The Physics of Electroweak-scale right-handed neutrinos

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Outline

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- The neutrino oscillation revolution.

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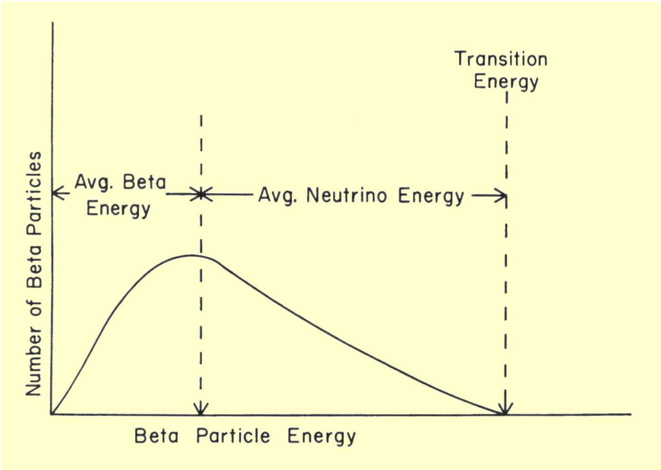
- The Standard Model
- Scenarios of neutrino masses
- Electroweak-scale right-handed neutrinos
- The LHC as the discovery tool for the origin of masses, including those of neutrinos.

A Brief History of Neutrinos

The Birth of the Neutrino

- The puzzle of β-decays:
  The electron (β) energy in the decay
  $A_Z \rightarrow A_{Z+1} + e^-$
  is not equal to the mass difference between
  A_Z and A_{Z+1}. In fact ...



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  $A_Z \rightarrow A_{Z+1} + e^- + unknown\, particle$
- Unknown Particle ("neutron" by Pauli):
  electrically neutral, spin 1/2 particle with mass less than 1% of the proton mass.
- In 1932, Chadwick discovered a electrically neutral, spin 1/2 particle with mass comparable to the proton mass: The real neutron and not Pauli's particle.

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- Neutrinos are elusive: light, electrically neutral and interacting weakly with matter. Hard to detect!
  If one uses a wall of lead, how thick should it be to stop a beam of neutrinos?

A Brief History of Neutrinos

- Typical low energy (MeV) cross section $\sigma \approx 10^{-47}\, m^2$.
  Mean free path for neutrinos going through e.g. Lead:
  - Number density of nucleons in Pb: $n = \frac{11400\, kg/m^3}{1.67 \times 10^{-27}\, kg}$.
  - Number of interaction per meter: $\sigma \times n = 10^{-47}\, m^2 \times \frac{11400\, kg/m^3}{1.67 \times 10^{-27}\, kg}$
  - Mean free path: $\lambda = \frac{1}{\sigma \times n} \approx 1.5 \times 10^{17}\, m \approx 1.6\, light\, years$

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- Huge detector and lots of neutrinos!

A Brief History of Neutrinos

The Age of Discovery

- Fred Reines and Clyde Cowan 1956's experiment: 200 liters of water (lots of protons!), 40 kg of cadmium chloride to capture neutrons, scintillators to detect the photons.

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- Source of neutrinos: Savannah River nuclear reactor, South Carolina: $\sim$ 10 trillions neutrinos/$sec.cm^2$ in the form of $\bar{\nu}_e$.

A Brief History of Neutrinos

- Reaction in detector: $\bar{\nu}_e + p \rightarrow n + e^+$ followed by $e^+ + e^- \rightarrow 2\,\gamma$ and $n +^{108} Cd \rightarrow^{109} Cd^* \rightarrow^{109} Cd + \gamma$

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- Nobel Prize in 1995 (Reines). Almost 40 years after the discovery of ν_e!

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- Discovery of 3rd charged lepton in 1975 by Marty Perl (Nobel Prize 1995). Postulate of a 3rd neutrino ν_τ. Observed in 2000 at Fermilab(Nobel Prize in 2020-2030?).

Neutrino Oscillation Revolution

The Age of Astrophysical Neutrinos

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- Ray Davis's Homestake Experiment in South Dakota: 615 tonne of tetrachloroethylene (dry cleaning fluid) in a tank 4,800 feet underground.

Neutrino Oscillation Revolution

- 1968 result: neutrino count $\sim 1/3$ of John Bahcall's calculation!
  Two possibilities (assuming the experiment is right):
  - The solar model is wrong.
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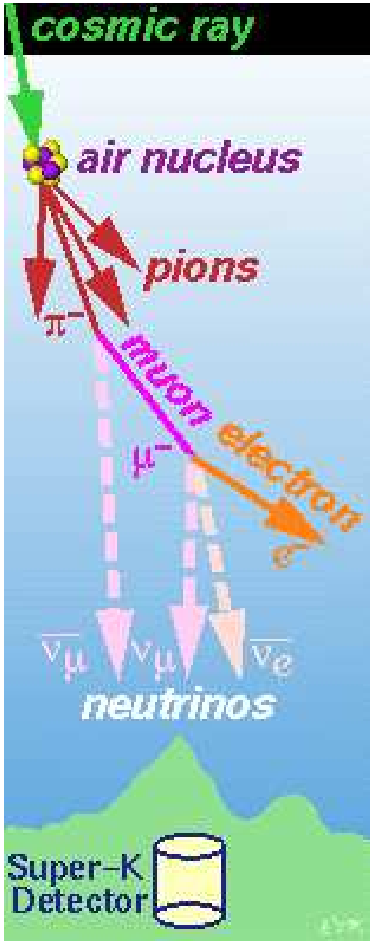
- This is the so-called Solar Neutrino Problem. What happens to ν_e's on their way from the Sun to Earth?

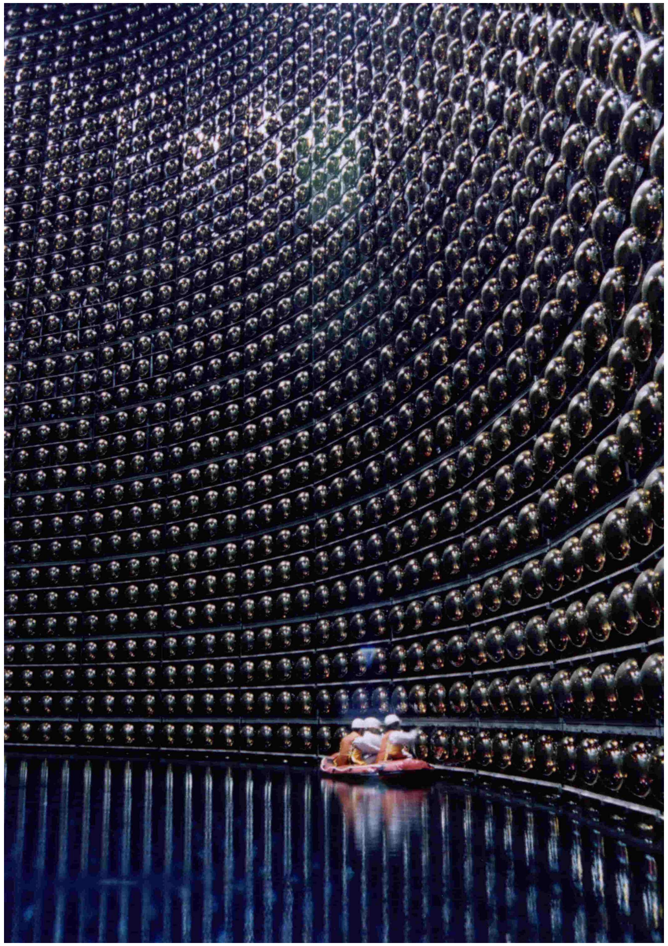
Neutrino Oscillation Revolution

Atmospheric Neutrinos



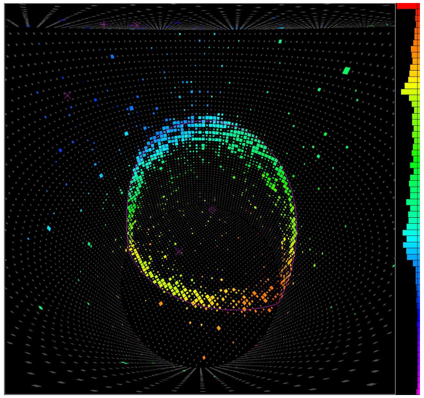
Neutrino Oscillation Revolution

Super-K Detector, Kamiokande, Japan



Neutrino Oscillation Revolution

- Relativistic muon from e.g. $\nu_\mu + n \rightarrow \mu^- + p$



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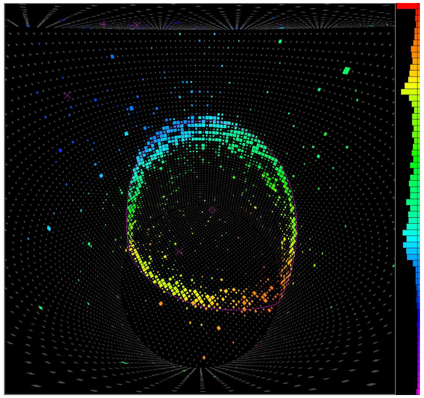

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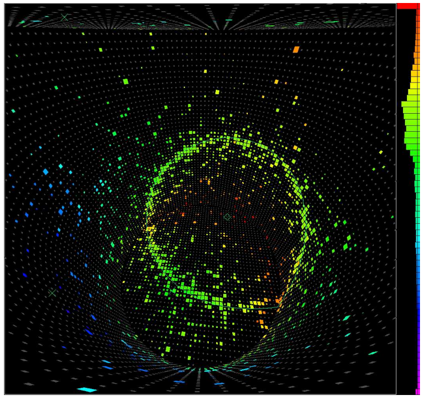
- Relativistic electron from e.g. $\nu_e + n \to e^- + p$



Fuzzy! Why?

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- How does one describe quantum mechanically the oscillation of one quantum state into another?
- Definition of flavor: $W^+ \rightarrow l_\alpha^+ + \nu_{alpha}$. l_α^+: charged lepton mass eigenstate of flavor α $(e, \mu, \tau, ..)$

Neutrino Oscillation Revolution

Simple example of Two Flavor Oscillation

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  $|\nu_i(L) >= e^{-im_i^2 L/2E}|\nu_i(0) >$

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- For example $|\nu_e(L) >= \cos\theta e^{-im_1^2 L/2E}|\nu_1 >$ $+ \sin\theta e^{-im_2^2 L/2E}|\nu_2 >$

Neutrino Oscillation Revolution

- Probability for a neutrino of born with flavor α to change into one with one with with a different flavor β at a distance L

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(1.267 \frac{\Delta m_{12}^2 L}{E} \frac{GeV}{eV^2\, km})$$

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- Choose L and E such that $\Delta m_{12}^2 L/E \approx O(1)$.

Neutrino Oscillation Revolution

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  $|\nu_\alpha(0)>= \sum_i U^{lepton}_{\alpha\, i} |\nu_i(0)>$

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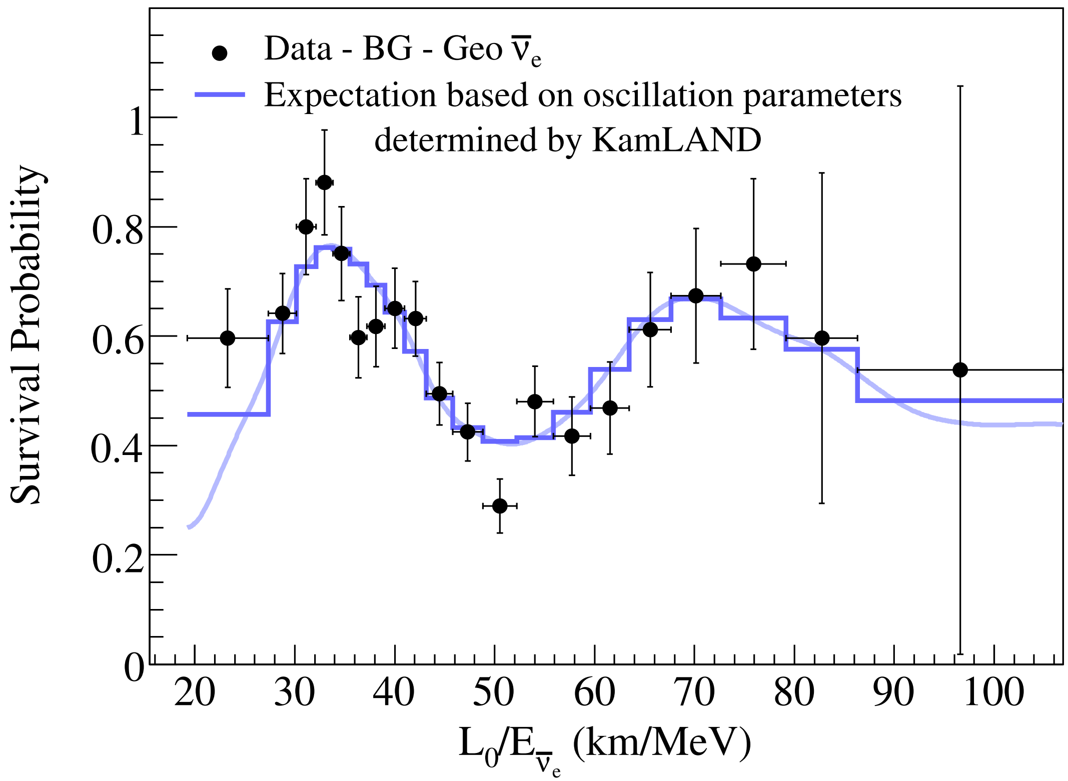
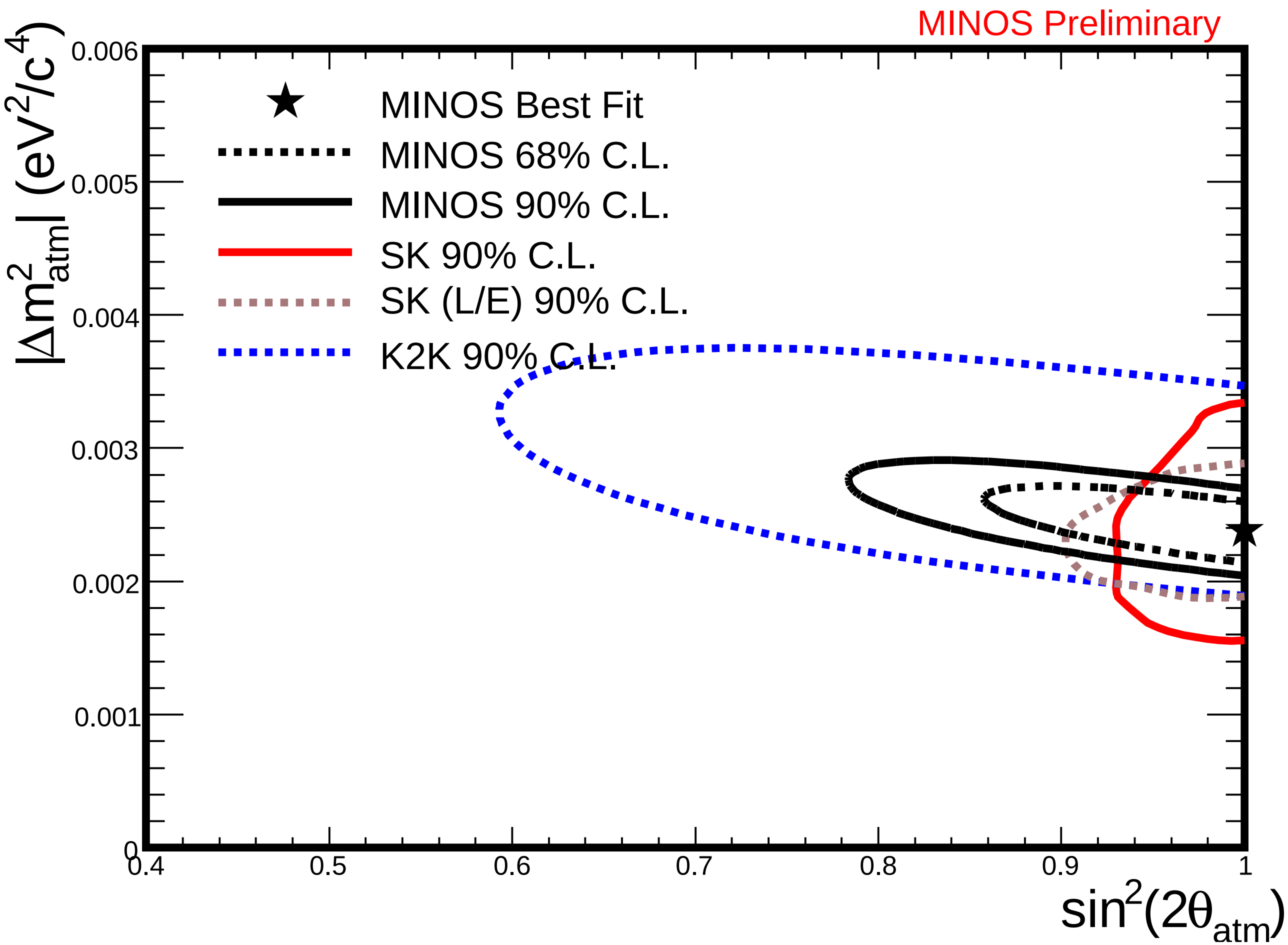
- To a good approximation, many experiments used the two-flavor oscillation formula. See lectures on neutrinos.

Neutrino Oscillation Revolution



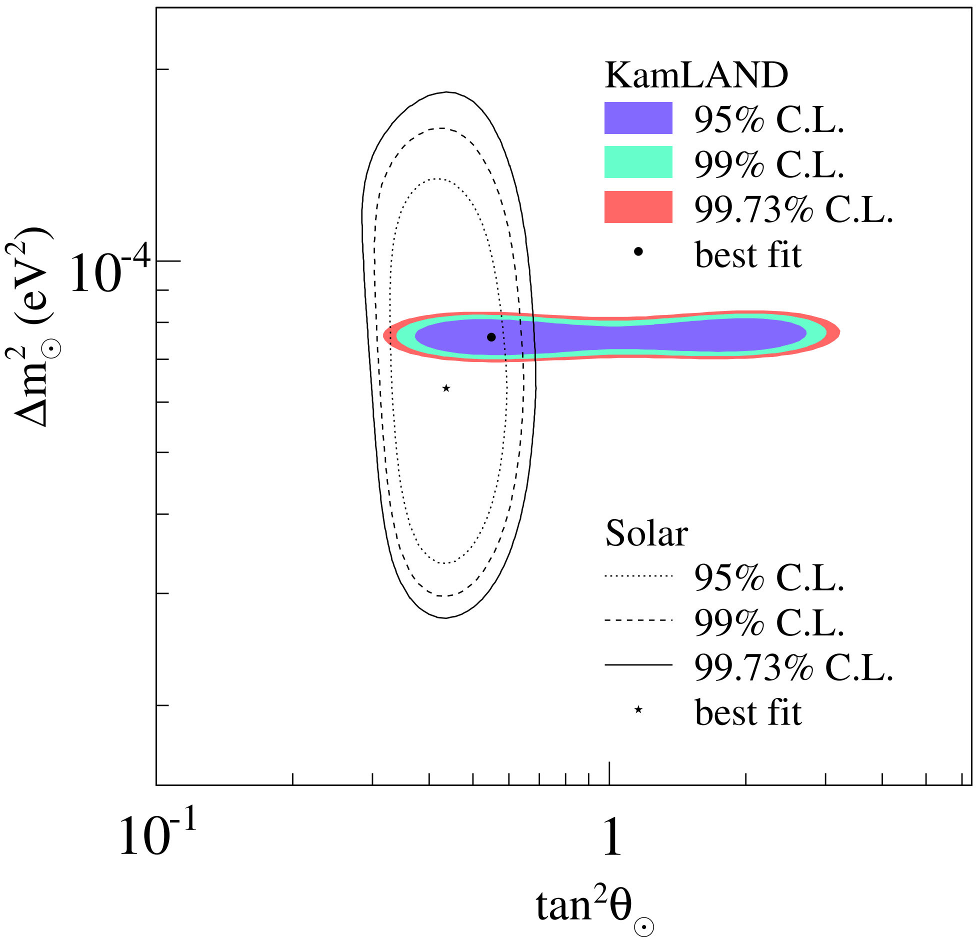
$P(\bar{\nu}_e \to \bar{\nu}_e)$ in KamLAND

Neutrino Oscillation Revolution



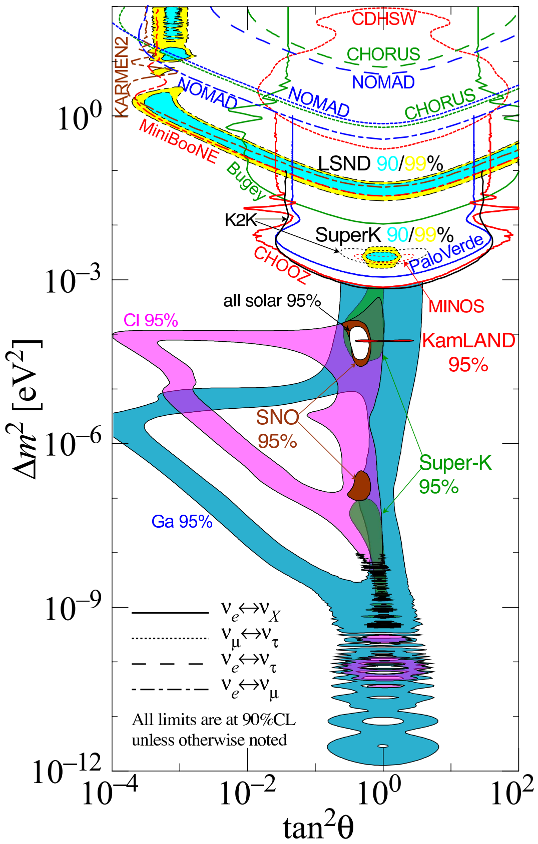
Δm^2 from Atmospheric Neutrinos

Neutrino Oscillation Revolution



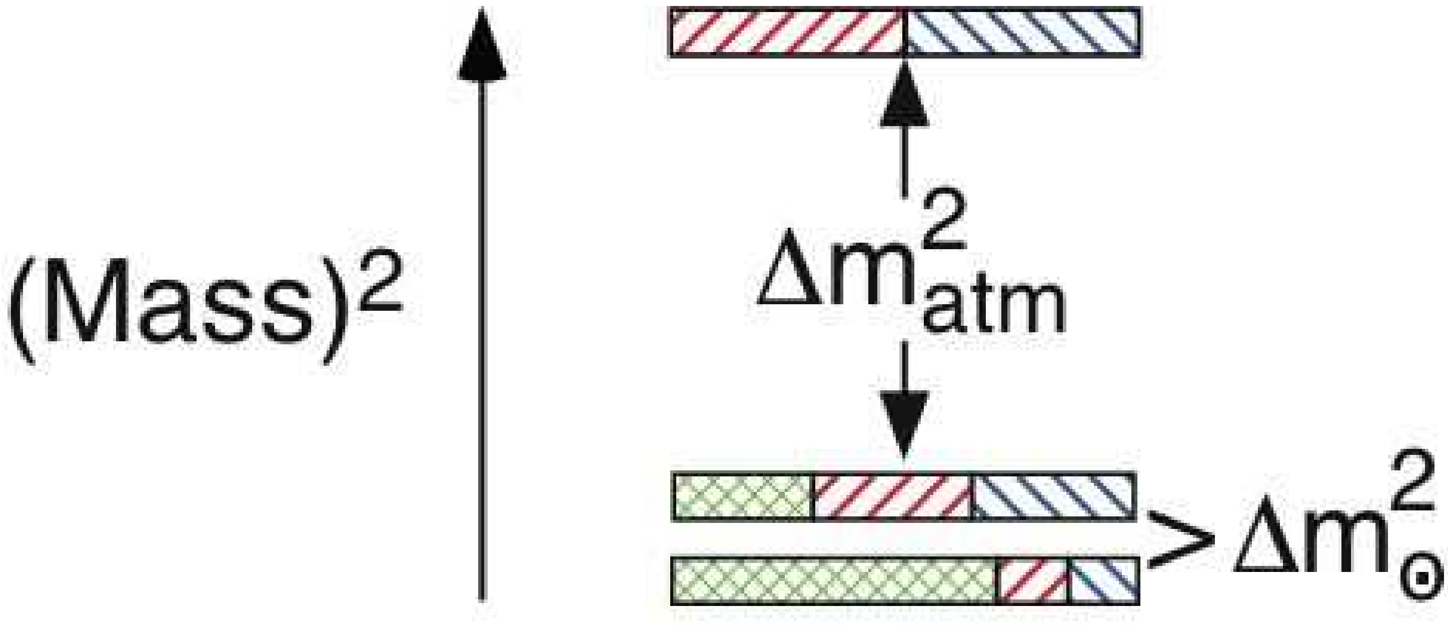
Solar neutrinos $\nu_e \to \nu_X$

Neutrino Oscillation Revolution



Compilation of experimental results

Neutrino Oscillation Revolution



Flavor composition: cross-hatched ν_e;
left-leaning ν_τ; right-leaning ν_μ

Neutrino Oscillation Revolution

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- Cosmology + oscillation:
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- Lepton mixing as deduced from neutrino oscillation data very different from quark mixing.

Neutrino Oscillation Revolution

- Lepton mixing:

$$U_{PMNS} \sim \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

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- Quark mixing with $\lambda \sim 0.2$

$$U_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

Neutrino Oscillation Revolution

The Standard Model