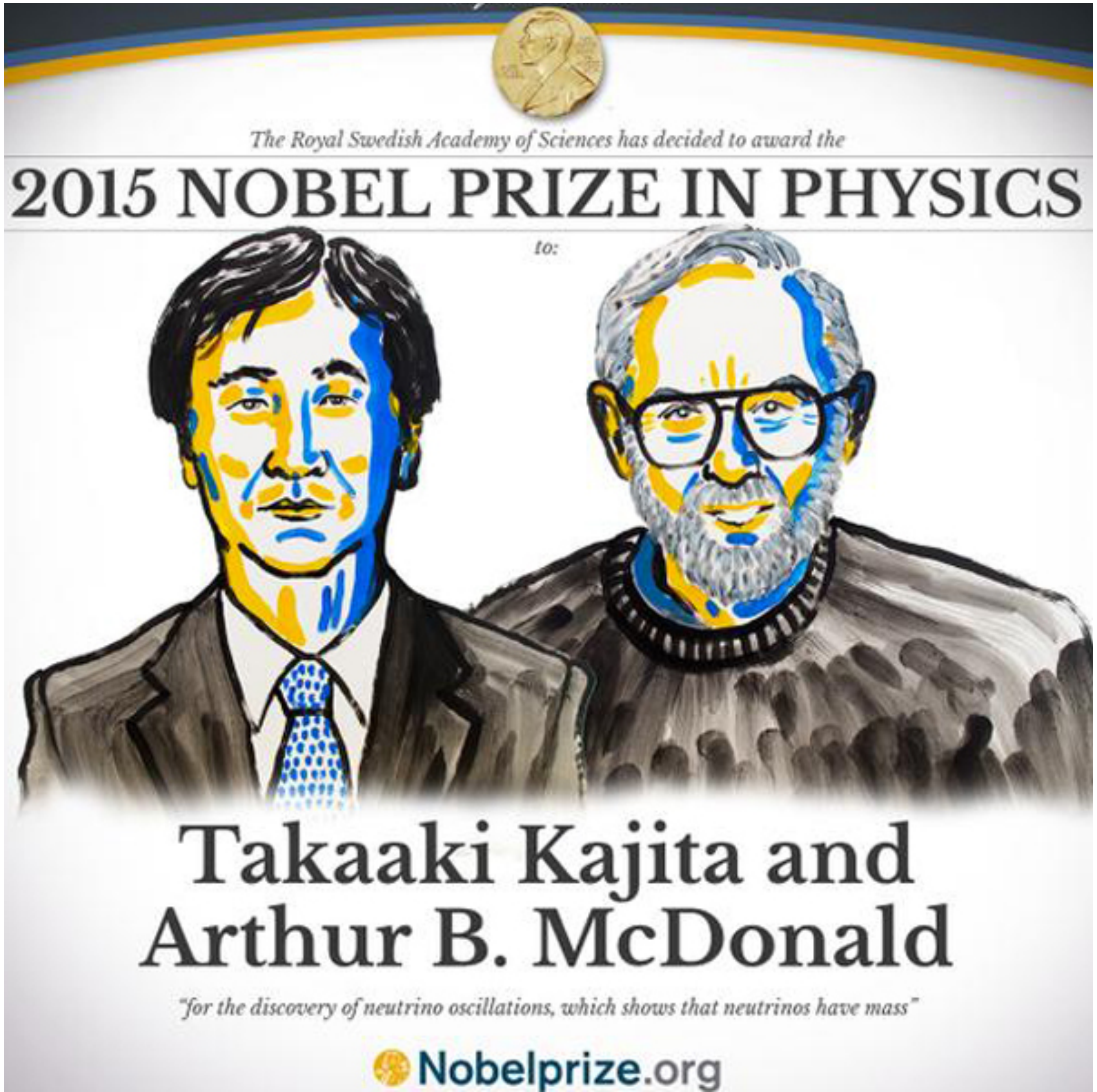
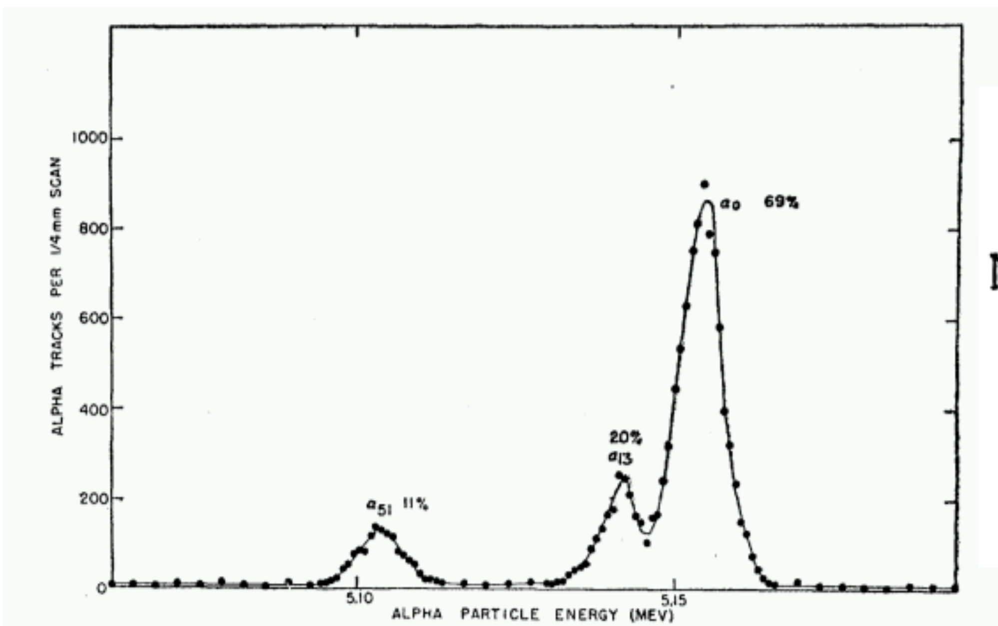
Neutrino Physics 1



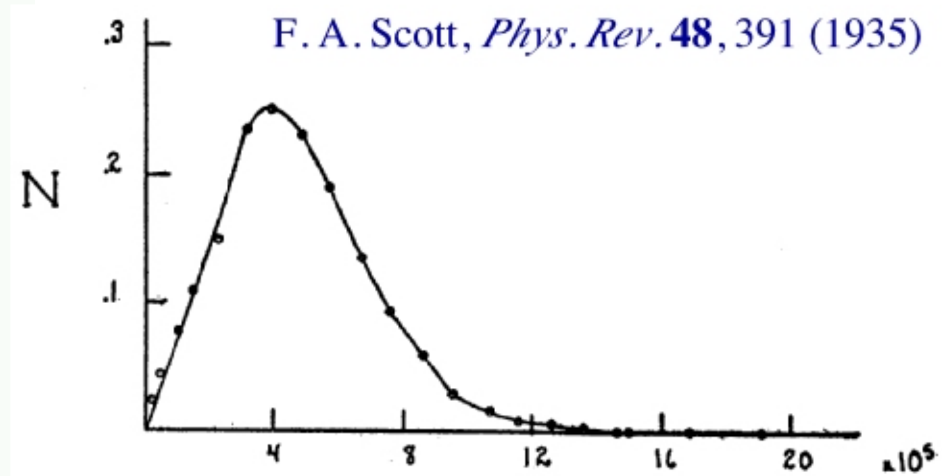
Michelle Dolinski
Drexel University
NNPSS, 10 July 2019

Birth of neutrinos

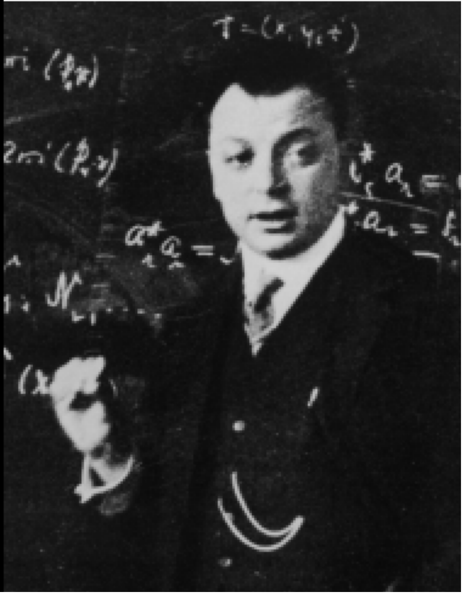
β-decay doesn't seem to conserve energy!



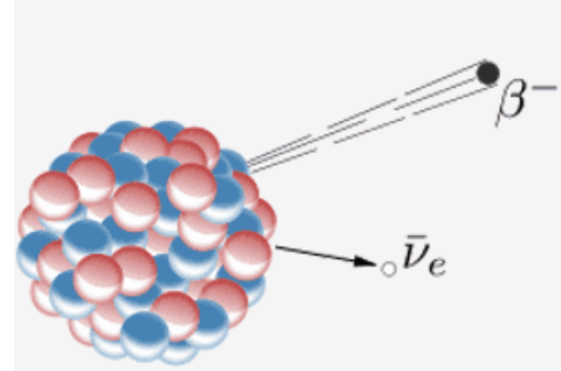
α-decay spectrum



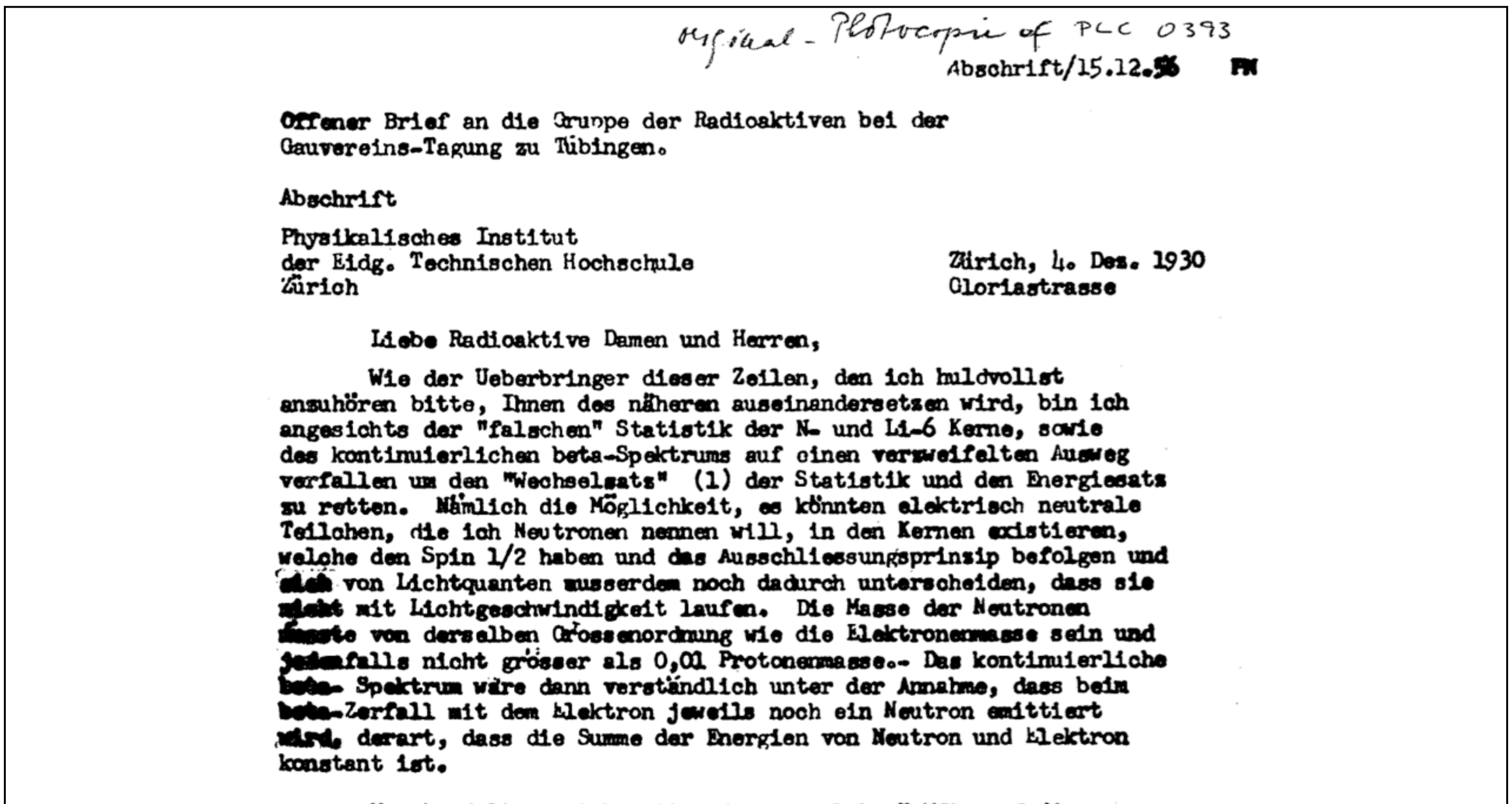
β-decay spectrum



Neutrinos



In 1930, Wolfgang Pauli proposes the neutrino, but it's also the birth of another force, the weak force!



original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

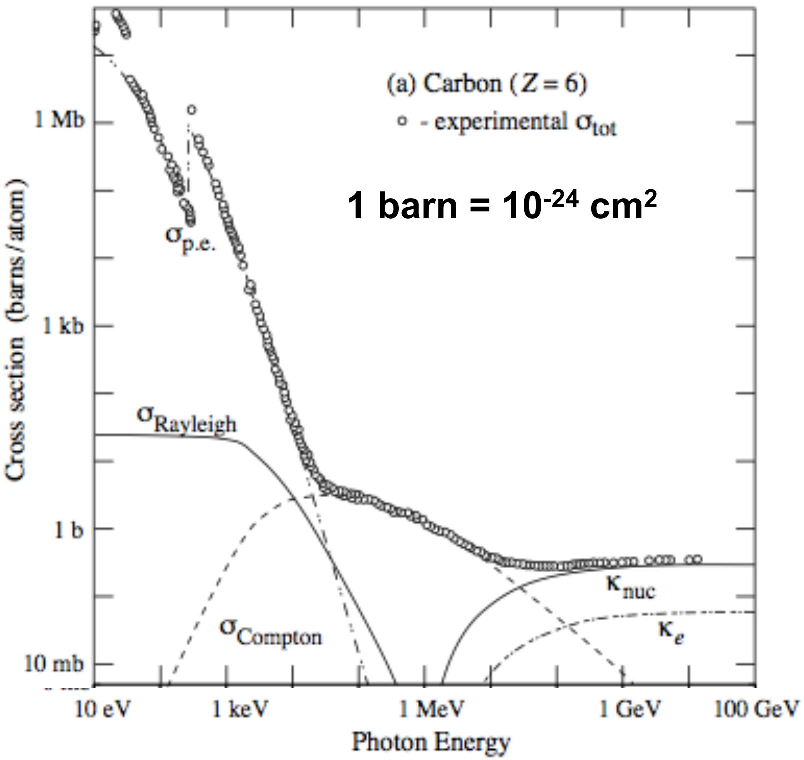
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Detecting neutrinos is hard

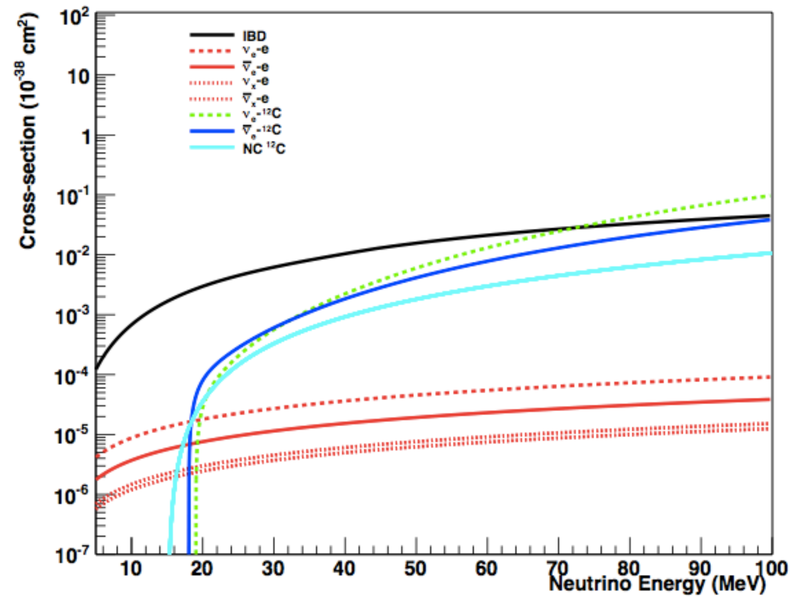
Photon-matter cross-sections



~10^{-24} cm^2

Slide: Kate Scholberg

Neutrino-matter cross-sections

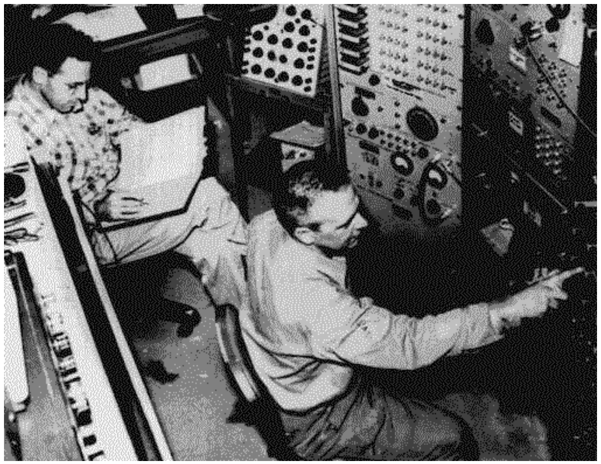


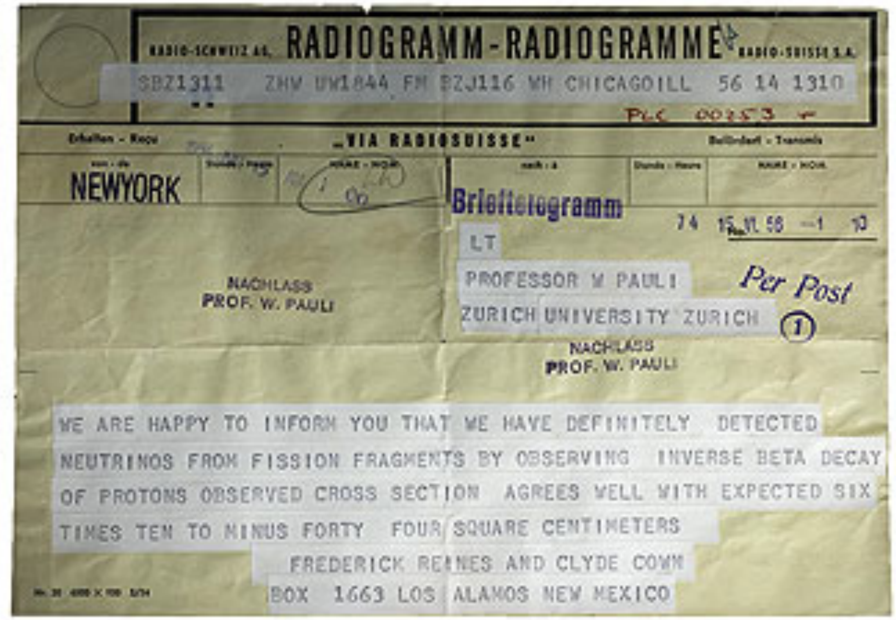
~10^{-40} cm^2

~16-17 orders of magnitude smaller

Discovery of the Neutrino

1956 - "Observation of the Free Antineutrino" by Reines and Cowan





RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.
SBZ1311 ZHW UW1844 FN BZJ116 WH CHICAGOILL 56 14 1310
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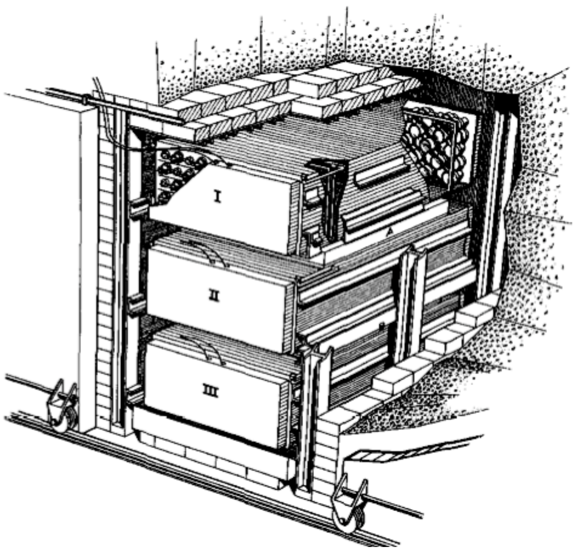
Briefteleqramm
74 15 VI 56 -1 10
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI

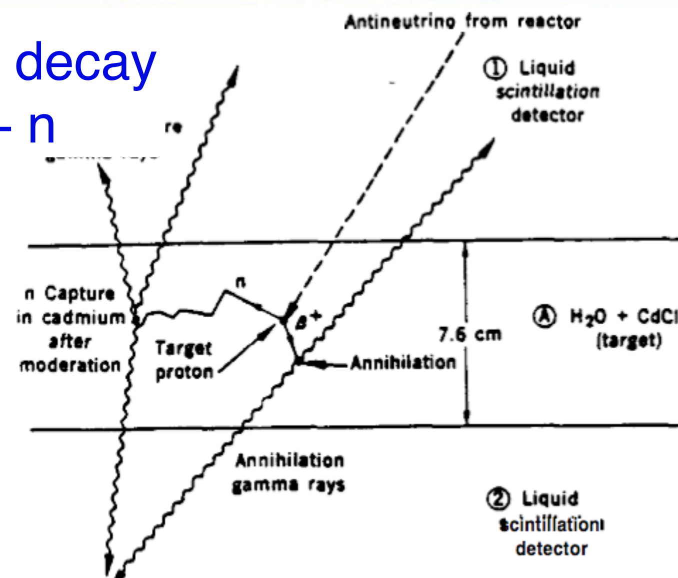
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO



inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$

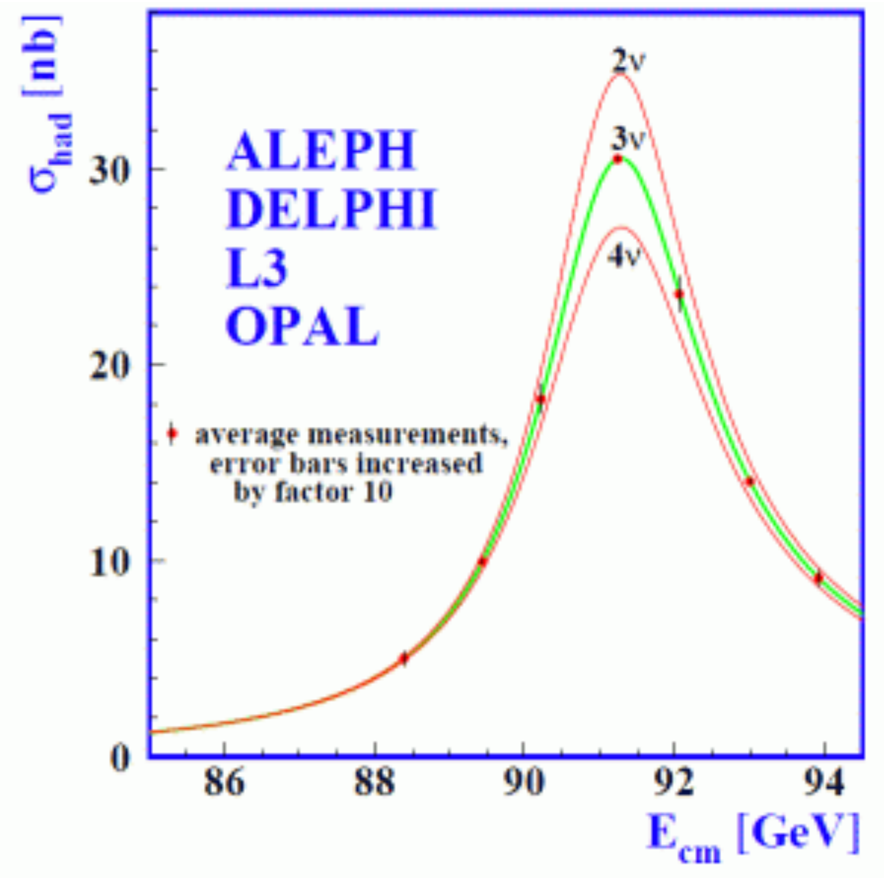


Three types of ν

1953 (confirmed 1956) - Reines and Cowan discover the electron neutrino (Nobel Prize for Fred Reines in 1995). 

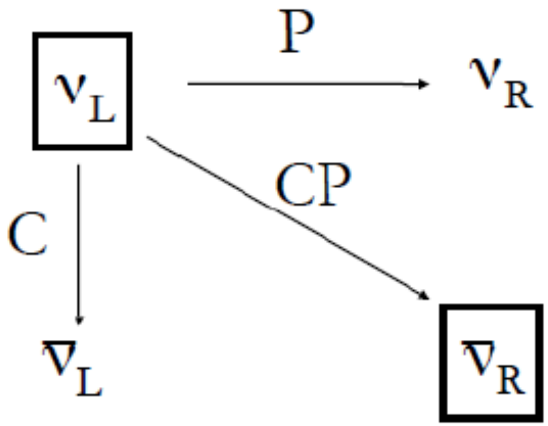
1962 - Danby, et. al., discover the muon neutrino (Nobel Prize 1988). 

2000 - DONUT collaboration discovers the tau neutrino.



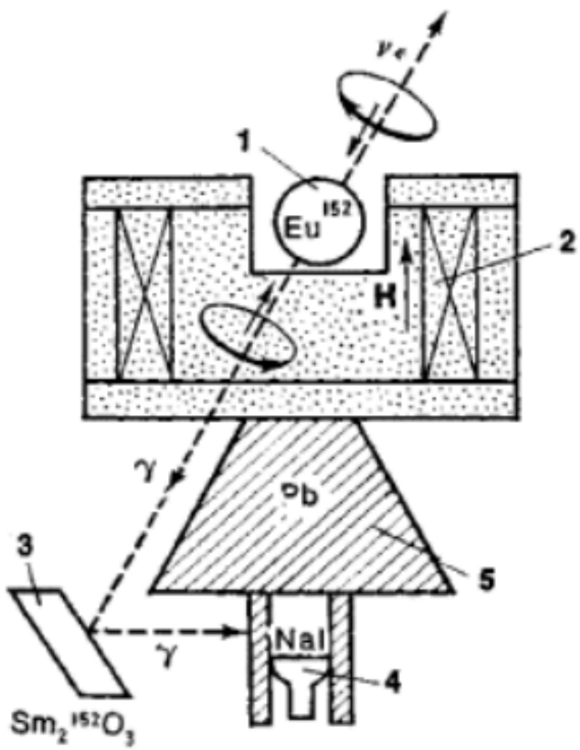
Cosmology can also measure the total number of neutrino species, consistent with 3!

Goldhaber experiment



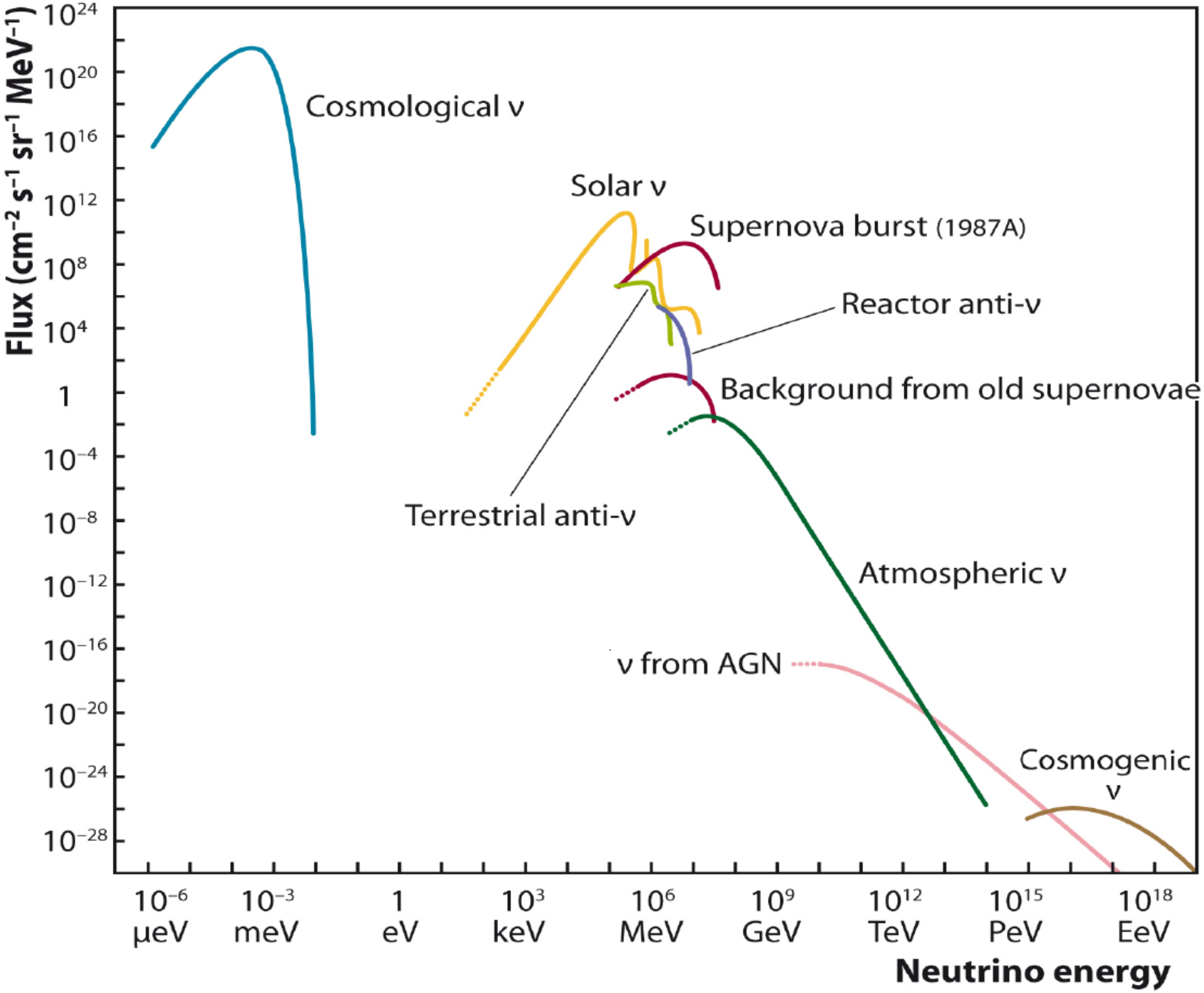
Only left-handed neutrinos ν_L and right-handed antineutrinos $\bar{\nu}_R$ are observed in nature!

Confirmed by Maurice Goldhaber, but measuring photon polarization and using conservation of angular momentum!



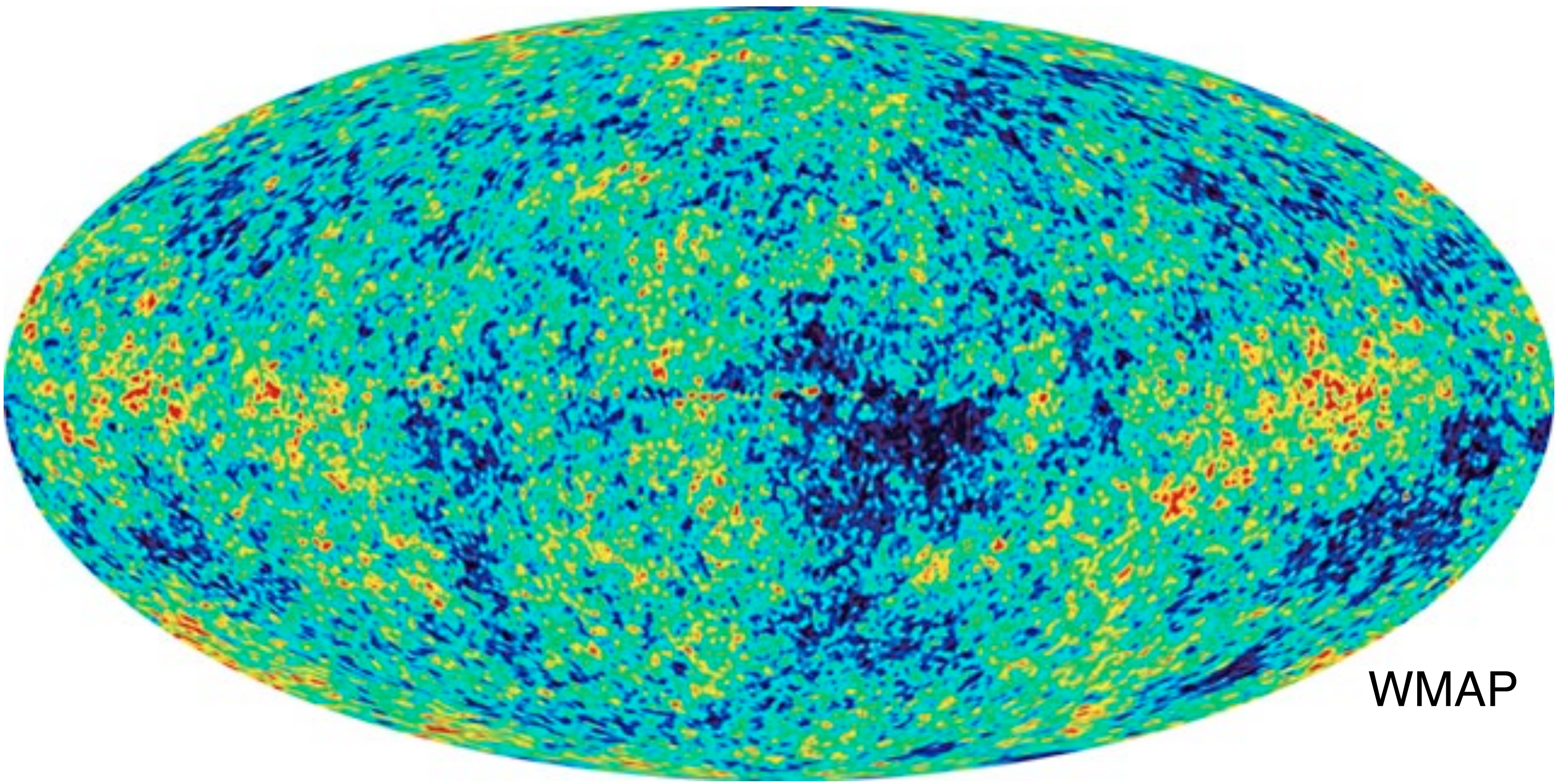
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Phys. Rev. **109**, 1015 (1958)

Sources of Neutrinos



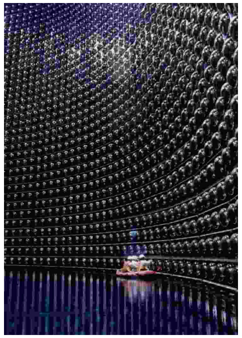
Katz, *Prog. Part. Nucl. Phys.* **67** (2012) 651

Cosmic neutrino background



The cosmic microwave background map is **the** baby picture of the universe…for now!

Milestones in Neutrino Oscillations

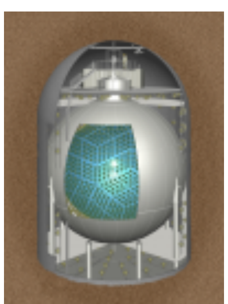


Solar neutrino problem is born when Ray Davis's Cl experiment in the Homestake mine shows ~1/3 expected solar ν_e flux.

•Solar neutrino deficit confirmed by GALLEX/GNO and SAGE.

Disappearance of atmospheric ν_μ's measured by SuperKamiokande.

SNO confirms flavor change in solar neutrinos by measuring Φ_{CC}/Φ_{NC}.

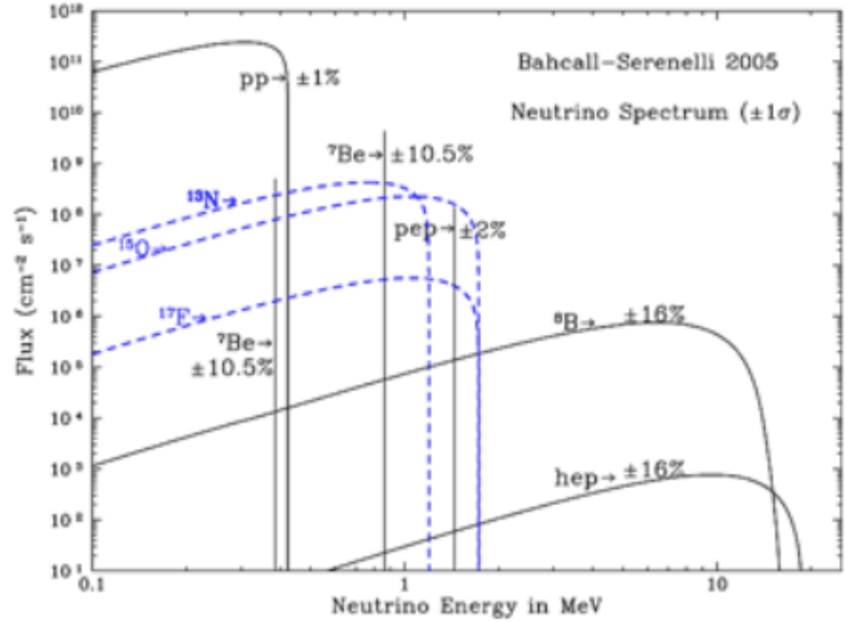


•KamLAND observes neutrino oscillations with reactor anti-neutrinos.

•Double Chooz/Daya Bay/RENO measure θ_{13}.

Homestake

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

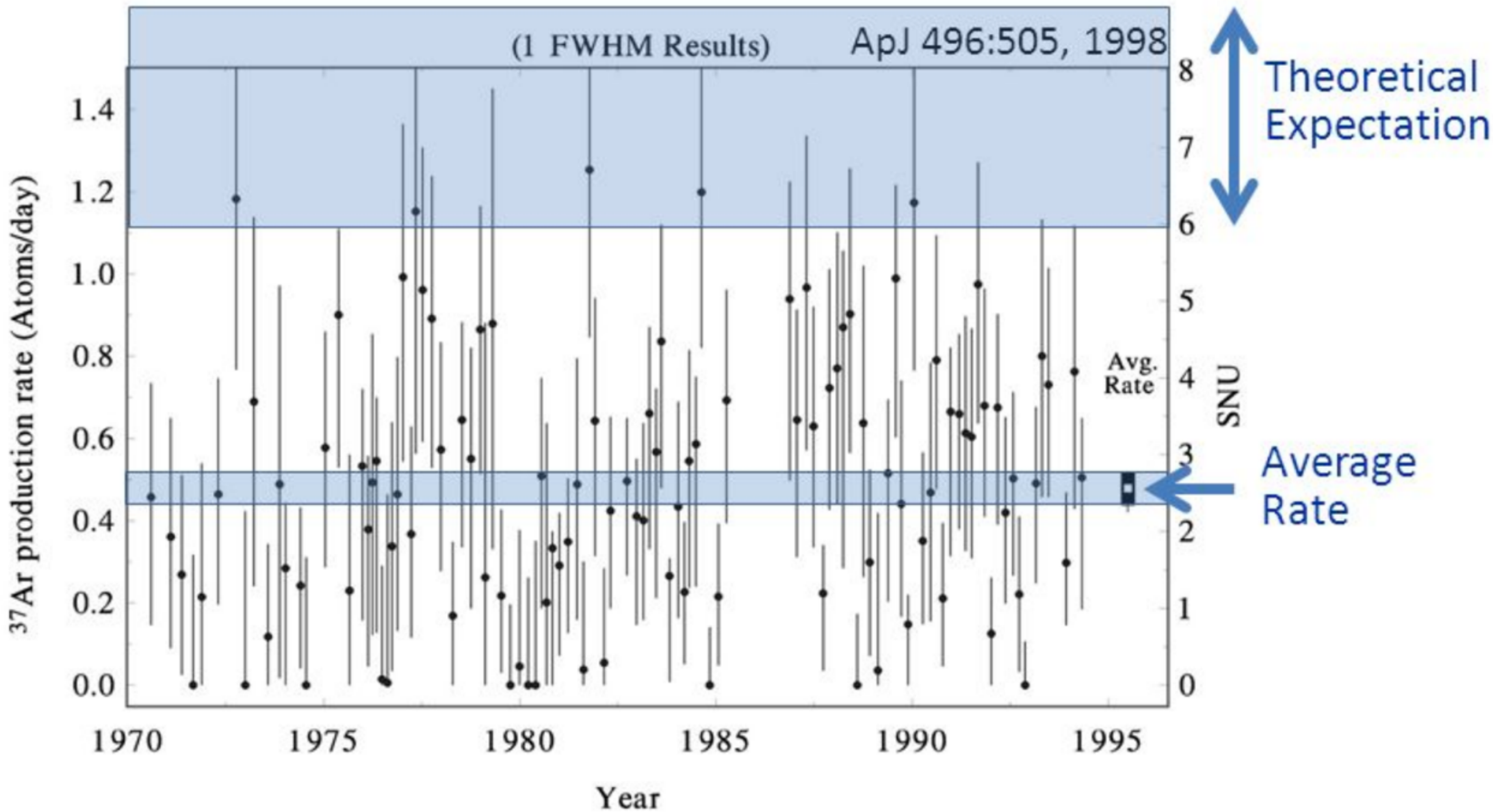


The Homestake detector was built by Ray Davis (Nobel 2002) to test John Bahcall's Standard Solar Model.

Surprisingly, the Homestake experiment only saw ~1/3 the expected flux of neutrinos.

Slide: Georg Raffelt

Homestake



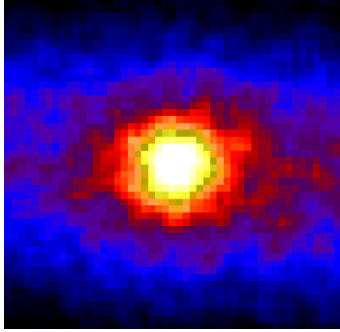
Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

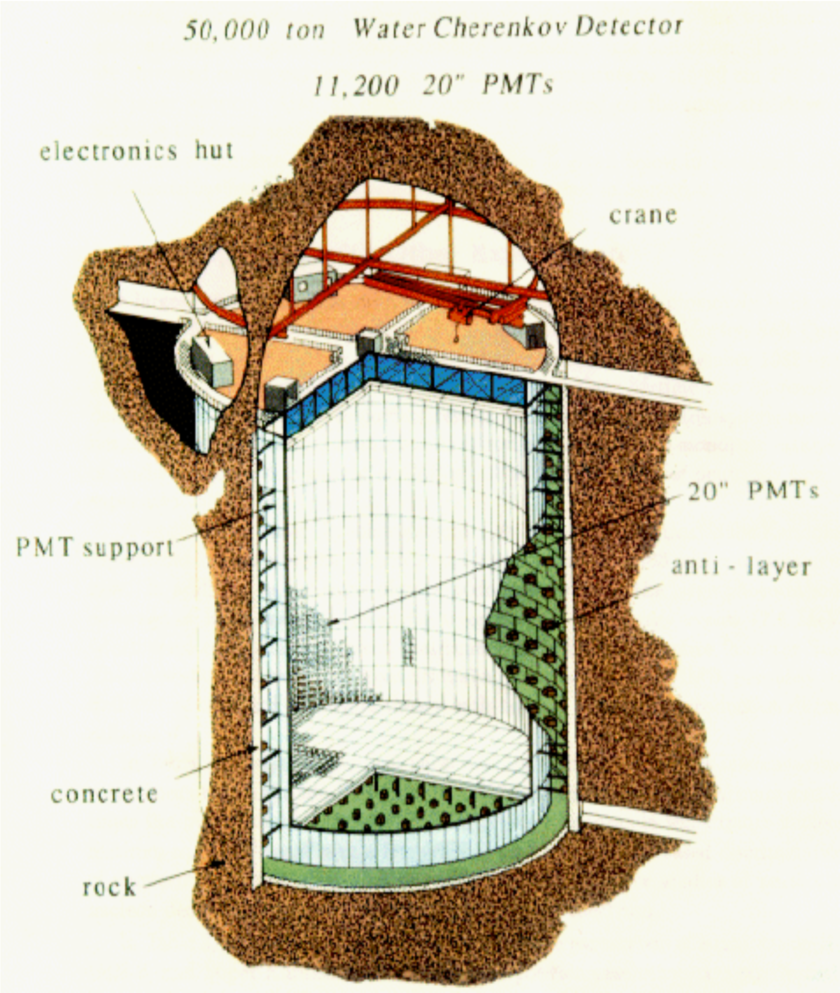
(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

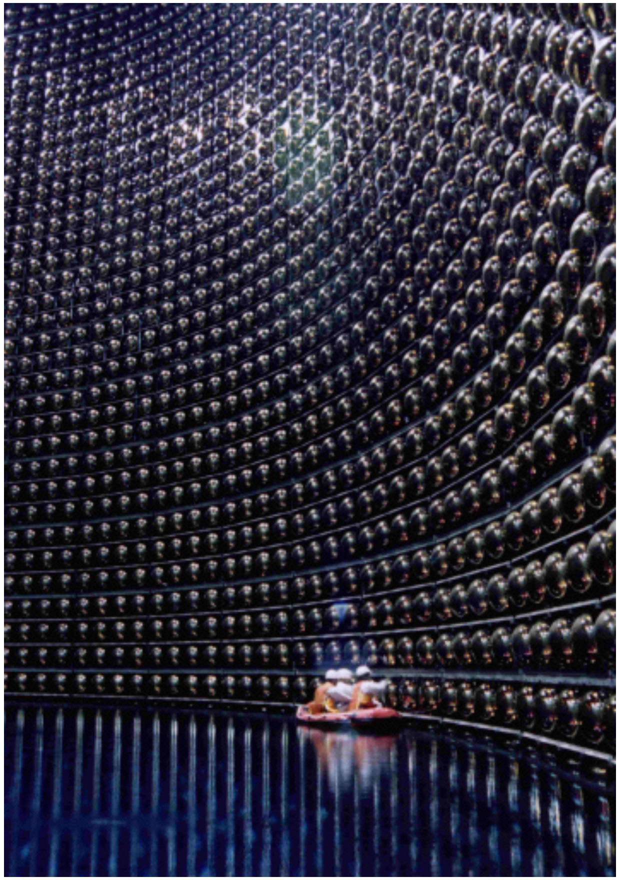
Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Super KamiokaNDE

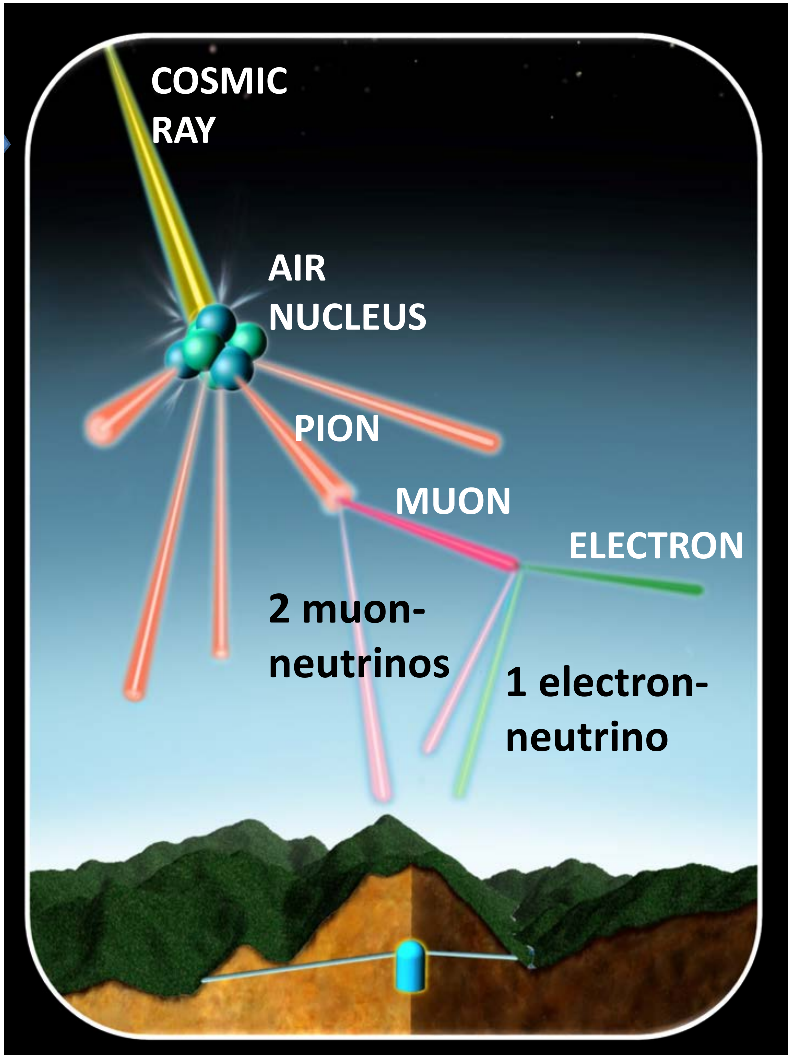


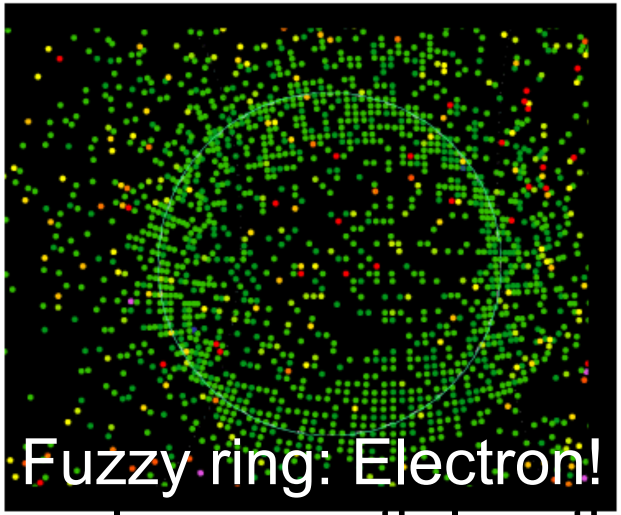




Super KamiokaNDE

Graphics: SuperK

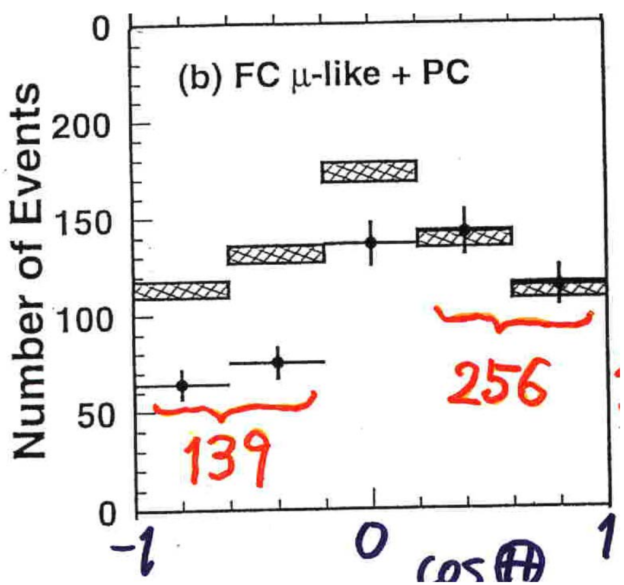


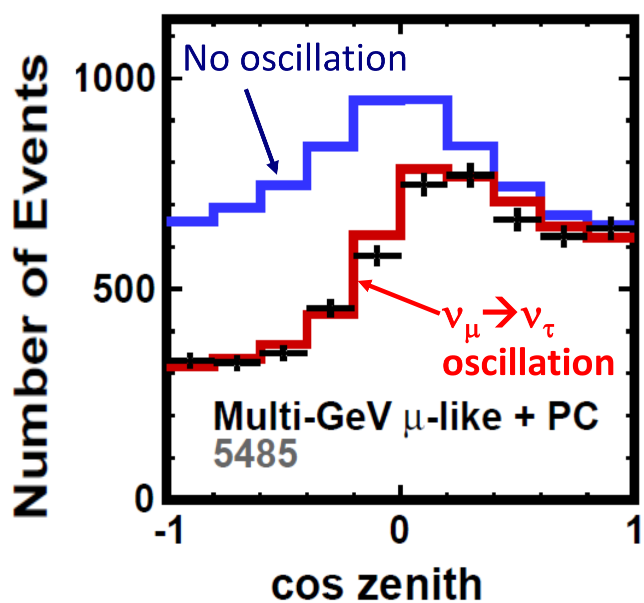


Oscillation path length depends on angle – longer path length through the earth

SuperK results

Super-K @Neutrino98 → Super-K (2015)





Takaaki Kajita, Nobel Prize Lecture, 2015

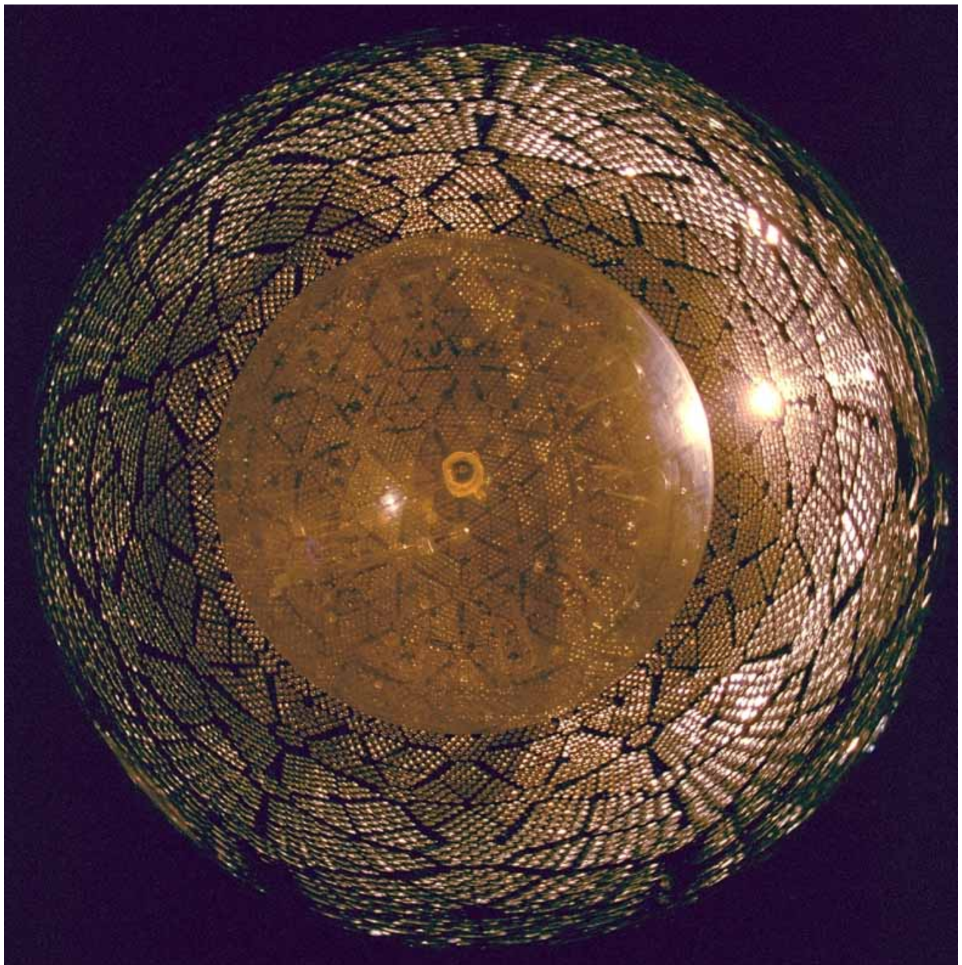
Number of events plotted:

531 events → 5485 events

SNO

Sudbury Neutrino Observatory: combine CC, NC sensitivity

- Measure both ν_e disappearance AND total ν_X flux
- Confirm where missing electron neutrinos went



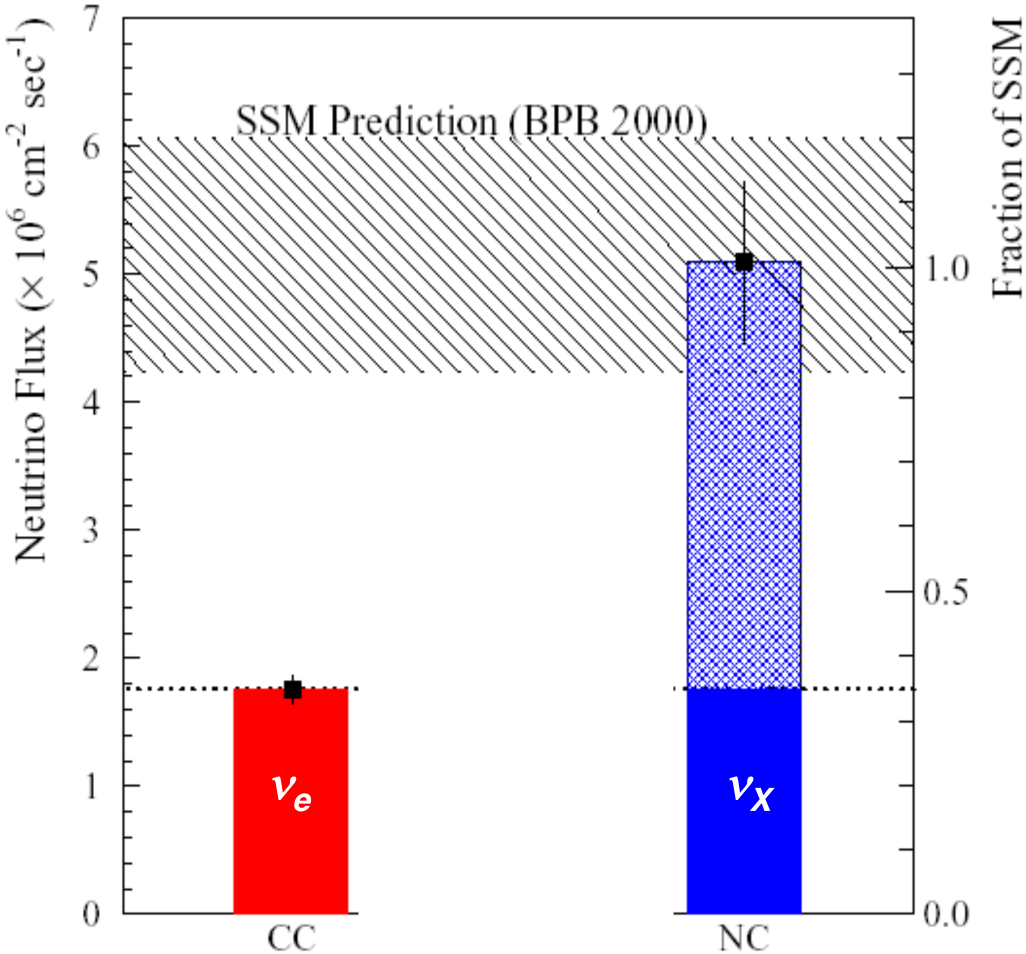
1000 tonnes of ultra-pure heavy water (D_2O) housed in a clear acrylic vessel 12 m in diameter, located a mile underground in a nickel mine in Sudbury, Ontario, Canada.

SNO results

Charged Current Reaction (CC): $\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + e^-$

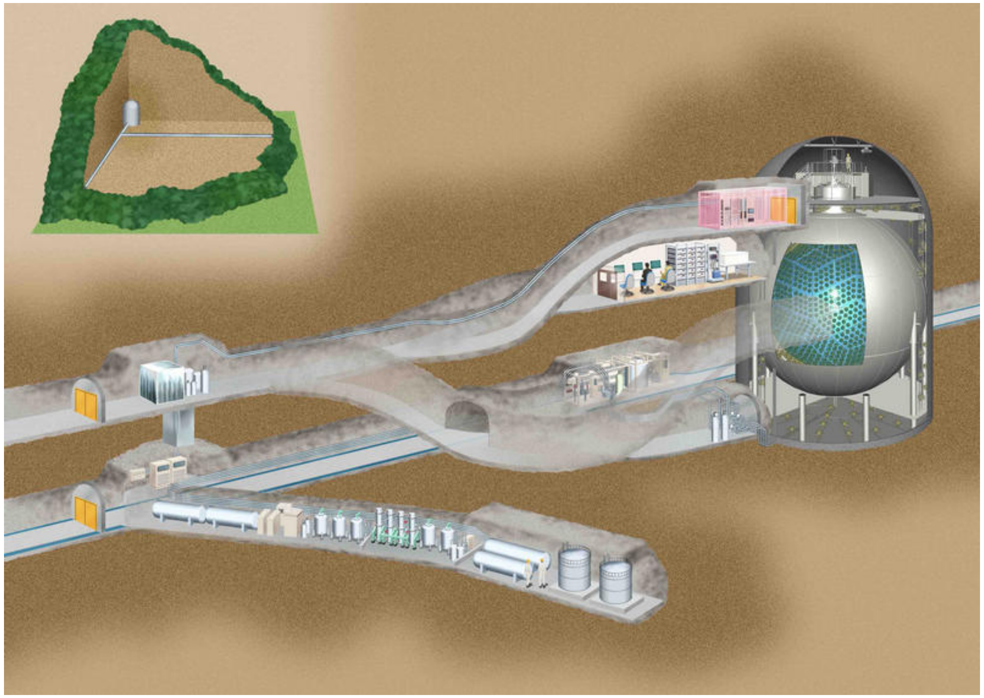
Elastic Scattering Reaction (ES): $\nu_x + e^- \longrightarrow \nu_x + e^-$

Neutral Current Reaction (NC): $\nu_x + \mathrm{d} \longrightarrow \nu_x + \mathrm{p} + \mathrm{n}.$

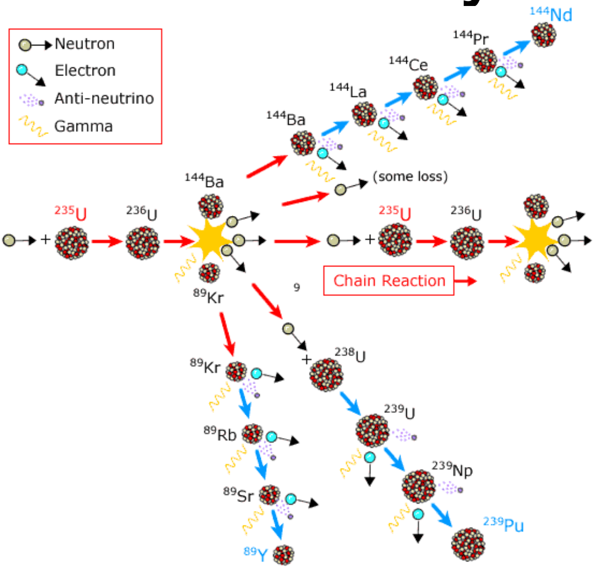


Art McDonald,
Nobel Prize Lecture,
2015

KamLAND



Neutrino Physics at Reactors



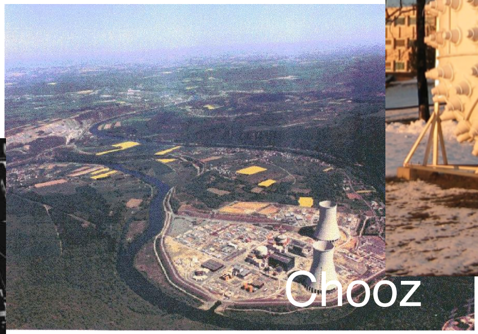
Next - Discovery and precision measurement of θ_{13}

2008 - Precision measurement of $(\Delta m_{12})^2$. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

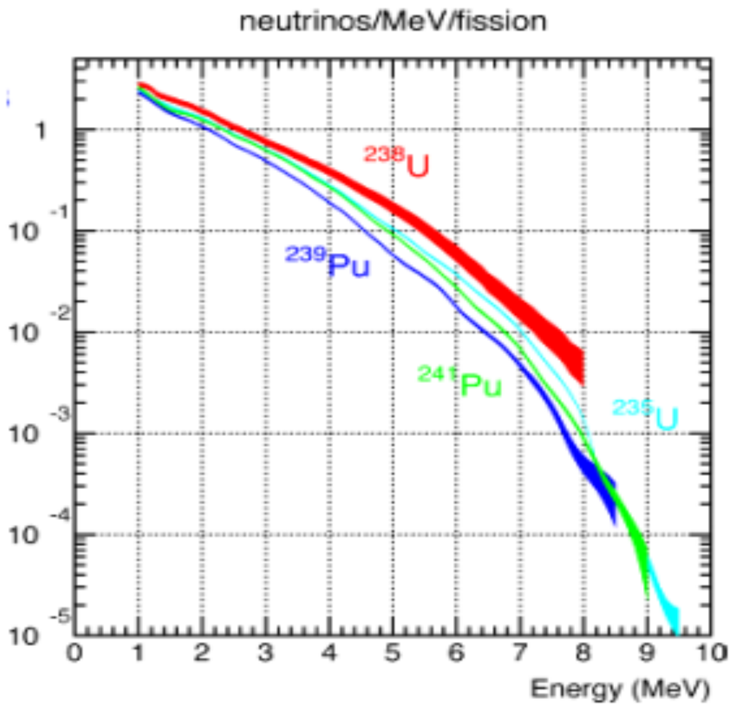


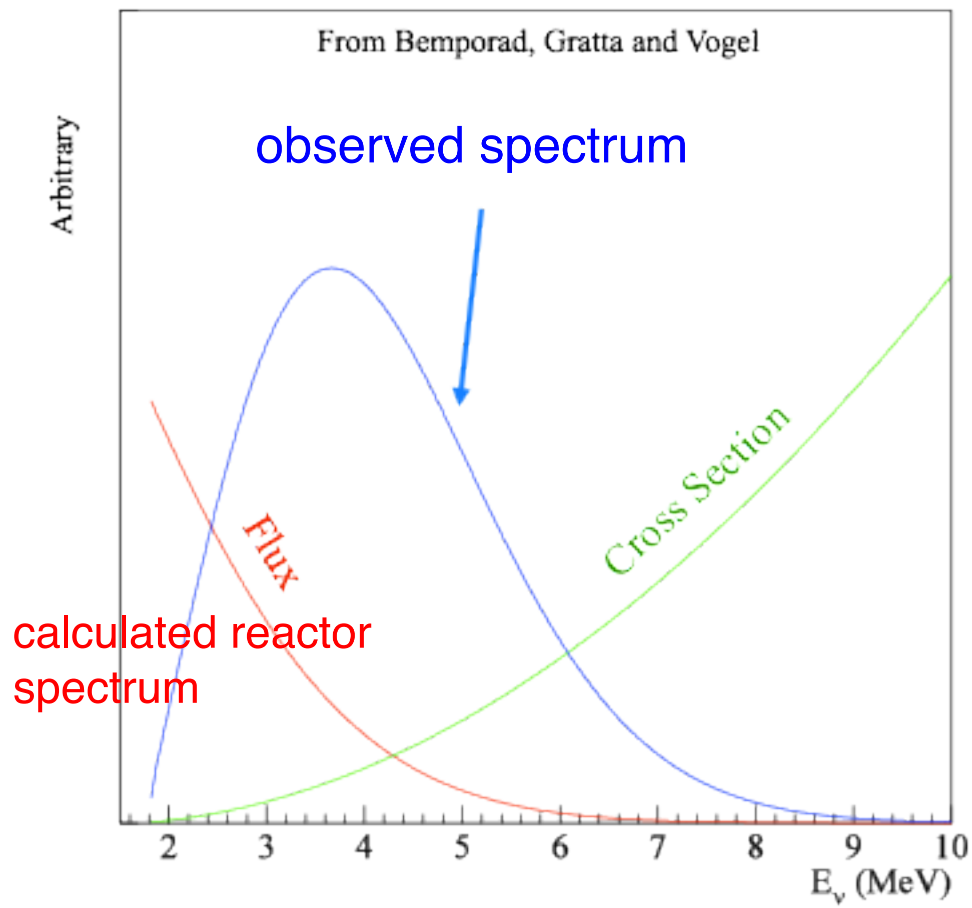
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

63 years of liquid scintillator detectors
a story of varying baselines...

Reactor Antineutrinos

$\overline{\nu}_e$ from n-rich fission products





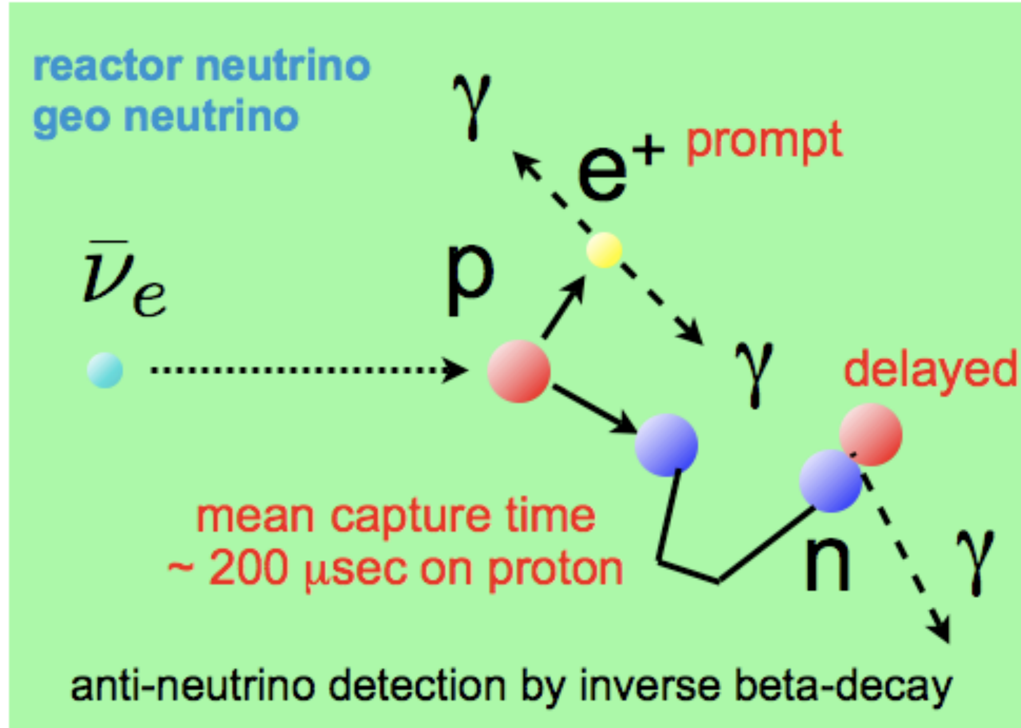
~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission on average, only ~ 1.5 $\bar{\nu}_e$/fission can be detected

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec

Inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$



coincidence signature

prompt e⁺ and delayed neutron capture

powerful background suppression technique

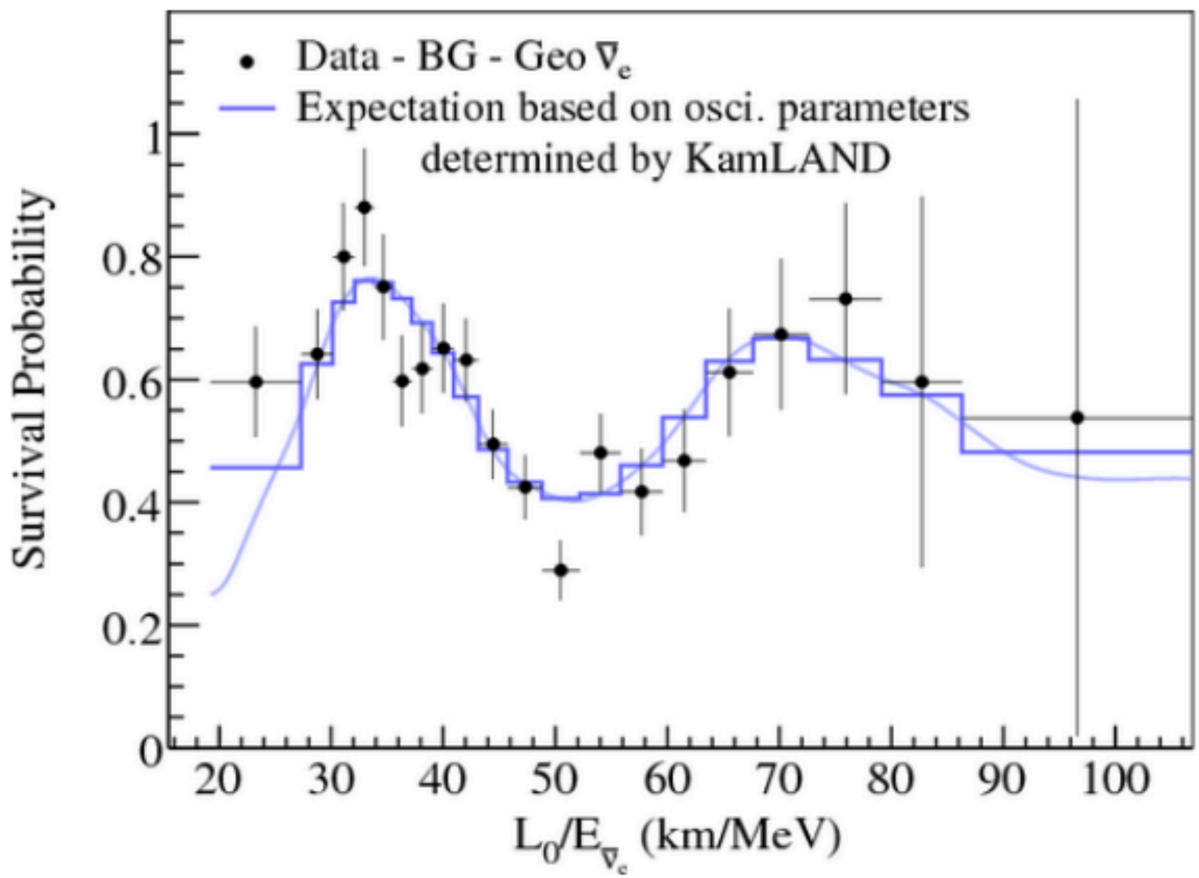
10-100 keV

1.805 MeV

$$E_{\overline{\nu}_e} \cong E_{e^+} + E_n + (M_n - M_p) + m_{e^+}$$

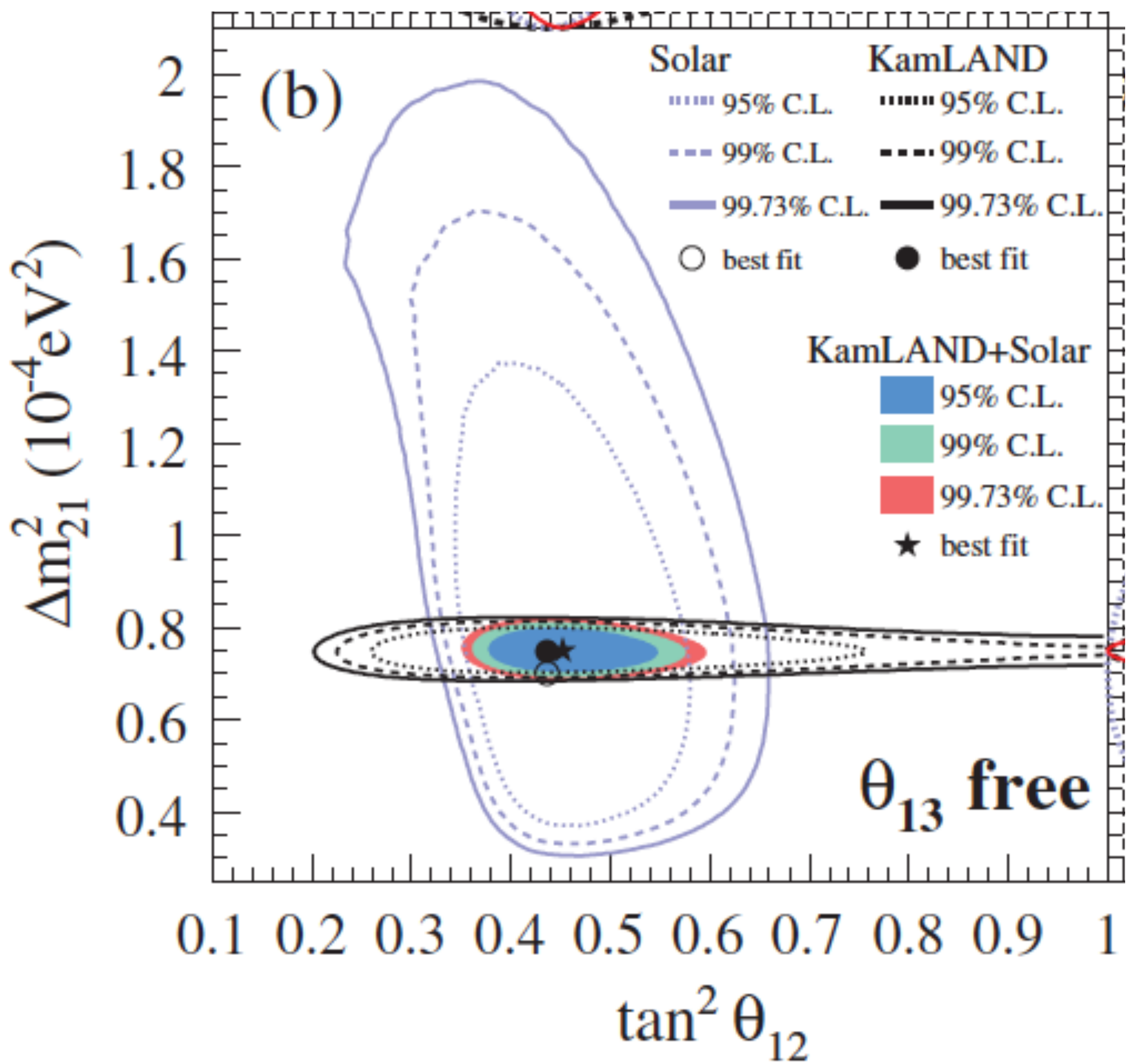
Neutrino oscillations with KamLAND

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.3\Delta m^2 L}{E}$$



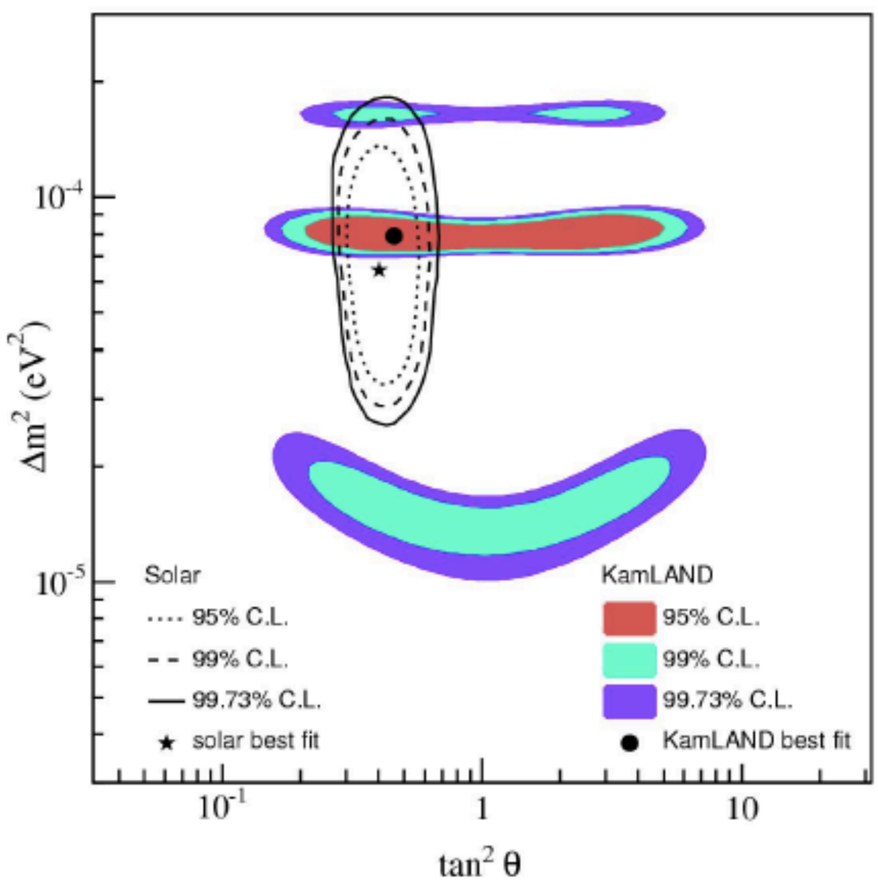
KamLAND result. A. Gando et al., Phys. Rev. D83 (2011) 052002

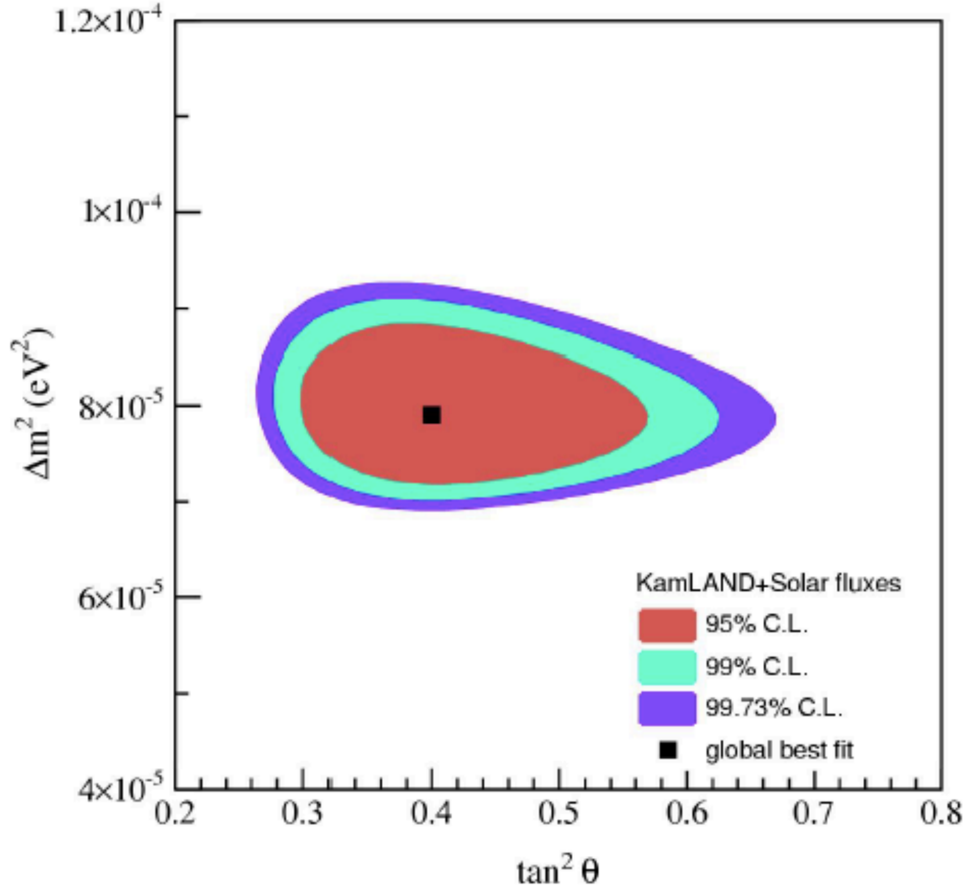
Neutrino oscillations with KamLAND



KamLAND result. A. Gando et al., Phys. Rev. D83 (2011) 052002

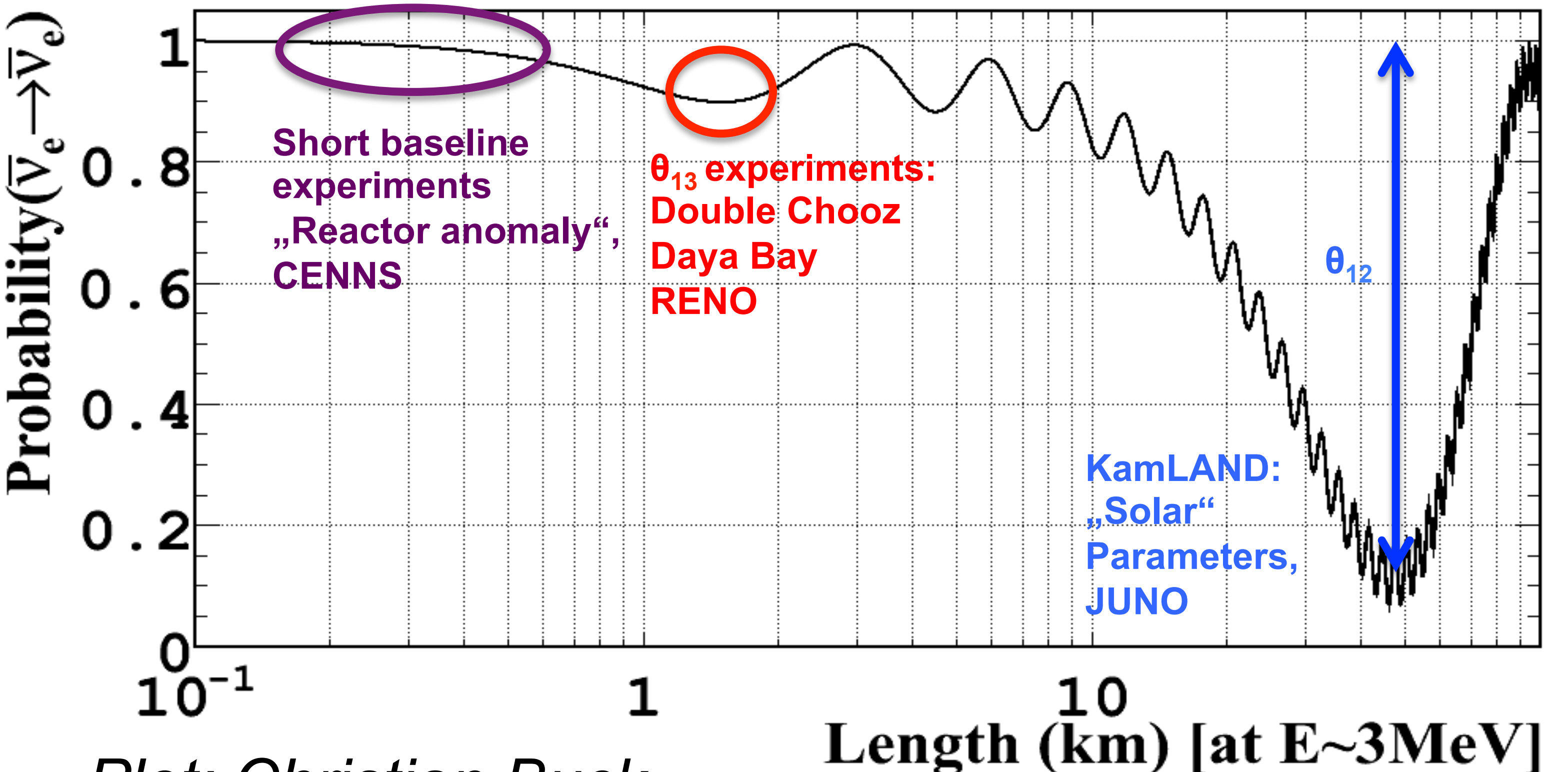
Matter effects





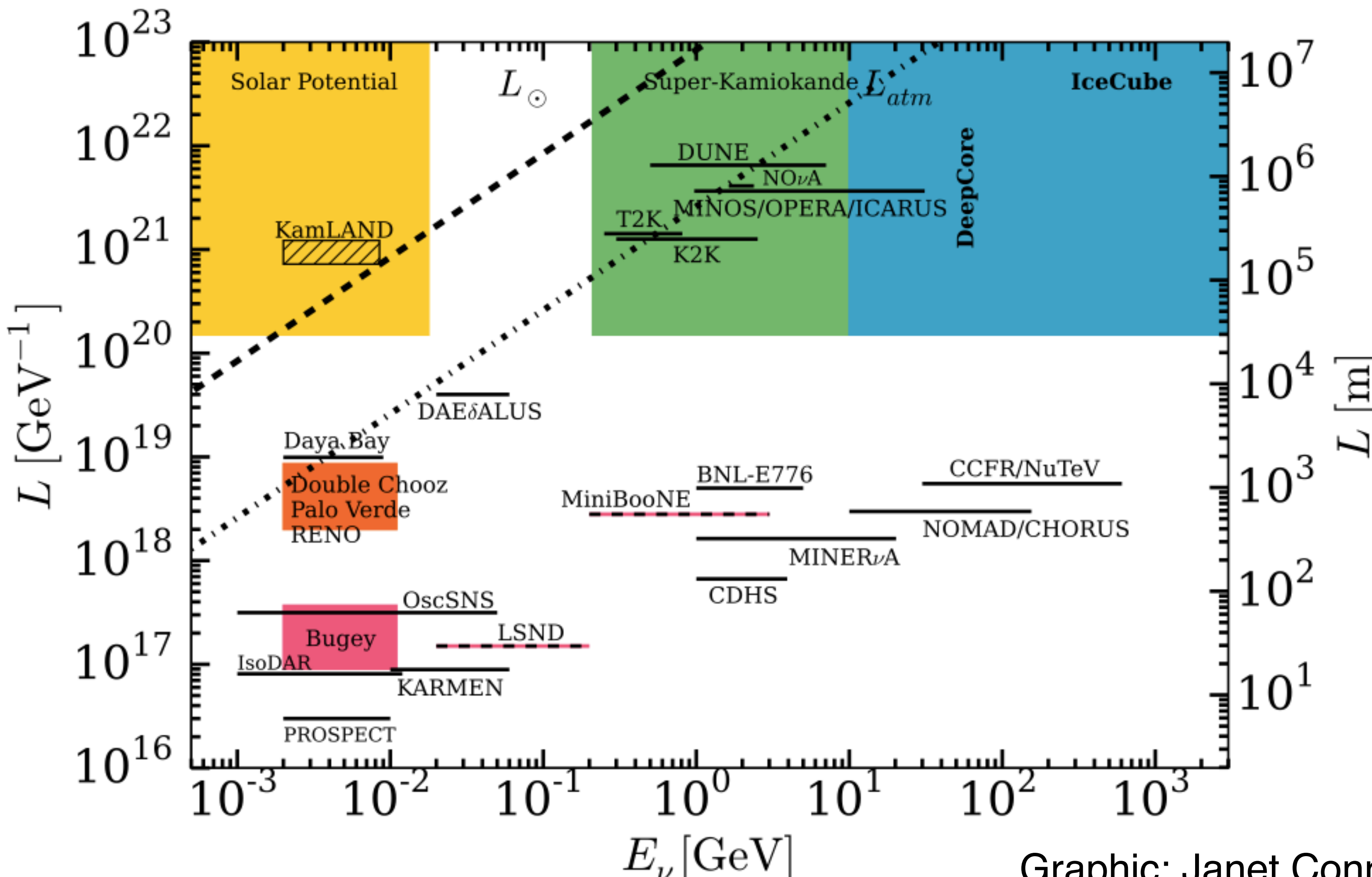
There's actually something very special going on with solar neutrinos. They're experience a resonance due to their interaction with the dense matter in the sun. This is known as the MSW effect, and it lets us tell that $m_1 < m_2$.

Oscillations vs baseline



Plot: Christian Buck

Energy and baseline

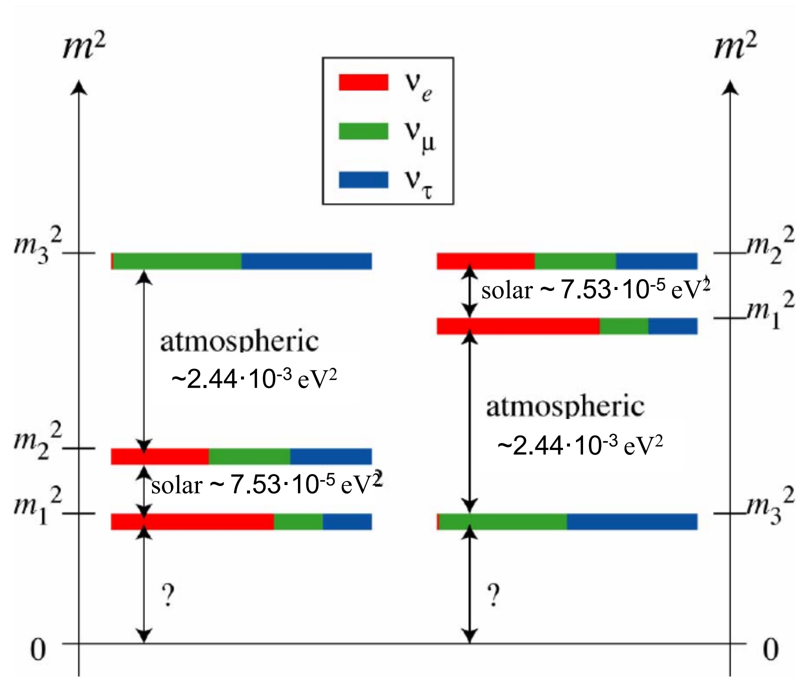


Graphic: Janet Conrad

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

$\sin^2(\theta_{12})$	0.307 ± 0.013
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23})$	$0.536^{+0.023}_{-0.028}$ ...
Δm^2_{32}	0.002444 ± 0.000034 eV^2
$\sin^2(\theta_{13})$	0.0218 ± 0.0007



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{"atmospheric"}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{"reactor"}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{"solar"}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$\sin^2\theta_{23}$ $\sin^2\theta_{13}$ $\sin^2\theta_{12}$

Precision measurments can be made with neutrino beams!

Appearance experiments

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

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

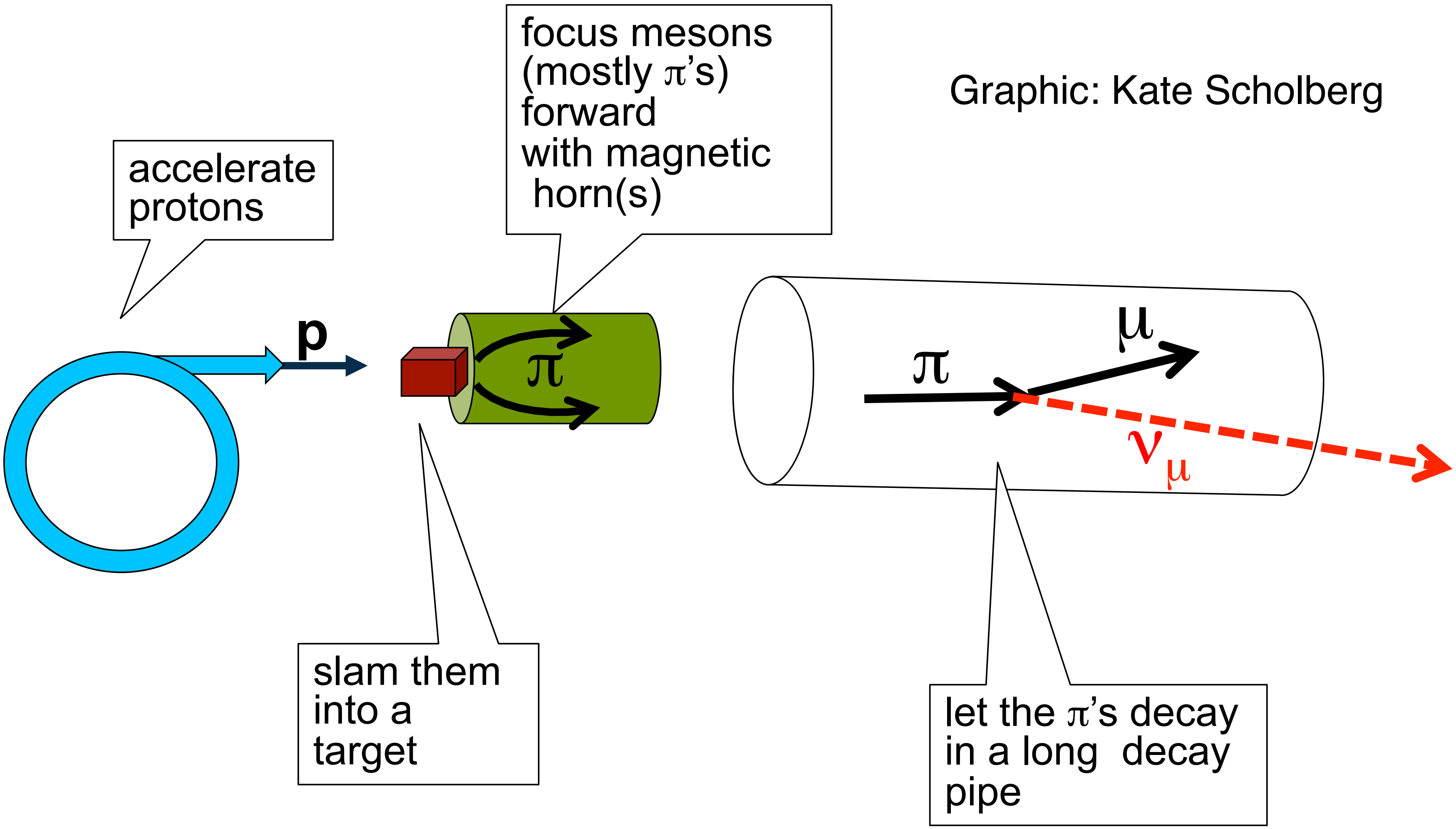
$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

- Depends some on *every* oscillation parameter.
- **Benefit**: can answer more questions.
- **Drawback**: degeneracies make things difficult.

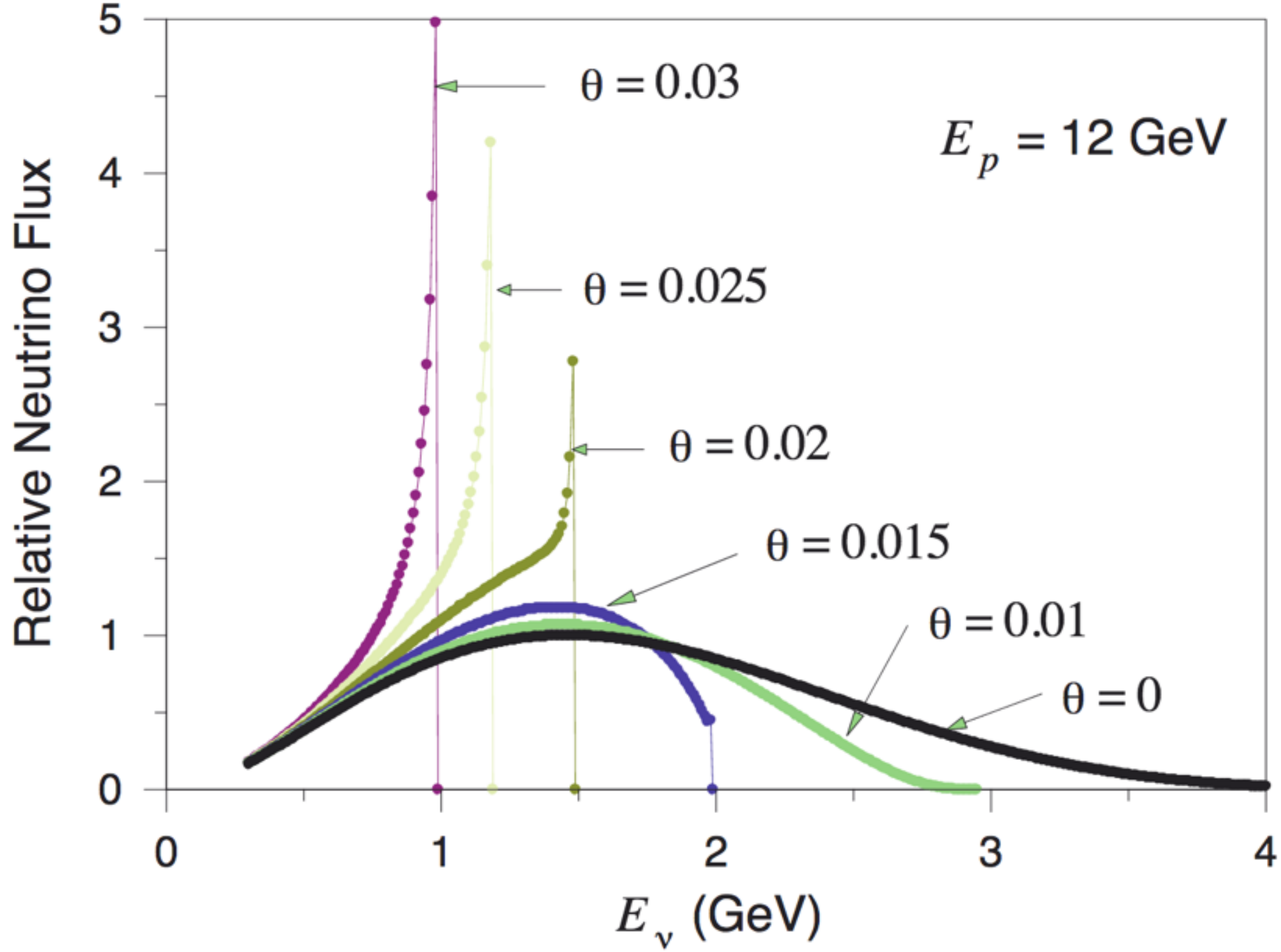
Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Making a neutrino beam

Graphic: Kate Scholberg

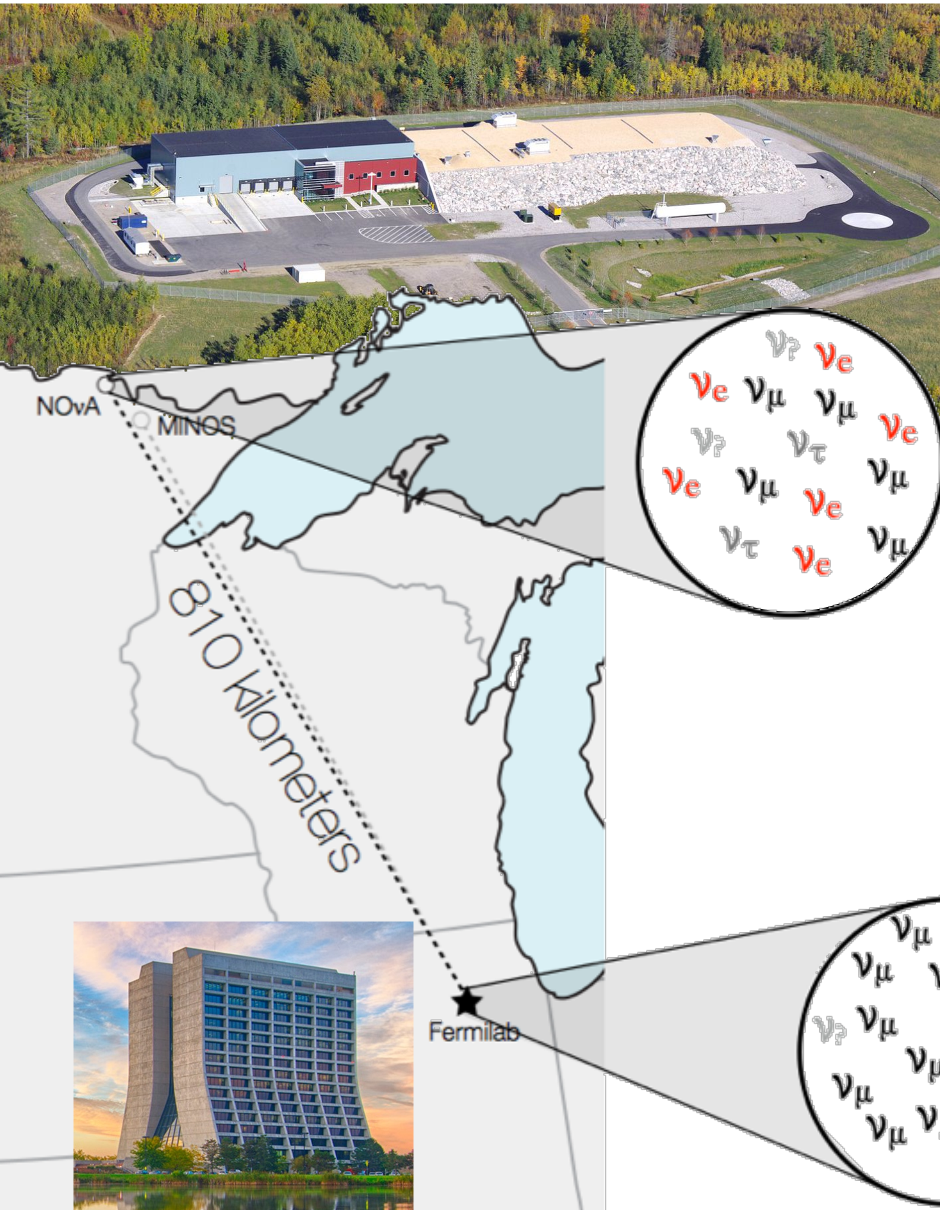


Off axis trick

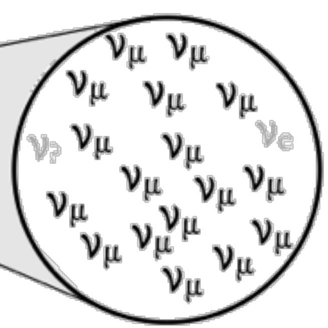


McDonald, arXiv: 0111033

NOνA



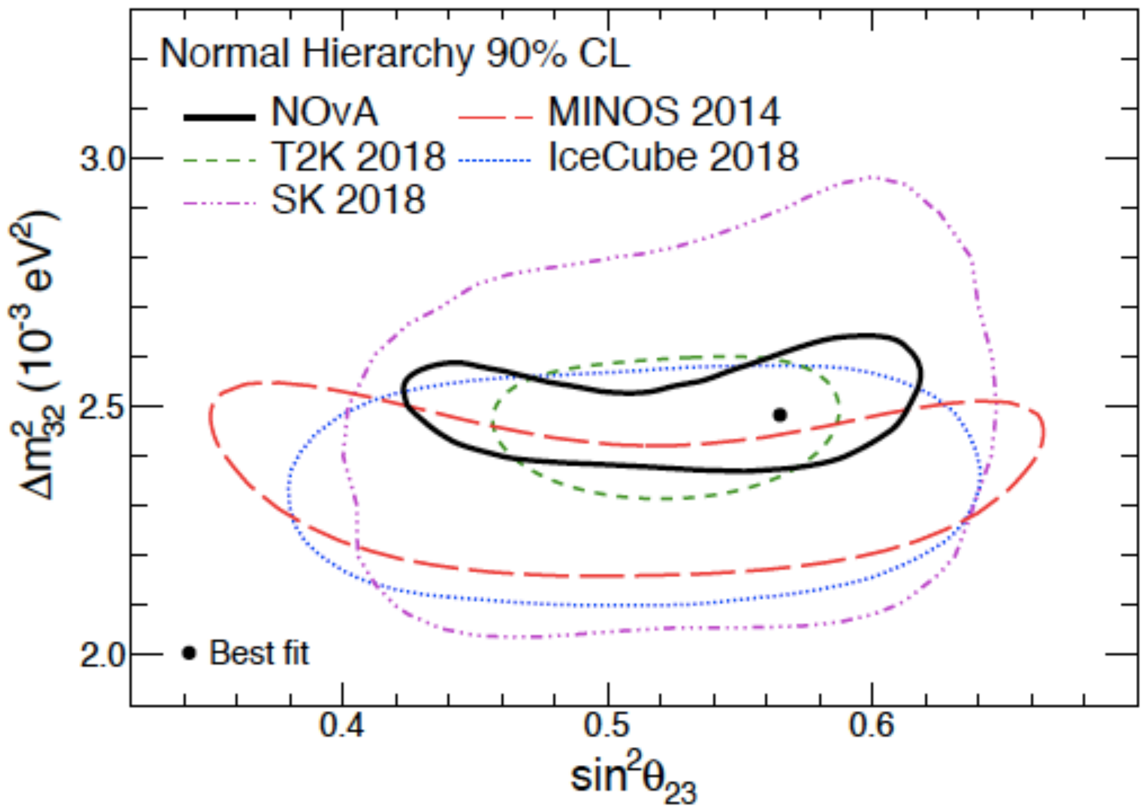
- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab
  - **Near Detector** to measure the beam before oscillations
  - **Far Detector** measures the oscillated spectrum.
- **Primary goal**: measurement of 3-flavor oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

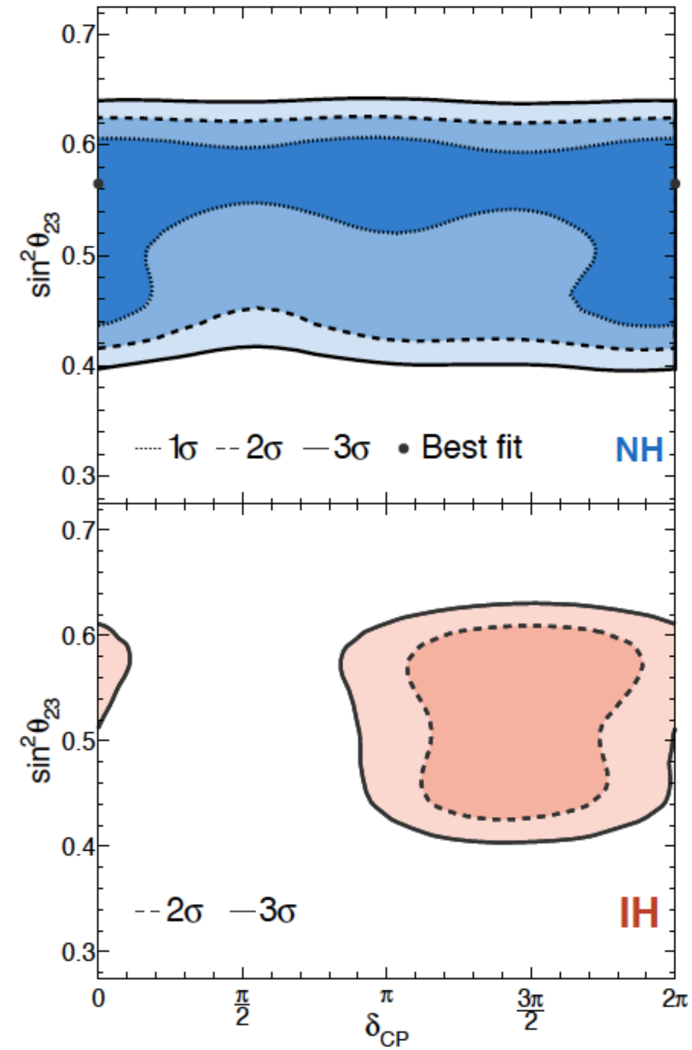


Slide: Alex Himmel

NOνA recent results

arXiv:1906.04907v2 (14 June 2019)



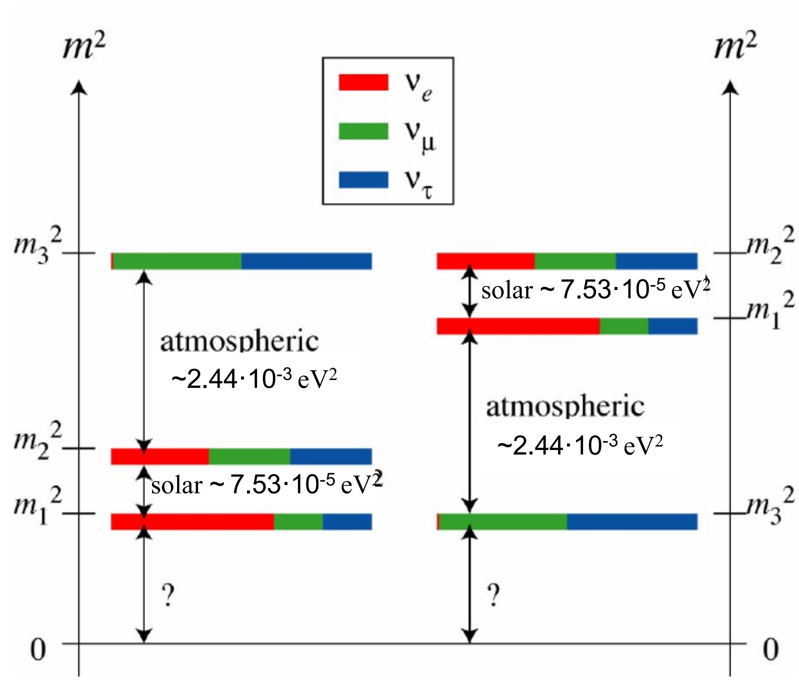


$$|\Delta m^2_{32}| = 2.48^{+0.11}_{-0.06} \times 10^{-3}\ \mathrm{eV}^2/c^4,\ \sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

The data favor the normal neutrino mass hierarchy by 1.9σ

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

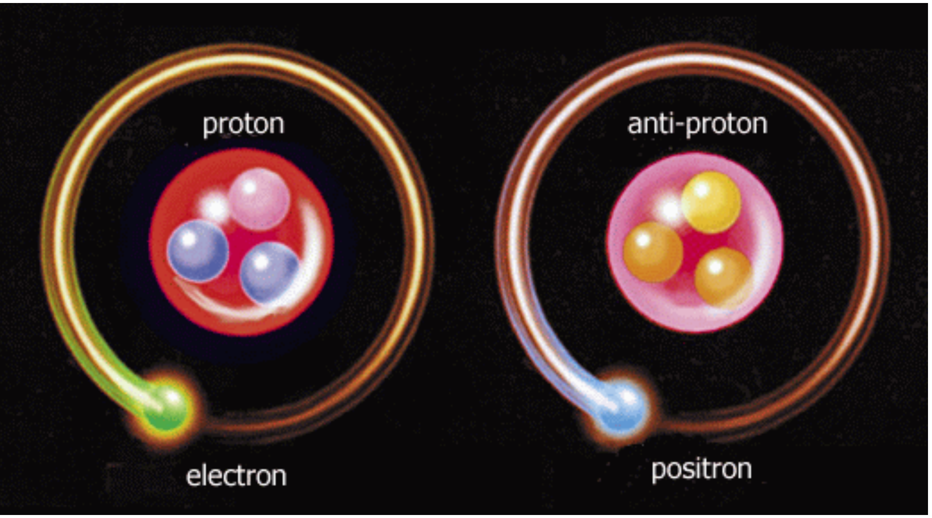


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{“atmospheric”}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{“reactor"}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“solar”}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$$\sin^2\theta_{23} \qquad \sin^2\theta_{13} \qquad \sin^2\theta_{12}$$

The matter-antimatter asymmetry



"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science."

How do we generate a matter-antimatter asymmetry?

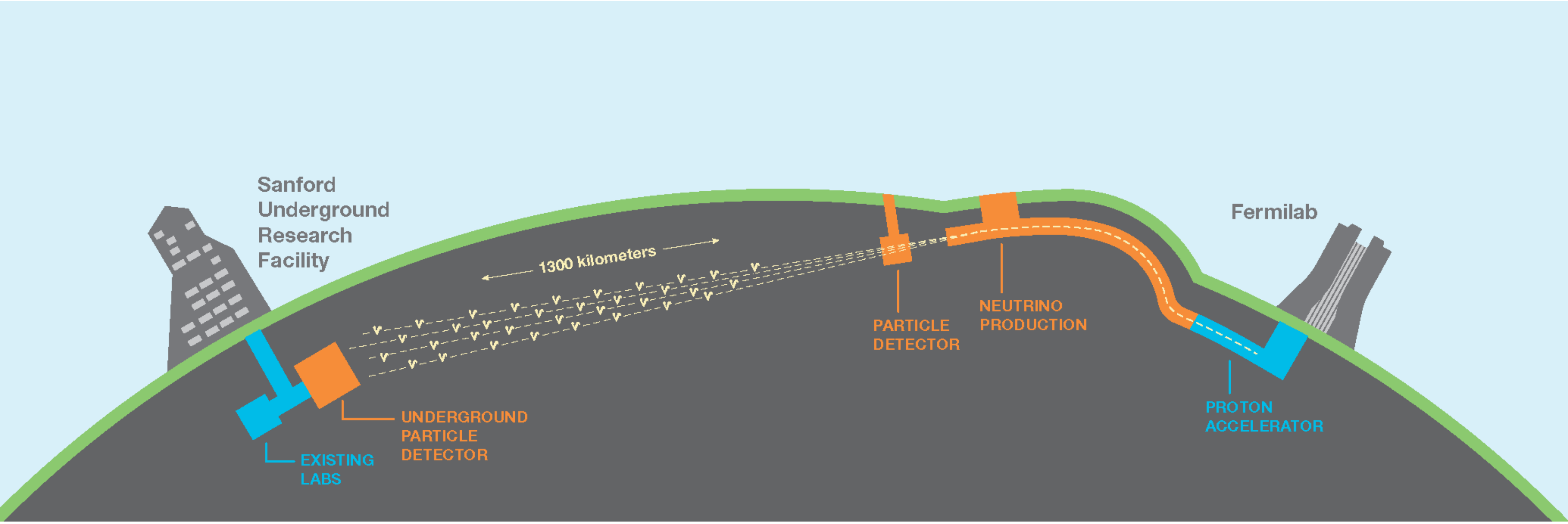
Sakharov (1967) conditions for baryogenesis:

1. Baryon number violation
2. C and CP violation
3. Out of thermal equilibrium

Instead of starting with a baryon number violating process (baryogensis), leptogenesis relies on violating **lepton number**, *then* converting *L* into *B*.

Neutrinos could be the key to explaining the matter-antimatter asymmetry in the universe…

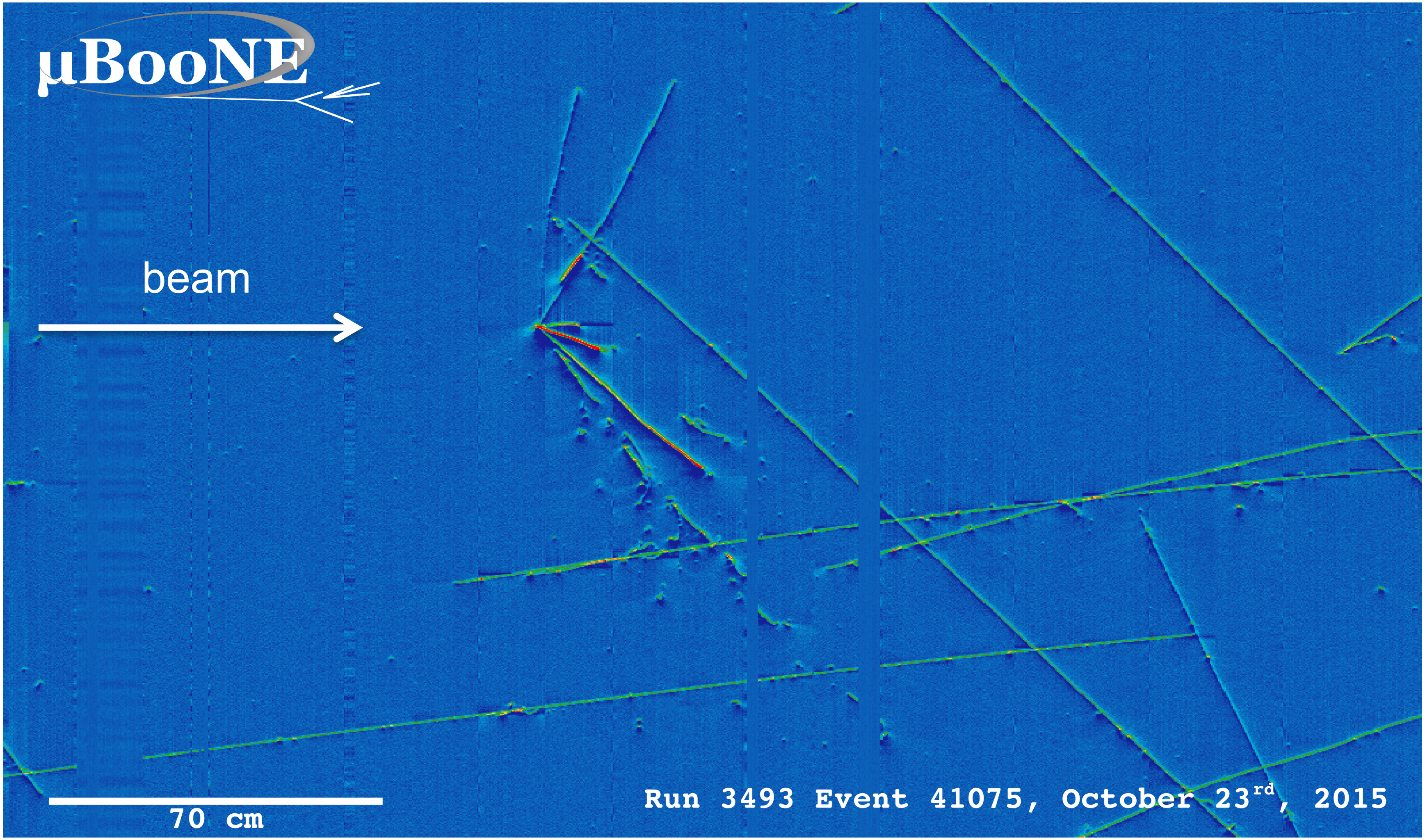
DUNE: Deep Underground Neutrino Experiment



$\nu_\mu \rightarrow \nu_e$ appearance experiment, where δ_{CP} is measured by combining neutrino and anti-neutrino data

https://www.dunescience.org/

Liquid Ar TPC far detector

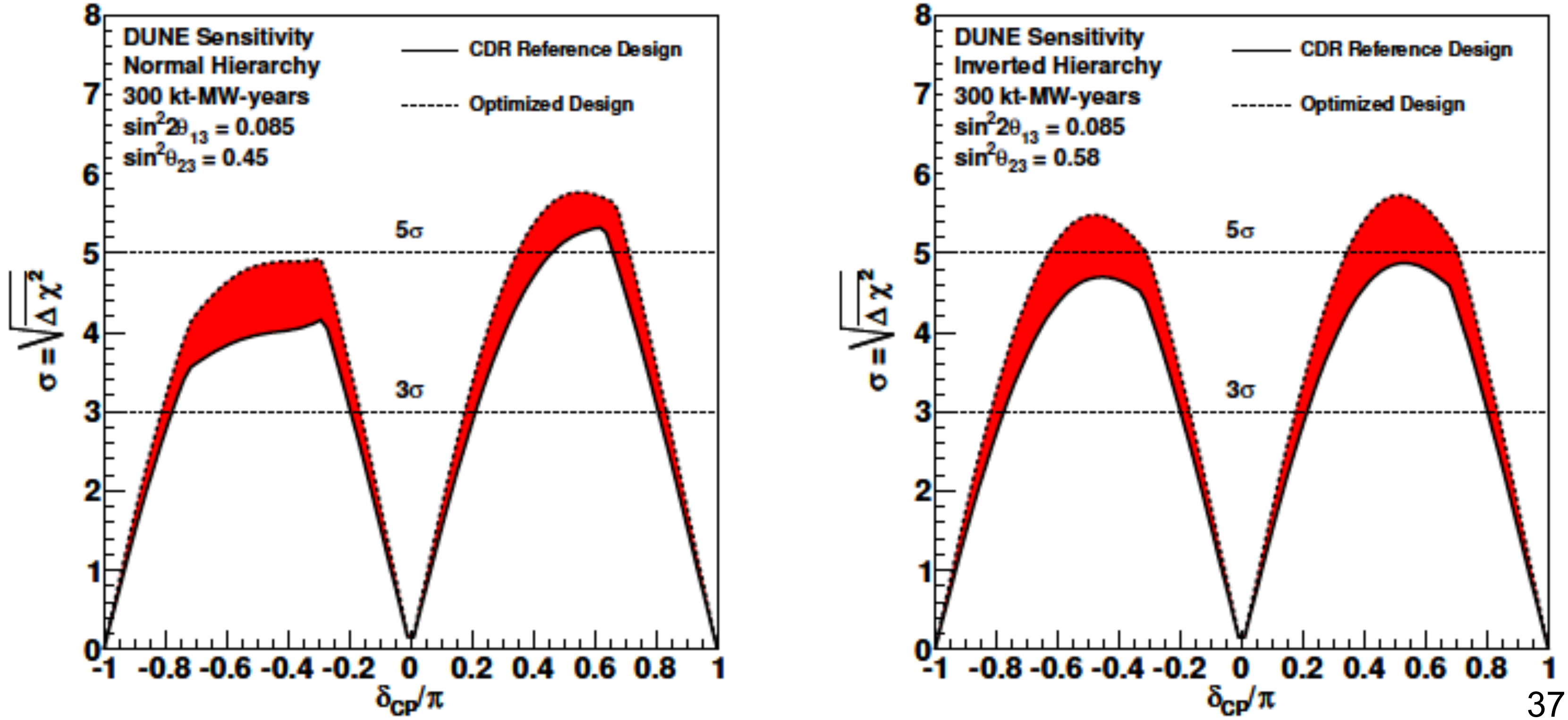


DUNE Sensitivity

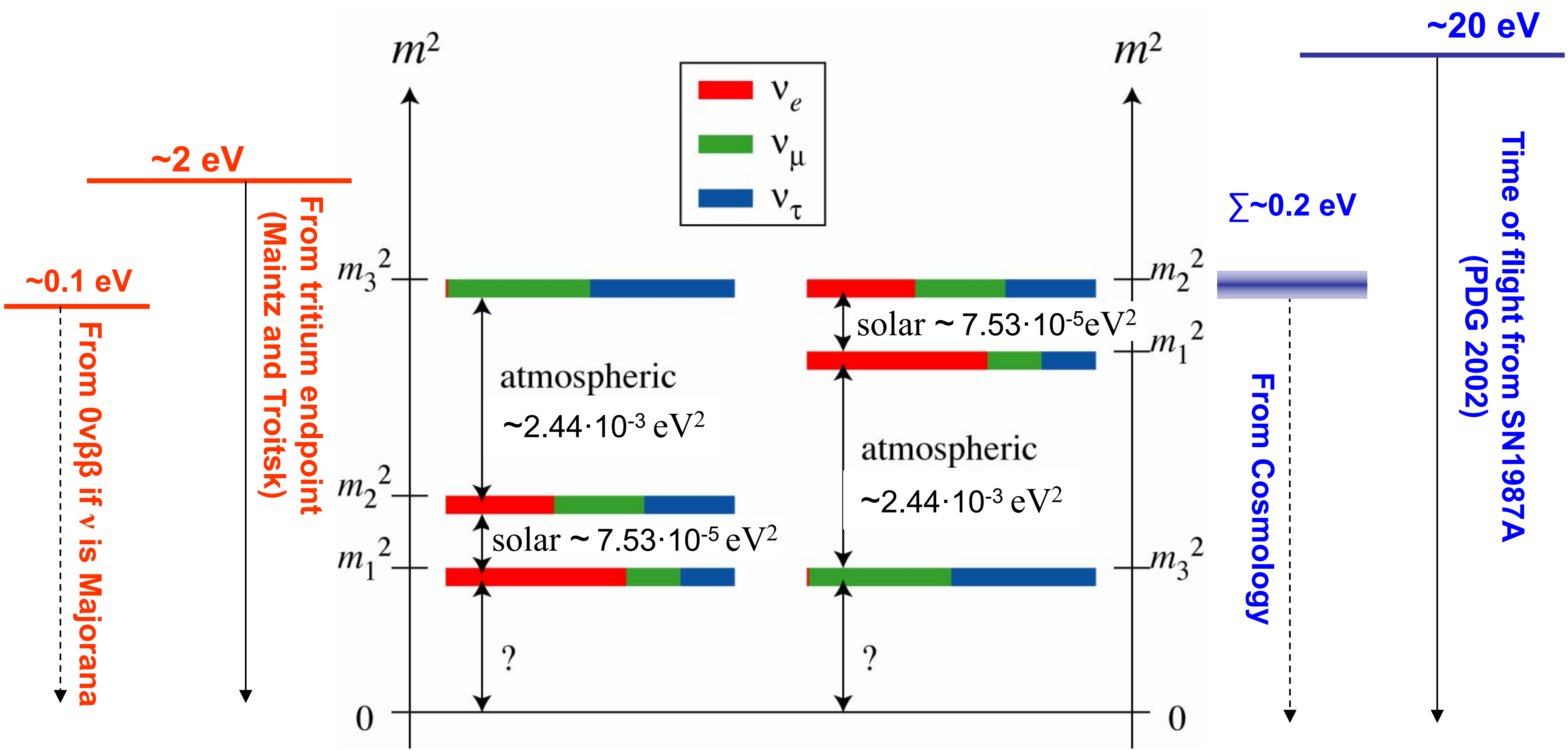
arXiv:1512.06148

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$



The 3 ν picture



Physicists Say They Have Evidence For A New Fundamental Particle

June 5, 2018 · 5:13 AM ET
Heard on Morning Edition

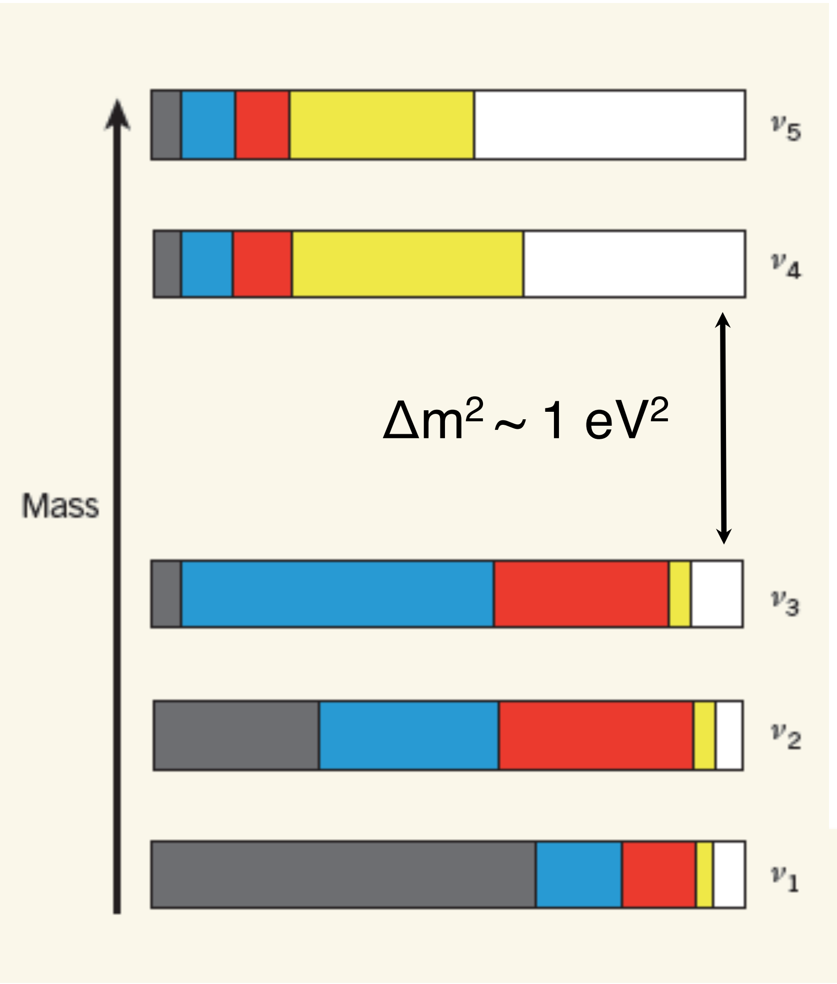
https://www.npr.org/2018/06/05/616803143/physicists-say-they-have-evidence-for-a-new-fundamental-particle

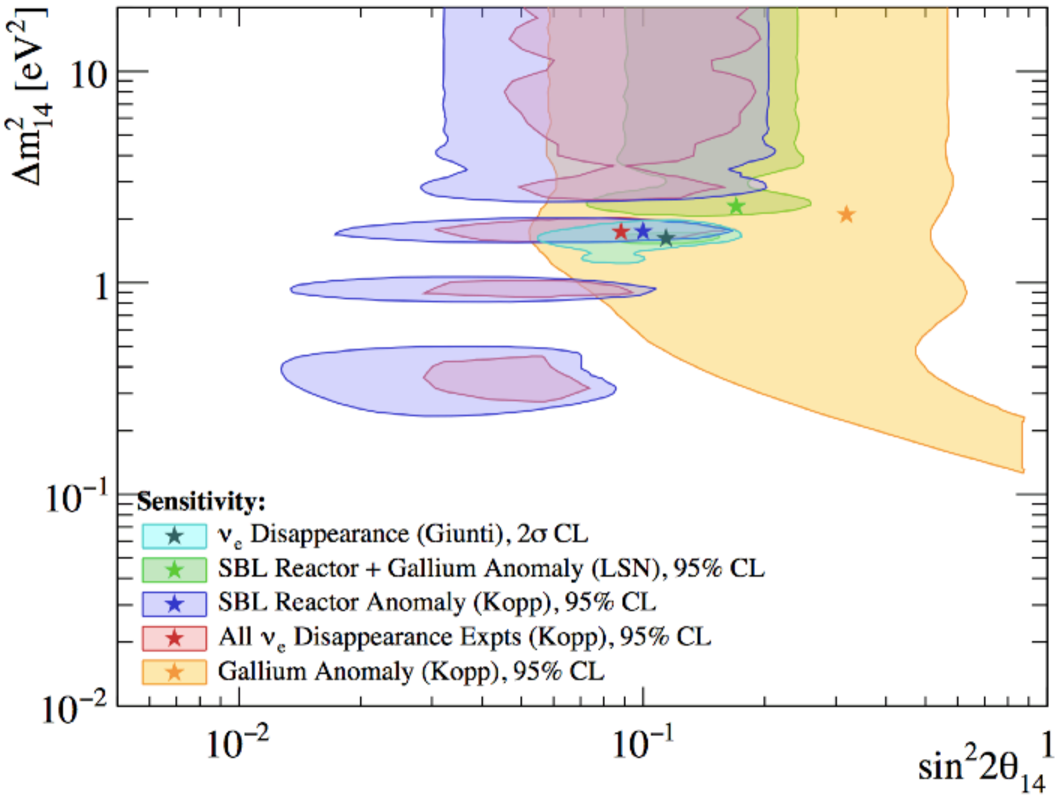
JOE PALCA

Physicists' understanding of the nature of the universe has taken a blow. An experiment with neutrinos has produced a result that breaks the rules scientists think govern the subatomic world.

Sterile neutrinos

What does the hypothesis of 4th or 5th "sterile" neutrino imply?

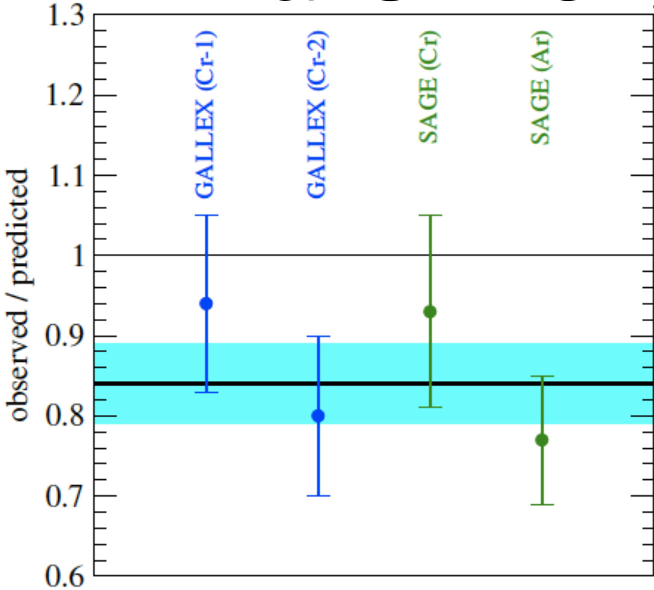




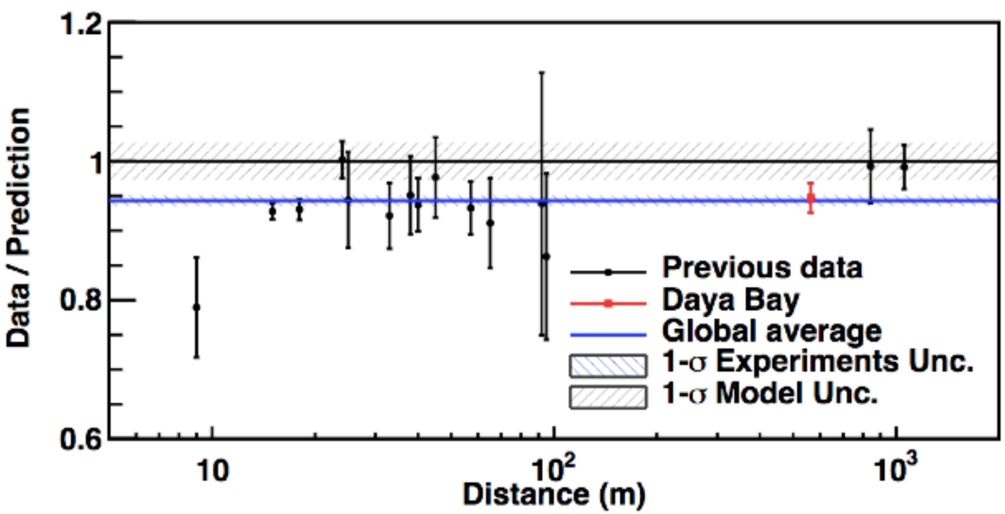
PROSPECT, *J Phys G* **43** (2016)

What's wrong with the 3ν picture? Pt. 1

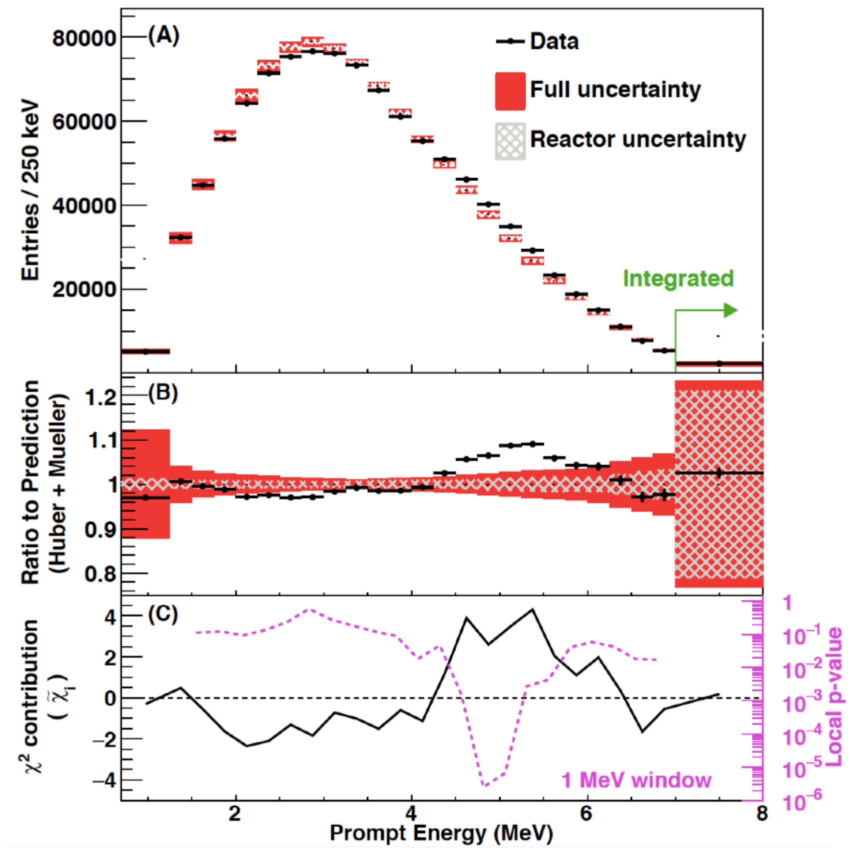
ν_e disappearance!
(ν_s appearance?)



Ga anomaly



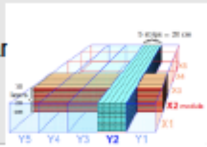
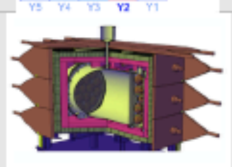
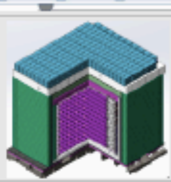
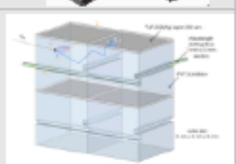
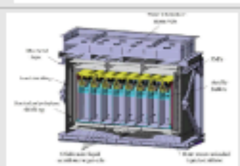
Reactor flux anomaly



Reactor spectrum anomaly

Daya Bay, *CPC* **41**, 1 (2017)

How do we test the reactor anomaly?

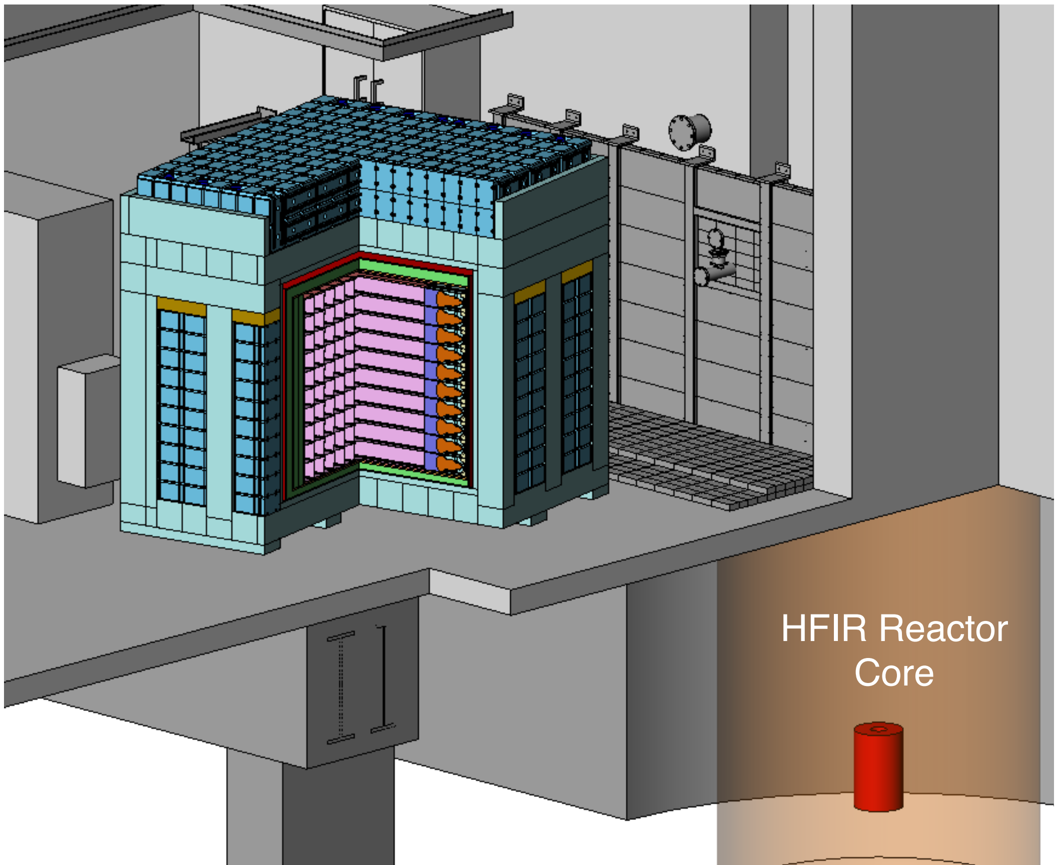
Experiment	Reactor/Fuel	Baseline (m)	Mobility	Detection Material	Segmentation	Readout	Energy Resolution	PID	Status
DANSS Kalinin nuclear reactor (Russia) 	3000 MWth LEU	10.7-12.7	Yes	PS+Gd Sheets	2D, 5mm	WLS fibers + SiPM and PMT	25%/√E	Topology	Collecting data
NEOS Hanbit nuclear power complex (Korea) 	2800 MWth LEU	~24	No	GdLS	-	PMT Double-ended	5% @ 1MeV	Recoil PSD	Phase-1 complete
Neutrino-4 SM-3 reactor (Russia) 	100 MWth HEU	6-12	Yes	GdLS	2D, 10 cm	PMT Single-ended	Not available	Topology	Phase-1 complete
PROSPECT High Flux Isotope Reactor (USA) 	**85 MWth HEU**	**7-12**	**Yes**	**^{6}LiLS**	**2D, 14.6 cm**	**PMT Double-ended**	**4.5%/√E**	**Topology + recoil and capture PSD**	**Commissioning and installation in progress**
Soliδ BR2 research reactor (Belgium) 	40-80 MWth HEU	6-9	No	PVT cubes+ ^{6}Li:ZnS(Ag) sheets	3D, 5 cm	WLS fibers + SiPM	20%/√E	Topology + capture PSD	Collecting data
STEREO ILL research reactor (France) 	58 MWth HEU	9-11	No	GdLS	2D, 25 cm	PMT Single-ended	12% @ 2 MeV	Recoil PSD	Collecting data

Some values from Mauro Mezzetto, neutrino 2016

PRecision Oscillation and SPECTrum experiment

Physics objectives:

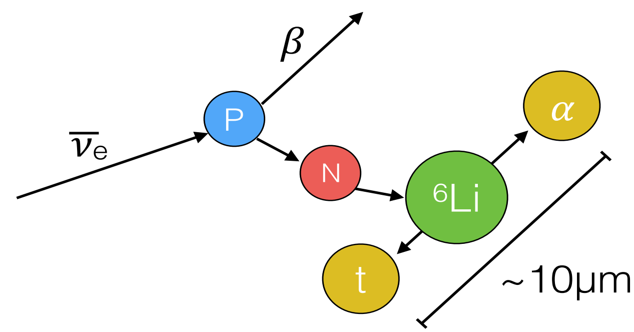
- Precision measurement of ^{235}U energy spectrum
- Search for eV-scale sterile neutrinos via oscillations at short baselines



PROSPECT, *NIM* A 922 (2018) 287

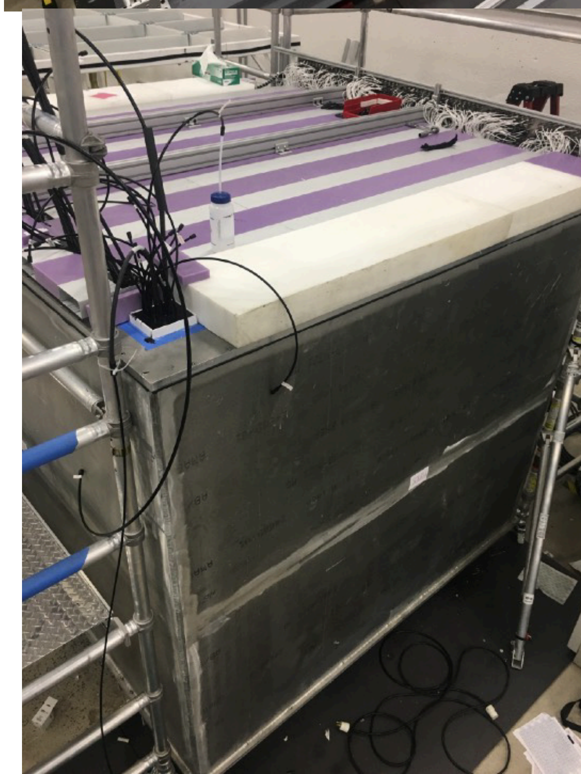
Design:

- 4-ton ^{6}Li-loaded liquid scintillator optically segmented detector.

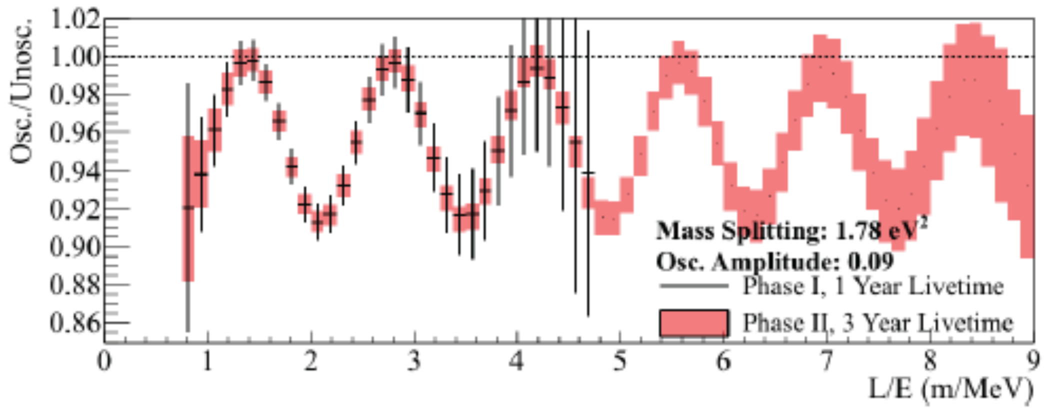


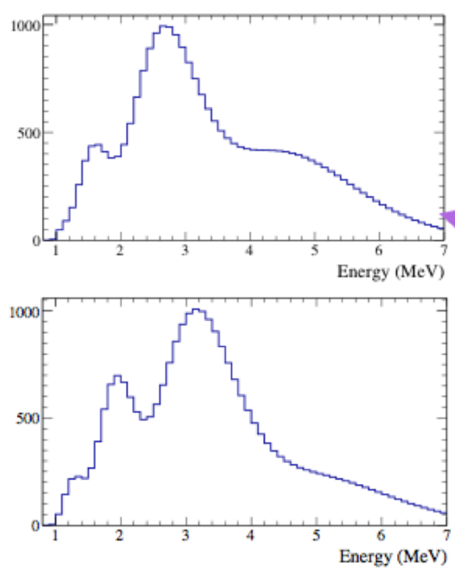
- Measures inverse beta decay event rate and energy spectrum at baselines of 7 – 12 m from HFIR reactor.

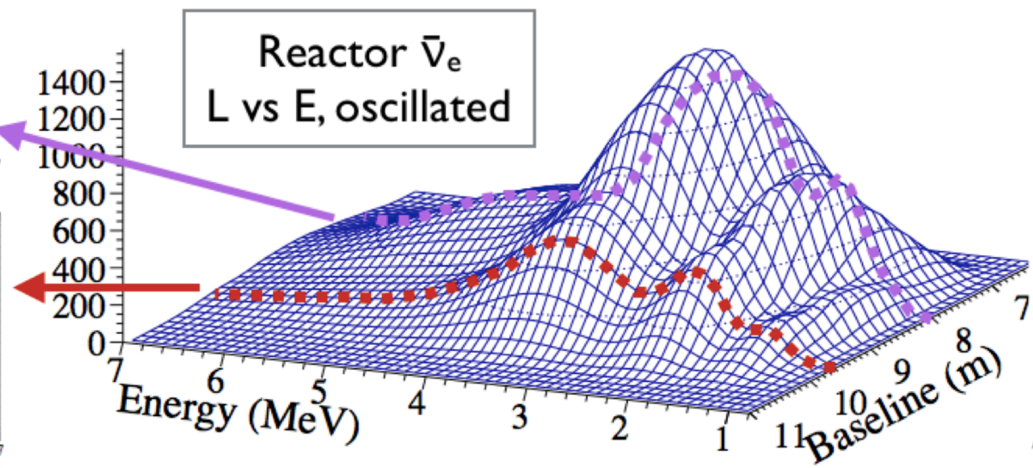


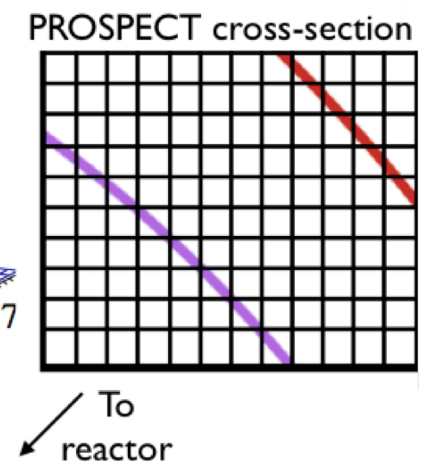



Sterile neutrino search









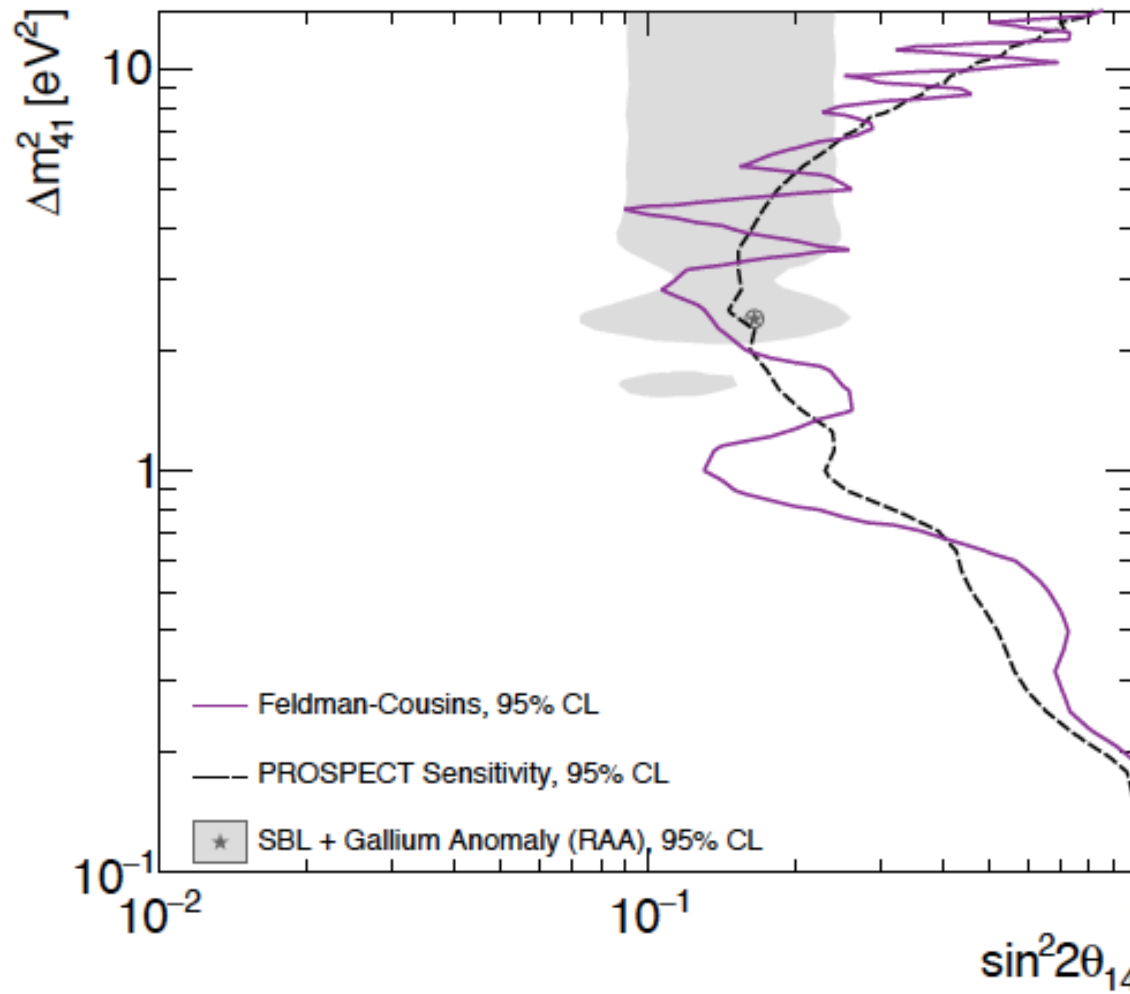
Relative measurement between 154 detector segments – no spectrum dependence.

Sterile neutrino search

PROSPECT operated at HFIR from March to October 2018.

- 33 days reactor ON
- 28 days reactor OFF
- ~750 inverse beta decay events/day
- Preliminary analysis disfavors RAA best-fit point at >95% C.L.

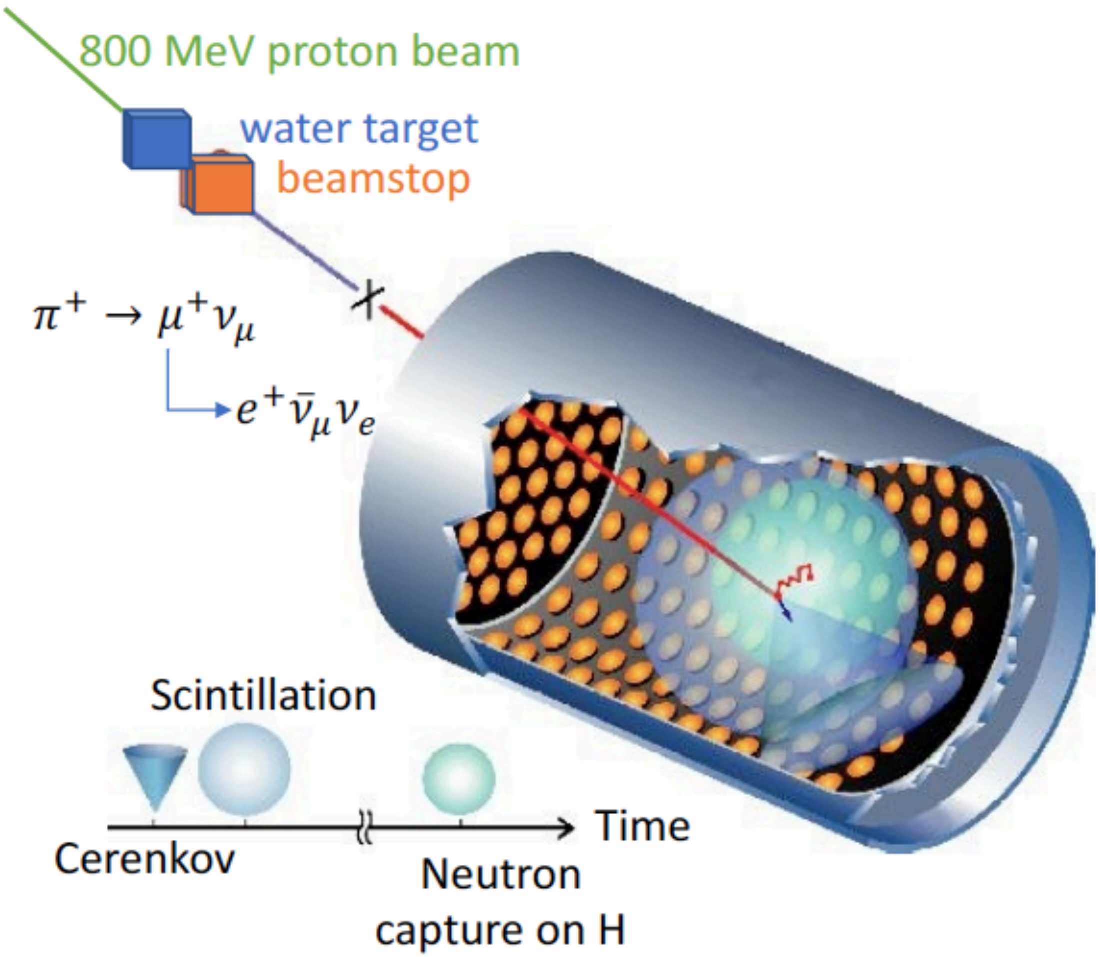
Similar exclusions by other short baseline reactor experiments!



PROSPECT, *PRL* 121, 251802 (2018)

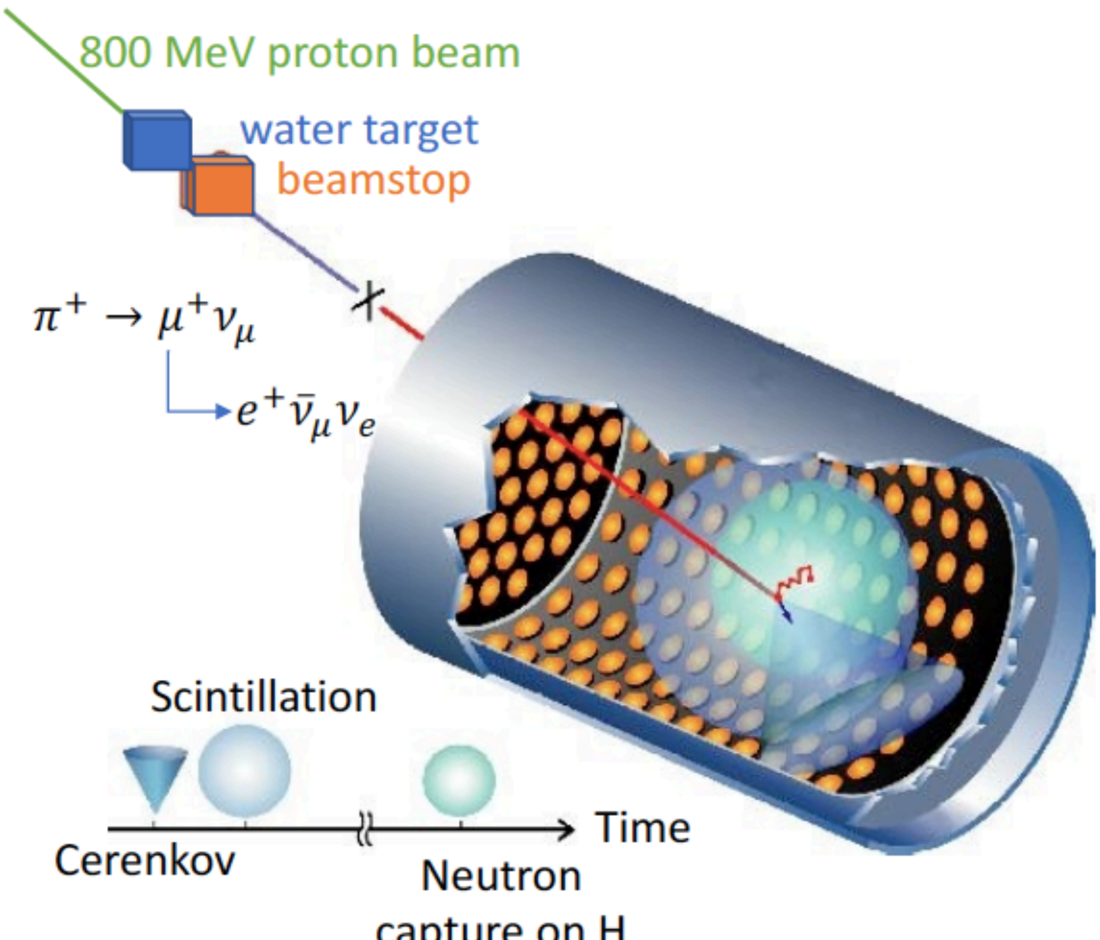
What's wrong with the 3ν picture? Pt. 2

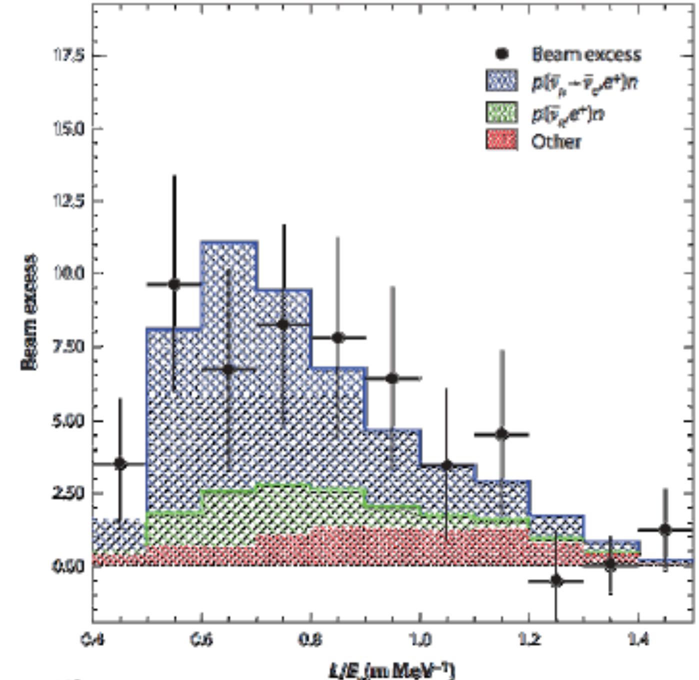
ν_e appearance!
(mediated by ν_s?)

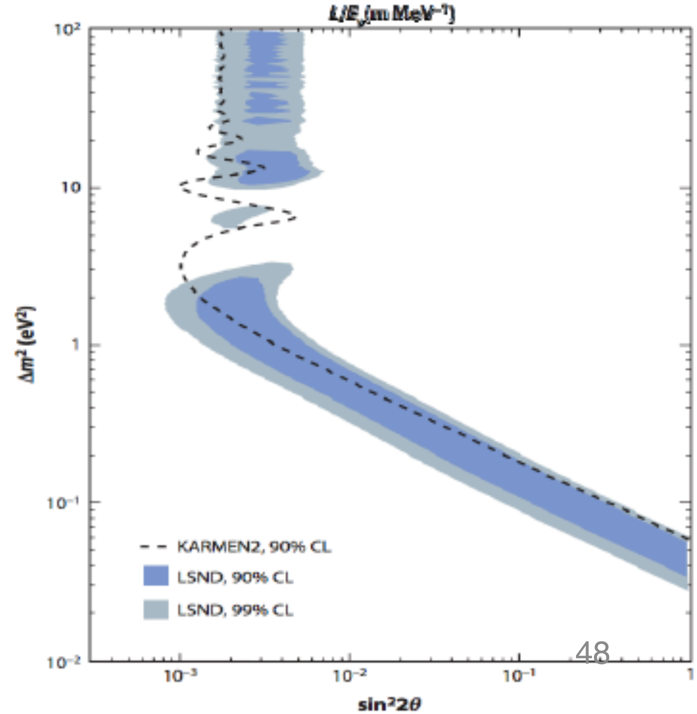


En-Chuan Huang, Neutrino 2018

LSND Anomaly





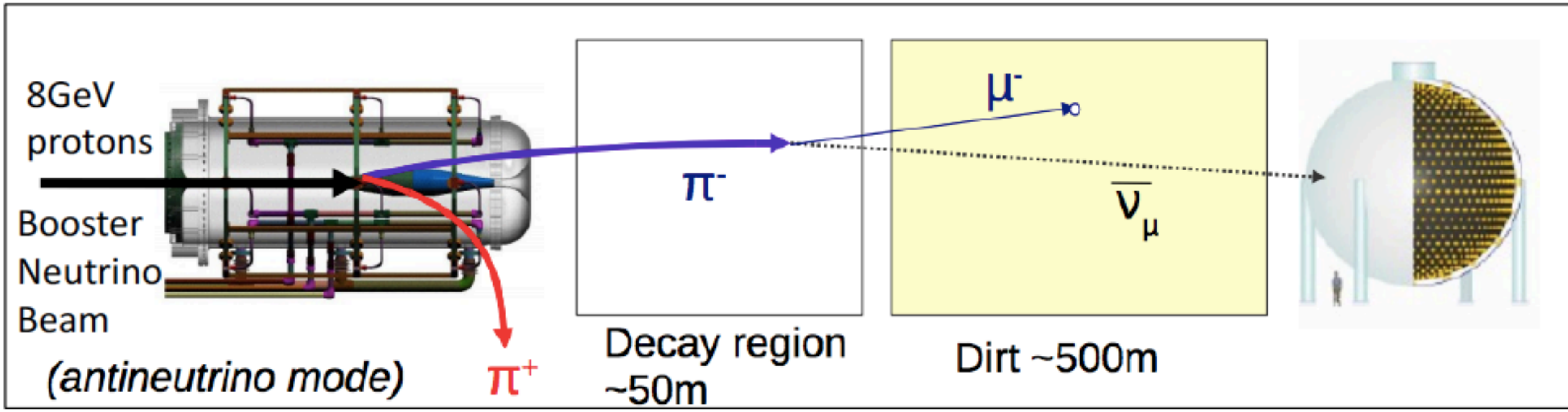


LSND observed a 3.8σ excess

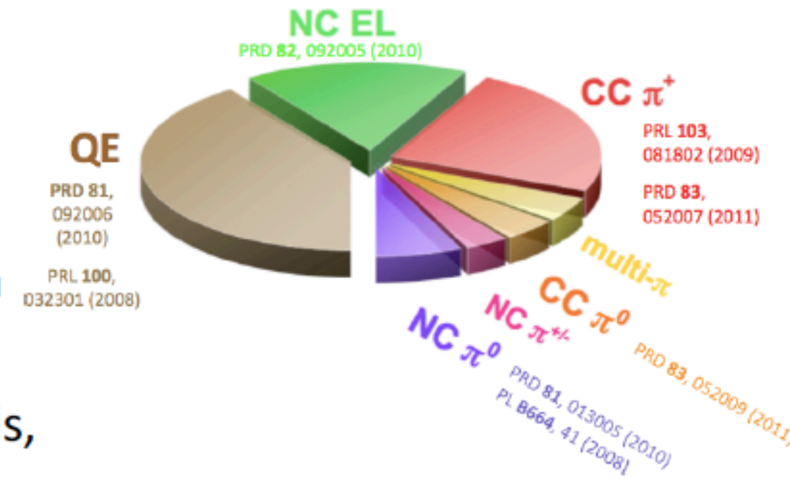
Annu. Rev. Nucl. Part. Sci., *63*(1), 45–67.

En-Chuan Huang, Neutrino 2018

MiniBooNE



- Similar L/E
  - MiniBooNE ~500m/500MeV
  - LSND ~30m/30MeV
- 800-ton mineral oil Cherenkov detector
- Different systematics
  - Different flux, event signatures, and backgrounds from LSND
- Horn polarity determines ν or $\bar{\nu}$ mode
- Flux monitor for short baseline neutrino program (SBN)
- Well-understood detector with 26 publications(4900+ citations) in different channels, as well as recent
  - ν_μ from K^+ decay at rest from NuMI beam
  - Dark matter search



The new MiniBooNE result

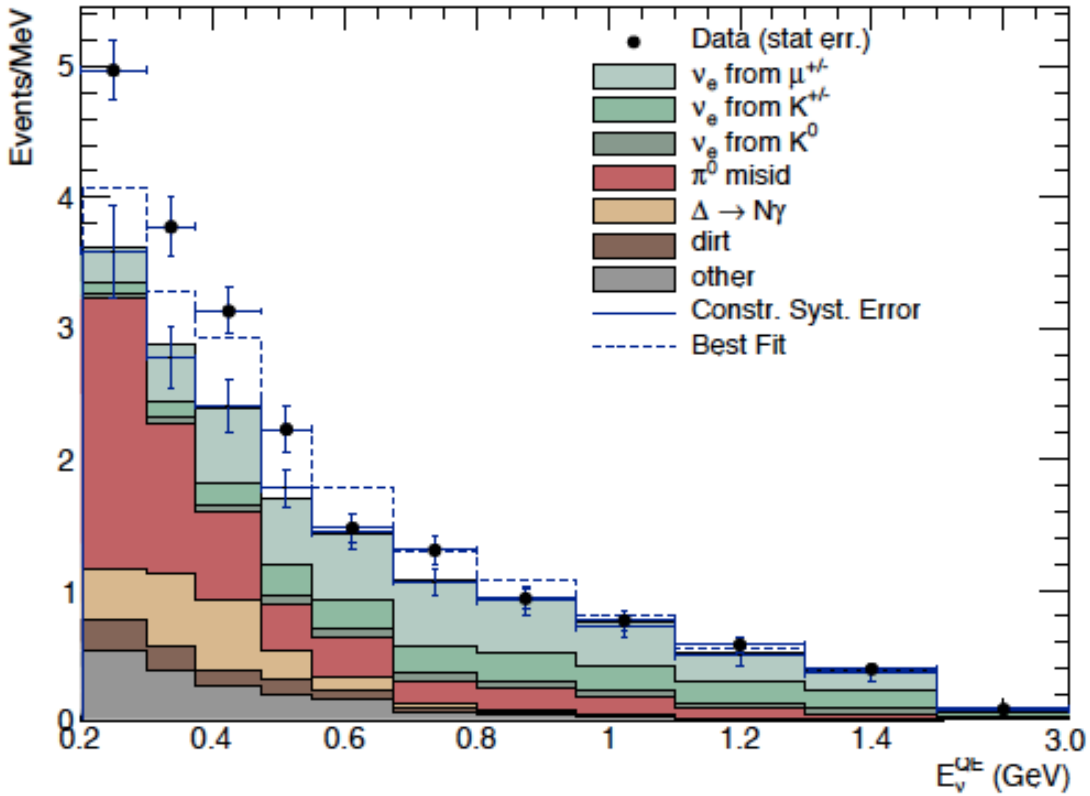


FIG. 1: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming standard two-neutrino oscillations.

arXiv:1805.12028

Comparison with LSND

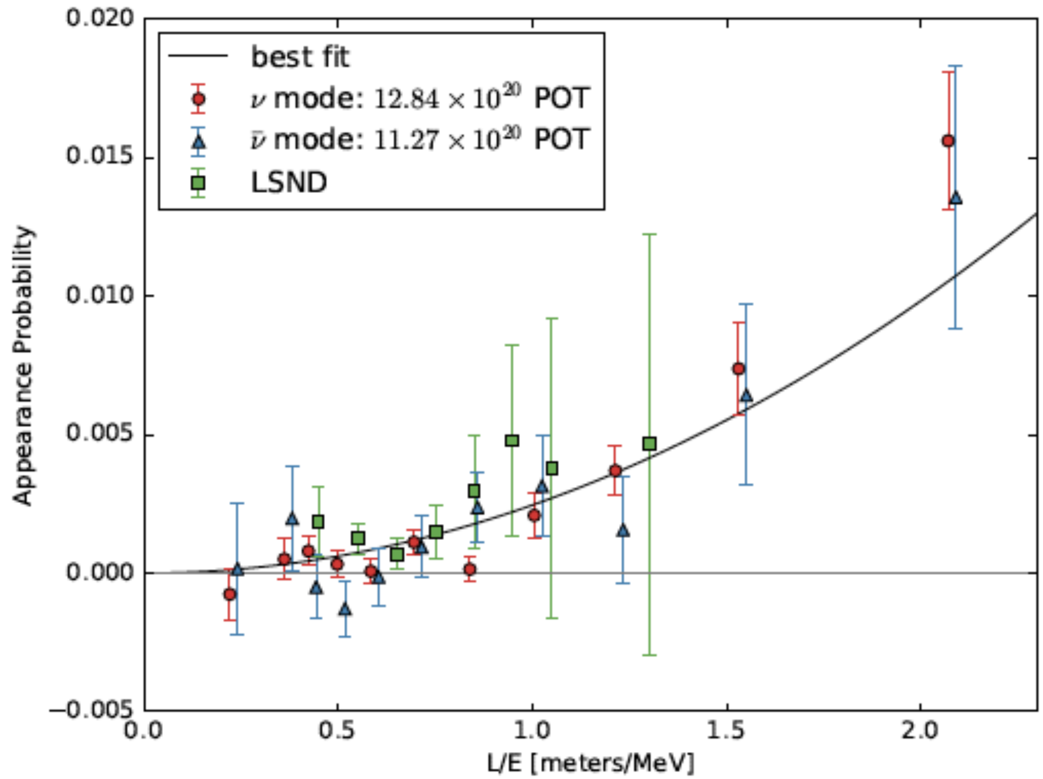
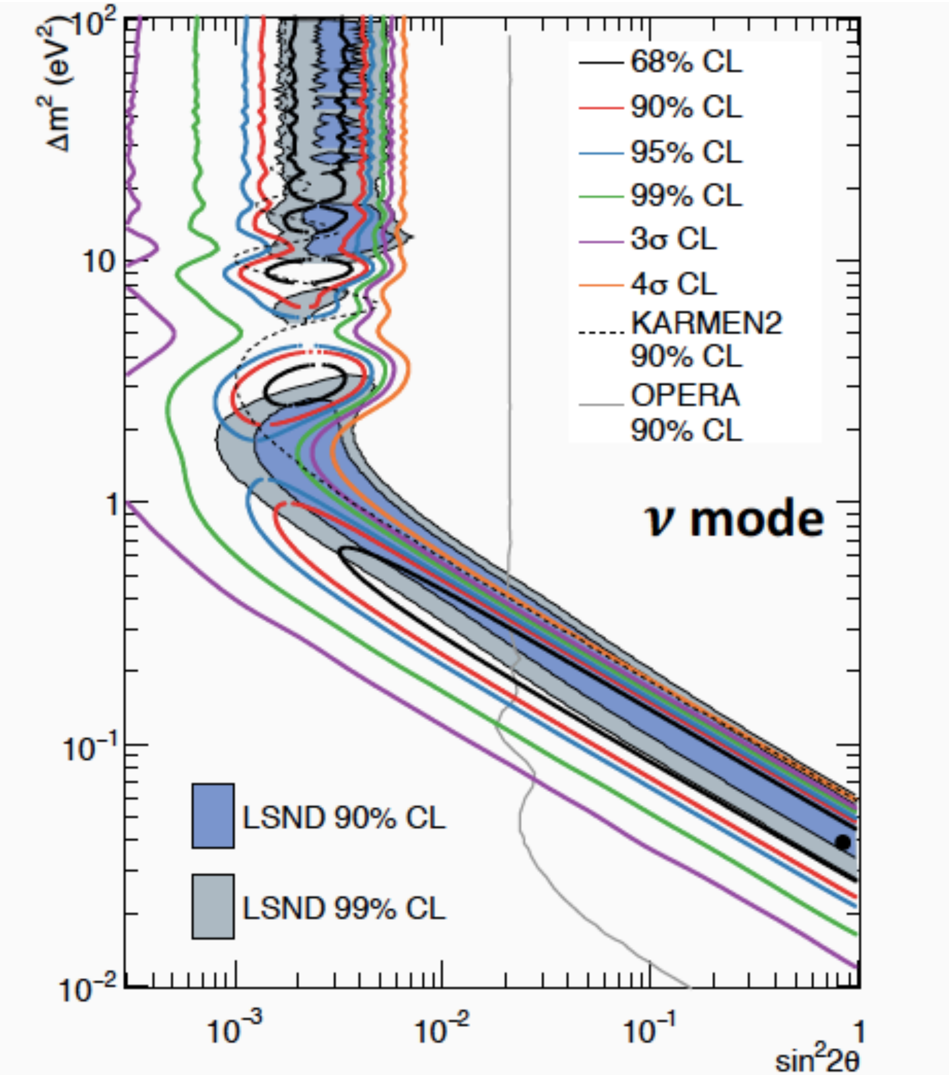


FIG. 3: A comparison between the L/E_ν^{QE} distributions for the MiniBooNE data excesses in neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) to the L/E distribution from LSND [1]. The error bars show statistical uncertainties only. The solid curve shows the best fit to the LSND and MiniBooNE data assuming standard two-neutrino oscillations. The excess of MiniBooNE electron-neutrino candidate events is consistent with the LSND excess.

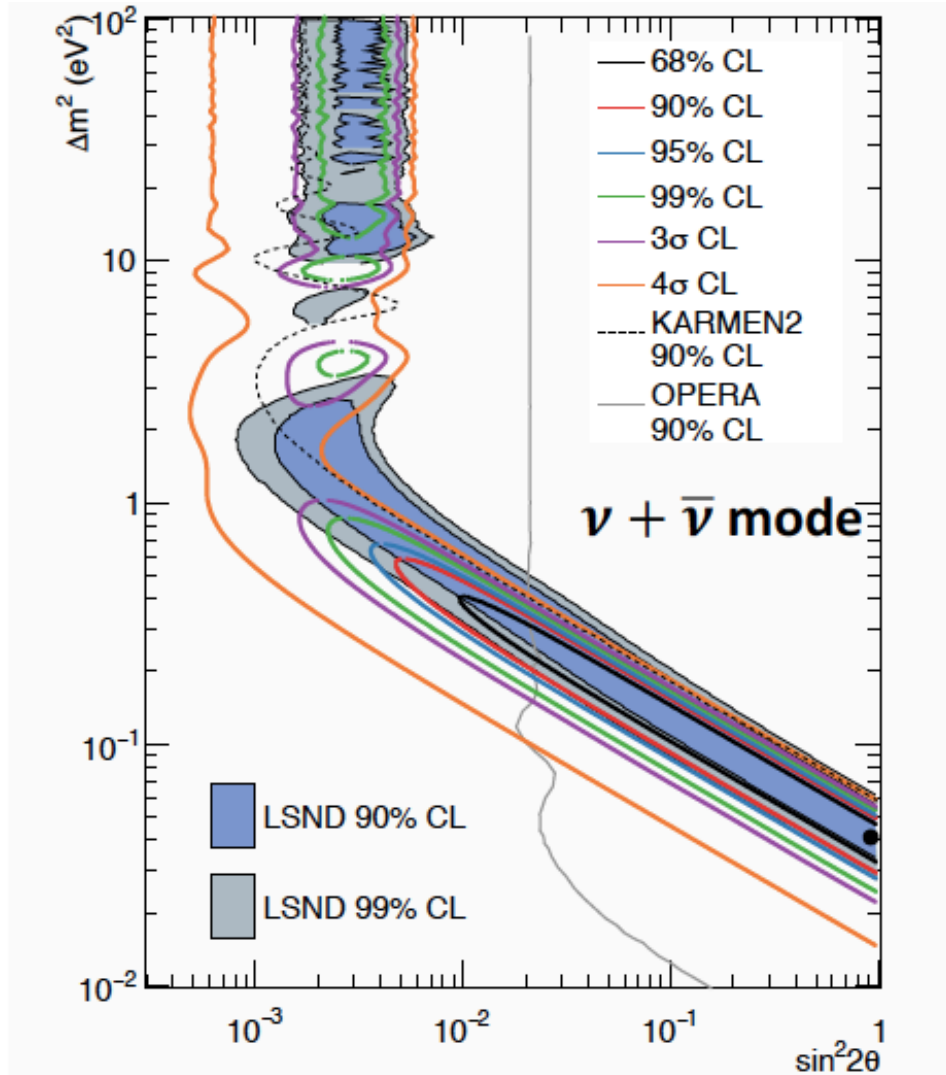
arXiv:1805.12028

En-Chuan Huang, Neutrino 2018



$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$

$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

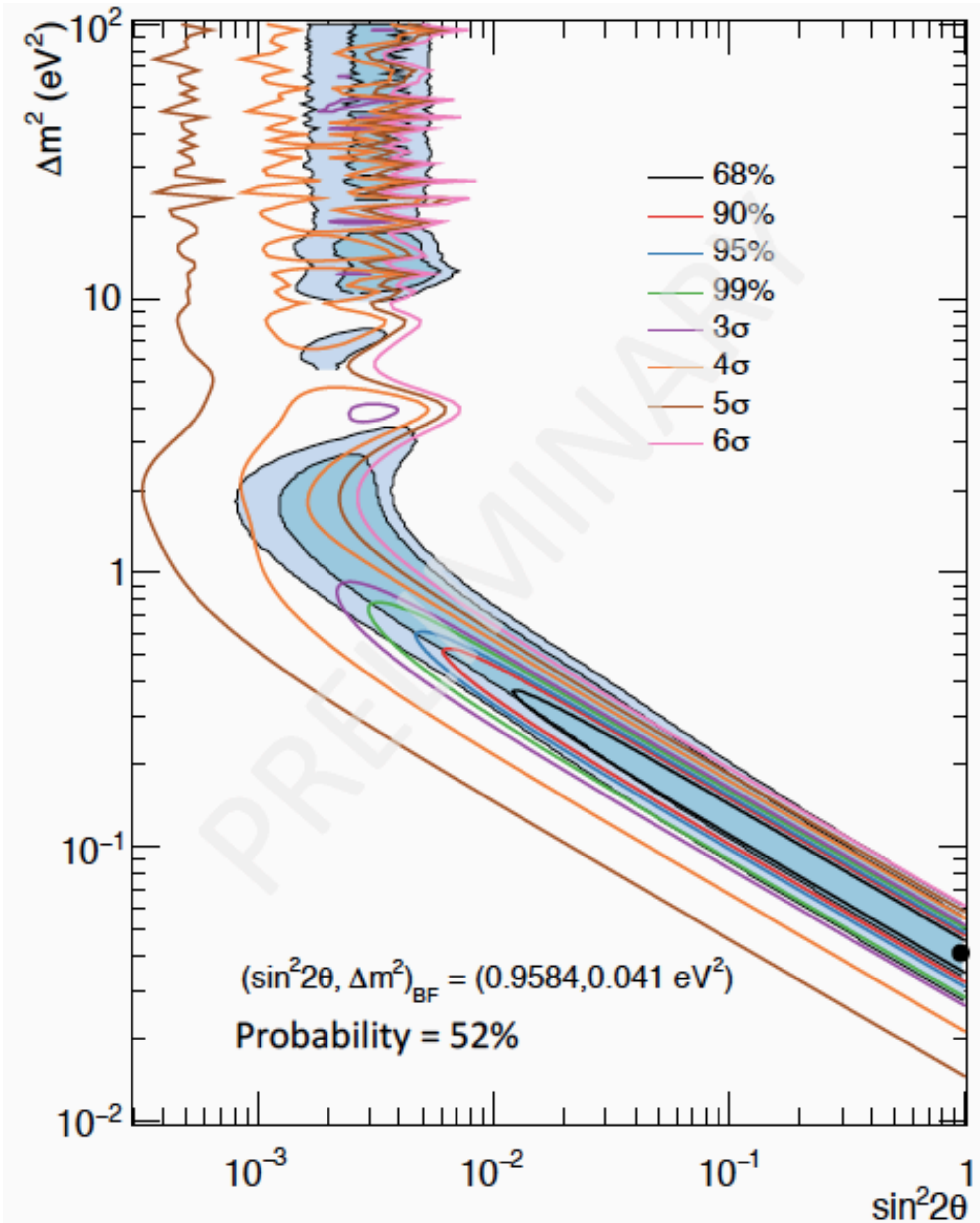


$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$

$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

arXiv:1805.12028

Combination with LSND



Combe MiniBooNE with LSND to achieve claimed 6σ fit:

- Assumes no correlation between the two experiments.
- Consistent best fit results.

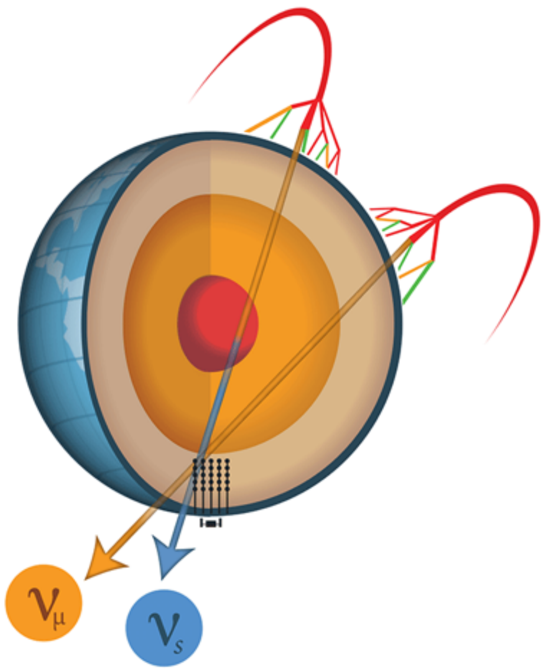
En-Chuan Huang, Neutrino 2018

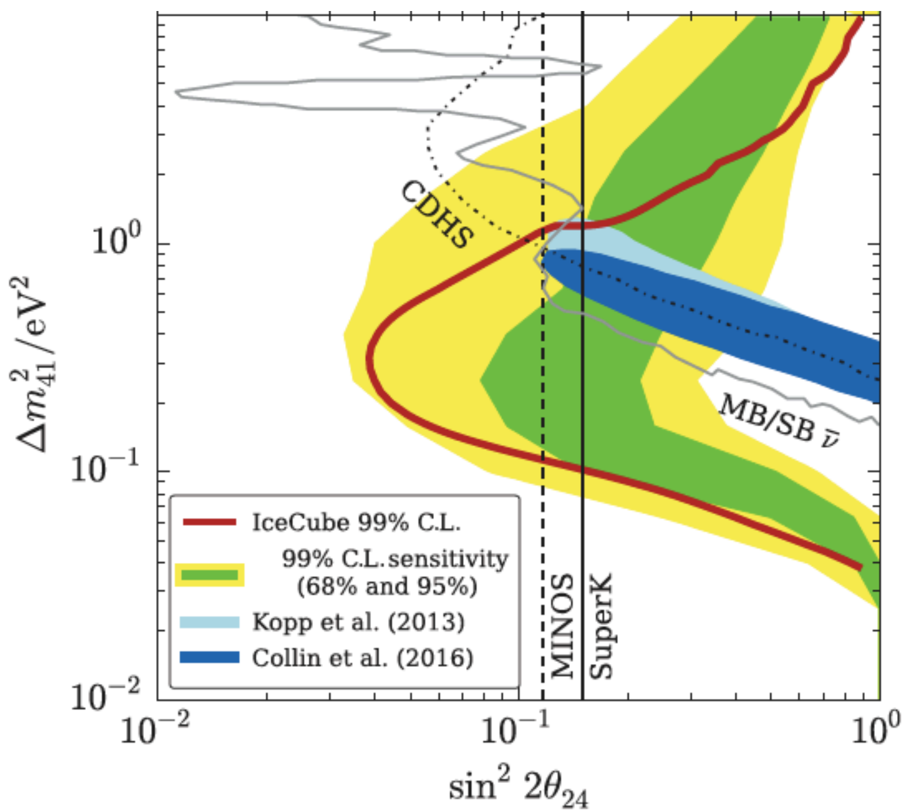
The spoiler: ν_μ disappearance

(3+1): $P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e\to\nu_e}\,, \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu}\,; \end{cases}$

We don't see it!

hence, $P_{\nu_\mu\to\nu_e} > 0$ requires $\begin{cases} P_{\nu_e\to\nu_e} > 0\,, \\ P_{\nu_\mu\to\nu_\mu} > 0\,; \end{cases}$





IceCube Collaboration, *PRL* **117**, 071801 (2016)

Physics Today **69**, 10, 15 (2016); https://doi.org/10.1063/PT.3.3316

SEARCH & DISCOVERY

Sterile neutrinos give IceCube and other experiments the cold shoulder

Recent null results heighten the tension between the bulk of neutrino experiments and the few that hint at the putative particle's existence.

Under kilometers of ice at the South Pole, the IceCube Neutrino Observatory's 5160 optical detectors keep watch for neutrinos that have traveled through Earth from the opposite side of the globe. (See the article by Francis Halzen and Spencer R. Klein, PHYSICS TODAY, May 2008, page 29.) The observatory was built primarily to serve as a telescope to study neutrinos from astrophysical sources. However, it also detects neutrinos born in the aftermath of cosmic-ray protons crashing into nuclei in the upper atmosphere. About once every six minutes, one of those atmospheric neutrinos finds its way to IceCube's monitoring zone, collides with a nucleus in the ice or bedrock, and produces a charged particle that can be detected from the Cherenkov light it gives off. Figure 1 shows the IceCube Laboratory, which houses the computers that

reactor-neutrino experiment in France,

FIGURE 1. THE ICECUBE LABORATORY

Summary

- 60+ years of experimental neutrino physics!
- Oscillations prove that neutrinos have mass, and their flavor states are superpositions of mass states. We are in an era of precision oscillation physics.
- Next step is to search for CP violation and a clue about the origin of matter in the universe.
- The ν_e appearance and disappearance anomalies motivate the search for sterile neutrinos, but so far no hard evidence has been found. Still, the hunt will continue with future experiments such as the SBN program at Fermilab.