# Neutrino masses, oscillations and implications for neutrino astronomy

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We discuss the phenomenon of neutrino oscillations, recalling the experimental observations that support an evidence of this phenomenon, and stressing the meaning of neutrino masses for future experiments and for particle physics. We consider the implications for neutrino astronomy, focussing in particular on neutrinos from core collapse supernovae and on neutrinos from supernova remnants.

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# 1 Oscillations, neutrino masses, and all that

The only evidence (or strong hint?) of neutrino masses comes from oscillations. The potential of this phenomenon was immediately understood by Pontecorvo and it is today clear to everybody.

Other approaches, such as cosmology or the search of imprints on the $\beta$-decay spectrum produced upper bounds. Perhaps the exception is $0\nu2\beta$, a process possible for massive Majorana neutrinos.

*It is probably fair to say that a reference minimal picture with 3 massive* $\nu$ *accounts for the main experimental facts.*

## 1.1 Pontecorvo theory of vacuum oscillations

Think to a $\nu_e$ produced by weak interaction as a quantum state

$$|\nu_e\rangle = \cos\theta \; |\nu_1\rangle + \sin\theta \; |\nu_2\rangle$$

During propagation, the two states $|\nu_i\rangle$ get different propagation phases since the energies $E_i = \sqrt{p^2 + m_i^2}$ are different:

$$\phi_i = E_i t - \vec{p}\cdot\vec{x} \approx pt - \vec{p}\vec{x} + \frac{m_i^2 t}{2p}, \quad i = 1, 2$$

After a time such that $\phi_1 - \phi_2 \sim 1$, $|\nu_e, t\rangle$ is not anymore a $|\nu_e\rangle$: it has a reduced overlap with $|\nu_e\rangle$, and it acquires a finite overlap with the other states such as $|\nu_\mu\rangle$.

(all this if $\theta \neq 0$, $\theta \neq \pi$ and $m_1 \neq m_2$)

### 1.1.1 Simple and useful: 2F vacuum oscillations

$$P_{\nu_\ell\to\nu_\ell} = 1 - \sin^2 2\theta \cdot \sin^2(\Delta m^2 L/4E)$$

*Notes:* *1)* $\sin^2 \longrightarrow 1/2$ *when averaged,*
*2) the symmetry* $\theta \longrightarrow 90^\circ - \theta$*,*
*3) the maximum effect is for* $\theta = 45^\circ$

Enough to explain the observations of:

1. SK ($\nu_{atm}$), K2K & MINOS ($\nu_\mu$ accel.) $\theta_{23} \sim 45^\circ$
2. CHOOZ ($\bar{\nu}_e$ react.) $\theta_{13} < 8^\circ$
3. KamLAND ($\bar{\nu}_e$ react.) $\theta_{12} \sim 34^\circ$
4. Gallex/GNO-SAGE (solar $\nu_e$, low $E_\nu$) (same angle)
5. LSND, Karmen ($\bar{\nu}_e$ from $\pi^+$ at rest) [if confirmed!] $\theta_{14} \sim 1^\circ$

## 1.2 $\nu_\odot$'s feel the matter effect at high energy

Charged current interactions provide an additional term to the phase of propagation of $|\nu_e\rangle$ in matter: $\frac{d}{dt}|\nu_e\rangle = i\sqrt{2}\, G_F\ \rho_e(x)|\nu_e\rangle$ :

$$\nu_e = \begin{cases} \cos\theta\ \nu_1 + \sin\theta\ \nu_2 \to \cos\theta\ \nu_1 + \sin\theta\ \nu_2\ e^{i\infty}, & E < 1 \text{ MeV} \\ \nu_2(\rho) \to \nu_2(0) \equiv \nu_2, & E > 5 \text{ MeV} \end{cases}$$

taking the overlap with $\nu_e$,

$$P_{ee} = \begin{cases} \cos^4\theta + \sin^4\theta \sim 0.6, & \text{Gallex/GNO \& SAGE} \\ \sin^2\theta \sim 0.3, & \text{SNO, SK} \end{cases}$$

*In short:*

*oscillations in matter have a peculiar character & are a bit more complicated*

### 1.2.1 Picture of $P_{ee}$ for solar $\nu$ energies – and beyond

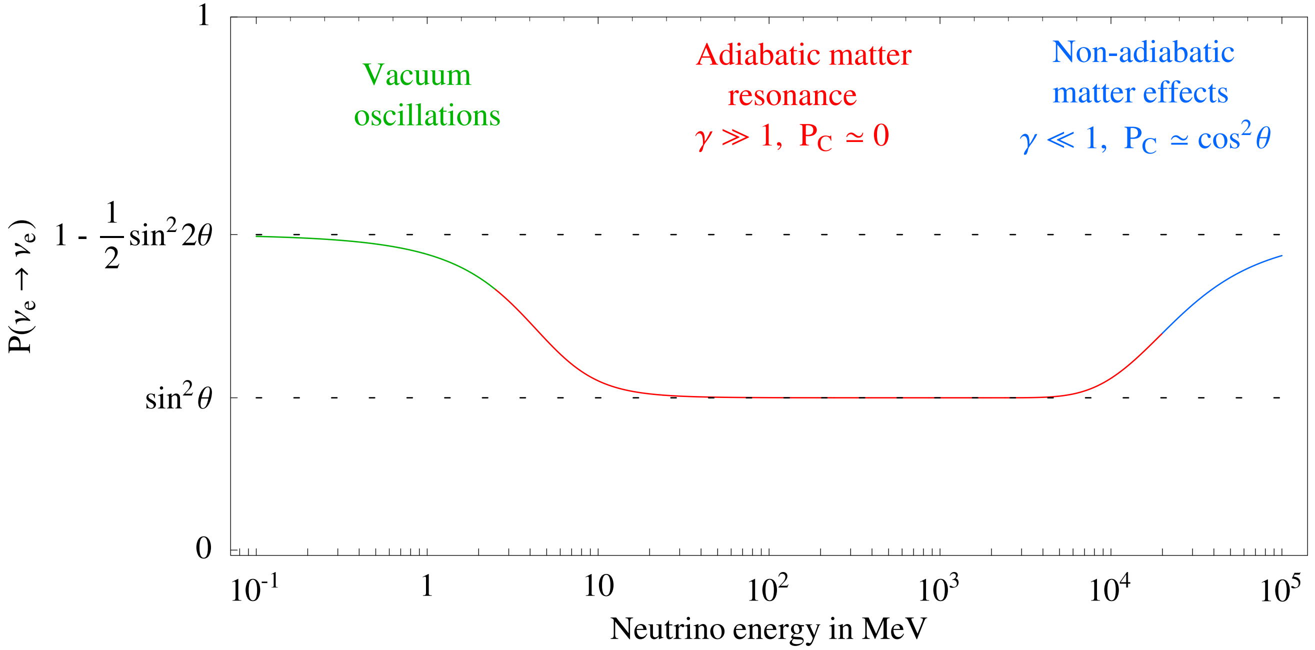


Figure 1: *Solar $\nu_e$ of relatively high energy undergo MSW (matter enhanced) conversion: the symmetry $\theta \to 90^\circ - \theta$ is broken and $\theta = \theta_{12}$ can be determined by observations, e.g., at SNO (SK).*

## 1.3 Status of the three flavor picture

When we assume oscillations, the main experimental observations determine 2 mass differences squared and 2 mixing angles:

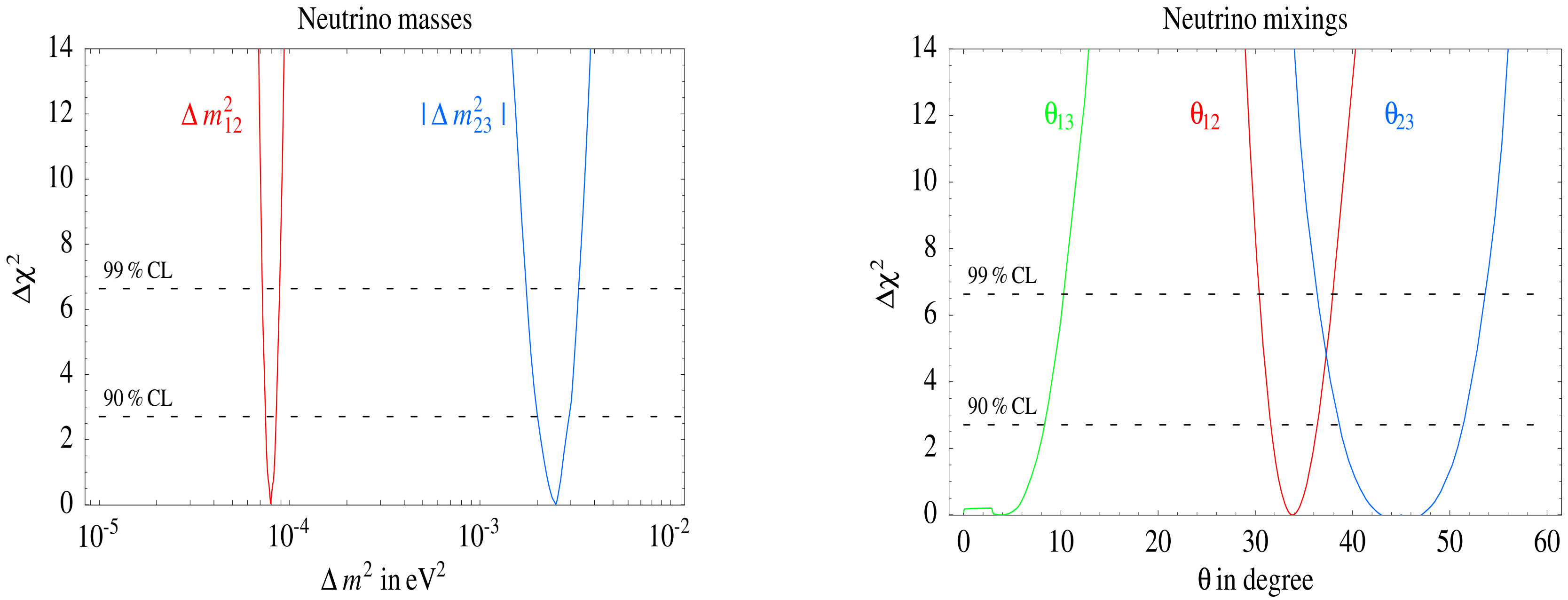
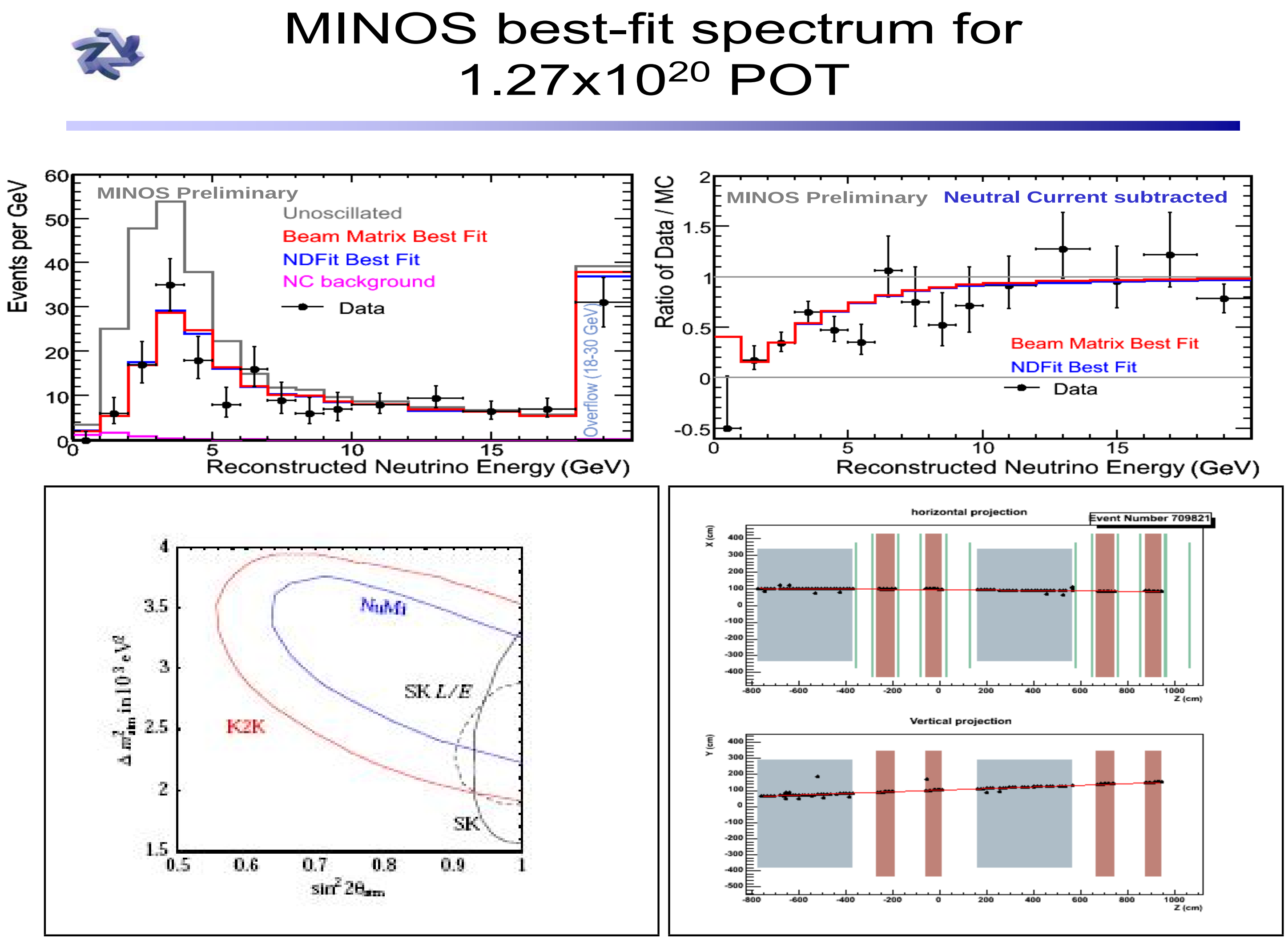


Figure 2: *Summary of what we know on the parameters of oscillations, the CP phase being simply unknown;* $\Delta m^2_{23}$ *is improving.*



MINOS best-fit spectrum for $1.27\text{x}10^{20}$ POT

Figure 3: $1^{st}$ *MINOS results; impact on oscillations;* $1^{st}$ *event in OPERA.*

### 1.3.1 Next steps with $\nu$ experiments

**Solar $\nu$** (Borexino, KamLAND, SNO)
Measure beryllium and low energy neutrinos; improve on $\theta_{12}$; geo-$\nu$; unexpected such as long wavelength oscillations, CPT viol. ...

**Atmospheric $\nu$** (Mton WČ, IceCUBE, or 'fine grained')
$L/E$ and $\theta_{23}$; $\theta_{13}$ requires $\mathcal{O}$(Mton) mass. The detectors should be multipurpose: again for solar $\nu$, nucleon decay, supernova $\nu$ ...

**Artificial beams** (NuMi, CNGS; T2K, NO$\nu$A; 2CHOOZ)
Confirming oscillations; find $\theta_{13}$! (see next figure)

### 1.3.2 The missing mixing

In order to proceed with oscillations (=with mass hierarchy and with CP phase) the first step is to know the size of the mixing $\theta_{13}$.

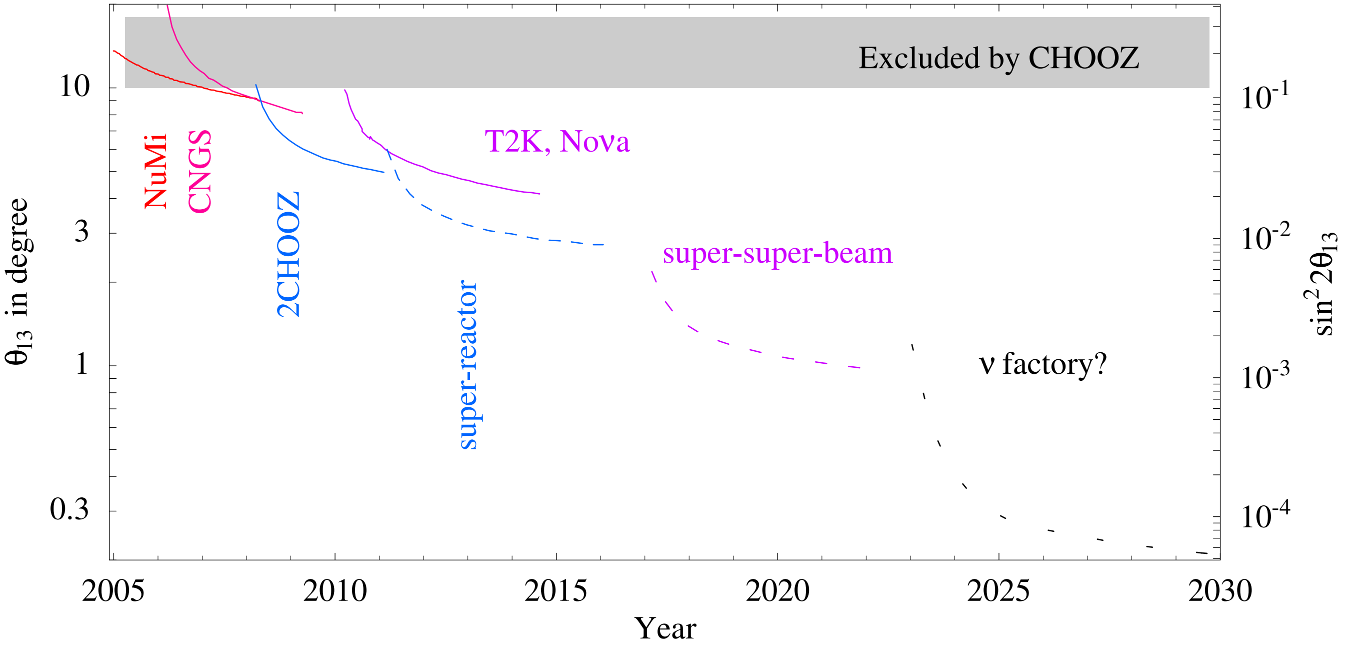


Figure 4: *Expected sensitivity of planned and future experiments.*

## 1.4 Other observables

Besides oscillations, there are other probes of $\nu$ masses.

1. $m_\beta^2 = \sum_i |U_{ei}^2| \times m_i^2$ β-decay
2. $m_{\rm cosm} = \sum_i m_i$ cosmology
3. $M_{ee} = |\sum_i U_{ei}^2 \times m_i|$ $0\nu 2\beta$-decay

Last one assuming Majorana mass $\mathcal{L} \sim \nu_L^t M \nu_L$ with $M = U^* m U^\dagger$

- *More observables possible, but none reaches a useful sensitivity.*
- *Correct in 3F picture: e.g., "large" $\nu$ mass means kinks in $\beta$ spectrum.*
- *If Dirac mass: $7 = 9 - 2$ param.s & $0\nu 2\beta$ absent, the rest unchanged.*

### 1.4.1 E.g., $0\nu2\beta$ - neutrinoless double beta decay

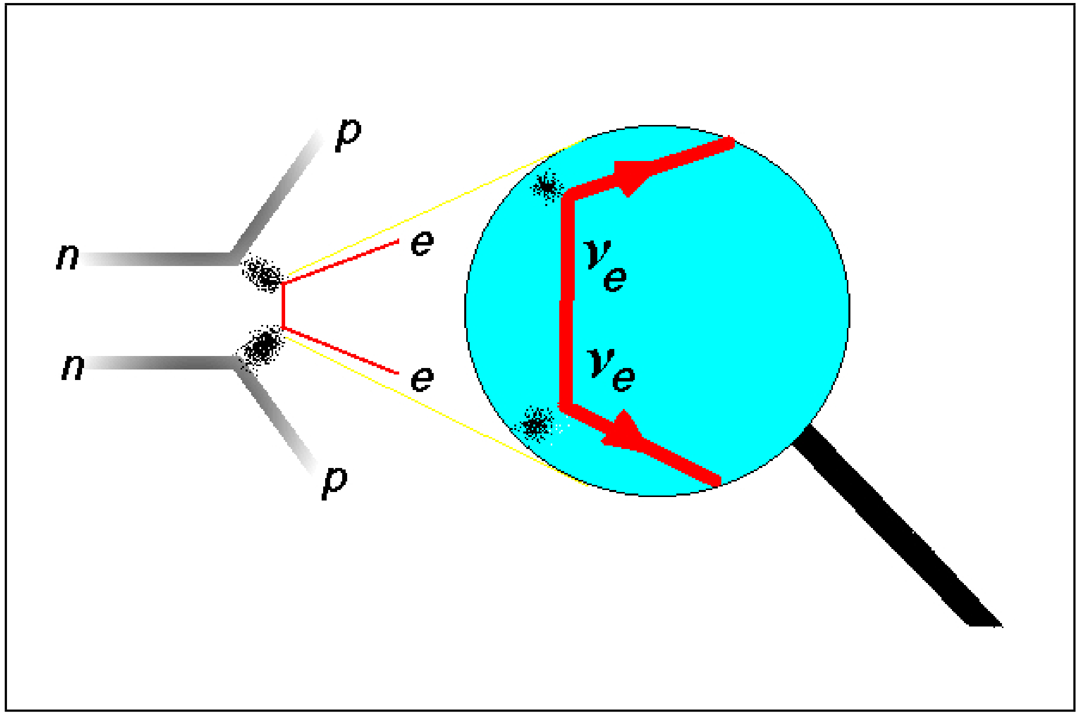


Figure 5: $(A,Z)\to(A,Z+2)+2e^-$ *arises with* $\Delta L_e=2$, *e.g., Majorana neutrino masses, with structure* $\nu_L^t M\nu_L$. *If the* $\beta$*-decay is forbidden,* $0\nu2\beta$ *could be searched seen as a peak in the endpoint of* $2\nu2\beta$.

### 1.4.2 Already seen?

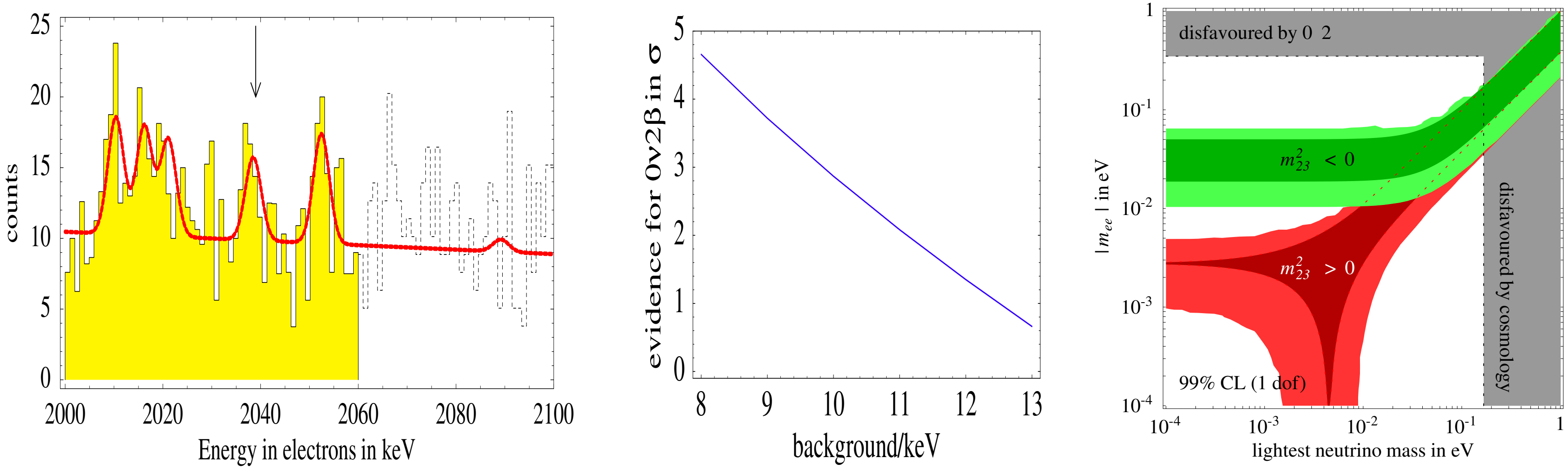


Figure 6: *a) Final Heidelberg-Moscow spectrum (yellow) and possible peaks (red) resulting from a fit. b) Confidence level of the* $0\nu2\beta$ *peak as a function of the background level. c) Expectations for* $0\nu2\beta$ *on the basis of oscillations; the lightest* $\nu$ *mass is a free parameter.*

# 2 Theoretical particle physics aspects

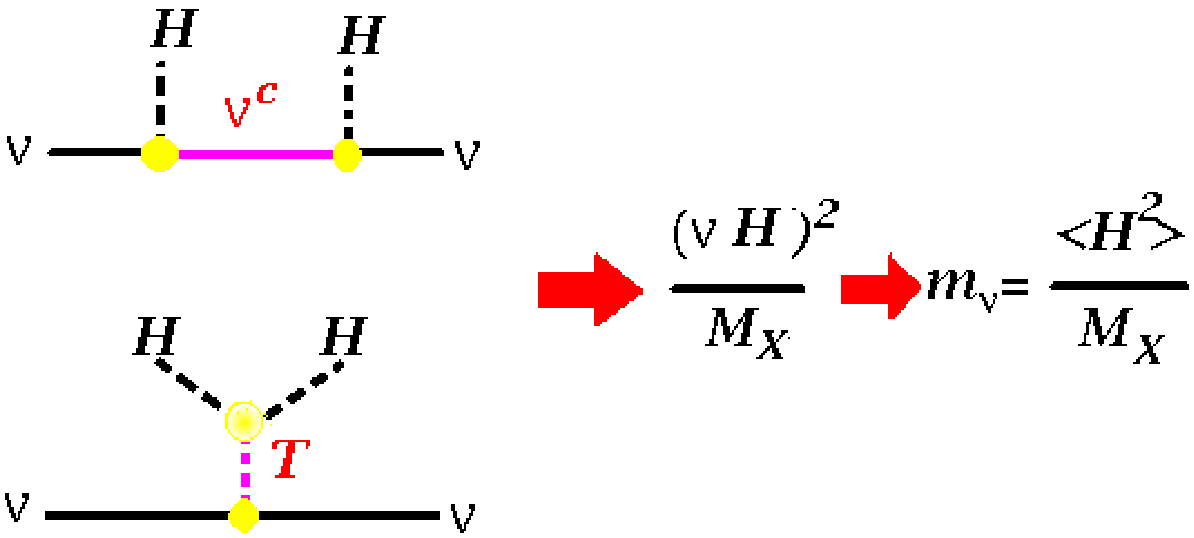
Some people think that a Dirac neutrino mass $\bar{\nu}_L \nu_R$ is more economical (or attractive) than Majorana's.

> *However, this requires adding a $\nu_R$, a particle without SM gauge interactions; thus, a Majorana mass $\nu_R^t M \nu_R$ is always possible. The new mass scale $M$ has nothing to do with $M_W$.*
>
> *Also: adding $\nu_R$ makes the spectrum fully left-right symmetric, that suggests strongly that SU(2)$_R$ has a dynamical meaning.*

This is why I like better (and hereon consider) only Majorana masses.

## 2.1 Seesaw as an answer and as a question

Light $\nu$ masses could witness the existence of new physics scale:



Is this situation ☺ , or it is ☹ ? Probably, it is simply 😐 .

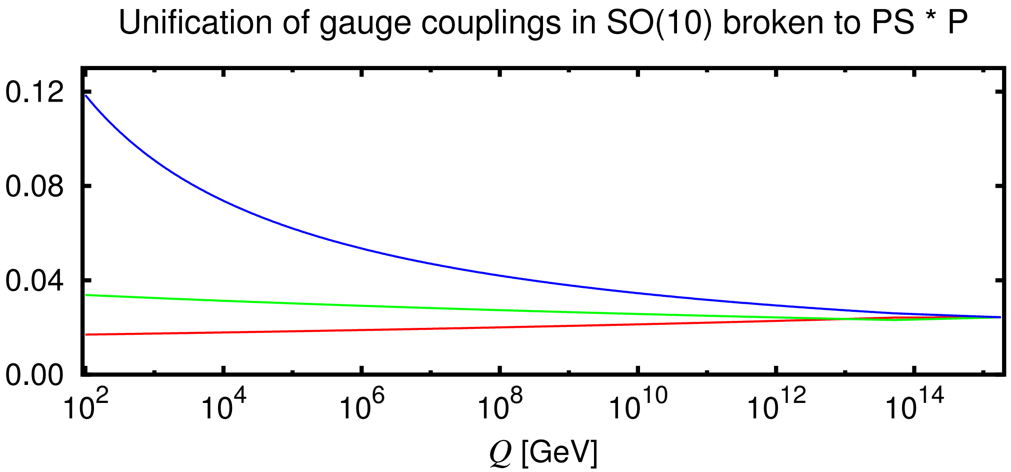
*More discussion follows.*

## 2.2 The power of GUT

*The spinor of 16 of SO(10) contains all fermions of SM, including* $\nu_R$

Consider a non-supers. SO(10) model where gauge unif. happens via

$$\text{SO(10)} \xrightarrow{54_H} \text{Pati-Salam}\times\text{Parity} \xrightarrow{126_H} \text{SM}$$



$\nu$ *masses get tied to gauge scales,* $M_{interm.} \approx 5\times 10^{13}$ *GeV.*

(This model has a rapid $p\to\pi^0 e^+$. Perhaps excluded, but for the definitive sentence we need studying fermion masses and heavy spectrum)

## 2.3 Why leptonic mixings $\gg$ quark mixings?

*Is this question meaningful? Surely, we have not the right to ask why the electron is so much lighter than the top in the SM.*

It is funny and perhaps instructive that in SO(10) models, for certain choices of the Higgs fields we have the opposite problem:

$$|V_{cb}| = \frac{m_s}{m_b} \times \cos 2\theta_{atm} \ \Rightarrow \ \frac{1}{20} < \frac{1}{100}$$

*My opinion is simply that some interesting questions like this have to be discussed within motivated and well-specified extensions of the SM.*

## 2.4 Do we descend from $\nu$'s?

The SM is *quantitatively* unable to produce the baryon asymmetry in the course of the big-bang (the program of Sakharov). But since we should modify SM anyways, what about the model with massive $\nu$?

*The decay of $N = \nu_R + \nu_R^c$ can produce a lepton asymmetry, that SM non-perturbative effect translate into a baryon asymmetry (Fukugita & Yanagida); this is very promising, despite model dependence.*

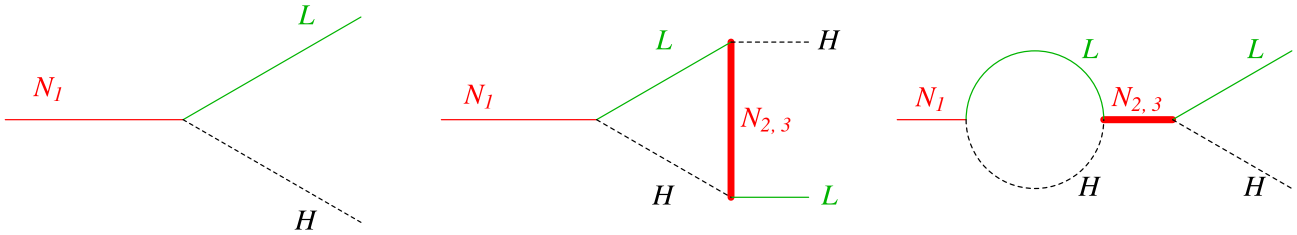


Figure 7: *The interference term leads to CP violation.*

# 3 Implications for neutrino astronomy

*There is a wide interest in the detection of neutrinos from cosmic sources. This is largely an open field.*

Oscillations and other particle physics effects (on $\nu$ and/or on the sources) can affect the observables in many ways.

Yet there are large uncertainties on the expectations, so that the primary aim seems to be $\nu$ astronomy & astrophysics.

*That's why the title and why the last part of this talk.*

## 3.1 Core collapse SN

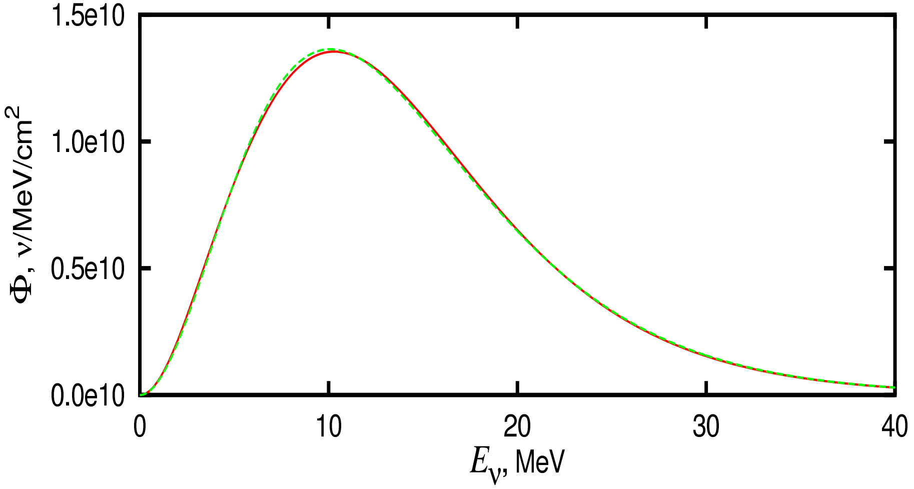
*Super-K, LVD, KamLAND, SNO, Baksan, ...* [10 MeV range]

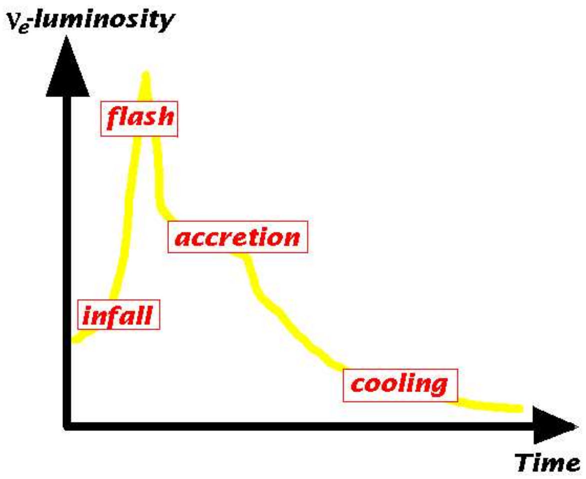
Most of the gravitational energy from neutron star (black hole) formation $\sim 10$ % $M_\odot \times c^2$ goes in $\nu$ radiation, emitted in $\sim 10 - 100$ s.

SN1987A GAVE US THE ONLY $\nu$ SIGNAL WE HAVE.

### 3.1.1 (Anti)neutrino flux (fluence)

The fluences are thought to be well approximated by quasi-thermal distributions, with two key parameters: the average energy $\langle E_{\bar{\nu}_e} \rangle$ and the total energy $\mathcal{E}_{\bar{\nu}_e}$ irradiated in $\bar{\nu}_e$.





Most of the energy is emitted in a quiet thermal phase called 'cooling'.

The phase that is thought to be responsible of the explosion is the one named 'accretion'; it involves only $10 - 20$ % of the emitted energy.

### 3.1.2 Expected signal in neutrino detectors

*In water Čerenkov detectors or scintillators the signal (visible energy) is due to electrons, positrons, and occasionally photons:*

The main reaction is 'inverse beta decay' (IBD) weakly directional:

$$\bar{\nu}_e p \to e^+ n, \quad e^+ e^- \to \text{some } \gamma$$

$$\text{followed by } np \to D\ \gamma(2.2 \text{ MeV})$$

Elastic scatterings (CC and NC) give a directional event:

$$\nu\ e \to \nu\ e,\ \text{where } \nu = \nu_e, \bar{\nu}_e, \nu_x$$

we can neglect other reactions in view of the expected flux and of the small samples of events from SN1987A

### 3.1.3 The events

*The neutrino and gravitational wave detectors searched for a signal in the few hours preceeding the astronomical observation.*

LSD neutrino detector (90 t of scintillator, 200 t of iron) saw 5 events, possibly correlated with Geograv detector. 4.5 hours later:

| | |
|---|---|
| • Kamiokande-II ($H_2O$, 2140 tons) saw | 11 or 12 events |
| • IMB ($H_2O$, 6800 tons) saw | 8 events |
| • Baksan ($C_9H_{20}$, 200 tons) saw | 5 events |
| | 25 events |

*The discrepancy in time could indicate a 2 stage collapse. We focus on the second group of events in the following.*

### 3.1.4 At first sight, almost everything is OK

For reasonable models, it is a fact that most events are $\bar{\nu}_e p \to e^+ n$. The IBD hypothesis is that all observed events are due to this reactions.

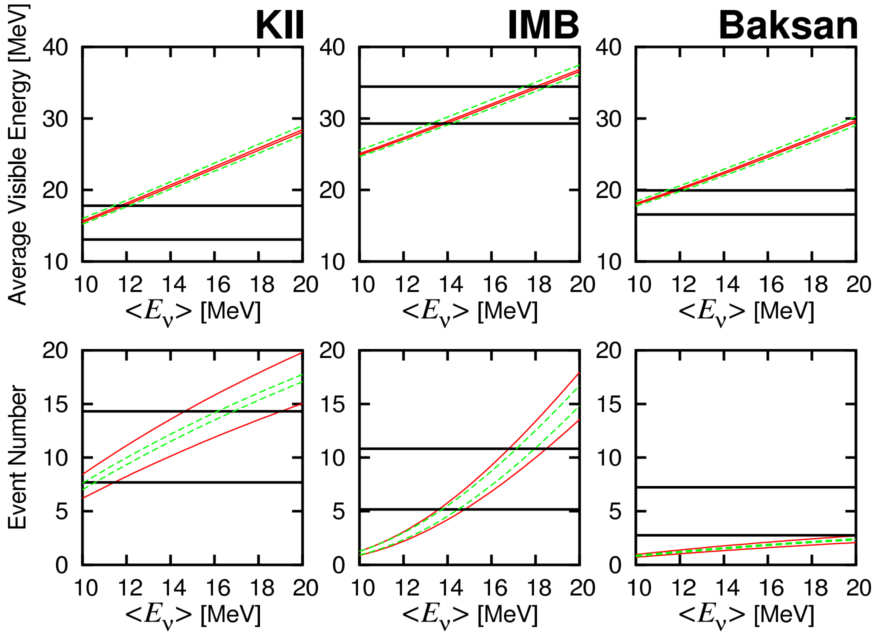


Figure 8: *Horizontal lines, experimental values; inclined lines, theoretical values, varying the average $\bar{\nu}_e$ energy. The errorbands in expectations are due to the uncertainties of the $\bar{\nu}_x$ contribution (implied by oscillations).*

### 3.1.5 A closer look to 12 KII events...reveals troubles?

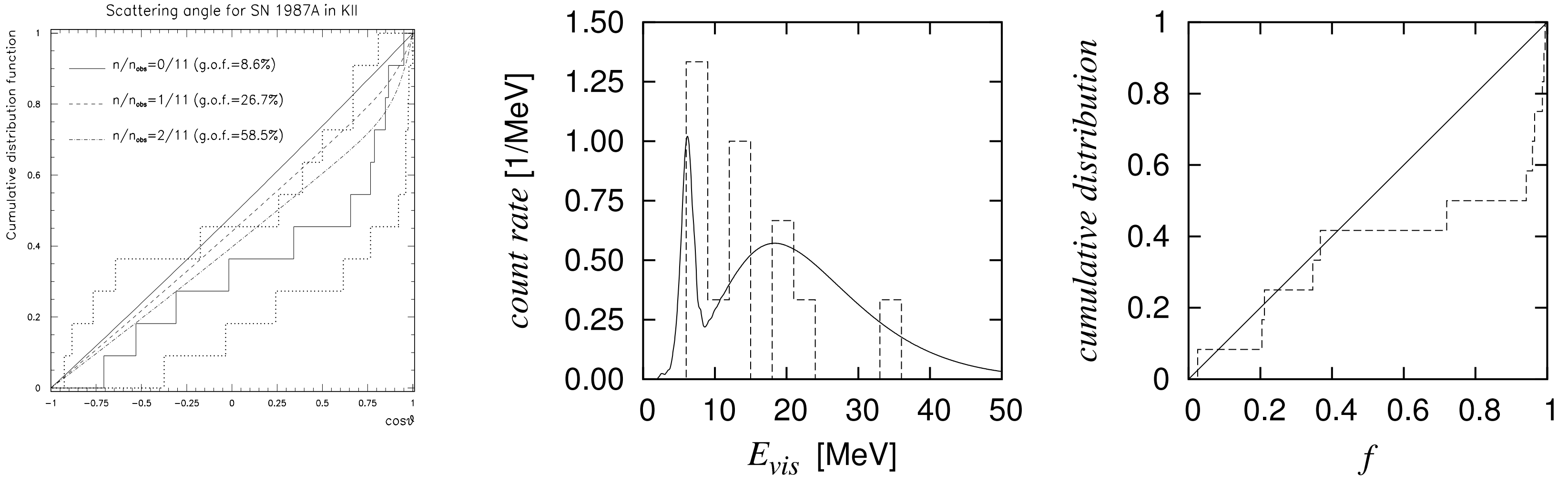
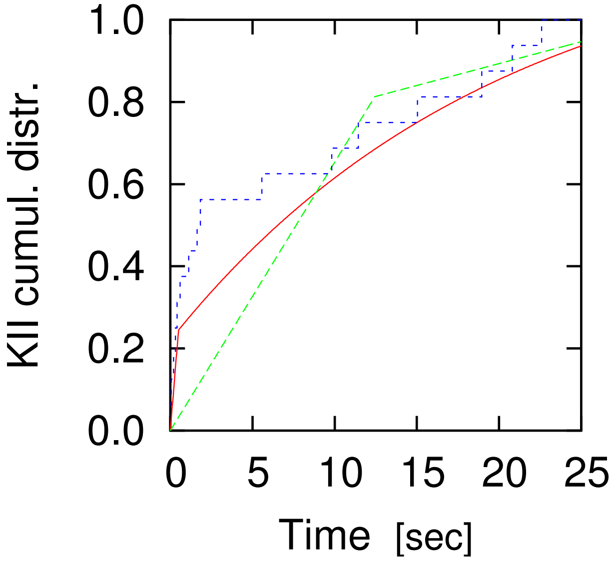


Figure 9: *Distributions on the angle with SN1987A (cumulative), on the energy (differential); on the volume (cumulative). The $1^{st}$ plot shows the possible presence of a elastic scattering event(s); the last two suggest background events of low energy* and *on the periphery of the detector.*

### 3.1.6 But time distr. suggests we are on the right track!

Figure 10: *Cumulative distribution for KII events on time window of 30 sec that includes 4 more events (most probably background)*



The hypothesis of constant luminosity has a GOF of 2 %, whereas accretion+thermal phases the GOF is larger than 50 %.

Thus: the more reasonable theoretical model fares much better.

### 3.1.7 What about fitting model parameters?

- ⋆ Best fit of data for simple exponential cooling model:

$$T_0 = 4.6 \text{ MeV} , \tau = 15 \text{ sec} , R = 26 \text{ km}$$

the released energy is $3.8 \times 10^{53}$ erg.

- ⋆ Best fit for a model with an accretion phase:

$$T_0' = 2.0 \text{ MeV} , \tau' = 0.7 \text{ sec}$$
$$T_0 = 5.7 \text{ MeV} , \tau = 17 \text{ sec} , R = 11 \text{ km}$$

the released energy is $2.4 \times 10^{53}$ erg, about 20 % in accretion phase.

*However, the likelihood of the second model is 1000 times higher.*

What about the role of oscillations?

*They can exchange the various neutrinos:*

$$F_{\bar{\nu}_e} = \bar{P}_{ee} F^0_{\bar{\nu}_e} + (1 - \bar{P}_{ee}) F^0_{\bar{\nu}_\mu}$$

*For normal mass hierarchy,* $P_{ee} = \cos\theta_{12} \approx 0.7$.

So, the impact of oscillation is model dependent:

- According to Keil03, $T_\mu \sim T_e$: oscillations have a minor effect.
- According to Bruenn87, $T_\mu \sim 2T_e$: oscillations are important.

Which one fits better the data (if any)? I am sorry, I can only say that:

*Our calculations are in progress!*

# 3.2 Supernova remnants

*IceCUBE, KM3NeT* [10 TeV range]

Strongly suspected to be the accelerators of CR in our Galaxy

New VHE $\gamma$-rays observations (H.E.S.S., Magic) suggest $pp \to \pi^0\ X$.

*$\nu$s also produced $pp \to \pi^\pm\ X$, in principle can give a proof*

A POSSIBLE PROBLEM: THE LOW COUNTING RATES.

### 3.2.1 The cosmic ray/SNR connection

*Supernovae are suspected to be the cosmic ray (CR) accelerators since '34 (Baade & Zwicky).*

30 year later, Ginzburg & Syrovatsky remarked that if 10 % or so of the SNR kinetic energy $\mathcal{E}_{SN} \approx 10^{51}$ erg (=1 foe) goes in CR, the CR losses of the Milky Way are compensated:

$$\frac{V_{CR}\,\rho_{CR}}{\tau_{CR}} \approx 0.1 \times \frac{\mathcal{E}_{SN}}{\tau_{SN}}$$

where $V_{CR} = \pi R^2 H$ ($R = 15$ kpc, $H = 5$ kpc) and $\tau_{SN} = 30$ yr.

*Based on Fermi ideas, a mechanism called 'diffusive shock wave acceleration' is being developed to understand CR acceleration in SNR.*

The acceleration happens in the expanding SNR shock wave of size $R = u\ t$ ($u \sim$ 5,000 km/s), and it is mostly active in the first 1,000 years, as determined by $M_{ejecta} \sim {}^{4\pi}/_{3}\ R^3\ n_{ISM}$.

There are many open and possibly connected questions, e.g., Hillas '05:

- ○ How to "inject" $e^-$? *["diffusive shock acceleration" is incomplete?]*
- ○ Why isotropy? How $\Gamma = 2.1 \to 2.7$? *[imply propagation / reacceleration?]*
- ○ $E_{\max}$? *[limited by $R \sim D_{Bohm}/u$ but countered by Bell & Lucek]*
- We expected many point sources of hadronic VHE $\gamma$. Is this a real problem or expectations were too optimistic?
- How to firmly exclude a leptonic origin? Seeing $\nu$?

### 3.2.2 Interesting shell-type SNR

| Name | TeV $\gamma$ obs. | decl. $\delta$ | distance | size | age |
|---|---|---|---|---|---|
| Vela Jr | $< 20$ TeV (HESS) | $-46^\circ 22'$ | 0.2 kpc | $2^\circ$ | 680 yr |
| RX J1713-3946 | $< 40$ TeV (HESS) | $-39^\circ 46'$ | 1 kpc | $1^\circ$ | 1,600 yr |
| SN 1006 | no (HESS close?) | $-41^\circ 53'$ | 2 kpc | $36'$ | 1,000 yr |
| Cas A | HEGRA (maybe) | $58^\circ 08'$ | 3 kpc | $6'$ | 320 yr |

Some useful link:

. *Catalogue of SNR*, `www.mrao.cam.ac.uk/surveys/snrs/` [D. Green]

. *H.E.S.S. Source Catalogue*, `www.mpi-hd.mpg.de/hfm/HESS/` [W. Hofmann]

. Review on *Shell-type SNR*, `arXiv.org/astro-ph/0603502` [H.J. Völk]

### 3.2.3 The best known spectrum: RX J1713.7-3946

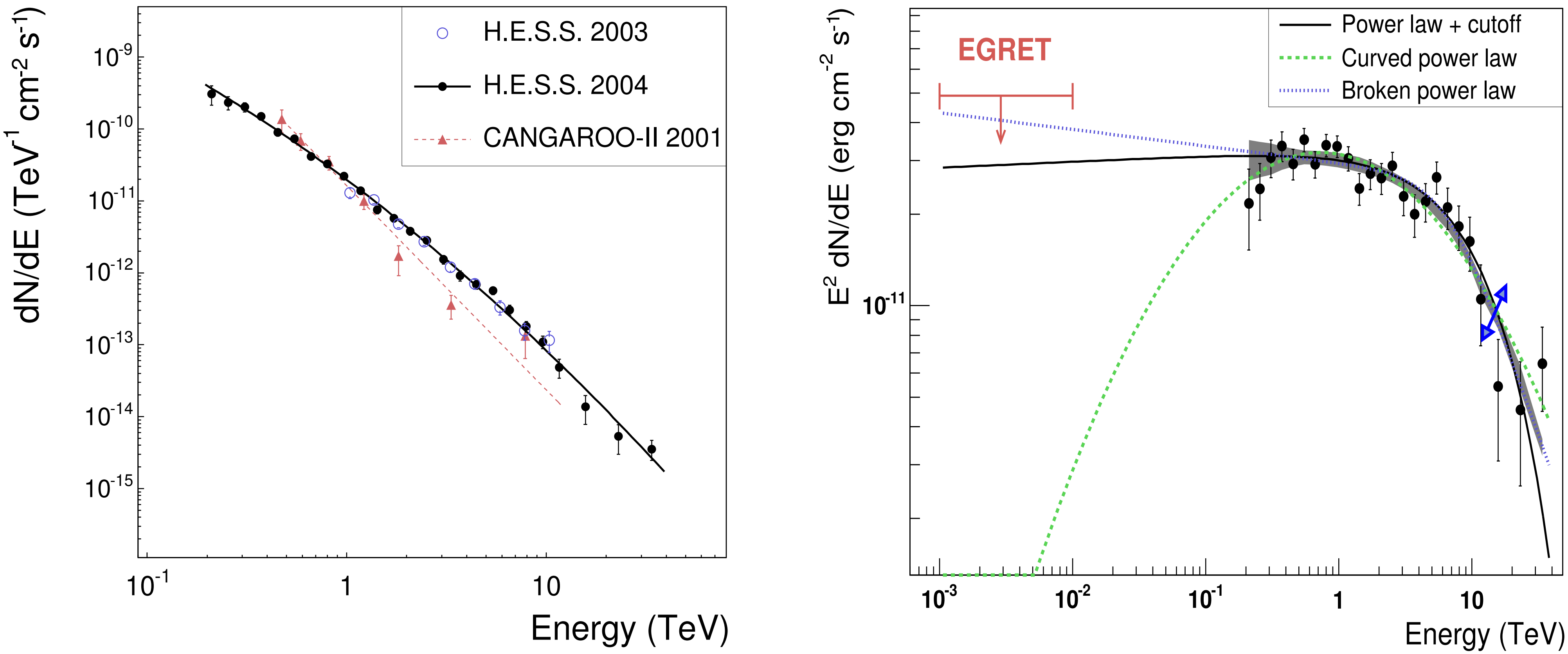


Figure 11: *Determination of VHE $\gamma$ spectrum by the H.E.S.S. IACT array*

## Summary, remarks, end of introduction to SNR

*The hypothesis that shell-type young SNR accelerate CR (perhaps till the knee) seems to be still valid and is actively debated. For 2 SNR observed in VHE $\gamma$, the "hadronic" hypothesis looks plausible.*

> Specific models for CR acceleration in RX J1713.7-3946: 1) Malkov, Diamond, Sagdeev '05 suggest that the nearby molecular cloud has a main role for CR interactions; 2) Berezhko & Völk '06 fit H.E.S.S. observations starting from the opposite view.

*Future observations of H.E.S.S. (and of VERITAS and MAGIC) will provide more data permitting more crucial tests.*

# TeV neutrinos from SNR

*Motivated by the (shell-type, young) SNR / CR connection and by the existing plans for large neutrino telescopes, we calculated the flux of TeV neutrinos from the SNR with known VHE $\gamma$-ray spectrum.*

> Indeed, during CR acceleration the SNR are transparent to their $\gamma$ radiation. Thus, we can convert the measured $\gamma$ ray flux (from $\pi^0$) into an expectation for the neutrino flux (from $\pi^\pm$ and $K^\pm$) under the hypothesis that the radiation is of hadronic origin.

*We begin by discussing flavor oscillations, then describe the $\gamma/\nu$ connection and finally estimate the rate of events in neutrino telescopes.*

### 3.2.4 Oscillations

The flux of neutrinos from meson decays are modified:

$$F_{\nu_\mu} = F^0_{\nu_\mu} P_{\mu\mu} + F^0_{\nu_e} P_{e\mu}$$

where the oscillation probabilities takes the simplest form,
Gribov-Pontecorvo's (namely, the one of low energy solar neutrinos):

$$P_{\ell\ell'} = \sum_{i=1}^{3} |U^2_{\ell i}|\ |U^2_{\ell' i}| \quad \text{with } \ell, \ell' = e, \mu, \tau$$

There is no MSW effect, for matter term is negligible close to the SNR and too large in the Earth

*With central values of the mixing elements $U_{\ell i}$ we get $P_{\mu\mu} \sim 0.4$ and $P_{e\mu} \sim 0.2$; that is, $^1/_2$ of the original $\nu_\mu$ and $\bar{\nu}_\mu$ fluxes reach the detector.*

## Sophistications

We performed a more detailed analysis

$$\mathcal{L}(P_{\mu\mu}) \propto \min{}_{\theta} \left[ e^{-\frac{(P_{\mu\mu}-P_{\mu\mu}(\theta))^2}{2\sigma^2}} \times \mathcal{L}(\theta) \right] \text{ with } \sigma \to 0$$

where $\theta$=measured parameters (from Strumia & V '05). We get $P_{\mu\mu} = 0.39 \pm 0.05$ and $P_{e\mu} = 0.22 \mp 0.05$ as before; most of the error (0.04) is due to $\theta_{23}$.

To understand the uncertainty budget use an expansion in the small parameters (Costantini & V '04):

$$P_{\mu\mu} \simeq {}^1\!/_2 - {}^x\!/_2 - y \text{ and } P_{e\mu} \simeq {}^x\!/_2 + y,$$

$$\text{where } \begin{array}{l} x = \sin^2 2\theta_{12}, \\ y = \cos 2\theta_{23}\ {}^x\!/_4 + \theta_{13}\ \cos\delta_{\rm CP}\ {}^{\sqrt{x(1-x)}}\!/_2. \end{array}$$

### 3.2.5 The connection between $\gamma$ and $\nu$

*For RX J1713.7-3946 there are 2 calculations in the literature:*

1. Alvarez-Muñiz & Halzen '02 use $F_\gamma \propto E^{-2}$ suggested by CANGAROO results and obtain $F_{\nu_\mu} = F^0_{\nu_\mu} \propto F_\gamma$ by

$$\int_{E_p^{\min}/12}^{E_p^{\max}/12} dE_\nu \; E_\nu F_\nu(E_\nu) = \int_{E_p^{\min}/6}^{E_p^{\max}/6} dE_\gamma \; E_\gamma F_\gamma(E_\gamma)$$

2. Costantini & V '04 use $F_\gamma \propto E^{-2.2}$ as extrapolated from early H.E.S.S. results and adopt standard techniques (e.g., Gaisser '90)

$$F_\gamma = \frac{\Delta X}{\lambda_p} \frac{2 Z_{p\pi^0}}{\Gamma} F_p \text{ and similarly for } F_\nu$$

*Both methods are tailored for power law spectra.*

# New evaluation, elaborating on Lipari '88

From $F_\gamma(E) = \int_E^\infty dE' \; 2 \; F_{\pi^0}(E')/E'$ valid for VHE $\gamma$-rays we find:

$$F_{\pi^0}(E) = -\frac{E}{2} \frac{dF_\gamma}{dE} \tag{1}$$

Due to the approximate isospin-invariant distribution of pions, $F_\pi \equiv F_{\pi^0} \approx F_{\pi^+} \approx F_{\pi^-}$, we find for the neutrino from $\pi^+ \to \mu^+ \nu_\mu$:

$$F_{\nu_\mu}(E) = \int_{E/(1-r)}^\infty \frac{dE'}{1-r} \frac{F_\pi(E')}{E'} = \frac{F_\gamma(E/(1-r))}{2(1-r)} \tag{2}$$

where $r = (m_\mu/m_\pi)^2$. The neutrinos $\nu = \bar{\nu}_\mu, \nu_e$ from $\mu^+$ decay are:

$$F_\nu(E_\nu) = \int_0^1 \frac{dy}{y} \; F_\mu(E_\mu) \; [g_0(y) - \bar{P}_\mu(E_\mu) \; g_1(y)] \text{ where } E_\mu = \frac{E_\nu}{y} \tag{3}$$

$g_i$ are polynomials, $F_\mu$ and $\overline{P}_\mu$ (=polarization averaged over $\pi$ distribution) also known. $K \to \mu\nu$ described in the same manner but weighted by $0.635 \times 0.12$.

### 3.2.6 Neutrinos from RX J1713.7-3946

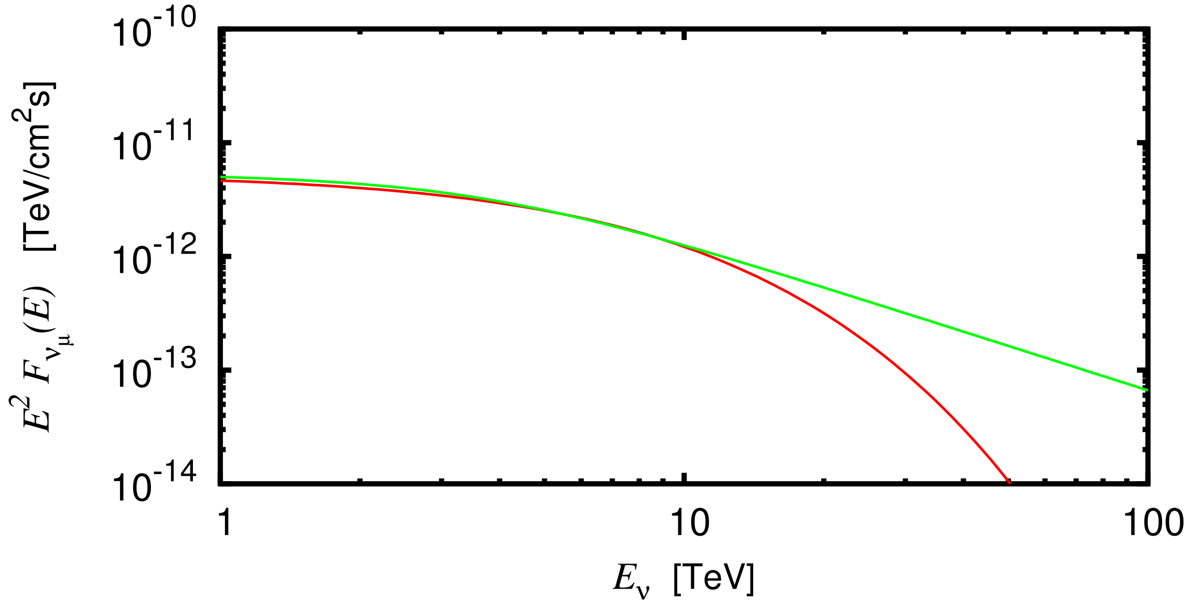


Figure 12: $\nu_\mu$ *spectra, corresponding to 2 (out of 3) fits of the H.E.S.S. VHE* $\gamma$*-rays: a broken power law and a power law with exponential cutoff (the curved power law was discarded, since it increases before 40 GeV).*

### 3.2.7 Events in neutrino telescopes

Now we can calculate $N_\mu + N_{\bar\mu}$ using e.g.:

$$N_\mu = A \cdot T \cdot f_{liv} \cdot \int_{E_{th}}^{\infty} dE_\nu \; F_{\nu_\mu}(E_\nu) Y_\mu(E_\nu, E_{th})(1 - \overline{a}_{\nu_\mu}(E_\nu))$$

where $E_\nu$ is the neutrino energy before the interaction point and:

- *A=1 km$^2$ and T=1 solar year.*
- *Source is below ANTARES horizon (=visible) for $f_{liv} = 78$ %.*
- *The threshold for muon detection is $E_{th} = 50$ GeV.*
- *The muon range (in the yield $Y_\mu$) is calculated for water.*
- *The neutrino absorption coefficient $a_{\nu_\mu}$, averaged over the daily location of the source, is calculated for standard rock.*

## cont.d (number of events from RX J1713.7-3946)

We find that the number of events does not depend crucially on the extrapolation:

$$N_\mu + N_{\bar{\mu}} = \begin{cases} 4.8 \text{ per km}^2 \text{ per year} & \text{[exponential cutoff]} \\ 5.3 \text{ per km}^2 \text{ per year} & \text{[broken power law]} \end{cases}$$

This can be compared with the 9 events in Costantini & V '04 (power law $F_\gamma \propto E^{-2.2}$ extended till 1 PeV) and the 40 events in Alvarez-Muñiz & Halzen '02 ($F_\gamma \propto E^{-2}$, oscillations, livetime and absorption ignored)

> *The effects of detection efficiency are not included (ideal detector); they are likely to be important since the median energy is $E_\nu = 3$ TeV.*

# 4 Conclusions and outlook

Neutrino physics is providing us new data, surprises and lot of excitement. More interesting observations, measurements and even discoveries can be expected for the near future.

Theoretical particle physics of $\nu$ is in a difficult position since several open questions regard ultrahigh energy scales. Yet, I feel that several ideas deserve to be explored/updated (GUT, leptogenesis, etc.). Also, theory can offer connections with other fields & observables.

Finally, I wish to stress that $\nu$s do not belong exclusively to *particle* physics! Interesting $\nu$ things are happening in other sectors of physics and there is a lot of work to be done–also for theorists, in my view.

*Thanks for the attention!*

# 5 Appendices

A few backup slides, in case you want to know more on:

- ⋆ The interpretation of LSND anomaly, today
- ⋆ Other hypothetical neutrino sources
- ⋆ IBD cross section;
- ⋆ Fits of SN1987A data
- ⋆ Extension of IBD hypothesis
- ⋆ The adopted statistical tool
- ⋆ Non-thermal effects in the expected neutrinos fluxes
- ⋆ A speculative possibility of large effects due to oscillations
- ⋆ Historical notes

## 5.1 LSND before MiniBOONE

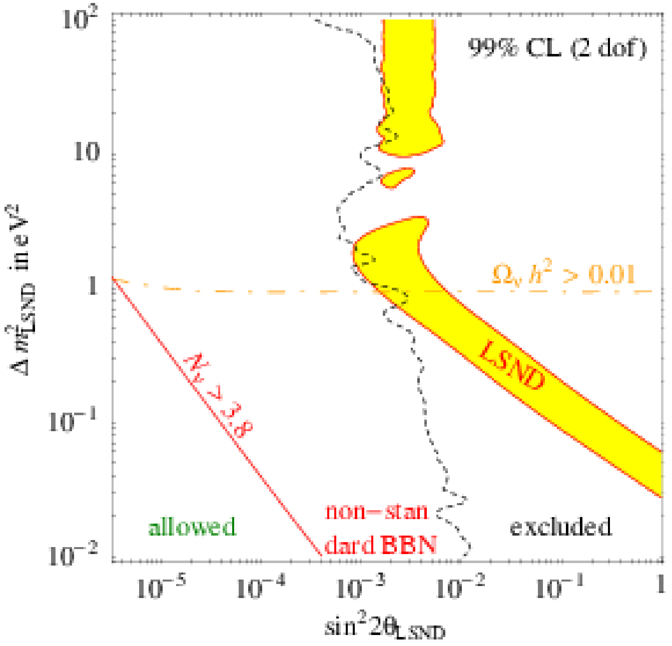


Figure 13: *Interpretation of LSND in the 3+1 scheme. the allowed region is compared with the excluded one (both at 99 %). Also shown: BBN region with* $N_\nu = 3.8$ *and cosmological region with* $\Omega_\nu h^2 = 0.01$.

## 5.2 Frontiers and exotic neutrino sources

*Auger, ANITA* [EeV range]

AGN as plausible sources of UHE CR and thus of $\nu$ *and/or possibly* cosmogenic $\nu$ from collisions with CMB (Berezinsky & Zatsepin 69)

---

*IceCUBE, KM3NeT, Mton WČ* [GeV-TeV range]

Annihilation of dark matter in Earth or Sun

# [ if you can dream we will detect some DM neutrinos... ]

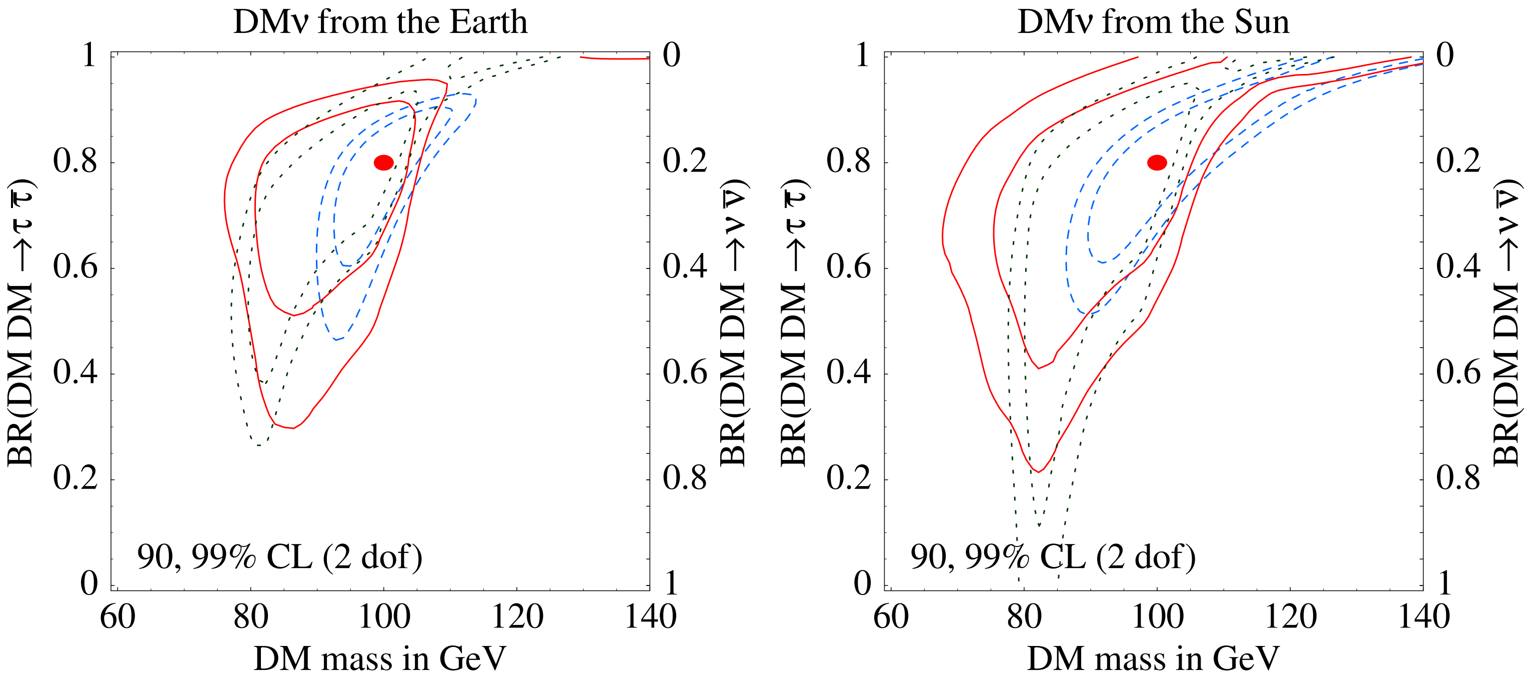


Figure 14: *Reconstruction of the DM properties from hypothetical samples of 1000 thoroughgoing* $\mu$*, 100 contained* $\mu$*, 200 showers.*

## 5.3 IBD cross section

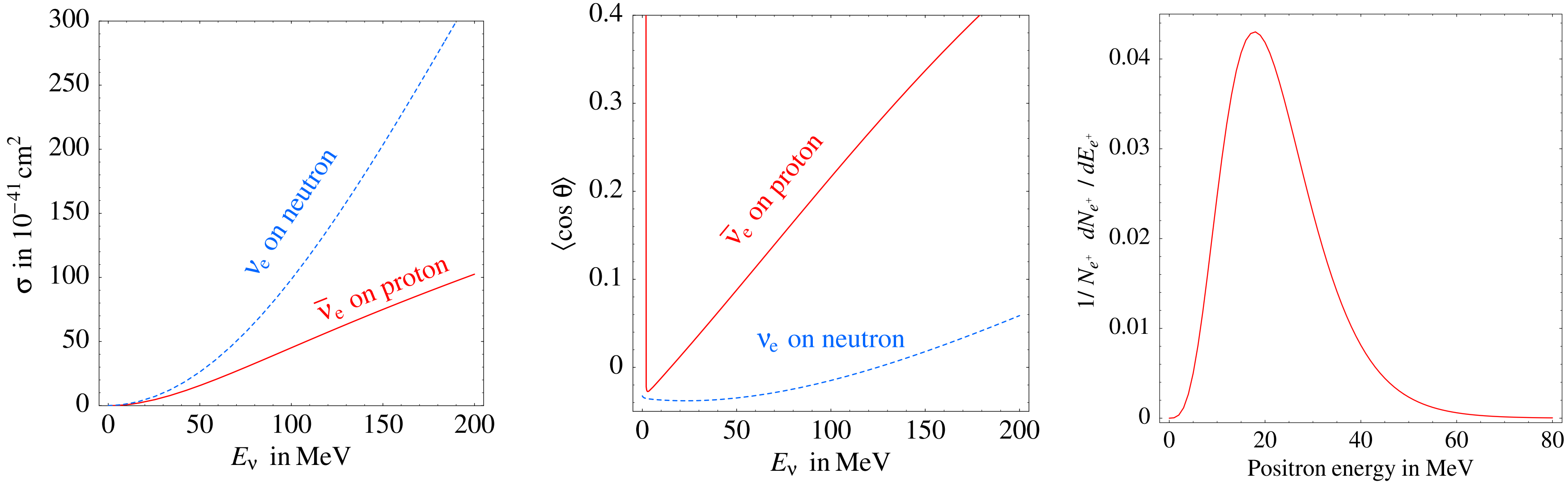


Figure 15: *i) Cross section for the IBD reaction (and analogous reaction on free neutrons); ii) average scattering angle; iii) distribution in visible positron energy from supernova* $\bar{\nu}_e$ *where* $T_{\bar{\nu}_e} = 4.5$ *MeV.*

## 5.4 One fit of SN1987A data

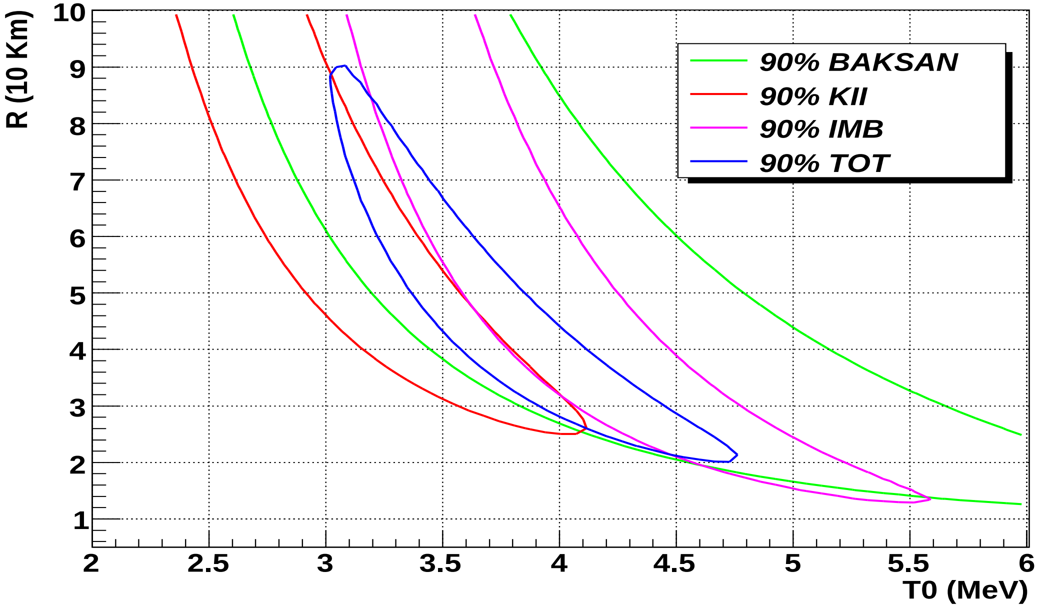
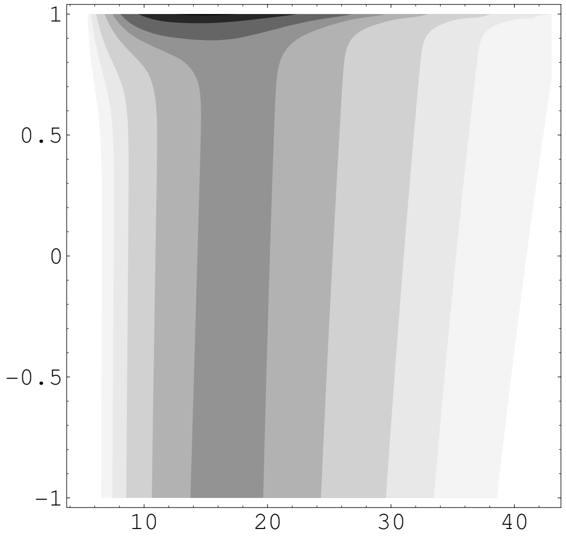


Figure 16: *90 % CL likelihood contours for exponential cooling (3+3 param.s) using time & energy of the 25 observed events; the best fit value of the time constant is 4 s. Note: 1) the vertical scale unit is 10 km; 2) the expected values are in the lower & rightmost corner; 3) due to the different obs. energies, IMB and KII are only marginally compatible.*

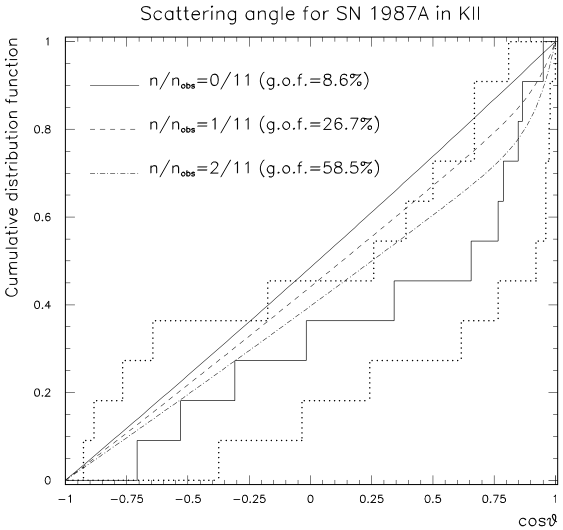
## 5.5 An extension of IBD hypothesis

Figure 17: *Expected 2-dimentional (energy,cosine)-distribution for KII. The angular distribution of ES events is dictated by instrumental effects.*



Assuming 'equipartition' within a factor of 2 (Janka), the probability that the most directional event of KII is due to ES reaches 30 % (or perhaps somewhat more if early neutrinos were more energetic)

## Figure 18: *Cumulative angular distributions of SN1987A events in KII*



With the correct angular distribution, no need of a deviations from IBD hypothesis; however, $N_{ES} = 0.3 - 0.6$ are *expected* which means that 1 or 2 ES events have a GOF of 42% or 15% for reference model. Unfortunately, ES events do not help for the energy distribution.

*My bottomline: we should live with some amount of discrepancy; same in IMB, where the new xsec and angular bias leads to a GOF of 6.4 %*

# 5.6 The adopted statistical tools

## (or, how to measure the GOF)

Consider a set of $n$ data $x_1 \leq x_2, \ldots \leq x_n$; calculate the values of the expected cumulative distribution function $F[x]$

$$F_j = F[x_j]$$

and compare the empirical cumulative distribution function $F_n[x]$ (that counts the number of events below $x$) with the expected one

$$W^2 \equiv n \int_0^1 (F_n[x] - u)^2 \ \psi(u) \ du \ \Big|_{F[x]=u}$$

$\psi = 1$ gives the Smirnov-Cramèr-Von Mises test;
$\psi = 1/(u(1-u))$ the two sided (traditional) Anderson-Darling test;
$\psi = 1/(1-u)$ the one sided Anderson-Darling test.

*The latest two give more emphasis to the data in the periphery.*

## 5.7 Non-thermal effects in neutrinos fluxes

The non-thermal effects are small. A comparison of various parameterization that are common in the literature shows that the differences amount to $\sim 5$ % for analysis of SN1987A events.

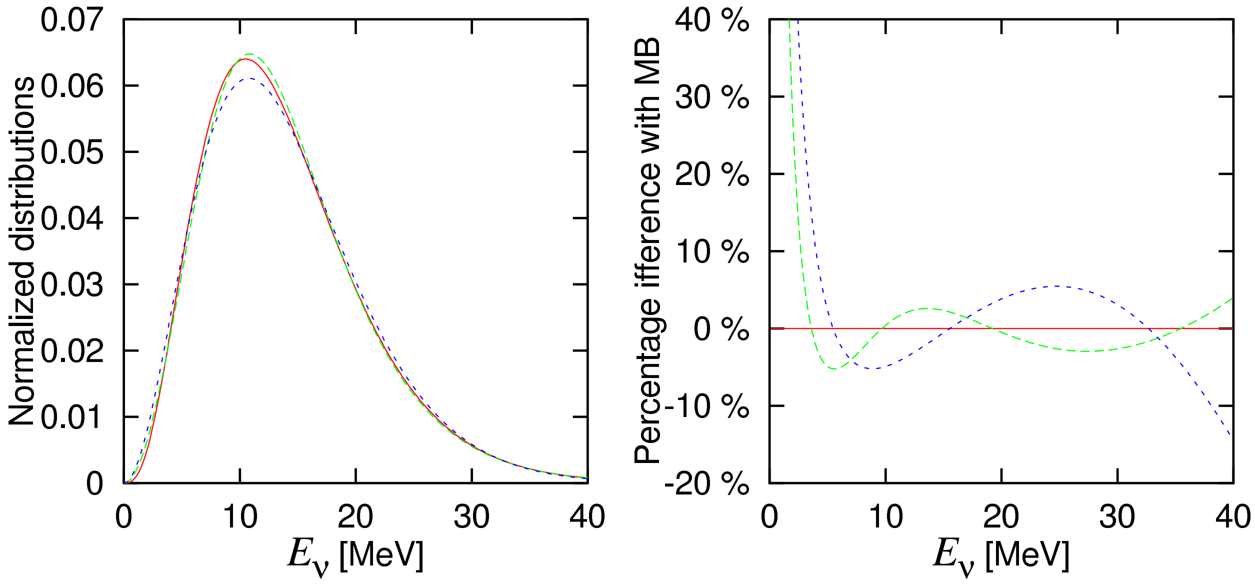


Figure 19: *Modified MB, pinched FD and Gassian cut FD distributions with average neutrino energy 14 MeV and spread $\delta E_\nu = 7$ MeV*

## 5.8 A possibility of large effects due to oscillations

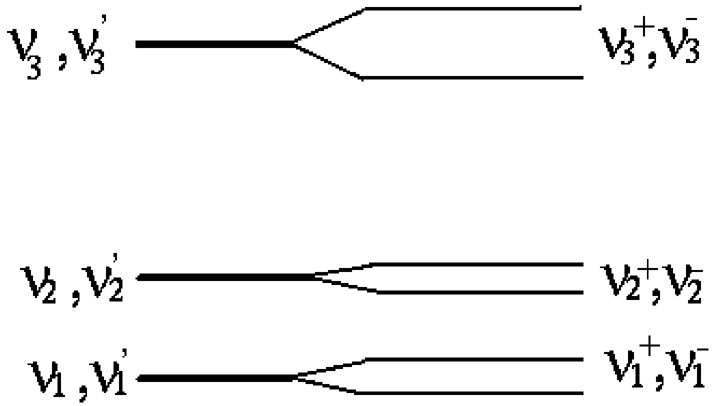


Figure 20: *In models with mirror matter new long wavelength vacuum oscillations could diminish by* $1/2$ *the observable energy or lead to a signal from a 'mirror' (and otherwise invisible) supernova.*

## 5.9 Historical notes

A very good reference on historical $\nu$ matter till 1980 is the review of Pontecorvo on Uspekhi, Pages in the development of neutrino physics.

First 4 tables:
tab. I, *1896-1956*, from radioactivity till discovery of free $\nu$;
tab. II, *1941-1967*, weak processes beyond $\beta$ decay;
tab. III, *1959-1980*, high energy $\nu$, 2 $\nu$, EW interactions;
tab. IV, *1939-1980*, $\nu$ in astrophysics, astronomy and cosmology.

*Several new facts since then, I recall the main ones. including interesting points made in theoretical particle physics.*

## Experiments / observations

SOLAR $\nu$: Gallex/GNO & SAGE 91-, SNO 01-, KamLAND 03-

ATMOSPHERIC $\nu$: Super-Kamiokande 98- (Macro, Soudan etc)

$\bar{\nu}_e$ DETECTORS: CHOOZ 97. LSND 98.

LONGBASELINE: K2K 01, NuMi 06, CNGS 06-

SUPERNOVA $\nu$: IMB, KamiokandeII, Baksan, Mont Blanc(?), 87

NON OSCILLATIONS: Mainz & Troitsk; Heidelberg-Moscow, IGEX, Cuoricino ...; cmb & lss observations.

ALSO: $N_\nu = 3$ from bbn & lep; bounds on $\mu_\nu$, lfv, p-decay...

## Phenomenology / theory

MATTER EFFECT: Wolfenstein 78, Mikheyev Smirnov 86

BARYOGENESIS / LEPTOGENESIS: Sakharov 67, 't Hooft 76, Manton 83; Kuzmin Rubakov Shaposhnikov 85; Fukugita Yanagida 86.

$\nu$ IN GAUGE THEORIES, SEESAW: Minkowski 77; Yanagida 79, Gell-Mann Ramond Slansky 79, Mohapatra Senjanovic 79. Lazarides Shafi Wetterich 81, Mohapatra Senjanovic 81.

$\nu$ IN GAUGE THEORIES, GUT: Pati Salam 74; Georgi Glashow 74; Fritzsch Minkowski 75, Georgi 75.