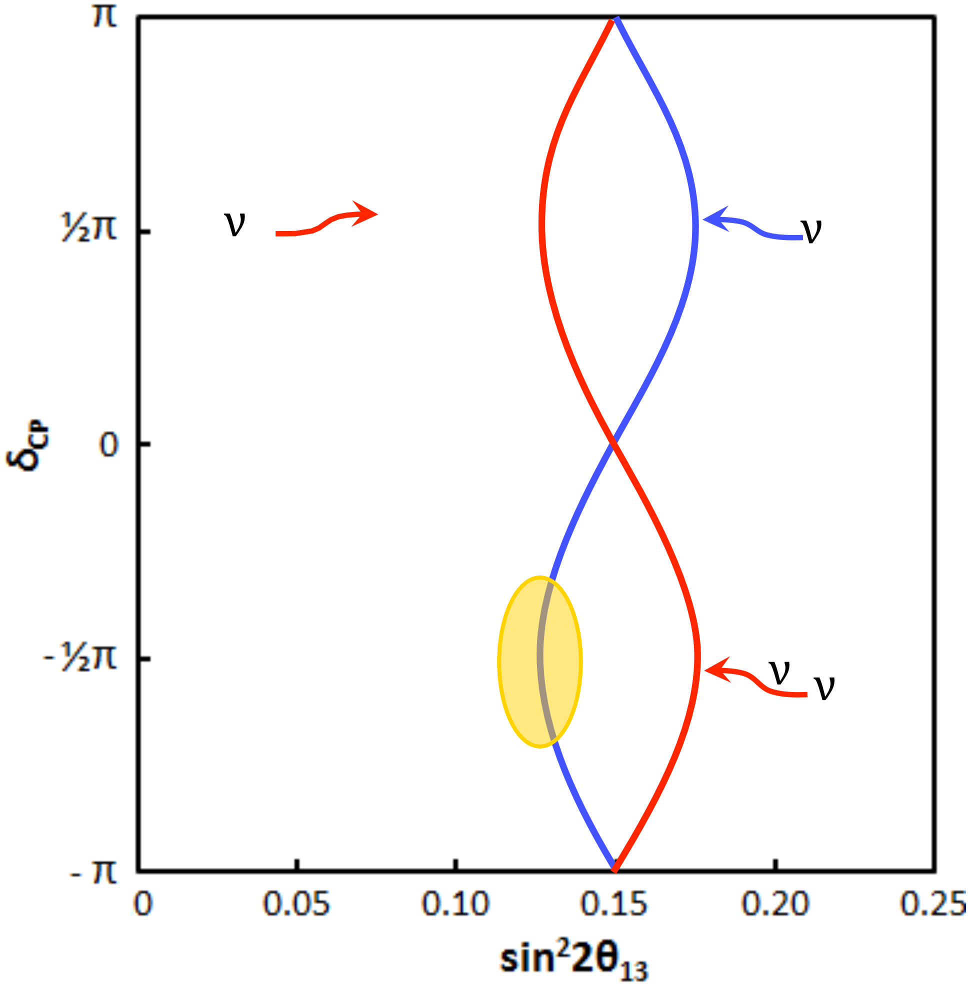

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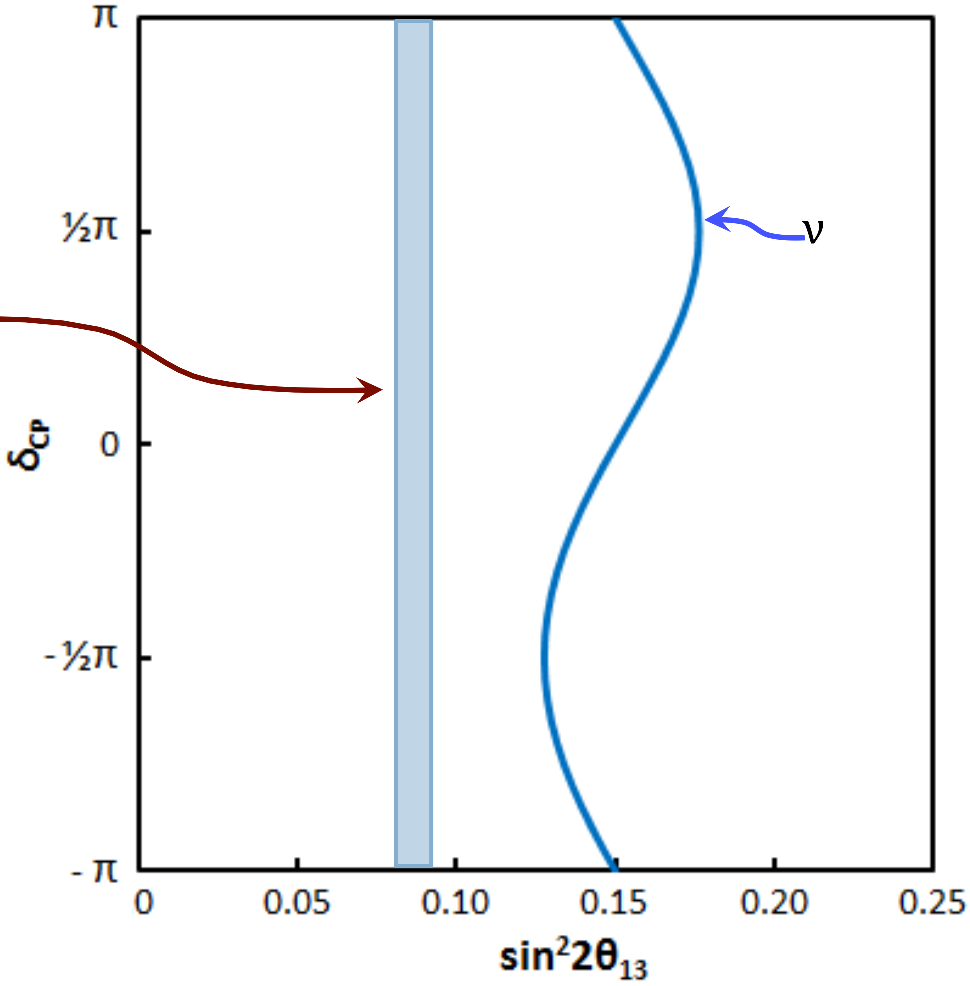
Reactor Measurement of $\sin^2 2\theta_{13}$



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$$+ \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(\Delta m_{21}^2 \; L/4E)$$ Solar

ν
ν

$$\mp J \sin\delta \sin(\Delta m_{\mu\mu}^2 \; L/4E)$$ CP Violating

$$+ J \cos\delta \cos(\Delta m_{\mu\mu}^2 \; L/4E)$$ Interference Terms

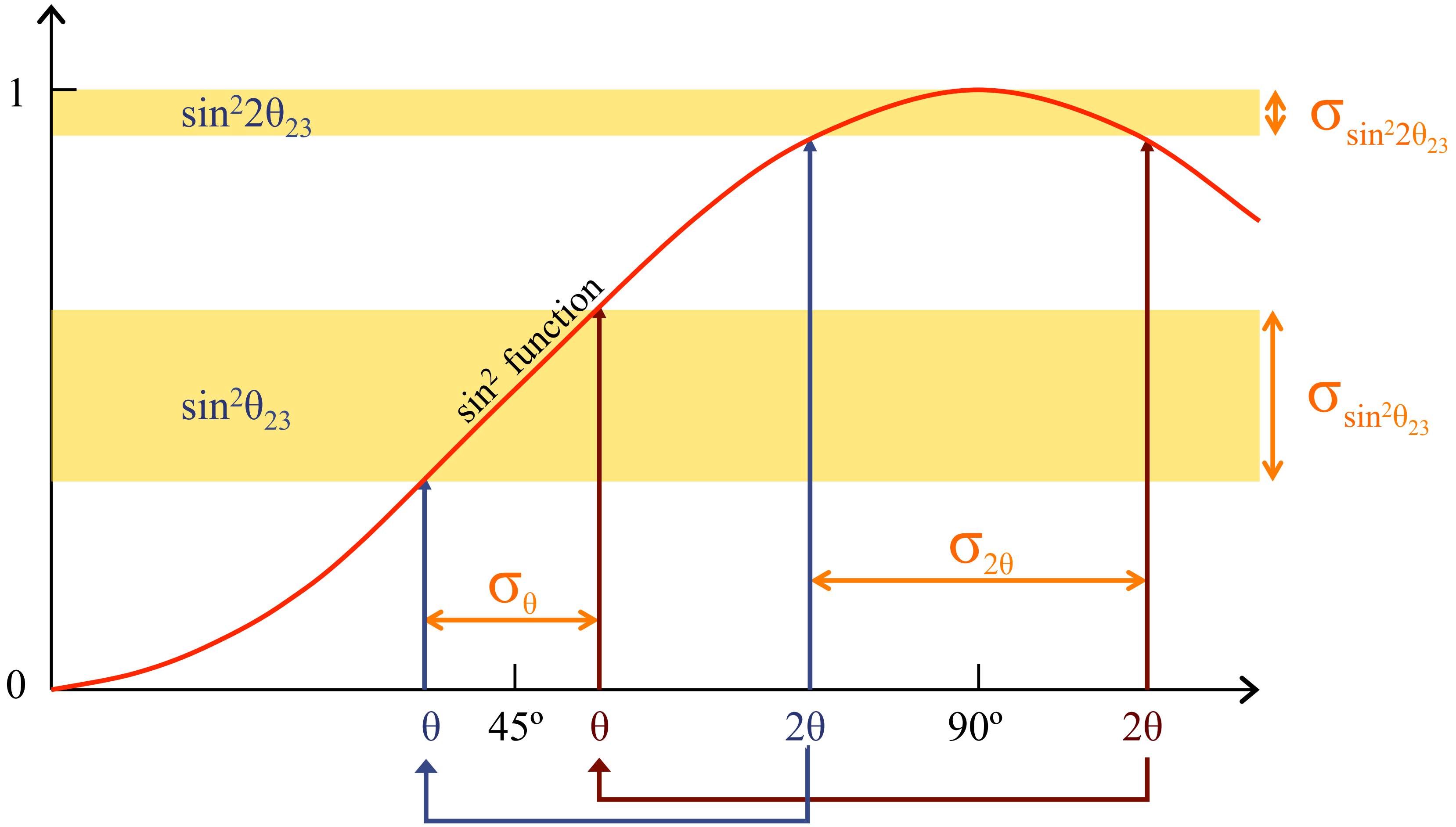
with $J = \cos\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin(\Delta m_{\mu\mu}^2 \; L/4E) \sin(\Delta m_{21}^2 \; L/4E)$

The ν_μ Disappearance Probability:

$$P(\nu_\mu \nrightarrow \nu_\mu) = \sin^2 \cancel{2}\theta_{23} \sin^2(\Delta m_{\mu\mu}^2 \; L/4E)$$

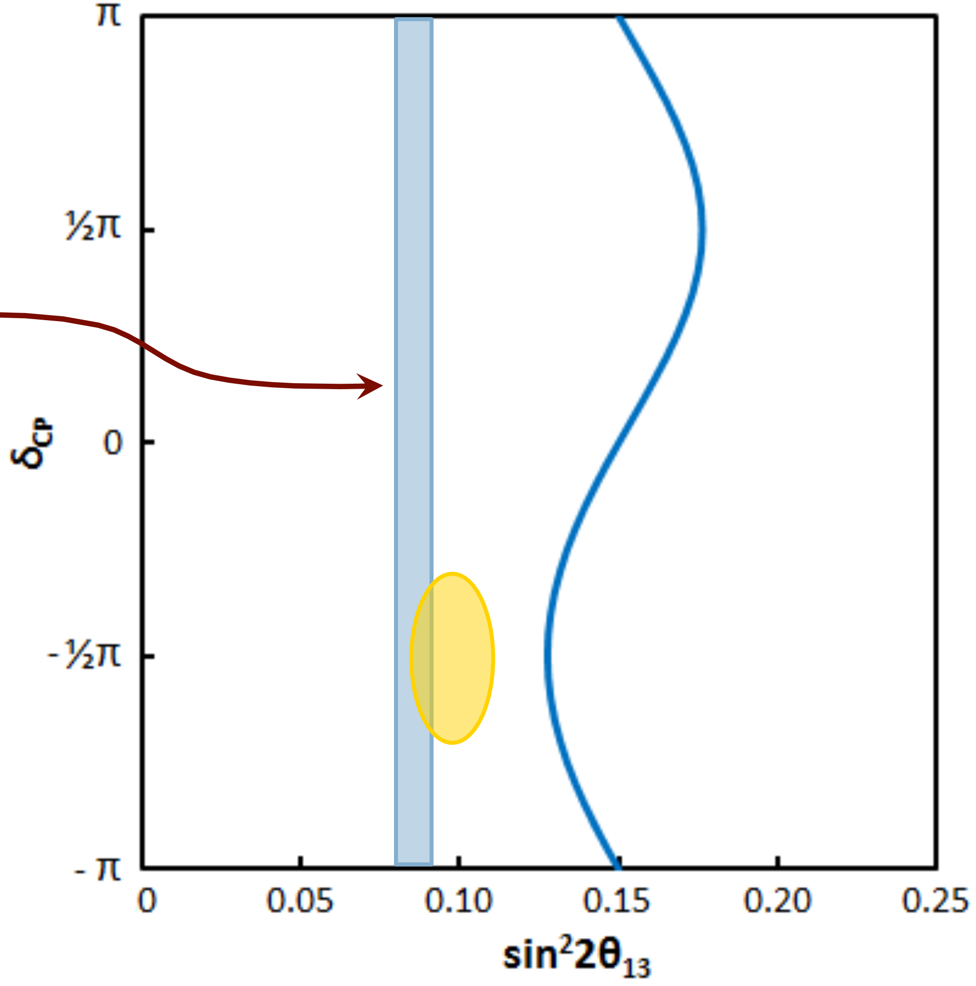
The θ_{23} Octant

When $\sin^2 2\theta_{23}$ is near maximal, a small uncertainty in $\sin^2 2\theta_{23}$ translate into a larger uncertainty in $\sin^2\theta_{23}$.



Impact of the θ_{23} Octant

With a measured appearance rate in a long-baseline experiment, the value of $\sin^2 2\theta_{13}$ is dependent on δ and the octant of θ_{23}…



Reactor Measurement of $\sin^2 2\theta_{13}$

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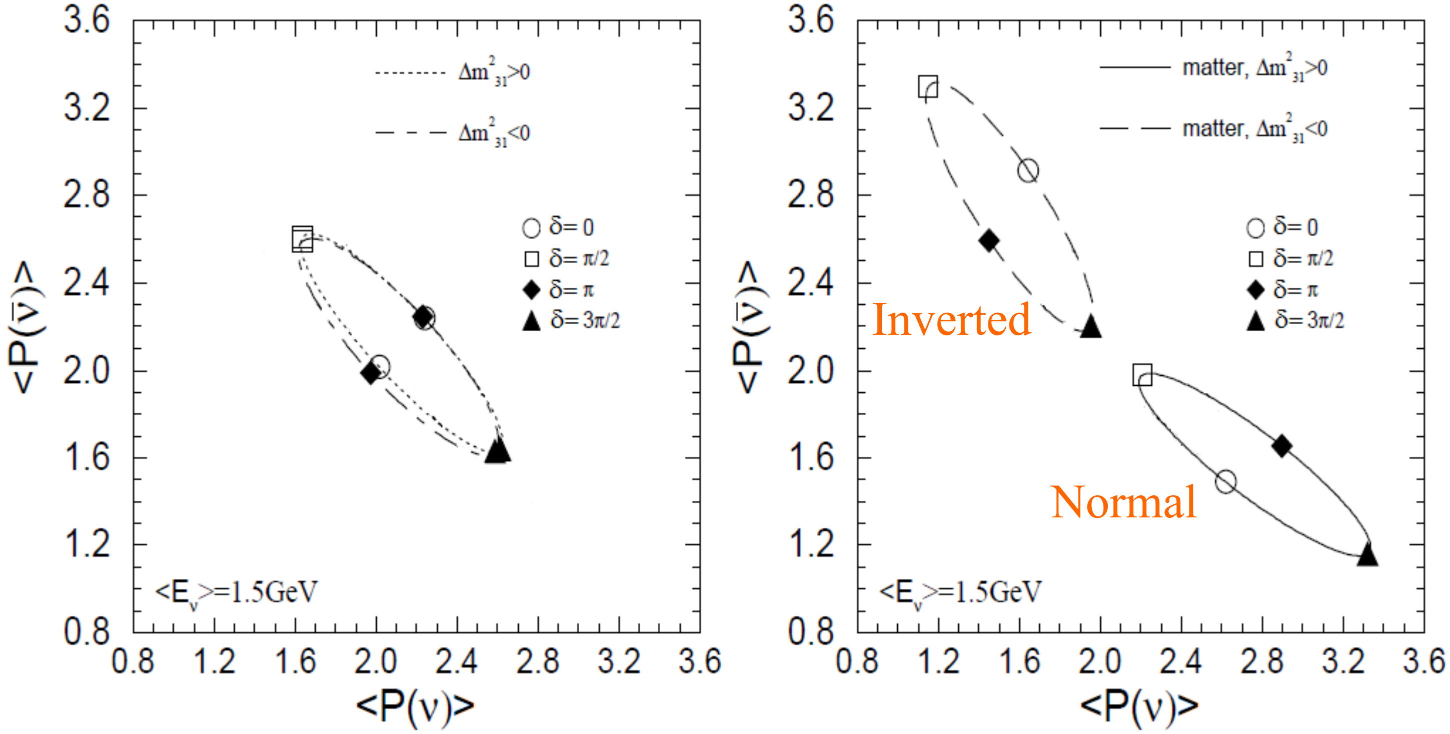
Matter Effects and Mass Hierarchy

The forward scattering of neutrinos on electrons in matter adds to the effective mass of the neutrino and therefore impacts the oscillation.

JHEP 0110, 001 (2001)

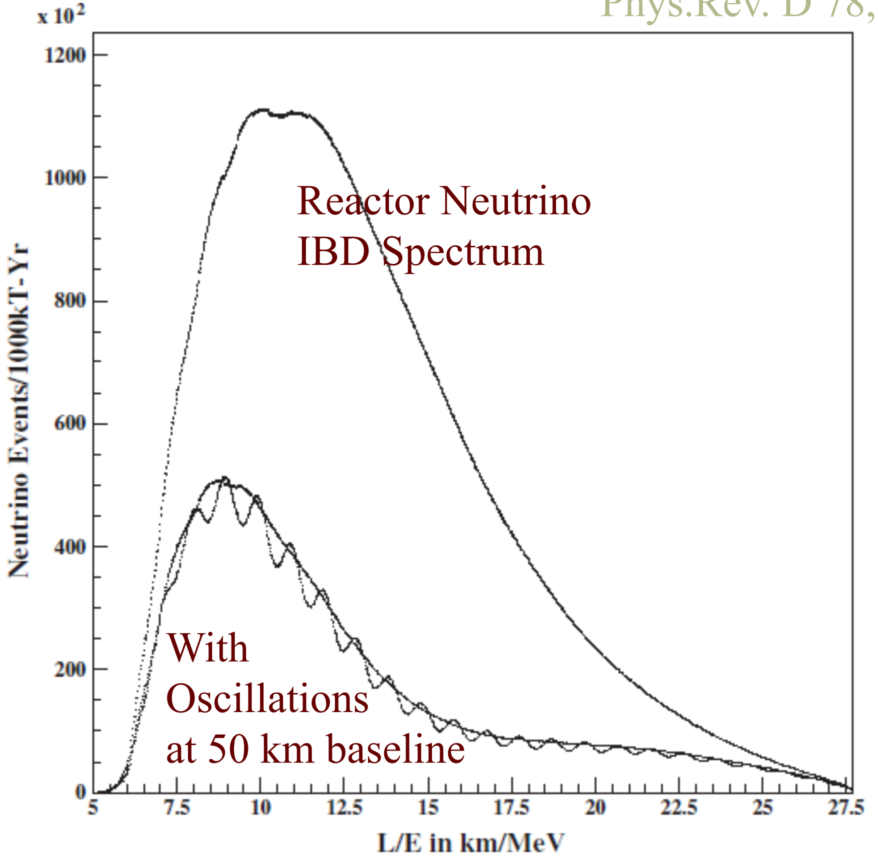


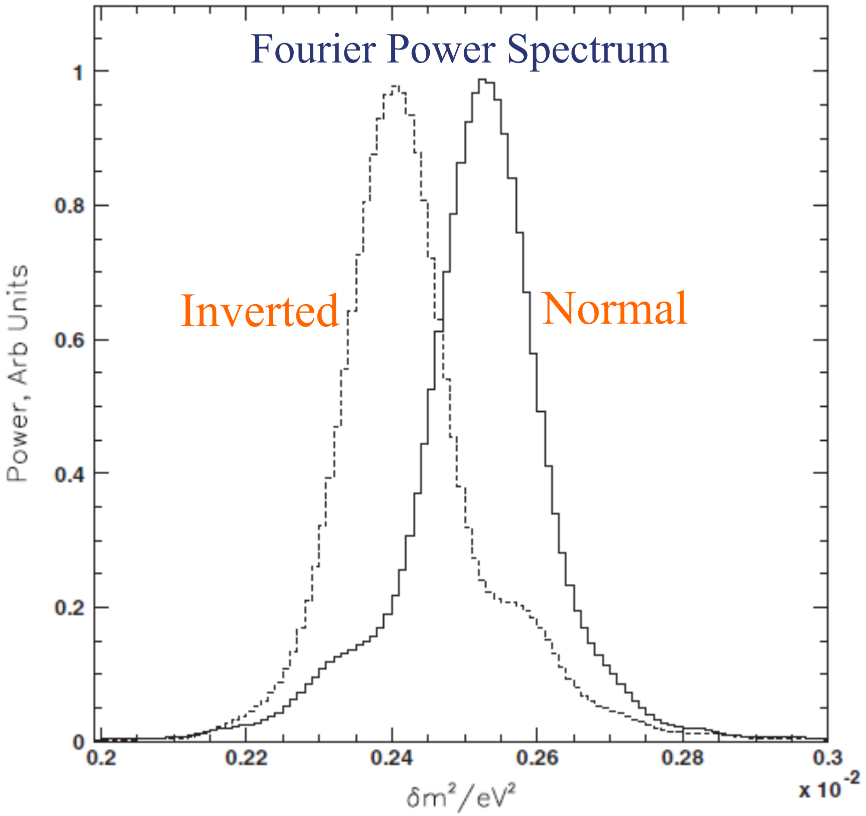
With the electron densities in the Earth, these effects are larger for higher energy neutrinos over longer baselines.

Direct Measurements of the Mass Hierarchy

With a precision reactor experiment, the difference between Δm_{31}^2 and Δm_{32}^2 can be directly measured.

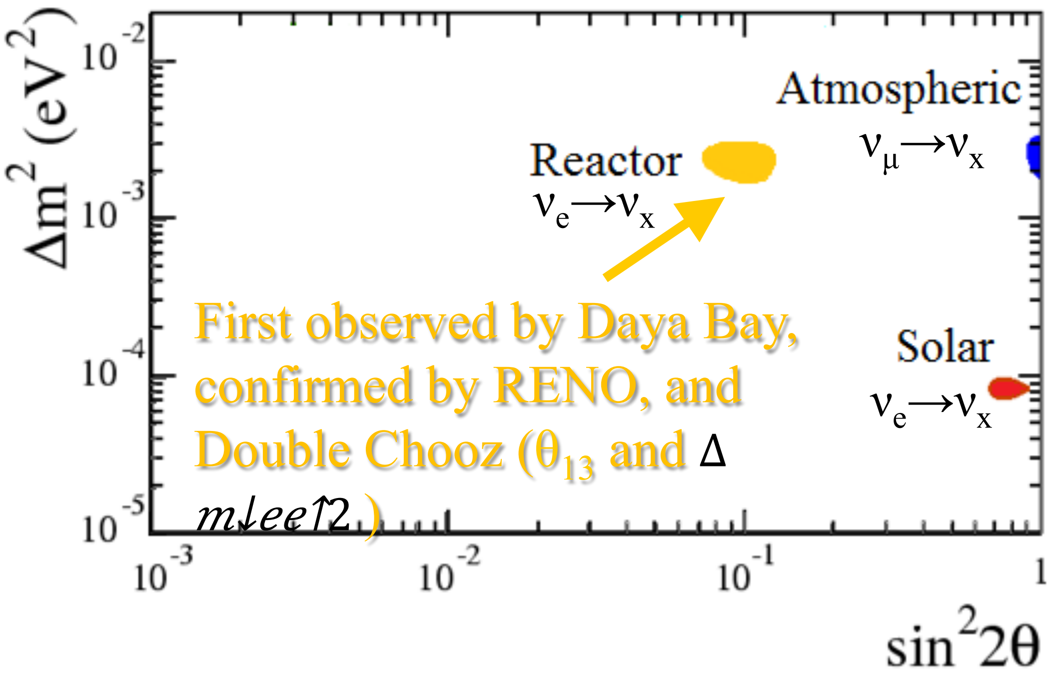
Phys.Rev. D 78, 071302(R) (2008)





See JUNO talk by Yueken Heng

Neutrino Oscillation Data



First observed by Daya Bay, confirmed by RENO, and Double Chooz (θ_{13} and Δm_{ee}^{2})

Seen by Super-K, confirmed by K2K, Minos, T2K and NOvA (θ_{23} and $\Delta m_{\mu\mu}^{2}$)

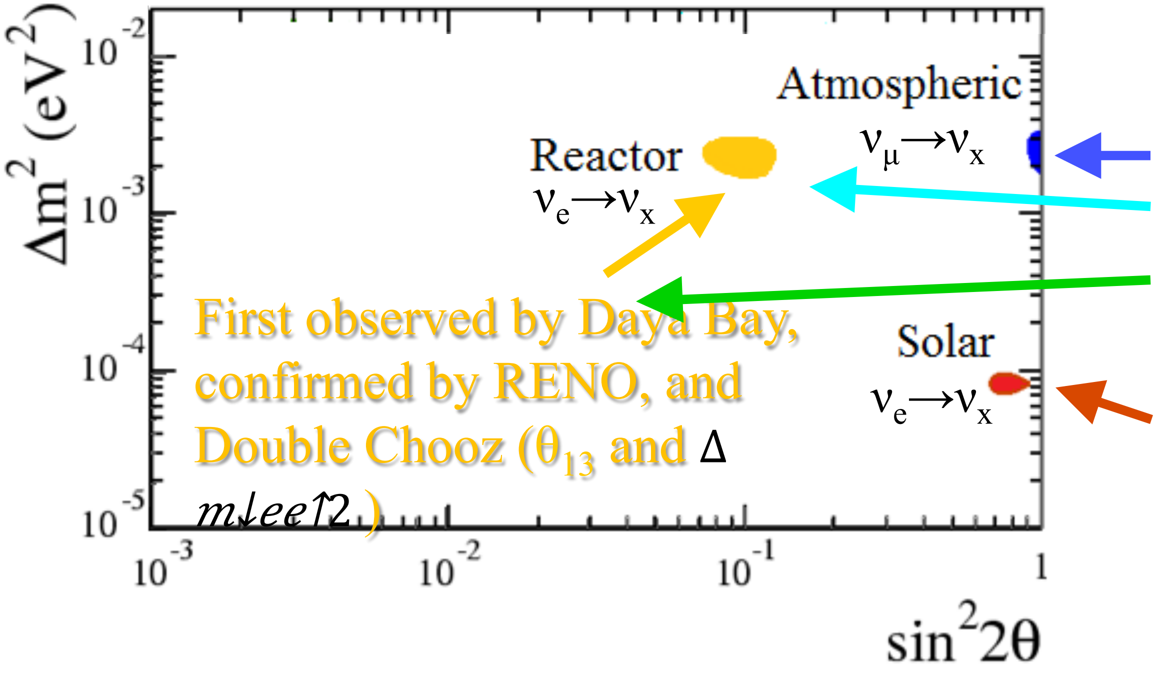
First observed by Ray Davis. Nailed down by Super-K, SNO and KamLAND. Dominated by mixing of mass states 1 and 2 (θ_{12} and Δm_{21}^{2})

The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent.

Specifically, Δm_{ee}^{2} and $\Delta m_{\mu\mu}^{2}$, which are different linear combinations of Δm_{31}^{2} and Δm_{32}^{2}, did not have to agree to within Δm_{21}^{2}.

Neutrino Oscillation Data

…and Then Some…



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Short-Baseline anomalies observed by: Reactors, Gallium Source Experiments, T2K LSND and MiniBooNE (θ_{x4} and Δm_{4x}^2)

First observed by Ray Davis. Nailed down by Super-K, SNO and KamLAND. Dominated by mixing of mass states 1 and 2 (θ_{12} and Δm_{21}^2)

Sterile Neutrino

(Bacon Flavor)

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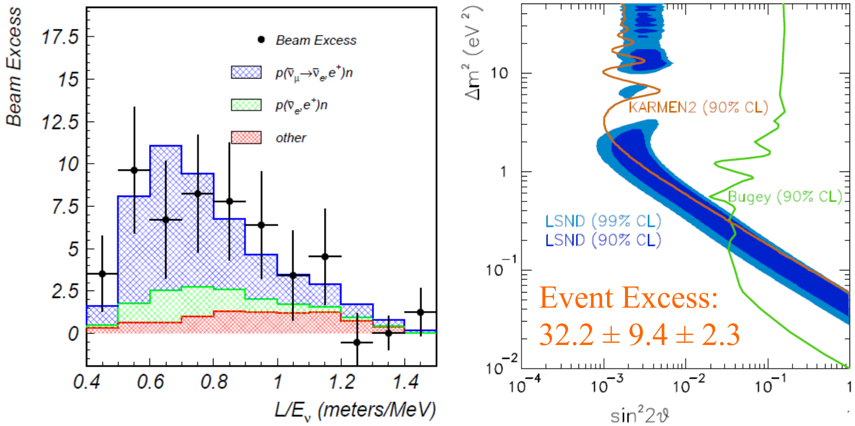
Specifically, Δm_{ee}^2 and $\Delta m_{\mu\mu}^2$, which are different linear combinations of Δm_{31}^2 and Δm_{32}^2, did not have to agree to within Δm_{21}^2.

The Evidence for Sterile Neutrinos

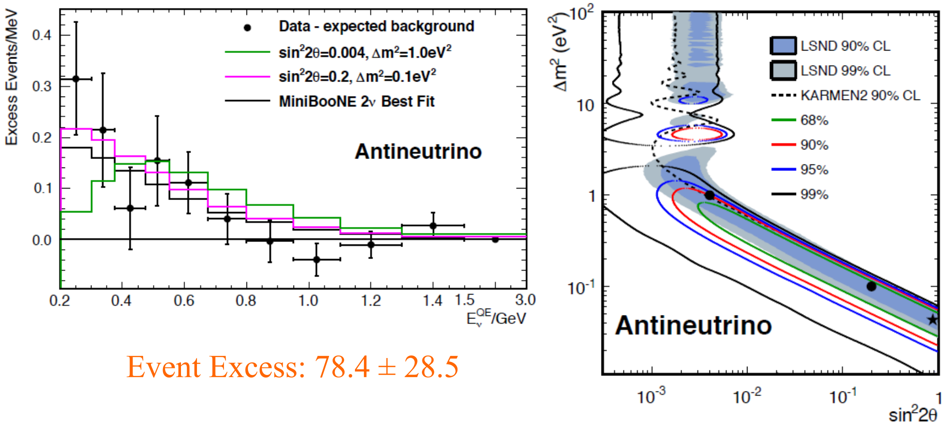
LSND (ν ↓μ →ν ↓e)



Event Excess:
32.2 ± 9.4 ± 2.3

Aguilar-Arevalo *et al.*, Phys.Rev.D64, 112007 (2001)

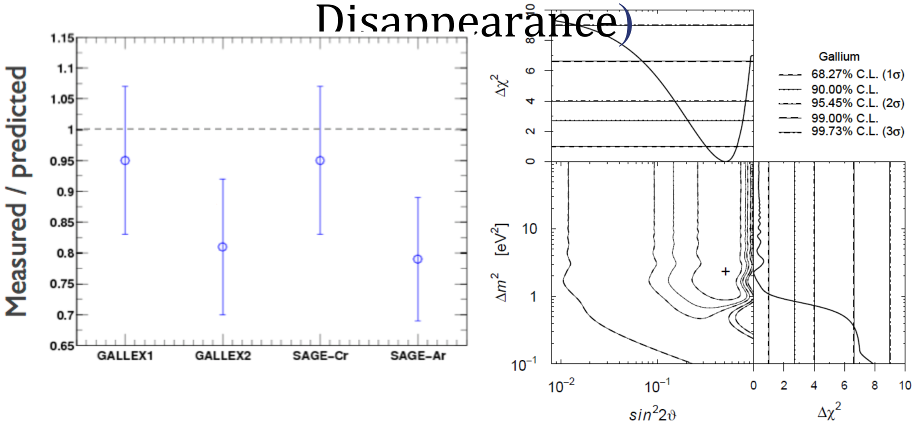
MiniBooNE (ν ↓μ →ν ↓e)



Event Excess: 78.4 ± 28.5

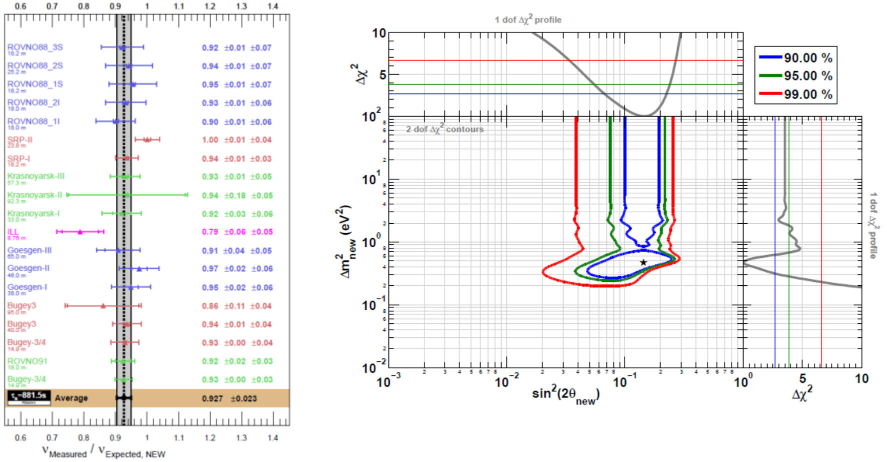
Aguilar-Arevalo *et al.*, Phys.Rev.Lett. 110, 161801 (2013)

Gallium Anomaly (ν↓e Disappearance)



Giunti and Laveder, Phys.Rev.C83, 065504(2011)

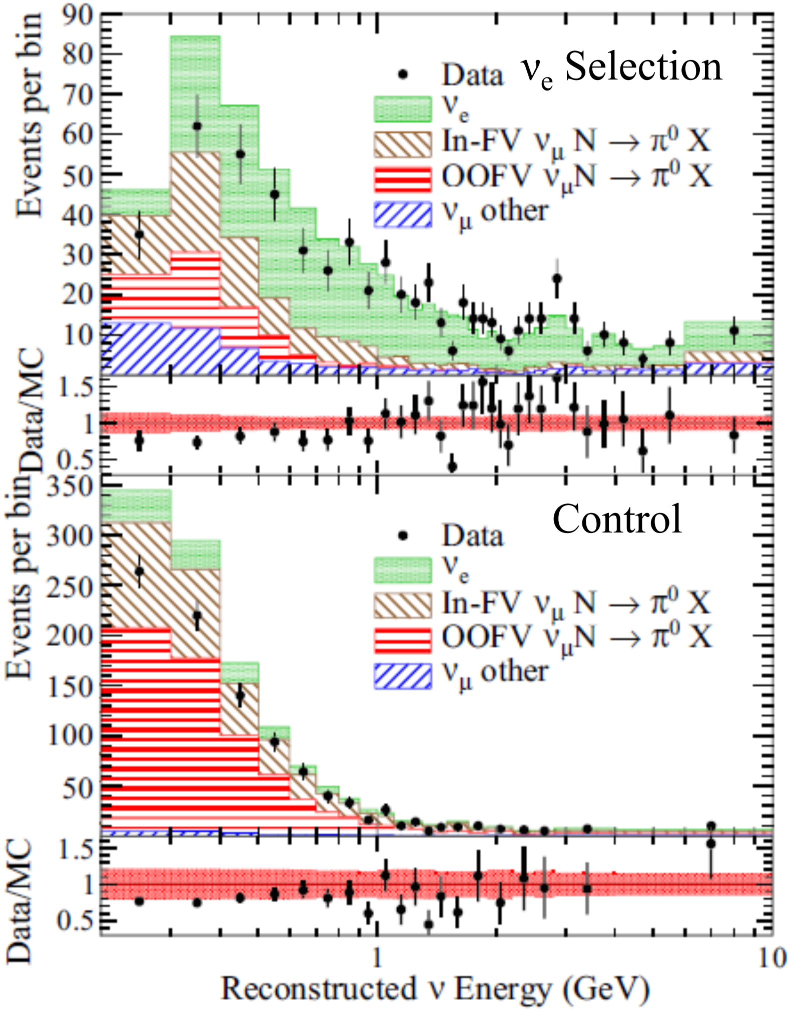
Reactor Anomaly (ν ↓e Disappearance)



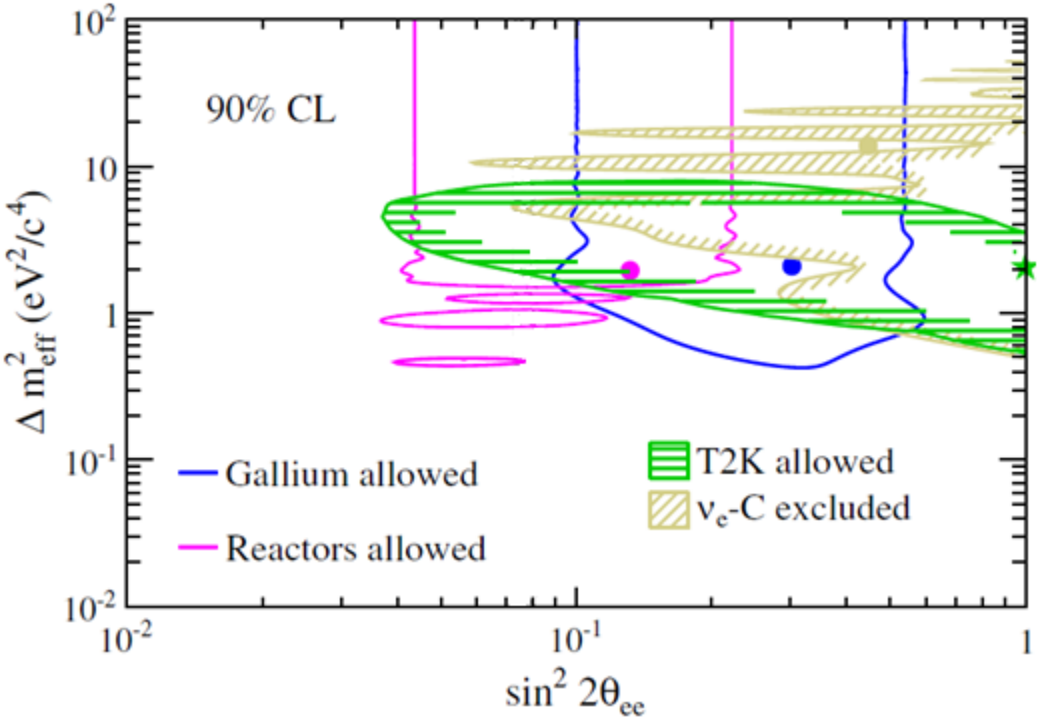
Mention *et al.*, Phys.Rev.D83 073006 (2011)

T2K Near Detector ν_e Disappearance

Although the T2K beam is predominantly a ν_μ beam, the small ν_e component can be used in the near detector for a ν_e disappearance search.

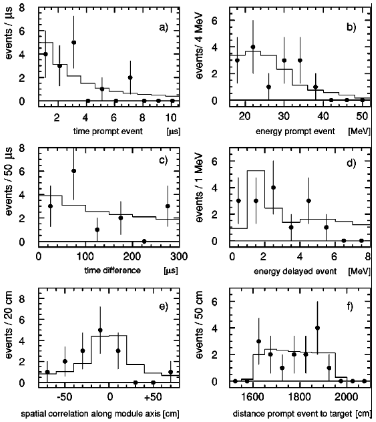


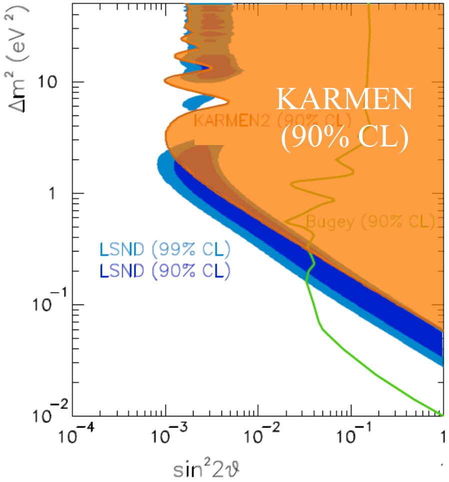
Phys.Rev. D91, 051102(R) (2015)



Evidence Against the ~1 eV^2 Sterile Neutrino

KARMEN (ν ↓μ →ν ↓e)

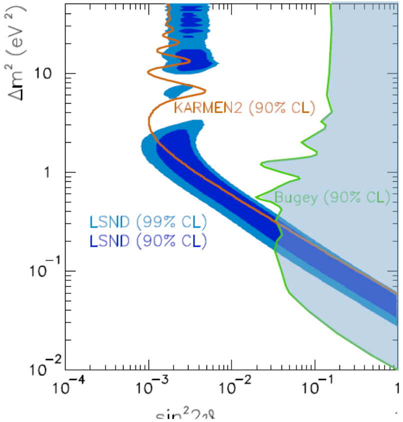


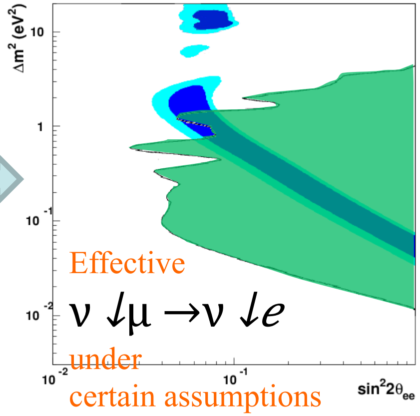


No ν ↓e Excess

Armbruster *et al.*, Phys.Rev.D65 112001 (2002)

Bugey Reactor (ν ↓e Disappearance)

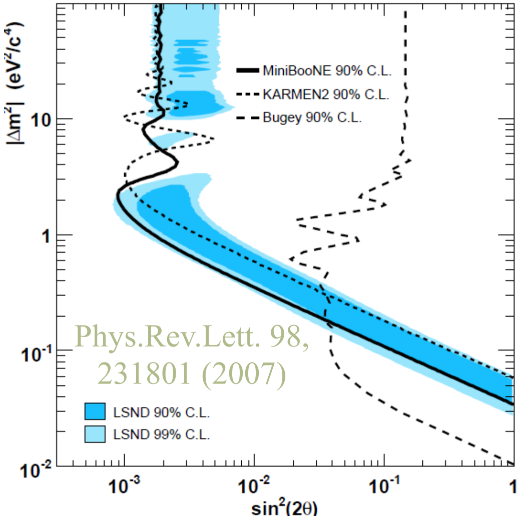




Effective ν ↓μ →ν ↓e under certain assumptions

Achkar *et al.*, Nucl.Phys.B434, 503 (1995)

MiniBooNE ($\nu_\mu \to \nu_e$ Appearance)



Phys.Rev.Lett. 98, 231801 (2007)

ν_μ Disappearance

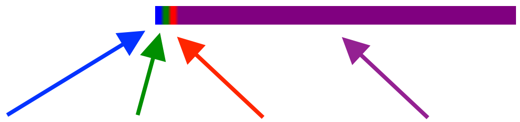
(where is it?)

For ν↓μ →ν↓e to happen there must be both ν↓e and ν↓μ disappearance

Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent Δm^2s.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left(\begin{matrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\\ U_{s1} & U_{s2} & U_{s3}\end{matrix}\;\boxed{\begin{matrix}U_{e4}\\ U_{\mu4}\\ U_{\tau4}\\ U_{s4}\end{matrix}}\right)\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$



$$U_{e4}^2 + U_{\mu4}^2 + U_{\tau4}^2 + U_{s4}^2 = \mathbf{1}$$ (PMNS Unitarty)

The appearance probability ($\nu_\mu \rightarrow \nu_e$):

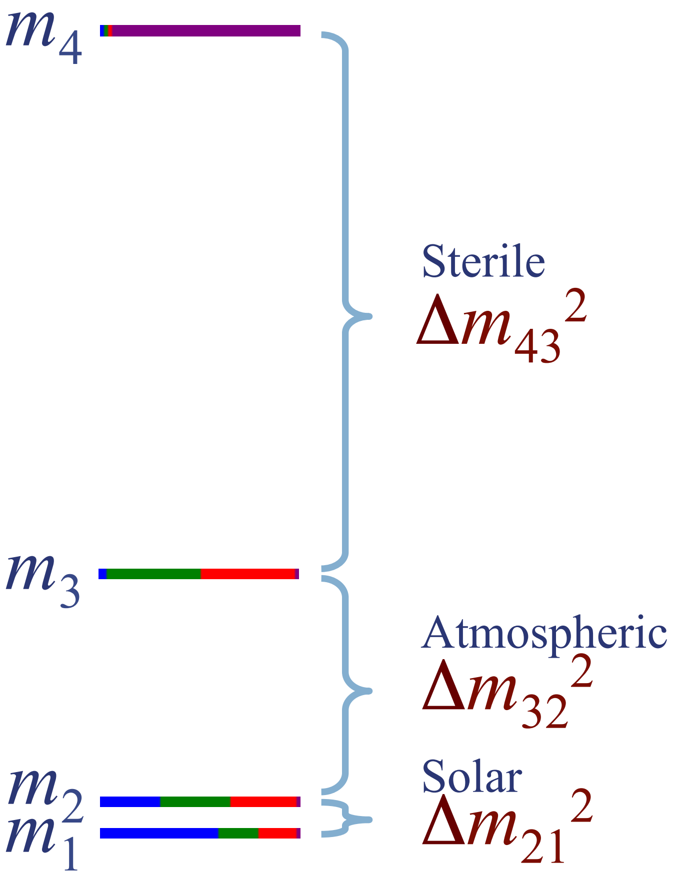
$$P_{\mu e} = 4U_{e4}^2\, U_{\mu4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_e disappearance probability:

$$P_{e\cancel{e}} \approx P_{es} = 4U_{e4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_μ disappearance probability:

$$P_{\mu\cancel{\mu}} \approx 4U_{\mu4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

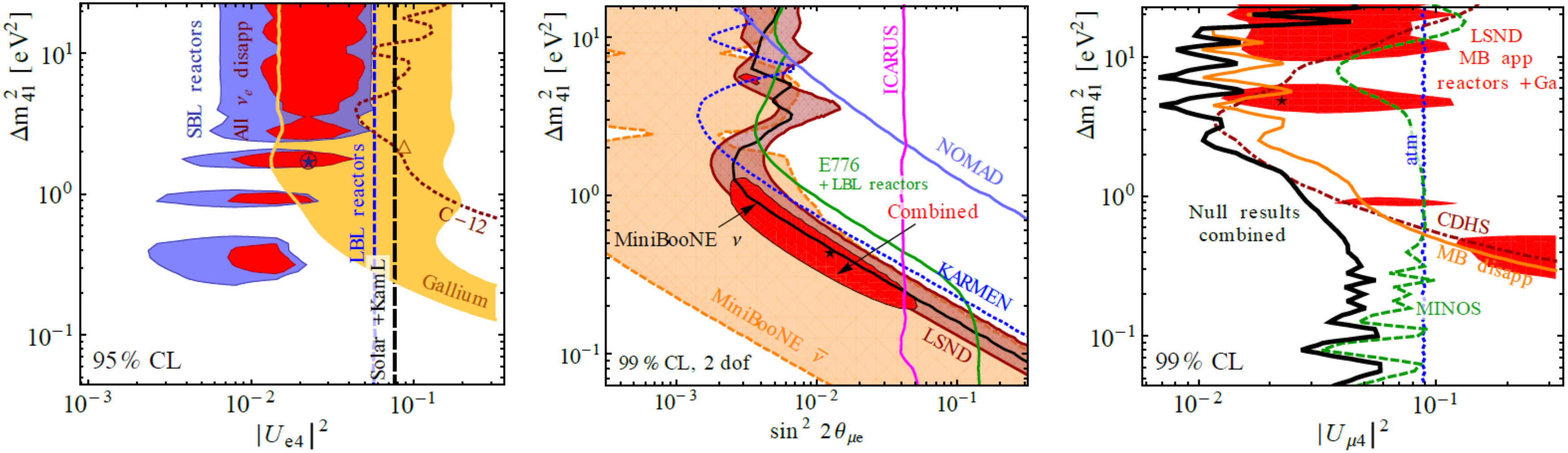


Appearance vs. Disappearance

1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

$$P_{\mu e} \approx 1/4 \; P_{ee} \times P_{\mu\mu}$$

2. $P_{\mu e}$ depends on both U_{e4} and $U_{\mu4}$, so you can have ν_e disappearance without ν_e appearance, but you can't have ν_e appearance without ν_μ disappearance.



ν_e Disappearance

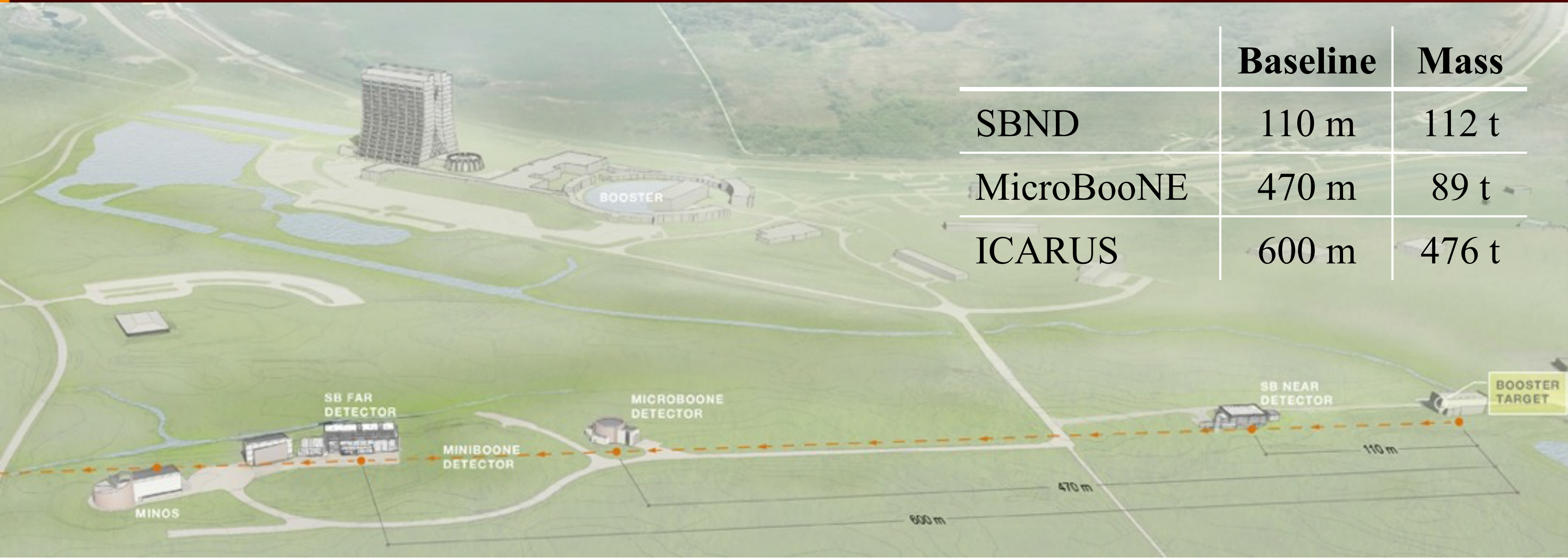
$\nu_\mu \rightarrow \nu_e$ Appearance

ν_μ Disappearance

Global fit from Kopp *et al.* JHEP 1305, 050 (2013)

The absence of ν_μ disappearance is a huge problem for the LSND and MiniBooNE signals, while the ν_e disappearance anomalies are consistent with all existing data.

ν_e Appearance & Fermilab Short-Baseline



	Baseline	Mass
SBND	110 m	112 t
MicroBooNE	470 m	89 t
ICARUS	600 m	476 t

The anticipated program has liquid argon TPCs at there three baselines in the Booster Neutrino Beam.

The program may be able to discover or rule out $\nu_\mu \rightarrow \nu_e$ appearance, but it will say nothing about ν_e disappearance.

See MircoBooNE talk by Roxanne Guenette

ν↓e and ν ↓e Disappearance Experiments

Reactor Experiments:

Radioactive Source Experiments:

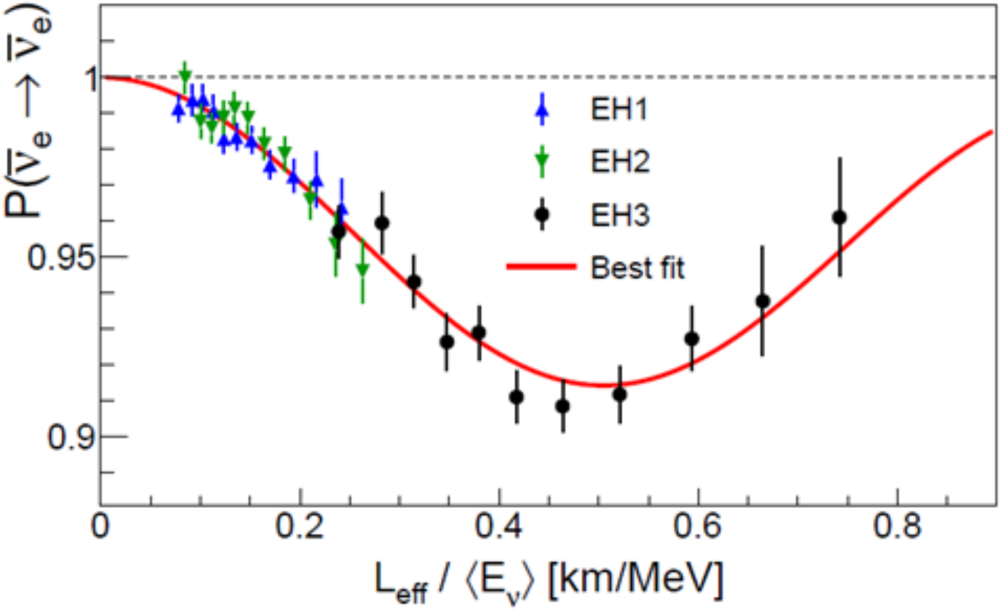
Requirement for Disappearance Experiments

“It don’t mean a thing if it ain’t got that swing”

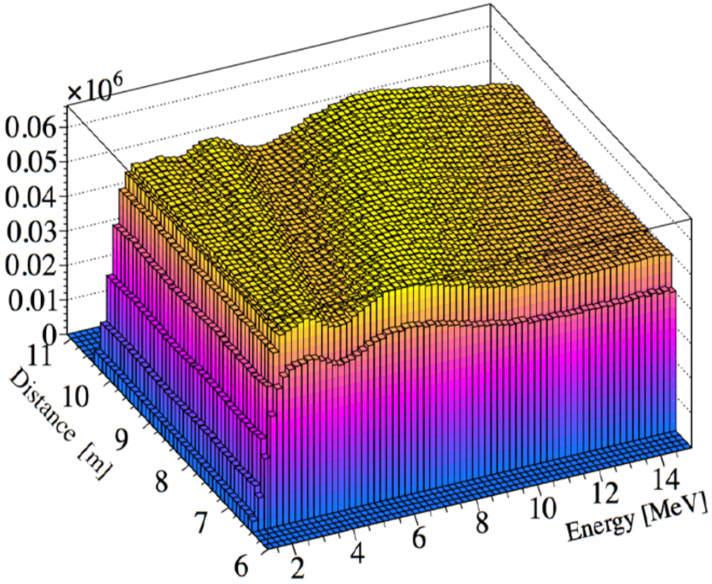
–American jazz great Duke Ellington

Definition:

oscillometry, *n.*, The observation and measurement of oscillations.



Daya Bay, Phys.Rev.Lett. 115,111802 (2015)



Possible oscillations in a short-baseline reactor experiment

In disappearance experiments the existence of sterile neutrinos can ***only*** be convincingly established through oscillometry.

ν↓e and ν ↓e Disappearance Experiments

Reactor Experiments:

- Short baselines (5 to 20 m)
- High backgrounds requires new detector technologies
- Significant (and costly) shielding may be required
- The source is typically free and renewable
- There are many proposed and active projects around the world

See Prospect talk by Jason Broadsky

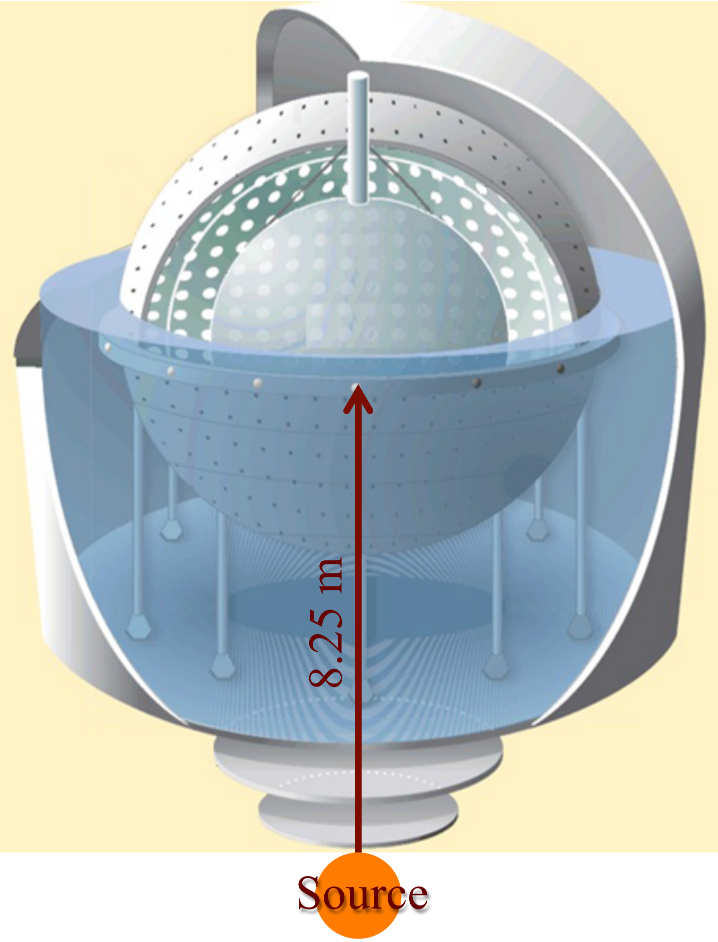
Radioactive Source Experiments:

- Even shorter baselines (1 to 5 m)
- Leverages detectors built for other applications
- Very low backgrounds are required and available
- There are a few ideas and one approved experiment (with two sources)

Source Experiment: SOX

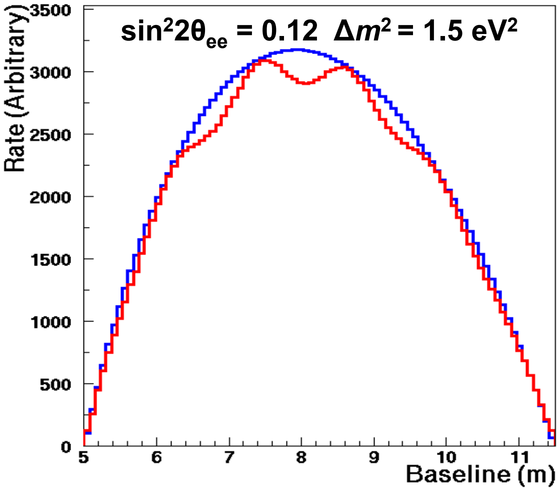
Combines the Borexino detector with a ^{144}Ce ν_e source and/or a ^{51}Cr ν_e source.

JHEP 1308, 038 (2013)

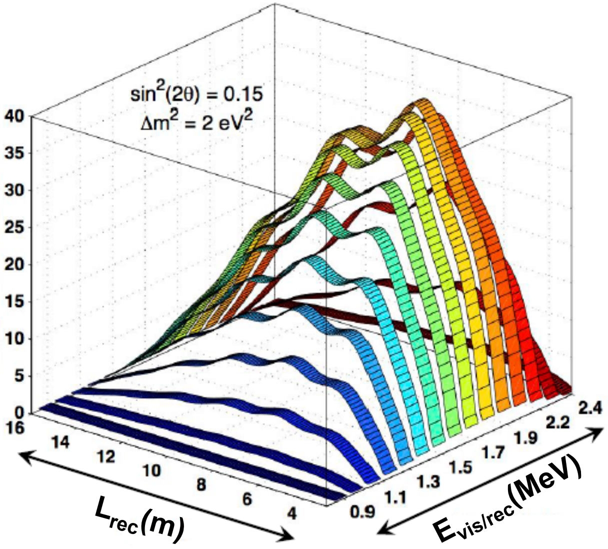


At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

^{51}Cr Source



^{144}Ce Source



Source Experiment: SOX

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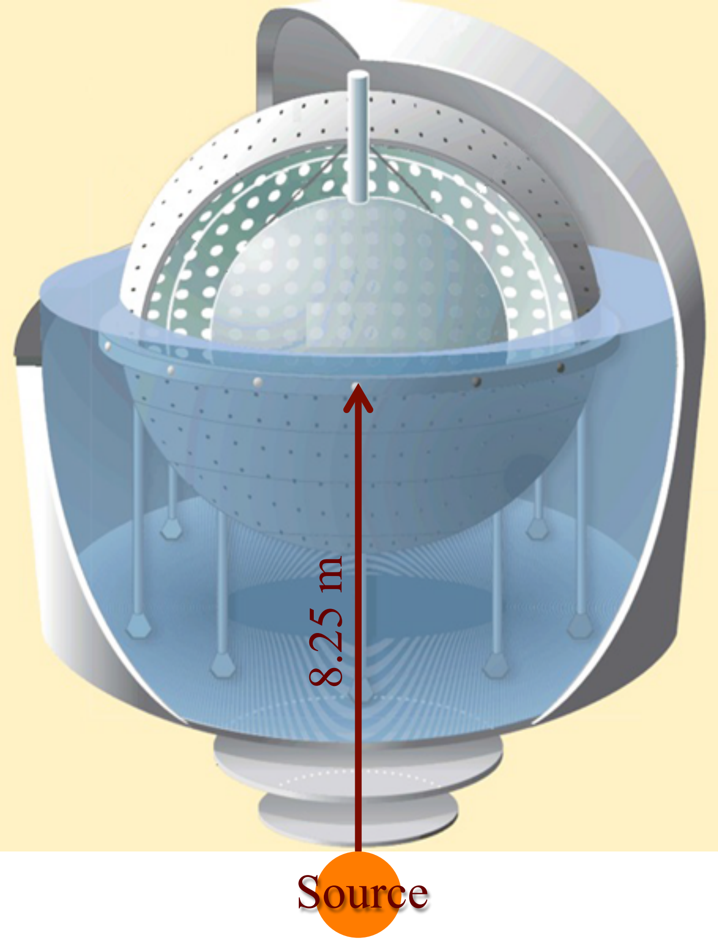
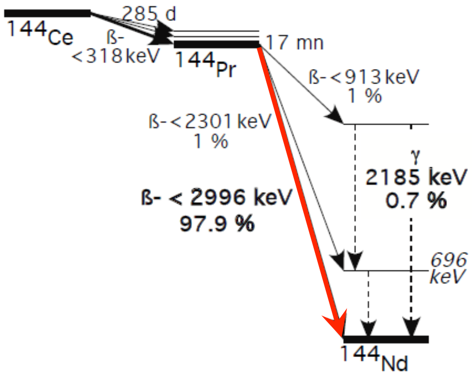
JHEP 1308, 038 (2013)

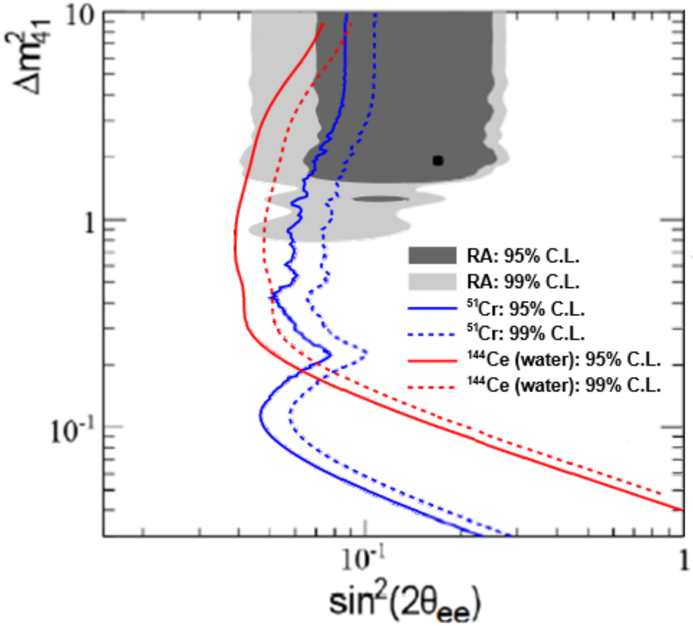


At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

^{144}Ce ν ↓e neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.

^{144}Ce-^{144}Pr Decay

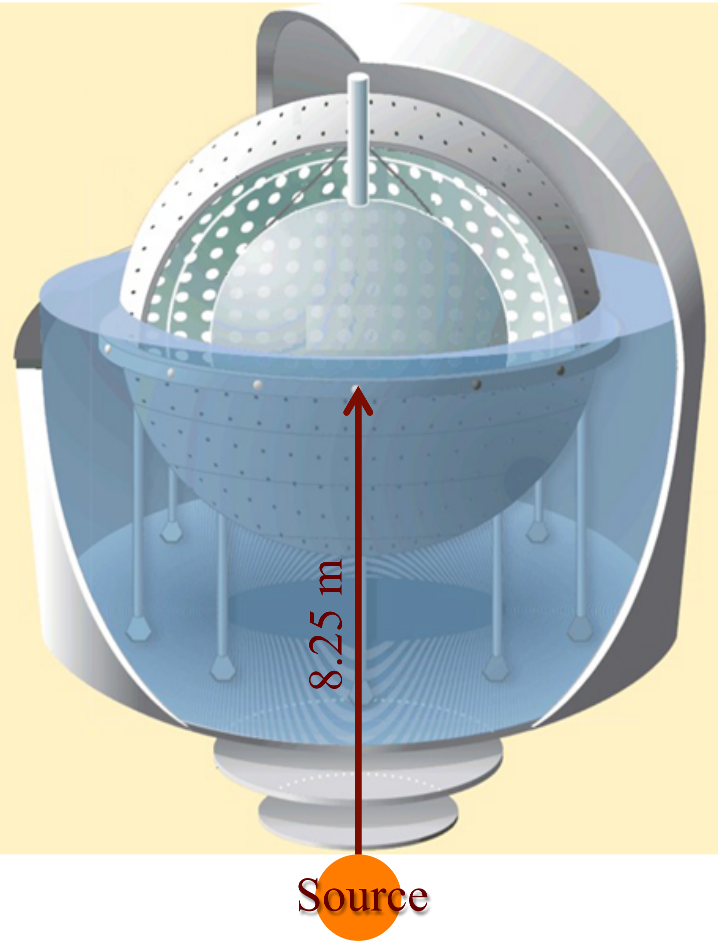




Source Experiment: SOX

Combines the Borexino detector with a ^{144}Ce ν↓e source and/or a ^{51}Cr ν↓e source.

JHEP 1308, 038 (2013)



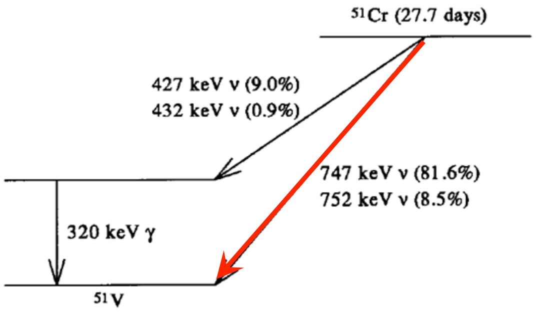
At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

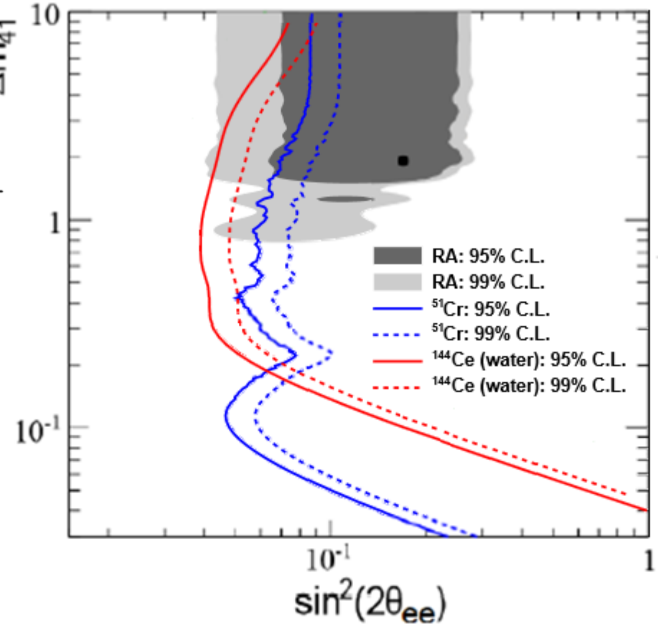
^{144}Ce ν↓e neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.

Mono-energetic ^{51}Cr ν↓e oscillate as a pure function of *L*, and are

scattering.

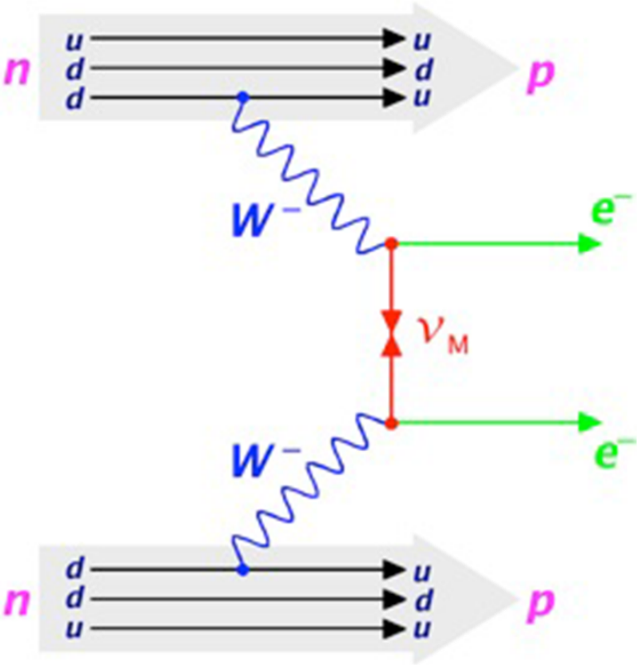
^{51}Cr Decay





Neutrinoless Double Beta Decay

0ν Double Beta Decay



Requires the neutrino to be its own antiparticle (A Majorana particle with $\nu_{eL} = \nu_{eR}$)

This helicity suppresses process is only possible if neutrinos have mass and is a strong function mass.

Probes the effective mass of the electron neutrino:

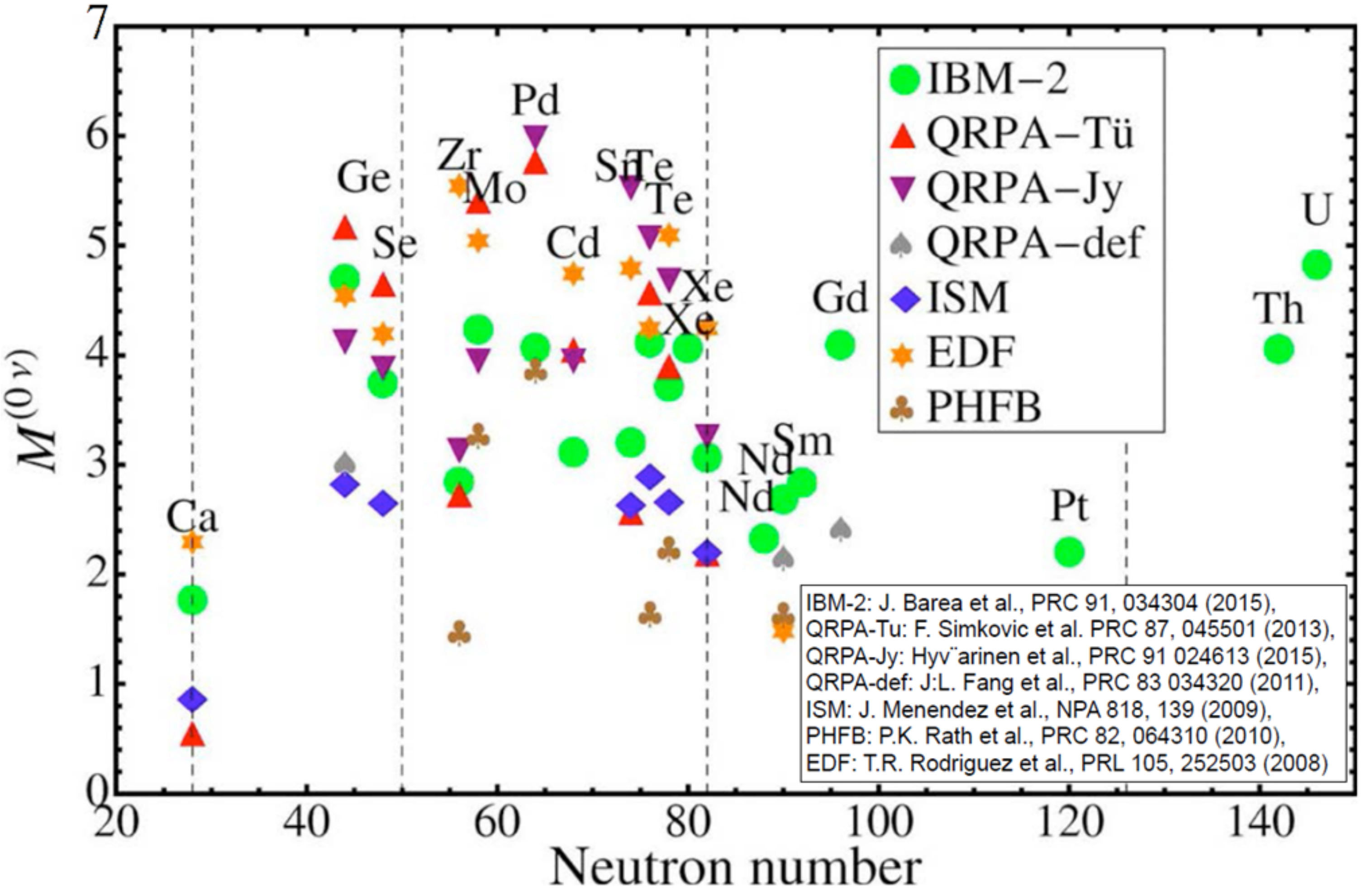
$$\langle m_{\beta\beta} \rangle = \sum_i |U_{ei}|^2 m_i$$

The decay rate is a function of both the effective mass and nuclear matric element:

$$\lambda = G_{0\nu}(Q,Z)\,|M^{0\nu}|^2\,|\langle m_{\beta\beta} \rangle|^2$$

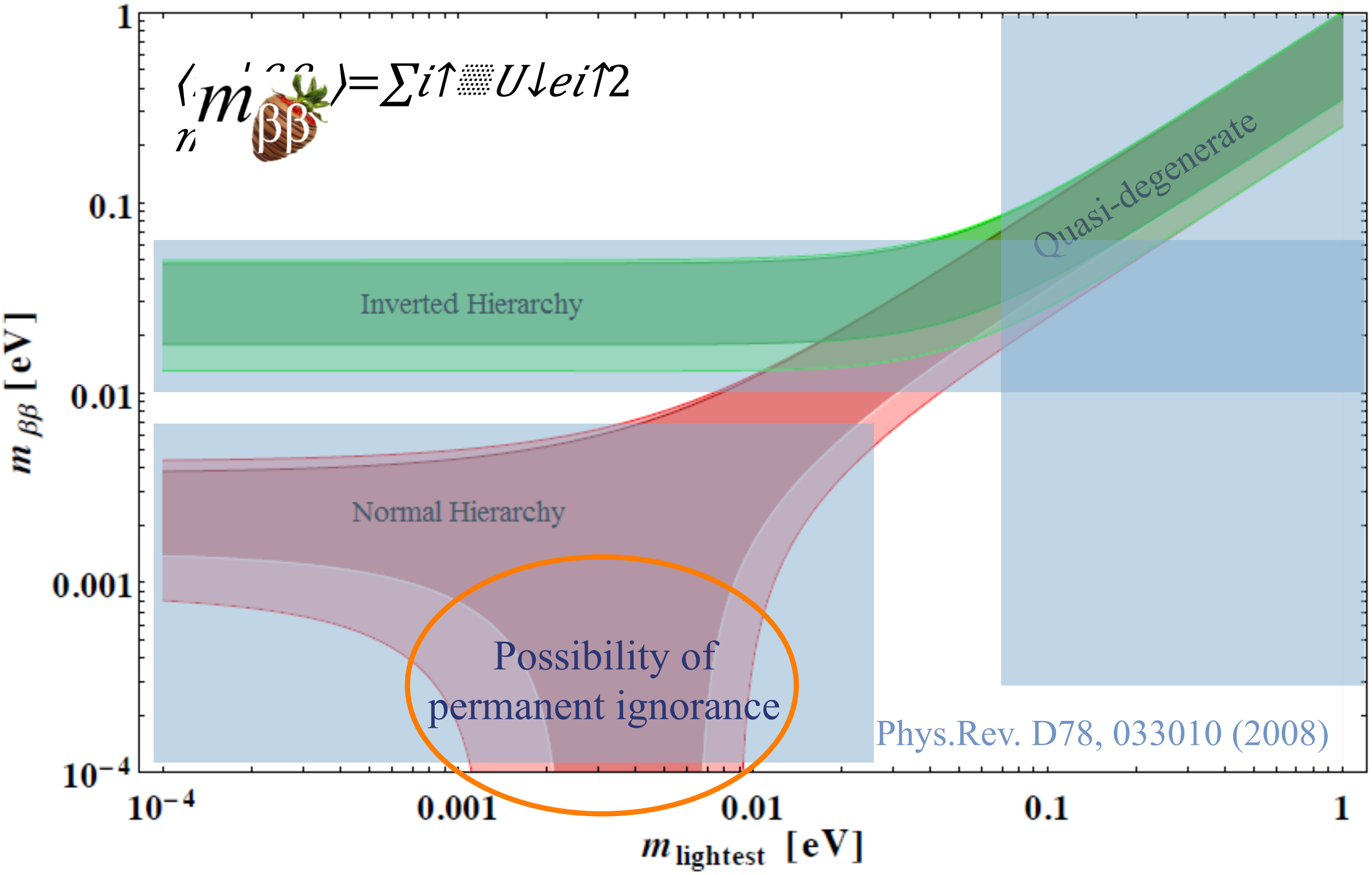
Nuclear Matrix Elements Calculations

There is a large uncertainty in the calculation of the nuclear matrix element.



IBM-2: J. Barea et al., PRC 91, 034304 (2015),
QRPA-Tu: F. Simkovic et al. PRC 87, 045501 (2013),
QRPA-Jy: Hyv¨arinen et al., PRC 91 024613 (2015),
QRPA-def: J:L. Fang et al., PRC 83 034320 (2011),
ISM: J. Menendez et al., NPA 818, 139 (2009),
PHFB: P.K. Rath et al., PRC 82, 064310 (2010),
EDF: T.R. Rodriguez et al., PRL 105, 252503 (2008)

Sensitivity as a Function of Neutrino Mass



Possibility of permanent ignorance

Phys.Rev. D78, 033010 (2008)

If the lightest neutrino mass is just below current limits we may see 0ν2β in the next few years.

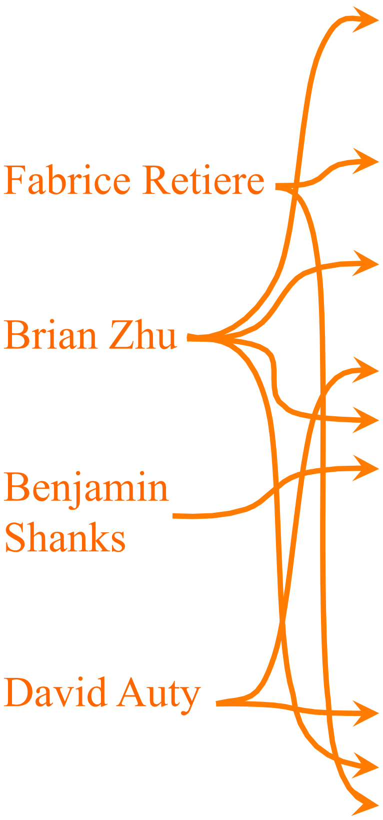
If the mass hierarchy is inverted, the currently conceived experimental program will eventually tell us if neutrinos are Majorana of Dirac.

But if the hierarchy is normal…

Majorana Phases

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinoless Double Beta Decay Experiments



Talks by:

Fabrice Retiere

Brian Zhu

Benjamin Shanks

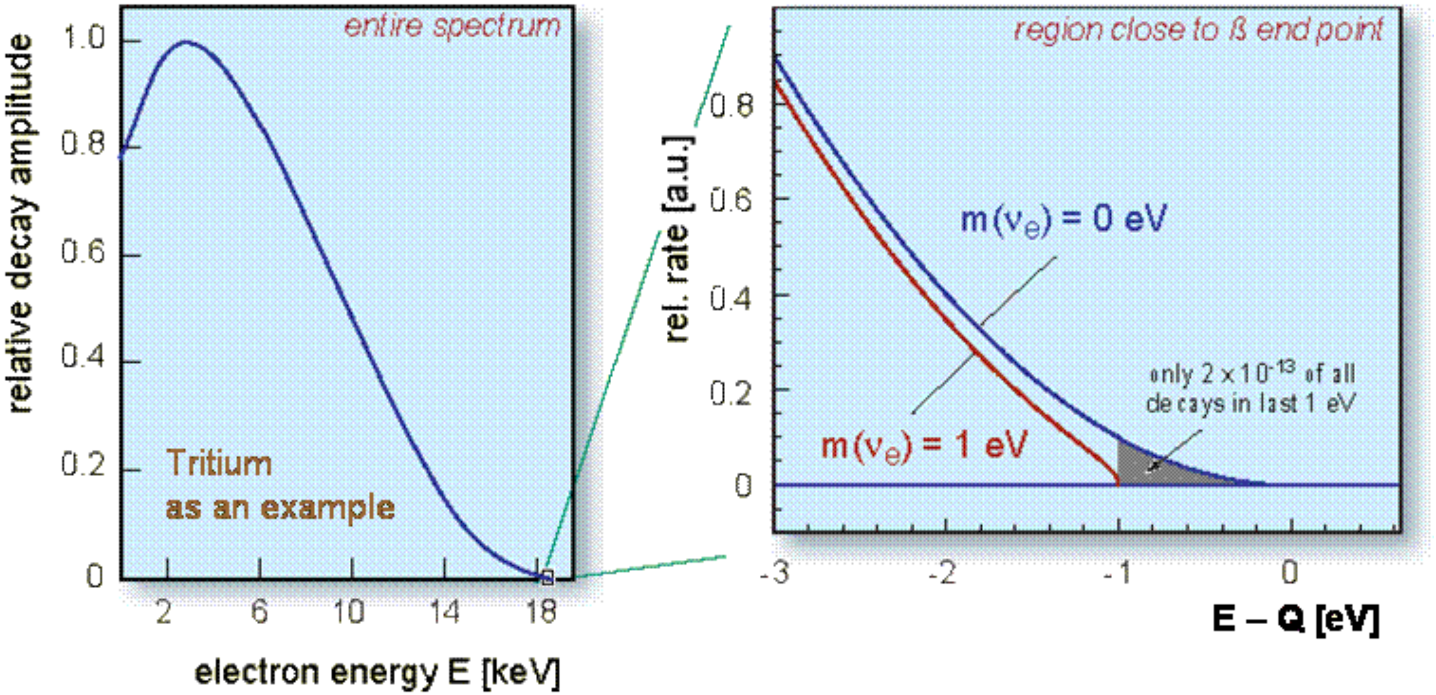
David Auty

Experiment	Isotope	Technique	Mass $\beta\beta(0\nu)$ isotope	Status
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
NEMO3	100Mo/82Se	Foils with tracking	6.9/0.9 kg	Complete
GERDA I	76Ge	Ge diodes in LAr	15 kg	Complete
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	30+35 kg	Commissioning
Majorana D	76Ge	Point contact Ge	30 kg	Commissioning
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.3% natTe suspended in Scint	55 kg	Construction
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	Construction
1TGe (GERDA+MJ)	76Ge	Best of GERDA and MAJORANA	~ tonne	R&D
CUPID	-	Hybrid Bolometers	~ tonne	R&D
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

From Oliviero Cremonesi, TAUP 2015

Direct Mass Measurements

Precision measurement of the beta-decay endpoint would show modifications due to non-zero effective neutrino mass.

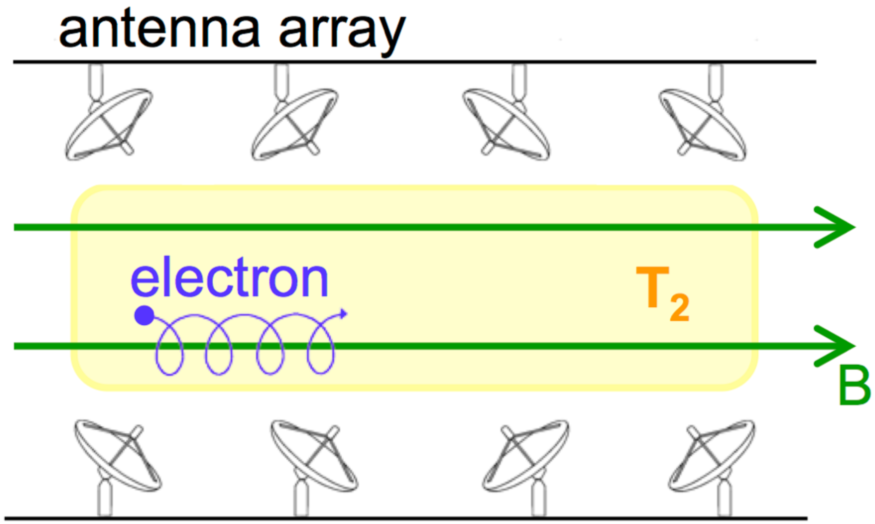


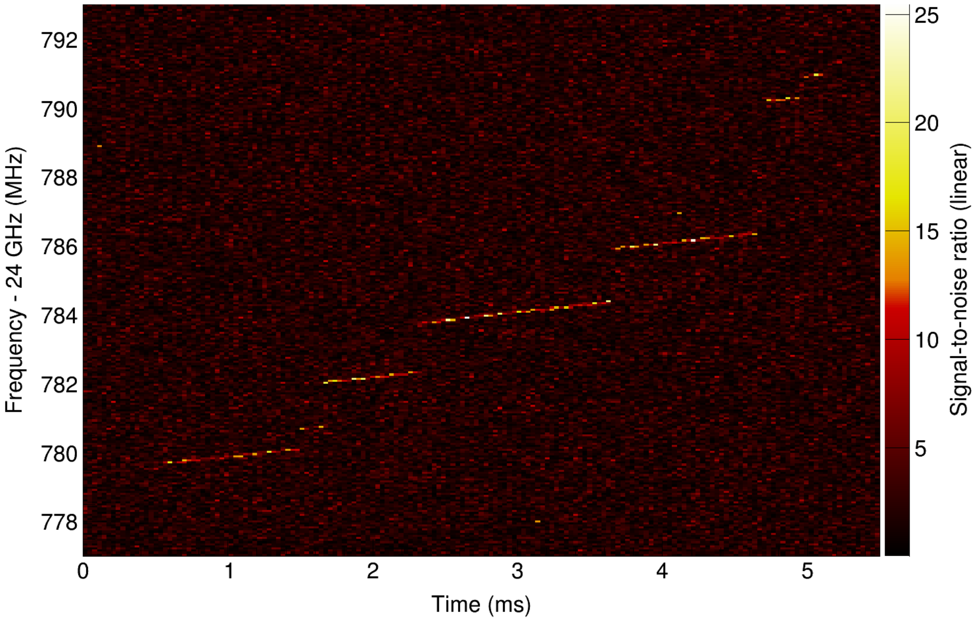
The current state-of-the-art uses a massive magnetic spectrometer and filter which selects only the electrons closest to the endpoint.

See Katrin talk by Florian Fraenkle

Direct Mass Measurements

The Project 8 concept is to measure the frequency of the cyclotron radiation from individual beta decay electrons





Neutrino Telescopes

Astrophysical neutrinos bring us information about some of the most extreme environments in the universe:

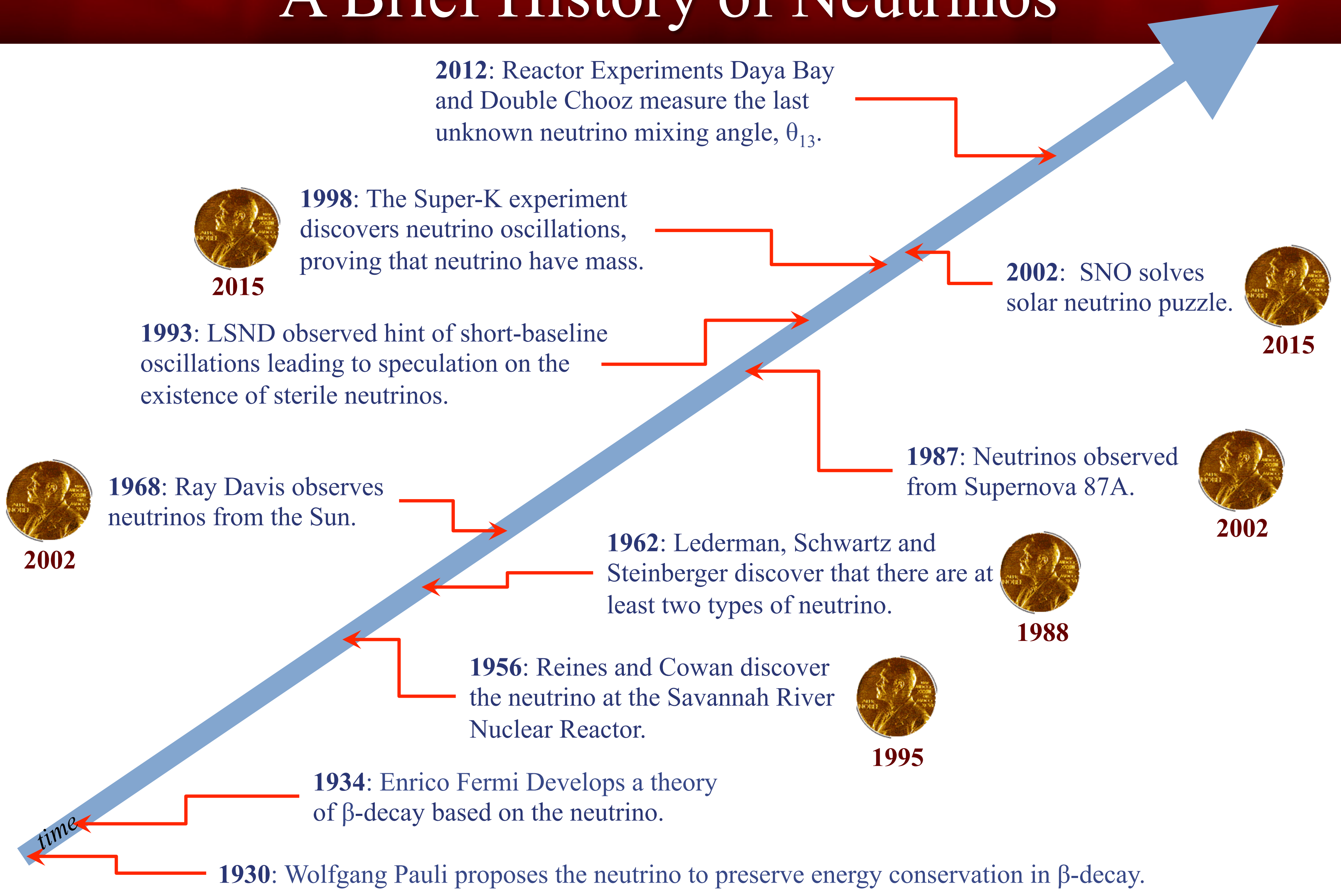
- The core of a star
- The heart of a supernova
- Distant astrophysical objects providing massive particle acceleration
- The universe as it was 1.5 s after the big bang

See talks on:

KM3NeT by Alexis Coleiro
ARA by Ming-Yuan Lu
IceCube by Stefan Coenders

JUNO by Yueken Heng
DUNE by Norm Buchanan
Hyper-K by Hirohisa Tanaka

A Brief History of Neutrinos



2012: Reactor Experiments Daya Bay and Double Chooz measure the last unknown neutrino mixing angle, θ_{13}.

1998: The Super-K experiment discovers neutrino oscillations, proving that neutrino have mass.

2002: SNO solves solar neutrino puzzle.

1993: LSND observed hint of short-baseline oscillations leading to speculation on the existence of sterile neutrinos.

1987: Neutrinos observed from Supernova 87A.

1968: Ray Davis observes neutrinos from the Sun.

1962: Lederman, Schwartz and Steinberger discover that there are at least two types of neutrino.

1956: Reines and Cowan discover the neutrino at the Savannah River Nuclear Reactor.

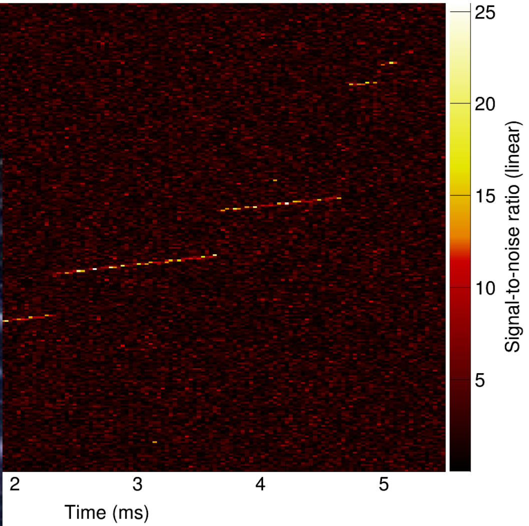
1934: Enrico Fermi Develops a theory of β-decay based on the neutrino.

1930: Wolfgang Pauli proposes the neutrino to preserve energy conservation in β-decay.

Where's the Next Nobel Prize Coming From?

Sterile Neutrinos

Direct Mass Measurement



Neutrinoless Double Beta Decay

Cosmic Neutrino Background (CνB)

stronomy