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Astroparticle Physics: Present and Future

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Astroparticle Physics: Present and Future

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The solar neutrinos, next SN and the dark matter are reviewed and analyzed from the point of view of future observations. For solar neutrinos much attention is given to an astrophysical solution of the problem. It is shown to be excluded unless the $\nu^{37}\text{Cl}$ -cross-section is considerably underestimated or unless there are large systematic errors in the Homestake or Kamiokande experiments. For the next SN the main emphasis is made on the time-sequence of phenomena and on the possibilities of their observations. The neutralinos and neutrinos are discussed as the dark matter components for the Mixed Dark Matter model.

1. Introduction

Astroparticle Physics: Present and Future - this is what I was asked to speak about. An astrophysicist can manage with the *present*; for the *future* an astrologist is better. The science is moving by a zig-zag, where each step is a discovery. One can imagine the predicted future of solar neutrino physics made at 1984, before the discovery of the MSW effect. Or let us look at the invisible dark matter, as it was seen in 1980. Then the neutrino was a favorite candidate for the Dark Matter Particle. It was assumed that the density of all other particles in the Universe is small, and therefore the density of neutrinos is fixed by the Planck mass m_{Pl} and the Hubble constant as

$$\rho_\nu = (3/8\pi)H_0^2 m_{Pl}^2 \quad (1)$$

Why in this model the mass of neutrino, given by $\rho_\nu = 115(T_\gamma/2.75K)^3 m_\nu$, is fine-tuned to H_0 ?

Because for the considered model it is a wrong question. It is not the neutrino mass, which is determined by the Hubble constant, but vice versa: the Hubble constant is *predicted* by the neutrino mass according to Eq.(1).

In this model the neutrino mass determines not only the Hubble constant, but also the characteristic mass of the Universe structures. The latter is given by the Jeans mass for the neutrino gas:

$$M_J = M_{Pl}^3 / m_\nu^2. \quad (2)$$

This value is equal to the mass of the largest structure in the Universe, a supercluster of galaxies.

Finally, for this model we had the theory of galaxy formation developed by Zeldovich et al [1]. This the-

ory explained the formation of smaller structures due to fragmentation of the baryonic gas inside the superclusters - neutrino pancakes. The remarkable feature of this theory is that it could explain the rotation of galaxies, which is a serious problem for other models.

This beautiful theory is now rejected by the observations. It is a pity that Ya.B.Zeldovich did not participate in creating the Universe.

For the Mixed Dark Matter Model, with 60 – 70% of neutralinos, 20-30% of neutrinos and $\sim 10\%$ of baryons, Eq.(1) with ρ_c substituted for ρ_ν , implies the relation between the neutrino mass and the neutralino-neutralino annihilation cross-section. We are not aware of such relation in elementary particle physics.

It is easy to discuss the future for the observation of the next SN, because, as B.Pontecorvo said, we had the main rehearsal - the SN 1987A. Everything which could be broken during this rehearsal was broken, and those things which just could not be broken, were also broken - including the Japanese watch. However, we are now better prepared for the performance. We know what sequence of events we must be ready to observe. The discussion of the phenomena expected for SN 1987A is actually a program of the observations for the next SN. One lesson is obvious and important: the coordinated network for the observations of neutrino, infrared, radio, X-ray and gamma-ray radiations is just imperative.

SN is a heart of modern astrophysics. The wisdom of astrophysics says: Everything that we do not observe at birth in our Galaxy is produced by SN's. It includes the production of heavy nuclei, cosmic rays, single pulsars etc. The time scale for SN observation

is now comparable with that for building the large accelerators. The difference is that the SN explosion has already occurred. The signal is approaching us, and even such a powerful institution as the US Congress cannot dismiss it.

The paper is organized in the following way: section 2 - solar neutrinos, section 3 - next SN and section 4 - dark matter.

2. Solar Neutrinos

The model of the Sun is the most elaborated stellar model. The modern status of the Standard Solar Model (SSM) is described in ref. [2,3]. There are at least 11 recently published calculations [4 - 14] for the SSM. In all these works the physics included is basically the same. The slight difference in the results is caused by the different input parameters, most notably by the opacity of the Sun. The calculated parameter which is most important for the solar neutrino fluxes is the central temperature. It varies by $\pm 1\%$ in the above cited calculations. The results are summarized in ref.[15] as

$$T_c = (15.55 \pm 0.15) \cdot 10^6 K$$

The detection of solar neutrinos confirmed the basic principles of the SSM, however, the counting rates in all four neutrino experiments are lower than those predicted by the SSM.

The numerical predictions of the SSM are questioned by uncertainties most notably in the rate of nuclear reactions [2,4], in the opacity coefficients [2,3]. They can be also seriously influenced by the presence of such hypothetical physical processes as periodical mixing in the core triggered by some instabilities (see [2] with the references therein and [16]).

The status of solar neutrino observation in comparison with SSM predictions [7] looks in 1994 as follows
GALLEX[17]: $87 \pm 14 \pm 7 SNU$,
 predicted $131 \pm 7 SNU$,

$$data/SSM = 0.66 \pm 0.11 \pm 0.05 \quad (3)$$

$$\text{SAGE [18]: } 70 \pm 19 \pm 10$$

$$data/SSM = 0.53 \pm 0.15 \pm 0.06 \quad (4)$$

$$\text{Kamiokande[19]:}$$

$$data/SSM = 0.48 \pm 0.05 \pm 0.06 \quad (5)$$

$$\text{Homestake[20]: } 2.33 \pm 0.25 SNU, \\ \text{predicted } 8.0 \pm 3.0 SNU$$

$$data/SSM = 0.29 \pm 0.03 \pm 0.09. \quad (6)$$

The Homestake and Kamiokande experiments demonstrate the most dramatic contradiction to the SSM predictions. At the first glance this fact gives a chance for an astrophysical solution, since both experiments are very sensitive to B-neutrinos (100 % for Kamiokande and 78 % for Homestake) and because the flux of B-neutrinos depends very strongly on the central temperature $T_c : \phi(B) \sim T_c^{18}$. One might hope that it is enough to diminish slightly T_c (e.g. due to some variations of input parameters or due to some unconventional processes) to bring the solar model in agreement with the two above-mentioned neutrino experiments. As we shall show below, the agreement cannot be reached in this way.

The most successful explanation of the solar neutrino problem can be given in terms of neutrino oscillations. In Fig. 1 we show the regions in the $\Delta m^2 - \sin^2 2\theta$ plot which explains simultaneously the results of all four neutrino experiments. The two upper regions are related to MSW matter oscillations [21] according to the recent calculations of ref [22], and the lower region is for vacuum oscillations according to calculations of ref. [23].

The small-angle MSW solution is very attractive from the point of view of neutrino-mass hierarchy. If this solution is interpreted as $\nu_e \leftrightarrow \nu_\mu$ oscillations then the mass of muon neutrino is $m_{\nu_\mu} \approx (\Delta m^2)^{1/2} \approx (1.7 - 3) 10^{-3} eV$ and the mixing angle is $\sin^2 2\theta_{e\mu} \approx (0.4 - 1.5) 10^{-2}$. In the see-saw model the neutrino mass matrix in the basis of left-handed neutrino ν_L and a superheavy right-handed Majorana neutrino N_R is given (for each generation) by

$$\begin{pmatrix} 0 & M_D \\ m_D & M_R \end{pmatrix} \quad (7)$$

where m_D and M_R are Dirac ($m_D \bar{\nu}_L N_R$) and Majorana ($M_R \bar{N}_L^c N_R$) masses, respectively. Diagonalization of the mass matrix (7) results in two mass eigenstates, the lightest of which has a mass

$$m_\nu \approx m_D^2 / M_R. \quad (8)$$

To proceed further one can make two assumptions. The first one, inspired by GUT models, suggests

$m_D \sim m_{up}$ (or $m_D = m_{up}$) for each generation, where m_{up} is the mass of up-quark. Under the second assumption, the superheavy mass M_R is the same for all three generations (notice however, that the assumption $M_R^i \sim m_{up}^i$ for $i = 1, 2, 3$ is also plausible). Then we arrive at the following relations for neutrino masses

$$m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} = m_u^2 : m_c^2 : m_t^2 \quad (9)$$

and for mixing angles for neutrinos of different generations i and k :

$$\theta_{ik} \approx (m_D^i / m_D^k)^{1/2} \approx (m_{up}^i / m_{up}^k)^{1/2}. \quad (10)$$

For the mixing of ν_e - and ν_μ -neutrinos, one obtains

$$\theta_{e\mu} \approx 6 \cdot 10^{-2}$$

in good agreement with the MSW small-angle solution $\sin^2 2\theta_{e\mu} \approx (0.4 - 1.5)10^{-2}$.

From the relation (9) one can estimate the ν_e and ν_τ neutrino masses. Using $m_{\nu_\mu} = (2.4 \pm 0.6) \cdot 10^{-3} eV$ we obtain $m_{\nu_e} \approx 4 \cdot 10^{-8} eV$. The mass of the τ -neutrino suffers from large uncertainties due to the poor knowledge of the top-quark mass $m_t \approx 166 \pm {}^{17}_{19} \pm {}^{19}_2 GeV$, and

$$m_{\nu_\tau} \approx 30 \pm 13 eV, \quad (11)$$

in marginal agreement with the mass of the Hot Dark Matter particle needed for the Mixed Dark Matter Model [24, 25]:

$$m_{\nu_\tau} = 27.6(\Omega_{0\nu}/0.3)h^2 \quad (12)$$

where $\Omega_{0\nu} = \rho_\nu / \rho_{cr}$ is the fraction of critical density in the form of neutrinos, and h is the dimensionless Hubble constant, $h = H_0 / 100 km/s Mpc$.

In the end we shall list some other phenomena connected with properties of neutrinos which can affect the predicted neutrino fluxes: spin-flip in the solar magnetic field [26], resonant spin flavour conversion [27], neutrino decay [28-30], $\nu_e \rightarrow \bar{\nu}_e$ oscillations [31], contribution of a new neutral boson to the scattering of neutrinos off d-quarks [32] and some others.

Fig 1. $\Delta m^2 - \sin^2 2\theta$ plot for neutrino oscillations. The dotted regions in the plot explain at 90%CL the results of all four neutrino experiments. MSW solutions are taken from ref [22] and the vacuum oscillation solution - from ref [23].

2.1. Uncertainties due to Astrophysics and Nuclear Physics

The SSM is based on reliable physics and its predictions agree at a level 0.5 % with helioseismological observations, valid to the distances down to $0.2R_\odot$.

[3,34]. The uncertainties involved in the calculations are mainly connected to the rates of *nuclear reactions* and to the *opacity* of the solar material.

The uncertainties in nuclear cross-sections arise because energies of particles in the Sun are considerably lower than in the laboratory experiments. These uncertainties can be crucial for the solar neutrino problem. For example, if a resonance [35] in the ${}^3\text{He}+{}^3\text{He}$ system really existed at low energy, the pp -chain of the reactions would finish practically entirely by the reaction ${}^3\text{He}+{}^3\text{He} \rightarrow {}^4\text{He}+2p$, and B - Be -neutrinos would be drastically suppressed. Even now in the light of the new experimental data this phenomenon cannot be yet completely excluded [4]. Another important reaction, which regulates the ratio of fluxes of Be - and B -neutrinos, is $p + Be \rightarrow {}^8B + \gamma$. Its cross-section at energies of interest is also badly known. Finally the calculations of the electron screening in the nuclear reactions can involve considerable errors.

The second class of uncertainties is connected with physical phenomena not included in the SSM. In ref. [2] a long list of these phenomena is critically analyzed. It includes rotation, magnetic field, influence of Weak Interacting Relic Particles, mixing in the solar core etc. The most interesting phenomenon is probably instability. The absence of instabilities is one of the basic assumptions of the SSM. The Sun is an extremely stable object. The only known serious challenge to stability is a density gradient of ${}^3\text{He}$ which can excite g -modes of solar oscillations [33].

Phenomenologically, all suggested new phenomena influence the neutrino flux through the variation of the central temperature T_c of the Sun. Therefore, if we could exclude a case that a low T_c is responsible for the solar neutrino deficit, we reject all known non-standard and exotic phenomena suggested so far.

2.2. Kamiokande/Homestake counting-rate ratio

In several recent works it has been claimed that an astrophysical solution is excluded or strongly disfavored on the basis of a comparison of the Kamiokande and Homestake results. The point is that the suppression of the SSM flux for the Homestake detector (data/SSM = 0.29) is stronger than for Kamiokande (data/SSM = 0.48). However, Homestake detects the same boron neutrinos as Kamiokande, and additionally Be -neutrinos. This argument was considered quantitatively by Bahcall and Bethe [36]. Using

the known relative efficiencies of the two detectors, they found that the counting rate due to boron neutrinos in the Homestake detector calculated from the Kamiokande data to be 2.8 ± 0.3 SNU. It has to be compared with the total counting rate, 2.33 ± 0.25 SNU, which includes Be -neutrinos, pep -neutrinos etc. For this latter contribution the authors suggested to use the SSM calculations. The two above-mentioned sources give 2.24 ± 0.28 SNU and therefore the total counting rate should be 5.0 ± 0.41 SNU, to be compared with 2.33 ± 0.25 SNU observed. Some weakness of this argument is that part of the flux is still estimated within the SSM.

A remark is in order.

The uncertainties in nuclear cross-sections cannot help to resolve the conflict between the Homestake and Kamiokande results. One can see that only p^7Be -cross-section is involved in this problem. A larger p^7Be -cross-section results in a larger predicted flux of B -neutrinos, in conflict with the Kamiokande data. On the other hand, if one assumes a lower p^7Be -cross-section, the ratio $\phi_\nu(Be)/\phi_\nu(B)$ becomes larger, because this ratio is inversely proportional to the p^7Be -cross-section. This further deepens the conflict between the Homestake and Kamiokande measurements.

In ref. [37] the counting rate in the Homestake detector is compared to the predictions of 1000 solar models, in which all input parameters, such as the nuclear reaction rates, the solar composition, the solar age and the opacity, were randomly changed. Even if a solar model is artificially brought into agreement with the boron-neutrino flux measured in the Kamiokande experiment, its prediction for the Homestake experiment is too high.

For the most general analysis of the astrophysical solution one can use the constraints on the fluxes from Kamiokande, chlorine and gallium experiments, combined with the constraint due to the known solar luminosity $L_\odot$. This approach was used in ref. [4,38].

Let us consider first the solar-luminosity constraint.

Basically it comes from the fact that $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$ conversion gives a $q \sim 26$ MeV contribution to the solar luminosity accompanied by radiation of two neutrinos. Therefore, the total neutrino flux is $\dot{N}_\nu \sim 2L_\odot/q$. Taking into account the energy carried away by the neutrinos, we obtain the following

solar-luminosity sum rule:

$$\sum_i \phi_i (1 - 2\bar{E}_i/\bar{Q}) = 2L_\odot / (4\pi r^2 \bar{Q}) \quad (13)$$

where ϕ_i are the solar-neutrino fluxes at the Earth ($i = pp, Be, B$ etc), $\bar{Q} = 26.8 \text{ MeV}$ is the average value for $Q_I = 26.73 \text{ MeV}$ and $Q_{II} = 27.2 \text{ MeV}$, r is the distance between the Earth and the Sun and $\bar{E}_i = \phi_i^{-1} \int \phi_i(E) E dE$ is the mean energy of i -type of neutrinos. Neutrino fluxes calculated in the SSM (e.g. ref. [2,4]) satisfy Eq. (13) with an accuracy $\sim 2\%$.

Using the spectra given in ref. [2] for calculating $\bar{E}_i$ (e.g. $\bar{E}_{pp} = 0.264 \text{ MeV}$) we obtain numerically

$$\phi(pp) + 0.954\phi(Be) + \dots = 6.45 \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \quad (14)$$

It is easy to verify by using the SSM for estimates that the other fluxes ($\phi(B)$, $\phi(pep)$ etc.) provide only small contributions to Eq. (14).

To the relation (14) we can add a set of restrictions imposed by the Kamiokande, chlorine and gallium experiments in the form suggested in ref. [4]

$$S_{Kam} = \xi_{Kam}^B \phi(B) \quad (15)$$

$$S_{Cl} = \xi_{Cl}^B \phi(B) + \xi_{Cl}^{Be} \phi(Be) + S_{Cl}^{other} \quad (16)$$

$$S_{Ga} = \xi_{Ga}^{pp} \phi(pp) + \xi_{Ga}^B \phi(B) + S_{Ga}^{other} \quad (17)$$

where S_a is the counting rate in a detector (in SNU for chlorine and gallium detectors) and ξ_i^K are coefficients which depend on the interaction of neutrinos in the detector, but not on the neutrino fluxes. Excluding $\phi(pp)$ with the help of Eqs. (14) and (17) one obtains a set of three restrictions in the $\phi(Be) - \phi(B)$ plot shown in Fig's 2 and 3.

The analysis of ref. [4] is presented in Fig. 2. For estimates of S_{Cl}^{other} and S_{Ga}^{other} the authors used the SSM neutrino fluxes. One can see that there is no region of intersection for the three experiments, though

Fig.2. $\phi(Be) - \phi(B)$ plot from ref.[4]. The black areas show the regions allowed by the Homestake and Kamiokande experiments with 1σ uncertainties.

for $\phi(Be)$ near zero they are very close.

We can add to this graph one more limit coming from the assumption that the reduction of neutrino fluxes is due to a diminishing of central temperature T_c . In this case we obtain

$$\phi(Be)/\phi(B) = (1.21 \pm 0.36) \cdot 10^3, \quad (18)$$

which is plotted in Fig. 2. There is no intersection within the "temperature solution corridor" with the Homestake and Kamiokande data simultaneously. The best fit region, the hatched triangle, is separated by 2σ from both Homestake and Kamiokande mean allowed values (see Fig. 2). The weakness of this proof consists in using the SSM model to estimate S_{Cl}^{other} . The authors do not exclude a possibility of a "nuclear solution" of the solar neutrino problem.

Fig.3. $\phi(Be) - \phi(B)$ plot from ref.[38]. The curves labelled by Ga, Cl and Kamiokande show the limits from these experiments. The prediction of the SSM is shown in the upper-right corner.

A strong conclusion about the exclusion of the astrophysical solution is reached in ref. [38]. The main result of this work is presented in Fig. 3. The combined constraint from Ga- experiments and solar-neutrino sum rule is obtained minimizing χ^2 with respect to the fluxes of pp - and CNO -neutrinos. The region of intersection for all three limits is located near

$\phi(B) \approx 0$ and is characterized by large χ^2 value equal to 5.6. Therefore, as the authors conclude, an astrophysical solution is incompatible with the observed data.

2.3. Fixed-Spectrum Relation

We can add to the proofs given above one more, which essentially uses only one assumption, namely, that the spectrum of boron-decay neutrinos is not changed in the solar medium (see ref.[39], where the smallness of corrections is demonstrated).

Let us choose some trial model, for definiteness the Bahcall-Pinsonneault model with helium diffusion [7], as the most advanced model. The neutrino fluxes predicted by this model are $\phi_{SSM}(B)$, $\phi_{SSM}(Be)$ and $\phi_{SSM}(other)$. The fluxes in some unspecified astrophysical model which agrees with Homestake and Kamiokande observations are given by $\phi(B) = R_B \phi_{SSM}(B)$, $\phi(Be) = R_{Be} \phi_{SSM}(Be)$ etc. where the coefficients R will be called the suppression factors. Note, that suppression factors are not universal, they are determined for the particular reference model [7] we have chosen.

The only restriction we impose on R_B is that astrophysical conditions do not change the spectrum of boron neutrinos. In particular, arbitrary changes are allowed for the nuclear rates.

It is clear that the rate of events I can be calculated from the rate of events for our trial model I^{SSM} as

$$I_{Kam} = R_B I_{Kam}^{SSM} \quad (19)$$

$$I_{Cl} = R_B I_{Cl}^{SSM}(B) + R_{Be} I_{Cl}^{SSM}(Be) + \dots \quad (20)$$

Then the suppression factors for Kamiokande and Homestake experiments are given by

$$R_{Kam} \equiv I_{Kam}/I_{Kam}^{SSM} = R_B, \quad (21)$$

$$R_{Cl} \equiv I_{Cl}/I_{Cl}^{SSM} = R_B f_B^{SSM} + R_{Be} f_{Be}^{SSM} + \dots \quad (22)$$

where f_B^{SSM} is the fraction of events in the chlorine detector due to boron neutrinos in the SSM model [7]. From the last two equations we have

$$R_{Cl}/R_{Kam} = f_B^{SSM} + f_{Be}^{SSM}(R_{Be}/R_B) + \dots \quad (23)$$

Using the numerical values for the parameters of the SSM model [7] and observational data of the Kamiokande and chlorine detectors, namely $R_{Cl}/R_{Kam} = 0.62 \pm 0.07$, $f_B^{SSM} = 0.778$ and $f_{Be} = 0.146$, we obtain from (23)

$$R_{Be}/R_B < -1.08 \pm 0.48. \quad (24)$$

It is reasonable to compare the numerical value (24) with the value of R_{Be}/R_B obtained under assumption that a diminishing of central temperature T_c relative to T_{SSM} is responsible for low neutrino fluxes. Then using the set of equalities

$$R_B = (T_c/T_{SSM})^{18}, \quad R_{Be} = (T_c/T_{SSM})^8$$

and $R_B = R_{Kam} = 0.47 \pm 0.05$,
we obtain

$$R_{Be}/R_B = R_{Kam}^{-5/9} = 1.5. \quad (25)$$

From Eq.(24) one can conclude that R_{Be}/R_B ratio contradicts to the minimal value $R_{Be}/R_B = 0$ and strongly contradicts to the temperature solution (25) (see also ref.[40]). Note, that uncertainties in nuclear cross-sections are included in this proof (see also the remark to the Bahcall-Bethe analysis)

The only way to avoid the contradiction given by Eq.(24) is to assume that there is some considerable error in the calculations of $\nu^{37}Cl$ cross- section (see however ref.[2] for the detailed analysis) or that at least one of the two experiments (Homestake and Kamiokande) has a large systematic error.

2.4. The Nearest-Future Experiments

In the future experiments the astrophysical solution can be tested in a direct and unambiguous way. The nearest-future detectors are SNO [41] (to be in operation from 1995), Superkamiokande [42](from 1996) and probably Borexino [43].

In the 50 kt Superkamiokande detector the expected statistics for νe -scattering will reach [3] ~ 2000 events/yr. With this statistics the spectrum of boron neutrinos at $E > 7 MeV$ will be reliably measured. Both neutrino oscillation solutions, vacuum and matter oscillations, predict a distortion of this part of the spectrum. In case of an astrophysical solution the spectrum cannot be changed.

SNO and Borexino can effectively separate neutral current (NC) events. In case of an astrophysical solution, electron neutrinos retain their identity and we obtain the ratio

$$(NC/CC)_{obs}/(NC/CC)_{\nu_e} = 1.$$

In case of oscillations part of the ν_e are converted into ν_μ and/or ν_τ which have only NC interactions. Therefore, the above written ratio must be *larger* than one.

In a few years the combined results of SNO and Superkamiokande experiments will perform a direct test of the astrophysical solution. The Superkamiokande experiment with its huge statistics will give the energy spectrum of boron neutrinos. Any distortion of the SSM spectrum is incompatible with an astrophysical solution. The SNO detector will measure the ratio of NC/CC events. In case of an astrophysical solution this must be equal to the $(NC/CC)_{\nu_e}$ -ratio calculated for ν_e -neutrinos. The observed ratio being larger than this calculated value is incompatible with an astrophysical solution.

The future experiments, SNO, Superkamiokande, Borexino and ICARUS, will be able to distinguish between vacuum and matter oscillations and between different types of matter oscillations (see ref's [44-46] for the detailed analysis). In particular, a very clear way to distinguish between vacuum and matter oscillations is to use the seasonal variation of the neutrino flux. Apart from a trivial $1/\tau^2$ effect, which results in a $\sim 7\%$ variation of neutrino flux, there is an additional variation of the flux in the case of vacuum oscillations due to oscillations in the space between the Earth and the Sun. This effect is especially strong for Be neutrinos, and it diminishes the $1/\tau^2$ variation of the flux [45-46]. The matter oscillations occur inside the Sun and hence the distance variations between the Sun and the Earth do not affect the flux beyond the $1/\tau^2$ dependence.

3. Next Supernova

SN 1987A was a triumph of the theory. The observations have confirmed the basic principles of the stellar collapse:

Detection of the cobalt lines in the infrared (e.g. $\lambda = 1.547 \mu m$ and $10.52 \mu m$) and gamma ($E_\gamma = 0.847 MeV$ and $E_\gamma = 1.238 MeV$) radiations have shown that the contraction of the star proceeded through a stage of a synthesis of the iron group nuclei.

Detection of neutrino radiation [47] has clearly evidenced for the gravitational collapse. It is triggered by loss of pressure support, which in its turn is caused by loss of energy due to photo-dissintegration of the iron nuclei and electron capture by protons. Duration of the observed neutrino signal ($\sim 10s$) coincides well with the expected [48] time of the Kelvin-Helmholtz stage of neutrino cooling.

The measurements of the light curve reliably demonstrated that the energy inside expanding shell is supplied by the chain of radioactive decays $Ni \rightarrow Co \rightarrow Fe$ [49].

The detection of radioburst [50] signalled about the moment when the shock traversed the shell and reached its surface.

The information from SN 1987A is to change the strategy for the observation of the next SN. The detectors are now required to provide us with more detailed information, beyond what was listed above.

The interest to the neutrino observations will be most probably concentrated on the fine details of the spectra and time profile of the signal. The problems of interest are the difference in the temperature of ν_e , ν_μ and ν_τ radiations, a search for the new weakly interacting particles and some others. In short, it is not enough to think of the future neutrino detectors only in terms of discovering the fact of neutrino radiation.

Fig.4. The light curve of SN 1987A, ref.[51]

While the observations of SN 1987A have confirmed the basic principles of the theory, many details of the theory still remains unclear. One example is a problem of a compact object in the SN remnant: By all what was said above, it must exist. By all what we know, it is not seen. Both the synthesis of the iron group nuclei and neutrino radiation are the signature

of a production of a compact object in the form of a neutron star or of a black hole (the relatively large duration of the observed neutrino pulse is better described by the formation of the neutron star). The radiation from this compact object can reveal itself by the distortion of the exponential light curve.

The light curve for 1500 days of observations of SN 1987A is shown in Fig.4. (ref [51]). It is well described by the decays of ^{56}Co and ^{57}Co if $0.075 M_\odot$ of ^{56}Co and $0.009 M_\odot$ of ^{57}Co were injected into the expanding shell. The absence of the distortion of this curve gives very stringent limit on the luminosity of the compact object: $L < 1 \cdot 10^{37} \text{ erg/s}$.

The direct observations did not show any evidence for X-ray or optical radiation.

Probably, the easiest explanation can be given in terms of anomalously small angular momentum of the presupernova. In this case the compact object is the slow rotating star, while the known mechanisms of radiation are connected with the rotation (accretion discs, pulsar magnetosphere etc). It brings us back to the neutrino radiation. The observed flux agrees well with the calculations without rotation, while fast rotation is expected to reduce considerably the predicted flux [52].

Till now we do not have a satisfactory explanation for the origin of the *explosion*. How inward motion of the gas is reversed?

A very attractive qualitative explanation is given by *bounce* [53]. The collapse starts due to loss of the pressure support. However, in the process of the fast contraction (almost in the free-fall regime) the density and temperature of the inner core increase tremendously. A pressure wave, started in the inner layers, propagates outwards in the infalling matter and is turned into the shock wave. Unless it is strongly revived by the neutrinos, the shock probably is too weak to explain SN explosion [54, 55]. Whatever mechanism is responsible for reversing the motion of the gas, the physical processes must be unstable during this period and the relevant information can be imprinted into neutrino flux in the form of the time variations or the change of the energy spectra. In particular, the postshock accretion onto the core can produce a tail in the neutrino signal.

The interesting fine-structure phenomenon is the *neutronization burst*. Produced in $e + p \rightarrow n + \nu_e$ scattering, neutrinos are trapped in the core until the

shock wave reaches the neutrinosphere [55, 56]. At this moment they are radiated away in a form of a short burst (~ 5 ms), with the total energy release $\sim 10^{51}$ ergs [56]. Apart from the confirmation of this interesting stage, the detection of the neutronization burst will put the strong constraints on the properties of τ -neutrinos. For a density profile like in SN 1987A, ν_e -neutrinos are converted to ν_τ -neutrinos due to the MSW oscillations (see calculations in ref[57]), if $5 < m_{\nu_\tau} < 30$ eV and $\sin^2 2\theta > 1 \cdot 10^{-7}$. Survival of the neutronization burst in the form of ν_e -neutrinos can exclude τ -neutrinos with the parameters of great cosmological interest.

Another manifestation of MSW oscillations is the conversion $\nu_\tau \rightarrow \nu_e$ (or $\nu_\mu \rightarrow \nu_e$) during the Kelvin-Helmholtz stage. The energies of ν_μ and ν_τ are higher than those of ν_e and therefore this conversion results in the appearance of ν_e with higher energies. This effect was studied in ref[58]. It was demonstrated that $\nu_\tau \rightarrow \nu_e$ (or $\nu_\mu \rightarrow \nu_e$) conversion increases the mean observed energy in $\nu_e + D \rightarrow e + 2p$ reaction (detected by SNO) from 14 MeV to 22 MeV. At this conference it was shown [59] that this effect can be also studied with help of reaction $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N} + e$ in the LVD detector.

SN 1987A has provided us with the elementary-particle information. Following ref's [60, 61] the obtained limits can be summarized as:

- $m_{\nu} < 23$ eV – for the mass of ν_e -neutrino from the dispersion of neutrino signal.
- $m_{\nu_\mu}, m_{\nu_\tau} < 25$ keV – for the mass of the Dirac neutrinos from the helicity flip and cooling of the core.
- $\mu < 10^{-12} \mu_B$ – for the magnetic moment of ν_e from cooling of the core.
- $\tau_\nu / m_\nu > 2 \cdot 10^{15}$ s/eV – for the life-time of radiative decay, $\nu_H \rightarrow \nu + \gamma$, from absence of gamma-burst accompanying the observed neutrino burst.
- $G_{RH} < .3 \cdot 10^{-4} G_F$ – for the right-handed Fermi constant.
- $10^{-3} < m_a < 2$ eV – for the excluded masses of the axion.

This list of particle properties outlines the problems and the ranges for a future search.

3.1. Detection of SN radiations

The *earliest* signals from the Galactic SN are expected due to neutrino and gravitational radiations. The neutrino pulse can be accompanied by the prompt gamma radiation with $E_\gamma \sim E_\nu$ from $\nu_H \rightarrow \nu + \gamma$ decay. To detect it we should have a satellite gamma-ray detector operating at the time of SN explosion, as it happened in the case of SN 1987A.

The next group of signals is expected in a few hours when the shock reaches the surface.

It includes the infrared radiation (IR), which is an effective tool to search for SN [62]. It has two important properties: first, it is weakly absorbed by dust in the Galaxy and, second, unlike neutrino and gravitational radiation it gives the direction to the source.

Fig.5. The expected distribution of SN's in the Galactic disc with respect to the apparent magnitude m . The upper panel gives the distribution as observed in optical radiation at $\lambda = 5500\text{\AA}$ and the low panel is for IR with $\lambda = 2.2 \mu\text{m}$.

The minimum IR flux can be estimated as the black-body extrapolation of the optical radiation. Under this assumption, the IR light curve should be identical to the optical light curve. SN can be detected early, at the stage of the rising part of the IR light curve. The distribution of SN's with respect to the apparent magnitude m is shown in Fig.5 [62]. In these calculations SN's with the absolute magnitude $M = -18.0$ were assumed to be distributed uniformly in the Galactic disc; the distribution over m is mostly affected by the absorption on the dust. From Fig.5 one can see that that in optical radiation at $\lambda = 5500\text{\AA}$ most

of SN's are seen as the very faint objects, which are usually lost at the surveys (upper panel), while in IR at $\lambda = 2.2\mu m$ all sources are very bright (the low panel). The IR observations are crucially important to search for SN I, since in this case no neutrino and gravitational radiation is expected and thus IR provides the earliest signal from SN. The IR patrol survey of the Galactic disc seems to be a plausible task.

The interaction of the shock with the stellar wind, left behind by the presupernova, is expected to result in the radio and X-ray bursts [63]. The further propagation of the shock in the stellar wind is accompanied by the acceleration of the particles and by the production of high-energy gamma-rays (with $E_\gamma > 100 MeV$ and $E_\gamma > 1 TeV$) and high energy neutrinos [64]. The radiations remain detectable up to 1 yr and can be discovered by the existing arrays.

The inner radiation from the young SN shell can be caused by several mechanisms. The γ -ray photons from the radioactive decays of ^{56}Co , ^{57}Co etc scattering off the electrons, are converted into X-ray photons [65]. Particles can be accelerated inside the shell by a pulsar [66], due to turbulence [67] and by the shock produced in the e^+e^- wind [68]. The interaction of accelerated particles with the gas in the shell results in the production of high energy gamma and neutrino radiations.

The radiations described above need a network of the detectors for the observations. The MeV neutrinos from the collapse can be studied in detail by the existing and future detectors such as Baksan, MACRO, LVD, SNO and SuperKamiokande. High energy neutrinos can be detected by "Baikal", MACRO and LVD. There are projects for the observations of gravitational radiation [69].

The survey of the Galactic disc in IR seems to be a plausible and important task. IR can be the first signal which gives the direction to SN and as such it will trigger the search for SN in the radio and optical diaposons. For high-energy gamma-radiation there is time of order a month to start the observations. The most difficult part of the network is providing the satellite observations of soft gamma-ray ($E_\gamma \sim 10 MeV$) and X-ray radiations.

With the technique of communication presently available the network of the detectors can be spread over the Earth. However, the large number of the detectors in Gran Sasso Laboratory (MACRO, LVD

and EASTOP as a gamma-ray detector) makes this laboratory a plausible candidate for the coordinating center.

3.2. Dark Matter

The measurements of the perturbation spectrum by COBE, IRAS and CfA have excluded both the pure Hot Dark Matter (HDM) and the pure Cold Dark Matter (CDM) models. The HDM model predicts too small amplitudes of perturbations on the small scales ($\lambda < 10 Mpc$), while the CDM spectrum, if normalized by the IRAS and CfA data, results in too small amplitudes for the large scales ($\lambda > 100 Mpc$). The simplest explanation of the observed spectrum is given by the Mixed Dark Matter (MDM) model [24,25]. As shown in Fig.6, the best fit to the observed spectrum is given by [25] $\Omega_{CDM} = 0.69$, $\Omega_{HDM} = 0.3$ and $\Omega_B = 0.01$, where $\Omega = \rho/\rho_c$, ρ_c is the critical density and the subscript B refers to the baryons.

Fig.6. Perturbation spectrum for the MDM model ($\Omega_{CDM} = 0.69$, $\Omega_\nu = 0.3$, $\Omega_B = 0.01$ and $h = 0.5$) in comparison with the observational data (ref[25]).

The most plausible candidates for the MDM model are τ -neutrino as HDM particle and the neutralino as the CDM particle. The mass of τ -neutrino is given by (12) and it equals to 7 eV for $h = 0.5$ and 16 eV for $h = 0.75$.

According to this model $\delta M/M$ on the galactic scale is dominated by CDM particles. The galactic potential well is build by the space distribution of these

particles. The baryons, which decoupled from the radiation much later than CDM particles, are streaming into these potential wells. Therefore, in this model it is difficult to expect that baryons provide the dominant contribution to the DM density in the galactic halos. As a rough estimate of the average fraction of the baryon density in the halo, one can take Ω_B/Ω_{CDM} . At this Conference the detection of the MACHO's was reported. Microlensing is sensitive to the density of MACHO's not too far from the Galactic disk and therefore these observations do not contradict the conclusion about dominance of CDM particles in the whole halo.

On the scales $\lambda \sim 10 - 100 Mpc$, $\delta M/M$ is dominated by neutrinos. The formation of the potential well on this, supercluster, scale started later, when neutrino gas becomes unstable. At this moment the perturbations in the neutralino gas are already well developed.

Therefore, the MDM model incorporates both phenomena: the early galaxy formation and the neutrino pancakes for the large-scale (supercluster) structures.

3.3. Neutralino

Can the neutralino be a DM particle?

By many reasons the neutralino heads a list of candidates for the CDM particles (for the references and recent calculations see [70]).

I will address here only one problem: does the neutralino demand fine-tuning to be the DM particle? In fact, this is a serious problem. One of the motivation for introducing the supersymmetry was to eliminate fine-tuning in GUT theories. A priority must be given to the composition of neutralino, which does not destroy the mechanism of the supersymmetric suppression of radiative corrections to the masses of the higgses and "light" gauge bosons.

Neutralino is a linear superposition of four neutral, spin 1/2 fields in the MSSM:

$$\chi = Z_{11}\tilde{W}_3 + Z_{12}\tilde{B} + Z_{13}\tilde{H}_1 + Z_{13}\tilde{H}_2 \quad (26)$$

where $\tilde{W}_3$ and $\tilde{B}$ are the wino and bino and $\tilde{H}_1$ and $\tilde{H}_2$ are two higgsinos. The neutralino is the lightest mass eigenstate, four of which diagonalize the mass matrix. It is a Majorana particle.

The space of all allowed neutralino states is described by three independent parameters: mass of the wino M_2 , the mixing parameter of two higgsi-

nos $\mu\tilde{H}_1\tilde{H}_2$ and $\tan\beta = v_2/v_1$, where v_1 and v_2 are the vacuum expectation values of two higgs fields of the model. This three-dimensional volume is strongly limited by experimental data of LEP and CDF combined with the theoretical assumptions. The main of them are the following.

The MSSM model is assumed to be embedded in GUT SU(5) model. In this model there is the remarkable crossing of the three coupling constants at the unification point ($\alpha_{GUT} \approx 0.04$ and $M_{GUT} \approx 1 \cdot 10^{16} GeV$). Unification imposes the relation between Majorana masses of the wino (M_2) and the gluino ($M_{\tilde{g}}$):

$$M_2 = (\alpha_2/\alpha_3)m_{\tilde{g}} \quad (27)$$

The second relevant theoretical element is fine-tuning: the supersymmetry scale should be low enough to defend light higgses from acquiring (through radiative corrections) the mass of order αM_{GUT} .

The LEP and CDF data with the use of Eq.(27)) give the lower bound for the neutralino mass.

$$m_\chi \geq 23 GeV \quad (28)$$

These limits are exposed in Fig.7 for negative values of μ and for $\tan\beta = 2$.

The fine-tuning arguments strongly limit the allowed region. The quantitative analysis of fine-tuning problem is given in ref.[71]. Under assumption that compensation should not diminish the initial value by a factor larger than $\Delta = 10$, one obtains from the calculations of ref.[71] for the mass of the top quark $m_t = 130 GeV$

$$m_{\tilde{g}} \leq 400 GeV \text{ and } \mu \leq 180 GeV, \quad (29)$$

where μ is renormalized to the low energy scale. With the help of Eq.(27) this limit on the gluino mass can be translated into $M_2 \leq 120 GeV$. The fine-tuning limits combined with the LEP and CDF bounds leave only a small box of allowed states shown in Fig.7. If one takes $m_{\tilde{g}} < 1 TeV$ (or equivalently $m_\chi < 150 GeV$) the fine-tuning is characterized by $\Delta \sim 100$. This limit is shown in Fig.7 by the dashed horizontal line.

The relic neutralino density is displayed in Fig.7 according to the calculations of ref.[72] for the following set of parameters : $\tan\beta = 2$, the pseudoscalar higgs mass $m_A = 200 GeV$, the selectron mass $m_{\tilde{e}} = 80 GeV$ and all other stermion masses

$m_{\tilde{q}} = 1 \text{ TeV}$. The hatched area corresponds to $0.25 \leq \Omega_\chi h^2 \leq 0.5$, i.e. $\rho_\chi \sim \rho_{cr}$ at $h \sim 0.75$. Within the dotted area $0.025 \leq \Omega_\chi h^2 \leq 0.1$ which corresponds to $\Omega_\chi \leq 0.4$ for $h = 0.5$. It creates the problem for the SC box with $\Delta = 10$.

Fig.7. Neutralino composition plot in $M_2 - \mu$ parameter space for $\tan\beta = 2$ and for other parameters given in the text. The box in the lower-right side of the picture is the region with the compensation $\Delta \leq 10$. The full diagonal line separates gaugino dominated states (below the line) from higgsino dominated states (above the line). The full curves marked 25, 60, 150 and 300 are neutralino isomass curves with the corresponding masses in GeV. The cosmologically excluded region $\Omega_\chi h^2 > 1$ is shown by black, the hatched area corresponds to $0.25 \leq \Omega_\chi h^2 \leq 0.5$ and in the dotted area $0.025 \leq \Omega_\chi h^2 \leq 0.1$ (calculations of ref.[72])

The mass of squarks used in the calculations [72] is $m_{\tilde{q}} = 1 \text{ TeV}$, while the limit of ref.[71] is $m_{\tilde{q}} \leq 600 \text{ GeV}$. Decrease of $m_{\tilde{q}}$ results in increase of

the annihilation cross-section in gaugino-dominated area and therefore Ω_χ further decreases.

Most probably the neutralino as CDM particle needs fine-tuning with about two orders of magnitude compensation. However, for this conclusion the more extensive numerical calculations are needed.

3.4. Detection

Since the density of *neutrinos* in the space is reliably known, the direct search for neutrinos as DM particles is given by the measurements of their mass. To provide $\Omega_\nu \sim 0.3$ the mass of ν_τ , given by (12), must be between 7 and 25 eV. There is the consensus between all workers [73] that such low mass cannot be found using the dispersion of neutrino signal from the next SN. The search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the accelerator experiments (the projects CHORUS and NOMAD [74]) can discover τ -neutrino with the mass as low as 5 eV, if the mixing angle $\theta_{\mu\tau} > 0.01$. The indirect methods of neutrino DM detection (e.g. due to radiative decays) for the neutrino masses of a few eV do not look promising.

For the "light" neutralino with $m_\chi < 50 \text{ GeV}$ the direct methods of detection (due to elastic scattering on nuclei) are most effective. For heavy neutralinos with $m_\chi > 100 \text{ GeV}$ the indirect methods become more efficient (e.g. annihilation of neutralinos in the Earth and the Sun with the production of high energy neutrinos, and decay of neutralinos in case of weak R-parity violation).

4. Conclusions

The astrophysical solution to the *solar neutrino* problem is excluded unless the $\nu^{37}\text{Cl}$ -cross-section is considerably underestimated or unless there are large systematic errors in the Homestake or Kamiokande experiments. New astrophysical phenomena, not included in the SSM, and uncertainties in the nuclear rates in the core of the Sun cannot explain the observational data of the Homestake and Kamiokande detectors simultaneously.

This implies neutrino oscillations as the solution to the solar neutrino problem and as the first evidence for a phenomenon beyond the standard model, connected to the neutrino masses and neutrino mixing. The most probable interpretation of all solar neutrino data, MSW matter oscillation solution, combined with

the see-saw mechanism, GUT and universality of the mass of right-handed neutrino for all three generations, suggests the following hierarchy of neutrino masses: $m_{\nu_e} \sim 4 \cdot 10^{-8} \text{ eV}$, $m_{\nu_\mu} \sim 2 \cdot 10^{-3} \text{ eV}$ and $m_{\nu_\tau} \sim 20 - 40 \text{ eV}$.

In a few years the combined SNO and Superkamiokande observations will perform a direct test of the astrophysical solution. The Superkamiokande experiment will give the energy spectrum of boron neutrinos. Any distortion of the SSM spectrum is incompatible with an astrophysical solution. The SNO detector will measure the ratio of NC/CC events. In case of an astrophysical solution this must be equal to the $(NC/CC)_{\nu_e}$ -ratio calculated for ν_e -neutrinos. The observed ratio being larger than this calculated value is incompatible with an astrophysical solution.

The future experiments, SNO, Superkamiokande, Borexino and ICARUS, will be able to distinguish between vacuum and matter oscillations and between different types of matter oscillations.

It is not enough to think about *neutrino observations* of the *next galactic SN* only in terms of discovering neutrino radiation. We expect from these observations the information about fine structure of the neutrino signal, such as neutronization burst, time variation of the flux during the reversing of the motion of the infalling gas, the flavour composition of the neutrino signal etc.

The coordinated network for the SN observation using the different radiations must be elaborated. The very important element of this network is the infrared patrol of our Galaxy to search for SN's.

The *Mixed Dark Matter* model gives the simplest way to fit the observed spectrum of perturbations. This model needs $\sim 60 - 70\%$ CDM, $\sim 25 - 30\%$ HDM and $\sim 6\%$ baryonic matter. The most probable particle candidates for DM are τ -neutrinos for HDM and neutralinos for CDM. There is no confrontation of this model with the recent detection of MACHO's: most probably MACHO's contribute not more than $\sim 10\%$ to the *total mass* of the galactic halo.

To be the CDM particle, the *neutralino* seems to require fine-tuning. It needs as well R-parity conservation or very weak R-parity violation, which also implies fine-tuning. The neutralino can be searched

for by the direct detection or by indirect methods due to neutralino-neutralino annihilation or neutralino decay.

Neutrino as the HDM particle must be light ($m_{\nu_\tau} \sim 5 - 25 \text{ eV}$). Since the space density of τ -neutrinos is reliably known, the direct search for them consists in measuring ν_τ -mass. The MSW solution to the solar neutrino problem implies m_{ν_τ} given by Eq.(11) with the mixing angle $\theta_{\mu\tau} \sim 0.1$. ν_τ -Neutrinos with these properties can be found in the accelerator oscillation experiments [71], discovering thus the HDM particle.

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