NEUTRINOS

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Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Effects of ν Mass. Neutrino Oscillations in Vacuum and Matter

III. The Data and The Emerging Picture. Some Implications

Plan of Lecture I

Historic Introduction

Neutrinos in the SM

Neutrino Properties:
Helicity versus Chirality, Majorana versus Dirac

Neutrino Mass Terms Beyond the SM
Dirac vs Majorana, Lepton Mixing

Direct Probes of Neutrino Mass Scale

Discovery of ν's

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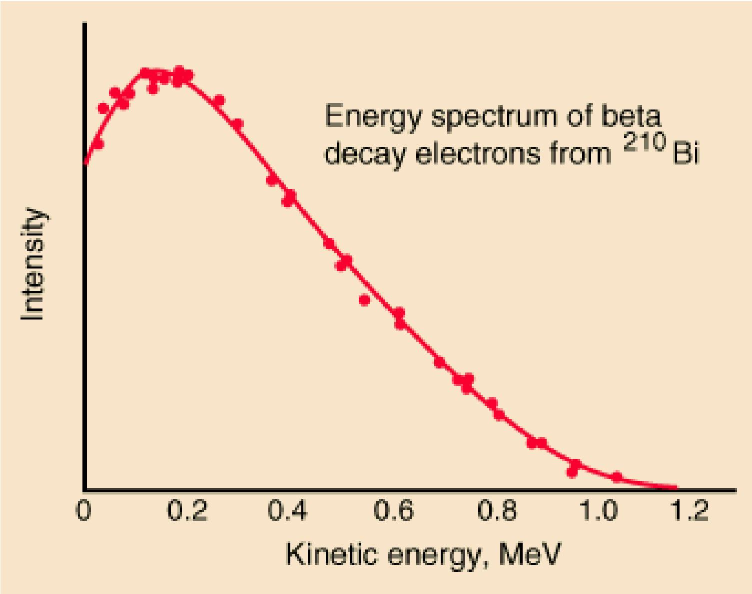

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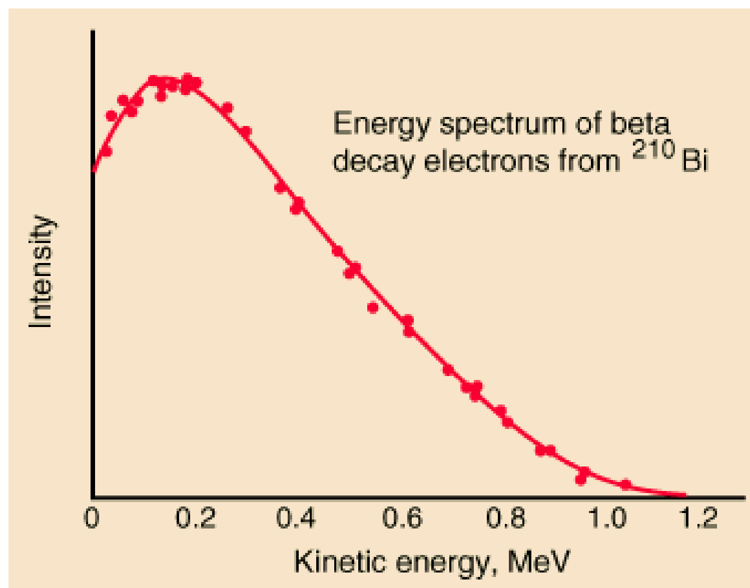

Do we throw away the energy conservation?

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 Tubingen. 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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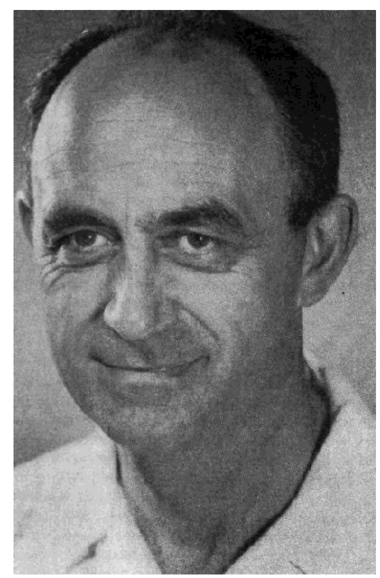

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• In order to distinguish them from heavy neutrons, Fermi proposed to name them neutrinos.

First Detection of ν's

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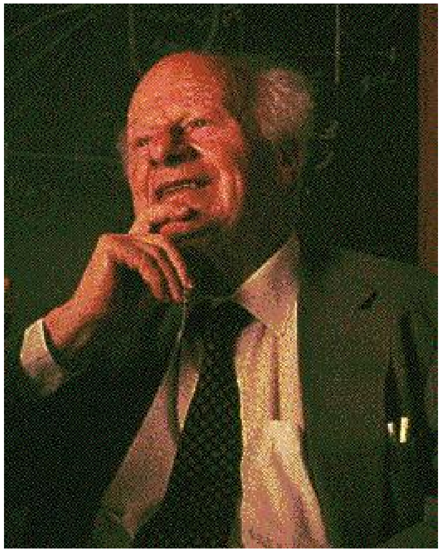

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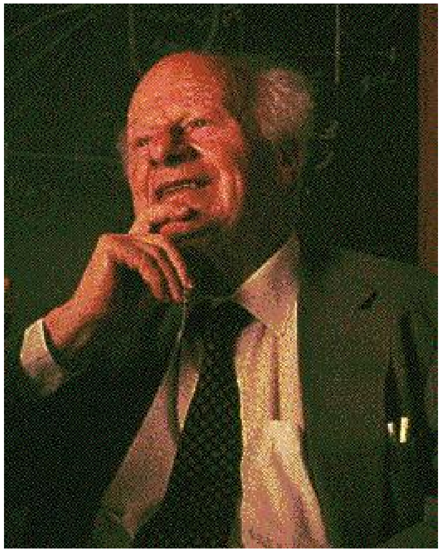

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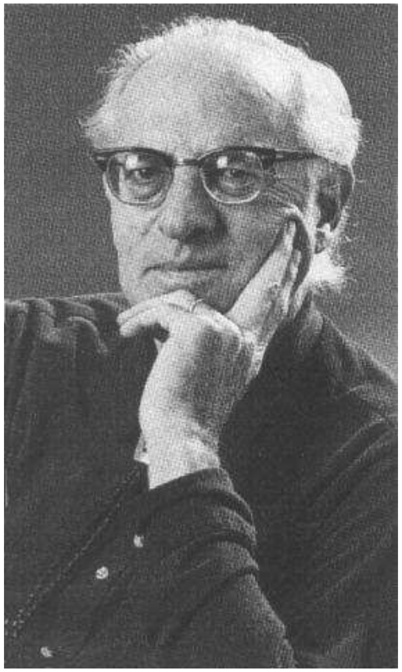

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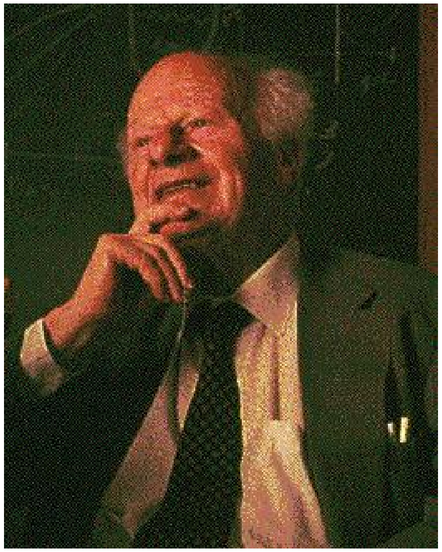

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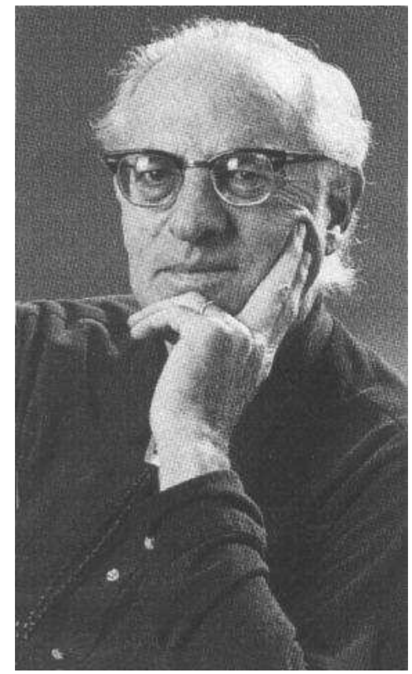

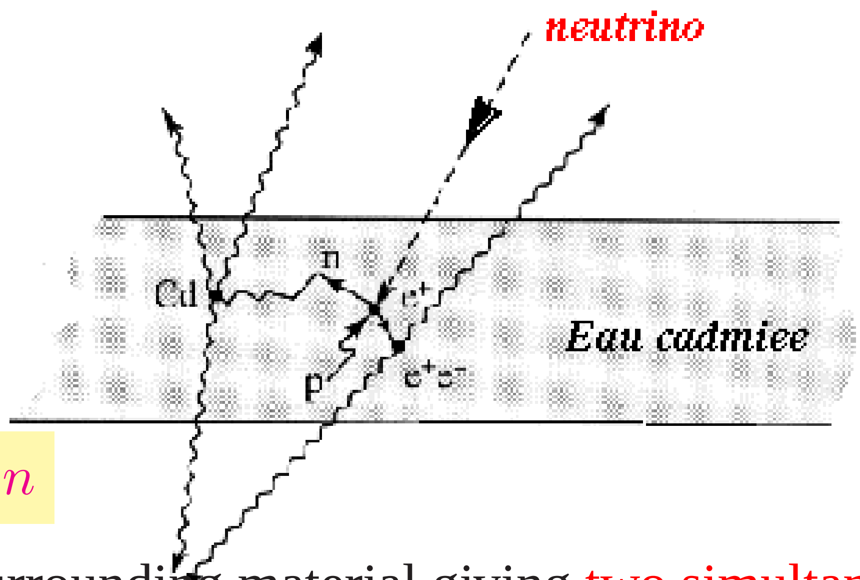

400 litters of water and cadmium chloride.

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

e^+ annihilates e^- of the surrounding material giving two simultaneous γ's.

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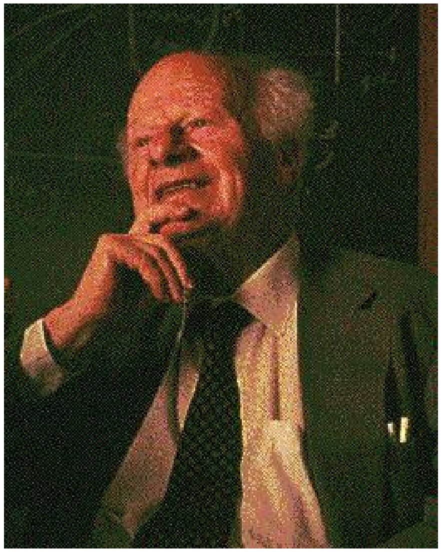

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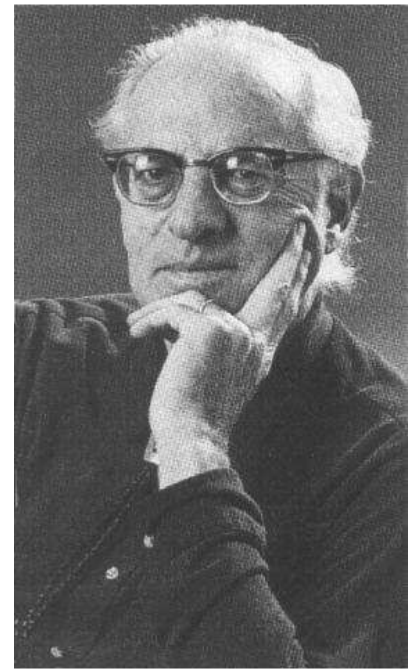

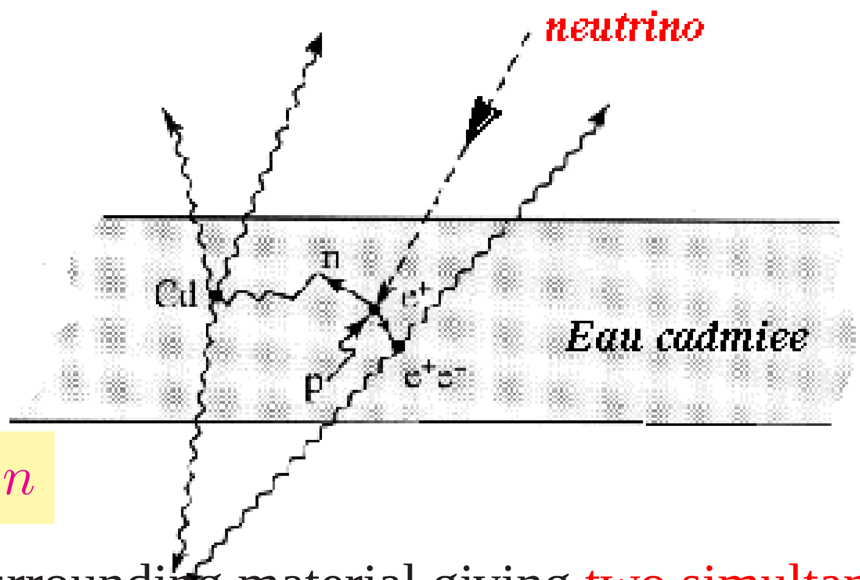

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The neutrino was there. Its tag was clearly visible

Neutrino Helicity

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

- Using the electron capture reaction

$$e^- + {}^{152}Eu \to \nu + {}^{152}Sm^* \to {}^{152}Sm + \gamma$$

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- Goldhaber et al found γ had negative helicity $\Rightarrow$ ν has helicity -1

The Other Flavours

ν coming out of a nuclear reactor is $\overline{\nu}_e$ 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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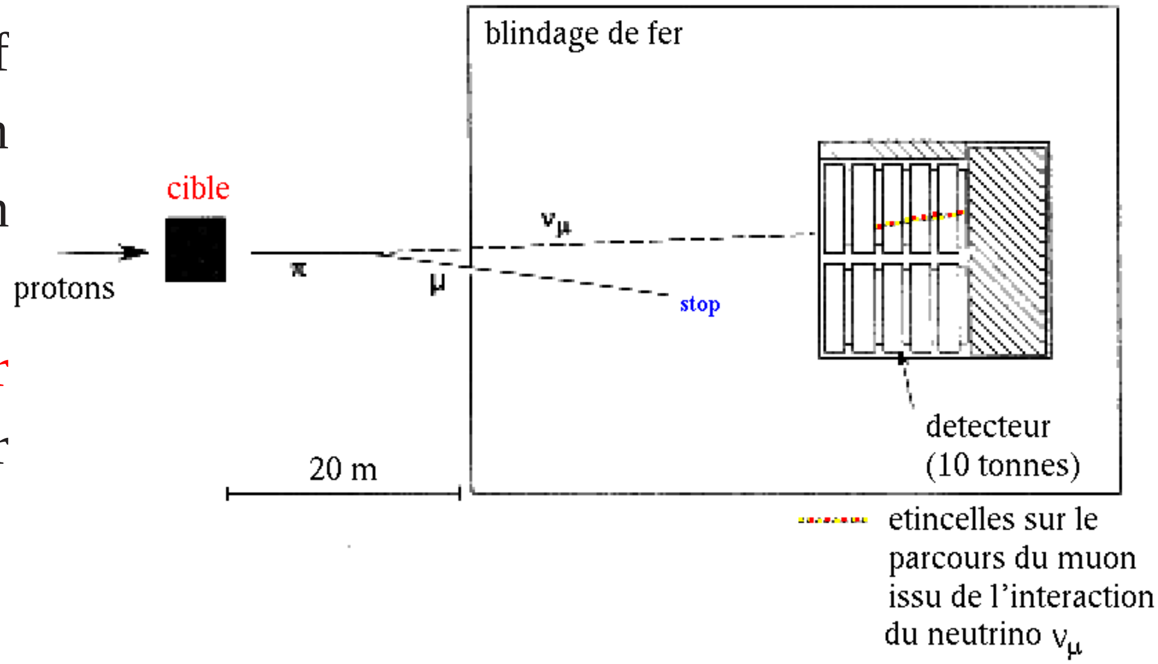

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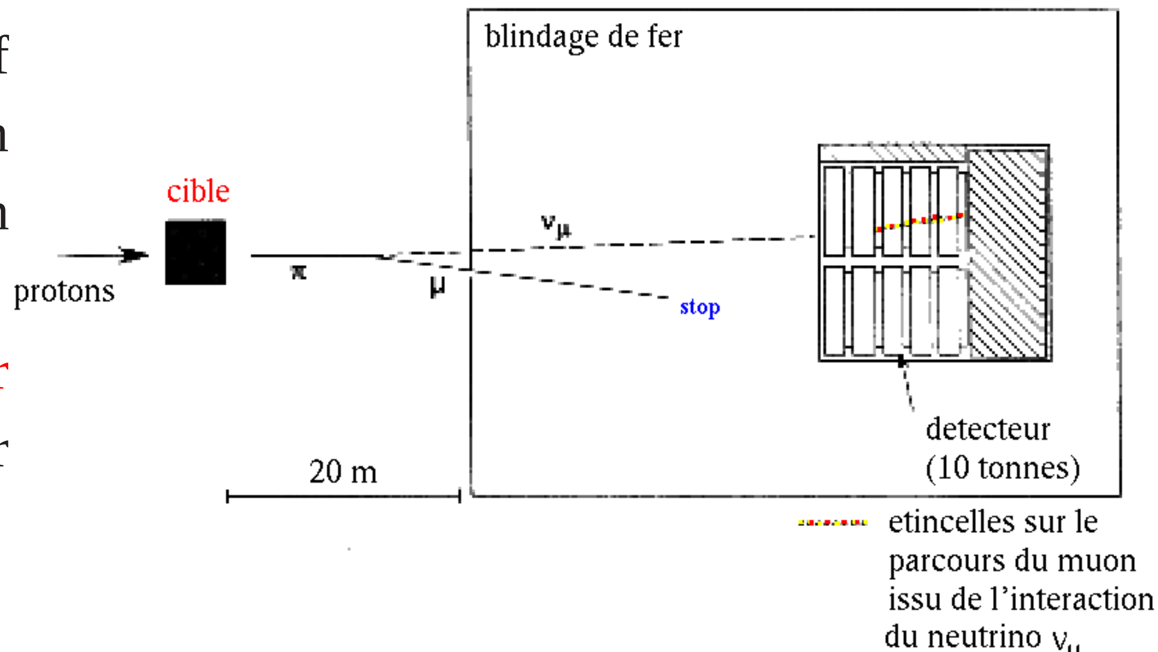

They observe 40 ν interactions: in 6 an e^- comes out and in 34 a μ^- comes out.

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

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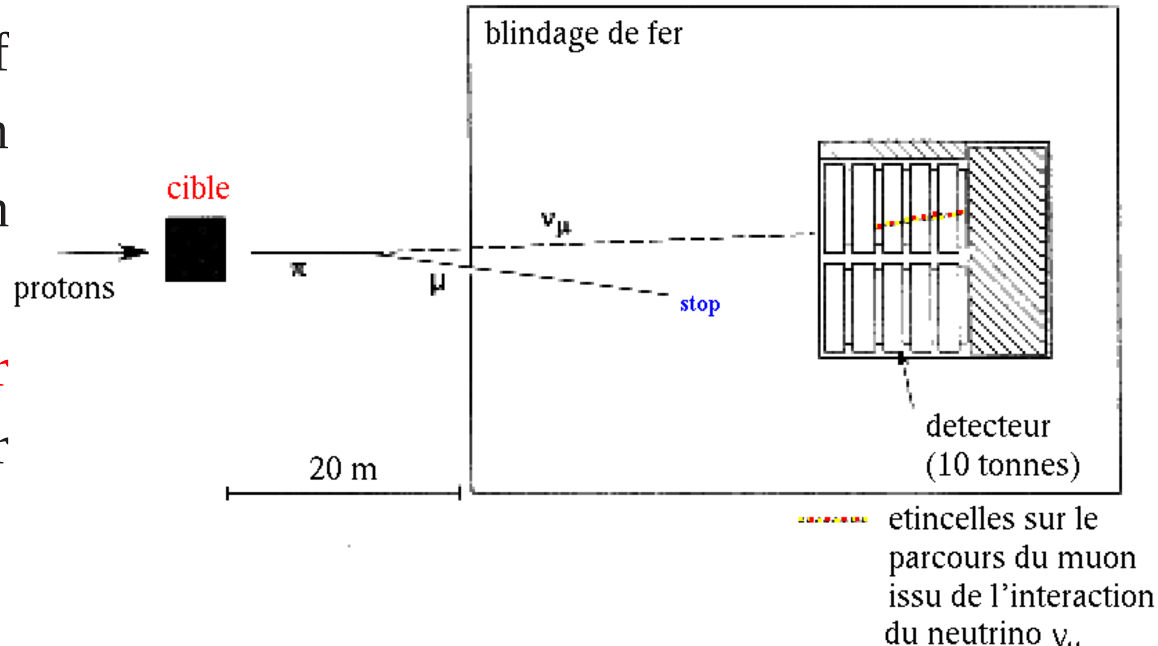

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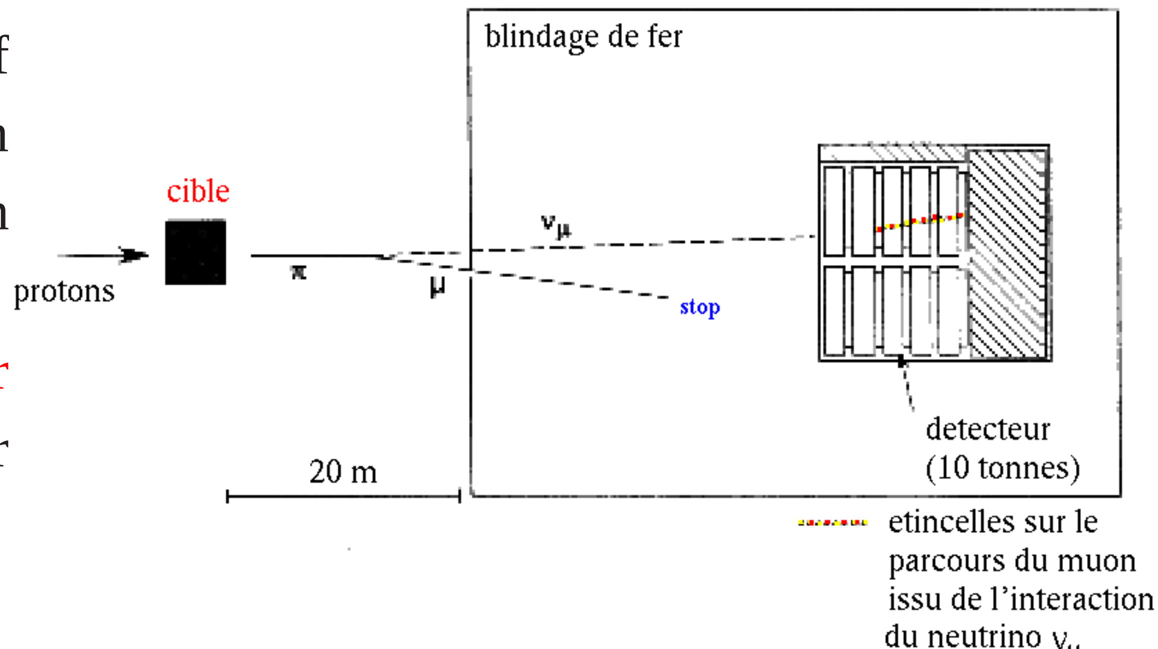

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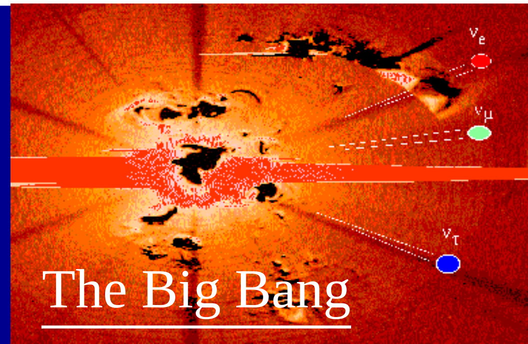
In 1977 Martin Perl discovers the particle tau $\equiv$ the third lepton family.

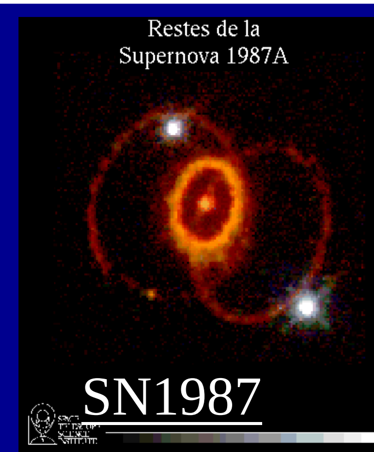
The ν_τ was observed by DONUT experiment at FNAL in 1998 (*officially* in Dec. 2000).

Sources of ν's



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

E_ν =0.0004 eV



$E_\nu \sim$ MeV

The Sun

ν_e

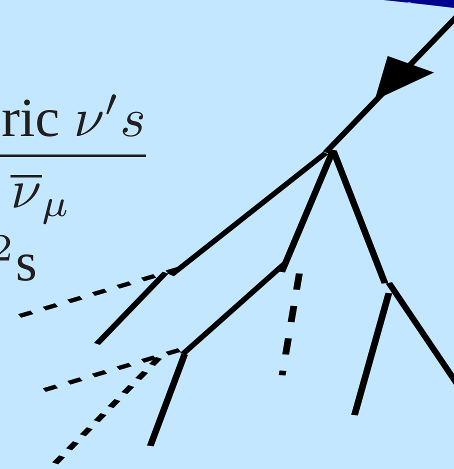
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\mathrm{cm}^2\mathrm{s}$

$E_\nu \sim$ 0.1–20 MeV

Atmospheric $\nu' s$

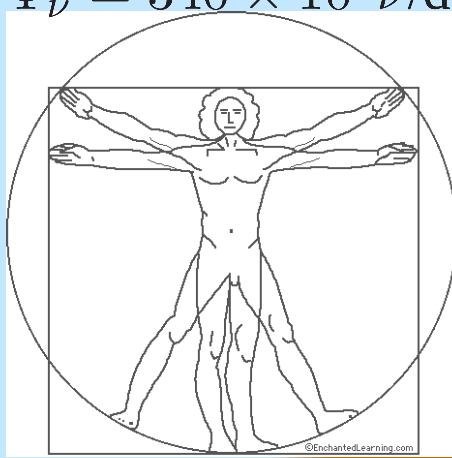
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

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



Human Body

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



Nuclear Reactors

$E_\nu \sim$ few MeV

$\overline{\nu}_e$

Earth's radioactivity

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

Accelerators

$E_\nu \simeq$ 0.3–30 GeV

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- 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^i_L	E_R	U^i_R	D^i_R
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	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

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

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

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

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

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

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

SM Fermion Lagrangian

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\begin{aligned}
\mathcal{L} \;=\; & \sum_{k=1}^{3}\sum_{i,j=1}^{3} \overline{Q^i_{L,k}}\gamma^\mu \left(i\partial_\mu - g_s \frac{\lambda_{a,ij}}{2} G^a_\mu - g\frac{\tau_a}{2}\delta_{ij} W^a_\mu - g'\frac{Y}{2}\delta_{ij} B_\mu\right) Q^j_{L,k} \\
& \sum_{k=1}^{3}\sum_{i,j=1}^{3} + \overline{U^i_{R,k}}\gamma^\mu \left(i\partial_\mu - g_s \frac{\lambda_{a,ij}}{2} G^a_\mu - g'\frac{Y}{2}\delta_{ij} B_\mu\right) U^j_{R,k} \\
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& \sum_{k=1}^{3} + \overline{L_{L,k}}\gamma^\mu \left(i\partial_\mu - g\frac{\tau_i}{2} W^i_\mu - g'\frac{Y}{2} B_\mu\right) L_{L,k} + \overline{E_{R,k}}\gamma^\mu \left(i\partial_\mu - g'\frac{Y}{2} B_\mu\right) E_{R,k} \\
& - \sum_{k,k'=1}^{3} \left(\lambda^u_{kk'} \overline{Q}_{L,k}(i\tau_2)\phi U_{R,k'} + \lambda^d_{kk'}\overline{Q}_{L,k}\phi D_{R,k'} + \lambda^l_{kk'}\overline{L}_{L,k}\phi E_{R,k'} + h.c.\right)
\end{aligned}
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- Invariant under global rotations

$$
q_i \to e^{i\alpha_B/3} q_i \qquad l_i \to e^{i\alpha_{L_i}/3} l_i \qquad \nu_i \to e^{i\alpha_{L_i}/3} \nu_i
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SM Fermion Lagrangian

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$$\sum_{k=1}^{3}\sum_{i,j=1}^{3} + \overline{U^i_{R,k}}\gamma^\mu \left(i\partial_\mu - g_s\frac{\lambda_{a,ij}}{2}G^a_\mu - g'\frac{Y}{2}\delta_{ij}B_\mu\right) U^j_{R,k}$$

$$\sum_{k=1}^{3}\sum_{i,j=1}^{3} + \overline{D^i_{R,k}}\gamma^\mu \left(i\partial_\mu - g_s\frac{\lambda_{a,ij}}{2}G^a_\mu - g'\frac{Y}{2}\delta_{ij}B_\mu\right) D^j_{R,k}$$

$$\sum_{k=1}^{3} + \overline{L_{L,k}}\gamma^\mu \left(i\partial_\mu - g\frac{\tau_i}{2}W^i_\mu - g'\frac{Y}{2}B_\mu\right) L_{L,k} + \overline{E_{R,k}}\gamma^\mu \left(i\partial_\mu - g'\frac{Y}{2}B_\mu\right) E_{R,k}$$

$$-\sum_{k,k'=1}^{3}\left(\lambda^u_{kk'}\overline{Q}_{L,k}(i\tau_2)\phi U_{R,k'} + \lambda^d_{kk'}\overline{Q}_{L,k}\phi D_{R,k'} + \lambda^l_{kk'}\overline{L}_{L,k}\phi E_{R,k'} + h.c.\right)$$

- Invariant under global rotations

$$q_i \to e^{i\alpha_B/3}q_i \qquad l_i \to e^{i\alpha_{L_i}/3}l_i \qquad \nu_i \to e^{i\alpha_{L_i}/3}\nu_i$$

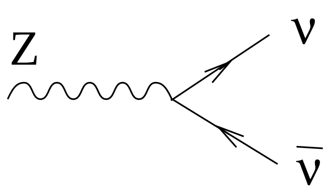
⇒ *Accidental (≡ not imposed)* global symmetry: $B \times L_e \times L_\mu \times L_\tau$

⇒ Each lepton flavour, L_i, is conserved

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

Number of Neutrinos

• The counting of light active left-handed neutrinos is based on the family structure of the SM assuming a universal diagonal NC coupling:



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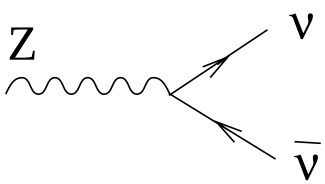

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$$\begin{aligned} N_\nu &= \frac{\Gamma_{\rm inv}}{\Gamma_\nu} \equiv \frac{1}{\Gamma_\nu}(\Gamma_Z - \Gamma_h - 3\Gamma_\ell) \\ &= \frac{\Gamma_\ell}{\Gamma_\nu}\left[\sqrt{\frac{12\pi R_{h\ell}}{\sigma_h^0 m_Z^2}} - R_{h\ell} - 3\right] \end{aligned}$$

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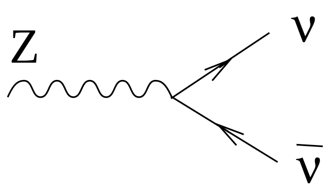

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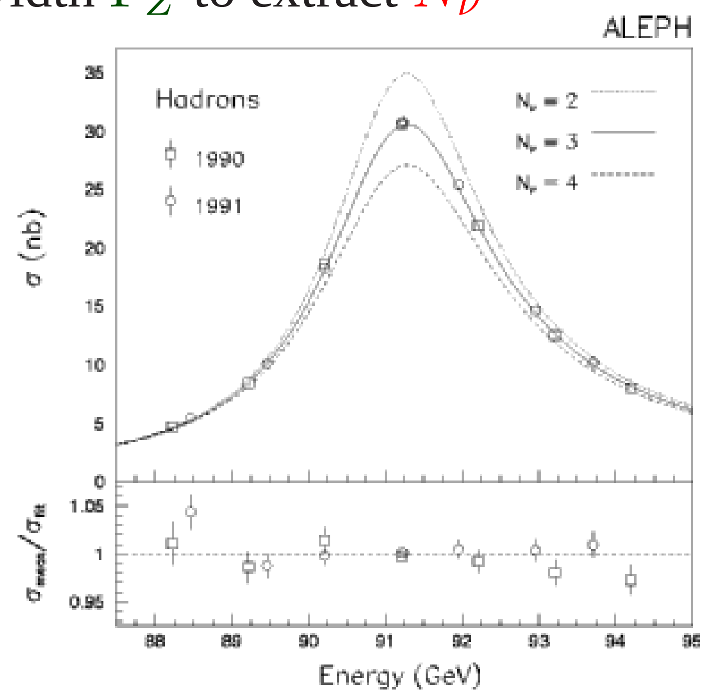

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Leads $N_\nu = 2.9840 \pm 0.0082$

Fermion Masses in SM

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$$m_f \overline{f_L} f_R + h.c. \quad \text{(this is not } SU(2)_L \text{ gauge invariant)}$$

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In SM Neutrinos are *Strictly* Massless

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

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- For massive spinors at high energies ($E \gg m$)

$$u_{\pm\frac{1}{2}}(p) \equiv P_\pm u(p) \to P_{R,L}u(p) \equiv u_{R,L}(p)$$

$$v_{\pm\frac{1}{2}}(p) \equiv P_\mp v(p) \to P_{L,R}v(p) \equiv v_{L,R}(p)$$

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- In the SM neutral bosons can be of two type:
  - Their own antiparticle such as γ, π^0 ...
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$$\nu^C \equiv \mathcal{C}\, \nu\, \mathcal{C}^{-1} = \sum_{s,\vec{p}} \left[b_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right] = -\, C\, \overline{\nu}^T = -i\gamma^2\, \nu^*$$

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$\Rightarrow$ These two fields can rewritten in terms of 4 chiral fields

$\nu_L\ ,\ \nu_R\ ,\ (\nu_R)^C\ ,\ (\nu_L)^C$ with $\nu = \nu_L + \nu_R$ and $\nu^C = (\nu_L)^C + (\nu_R)^C$

(Notice that $(\nu_L)^C$ is the right-handed part of ν^C and $(\nu_R)^C$ is the left)

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$\Rightarrow$ So we can rewrite the field $\nu_M = \sum_{s,\vec{p}} \left[a_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right]$

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The difference arises from *the mass term*

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• in SM $B - L$ is non anomalous $\Rightarrow \mathcal{L}_{\rm mass}^{\rm (Maj)}$ not generated non-perturbatively in SM

Lepton Mixing

- Charged current and mass for 3 charged leptons ℓ_i and N neutrinos ν_j in weak basis

$$\mathcal{L}_{CC}+\mathcal{L}_M = -\frac{g}{\sqrt{2}}\sum_{i=1}^{3}\overline{\ell^W_{L,i}}\gamma^\mu\nu^W_i W^+_\mu - \sum_{i,j=1}^{3}\overline{\ell^W_{L,i}}M_{\ell\, ij}\ell^W_{R,j} - \frac{1}{2}\sum_{i,j=1}^{N}\overline{\nu^{c\,W}_i}M_{\nu\, ij}\nu^W_j + \text{h.c.}$$

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- For example for 3 Dirac ν's : 3 Mixing angles + 1 Dirac Phase

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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- P^{ν}_{kk} phase absorbed in ν_i (only possible if ν_i is Dirac)
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- For example for 3 Dirac ν's : 3 Mixing angles + 1 Dirac Phase

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- For 3 Majorana ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

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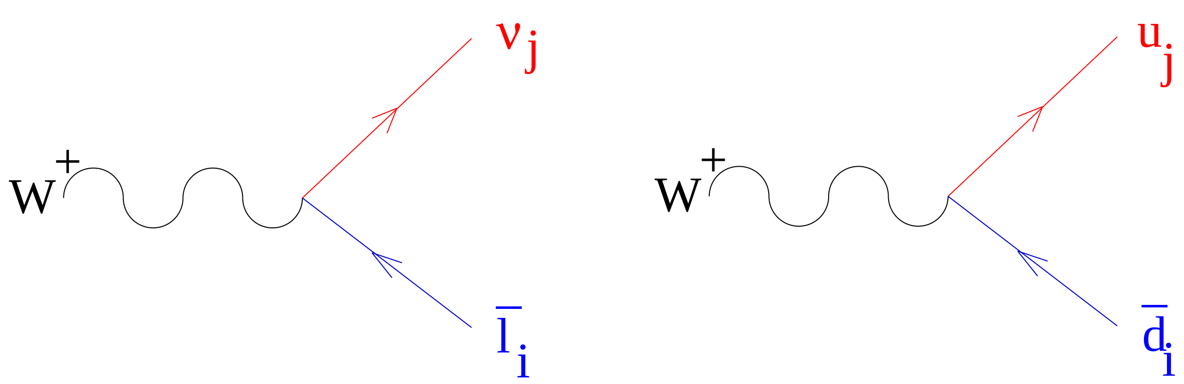

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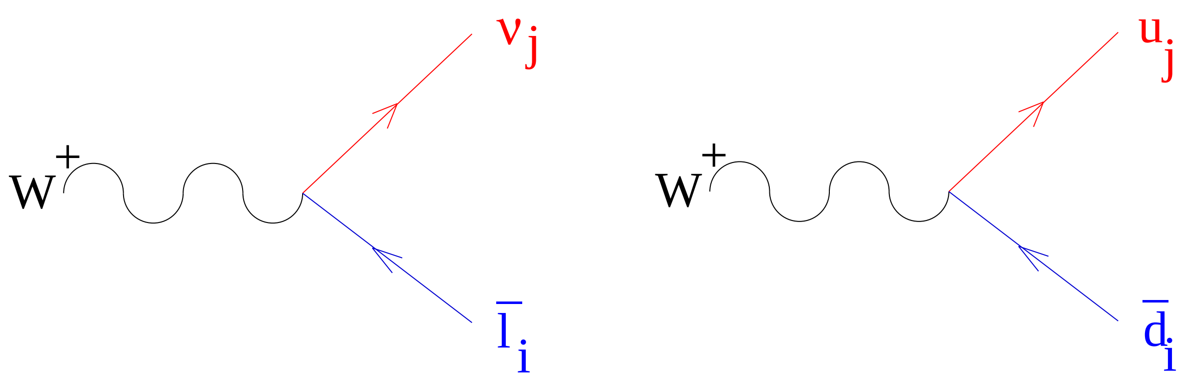

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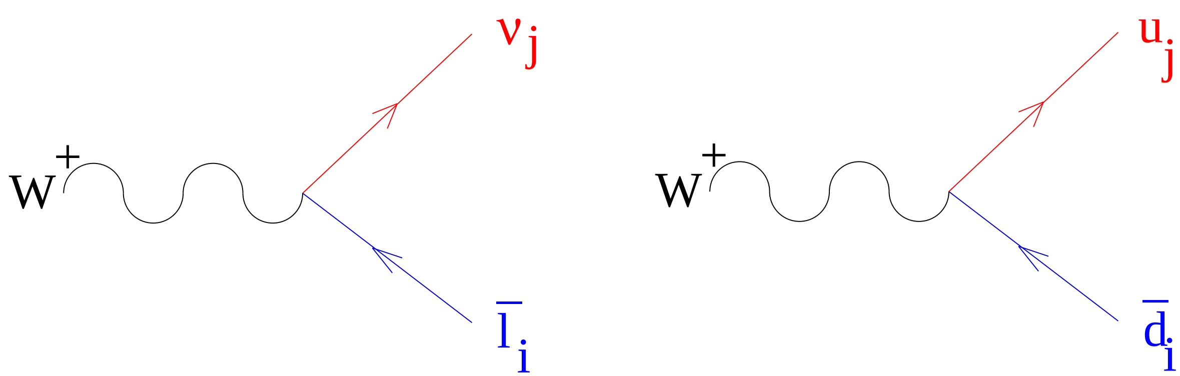

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- Total lepton number $U(1)_L = U(1)_{Le+L_\mu+L_\tau}$ can be or cannot be still a symmetry depending on whether neutrinos are Dirac or Majorana

Neutrino Mass Scale: Tritium β Decay

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$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{C p\, E\, F(E)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\beta^2}}$$

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

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$$m_\beta = 0 \;\Rightarrow\; T_{\max} = Q$$
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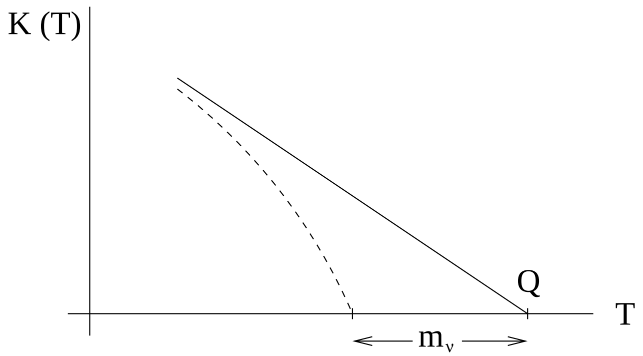

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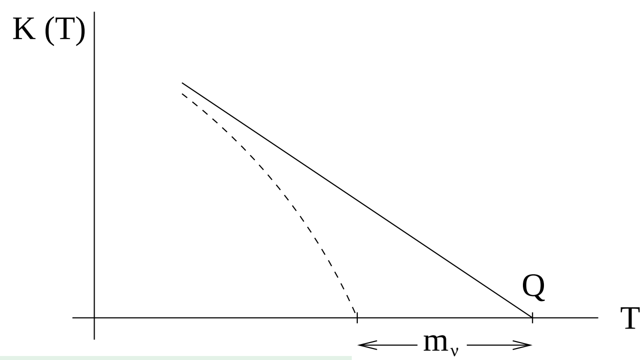

– At present only a bound: $m_\beta < 2.2$ eV (at 95 % CL) (Mainz & Troisk experiments)

– Katrin operating to improve present sensitivity to $m_\beta \sim 0.3\,$eV

Neutrino Mass Scale: Other Channels

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Muon neutrino mass

• From the two body decay at rest

$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu$$

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$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + \sqrt{p_\mu^2 + m_\nu^2}$$
$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 + m_\mu \sqrt{p^2 + m_\pi^2}$$

• Measurement of p_μ plus the precise knowledge of m_π and $m_\mu \Rightarrow m_\nu$

• The present experimental result bound:

$$\boxed{m_{\nu_\mu}^{eff} \equiv \sqrt{\sum m_j^2 |U_{\mu j}|^2} < 190 \text{ KeV}}$$

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Tau neutrino mass

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

• The best precision is obtained from hadronic final states

$$\tau \to n\pi + \nu_\tau \quad \text{with } n \geq 3$$

• Lep I experiments obtain:

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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

ν-less Double-β Decay

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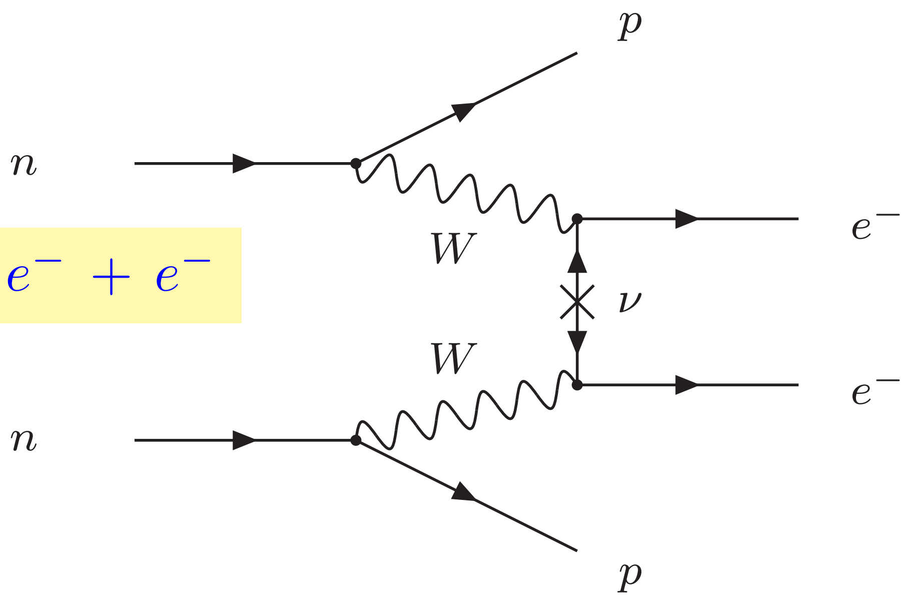
$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$



- Amplitude involves the product of two leptonic currents: $\left[\overline{e}\gamma^\mu L \nu\right]\left[\overline{e}\gamma^\mu L \nu\right]$

ν-less Double-β Decay

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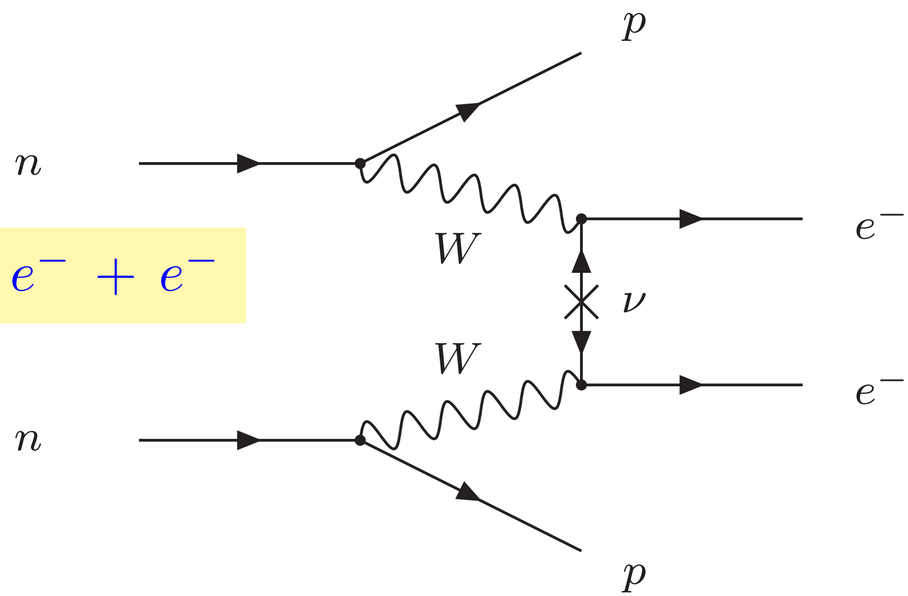

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    $\Rightarrow$ no same state $\Rightarrow$ Amplitude = 0
  - If ν Majorana $\Rightarrow$ $\nu = \nu^c$ *annihilates and creates* a *neutrino=antineutrino*
    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto \overbrace{\nu\ (\nu^c)}^{}{}^T \neq 0$
- Amplitude of ν-less-$\beta\beta$ decay is proportional to $|\langle m_{\beta\beta}\rangle| = |\sum U_{ej}^2 m_j|$

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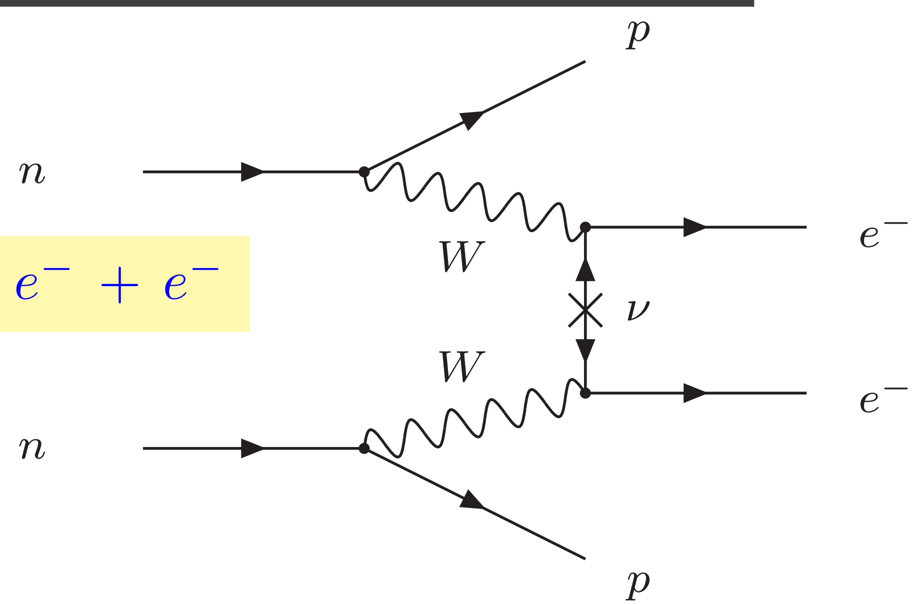

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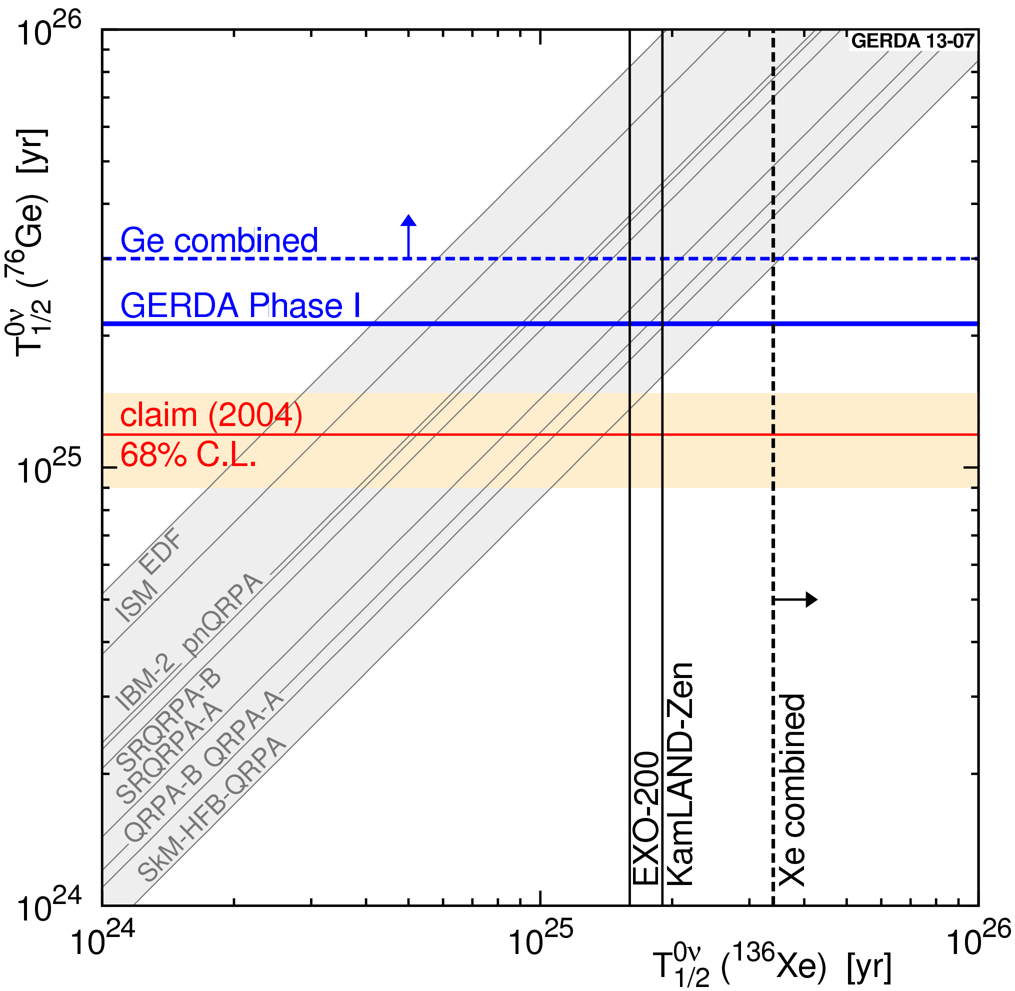
- Amplitude of ν-less-$\beta\beta$ decay is proportional to $|\langle m_{\beta\beta}\rangle| = |\sum U_{ej}^2 m_j|$
- Problem is uncertainty in the nuclear matter elements

$0\nu\beta\beta$ Decay: Circa 2013

- Bounds from ^{136}Xe exp EXO and KamLAND-ZEN, and from ^{76}Ge exp Gerda

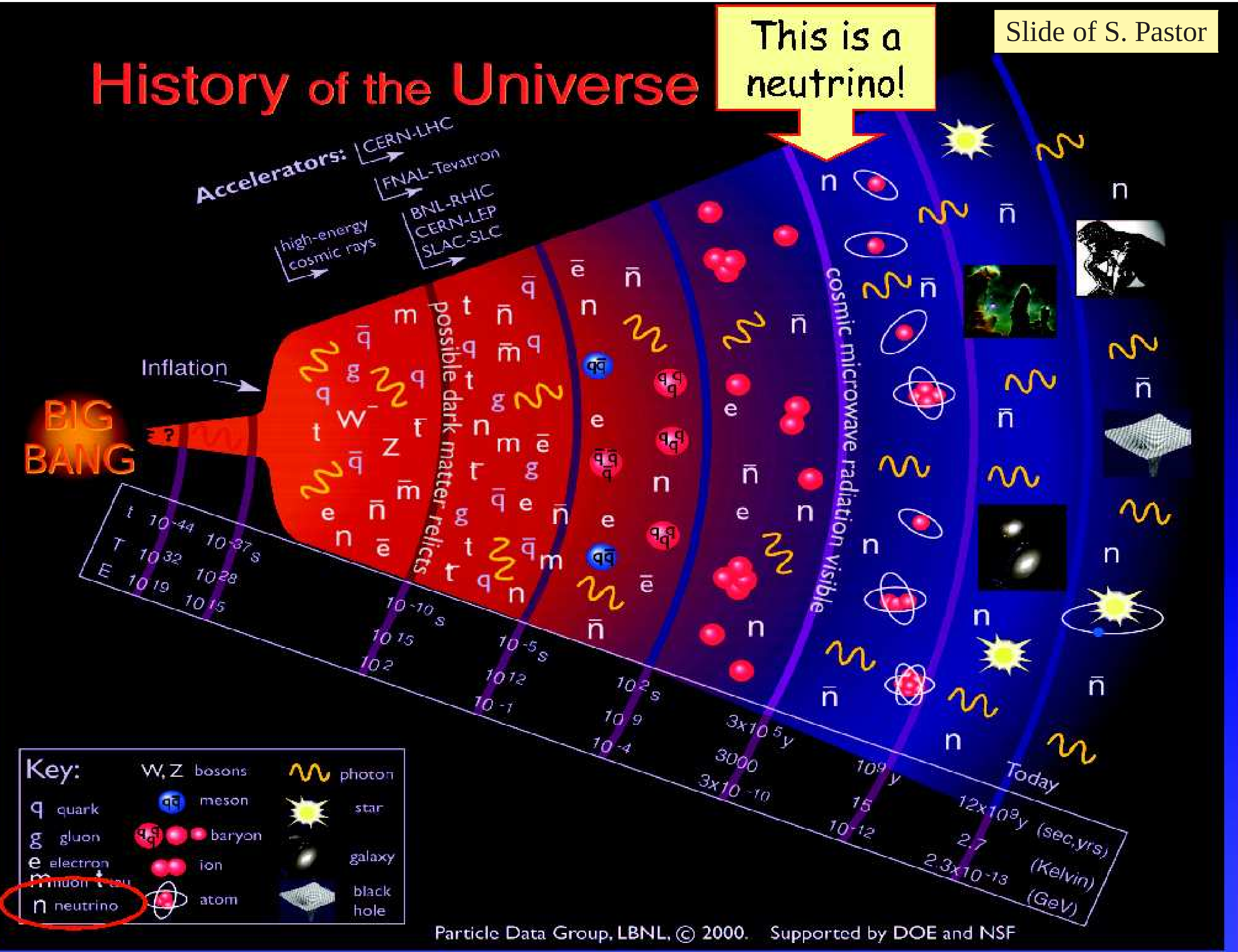


$$m_{\beta\beta} \lesssim 0.15 - 0.5 \text{ eV}$$

$0\nu\beta\beta$ Decay: Future

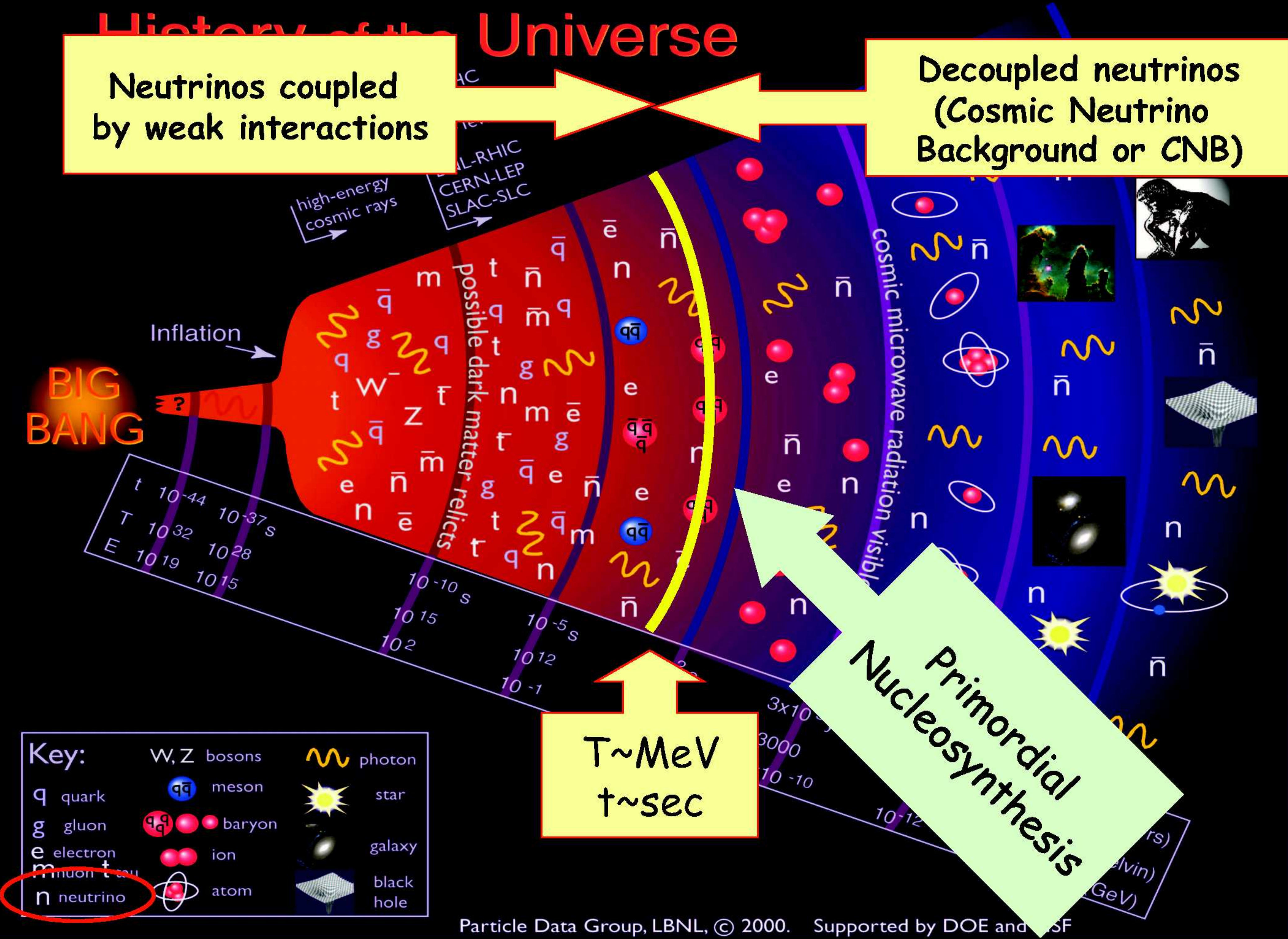
JJ Gomez-Cadenas, sl etal ArXiv:1109.5515

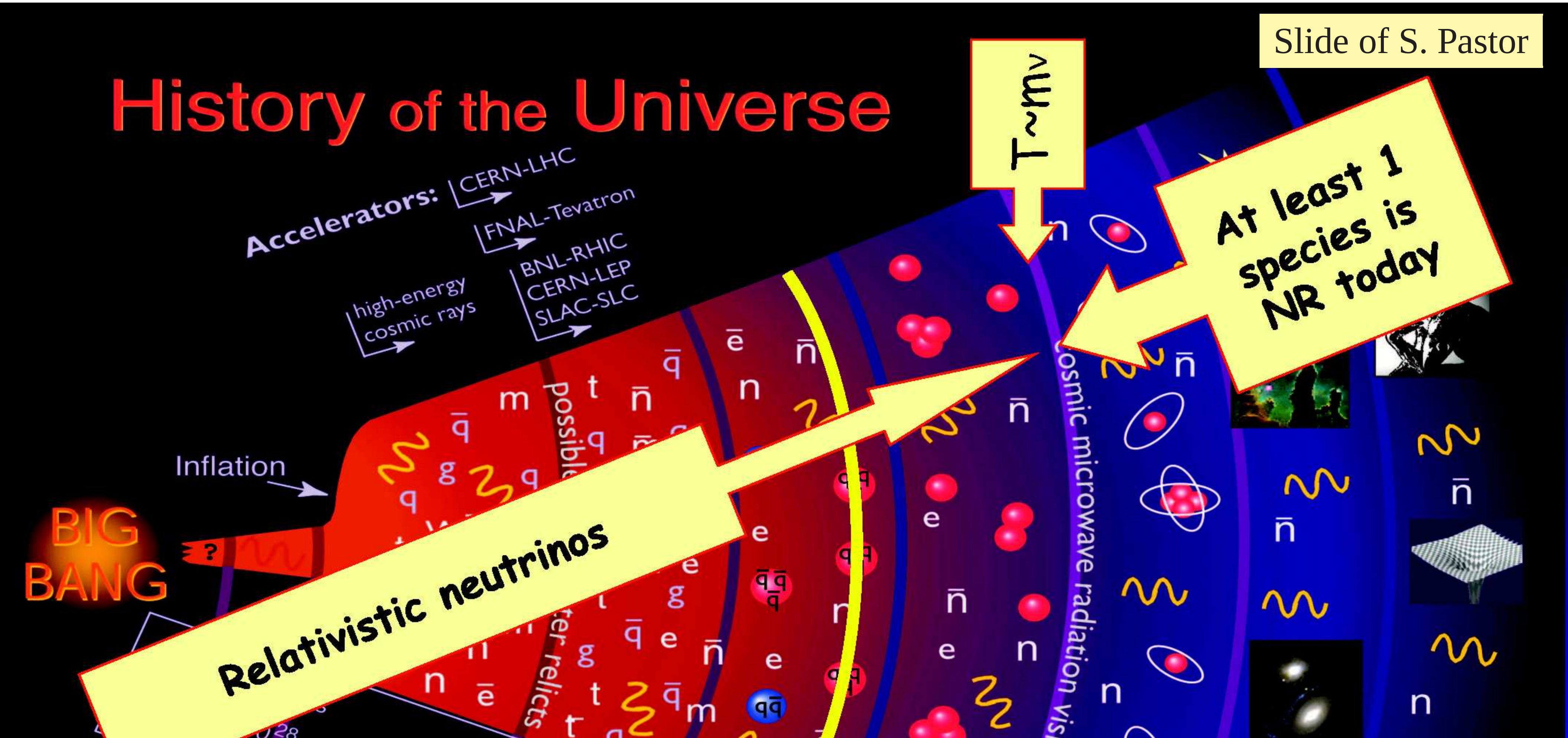
Experiment	$M_{\beta\beta}$ (kg$_{\beta\beta}$)	ε	ΔE (keV)	c (10^{-3} counts/(keV $\cdot$ kg$_{\beta\beta}$ $\cdot$ year))	Bgr/ROI (cts/yr)
EXO-200	141	0.34	100	0.78–5	11–71
GERDA-1	15.2	0.95	4.2	12–70	0.77–4.5
GERDA-2	30.4	0.84	2	1.2–7	0.07–0.43
CUORE-0	10.9	0.83	5	180–390	9.8–21.3
CUORE	206	0.83	5	36–130	37.1–134
KamLAND-Zen	357	0.61	250	0.22–1.8	19.6–161
MAJORANA Demonstrator	17.2	0.85	2	1.2–12	0.04–0.41
SNO+	44	0.50	220	9–70	87–680
NEXT	89.2	0.33	18	0.2–1	0.32–1.6
SuperNEMO Demonstrator	7	0.28	130	0.6–6	0.55–5.5



Slide of S. Pastor
History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y
2.7
2.3x10-13
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Slide of S. Pastor





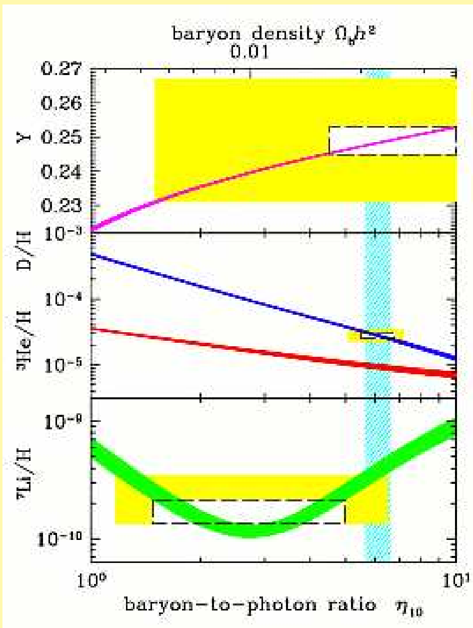
Neutrino cosmology is interesting because Relic neutrinos are very abundant:

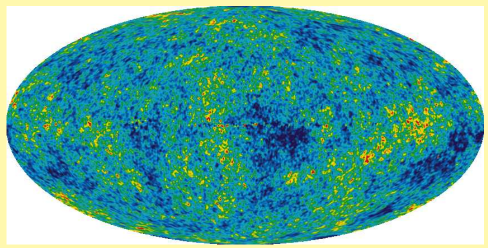
- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)

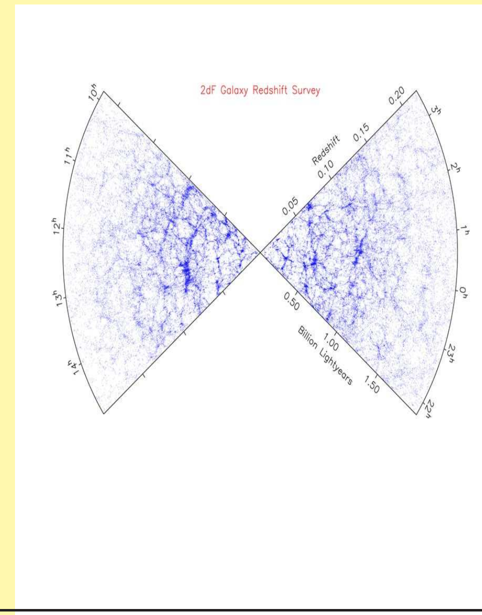
- Cosmological observables can be used to test standard or non-standard neutrino properties

Massive ν in Cosmology

Relic $\nu' s$: Effects in several cosmological observations at several epochs





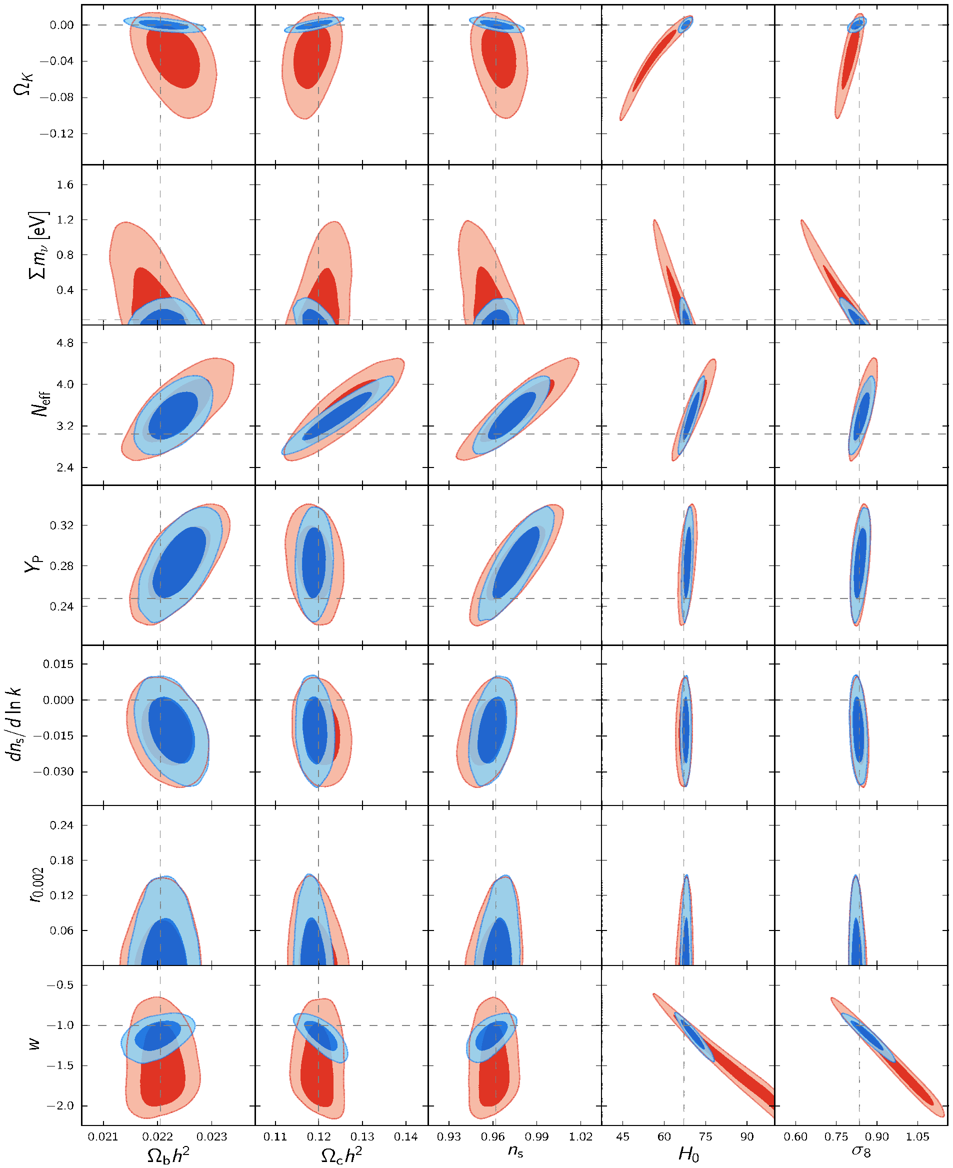


Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Large Scale Structure Formation LSS
$T \sim$ MeV	$T \lesssim$ eV	
Number of $\nu' s$ ($N_{\rm rel}$)	$N_{\rm rel}$ and $\sum m_\nu$	

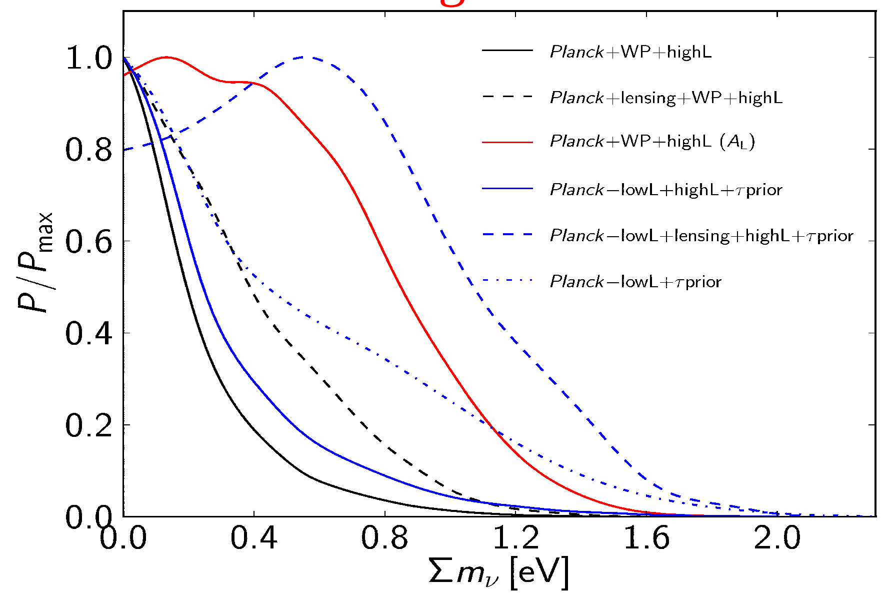
Observables also depend on all other cosmological parameters

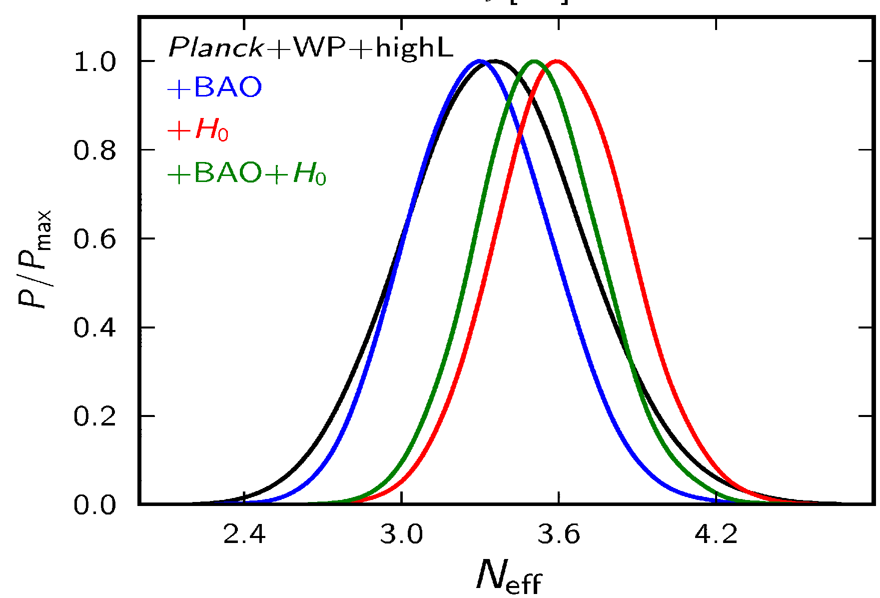
Cosmological Analysis by Planck

Correlations



Range of Bounds





Example of cosmological bounds on m_ν

Dependence on Data Samples and Cosmological Model

Model	Observables	Σm_ν (eV) 95%
$\Lambda\mathrm{CDM} + m_\nu$	Planck-lowL+τprior	≤ 1.31
$\Lambda\mathrm{CDM} + m_\nu$	Planck+WP+highL(A_L)	≤ 1.08
$\Lambda\mathrm{CDM} + m_\nu$	Planck+Lens+WP+highL(A_L)	≤ 0.85
$\Lambda\mathrm{CDM} + m_\nu$	Planck+WP+highL	≤ 0.66
$o\Lambda\mathrm{CDM} + m_\nu$	Planck+WP+highL	≤ 0.98
$\Lambda\mathrm{CDM} + m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.25
$o\Lambda\mathrm{CDM} + m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.36

Lesson for Particle Physicists:

Careful with what you call *Cosmological bound on* m_ν

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  - Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau \leftrightarrow m_\nu \equiv 0$
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  Answer:

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