Neutrino experiments - selected topics

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Outline

- Neutrinos from the sun and their flavor oscillation
- Neutrinos from nuclear reactors
  - “Reactor neutrino anomaly”
  - Digression: 17 keV neutrino anomaly
  - Mass ordering and the JUNO experiment
- Neutrinoless double beta decay

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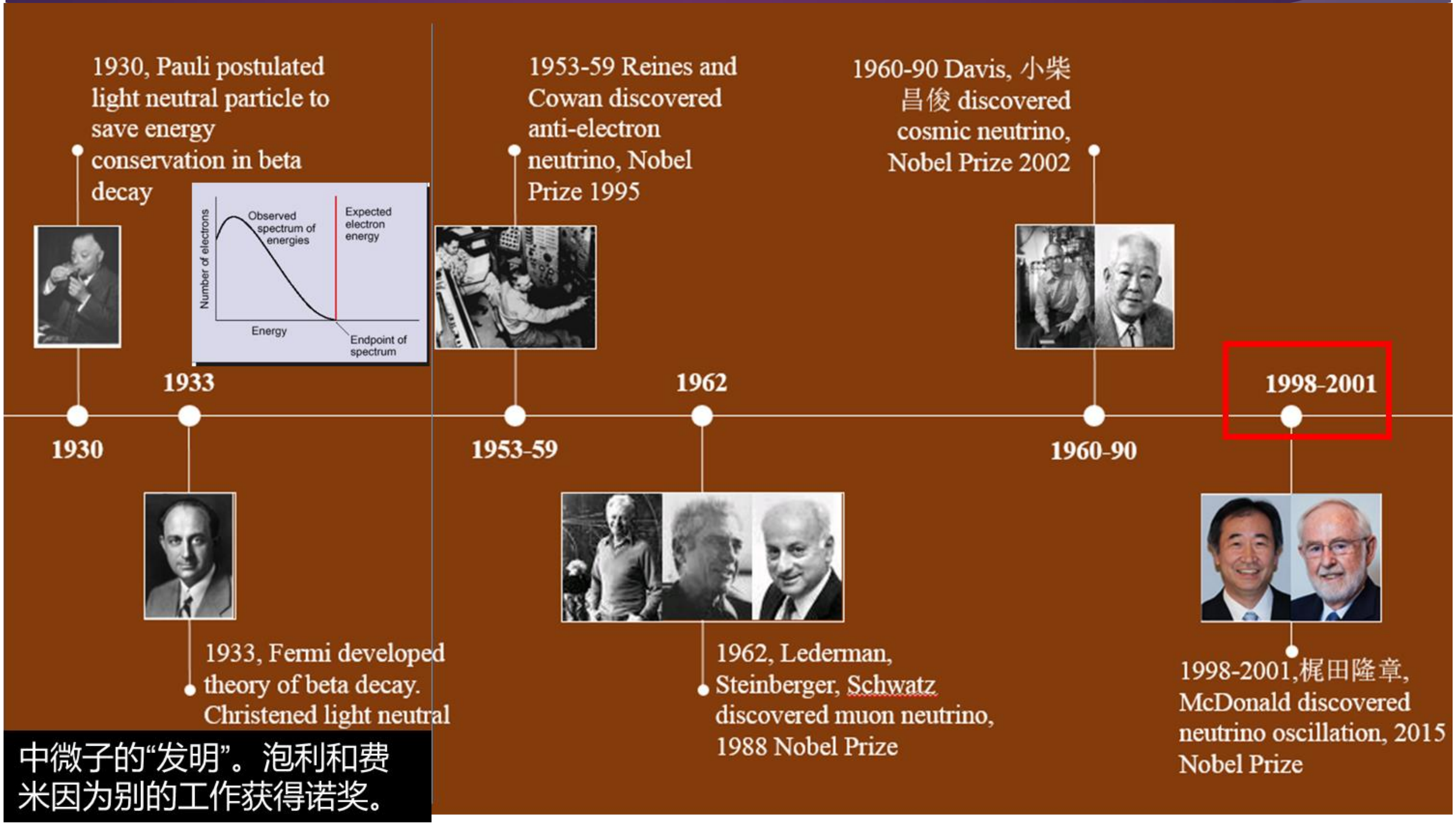
Neutrinos: glories in the past century



1930, Pauli postulated light neutral particle to save energy conservation in beta decay

1933, Fermi developed theory of beta decay. Christened light neutral

1953-59 Reines and Cowan discovered anti-electron neutrino, Nobel Prize 1995

1962, Lederman, Steinberger, Schwatz discovered muon neutrino, 1988 Nobel Prize

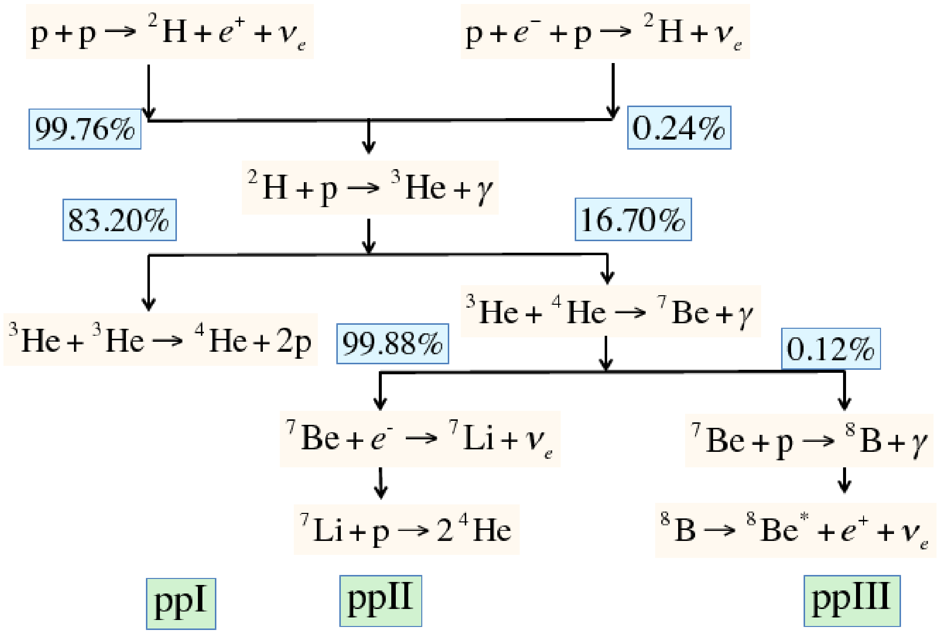
1960-90 Davis, 小柴昌俊 discovered cosmic neutrino, Nobel Prize 2002

1998-2001,梶田隆章, McDonald discovered neutrino oscillation, 2015 Nobel Prize

中微子的“发明”。泡利和费米因为别的工作获得诺奖。

Historically: solar neutrino puzzle

$$p + p + p + p \Rightarrow \alpha + e^+ + e^+ + \nu_e + \nu_e$$



$p + p \rightarrow {}^2H + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2H + \nu_e$

99.76%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

83.20%

16.70%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.88%

0.12%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Li + p \rightarrow 2\,{}^4He$

${}^7Be + p \rightarrow {}^8B + \gamma$

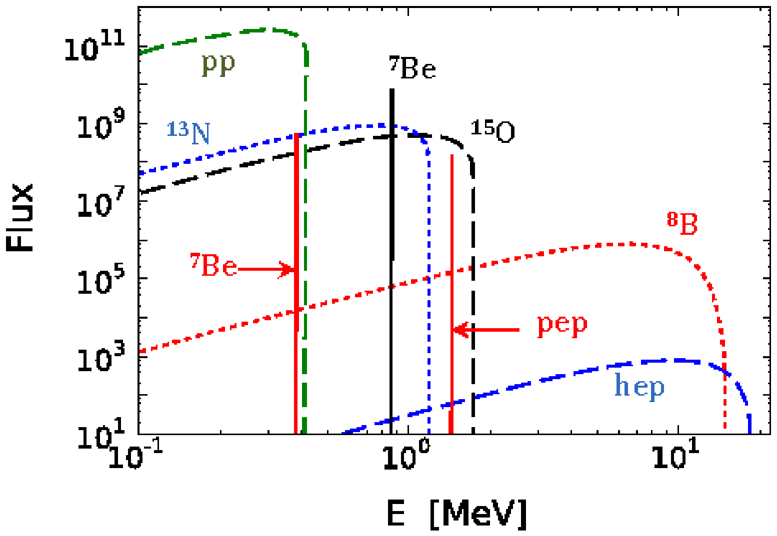
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

ppI

ppII

ppIII

John Bahcall's standard solar model

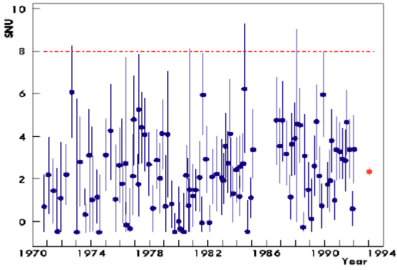


Pioneers on solar neutrinos

1963, John Bahcall predicted ^{8}B solar neutrino flux (SSM)

1968, Ray Davis in Homestake mine detected significant deficit of ^{8}B solar neutrino flux (only ~1/3 detected!)

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

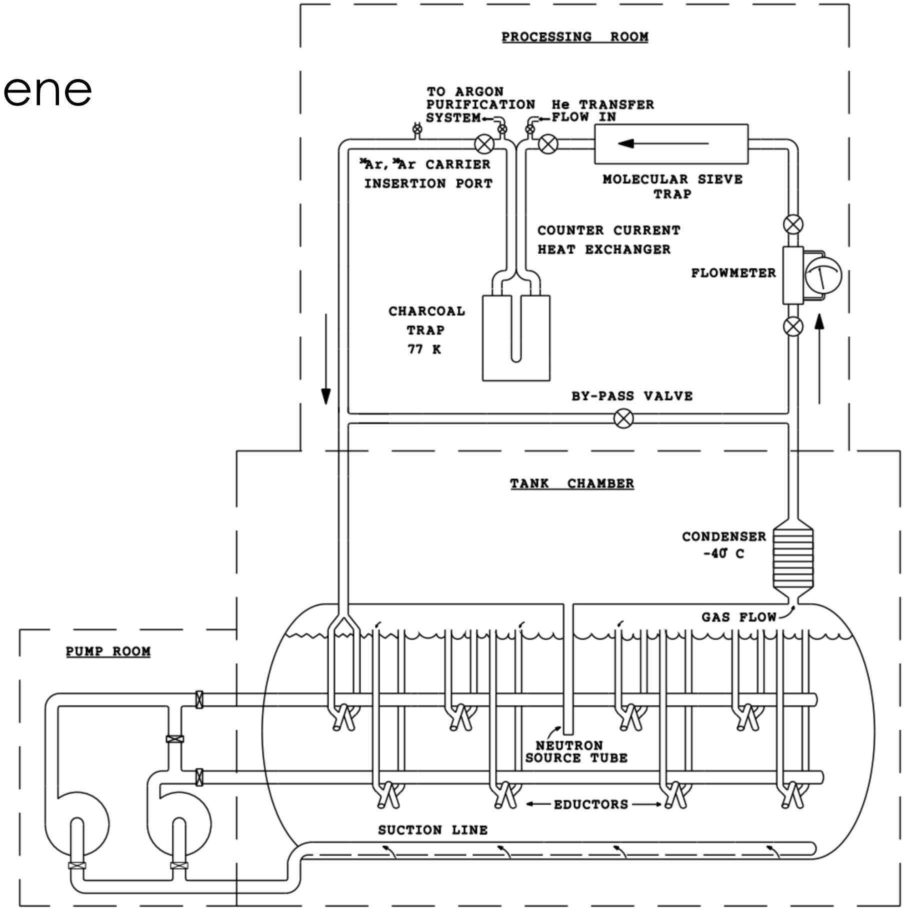


Theory is wrong? Experiment is wrong? Or Both are wrong?

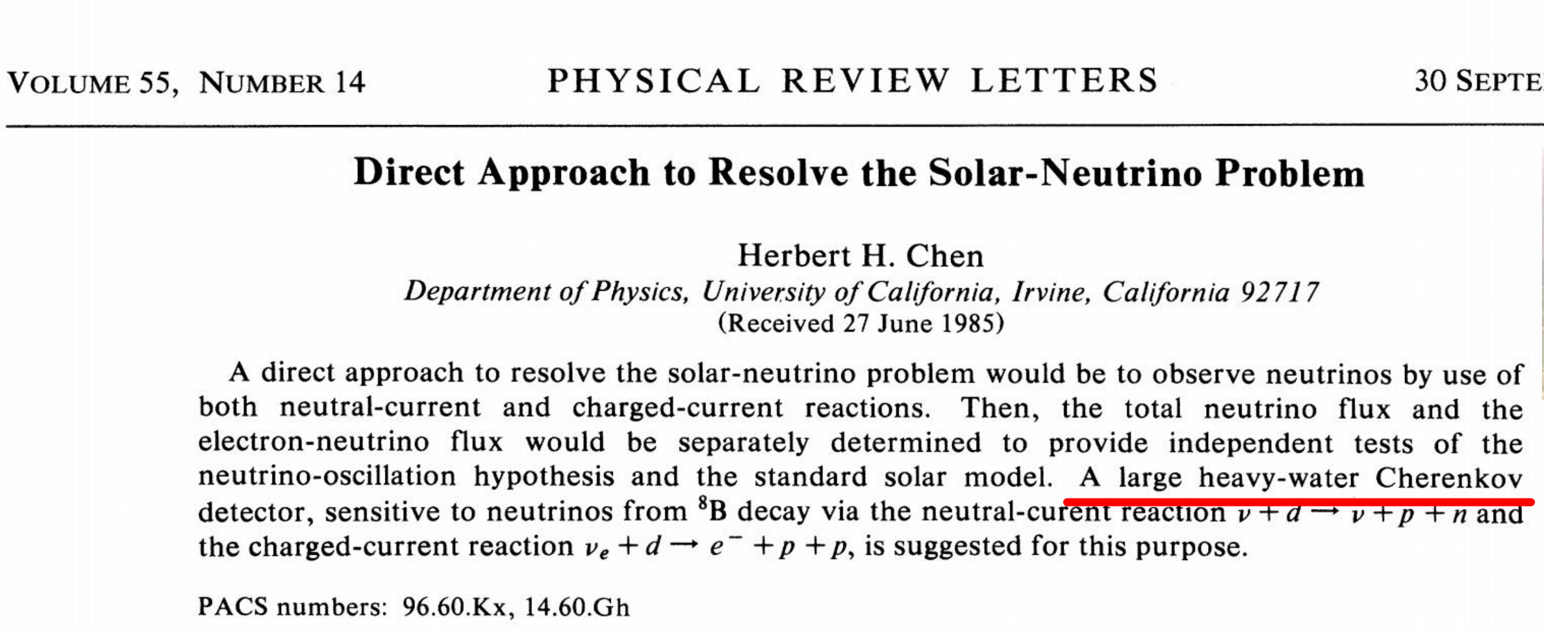
Davis's experiment

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

615 T of C_2Cl_2
tetrachloroethylene



Heavy water experiment



VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717

(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

1942-1987

Solar neutrino on D2O

$$\nu_e + {}^2H \rightarrow e^- + p + p \quad \text{(CC)}$$

Charge current：电荷流

CC = e

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \text{(ES)}$$

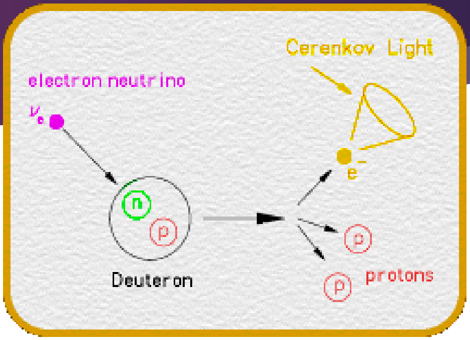
Elastic scattering: 弹性散射

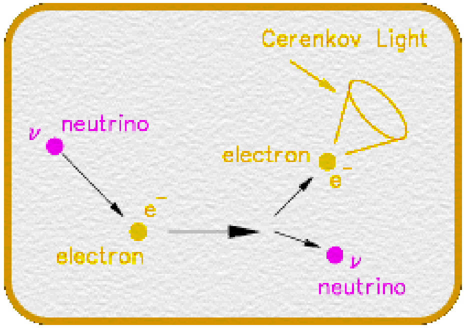
ES = 1 e + 1/7 x

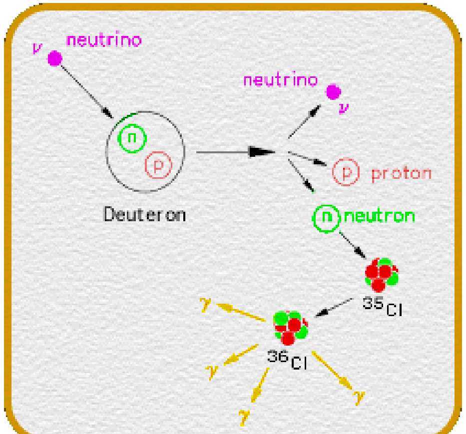
$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad \text{(NC)}$$

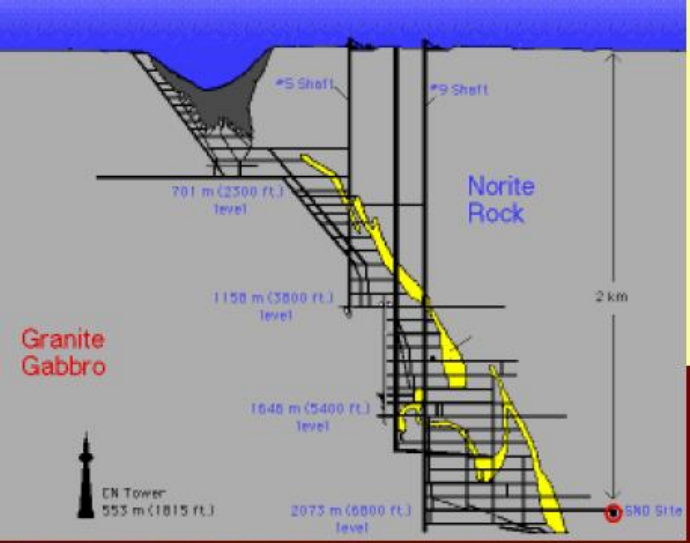
Neutral current: 中性流

NC = 1 e + 1 x





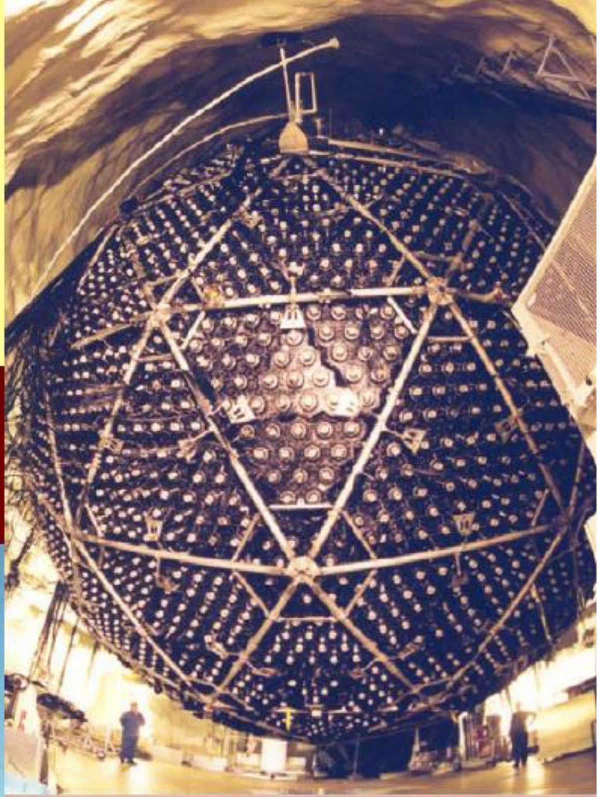


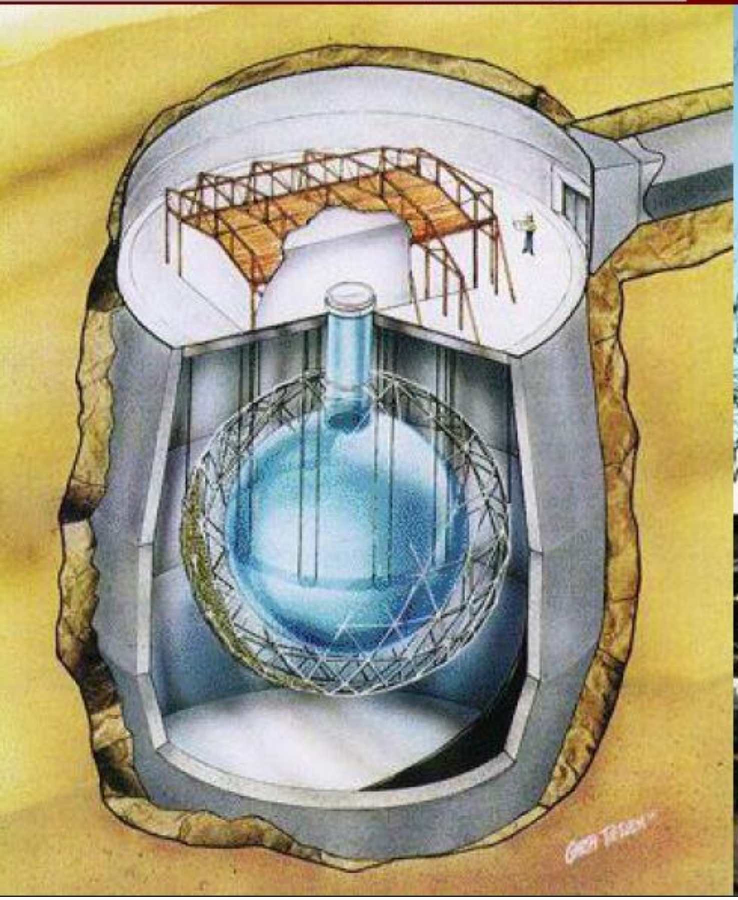


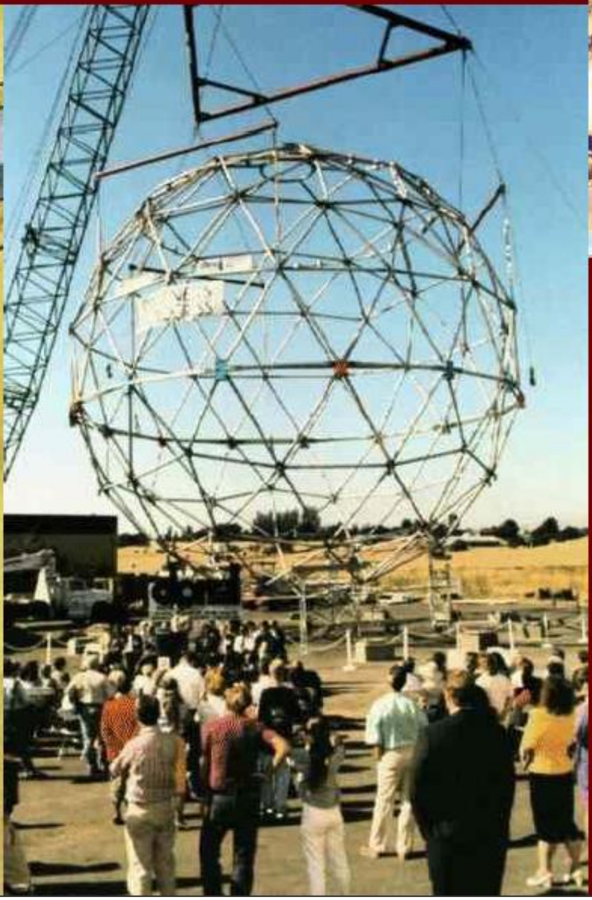
SNO

Sudbury Neutrino Observatory

In Sudbury, Ontario

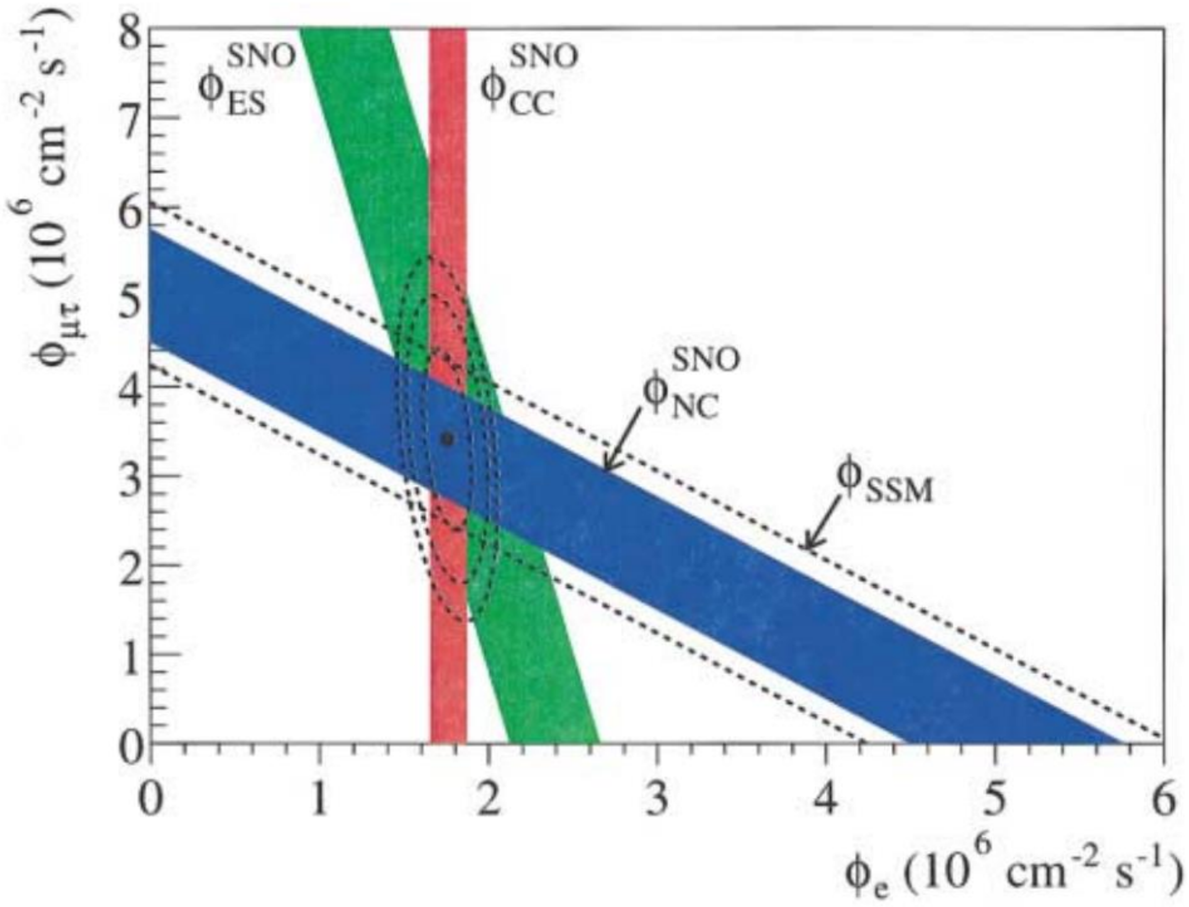






- Cerenkov detector
- Heavy water (can do solar model independent measurements)
- 6800 feet underground
- 9600 PMTs

SNO's discovery paper



CC = e

ES = 1 e + 1/7 x

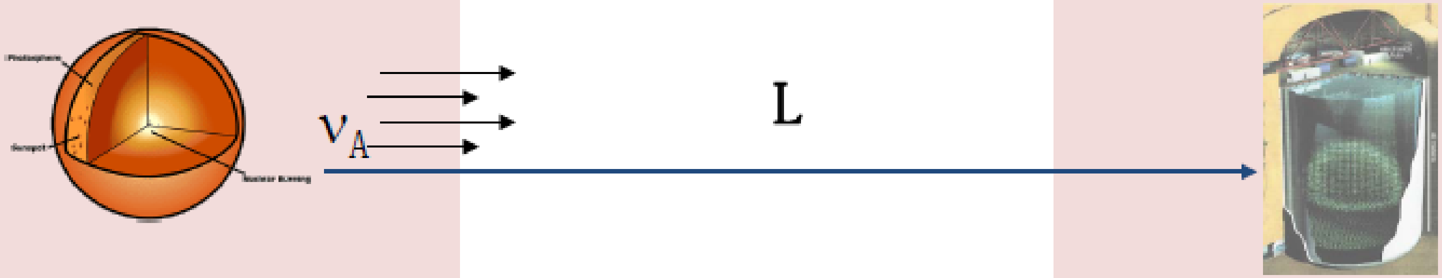
NC = 1 e + 1 x

Neutrino Oscillation

Source

Fly In Space

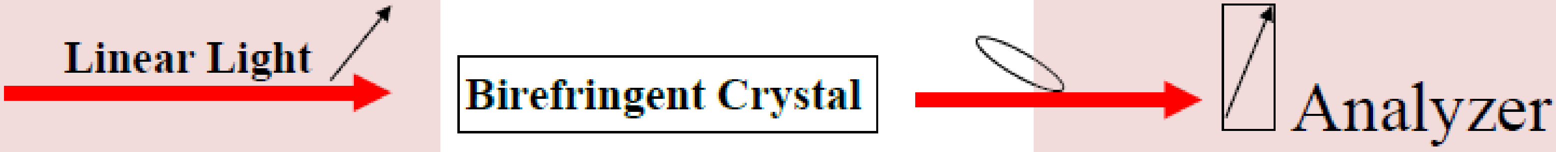
Detection



$$|\nu(x_0)\rangle = |\nu_A\rangle$$
$$= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu(\vec{x},t)\rangle = \cos\theta|\nu_1\rangle e^{i(Et-\vec{k}_1\cdot\vec{x})}$$
$$+ \sin\theta|\nu_2\rangle e^{i(Et-\vec{k}_2\cdot\vec{x})}$$

$$P(\nu_A \to \nu_A) = |\langle\nu_A|\nu(t)\rangle|^2$$



Linear Light

Birefringent Crystal

Analyzer

Two-flavor Neutrino Oscillation in Vacuum

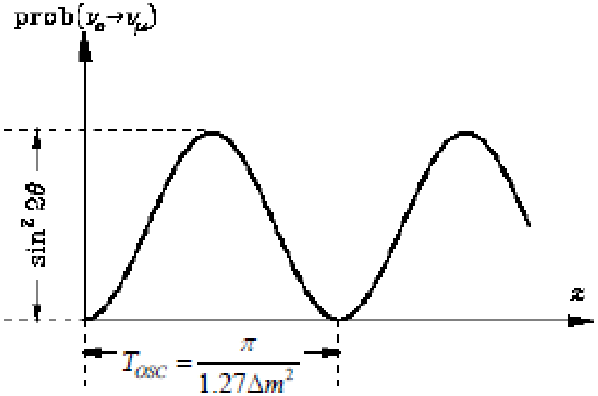
$$\begin{pmatrix} \nu_A \\ \nu_B \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$P(A \rightarrow B, \text{appearance}) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

$P(A \rightarrow A, \text{survival}) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

$\Delta m^2 = m_1^2 - m_2^2$ in eV^2

L in m, E in MeV

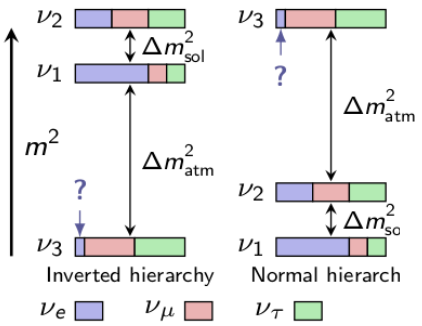


Given L/E sensitive to a range of Δm^2: MeV neutrino & 1000 m ⇒ $\Delta m^2 \sim 10^{-3}$eV^2

Neutrino mixing

Transformation from mass to weak eigenstates

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



$\Delta m^2_{\rm atm} = 2.4\times10^{-3}$ eV^2

$\Delta m^2_{\rm sol} \sim 7.6\times10^{-5}$ eV^2

Solar: θ_{12}~32°

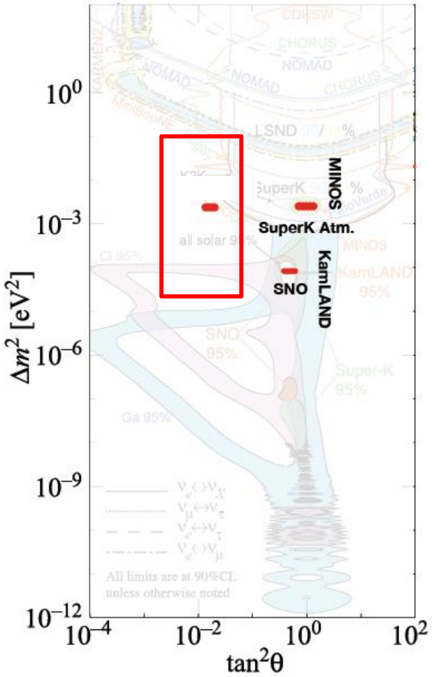
Atmospheric: θ_{23}~45°

$$U_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

θ_{13}~9°

δ: CP Violation Phase

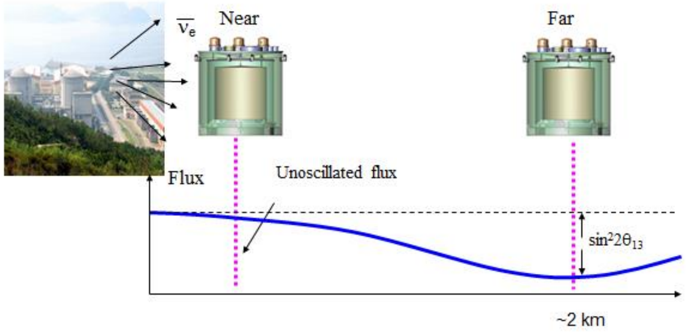


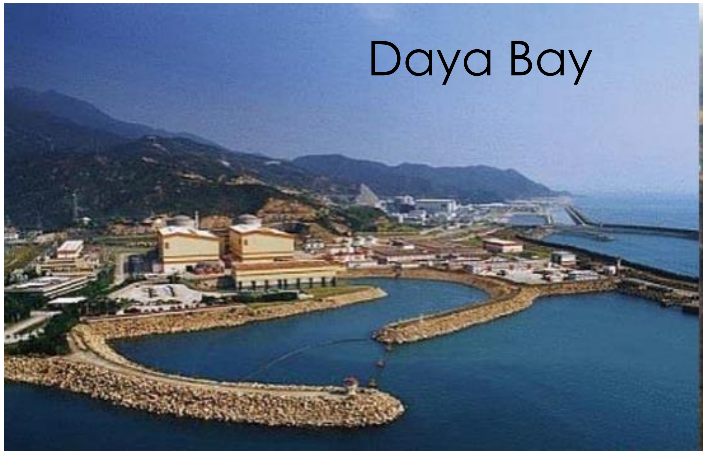
The last mixing angles θ_{13}

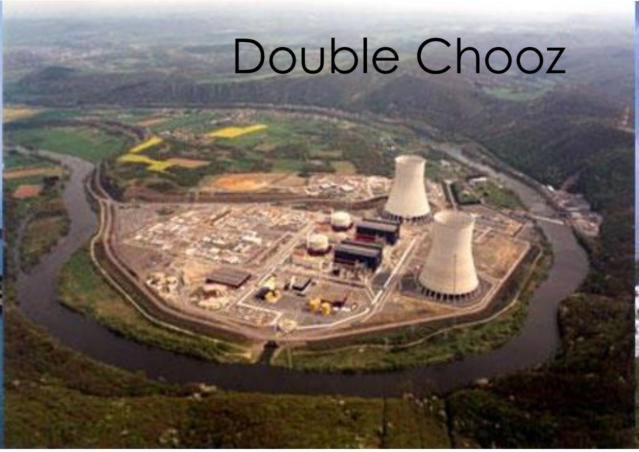
$$P(\nu_e \rightarrow \nu_e) = 1 - \boxed{\sin^2 2\theta_{13}}\left(\cos^2\theta_{12}\boxed{\sin^2\Delta_{31}} + \sin^2\theta_{12}\boxed{\sin^2\Delta_{32}}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

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

$\Delta m_{31}^2 = 2.4\times10^{-3}\ \mathrm{eV}^2$, reactor neutrino $E\nu \sim 4$ MeV, $L = 2$ km



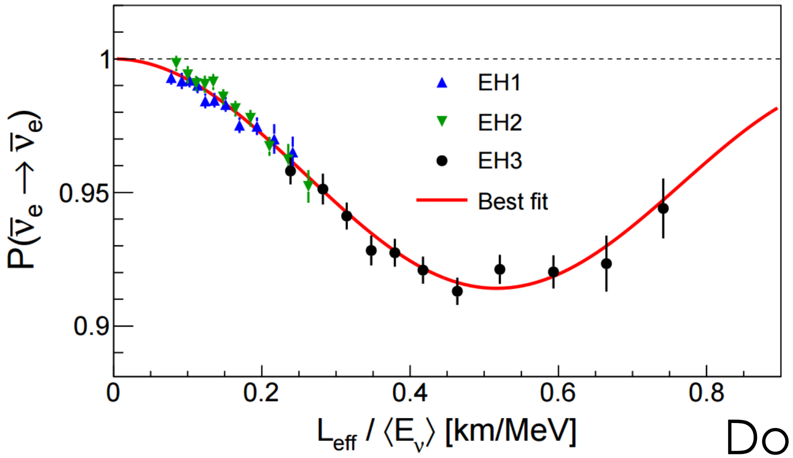

Daya Bay


Double Chooz

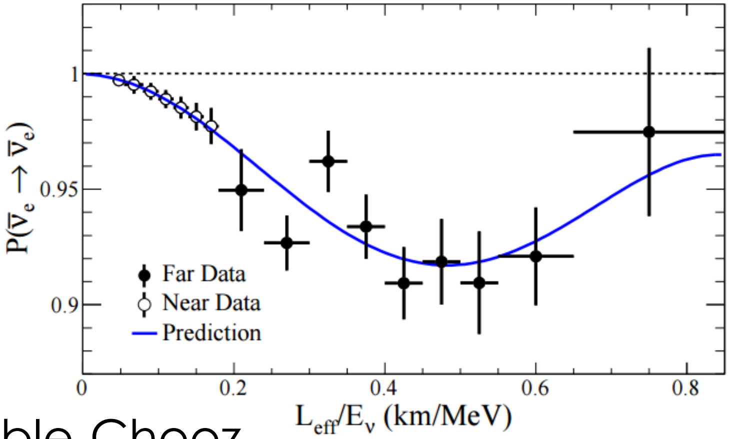

RENO

All three experiments with multiple detector

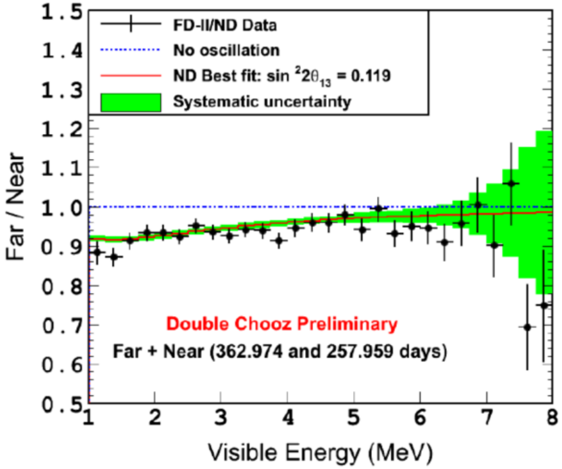
Daya Bay (arXiv:1610.04802)



RENO (arXiv:1610.04326)

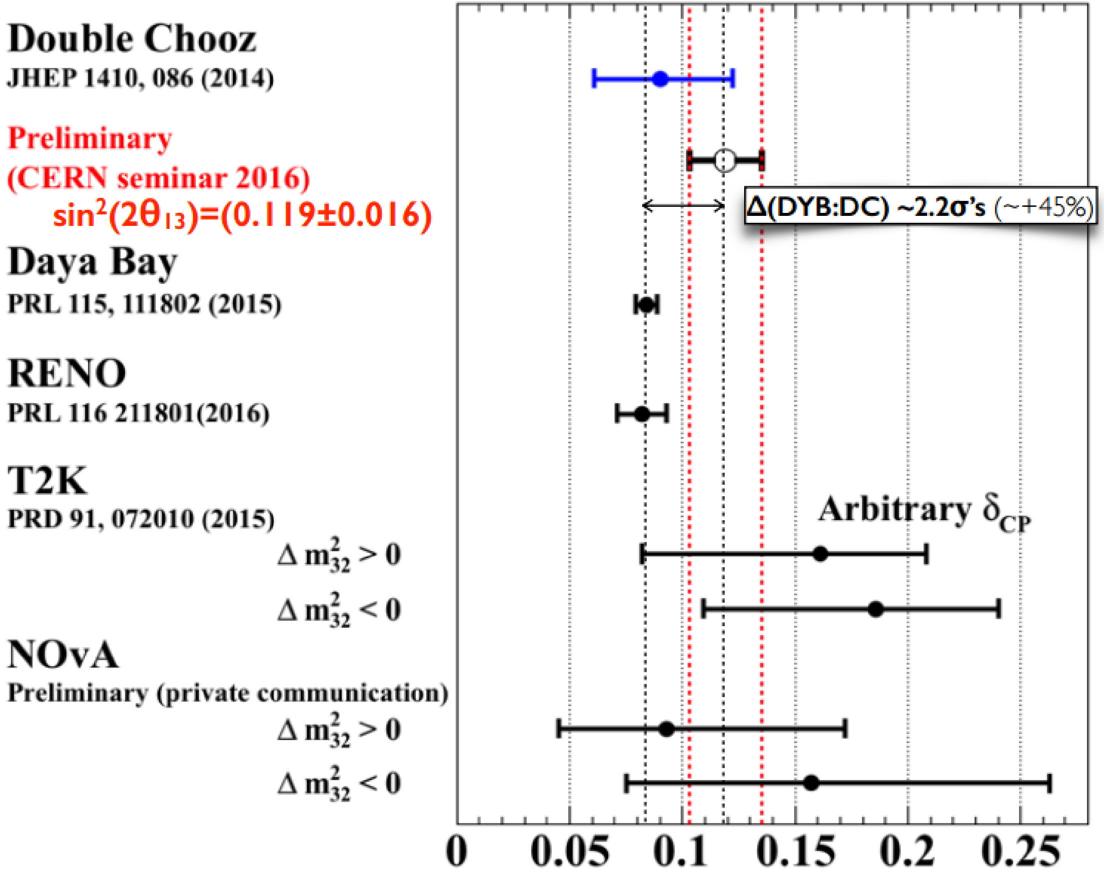


Double-Chooz



CERN seminar,
Sep. 2016

Impressive world data on θ_{13}



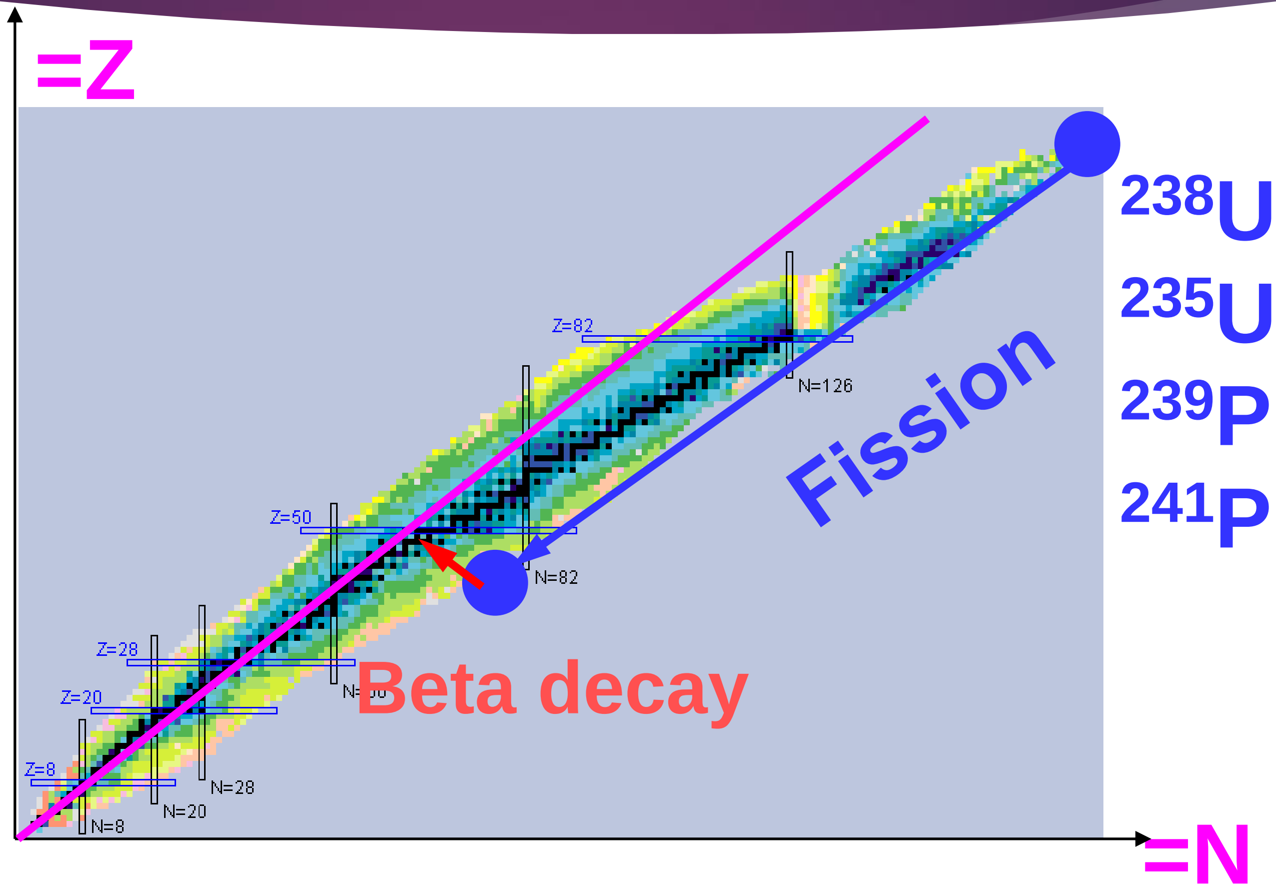
A. Cabrera, DC release talk, 09-20-2016

Daya Bay, RENO, and Double Chooz are now sitting together (first meeting Oct 2016) and discussing combined analysis

Outline

- Neutrinos from the sun and their flavor oscillation
- Neutrinos from nuclear reactors
  - “Reactor neutrino anomaly”
  - Digression: 17 keV neutrino anomaly
  - Mass ordering and the JUNO experiment
- Neutrinoless double beta decay

Nuclear reactors



^{238}U

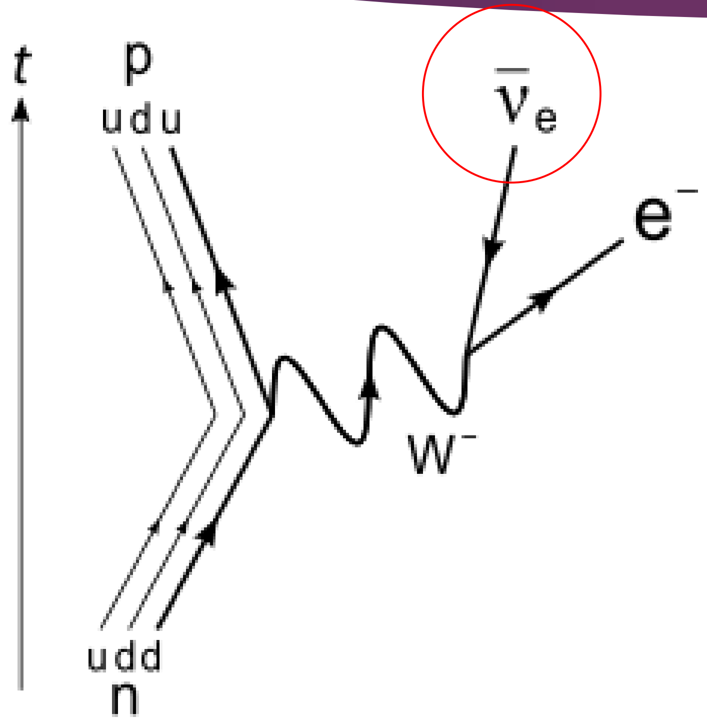
^{235}U

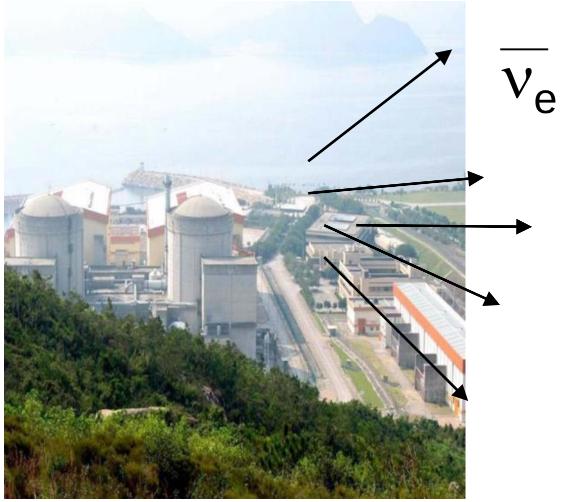
^{239}Pu

^{241}Pu

1 Fission ⇔ 200 MeV

Reactor neutrinos



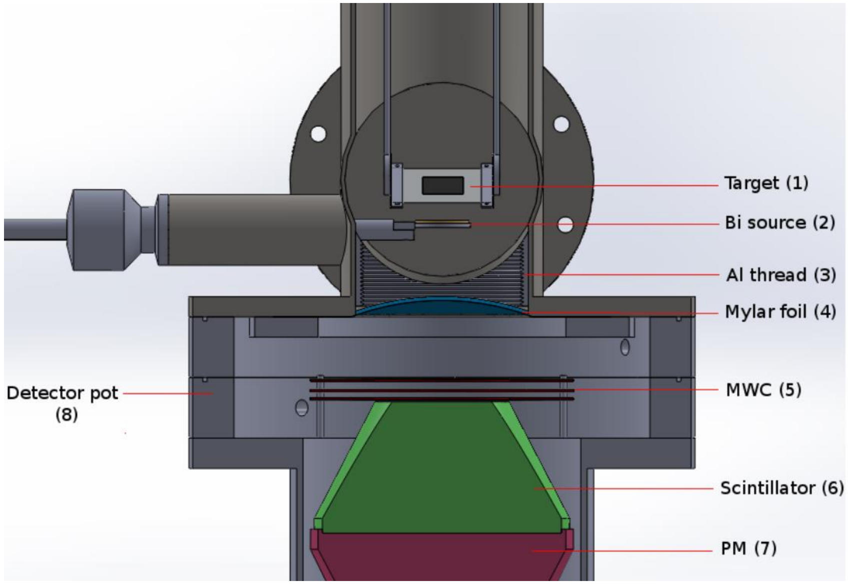


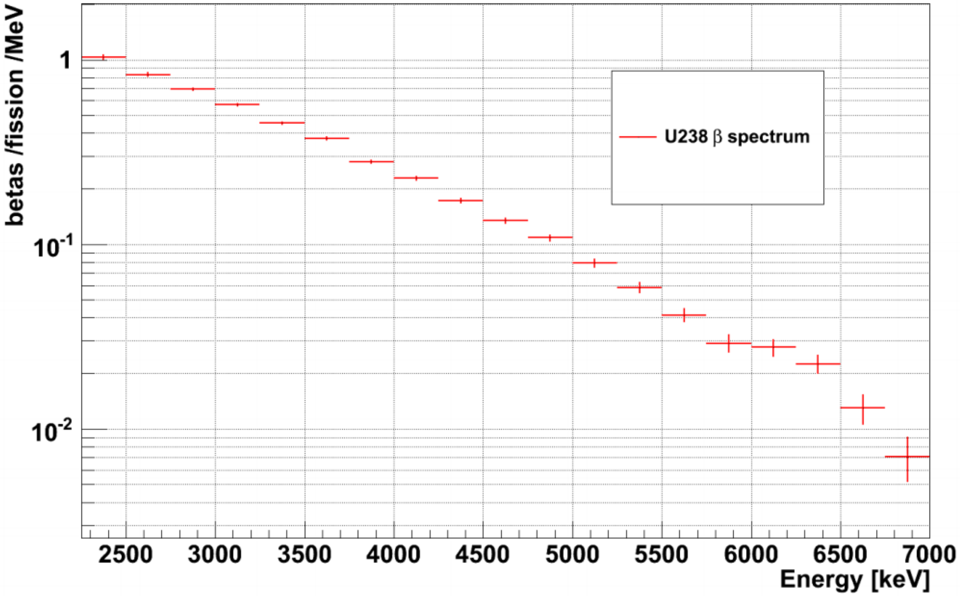
So 1 GWth (typical power reactor)$\Rightarrow 2\times10^{20}\ \bar{\nu}_e$ /s

Beta spectrum measurement from fission fuels

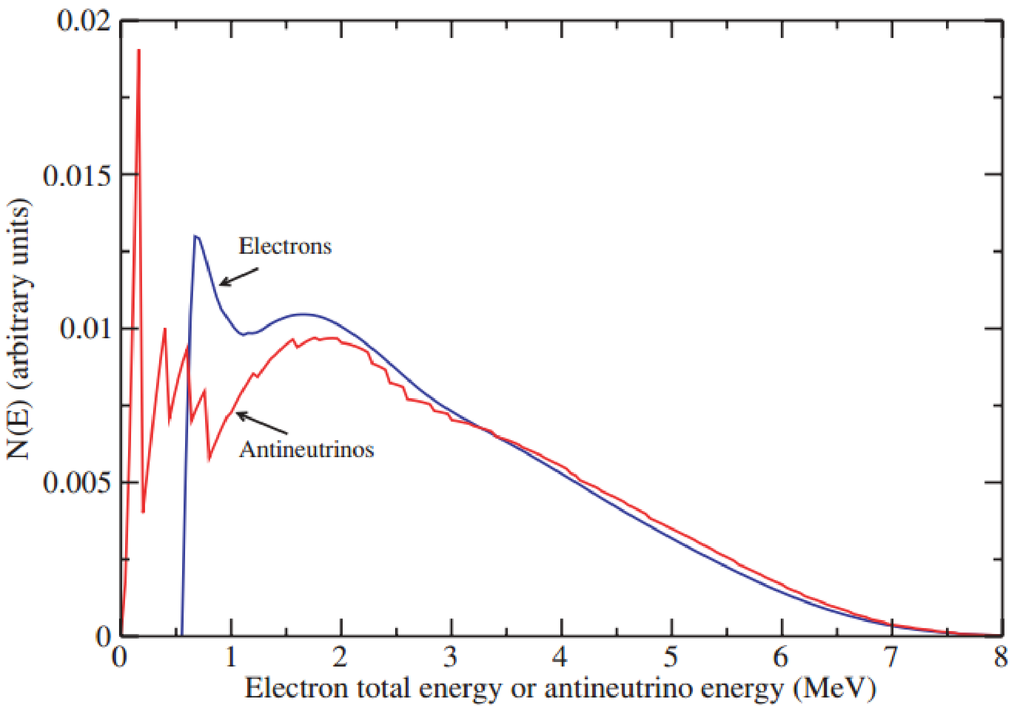
- E.g. recent measurement by Haag et al.

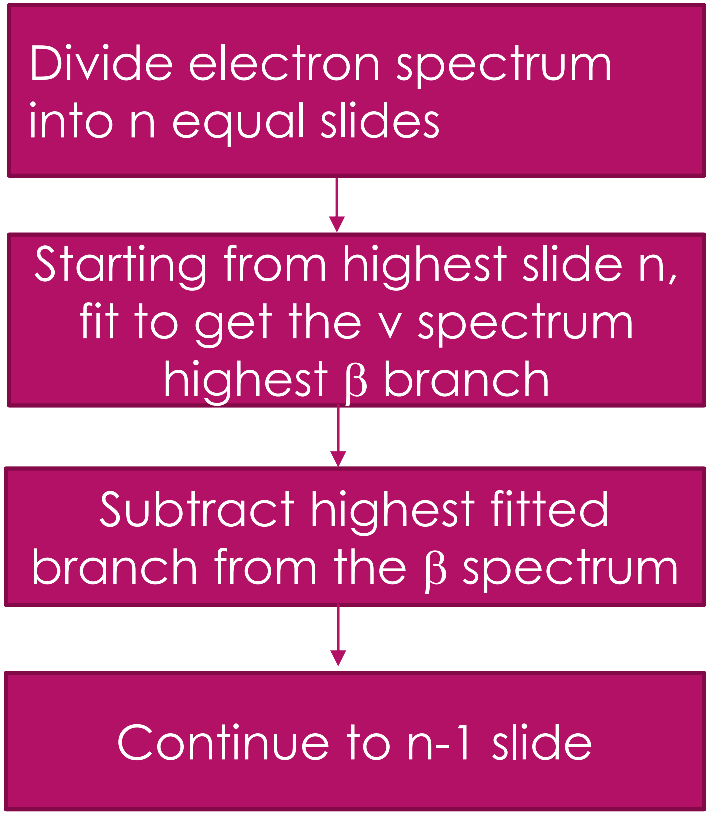
Phys.Rev.Lett. 112, 202501 (2014)





Beta conversion method





Divide electron spectrum into n equal slides

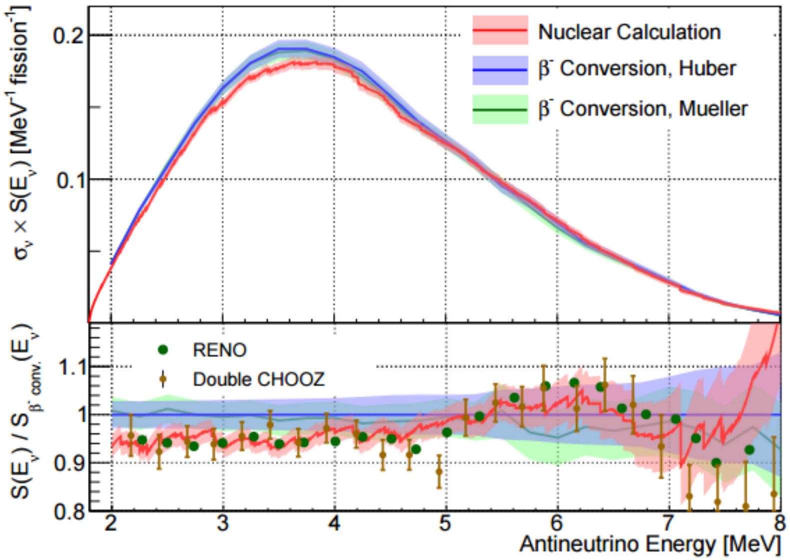
Starting from highest slide n, fit to get the ν spectrum highest β branch

Subtract highest fitted branch from the β spectrum

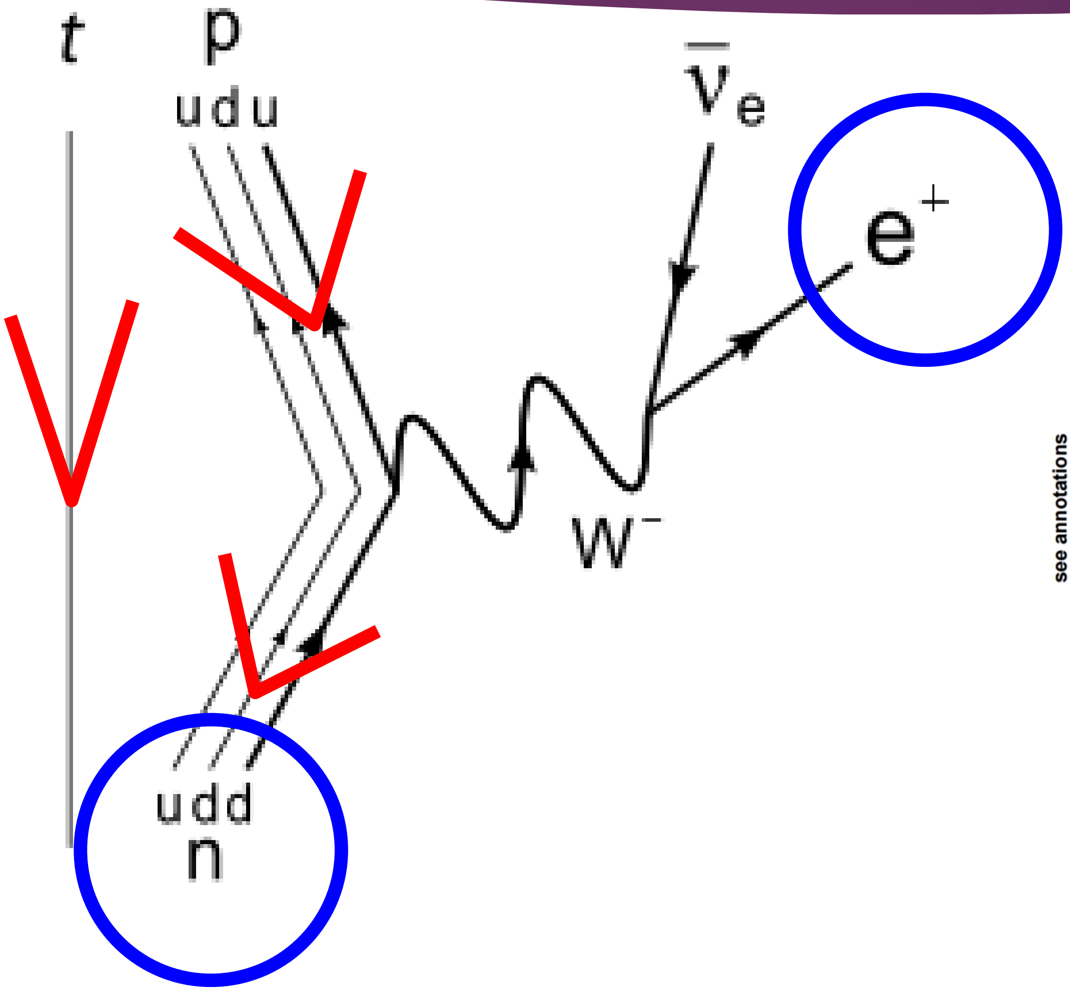
Continue to n-1 slide

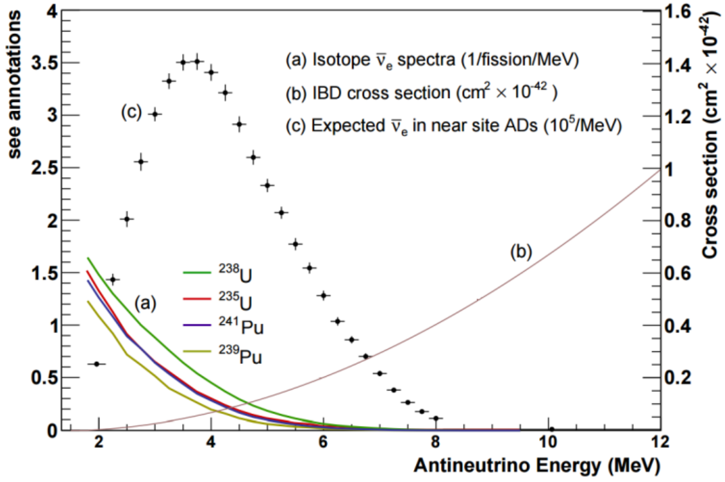
“ab initio” method

- Based on ENDF database for all possible decay branches (4000 branches): e.g. Dwyer & Langford, Phys. Rev. Lett. 114, 012502 (2015)
- Up to 10% branches may still be missing



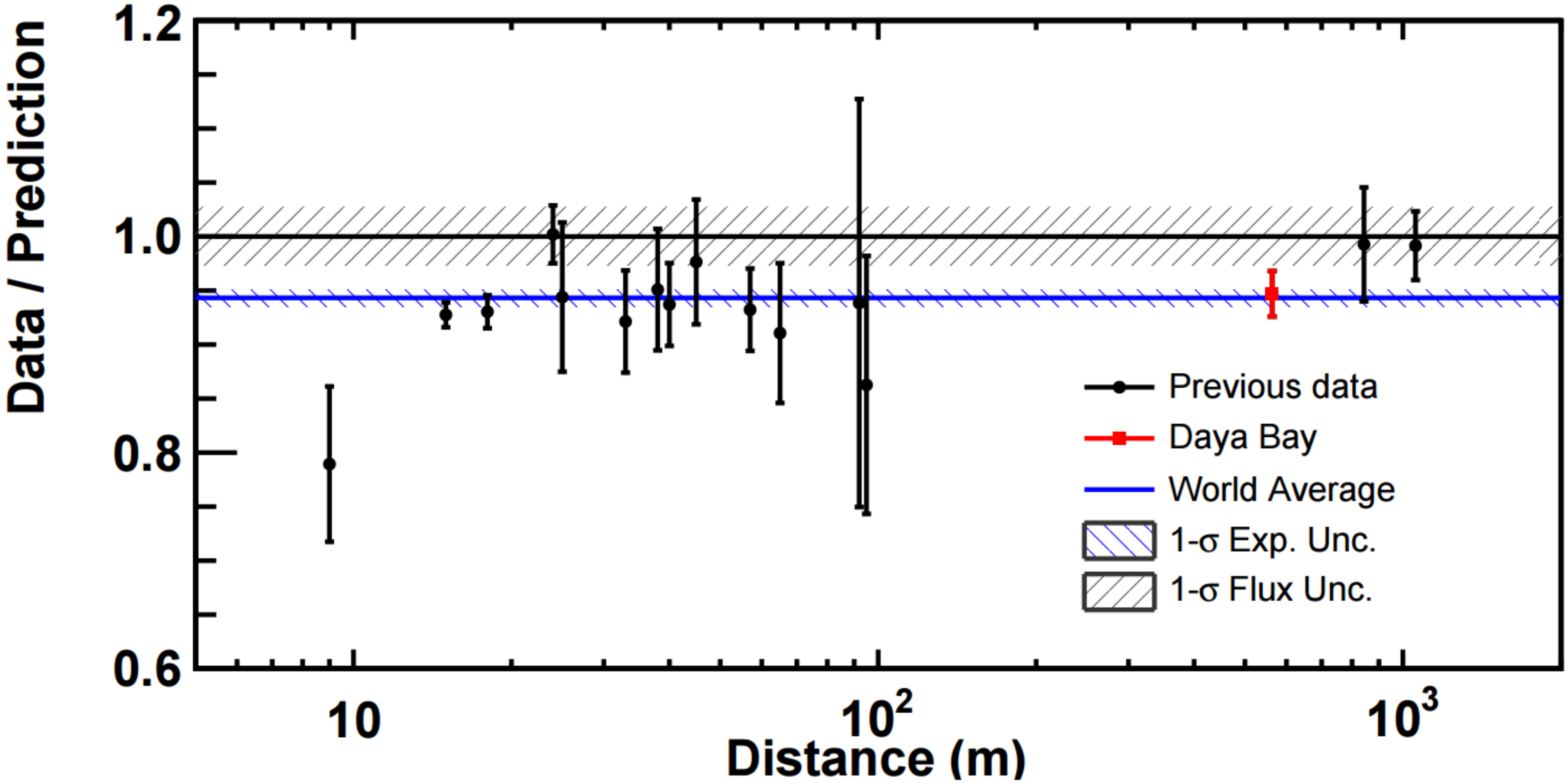
Experimental measurement of beta spectrum



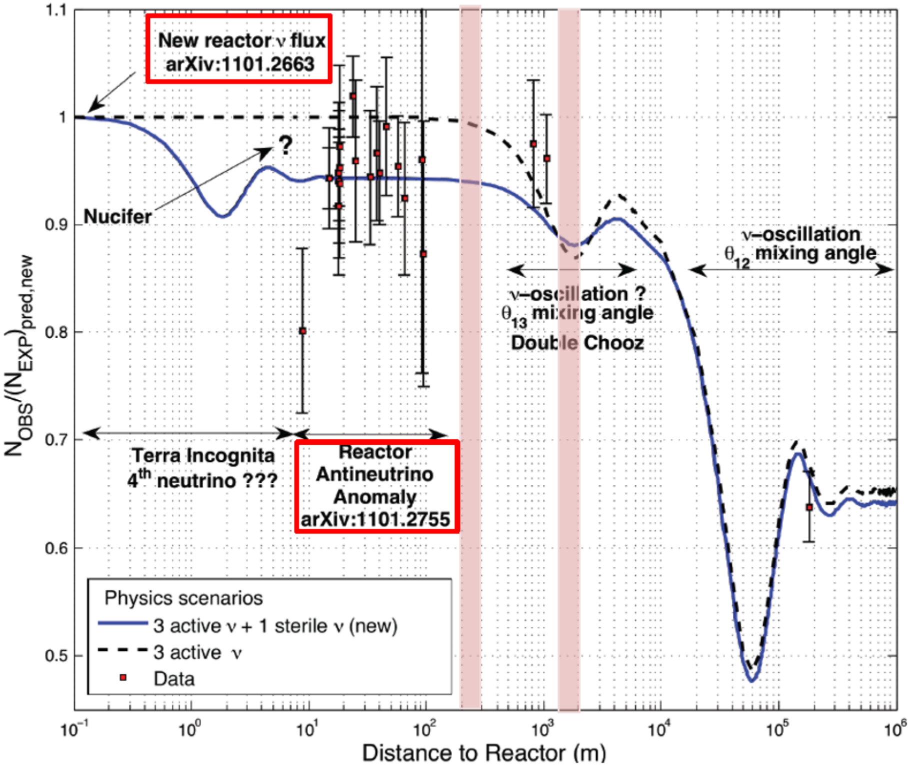


Reactor anomaly

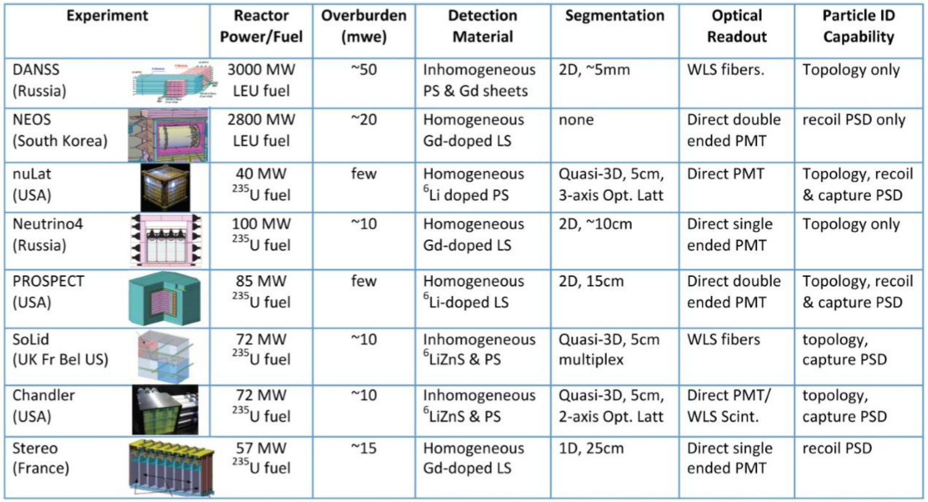
arXiv:1607.05378



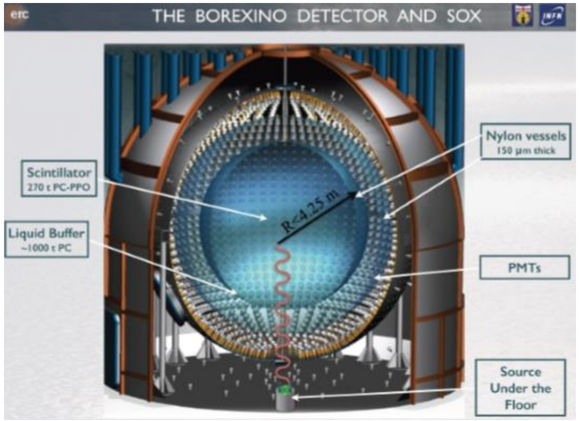
Sterile neutrino?



Thierry Lasserre, TAUP 2011



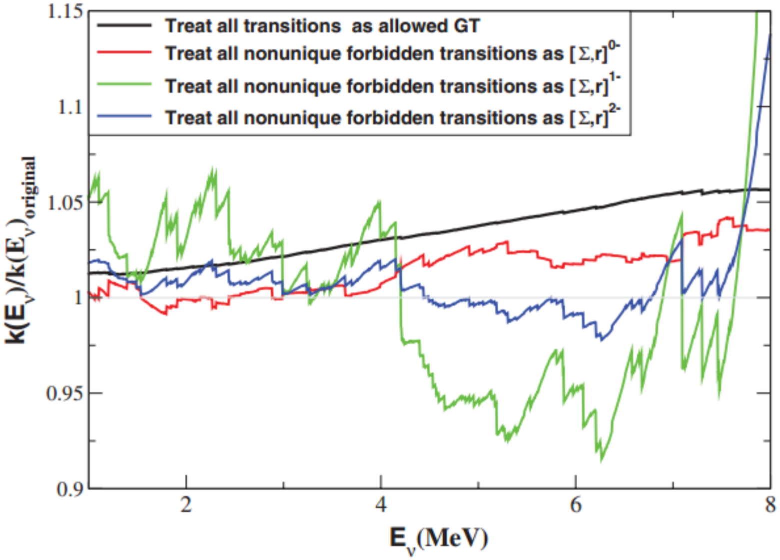
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD



Uncertainty to flux prediction

- Flux very uncertain due to forbidden decays, even under identical beta spectrum
- Uncertainty as large as the "anomaly"

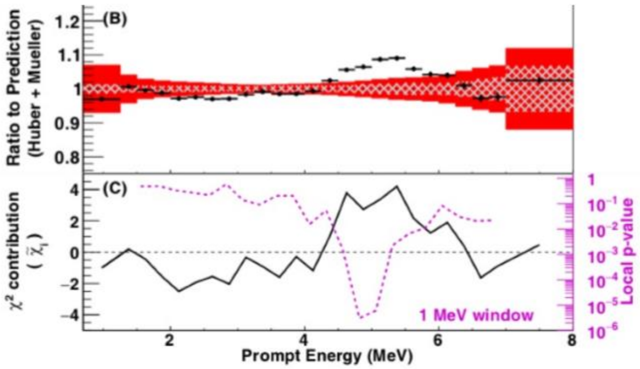
A. C. Hayes, et al.
Phys. Rev. Lett. **112**, 202501



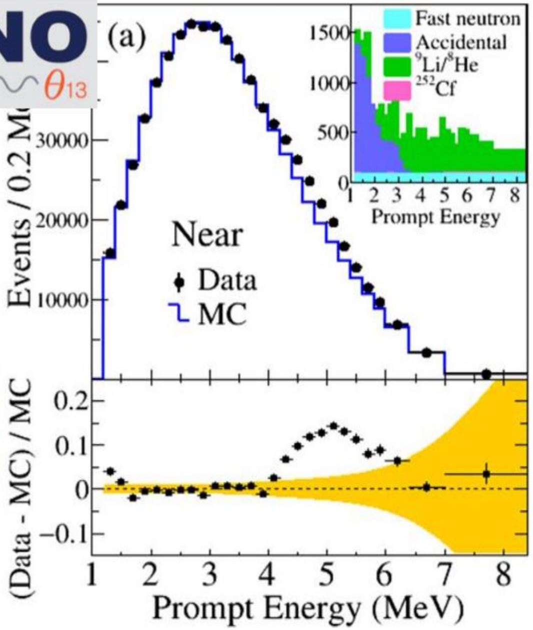
“5 MeV” bump

- All three reactor neutrino experiments observed a bump at 5 MeV
- No oscillation interpretation

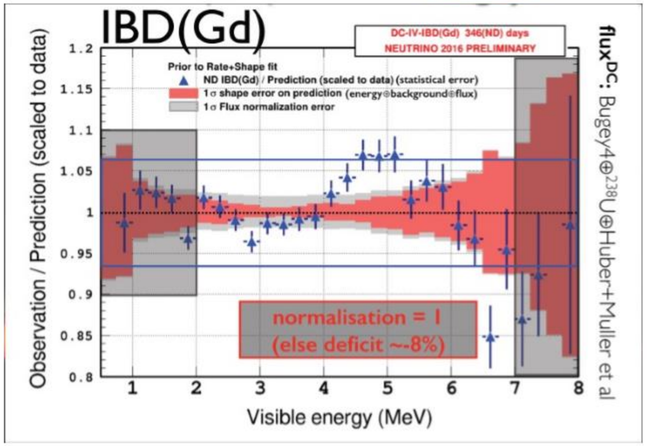
Daya Bay



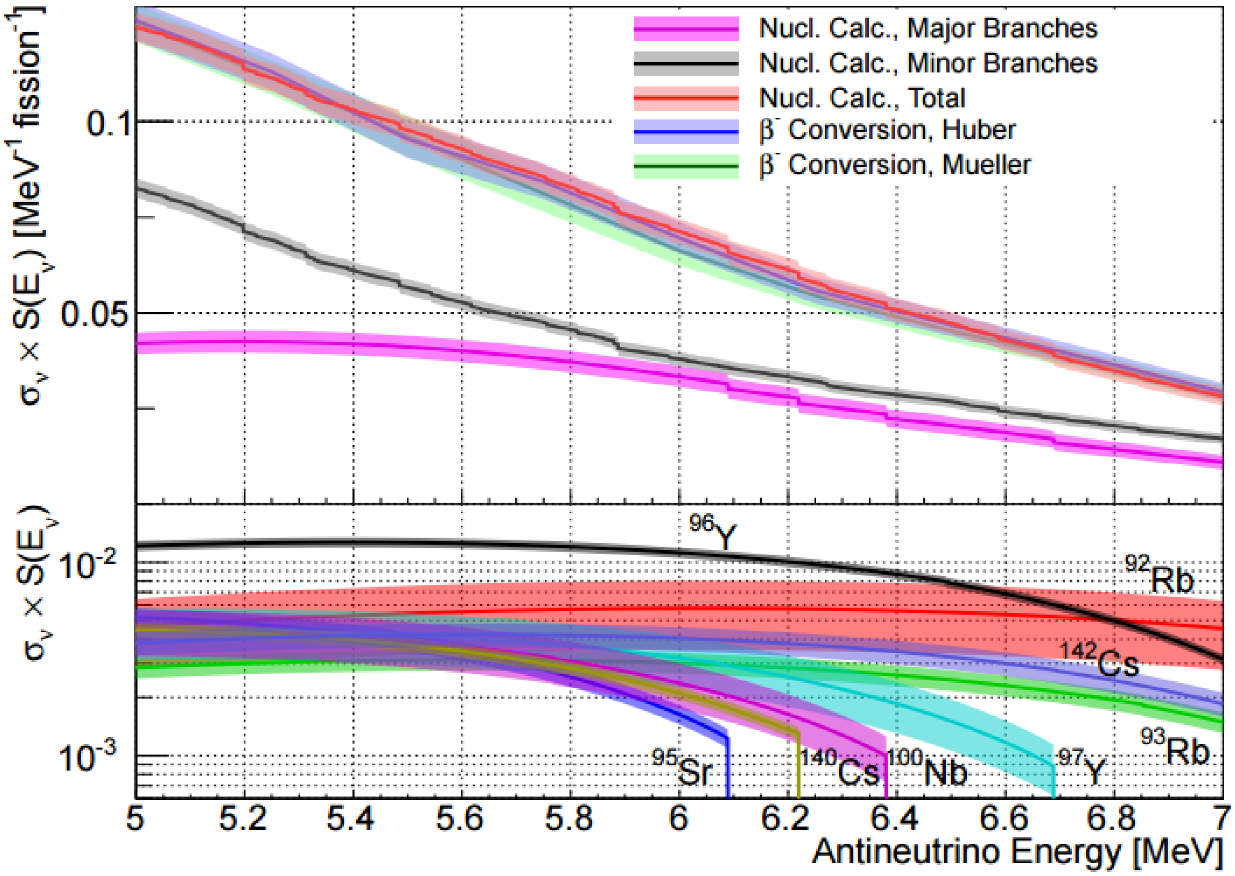
RENO



DOUBLE CHOOZ



Cause of the bump



Dwyer and Langford

"A spectral bump due to prominent beta decay branches in the 5–7 MeV region is similar to that seen in recent measurements."

High precision reactor spectrum can help!

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- Neutrinoless double beta decay

Back to Fermi's β spectrum

$$\frac{dN(E, m_\nu)}{dE} \propto F(Z, E) pE (Q - E) \left[(Q - E)^2 - m_\nu^2\right]^{1/2}$$

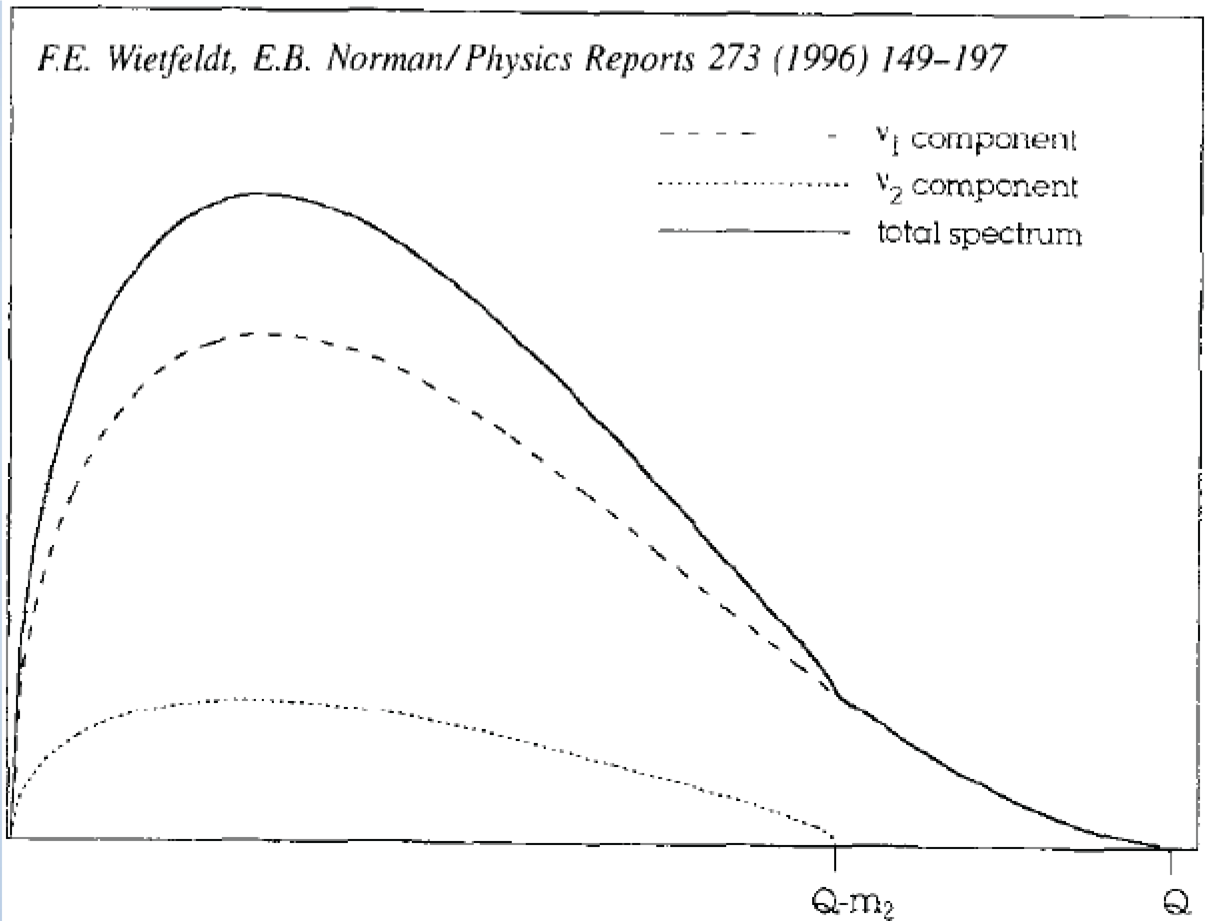
- However, emitted electron neutrino is a mixture of mass states. In two-flavor model

$$|\nu_e\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

- The spectrum now becomes

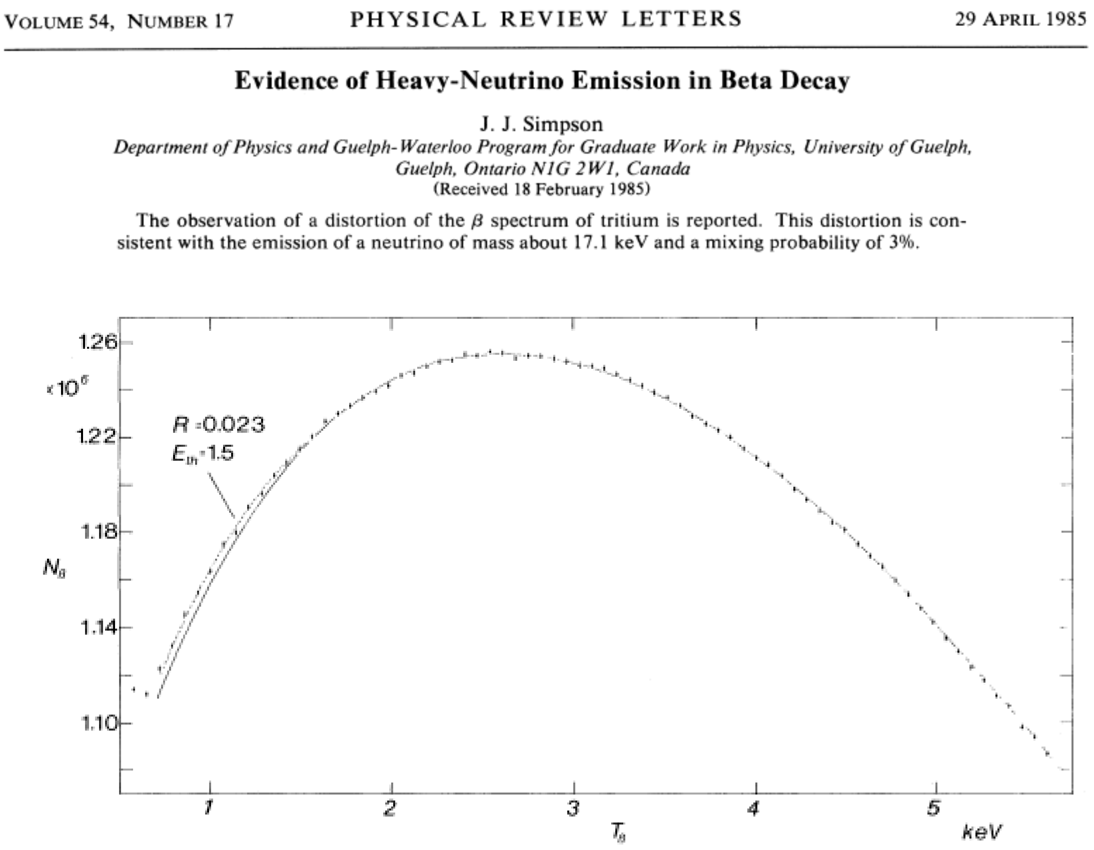
$$\frac{dN(E)}{dE} = \cos^2\theta \frac{dN(E, m_1)}{dE} + \sin^2\theta \frac{dN(E, m_2)}{dE}$$

Kink in β spectrum



F.E. Wietfeldt, E.B. Norman/ Physics Reports 273 (1996) 149–197

Observation of a kink in 1985!



VOLUME 54, NUMBER 17 PHYSICAL REVIEW LETTERS 29 APRIL 1985

Evidence of Heavy-Neutrino Emission in Beta Decay

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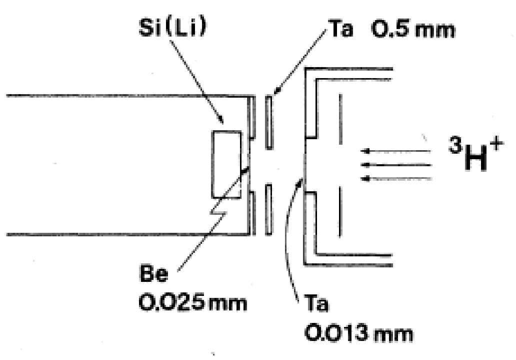
(Received 18 February 1985)

The observation of a distortion of the β spectrum of tritium is reported. This distortion is consistent with the emission of a neutrino of mass about 17.1 keV and a mixing probability of 3%.

Tritium implanted in Si(Li) detector



Consistent with a **17.1 keV** neutrinos with 3% mixing $\sin^2\theta$ with ν_1

Situation at 1991: Peak of the Controversy

Wietfeldt & Norman, Physics Report 237, 149 (1996)

Morrison, Nature 336, 29 (1993)

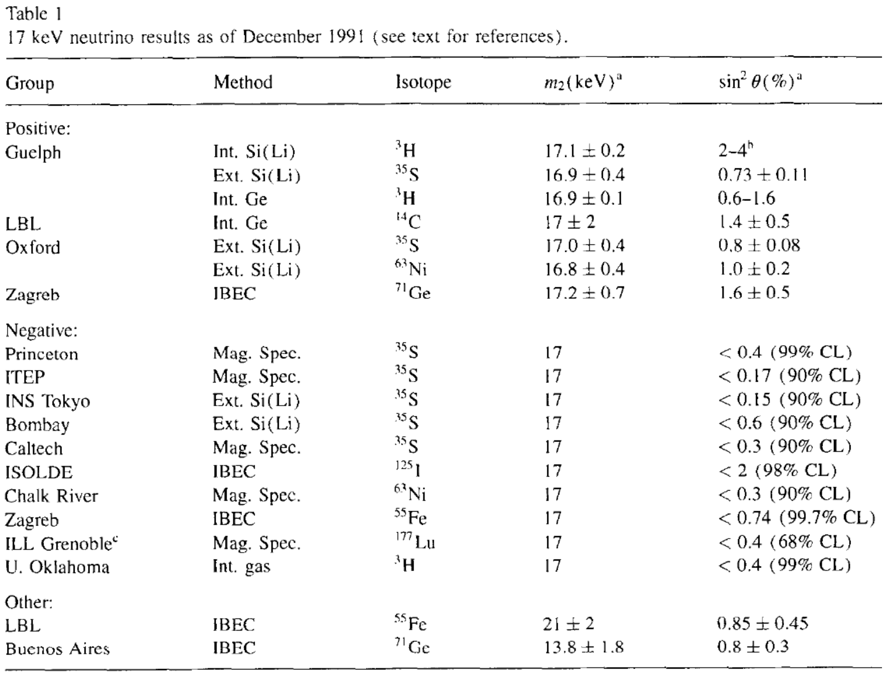


Table 1
17 keV neutrino results as of December 1991 (see text for references).

Group	Method	Isotope	m_2(keV)^a	$\sin^2\theta$(%)^a
Positive:				
Guelph	Int. Si(Li)	^{3}H	17.1 ± 0.2	2–4^b
	Ext. Si(Li)	^{35}S	16.9 ± 0.4	0.73 ± 0.11
	Int. Ge	^{3}H	16.9 ± 0.1	0.6–1.6
LBL	Int. Ge	^{14}C	17 ± 2	1.4 ± 0.5
Oxford	Ext. Si(Li)	^{35}S	17.0 ± 0.4	0.8 ± 0.08
	Ext. Si(Li)	^{63}Ni	16.8 ± 0.4	1.0 ± 0.2
Zagreb	IBEC	^{71}Ge	17.2 ± 0.7	1.6 ± 0.5
Negative:				
Princeton	Mag. Spec.	^{35}S	17	< 0.4 (99% CL)
ITEP	Mag. Spec.	^{35}S	17	< 0.17 (90% CL)
INS Tokyo	Ext. Si(Li)	^{35}S	17	< 0.15 (90% CL)
Bombay	Ext. Si(Li)	^{35}S	17	< 0.6 (90% CL)
Caltech	Mag. Spec.	^{35}S	17	< 0.3 (90% CL)
ISOLDE	IBEC	^{125}I	17	< 2 (98% CL)
Chalk River	Mag. Spec.	^{63}Ni	17	< 0.3 (90% CL)
Zagreb	IBEC	^{55}Fe	17	< 0.74 (99.7% CL)
ILL Grenoble^c	Mag. Spec.	^{177}Lu	17	< 0.4 (68% CL)
U. Oklahoma	Int. gas	^{3}H	17	< 0.4 (99% CL)
Other:				
LBL	IBEC	^{55}Fe	21 ± 2	0.85 ± 0.45
Buenos Aires	IBEC	^{71}Ge	13.8 ± 1.8	0.8 ± 0.3

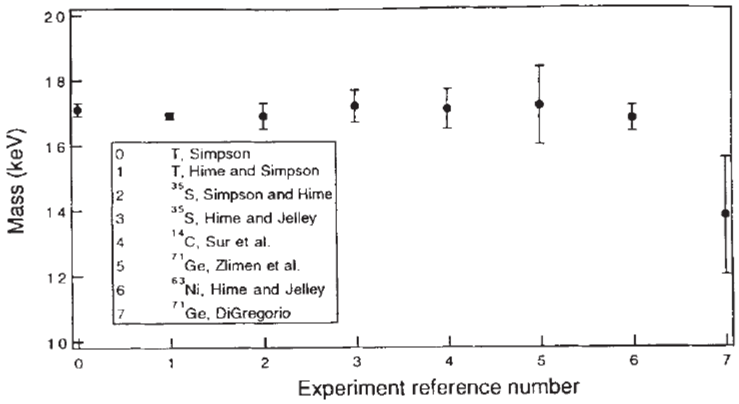


FIG. 4 Values of the mass of a heavy neutrino from positive determinations, from ref. 43.

1993: Bugs found!

- Hime’s reanalysis taking into account the scattering effects

Phys.Lett. B299 (1993) 165-173

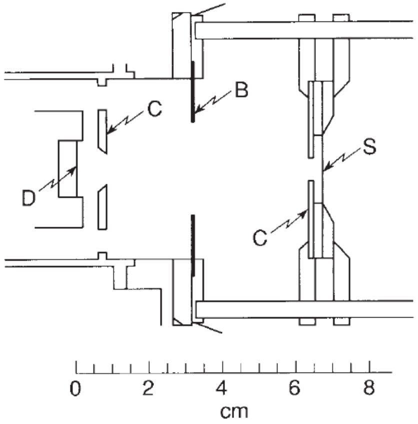


FIG. 3 Inner part of the experimental apparatus used by Hime and Jelley[17,19]. B is the annular baffle that caused problems, S is the source from which the decay electrons emerge, D is the solid-state detector and C represents the two collimators around the source and the detector.

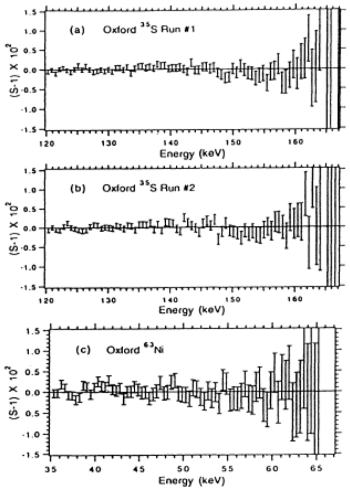
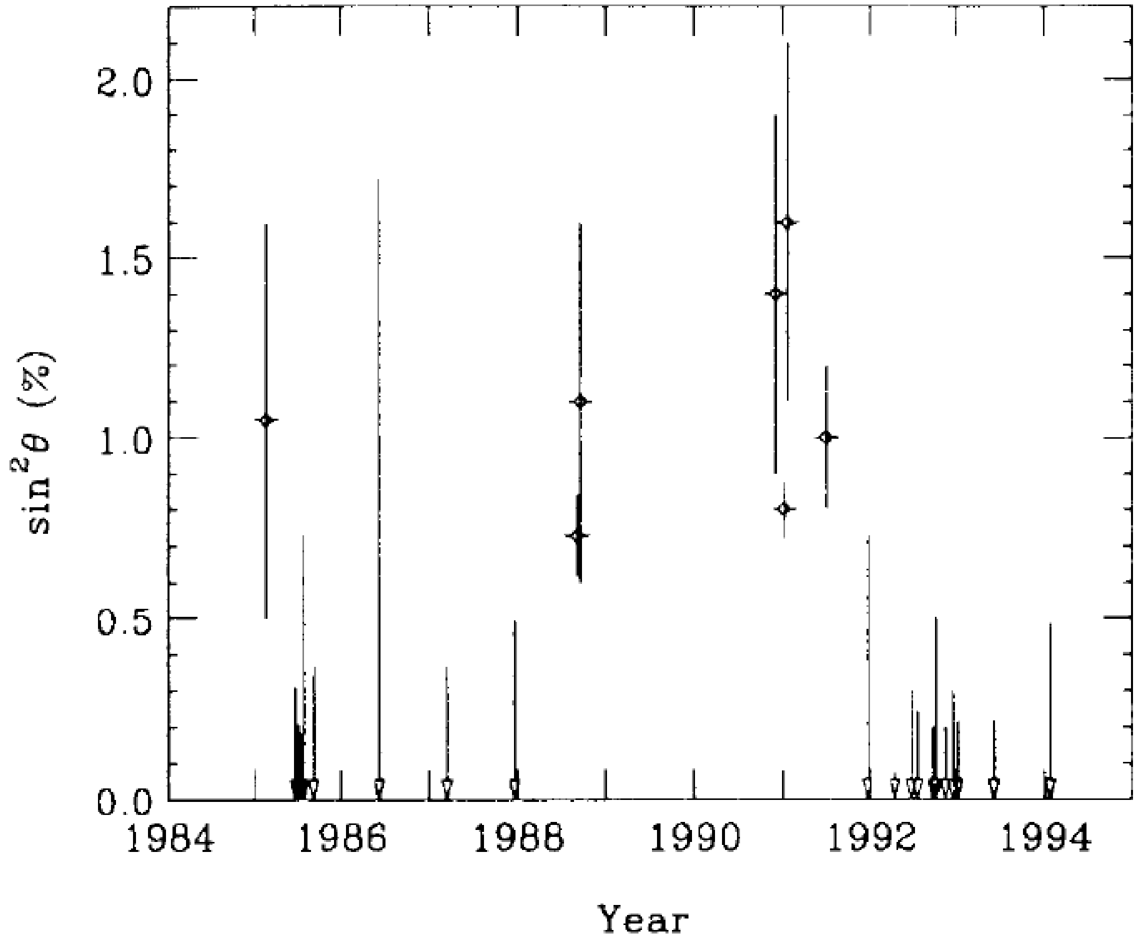


FIG. 28. Shape factors extracted from Oxford data for (a) ^{35}S run #1, (b) ^{35}S run #2, and (c) ^{63}Ni, after implementing the best-fit theoretical spectrum including intermediate scattering effects and assuming a single-component, massless neutrino. From Hime (1993).

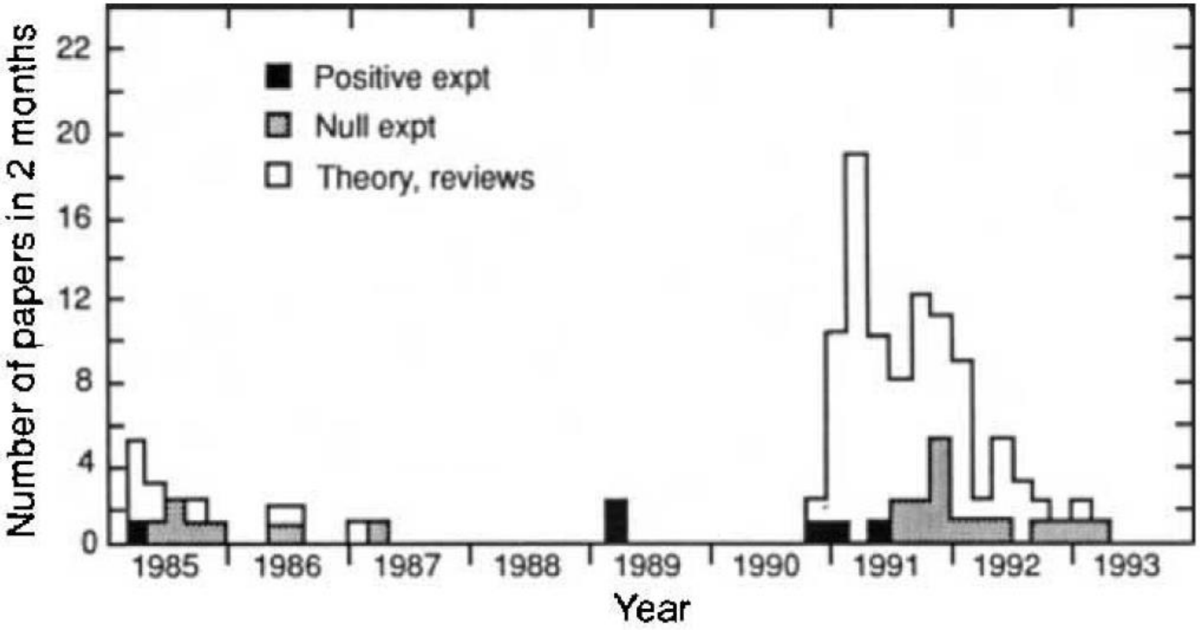
- Berkeley ^{14}C experiment: events in the guard ring of

HPGe with insufficient energy deposition

1994: 17 keV Neutrino Dead



Experiment-theory sociology



- 17 keV neutrinos are in conflict with LEP, Cosmology constraints, and SN1987A, but still there are numbers of viable (but contrived) theoretical models derived.
- At least in this case, nature chooses to be "pretty"

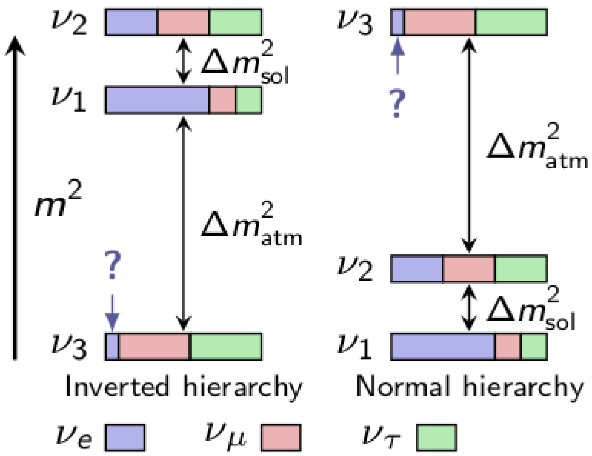
Outline

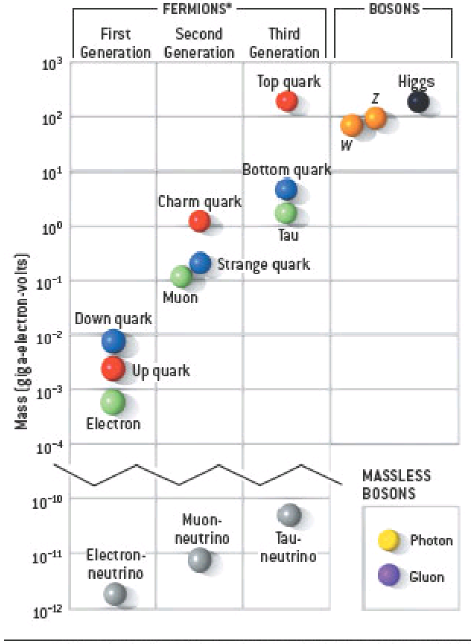
- Neutrinos from the sun and their flavor oscillation
- Neutrinos from nuclear reactors
    - “Reactor neutrino anomaly”
    - Digression: 17 keV neutrino anomaly
    - Mass ordering and the JUNO experiment
- Neutrinoless double beta decay

Mass hierarchy?

- $|\Delta m_{31}{}^2| = 2.4\times10^{-3}\ \text{eV}^2$, $\Delta m_{21}{}^2 = 7.5\times10^{-5}\ \text{eV}^2$
- Mass hierarchy:

  Is m_1 the lightest (normal) or m_3 the lightest (inverted)?
- Can loosely translate to: is electron neutrino the lightest?

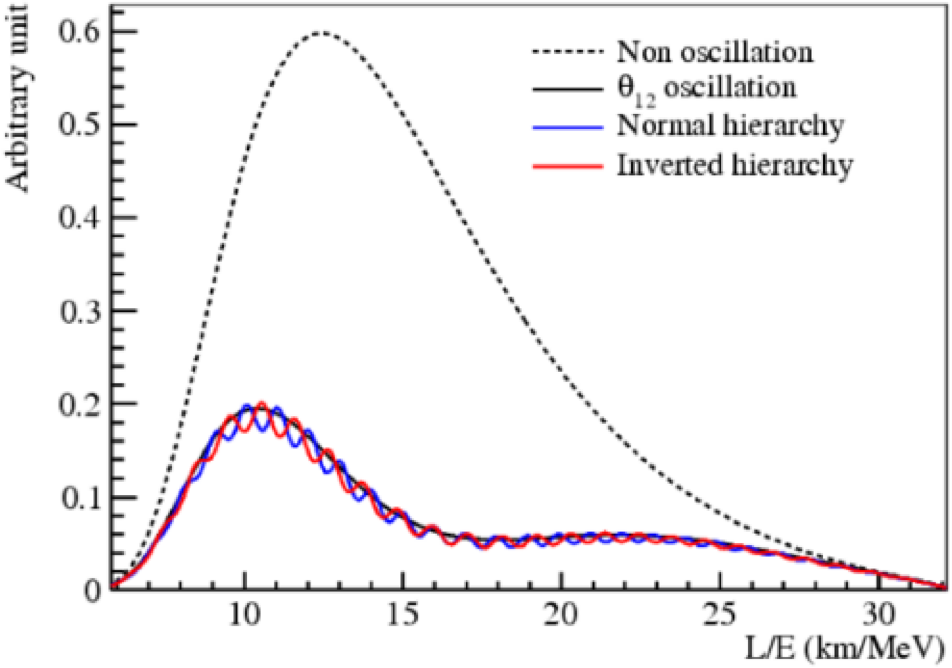




*The fermions are subdivided into quarks and leptons, with

JUNO experiment

$$
\begin{aligned}
P_{ee} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\
&- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\
&- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\
&\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)\,,
\end{aligned}
$$

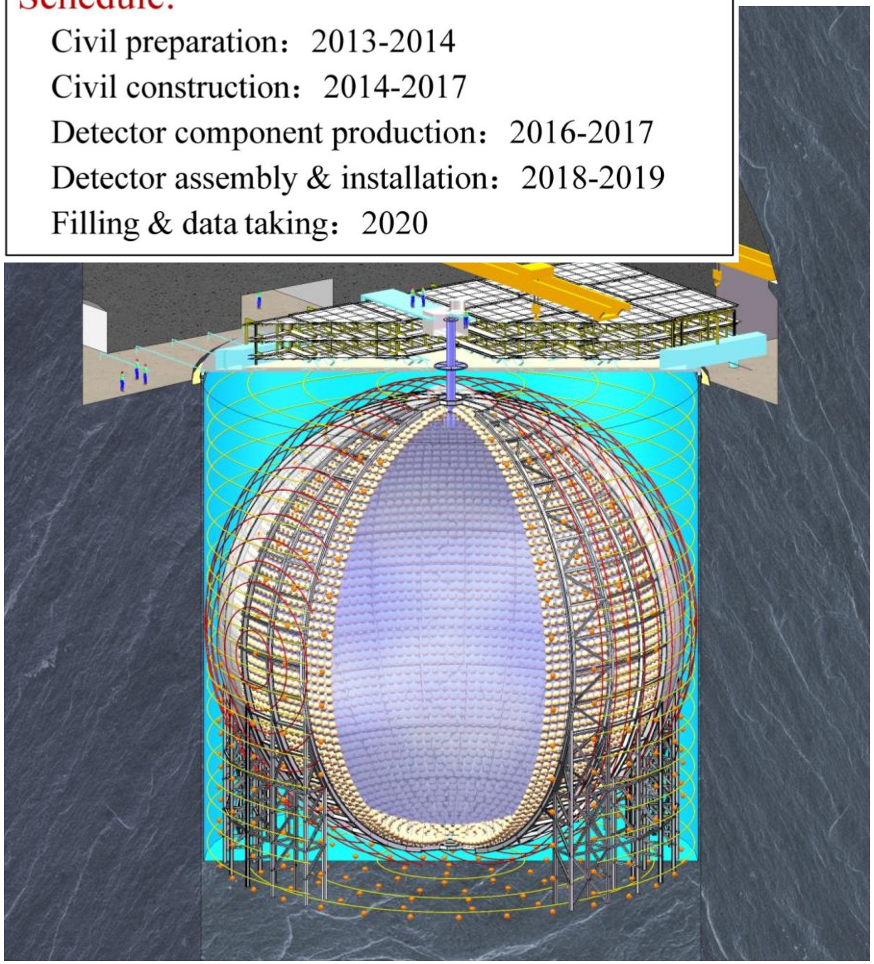


- 20k-ton multi-purpose LS detector
- Construction phase: 2013-2020
- 66 institutes, 444 collaborators

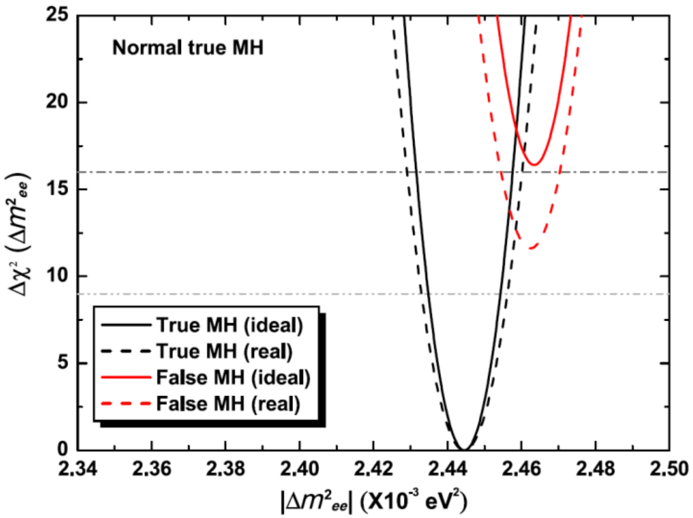
JUNO experiment

Schedule:

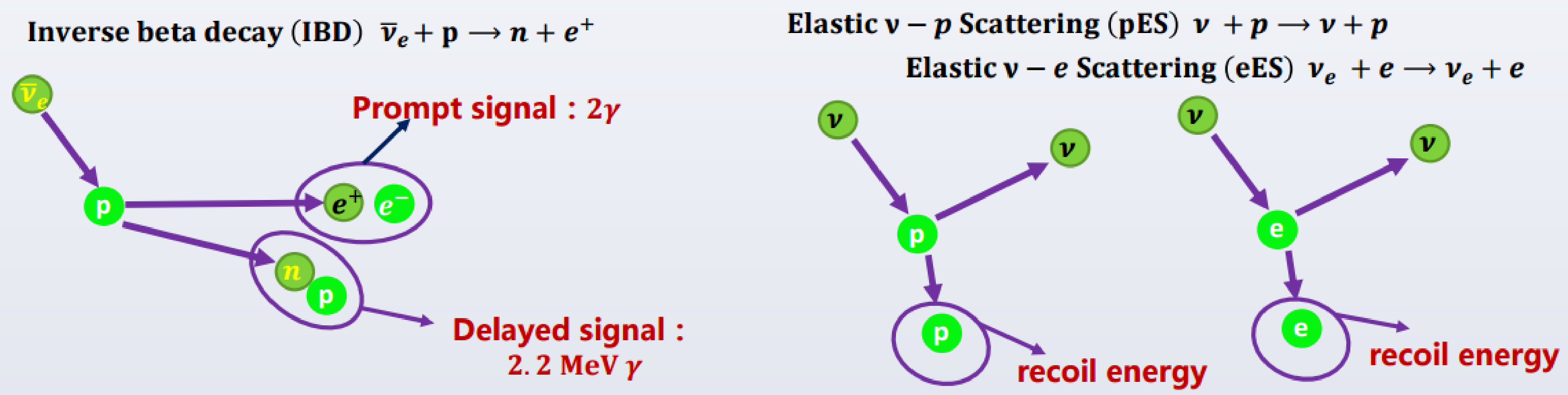
Civil preparation： 2013-2014
Civil construction： 2014-2017
Detector component production： 2016-2017
Detector assembly & installation： 2018-2019
Filling & data taking： 2020



- 27-36 GW reactor power, 20k ton LS detector
- **3%/√E** energy resolution, **<1%** energy scale uncertainty
- $>3\sigma$ (4σ) 6-years MH determination JUNO-alone (JUNO+accelerator exps)



Supernovae neutrino in JUNO



Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

10 kpc glactic SN

Outline

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- Neutrinoless double beta decay

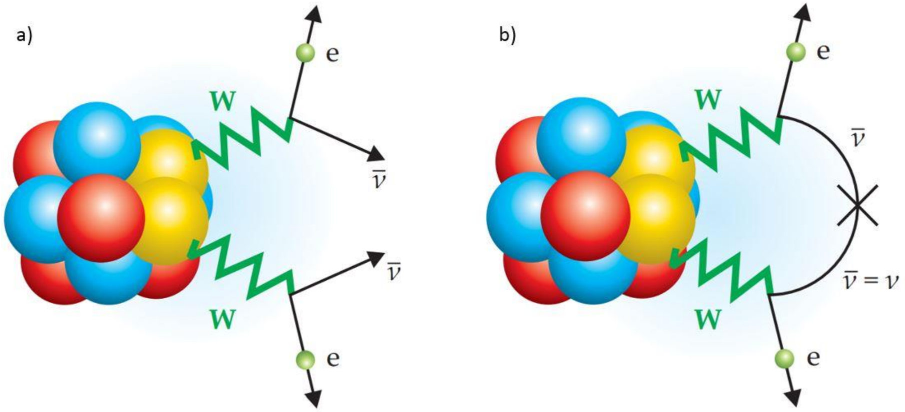
Majorana particles

Majorana mass term:

$$m_R \overline{\nu_R^C} \nu_R$$

- Majorana, 1937
- Can be tested via neutrinoless double β decay, W. Furry, 1939

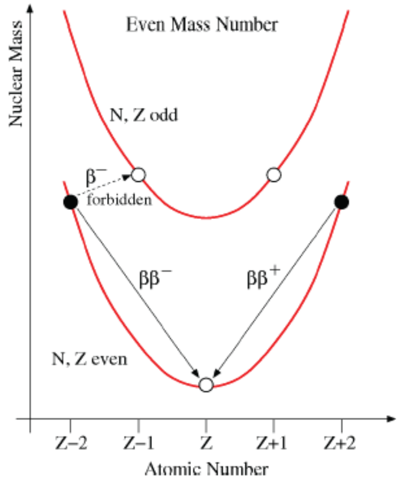
Neutrinoless double beta decay

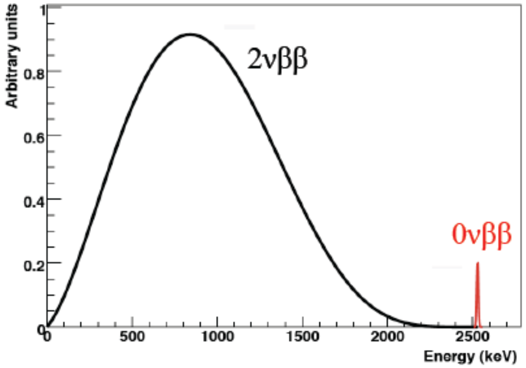


- Neutrinoless double beta decay
  - The nature of neutrinos, Dirac or Majorana
  - lepton number violation
- Extremely rare events T > 10^{24} year.

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

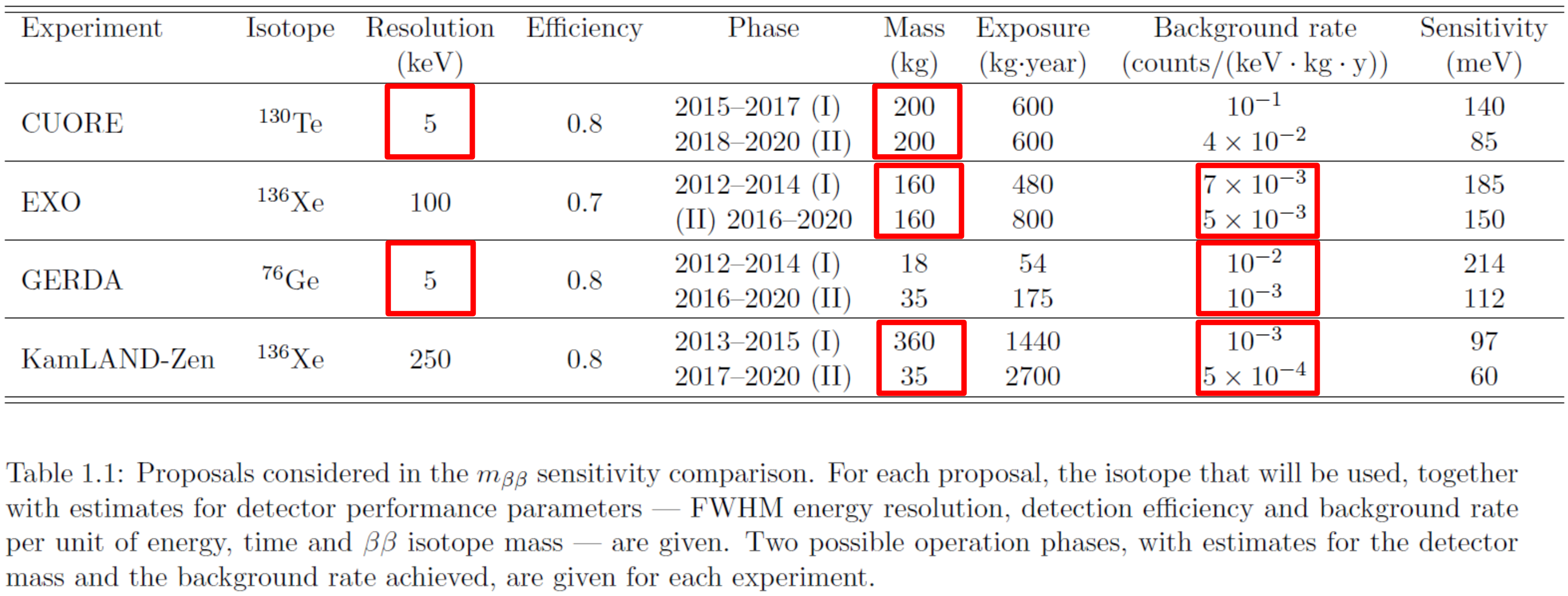
$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right| .$$





Sum of electrons energy

Front runners



Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
CUORE	^{130}Te	5	0.8	2015–2017 (I)	200	600	10^{-1}	140
				2018–2020 (II)	200	600	4×10^{-2}	85
EXO	^{136}Xe	100	0.7	2012–2014 (I)	160	480	7×10^{-3}	185
				(II) 2016–2020	160	800	5×10^{-3}	150
GERDA	^{76}Ge	5	0.8	2012–2014 (I)	18	54	10^{-2}	214
				2016–2020 (II)	35	175	10^{-3}	112
KamLAND-Zen	^{136}Xe	250	0.8	2013–2015 (I)	360	1440	10^{-3}	97
				2017–2020 (II)	35	2700	5×10^{-4}	60

Table 1.1: Proposals considered in the $m_{\beta\beta}$ sensitivity comparison. For each proposal, the isotope that will be used, together with estimates for detector performance parameters — FWHM energy resolution, detection efficiency and background rate per unit of energy, time and $\beta\beta$ isotope mass — are given. Two possible operation phases, with estimates for the detector mass and the background rate achieved, are given for each experiment.

Front runners

Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
				2015–2017 (I)	200	600	10^{-1}	140
				2018–2020 (II)	200	600	4×10^{-2}	85

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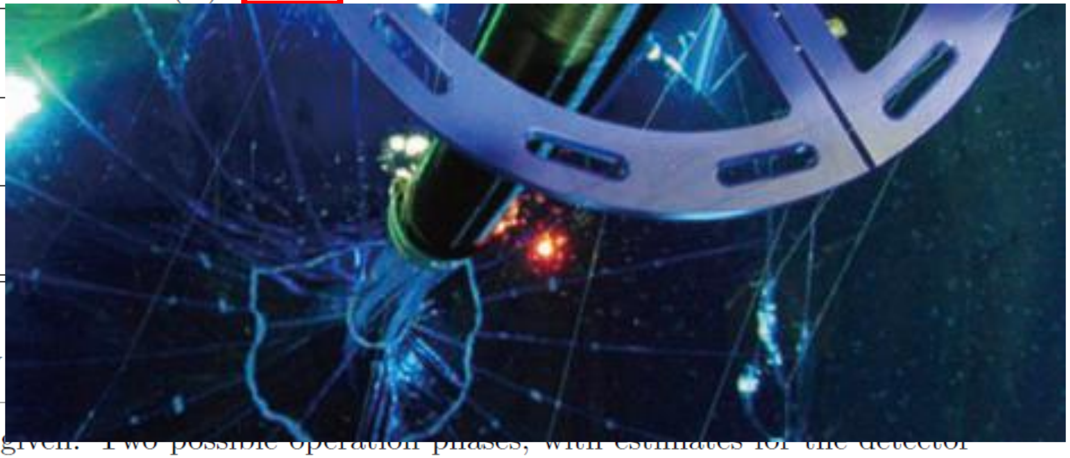
s –

e given. Two possible operation phases, with estimates for the detector

for each experiment.

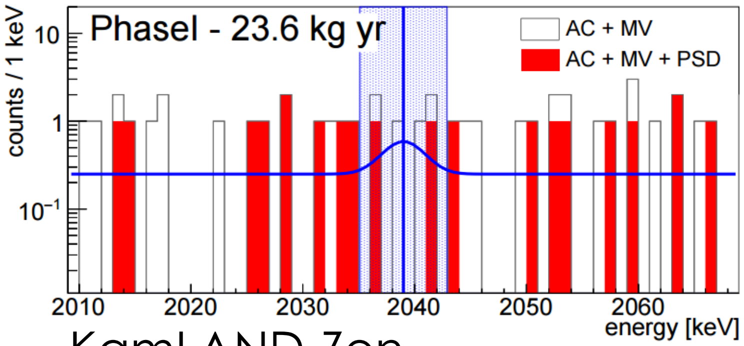
GERDA, ^{76}Ge



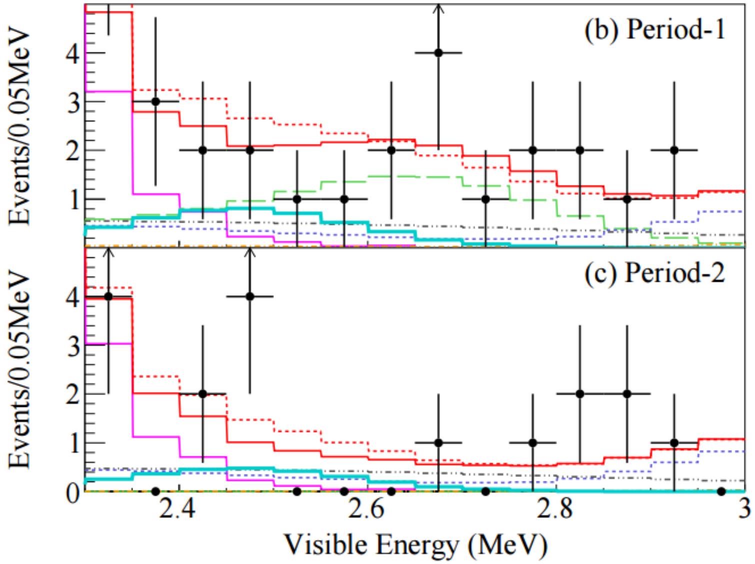
KamLAND-Zen, ^{136}Xe

Constraints from non-discovery

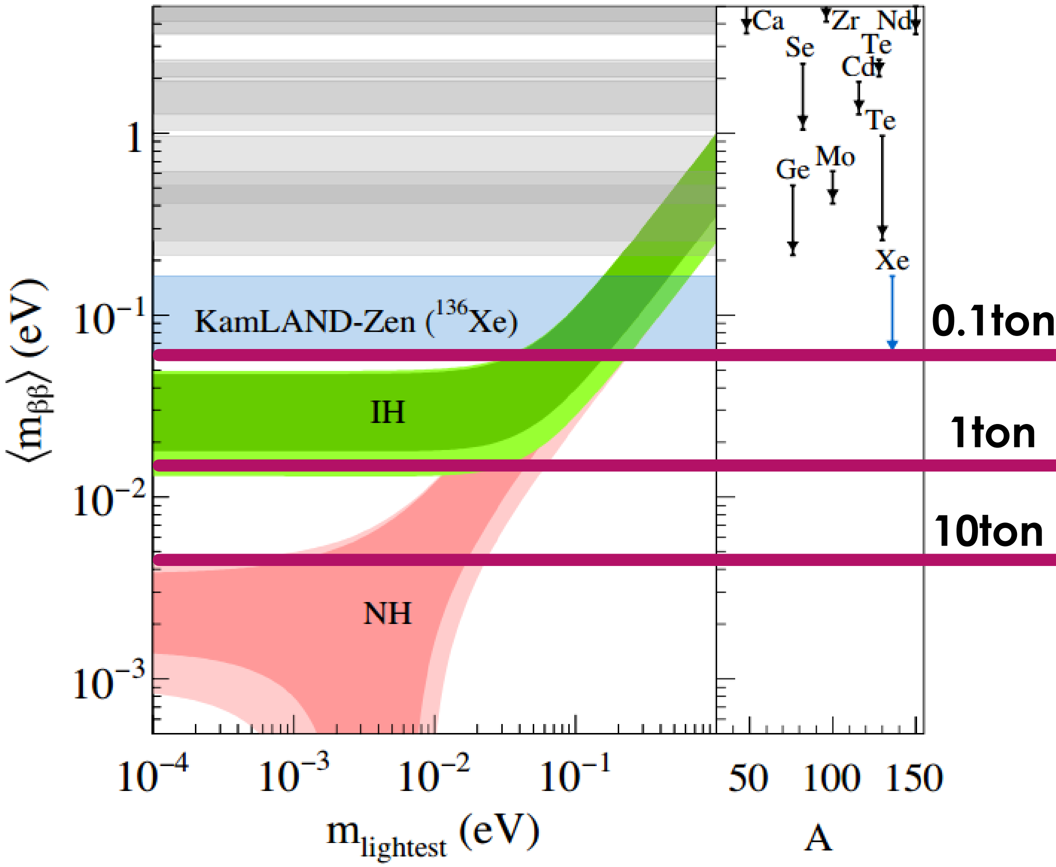
GERDA Phase-I



KamLAND-Zen



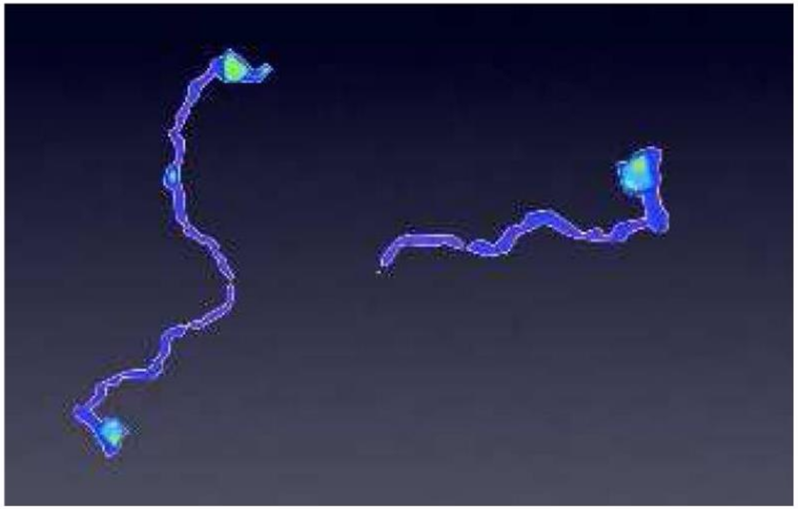
Phys. Rev. Lett. 117, 082503 (2016)

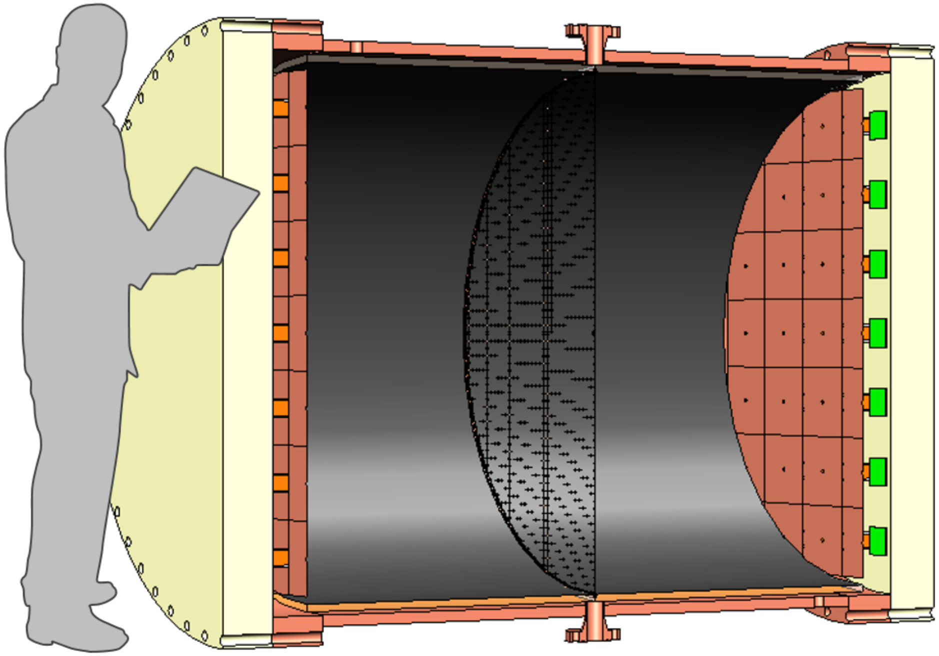


Gaseous ^{136}Xe

PANDA X

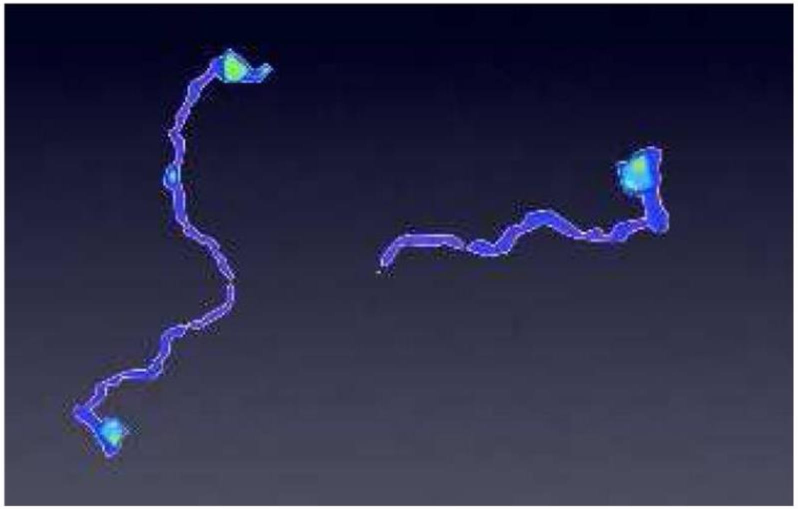
Tracking: smoking guy for discovery





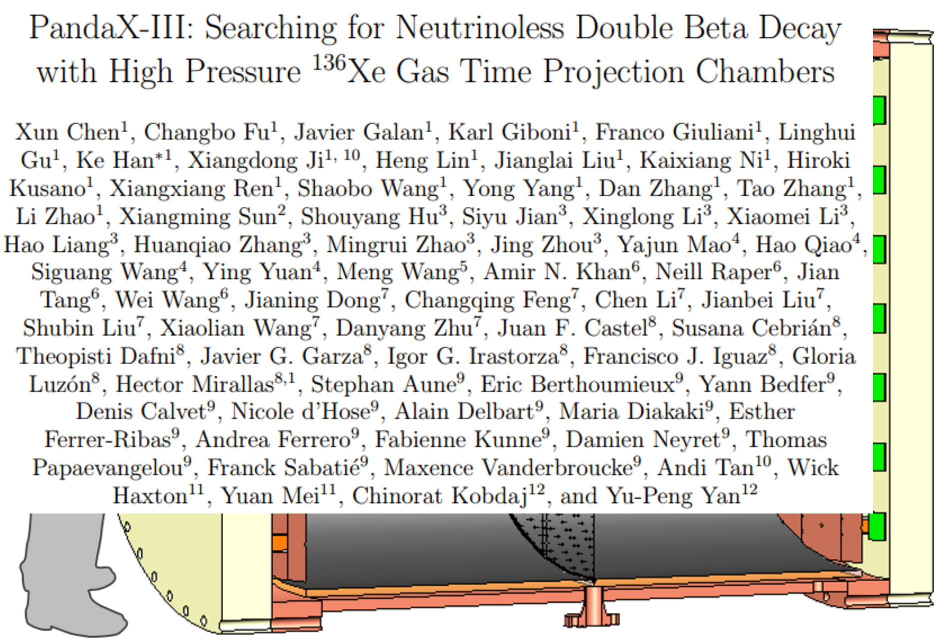
Gaseous ^{136}Xe

Tracking: smoking guy for discovery



PANDA X

arXiv:1610.08883



PandaX-III: Searching for Neutrinoless Double Beta Decay with High Pressure ^{136}Xe Gas Time Projection Chambers

Xun Chen[1], Changbo Fu[1], Javier Galan[1], Karl Giboni[1], Franco Giuliani[1], Linghui Gu[1], Ke Han[*1], Xiangdong Ji[1, 10], Heng Lin[1], Jianglai Liu[1], Kaixiang Ni[1], Hiroki Kusano[1], Xiangxiang Ren[1], Shaobo Wang[1], Yong Yang[1], Dan Zhang[1], Tao Zhang[1], Li Zhao[1], Xiangming Sun[2], Shouyang Hu[3], Siyu Jian[3], Xinglong Li[3], Xiaomei Li[3], Hao Liang[3], Huanqiao Zhang[3], Mingrui Zhao[3], Jing Zhou[3], Yajun Mao[4], Hao Qiao[4], Siguang Wang[4], Ying Yuan[4], Meng Wang[5], Amir N. Khan[6], Neill Raper[6], Jian Tang[6], Wei Wang[6], Jianing Dong[7], Changqing Feng[7], Chen Li[7], Jianbei Liu[7], Shubin Liu[7], Xiaolian Wang[7], Danyang Zhu[7], Juan F. Castel[8], Susana Cebrián[8], Theopisti Dafni[8], Javier G. Garza[8], Igor G. Irastorza[8], Francisco J. Iguaz[8], Gloria Luzón[8], Hector Mirallas[8,1], Stephan Aune[9], Eric Berthoumieux[9], Yann Bedfer[9], Denis Calvet[9], Nicole d'Hose[9], Alain Delbart[9], Maria Diakaki[9], Esther Ferrer-Ribas[9], Andrea Ferrero[9], Fabienne Kunne[9], Damien Neyret[9], Thomas Papaevangelou[9], Franck Sabatié[9], Maxence Vanderbroucke[9], Andi Tan[10], Wick Haxton[11], Yuan Mei[11], Chinorat Kobdaj[12], and Yu-Peng Yan[12]