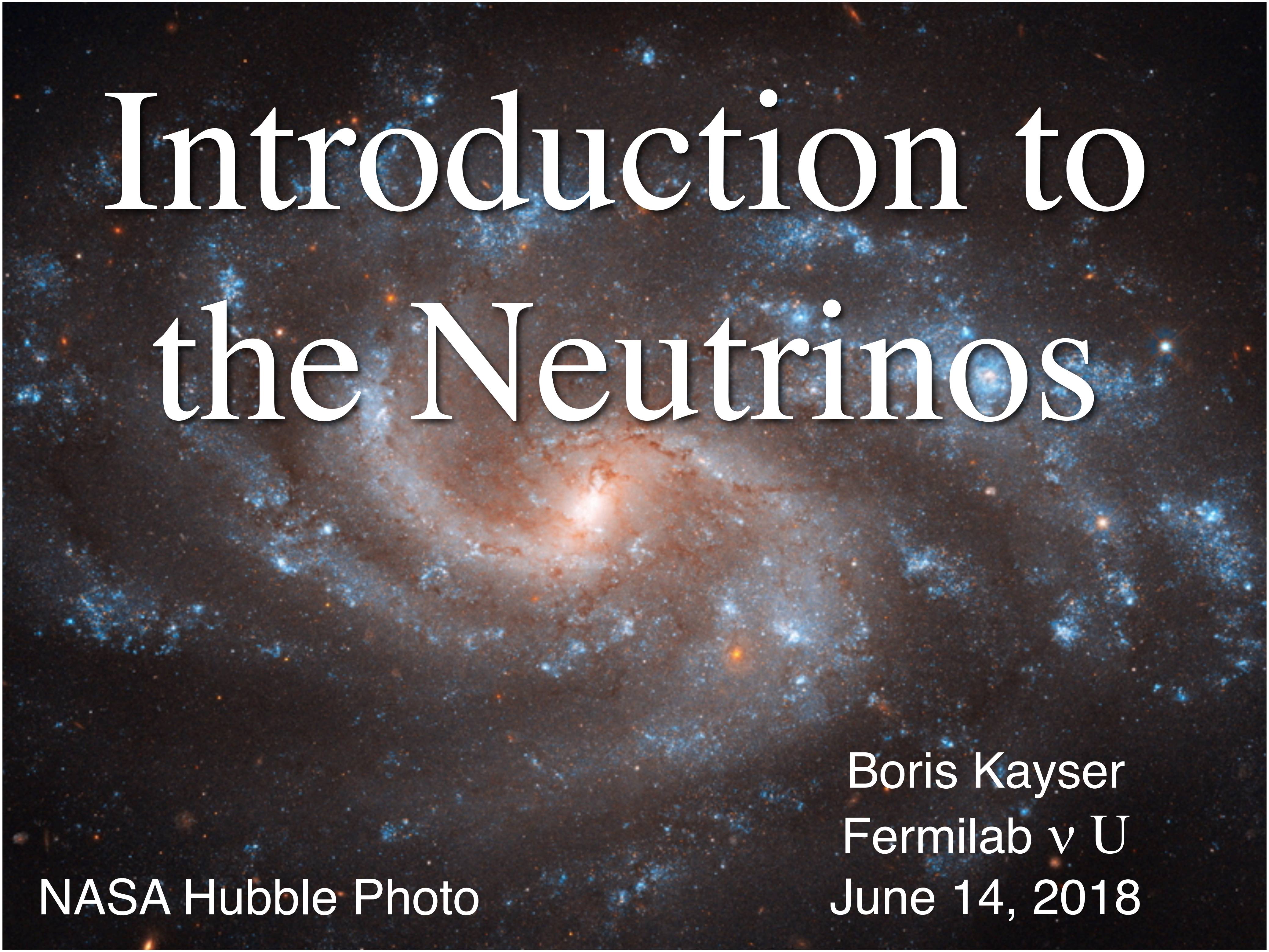


Introduction to the Neutrinos

Boris Kayser
Fermilab ν U
June 14, 2018

NASA Hubble Photo

Over 100 years ago, people were studying beta decay, which they ***thought*** was the process —

Nucleus(i) → Nucleus(f) + Electron

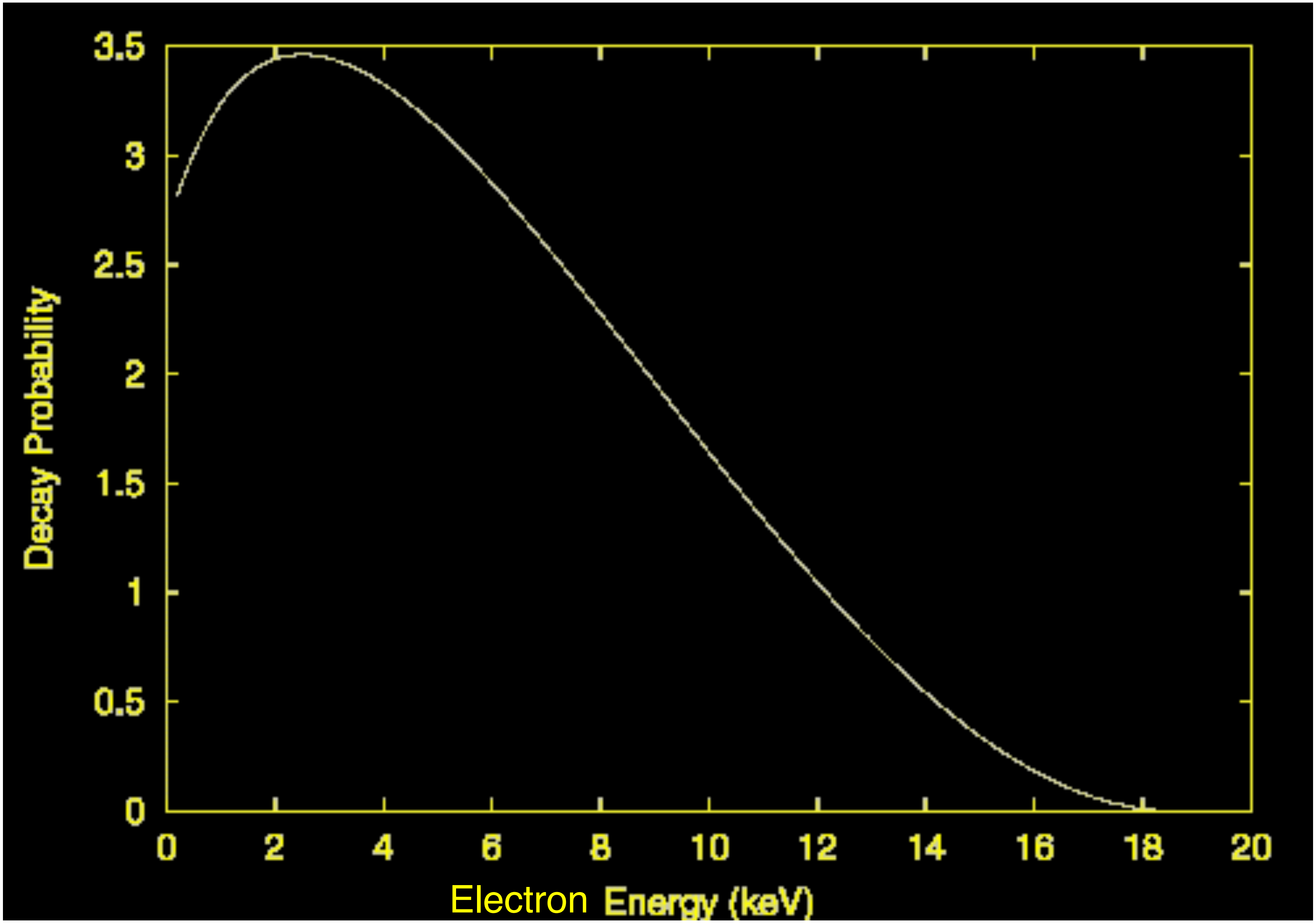
Had there really been only **2 particles** in the final state, then for given initial and final nuclei *i* and *f*, the electron would always have had the same kinetic energy:

$$T_e = \frac{(\overset{\substack{\text{Mass of nucleus}(i)\\ \downarrow}}{m_i} - m_e)^2 - m_f^2}{2m_i}\underset{\substack{\uparrow\\ \text{Speed of light}}}{c^2}$$

However, what was observed instead was —

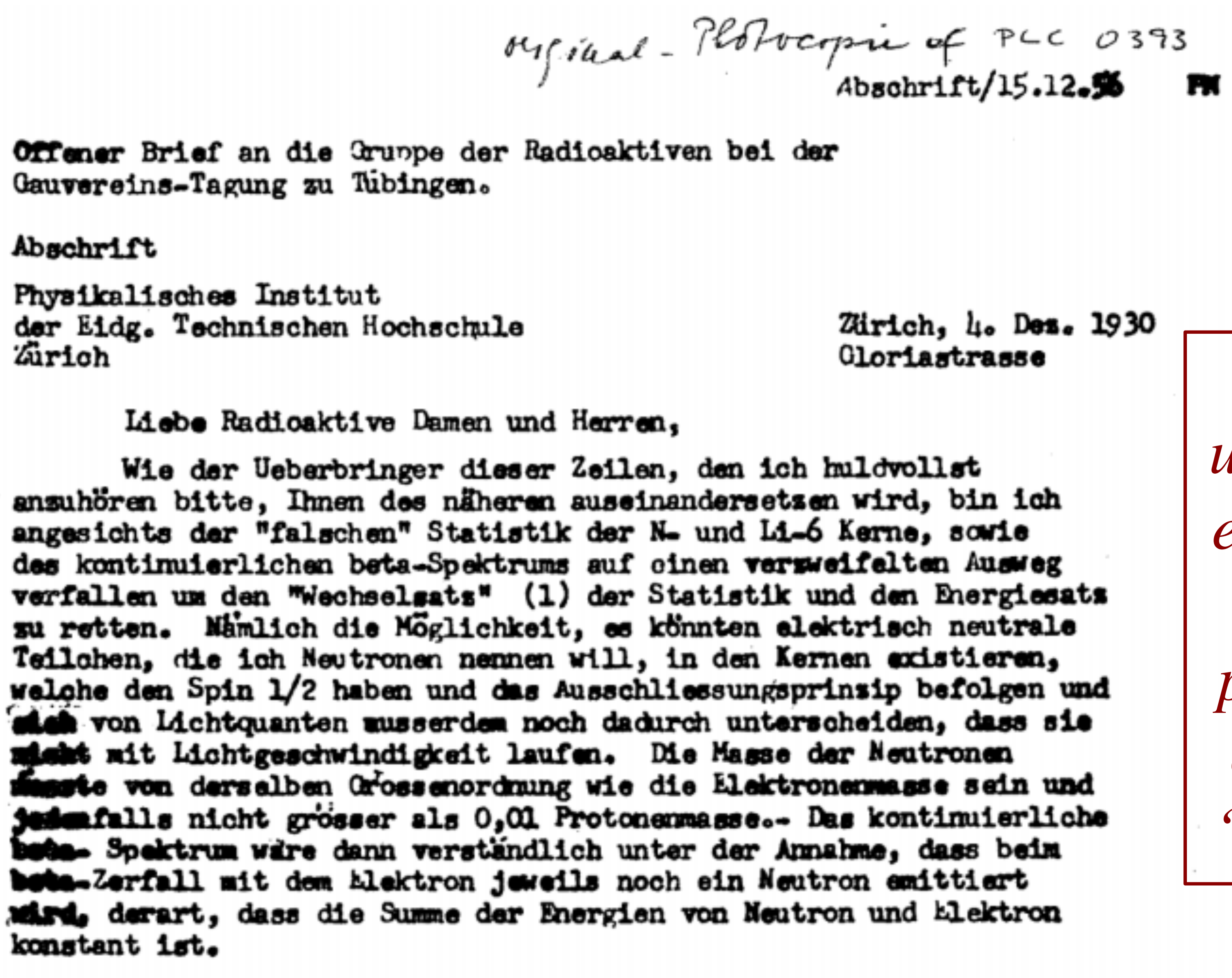
A modern example –

Tritium beta decay: (pnn) → (ppn) + e^-



In addition, a process like $(pnn) \rightarrow (ppn) + e^-$ could not possibly conserve angular momentum.

Pauli’s Radical Solution



original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung 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.

A new, undetected, electrically neutral particle he called the “neutron”.

Pauli's idea was that beta decay is really the **3 – body** decay:

Nucleus(i) → Nucleus(f) + Electron **+ *"Neutron"***

The "neutron" carries away some of the energy released in the decay. The amount it takes away can vary. Also, angular momentum can now be conserved.

Fermi renamed Pauli's hypothetical particle the ***neutrino***.

In 1956, Cowan and Reines confirmed experimentally that ***the neutrino actually exists!***

What Are Neutrinos?

The Constituents of Matter

(All have spin ½)

				$\frac{\text{Charge}}{\text{Charge(proton)}}$
Leptons	ν_1	ν_2	ν_3	0
	e	μ	τ	– 1
Quarks	u	c	t	2/3
	d	s	b	– 1/3

Everyday matter on earth

Among the constituents of matter, the neutrinos are special:

- **Most abundant constituents by far**
- **Most penetrating ones by far**
- **Lightest ones by far (but they do have tiny masses)**
- **Only electrically neutral ones**
- **Their masses may well have a different origin than those of all other constituents**

Why Neutrinos Are So Penetrating

Despite appearances, ordinary matter (including us)
is almost completely ***empty space***.

There is an electron here, and a quark there,
but mostly just empty space.

Object	**Size (cm)**
Atom	10^{-8}
Nucleus	10^{-12}
Nucleon	10^{-13}
Electron or Quark	10^{-16}

All the constituents of matter are $\sim 10^{-16}$ cm in diameter.

A neutrino does not interact appreciably with another constituent of matter unless it is within $\sim 10^{-16}$ cm of it.

In other words, it must make a direct hit, or it will just pass by. That is why neutrinos pass so easily through matter.

The Challenge of Detecting Neutrinos

Owing to the tremendous penetrating power of neutrinos, most will pass right through any detector undetected.

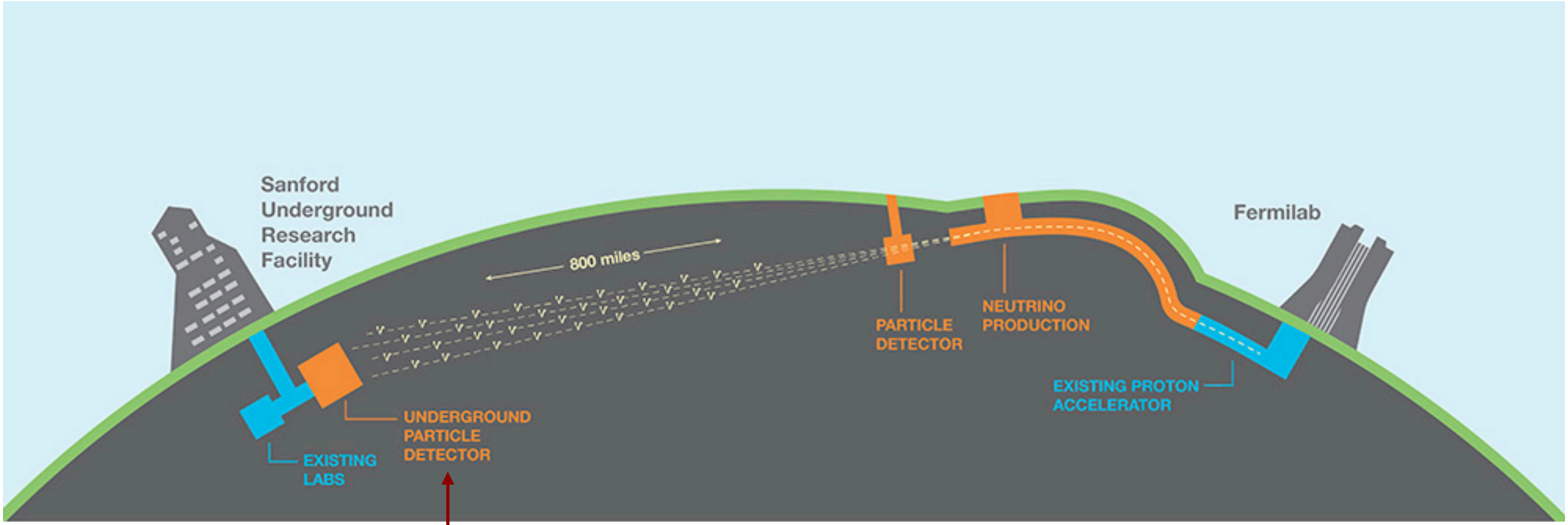
Neutrino detectors must be very **massive**.

Since neutrino events can be very rare, neutrino detectors must defeat cosmic-ray backgrounds.

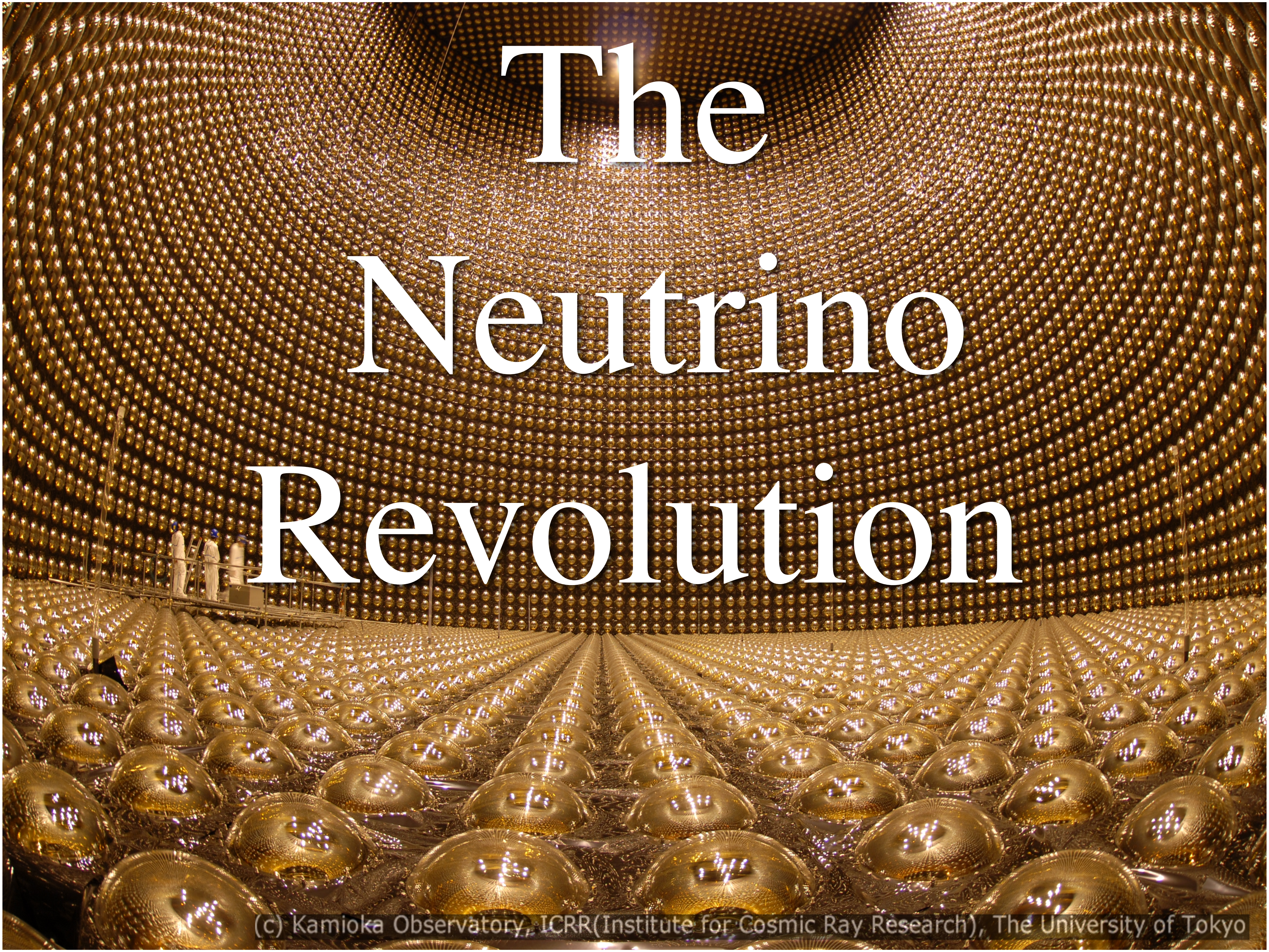
For this reason, some neutrino detectors are placed deep underground.

In a mine, or beside the middle of a vehicular tunnel through a mountain.

Example: The Deep Underground Neutrino Experiment (DUNE)



40 kton liquid argon detector, 4850 ft down



The Neutrino Revolution

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Over the years, we learned that neutrinos interact with other particles through the (short-range) ***weak interaction*** that is very successfully described by the Standard Model of elementary particle physics.

For decades, we learned little else about them.

Then —

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!

These discoveries have opened a whole new world to explore.

The 2015 Nobel Prize in Physics went to **Takaaki Kajita** and **Art McDonald** for the experiments that proved this.

Super-Kamiokande, Japan

Sudbury Neutrino Observatory, Canada

The Origin of Neutrino Mass

One of the most fundamental questions we ask
in elementary particle physics is:

What is the origin of mass?

The fundamental constituents of matter
are the ***quarks***, the ***charged leptons***,
and the ***neutrinos***.

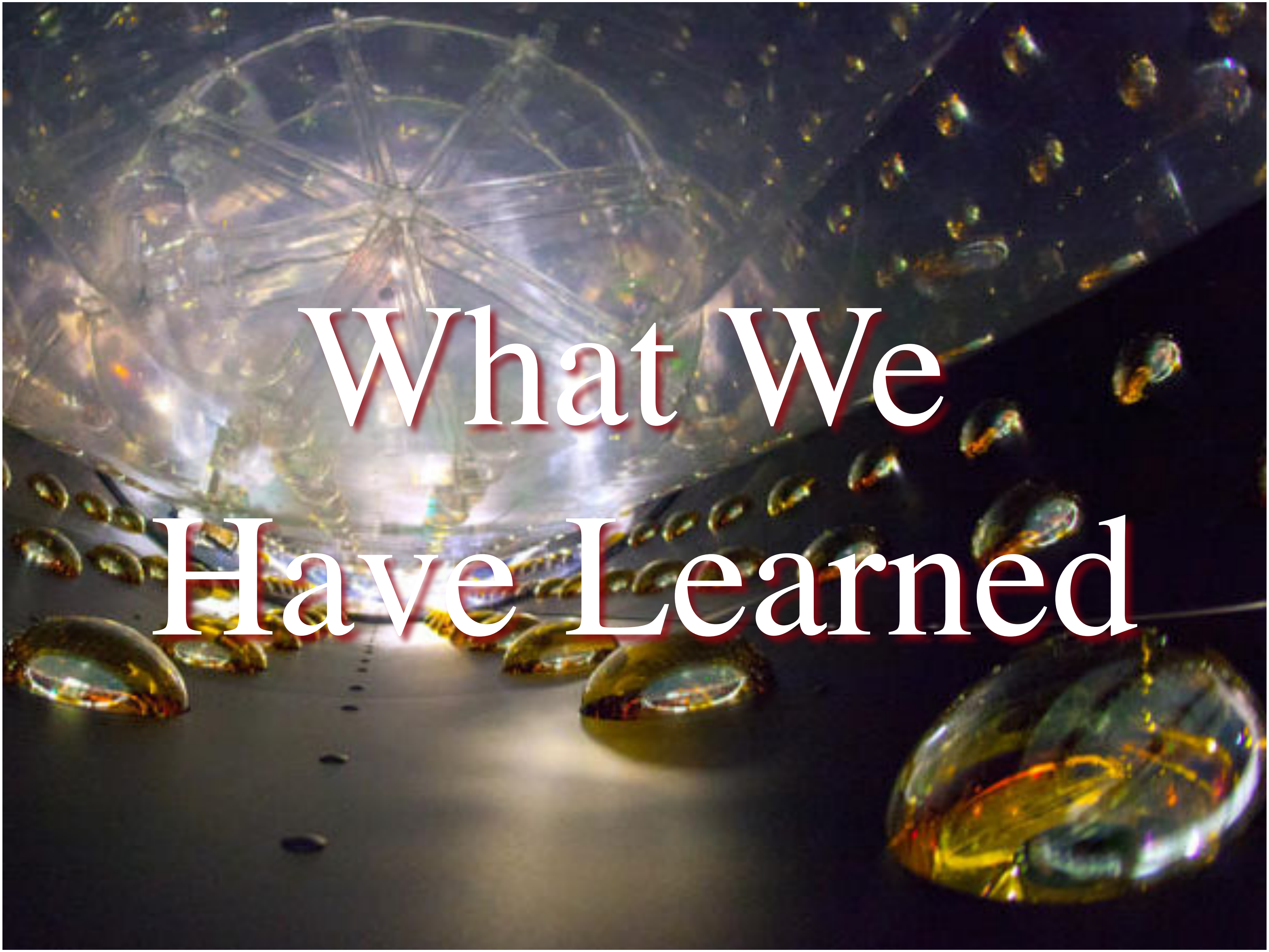
The discovery and study of the ***Higgs boson*** at
CERN's Large Hadron Collider has provided strong
evidence that the ***quarks*** and ***charged leptons*** derive
their masses from an interaction with the ***Higgs field***.

Most theorists strongly suspect that the origin of the neutrino masses is different from the origin of the quark and charged lepton masses.

The Standard-Model ***Higgs field*** is probably still involved,
but there is probably something more —
something way outside the Standard Model —

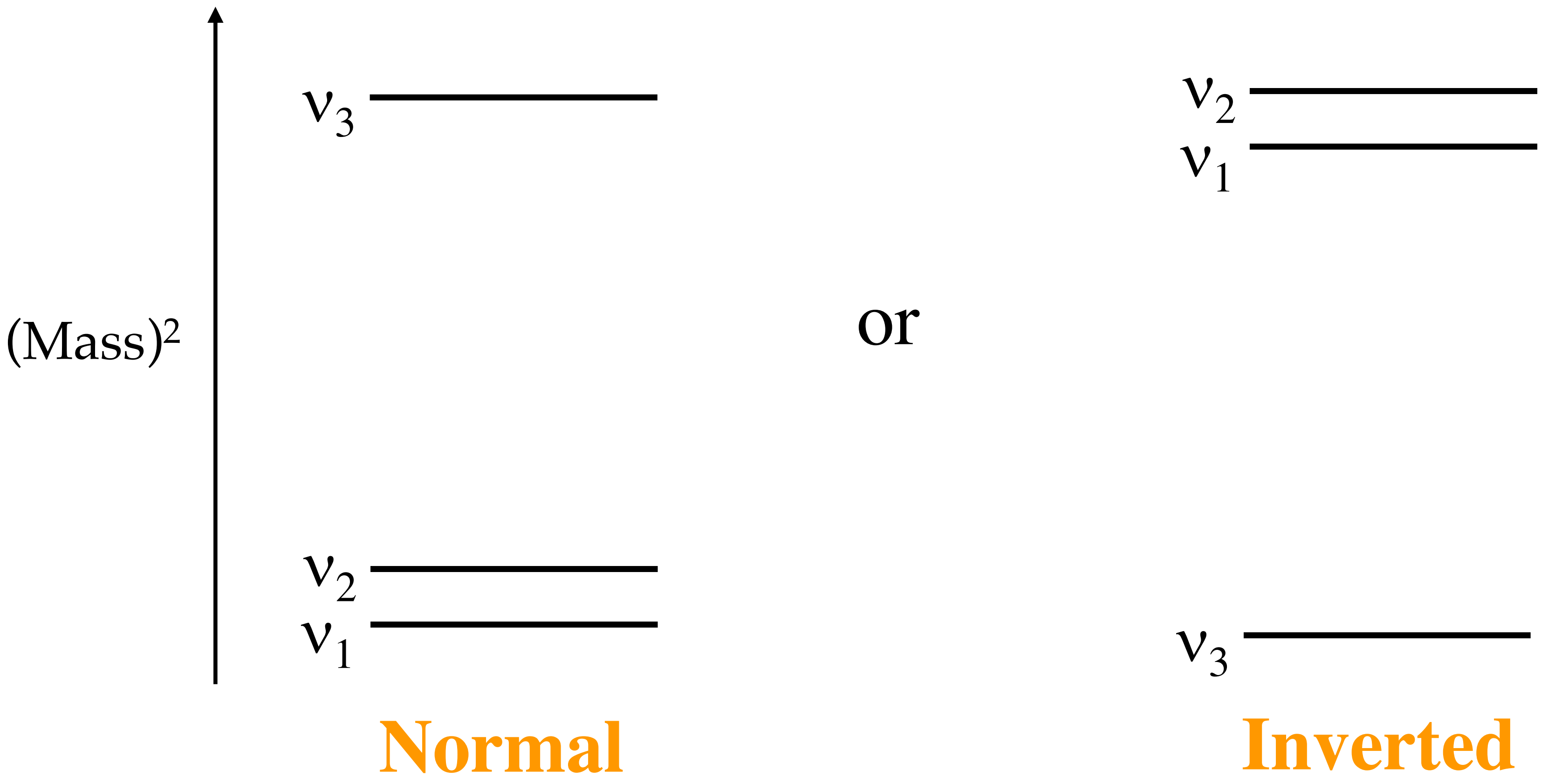
Majorana masses.

More later ……..



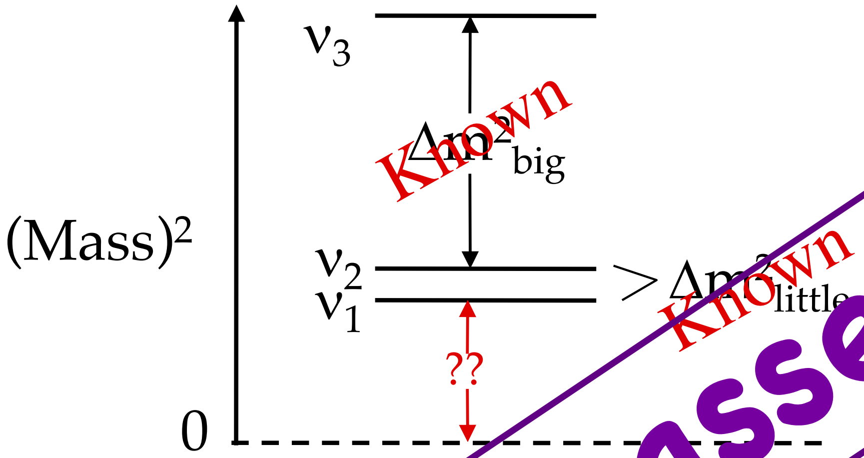
What We Have Learned

The Three – Neutrino (Mass)^2 Spectrum



$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \text{ x } 10^{-5} \text{ eV}^2 , \quad \Delta m^2_{32} \cong 33\, \Delta m^2_{21}$$

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Neutrino masses are tiny

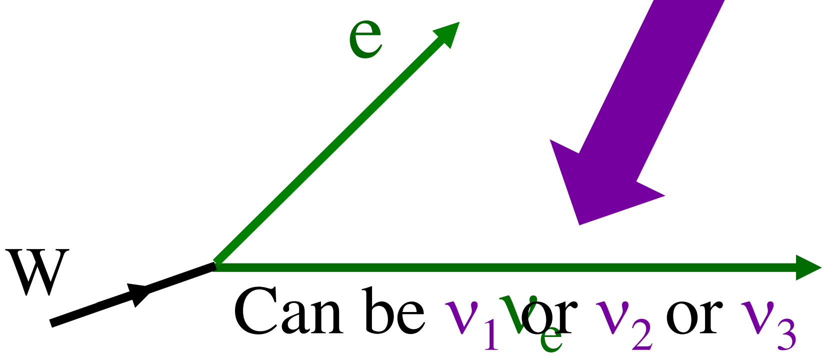
Cosmology, *under certain assumptions* → $\sum m(\nu_i) < 0.2$ eV
All *i*

Lab. Exp. → $\sqrt{0.69m^2(\nu_1)+0.29m^2(\nu_2)+0.02m^2(\nu_3)} < 2$ eV

Mass[Heaviest ν_i] > $\sqrt{\Delta m^2_{big}}$ > 0.05 eV

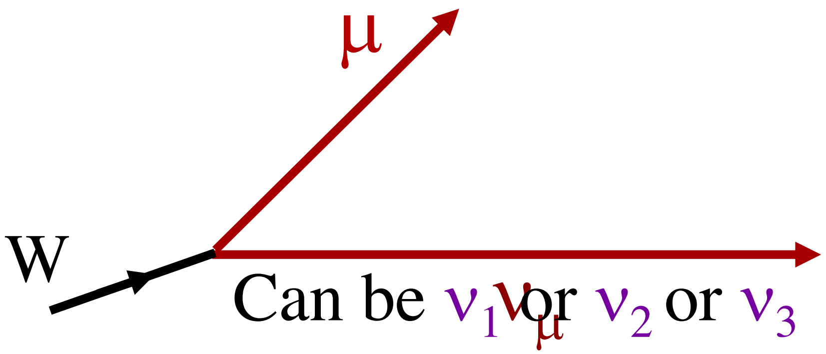
Leptonic Mixing

One way to make leptons is to first make the very heavy W particle, which will quickly decay into either quarks or leptons. The leptonic decays are —



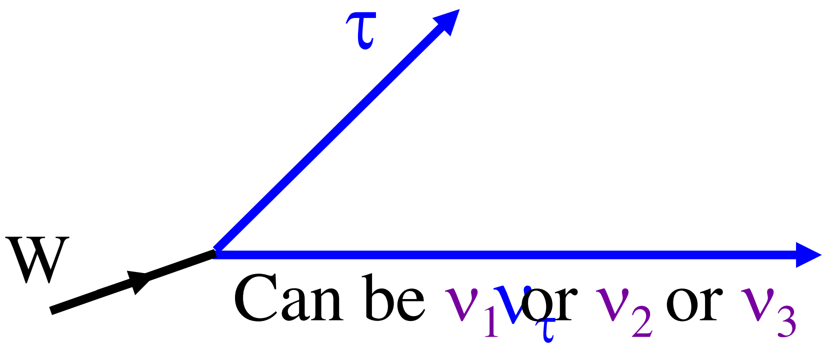
Can be ν_1 or ν_2 or ν_3

ν_e



Can be ν_1 or ν_2 or ν_3

ν_μ



Can be ν_1 or ν_2 or ν_3

ν_τ

The probability for getting any given neutrino in combination with any given charged lepton is known.

Flavor

We speak of e, μ, and τ as the three flavors of charged lepton.

Correspondingly, we speak of ν_e, ν_μ, and ν_τ as the three flavors of neutrino.

Caution: The language can be misleading: e, μ, and τ are particles (mass eigenstates), but ν_e, ν_μ, and ν_τ are not. Each of them is a different ***superposition***, or ***mixture***, of the particles ν_1, ν_2, and ν_3:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

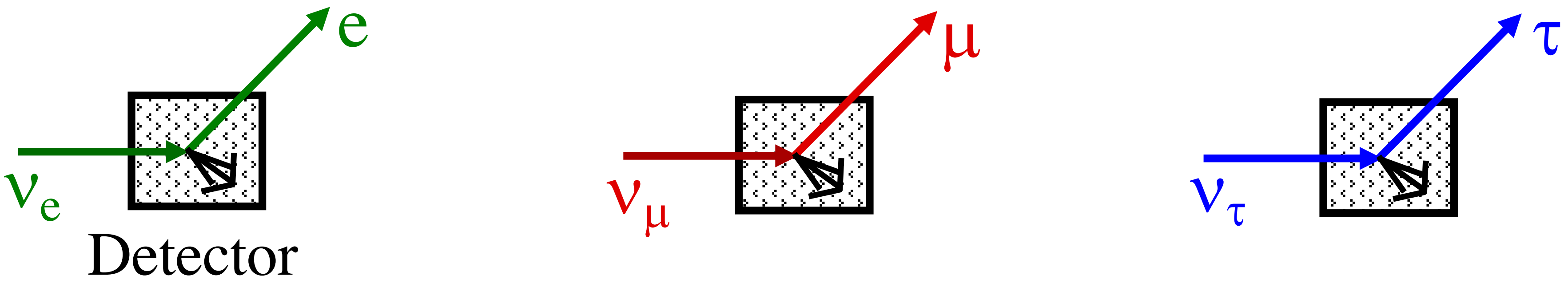
1, 2, or 3

e, μ, or τ

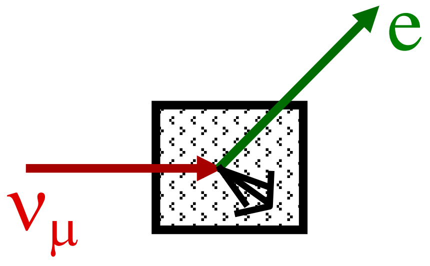
Leptonic Mixing Matrix

When a neutrino does interact in a detector, typically it creates a charged lepton.

As far as we know, if the neutrino is one of definite flavor, that charged lepton will always be of the same flavor as the neutrino.



but not



The Mixing Matrix *U*

$$U = \begin{array}{c|ccc|} & \nu_1 & \nu_2 & \nu_3 \\ \nu_e & U_{e1} & U_{e2} & U_{e3} \\ \nu_\mu & U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ \nu_\tau & U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{array}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$

$$s_{ij} \equiv \sin\theta_{ij}$$

Mixing angles

The phases, if not 0° or 180°, violate CP.

Leptonic CP Violation

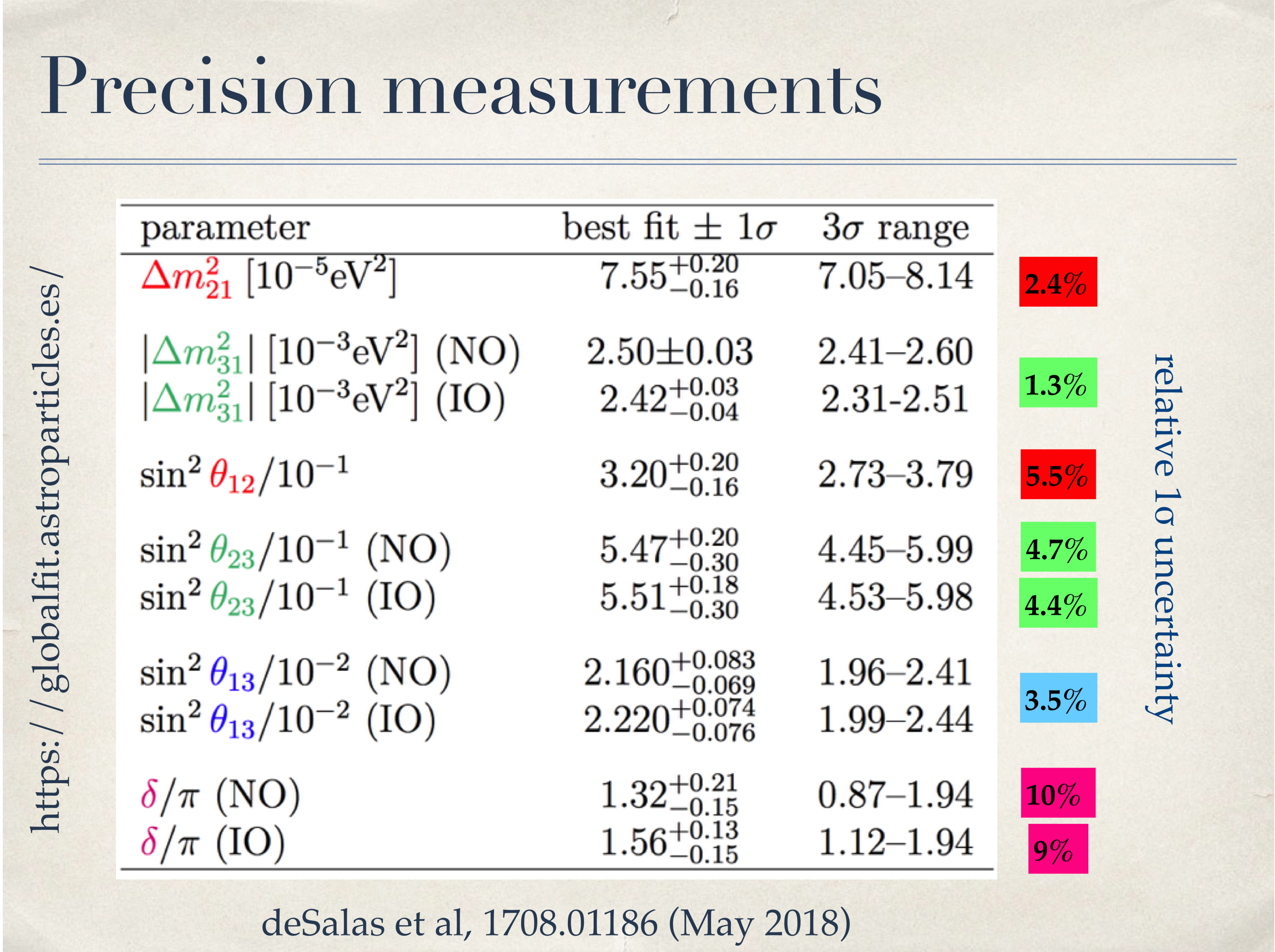
Any particle p has an antiparticle $\bar{p}$. p and $\bar{p}$ have the same mass, opposite electric charge, and opposite values of any other charge-like attribute.

CP[Particle] = Antiparticle

CP violation: Particle and Antiparticle behave differently.

(Matter and Antimatter behave differently.)

So far, CP violation has been seen in the laboratory only among the quarks. *Do the leptons violate CP too?*



Precision measurements

https://globalfit.astroparticles.es/

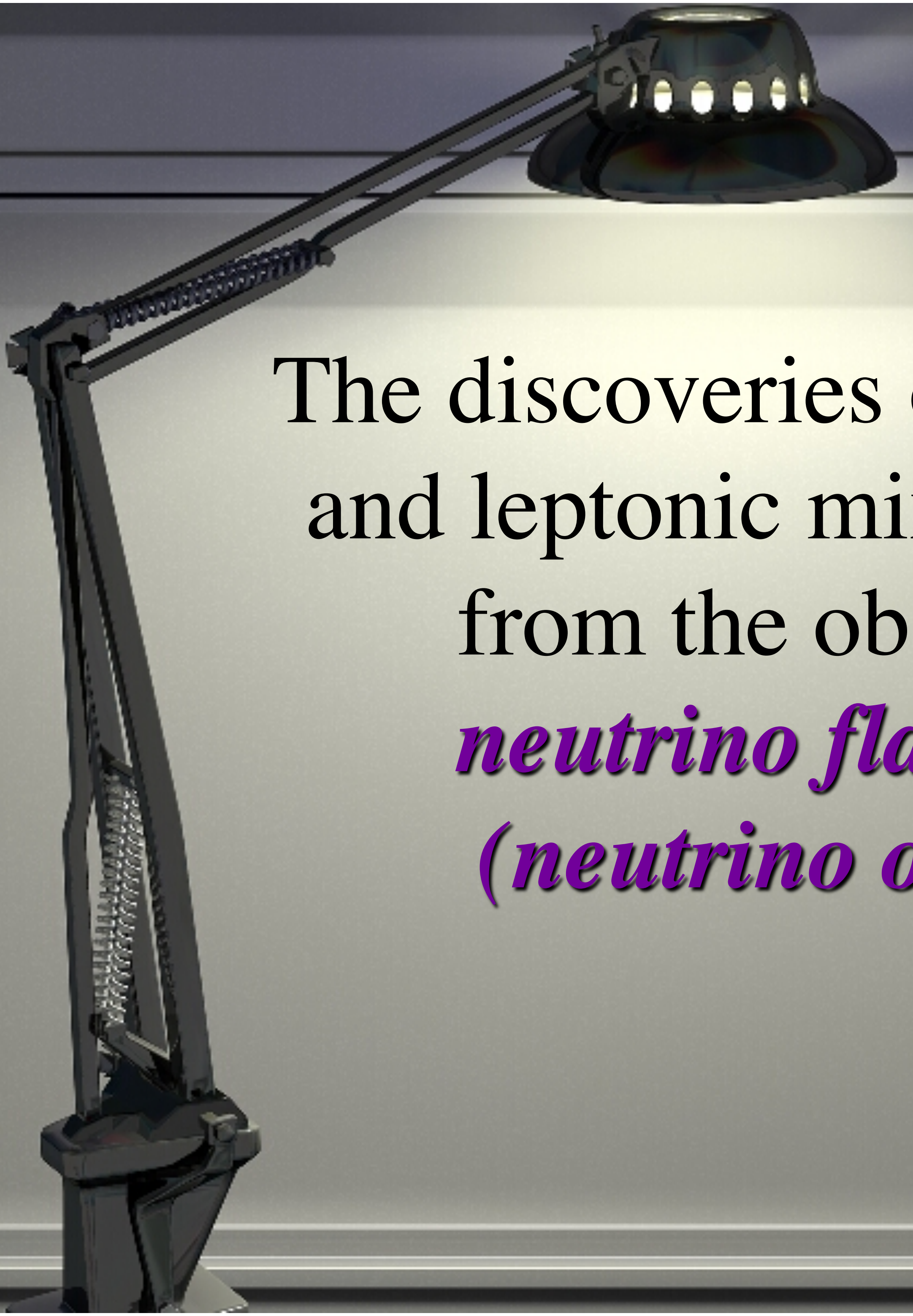
parameter	best fit ± 1σ	3σ range	
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

relative 1σ uncertainty

deSalas et al, 1708.01186 (May 2018)

From M. Tortola, at a neutrino conference last week.

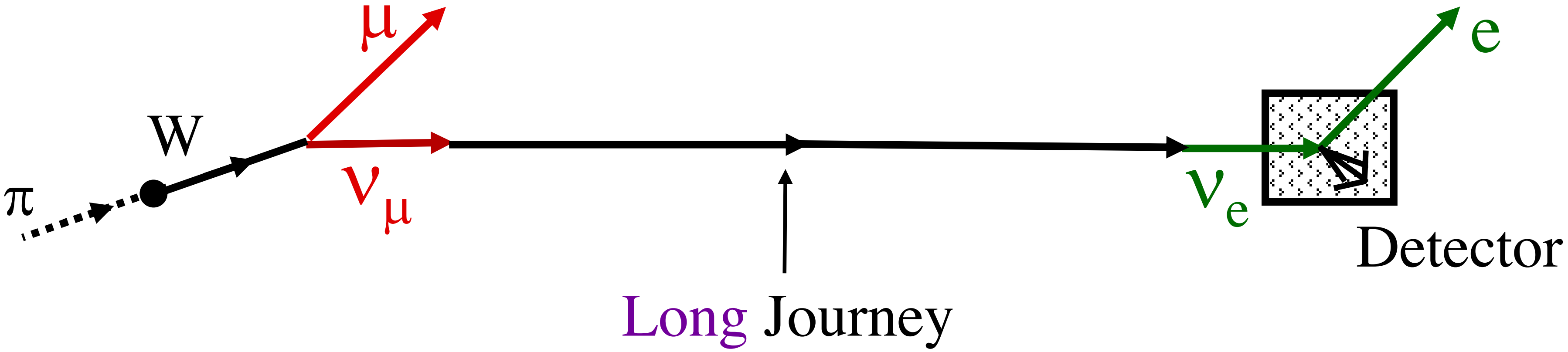
How We Have Learned What We Know



The discoveries of neutrino mass and leptonic mixing have come from the observation of ***neutrino flavor change (neutrino oscillation)***.

What Is Neutrino Flavor Change?

If neutrinos have masses, and leptons mix, we can have —



Give a ν time to change character, and you can have

for example: $\nu_\mu \longrightarrow \nu_e$

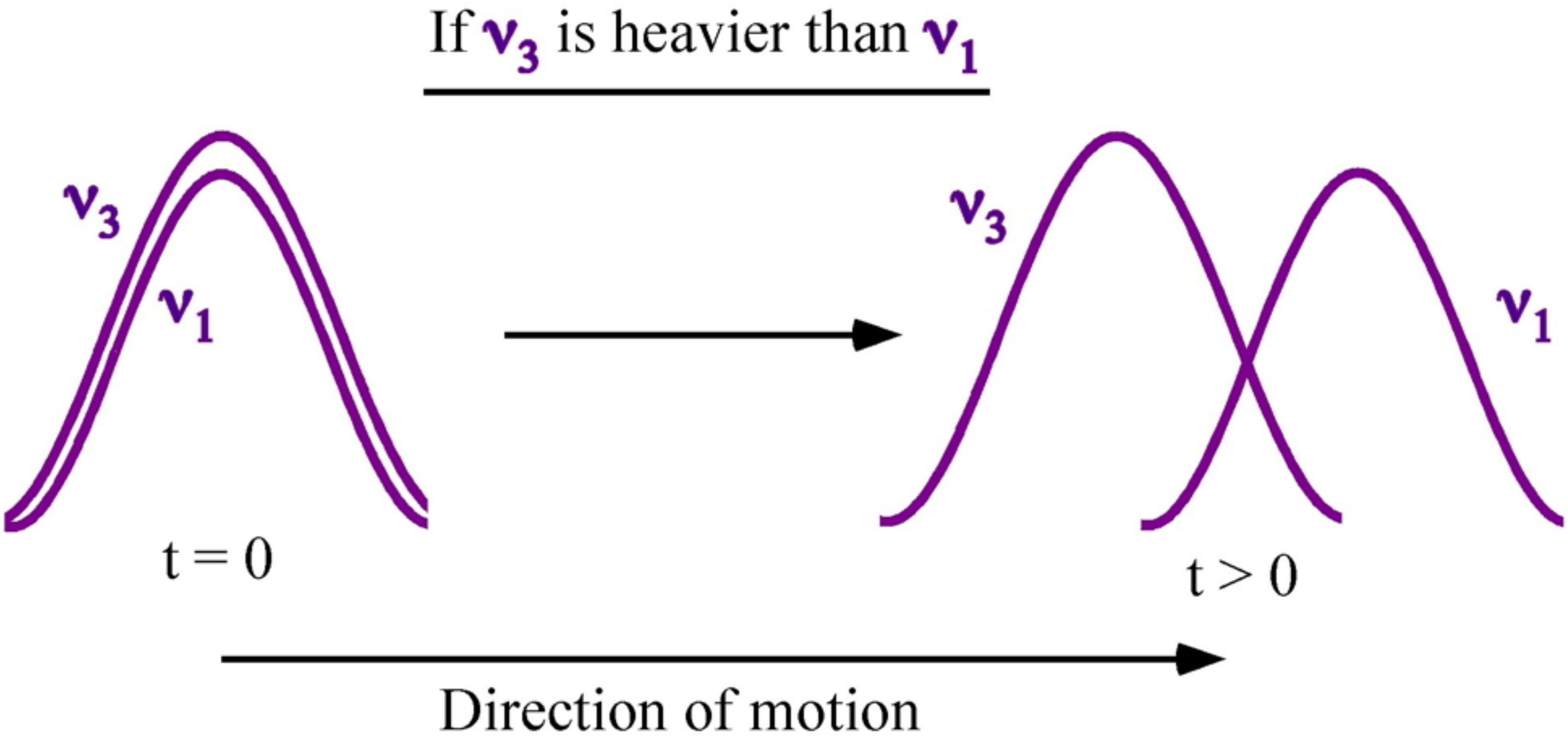
The last 20 years have brought us compelling evidence that such flavor changes actually occur.

How Does Flavor Change Come About?

In quantum mechanics, particles behave like waves.

When $\nu_\mu \longrightarrow \nu_e$, the superposition of ν_1, ν_2, and ν_3 waves that is ν_μ changes into the different superposition of ν_1, ν_2, and ν_3 waves that is ν_e.

The change from one superposition to another occurs because, if ν_1, ν_2, and ν_3 have different masses, then their waves propagate at different speeds at any given energy.



At any one point, the interference between the different waves changes as the waves propagate.

Applying quantum mechanics, we find that, neglecting the mass splitting between ν_2 and ν_1, the probability $P\left[\nu_\mu \to \nu_e\right]$ for $\nu_\mu \to \nu_e$ is given by

$$\boxed{P\left[\nu_\mu \to \nu_e\right] = \sin^2 2\theta \sin^2\left[1.27\Delta m_{32}^2 \left(\frac{(\mathrm{eV})^2}{c^2}\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]}$$

$\theta =$ Mixing angle

$c =$ Speed of light

$L =$ Travel distance

$E =$ Energy

$$1\,\mathrm{GeV} = 10^9\,\mathrm{eV}$$

Note that neutrino flavor change oscillates, and requires neutrino mass and leptonic mixing.

— Not Neglecting Δm^2_{21} —

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\mathrm{Amp}\left(\nu_\alpha \to \nu_\beta\right)\right|^2 =$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

$$+2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\Delta m^2_{ij} \frac{L}{2E}\right)$$

where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$.

Neutrino flavor change implies neutrino mass!

Neutrinos vs. Antineutrinos

(omitting helicity-related details)

$$\left[\bar{\nu}_\alpha \to \bar{\nu}_\beta\right] = \mathrm{CP}\left[\nu_\alpha \to \nu_\beta\right]$$

A difference between the probabilities of these two oscillations in vacuum would be a leptonic violation of CP invariance.

If quantum field theory describes nature, then processes are invariant under CPT.

Reverses the arrow of time ↑

Then $P\left[\bar{\nu}_\alpha \to \bar{\nu}_\beta\right] = P\left[\nu_\beta \to \nu_\alpha\right]$

$$P\left(\overset{(-)}{\nu}_{\alpha}\rightarrow\overset{(-)}{\nu}_{\beta}\right)=$$

$$=\delta_{\alpha\beta}-4\sum_{i>j}\mathrm{Re}\left(U^{*}_{\alpha i}U_{\beta i}U_{\alpha j}U^{*}_{\beta j}\right)\sin^{2}\left(\Delta m^{2}_{ij}\frac{L}{4E}\right)$$

$$\underset{(-)}{+}2\sum_{i>j}\mathrm{Im}\left(U^{*}_{\alpha i}U_{\beta i}U_{\alpha j}U^{*}_{\beta j}\right)\sin\left(\Delta m^{2}_{ij}\frac{L}{2E}\right)$$

In neutrino oscillation, CP non-invariance comes from phases in the leptonic mixing matrix U.

Neutrino Flavor Change In Matter

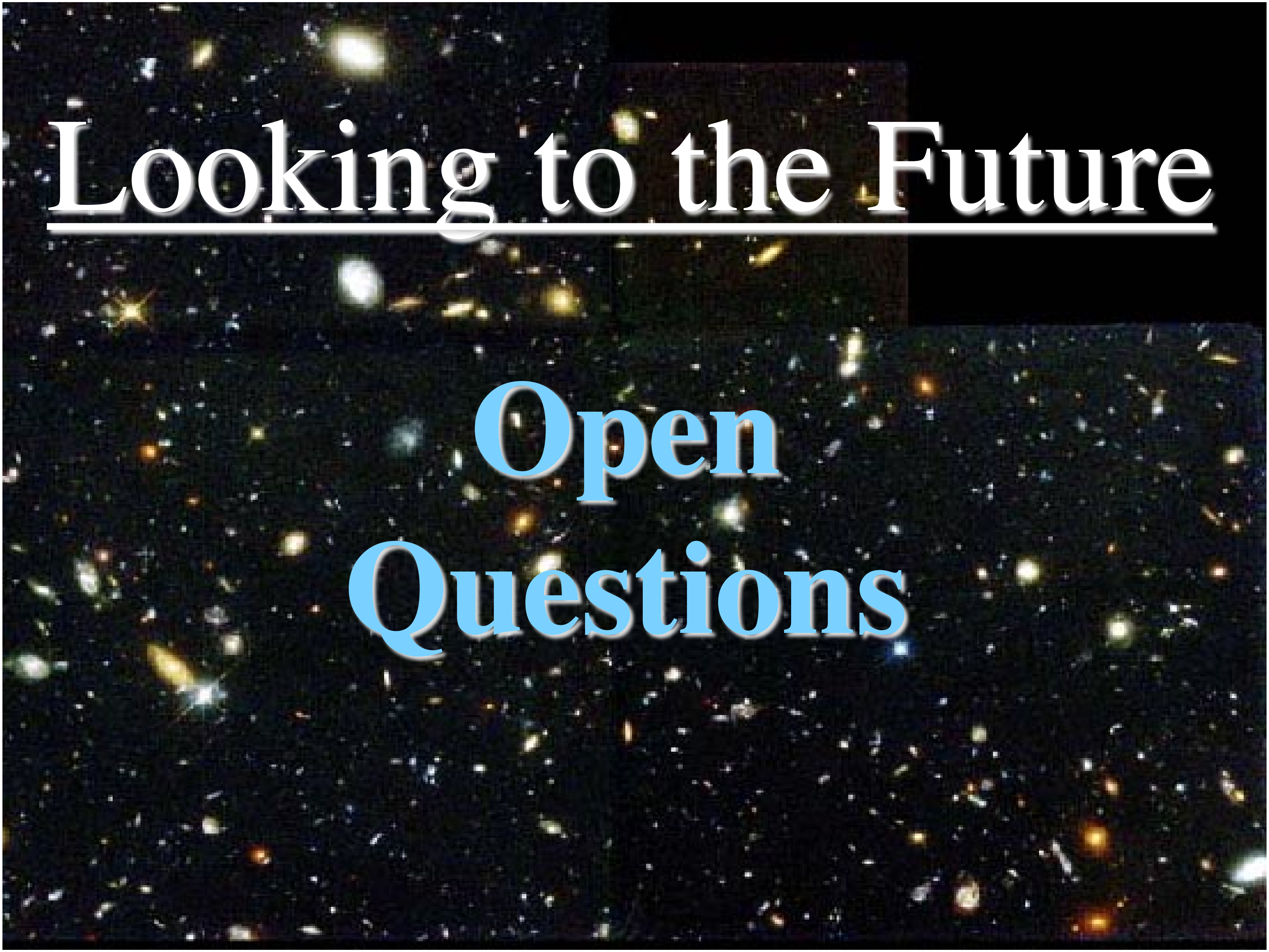
We have been talking about neutrino flavor change in ***vacuum***.

In many experiments, the neutrinos pass through enough ***matter*** that coherent forward scattering from particles in the matter significantly affects the flavor content of the beam.

This has to be taken into account.

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (Long-Baseline)	Compelling
Atmospheric	Compelling
Accelerator (Long-Baseline)	Compelling
Accelerator, Reactor, and Radioactive Sources (Short-Baseline)	“Interesting”



Looking to the Future

Open Questions

- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?
- Are neutrinos their own antiparticles?

- What is the absolute scale of neutrino mass?

- Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

Is $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$?

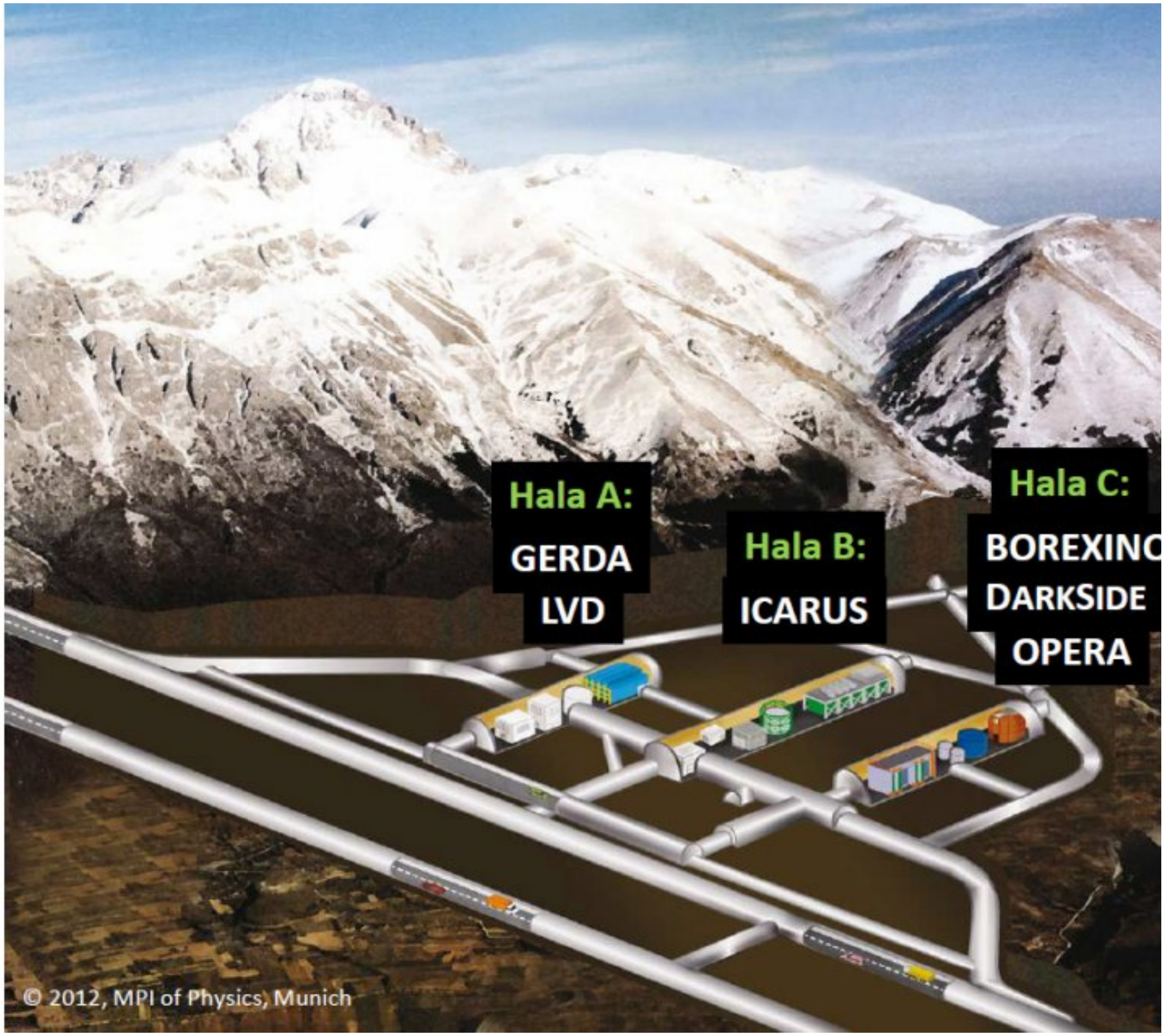
- Is CP violation involving neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- Are we descended from heavy neutrinos?

- What can neutrinos and the universe tell us about one another?

- Are there ***more*** than 3 mass eigenstates?
  - Are there “sterile” neutrinos that don’t feel any known force except gravity?

- Do neutrinos feel forces we don’t know about?

- Do neutrinos break the rules?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?



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Is the Origin of Neutrino Mass Different?

Do neutrinos have *Majorana masses*?

Majorana masses do not conserve any charge-like attribute of a particle. Thus, the ***quarks*** and ***charged leptons***, which carry electric charge, cannot have Majorana masses.

But the ***neutrinos*** — alone among the constituents of matter — are ***electrically neutral***.

Thus, perhaps ***neutrinos*** do have Majorana masses.

But wait: Maybe neutrinos carry some conserved ***non-electric*** charge-like attribute.

Perhaps there is in nature a conserved charge-like
Lepton Number *L* that distinguishes
between leptons and antileptons.

L would be defined by —

$$L\Big(\overset{e^-,\ \mu^-\text{, or }\tau^-}{\ell^-}\Big) = L\big(\underset{\nu_1,\ \nu_2\text{, or }\nu_3}{\nu}\big) = -L\Big(\overset{e^+,\ \mu^+\text{, or }\tau^+}{\ell^+}\Big) = -L\big(\underset{\overline{\nu}_1,\ \overline{\nu}_2\text{, or }\overline{\nu}_3}{\overline{\nu}}\big) = 1$$

If neutrinos have Majorana masses,
then L is not conserved.

Then there is nothing to distinguish an antineutrino from a neutrino. They are the same particle!

To See If *L* Is Not Conserved— Seek Neutrinoless Double Beta Decay [0νββ]

L(final) – L(initial) = 2 ≠ 0

It can be shown that if this process is observed, then neutrinos not only can, but *do*, have Majorana masses.

A number of searches for 0νββ are in progress
or being planned throughout the world.
They too must be underground.

Do Neutrino Interactions Violate CP?

Are We Descended From Heavy Neutrinos?

NASA Hubble Photo

A Cosmic Challenge: The Matter-Antimatter Asymmetry

Cosmologists: Just after the Big Bang, the universe contained equal amounts of ***matter*** and ***antimatter***.

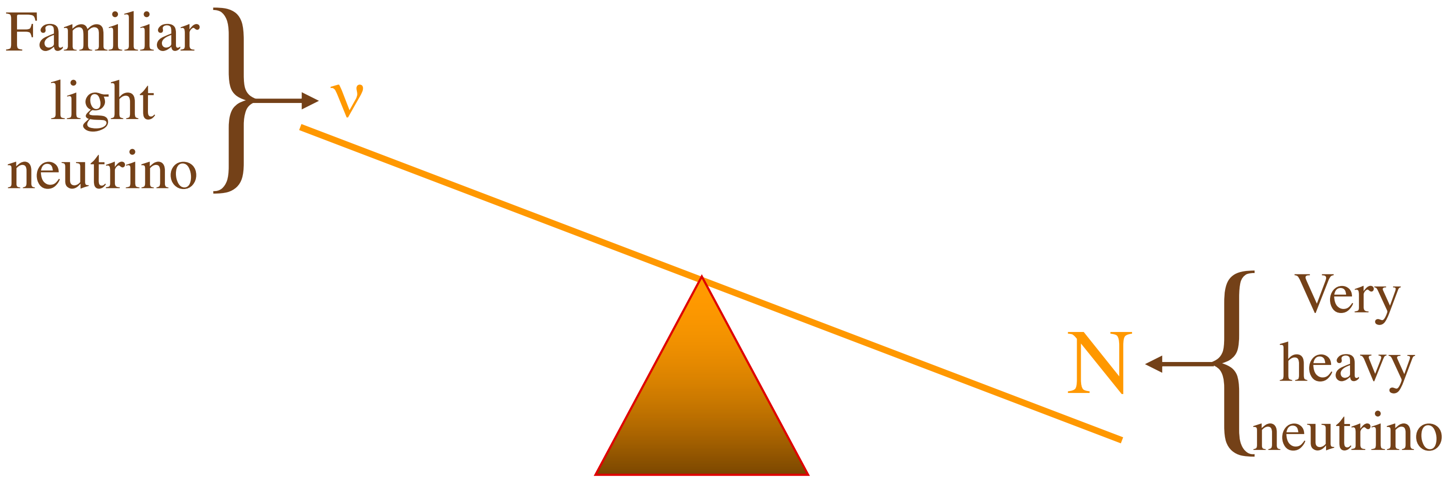
Today: The universe contains ***matter (atoms)*** but essentially no ***antimatter (anti-atoms)***.

This change requires that ***matter*** and ***antimatter*** behave differently (CP violation).

The only CP violation we've seen, among quarks, cannot explain the universe.

But *Leptogenesis*, a scenario based on CP violation among *leptons*, *can* explain it.

Leptogenesis is a natural consequence of the ***See-Saw*** theory of why neutrino masses are so small.



$$M_\nu \propto 1/M_N$$

Conditions right after the Big Bang were right to make a large number of the heavy neutrinos N.

N Decay

The See-Saw predicts that $\overline{N} = N$.

An N is neither a **Lepton** nor an **Antilepton**, and can decay into either an e^- or an e^+.

If **Leptons** and **Antileptons** interact differently with N (CP violation), then in the early universe —

$$\text{Probability}\,[\,N \to \underset{\uparrow \atop \textbf{Lepton}}{e^-} + \ldots\,] \neq \text{Probability}\,[\,N \to \underset{\uparrow \atop \textbf{Antilepton}}{e^+} + \ldots\,]$$

This phenomenon would have led to a universe containing ***unequal numbers*** of **Leptons** and **Antileptons** .

The tremendously successful *Standard Model* of physics predicts that a universe with unequal numbers of **Leptons** and **Antileptons** would then evolve into one with unequal numbers of **atoms** and **Anti-atoms**.

If we started with more **Antileptons** than **Leptons**, today the universe would contain almost no **Anti-atoms**.

And this is what we see!

If N decays led to the present preponderance of ATOMS over ANTI-ATOMS, then we are all descendants of Heavy Neutrinos.

The key ingredients of Leptogenesis are —

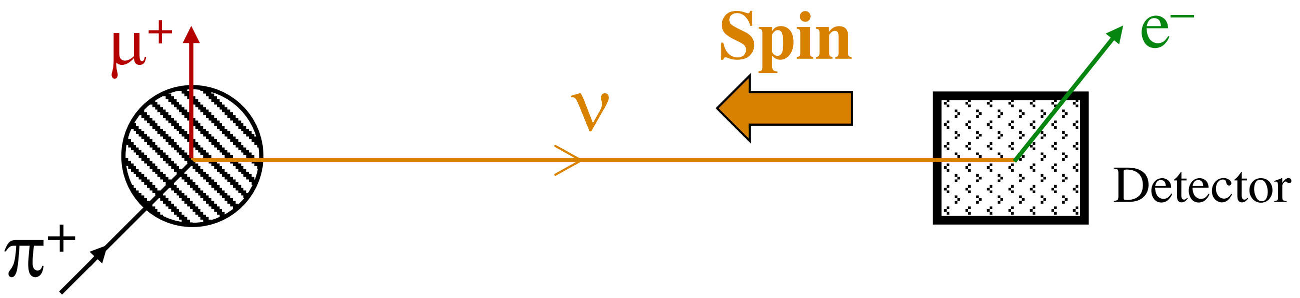
CP violation among the leptons

Confirm via observation of
CP violation in neutrino oscillation.

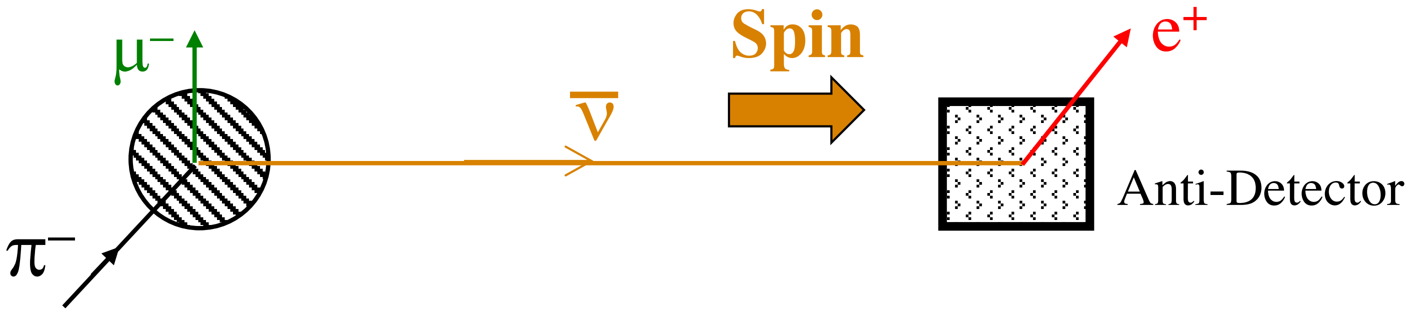
Non-conservation of Lepton Number L

Confirm via observation of
neutrinoless double beta decay.

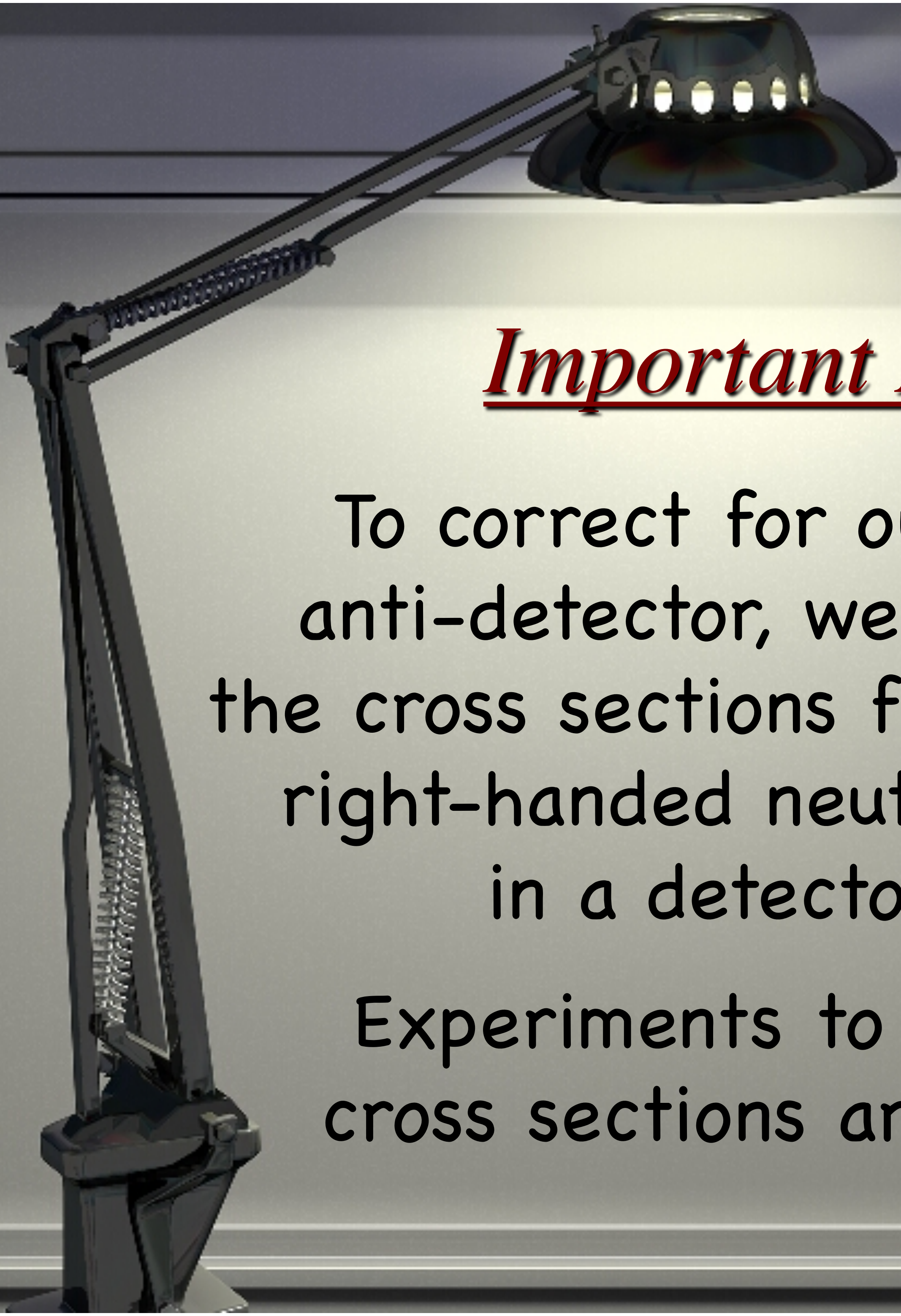
To confirm leptonic CP violation, compare two CP-mirror-image neutrino oscillations.



vs.



Do these two CP-mirror-image processes have different rates?

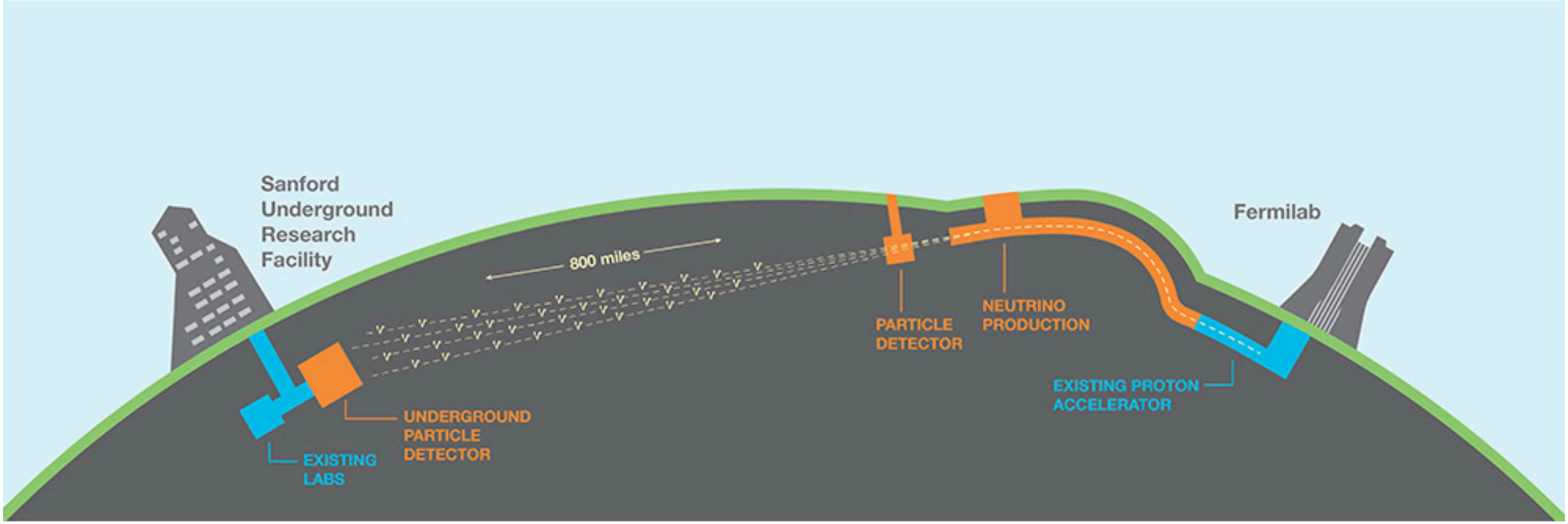


Important Notice

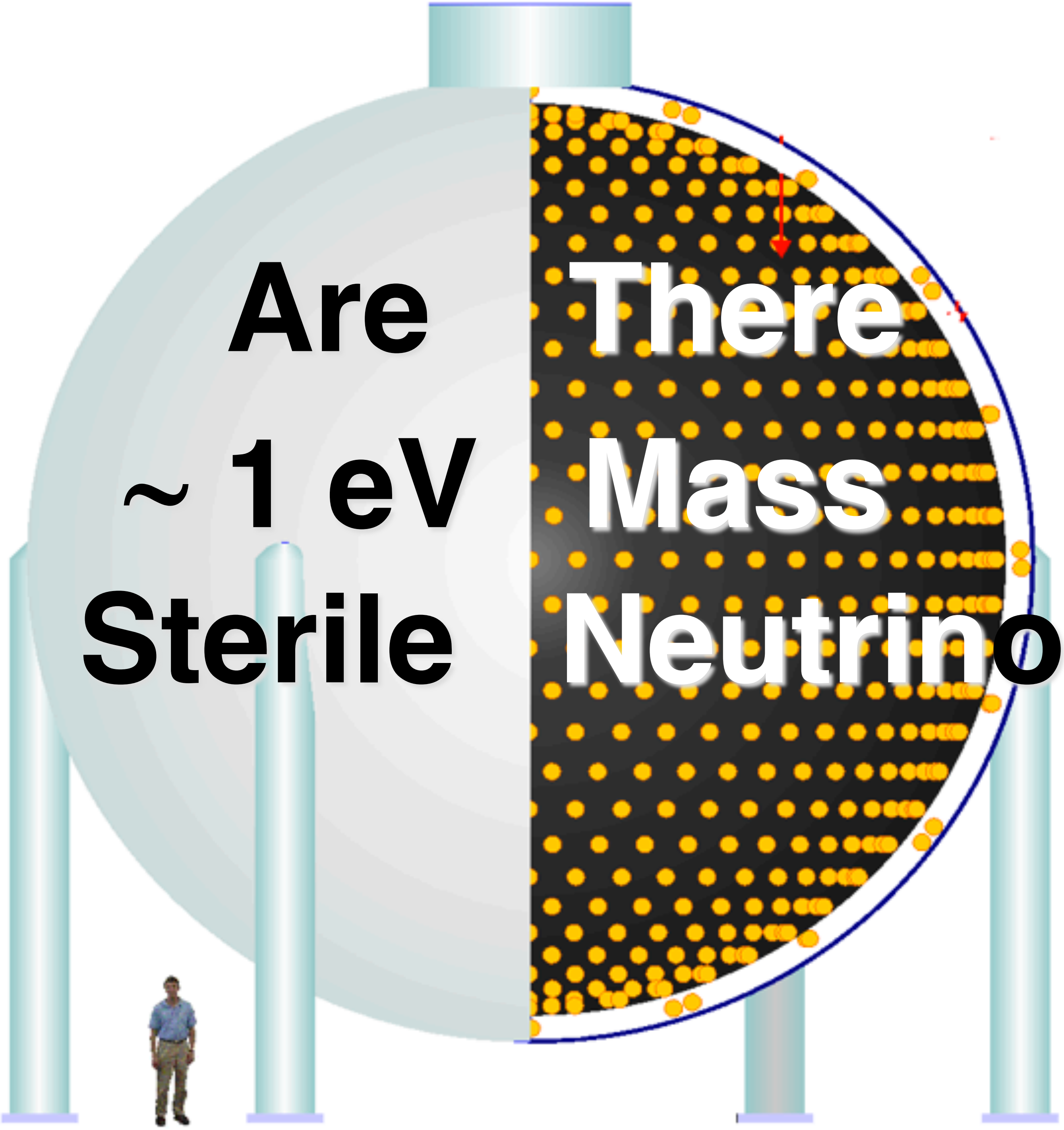
To correct for our not using an anti-detector, we must know how the cross sections for left-handed and right-handed neutrinos to interact in a detector compare.

Experiments to determine these cross sections are very important.

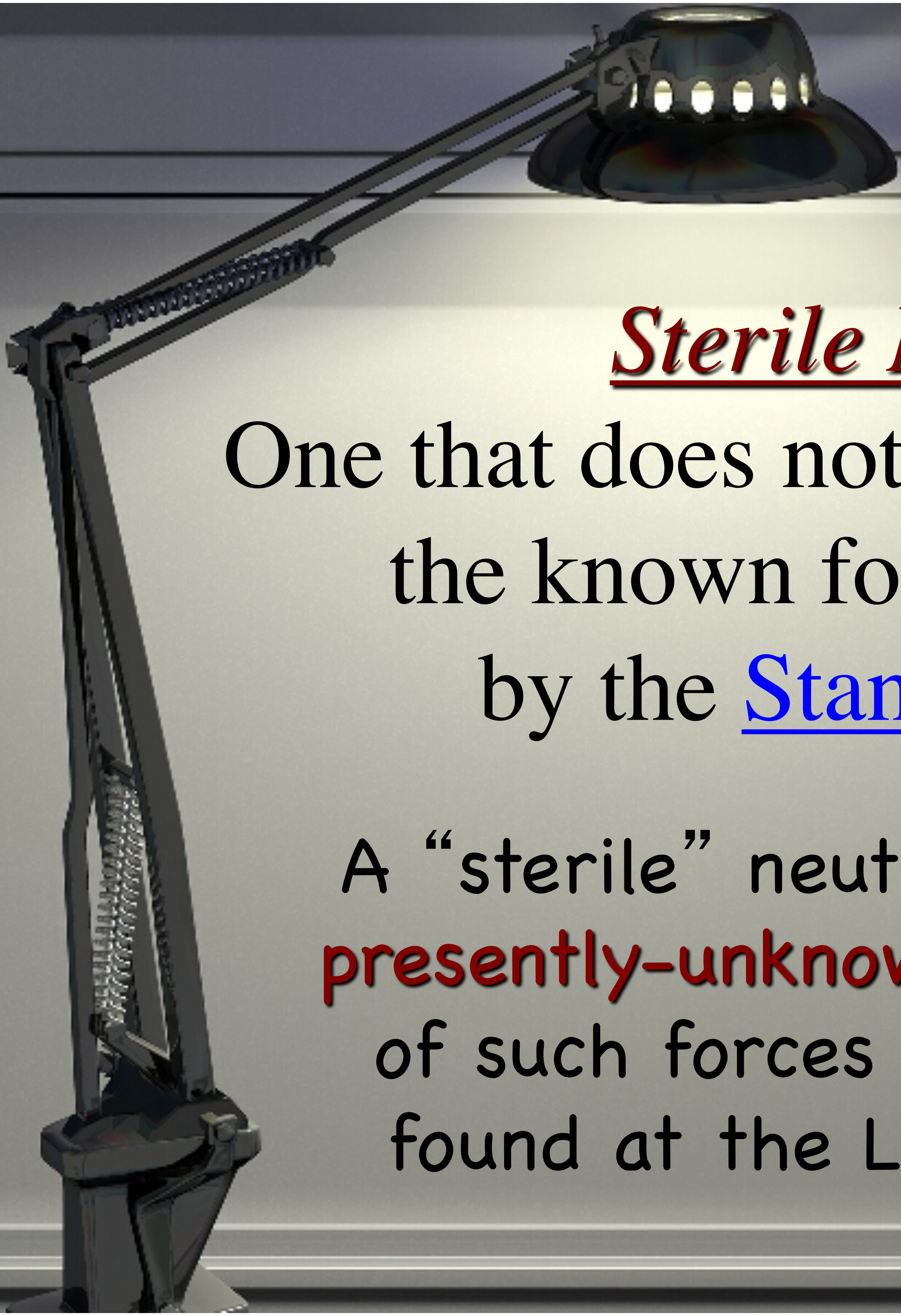
The Deep Underground Neutrino Experiment (DUNE)



Seeing this violation of CP invariance is a major goal of DUNE.



Are ~ 1 eV Sterile There Mass Neutrinos?



Sterile Neutrino

One that does not experience any of the known forces described by the Standard Model

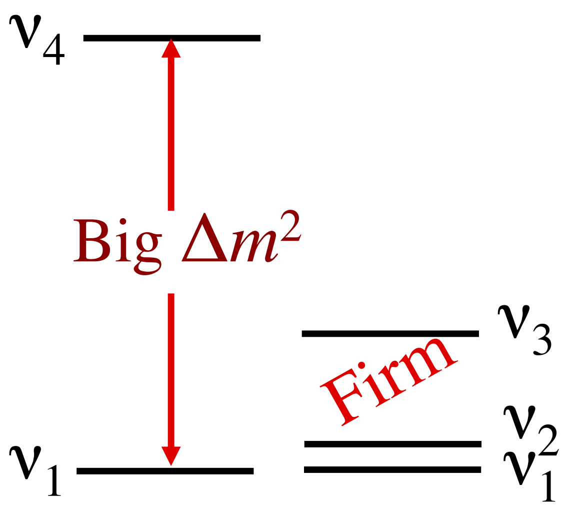
A "sterile" neutrino may well feel **presently-unknown** forces. Evidence of such forces could perhaps be found at the LHC or elsewhere.

The Hints of Sterile Neutrinos

The probability of an oscillation driven by a mass-squared splitting Δm^2 is —

$$P\left[\nu_\mu \rightarrow \nu_e\right] = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(\left(\frac{\text{eV}}{c^2}\right)^2\right)\frac{L(\text{km})}{E(\text{GeV})}\right]$$

There are several hints of ***rapid*** oscillations with $L(\text{km})/E(\text{GeV}) \sim 1$, implying a Δm^2 more than 10 times bigger than the two established splittings.



If the big Δm^2 is real, there must be at least ***4*** neutrinos.

An experimental result from CERN implies that only
3 neutrinos experience the “weak force”
of the Standard Model.

Thus, if there are ***4*** neutrinos, one of them is sterile.
(More precisely, largely sterile.)

Interesting experiments to determine
whether the sterile neutrinos are real
are in progress or planned.

There is strong tension between the evidence for rapid $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, and the limits on rapid $\nu_\mu \rightarrow \nu_{\cancel{\mu}}$ and $\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}}$.

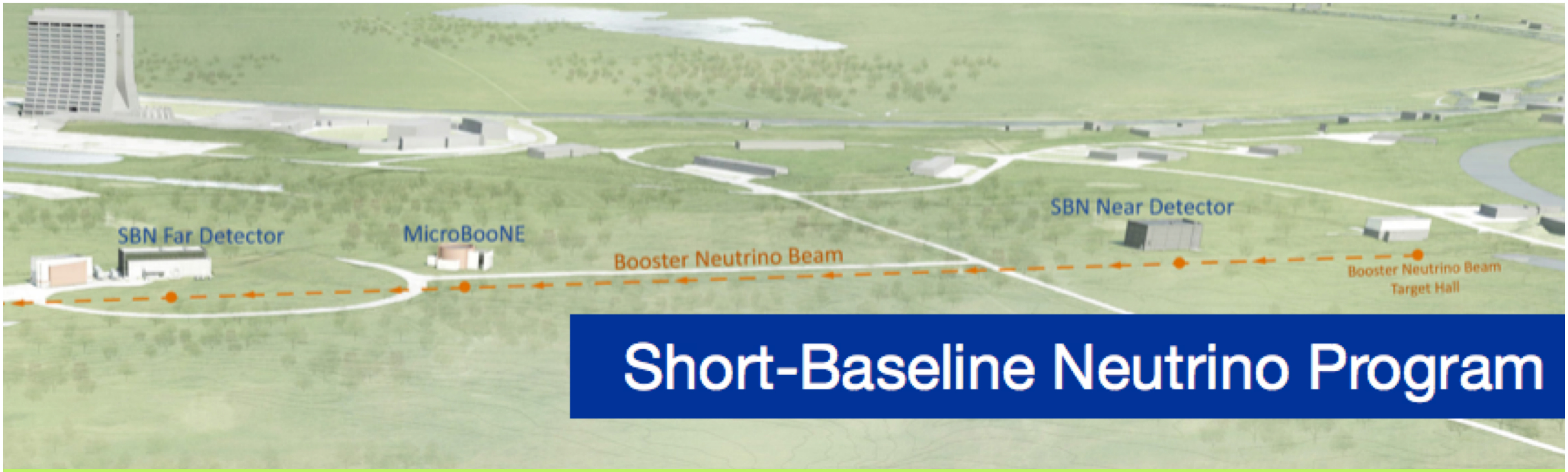
(Dentler et al.)

A very recent paper shows interesting consistency between the positive indications of ***something*** going on ***(a sterile neutrino???)*** in the MiniBooNE and LSND experiments.

(Aguilar-Arevalo et al.)

Last week's Neutrino 2018 conference left the existence of sterile neutrinos an open question.

Hopefully, the Fermilab Short-Baseline Neutrino (SBN) Program will help to answer the question.



Summary

Neutrinos are a major component of our universe.

The discovery that neutrinos have nonzero masses has raised very interesting questions.

Probing these questions is the goal of a major international experimental program, with Fermilab playing a leading role.