Neutrinos Get Under Your Skin

Inside each person:

> $10^7$ neutrinos from the Big Bang

~$10^{14}$ solar neutrinos zip through every second.
Neutrinos are Abundant

We humans, and all everyday objects, are made of electrons, protons, and neutrons.

But in the universe as a whole —

$\sim 10^9$ neutrinos for each electron, proton, or neutron.

Neutrinos and photons are the most abundant particles in the universe.

If we wish to understand the universe, we must understand neutrinos.
The Growing Excitement of Neutrino Physics

1930
- Pauli Predicts the Neutrino

1955
- Fermi's theory of weak interactions
- Reines & Cowan discover (anti)neutrinos

1980
- 2 distinct flavors identified
- Davis discovers the solar deficit
- Kamioka II confirms solar deficit
- LEP shows 3 active flavors

2005
- K2K confirms atmospheric oscillations
- KamLAND confirms solar oscillations
- Nobel Prize for neutrino astroparticle physics!
- SNO shows solar oscillation to active flavor
- Super K confirms solar deficit and "images" sun
- Super K sees evidence of atmospheric neutrino oscillations
- Nobel Prize for $\bar{\nu}$ discovery!
- LSND sees possible indication of oscillation signal
- Nobel prize for discovery of distinct flavors!
- Kamioka II and IMB see supernova neutrinos
- Kamioka II and IMB see atmospheric neutrino anomaly
- SAGE and Gallex see the solar deficit
What Have We Learned?
## The Leptons and their Flavors

<table>
<thead>
<tr>
<th>Charged Lepton</th>
<th>Mass</th>
<th>Associated Neutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron (e)</td>
<td>1</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>Muon ((\mu))</td>
<td>200</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>Tau ((\tau))</td>
<td>3500</td>
<td>$\nu_\tau$</td>
</tr>
</tbody>
</table>

What does “associated” mean?
A neutrino is created together with a charged lepton.

When a neutrino interacts with a detector, it creates a charged lepton.

The neutrino and charged lepton flavors match:

**Short journey**

Source: $\nu$ → $\nu$, $e$ → $e$

Detector: $\nu$ → $\nu$, $e$ → $e$

or —

Source: $\nu$ → $\nu$, $\mu$ → $\mu$

Detector: $\nu$ → $\nu$, $\mu$ → $\mu$

**Same flavor**
Neutrino Flavor Change

In the core of the sun —

Solar neutrinos are all born as $\nu_e$, not $\nu_\mu$ or $\nu_\tau$. 
In the Creighton nickel mine, 6800 feet below Sudbury, Canada, is the **Sudbury Neutrino Observatory (SNO)**.
The **SNO** detector.

The central sphere is 40 feet across, and is filled with heavy water.
SNO detects solar neutrinos in several different ways.

One way counts ———

Number ($\nu_e$).

Another counts ———

Number ($\nu_e$) + Number ($\nu_\mu$) + Number ($\nu_\tau$).

SNO finds ———

$$\frac{\text{Number (}\nu_e\text{)}}{\text{Number (}\nu_e\text{) + Number (}\nu_\mu\text{) + Number (}\nu_\tau\text{)}} = \frac{1}{3}.$$
All the solar neutrinos are born as $\nu_e$.  

But 2/3 of them morph into $\nu_\mu$ or $\nu_\tau$ before they reach earth. 

**Given time, neutrinos can change flavor.**

Once a proton, always a proton (until death).  

But once a $\nu_e$, **not** always a $\nu_e$.  

<table>
<thead>
<tr>
<th>Neutrinos</th>
<th>Evidence of Flavor Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Compelling</td>
</tr>
<tr>
<td>Reactor</td>
<td>Very Strong</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>Compelling</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Strong</td>
</tr>
</tbody>
</table>

Almost all of these flavor changes are predicted to have an oscillatory character.
Neutrino Oscillation

\[ \nu_\mu \]
Neutrino Mass

Neutrinos have long been known to be very much lighter than the other known particles.

Are neutrinos —

— **Massless** bundles of pure energy, like photons?

or

— **Particles with Masses**, like the quarks?

Neutrino flavor change with time

⇒ Neutrinos have nonzero **Masses**.
Change of neutrino flavor *with time*

⇒ A ν has a sense of time.

Einstein ⇒ Only a particle with mass can have a sense of time.

Therefore, neutrinos have nonzero masses.
The Neutrino Spectrum

There are at least 3 neutrinos of definite mass. They are called $\nu_1$, $\nu_2$, and $\nu_3$, and account for all observed flavor changes except the one reported by the Liquid Scintillator Neutrino Detector (LSND).

The spectrum could be

$\frac{(\text{mass})^2}{(\text{electron mass})^2}$

$\nu_1$ $\nu_2$ $\nu_3$

$10^{-14}$ $3 \times 10^{-16}$

The Atmospheric Gap

The Solar Gap

The spectrum could be

instead of

$\frac{(\text{mass})^2}{(\text{electron mass})^2}$
Neutrino Mixing

A $\nu_\mu$ can morph into a $\nu_\tau$ because neither is a particle.

The neutrino particles – the objects with definite masses – are $\nu_1$, $\nu_2$, and $\nu_3$.

$\nu_e$, $\nu_\mu$, and $\nu_\tau$ are different mixtures of $\nu_1$, $\nu_2$, and $\nu_3$.

This is called neutrino mixing.

During travel, the $\nu_\mu$ mixture can evolve into the $\nu_\tau$ mixture.
In —

the charged lepton can be an $e$, $\mu$, or $\tau$.

Similarly for an incoming $\nu_2$ or $\nu_3$. 
The Spectrum, Showing the Flavor Probabilities

\[ (\text{mass})^2 \]

\( \nu_1 \)
\( \nu_2 \)
\( \nu_3 \)

- **Yellow** - Probability of yielding an \( e \)
- **Blue** - \( \mu \)
- **Red** - \( \tau \)
The Liquid Scintillator Neutrino Detector (LSND) Oscillation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Quarks</td>
<td>u</td>
<td>c</td>
<td>t</td>
<td>3</td>
</tr>
<tr>
<td>Negative Quarks</td>
<td>d</td>
<td>s</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td>Charged Leptons</td>
<td>e</td>
<td>μ</td>
<td>τ</td>
<td>3</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>ν₁</td>
<td>ν₂</td>
<td>ν₃</td>
<td>?</td>
</tr>
</tbody>
</table>

If LSND is confirmed, there are at least 4 neutrinos, ν₁, ν₂, ν₃, and ν₄, breaking the symmetry.

One mixture of these 4 neutrinos, a sterile neutrino, doesn’t experience any of the known forces except gravity.
The Open Questions
The discovery of neutrino mass and mixing

Open questions about neutrinos and their connections to other physics

Need for a coherent strategy for getting answers
A year-long study of the future of neutrino physics, sponsored by the American Physical Society Divisions of –

- Nuclear Physics
- Particles and Fields
- Astrophysics
- Physics of Beams
The APS Multi-Divisional Neutrino Study

- Over 200 Participants
- Seven Working Groups
- Organizing Committee (Four members from abroad): Janet Conrad, Guido Drexlin, Belen Gavela, Takaaki Kajita, Paul Langacker, Keith Olive, Bob Palmer, Georg Raffelt, Hamish Robertson, Stan Wojcicki, Lincoln Wolfenstein
- Co-Chairpersons: Stuart Freedman, Boris Kayser
Neutrinos and the New Paradigm

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate matter–antimatter symmetry?
Neutrinos and the Unexpected

• Are there “sterile” neutrinos?
• Do neutrinos have unexpected or exotic properties?
• What can neutrinos tell us about the models of new physics beyond the Standard Model?
Neutrinos and the Cosmos

• What is the role of neutrinos in shaping the universe?
• Are neutrinos behind the matter – antimatter asymmetry of the universe?
• What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?
Some Highlights

★ What are the masses of the neutrinos?

\[ \nu_1 \quad \nu_2 \quad \nu_3 \]

What is
The grand unified theories (GUTS) that unify the strong nuclear, electromagnetic, and weak forces favor –

GUTS relate the Leptons to the Quarks.

ν behavior in earth matter can distinguish.

is un-quark-like.
The Distance from Zero

A Cosmic Connection

Cosmological Data + Cosmological Assumptions ⇒

If there are only 3 neutrinos in the spectrum, the Mass of each of them is less than —

\[
\text{Mass of an electron} \div 2,500,000.
\]

Can cosmology turn this into a number??
Are neutrinos their own antiparticles?

\[ e^+ \neq e^- \text{ since } \text{Charge}(e^+) = -\text{Charge}(e^-). \]

Similarly for the quarks.

But neutrinos have no electric charge.

Do they carry a conserved “Leptonic Charge L” that distinguishes leptons from antileptons?

\[ L(\nu) = L(e^-) = +1 \]

but

\[ L(\bar{\nu}) = L(e^+) = -1 \]

Widespread theoretical prejudice: NO.
No conserved $L \quad \Rightarrow \quad \bar{\nu} = \nu$

To confirm there is no conserved $L$, seek —

**Neutrinoless Double Beta Decay**

Nucleus $\rightarrow$ New Nucleus + $e^- + e^-$

Observation would establish that —

• Neutrinos are their own antiparticles.

• The origin of neutrino mass involves physics different from that which gives masses to electrons, quarks, protons, neutrons, humans, the earth, and galaxies.

Then neutrinos and their masses are **very** distinctive.
The Quest for the Origin of Mass

Neutrino experiments and the search for the Higgs boson both probe the origin of mass.

Theoretical arguments suggest that the physics behind neutrino mass resides at the extremely high energy where Grand Unified Theories say all the forces of nature, save gravity, become one.
Are neutrinos behind the matter–antimatter asymmetry of the universe?

The universe contains **Matter**, but essentially no **antimatter**. Good thing for us: Matter and antimatter annihilate each other.

This preponderance of **Matter** over **antimatter** could not have developed unless the two behave differently.

The observed difference between **Quark** and **antiquark** behavior, as described by the Standard Model, is inadequate.

Could the interactions of **Matter** and **antimatter** with neutrinos provide the crucial difference?
There is a natural way in which they could.

The most popular theory of why neutrinos are so light is the —

**See-Saw Mechanism**

The heavy neutrinos \( N \) would have been made in the hot Big Bang.
If **MATTER** and antimatter interact differently with these heavy neutrinos $N$, then we can have —

\[
\text{Probability } [ \ N \rightarrow e^- + \ldots \ ] \neq \text{Probability } [ \ N \rightarrow e^+ + \ldots \ ]
\]

\[\uparrow\]

MATTER

antimatter

in the early universe.

This phenomenon would have led to a universe containing unequal amounts of **MATTER** and antimatter.
We cannot repeat the early universe.

But, if **Matter** and **antimatter** interact differently with today’s light neutrinos $\nu$, then quite likely

\[
\text{Probability } [ \, N \rightarrow e^- + \ldots \, ] \neq \text{Probability } [ \, N \rightarrow e^+ + \ldots \, ]
\]

Confirm that **Matter** and **antimatter** do interact differently with the light neutrinos.

Such a difference is referred to as **CP violation among neutrinos**.
Principal Recommendations of the APS Multi-Divisional Neutrino Study

We recommend, as a high priority, that a phased program of increasingly sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.
We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.
The ease of finding CP violation and settling both depend on the size of \( \nu_3 \) vs. \( \nu_2 \) vs. \( \nu_1 \).

- Small part of \( \nu_3 \): Know only upper bound
- \( (\text{mass})^2 \): Probability of yielding an e, \( \mu \), \( \tau \)
Components of The Program

- An expeditiously deployed reactor experiment twenty times more sensitive to the small part of $\nu_3$ than previous experiments.

- A timely accelerator experiment with comparable sensitivity to the small part of $\nu_3$, and with sensitivity to the character of the mass spectrum.

- A proton accelerator delivering approximately ten times as many neutrinos as current ones, and an appropriately large neutrino detector giving substantial sensitivity to CP violation.
We recommend the development of a solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.

Main Report and Working Group Reports are at —

www.aps.org/neutrino.
Conclusion

We have a very rich opportunity to do exciting physics.

Neutrino physics has connections to —

Cosmology, astrophysics, nuclear physics, the origin of mass, the relation between matter and antimatter, the symmetries of nature, physics at energies where the forces of nature become unified, …

With our new-found ability to study neutrinos, they will be an important part of our quest for understanding of the physical world.