

Progresses in Neutrinos Astronomy

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Neutrino astronomy is a discipline aimed at investigating a class of high energy phenomena, by exploiting certain specific nuclear reactions. It enjoys a steadily improving instrumentation and observational successes, whereas theoretical investigations often suffer of an artificial separations among astrophysics, nuclear and particle physics. We review recent progresses focussing in particular on the sub MeV–100 MeV energy region.

With E. Bernardini, M.L. Costantini, W. Fulgione, A. Ianni, G. Pagliaroli, F.L. Villante.

(2 very important)
NEUTRINO
INTERACTIONS

Elastic scattering (ES) reaction

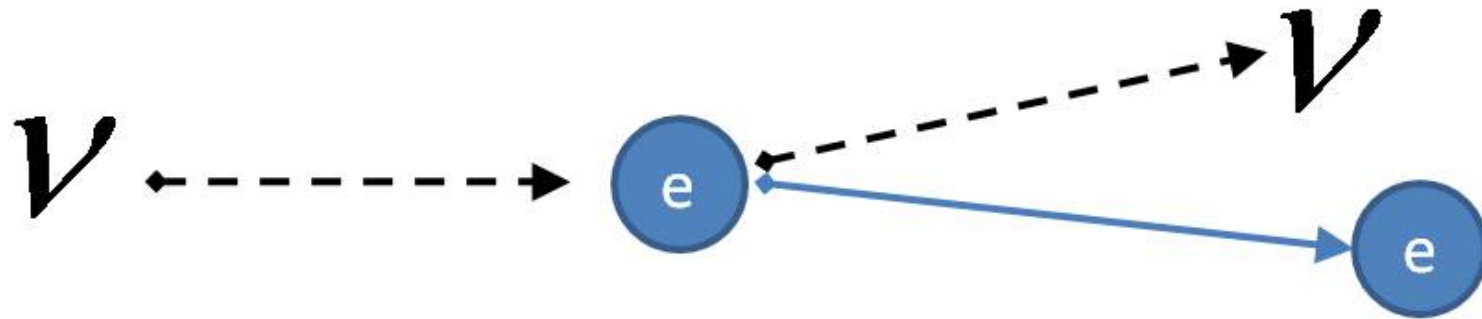


Figure 1: *Due to the ES reaction, the (anti) neutrinos of several MeV hit the atomic electrons and produce events in the forward direction. We can distinguish ES events if we know the direction of the source.*

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

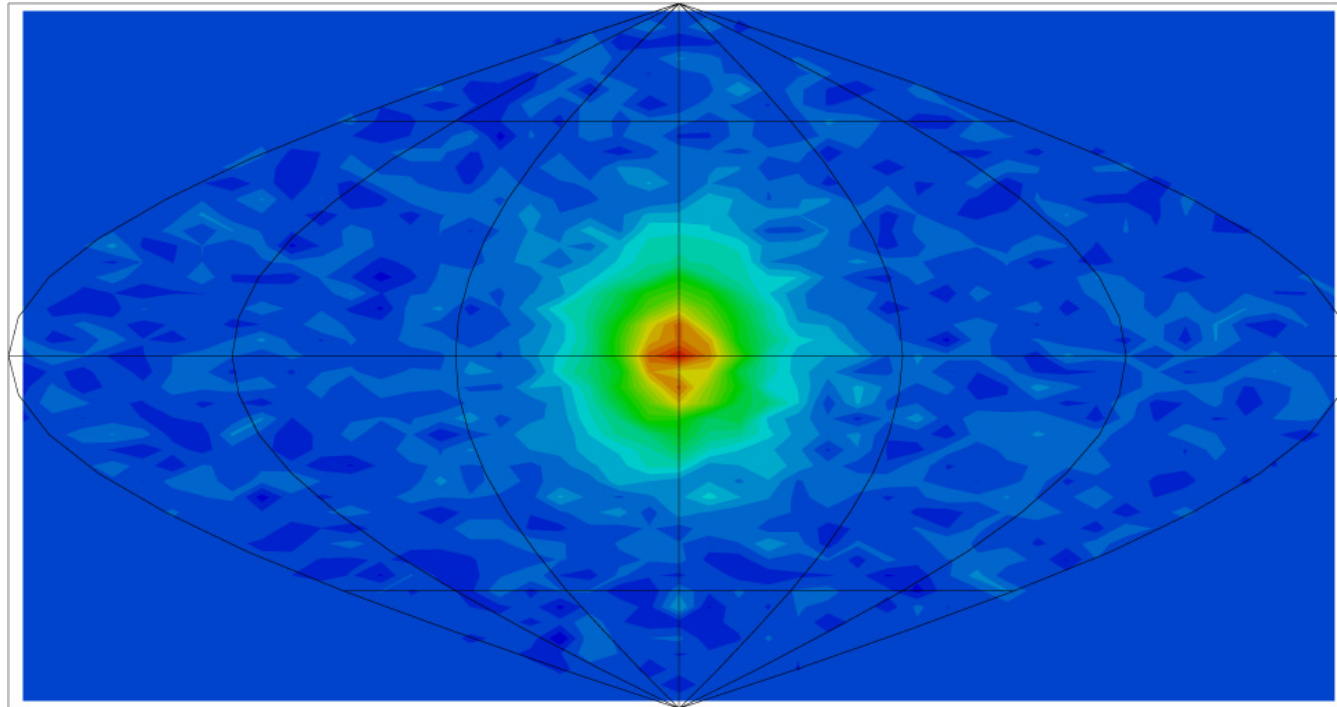


Figure 2: *Image of the Sun obtained by exploiting the electrons from the ES reaction as obtained by the Super-Kamiokande neutrino telescope, to be discussed in a while.*

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

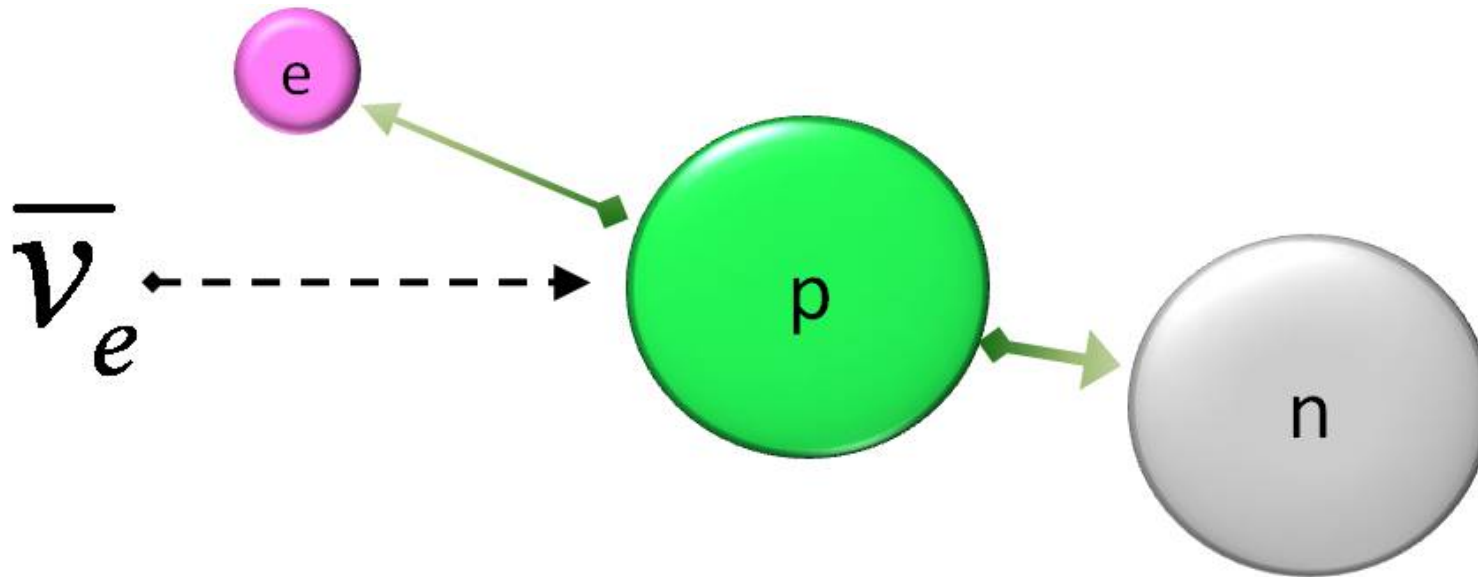


Figure 3: *IBD: an almost isotropic reaction occurring when $E_\nu > 1.8\text{MeV}$ with a much larger cross section: $\sigma_{\text{IBD}} \sim G_F^2 m_p E_\nu$ whereas $\sigma_{\text{ES}} \sim G_F^2 m_e E_\nu$. This reaction is important, for free **protons** abundant in H_2O and C_nH_m targets.*

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

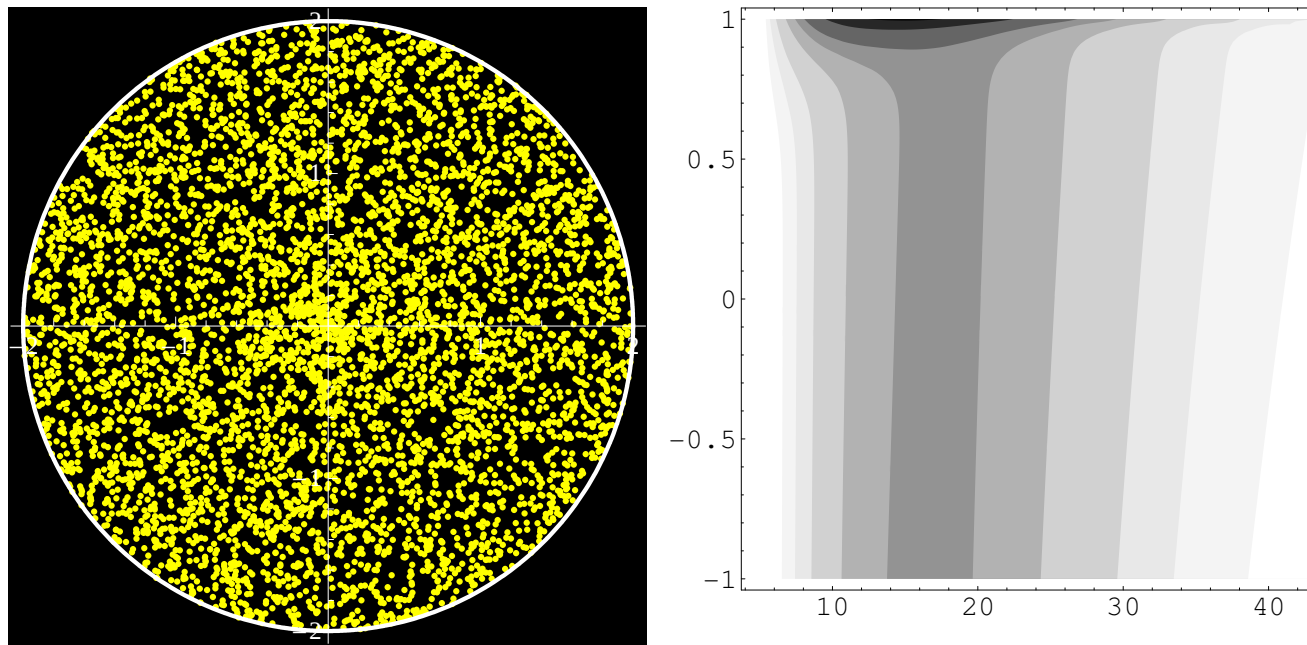


Figure 4: *Left panel: direction of the events from a future galactic supernova; ES events are mostly in the center, IBD events are instead almost isotropical. Right panel: expected energy-cosine distribution of the events; energy is in MeV.*

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

(some modern & active)
NEUTRINO
TELESCOPES

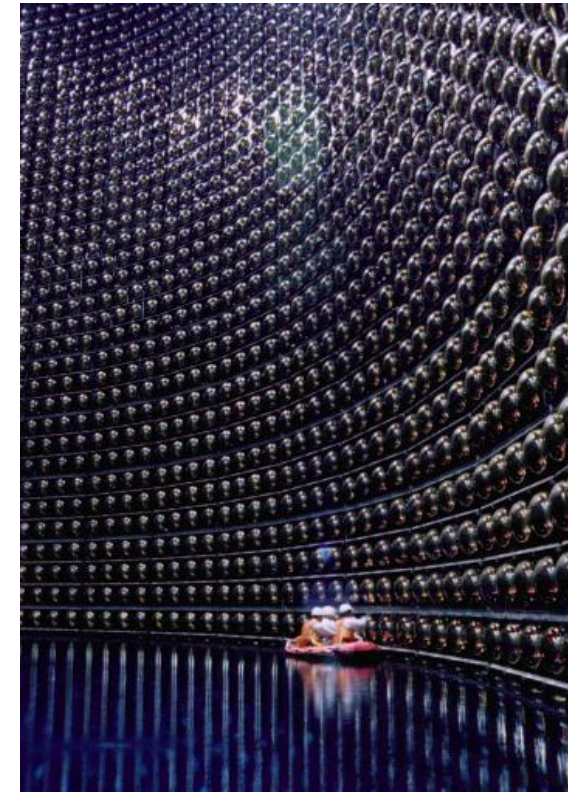
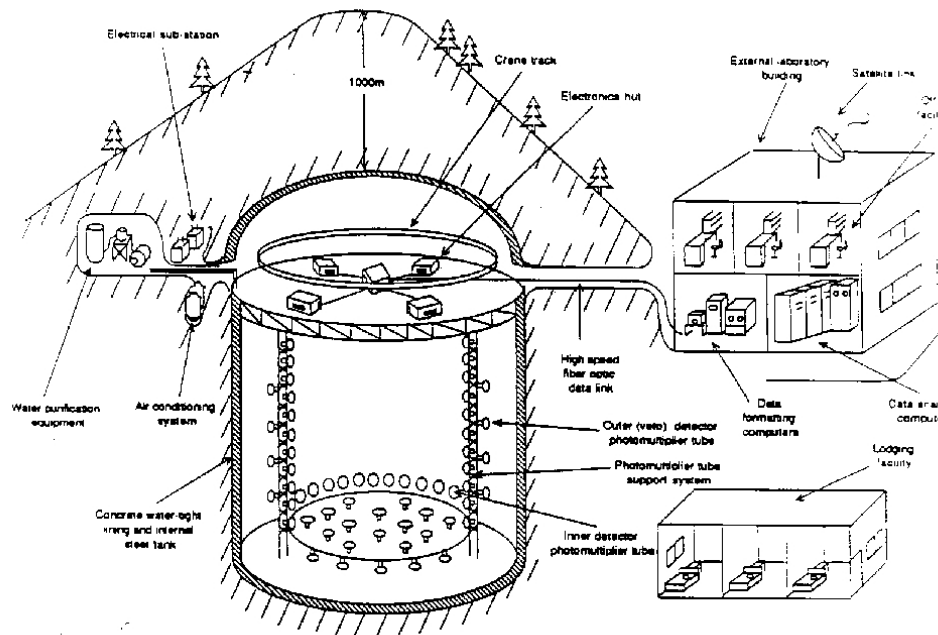


Figure 5: *The Super-Kamiokande detector, located in the Kamioka mine (Japan). It reveals ultrarelativistic charged particles thanks to their Čerenkov-Vavilov radiation.*

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

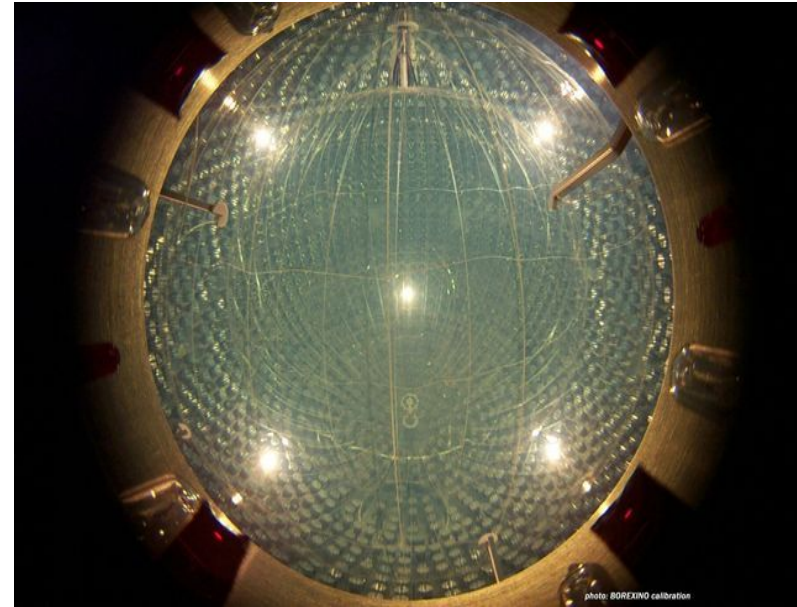
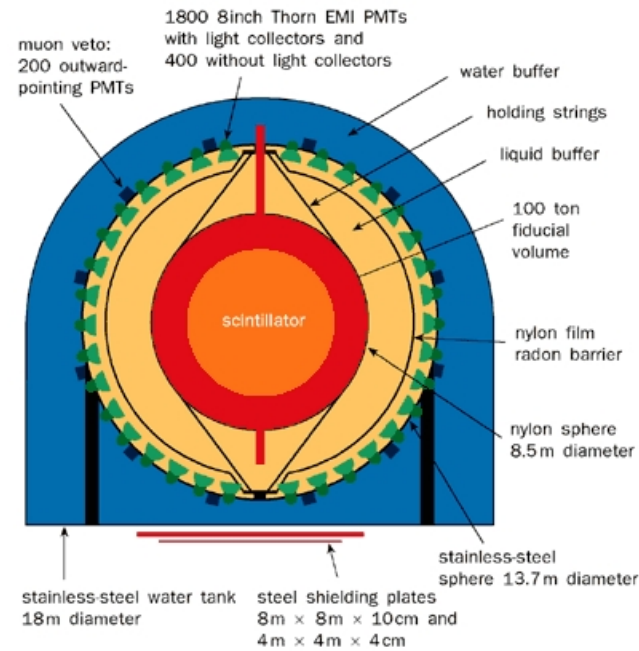


Figure 6: *The Borexino detector, located in the Gran Sasso laboratory (Italy). Its ultrapure scintillator permits us to observe the electrons-or positrons-which are occasionally hit by neutrinos-or antineutrinos, even when their energy is below MeV.*

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

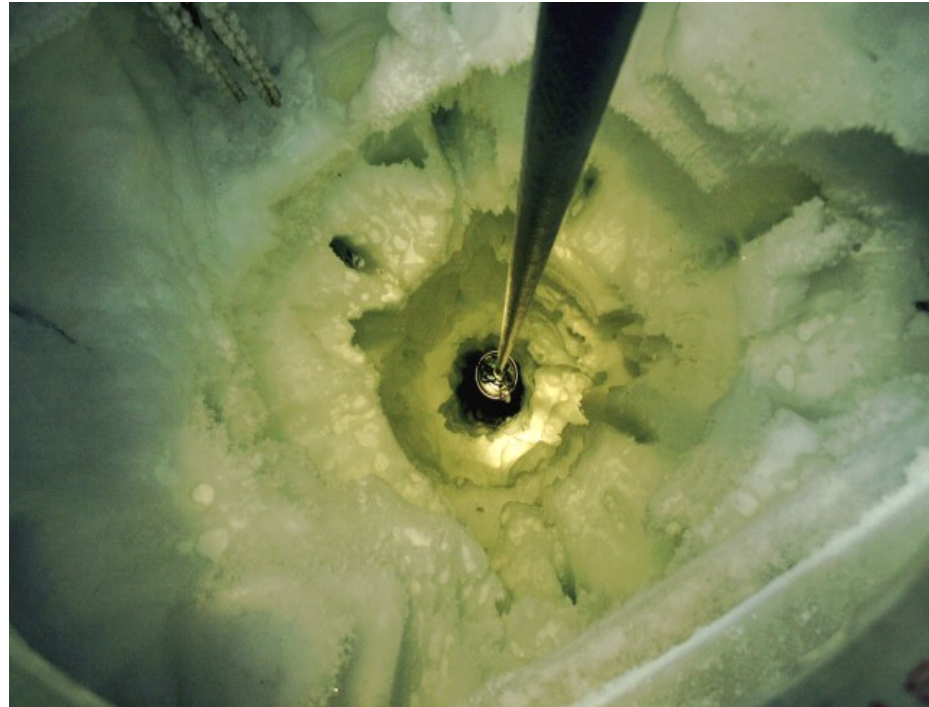
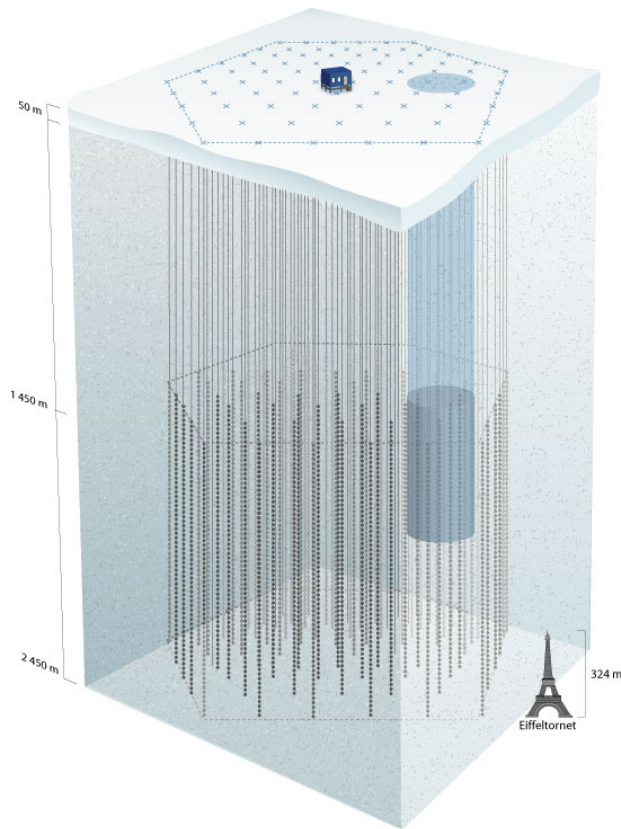


Figure 7: *The IceCUBE detector (South Pole). It reveals the (anti) muons occasionally produced by (anti) neutrinos. It can get some information on supernova (~ 10 MeV) $\bar{\nu}_e$'s thanks to its huge mass but it is optimized for high energy ($> \text{TeV}$) neutrinos.*

SOLAR NEUTRINOS

La catena PP

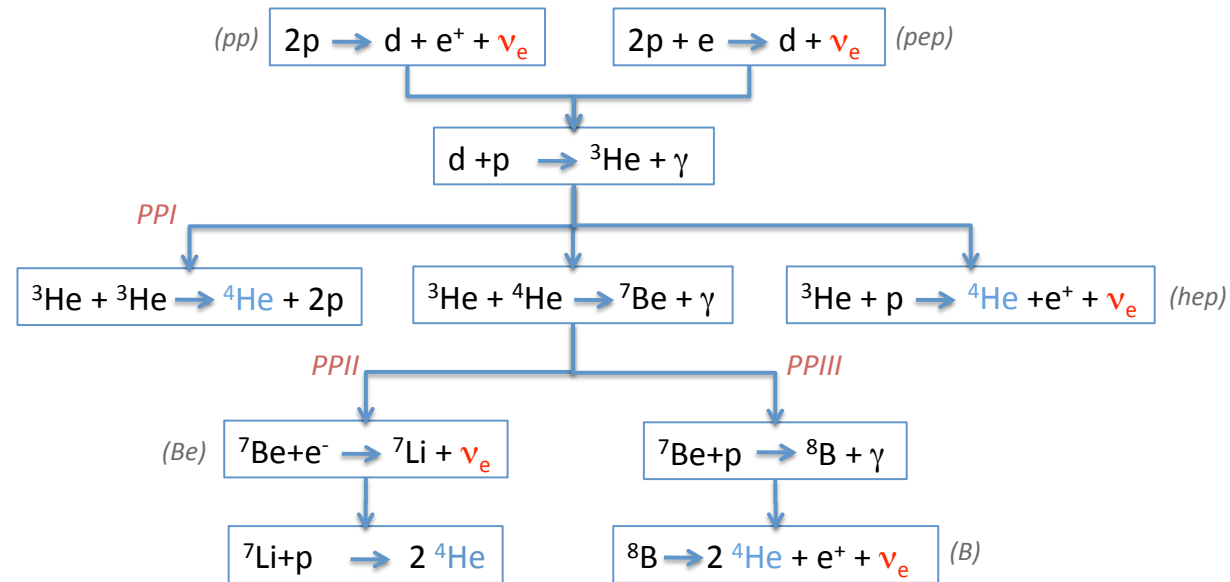


Figure 8: *The main chain of nuclear energy generation in the Sun.*

Directly tested by the relatively rare but energetic ν_e from PPIII branch (Super-Kamiokande, SNO, Borexino) and by the more important PPII (Borexino). The PPI neutrinos are determined indirectly, i.e., from luminosity constraint, if we *assume* the Sun in equilibrium state.

Recent measurements of the PPIII neutrinos

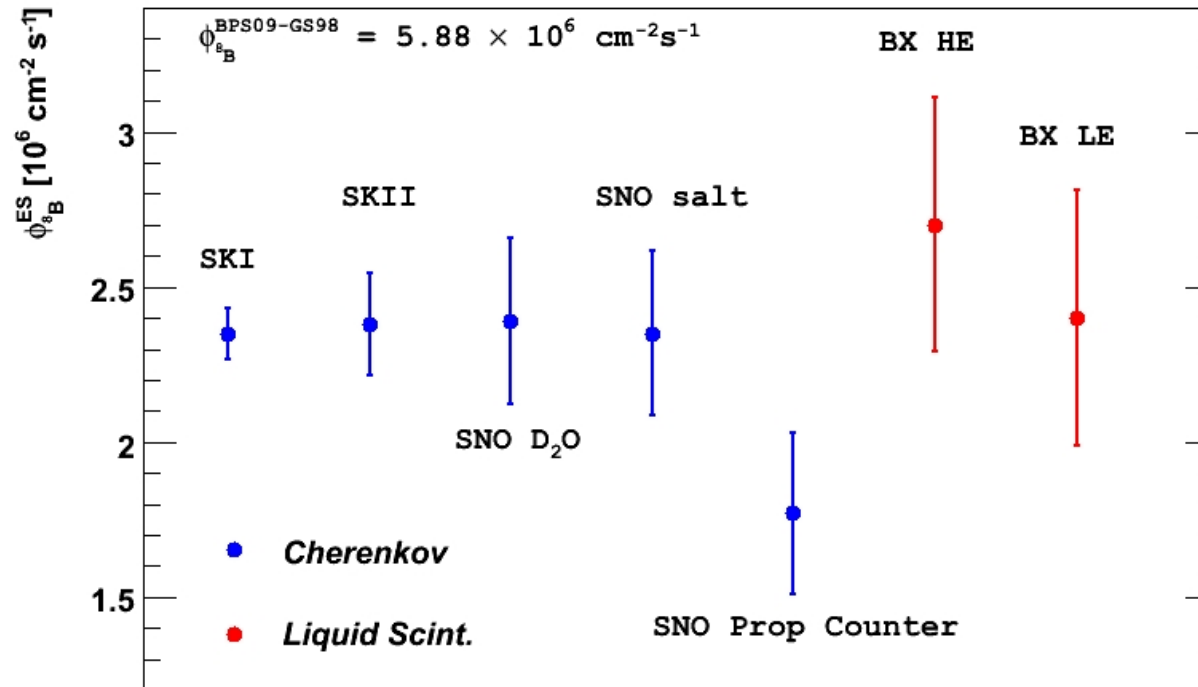


Figure 9: Recent measurements of Boron-8 neutrinos (PPIII branch); 'salt' and 'prop. counter' measure the neutron from $\nu D \rightarrow \nu p n$ reaction [i.e., deuterium dissociation by neutral currents]. SK=Super-Kamiokande; BX=Borexino. The last points are new.

Energy dependence of solar neutrino oscillations

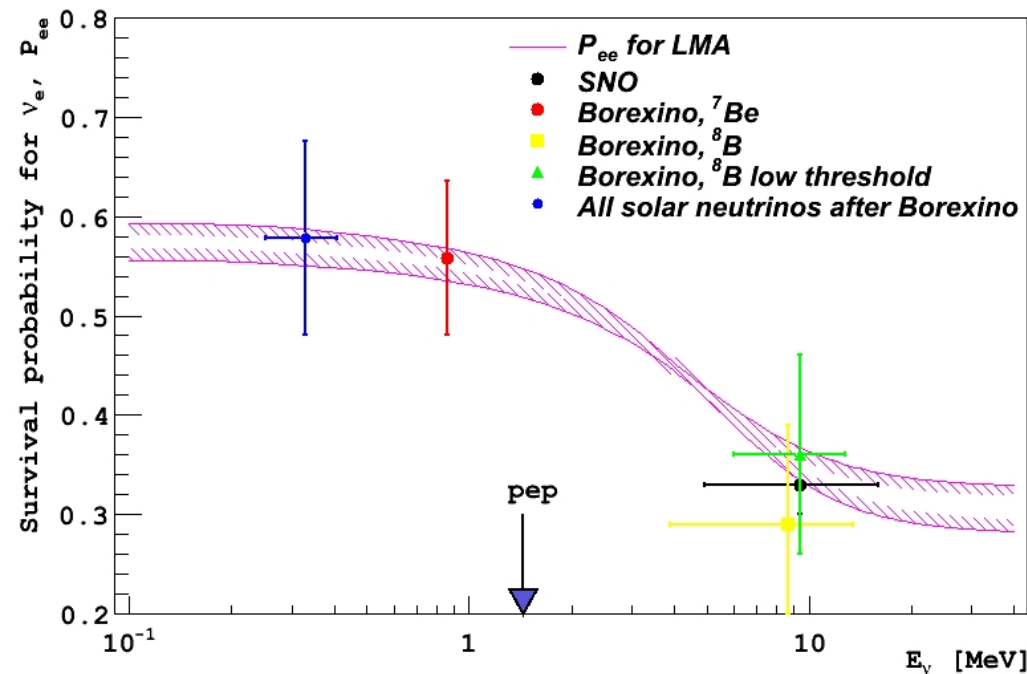


Figure 10: *The solar neutrino conversion probability* [Ianni 2010]

The downturn at high energies is neatly explained by matter (MSW) effect, i.e., coherent scattering of electron neutrinos on solar electrons, which is not relevant for atmospheric neutrino oscillations instead.

Recent measurements of photospheric heavy element abundances lead to solar models *unable* to reproduce the helioseismic results.

This “solar composition problem” demands a re-analysis of inputs and assumptions; opacity, distribution of the metals, tests of secondary chain (i.e., CNO neutrinos); role of helioseismological constraints.

.....

This can be explored efficiently approximating in linear response the output of evolutionary solar codes: the **linear solar model** [Villante Ricci 2009].

E.g.; this new tool has been recently used to argue against speculations on “dark baryons” in the core of the sun [Villante 2010].

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.

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

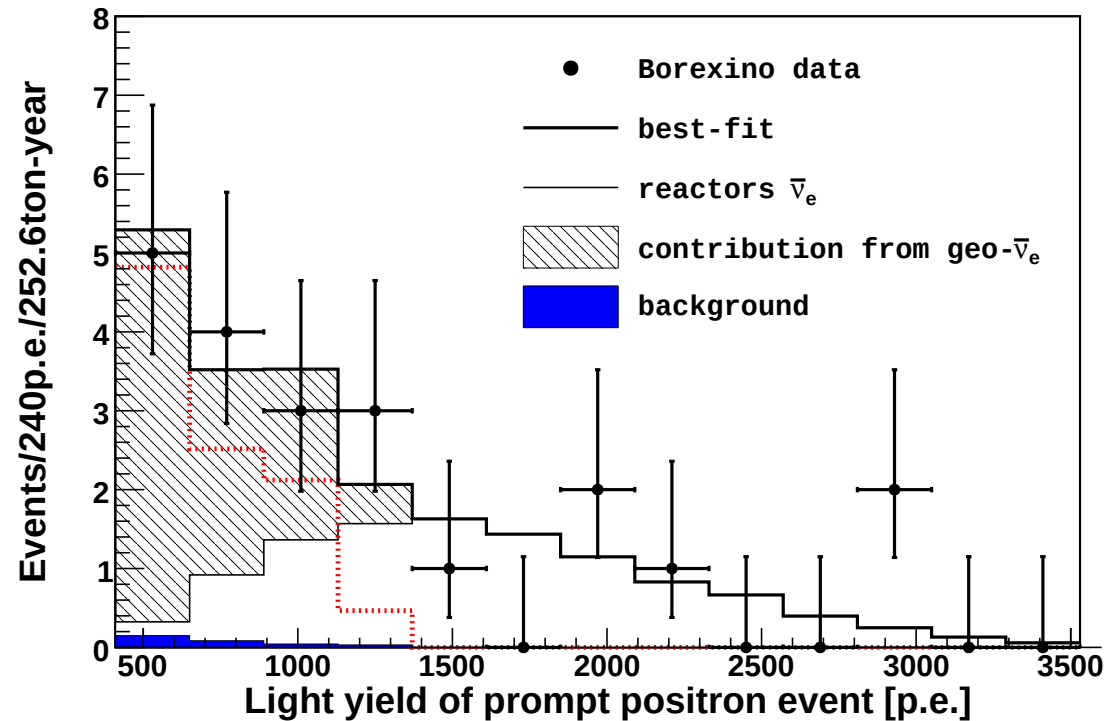


Figure 11: The $\bar{\nu}_e$ signal is due in equal proportions to $\bar{\nu}_e$'s from far away reactors and those from terrestrial radioactivity: The latter component dominates at low energies.

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

SUPERNOVA (anti)NEUTRINOS

Appointment with the next galactic supernova

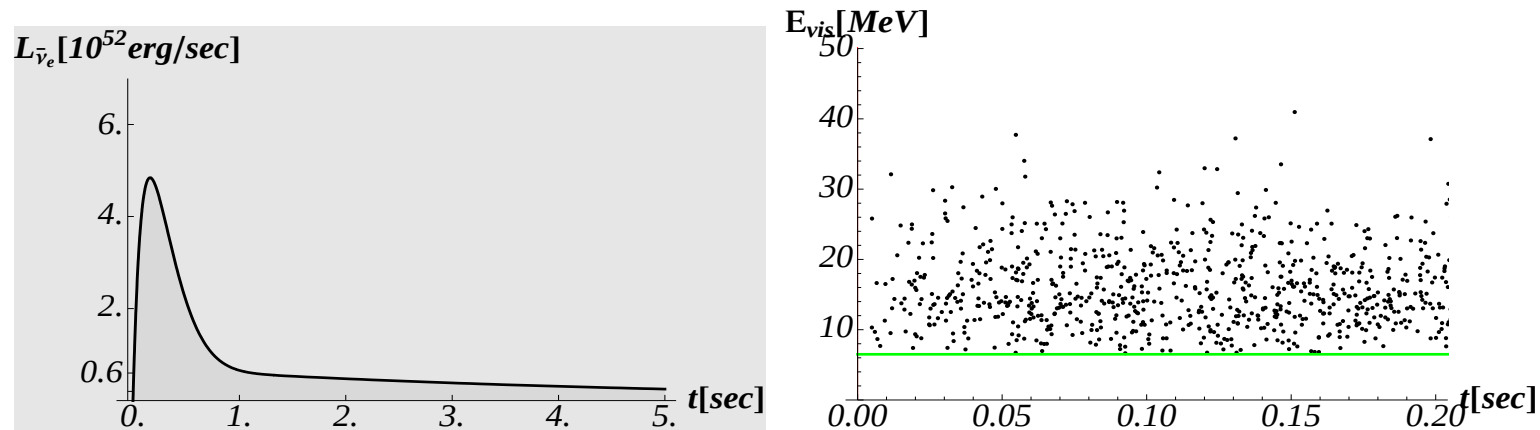


Figure 12: *Left: luminosity of $\bar{\nu}_e$ as deduced from SN1987A observations. Right: simulated events in Super-Kamiokande, assuming a supernova located at 10 kpc.*

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!

One practical problem with supernovae

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.

How could we possibly 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:

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

[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.

Let us discuss the present chances to detect it.

1) there is a window for the experimental search

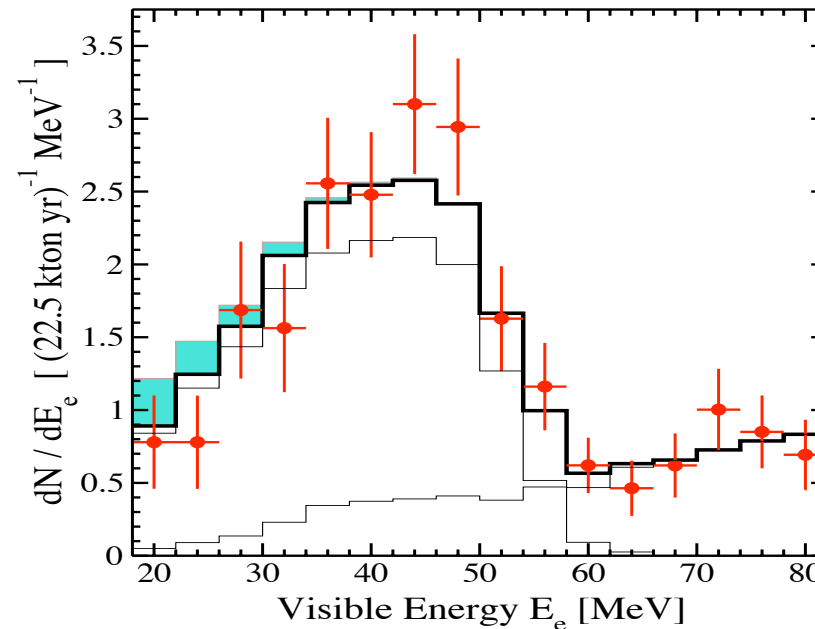


Figure 13: 2003 spectrum of Super-Kamiokande. The maximum relic supernova $\bar{\nu}_e$ signal is shown in light blue. Energy threshold set at 19.3 MeV [Malek et al., 2003]

Causes of background: atmospheric neutrinos at high energies; muons below the threshold for light at low energies. If the IBD neutron could be seen, background could be decreased & energy threshold lowered.

2) cosmic rate of supernovae is to some extent known

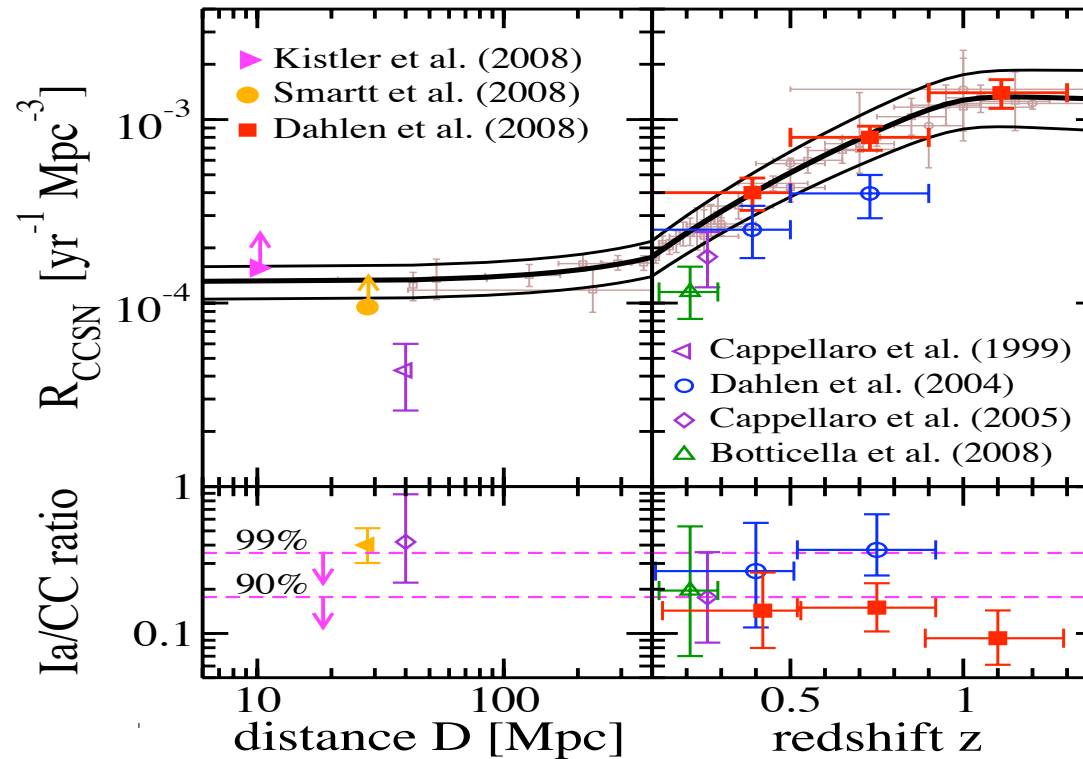


Figure 14: *The cosmic density rate of core collapse supernovae $R_{\text{SN}}(z)$ obtained rescaling the star formation rate (light brown points) does not disagree much with direct supernova observations [according to Beacom 2010].*

3) obstruction for a neat theoretical prediction

We ignore the high energy emission of the average supernova. Lacking a definitive theoretical model, we explore the consequences of the assumption that SN1987A $\bar{\nu}_e$ emission is the typical outcome [Pagliaroli, FV, Astr. Lett. 2009].

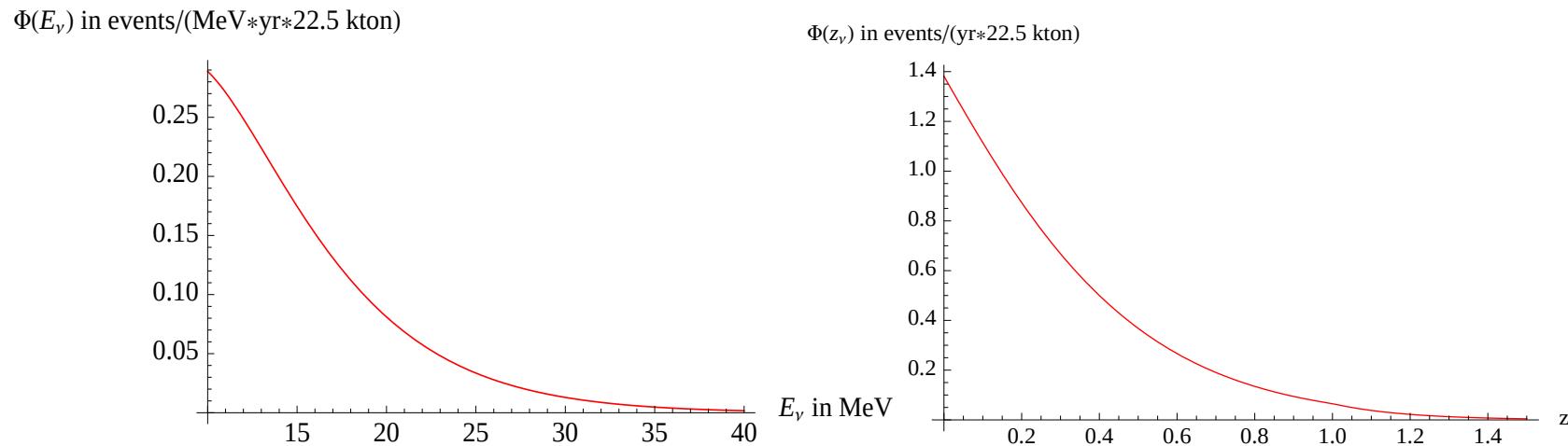


Figure 15: *Differential distributions of the event rate in 22.5 kton (Super-Kamiokande fiducial volume). Left panel: Events per MeV per year. Right panel: distribution in redshift, for the events above 19.3 MeV (Super-Kamiokande threshold).*

For a summary, it is enough to know just a pair of numbers:

$E_{\bar{\nu}_e}^{thr.}$	$z < 0.3$	$0.3 < z < 1$	$z > 1$	total
19.3 MeV	0.3	0.2	0.0	0.5
11.3 MeV	0.7	0.9	0.2	1.9

Table 1: *Events per year in 22.5 kton (Super-Kamiokande) for two values of the threshold: the one used in 2003 and a value allowed by neutron detection.*

Thus, the hypothesis that SN1987A was **typical** implies that:

- Very important to observe the neutron and lower the threshold!
- Search for these ν s will be tough but perhaps not impossible already with Super-Kamiokande.

HIGH ENERGY NEUTRINO DETECTORS

Theoretical expectations

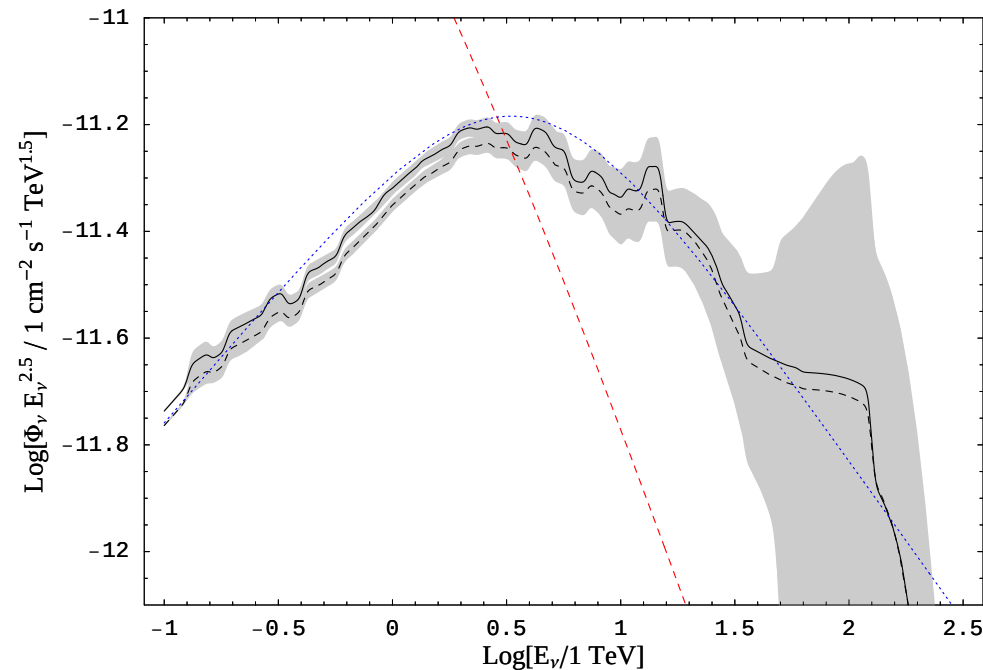
Certain astronomical objects are thought to be ‘point sources’ of very high energy ν , whose detection is the dream of modern neutrino astronomy. A principal example is provided by supernova remnants:

A COSMIC BEAM DUMP



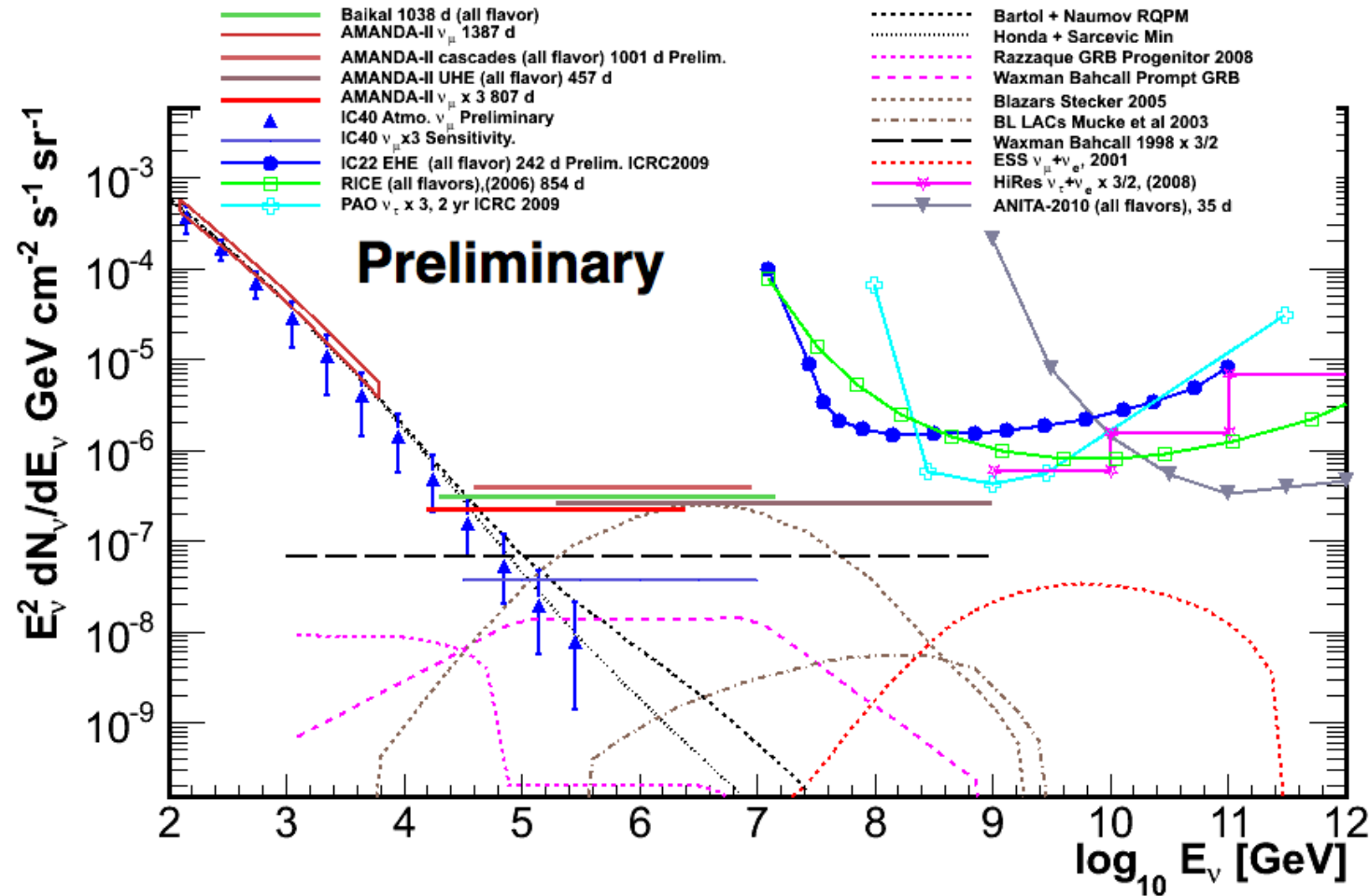
Figure 16: *Left: a supernova remnants that accelerates CR's, subsequently interacting with a molecular cloud [Drury, Volk, Aharonian 94]. Right: The principle of detection of ν_μ : the induced, upgoing muon flux [Zheleznik 57; Markov 60, Greisen 60].*

Mesons yield neutrinos, e.g., $\pi^\pm \rightarrow \mu^\pm \nu_\mu^{(-)}$ but we have also $\pi^0 \rightarrow \gamma\gamma$!
 Thus, when VHE gamma's are measured, we get an **upper bound** on neutrinos.



*For a detector of 1 km², with threshold set at 1 TeV, we expect **up to 2.5 signal events** per year from RX J1713-7-3946 and 1 background event [Villante, FV 08].*

An overview of the experimental progresses



[Compiled by IceCUBE collaboration]

- Neutrino astronomy is a stimulating field, often considered a branch of particle physics, but belonging with the same / or more / rights to astronomy.
- Observations of low energy ν s in very good shape, thanks to solar ν s and to a new branch: geo-neutrinos.
- Theory of solar and supernova ν s also proceed, though slowly. Speculations and overoptimistic statements are common in / low and high energy / neutrino astronomy.
- High energy ν telescopes are a reality. Till now, no source seen yet, but observational prospects are becoming more definite. There is space for progresses and perhaps surprises.