Constraining Neutrino Mass Hierarchy and θ_{13} with Supernova Neutrino Data

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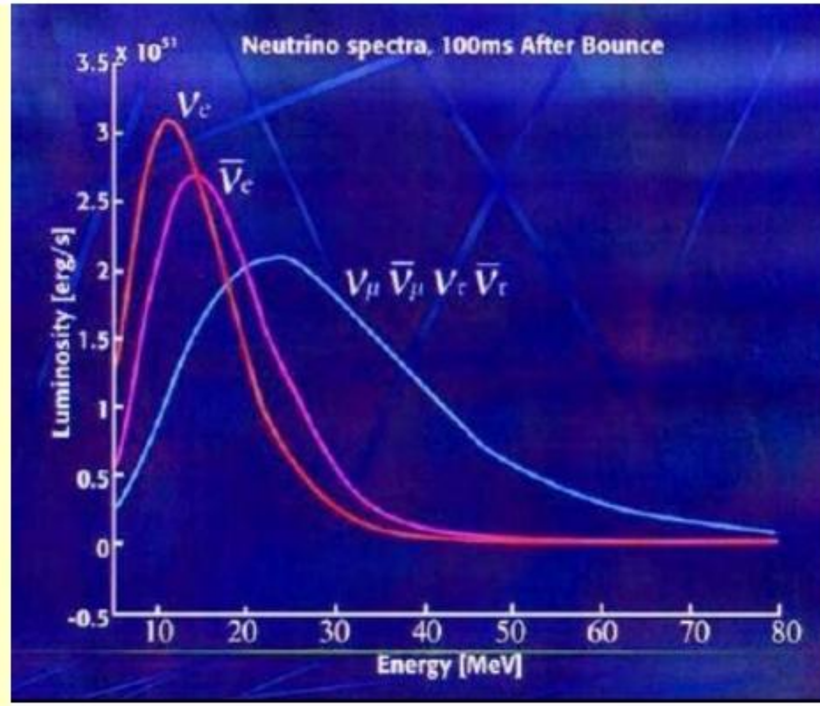
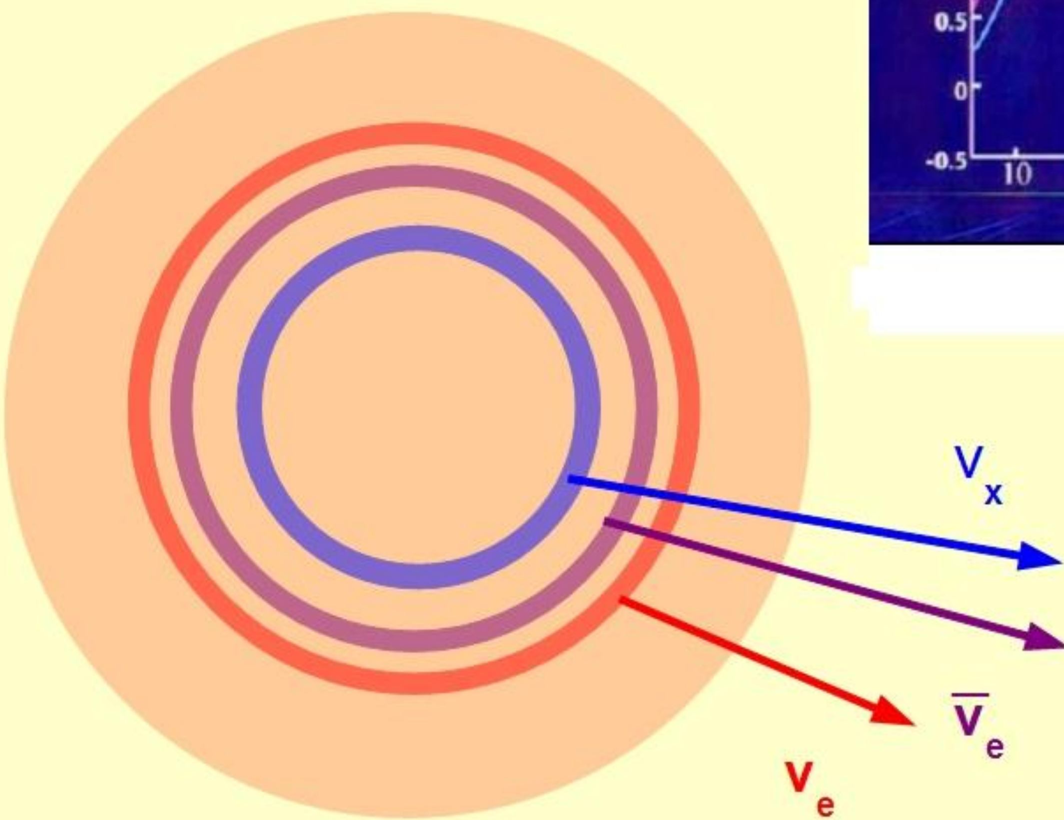
Neutrino emission in a core-collapse supernova: ν's trapped and thermalized.

Neutrinosphere = surface of last scattering





initial flavours transformed by ν-e (MSW) and ν-ν induced oscillations

The final neutrino spectra observed on earth depend both on the astrophysics of the supernova (mass, temperature, density profile, equation of state) which determine what the initial (unoscillated) neutrino spectra look like

and on currently unknown neutrino properties (mass hierarchy, θ_{13}) which will determine the flavour transitions that occur.

The observed rate in any single detector alone will not constrain the oscillation scenarios. e.g. high rate in HALO could be due to bigger SN, nearer supernova, hotter SN, hotter spectrum due to flavour swapping

What follows will be an exploratory work to see if we can constrain mass hierarchy and θ_{13} despite the model uncertainties of what the initial (unoscillated) neutrino spectra look like.

General idea: to use several detectors/reactions with different neutrino flavour sensitivies to constrain what oscillations may have occurred.

Flavour sensitivity of different detector materials:

Hydrogenous detectors (water Cerenkov and organic scintillators) are primarily sensitive to charged current anti-ν_e via

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Sensitivity to ν_e would be achieved using a neutron target, via the charged current reaction

$$\nu_e + n \rightarrow e^- + p$$

but a sufficient density of free neutrons is not available. The best we can do is to use a neutron-rich target N>Z, e.g. HALO uses lead (Z=82, N=126 for ^{208}Pb)

Target materials with N≈Z do not discriminate strongly between neutrinos and anti-neutrinos and are best suited for detecting neutral currents, which are blind to the neutrino flavour. Neutral current excitation is thus a valuable invariant to measure, in the midst of possible flavour changes between electron and non-electron flavours. However, ICARUS (liquid Ar TPC) will be a superb ν_e detector with pointing capability via the reaction

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

The rate in 600 tons LAr is roughly equal to 76 tons of Pb, reflecting the larger number of active neutrons in Pb compared to Ar and the strong Coulomb enhancement in Pb.

Supernova ν flux models

Use 3 different models for initial ν flux

'DD' = Das Gupta and Dighe, PRD 77, 113002

'Garching' = Raffelt et al. astro-ph/0303226

'Livermore' = Totani et al. APJ 496, 216 (1998)

Neutrino fluxes:

$$F^0_{\nu_i} = \frac{\Phi_0}{E_0} \frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \left(\frac{E}{E_0}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E}{E_0}\right]$$

E_0, α: in general time dependent

- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$

Model	$\langle E_0(\nu_e)\rangle$	$\langle E_0(\bar{\nu}_e)\rangle$	$\langle E_0(\nu_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
Garching (G)	12	15	18	0.8	0.8
Livermore (L)	12	15	24	2.0	1.6
DD	**10**	**15**	**20**	**2.0**	**1.33**

Adapted from A. Dighe, NUFACT07 presentation

The 'DD' parameterization has the softest ν_e spectrum and an anti- ν_e midway between the the Garching and Livermore parameterizations.

Subsequent oscillations

The initial fluxes are transformed by electron-neutrino (MSW) oscillations at larger distances from the core, and by collective ν-ν oscillations at smaller distances.

Only place in the universe with enough ν density

to see effects of ν-ν scattering and collective behaviour of an ensemble of ν's in thermal equilibrium.

The latter have been understood only in the past ~3 years and are not well-established experimentally.

Further uncertainties are the size of the mixing angle

θ_{13} and whether the neutrino mass hierarchy is normal or inverted.

References:

Dighe NuFact07 arXiv:hep-ph/0712.4386 (MSW only)

Dighe Neutrino08 arXiv:hep-ph/0809.2977 (MSW+collective νν)

summarized and expanded in

Dasgupta and Dighe, PRD 77, 113002 (2008)

These give prescriptions for the final ν fluxes after MSW and MSW+collective νν flavour transitions as understood 2 years ago **before the more recent "complicated but understandable mess" that Dasgupta described on Monday!**

May be still valid in accretion phase.

ν-Pb cross secs of →

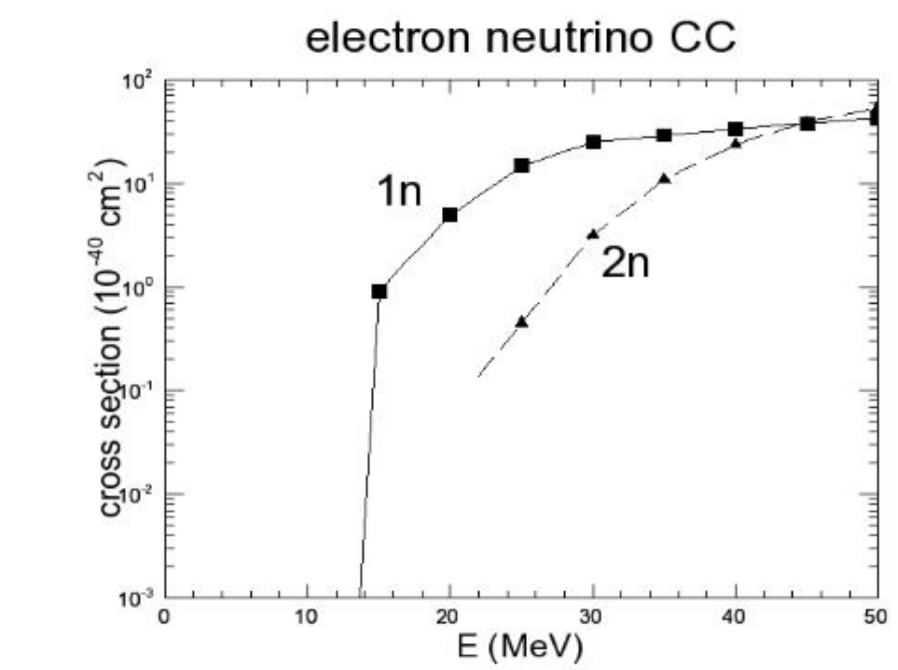
Engel, McLaughlin, Volpe

PR D67 013005 (2003)

arXiv:hep-ph/0209267

ν-C cross secs Burrows

PRD 45, 3361 (1992).



Following Dighe (with a change of notation for simplicity)

Let F^0, F denote initial, final flux of ν_e
G^0, G denote initial, final flux of anti- ν_e
H^0, H denote initial, final flux of ν_x (flux for any 1 of 4 non-electron types)

The final fluxes are obtained from the initial fluxes by

$$F = p\,F^0 + (1-p)\,H^0$$
$$G = q\,G^0 + (1-q)\,H^0$$
$$4\,H = (1-p)\,F^0 + (1-q)\,G^0 + (2+p+q)\,H^0$$

where the values of p and q are given on the next slide

We use the abbreviation
$s^2 = \sin^2\theta_{solar} = \sin^2\theta_{12} = \sin^2(33.9°) = 0.31108$
$c^2 = \cos^2\theta_{solar} = \cos^2\theta_{12} = \cos^2(33.9°) = 0.68892$

and "large" θ_{13} means $\sin^2\theta_{13} \geq 10^{-3}$ (limit for next generation expts)
"small" θ_{13} means $\sin^2\theta_{13} \leq 10^{-5}$
(the current CHOOZ limit is $\sin^2 2\theta_{13} < 0.2$)

The transformation coefficients p and q for the various scenarios are tabulated below:

Scenario	transition	hierarchy	θ_{13}	p	q
0	none			1	1
1	MSW	normal	large	0	c^2
2	MSW	inverted	large	s^2	0
3	MSW	normal	small	s^2	c^2
4	MSW	inverted	small	s^2	c^2
5	MSW+νν	normal	large	0	c^2
6	MSW+νν	inverted	large	s^2 | 0	c^2
7	MSW+νν	normal	small	s^2	c^2
8	MSW+νν	inverted	small	s^2 | 0	0

s^2 | 0 means use s^2 if the neutrino energy is less than the critical energy of ~7 MeV, 0 otherwise. This leads to the discontinuity known as ‘spectral splitting in the case of an inverted mass hierarchy, but not observable in HALO since it has a high (~18 MeV) detection threshold.

For HALO, there are 5 different scenarios: 0, 2, 8, and the repeats (1,5,6) and (3,4,7) .

We have at SNOLAB two detectors with complementary neutrino flavour sensitivities. **Important to have sensitivity to all flavours at one location, to avoid complications due to ν-Earth interactions.**

SNO+ predominantly sensitive to $\bar{\nu}_e$ via CC on protons

some sensitivity to all ν flavours via NC processes, e.g.
excitation of 15.11 MeV state in ^{12}C, or
νp elastic scattering

HALO large neutron excess in Pb, predominantly sensitive to ν_e
via CC excitation of states in Bi, but with significant (~20%)
contribution from NC excitation.

We have in principle sensitivity to ν_e, $\bar{\nu}_e$ and ν_x and can do a flavour decomposition of the neutrino flux from a supernova.

How can we use the data from HALO and SNO+ to put constraints on which one of these 9 scenarios actually occurs in a supernova?

The experimental observables are:

1. Neutron detection rate in HALO, from a sum of mostly charged current (CC) and some neutral current (NC) interactions in Pb, with no ability to distinguish these.
   No measure of incident ν energy. → **ν_e flux / energy**

2. Ratio of 2-neutron to 1-neutron emission events in HALO
   → **crude measure of ν_e energy** **(not used in this analysis)**

3. The **energy spectrum and flux of $\bar{\nu}_e$** from SNO+, via CC interactions on protons.

4. The gamma detection rate from the decay of the 15.11 MeV state in ^{12}C, excited by NC interactions in SNO+ (alternatively, rate for νp elastic scattering). **All ν flavours contribute equally**

Now consider scenario 8 in the table:

Scenario	transition	hierarchy	θ_{13}	p	q
0	none			1	1
1	MSW	normal	large	0	c^2
2	MSW	inverted	large	s^2	0
3	MSW	normal	small	s^2	c^2
4	MSW	inverted	small	s^2	c^2
5	MSW+νν	normal	large	0	c^2
6	MSW+νν	inverted	large	s^2 | 0	c^2
7	MSW+νν	normal	small	s^2	c^2
8	MSW+νν	inverted	small	s^2 | 0	0

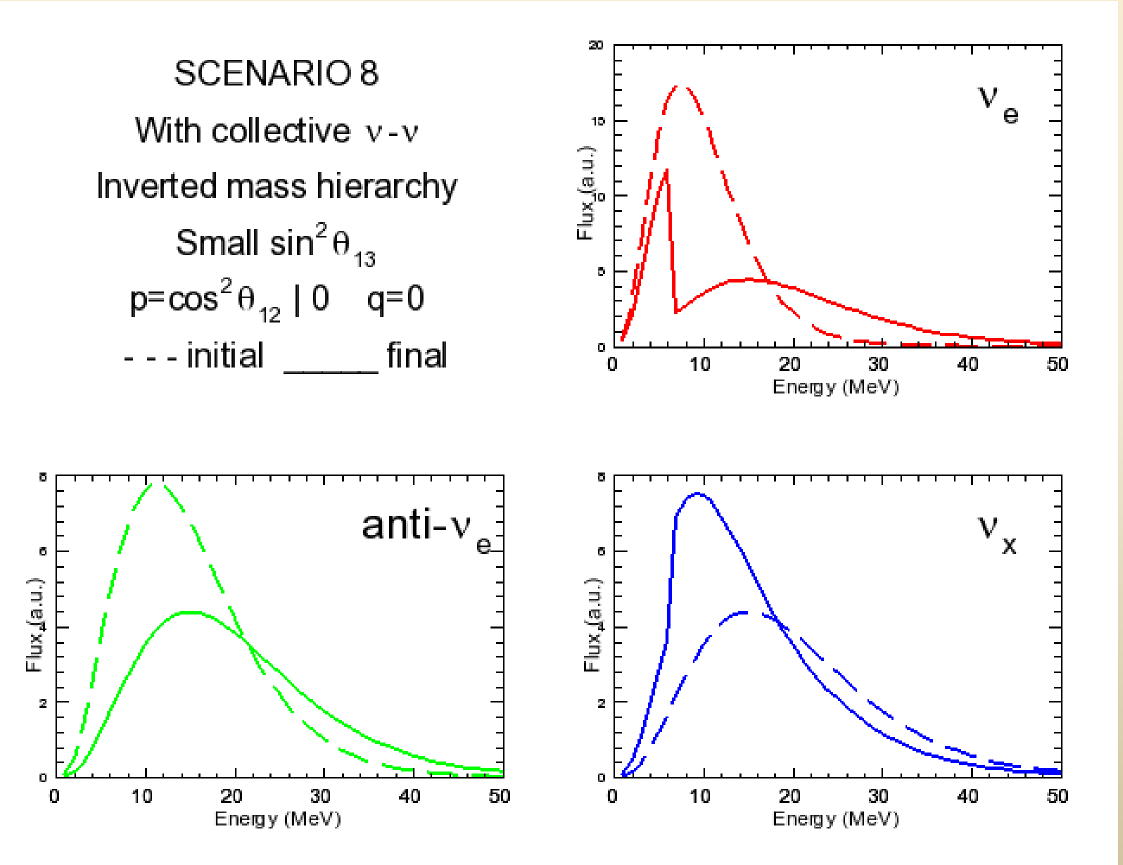
Since HALO has a high threshold above the critical energy, the values of p and q are both 0. Thus, the final electron neutrino and anti-neutrino fluxes F and G are related to the initial ones F^0 and G^0 by

$F = H^0$ $G = H^0$ where H denotes the ν_x flux

After the flavour transformation, the final ν_e and anti-ν_e spectra <u>are the same</u>. The ν_e , which initially had the lowest energy of all neutrino species, ends up with the energy of the ν_x , which had the highest energy. This flavour swapping increases the ν_e energy and the rate of CC interactions in Pb.

This is what the initial and final fluxes look like, under scenario 8, with the 'DD' initial fluxes.

Note that 1. final ν_e spectrum has an enhanced high-energy tail,
and 2. over 7 MeV, final ν_e and anti- ν_e spectra are the same



In scenario 8, the final ν_e and anti-ν_e spectra <u>are the same</u> . In all other scenarios, they are different, to varying degrees. A useful parameter to distinguish the different oscillation scenarios would be a measure of how different these two spectra are.

We can measure the $\bar{\nu}_e$ spectrum in SNO+. If the final $\bar{\nu}_e$ and ν_e

spectra are the same, then using the measured $\bar{\nu}_e$ spectrum as a proxy for the ν_e spectrum and folding this with the Pb CC cross sections of Engel et al. should give a good reproduction of the experimental Pb CC rate.

$$\text{Let } y = \frac{\text{Proxy[Pb(CC)]+Estimated[Pb(NC)]}}{\text{Measured [Pb(CC+NC)]}} \qquad (1)$$

← **measured rate in HALO mostly CC**

so y=1 means the ν_e and anti-ν_e spectra are the same.

How do we estimate the NC rate in Pb?

We estimate the NC rate on Pb from the measured NC excitation rate for 15.11 MeV state in C where 'rate' = ν flux * cross section.

For the 3 ν flux models (DD, Garching and Livermore) and the 9 oscillation scenarios for each model (0-8 in table), we calculate the NC rates on Pb and C, and obtain mean values of

R(Pb, 1n) = 37.6 ± 0.8 * R(C, 15.11)
R(Pb,2n) = 9.6 ± 1.5 * R(C, 15.11)
R(Pb, 1n+2n) = 47.2 ± 2.3 * R(C, 15.11)
R(Pb, 0n+1n+2n) = 56.8 ± 2.1 * R(C, 15.11)

Use these to get the 2nd term in the numerator of eq. (1) on the previous slide.

We define a second variable to distinguish the various scenarios.

Measured Pb(CC+NC) rate ← numerator dominated by ν_e CC

Let x = --

Measured C(15.11 NC) rate ← denominator sensitive to all ν flavours

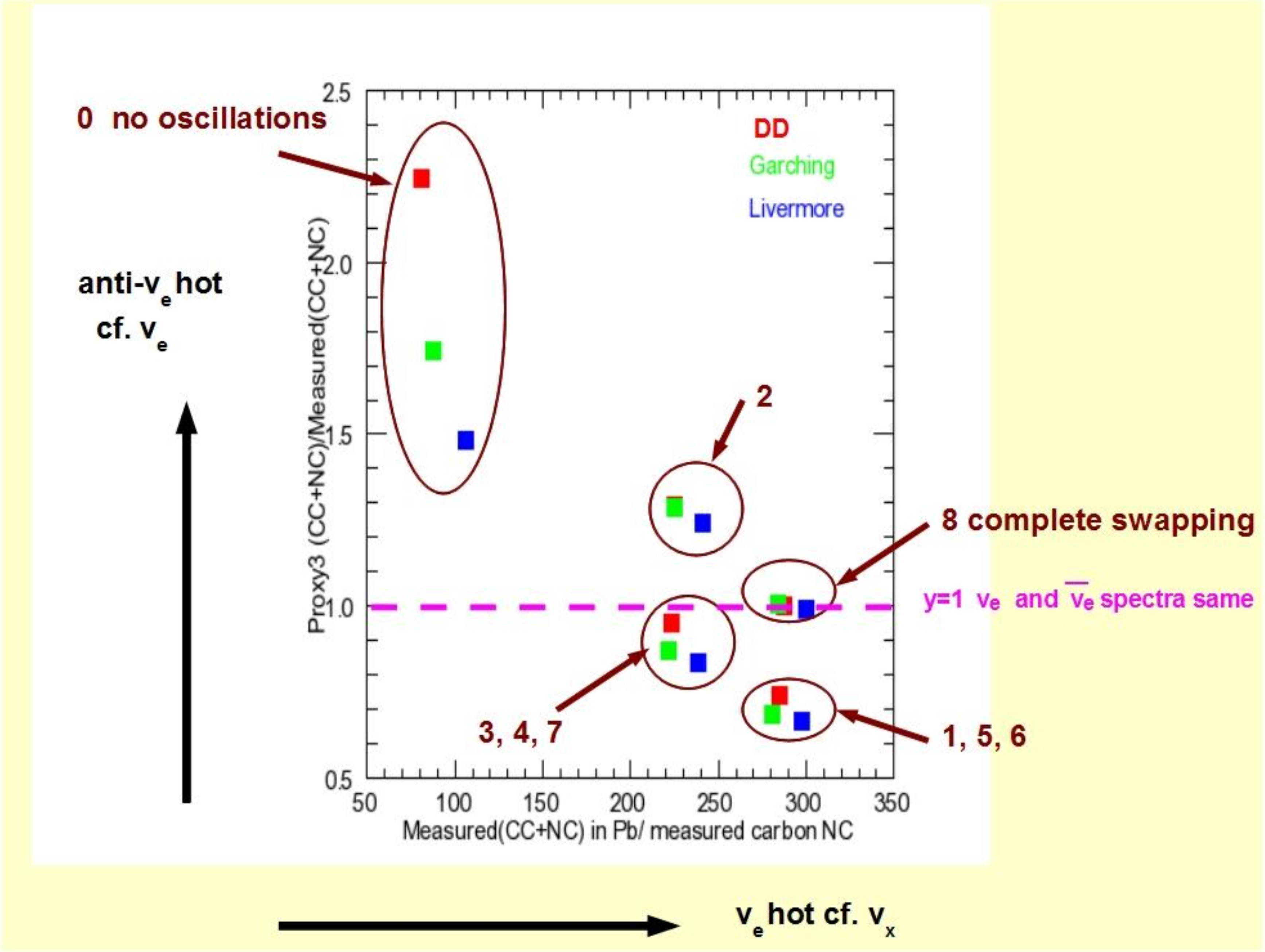
Since flavour-transitions tend to raise the energy of the ν_e's responsible for Pb(CC), to various degrees depending on the scenario, x is a measure of the "hotness" of the ν_e spectrum (numerator) compared to all neutrino flavours (denominator).

Notice that we have defined both x and y to be ratios, which are independent of the absolute flux of neutrinos. This means that these are robust quantities which do not depend on knowing the distance to the supernova or its absolute luminosity.

We now plot x versus y for the 9 scenarios, for each of the 3 supernova flux models.

x = hotness of ν_e compared to ν_x

y = hotness of anti-ν_e compared to ν_e


0 no oscillations
anti-ν$_e$ hot
cf. ν$_e$
DD
Garching
Livermore
2
8 complete swapping
y=1 ν$_e$ and $\overline{\nu}_e$ spectra same
3, 4, 7
1, 5, 6
Proxy3 (CC+NC)/Measured(CC+NC)
Measured(CC+NC) in Pb/ measured carbon NC
ν$_e$ hot cf. ν$_x$

It is evident that the different oscillation scenarios populate different regions of x-y space. Points from different initial flux models still cluster together according to oscillation scenario. We see 5 clusters corresponding to the 5 distinct oscillation scenarios.

The non-oscillation scenario 0 is characterized by low x
(i.e. cool ν_e spectrum)
and is clearly separated from all other oscillation scenarios.

The full flavour swapping scenario 8 results in y=1, regardless of which initial flux model is used.

By plotting actual supernova neutrino data on an x-y plot of this type, and seeing where the point lies in x-y space, we can select the most likely oscillation scenario and put constraints on (but not fully resolve) the questions of mass hierarchy and the value of θ_{13} .

Since x and y are ratios of rates in different detectors, this technique is completely insensitive to questions of overall normalization, e.g.

how distant is the SN?
how massive is the collapsed core?

and depends only on how hot the ν_e , anti- ν_e and ν_x are with respect to one another.

This techniques works only if we have accurate knowledge of the Pb-ν cross sections, for all isotopes of Pb. Much more experimental and theoretical work is required in this regard.

Theory: Substantial differences (20-30% in CC and 15% in NC) between the calculation of Engel, McLaughlin and Volpe for the ν+Pb cross sections used in this work, and the calculation of Kolbe and Langanke Phys. Rev. C63, 025801 (2001). Can we do better with modern computational techniques? Calculate all isotopes, not just ^{208}Pb.

Experiment: Even the total ν+Pb cross section at a single energy has not been measured experimentally, not to mention the partial cross sections for 1- and 2-neutron emission as a function of neutrino energy.

Neutral current:

A good neutral current measurement is necessary for this technique to work. NC gives an overall flavour-insensitive normalization to the CC data.

SNO+ must maximize its sensitivity to NC processes which are our only handle on the ν_x flavours.

i.e. good energy resolution to resolve γ-ray following excitation of 15.11 MeV state in ^{12}C

and

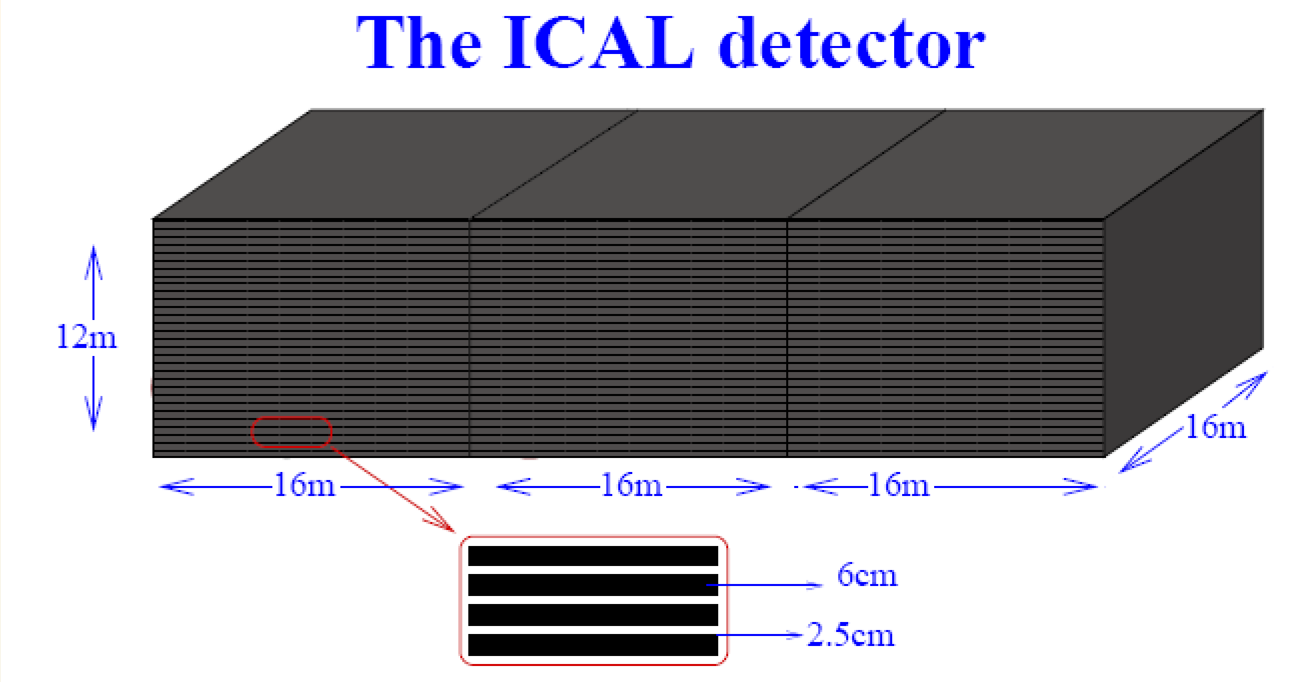
low energy threshold to pick up signals of recoiling protons from νp elastic scattering.

Statistics in SNO+ are small (~ 20-30 events for SN at 10 kpc)

Maybe need to supplement HALO and SNO+ with a NC sensitive detector using N≈Z material, e.g. several kilotons of iron?

Does anybody have a kiloton of iron or lead for a SN detector?

INO – India Neutrino Observatory

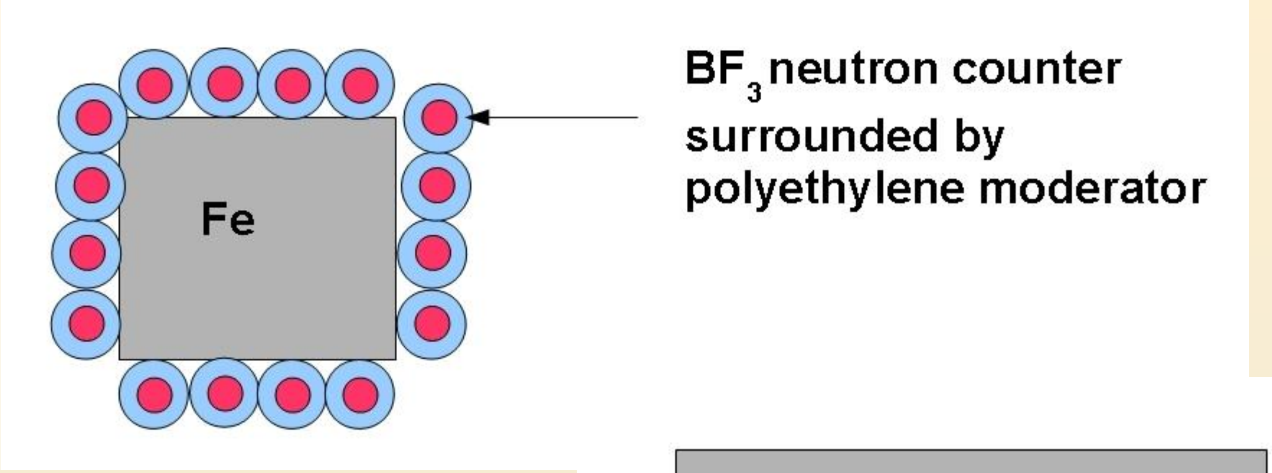


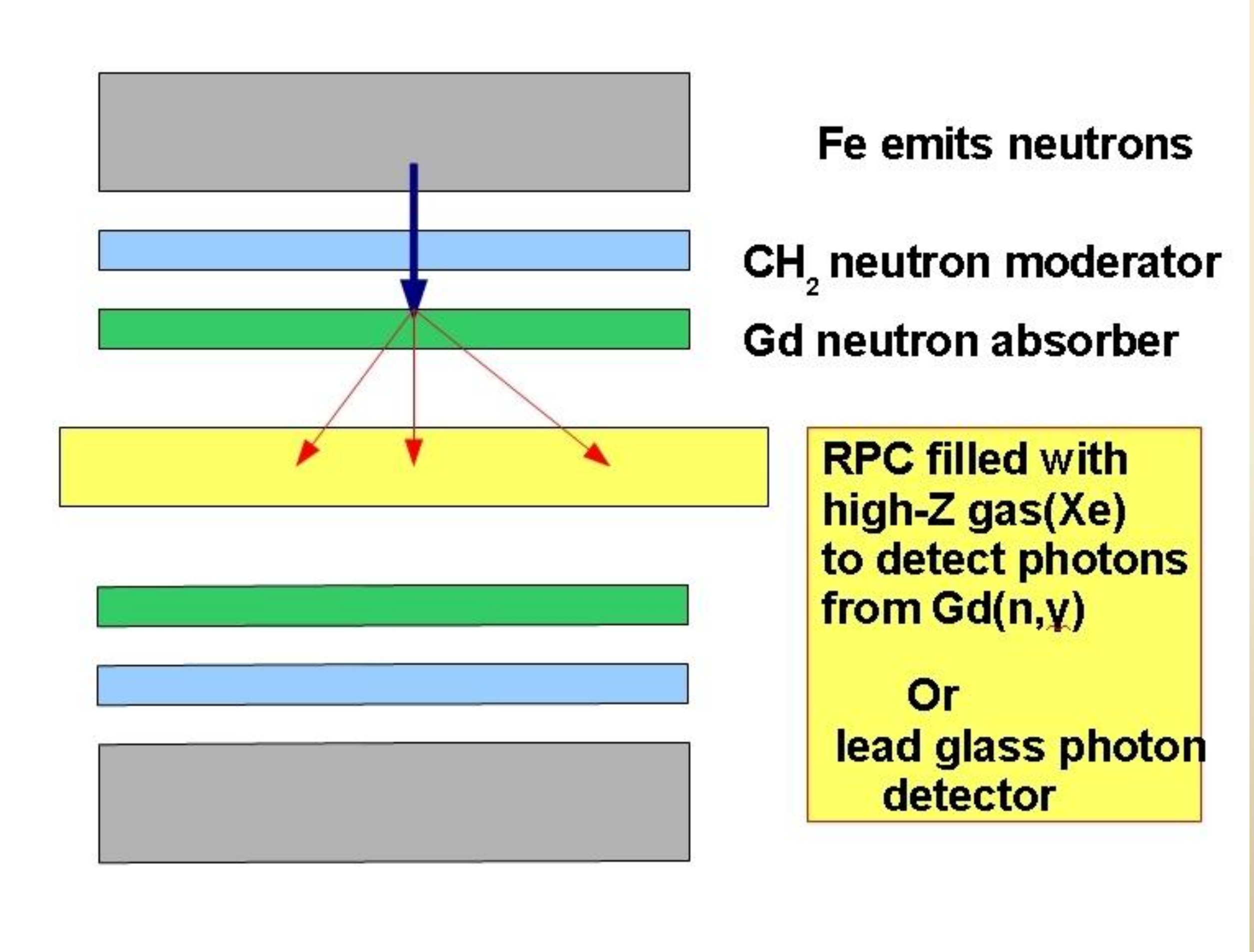
From lecture
D. Indumathi

50 kilotons of magnetized iron in 6 cm thick plates, separated by gas-filled resistive plate counters – for > 1 GeV muons, not suitable for SN detection.

But Fe(ν,ν'n) neutron knockout would make a good NC detector for SN neutrinos. (Kolbe & Langanke, Phys. Rev. C63, 025801 (2001)).
Make INO detector sensitive to neutrons by adding polyethylene moderator + a neutron-absorbing gas e.g. BF_3 or ^3He in the detectors?

Other possible INO neutron detection schemes





Summary

I have described a possible technique to distinguish different neutrino oscillation scenarios in a supernova, which depend on the presence/absence of collective ν-ν effects, the size of mixing angle θ_{13} , and the neutrino mass hierarchy.

By comparing the measured rates of different neutrino reactions with different detector materials, it is possible to extract an experimental signature which distinguishes the different scenarios, and constrains the presently-unknown values of θ_{13} and the mass hierarchy.

Substantial theoretical and experimental uncertainties with regards to the cross section for neutron emission on lead must be resolved before this technique will work.

Possibility of using INO as large neutral current detector for SN neutrinos maybe worth considering.