Neutrino Oscillometry - Fancy neutrino oscillation experiments

(LOW ENERGY NEUTRINOS IN A BOX)

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Neutrino20010
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I:NOSTOS: SPHERICAL gaseous TPC's for detecting Earth or sky neutrinos

- A) LOW ENERGY NEUTRINOS
  (electron recoils from low energy neutrinos)
- B) A Network of
  Neutral Current Spherical TPC's
  for Dedicated
  SUPERNOVA NEUTRINO DETECTION

II. The LENA detector:

(Electron detection Liquid Ar)

Table I: Best fit values from global data (solar, atmospheric, reactor (KamLand and CHOOZE) and K2K experiments)

parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.23}_{-0.18}$	7.22–8.03	7.03–8.27
$\|\Delta m^2_{31}\|\ [10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36	0.27–0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

In (ν_e, e) detector all flavors contribute $\sigma_e(E_\nu, L, T_{th}) = \sigma_e(E_\nu, 0, T_{th})\, P(E_\nu, L; \nu_e \to \nu_e)$

- $\sigma_e(E_\nu, 0, T_{th})$ is the standard cross section in the absence of oscillation.
- The oscillation probabilities appear as:
- $P(\nu_e \to \nu_e) \approx 1 - \chi(E_\nu)$

  $\{\sin^2(2\theta_{12}) \sin^2[\pi(L \backslash L_{12})] +$

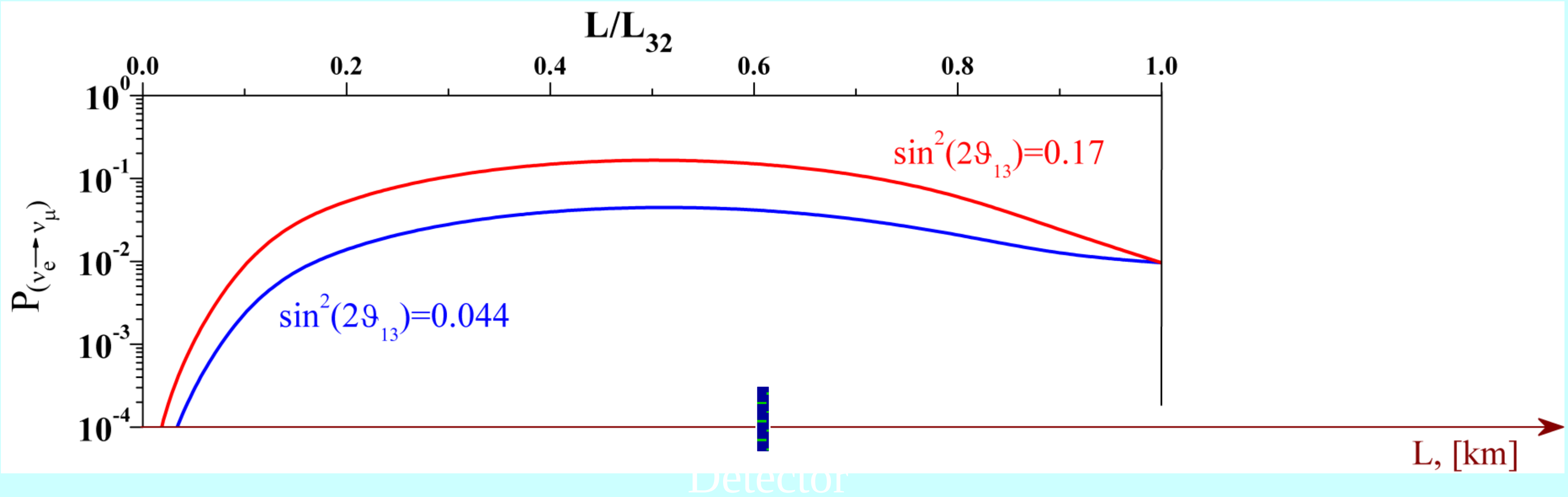
  $\sin^2(2\theta_{13}) \sin^2[\pi(L \backslash L_{13})]\}$
- $P(\nu_e \to \nu_\mu \text{ or } \nu_\tau) \approx \chi(E_\nu)$

  $\{\sin^2(2\theta_{12}) \sin^2[\pi(L \backslash L_{12})] +$

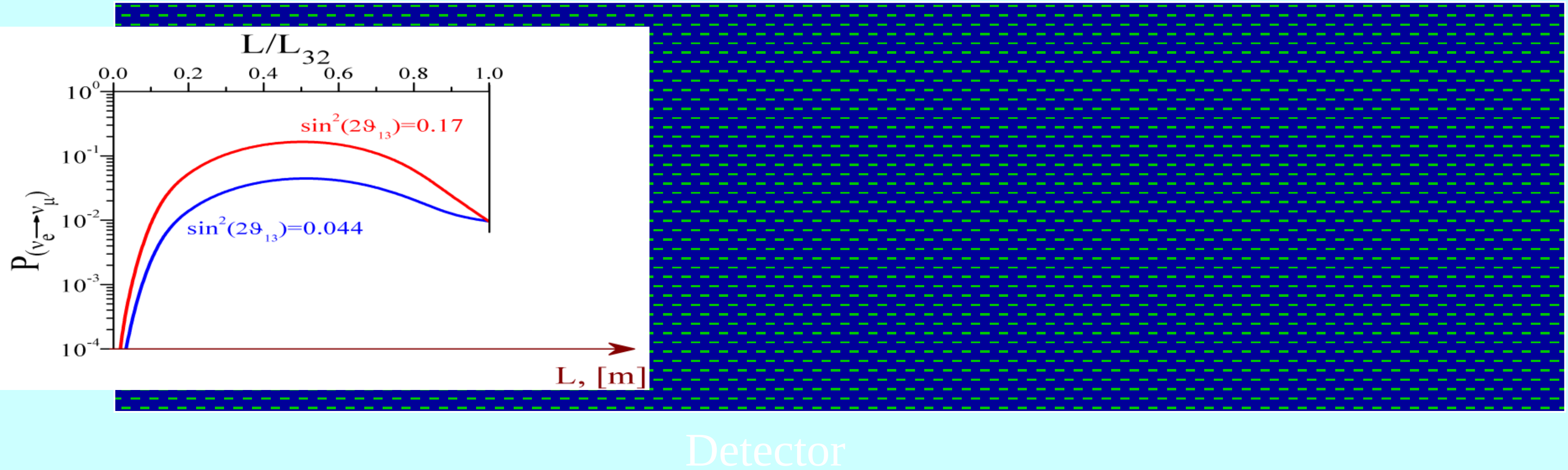
  $\sin^2(2\theta_{13}) \sin^2[\pi(L \backslash L_{13})]\}$

$L_{12} = 32\, L_{13}$ (oscillation lengths)

Long baseline (E_ν >> 1 MeV)→ L in [km]



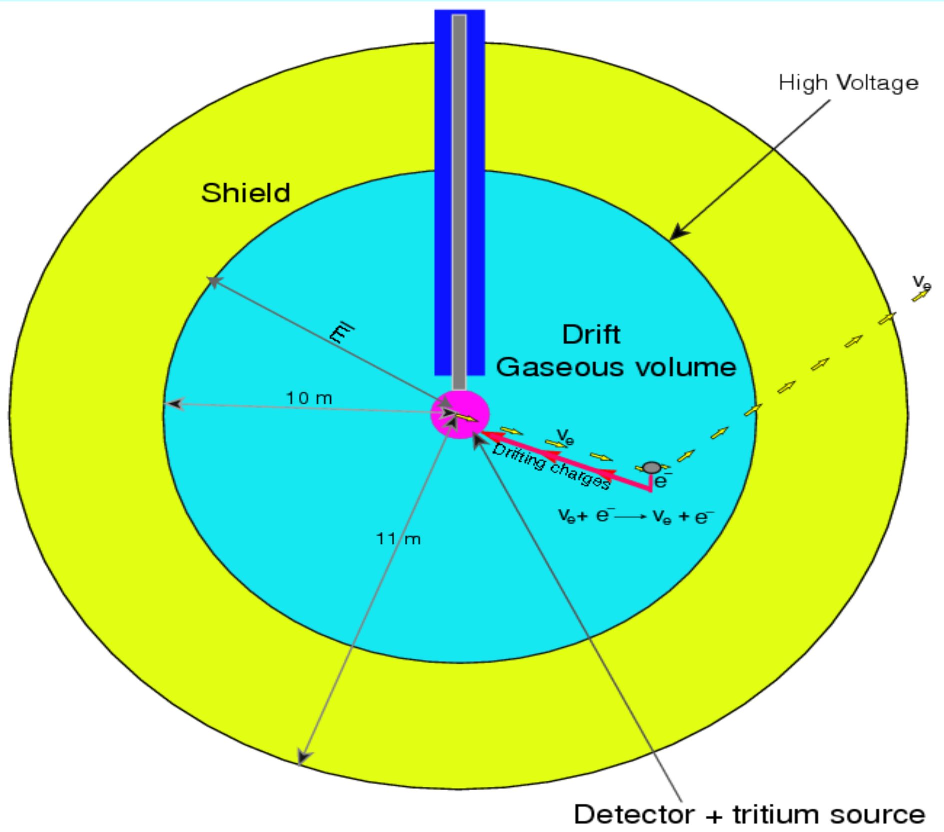
Short baseline (E_ν << 1 MeV)→ L in [m] - **oscillometry**



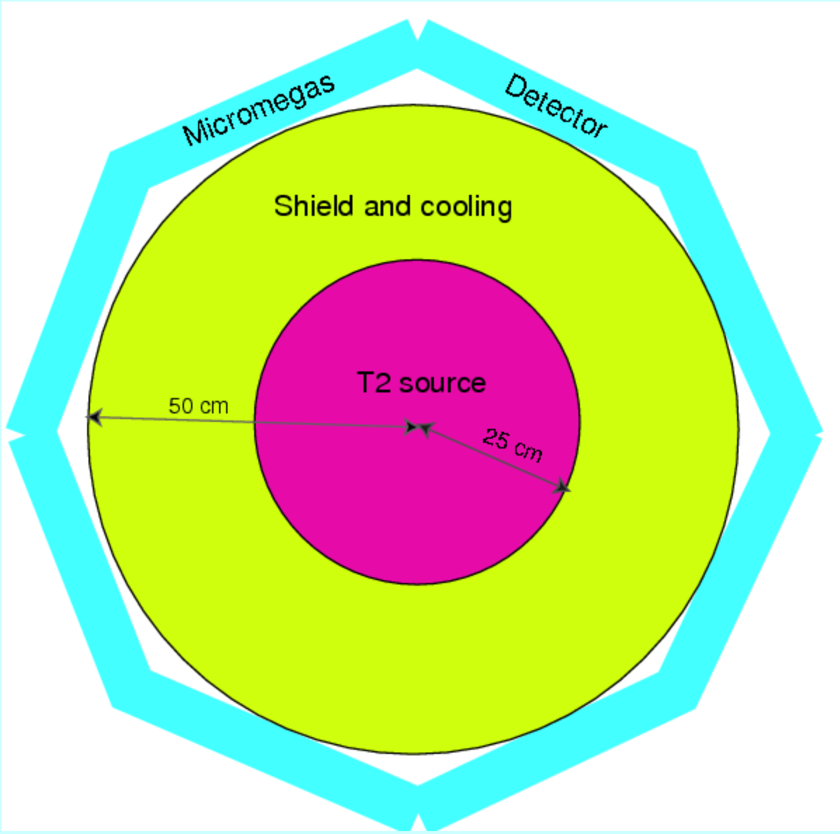
Part I:

The NOSTOS Set Up (the position is determined via a radial Electric field)

The detector



The neutrino source



II: Measure the Weinberg angle at very low momentum transfers

$$\left(\frac{d\sigma}{dT}\right)_{weak} = \frac{G_F^2 m_e}{2\pi}\left[\left(2sin^2\theta_W\right)^2 \right. \qquad (1.12)$$

$$+\left(1+2\sin^2\theta_W\right)^2\left(1-T/E_\nu\right)^2$$

$$\left. -2sin^2\theta_W\left(1+2\sin^2\theta_W\right)\left(m_e T/E_\nu^2\right)\right]$$

III : At low neutrino energies: The EM interaction competes with the weak

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \xi_1^2 \left(\frac{d\sigma}{dT}\right)_{Weak} \left(\frac{\mu_l}{10^{-12}\mu_B}\right)^2 \frac{0.1KeV}{T} \left(1 - \frac{T}{E_\nu}\right) \quad (1.15)$$

- With μ_ν the neutrino magnetic moment and $\xi_1 \approx 0.25$
- Thus we can obtain the limit: $\mu_\nu \leq 10^{-12}\,\mu_B$
- (present limit: $\mu_\nu \leq 10^{-10}\,\mu_B$)

Some sources of low energy Mono-energetic Neutrinos suitable for a spherical gaseous TPC

Nuclide	$T_{1/2}$	Q_e (keV)	E_ν (keV)	$L_{23}/2$ (m)	$E_{e,max}$ (keV)	weight gr	N_ν (s^{-1})
^{41}Ca	10^5y	421	417	208	260	400	10^{12}
^{55}Fe	**2.7 y**	**232**	**226**	**110**	**106**	**4000**	**$5\text{x}10^{17}$**
^{71}Ge	**11 d**	**232**	**222**	**110**	**100**	**300**	**$2\text{x}10^{18}$**
^{109}Cd	460 d	214	101	50	30	50	$5\text{x}10^{15}$
^{139}Ce	138 d	113	74	37	20	1.5	$2\text{x}10^{14}$
^{157}Tb	70 y	60.0(3)	9.8	5	0.4	200	$2\text{x}10^{14}$
^{163}Ho	4500 y	$\approx$ 2.6	$0.5 - 2.6$	0.2-1.3	$\leq$ 0.03	250	$5\text{x}10^{12}$
^{193}Pt	50y	568.0(3)	44(70%) 54(30%)	22 27	6.5 9	300	5×10^{14}

The number of events for a spherical gaseous detector (source at the origin)

The number of events between L and $L + dL$ is given by:

$$dN = N_\nu n_e \frac{4\pi L^2 dL}{4\pi L^2} \sigma(L, x, y_{\text{th}}) = N_\nu n_e dL \sigma(L, x, y_{\text{th}}) \qquad (5.22)$$

or

$$\frac{dN}{dL} = N_\nu n_e (L, x, y_{\text{th}}), \quad x = \frac{E_\nu}{m_e}, \quad y_{\text{th}} = \frac{(T_e)_{\text{th}}}{m_e} \qquad (5.23)$$

To compare with other geometries we rewrite this as follows:

$$R_0 \frac{dN}{dL} = R_0 N_\nu n_e \sigma(L, x, y_{\text{th}}) \qquad (5.24)$$

or

$$R_0 \frac{dN}{dL} = \Lambda g_s(L/R_0) \tilde{\sigma}(L, x, y_{\text{th}}), \quad g_s(L/R_0) = 1 \qquad (5.25)$$

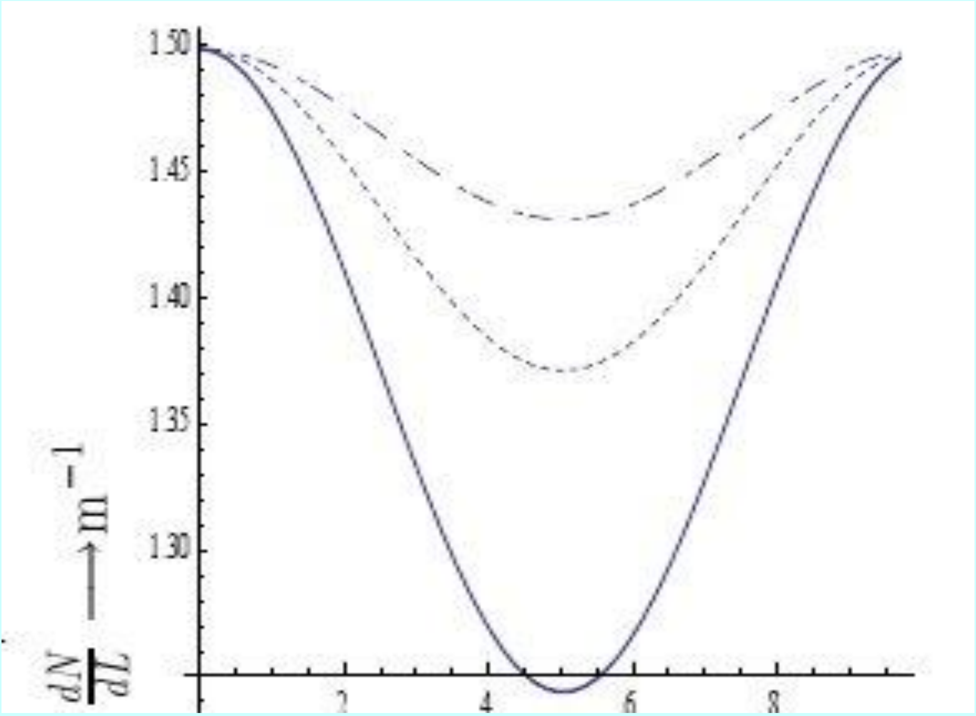
where

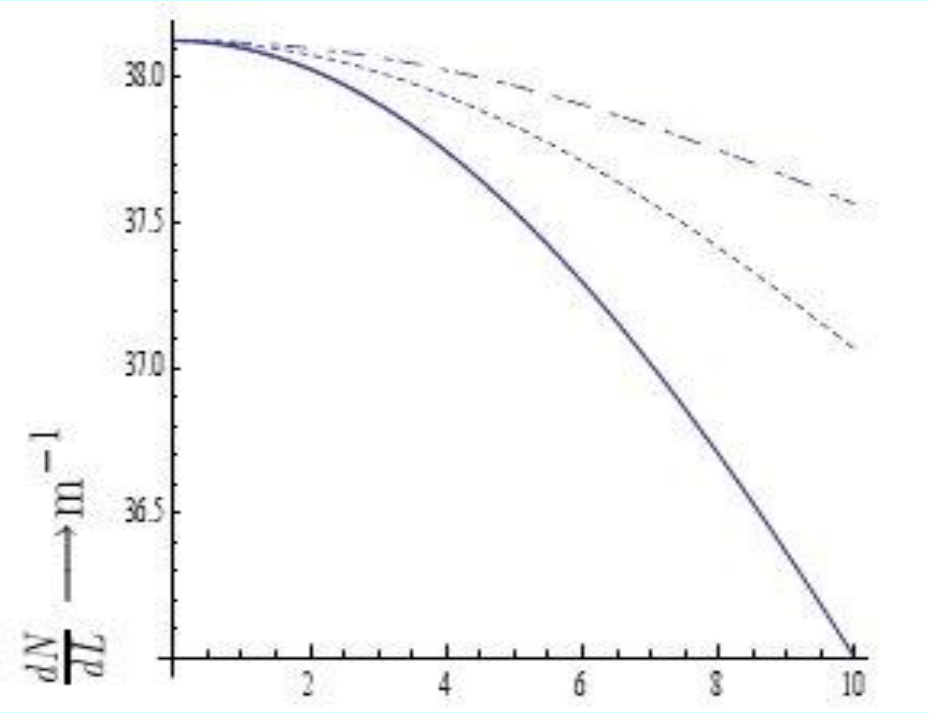
$$\Lambda = \frac{G_F^2 m_e^2}{2\pi} R_0 N_\nu n_e \qquad (5.26)$$

Event rate dN/dL(per m), P=10Atm, Ar target for m=0.2 and 0.3 kg of source

T_{th}=0.1keV

L=10m, E_ν=9.8 keV (^{157}Tb) **L=50m, E_ν=50 keV (^{193}Pt)**



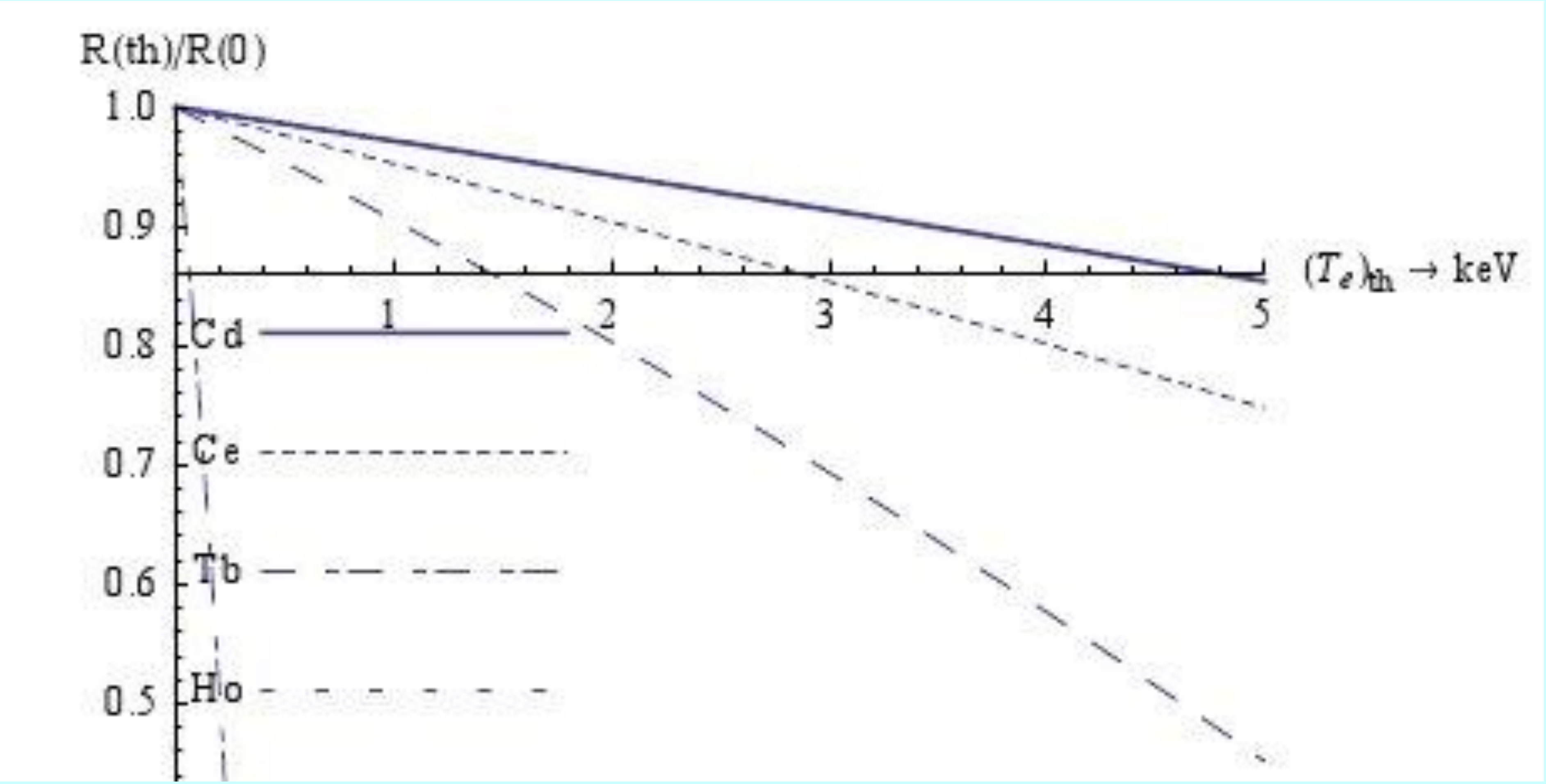


L->m L->m

Other detectors and geometries

- The gaseous TPC detector has many advantages. However
- The gas has small density→ few events
- One may have to go to higher neutrino energies to obtain a sizable cross sections. Longer L require large spheres, which are hard to construct.
- So one may have to consider cylindrical liquid detectors, which exist for other purposes.

Threshold effects for gaseous spherical TPC: Under Control



LENA detector layout

Mono-energeic Neutrino sources suitable for the LENA detector

Nuclide	$T_{1/2}$ d	m_t (kg)	t_{ir} (d)	$E_{e,max}$ (keV)	m_s(g) (g)	N_ν (s^{-1})	N_{ir}
^{37}Ar	35 d	0.36 (^{36}Ar)	30	617	2.2	10^{16}	5
^{51}Cr	27.7 d	15 (^{50}Cr)	30	560	209	7×10^{17}	5
^{75}Se	120 d	1000	100	287	1475	8×10^{17}	3
^{85}Sr	64.9 d	1000	60	363	8.64	7.5×10^{15}	5
^{103}Pd	17 d	1000	10	315	11.5	3×10^{16}	5
^{113}Sn	115 d	1000	100	436	17.3	6.4×10^{15}	3
^{121}Te	16.8 d	1000	10	280	1.6	3.8×10^{15}	5
^{145}Sm	340 d	1000	300	340	480	4.7×10^{16}	1
^{169}Yb	32 d	1000	30	304	3000	2.8×10^{18}	5

Cylindrical geometry (2 coordinates)

Spherical source at the top base of the cylinder

The number of events between r and $r+dr$ and z and $z+dz$ is now given by:

$$dN = N_\nu n_e \frac{2\pi r dr dz}{4\pi(r^2+z^2)} \sigma(\sqrt{r^2+z^2}, x, y_{\rm th}) \qquad (5.27)$$

which yields

$$\frac{dN}{d\rho d\zeta} = N_\nu n_e R_0 \frac{1}{2} \frac{u\rho}{\zeta^2+u^2\rho^2} \sigma(\frac{R_0}{u}\sqrt{\zeta^2+u^2\rho^2}, x, y_{\rm th}) \qquad (5.28)$$

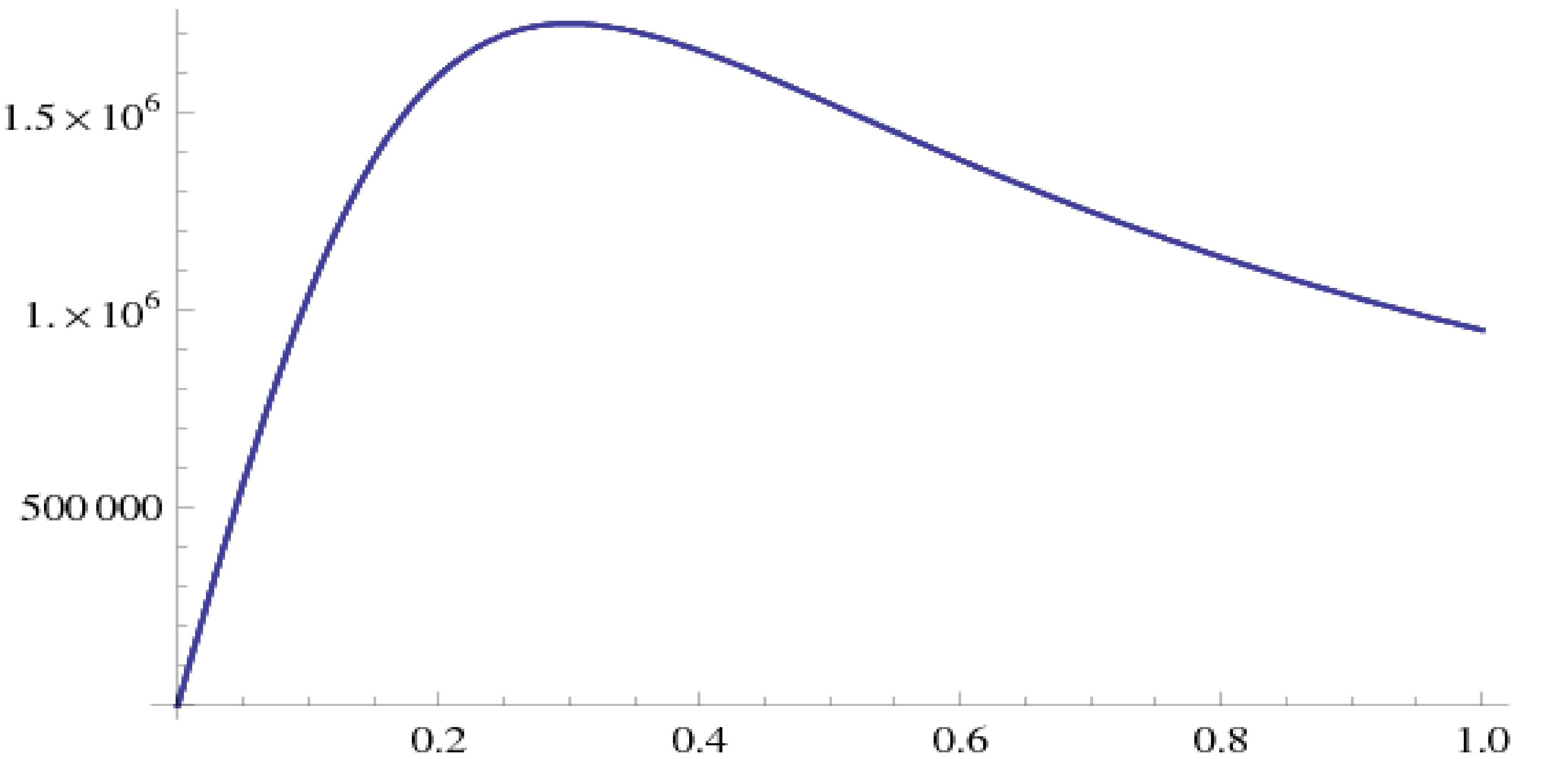
where R_0 is the radius of the cylinder, $u = R_0/h$ (h is the length of the cylinder), $\rho = r/R_0$ and $\zeta = z/h$. This can be written as

$$\frac{dN}{d\rho d\zeta} = \Lambda g_c(\rho, \zeta, u, R_0) \frac{1}{2} \tilde{\sigma}(\frac{R_0}{u}\sqrt{\zeta^2+u^2\rho^2}, x, y_{\rm th}), \qquad (5.29)$$

$$g_c(\rho, \zeta, u, R) = \frac{u\rho}{\zeta^2+u^2\rho^2} \quad , \quad \Lambda = \frac{G_F^2 m_e^2}{2\pi} R_0 N_\nu n_e \qquad (5.30)$$

Note that the geometric factor $g_c(\rho, \zeta, u, R)$, which is absent in the spherical geometry, in this case is less than unity.

The event rate dN/dρdζ (arbitrary units) for ζ=0.05(z=4.5m) as a function of ρ. Η ταλάντωση (εξάρτηση από τη γωνία θ_{13}) δεν διακρίνεται.

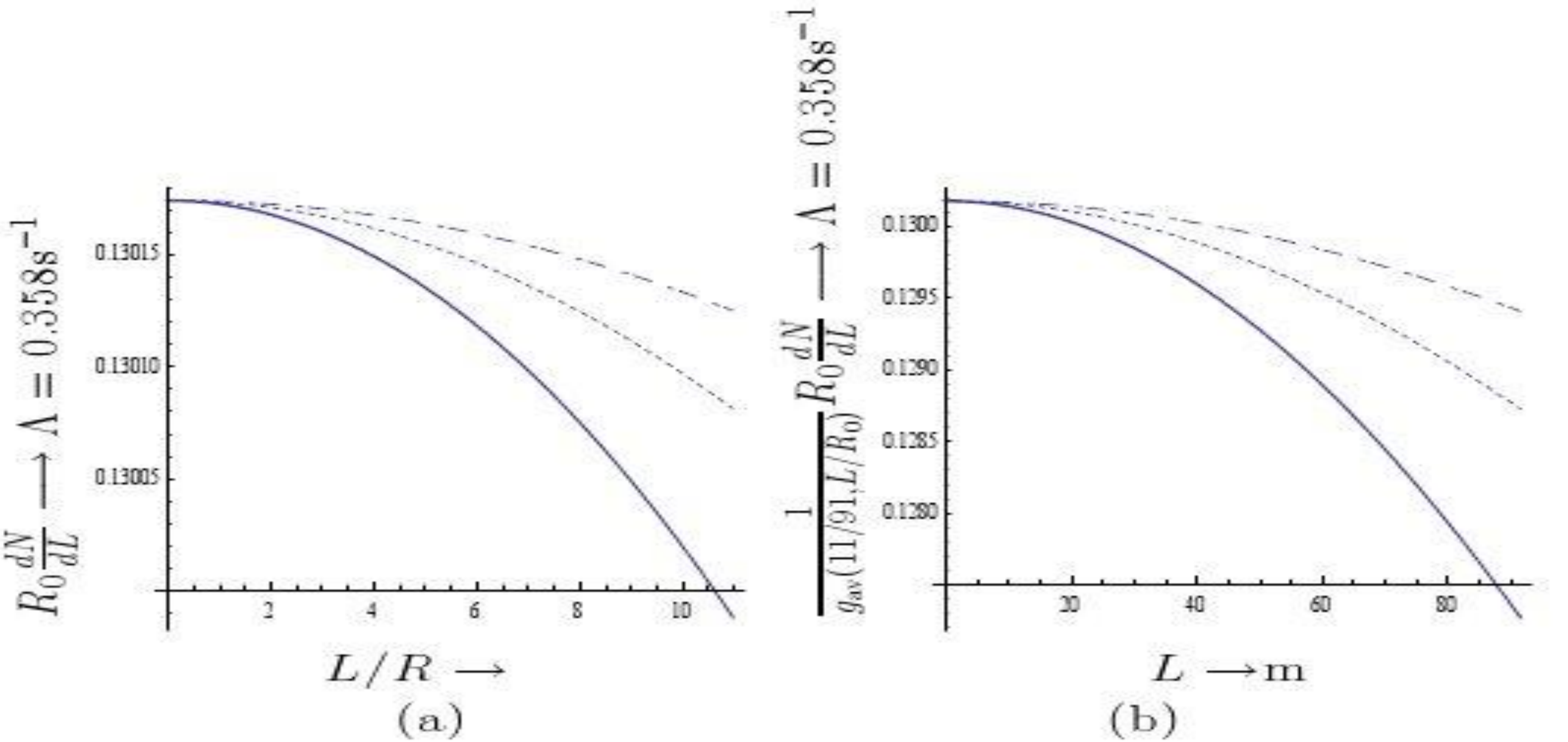


What next? An analysis trick!

- We divide the measured rate by the calculated geometric factor $g_c(\rho,\zeta,u,R)$, R the cylinder radius, h the length of the cylinder, $u=R/h$
- Plot the resulting expression as a function of $\zeta=z/h$ for various values of $\rho=r/R$
- Make the plot in units of $\Lambda=(G_F m_e)^2/(2\pi)RN_\nu n_e$ (dimensions inverse time)

The event rate /geometric factor: ^{51}Cr (E_ν=763 keV) $n_e=2\times10^{29}\ m^{-3}$

T_{th}=500keV ρ=0.4 (a), ρ=1.0 (b)



Can we do better?

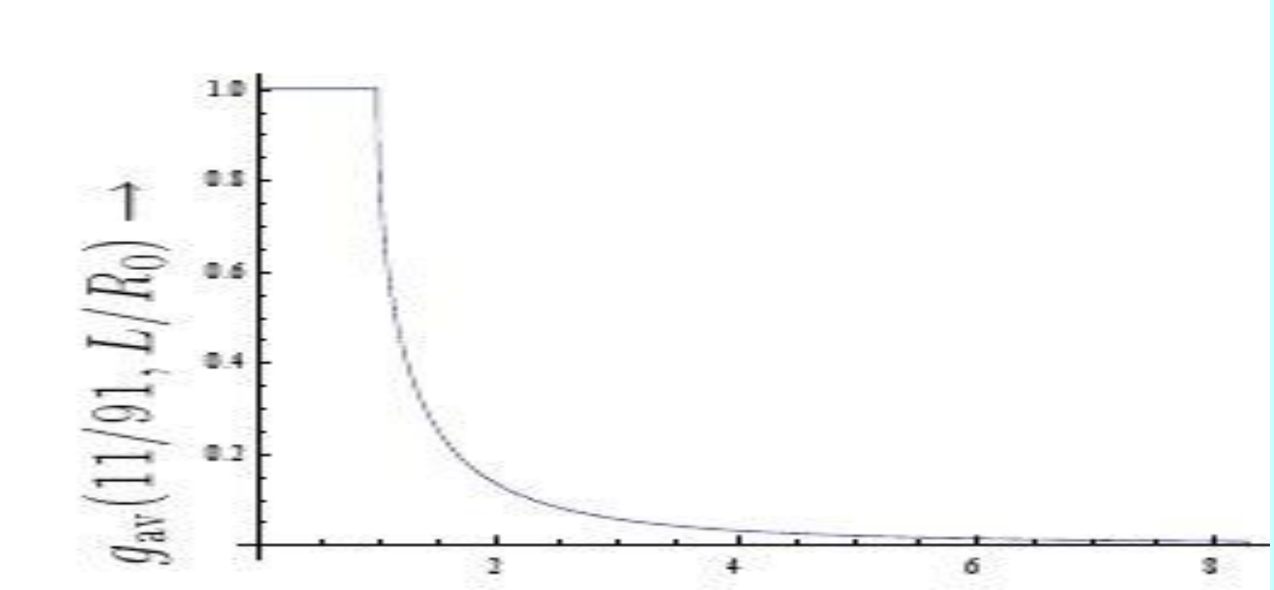
- The experimentalists would still like to analyze the data in terms of a single variable L (the source detector distance).
- How do we do it without sacrificing useful information?
- We tried the change of variables

$$(r\ ,\ z) \to (L, \varphi)$$ and integrate over φ.

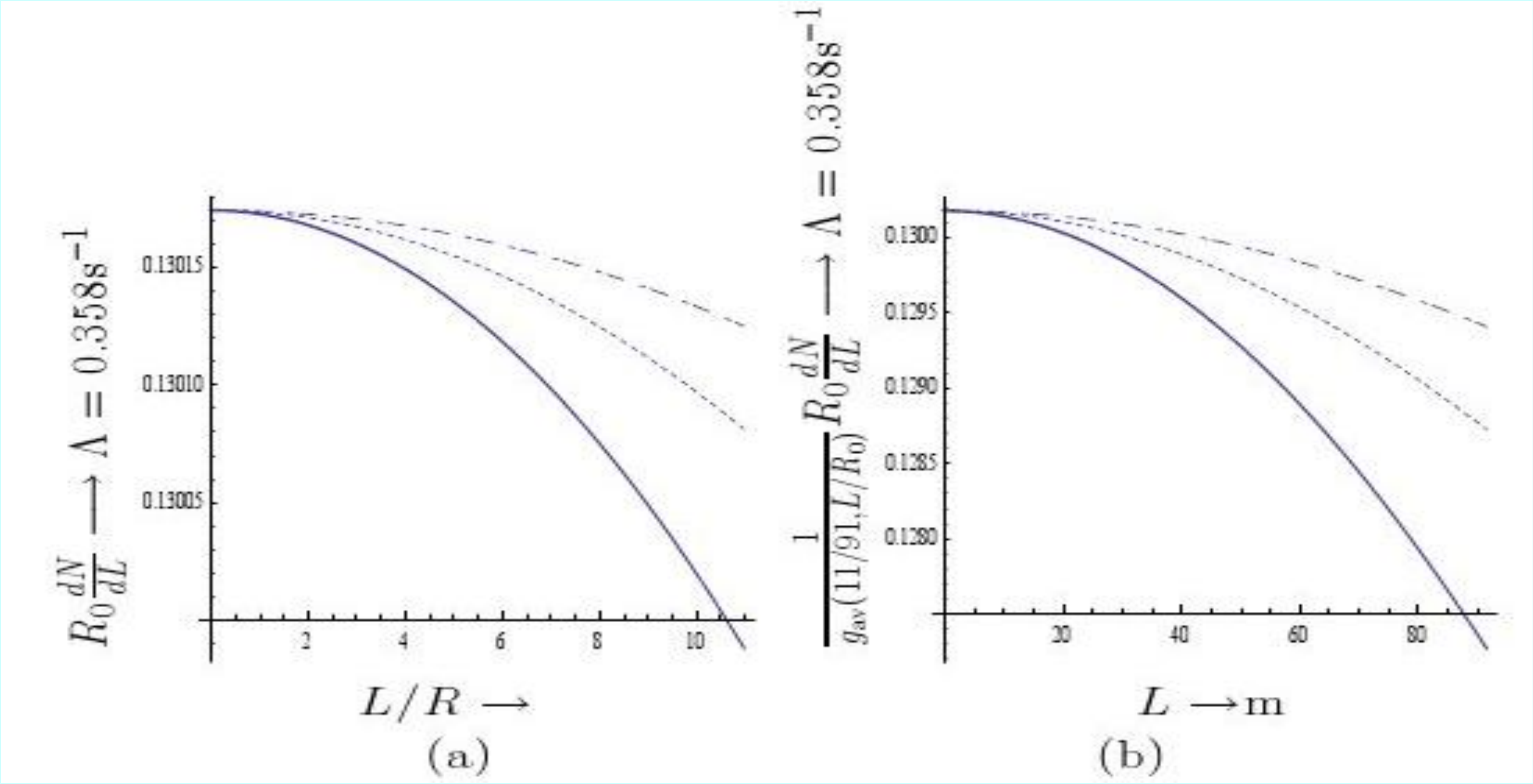
The event rate in terms of L (u=L/R, u=R/h=11/91)

$$R_0 \frac{dN}{dL} = N_\nu n_e R_0 \frac{1}{2} g_{\rm av}(u, L/R_0) \sigma(L, x, y_{\rm yh})$$
$$= \Lambda \frac{1}{2} g_{\rm av}(u, L/R_0) \tilde{\sigma}(L, x, y_{\rm yh} \qquad (7.36)$$

where $g_{\rm av}(u, L/R_0)$ is a geometric factor that takes care of the variation of the neutrino flux in the various positions described

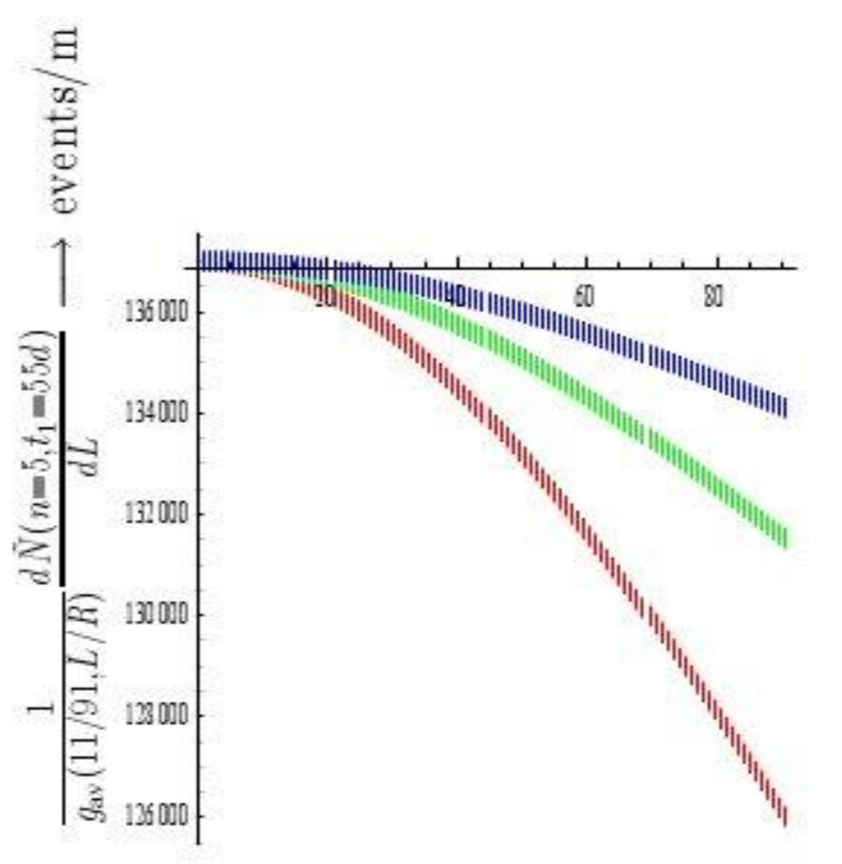


The rate (RdN/dL)/g_{av}(R/h,L/R) for ^{51}Cr (E_ν=753 keV) without the geometric factor (a) and with the geometric factor (b); $n_e = 2\times10^{29}\ m^{-3}$

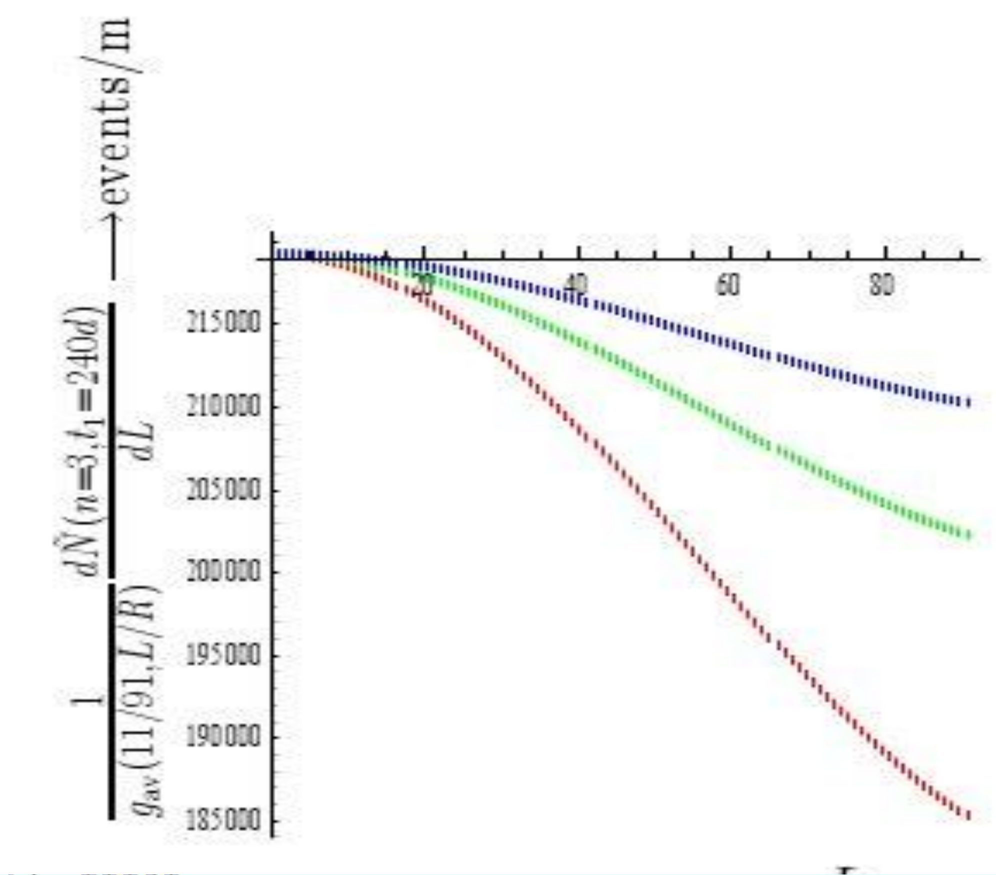


The rate $(R_0 dN/dL)/g_{av}(R_0/h, L/R_0)$ for ^{51}Cr (E_ν=753 keV) on the left & ^{75}Se (E_ν=450 keV) on the right. $n_e = 2\times10^{29}\ m^{-3}$; T_{th}=500keV

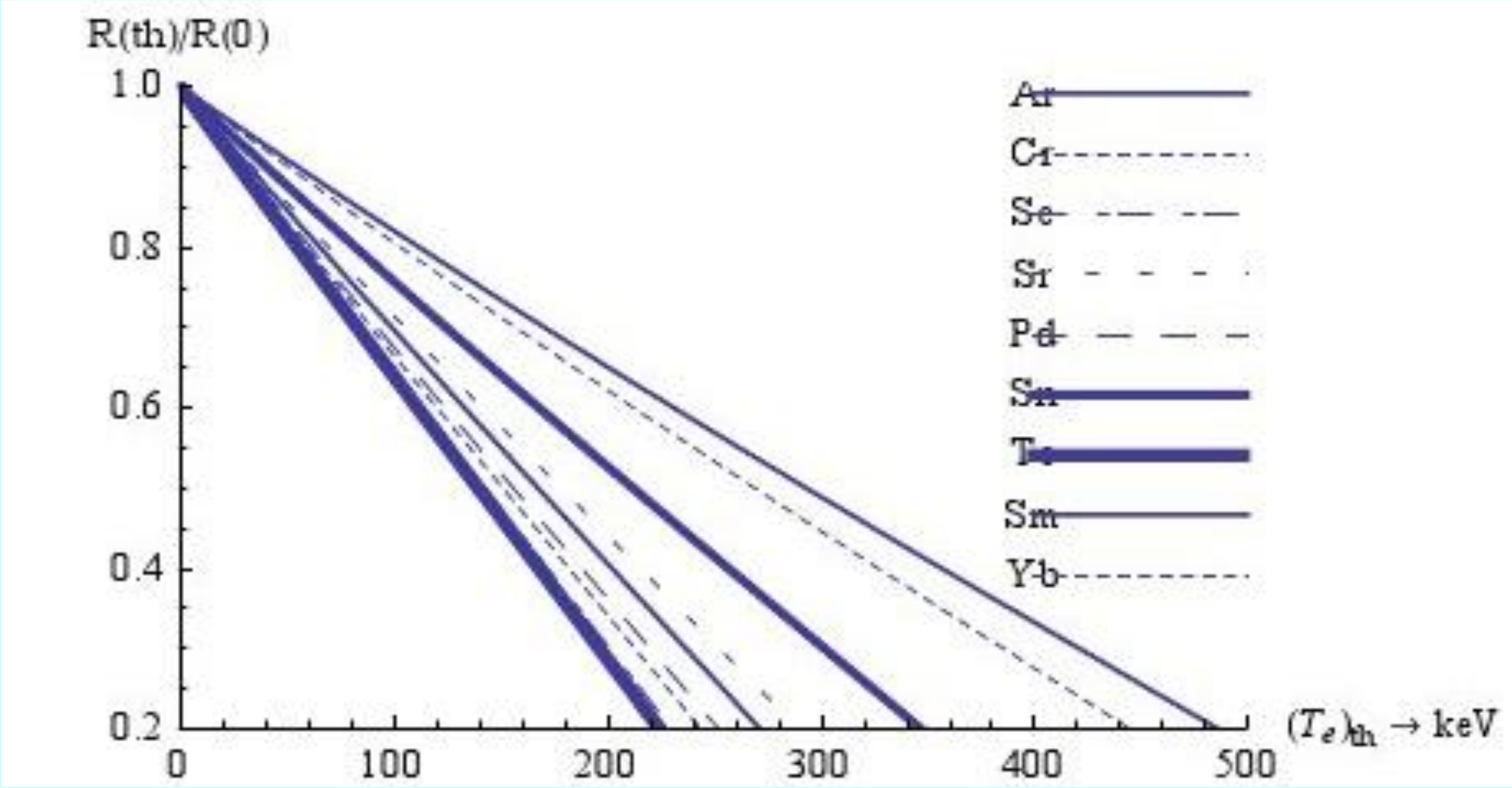
5 implantations 55 d each



3 implantations 240 d each



Threshold for the LENA detector – It needs improvement

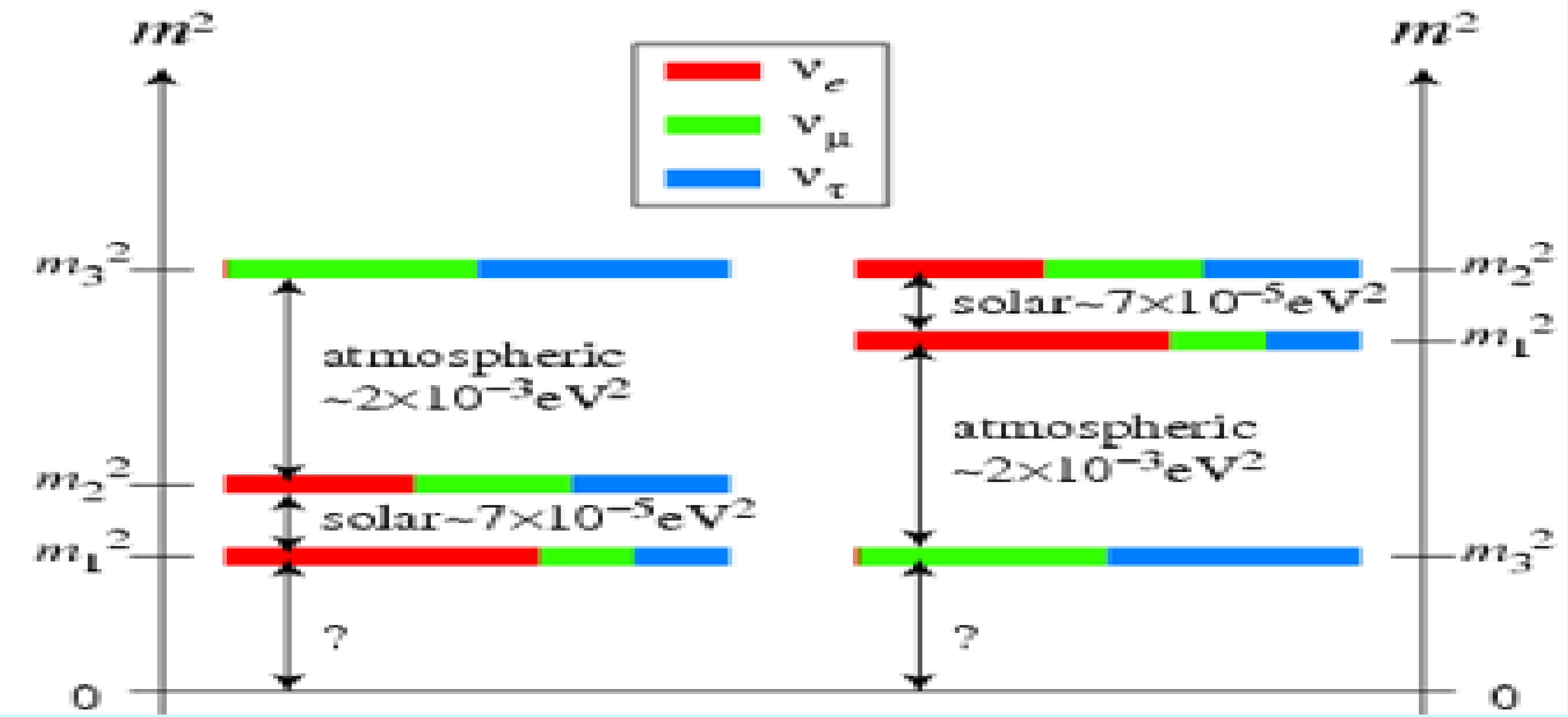


Conclusions:

- The discovery of neutrino oscillations gave neutrino physics and astrophysics a new momentum.
- The two mass square differences, except for a sign, are known
- The mixing angles θ_{12} and θ_{23} are understood.
- The angle θ_{13} and the phase δ_{13} are unknown.
- Short Baseline Neutrino Oscillations like NOSTOS – LENA are complementary to other experiments (Double Chooze, T2K, Reno etc)
- NOSTOS-LENA experiments will unambiguously determine θ_{13}, provided it is not too small, since they do not suffer from the 8-fold ambiguity.

- THE END

Questions that cannot be answered by neutrino oscillations: The mass scale and the sign of Δm^2_{31} (normal vs inverted hierarchy or almost degenerate scenario)



Conclusions B

- The absolute scale of neutrino mass is still elusive. (neutrinoless double beta decay, triton decay, astrophysics may provide the answer)
- We do not know whether the neutrinos are Dirac or Majorana type particles (only neutrinoless double beta decay can settle this issue)
- Neutrinos may be the best probes for studying the deep sky and the interior of dense objects, like supernovae. NOSTOS maybe a useful tool.
- Shall we ever see the neutrino background radiation? Will we see it before the gravitational background radiation?

Neutrino mass terms- Dirac mass term M_D

1. Dirac mass terms like in the charged fermions:

$$\bar{\nu}_L^0(\mathcal{M}_D)\nu_R^0 + H.C.$$

- It is absent in the SM (the right handed neutrino does not exist).
- If this is the only mass term, the **neutrinos are Dirac particles**.
- It cannot occur by itself (in GUT's the neutrino should be as heavy as the up-quarks).
- In extra dimensions one can have a small such matrix, but one also has Majorana mass terms.

Neutrino mass terms- Majorana mass terms M_ν & M_N

2. Majorana mass terms:

$$\bar{\nu}^0_L(\mathcal{M}_\nu)\nu^{0C}_R + \bar{\nu}^{0C}_L(\mathcal{M}_N)\nu^0_R + H.C.$$

- These presuppose lepton violating interactions.
- If any of them occurs **the neutrinos are Majorana particles**.
- The term $\bar{\nu}^{0C}_L(\mathcal{M}_N)\nu^0_R$ can occur in any theory, since the right handed neutrino carries no standard model quantum numbers.
- The term $\bar{\nu}^0_L(\mathcal{M}_\nu)\nu^{0C}_R$ is much harder to get.

Generic Models of neutrino mass – See-saw

1. No light Majorana mass term, $\bar{\nu}_L^0(\mathcal{M}_\nu)\nu_R^{0C} = 0$

- one can get an effective light majorana mass term of the form

$$\bar{\nu}_L^0(-)(\mathcal{M}_D)(\mathcal{M}_N)^{-1}(\mathcal{M}_D)^T\nu_R^{0C}$$

- This is the celebrated "see-saw mechanism"
- The neutrinos are light, so long as the right handed Majorana mass is superheavy.

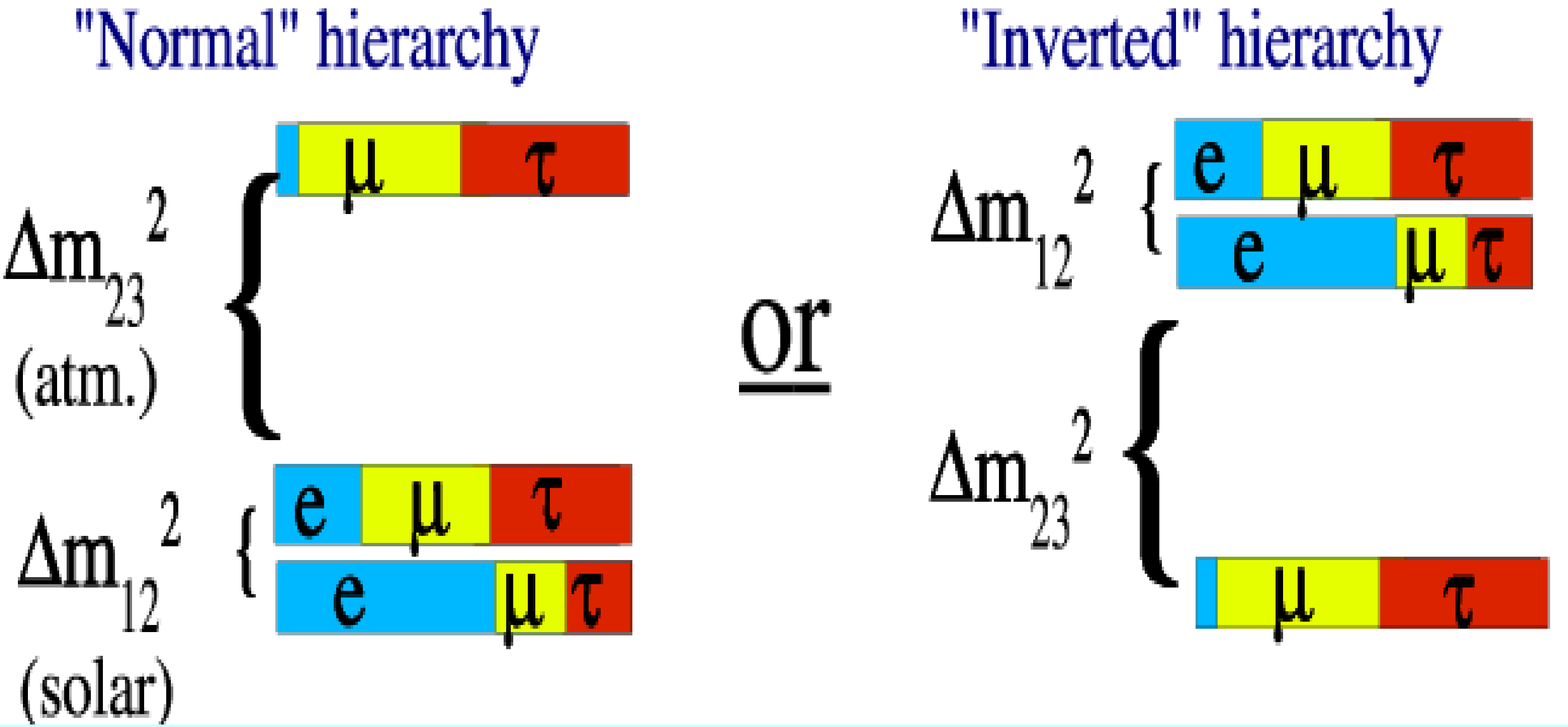
Majorana neutrino mass

2. $\bar{\nu}_L^0(\mathcal{M}_\nu)\nu_R^{0C}\#0 \Longrightarrow$

No need of right handed neutrino. Such matrix is obtained:

- Via isotriplet of Higgs scalars (not without tears).
- Radiatively at one loop level or higher (two Higgs isodoublets).
- Via SUSY R-parity (and hence lepton number) violating interactions

The Mass Hierarchies
- Flavor Content



(1):Astrophysics Mass Limit

$\Sigma_k m_k = m_{astro}$=0.71eV

- Normal Hierarchy:

$$\Delta m^2_{SUN} = m_2^2 - m_1^2 \,,\; \Delta m^2_{ATM} = m_3^2 - m_1^2$$

$$m_1 + \sqrt{\Delta m^2_{SUN} + m_1^2} + \sqrt{\Delta m^2_{ATM} + m_1^2} \leq m_{astro}$$

- Inverted Hierarchy:

$$\Delta m^2_{SUN} = m_2^2 - m_1^2 \,,\; \Delta m^2_{ATM} = m_2^2 - m_3^2$$

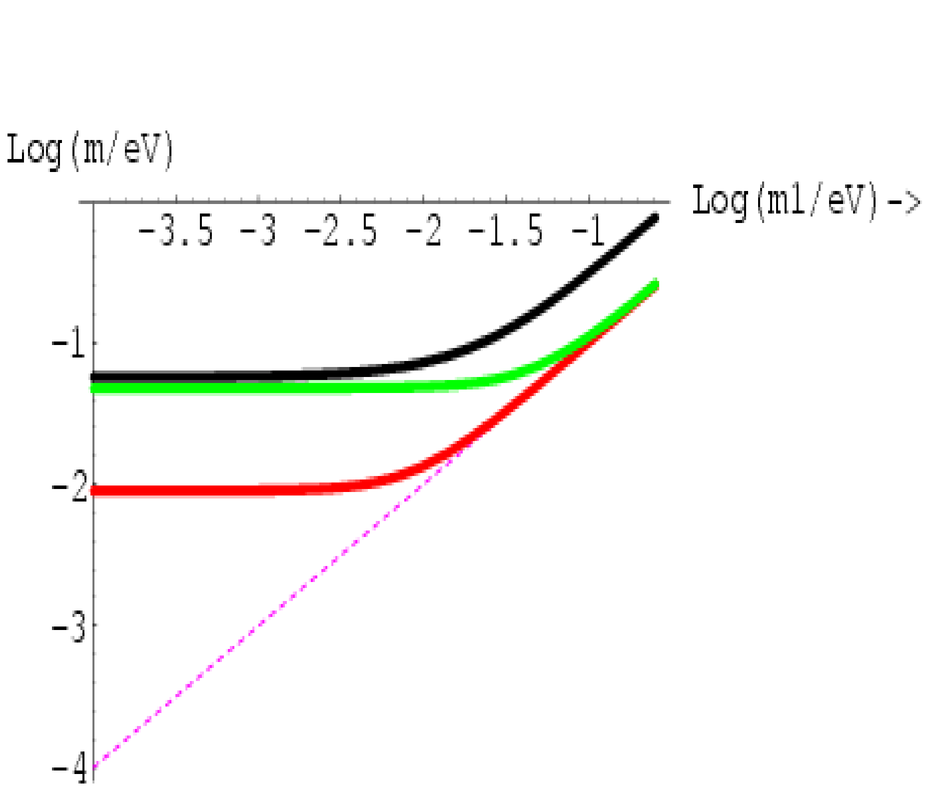
$$m_3 + \sqrt{\Delta m^2_{ATM} + m_3^2} + \sqrt{\Delta m^2_{ATM} - \Delta m^2_{SUN} + m_3^2} \leq m_{astro}$$

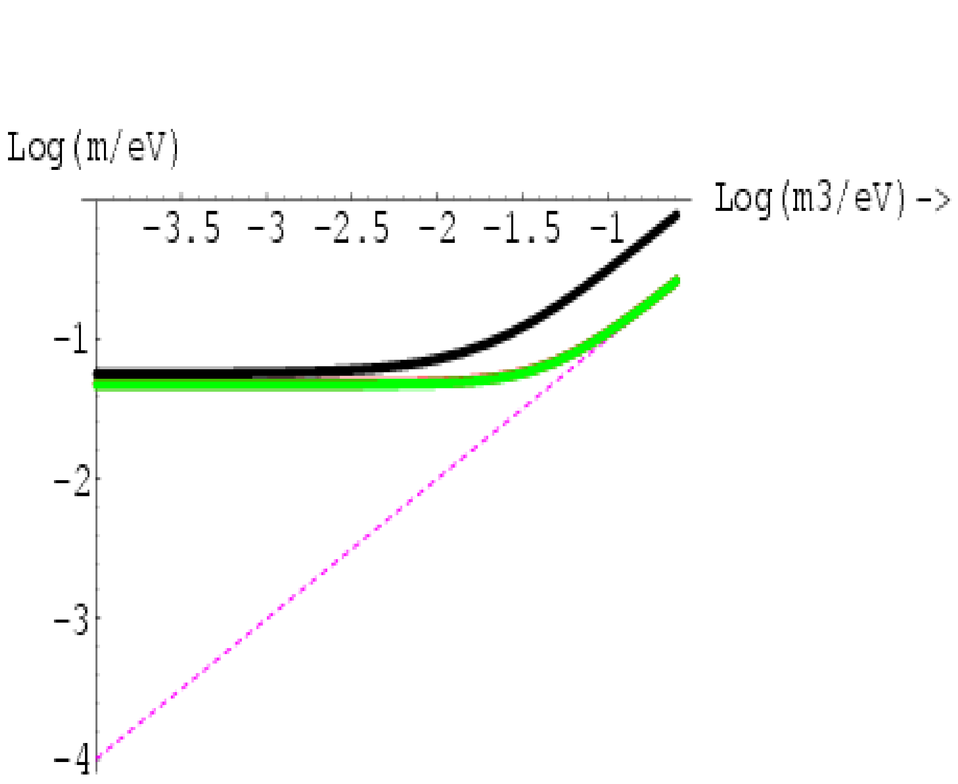
Astrophysics bound: 0.71 eV, Log(0.71)=-0.15

black $\Leftrightarrow \Sigma m_k$,

green$\Leftrightarrow m_3$ green $\Leftrightarrow m_1$

dotted $\Leftrightarrow m_1$, red$\Leftrightarrow$ m_2 dotted $\Leftrightarrow m_3$, red$\Leftrightarrow m_2$





(2): Triton decay mass limit

m_{decay}=2.2eV

- Normal Hierarchy:

$$\Delta m^2_{SUN} = m^2_2 - m^2_1 \ , \ \Delta m^2_{ATM} = m^2_3 - m^2_1$$

The condition is:

$$c^2_{12}c^2_{13}m^2_1 + s^2_{12}c^2_{13}(\Delta m^2_{SUN} + m^2_1) + s^2_{13}(\Delta m^2_{ATM} + m^2_1)$$
$$\leq m^2_{decay}$$

- Inverted Hierarchy:

$$\Delta m^2_{SUN} = m^2_2 - m^2_1 \ , \ \Delta m^2_{ATM} = m^2_2 - m^2_3$$

The condition is:

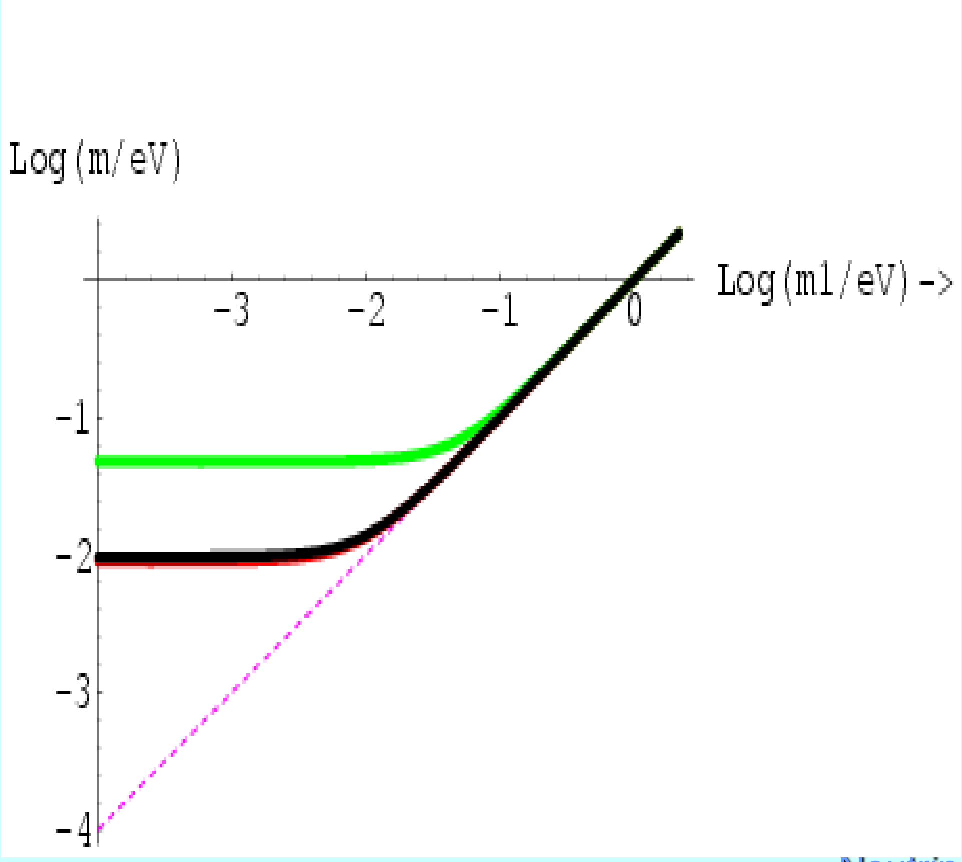
$$s^2_{13}m^2_3 + s^2_{12}c^2_{13}(\Delta m^2_{ATM} + m^2_3) +$$
$$+ c^2_{12}c^2_{13}(\Delta m^2_{ATM} - \Delta m^2_{SUN} + m^2_3) \leq m^2_{decay}$$

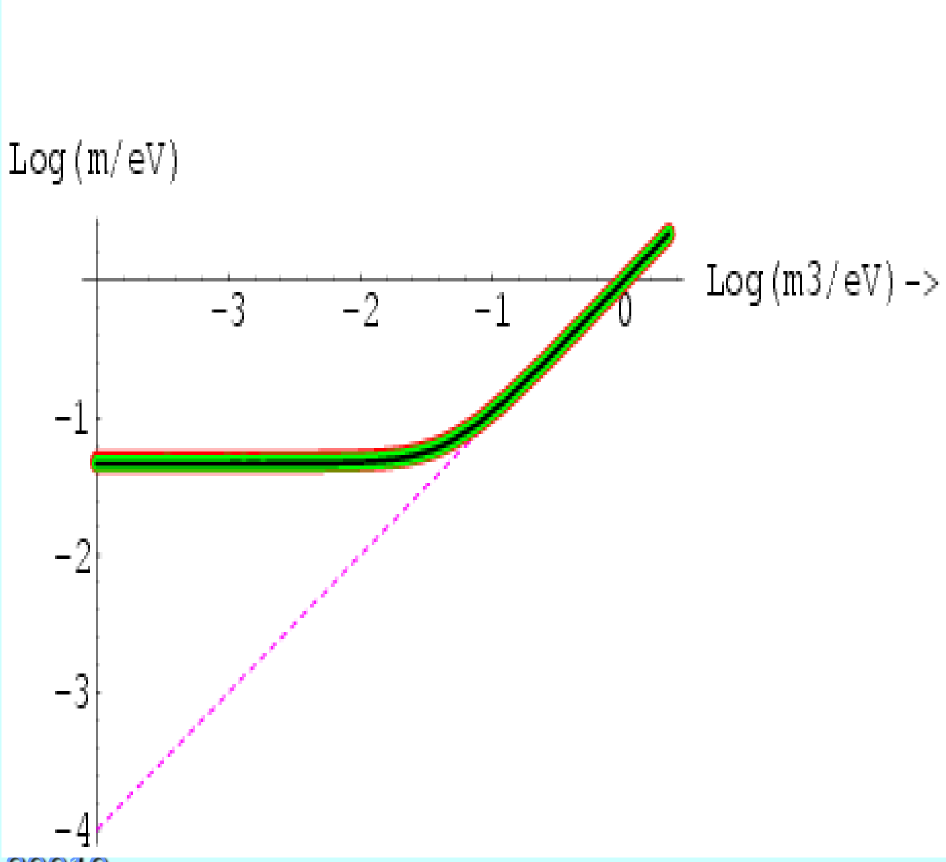
Triton decay limit: m_{decay}=2.2eV, Log(2.2)=0.34

KATRIN⇒0.2 eV, Log(0.2)=-0.7; Black⇔$m_{decay}(m_1)$,

green⇔m_3 $m_1 \approx m_2 \approx m_{decay}$

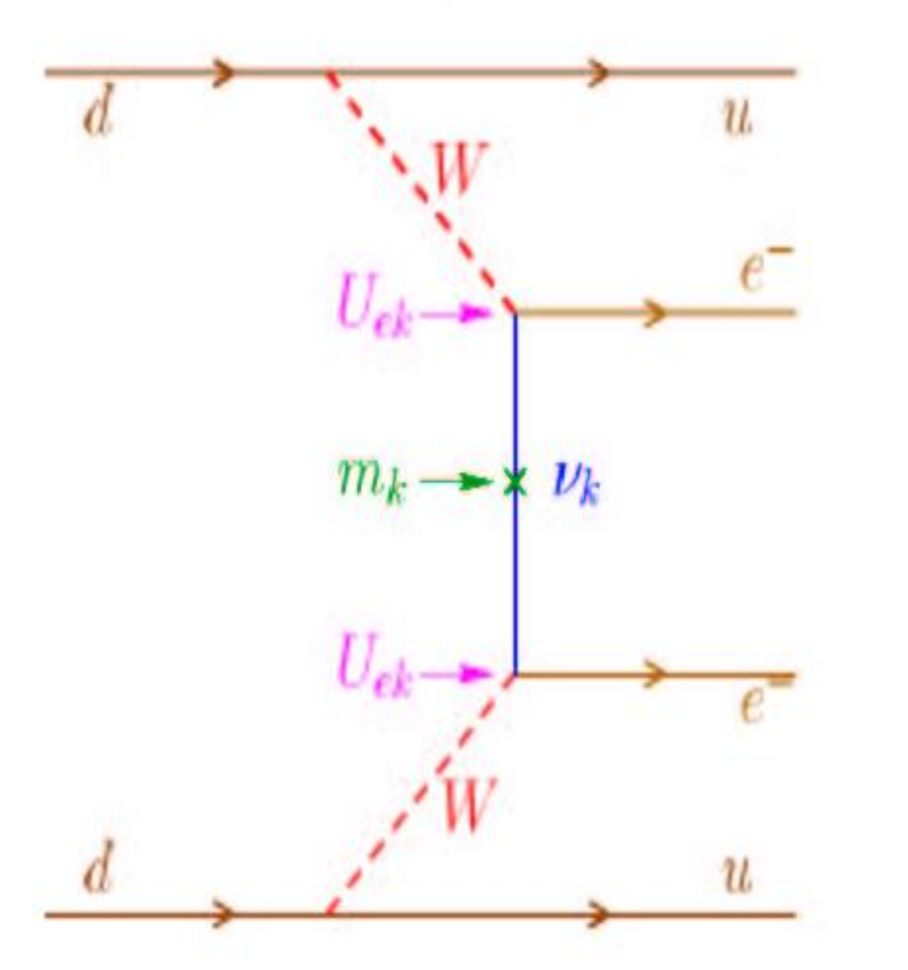
dotted ⇔m_1, red⇔ m_2 dotted ⇔m_3 ,

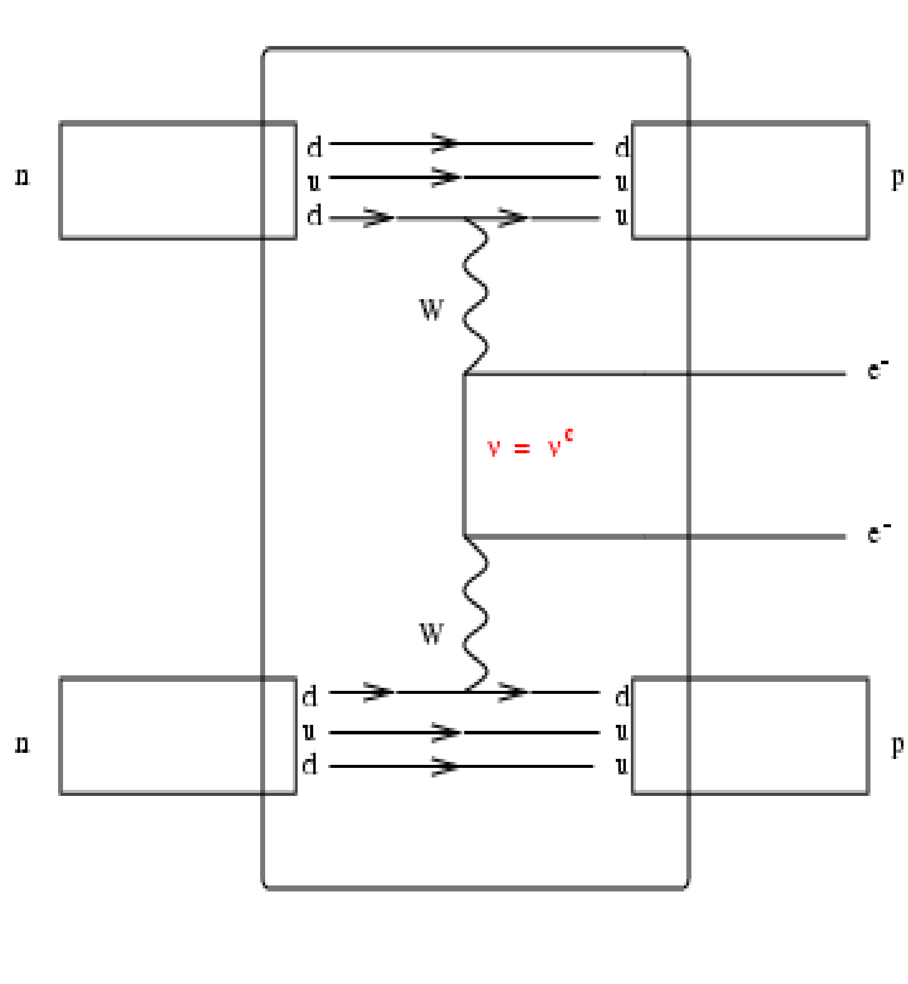




Majorana Mass Mechanism

$(\nu)^c = e^{i\varphi}\nu$, $\varphi=\alpha_k$ (Majorana condition)





Effective neutrino mass $<m_\nu>$ encountered in 0ν ββ-decay

[$\alpha=\alpha_2-\alpha_1$, $\beta=\alpha_3-\alpha_1+2\delta_{13}$,
$\alpha 1$, α_2 , α_3 Majorana phases]

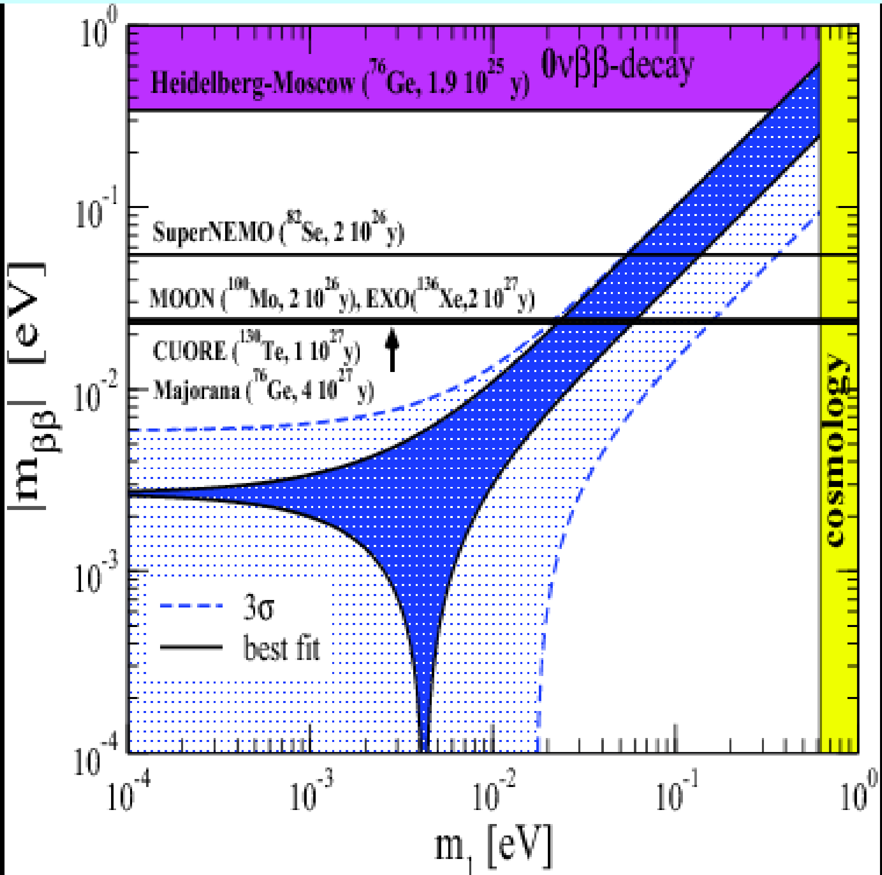
Mass scale: m_1 (normal); m_3 (inverted)

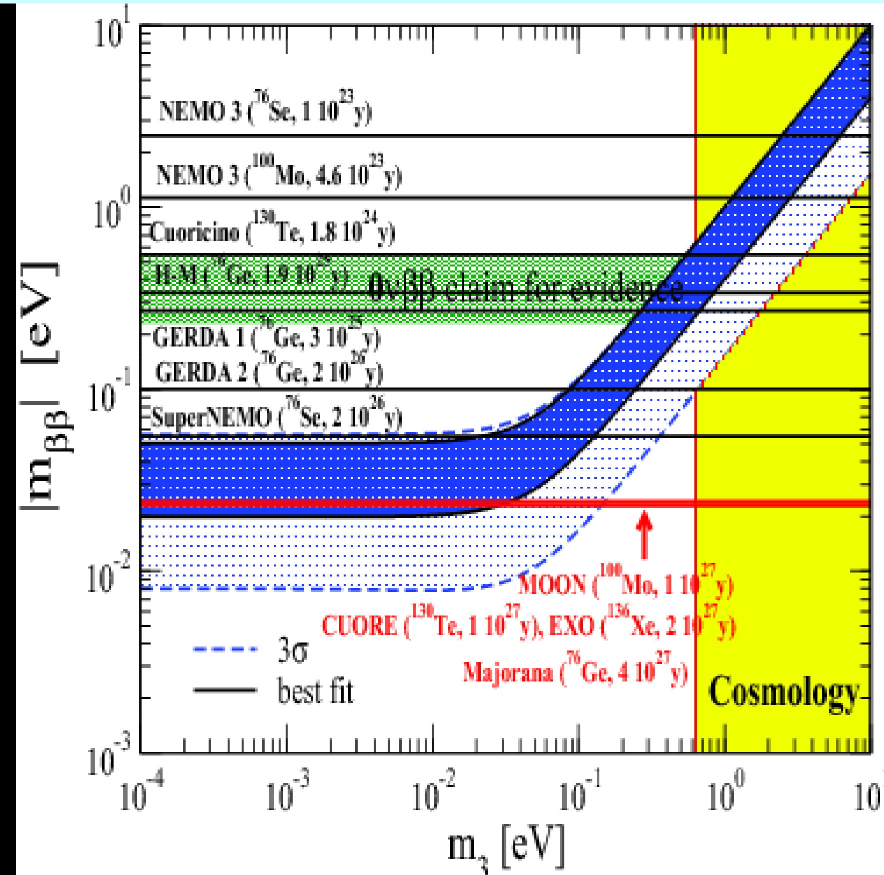
$$\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

lower m_{ee} bound from 0ν ββ-decay

(From J Valle)

Normal hierarchy Inverted





NME from Rodin, Faessler, Simkovic, Vogel

SPECTRUM + ABSOLUTE SCALE + MAJ. PHASE

The (v,e) scattering cross section

The total neutrinoelectron scattering cross section as a function of x and L can be cast in the form:

$$\sigma(L,x) = \sigma(0,x)\,(1 - \chi(x)p(L,x)) \qquad (4.12)$$

with $x = \frac{E_\nu}{m_e}$ and

$$\sigma(0,x) = \frac{G_F^2 m_e^2}{2\pi} \frac{x^2\,(17.7464x^2 + 15.3098x + 3.36245)}{(2x+1)^3} \qquad (4.13)$$

is the total cross section in the absence of oscillations. Furthermore

$$p(L,x) = \sin^2\left(\frac{0.122959L}{330x}\right)\sin^2(2\theta_{solar}) + \sin^2\left(\frac{0.122959L}{10x}\right)\sin^2(2\theta_{13}) \qquad (4.14)$$

with L the source detector distance in meters and

$$\chi(x) = \frac{2.8664x^2 + 4.1498x + 1.50245}{17.7464x^2 + 15.3098x + 3.36245} \qquad (4.15)$$

Minimal set of Neutrino Parameters

- 3 masses
- 3 angles θ_{ij} — 23=atm 12=sol 13=reac
- 3 phases

  1 KM-like phase — oscillations — δ

  2 Majorana phases — $\beta\beta_{0\nu}$ — α , β

- simplest form of 3-f lepton mixing $K = \omega_{23}\omega_{13}\omega_{12}$

  with each factor $\begin{pmatrix} c_{12} & e^{i\phi_{12}} s_{12} \\ -e^{-i\phi_{12}} s_{12} & c_{12} \end{pmatrix}$

- for $\Delta L = 0$ oscillations we can drop Maj phases & take KM-like form

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

CAST:Another "Greek" Collaboration

- **Probing eV-scale axions with CAST**
- E. Arik , S. Aune , D. Autiero , K. Barth , A. Belov , B. Beltrán , S. Borghi , G. Bourlis , F.S. Boydag , H. Bräuninger , J.M. Carmona , S. Cebrián , S.A. Cetin , J.I. Collar , T. Dafni , M. Davenport , L. Di Lella , O.B. Dogan , C. Eleftheriadis , N. Elias , G. Fanourakis , E. Ferrer-Ribas , H. Fischer , P. Friedrich , J. Franz , J. Galán , T. Geralis , I. Giomataris , S. Gninenko , H. Gómez , R. Hartmann , M. Hasinoff , F.H. Heinsius , I. Hikmet , D.H.H. Hoffmann , I.G. Irastorza , J. Jacoby , K. Jakovčić , D. Kang , K. Königsmann , R. Kotthaus , M. Krčmar , K. Kousouris , M. Kuster , B. Lakić , C. Lasseur , A. Liolios , A. Ljubičić , G. Lutz , G. Luzón , D. Miller , J. Morales , T. Niinikoski , A. Nordt , A. Ortiz , T. Papaevangelou , M.J. Pivovaroff , A. Placci , G. Raffelt , H. Riege , A. Rodríguez , J. Ruz , I. Savvidis , Y. Semertzidis , P. Serpico , R. Soufli , L. Stewart , K. van Bibber , J. Villar , J. Vogel , L. Walckiers and K. Zioutas
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