Progress and Prospects in Neutrino Astronomy

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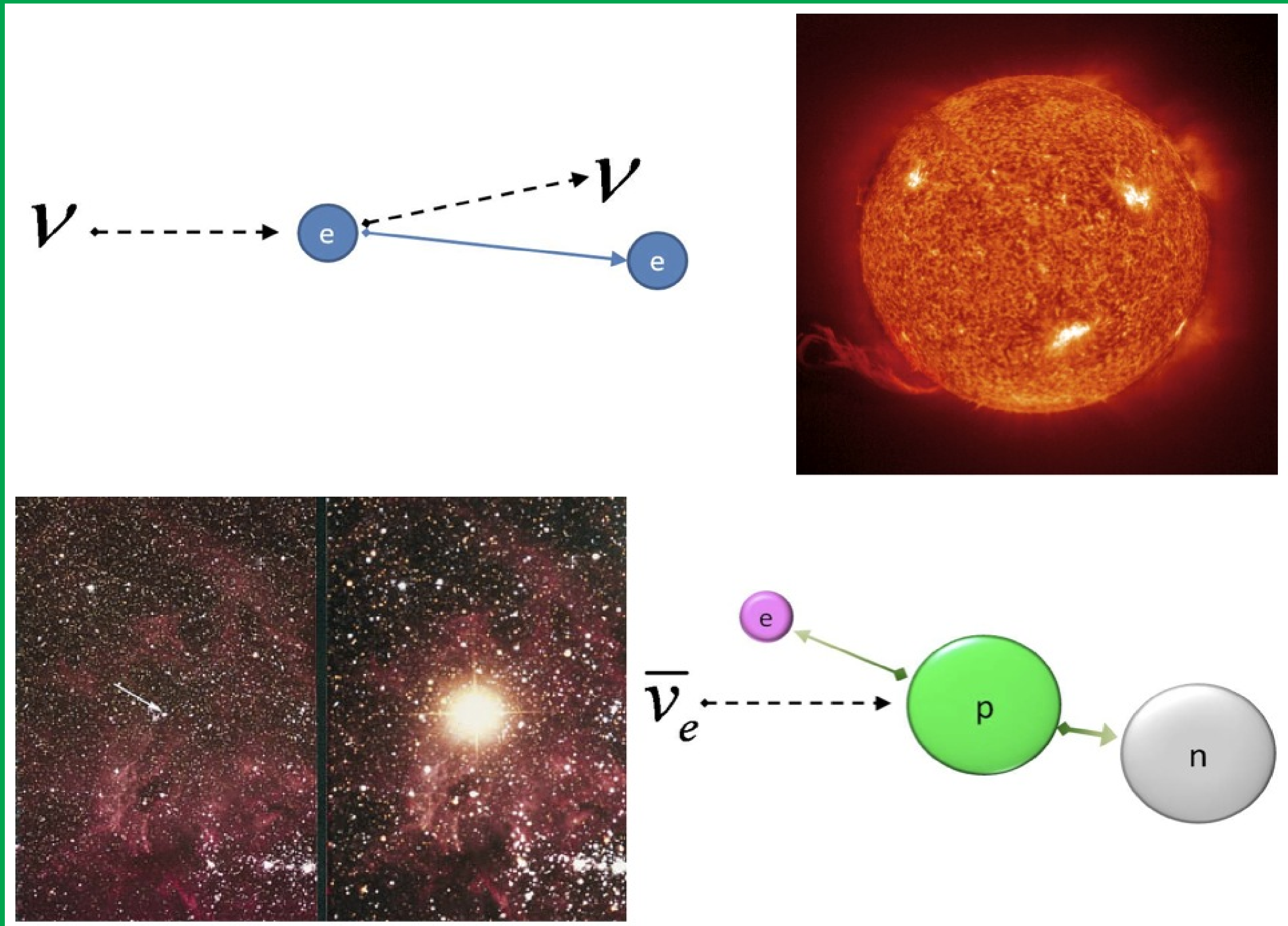
Neutrino astronomy has stimulated great progress in particle physics, and it is a discipline between physics and astrophysics that is still in rapid developement, in which INFN is amply committed. In this talk, we review various recent achievements and we consider the near future prospects of neutrino astronomy, concerning the domains of low- and high-energies.

A recognized discipline – Nobel Prize 2002

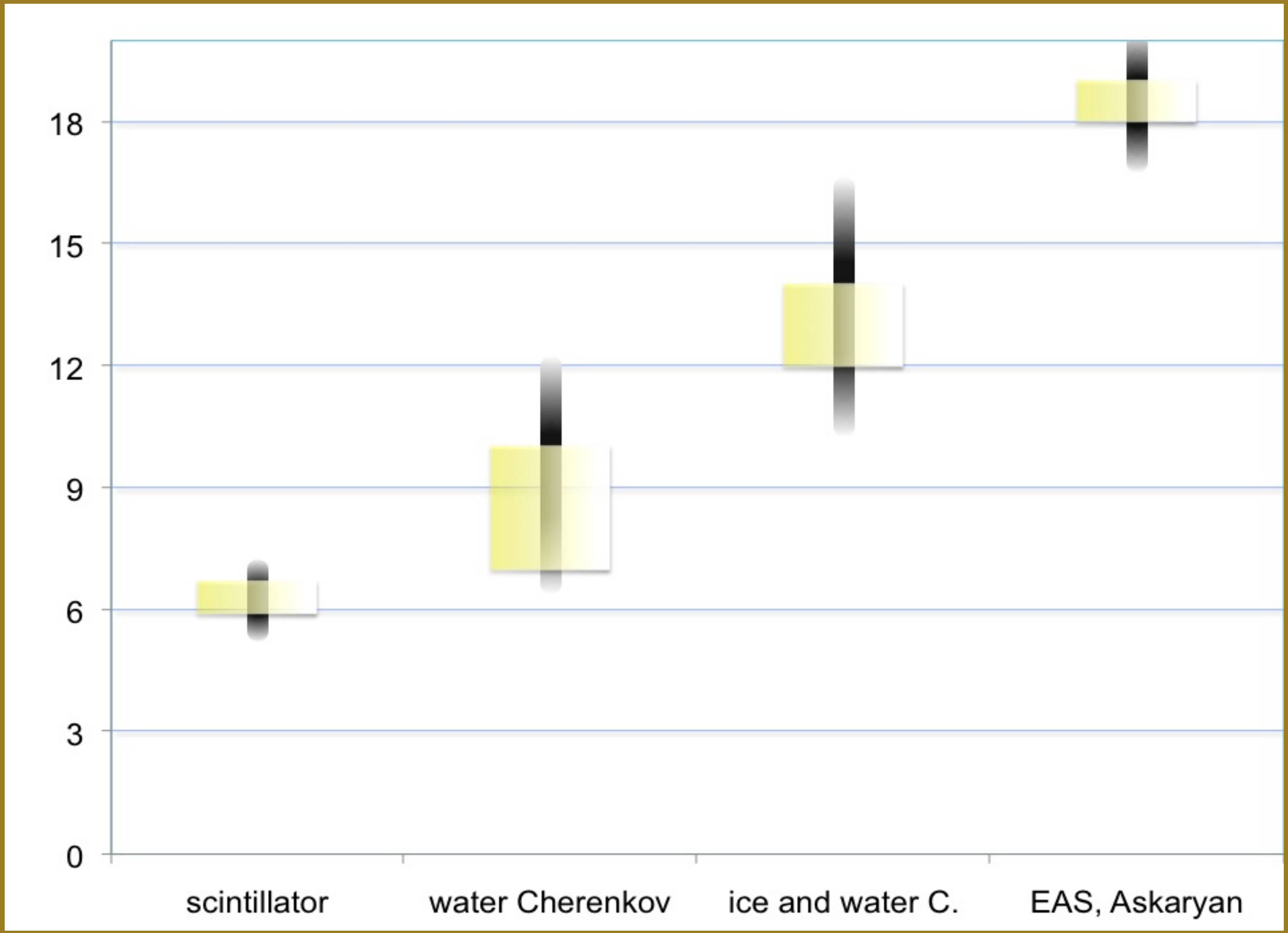


Till now, successful astronomical observations concerned processess of the ‘classical’ nuclear regime $E < 100$ MeV.

They led us to various achievements, also on basic neutrino properties, and have still important possibilites to progress, e.g., with geoneutrinos, solar (CNO) neutrinos, and even more with supernova neutrinos.

The obtained knowledge and the increased confidence motivate us to continue, widening scope and field of investigation.

We are now monitoring a huge range of energies



Elastic scattering (ES) reaction

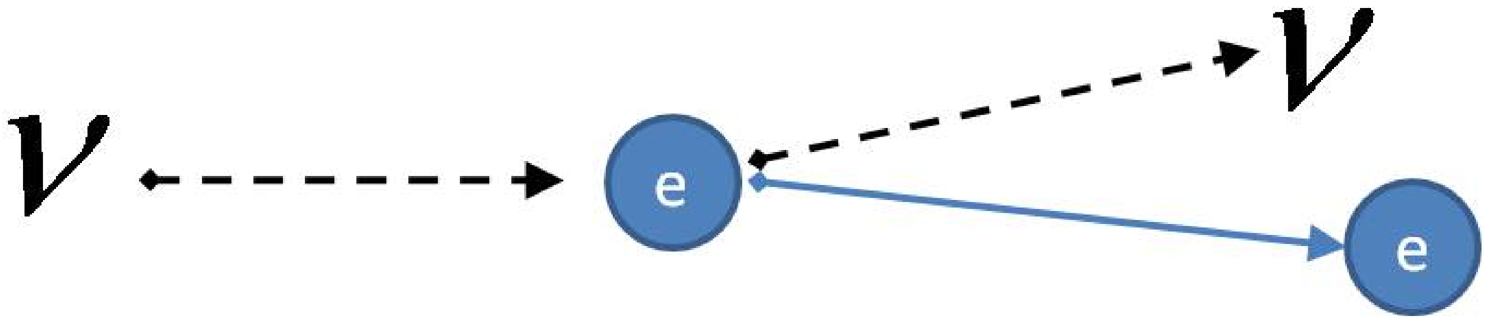


Figure 1: *Due to the ES reaction, the (anti) neutrinos of several MeV hit the atomic electrons and produce events in the forward direction. We can distinguish ES events if we know the direction of the source.*

`A sample of electrons from ES events locates its source, even if not identified by more conventional astronomical means.`

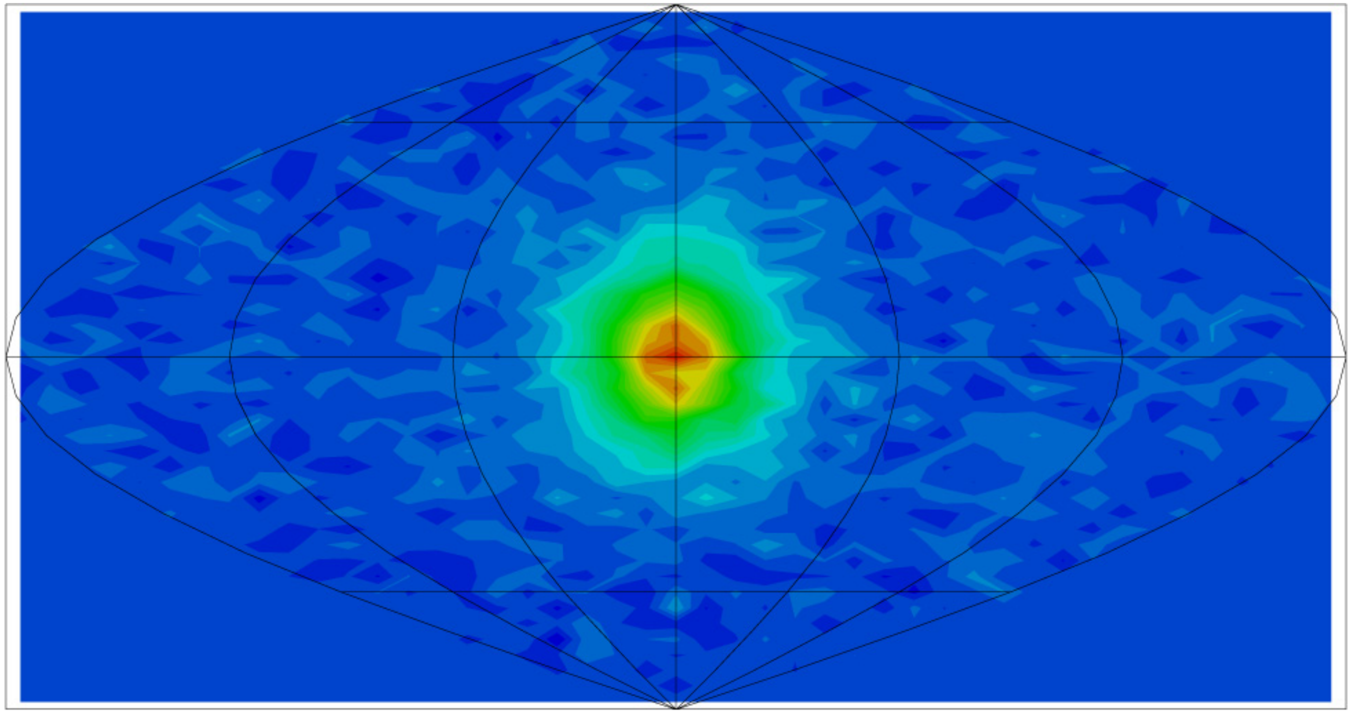


Figure 2: *Image of the Sun obtained by exploing the electrons from the ES reaction as obtained by the Super-Kamiokande neutrino telescope, to be discussed in a while.*

Similar results first obtained by Kamiokande and the detection of SN1987A are the reasons of 2002 Nobel prize awarded to Koshiba.

Inverse beta decay (IBD) reaction

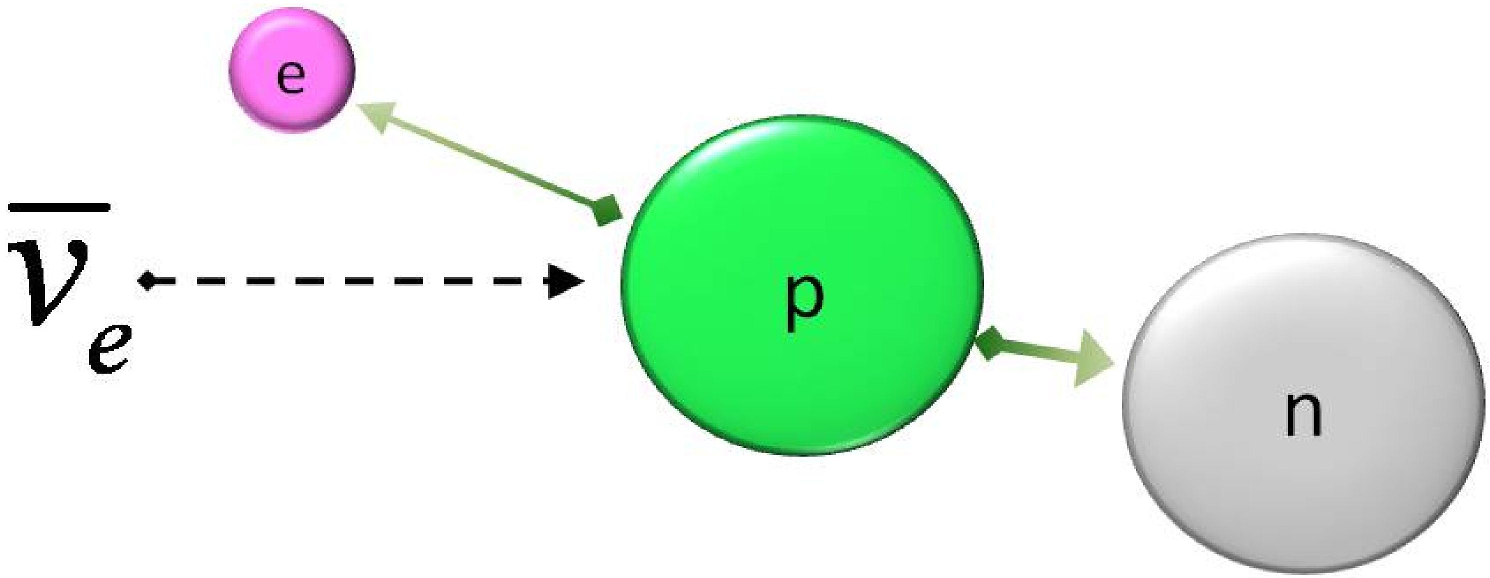


Figure 3: *IBD: an almost isotropic reaction occurring when* $E_\nu > 1.8MeV$ *with a much larger cross section:* $\sigma_{\rm IBD} \sim G_F^2 m_p E_\nu$ *whereas* $\sigma_{\rm ES} \sim G_F^2 m_e E_\nu$. *This reaction is important, for free protons abundant in* H_2O *and* C_nH_m *targets.*

Positron is the footprint of the reaction; occasionally, even the neutron can be observed, providing a double tag.

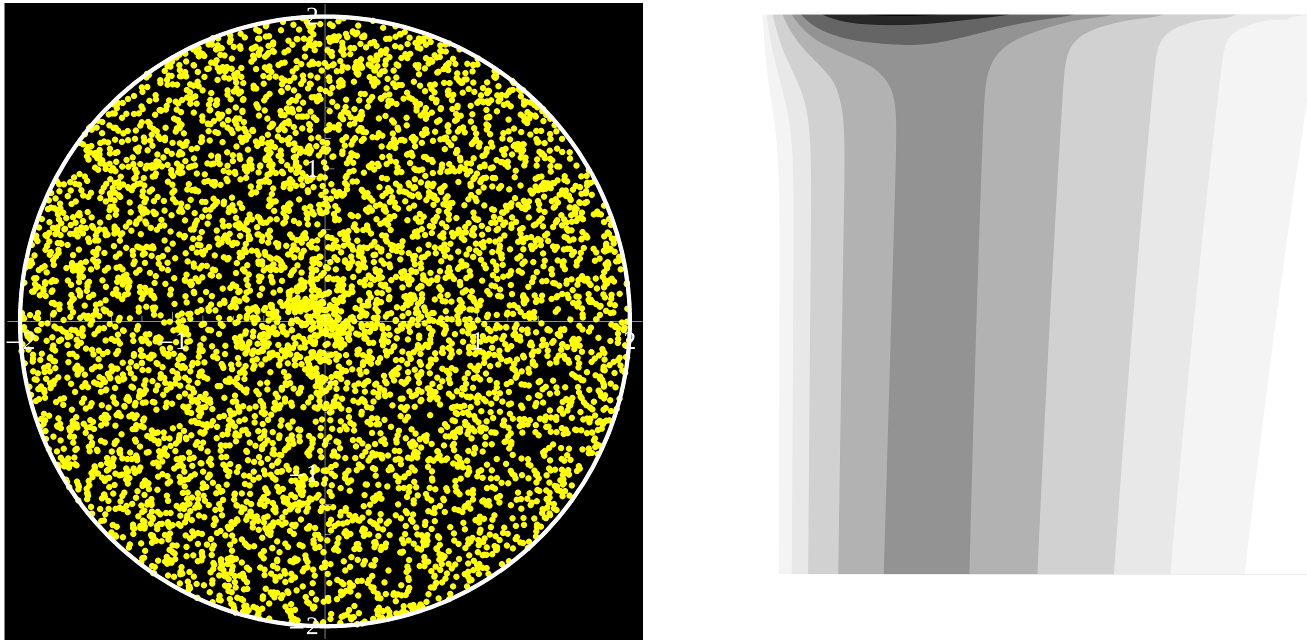
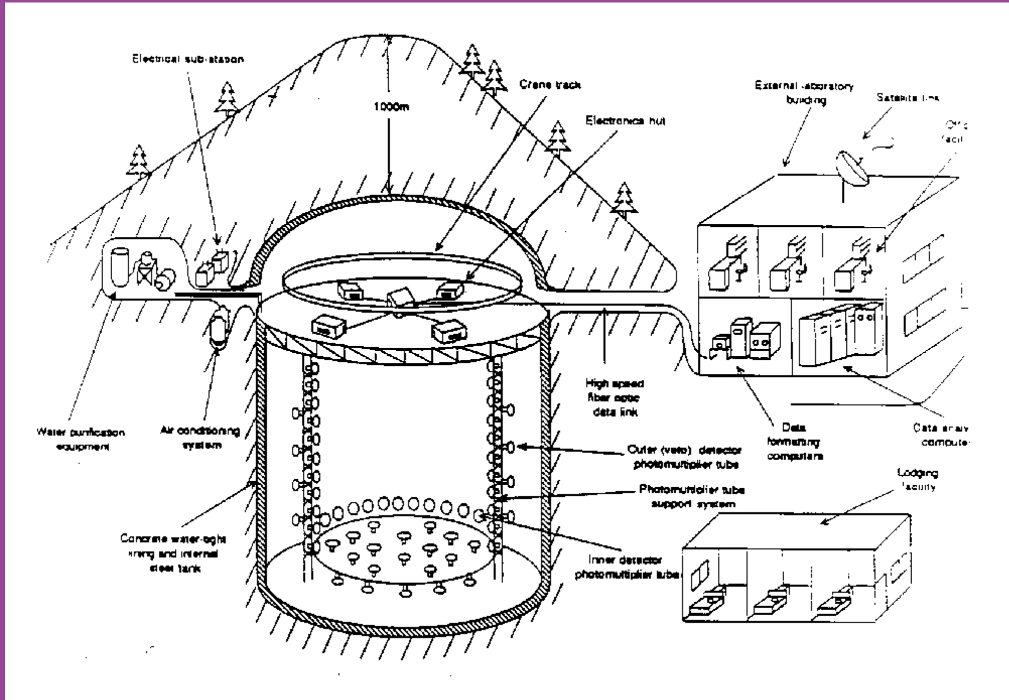


Figure 4: *Left panel: direction of the events from a future galactic supernova; ES events are mostly in the center, IBD events are instead almost isotropical. Right panel: expected energy-cosine distribution of the events; energy is in MeV.*

...of course these are simulated events!!!

NEUTRINO TELESCOPES



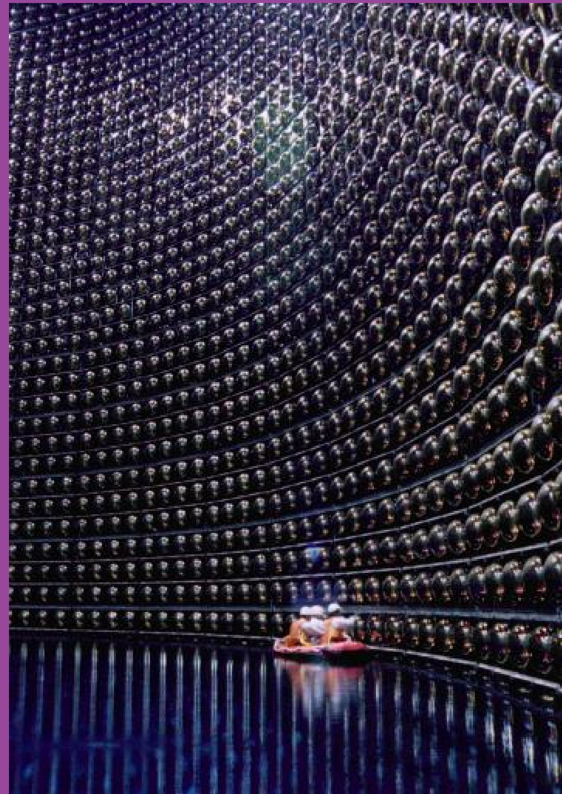
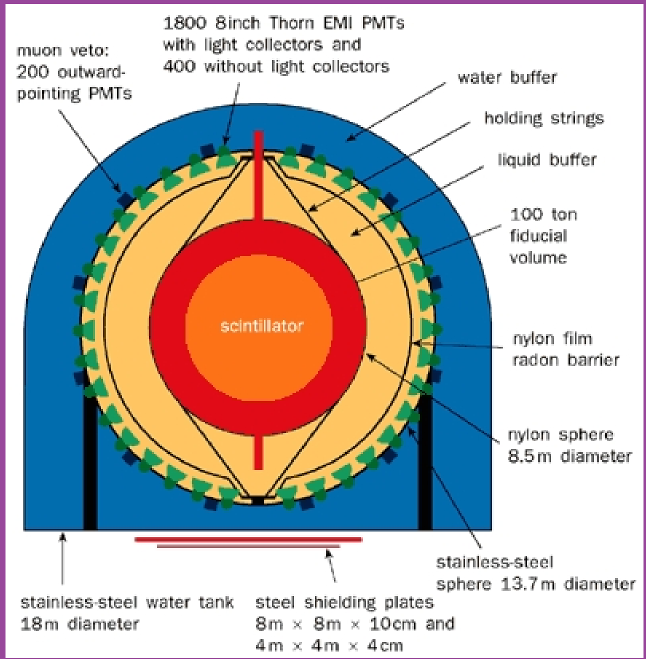


Figure 5: *The Super-Kamiokande detector, located in the Kamioka mine (Japan). It reveals ultrarelativistic charged particles thanks to their Čerenkov-Vavilov radiation.*

Observes the electrons/positrons produced by neutrinos/antineutrinos above ~ 5 MeV. Very high statistics, thanks to its 50 kton mass of H_2O.



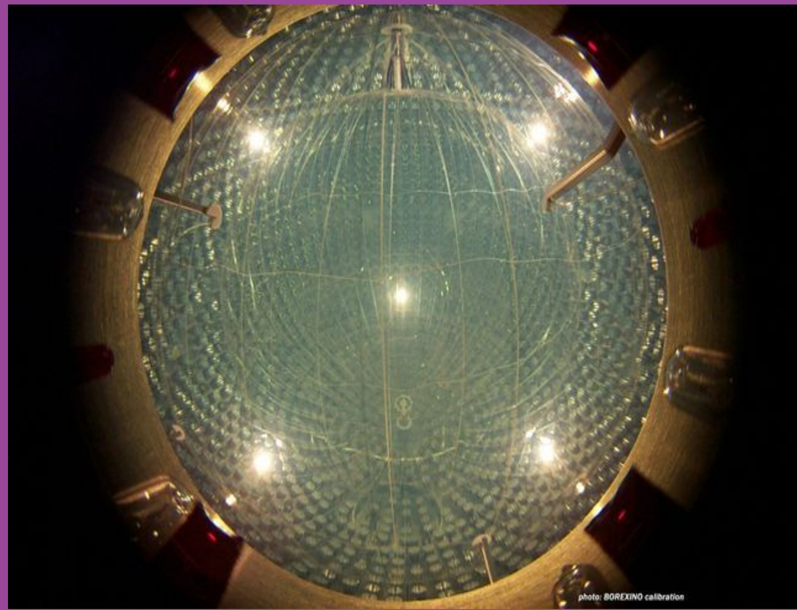
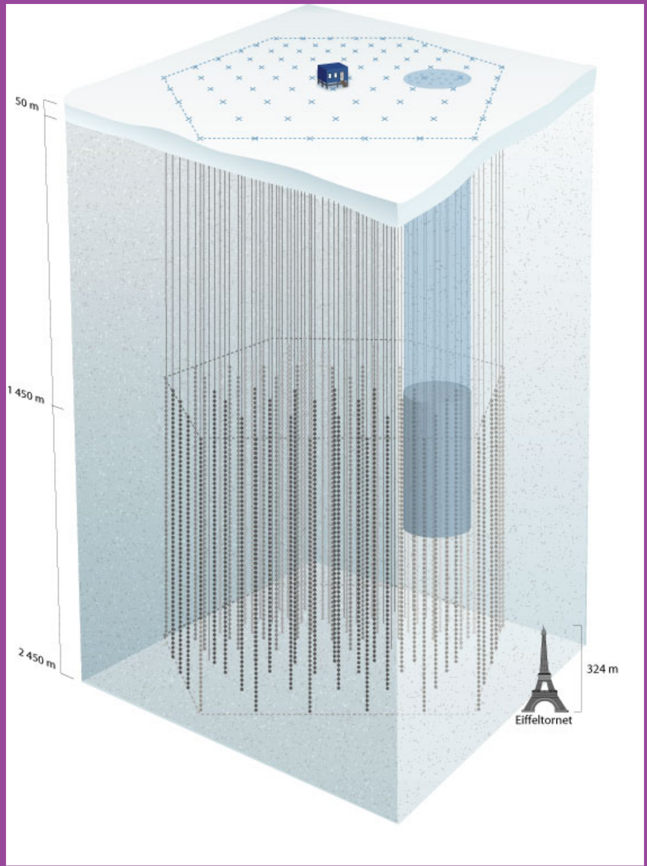


Figure 6: *The Borexino detector, located in the Gran Sasso laboratory (Italy). Its ultrapure scintillator permits us to observe the electrons-or positrons-which are occasionally hitted by neutrinos-or antineutrinos, even when their energy is below MeV.*

Observes another signature of $\bar{\nu}_e$: the neutron that follows from IBD and that reacts with free protons by $n + p \to D + \gamma(2.2\ \text{MeV})$.



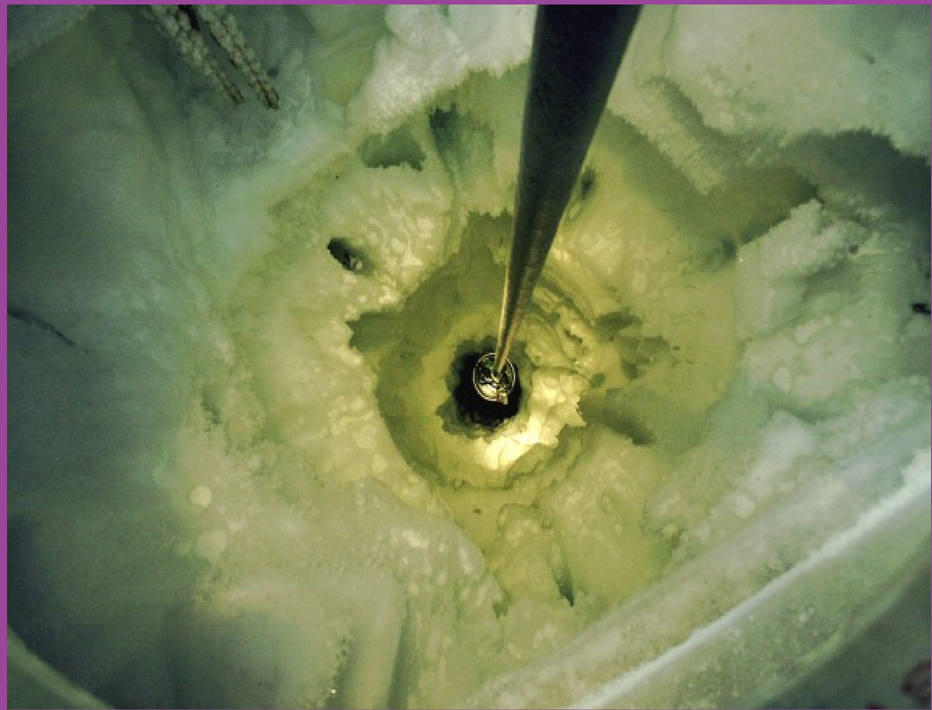


Figure 7: *The IceCUBE detector (South Pole). It reveals the (anti) muons occasionally produced by (anti) neutrinos. It can get some information on supernova (~ 10 MeV) $\bar{\nu}_e$'s thanks to its huge mass but it is optimized for high energy ($>$TeV) neutrinos.*

SOLAR NEUTRINOS

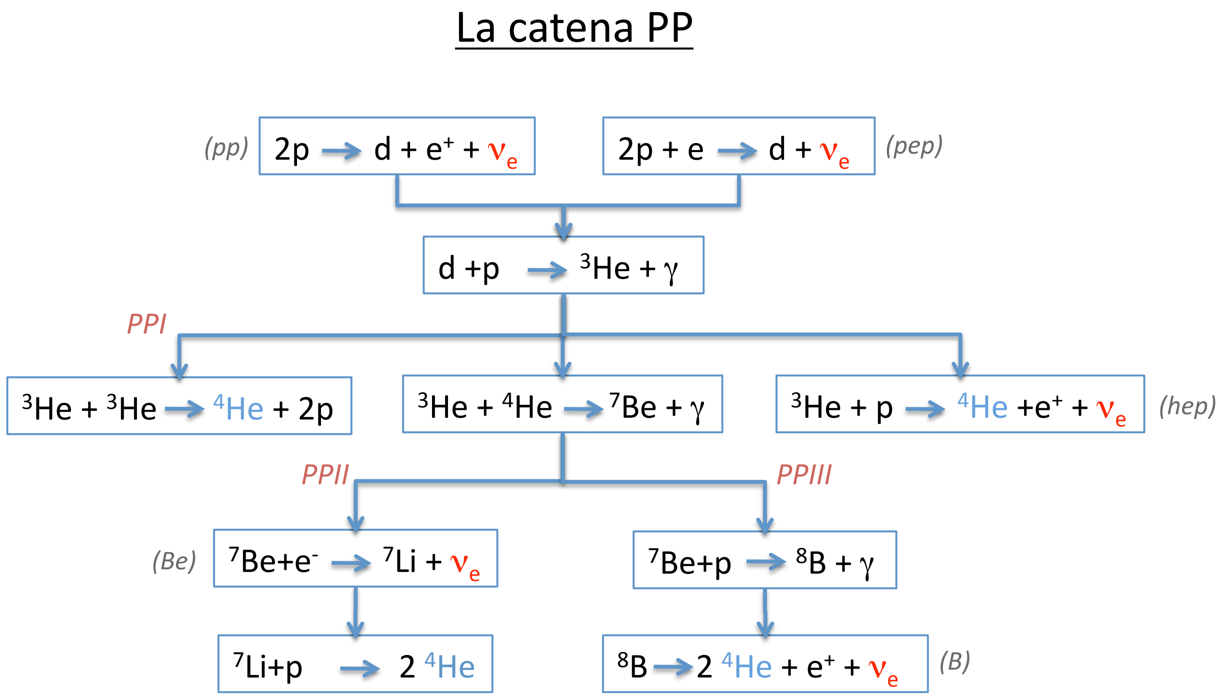


Figure 8: *The main chain of nuclear energy generation in the Sun.*

Tested seeing the ν_e from PPIII branch (i.e., $\mathbf{B}$) Super-Kamiokande, SNO, Borexino and by the more important $\mathbf{pep}$ and $\mathbf{Be}$ Borexino. If we *assume* the Sun in equilibrium state, i.e., using the luminosity constraint, the $\mathbf{pp}$ neutrinos are determined.

High energy solar neutrino measurements: a zoom

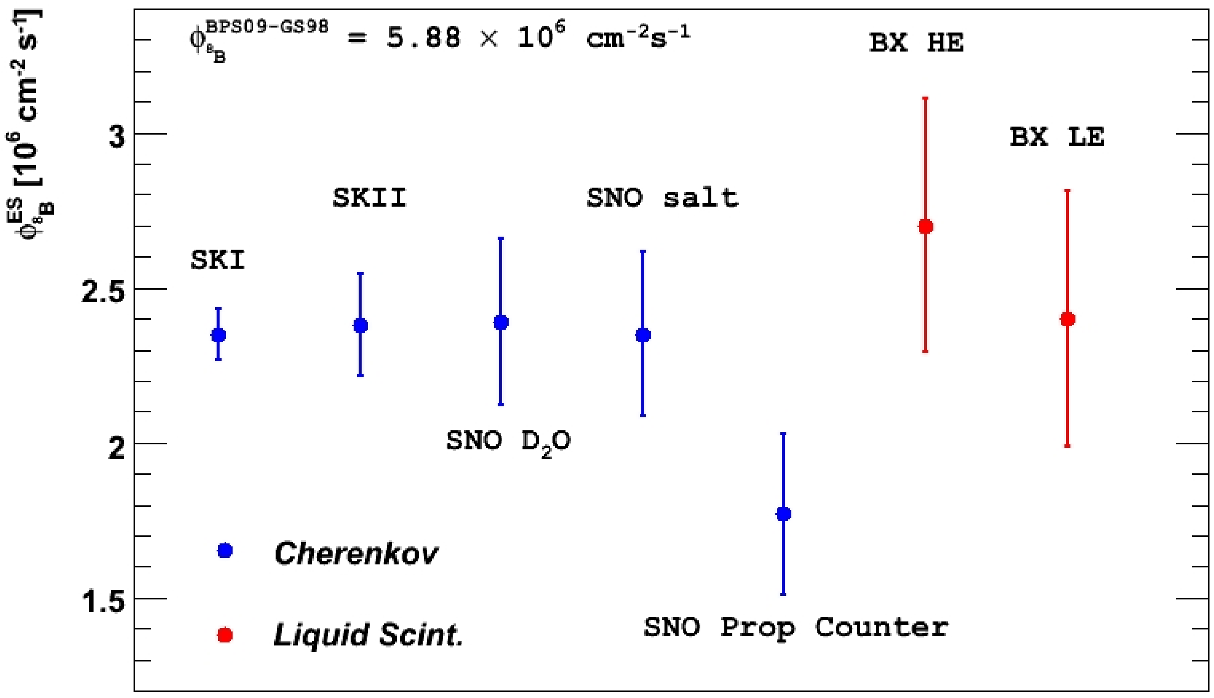


Figure 9: *Measurements of PPIII branch (Boron neutrinos); SK=Super-Kamiokande; BX=Borexino. The expectation is recalled in the upper-left corner.*

Energy dependence of solar neutrino oscillations

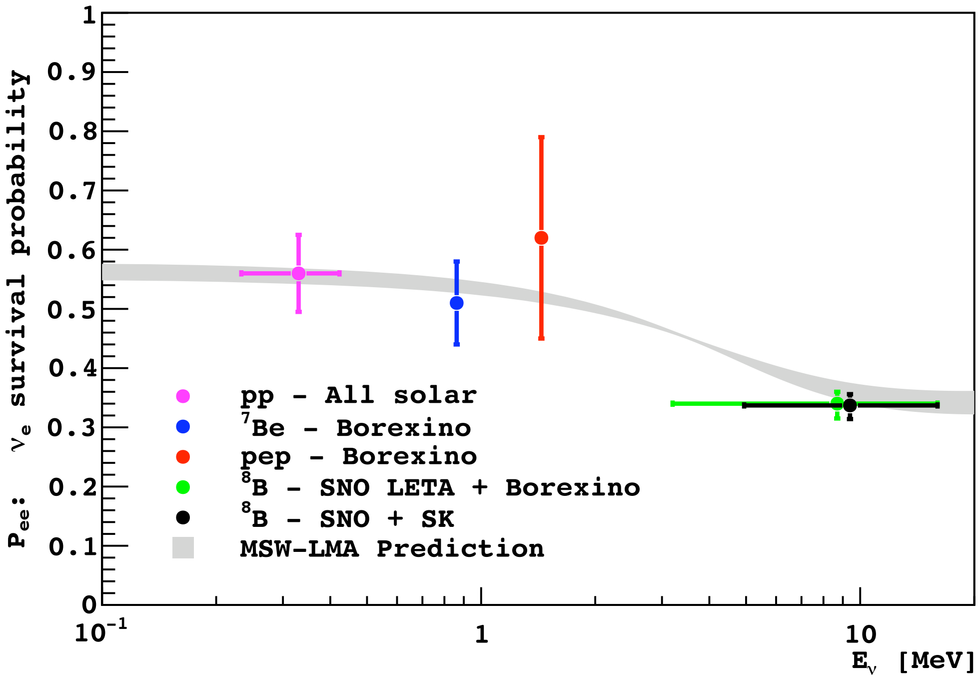


Figure 10: *The solar neutrino conversion probability* [Borexino 2012]

The downturn at high energies is neatly explained by matter (MSW) effect, i.e., coherent scattering of electron neutrinos on solar electrons

(which is much less relevant for atmospheric neutrino oscillations instead).

The current investigations, directly related to observations, include:

measurement of the secondary cycle ($\mathbf{CNO}$); observation of $\mathbf{pp}$ neutrinos; study of the transition region; measure DN asymmetry, now 2 sigma; (search for/bound new fenomena in particle physics as sterile neutrinos, magnetic moment, etc).

Newest analyses of photospheric abundances of heavy element led to solar models *unable* to reproduce the helioseismic results.

This led to extensive and inconclusive checks. The present most common attitude, is that it is too early to accept the new analysis. A valuable test from the measurement of the secondary chain, i.e., CNO neutrinos.

For detailed reports see PHYSUN conference series, last one being
`http://agenda.infn.it/conferenceProgram.py?confId=5284`

ANTINEUTRINOS
from
THE EARTH

$\bar{\nu}_e$ from terrestrial radioactivity

^{232}Th and ^{238}U beta-decay chains give rise to observable $\bar{\nu}_e$ [Eder 66; Marx 69].

The first type of nuclei are 4 times more abundant; positrons produced in the IBD reactions extend to ~ 1.5 MeV and ~ 2.5 MeV, respectively.

A hint of observation is due to KamLAND in 2005, 2008 in noisy conditions and concurrent $\bar{\nu}_e$ signal resulting from nuclear reactors.

More recently, the first high confidence detection in a clean detector was obtained by Borexino, putting geo-neutrino science on firm observational bases.

For details see Neutrino GEOSCIENCE 2010
`http://geoscience.lngs.infn.it/Program.htm`

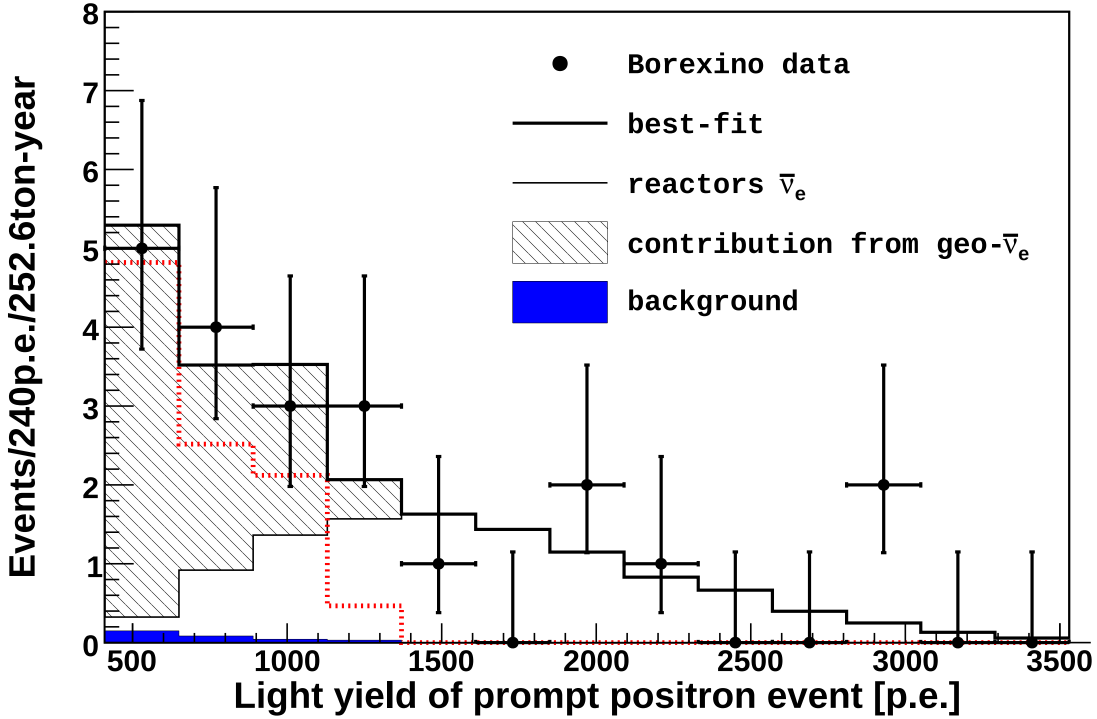


Figure 11: *The $\bar{\nu}_e$ signal is due in equal proportions to $\bar{\nu}_e$'s from far away reactors and those from terrestrial radioactivity: The latter component dominates at low energies.*

By future data, ^{232}Th and ^{238}U components should be distinguishable.

SUPERNOVA (anti)NEUTRINOS

Appointment with the next galactic supernova

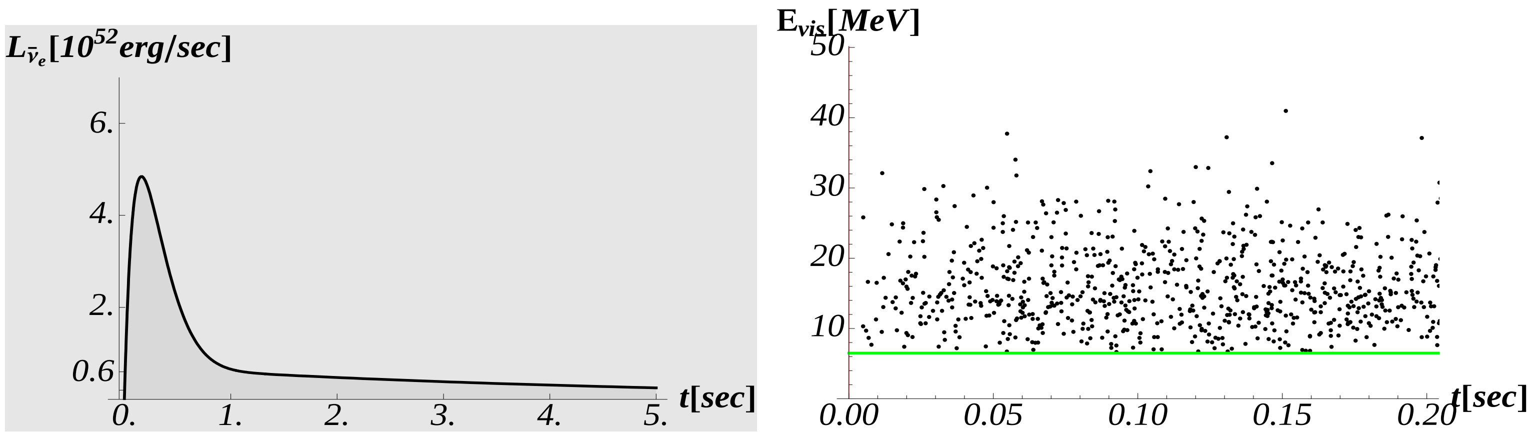


Figure 12: *Left: luminosity of $\bar{\nu}_e$ as deduced from SN1987A observations. Right: simulated events in Super-Kamiokande, assuming a supernova located at 10 kpc.*

Using the times of the neutrino events (IBD+ES) and their directions (ES), one can infer with a precision of at least ~ 10 ms the time of the burst, that is comparable with its expected duration [Pagliaroli et al., PRL 2009].

A precious information for Virgo and LIGO!

Supernovae are very important and interesting for astronomy, nuclear physics and particle physics. SN1987A shows that we can learn a lot studying their neutrinos.

But we have to face the following issue:

> *Galactic core collapse events are rare for human standards and neutrino experimentalists are definitively human.*

Is it possible to overcome this limitation?

The diffuse supernova neutrino background

From the cosmic density rate of core collapse supernovae, R_{SN}, and the average energy spectrum of $\bar{\nu}_e$, dn/dE, we calculate the diffuse flux:

$$\frac{dN_{\bar{\nu}_e}}{dt\ da\ dE} = \frac{c}{H_0}\int_0^{z_{\max}} dz \frac{R_{\mathsf{SN}}(z)}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \times \frac{dn}{dE}\,(E(1+z))$$

[Zel'dovich & Guseinov 65; Ruderman 65]

This is a steady signal: we do not need to wait our life to collect it!

NOTE THE COSMOLOGICAL REDSHIFT OF THE ENERGY SPECTRUM.

What are the chances to detect it?

Let us examine the 3 issues: experimental, astronomical, astrophysical.

1. There is a relatively clean window for the search for $E_{e^+} > 18$ MeV
2. The cosmic rate distribution is reasonably known Beacom 2008-2010
3. The $\bar{\nu}_e$ flux from SN1987A is rather similar to the newest theoretical calculations compare Pagliaroli et al., 2009 with e.g.., Janka 2012

Thus, we decided to evaluate the expectations and their errorbar [Pagliaroli & FV 2010].

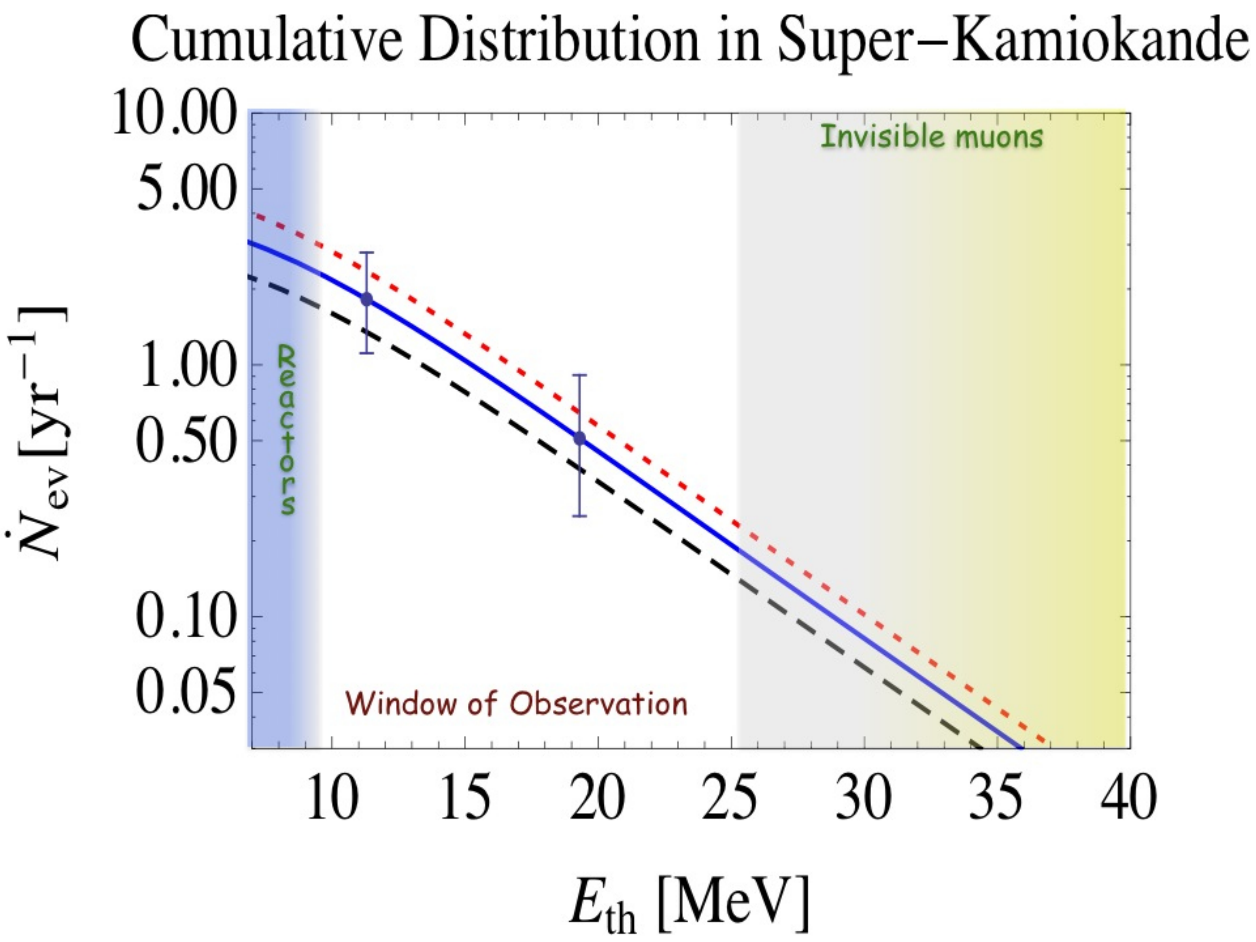


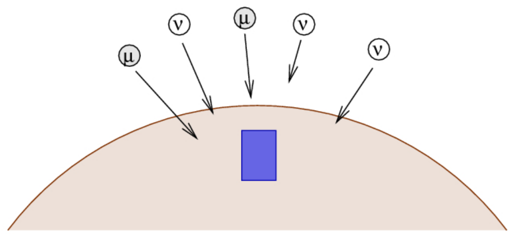
Figure 13: *The 3 lines correspond to the uncertainty in the cosmic rate of SN explosion. The error-bars are the 2 sigma ranges due to the uncertainties in the astrophysics of the explosion, as evaluated using SN1987A observations.*

Summary of low energy neutrino flux

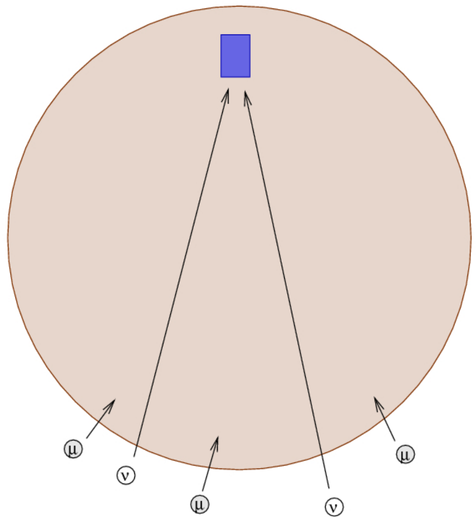
Source	Average energy	Flux or Intensity
Sun	$\langle E\rangle \sim$ 0.3 MeV	$F_\nu \sim 6\times 10^{10}$ cm^{-2} s^{-1}
Earth	$\langle E\rangle \sim$ 1 MeV	$F_\nu \sim 10^{6}$ cm^{-2} s^{-1}
Nuclear reactor	$\langle E\rangle \sim$ 3 MeV	$I_\nu \sim 10^{20}$ ν/s (1800 MW)
Supernovae	$\langle E\rangle \sim$ 20 MeV	$I_\nu \sim 10^{57}$ ν/s in ~ 10 s
Relic Supernova	$\langle E\rangle \sim$ 10 MeV	$F_\nu \sim$ 2.5 cm^{-2} s^{-1}
Atmosphere	$\langle E\rangle \sim$ 1 GeV	$F_\nu \sim$ 1 cm^{-2} s^{-1} at sea level
Accelerator	$\langle E\rangle \sim$ 10 GeV	$F_\nu \sim 6\times 10^{6}$ cm^{-2} yr^{-1}

HIGH ENERGY NEUTRINOS

High energy neutrinos telescopes – the beginning



Induced μ's are the main practical way to cope with atmospheric μ's and probe high energy neutrinos, as understood by Markov end of 50's.



The muon range, dictated by e.m. interactions

$$R(E_\mu, E_{th}) \approx \mathbf{2.5\ km\ w.e.} \times \log \left[\frac{1 + \frac{E_\mu}{0.5\ \text{TeV}}}{1 + \frac{E_{th}}{0.5\ \text{TeV}}} \right]$$

already indicates the size of ~ 1 km of ideal HE neutrino detectors.

The interest in searching for cosmic sources of H.E. neutrinos has also a long history, beginning, again, in Markov's group.

In the thesis of Zheleznykh (1958) we read,

1. *"γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos"*
2. *"worth searching especially if HE γ beyond atmosphere were found"*
3. *from new star's shell as Crab* "the flux could equal the atmospheric one"
4. *from old CR population as GC* "could be large if attenuation is essential"

In view of the gamma ray measurement and also of various theoretical works, most these points remained valid till today.

The hope to see something

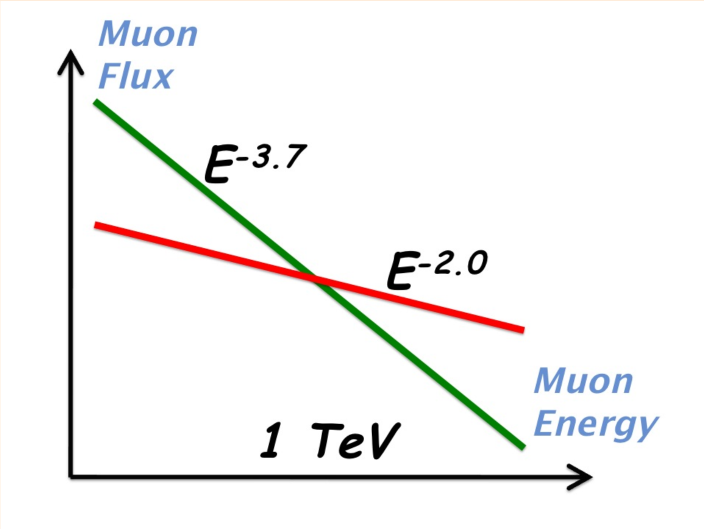


Figure 14: *If CR are produced according to Fermi, $F \sim E^{-2}$, those that interact produce neutrinos. Their spectra should follow the one of CR, thus being much harder than atmospheric ones.*

It is important to recall the key reason, that concerns pion pathlength:

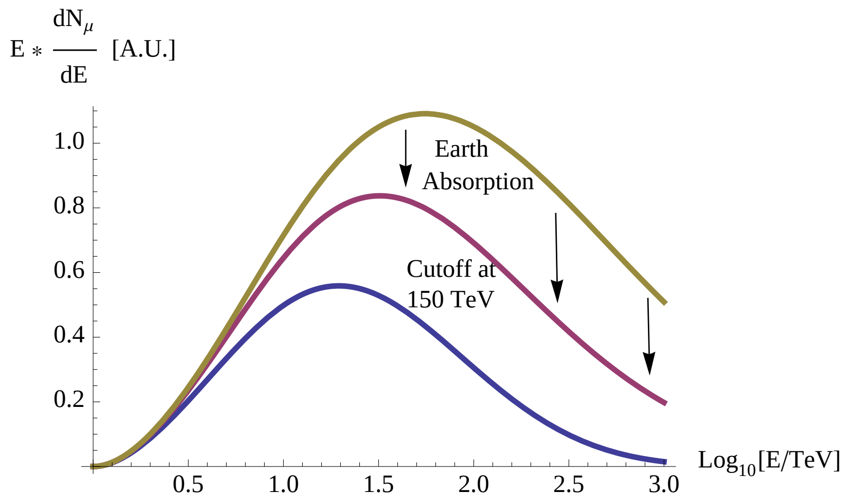
At TeV, $d_\pi = c\tau_\pi \times \gamma = 55\text{km} \times \frac{E_\pi}{1\ \text{TeV}}$; *thus atmospheric ν_μ flux is depressed.*

The conversion of muon neutrinos into muons is simple:

$$P_{\nu_\mu\to\mu} = \int_{E_{th}}^{E} dE_\mu \frac{d\sigma_{cc}}{dE_\mu} R_\mu/m_n \qquad \text{[say, } 10^{-35}\text{ cm}^2 \times N_A/\beta \sim 10^{-6}\text{]}$$

$$A_{\nu_\mu} = A_\mu(\theta) \times P_{\nu_\mu\to\mu}(E,\theta) \times e^{-\sigma\ z/m_n} \quad \text{[say, 1 km}^2 \times 10^{-6} \sim 1\text{ m}^2\text{]}$$

Distribution of ν_μ leading to muons, assuming E^{-2} primary spectrum (sienna); then, including Earth absorption, for a source at $\delta = -39^\circ$ as seen from Antares (purple); then with a spectrum $E^{-2}e^{-\sqrt{E/150\text{ TeV}}}$ (blue), i.e., with primaries cutoffed at $\sim$3 PeV.



The shape of the spectrum is based on the assumption that the primaries have an exponential cutoff *(Ke'lner Aharonian 06; Kappes et al 07)*

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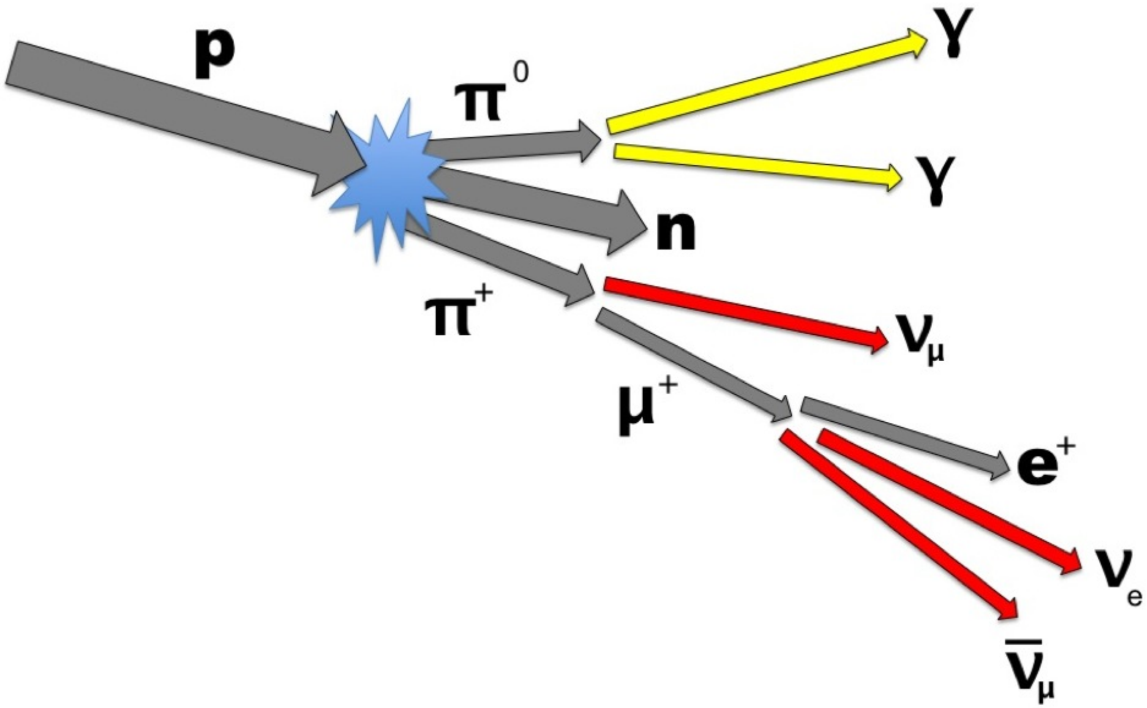
NEUTRINOS AND GAMMA RAYS

Let us **quantify** the relation between photons and neutrinos, assuming that:

(1) the sources are transparent to the gamma rays;

(2) the CR collide with protons;

that are reasonable hypotheses for certain galactic sources, such as SNR.



Both neutrinos and hadronic contribution to γ are linear functions of the cosmic ray intensity. Thus they are linked by a linear relation:

$$\Phi_{\nu_\mu}(E) = 0.380\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.013\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_\mu(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

$$\Phi_{\bar\nu_\mu}(E) = 0.278\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.009\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_{\bar\mu}(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

The first and second contributions are due to direct mesons decay into neutrinos, $r_x = (m_\mu/m_x)^2$ with $x = \pi, K$ and the third to μ decay, e.g.:

$$K_\mu(x) = \begin{cases} x^2(15.34 - 28.93x) & 0 < x < r_K \\ 0.0165 + 0.1193x + 3.747x^2 - 3.981x^3 & r_K < x < r_\pi \\ (1-x)^2(-0.6698 + 6.588x) & r_\pi < x < 1 \end{cases}$$

and similarly for antineutrinos; oscillations included FV'06; Villante & FV'08.

The HESS data on RX J1713.7-3946 permit us to evaluate a precise upper bound on the observable neutrino flux:

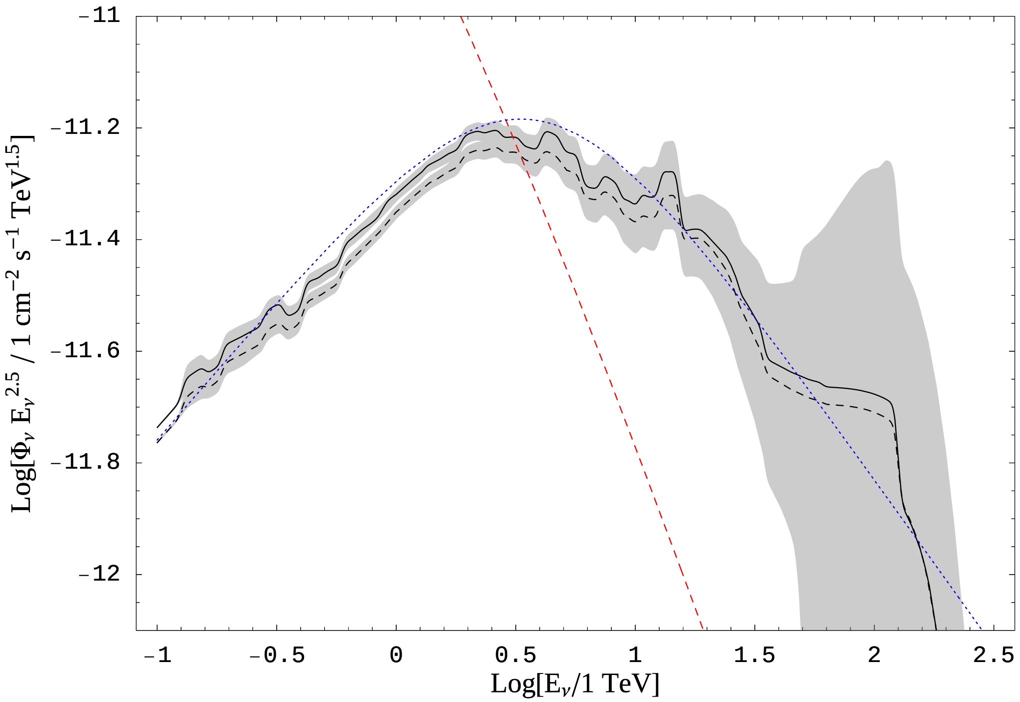
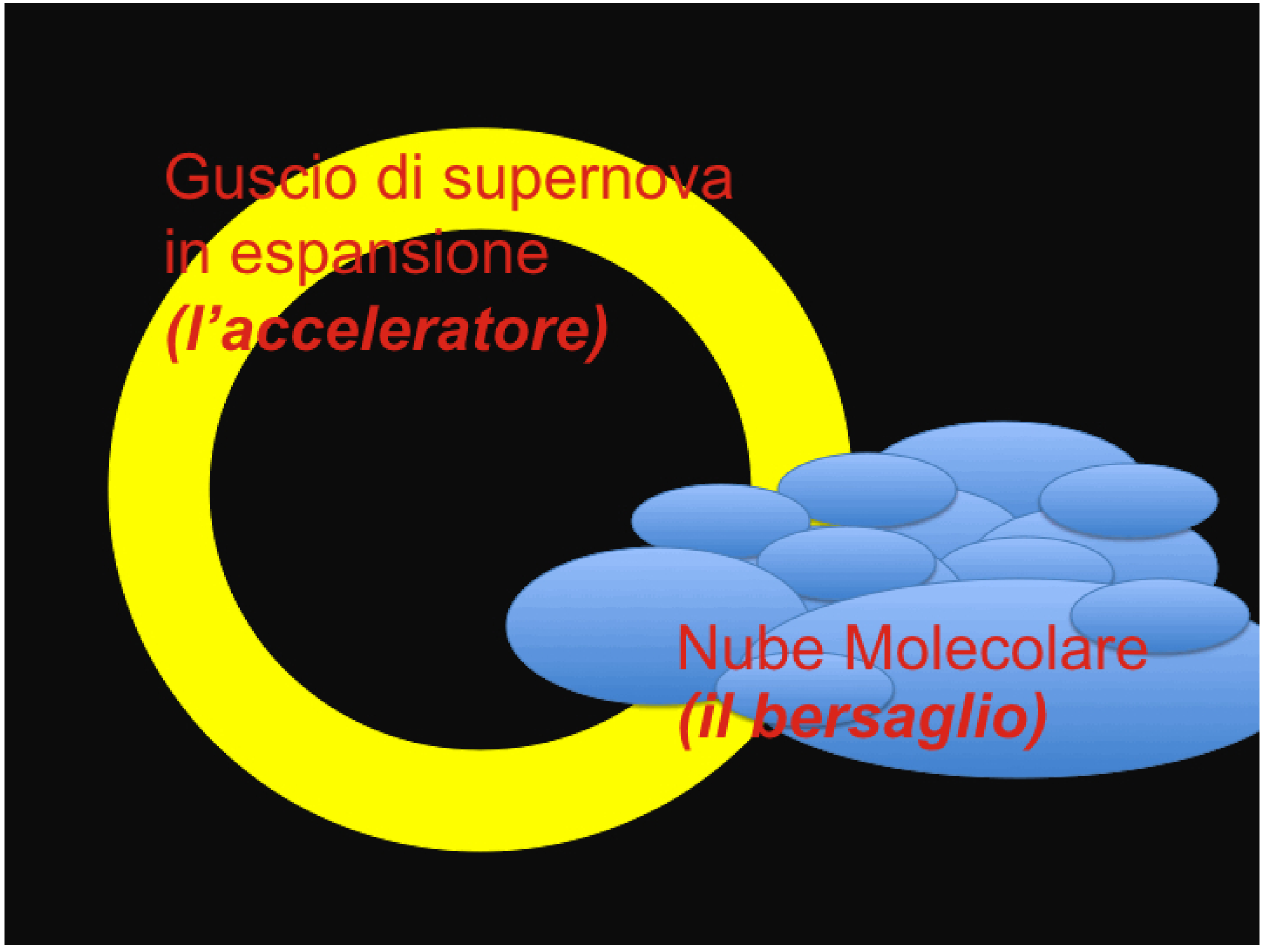


Figure 15: *ν_μ and $\bar{\nu}_\mu$ fluxes under the hypothesis of a hadronic γ-ray emission. The corresponding number of events above 1 TeV* (Villante & FV '08) *is:*
$I_{\mu+\bar{\mu}} = 2.4 \pm 0.3 \pm 0.5/km^2\ yr$

This is a also very well motivated potential source: a relatively young supernova remnant associated with molecular clouds.


Guscio di supernova
in espansione
(l'acceleratore)
Nube Molecolare
(il bersaglio)

Other possible souces

Source	Type	Challenge	$N(\mu+\bar{\mu})$
Vela Junior	SNR	Fermi	4
MGRO 2019+37	Star Form.+?	Argo, Veritas	1.5
MGRO 1908+06	Star Form.+?	HESS	2.5
Galactic Center	CR reservoire?	....	100

Approximate number of througoing muon events per km^2 above 1 TeV.

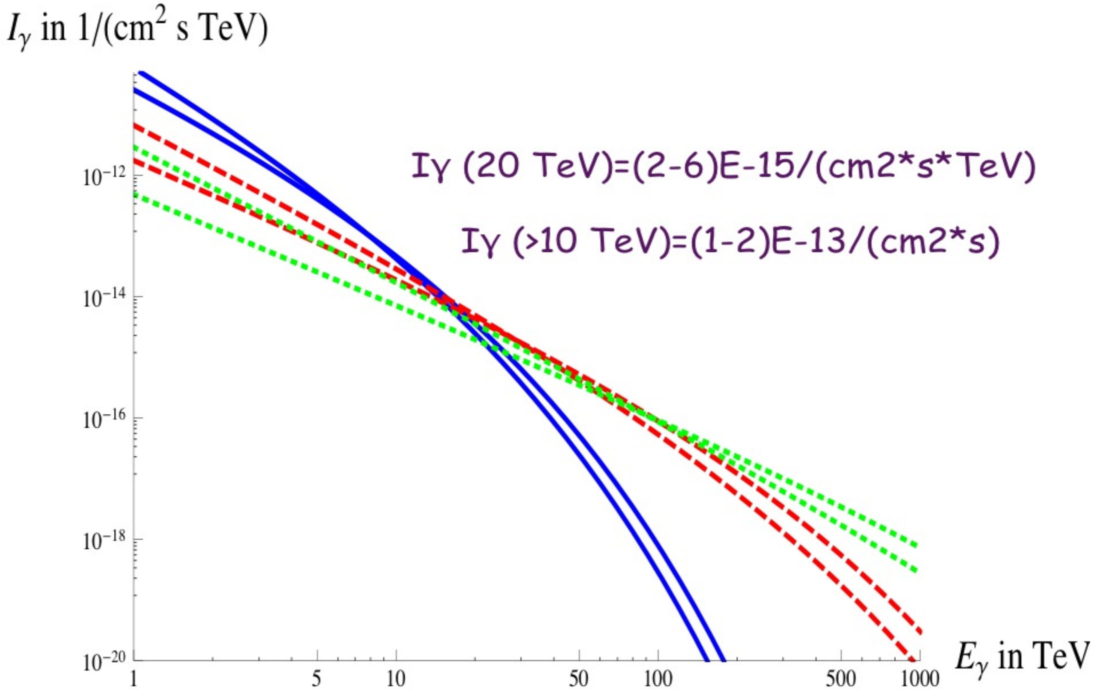
ALL NUMBERS BASED ON EXTRAPOLATIONS AT HIGH ENERGY.

Crocker, Aharonian, PRL106 (2011) 101102.
Aharonian & FV, NIM A692 (2012) 5 and ref.s therein;
Km3NeT Coll., http://arxiv.org/pdf/1208.1226v1.pdf.

Which γ-ray sources are potential neutrino sources?

They should be characterized by hadronic γ-rays distributed as $I_\gamma \propto E_\gamma^{-\alpha} e^{-\sqrt{E_\gamma/E_c}}$ with $\alpha = 1.8 - 2.2$ and $E_c =$ TeV$-$ PeV.

γ-ray intensities that correspond to a signal of one muon/km^{2}yr above 1 TeV. FV et al. 2011



The γ-ray flux above 10 TeV is almost universal!

All potential neutrinos sources have

$$I_\gamma(> 10 \text{ TeV}) = (1-2)\times 10^{-13}/(\text{cm}^2 \text{ s})$$

To collect ≥ 100 γ**'s in a reasonable time, km^2 area is needed:**

$$\textbf{Exposure} = L^2 \times T \sim 2\times \text{ km}^2 \times 10 \text{ h}$$

e.g., a 10×10 Cherenkov telescopes array, or one dedicated EAS array.

$\therefore$ *A large area* γ *apparatus, such as the high energy array in CTA or a custom instrument, would be invaluable for* ν *community.*

H.E. NEUTRINO SKY TODAY

Point sources

The neutrino sky is 'cloudy': At the moment we do not see anything else than atmospheric neutrinos – that should be very well understood for the next steps anyway, and that are all but uninteresting (e.g., large scale anisotropies revealed; charm contribution still searched).

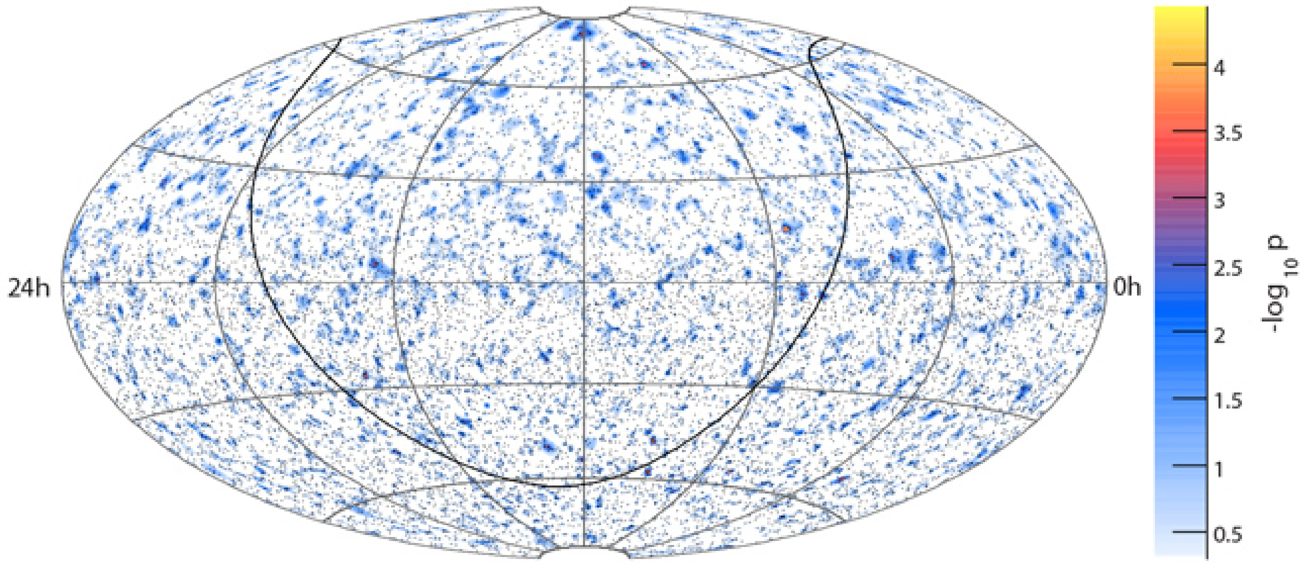


Figure 16: *A significance skymap of IceCube (from high energy muon events) in Galactic coordinates, assuming that the spectra of the neutrino sources is* E^{-2}.

Sporadic point sources

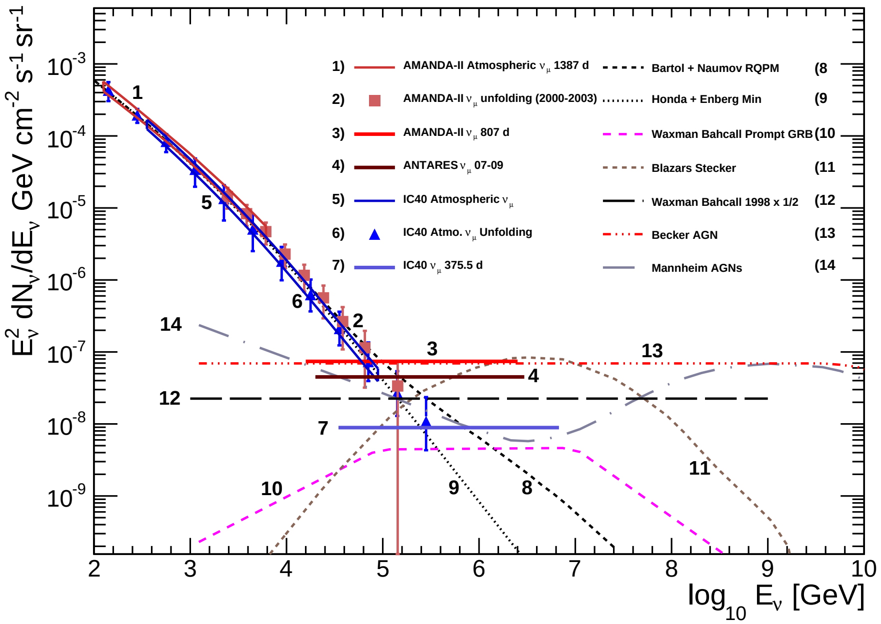
The hypothesis that GRB's are UHECR accelerators permits to estimate neutrino emission (Waxman '95, WB '97).

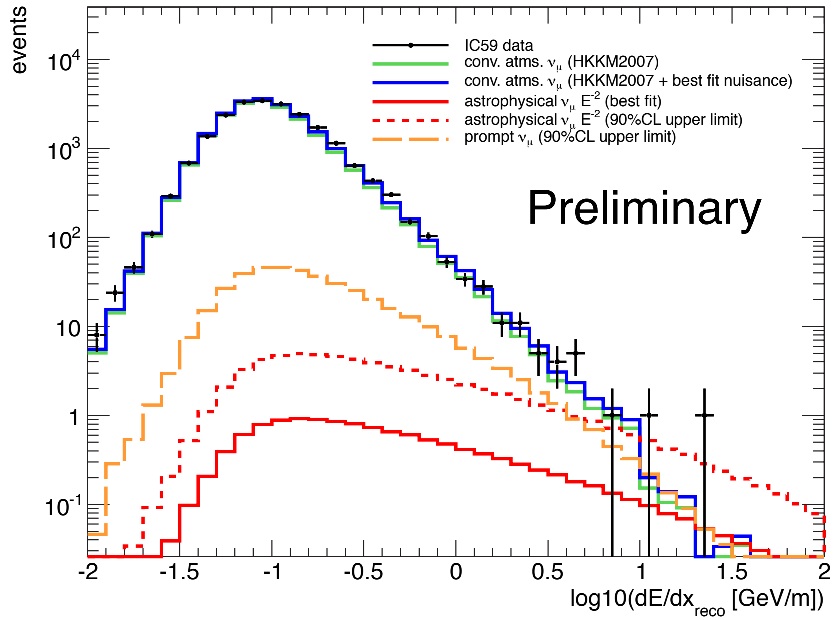
IceCube monitored about 100 GRB in the window of time when neutrinos were expected. Expected 0.1 background plus 3 signal events, saw none – that leaves a wide margin for further searching.

Theoretical uncertainties have been estimated to be a factor of 2 (Guetta et al., 04) but are presumably much larger (Meszaros et al, 2011).

Diffuse sources – conventional muon events

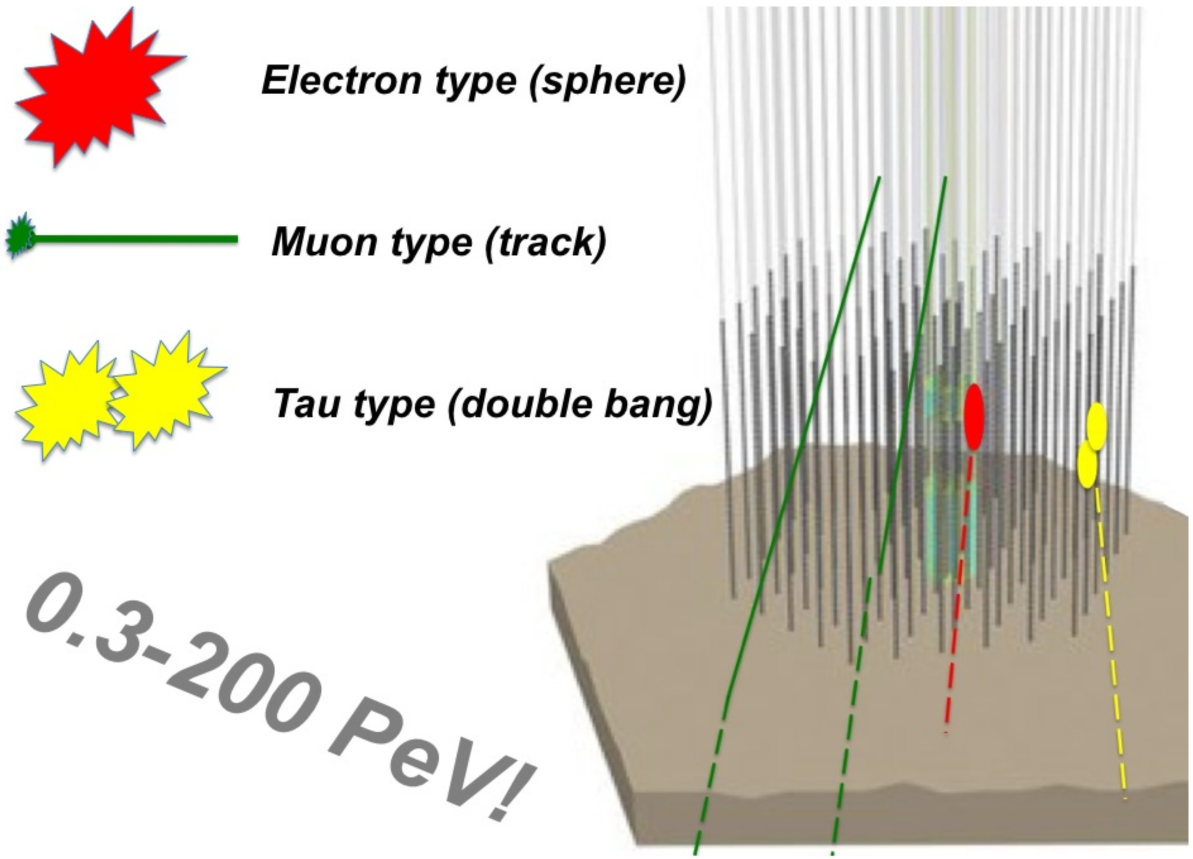
WB bound: UHECR observed energy should be exceed the one of secondary particles. In essence, it amounts to the statement that the accelerators are not (too) hidden.





Left: results on the diffuse flux of IC40, Abbasi, 2011 are below the WB bound – blue line. Right: preliminary analysis of IC59 (348d) with 2 σ a hint for something. Now, the exposure is increased by 672/348 80/59=2.5 times bigger – wait and see!

Diffuse sources – contained events (new!)



At IC22 (200d) Abbasi et al., PRD86 (2012) background events: $0.60 \pm 0.19^{+0.56}_{-0.58}$.
Claimed background at IC86 (673d) A. Ishihara at Neutrino 2012 is even *less.*

At even higher energies, the conventional atmospheric neutrinos fade out and one could search for events contained in the detector.

The prompt (charm decay) events should be rare, but in any case yield

$$\Phi_e^{prompt} \approx \Phi_\mu^{prompt}, \quad \Phi_\tau^{prompt} \approx 0$$

A cosmic (extragalactic) neutrino source should have tau neutrinos as well, due to oscillations

$$\Phi_e^{cosmic} \approx \Phi_\mu^{cosmic} \approx \Phi_\tau^{cosmic}$$

A cosmic source could show up as excess of contained events, but tau events could be the culprit.

The new data of IC86 (672d) have an exposure of about 2 km^3 yr. Consider a common flux for neutrinos/antineutrinos

$$E^2 F < \frac{10^{-9}\ \mathrm{GeV}}{\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr}}$$

It gives ~ 50 througoing muons events above 1 TeV in $\Omega = 2\pi$; the higher tail could be observable. The contained events with cuts as in IC22 paper on tau neutrinos are well characterized but also much less

$$N_e = 1.8,\ N_\mu = 0.7,\ N_\tau = 1.1$$

A. Ishihara at Neutrino 2012 showed 2 events at PeV possibily compatible with electron type.

Of course, next questions are: What is the background? How many taus? How many muons? What are the directions? Wait and see!

UHE neutrinos

Scattering of neutrinos above EeV causes impulsive radio emission, due to Cherenkov radiation from the subsequent bunch of negative particles (Askaryan effect).

ANITA experiment expected 1 background plus 0.3-30 signal events and saw 1 – thus proceeding much farther won't be easy.

However the key hypothesis, UHECR being protons (Berezinsky, Zatsepin), is called into cause by the recent studies of composition of Pierre Auger Observatory.

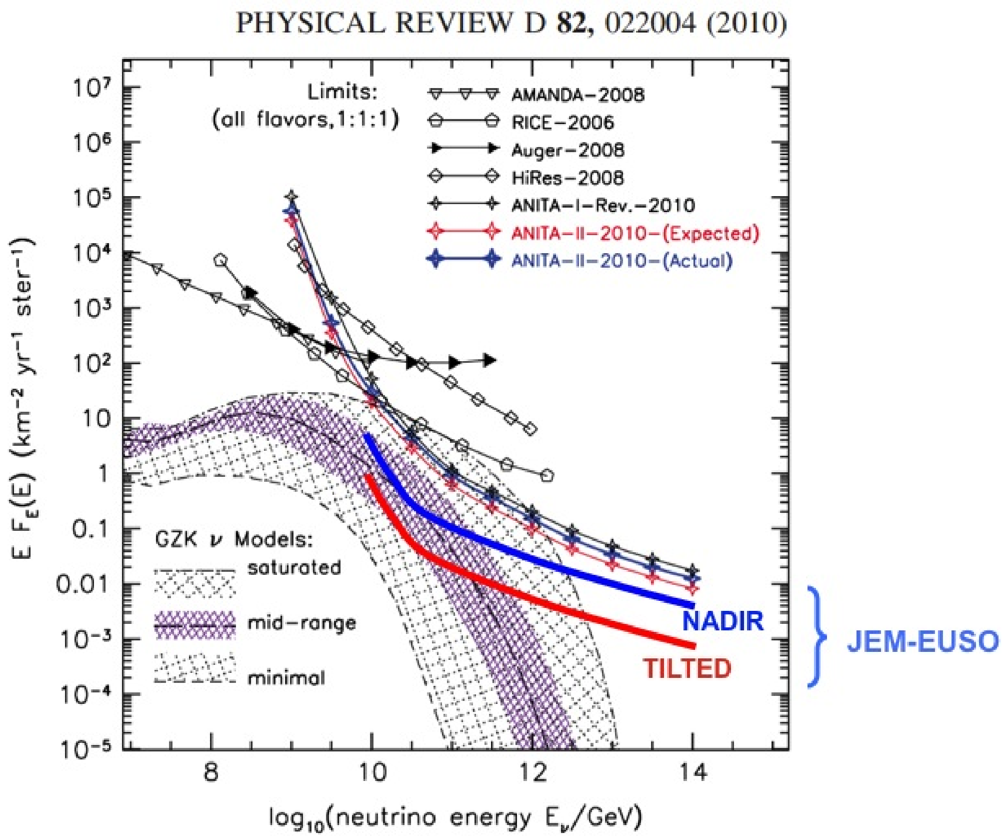


Figure 17: *Limits obtained by ANITA and RICE, by Amanda and by the UHECR observatories. The theoretical curves assume that UHECR are protons. In the future, JEM-EUSO could contribute to the search (curves drawn by Medina-Tanco).*

- Neutrino astronomy is a stimulating field, that merges competences of particle physics, nuclear physics, astronomy and astrophysics.

- Observations of low energy νs are in very good shape, and there are many important tasks still to be achieved. Here the Gran Sasso (Borexino!) is playing a key role.

- Solar and geo-ν on excellent bases, supernova's with margins of progress. High energy neutrinos need to exploit CR and γ connections and would profit of firmer theoretical expectations.

- High energy ν telescopes are operational and observational perspects are becoming more definite. Till now, no source seen yet but there is space for progresses and surprises.