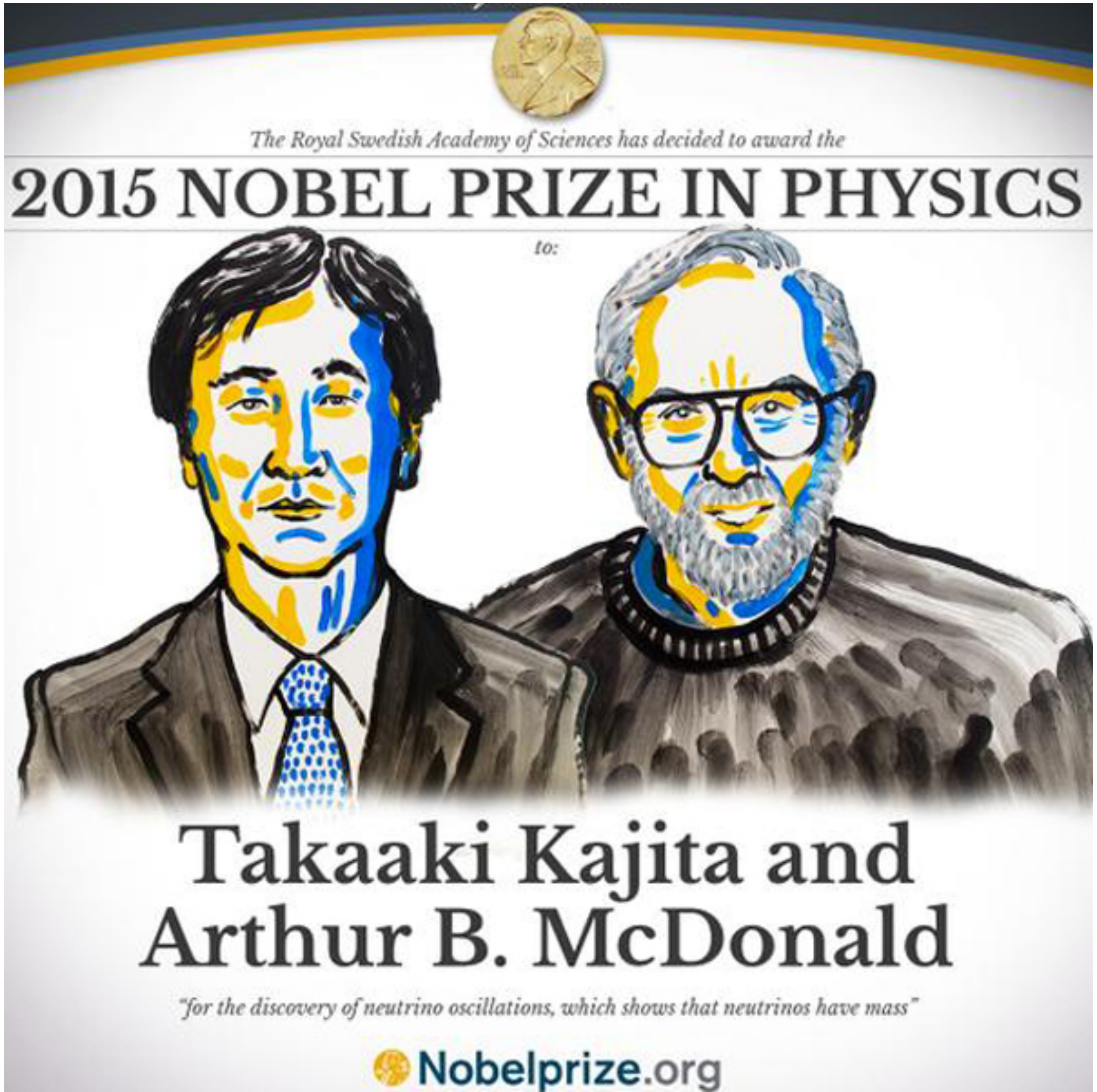
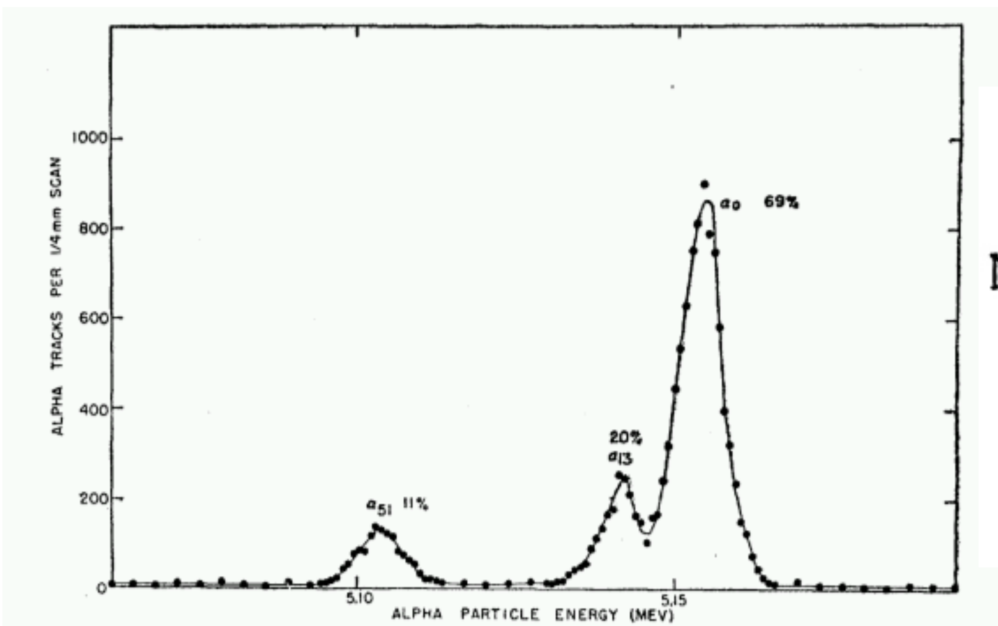
Neutrino Physics, Day 1



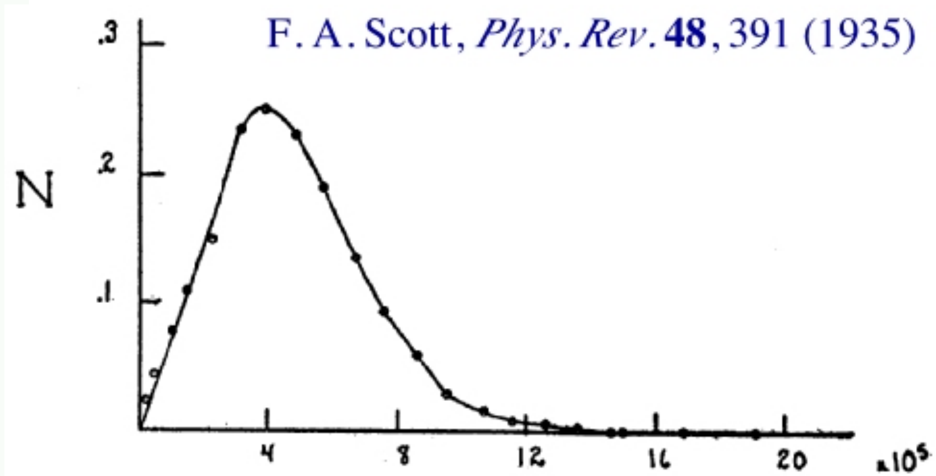
Michelle Dolinski
Drexel University
TRISEP, 14 June 2021

Birth of neutrinos

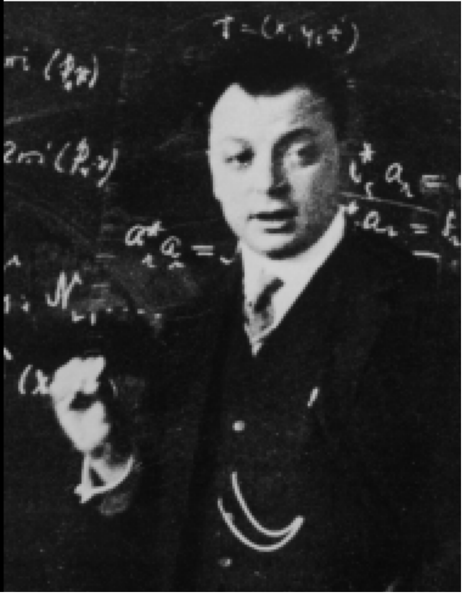
β-decay doesn't seem to conserve energy!



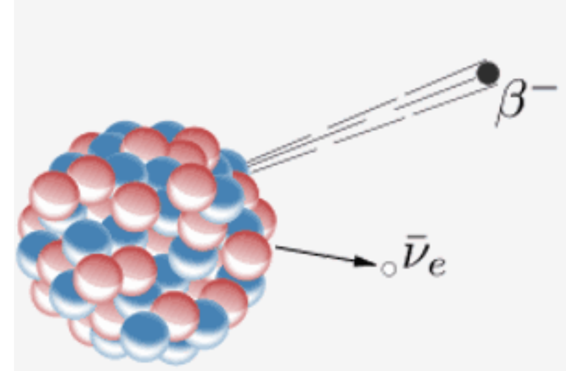
α-decay spectrum



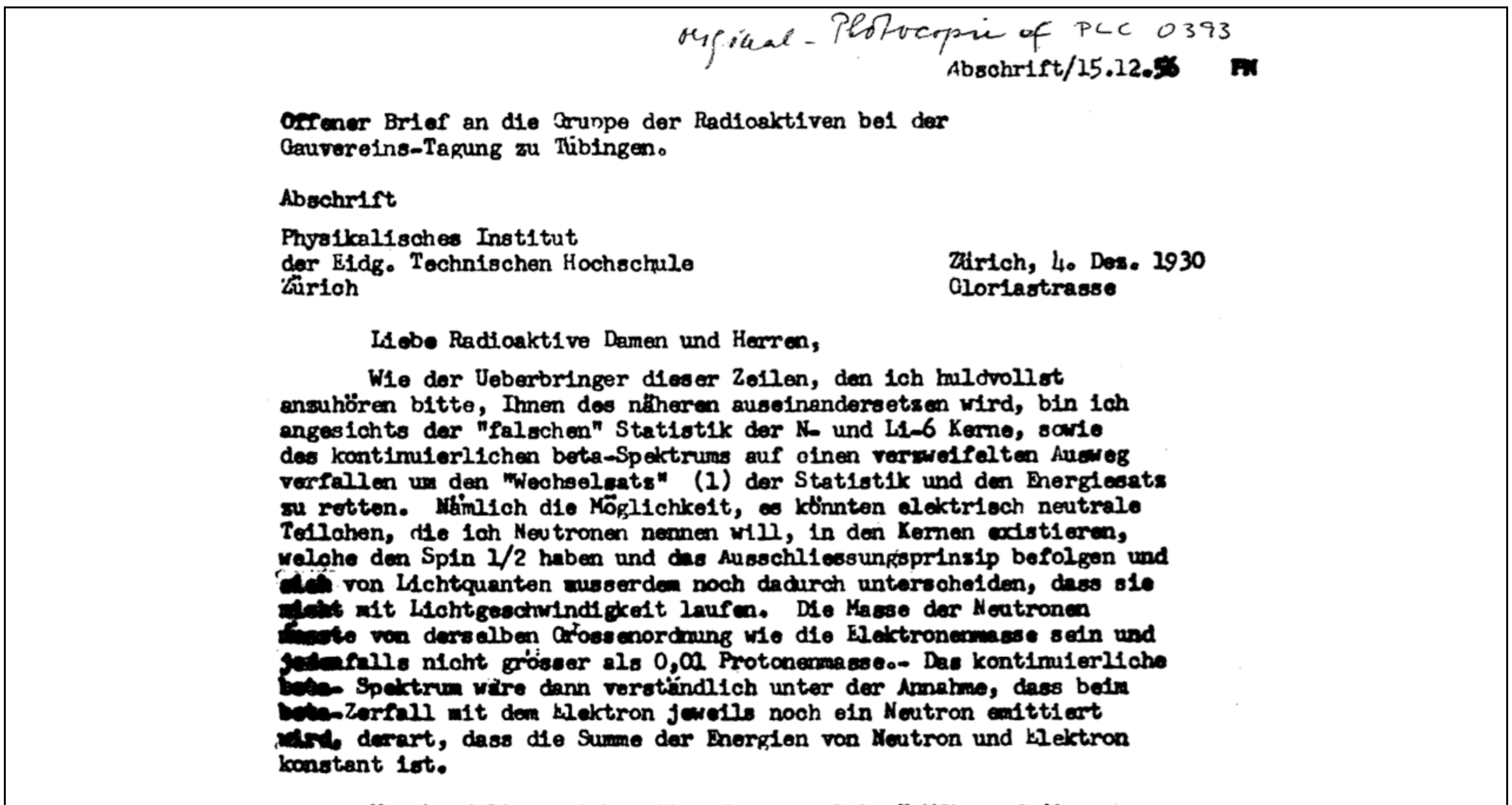
β-decay spectrum



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

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

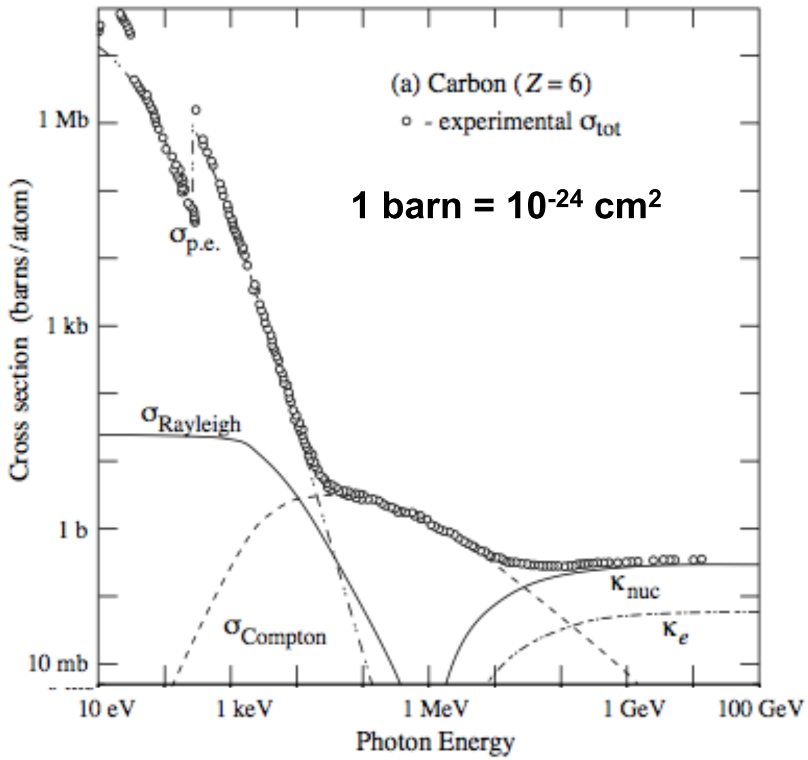
Zürich, 4. Dez. 1930
Gloriastrasse

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

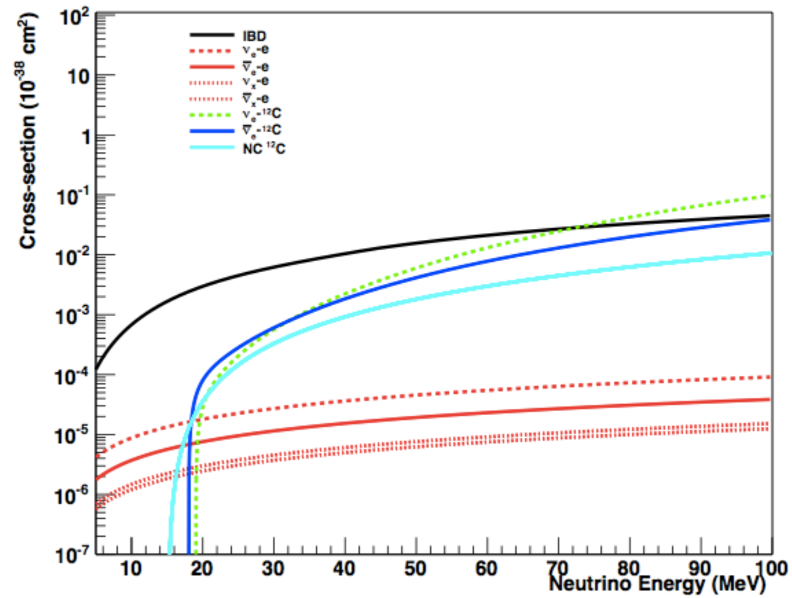
Photon-matter cross-sections



~10^{-24} cm^2

Slide: Kate Scholberg

Neutrino-matter cross-sections

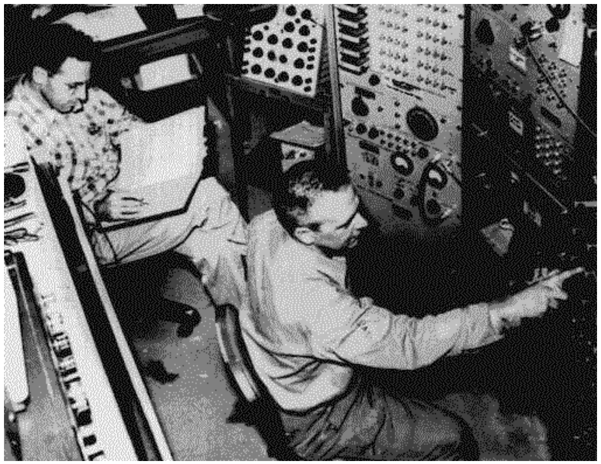


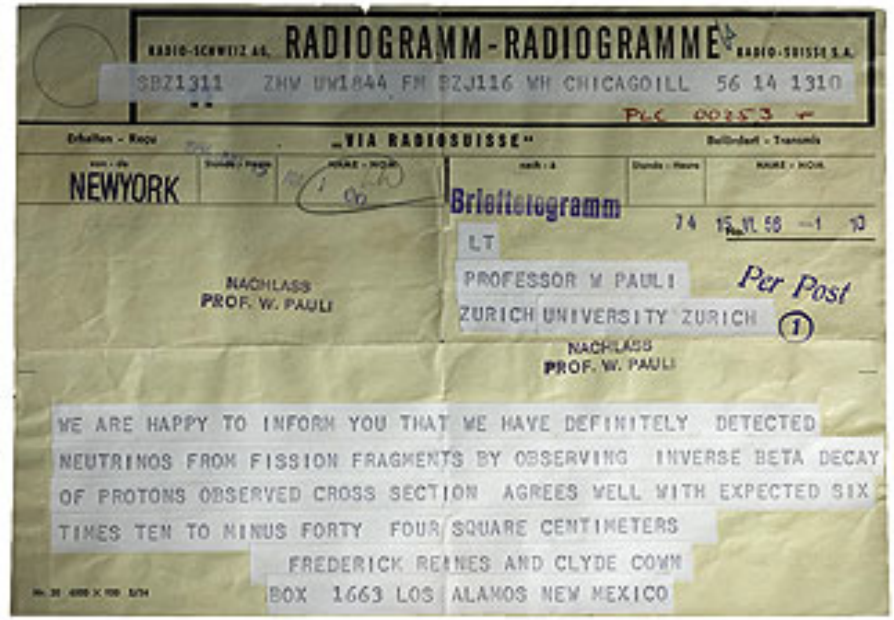
~10^{-40} cm^2

~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 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

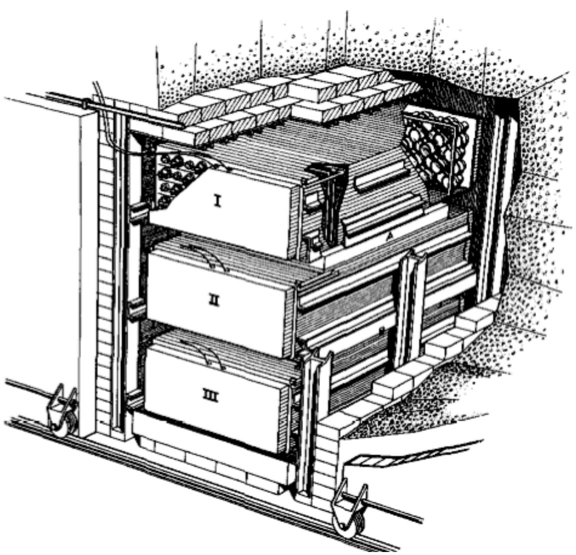
Per Post

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

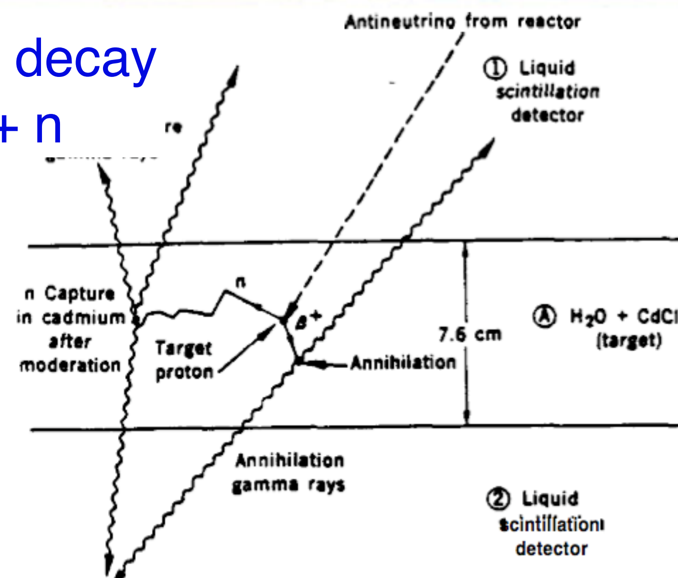
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO



inverse beta decay

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

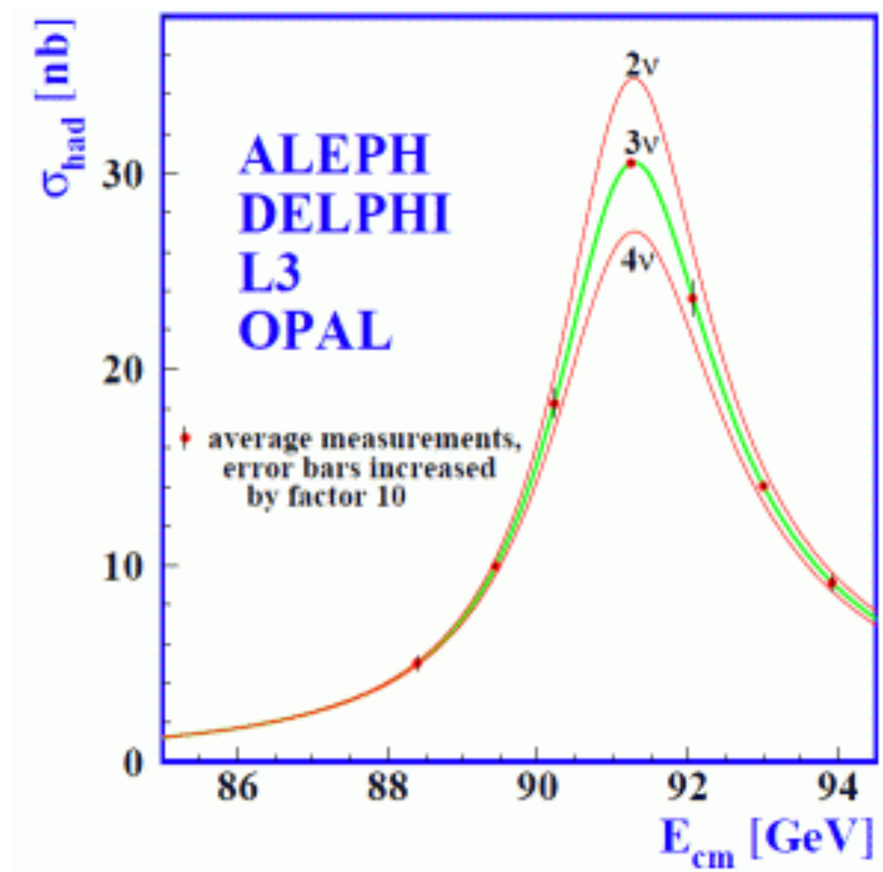


Three types of ν

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

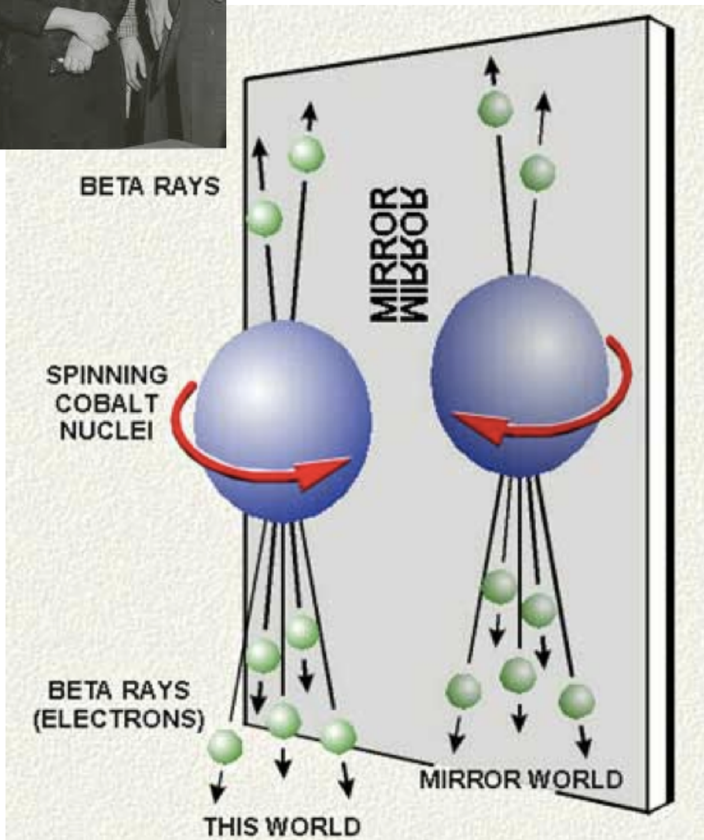
1962 - Danby, et. al., discover the muon neutrino (Nobel Prize 1988). 

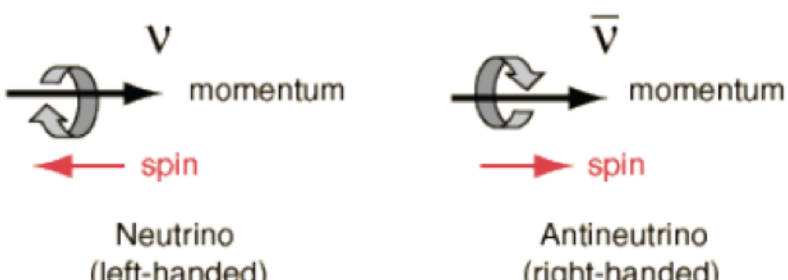
2000 - DONUT collaboration discovers the tau neutrino.



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

Parity violation and CP





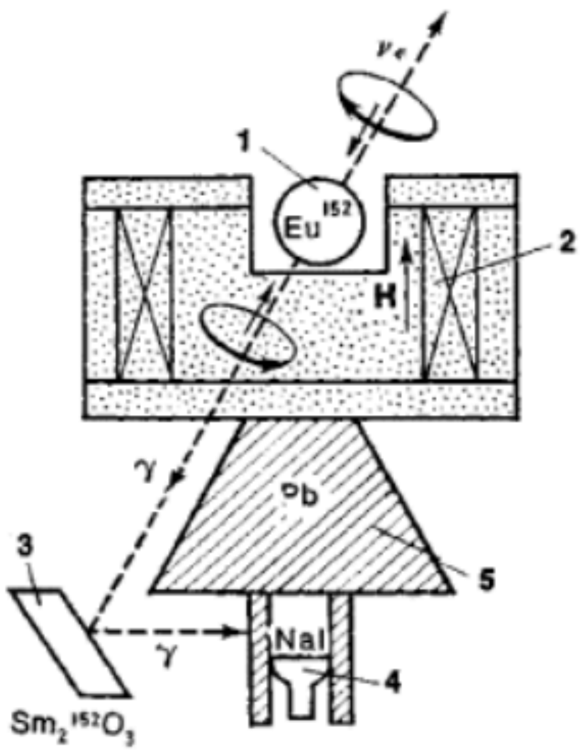
- You might think the laws of physics should remain unchanged in our world or in a mirror world, but weak interactions violate that symmetry dramatically [Wu, et al. Phys. Rev. 105, 1413]. Maybe CP is the right conserved quantity?
- We know that CP is also violated by weak interactions in the quark sector, but it's too weak to explain the matter-antimatter asymmetry.

Goldhaber experiment

$$\begin{tikzcd} \boxed{\nu_L} \arrow[r, "P"] \arrow[d, "C"'] \arrow[dr, "CP"] & \nu_R \\ \bar{\nu}_L & \boxed{\bar{\nu}_R} \end{tikzcd}$$

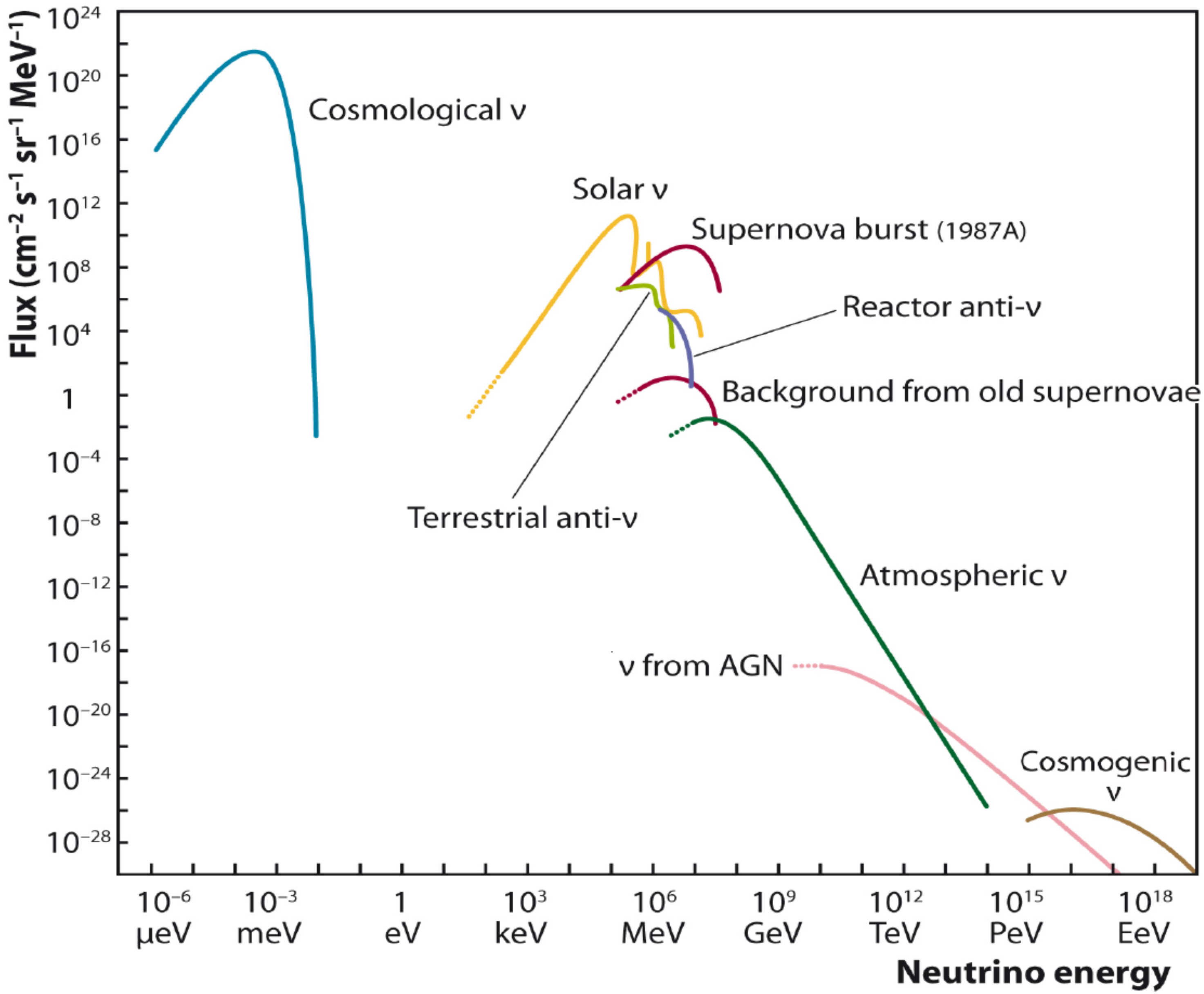
Only left-handed neutrinos ν_L and right-handed antineutrinos $\bar{\nu}_R$ are observed in nature!

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



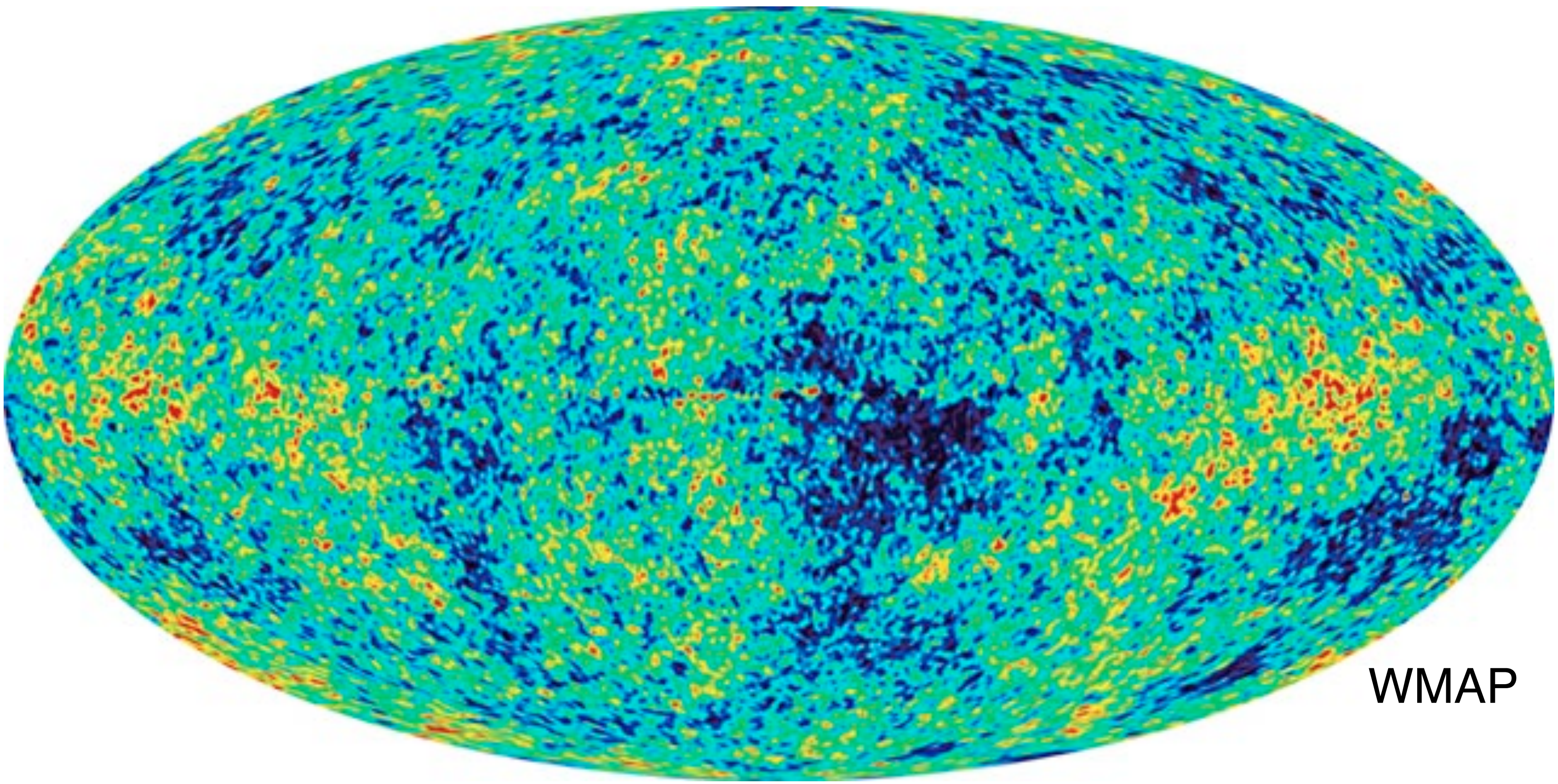
M. Goldhaber, L. Grodzins, and A. W. Sunyar *Phys. Rev.* **109**, 1015 (1958)

Sources of Neutrinos



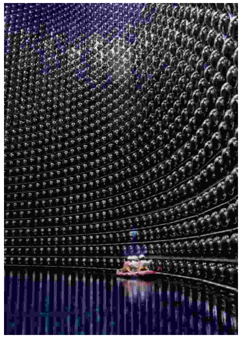
Katz, *Prog. Part. Nucl. Phys.* **67** (2012) 651

Cosmic neutrino background



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

Milestones in Neutrino Oscillations

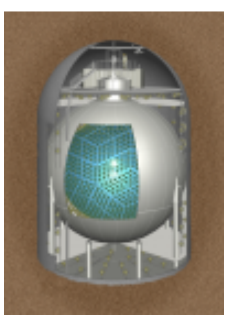


Solar neutrino problem is born when Ray Davis's Cl experiment in the Homestake mine shows ~1/3 expected solar ν_e flux.

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

Disappearance of atmospheric ν_μ's measured by SuperKamiokande.

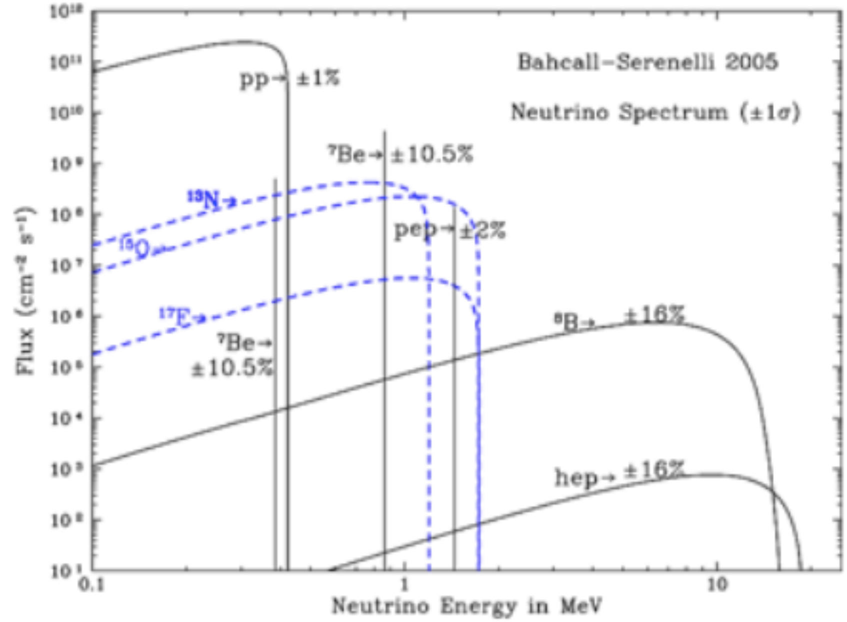
SNO confirms flavor change in solar neutrinos by measuring Φ_{CC}/Φ_{NC}.



•KamLAND observes neutrino oscillations with reactor anti-neutrinos.

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

Homestake

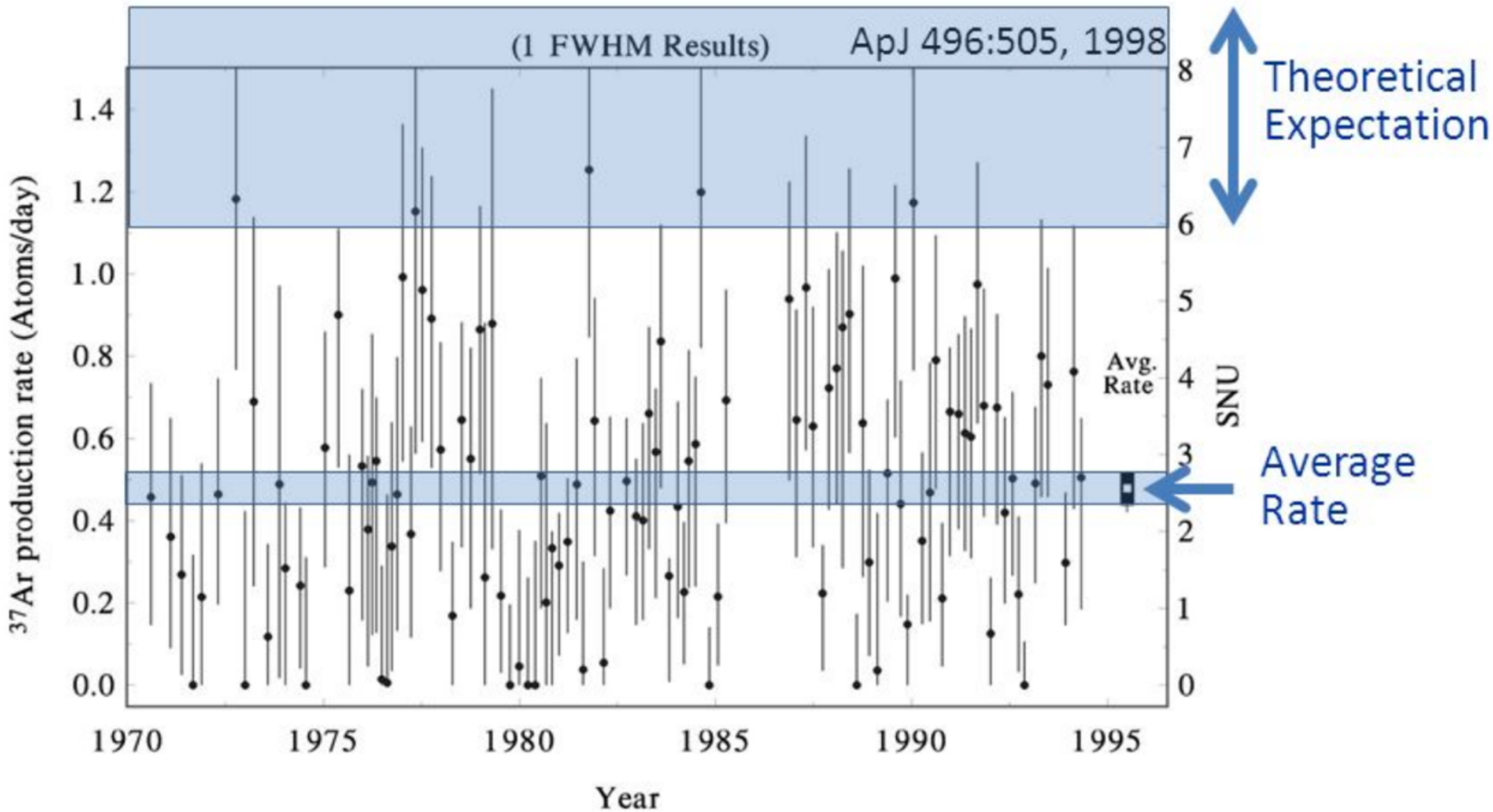


The Homestake detector was built by Ray Davis (Nobel 2002) to test John Bahcall's Standard Solar Model.

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

Slide: Georg Raffelt

Homestake



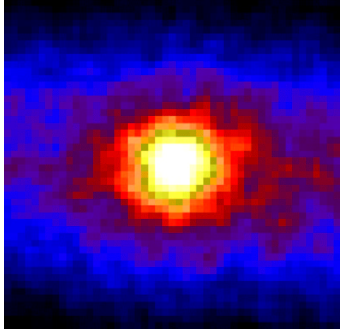
Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

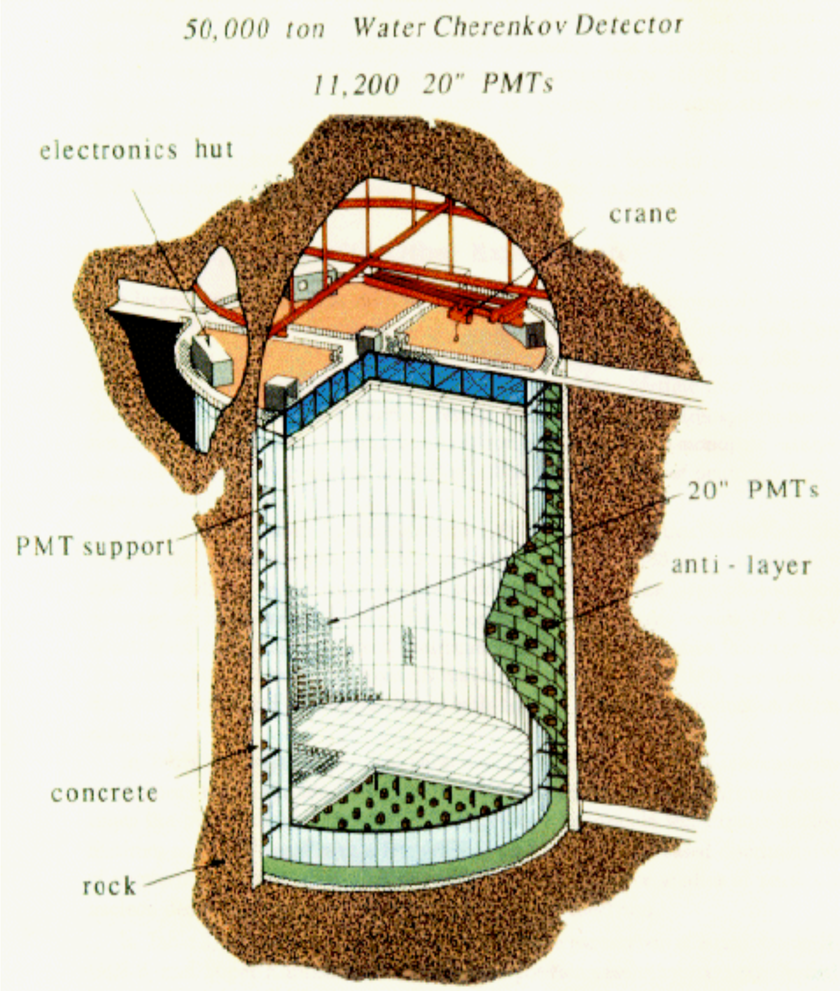
(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

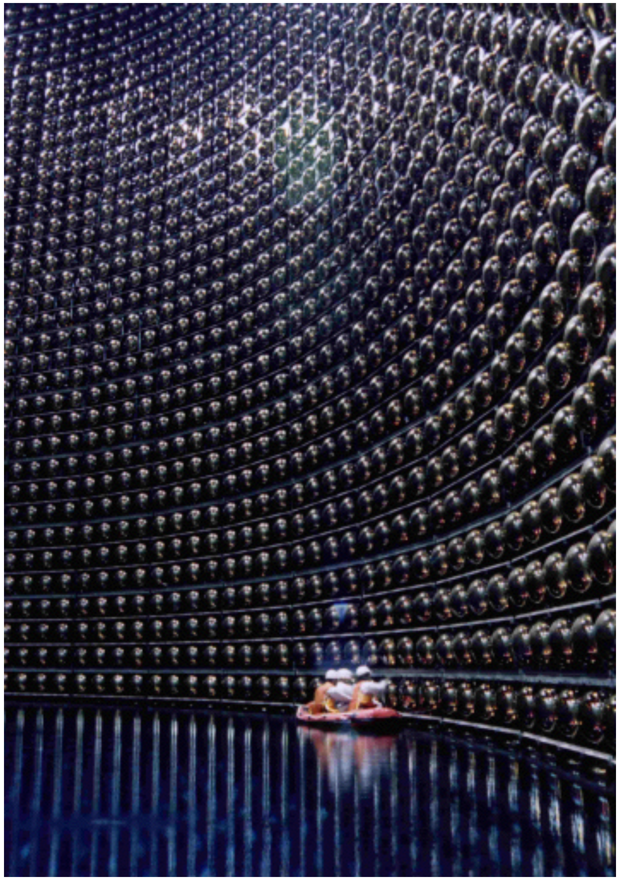
Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Super KamiokaNDE

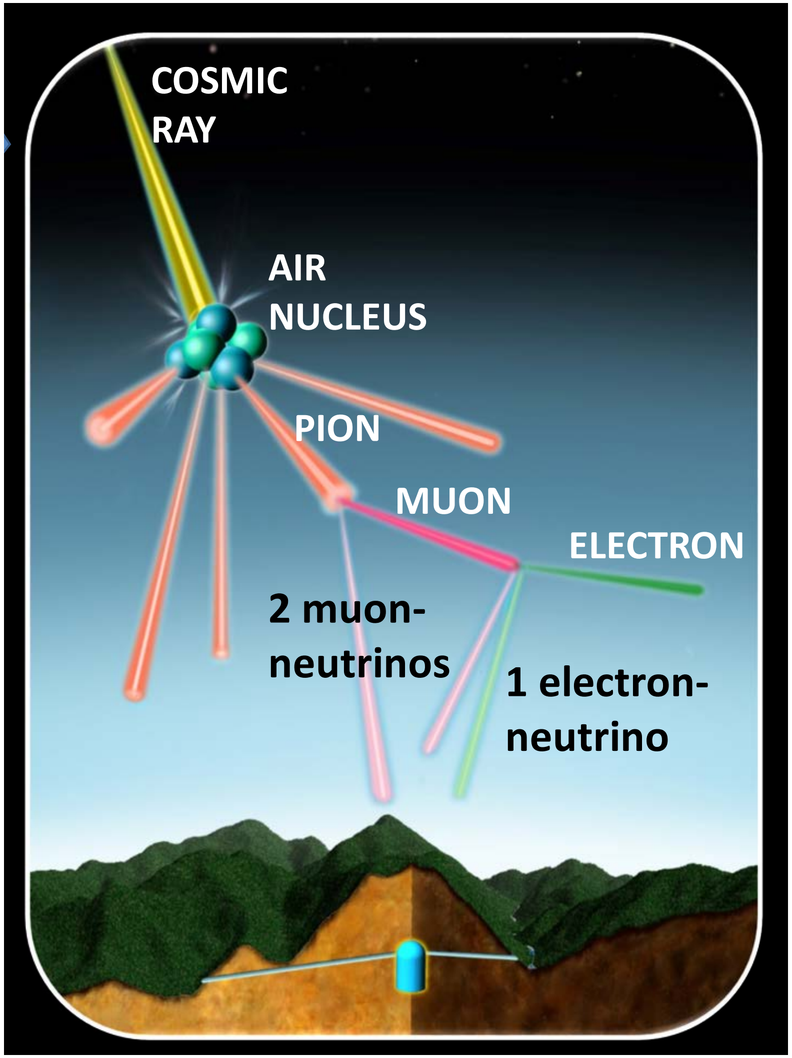


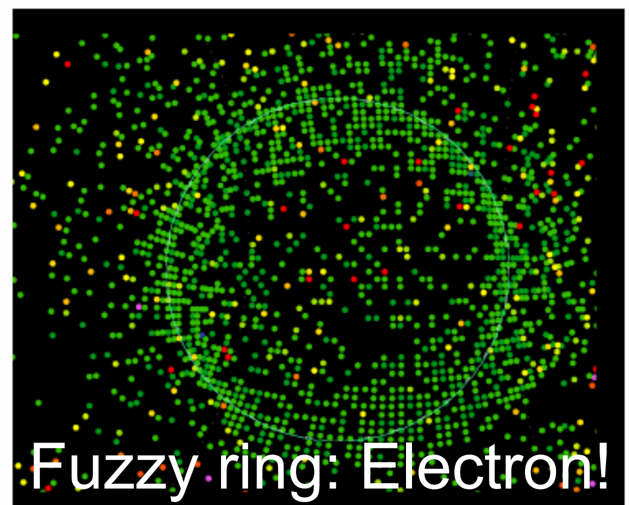




Super KamiokaNDE

Graphics: SuperK

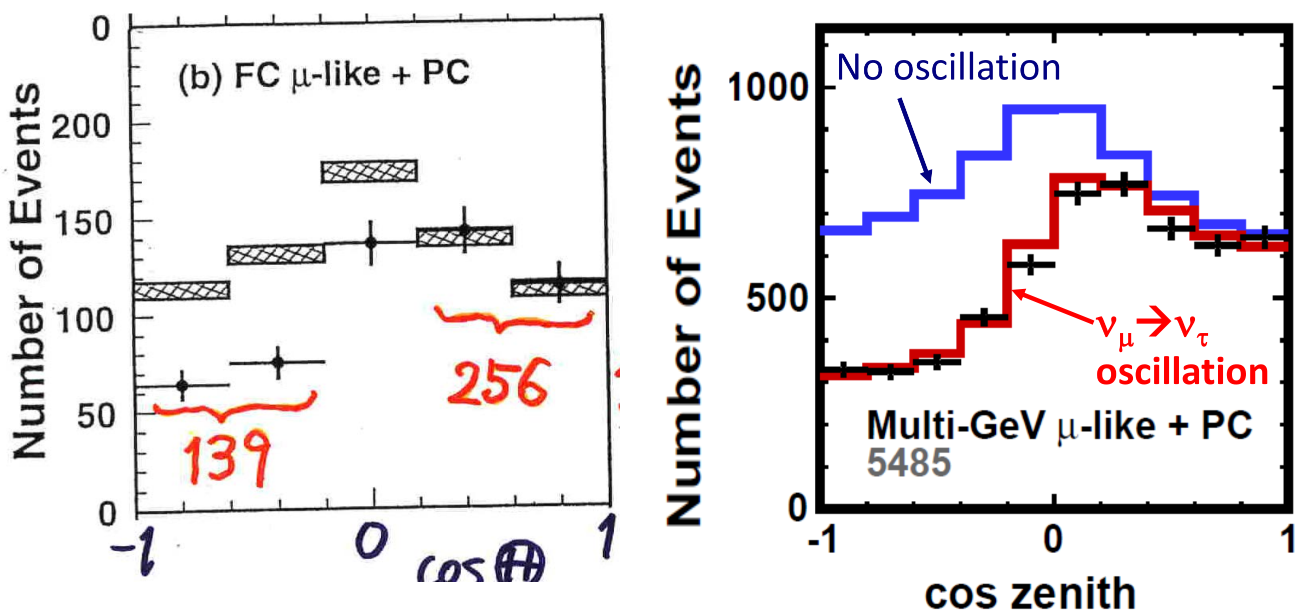




Oscillation path length depends on angle – longer path length through the earth

SuperK results

Super-K @Neutrino98 → Super-K (2015)



Takaaki Kajita, Nobel Prize Lecture, 2015

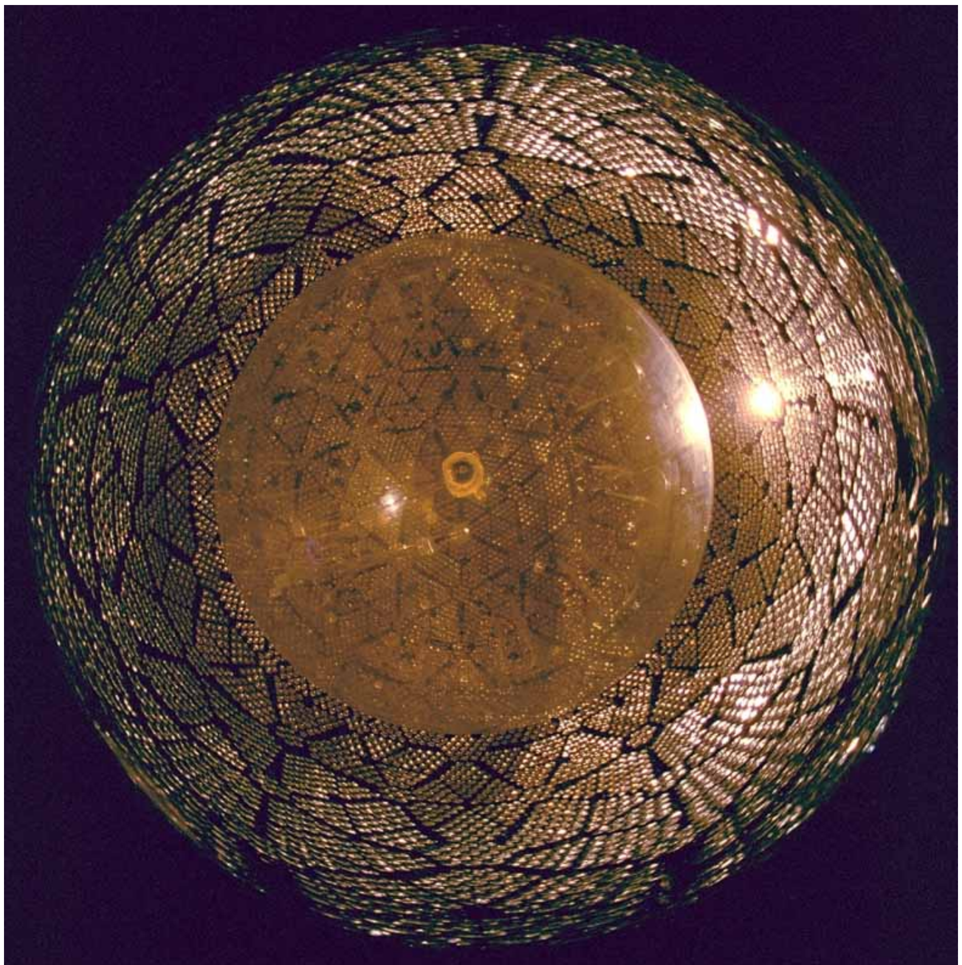
Number of events plotted:

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



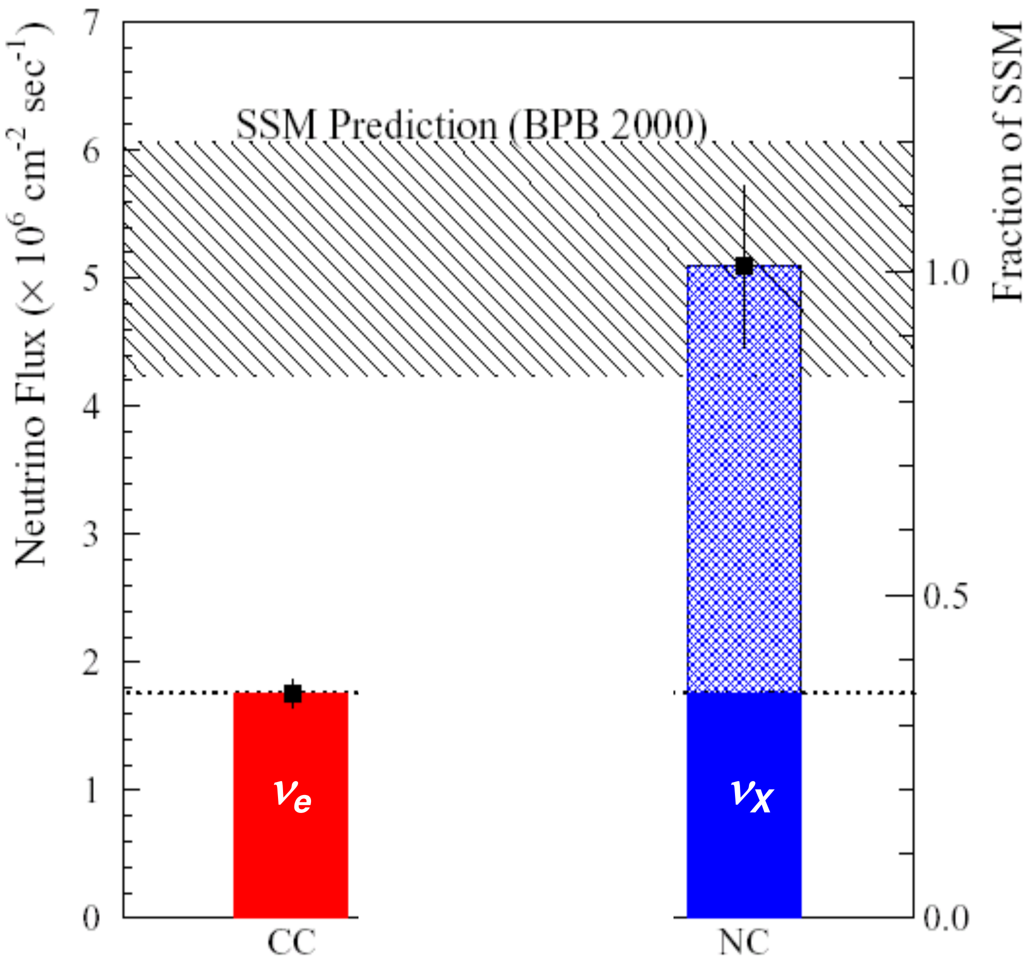
1000 tonnes of ultra-pure heavy water (D_2O) housed in a clear acrylic vessel 12 m in diameter, located a mile underground in a nickel mine in Sudbury, Ontario, Canada.

SNO results

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

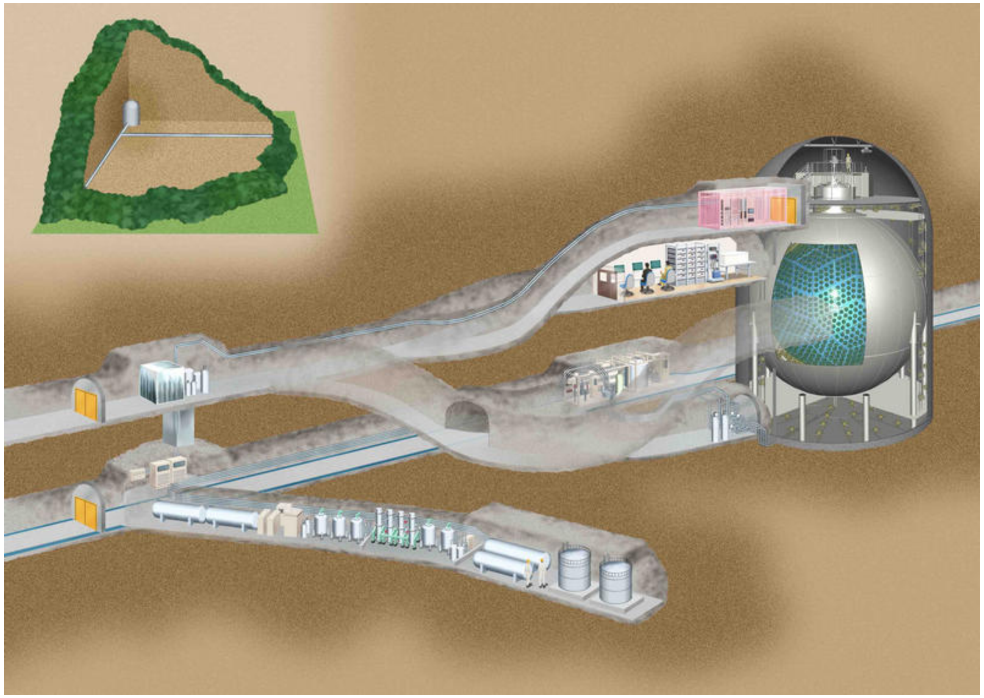
$$\text{Elastic Scattering Reaction (ES):} \quad \nu_x + e^- \longrightarrow \nu_x + e^-$$

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

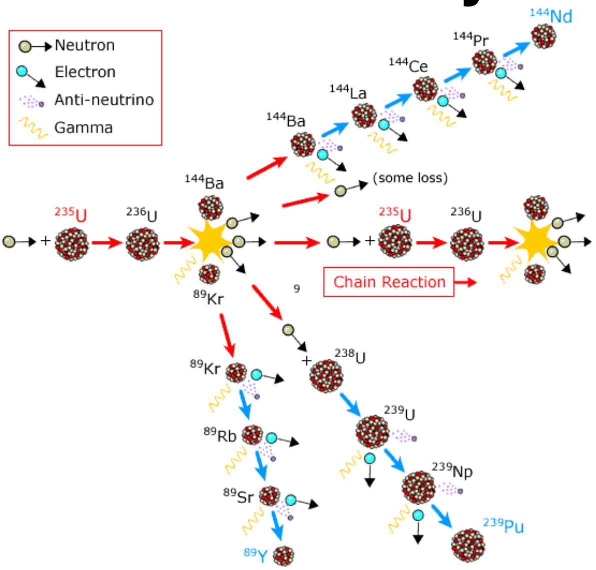


Art McDonald,
Nobel Prize Lecture,
2015

KamLAND



Neutrino Physics at Reactors



Next - Discovery and precision measurement of θ_{13}

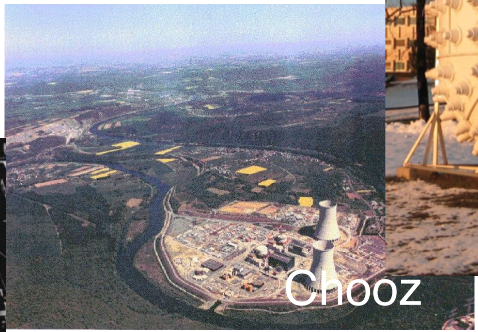
2008 - Precision measurement of $(\Delta m_{12})^2$. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

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

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

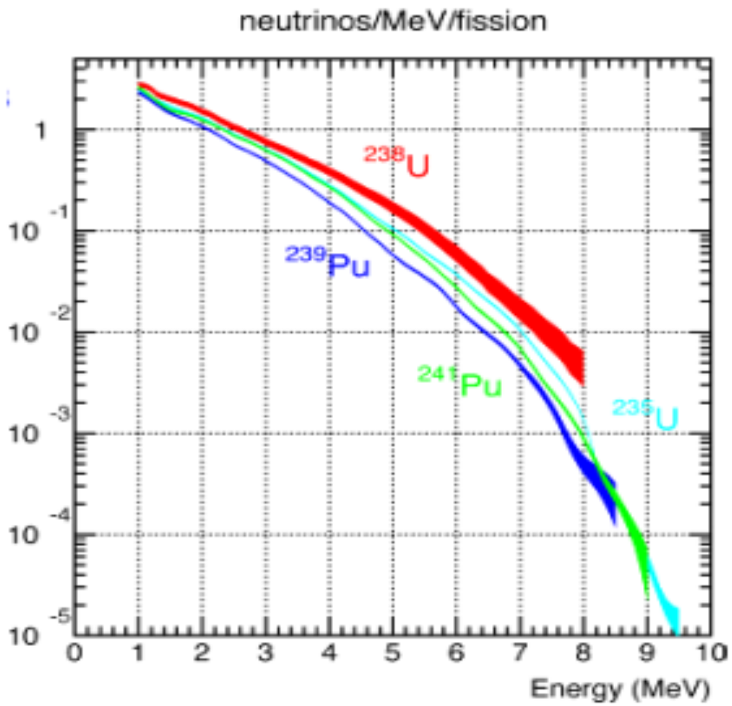
1956 - First observation of (anti)neutrinos

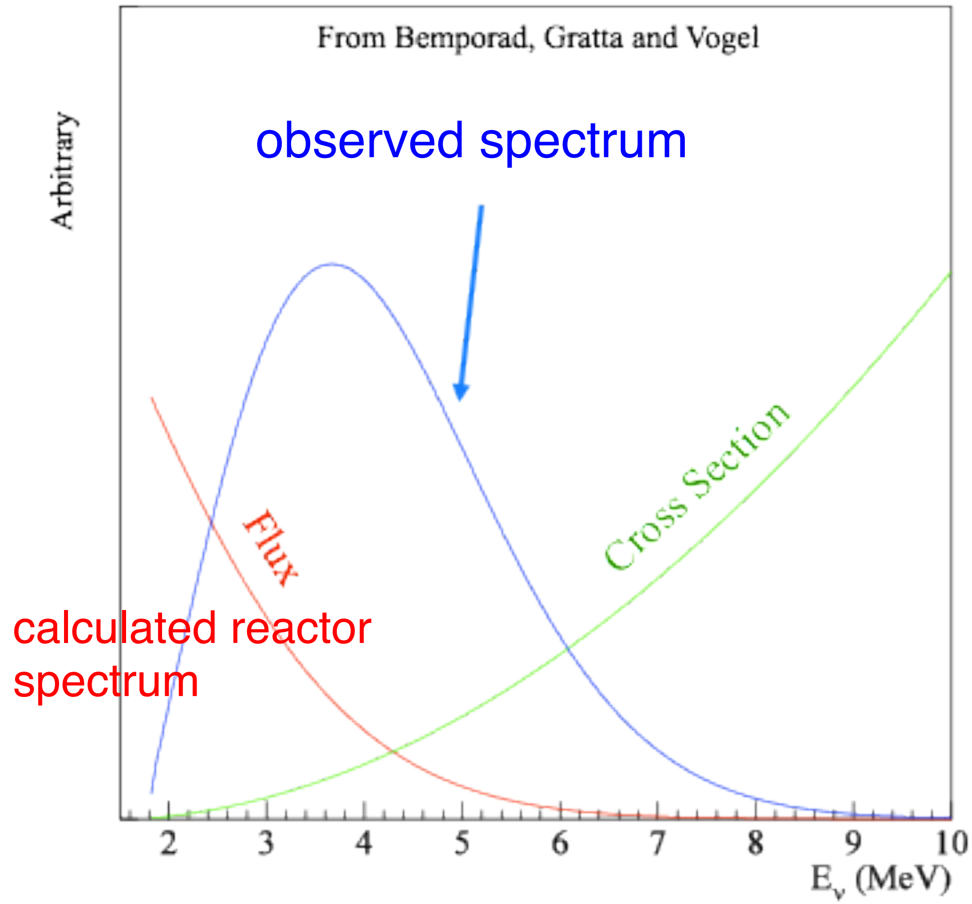


63 years of liquid scintillator detectors
a story of varying baselines...

Reactor Antineutrinos

$\overline{\nu_e}$ from n-rich fission products





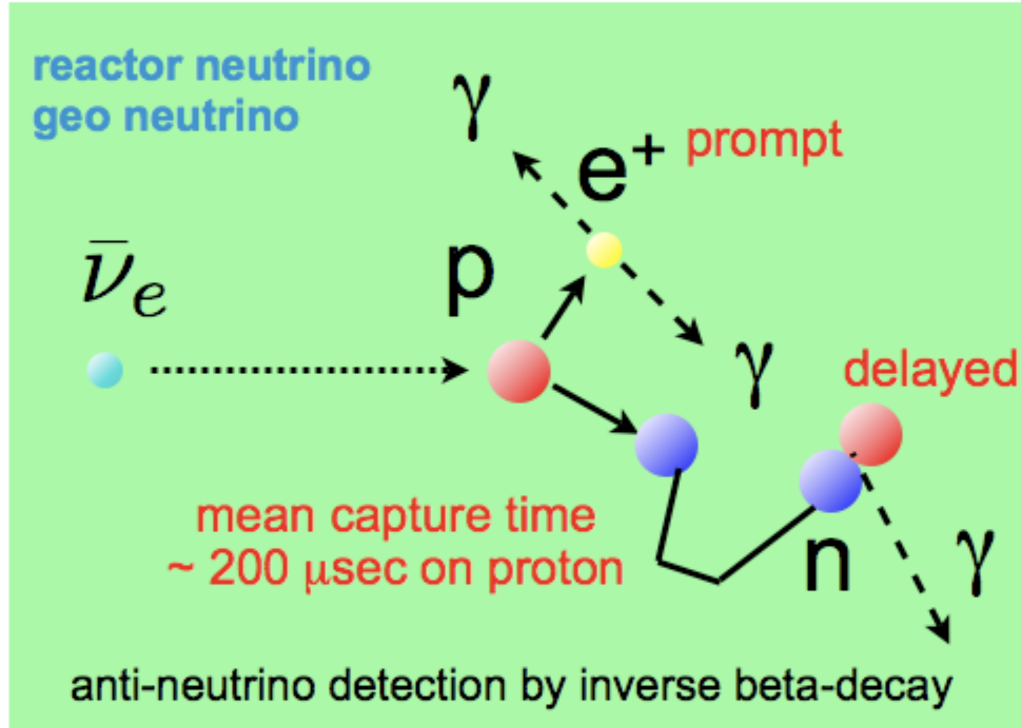
~ 200 MeV per fission

~ 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

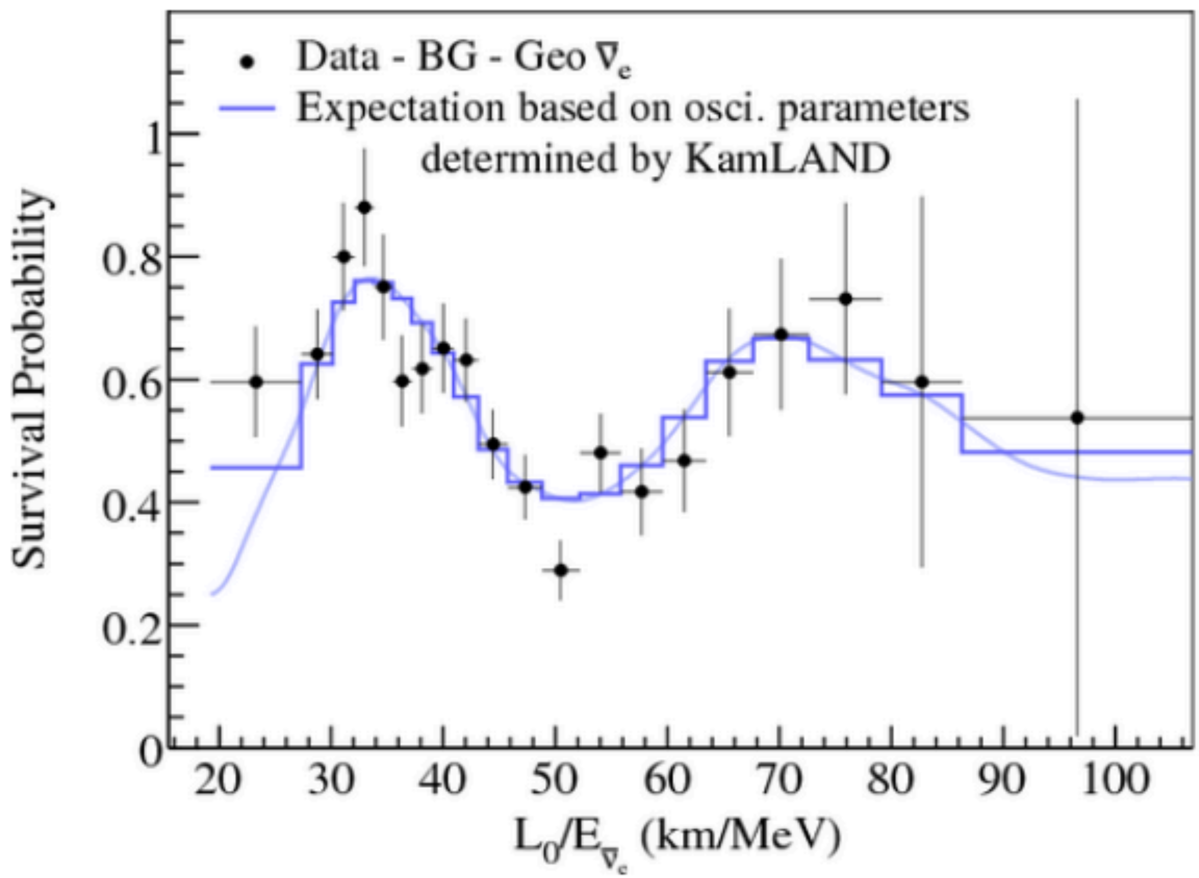
10-100 keV

1.805 MeV

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

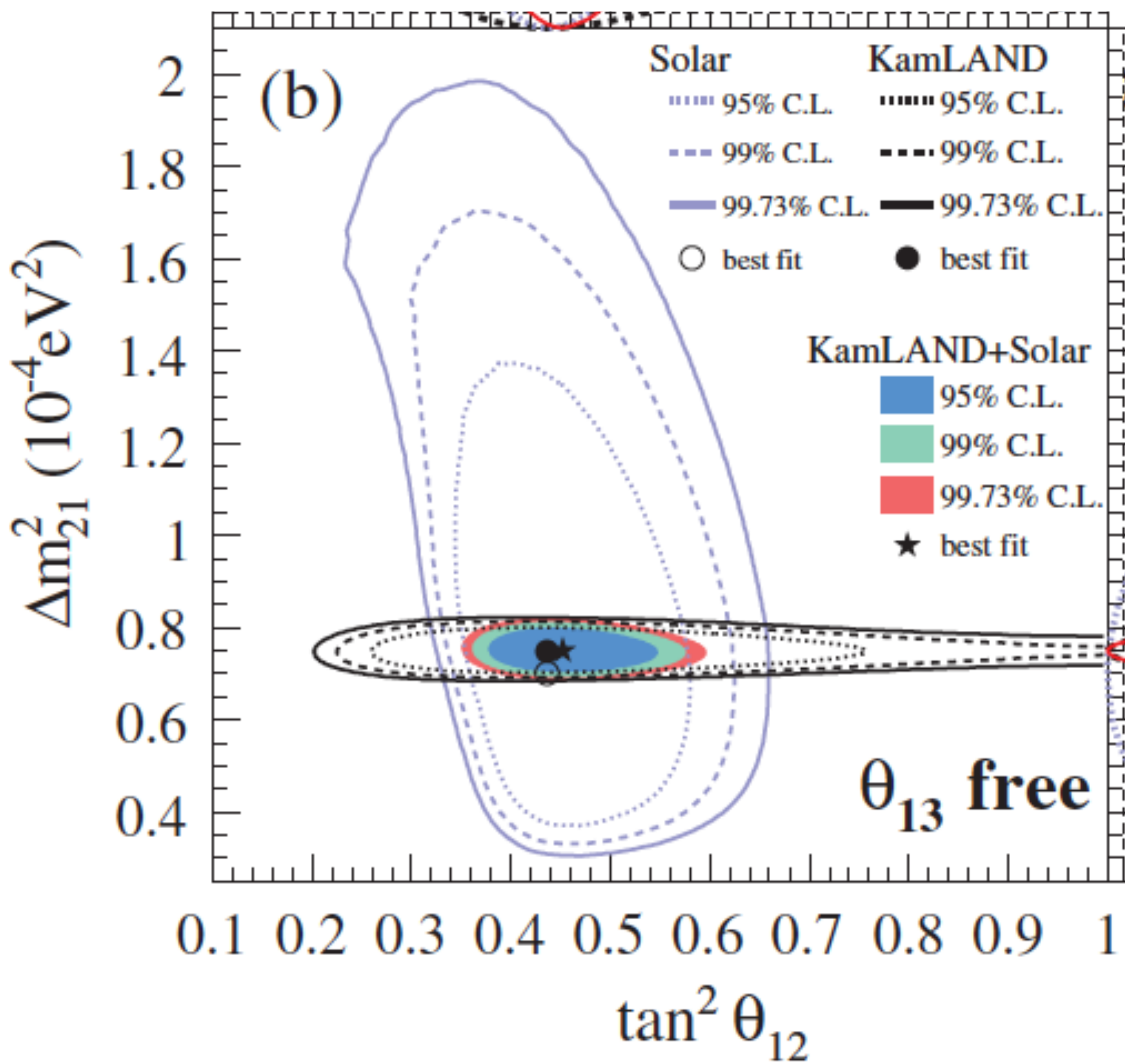
Neutrino oscillations with KamLAND

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



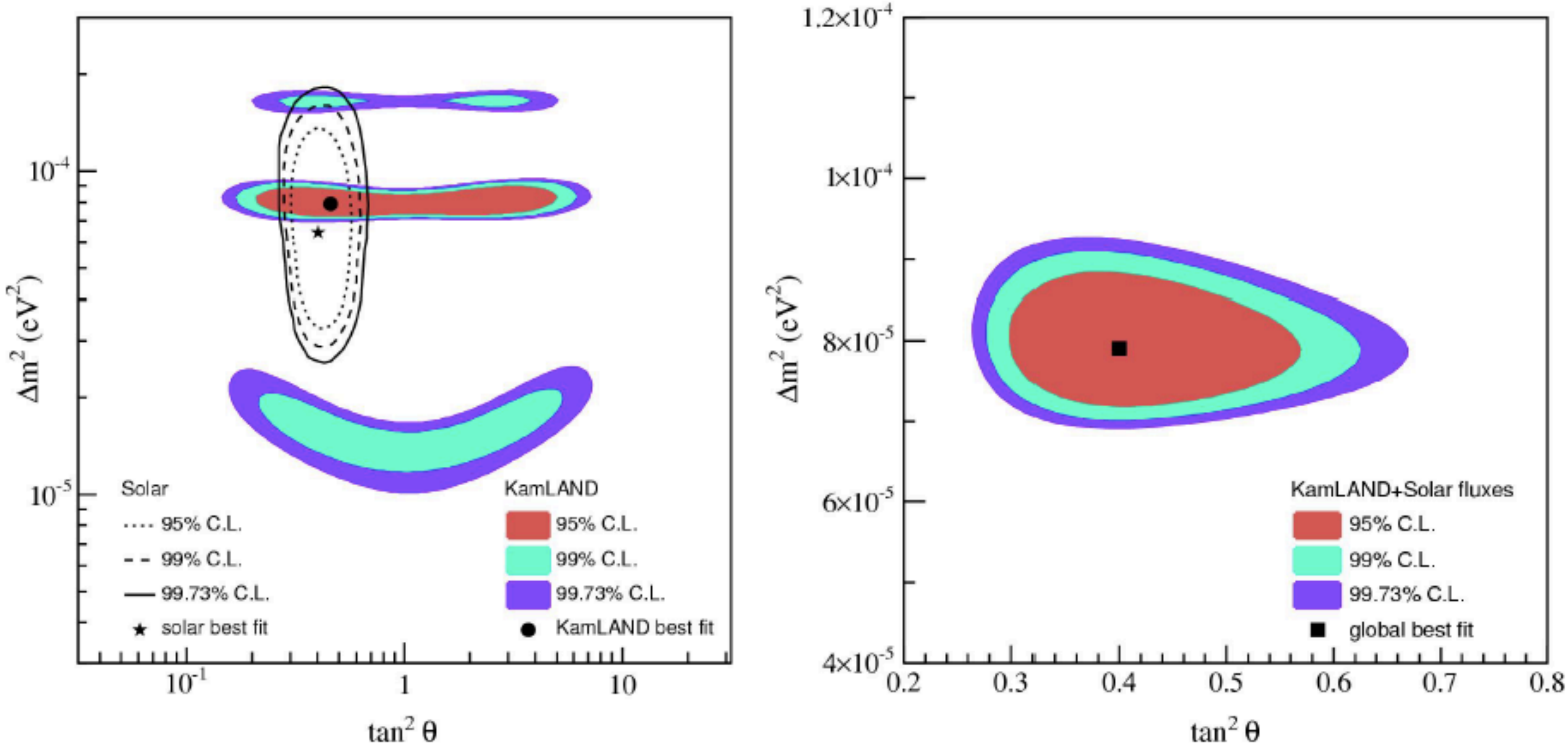
KamLAND result. A. Gando et al., Phys. Rev. D83 (2011) 052002

Neutrino oscillations with KamLAND



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

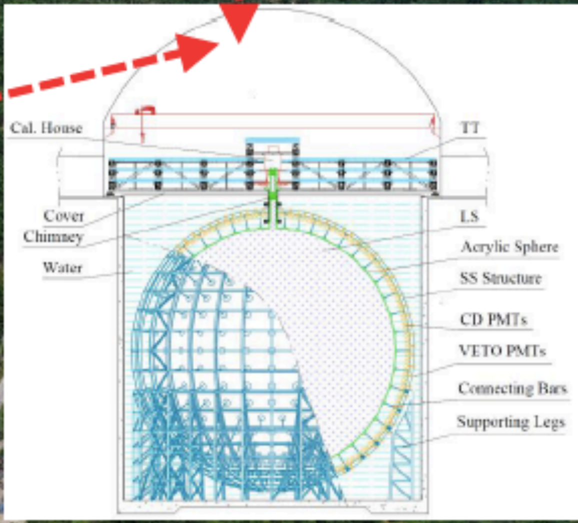
Mikheyev–Smirnov–Wolfenstein effect

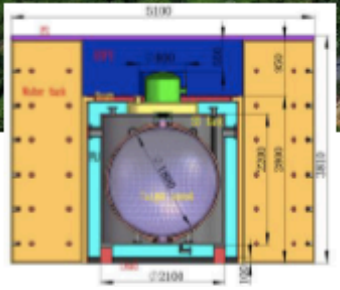


There's actually something very special going on with solar neutrinos. They're experience a resonance due to their interaction with the dense matter in the sun. This is known as the MSW effect, and it lets us tell that $m_1 < m_2$.

Jiangmen Underground Neutrino Observatory

- 20 kton liquid scintillator, 3% E reso, <1% E scale Uncer.
- Primary goals: ν mass ordering (3~4 σ, with 6 yrs data) & Precision measurement (<<1%)
- Rich physics: Supernova/Solar/Geo/Atmosphere neutrinos, nucleon decay

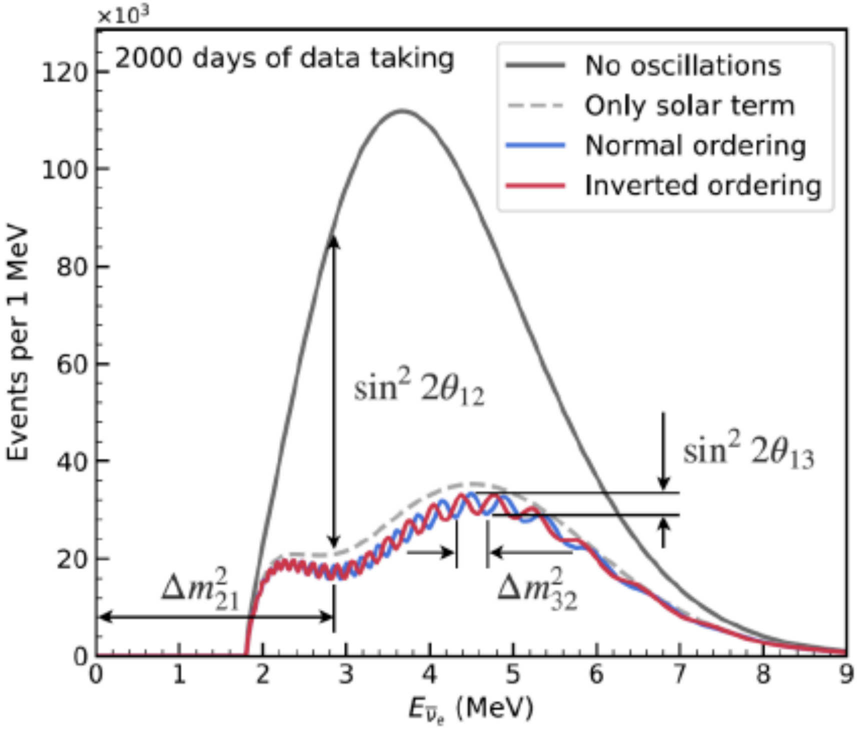




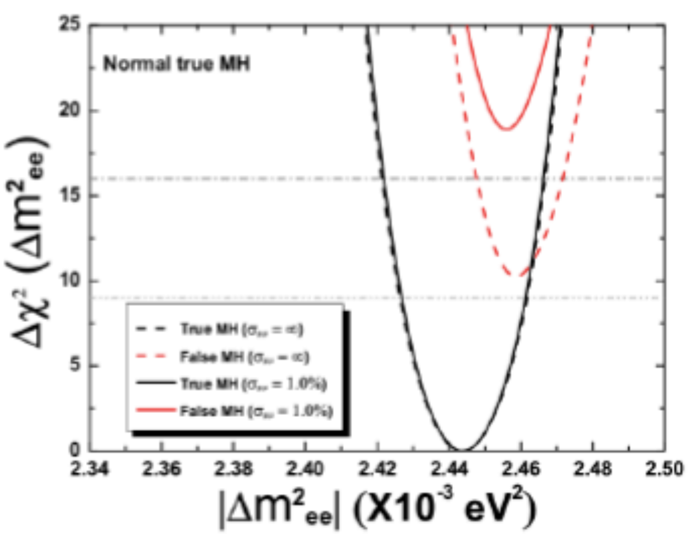
JUNO Physics Book, J. Phys. G43:030401 (2016)
JUNO-TAO CDR: arXiv:2005.08745
JUNO Physics and Detector, arXiv:2104.02565

Slides from L. Wen, WIN2021

ν mass ordering at JUNO



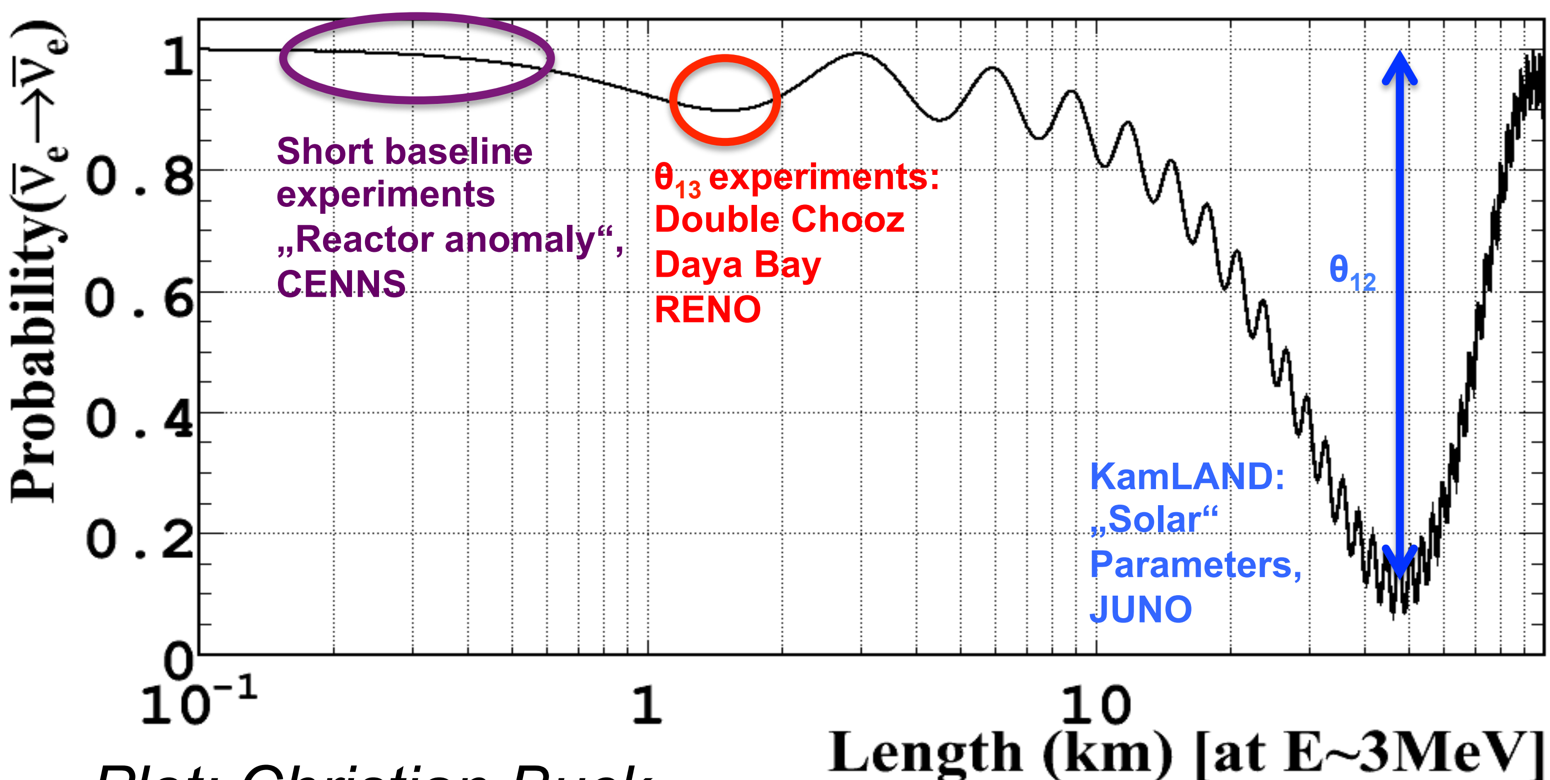
- Independent on $\boldsymbol{\delta}_{CP}$ and θ_{23}
  3σ sensitivity (6 yrs of data taking)
- Further improvement with precise $\Delta m^2_{\mu\mu}$
  > 4σ (in 6 yrs) if 1% external $\Delta m^2_{\mu\mu}$



- Precision measurement to two oscillations and related ν mixing parameters

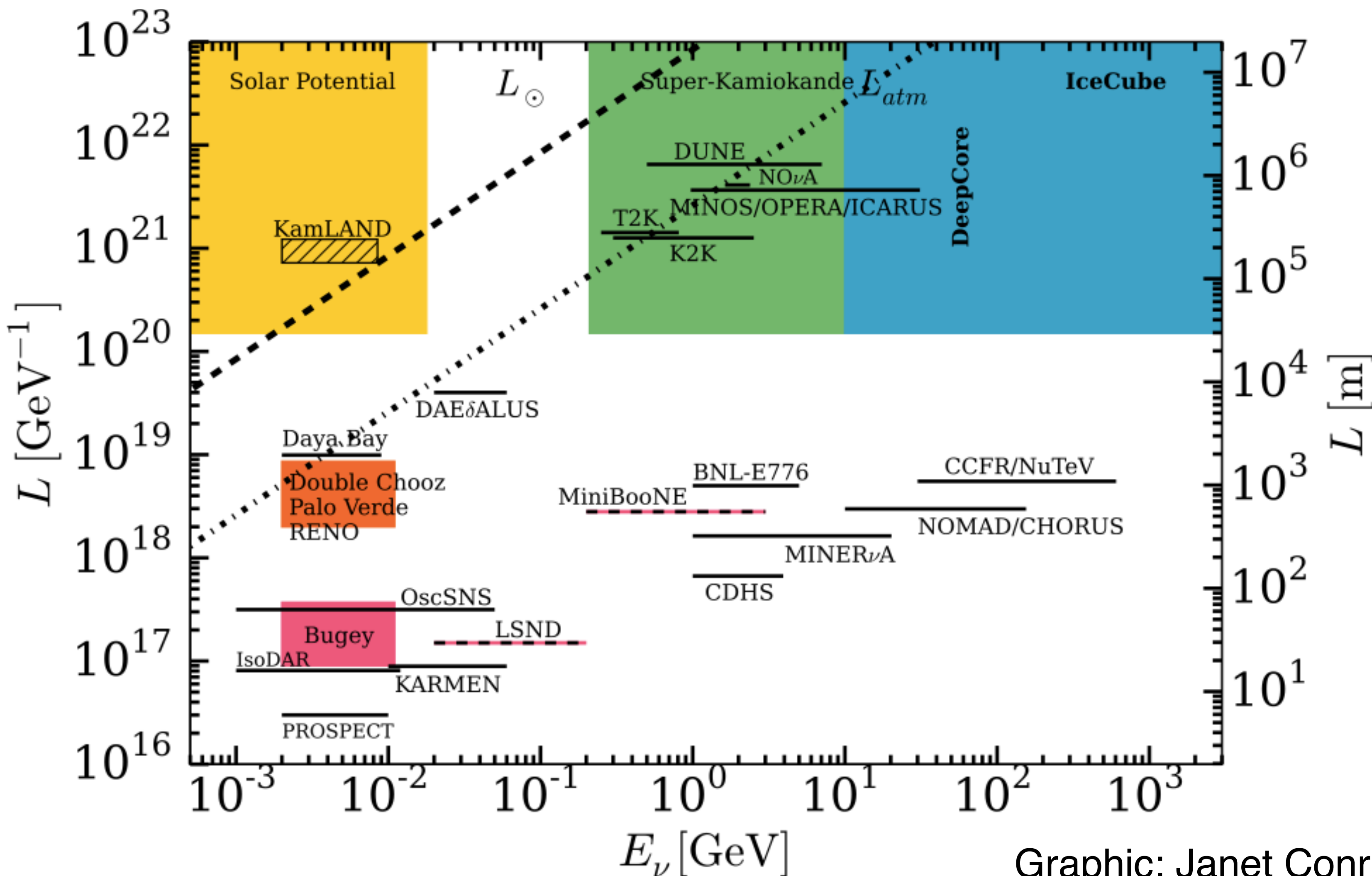
	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\Delta m^2_{31}/\Delta m^2_{32}$
Direct Meas. (Dominant Expts.)	4.7% (SNO)	2.5% (KamLAND)	3.2% (Daya Bay)	2.8% (Daya Bay/T2K/NOvA)
NuFIT	4.0%	2.8%	2.8%	1.1%
JUNO (6 yrs)	< 0.6%	< 0.6%	~ 10%	< 0.6%

Oscillations vs baseline



Plot: Christian Buck

Energy and baseline

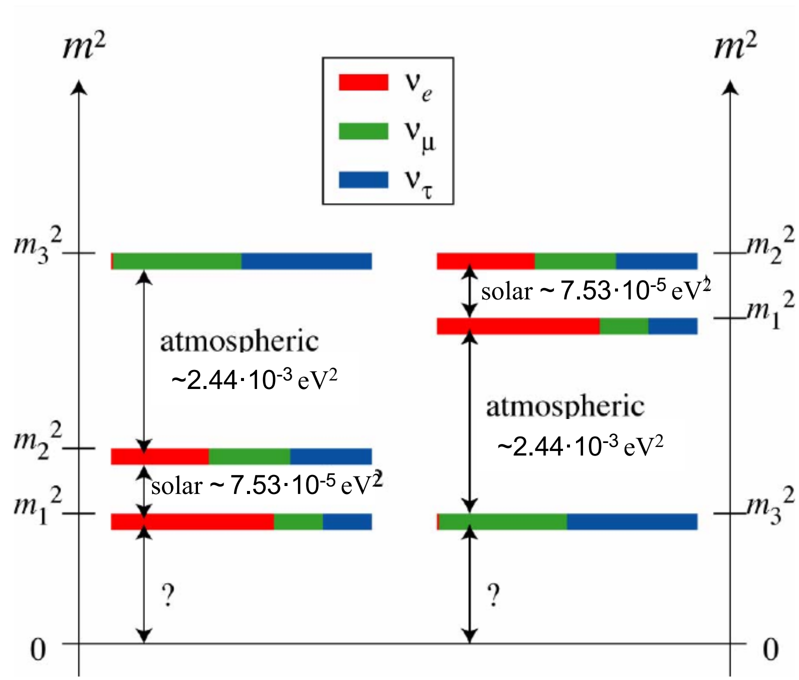


Graphic: Janet Conrad

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



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

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

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

Precision measurments can be made with neutrino beams!

Appearance experiments

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

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

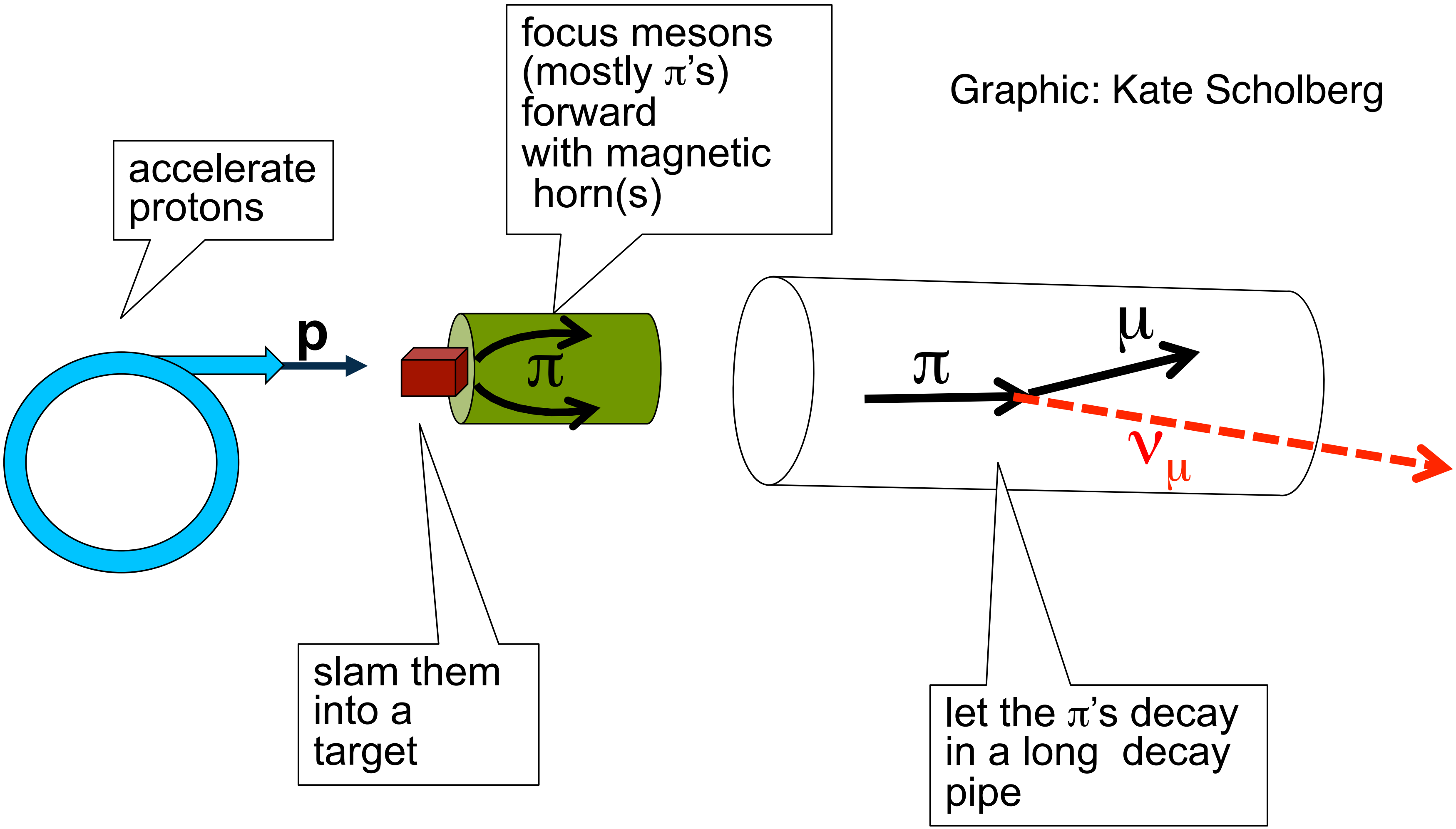
$$\sqrt{P_{\mathrm{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

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

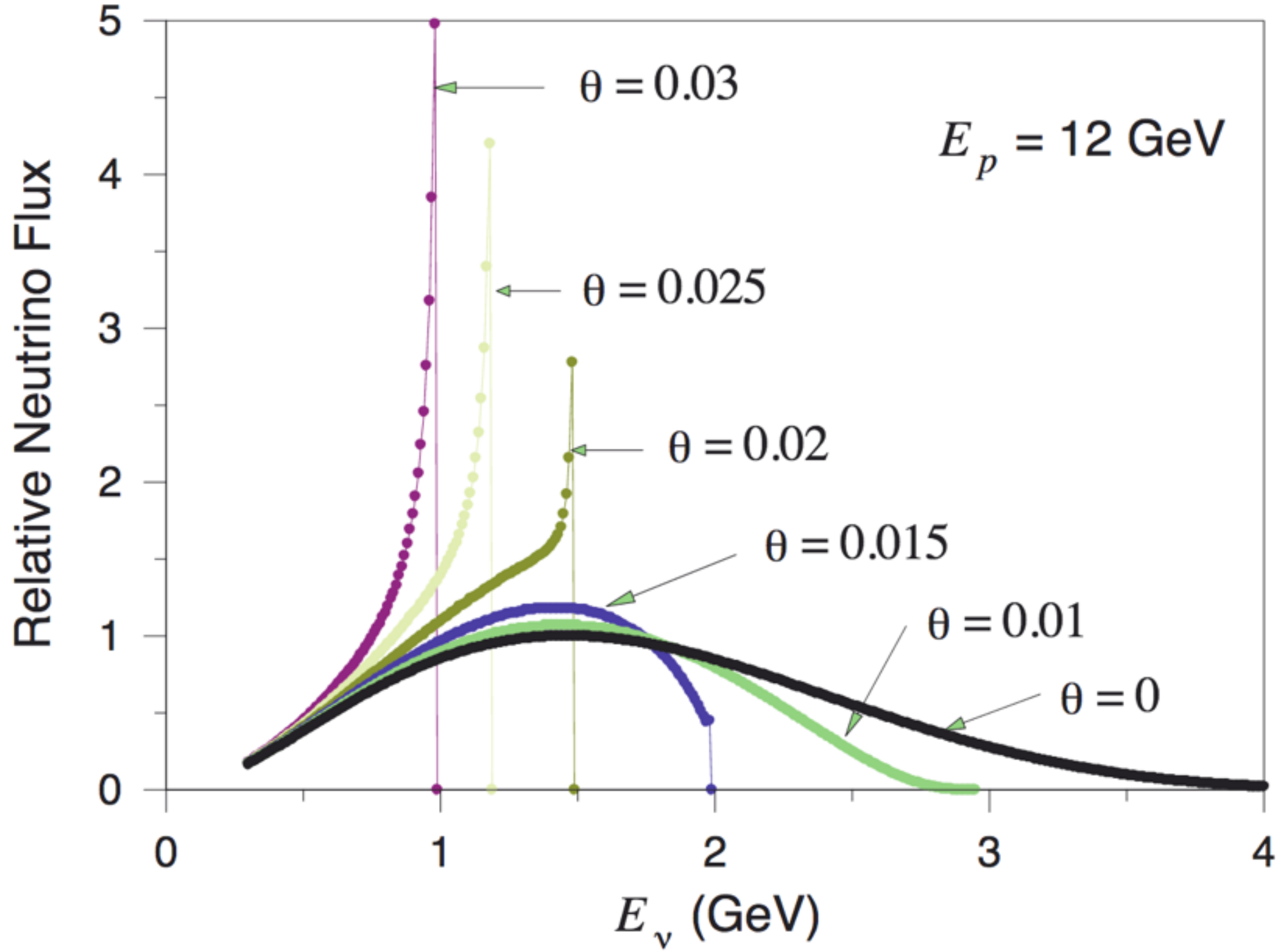
Nunokawa, Parke, Valle, in “CP Violation and Neutrino Oscillations”, Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Making a neutrino beam

Graphic: Kate Scholberg



Off axis trick

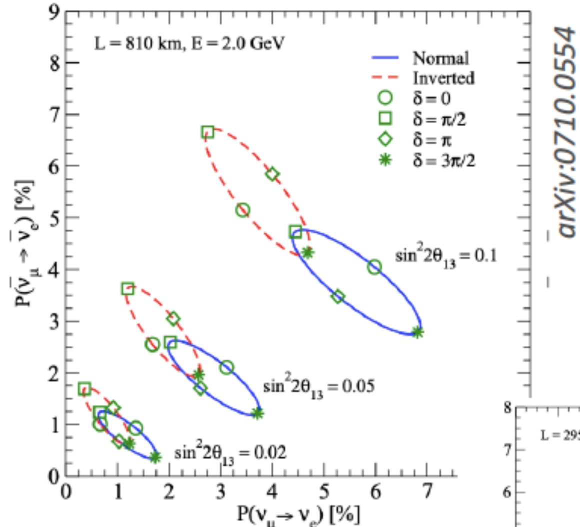


McDonald, arXiv: 0111033

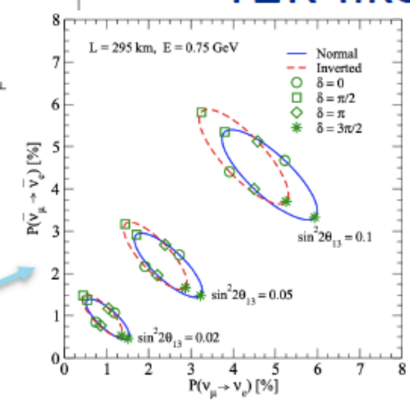
Long baseline oscillations

- Very simplified, the oscillation analysis is a counting experiment
- **In vacuum**, **no CP violation**, expect same probability for neutrino and antineutrino appearance/disappearance
- **With CP violation**, the measurement will be located on an **ellipse**
- Including **matter effects** (which are different for neutrinos and antineutrinos), the ellipses separate for the two **mass ordering** scenarios
  - Different baselines lead to different ambiguities

NOvA-like



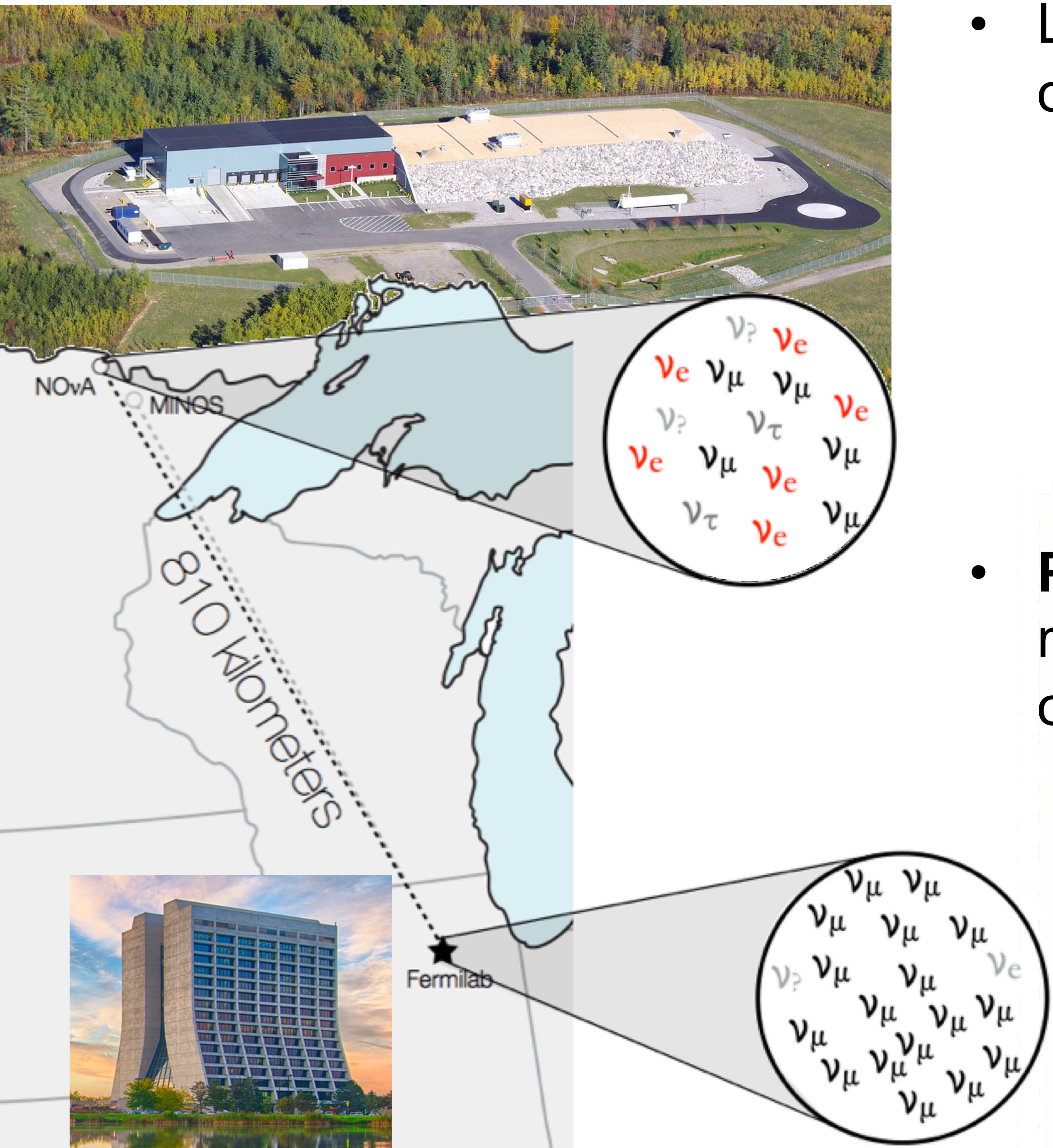
T2K-like



Shorter baseline
= less matter effects

Slide: A. Schukraft

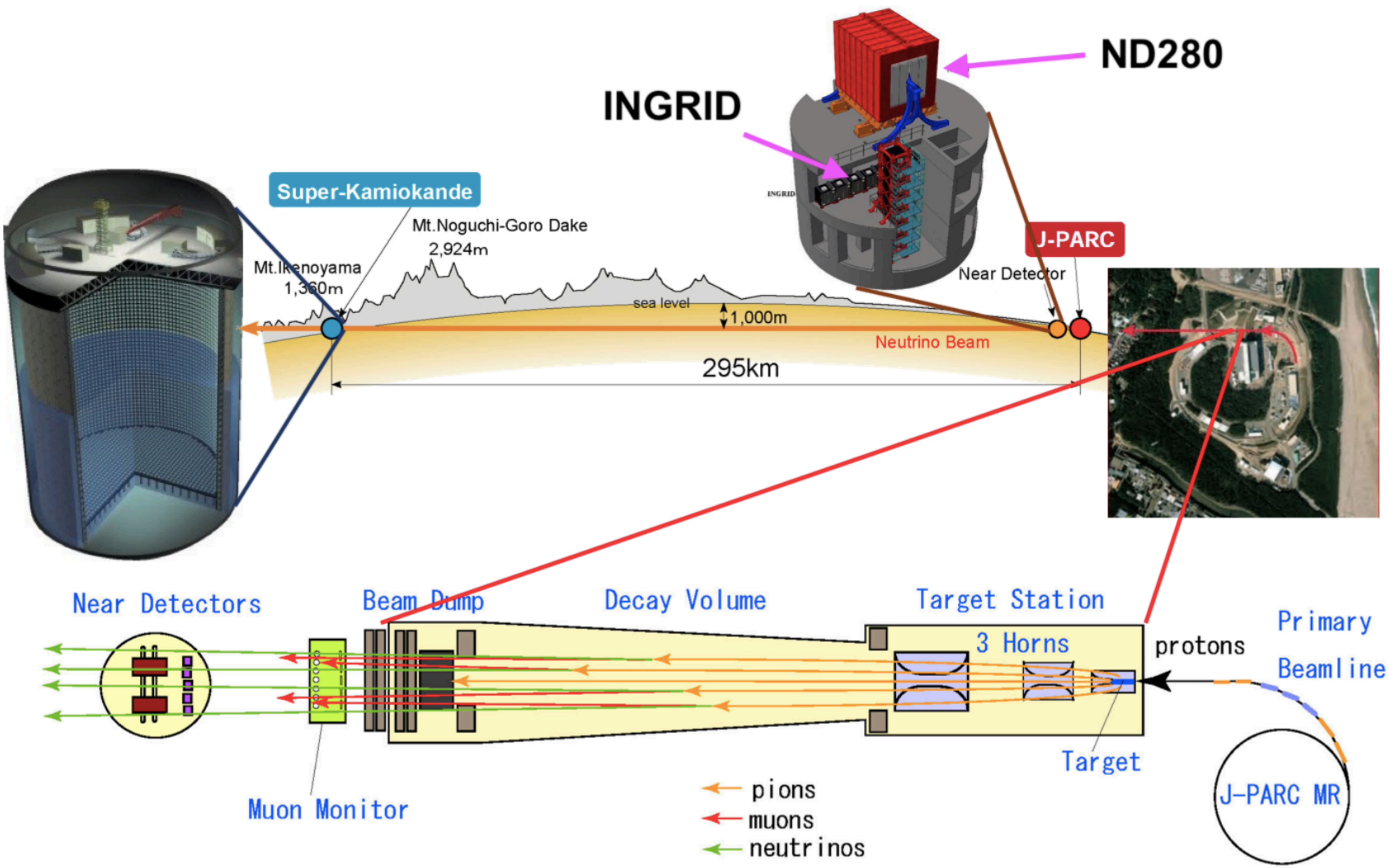
NOνA



- 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: A. Himmel

T2K



Slide: J. Walsh, NeuTel 2021

NOνA and T2K recent results

Global picture

- Results from NOvA and T2K in the $\delta_{CP} - \sin^2\theta_{23}$-plane are not inconsistent
  - More consistent for IO, but also for NO they are still statistically in agreement
- The best fit in the global analysis remains for Normal Ordering
  - but IO disfavored only with 1.6 σ
- T2K, NOvA and reactor experiments are statistically in agreement with each other
- Mild preference for the upper octant of θ_{23} ($\sin^2\theta_{23} > 0.5$)

Esteban et al., status of global fits 2020, arXiv:2007.14792

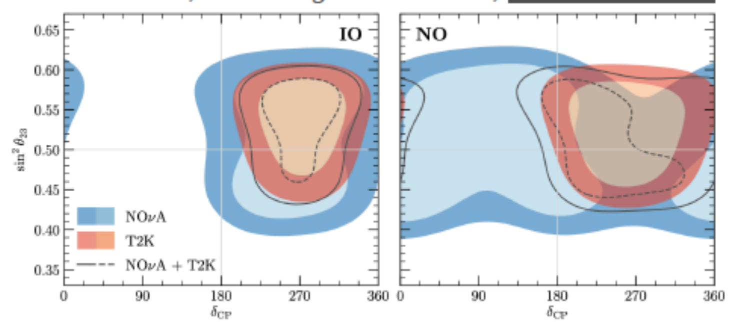
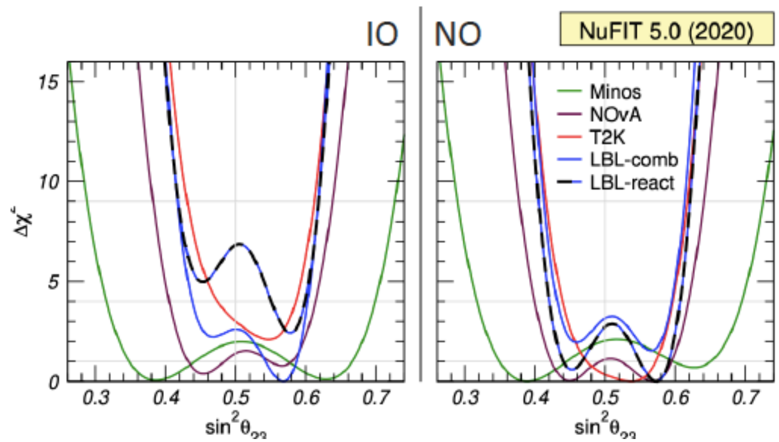


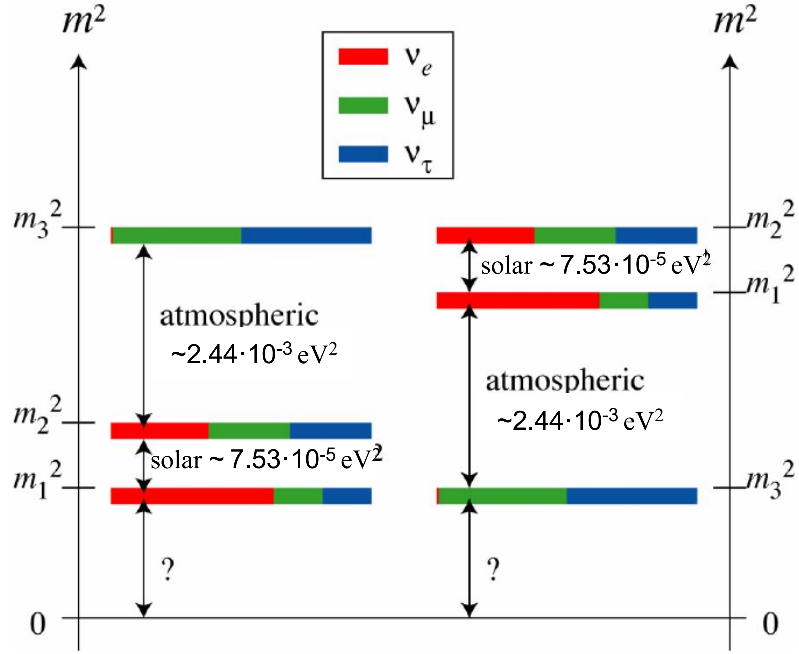
Figure 3. 1σ and 2σ allowed regions (2 dof) for T2K (red shading), NOvA (blue shading) and their combination (black curves). Contours are defined with respect to the local minimum for IO (left) or NO (right). We are fixing $\sin^2\theta_{13} = 0.0224$, $\sin^2\theta_{12} = 0.310$, $\Delta m^2_{21} = 7.40 \times 10^{-5}$ eV^2 and minimize with respect to $|\Delta m^2_{3\ell}|$.



Slide: A. Schukraft, WIN 2021

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

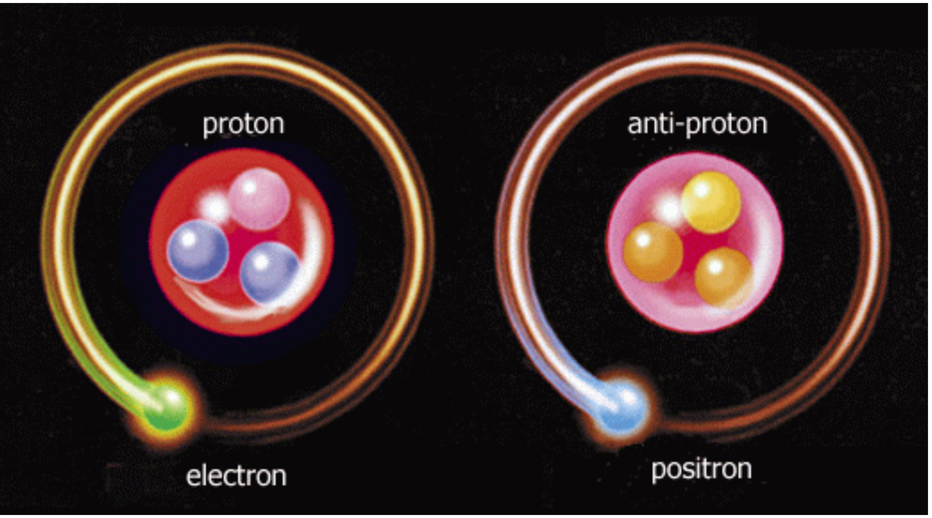


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

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

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

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?

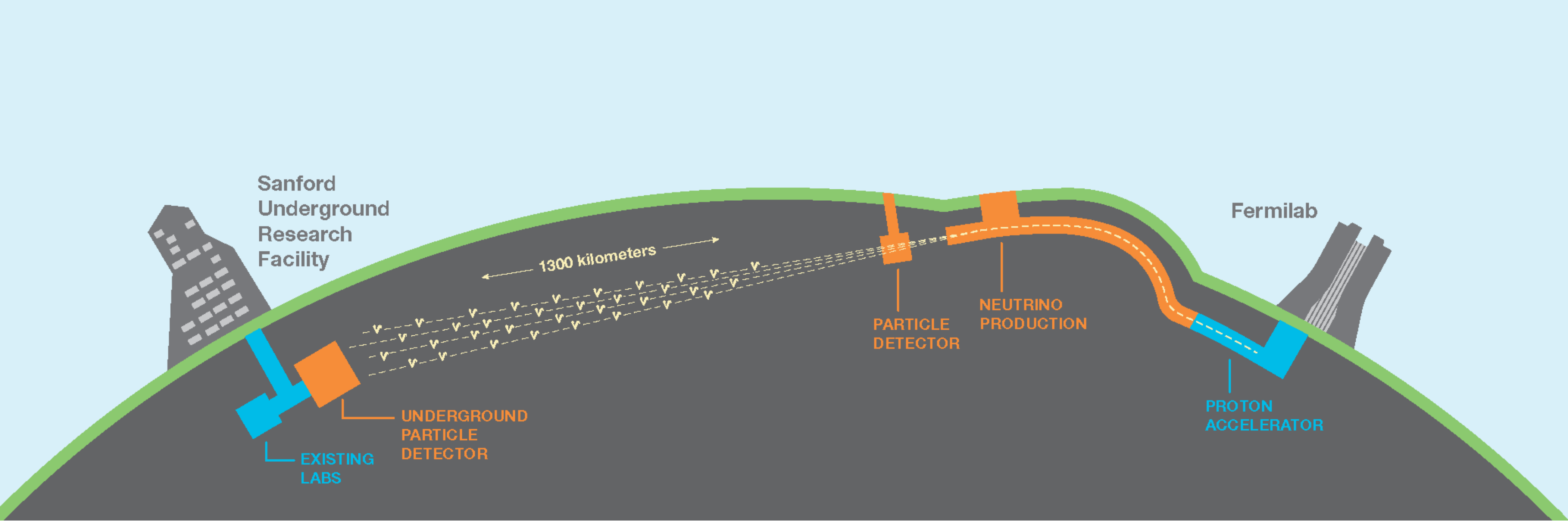
Sakharov (1967) conditions for baryogenesis:

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…

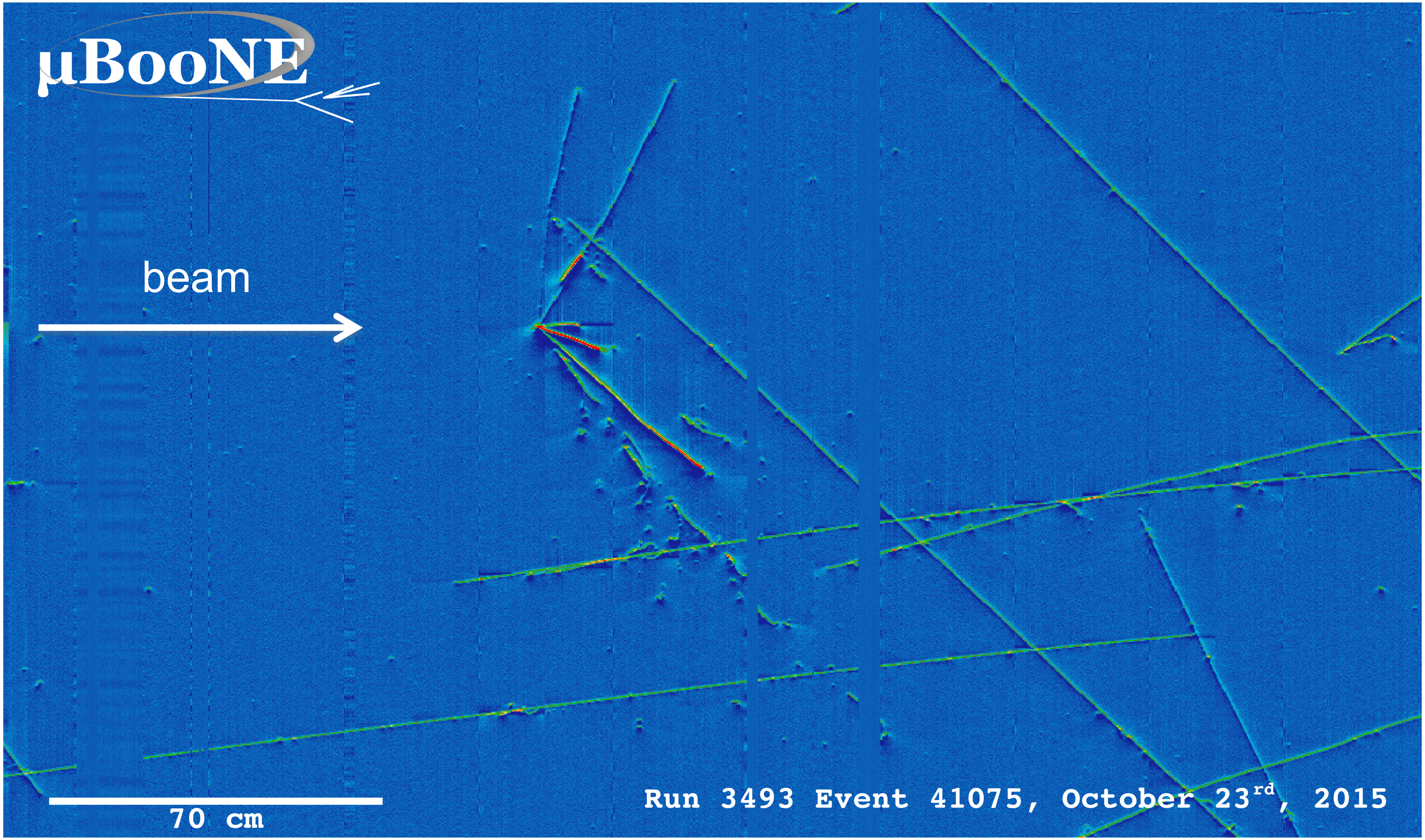
DUNE: Deep Underground Neutrino Experiment



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

https://www.dunescience.org/

Liquid Ar TPC far detector

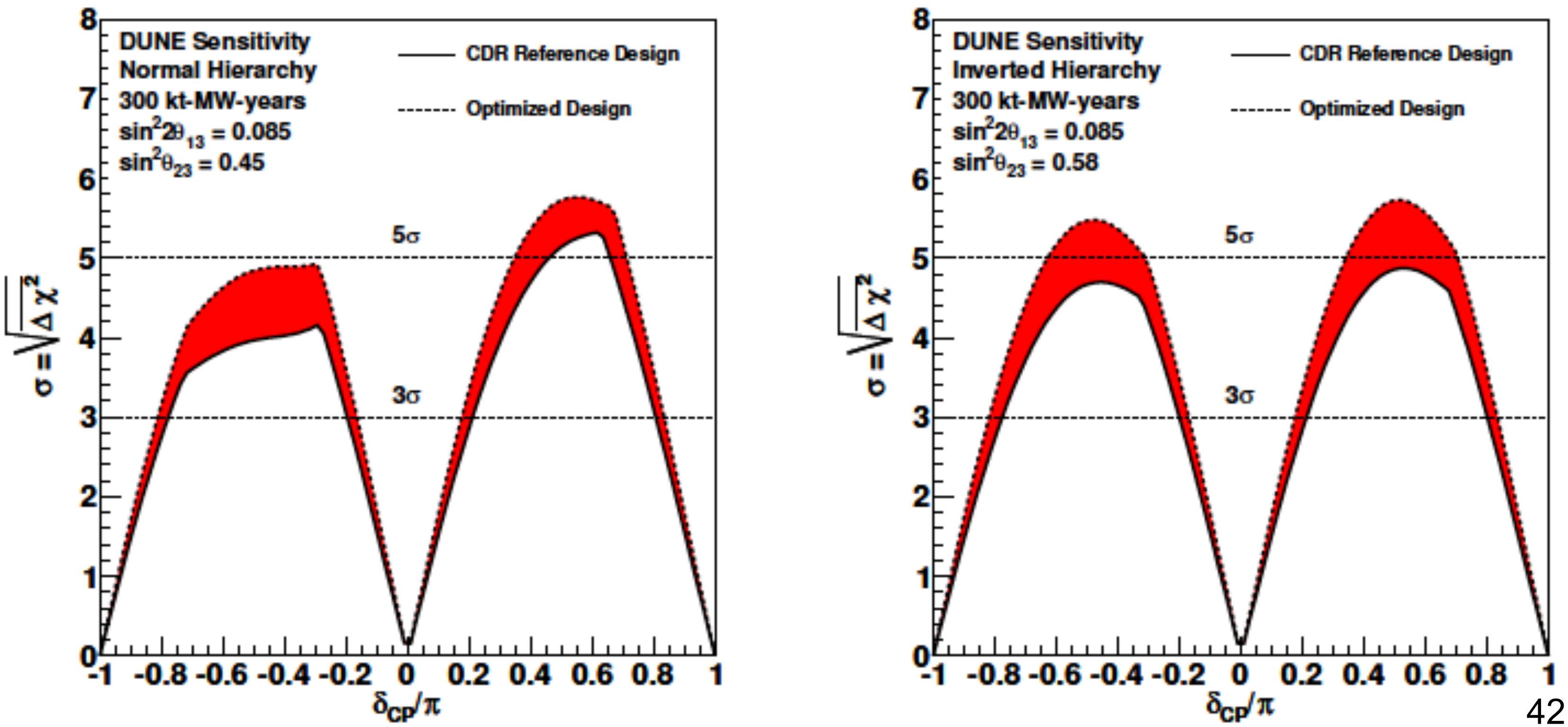


DUNE Sensitivity

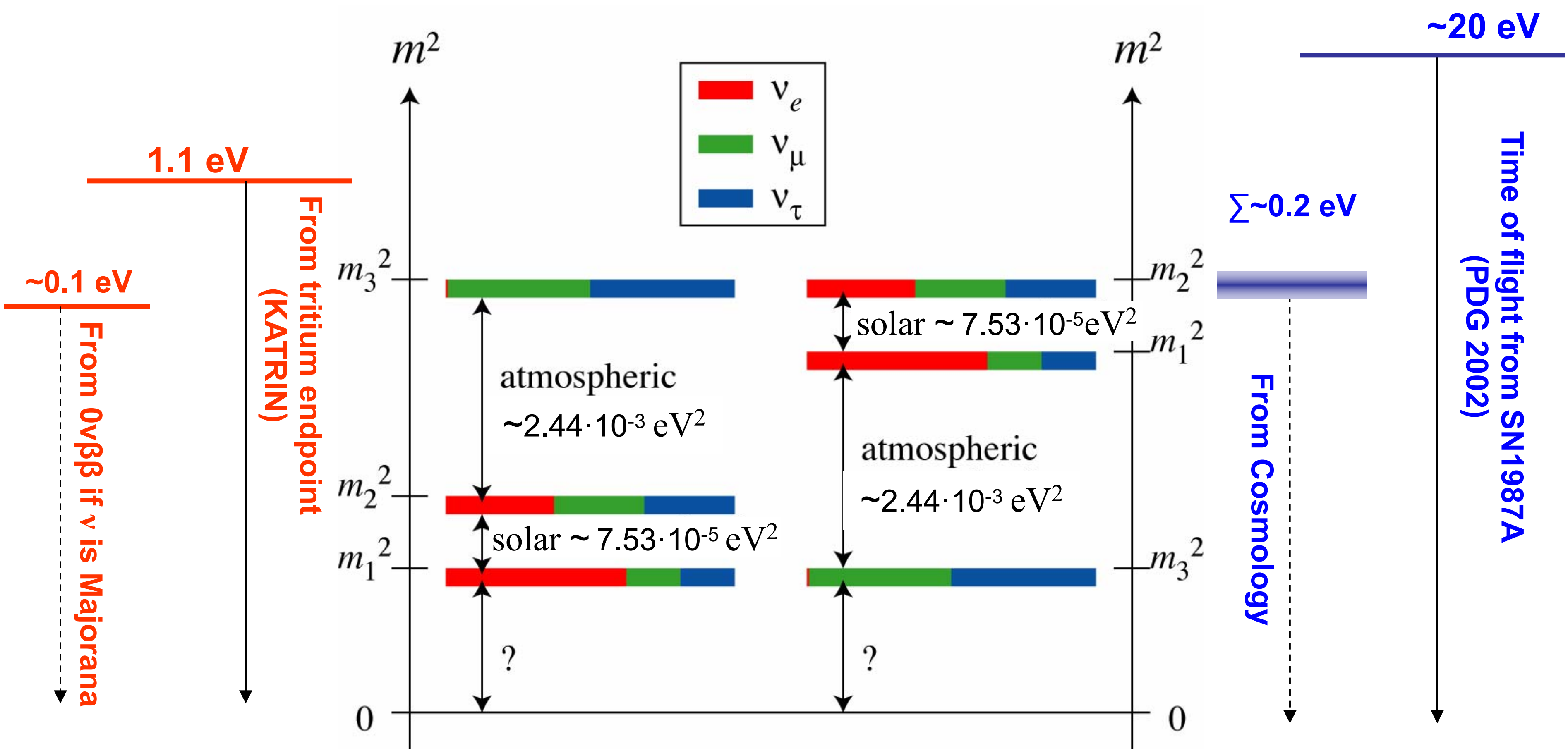
arXiv:1512.06148

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

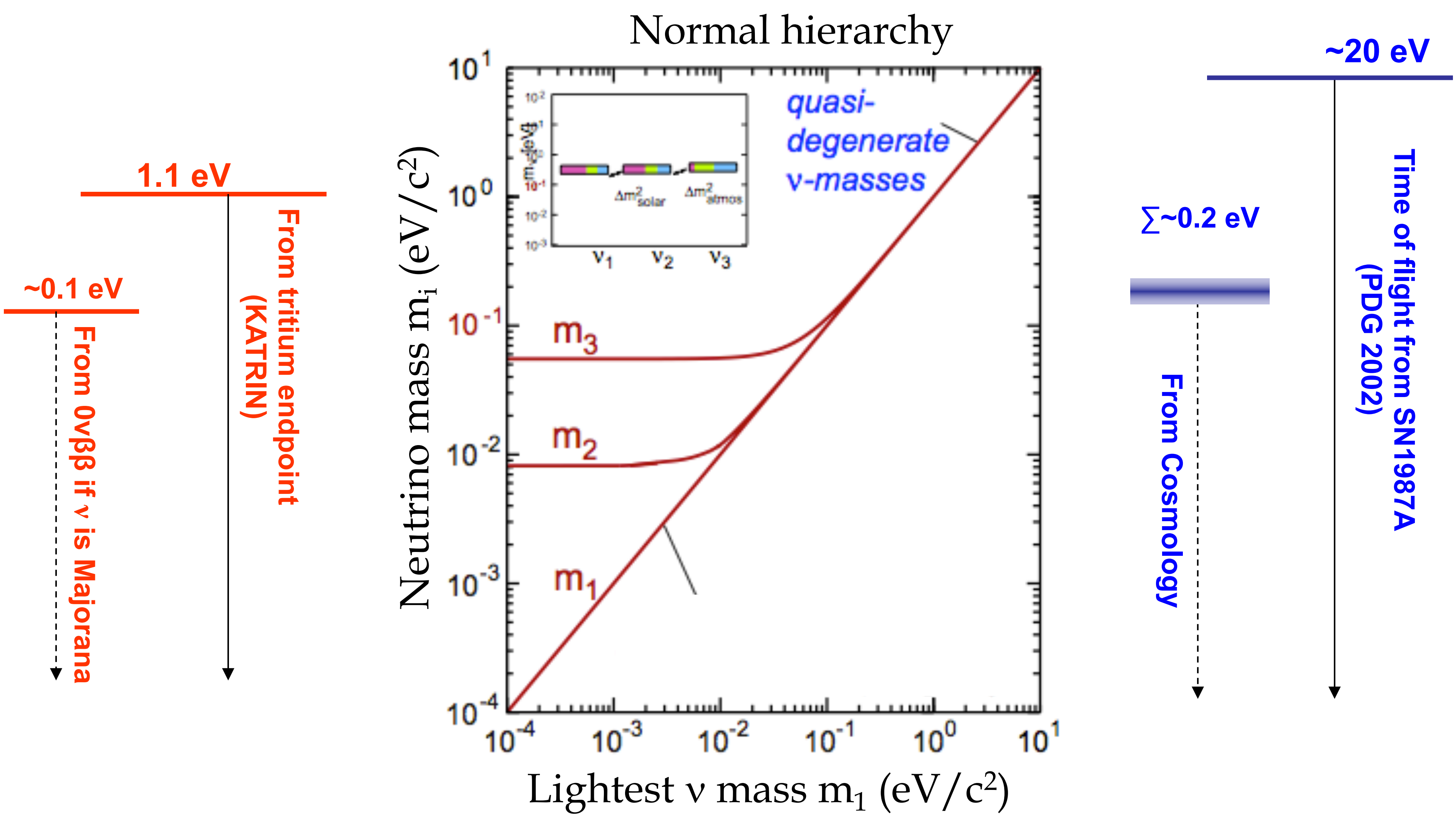
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$



The 3 ν picture

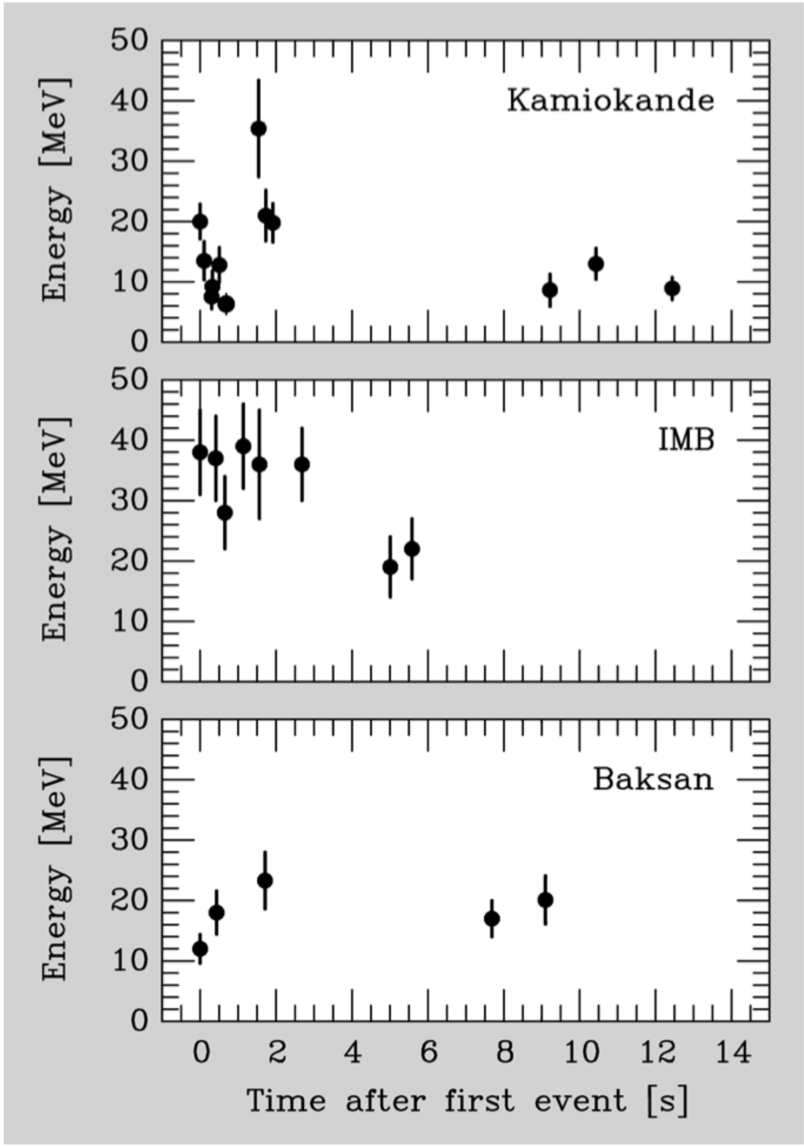


Absolute neutrino masses



How to weigh a neutrino?

Time of flight



Neutrino events from supernova 1987a (Large Magellanic Cloud) were detected in KamiokaNDE, IMB, and Baksan observatories.

With a model for neutrino production, it is possible to look for smearing due to neutrino mass. Early analyses gave limits ~20 eV.

Improved supernova modeling and Bayesian statistical approaches do better:

< 5.7 eV @ 95% C.L.

Loredo and Lamb, *PRD* 65 (2002)

Decay kinematics

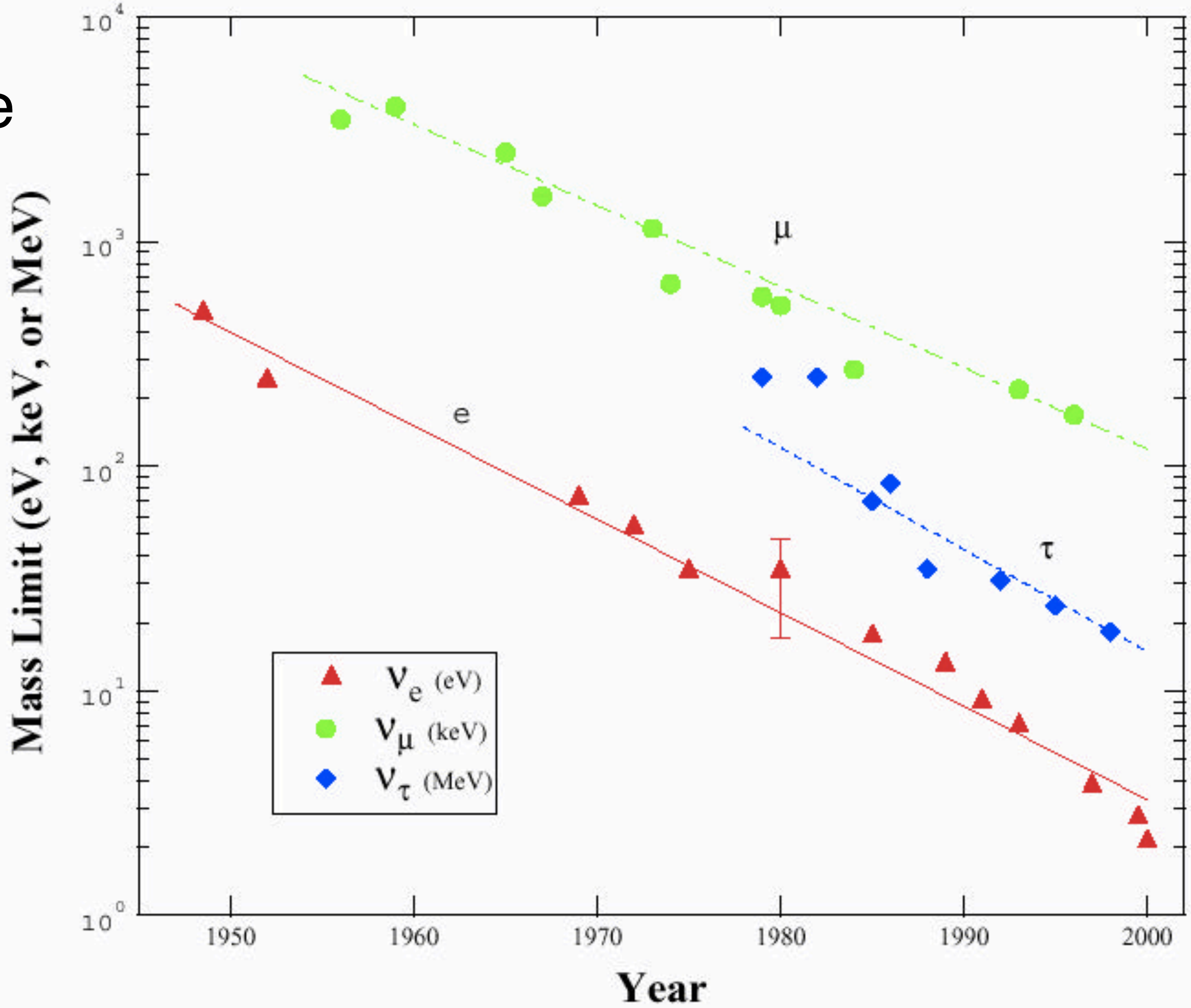
Look at the impact of non-zero ν mass on the following decays.

ν_e: beta decay

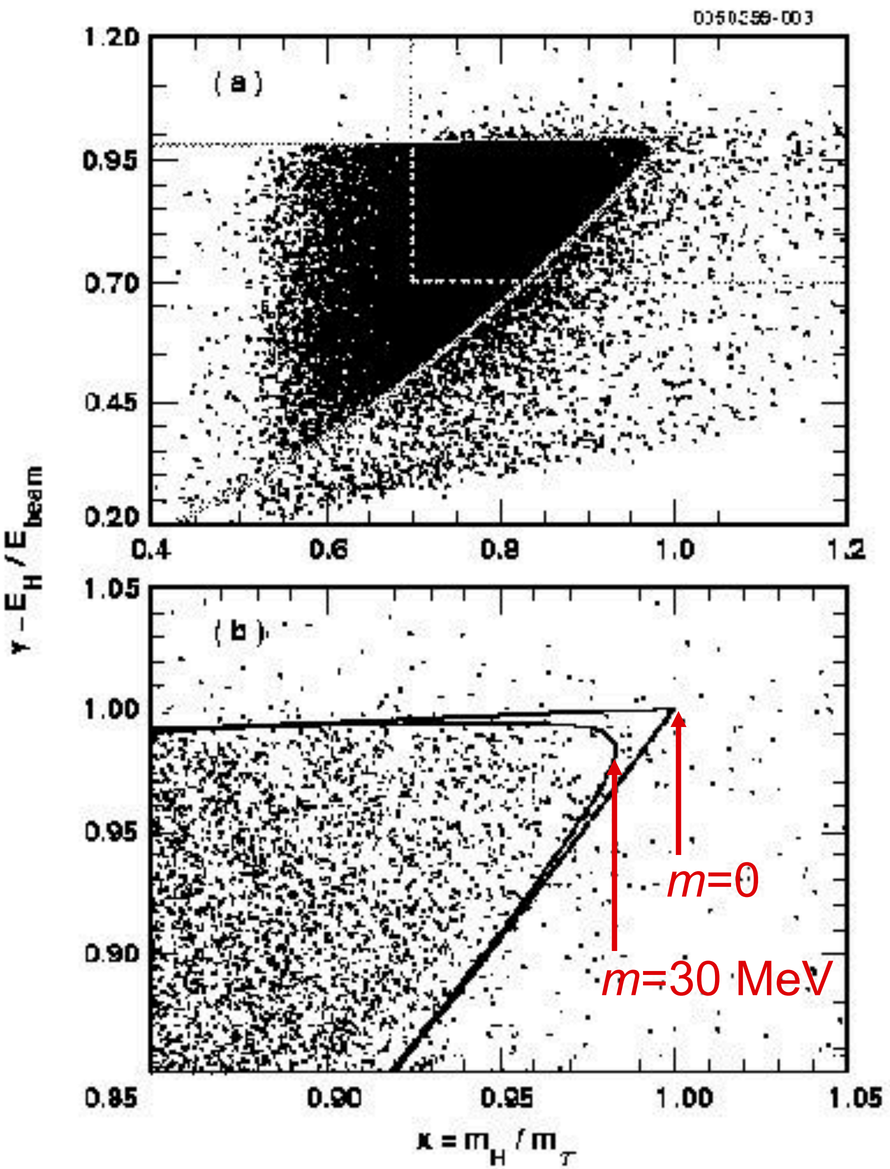
ν_μ: pion decay*

ν_τ: tau decay*

*thanks to Mike Shaevitz for next two slides, 2002 lectures at Lake Louise School



τ decay



Current best limit from studies of the kinematics of τ decays.

$$\tau^- \to 2\pi^- \pi^+ \nu_\tau$$
$$\tau^- \to 3\pi^- \; 2\pi^+ (\pi^0) \nu_\tau$$

•Fit to scaled visible energy vs. scaled invariant mass. Best limit

<18.2 MeV @ 95% C.L.
Aleph, EPJ C2 395 1998

Pion decay

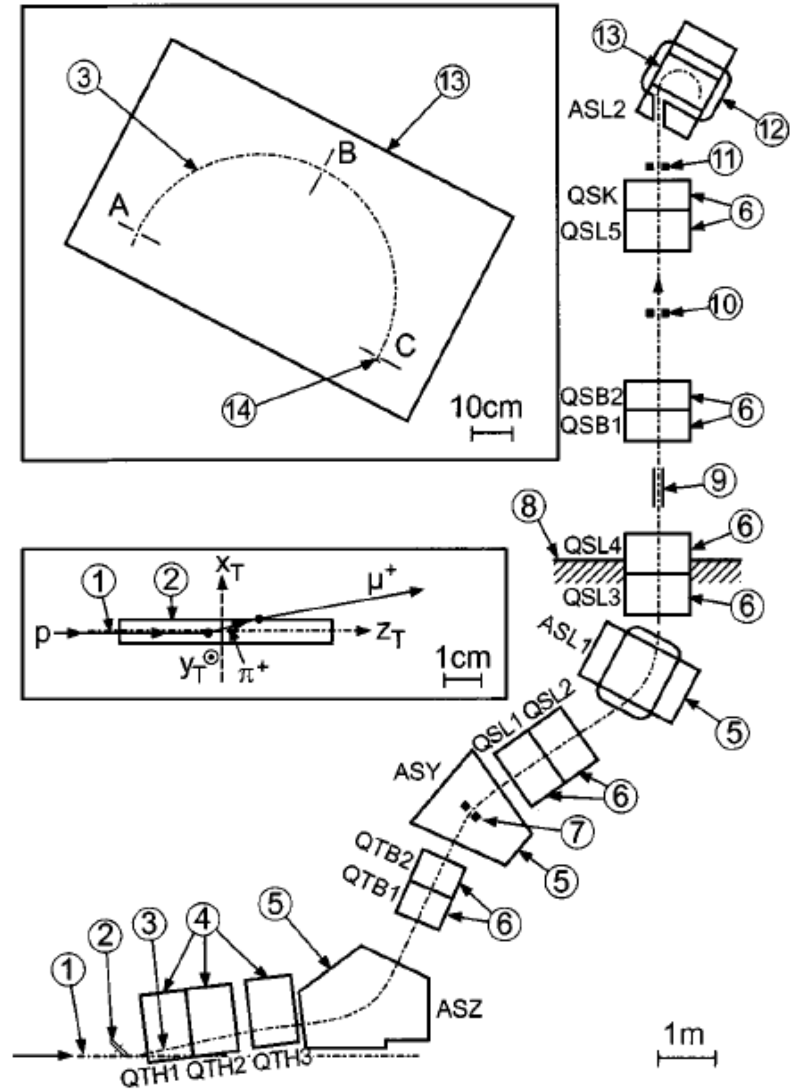
Current best limit from studies of the kinematics of $\pi \rightarrow \mu\nu_\mu$ decay.

$$p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2 / 4m_\pi^2$$

•Pion decay in flight is limited in practice by momentum resolution.
•Pion decay at rest is limited by pion mass uncertainty. This currently gives the best limits from PSI

<170 keV @ 95% C.L.
Assamagan et al., *PRD* (1996)

*Proposals exist to get this down to ~8 keV



Beta decay

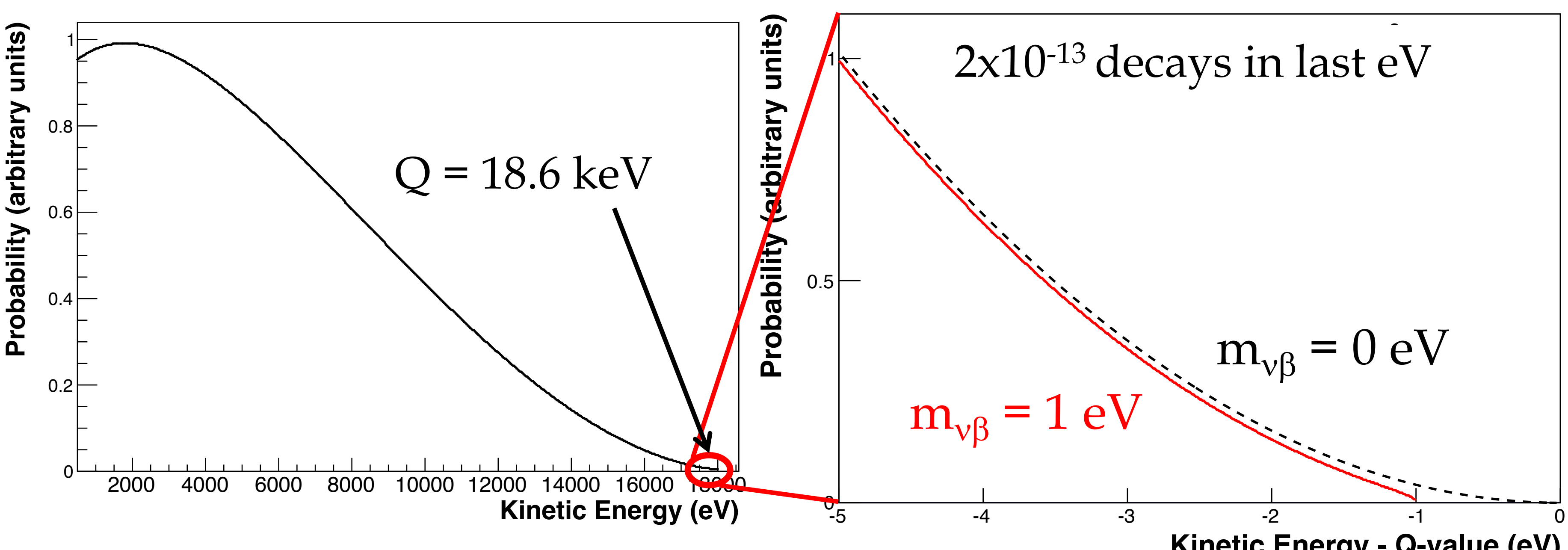
Taking into account ν mass eigenstates, the original spectrum

$$dN(E) = K|M|^2F(Z,R,E)\, p_eE\, (E_0-E)\, \{(E_0-E)^2-m^2_{\nu_e}c^4\}^{1/2}\, dE$$

becomes

$$dN(E) = K|M|^2F(Z,R,E)\, p_eE\, (E_0-E) \sum_i |U_{ei}|^2\, \{(E_0-E)^2-m^2_{\nu_i}c^4\}^{1/2}\, dE$$

For 3 ν mass spectrum, with degenerate states, the beta spectrum simplifies to an "effective mass" : $m_\beta = \sum |U_{ei}|^2 m^2_{\nu_i}$



Beta decay limits

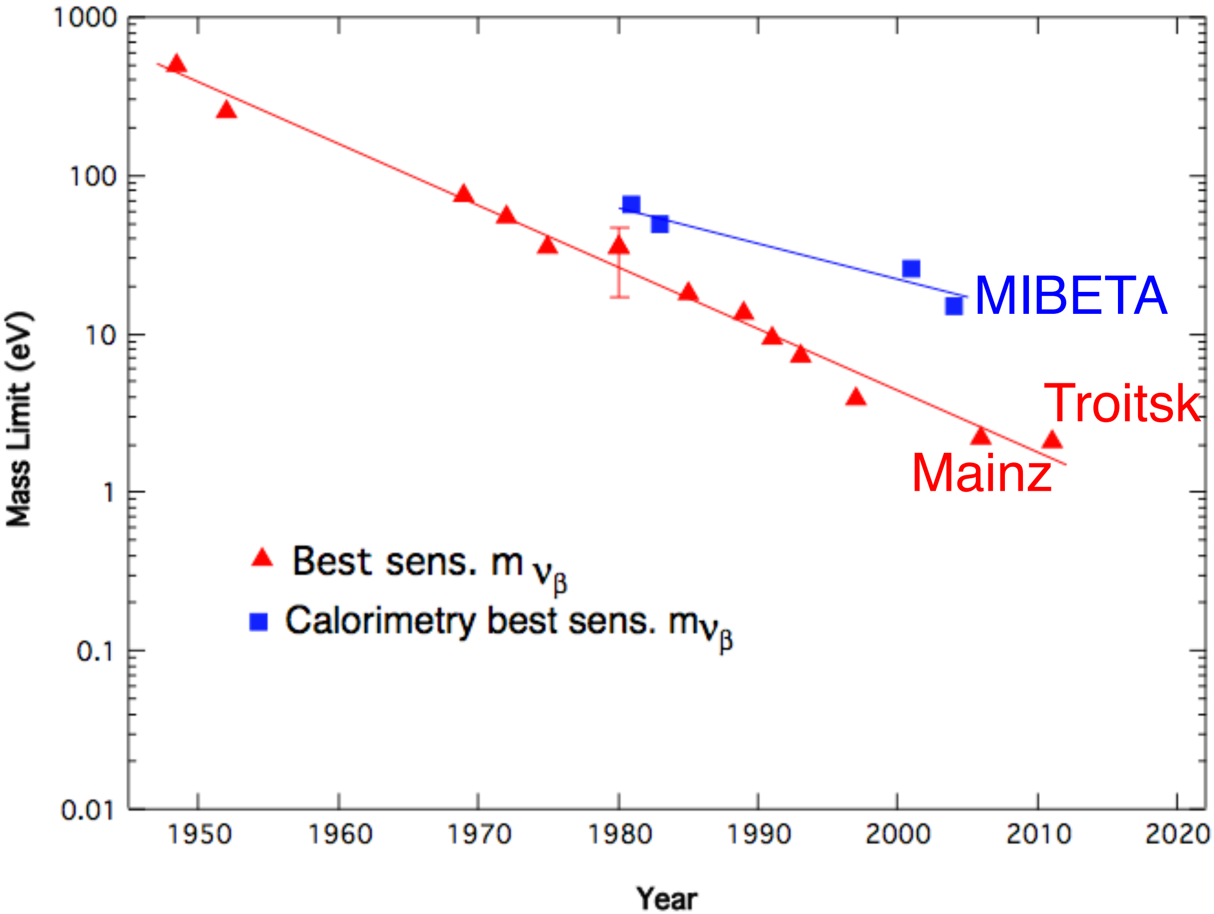


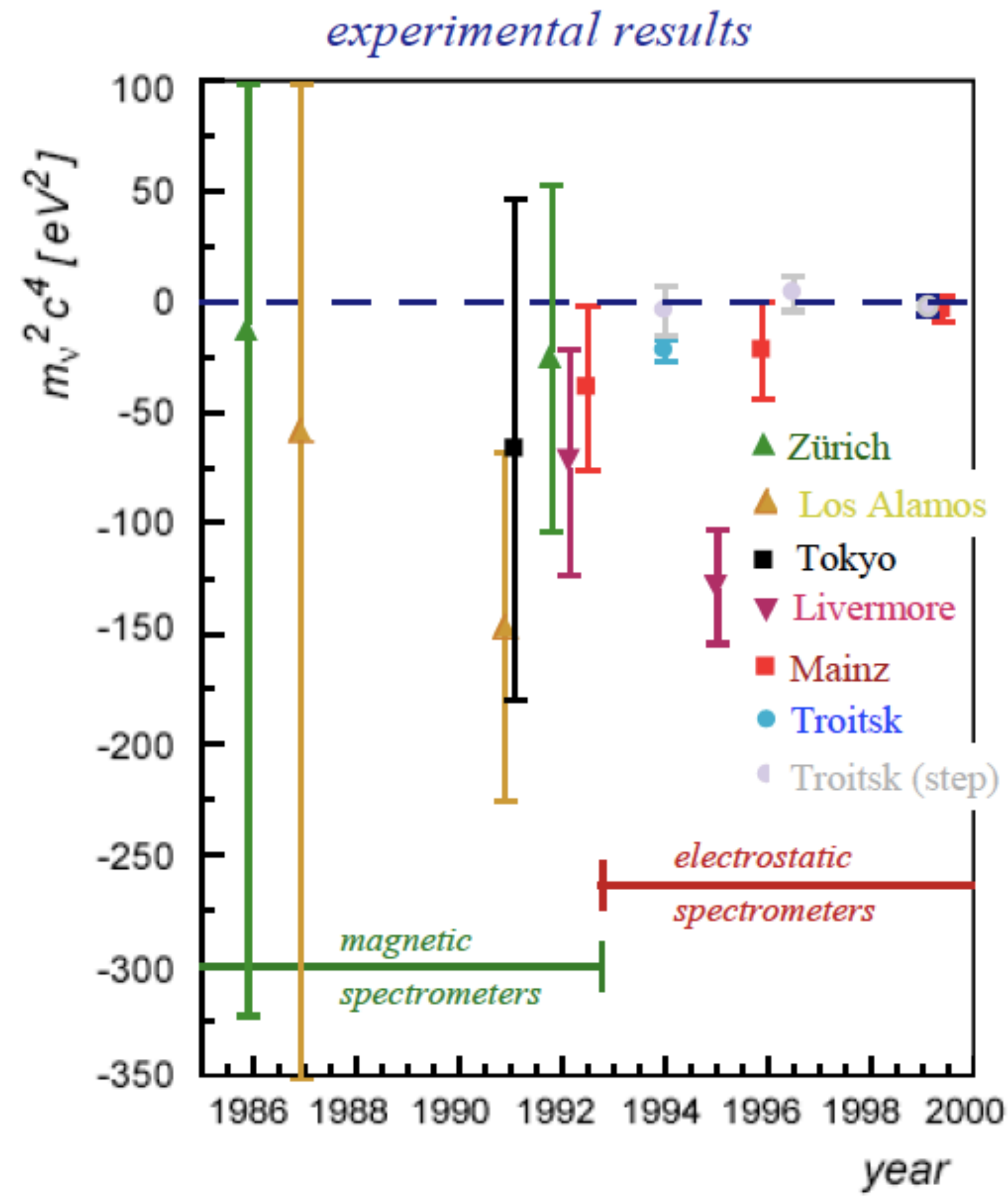
Figure from J. Wilkerson, Neutrino 2012

^{187}Re
Q = 2.47 keV
$t_{1/2}$ = 4.5 x 10^9 years
Forbidden

^{3}H (tritium)
Q = 18.6 keV
$t_{1/2}$ = 12.3 years
Super-allowed

Existing tritium results

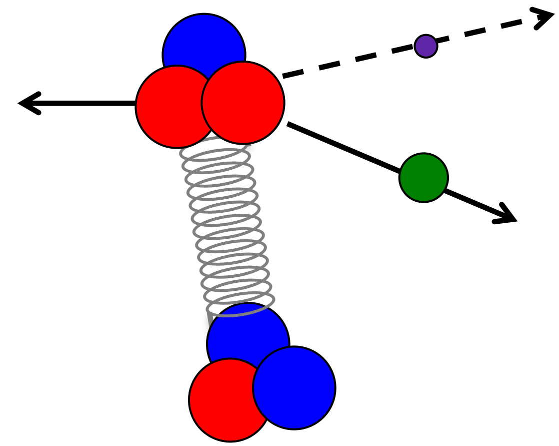
	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokyo *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	(< 2.5 eV)



Tritium gas sources

Gas sources give the best results, but we're limited to using molecular tritium.

- Electronic excitations in T atoms
- Excitations in T_2 gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies V_k and probabilities P_k
- KATRIN needs 1% uncertainties on final state distribution.

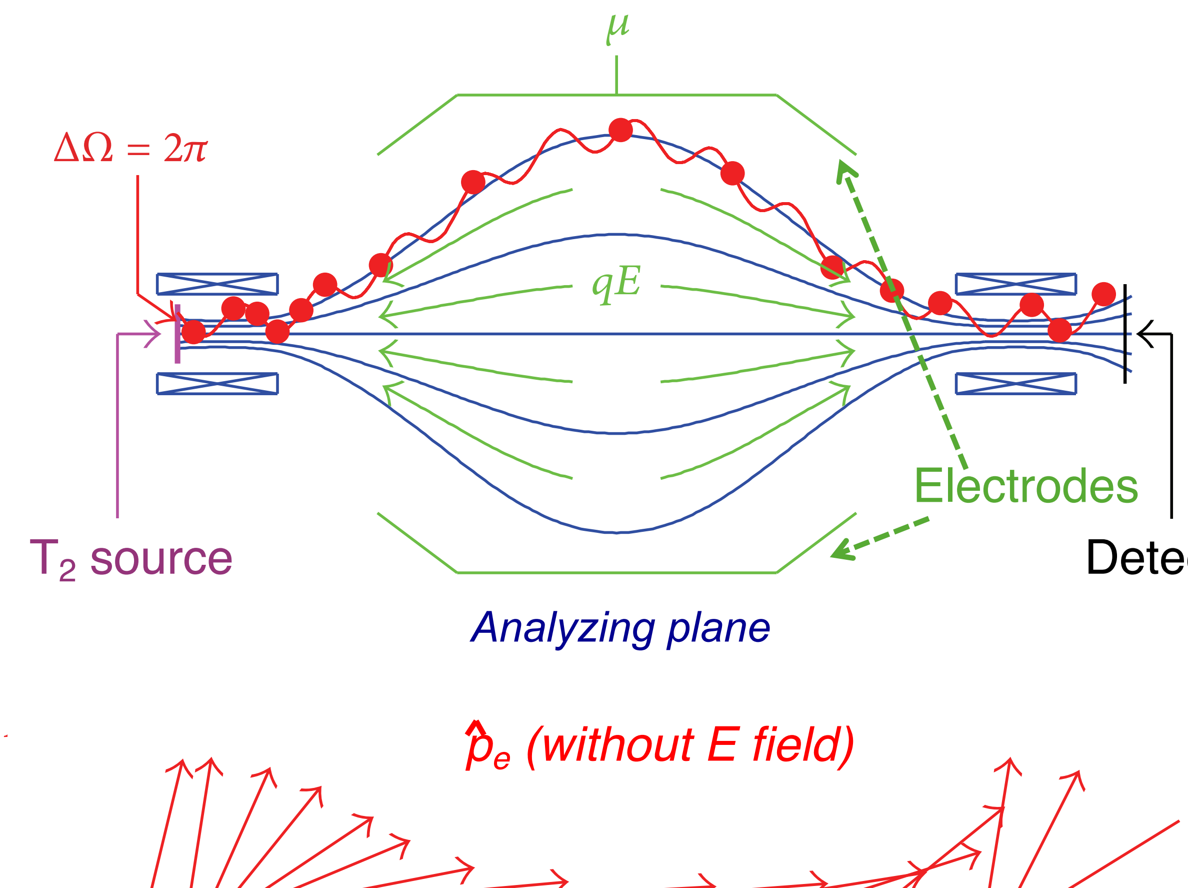


$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\mathrm{nuc}}|^2 F(Z, E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k)$$
$$\times \sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\max} - E_e - V_k - m_{\nu i})$$

MAC-E filter

Magnetic Adiabatic Collimation and Electrostatic filter

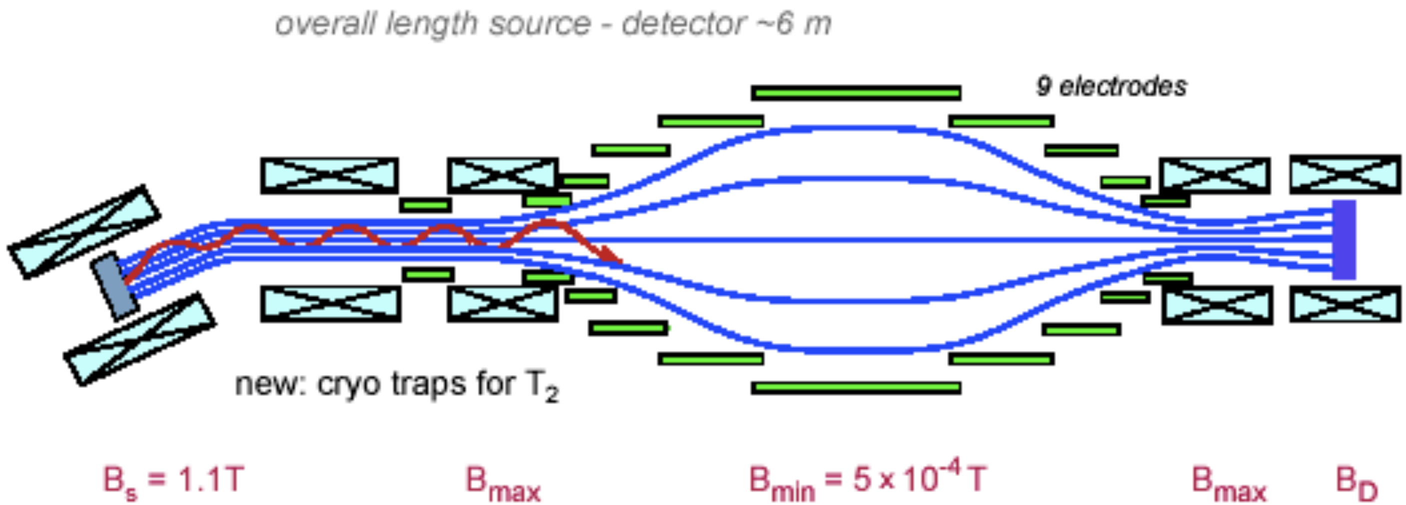
The MAC-E filter allows measurement of integral spectrum with an adjustable threshold. Only see the endpoint of the decay!



$$\boxed{\mu = \frac{E_\perp}{B} = \text{const}}$$

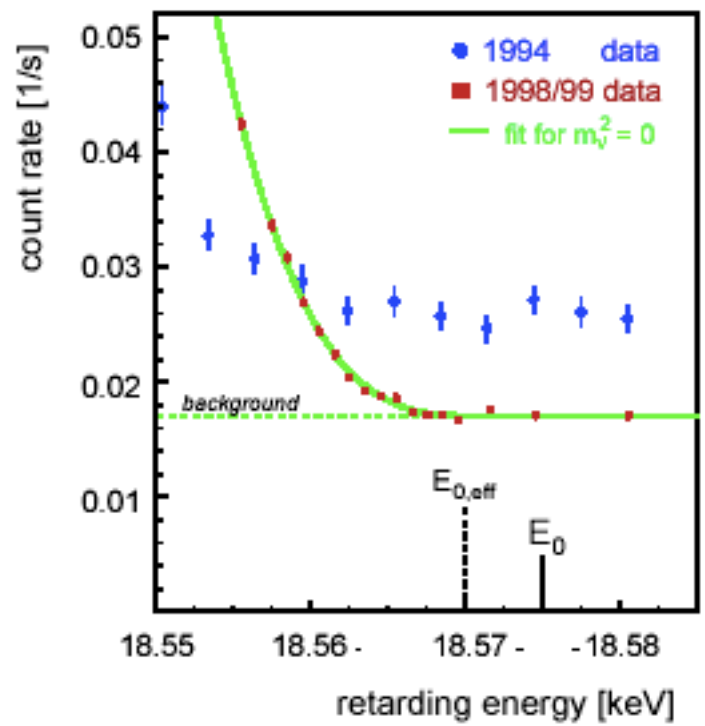
$$\boxed{\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}}$$

MAINZ



- Quench condensed solid T_2 source
- Early results (1994) showed systematic effects, traced to source film roughening transition (fixed by lowering temperature)
- 1995-1997 significant background reduction, signal improvement
- Best limit

< 2.2 eV @ 90% C.L.



Weinheimer et al., *Phys. Lett.* B 460219 (1999)

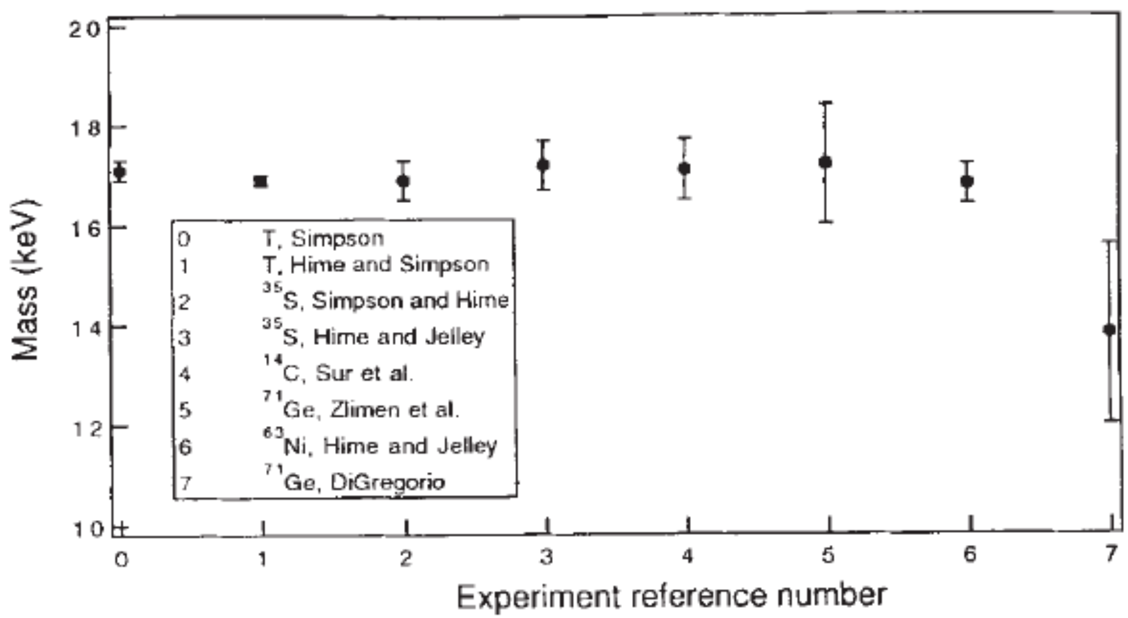
Speaking of anomalous results…

The rise and fall of the 17-keV neutrino

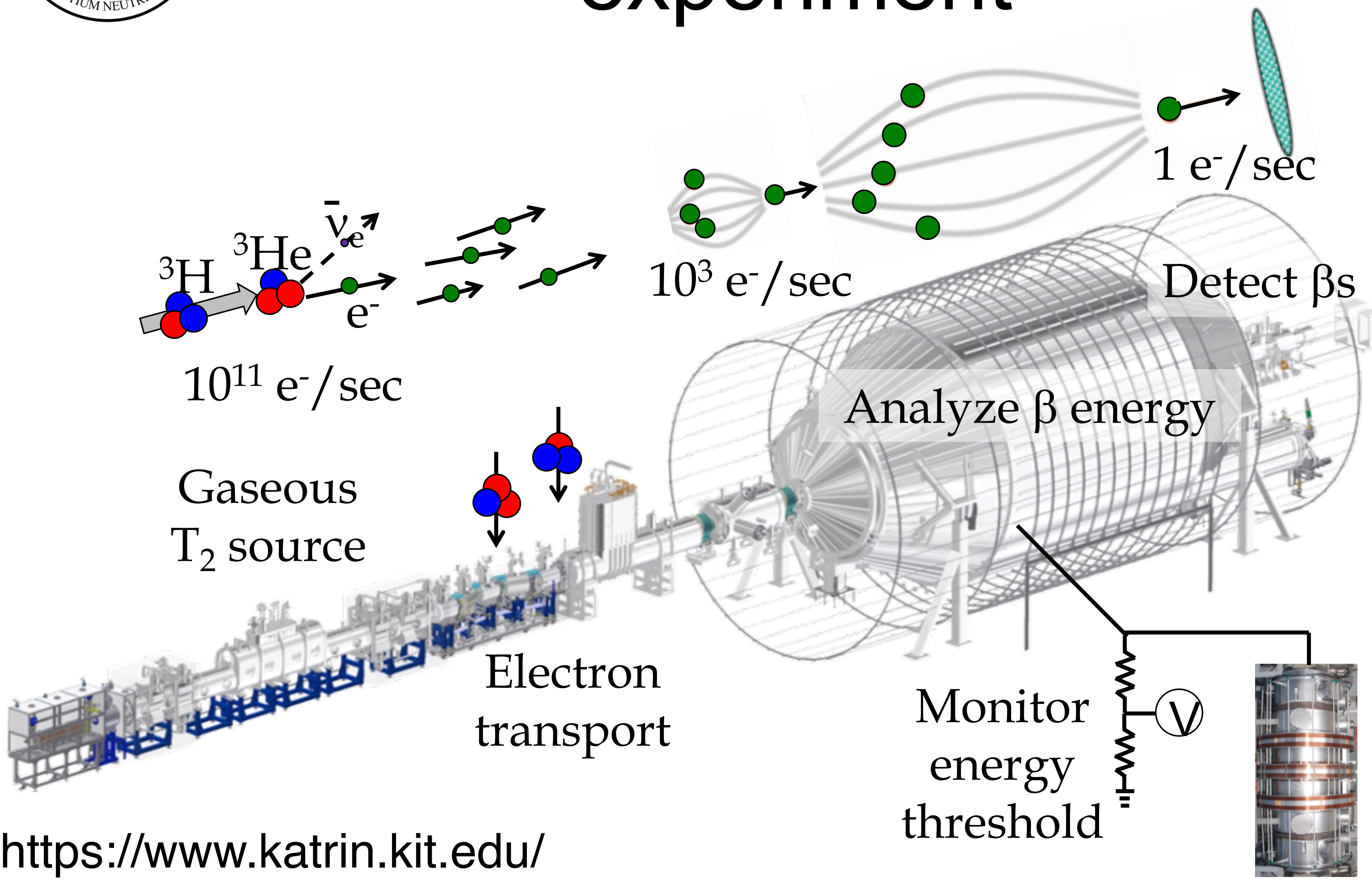
Douglas R. O. Morrison

Nature **366**, 29 - 32 (04 November 1993)

Experiments showing evidence for a heavy neutrino with a mass of 17 keV launched the new particle on an erratic eight-year career, during which it raised questions about the Standard Model of particle physics and about cosmological theories, stimulated many theoretical papers and pushed experimental techniques to their limit. Its demise provides grounds for faith in the efficacy of the scientific method.



KArlsruhe **TRI**tium **N**eutrino experiment

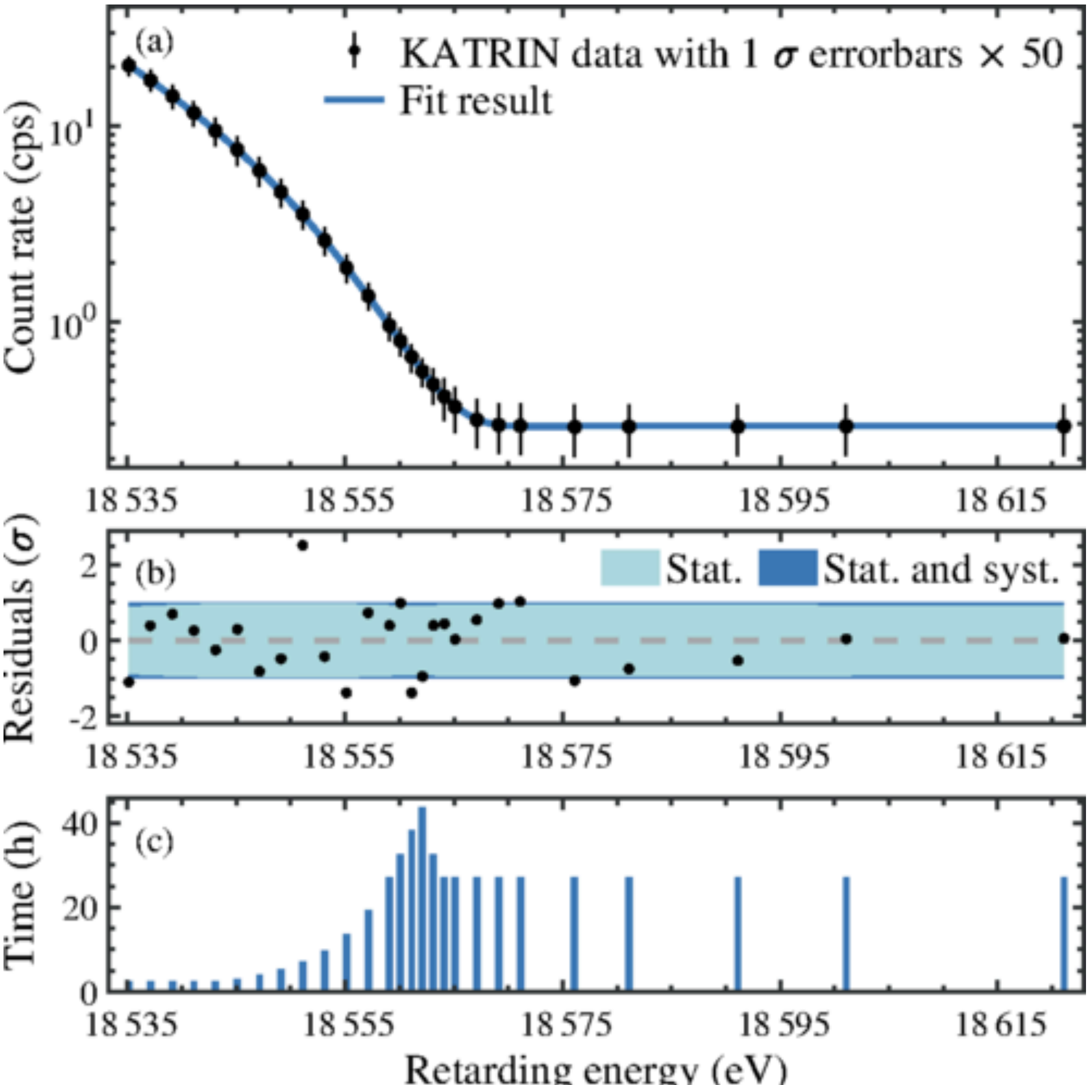


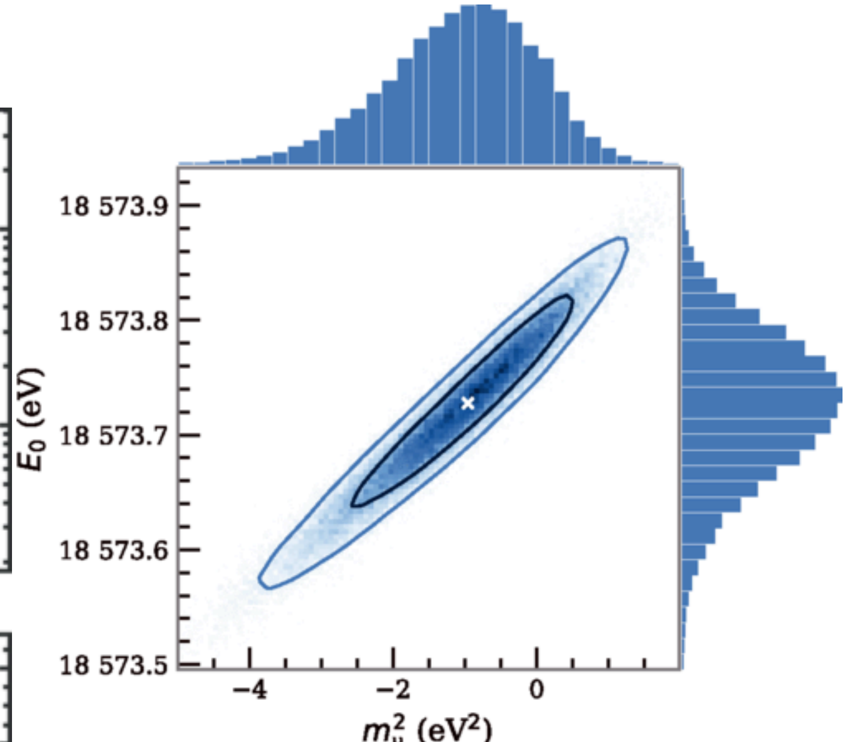
https://www.katrin.kit.edu/

KATRIN outlook

- Intense T_2 source (10^{11} decays/second)
- Spectrum analysis with electromagnetic filter
- Design resolution 0.93 eV
- Design m_β sensitivity: **0.2 eV/c^2 at 90% C.L.**

First KATRIN results



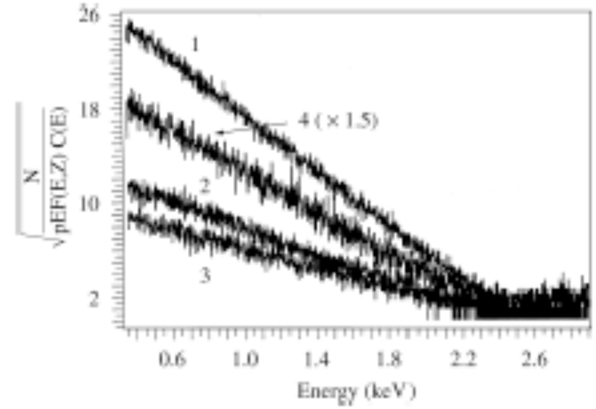


m_ν < 1.1 eV at 90% C.L.

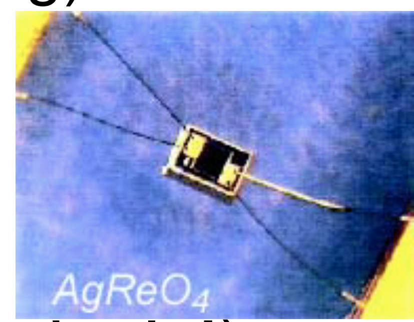
Phys. Rev. Lett. 123, 221802

MIBETA and MARE

Bolometric measurements on ^{187}Re



- ~15 eV sensitivity for MiBETA (2004)
- R&D by MARE collaboration
  - Metallic Re (superconducting)
    - Complex thermalization
  - Dielectric $AgReO_4$
    - Long response time
- Low specific activity (10^5 pixels!)

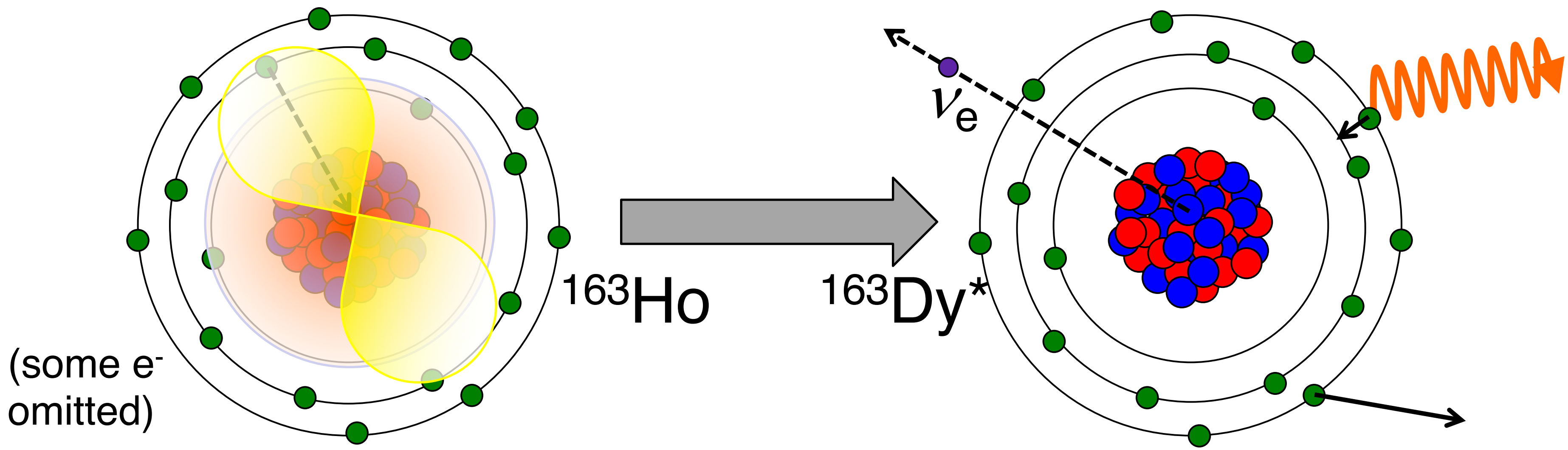


Community has moved on to ^{163}Ho

Nucciotti, arXiv:1511.00968

Holmium decay

$^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^{*} + \nu_e$



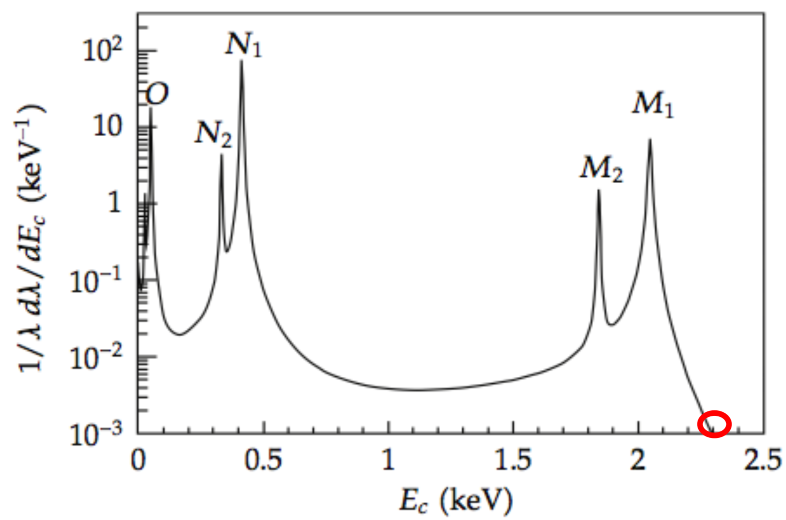
^{163}Ho

$Q = 2.83$ keV

$t_{½} = 4750$ years

*De Rújula and Lusignoli, Phys. Lett. B **118** (1982) 429*

*Lusignoli and Vignati, Phys. Lett. B **697** (2011)*

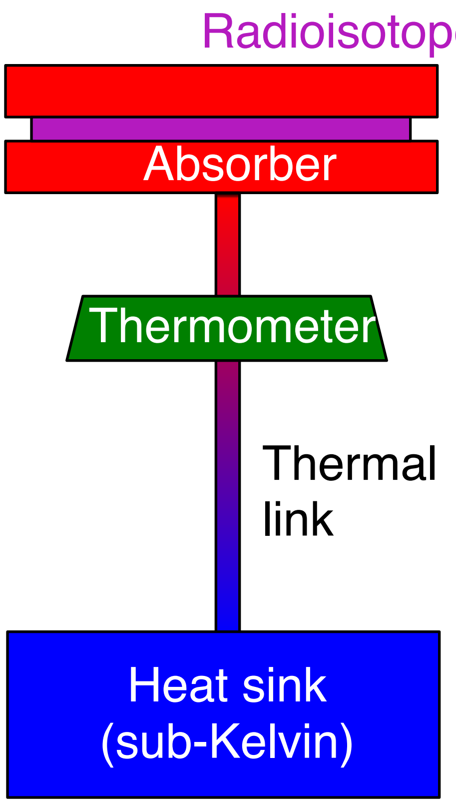


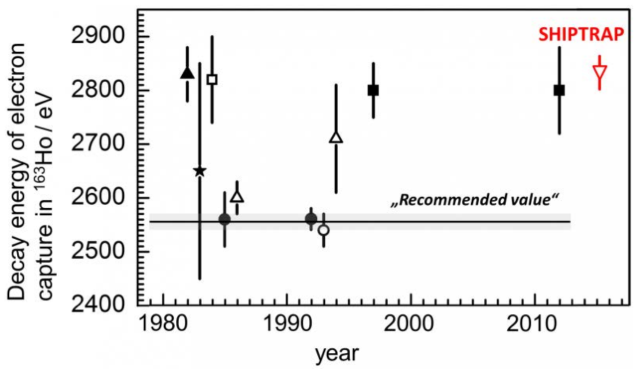
Holmium experiments

Holmium microcalorimetry, two competing experiments.

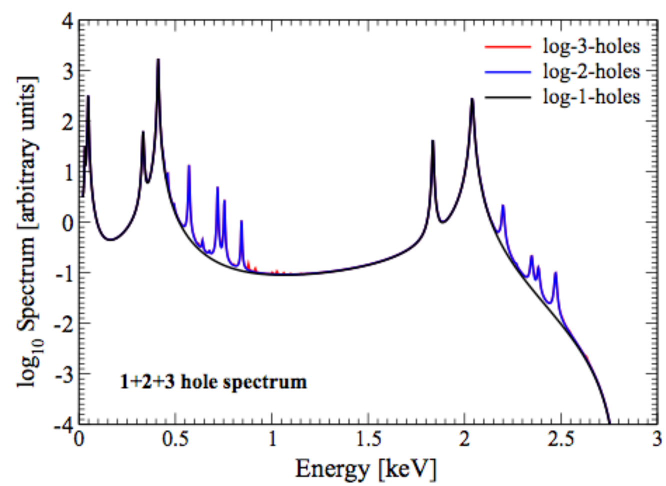
- HOLMES uses MKID sensor technology, ECHo uses MMCs

Big problems with the endpoint and theory





Eliseev et al., PRL ***115*** *(2015) 062501*



Faessler et al., PRC ***91*** *(2015) 064302*

A new approach: PROJECT 8

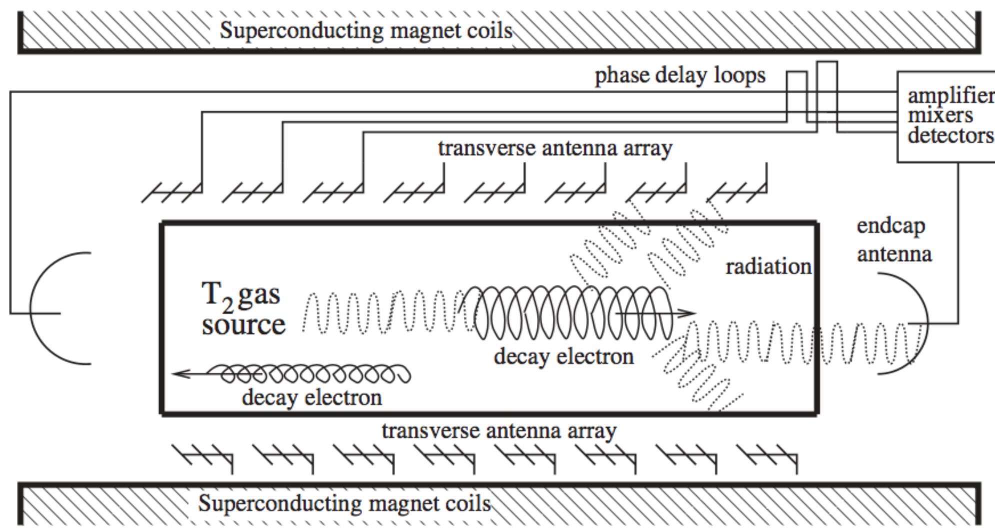
Never measure anything but frequency.

-Arthur Schawlow

An electron in a magnetic field will radiate at:

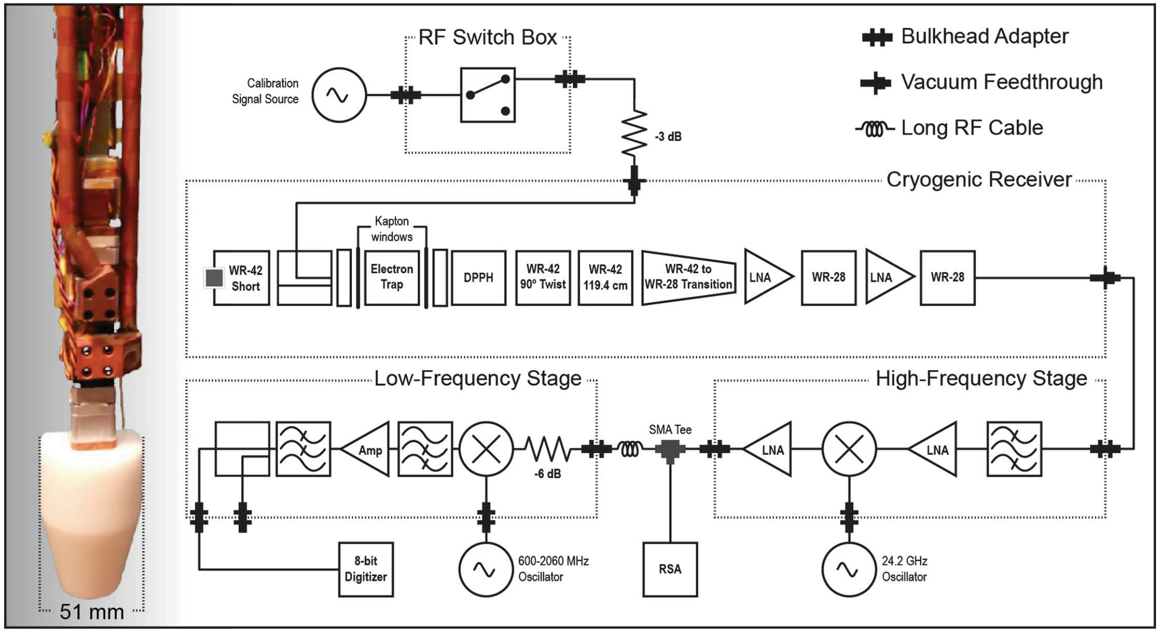
$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi} \frac{1}{m_e + \frac{1}{c^2} E_\beta}$$

Measure entire beta spectrum at once: **C**yclotron **R**adiation **E**mission **S**pectroscopy (**CRES**)



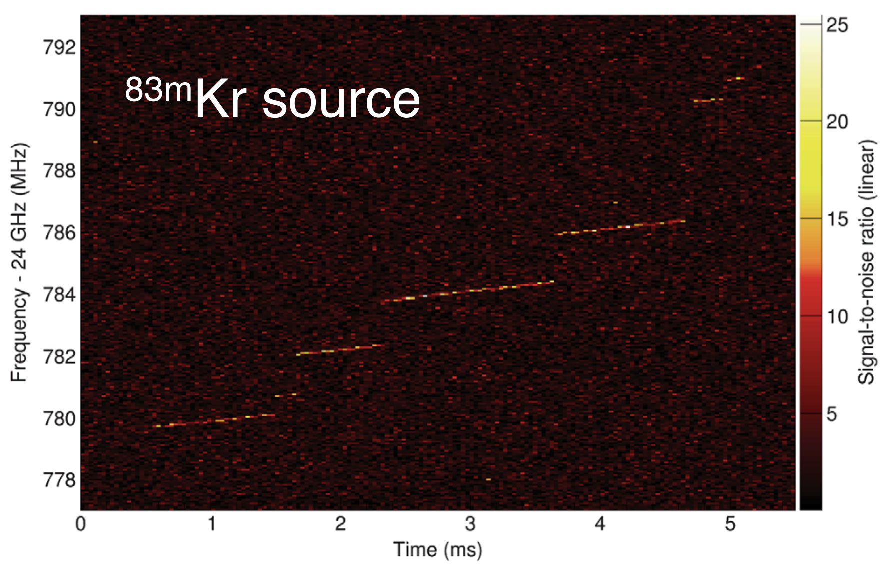
*Monreal and Formaggio, PRD **80** (2009)*

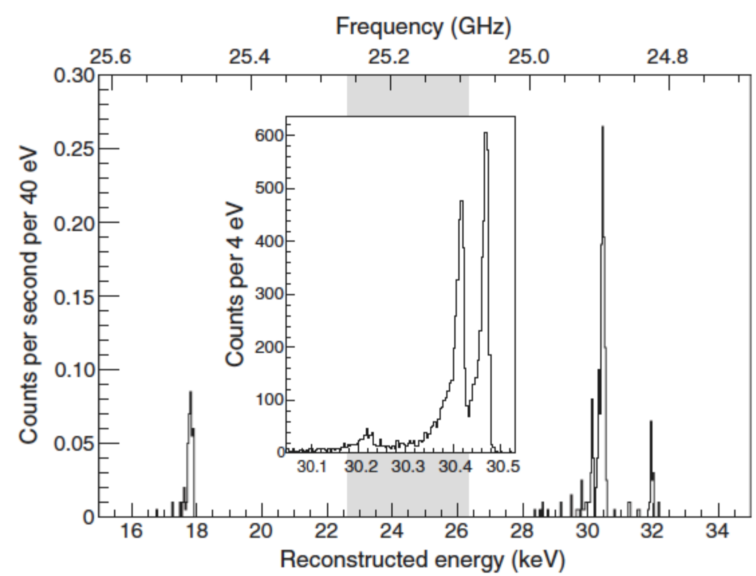
CRES single electron detection



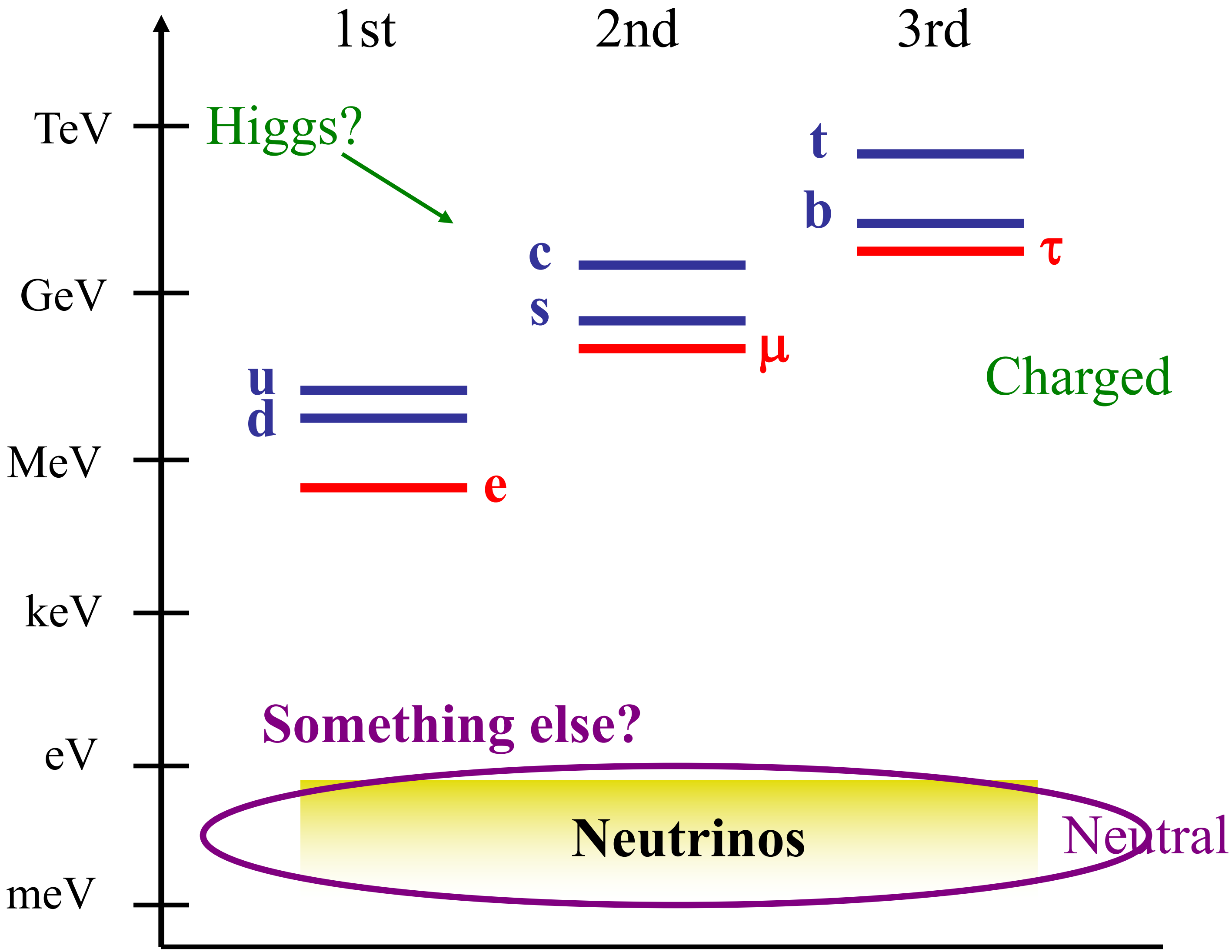
PROJECT 8

PRL 114, 162501 (2015)



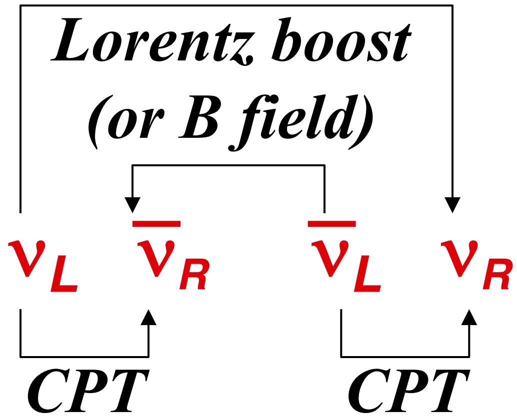


Neutrino mass puzzle



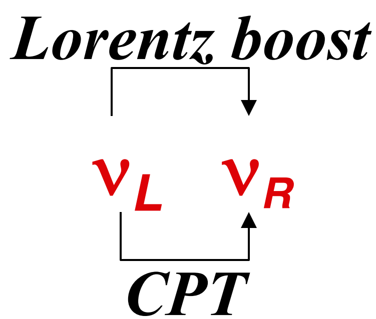
Massive neutrinos

“Dirac” neutrinos



“Majorana” neutrinos

No lepton number conservation!



The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Seesaw mechanism

Experimentally, it is an open question whether neutrinos are Majorana or Dirac, but Majorana neutrinos are strongly preferred by theorists. Seesaw mechanism can be used to explain small neutrino masses (see 2019 PDG). Type I seesaw mechanism (Gell-Mann, Ramond, Slansky and Yanagida, 1979):

$$\mathcal{L}_{\mathrm{Y,M}}(x) = \left(\lambda_{il}\,\overline{N_{iR}}(x)\,\Phi^{\dagger}(x)\,\psi_{lL}(x) + \text{h.c.}\right) - \frac{1}{2}M_i\,\overline{N_i}(x)\,N_i(x)$$

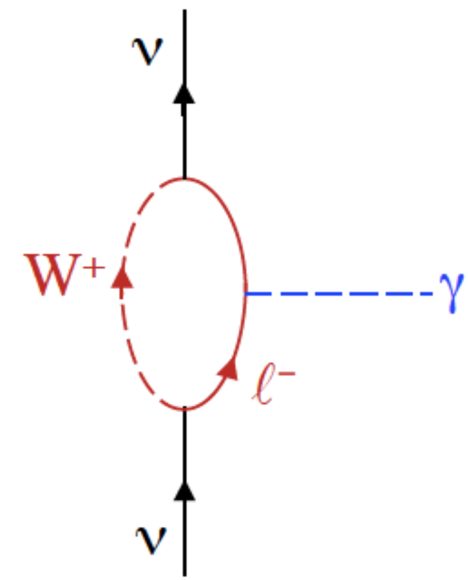
$$m^{LL}_{l'l} \cong -(m^D)^T_{l'j}M_j^{-1}m^D_{jl} = -v^2(\lambda)^T_{l'j}M_j^{-1}\lambda_{jl}$$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}$$

$$Z^T M_\nu Z = D_\nu = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \approx \begin{bmatrix} m_D^2 / m_R & 0 \\ 0 & m_R \end{bmatrix}$$

Electromagnetic properties of ν

Electromagnetic properties arise at the loop level. Dirac masses in the standard model give a prediction that the diagonal moments are proportional to the neutrino mass:



$$\mu_\nu = \frac{3 m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV}\right) \mu_B$$

In an extension with right handed neutrinos, the electric dipole vanishes for both Dirac and Majorana neutrinos, but the magnet moment also vanishes for Majorana neutrinos (can still have transition magnetic moments).

Experimental search for μ_ν

$$\mu_\nu = \frac{3m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV}\right) \mu_B$$

With known limits on neutrino mass, the "SM prediction" is small, so experimentally the search is for an anomalous magnetic moment of the neutrino. This is typically done by solar or reactor neutrino experiments, and neutrino oscillation parameters are taken into account.

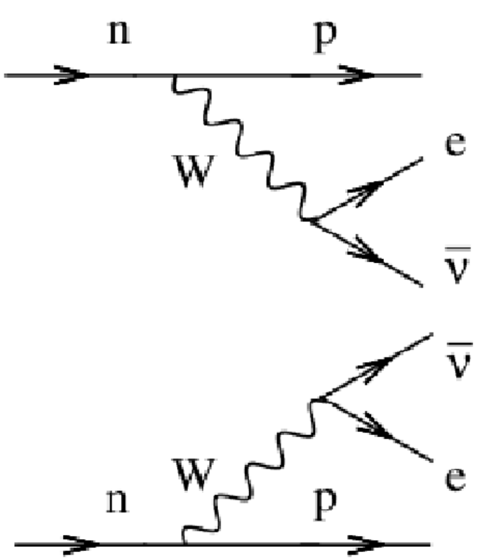
The best direct limit comes from Borexino using the spectral shape of electron recoils due to solar neutrinos (which would be affected if there were additional contributions to the cross-section due to an electromagnetic interaction term):

$$\mu_\nu^{eff} < 2.8 \cdot 10^{-11} \ \mu_B \text{ at } 90\% \text{ c.l.}$$

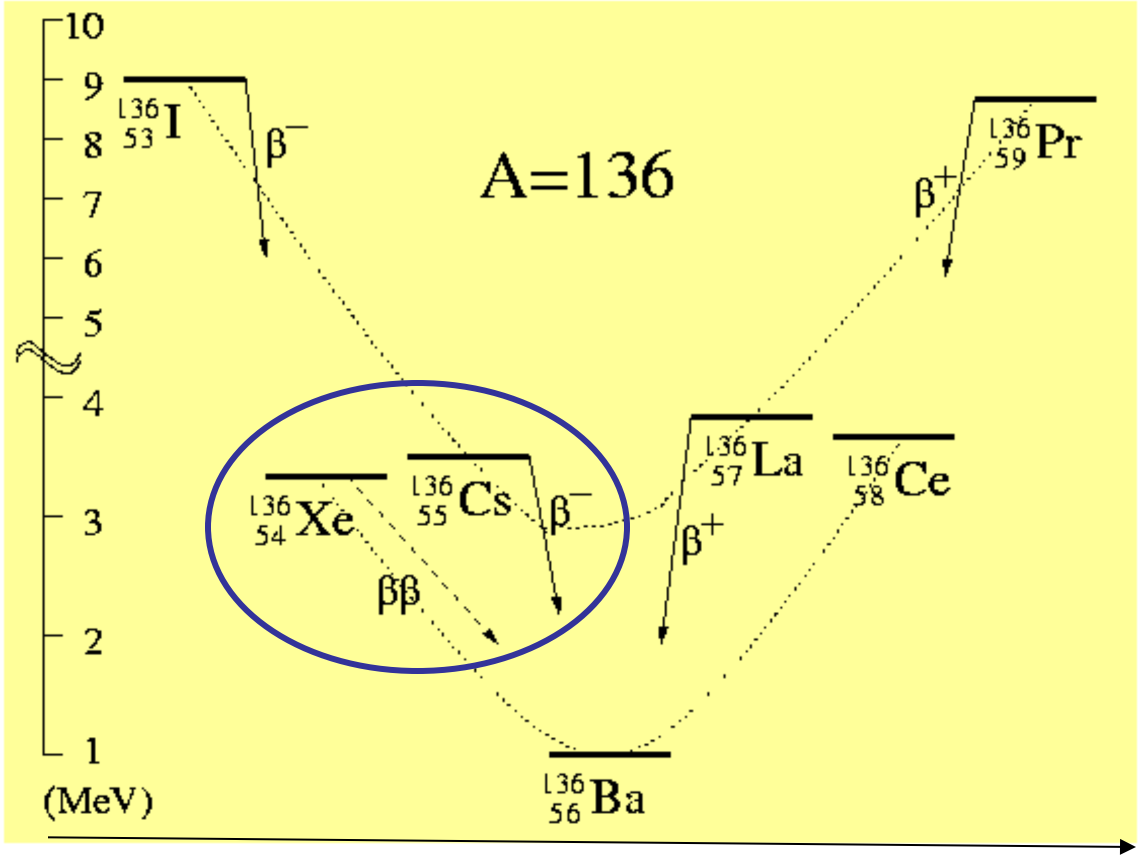
Agostini et al. Phys. Rev. D 96, 091103 (2017)

Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512



$2\nu\beta\beta$



Atomic number (Z)

Some candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

S. R. Elliott, A. A. Hahn, and M. K. Moe
Department of Physics, University of California, Irvine, Irvine, California 92717
(Received 31 August 1987)

The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times 10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

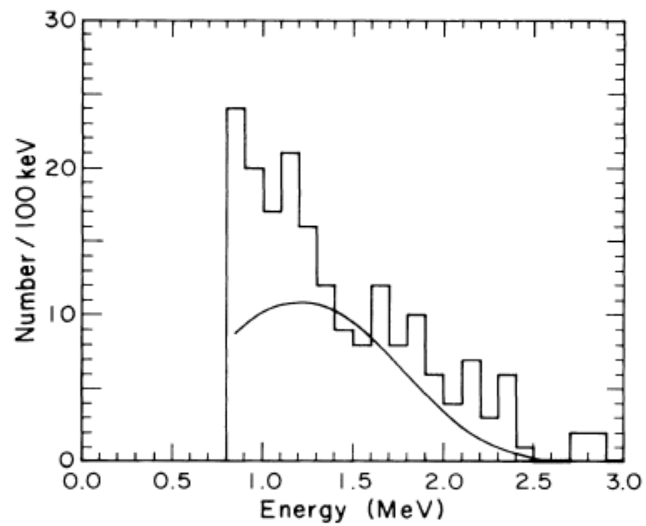
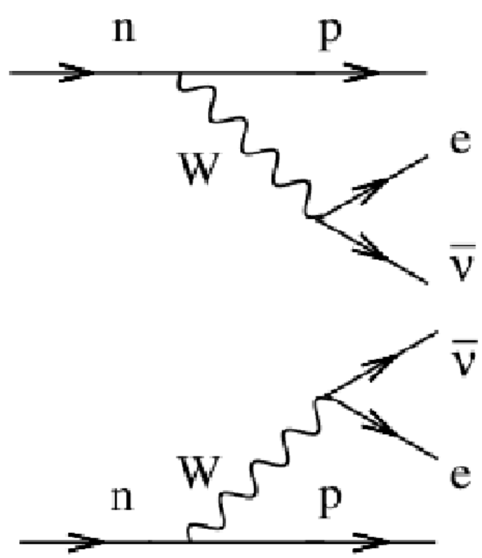


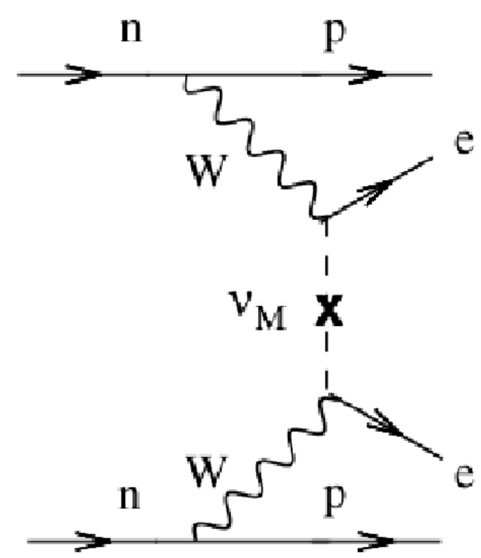
FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

S.R. Elliott, A.A. Hahn, M.K. Moe *Phys. Rev. Lett.* **59** (1987) 2020-2023

Neutrinoless double beta decay



2νββ

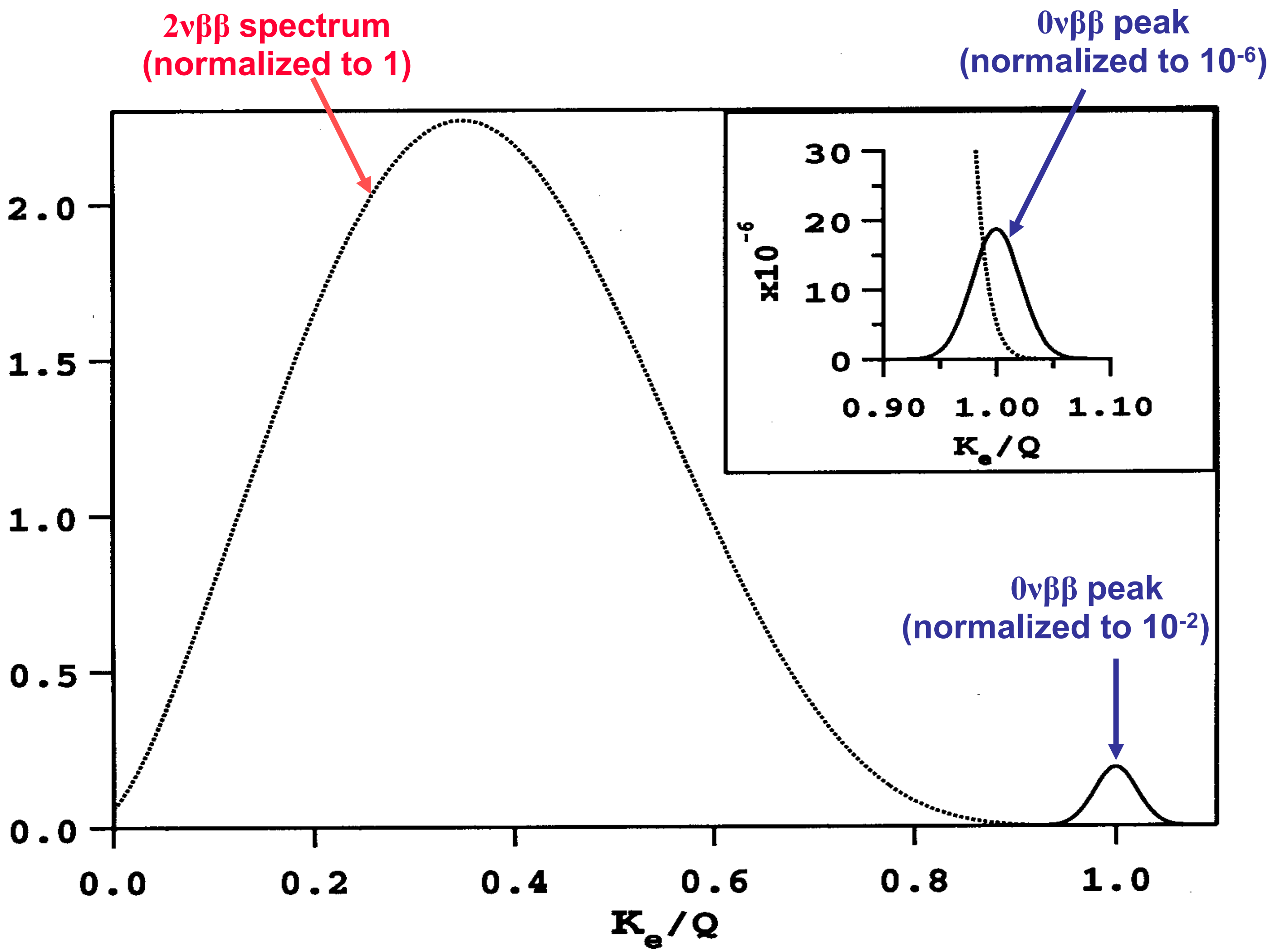


0νββ

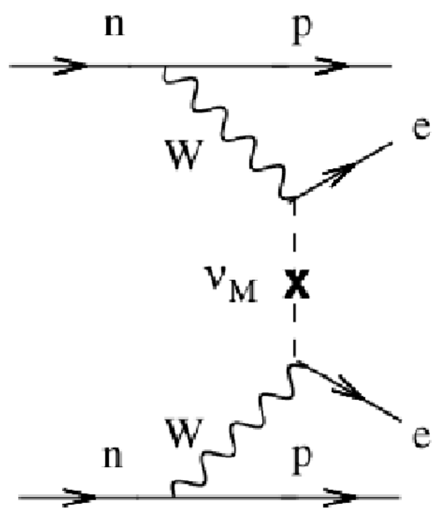
This process can only occur for a Majorana neutrino!

Same candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Double beta decay spectrum



$0\nu\beta\beta$ rate



If we assume that the mechanism is light neutrino exchange, we can write the rate for $0\nu\beta\beta$:

Phase space factor ~Q^5

Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \left\langle m_\nu \right\rangle^2$$

Nuclear matrix element

Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \left\langle m_{\beta\beta}\right\rangle^2$$

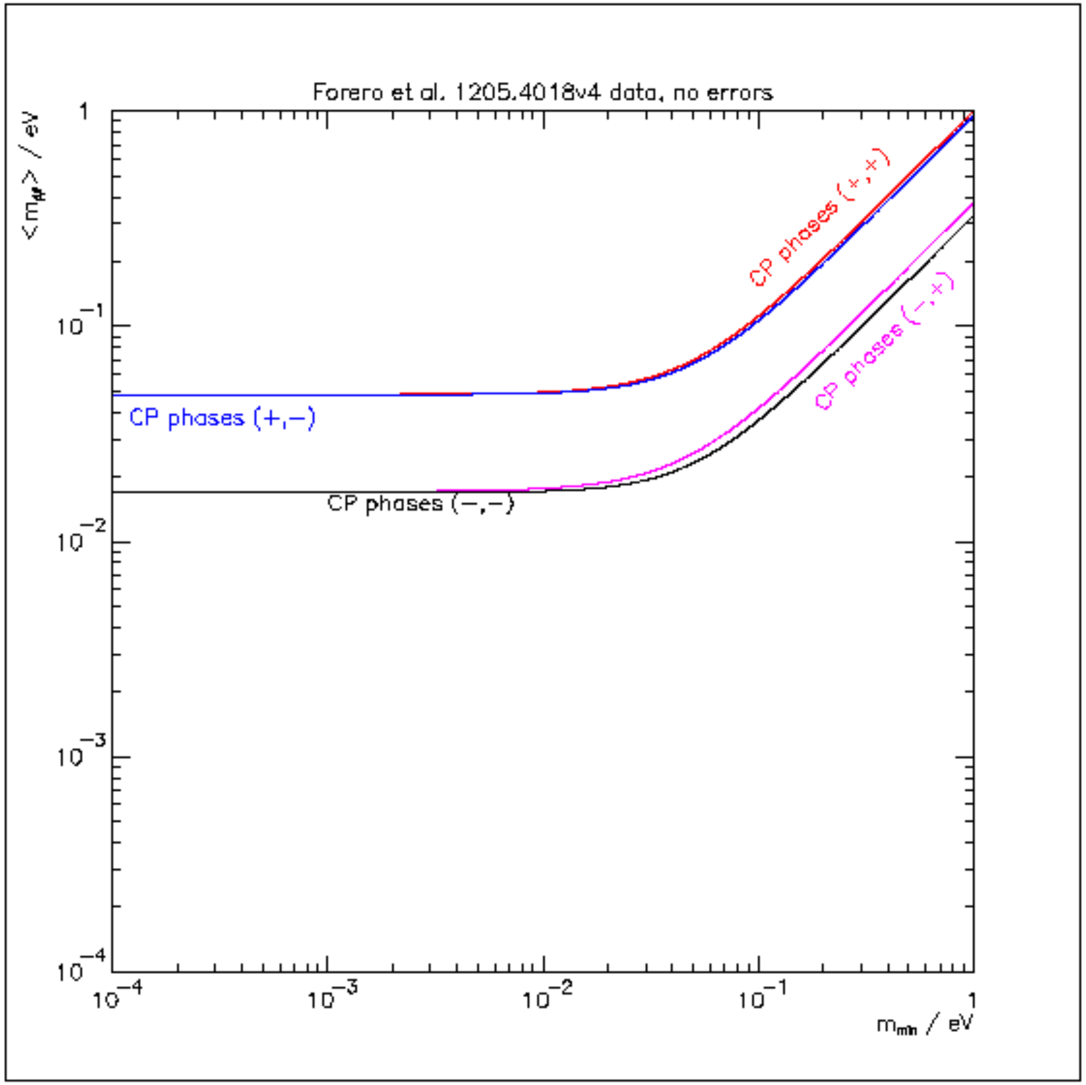
Using the standard representation of the PNMS matrix, the effective Majorana neutrino mass is given as:

$$\begin{aligned}\left\langle \mathrm{m}_{\beta\beta}\right\rangle = \Big| & \mathrm{m}_1 \cdot \left(1-\sin^2\theta_{12}\right)\cdot\left(1-\sin^2\theta_{13}\right) + \\ & \mathrm{m}_2 \cdot \sin^2\theta_{12} \cdot \left(1-\sin^2\theta_{13}\right)\cdot e^{i\cdot(\alpha_2-\alpha_1)} + \\ & \mathrm{m}_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3}\Big|\end{aligned}$$

The three CP phases α_1, α_2, and α_3 are unknown. This uncertainty is expressed by varying:

$$\begin{aligned}\left\langle \mathrm{m}_{\beta\beta}\right\rangle = \Big| & \mathrm{m}_1 \cdot \left(1-\sin^2\theta_{12}\right)\cdot\left(1-\sin^2\theta_{13}\right) \pm_{(1)} \mathrm{m}_2 \cdot \sin^2\theta_{12} \cdot \left(1-\sin^2\theta_{13}\right) \\ & \pm_{(2)} \mathrm{m}_3 \cdot \sin^2\theta_{13}\Big|\end{aligned}$$

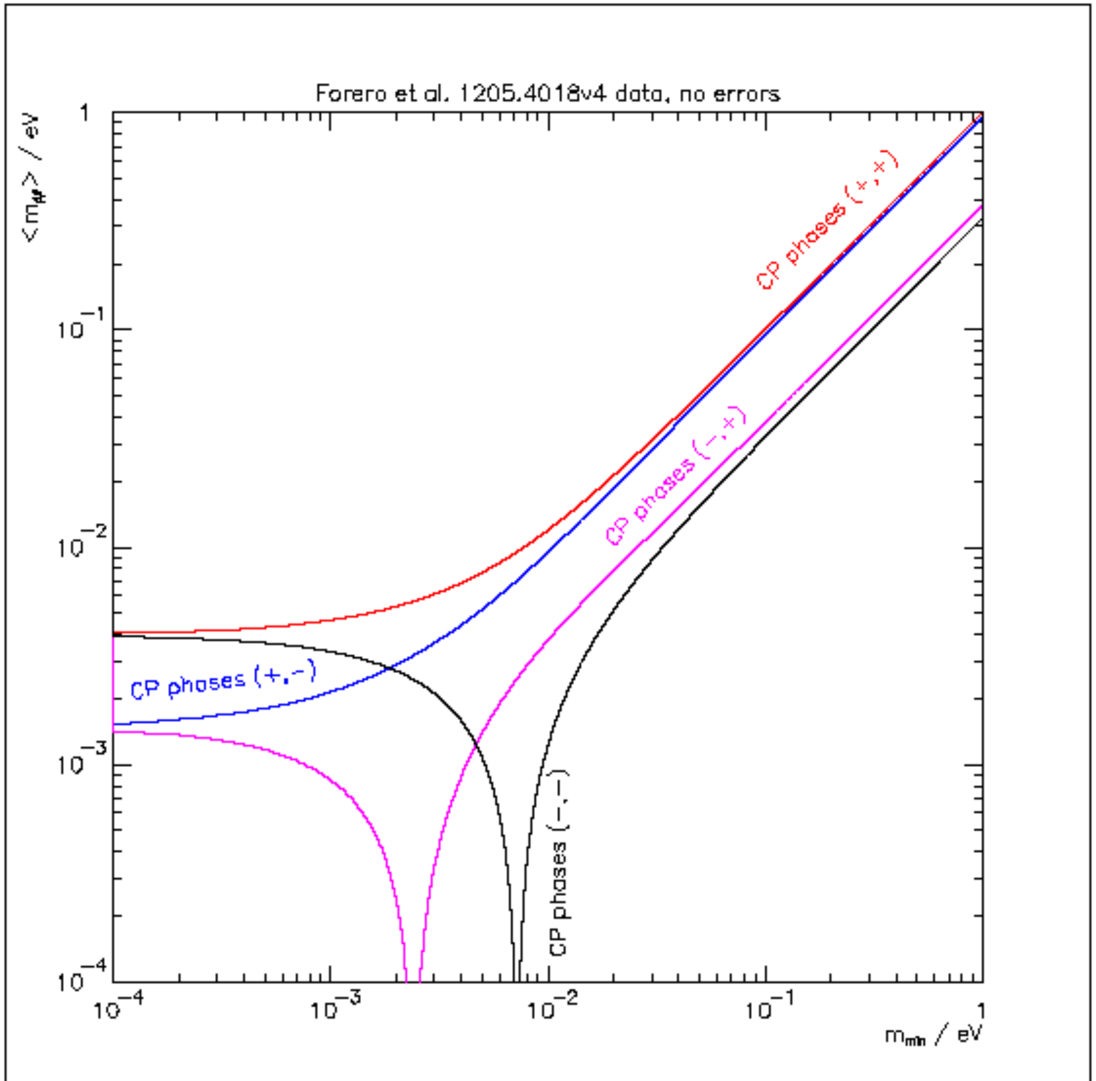
Inverted hierarchy



Now we insert the standard neutrino oscillation parameters (central values). No total cancellation is possible for the inverted hierarchy.

Plots courtesy Andreas Piepke.

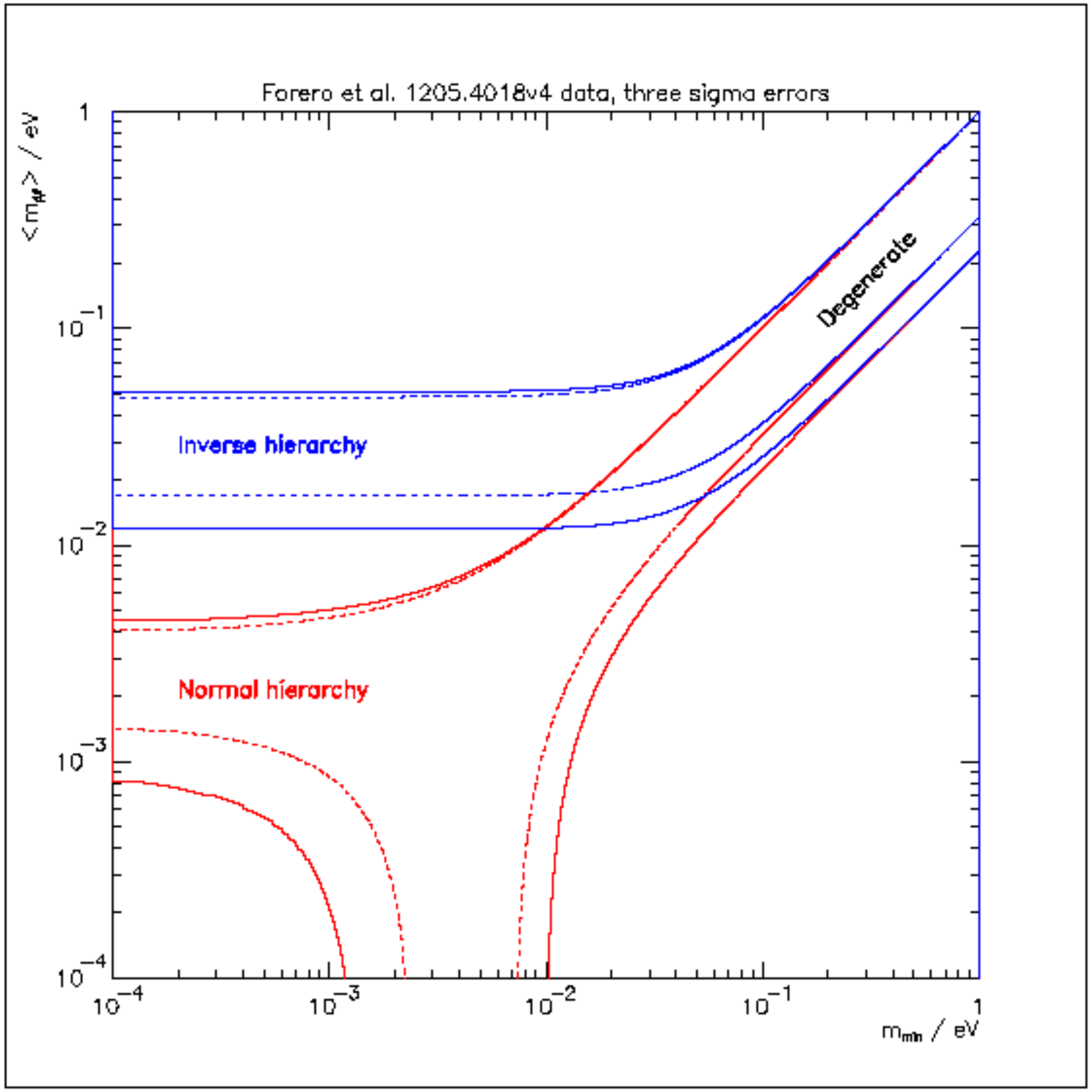
Normal hierarchy



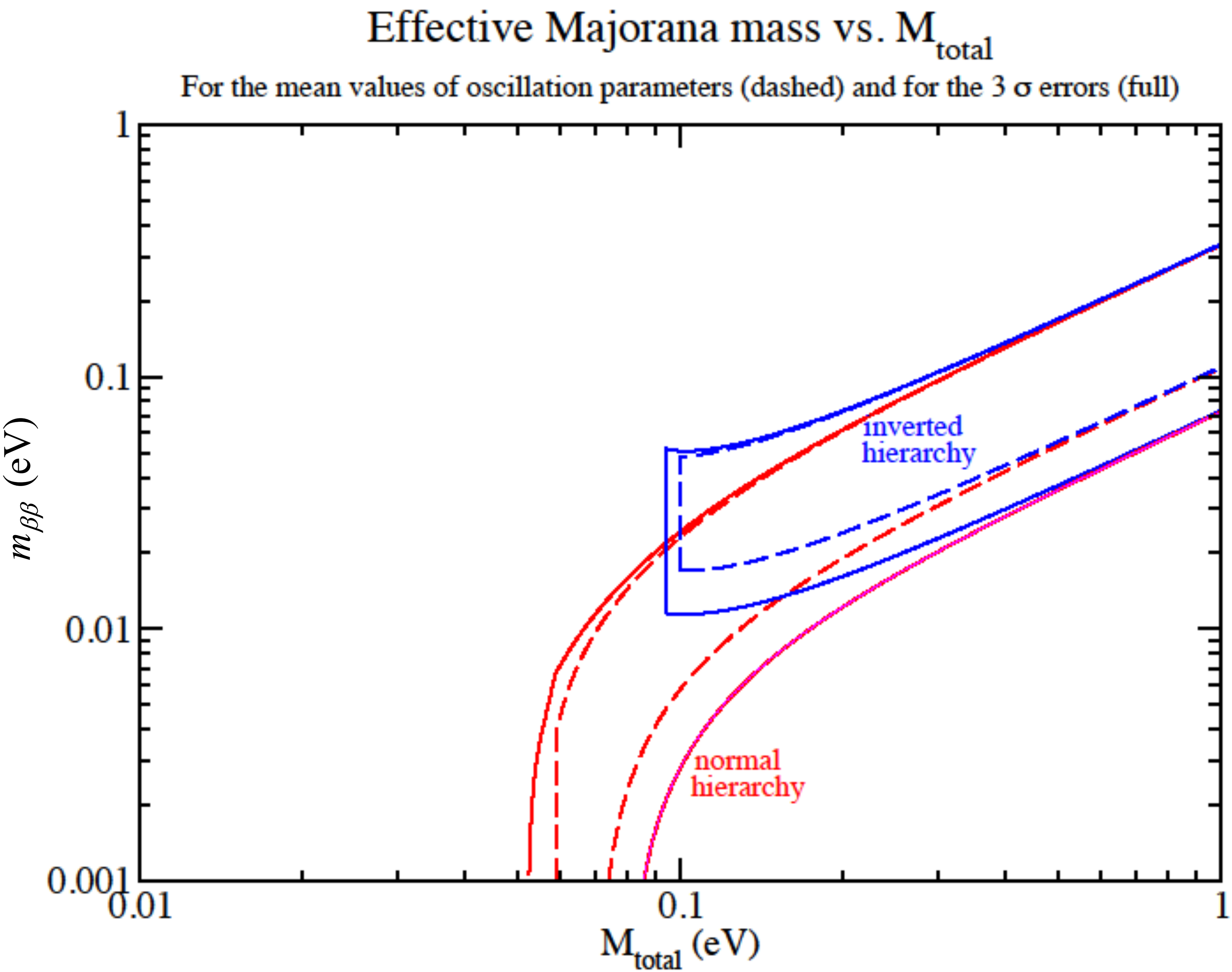
For the normal hierarchy variation of the unknown CP-phases introduces:

1) considerable variation of the effective mass,
2) allows destructive interference for certain values of $m_{\min}$ and choice of phases.

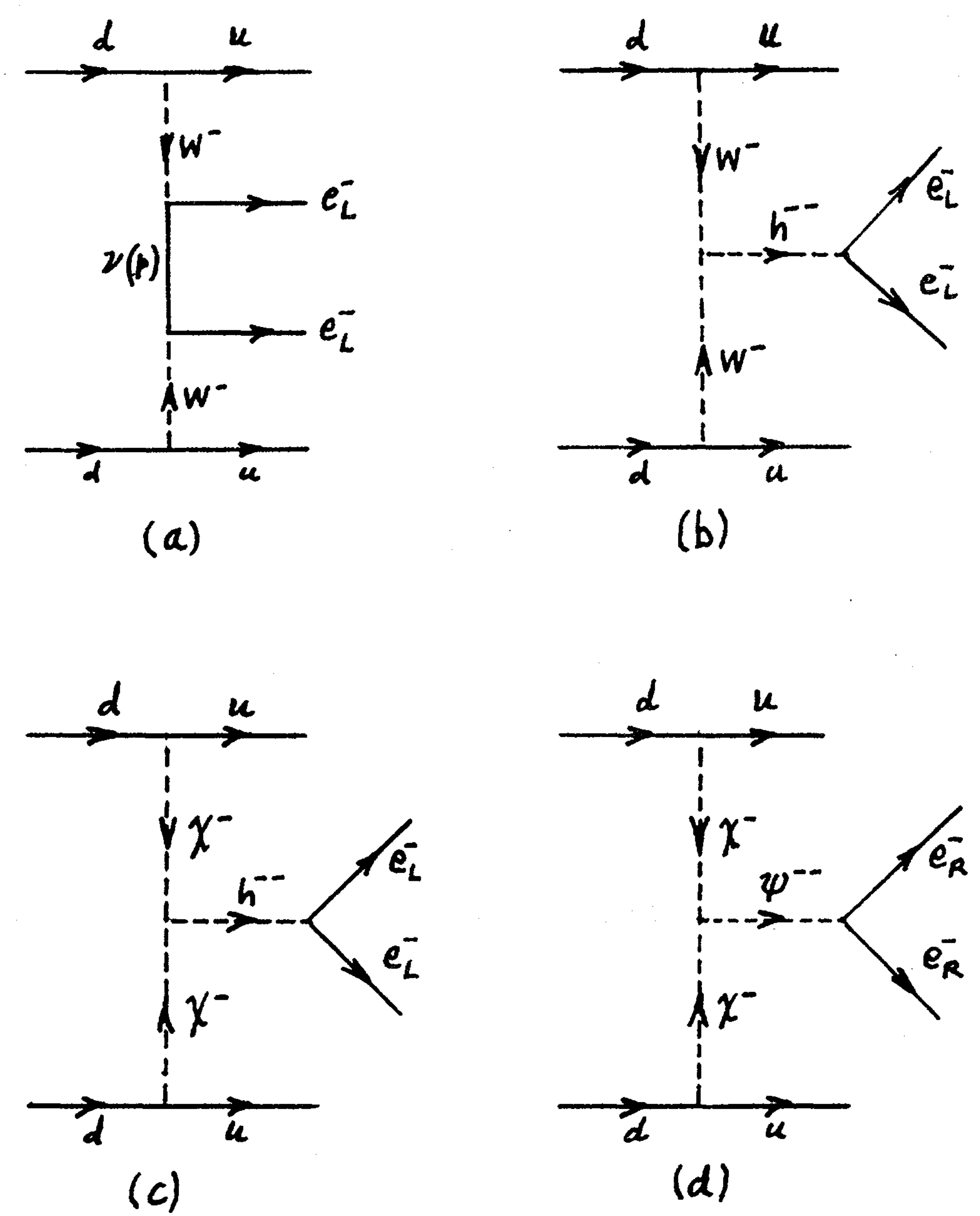
Combined phase space



Inverted and normal hierarchy including 3σ errors on oscillation parameters.


Effective Majorana mass vs. M_{total}
For the mean values of oscillation parameters (dashed) and for the 3 σ errors (full)
1
0.1
0.01
0.001
$m_{\beta\beta}$ (eV)
0.01
0.1
1
M_{total} (eV)
inverted hierarchy
normal hierarchy

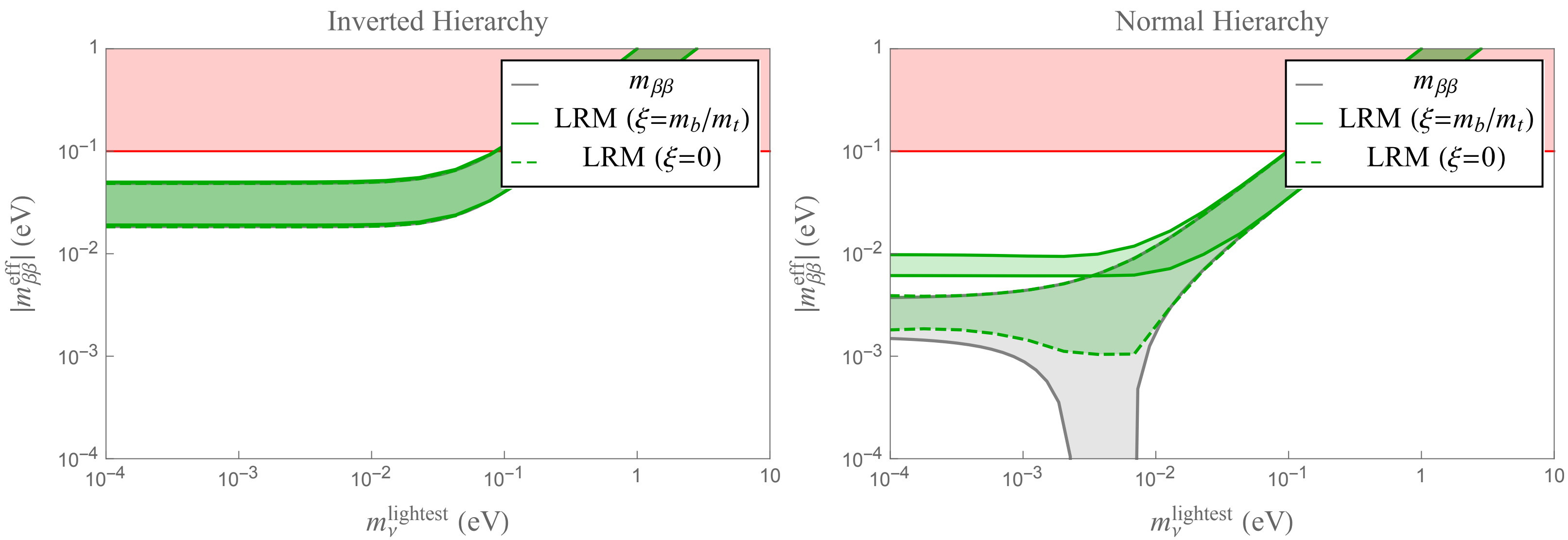
Mechanism?



In some cases, it's possible to determine the mechanism by measuring the opening angle between the electrons.

Other mechanisms

While it is convenient to think in terms of the light neutrino exchange mechanism, no reason to think it's dominant!



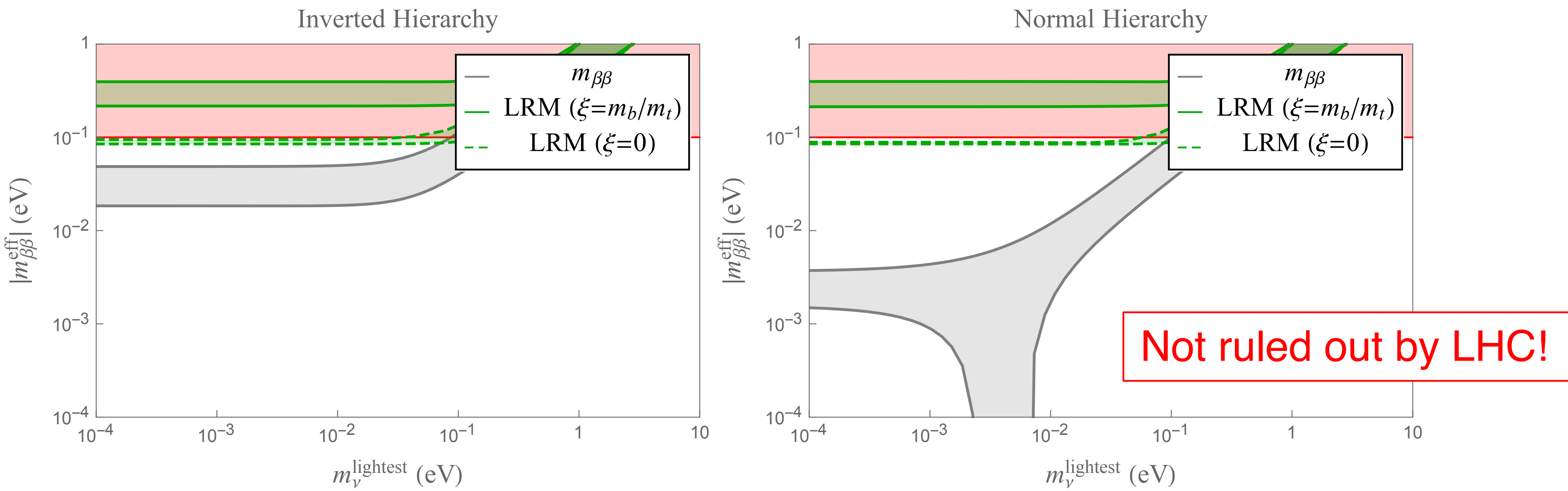
Consider a model with 10 TeV right-handed neutrinos in the minimal left-right symmetric model, symmetric under charge conjugation (assuming that the mixing matrix of the right-handed neutrinos is the same as the PMNS matrix).

See Cirigliano, V., Dekens, W., de Vries, J. et al. "A neutrinoless double beta decay master formula from effective field theory," J. High Energ. Phys. (2018) 2018: 97.

Thanks to Wouter Dekens for help with this material.

Other mechanisms

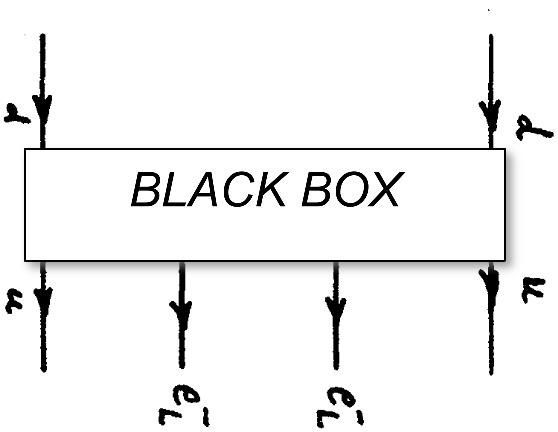
While it is convenient to think in terms of the light neutrino exchange mechanism, no reason to think it's dominant!

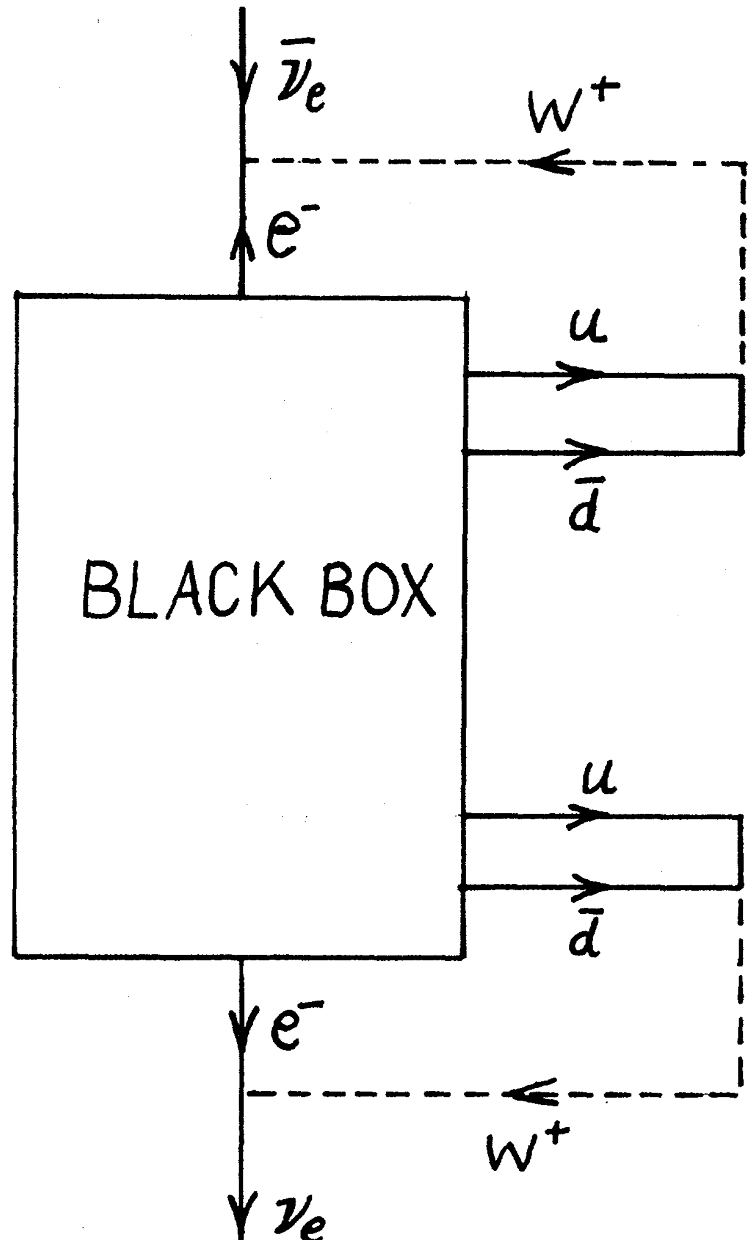


Now consider the same model with 10 GeV right-handed neutrinos in the minimal left-right symmetric model, symmetric under charge conjugation. Alternate mechanism would dominate over light Majorana neutrino exchange.

See Cirigliano, V., Dekens, W., de Vries, J. et al. "A neutrinoless double beta decay master formula from effective field theory," J. High Energ. Phys. (2018) 2018: 97. Thanks to Wouter Dekens for help with this material.

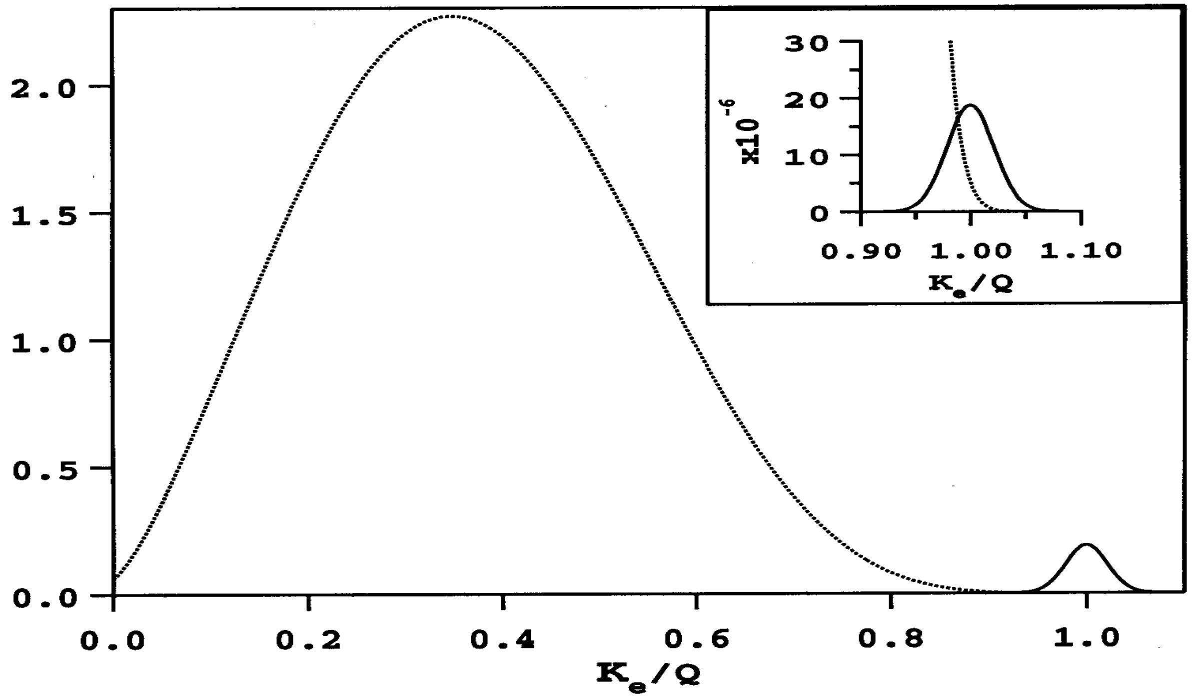
Black box theorem (Schechter and Valle)





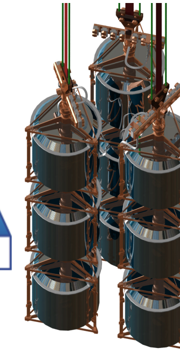
See also JHEP 1106:091, 2011

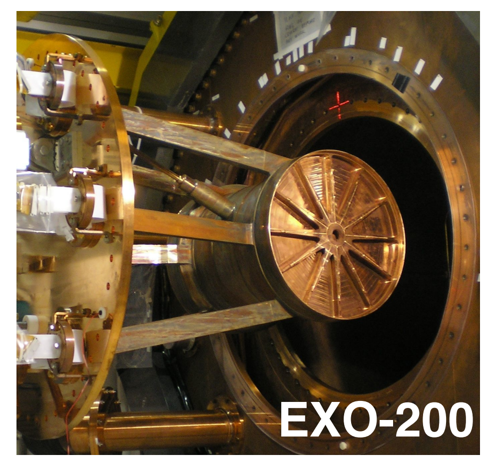
How to search for $0\nu\beta\beta$



- **Large exposure**
- **Low background**
- Good energy resolution
- High detection efficiency
- **Detection in multiple isotopes!**

GERDA





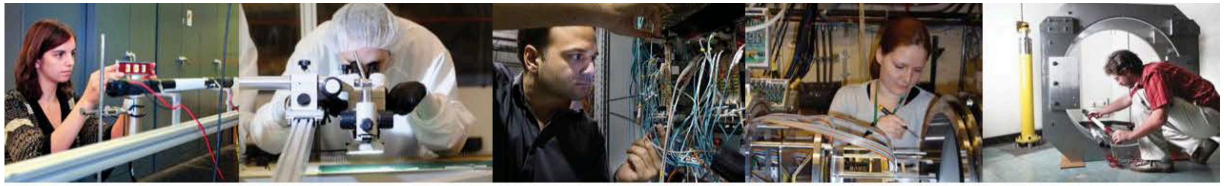
Current best $0\nu\beta\beta$ sensitivities

Isotope	Experiment	Exposure (kg yr)	Average half-life sensitivity (10^{25} y)	Half-life limit (10^{25} y) 90% C.L.	Effective mass limit (meV) Range from NME*	Reference
^{76}Ge	GERDA	127.2	18	> 18	< 79−180	Agostini et al. PRL 125, 252502 (2020)
	MJD	26.0	4.8	> 2.7	< 200-433	Alvis et al. Phys Rev C 100, 025501 (2019)
^{130}Te	CUORE	288	2.8	> 2.2	< 90-305	Adams et al. arXiv:2104.06906 (2021)
^{136}Xe	EXO-200	234.1	5.0	> 3.5	< 93-286	Anton et al. PRL 123, 161802 (2019)
	KamLAND-ZEN	504	5.6	> 10.7	< 60-161	Gando et al., PRL 117, 082503 (2016)

*Note that the range of NME is chosen by the experiments.

To achieve higher sensitivity, the next generation of experiments will be at the tonne-scale.

A priority for US nuclear physics



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

RECOMMENDATION II:
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.
"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

INITIATIVE B:
"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

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 (see Long Baseline Oscillations lectures later this week).
- There are several experimental approaches for weighing neutrinos in the laboratory!
- The next generation of neutrinoless double beta decay experiments are poised to determine the nature of that mass (see Neutrinoless Double Beta Decay lectures later this week).