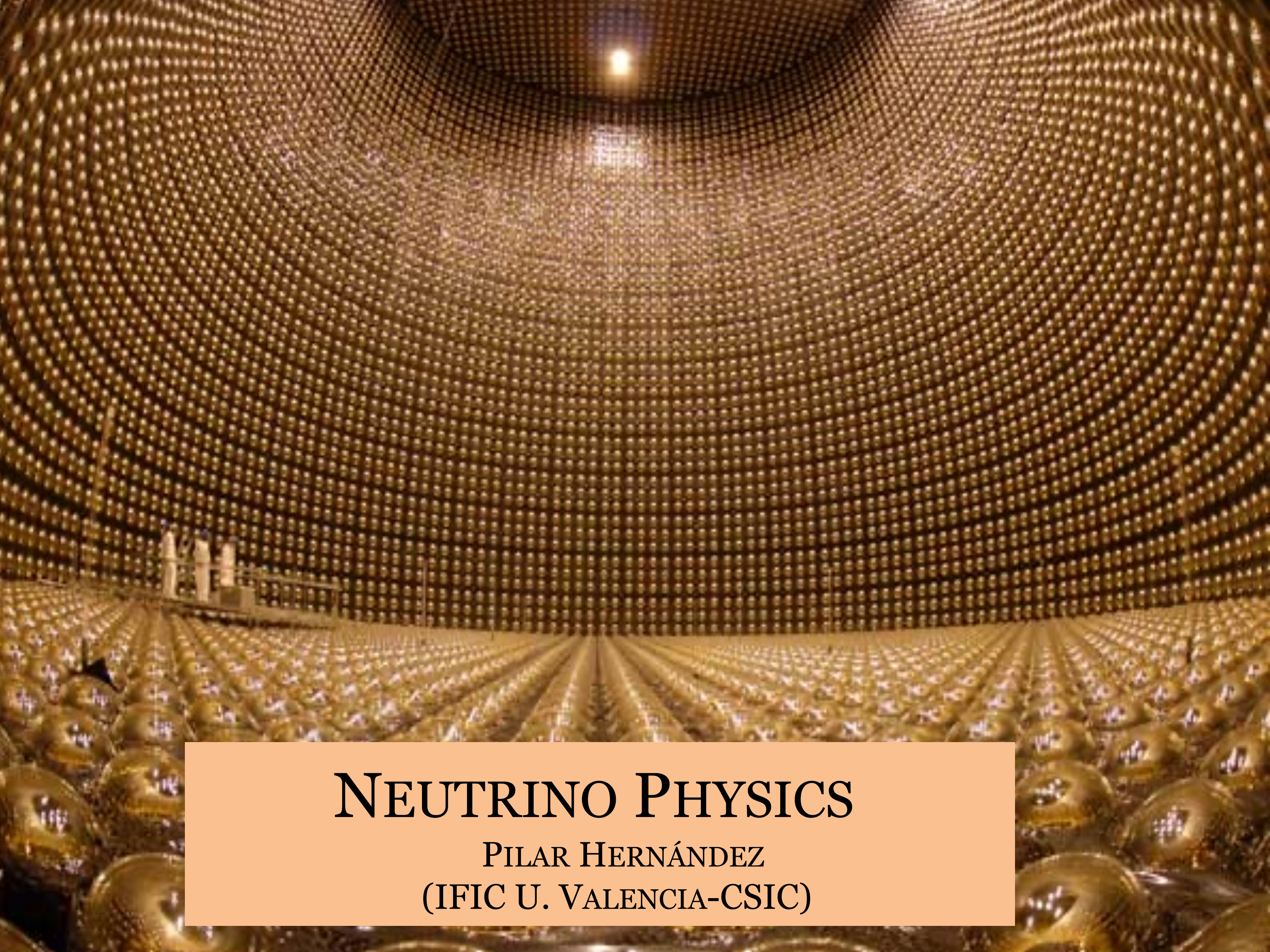


NEUTRINO PHYSICS

PILAR HERNÁNDEZ
(IFIC U. VALENCIA-CSIC)

PLAN

Lecture I:

- Introduction: Neutrinos in the Standard Model
- Neutrino masses and mixing : Majorana versus Dirac
- Neutrino oscillations in vacuum and in matter
- Experimental evidence for neutrino masses & mixings

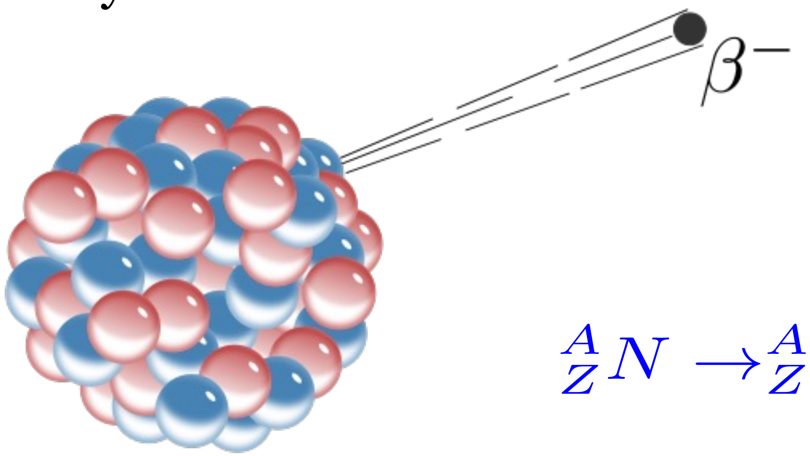
Lecture II:

- The standard 3ν scenario and its unknowns: status and prospects
- Neutrinos and beyond the Standard Model physics
- Leptogenesis

Neutrino: the dark particle

1900 Radioactivity: Becquerel, M & P Curie, Rutherford....

β decay



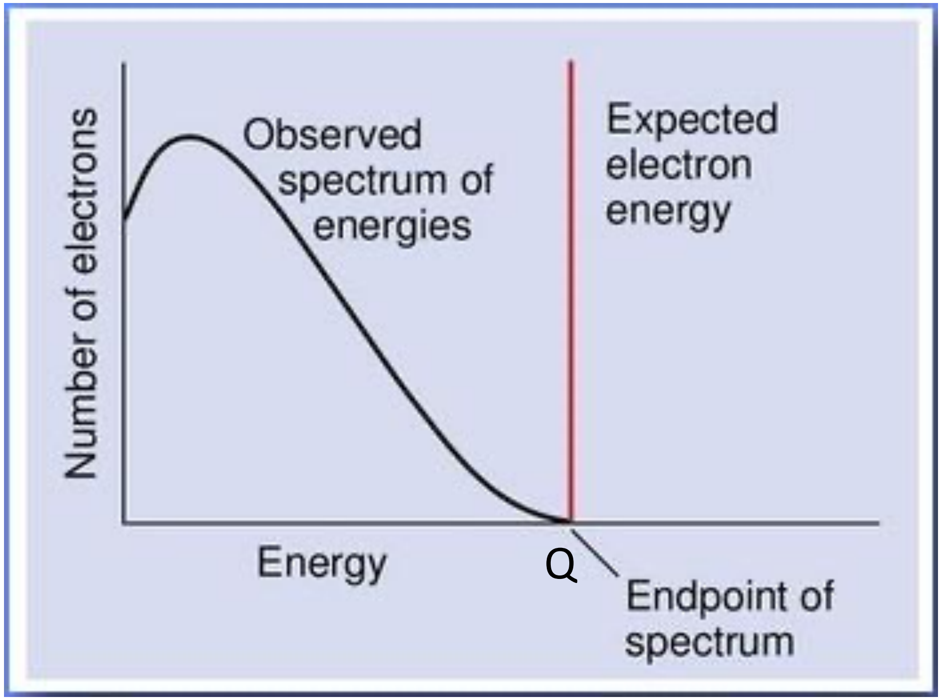
$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^- $$

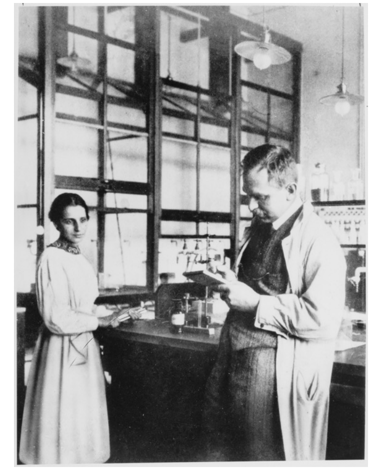
Energy-momentum conservation:

$$ E_{\text{electron}} \simeq (M_N - M_{N'})c^2 = Q = \text{constante} $$

1911/1914

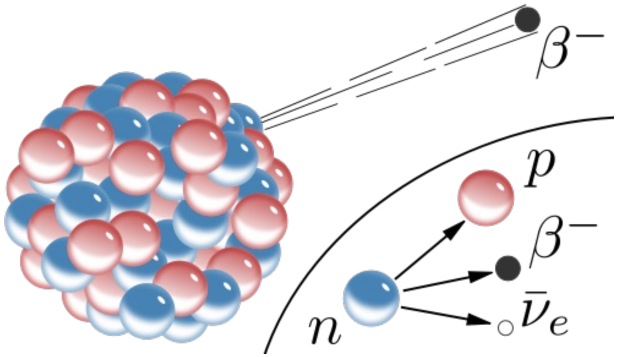
Electron spectrum:





Meitner, Hahn
(Nobel 1944 only him!)

Chadwick (Nobel 1935)



1930

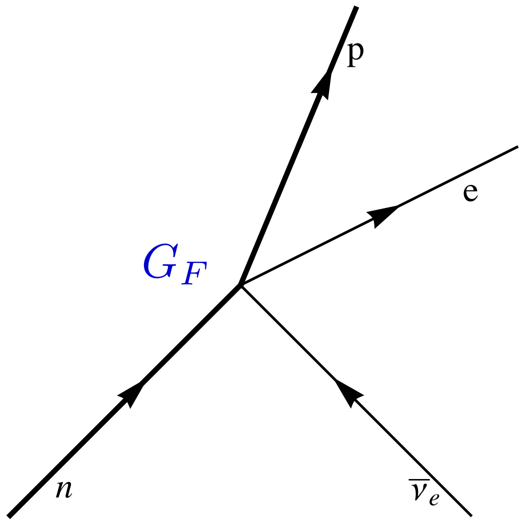
Pauli (Nobel 1945)

Dear Radioactive Ladies and Gentlemen,

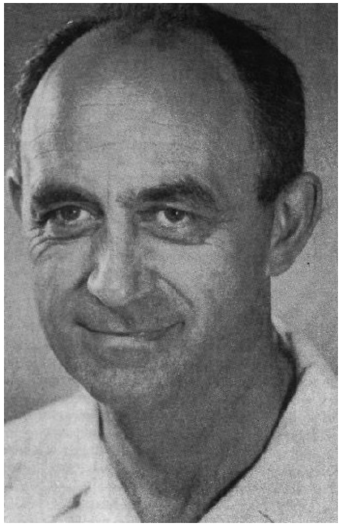
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li⁶ nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the"exchange theorem" of statistics and the law of conservation 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...

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7….

1934: Theory of beta decay



$$n + \nu \to p + e^-$$
$$p + \bar{\nu} \to n + e^+$$



E. Fermi
(Nobel 1938)

Nature did not publish his article: "contained speculations too remote from reality to be of interest to the reader…"

Bethe-Peierls (1934): compute the neutrino cross section using this theory

$$\sigma \simeq 10^{-44} cm^2, \ E(\bar{\nu}) = 2 \text{ MeV}$$

"there is not practically possible way of detecting a neutrino"

How to detect them ?

$$\lambda \simeq \frac{1}{n\sigma}$$

$$\lambda|_{@\mathrm{water}} \simeq 1.5 \times 10^{21}\ cm \simeq 1600\ \mathrm{Light\ Years}$$

$$\lambda|_{@\mathrm{interstelar}} \simeq 10^{44}\ cm \simeq 10^{26}\ \mathrm{Light\ Years}$$

"I have done a terrible thing. I have postulated a particle that cannot be detected"

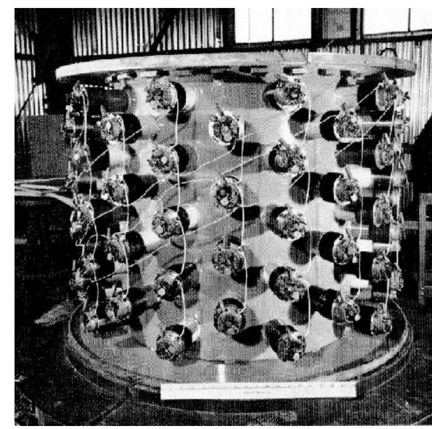
W. Pauli

Pauli's worst insult to a theory: "Not even wrong"

Revealing Pauli's dark matter was just a question of time and ingenuity...

Reactors: ~ isotropic flux of 10^{20} ν/second!

100m

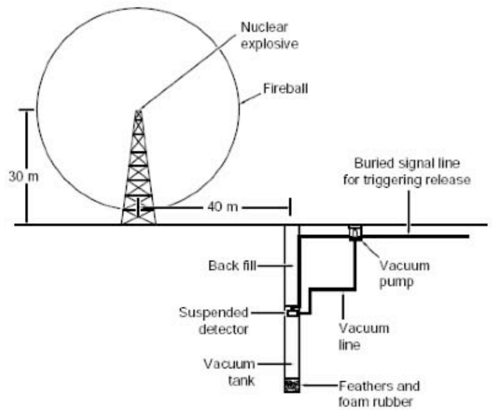


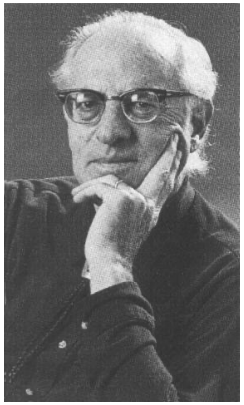
10^{11} ν/s and 1t detector, a few events per day

1956 anti-neutrino detection

Poltergeist project

First idea: put the detector close to a nuclear explosion !

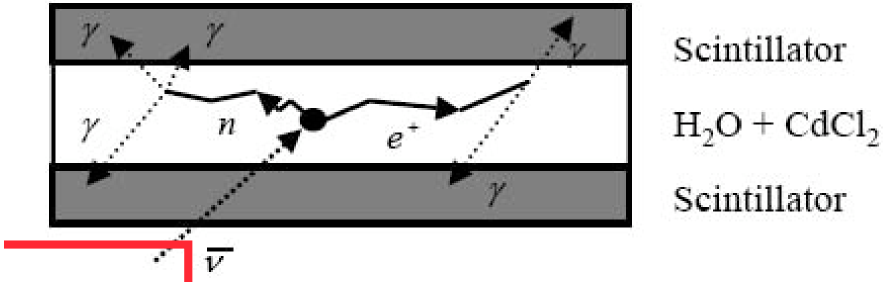




Reines Nobel 95 Cowan (died 74)

Finally used the reactor Savannah River to discover the anti-neutrino

Golden signal



Modern versions of Reines&Cowan experiment: Chooz, DChooz, Daya Bay, RENO… still making discoveries today !

The flavour of neutrinos

1937 μ discovered in cosmic rays

Pontecorvo

Is a heavy version of the electron and not the nuclear agent (pion)

$$\pi \to \mu\ \bar{\nu}_\mu$$

The neutrino that accompanies the μ is different to that in beta decay

Neutrino cross section in Fermi theory grows with energy, it should be easier to observe: the first experiment with an accelerator neutrino beam !

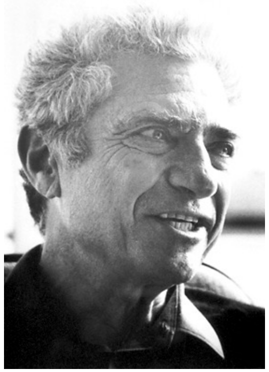
$$\sigma_\nu \propto G_F^2 E_\nu^2, \qquad E_\nu \ll m_p$$

Neutrino Flavour 1962

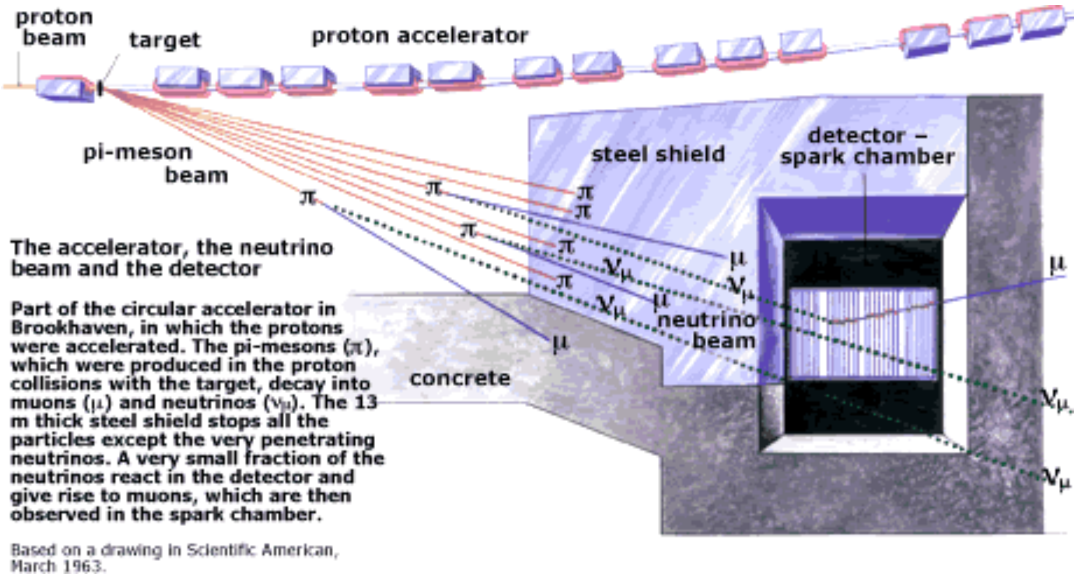
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$


Lederman


Schwartz


Steinberger

Nobel 1988

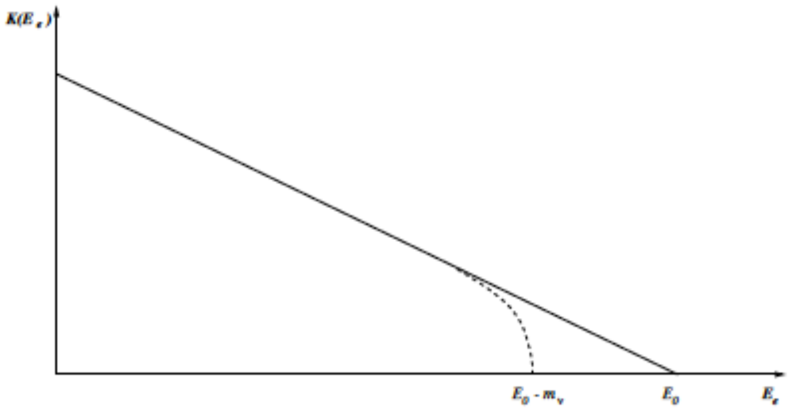


Modern versions of Lederman, Schwartz, Steinberger experiment are accelerator neutrino experiments: MINOS, OPERA, T2K, NoVA,...

Kinematical effects of neutrino mass

Most stringent from Tritium beta-decay

$$H^3 \rightarrow^3 He + e^- + \bar{\nu}_e$$



$$m_{\nu_e} < 1.1\text{eV}(\text{Katrin})$$

$$m_{\nu_\nu} < 170\text{keV}(\text{PSI}: \pi^+ \rightarrow \mu^+\nu_\mu)$$

$$m_{\nu_\tau} < 18.2\text{MeV}(\text{LEP}: \tau^- \rightarrow 5\pi\nu_\tau)$$

Standard Model neutrinos assumed massless

State-of-the-art tritium beta-decay experiment: Katrin

Goal: $m_{\nu e} < 0.2$ eV

Neutrinos in the Standard Model

$SU(3) \times SU(2) \times U(1)_Y$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

Neutrinos in the Standard Model

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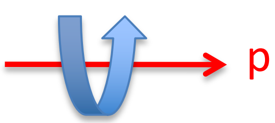
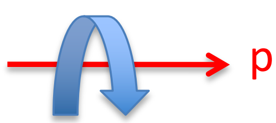
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

Left-handed



Right-handed



Neutrinos in the Standard Model

$$SU(3) \times SU(2) \times U(1)_Y$$

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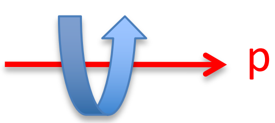
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

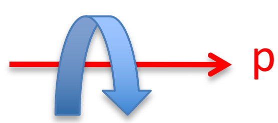
$$\Psi_{L/R} \equiv P_{L/R}\Psi$$

$$P_{L/R} \equiv \frac{1 \mp \gamma_5}{2}$$

Left-handed



Right-handed

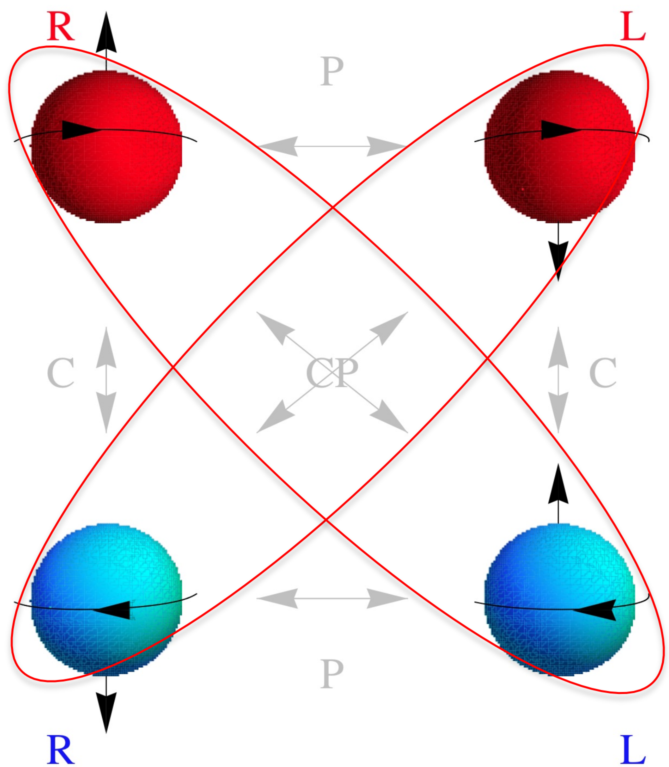


$$\underbrace{P_{L,R}}_{\text{chiral projector}} \simeq_{v\to c} \underbrace{P_{\mp}}_{\text{helicity projector}}$$

Causal quantum fields representing spin ½ particles

Dirac fermion= 4-component spinor $\psi = \psi_L + \psi_R$

(Minimal spin ½ + Parity)



ψ_L

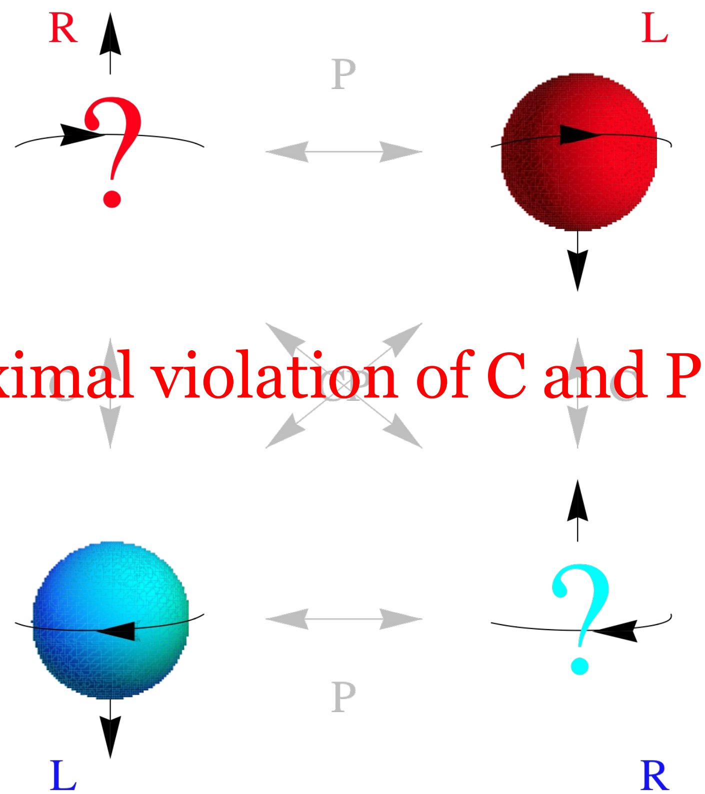
ψ_R

Particle+antiparticle with either helicity

Causal quantum fields representing spin ½ particles

Weyl fermion= 2-component spinor ψ_L

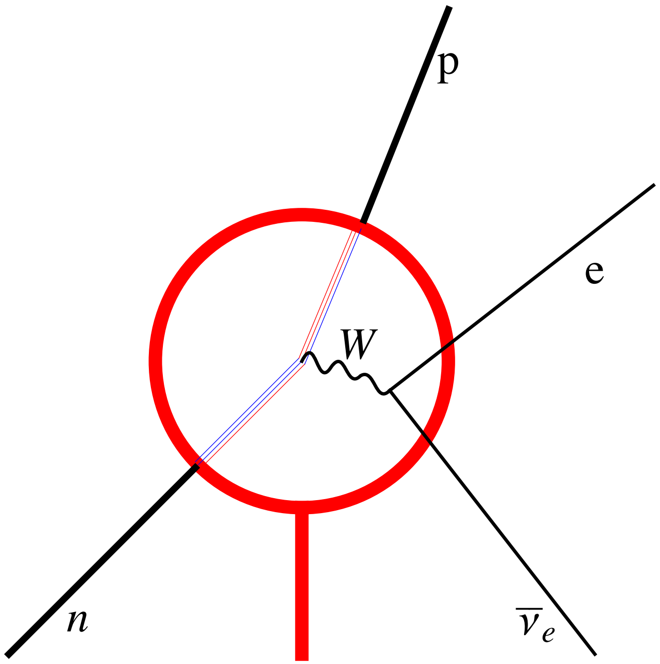
(Minimal spin ½)



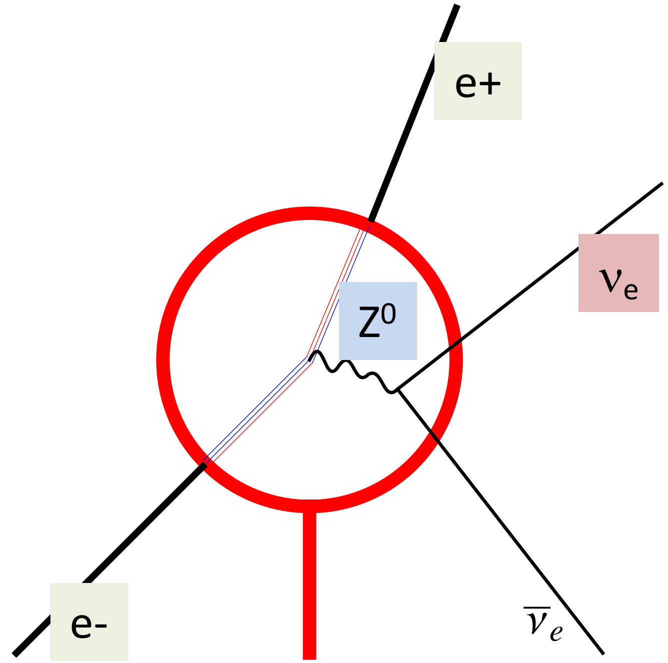
Maximal violation of C and Parity!

Neutrinos are Weyl fermions: two component spinor describing a massless particle with negative helicity + antiparticle with positive helicity

Neutrinos interactions in the SM



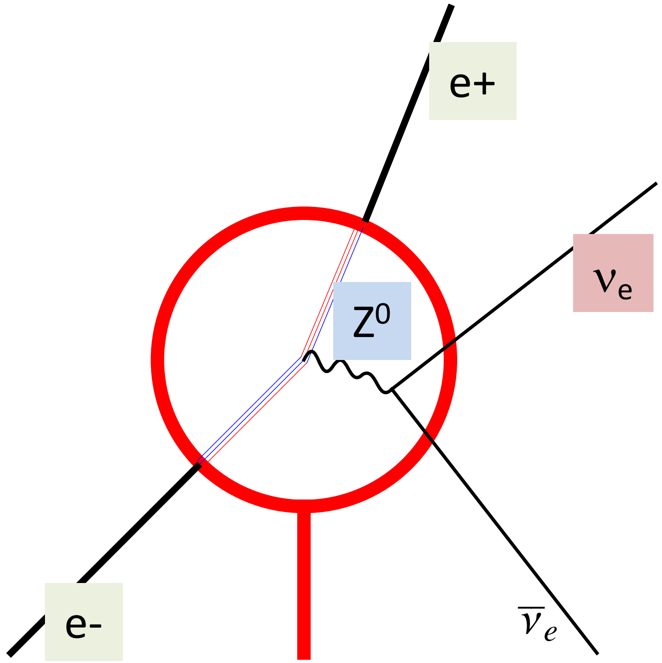
Charged currents: CC



Neutral currents: NC

$$\mathcal{L}_{SM} \supset -\frac{g}{\sqrt{2}} \sum_f \bar{\nu}_{Lf} \gamma_\mu l_{Lf} W_\mu^+ - \frac{g}{2\cos\theta_W} \sum_f \bar{\nu}_{Lf} \gamma_\mu \nu_{Lf} Z_\mu + h.c.$$

Neutrinos in the Standard Model



Neutral currents: NC

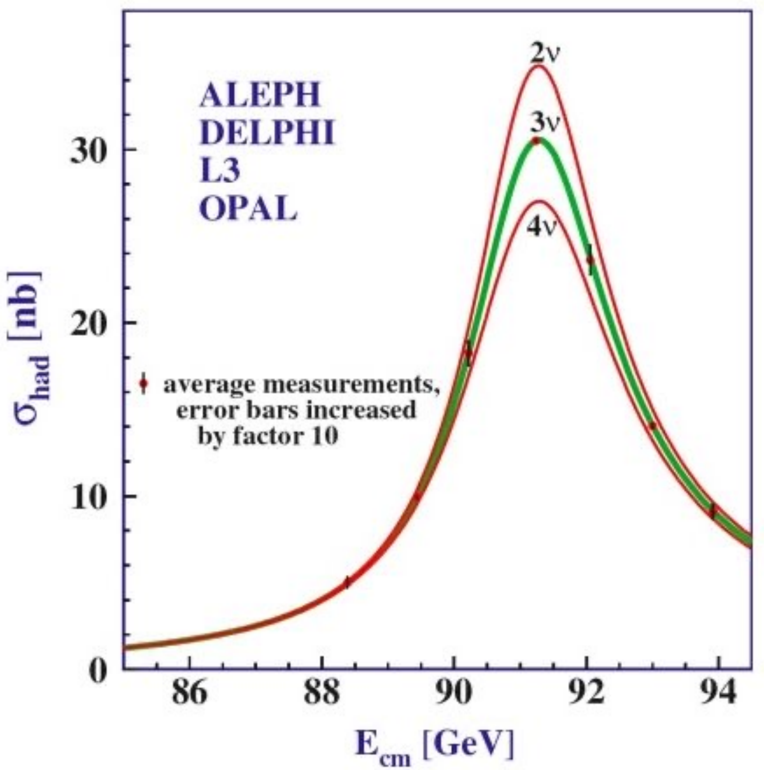
$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$$

Updated in 2020!

At LEP:

$$e^+e^- \to Z^0 \to f\bar{f}$$

Only three neutrinos -> three SM families



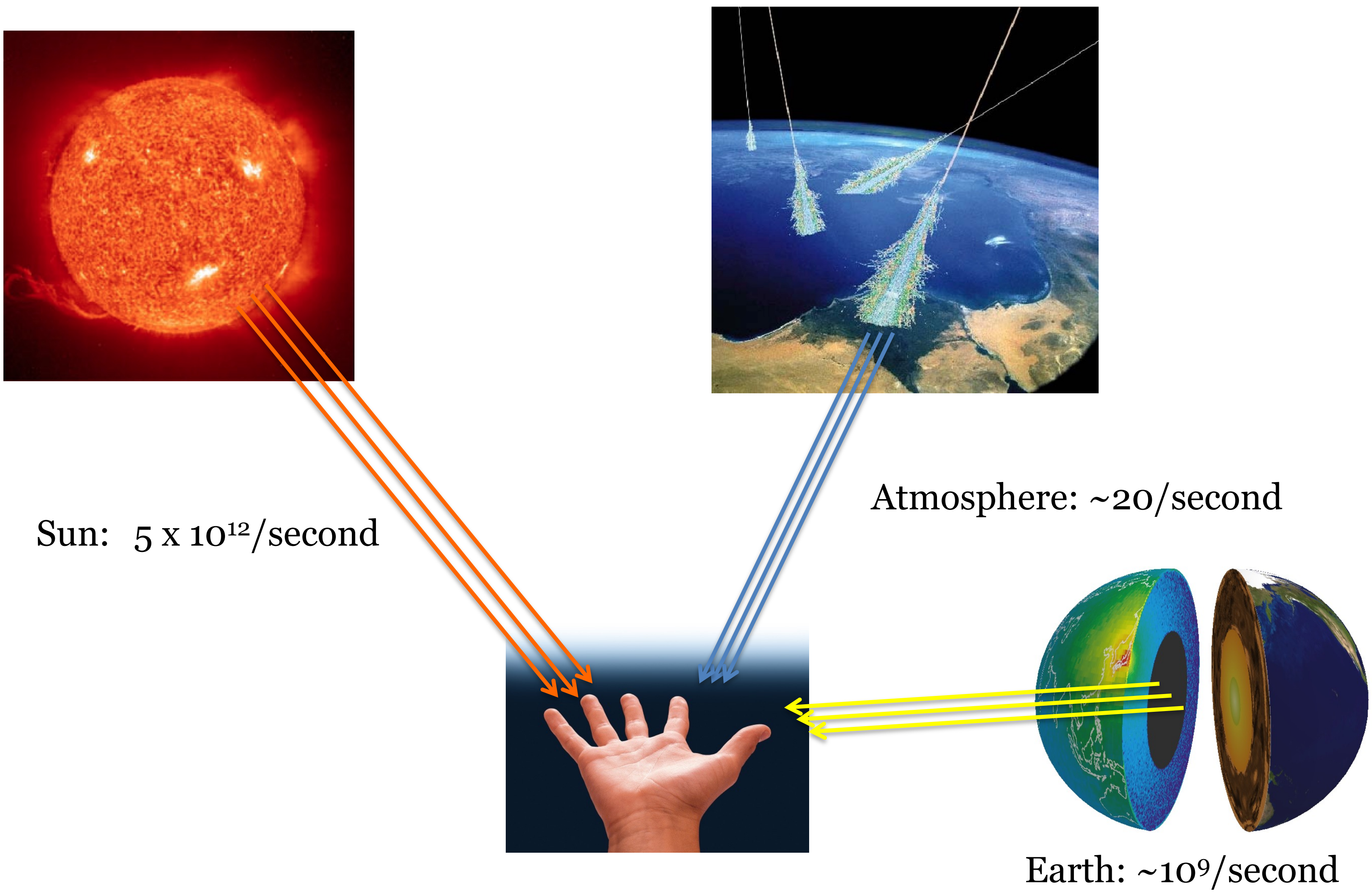
The most elusives particles have been key in the discovery of the weak interactions and in establishing the two most intringuing features of the SM:

3-fold repetition of family structures

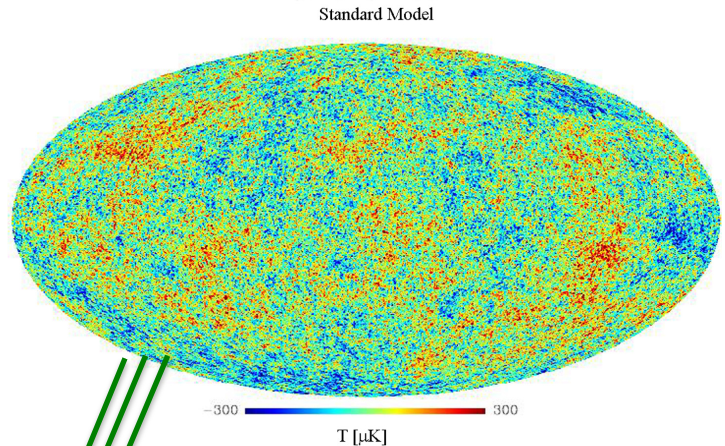
chiral nature of the weak interactions

Ubiquitous Neutrinos

They are everywhere…



Ubiquitous Neutrinos



Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

Big Bang: ~2 x 10^{12}/second

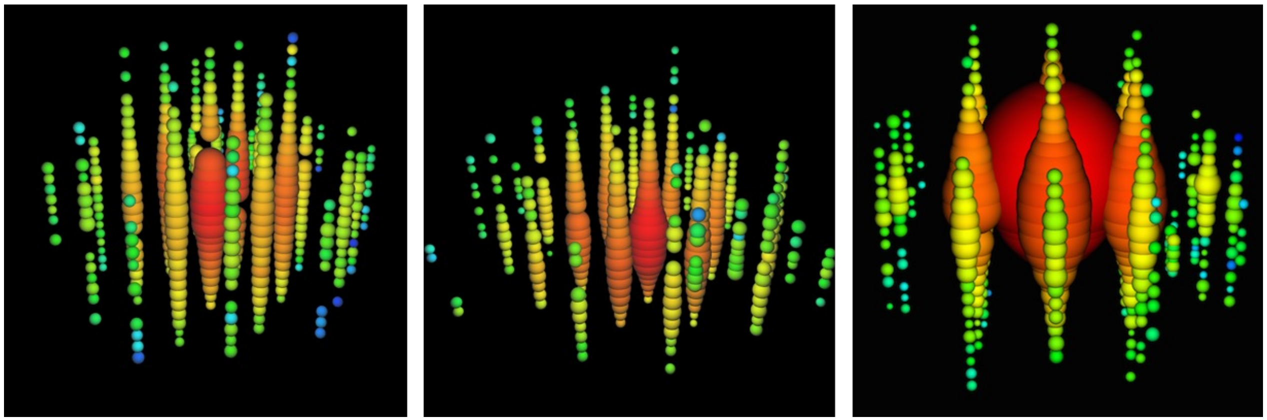
Supernova 1987: ~10^{12}/second

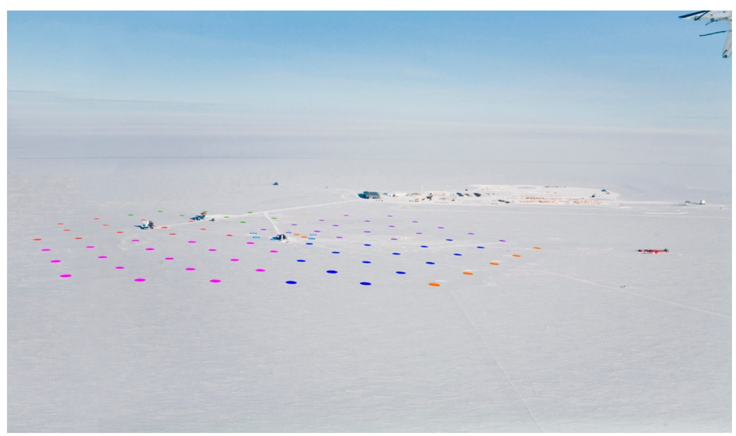
@168000 Light years!

10^8 farther from Earth

Ubiquitous Neutrinos

PeV neutrinos from still unknown (?) sources…

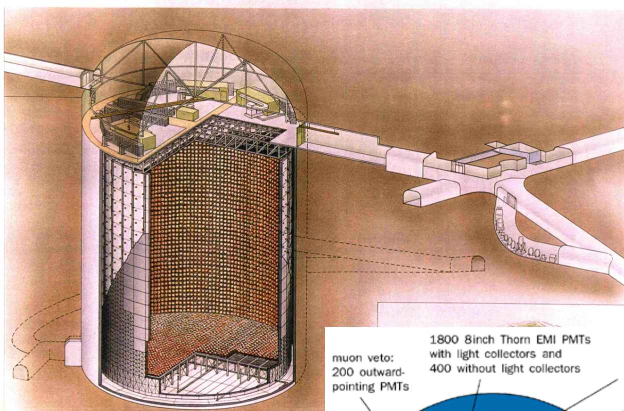




Icecube

Using many of these sources, and others man-made, two decades of revolutionary neutrino experiments have demonstrated that neutrinos are not quite standard, because they have a tiny mass & massive neutrinos require to extend the SM!

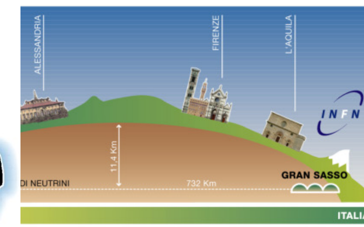
SuperKamiokande



KamLAND

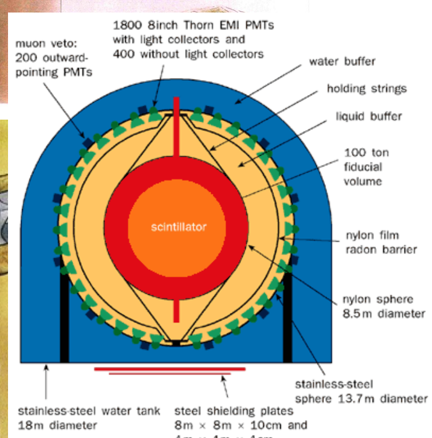
Kamioka Liquid scintillator Anti-Neutrino Detector

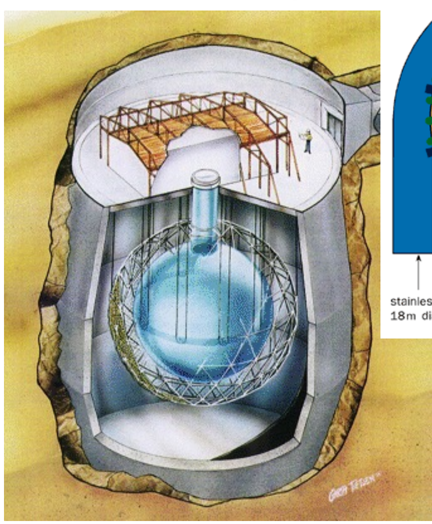
MINOS, Opera



T2K

NOvA





Borexino

SNO

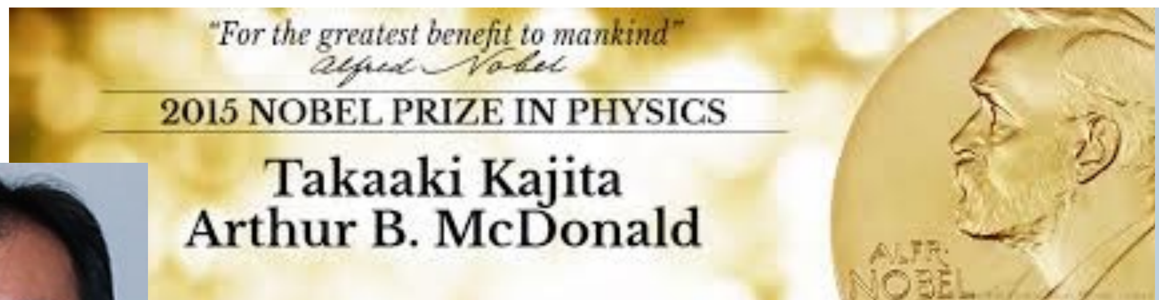
DOUBLE CHOOZ

Daya Bay θ_{13}

RENO ν θ_{13}

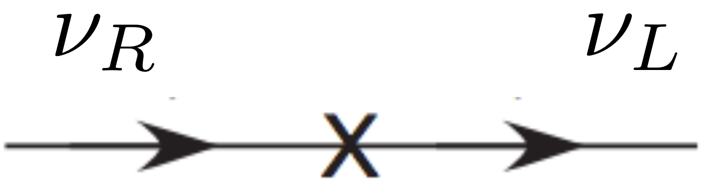
...and more

"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"



Massive (free) fermions

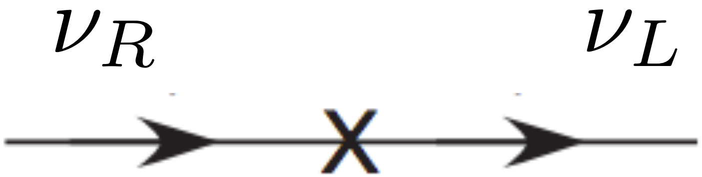
Dirac fermion of mass m:



Massive (free) fermions

Dirac fermion of mass m:

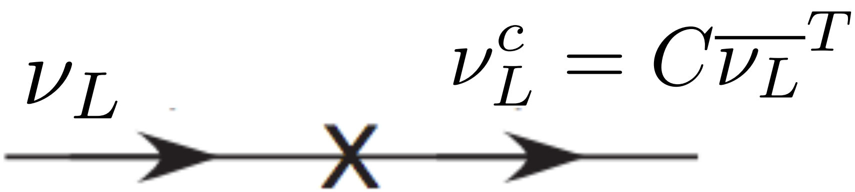
$$-\mathcal{L}_m^{\mathrm{Dirac}} = m\bar{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$



A massive particle must have both helicities... $\nu_{\mathrm{D}} = \nu_L + \nu_R$

Massive (free) fermions

Majorana fermion of mass m (Weyl representation)



Massive (free) fermions

Majorana fermion of mass m (Weyl representation)

$$-\mathcal{L}_m^{Majorana} = \frac{m}{2}\overline{\psi^c}\psi + \frac{m}{2}\overline{\psi}\psi^c \equiv \frac{m}{2}\psi^T C \psi + \frac{m}{2}\bar{\psi} C \bar{\psi}^T,$$

$$\psi^c \equiv C\bar{\psi}^T = C\gamma_0\psi^* \qquad C = i\gamma_2\gamma_0$$

$$\nu_L \qquad \nu_L^c = C\overline{\nu_L}^T$$

Massive field is both particle and antiparticle $\quad \nu_M = \nu_L + \nu_L^c$

Exercise: 1) Lorentz Invariant , 2) only couples one chirality, 3) massive particle

Massive fermions & Weak Interactions ?

Dirac fermion of mass m:

$$-\mathcal{L}_m^{\text{Dirac}} = m\bar{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

Breaks SU(2) x U(1) gauge invariance!

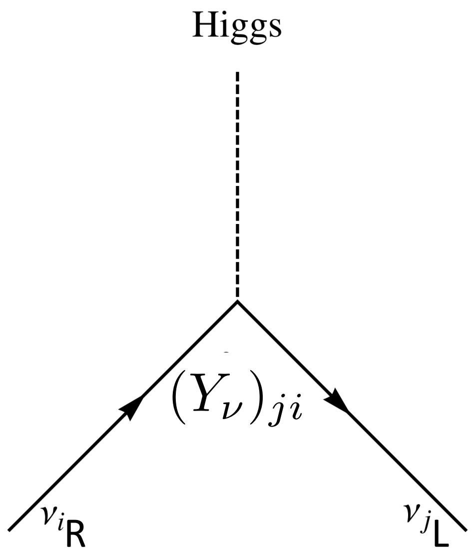
Majorana fermion of mass m (Weyl representation)

$$-\mathcal{L}_m^{Majorana} = \frac{m}{2}\overline{\psi^c}\psi + \frac{m}{2}\overline{\psi}\psi^c \equiv \frac{m}{2}\psi^T C\psi + \frac{m}{2}\bar{\psi}C\bar{\psi}^T,$$

No gauge/global symmetry of ψ possible!

Massive Dirac neutrinos & SSB ?

Massive Dirac neutrino via Yukawa coupling: SM + ν_R

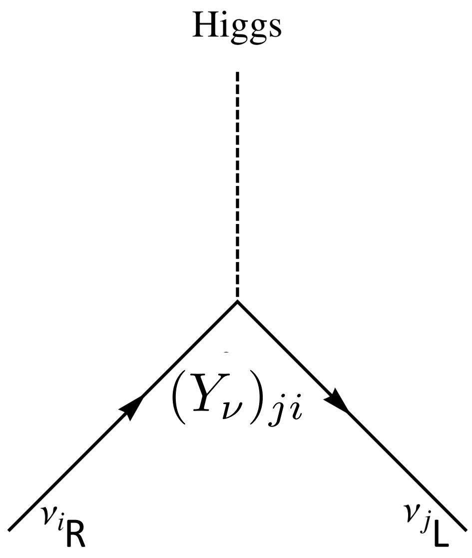


Massive Dirac neutrinos & SSB ?

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-1/2}, \quad \langle \tilde{\phi} \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$

Massive Dirac neutrino via Yukawa coupling: SM + ν_R

$$-\mathcal{L}_m^{\text{Dirac}} = Y_\nu \underbrace{\bar{L}\,\tilde{\phi}}_{(1,1,0)} \underbrace{\nu_R}_{(1,1,0)} + h.c \rightarrow SSB \rightarrow Y_\nu \bar{\nu}_L \frac{v}{\sqrt{2}} \nu_R + h.c.$$

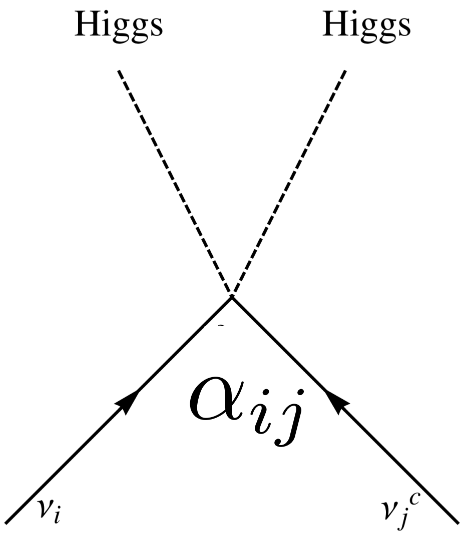


$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

Massive Majorana neutrinos & SSB ?

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-1/2}, \quad \langle \tilde{\phi} \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$

Massive Majorana neutrino via Weinberg's coupling



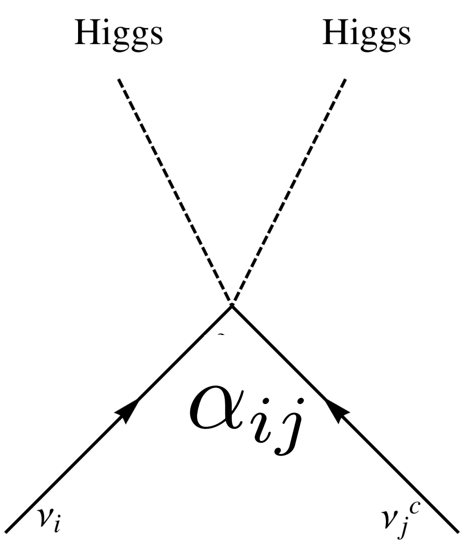
Implies the existence of a new physics scale unrelated to v !

Massive Majorana neutrinos & SSB ?

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-1/2}, \quad \langle \tilde{\phi} \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$

Massive Majorana neutrino via Weinberg's coupling

$$-\mathcal{L}^{\mathrm{Majorana}} = \alpha \bar{L} \, \tilde{\phi} \, C \tilde{\phi}^T \bar{L}^T + h.c. \to SSB \to \alpha \frac{v^2}{2} \bar{\nu}_L C \bar{\nu}_L^T + h.c.$$



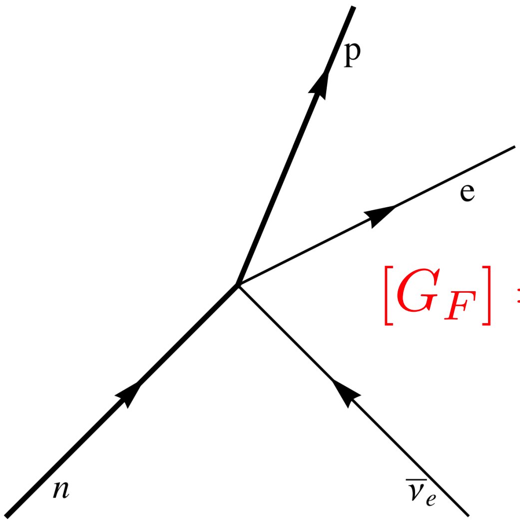
$$m_\nu = \alpha v^2$$

$$[\alpha] = -1$$

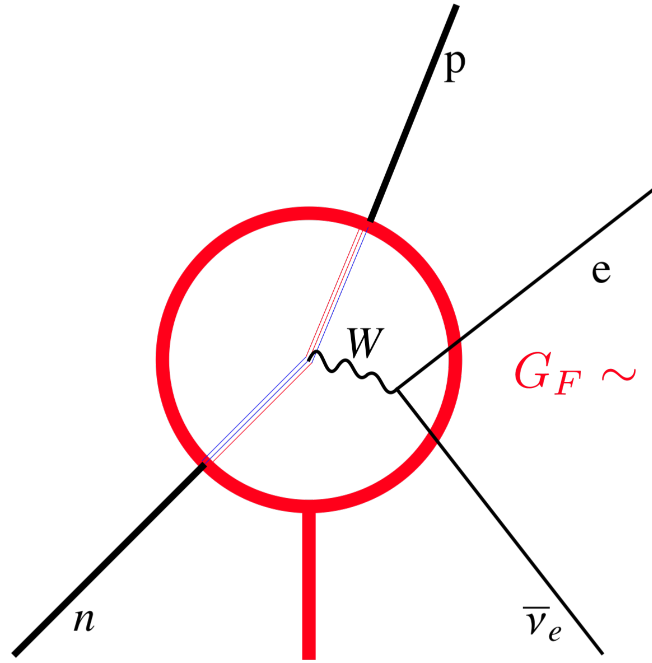
$$\alpha \equiv \frac{\lambda}{\Lambda}$$

Implies the existence of a new physics scale unrelated to v !

Neutrinos have tiny masses -> a new physics scale, what ?

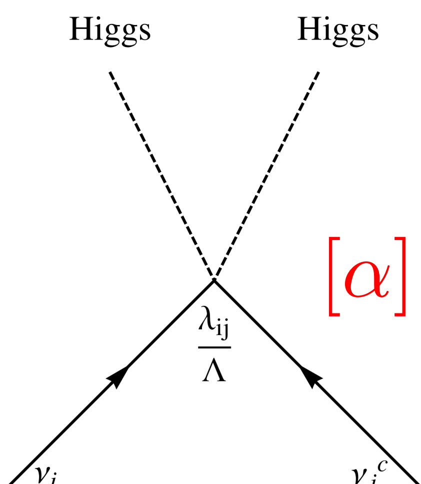


$$[G_F] = -2$$



$$G_F \sim \frac{1}{M_W^2}$$

SM



$$[\alpha] = -1$$ →

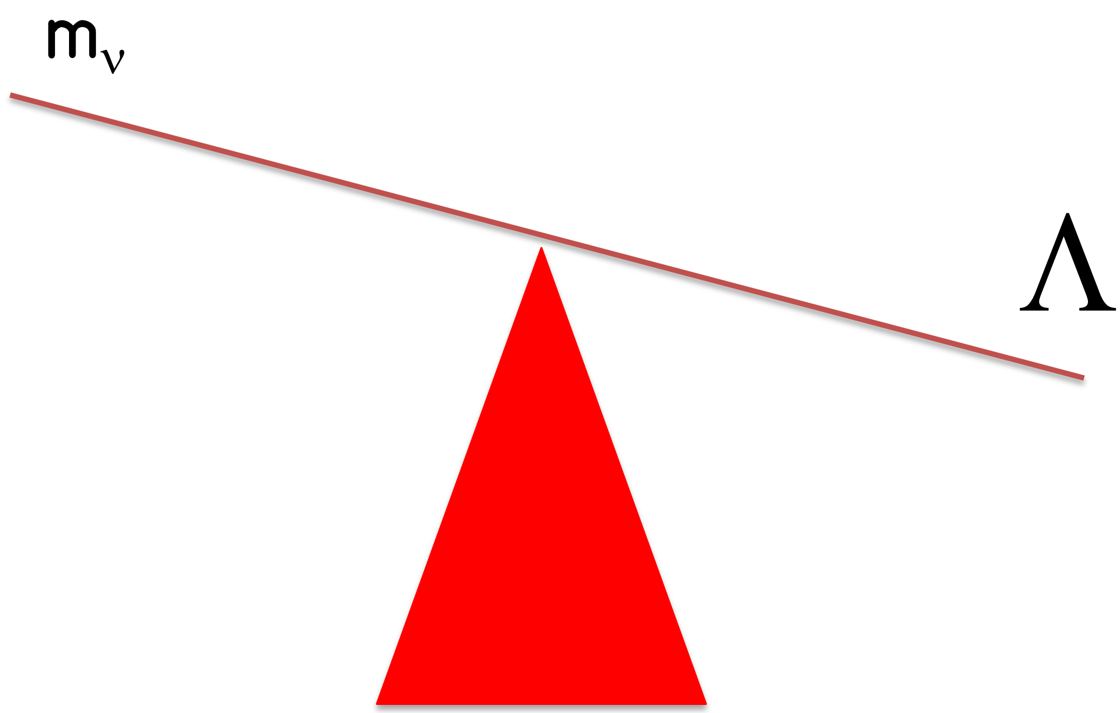
νSM ?

$$m_\nu = \lambda \frac{v^2}{\Lambda}$$

Scale at which new particles will show up

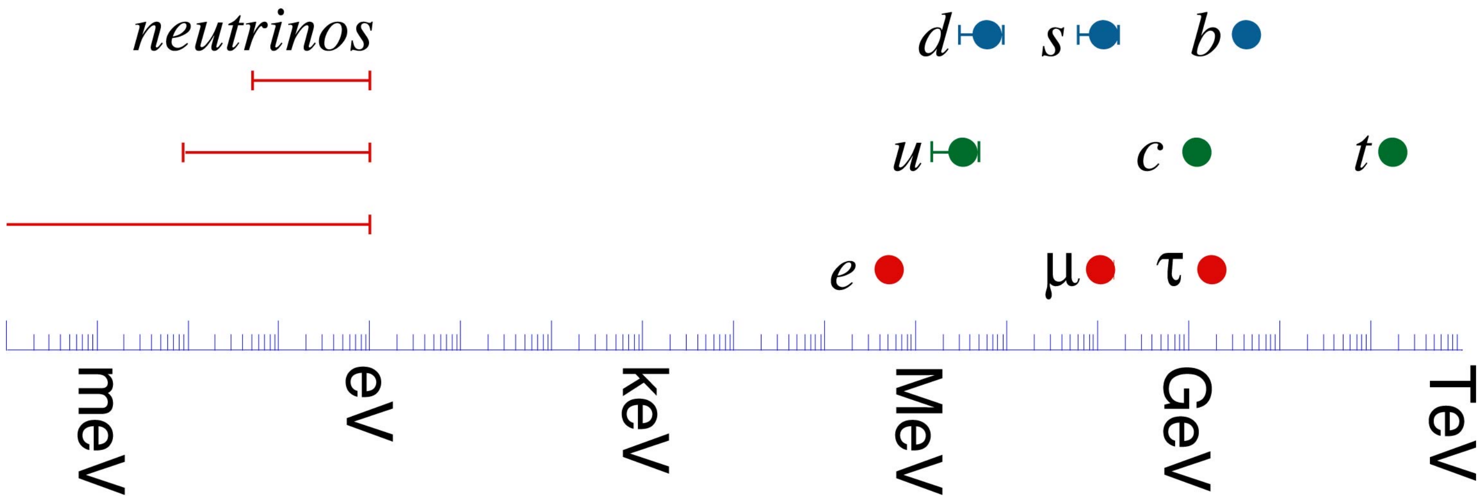
Seesaw mechanism:

Minkowski
Gell-Mann, Ramond Slansky
Yanagida, Glashow
Mohapatra, Senjanovic



Massive Majorana neutrinos & SSB ?

If $\Lambda >> v$ natural explanation for the smallness of neutrino mass



$$m_f(charged) \sim Y v, \quad m_\nu \sim Y \frac{v^2}{\Lambda} \sim m_f \frac{v}{\Lambda}$$

Neutrino masses & lepton family mixing (Dirac)

Yukawa couplings are generic complex matrices in flavour space

$$(M_f)_{ij} = Y_{ij}\frac{v}{\sqrt{2}}$$

$$-\mathcal{L}_m^{lepton} = \bar{\nu}_{Li}\underbrace{(M_\nu)_{ij}}_{3\times n_R}\nu_{Rj} + \bar{l}_{Li}\underbrace{(M_l)_{ij}}_{3\times 3} l_{Rj} + h.c.$$

$$M_\nu = U_\nu^\dagger \ \mathrm{Diag}(m_1, m_2, m_3)\ V_\nu, \ \ M_l = U_l^\dagger \ \mathrm{Diag}(m_e, m_\mu, m_\tau)\ V_l$$

In the mass eigenbasis

$$\mathcal{L}_{\mathrm{gauge-lepton}} \supset -\frac{g}{\sqrt{2}}\bar{l}'_{Li}\underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}}\gamma_\mu W_\mu^- \nu'_{Lj} + h.c.$$

Pontecorvo-Maki-Nakagawa-Sakata

$U_{\mathrm{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ unitary matrix analogous to CKM

Neutrino masses & lepton family mixing (Majorana)

Are generic complex matrices in flavour space

$$-\mathcal{L}_m^{lepton} = \frac{1}{2}\bar{\nu}_{Li}(M_\nu)_{ij}\nu^c_{Lj} + \bar{l}_{Li}(M_l)_{ij}l_{Rj} + h.c.$$

$$M_\nu^T = M_\nu \to M_\nu = U_\nu^T \,\mathrm{Diag}(m_1, m_2, m_3) U_\nu$$

In the mass eigenbasis

$$\mathcal{L}_{\mathrm{gauge-lepton}} \supset -\frac{g}{\sqrt{2}}\bar{l}'_{Li}\underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}}\gamma_\mu W^-_\mu \nu'_{Lj} + h.c.$$

$U_{\mathrm{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \alpha_1, \alpha_2)$ depends on three CP phases

Exercise: make sure you agree with the statement that there are 3 physical phases

Neutrino Mixing

flavour eigenstates (in combination with e, μ, τ)

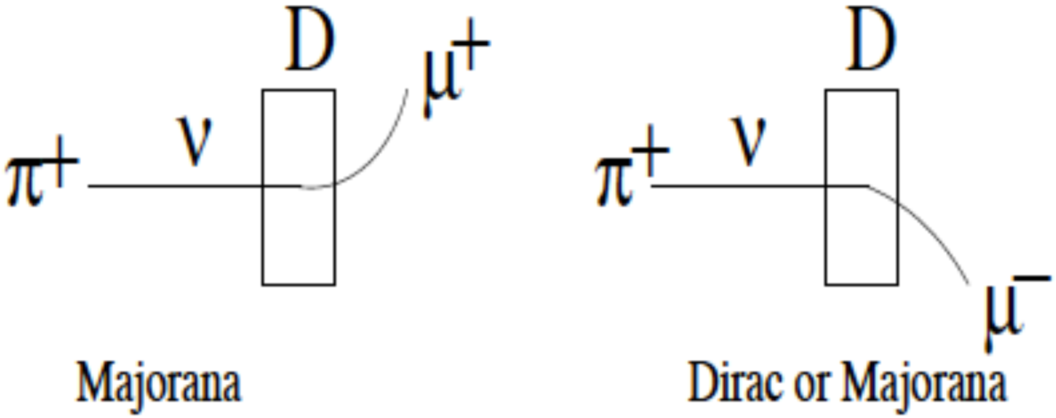
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}}_{\text{Majorana phases}}$$

$$c_{ij} \equiv \cos\theta_{ij} \;\; s_{ij} \equiv \sin\theta_{ij}$$

Majorana versus Dirac

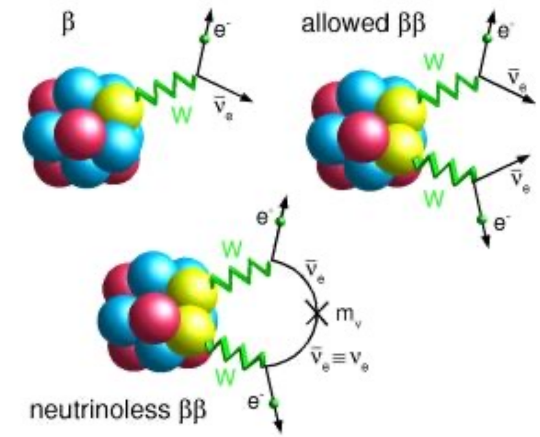
In principle clear experimental signatures $\pi^+ \to \nu_\mu \mu^+$



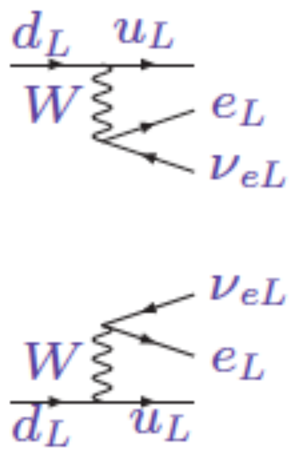
In practice theses processes are extremely rare:

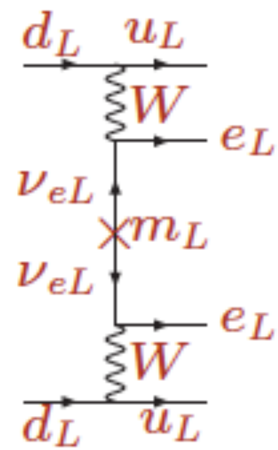
$$\text{Rate}(+) = \text{Rate}(-)\left(\frac{m_\nu}{E}\right)^2$$

Neutrinoless double-β decay



Best hope is neutrinoless double-β decay





$T_{2\beta 2\nu} \sim 10^{18} - 10^{21}$ years

$$T^{-1}_{2\beta 0\nu} \sim \left(\frac{m_\nu}{E}\right)^2 10^9 \, T^{-1}_{2\beta 2\nu}$$

If neutrinos are Majorana this process must be there at some level

Neutrinoless double-β decay

$$T_{2\beta0\nu}^{-1} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V_{MNS}^{ei}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

Present bounds:

PDG 19

VALUE (eV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.07–0.16	^{76}Ge	GERDA	[1] AGOSTINI	19
< 1.2–2.1	^{100}Mo	AMoRE	[2] ALENKOV	19
< 0.200–0.433	^{76}Ge	MAJORANA	[3] ALVIS	19
< 0.093–0.286	^{136}Xe	EXO-200	[4] ANTON	19
< 0.311–0.638	^{82}Se	CUPID-0	[5] AZZOLINI	19
< 0.11–0.52	^{130}Te	CUORE	[10] ALDUINO	18
< 0.061–0.165	^{136}Xe	KamLAND-Zen	[18] GANDO	16

Global Symmetries

Massive neutrinos imply that family number is not conserved

Dirac neutrinos conserve total lepton number:

$$L_\alpha \to e^{i\theta} L_\alpha, l_{R\alpha} \to e^{i\theta} l_{R\alpha}, \nu_{R\alpha} \to e^{i\theta} \nu_{R\alpha}$$

Majorana neutrinos violate this global symmetry

-> a new mechanism to explain the matter/antimatter asymmetry emerges

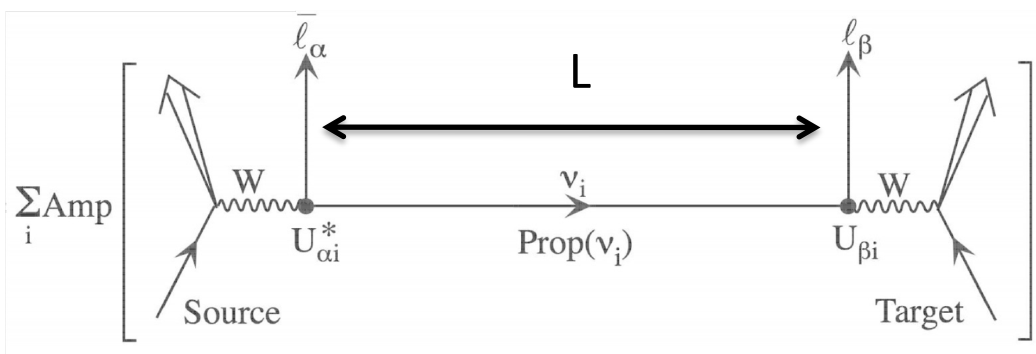
Neutrino oscillations

1968 Pontecorvo

If neutrinos are massive

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !



ν_i pick up different phases when travelling in vacuum

Neutrino oscillations in QM (plane waves)

$$|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i}|\nu_i(\mathbf{p})\rangle, \qquad \hat{H}|\nu_i(\mathbf{p})\rangle = E_i(\mathbf{p})|\nu_i(\mathbf{p})\rangle, \quad \mathbf{p}^2 + m_i^2 = E_i^2(\mathbf{p})$$

$\downarrow$ time evolution

$$|\nu_\alpha(t)\rangle = \sum_i U^*_{\alpha i} e^{-iE_i(\mathbf{p})(t-t_0)}|\nu_i(\mathbf{p})\rangle$$

$$P(\nu_\alpha \to \nu_\beta)(t) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = |\sum_i U_{\beta i}U^*_{\alpha i} e^{-iE_i(t-t_0)}|^2$$

$$= \sum_{i,j} e^{-i(E_i - E_j)(t-t_0)} U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}$$

$$E_i(\mathbf{p}) - E_j(\mathbf{p}) \simeq \frac{1}{2}\frac{m_i^2 - m_j^2}{|\mathbf{p}|} + \mathcal{O}(m^4) \qquad L \simeq t - t_0, v_i \simeq c$$

$$P(\nu_\alpha \to \nu_\beta)(L) \simeq \sum_{i,j} e^{i\frac{\Delta m^2_{ji} L}{2E}} U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}$$

Neutrino oscillations in QM (plane waves)

Well founded criticism to this derivation

Why same p for the i-th states ?

Why plane waves if the neutrino source is localized ?

Why t <-> L conversion ?

Neutrino oscillations

Two basic ingredients:

✓ Uncertainty in momentum at production & detection (they must be better localized than baseline)

✓ Coherence of mass eigenstates over macroscopic distances

Quantum mechanics with neutrinos as wave packets

Quantum Field Theory <-> neutrinos as intermediate states

Neutrino oscillations in QM (wavepackets)

B. Kayser '81,... many more authors...

Wave packet created at source @ $(t_0, \mathbf{x}_0) = (0, \mathbf{0})$

$$|\nu_\alpha(t,\mathbf{x})\rangle = \sum_i U^*_{\alpha i} \int_{\mathbf{p}} \underbrace{f_i^S(\mathbf{p}-\mathbf{Q}_i)}_{\text{Wave packet at source}} \; e^{-iE_i(\mathbf{p})t} \; e^{i\mathbf{p}\cdot\mathbf{x}} \; |\nu_i\rangle$$

$$E_i(\mathbf{p}) \equiv \sqrt{\mathbf{p}^2 + m_i^2}$$

For example: $f_i^S(\mathbf{p}-\mathbf{Q}_i) \simeq e^{-(\mathbf{p}-\mathbf{Q}_i)^2/2\sigma_S^2}$

$\sigma_S \leftrightarrow$ momentum uncertainty

$\mathbf{Q}_i \leftrightarrow$ average momentum of i − th wavepacket

Wave packet created at detector @ $(t_0, \mathbf{x}_0) = (t, \mathbf{L})$

$$|\nu_\beta(t,\mathbf{x})\rangle = \sum_j U^*_{\beta j} \int_{\mathbf{p}} f_j^D(\mathbf{p}-\mathbf{Q}'_j) \; e^{-iE_j(\mathbf{p})(t-T)} \; e^{i\mathbf{p}(\mathbf{x}-\mathbf{L})} \; |\nu_j\rangle$$

Neutrino oscillations in QM (wavepackets)

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) = \int_{\mathbf{x}} \langle \nu_\beta(t,\mathbf{x}) | \nu_\alpha(t,\mathbf{x}) \rangle$$
$$= \sum_i U^*_{\alpha i} U_{\beta i} \int_{\mathbf{p}} e^{iE_i(\mathbf{p})T}\ e^{-i\mathbf{p}\mathbf{L}}\ \underbrace{f_i^{D*}(\mathbf{p}-\mathbf{Q}'_i) f_i^S(\mathbf{p}-\mathbf{Q}_i)}_{overlap}$$

For Gaussian wave packets overlap is also gaussian:

$$f_i^{D*} f_i^S = f_i^{ov}(\mathbf{p} - \langle \mathbf{Q} \rangle_i)\ e^{-(\mathbf{Q}_i - \mathbf{Q}'_i)^2/4/(\sigma_S^2+\sigma_D^2)}$$

$$\langle \mathbf{Q} \rangle_i \equiv \left(\frac{\mathbf{Q}_i}{\sigma_S^2} + \frac{\mathbf{Q}'_i}{\sigma_D^2} \right) \sigma_{ov}^2$$
$$\sigma_{ov}^2 \equiv \frac{1}{1/\sigma_S^2 + 1/\sigma_D^2}$$

$\mathbf{v}_i$ group velocity

$$E_i(\mathbf{p}) \simeq E_i(\langle \mathbf{Q} \rangle_i) + \overbrace{\left.\frac{\partial E}{\partial p_k}\right|_{\langle \mathbf{Q} \rangle_i}}^{\mathbf{v}_i} (p_k - \langle Q_k \rangle_i) + \mathcal{O}(p_k - \langle Q_k \rangle_i)^2$$

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) \propto \sum_i U^*_{\alpha i} U_{\beta i}\ e^{iE_i(\langle \mathbf{Q} \rangle_i)T}\ e^{-i\langle \mathbf{Q} \rangle_i \mathbf{L}}\ e^{-(\mathbf{Q}_i - \mathbf{Q}'_i)^2/4/(\sigma_S^2+\sigma_D^2)}\ e^{-(\mathbf{L}-\mathbf{v}_i T)^2 \sigma_{ov}^2/2}$$

Neutrino oscillations in QM (wavepackets)

$$P(\nu_\alpha \to \nu_\beta) \quad \propto \quad \int_{-\infty}^{\infty} dT \; |\mathcal{A}(\nu_\alpha \to \nu_\beta)|^2$$

$$\propto \quad \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \; e^{i \frac{m_j^2 - m_i^2}{2E} L} \times e^{-L^2/L_{coh}(i,j)^2} \times e^{-\left(\frac{\Delta_{ij} E(\langle Q \rangle)}{2\sigma_{ov} \langle v \rangle}\right)^2},$$

L > L_{coh} coherence is lost $\quad L^{-1}_{coh}(i,j) \sim \sigma_{ov} \frac{|\mathbf{v}_i - \mathbf{v}_j|}{\sqrt{\mathbf{v}_i^2 + \mathbf{v}_j^2}} \simeq \frac{|m_j^2 - m_i^2|}{2\langle Q \rangle} \frac{\sigma_{ov}}{\langle Q \rangle}$

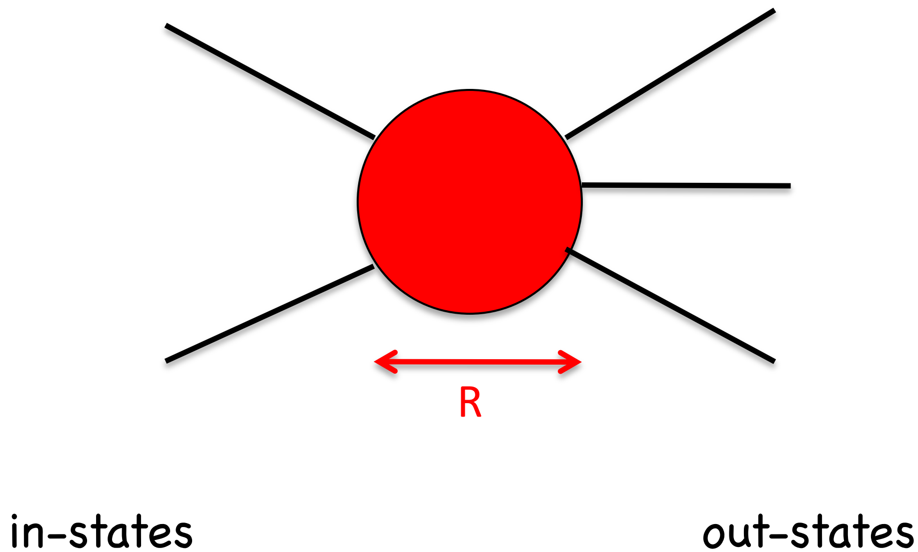
There must be sufficient uncertainty in production & detection so that wave packets include all mass eigenstates: **ΔE << σ** $\quad \sigma^2_{\rm ov} \equiv \frac{1}{1/\sigma_S^2 + 1/\sigma_D^2}$

Problems: normalization is arbitrary, needs to be imposed a posteriori

$$\sum_\beta P(\nu_\alpha \to \nu_\beta) = 1$$

Can be cured in QFT...

Neutrino oscillations in QFT



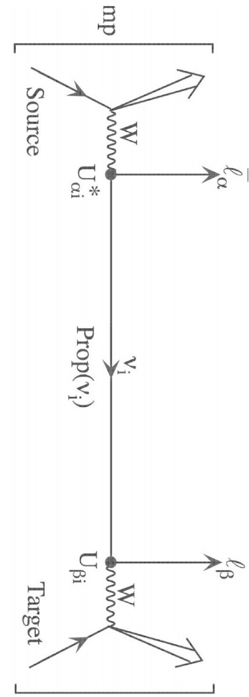
Idealization: asymptotic states are plane waves if R << Compton wavelength, in reality in-states are wave packets

$$\mathcal{A} = \langle \mathrm{out}; p'_1, \ldots, p'_n | \mathrm{in}; p_1, p_2 \rangle$$

Neutrino oscillations in QFT

Neutrinos are not the asymptotic states…

in-states



out-states

$$\mathcal{A} \sim \sum_i \mathcal{A}_S \, U^*_{\beta i} \, \frac{i}{\not{p} - m_i} U_{i\alpha} \mathcal{A}_D$$

Neutrino propagator: intermediate state

Neutrino oscillations in QFT

Necessary to adapt standard formalism:

1) macroscopic separation of Source and Detector L (eg. localized wave packets of in-states + static approximation)

2) oscillation probability from factorization:

decay x propagation x ν cross-section

$$\frac{dW(\pi n \to p \mu l_\beta)}{dt dp_\mu dp_p dp_l} = \int d|q| \underbrace{\frac{dW(\pi \to \mu\nu)}{L^2 dt d\Omega_\nu d|q| dp_\mu}}_{\text{Flux per unit neutrino momentum}} \times P(\nu_\mu \to \nu_\beta) \times \underbrace{\frac{1}{2|q|}\frac{dW(\nu n \to pl)}{dt dp_p dp_l}}_{\text{interaction probability per unit flux}}$$

Oscillation probability is indeed properly normalized!

Exercise: do leptons oscillate?
(hint: be precise about what you mean)

Neutrino Oscillation

$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{(m_i^2 - m_j^2)L}{2E}}$$

$\alpha \neq \beta$ appearance probability
$\alpha = \beta$ disappearance or survival probability

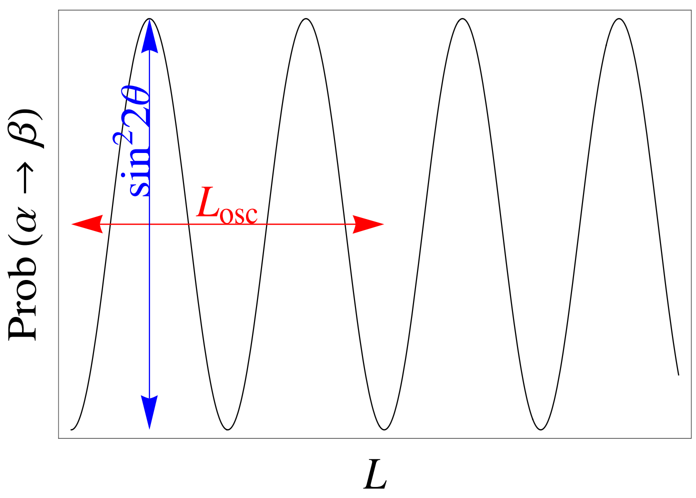
$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$

In principle all flavours oscillate with the same wave lengths and different amplitudes

Neutrino Oscillation: 2ν

Only one oscillation frequency, $U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$



$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

$$L_{osc}(km) = \frac{\pi}{1.27}\frac{E(GeV)}{\Delta m^2(eV^2)}$$

Neutrino Oscillation: 2ν

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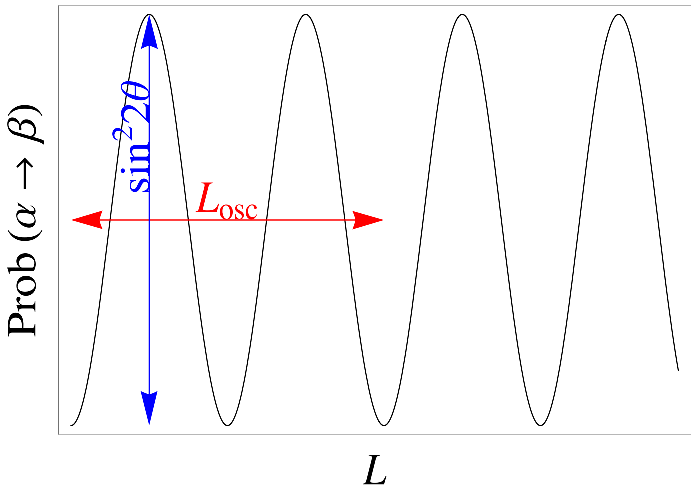

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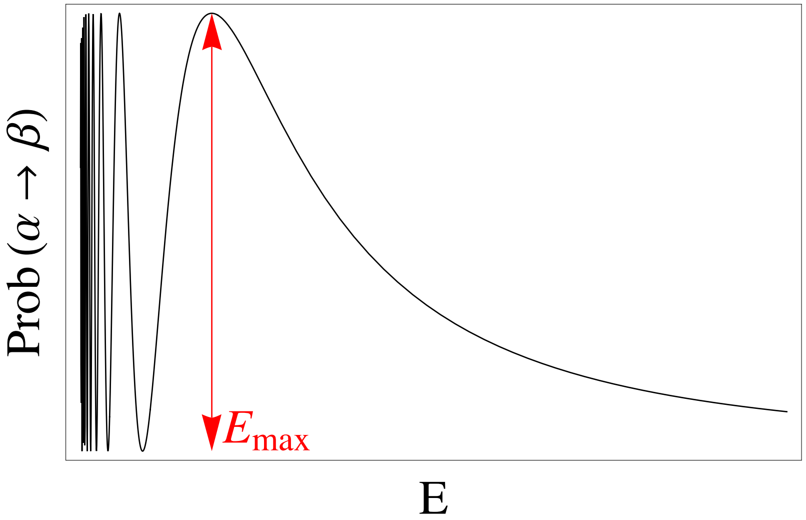


$$E_{max}(GeV) = 1.27 \frac{\Delta m^2 (eV^2) L(km)}{\pi/2}$$

L, E dependence give Δm^2 amplitude of oscillation gives θ

Optimal experiment: $\frac{E}{L} \sim \Delta m^2$

$\frac{E}{L} \gg \Delta m^2$ Oscillation suppressed

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2 2\theta \left(\Delta m^2\right)^2$$

$\frac{E}{L} \ll \Delta m^2$ Fast oscillation regime

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \, \langle \sin^2 \frac{\Delta m^2 L}{4E} \rangle \simeq \frac{1}{2} \sin^2 2\theta = |U^*_{\alpha 1} U_{\beta 1}|^2 + |U^*_{\alpha 2} U_{\beta 2}|^2$$

Equivalent to incoherent propagation: sensitivity to mass splitting is lost

Neutrino vs Antineutrino: CP

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{2\sum_{i<j} Re[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}] + \sum_{i=j} |U_{\alpha i}|^2|U_{\beta i}|^2}_{\delta_{\alpha\beta}}$$

CP-even

$$- \quad 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}]\sin^2\left[\frac{\Delta m^2_{ji}L}{4E}\right]$$

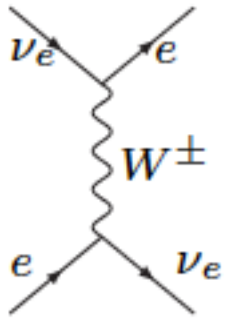
CP-odd

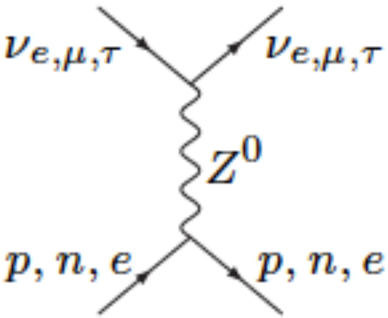
$$- \quad 2\sum_{i<j} \mathrm{Im}[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}]\sin\left[\frac{\Delta m^2_{ji}L}{2E}\right]$$

Exercise: check that Majorana phases do not contribute to this.

Neutrino Oscillations in matter

Many neutrino oscillation experiments involve neutrinos propagating in matter (Earth for atmospheric neutrinos or accelerator experiments, Sun for solar neutrinos)





Wolfenstein

Index of refraction (coherent forward scattering) can strongly affect the oscillation probability

Neutrino Oscillations in matter

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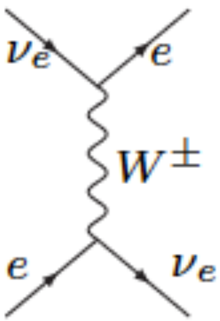
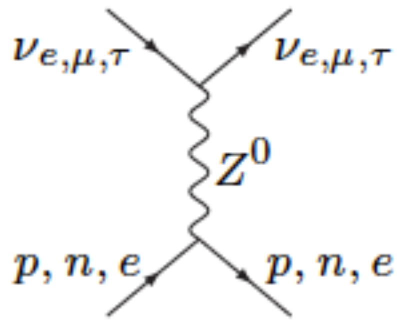
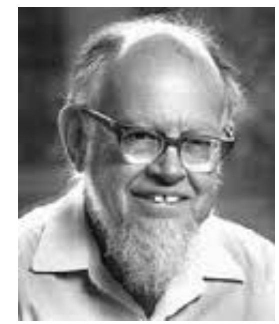






Wolfenstein

Index of refraction (coherent forward scattering) can strongly affect the oscillation probability

$$\mathcal{H}_{CC} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e][\bar{\nu}_e\gamma^\mu(1-\gamma_5)e] = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)e][\bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e]$$

$$\langle \bar{e}\gamma_\mu(1-\gamma_5)e\rangle_{\text{unpol.medium}} = \delta_{\mu 0}N_e$$

Neutrino propagation in matter

$$\langle \mathcal{H}_{CC} + \mathcal{H}_{NC} \rangle_{\rm medium} = \sqrt{2}\, G_F\, \bar{\nu}\, \gamma_0 \begin{pmatrix} N_e - \frac{N_n}{2} & & \\ & -\frac{N_n}{2} & \\ & & -\frac{N_n}{2} \end{pmatrix} \nu \equiv \bar{\nu}\, \gamma_0 V_m \nu$$

$$\mathcal{L} \simeq \bar{\nu}\, (i\partial\!\!\!/ - M_\nu - \gamma_0 V_m)\, \nu + \dots$$

$$\mathcal{O}(V_m^2, M_\nu^2 V_m)$$

$$E^2 - \mathbf{p}^2 \quad = \quad \pm 2\, V_m E + M_\nu^2$$

Earth: $V_m \simeq 10^{-13} eV \to 2V_m E \simeq 10^{-4} eV^2 \left[\frac{E}{1GeV}\right]$

Sun: $V_m \simeq 10^{-12} eV \to 2V_m E \simeq 10^{-6} eV^2 \left[\frac{E}{1MeV}\right]$

Oscillations in constant matter density

Effective mixing angles and masses depend on energy

$$\begin{pmatrix} \tilde{m}_1^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} = \tilde{U}^\dagger_{\mathrm{PMNS}} \left(M_\nu^2 \pm 2E \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix} \right) \tilde{U}_{\mathrm{PMNS}}$$

For two families

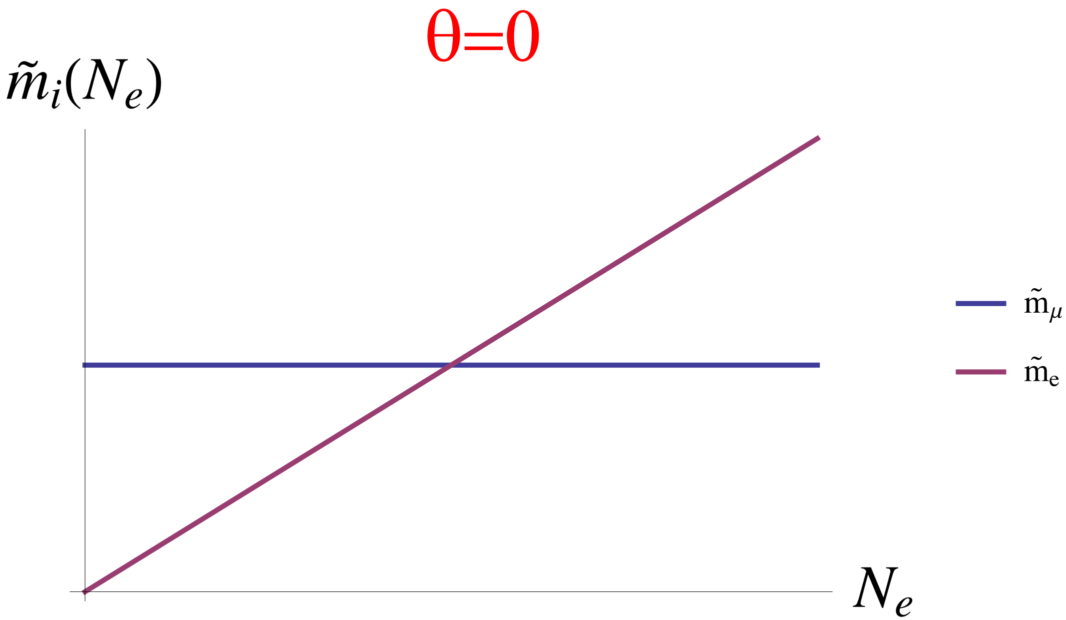
$$\sin^2 2\tilde{\theta} = \frac{(\Delta m^2 \sin 2\theta)^2}{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F E N_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\Delta \tilde{m}^2 = \sqrt{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F E N_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F E_{\mathrm{res}} N_e = 0 \qquad \sin^2 2\tilde{\theta} = 1, \quad \Delta \tilde{m}^2 = \Delta m^2 \sin 2\theta$$

MSW resonance

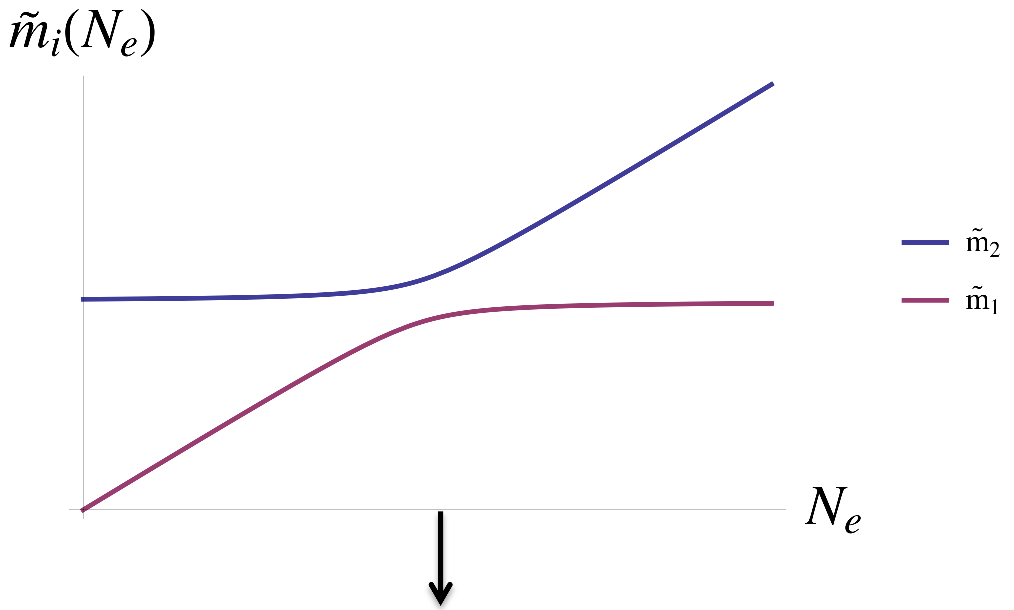
Mikheyev, Smirnov '85



MSW resonance

Mikheyev, Smirnov ‘85

θ≠0



$$\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F E N_e^{\text{res}} = 0$$

MSW Resonance:

-Only for ν or $\bar{\nu}$, not both

-Only for one sign of $\Delta m^2 \cos 2\theta$

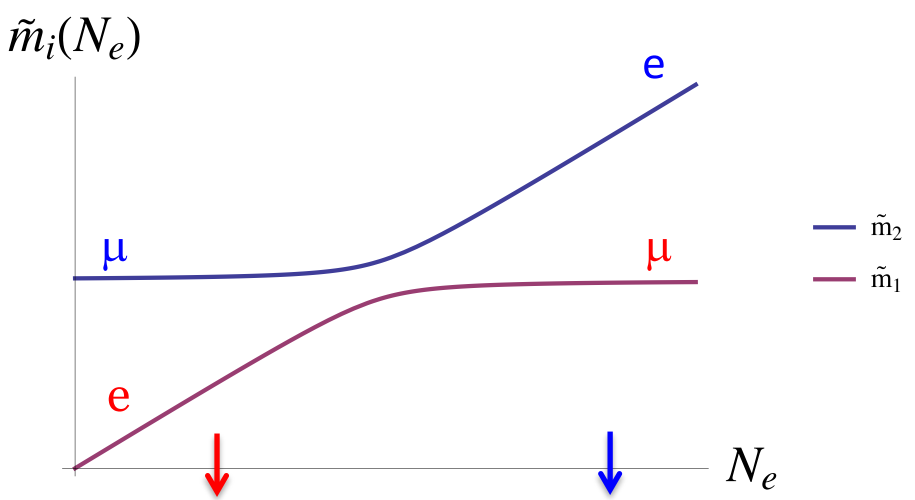
Neutrinos in variable matter

Solar neutrinos propagate in variable matter:

$$N_e(r) \propto N_e(0)e^{-r/R}$$

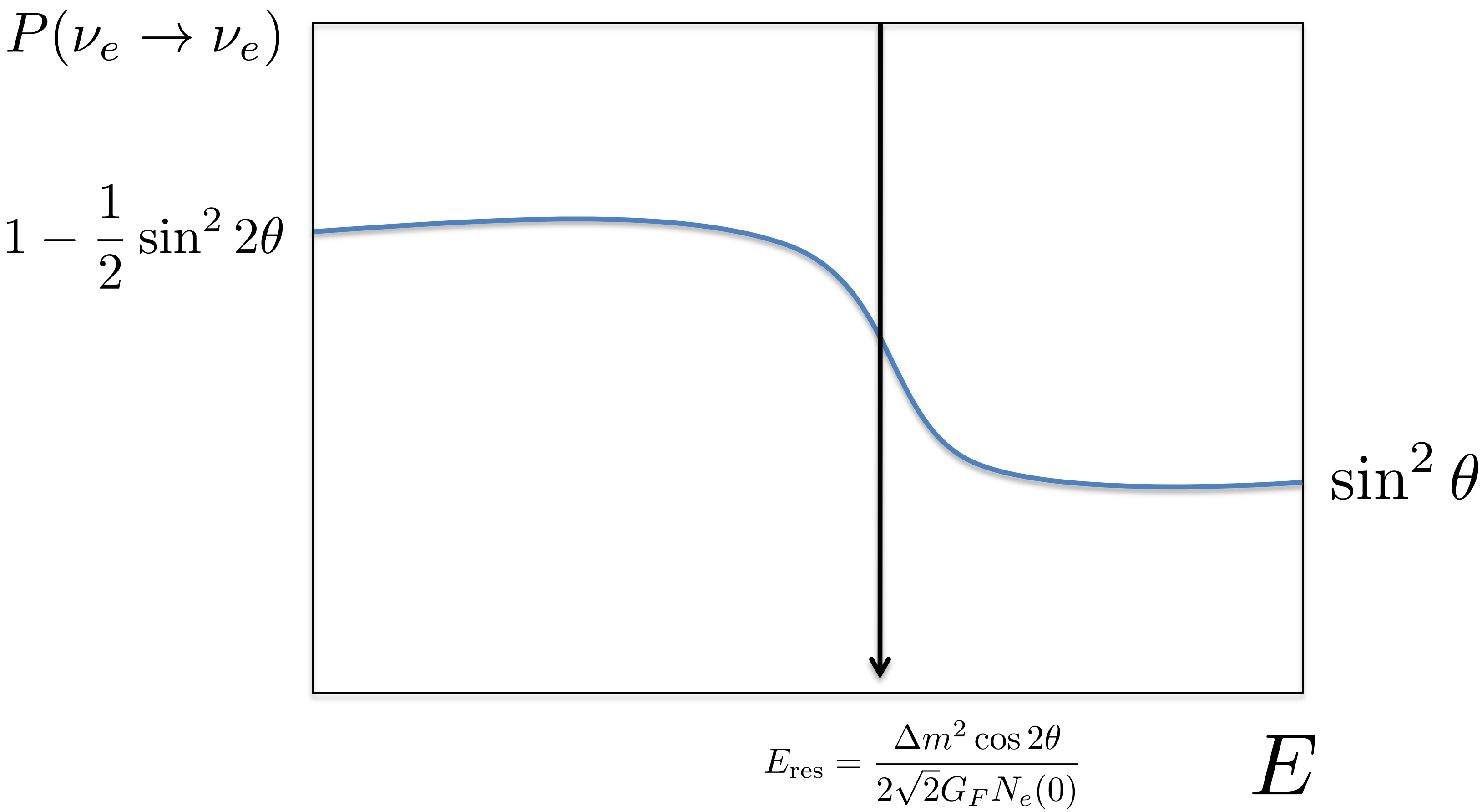
If the variation is slow enough: adiabatic approximation (if a state is at r=0 in an eigenstate $\tilde{m}_i^2(0)$ it remains in the i-th eigenstate until it exits the sun)

$$P(\nu_e \to \nu_e) = \sum_i |\langle \nu_e | \tilde{\nu}_i(\infty)\rangle|^2 |\langle \tilde{\nu}_i(0)|\nu_e\rangle|^2$$



$P(\nu_e \to \nu_e) \simeq 1 - \frac{1}{2}\sin^2 2\theta$ $\quad$ $P(\nu_e \to \nu_e) \simeq \sin^2\theta$

Solar neutrinos



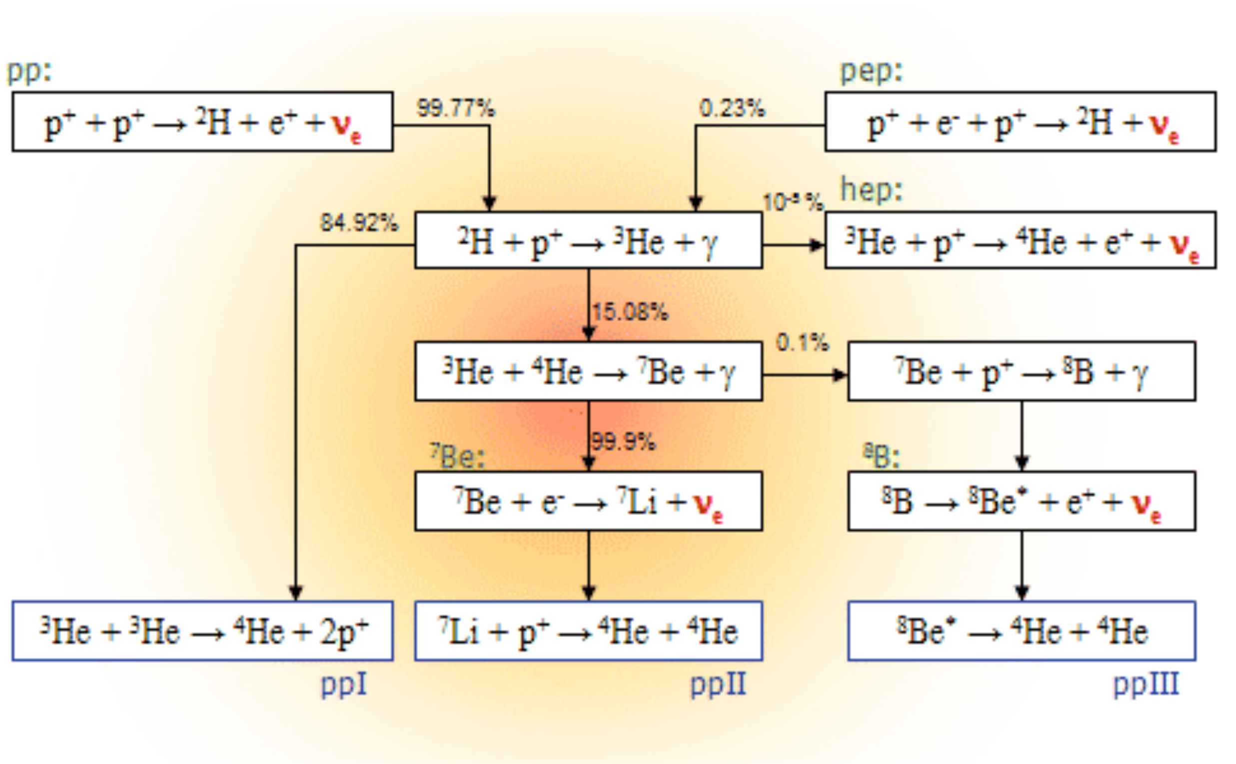
MSW resonance energy

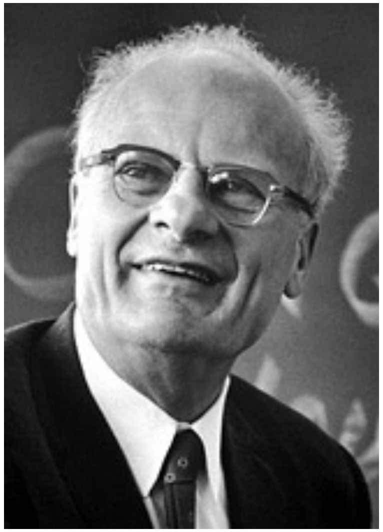
In most physical situations: piece-wise constant matter or adiabatic approx. good enough

Stars shine neutrinos

1939 Bethe

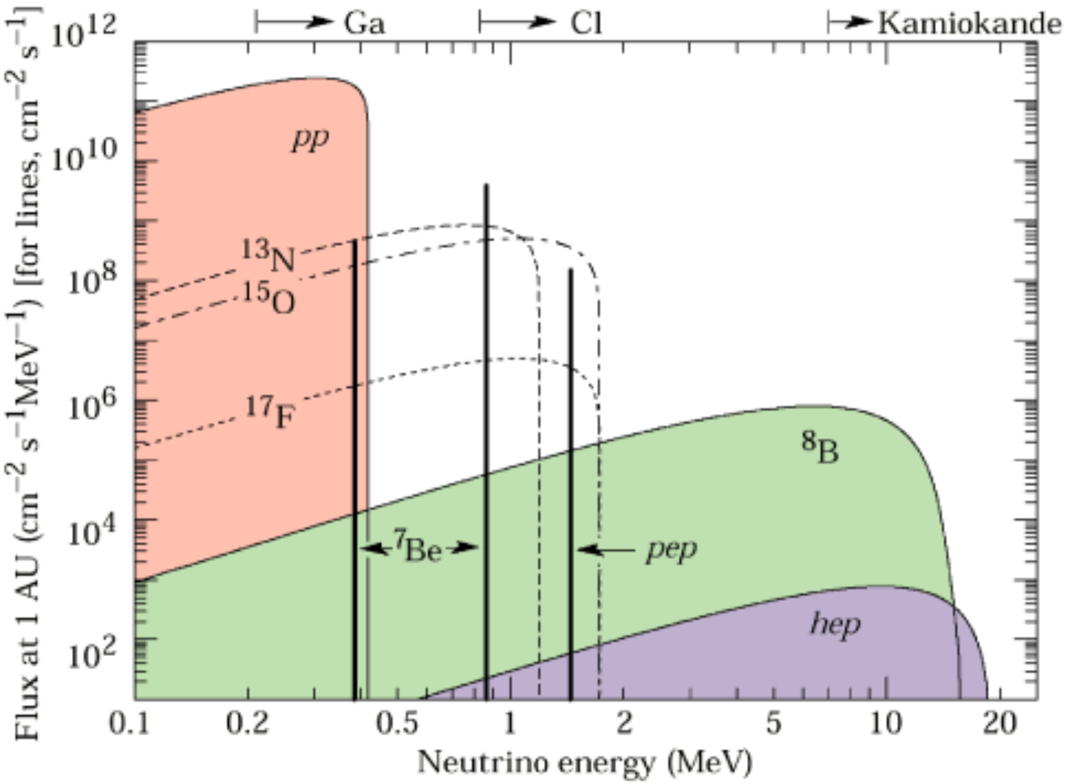
Stablishes the theory of stelar nucleosynthesis





Nobel 1967

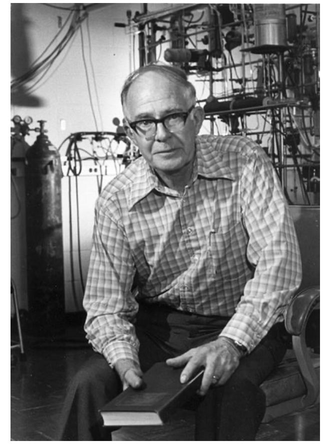
¿How many neutrinos from the Sun ?



Bahcall

The hero of the caves

1966 detects for the first time
solar neutrinos in a tank of
400k liters 1280m underground
(Homestake mine)



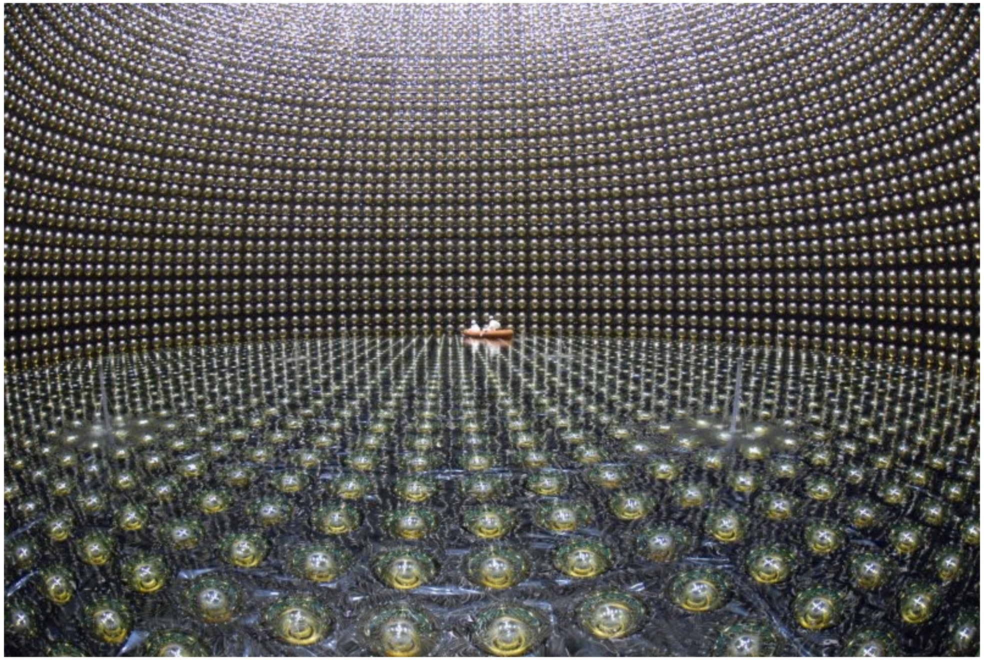
R. Davis
Nobel 2002

$$^{37}\mathrm{Cl} + \nu_e \rightarrow ^{37}\mathrm{Ar} + e^-$$

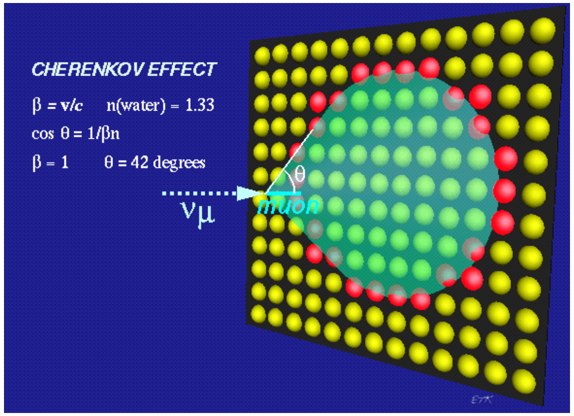
Did not convince because he saw 0.4 of the expected....

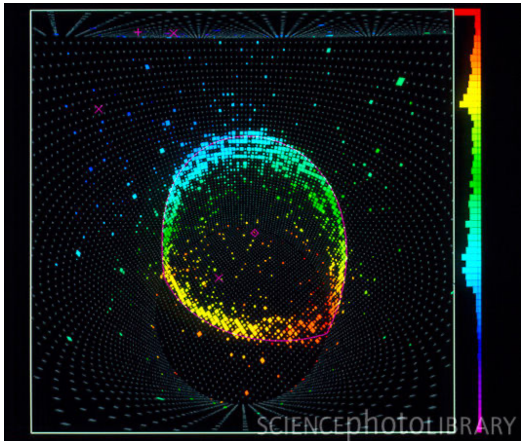
Problem in detector ? In solar model ? In neutrinos ?

Underground cathedrals of light



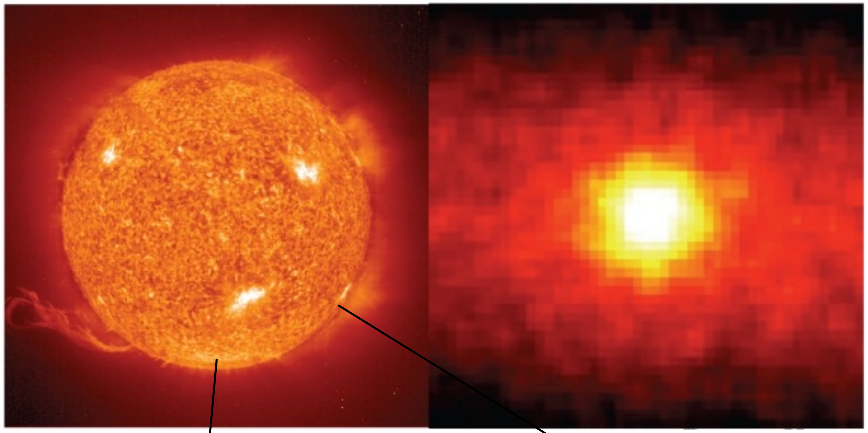
Koshiba (Nobel 2002)





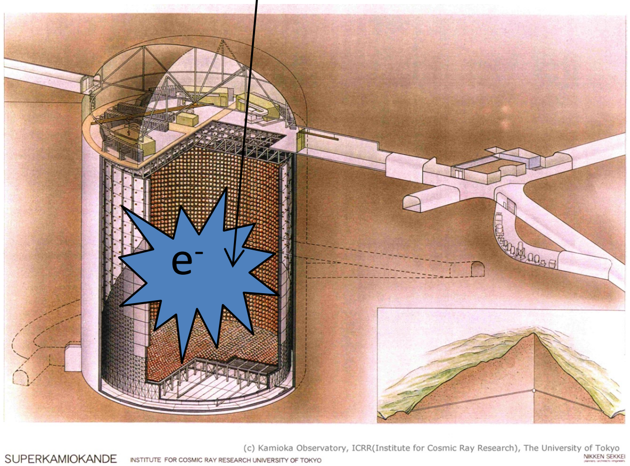
Allows to reconstruct velocity and direction, e/μ particle identification

Solar Neutrinos



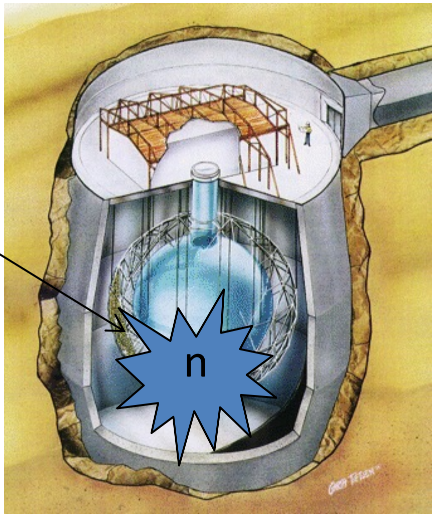
Neutrinography of the sun

SuperKamiokande (22.5 kton)



$$\nu_e + e^- \rightarrow \nu_e + e^-$$

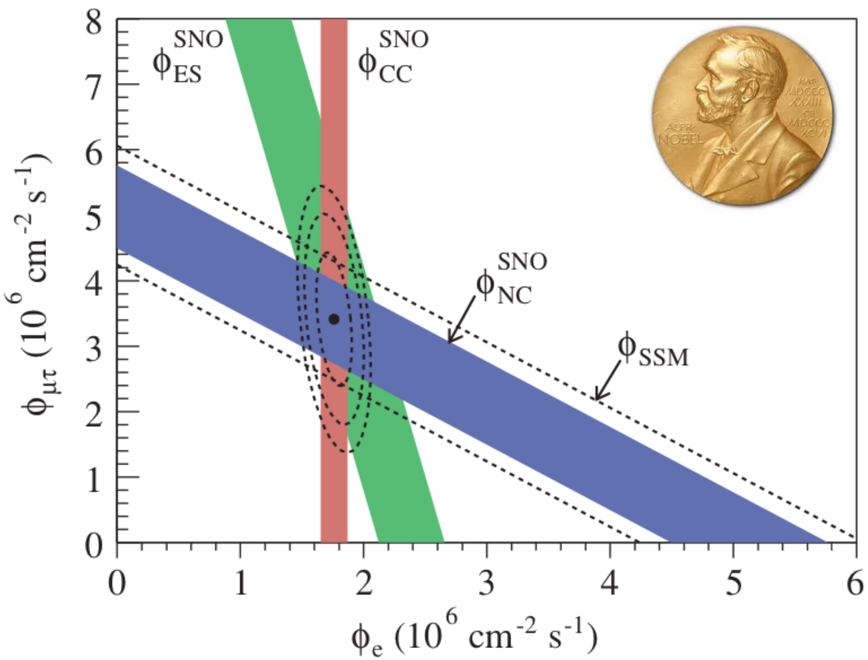
SNO

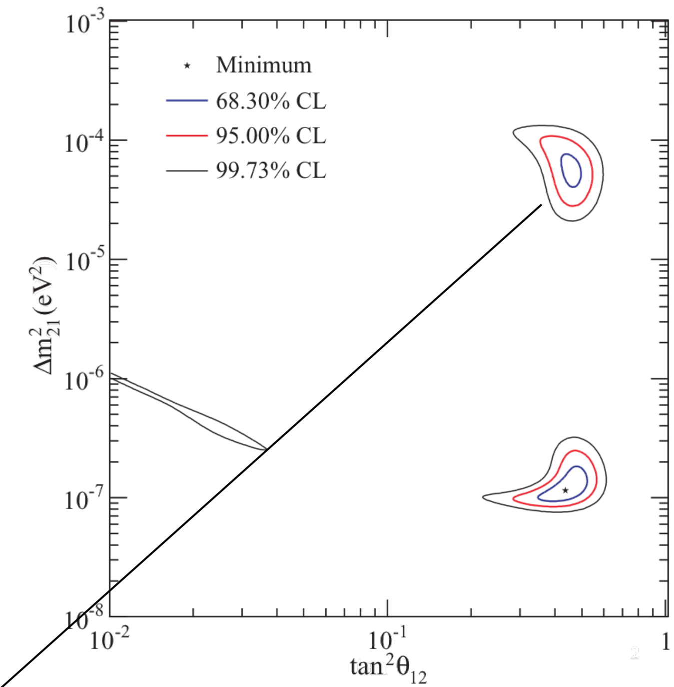


$$NC: \quad \nu_i + d \rightarrow p + n + \nu_i$$

$$CC: \quad \nu_e + d \rightarrow p + p + e^-$$

Flavour of solar neutrinos





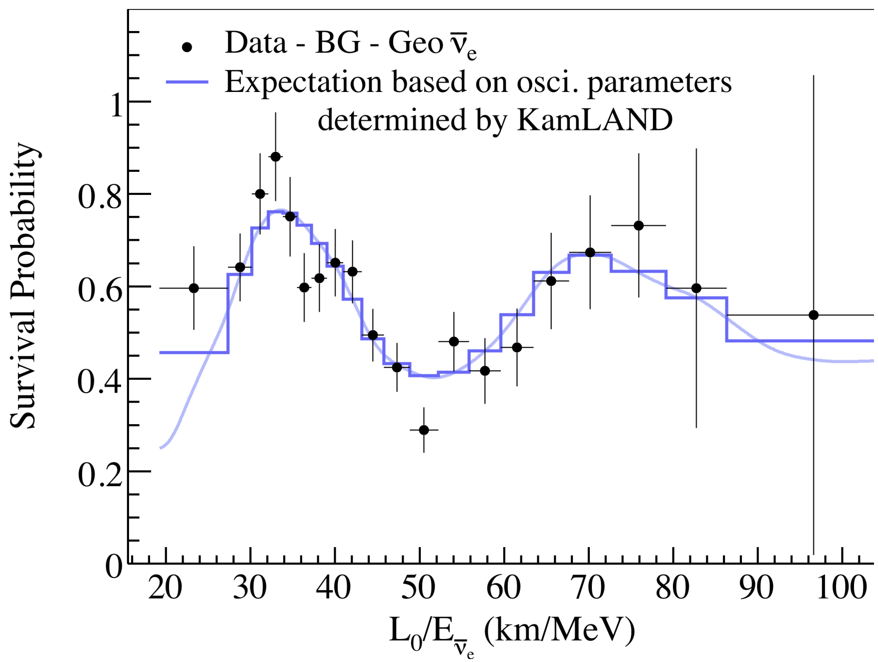
$$|\Delta m^2|^{-1} \sim \frac{O(100Km)}{O(MeV)}$$

Can be tested in the Earth with Reines&Cowen experiment !

KamLAND: solar oscillation

$$\overline{\nu}_e \to \overline{\nu}_e$$

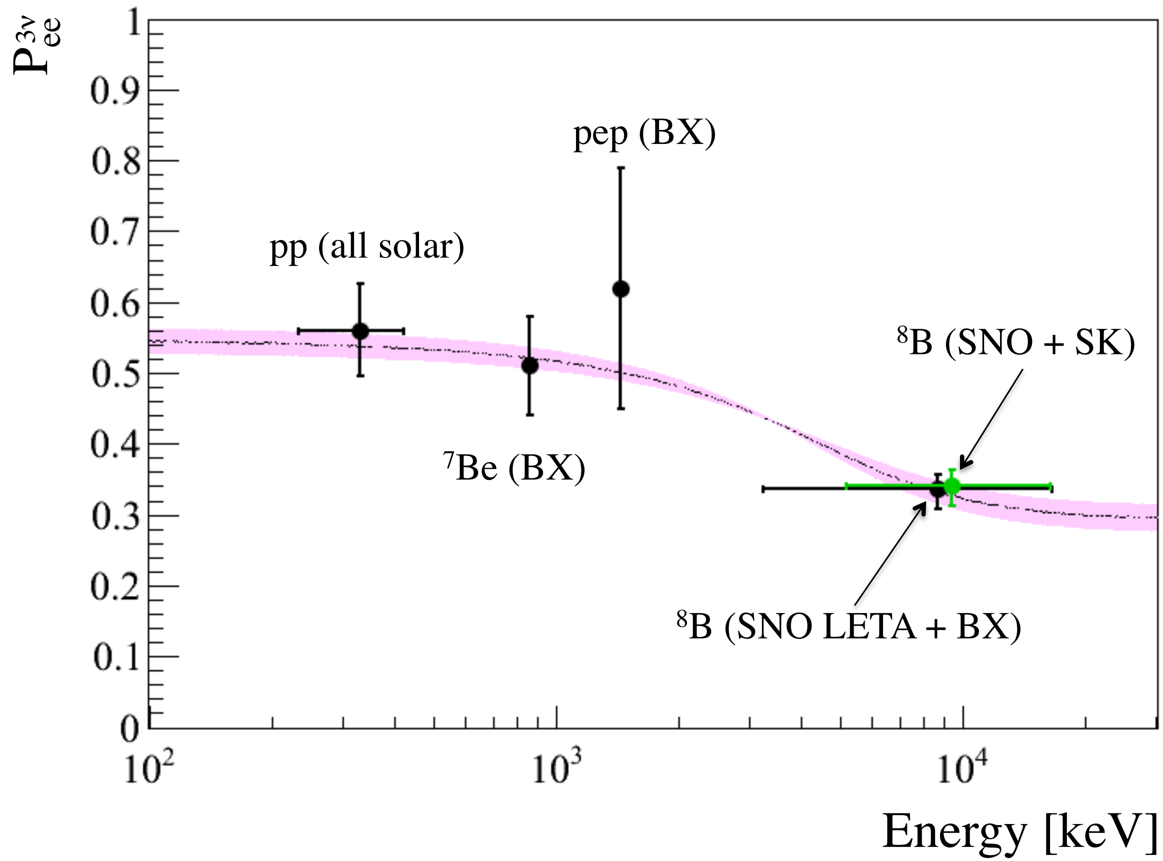
Reines&Cowan experiment ½ century later at 170 km from Japanese reactors ...



$$\Delta m^2_{\mathrm{solar}} \simeq 8 \times 10^{-5}\ eV^2$$

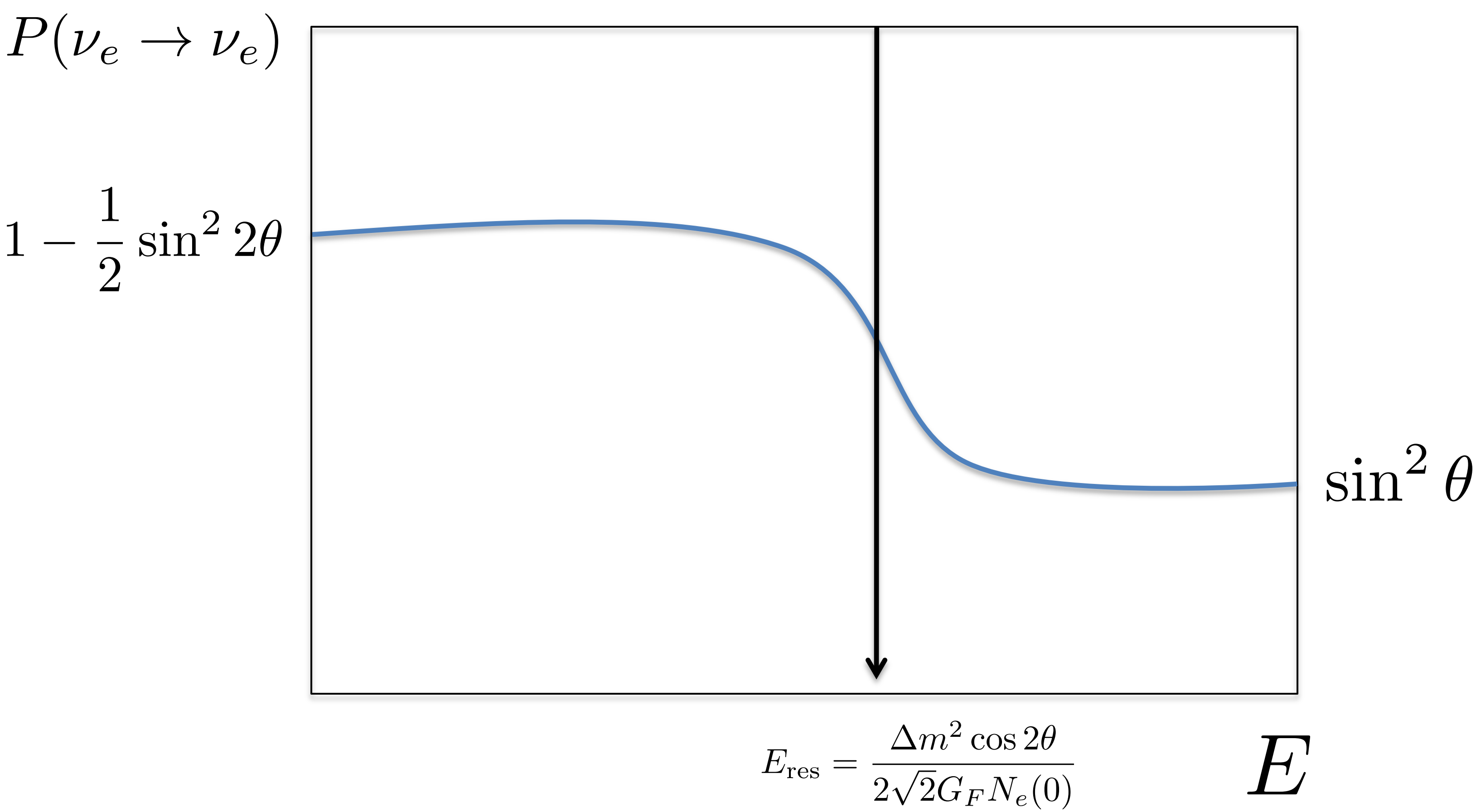
Large mixing angle

Solar neutrinos and MSW



Borexino

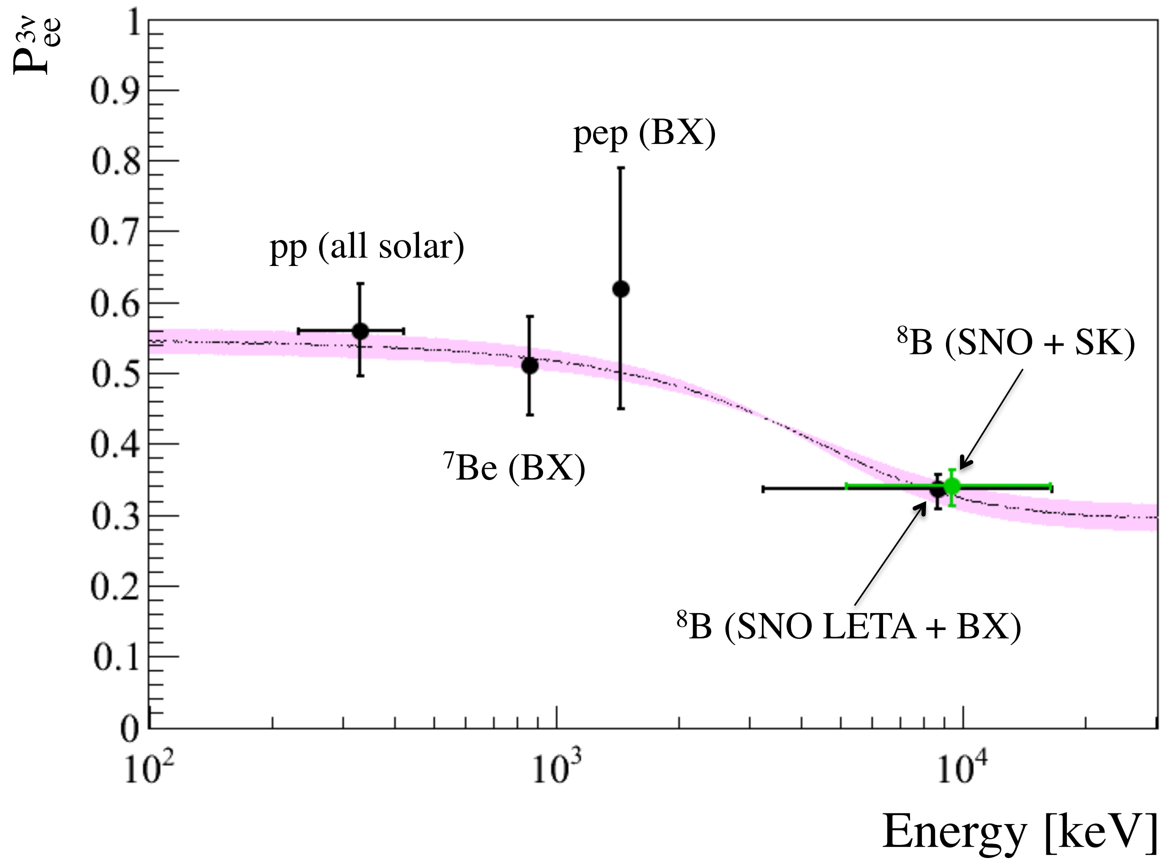
Solar neutrinos



MSW resonance energy

In most physical situations: piece-wise constant matter or adiabatic approx. good enough

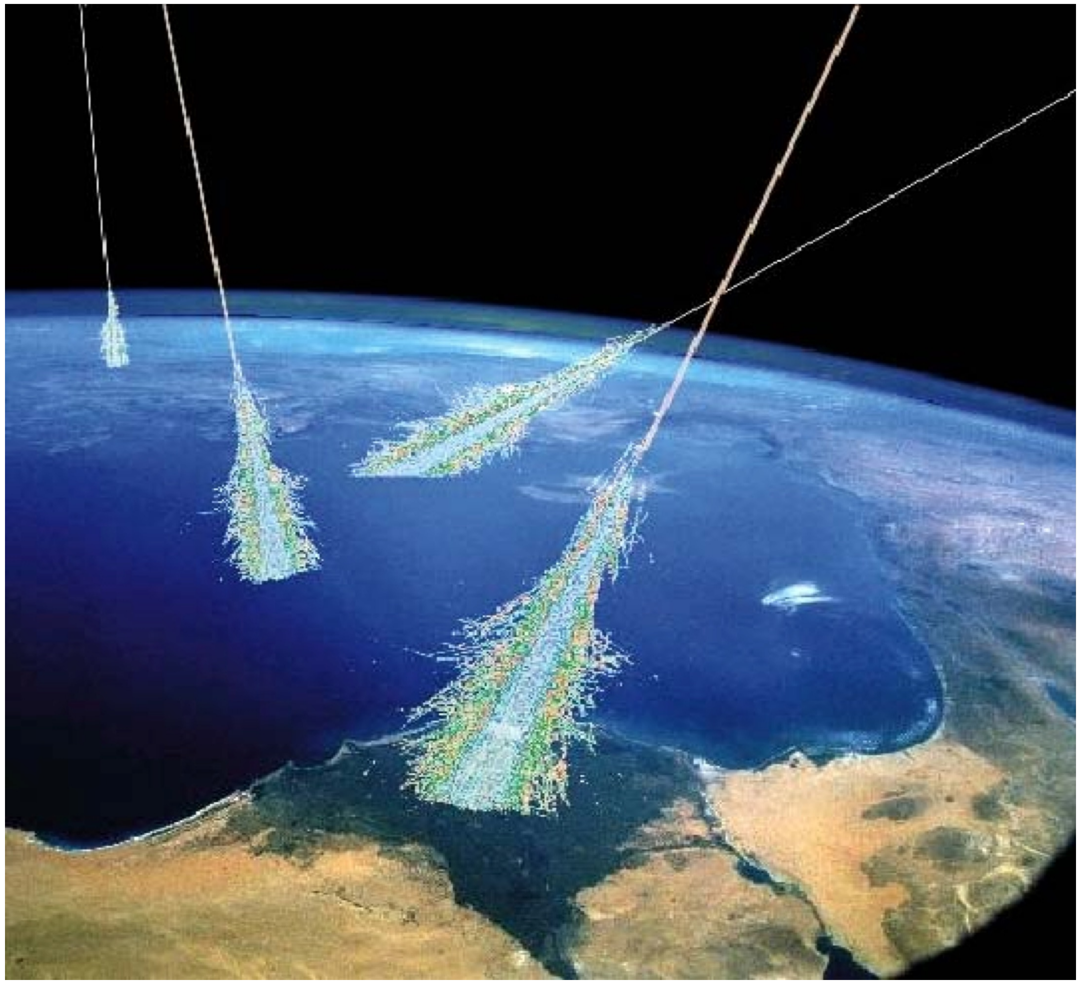
Solar neutrinos and MSW



$\sin^2 \theta_{\text{solar}} \simeq 0.3$

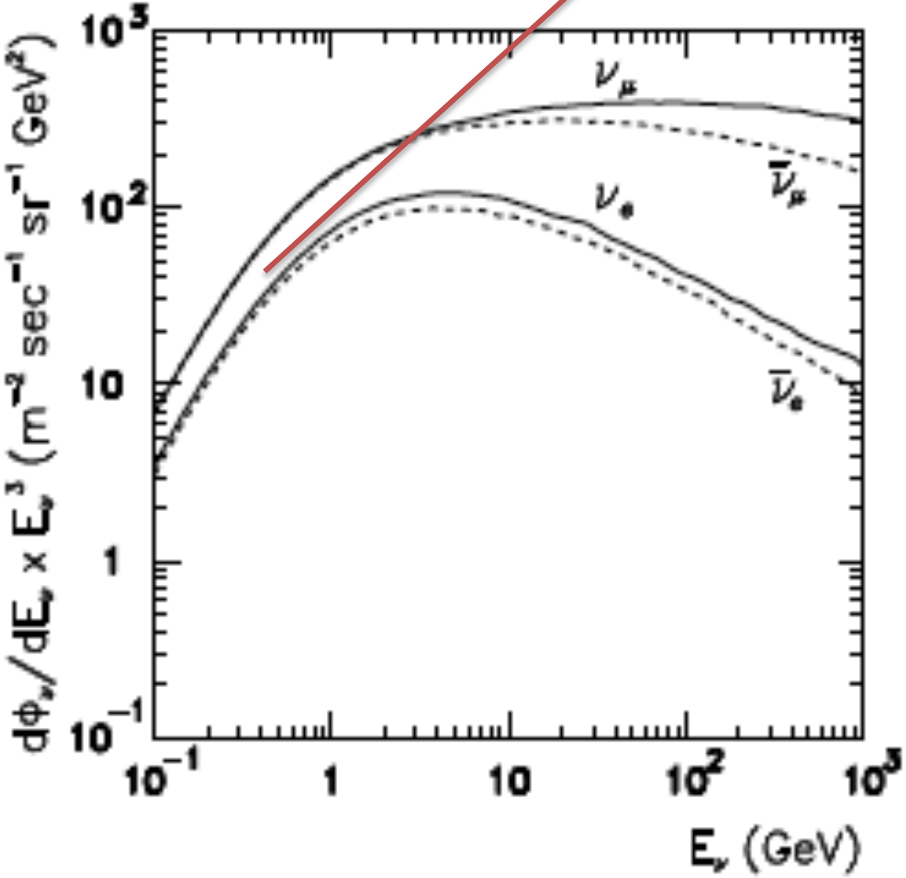
Borexino

Atmospheric Neutrinos



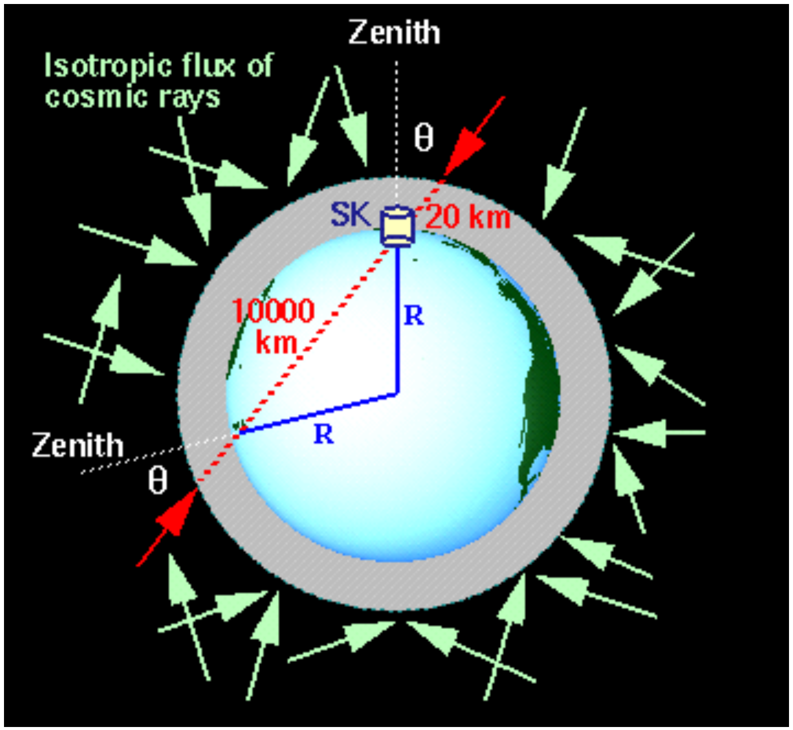
Atmospheric Neutrinos

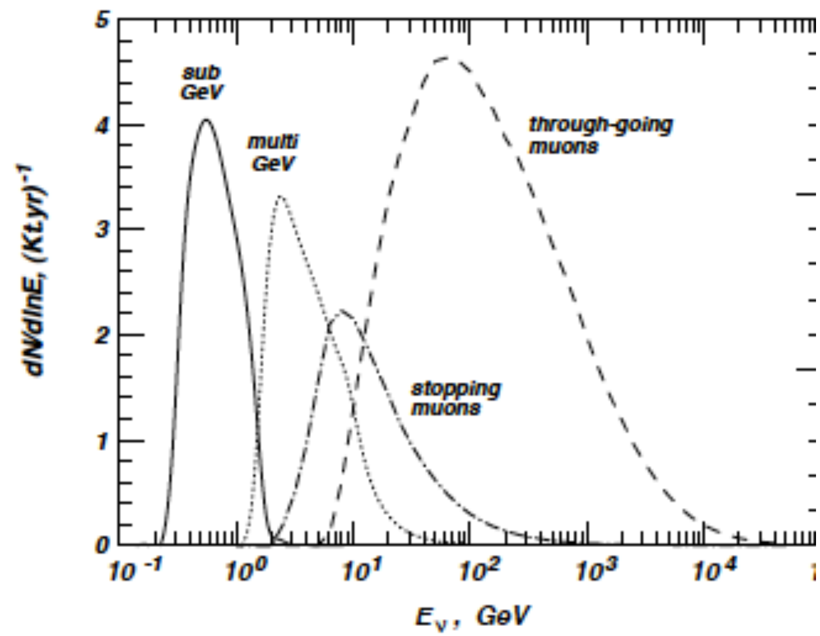
$\nu_\mu/\nu_e \sim 2$



Produced in the atmosphere when primary cosmic rays collide with it, producing π, K

Atmospheric Neutrinos

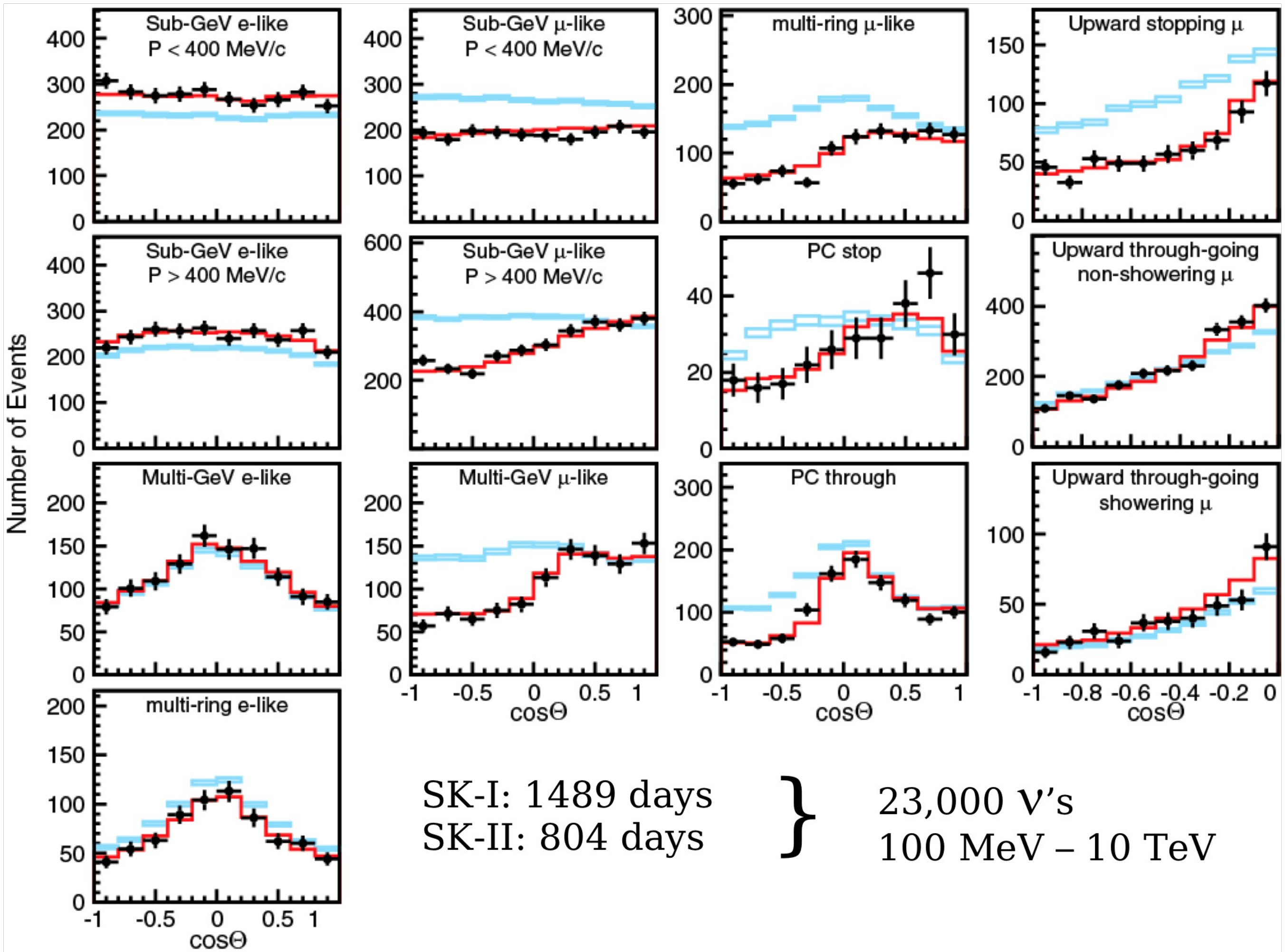




$$L = 10 - 10^4 \text{ Km}$$

Measuring the energy dependence and the zenith angle E/L spans many orders of magnitude

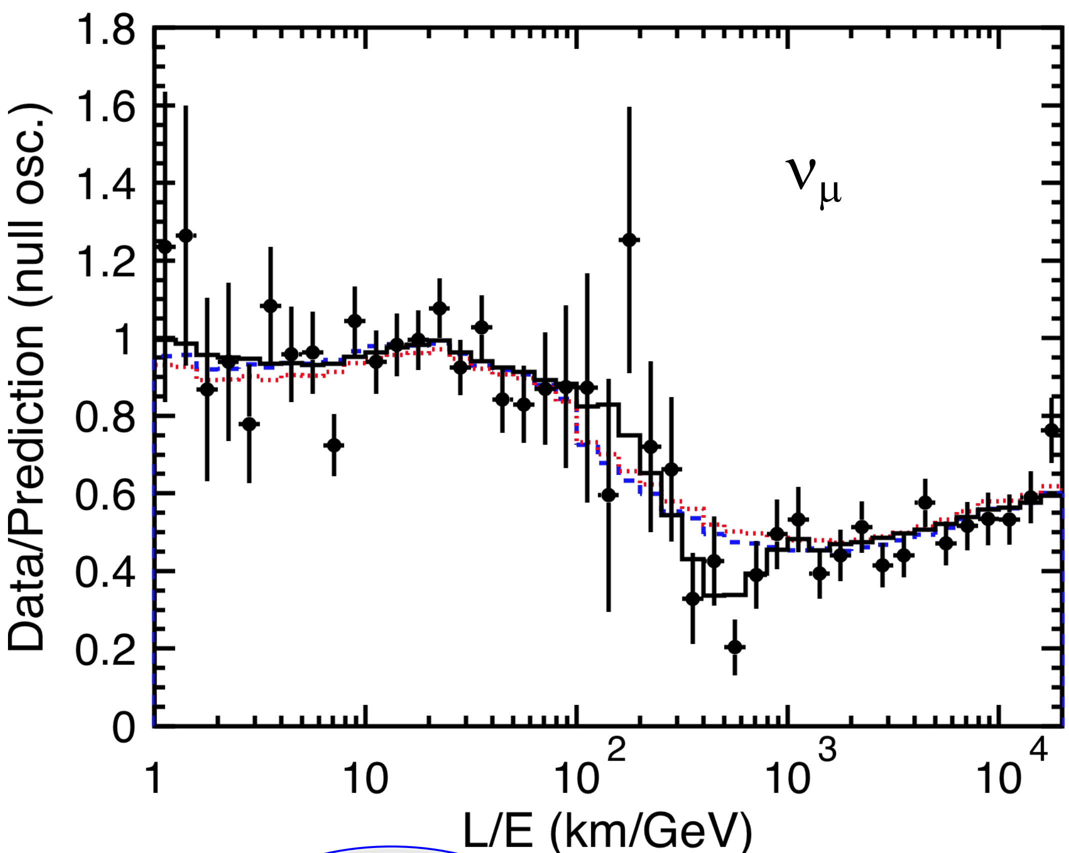
Oscillation of Atmospheric Neutrinos



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Atmospheric Oscillation



$$\Delta m^2_{\rm atm} = 2.5 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{\rm atmos} \simeq 1$$

$$|\Delta m^2|^{-1} \sim \frac{O(1000Km)}{O(GeV)} \sim \frac{O(1km)}{O(MeV)}$$

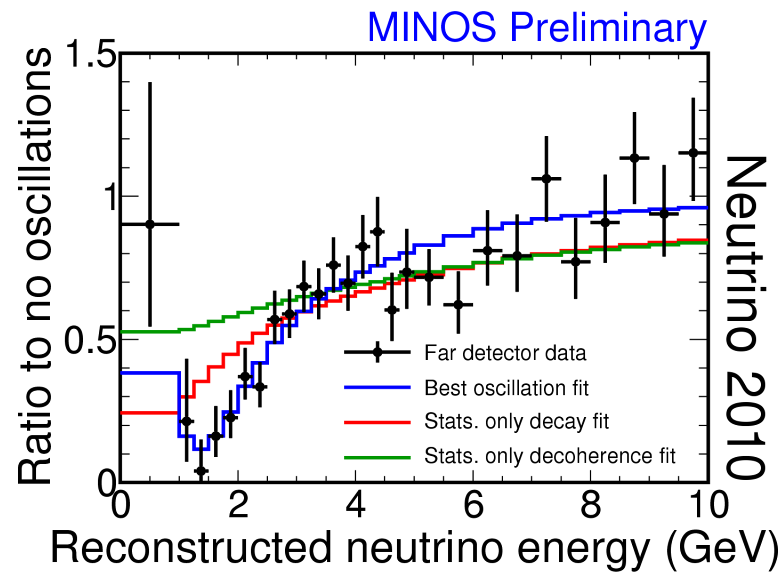
Reines&Cowan experiment at 1km!

Lederman&co experiment at 1000km!

Accelerator Neutrinos oscillate with the atmospheric wavelength

Pulsed neutrino beams to 700 km baselines $\nu_\mu \rightarrow \nu_\mu$

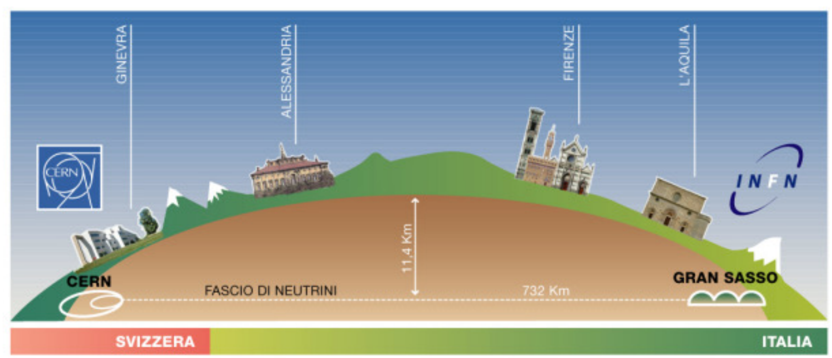
MINOS



$\nu_\mu \rightarrow \nu_\tau$ OPERA

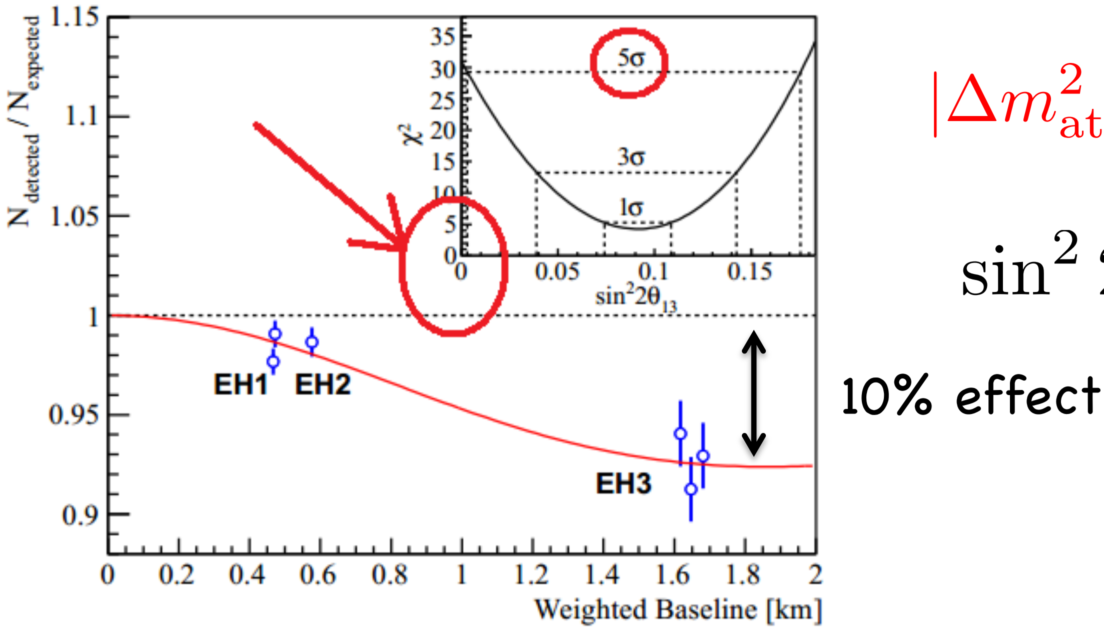
$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_{\rm atmos} \simeq 1$$



Reactor neutrinos oscillate with atmospheric wavelength

Double Chooz, Daya Bay, RENO $\bar{\nu}_e \to \bar{\nu}_e$

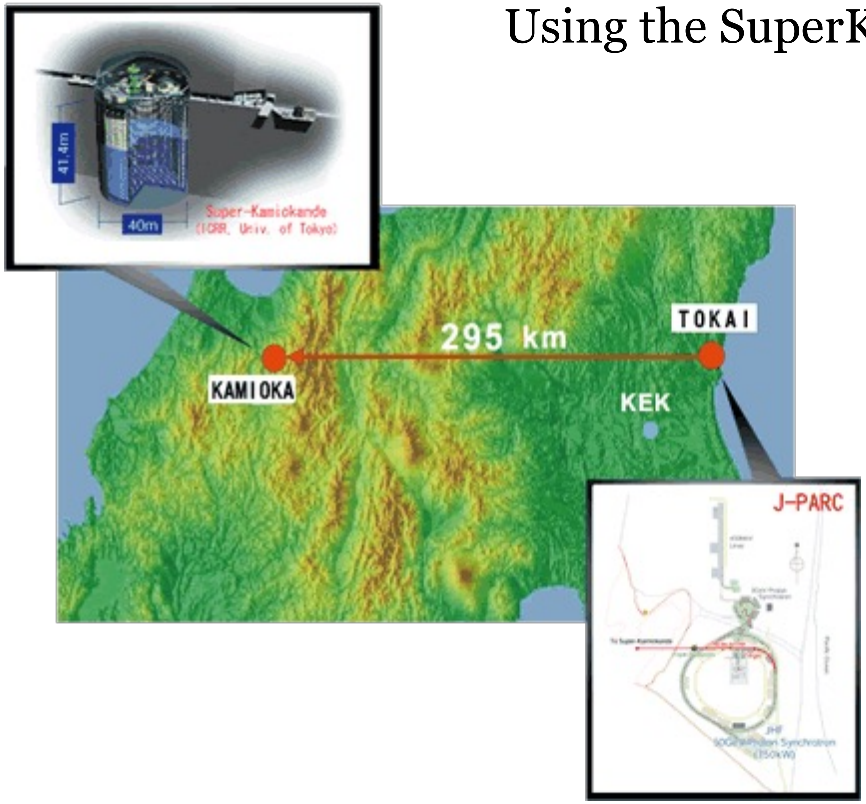


$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

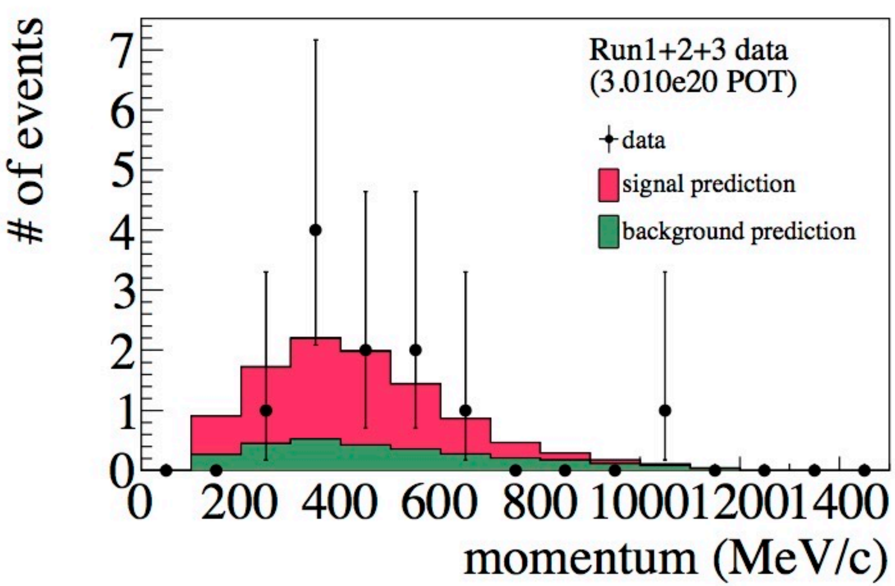
$$\sin^2 2\theta_r = 0.1 \Rightarrow \theta_r \sim 9^\circ$$

Accelerator Neutrinos :T2K

Using the SuperKamiokande detector!

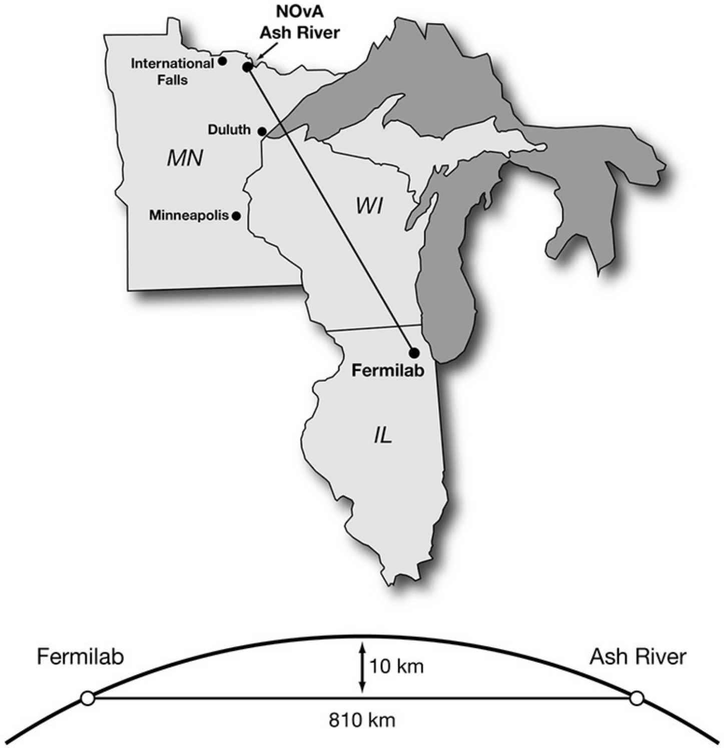


$$\nu_\mu \to \nu_e$$ @L=300km

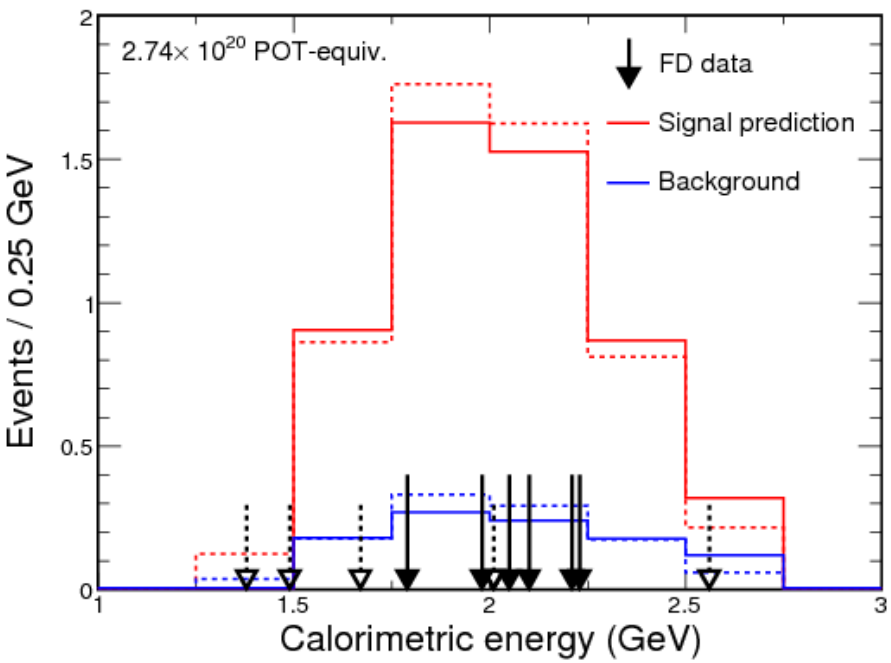


$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

Accelerator Neutrinos : NOνA



$\nu_\mu \rightarrow \nu_e$ @ L=810km



$$|\Delta m^2_{\text{atmos}}| \simeq 2.5 \times 10^{-3}\ eV^2$$