Neutrinos Theory

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1 kton water + Gd guided by KamLAND

KamLAND 1kton LS, 2000 PMT, 33% cov (1.4 yr, 90%)

Supernova (8.5 kpc) : 300 events

Relic Supernova (E>6MeV) ~ 0.4 events/yr

	bck	React	Geov
Bin1	125.2 (24.6)	2.3	6.3
Bin2	24.6 (19.8)	19.5	7.4
Bin3	12.9 (9.8)	35.1	3.9
Bin4	5.9 (3.9)	36.1	2.8

1 kton water + Gd guided by KamLAND

Gd-1kton, 2000 PMT, 33% cov
(1.4 yr, 90%)

Supernova (8.5 kpc) : 300 events
Relic Supernova (E>5MeV) ~ 0.5 events/yr

	bck	React	Geov
Bin1	12[illegible].2 (24.6)	~0	~7
Bin2	24.6 (19.8)	~1	~8.5
Bin3	12.9 (9.8)	~2	~4.5
Bin4	5.9 (3.9)	~2	~3

?

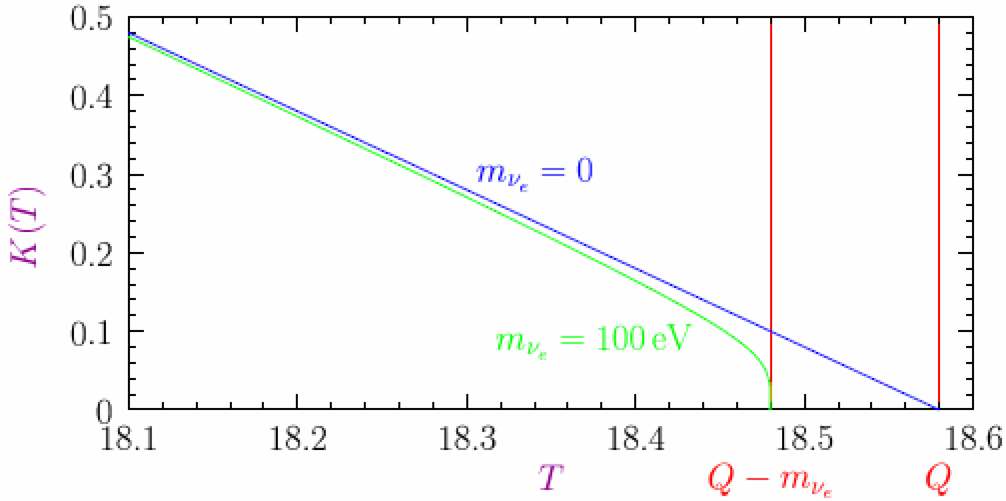
Neutrino mass : Direct methods

Tritium β Decay: ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q - T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

Kurie plot: $K(T) = \sqrt{\dfrac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$



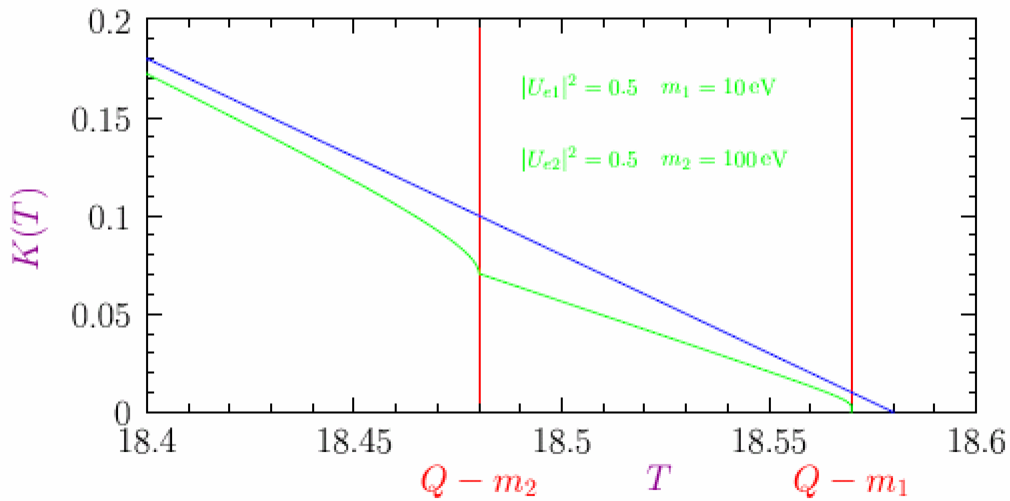
$m_{\nu_e} < 2.2\,\mathrm{eV}$ (95% C.L.)

[Mainz, Troitsk, hep-ex/0210050]

Future: KATRIN [hep-ex/0109033]

sensitivity: $m_{\nu_e} \gtrsim 0.3\,\mathrm{eV}$

Neutrino Mixing $\Longrightarrow$ $K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



analysis of data is different from the no-mixing case: $2N - 1$ parameters

$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

if experiment is not sensitive to masses ($m_k \ll Q - T$) $\Longrightarrow$ effective mass

$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$\begin{aligned} K^2 &= (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right] \\ &= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2} \end{aligned}$$

Plan

I. Neutrinos as Dirac Particles

II. Making Neutrinos

III. Neutrinos as Majorana Particles

Massive Neutrinos : Dirac

$\nu(p,h) \longleftrightarrow \bar{\nu}(p,-h)$ (*CPT*)

$\updownarrow$ *Boost, if $m \neq 0$* $\qquad$ *Boost, if $m \neq 0$* $\updownarrow$

$\nu(p,-h) \longleftrightarrow \bar{\nu}(p,h)$ (*CPT*)

Chirality vs Helicity

$$\nu_{Li} \propto \nu_i(p,h) + O(m_i / E)\,\nu_i(p,-h)$$

$$\bar{\nu}_{Li} \propto \bar{\nu}_i(p,-h) + O(m_i / E)\,\bar{\nu}_i(p,h)$$

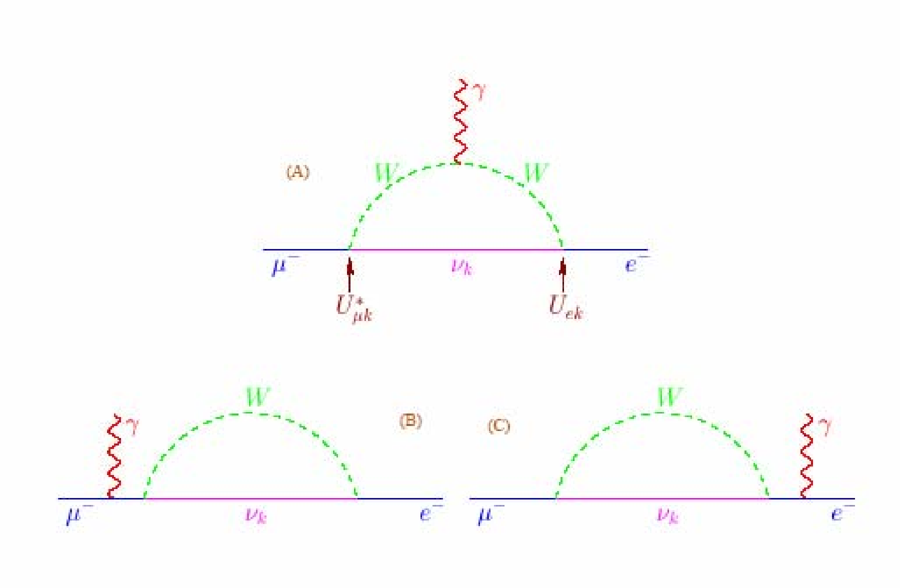
$$\mathrm{m}_{i}\bar{\nu}_i\nu_i = \frac{y\,\mathrm{v}}{\sqrt{2}}(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$$

Example : $\mu \to e\,\gamma$

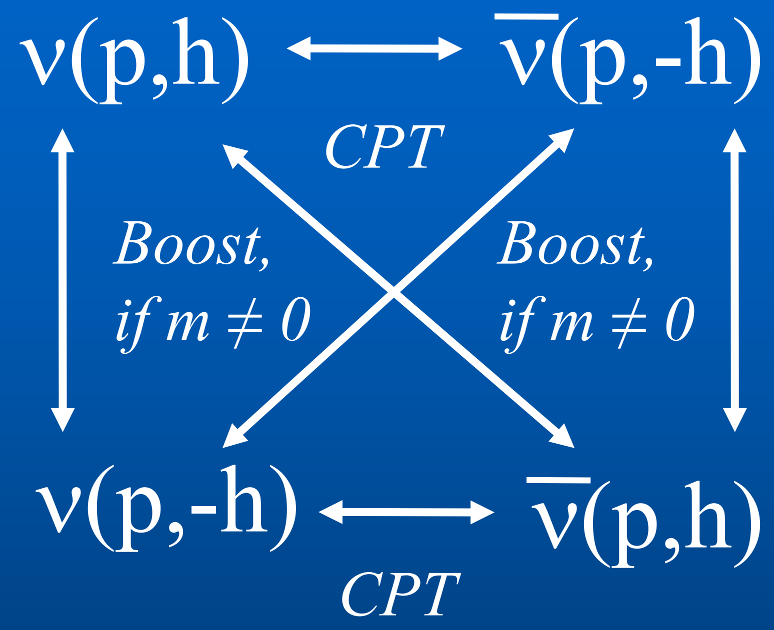
$$\sum U^*_{\mu k} U_{ek} = 0 \Rightarrow GIM \text{ mechanism}$$

$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\frac{3\alpha}{32\pi}\left|\sum U^*_{\mu k} U_{ek}\frac{m_j^2}{m_W^2}\right|^2 < 10^{-25}\frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$\Gamma_{\exp} < 10^{-11}\frac{G_F^2 m_\mu^5}{192\pi^3}$$



Massive Neutrinos : Majorana

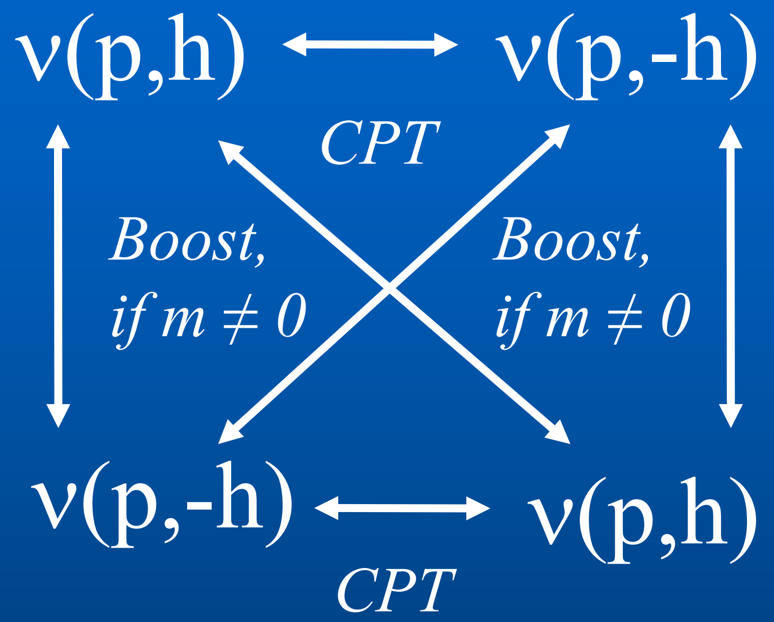


$$\mathcal{L}_\nu = i\,\bar{\nu}_i \gamma^\mu \partial_\mu \nu_i - \frac{g}{2\cos\theta_W}\bar{\nu}_i \gamma^\mu Z^0_\mu \nu_i$$

$$- \frac{g}{2\cos\theta_W}\bar{l}_i \gamma^\mu U_{ij} W^-_\mu \nu_i + \text{h.c.}$$

$$+ \mathrm{m}_i \bar{\nu}_i \nu_i + m_{Ri}\bar{\nu}^c_{Ri}\nu_{Ri} + \text{h.c.} + \ldots$$

Massive Neutrinos : Majorana



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$$+ \mathrm{m}_i\bar{\nu}_i\nu_i + m_{Ri}\bar{\nu}^c_{Ri}\nu_{Ri} + \text{h.c.} + \ldots$$

Parameters : Majorana

$$U_{\alpha i}=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\cdot\begin{pmatrix} c_{13} & 0 & s_{13}e^{+i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}\cdot\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

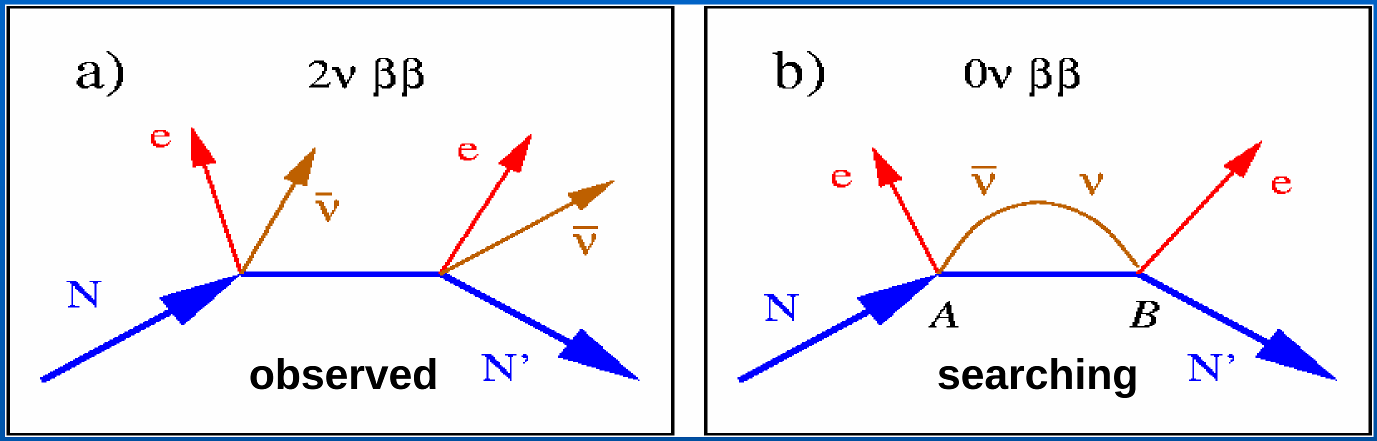
$$\cdot\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{+i\lambda_{21}} & 0 \\ 0 & 0 & e^{+i\lambda_{31}} \end{pmatrix}$$

Majorana phases only relevant in processes involving Lepton Number Violation $(\nu_\alpha - \bar{\nu}_\beta)$

Previous discussion on neutrino osc. is valid for Majorana !

Helicity suppressed by smallness of neutrino masses

Majorana vs Dirac : 0νββ decay



$0\,\nu\beta\beta$: $nn \rightarrow ppe^{-}e^{-}$ (without neutrinos)

$$|\langle m^{\nu}_{ee}\rangle| = \frac{m_e}{(T_{1/2}\,F_N)^{1/2}}$$

$$F_N = G^{0\nu}\,|M^{0\nu}{}_f - (g_A/\,g_V)^2\,M^{0\nu}{}_{GT}\,|^2$$

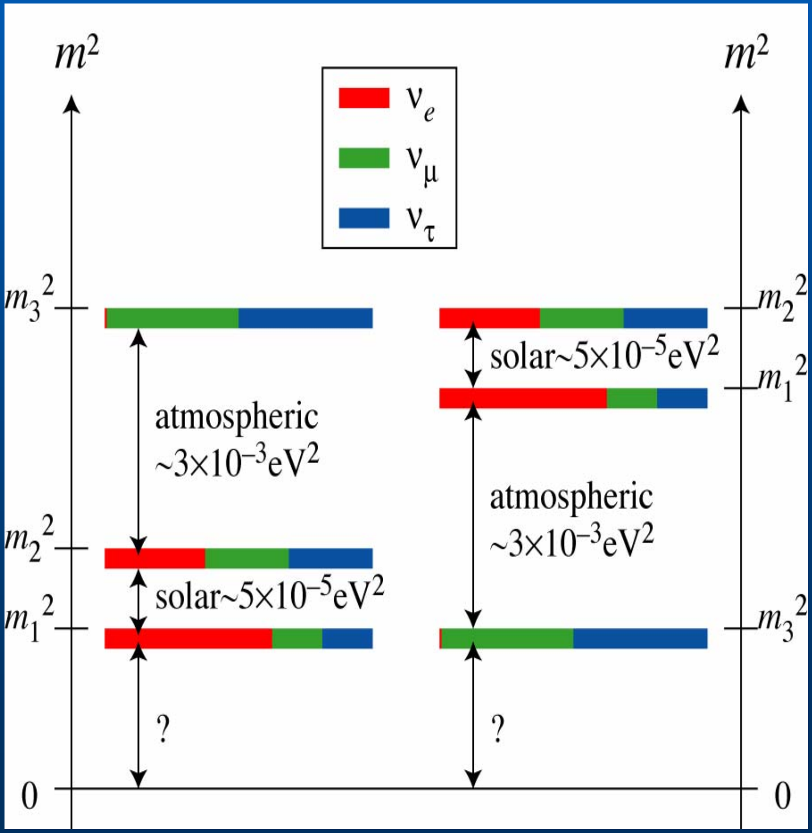
Connection with neutrino parameters :

$$|\langle m^{\nu}_{ee}\rangle| = |\Sigma m_j\, U_{ej}^{2}\,| = |\Sigma m_j\, |U_{ej}|^{2}\, e^{i\phi_j}\,|$$

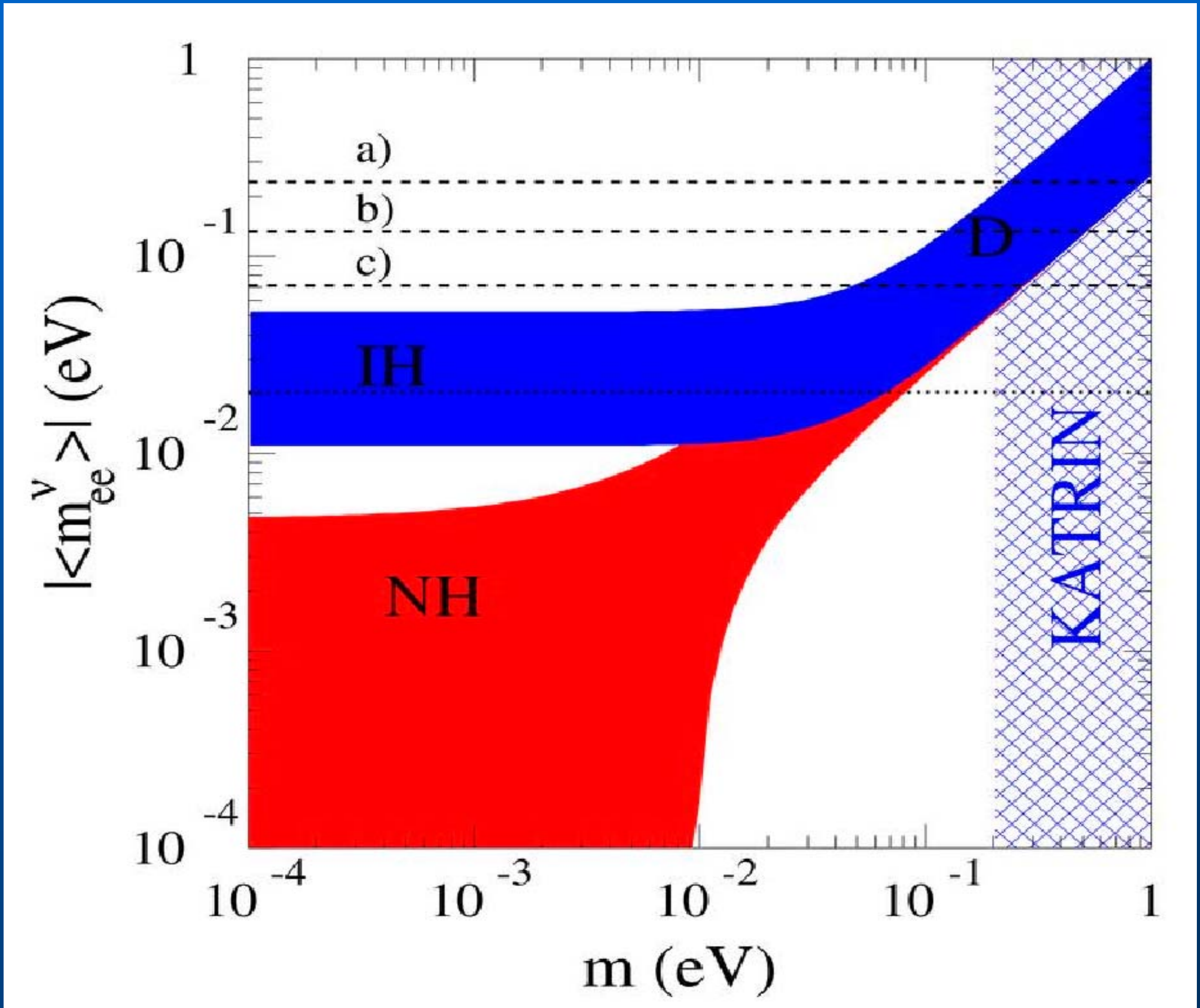
Normal Hierarchy

Inverted Hierarchy

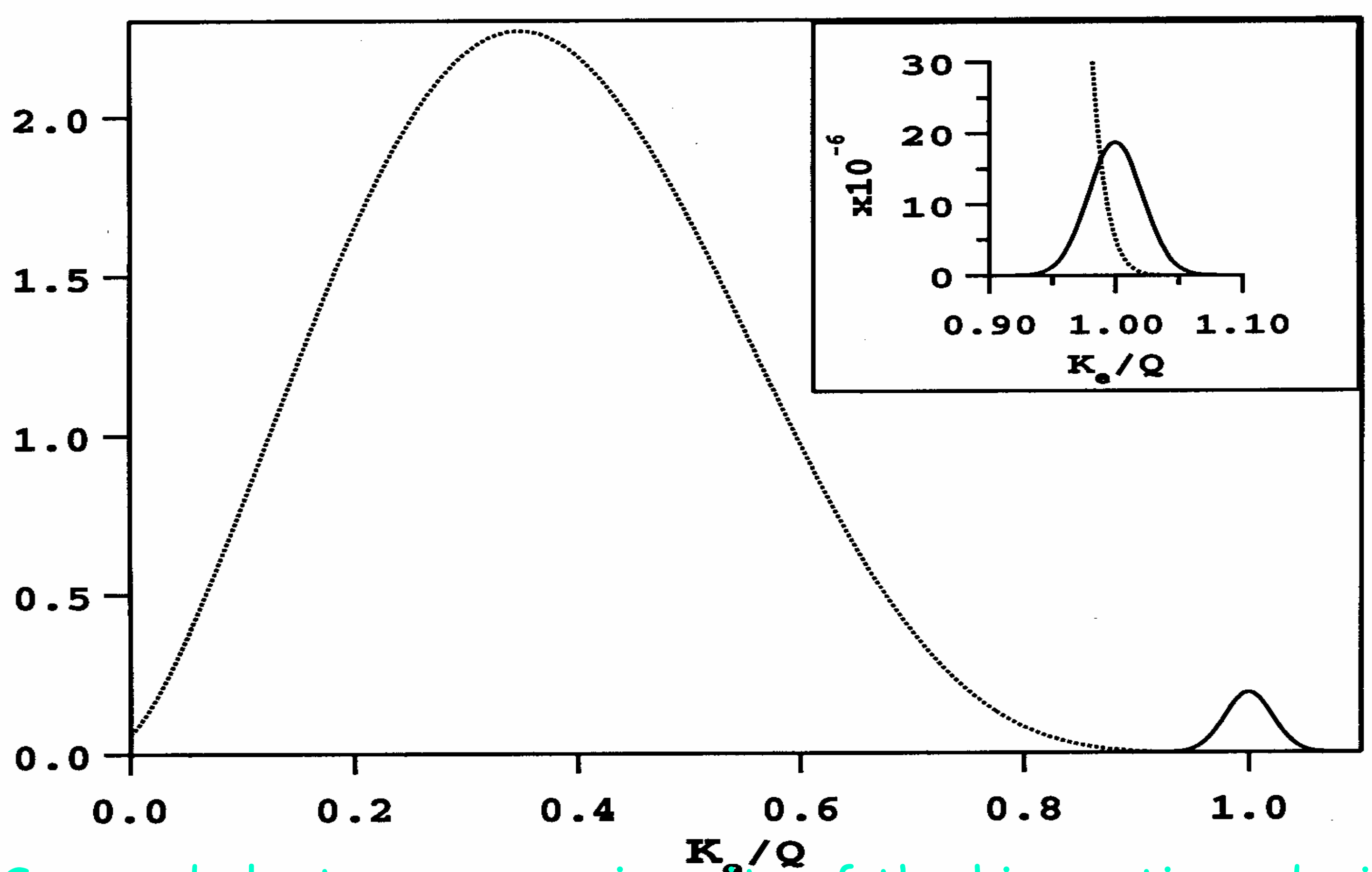
Degenerate



From Osc. Data :

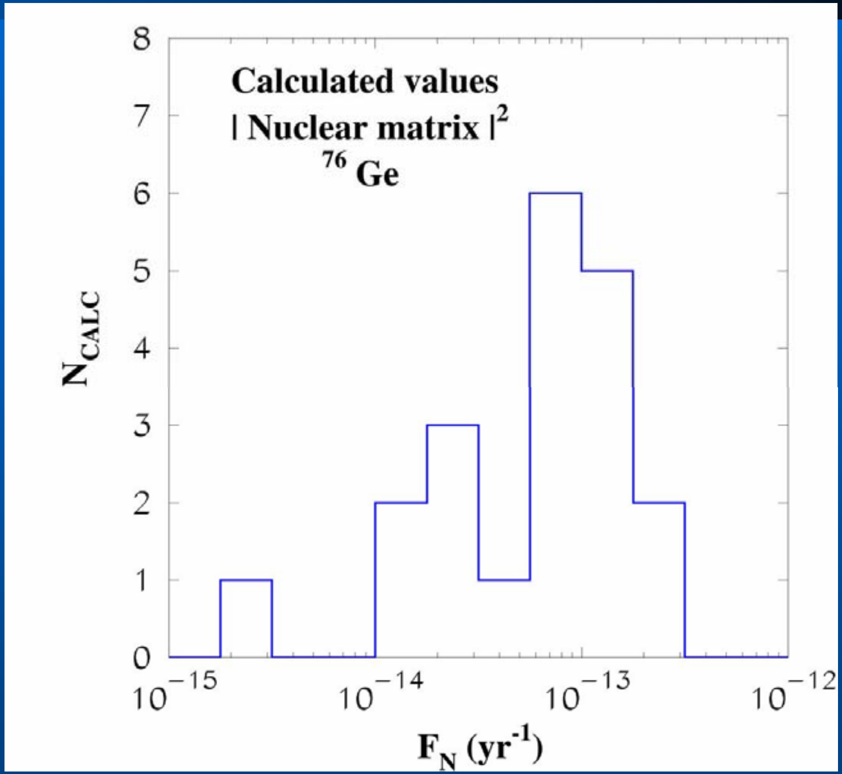


Signal : Energy Resolution required



Summed electron energy in units of the kinematic endpoint (Q)

nuclear matrix elements?



Nuclear Physics methods :

QRPA, SM

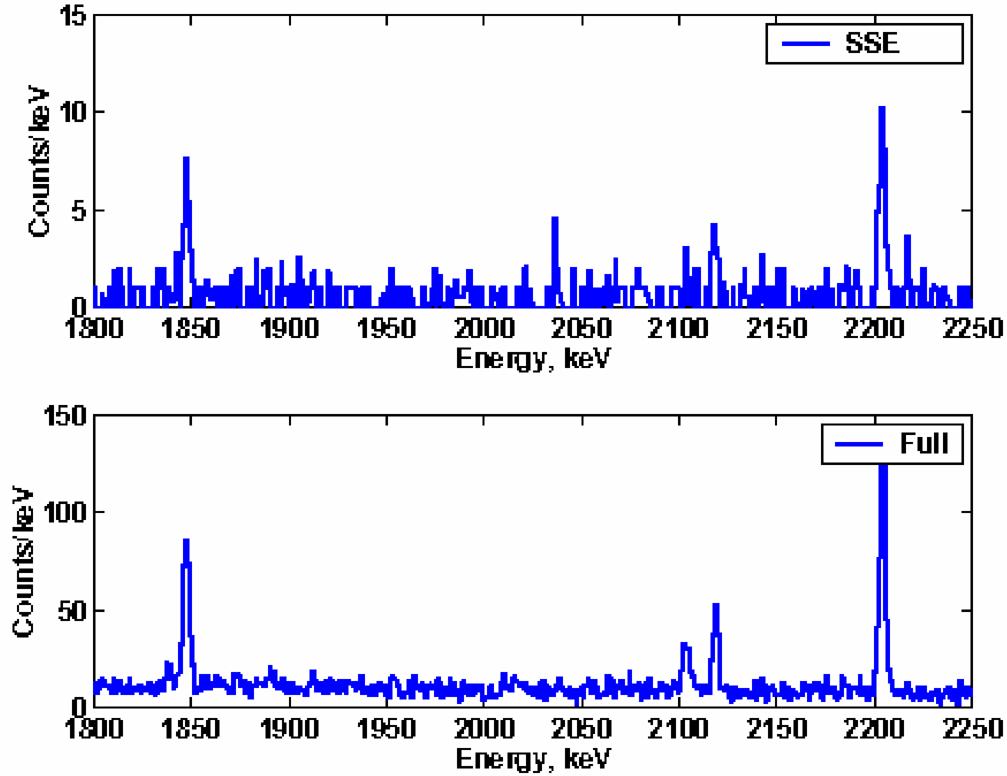
Next Generation experiments :

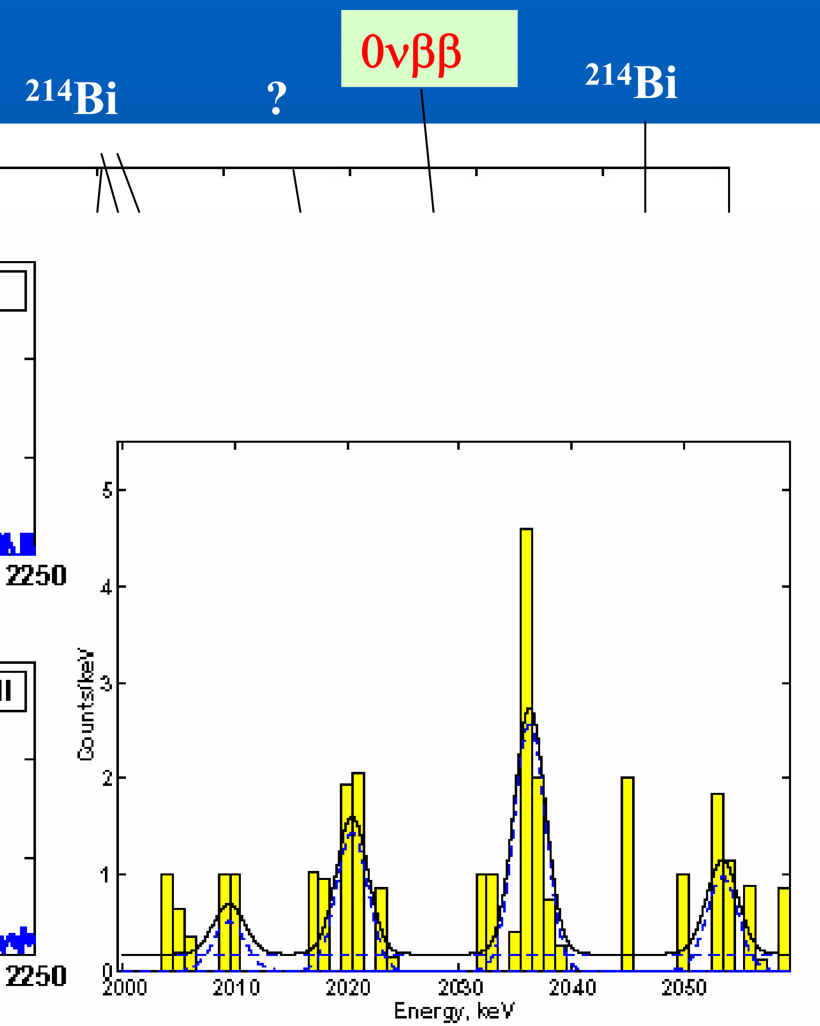
Observed : Neutrinos are Majorana

Not observed : Hard to extract neutrino parameters, and exclude Dirac.

Positive signal ?

Klapdor et al (part of HM)
28.8 (6.9) –> 3-4σ
Bckg ~ 60 ev.





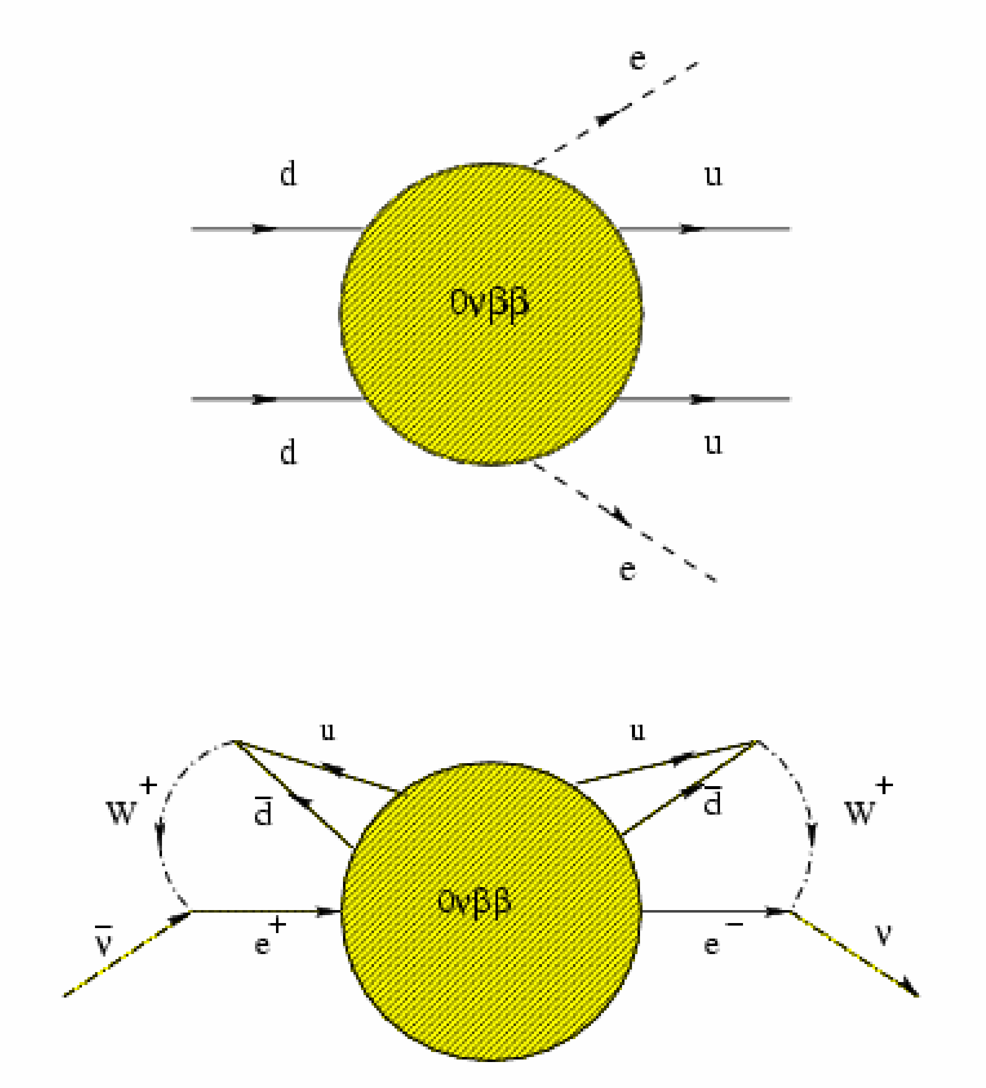
Present Limits :

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	$\langle m \rangle$ (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	$<1.1 - 2.6$
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Projected/proposed

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	$< m_\nu >$ eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
Gertha	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	$> 10^{26}$	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

Theorem 0νββ ←→ Majorana

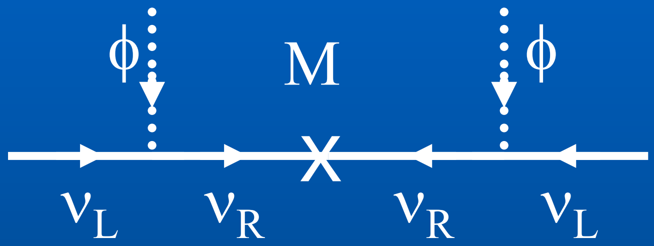


in gauge theories with SSB

Seesaw mechanism

$$\mathcal{L}_{\nu} \prec \mathrm{m}_{\mathrm{i}} \overline{\nu}_{i} \nu_{i} + m_{Ri} \overline{\nu}^{c}_{Ri} \nu_{Ri} + \mathrm{h.c.} + \ldots$$

Integrating out the heavy field



ν_R $m_R >> <\phi>$:

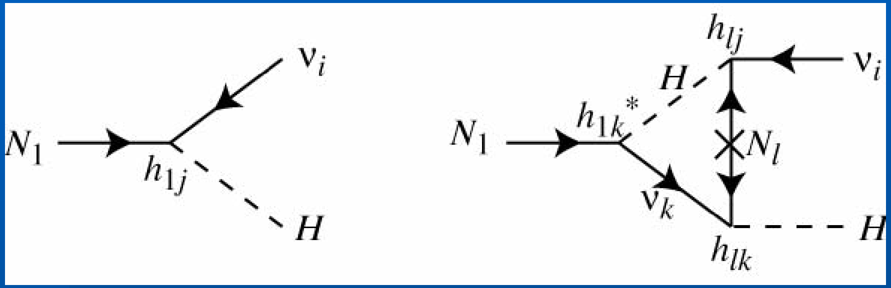
$$\mathcal{L}_{eff} \prec \frac{\mathrm{m}^{2}_{\mathrm{i}}}{4\mathrm{m}_{\mathrm{Ri}}} \overline{\nu}^{c}_{Li} \nu_{Li}$$

Equivalenly, diagonalize the mass matrix in ν_L-ν_R basis

$$\begin{bmatrix} 0 & m \\ m & m_R \end{bmatrix}$$

Leptogenesis

Generate L asymmetry from direct CP violation in right handed decay



Net effect (2 families needed):

$$\varepsilon = \frac{\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H)}{\Gamma(N_1 \to \nu_i H) + \Gamma(N_1 \to \bar{\nu}_i H)} \sim \frac{1}{8\pi} \frac{\mathrm{Im}(h_{13} h_{13} h_{33}^* h_{33}^*)}{|h_{13}|^2} \frac{M_1}{M_3}$$

Convert L into B via anomaly

–> Matter- Antimatter asymmetry

Summary

Neutrinos oscillate, refract, decohere,…

–> test sources and explore mixing matrix

The field is open with a well defined program:

- Complete the mixing matrix : θ_{13} and δ_{CP}
- $0\nu\beta\beta$: Dirac vs Majorana
- Test sources (Solar luminosity with neutrinos,…)

Expand to discovery regions :

-Low energies : solar, (s. DM searches), terrestrial, SN, …

-High energies : hadronic acceleration sources, CR connection

Be ready for surprises