Roadmap of INFN Commissione II

Line 1: Neutrino Physics

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1. Neutrino oscillations with artificial neutrino sources[1]

There is compelling experimental evidence that the three known neutrino states with definite flavor are linear combinations of states with definite mass. The evidence for flavor non-conservation (i.e., “neutrino oscillations”) comes from a series of experiments performed during about four decades of research with very different neutrino beams and detection techniques: the solar neutrino experiments (Homestake, Kamiokande, SAGE, GALLEX-GNO, SuperKamiokande (SK) and SNO); the long-baseline reactor neutrino experiment (KamLAND), the atmospheric neutrino experiments (SK, MACRO, and Soudan-2); and the long-baseline accelerator neutrino experiment (K2K).

Together with the null results from CHOOZ, the above oscillation data provide stringent constraints on the neutrino mixing matrix, on the splitting between squared neutrino masses, and on matter effects. The absolute neutrino masses are being probed by different, non-oscillation searches: β decay experiments, $0\nu\beta\beta$ decay searches, and precision cosmology. Current non-oscillation data provide only upper limits on neutrino masses, with the only exception of the Heidelberg-Moscow experiment, whose claimed signal implies a lower bound on neutrino masses.

Basically all the data are consistent with the simplest extension of the standard electroweak model needed to accommodate nonzero neutrino masses and mixings, namely, with a scenario where the three known flavor states are mixed with only three mass states, no other states or new neutrino interactions being needed. This “standard three-neutrino framework” will be tested, refined, and possibly challenged by a series of new, more sensitive experiments planned for the next few years or even for the next decades. The only piece of data in contrast with the above picture comes from the controversial result of LSND, that will be probed very soon by MiniBooNE.

If LSND result is not taken into account, present data indicate that mixing of ν_2 and ν_3 is consistent with maximal, that mixing between ν_1 and ν_2 is large but not maximal and that mixing between ν_1 and ν_3 is small and compatible with zero. Squares of neutrino mass differences are measured to within 20% for ν_2 and ν_3 and less than 2% for ν_1 and ν_2, while the sign (mass hierarchy) is still unknown together with the remaining mixing parameter: the CP violating phase.

Next steps are the final confirmation of the evidence of oscillation observed in atmospheric neutrinos by laboratory based experiments and the determination of the detailed structure of the mass and mixing, in particular, measurements of the deviations of ν_2 and ν_3 mixing from maximal and of ν_1 and ν_3 mixing from zero.

1.1 Present and next generation of long-baseline experiments[2]

Over the next five years the present generation of oscillation experiments at accelerators with long-baseline ν_μ beams, MINOS at the NUMI beam from FNAL and OPERA and

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[1] Introduction freely adapted from a review from G.L. Fogli et al., HEP-PH/0506307 (2005).

[2] See also A. Guglielmi, M. Mezzetto, P. Migliozzi and F. Terranova, HEP-PH/0508034 (2005).

ICARUS at the CNGS beam are expected to confirm the atmospheric evidence of oscillations by observation of direct appearance of ν_τ in the ν_μ beam. MINOS is looking for ν_μ disappearance in the beam as a function of neutrino energy. **OPERA and ICARUS at CNGS beam represent the largest effort currently made by INFN in Commissione II and will search for evidence of ν_τ interactions in the ν_μ beam**, the final proof of ν_μ to ν_τ oscillations. MINOS has started data taking beginning 2005. CNGS is expected to start operations in the second half of 2006.

Current long-baseline experiments with conventional neutrino beams can also look for ν_μ to ν_e oscillations even if they are not optimized for θ_{13} studies. MINOS is expected to reach a sensitivity of $sin^2 2\theta_{13} = 0.08$ in 5 years. OPERA can reach a 90% C.L. combined sensitivity $sin^2 2\theta_{13} = 0.06$ (for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2), a factor $\approx$ 3 better than the present Chooz limit for five years exposure to the CNGS beam at the nominal intensity: 4.5×10^{19} pot/yr. ICARUS, with the present T600 module, could improve by some factor the OPERA sensitivity to $sin^2 2\theta_{13}$ and, depending on the value of Δm^2_{23}, could add independent confirmation of the ν_τ appearance eventually observed by OPERA. The CNGS beam intensity could be improved by a factor 1.5, allowing for more sensitive neutrino oscillation searches for OPERA and ICARUS.

Another approach to search for non-vanishing θ_{13} is to look at anti-ν_e disappearance using nuclear reactors as neutrino source. A follow-up of Chooz, Double Chooz, has been proposed to start in 2008 with a two detectors setup, capable to push systematic errors down to 0.6 % and to reach a sensitivity on $sin^2 2\theta_{13} \approx 0.024$ in a 3 years run.

Next generation experiments, that still will be using conventional neutrino beams, are optimized for θ_{13} studies through the observation of ν_μ to ν_e transitions in the appearance channel. There are two of such experiments currently planned or under discussion: T2K (Tokai to Kamioka) in Japan, and NOνA in US. For both experiments the far detector is placed few degrees off-axis with respect to the beam line in order to select a purer beam with a well defined energy (or, equivalently, L/E).

The T2K experiment uses a neutrino beam produced at the JPARC complex starting from a 0.75 MW proton beam accelerated to 50 GeV. The neutrino beam is directed to SK (at a distance of 295 km) tilted by 2.5° with respect to the detector location (neutrino energy $\approx$ 0.7 GeV at the far detector). A near detector, placed at 280 m from the proton target, will measure the unoscillated beam characteristics to reduce systematics to below the expected statistical errors.

The experiment is approved: data taking is scheduled to start in 2009 and the beam is expected to reach full intensity in 2011. It will reach a 90 % C.L. sensitivity $sin^2 2\theta_{13} \approx 0.006$ in five years, assuming $\delta_{CP} = 0$. T2K will also measure Δm^2_{23} and $sin^2 2\theta_{23}$ with 2% precision, detecting ν_μ disappearance, and it will perform a sensitive search for sterile neutrinos through the detection of neutral current event disappearance.

The NOνA experiment with an upgraded NuMI Off-Axis neutrino beam with $E_\nu \approx$ 2 GeV and with a baseline of 810 Km (12 km Off-Axis), was recently proposed at FNAL with the aim to explore the ν_μ to ν_e oscillations with a sensitivity 10 times better than MINOS. If approved in 2006 the experiment could start data taking in 2011. The experiment will use a near and a far detector, both using liquid scintillator. In 5 years of data taking, with 30000 tons active mass far detector a sensitivity on $sin^2 2\theta_{13}$ slightly better than T2K, as well as a precise measurement on Δm^2_{23} and $sin^2 2\theta_{13}$ can be achieved. NOνA can also allow to solve the mass hierarchy problem for a limited range of the δ_{CP} and sign(Δm^2_{23}) parameters.

There is a request for participation to T2K, with contributions to the realization of the near detector, from INFN groups currently being evaluated by Commissione II, while there are expressions of interest from other INFN groups for participating to NOνA not yet established in a formal proposal. We recall that there is not a European program for the next generation of experiments.

A summary of θ_{13} sensitivities for the present and next generation of experiments is reported in Figure 1 as a function of the time, following the schedule reported in the experimental proposals.

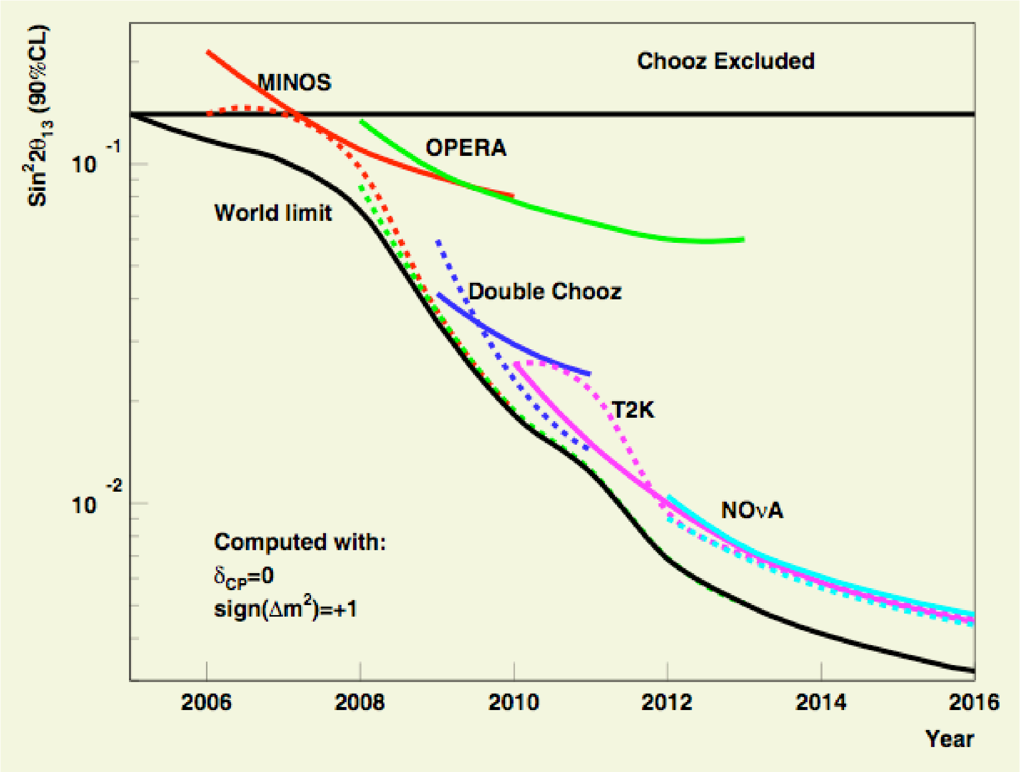

Figure 1: Evolution of sensitivities on $sin^2\theta_{13}$ as function of time. For each experiment are displayed the sensitivity as function of time (solid line) and the world sensitivity computed without the experiment (dashed line). The comparison of the two curves shows the discovery potential of the experiment along its data taking. The world overall sensitivity along the time is also displayed. The comparison of the overall world sensitivity with the world sensitivity computed without a single experiment shows the impact of the results of the single experiment. Experiments are assumed to provide results after the first year of data taking.

Looking further on towards the next steps of neutrino physics it is clear that one has to overcome the intrinsic limitations of conventional neutrino beams. This can be achieved if the neutrino parents can be fully selected, collimated and accelerated to a given energy. This can be attempted within the muon or a beta decaying ion lifetimes. The neutrino beams from their decays would then be pure and perfectly predictable. The first approach brings to the Neutrino Factories, the second to the BetaBeams. However, the technical difficulties associated with developing and building these novel conception neutrino eventually require to improve the conventional beams by new high intensity proton machines, optimizing the beams for the ν_μ to ν_e oscillation searches. This leads to the so called SuperBeams as they are under implementation, at least in a preliminary way, in T2K and NOνA. These programs, are to be seen as ancillary to the following phase, both from the scientific point of view (results on the oscillation parameters pattern) and from the technical one.

Different detection techniques of neutrino interactions based on water Cerenkov (WC), liquid Argon (LAr), nuclear emulsions and calorimetry are available to build very massive detectors according to the intrinsic neutrino beam characteristics, energy and composition. Compared with other high energy detectors, they must offer unprecedented fiducial masses, instrumented with cheap and reliable active detector technologies guarantying high granularity, good energy resolution and excellent particle identification capability.

There is a specific activity in Commissione II aiming at the study of such "third generation" long baseline neutrino experiments: BENE. Within the framework of an EU programme, CARE, and with the participation of representatives of the main experiments and accelerator laboratories, a group is working to setup a proposal for the Design Study of a Europen neutrino facility (including the detector) to be submitted within the context of the seventh EU framework programme.

2. Atmospheric neutrino measurements

The experimental study of atmospheric neutrinos has given the first piece of evidence of the existence of flavor oscillations and therefore of the existence of a non null neutrino mass. Together with the experimental data from solar and reactor neutrinos, the atmospheric data allowed to measure many parameters of the neutrino mass matrix[3].

Icarus, with the T600, will be the only new experiment looking at atmospheric neutrinos, since, at present, there are no other experimental proposal addressing atmospheric neutrinos in a competitive way for the next few years. Due to the limited active mass, it is not expected that Icarus will change significantly the present picture for oscillations although, thanks to the superior quality of the data, a better knowledge of atmospheric neutrinos composition and spectrum should be achieved especially in the low energy range.

It should be remarked that **there is still a high scientific interest for atmospheric neutrinos[4].**

In particular it has been suggested the possibility of performing a high precision measurement of θ_{23} in order to measure the actual deviation of θ_{23} from the maximal value together with the sign of this deviation, which is normally not accessible since the fundamental oscillations are proportional to $sin^2\theta_{23}$. Here the clue are the effects, proportional instead to $sin^2\theta_{23}$ which are induced by the solar sector of the mixing matrix on the oscillation of the low energy part of atmospheric electron neutrinos (those who are usually referred to as the Sub-GeV sample), exploiting the fact that both Δm^2_{12} and θ_{12} are well measured in solar experiments. The sign of Δm^2_{23} also determines the difference in matter effects in neutrinos and antineutrinos, which could be investigated in the multi-GeV sector, possibly with detectors capable of distinguishing the lepton sign. However all these effects summarized here are small. Their investigation requires at the same time a large statistical sample and a significant reduction of the systematic errors. In principle, an exposure at least 20 times larger than that of SK sample is needed, thus making appealing the possibilities offered by proposals which are presently under discussion as long term options, such as a megaton scale water detector. Alternatively, a reduced exposure giving the same measurement possibilities could be probably achieved considering other

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[3] The final analysis of SK-I data (1489 days of fully- and partially-contained events plus 1646 days of upward going muons) is reported in Y. Ashie et al. (SK Collaboration) Phys.Rev.D71:112005 (2005).

[4] The topics addressed here have been extensively discussed at the "*RCCN International Workshop on sub-dominant oscillation effects in atmospheric neutrino experiments*", Dec. 2004 , ICRR, Kashiwa, Japan. Proceedings are available at http://www-rccn.icrr.u-tokyo.ac.jp/rccnws04/

techniques, like a very large (of the order of at least 50kTon) liquid argon TPC, where experimental systematics are expected to be less relevant. However systematic contributions of theoretical nature must also be reduced. These are associated with the present uncertainties in the knowledge of the atmospheric neutrino spectrum and neutrino-nucleus cross sections. These improvements would also allow to investigate with amospheric neutrinos possible effects due to non zero θ_{13} values.

3. Solar neutrinos[5]

Solar neutrinos have been measured by a number of experiments during the last 40 years. At present solar neutrinos are measured by SNO, which is planned to be shut down in 2007, SuperKamiokande, which will start soon the phase III after full reconstruction, and SAGE, which is presently the only sensitive to low-energy solar neutrinos. In the near future (2007) they will be also studied by Borexino and KamLAND-II. We recall that 99.99% of solar neutrinos have energy below 5 MeV, the present threshold of SK.

At present the favourite interpretation of the solar neutrino phenomenology is the MSW-LMA solution. The matter-vacuum transition of the survival probability can only be measured by low-energy solar neutrino experiments such as Borexino and KamLAND-II. The spectral distortion and the day-night asymmetry, expected at the level of 1-3% in SK and SNO have not been measured yet due to systematic uncertainties and still poor statistics. Therefore, **future solar neutrino observations aim to confirm the MSW-LMA effect, to improve the measurement of θ_{12}, to search for non-standard sub-leading effects such as non-standard neutrino interactions, including a possible light sterile neutrino and, mass-varying neutrinos on the physics side and, to an accurate measurement of the solar neutrino luminosity (test equality of photon and neutrino luminosity) and the CNO contribution on the astrophysics side.**

SK-III could improve the present measurement of the MSW-LMA effects. Borexino and KamLAND-II will open a new window with a measurement of low-energy solar neutrinos.

It is worth mentioning the possibility to search for pep solar neutrinos with KamLAND-II and, in particular, with Borexino.

As long-term options (>2010) for solar neutrinos we mention a possible Mton water Cherenkov detector and a 10-kton scale liquid argon detector to search for ^{8}B neutrinos and measure accurately the MSW-LMA effects, a 10-ton scale detector based on either liquid Xe (XMASS) or liquid Ne (CLEAN) to search for pp solar neutrinos and, a 1-kton liquid scintillator detector proposed for SNOlab (SNO+) and a 30kton scale liquid scintillator detector (LENA) proposed for the Phyasalmi mine in Finland. We also mention that, among the long-term options, there are R&D's about new experimental techniques based on charged-current interactions for pp solar neutrinos, namely LENS and MOON.

4. Neutrinos from SuperNovae[6]

At present, only one experimental evidence of supernova neutrinos (SN1987A) exists. This evidence shows a number of puzzling features.

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[5] For a review on experimental techniques see: A.B. McDonald, C. Spiering, S. Schoenert, E.T. Kearns and T. Kajita Rev.Sci.Instrum. 75 (2004) 293-316. For a comprehensive phenomenological analysis of neutrino oscillations see: G.L. Fogli, E. Lisi, A. Marrone and A. Palazzo, hep-ph/0506083.

[6] For a review see: K. Kotake, K. Sato, K. Takahashi, astro-ph/0509456

The estimated rate for a Galactic supernova is on the order of 40±10 years/supernova. Therefore, the long-term stability of a supernova detector is an important parameter to be considered.

The goal of a new supernova observations is to improve our understanding of a core-collapse explosion mechanism. In particular, it would be necessary to measure the temperature and energy of the different neutrino flavours for comparison with numerical models. For the next supernova almost all of the detected events will come from the inverse-beta decay charged-current reaction and, because of kinematic thresholds, $\nu_{\mu,\tau}$'s can be detected only by neutral-current reactions.

Neutrino masses can also be measured with a supernova. A Galactic supernova allows to test m_ν for anti-ν_e at the level of 3 eV. Limits on m_ν for $\nu_{\mu,\tau}$ of the order of 30-60 eV (90% C.L.) can be placed with neutral-current interactions in SK and SNO for a Galactic supernova.

At present supernova neutrinos can be searched by (water Cherenkov detectors) SK and SNO (which is planned to be shut down in 2007) and, by (liquid scintillators) KamLAND, MiniBooNE, Baksan and LVD. For a *standard* supernova at the Galactic center (10kpc) we expect ~8000 events from the inverse-beta decay channel and ~700 from neutral current on ^{16}O in SK. We notice that the large target mass in SK it sill makes possible a detection of a supernova in the LMC at about 50kpc with ~300 events from anti-ν_e. In SNO we expect ~580 events for a supernova at 10kpc from neutral-current interactions on deuterium. For LVD the expected number of events is 570, mostly coming from inverse-beta decay (≈400) but also from NC and CC on ^{12}C and ^{36}Fe (≈145).

Borexino and KamLAND-II (in its solar neutrino phase) can probe a very promising interaction channel, namely the neutrino-proton elastic scattering. This channel is interesting because, in order to measure the temperature and energy of $\nu_{\mu,\tau}$'s and their antiparticles, one needs a spectral signature. Neutral-current interactions on ^{16}O and ^{12}C measure only the total number of events. On the contrary, the neutrino-proton elastic scattering via a neutral-current interaction gives spectral information and allow to separately determine the temperature and energy carried by $\nu_{\mu,\tau}$'s and their antiparticles. We notice that ~93% of the signal in Borexino comes from $\nu_{\mu,\tau}$'s and their antiparticles. However, due to quenching effects on the scattered protons in the target liquid scintillator, the detection threshold must be on the order of 0.2 MeV to have a significant number of events. This explains why LVD cannot exploit this detection channel as it can be done in Borexino.

ICARUS T600 will look at supernovae neutrinos through two interaction channels (elastic scattering $\nu_x \rightarrow \nu_x$ and inverse beta $\nu_e + {}^{40}Ar \rightarrow e^+ + {}^{39}K^*$) allowing to distinguish between different neutrino species and to measure the ν_e's spectrum.

SNO has a unique detection charged-current channel for ν_e's ($\nu_e + d \rightarrow ppe^-$). However, due to the fact that SNO is going to be shut down in 2007, ν_e's will be identified after SNO via a charged-current channel with a correlated delayed event in Borexino and, with larger statistics, in LVD.

We mention that LVD has shown that a detector based on liquid scintillator can operate for more than 10 years and this fact is of a great importance for neutrino supernova searches.

Among the long-term options (>2010) we recall a possible Mton water Cherenkov, a 50 kton-scale LAr detector, a 50kton-scale liquid scintillator detector (LENA), a 10-kton scale Fe/Pb detector (OMNIS) and IceCube. Each of these proposed projects has its peculiar feature. LENA, due to its energy resolution and low threshold detection energy, can probe the modulations expected in the energy spectrum due to oscillations and can explore the neutrino-proton interaction channel with ~10^3 events. A Mton detector with 5 MeV threshold will be able to collect ~10^4 for a supernova at ~50kpc (LMC).

5. Geoneutrinos[7]

The Earth is a source of ν_e and anti-ν_e from decays of ^{238}U, ^{232}Th and ^{40}K. These neutrinos and antineutrinos are referred to as *geoneutrinos*. Geoneutrinos from ^{238}U, ^{232}Th can be detected by inverse-beta decay reaction: the maximum neutrino energy from ^{238}U and ^{232}Th are about 3.3 MeV and 2.3 MeV, respectively. Liquid scintillator detectors such as Borexino and KamLAND can be used for geoneutrinos measurement. KamLAND has claimed the first geoneutrino measurement in 2005. However, the present KamLAND result is affected by a high background from nuclear reactors and ^{210}Pb contamination in the liquid scintillator. Borexino is well suited to perform a geoneutrino measurement. A signal-to-noise ratio at the level of 1.2 is expected in Borexino for geoneutrinos versus reactor antineutrinos.

The future of geoneutrinos after Borexino and KamLAND is under study and looks toward a detector in the middle of the oceanic crust, where the contribution to the signal from the mantle can be disentangle from that from the crust and, to a detector which makes use of a new, not yet identified, liquid scintillator which is able either to measure the direction of the incoming neutrinos or to tag the low energy ^{40}K neutrinos.

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[7] T. Araki, et al., KamLAND collaboration, Nature 436 (2005) 499. F. Mantovani et al., Phys. Rev. D69 (2004) 013001. For future projects see : Neutrino Geophysics, 14-16 December 2005; Neutrino Sciences 2005 "Neutrino Geophysics" Honolulu, Hawaii. See also: http://www.phys.hawaii.edu/~sdye/hnsc.html.

The following table contains some summary information about the experiments presently supported or under discussion by Commissione II. The Operatring cost is intended as the cost for INFN.

	Brief Description	**Physics Case**	**Level of the initiative**	**International Competition and Competitivity**	**Start constr. and constr. Time**	**Cost**	**Cost Sharing**	**Operating Cost**	**Duration**	**FTE**
OPERA	Spectrometer and lead/emulsion target (1800 tons)	Neutrino oscillations, nu-tau appearance	Global INFN, Japan, Europe	Minos , that however does not observe tau appearance	May 2003 Data taking from 2006 For 5 years	60 M€	INFN 30% Japan 50% Europe ≈ 20%	2.5-3 M€/ yr	5-6 years until 2012	56
ICARUS	Liquid Argon Time Projection Chamber	Undergrd physics:atmosh., solar and SN ν's; proton decay, cosmic rays	Global		1997-2001 Data taking from 2007	15 M€ + 20M€ for future developments	INFN 95%	450 k€/ yr	Until 2011	33
T2K	ν_μ beam from JParc to SuperK (295 km) Near Det. at 280 m	Precision meas. Δm^2_{23} and θ_{23}; θ_{13} meas. Search for $\nu_\mu \rightarrow \nu_s$	Global USA, Japan, Canada, Europe	NOvA (under discussion for approval)	Start Near Detector 2007 Data taking from 2009.	Near detect. ~10 M$. (Int. Collab.) Beam ~ 150 M$ (Japan)	INFN: ~7% Near Detector	~150 k€/yr	5 years (minim.)	3.3
NOvA	NUMI off axis Beam; Far Detector at 810 km	Precision meas. Δm^2_{23} and θ_{23}; θ_{13} meas. Mass hierarchy	USA, Italy...	T2K	If approved in 2008 Data taking from 2011	-		-	-	
BOREX	300 ton ultrapure scintillator	Solar ν's spectrum at <1 MeV and check of oscillation models	Global USA, Europa	Kamland	Start 1998 End 2006	27 M€	INFN 70% USA 20% Deuts. 10%	1.1M€/ yr	10 years until 2016	23
LVD	Large mass scintillator counters (1000 tons)	Study of ν bursts from stellar collapses	Global	SK, Kamland, SNO	Start 1985 Data taking from 2001	13.5 M€	INFN 70% INR 30%	300 k€/ yr	until 2011	13