# Supernova Neutrinos: Risks and Opportunities

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The observation of a neutrinos from a galactic supernova will allow us to monitor the first instants of the explosion and the formation of the compact remnant. Are we ready for this epoch-making event? What can we observe? What could we miss? In the hope to trigger a discussion, we present in this talk a few selected topics emphasizing: specific issues of supernova neutrino astronomy, expectations and uncertainties on time and energy distributions, description of oscillations, physics with scintillators, role of neutral current events

## Many points of view:

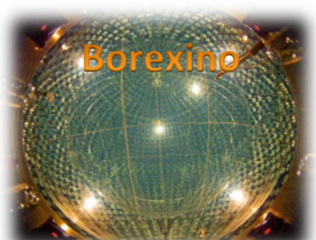
- astronomy
- astrophysics
- particle physics (exp)
- particle physics (theo)
- nuclear physics

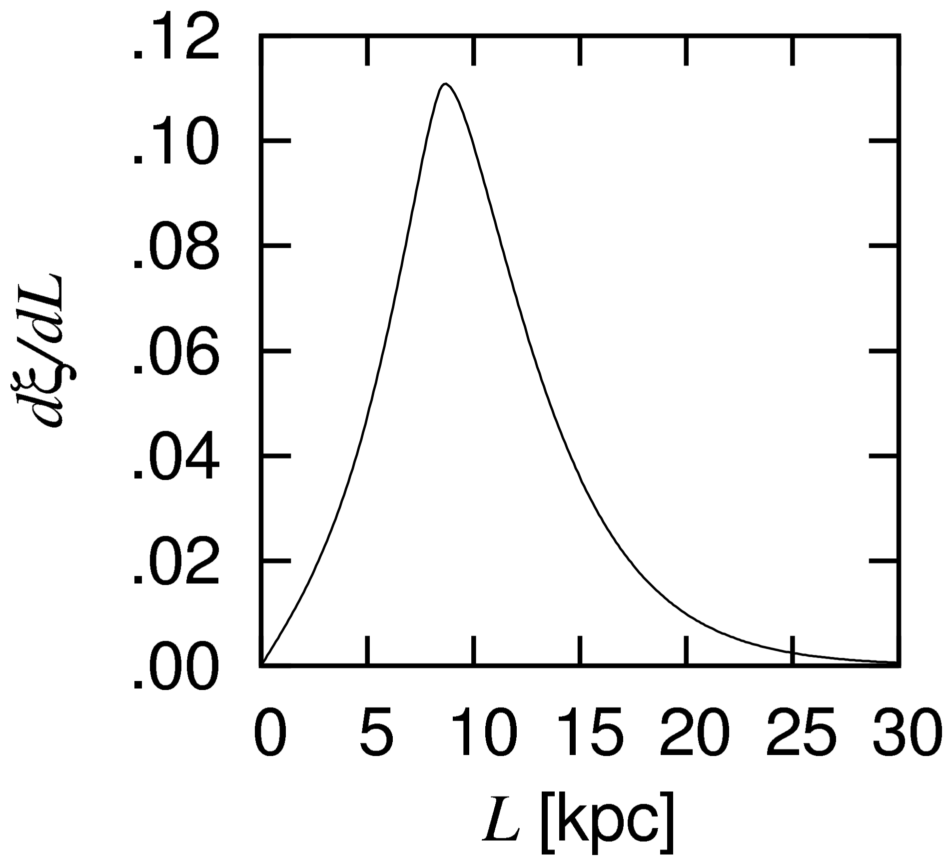
**here, aspects relevant to neutrino telescopes are emphasized.**







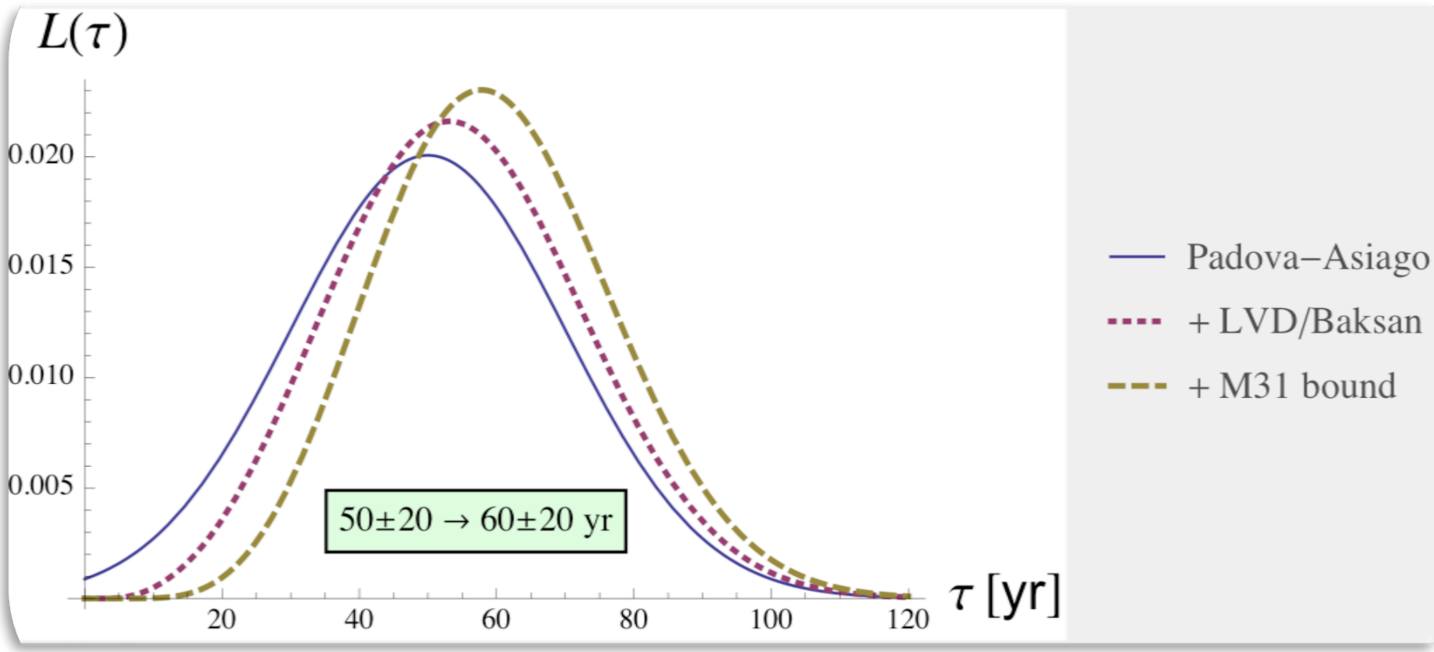




**The typical galactic distance: 10 ± 5 kpc**

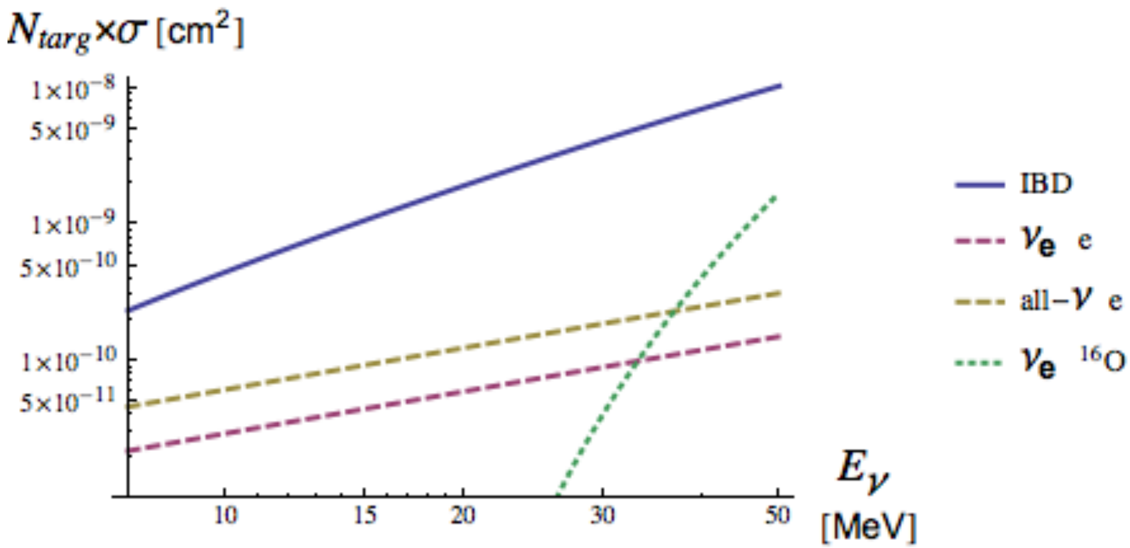
Assume that supernovae track Milky Way's matter distribution. Additional contribution of a `bar' in the Galaxy or conversely lack of contribution from the region around the galactic center does not change much the expectation (Costantini, FV et al, NPB PrSup 139, 2005; Mirizzi, Raffelt et al, JCAP 2006)

# Time of occurrence in the Milky Way?

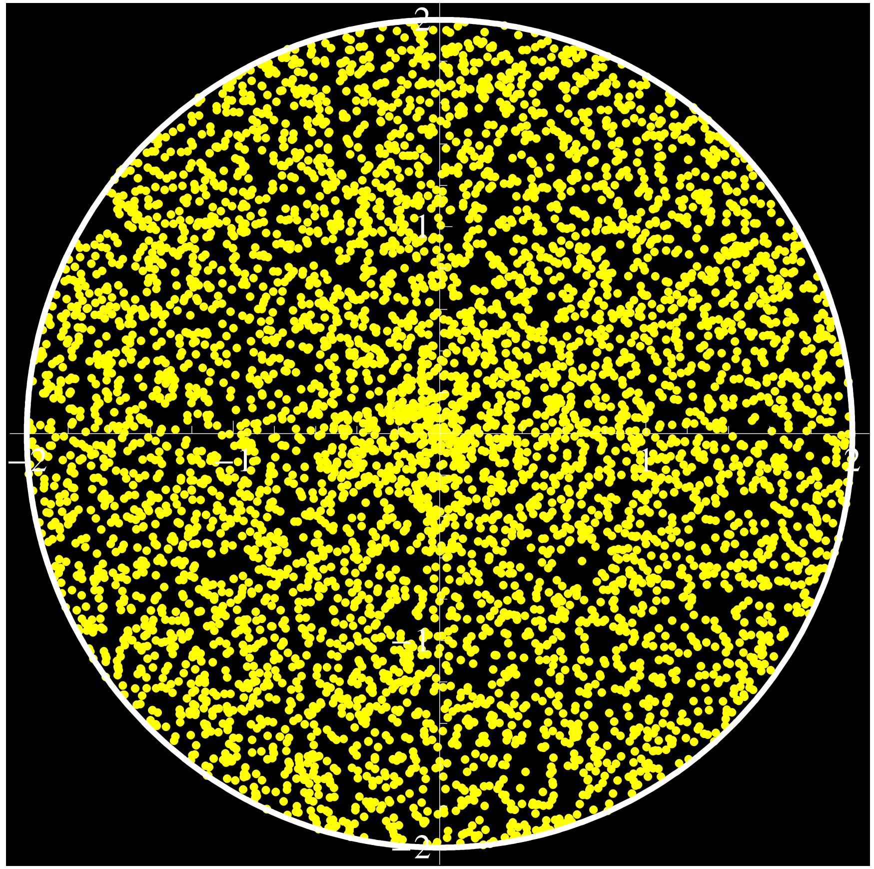



$\tau$=50 yr agrees with Cappellaro et al 0310859 and Diehl etal 0601015. Predictions are uncertain (Botticella 1111.1692) but null search plays some role (Agafonova et a 1411.1709; FV et al, NCim C32, 2009).

# 1 kton Water Cherenkov



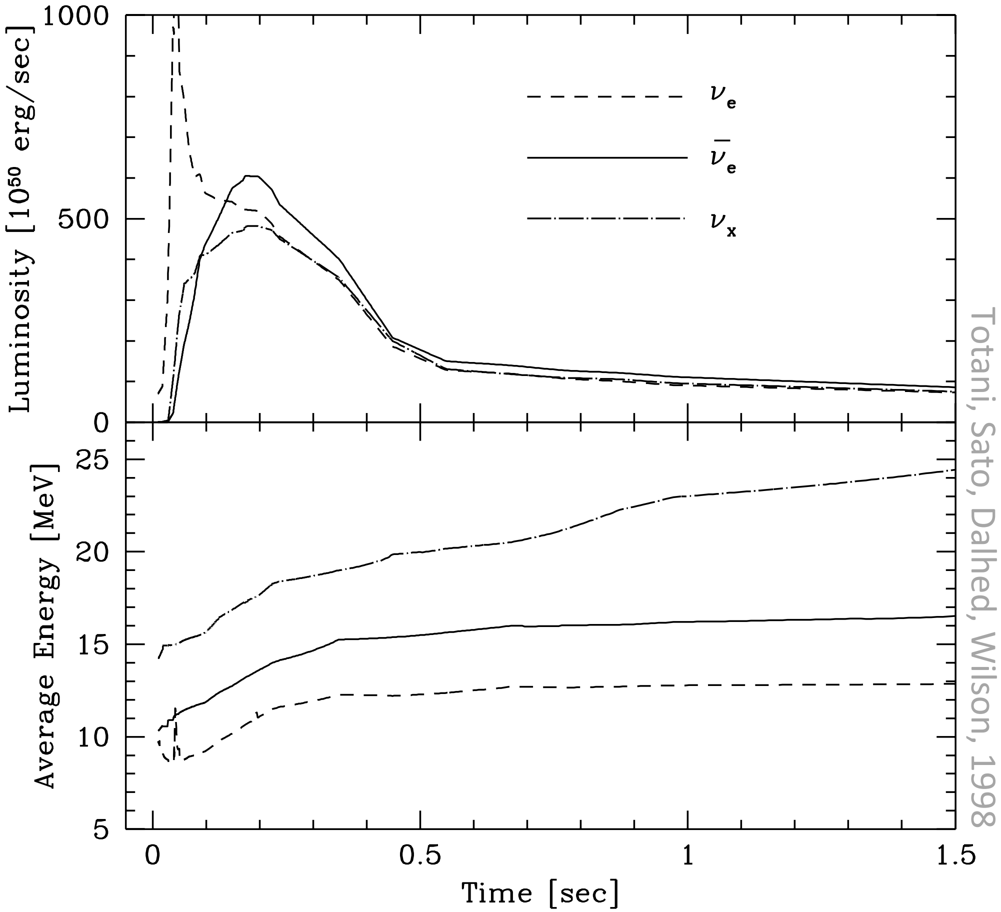

The electron antineutrino reaction on protons (IBD) is by far the largest. High energy electron neutrinos interact with oxygen nuclei. The elastic scattering on electrons (ES) is directional.




## Distribution of the directions - simulation

We consider a supernova event at 10 kpc in 32 kton of water (Super-Kamiokande). Most events about 5,000  are due to IBD; a cluster iof 300 ES in the center of the figure is also visible (Tomas et al PRD 2003; FV et al 2009)

# Expected time distribution



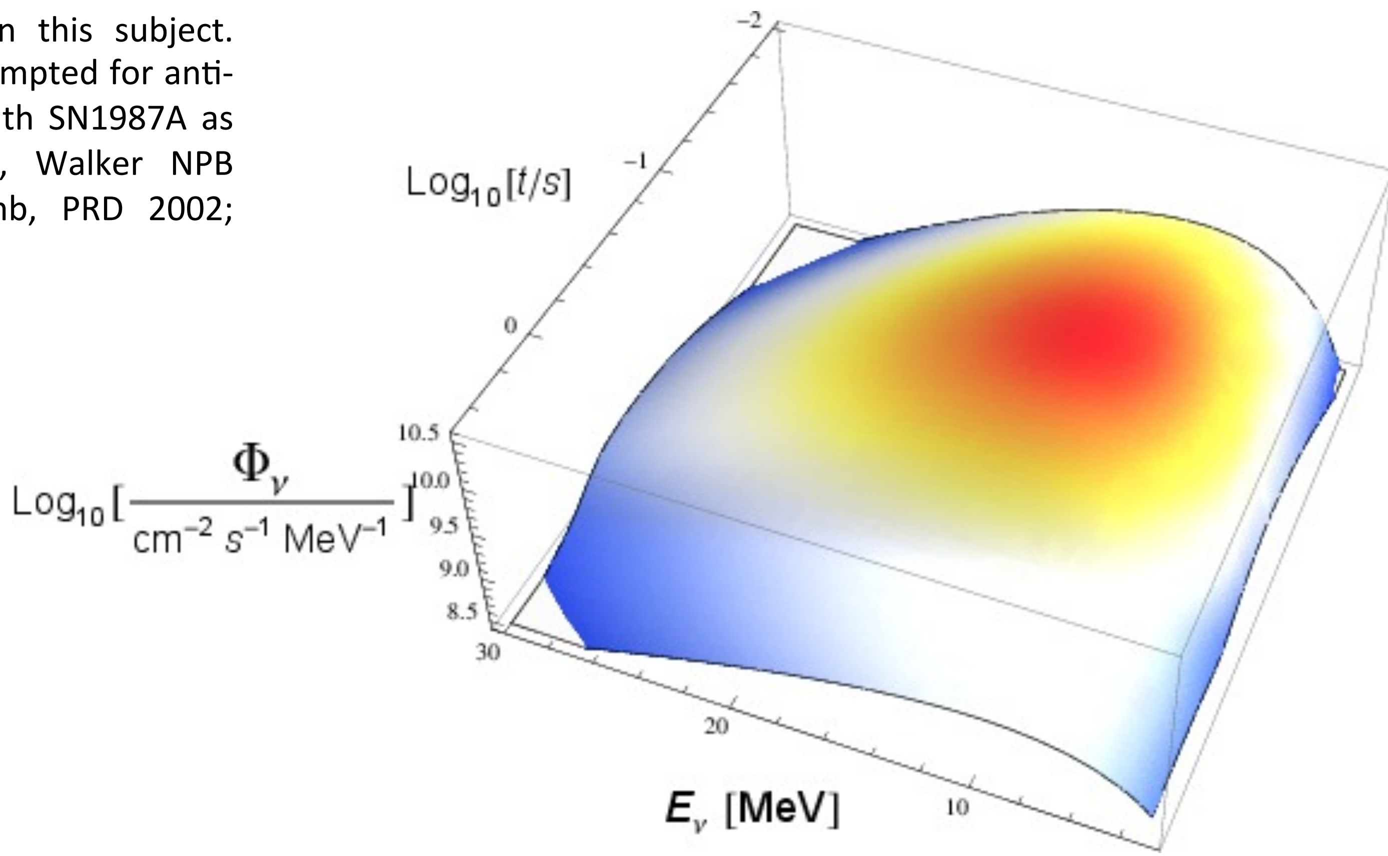

Needs numerical calculations, but there are several stable features:

- neutronization
- accretion
- cooling

The 2nd one is thought to be important for explosion but poorly understood.

# Parameterized flux will be needed for data analyses

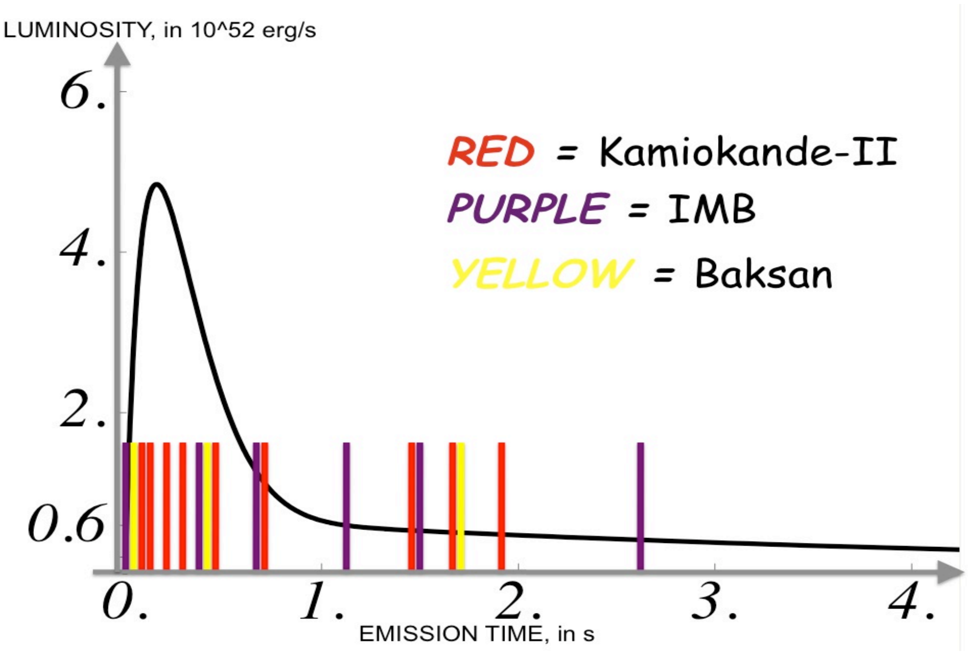
Only few works on this subject. Something was attempted for anti-$\nu_e$ in connection with SN1987A as Abbott, De Rujula, Walker NPB 1988; Loredo, Lamb, PRD 2002; Pagliaroli, FV, 2009.




http://theory.lngs.infn.it/astroparticle/sn.html

# Details cannot be studied with SN1987A…

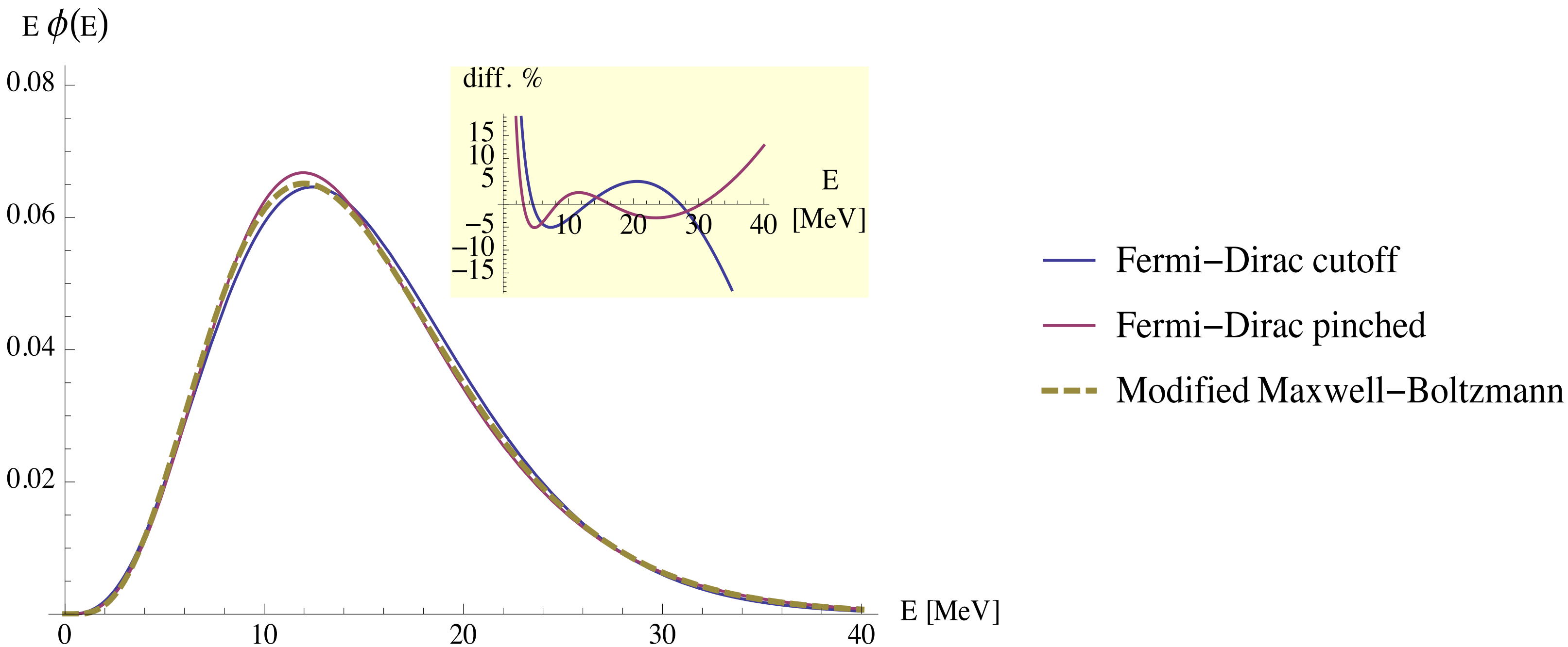
See e.g. my talk at NO-VE 2009




… but we have few sigma hint for a luminous initial emission phase. Surely time-distribution studies will be a major goal of multi-kton detectors

# Energy distribution

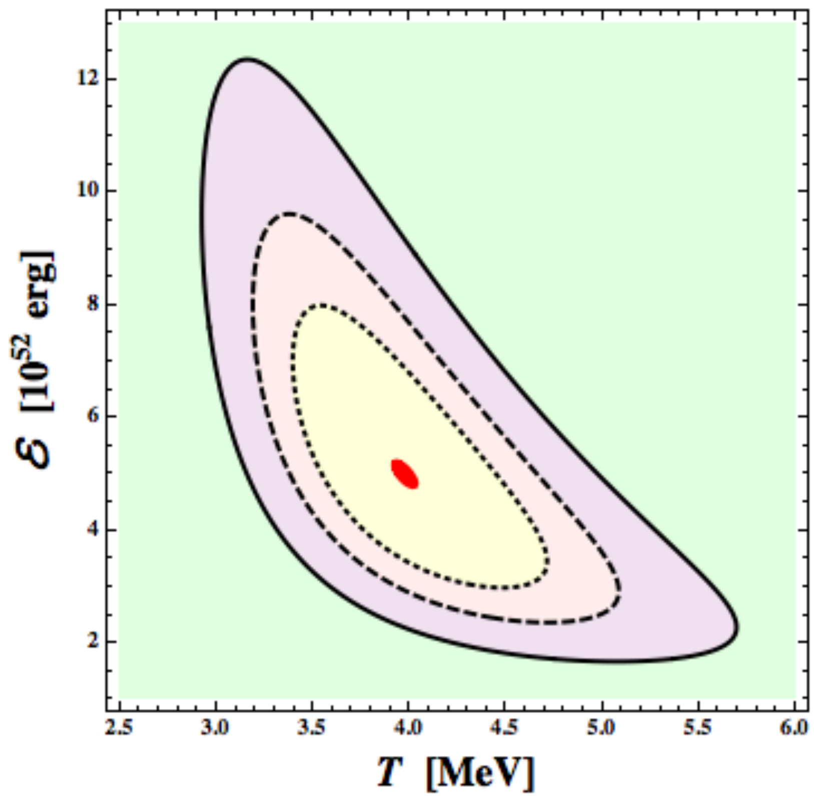
- Neutrinos carry away (2-3) × $10^{53}$ erg
- Approximate energy equipartition among 6 species
- Quasi-thermal spectra with <E>≈12 MeV




**Emission parameters are uncertain**

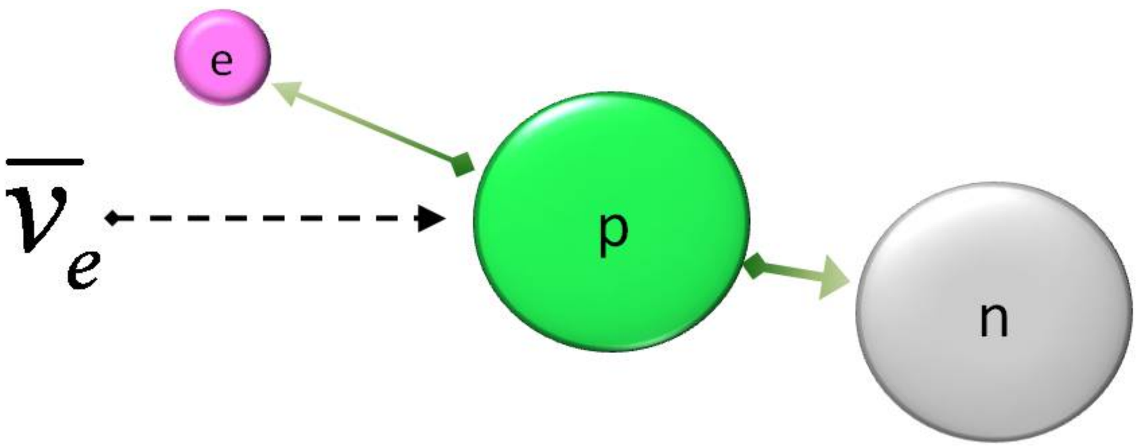
# The picture is validated by SN1987A observations

Stable indications for values close to those suggested by most recent numerical calculations: total energy $3\times10^{53}$ erg, assuming equipartition, and <E>=12 MeV. Errors can be estimated. From my review on JPG, 2015.



## But *all* we have seen are electron antineutrinos!

It is doubtful that we have seen any other reaction besides this one, in contrast with what was thought just after SN1987A (see again my review on JPG). Most of the energy radiated went unmeasured.



# Oscillations [1/2]

- We are sure that 3-flavor neutrino oscillations occur
- We have reliable formulae for matter effect on electrons (MSW)

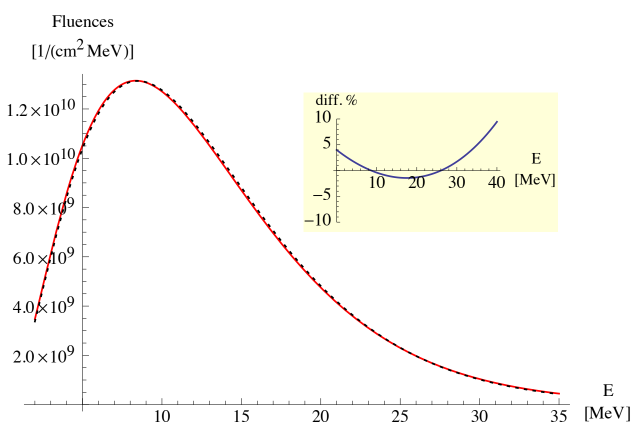
(Dighe & Smirnov PRD 2000)

- But very tough to account for neutrino-neutrino refraction

(Pantaleone PLB 1992 ...)

# Oscillations [2/2]

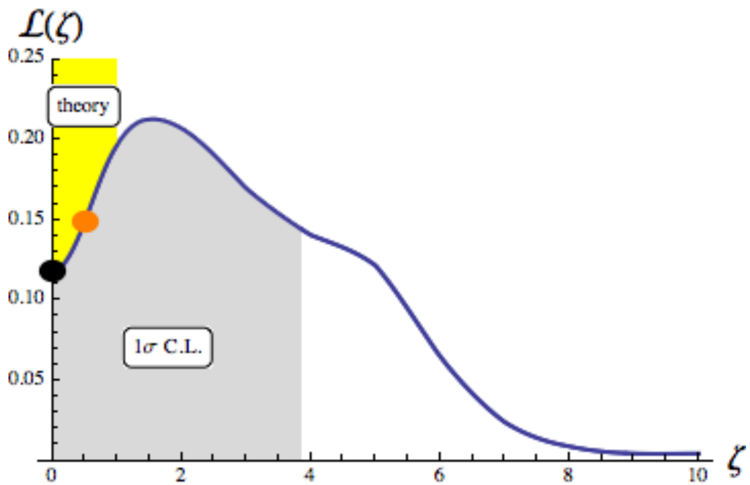
Depend on the difference between fluxes/fluences. Large in early calculations of the fluence, small in modern ones (e.g. Mueller et al, ApJ 2014)




Effect of usual MSW oscillations assuming 20% difference between the anti-$\nu_e$ and anti-$\nu_\mu$ average energies.

- Oscillations seem better understood in the first emission stages (Chakraborty et al PRL 2011)
- Perhaps we have the chance to see them during accretion? (Pagliaroli et al 0705.4032 and ApPh 2009; Serpico et al PRD 2012)

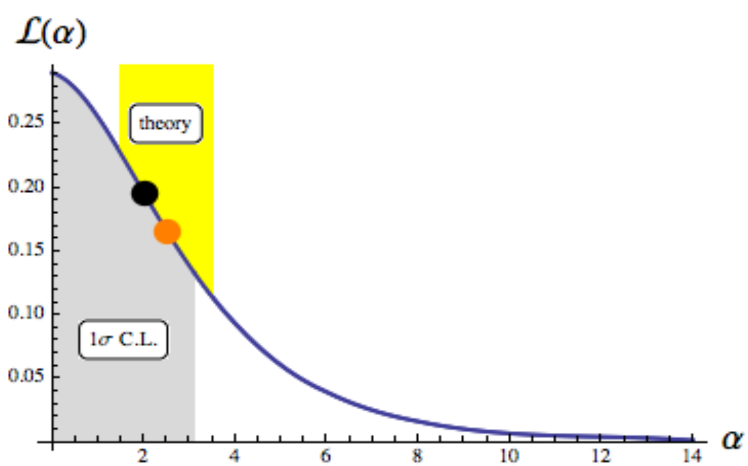
# Uncertainties, uncertainties, and more uncertainties




3ν oscillations are expected but not significantly probed from SN1987A.

Here, we suppose P(surv.)=0.67, equi-partition and T(bar-$\nu_e$)=(1+ζ) T(bar-$\nu_x$)

(FV, JPG 2015; compare Smirnov et al. 94; Lunardini 06)



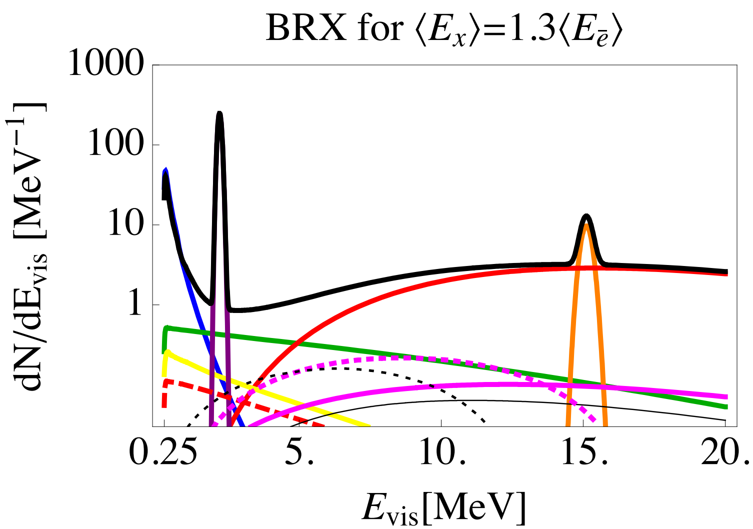

Pinching is expected and barely probed.

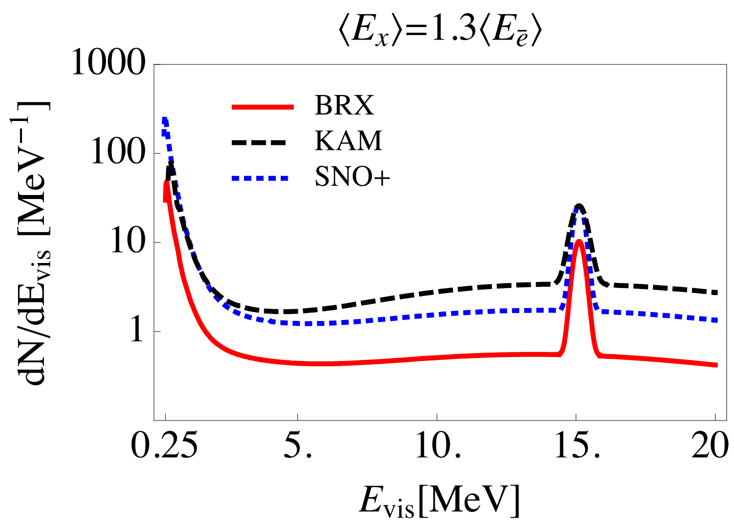
Here, we use Keil et al. parameterization of the fluence, $E^\alpha e^{-E/T}$

(FV, JPG 2015; compare Janka & Hillebrandt 89; Mirizzi & Raffelt 05)

# Scintillators come to our rescue

| Channel | Color code | Signal | BRX | KAM | SNO+ |
|---|---|---|---|---|---|
| $\bar{\nu}_e + p \to n + e^+$ | red | $e^+$ | 54.1 (49.6) | 256.5 (235.3) | 175.8 (161.2) |
| $n + p \to D + \gamma_{2.2\ \mathrm{MeV}}$ | purple | $\gamma$ | 46.0 (42.1) | 200.1(183.5) | 149.4 (137.1) |
| $\nu + p \to \nu + p$ | blue | $p$ | 12.7 (3.8) | 29.0 (6.2) | 74.9 (29.2) |
| $\nu +^{12} C \to \nu +^{12} C^*$ | orange | $\gamma$ | 4.7 (2.1) | 15.0 (6.7) | 12.3 (5.5) |
| $\nu + e^- \to \nu + e^-$ | green | $e^-$ | 4.4 (4.5) | 14.8 (15.5) | 12.0 (12.4) |
| $\nu_e +^{12} C \to e^- +^{12} N$ | magenta | $e^-$ | 2.0 (0.7) | 6.4 (2.1) | 5.3 (1.7) |
| $\bar{\nu}_e +^{12} C \to e^+ +^{12} B$ | black thin | $e^+$ | 1.2 (0.8) | 3.7 (2.6) | 3.0 (2.1) |
| $\nu +^{12} C \to \nu + p +^{11} B$ | yellow | $p$ | 0.7 (0.2) | 2.4 (0.6) | 2.1 (0.6) |
| $\nu_e +^{12} C \to e^- + p +^{11} C$ | red dashed | $p$ | 0.5 (0.1) | 1.5 (0.3) | 1.3 (0.2) |



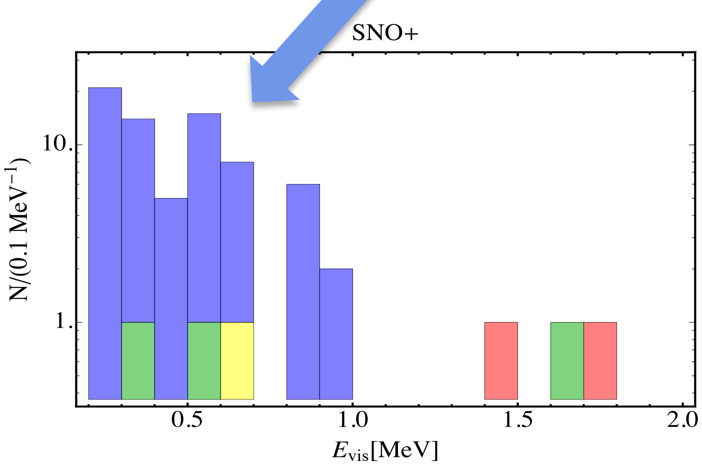



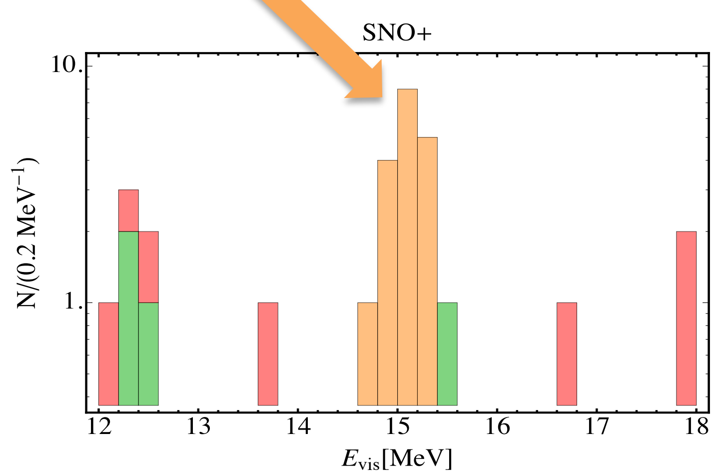

Lujan-Peschard et al JCAP, 2014

# Neutral currents!

Ultrapure scintillators will measure neutral current events from supernovae with:
15.1 MeV gamma line from C, and
nu-P elastic scattering

| | $[E_{thr}, 1.8]$ MeV | | [14,17] MeV | |
|---|---|---|---|---|
| | NC$\pm$ stat $\pm$ syst | Background | NC$\pm$ stat $\pm$ syst | Background |
| BRX | $13.0 \pm 3.6 \pm 2.6$ | 0.9 | $4.7 \pm 2.2 \pm 0.9$ | 1.6 |
| KAM | $28.9 \pm 5.4 \pm 5.8$ | 2.8 | $15.0 \pm 3.9 \pm 3.0$ | 10.0 |
| SNO+ | $74.9 \pm 8.7 \pm 14.9$ | 2.5 | $12.3 \pm 3.5 \pm 2.5$ | 5.0 |



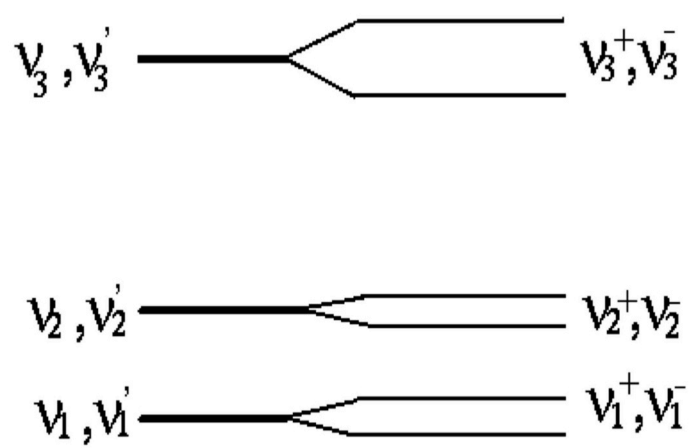

Lujan-Peschard et al JCAP, 2014

# How large the energy loss?

In certain models, such as

- Mirror neutrinos (Berezinsky et al, NPB 2003)
- Pseudo-Dirac neutrinos (Beacom et al, PRL 2004)

only *half* of the neutrino flux reach us due to new oscillations:



With SN1987A wide ranges of oscillation parameters are tested

$$10^{-20}\,eV^2 < \Delta m^2 < 10^{-12}\,eV^2$$

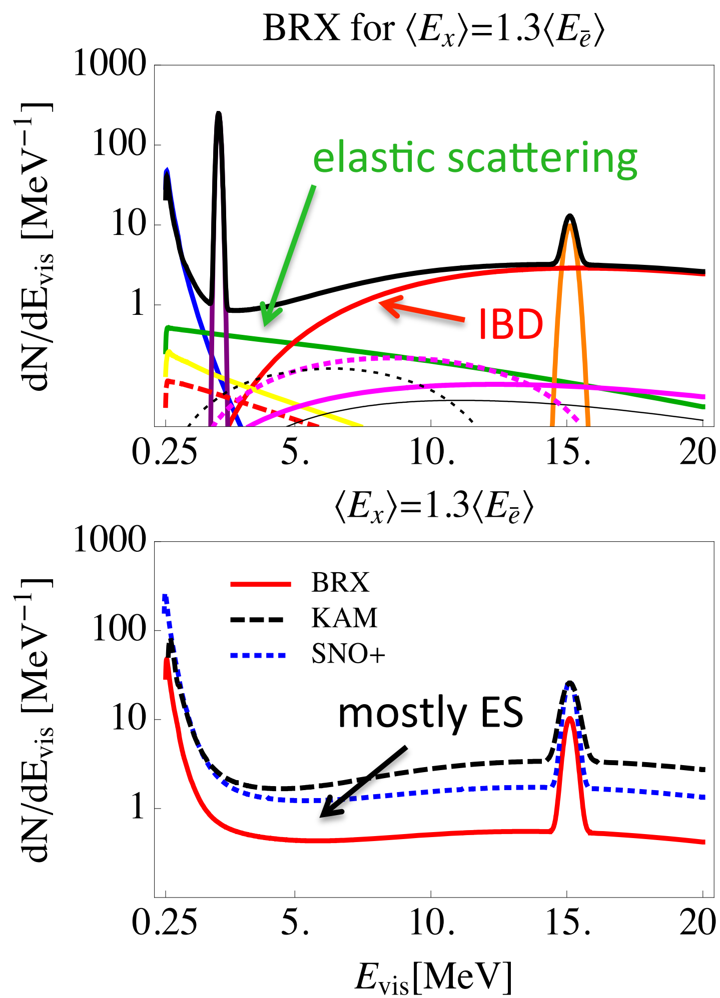
The 8+11 events seen in IMB+Kamiokande-II favor the absence of new oscillations, but the inference depends crucially on what we know on supernova neutrino emission:

| | $p(H_0)$ | $p(H_1)$ | $p(H_1)/p(H_0)$ |
|---|---|---|---|
| without uncertainties | 9 % | 0.3 % | 0.04 |
| with uncertainties | 4.2 % | 1.8 % | 0.42 |

The conclusion is that we need better theory. This could be partially replaced by better measurements – including neutral currents.

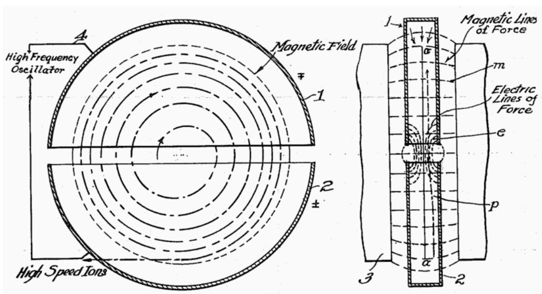
# How to observe electron neutrinos?

- We have carbon excitation in scintillator; reactions on argon; oxygen reactions in water Cherenkov; … does not seem so difficult.
- But the question is to observe the *original* electron neutrinos, not those after oscillations.
- Neutronization is well-characterized in time, but if oscillations transform $\nu_e \rightarrow \nu_{x,}$ gives only O(1) event in SK at 10 kpc. (What about accretion?)
- Elastic scattering offers us one of the best chances (Beacom et al 2014)
- Wih full $\nu_e \rightarrow \nu_x$ swap, O(1) events/kton from the original fluxes (entangled with the other ones) in water Cherenkov or scintillators

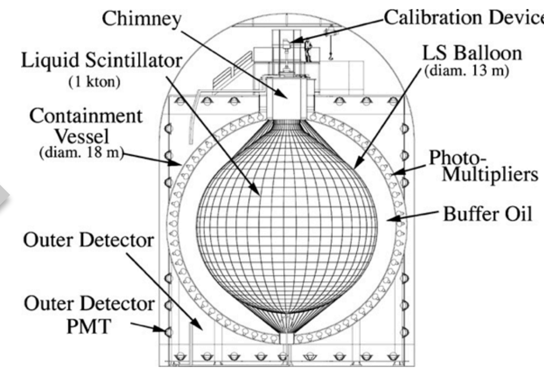



Lujan-Peschard et al JCAP, 2014

# M.M.S.S. (=man-made supernova signal)

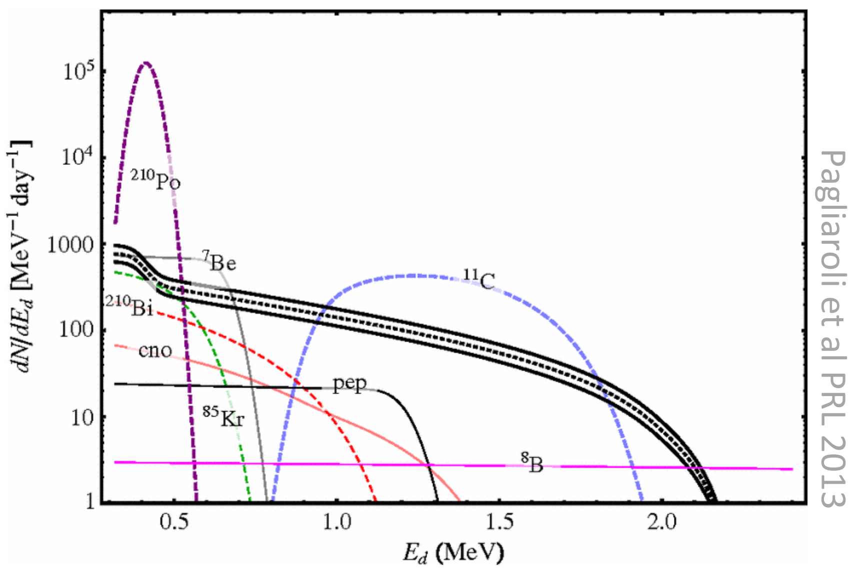



100 m of rock




source of pions at rest

ultrapure scintillator




Possible to study elastic neutrino-proton scattering, as originally planned by LSND.

[In Borexino, quenching is such that $E_d$=250 keV means $E_p$=1.3 MeV, that implies $E_\nu$=25 MeV.]

# DISCUSSION

- The general picture of supernova neutrino emission seems reliable but the uncertainties are considerable and not precisely quantified.

- Important discussions do not converge yet; conversely, not all relevant issues are actively discussed.

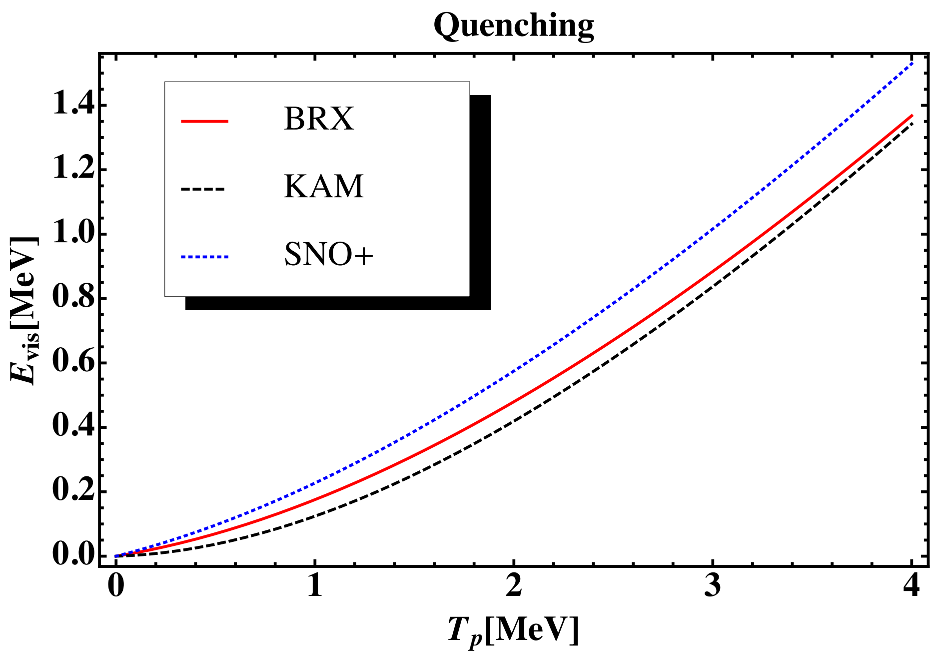
- It would be useful to have reliable predictions and error bars and probably we can improve on that.

- One risk is that we observe a signal but we aren't ready to understand it. E.g. it would be shocking to realize that our detectors were not *sufficient*.

- Surprises are possible but we should avoid wasting a unique opportunity.

Thanks for the attention and wish you a nice supernova

# Spare slides




# Quenching

Protons release less energy than the electrons in a scintillator. Above, the quantitative relationship, depicted for three detectors.

# Determining the Time of Bounce

Pagliaroli et al 09; Halzen & Raffelt 09

$$T_{bounce} = T_{1st} - (t_{GW} + t_{mass} \pm t_{fly} + t_{resp})$$

$$\delta T_{bounce} = \sqrt{\sum_i (\delta t_i)^2}$$ GOAL ➡ $\delta T_{bounce} \approx 10\text{ms}$

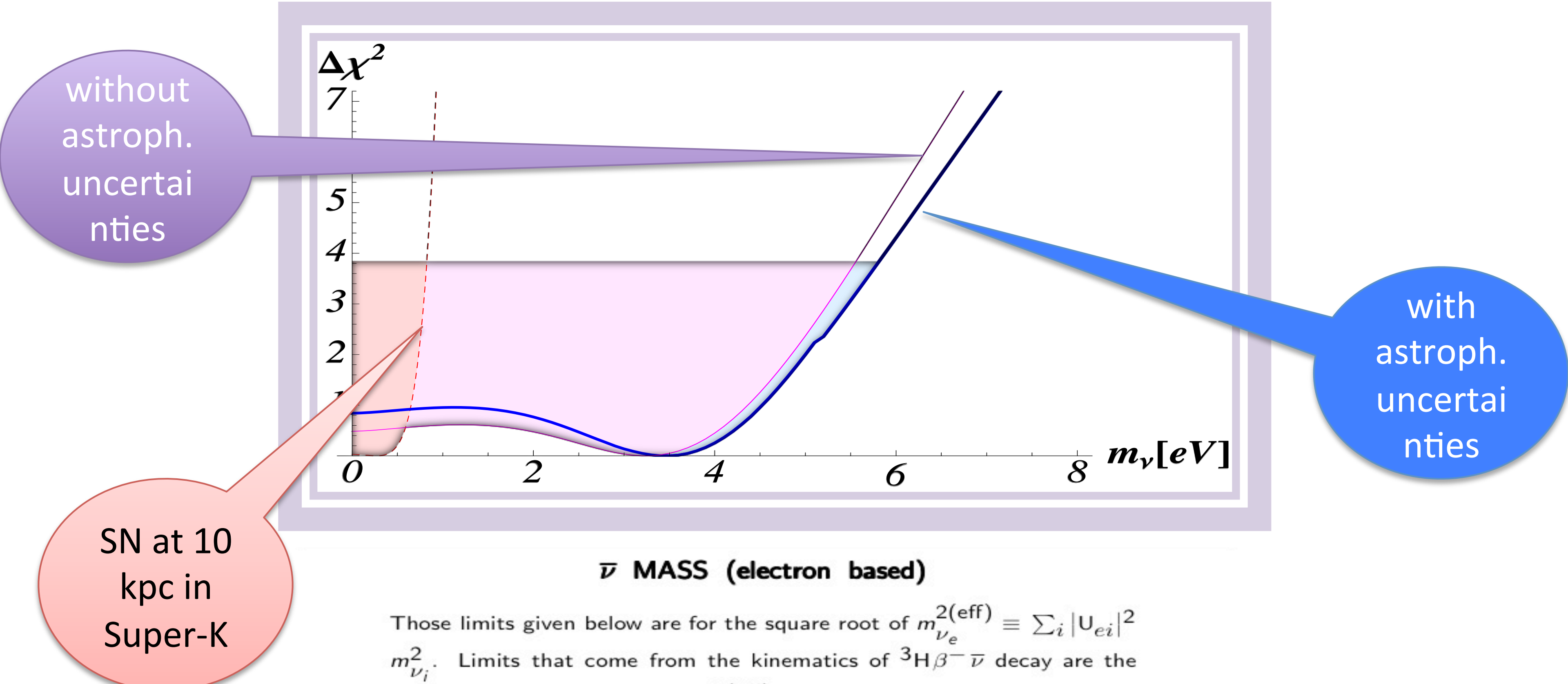
$t_{GW} = (1.5 - 4.5)\text{ms}$ ➡ $\delta t_{GW} : 1.5\text{ms}$

$t_{mass} \sim 0.27 \left(\frac{m_\nu}{0.23}\right)^2 \left(\frac{10\text{MeV}}{E_\nu}\right)^2 \left(\frac{D}{10\text{kpc}}\right)\text{ms}$ ➡ $\delta t_{mass}$ negligible

The dominant terms are the last two

Both can be determined using Neutrinos Data

# Mass Bound from SN1987A

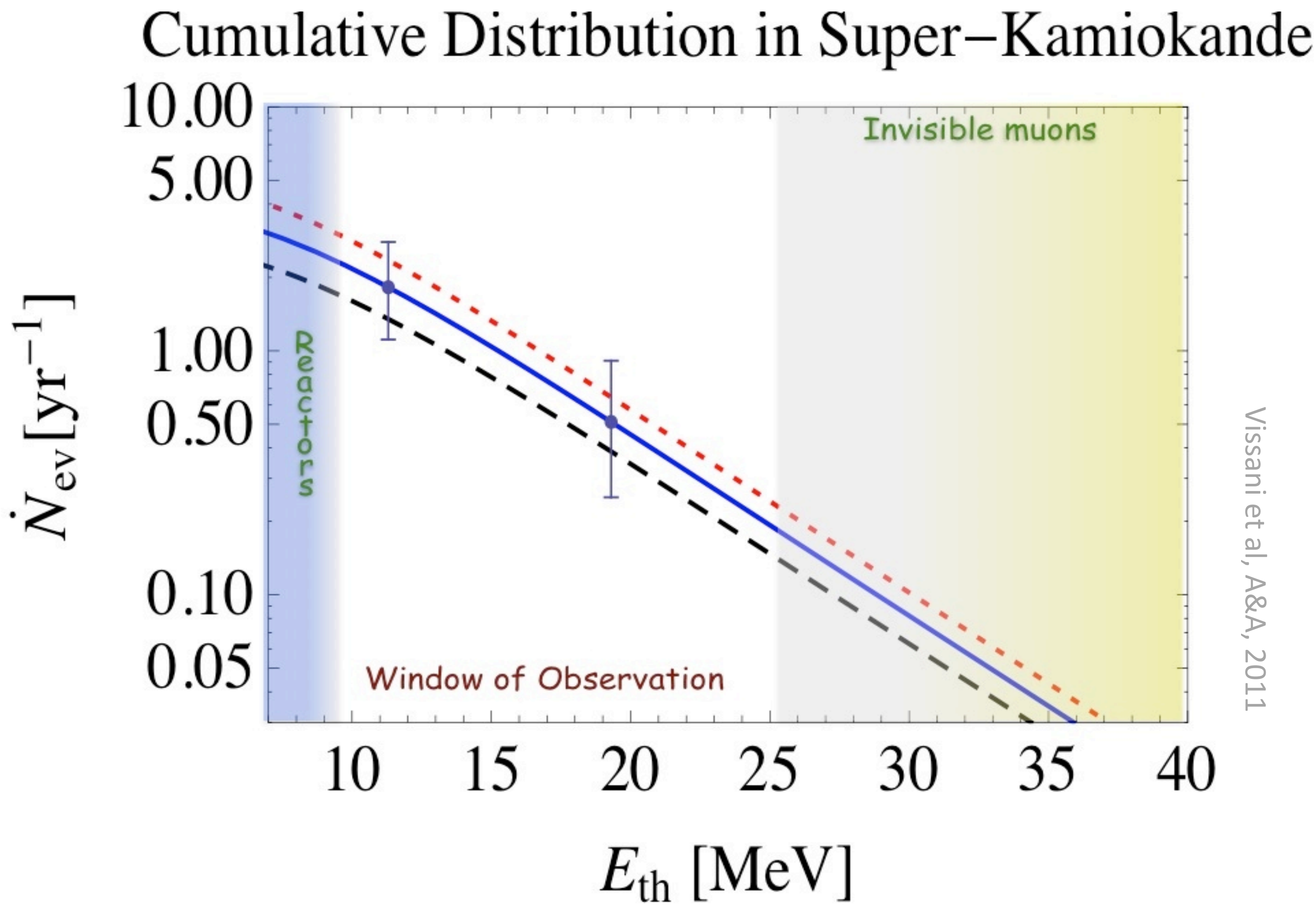



**$\overline{\nu}$ MASS (electron based)**

Those limits given below are for the square root of $m^{2(\text{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of $^3$H$\beta^- \overline{\nu}$ decay are the square roots of the limits for $m^{2(\text{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

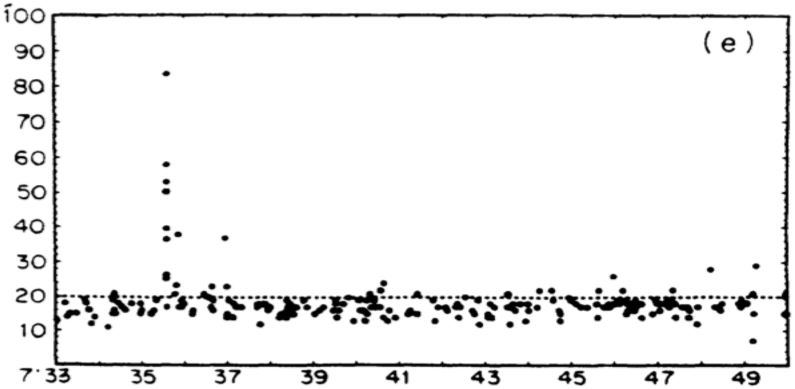
| VALUE (eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **< 2** | **OUR EVALUATION** | | | | |
| < 2.3 | 95 | [1] KRAUS | 05 | SPEC | $^3$H $\beta$ decay |
| < 2.5 | 95 | [2] LOBASHEV | 99 | SPEC | $^3$H $\beta$ decay |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 5.8 | 95 | [3] PAGLIAROLI | 10 | ASTR | SN1987A |
| <21.7 | 90 | [4] ARNABOLDI | 03A | BOLO | $^{187}$Re $\beta$-decay |
| < 5.7 | 95 | [5] LOREDO | 02 | ASTR | SN1987A |
| < 2.8 | 95 | [6] WEINHEIMER | 99 | SPEC | $^3$H $\beta$ decay |

# Relic supernova neutrinos




Vissani et al, A&A, 2011

# Kamiokande-II



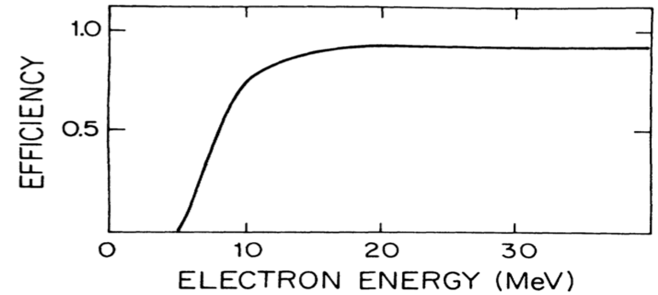
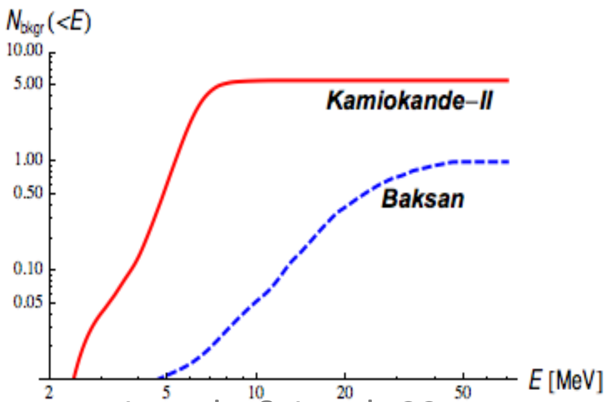
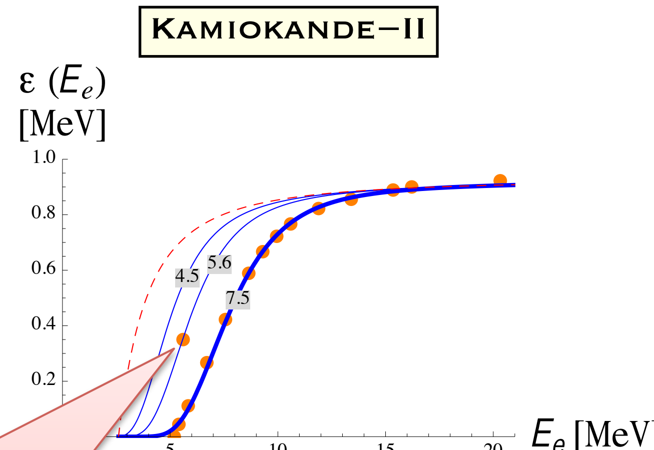




FIG. 3. Trigger efficiency vs electron energy for the 2140-ton fiducial volume. There are 948 PMT's in the central detector and 123 PMT's in the surrounding anticounter.

Hirata et al 87 & 88



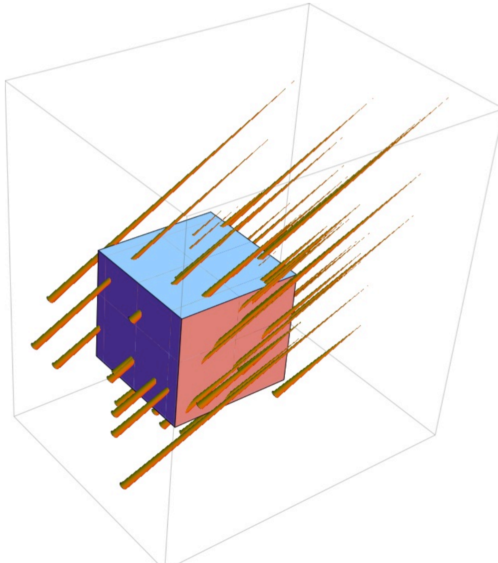

Loredo & Lamb 02

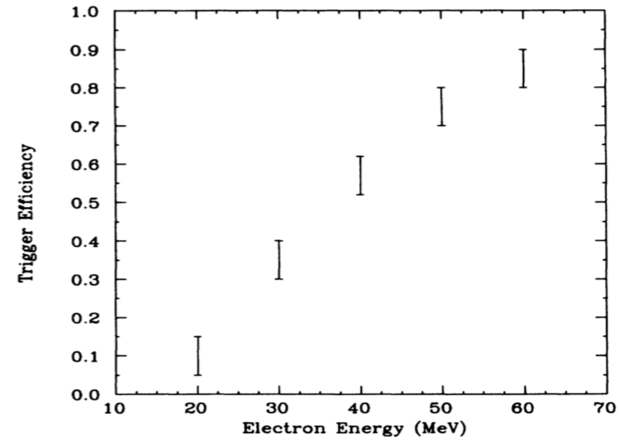



extends Jegerlehner et al 96

Finally, a sample of triggers was chosen primarily to monitor the trigger rate, for which the trigger threshold was lowered to $N_{hit} \approx 14$, corresponding to 5.6 MeV at which energy the efficiency was roughly 35%. During

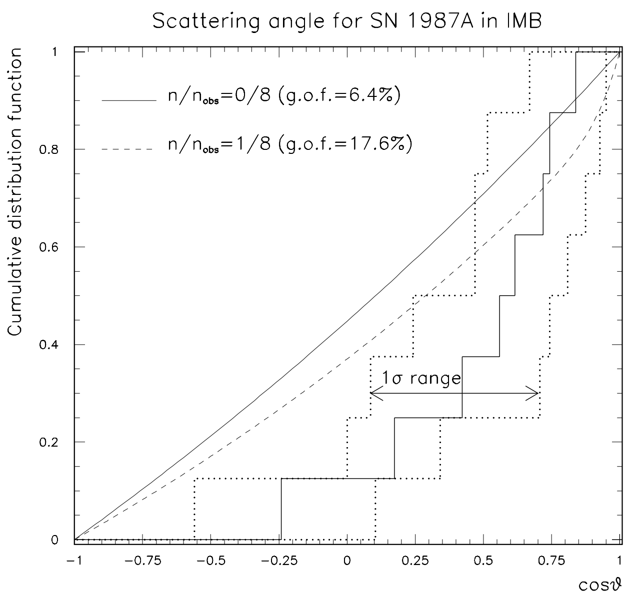
# IMB





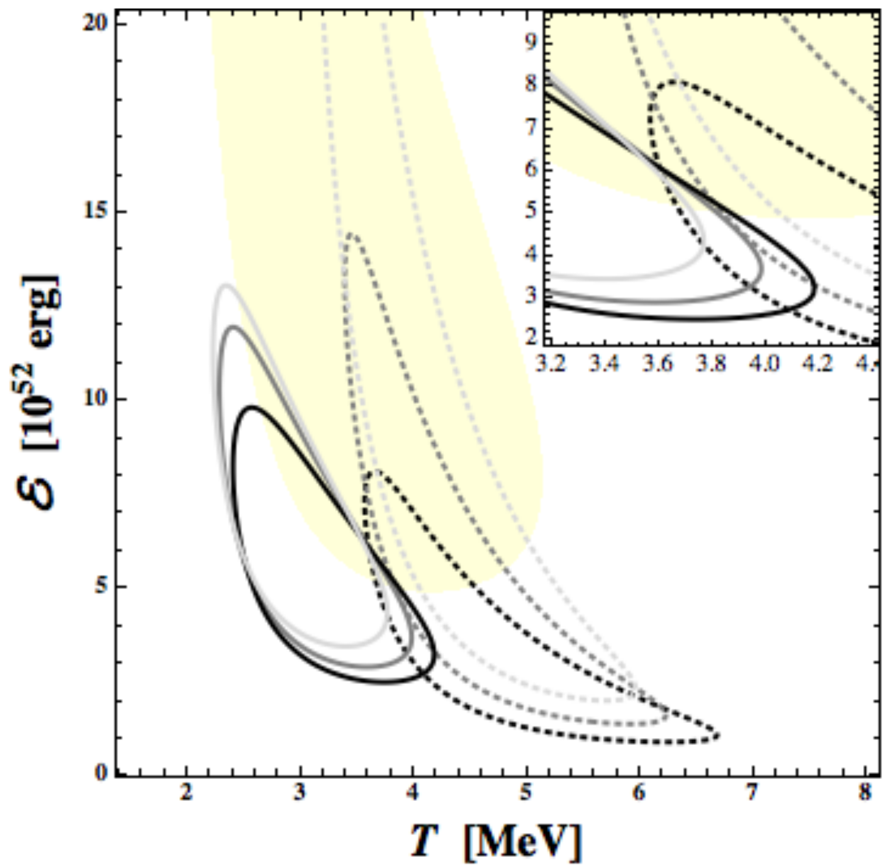

Bratton et al 88

FIG. 1. Trigger efficiency vs electron (or positron) energy averaged over an isotropic distribution in the full 6800-m$^3$ volume of the detector. Error bars represent systematic uncertainty in efficiency (see text).




Costantini et al 04

IMB was only partly operative: the blue walls of the sketch are off. This causes a bias toward higher energies and somewhat favors forward events, $dP/dc=(1+0.1\,c)/2$.



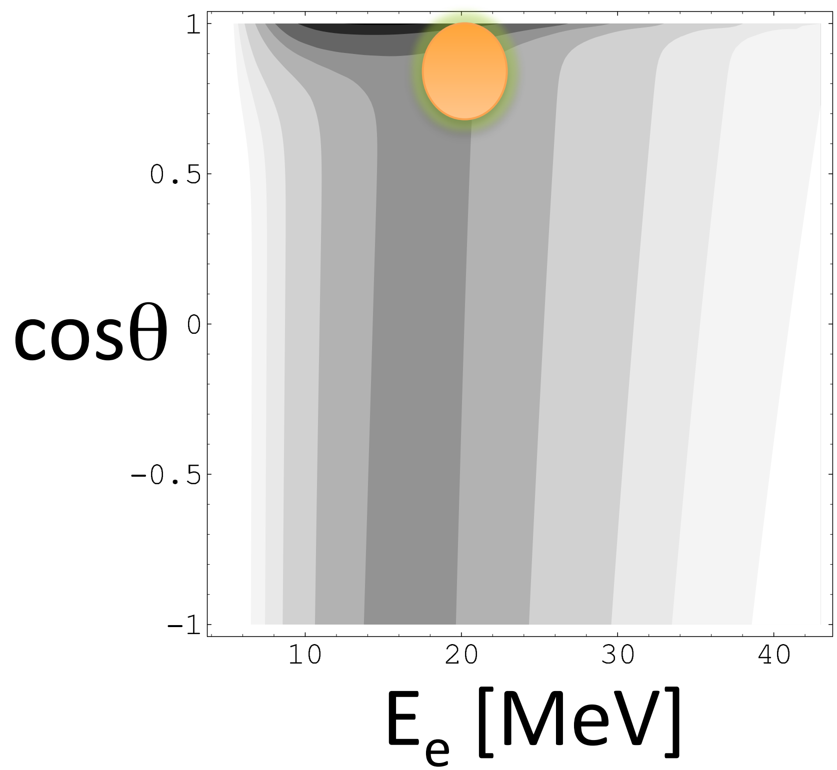

## The data are compatible

Here shown the 68.3% regions for Kamiokande-II (contnuous lines) IMB (dotted line) and Baksan (yellow region).

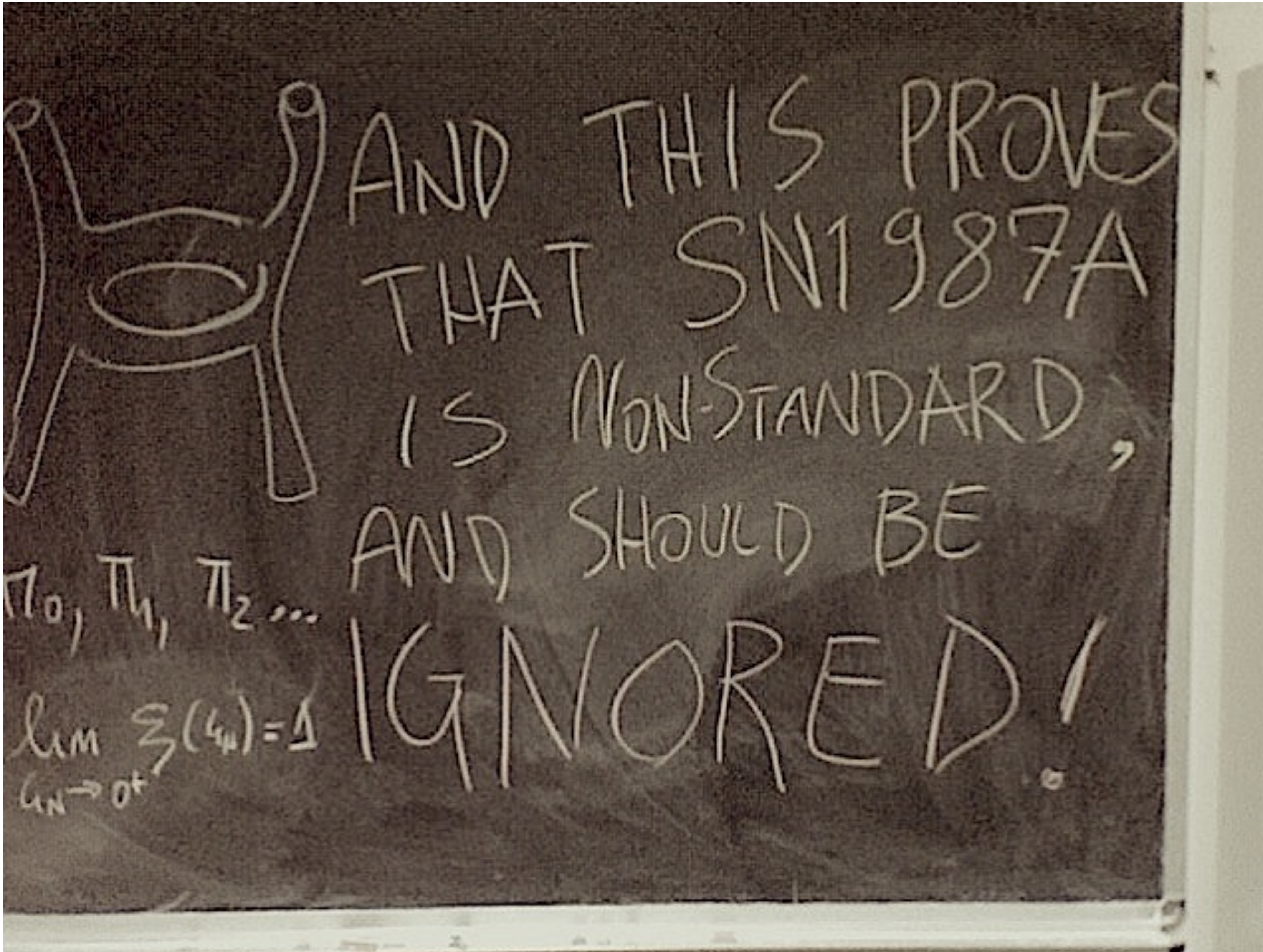
# Open Issues and Doubts

1. Missing neutron star
2. LSD (Mont Blanc) events
3. Excess of directionality of the events

The probability a posteriori that one event, the first of Kamiokande-II, was due to elastic scattering is about 1/3, since its direction is not really forward and its energy is large. This is about the same as the a priori probability to find one elastic scattering event in Kamiokande-II whereas the expectation in IMB is much less.




Pagliaroli & FV 09


AND THIS PROVES
THAT SN1987A
IS NON-STANDARD,
AND SHOULD BE
IGNORED!
$\Pi_0, \Pi_1, \Pi_2 \ldots$