Neutrino Physics - Theory

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IFIC INSTITUT DE FÍSICA CORPUSCULAR
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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
GENERALITAT VALENCIANA Conselleria d'Educació, Investigació, Cultura i Esport

Lecture 1

- Historical introduction to neutrino physics

Neutrinos in the SM

- Neutrino interactions
- Neutrino mass in the SM

Neutrino oscillations

- First evidences and discovery
- Flavor oscillations in vacuum
- Flavor oscillations in matter

Lecture 2

Neutrino masses

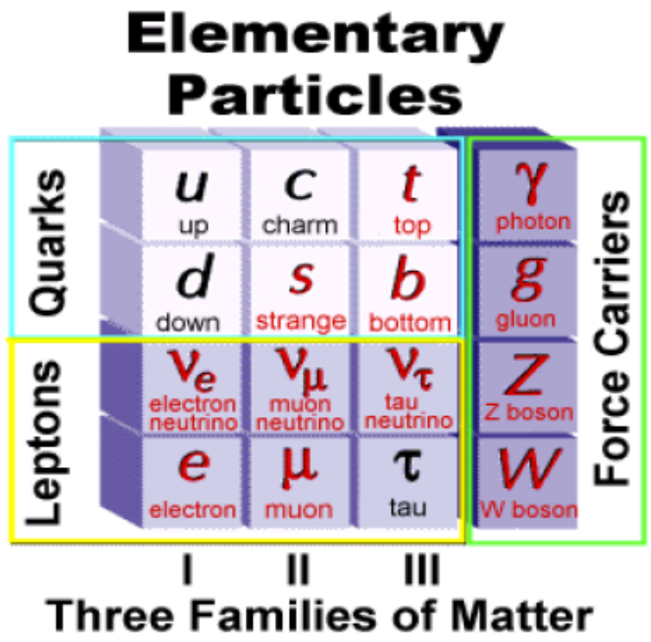
- Current limits
- Neutrino mass models

Neutrino physics BSM

- Light sterile neutrinos
- Non-unitary neutrino mixing
- Non-standard interactions
- BSM searches with CEvNS

What is a neutrino?

- spin 1/2 particle
- massless particle (almost)
- neutral
- 3 flavors (mixing)



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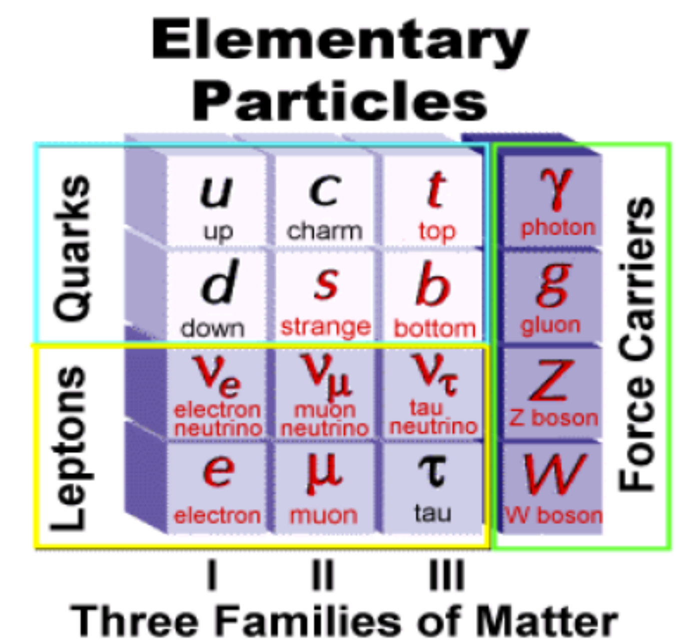

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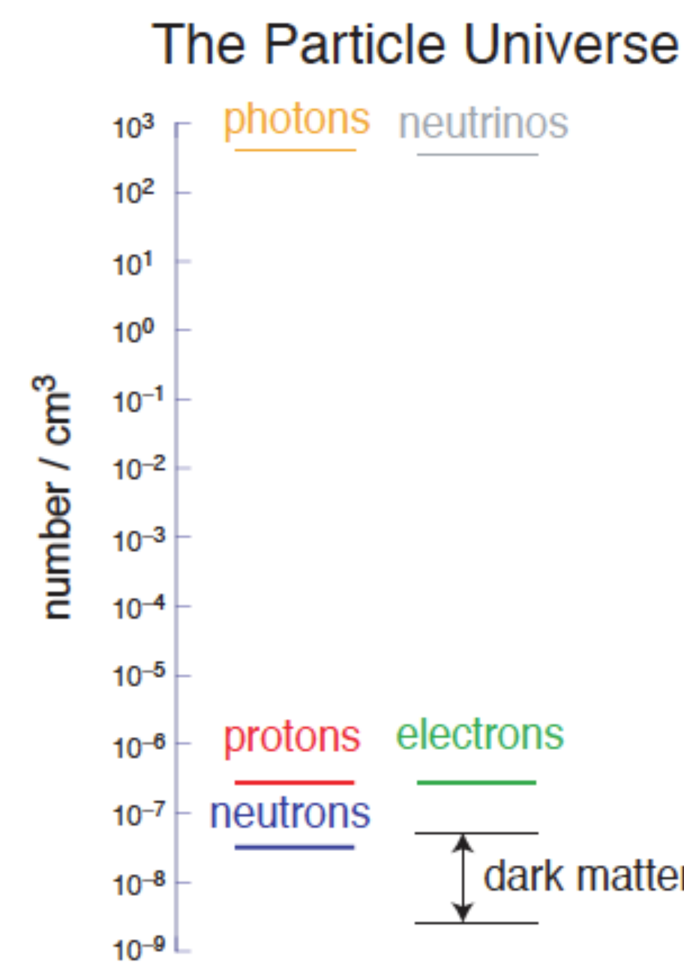
Anything else?

Every second we are traversed by:

- $400\text{x}10^{12}$ neutrinos from the Sun
- $50\text{x}10^{9}$ neutrinos from natural radioactivity
- $10\text{x}10^{9}$ neutrinos from nuclear power plants

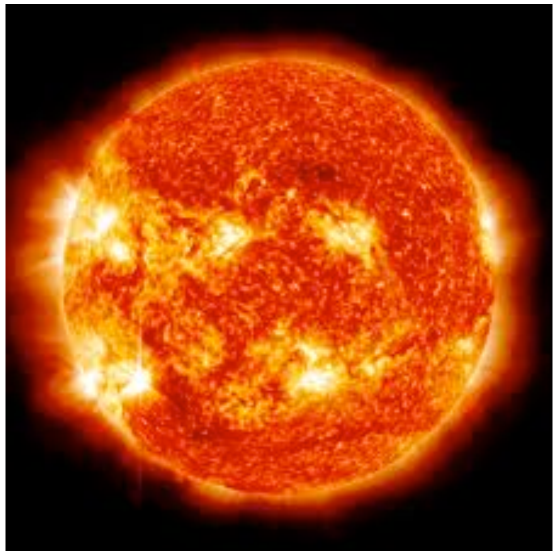
Moreover:

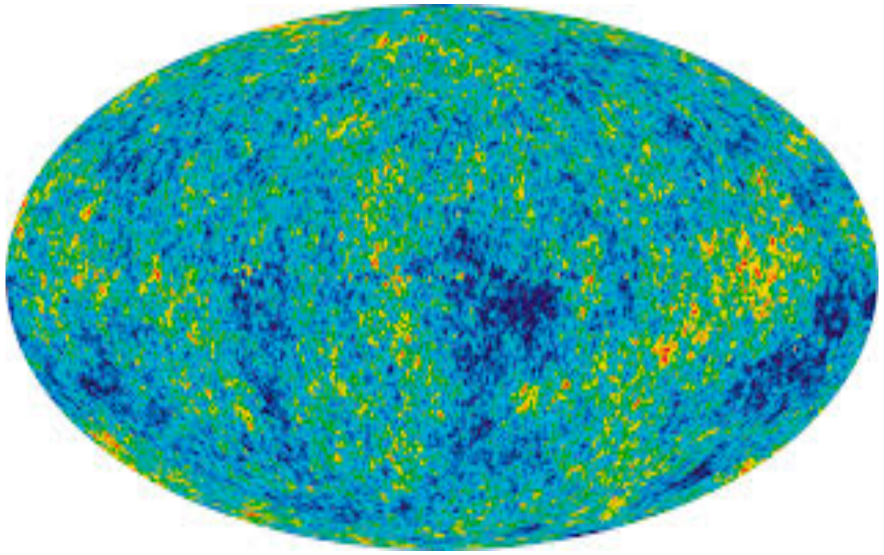
- our body emits 4000 neutrinos/s (^{40}K decay)
- the Universe contains ~ $330\text{x}10^{6}$ neutrinos/m^3



Why neutrinos are so important?

- They can probe environments that other techniques cannot: SN explosions, the core of the Sun,...
- Their role is crucial for the evolution of the universe (Big Bang Nucleosynthesis, structure formation).
- They could help explaining the matter-antimatter asymmetry of the Universe (leptogenesis mechanism).
- They could be a component of the dark matter of the universe.
- They provide the first evidence for physics beyond the SM!!!



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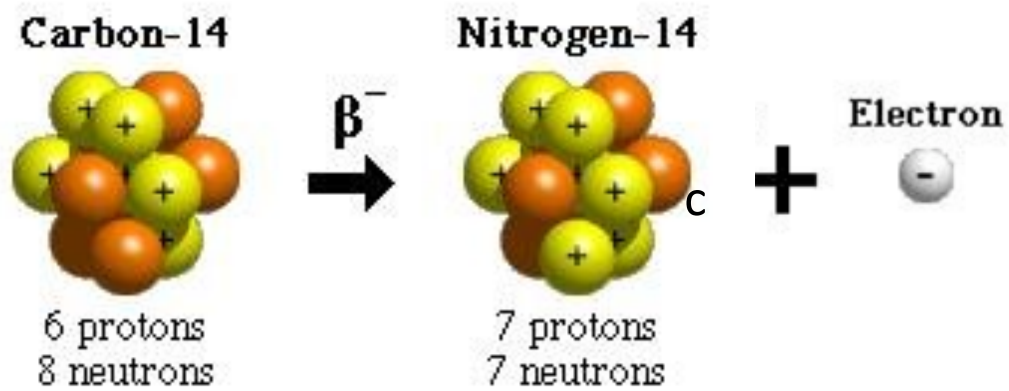
However: there are still many open questions in neutrino physics

Historical introduction to neutrino physics

The proposal of the neutrino

1910-1920: Experiments on radioactive decay of atomic nuclei



Lise Meitner and Otto Hahn

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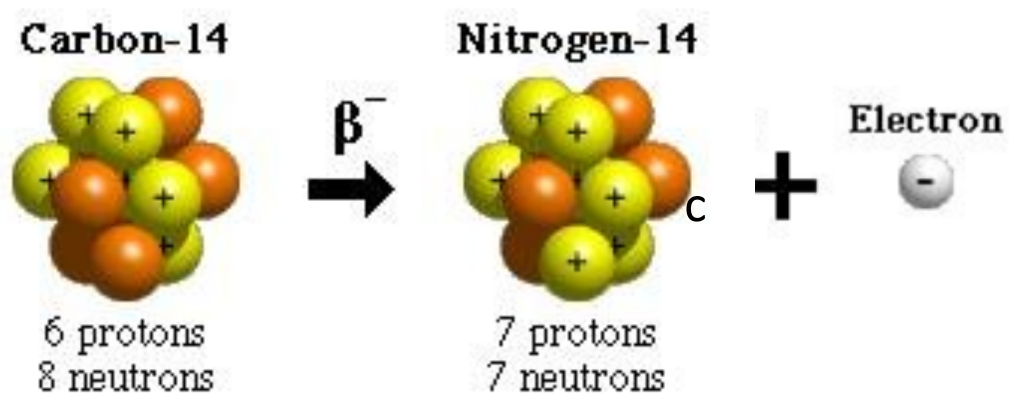

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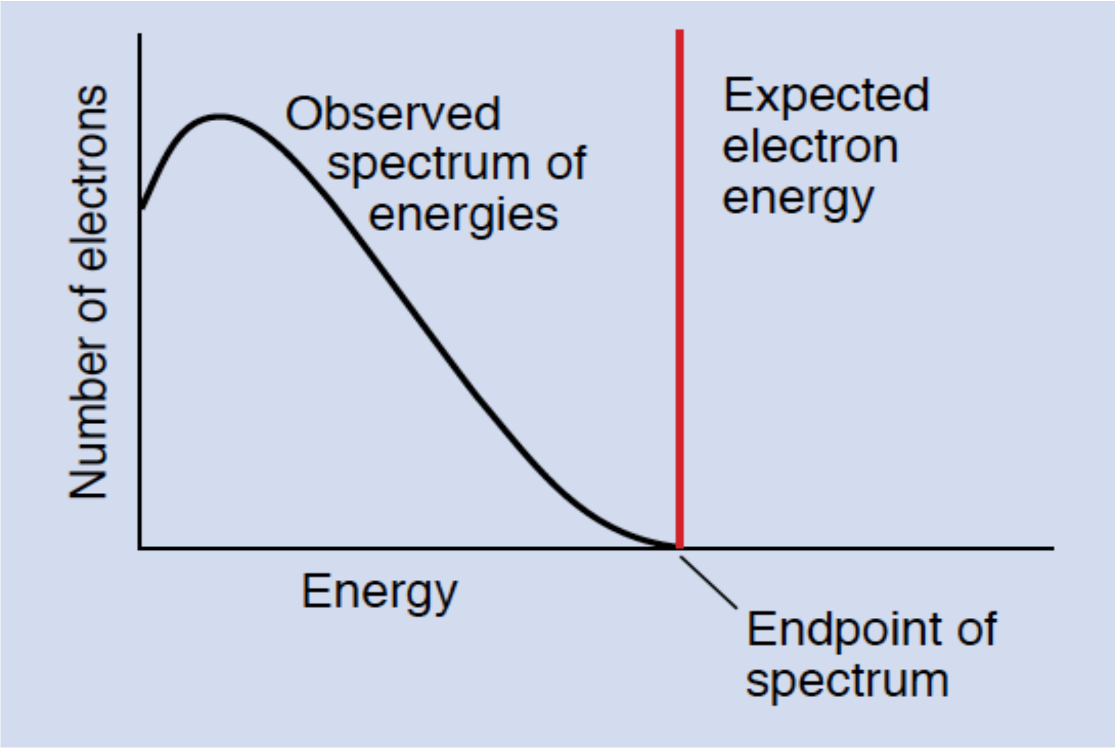
Energy and momentum conservation

⇒ emitted electrons should have a fixed energy



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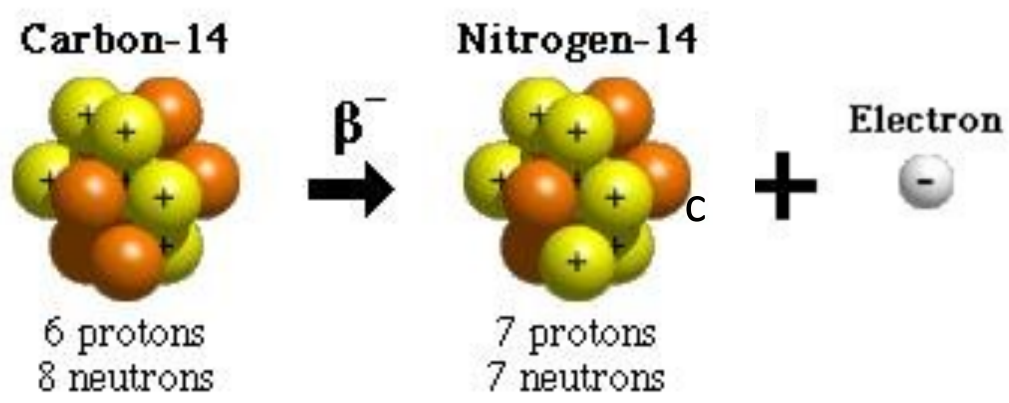

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Energy and momentum conservation
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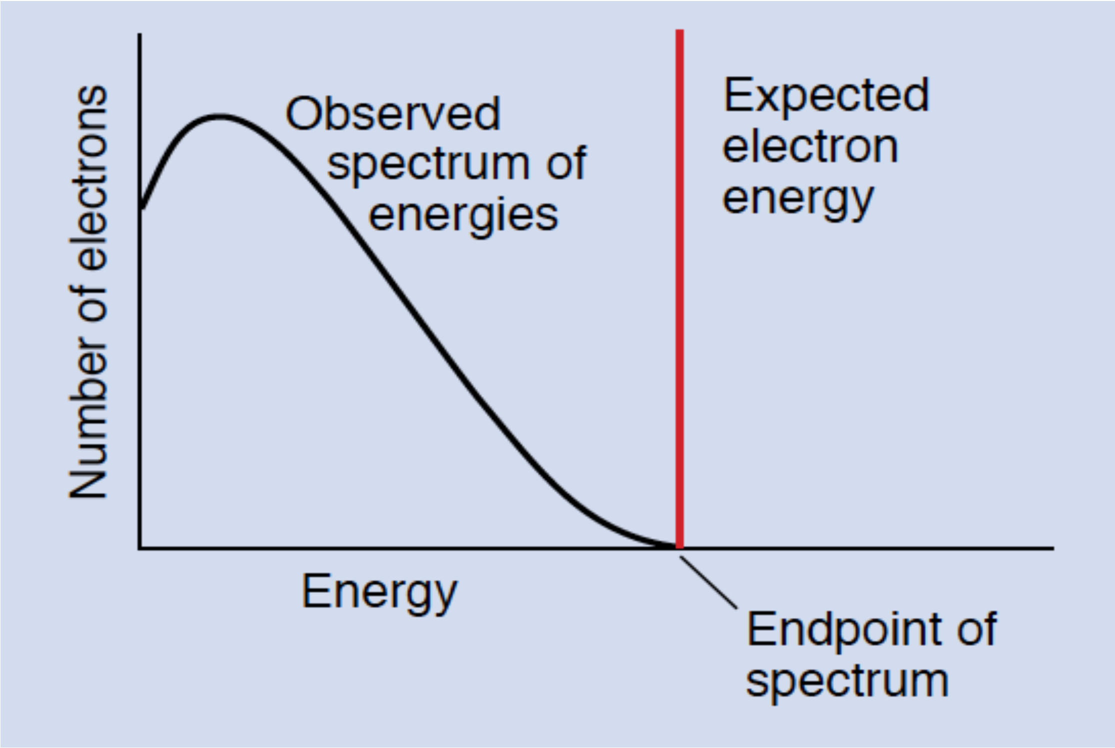
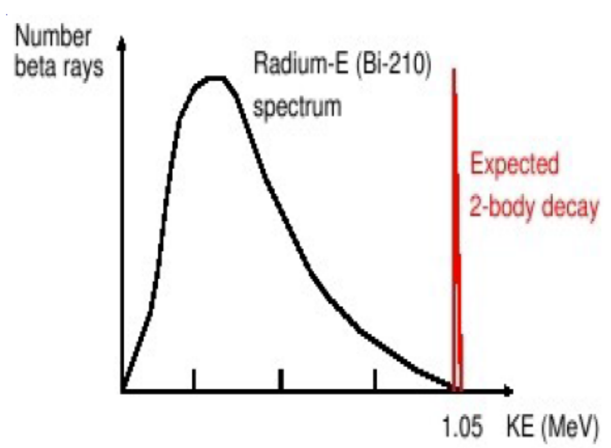
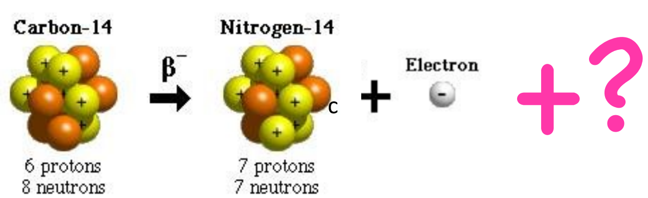
Niels Bohr suggested that energy may not be conserved in individual nuclear processes



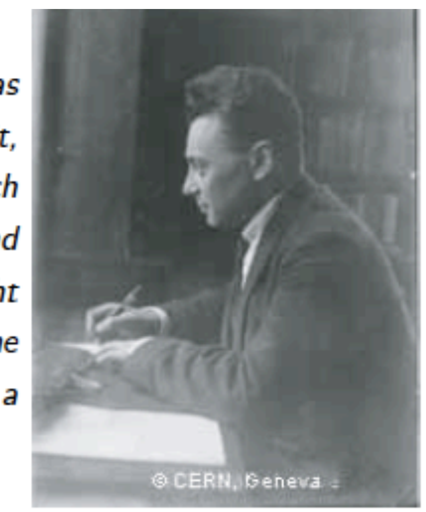
The proposal of the neutrino

1930: Pauli introduced the neutrino to explain the continuous electron spectrum





"*Dear radioactive ladies and gentlemen,*
I have come upon a desperate way out regarding . . . [some fairly obscure data], as well as to the continuous β-spectrum, in order to save . . . The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin 1/2 and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. . . . The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant."



➡ from conservation of angular momentum: spin 1/2

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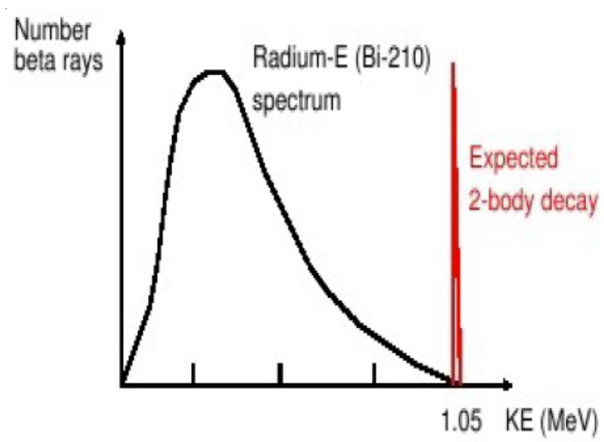

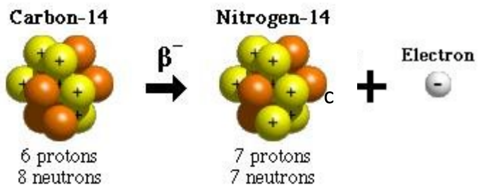

+?

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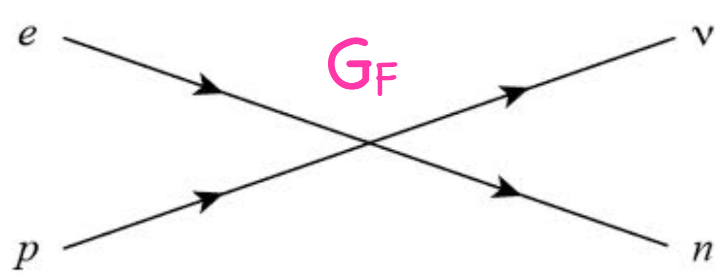
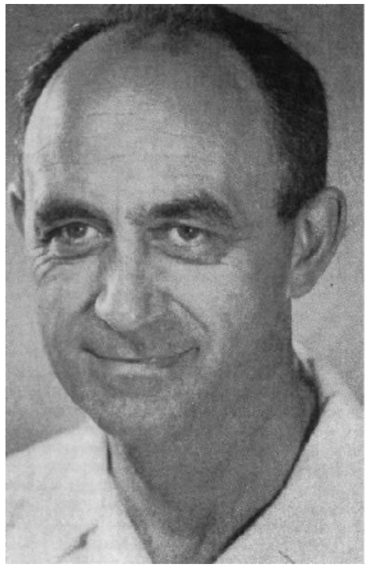
1933: Fermi postulated the first theory of nuclear beta decay, the theory of weak interactions

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

➡ new name for particle: **neutrino**





Where was the neutrino?

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$\sigma \sim 5\text{x}10^{-44}\ \text{cm}^2$ for a 2 MeV neutrino

(to be compared with $\sigma_{\gamma p} \sim 10^{-25}\ \text{cm}^2$) !!!

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→ mean free path of neutrinos in **water**: $\lambda_{water} \approx 1.7\mathrm{x}10^{18}$ m ~ 150 ly (only free p)
(assuming interaction with all nucleons: $\lambda_{water} \approx 1.7\mathrm{x}10^{17}$ m ~ 15 ly)

→ mean free path of neutrinos in **lead**: $\lambda_{lead} \approx 1.5\mathrm{x}10^{16}$ m ~ 1.5 ly (all nucleons)

Neutrino: impossible to detect?

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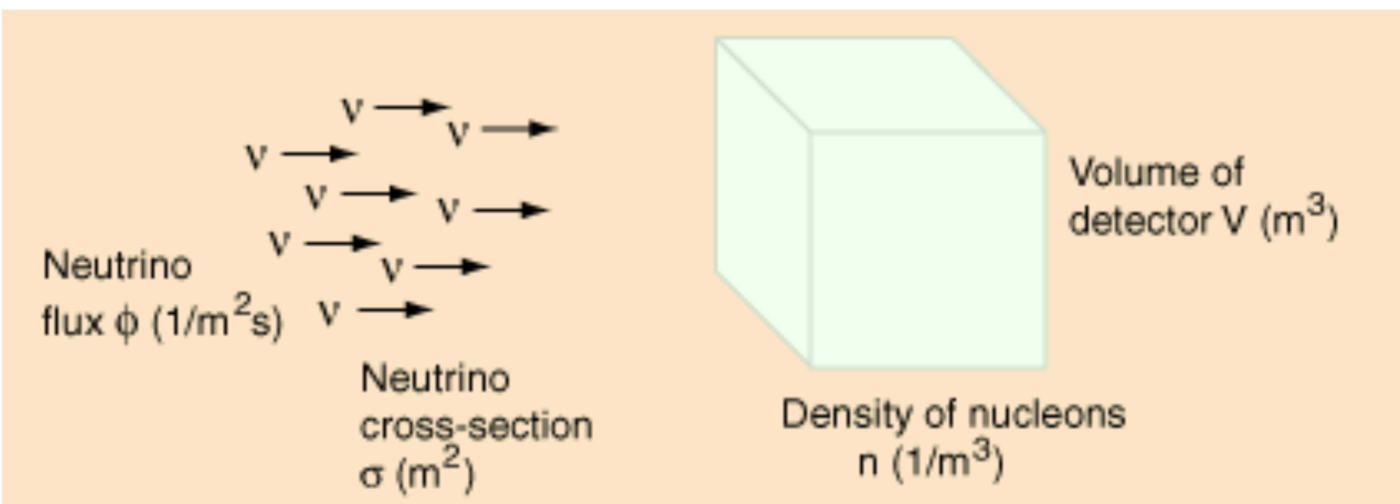

$$N = \varphi\, \sigma\, N_{targ}\, \Delta t$$

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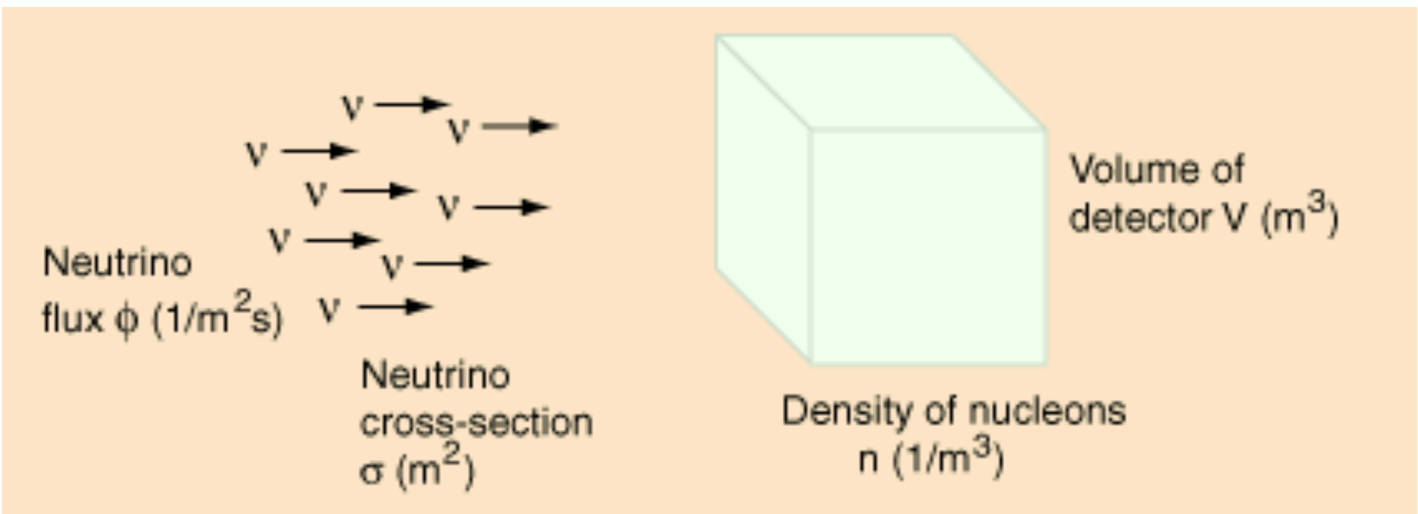

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with a 1000 kg detector and a flux of 10^{10} ν/s: few ν events/day

→ solar neutrino flux ~ 7×10^{10} ν/cm²/s

→ reactor neutrino flux ~ 10^{20} ν/s

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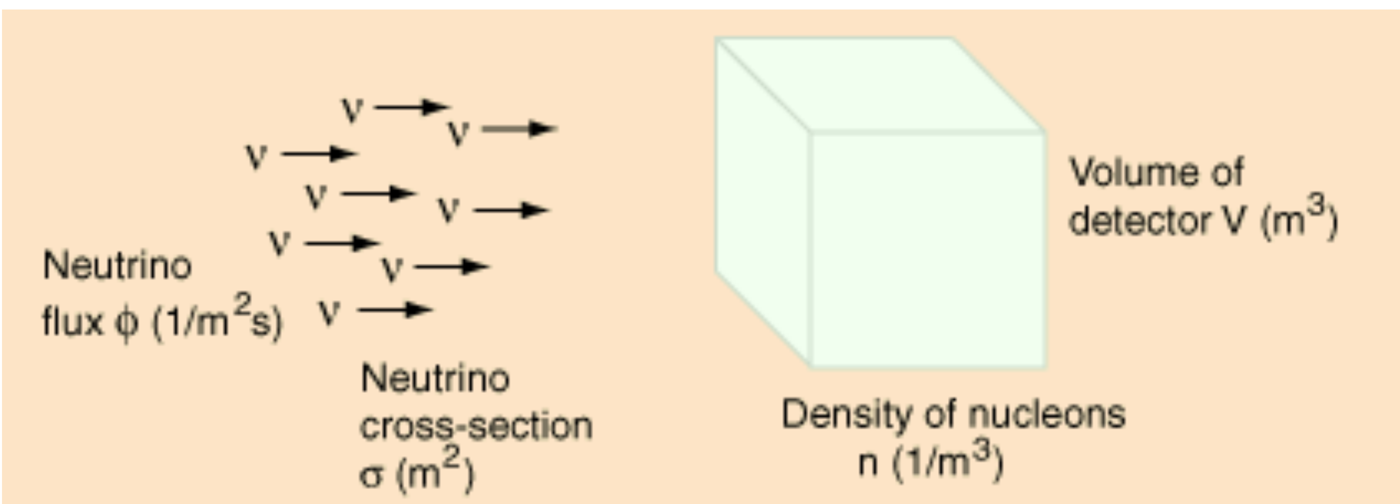

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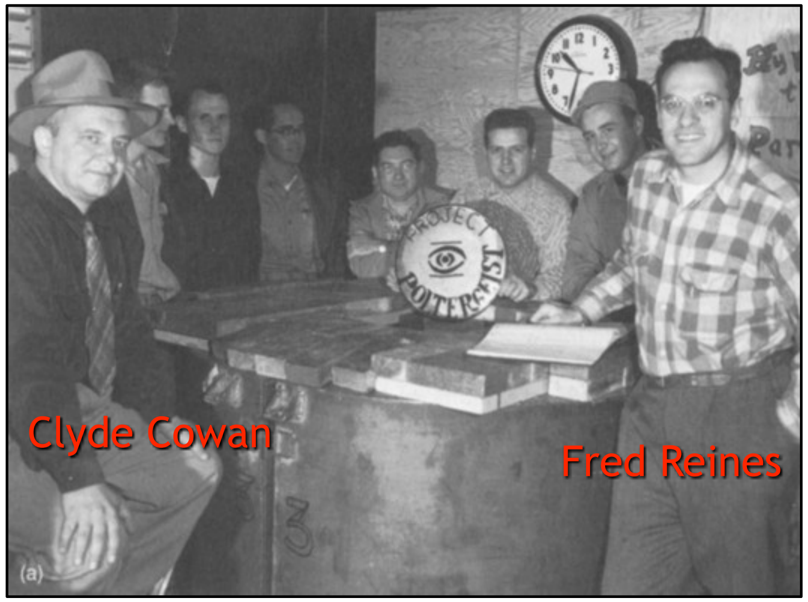
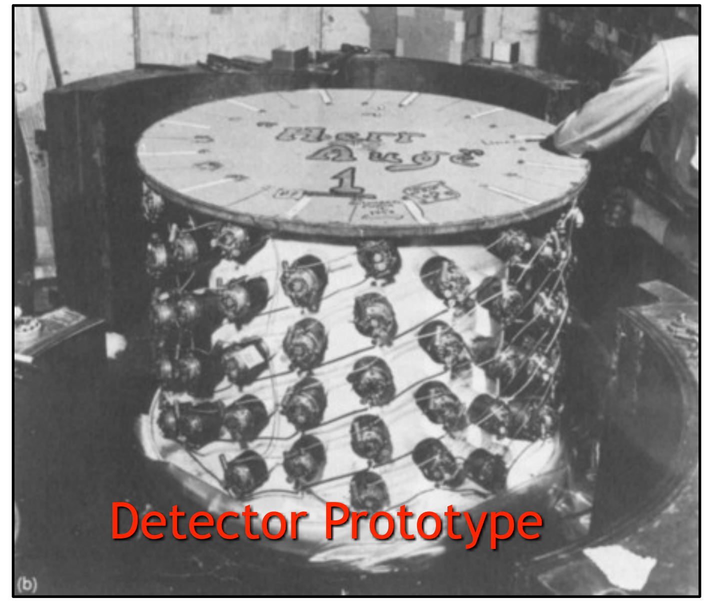
Difficult but not impossible!

Discovery of the neutrino

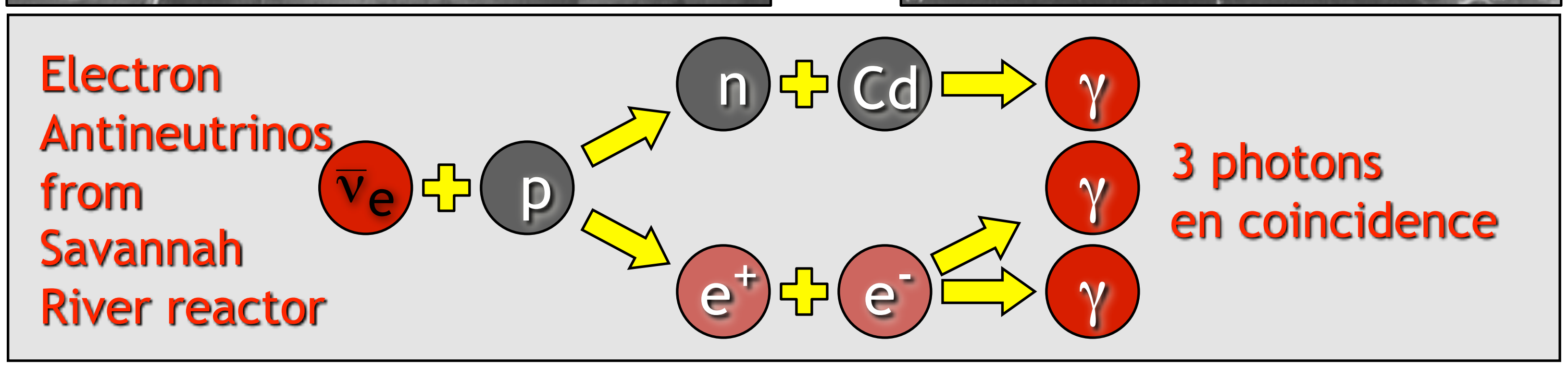
1956: First observation of reactor ν_e by Reines and Cowan.





2 tanks with
200 liters H_2O
+
40 kg $CdCl_2$

3 scintillator
layers with PMTs



1995: Nobel
Prize in Physics
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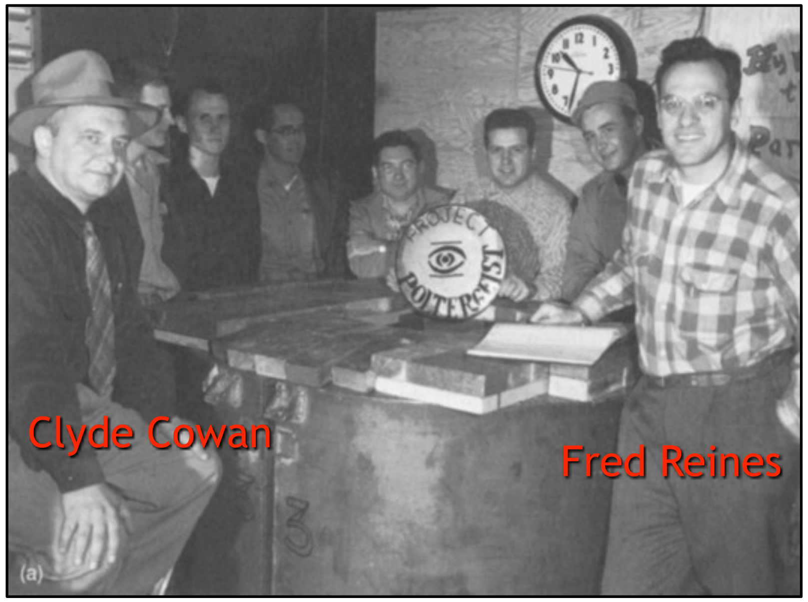

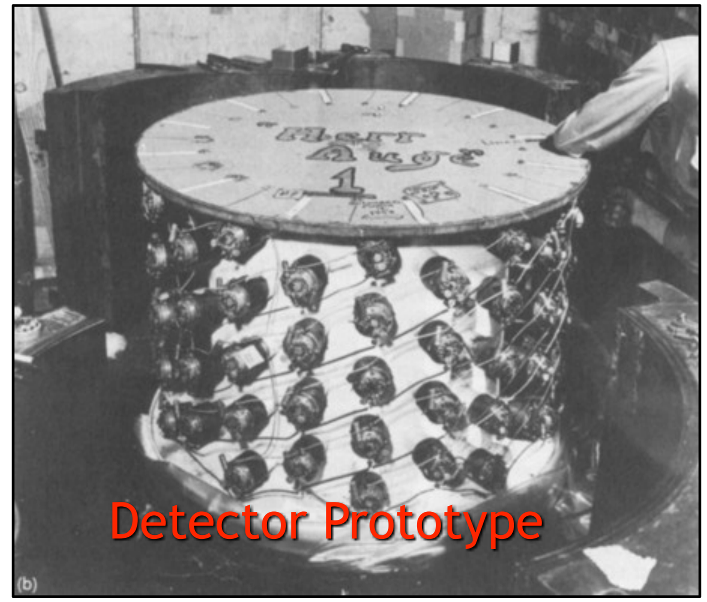

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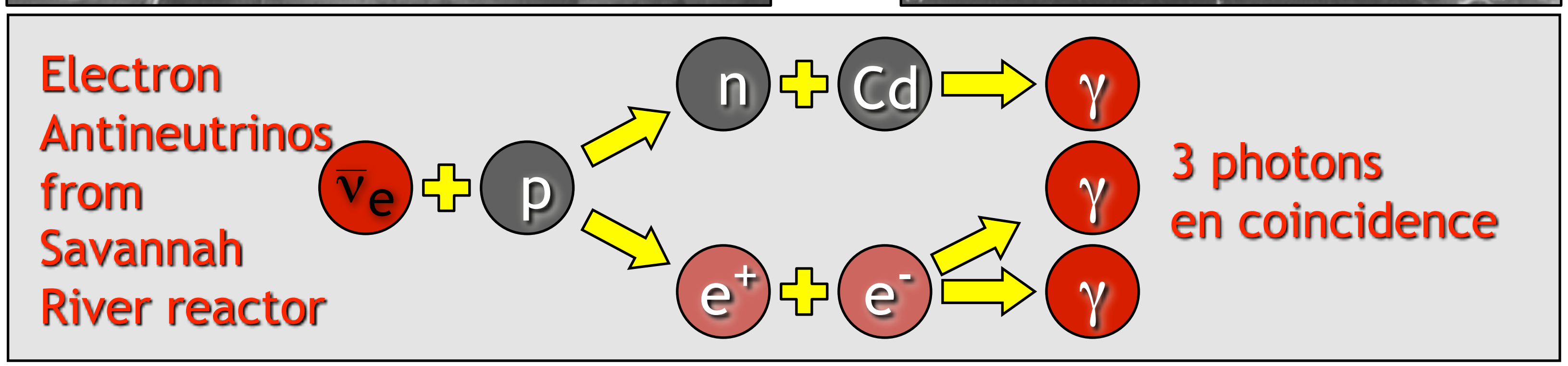

1995: Nobel
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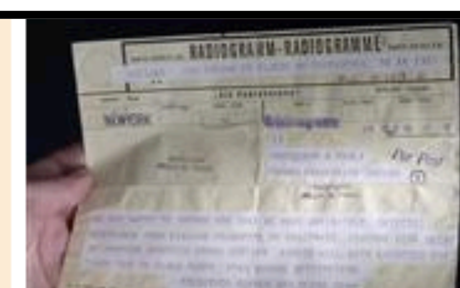
Telegram to Pauli on 12/06/1956

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters"



More than one neutrino flavour?

1959: Pontecorvo suggested the existence of a different neutrino, associated to muon decay and proposed an experiment to check it.

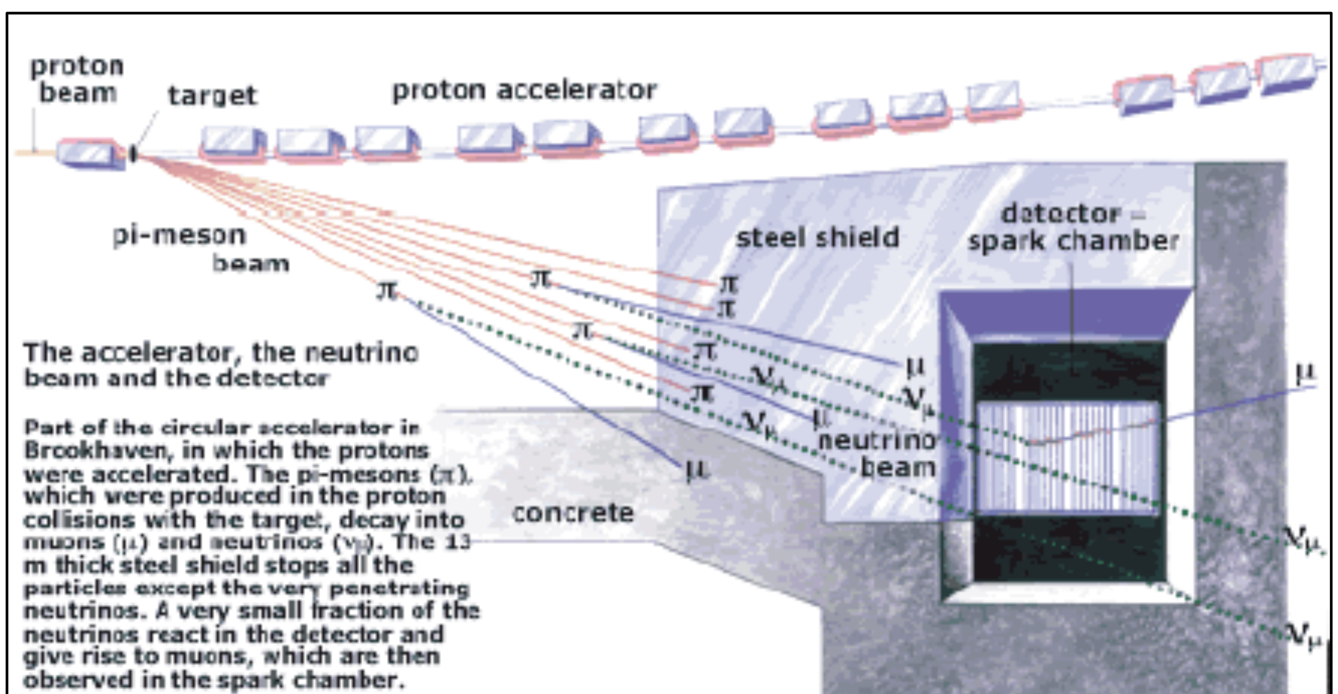
$$\nu_{\rm acc} + n \to p + (e^- \text{ or } \mu^- ?)$$

1962: Discovery of ν_μ by Lederman, Schwartz and Steinberger

$$\pi^+ \to \mu^+ + \nu_\mu$$

not e-

$$\nu_\mu + n \to p + \mu^-$$




Leon M. Lederman


Melvin Schwartz

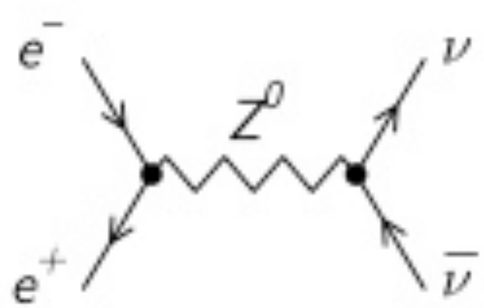

Jack Steinberger

1988: Nobel Prize in Physics

More than two neutrino flavours?

1978: Discovery of τ at SLAC → imbalance of energy in τ decay suggests the existence of a third neutrino.

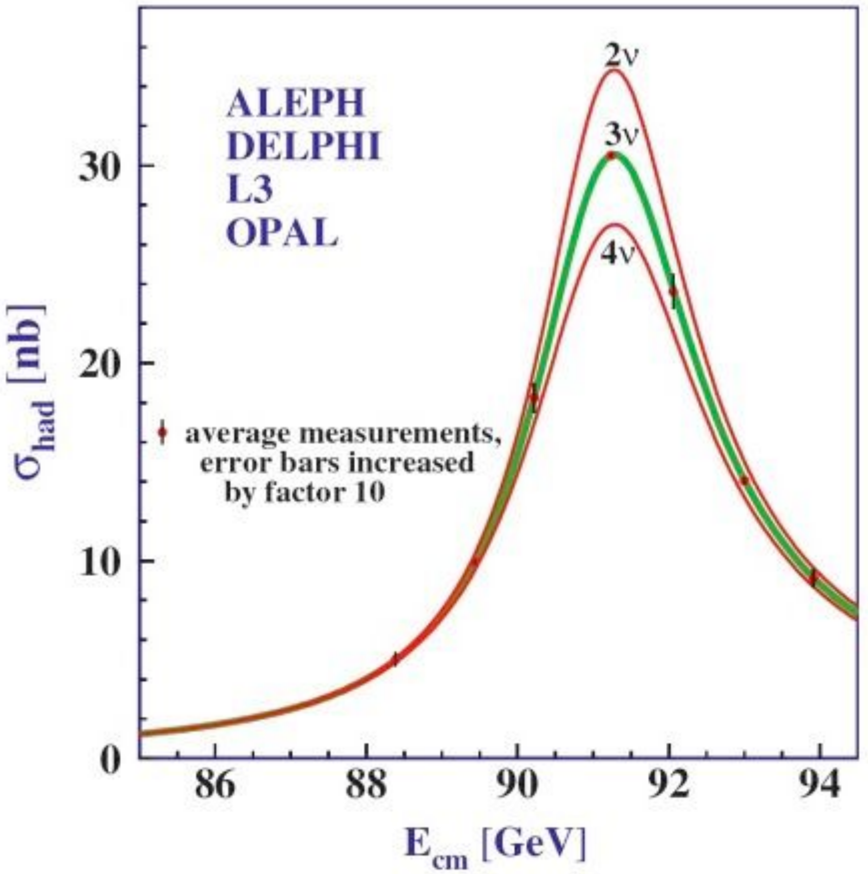
1989: LEP measurements of the invisible decay width of Z boson



$$\Gamma_{\rm inv} \equiv \Gamma_Z - \Gamma_{\rm had} - 3\Gamma_{\rm lep}$$

$$N_\nu = \Gamma_{\rm inv}/\Gamma_{\rm SM}(Z \to \nu_i \overline{\nu}_i)$$

→ $N_\nu = 2.984 \pm 0.008$



2000: Discovery of ν_τ by the DONUT Collaboration.

800 GeV p ⇒ Ds meson (≡$c\bar{s}$) → ν_τ τ ⇒ τ detected

Parity violation in weak interactions

τ-θ puzzle:

$$\Theta^+ \to \pi^+ + \pi^0$$

$$\tau^+ \to \pi^+ + \pi^+ + \pi^-$$

P = (-1)(-1) = +1

P = (-1)(-1)(-1) = -1

($\tau^+ = \theta^+ = K^+$)

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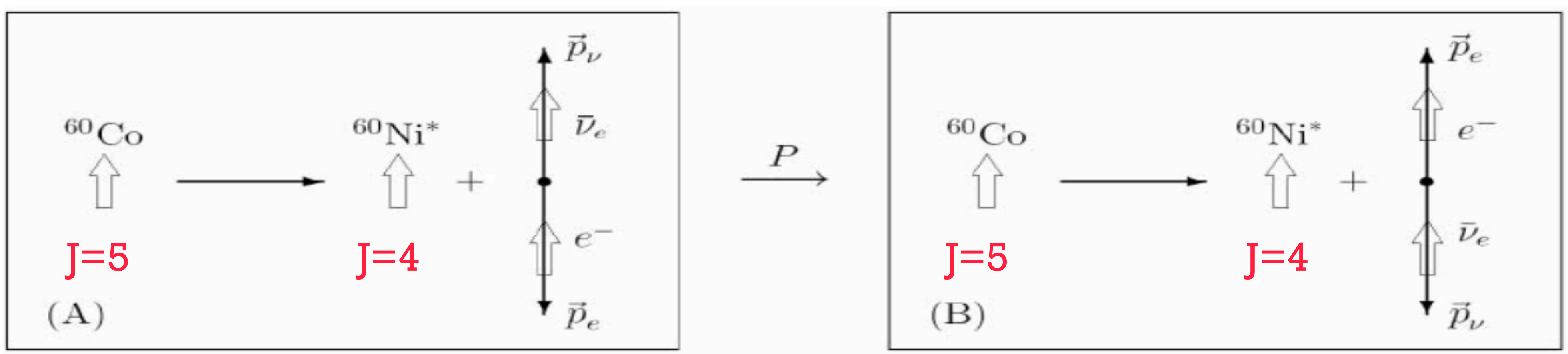
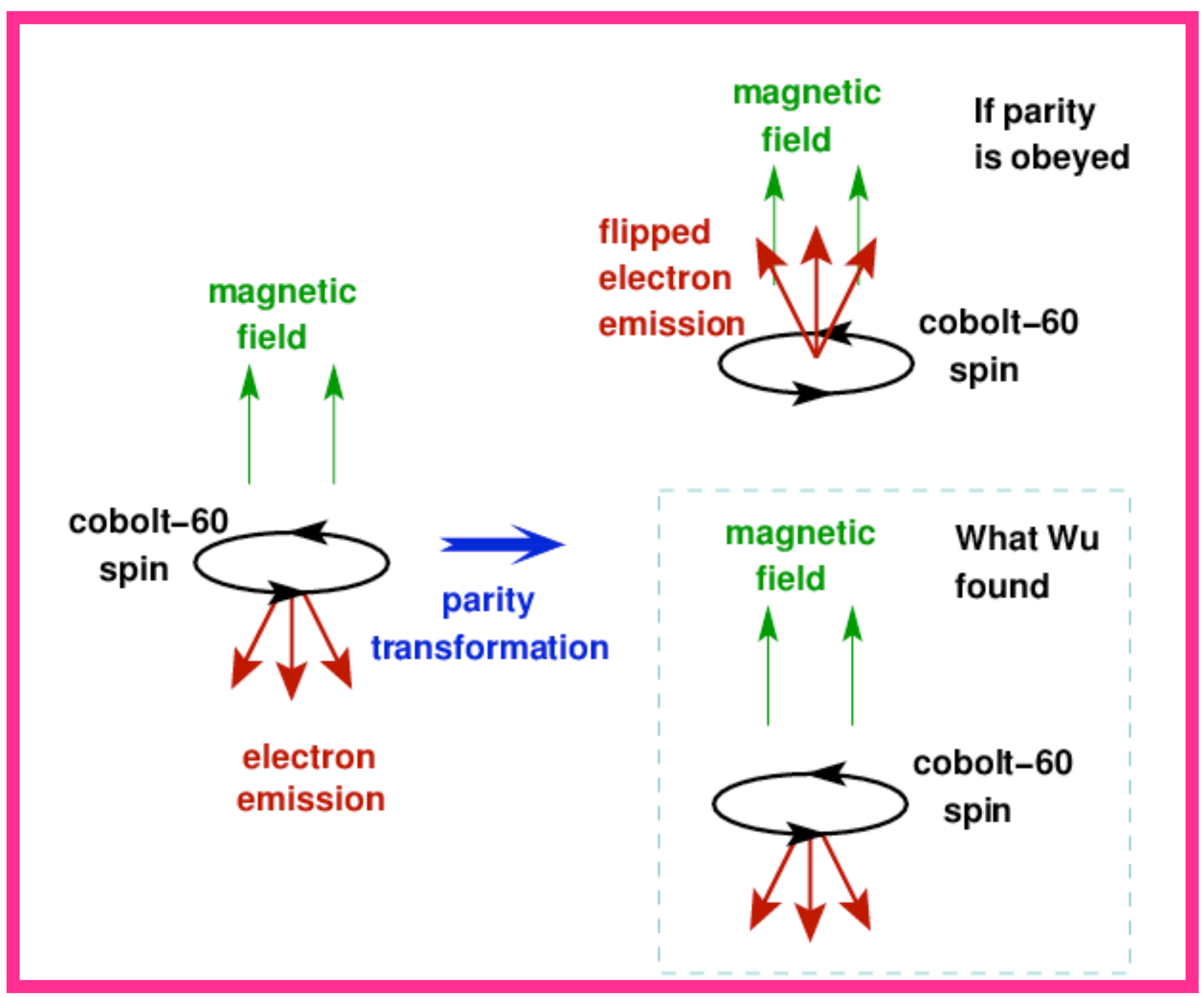
Parity violation in Wu experiment



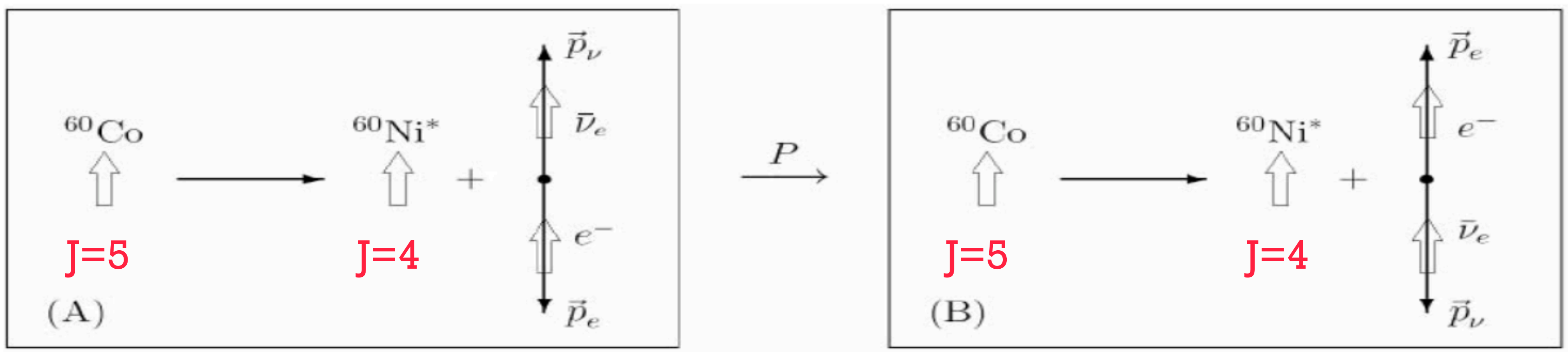


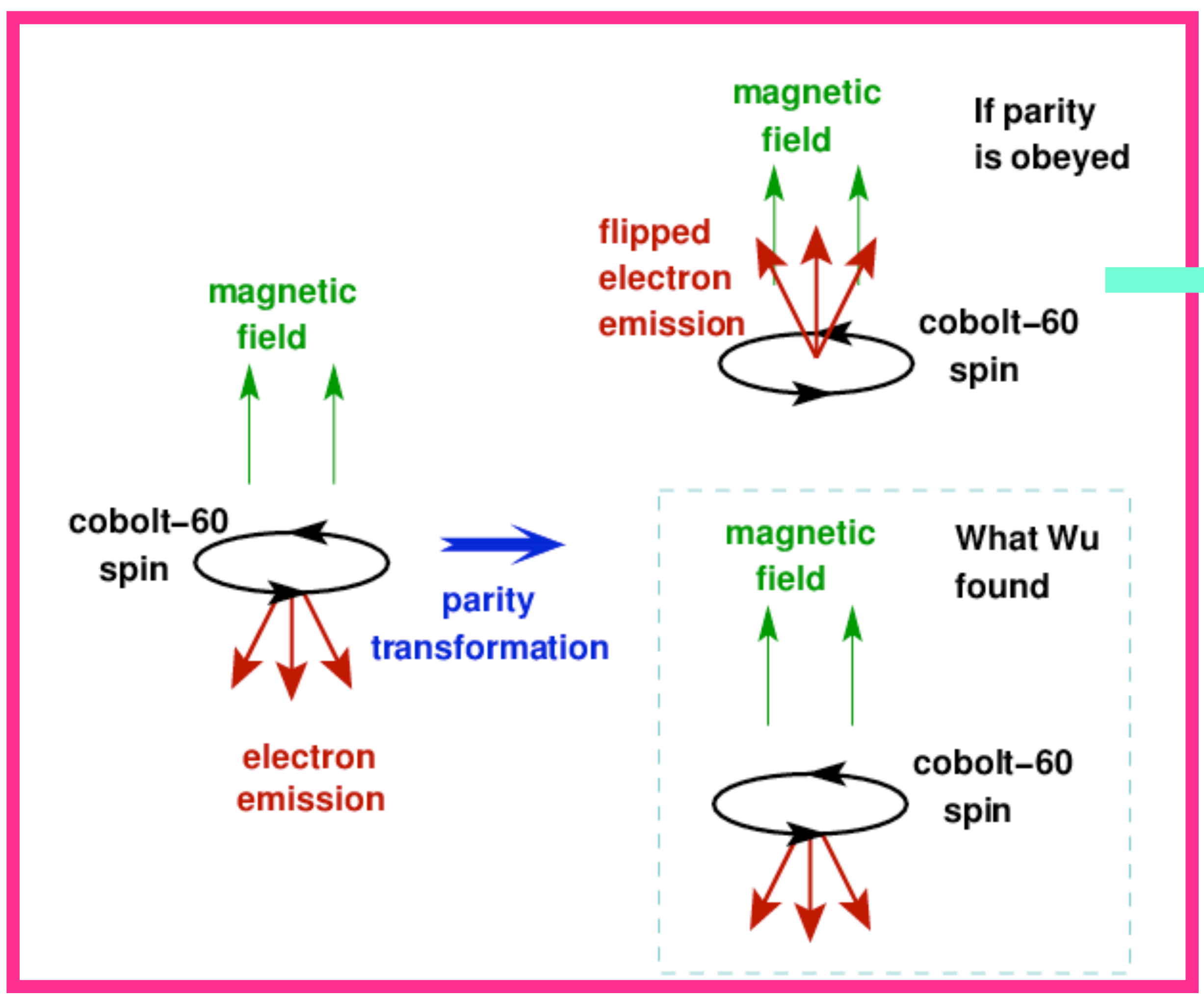
Fewer electrons emitted in the direction of the magnetic field!

Antineutrinos are preferably emitted in the direction of the field (in parallel to their spin)

Wu et al, Phys. Rev. 105 (1957)1413.

Parity violation in Wu experiment





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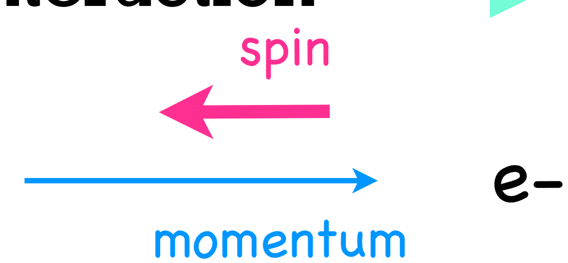
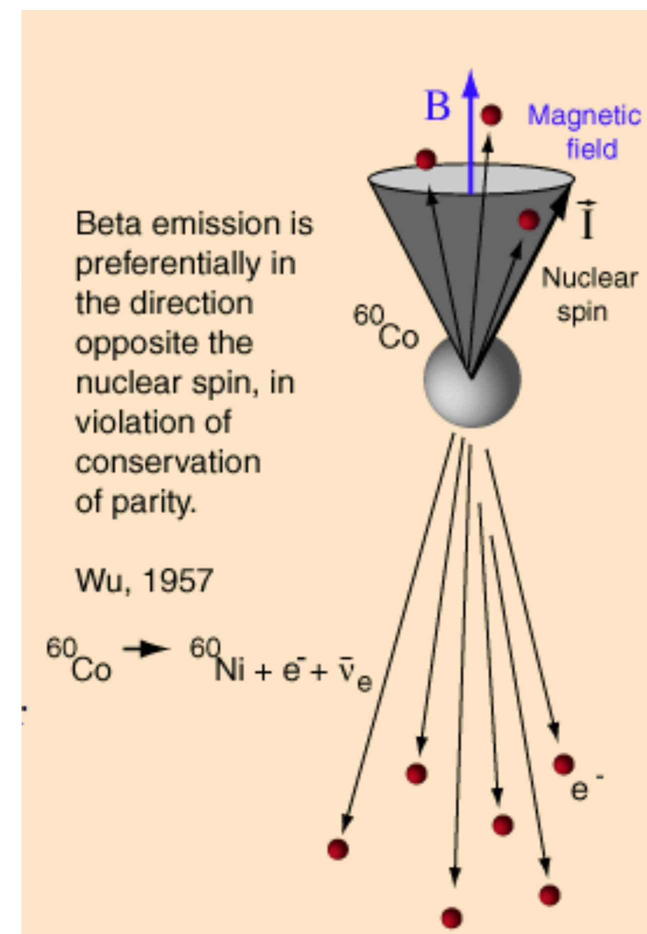


1957: Nobel Prize in Physics (Lee & Yang)

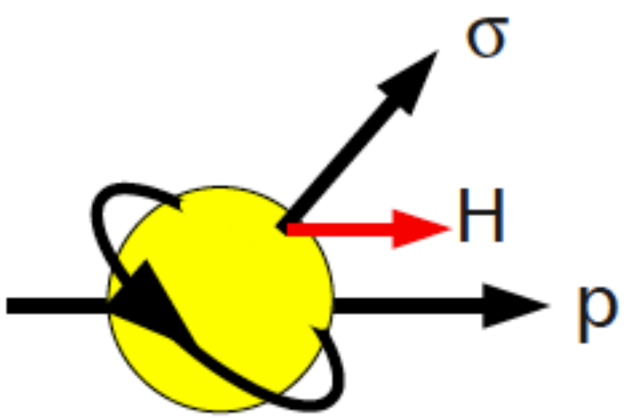
1978: Wolf Prize in Physics (C.S. Wu)



1958: Goldhaber et al. showed that neutrinos can only be emitted with their spin anti-parallel to their momentum direction.

Helicity and Chirality

Helicity is the projection of spin along the momentum direction



$$\hat{H} = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$$

→ Lorentz-invariant only for massless particles

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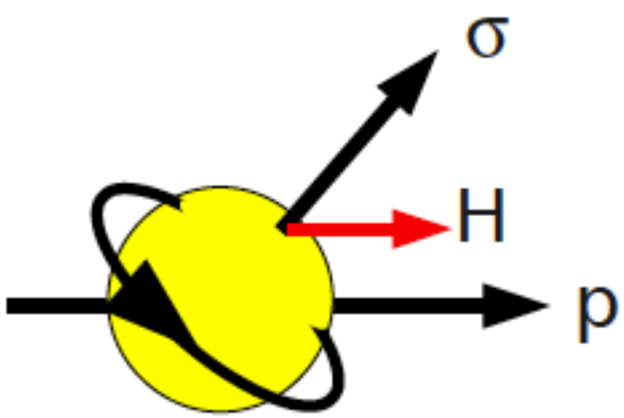

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Chirality is an asymmetry property: a chiral object is not identical to its mirror image, cannot be superimposed on it.

$$P_{\mathrm{L,R}} = \frac{1 \mp \gamma_5}{2}\,,\ \psi_{\mathrm{L,R}} = P_{\mathrm{L,R}}\psi$$

→ Handedness = Chirality

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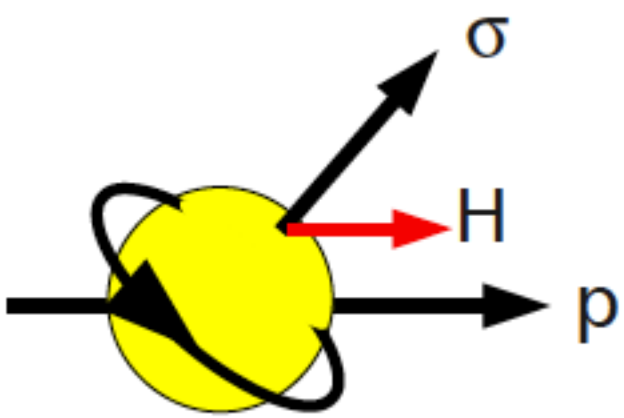

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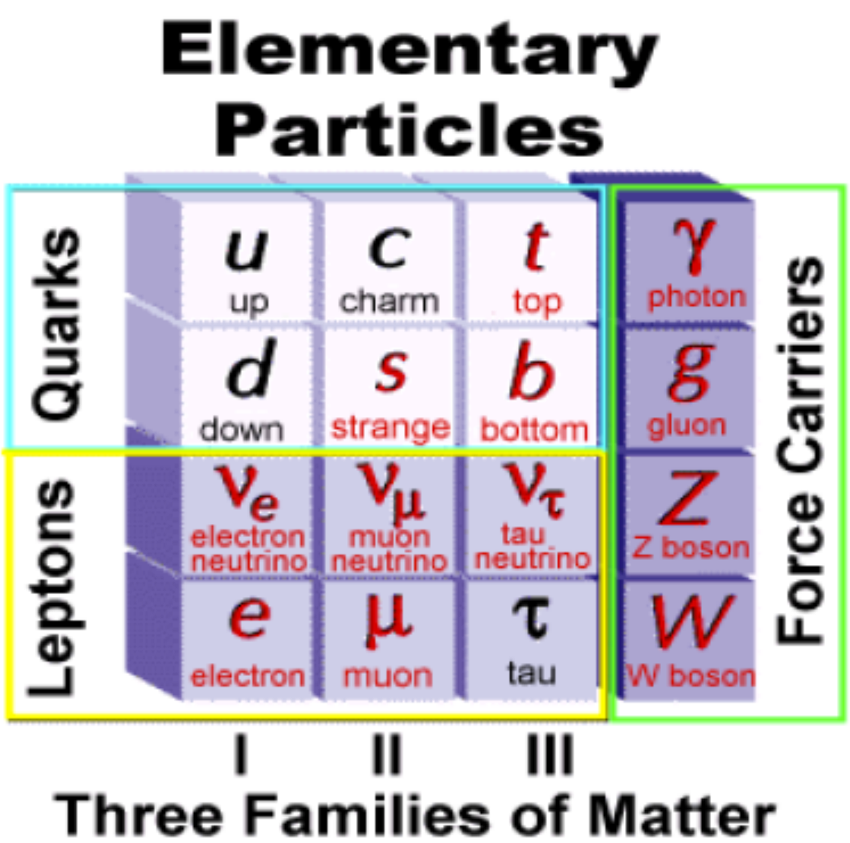
Massless particles: Helicity = Chirality

Massive particles: Chiral states contain contributions from both helicity states

Ultra-relativistic particles: LH (RH) chiral projection dominated by a - (+) helicity state

Neutrinos in the Standard Model

The Standard Model of particle physics



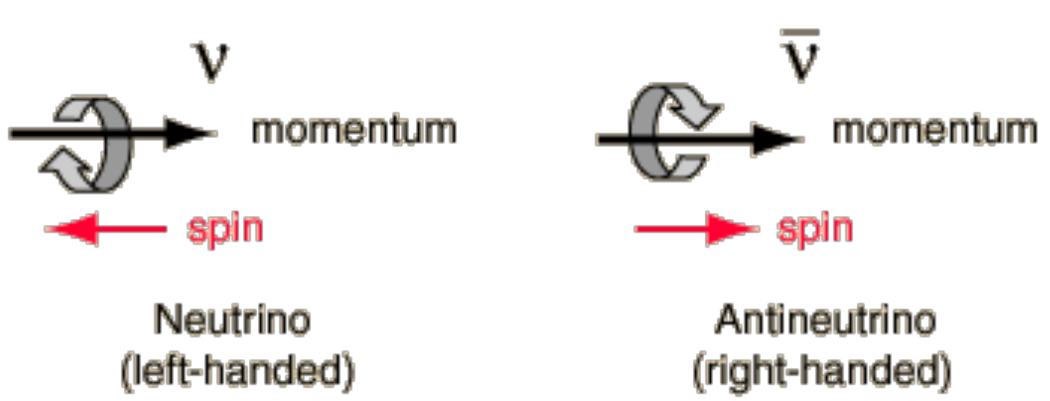
- Neutrinos come in 3 flavours, corresponding to the charged lepton associated

- Leptons are described as $SU(2)_L$ doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

- Only two types of neutrinos have been observed in nature:
  - left-handed neutrino
  - right-handed antineutrino

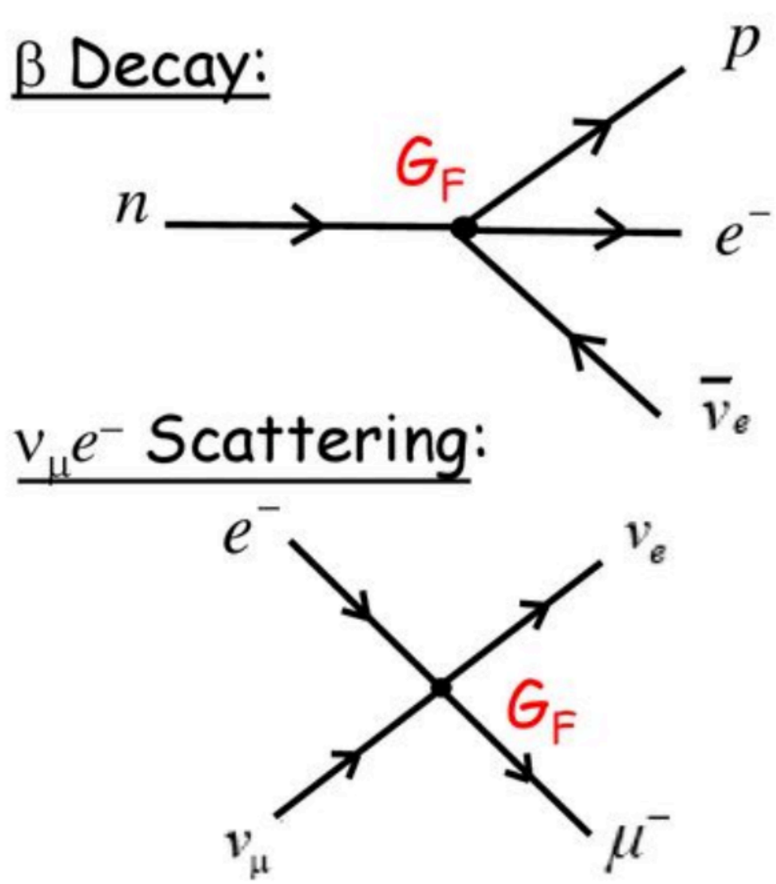
[no SU(2) neutrino singlets in the SM]



Neutrino interactions with charged leptons

- Neutrinos were first detected through their weak interactions with charged leptons, known as Charged Current (CC) interactions.

- CC weak interactions first described by Fermi as point-like 4-fermion vertex.



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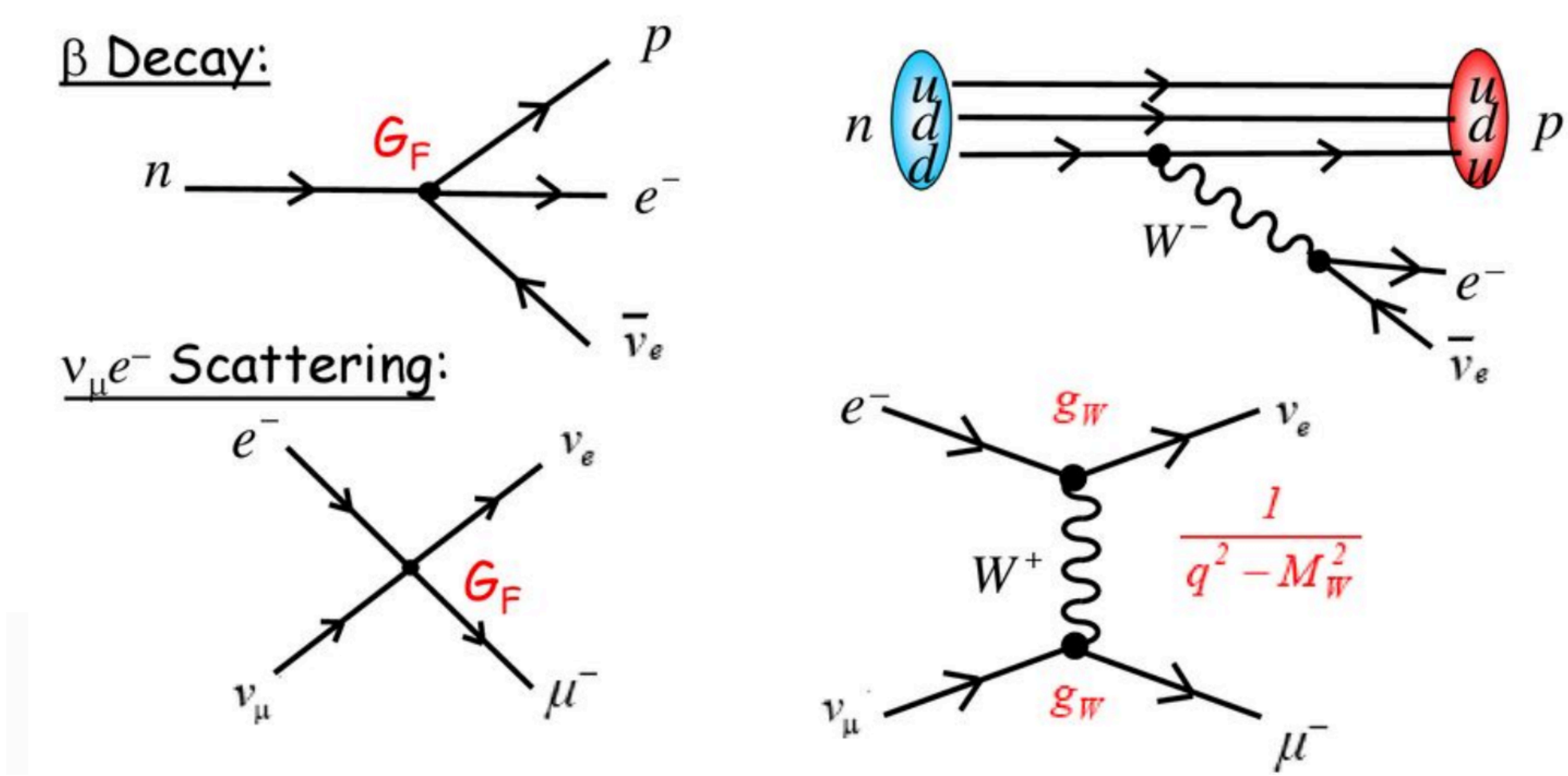

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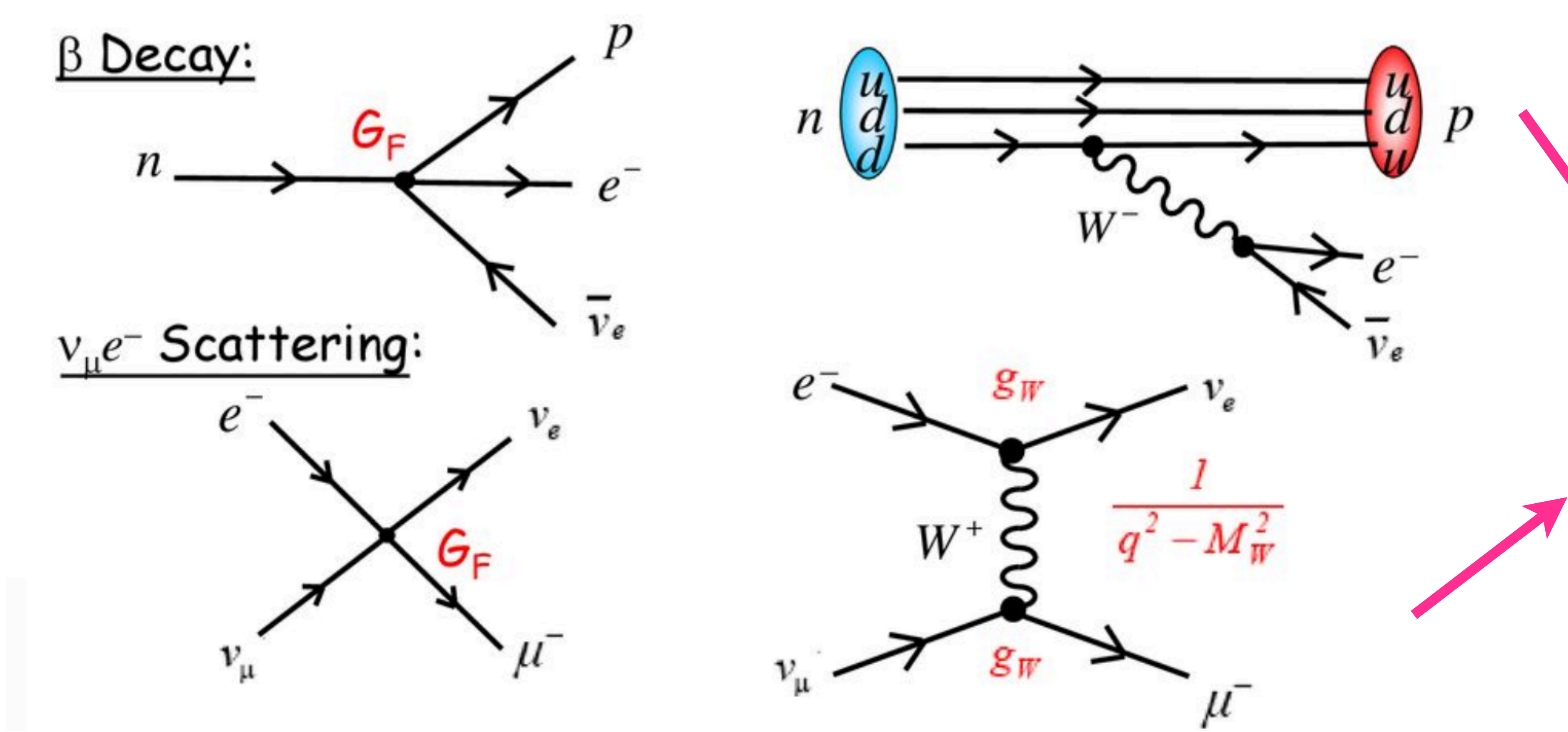
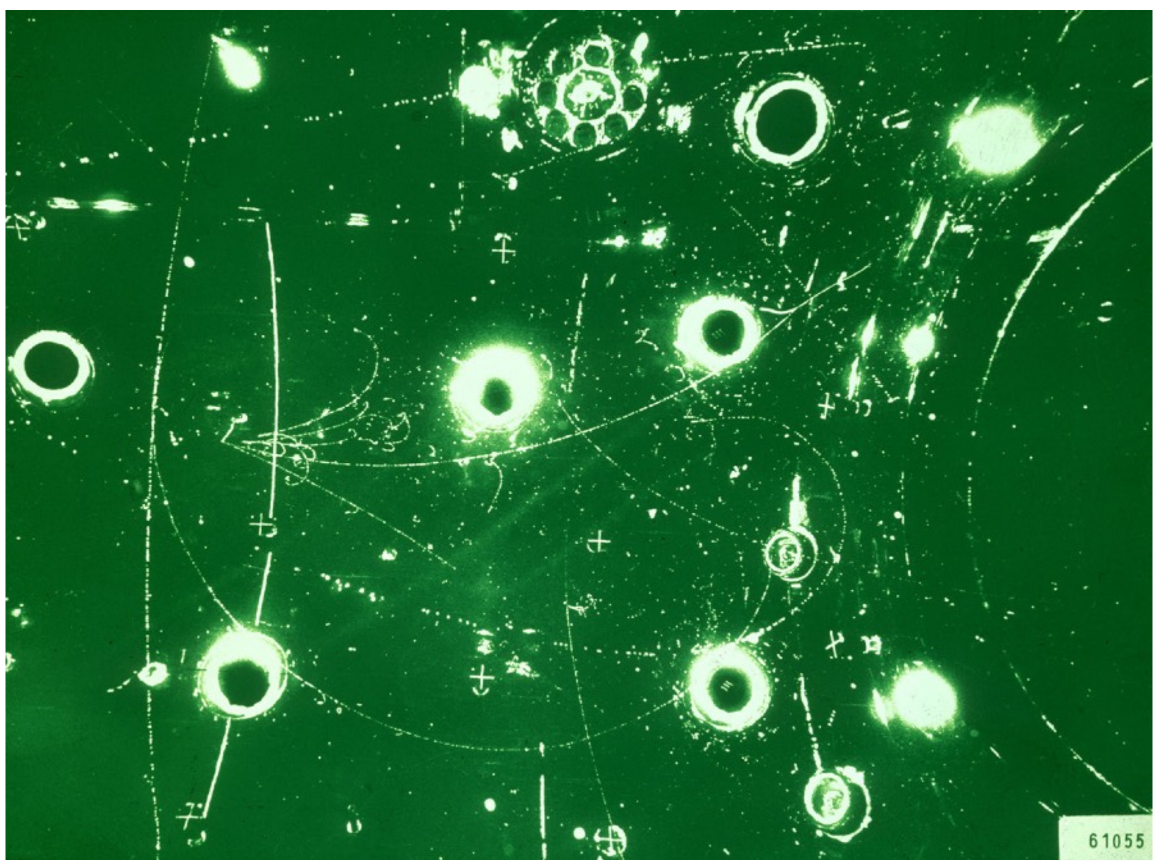


W's couple to leptons in the same doublet

Discovery of Neutral Currents

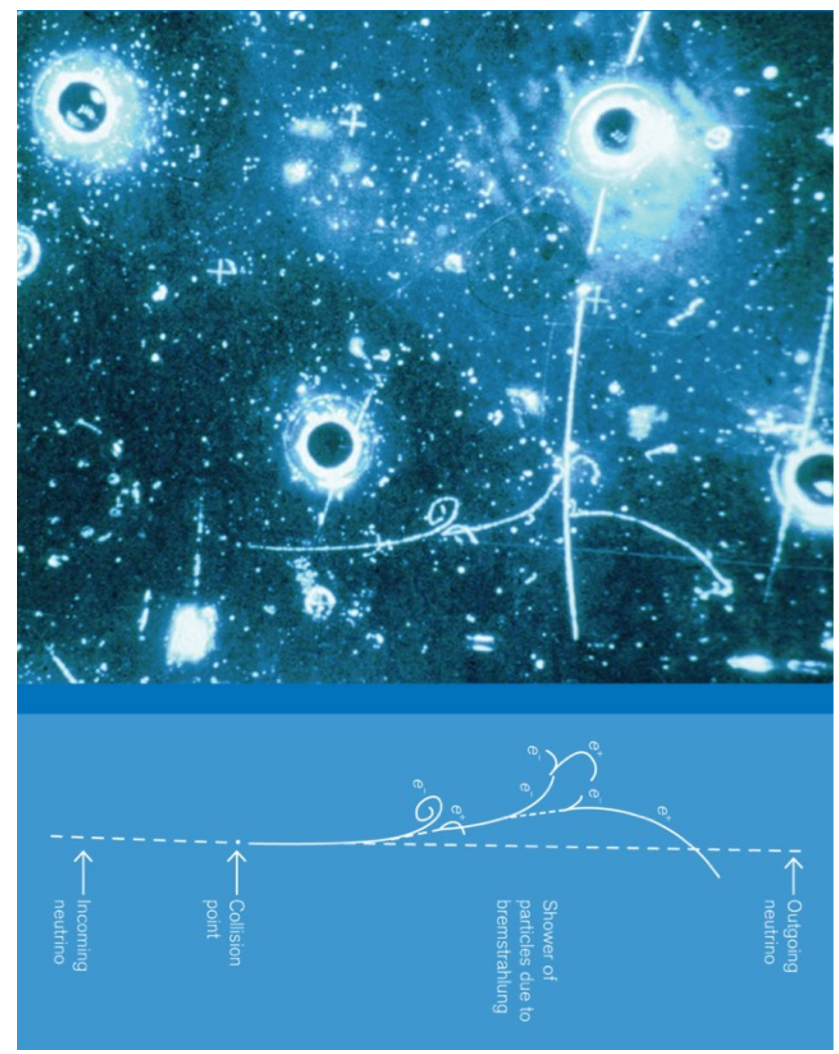
- The Glashow-Weinberg-Salam model predicted the existence of weak interactions mediated by a neutral vector boson, the Z^0
- Neutral Current interactions were first observed in 1973 with Gargamelle bubble chamber

$$\overline{\nu}_\mu + N \to \overline{\nu}_\mu + \text{hadrons}$$



Hasert et al, Phys. Lett. B 46 (1973) 138.

$$\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$$



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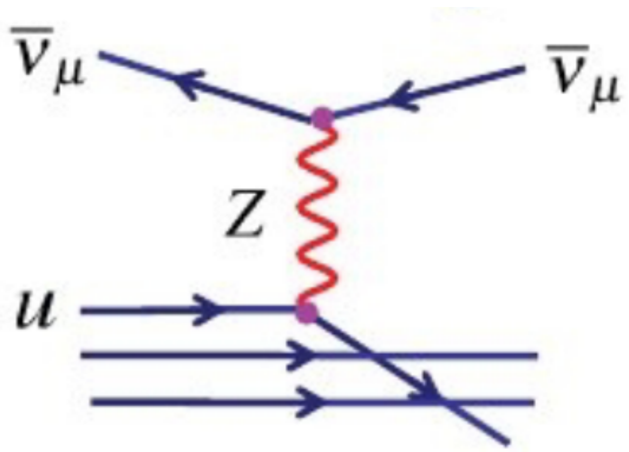

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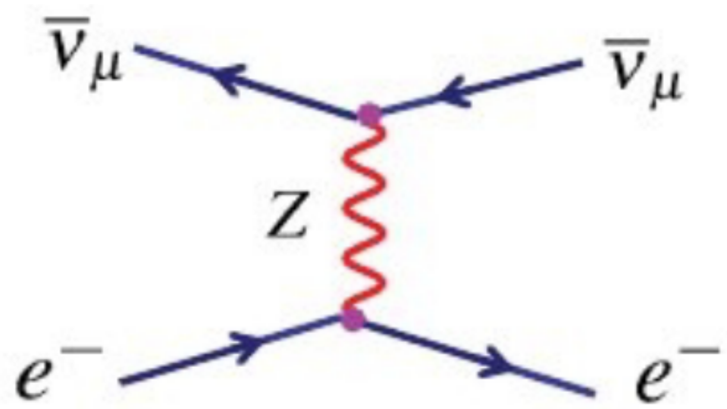
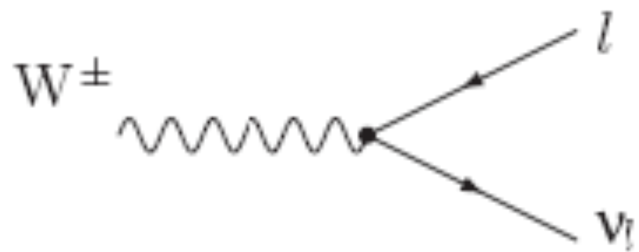


→ First evidence for Z boson

Hasert et al, Phys. Lett. B 46 (1973) 138.

Neutrino interactions in the SM

Charged Current (CC):



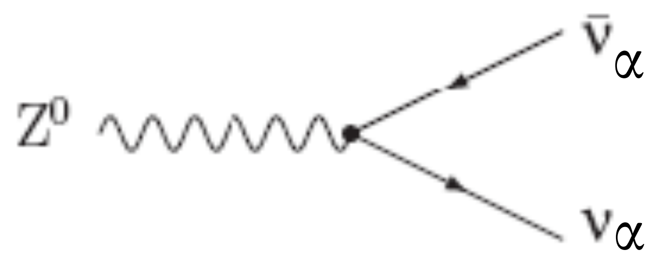
$$W^- \to l_\alpha^- + \overline{\nu}_\alpha$$

$$W^+ \to l_\alpha^+ + \nu_\alpha$$

$$(\alpha = e, \mu, \tau)$$

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu l_{\alpha L} W_\mu + \text{h.c.}$$

Neutral Current (NC):



$$Z^0 \to \nu_\alpha \overline{\nu}_\alpha$$

$$\mathcal{L}_{\rm NC} = -\frac{g}{2\cos\theta_W} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z_\mu^0$$

in the SM, only LH neutrinos and RH antineutrinos participate in weak interactions

- Interactions conserve total Lepton Number L: $L(l^-) = L(\nu) = -L(l^+) = -L(\overline{\nu}) = 1$

- Family lepton numbers L_e, L_μ, L_τ are also conserved (1998: nu oscill !!)

Fermion masses in the SM lagrangian

✦ In the SM, fermion masses appear in the lagrangian with terms like:

$$m\overline{\psi}\psi \qquad \rightarrow \textbf{Dirac mass term}$$

decomposing into its chiral states: $\psi \equiv \psi_L + \psi_R$

$$\Rightarrow \quad m\overline{\psi}\psi = m\overline{\psi}_L\psi_R + m\overline{\psi}_R\psi_L$$

→ forbidden: not invariant under SU(2): it couples ψ_L with ψ_R ($I_W=1/2$)

→ solved by Higgs mechanism: after SSB, Dirac mass terms appear from Yukawa couplings:

$$\mathcal{L}_{\mathrm{Yukawa}} = Y\overline{\psi}_L\phi\psi_R + \mathrm{h.c.} \qquad \langle\phi^0\rangle = v$$

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What about a Majorana mass term??

Majorana neutrino mass

Majorana, ~1930

✦ We build a R-chiral field from a L-chiral field by charge conjugation:

$$\psi_R \equiv \psi_L^C = \hat{C}\overline{\psi}^T \qquad \hat{C} = i\gamma^2\gamma^0$$

→ the total neutrino field is: $\psi = \psi_L + \psi_R = \psi_L + \psi_L^C$

→ taking the charge conjugate: $\psi^C = (\psi_L + \psi_R)^C = \psi_L^C + \psi_L = \psi$

$$\psi = \nu = \nu_L + \nu_L^C$$

neutrino = antineutrino

Majorana mass term:

$$-\mathcal{L}_M = \frac{1}{2} m \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

Not invariant under U(1) transformations

However: this mass term not invariant under weak isospin (I_W=1)

→ solved with a Higgs triplet BUT it is not included in the SM.

→ solved with a dim-5 operator (Weinberg operator) BUT non-renormalizable

Neutrino mass in the SM

- Since the SM does not contain right-handed neutrinos: a Dirac mass term as for the rest of fermions is not allowed.
- The SM only contains one Higgs doublet: no Higgs triplet to build a Majorana mass term
- The SM is renomalizable and, therefore, dim-5 terms as the Weinberg operator are not allowed.

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→ **Neutrinos are strictly massless in the Standard Model!**

Neutrino oscillations

nobelprize.org

Neutrino oscillations

1957: Pontecorvo suggests oscillations between neutrinos & antineutrinos (only ν_e).

B. Pontecorvo, J. Exp. Theor. Phys. 33 (1957) 549.
B. Pontecorvo, J. Exp. Theor. Phys. 34 (1958) 247.

1962: Maki, Nakagawa and Sakata propose neutrino mixing between flavor eigenstates

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

true neutrinos   weak neutrinos

2ν mixing

Z. Maki, M. Nakagawa, S. Sakata, Prog. Theor. Phys. 28 (1962) 870.

1969: Gribov & Pontecorvo calculated the neutrino oscillation probability (in vacuum) for the first time

V. Gribov, B. Pontecorvo, Phys. Lett. B28 (1969) 493.

First indication of ν oscillations

1968: First observation of solar neutrinos by R. Davis in Homestake.

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

➡ 1/3 of the Standard Solar Model prediction !!

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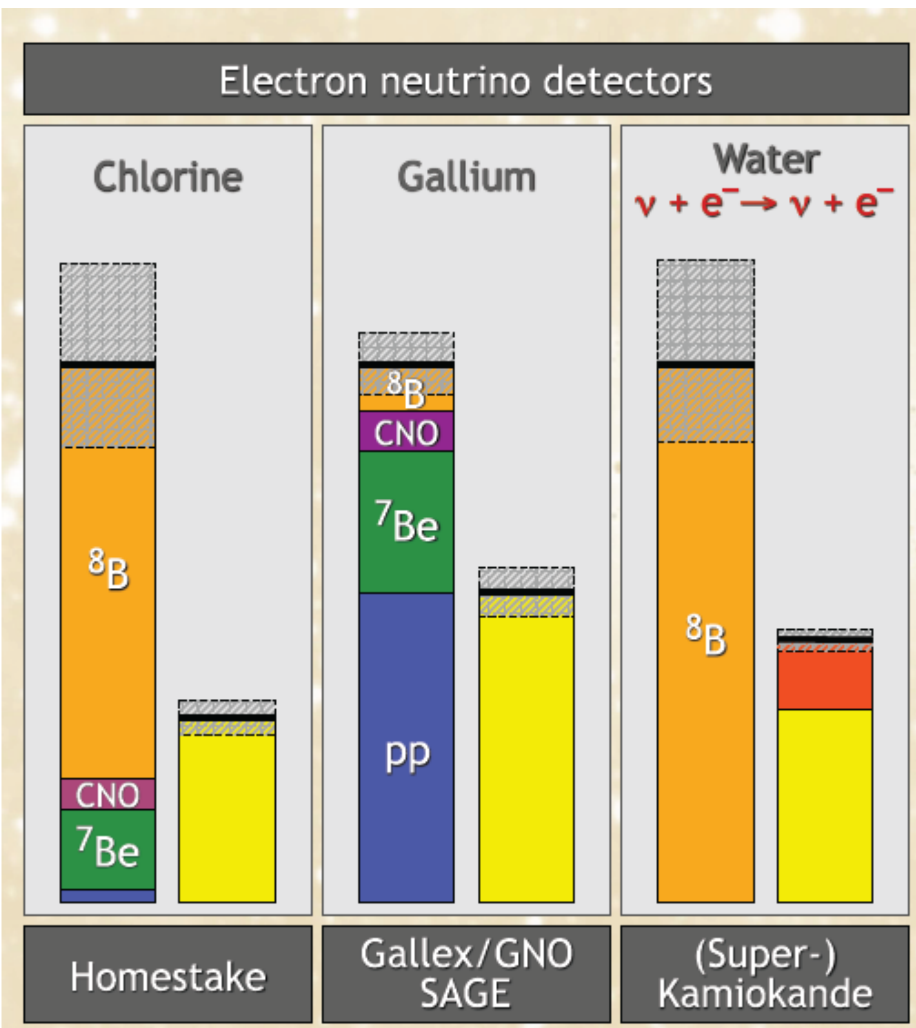

~30% ~50% ~40%

→ confirmed by the following solar experiments

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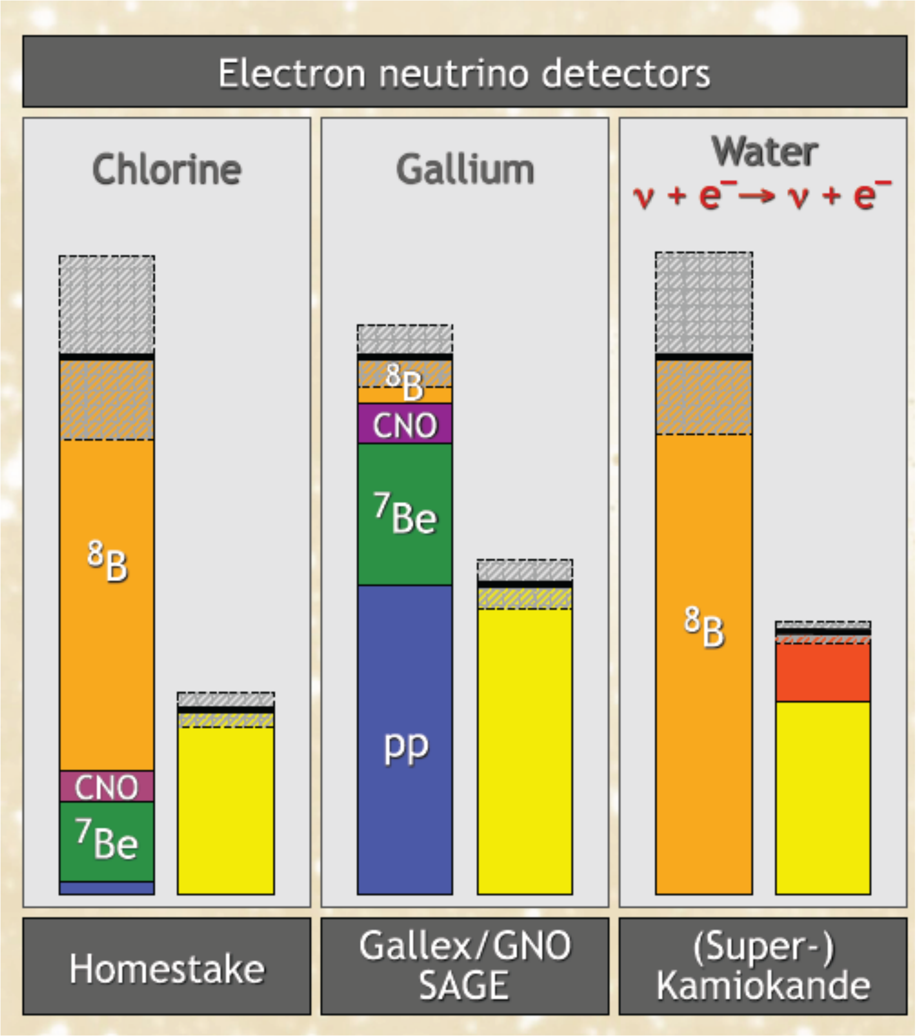

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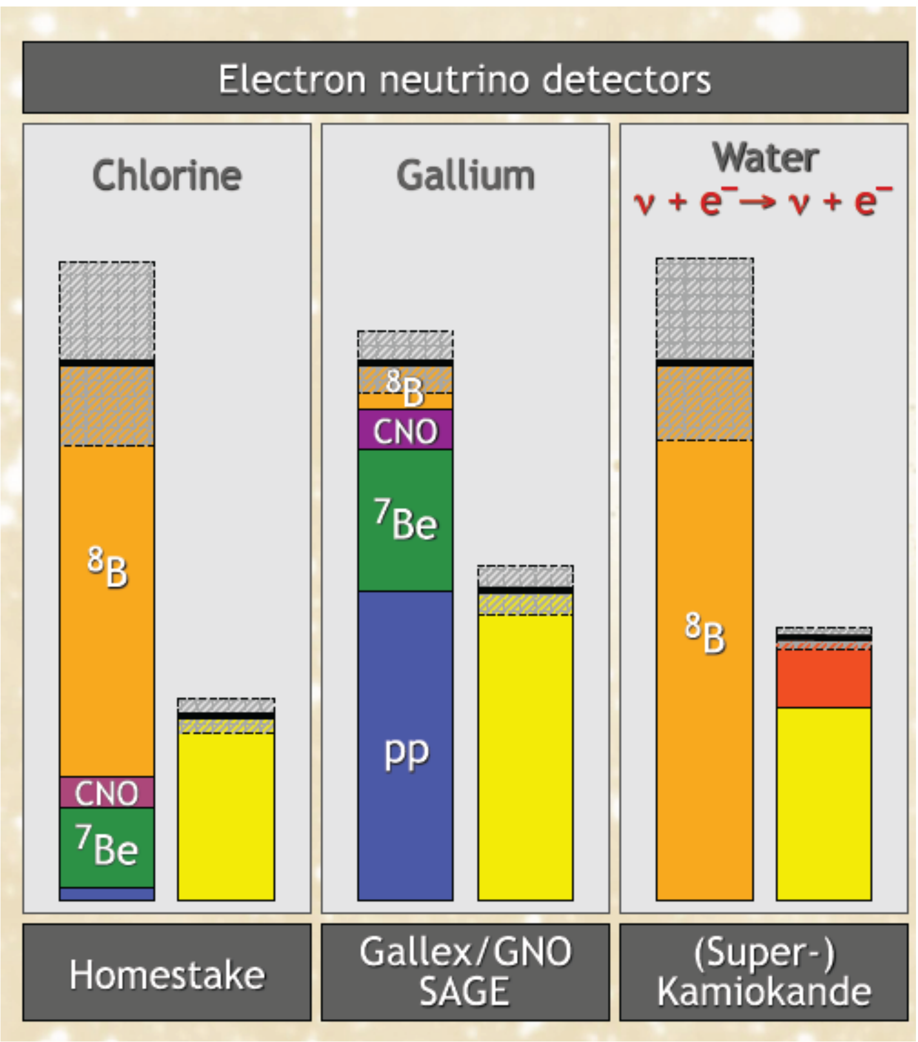

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2002 Nobel Prize in Physics

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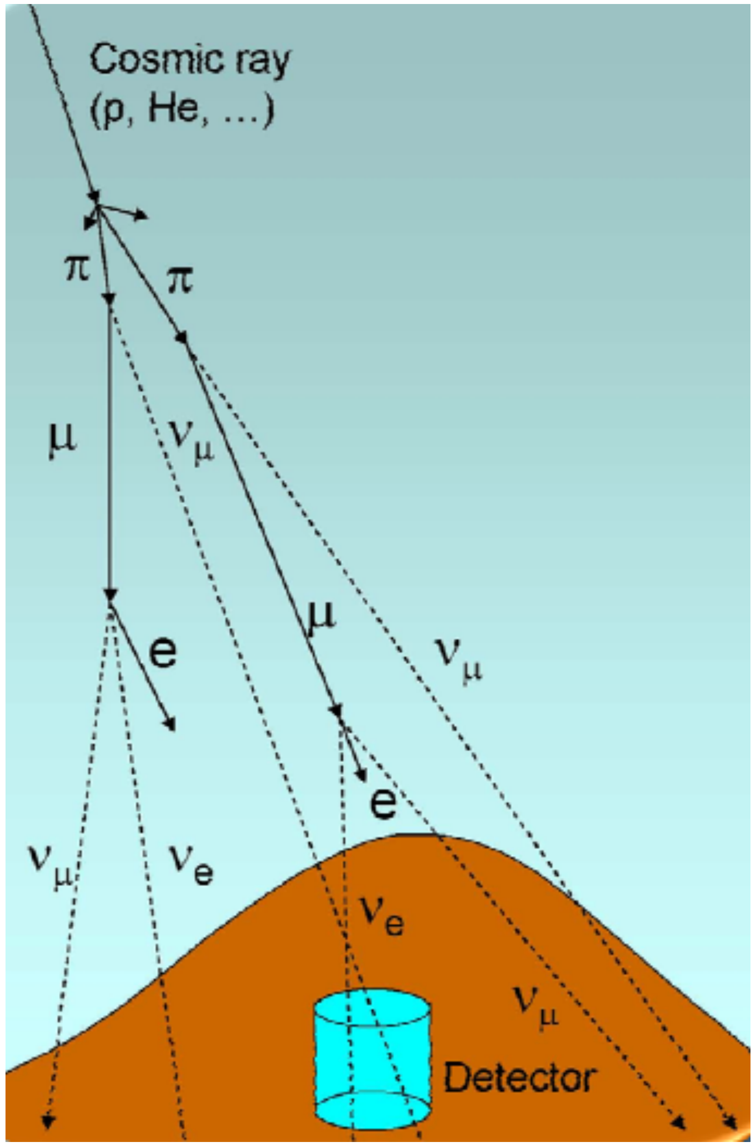
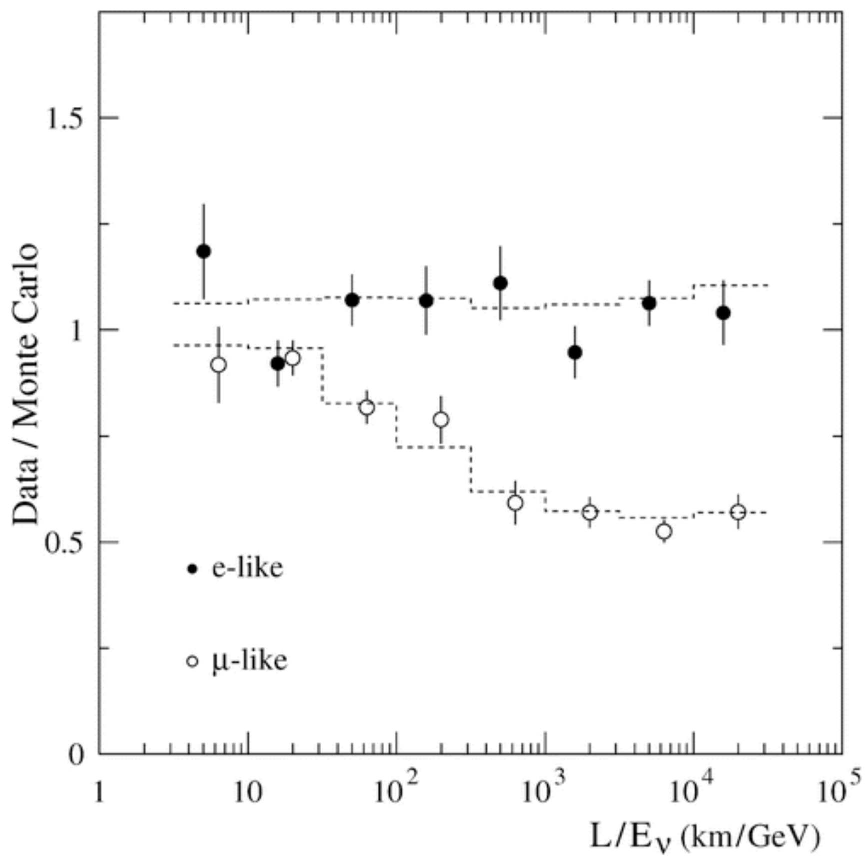
The atmospheric neutrino anomaly



1985: First indications of a deficit in the observed number of atmospheric ν_μ at the IMB experiment.

1994: Kamiokande finds the ν_μ deficit depends on the distance travelled by the neutrino and its energy.



1998: Discovery of atmospheric neutrino oscillations in Super-Kamiokande.

$\boxed{\text{oscillation channel } \nu_\mu \to \nu_\tau}$

➡ first evidence for non-zero **neutrino masses.**

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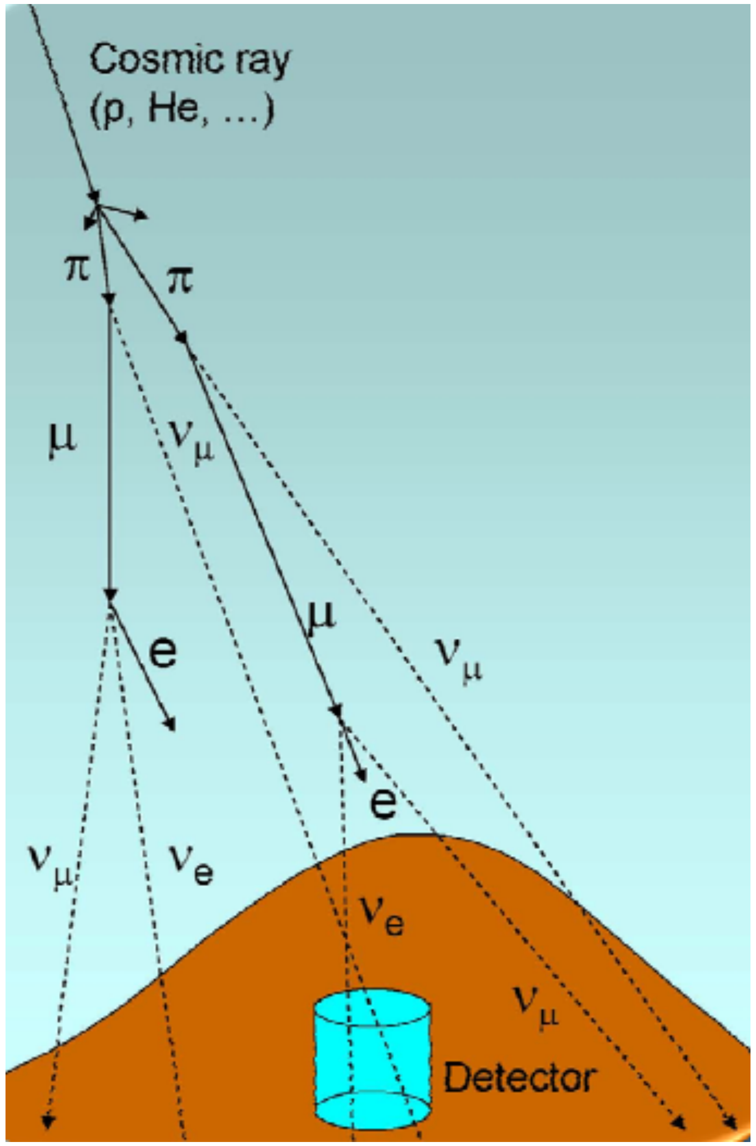

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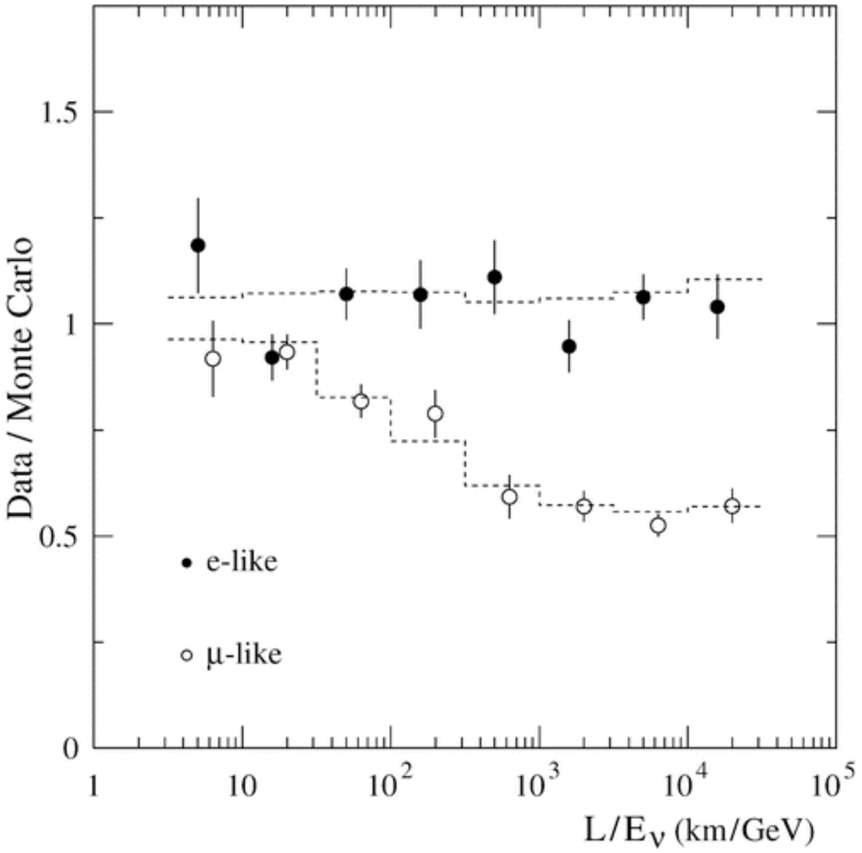

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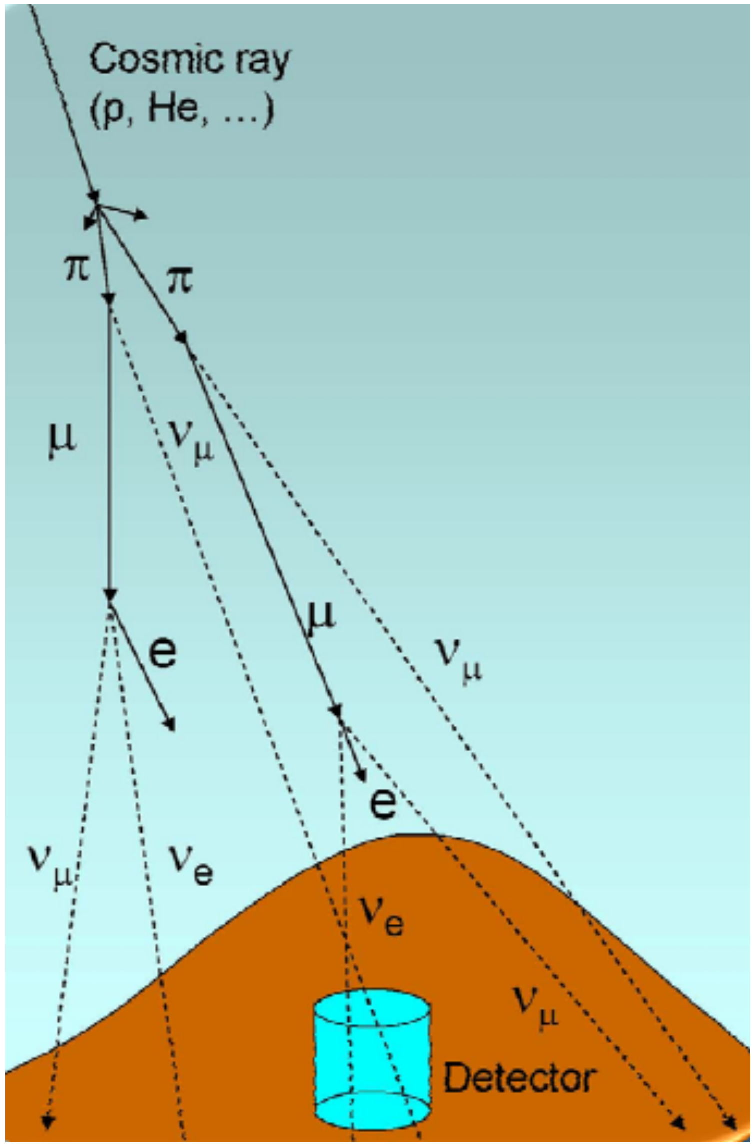

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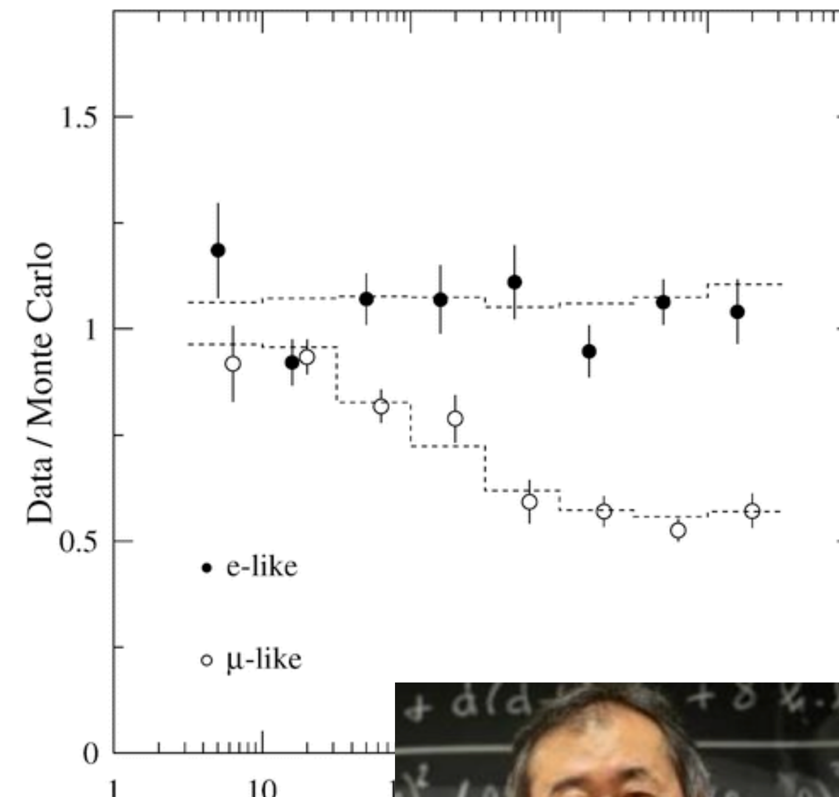

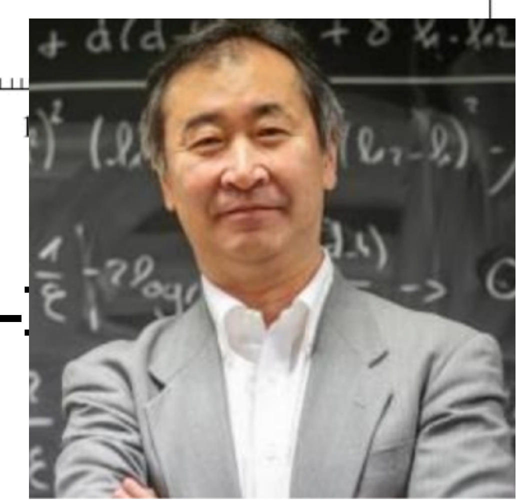

2015 Nobel Prize in Physics

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The Sudbury Neutrino Observatory

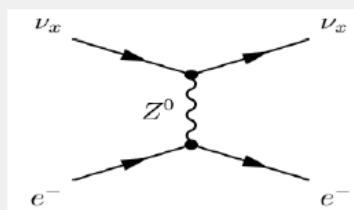
2001: Confirmation of flavor conversion in solar neutrinos in SNO.

SNO Coll, PRL89 (2002) 011301

SNO interactions

Elastic-scattering (ES):

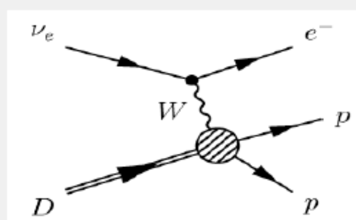
$\nu_x + e^- \rightarrow \nu_x + e^-$



ν_e mainly
strong directional sensitivity

Charged-currents (CC):

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



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E_e well correlated with E_ν

Neutral-currents (NC):

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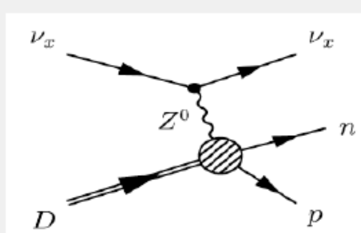
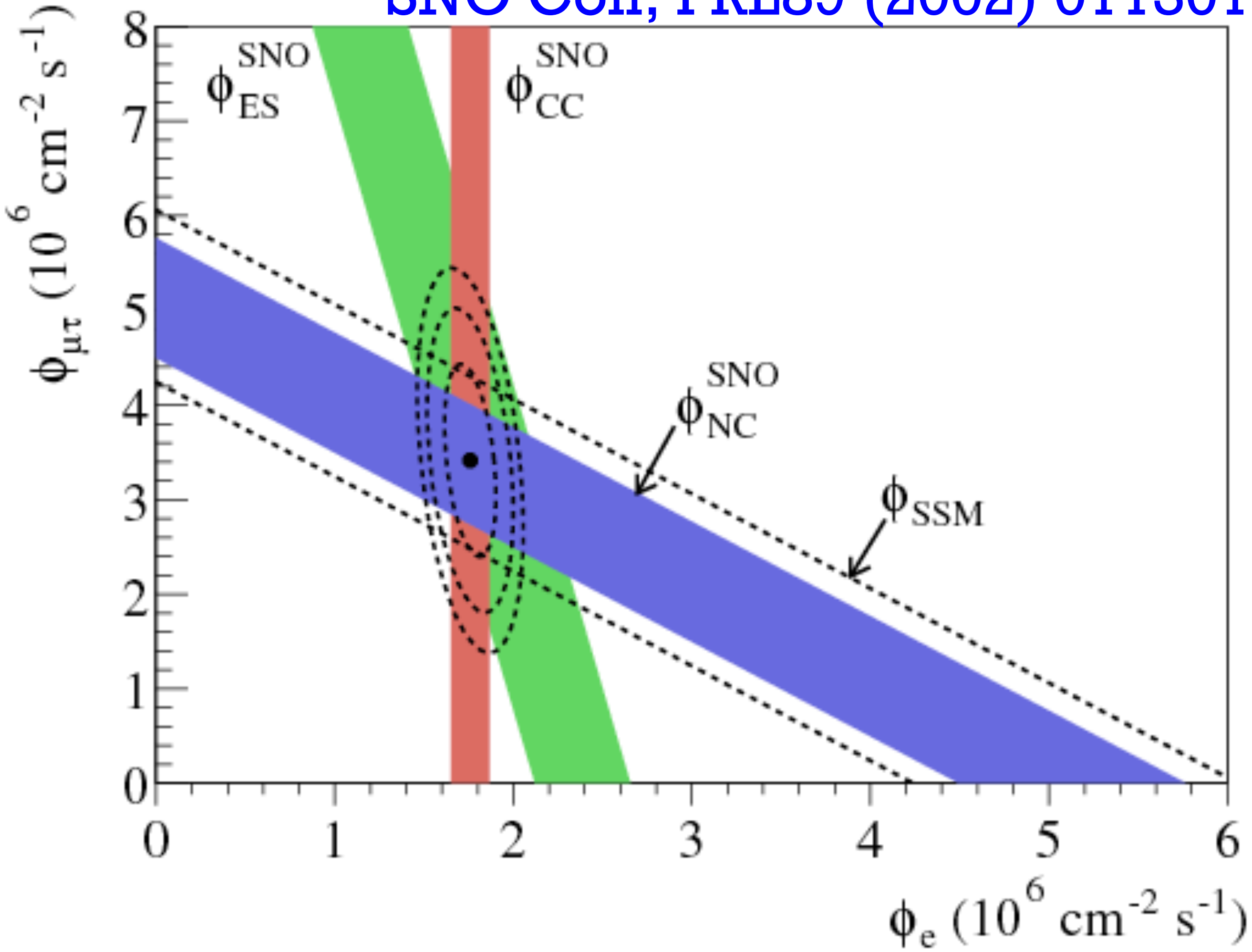


All flavors equally
Total neutrino flux



$$\frac{\phi_{\rm CC}^{\rm SNO}}{\phi_{\rm NC}^{\rm SNO}} = 0.301 \pm 0.033$$ → 30% of solar neutrinos are detected as ν_e

$$\phi_{\rm NC}^{\rm SNO} \simeq \phi_{^8{\rm B}}^{\rm SSM}$$ → $\boxed{\text{conversion } \nu_e \rightarrow \nu_{\mu\tau}}$

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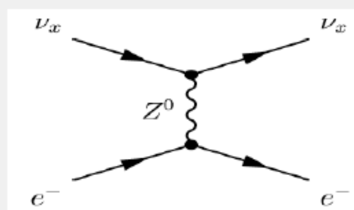

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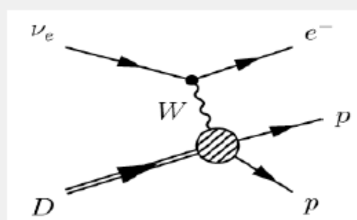

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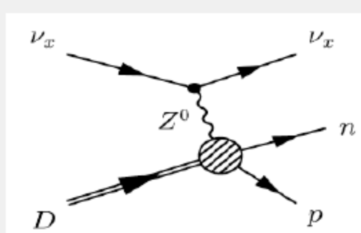

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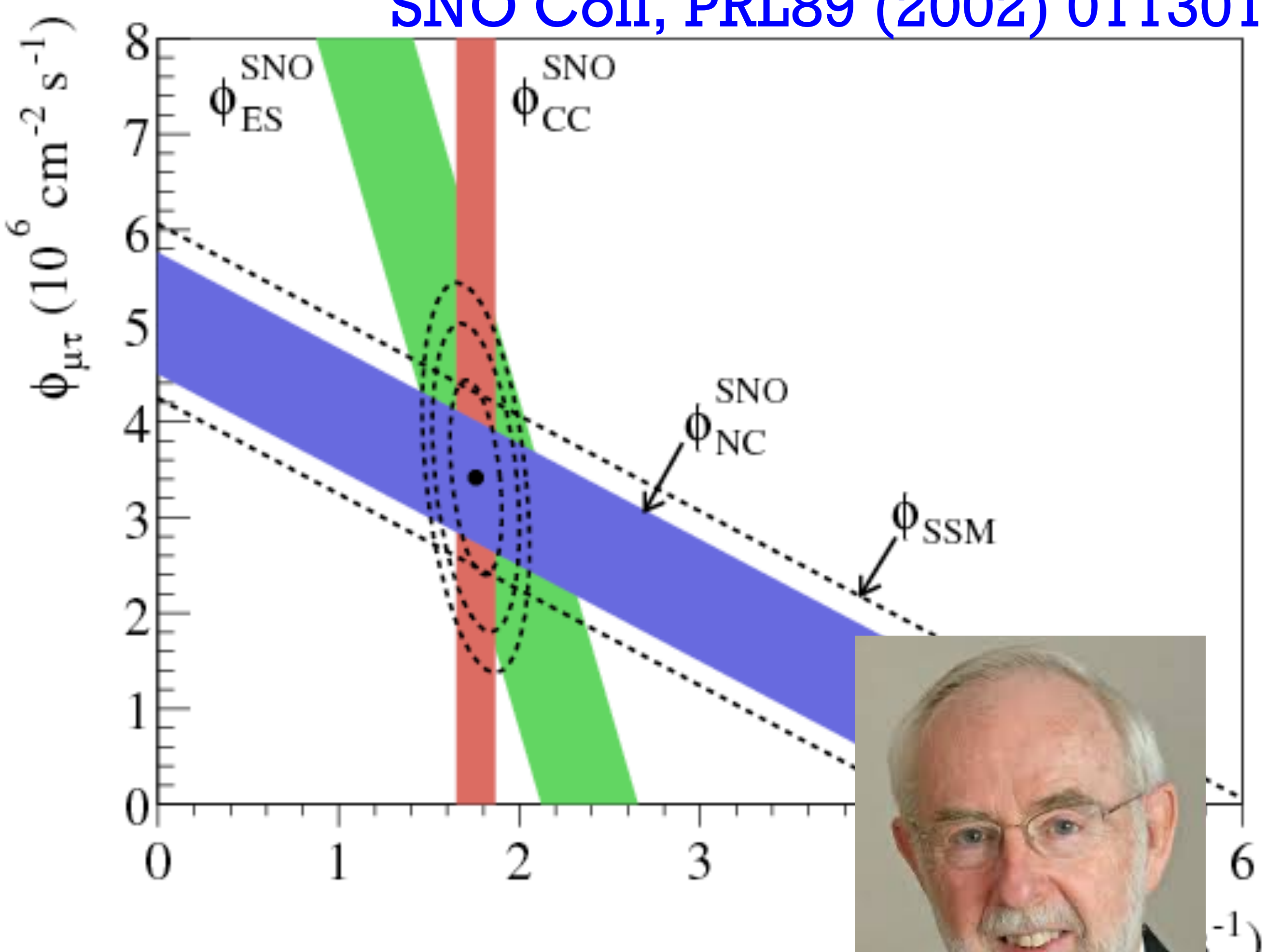
SNO Coll, PRL89 (2002) 011301



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$$\phi_{NC}^{SNO} \simeq \phi_{^8B}^{SSM}$$

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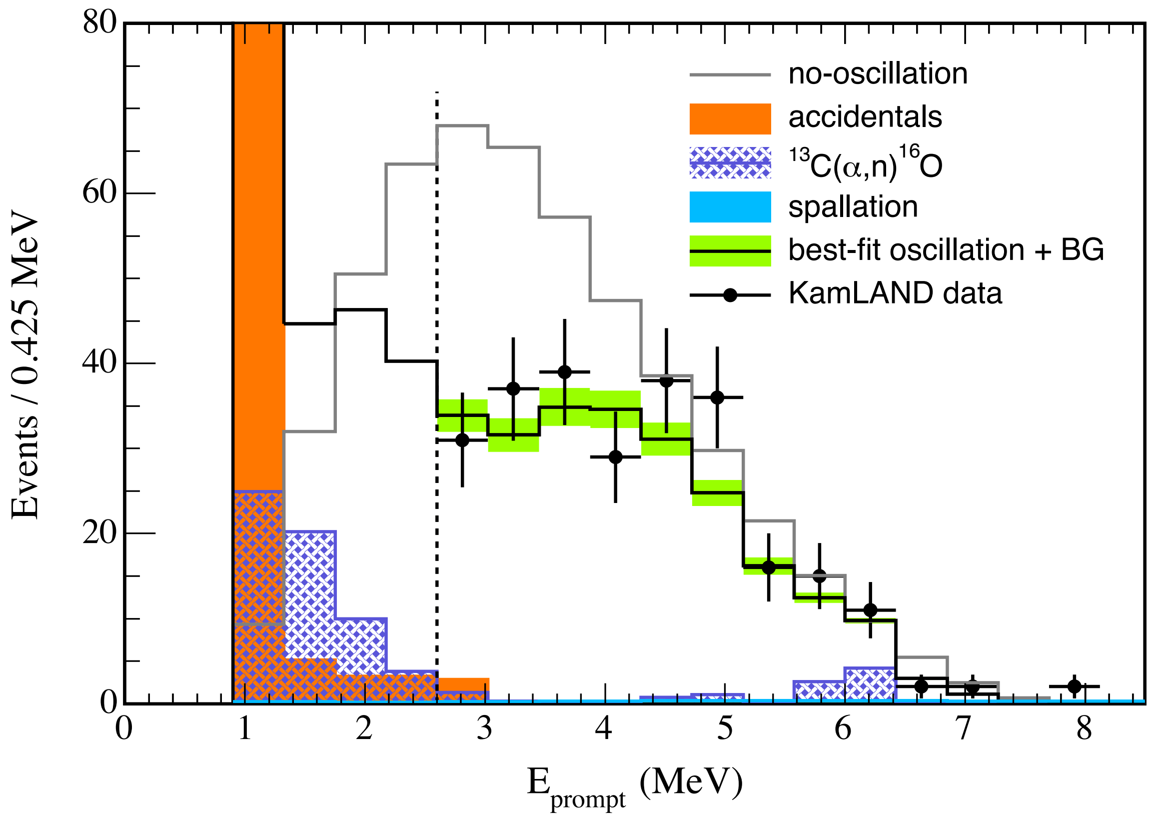
2015 Nobel Prize in Physics

Other important results

2002: The reactor experiment KamLAND observed neutrino oscillations consistent with the solar anomaly.



KamLAND Coll, PRL 90 (2003) 021802

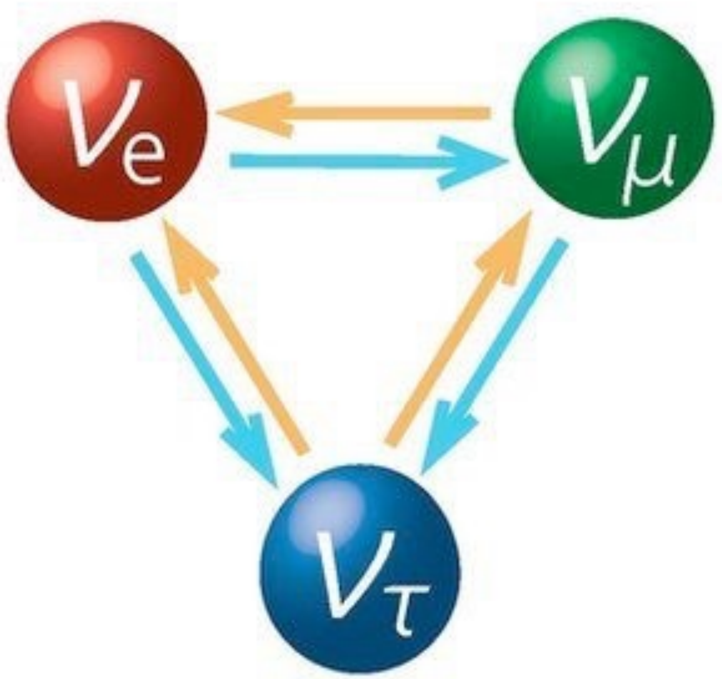
2002: Results of the accelerator experiment K2K consistent with ν_μ oscillations as in the atmospheric anomaly (MINOS, T2K, NOvA).

2011: $\nu_\mu \rightarrow \nu_e$ oscillations observed in long-baseline accelerator experiments.

2011: Double Chooz confirmed reactor antineutrino oscillations in a baseline of ~1 km (Daya Bay, RENO).

neutrino oscillations have been observed in solar, atmospheric, reactor and accelerator neutrino experiments.

Neutrino oscillations: formalism



Neutrino mixing

✦ Mixing described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

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+ common rephasing of fields leaves current unchanged

2N-1 arbitrary phases can be eliminated from U: (N-1)(N-2)/2 physical phases

Neutrino mixing

✦ For **Majorana neutrinos**, the lagrangian is NOT invariant under global phase transformations of the Majorana fields:

$$\nu_k \to e^{i\phi_k}\nu_k \quad \Rightarrow \quad \nu_{kL}^T \mathcal{C}^\dagger \nu_{kL} \to e^{2i\phi_k}\nu_{kL}^T \mathcal{C}^\dagger \nu_{kL}$$

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$$\nu_k \to e^{i\phi_k}\nu_k \quad \Rightarrow \quad \nu_{kL}^T \mathcal{C}^\dagger \nu_{kL} \to e^{2i\phi_k}\nu_{kL}^T \mathcal{C}^\dagger \nu_{kL}$$

→ only N phases can be eliminated by rephasing charged lepton fields (neutrino fields can not be rephased!!):

$$j_\rho^{\mathrm{CC}\dagger} \to 2\sum_{\alpha,k} \overline{\alpha_L} \underbrace{e^{-i\theta_\alpha}}_{\mathbf{N}} \gamma_\rho U_{\alpha k}\nu_{kL}$$

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(N-1) Majorana phases

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N(N+1)/2 - N = N(N-1)/2 physical phases for Majorana neutrinos

→ N(N-1)/2 **physical phases:** (N-1)(N-2)/2 Dirac phases → effect in ν oscil.

(N-1) Majorana phases → relevant for 0νββ

Neutrino mixing

- 2-neutrino mixing depends on 1 angle only (+1 Majorana phase)

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 3-neutrino mixing is described by 3 angles and 1 Dirac (+2 Majorana) CP violating phases.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL　　　reactor + LBL　　　solar + KamLAND

Neutrino oscillations

✦ Flavour states are admixtures of mass eigenstates: $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$

✦ Neutrino evolution equation: $$-i \frac{d}{dt} |\nu\rangle = H |\nu\rangle$$

in the neutrino mass eigenstates basis ν_j :

$$H = \begin{pmatrix} E_i & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}$$

→ neutrino mass eigenstates evolve as planes waves *:

$$|\nu_j(t)\rangle = e^{-iE_j t} |\nu_j\rangle$$

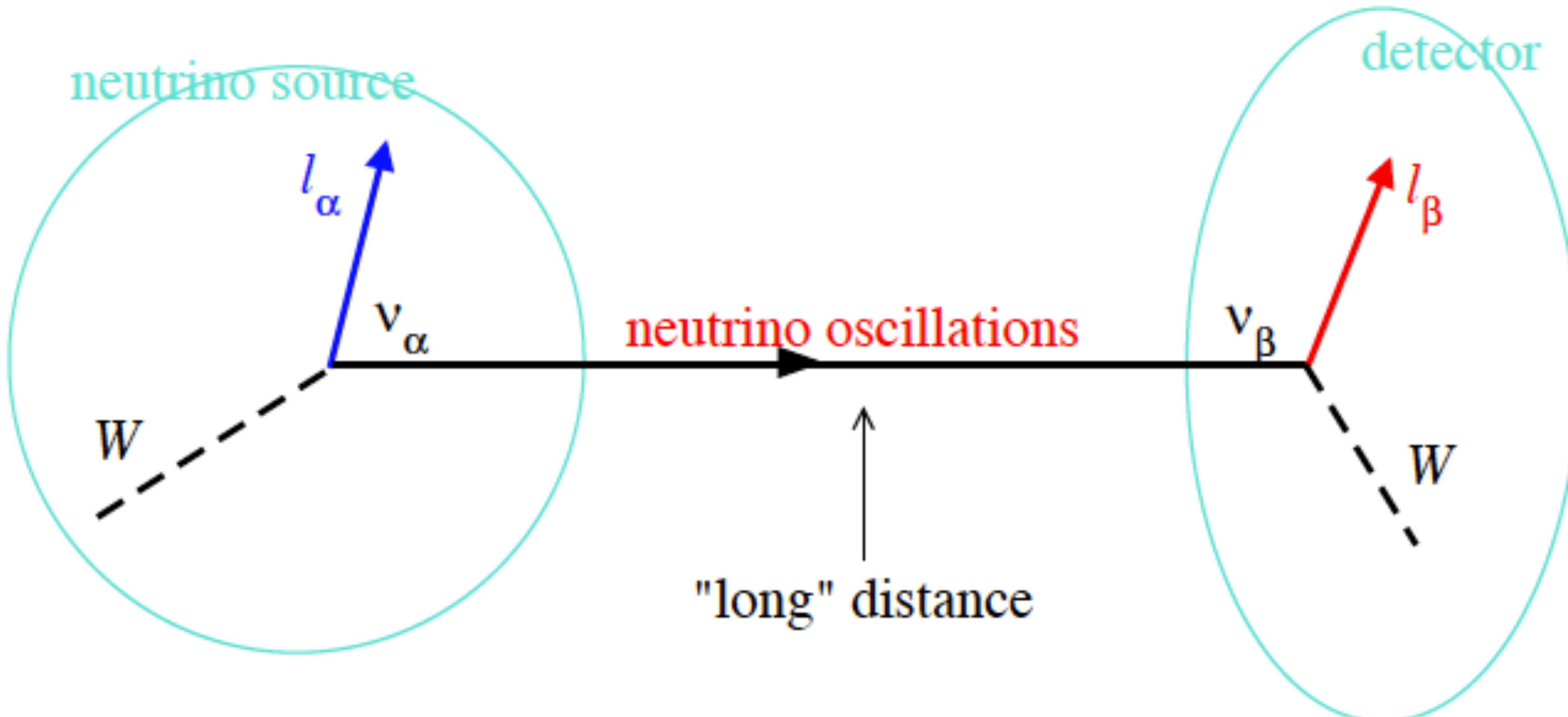
✦ For ultrarelativistic neutrinos: $$E_j \simeq E + \frac{m_j^2}{2E}$$

and t = L:

$$\rightarrow \quad |\nu_j(t)\rangle = e^{-iEL} e^{-i \frac{m_j^2 L}{2E}} |\nu_j\rangle \rightarrow e^{-i \frac{m_j^2 L}{2E}} |\nu_j\rangle$$

* For a wave-packet treatment see: Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics. Oxford University Press, 2007.

Neutrino oscillations picture



Production

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

coherent superposition of massive states

Propagation

$$\nu_j : e^{-i\frac{m_j^2 L}{2E}}$$

different propagation phases change ν_j composition

Detection

$$\langle\nu_\beta| = \sum_j \langle\nu_j|U_{\beta j}$$

projection over flavour eigenstates

Neutrino oscillation probability

Neutrino oscillation amplitude:

detection production

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta(t) | \nu_\alpha(0) \rangle = \sum_j \langle \nu_\beta | \nu_j(t) \rangle \langle \nu_j(t) | \nu_j(0) \rangle \langle \nu_j(0) | \nu_\alpha \rangle$$

propagation

$$= \sum_j U_{\beta j} e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j}^*$$

Neutrino oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_j U_{\beta j} e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j}^* \right|^2$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} Re\left(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*\right) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) +$$

$$+ 2 \sum_{i>j} Im\left(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*\right) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

General properties of neutrino oscillations

✦ Conservation of probability: $$\sum_{\beta} P(\nu_\alpha \to \nu_\beta) = 1$$

✦ For **antineutrinos**: U →U*

✦ Neutrino oscillations violate flavour **lepton number conservation** but conserve total lepton number.

✦ Phases in the mixing matrix induce **CP violation**:

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$

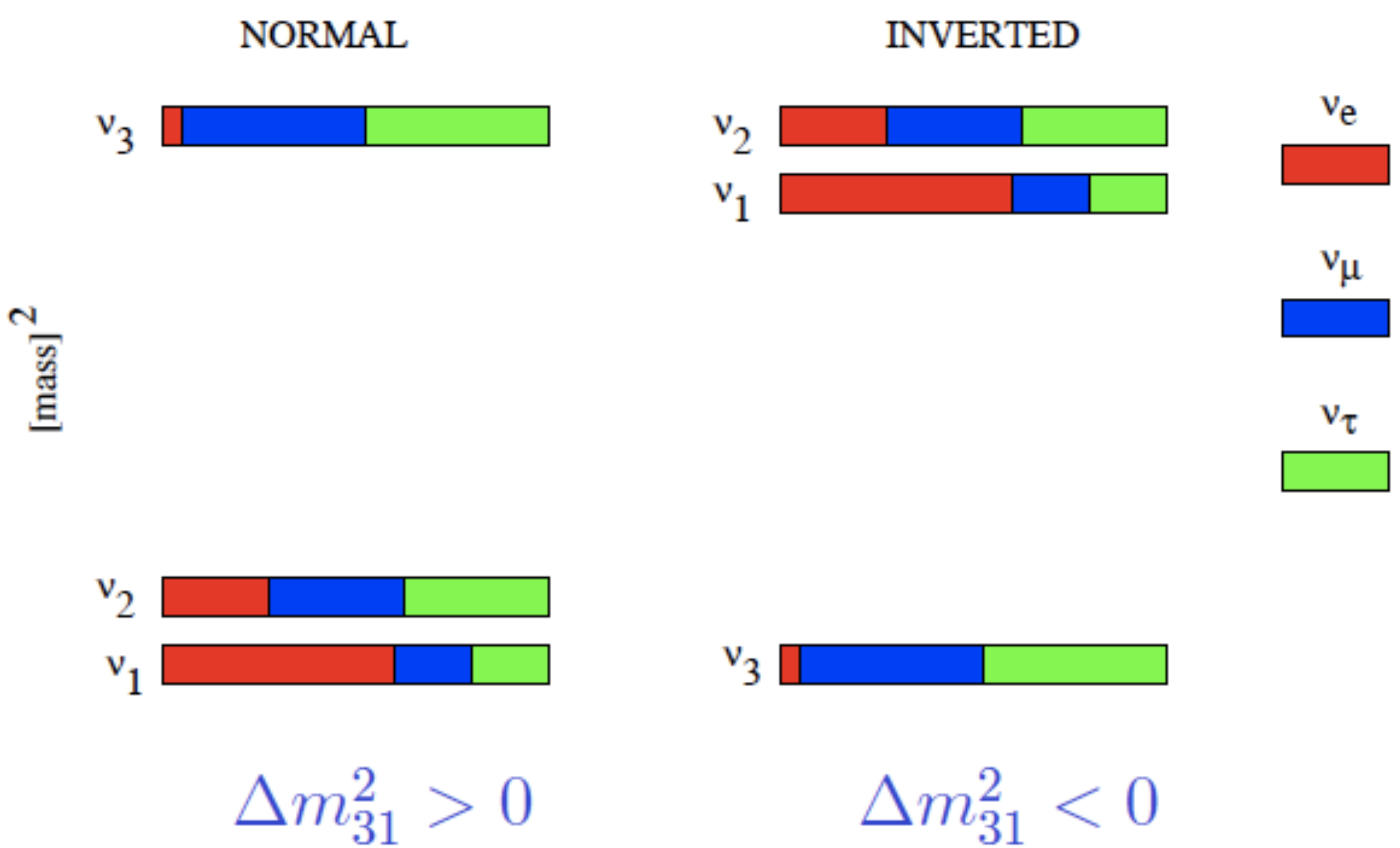
✦ Neutrino oscillations do not depend on the absolute neutrino mass scale and Majorana phases.

✦ Neutrino oscillations are sensitive only to **mass squared differences**:

$$\Delta m^2_{kj} = m^2_k - m^2_j$$

Two possible mass orderings

- Δm^2_{21} : solar + KamLAND (positive)
- Δm^2_{31} : atmospheric + LBL accelerator + SBL reactor (sign?)



Two-neutrino oscillations

- Two-neutrino mixing matrix: $\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

- Two-neutrino oscillation probability (α≠β):

$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} e^{-i\frac{\Delta m^2_{21} L}{2E}} \right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- The **oscillation phase**:

$$\phi = \frac{\Delta m^2_{21} L}{4E} = 1.27 \frac{\Delta m^2_{21}[\mathrm{eV}^2] L[\mathrm{km}]}{E[GeV]}$$

→ short distances, ϕ << 1: oscillations do not develop, $P_{\alpha\beta} = 0$

→ long distance, ϕ ~ 1: oscillations are observable

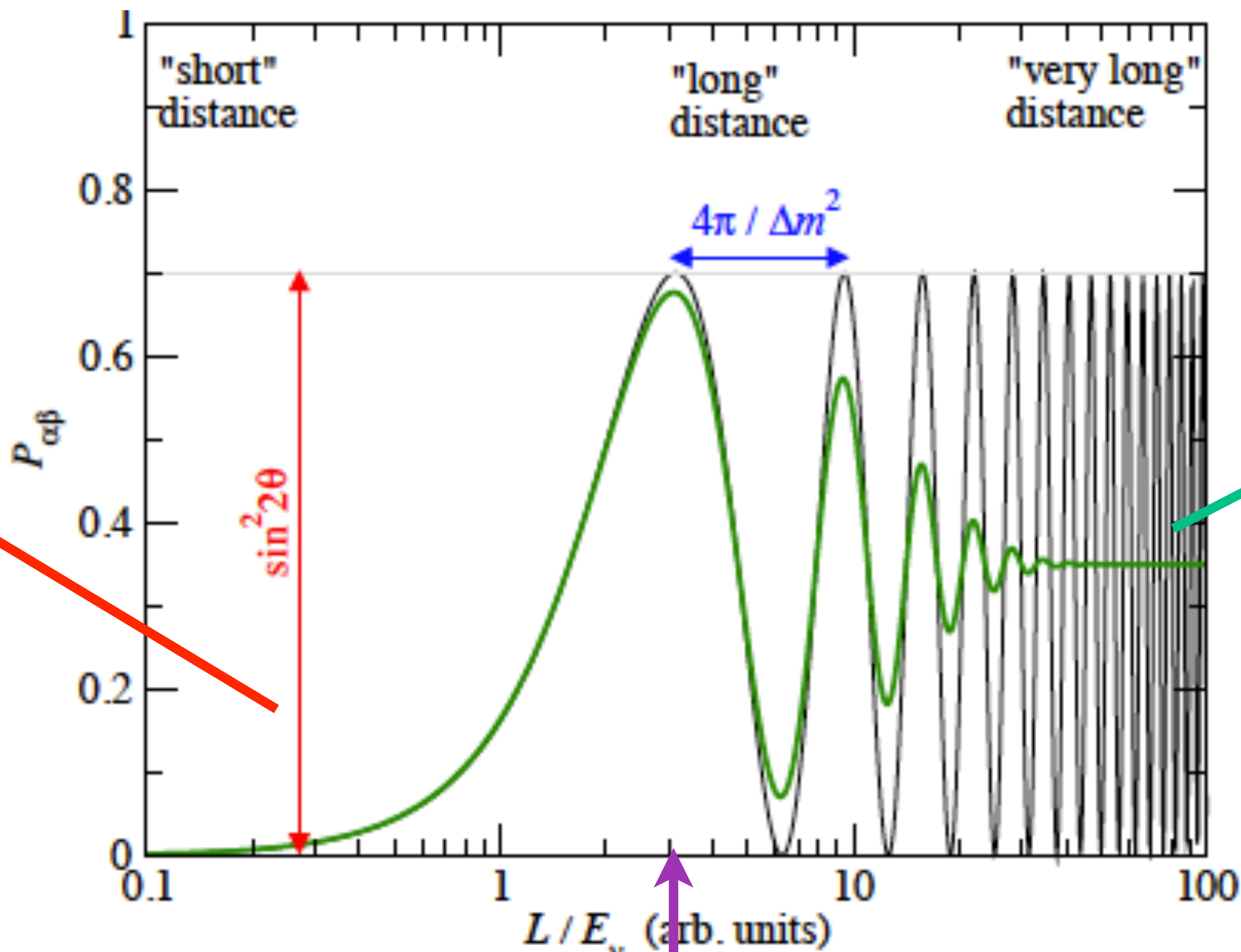
→ very long distances, ϕ >> 1: oscillations are averaged out:

$$P_{\alpha\beta} \simeq \frac{1}{2} \sin^2 2\theta$$

2-neutrino oscillation probability

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

oscillation amplitude



averaged oscillations

oscillation length:

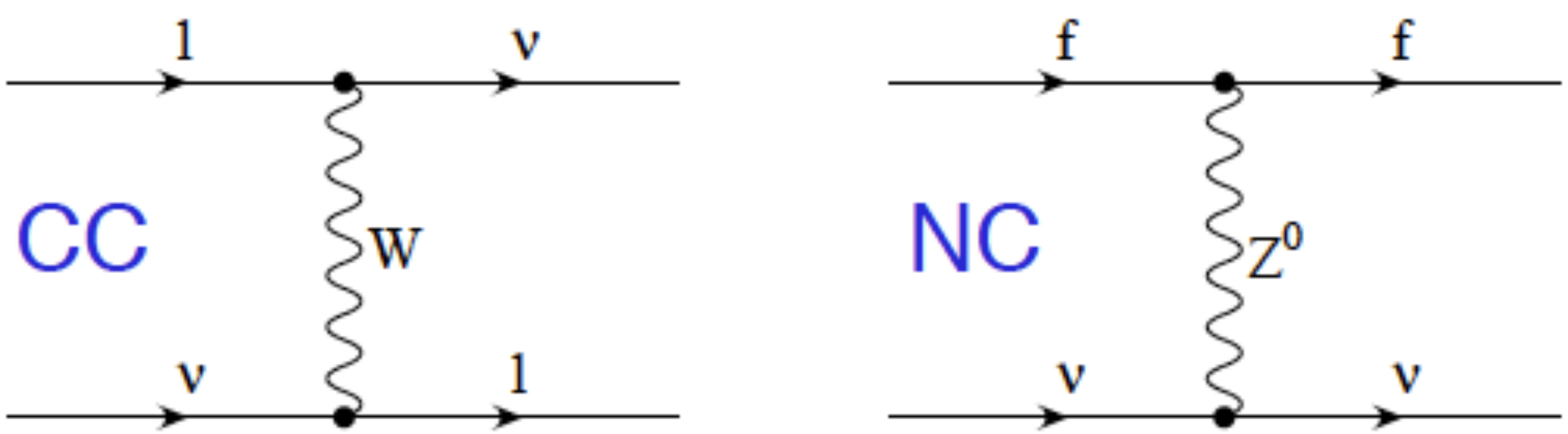
$$L_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}$$

first oscillation maximum:

Matter effects on neutrino oscillations

✦When neutrinos pass trough matter, the interactions with the particles in the medium induce an **effective potential** for neutrinos.

[→ the coherent forward scattering amplitude leads to an index of refraction for neutrinos. **L. Wolfenstein, 1978**]



→ modifies the **mixing between flavor states and mass eigenstates** as well as the eigenvalues of the Hamiltonian, leading to a different oscillation probability with respect to vacuum oscillations.

Effective matter potential

- Effective four-fermion interaction Hamiltonian (CC+NC)

$$H_{\rm int}^{\nu_\alpha} = \frac{G_F}{\sqrt{2}}\overline{\nu_\alpha}\gamma_\mu(1-\gamma_5)\nu_\alpha \sum_j \overline{f}\gamma_\mu(g_V^{\alpha,f} - g_A^{\alpha,f}\gamma_5)f$$

in ordinary matter: f=e$^-$,p,n

To obtain the **matter-induced potential** we integrate over f-variables,
For a non-relativistic unpolarised neutral medium

$$V_{\rm matt} = \sqrt{2}G_F\,{\rm diag}(N_e - \frac{1}{2}N_n, -\frac{1}{2}N_n, -\frac{1}{2}N_n)$$

- only ν_e are sensitive to CC (no μ,τ in ordinary matter)
- **NC** has the same effect for all flavours → it has **no effect on evolution**

  (however it can be important in presence of sterile neutrinos)
- for **antineutrinos** the potential has opposite sign

2-neutrino oscillations in matter

- Hamiltonian in **vacuum** in the flavour basis:

$$H_f^{\rm vac} = U H_m U^\dagger = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

- Effective hamiltonian in **matter**

$$H_f^{\rm matt} = H_f^{\rm vac} + V_{\rm eff} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + V_{CC} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$V_{CC} = \sqrt{2} G_F N_e$$

Diagonalizing the Hamiltonian, we identify the mixing angle and mass splitting in matter:

$$H_f^{\rm matt} = \frac{\Delta M^2}{4E} \begin{pmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{pmatrix}$$

In general: $N_e = N_e(x)$, so θ_M and ΔM^2 will be function of x as well

→ however, in some cases analytical solutions can be obtained

2-ν oscillations in constant matter

- If N_e is constant (good approximation for oscillations in the Earth crust):

  → θ_M and ΔM^2 are constant as well

  → we can use vacuum expression for oscillation probability, replacing "vacuum" parameters by "matter" parameters:

$$\boxed{P_{\alpha\beta} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta M^2 L}{4E}\right)}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

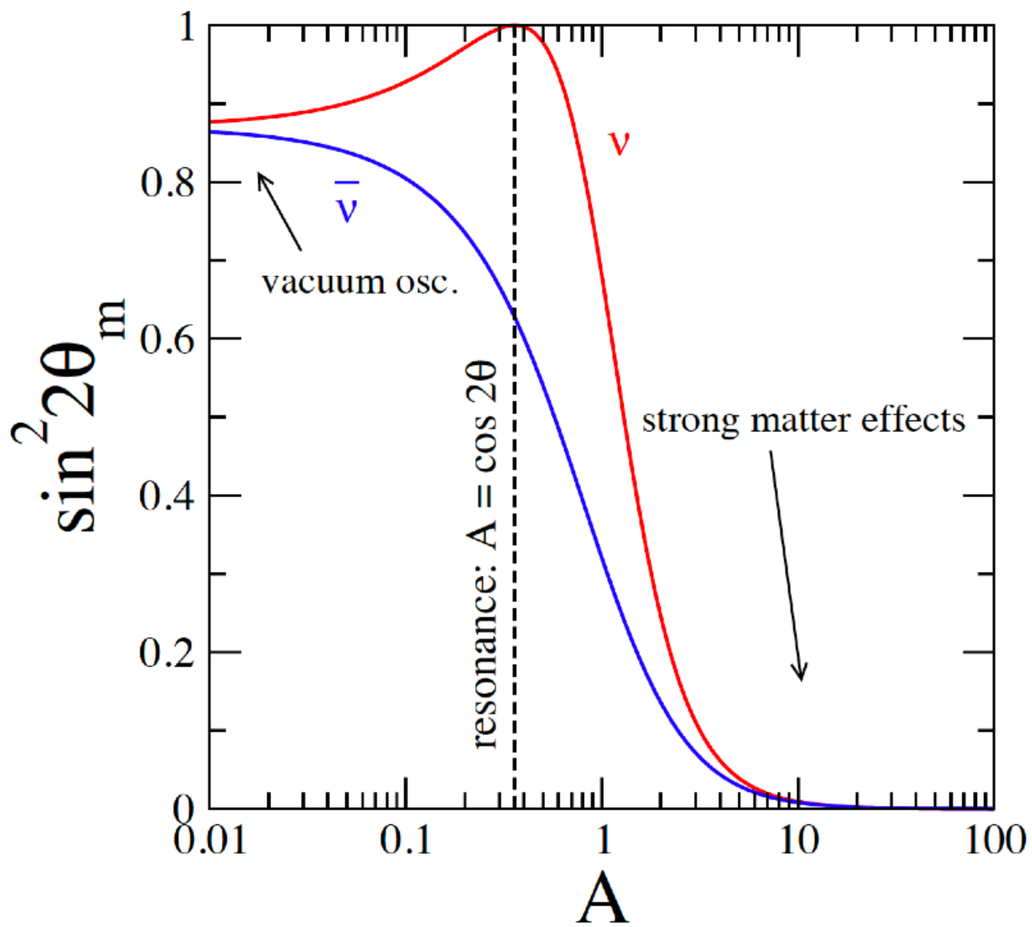
$$A = \frac{2EV}{\Delta m^2}$$

$$\Delta M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

There is a **resonance** effect for A = cos2θ → **MSW effect**

Wolfenstein, 1978. Mikheyev & Smirnov, 1986

2-ν oscillations in constant matter



mixing angle in matter:

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

$$A = \frac{2EV}{\Delta m^2}$$

- ✦ A << cos2θ, small matter effect → vacuum oscillations: $\theta_M = \theta$
- ✦ A >> cos2θ, matter effects dominate → oscillations suppressed: $\theta_M \approx \pi/2$
- ✦ A = cos2θ, resonance takes place → maximal mixing $\theta_M \approx \pi/4$

→ **resonance condition** is satisfied for neutrinos for $\Delta m^2 > 0$

for antineutrinos for $\Delta m^2 < 0$

Solar neutrinos: the MSW effect

- neutrino oscillations in matter were first discussed by Wolfenstein, Mikheyev and Smirnov (MSW effect)

- electron neutrino is born at the center of the Sun as:

$$|\nu_e\rangle = \cos\theta_M |\nu_1^m\rangle + \sin\theta_M |\nu_2^m\rangle$$

→ ν_1^m and ν_2^m evolve adiabatically until the solar surface and propagate in vacuum from the Sun to the Earth:

$$P(\nu_e \to \nu_e) = P_{e1}^{\rm prod} P_{1e}^{\rm det} + P_{e2}^{\rm prod} P_{2e}^{\rm det}$$

$$P_{e1}^{\rm prod} = \cos^2\theta_M\,, \quad P_{1e}^{\rm det} = \cos^2\theta$$
$$P_{e2}^{\rm prod} = \sin^2\theta_M\,, \quad P_{2e}^{\rm det} = \sin^2\theta$$

$$\Rightarrow \quad \boxed{P_{ee} = \cos^2\theta_M \cos^2\theta + \sin^2\theta_M \sin^2\theta}$$

Solar neutrinos: the MSW effect

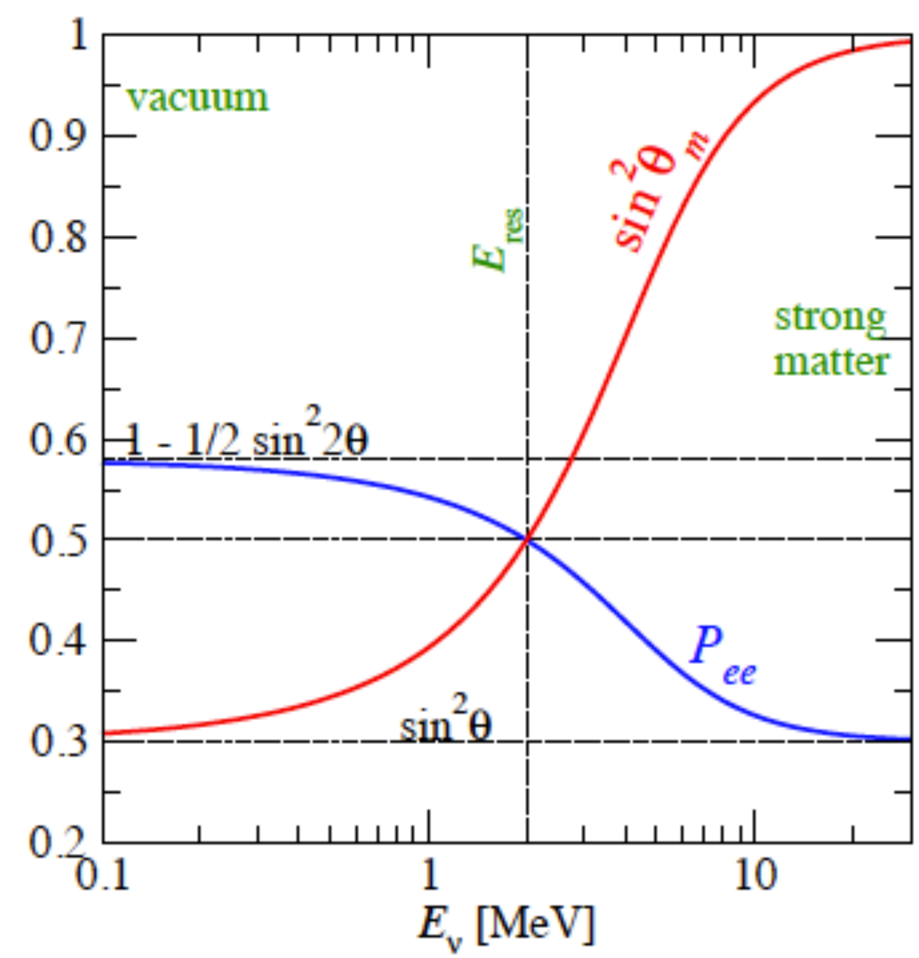
$$P_{ee} = \cos^2\theta_M \cos^2\theta + \sin^2\theta_M \sin^2\theta$$

- In the center of the Sun:

$$A = \frac{2EV}{\Delta m^2} \simeq 0.2 \left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{8\times 10^{-5}\mathrm{eV}^2}{\Delta m^2}\right)$$

and resonance occurs for A = cos(2θ) = 0.4

→ $E_{res} \approx 2$ MeV



- For E < 2 MeV → vacuum osc: $\theta_M = \theta$:

$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta$$

- For E > 2 MeV → strong matter effect: $\theta_M = \pi/2$: $P_{ee} = \sin^2\theta$

→ P_{ee} (E) will be crucial to understand solar neutrino data

Mass hierarchy in solar neutrinos

✦ Mixing angle in matter:

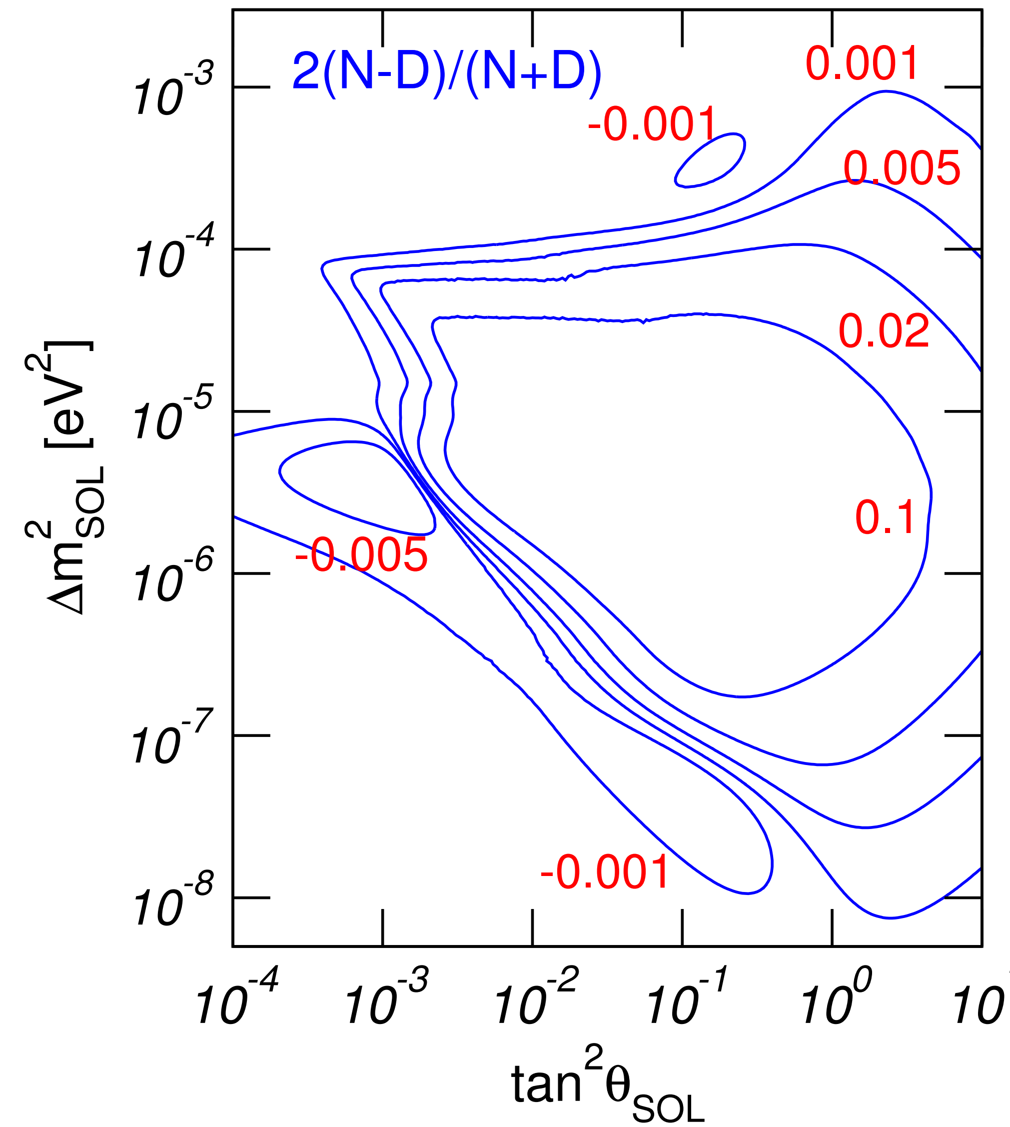
$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

→ **resonance condition** A = cos2θ is satisfied for neutrinos for $\Delta m^2 > 0$ and for antineutrinos for $\Delta m^2 < 0$ (change of sign in Vcc)

✦ Matter effects observed in solar neutrino data are in agreement with the presence of a resonance as predicted above:

→ since solar neutrinos are ν_e: $\Delta m_{21}^2 > 0 \rightarrow m_2^2 > m_1^2$

Earth regeneration effect



- Neutrinos observed at night are also affected by Earth matter effects

- If neutrinos cross only the Earth mantle, P_{2e}^{det} is well approximated by the evolution of a constant potential:

$$P_{2e}^{\rm det} = \sin^2\theta + f_{\rm reg}$$

prob. during day

regeneration term

$$f_{\rm reg} = \frac{4EV_{CC}}{\Delta m^2}\sin^2 2\theta_E \sin^2\frac{\pi L}{L_{\rm osc}}$$

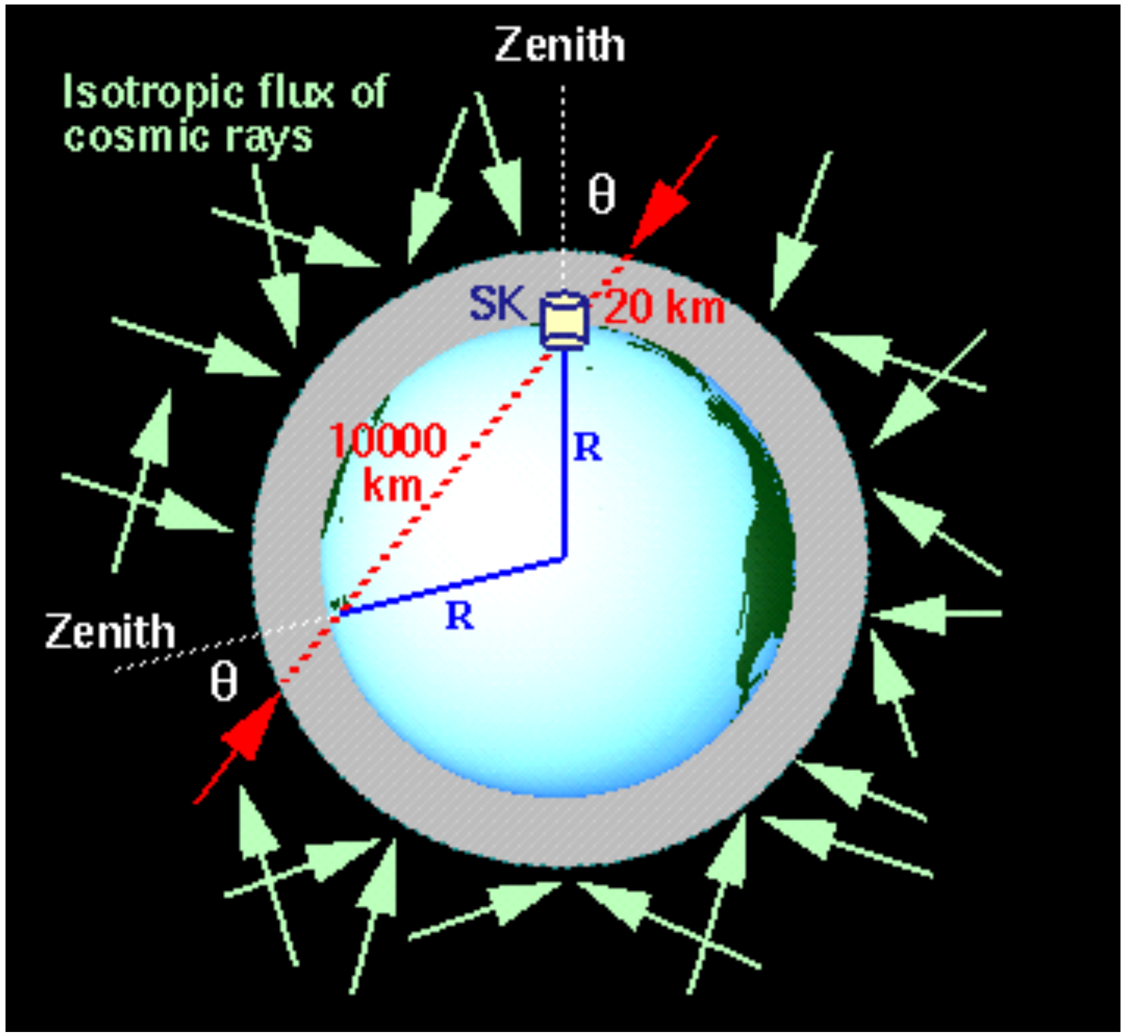
$$P_{ee}^{\rm night} = P_{ee}^{\rm day} - \cos 2\theta_M f_{\rm reg}$$

$\rightarrow$ day-night asymmetry:

$$A_{\rm DN} \equiv 2\frac{(P_N - P_D)}{P_N + P_D}$$

- For the measured solar neutrino parameters $f_{reg} \sim +1\%$

Matter effects in atmospheric ν's



✦ Atmospheric neutrinos interact with the Earth mantle and core

✓ no matter effects in $\nu_\mu \to \nu_\tau$ channel

✓ MSW resonance in $\nu_\mu \to \nu_e$ channel

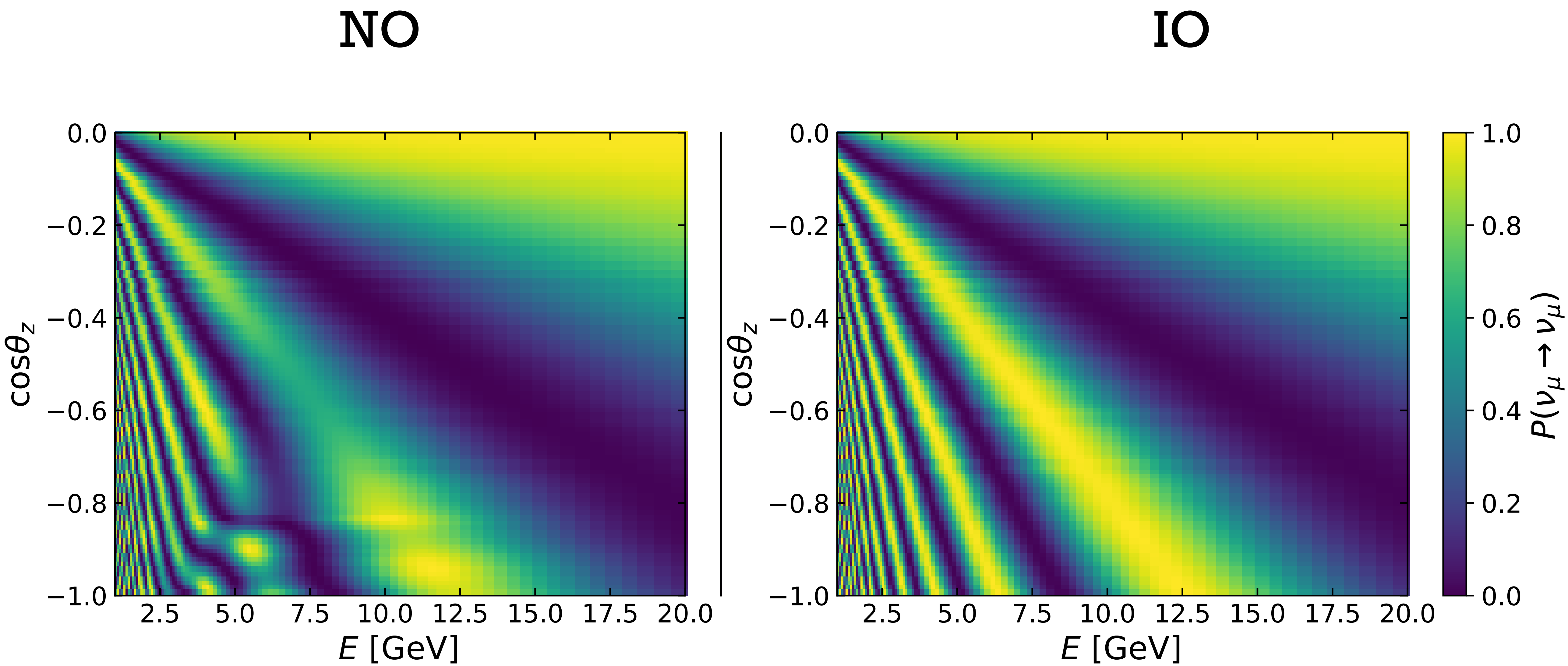
$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{4E}\sin 2\theta}{\frac{\Delta m^2}{4E}\cos 2\theta \mp \sqrt{2} G_F N_e}$$

(-) neutrinos (+)antineutrinos

➙ Matter effects on the atmospheric neutrino flux are sensitive to the mass ordering.

➙ they are harder to observe since $P_{\mu e} \propto \theta_{13}$

Matter effects in atmospheric ν's

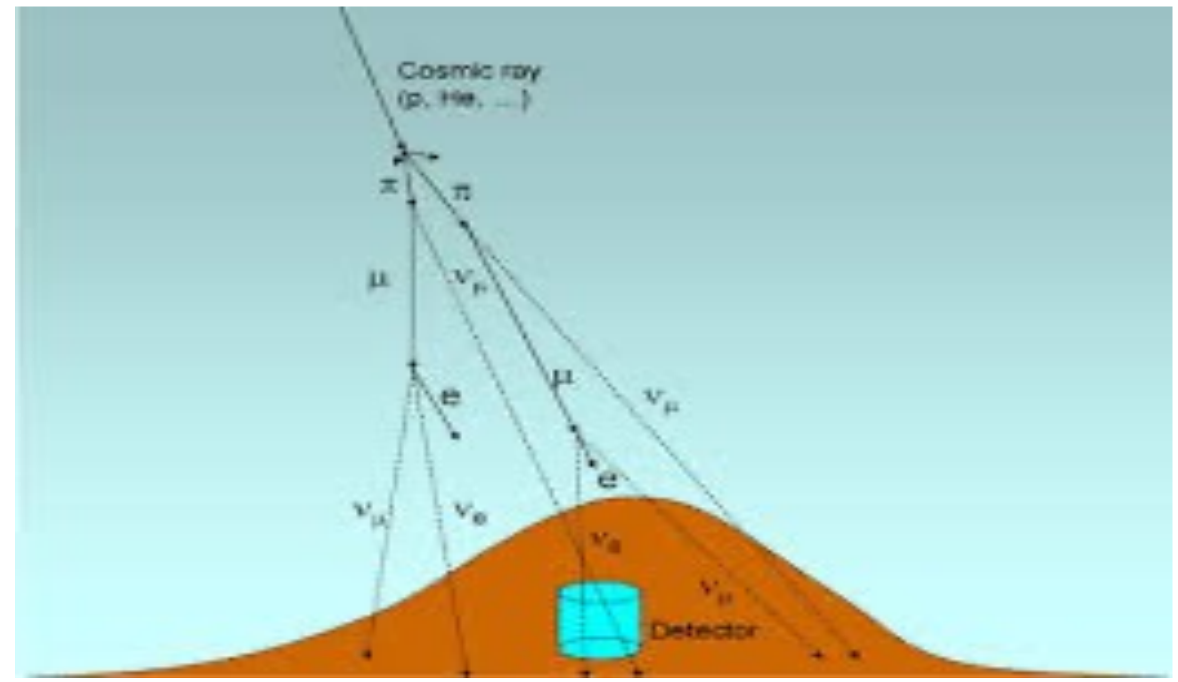


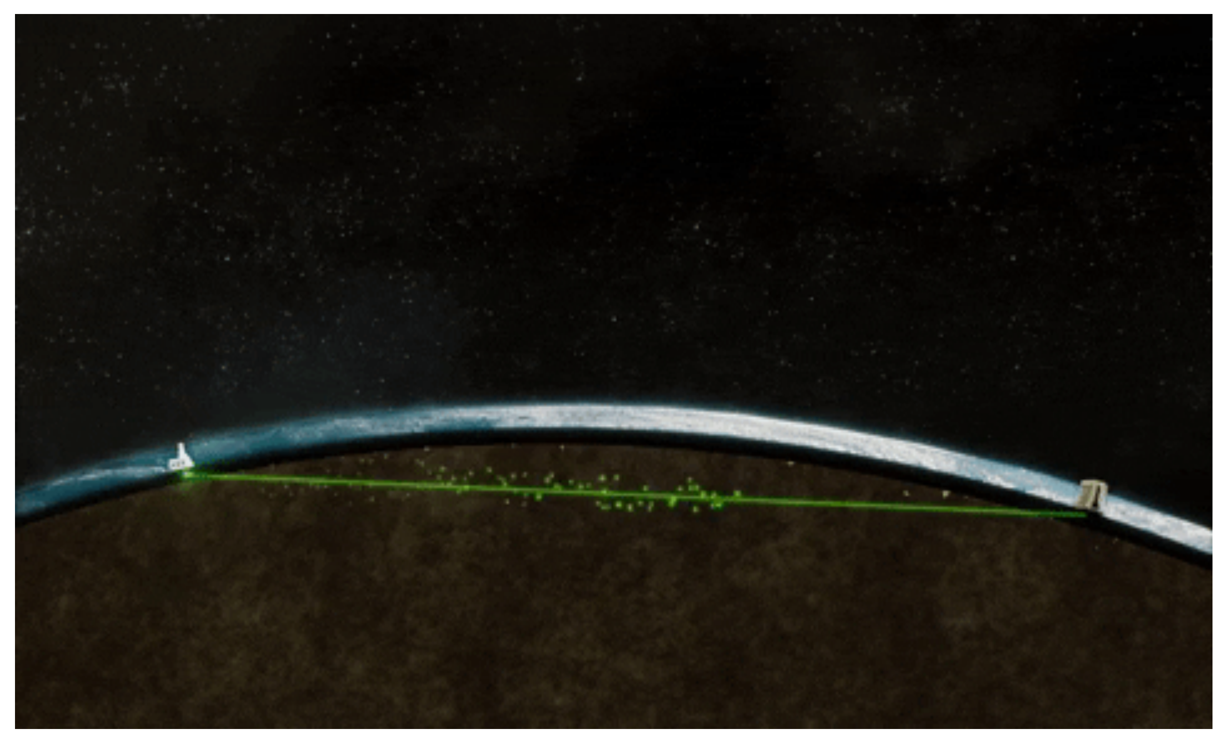
de Salas et al, arXiv:1806.11051

At E~ 3-8 GeV: MSW resonance for neutrinos and NO mass spectrum.

For antineutrinos ⟹ the resonance appears in IO

Neutrino oscillation experiments





Neutrino oscillation experiments