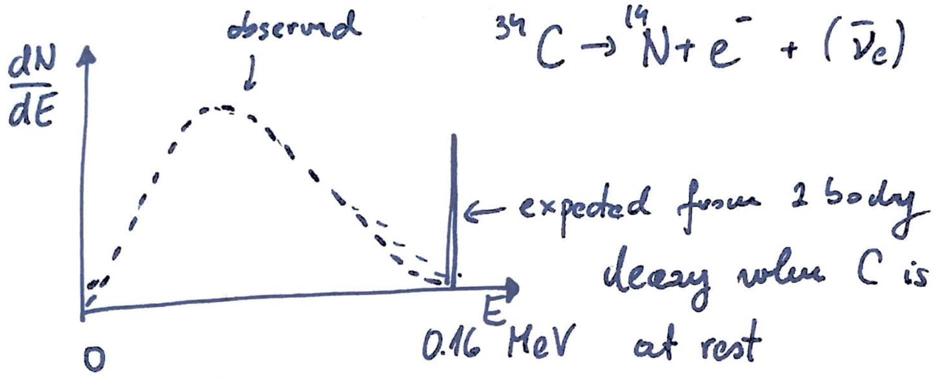
FABRIZIO'S LECTURES 25.2. & 26.2.2021

1) Neutrinos oscillations

Astophysics, LHC, Flavor, Cosmology, $0\nu 2\beta$, Higgs

Chadwick, '14

$^{34}C \to {}^{14}N + e^- + (\bar{\nu}_e)$



Pauli, '30

↓

letter to friends → introduces the "neutron"

Chadwick '30 - '34 → discovers the real neutron

$L_\nu \sim 10^{24}$ cm ... mean free path ~ size of the Universe

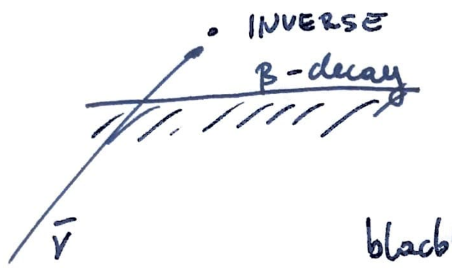
$\sim 1.6 \cdot 10^3$ tyr

SOURCES

- Big bang ($C\nu B$)
- Stars $10^{37}/s \to 10^{10}/s$ on Earth
- Sun ↗
- Nuclear plants $10^{23}/s$
- Natural radioactivity (~ 5000/s from Potassium, like in bananas)

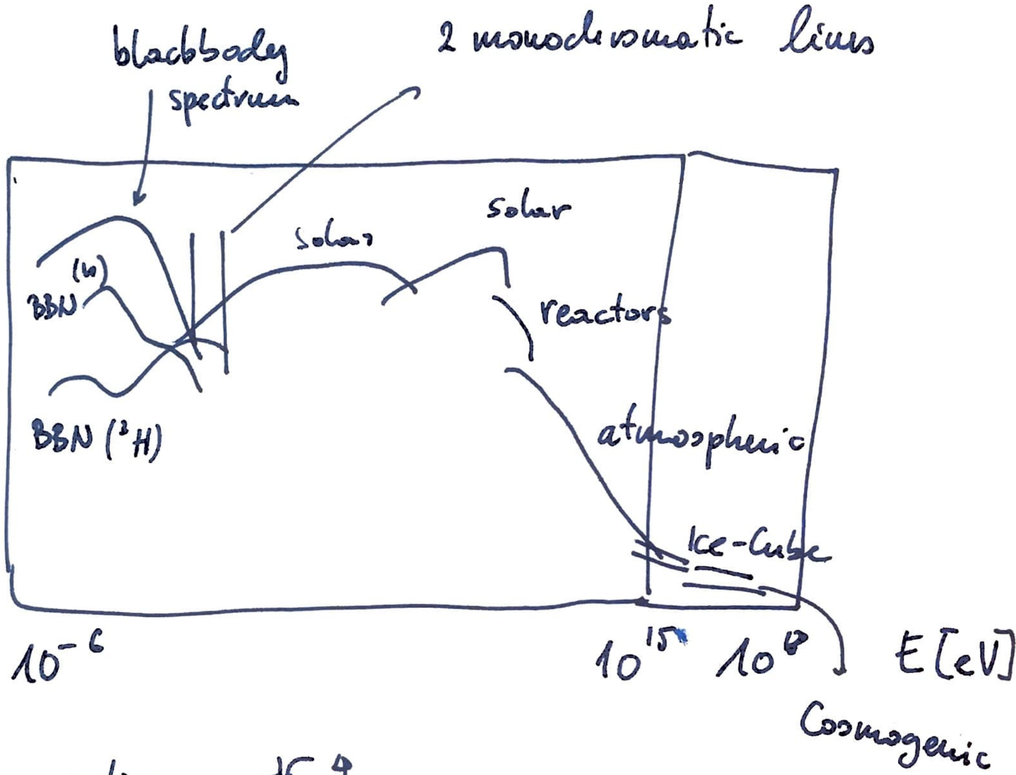
'56 Reines & Cowan : "Poltergeist" experiment

SCINTILLATOR



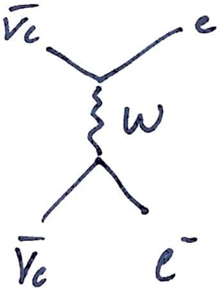
$H_2O + CdCl_2$

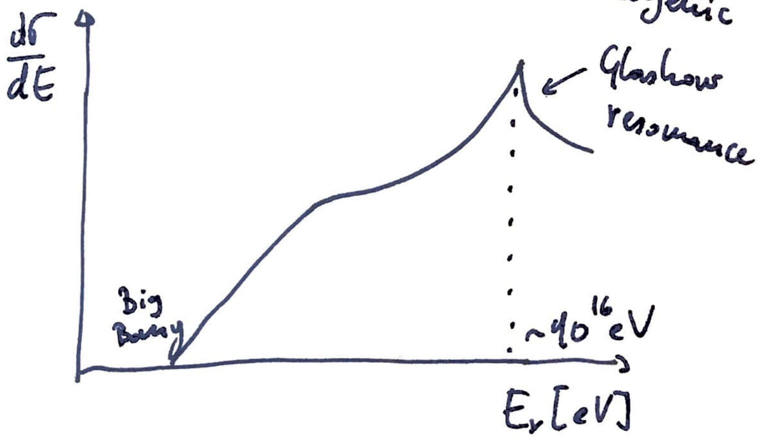
"GUNS" plot



• neutrino cross-section

$\sigma \propto G_F^2 \cdot s$





• on the resonance :

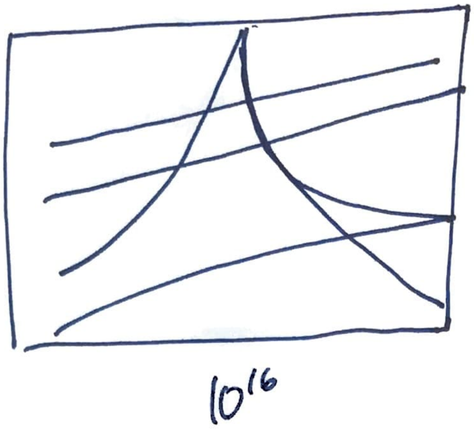
$$s = Q^2 = (p_e + p_\nu)^2 = \overset{= 0}{m_e^2} + \overset{= 0}{m_\nu^2} + 2 p_e p_\nu \simeq 2 E_\nu m_e \sim M_W^2$$

$p_e \sim (m_e, \vec{0})$

$p_\nu \sim (E_\nu, E_\nu)$

$$\Rightarrow E_\nu = \frac{M_W^2}{2\cancel{E}m_e} \sim \frac{(80\,\mathrm{GeV})^2}{2 \cdot 0{,}5\,\mathrm{MeV}} = 10^{16}\mathrm{e}$$

- Resonance in more detail:



Glashow resonance

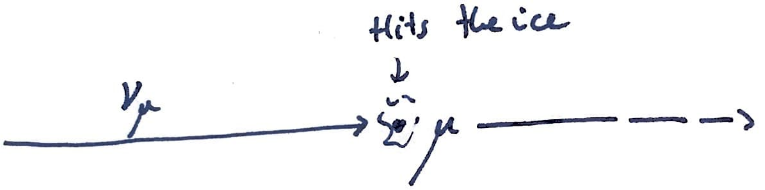
$\Downarrow$

$M_W \sim 80\,\text{GeV}$

- could also probe new physics @ higher masses.

- Ice Cube Halzen '21 $E_\nu \sim 6.3\,\text{PeV}$,

  - sources AGN, Blazars



  - delayed coincidence of light wrt. ν's.

OSCILLATIONS

'57, Pontecorvo $\nu - \bar{\nu}$ oscillations like $K^0 - \bar{K}^0$

'62, Maki, Nakagawa, Sakata

'69, Gribov, Pontecorvo → full theory

Neutrino oscillation theory

PMNS mixing matrix for neutrinos, like the CKM mixing for quarks

- Charged lepton masses

$$\mathcal{L}_Y = \bar{L}'_L M^{(e)} l'_R \quad , \quad \vec{l}' = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

- In general, M is $\mathbb{C}$ and non-diagonal, need to perform a bi-unitary transformation

$$M^{(e)} = U_L \hat{M}^{(e)} V_L^+$$

- These two matrices will rotate the fields from their gauge basis L' to the mass basis

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} W_\mu^- \bar{l}'_L \gamma^\mu \nu'_L$$

$$= \frac{g}{\sqrt{2}} W^- \underbrace{\bar{l}'_L U_L} \gamma^\mu \overbrace{U_L^+ U_\nu}^{V_{PMNS}} \nu_L$$

mass eigenstate $\bar{l}_L \hat{M} l_R$

- If neutrinos are massless (or degenerate), the PMNS has no physical significance. If $m_\nu \neq 0$ U_{PMNS} has an impact.

→ The charged current mass becomes

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} W^-_\mu \bar{l}_L \gamma^\mu \underbrace{U_{PMNS} \overset{\text{mass eigenstate}}{\nu_L}}_{\nu_L' \text{ flavor eigenstate}}$$

mass eigenstate

in the mass basis, where the particles propagate

U_{ei} ... $N \times N$ matrix between (e, μ, τ) & (ν_1, ν_2, ν_3)

→ # of parameters

U_{PMNS} - unitary $U^\dagger_{PMNS} U_{PMNS} = 1$

→ replace N, $N^2 - N = N(N-1)$

- Some are angles $SO(N) \to \frac{N(N-1)}{2}$

$$\Rightarrow \# \text{ par} = \underbrace{\frac{N(N-1)}{2}}_{\text{angles}} + \underbrace{\frac{N(N-1)}{2}}_{\text{phases}}$$

; of which $N-1$ are external (Majorana) and $\frac{(N-1)(N-2)}{2}$ are inside the PMNS (Dirac)

- for $N=3$ generations, we have 3 angles and
2 Majorana phases and
1 Dirac phase

V_{PMNS} can be parametrized in $\overset{\text{many}}{\infty}$ ways, the standard one is (PDG)

the Dirac phase, δ

$$U_{\ell i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

three angles θ_{12}, θ_{23}, θ_{13}

two Majorana phases, α, β

- Now we can go to neutrino oscillations

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \bar{\ell}_{L\ell} U^{PMNS}_{\ell i} W^{\mu} \gamma_{\mu} \nu_{Li} + h.c. \qquad \ell = e, \mu, \tau$$

- Consider generating a beam of $\nu_{\ell = e,\mu,\tau} = \sum_{i=1}^{3} U_{\ell i} \nu_i$

flavor eigenstate

CERN : $p + \text{target} \to \pi^+ \to \mu^+ \nu_\mu$

SPS

$E_{\nu_\mu} \sim (10-30)$ GeV

$$\boxed{|\nu_\ell\rangle = U_{\ell i} \, |\nu_i\rangle} \quad , \quad U_{\ell i} = \text{unitary}$$

this is a flavor eigenstate, not an eigenstate of the Hamiltonian, which defines the time evolution

$$|\nu_e(t)\rangle = \sum_i U_{ei}\, e^{-iE_it} \quad , E_i^2 = p_i^2 + m_i^2$$

we produce a particle with a definite momentum but masses are different

so if $p_1 = p_2 = p_3$, $E_1 \neq E_2 \neq E_3$

- Amplitude for the $\ell \to \ell'$ transition

$$A_{\to e'}(t) = \langle \overset{\text{final}}{\nu_{e'}} | \overset{\text{initial}}{\nu_e(t)} \rangle$$

$$= \sum_{i,j} U^*_{e'j}\, U_{ei}\, e^{-iE_it} \underbrace{\langle \nu_j | \nu_i \rangle}_{=\delta_{ij}}$$

$$= \sum_i U^*_{e'i}\, U_{ei}\, e^{-iE_it} \xrightarrow{t=0} \delta_{ee'} = A$$

- The probability of conversion $\propto |A_{e\to e'}(t)|^2$

$$P_{e\to e'}(t) = |\langle \nu_{e'} | \nu_e(t)\rangle|^2 = \sum_{i,j} |U_{ei}\, U^*_{e'i}\, U^*_{ej}\, U_{e'j}| \cdot \cos[(E_i - E_j)t - \varphi_{ee'ij}]$$

comes from the phase in U_{PMNS}, $\varphi_{ee'ij} = \arg(U_{ei}\, U^*_{e'i}\, U_{ej}\, U_{e'j}$

- Let's ignore the CP-violating phase and consider the CP-conserving oscillations

- ν's have $E \sim$ MeV - GeV thus <u>very</u> relativistic

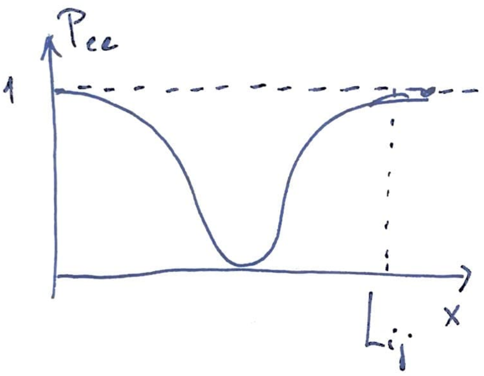
$p \gg m$: $E \sim p + \frac{m^2}{2p} \longrightarrow p$ when $m = 0$

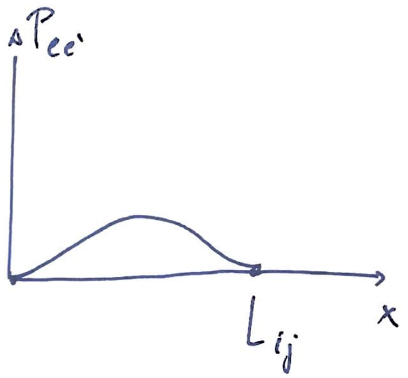
In this approximation : $P_{ee'}(t) = \sum |U_e U_e^* U_{ei}^* U_{e'j}|$

$x \sim t$ for $v \sim c = 1$ $\quad \times \cos\left(2\pi \frac{\overset{\sim t}{x}}{L_{ij}} - \varphi\right)$

$L_{ij} = \frac{4\pi |p|}{\Delta m_{ij}^2}$, $\Delta m_{ij}^2 = m_i^2 - m_j^2$, x... distance travelled

Oscillations :





$\downarrow$

The change of flavor only due to time evolution of the Hamiltonian on a state, which is a linear superposition of eigenstates.

use $\cos x = 1 - 2\sin^2\frac{x}{2}$

$\searrow$

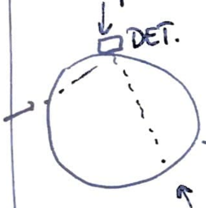
$$P_{ee'}(t) = \delta_{ee'} - 4\sum_{i>j} |U_{ei} U_{e'i}^* U_{ej}^* U_{e'j}| \sin^2\left(\frac{\Delta m_{ij}^2 x}{4E}\right)$$

(here we neglected $\varphi = 0$)

- what are the relevant numbers / units

$$\frac{\Delta m_{ij}^2}{4E} \cdot \left(\frac{c}{\hbar}\right) = 1.27 \left(\frac{\Delta m^2}{eV}\right)\left(\frac{L}{km}\right)\left(\frac{GeV}{E}\right)$$

- With these, we can estimate the sensitivities

	L [km]	E [GeV]	Δm^2
Reactor SBL	0.1	10^{-3}	$10^{-5} - 10^{-1}$
LBL	100		
Accelerators SBL	1	0.1 – 10	$10 - 10^{-2}$
LBL	100		
Atmosphere 	few – 1000 km	0.1 – 100 ↑ E of atm.	$> 10^{-3}$
Sun	10^8 km	10^{-3}	10^{-11} !

neutrinos oscillate a lot, about 10^6 times, then coherence is lost

TWO FLAVORS : $U_{ei} = \begin{pmatrix} \cos\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$, $|UUUU| = \frac{1}{4}\sin^2 2\theta$

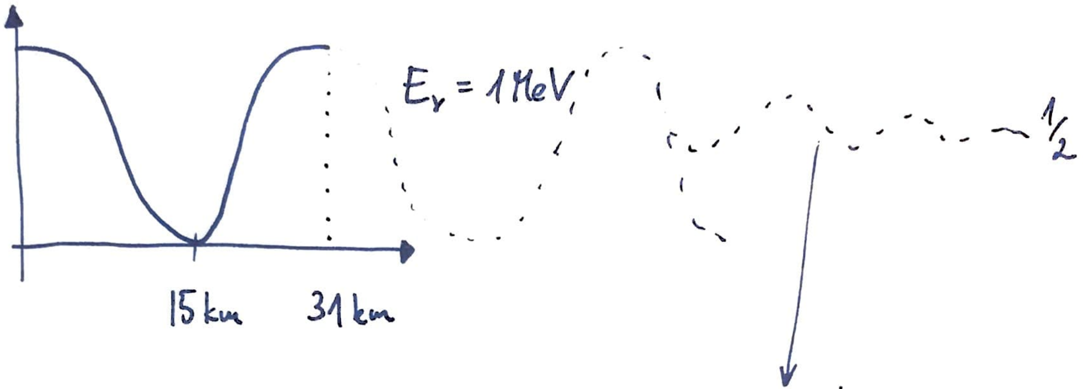
$$\boxed{P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4E} x\right)}$$

↑ appearance of muon neutrinos

1) ∝ $\sin^2(\Delta m^2)$ ⇒ insensitive to the sign of mass ordering, NH vs. IH

- Experiment : $\Delta m^2_{12} = 3 \cdot 10^{-5} eV^2 = (0.09 eV)^2$

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = \underline{31 \, km} \, \frac{E}{MeV}$$



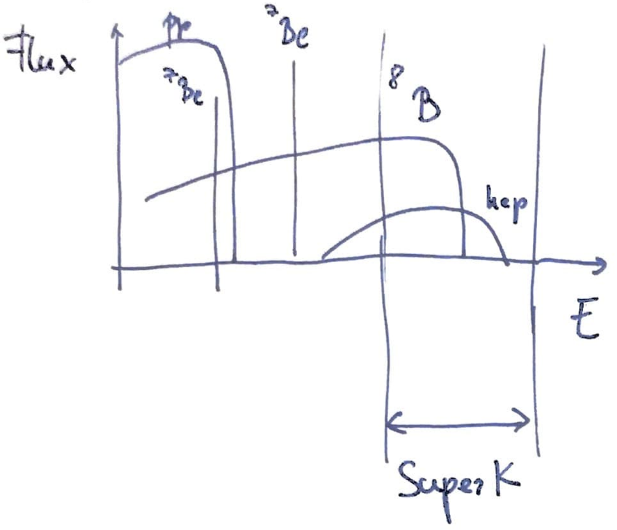
Loss of coherence : after many oscillations, the probabilities are averaged over different p's and in the 2-flavor case go to 1/2

[Mathematica demonstration project]

- e.g. solar neutrinos flux from the initial ν_e flux

→ for solar ν's we observe the averaged probabilities, for atmospherics neutrinos the oscillations are visible and reconstructed

SOLAR NEUTRINO PUZZLE

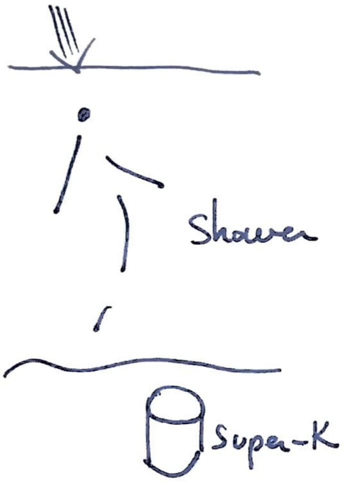


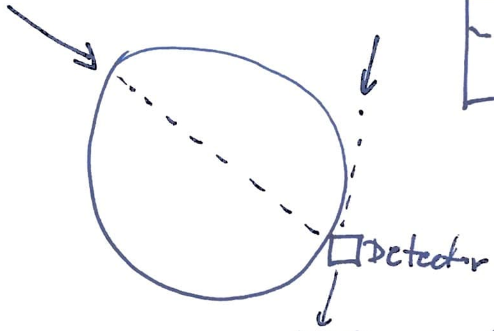
'60-'90 Bahcall = Solar model

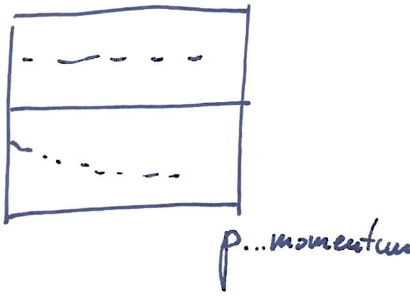
Davis => Homestake exp. in the South Dakota mine

2/3 missing!

ATMOSPHERIC NEUTRINOS



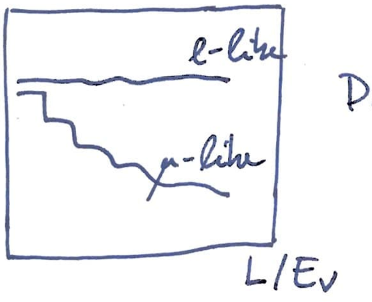




MACRO in Gran Sasso, Italy

SK... Super-Kamiokande in Jap

SK results:



DATA finds oscillations

- SNO (Sudbury Neutrino Observatory) also finds signals from neutral interactions. PRL '02 → 5σ
- KAMLAND ('02) : reactor neutrinos ~ 10^5 cm away (LBL)

150 km

PRESENT SITUATION

* T2K (Tokai to Kamioka): CPV & CPC parts

↳ sensitive to the Dirac phase and the hierarchy

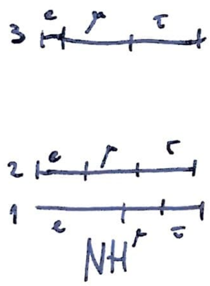
* Reactor anomalies and searches for sterile neutrinos.

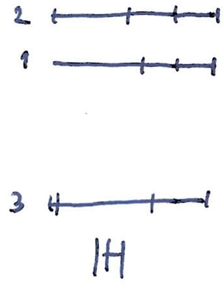
↳ not easy to estimate the neutrino reactor fluxes

SUMMARY: $\theta_{23} \sim 45$ $\theta_{12} \sim 34^\circ$ $\theta_{13} \sim 9^\circ$ δ_{CP}

$\Delta m^2_{12} \sim (0.01)^2 eV^2$ $\Delta m^2_{23} \sim (0.05)^2 eV^2$

★: We don't know: absolute mass scale, NH vs. IH,
(cosmology)
CP phases and Dirac vs. Majorana





- Neutrino physics applications
  - picture of the moon, reactors, tomography
  search for oil, communications, energy sources