Neutr nos are a thing

Neutr no Interactions Lecture 1

Hampton University Graduate Studies (HUGS) Program 2024

Week 2 — June 3rd, 2024

Bryan Ramson
Associate Scientist & Adjunct Assistant Professor
Fermilab & Michigan State University

Fermilab

First a bit about me…

An overview of my curriculum vitae

- **Born and raised in New Orleans, LA**
- **Attended Benjamin Franklin High School**
- **Went to Howard and University of Michigan**
  - Full ride to Howard from the NOAA
    - Dual Bachelors in Mathematics & Physics (with Honors)
    - Masters in Physics
  - Applied Physics Program at University of Michigan
    - Masters in Applied Physics
    - Doctorate in Nuclear & Particle Physics
  - Multiple Internships at NASA, Argonne, & Yale
  - For PhD analyzed the light quark flavor asymmetry at E906/SeaQuest
- **Fermilab Research Associate**
  - Work on the Long Baseline Neutrino Oscillation Experiments NOvA and DUNE
- **Promoted to Associate Scientist/Adjunct Associate Professor**
  - Measuring neutrino oscillations and neutrino-nucleus scattering using NOvA
    - Cross-section modeling convener for NOvA
  - Light contributions to DUNE through students and research associates
  - Working on a lab supported project to make a new generation of Bubble Chambers

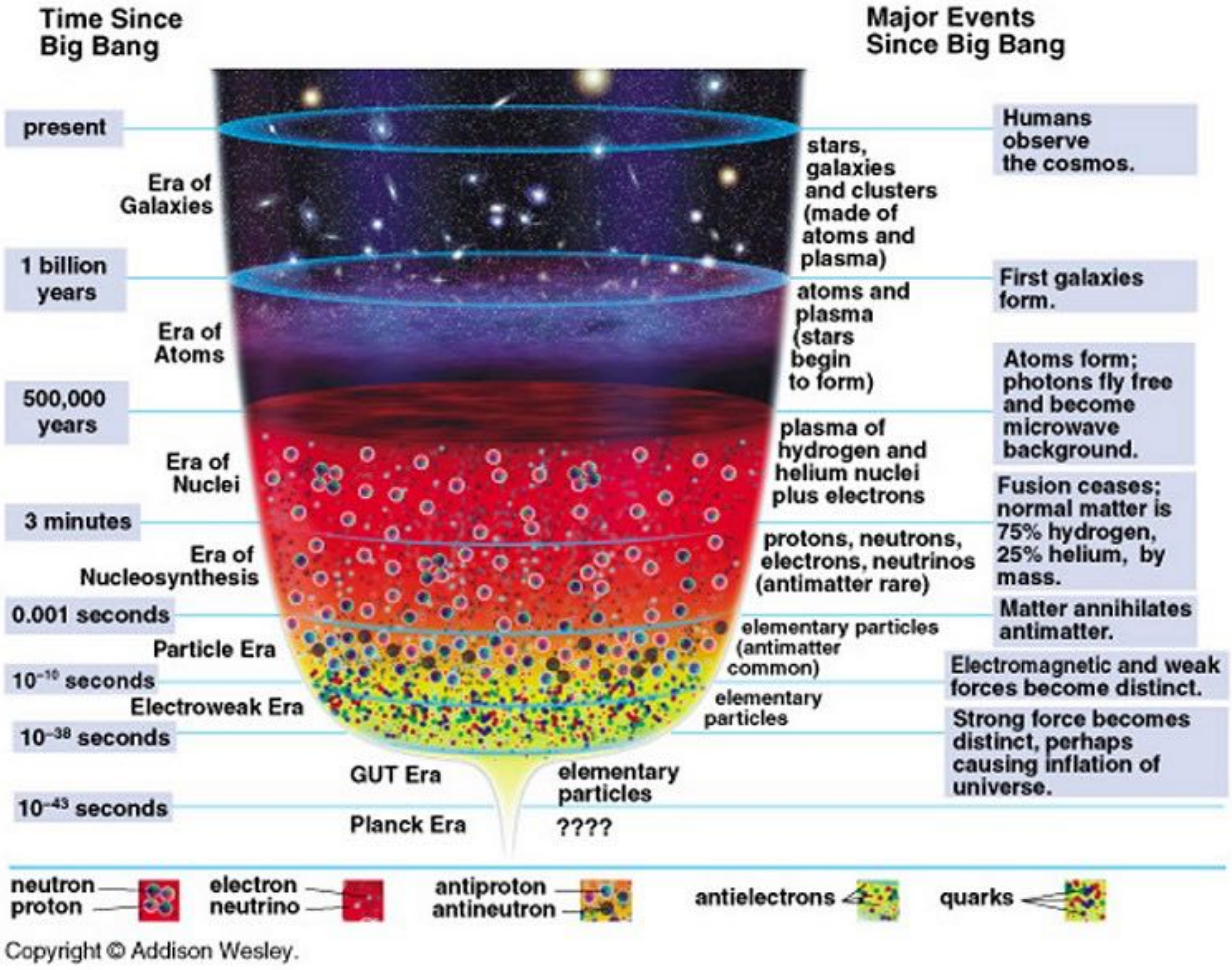
First a bit about me…

‘dis me tho’

- Born and bred in New Orleans.
- I *like* video games (Baldur’s Gate 3/D&D3.5e/5e, Cyberpunk 2077/Red, BotW/TotK, GoW, Hades/Hades II), music, anime, books, cars, food, and life.
- I travel a lot and have been all over the world!
- I love Illinois and Louisiana and Michigan and DC. America is great most of the time.
- I’m a landlord and elected official in Chicago.

Let’s Start From the Beginning…

How does the Universe start?

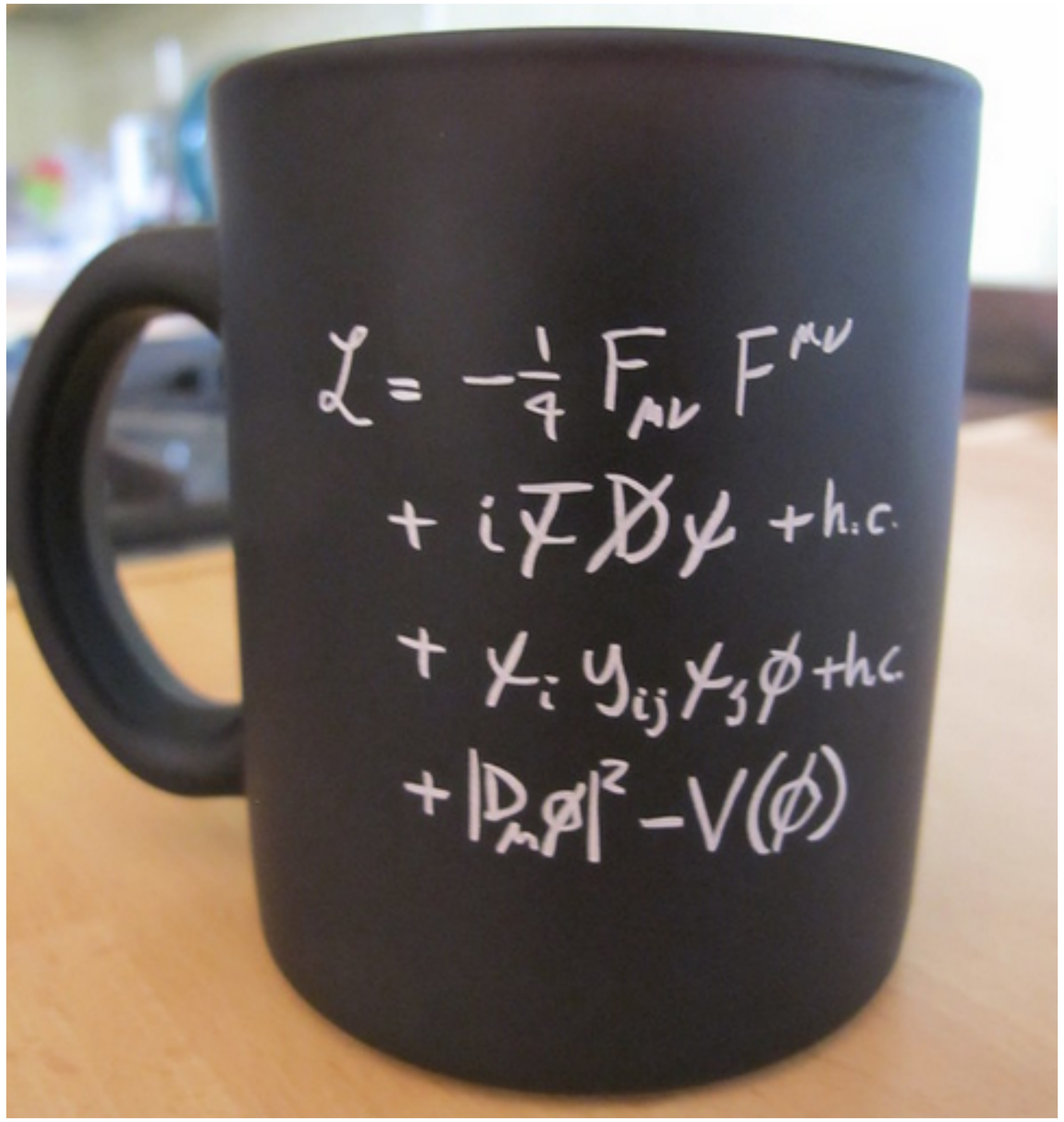


- Matter and antimatter created in ‘almost’ equal amounts.
  - For every 10 billion antimatter particles one extra matter particle!
- Once the universe cooled, matter was left over and became us!
- But the standard model predicts matter and antimatter in equal amounts…

What can neutrinos tell us about this asymmetry?

A Brief Reintroduction to Particle Physics

The Theory of Almost Everything…



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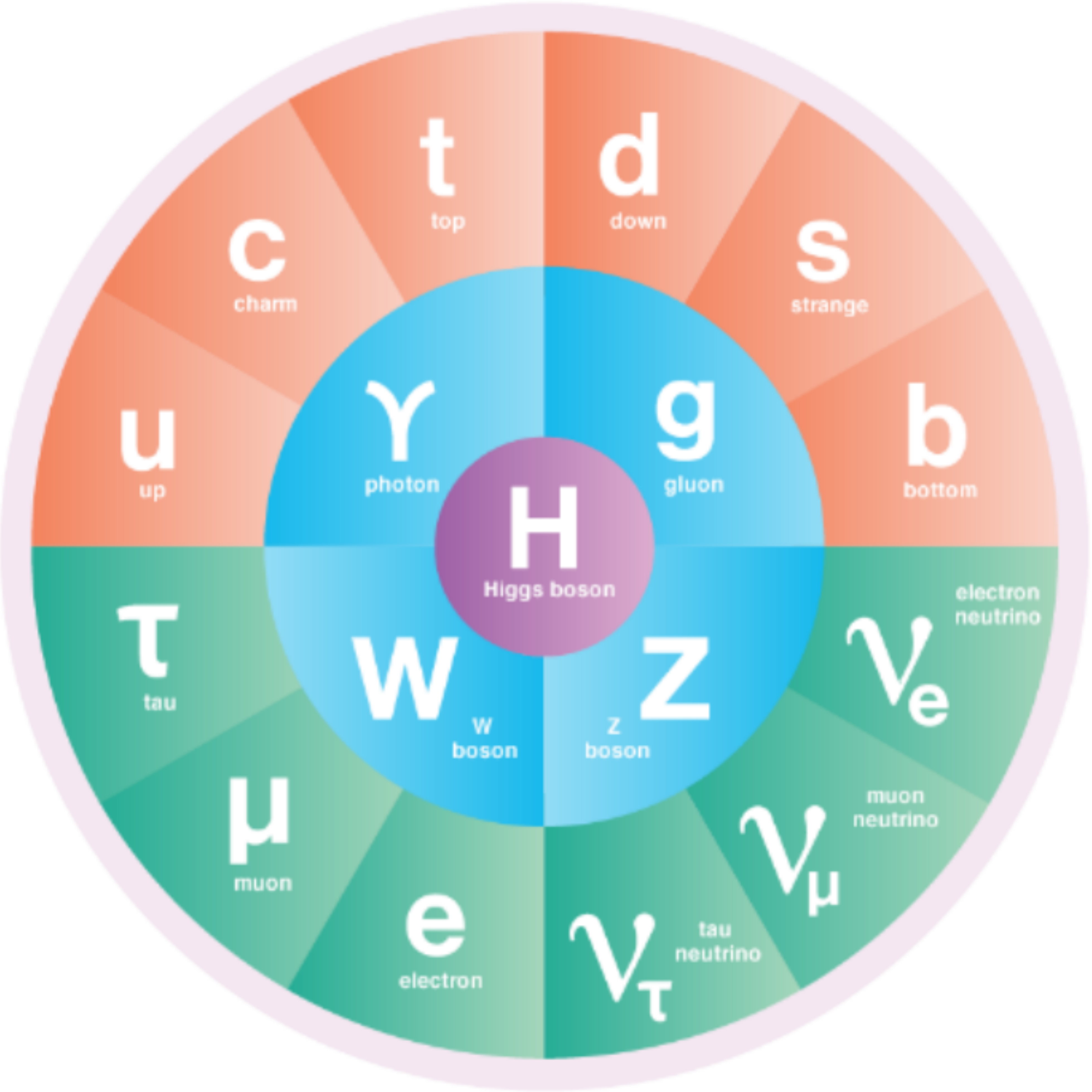
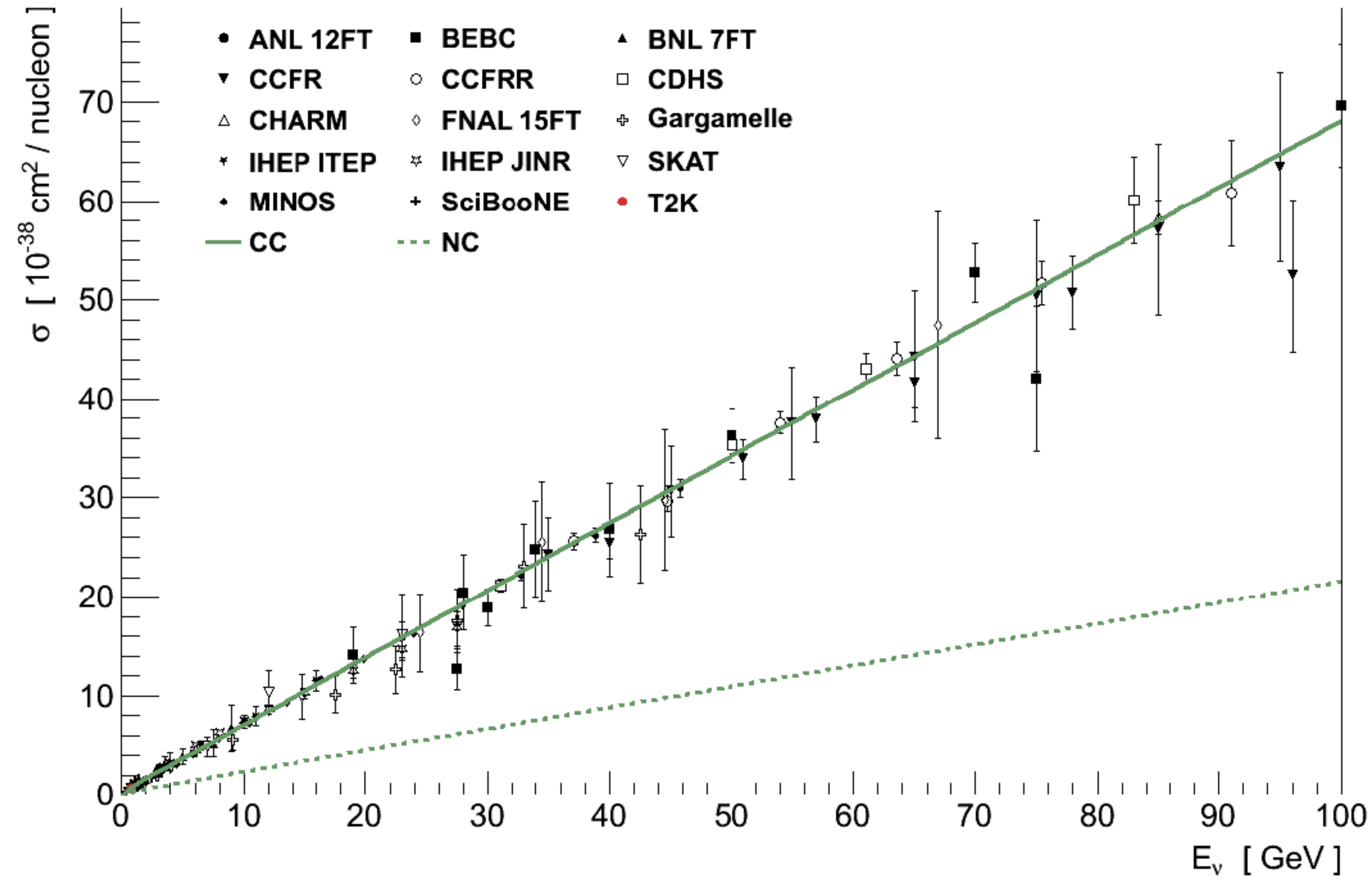


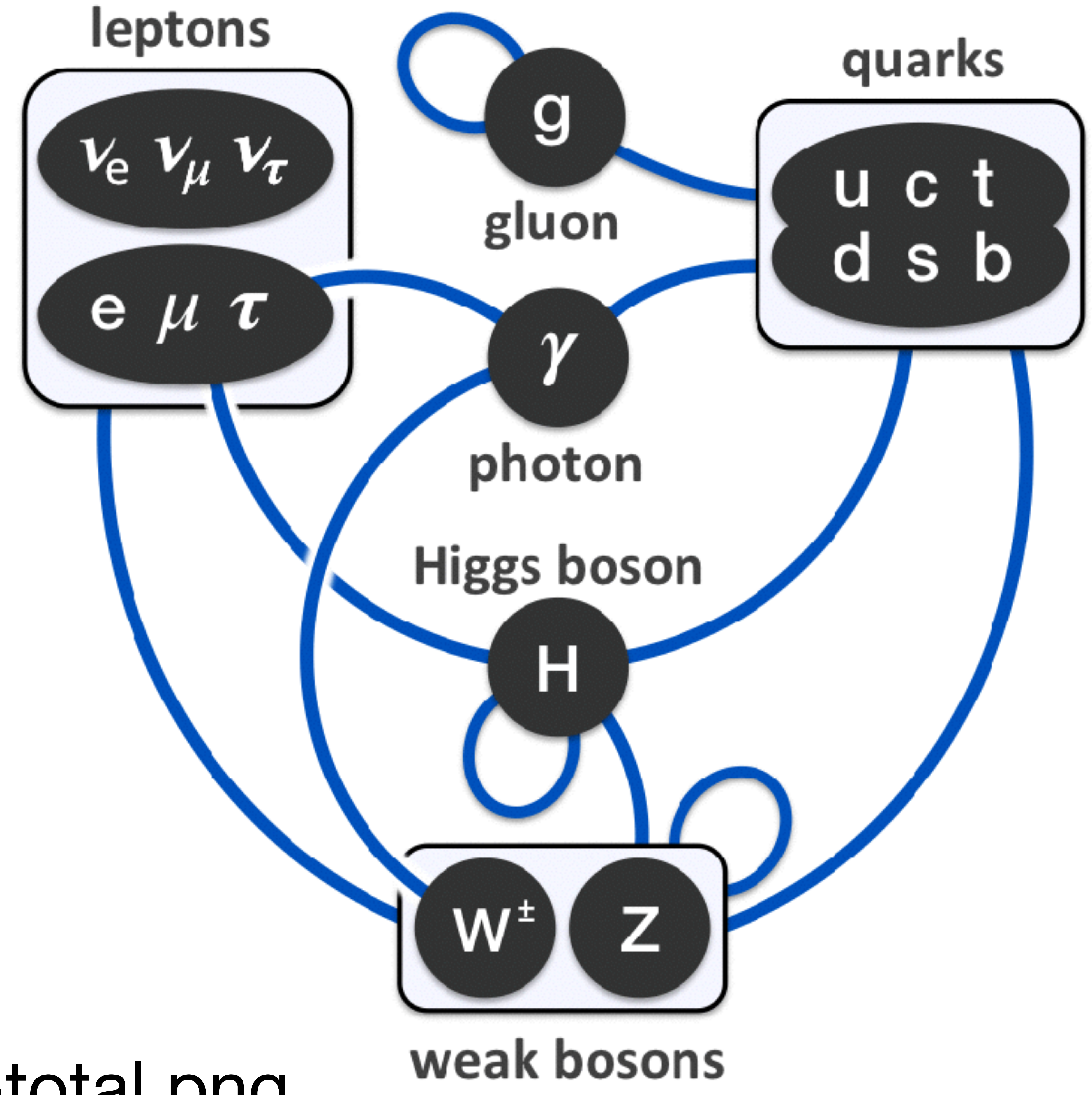
https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics

It describes the underlying symmetries governing the scattering, creation, and annihilation of particles. It only excludes gravity. **Doing a nuclear/particle physic means testing parts of the standard model.**

The Ghos ly Neutr no

Nature's smallest and most interesting magician





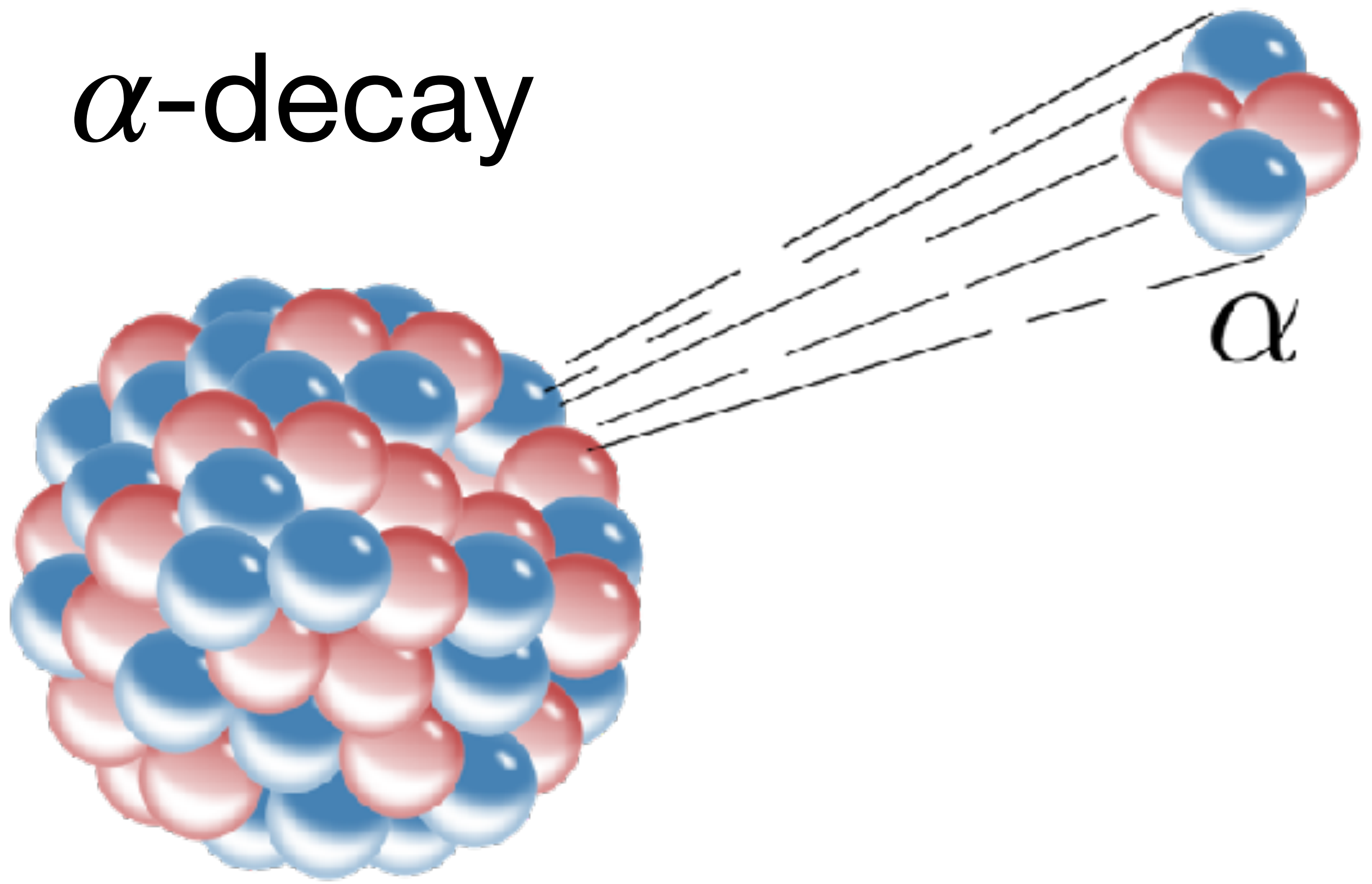
https://danielscully.uk/thesis/img/figure-interactions-total.png

Neutr nos have a very low cross-section and thus interact very rarely compared to other types of particles (10^{-14} difference from electron scattering). Electrically neutral!

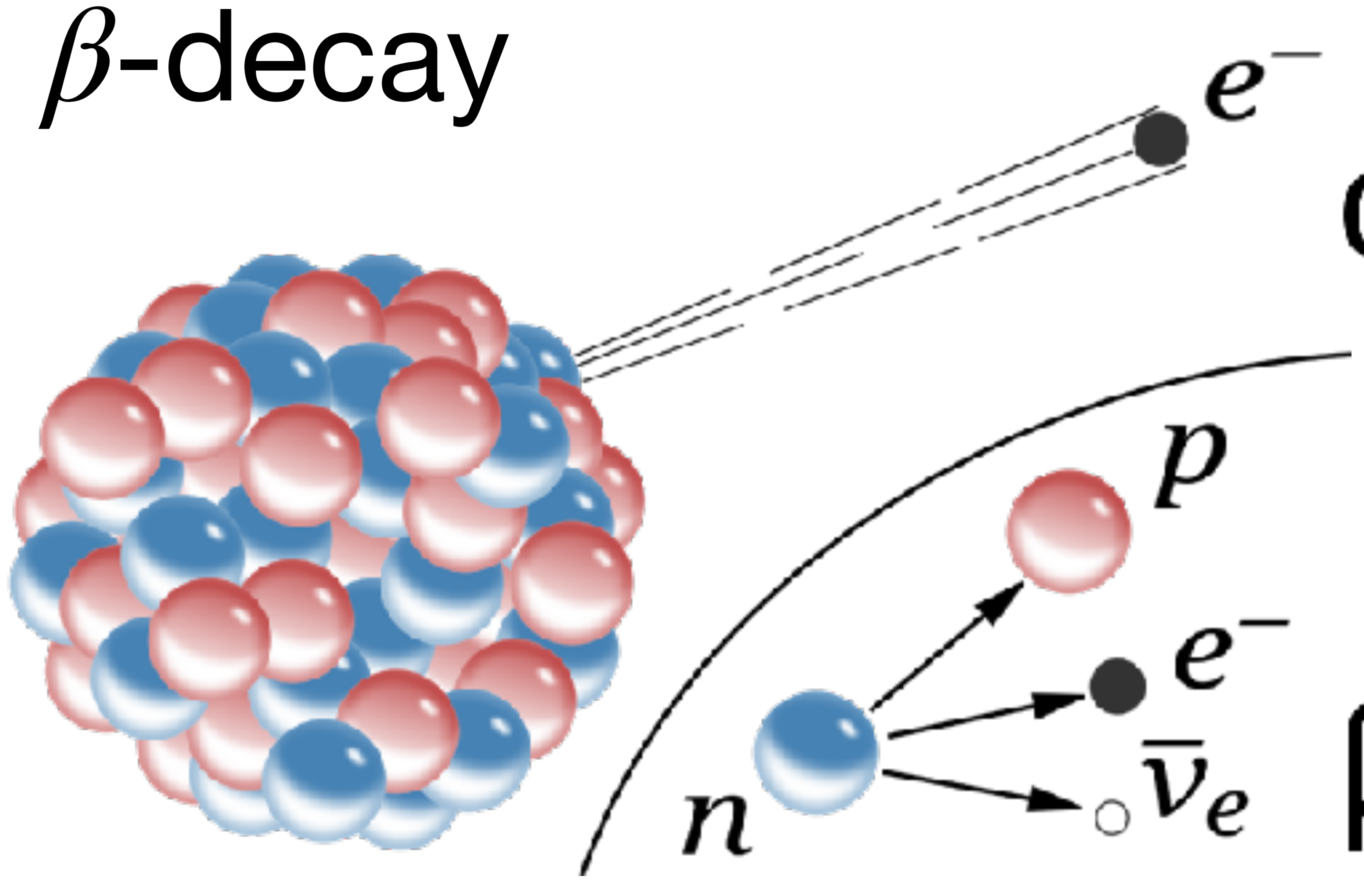
The Menu of Nuclear Decays

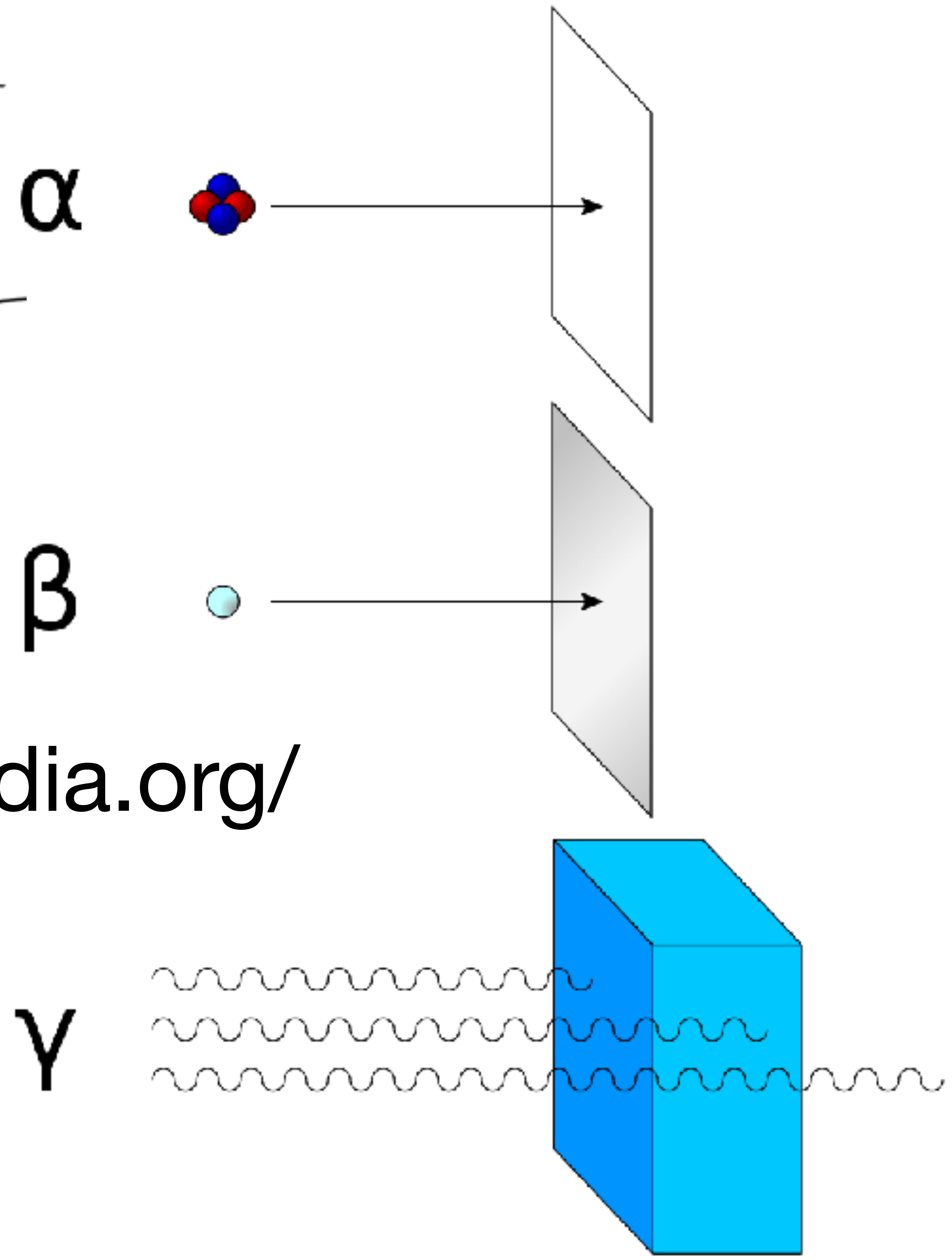
What particle physics looked like 100 years ago…

α-decay



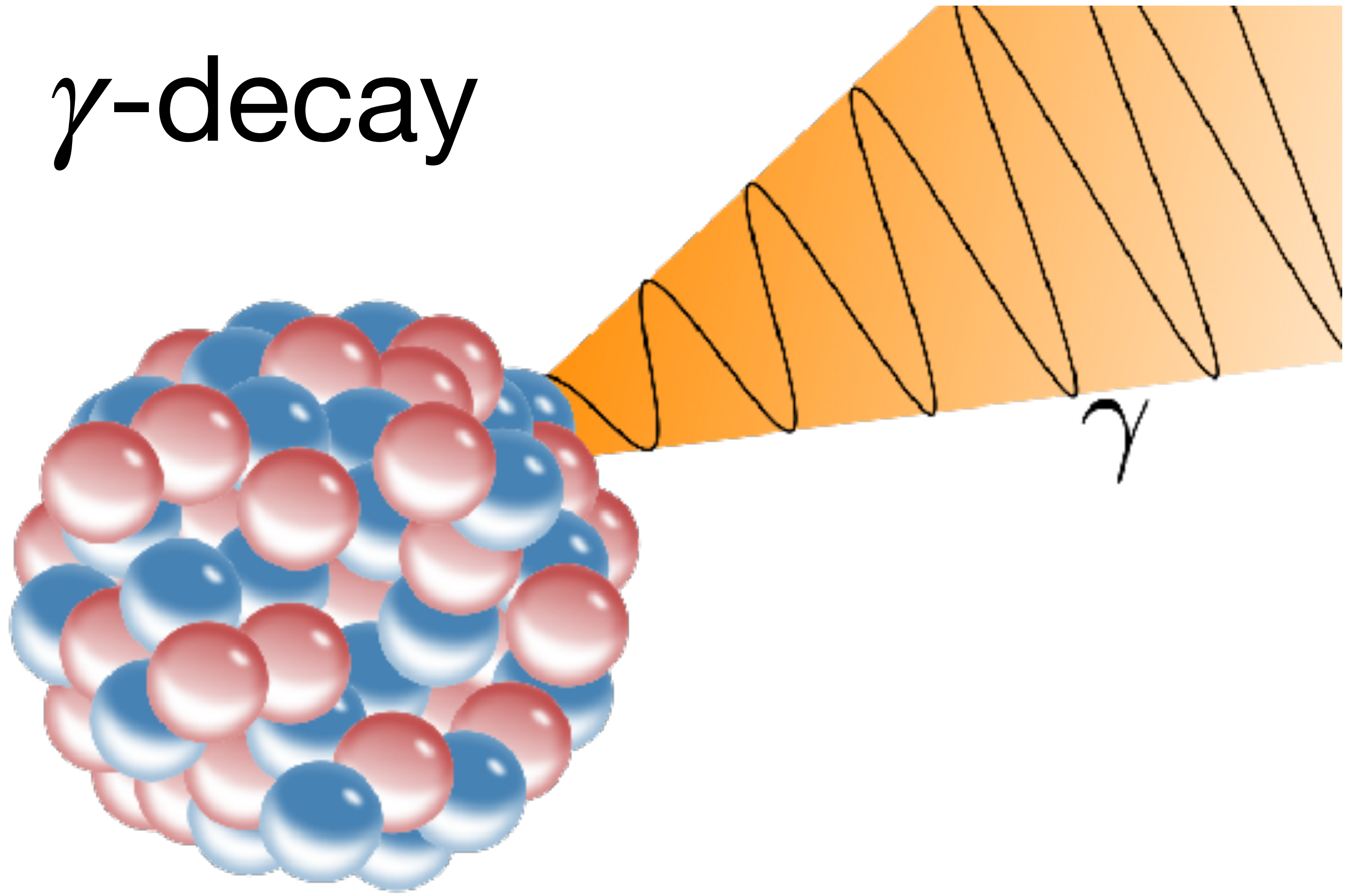
β-decay





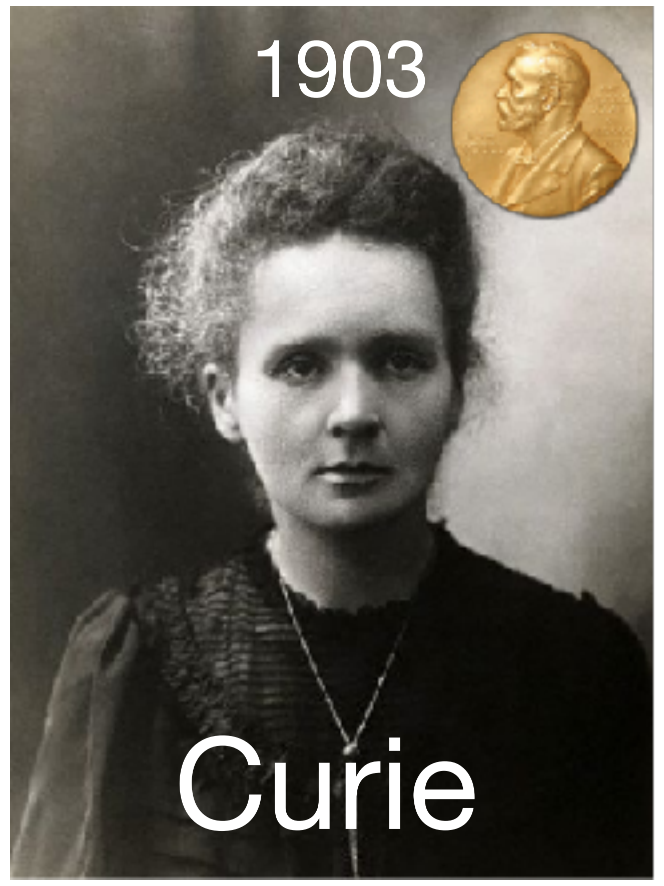
https://en.wikipedia.org/

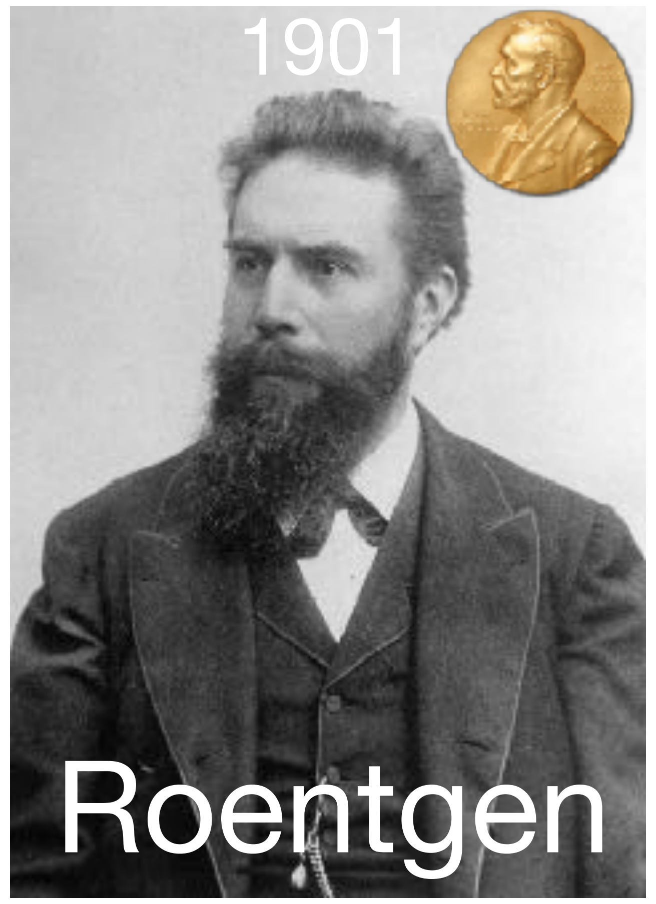
γ-decay

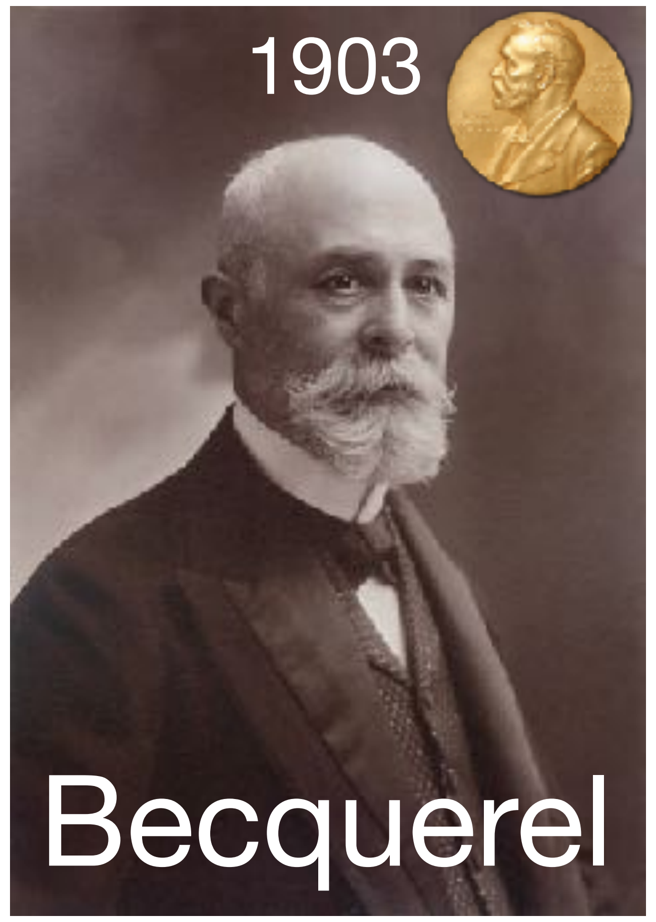


The standard model had not yet been created and scientists like Roentgen, the Curies, and Becquerel were investigating a weird new source of energy!

What they were really discovering was another application of the conservation of energy and momentum but, at a subatomic level! *They did not know that at the time!*

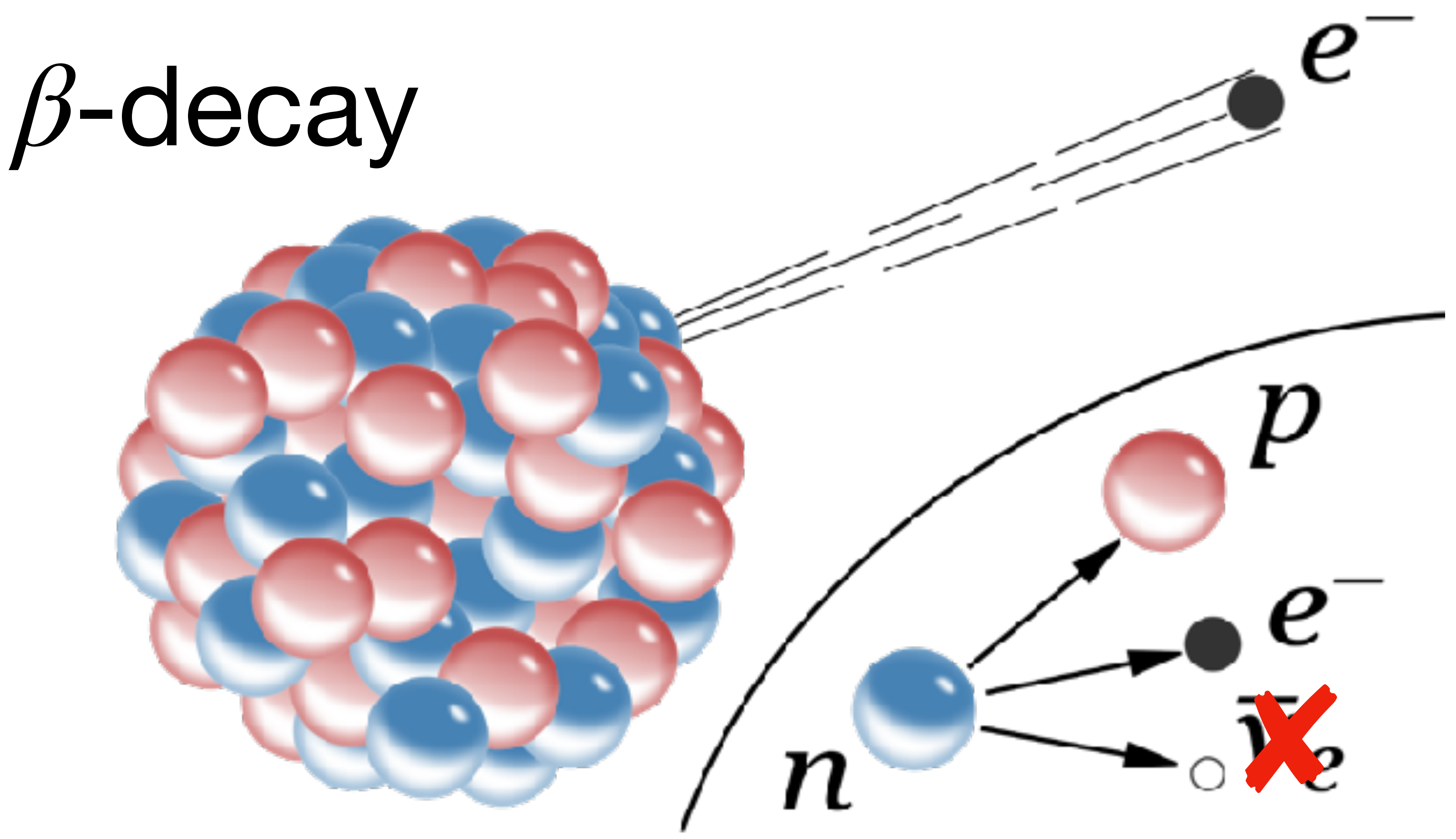






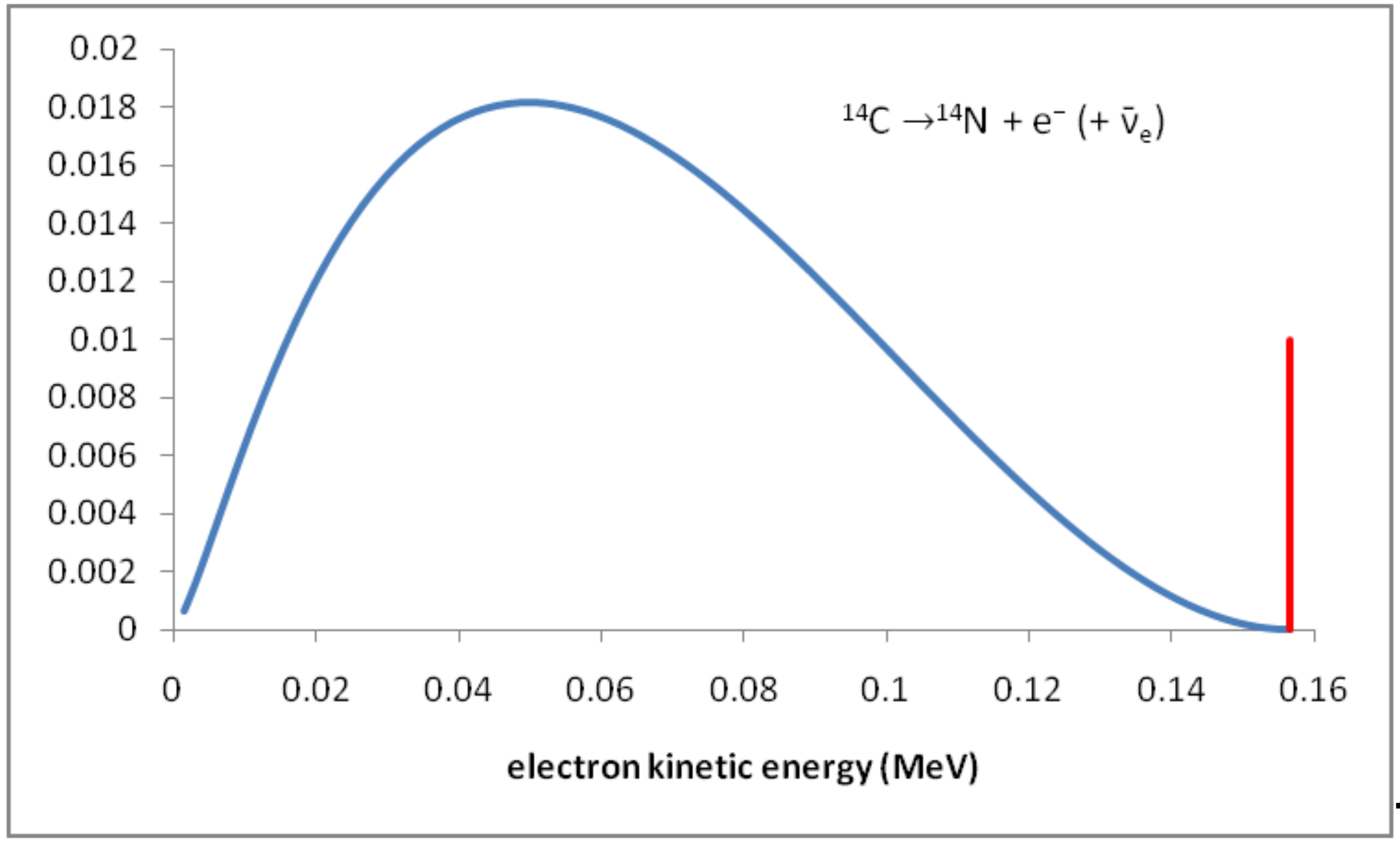
The Conundrum of β-decay

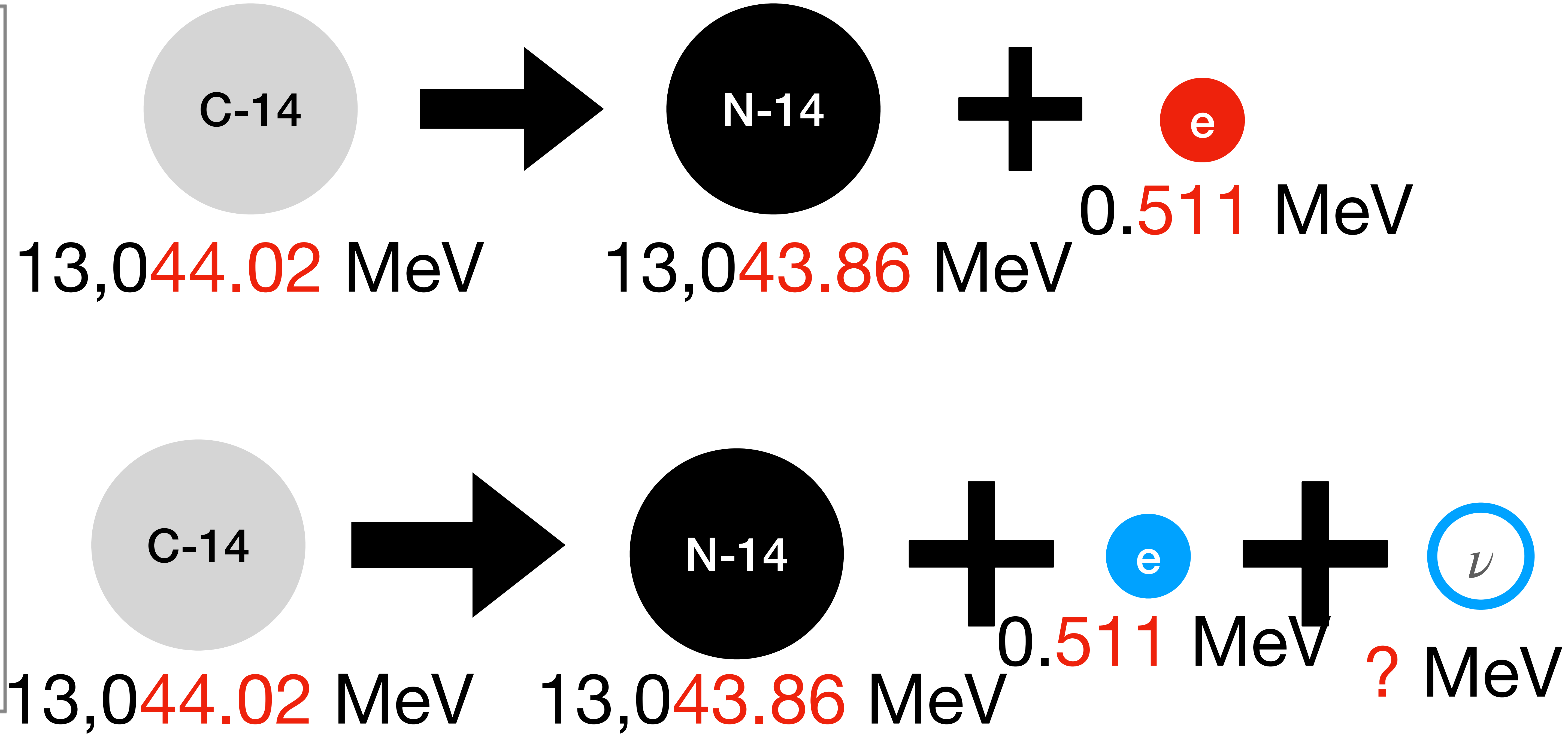
A problem of missing energy…



As an example: Radioactive Carbon Dating requires an isotope, Carbon-14 to decay to Nitrogen-14. Without neutrinos, electron production should be mono energetic.

Experiment shows clear distribution of kinetic energy which requires an additional particle to conserve both energy and momentum.





The Conundrum of β-decay

An unlikely solution…

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. Des. 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 Des. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}$ cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

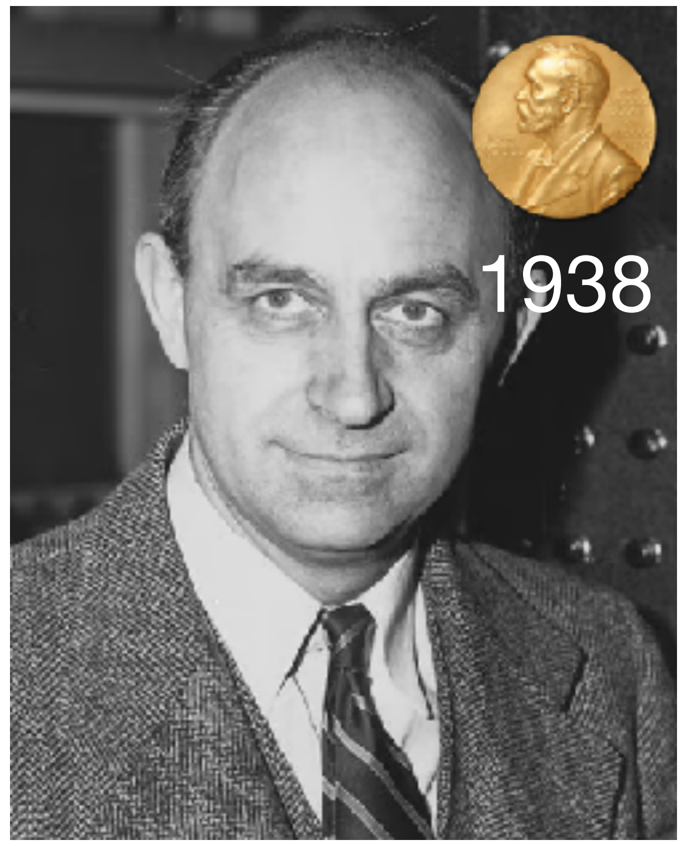
signed W. Pauli

[Translation: Kurt Riesselmann]

The neutron was discovered in 1930, so this particle was called the "little neutral one" by Enrico Fermi *in Italian* after positing the process for generation. *Thus the neutrino was born.*

In 2023, we know this was the *correct* answer but in 1930 it was a bit *cringe…*

Wolfgang Pauli



Enrico Fermi

Revisiting Neutrino Properties

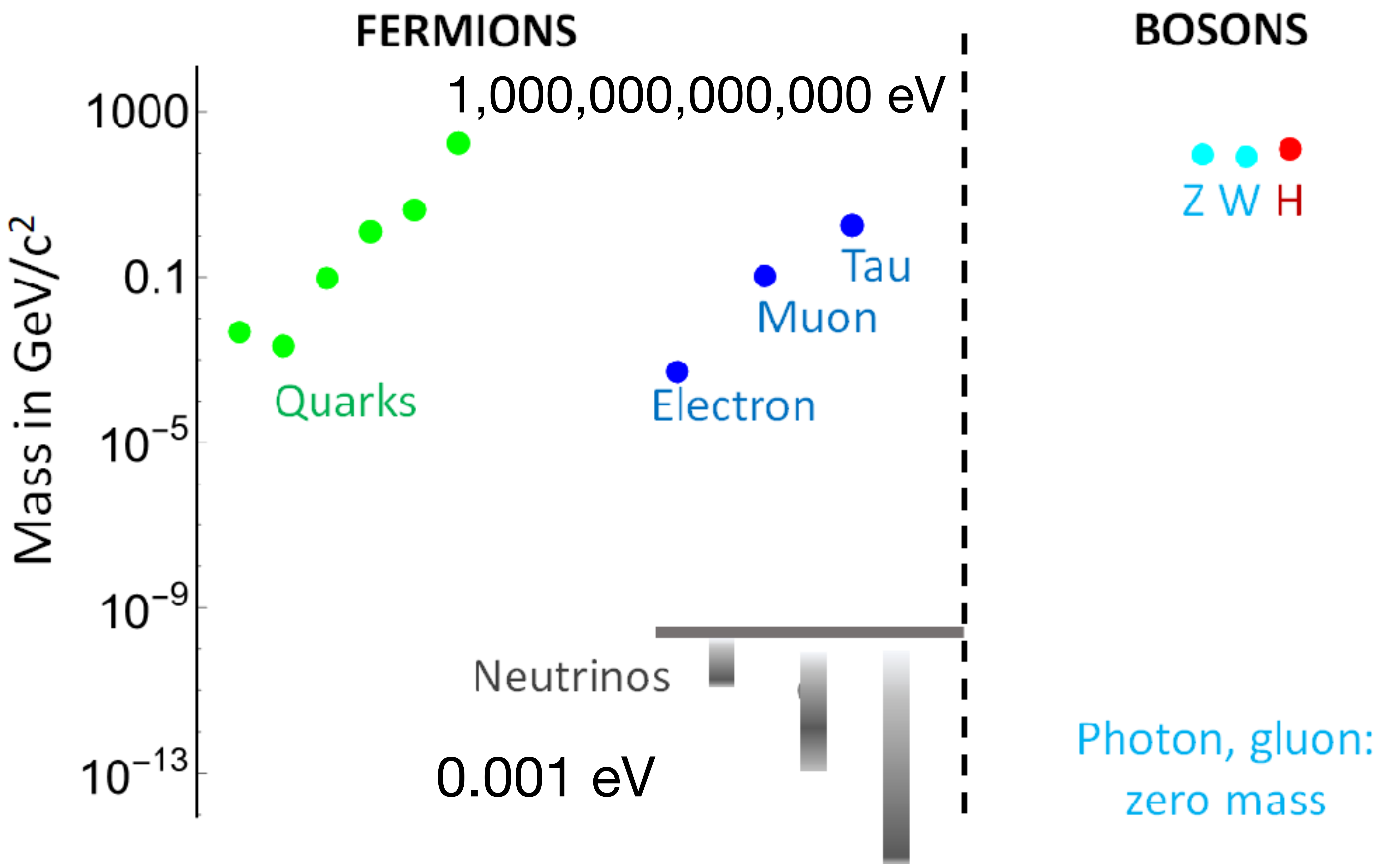
As formulated back then…

In 2023, we know this was the *correct* answer, but in 1930 it was a bit *cringe but… Why?*

Neutrinos *must* be neutral or they would interact like electrons.

Neutrinos *must* be unfathomably *light* or they would interact like neutrons.

When Fermi tried to publish this theory in *Nature*, the paper was *rejected*! ***Impossible to detect***!



Neutrinos would have to span at least 12 orders of magnitude to reach the electron and 15 orders to look like a neutron!

The First Neutr no Experiments

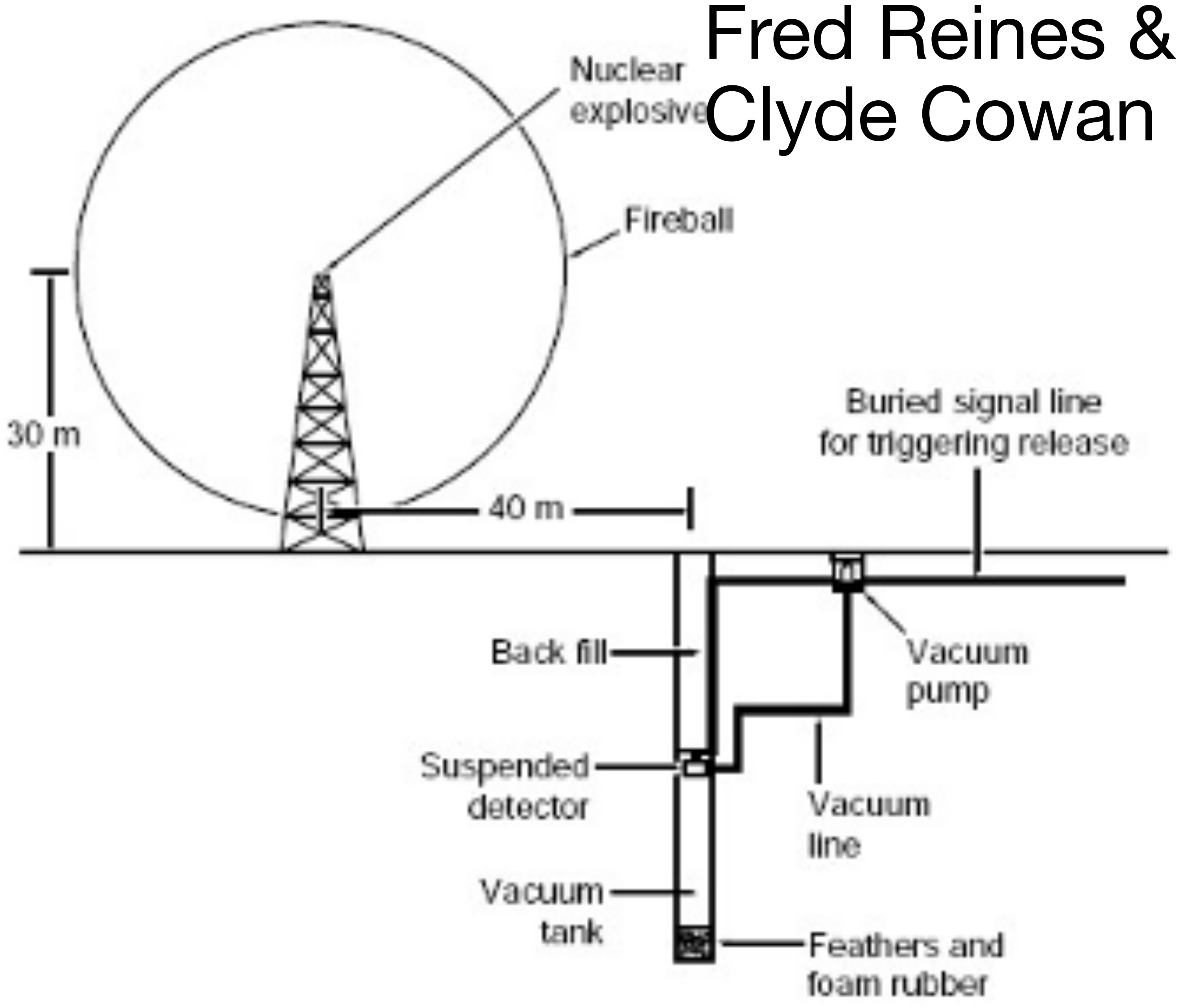
Physicists back then were cowboys…

How to measure something that is effectively ***matter-phobic***?

$\times\ 10^5$

We use specially built particle detectors and large sources of neutrinos

First proposals involved… *exotic sources*



Fred Reines &
Clyde Cowan

First Project Poltergeist Proposal

Plan was to detonate the bomb and drop a detector…

~100m away

…at the same time!

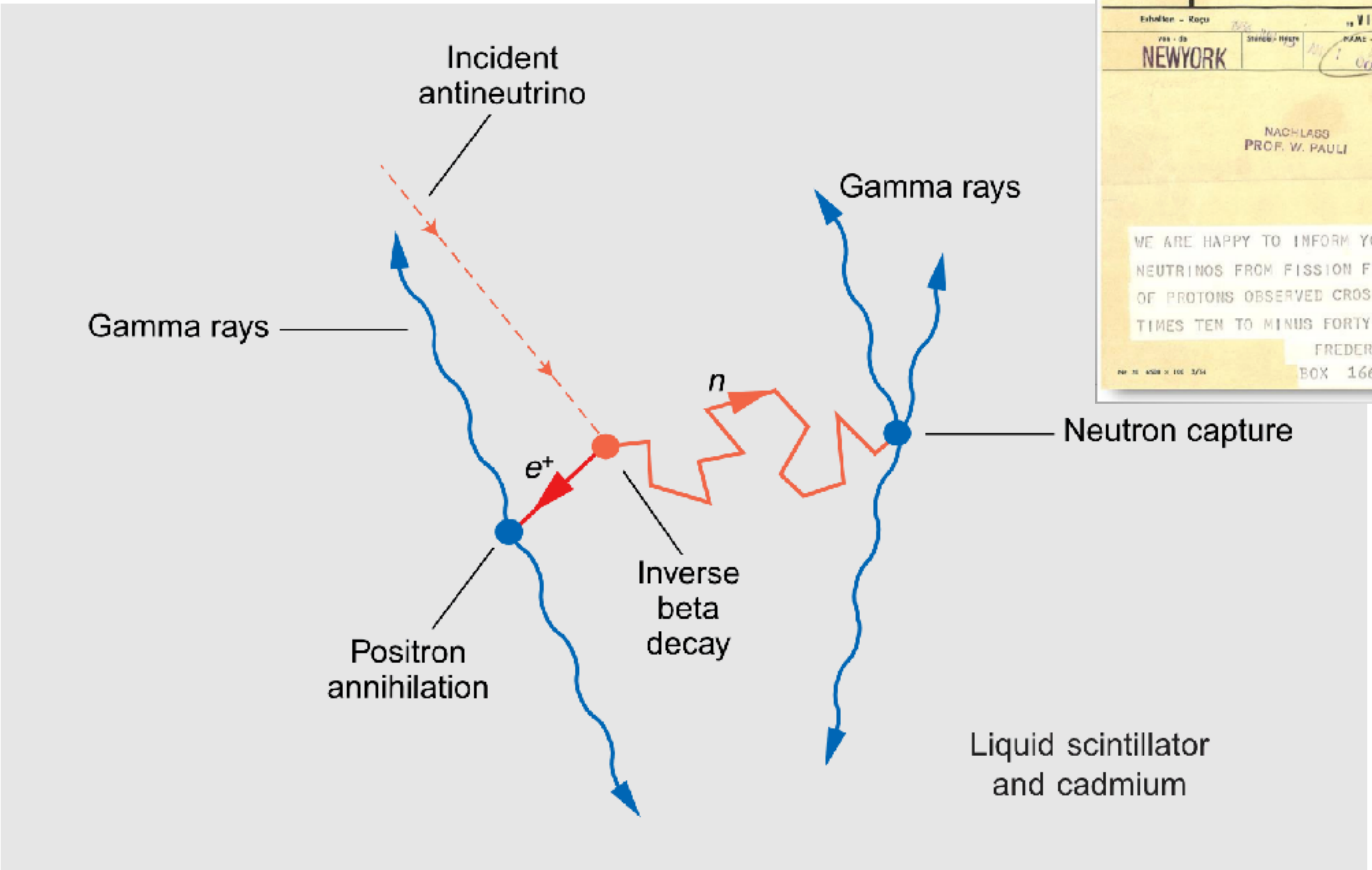
Hard to verify because detector, must be sensitive and durable and this was the 1950s.

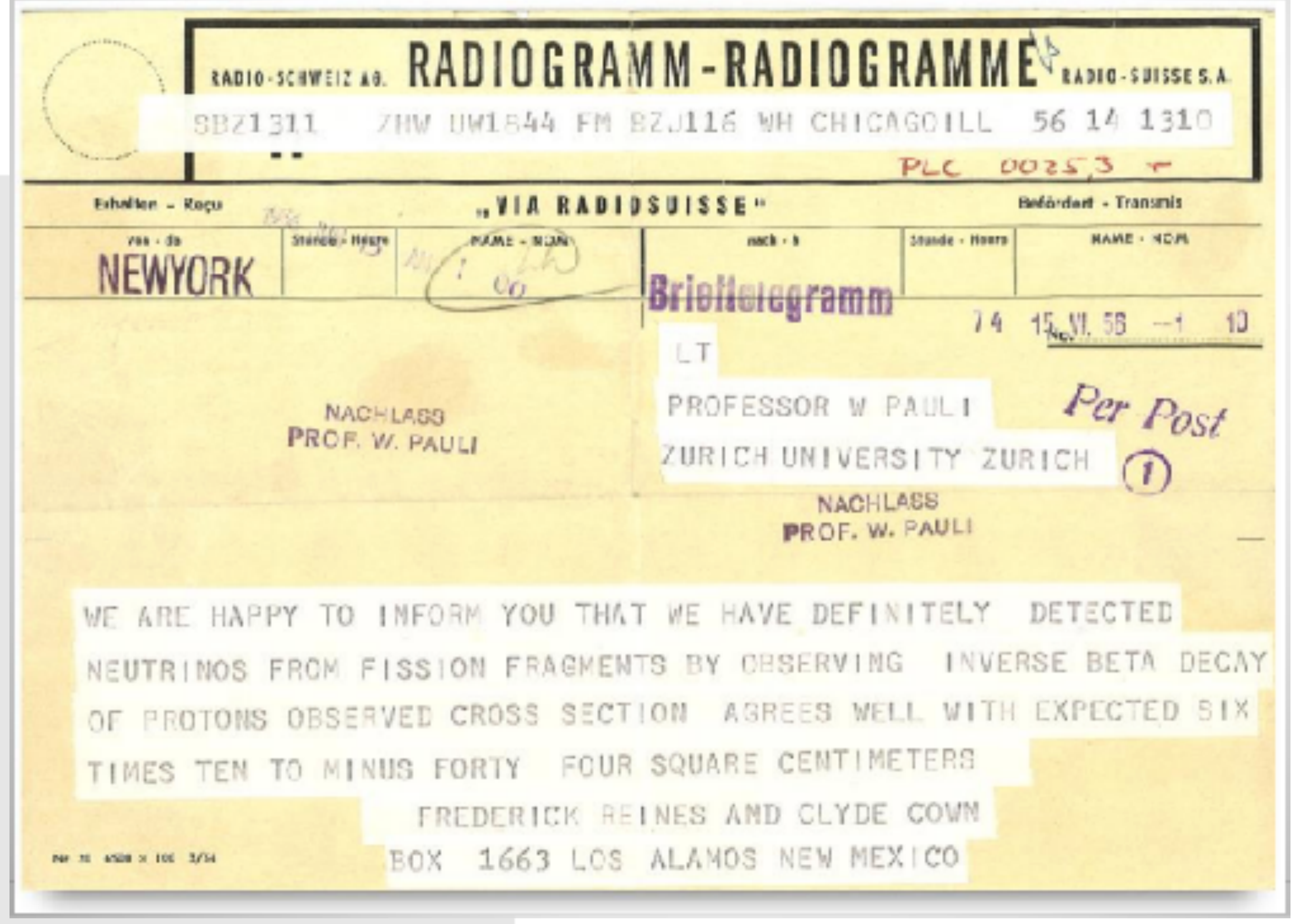
The First Neutrino Experiments

First Detection of Neutrinos (1956)

Why not use a better detector but maybe put it in a more stable environment?

In 1956 Reines & Cowan announced discovery after the Hanford and Savannah River Experiments use nuclear reactors.





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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

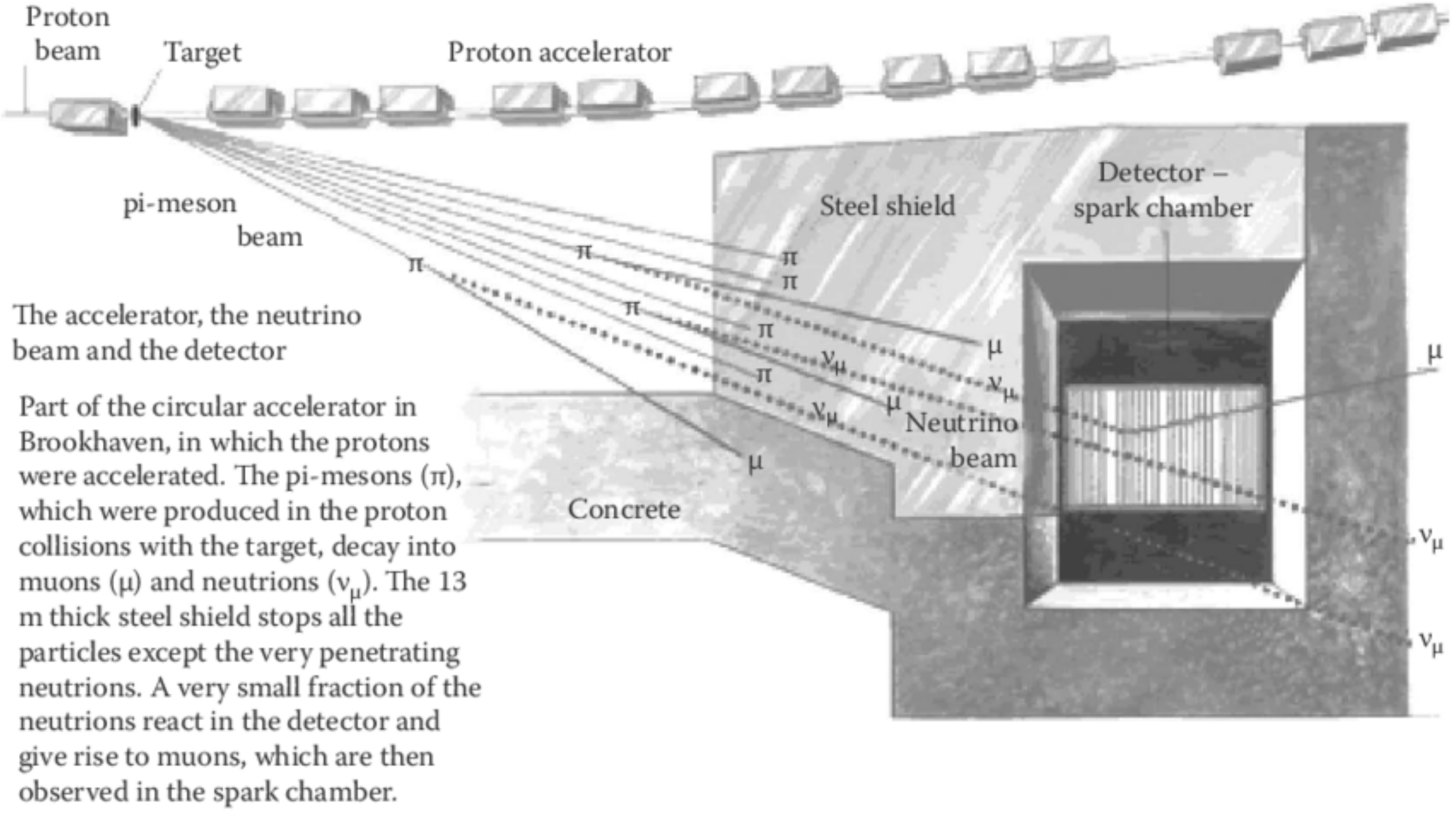
Discovery of the Muon-Neutrino

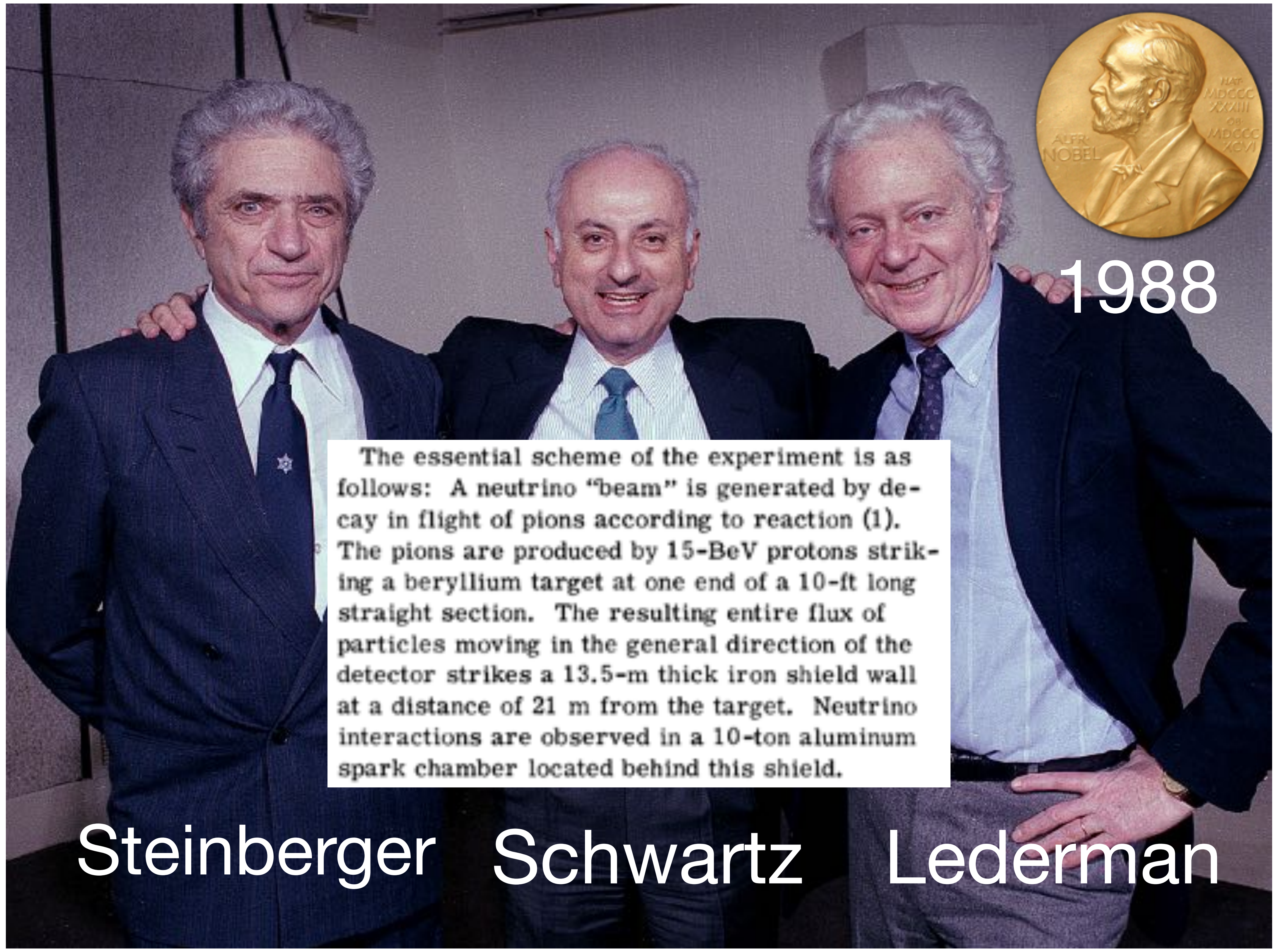
Neutral Lepton Generations (1962)?

The race was on to harness new sources and to find out more about neutrinos!

One of the first investigations was of neutrinos of different flavors. Given that generations of charged leptons exist do generations of neutral leptons exist?

AGL beam line tries to answer this question by creating neutrino "beams" at Brookhaven National Laboratory.

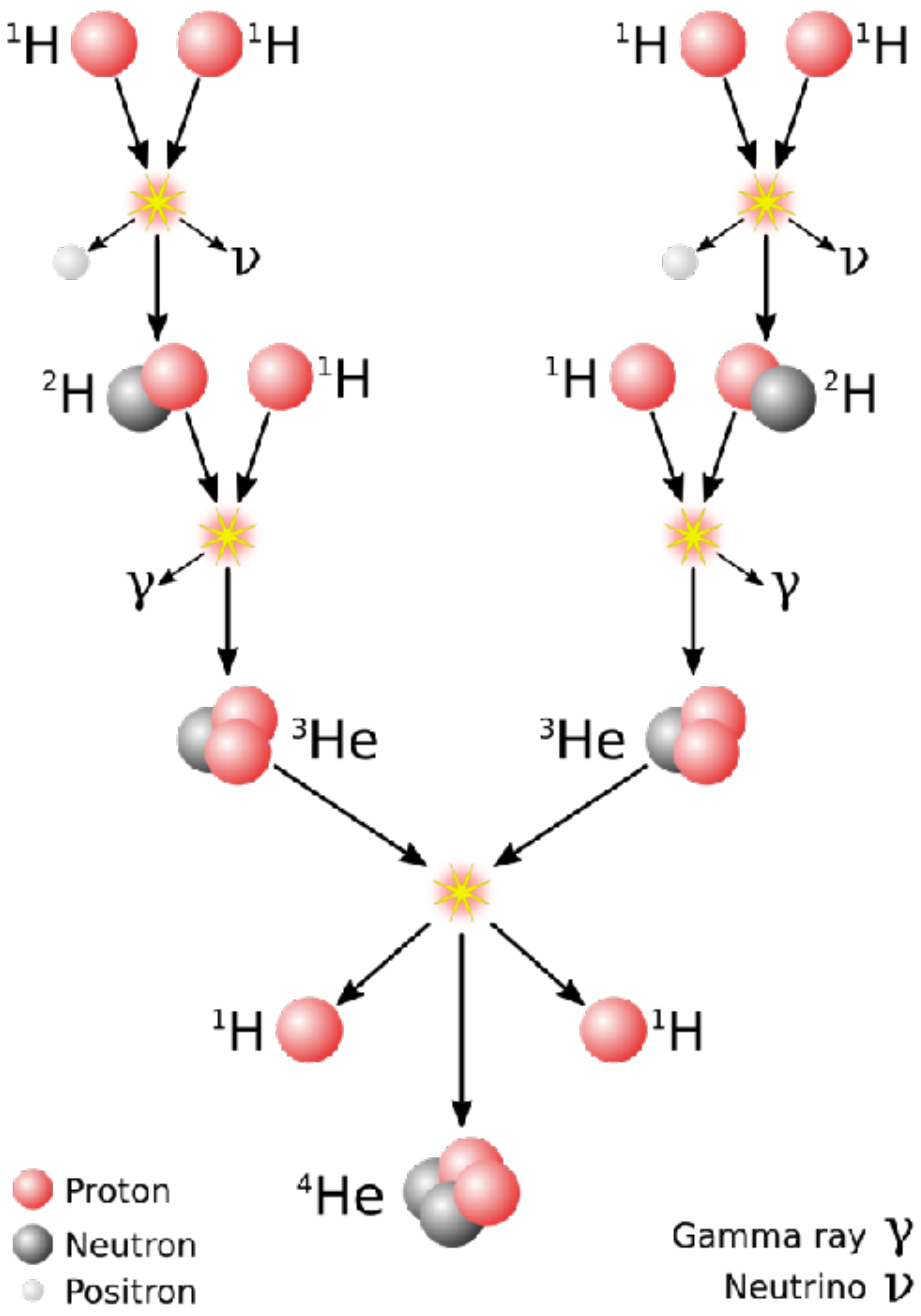


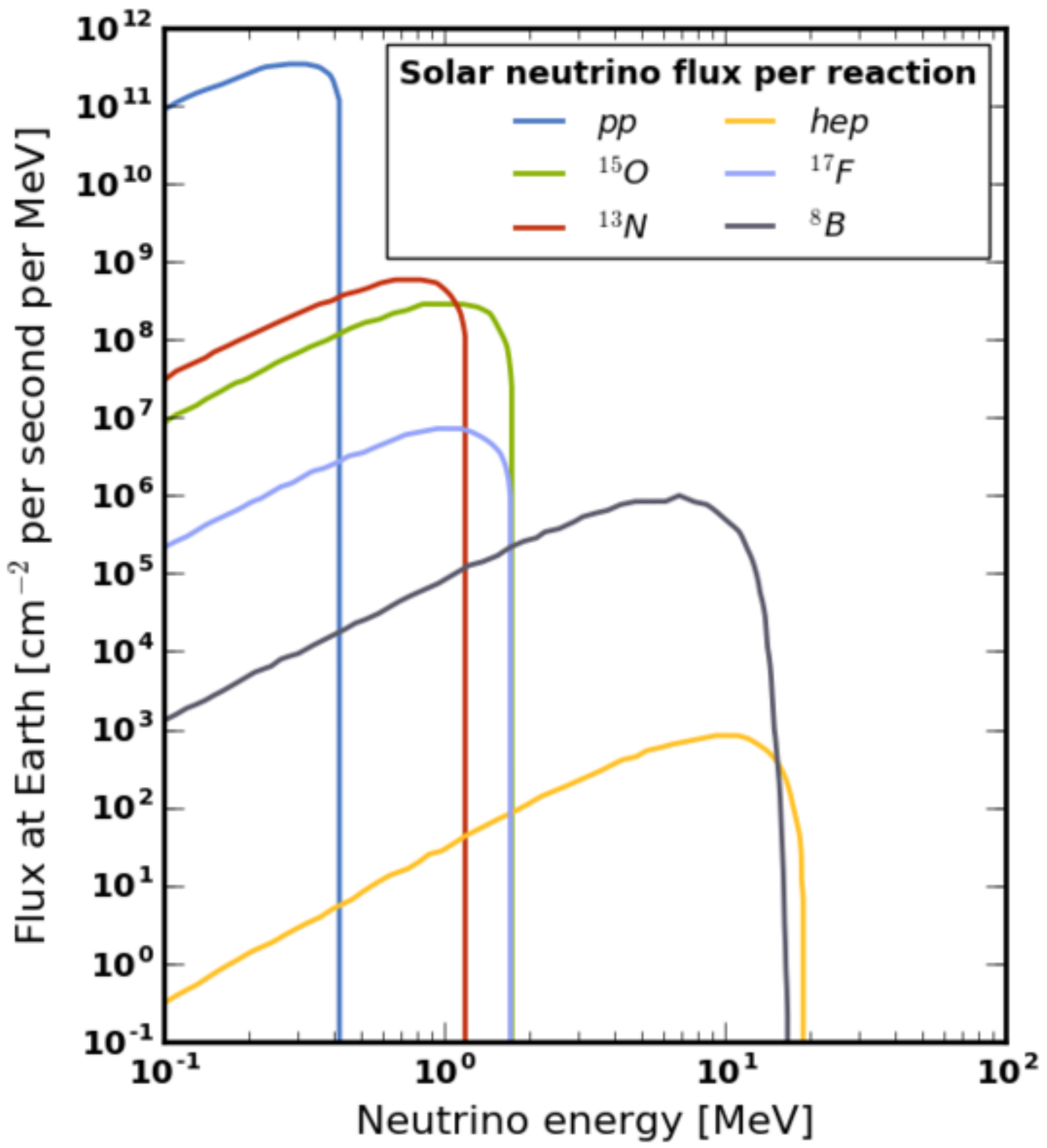


Solar Neutrino Sources

Hints about the Structure of the Sun

Neutrinos are also produced in great amounts by the sun but at low energy!





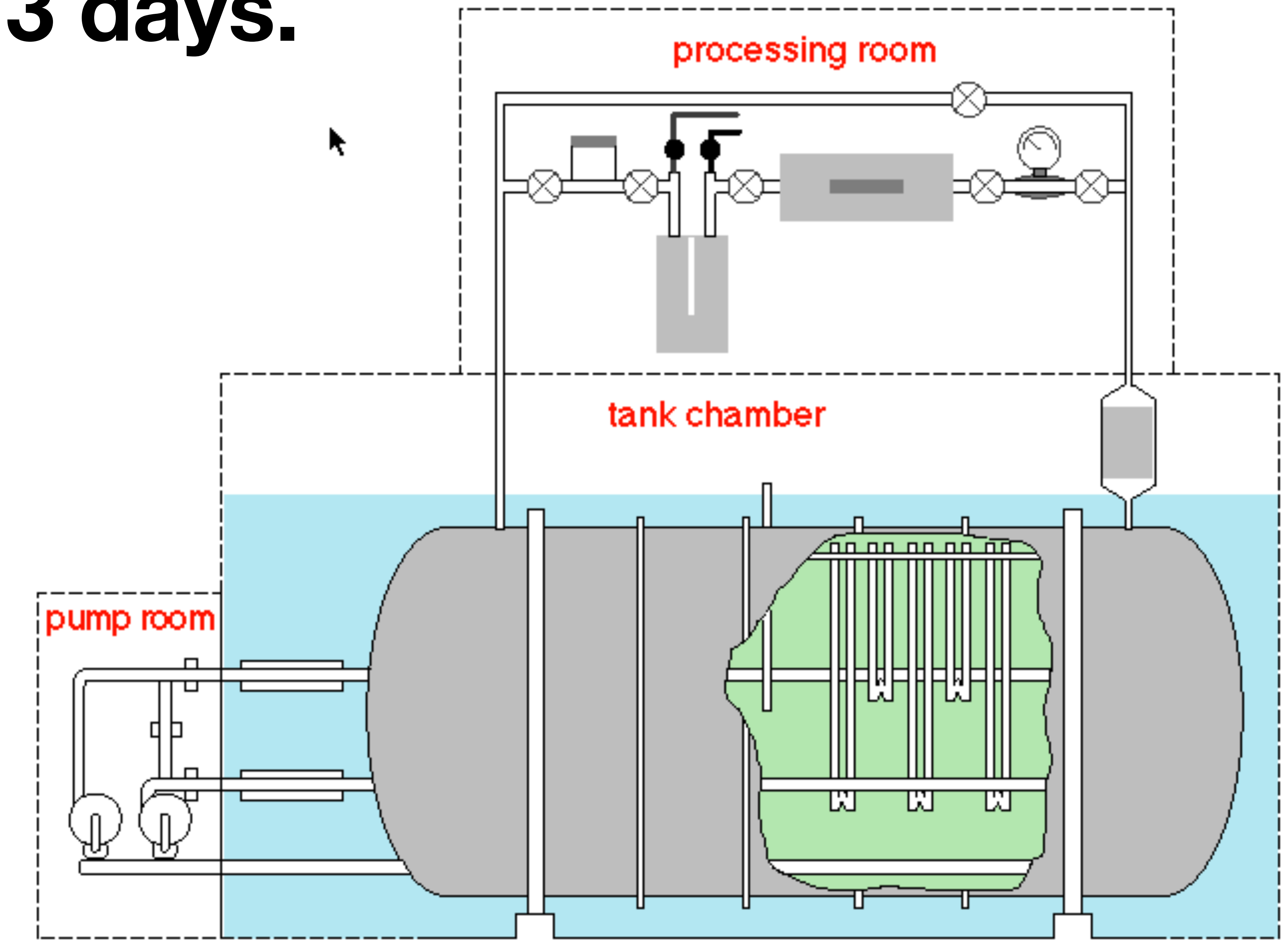
Main sequence process for fusing hydrogen into helium producing neutrinos!

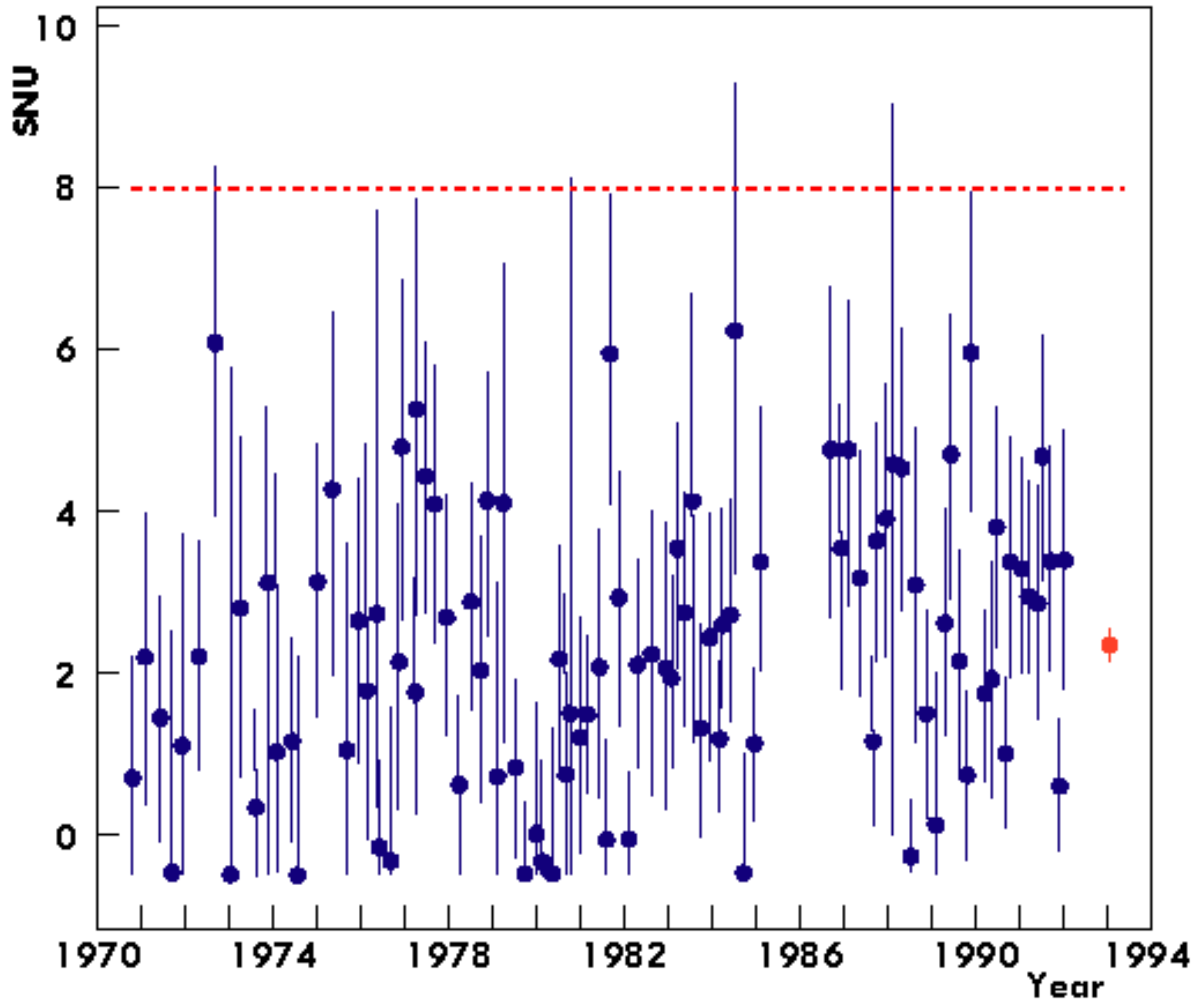
The Solar Neutr no "Problem"

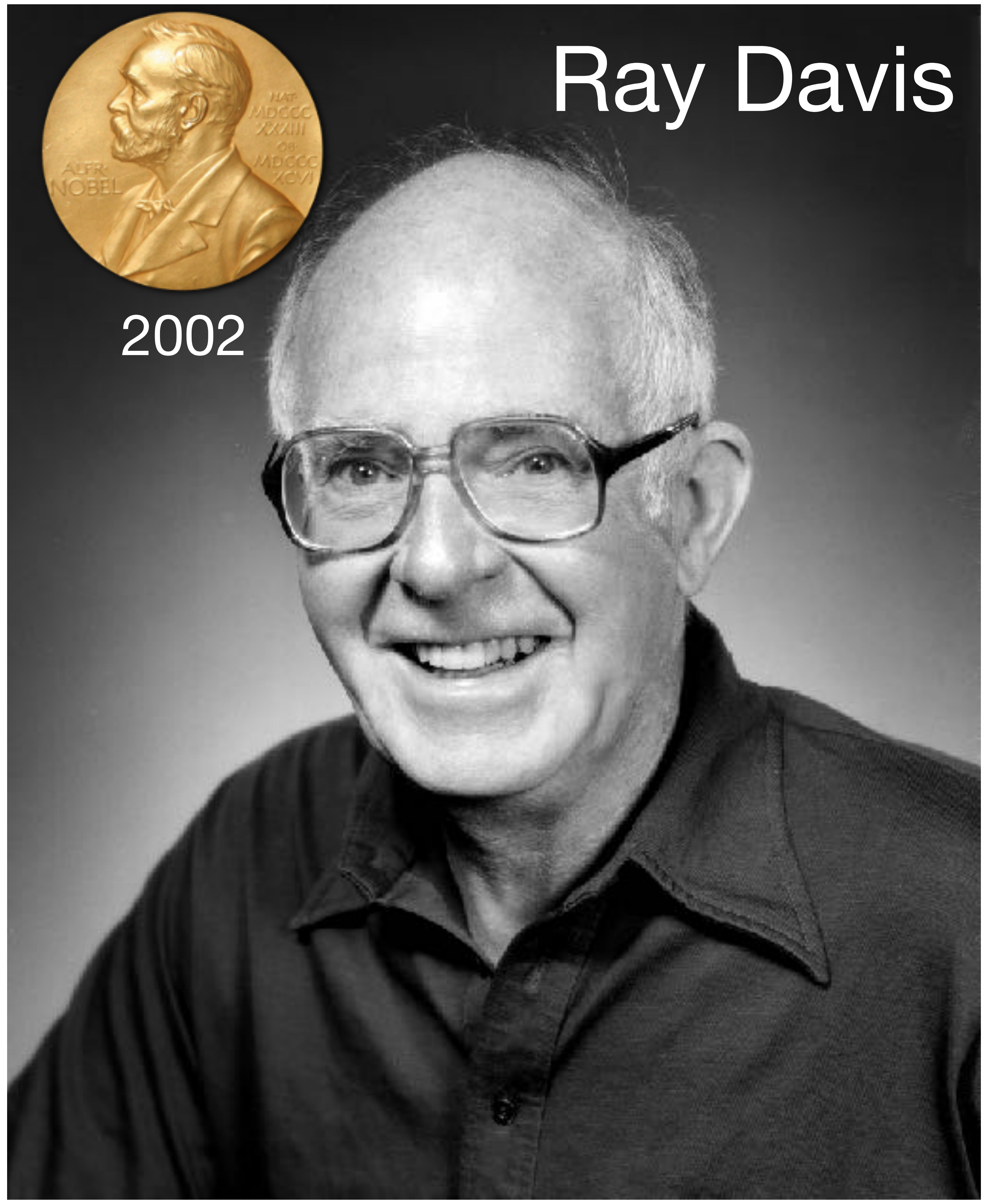
First Hints at Oscillation (1968)

In 1968, Ray Davis proposed an experiment to measure neutr no flux as a way of understanding the structure of the sun!

The HomeStake Experiment experiment measured neutr no inverse beta decay on 3.75×10^5 liters of cleaning fluid (mostly chlorine) in a converted Gold Mine and was thus only sensitive to electron-neutr nos. **Ran for 25 years seeing about 1 event every 3 days.**



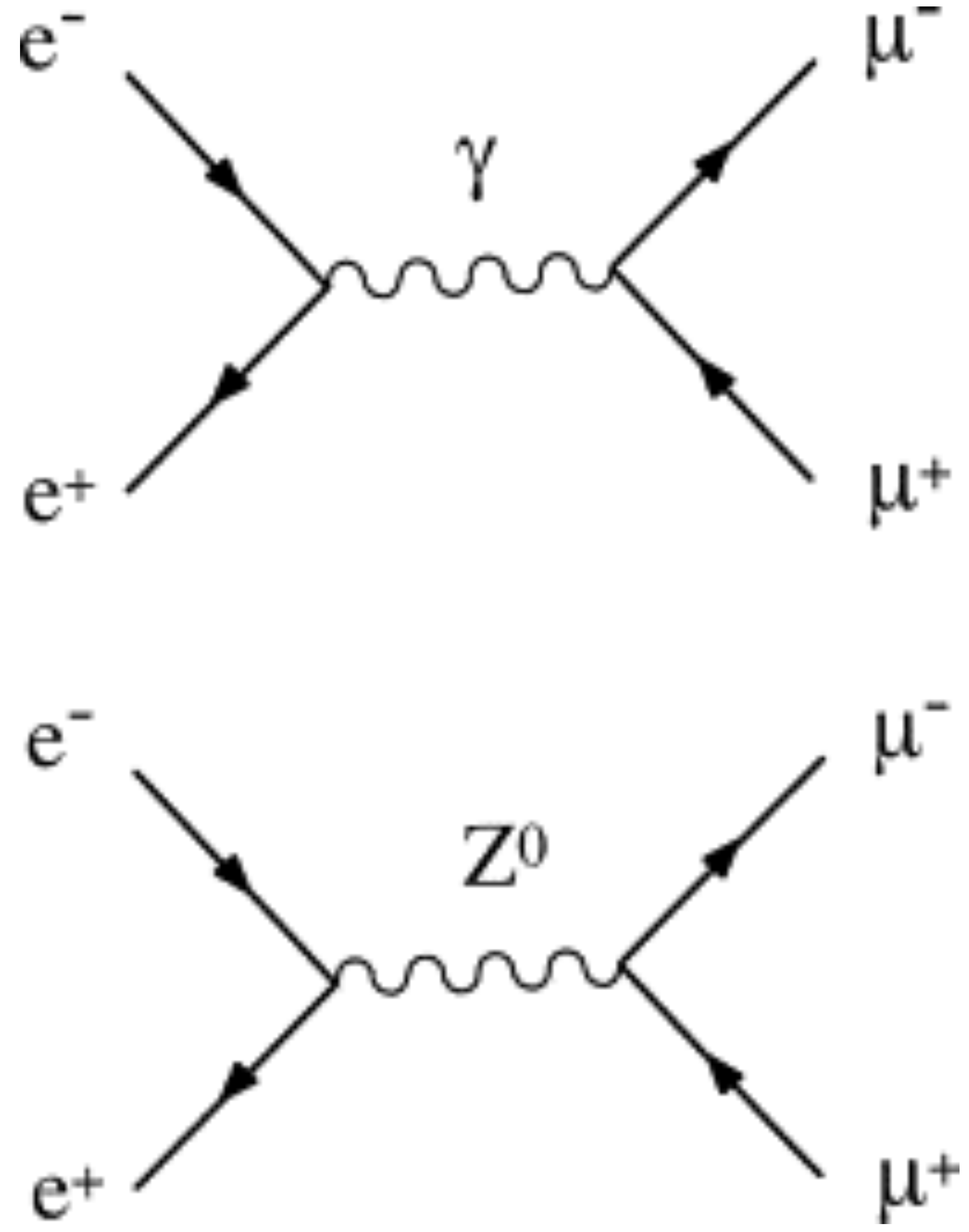




Experiment only saw 1/3 of expected events from the sun. **Where did the neutr nos go?**

First Observation of the Neutral Current

Neutr nos are the key to Electroweak Unification? (1973)

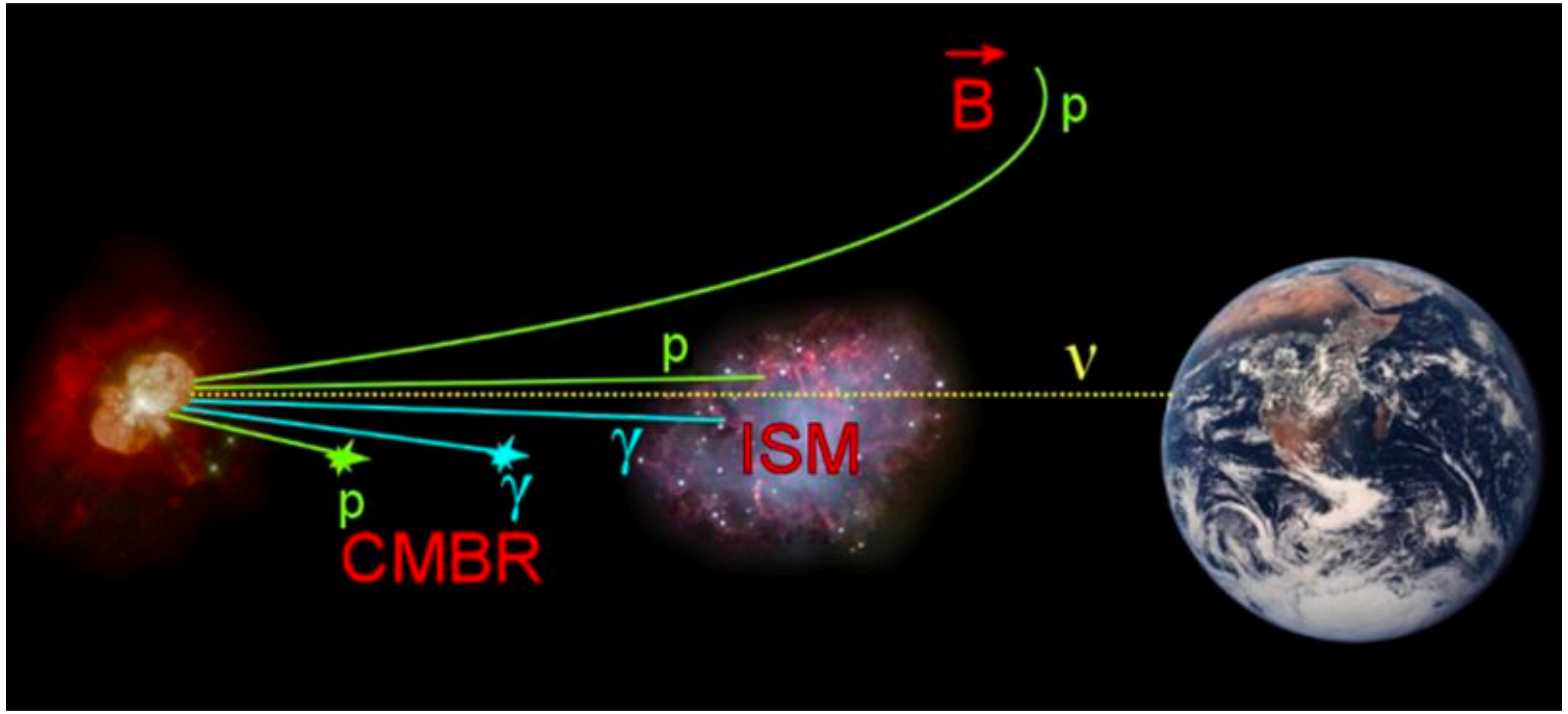


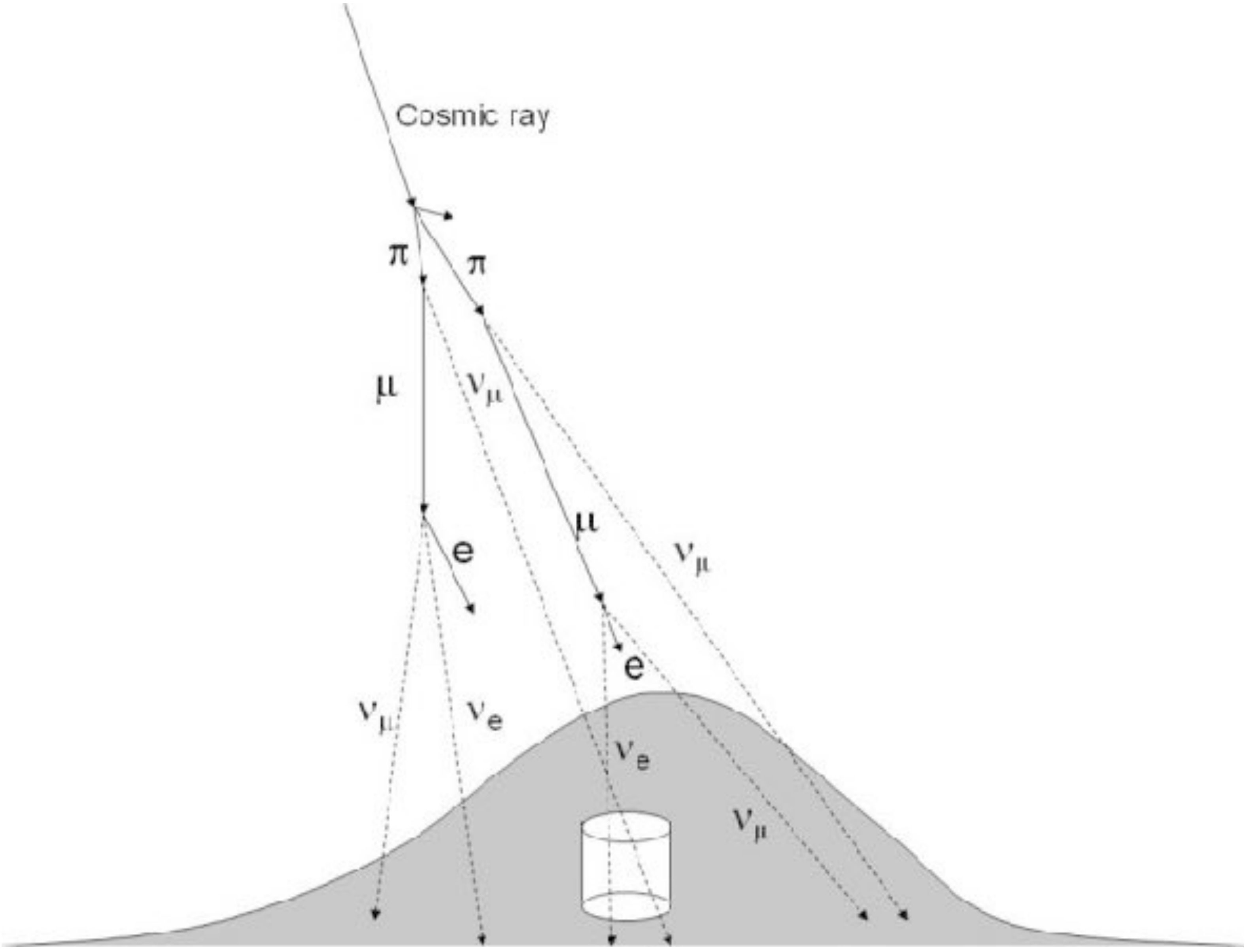
M. Betancourt, INSS 2018

Electroweak unification required observation of the neutral current but the EM force overpowers observation. Must use neutr nos to observe at intermediate energies. (Nobel Prize went to Glashow, Salam, and Weinberg).

Cosmic & Atmospheric Neutrino Sources

Spacefaring Particles Sometimes Interact or Create Neutrinos





Some interesting stellar objects can create a shower of particles in space that are absorbed by various interstellar media or even remnant particles from the Big Bang!

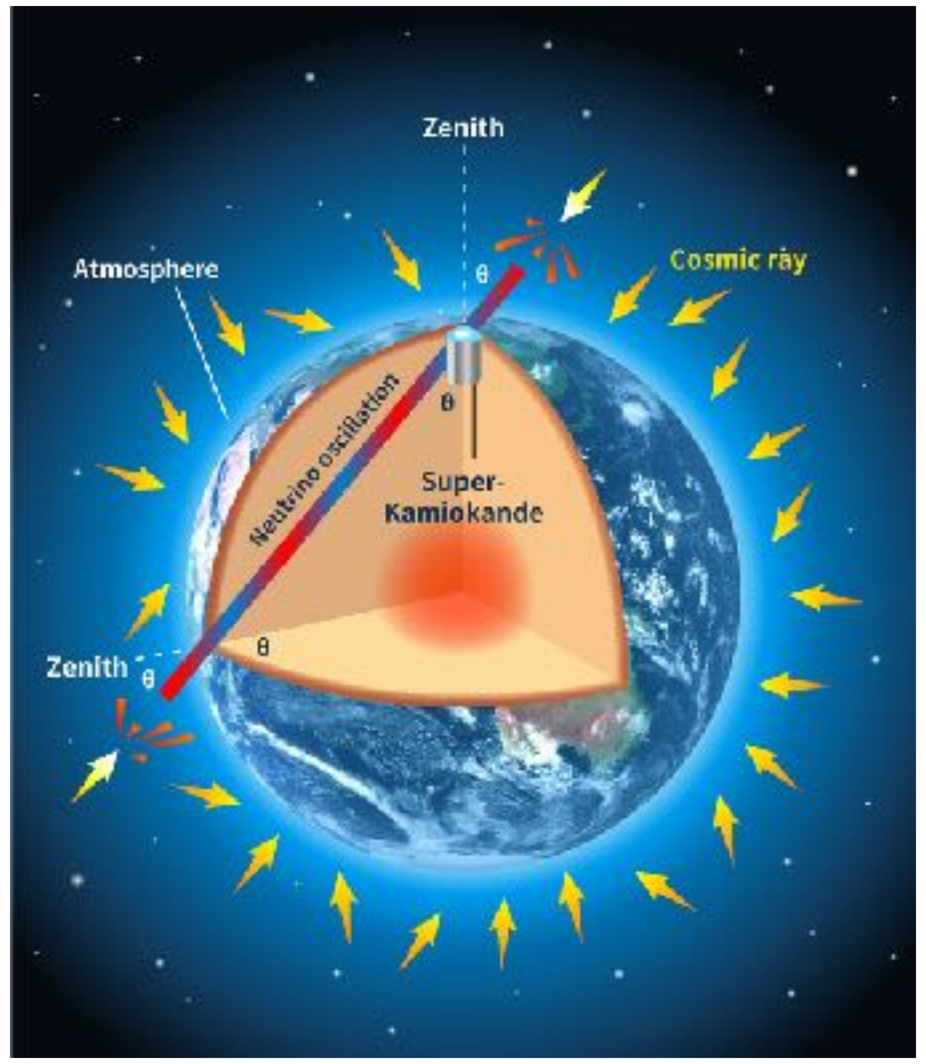
Sometimes cosmic showers interact in the atmosphere and produce showers of particles which are low energy and should be isotropic in the atmosphere.

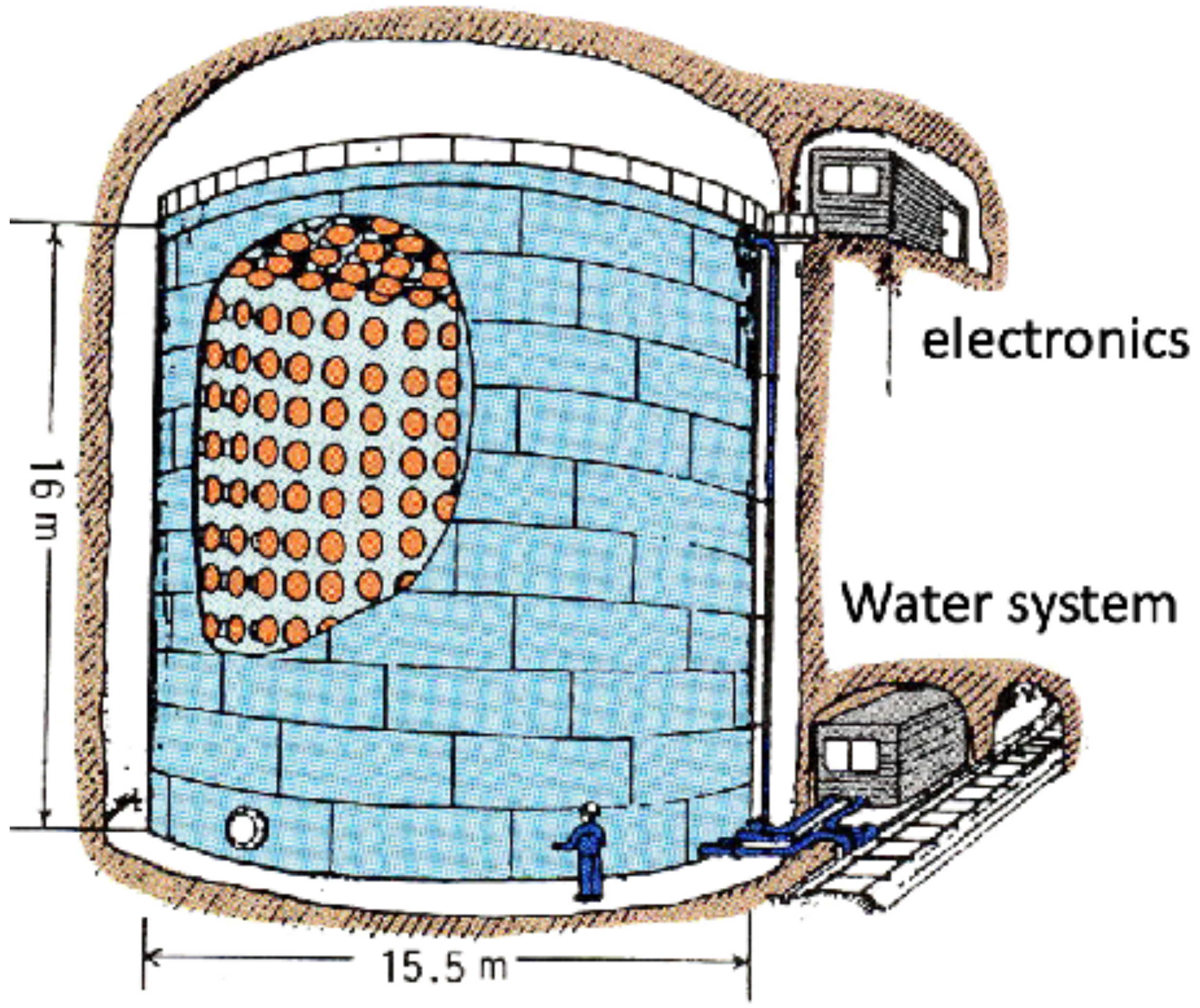
Neutrinos are also the most abundant particles in the universe!

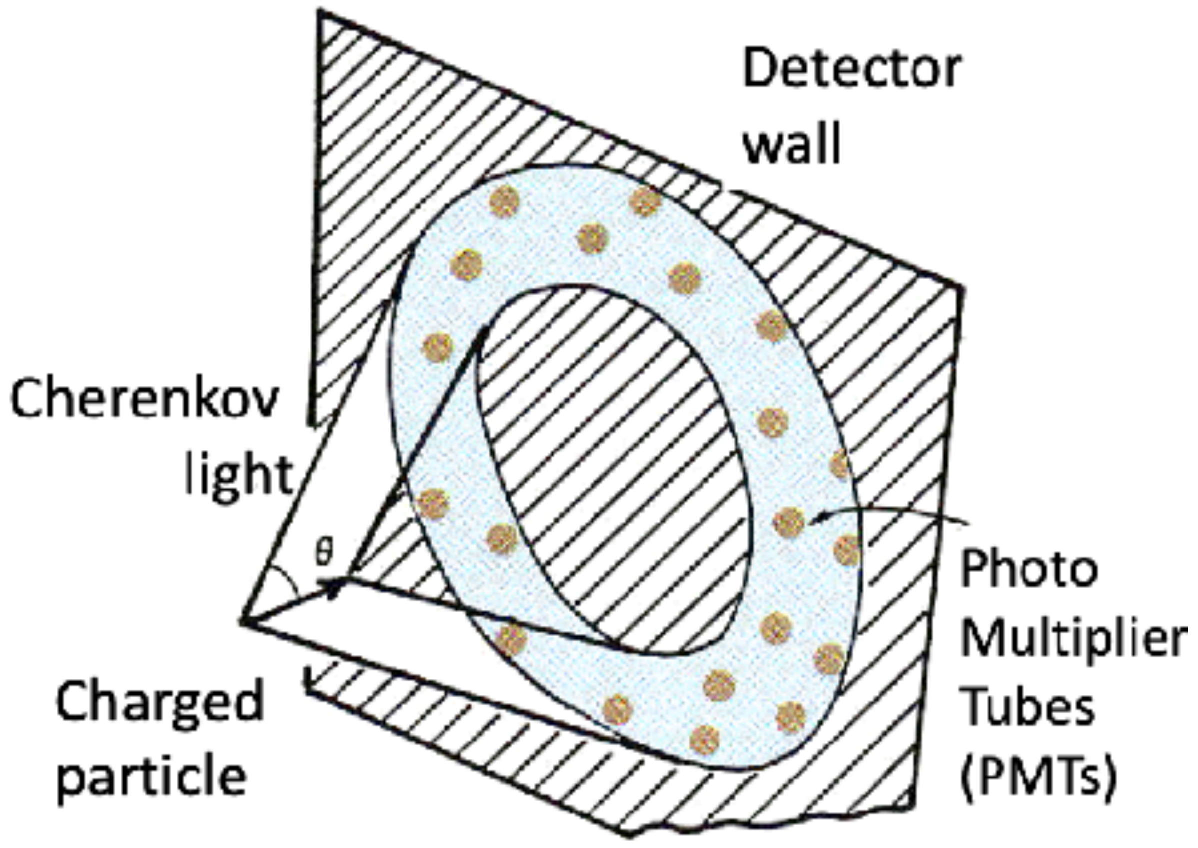
The Atmospheric Neutrino “Problem”

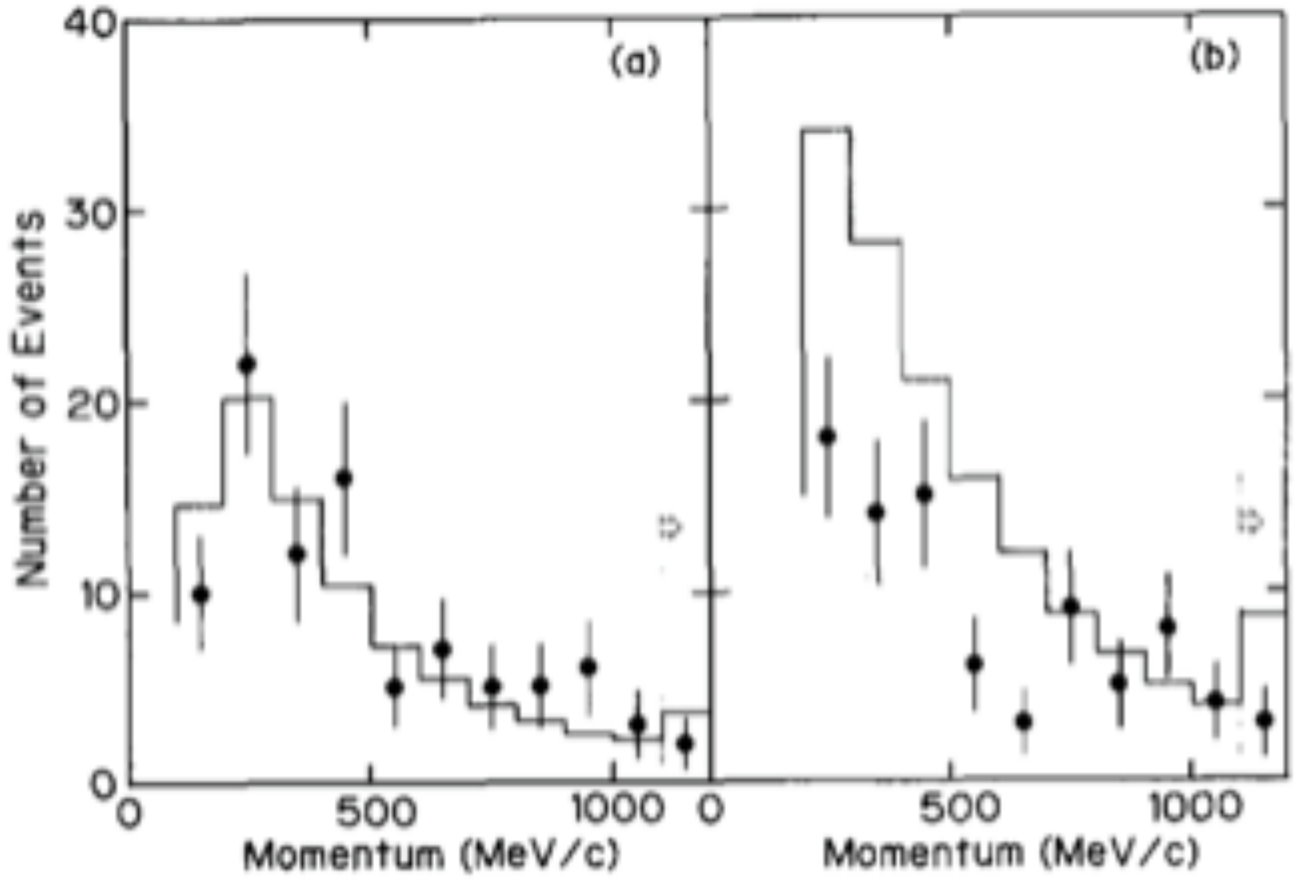
Second Hint at Oscillations (1988)

Kamiokande was designed to look for proton decay but also saw cosmic and atmospheric neutrinos as a background.







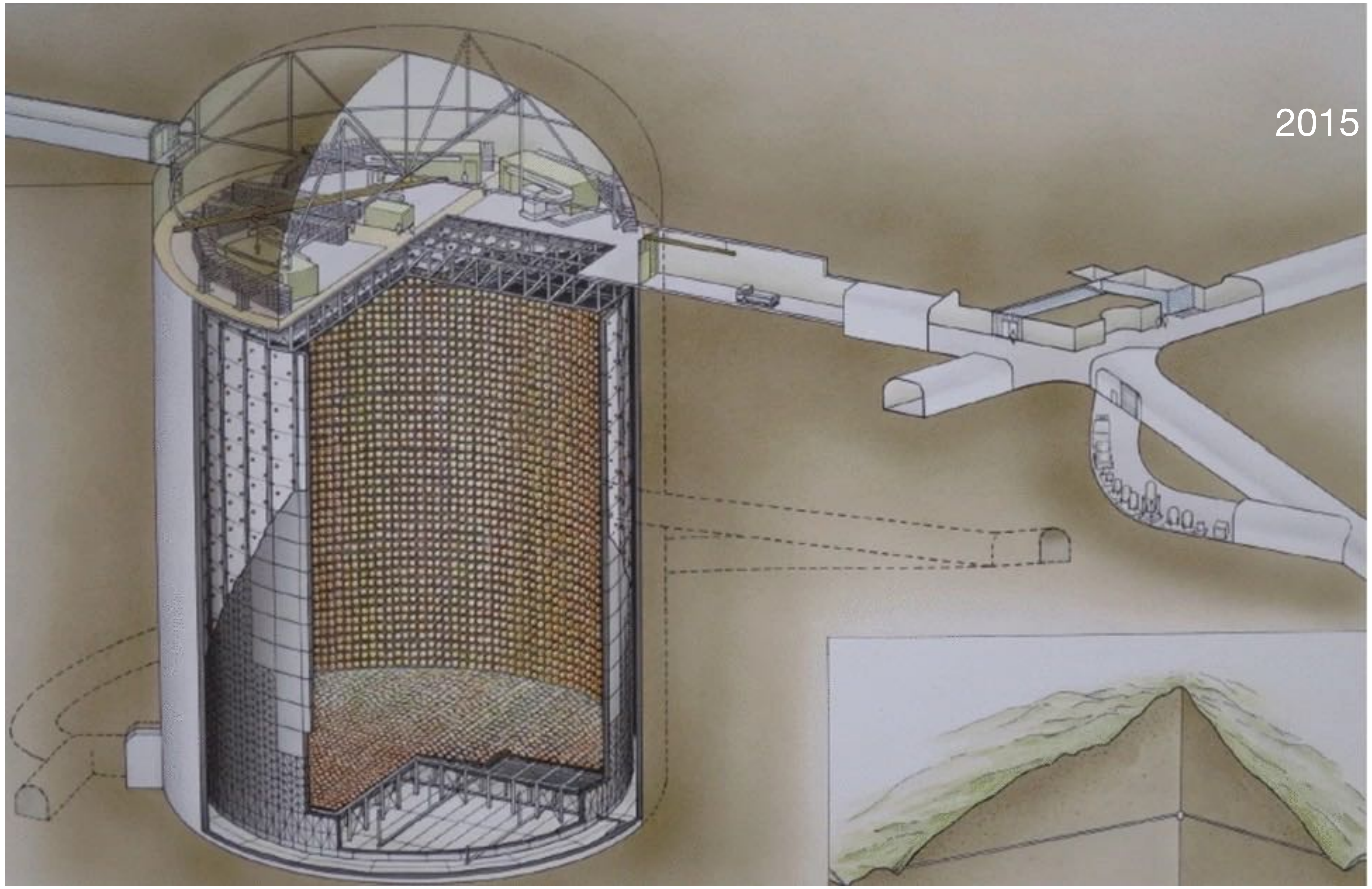


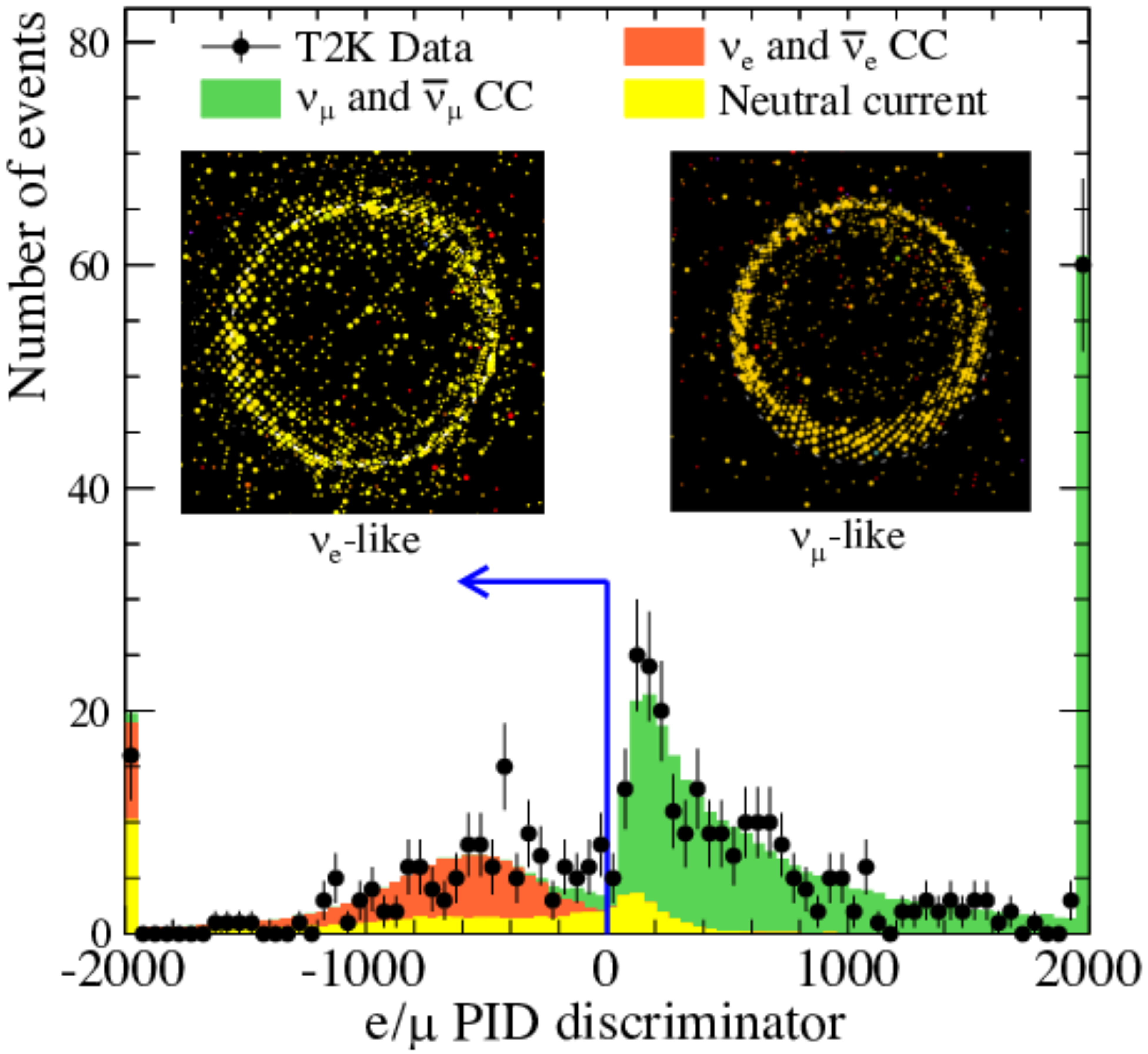
Expected: two muon-neutrinos for electron-neutrino from atmospheric sources.

Observed: expected number of electron-neutrinos, but were missing muon-neutrinos. Also did a zenith angle distribution which showed curious result but only at 2.8 sigma significance.

Solving the Neutrino Problem (Part 1)

Super-Kamiokande Offers Part of a Solution (1998)

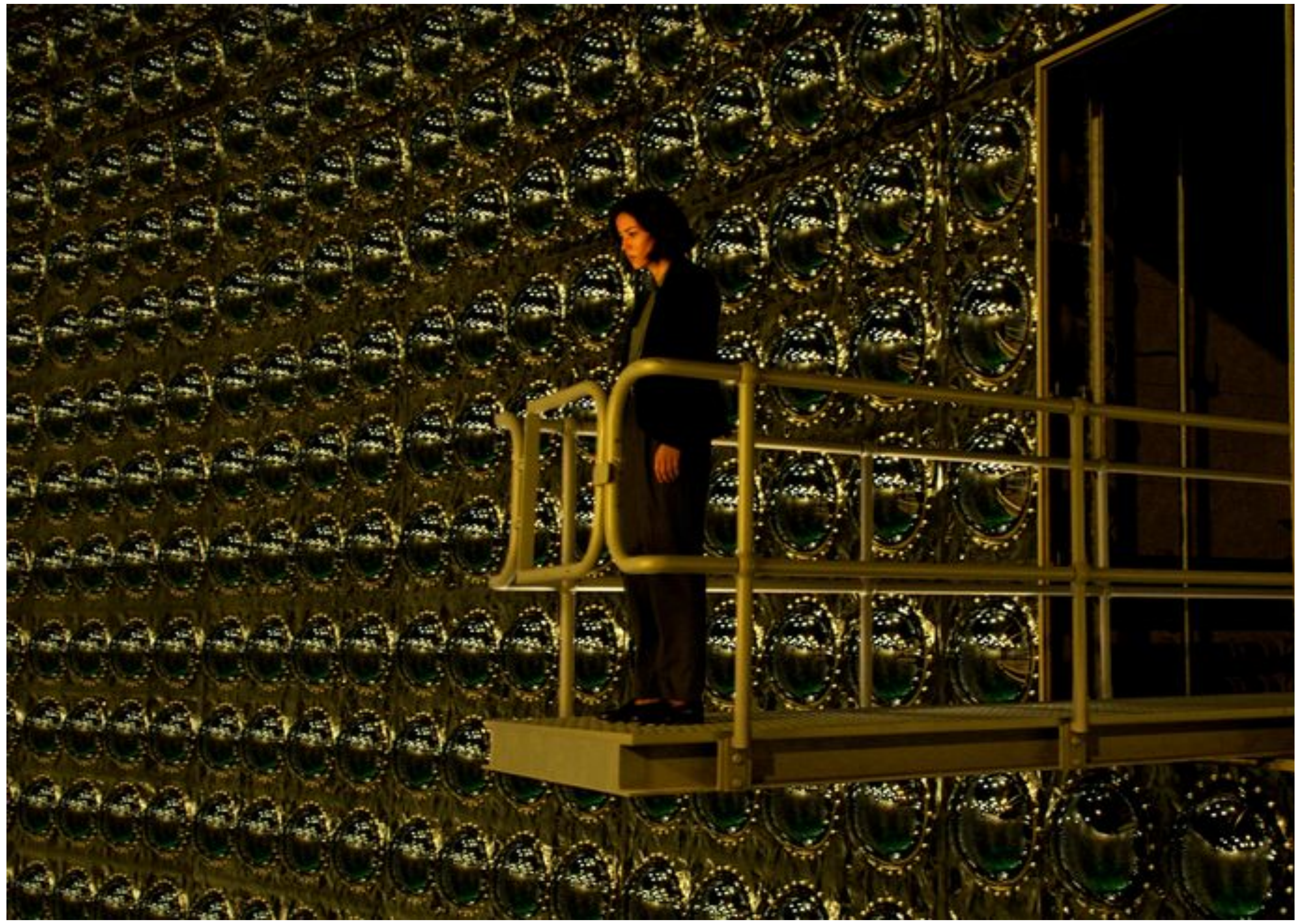




Super-Kamiokande followed up with improved analysis and a 10x size detector place 1,000 meters under a mountain! Observed the same deficit in muon-neutrinos but ~5 sigma significance!

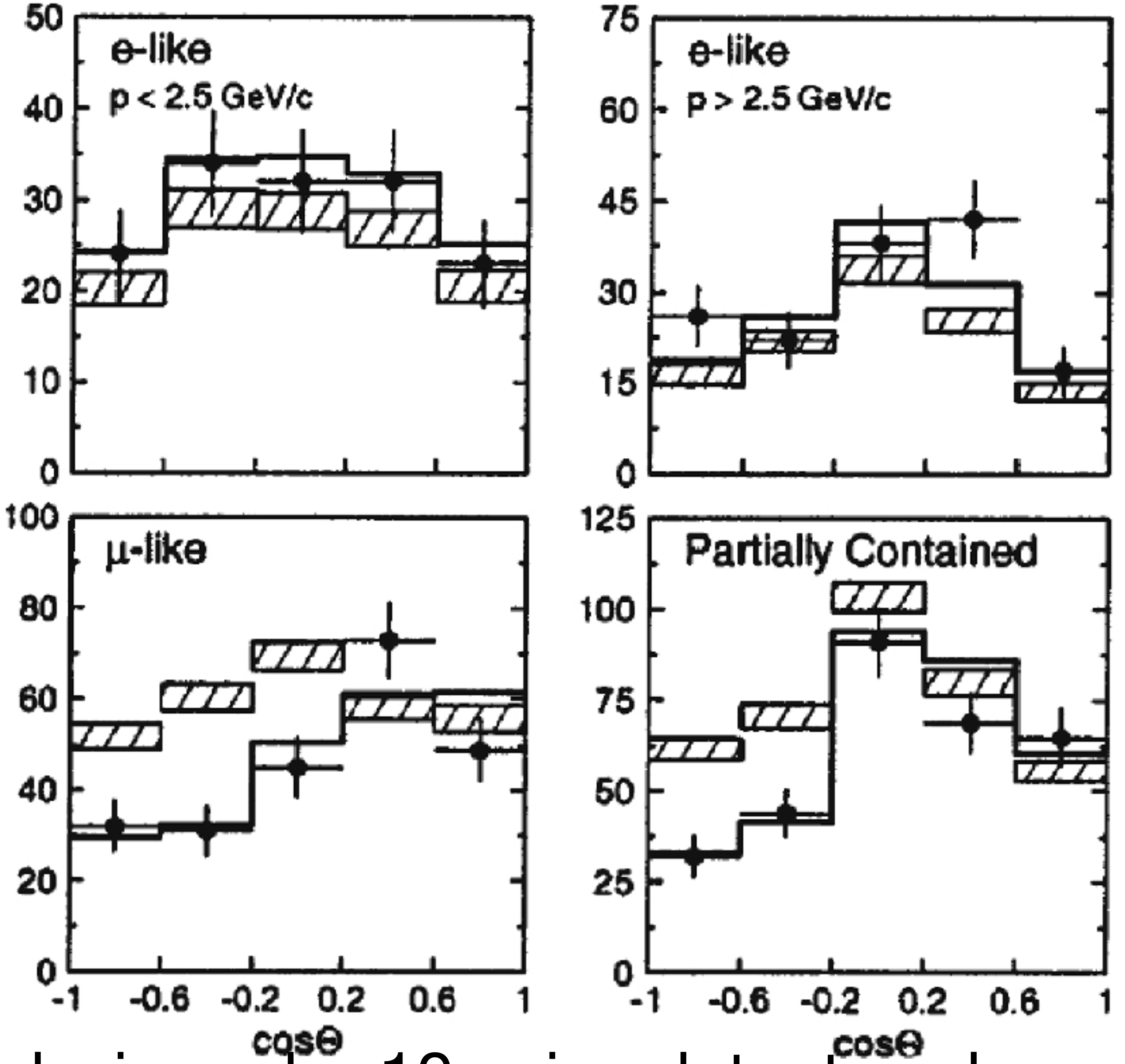
Solving the Neutrino Problem (Part 1)

Super-Kamiokande Offers Part of a Solution (1998)



© Nobel Media AB. Photo: A. Mahmoud

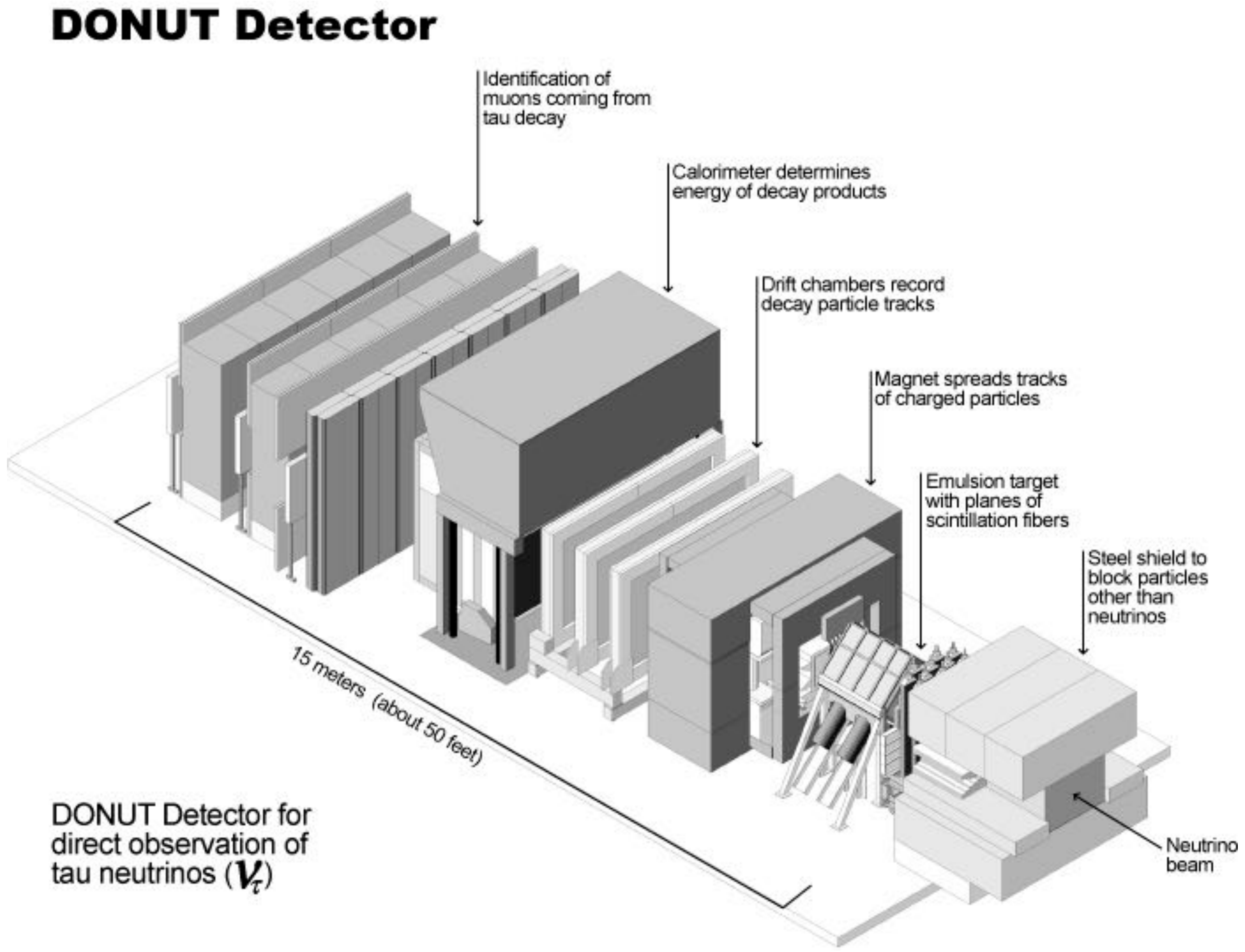
Takaaki Kajita

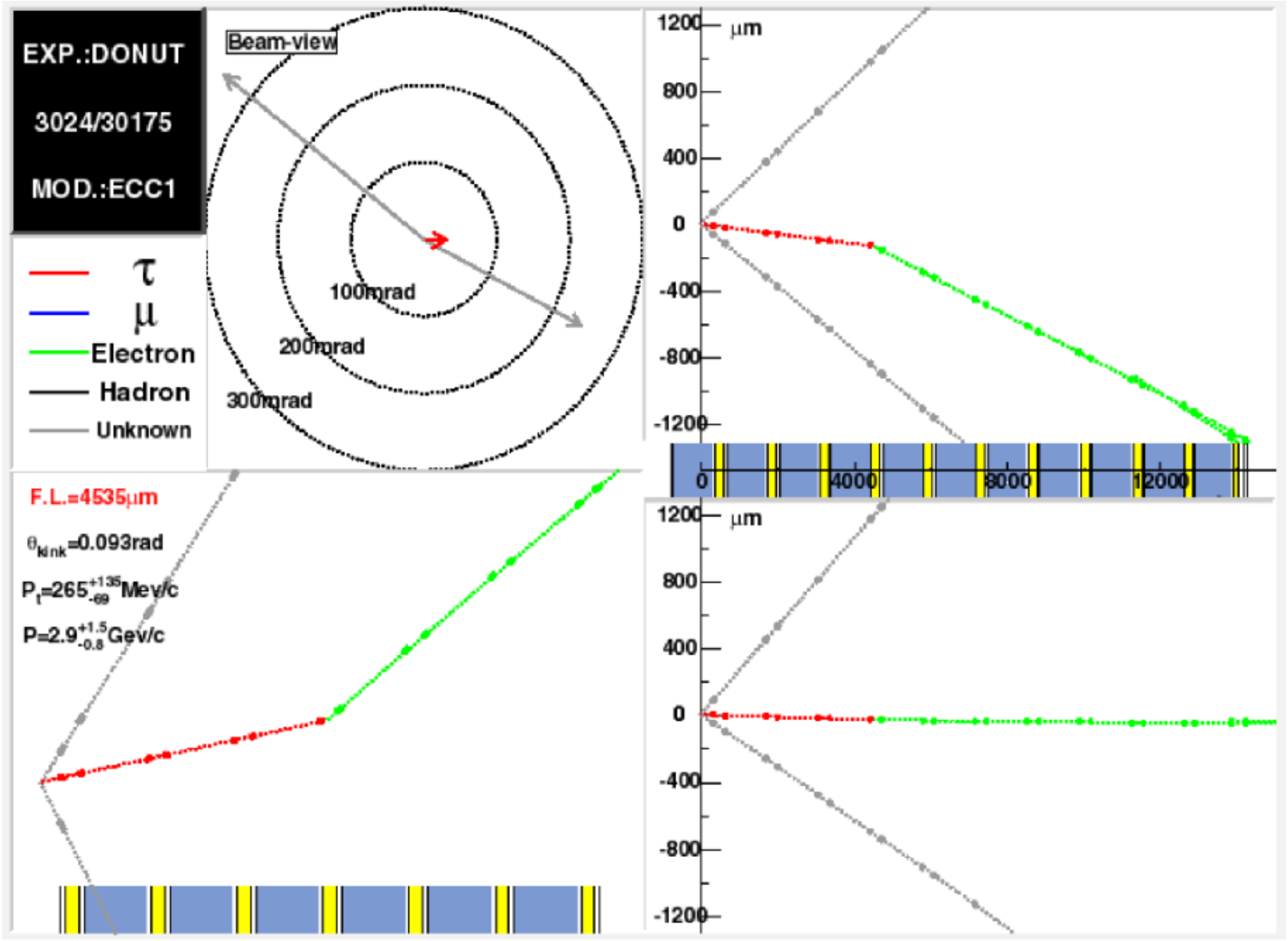


Super-Kamiokande followed up with improved analysis and a 10x size detector place 1,000 meters under a mountain! Observed the same deficit in muon-neutrinos but ~5 sigma significance!

Observation of the Third Neutr no Flavor

The last fermion observed in the Standard Model (2000)

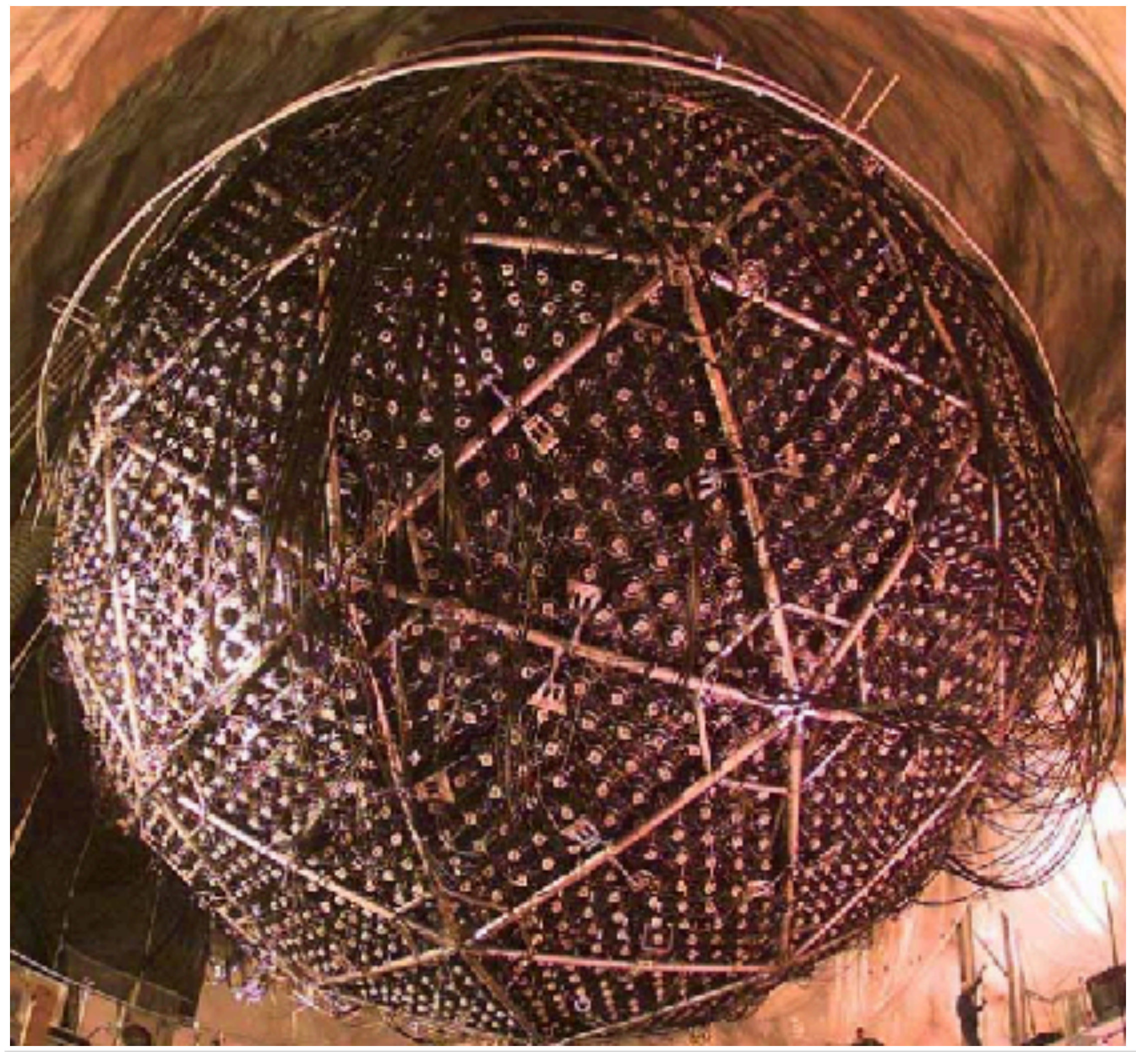


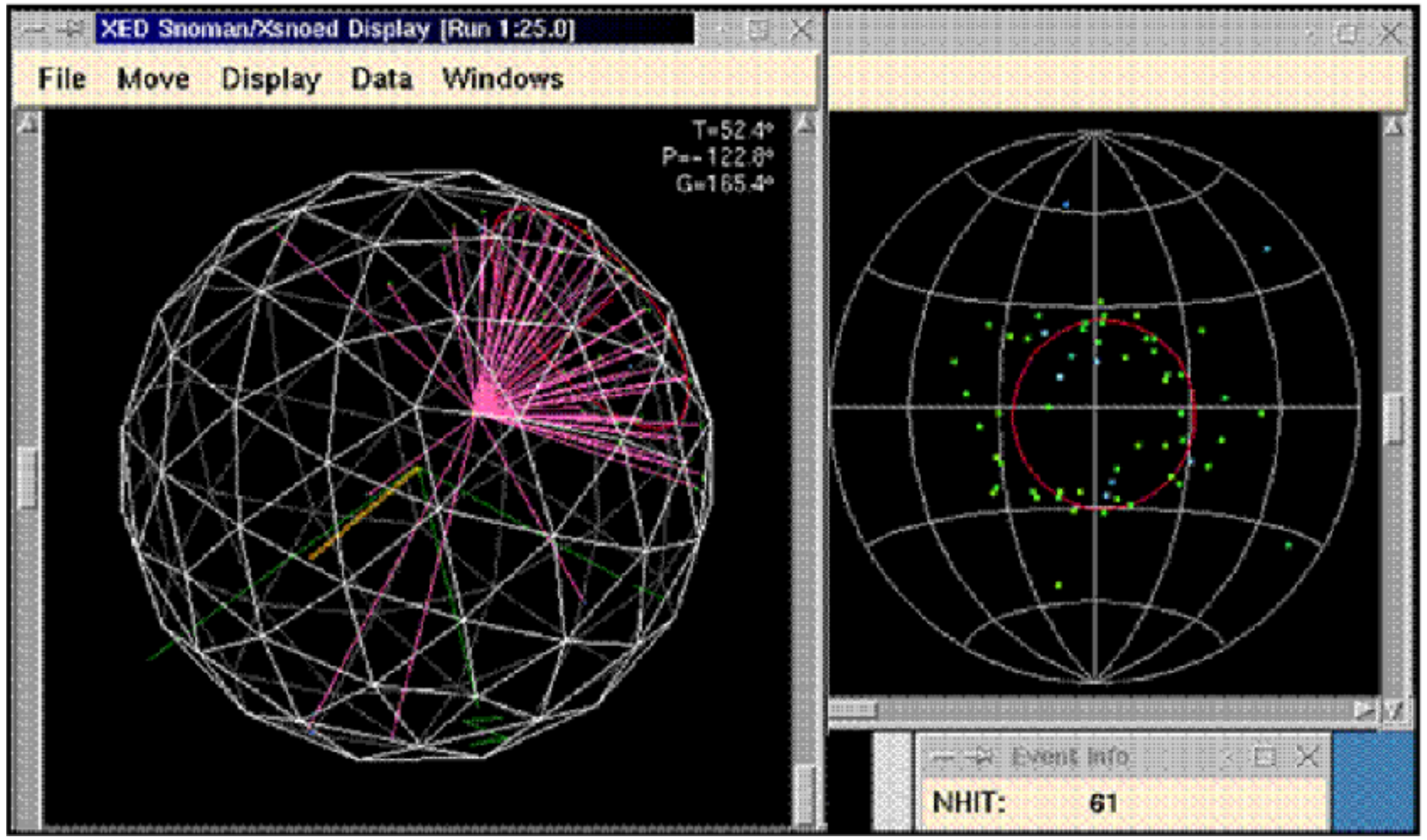


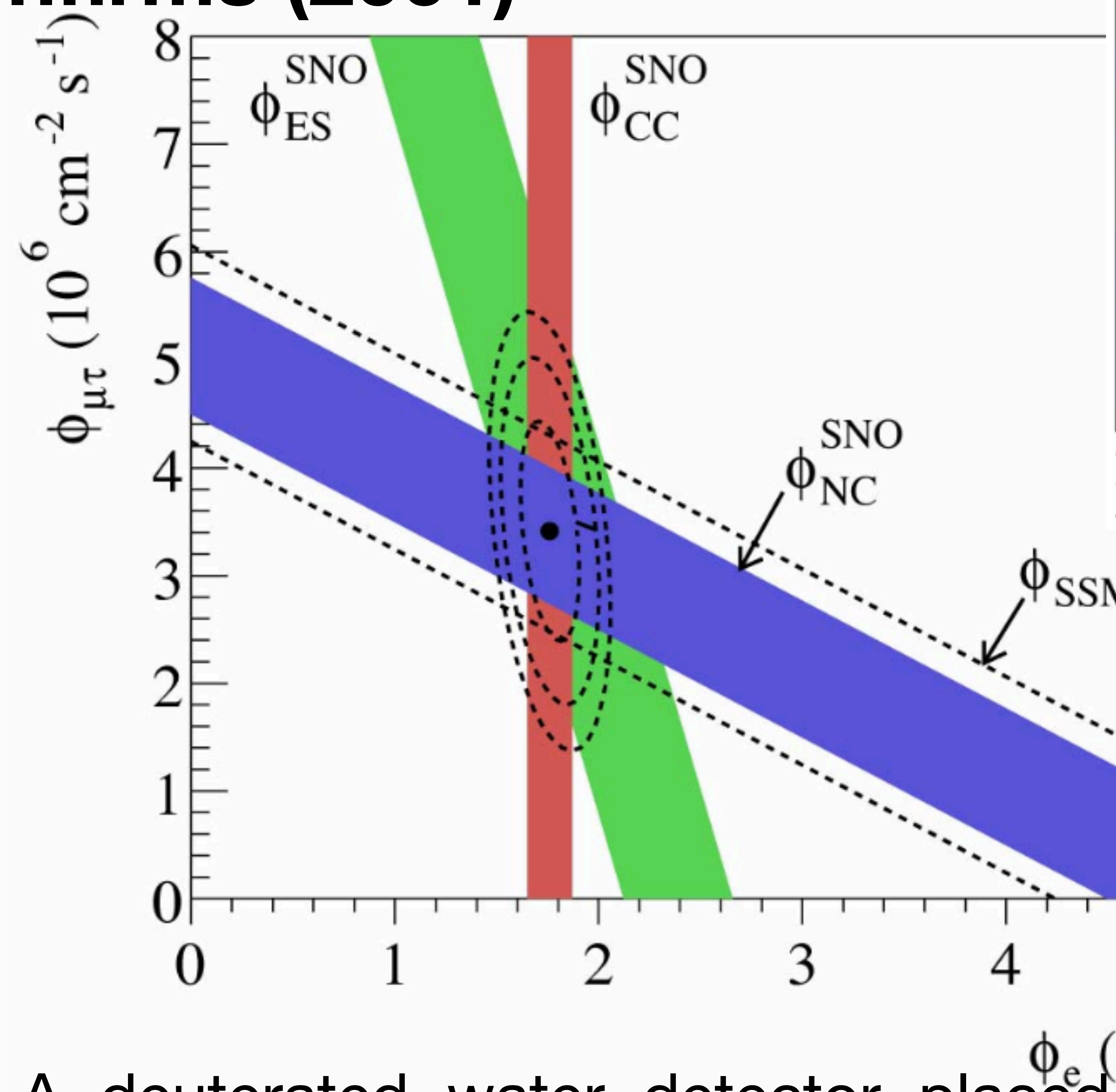
The DONuT Detector was designed solely to observe tau-neutr nos, completing the 3-flavor picture of neutr nos and the description of matter in the standard model. Of course, they did not realize they had done that at the time…

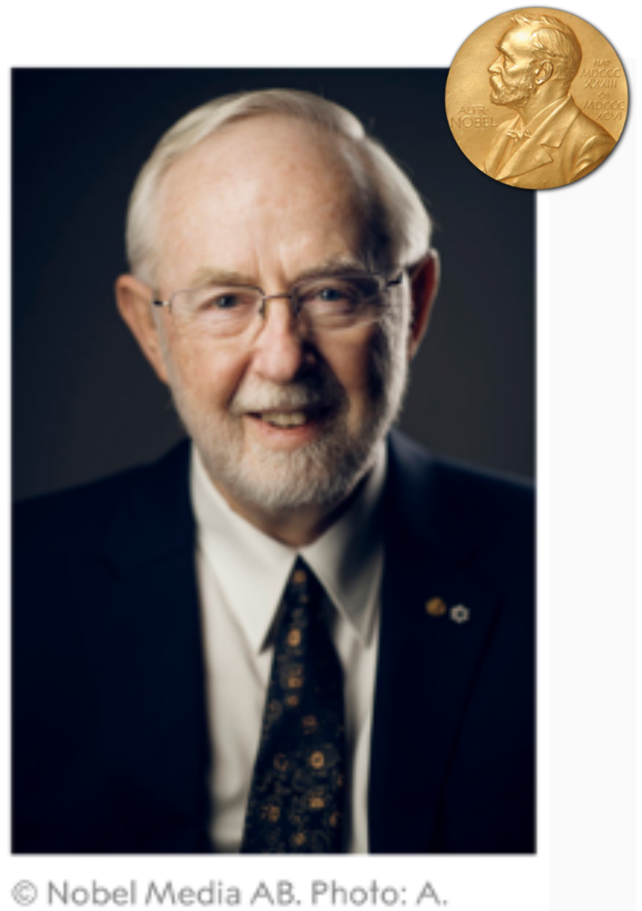
Solving the Neutr no Problem (Part 2)

Sudbury Neutr no Observatory Confirms (2001)









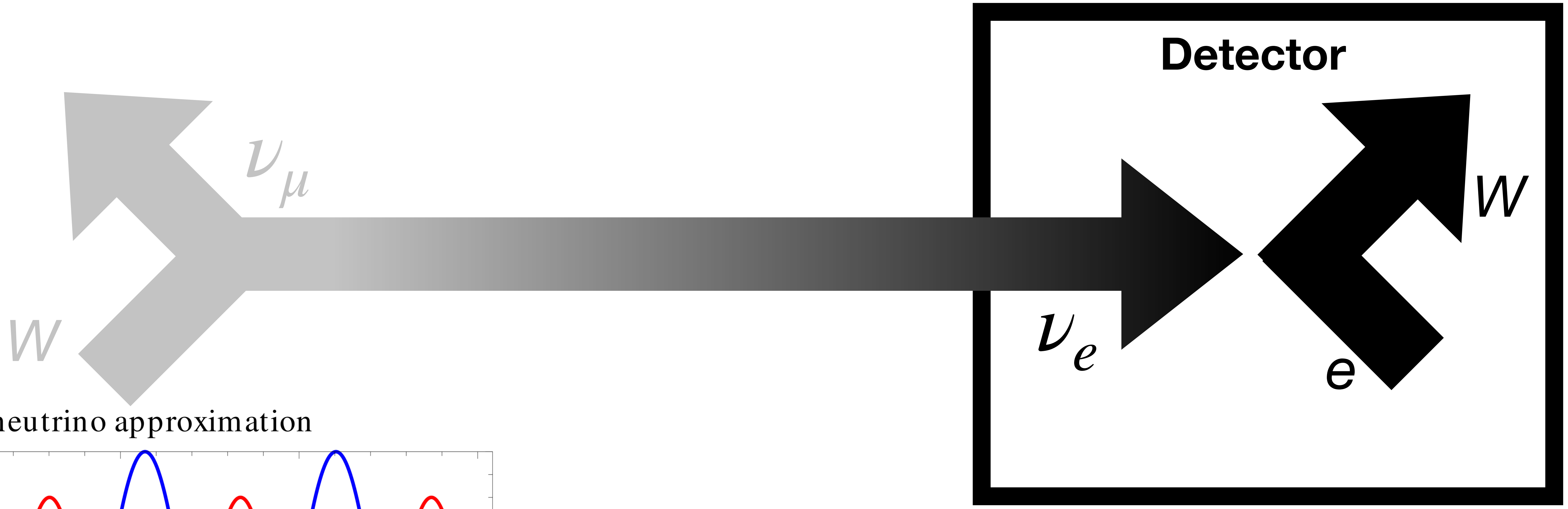
A deuterated water detector placed underground measured both CC and NC processes to understand the total number of neutrinos from the sun. **The only explanation is neutr no flavor oscillation.**

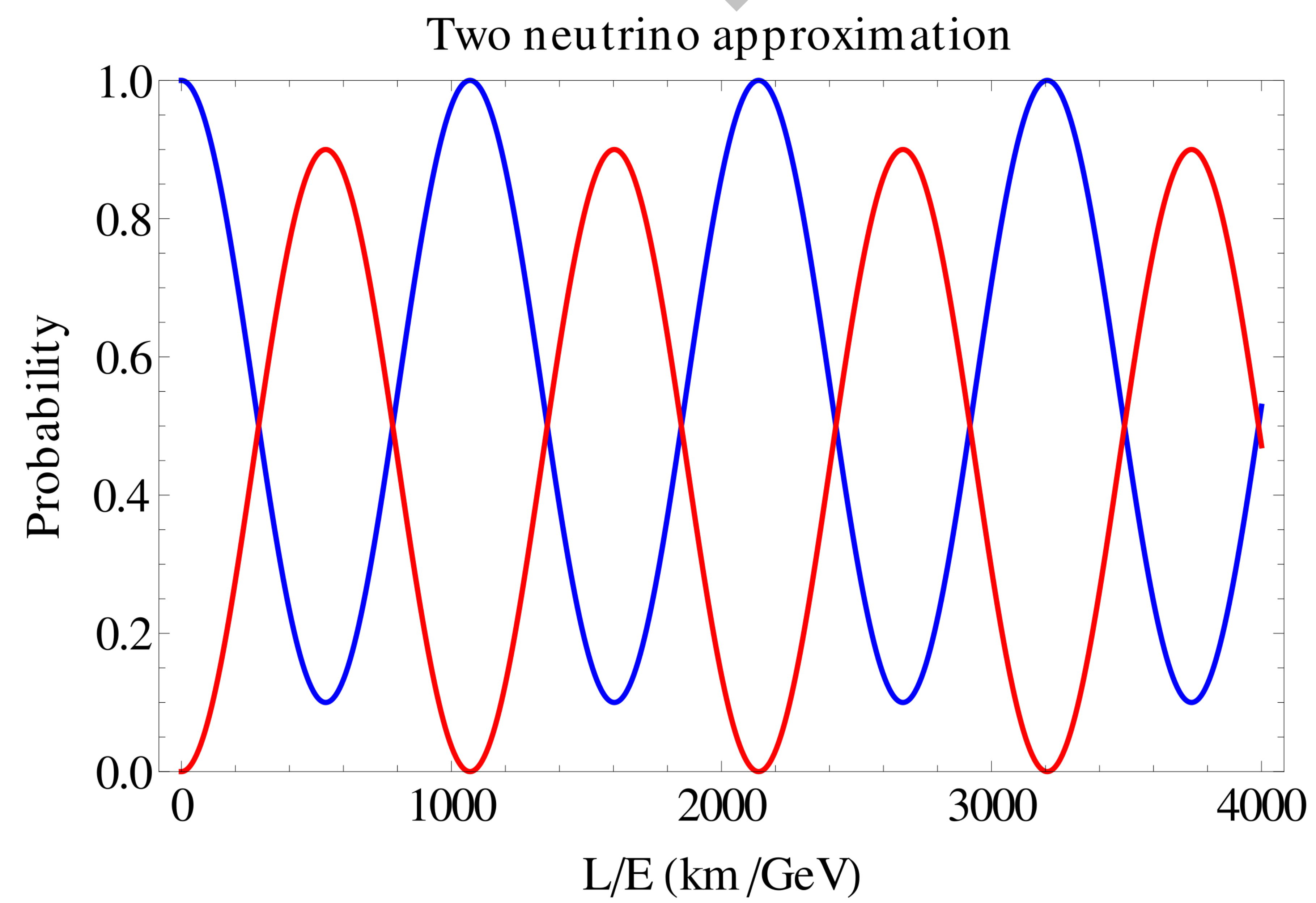
Intermission

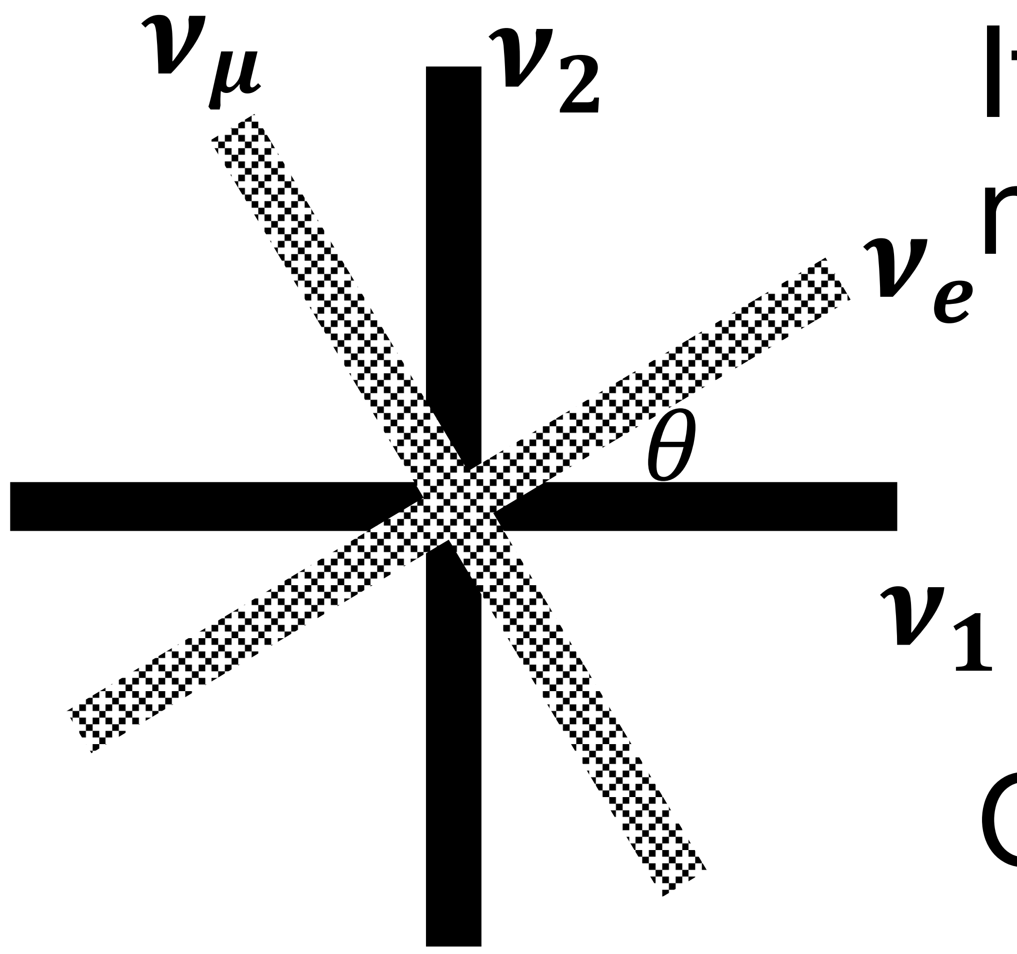
Neutrinos and Oscillation Physics (Part One)

Paths to Beyond the Standard Model Physics

$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L}\gamma^\mu \nu_{\alpha L} + {\rm h.c.} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L}\gamma^\mu \sum_{i=1,2,3} U_{\alpha i}\,\nu_{iL} + {\rm h.c.}$$







If we assume only two flavor and mass states:

$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \mathcal{R}(\theta)\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

Only one Euler angle is needed.

Neutrinos and Oscillation Physics (Part Two)

Paths to Beyond the Standard Model Physics

$$\mathcal{L}_{\text{CC}} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \nu_{\alpha L} + \text{h.c.} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \sum_{i=1,2,3} U_{\alpha i}\, \nu_{iL} + \text{h.c.}$$

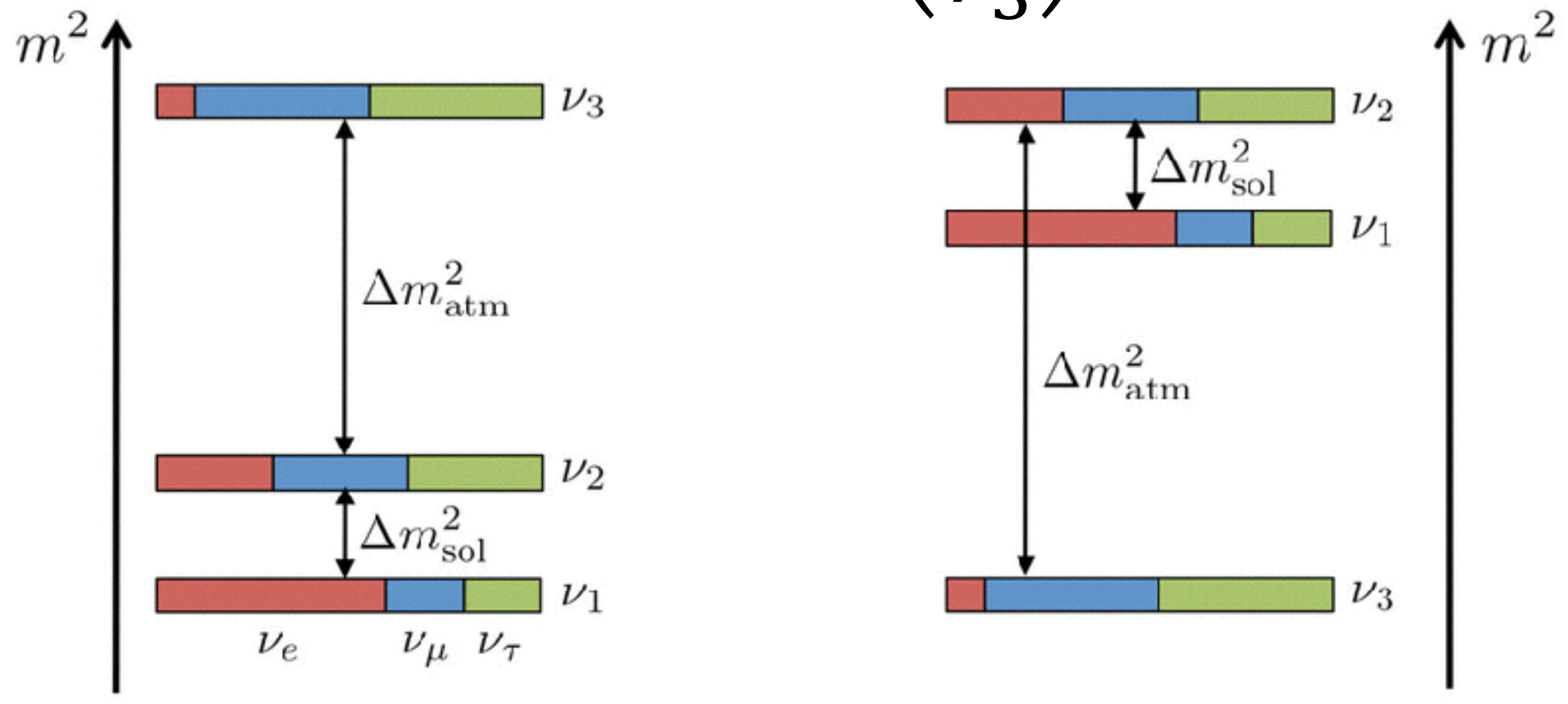
PMNS Matrix — Atmospheric — Reactor — Solar

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$U_{\alpha i}: \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{R}_{Atmos}(\theta_{23}) \cdot \mathcal{R}_{React}(\theta_{13}, \delta_{CP}) \cdot \mathcal{R}_{Solar}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The neutrino mixing matrix has parameters and coefficients directly describing the splitting of the mass states and asymmetry between neutrino and anti-neutrinos!

Leptonic CP-violation serves as a proof of concept for the matter-antimatter asymmetry!



Neutrinos and Oscillation Physics (Part Three)

Paths to Beyond the Standard Model Physics

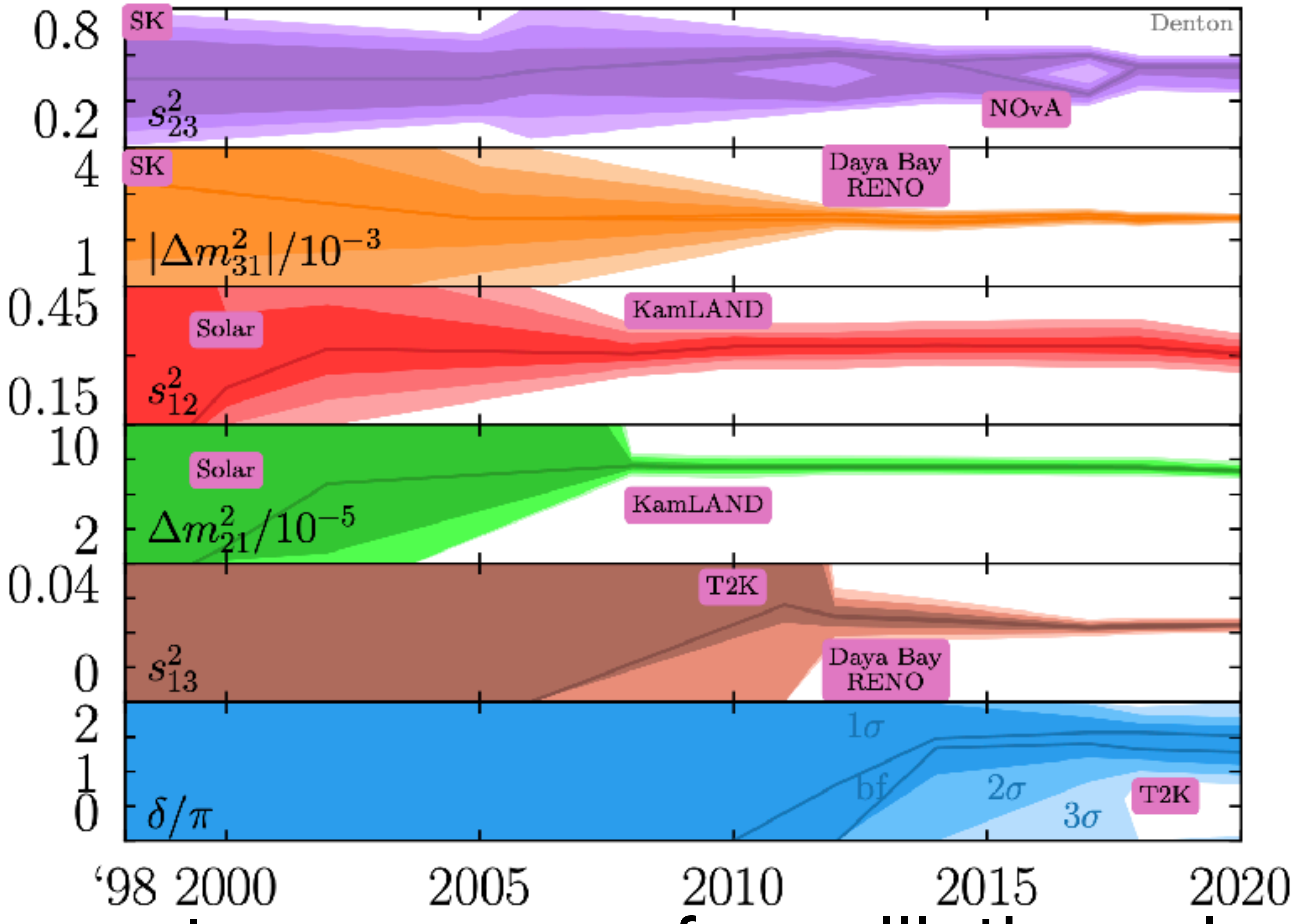
Neutrinos and Oscillation Physics (Part Four)

Paths to Beyond the Standard Model Physics

PMNS Matrix

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

NuFit 5.1, October 2021



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

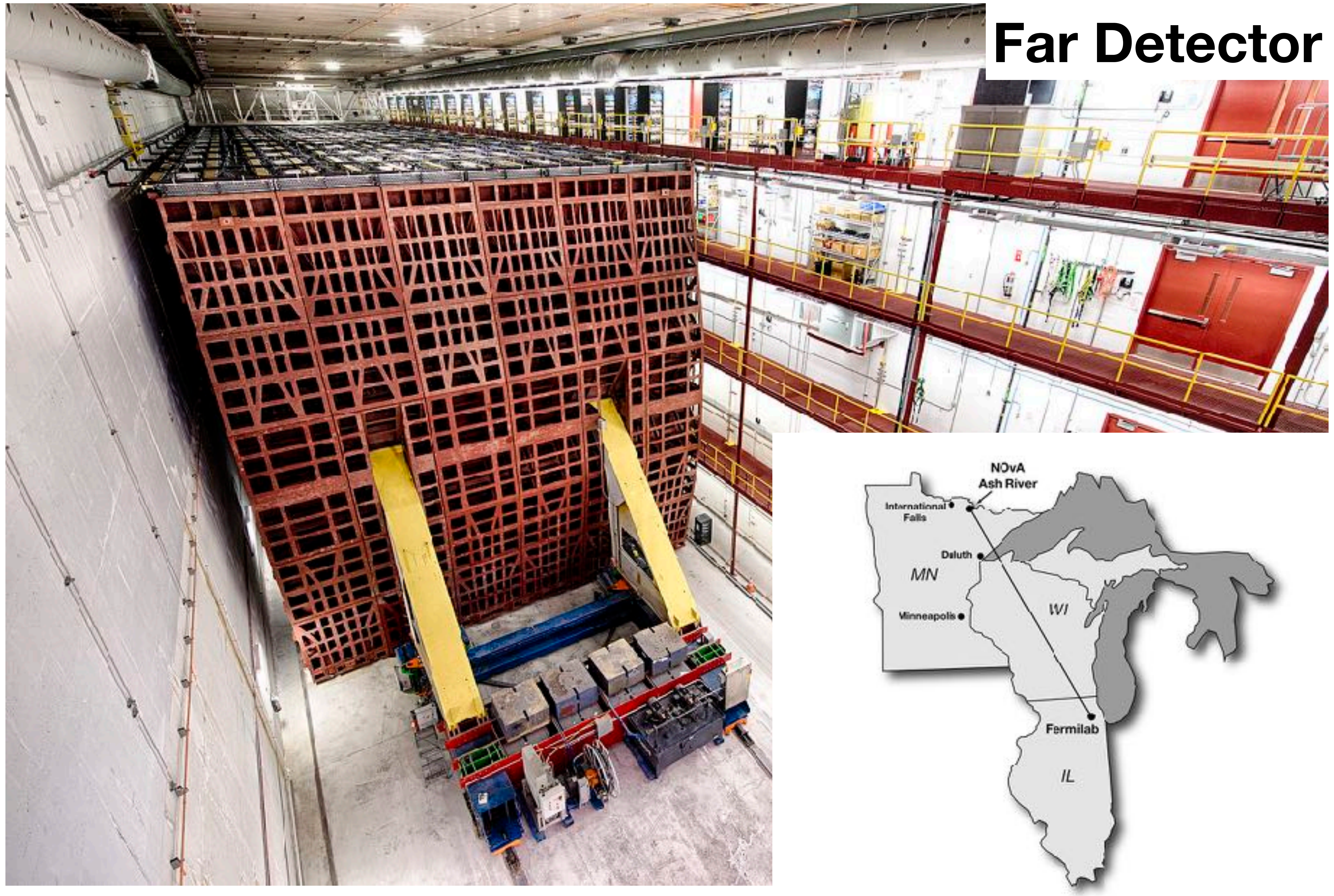
Current progress of oscillation shows the Euler angles and mass splittings are resolved to the few percent level! Largest uncertainties on mass ordering and δ_{CP}.

Current Generation Long Baseline Oscillation Experiments

The NuMI Off-axis ν_e Appearance (NOvA) Experiment

Near Detector

Far Detector

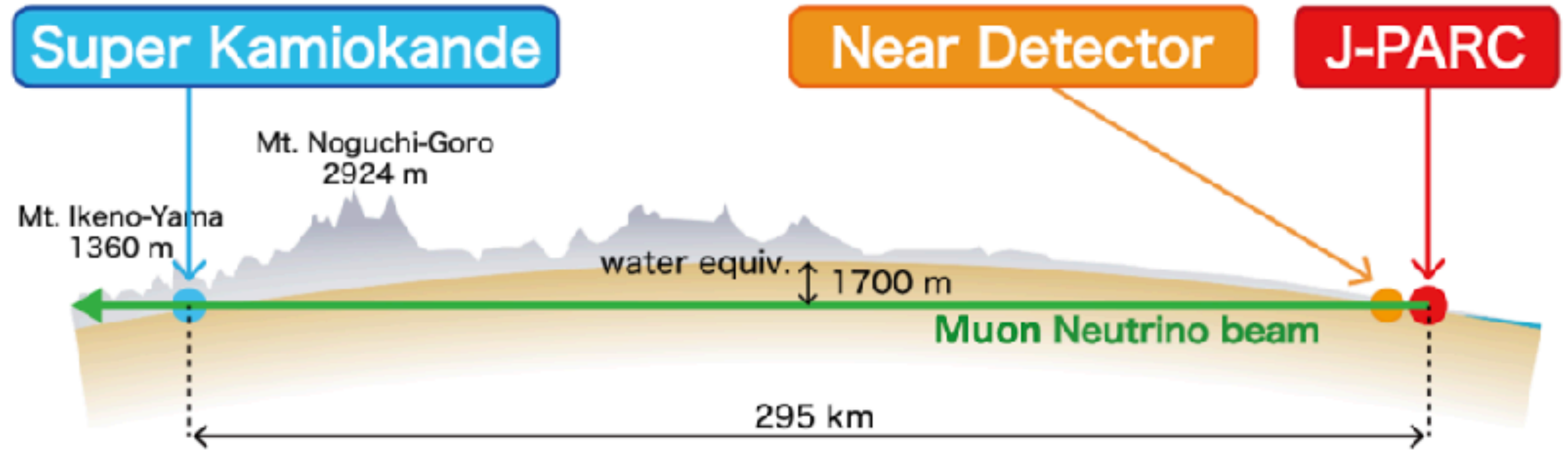


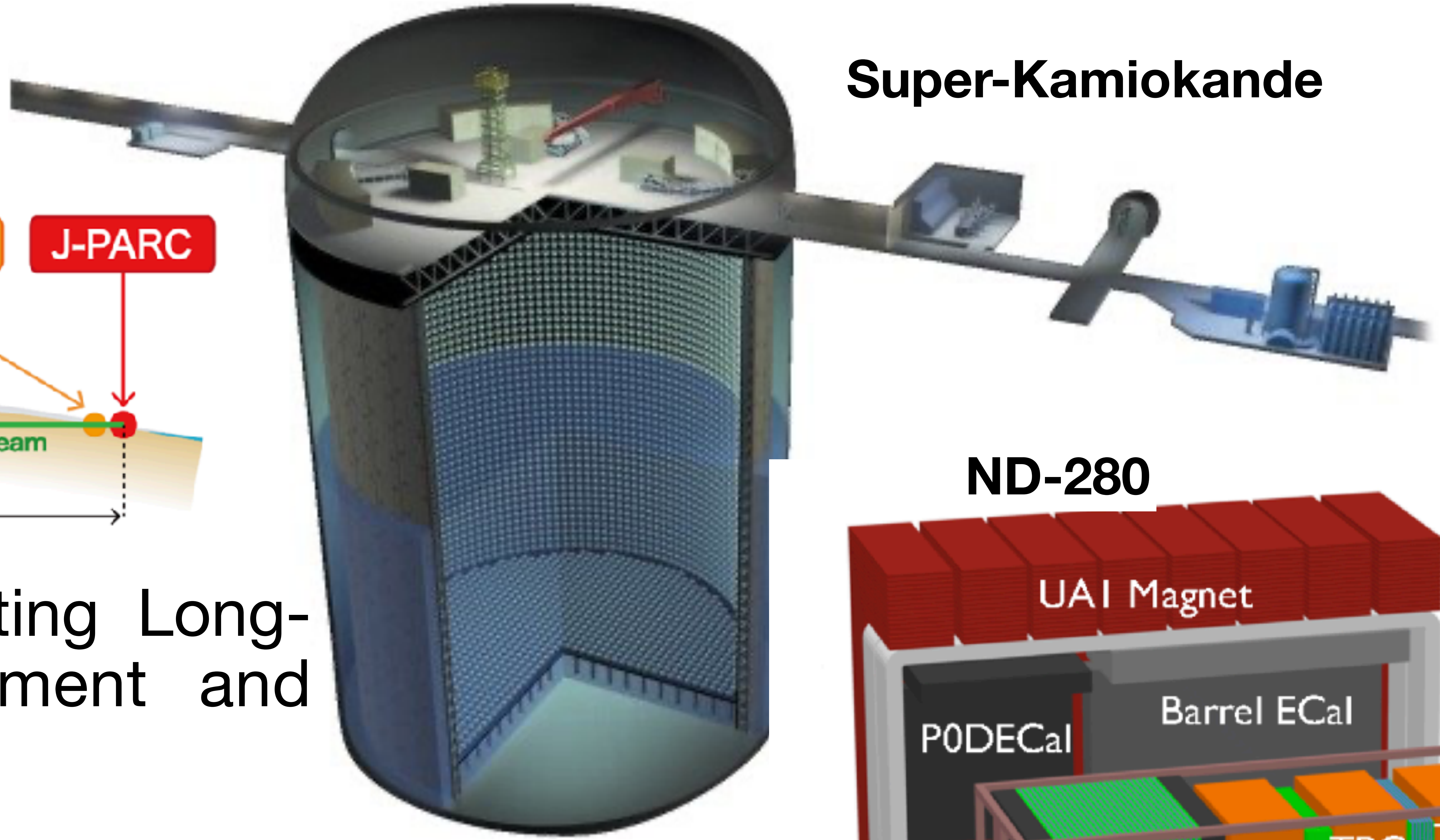
NOvA is the current state-of-art US neutr no experiment after the operation of MINOS. Beam flux averages around 2 GeV and the baseline is around 800km/500mi. The detector is mostly mineral oil and Polyvinyl Chloride (PVC) with scintillator material in each cell. Interaction target is mostly carbon.

Near and Far Detector are the Same Materials…

Current Generation Long Baseline Oscillation Experiments

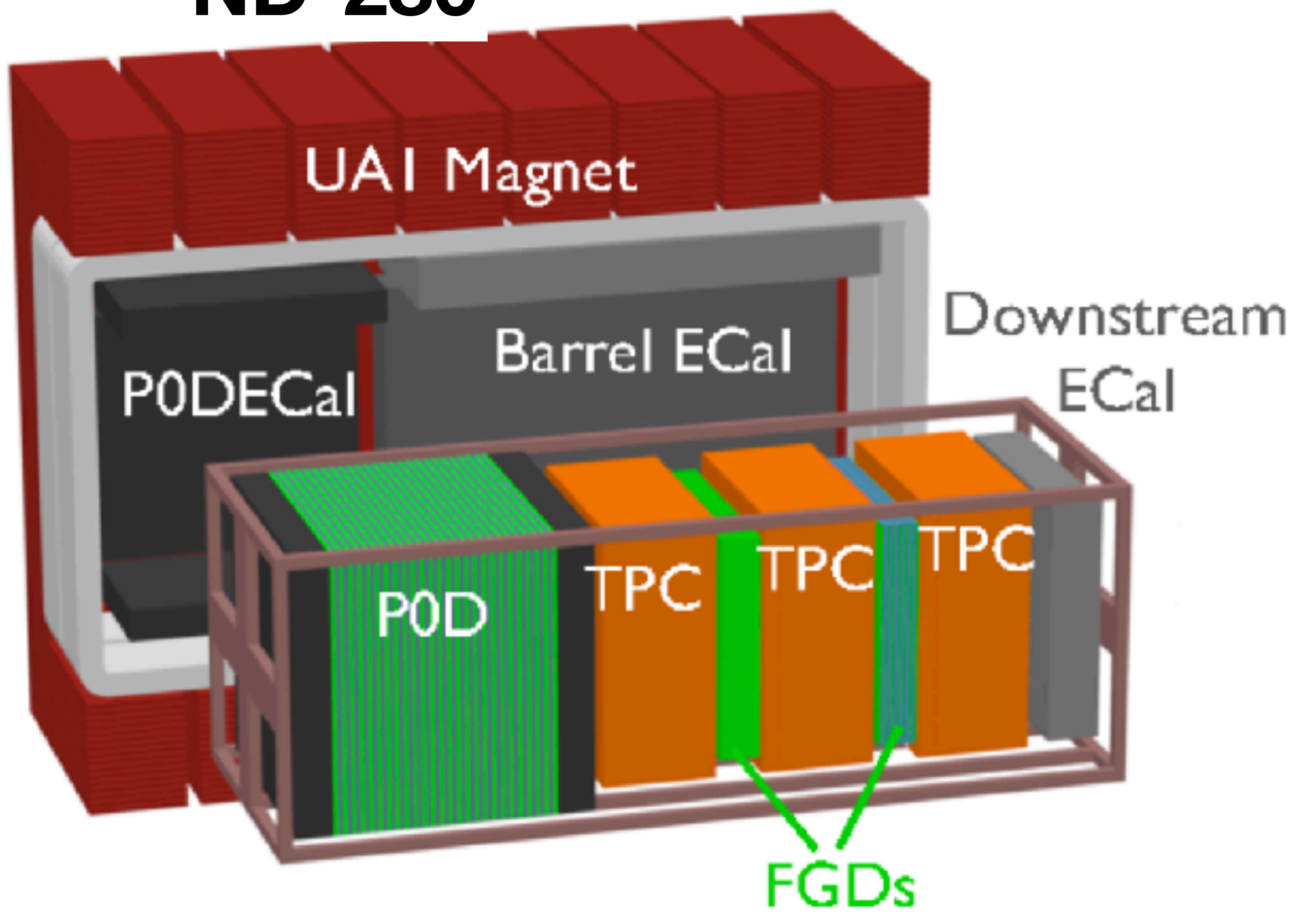
The Tokoi-to-Kamioka (T2K) Experiment





Super-Kamiokande

ND-280



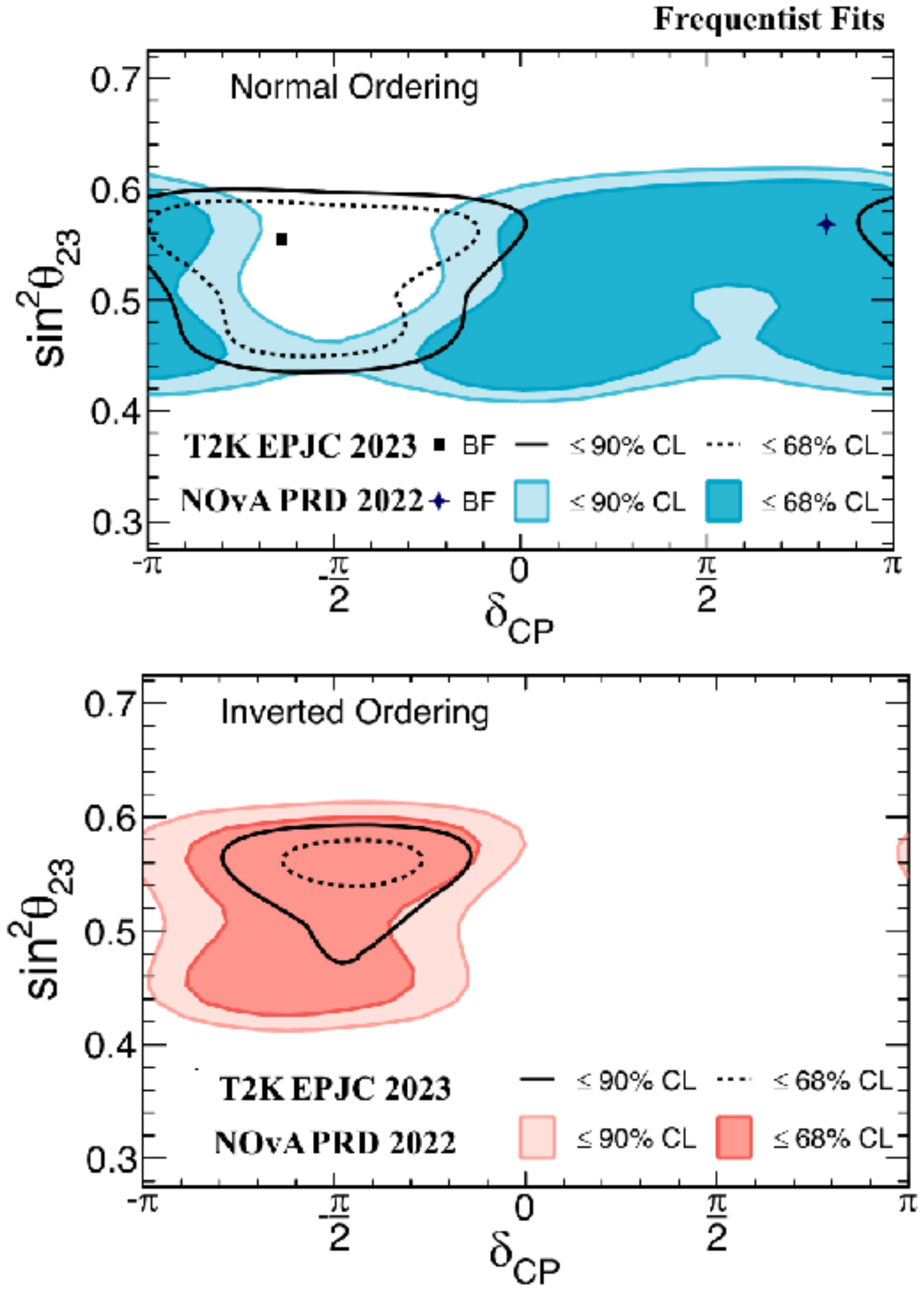
T2K is the only other operating Long-Baseline Oscillations Experiment and came about after K2K

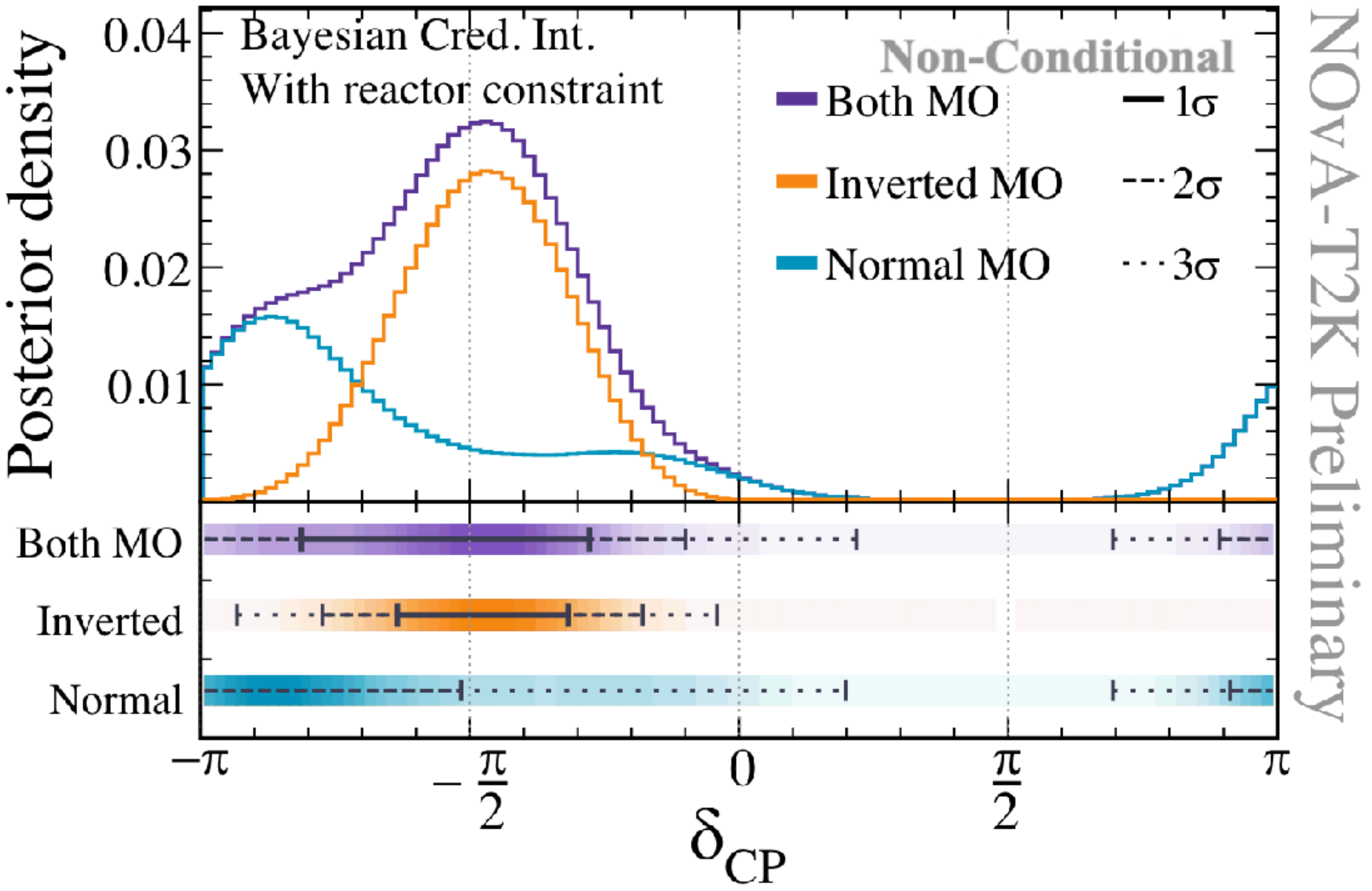
T2K expands the applicability of Super-Kamiokande by using it as an oscillations target with a well understood near detector.

Near and Far Detector are Different Materials…

Results of the Current Generation of Long Baseline Experiments

Current State-of-the-Art Measurement



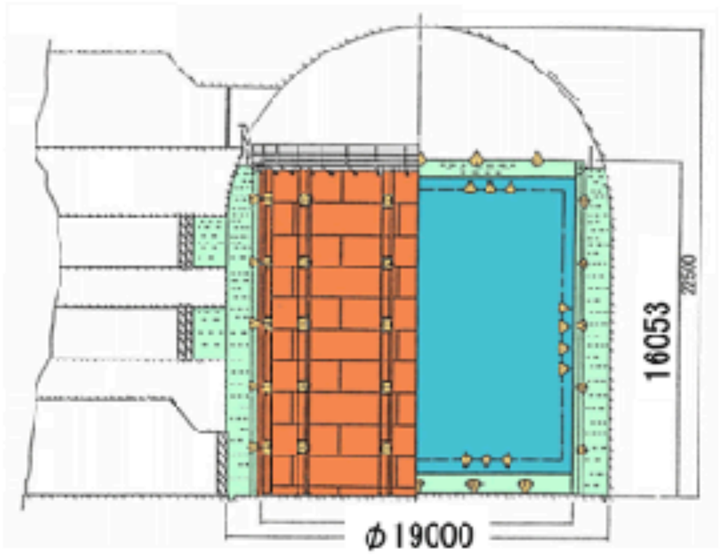
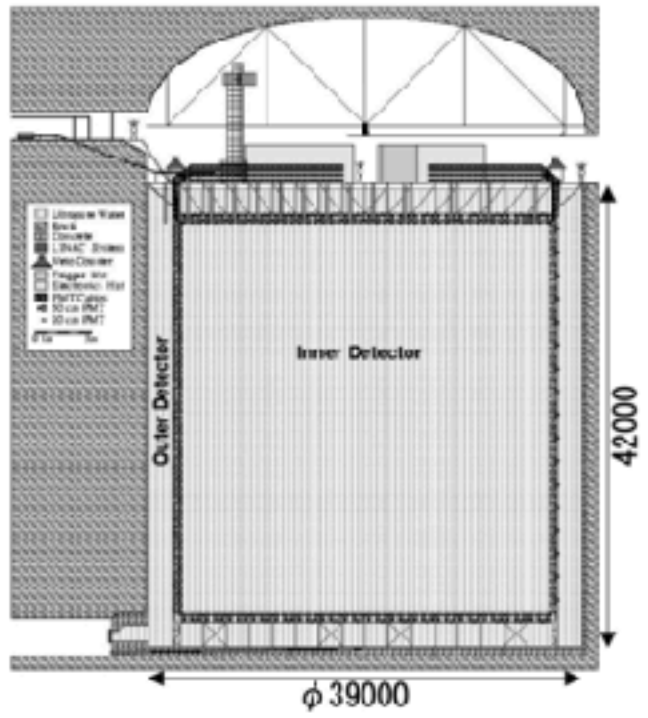
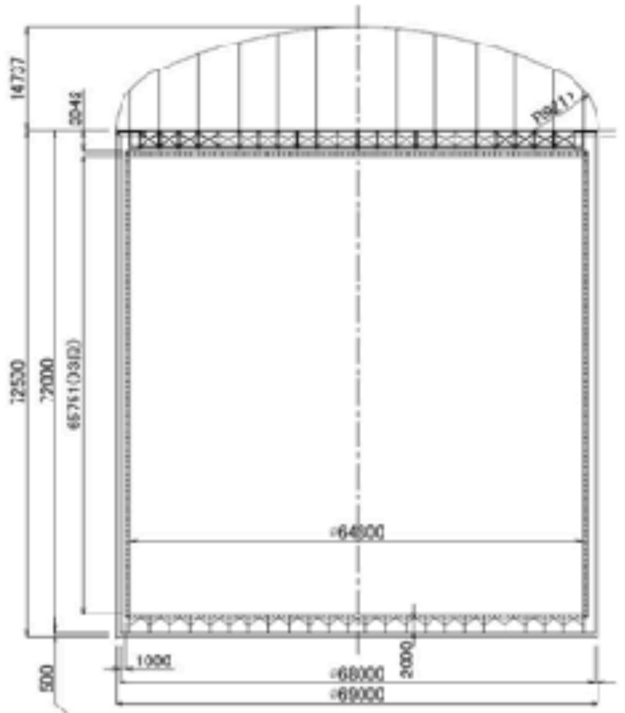


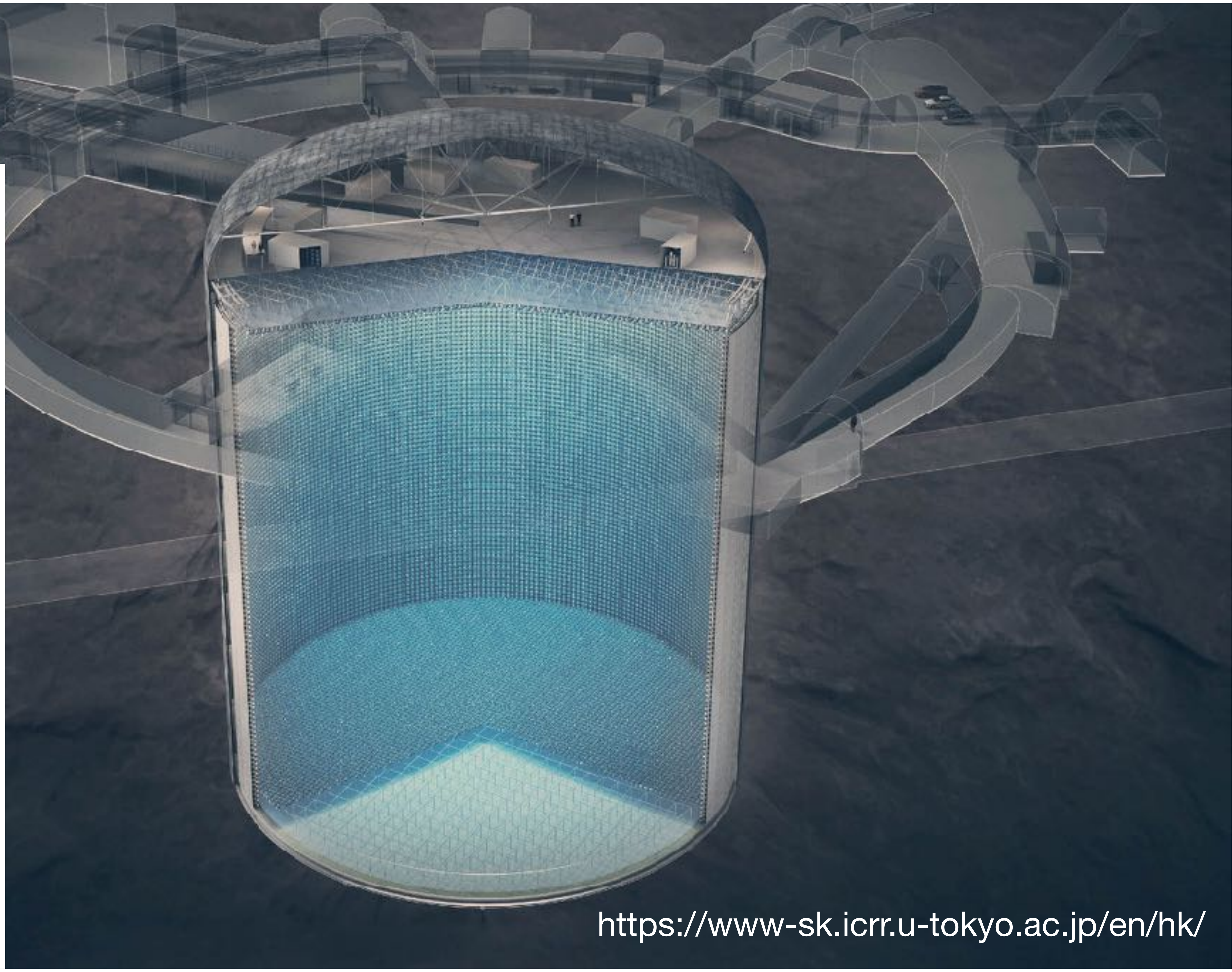
Best fit results from both experiments interesting relationship to each other.

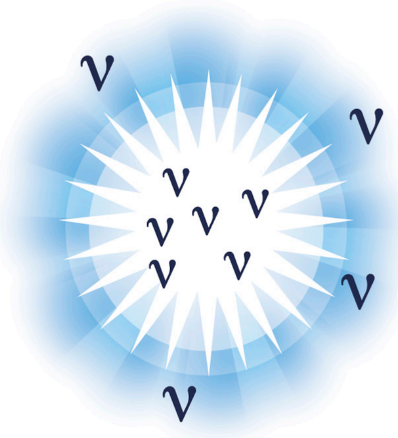
Joint fit of NOvA and T2K still does constrain δ_{CP} considerably more than either experiment alone.

Next Generation of Long-Baseline Experiments

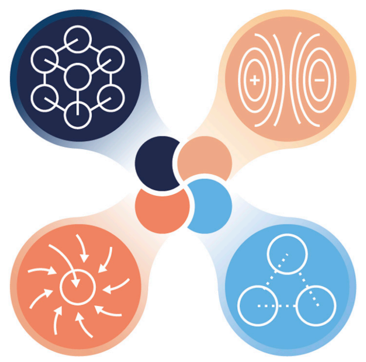
Hyper-Kamiokande: the Japanese future long-baseline oscillation experiment

4,500 Tons	50,000 Tons	260,000 Tons
Kamiokande	**Super-Kamiokande**	**Hyper-Kamiokande**
1983~1996	1996~Present	Aiming to start observation in 2027
		
Size		
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight





- Leptonic CP-violation ($\delta_{CP}, \Delta L = 0?$)
- Oscillation Parameters (θ_{23})
- Neutrino Mass Hierarchy (NH/IH?)

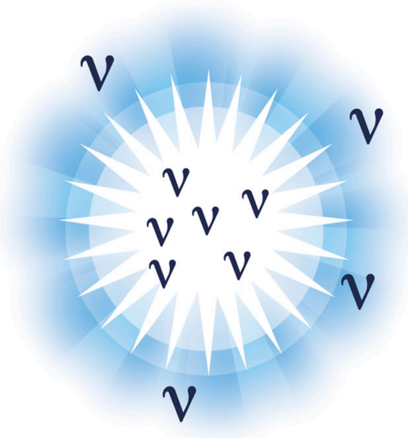


- Proton Decay (GUT?)

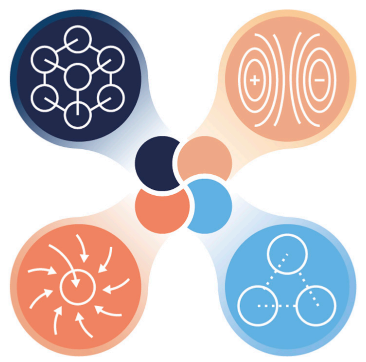
- Supernova Burst Neutrinos

Next Generation of Long-Baseline Experiments

DUNE: The American Long-Baseline Oscillation Experiment



- Leptonic CP-violation ($\delta_{CP}, \Delta L = 0$?)
- Oscillation Parameters (θ_{23})
- Neutrino Mass Hierarchy (NH/IH?)



- Proton Decay (GUT?)

- Supernova Burst Neutrinos

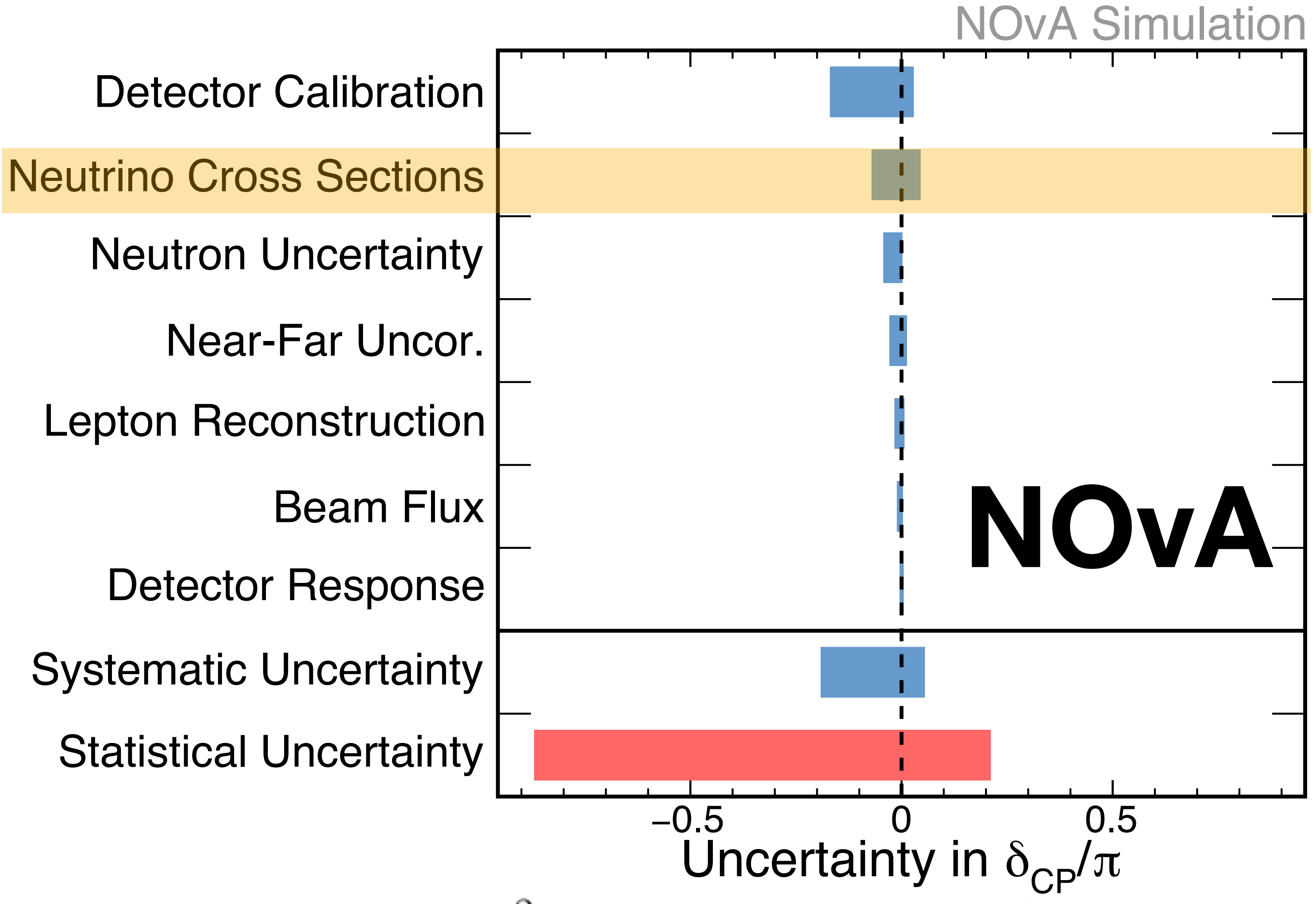
Next Generation of Long-Baseline Experiments
DUNE: The American Long-Baseline Oscillation Experiment

Uncertainties in Oscillation Analyses

A Brief Look at Uncertainties on δ_{CP}

Supplementary Table 1: The systematic uncertainty on the predicted relative number of electron neutrino and electron antineutrino candidates in the Super-K samples with no decay electrons.

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

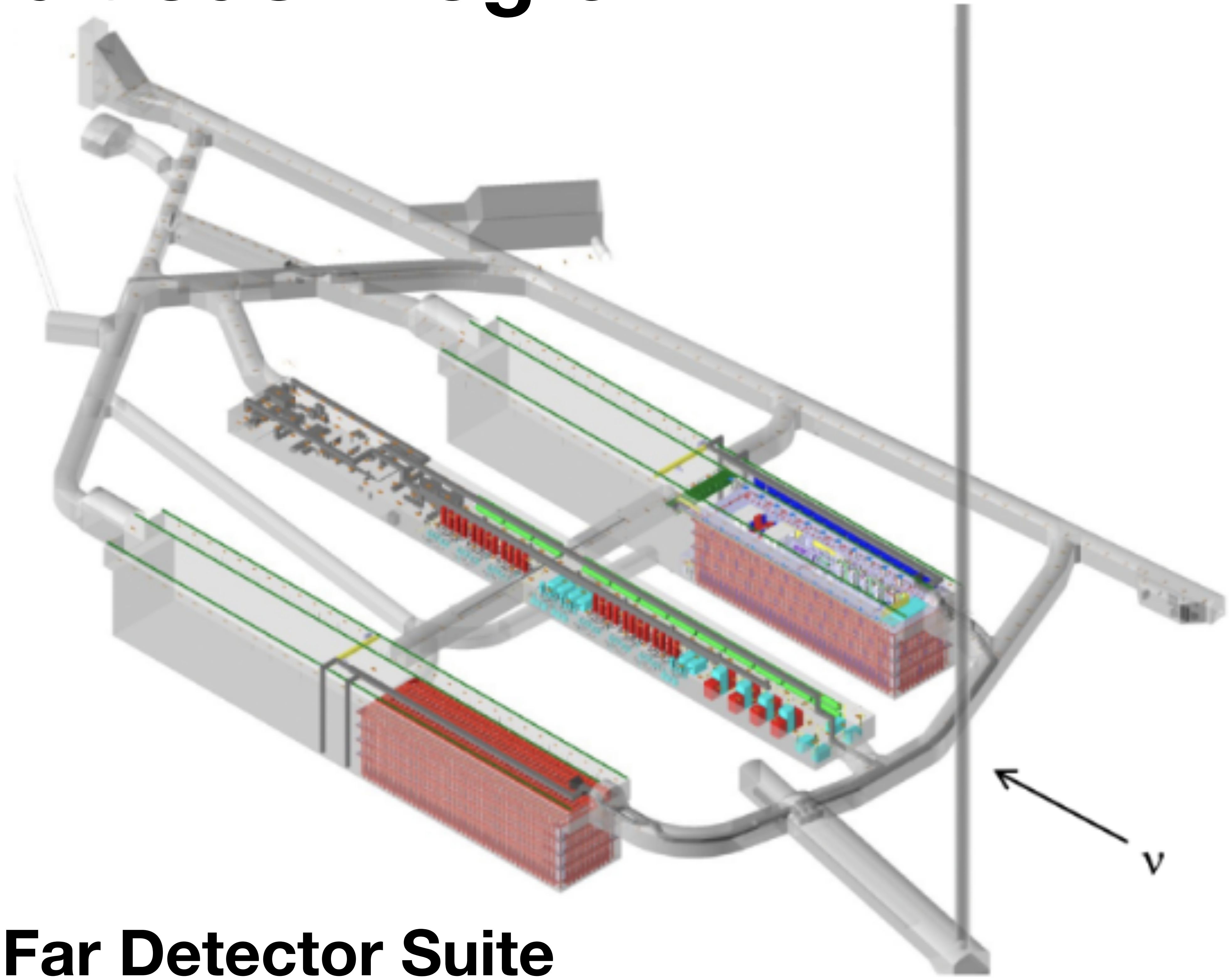


Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -0.0085
Lepton Reconstruction	+0.0026 / -0.002	+0.006 / -0.016	+0.0094 / -0.015
Near-Far Uncor.	+0.002 / -0.0016	+0.012 / -0.028	+0.0013 / -0.0048
Neutrino Cross Sections	+0.0027 / -0.0034	+0.044 / -0.07	+0.0066 / -0.012
Neutron Uncertainty	+0.0049 / -0.0078	+0.0012 / -0.042	+0.011 / -0.017
Systematic Uncertainty	+0.0083 / -0.027	+0.054 / -0.19	+0.024 / -0.028
Statistical Uncertainty	+0.022 / -0.033	+0.21 / -0.87	+0.043 / -0.055

As of 2022, largest uncertainties on current generation experiments are due to statistics. How to proceed with the next generation of experiments?

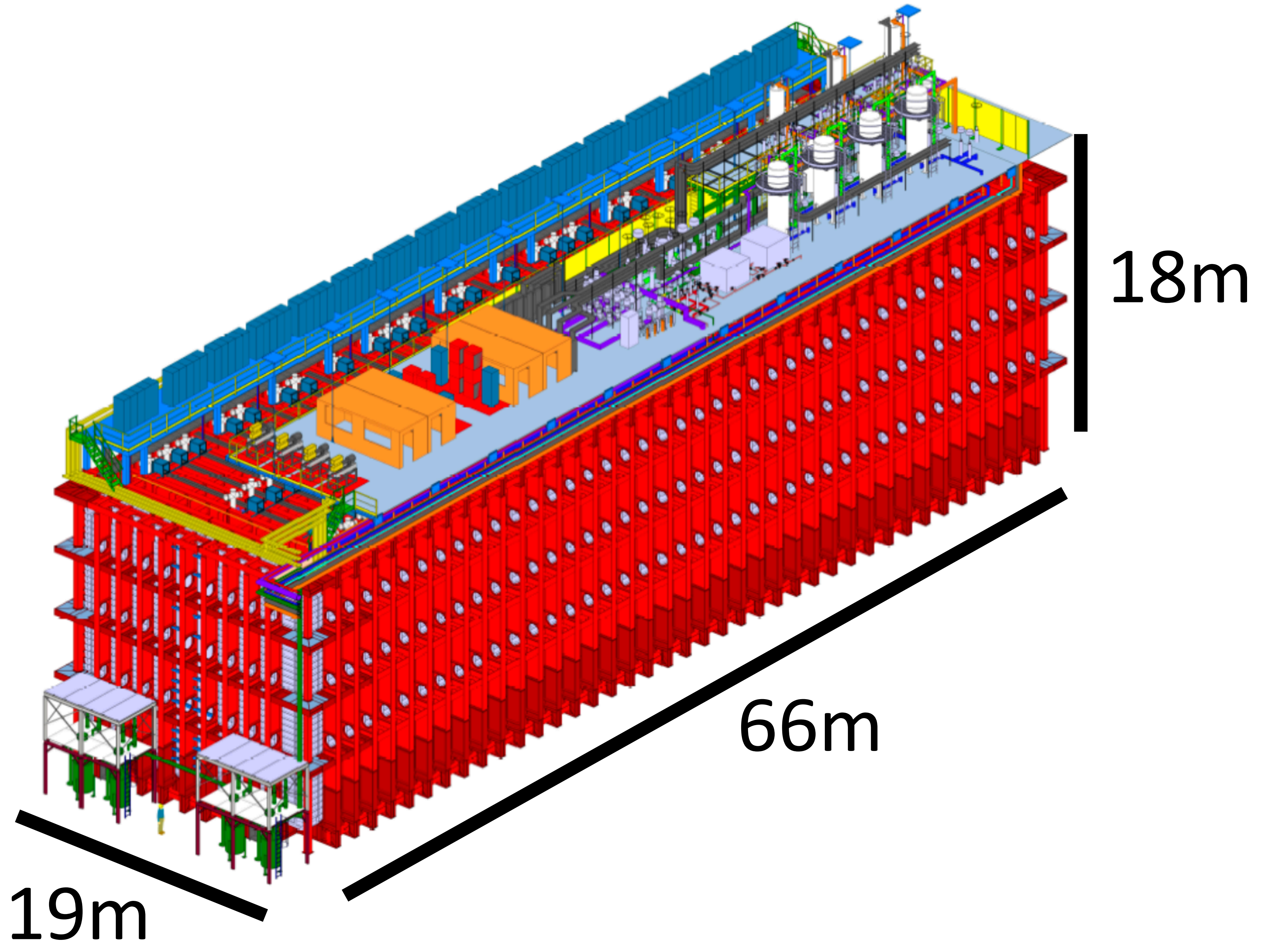
New Liquid Argon Technology

An Ambitious Program



Far Detector Suite

Far Detector Module Design

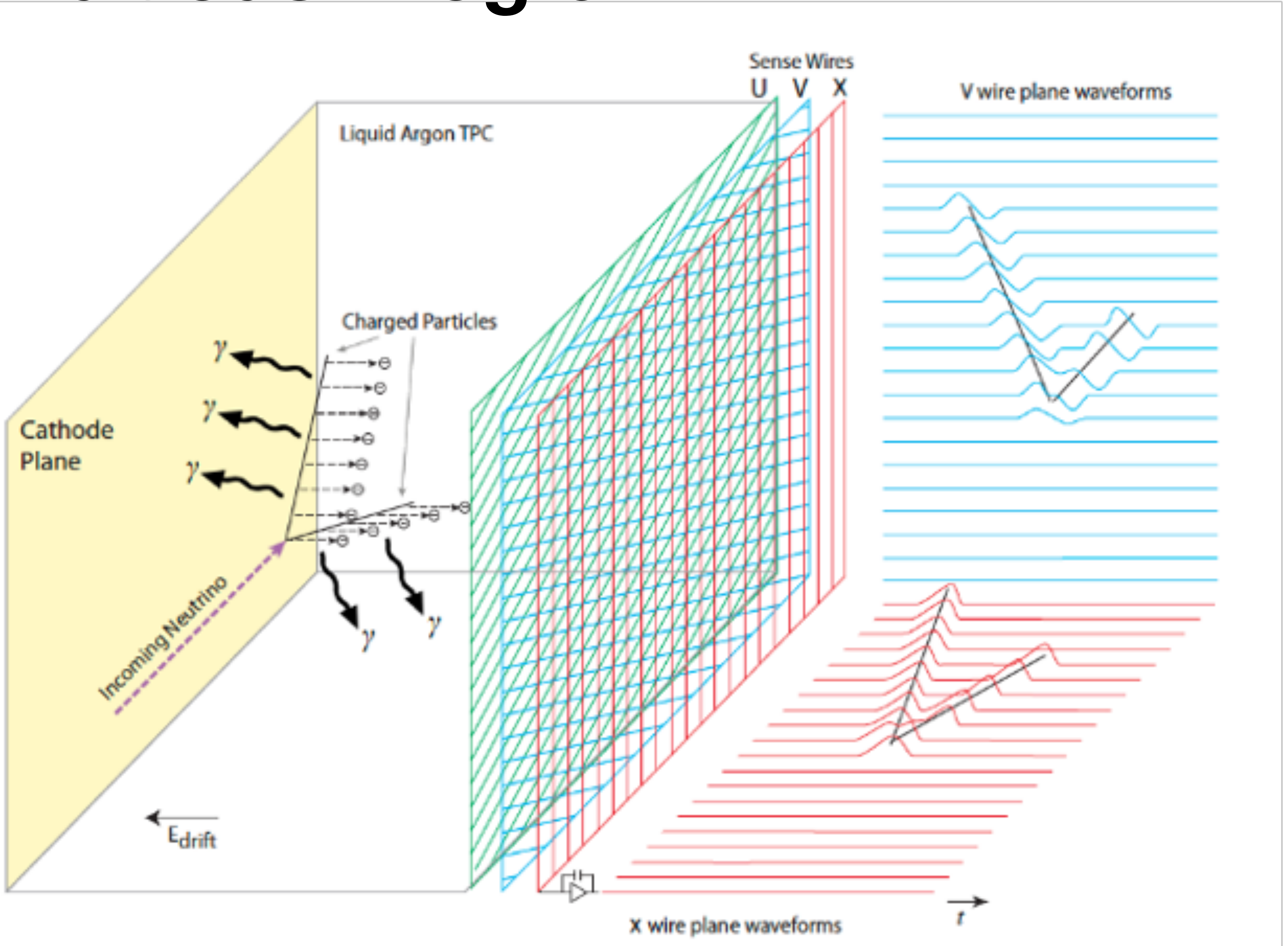


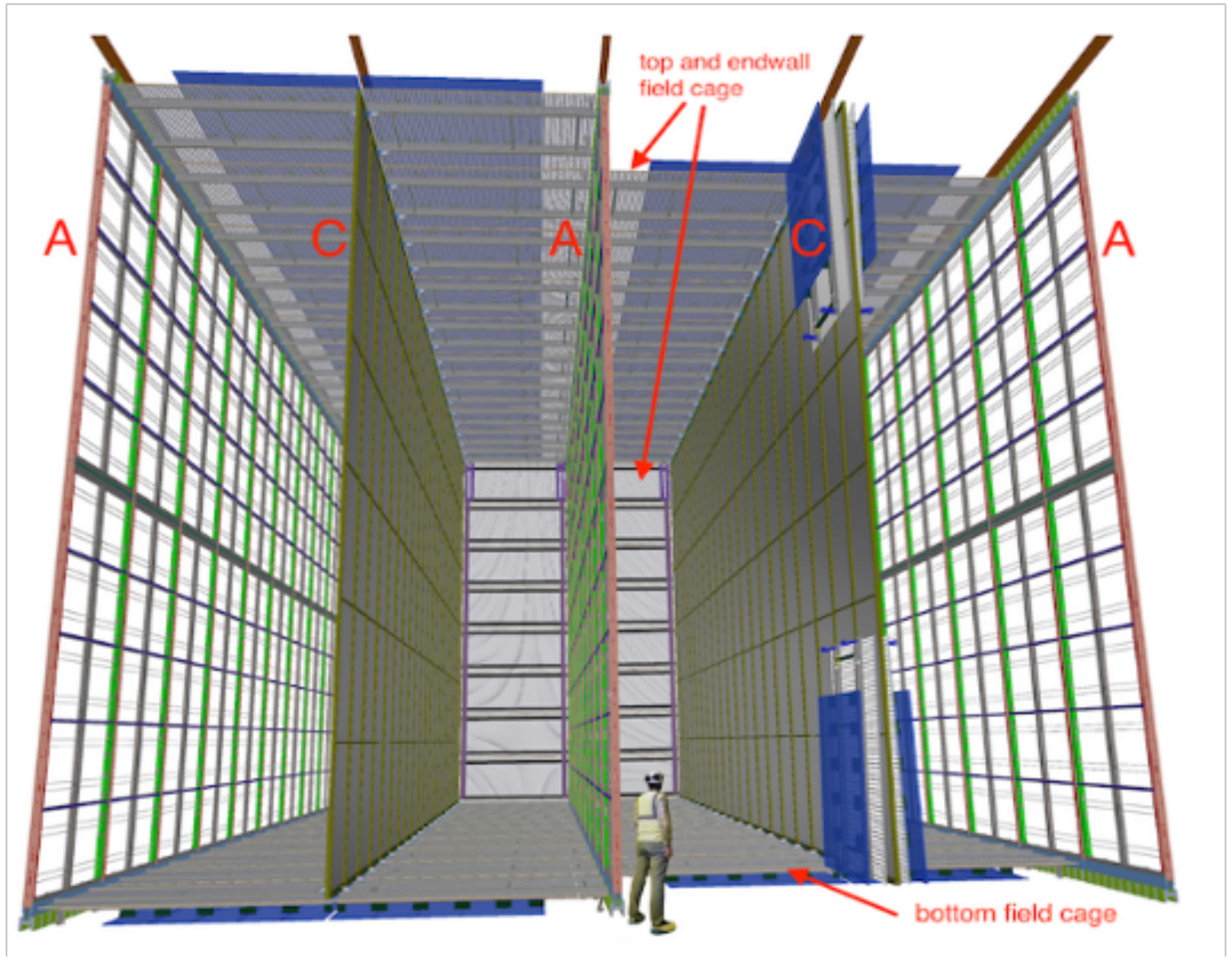
First order of business is to build an absolutely humongous (17kt fiducial volume/module) Far Detector to observe oscillations over a 1,300km/800mi baseline.

Second order of business is to commandeer an old converted gold mine to isolate it from cosmic rays.

New Liquid Argon Technology

An Ambitious Program



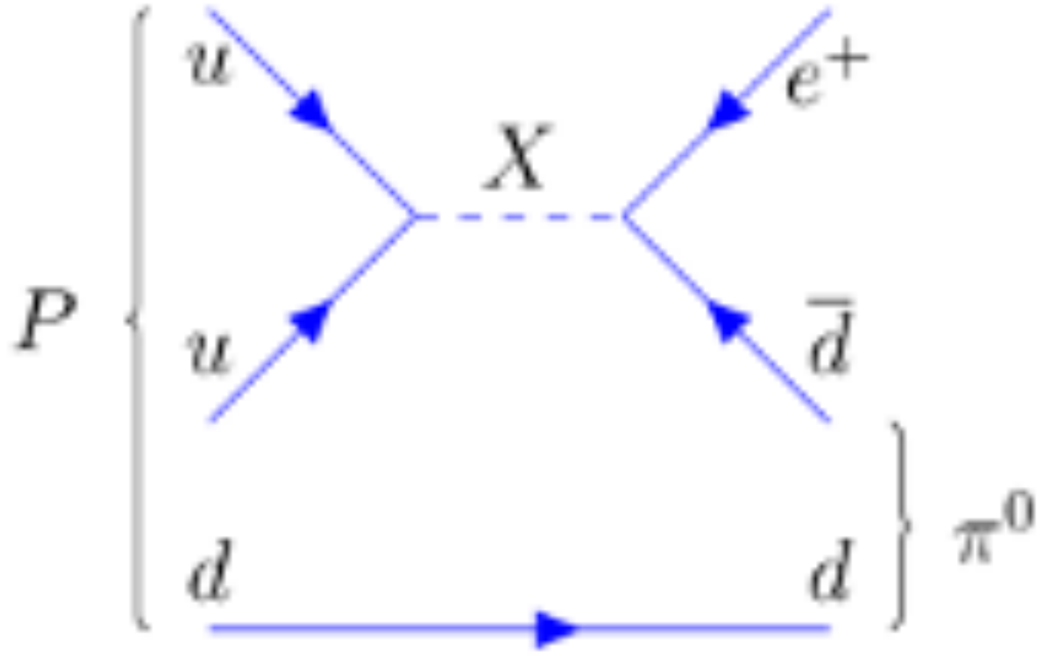


The third order of business is to develop a new type of neutrino detector that is simultaneously inexpensive and highly sensitive to fairly quiet events. (i.e. Borrow from Dark Matter Experiments)

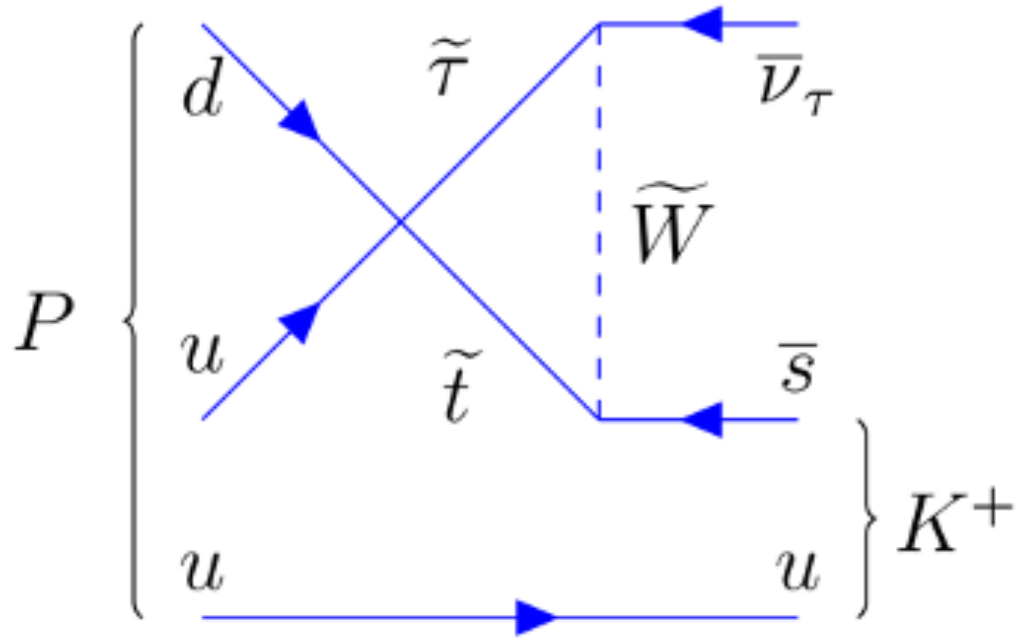
Liquid argon provides similar sensitivity as NOvA and the target density of Super-Kamiokande but without the isolated detectors planes. Also scintillation can be used for event timing!

A Broad Neutrino Physics Program

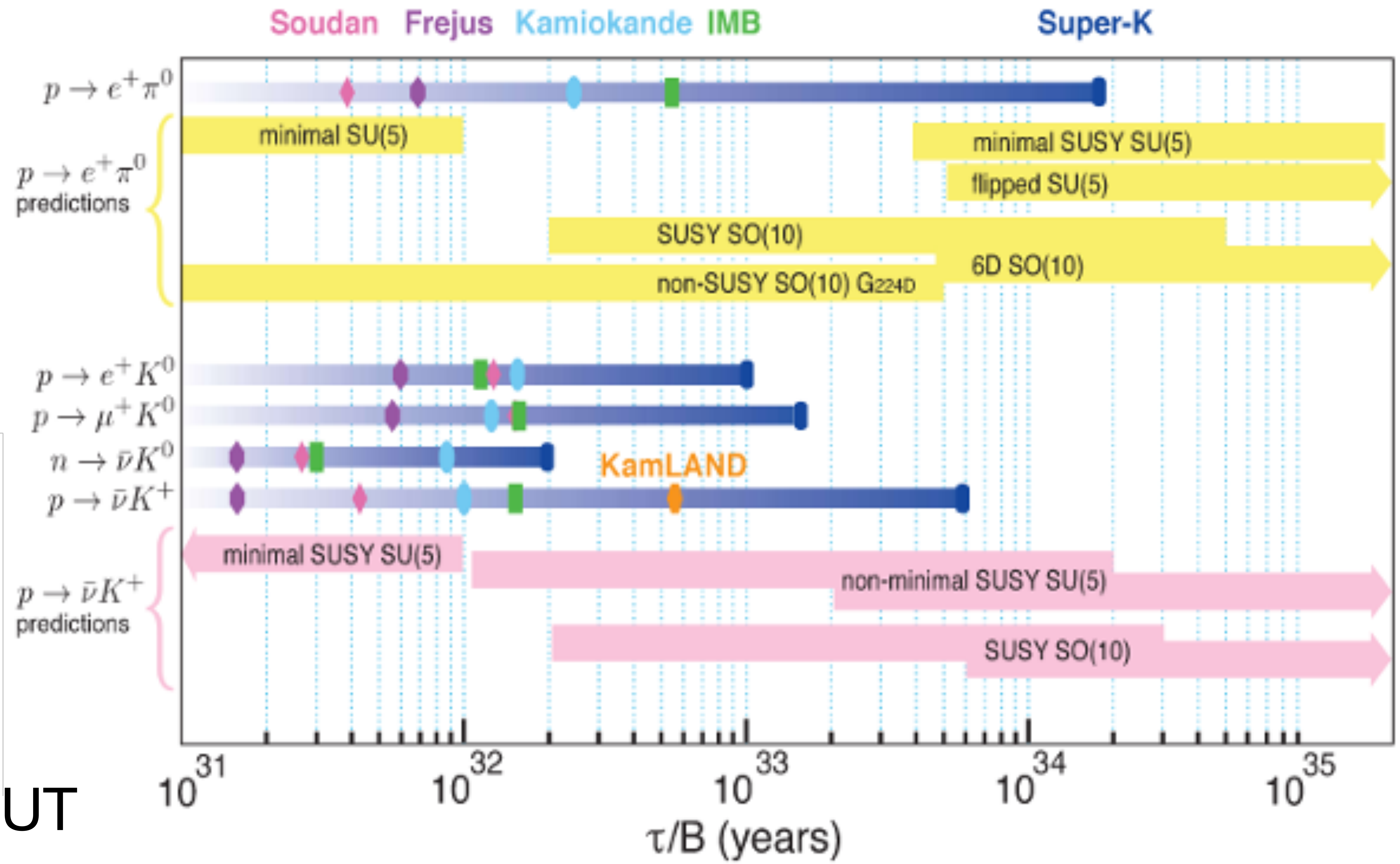
Searches for Grand Unified Theories (GUTs)



SU(5) Gauge Mediated GUT



Supersymmetric GUT

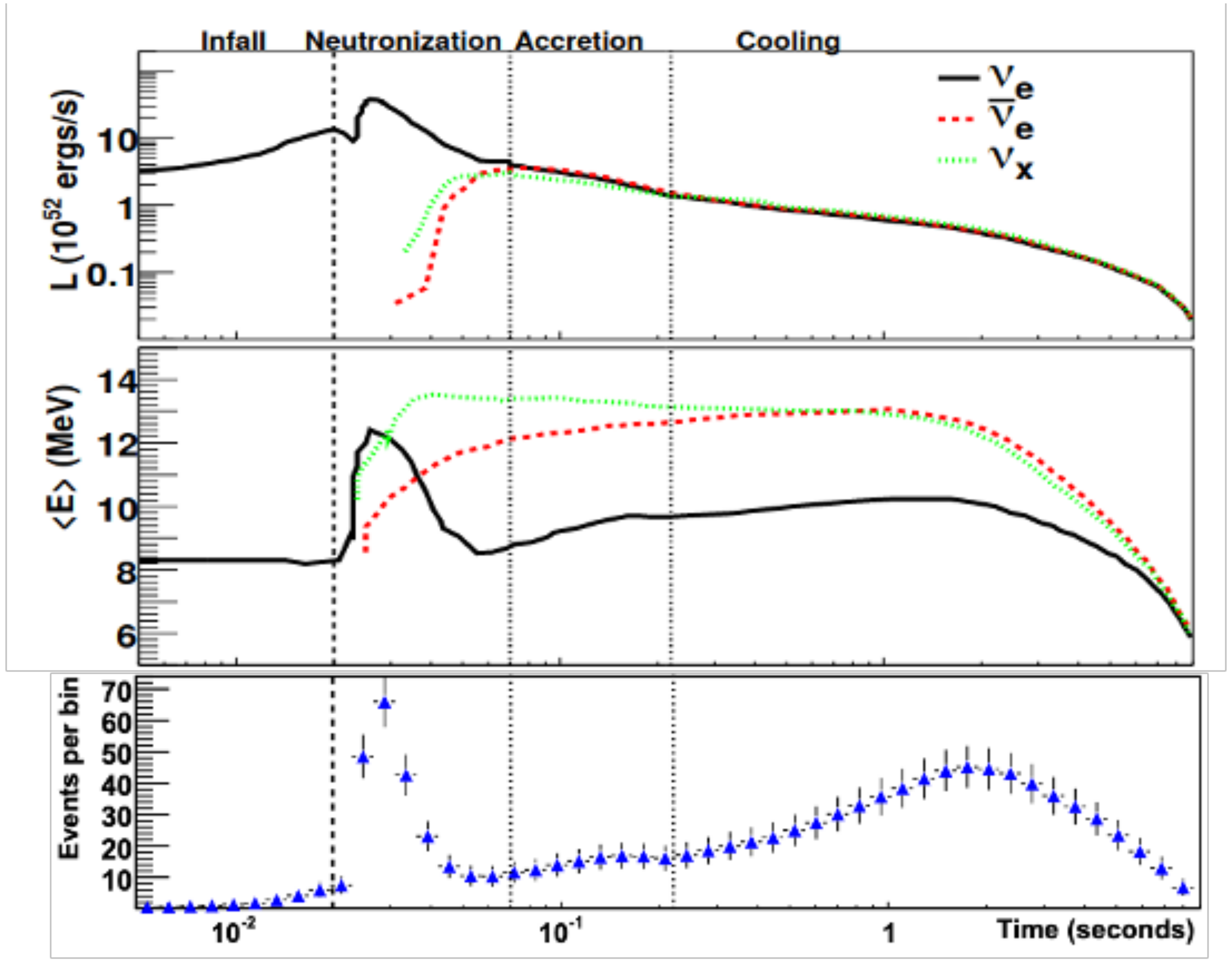


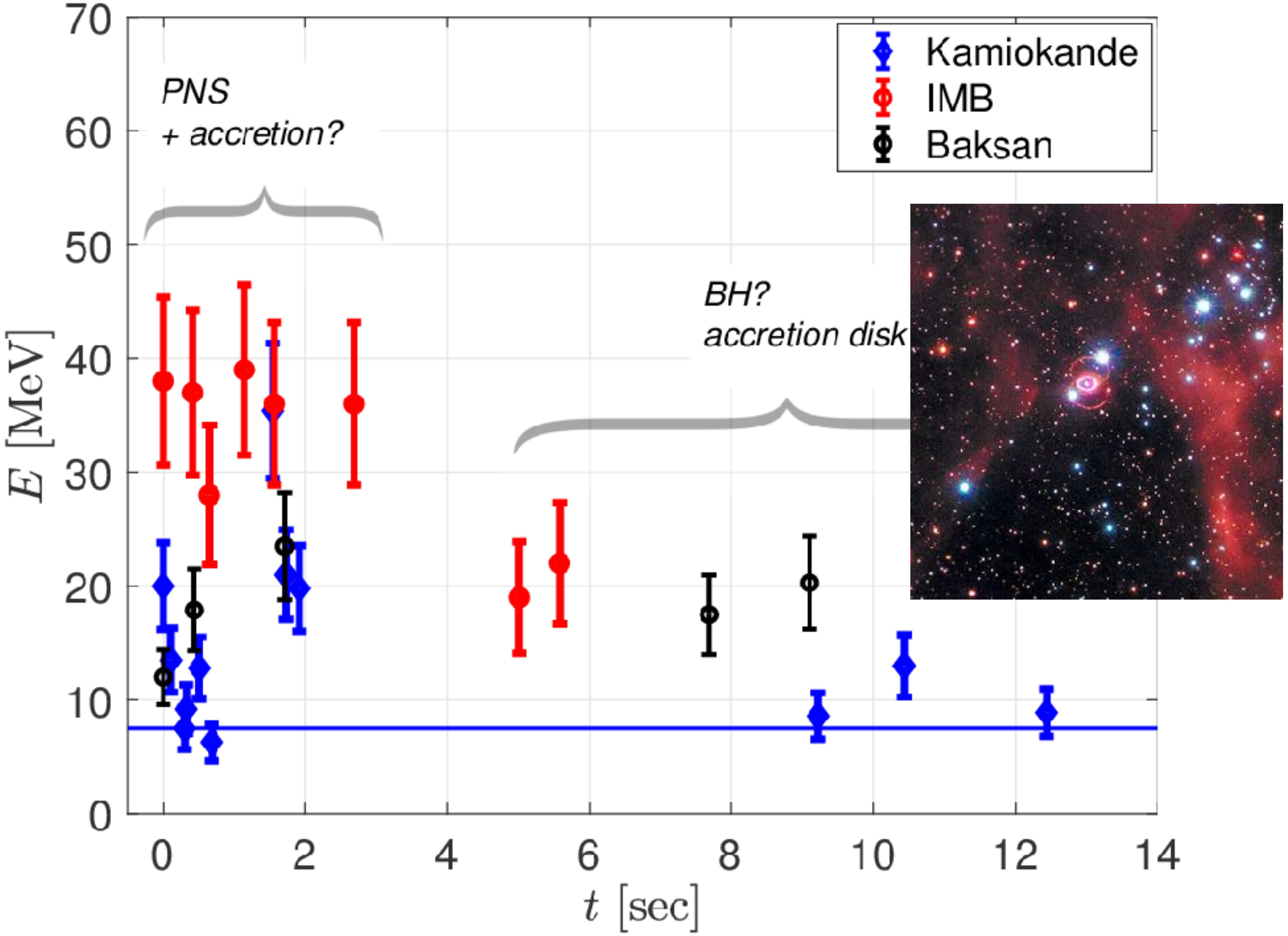
Due to the sheer amount of nucleons (About 5.5×10^{32} nucleons) in such a well instrumented quiet area, DUNE (and Hyper-Kamiokande) will set new limits on proton decay. DUNE has special applications to strangeness

A Broad Neutrino Physics Program

Sensitivity to Supernova Bursts

SN1987A



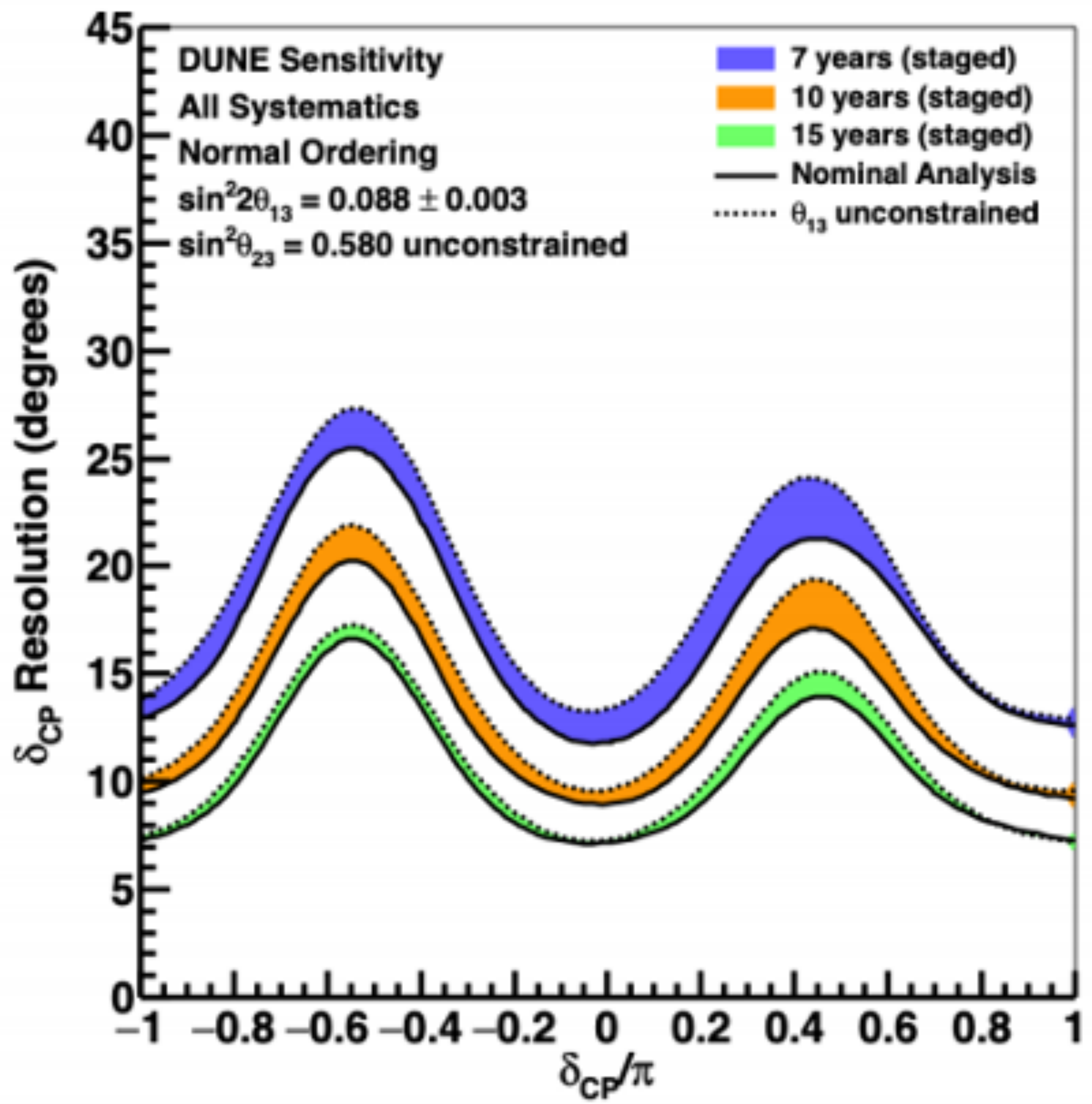


Supernova explosions within 1 kiloparsec are estimated to be once every 100 years of so.

Last supernova was SN1987A and only about 25 events, between a few and tens of MeV were observed worldwide.

Projected Sensitivities for the Oscillation Program

A Very Capable Detector



Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

Detection capability depends on how quickly all four modules can be established but real physics goals can be reached quickly. Discovery of δ_{CP} depends on its actual value.

Conclusions and Summary

The ride is still going and we're still cowboys…

The neutr no first proposed in 1930s as a last-ditch solution to energy conservation in nuclear beta decay problem.

Neutr nos have a ton of weird properties.

Neutr nos oscillations in flavor were a large mystery for a few decades, finally figured out by teams of hundreds of physicists doing science!

Neutr no could potentially explain why there is a difference between matter and antimatter in the universe.

Also, still many open questions:

Why are neutr no masses so small?

What is the neutr no mass scale?

Where does neutr no mass come from?

Are there more neutr nos than 3?

Is the neutr no its own antiparticle?

What can neutr nos tell us about nuclear physics?