LMU Neutrino Course

Lecture VI

30/4/2021

LMU
Spring 2021

Origin and nature of (neutrino) mass

$\boxed{\text{What is mass?}}$

$$E^2 = \vec{p}^{\,2} + m^2$$

(Dirac)

(mass) def. of mass

$$\boxed{\begin{array}{l} \mathcal{L}_f = i \bar{f} \gamma^\mu D_\mu f - m_f \bar{f} f \\ \qquad f = \text{lepton} \\ \neq \quad f = \text{quark} \end{array}}$$

(new) $\boxed{\text{definition of mass}}$

<u>neutrino:</u> $E^2 = p^2 + m^2$

not measured yet

$H^3 \to He^3 + e + \bar{\nu}_e$ $\boxed{\text{KATRIN}}$

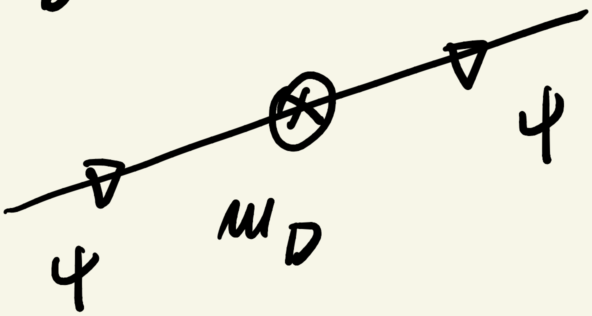
direct $\Rightarrow m_\nu \lesssim 1\,eV$

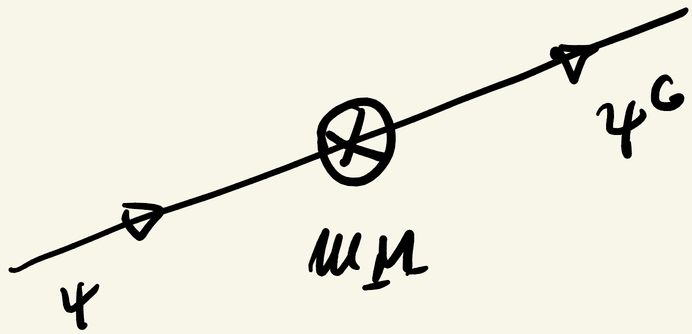
$\boxed{\text{Nature of (neutrino) mass}}$

Dirac

Majorana

$m_D \, \bar{\psi} \psi$ $\qquad$ $m_M \, \overline{\psi^c} \, \psi$





ψ = spinor , $\psi^c \equiv C \bar{\psi}^T$ = spinor

conserve Q_ψ $\qquad$ breaks Q_ψ

Dirac $\Rightarrow$ electron $\qquad$ Majorana $\Rightarrow$ neutrino

Q_e = conserved $\qquad$ $Q_\nu = 0$

$\Downarrow$ $\qquad$ $\Downarrow$

only m_D for e $\qquad$ natural for neutrino

$\downarrow$

$\bar{\psi} \psi = \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L$ $\qquad$ $\psi = \psi_L$

$\Downarrow$

$$\overline{\psi^c}\,\psi = \psi_L^T C \psi_L$$

$$\Downarrow$$

- **"Dirac" mass terms**

$$e = e_L + e_R$$

(i) electron : $\bar{e}e = \bar{e}_L e_R + \bar{e}_R e_L$

(ii) neutrino : $\nu = \nu_L$

$$\nu_M = \nu_L + C\bar{\nu}_L^T \quad \text{(4 comp.)}$$

$$\bar{\nu}_M \nu_M = \bar{\nu}_L C \bar{\nu}_L^T + \overline{C\bar{\nu}_L^T}\,\nu_L$$

$$= \underbrace{\nu_L^T C \nu_L}_{\text{Majorana}} + \nu_L^\dagger C^\dagger \nu_L^*$$

- "Majorana" mass (way of writing)

$$(\psi_{1L}^T \, C \, \psi_{2L})$$

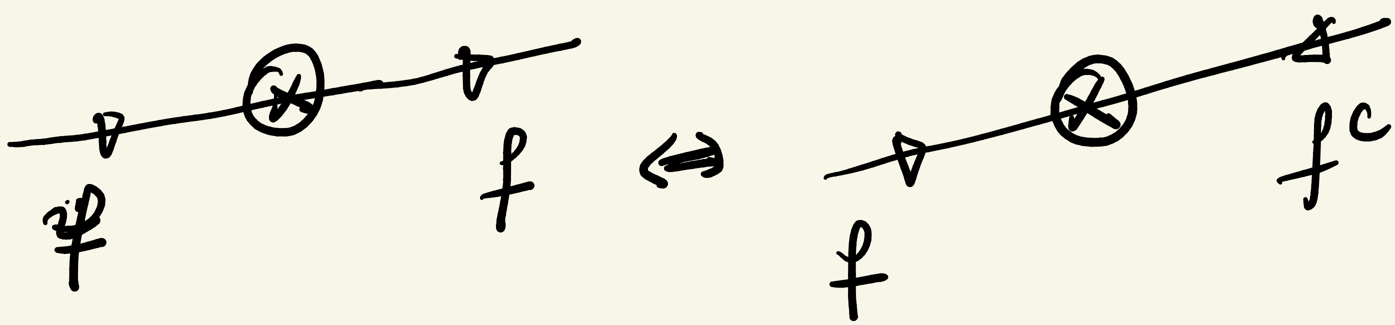
$\overline{e}_R e_L$?

$$(e^c)_L \equiv C \overline{e}_R^T$$

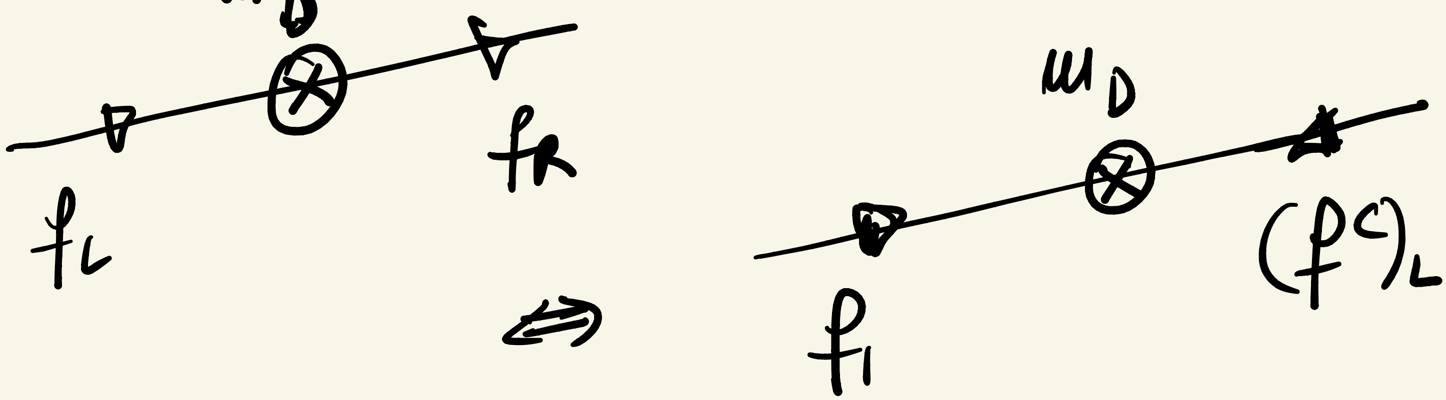
$$\Downarrow$$

$$(D) \quad \underbrace{(e^c)_L^T C e_L} = (C \overline{e}_R^T)^T C e_L$$

$$= \overline{e}_R \underbrace{C^T C}_{1} e_L = \overline{e}_R e_L$$



$\Downarrow$



Summarize

Dirac f : 4 d.o.f. (u_L, u_R)

Majorana f : 2 d.o.f (u_L)

u_R played by u_L^*

Dirac: all conserved

Majorana: all broken

$$\boxed{e: \quad m_M^e / m_D^e \le 10^{-20}}$$

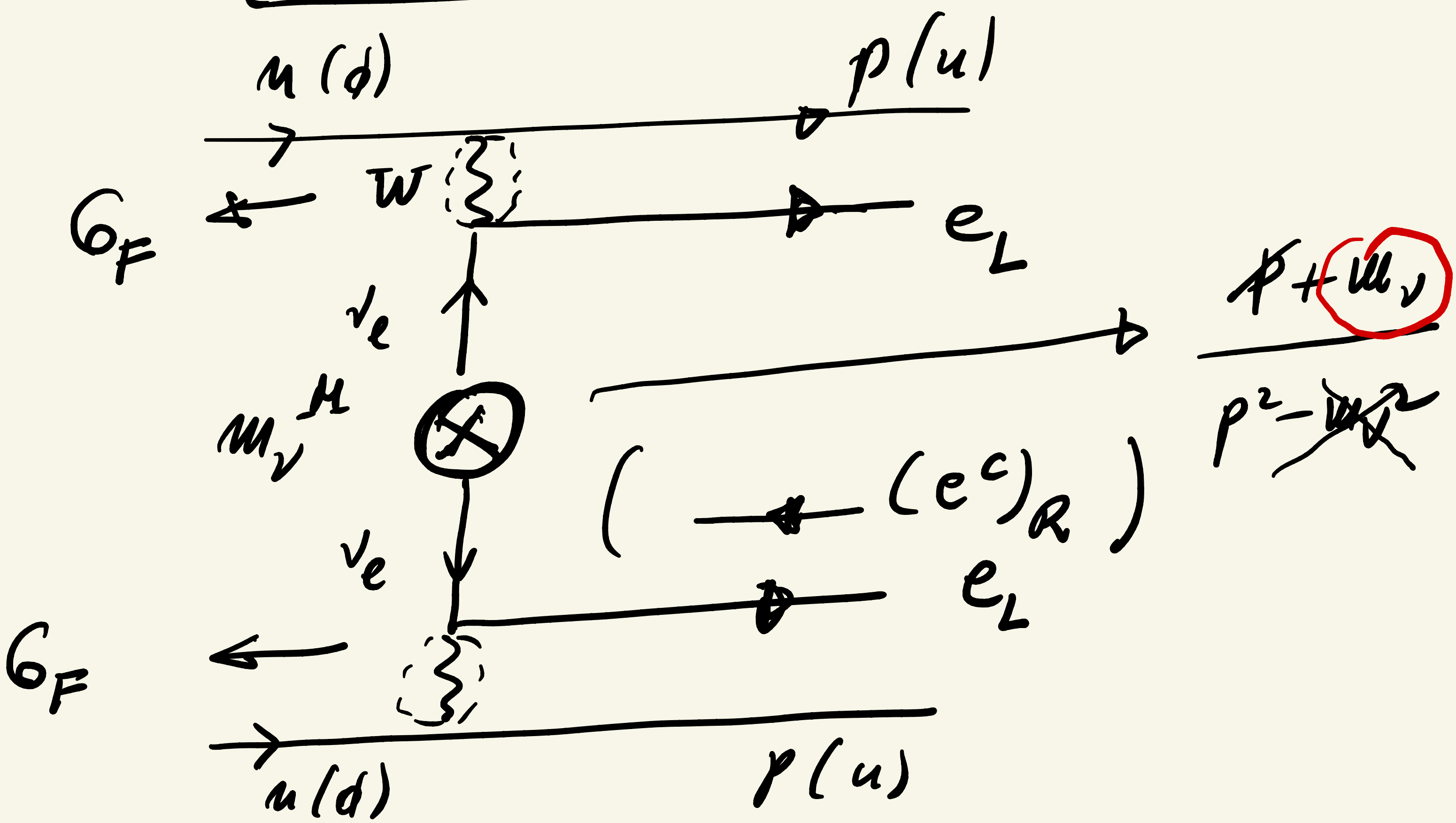
$\Downarrow$

Majorana '37

Majorana physics

- text - book '38

$\boxed{0\nu 2\beta}$



$$\tau_{0\nu 2\beta} \gtrsim 10^{25}\, yr$$

$$\Rightarrow \boxed{m_\nu^M < 1\, eV}$$

$$\mathcal{H}_{eff} \simeq G_F^2 \underbrace{\frac{m_\nu}{p^2}}_{} \underbrace{(\bar{u}\bar{u})(\bar{e}\bar{e})(dd)}_{6f}$$

$$= A_\nu \qquad d = -5 \qquad\qquad d = 9 \quad (d_f = 3/2)$$

$$p \simeq 100\, MeV$$

near future exp. : $\boxed{m_\nu^M \simeq 0.1\, eV}$

$$A_\nu \simeq 10^{-10} \cdot 10^{-10} \cdot 10^{2}\, GeV^{-5}$$

$$A_\nu \simeq 10^{-18}\,\mathrm{GeV}^{-5}$$

$$\Downarrow$$

$$\boxed{A^{exp}_{0\nu 2\beta} \simeq 10^{-18}\,\mathrm{GeV}^{-5}}$$

- $0\nu 2\beta$ = observed

  e chirality ?

  $\Rightarrow e = e_R$ (same)

$$\Downarrow$$

New Physics $\to$ $0\nu 2\beta$

$$\Downarrow$$

β decay:

$\boxed{d=4}$

$$\mathcal{H}_{eff}^{(\beta)} = G_F \left(= \frac{1}{\Lambda_F^2} \right) \underbrace{(\bar{u} d \bar{e} \nu)}_{d=6}$$

$$\left(\frac{g^2}{8 M_W^2} \right)$$

$$\Lambda_F \simeq 300 \text{ GeV}$$

$$\Lambda_F \equiv \Lambda_\beta$$

0ν2β decay

$$\mathcal{H}_{eff}^{(0\nu 2\beta)} = \frac{1}{\Lambda_{0\nu 2\beta}^5} \underbrace{(\bar{u}\bar{u}\bar{e}\bar{e} d d)}_{d=9}$$

$\boxed{d=4}$

$$\Downarrow$$

$$A_{0\nu 2\beta} = \Lambda_{0\nu 2\beta}^{-5} \overset{exp}{\cong} 10^{-18} \text{ GeV}^{-5}$$

$$\Downarrow$$

$$\boxed{\Lambda_{0\nu 2\beta} \simeq 3 \times 10^3 \ \text{GeV} \simeq 3 \ \text{TeV}}$$

$e = e_R \Rightarrow$ must

LHC !

$$\boxed{0\nu 2\beta \neq \text{probe of Majorana neutrino mass}}$$

Feinberg, Goldhaber '58

Pontecorvo '60s

Mohapatra, G.S. '79

$\Downarrow$

$$\boxed{\begin{gathered}\textbf{LHC}\ (\text{next collider}) = \\ = \text{neutrino machines}\end{gathered}}$$

$\Uparrow$

if $\nu =$ Majorana $\Leftarrow$ NP (New Physics)

$e = e_R$

$$\boxed{\Lambda_{NP} \simeq 3 \text{ TeV}}$$

- what $e = e_L$ (both of them)?

Dvali, Maiezza,

$\Downarrow$

Tello, G. S. 2021

(i) ν mass as a source

(ii) NP possible as a source

→ to be answered in the course

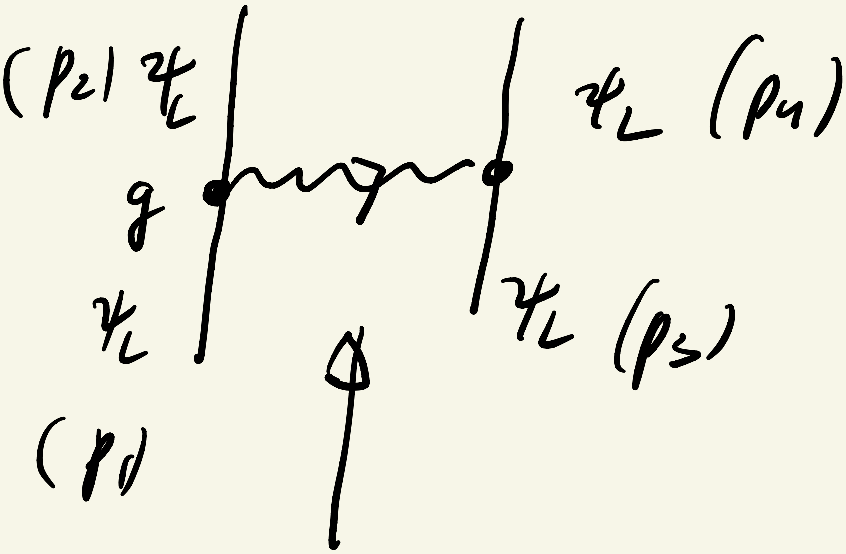
Comment on HW

propagator of Proca =

= massive "photon"

- $q = 0$ (q = exchange momentum)

$$\Delta(A) \sim \frac{1}{M_A^2} \Rightarrow G_F = \frac{g^2}{\cdots M_W^2}$$



$$q = p_1 - p_2 = p_4 - p_3$$

$$\Delta_{\mu\nu}(A) = a(g_{\mu\nu}) + b\,(q_\mu q_\nu)$$

+ Dirac eq.

$$\boxed{q \to 0 \text{ limit!}}$$

Cosmology and neutrino

$(u+d+e)$

world: $p+n+e$ matter

photons CMB

ν_e ? —"—

• $\underbrace{c+s+\mu}+\nu_\mu$ (stable)

• $\underbrace{t+b+\tau}+\nu_\tau$

decay $\mu \to e+\bar{\nu}_e+\nu_\mu$

$$\boxed{m_\nu < eV}$$

Atmosphere: $\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$ cosmic rays

$\uparrow$

how ?

β: $n \to p + \boxed{e + \bar{\nu}_e}$

(reactors)

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

Reines + Cowan '56

? $\cancel{\bar{\nu}_\mu + p \to n + \bar{e}}$

$\to n + \bar{\mu}$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \rightsquigarrow \boxed{\bar{\nu}_e \gamma^\mu e \, W^+_\mu} \; (e + \bar{\nu}_e)$

$\nu_e \leftrightarrow e$

$\nu_\mu \leftrightarrow \mu$

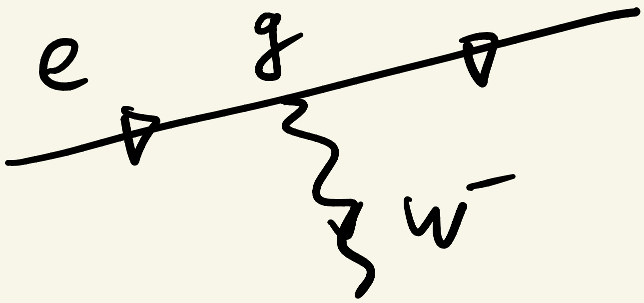
$\nu_\tau \leftrightarrow \tau$

young = hot
old = cold

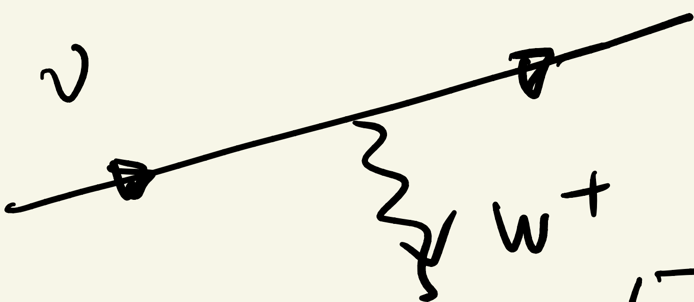
big - bang:

---

digression:



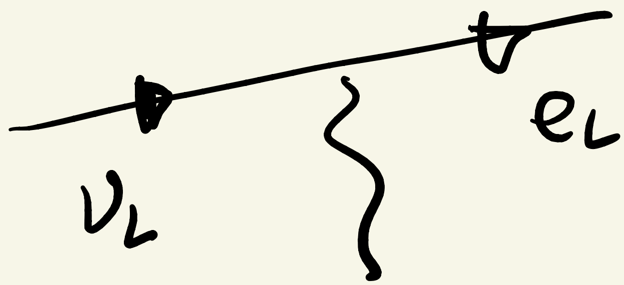
$$g\, \bar{\nu} \gamma^\mu e\, W_\mu^+$$



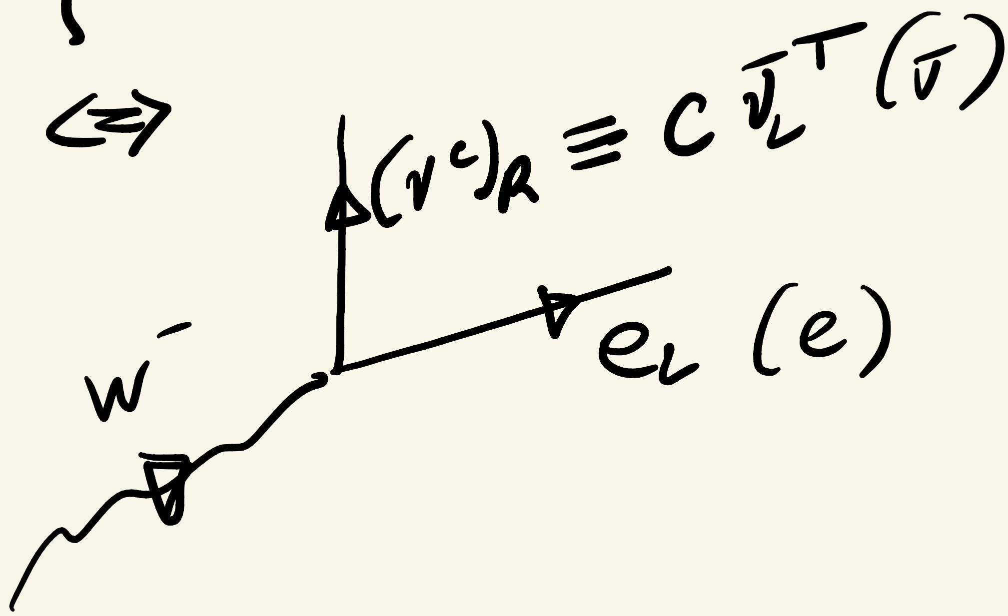
$$g\, \bar{e} \gamma^\mu \nu\, W_\mu^-$$

$\Updownarrow$

$$\boxed{e + \bar{\nu} = \text{out}}$$



$\Longleftrightarrow$



$$t_\nu \simeq 10^{10}\,yr \simeq 10^{28}\,cm$$

$\left(H \equiv \dfrac{1}{t} \Rightarrow \right.$ expansion rate $\left. \right)$

Hubble constant

$$\left(t = \frac{M_{pl}}{T^2} \right) \qquad M_{pl} = 10^{19}\,GeV$$

$$G_N = \frac{1}{M_{pl}^2}$$

$T \gtrsim 10\ \mathrm{MeV} \geq m_e$

$\hookrightarrow e + \bar{e} \longleftrightarrow 2\gamma$

$\downarrow$ cooling

photons in the universe

$T \ll m_e$

"photon sea"

$e + \bar{e} \longrightarrow 2\gamma$

$\boxed{\text{Penzias Wilson '67}}$

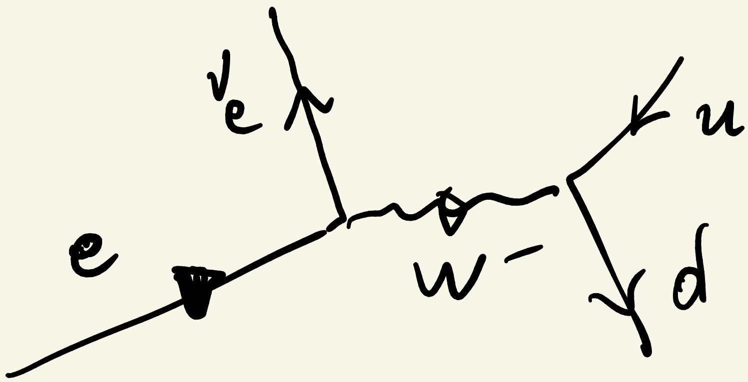
$T \simeq 10^{-4}\ \mathrm{eV}$ CMB

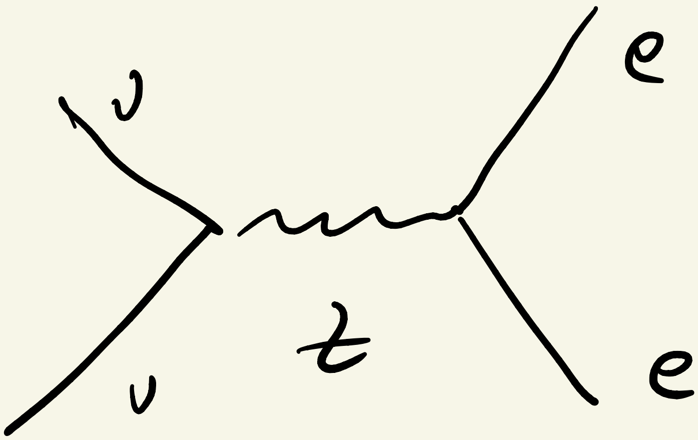
$\Downarrow$

"First three minutes" Weinberg

$n_\gamma \simeq T^3 \simeq 400/\mathrm{cm}^3$

($m_\gamma \ll 10^{-4}$ eV)   (check!)





ν was in equilibrium at high T

$\Rightarrow$ $\boxed{\text{neutrino sea}}$ $T_\nu \simeq T_\gamma$

$n_\nu \simeq n_\gamma \simeq 400/\text{cm}^3$ (density)

($\nu_e + \nu_\mu + \nu_\tau$)

$\Uparrow$

$\boxed{\text{Holy Grail of cosmology}}$

$$\boxed{n_B \simeq 10^{-10}\, n_\gamma}$$

baryons

$$n_B \simeq 10^{9}\, eV$$

$$\Downarrow$$

$$\boxed{m_\nu \leq 1\, eV}$$

Dark Matter

direct limit (KATRIN) $m_\nu \leq eV$

$0\nu 2\beta$ (Majorana) $m_\nu^M \leq eV$

cosmolog $m_\nu \leq eV$