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NEUTRINOS AS ASTROPHYSICAL PROBES

F. VISSANI
INFN, Gran Sasso
Italy

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strada costiera, 11 - 34014 trieste italy - tel. +39 0402240111 fax +39 040224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

NEUTRINOS AS ASTROPHYSICAL PROBES

F. Vissani (INFN, LNGS), in collaboration with
F. Cavanna (L'Aquila U), G. Di Carlo (LNGS)
W. Fulgione (Turin U.), P.L. Ghia (CNR Turin)
O. Palamara (LNGS), A. Strumia (CERN & Pisa U.)
[vissani@lngs.infn.it]

1 - Methods & goals of ν astronomy
[= introduction]

2 - A promising source: supernovae of type II
[= gravitational collapse ; core-collapse supernovae]

3 - Impact of flavor oscillations
[= the change of perspective due
to the recent achievements]

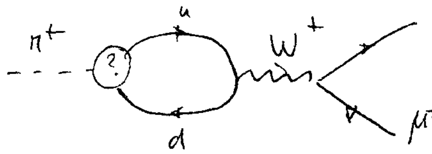
[redacted]

ICTP Summer School on Astroparticle Physics and Cosmology, Trieste, June 27, 2002.

NEUTRINOS

- Definitions: those neutral particles coupled to charged leptons by charged weak interactions (CC = charged currents)

$\pi^+ \to \mu^+ \nu_\mu$ means



A MUON NEUTRINO

(A MUON)

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ means

AN ELECTRON NEUTRINO

(A POSITRON)

A MUON ANTINEUTRINO

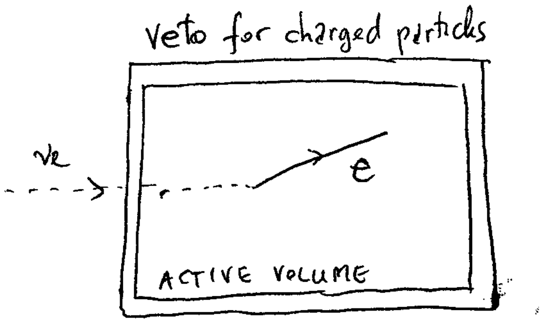
- Neutrinos are typically invisible, but can reveal their presence ~~by~~ depositing (or carrying away) energy, e.g. in the following interactions:

A LIST OF IMPORTANT CC REACTIONS.

REACTIONS	XSECTION	COMMENTS
$\nu_e\, e^- \longrightarrow \nu_e\, e^-$ $\nu_\mu\, e^- \longrightarrow \nu_\mu\, e^-$	$\sigma \sim G_F^2 m_e E_\nu$	electron, originally at rest, is hit by neutrino. Note that when $E_\nu \gg m_e$, e^- maintains the ν direction (DIRECTIONALITY)
$\bar{\nu}_e\, p \longrightarrow e^+ n$ $\nu_e\, n \longrightarrow e^- p$	$\sigma \sim G_F^2 E_\nu^2$ (but threshold is important)	this has large cross section. Note that free neutrons are present only in particular situations, e.g. Early Universe
$\nu_e\, (A,Z) \longrightarrow e^-\, (A, Z+1)$	$\sigma \propto A^2$ at intermediate energies	
$\nu_\ell\, N \longrightarrow \ell^- X$ $\bar{\nu}_\ell\, N \longrightarrow \ell^+ X$	$\sigma \sim G_F^2 m_p E_\nu$	$N = n, p$, or nucleus. X = whatever hadronic state - $\ell = e, \mu, \tau$. (Called Deep Inelastic Scattering)

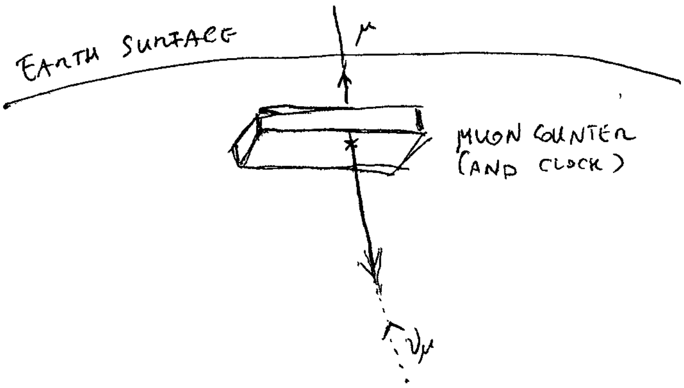
- Usual neutrino trackers: $e^\pm$, $\mu^\pm$, γ IN FINAL STATES (a γ CAN BE PRODUCED BY NUCLEAR RADIATION, OR CAN BE DUE TO NEUTRON: $n + \text{Nucleus} \to \text{Nucleus}^* \to \text{Nucleus}' + \gamma$)

- We show <u>some</u> conceptual detector, to illustrate how neutrinos are searched experimentally:



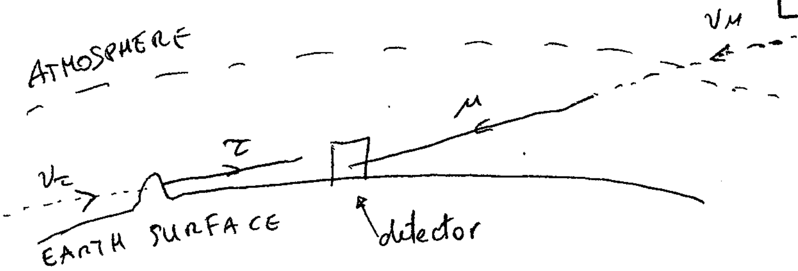
ACTIVE VOLUME CAN BE CHERENKOV RADIATOR; SCINTILLATOR; LAYERED TARGET - SCINTILLATOR; etc.
FROM MeV TO FEW GeV ENERGIES (track containment)

$$\boxed{\#_{events} = \#_{targets} \cdot \sigma_\nu \cdot Flux_\nu \cdot TIME \quad \propto \text{VOLUME of DETECTOR}}$$



LOCATED UNDERGROUND (UNDERWATER, UNDER ICE) TO AVOID BACKGROUND FROM CR
FROM FEW GeV TO ~100 TeV (Earth crossing)

$$\boxed{\begin{aligned} F_\mu &= F_{\nu_\mu} \cdot \left(\sigma_{\nu_\mu} \cdot N_A \cdot Range_\mu\right) \\ \#_{events} &= A \cdot F_\mu \cdot TIME \\ &\propto \text{AREA of DETECTOR} \end{aligned}}$$



VERY HIGH ENERGY (POSSIBLY WITH EXOTIC CROSS SECTIONS)

- In principle, we can <u>measure</u> many quantities:

a_ direction of charged lepton
b_ energy " " "
c_ charge " " "
d_ tag flavor
e_ time of arrival
f_ secondary products (n, γ, hadrons)

NEUTRINO "ASTRONOMY"

The goal is to use ν to probe astrophysical sources (in much the same manner as done by photons).

Neutrino information can be complementary; since they have different interactions than γ (that could be absorbed). Some important example follow:

ex. (1) Atmospheric neutrinos (not classified as "astronomy" usually) [0.1–1000 GeV]

CR, normally, come isotropically and are not completely understood. The study of atmospheric neutrinos however permits to learn on CR spectra and interactions with Atmosphere (and as everybody knows, they indicate OSCILLATIONS) $\boxed{\text{at } 15\sigma}$

ex. (2) Neutrinos from cosmic sources. [0.1–10^5 GeV]

By selecting an solid angle observation window around a cosmic object (say, an AGN) one can search for excess of neutrino events over atmospheric background. Crucial: large area of installation, good pointing to the source. (~Important: energy determin., if possible)

[see table ~~of~~ MACRO results].

Very important future goal (at the moment, only upper bounds) ex. (3) Solar neutrinos [0.1 – 20 MeV]

Very little doubts that these has to be classified as ~~...~~ neutrino astronomy. Some of major results are:

* confirm that solar energy source is nuclear reactions initiated by $pp \to D e^+ \nu_e$.

* strongly suggest OSCILLATIONS (an 8σ effect) [see Smirnov lecture!]. For instance recent SNO experiment result on neutron counting indicate that the ~~...~~ Total flux of high energy ν's in agreement with solar model predictions; however, there ~~are~~ only 1/3 of ν_e neutrinos expected.

(SNO is heavy water detector)

* $\nu_\ell D \to \nu_\ell p n$ followed by $n D \to T \gamma$ (6.3 MeV) MEASURES TOTAL FLUX.

* $\nu_e D \to e^- p p$ MEASURES ν_e ONLY.

* probe physics in the center of our sun (ρ_0 (central) ~ 150 gr/cc) and are consistent with the theory of solar oscillation eigenmodes (= helioseismology).

ex. (4) Supernova Neutrinos [1 – 100 MeV]

(the topic of the rest of this lecture)

EXPECTED RATE OF OCCURRENCE: 1–4 per CENTURY.

Most of Supernova type II energy carried off by neutrinos (of all ~~...~~ flavours)

~20 ν detected in 1987 from a LMC supernova (SN1987A). Good agreement with expectations, beginning of extrasolar ν astronomy.

Many detectors operate (or will operate) in the future; promise of big payoff in (astro) physics currency.

MACRO LIMITS ON COSMIC SOURCES

TERESA MONTARULI, hep-ex / 9905020 (MACRO AS ν TELESCOPE)

LOCATION

SELECTED ANGULAR WINDOW

REMARK: other options for bigger reduction, is to search for TIME VARIABLE SOURCE (namely, some episodic ν_μ bursts)

Source	δ	Data (3°)	Backg.(3°)	μ-Flux limit 1 $cm^{-2}\ s^{-1}$	~~μ-Flux limit 2 $cm^{-2}\ s^{-1}$~~	~~Prev. best μ limit $cm^{-2}\ s^{-1}$~~	ν-Flux limit $cm^{-2}\ s^{-1}$
SMCX-1	-73.5°	3	1.87	$0.60 \cdot 10^{-14}$	~~$0.67 \cdot 10^{-14}$~~	~~-~~	$0.19 \cdot 10^{-5}$
SN1987A	-69.3°	0	1.79	$0.29 \cdot 10^{-14}$	~~$0.16 \cdot 10^{-14}$~~	~~$1.15 \cdot 10^{-14}$ B~~	$0.09 \cdot 10^{-5}$
Vela P	-45.2°	1	1.40	$0.56 \cdot 10^{-14}$	~~$0.53 \cdot 10^{-14}$~~	~~$0.78 \cdot 10^{-14}$ I~~	$0.17 \cdot 10^{-5}$
SN1006	-41.7°	1	1.21	$0.58 \cdot 10^{-14}$	~~$0.58 \cdot 10^{-14}$~~	~~-~~	$0.18 \cdot 10^{-5}$
Gal.Cen.	-28.9°	0	0.86	$0.48 \cdot 10^{-14}$	~~$0.35 \cdot 10^{-14}$~~	~~$0.95 \cdot 10^{-14}$ B~~	$0.15 \cdot 10^{-5}$
Kep1604	-21.5°	2	0.82	$1.04 \cdot 10^{-14}$	~~$1.15 \cdot 10^{-14}$~~	~~-~~	$0.32 \cdot 10^{-5}$
ScoXR-1	-15.6°	1	0.76	$0.85 \cdot 10^{-14}$	~~$0.90 \cdot 10^{-14}$~~	~~$1.5 \cdot 10^{-14}$ B~~	$0.26 \cdot 10^{-5}$
Geminga	18.3°	0	0.42	$1.34 \cdot 10^{-14}$	~~$1.17 \cdot 10^{-14}$~~	~~$3.1 \cdot 10^{-14}$ I~~	$0.41 \cdot 10^{-5}$
Crab	22.0°	1	0.40	$2.22 \cdot 10^{-14}$	~~$2.22 \cdot 10^{-14}$~~	~~$2.6 \cdot 10^{-14}$ B~~	$0.68 \cdot 10^{-5}$
MRK501	38.8°	0	0.12	$5.40 \cdot 10^{-14}$	~~$5.44 \cdot 10^{-14}$~~		$1.66 \cdot 10^{-5}$

Table 2: μ flux limits for some sources (90% c.l.) calculated using the classical Poissonian method (μ flux limit 1) and the prescriptions in Feldman, & Cousins, 1998 (μ flux limit 2). Previous best limits (Gaisser, 1996): B is for Baksan, I for IMB. Neutrino flux limits are given.

checked with the moon shadow measurement (Ambrosio et al., 1999)). The rock absorber inside the lower half of MACRO imposes an energy threshold to vertical muons of $\sim$ 1 GeV. The data used for the upward-going muon analysis has been collected since Mar. 89 with the incomplete detector (Ahlen et al., 1995), since Apr. 94 the full detector has been taking data (Ambrosio et al., 1998). In addition to $\sim 33 \cdot 10^6$ atmospheric μs, 990 upwardgoing μs with $-1.25 < 1/\beta < -0.75$ are selected with an automated analysis. $1/\beta = \Delta Tc/L$, ΔT being the measured T.o.F. and L the track length, is $\sim$ 1 for downward-going muons and ~ -1 for upward-going muons. Among these 990 events, 890 are measured with the full detector. The T.o.F. measurement is used to select upward-going μs produced in the rock below and inside the apparatus by atmospheric neutrinos of average energy $\langle E_\nu \rangle \sim$ 100 GeV and $\langle E_\nu \rangle \sim$ 4 GeV, respectively, from atmospheric downward-going muons. The main requirement to reject events with incorrect β measurement is that the position along the scintillation boxes measured using the times at the 2 ends (spatial resolution $\sim$ 11 cm) and the position obtained using the streamer track (spatial resolution of $\sim$ 1 cm) are in agreement within 70 cm.

The sample used for this analysis is larger than the one used for the neutrino oscillation analysis (Ronga et al., 1999) because we remove the requirement that 2 m of absorber are crossed in the lower part of the MACRO and we include a period in which MACRO was under construction. In fact, when calculating upper limits, the benefit of increasing the exposure offsets the slight increase of the background. We look for statistically significant excesses of upward-going muons in the direction of known sources (a list we have compiled of 40 selected sources, 129 Egret sources (Thompson et al, 1995), 220 SNRs (Green, 1998), 7 sources with γ emission above 1 TeV, 2328 GRBs in the BATSE Catalogue (Meegan et al., 1997)) or around the direction of any of the detected neutrino events. For this directional search it is important to consider the angular spread between the detected μ and the parent ν due to the ν spectrum which determines the kinematics of the charged current interaction, the μ propagation from production to detection and the angular resolution of the apparatus. In Tab. 1 we show the fraction of events accepted in a cone of 3° for various differential ν spectral indices γ and muon directions. We have considered cones with half- widths of 1.5°,3°,5° and 10° around the direction of known sources or of the detected upward-going

E_ν (GeV)	$P_{\nu\to\mu^-}$	$P_{\bar\nu\to\mu^+}$
10	1.27×10^{-10}	9.25×10^{-11}
10^2	9.73×10^{-9}	6.68×10^{-9}
10^3	5.99×10^{-7}	4.12×10^{-7}
10^4	1.56×10^{-5}	1.14×10^{-5}
10^5	1.39×10^{-4}	1.21×10^{-4}

Table 3: Probabilities for νs and $\bar\nu$s with energy E_ν to produce a μ with $E_\mu \geq 1$ GeV.

YIELD TABLE (denoted by P)

$P_{\nu\to\mu} = \sigma_{\nu_\mu} N_A R_{\mu}$

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CHANCES FOR ν ASTRONOMY & other (= hopes for the future)

FRANCIS HALZEN astroph/9710029 (review talk) (quest for km scale detector)

Notice

Basic motivation for km (volume or area) detector is just due to energy loss formula

$$\frac{dE_\mu}{dR} = \alpha + \beta \cdot E_\mu$$

(continuous energy loss) (catastrophic energy loss)

At $E_\mu^{cr} \gtrsim \alpha/\beta \sim 500$ GeV second term dominates, and range R is cutoff. $E_\mu^{cr} \Rightarrow R_\mu^{cr} \sim 1$ km in water.

Many projects in this direction underwater (ANTARES, NEMO) & under ice (AMANDA).

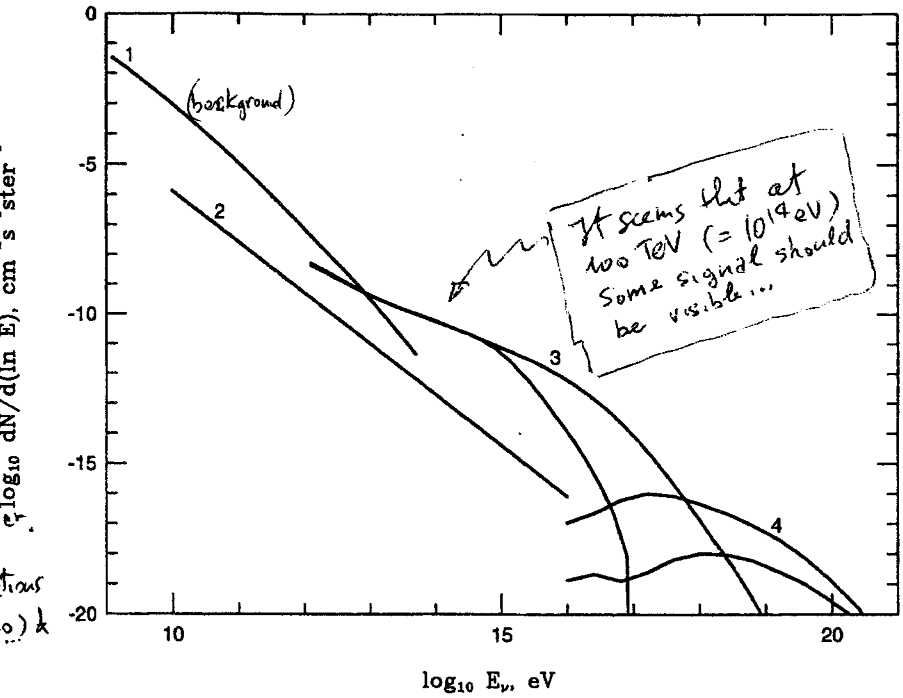


Figure 1: Summary of isotropic neutrino fluxes of energy above 1 GeV. (1) atmospheric neutrinos; (2) diffuse galactic neutrinos; (3) diffuse extragalactic neutrinos — maximum and minimum predictions; (4) cosmological neutrinos — maximum and minimum predictions. From Ref. [1] → P. Rep. 258, 173 (1995)

Consisting of several thousand optical modules (OM: pressure vessel containing a conventional photomultiplier tube and, possibly, data acquisition electronics) deployed in natural water or ice, even the ultimate scope of these detectors is similar to that of the Superkamiokande or ~~SNO solar neutrino~~ experiments[2]. Being optimized for large effective area rather than low threshold (GeV or more, rather than MeV), they are complementary to these detectors. The challenge to deploy the components in an unfriendly environment is, however, considerable. With a price tag which may be as low as a relatively cheap fixed-target experiment at an accelerator, ~~but could be as~~ high as that of a LHC detector, this must be one of the best motivated large-scale scientific endeavors ever.

As for conventional telescopes, at least two are required to cover the sky. As with particle physics collider experiments, it is very advantageous to explore a new frontier with two or more instruments, preferably using different techniques. This goal may be achieved by exploiting the parallel efforts to use natural water ~~and~~ ice as a Cherenkov medium for particle detection.

2 Detection Techniques[3]

One can picture a neutrino telescope as a collection of strings (actually cables transmitting the signals) spaced by a distance d_{string} of several tens of meters. The OMs are deployed as

2nd enclosed xcopy

SN 1987A

t in sec	E_e in MeV	ϑ_e in $^\circ$
0	20 ± 2.9	18 ± 18
0.107	13.5 ± 3.2	40 ± 27
0.303	7.5 ± 2.0	108 ± 32
0.324	9.2 ± 2.7	70 ± 30
0.507	12.8 ± 2.9	135 ± 23
0.686	6.3 ± 1.7	68 ± 77
1.541	35.4 ± 8	32 ± 16
1.728	21.0 ± 4.2	30 ± 18
1.915	19.8 ± 3.2	38 ± 22
9.219	8.6 ± 2.7	122 ± 30
10.433	13.0 ± 2.6	49 ± 26
12.439	8.9 ± 1.9	91 ± 39

Events at Kamiokande 2

t	E_e	ϑ_e
0	38 ± 7	80 ± 10
0.412	37 ± 7	44 ± 15
0.650	28 ± 6	56 ± 20
1.141	39 ± 7	65 ± 20
1.562	36 ± 9	33 ± 15
2.684	36 ± 6	52 ± 10
5.010	19 ± 5	42 ± 20
5.586	22 ± 5	104 ± 20

Events at IMB

+ 5 events at BAKSAN, and 5 event at Mont Blanc (but with wrong time)

Distance to Earth D	~ 50 kpc (1 pc = 3.2 yl)
Radius of core R_c	10 km
Core density at bounce ρ_c	8×10^{14} g/cc
Core Mass M_c	$(1.4 - 2)\, M_\odot$
Binding Energy E_B	$(2-4)\, 10^{53}$ erg
Core temperature T_c	$30 - 80$ MeV
Fractional density of e^- Y_e	0.4
" " of ν	0.04

SN1987A PARAMETERS (don't take this too seriously)

Agreement between theor. expectations and observation

ν events attributed to $\bar{\nu}_e\, p \to e^+ n$ ONLY, which has by far the largest cross section.

GRAVITATIONAL COLLAPSE

STAR EQUILIBRIUM

gravity $\rightleftarrows$ nuclear reactions

For large mass stars, Fe core is formed. Fe is most stable nucleus, does not contrib. to nuclear reactions.

When gravitational pressure $P_g \sim \frac{G_N M^2}{R^2}$ overtakes?

$$P(\text{electron degeneracy}) \sim \begin{cases} (p_F^2/2m_e)/v = \hbar^2/2m_e \, n_e^{5/3} & \text{if electron is non-relativistic} \\ (c p_F)/v = \hbar c \, n_e^{4/3} & \text{" " relativistic} \end{cases}$$

For non-relativistic case, P_{deg} can support the star, since $n_e \sim M/(R^3 m_n)$ (P_{deg} increases faster than P_g with smaller R)

For relativistic case, one realizes the existence of a mass (Chandrasekhar mass)

$$M \sim \left(\frac{\hbar c}{G_N}\right)^{3/2} \frac{1}{m_n^2} \sim 1.4 \, M_\odot \quad (\text{with } O(1) \text{ coeff.})$$

such that gravity wins, and collapse begins.

This happens for large mass stars, $\gtrsim 8 M_\odot$ (In all previous equations, M should be thought as the IRON core mass).

ENERGETIC OF THE COLLAPSE

Let us recall that $M_\odot c^2 \sim 2 \cdot 10^{54}$ erg. With this in mind, one is impressed by gravitational energy released in the collapse:

$$E_B = \frac{3}{5}\frac{G_N M_c^2}{R} = \left(\frac{M_c}{1.4 M_\odot}\right)^2 \cdot \left(\frac{10\,km}{R}\right) \cdot 3\,10^{53}\ erg\ !$$

(factor 3/5 correct for uniform density)

Much bigger than kinetic energy of the explosion; if $M \sim 10\, M_\odot$, $v \sim 5000$ km/sec,

$E_{kin} = \frac{1}{2} M v^2 \sim 2.5 \cdot 10^{51}$ erg.

Also bigger than energy necessary to dissociate fully the iron core (though this does not happen) : indeed $^{56}Fe \to 13\alpha + 4n - 124$ MeV, so that $E_{diss} = \frac{M_c}{m_n} \cdot 2.2$ MeV $\sim 4 \cdot 10^{51}$ erg.

Optical energy $\lesssim 10^{49}$ erg, gravitational energy much smaller.

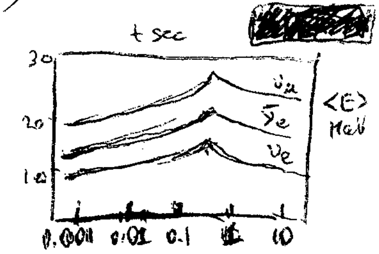
It is neutrinos of all species that carry away 99% of the gravitational energy E_B.

SN NEUTRINOS : TIMESCALES AND ENERGIES

Various phase of the collapse lead to various fluxes of neutrinos (time dependent fluxes) described below

CONVENTIONAL NAME	DESCRIPTION	TIME	% of E_B
infall [only ν_e]	collapse begins. $ep \to \nu_e n$. ν trapping increases	~ 100 msec	> 1%
flash [only ν_e]	Bounce. When reaches ν-sphere flash obtains (ν_e are liberated)	few msec [$t \equiv 0$]	~ 1%
accretion	~~Schock~~ Shock stalls. $e^+e^- \to \nu_e \bar{\nu}_e$, all type ν are produced. Explosion resumes due to ν pressure + turbulence + ?	0.5 sec	~ 20%
cooling	Proto NS cools emitting ν's	till 10 - 100 sec	~ 80%

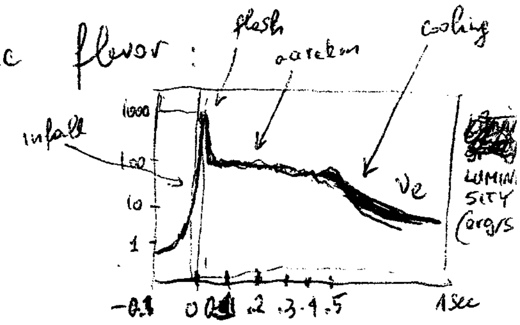
- Average ν energies ($\nu_x \equiv \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)



$$\begin{cases} \langle E_{\nu_e} \rangle = 10-12 \text{ MeV} \\ \langle E_{\bar{\nu}_e} \rangle = 14-17 \text{ MeV} \\ \langle E_{\nu_x} \rangle = 22-27 \text{ MeV} \end{cases}$$

(neutrinos that interact more, decouple in more external regions; this explains temperature ladder)

- Total energy carried away in specific flavor:



$$\begin{cases} \mathcal{E}_{\nu_e} = 17-22\ \%\ E_B \\ \mathcal{E}_{\bar{\nu}_e} = 17-28\ \%\ E_B \\ \mathcal{E}_{\nu_x} = 16-12\ \% \cdot E_B \end{cases}$$

(this numerical result called "equipartition" though it seems not to be due to some profound reason)

~~NEUTRINO~~ SPECTRUM, LUMINOSITY, FLUX

- AT ANY TIME t, A CONVENIENT PARAMETERISATION IS

$$\frac{dN_\nu}{dE} = \frac{\mathcal{L}_\nu(t)}{T_\nu^4 F_3(\eta_\nu)} \frac{E^2}{1+e^{E/T_\nu - \eta_\nu}}$$

Neutrino (number) spectrum per unit energy, ν/(sec MeV)

THIS IS NORMALISED AT FIXEX LUMINOSITY:

$$\int dl_\nu \equiv \int E \cdot dN_\nu = \frac{\mathcal{L}_\nu(t)}{F_3(\eta_\nu)} \int \frac{E^3\, dE}{1+e^{E/T_\nu - \eta}} = \mathcal{L}_\nu(t)$$

Neutrino luminosity erg/(sec MeV)

- ONE NEEDS 3 QUANTITIES FROM NUMERICAL CALCULATIONS:

$$\begin{cases} \mathcal{L}_\nu(t) = \text{(instantaneous) LUMINOSITY} & \text{erg/sec} \\ T_\nu(t) = \quad \text{"} \quad \text{TEMPERATURE} & \text{MeV} \\ \eta_\nu(t) = \quad \text{"} \quad \text{"PINCHING" PARAM.} & \text{adim.} \end{cases}$$

(not subject to $\eta_\nu = -\eta_{\bar\nu}$)

(IN PRACTICE, ONE USES $\langle E \rangle$ and $\langle E^2 \rangle$ TO DERIVE T_ν AND η_ν)

- NEUTRINO FLUX FROM $dF_\nu = dN_\nu/(4\pi D^2)$:

$$\boxed{\frac{dF_\nu}{dE} = \frac{1}{4\pi D^2} \frac{\mathcal{L}_\nu(t)}{T_\nu^4 F_3(\eta_\nu)} \frac{E^2}{1+e^{E/T_\nu - \eta}}}$$

Neutrino flux ν/(cm^2 sec MeV)

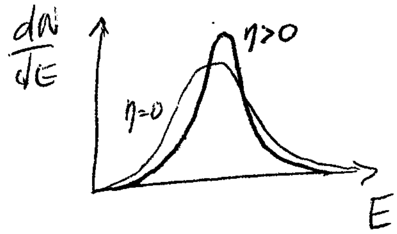
EFFECT OF NON-THERMAL DISTRIBUTION

- Consider the distribution at fixed luminosity $\mathcal{L}$ and average energy $\langle E \rangle$:

$$\frac{dN}{dE}(\eta) = \frac{\mathcal{L}}{T^4 F_3(\eta)} \frac{E^2}{1+e^{E/T-\eta}} \Bigg|_{T=\langle E\rangle \cdot F_2(\eta)/F_3(\eta)}$$

The parameter η describes the effect of a <u>non-thermal distribution</u>: that is an increase at intermediate energies, and a decrease elsewhere*.

This is called 'pinching'.



- A typical cross section that increase fast at high energies and has large threshold is $\nu_e\, {}^{12}C \to e^-\, {}^{12}N$. In this case, moving η from 0 to 2 leads to a ~20% decrease of event #, if $\langle E\rangle = 23$ MeV.

- Also, energy transfer to the star diminishes with increasing η.

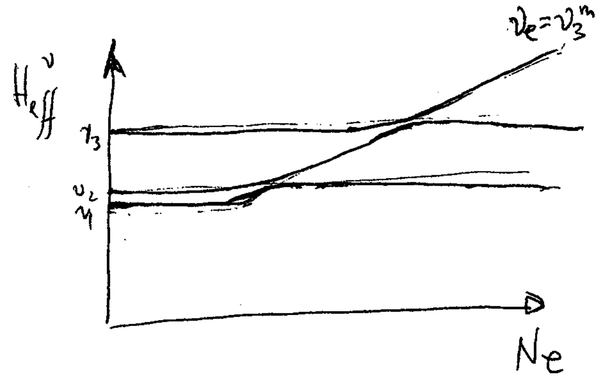
---

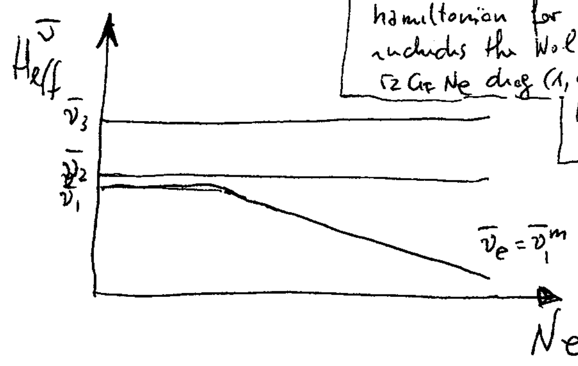
* low energies: 'neutrinosphere' depend on energy, smaller at these energies

high energies: these neutrinos are in contact with cooler regions of the star.

3 FLAVOR OSCILLATIONS (a BIG effect on ν_e)

These two plots are the energy levels of ν and $\bar{\nu}$ inside the star. H_{eff} is the hamiltonian for propagation that includes the Wolfestein term $\sqrt{2} G_F N_e \, \mathrm{diag}(1,0,0)$ (see Smirnov Lecture and Appendix B)





$$\Rightarrow P_{ee} = |\langle \nu_e | \nu_{e,t} \rangle|^2 = \begin{cases} U_{e3}^2 \sim 0 & \text{if } \theta_{13} \gtrsim 1^\circ \\ U_{e2}^2 \sim 0.3 & \text{if } \theta_{13} \lesssim 0.1^\circ \end{cases}$$

'ADIABATIC CONVERSION' OF $\nu_e \to \nu_3$

" OF $\nu_e \to \nu_2$

$$\Rightarrow P_{\bar{e}\bar{e}} = \langle \bar{\nu}_e | \bar{\nu}_{e,t} \rangle = U_{e1}^2 \sim 0.7$$

" OF $\bar{\nu}_e \to \bar{\nu}_1$

N.B. Assumed LMA solution is correct (see Smirnov lecture).
Also, it could be that the mass spectrum is inverted:
(we will not stress this case much)

So, electron neutrino flux is greatly effected:

$$F_e = F_e^0 P_{ee} + F_\mu^0 P_{\mu e} + F_\tau^0 P_{\tau e}$$

[$F_\mu^0 = F_\tau^0$, ONLY NC generate them]

$$\simeq F_e^0 P_{ee} + F_\mu^0 (P_{\mu e} + P_{\tau e})$$

[USE UNITARITY $\Leftrightarrow$ probab. conservation]

$$= F_e^0 \cdot P_{ee} + F_\mu^0 (1 - P_{ee})$$

$$\simeq \begin{cases} F_\mu^0 & \text{if } \vartheta_{13} \gtrsim 1^\circ \\ 0.3 \cdot F_e^0 + 0.7 \cdot F_\mu^0 & \text{if } \vartheta_{13} \lesssim 0.1^\circ \end{cases}$$

Note that the effect of the unknown mixing U_{e3} is of 30%: large but not huge.

Therefore, since $F_e^0 \neq F_\mu^0$, this effect might be seen.
(similarly for $F_{\bar{e}}$, antineutrino flux)

EFFECT OF CHANGING THE ν TEMPERATURE ON NUMBER OF EVENTS

P. ANTONIOLI et al
astro-ph/0112312
(ν oscillations and LVD experiment)

⋆ We did not include Earth matter effects ("open sky" neutrino burst).

Fig.1 shows the number of expected events ver-

$\bar{\nu}_e$ inverse β-decay events

(usually, the biggest set of events)

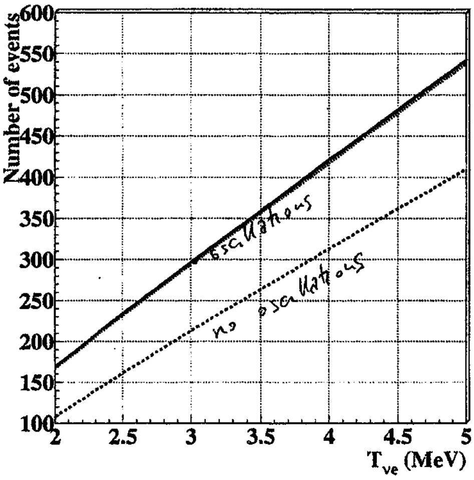


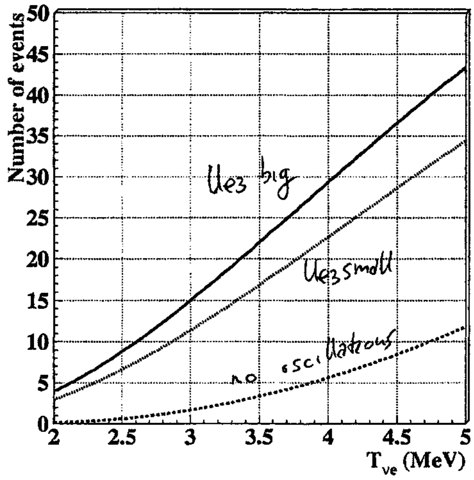
Figure 1. Number of events expected in LVD, in the reaction $\bar{\nu}_e p, ne^+$, as a function of $T_{\bar{\nu}_e} \equiv T_{\nu_e}$: the dashed line represents the no-oscillation case, while full and dotted lines represent the oscillation case, adiabatic and non adiabatic, respectively.

sus T_{ν_e} in the inverse β decay $\bar{\nu}_e$ reaction: a large increase due to ν mixing is clearly visible, with respect to the no-oscillation case. It should be noted that the number of $\bar{\nu}_e p$ events is practically the same both for adiabatic and non-adiabatic conditions, since, for normal mass hierarchy, MSW effect takes place in the neutrino sector only. Quite a different picture would appear, if we were to assume inverse mass hierarchy.

Fig.2 shows the expected total number of c.c. interactions with ^{12}C, due to both ν_e and $\bar{\nu}_e$.[3] The mixing results in an increase of the number of events, either for adiabatic or for non adiabatic conditions: in case of adiabaticity the increase is larger, and this is solely due to ν_e interactions.

Finally, the expected number of events in neutral currents (n.c.) interactions with ^{12}C is shown in Fig.3: they are of course insensitive to ν

[3] Since mean life times of $\beta^{\pm}$ decay are similar (see Sect.2), ν_e and $\bar{\nu}_e$ are distinguishable only on statistical basis. Note that, at $T = 4$ MeV, we expect 6 events due to $\bar{\nu}_e\,^{12}$C,^{12}B e^+ in both cases with oscillations.



2 HIT events, namely

$\nu_e\,^{12}C \to e^-\,^{12}N$ ↳ $e^+\nu_e$

+

$\bar{\nu}_e\,^{12}C \to e^+\,^{12}B$ ↳ $e^-\bar{\nu}_e$

Figure 2. Number of events expected in LVD, in c.c. interactions with ^{12}C as a function of $T_{\bar{\nu}_e} \equiv T_{\nu_e}$: the dashed line represents the no-oscillation case, while full and dotted lines represent the oscillation case, adiabatic and non adiabatic, respectively.

mixing. However, the number of carbon de-excitations can test the temperature of neutrinospheres at the source [14], and therefore could be used in combination with c.c. data to overcome theoretical uncertainties on the temperature.

4. Conclusions and discussion

The observation of a neutrino burst due to the explosion of a galactic supernova can add precious information about neutrino mass and mixing scenarios, in a complementary way with respect to solar, atmospheric and terrestrial ν experiments.

We have studied the signal at LVD from a SN exploding ~~at~~ $D = 10$ kpc for 3-flavor ν oscillation, assuming the LMA-MSW solution for solar ν and normal mass hierarchy. We calculated the expected number of events for extreme values of U_{e3}^2. Varying oscillation parameters, we found an increase up to 50% of the signal due to ~~inverse~~ β decay, and an increase by almost one order of magnitude of the signal due to c.c. reactions on carbon. We remind the reader that the signatures of these reactions in LVD are very clear.

We plan to extend the calculation to include

- $E_{BINDING} = 3\ 10^{53}$ erg.
- ENERGY EQUIPARTITION
- $D = 10$ kpc
- $T_{\nu_e} = T_{\bar{\nu}_e} = T_{\nu_x}/2$

- $\Delta m^2_{12} = 5 \cdot 10^{-5}$ eV^2 $\quad \theta_{12} = 35°$
- $\Delta m^2_{23} = 2.5\ 10^{-3}$ eV^2 $\quad \vartheta_{13} = 6°$ or $(6 \cdot 10^{-2})°$.
- Detector efficiencies included.

- Fermi-Dirac spectra
- no pinching
- no Earth matter effect.

[illegible]

EARTH MATTER EFFECT

As we saw, if $|\nu_e\rangle \to |\nu_2\rangle$ and $|\bar\nu_e\rangle \to |\bar\nu_2\rangle$ by MSW (matter) effect in supernova, $P_{ee} = \sin^2\theta_{12}$ and $P_{\bar e \bar e} = \cos^2\theta_{12}$. But what if (cont.) neutrinos cross the Earth before hitting the detector? Since $|\nu_{1,2}\rangle$ are not ~~mass~~ propagation eigenstates, P_{ee} and $P_{\bar e\bar e}$ change. In constant matter (Earth mantle)

$$P_{ee} = \sin^2\theta \cdot \left[1 + \frac{4\varepsilon\cos^2\theta}{(1+\varepsilon)^2 - 4\varepsilon\cos^2\theta} \sin^2\left(\frac{\Delta m^2 L}{4E} \sqrt{(1+\varepsilon)^2 - 4\varepsilon\cos^2\theta} \right) \right]$$

where:

$$\epsilon = \frac{\sqrt{2} G_F N_{e\oplus}}{\Delta m^2/2E} \simeq 12\% \cdot \frac{\rho_\oplus(\mathrm{gr/cc}) \cdot E/(20\,\mathrm{MeV})}{\Delta m^2/(5\cdot 10^{-5}\,\mathrm{eV}^2)}$$

(for $\bar\nu_e$, replace $\vartheta \to 90^\circ - \theta$).

Can give rise to spectacular wiggles (especially if ν_e neutrinos are clearly detected, Δm^2_{12} is on low side, large energies are achieved).

EVALUATION OF EARTH MATTER EFFECT ON 3 EXISTING DETECTORS

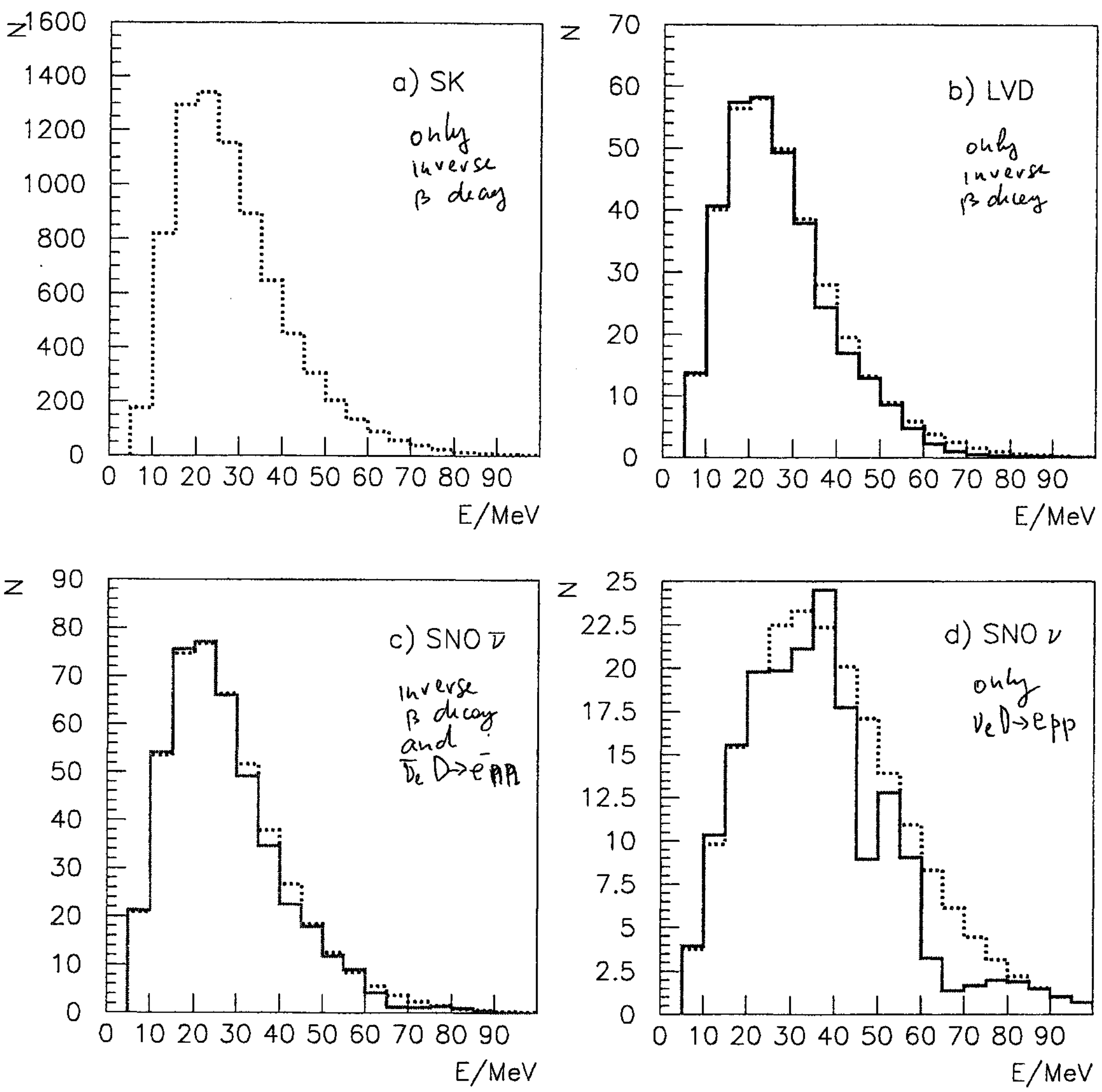
(also: comparison of SN signal in different type of detectors)

C. CUNARDINI, A. Yu. SMIRNOV
hep-ph/0106149
(SN ν: Earth matter effect and neutrino mass spectrum)

... at a certain time, supernova explodes

t=17 hours

SK = Super-Kamiokande (Japan)
LVD = Large Volume Detector (Italy)
SNO = Sudbury Neutrino Observatory (Canada)



(Number of events per bin of 5 MeV width)

Figure 19: The same as fig. 16 for $t = 17$ hours of fig. 1 a). For this configuration SK is unshielded by the Earth.

DECLINATION $\delta_S = -28.9^\circ$; $t = \emptyset$ at Greenwich meridian alignment.
$T_e, T_{\bar{e}}, T_x = 3.5, 5, 8$ MeV . $\Delta m^2_{12} = 5\,10^{-5}\,eV^2$, $\sin^2 2\theta_{12} = 0.75$, θ_{13} small.
$D = 10$ kpc , $E_{Binding} = 3\cdot 10^{53}$ erg, ENERGY EQUIPARTITION, FERMI-DIRAC SPECTRA, NO PINCHING.

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SUMMARY

- ν ASTRONOMY, THEORETICALLY APPEALING AND RICH OF PROMISES

- REASONABLE AGREEMENT OF THEORY AND SN1987A OBSERVATION INCREASE CONFIDENCE IN GENERAL PICTURE

- BUT NEXT SN WILL (PRESUMABLY) PERMIT MORE PRECISE OBSERVATIONS, AND WILL REQUIRE BETTER UNDERSTANDING AND CONTROL OF SN THEORY.

- EFFECTS OF OSCILLATIONS ARE IMPORTANT, HOWEVER, WE NEED UNDERSTAND WELL ASTROPHYSICAL UNCERTAINTIES (among systematics); AND/OR TO COMBINE MORE EXPERIMENTS TO MAKE CLEANER INFERENCES.
  THERE ARE CHANCES TO LEARN SOMETHING ALSO ON ν's

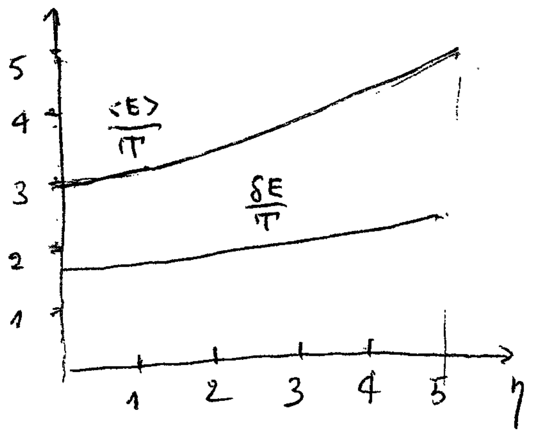
- WE JUST NEED A BIT OF PATIENCE (0–100 years).

(A) Polylogarithm and Fermi integrals

$$F_n(\eta) = \int_0^\infty \frac{x^n}{1+e^{x-\eta}}\,dx = \text{Fermi integrals}$$

$$= -\,P(n+1, -e^\eta)\cdot n!$$

$$\langle E\rangle = T\cdot\frac{F_3(\eta)}{F_2(\eta)}, \quad \langle E^2\rangle = T^2\,\frac{F_4(\eta)}{F_2(\eta)}, \quad \delta E = \sqrt{\langle E^2\rangle - \langle E\rangle^2}$$



$$\frac{F_3(0)}{F_2(0)} = 3.15\ldots$$

$$\frac{F_4(0)}{F_2(0)} = 13.8\ldots$$

$$P(n,z) = \sum_{m=1}^{\infty}\frac{z^m}{m^n} \quad \text{Polylogarithm}$$

$$P(0,z) = z + z^2 + z^3 \ldots = \frac{1}{1-z} - 1 = \frac{z}{1-z}$$

$$P(1,z) = \int_0^z \frac{d\tau}{\tau}(\tau+\tau^2+\tau^3\ldots) = -\log(1-z)$$

$$P(n+1,z) = \int_0^z \frac{d\tau}{\tau}\left(\tau + \frac{\tau^2}{2^n} + \frac{\tau^3}{3^n} + \ldots\right) = \int_0^z \frac{d\tau}{\tau} P(n,z)$$

$P(n,1) = Z(n)$ $\quad$ Z-function $\quad$ $(Z(2,3,4,5) = 1.645,\ 1.202,\ 1.082,\ 1.037)$

$$P(n,-1) = -\left(1 - \frac{1}{2^{n-1}}\right) Z(n)$$

(B) A reminder on oscillations

(1) $\nu_\ell = U_{\ell i}\, \nu_i \quad \ell = e,\mu,\tau\ ;\ i=1,2,3$ (NEUTRINO MIXING)

since $\nu_\ell = \sum_{\vec p \lambda} \left(a_{\ell \vec p \lambda}\, u_{\ell \vec p \lambda}\, e^{ipx} + b^+_{\ell \vec p \lambda}\, v_{\ell \vec p \lambda}\, e^{-ipx} \right)$

$$\begin{cases} a^+_\ell = U^*_{\ell i}\, a_i \\ b^+_\ell = U_{\ell i}\, b^+_i \end{cases} \Rightarrow \begin{cases} |\nu_\ell\rangle = U^*_{\ell i}\, |\nu_i\rangle \\ |\bar\nu_\ell\rangle = U_{\ell i}\, |\bar\nu_i\rangle \end{cases}$$

[Nothing changes if mass is Dirac instead than Majorana (my favorite option)]

(2) $|\nu_{\ell,t}\rangle = U^*_{\ell i}\, |\nu_{i,t}\rangle = U^*_{\ell i}\, e^{-i(E_i t - \vec p \vec x)} |\nu_{i,0}\rangle$;

$a_{\ell'}(t) \equiv \langle \nu_{\ell'} | \nu_{\ell,t}\rangle = (\text{irrelev. phase}) \left(U_{\ell' i}\, e^{-i\frac{m_i^2 t}{2p}}\, U^*_{\ell i} \right)$;

$P_{\ell\to\ell'}(t) = |a_{\ell'}(t)|^2$; $\quad i\frac{\partial}{\partial t} a_\ell = (H_{eff})_{\ell\ell'}\, a_{\ell'}$, $\quad H_{eff} = U \cdot \mathrm{diag}\left(e^{-i\frac{m_i^2 t}{2p}}\right) \cdot U^+$.

(3) If ν propagate in matter, there is a new piece of the effective hamiltonian: $\pm\sqrt{2}\, G_F N_e\, \mathrm{diag}(1,0,0)$, with N_e = electr. # density ($\pm$ for neutrinos and antineutrinos). This leads to important effects, that might be proved in a short term. (see Smirnov's lecture)

(4) Putting aside LSND indication, we know from a number of experiments that oscillations are very likely to occurr (see also next page)

$m_3^2 - m_2^2 \simeq 2.5 \cdot 10^{-3}\ eV^2$	$\vartheta_{23} \sim (45 \pm 10)^\circ$	[ATM. NEUTRINOS]
$m_2^2 - m_1^2 \simeq 5 \cdot 10^{-5}\ eV^2$	$\vartheta_{12} \sim 30^\circ$	[SOL. NEUTRINOS – LMA]
	$\vartheta_{13} \le 15^\circ$	[CHOOZ]

where $|U_{e3}| \equiv \sin\theta_{13}$, $|U_{e2}/U_{e1}| = \tan\theta_{12}$, $|U_{\mu 3}/U_{\tau 3}| = \tan\theta_{23}$.

(5) β decay: $\left|\sum |U_{ei}^2|\, m_i^2\right| < 2.2\, eV$; $0\nu 2\beta$ decay: $\left|\sum U_{ei}^2\, m_i\right| < 0.3 - 1\, eV$; 2DF: $\sum m_i < 1.8\, eV$

IT LOOKS DIFFICULT TO SEE KINEMATIC EFFECTS ON SN NEUTRINOS.

VALUES OF OSCILLATION PARAMETERS
IN A 3 FLAVOR SCHEME

Ferruccio Feruglio,
Alessandro Strumia, F.V.
hep-ph/0201291
(ν oscill. & signals in β
and 0ν2β experiments)

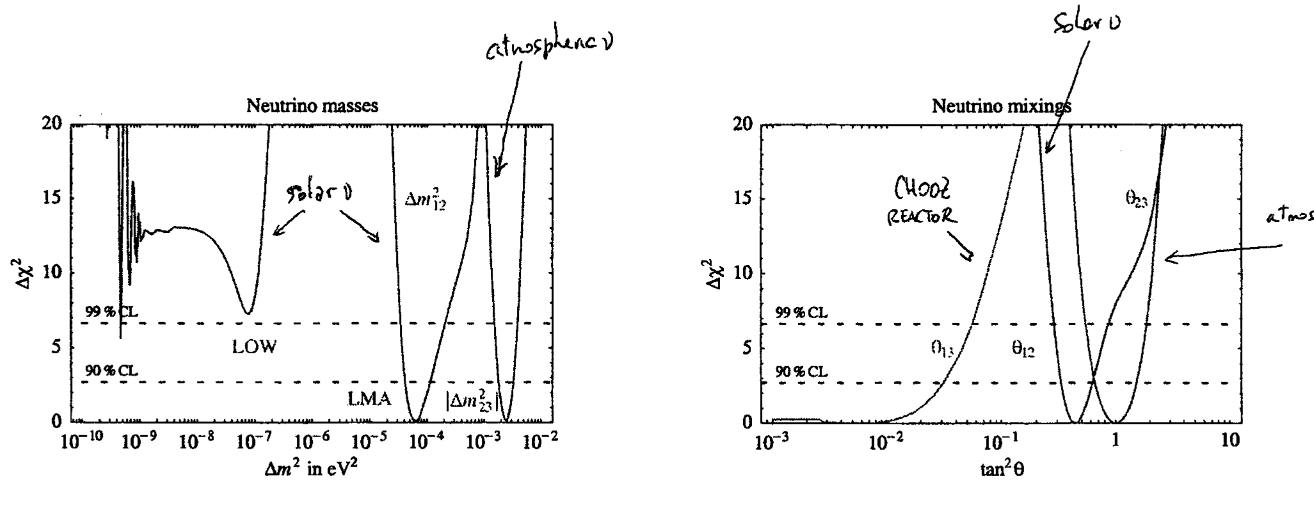


Figure 1: *Summary of present data on neutrino masses and mixings.*

(1) In the frequentistic framework $\Delta\chi^2(p)$ is distributed as a χ^2 with *one* degree of freedom. (2) In the Bayesian framework $\exp[-\Delta\chi^2(p)/2]$ is the probability of different p values, up to a normalization factor. Our inferences on m_{ee} also depend on unknown parameters (θ_{13} and the CP-violating phases): using the Gaussian approximation we obtain more simple and conservative results, as explained in section 2.2.

In fig. 1 and in the rest of the paper we do not include the significant but controversial information from SN1987A, that would disfavour $\theta_{13} \gtrsim 1^\circ$ (if $\Delta m^2_{23} < 0$) *and* solar solutions with large mixing angle [9, 10]. However, we recall here the origin of these bounds. The average $\bar{\nu}_e$ energy deduced from Kamiokande II and IMB data is $E_{\bar{\nu}_e} \sim 11\,\mathrm{MeV}$, assuming the overall flux suggested by supernova simulations (experimental data alone do not allow to extract both quantities accurately). This is somehow smaller than the value suggested by supernova simulations in absence of oscillations, $E_{\bar{\nu}_e} \sim 15\,\mathrm{MeV}$. For both figures it is difficult to properly assign errors; but oscillations that convert $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ increase the disagreement, since supernova simulations suggest $E_{\bar{\nu}_{\mu,\tau}} \sim 25\,\mathrm{MeV}$. With an inverted hierarchy, $\theta_{13} \gtrsim 1^\circ$ gives rise to adiabatic MSW conversion, swapping $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ completely. This is why this case is 'disfavoured' if the predictions of supernova models on neutrino energy and flux are correct. The same argument applies to large solar mixing angles: $\theta_{12} \sim 1$ induces a partial swap of the $\bar{\nu}_e$ into $\bar{\nu}_{\mu,\tau}$, whatever the mass spectrum of neutrinos. LMA oscillations have a smaller θ_{12} and a larger Δm^2_{12} than LOW and (Q)VO, and are therefore less 'disfavoured'. SMA gives almost no $\bar{\nu}_e$ oscillations, but is strongly disfavoured by solar data. For a full analysis, see [10].

1.2 Perspectives of improvement

Future oscillation experiments can significantly improve the situation. Concerning the 'solar' parameters, SNO, KamLAND and Borexino can reduce the error on $\sin^2 2\theta_{12}$ down to around 5%, and measure Δm^2_{12} to few per-mille (if it lies in the VO or QVO regions), or few per-cent (in the LMA region), or around 10% (in the LOW region) [11].[2] Concerning the 'atmospheric' parameters, K2K, Minos or CNGS can reduce the error on $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$ down to about 10% and discover θ_{13} if larger than few degrees [13, 14] (the precise value strongly depends on $|\Delta m^2_{23}|$). Far future long-baseline experiments can reduce the error on $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$ down to few % (with a conventional beam [15]) and maybe 1% (with a neutrino factory beam [16]). These experiments could also discover a θ_{13} larger than 0.5° and tell something about ϕ, if LMA is the true solution of the solar neutrino problem. Future reactor experiments [17] can be sensitive to a $\theta_{13} \gtrsim 3^\circ$.

[2] If $\Delta m^2_{12} \gtrsim 2\ 10^{-4}$ a new reactor experiment with a shorter baseline than KamLAND would be necessary [11, 12]. If $\Delta m^2_{12} \approx 10^{-8}\ \mathrm{eV}^2$ Borexino and KamLAND will not see a inequivocable signal.

(5th enclosed Xcopy)