Neutrino Physics

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1. *history of neutrinos, ancient and modern*
2. *oscillations in quantum mechanics*
   (why can one use a Schrodinger Eqn ?)
3. from quantum mechanics to physics
   Beyond-the-Standard-Model
4. the scale of neutrino masses
5. leptogenesis ?

Why are neutrinos interesting ?

1. they are *Beyond the Standard Model* !
   the SM must be extended to include their small masses
2. they interact (only) weakly
   = probe otherwise-unattainable places (nuclear reactors, star interiors, waay back in cosmology...)
3. can calculate with quantum mechanics !
   (not need QuantumFieldTheory)

References (old)

other version of these lectures (2017 CERN school) : https ://physicschool.web.cern.ch/ESHEP/previous_eshep.html

Giunti website "neutrino unbound" : http ://www.nu.to.infn.it/

fits : http ://www.nu-fit.org/

Raffelt talks (astropart) :http ://wwwth.mpp.mpg.de/members/raffelt/

Plots thanks to Strumia + Vissani : hep-ph/0606054

simple 3-gen probabilities for LBL :Cervera etal 0002108 (+ later versions)

current state of oscillation measurements : Gonzalez-Garcia @ CERN ν plafform kickoff : https ://indico.cern.ch/event/572831/

neutrino cosmology : Lesgourgues at CERN ν plafform kickoff : https ://indico.cern.ch/event/572831/

(hypothetical/ /known) history of neutrinos (shy in the lab, relevant in cosmo)

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- inflation (gives large scale CMB fluctuations) (?driven by sneutrino ?)
- baryogenesis (excess of matter over anti-matter)via leptogenesis ?
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  $\Leftrightarrow$ 3 species of relativistic ν in the thermal soup
- decoupling of photons — $e + p \to H$ (CMB spectrum today)
  cares about radiation density $\leftrightarrow N_\nu, m_\nu$
- for 10^{10} yrs —stars are born, radiate (γ, ν), and die
- supernovae explode (?thanks to ν ?) spreading heavy elements

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- 1930 : Pauli hypothesises the "neutrino", to conserve E in $n \to p + e(+\nu)$
- 1953 Reines and Cowan : neutrino CC interactions in detector near a reactor
- invention of the Standard Model (SM) : massless ν
-
- **neutrinos have mass ! There is more in the Lagrangian than the SM...**

$\sim$ 1930 **:predicting the neutrino** :
observe β-decay : $(A, Z) \to (A, Z-1) + e^{+} (+\nu)$
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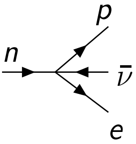
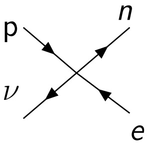
$\sim$ 1956 **:confirming the neutrino**
near a nuclear reactor (produces $\overline{\nu}$ flux : $n \rightarrow p + e + \overline{\nu}$)
Reines+Cowan detect $\overline{\nu} + p \rightarrow n + e^+$, $e^+ + e^- \rightarrow \gamma\gamma$
$\Rightarrow$ **ν exist, and have only weak interactions** (and gravity)



($t \longrightarrow$ in diagrams)



antiparticles

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$E^2 - |\vec{p}|^2 = m^2 \Rightarrow E = \pm\sqrt{m^2 + |\vec{p}|^2}$
NR limit : $E \simeq m + |\vec{p}|^2/2m + \ldots$?where went -ve E solns ?

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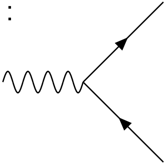

travels backwards-in-time from future
costs $+E$ in "my" frame

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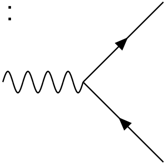

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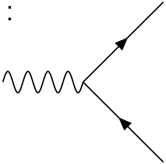

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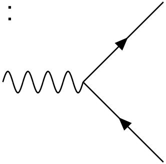

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How to tell particle from antiparticle ?
charges reversed : electron=$e = e^- \leftrightarrow e^+ = \bar{e}$=positron
no conserved charge ? Maybe part=$\overline{\mathrm{part}}$ (like photon = γ)
Is neutrino its own antiparticle ?

Interactions of neutrino($\equiv \nu$)

- "weak" interactions are weak (at low energy) :

we stand on earth ; most ν go through

$\sim$2 sec. for ν to escape sun, vs $\sim 10^3 \to 10^6$ yrs for γ(photon)

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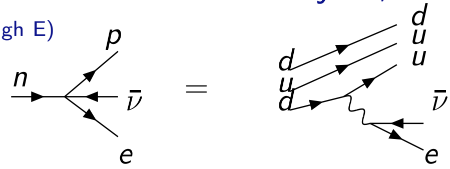

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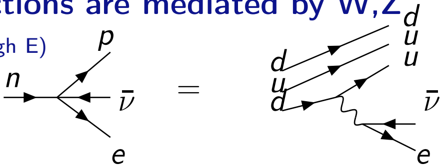

$$\mathcal{A} \sim \text{current} \times \text{propagator} \times \text{current} \quad , \quad p_n = p_p + p_{\bar{\nu}} + p_e$$

$$\sim g^2(\bar{u}\gamma^\alpha d_L)\frac{1}{p_W^2 - m_W^2}(\bar{e}\gamma_\alpha \nu_L) \quad p_W = p_n - p_p = p_{\bar{\nu}} + p_e$$

$$p_W^2 \sim (m_n - m_p)^2 \sim (0.1 \text{ GeV})^2 \ll m_W^2 \sim (80\text{GeV})^2$$

$$\sim \frac{g^2}{m_W^2}(\bar{u}\gamma^\alpha d_L)(\bar{e}\gamma_\alpha \nu_L)$$

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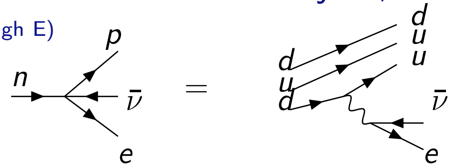

- **at least three neutrinos**

3 charged leptons= $\{e, \ \mu, \ \tau\}$. Observe each has own ν

(fermion wo strong int. ; (.5, 105, 1770 MeV)

$$\left\{ \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} , \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} , \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \right\}$$

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To calculate in a theory, evaluate PI : $\sim$ perturb in cplg ctes.
Can read particle properties/interactions from $\mathcal{L}$.

Historical problems : neutrinos disappear...

solar ν prob. ($>$50 years, many expts)

sun ($T_{core} \sim 2$ keV, $T_{surf} \sim .5$ eV$\approx$6000 ^oK, $R \sim 6 \times 10^{10}$cm)

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ν escape, γ diffuse to surface ($10^3 \to 10^6$yrs)
ν_e flux $\sim .3 \to .5$ expected from solar energy output

Flux in $\sum$ flavours $\sim$ expected (SNO).

Nobel-winning plot # 2 : SNO
solar ν_e deficit, but expected $\sum \nu_\alpha$ flux(PRL 89 (2002) 011301)

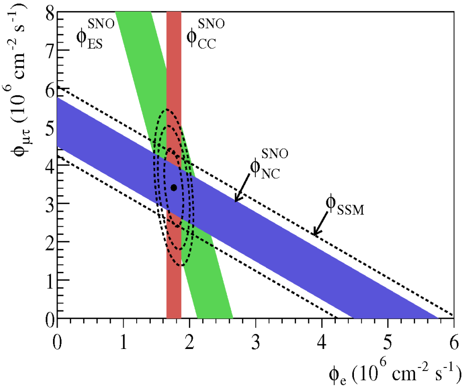


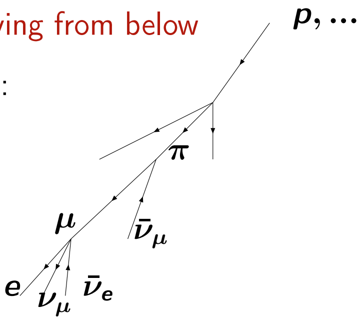
FIG. 3: Flux of ^{8}B solar neutrinos which are μ or τ flavor vs flux of electron neutrinos deduced from the three neutrino reactions in SNO. The diagonal bands show the total ^{8}B flux as predicted by the SSM [11] (dashed lines) and that measured

Sudbury Neutrino Expt

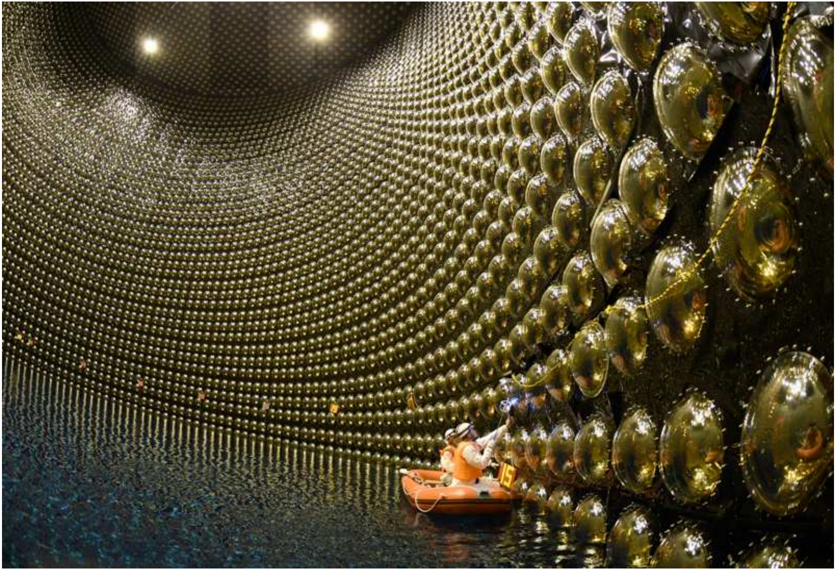
Atmospheric ν problem : deficit of ν_μ arriving from below

ν produced in cosmic ray interactions :
expect $N(\nu_\mu + \bar{\nu}_\mu) \simeq 2N(\nu_e + \bar{\nu}_e)$

height atmosphere $\sim$ 10-100km,
$R_{earth} \sim$ 6000km

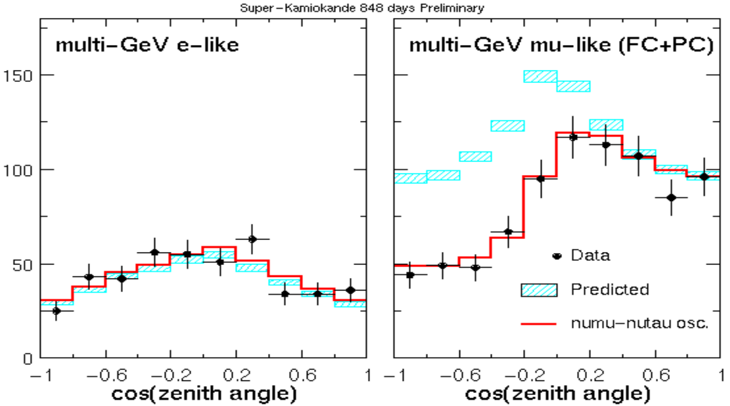


...see deficit of $\nu_\mu, \bar{\nu}_\mu$ from below



(photo courtesy of SK)

Nobel plot #1 : SK-98 :
$\nu_\mu + H_20 \to \mu + ..$, deficit in ν_μ from below (PRL 81 (1998) 1562-1567)



upwards $\leftrightarrow$ cos= -1 ; down $\leftrightarrow$ cos= + 1.
L : 20 km $\leftrightarrow$ 10 000 km.

Lets calculate !

oscillations of massive ν

a relativistic muon decays at the top of the atmosphere, produces a ν.
Suppose massive ν_2, ν_3, but not reconstruct $(E_\nu, \vec{k}_\nu)$ well enough to identify if ν is ν_3 or ν_2...
The ν travels to the SK detector, where it produces another μ

$\Rightarrow$ must sum in *amplitude* possibility to travel as ν_2 or ν_3
$\Leftrightarrow$ neutrino propagation is a quantum process

neutrinos “oscillate”(QM version : easy to rederive)

A relativistic neutrino, with momentum $\vec{k}$, is produced in muon decay at $t = 0$ (at Tokai/edge atmosphere). Describe as a quantum mechanical state :

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It travels a distance L in time t to the detector (SuperK)

$$|\nu(t)\rangle$$

where it produces an μ in CC scattering. With what probability ?

$$\mathcal{P}_{\mu\to\mu}(t) = |\langle\nu_\mu|\nu(t)\rangle|^2 \quad = \quad ?$$

1. Suppose massive neutrinos (two generations for simplicity).
   Flavour and mass eigenstates related by : $\nu_\alpha = U_{\alpha i}\nu_i$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}.$$

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3. If produce relativistic ν_μ at $t = 0$, then at t later :

$$|\nu(t)\rangle = \sum_j U_{\mu j}|\nu_j(t)\rangle = \sum_j U_{\mu j} e^{-iE_j t}|\nu_j\rangle$$

Amplitude for neutrino to produce charged lepton α in CC scattering in detector after t :

$$|\langle \nu_\alpha | \nu(t) \rangle| = \left| \sum_j U_{\mu j} e^{-iE_j t} U^*_{\alpha j} \right|$$

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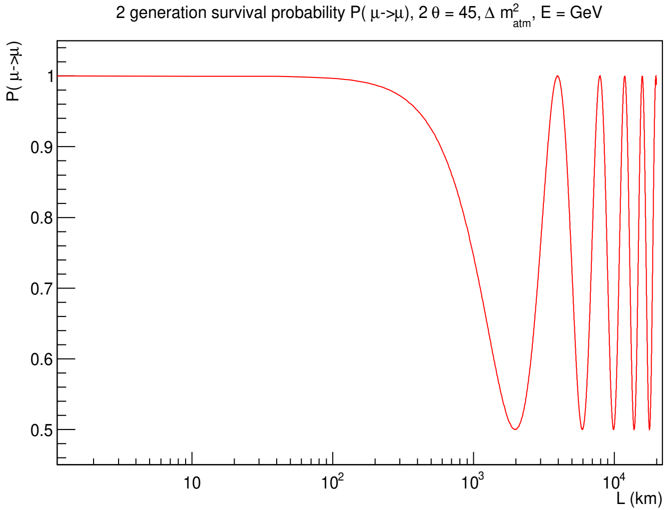
So in 2 generation case, using $t = L$, $E_3 - E_2 \simeq \frac{m_3^2 - m_2^2}{2E} \equiv \frac{\Delta^2_{32}}{2E}$:

$$\mathcal{P}_{\mu\to\tau}(t) = \left|\sin\theta\cos\theta\left(e^{i\Delta^2_{32}L/4E} - e^{-i\Delta^2_{32}L/4E}\right)\right|^2$$
$$= \sin^2(2\theta)\sin^2\left(L\frac{\Delta^2_{32}}{4E}\right)$$
$$\mathcal{P}_{\mu\to\mu}(t) = 1 - \sin^2(2\theta)\sin^2\left(L\frac{\Delta^2}{4E}\right) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{L}{km}\frac{\Delta^2}{\mathrm{eV}^2}\frac{\mathrm{GeV}}{4E}\right)$$

$E{=}\nu$ energy, L source-detector distance, $\Delta^2_{32} \sim 10^{-3}\mathrm{eV}^2$
$E \sim 10$ GeV for atmospheric νs ; L : $20km \to 10000km$



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$$\begin{aligned}\Delta^2_{32} &= 2.5\times10^{-3}\mathrm{eV}^2\\ E &\sim 0.6\mathrm{GeV(T2K)}\\ &\sim \mathrm{MeV(reactors)}\\ &\sim 10\mathrm{GeV(atmosphe}\end{aligned}$$

Schrodinger Eqn for relativistic particles ?
is ok : have Eqn for the number operator $\hat{n}_p \equiv \hat{a}_p^\dagger \hat{a}_p$:

$$i\frac{\partial}{\partial t}\hat{n} = [\hat{H}, \hat{n}]$$

...take expectation values and get QM version.
quantum coherence over km ?
• $m_\nu \ll$, so $\Delta_{expt}\sqrt{E_\nu^2 - |\vec{p}_\nu|^2} \gg m_\nu$ (decoherence slide)
• recall ν only interact *weakly*, can cross earth without interaction (no "observations" to collapse wavefns)
But...there is forward scattering $\Rightarrow$ effective contribution to m_ν from matter in sun, earth and supernovae (more later, maybe)

decoherence of neutrinos for large $L/E \gg 1/\Delta^2$

- at production, 2 superposed wavepackets of masses m_2,m_3.
- group velocity of packets

$$v_i = \frac{\partial E}{\partial p} = \frac{p}{E} \simeq 1 - \frac{m_i^2}{2E^2}$$

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- at production, 2 superposed wavepackets of masses m_2,m_3.
- group velocity of packets

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- no interference if larger than size of packets $\sim 1/(\delta E)$ where packet energy uncertain by δE. so no oscillations once

$$\frac{L}{\ell_{osc}} \gtrsim \frac{E}{\delta E}$$

can make similar estimate doing sum over paths, phases should sum coherently

Massive ν in the Standard Model

From antique 2-flavour QM calculation and astro problems to $\geq$ three light ν in a lively exptal programme using reactors, accelerators and astro sources

What masses ?

oscillations say there are mass differences : (global fits of www.nu-fit.org)

$$|\Delta^2_{atm}| = |\Delta^2_{3j}| = |m_3^2 - m_j^2| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$
$$\gg \Delta m^2_{21} \simeq 7.50 \pm 0.2 \times 10^{-5}\ \mathrm{eV}^2$$
$$\sqrt{\Delta m^2_{31}} \simeq 0.05\ \mathrm{eV} \qquad \sqrt{\Delta m^2_{21}} \simeq 0.008\ \mathrm{eV}$$

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\sqrt{\Delta m^2_{31}} &\simeq 0.05\ \mathrm{eV} \qquad \sqrt{\Delta m^2_{21}} \simeq 0.008\ \mathrm{eV}
\end{aligned}
$$

mass scale $\lesssim$ eV from

- cosmology : massive ν are DM today, and affect CMB.
- spectrum of e in β decay : Katrin expt
- $0\nu 2\beta$... if ν own antiparticle

And there are mixing angles

In 2 flavour, wrote :

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}.$$

but there are three lepton flavours in SM, should write

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} \\ & U & \\ \\ \end{bmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

U

Can write as :

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} P$$

$$\text{atm. + LBL disa.} \quad \text{reac.disa. + LBL app.} \quad \text{sol + reac.disa.}$$

$$= \begin{bmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{bmatrix} P$$

$$\theta_{23} \simeq \pi/4 \pm \pi/40 \quad \theta_{12} \simeq \pi/6 \quad \theta_{13} \simeq 8^o$$

(global fits of www.nu-fit.org)

Where to put U in SM ?

Previously wrote

$$\left\{ \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \;,\; \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \;,\; \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \right\}$$

write ν in mass eigenstates too(propagate eigenstates of Hamiltonian...)

Where to put U in SM ?

$$\ell_L^e \equiv \begin{pmatrix} U_{ei}\nu_L^i \\ e_L \end{pmatrix} \;, \; \ell_L^\mu \equiv \begin{pmatrix} U_{\mu j}\nu_L^j \\ \mu_L \end{pmatrix} \;, \ell_L^\tau \equiv \begin{pmatrix} U_{\tau k}\nu_L^k \\ \tau_L \end{pmatrix}$$

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3×3 mixing matrix $U_{\alpha,i}$ appears at $W^\pm$ vertices (like CKM)

$$\rightarrow \quad -i\,\frac{gU_{ej}^*}{\sqrt{2}}\overline{\nu_L^j}\gamma^\mu W_\mu^+ e_L + \ldots$$

but flavour-diagonal Z vertex :

$$\propto \sum_\alpha -i\,\frac{g}{2}U_{\alpha j}^*\overline{\nu_L^j}\gamma^\mu Z_\mu^+ U_{\alpha k}\nu_L^k = \delta_{jk}\frac{g}{2}\overline{\nu_L^j}\gamma^\mu Z_\mu^+ \nu_L^k$$

The drunken Unitarity triangle

Not hear much about “leptonic unitarity triangle”
1.not measure elements at tree in CC
2. Also, it drinks.

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Amplitude to oscillate from flavour α to β over distance L :

$$\mathcal{A}_{\alpha\beta}(L) = U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} e^{-i(m_2^2 - m_1^2)L/(2E)} + U_{\alpha 3} U^*_{\beta 3} e^{-i(m_3^2 - m_1^2)L/(2E)}$$

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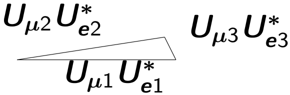
at $L = 0$ unitarity : $\Rightarrow \mathcal{A}_{\alpha\beta} = 1$ for $\alpha = \beta$
$\mathcal{A}_{\alpha\beta} = 0$ for $\alpha \neq \beta$

$\Leftrightarrow$ unitarity triangle(in complex plane)



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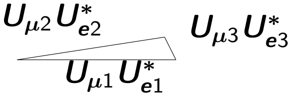

At $L = t \neq 0$, two of the vectors rotate in the complex plane, with frequencies $(m_j^2 - m_1^2)/2E$
oscillations $\leftrightarrow$ time-dependent non-unitarity

About two- flavour analyses : atm/LBL ν_μ disappearance

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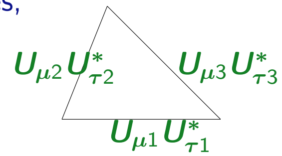
At $L \sim E/(m_3^2 - m_1^2)$, vector "3" rotates,
frequency $(m_j^2 - m_1^2)/2E$



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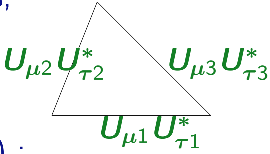


$\Rightarrow$ "Atmospheric" neutrinos, also LBL
(ν_μ disappearance via Δm^2_{31} oscillations) :

$$\mathcal{A}_{\mu\tau}(L) \simeq U_{\mu 1}U^*_{\tau 1} + U_{\mu 2}U^*_{\tau 2} + U_{\mu 3}U^*_{\tau 3}e^{-i(m_3^2-m_1^2)L/(2E)}$$

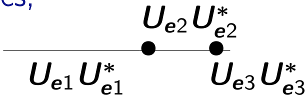
$U_{\mu 3}U^*_{\tau 3}$ oscillates on timescale $t = L \sim (m_3^2 - m_1^2)/E$
$U_{\mu 2}U^*_{\tau 2} \sim$ stationary, measure θ_{23}

About two- flavour analyses : solar and Kamland

Amplitude to oscillate from flavour e to e over distance L :

$$\mathcal{A}_{ee}(L) = U_{e1}U^*_{e1} + U_{e2}U^*_{e2}e^{-i(m_2^2-m_1^2)L/(2E)} + U_{e3}U^*_{e3}e^{-i(m_3^2-m_1^2)L/(2E)}$$

At $L \sim 2E/(m_2^2 - m_1^2)$, vector 2 rotates,
frequency $(m_2^2 - m_1^2)/2E$
vec. 3 spins rapidly



$\Rightarrow$ "Solar" + "KamLAND" (reactor $\overline{\nu_e}$ for $L \sim 100$ km) neutrinos
$\Leftrightarrow$ ν_e disappearance over long baselines $L \sim (m_2^2 - m_1^2)/2E$
two-ν approx works because θ_{13} is small ($U_{e3} = sin\theta_{13}$) :

$$\mathcal{A}_{ee} \simeq |U_{e1}|^2 + |U_{e2}|^2 e^{-i(m_2^2-m_1^2)\tau/(2E)}$$

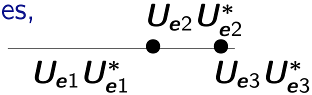
measure θ_{12}

About two- flavour analyses : θ_{13} at reactors

Amplitude to oscillate from flavour e to e over distance L :

$$\mathcal{A}_{ee}(L) = U_{e1}U_{e1}^* + U_{e2}U_{e2}^* e^{-i(m_2^2 - m_1^2)L/(2E)} + U_{e3}U_{e3}^* e^{-i(m_3^2 - m_1^2)L/(2E)}$$

At short enough L, only third vector rotates,
frequency $(m_3^2 - m_1^2)/2E$



$\Rightarrow$ reactor θ_{13} by $\overline{\nu_e}$ disappearance ; select short baseline such that only $|U_{e3}(t)|^2$ moves

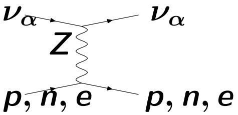
$$\begin{aligned} \mathcal{A}_{ee} &\simeq (|U_{e1}|^2 + |U_{e2}|^2) + |U_{e3}|^2 e^{-i(m_3^2 - m_1^2)L/(2E)} \\ &= c_{13}^2(c_{12}^2 + s_{12}^2) + s_{13}^2 e^{-i(m_3^2 - m_1^2)L/(2E)} \end{aligned}$$

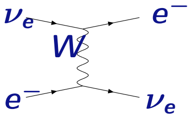
Flavour transition in matter

oscillations and adiabatic

Flavour transitions in matter

Coherent forward scattering of ν in matter give extra contribution to the Hamiltonian :





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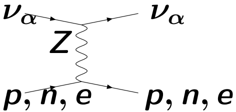

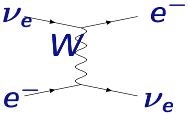

To see : use $\mathcal{H}_{\rm mat} = \mathcal{H}_0 + \mathcal{H}_{int}$ in QFT oscillation derivation,

$$\mathcal{H}_{int} \simeq 2\sqrt{2} G_F \int d^4x (\overline{\hat{\nu}_e}(x) \gamma^\alpha P_L \hat{\nu}_e)(\overline{\hat{e}} \gamma_\alpha P_L \hat{e}(x))$$

evaluated in a medium with electrons (NC irrelevant ; same for all ν generations = add unit matrix to H. And no μ or τ in the matter.)

$$\langle \mathrm{medium} | \overline{e} \gamma_\alpha P_L e(x) | \mathrm{medium} \rangle \to \delta_{\alpha 0} \frac{n_e}{2}$$

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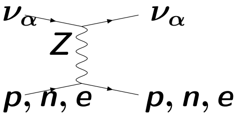

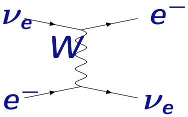

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$H_{\rm mat}$ in flavour basis $(\nu_e, (\nu_\tau - \nu_\mu)/\sqrt{2})$, $V_e = \sqrt{2}G_F n_e$:

$$H_{\rm mat} = ... + \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} 0 & 0 \\ 0 & \Delta^2/(2E) \end{bmatrix}\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} + \begin{bmatrix} V_e & 0 \\ 0 & 0 \end{bmatrix}$$

Oscillations in matter — ctd

$H_{\rm mat}$ in flavour basis $(\nu_e, (\nu_\mu + \nu_\tau)/\sqrt{2})$:

$$H_{\rm mat} \quad = \quad ... + \begin{bmatrix} -\frac{\Delta^2}{4E}\cos 2\theta + V_e & \frac{\Delta^2}{4E}\sin 2\theta \\ \frac{\Delta^2}{4E}\sin 2\theta & \frac{\Delta^2}{4E}\cos 2\theta \end{bmatrix}$$

With $U_{mat}^T H_{mat} U_{mat}^* =$ diagonal :

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$$\tan(2\theta_{\rm mat}) = \frac{\Delta^2 \sin(2\theta_{21})}{2EV_e - \Delta^2\cos(2\theta_{21})} \xrightarrow{2EV_e \to \Delta^2 c2\theta} \text{large}$$

$$\Delta^2_{\rm mat} = \sqrt{(\Delta^2 c2\theta - 2EV)^2 + (\Delta^2 s2\theta)^2}$$

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- for $V_e \ll \frac{\Delta^2}{2E}\cos(2\theta_{21})$, matter effects negligeable
- $\theta_{mat} \to \pi/4$ ("resonance") at $V_e = \frac{\Delta^2}{2E}\cos(2\theta_{21})$
- $V \gg \frac{\Delta^2}{2E}\cos(2\theta_{21})$: $\nu_e \sim$ mass eigenstate

What is V_e ?

$$H_{\rm mat} = \ldots + \begin{bmatrix} -\frac{\Delta^2}{4E}\cos 2\theta + V_e & \frac{\Delta^2}{4E}\sin 2\theta \\ \frac{\Delta^2}{4E}\sin 2\theta & \frac{\Delta^2}{4E}\cos 2\theta \end{bmatrix}$$

$$\tan(2\theta_{\rm mat}) = \frac{\Delta^2 \sin(2\theta_{21})}{2EV_e - \Delta^2\cos(2\theta_{21})}$$

$$\Delta m^2_{21} \simeq 7.5 \pm \times 10^{-5}\ \mathrm{eV}^2$$

$$V_e = \sqrt{2} G_F n_e \simeq 8\ \mathrm{eV} \frac{\rho Y_e}{10^{14} g/cm^3}$$

$$Y_e = \frac{n_e}{n_n + n_p}\ ,\ \rho = \begin{cases} 10 g/cm^3 & \mathrm{earth} \\ 100 g/cm^3 & \mathrm{sun} \\ 10^{14} g/cm^3 & \mathrm{SN} \end{cases}$$

For $\bar{\nu}$ V_e of opposite sign ! (because $\langle out|\bar{\hat{\nu}}\hat{\nu}|in\rangle \sim \langle out|\hat{a}^\dagger\hat{a} + \hat{b}\hat{b}^\dagger|in\rangle$)

$\Rightarrow$ solar matter effect for ν_e,not $\bar{\nu}_e$, fixes sign of $m_2^2 - m_1^2 > 0$.

Mass scale

First of 3 probes of the mass scale :cosmology

- **a late contribution to DM in cosmology :**

relic ν free-stream til they become non-rel. (after recomb. for $\Sigma \lesssim$ eV), then contribute to DM $\propto \sum_i |m_i| \equiv \Sigma$.

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• Σ has effects on CMB :

Relativistic $\rightarrow$ non-rel transition affects CMB propagation...parameter in cosmological fits :

Lesgourgues book

$$\sum \quad \lesssim \quad 0.1 \rightarrow .6\ eV \quad now: \ PLANCK, +LSS/Ly\alpha\ (in\ \Lambda CDM)$$

$$\lesssim \quad 0.6\ eV \quad now: \ PLANCK + BAO\ (in\ 12\ param\ \Lambda CDM$$

$$\rightarrow \ \lesssim 2m_{atm} \quad cosmo.indep.\ (Planck + EUCLID...)$$

$$\sim m_{atm} \quad \Lambda CDM$$

DiValentino etal
1507.06646

m_ν^2 distorts e spectrum in $n \to p + e + \bar{\nu}$ $\Leftrightarrow$bound
Consider Tritium β decay :
$^3H \to ^3 He + e + \bar{\nu}_e$, $Q = E_e + E_\nu = 18.6\mathrm{eV}$
where $E_e = Q - E_\nu \leq Q -$ "m_{e_ν}"

beta decay

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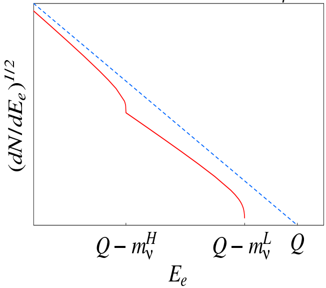
Endpoint of e spectrum :

$\frac{dN_e}{dE_e} \propto \sum_i |U_{ei}|^2 \sqrt{(18.6 \text{ keV} - E_e)^2 - m_{\nu_i}^2}$



Current Katrin bound $\gtrsim$ 0.3 eV.

beta decay

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Neutrinoless double beta decay : looking for lepton *number* violation

Single β decay kinematically forbidden for some nuclei
(eg ${}^{76}_{32}Ge$ lighter than ${}^{76}_{33}As$, so ${}^{76}_{32}Ge \rightarrow {}^{76}_{34}Se + ee\bar{\nu}_e\bar{\nu}_e$. $\tau \sim 10^{21}$ yrs)

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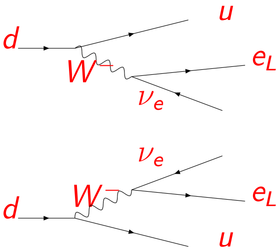

Single β decay kinematically forbidden for some nuclei
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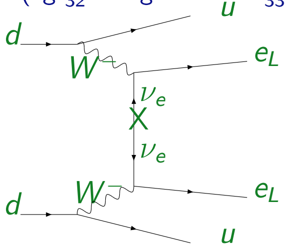
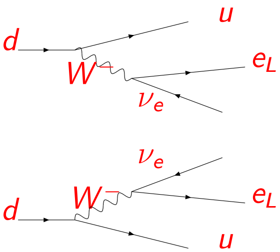
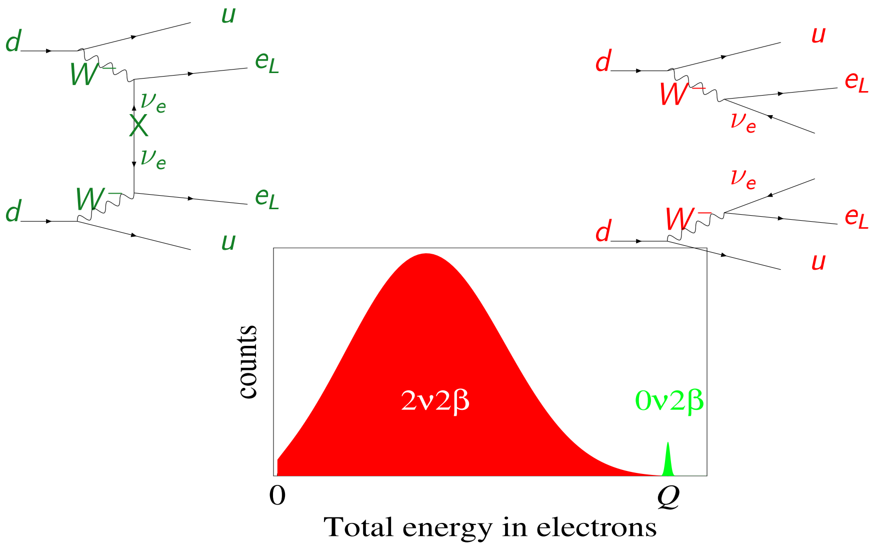




for majorana neutrinos, or other LNV, but not Dirac neutrinos.

Neutrinoless double beta decay : $(Z, A) \to (Z+2, A) + 2e$



Summary

1. neutrinos are crucial astrophysical and cosmological participants in the history of our Universe...much yet to learn about what they do
2. neutrinos are massive — we see oscillations— but we don't know how many light neutrinos, whether $\nu = \bar{\nu}$, whether there is CP violation, ...
3. neutrinos share a weak doublet with charged leptons : maybe we can learn about neutrino mass mechanism by studying flavour-change among charged leptons ?
4. although at colliders, neutrinos are just missing energy :(

Can neutrinos make the Universe we see ? *Leptogenesis*

a class of recipes, that use majorana neutrino mass models to generate the matter excess

- what matter excess ?
- required ingredients ?
- a simple seesaw model
- how it works...

Preamble

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$\Rightarrow$ Question : where did that excess come from ?

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   X no ! After birth of U, there was "inflation"
   - (only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions today...)
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3. created/generated/cooked after inflation...

Three ingredients to prepare in the early U (old russian recipe)

1. B violation : if Universe starts in state of $n_B - n_{\bar{B}} = 0$, need $\not{B}$ to evolve to $n_B - n_{\bar{B}} \neq 0$ Sakharov

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   From end inflation → BBN, Universe is an expanding, cooling thermal bath, so non-equilibrium from :
   - slow interactions : $\tau_{int} \gg \tau_U$ = age of Universe ($\Gamma_{int} \ll H$)
   - phase transitions :

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Yes ? proton appears stable :$\tau_p \gtrsim 10^{33}$ yrs ($\tau_U \sim 10^{10}$ yrs).

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Electroweak field configurations "of non-zero winding number" are sources of a doublet lepton and three (for colour) doublet quarks for each generation.

SM B+L violation : rates

't Hooft
Kuzmin Rubakov+
Shaposhnikov

At $T = 0$ is tunneling process (from winding # to next, "instanton") : $\Gamma \propto e^{-8\pi/g^2}$

At $0 < T < m_W$, can climb over the barrier :

$$\Gamma_{\not{B}+\not{L}} \sim \begin{cases} e^{-m_W/T} & T < m_W \\ \alpha^5 T & T > m_W \end{cases}$$

$\Rightarrow$ fast SM $\not{B}+\not{L}$ at $T > m_W$

SM $\not{B}+\not{L}$called "sphalerons"
$\Rightarrow$ if produce a lepton asym, "sphalerons" partially transform to a baryon asym. ! !
⋆⋆⋆ SM $\not{B}+\not{L}$is $\Delta B = \Delta L = 3$ $(= N_f)$. No proton decay ! ⋆⋆⋆

Summary of preliminaries : A Baryon excess today :

• Want to make a baryon excess $\equiv Y_B$ after inflation, that corresponds today to ~ 1 baryon per 10^{10} γs.
• Three required ingredients : $\not{B}$, $\not{CP}$, $\not{TE}$.
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⇒ *evidence for physics Beyond the Standard Model (BSM)*

One observation to fit, many new parameters...

⇒ *prefer BSM motivated by other data* ⇔ m_ν ⇔ *seesaw !* (uses non-pert. SM $\not{B+L}$)

Type 1 seesaw, one generation

Add to SM a massive N (right-handed neutrino), without weak interactions, but mass-mixing to ν_L :

$$+m_D \overline{\nu_L} N \qquad\qquad +\frac{M}{2}\overline{N^c} N + h.c.$$

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$\Rightarrow$ neutrino mass matrix :

$$\left(\begin{array}{cc} \overline{\nu_L} & \overline{N^c} \end{array} \right) \left[\begin{array}{cc} 0 & m_D \\ m_D & M \end{array} \right] \left(\begin{array}{c} \nu_L^c \\ N \end{array} \right) \qquad\qquad (\nu_L^c \equiv (\nu_L)^c)$$

$\Rightarrow$ eigenvectors $\simeq$: ν_L with $m_\nu \sim \frac{m_D^2}{M}$, N with mass $\sim M$

The type I seesaw, 3 generations

Minkowski, Yanagida
Gell-Mann Ramond Slansky

- add 3 singlet N to the SM in charged lepton and N mass bases :
$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}_{\alpha J} \overline{N}_J \ell_\alpha \cdot H - \frac{1}{2} \overline{N_J} M_J N_J^c$$

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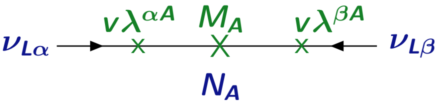

9 parameters :
m_1, m_2, m_3
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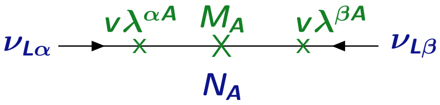

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$$[m_\nu] \;=\; \boldsymbol{\lambda} M^{-1} \boldsymbol{\lambda}^T v^2$$

$$\text{for} \quad \begin{array}{cc} \lambda \sim h_t \;, & M \sim 10^{15}\ \text{GeV} \\ \lambda \sim 10^{-6}, & M \sim \ \text{TeV} \end{array} \qquad \sim \quad .05\ \text{eV}$$

"natural" $m_\nu \ll m_f$, but N hard to detect ?

Leptogenesis in the type 1 seesaw : usually a Fairy Tale

Fukugita Yanagida
Buchmuller et al
Covi et al
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If this asymmetry can escape the big bad wolf of thermal equilibrium...

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2 The temperature drops below M, N population decays away.
3 In the $\not{CP}$ and $\not{L}$ interactions of the N, an asymmetry in SM leptons is created.
4 If asymmetry escapes the wolf of thermal equilibrium...
5 the lepton asym gets partially reprocessed to a baryon asym by non-perturbative $B + L$ -violating SM processes (“sphalerons”)
And the Universe lived happily ever after, containing many photons. And for every 10^{10} photons, there were 6 extra baryons (wrt anti-baryons).

Summary

Leptogenesis is a class of recipes, that use (majorana) neutrino mass models to generate the matter excess.
These scenarios generate a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses it to a baryon excess.
⋆ efficient, to use the BSM for m_ν to generate the Baryon Asym.
⋆ using SM B+L violn ($\Delta B = \Delta L = 3$) avoids proton lifetime bound
⋆ seems to work ...rather well, for a wide range of parameters