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Neutrinos from Supernovæ and Supernova Remnants

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Supernovae (SN) and supernova remnants (SNR) have key roles in galaxies, but their physical descriptions is still incomplete. Thus, it is of interest to study neutrino radiation to understand SN and SNR better. We will discuss: (1) The ∼10 MeV thermal neutrinos that arise from core collapse SN, that were observed for SN1987A, and can be seen with several existing or planned experiments. (2) The 10-100 TeV neutrinos expected from galactic SNRs (in particular from RX J1713.7-3946) targets of future underwater neutrino telescopes.

Overview

General Facts

⋆ **Massive stars live short: e.g., 2×10^7 yr for a $M = 12\ M_\odot$ star. They end their life cycle as supernovæ (SN).**

SN of type Ia are thought to originate from explosive nuclear reactions. *Very luminous; used as 'standard candles' of cosmology. Here, we are interested in them only as SNR precursors*

The other ones, II, Ib, Ic, from core collapse of a supermassive star, $M \geq 6 - 10\ M_\odot$. *Large variety of light curves, much less luminous. During the collapse, radiate a lot of ν's of $\sim 10\ MeV$*

⋆ **The leftover gas is the supernova remnant (SNR). Kinetic energies of a few times 10^{51} erg, or velocities ~ 4000 km/sec in free expansion.**

Various phases, according to the age of SNR. Various shapes (shell, plerionic, or mixed).

Guessing 'where'

The best guess I can propose for next galactic core collapse SN is

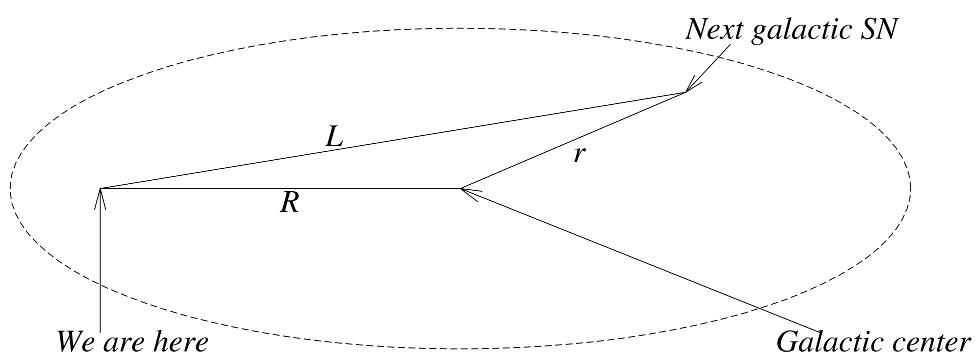
$$\langle L \rangle = 10 \pm 4.5 \text{ kpc}$$

and it is motivated as follows:

⋆ *We are $R = 8.5$ kpc from the galactic center.*

⋆ *Distribution of the matter that can go supernova:* $\rho \sim r e^{-r/r_0}$ *with r=distance from the center and* $r_0 = 3$ *kpc, possibly summing a* $\delta(r)$ *to describe the 'bar'*

⋆ *We calculate the distribution in function of L=distance from us, integrate over the galactic azimuth* θ *and get the result above.*



Guessing 'when'

⋆ **The rate of core collapse SN in the Milky Way is expected to be**

$$R_{SN} = 1/(\textbf{30-70 years})$$

The most reliable method is: count SN in other galaxies, and correlate with galactic type.

Padova-Asiago database includes several thousand SN. However, Milky Way type could be Sb or Sb/c, which means a factor 2 uncertainty

A similar rate expected for SN Ia.

⋆ **Possibly, we missed several galactic SN due to dust. For the future, better coverage with ν's, IR and perhaps gravitational waves**

⋆ **From absence of neutrino bursts, one derives**

$$R_{SN} > 1/(\textbf{20 years}) \text{ at } 1\sigma$$

Till 1986 only Baksan, with 90 % DAQ livetime, then assumes 100 % . Assumes Poisson statistics, $\exp(-TR_{SN}) > C.L$ **with** $T = 23$ **years**

We estimate the number of various interesting galactic objects assuming $R_{SN}^{tot} = 1/($25 years$)$

Object	Lifetime	Number
Pre-SN with ν	20 million y	400.000
Pulsars	2 million y	40.000
SNR	$100.000\ y$	2×2000
young SNR	$2000\ y$	2×40

Pre-SN with ν $\Rightarrow$core collapse SN. Recall that core collapse SN produce neutron stars (NS) or stellar BH, and that pulsars are 'active' NS. Type Ia make white dwarfs, but are also supposed to produce SNR (factor 2 above)

Several remarks:

⋆ *Young SNR could be the main source of cosmic rays (more on this later)*

⋆ *Perhaps relevant for the origin of magnetic fields*

⋆ *SN of all types form and redistribute heavy elements.*[a]

[a] Using the words of A. Sorrenti (1977) *noi siamo figli delle stelle*

Neutrinos from Core Collapse Supernovæ

Astrophysics of core collapse

(PRE-SN) **Giant stars burn in sequence H, He, C and Si, Ne, Mg, Na etc, form an "onion structure", with a inert 'iron' core in the center**

(MANTLE) **Violent stellar winds modify external mantle in latest stages, for certain masses; apparently, happened for SN1987A (was a $\sim 20\ M_\odot$ *blue* giant)**

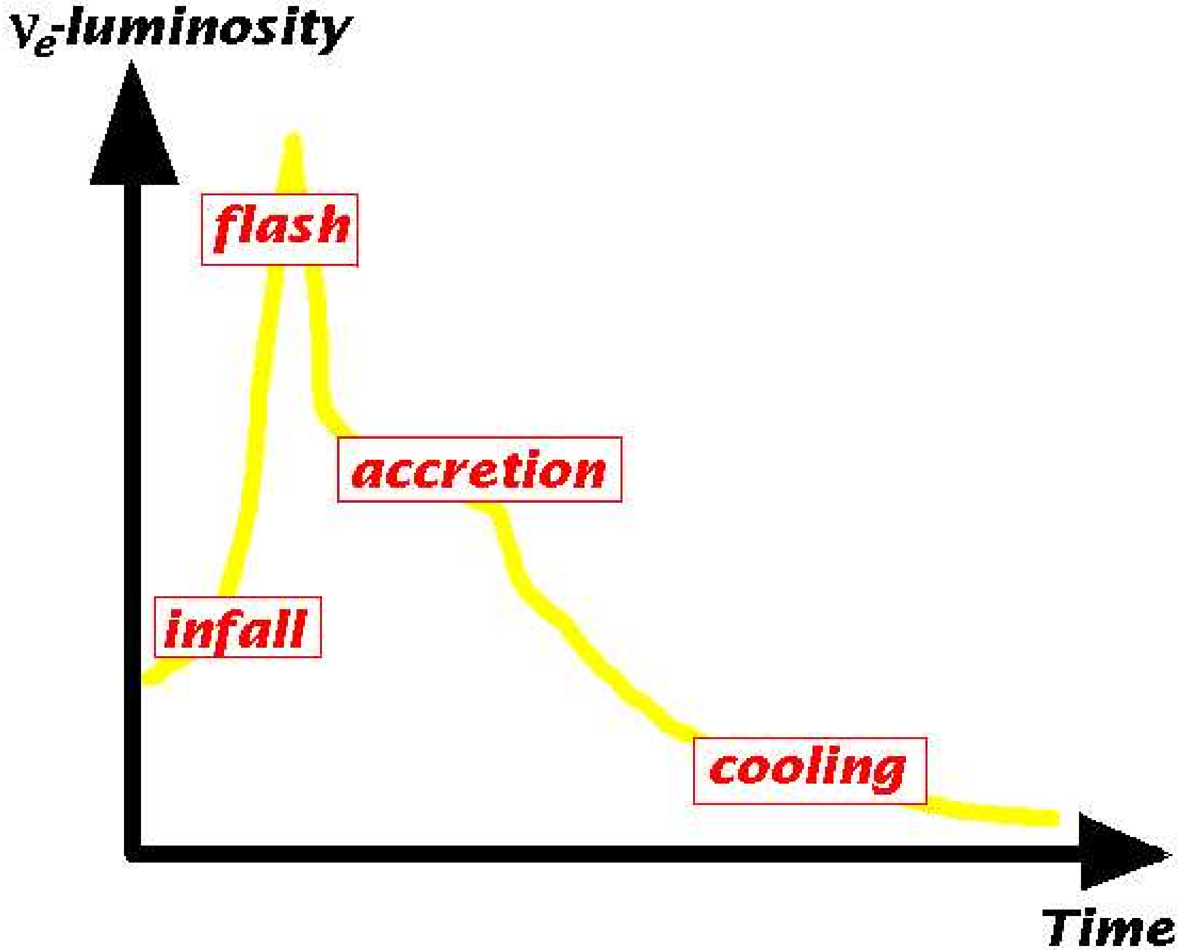
(CORE) **Gravitational pressure balanced by e^- degeneracy pressure ($\Rightarrow$ core grows). When e^- become relativistic, equilibrium is impossible. Iron core mass is $\sim 1.4\ M_\odot$**

(COLLAPSE) **The collapse begins. The sequence of the events becomes uncertain. More on the reference picture, the so-called "delayed scenario"**

(ENERGETICS) **Total energy of the collapse is very large; with $M_{ns}/M_\odot = 1-2$, $R_{ns} = 15$ km$(M_\odot/M_{ns})^{1/3}$,**

$$\mathcal{E} \simeq \frac{3 G_N M_{ns}^2}{7 R_{ns}} = (1-5)\times 10^{53}\ \text{erg}$$

Pictorial summary of the 'delayed scenario' (Wilson & Bethe):



The energy radiated in any neutrino species $e, \bar{e}, \mu, \bar{\mu}, \tau, \bar{\tau}$ is expected to be the same within a factor of two (Janka et al.)

$$\mathcal{E}_e \sim \mathcal{E}_{\bar{e}} \sim \mathcal{E}_x$$

x denotes any among μ, $\bar{\mu}$, τ, $\bar{\tau}$ since in this picture non-electronic neutrinos and antineutrinos are produced in a similar amount

Mostly emitted in cooling (80-90 %) and accretion (10-20 %)

Prescription for time integrated flux (fluence)

$$F_i(E) = \frac{\mathcal{E}_i}{4\pi D^2} \frac{N}{\langle E_i \rangle^2} z^\alpha e^{-(\alpha+1)z}, \qquad z = \frac{E}{\langle E_i \rangle}$$

$\langle E_i \rangle$ is the average energy of the neutrino species $i = e, \bar{e}, x$; N ensures that the total energy carried is $\mathcal{E}_i$.

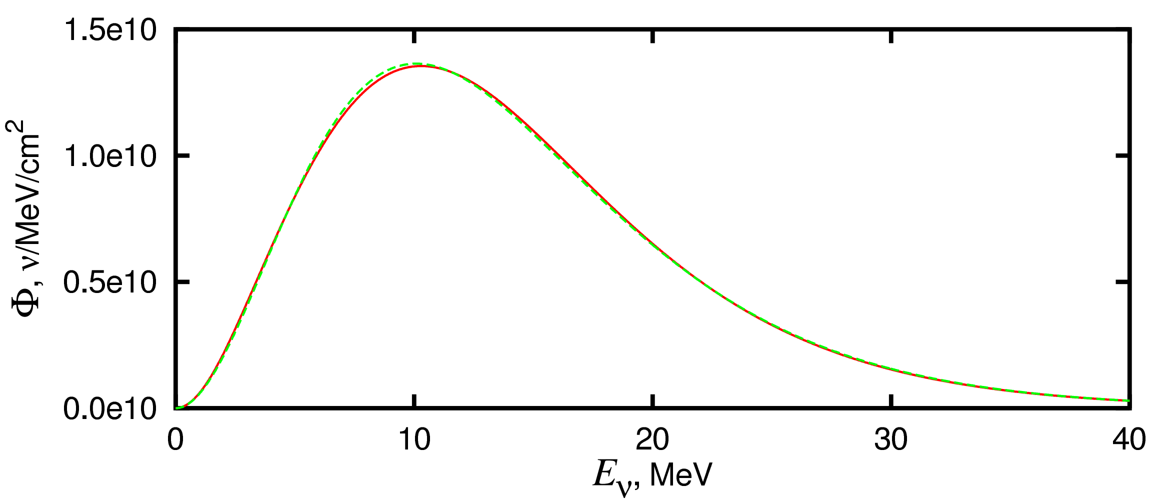
If one wants to describe time dependent situations, $\mathcal{E}_i \to L_i(t) \equiv d\mathcal{E}_i/dt$, $\langle E_i \rangle \to \langle E_i(t) \rangle$, $\alpha \to \alpha(t)$.

Expectations for time integrated quantities

$$\langle E_{\bar{e}} \rangle = 12 - 18 \text{ MeV}, \qquad \langle E_x \rangle / \langle E_{\bar{e}} \rangle = 1 - 1.2$$

$$\mathcal{E}_{\bar{e}} = (2 - 10) \times 10^{52} \text{ erg} \qquad \mathcal{E}_x / \mathcal{E}_{\bar{e}} = 1/2 - 2$$

One guesses $\mathcal{E}_e = \mathcal{E}_{\bar{e}}$ (not so important); ν_e temperature can be estimated from the emitted lepton number



A comparison between a reasonable time integrated flux and its analytical approximation

Oscillations of SN neutrinos

To account for oscillations we need to assign just 2 functions, P_{ee} and $P_{\bar{e}\bar{e}}$:

$$\bullet F_e = F_e^0 \; P_{ee} + F_\mu^0 \; P_{\mu e} + F_\tau^0 \; P_{\tau e}$$
$$= F_e^0 \; P_{ee} + F_x^0 \; (P_{\mu e} + P_{\tau e})$$
$$= F_e^0 \; P_{ee} + F_x^0 \; (1 - P_{ee})$$
$$\bullet F_e + F_\mu + F_\tau = F_e^0 + F_\mu^0 + F_\tau^0$$

- **(similar for antineutrinos)**

We consider only oscillations of massive νs
The relevant densities to calculate P_{ee} and $P_{\bar{e}\bar{e}}$ are $\rho_{sol} \sim 10$ gr/cc (C+O) and $\rho_{atm} \sim 10^3$ gr/cc (He)

Is there any other effect to be included?
The answer is conditional, that is no unless
1) μ and τ flux were different
2) there are sterile neutrinos, that can give more MSW or vacuum oscillations
3) there is something else beside oscillations of massive ν's say, large magnetic moments

We begin from $F_e = F_x^0 - P_{ee}(F_x^0 - F_e^0)$.
With normal mass hierarchy:

$$P_{ee} = \begin{cases} \sin^2\theta_{13} \sim 0 & \theta_{13} \text{ `large', } > 1^\circ \\ \sin^2\theta_{12} \sim 0.3 & \theta_{13} \text{ `small', } < 0.1^\circ \end{cases}$$

We ask a precise question on U_{e3}*:*
Can we distinguish the two cases?

Here is a check-list

Emission	Good	Bad	Remarks
cooling	**strong** ν **radiation**	**uncertainties, small effect**	$F_x^0 \sim F_e^0$
accretion	**strong** ν **radiation**	**uncertainties!**	$F_x^0 \sim F_e^0/2$
neutronization	**clean signal**	**weak** ν **radiation**	$F_x^0 \sim 0$
neutroniz.++ with rotation	**clean and strong sign.**	**uncertain!!**	$F_x^0 \sim 0$ *(LSD?)*

If the mantle is stripped off till $\rho > 10$ *gr/cc (e.g., with SN Ic) we have vacuum oscillations,* $0.3 \to 0.6$ *(Selvi).*
This is rare, but not impossible

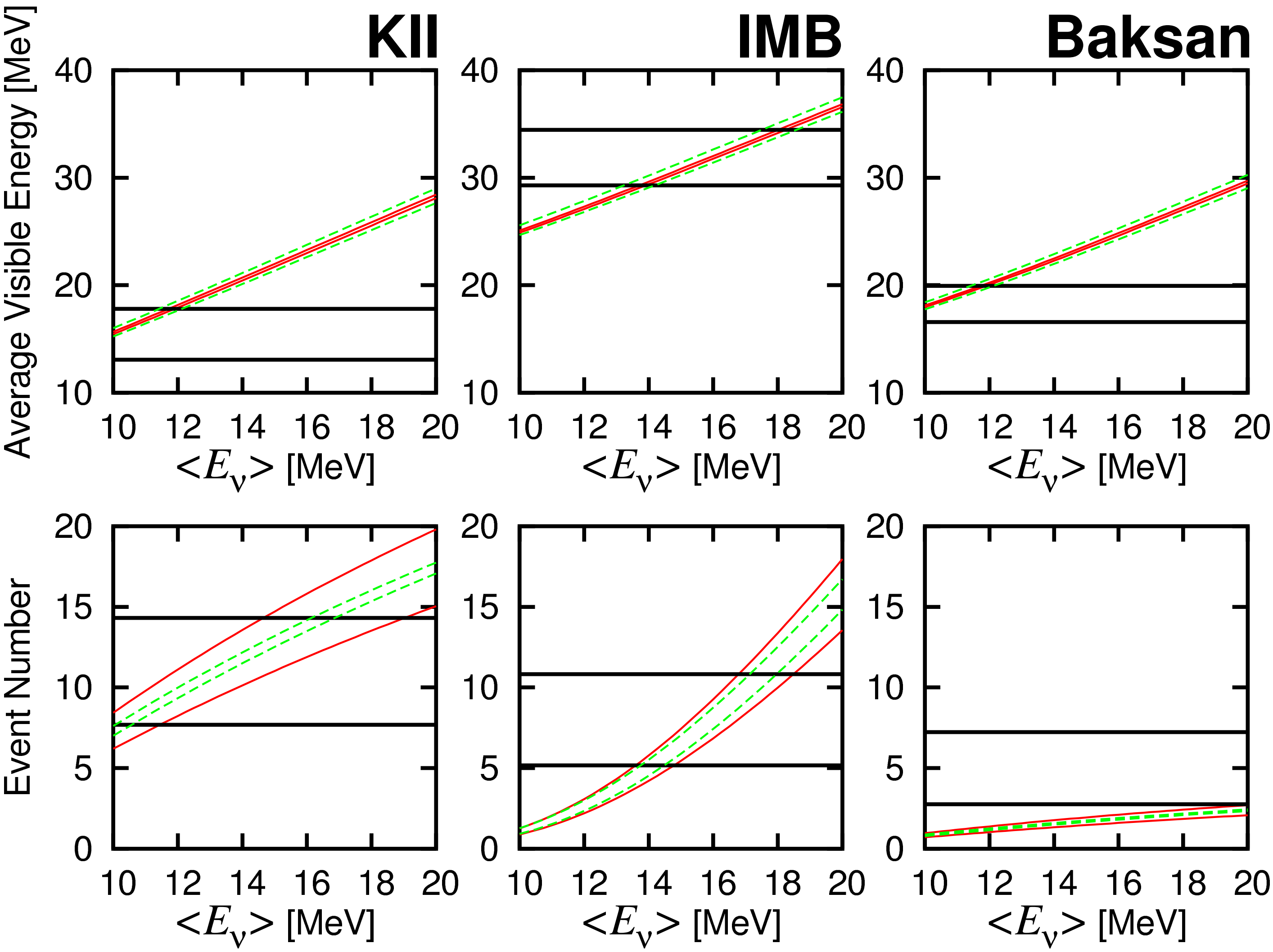
SN1987A

The detection of SN neutrino is of epochal importance.

These observations fit into the 'standard' picture for neutrino emission (see next figure), but there are some <u>puzzling</u> aspects:

1. *IMB and Kam-II find forward peaked distributions; e.g.,* $\langle \cos\theta \rangle$ *are* $\sim 2\ \sigma$ *above expectations*
2. $\langle E_{vis}^{\mathrm{KII}} \rangle \sim 15$ *MeV and* $\langle E_{vis}^{\mathrm{IMB}} \rangle \sim 30$ *MeV* (± 2.5 *MeV*) *are quite different even correcting for efficiencies*
3. *Time sequence of events looks different; when combined not so bad (but abs. time is unknown).*
4. *The 5 LSD events, occurred 4.5 hours before the main signal, cannot be accounted for.*

We stress the <u>consistency</u> 'standard' interpretation, but the space for non-standard ones is not small (not only due to limited statistics)



A reasonable agreement with expectations if

$\langle E_{\bar{e}} \rangle \equiv E_0 = 12 - 16$ **MeV**

$\mathcal{E} = (2-3) \times 10^{53}$ **erg**

zero or a few $\nu_e \; e \to \nu_e \; e$ **events in KII**

Neutrinos from Supernova Remnants

SNR and CR

An argument by Ginzburg and Syrovatskii suggests SNR as main source of galactic cosmic rays (CR).

The Milky Way irradiates CR. Take $V_{CR} = \pi R^2 H$ **with** $R \sim 15$ **kpc,** $H \sim 5$ **kpc as the volume of confinement. Take** $\tau_{CR} = 5 \times 10^7$ **years as CR lifetime in the Galaxy. We get:**

$$\mathcal{L}_{CR} = \frac{V_{CR} \cdot \rho_{CR}}{\tau_{CR}} = 0.9 \times 10^{41} \textbf{erg/s}$$

We have a new SN each $\tau_{SN} \sim 25$ **year, with about** $\mathcal{E} \sim 10^{51}$ **erg in kinetic energy, that is**

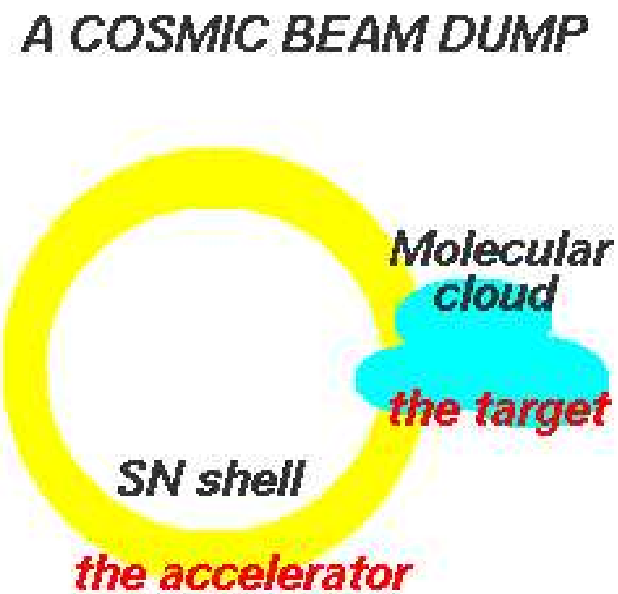
$$\mathcal{L}_{SN} = \frac{\mathcal{E}}{\tau_{SN}} = 1.2 \times 10^{42} \textbf{erg/s}$$

If a SNR is able to convert a fraction $f_{CR} \sim 5 - 10$ **% into CR, we are home.**

These numbers shouldn't be taken too seriously, but this 40-years-old arguments maintains its appeal!

In 2000 years, the SNR proceeds by ~ 10 *pc. The density is about 0.2 protons/cm*^{3}*.*

A molecular cloud can have a much larger density, till 10^4 *protons/cm*^{3}*. The 2 can form:*



This is ideal for detection!

$$\textbf{CR collisions} \rightarrow \begin{cases} \pi^0 \rightarrow & \textbf{high energy } \gamma \\ \pi^{\pm} \rightarrow & \textbf{high energy } \nu_\mu, \nu_e \end{cases}$$

Thus we should have γ *and* **neutrinos**

RX J1713.7-3946

Is it our first "cosmic beam dump"?

1) Seen in X-rays, with many details

2) Is in Chinese Annales, 393 A.D.

3) A molecular cloud seen in CO and 21 cm H line

4) Most interestingly, CANGAROO (since 2000) and H.E.S.S. (since 2004) do see TeV γ *rays*

The distance is 1 kpc, the angular size about 1°**, the density of the cloud** ~ 100 **part/cm**^{3}**. The source is transparent to gamma rays, neutrino flux can be calculated easily**

Be warned!!! What I discuss is just an interesting interpretation, but no item above is waterproof

The cosmic ray spectrum:

$$F_p = KE^{-\Gamma}, \quad \Gamma = 2 - 2.4$$

interacts with the molecular cloud. The chains $p \to \pi^0 \to \gamma$ *and* $p \to \pi^+ \to \mu^+ \to \nu_e$ *yield*

$$F_\Gamma = \frac{\Delta X}{\lambda_p} \frac{Z(p\pi^0)}{\Gamma} F_p \ , \quad F_{\nu_e} = \frac{\Delta X}{\lambda_p} Z(p\pi^+) f(\Gamma) F_p$$

Using the flux measured by H.E.S.S. between 1-10 TeV we get:

$$F^0_{\nu_\mu} = 7.3 \times 10^{-12} \ \left(\frac{E}{\mathrm{TeV}}\right)^{-2.2} \frac{1}{\mathrm{TeVcm^2s}}$$

$$F^0_{\overline{\nu}_\mu} = 7.4 \times 10^{-12} \ \left(\frac{E}{\mathrm{TeV}}\right)^{-2.2} \frac{1}{\mathrm{TeVcm^2s}}$$

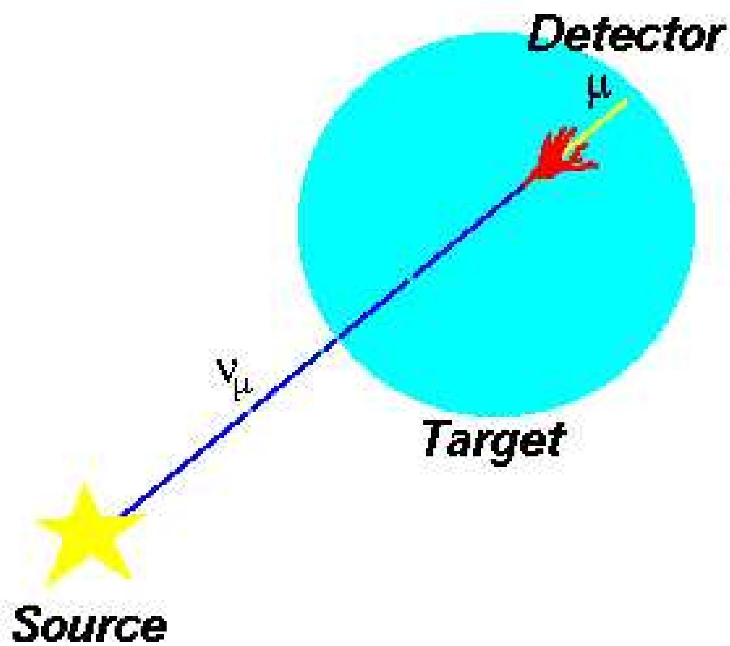
$$F^0_{\nu_e} = 4.7 \times 10^{-12} \ \left(\frac{E}{\mathrm{TeV}}\right)^{-2.2} \frac{1}{\mathrm{TeVcm^2s}}$$

$$F^0_{\overline{\nu}_e} = 3.0 \times 10^{-12} \ \left(\frac{E}{\mathrm{TeV}}\right)^{-2.2} \frac{1}{\mathrm{TeVcm^2s}}$$

Oscillations take the simplest form (vacuum averaged, or Gribov-Pontecorvo) and can be included easily.

Signals of neutrinos

ν interactions are due to deep elastic scattering. The simplest and most traditional observable is induced muons, that can be correlated to the source by mean of an angular cut.



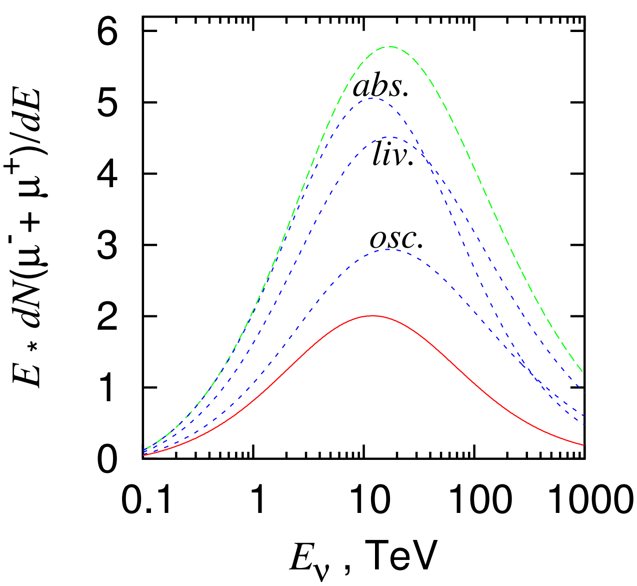
Recall that high energy ν_μ are to some extent absorbed from the Earth, and that when the source is above the horizon, it is impossible to see anything due to the background from atmospheric μ. Along with oscillations, these effect decrease the signal.

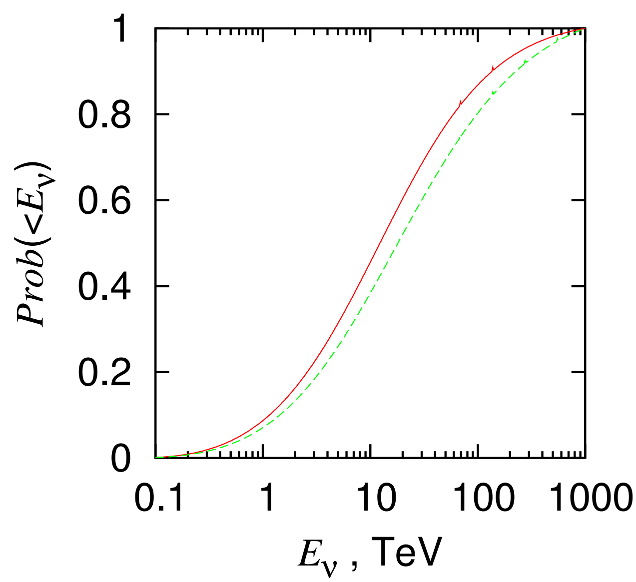
For an ideal detector, with

Area=1 km^2 Data taking=1 year $E_{thr.} = 50$ GeV

the number of events is about 10
(this was 30 if oscillations, absorption and μ-background were ignored, or even 40 if the slope was $\Gamma = 2.0$)

The differential and cumulative distributions in neutrino energy; absorption and livetime are calculated for a detector in the Mediterranean





Discussion and perspectives

⋆ We have not a clear understanding of how SN explode. Perhaps this is because it is a very difficult problem, perhaps there is some missing ingredient, perhaps the answer is not unique (a combination of various mechanisms?), ... perhaps the confusion will persist even after next galactic SN

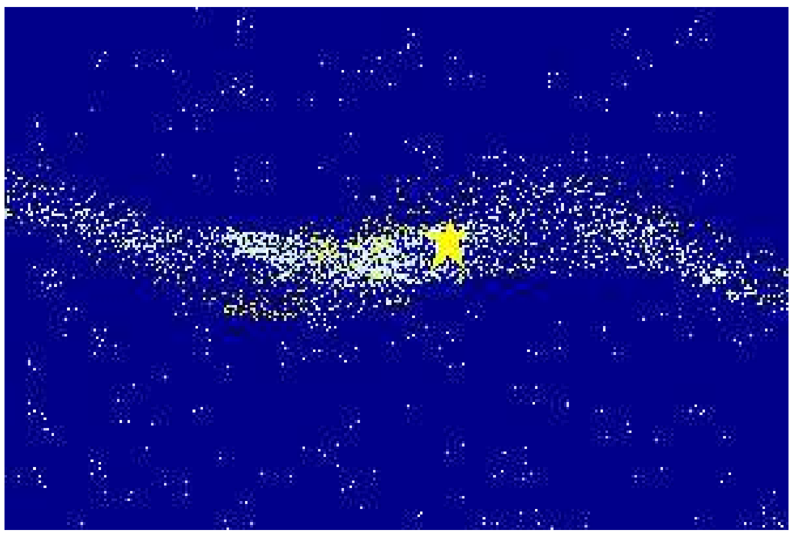
⋆ Neutrinos from next galactic SN have an impressive potential to orient our understanding. The hypothesis of an "accretion phase" can be certainly be tested. SN1987A does not contradict the 'delayed scenario' seriously (but does not help much either). There are some chances to learn on oscillations and more in general on particle physics. The possibility to use ν_e and neutral current events deserves more consideration.

⋆ Neutrinos from SNR are an uncharted territory. Recent results from γ rays motivated us to consider one specific SNR (however new results and perhaps surprises with γ rays are expected). Sure enough, CR acceleration in SNR cannot be considered understood, and there are several other possible sources for TeV ν astronomy, however the number of events we found (about 10/km^2 y) suggests the need of pretty large exposures.

Thank you for the attention!

References and credits

This talk is mostly based on 1) one Surveys in High En. Phys. with Cavanna, Costantini, Palamara; 2) one Phys.Rev.D and 3) one Nucl.Phys.Proc.Suppl. (NuINT04) with Costantini & Ianni; 4) one Astropart. Ph. with Costantini.

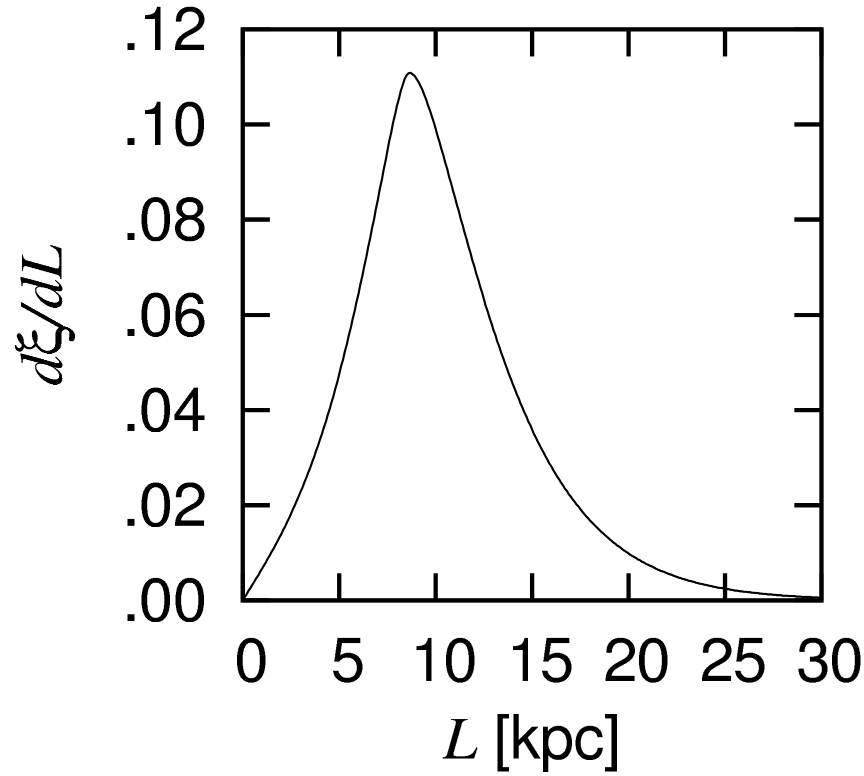


Many thanks to all other people (and they are a lot) who helped me with these topics, in particular J Beacom, V Berezinsky, A Bettini, M Cirelli, G Di Carlo, P Desiati, S Dugad, C Fryer, W Fulgione, P Galeotti, PL Ghia, VS Imshennik, HT Janka, T Montaruli, DK Nadyozhin, G Navarra, A Porta, OG Ryazhskaya, M Selvi, A Yu Smirnov, I Sokalsky, A Strumia, R Thorne, Y Uchiyama

Appendices

More on "guessing where"

Just for fun, this is the distribution in L that I find assuming no large contribution from a "bar"



Of course it would be much better to have a detailed map of young regions ('supernova explosive') of the Galaxy or even a complete enough catalog.

Do you know the right astronomer?

More on delayed scenario

Name	Description	Time	% $\mathcal{E}$
infall only ν_e	$ep \to \nu_e n$. ν-trapping	~ 100 msec	< 1
flash only ν_e	Bounce. ν-sphere is reached	$\sim$msec $[t \equiv 0]$	~ 1
accretion $\nu_e, \bar{\nu}_e, \nu_x?$	Stall. $e^+e^- \to \nu\bar{\nu}$ Shock resumes	0.5-1 sec	10-20
cooling $\nu_e, \bar{\nu}_e, \nu_x$	Proto NS cools and contracts	10-100 sec	80-90

Important remarks:

⋆ *Infall and flash=early neutronization. Can be much more important with rotation (Imshennik,+Ryazhskaya,Fryer&Heger)*

⋆ *Accretion: Explosion stalled in attempt to dissociate the iron core then resumed by ν energy deposition + convective motions*

⋆ *Cooling. Steady phase, probably accounts for most ν. This permits some prediction even in absence of a theory of explosion*

⋆ *Lamb & Loredo claim that accretion+cooling fits better the events from SN1987A*

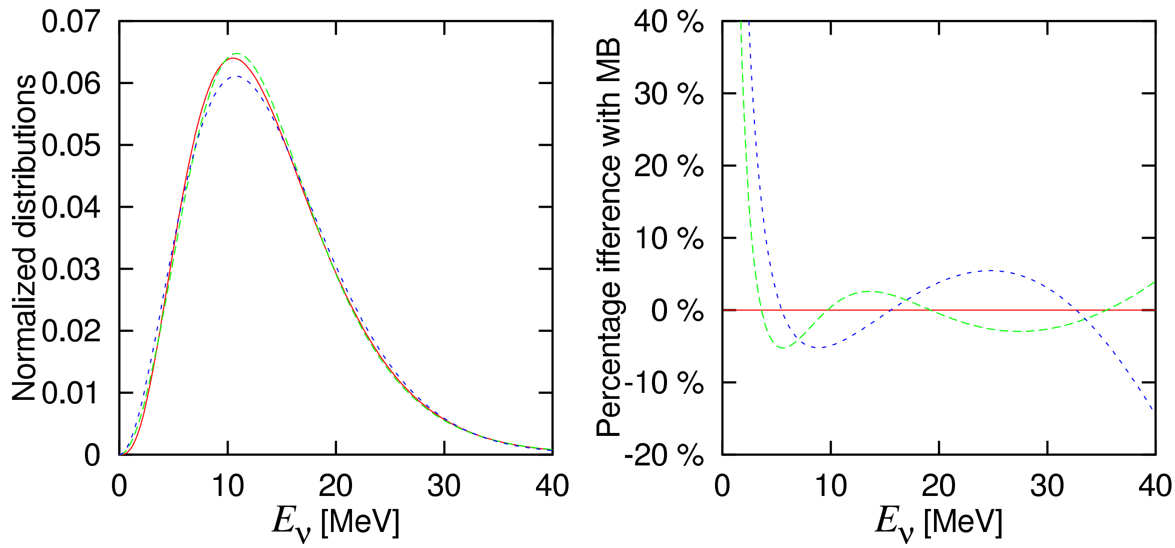
Energy distribution of SN neutrinos

In 1^{st} approximation, the neutrino flux is thermal.

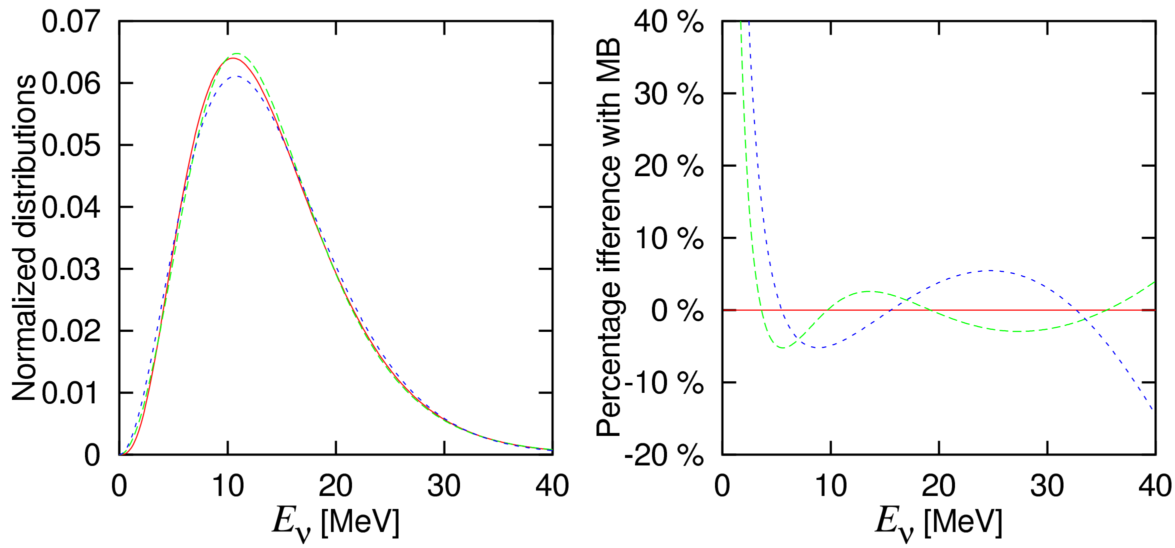
Small deviations described by the following analytical approximations:

$$F(E) \sim \begin{cases} \rho_{FD} = \dfrac{E^2}{1+e^{E/T}}\ e^{-(E/\epsilon)^2}, & \epsilon \neq \infty \\ \rho'_{FD} = \dfrac{E^2}{1+e^{E/T-\eta}}, & \eta \neq 0 \\ \rho_{MB} = E^\alpha\ e^{-E/T}, & \alpha \neq 2 \end{cases}$$

One parameter is the 'temperature' T; the other one accounts for (small) deviations from a thermal spectrum. They agree within 5 % for SN1987A.



We do not know with certainty SN properties, and thus the parameters of ν fluxes. But an 'intrinsic' ('limiting') uncertainty of ~ 5 % is just due to the choice of parameterization:



Indeed, the three distributions above have same $\langle E\rangle = 14$ MeV and $\sqrt{\langle E^2\rangle - \langle E\rangle^2} = 7$ MeV.

Color codes (see page 13):

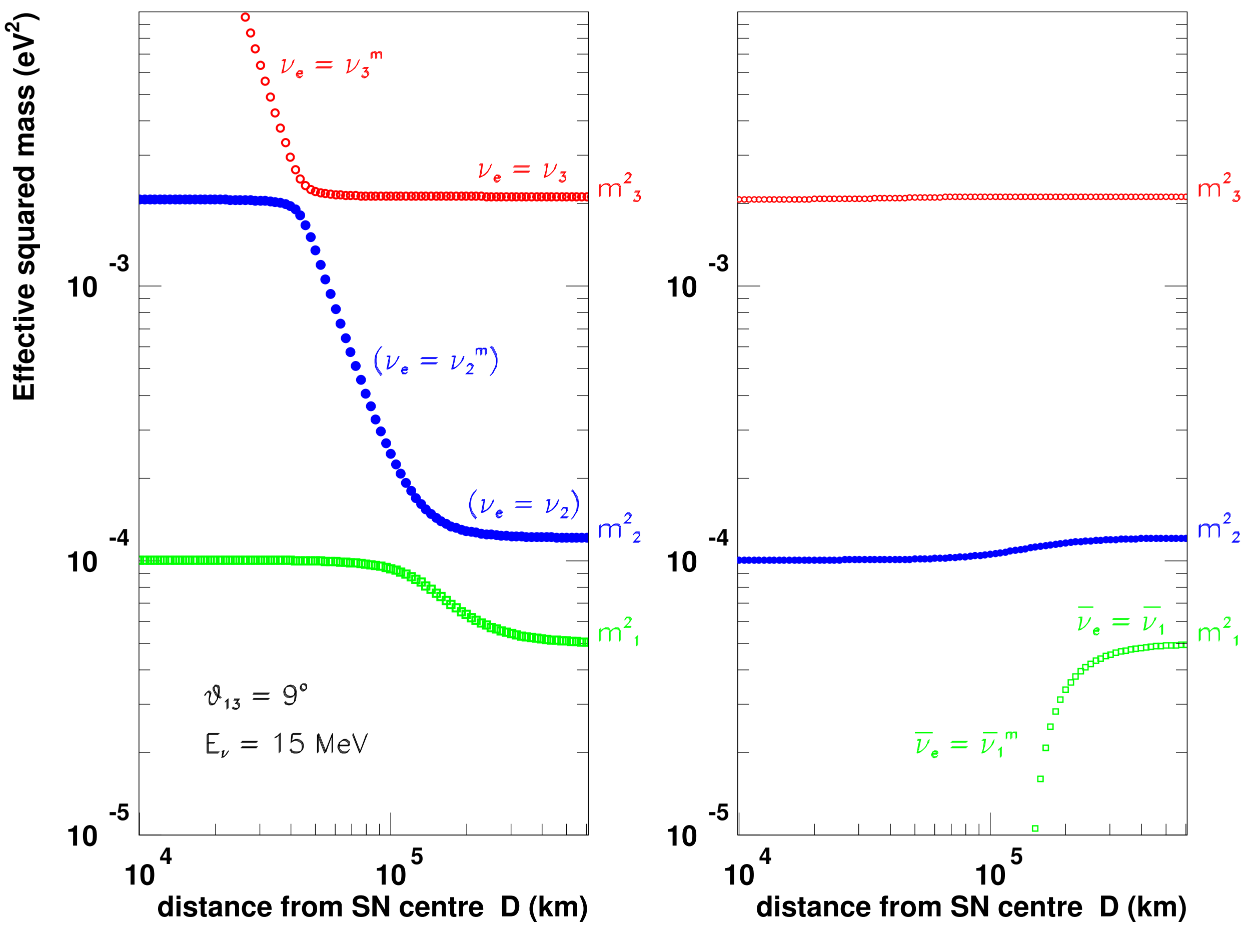
red=Maxwell-Boltzmann (with $\alpha = 3$),

green=Fermi-Dirac with pinching factor η,

blue=Fermi-Dirac with $\exp(-E^2)$

More on oscillations

The MSW effect for usual oscillations can be understood plotting the squared masses of neutrino and antineutrinos:



Thus, $\nu_e \longrightarrow \nu_3$, *and similarly* $\bar{\nu}_e \longrightarrow \bar{\nu}_1$*:*

$$P_{ee} = |\langle \nu_e | \nu_3 \rangle|^2 = \sin^2\theta_{13} \sim 0 \ \textit{(for large } \theta_{13}\textit{)}$$

$$P_{\bar{e}\bar{e}} = |\langle \bar{\nu}_e | \bar{\nu}_1 \rangle|^2 = \cos^2\theta_{12} \sim 0.7$$

⋆ **With current parameters, Earth Matter effect is not large (unless we see events with large E_ν)**

⋆ **This is clear from the explicit formula for constant density matter; for very small θ_{13}**

$$P_{ee} \approx s^2 \times (1 + 4\, c^2\, \epsilon \sin^2 \varphi)$$

where $\epsilon = 9\%$ when $\rho = 4$g/cc and $E = 20$ MeV ($s^2 = 0.3$, $c^2 = 1 - s^2$). The oscill. phase is

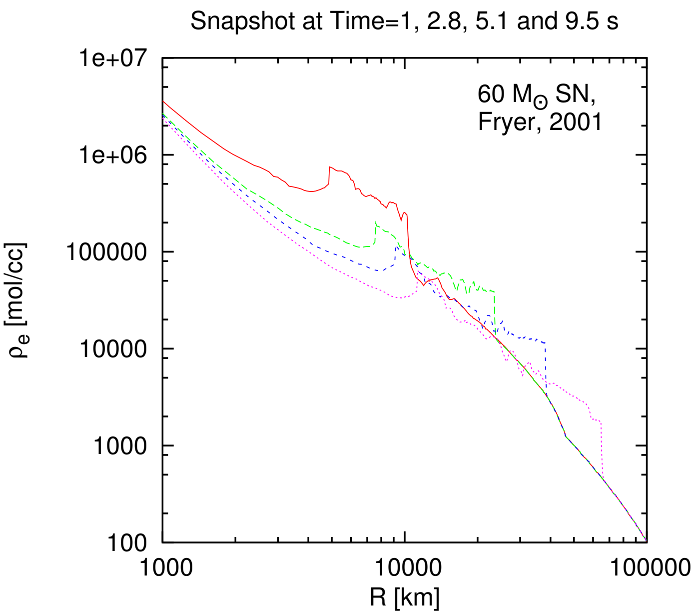
$$\varphi \approx (L/220 \text{ km}) \times (20 \text{ MeV}/E)$$

⋆ **For SN1987A:**
IMB had $\rho = 4.5$ gr/cc and $L = 8500$ km,
while KII had $\rho = 3.5$ gr/cc and $L = 4400$ km.

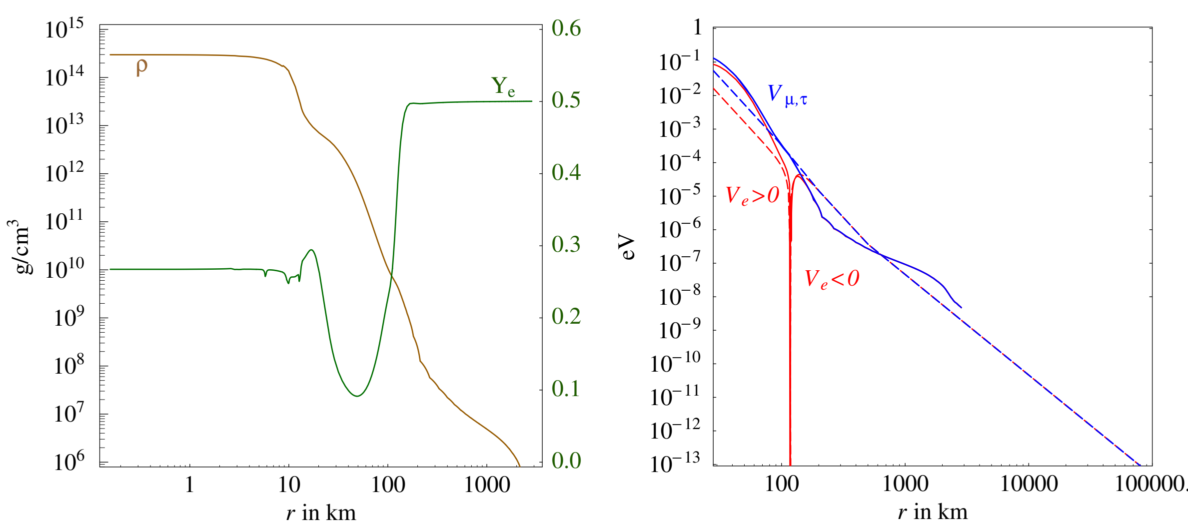
⋆ **Could be interesting if SN explodes just below the horizon, $L =$ few hundred km (Cavanna et al.)**

Matter Distribution Around Collapsing Stars

Propagation of shock wave (Fryer 2001, unpublished)



When $Y_e < 1/3$, sterile ν ‘MSW-resonate’ (Cirelli et al.)



Remarks on the interactions

The adopted cross section (Strumia, FV) includes

- **terms order $m_n - m_p$ and m_ℓ, $\ell = e, \mu, \tau$–it improves on famous Llewellyn-Smith formula**
- **the (few %) QED radiative corrections**
- **updated input parameters as axial charge and Cabibbo angle**

Estimated precision is better than 1 %, and could be important to interpret the result from next SN.

(Other application include analysis of low energy atm. data, supernova simulation, etc. The behavior of form factors in the region above 100 MeV is rather uncertain but this will matter only for very accurate measurements).

For the future, we would like to know detailed $\bar{\nu}_e$ spectra (IBD) and clear ES signal, and also:

Reactions for ν_e

$$\nu_e + {}^{12}C \to e + N, \quad N \to C + e^+ + \nu_e$$

$$\nu_e + D \to e + p + p$$

$$\nu_e + {}^{16}O \to e + F$$

$$\nu_e + {}^{40}Ar \to e + K^*$$

$$\nu_e + Fe \to e + Co$$

NC reactions

Most of them can just count events, e.g.

$$\nu + C \to \nu + C^*, \quad C^* \to C + \gamma(15.1\ MeV)$$

$$\nu + D \to \nu + p + n$$

An exception is

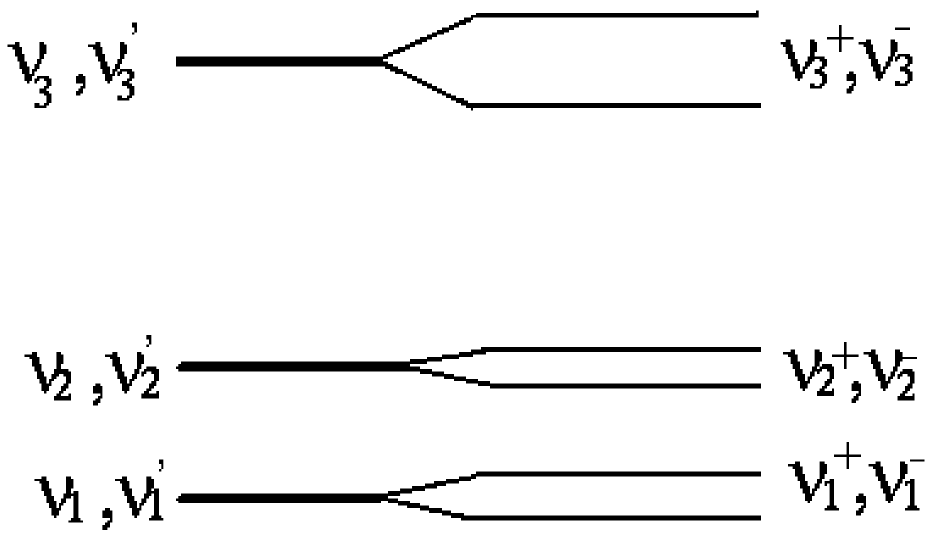
$$\nu + p \to \nu + p$$

that needs sensitivity to $\sim MeV$ neutrinos

$\star$ *More (precise) calculations/measurements welcome* $\star$

New Vacuum Oscillations?

What could happen if there are new $\Delta m^2 > 10^{-18}$ eV^2 motivated in models with 'mirror' matter (Berezinsky, Narayan, FV)



The observed neutrino energy halves; or, what we believe we observed should be doubled. For SN1987A, we get $\mathcal{E} \sim (2-3) \times 10^{53}$ erg. The real question is:

Can we compute $\mathcal{E}$ up to a factor of 2?