

INTRO TO PHENOMENOLOGY WITH MASSIVE NEUTRINOS

Concha Gonzalez-Garcia

(YITP-Stony Brook & ICREA-University of Barcelona)

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INTRO TO PHENOMENOLOGY WITH MASSIVE NEUTRINOS: LECTURE I

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OUTLINE

- Historic Introduction to the SM of Massless Neutrinos
- Neutrino Properties relevant to ν mass::
Helicity versus Chirality, Majorana versus Dirac, Leptonic Mixing
- Probes of Neutrino Mass Scale

Discovery of ν 's

- At end of 1800's radioactivity was discovered and three types identified: α , β , γ
 β : an electron comes out of the radioactive nucleus.
- Energy conservation $\Rightarrow e^-$ should have had a fixed energy

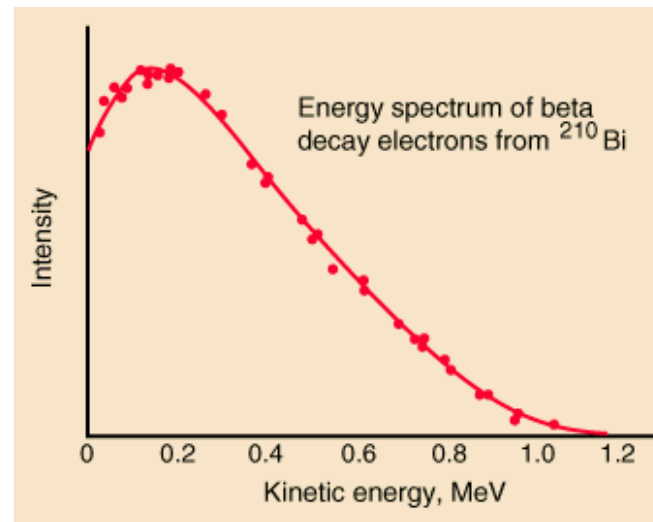
$$(A, Z) \rightarrow (A, Z + 1) + e^- \Rightarrow E_e = M(A, Z + 1) - M(A, Z)$$

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But 1914 $(A, Z) \rightarrow (A, Z + 1) + e^- \Rightarrow E_e = M(A, Z + 1) - M(A, Z)$
 James Chadwick showed that the electron energy spectrum is continuous

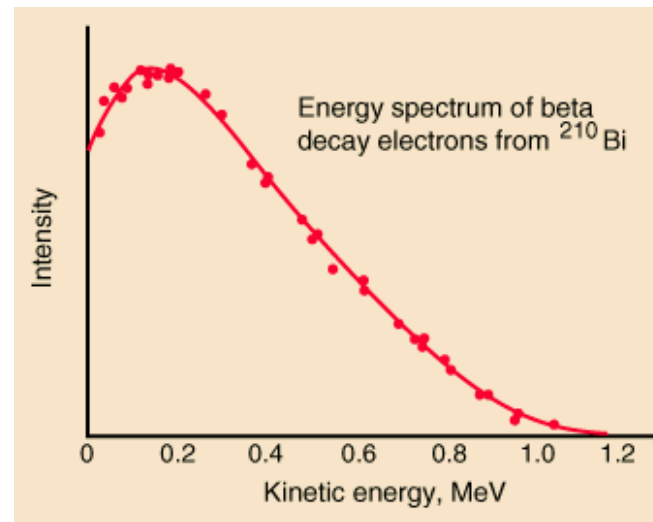


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Do we throw away the energy conservation?

Bohr: *we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β ray disintegrations*

Discovery of ν 's

- The idea of the **neutrino** came in 1930, when **W. Pauli** tried a desperate saving operation of "the energy conservation principle".



In his letter addressed to the *Liebe Radioaktive Damen und Herren* (Dear Radioactive Ladies and Gentlemen), the participants of a meeting in Tübingen. He put forward the hypothesis that a new particle exists as *constituent of nuclei, the neutron ν* , able to explain the continuous spectrum of nuclear beta decay

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

- The ν is **light** (in Pauli's words: m_ν should be of the same order as the m_e), **neutral** and has **spin 1/2**

Discovery of ν 's

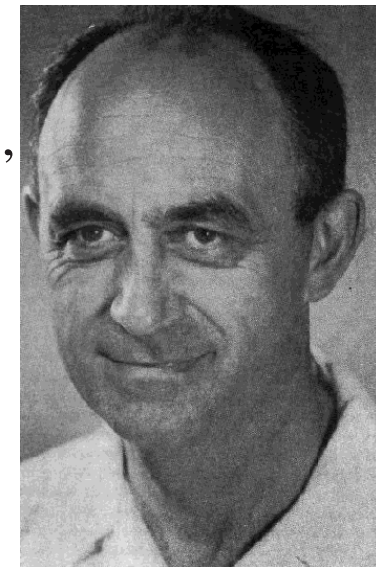
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- The ν is **light** (in Pauli's words: *m_ν should be of the same order as the m_e*), **neutral** and has **spin 1/2**
- In order to distinguish them from heavy neutrons, **Fermi** proposed to name them **neutrinos**.

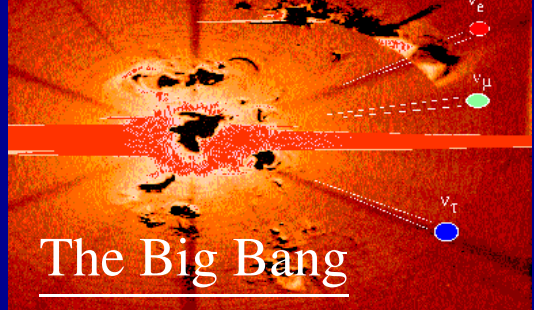


Neutrino Detection

Fighting Pauli's "Curse":

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

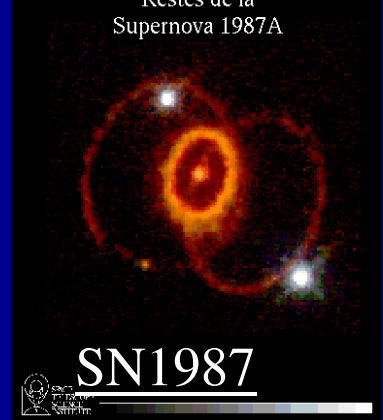
Sources of ν 's



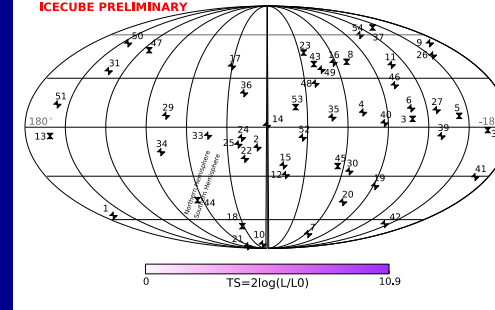
The Big Bang

$$\rho_\nu = 330/\text{cm}^3$$

$$p_\nu = 0.0004 \text{ eV}$$



$E_\nu \sim \text{MeV}$



ExtraGalactic

$$E_\nu \gtrsim 30 \text{ TeV}$$

The Sun

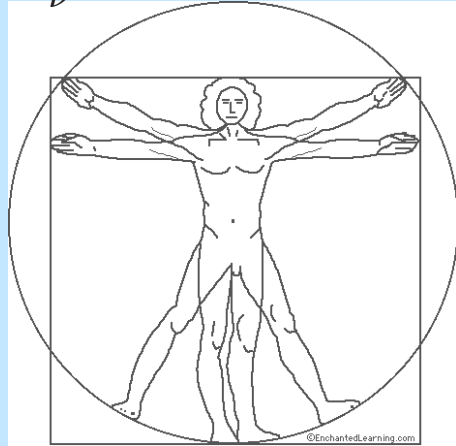
ν_e

$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$

$E_\nu \sim 0.1\text{--}20 \text{ MeV}$

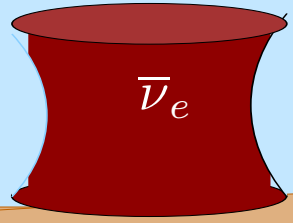
Human Body

$$\Phi_\nu = 340 \times 10^6 \nu/\text{day}$$



Nuclear Reactors

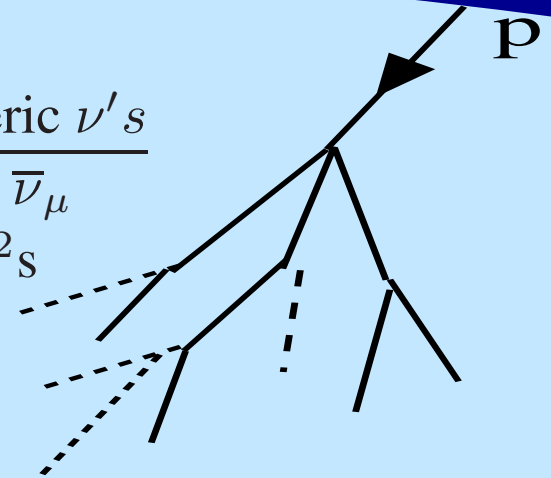
$$E_\nu \sim \text{few MeV}$$



Atmospheric ν 's

$$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$$

$$\Phi_\nu \sim 1 \nu/\text{cm}^2\text{s}$$



Earth's radioactivity

$$\Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s}$$

Accelerators

$$E_\nu \simeq 0.3\text{--}30 \text{ GeV}$$



NSS

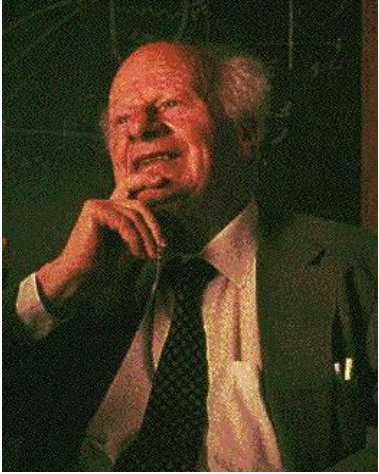
$$E_\nu \sim \text{MeV}$$

Neutrino Detection

But in principle seems easy!: If β decay $n \rightarrow p + e^- + \nu$

Then $\nu + p \rightarrow e^+ + n$

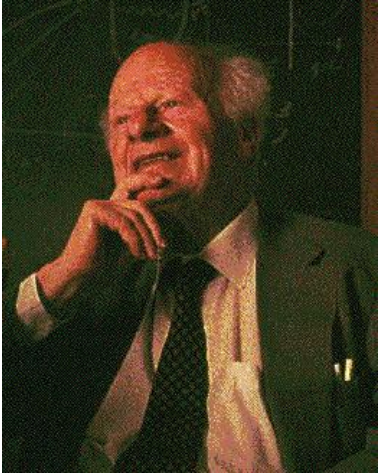
Neutrino Detection



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Problem: Already in 1934, **Hans Bethe** showed that the probability of this interaction was so small that a solar ν could cross the whole Earth without ever interacting with it

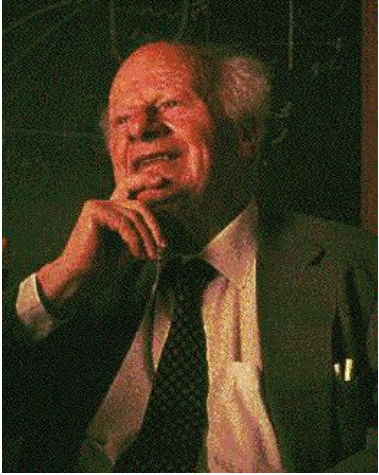


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$$\sigma^{\nu p} \sim 10^{-38} \text{cm}^2 \frac{E_\nu}{\text{GeV}}$$



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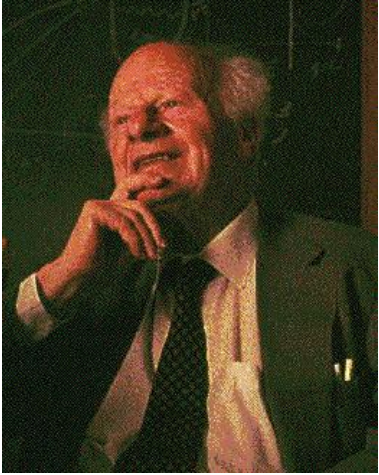
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- So let's consider the atmospheric ν 's:

$$\Phi_\nu^{\text{ATM}} = 1 \nu / (\text{cm}^2 \text{ second}) \quad \text{y} \quad \langle E_\nu \rangle = 1 \text{ GeV}$$

- How many interact?



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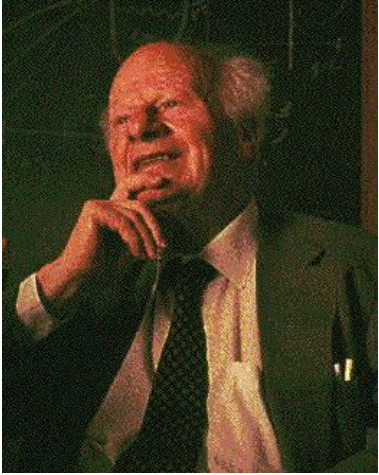
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- How many interact? In a human body

$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu p} \times N_{\text{prot}}^{\text{human}} \times T_{\text{life}}^{\text{human}}$$

$$\left. \begin{aligned} N_{\text{protons}}^{\text{human}} &= \frac{M^{\text{human}}}{m_p} \times N_A = 80 \text{kg} \times N_A \sim 5 \times 10^{28} \text{ protons} \\ T^{\text{human}} &= 80 \text{ years} = 2 \times 10^9 \text{ sec} \end{aligned} \right\} \begin{aligned} &(M \times T \equiv \text{Exposure}) \\ &\text{Exposure}_{\text{human}} \\ &\sim \text{Ton} \times \text{year} \end{aligned}$$



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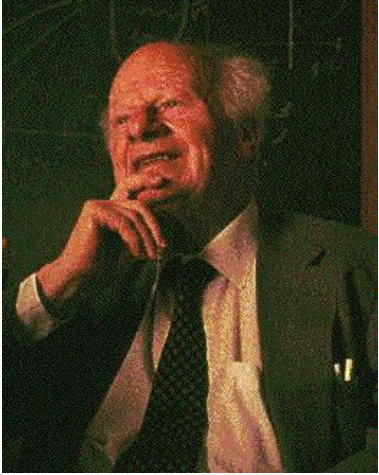
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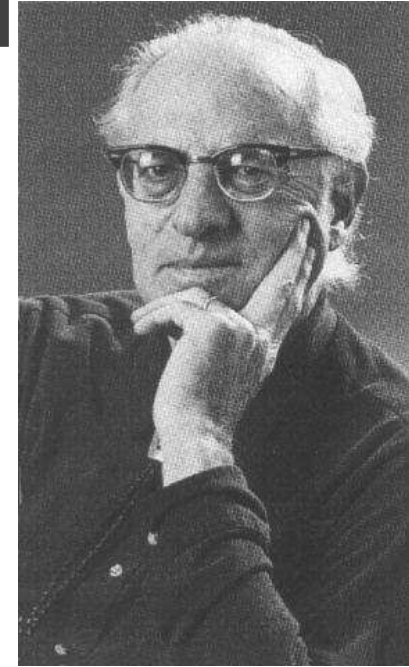
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To detect neutrinos we need very intense source and/or
a huge detector with Exposure $\sim \text{Kton} \times \text{year}$

First Neutrino Detection

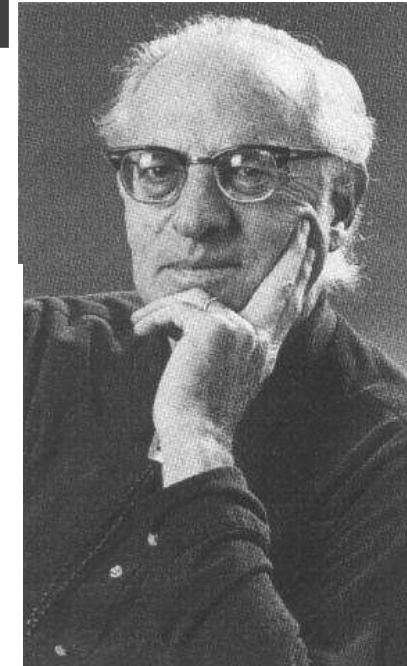
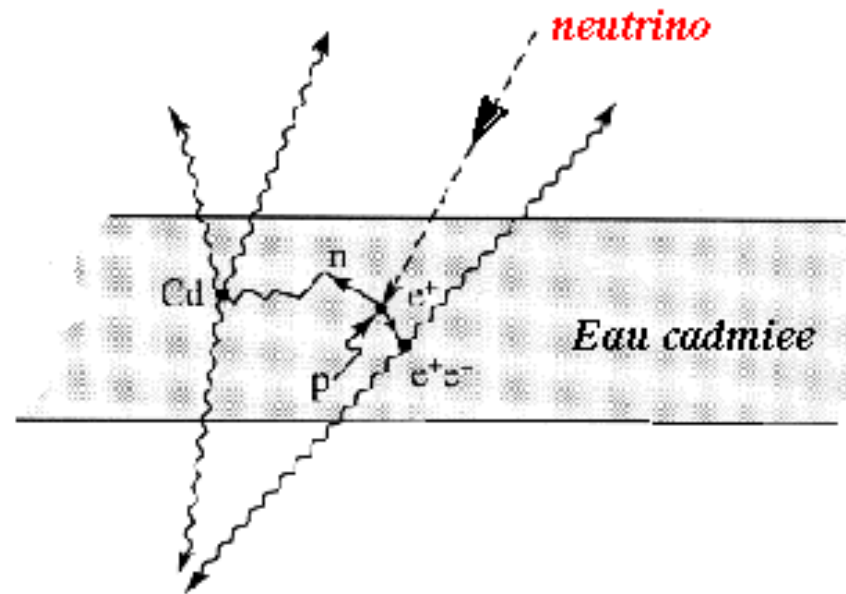
In 1953 **Frederick Reines** and **Clyde Cowan** put a detector near a nuclear reactor (**the most intense source available**)



First Neutrino Detection

In 1953 **Frederick Reines** and **Clyde Cowan** put a detector near a nuclear reactor (the most intense source available)

400 l of water
and Cadmium Chloride.



e^+ annihilates with e^- in the water and produces two γ 's simultaneously.

neutron is captured by the cadmium and a γ 's is emitted 15 msec later

Reines y Clyde saw clearly this signature: the first neutrino had been detected

The Other Flavours

ν coming out of a nuclear reactor is $\bar{\nu}_e$ because it is emitted together with an e^-

Question: Is it different from the muon type neutrino ν_μ that could be associated to the muon? Or is this difference a theoretical arbitrary convention?

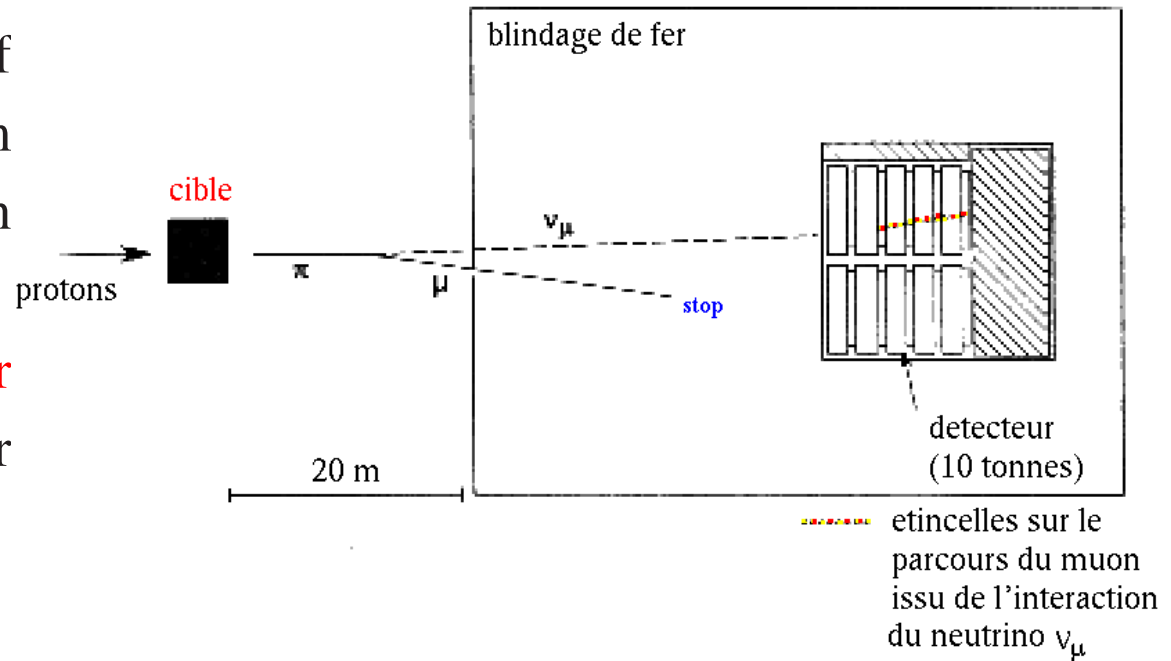
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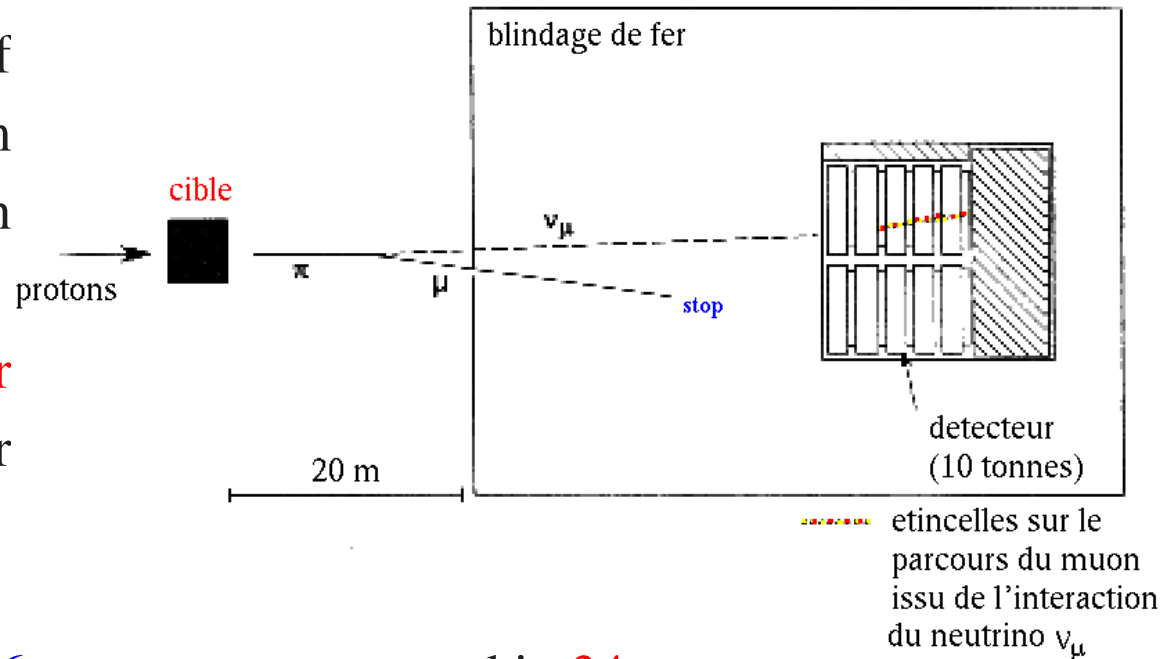
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They observe 40 ν interactions: in 6 an e^- comes out and in 34 a μ^- comes out.

If $\nu_\mu \equiv \nu_e \Rightarrow$ equal numbers of μ^- and e^-

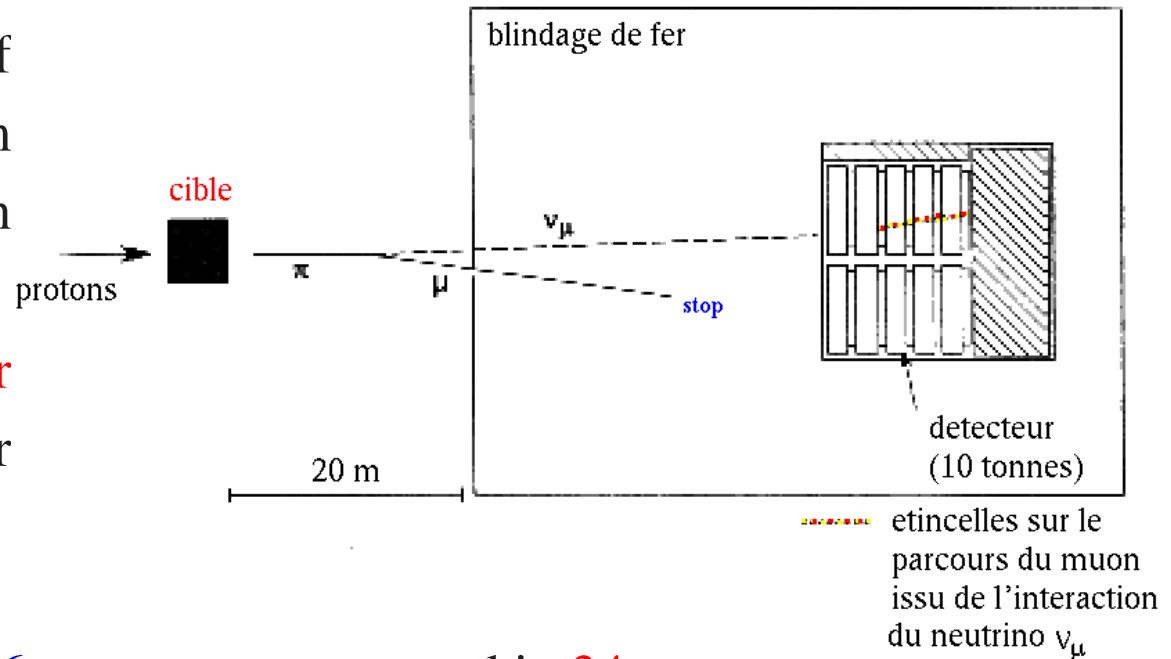
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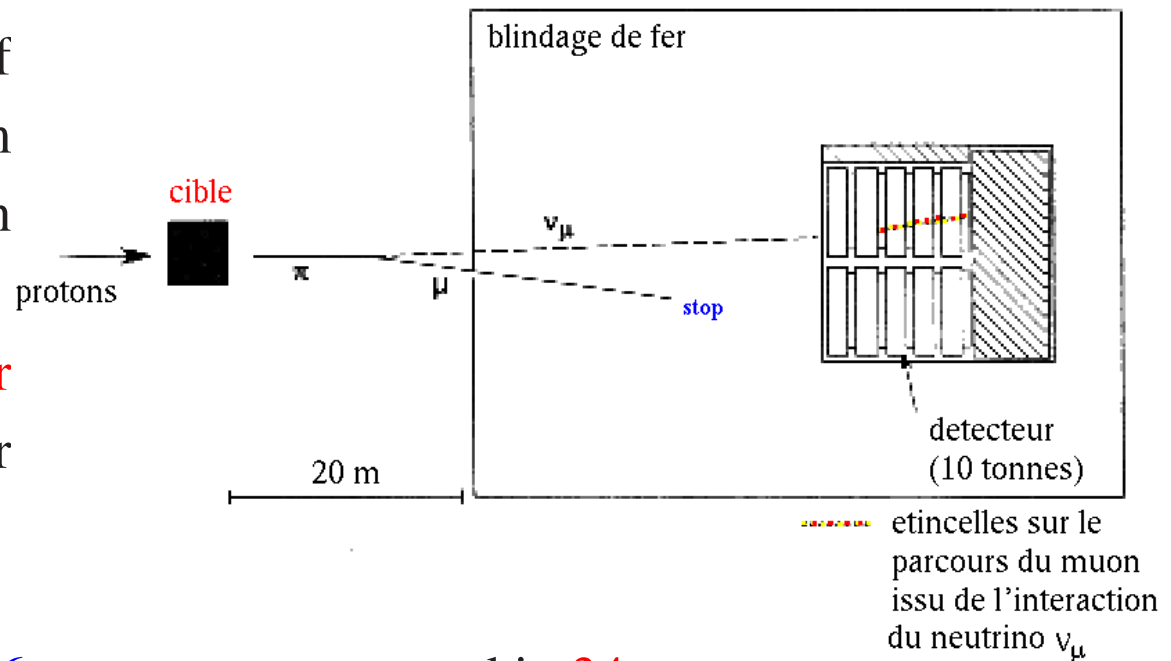
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In 1977 **Martin Perl** discovers the particle tau \equiv the third lepton family.

The ν_τ was observed by **DONUT** experiment at FNAL in 1998 (officially in Dec. 2000).

Neutrinos = “Left-handed”

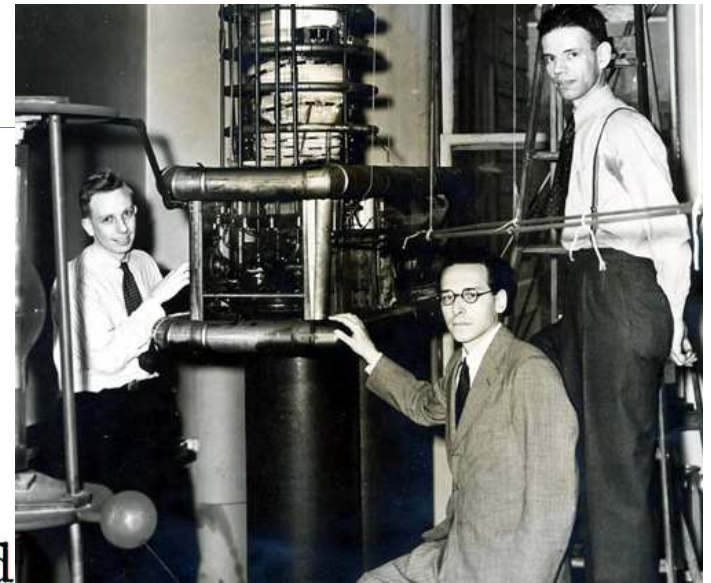
Helicity of Neutrinos*

M. GOLDBABER, L. GRODZINS, AND A. W. SUNYAR

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m} , which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,¹ 0^- , we find that the neutrino is “left-handed,” i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

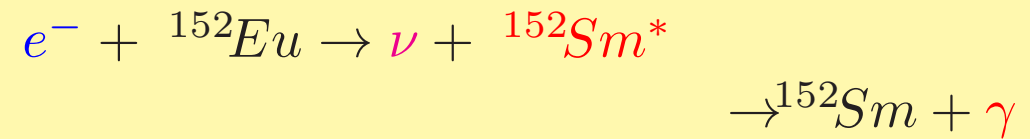


Neutrino Helicity

Neutrino Helicity

- The neutrino helicity was measured in 1957 in a experiment by Goldhaber et al.

- Using the electron capture reaction

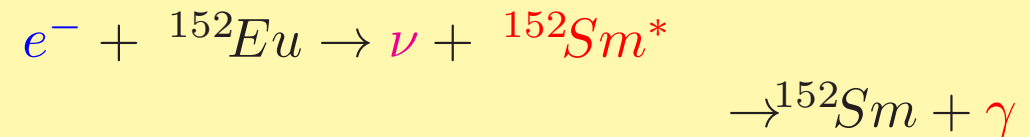


with $J({}^{152}\text{Eu}) = J({}^{152}\text{Sm}) = 0$ and $L(e^{-}) = 0$

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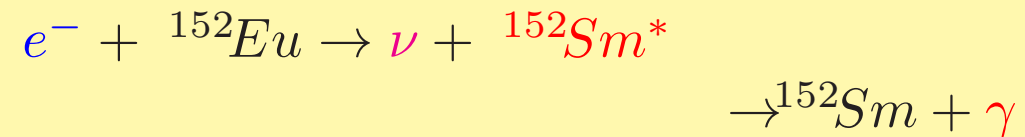
- Angular momentum conservation \Rightarrow

$$\left\{ \begin{array}{lcl} J_z(e^{-}) & = & J_z(\nu) + J_z(\text{Sm}^{*}) \\ & = & J_z(\nu) + J_z(\gamma) \\ \pm \frac{1}{2} & = & \mp \frac{1}{2} \quad \pm 1 \Rightarrow J_z(\nu) = -\frac{1}{2} J_z(\gamma) \end{array} \right.$$

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- Nuclei are heavy $\Rightarrow \vec{p}({}^{152}\text{Eu}) \simeq \vec{p}({}^{152}\text{Sm}) \simeq \vec{p}({}^{152}\text{Sm}^{*}) = 0$

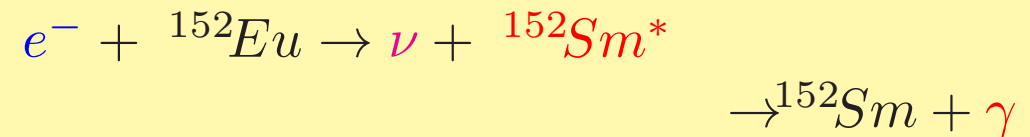
So momentum conservation $\Rightarrow \vec{p}_{\nu} = -\vec{p}_{\gamma}$

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- Goldhaber et al found γ had negative helicity $\Rightarrow \nu$ has negative helicity

ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- 3 Generations of Fermions:

$(1, 2, -\frac{1}{2})$	$(3, 2, \frac{1}{6})$	$(1, 1, -1)$	$(3, 1, \frac{2}{3})$	$(3, 1, -\frac{1}{3})$
L_L	Q_L^i	E_R	U_R^i	D_R^i
$\begin{pmatrix} \nu_e \\ e \\ \nu_\mu \\ \mu \\ \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \\ c^i \\ s^i \\ t^i \\ b^i \end{pmatrix}_L$	$\begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$	$\begin{pmatrix} u_R^i \\ c_R^i \\ t_R^i \end{pmatrix}$	$\begin{pmatrix} d_R^i \\ s_R^i \\ b_R^i \end{pmatrix}$

- Spin-0 particle ϕ : $(1, 2, \frac{1}{2})$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{SSB} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

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$$Q_{EM} = T_{L3} + Y$$

- ν 's are $T_{L3} = \frac{1}{2}$ components of L_L
- ν 's have no strong or EM interactions
- No ν_R (\equiv singlets of gauge group)

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ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- 3 Generations of Fermions:

$(1, 2, -\frac{1}{2})$	$(3, 2, \frac{1}{6})$	$(1, 1, -1)$	$(3, 1, \frac{2}{3})$	$(3, 1, -\frac{1}{3})$
L_L	Q_L^i	E_R	U_R^i	D_R^i
$\begin{pmatrix} \nu_e \\ e \\ \nu_\mu \\ \mu \\ \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \\ c^i \\ s^i \\ t^i \\ b^i \end{pmatrix}_L$	e_R	u_R^i	d_R^i
		μ_R	c_R^i	s_R^i
		τ_R	t_R^i	b_R^i

$$Q_{EM} = T_{L3} + Y$$

- ν 's are $T_{L3} = \frac{1}{2}$ components of L_L
- ν 's have no strong or EM interactions
- No ν_R (\equiv singlets of gauge group)

However what Goldhaber measured was the helicity not the chirality of ν

- Spin-0 particle ϕ : $(1, 2, \frac{1}{2})$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{SSB} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

- We define the **chiral** projections $\mathcal{P}_{R,L} = \frac{1 \pm \gamma_5}{2} \Rightarrow \psi_L = \frac{1 - \gamma_5}{2} \psi \quad \psi_R = \frac{1 + \gamma_5}{2} \psi$

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- The Hamiltonian for a massive fermion ψ is $H = \bar{\psi}(x) \left(-i \sum_j \gamma^j \partial_j + m \right) \psi(x)$
- 4 states with $(E = \sqrt{|\vec{p}|^2 + m^2}, \vec{p})$

$$(\gamma^\mu p_\mu - m) u_s(\vec{p}) = 0 \quad (\gamma^\mu p_\mu + m) v_s(\vec{p}) = 0 \quad s = 1, 2$$

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$$\mathcal{P}_\pm = \frac{1}{2} \left(1 \pm 2 \vec{J} \frac{\vec{P}}{|\vec{P}|} \right) = \frac{1}{2} \left(1 \pm \vec{\Sigma} \frac{\vec{P}}{|\vec{P}|} \right)$$

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- For **massless** fermions using the Dirac equation:

$$\vec{\Sigma} \cdot \vec{P} \psi = -\gamma^0 \gamma^5 \vec{\gamma} \cdot \vec{p} \psi = -\gamma^0 \gamma^5 \gamma^0 E \psi = \gamma^5 E \psi \Rightarrow \text{For } m = 0 \quad \mathcal{P}_\pm = \mathcal{P}_{R,L}$$

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Only for **massless** fermions **Helicity** and **chirality** states are the same.

SM Fermion Lagrangian

$$\begin{aligned}
\mathcal{L} = & \sum_{k=1}^3 \sum_{i,j=1}^3 \overline{Q_{L,k}^i} \gamma^\mu \left(i\partial_\mu - g_s \frac{\lambda_{a,ij}}{2} G_\mu^a - g \frac{\tau_a}{2} \delta_{ij} W_\mu^a - g' \frac{1}{6} \delta_{ij} B_\mu \right) Q_{L,k}^j \\
& + \sum_{k=1}^3 \sum_{i,j=1}^3 \overline{U_{R,k}^i} \gamma^\mu \left(i\partial_\mu - g_s \frac{\lambda_{a,ij}}{2} G_\mu^a - g' \frac{2}{3} \delta_{ij} B_\mu \right) U_{R,k}^j \\
& + \sum_{k=1}^3 \sum_{i,j=1}^3 \overline{D_{R,k}^i} \gamma^\mu \left(i\partial_\mu - g_s \frac{\lambda_{a,ij}}{2} G_\mu^a + g' \frac{1}{3} \delta_{ij} B_\mu \right) D_{R,k}^j \\
& + \sum_{k=1}^3 \overline{L_{L,k}} \gamma^\mu \left(i\partial_\mu - g \frac{\tau_i}{2} W_\mu^i + g' \frac{1}{2} B_\mu \right) L_{L,k} + \overline{E_{R,k}} \gamma^\mu (i\partial_\mu + g' B_\mu) E_{R,k} \\
& - \sum_{k,k'=1}^3 \left[\sum_{i=1}^3 \left(\lambda_{kk'}^u \overline{Q_{L,k}^i} (i\tau_2) \phi^* U_{R,k'}^i + \lambda_{kk'}^d \overline{Q_{L,k}^i} \phi D_{R,k'}^i \right) + \lambda_{kk'}^l \overline{L_{L,k}} \phi E_{R,k'} + h.c. \right]
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- Invariant under global rotations

$$Q_{L,k}^i \rightarrow e^{i\alpha_B/3} Q_{L,k}^i \quad U_{R,k}^i \rightarrow e^{i\alpha_B/3} U_{R,k}^i \quad D_{R,k}^i \rightarrow e^{i\alpha_B/3} D_{R,k}^i \quad L_{L,k} \rightarrow e^{i\alpha_{L_k}/3} L_{L,k} \quad E_{R,k} \rightarrow e^{i\alpha_{L_k}/3} E_{R,k}$$

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\Rightarrow **Accidental** (\equiv *not imposed*) global **symmetry**: $U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$

\Rightarrow **Each lepton flavour**, L_i , is conserved

\Rightarrow **Total lepton number** $L = L_e + L_\mu + L_\tau$ is conserved

- A **fermion mass** can be seen as at a **Left-Right** transition

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- There are no right-handed neutrinos
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In SM ν 's are *Strictly* Massless & Lepton Flavours are *Strictly* Conserved

- We have observed with high (or good) precision:
 - * Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**, MINOS, ICECUBE)
 - * Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (**K2K**, **T2K**, **MINOS**, **NO ν A**)
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All this implies that L_α are violated

and There is Physics Beyond SM

Dirac versus Majorana Neutrinos

- In the SM neutral bosons can be of two type:
 - Their own antiparticle such as γ , π^0 ...
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- In the SM ν are the only *neutral fermions*

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⇒ And the charged conjugate neutrino field \equiv the antineutrino field

$$\nu^C = C \nu C^{-1} = \sum_{s, \vec{p}} \left[b_s(\vec{p}) u_s(\vec{p}) e^{-i p x} + a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{i p x} \right] = -C \bar{\nu}^T$$

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\Rightarrow 4 chiral fields

$$\nu_L, \nu_R, (\nu_L)^C, (\nu_R)^C \quad \text{with} \quad \nu = \nu_L + \nu_R \quad \text{and} \quad \nu^C = (\nu_L)^C + (\nu_R)^C$$

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The difference arises when including *a neutrino mass*

Adding ν Mass: Dirac Mass

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\Rightarrow **Total Lepton number** is **conserved** by construction (not accidentally):

$$\left. \begin{array}{l} U(1)_L : \nu \rightarrow e^{i\alpha} \nu \quad \text{and} \quad \overline{\nu} \rightarrow e^{-i\alpha} \overline{\nu} \\ U(1)_L : \nu^c \rightarrow e^{-i\alpha} \nu^c \quad \text{and} \quad \overline{\nu^c} \rightarrow e^{i\alpha} \overline{\nu^c} \end{array} \right\} \Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})} \rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})}$$

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\Rightarrow **Breaks Total Lepton Number** $\Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Maj})}$ **not generated at any order in the SM**

ν Mass \Rightarrow Lepton Mixing

- CC and mass for 3 charged leptons ℓ_i and N neutrinos in weak basis $\nu^W \equiv \begin{pmatrix} \nu_{L,e} \\ \nu_{L,\mu} \\ \nu_{L,\tau} \\ (\nu_{R,1})^C \\ \vdots \\ \vdots \end{pmatrix}$
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- $U_{\text{LEP}} \equiv 3 \times N$ matrix $U_{\text{LEP}} U_{\text{LEP}}^\dagger = I_{3 \times 3}$ but in general $U_{\text{LEP}}^\dagger U_{\text{LEP}} \neq I_{N \times N}$

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- \Rightarrow For $N = 3 + s$: $U_{\text{LEP}} \supset 3(1+s)$ angles + $(2s+1)$ Dirac phases + $(s+2)$ Maj phases

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Effects of ν Mass

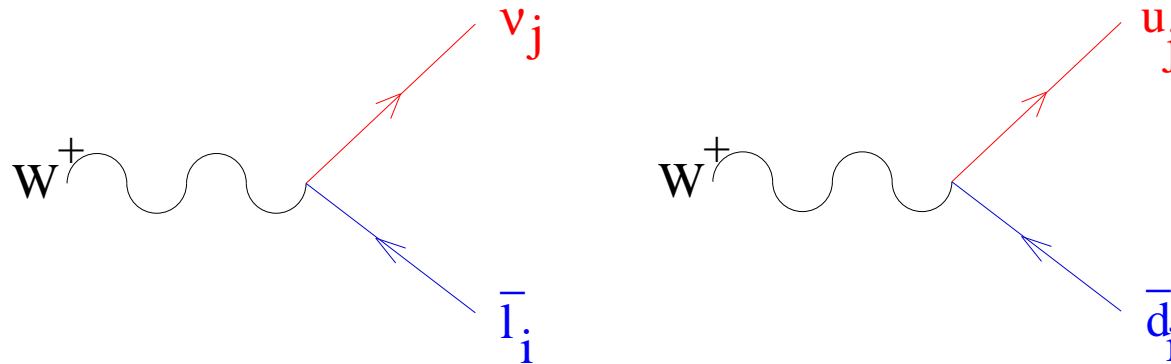
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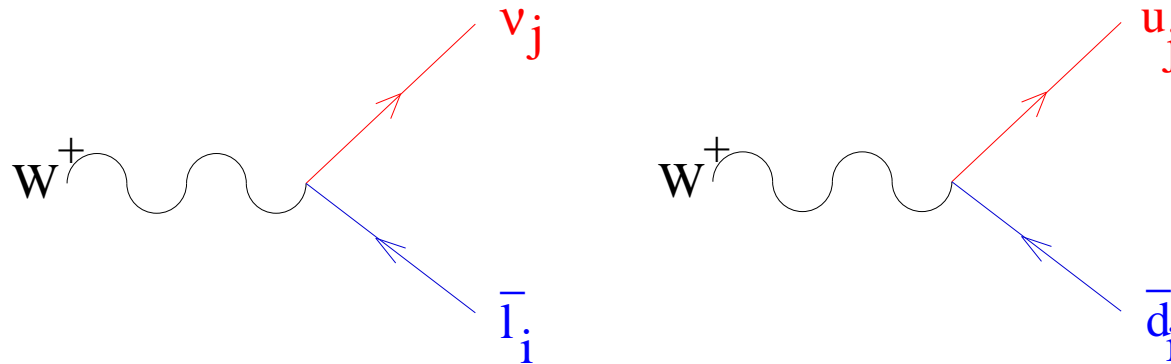
$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{LEP}^{ij} \bar{\ell}^i \gamma^\mu L \nu^j + U_{CKM}^{ij} \bar{U}^i \gamma^\mu L D^j \right) + h.c.$$



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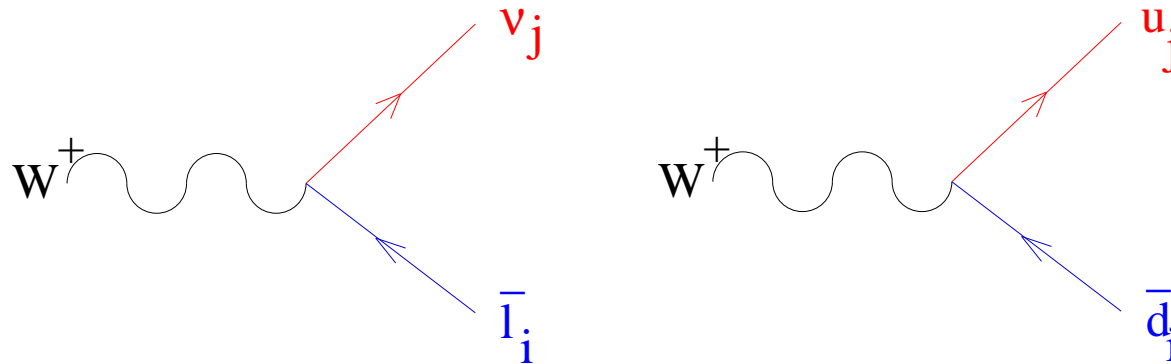


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- Total lepton number $U(1)_L = U(1)_{L_e + L_\mu + L_\tau}$ can be or cannot be still a symmetry depending on whether neutrinos are Dirac or Majorana

Neutrino Mass Scale: Tritium β Decay

- Fermi proposed a kinematic search of ν_e mass from beta spectra in ${}^3\text{H}$ beta decay



- For “allowed” nuclear transitions, the electron spectrum is given by phase space alone

$$K(T) \equiv \sqrt{\frac{dN}{dT} \frac{1}{C_p E F(E)}} \propto \sqrt{(Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}}$$

$T = E_e - m_e$, Q = maximum kinetic energy, (for ${}^3\text{H}$ beta decay $Q = 18.6$ KeV)

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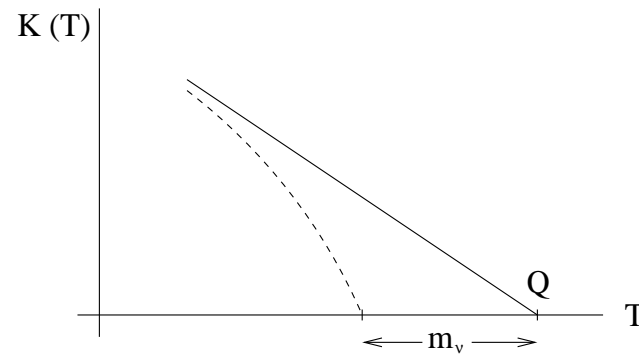
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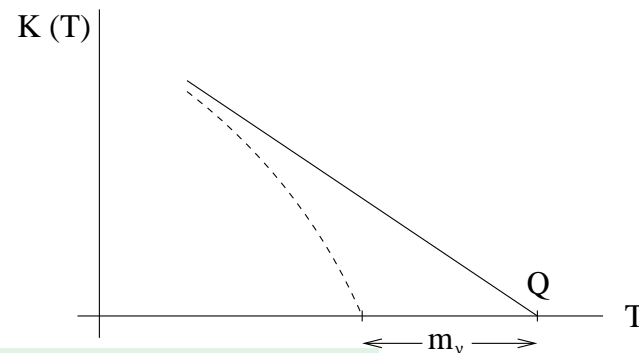
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– At present only a bound: $m_{\nu_e}^{\text{eff}} < 0.8$ eV (at 90 % CL) (KATRIN)

– KATRIN operating can improve present sensitivity to $m_{\nu_e}^{\text{eff}} \sim 0.3$ eV

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- From the two body decay at rest

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- The τ is much heavier $m_\tau = 1.776 \text{ GeV}$
 \Rightarrow Large phase space \Rightarrow difficult precision for m_ν

- The best precision is obtained from hadronic final states

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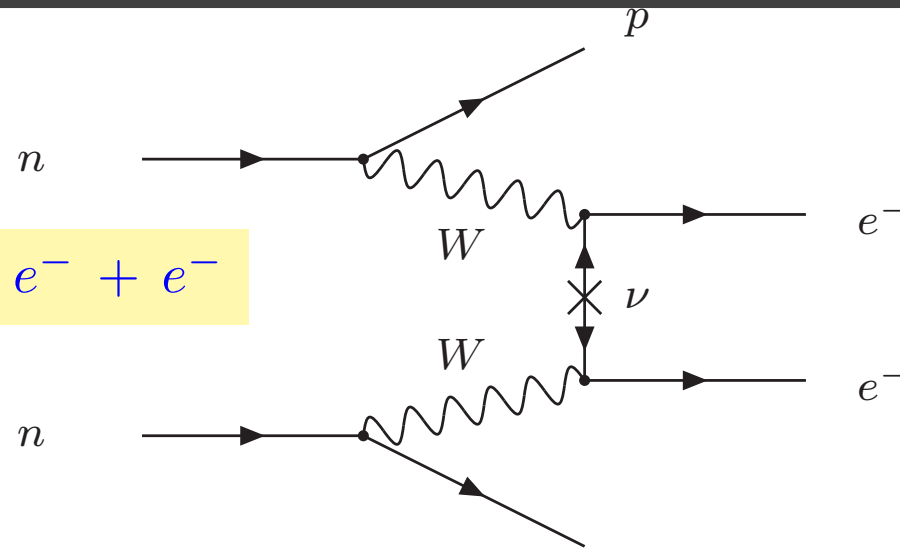
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\Rightarrow If mixing angles U_{ej} are not negligible

Best kinematic limit on Neutrino Mass Scale comes from Tritium Beta Decay

Dirac or Majorana? ν -less Double- β Decay

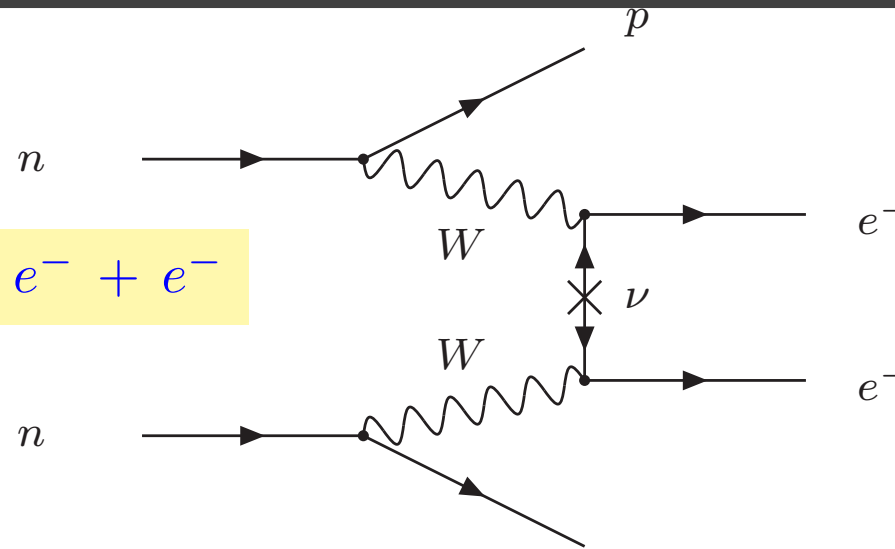
$$(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$$



- Amplitude includes
$$[\bar{e}\gamma^\mu L\nu_e][\bar{e}\gamma^\mu L\nu_e] = \sum_{ij} U_{ei}U_{ej}^p [\bar{e}\gamma^\mu \nu_i][\bar{e}\gamma^\mu \nu_j]$$

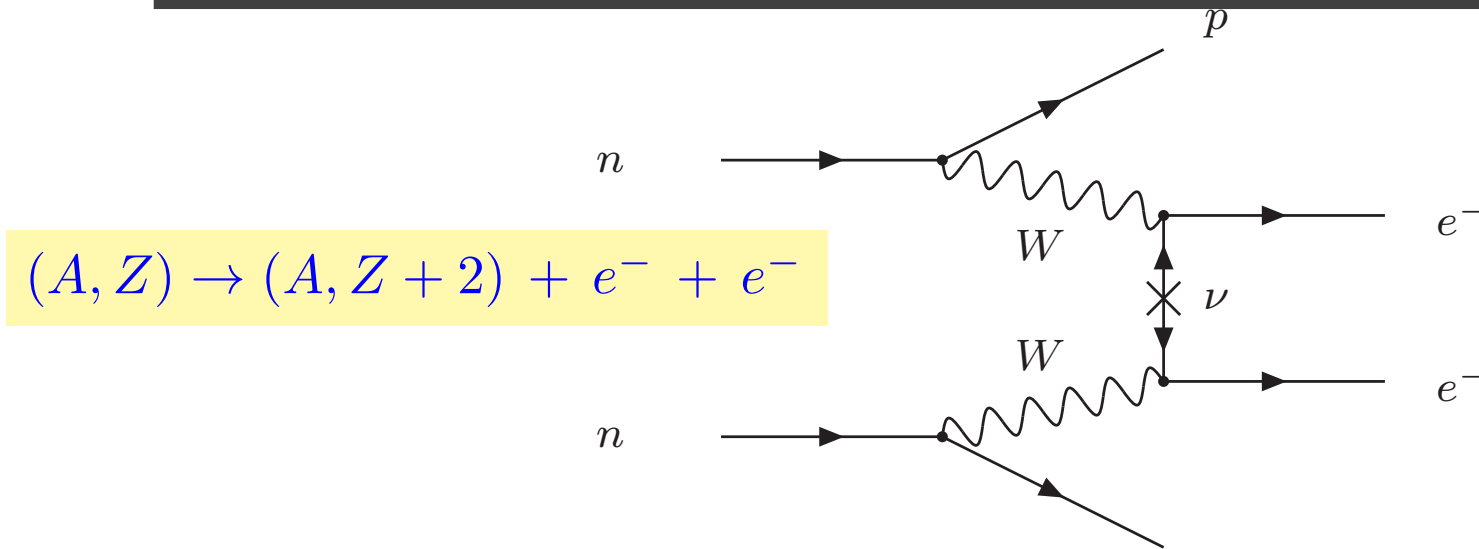
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- If Majorana m_ν only source of L -violation

\Rightarrow Amplitude of ν -less- $\beta\beta$ decay is proportional to $\langle m_{\beta\beta} \rangle = \sum_j U_{ej}^2 m_j$

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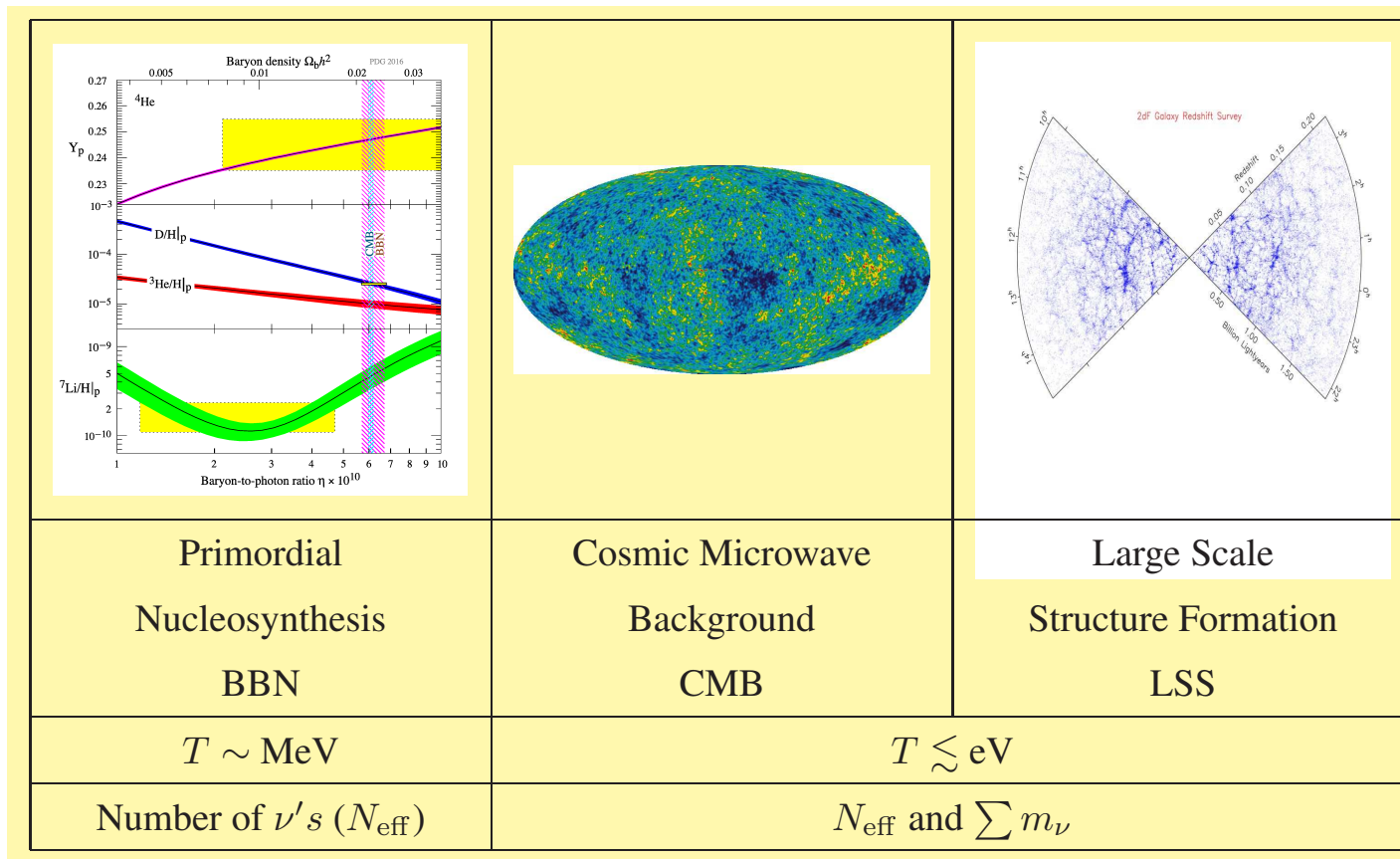
Question: How to search for $m_\nu \ll \mathcal{O}(eV)$?

Answer: **Neutrino Oscillations... Tomorrow**

Light massive ν in Cosmology

Relic ν 's: Effects in several cosmological observations at several epochs

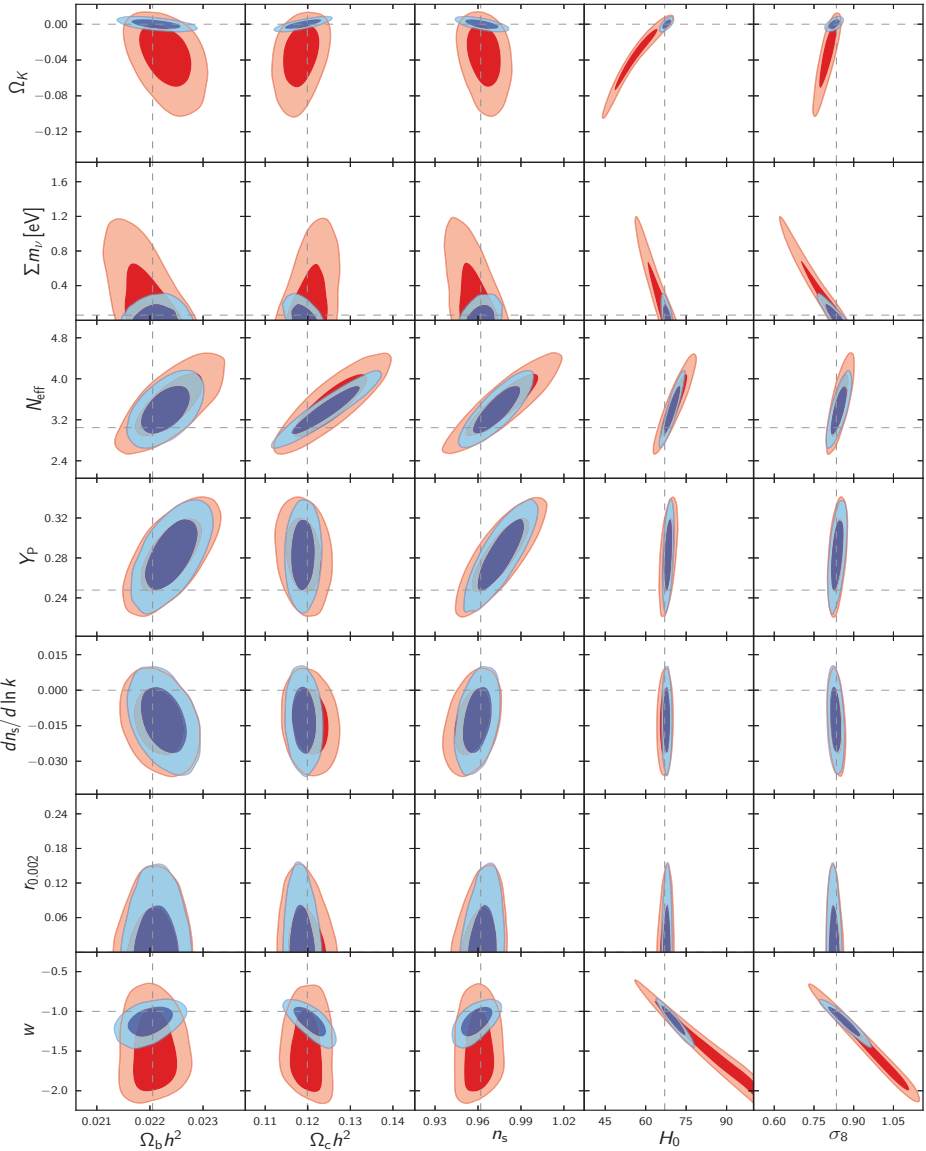
Mainly via two effects: $\rho_r = \left[1 + \frac{7}{8} \times \left(\frac{4}{11} \right)^{\frac{4}{3}} N_{\text{eff}} \right] \rho_\gamma$ and $\sum_i m_{\nu_i}$



BUT: Observables also depend on all other cosmo parameters (and assumptions)

Example: Cosmological Analysis by Planck

arXiv:1502.01589

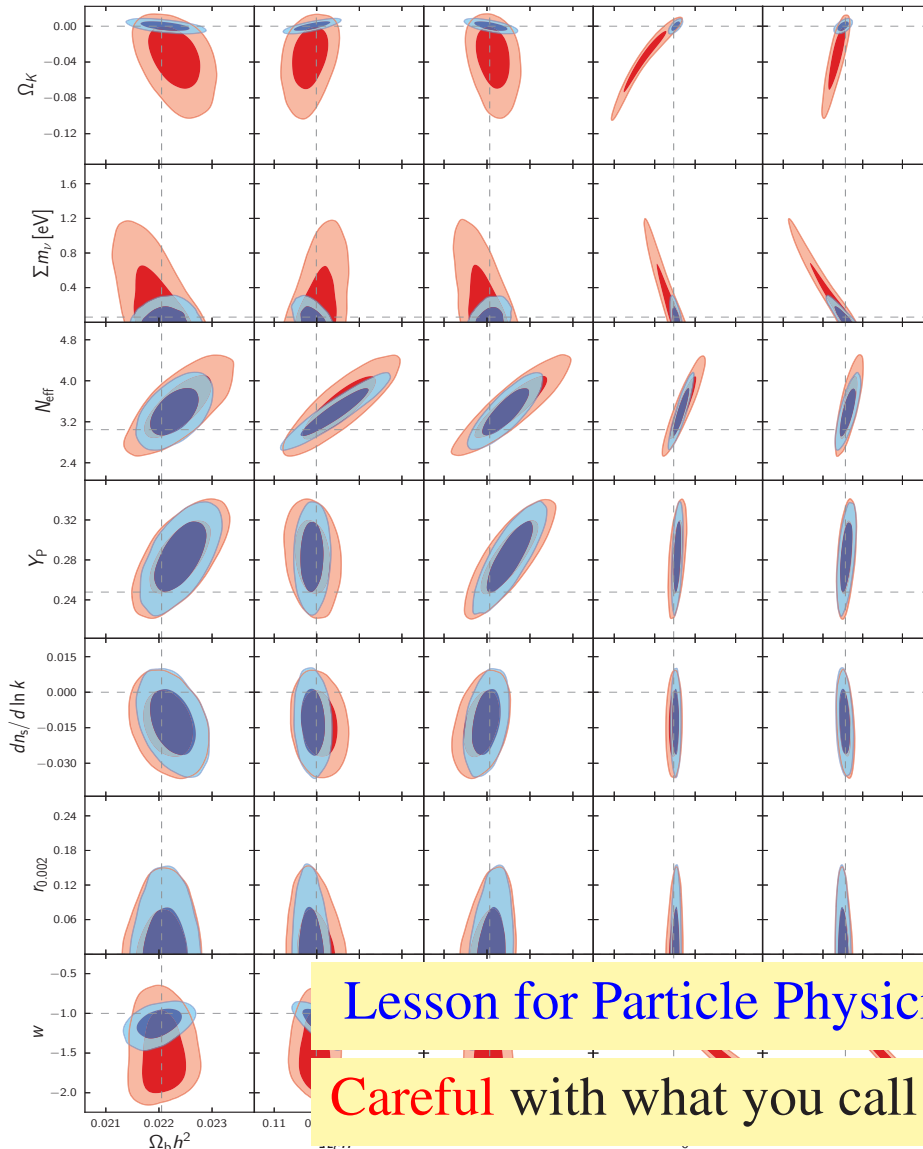


Range of Bounds in Λ CDM

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Lesson for Particle Physicists:

Careful with what you call *Cosmological bound on m_ν*