DESY THEORY WORKSHOP 2004

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PARTICLE COSMOLOGY

SUPERNOVA NEUTRINO PHYSICS WITH A MEGATON DETECTOR

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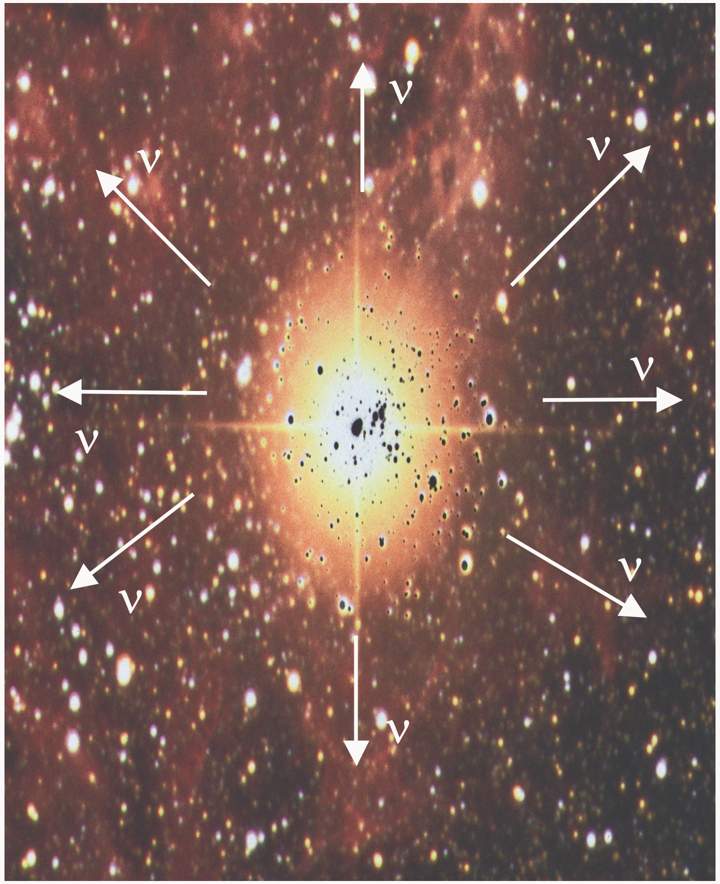
INTRODUCTION TO SUPERNOVA NEUTRINO PHYSICS

SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_{\odot}$] which becomes instable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.



- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED: 1-3 SN/century** in our galaxy (d $\approx \mathcal{O}$ (10) kpc).

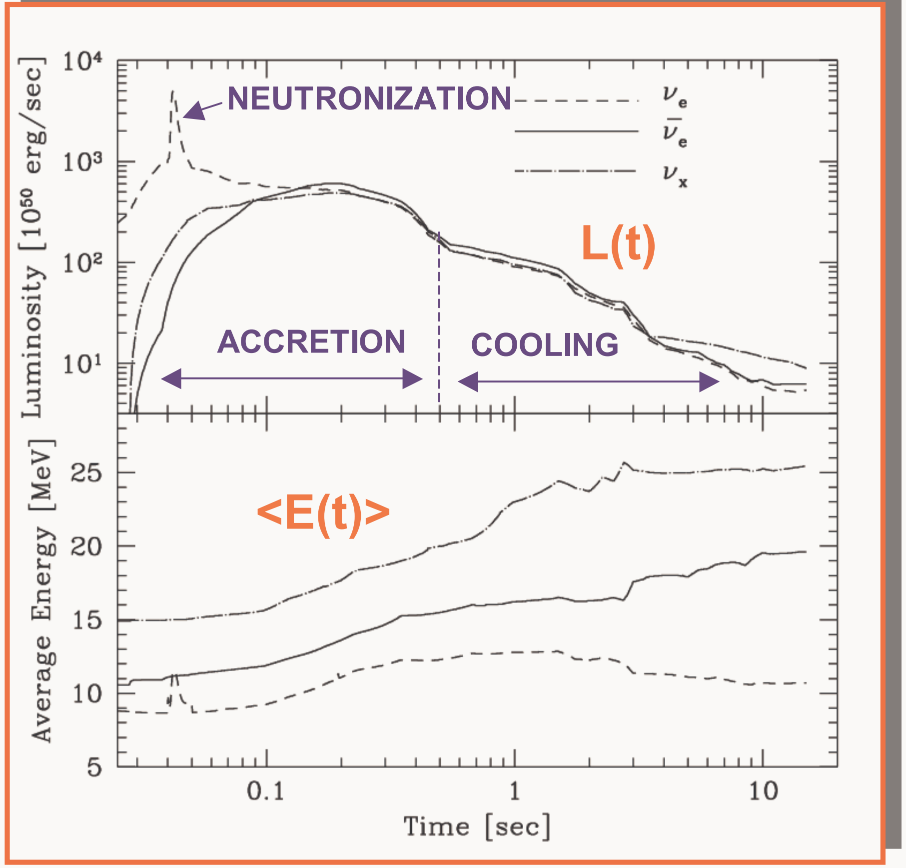
TIME EVOLUTION OF ν SIGNAL

Results of neutrino emission based on a numerical simulation of SN explosion performed by the Livermore group [see, e.g., T. Totani, K.Sato, H.E. Dalhed, and J.R. Wilson, Astrophys. J. **496**, 216 (1998)].

- **NEUTRONIZATION BURST**: ν_e
  - Duration: 10 –20 ms after the explosion
  - Emitted energy : E~ 10^{51} erg

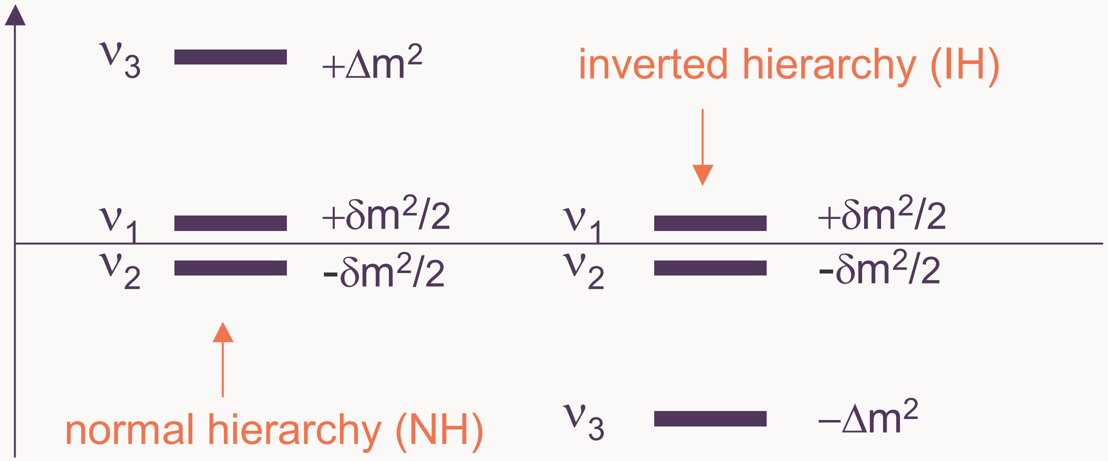
    (1/100 of total energy)

- **THERMAL BURST (ACCRETION + COOLING)**: ν_e , $\bar{\nu}_e$, ν_x , $\bar{\nu}_x$
  - Accretion: ~ 0.5 s
  - Cooling: ~ 10 s
  - Emitted energy: E~ 10^{53} erg



3 ν framework

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23})$ as for CKM matrix
- **Mass-gap parameters:** $M^2 = \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2 \right)$
  - $-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}$: "solar"
  - $\pm \Delta m^2$: "atmospheric"



$\delta m^2 \approx 8.3 \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{12} \approx 0.29$

$\Delta m^2 \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} \approx 0.5$

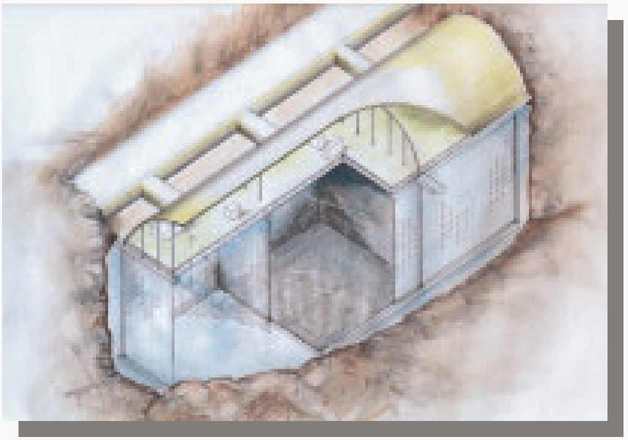
$\sin^2\theta_{13} \lesssim 0.05$

- **Matter effects:**

The stellar matter effects are parameterized in term of a **level crossing probability** **$P_H = P_H(\Delta m^2, \theta_{13})$** among the instantaneous eigenstates ("matter eigenstates") of the Hamiltonian. **$0 \leq P_H \leq 1$** depending on θ_{13}. In the following we consider only two limit case $P_H = 0$ (i.e. $\sin^2\theta_{13} \gtrsim 10^{-3}$) or $P_H = 1$ (i.e. $\sin^2\theta_{13} \lesssim 10^{-5}$).

SUPERNOVA NEUTRINO DETECTION WITH A 0.4 Mton DETECTOR

We consider a future large water Cherenkov detector with fiducial mass of 0.4 Mton, as proposed, e.g., by the UNO collaboration [C.K.Jung, hep-ex/0005046] in U.S.A.

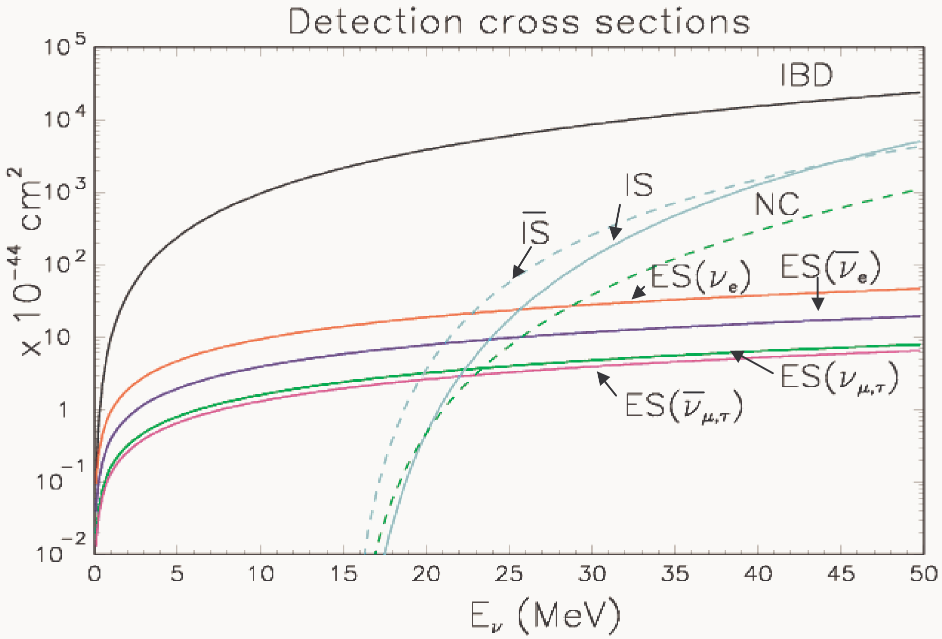


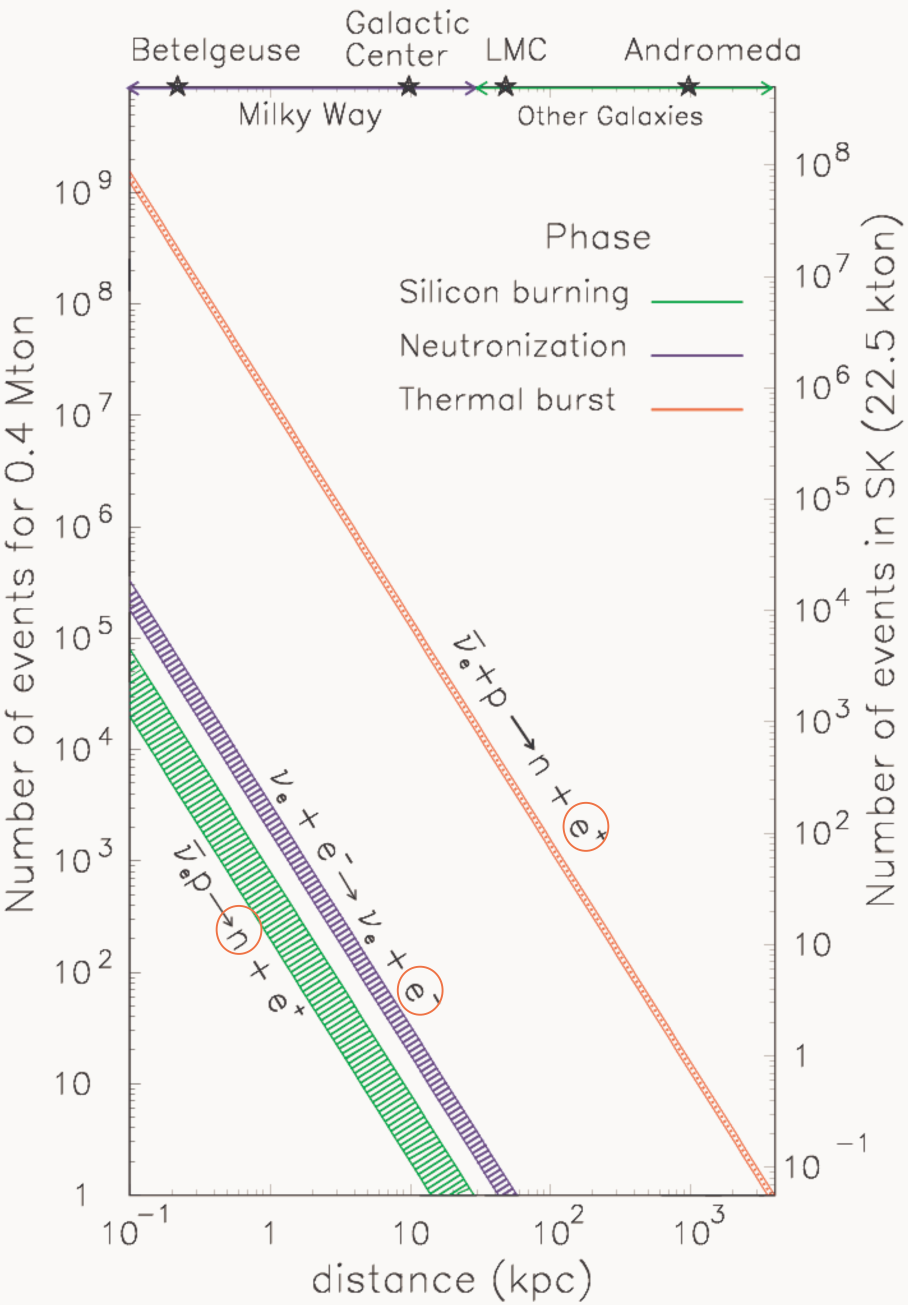
Similar projects in

- **Japan (Hyper-Kamiokande)**
- **Europe (Frejus Tunnel)**

Detection reactions

- $\bar{\nu}_e p \longrightarrow n\, e^+$ **inverse beta decay (IBD)**
- $\overset{(-)}{\nu}_{e,\mu,\tau}\, e^- \longrightarrow \overset{(-)}{\nu}_{e,\mu,\tau}\, e^-$ **elastic scattering (ES)**
- $\overset{(-)}{\nu}_e\, O \longrightarrow X\, e^{\pm}$ **inelastic scattering (IS)**
- $\nu\, O \longrightarrow \nu\, O\, \gamma$ **neutral current (NC)**

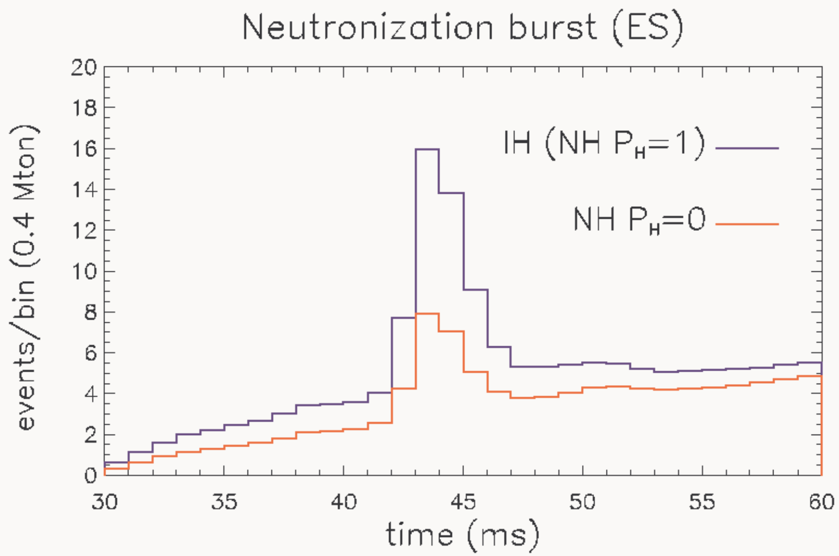




- **Very high statistics of events**
- **Possibility to follow the different phases of SN ν signal.**
- **Chance to detect ν from extragalactic SN, such as Andromeda (M31).**

A 0.4 Mton detector might open a new era in SN neutrino detection.

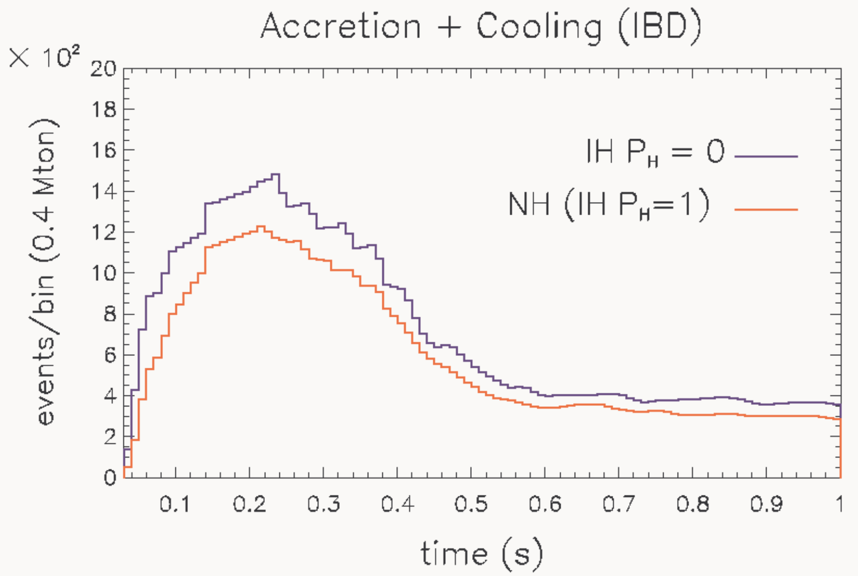
In the following we will mainly focus on the possibility to detect the time structure of the ν signal for a typical galactic SN explosion (d = 10 kpc).



Neutronization burst

Detection reaction: $\nu_e\, e^- \rightarrow \nu_e\, e^-$ (ES)

20–50 events in ~10 ms,depending on the hierarchy and on θ_{13}.

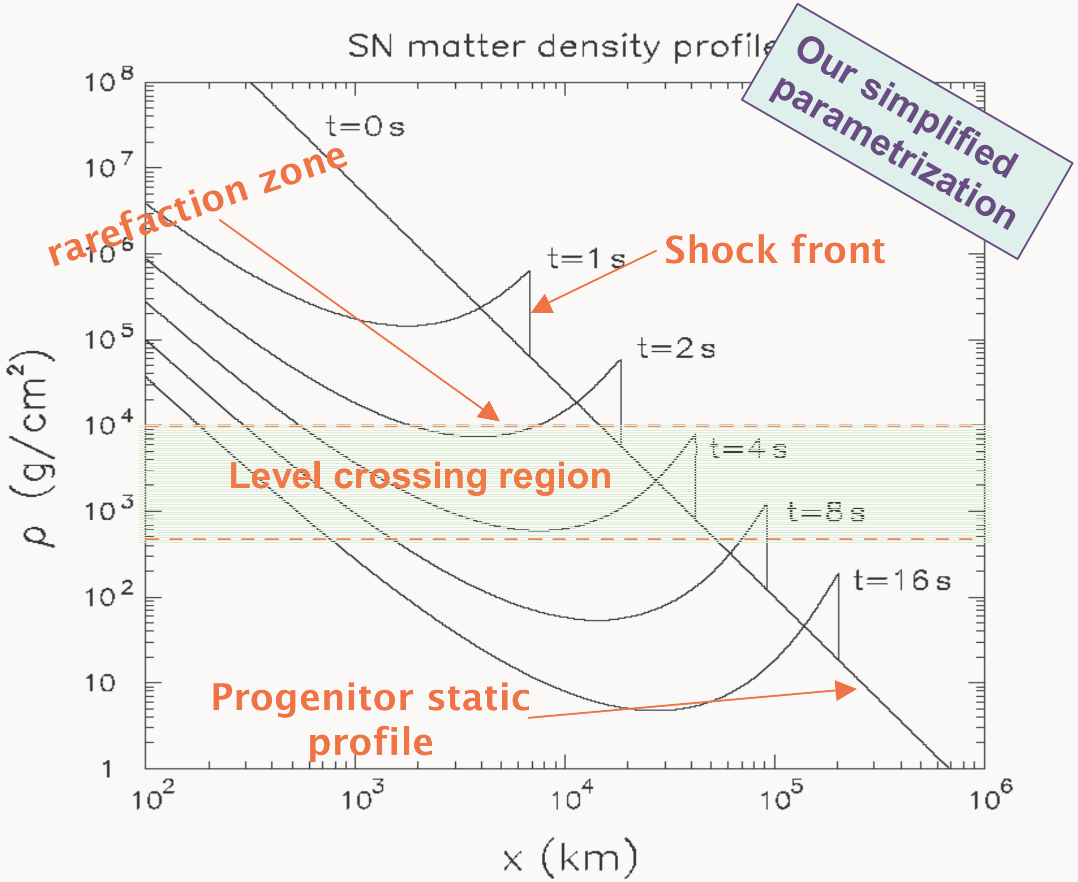


Thermal burst

Detection reaction: $\bar{\nu}_e p \rightarrow n\, e^+$ (IBD)

- **Accretion :** "Hump" in ν luminosity.
- **Cooling :** ν luminosity falls steadily.

SHOCK-WAVE PROPAGATION

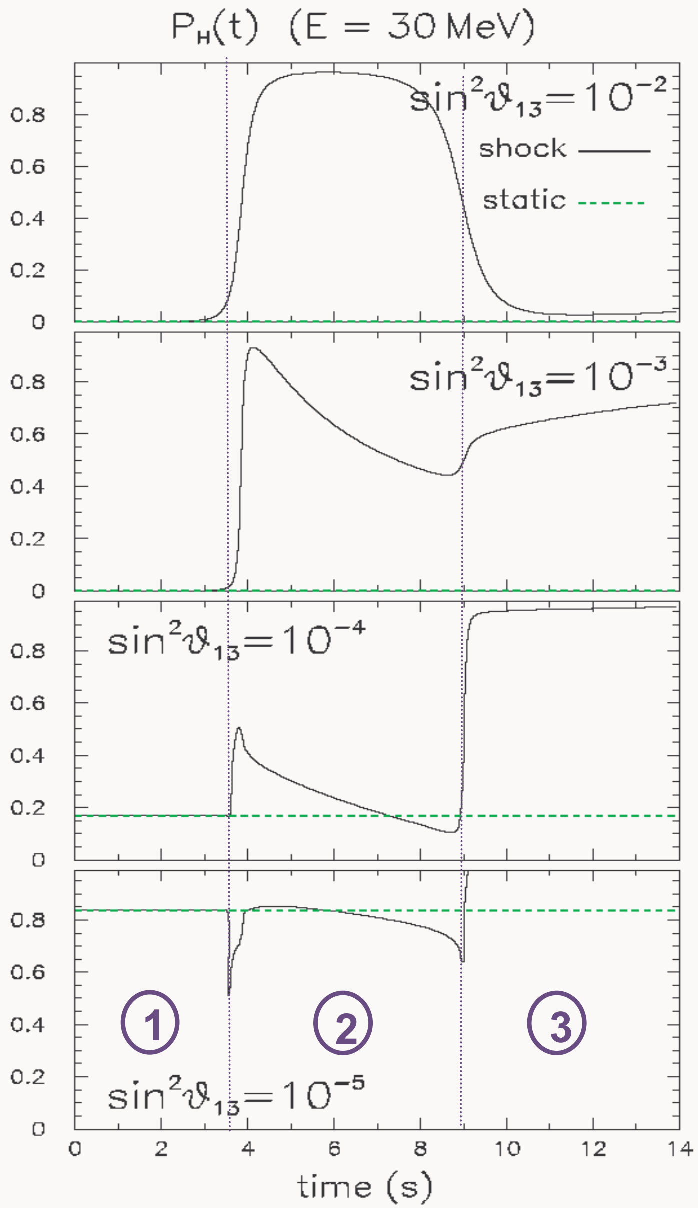


The main feature of shock wave physics [see,e.g., R.C. Schirato, and G.M. Fuller, astro-ph/0205390] is that the matter density profile is

- nonmonotonic and time-dependent
- step-like at the shock front

Peculiar modifications of the crossing probability P_H, w.r.t. to the case of a static matter density profile (see our hep-ph/0304056)

Neutrino oscillations as a "camera" for shock wave propagation

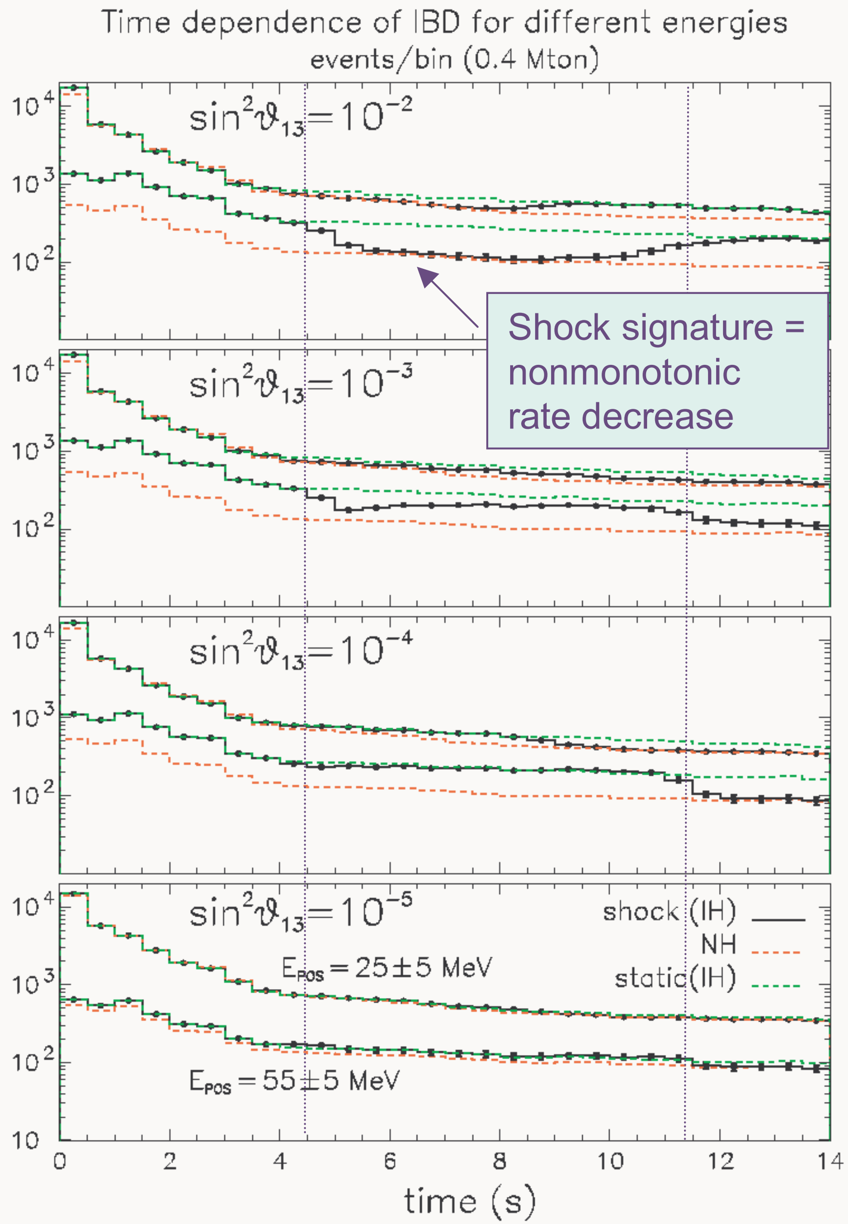


1. **Neutrino level crossing along the progenitor static profile …**
2. **… along the shock front (from the bottom of the rarefaction zone to the top of the shock front)…**
3. **… and along the rarefaction zone.**

Shock-wave effects on P_H strongly dependent on θ_{13}.

Present on $\bar{\nu}_e$ only in IH due to P_H.

SHOCK-WAVE EFFECTS ON TIME SPECTRA

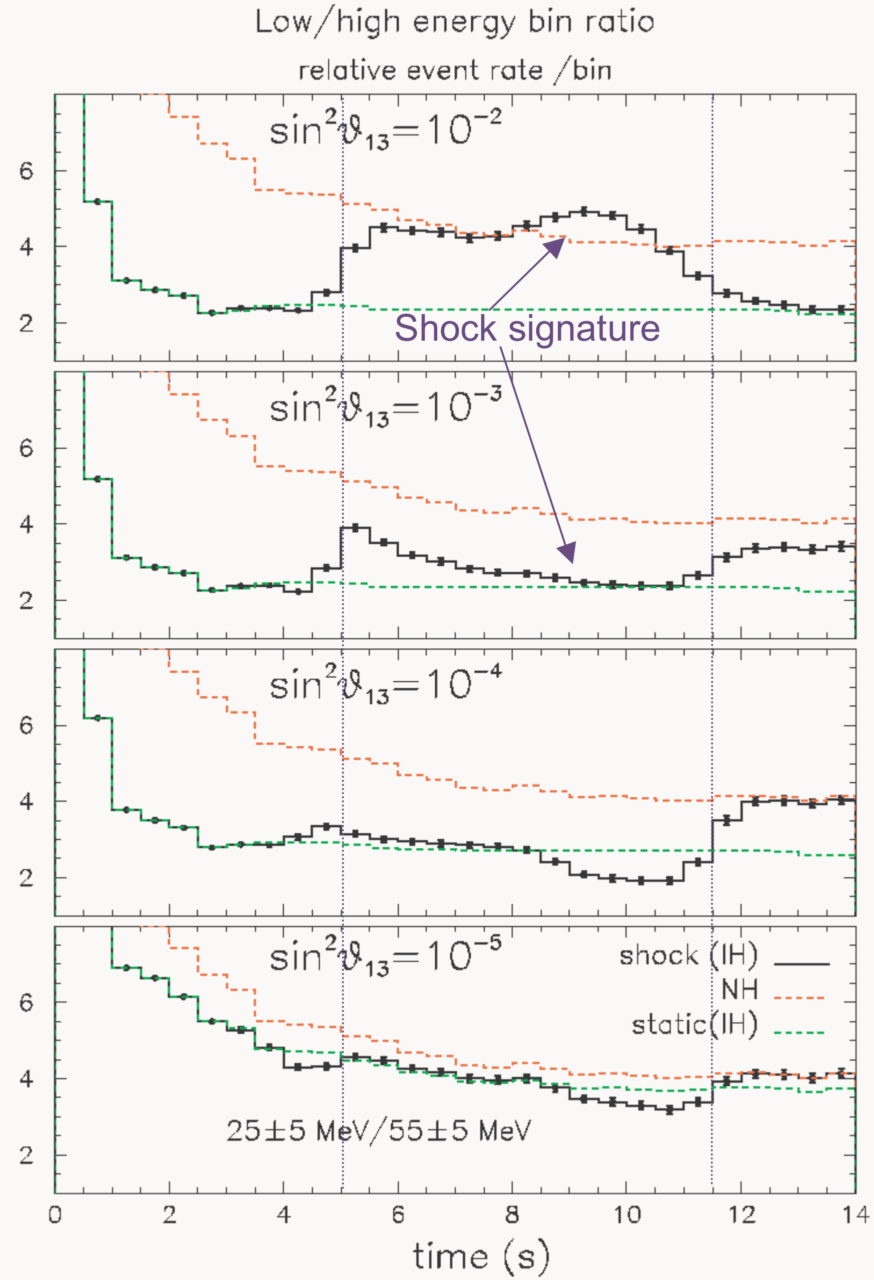


Peculiar deformations in the decrease of luminosity in IH, very sensitive to θ_{13}.

The observation of a nonmonotonic rate decrease would

- provide a "movie" of the shock wave propagation
- prove that neutrino mass hierarchy is inverted
- put a significative lower bound on $\sin^2\theta_{13}$.

How to extract a model-independent signature of shock-wave propagation?

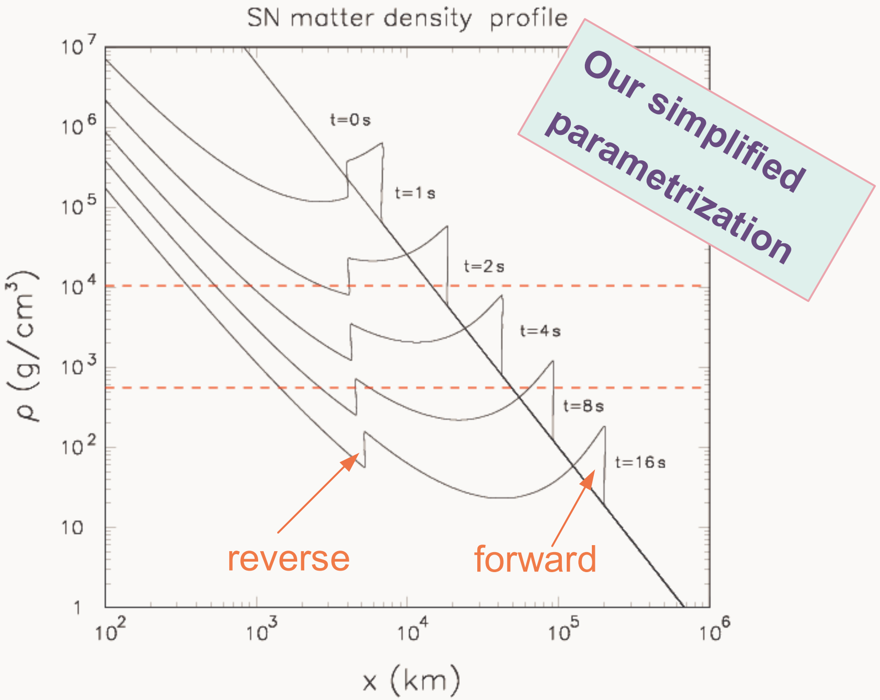


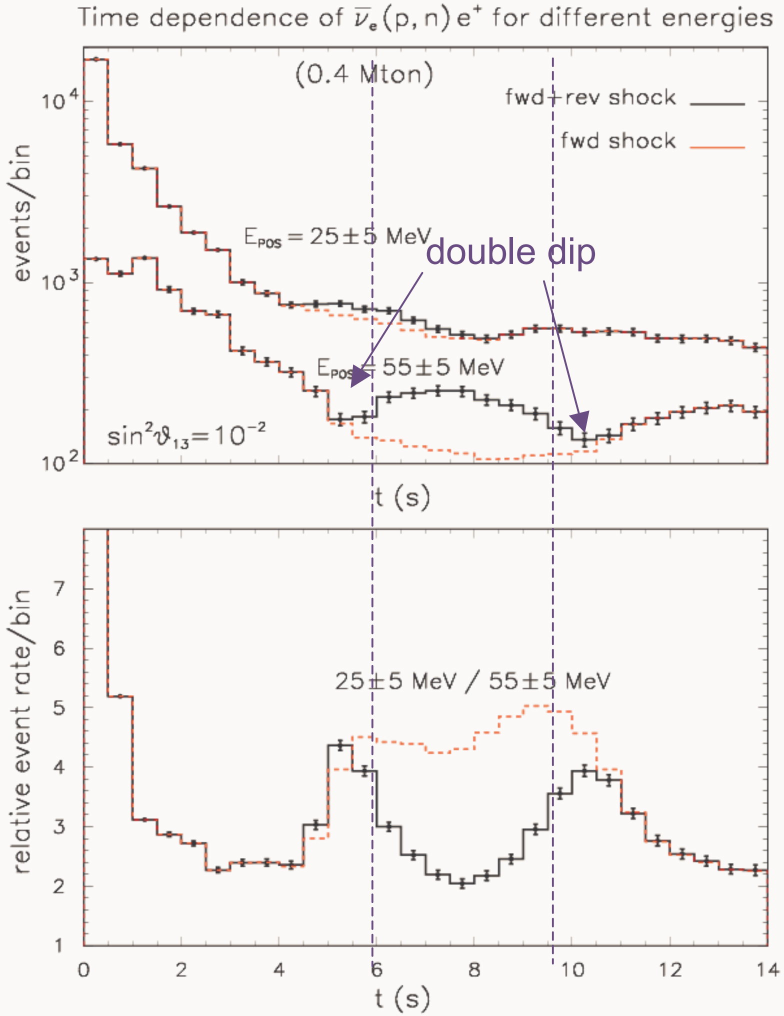
A way to extract a signature of the shock-wave is to evaluate the ratio of events in a bin at "low" energy (as a reference signal) w.r.t. one at "high" energy.

Shock effects will produce a time-dependent nonmonotonic behavior of the ratio, which cannot be mimicked by any other known effects.

NEW: THE REVERSE SHOCK

New Garching SN simulations show an additional **reverse shock** [see R.Tomas, M.Kachelriess, G.Raffelt, A.Dighe, H.T.Janka and L.Sheck, astro-ph/0407132].

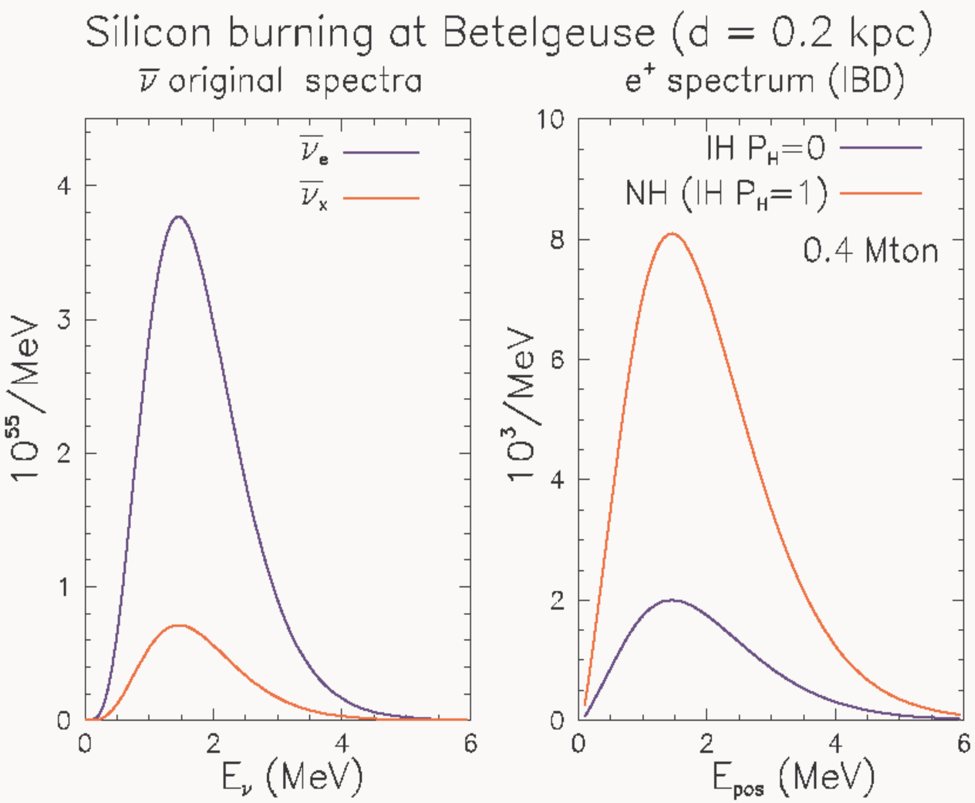




The characteristic signature for the presence of two shocks is the "double-dip" feature in the time spectra.

SILICON BURNING: SN SELF-ALERT

[A. Odrzywolek, M. Misiaszek, and M. Kutschera, astro-ph/0311012]

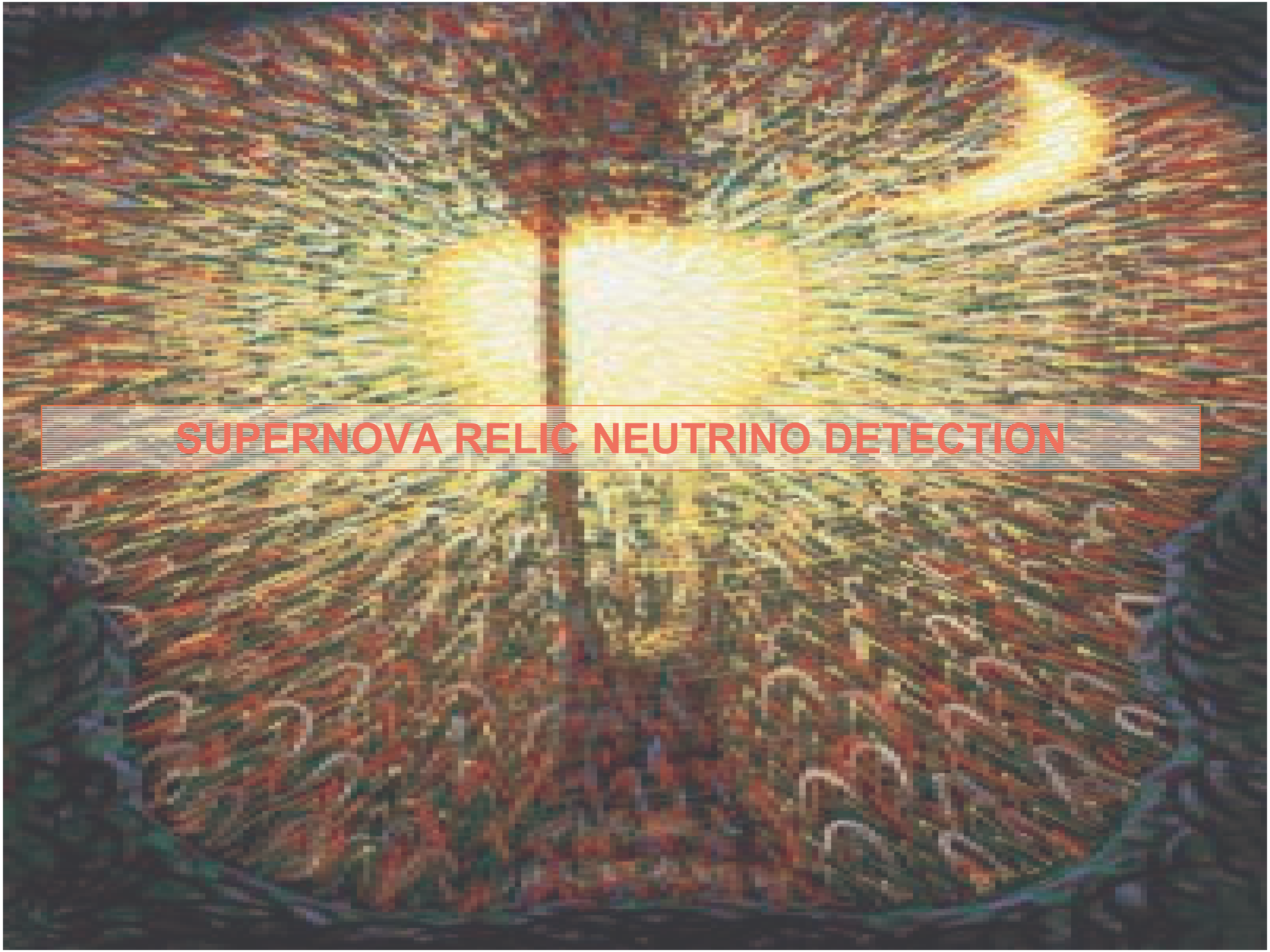


- **SILICON BURNING**
  - Duration: ~2 days before SN explosion
  - Reaction: $e^+ e^- \rightarrow \nu \bar{\nu}$

The detection of $\bar{\nu}_e$ by IBD is very difficult (because of the threshold E_{TH} = 5 MeV) , however ….

…. Adding gadolinium [J.F.Beacom, and M.R.Vagins, "*GADZOOKS! Antineutrino Spectroscopy with Large Water Cerenkov Detectors*", hep-ph/0309300], it would be possible to detect the associated neutron, but only for very close stars (d $\lesssim$ 2 kpc) because of the high neutron background (~2500 ev/day).

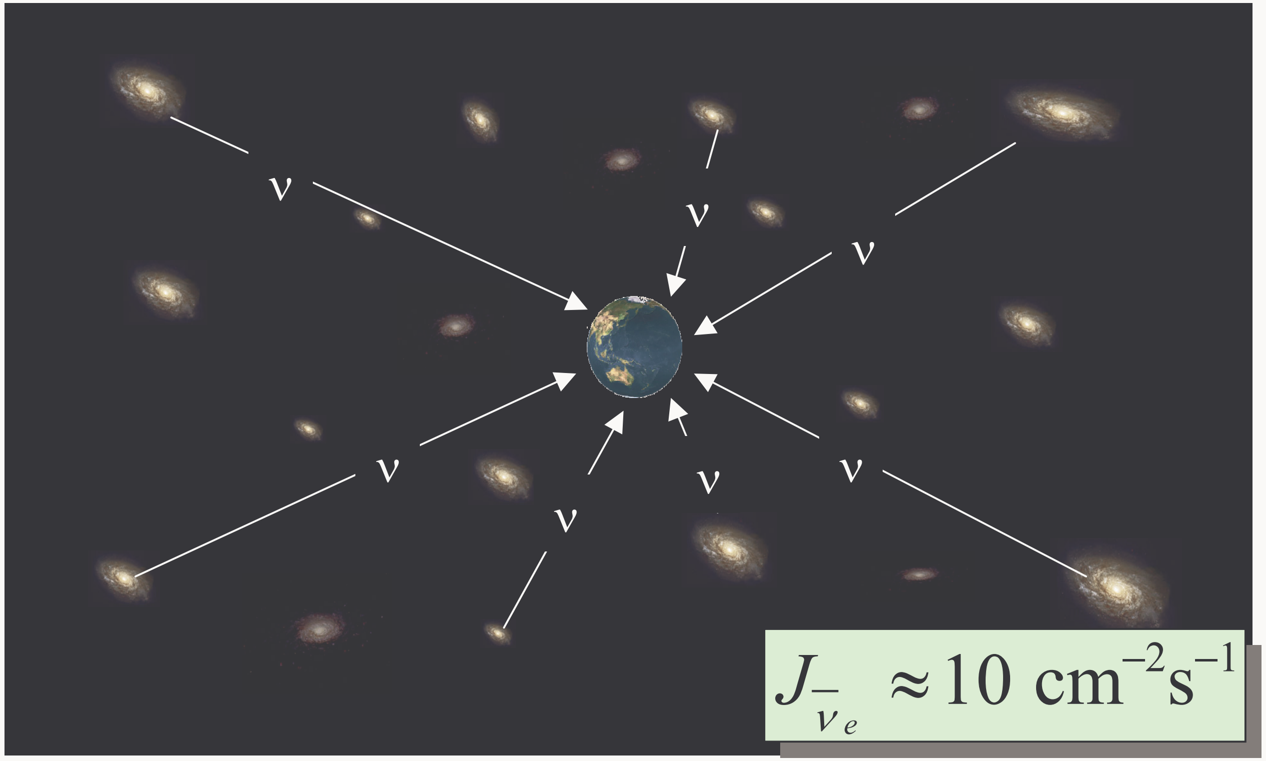
SUPERNOVA RELIC NEUTRINO DETECTION



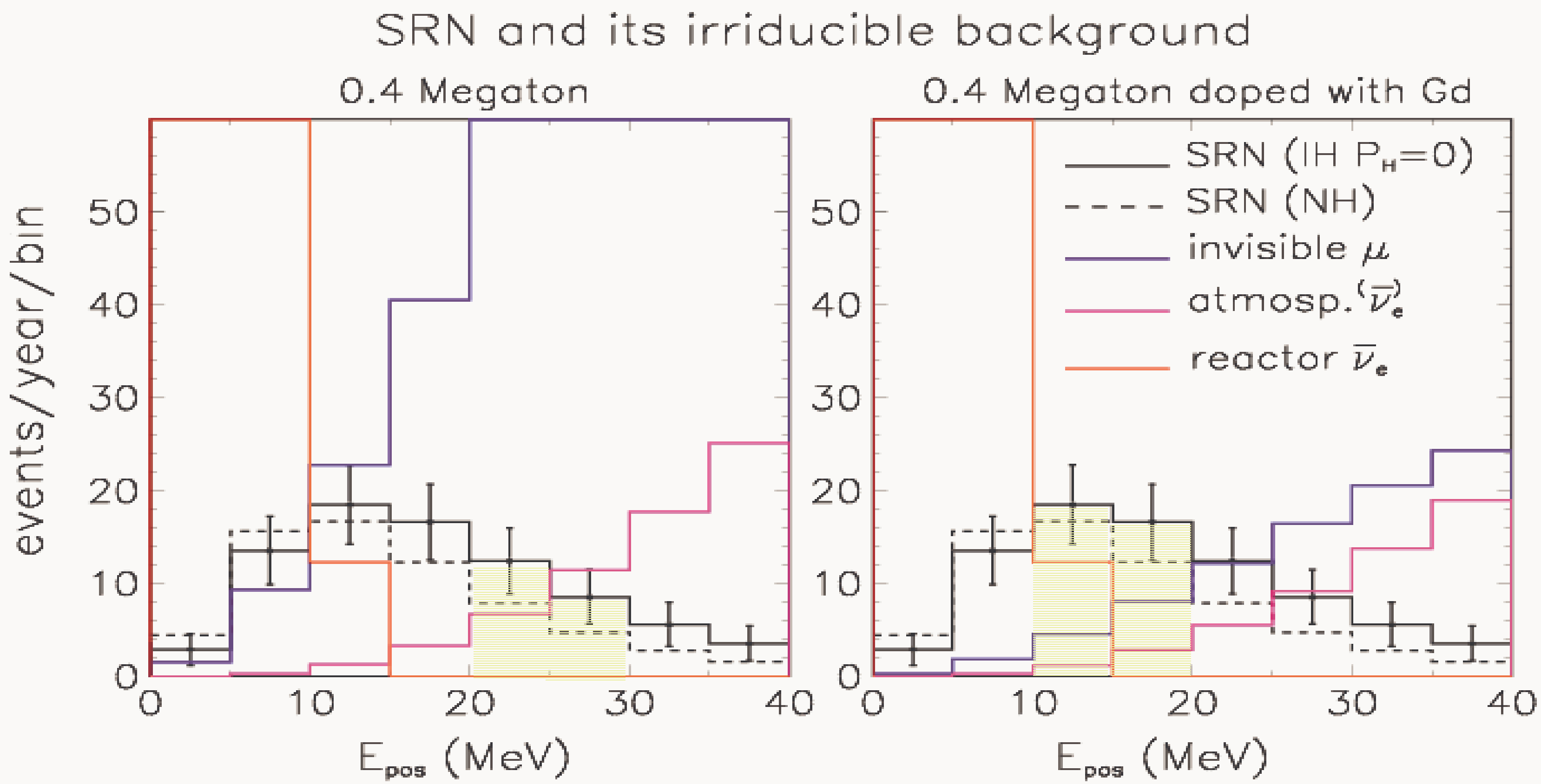
A galactic SN explosion is a spectacular event which will produce an enormous number of detectable ν, but it is a rare event (~ 3/century)

Conversly, there is a guaranteed ν background produced by all the past Supernovae in the Universe, but leading to much less detectable events.

A Megaton detector will be able to measure this background of neutrinos:
Supernova Relic Neutrinos (SRN)



$$J_{\bar{\nu}_e} \approx 10\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$



In the window $E_{pos} \in [20,30]$ MeV SRN = 21 ev/y (IH P_H =0), while bkgd = 161 ± 13 ev/y. SRN signal larger than 1σ error on the bkgd after 1 year of observations.

Adding Gd [J.F.Beacom, and M.R.Vagins, hep-ph/0309300**], spallation ~eliminated, invisible μ reduced by ~5. The analysis threshold lowered. In the window E_{pos} ∈ [10,20] MeV, SRN = 35 ev/y, bkgd = 34 ± 6 ev/y. In 1 year, the SRN signal detectable at 6σ level. Without Gd, the same measure will need ~ 36 years (at 6σ) !!**

SUMMARY AND CONCLUSIONS

The detection of neutrinos from supernovae is one the next frontiers of neutrino astrophysics.

The physics potential of a "Megaton" water detector in this context is enormous, both for particle physics and astrophysics.

In this context, we have investigated the discovery potential of a possible detector with a fiducial mass of 0.4 Mton in :

- **observing the neutronization and accretion ν bursts ;**
- **studying model-independent signatures of the shock-wave propagation in the time domain;**
- **seeing pre-SN ν signals during the silicon burning phase and thus "foreseeing" SN collapse (for close-by supernovae);**
- **detecting signals from extragalactic SN and from SRN.**

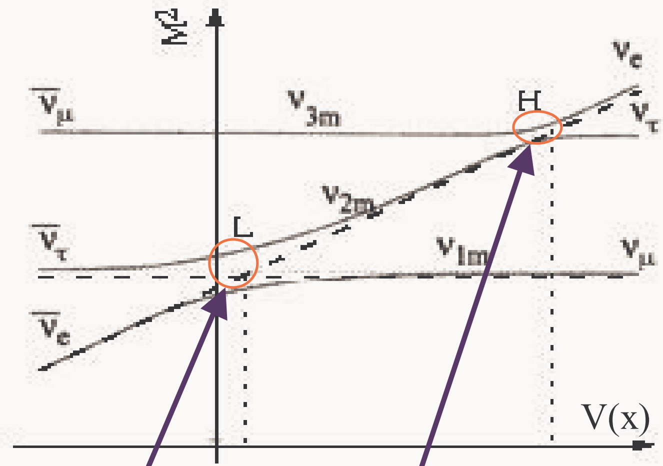
IN CONCLUSION

The SN ν physics program with 0.4 Mton detector is a no-loose project, and probably a high-winner one.

SUPERNOVA NEUTRINO OSCILLATIONS

Neutrino flavor evolution equations must be solved to obtain the relevant

$$P_{ee} = P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e) < 1$$



Final rotation to the flavor eigenstates in vacuum

Rotation to eigenstates in matter (at the neutrinosphere)

$$P_{ee} \cong \begin{pmatrix} U_{e1}^2 & U_{e2}^2 & U_{e3}^2 \end{pmatrix} \cdot \begin{pmatrix} 1-P_L & P_L & 0 \\ P_L & 1-P_L & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1-P_H & P_H \\ 0 & P_H & 1-P_H \end{pmatrix} \cdot \begin{pmatrix} U_{m,e1}^2 \\ U_{m,e2}^2 \\ U_{m,e3}^2 \end{pmatrix}$$

Lower level crossing transition.

$P_L \approx 0$ (adiabatic) since θ_{12} large and δm^2 small

Higher level crossing transition.

$0 \leq P_H \leq 1$ depending on θ_{13}

SURVIVAL PROBABILITY

The analytical form of P_{ee} is exceedingly simple

$$
\mathbf{P_{ee}} \approx \begin{cases} \sin^2\theta_{12}\mathbf{P_H} & (\nu,\ \text{normal}) \\ \cos^2\theta_{12} & (\bar{\nu},\ \text{normal}) \\ \sin^2\theta_{12} & (\nu,\ \text{inverted}) \\ \cos^2\theta_{12}\mathbf{P_H} & (\bar{\nu},\ \text{inverted}) \end{cases}
$$

$\mathbf{P_H}$ modulates $\mathbf{P_{ee}}$

In the next we will focus on the two extreme cases

- **$P_H \approx 0$ (i.e. $\sin^2\theta_{13} \gtrsim 10^{-3}$)**
- **$P_H \approx 1$ (i.e. $\sin^2\theta_{13} \lesssim 10^{-5}$)**

If $P_H \not\approx 1$ ($\sin^2\theta_{13} \gtrsim 10^{-5}$), it helps to discriminate mass hierarchy

SUPERNOVA RELIC NEUTRINO AND BACKGROUND

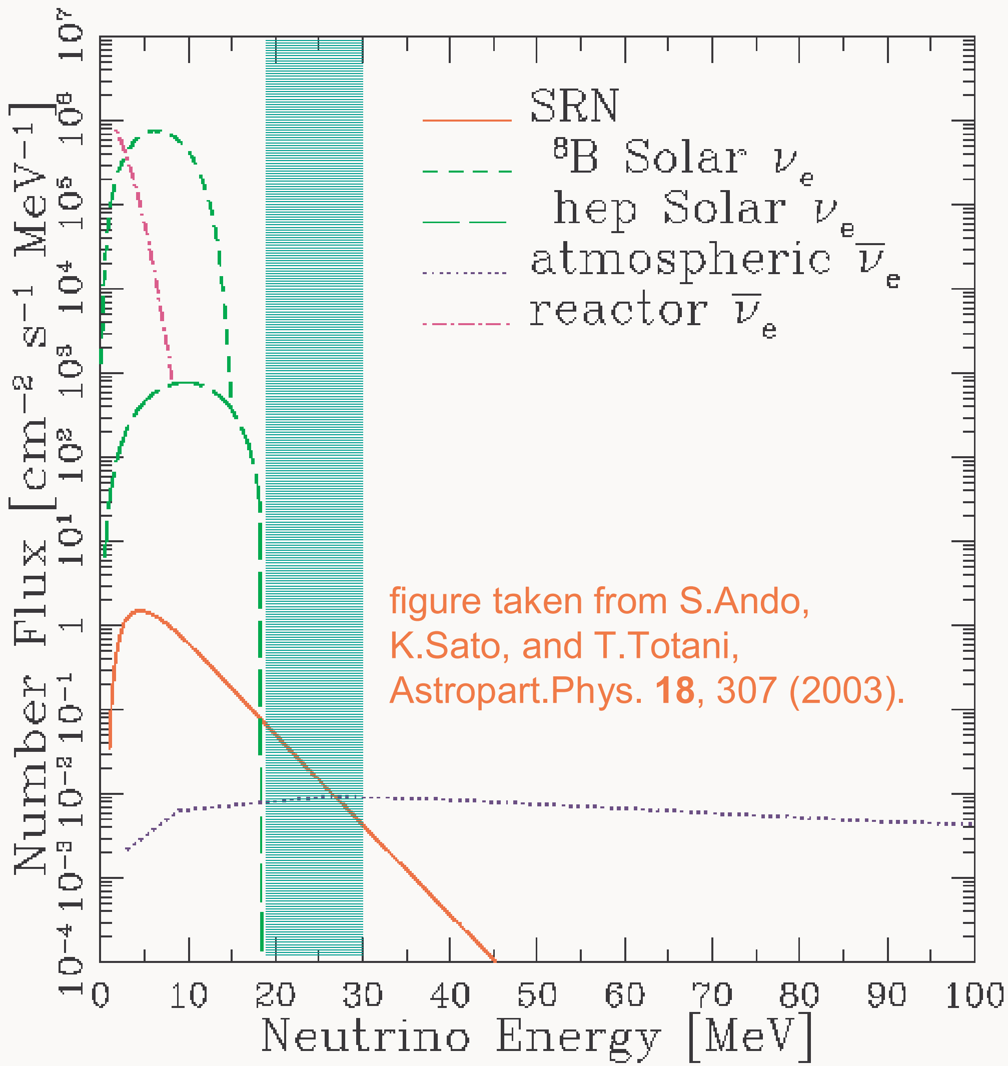


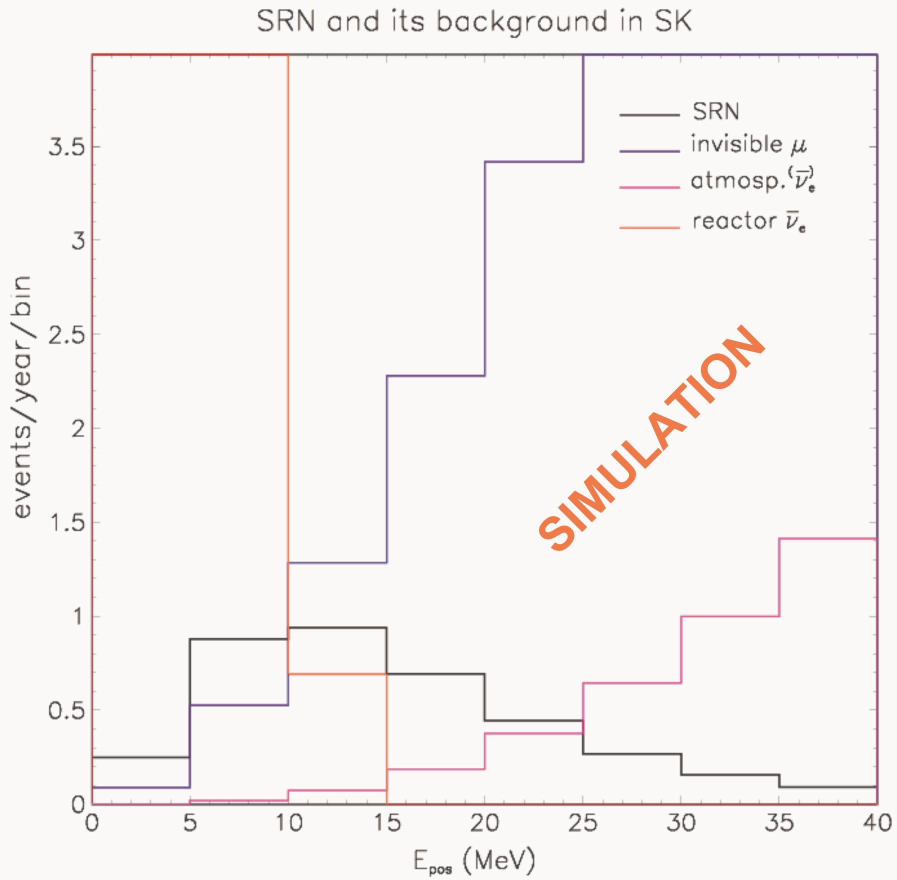
figure taken from S.Ando, K.Sato, and T.Totani, Astropart.Phys. **18**, 307 (2003).

Below ~15–20 MeV, bkgd dominated by spallation products (made by atmospheric μ) and by reactor $\overline{\nu}_e$.

For $E_\nu \in$ [20-30] MeV, the bkg of low-energy atmospheric $\overline{\nu}_e$ is relatively small.

But, in this window, there is a large background due to “invisible” μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\overline{\nu}_\mu$.

In conclusion, there is no energy window where SRN > background. SRN flux can be measured just as a distortion of the irriducible background.



SRN signal should manifest as distortion of the bkg spectra.

No distortion ⟶ flux limit

Super- Kamiokande collaboration has recently investigated the SRN flux using 1496 days of data [M.Malek et al., Phys.Rev.Lett. **90**, 061101 (2003)**]. It fixed an upper bound on SRN signal:**

$$J_{\bar{\nu}_e} \leq 30\,\mathrm{cm}^{-2}\ \ \mathrm{s}^{-1}$$

~ 3 times larger than "typical" theoretical predictions