NEUTRINO OSCILLOMETRY-
Neutrinos in a box

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**For the LENA Collaboration

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

- A) LOW ENERGY NEUTRINOS

  -A1: neutrino electron scattering for neutrino oscillations, θ_{13} and sterile neutrinos)

  - A2: Neutral current induced scattering for sterile neutrino detection.

- B) Neutral Current Spherical TPC's (Nuclear recoils) for Dedicated

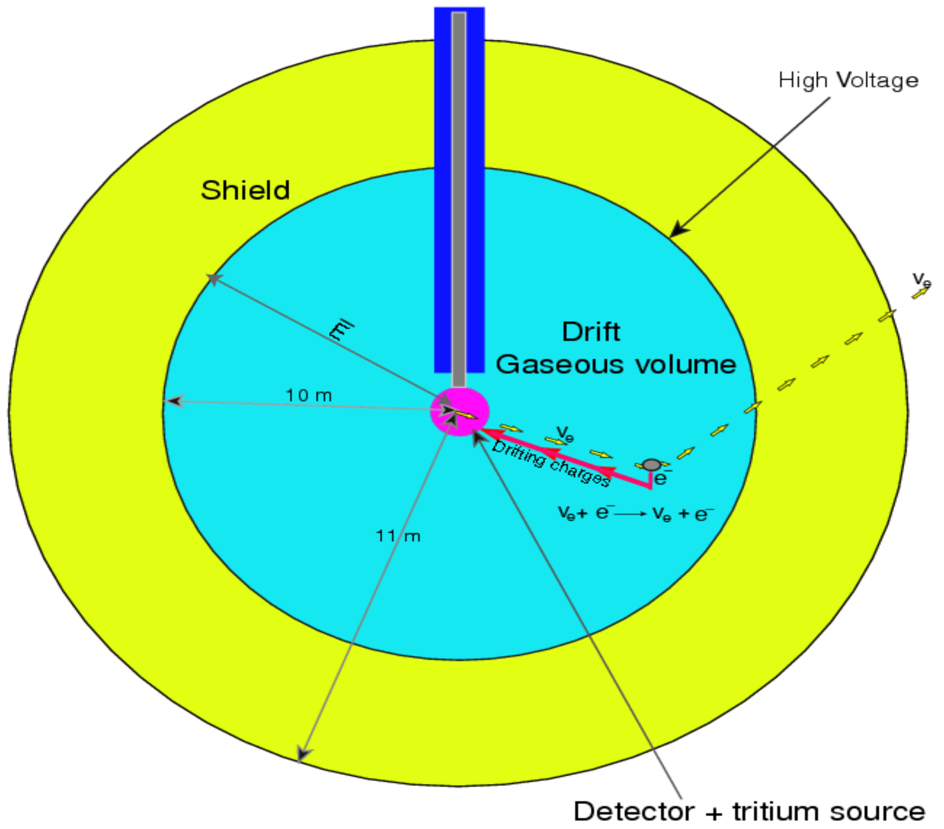
  SUPERNOVA NEUTRINO DETECTORS

II. The LENA detector:

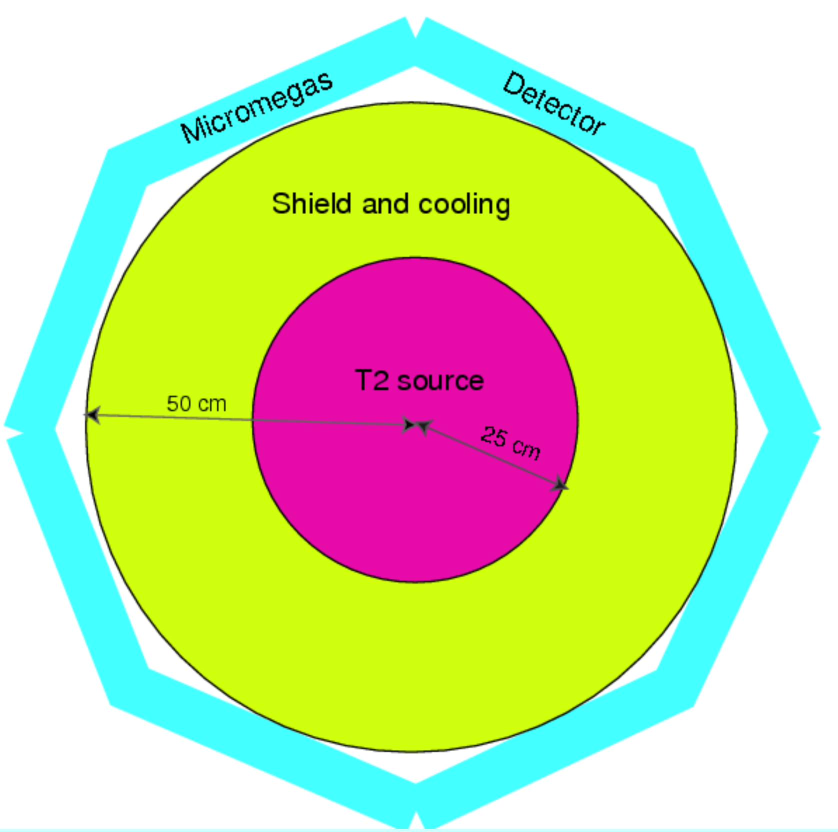
(Neutrino-electron scattering in Liquid Ar)

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

The detector



The neutrino source



I: Measure the Weinberg angle using (ν_e,e) scattering at very low momentum transfers (electron energy T)

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

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

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

II : Measure or set limit on the neutrino magnetic moment. At low energies the induced 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: $\mu_\nu \leq 10^{-10}\,\mu_B$)

III Neutrino oscillations (neutrino-electron scattering) “in a box”

- Measure small mixing angle:

  $\sin^2(2\theta_{13})$ and δm^2_{13}

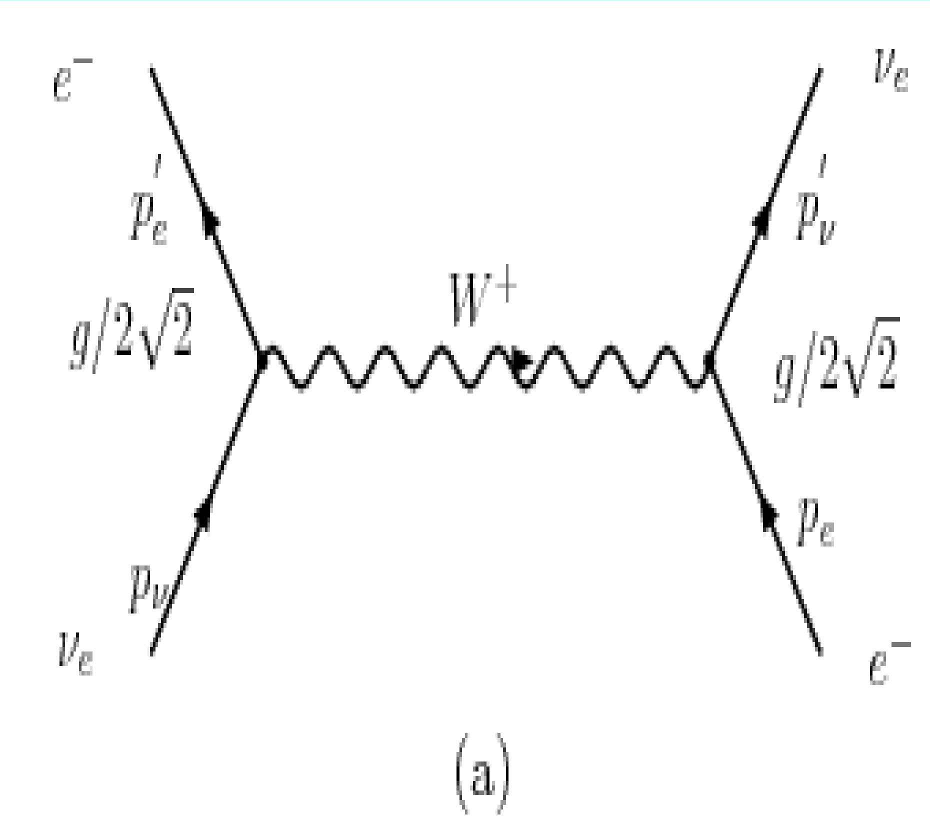
- Measure sterile neutrino mass and mixing:

  $\sin^2(2\theta_{14})$ and δm^2_{14}

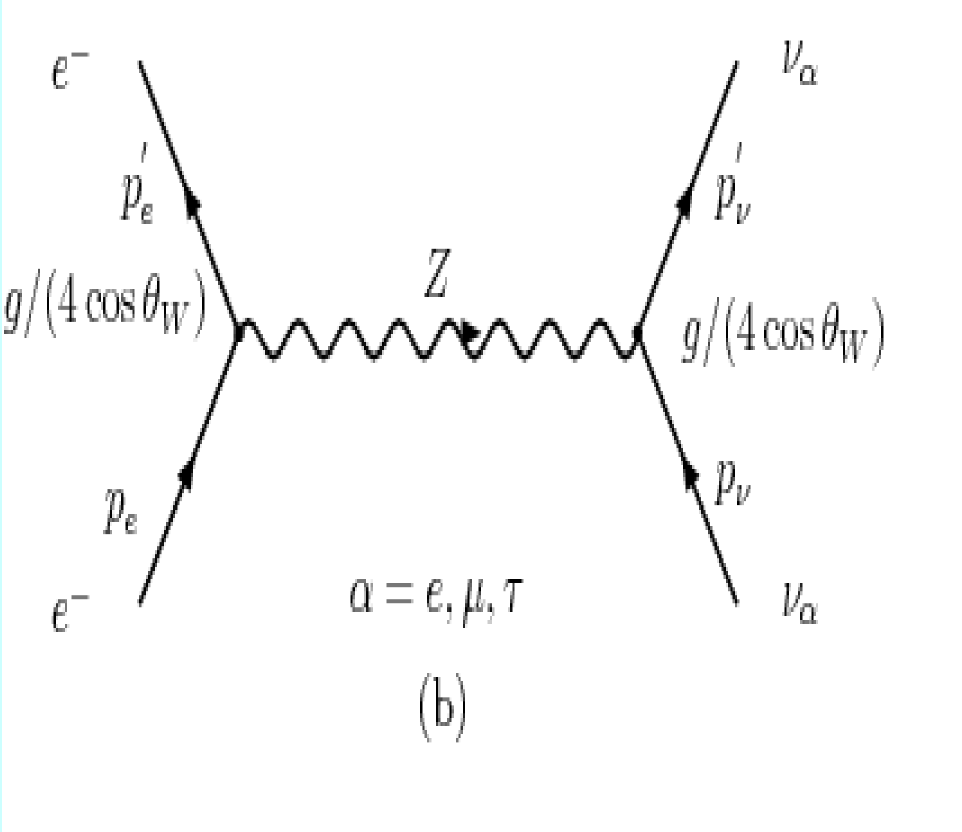
(The Reactor Neutrino anomaly, The Short Baseline Anomalies (LSND, MiniBooNE))

Neutrino Oscillations in Neutrino Electron Scattering

Charged current (v_ε only)



Neutral current (all flavors)



Part I: Measuring $\sin^2(2\theta_{13})$ and δm^2_{13} in (ν_e, e) scattering: $\sigma(L,E_\nu)= \sigma(0,E_\nu)P(\nu_e\to\nu_e)$

$$\sigma_{tot} = P(\nu_e \longrightarrow \nu_e)\sigma + \left(P(\nu_e \longrightarrow \nu_\mu) + P(\nu_e \longrightarrow \nu_\tau)\right)\sigma', \qquad (9)$$

where σ is the (ν_e, e) cross section, while σ' is the cross section for the other two flavors, (ν_α, e), $\alpha = \mu, \tau,$. Furthermore

$$P(\nu_e \longrightarrow \nu_e) = 1 - \left(P(\nu_e \longrightarrow \nu_\mu) + P(\nu_e \longrightarrow \nu_\tau)\right). \qquad (10)$$

$$\sigma_{tot} = \sigma\,[1 - \chi(E_\nu, T)$$
$$(\sin 2\theta_{12})^2 \sin^2(\pi\frac{L}{L_{21}}) + \sin^2(2\theta_{13})\sin^2(\pi\frac{L}{\bar{L}_{3i}}),$$
$$\sin^2(\pi\frac{L}{\bar{L}_{3i}}) = \cos^2\theta_{12}\sin^2(\pi\frac{L}{L_{31}}) + \sin^2\theta_{12}\sin^2(\pi\frac{L}{L_{32}})\Big] \qquad (3.13)$$

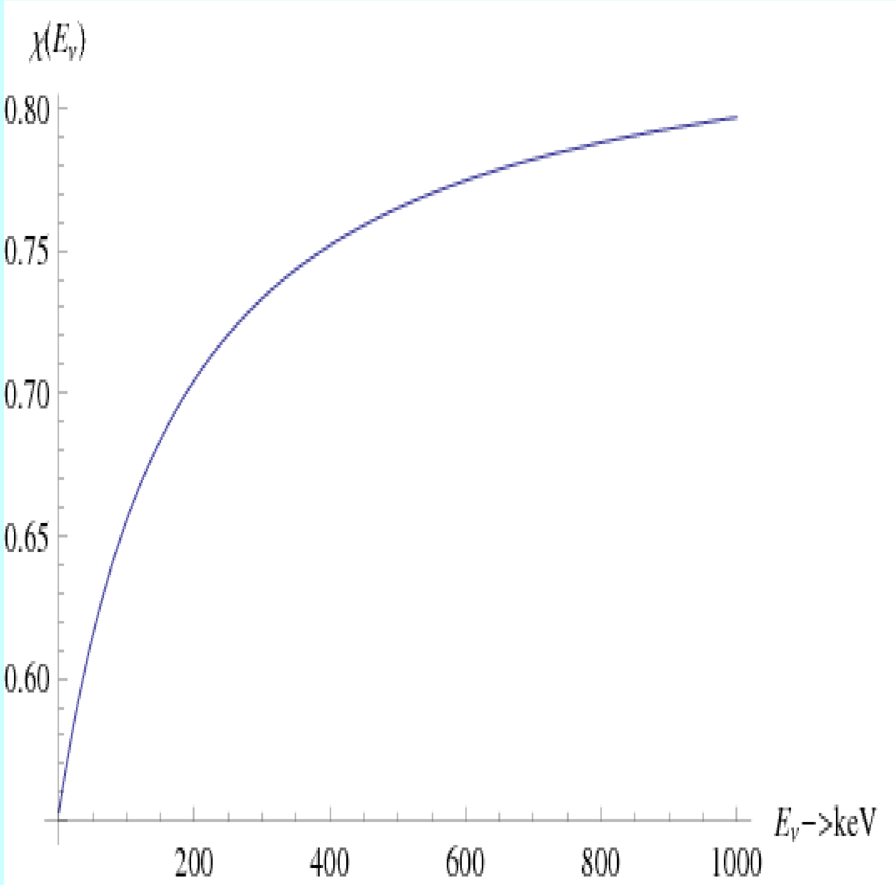
$\chi(E_\nu)=1-\sigma'/\sigma$

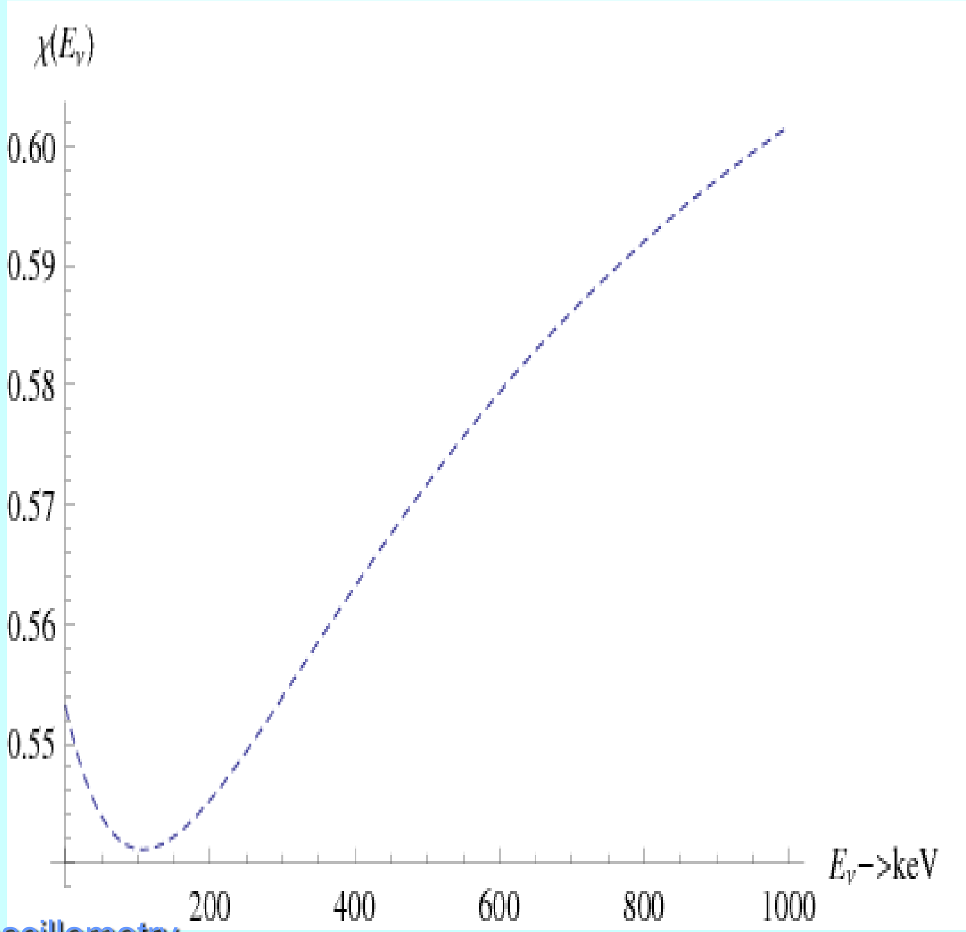
$$L_{ij} = \frac{4\pi E_\nu}{m_i^2 - m_j^2}$$

$$P(\nu_e \to \nu_e) = 1 - \chi(E_\nu, T)$$
$$(\sin 2\theta_{12})^2 \sin^2(\pi\frac{L}{L_{21}}) + \sin^2(2\theta_{13})\sin^2(\pi\frac{L}{\bar{L}_{3i}}),$$
$$\sin^2(\pi\frac{L}{\bar{L}_{3i}}) = \cos^2\theta_{12}\sin^2(\pi\frac{L}{L_{31}}) + \sin^2\theta_{12}\sin^2(\pi\frac{L}{L_{32}}) \qquad (3.14)$$

The function $\chi(E_\nu)$. It reduces the amplitude of oscillation

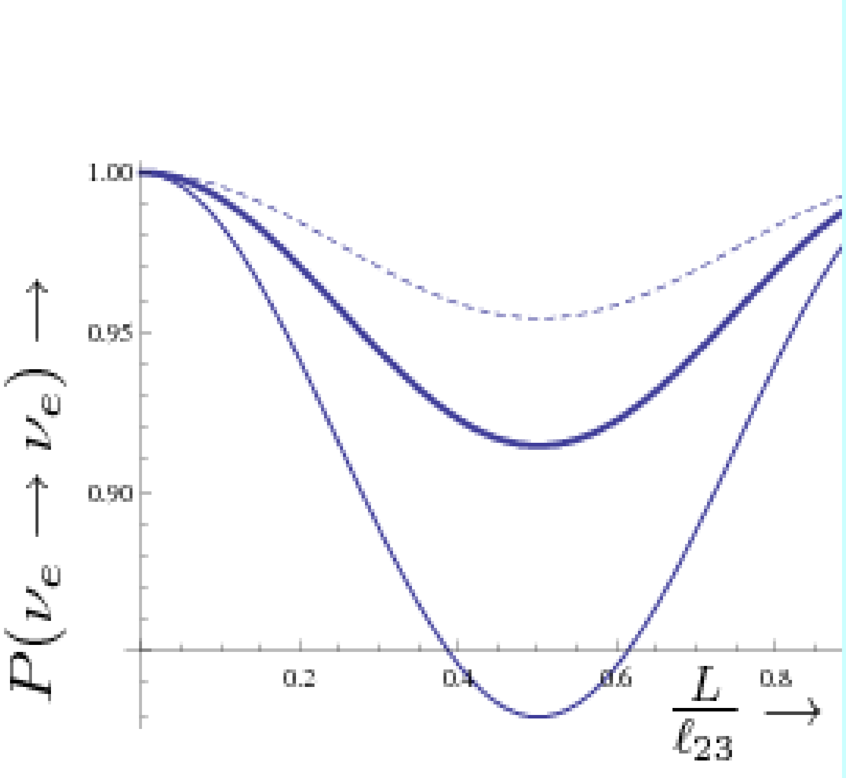
neutrinos **antineutrinos**



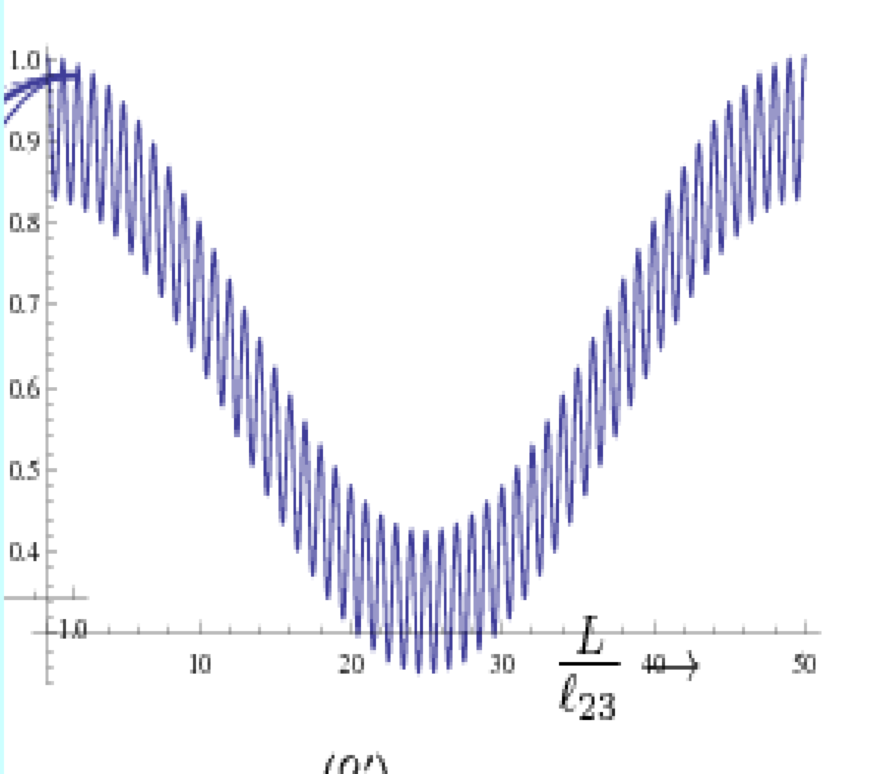


Sketch of ν_e disappearance probability: E_ν=13keV, $\theta_{12}=\pi/5$, $\sin^2 2\theta_{13}$=0.175,0.09,0.045

Detector close to the source **Detector far from the source**



(α')



(β')

Mono-energetic Neutrino sources 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:

$$dN = N_\nu n_e \frac{4\pi L^2 dL}{4\pi L^2}\sigma(L,E_\nu) = N_\nu n_e dL \sigma(L,E_\nu) \qquad (4.19)$$

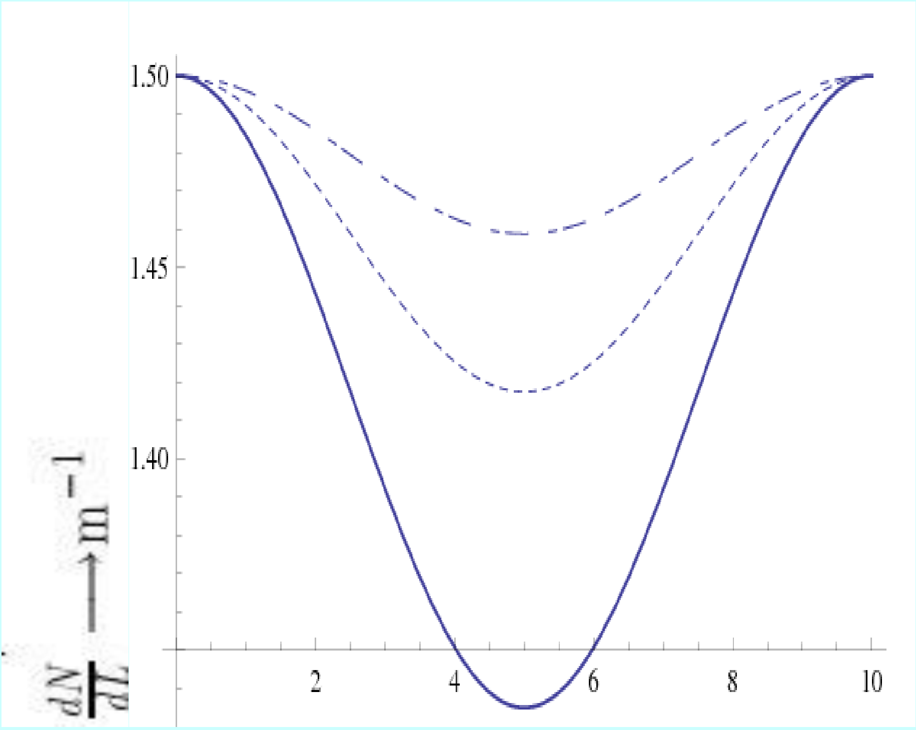
or

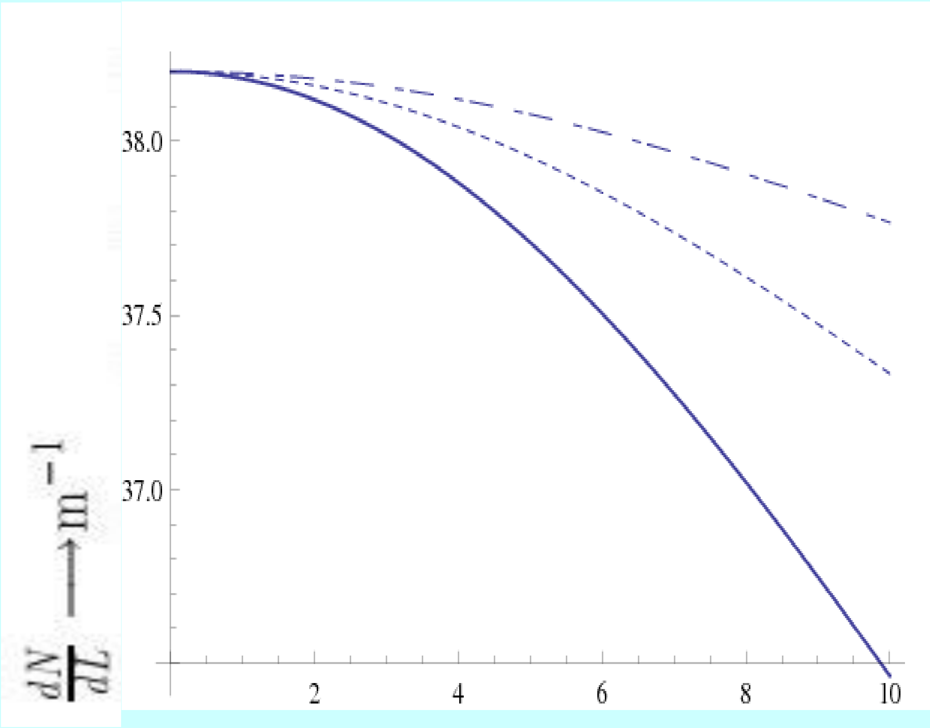
$$\frac{dN}{dL} = N_\nu n_e \sigma(L,E_\nu), \quad \sigma(L,E_\nu) = \sigma(0,E_\nu)P(\nu_e \rightarrow \nu_e) \quad (4.20)$$

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

$\sin^2 2\theta_{13}$=0.2,0.1,0.05 T_{th}=0.1keV

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





L->m

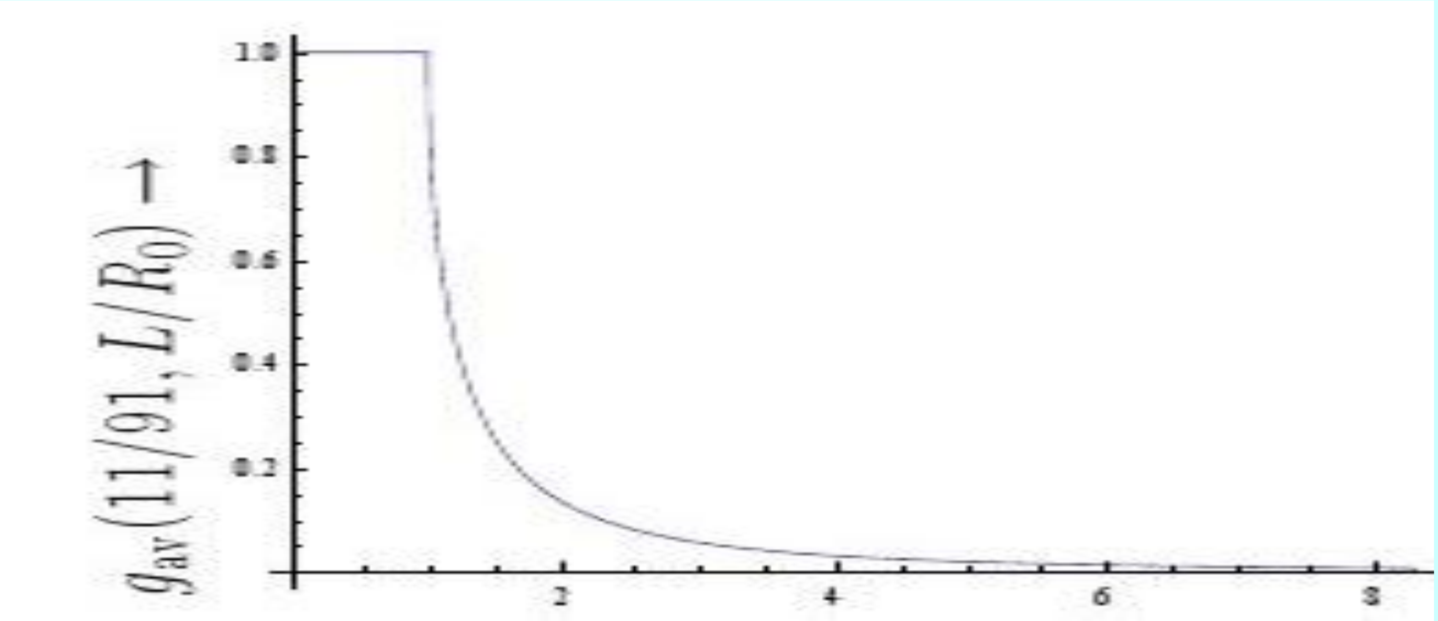
Other detectors and geometries

- The gaseous TPC detector has many advantages. However (low threshold 0.1 keV, high resolution)
- The gas has small density→ few events for small oscillation lengths
- 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. But then the threshold is much larger (200 keV)

LENA detector :R_0 =11m, h=91m

The event rate in terms of L
(u=R_0/h=11/91), x=E_ν/m_e, y=T_e/m

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

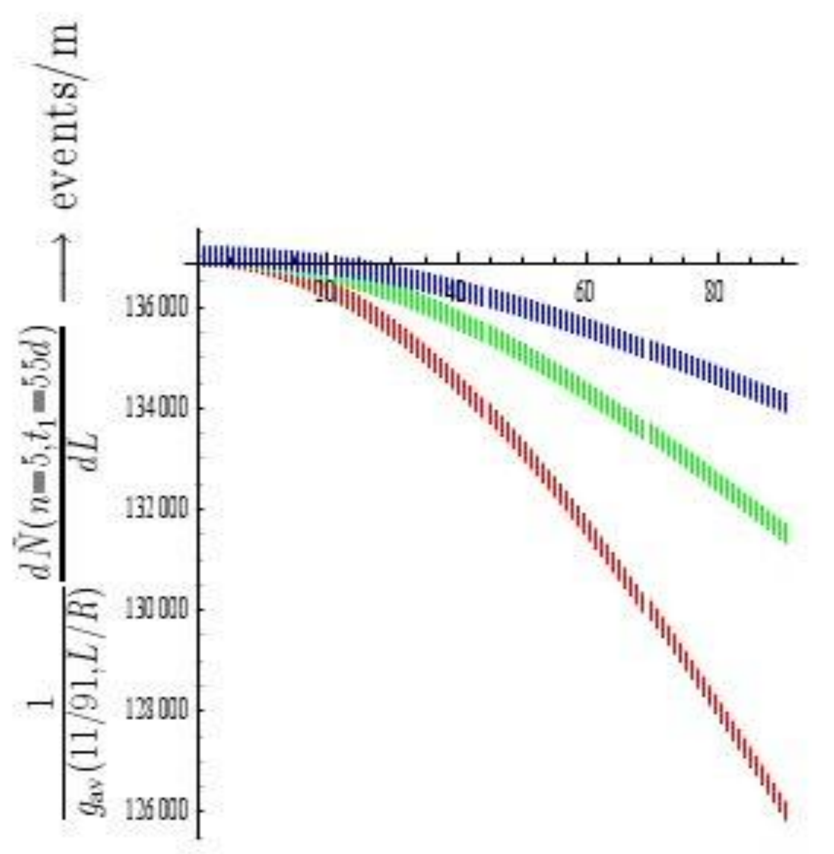


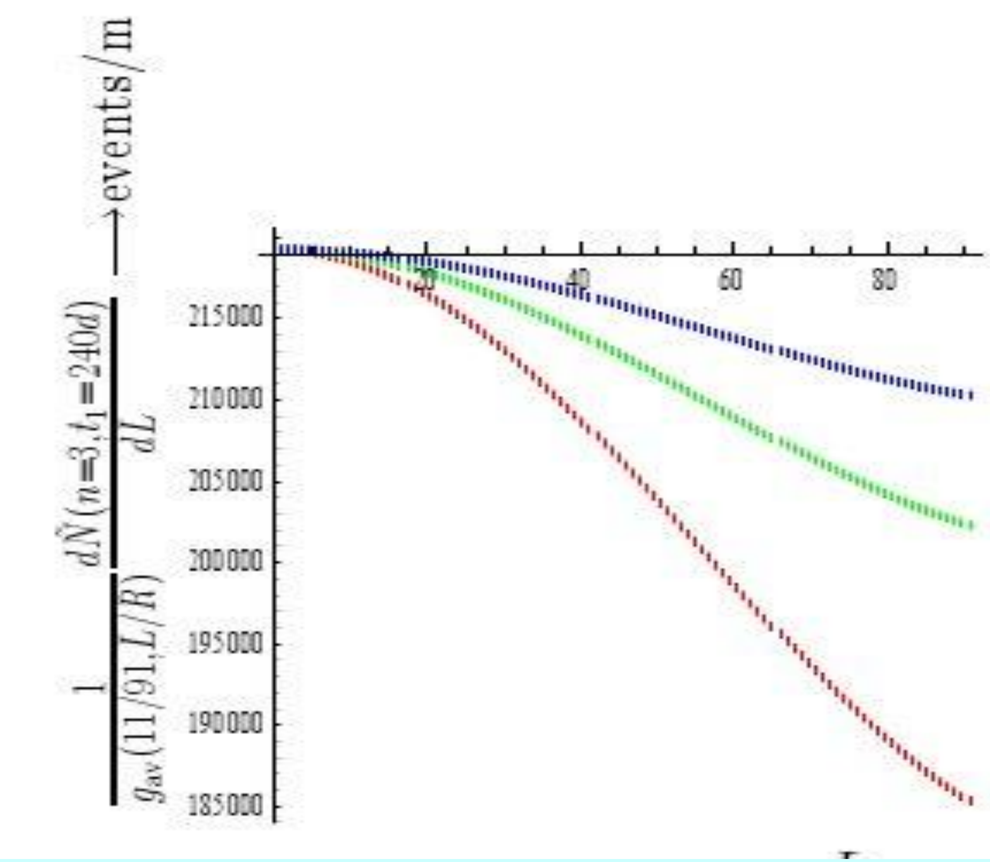
Mono-energetic neutrino sources suitable for the LENA detector

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	$7x10^{17}$	5
^{75}Se	120 d	1000	100	287	1475	$8x10^{17}$	3
^{85}Sr	64.9 d	1000	60	363	8.64	$7.5x10^{15}$	5
^{103}Pd	17 d	1000	10	315	11.5	$3x10^{16}$	5
^{113}Sn	115 d	1000	100	436	17.3	$6.4x10^{15}$	3
^{121}Te	16.8 d	1000	10	280	1.6	$3.8x10^{15}$	5
^{145}Sm	340 d	1000	300	340	480	$4.7x10^{16}$	1
^{169}Yb	32 d	1000	30	304	3000	$2.8x10^{18}$	5

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}=200keV

5 implantations 55 d each **3 implantations 240 d each**





Part II: (ν_e, e) scattering for oscillations to a Sterile Neutrino measuring* $\sin^2(2\theta_{14})$ and δm^2_{14}

- Motivated by
  The reactor neutrino anomaly and LSND:
  $\sin^2(2\theta_{14}) = 0.17 \pm 0.1 (95\%)$, $\delta m^2_{14} > 1.5$ eV^2

*Now δm^2 is larger ->The optimal ν-energy can be larger->Larger cross sections

ν_e disappearance in the presence of sterile neutrinos

Now $\delta m^2_{14} > 1.5\ eV^2$ <-> $E_\nu \sim MeV, L \sim 1m$

- The sterile neutrinos do not interact, but they simply remove flux. So:

$$P(\nu_e \to \nu_e) = 1 - \chi(E_\nu)\ \{\sin^2(2\theta_{12}) \sin^2[\pi(L \backslash L_{12})] + \sin^2(2\theta_{13}) \sin^2[\pi(L \backslash L_{13})]\} - \sin^2(2\theta_{14}) \sin^2[\pi(L \backslash L_{14})]$$

- Since the oscillation lengths are different
- $P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{14}) \sin^2[\pi(L \backslash L_{14})]$

Some sources (0.1 kg) of low energy Monoenergetic Neutrinos for measuring $\sin^2(2\theta_{14})$ and δm^2_{14} (electron recoils)

To check the Reactor neutrino anomaly

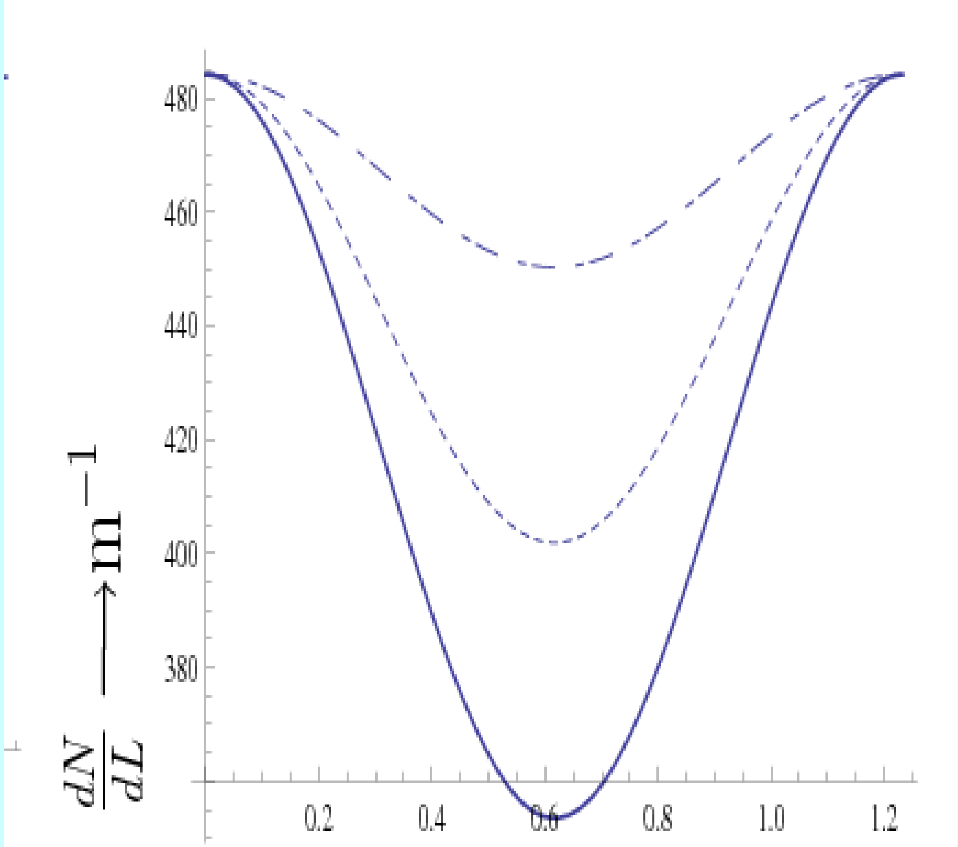
$\sin^2(2\theta_{14}) = 0.17 \pm 0.01$, $\delta m^2_{14} \approx 1.5\ \mathrm{eV}^2$

Nuclide	$T_{1/2}$ (d)	Q_{EC} (keV)	E_ν (keV)	L_{32} (m)	L_{42} (m)	$(E_e)_{\max}$ (keV)	$\sigma(0,x)$ $10^{-45}\mathrm{cm}^2$	N_ν (s^{-1})
^{37}Ar	35	814	811	842	1.35	617	5.69	3.7×10^{17}
^{51}Cr	27.7	753	747	742	1.23	556	5.12	4.1×10^{17}
^{65}Zn	244	1352	1343	1330	2.22	1128	10.5	3.0×10^{16}

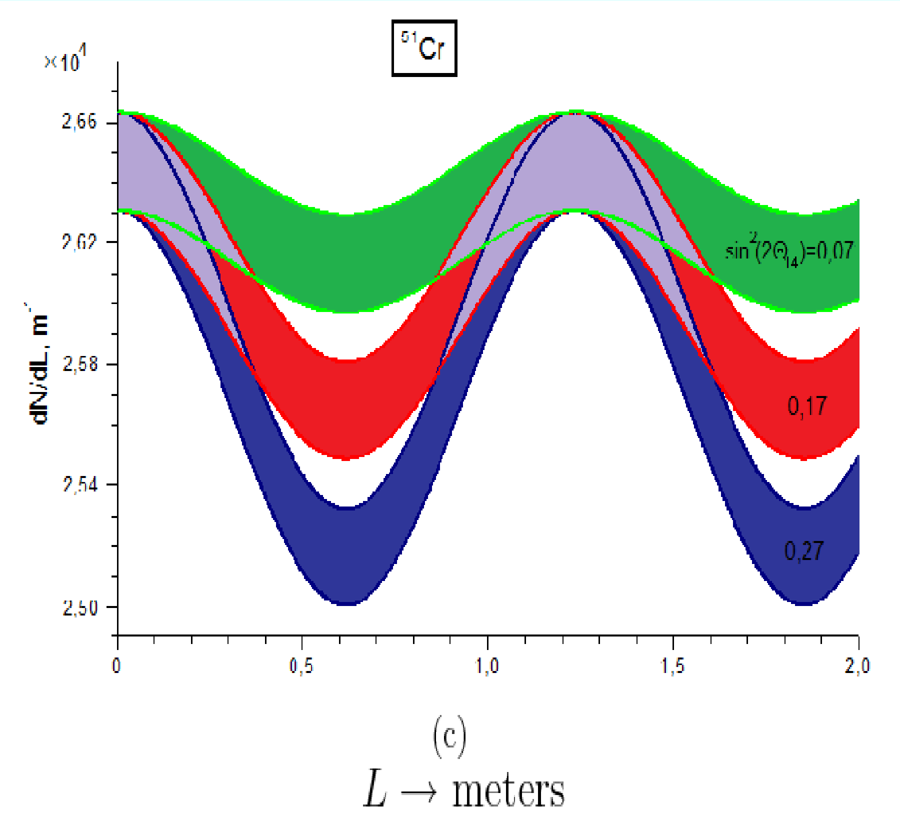
Sterile neutrino oscillations: R_0=4m,P=10 Atm

^{51}Cr, E_ν =747 keV; full, dotted, dashed curve ⇔ $\sin^2(2\theta_{14})$=0.27,0.17,0.07

Oscillation Pattern (10d)



Expected Spectra (55d)



Sterile neutrino detection via the neutral current interaction

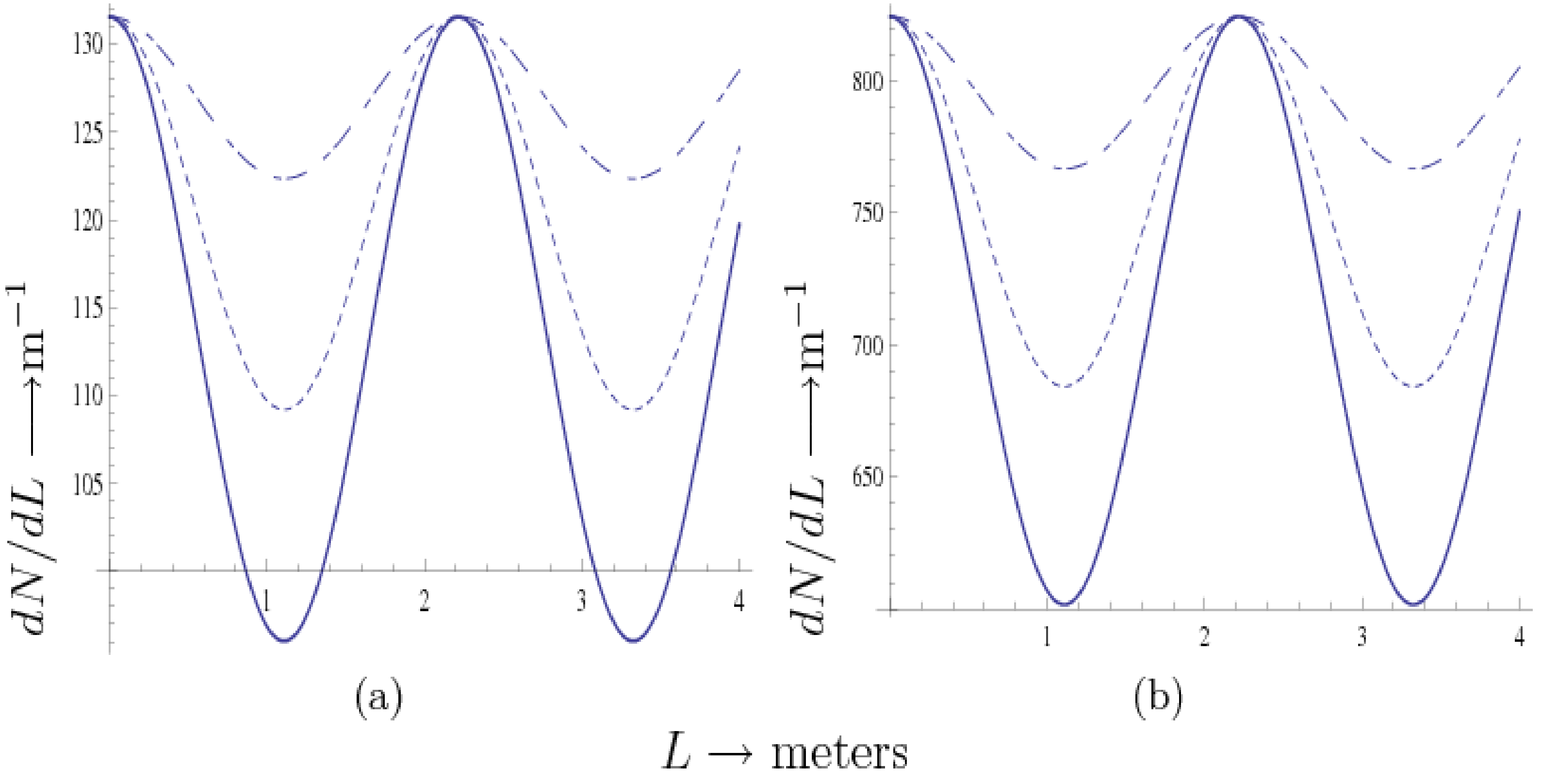
- Large number of events due to neutron coherence
- Sterile neutrinos do not interact, just they take way flux.

$$\sigma_{\text{tot}} = \left(1 - \sin^2 2\theta_{14} \sin^2 \pi \frac{L}{L_{14}}\right)\sigma.$$

Sterile neutrino oscillations: R_0=4m,P=10 Atm

E_ν =1343 keV; (NC) full, dotted, dashed curve ⇔ $\sin^2(2\theta_{14})$=0.27,0.17,0.07

source:^{65}Zn; target ^{20}Ne **source:^{65}Zn; target ^{4}He**



Detection of sky Neutrinos (From outside the solar system)

- With the exception of SN1987 events, nobody has observed such neutrinos
- The neutron coherence of the neutral current leads to large cross sections for observing nuclear recoils
- Supernova neutrinos originating with the galaxy (10 kpc) cannot be missed.

Advantages of a detector measuring nuclear recoils (Neutral Current interaction)

- All neutrinos contribute
- The event rate is not affected by neutrino oscillations
- Ideal probe for the neutrino source
- The cross section is coherent, i.e. proportional to the number of neutrons, N^2

  (The target proton contribution is negligible)
- Exploit the technology of dark matter searches

Differential cross sections

$$\left(\frac{d\sigma}{dT_A}\right)_w (T_A, E_\nu) = \frac{G_F^2 A m_N}{2\pi} (N^2/4) F_{coh}(T_A, E_\nu), \qquad (3)$$

with

$$F_{coh}(T_A, E_\nu) = F^2(q^2)\left(1 + (1 - \frac{T_A}{E_\nu})^2 - \frac{A m_N T_A}{E_\nu^2}\right) \qquad (4)$$

where N is the neutron number and $F(q^2) = F(T_A^2 + 2 A m_N T_A)$ is the nuclear form factor. The effect of the nuclear form factor depends on the target (see Fig. 4). Since the SN source is not "'monochromatic"' the above equation can be written as:

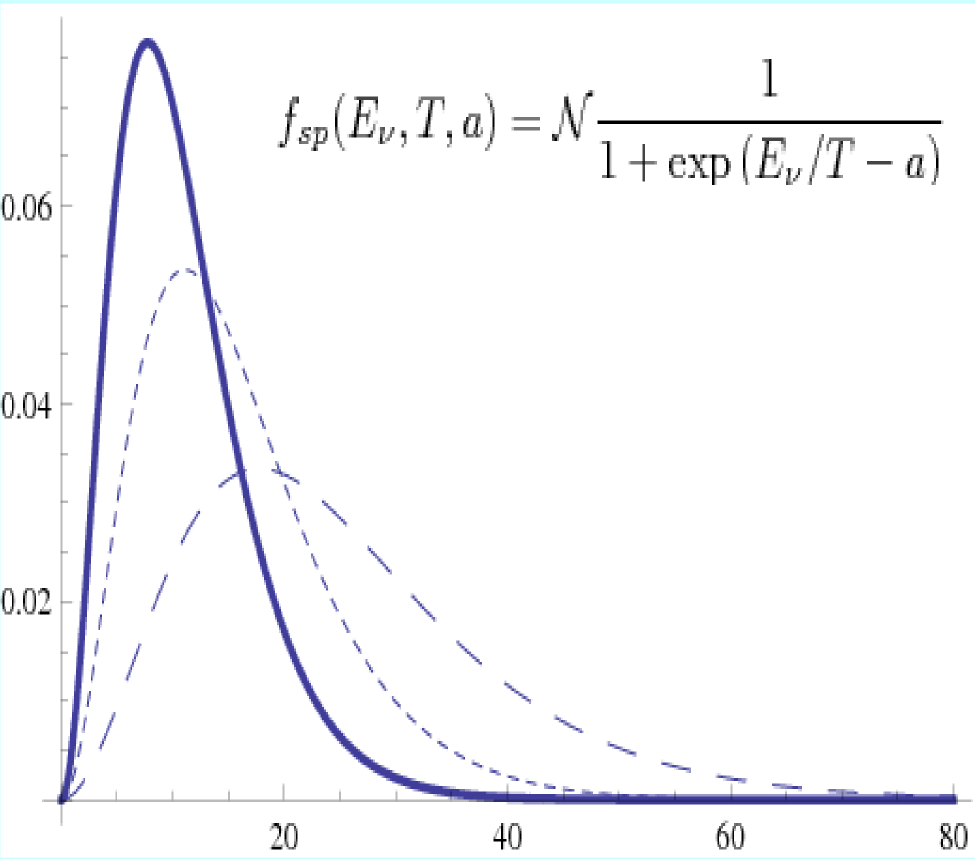
$$\frac{d\sigma}{dT_A} = \int_0^\infty \left(\frac{d\sigma}{dT_A}\right)_w (T_A, E_\nu) f_{sp}(E_\nu, T, a) dE_\nu \qquad (5)$$

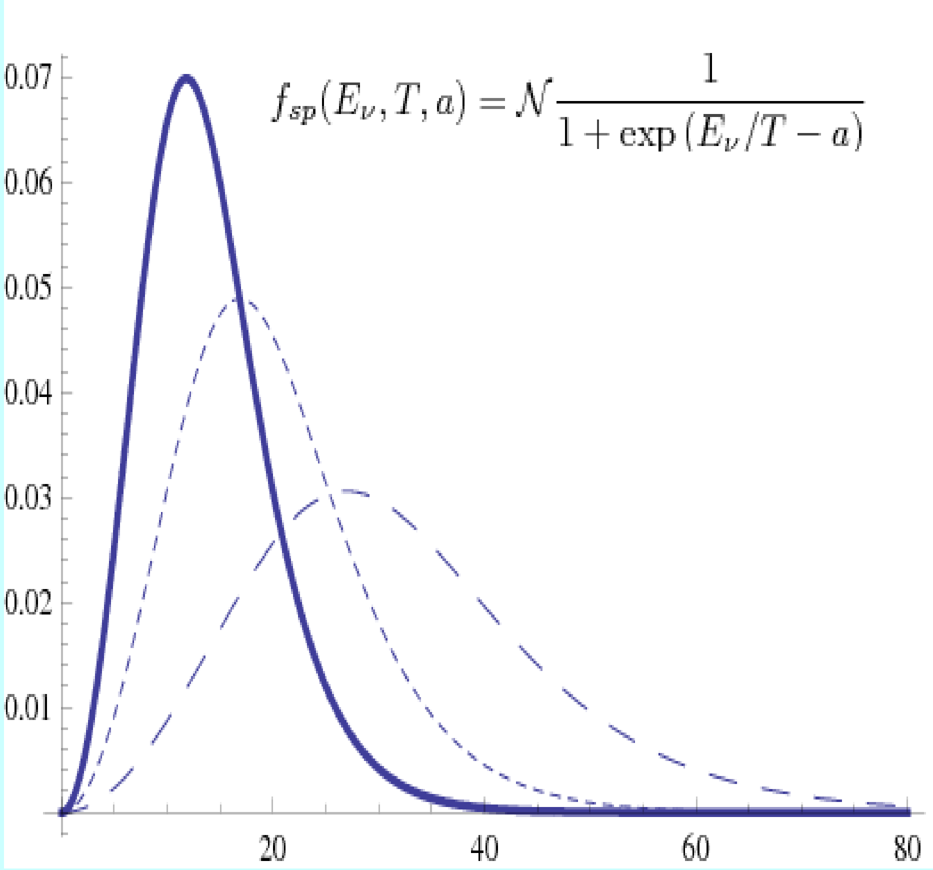
$$f_{sp}(E_\nu, T, a) = \mathcal{N} \frac{1}{1 + \exp\left(E_\nu/T - a\right)}$$

Normalized SN Neutrino Spectrum

continuous: ν_e, dotted: anti-ν_e, dashed: all others

a=μ/T=0 **a=μ/T=3 (degeneracy factor)**





Number of Events: Xe under P=10 Atm (to be reduced by 30%(50%) even at E_{th}=1keV)

Formulae

$$N_{ev}(a,T) = \Phi_\nu(a,T)\sigma(a,T,E_{th})N_N(P,T_0,R)$$

$$N_N(P,T_0,R) = \frac{P}{kT_0}\frac{4}{3}\pi R^3$$

$$N_N(P,T_0,R) = 1.04\times 10^{30}\frac{P}{10\text{ Atm}}\frac{300\,^0\text{K}}{T_0}\left(\frac{R}{10\text{m}}\right)^3$$

$$f_{sp}(E_\nu,T,a) = \mathcal{N}\frac{1}{1+\exp\left(E_\nu/T-a\right)}$$

for Xe target, E_{th} = 0

a	R=10m	R=4m
0	10872	696
0.75	11089	710
1.50	11427	731
2.00	11726	750
3.00	12483	799
4.00	13378	856
5.00	14288	914

SN neutrinos: Number of events for other gases (Since Xe is very expensive!) (to be reduced by 10%(30%) even at E_{th}=1keV)

Ar target , E_{th} = 0

a	R=10m 10 Atm	R=4m 10Atm	50 kton (coh)
0	193	12	2.8×10^4
0.75	197	13	2.8×10^4
1.50	203	13	2.9×10^4
2.00	209	13	3.0×10^4
3.00	223	14	3.2×10^4
4.00	242	15	3.5×10^4
5.00	262	17	3.8×10^4

Ne target , E_{th} = 0

a	R=10m	R=4m
0	160	10
0.75	163	10
1.50	167	11
2.00	170	11
3.00	177	11
4.00	185	12
5.00	190	12

Concluding remarks

THE NOSTOS Collaboration intends to:

- Use the Spallation Neutron Source (SNS) at Oak Ridge to test the coherent neutral current detector.
- Build a low cost, robust and easily maintainable gaseous TPC detector

  Design it so it can be easily maintained (even by students)
- Utilize a rich neutron target to exploit the coherence due to the neutral current. Even for Ar More than 200 events are expected in SN explosion in our galaxy.

  Note:
- No need to go underground. Just 100 m underwater to maintain the high pressure
- A cluster of such detectors could localize SN

- THE END