3 June, 2020

SAP Virtual Lecture Series

Neutrinos: an overview

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SNOLAB

Outline

- What ***IS*** a neutrino?

- What we ***DO*** know about neutrinos
  - How we know it - Experimental Perspective

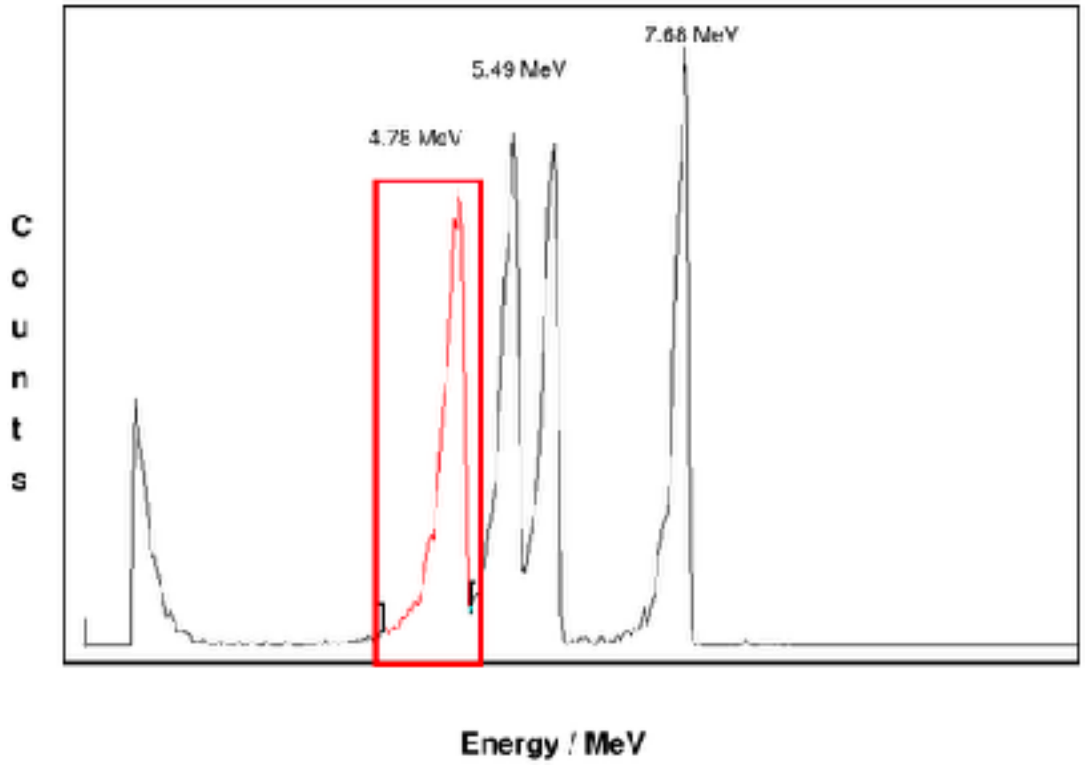
- What we still ***DON'T*** know about neutrinos
  - How we plan to find it out
  - Focus on 🇨🇦 experiments

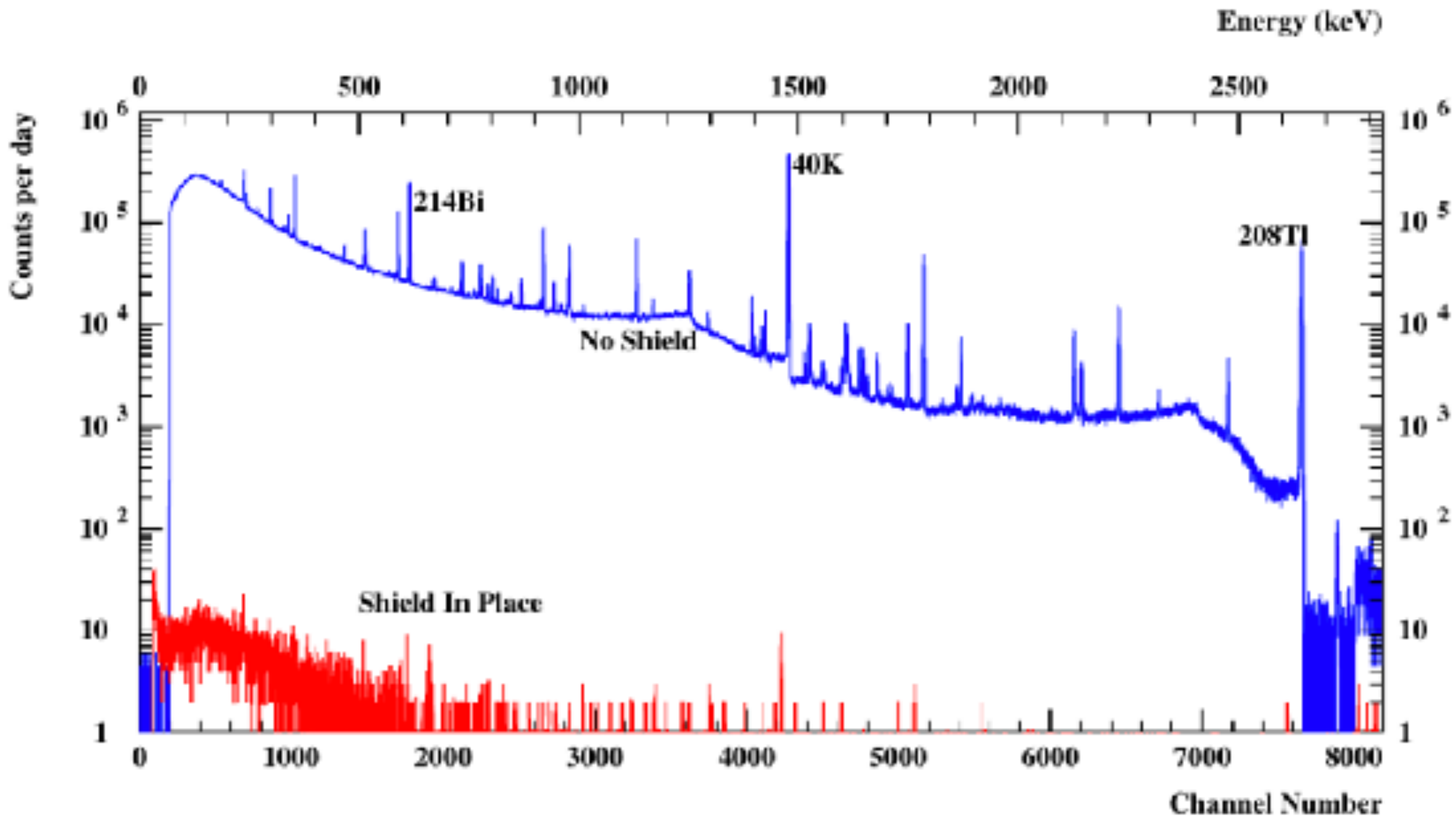
Neutrinos!

https://www.particlezoo.net/

1930: Beta Spectrum Problem

- Early particle physicists studied the energy spectra of collisions
- Alphas and gammas had sharp recognizable peaks





1930: Beta Spectrum Problem

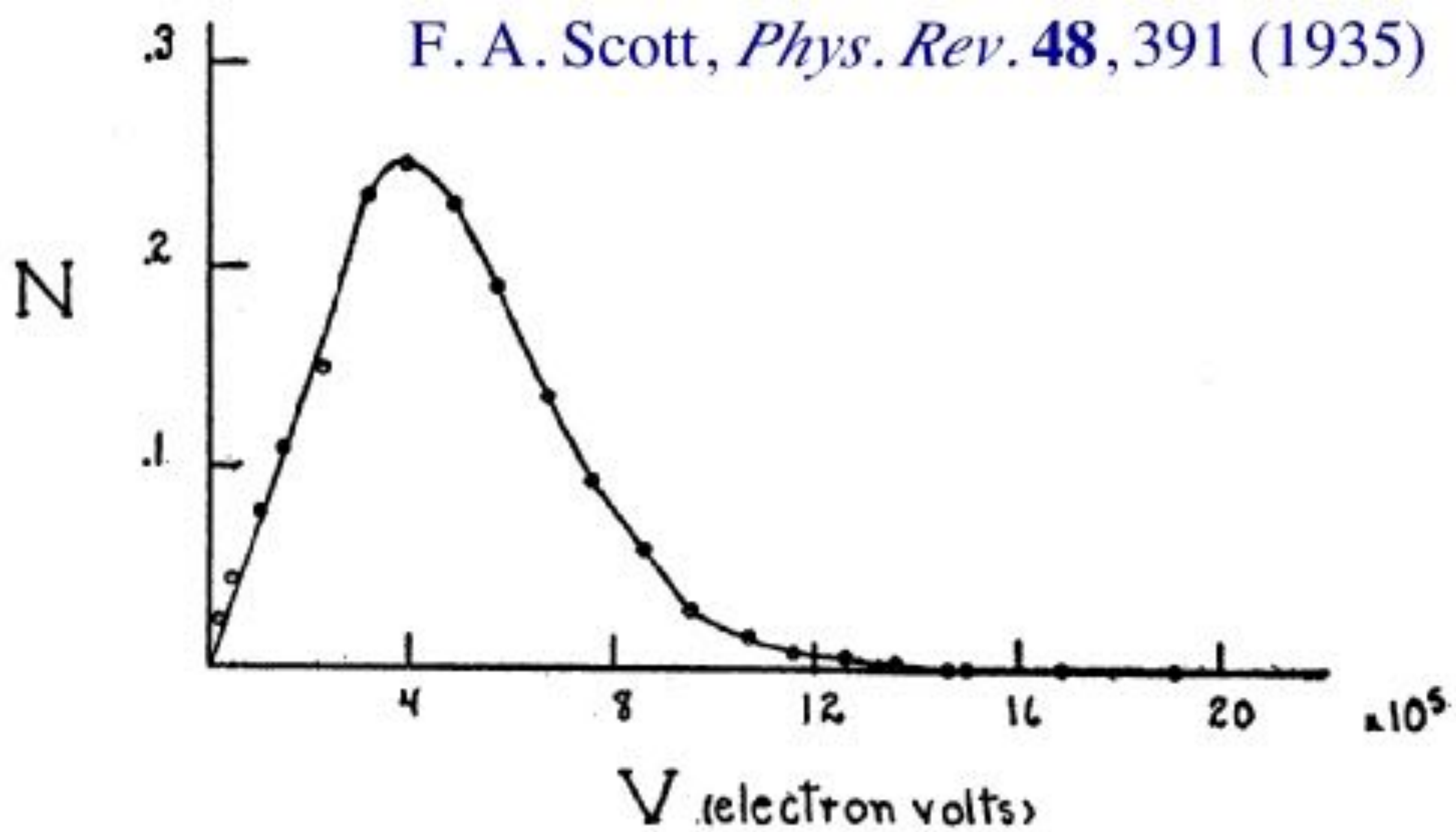
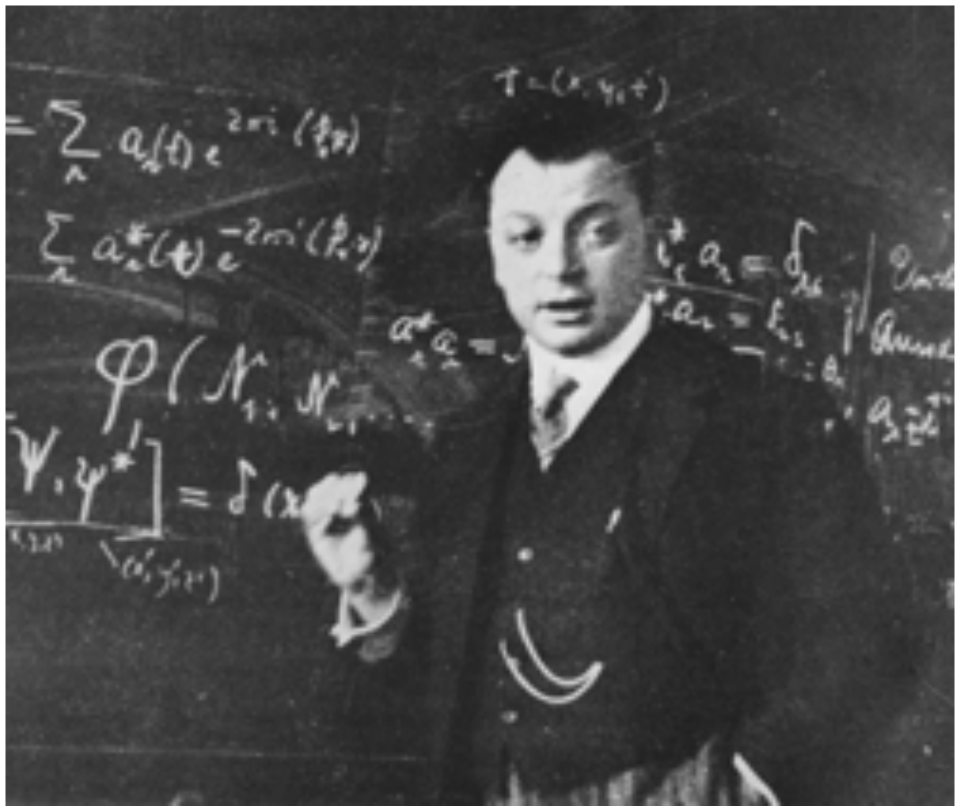


FIG. 5. Energy distribution curve of the beta-rays.

- Betas had broad spectra, which seemed to violate conservation of energy
- Reactions also violated conservation of momentum

1930: Beta Spectrum Problem



"I have done a terrible thing, I have predicted a particle that can never be detected."

-Wolfgang Pauli

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

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.

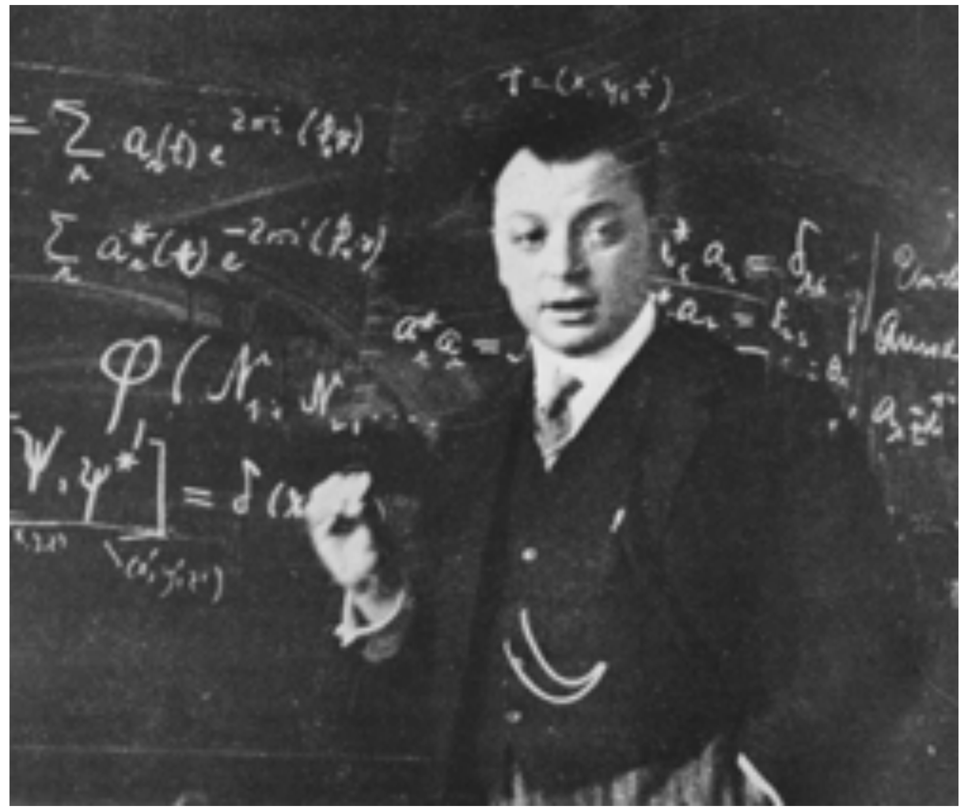
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

1930: Beta Spectrum Problem



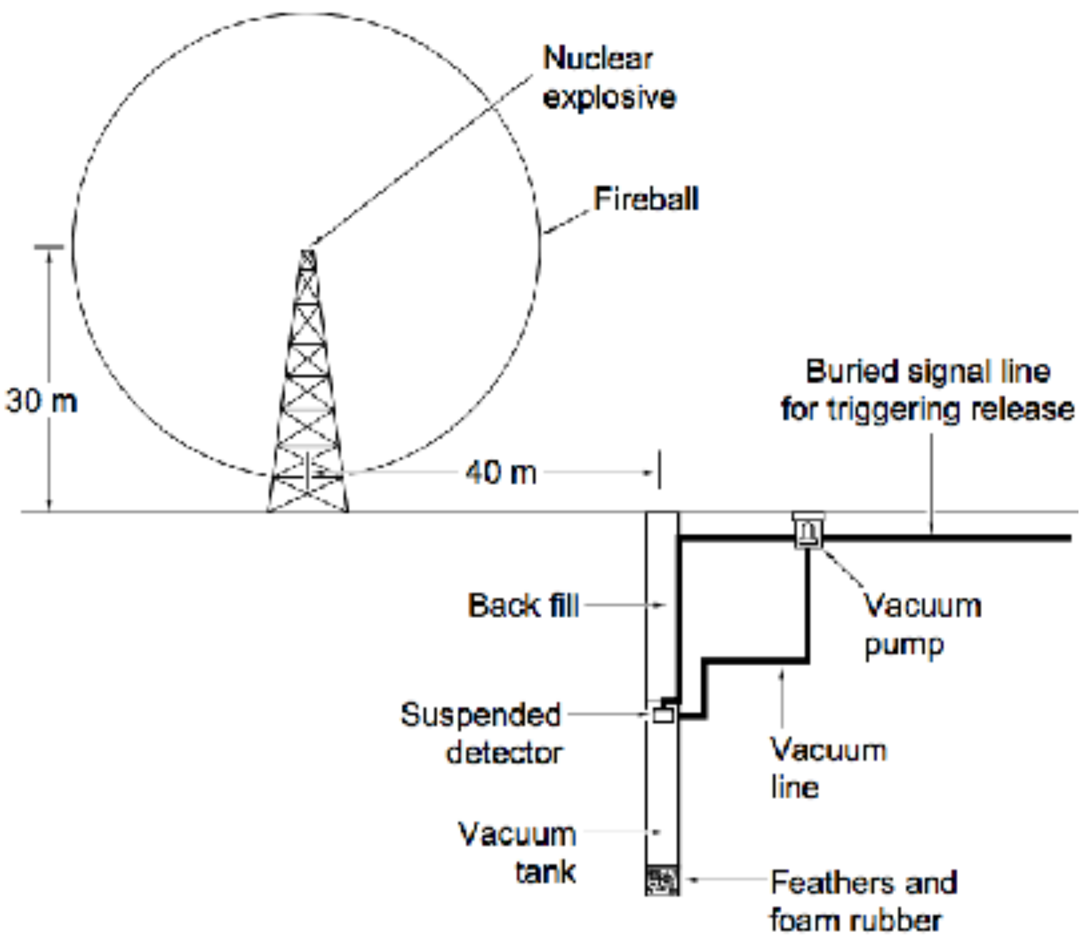
"I have done a terrible thing, I have predicted a particle that can never be detected."
-Wolfgang Pauli

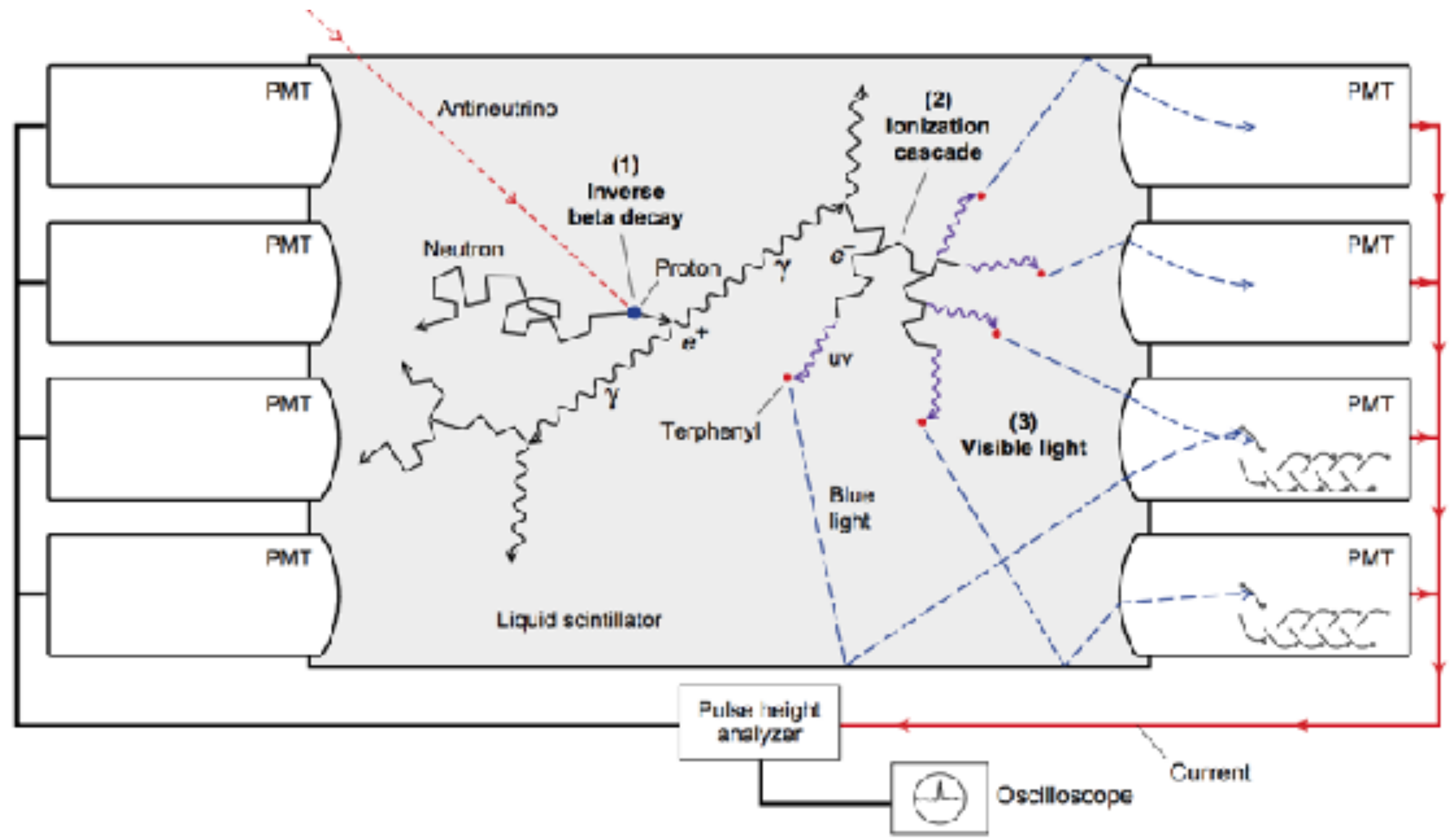
Reines-Cowan Experiment

Fred Reines

Clyde Cowan

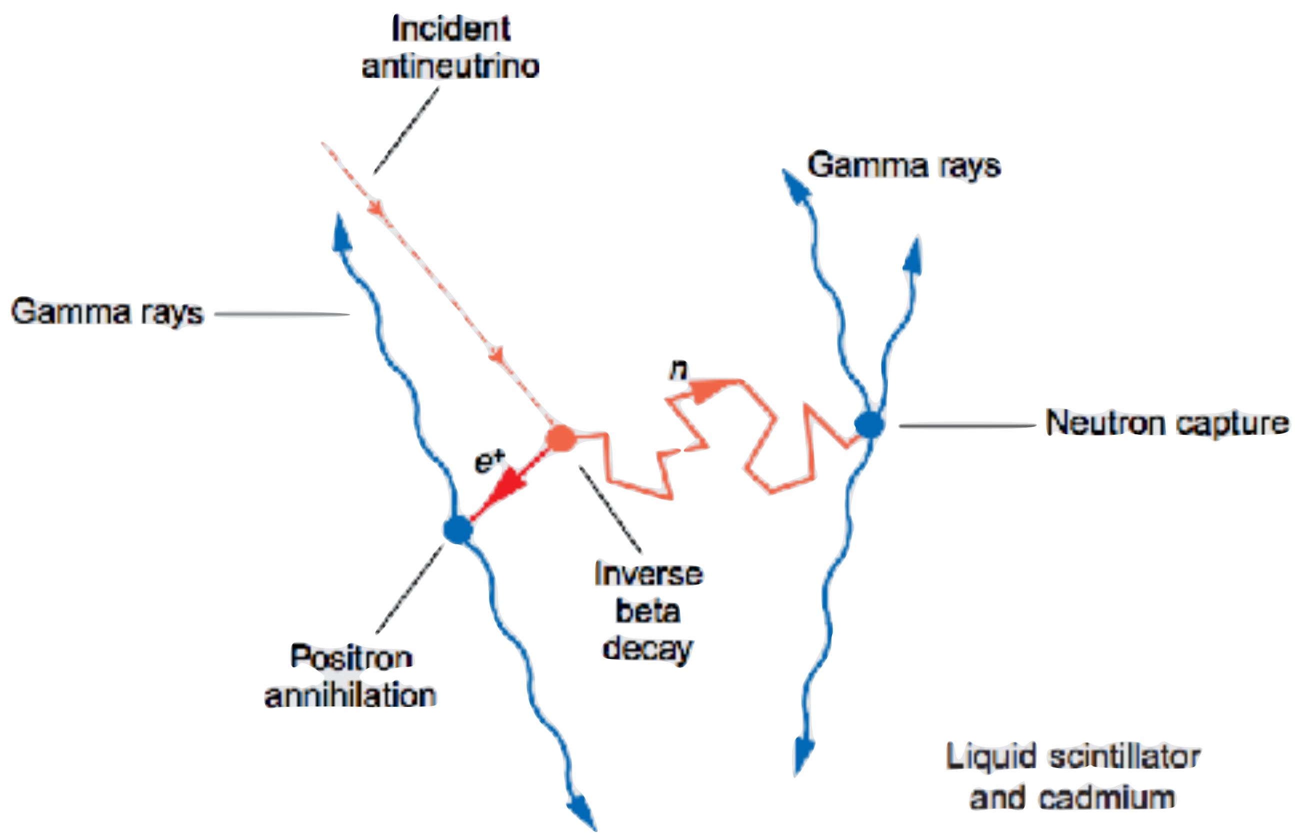
- In 1951, Reines had the idea to detect neutrinos from the explosions of atomic bombs!
- 1 T detector needed, 10^3 bigger than anything tried before.
- Scintillator detector - new technology then





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

Inverse Beta Decay

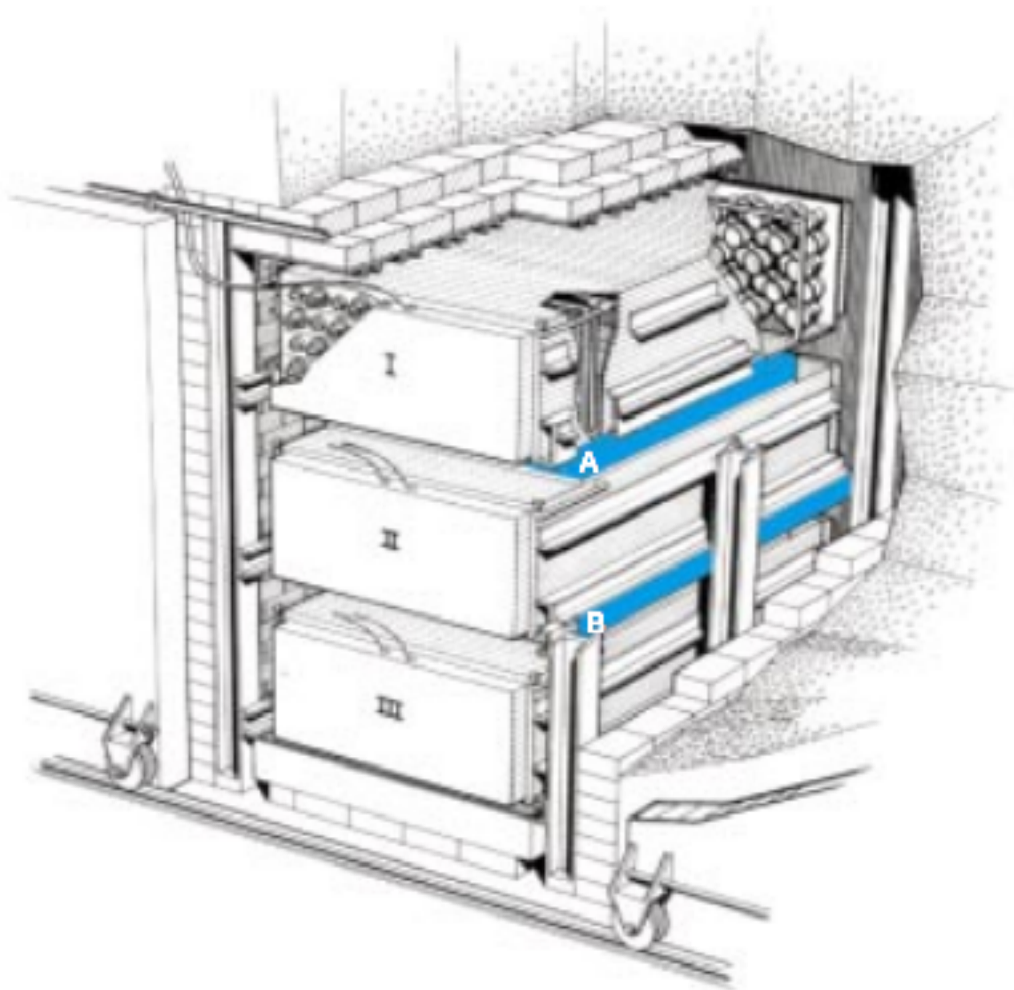


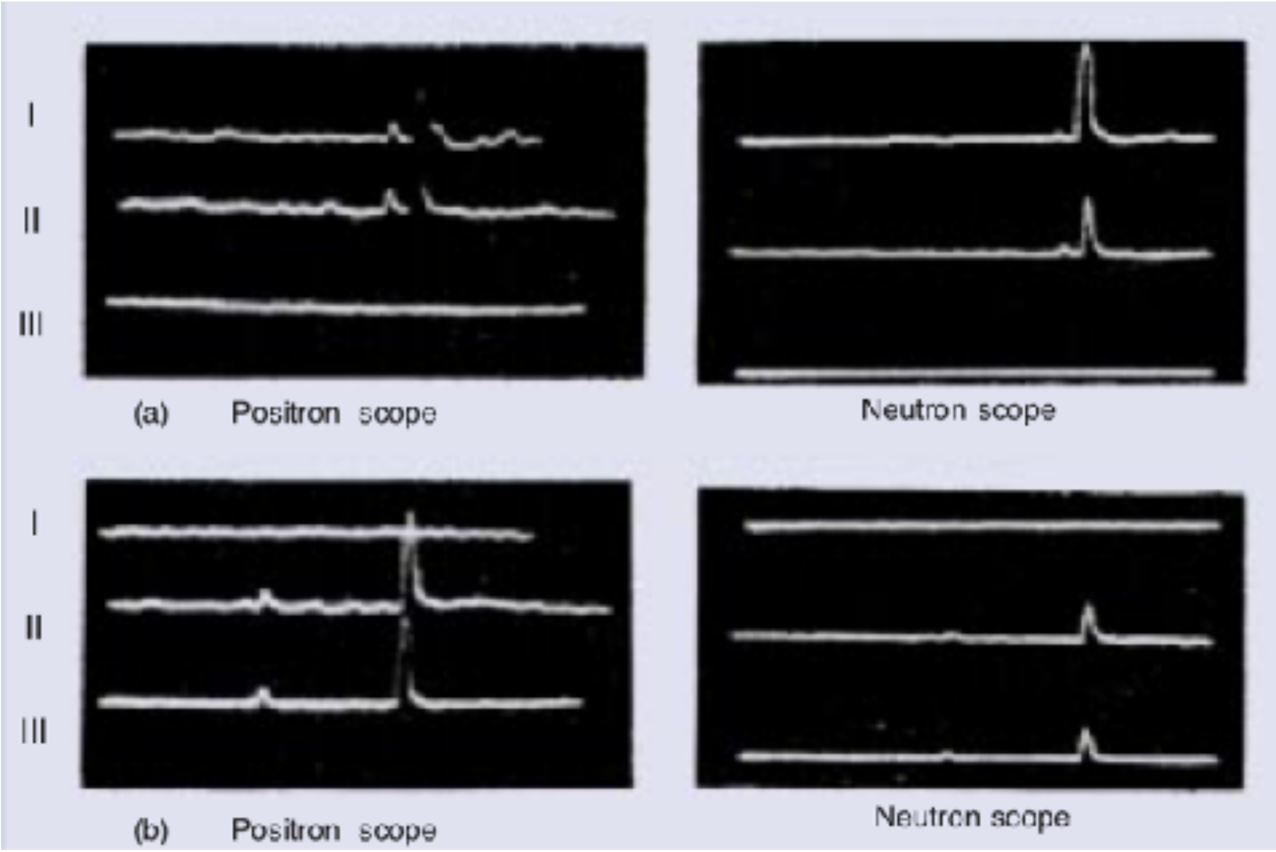
$$\bar{\nu}_e + p \rightarrow n + e^+$$

	σ [b]	E [MeV]
H	0.33	2.2
^{113}Cd	19820	9

- Electronic circuits could be designed to detect this "delayed-coincidence" signature, two well defined flashes of light separated by microseconds provide a powerful means to discriminate the signature of inverse beta decay from background noise.

1956: Savannah River Reactor

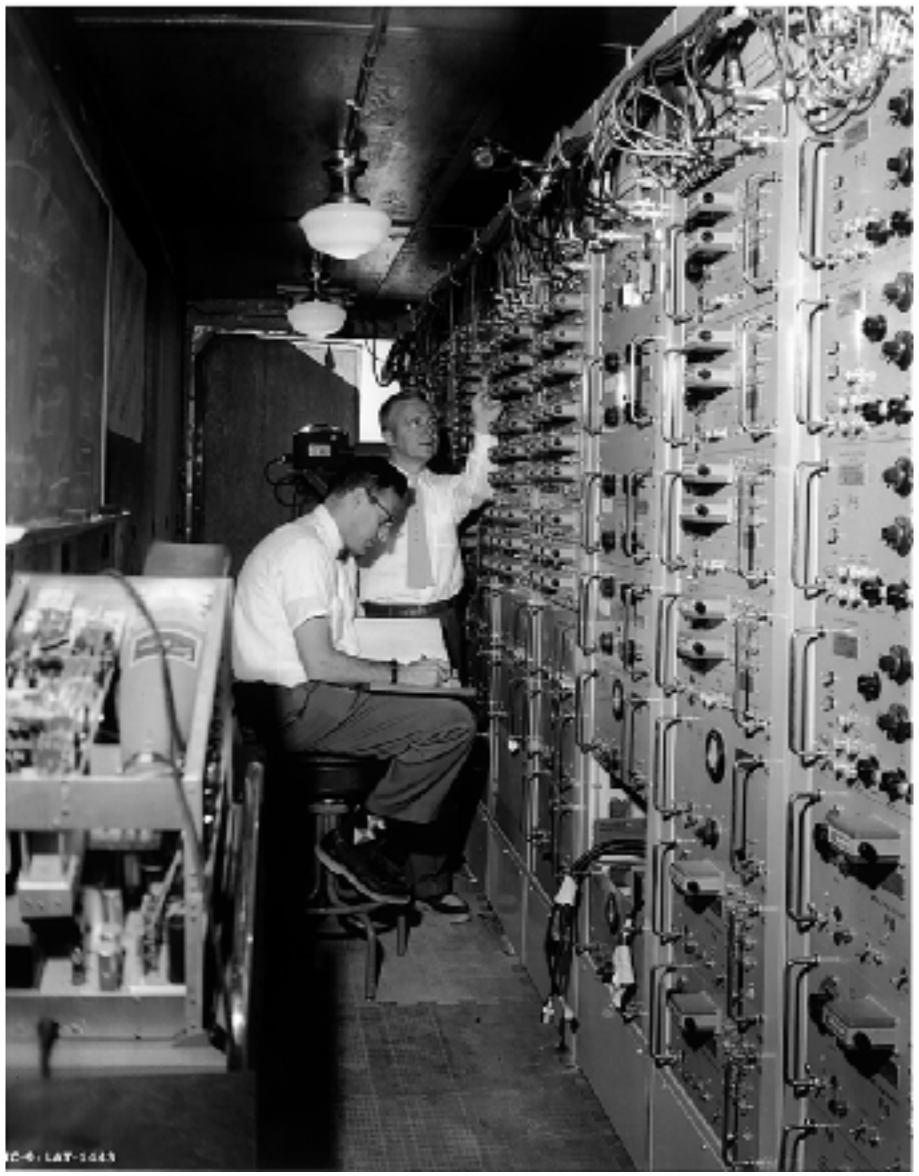




- Two large, flat plastic tanks filled with H2O as target for inverse beta decay
- Cd_2Cl_4 dissolved in the water for neutron capture
- The target tanks were sandwiched between three large scintillation detectors with 110 photomultiplier tubes to collect scintillation light

- Signal 5 times greater than when reactor on vs off, ~1 reactor-associated event per hour.

1956: Savannah River Reactor

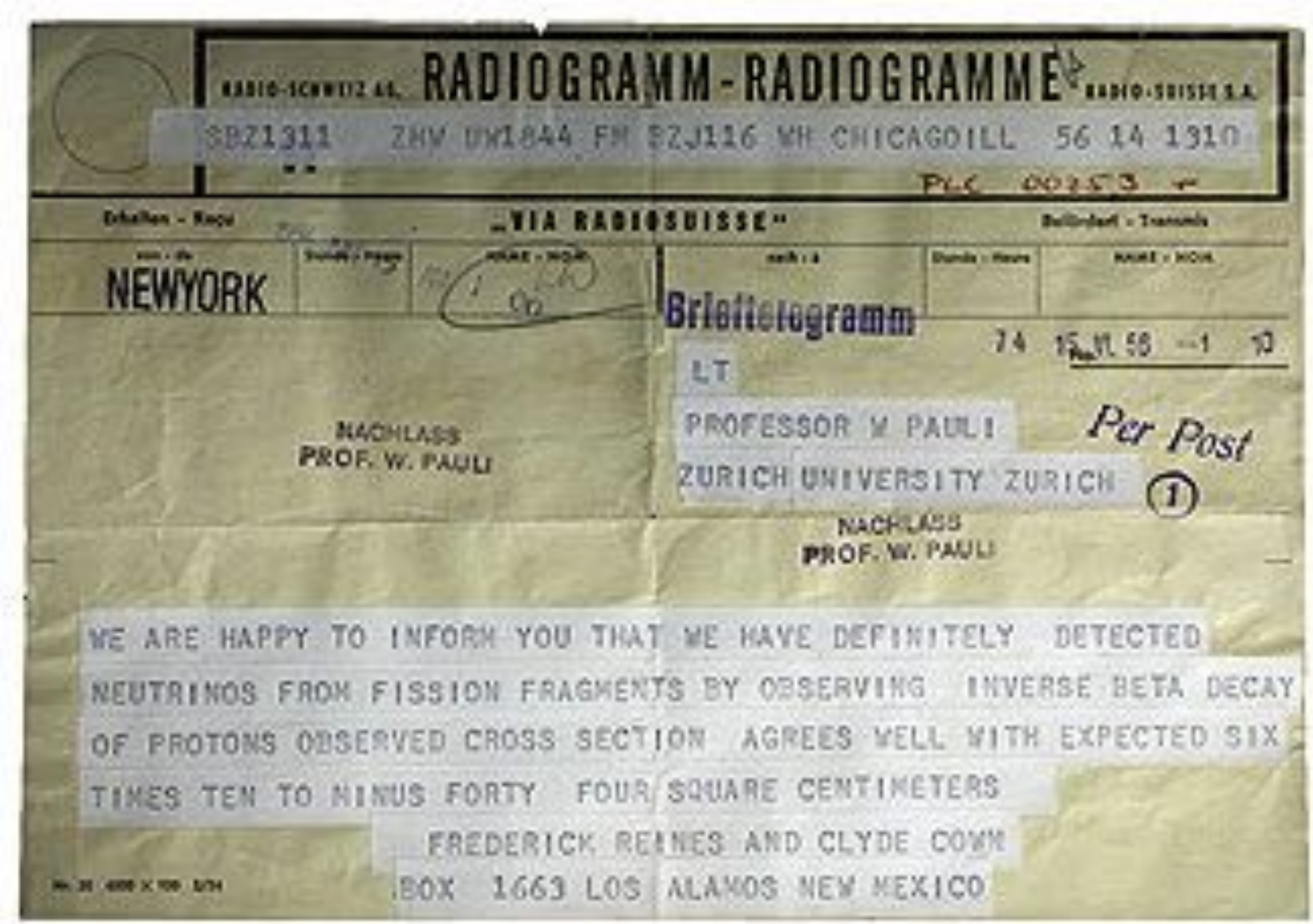


Experimentalists check their signal!

- Are coincidences from positron annihilation and neutron capture, rather than other processes?
    - Dissolve ^{64}Co in the water to understand what positrons look like
    - Doubled Cd_2Cl_4 in the water to watch the coincidence time decrease
- Does signal strength vary with number of protons?
    - Filled half of tanks with heavy water, decreased IBD cross section on deuterium
- Is signal really cosmic rays & reactor backgrounds?
    - varied the thickness and type of shielding

This and all other tests confirmed that the signal was indeed inverse beta decay of reactor antineutrinos!

1956: Discovery!



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„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

1956: Discovery!


RADIOGRAMM - RADIOGRAMME

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VIA RADIOSUISSE

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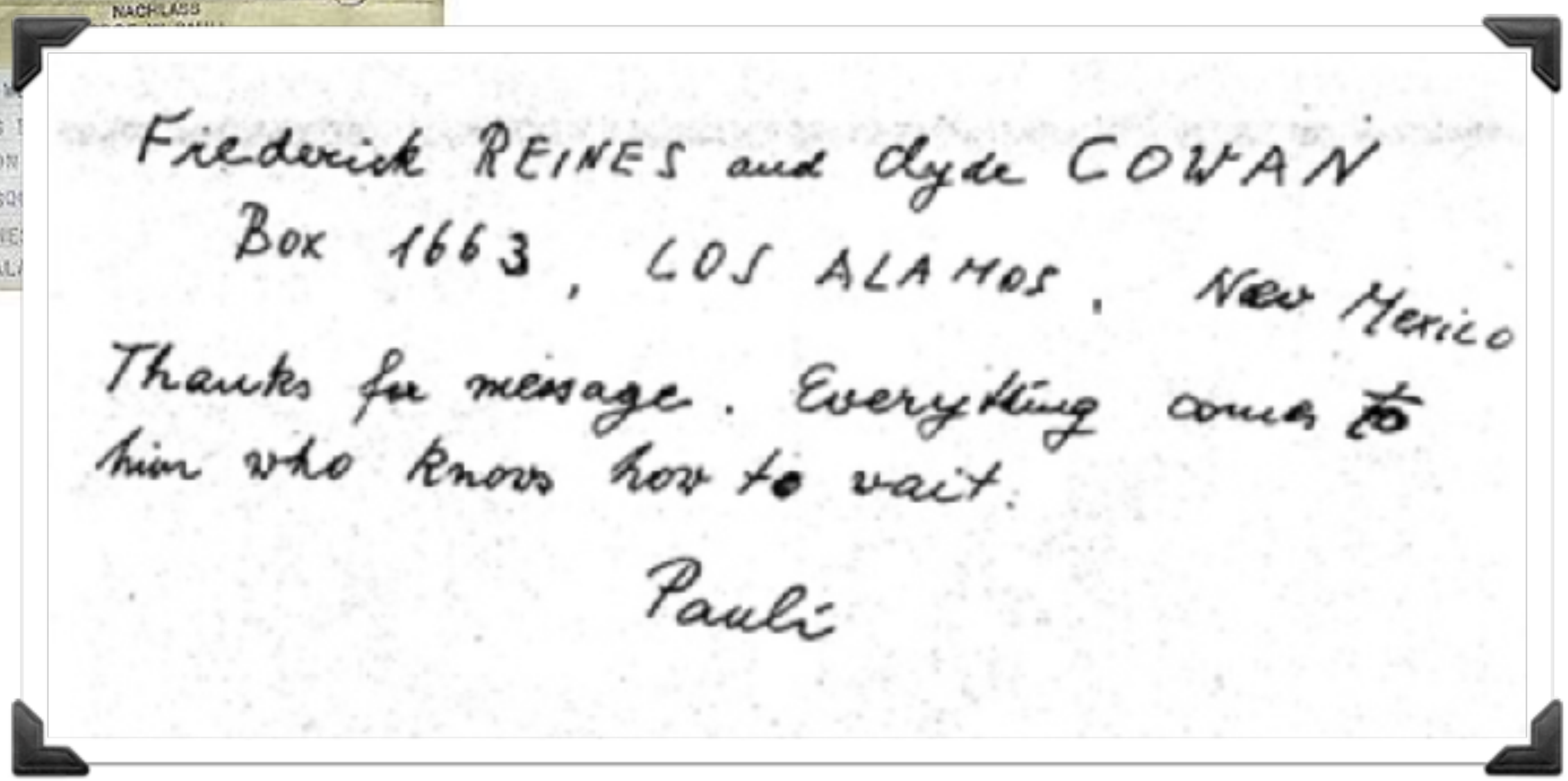
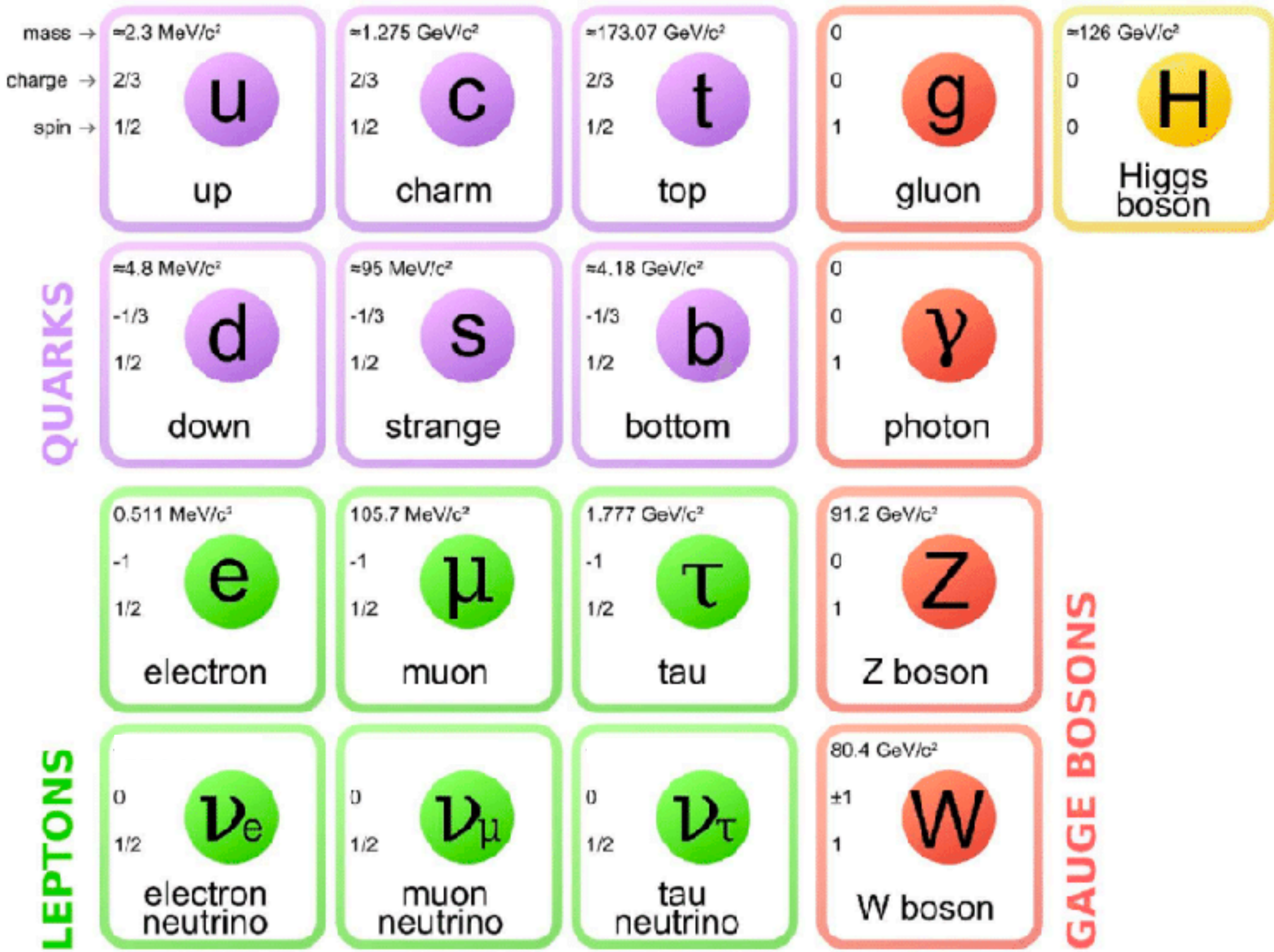
BOX 1663 LOS AL


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

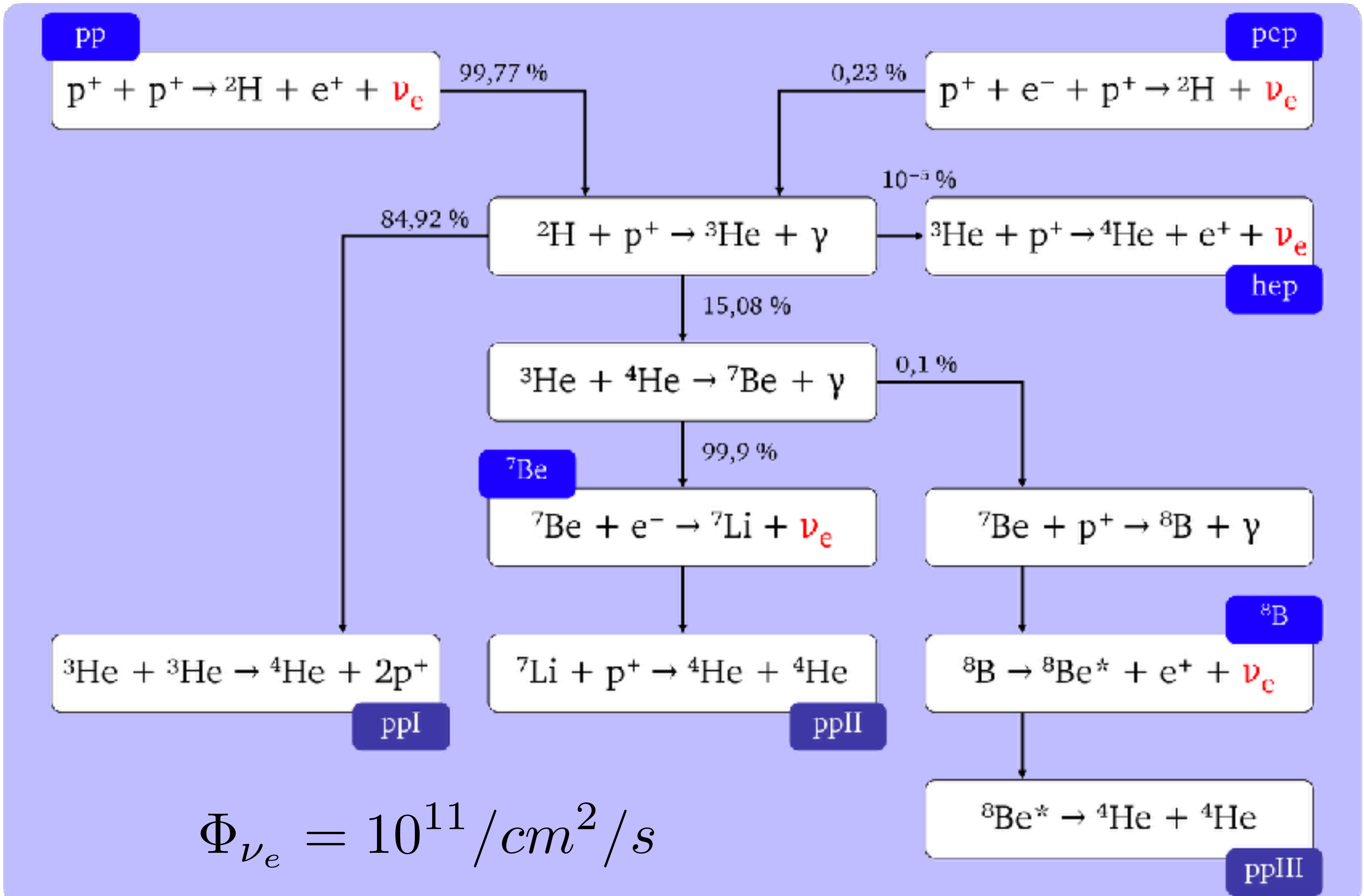
Thanks for message. Everything comes to him who knows how to wait.

Pauli

The Standard Model



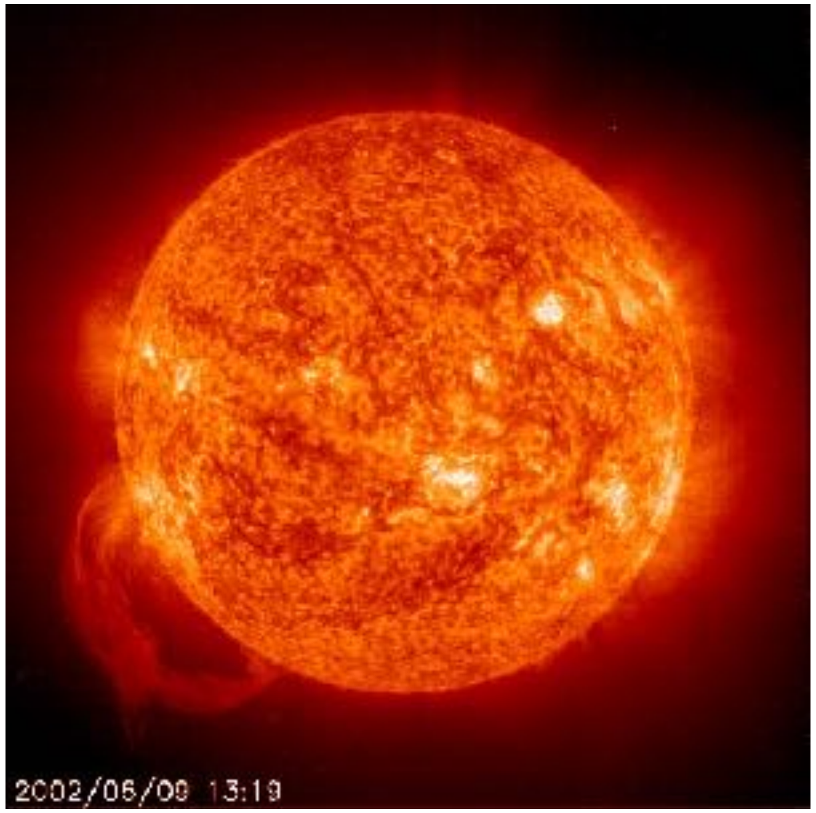
The Standard Solar Model



$$\Phi_{\nu_e} = 10^{11}/cm^2/s$$

https://en.wikipedia.org/wiki/Solar_neutrino

Solar Neutrinos!



$$\Phi_{\nu_e} = 10^{11}/cm^2/s$$

378 tonnes of C_2Cl_4

^{37}Cl is 25% of nat Cl

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

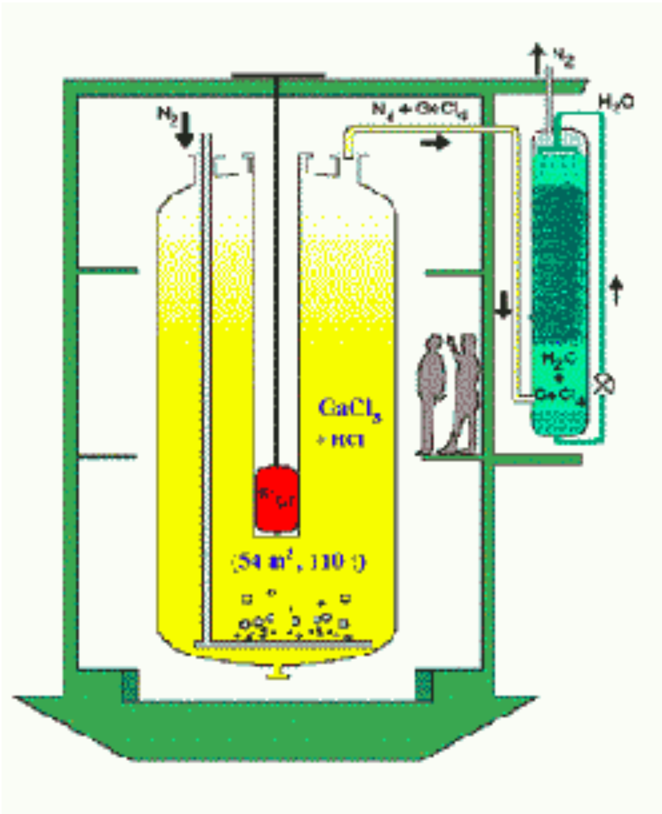
Homestake Experiment

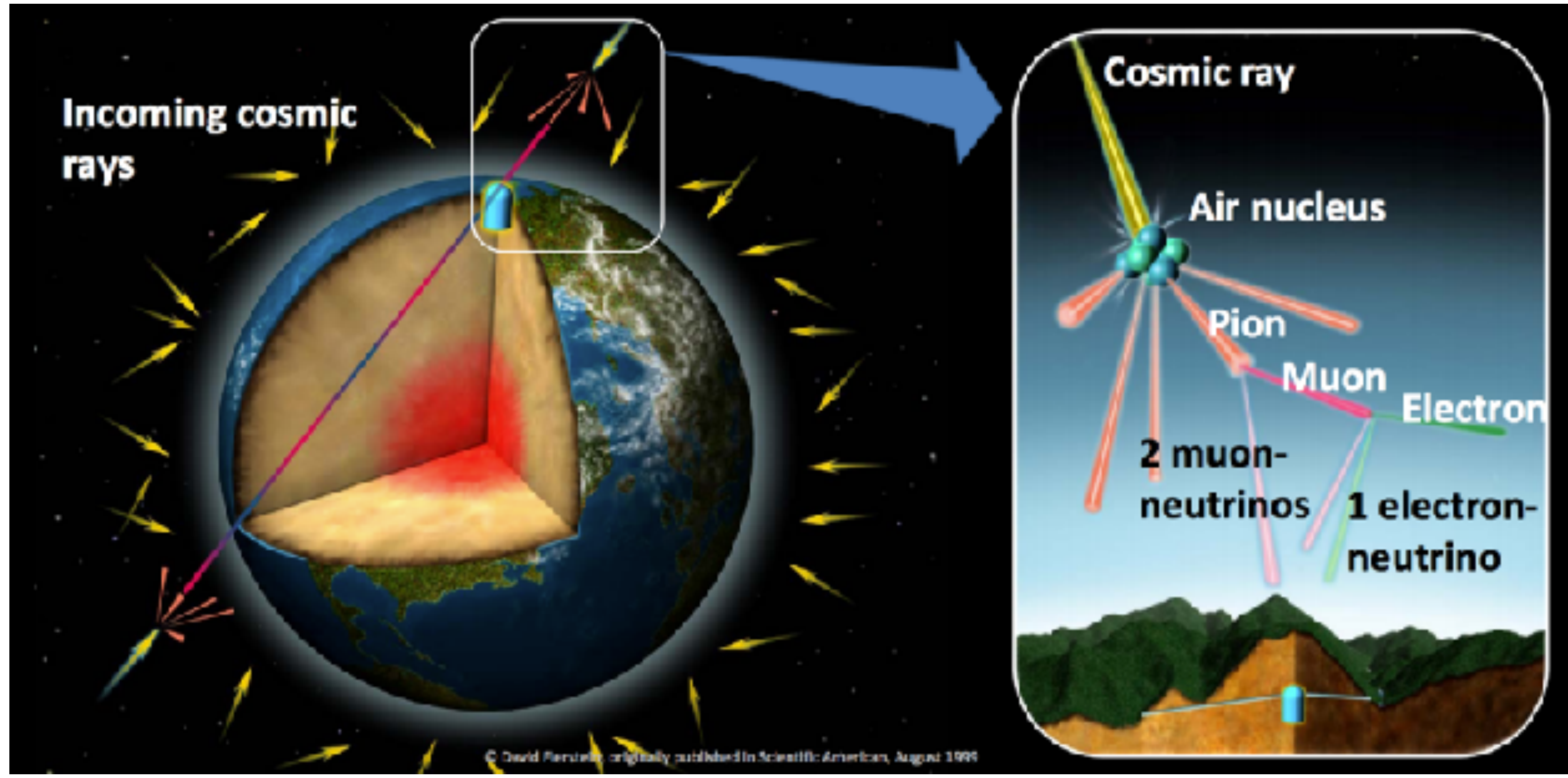
- The ^{37}Ar formed by neutrino capture is then removed from the bulk of the liquid by bubbling 280 lpm of helium gas through the system.
- After the sample of argon is purified chemically it is placed in a small counter holding about .5 ml of gas.
- The ^{37}Ar is unstable and reverts to ^{37}Cl by capturing one of its own orbital electrons. The decay releases a low-energy electron from the Ar, which is detected

- Bahcall: "Ray Davis tells me that the experiment is simple ('Only plumbing') and that the chemistry is 'standard.' The total number of atoms in the big tank is about 10^{30}. He is able to find and extract from the tank the few dozen atoms of ^{37}Ar that may be produced inside by the capture of solar neutrinos. **This makes looking for a needle in a haystack seem easy.**"

Only detected 1/3 of predicted flux

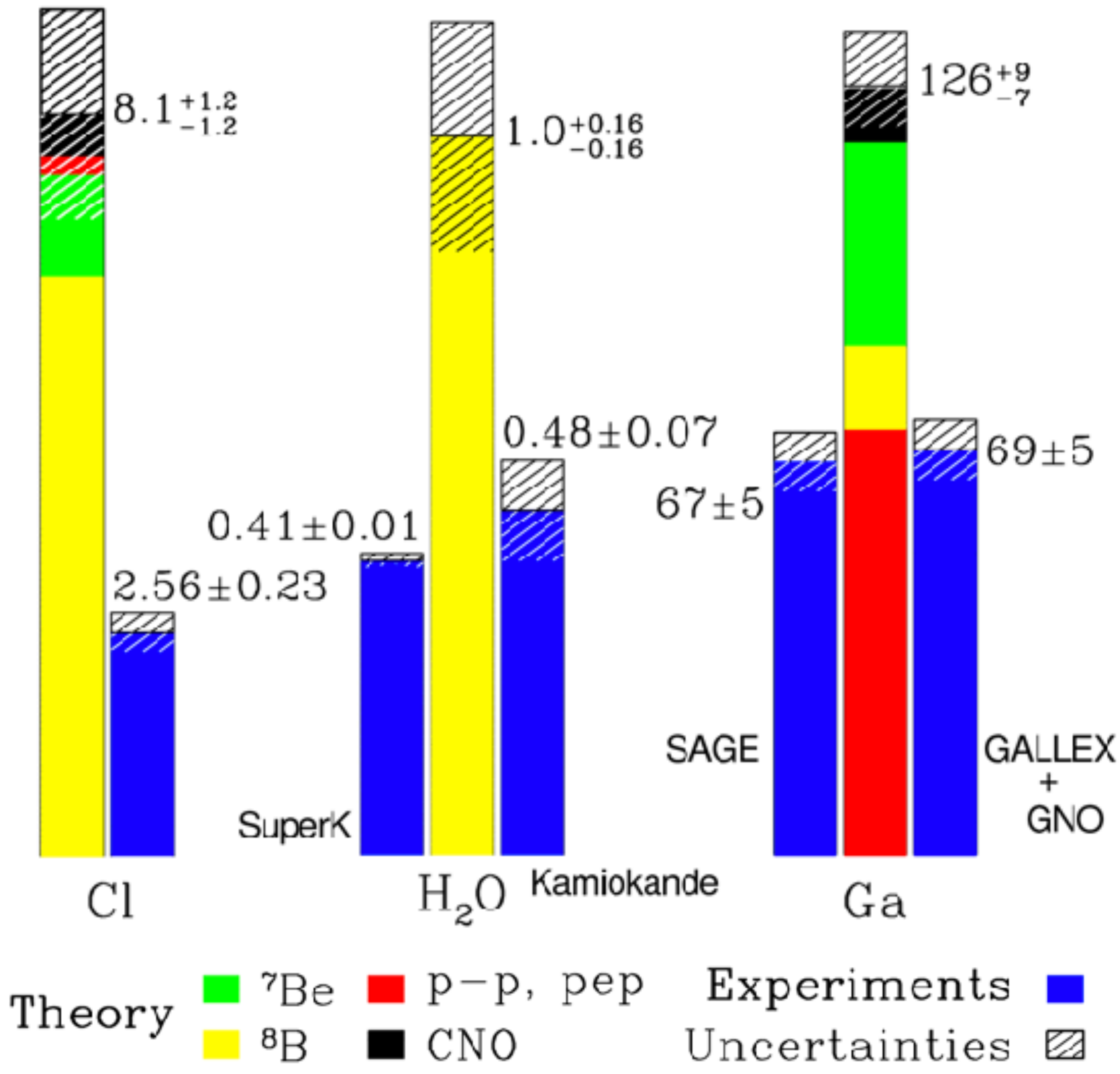
Neutrino Anomaly?



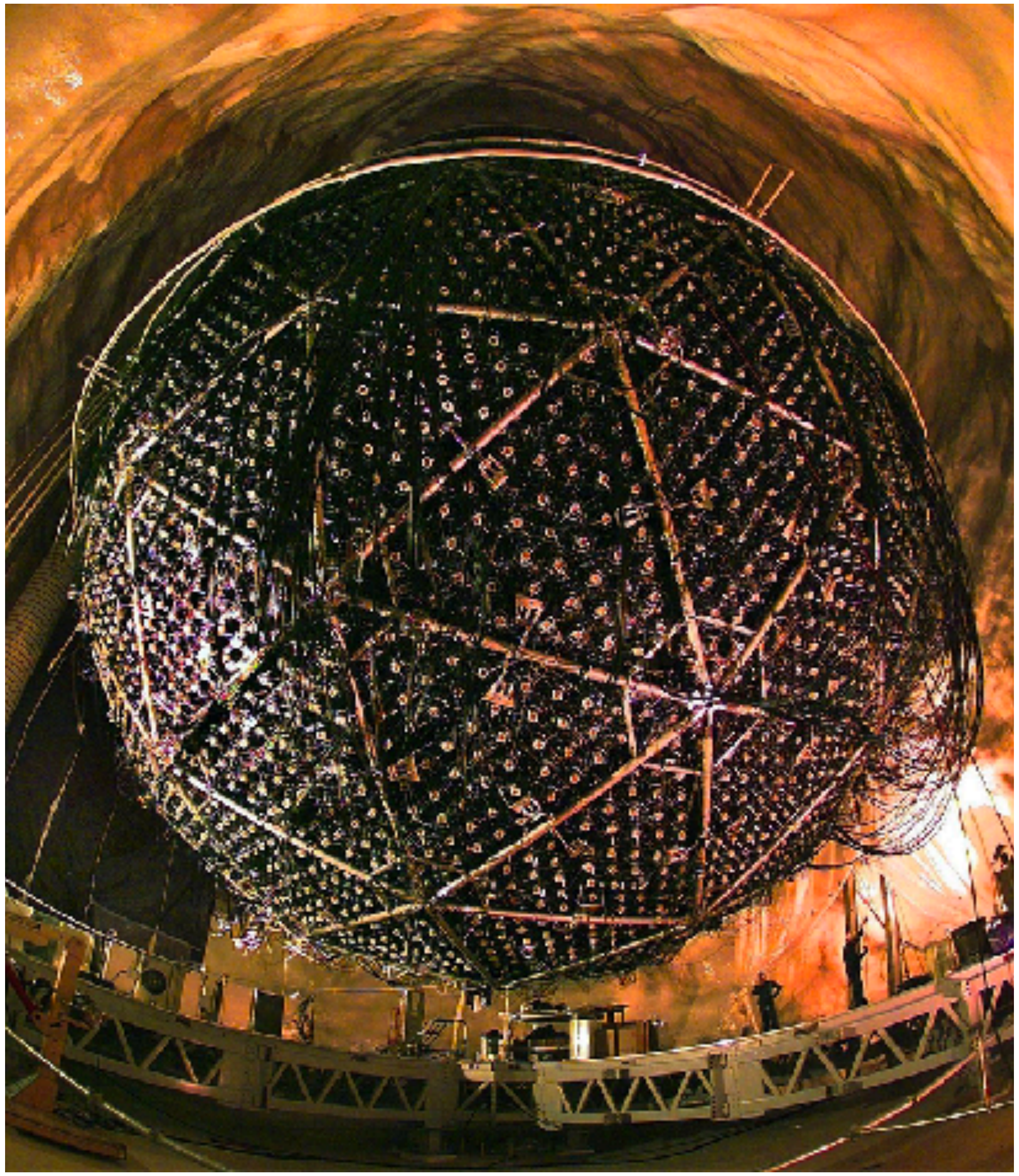


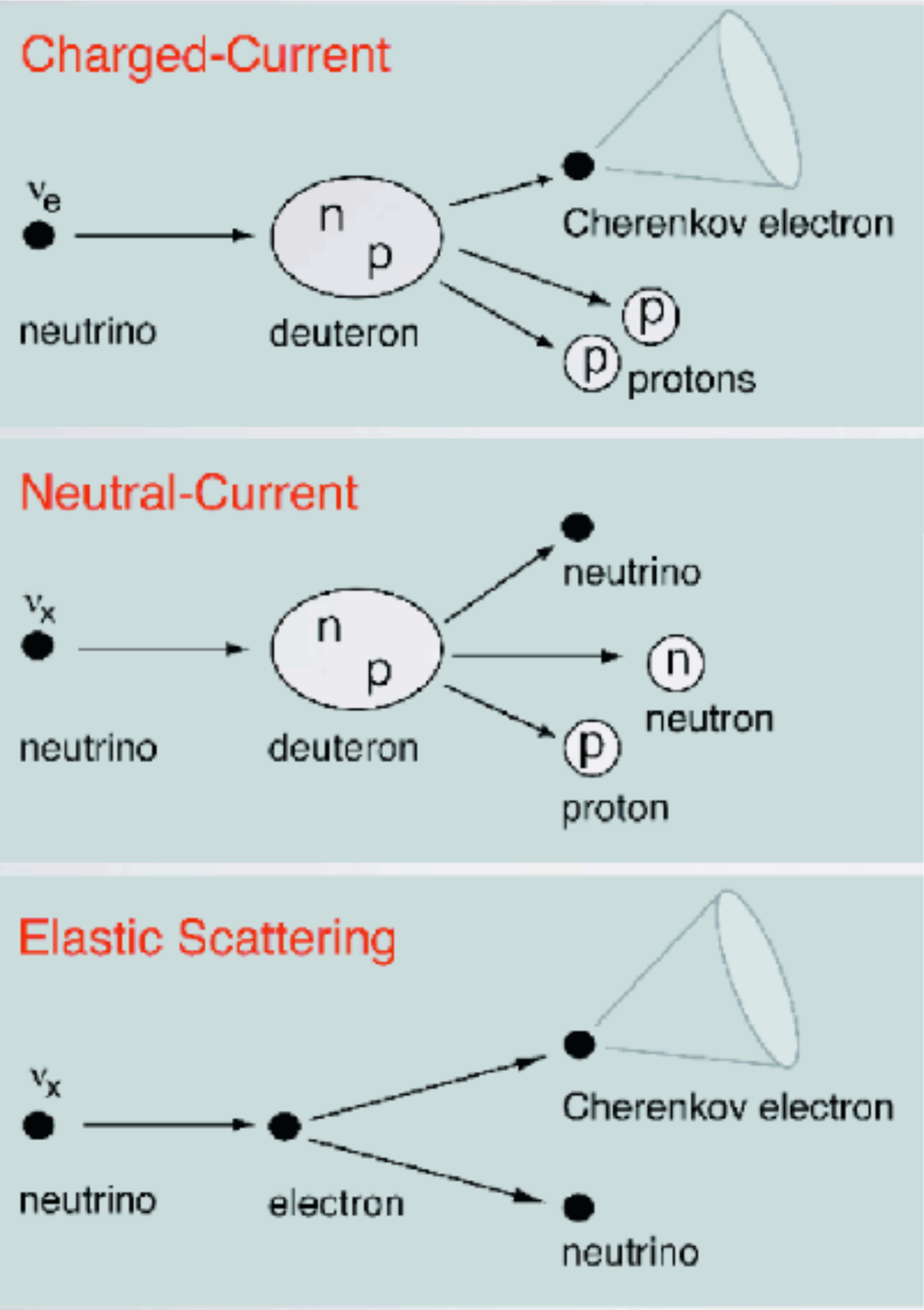
- Gallium Experiments looking for lower energy solar nus
  - $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- KamiokaNDE, MACRO, IMB looking for nucleon decay, observed atmospheric nus
  - Saw half of expected rate

Standard Model Rates vs Expt



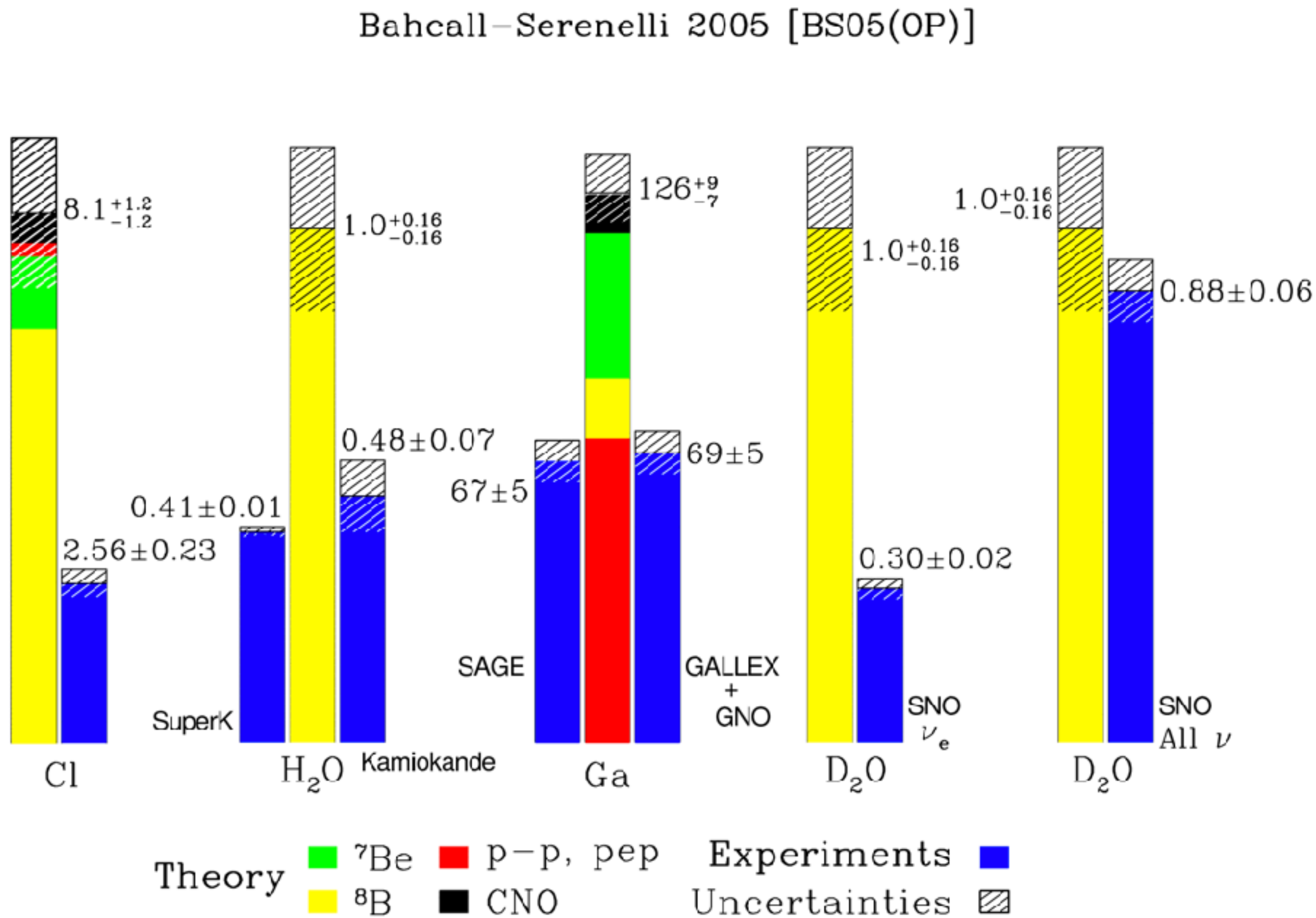
SNO



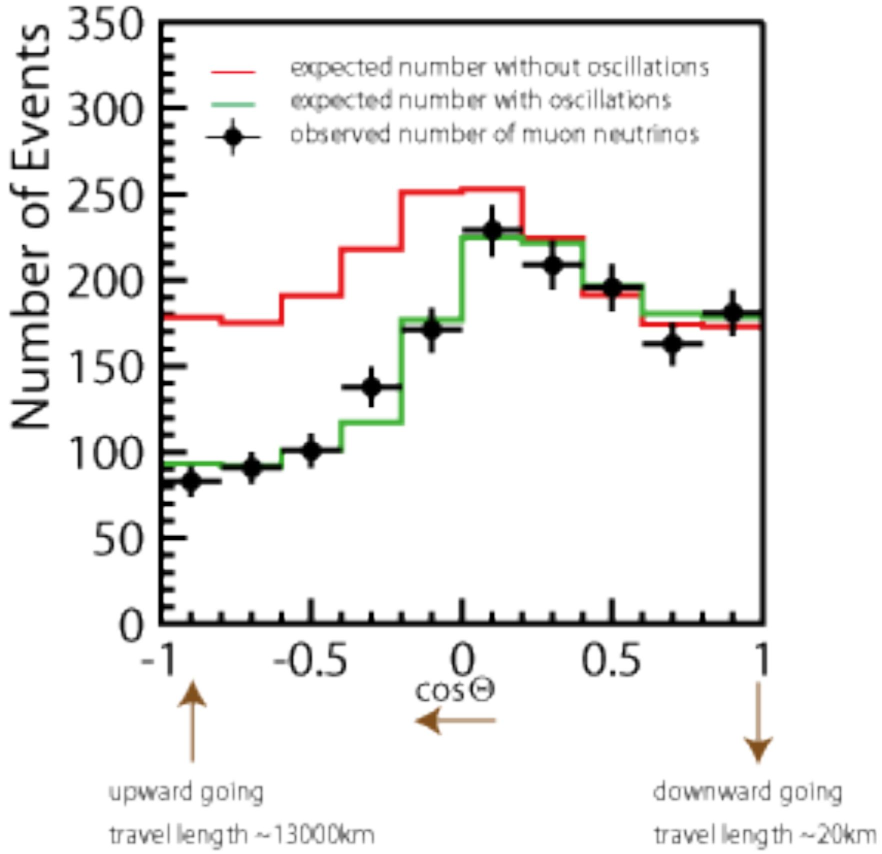


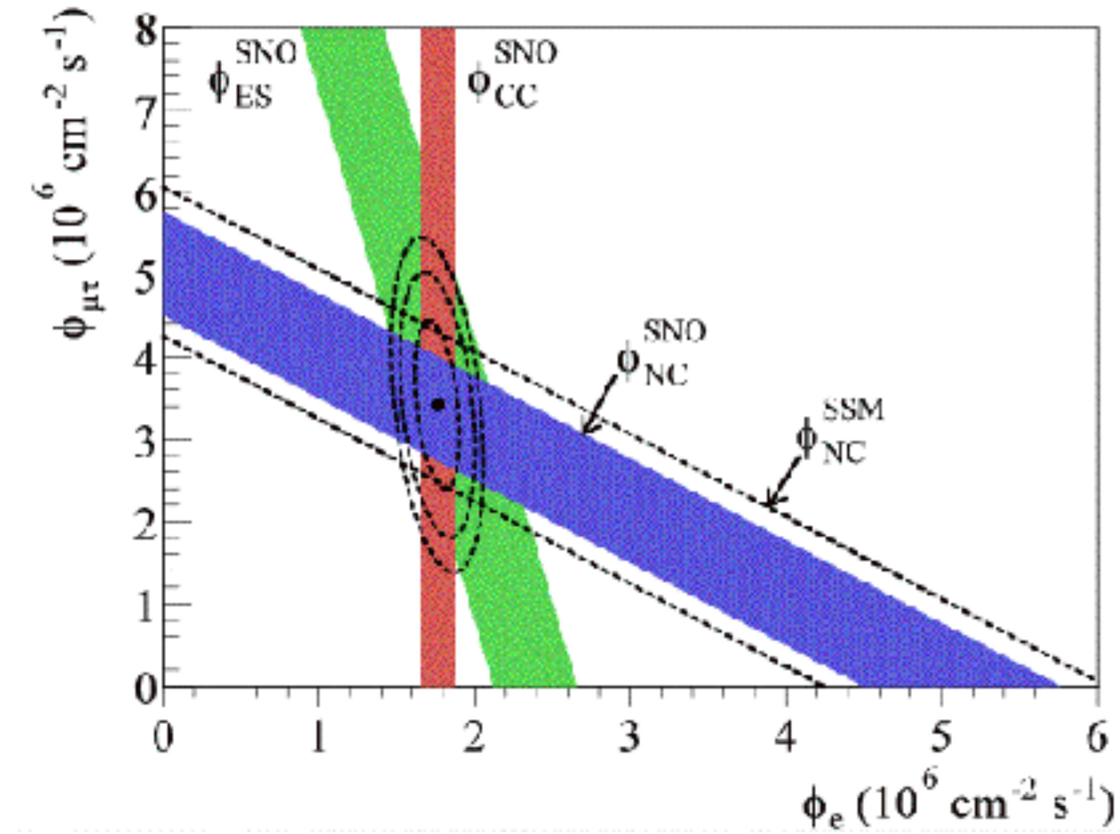
- 1 kT Heavy Water
- 2km underground in active mine
- Incredible cleanliness constraints

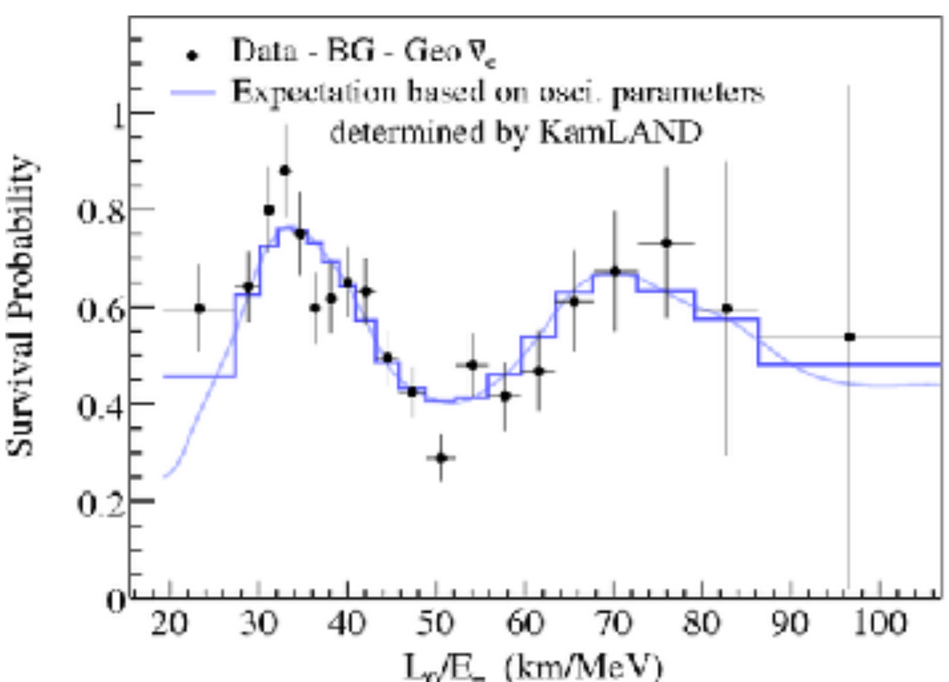
Standard Model Rates vs Expt

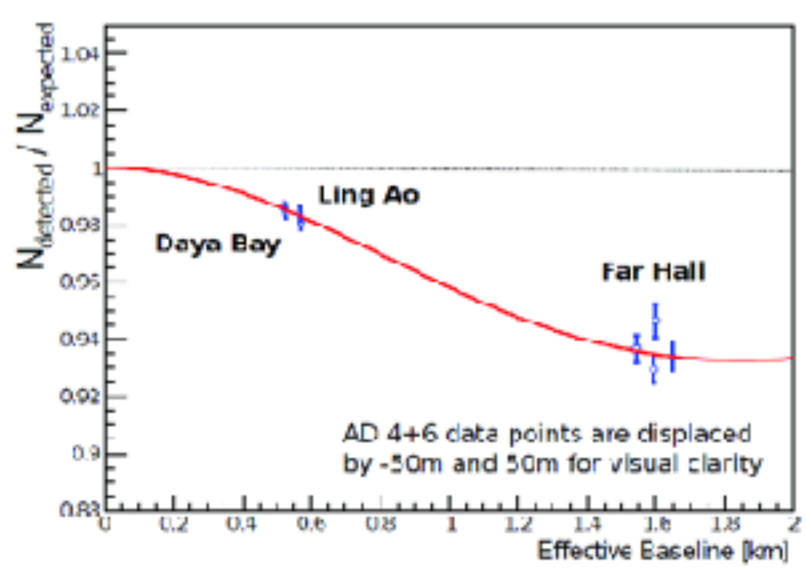


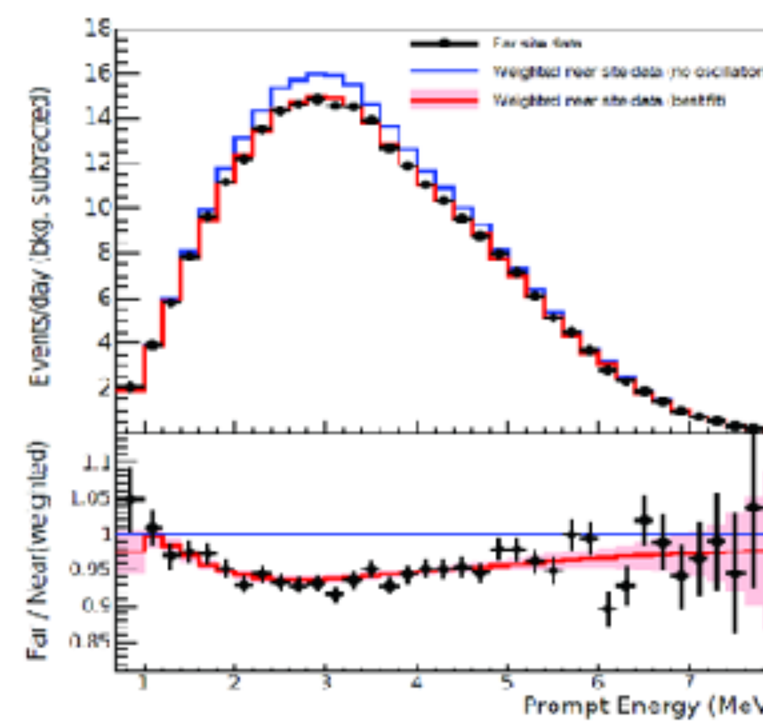
Neutrino Oscillations











http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

http://kamland.lbl.gov/research-projects/kamland/physics-impact

https://www.aps.org/units/dnp/research/sno.cfm

https://inspirehep.net/record/1332512/plots

Oscillations

$|\nu_\alpha\rangle$ is a neutrino with definite flavor α = e, μ, τ

$|\nu_i\rangle$ is a neutrino with definite mass m_i, i = 1, 2, 3

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$P_{\alpha\to\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric, Accelerator θ~45°	Reactor, Accelerator θ~9°	Solar, Reactor θ~32°	0νββ

What we DO know about neutrinos

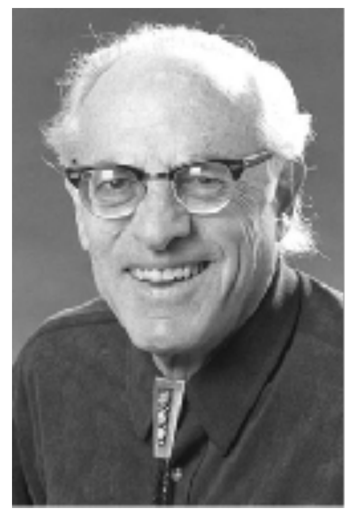
- Fermion: spin 1/2, electrically neutral
- Only experience the weak force, rarely interacting with anything
- They come in three flavors associated with three other fundamental particles (the electron, muon and tau)
- They change, or oscillate, from one type to another
- Most abundant massive particles in the universe, 340/cm^3

Neutrino Nobel Prizes:

1988

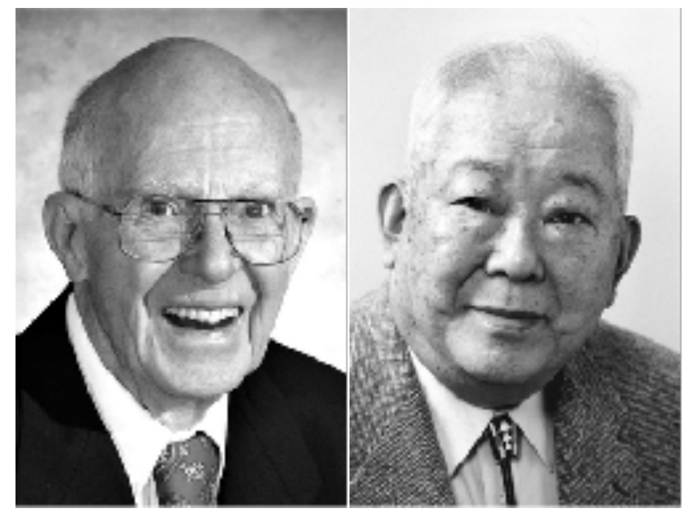
"neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino."

1995



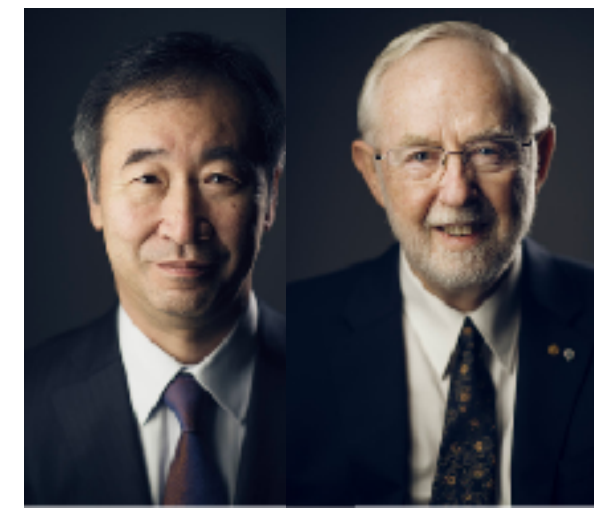
"detection of the neutrino."

2002



"pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

2015



"discovery of neutrino oscillations, which shows that neutrinos have mass."

What we still don't know!

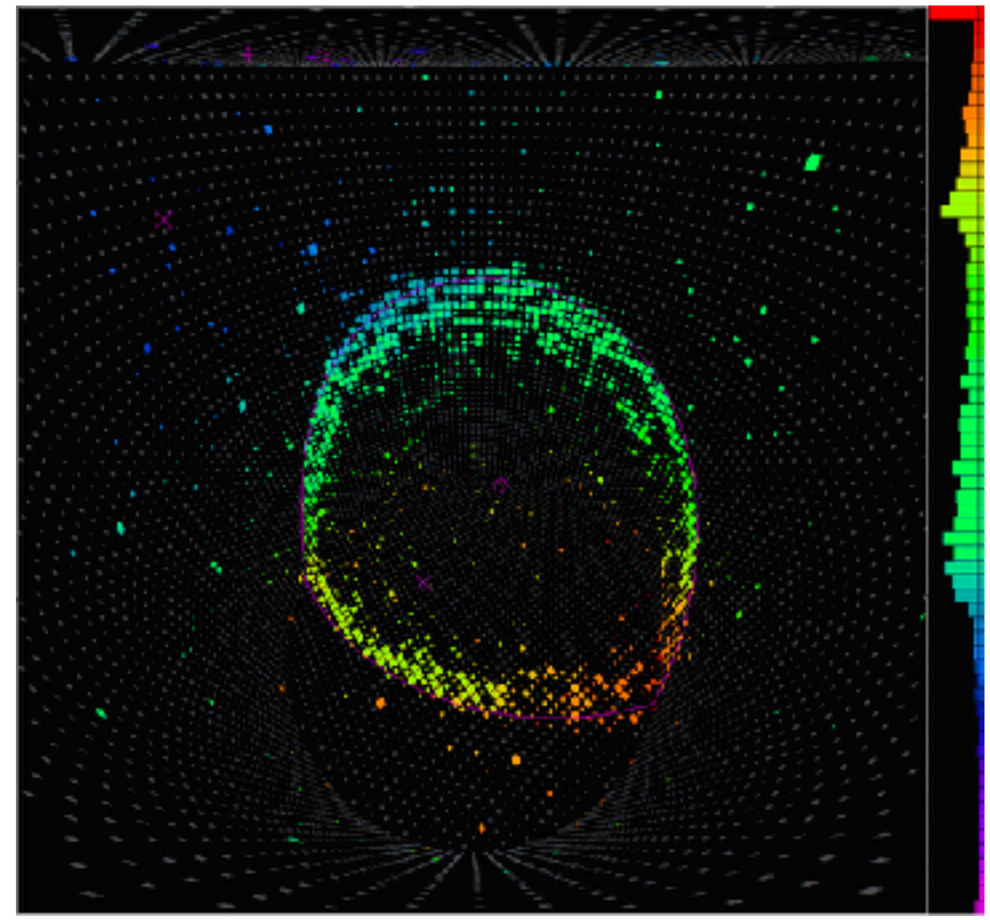
- How much do neutrinos weigh?
- Which neutrino is the heaviest?
- Are there more than three types of neutrinos?
- Do neutrinos and antineutrinos behave differently?
- Is the neutrino its own antiparticle?

- Is our picture of neutrinos correct?

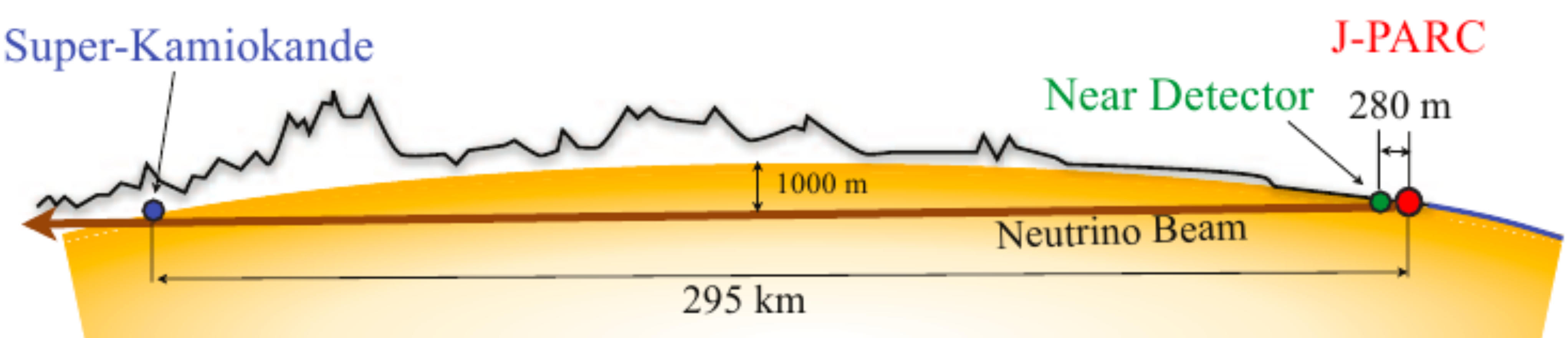
CP Violation

- Physicists once theorized that nothing would change about the laws of physics if every particle were replaced with its antiparticle. This is called charge-parity symmetry.
- *But* it turns out that matter and antimatter are not exactly mirror images, and this could explain why they exist in unbalanced quantities. Breaking charge-parity symmetry is called CP violation.
- If antineutrinos do not follow the same pattern as neutrinos when they change from one flavor to another, this is a signal of CP violation.
- The same mechanism that could cause neutrinos and antineutrinos to oscillate differently could have implications for the mechanism that would have led to an abundance of matter over antimatter in the early universe.
- In order to advance the theory that neutrinos tipped the balance between matter and antimatter, neutrino physicists need to observe CP violation in action.
- **T2K** is giving us hints towards the CP violation mystery.

CP Violation Determination



- JPARC's beam
- 295 km
- Water Cherenkov



http://t2k-experiment.org/t2k/

CP Violation Measurements

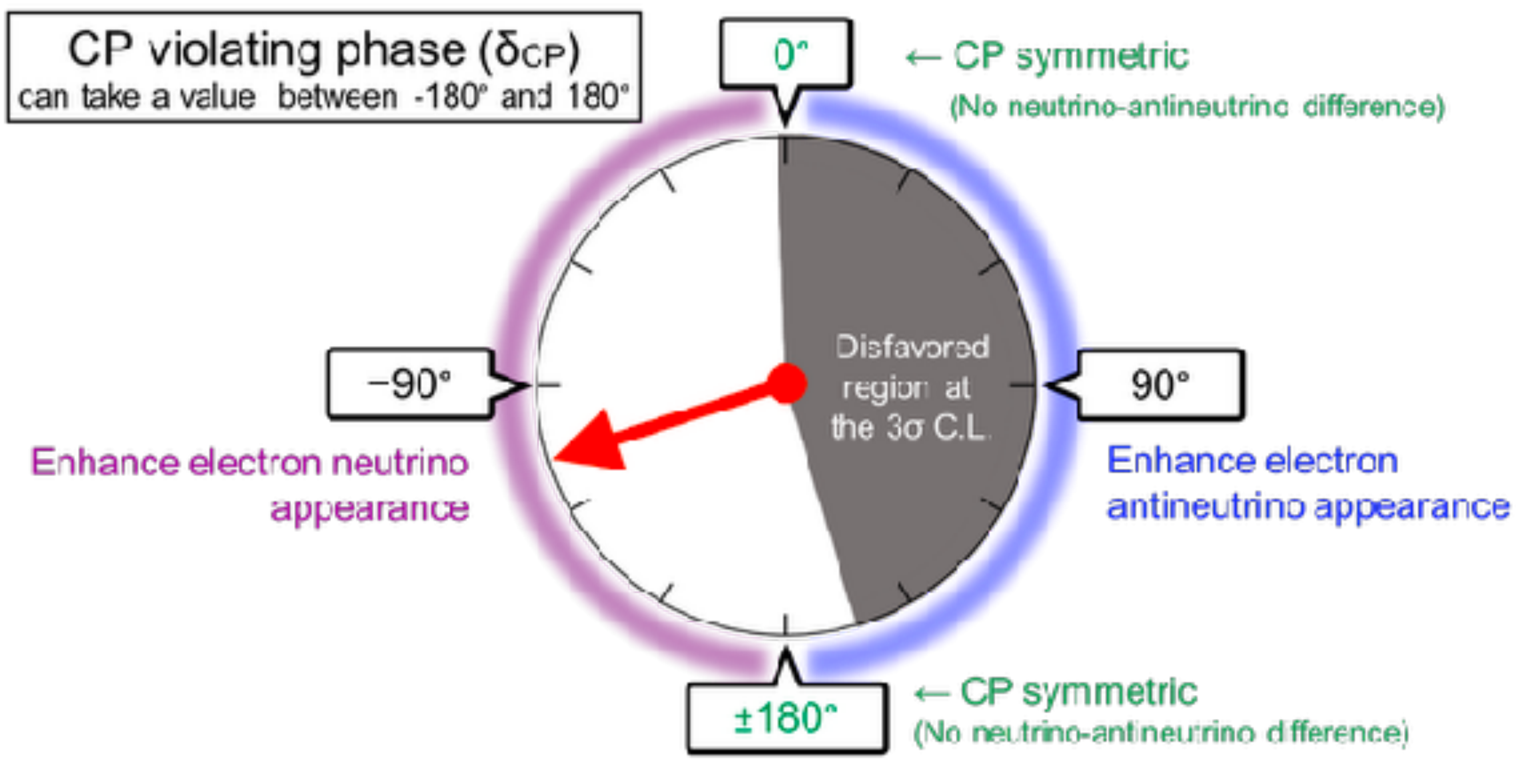
- The effect of the asymmetry between matter and antimatter is most apparent in the observation of the universe, which is composed of matter with little antimatter.
- For the universe to evolve to a state where matter dominates over antimatter, a necessary condition is the violation of the so-called Charge-Parity (CP) symmetry.
- T2K is now searching for a new source of CP symmetry violation in neutrino oscillations that would manifest as a difference in the measured oscillation probability for neutrinos and antineutrinos.

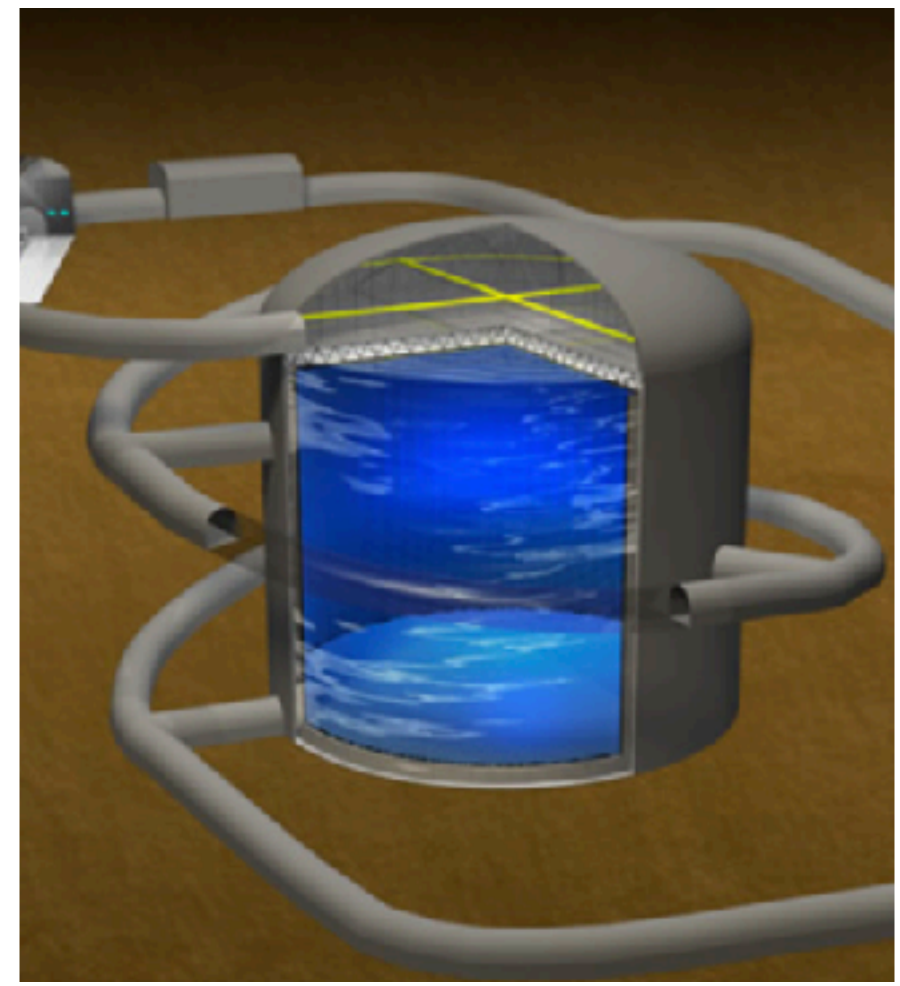
	Observed	Expectation	
		$\delta_{CP} = -90°$	$\delta_{CP} = +90°$
Electron neutrino	90	82	56
Electron antineutrino	15	17	22

- Using beams of muon neutrinos and muon antineutrinos, T2K has studied how these particles and antiparticles transition into electron neutrinos and electron antineutrinos, respectively.
- The T2K data is most compatible with a value close to $\delta_{cp}=-90°$ that significantly enhances the oscillation probability of neutrinos in the T2K experiment. Using this data, T2K evaluates confidence intervals for the parameter δ_{cp}. The disfavored region at the 3σ (99.7%) confidence level is $-2°$ to 165°. This result represents the strongest constraint on δ_{cp} to date.

http://t2k-experiment.org

CP Violation with T2K & Hyper-K





http://www.hyperk.org/

- Sensitivity to δ_{cp} will increased in HYPER-K
- Cylindrical tank, 60m × 74m, filled with 260 kt UPW
- 10x larger Water Cherenkov detector at same baseline

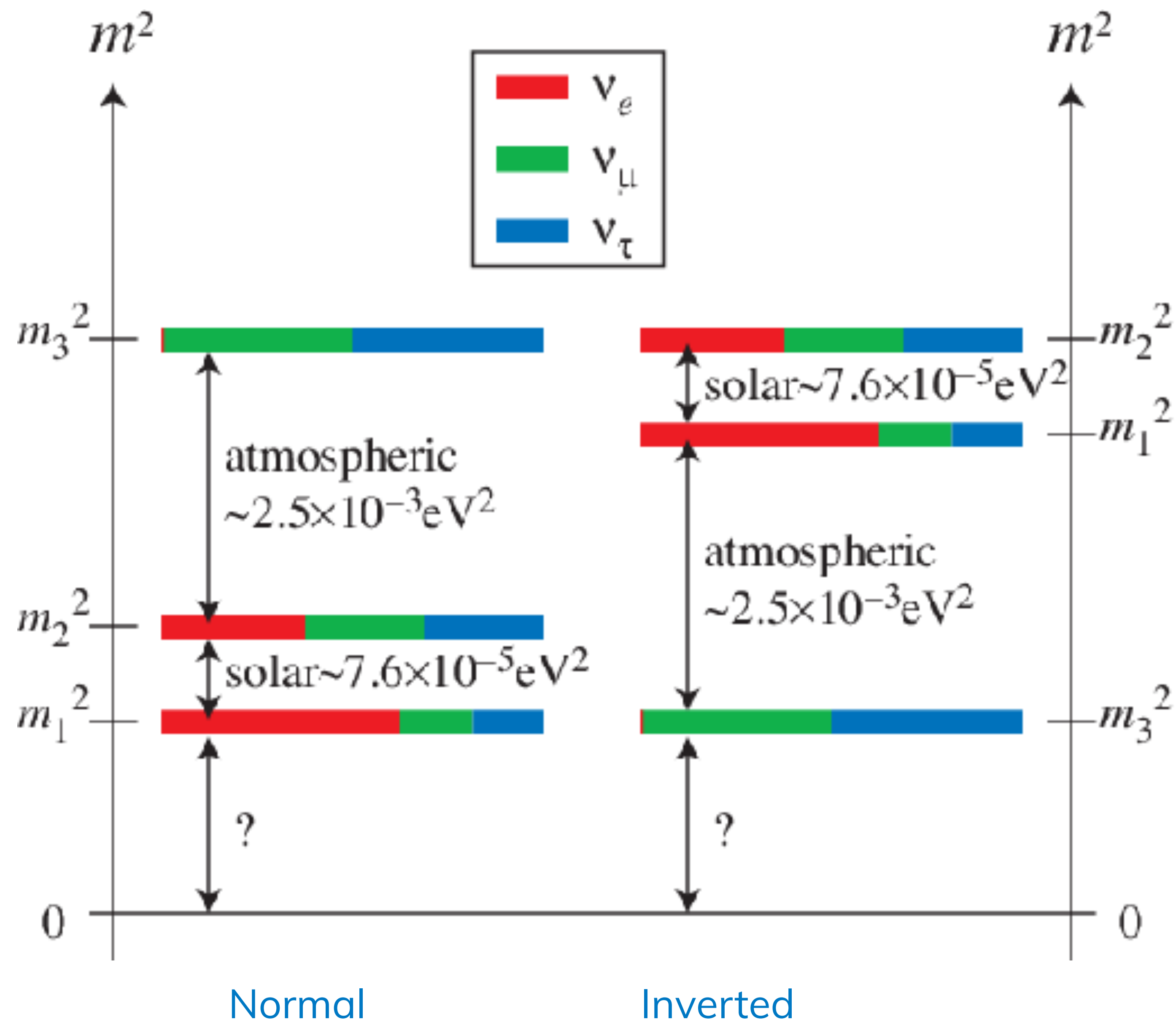
CP measurements are tangled with the mass hierarchy, and a longer baseline experiment is needed.

https://www.interactions.org/press-release/t2k-results-restrict-possible-values-neutrino-cp-phase

Mass Hierarchy

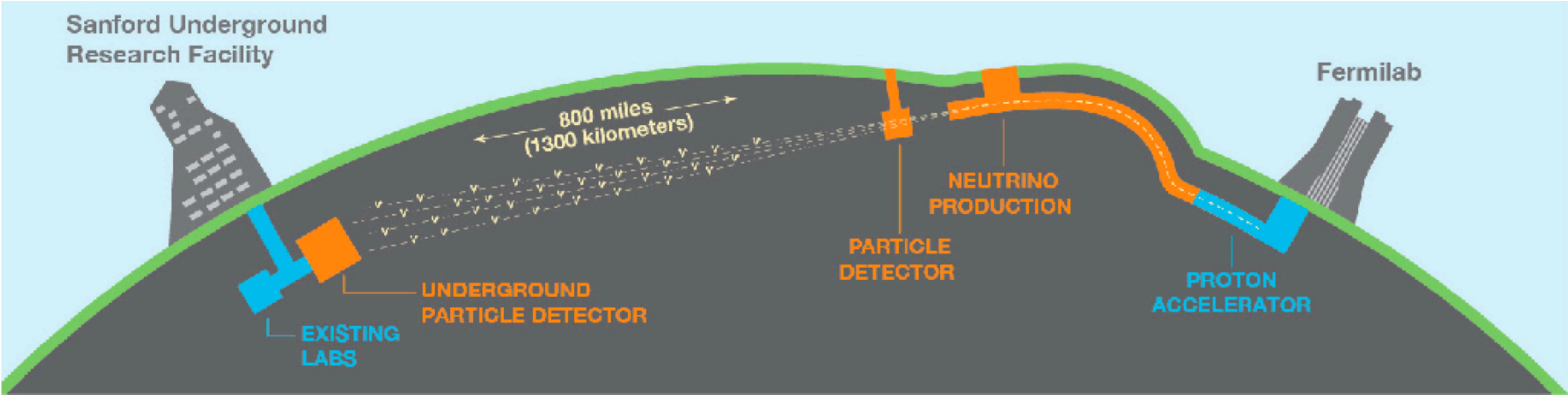
- Oscillation experiments give mass squared differences, no sign information
- m_1 : mainly electron flavored
- m_2 : even blend of electron, muon and tau
- m_3 : mostly muon and tau

- We know that the masses of the first two neutrinos are close together and that the third is the odd one out.
- What we *don't* know is whether the third one is lighter or heavier than the others.



Hierarchy Measurements

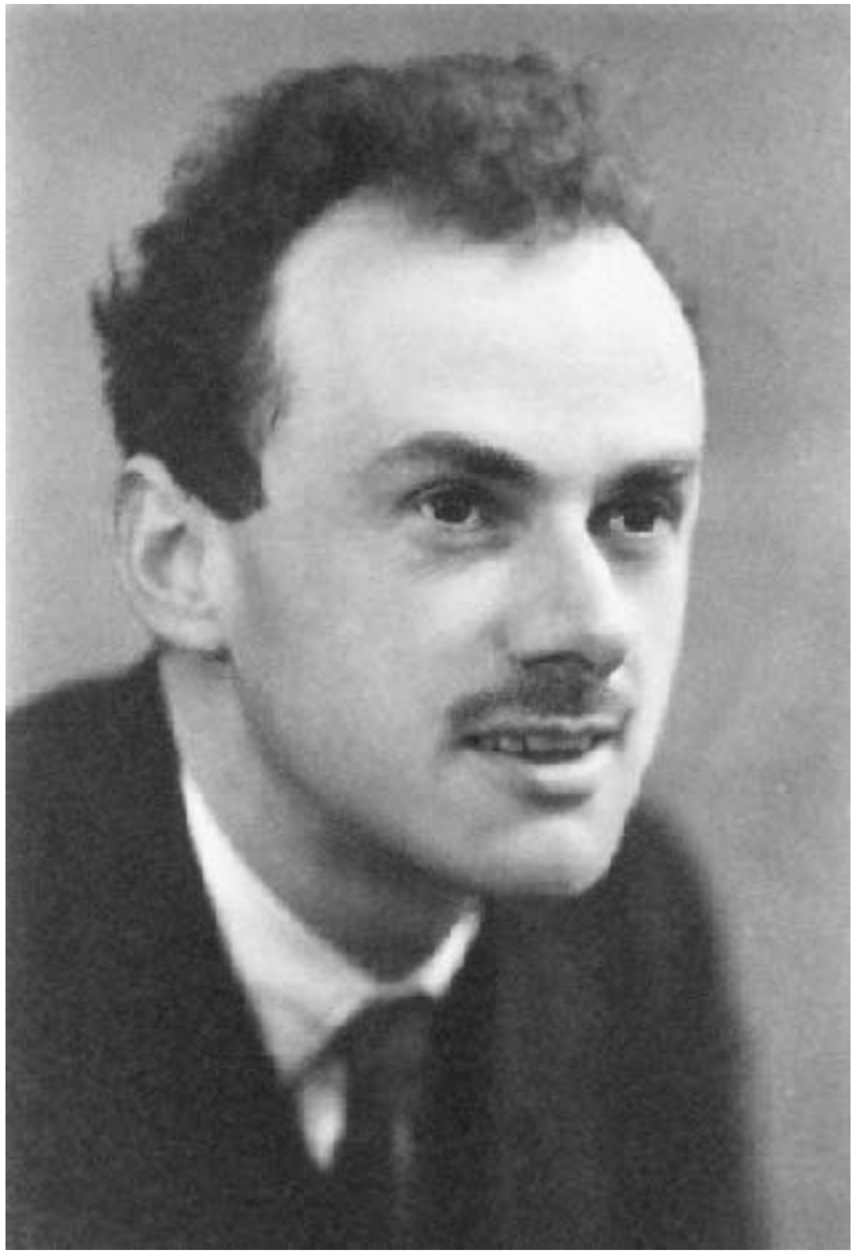
- Neutrinos travel hundreds of miles straight through the Earth, passing through trillions of electrons, affecting ONLY electron-flavor neutrinos making them seem more massive.
- Since the first and second mass states contain more electron flavor than the third, those two experience the strongest electron interactions as they move through the Earth.
- If the hierarchy is normal, muon neutrinos will be **more likely** to turn into electron neutrinos, and muon *anti*neutrinos will be **less likely** to turn into electron *anti*neutrinos.
- If the hierarchy is inverted, the opposite will happen.
- DUNE is 4x 10kT Liquid Argon Time Projection Chamber, 1300 km baseline



http://www.dunescience.org/

Dirac vs Majorana

P. Dirac (1902–1984)

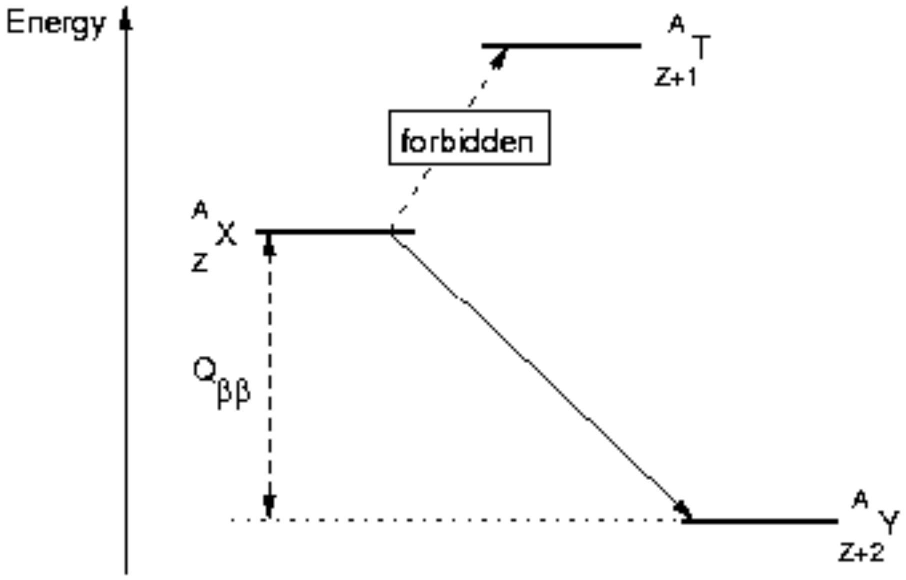


$$\nu \neq \bar{\nu}$$

E. Majorana (1906–1938)

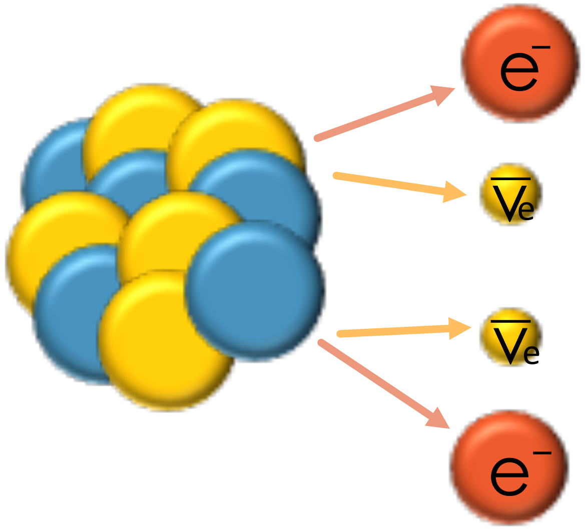
$$\nu \equiv \bar{\nu}$$

Double Beta Decay



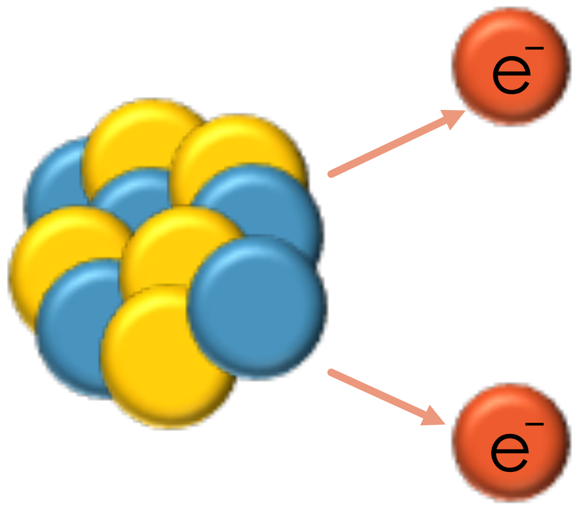
- Candidate isotopes: Even-even nuclei where single β decay is forbidden

2νββ



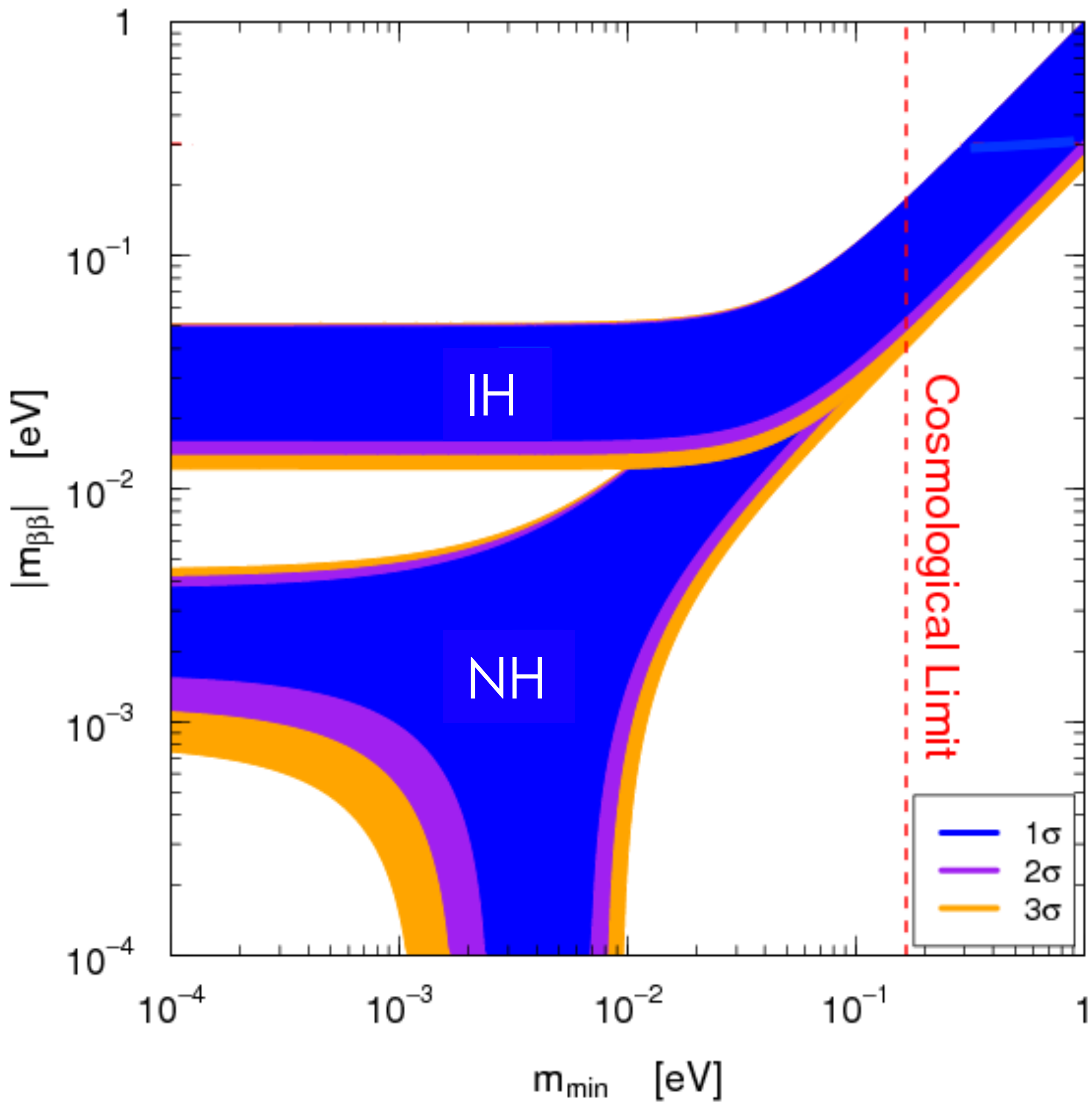
- Allowed in Standard Model
- Observed in 12 isotopes

0νββ



- Not yet observed
- Implies non-conservation of lepton number
- Implies neutrinos are Majorana particles

Double Beta Decay



The rate of 0νββ is given by

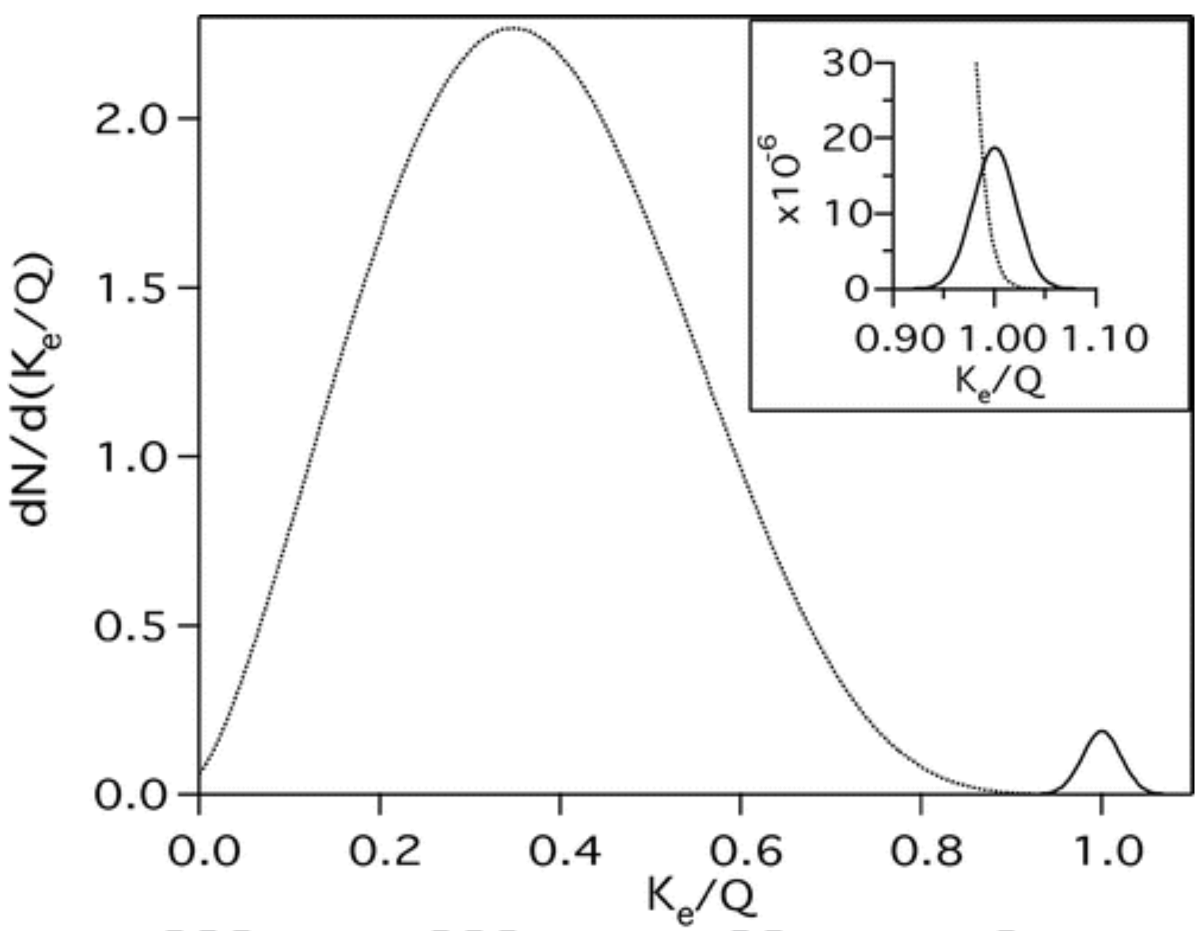
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

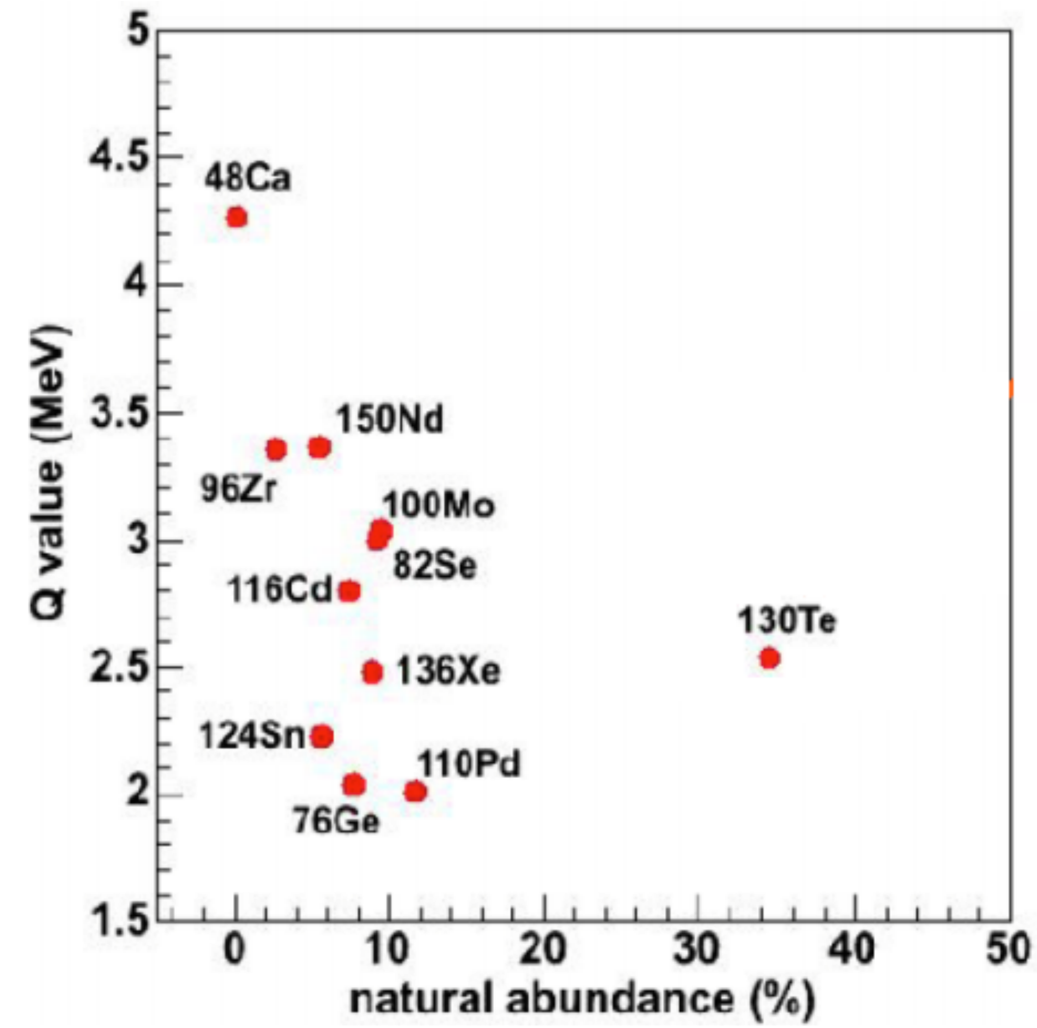
$T_{1/2}$: half-life
G: phase space factor
M: nuclear matrix element
$m_{\beta\beta}$: effective neutrino mass

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

Double Beta Decay

- Key experimental signature for 0νββ is a peak in visible energy at the Q-value of the nucleus, smeared by detector resolution.
- Requirements:
  - Large source mass
  - Low background
  - Good energy resolution

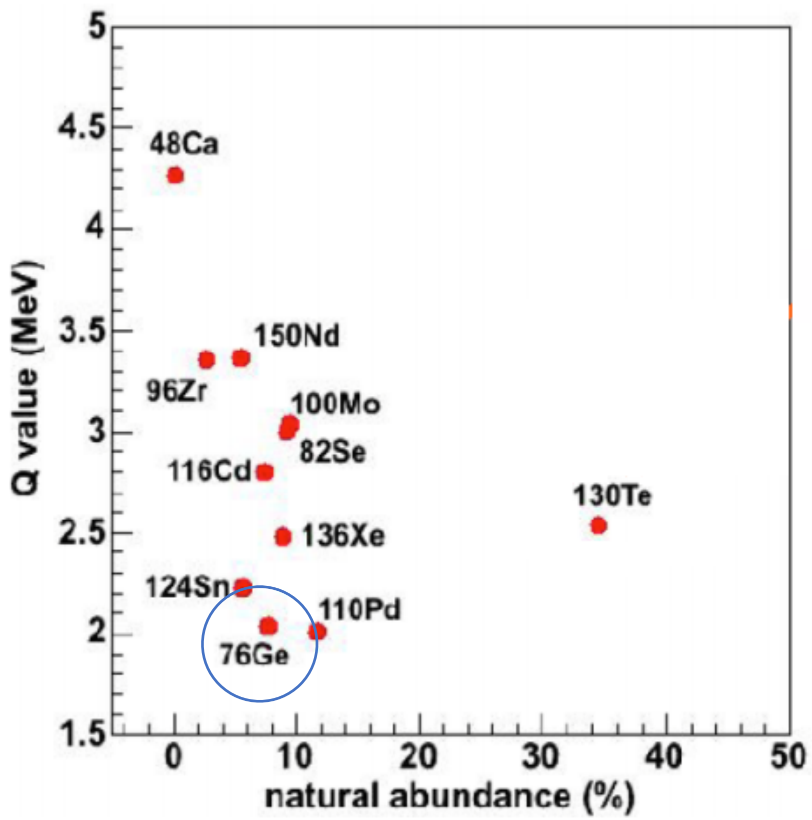


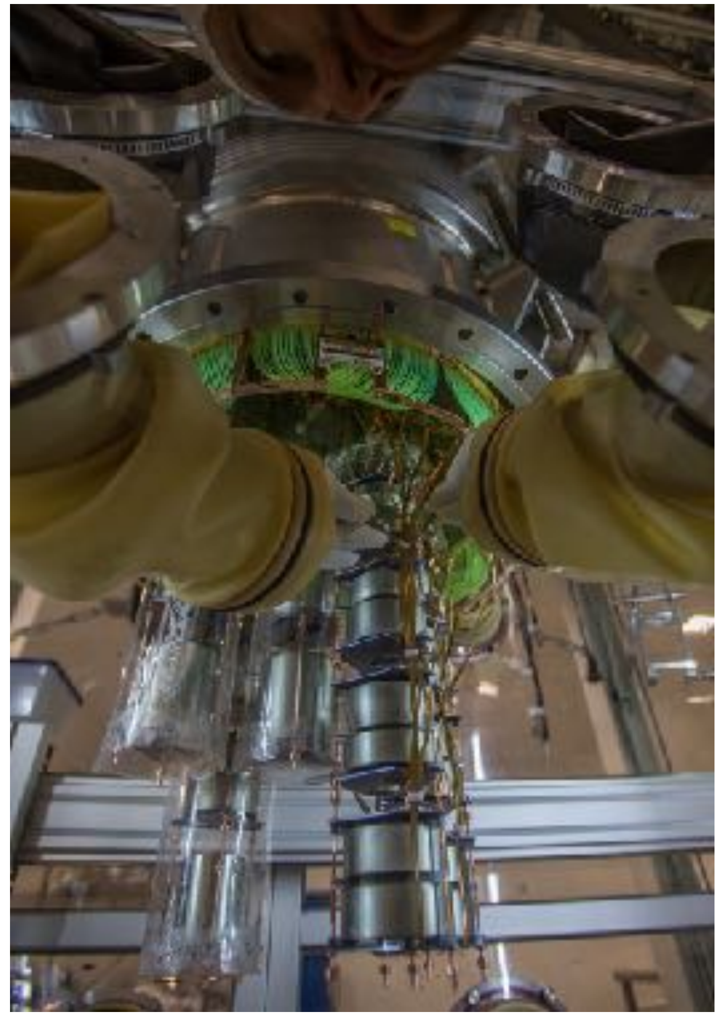


Chose Isotope based on

- 2νββ half-life
- Q-value
- Natural Abundance
- Detector Compatibility

DBD-76Ge: LEGEND-200



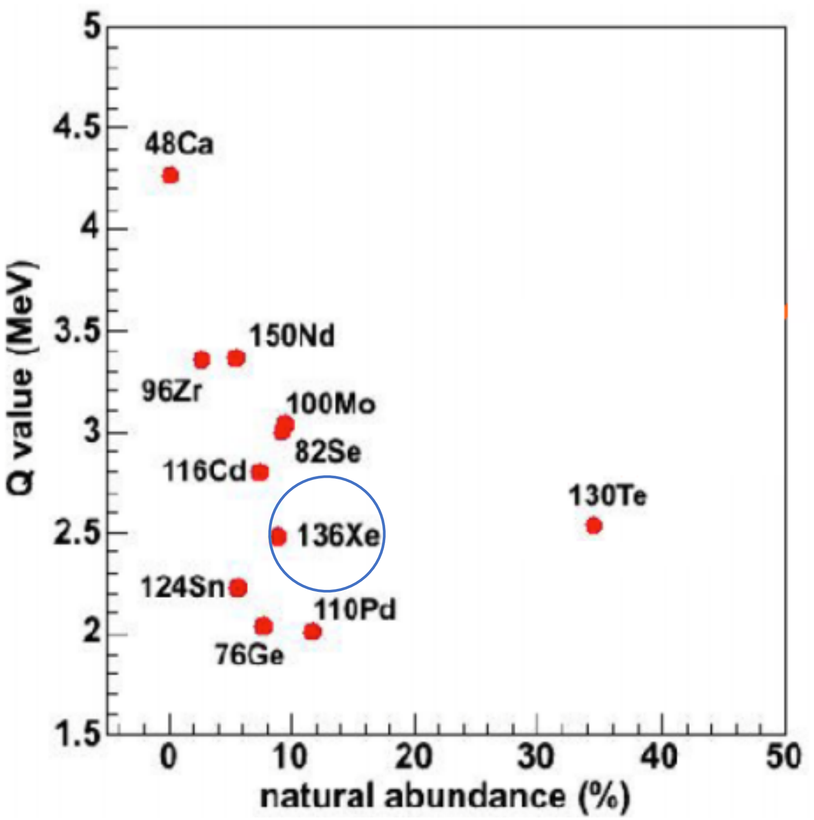


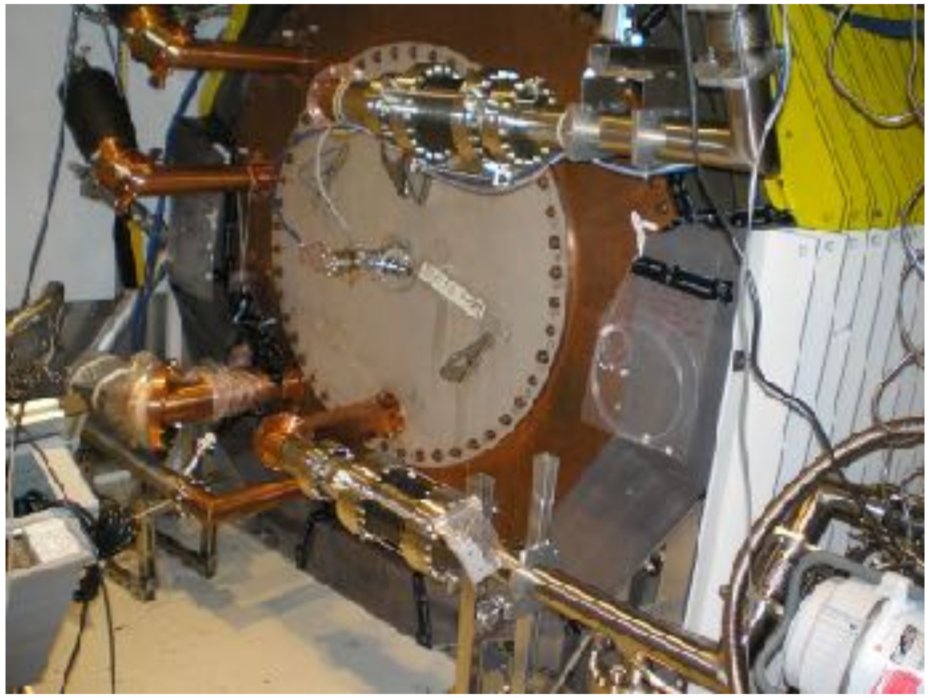
http://dx.doi.org/10.1038/nature21717

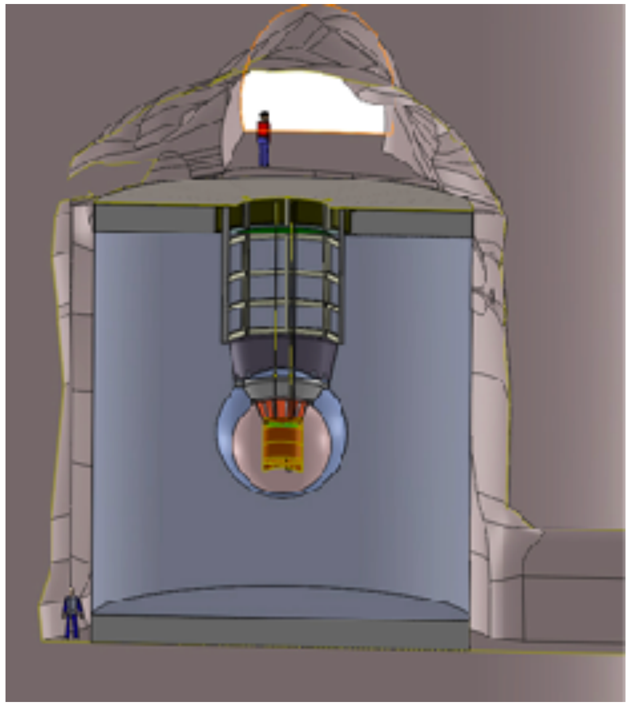
arXiv:1711.11145
arXiv:1810.00849

- LEGEND: Merger of MAJORANA and GERDA experiments
- Using ultraclean electroformed copper from MAJORANA
- LAr veto and cryostat from GERDA
- Planned 200 kg measurement, sensitivity > 10^{27} y

DBD-136Xe: nEXO



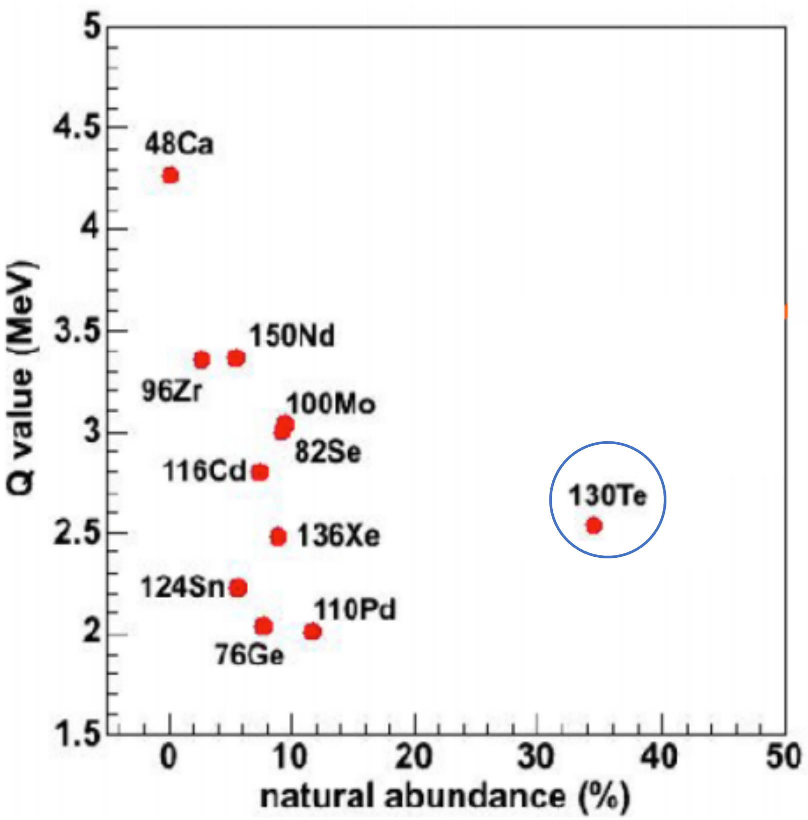


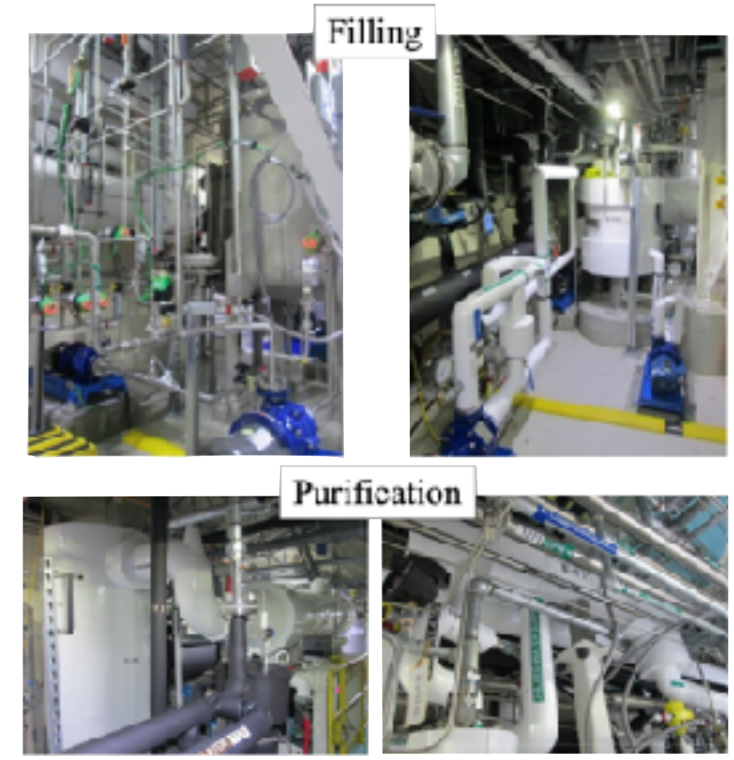


- Grown from EXO-200 experiment
- nEXO: Time Projection Chamber
- 5t LXe, 90% Enriched in ^{136}Xe
- Sensitivity > 10^{28} y

TRIUMF Carleton University Université de Sherbrooke McGill Laurentian University Université Laurentienne

DBD-130Te: SNO+





- SNO+: Te loaded Liquid Scintillator
- Sensitivity > 10^{26} y
- Phase 1: 1,330 kg ^{130}Te, can increase loading

What I didn't even try to cover...

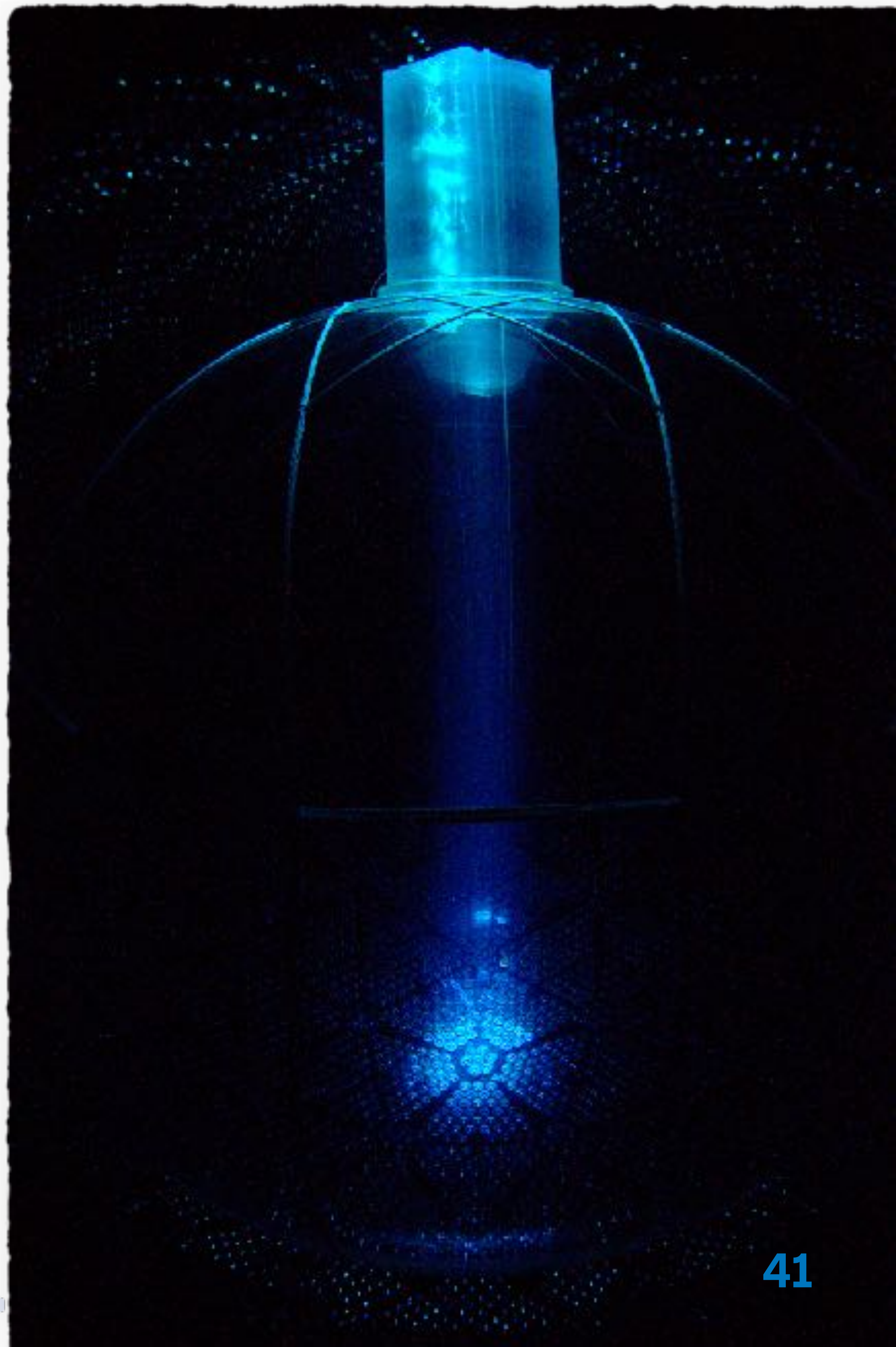
- Sterile Neutrinos
- Reactor Neutrino Anomaly
- Octant of θ_{23}
- Supernovae
- Cross Sections

- Apologies to experiments I didn't mention!

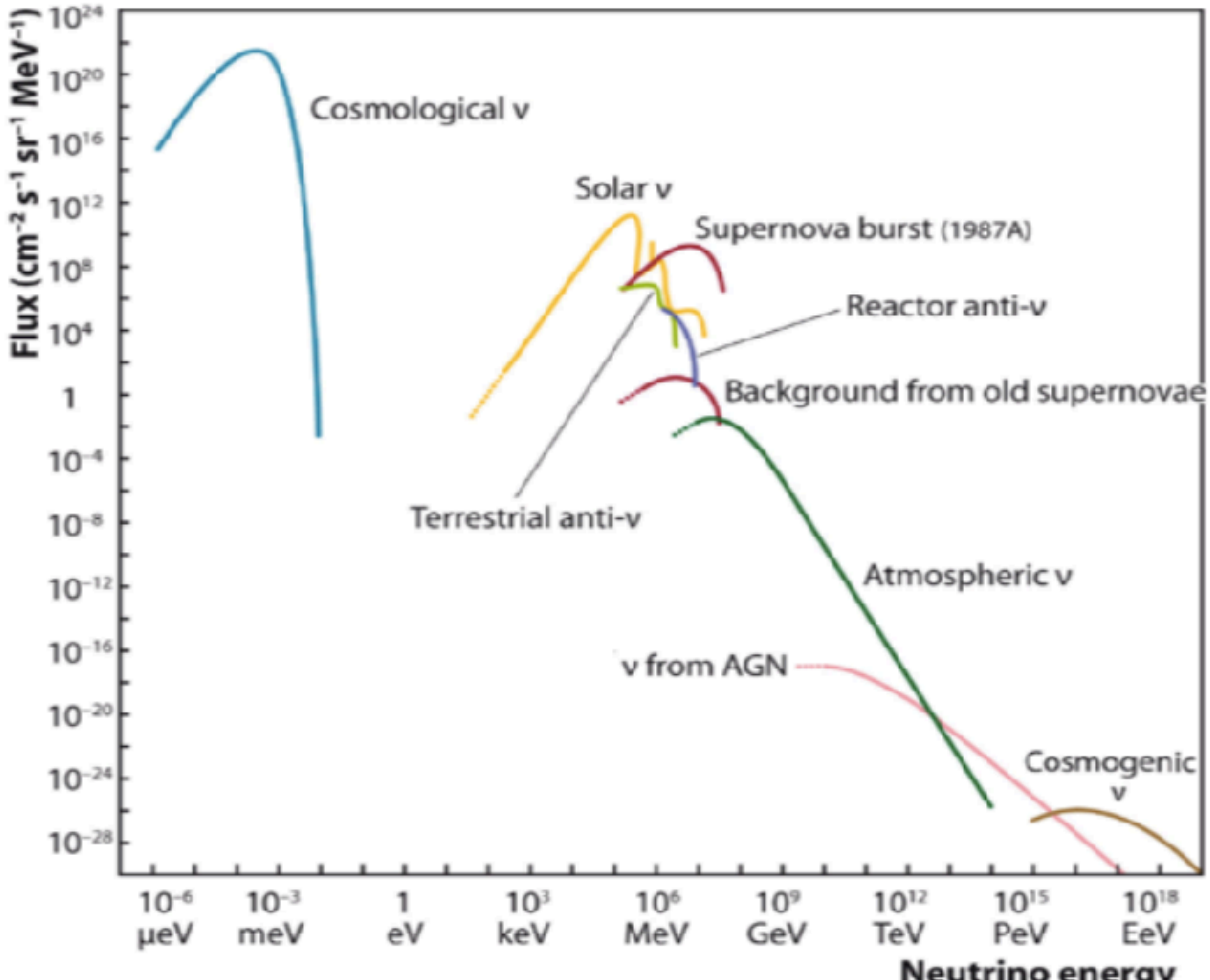
How we will learn about neutrinos!

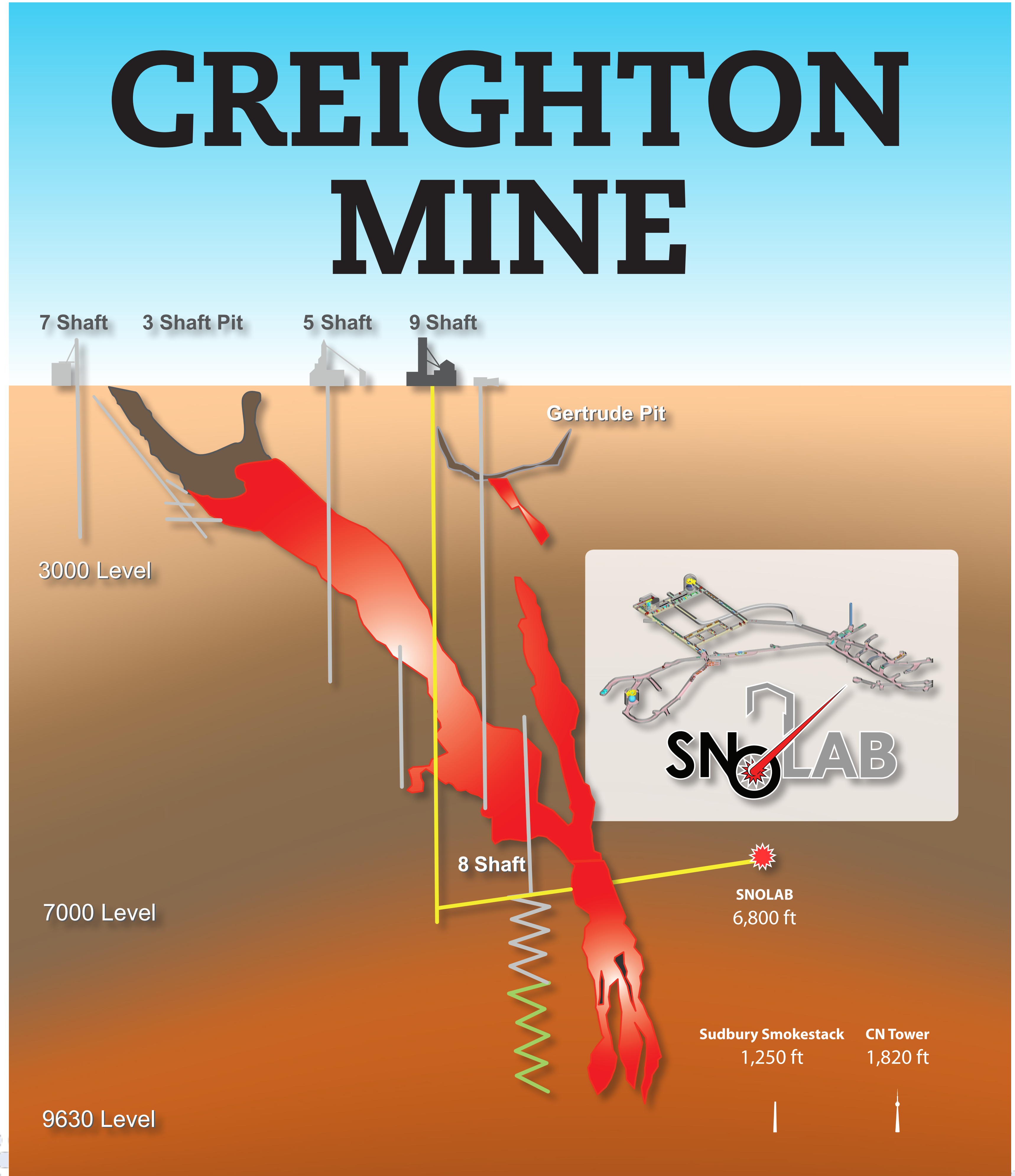
- Neutrinos are weird, wonderful particles that still hold many secrets
- What role did neutrinos play in the universe's initial matter/antimatter asymmetry?
  T2K, Hyper-K
- Which neutrino is the heaviest?
  DUNE
- What is the quantum nature of the neutrino – Dirac or Majorana?
  Double Beta Decay Experiments- many more than mentioned here

Thank You!

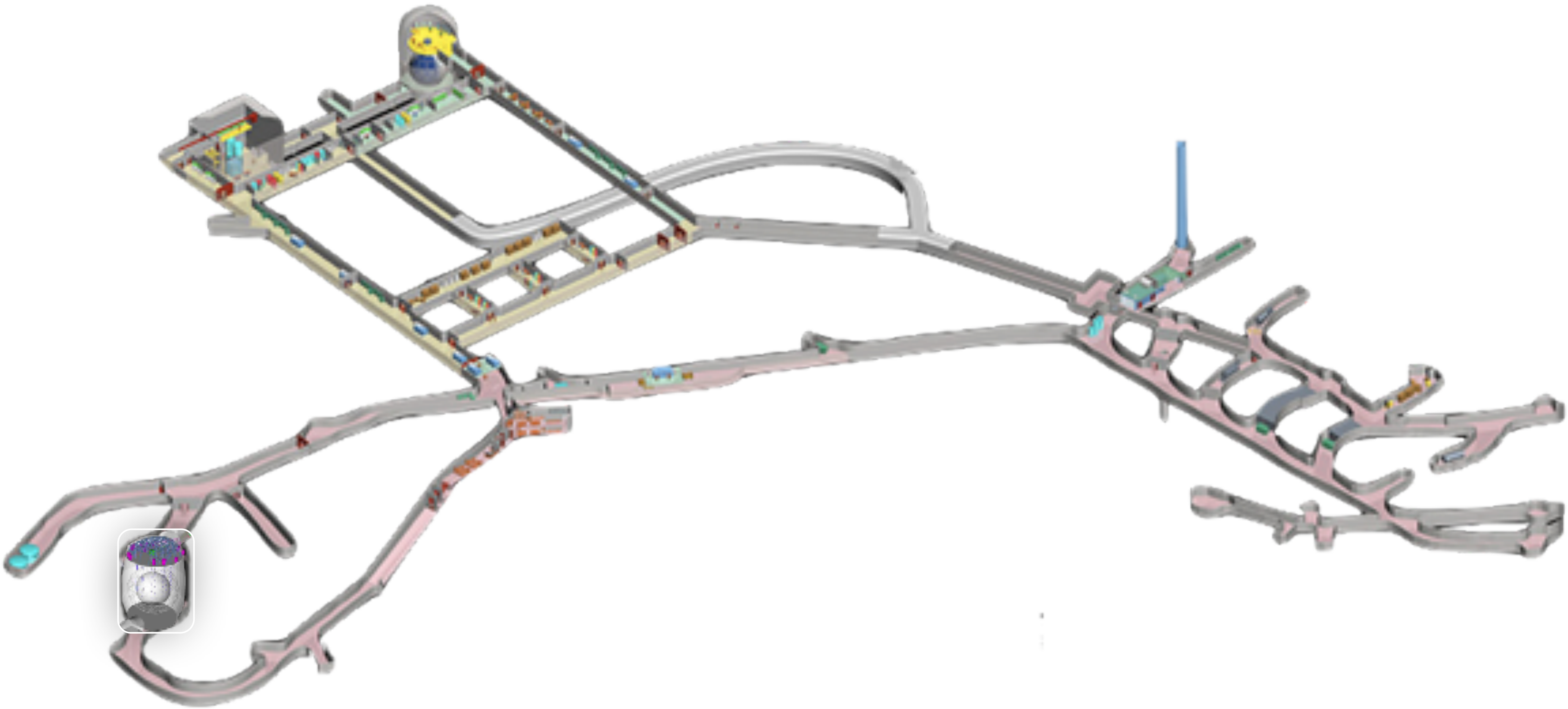


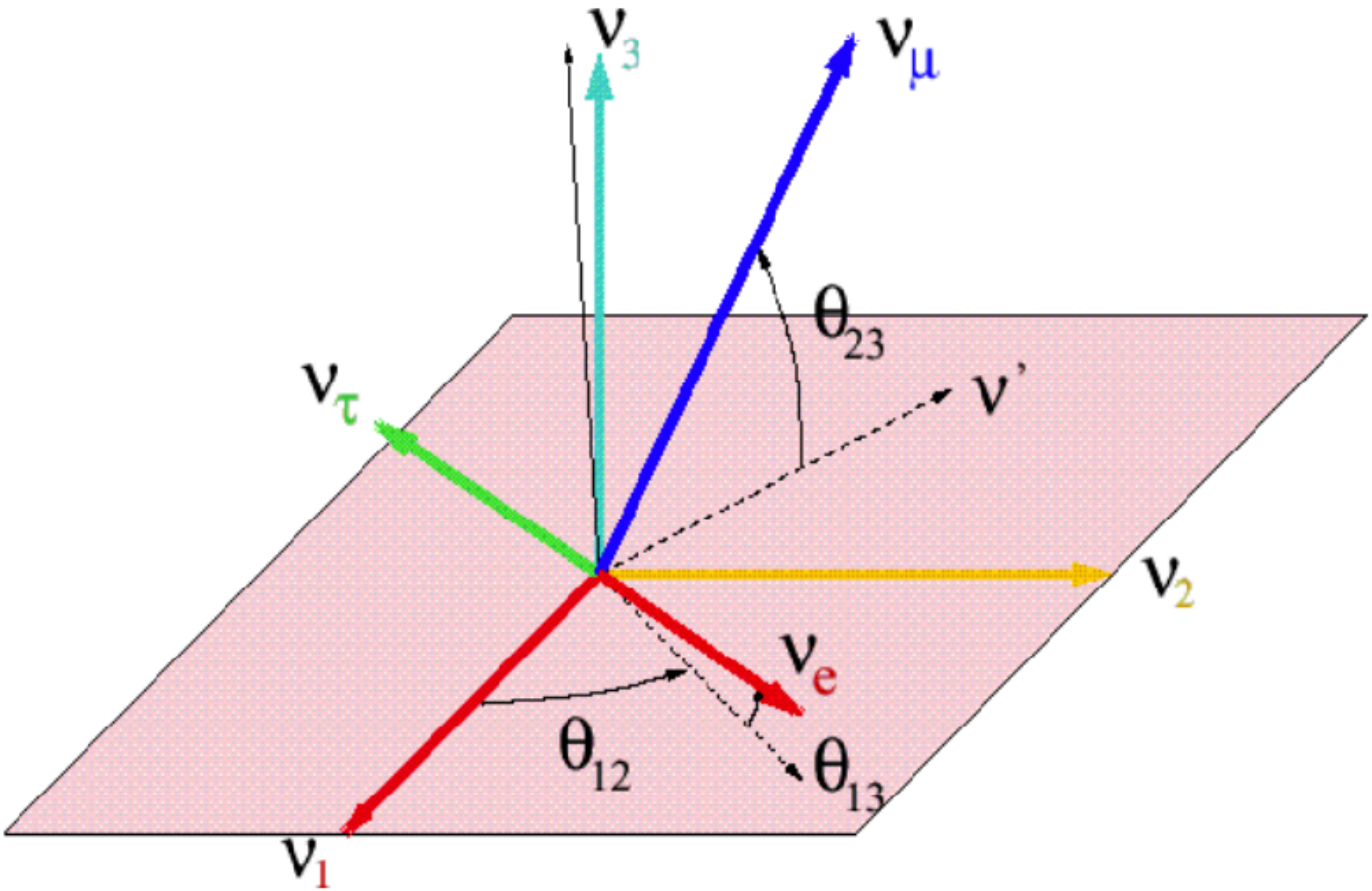
Neutrino Sources




CREIGHTON MINE
7 Shaft
3 Shaft Pit
5 Shaft
9 Shaft
Gertrude Pit
3000 Level
SNOLAB
8 Shaft
SNOLAB
6,800 ft
7000 Level
Sudbury Smokestack
1,250 ft
CN Tower
1,820 ft
9630 Level

SNOLAB





ν3
νμ
θ23
ντ
ν'
ν2
νe
θ12
θ13
ν1

Mass Hierarchy

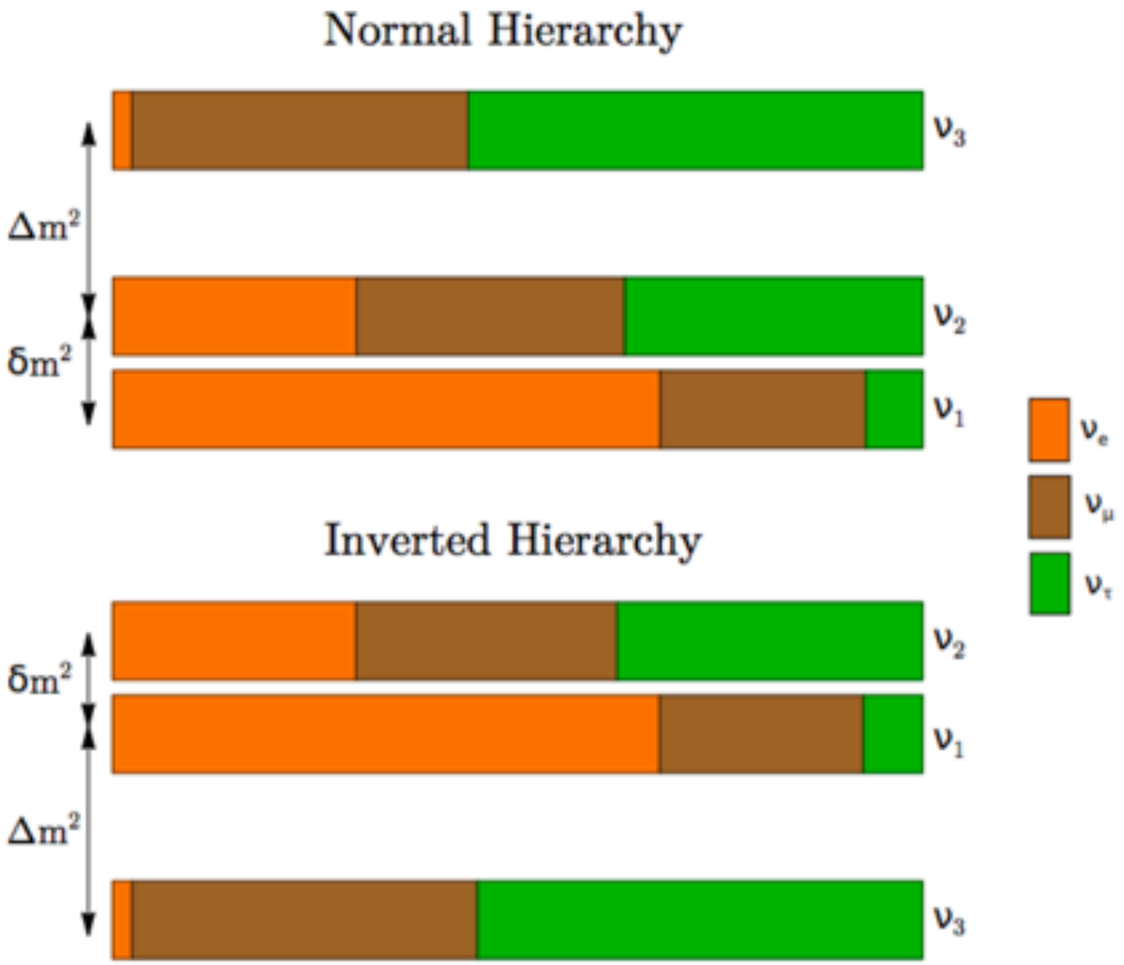
- The oscillation experiments can only measure Δm^2.

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Up to now, we have only determined the sign of $\delta m^2{}_{21}$. Thus, we don't know the ranking of m_3 relative to $m_{1,2}$

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} \mathrm{e}^{i\xi_i}\, |U^2_{\mathrm{e}i}|\, m_i\right|$$



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