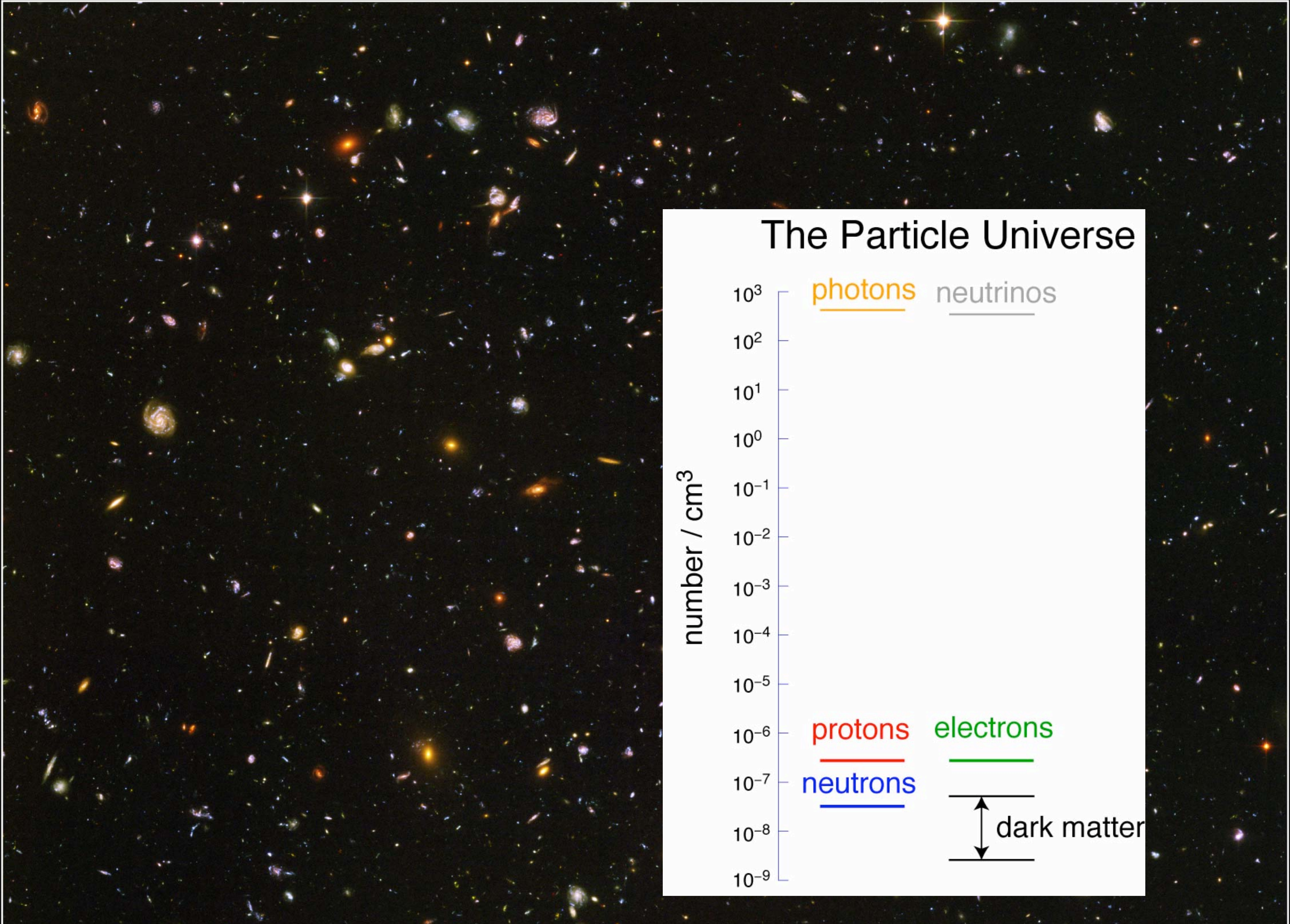
Theoretical Overview of Neutrino Physics I

Hitoshi Murayama (IPMU/Berkeley)

September 17th, 2008

九华山庄



The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter

"Wimpy and Abundant" Neutrinos are Everywhere

- They come from the Big Bang:
  - When the Universe was hot, neutrinos were created equally with any other particles
  - They are still left over: ~300 neutrinos per cm^3
- They come from the Sun:
  - Trillions of neutrinos going through your body every second
- They are shy:
  - If you want to stop them, you need to stack up lead shield up to three light-years

Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Implications of Neutrino Mass
- Why do we exist?

Neutrinos in the Standard Model

Puzzle with Beta Spectrum

- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because

$$E_{\alpha,\gamma} = E_i - E_f$$

- But β spectrum continuous

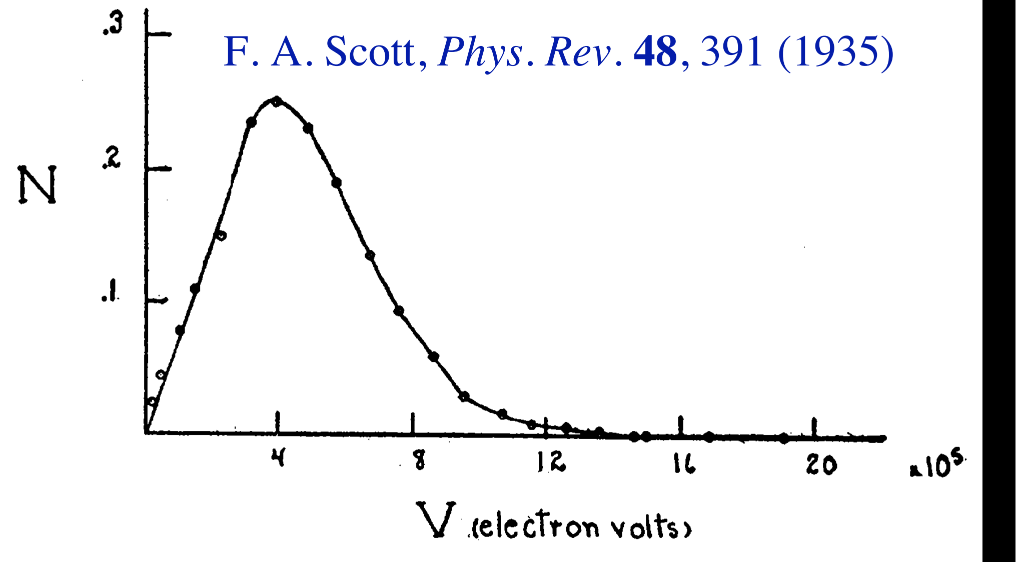


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*

Desperate Idea of Pauli

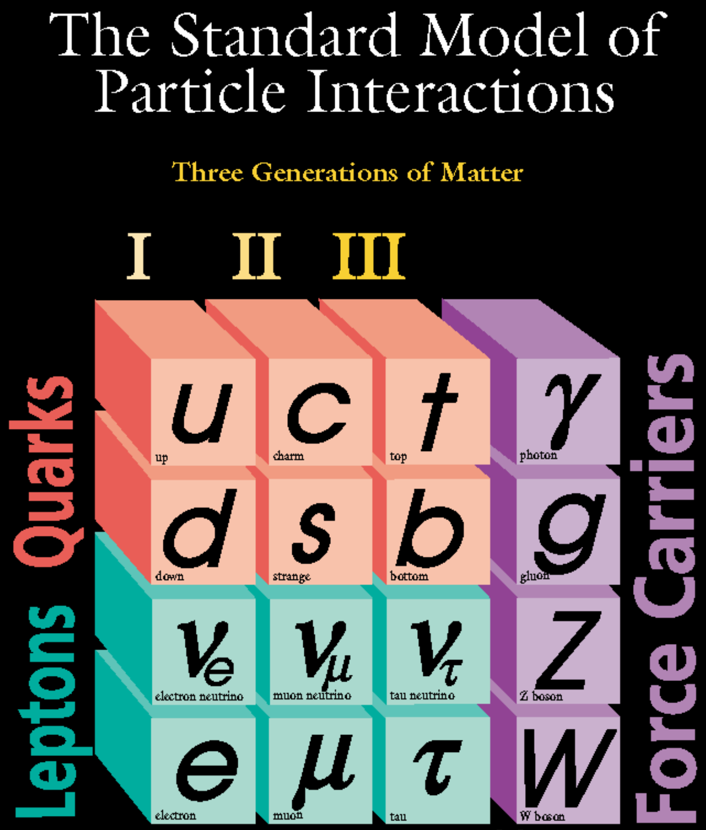
4th December 1930

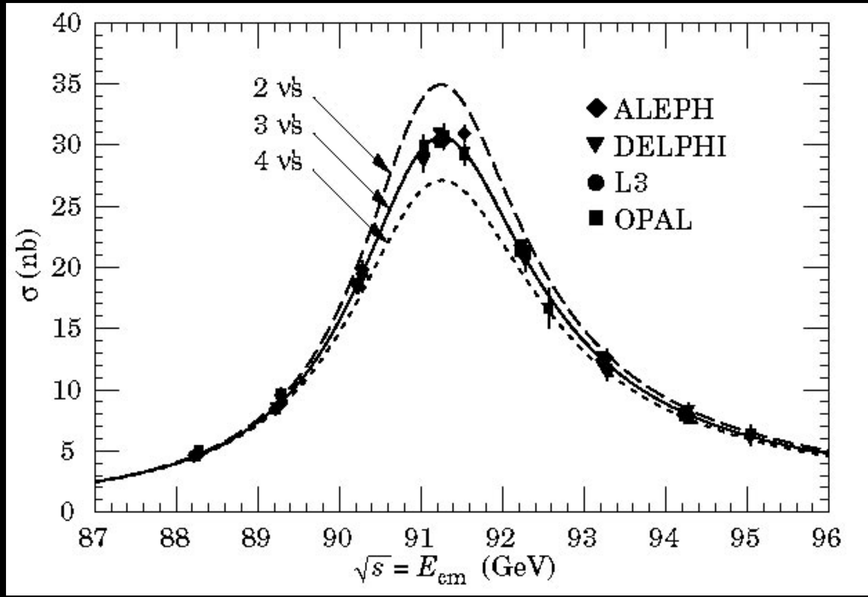
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how 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" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which 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 masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Three Kinds of Neutrinos

- There are three
- And no more





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Neutrinos are Left-handed

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

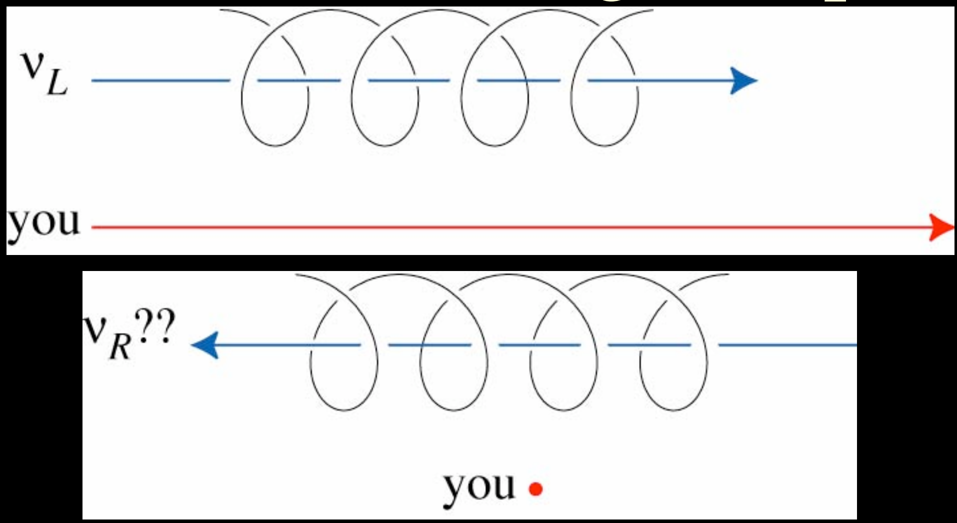
Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

- All neutrinos left-handed ⇒ massless
- If they have mass, can't go at speed of light.

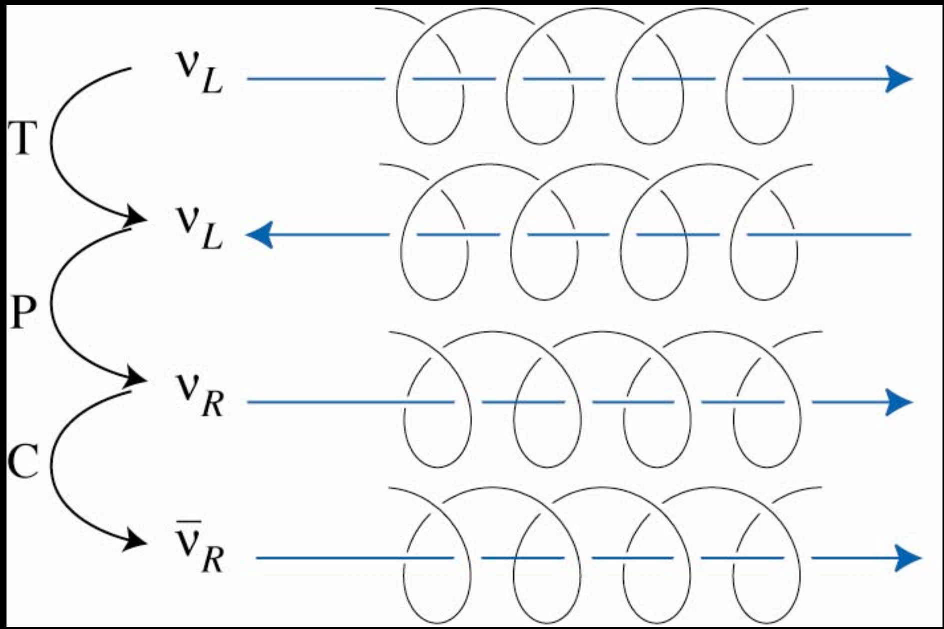


- Now neutrino right-handed??

  ⇒ contradiction ⇒ can't have a mass

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particles & anti -particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\bar{\nu}_R$



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Other Particles?

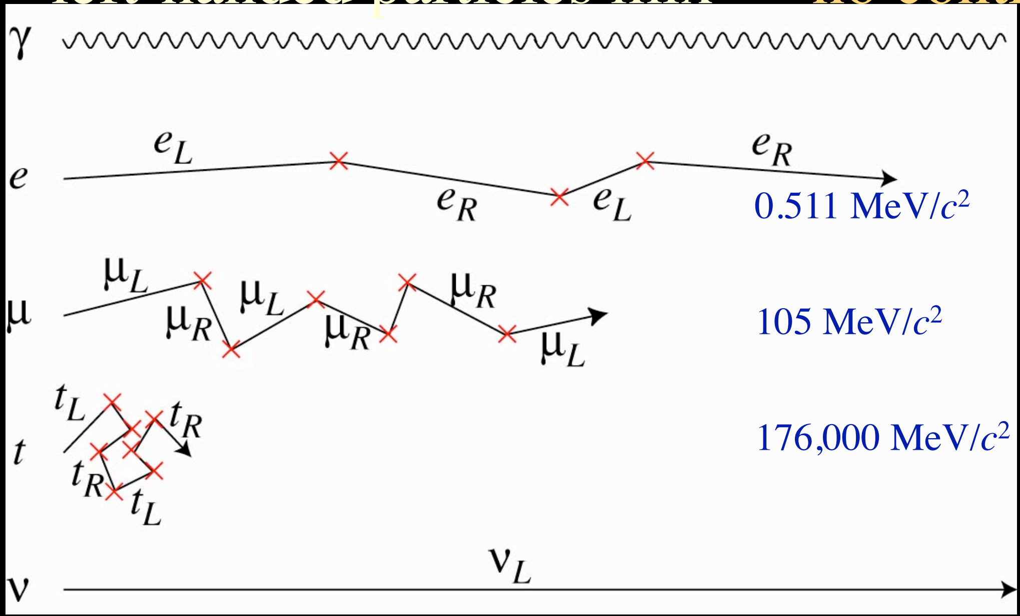
- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak force acts only on left-handed particles" yet they are massive.

Isn't this also a contradiction?

No, because we are swimming in a Bose-Einstein condensate in Universe

Universe is filled with Higgs

- "Empty" space filled with a BEC: cosmic superconductor
- Particles bump on it, but not photon because it is neutral.
- Can't go at speed of light (massive), and right-handed and left-handed particles mix ⇒ no contradiction



But neutrinos can't bump because there isn't a right-handed one ⇒ stays massless

Standard Model

- Therefore, neutrinos are strictly massless in the Standard Model of particle physics

  Finite mass of neutrinos imply the Standard Model is incomplete!
- Not just incomplete but probably a lot more profound

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Neutrinos from backstage to center stage

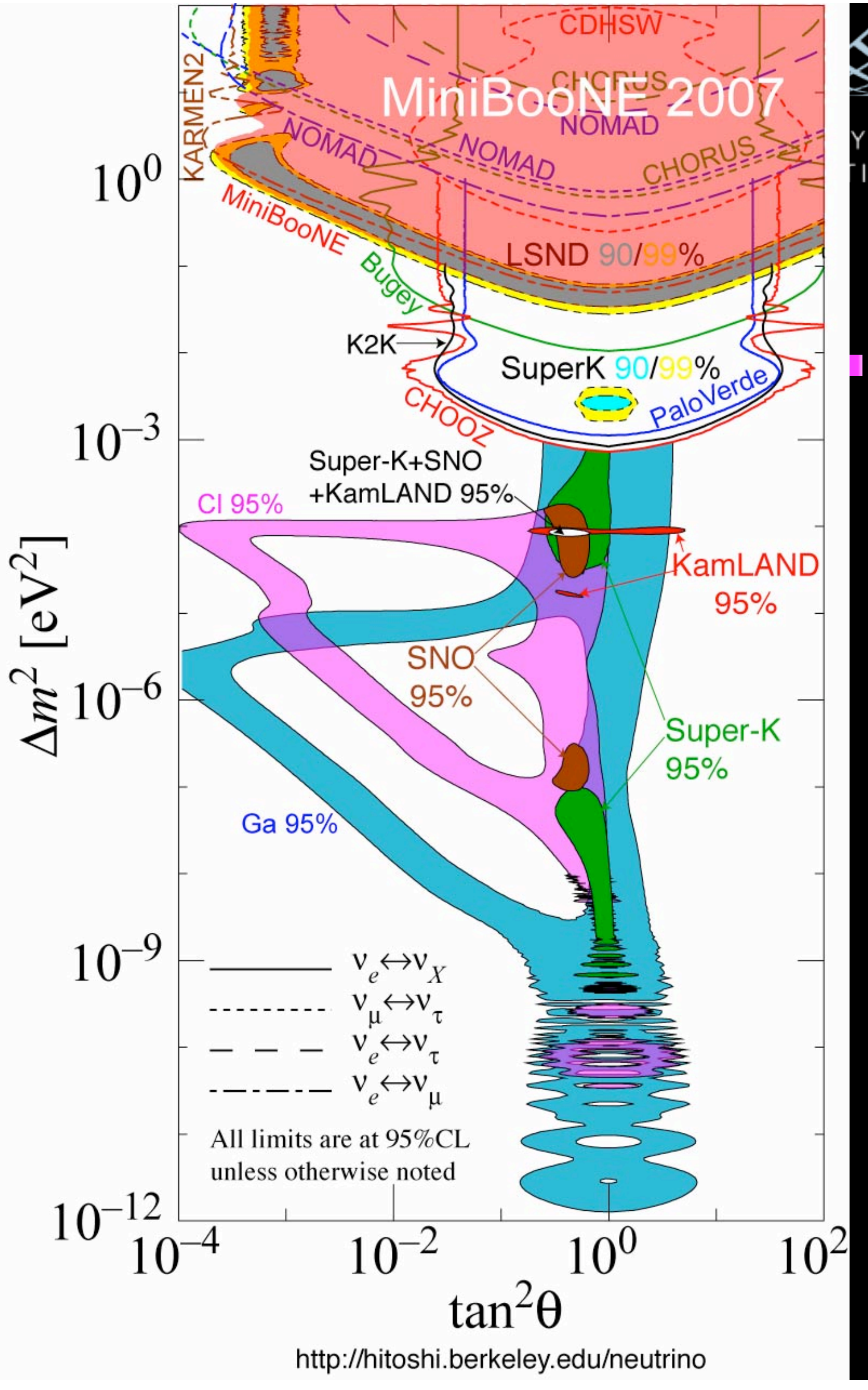
- Pauli bet a case of champagne that noone would discover neutrinos
- Finally discovered by Cowan and Reines using a nuclear reactor in 1958
- Massless Neutrinos in the Standard Model ('60s)
- Evidence for neutrino mass from SuperK (1998) and SNO (2002)

- *First evidence that the minimal Standard Model of particle physics is incomplete!*
- 2002 Nobel to pioneers: Davis and Koshiba

Lot of effort since '60s

Finally convincing evidence for "neutrino oscillation"

Neutrinos appear to have tiny but finite mass



Evidence for Neutrino Mass

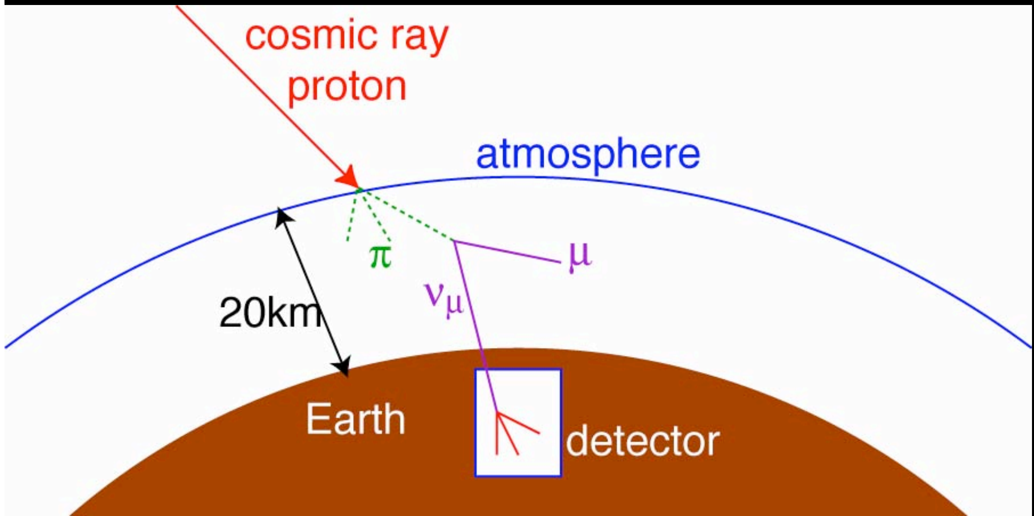
Super-Kamiokande (SuperK)

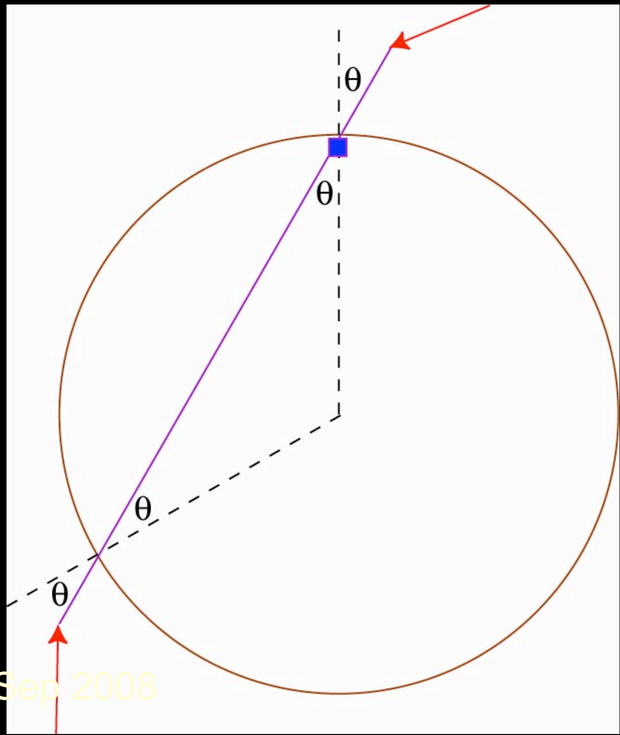
- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs

Michael Smy

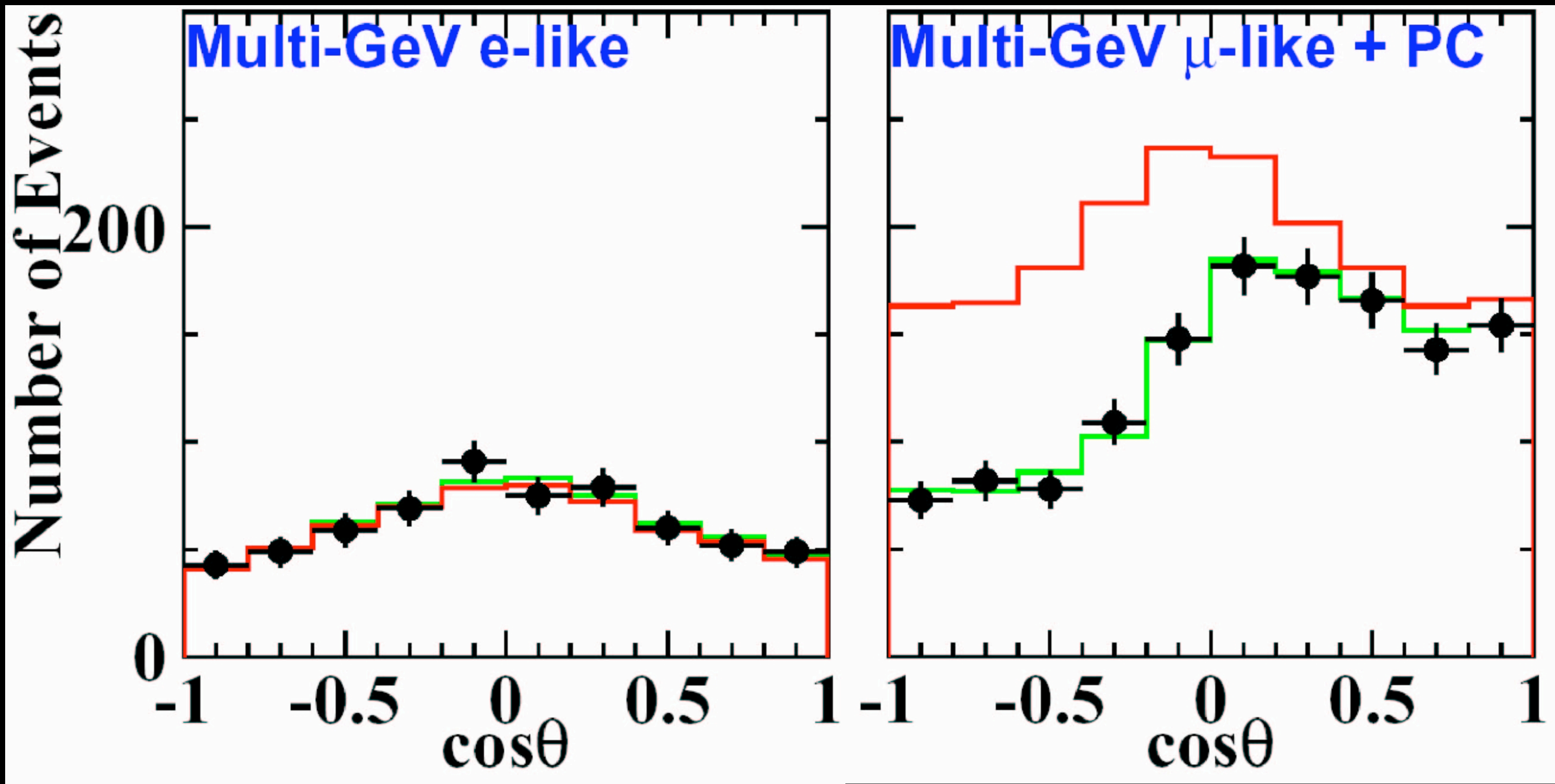
SuperKamiokaNDE *Nucleon Decay Experiment*

- $p \rightarrow e^+\pi^0$, $K^+\nu$, etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric





A half of ν_μ lost!



Neutrino's clock

- Time-dilation: the clock goes slower

$$\Delta\tau = \Delta t\sqrt{1 - \frac{v^2}{c^2}}$$

- At speed of light v=c, clock stops
- But something seems to happen to neutrinos *on their own*

- Neutrinos' clock is going
- Neutrinos must be slower than speed of light

⇒Neutrinos must have a mass

The Hamiltonian

- The Hamiltonian of a freely-propagating massive neutrino is simply

$$H = \sqrt{\vec{p}^2 + m^2} \approx p + \frac{m^2}{2p}$$

- But in quantum mechanics, mass is a matrix in general. 2×2 case:

$$M^2 = \begin{pmatrix} m^2{}_{11} & m^2{}_{12} \\ m^2{}_{21} & m^2{}_{22} \end{pmatrix}$$

$$M^2|1\rangle = m_1^2|1\rangle$$

$$M^2|2\rangle = m_2^2|2\rangle$$

Two-Neutrino Oscillation

- When produced ($e.g.$, $\pi^+ \rightarrow \mu^+ \nu_\mu$), neutrino is of a particular type

$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta \, e^{-im_1^2 t/4p} + |2\rangle \sin\theta \, e^{-im_2^2 t/4p}$$

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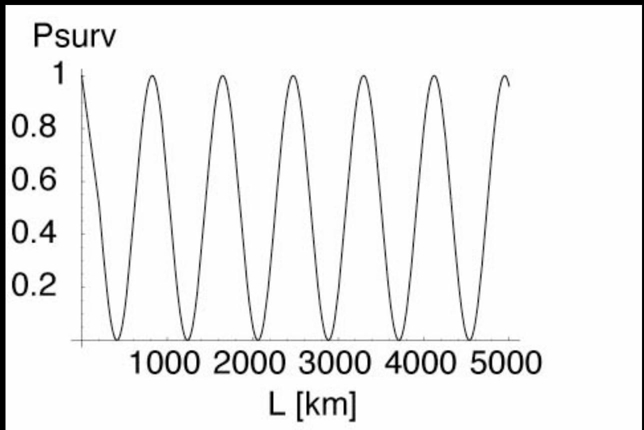
- No longer 100% ν_μ, partly ν_τ!
- "Survival probability" for ν_μ after t

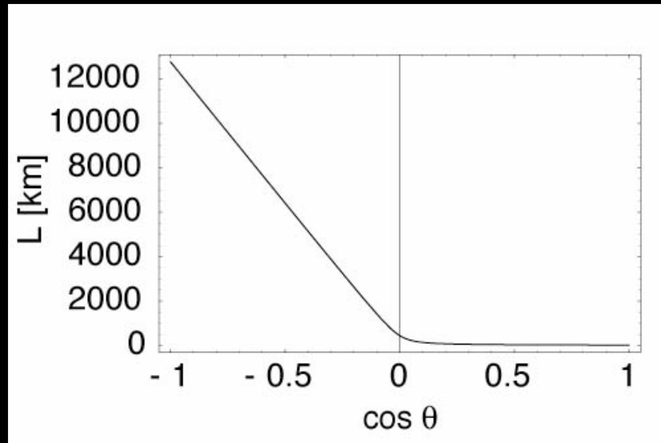
$$P = \left|\left\langle \nu_\mu \middle| \nu_\mu, t\right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\text{eV}^2} \frac{\text{GeV}}{c|\vec{p}|} \frac{ct}{\text{km}}\right)$$

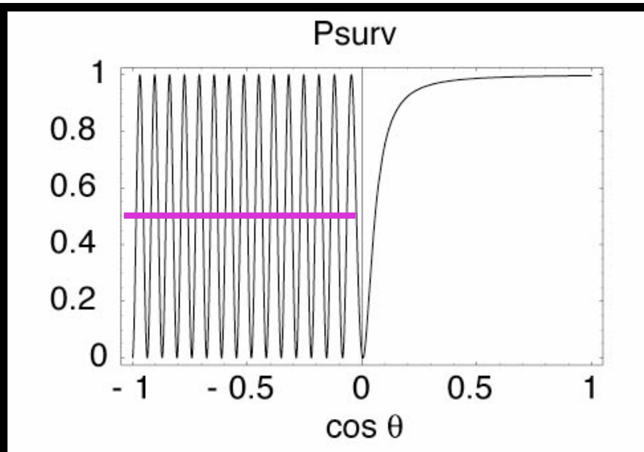
Survival Probability

p=1 GeV/c, $\sin^2 2\theta$=1

$\Delta m^2 = 3\times10^{-3}(\mathrm{eV}/c^2)^2$

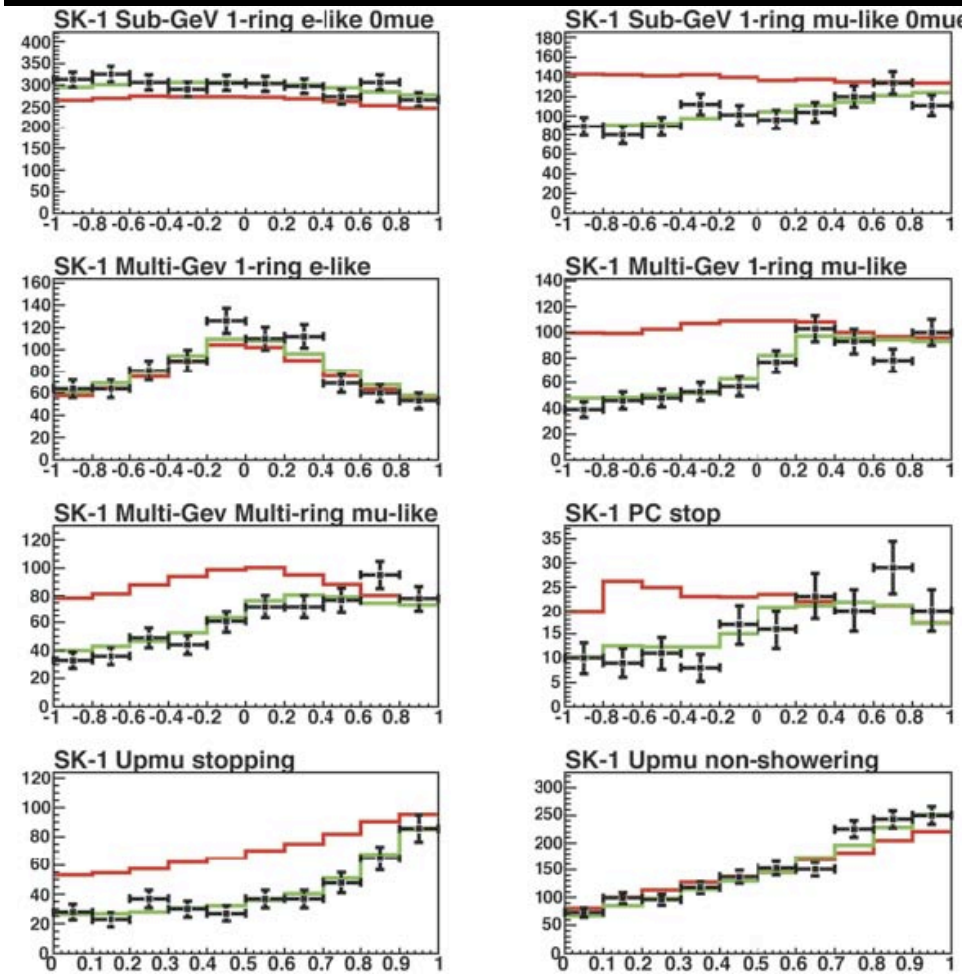


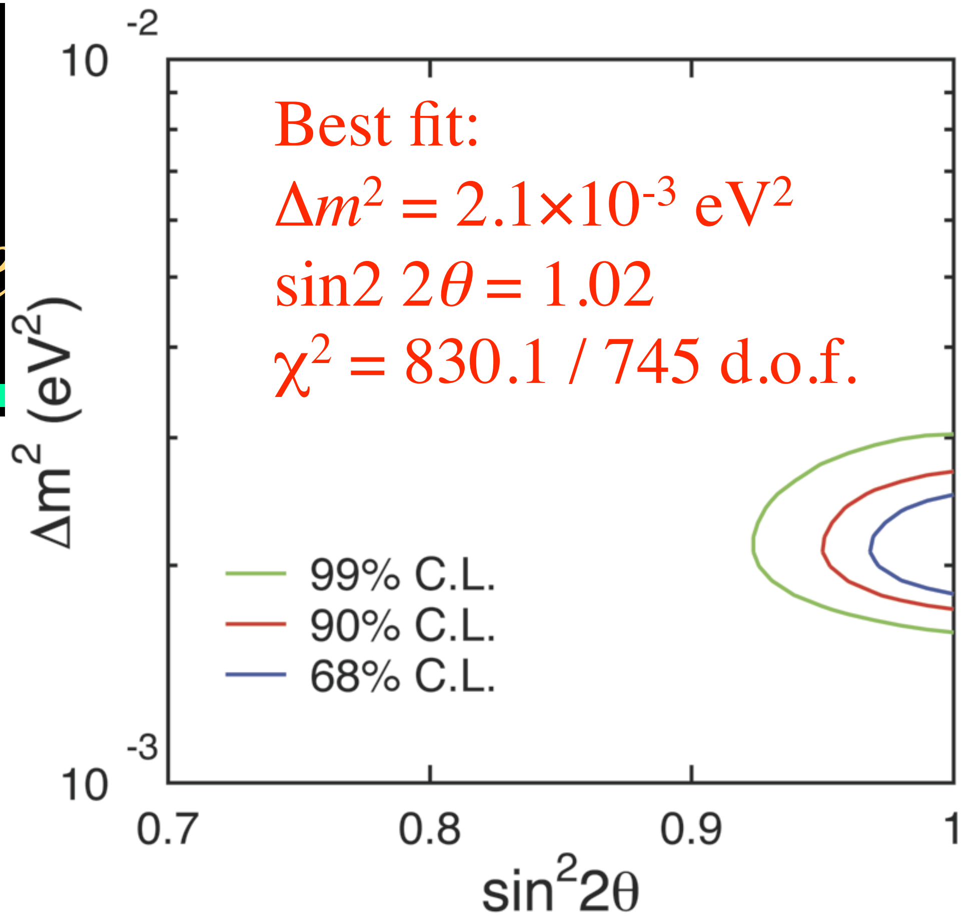


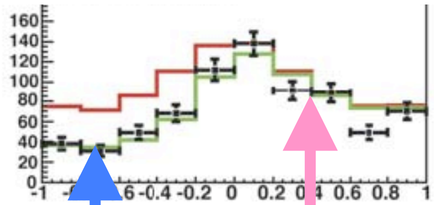


Half of the up-going ones get lost

Excelle



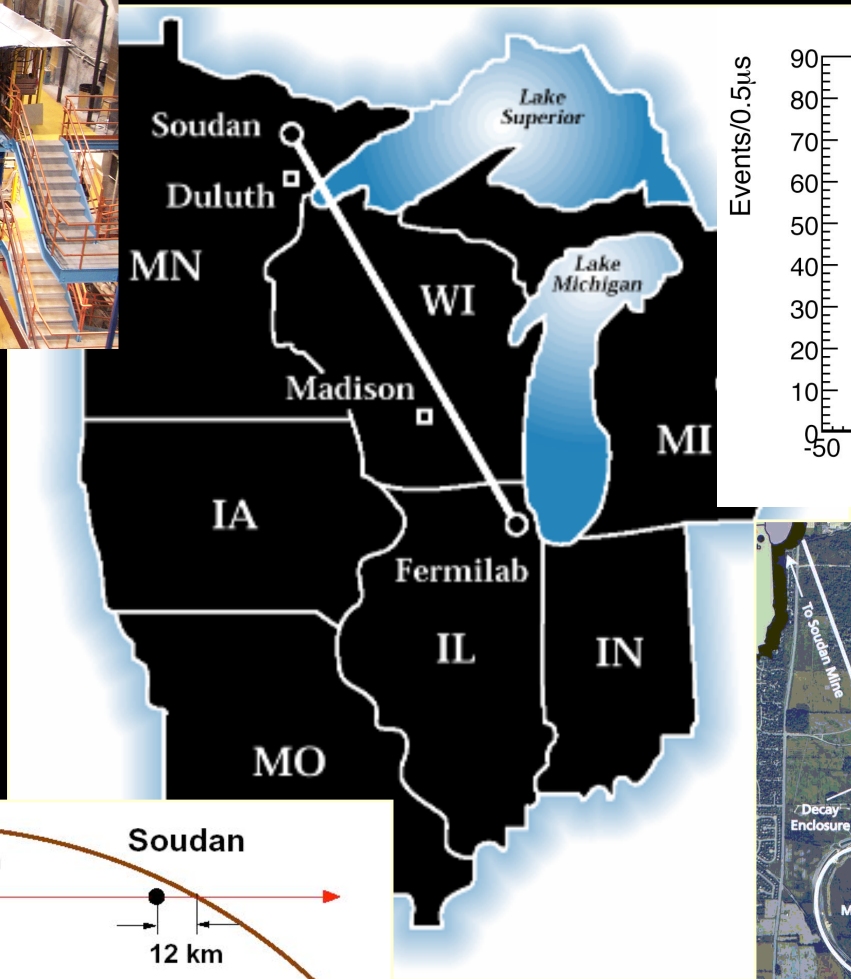


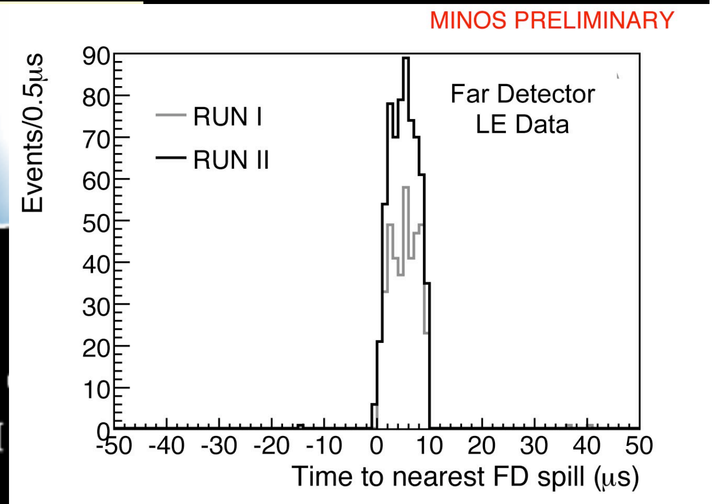


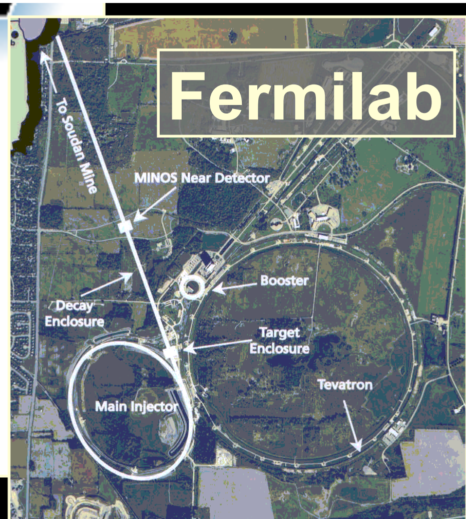
Downwards ν_μ's don't disappear

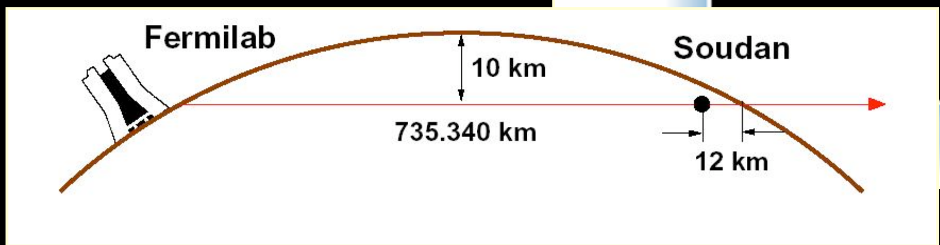
1/2 of upwards ν_μ's do disappear

Cross check with man-made ν's



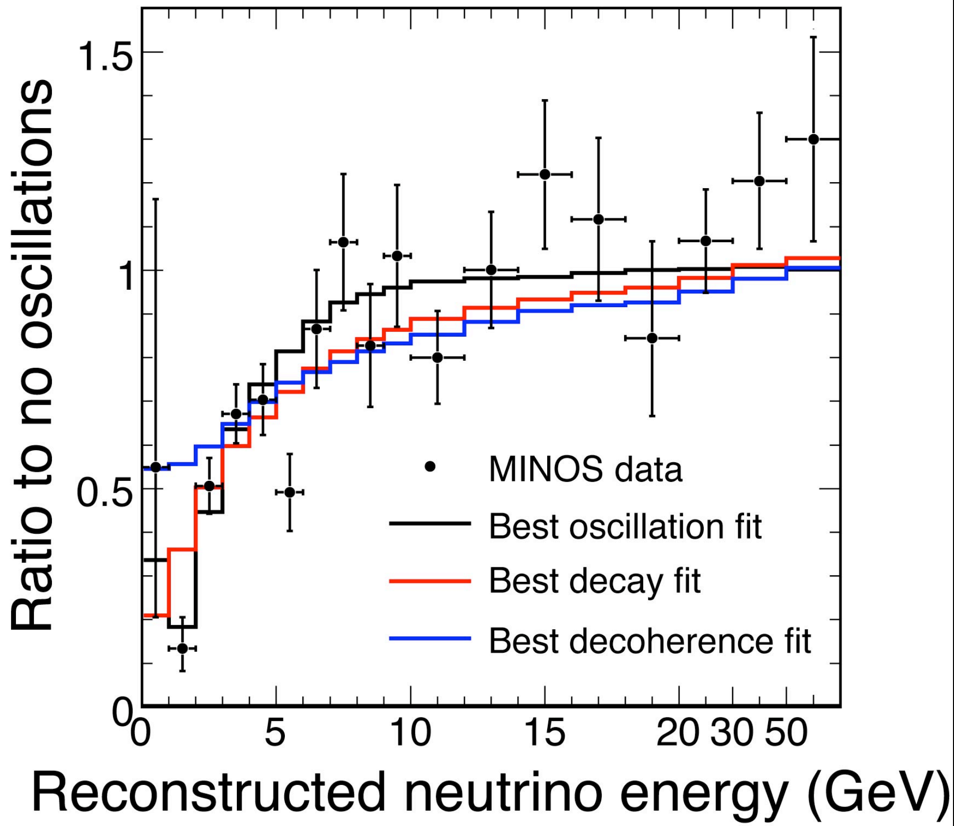


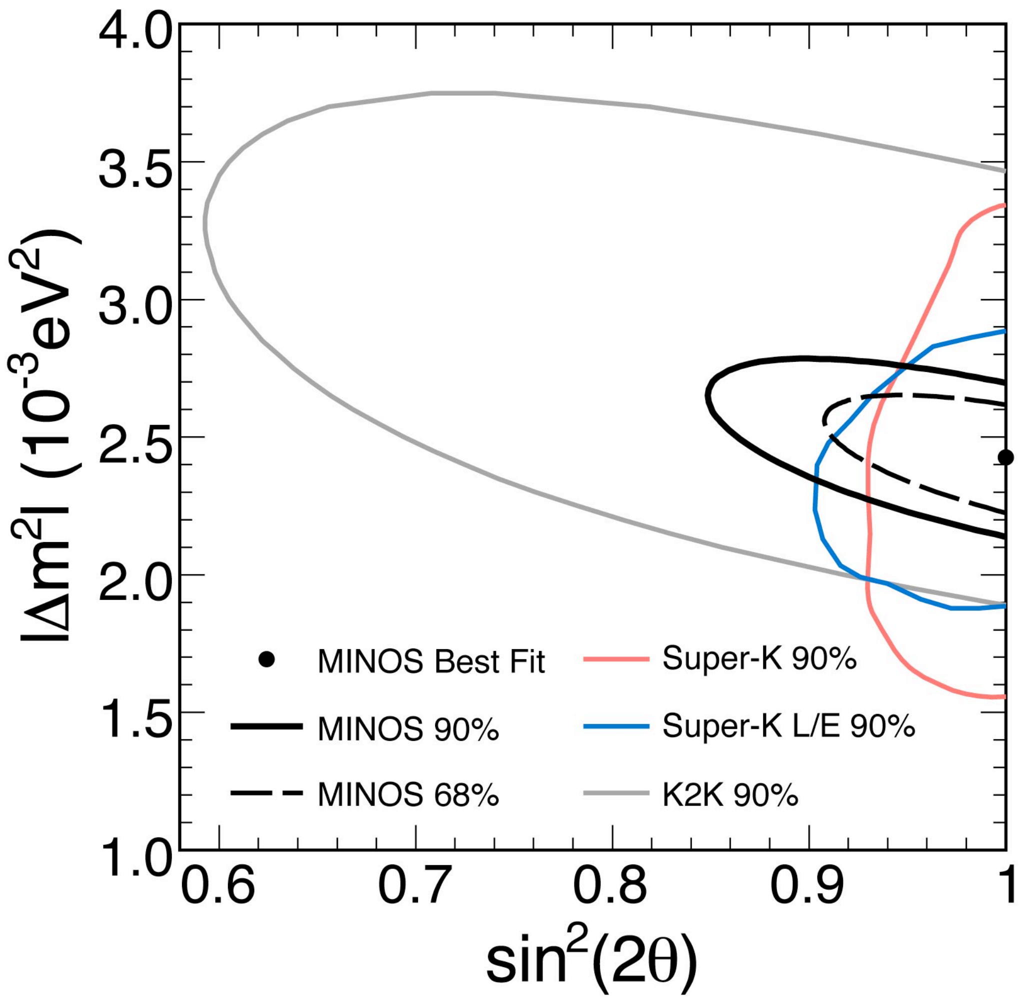




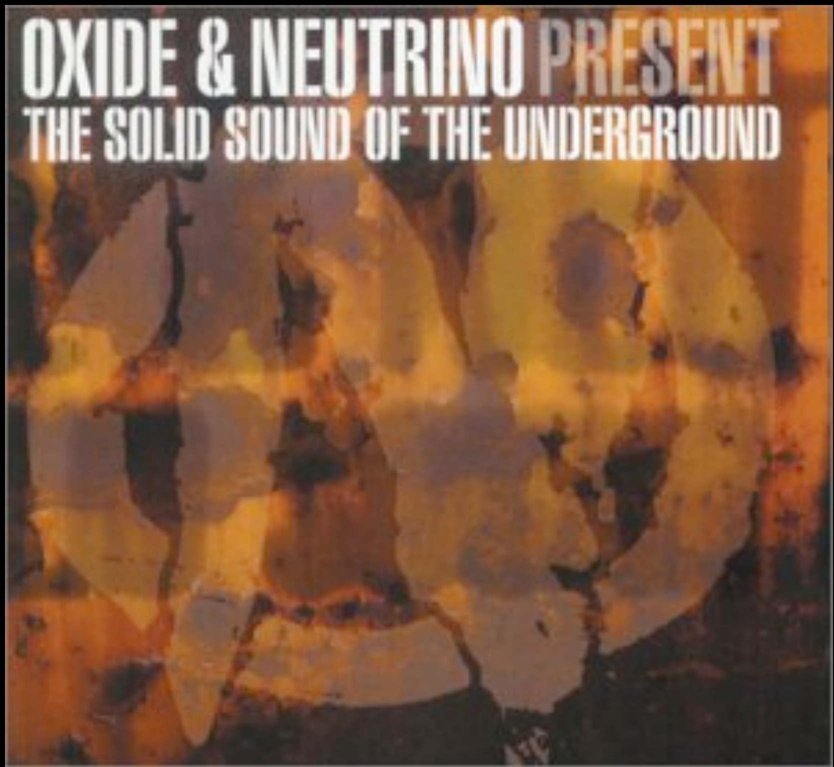
Good consistency!

- MINOS result 2008





Public Interest in Neutrinos

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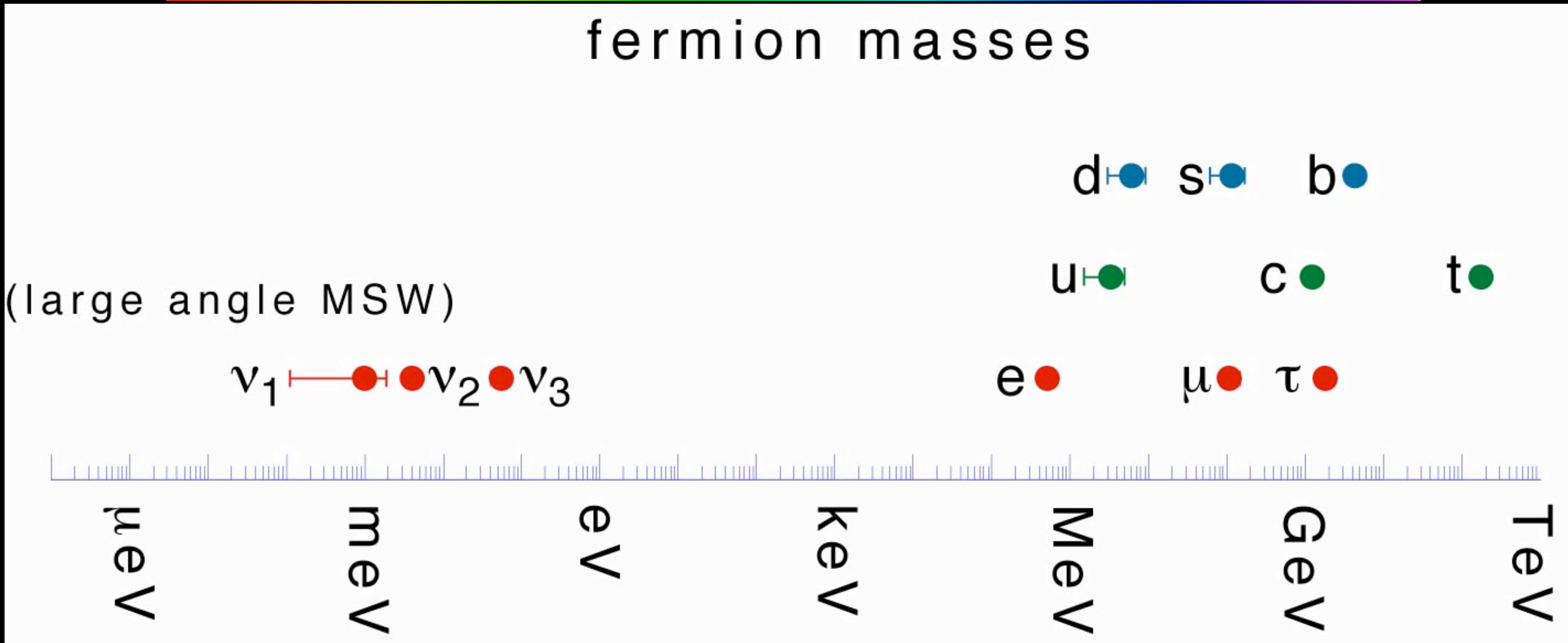
Implications of Neutrino Mass

Mass Spectrum



What do we do now?

Rare Effects from High-Energies

- Effects of physics beyond the SM as effective operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- Can be classified systematically (Weinberg)

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\begin{aligned}\mathcal{L}_6 &= QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ &\quad \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

Unique Role of Neutrino Mass

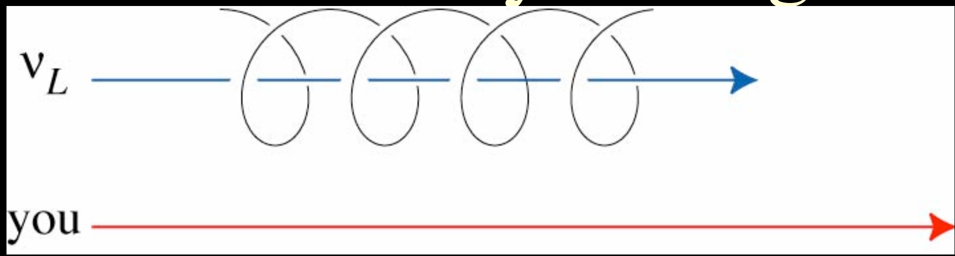
- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\text{eV/GeV})^2 = 10^{-20}$!
- Interferometry (*i.e.*, Michaelson-Morley)
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

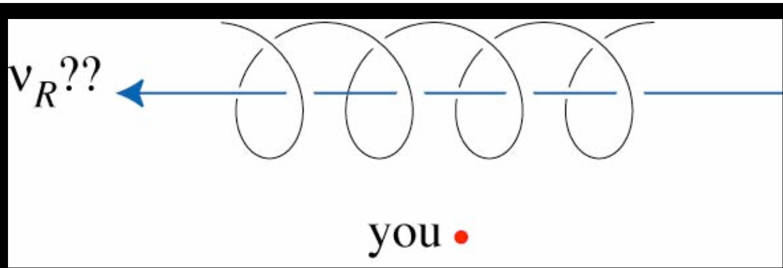
Nature was kind to provide all of them!

- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales

Neutrinos Have Mass

- They have mass. They can't go at speed of light.



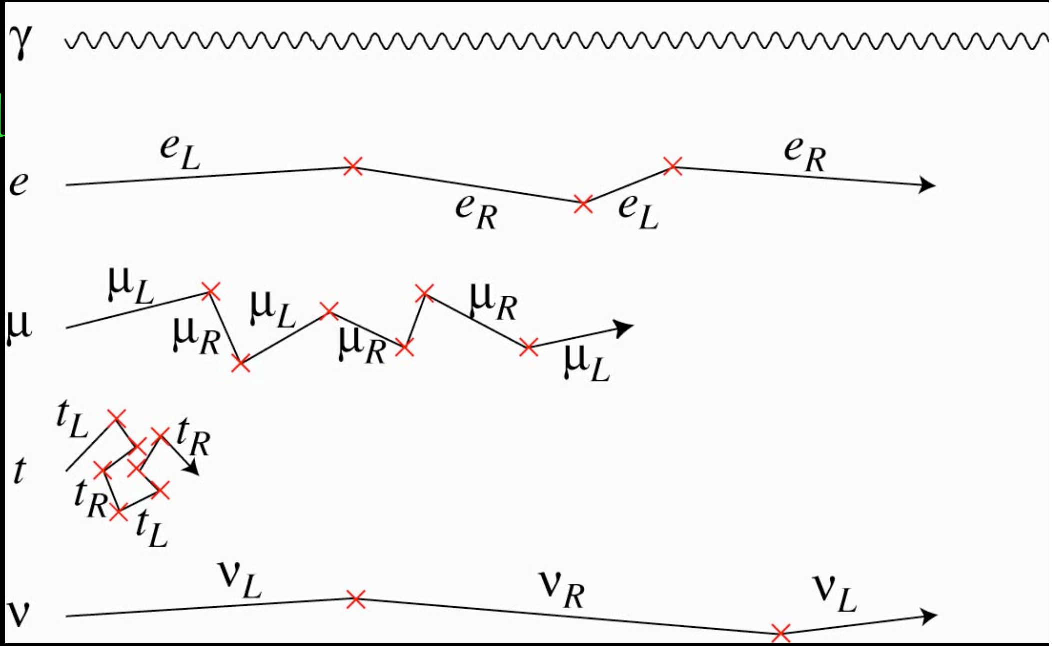


- What is this right-handed particle?
  – New particle: right-handed neutrino (Dirac)
  – Old anti-particle: right-handed anti-neutrino (Majorana)

Two ways to go

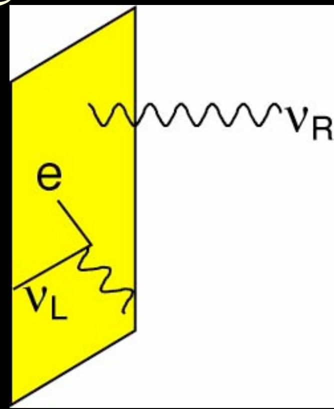
(1) Dirac Neutrinos:

- There are new particles, right-handed neutrinos, after all
- Why haven't we seen them?
- Right-handed neutrino must be *very very weakly coupled*
- Why?



Extra Dimension

- All charged particles are on a 3-brane
- Right-handed neutrinos SM gauge singlet
  ⇒ Can propagate in the "bulk"
- Makes neutrino mass small
  (Arkani-Hamed, Dimopoulos, Dvali, March-Russell; Dienes, Dudas, Gherghetta; Grossman, Neubert; Barbieri, Strumia)



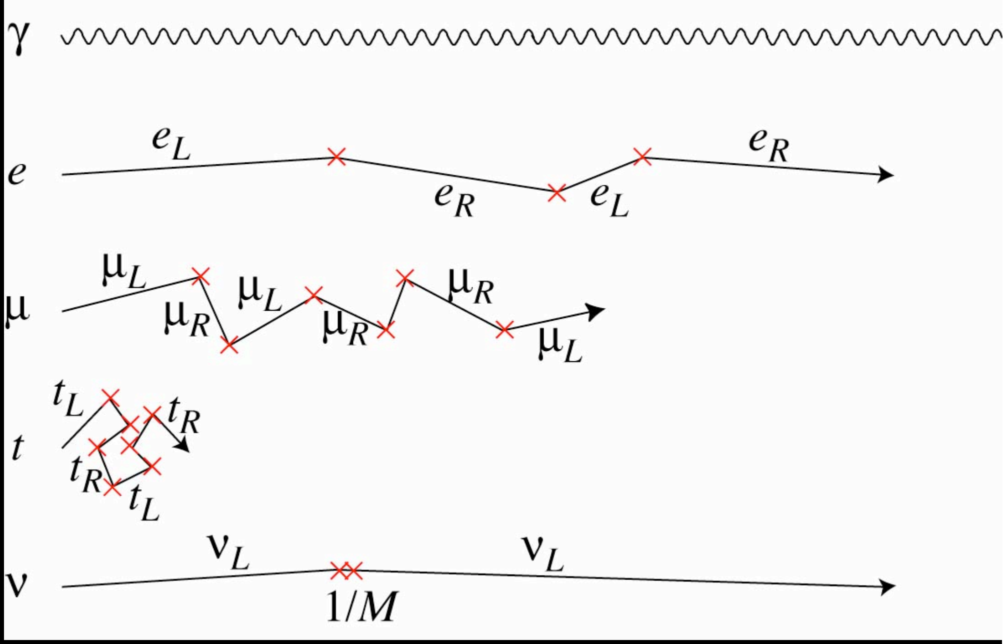
- Or SUSY breaking
  (Arkani-Hamed, Hall, HM, Smith, Weiner; Arkani-Hamed, Kaplan, HM, Nomura)

$$\int d^4\theta \frac{S^*}{M}(LH_uN)$$

Two ways to go

(2) Majorana Neutrinos:

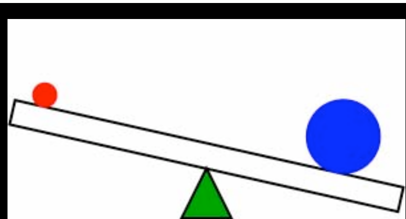
- There are no new light particles
- What if I pass a neutrino and look back?
- Must be right-handed *anti*-neutrinos
- No fundamental distinction between neutrinos and anti-neutrinos!



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV (GUT!)

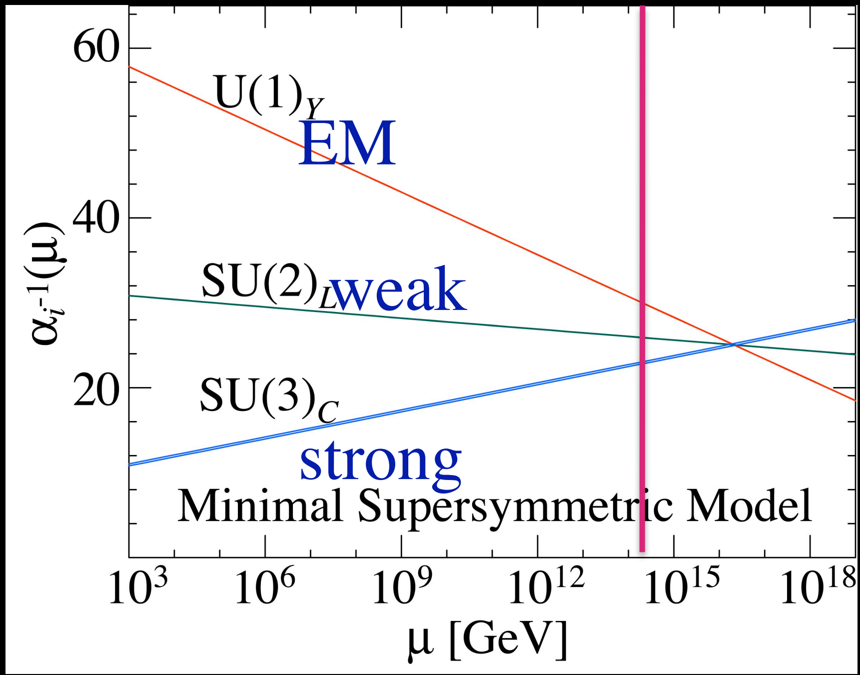
Grand Unification

M_3

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become *the same* at 10^{16} GeV if supersymmetry
- To obtain

$m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$

$\Rightarrow M_3 \sim 10^{14}$GeV!



Neutrino mass may be probing unification:

Einstein's dream