GRASPA

Neutrino physics

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Karlsruher Institut für Technologie

elusives
neutrinos, dark matter & dark energy physics
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Annecy-le-Vieux, 26 July 2016

Outline

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Neutrinos ...

- are particles with very small mass:

$$m_{\text{neutrino}} \lesssim 1\,\mathrm{eV} \sim 10^{-6}\, m_{\text{electron}}$$

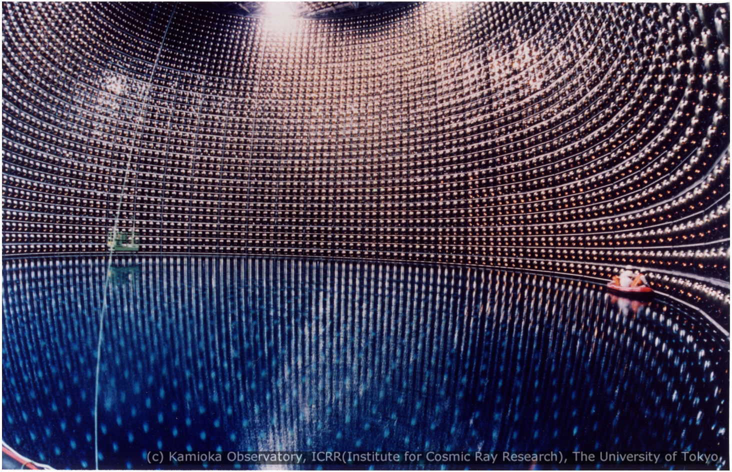
- have spin-1/2 (“matter particles” called “fermions”) like the electron, proton, quarks
- are the only known electrically neutral fermions
- participate only in weak interaction and gravitation (neither electro-magnetic nor strong force)

Neutrinos ...

- most abundant fermion in the Universe
  336 cosmic neutrinos/cm^3 (comparable to 411 CMB photons/cm^3)
- every second 10^{14} neutrinos from the Sun pass through your body
- neutrinos play a crucial role for our existence:
  - energy production in the Sun
  - Big Bang nucleo synthesis
  - generating the baryon asymmetry of the Universe (maybe)

How "weak" are weak interactions?

Super Kamiokande: 50 000 t water



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- Every second 10^{18} solar neutrinos are passing through the SuperKamiokande detector.
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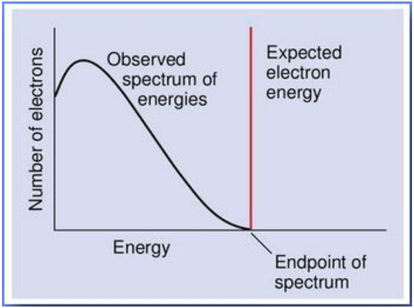
out of the 10^{18} neutrinos/s only 10^{14} are energetic enough to be seen by SuperK (^{8}B neutrinos) $\quad\rightarrow\quad 10^{19}$ ^{8}B neutrinos/day

"detection efficiency" of $14/10^{19} \simeq 10^{-18}$ (!)

Historical remarks

1930: missing energy in nuclear beta decay

$$(A, Z) \to (A, Z+1) + e^-$$



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$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

Wolfgang Pauli
(1900-1958)

Original - Photocopie of PLC 0393
Abschrift/15.12.56 PW

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

Historical remarks

- 1930: Wolfgang Pauli postulates “neutron” to save energy and angular momentum conservation in nuclear beta decay
- 1933: Enrico Fermi develops theory of beta decay and introduces the name “neutrino”
- 1956: first detection of neutrinos at a nuclear reactor by Frederick Reines and Clyde Cowan
- 1956/57: Wu demonstrates parity violation in weak interactions and Goldhaber shows that the neutrino is left-handed
- 1962: Discovery of a second neutrino kind (“flavour”) by Jack Steinberg, Melvin Schwartz and Leon Lederman
- 1969: detection of solar neutrinos by Ray Davis
- 1998, 2002: discovery of neutrino oscillations by the SuperKamiokande, SNO, KamLAND experiments proves that neutrinos have mass

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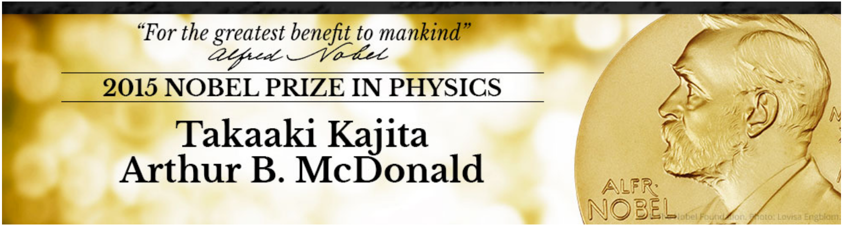
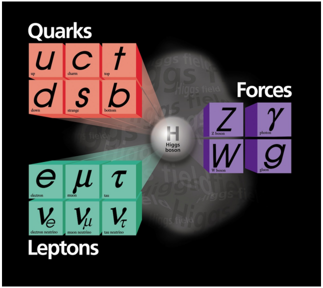


„…for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Outline

The Standard Model



Fermions in the Standard Model come in three generations ("Flavours")

Neutrinos are the "partners" of the charged leptons

for example: $\pi^+ \to \mu^+ \nu_\mu$

the muon neutrino ν_μ comes together with the charged muon μ^+

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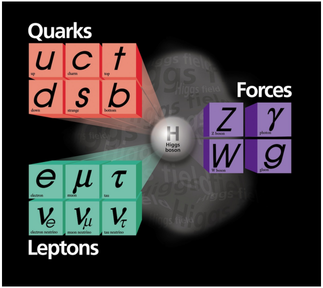

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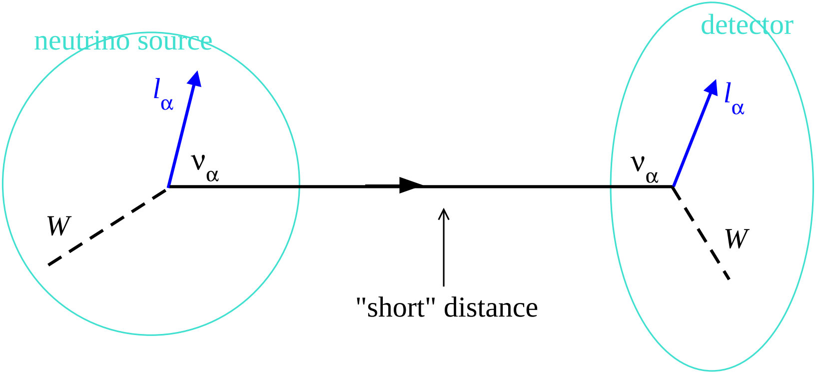
Flavour neutrinos



Lepton mixing

- Flavour neutrinos ν_α are superpositions of massive neutrinos ν_i:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \qquad (\alpha = e, \mu, \tau)$$

- $U_{\alpha i}$: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix
  $\rightarrow$ mismatch between mass and interaction basis

- Example for two neutrinos:

$$\begin{aligned} \nu_e &= \ \ \cos\theta\, \nu_1 + \sin\theta\, \nu_2 \\ \nu_\mu &= -\sin\theta\, \nu_1 + \cos\theta\, \nu_2 \end{aligned}$$

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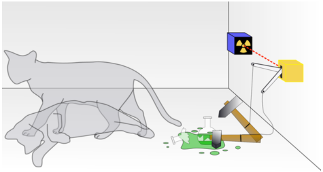

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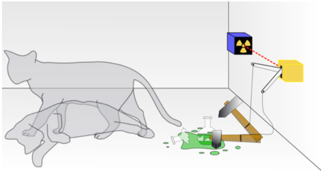
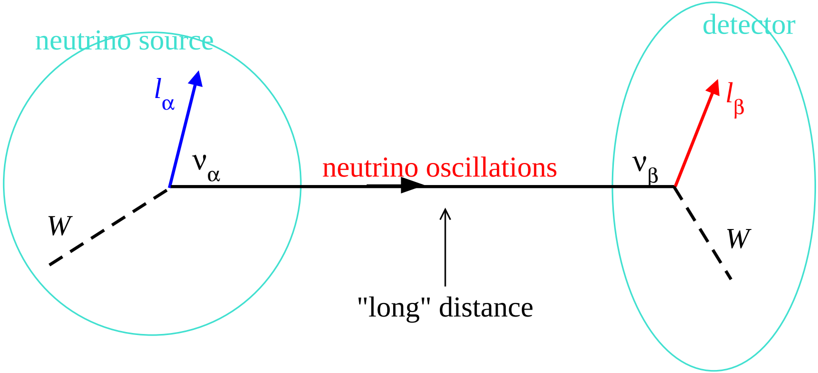


- The same phenomenon happens also for quarks (CKM)

Outline

Neutrino oscillations



$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$ $\qquad$ $e^{-i(E_i t - p_i x)}$ $\qquad$ $|\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$

Neutrino oscillations in vacuum

oscillation amplitude:

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta | \quad \text{propagation} \quad | \nu_\alpha \rangle$$

$$= \sum_{i,j} U_{\beta j} \langle \nu_j | \quad e^{-i(E_i t - p_i x)} \quad | \nu_i \rangle U^*_{\alpha i} = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i(E_i t - p_i x)}$$

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oscillation probability:

$$P_{\nu_\alpha\to\nu_\beta} = \left|\mathcal{A}_{\nu_\alpha\to\nu_\beta}\right|^2$$

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Evolution of flavour state can be described by effective Schrödinger equ.:

$$i \frac{d}{dt} \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} \qquad \text{where} \qquad H = U \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger$$

A hand-waving derivation for two flavours

oscillation phase:

$$\phi = (E_2 - E_1)t - (p_2 - p_1)x \quad \text{with} \quad E_i^2 = p_i^2 + m_i^2$$

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define: $\Delta E = E_2 - E_1, \quad \Delta E^2 = E_2^2 - E_1^2, \quad \bar{E} = (E_1 + E_2)/2$

then: $\Delta E^2 = 2\bar{E}\Delta E$ (similar for p and m)

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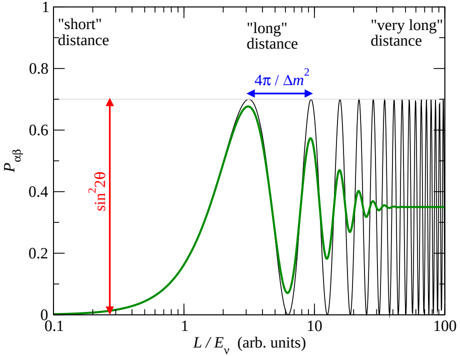
use "average velocity" of the neutrino $v = \bar{p}/\bar{E}$ and $x \approx vt$:

$$\boxed{\phi \approx \frac{\Delta m^2}{2\bar{p}} \approx \frac{\Delta m^2}{2\bar{E}}}$$

2-neutrino oscillations

Two-flavour limit:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



$$\frac{\Delta m^2 L}{4E_\nu} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}$$

to observe oscillations one needs

- non-trivial mixing θ
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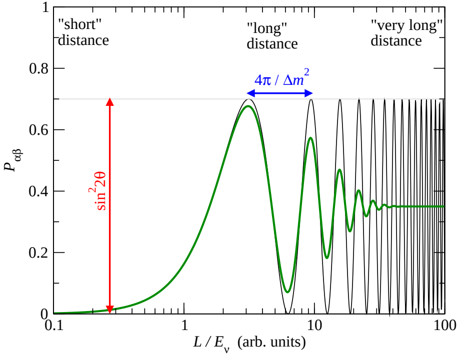

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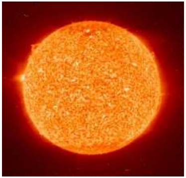
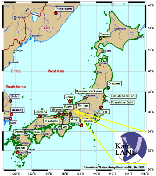
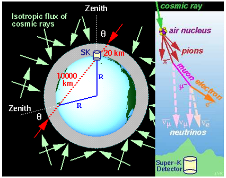
Global data on neutrino oscillations

various neutrino sources, vastly different energy and distance scales:

sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, D-CHOOZ DayaBay, RENO	SuperKamiokande	K2K, MINOS, T2K OPERA

- global data fits nicely with the 3 neutrinos from the SM
- a few “anomalies” at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum

Three-flavour oscillation parameters

2 mass-squared differences, 3 mixing angles, 1 complex phase
global fit results at www.nu-fit.org v2.1

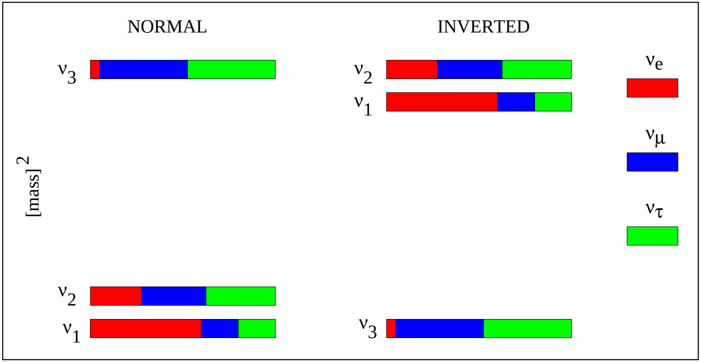
www.nu-fit.org

with C. Gonzalez-Garcia, M. Maltoni, 1409.5439

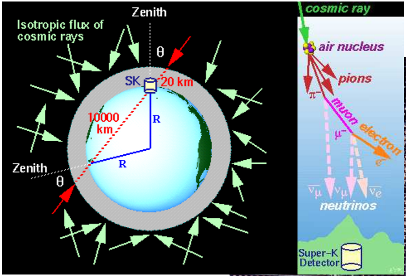
precision @ 3σ: $2\frac{x^{\rm up} - x^{\rm low}}{x^{\rm up} + x^{\rm low}}$

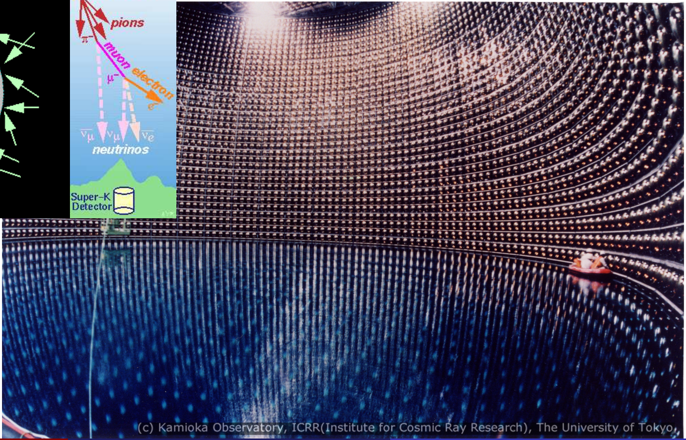
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range	
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$	14% (4.6°)
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$31.30 \to 35.90$	
$\sin^2\theta_{23}$	$0.451^{+0.051}_{-0.026}$	$0.382 \to 0.643$	$0.577^{+0.027}_{-0.035}$	$0.389 \to 0.644$	$0.385 \to 0.644$	32% (15°)
$\theta_{23}/^\circ$	$42.2^{+2.9}_{-1.5}$	$38.2 \to 53.3$	$49.4^{+1.6}_{-2.0}$	$38.6 \to 53.3$	$38.4 \to 53.3$	
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$	15% (1.2°)
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$	
$\delta_{\rm CP}/^\circ$	305^{+39}_{-51}	$0 \to 360$	251^{+66}_{-59}	$0 \to 360$	$0 \to 360$	∞
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$	14%
$\frac{\Delta m^2_{3i}}{10^{-3}\ {\rm eV}^2}$	$+2.458^{+0.046}_{-0.047}$	$+2.317 \to +2.607$	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix}+2.325 \to +2.599 \\ -2.590 \to -2.307\end{bmatrix}$	11%

Neutrino masses and mixing



Atmospheric neutrinos



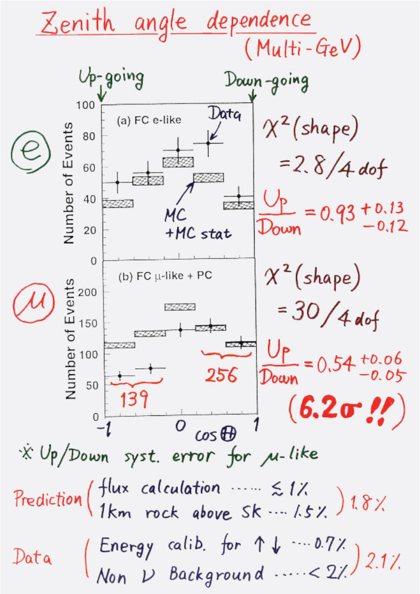


T. Kajita - atmospheric neutrinos oscillate

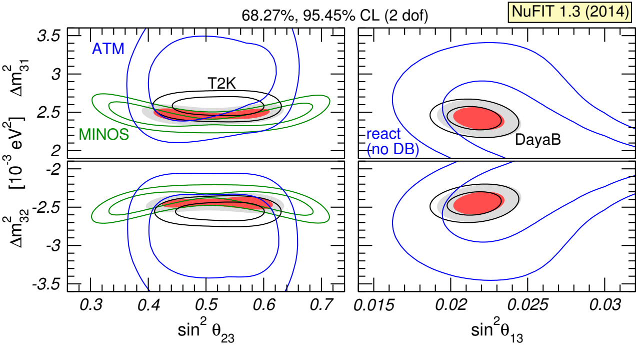
1998: SuperKamiokande atmospheric neutrinos

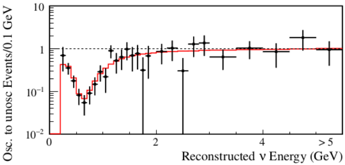
- zenith-angle dependent deficit of multi-GeV μ-like events
- consistent with $\nu_\mu \to \nu_\tau$ oscillations with

$\Delta m^2 \simeq 2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta \simeq 1$

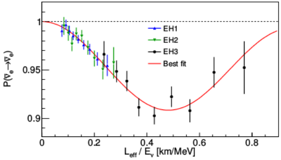


Oscillation parameters at the "atmospheric scale"



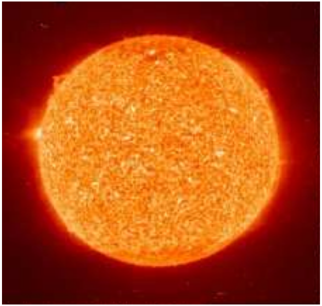


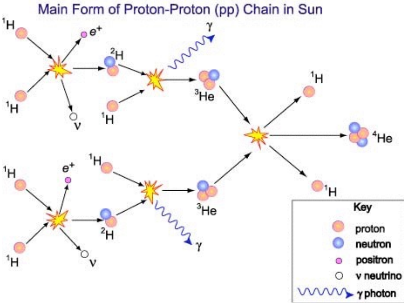
T2K, 2015 $\nu_\mu \to \nu_\mu$



DayaBay, 2013 $\bar{\nu}_e \to \bar{\nu}_e$

Solar neutrinos





long-standing solar neutrino problem (R. Davis, $\sim$ 1969)

The matter effect

When neutrinos pass through matter the interactions with the particles in the background induce an effective potential for the neutrinos

coherent forward scattering amplitude leads to an "index of refraction"
L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); *ibid.* D **20**, 2634 (1979)

- electron neutrinos recieve extra potential
  (only electrons in background medium, no μ and τ leptons)

Effective Schrödinger equation in matter

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

where

$$H = \underbrace{U \mathrm{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger}_{\text{vaccum}}$$

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$N_e(x)$: electron density along the neutrino path

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$N_e(x)$: electron density along the neutrino path

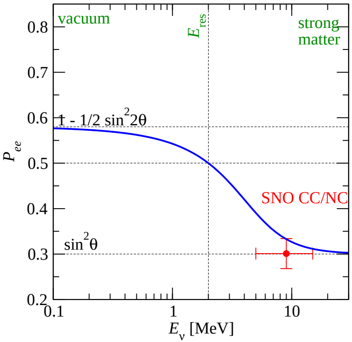
for non-constant matter: $H(t) \to$ time-dependent Schrödinger eq.
"MSW resonance" Mikheev, Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985)

A. McDonald - Sudbury Neutrino Observatory

2002: SNO: CC to NC ratio of solar neutrino flux

CC: $\nu_e + d \to p + p + e^-$
NC: $\nu_x + d \to p + n + \nu_x$

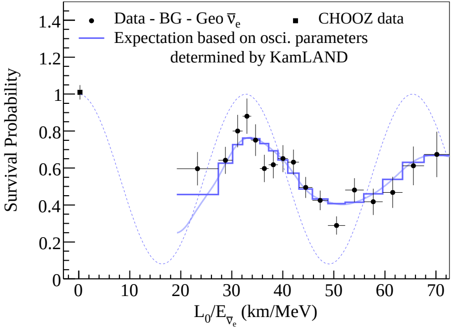
- evidence for $\nu_e \to \nu_\mu, \nu_\tau$ conversion
- MSW effect inside the sun adiabatic conversion through resonance

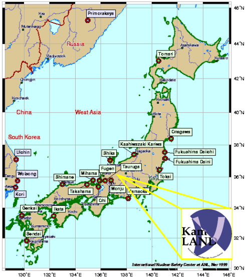


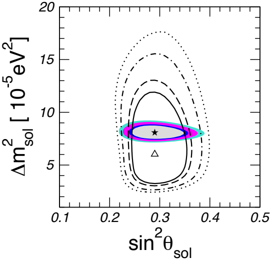
$$P_{ee} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau} = \frac{\phi_{\rm CC}}{\phi_{\rm NC}}$$

KamLAND reactor neutrino experiment

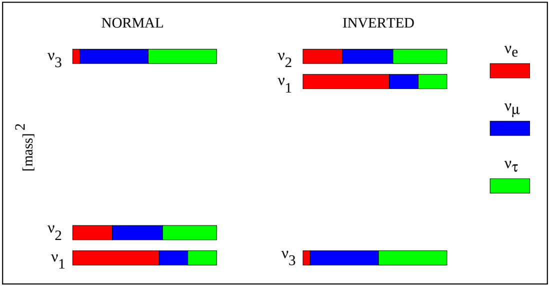
2004: evidence for spectral distortion







What do we know about mixing



- approx. equal mixing of ν_μ and ν_τ in all mass states: $\theta_{23} \approx 45^\circ$
- there is one mass state ("ν_1") which is dominantely ν_e ($\theta_{12} \approx 30^\circ$), and it is the lighter of the two states of the doublet with the small splitting (MSW in sun)
- there is a small ν_e component in the mass state ν_3: $\theta_{13} \approx 9^\circ$

The SM flavour puzzle

Lepton mixing:

$$\theta_{12} \approx 33^\circ \quad \theta_{23} \approx 45^\circ \quad \theta_{13} \approx 9^\circ$$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

Quark mixing:

$$\theta_{12} \approx 13^\circ \quad \theta_{23} \approx 2^\circ \quad \theta_{13} \approx 0.2^\circ$$

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & {\scriptstyle\epsilon} \\ \epsilon & 1 & {\scriptstyle\epsilon} \\ {\scriptstyle\epsilon} & {\scriptstyle\epsilon} & 1 \end{pmatrix}$$

What do we know about masses

- The two mass-squared differences are separated roughly by a factor 30

$$\Delta m^2_{21} \approx 7 \times 10^{-5}\text{eV}^2\,, \quad |\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2.4 \times 10^{-3}\text{eV}^2$$

- at least two neutrinos are massive
  (one could still be massless)
- typical mass scales

$$\sqrt{\Delta m^2_{21}} \sim 0.0086\,\text{eV}$$
$$\sqrt{\Delta m^2_{31}} \sim 0.05\,\text{eV}$$

  are much smaller than all other fermion masses
- we do not know absolute masses
- we do not know the mass ordering

Outline

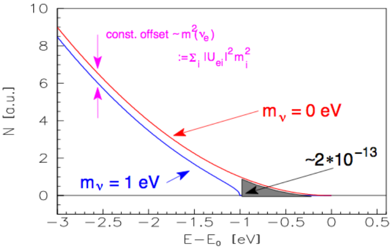
Three ways to measure absolute neutrino mass

- Endpoint of beta spectrum
- Cosmology
- Neutrinoless double beta-decay

Beta spectrum endpoint

measure spectrum of electrons from $(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$ close to the Q-value → neutrino nearly non-relativistic

- "direct" measurment of mass due to kinematics
- current limit around 2 eV, KATRIN sensitivity 0.2 eV
- sensitive to the combination $m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$



Tritium decay: $^3H \to ^3He + e^- + \bar{\nu}_e$ (endpoint: 18.57 keV)

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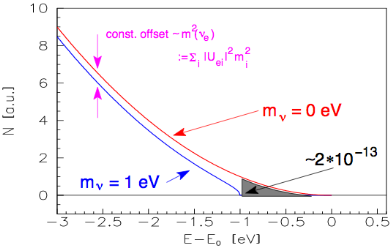


Tritium decay: $^3H \to ^3He + e^- + \bar{\nu}_e$ (endpoint: 18.57 keV)

We are "seeing" the cosmic neutrino background

- expect cosmic neutrino background, similar to CMB
- temperature slightly lower than CMB: $T_\nu = 1.95$ K
- PLANCK CMB + other cosmological data: $N_{eff} = 3.15 \pm 0.23$ [1502.01589]

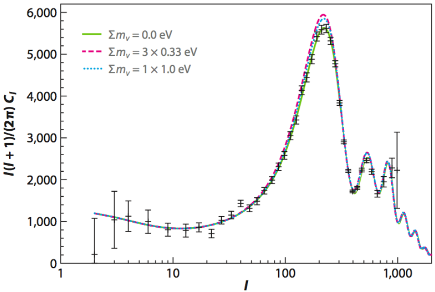
Contribution of neutrinos to the energy density

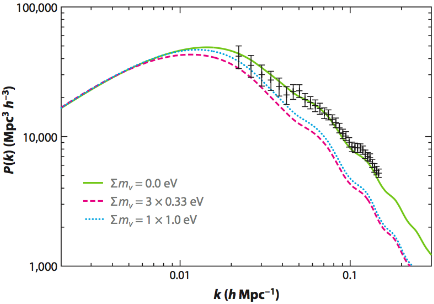
$$\Omega_\nu = \frac{\sum_i m_i}{93.14 h^2\,\mathrm{eV}} \qquad (h^2 \approx 0.5)$$

- non-trivial bound by requiring $\Omega_\nu < 1$
- somewhat stronger bound by using that $\Omega_\Lambda \approx 0.7 \to$

$$\Omega_\nu < 0.3 \to \sum_i m_i \lesssim 15\,\mathrm{eV}$$

Effect of neutrino mass on CMB and LSS



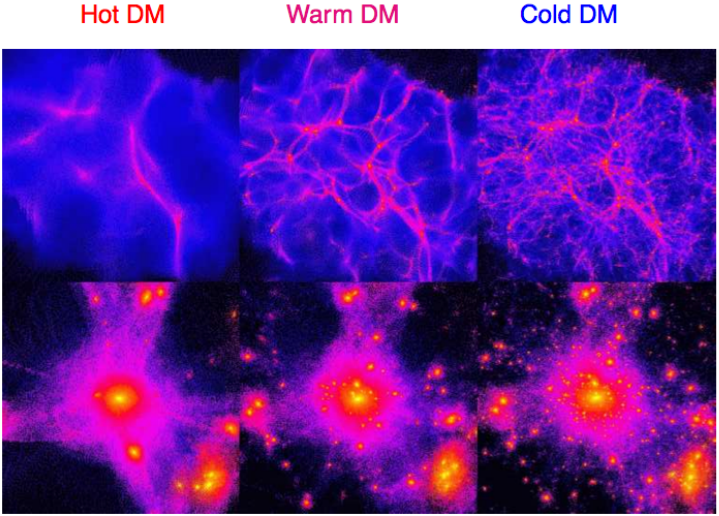


data points: WMAP 3yr and 2dF '05

Y.Y.Y. Wong, 1111.1436

- CMB: mainly height of 1st peak - degeneracies with other params
- LSS: suppression of structure at scales smaller than 1–10 Mpc

Hot versus cold DM



Ben Moore simulations

Effect of neutrino mass on CMB and LSS

- current data on CMB + LSS provides stringent limit on sum of neutrino masses
- depending on used data and complexity of the cosmological model:

$$\sum m_\nu < 0.14 - 0.23\,\text{eV}$$

- expect improvement by a factor ~ 10 from future large scale structure observations such as EUCLID or LSST

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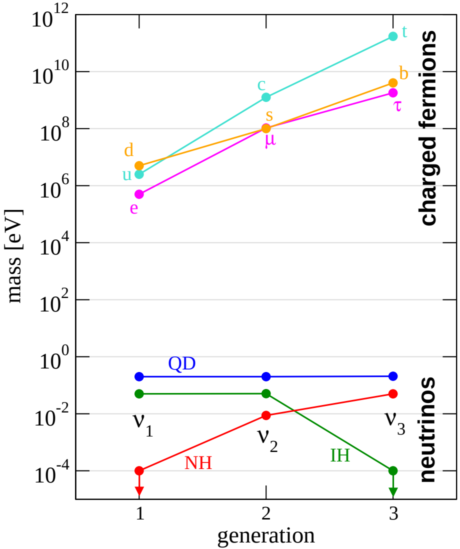
Outline

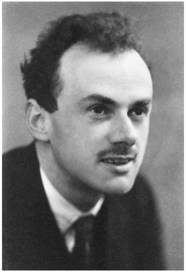
- In the Standard Model neutrinos are massless.
- The observation of neutrino oscillations implies that neutrinos have non-zero mass.

$\Rightarrow$ Neutrino mass implies physics beyond the Standard Model.

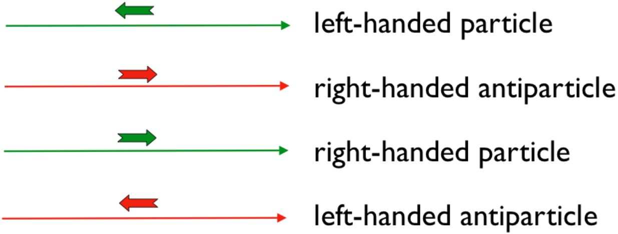


- Why are neutrino masses non-zero but so tiny?
- If the neutrino mass spectrum is inverted or quasi-degenerate it is very different from all other fermions in the SM

Masses in the Standard Model: Dirac fermions



Dirac: need 4 independent states to describe a massive fermion (spin-1/2 particle)



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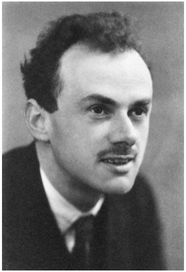
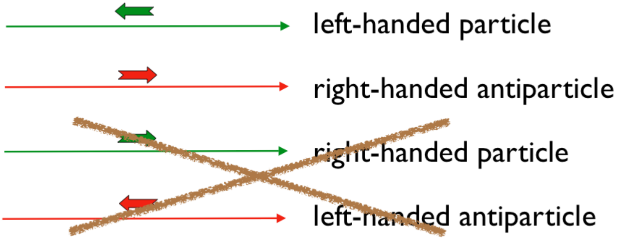


Dirac: need 4 independent states to describe a massive fermion (spin-1/2 particle)

BUT: in the SM there are no "right-handed neutrinos"

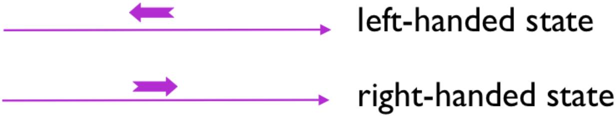
- complete gauge singlets
  (no interaction → "sterile neutrinos")
- no Dirac mass for neutrinos



Majorana fermions

Majorana: massive fermion out of only two states

- concept of “particle” and “antiparticle” disappears
- a Majorana fermion “is its own antiparticle”
- cannot asign a conserved quantum number $\rightarrow$ a charged particle cannot be Majorana



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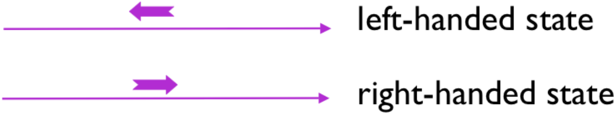

Lepton-number is an accidental symmetry in the SM $\rightarrow$ given the gauge symmetry and the field content of the SM we cannot construct a Majorana mass term for neutrinos (true at any loop order)

Adding right-handed neutrinos

- let's introduce right-handed neutrinos
- they are not protected by the SM symmetries
- their number needs not to be conserved and they may be Majorana particles
- they could be the source of Lepton number violation and induce a Majorana mass term for the SM neutrinos

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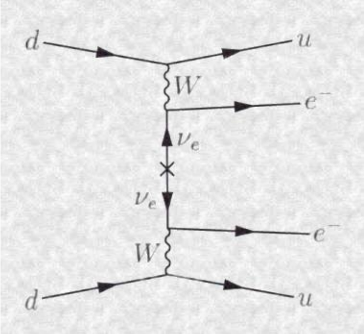
Seesaw mechanism:

ν_L are light because N_R are heavy

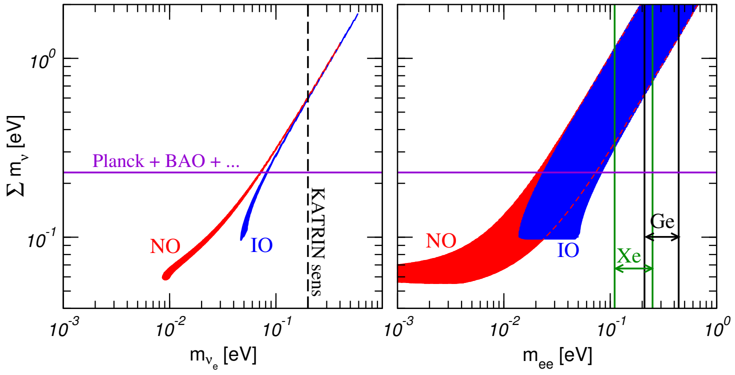
Neutrinoless double beta decay

search for lepton-number violation via $(A, Z) \to (A, Z+2) + 2e^-$



- absent for Dirac neutrinos
- rate of the process is proportional to $m_{ee} = |\sum_i U_{ei}^2 m_i|$

Complementarity



$0\nu\beta\beta$: Ge: GERDA + HDM + IGEX, Xe: KamLAND-Zen + EXO
ranges due to NME compilation from Dev et al., 1305.0056

What is the energy scale responsible for neutrino mass?