The Neutrino World:
Present and Future

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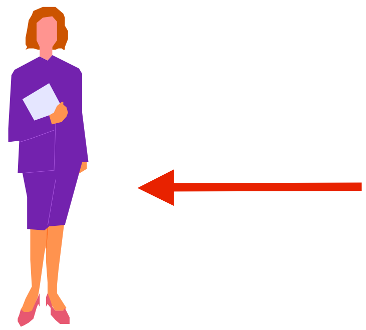
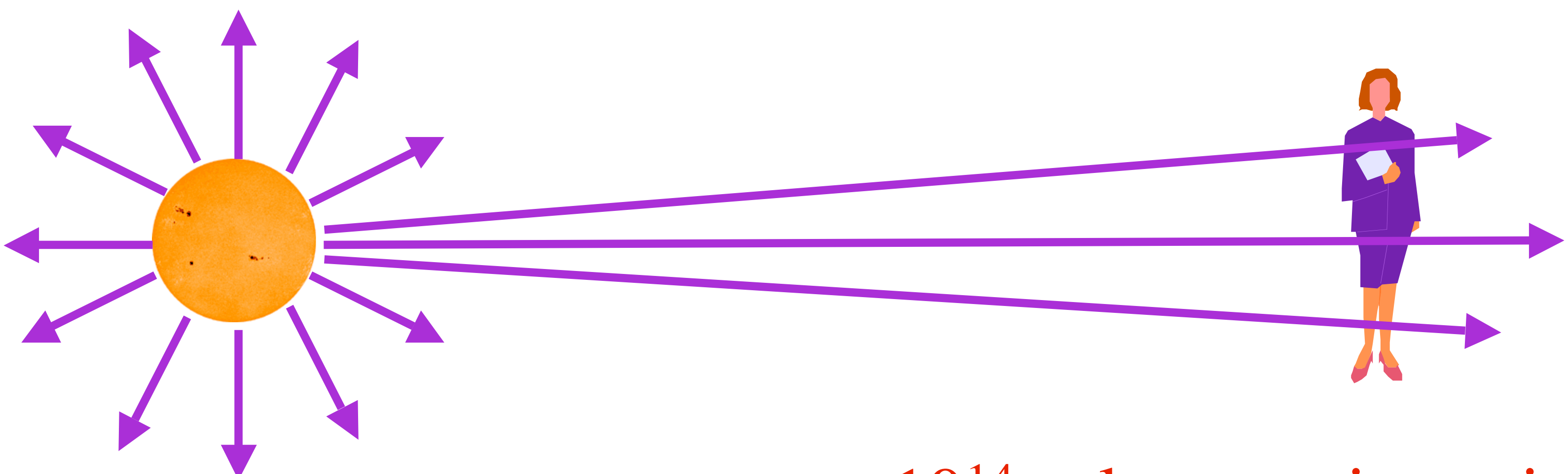
APS
May 2, 2004

Neutrinos Are Under Our Skin



Inside each person:

$> 10^7$ neutrinos from the Big Bang



$\sim 10^{14}$ solar neutrinos zip through every second.

Neutrinos are Abundant

In the universe —

$\sim 10^9$ neutrinos for each nucleon or electron

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

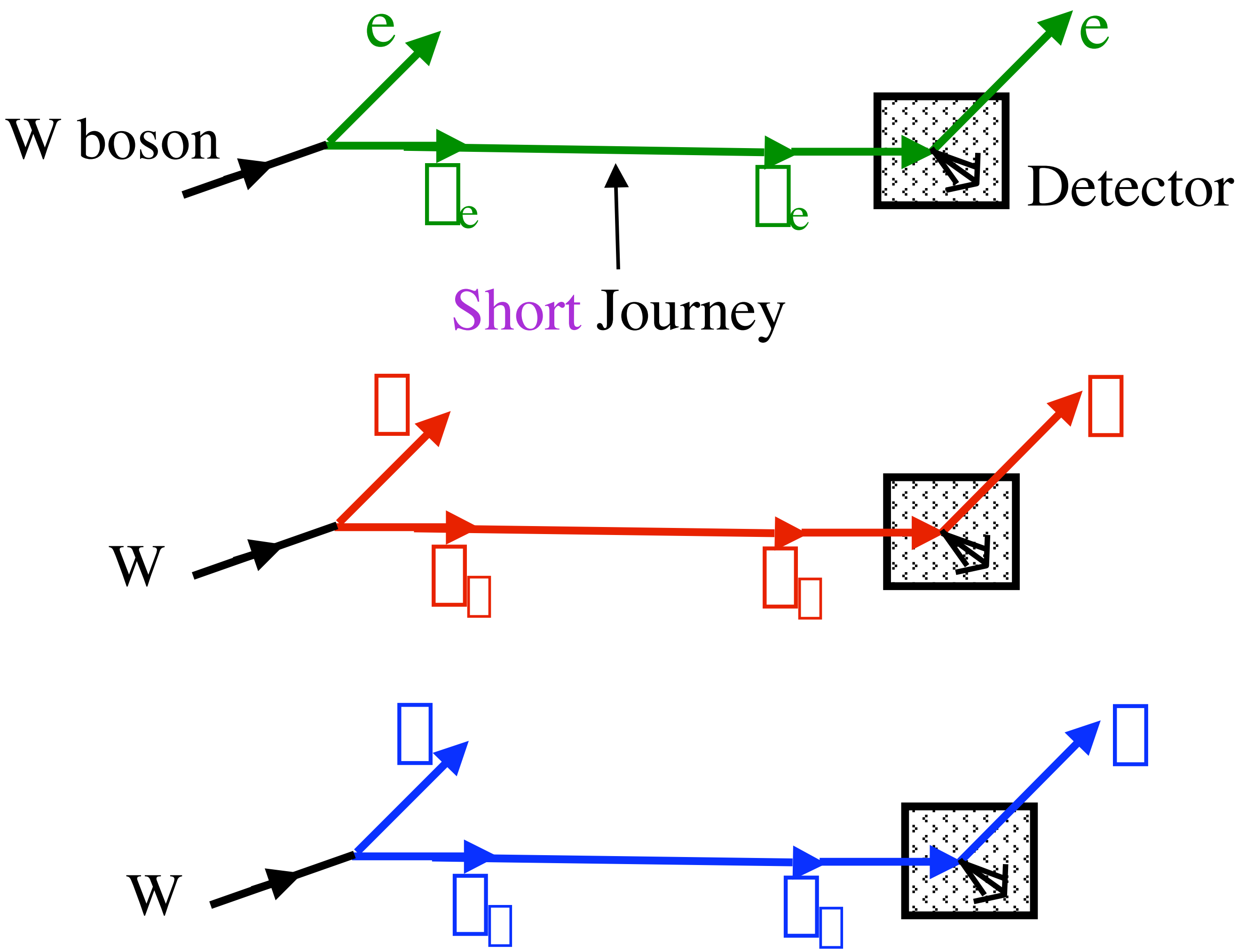
If we wish to understand the universe, we must understand neutrinos.

Neutrinos Come in at Least Three Flavors

The known neutrino flavors: ν_e , ν_μ , ν_τ

Each of these is associated with the corresponding charged-lepton flavor: e , μ , τ

The Meaning of this Association



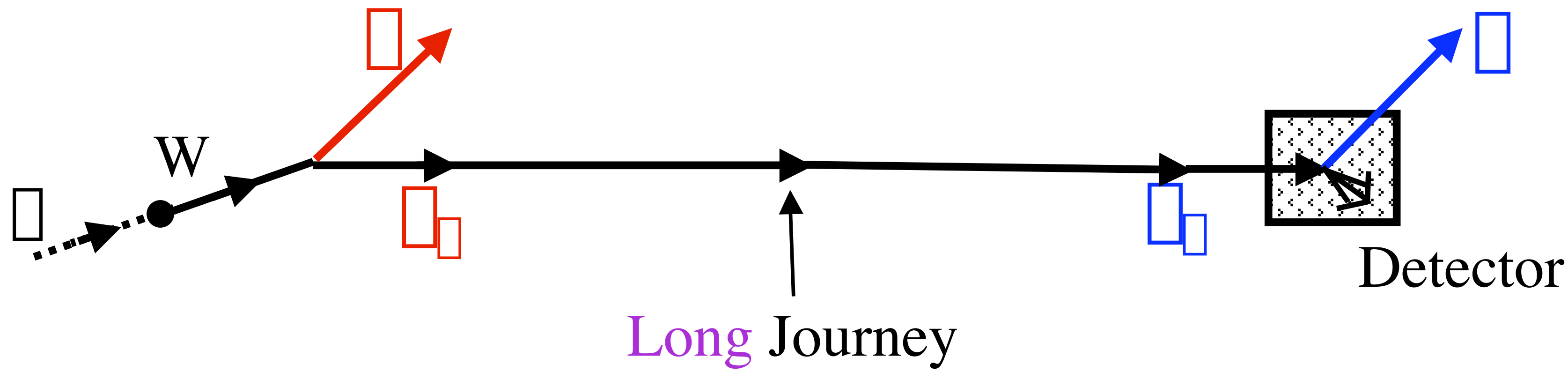
Do Neutrinos Have Mass?

Neutrino mass would lead to very interesting physics.

But neutrino masses, if nonzero, are extremely small.

How do you look for tiny neutrino masses?

Look for —



Give □ time to change character

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

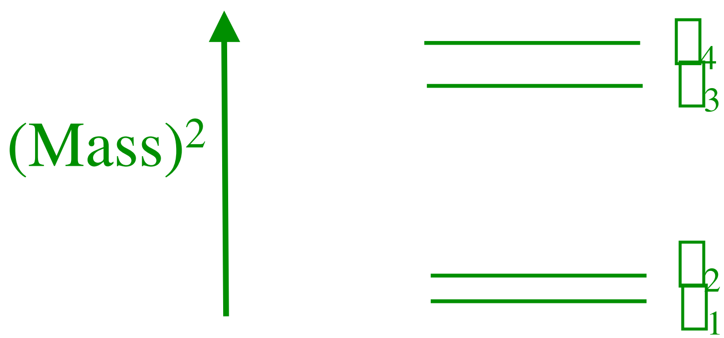
Neutrino Masses and Mixing

As we shall see —

Flavor Change □ Neutrino Mass and Mixing

Neutrino mass —

There is some spectrum of 3 or more neutrino mass eigenstates $□_i$:



Mass ($□_i$) ≡ m_i

Neutrino mixing —

$\ell_e \equiv e,\ \ell_\mu \equiv \mu,\ \ell_\tau \equiv \tau$

When $W^+ \rightarrow \ell_\alpha^+ + \nu_\alpha$,

α = e, μ, or τ

the produced neutrino state $|\nu_\alpha\rangle$ is

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \ .$$

Neutrino of flavor α ($|\nu_\alpha\rangle$)

Unitary Leptonic Mixing Matrix (U)

Neutrino of definite mass m_i ($|\nu_i\rangle$)

Flavor-α fraction of ν_i = $|\langle \nu_\alpha|\nu_i\rangle|^2 = |U_{\alpha i}|^2$.

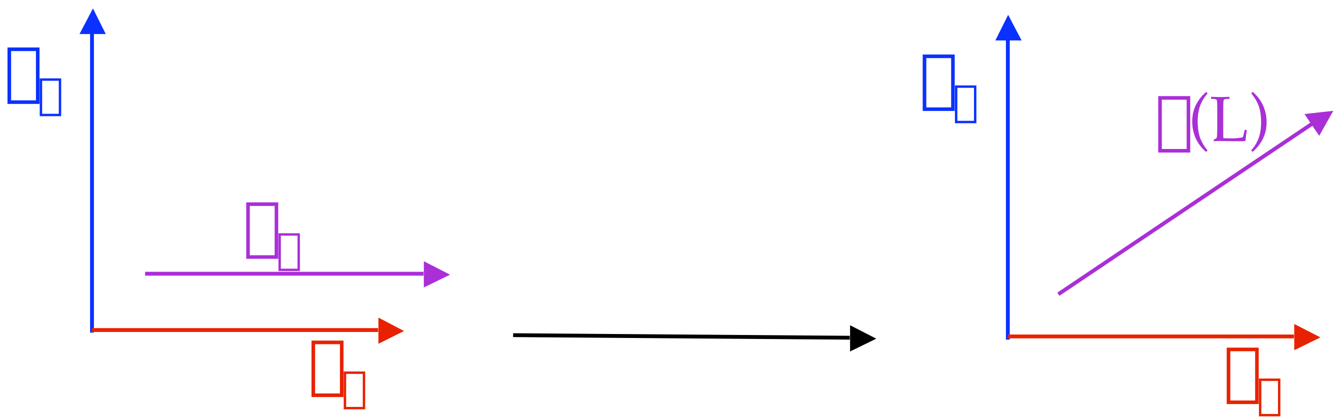
Neutrino Flavor Change ("Oscillation")

Suppose a neutrino is born with flavor α and energy E.

$$\nu_\alpha = \sum_i U^*_{\alpha i}\nu_i \;\longrightarrow_{\text{Distance L}}\; \sum_i U^*_{\alpha i}\nu_i e^{ip_i(E)L/\hbar} \equiv \nu(L) \neq \nu_\alpha$$

$$p_i(E) = \sqrt{E^2 - (m_i c^2)^2}\,/\,c$$

The neutrino has evolved into a mixture of the flavors.



Often, only 2 neutrinos need to be considered.

Then —

Mixing Angle

$$U = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

Then—

$$P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta \, \sin^2\left[1.27\, \Delta m^2(\mathrm{eV}^2)\, \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

Probability

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Neutrino oscillation ⇒ Neutrino mass & mixing

An experiment with given $\frac{L(\mathrm{km})}{E(\mathrm{GeV})}$ will be sensitive to

$$\Delta m^2\ (\mathrm{eV}^2) > \left(\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)^{-1}.$$

Tiny splittings Δm^2 can be probed.

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Very Strong
Atmospheric	Compelling
Accelerator (L = 250 km)	Interesting
Stopped □$^+$ Decay (LSND L □ 30 m)	Unconfirmed

Solar Neutrinos

Nuclear reactions in the core of the sun produce ν_e. Only ν_e.

Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\, p\, p \quad : \quad \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \quad : \quad \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.306 \pm 0.026\ (\text{stat}) \pm 0.024\ (\text{syst})$$

Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos do change flavor.

The now-established mechanism for solar $\nu_e \rightarrow \nu_\mu / \nu_\tau$ is not oscillation in vacuum but the —

Large Mixing Angle —

Mikheyev Smirnov Wolfenstein

— Effect.

This effect occurs as the neutrinos stream outward through solar material. It requires both interactions with matter and neutrino mass and mixing.

Reactor (Anti)Neutrinos

The neutrino properties Δm^2_{sol} and θ_{sol} implied by LMA-MSW $\Rightarrow$

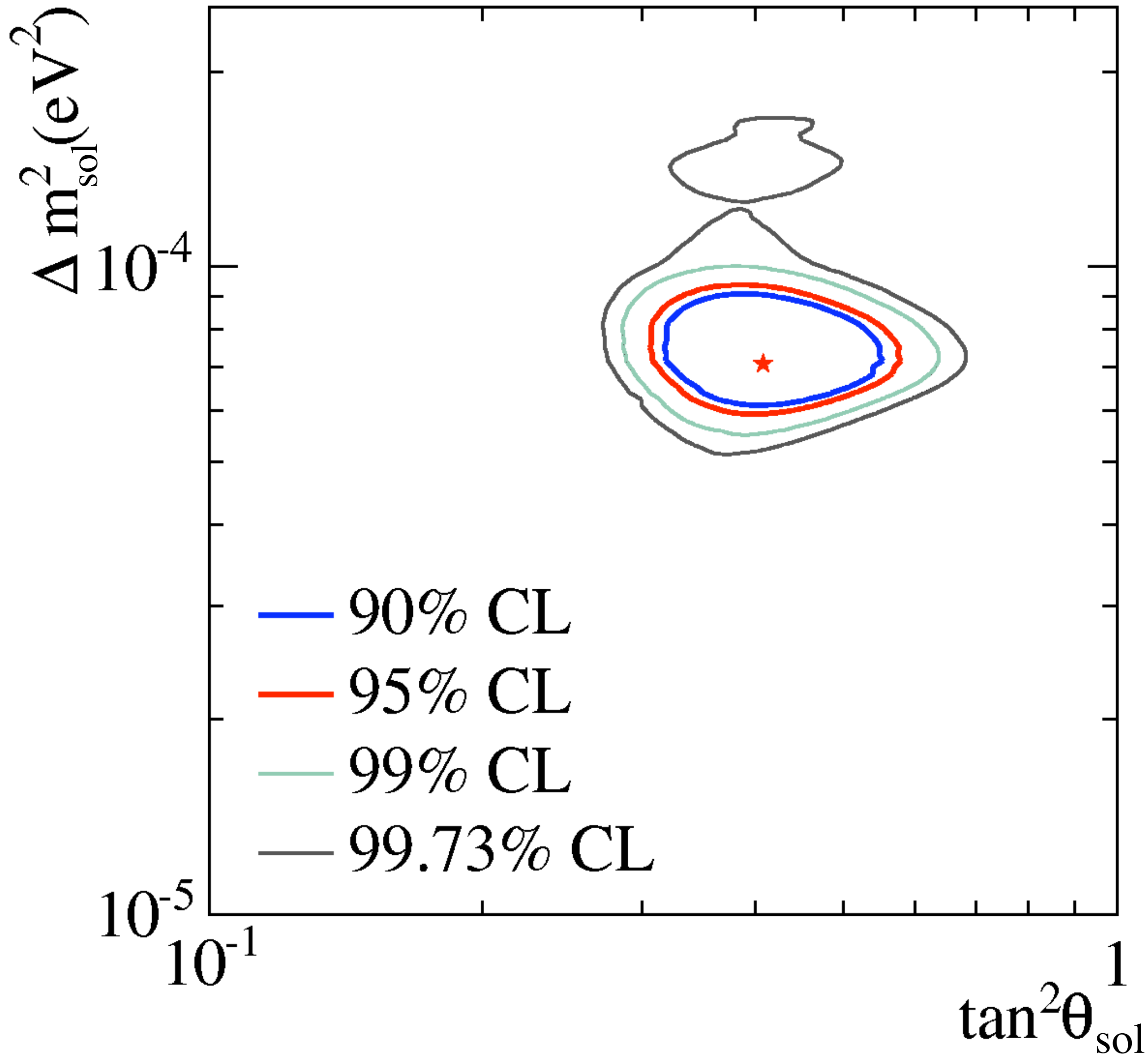
KamLAND, ~ 180 km from reactor $\bar{\nu}_e$ sources, should see substantial disappearance of $\bar{\nu}_e$ flux.

KamLAND actually does see —

$$\frac{\phi_{\bar{\nu}_e}}{\phi_{\bar{\nu}_e}\Big|_{\text{No Disappearance}}} = 0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$$

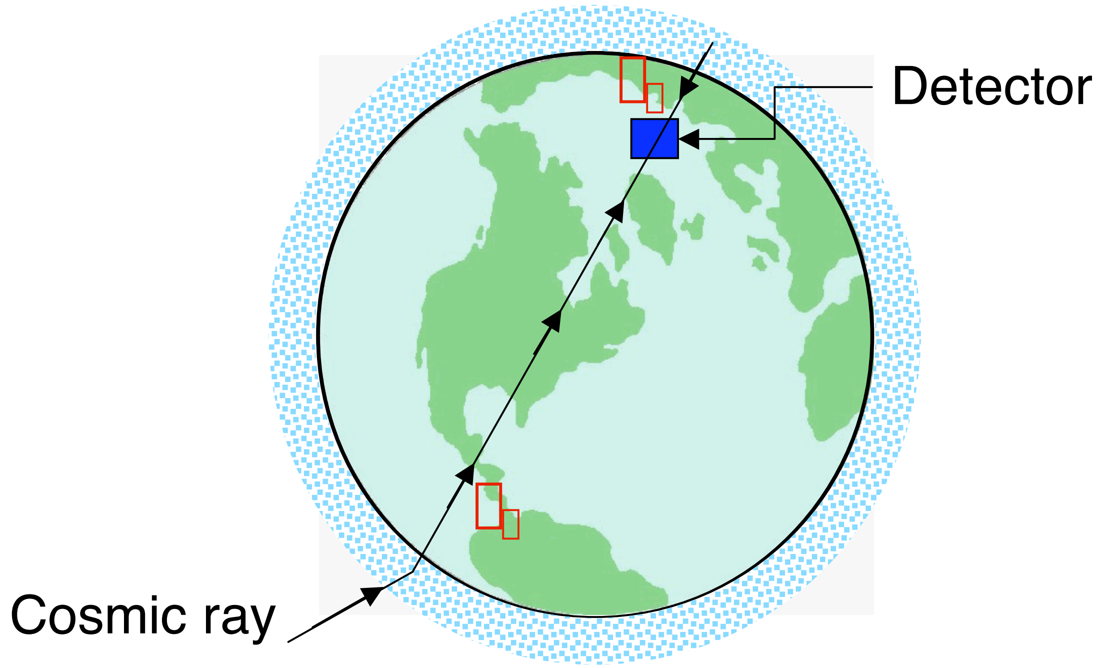
Reactor $\bar{\nu}_e$ do disappear.

Flavor change, with Δm^2_{sol} and θ_{sol} in the LMA-MSW range, fits both the solar and reactor data.



The fit to both the solar and reactor data.
SNO: nucl-ex/0309004 .

Atmospheric Neutrinos



Isotropy of the $\gtrsim$ 2 GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Rightarrow \quad \frac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} = 1 \; .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} = 0.54 \pm 0.04 \; .$$

Half of the upward-going, long-distance-traveling ν_μ are disappearing.

Voluminous atmospheric neutrino data are well described by —

$$\nu_\mu \longrightarrow \nu_\tau$$

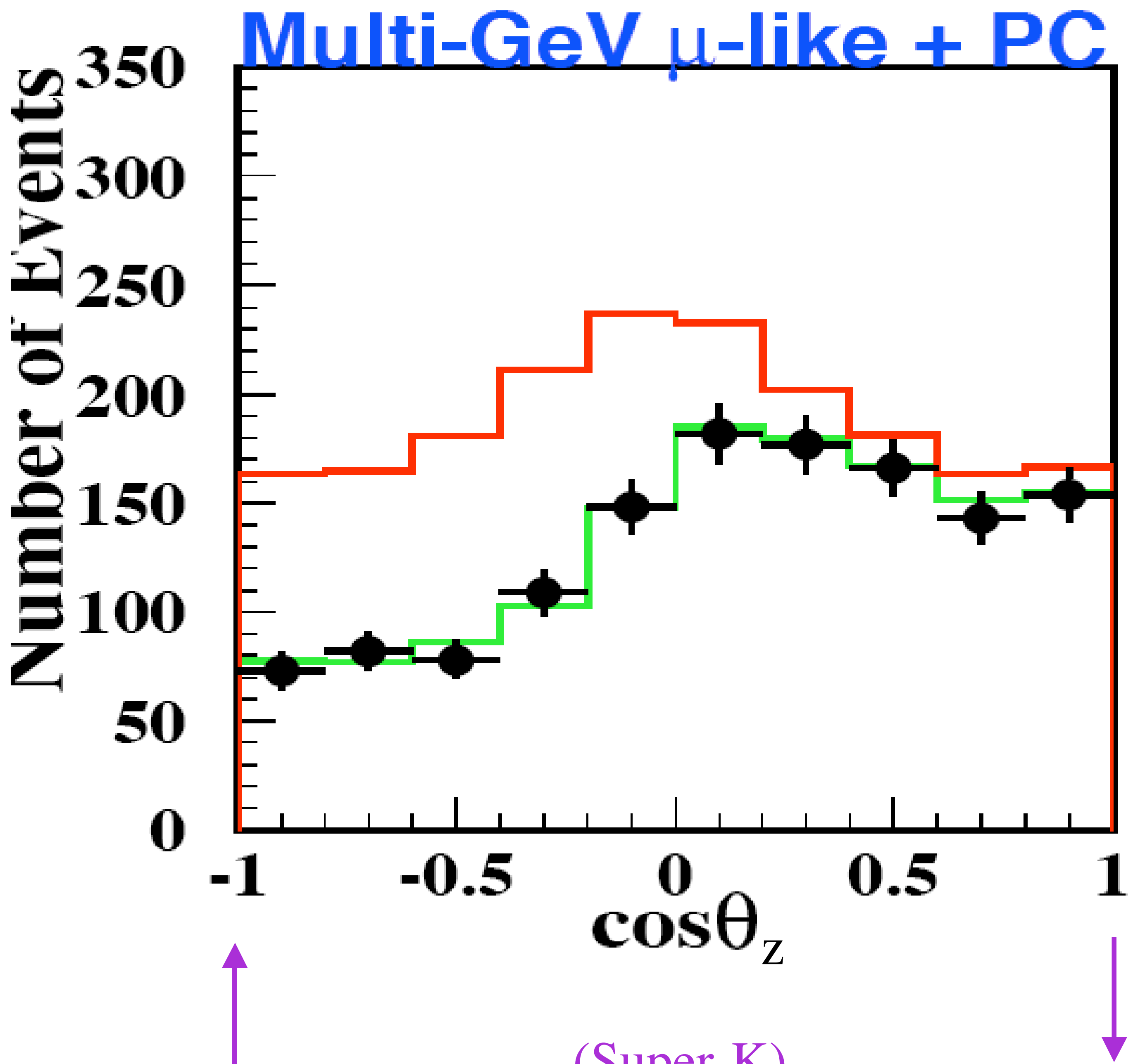
with —

$$1.9 \times 10^{-3} < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ eV^2$$

and —

$$\sin^2 2\theta_{atm} > 0.90$$

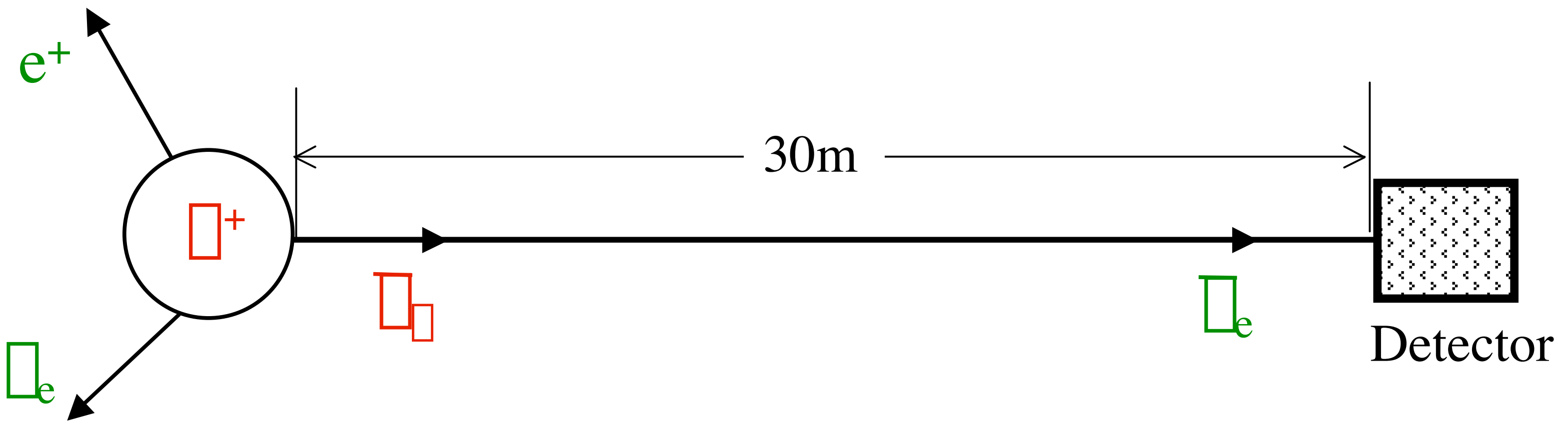
(Super-K 90%CL)


Multi-GeV μ-like + PC
Number of Events
350
300
250
200
150
100
50
0
-1
-0.5
0
0.5
1
cosθz

(Super-K)

L(iquid) S(cintillator) N(eutrino) D(etector)

Unconfirmed $\bar{□}_{□}$ □ $\bar{□}_e$ signal



Confirmation of the LSND oscillation would imply the existence of a fourth neutrino species:

the sterile neutrino.

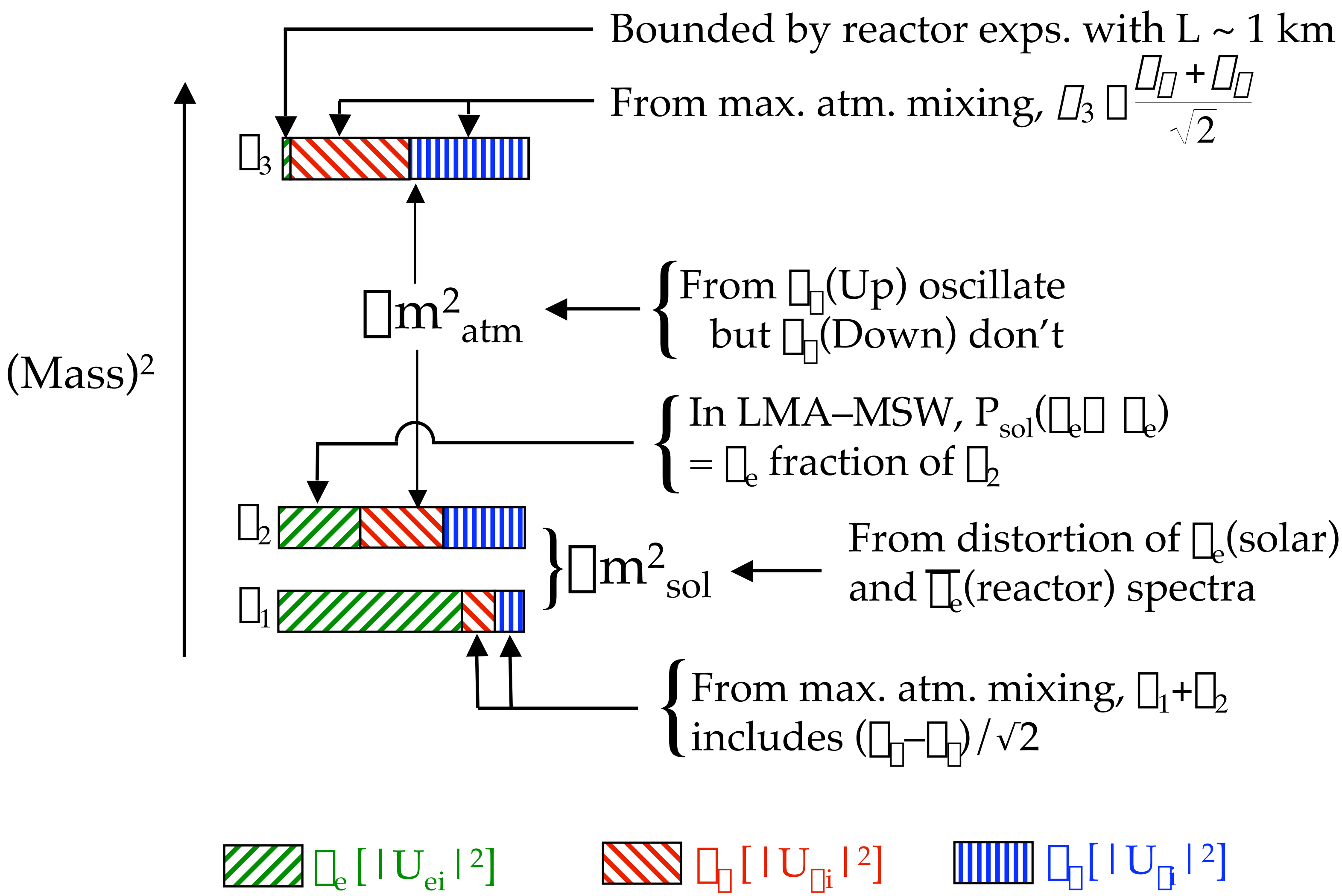
Unlike $□_e$, $□_{□}$, or $□_{□}$, a sterile neutrino does not interact even weakly.

What Have We Learned?

If LSND is confirmed, there are at least 4 neutrino species.

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then, from the existing data, the neutrino spectrum looks like —


Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, □3 □ (□□ + □□)/√2
□3
□m2atm
From □□(Up) oscillate but □□(Down) don't
(Mass)2
In LMA–MSW, Psol(□e□ □e) = □e fraction of □2
□2
□1
}□m2sol
From distortion of □e(solar) and □e(reactor) spectra
From max. atm. mixing, □1+□2 includes (□□–□□)/√2
□e [| Uei | 2]
□□ [| U□i | 2]
□□ [| U□i | 2]

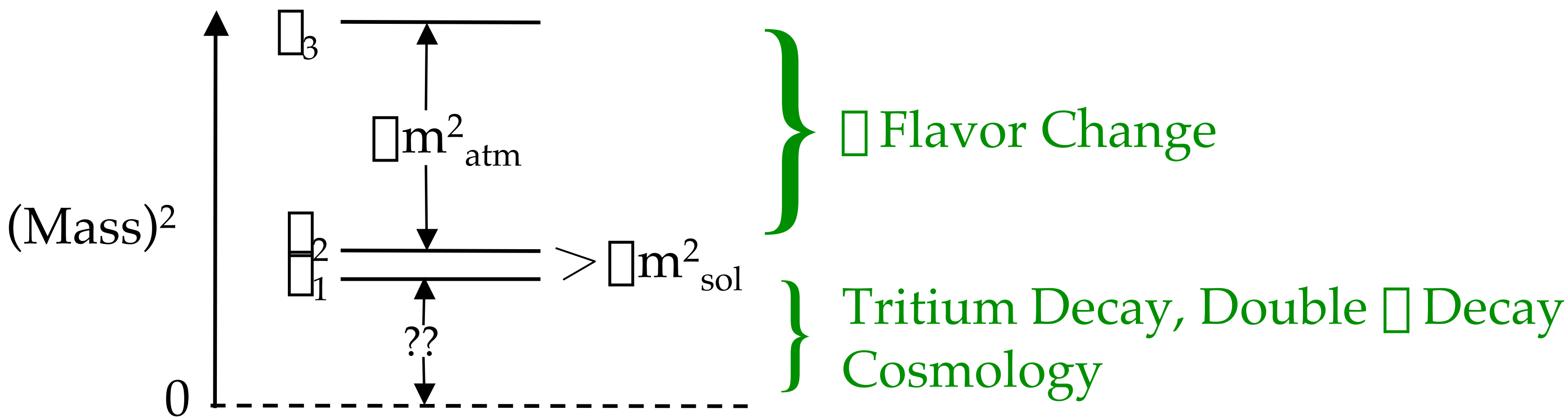
— The Future —

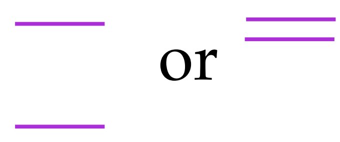
What We Would Like to Find Out

- How many neutrino species are there?
  Are there sterile neutrinos?

MiniBooNE will confirm or refute LSND.

- What are the masses of the mass eigenstates ν_i?



Is the spectral pattern  ?

$\overset{(-)}{\nu}$ behavior in earth matter can distinguish.

How far above zero is the whole pattern??

A Cosmic Connection

Cosmological Data + Cosmological Assumptions ⇒

$$\Sigma m_i < 0.71\ \text{eV} \; .$$

Mass(ν_i) → Σm_i

(95% CL
Spergel et al.)

If there are only 3 neutrinos,

$$0.04\ \text{eV} \lesssim \text{Mass[Heaviest } \nu_i] < 0.23\ \text{eV}$$

$\sqrt{\delta m^2_{atm}}$ → 0.04 eV

Cosmology → 0.23 eV

✠ Does —

- $\bar{\nu}_i = \nu_i$ (Majorana neutrinos)

or

- $\bar{\nu}_i \neq \nu_i$ (Dirac neutrinos) ?

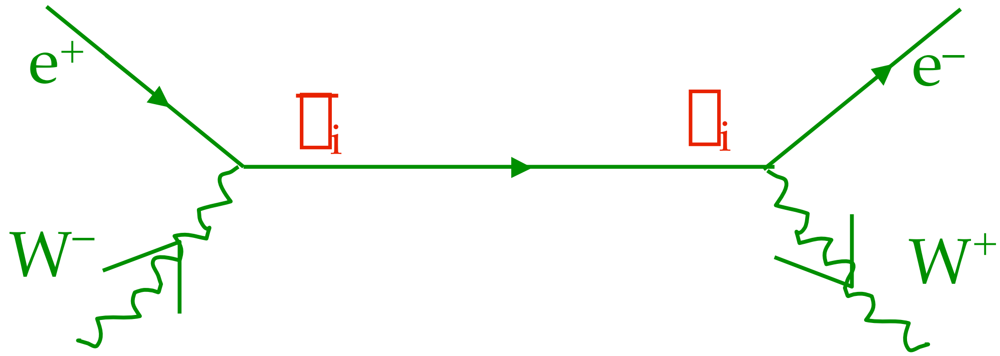
$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—

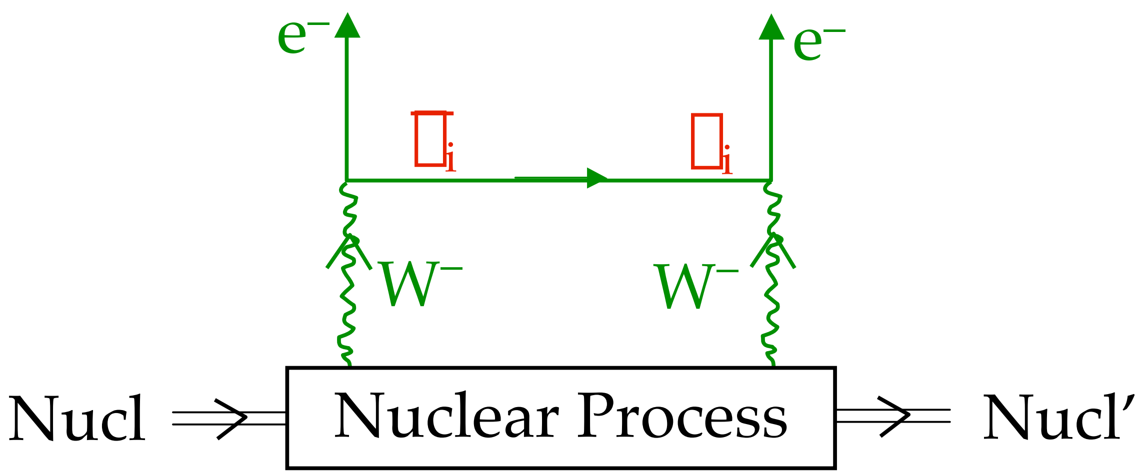
$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1$ may not exist.

If it does not, then we can have —



It is more practical to seek —

Neutrinoless Double Beta Decay



Observation would imply $\bar{\nu}_i = \nu_i$, making the neutrinos very different from the charged leptons and quarks.

* Are neutrinos the reason we exist?

The universe contains **MATTER**, but essentially no antimatter. Good thing for us:

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

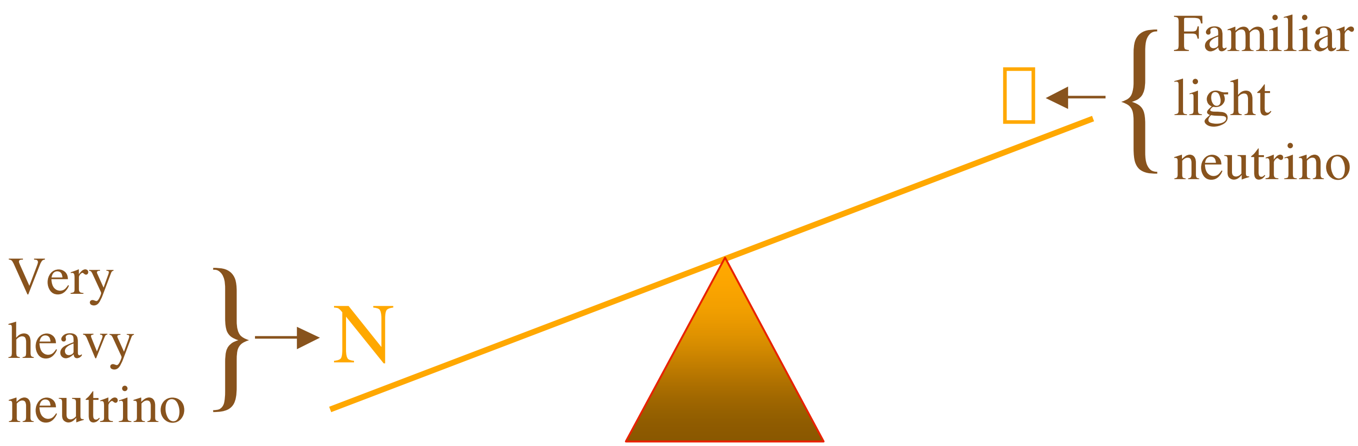
The observed difference between **QUARK** and antiquark behavior, as described by the Standard Model, is inadequate.

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 —

Probability [N □ e^- + …] ≠ Probability [N □ e^+ + …]

MATTER (↑ e^-) antimatter (↑ e^+)

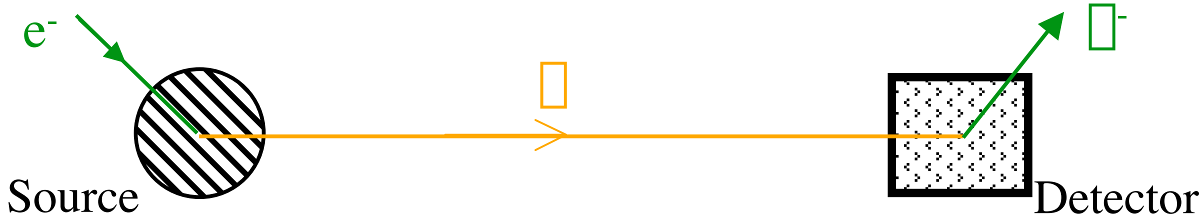
in the early universe.

This phenomenon (leptogenesis) would have led to a universe containing unequal amounts of **MATTER** and antimatter.

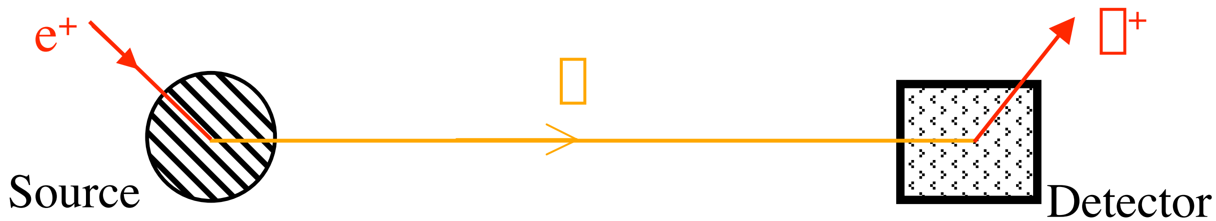
We cannot repeat the early universe.

But we can lend credibility to the hypothesis of leptogenesis by showing that **MATTER** and antimatter interact differently with the light neutrinos ν.

A neutrino flavor change involving **MATTER**:



A neutrino flavor change involving antimatter:



If these two flavor changes have different probabilities, then quite likely so do —

$N \rightarrow e^- + \ldots$ and $N \rightarrow e^+ + \ldots$

If N decays led to the present preponderance of **MATTER** over antimatter, then we are all descendants of heavy neutrinos.

Conclusion

Beautiful experiments have led to the discovery of neutrino mass.

This discovery has raised very interesting questions that we must now try to answer.

The American Physical Society Divisions of —

Particles and Fields
Nuclear Physics
Astrophysics
Physics of Beams

are sponsoring a year-long study, aimed at laying the groundwork for a sensible future program to answer the open questions.

Session L4 (Today at 14:30): Highlights of the study working group explorations

Session N1 (Today at 20:00): Town Meeting on "Our Neutrino Future"

PLEASE COME!