Neutrinos,

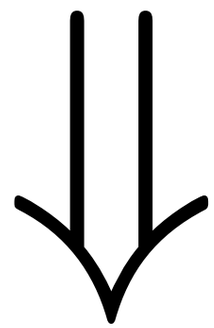
In and Beyond the Standard Model:

Stephen Parke
Fermilab

NEUTRINO MASS:

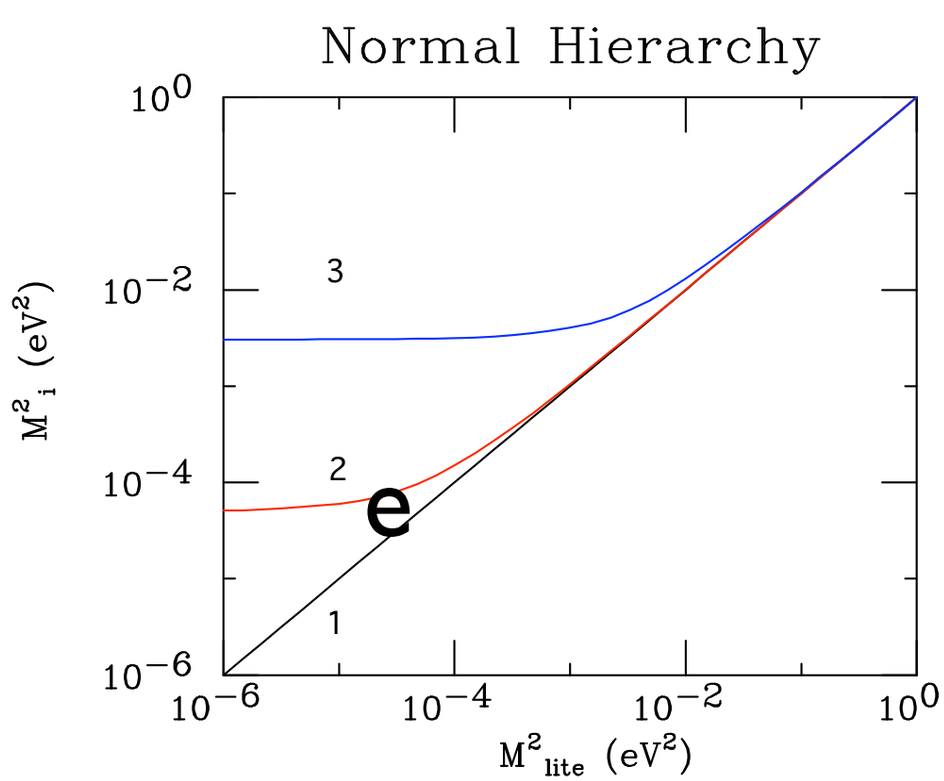
$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad L/E = 500\ km/GeV$$

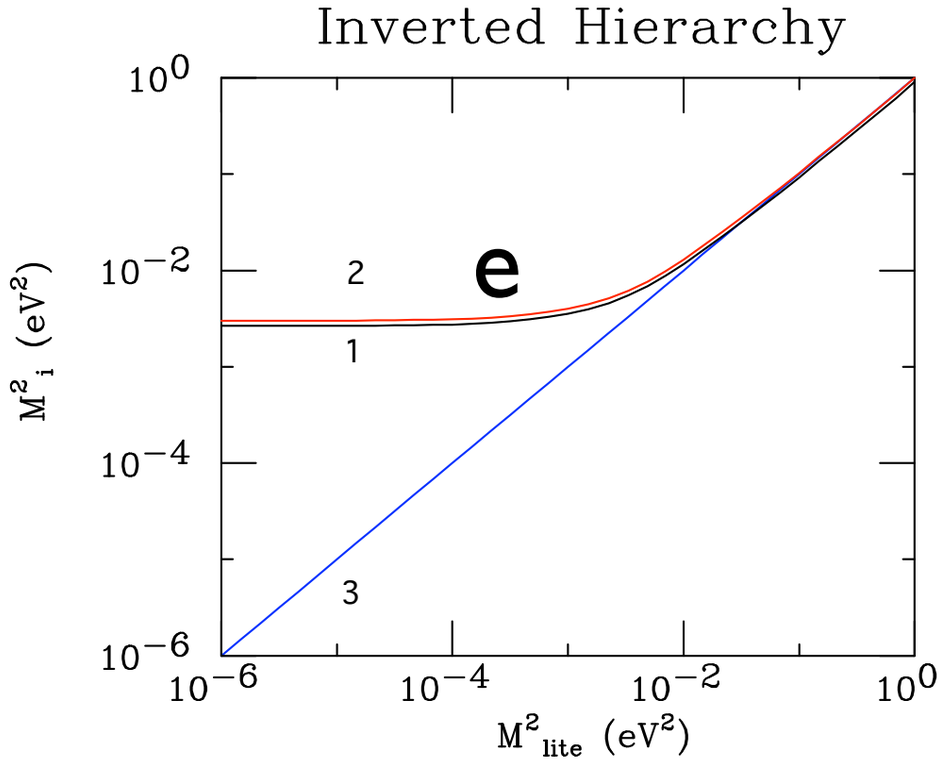
$$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2 \qquad L/E = 15\ km/MeV$$



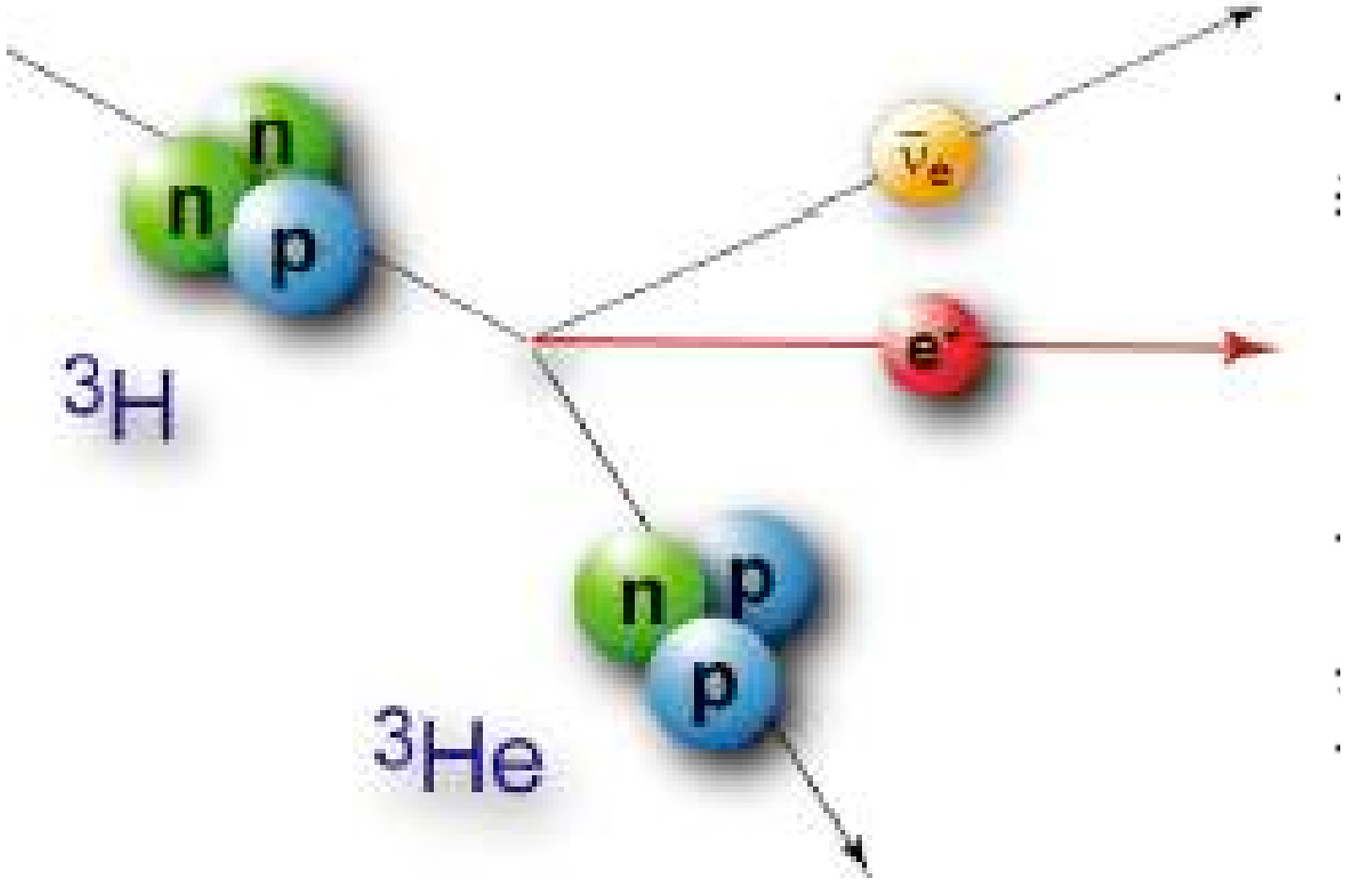
$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$

Masses:



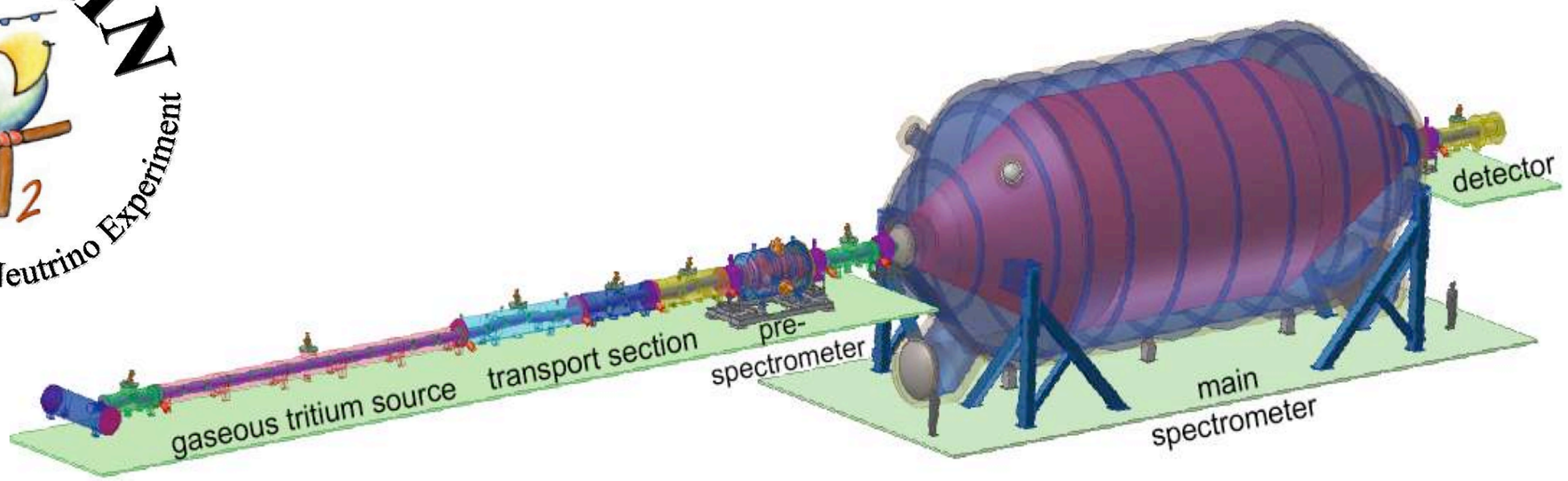


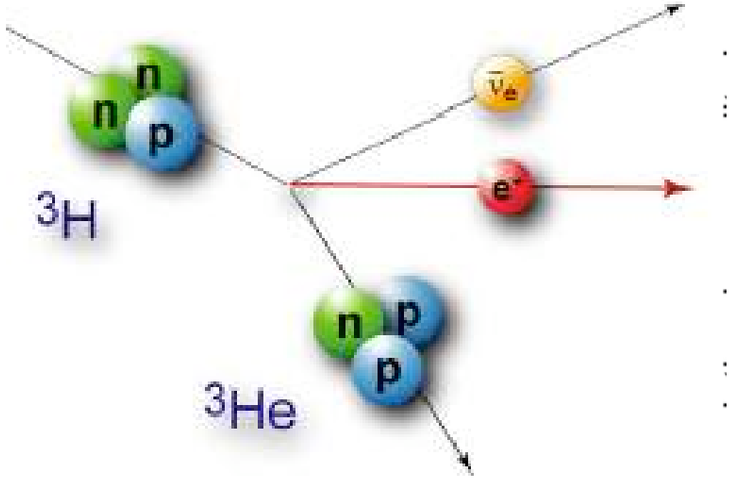
States 1 and 2 are ν_e rich.


n
n
p
^{3}H
$\bar{\nu}_e$
e$^-$
n
p
p
^{3}He

KATRIN

Karlsruhe Tritium Neutrino Experiment



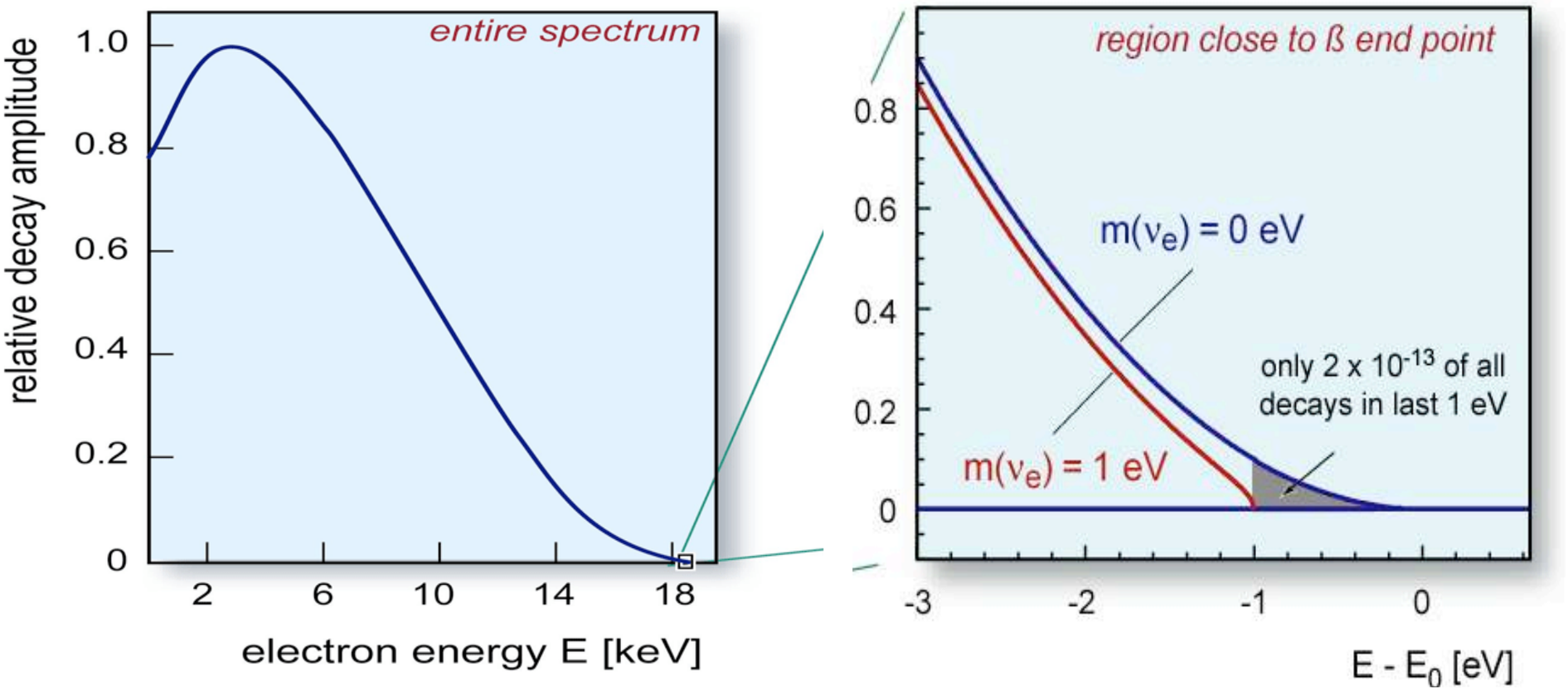


KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)

Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

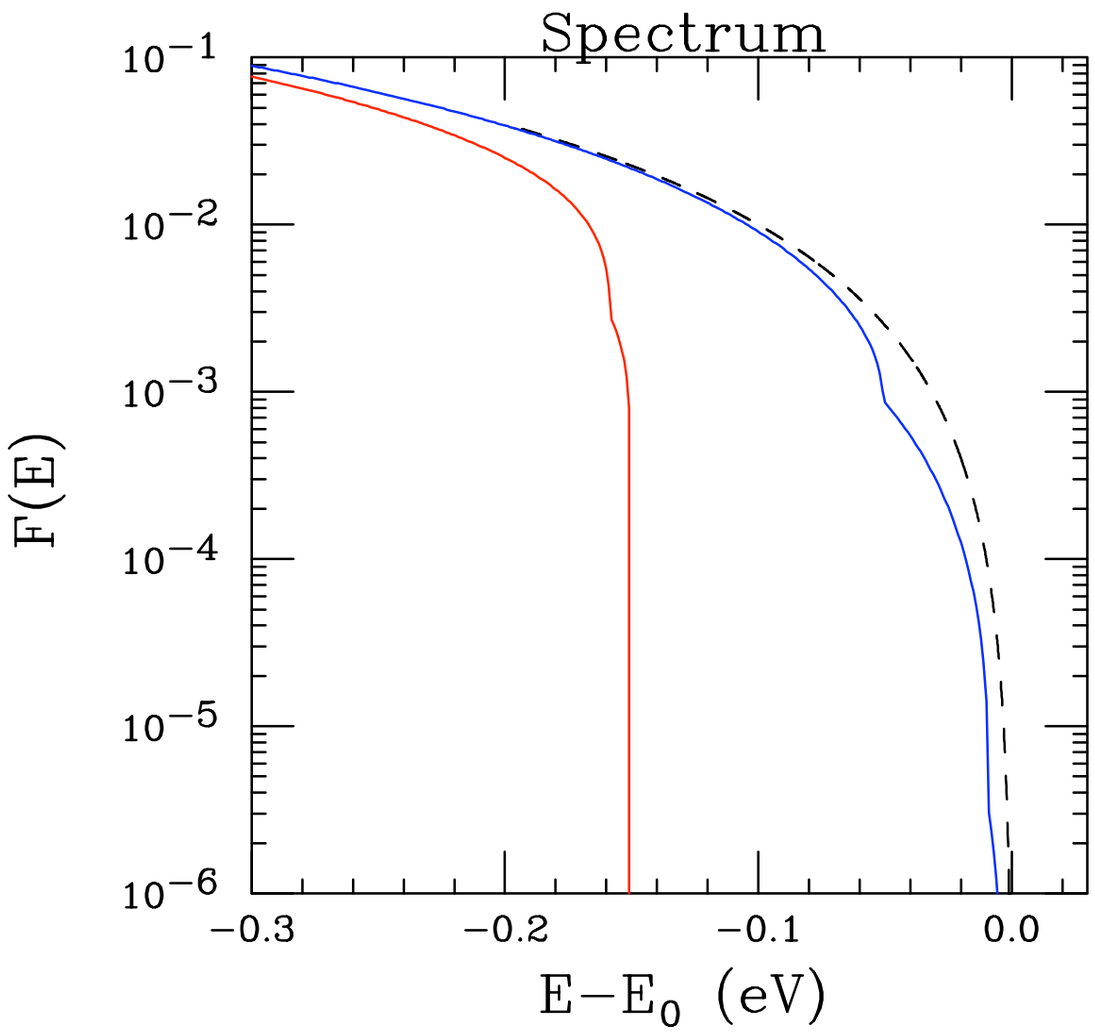


Decay Rate:

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$



E_0=18 KeV

Decay Rate:

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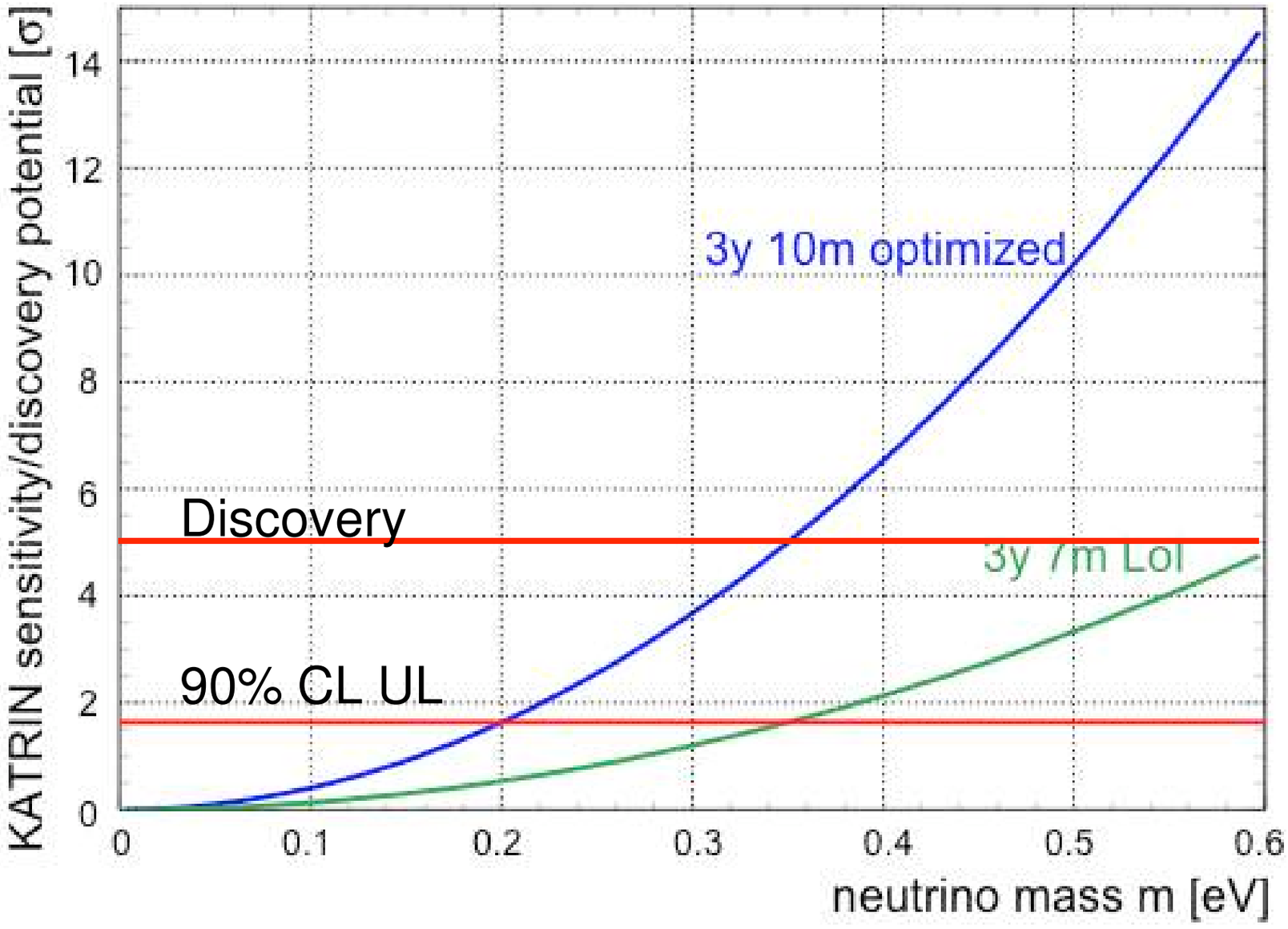
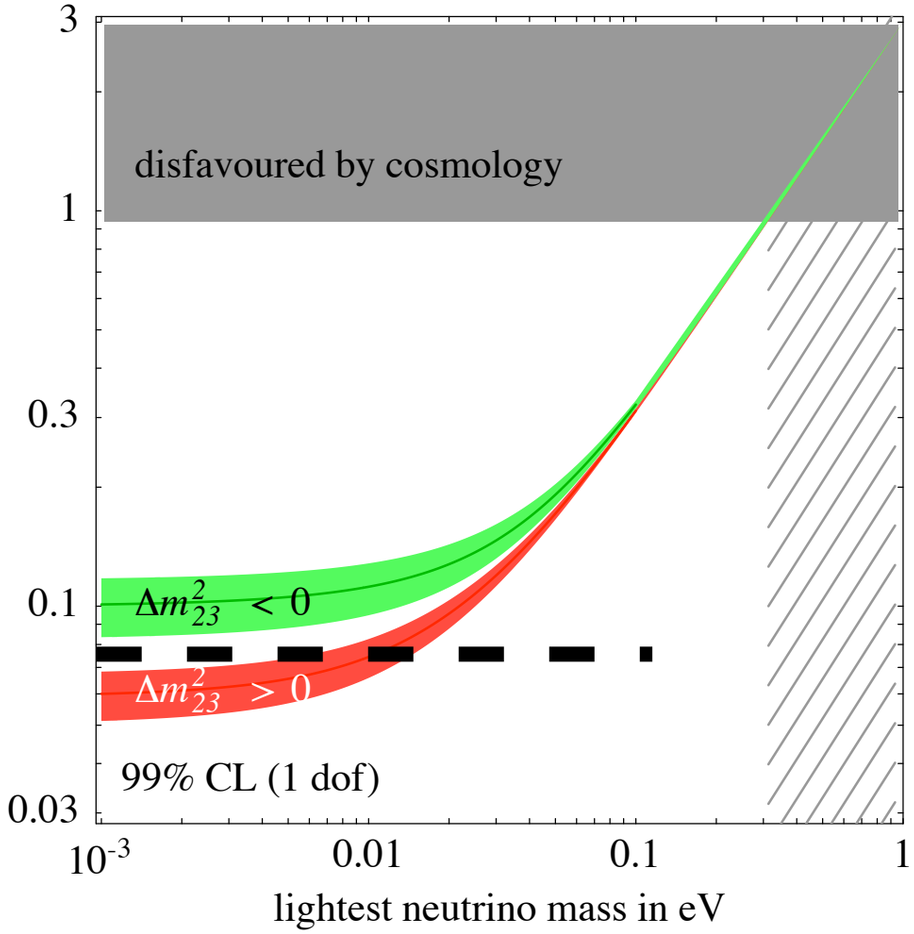
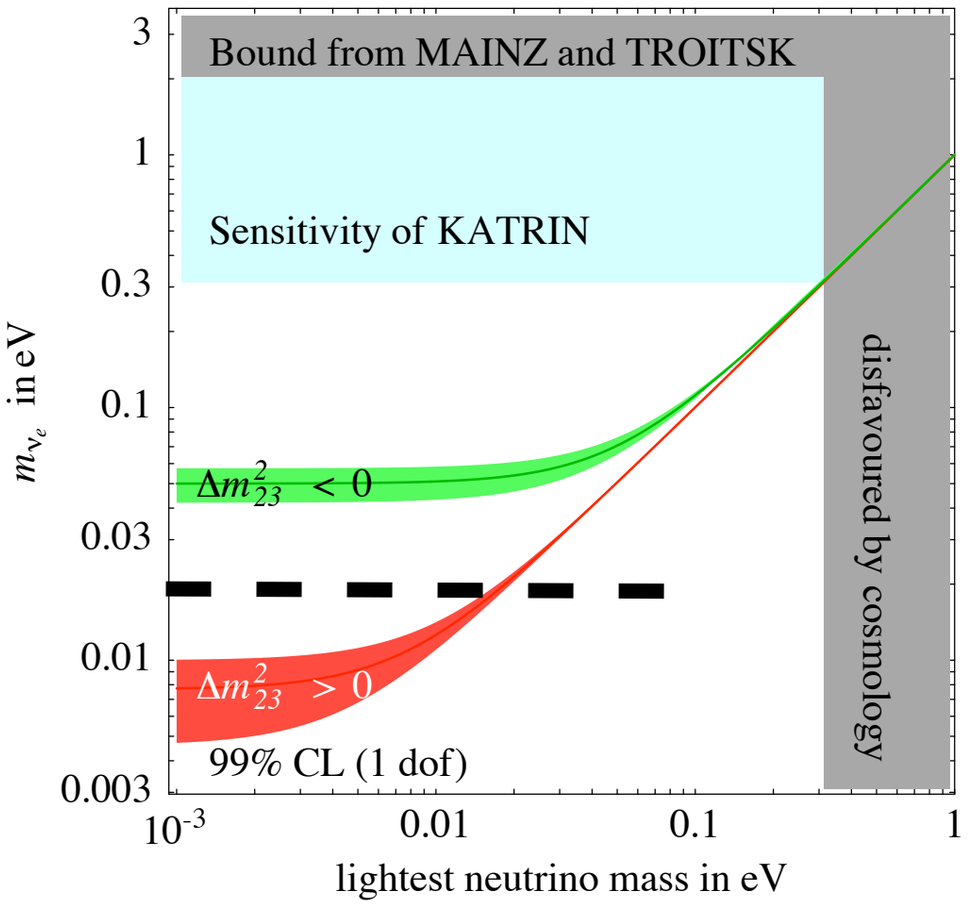


$\sum m_i$

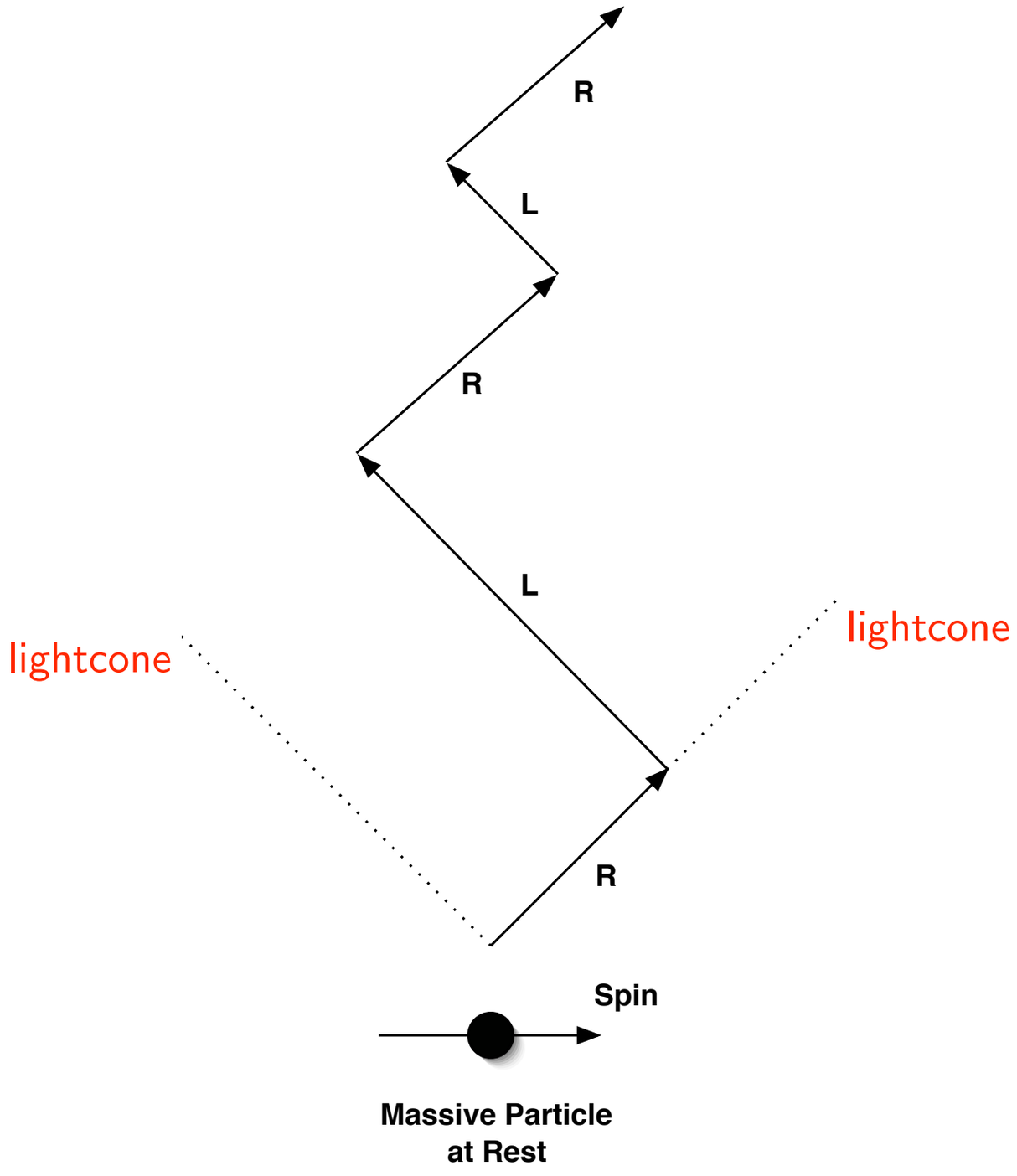




$\sum m_i \approx 60\ eV$ closes the Universe. Limit a few % of this number.

Similarly, if Tritium decay exp. (Hyper-Katrin)
could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, then Normal Hierarchy.

What is Fermion Mass ???


R
L
R
L
lightcone
lightcone
R
Spin
Massive Particle
at Rest

Fermion Masses:

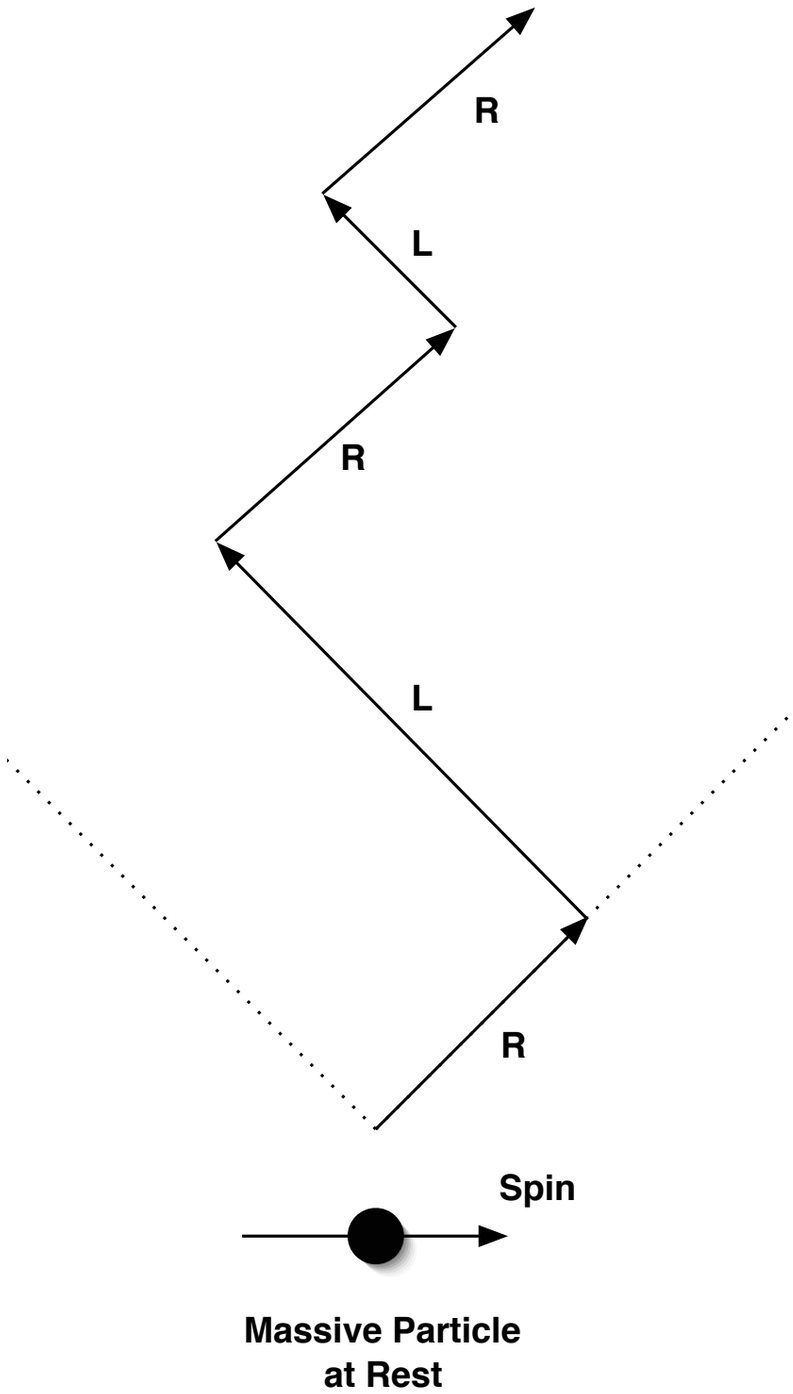
massless

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.



Mass couples L to R:

$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless left massless

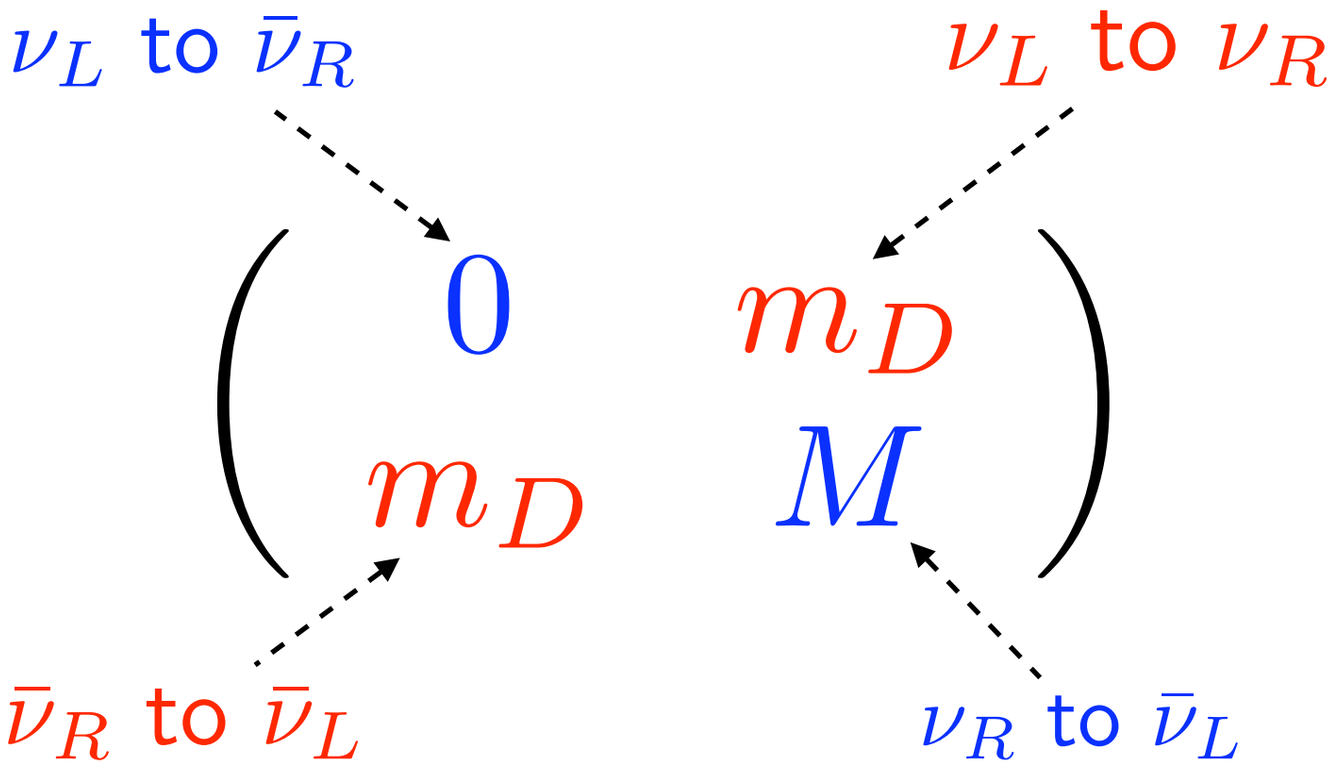
A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	ν_L	$\Leftrightarrow$	$\bar{\nu}_R$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	ν_R	$\Leftrightarrow$	$\bar{\nu}_L$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$



Two Majorana neutrinos with masses m_D^2/M and M

Seesaw:
Yanagida, Gell-man-Ramond-Slansky

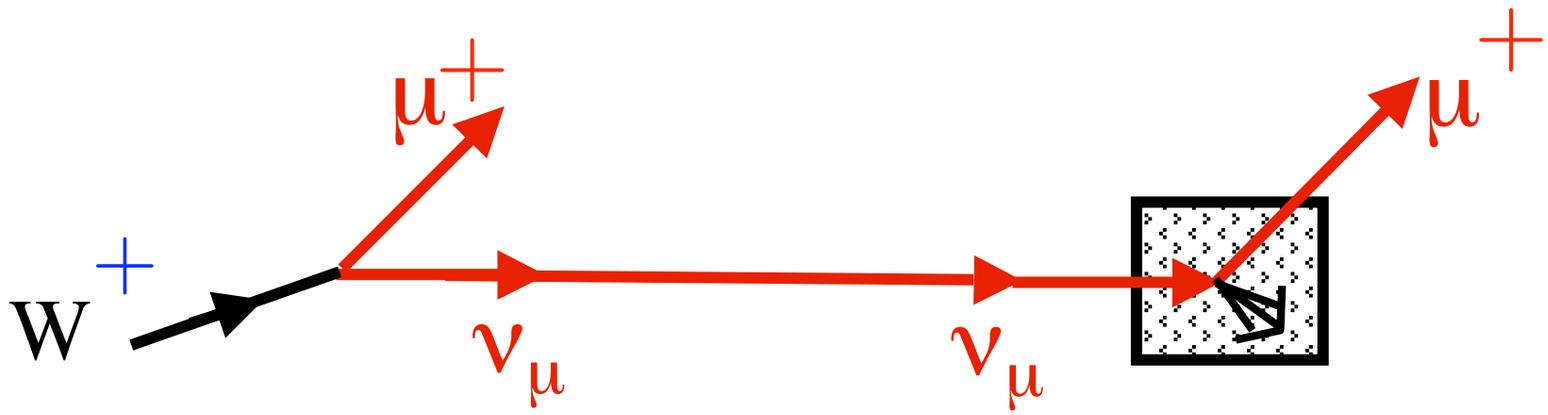
- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

miniBOONE ! later this year

For Majorana Neutrinos



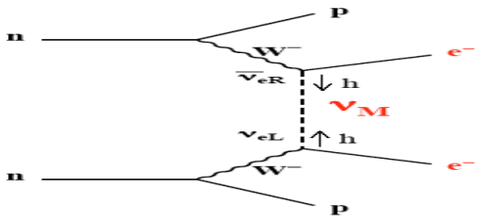
Not Observed

Allowed

BUT Suppressed by $\frac{m_\nu^2}{E^2} \sim 10^{-20}$!!!

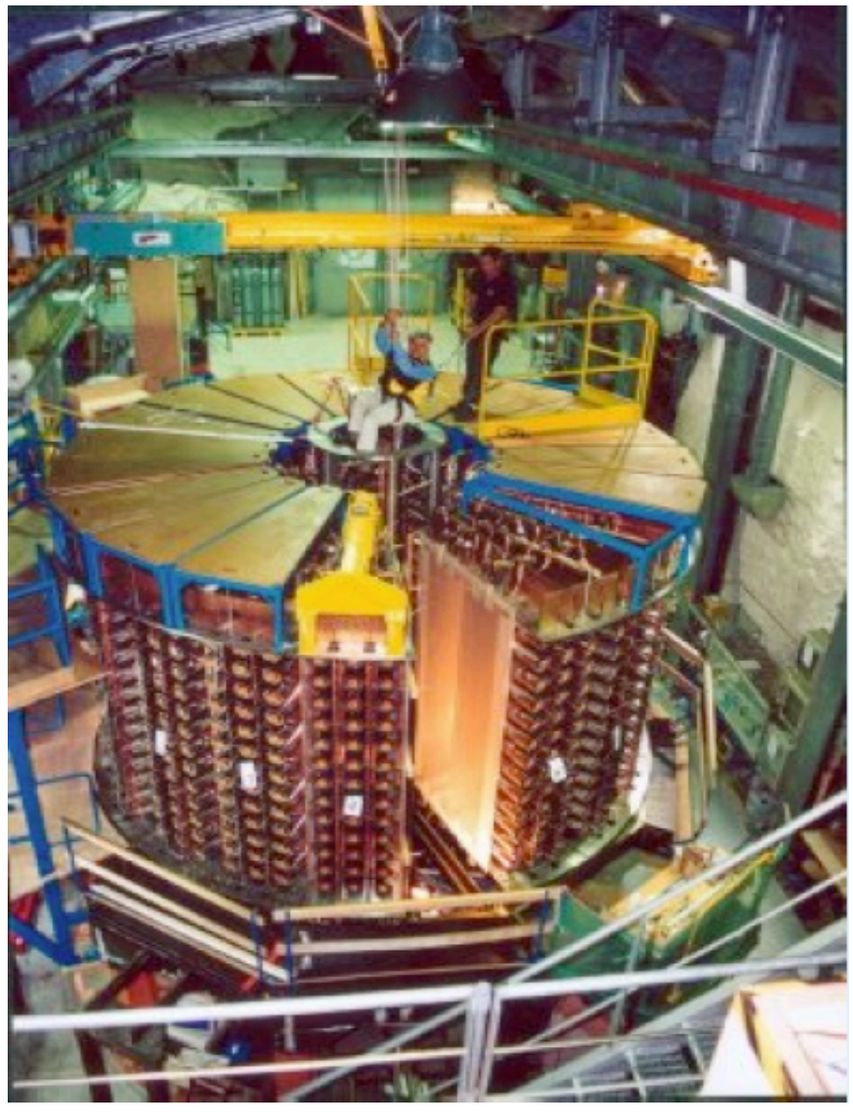
Neutrinoless double beta decay

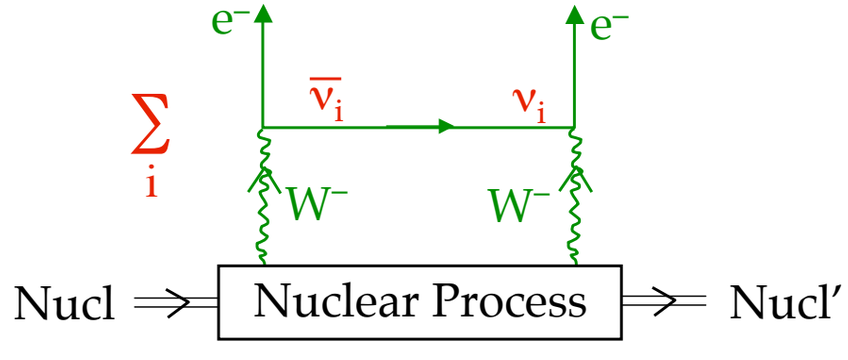
- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$





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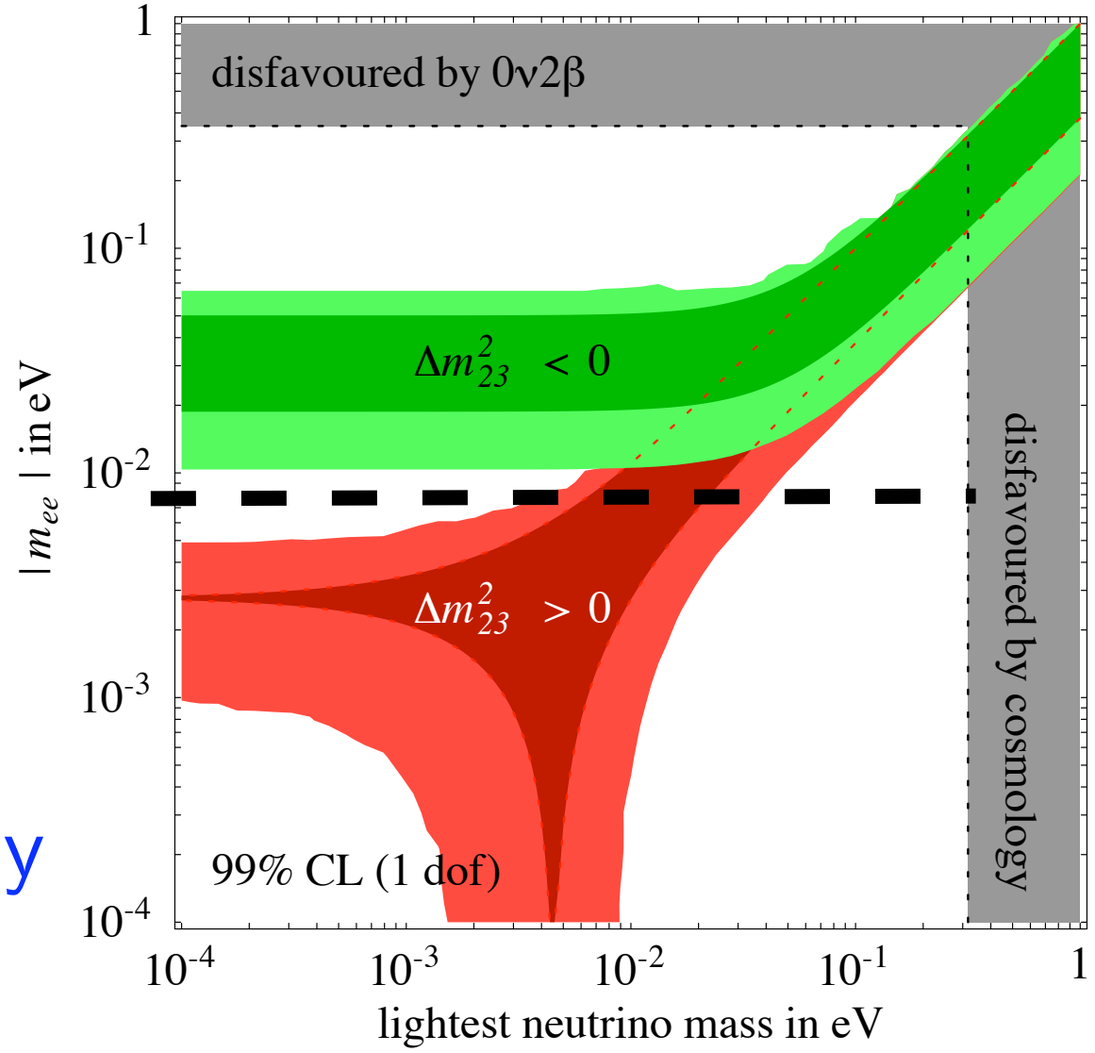
dividing point $m_{\beta\beta} \approx 10meV$ $\Rightarrow\Rightarrow$

Signal below $\sim$ 10 meV would imply Majorana and Normal Hierarchy!



Leptogenesis

Baryon Asymmetry is created by a Lepton Asymmetry produced by the decays of super heavy Majorana Neutrinos.

$$\frac{\Gamma(N\to l^+\phi^-)-\Gamma(N\to l^-\phi^+)}{\Gamma(N\to l^+\phi^-)+\Gamma(N\to l^-\phi^+)}$$

$\Gamma(N \to l^{\pm}\phi^{\mp})$ depends on the Majorana Phases in the MNS mixing matrix.

$$B_{now} = \tfrac{1}{2}(B-L) + \tfrac{1}{2}(B+L) = \tfrac{1}{2}(B-L)_{ini} = -\tfrac{1}{2}L_{ini}$$

$$\tfrac{1}{2}(B+L) \to 0$$

SUMMARY I

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$	Atmos. L/E $\mu \leftrightarrow e$	Solar L/E $e \to \mu, \tau$	$0\nu\beta\beta$ decay
500km/GeV		15km/MeV	

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad \delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2$$

$$\sin^2\theta_{12} = 0.31 \pm 0.03$$

$$\sin^2\theta_{23} = 0.50 \pm 0.14$$

$$\sin^2\theta_{13} < 0.04$$

SUMMARY

neutrino mass $\Leftrightarrow$ flavor change

Unknowns:

- Majorana v Dirac
- Light Steriles ???
- Mass Hierarchy $m_3 > m_2 > m_1$ OR $m_2 > m_1 > m_3$
  using $|U_{e3}|^2 < |U_{e2}|^2 < |U_{e1}|^2$
- fraction of ν_e in ν_3 ($< 4\%$)
- Is CP violated ? $\sin\delta \neq 0$
- Mass of Heaviest Neutrino
- Mass of Lightest Neutrino
- New Interactions, Surprises !!!

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RESERVE BANK OF
NEW ZEALAND
100
GOVERNOR
LORD
RUTHERFORD
OF
NELSON
THIS NOTE IS LEGAL TENDER FOR
ONE HUNDRED
DOLLARS
100