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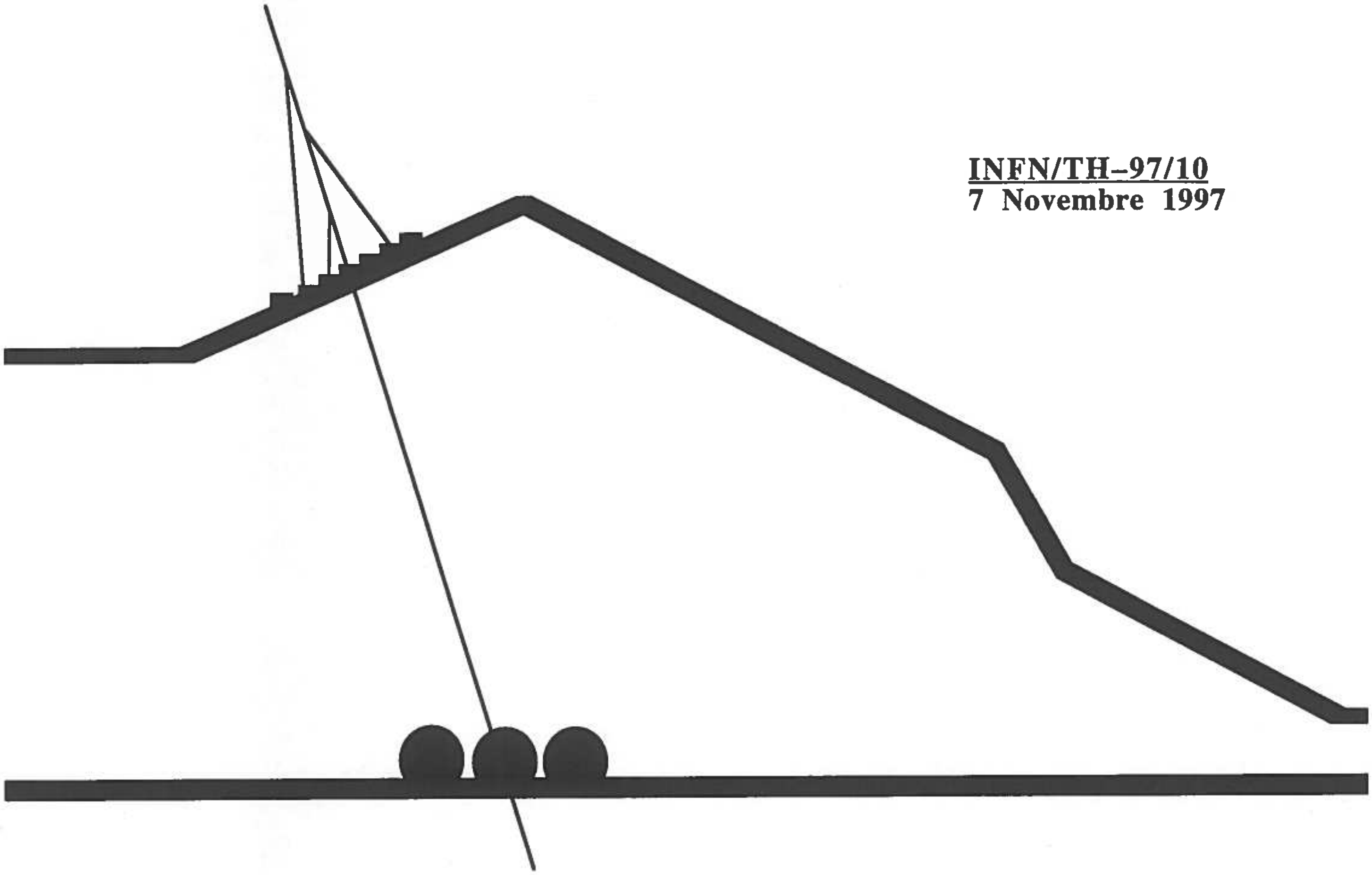

Baryonic and Cold Dark Matter

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Abstract

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1 Introduction

Presence of dark matter (DM) in the Universe is reliably established. DM in the form of compact microlensing objects (machos) are directly observed in the halo of our Galaxy by MACHO, EROS and OGLE collaborations. Rotation curves in our Galaxy and in many other galaxies provide evidence for large halos filled by nonluminous matter. The virial (gravitational) mass of clusters of galaxies is about ten times larger than their luminous masses. IRAS and POTENT demonstrate the presence of DM on the largest scale in the Universe.

The matter density in the Universe ρ is usually parametrized in terms of $\Omega = \rho/\rho_c$, where $\rho_c \approx 1.88 \cdot 10^{-29} h^2\ g/cm^3$ is the critical density and h is the dimensionless Hubble constant defined as $h = H_0/(100 km.s^{-1}.Mpc^{-1})$. Different measurements suggest generally $0.4 \leq h \leq 1$. The measurements of extragalactic Cepheids in Virgo and Coma clusters narrowed this interval to $0.6 \leq h \leq 0.9$. However, recent precise measurements of the Hipparcos satellite result in reconsideration of the distance scale. It has reduced the value of the best Cepheid Hubble constant from $h = 0.73 \pm 0.1$ [1] to $h = 0.68 \pm 0.09$ [2], in good agreement with SNIa determination $h = 0.67 \pm 0.08$.

Dark Matter can be subdivided in baryonic DM, hot DM (HDM) and cold DM (CDM).

The density of baryonic matter found from nucleosynthesis is given [3] as $0.009 \leq \Omega_b h^2 \leq 0.02$. The baryonic cosmological density provided by the mass of intracluster gas is very close to this value, $\Omega_b^{clust} h^{3/2} \approx 0.05$ [4] and references therein.

The structure formation in Universe put strong restrictions to the properties of DM in Universe. Universe with HDM plus baryonic DM has a wrong prediction for the spectrum of fluctuations as compared with measurements of

COBE, IRAS and CfA. CDM plus baryonic matter can explain the spectrum of fluctuations if total density $\Omega_0 \approx 0.3$.

There is one more form of energy density in the Universe, namely the vacuum energy described by the cosmological constant Λ. The corresponding energy density is given by $\Omega_\Lambda = \Lambda/(3H_0^2)$. Quasar lensing restricts the vacuum energy density: in terms of Ω_Λ it is less than 0.7 [5] . From SNIa it is restricted more severely [1] $\Omega_\Lambda < 0.51$.

Contribution of galactic halos to the total density is estimated as $\Omega \sim 0.03 - 0.1$ and clusters give $\Omega \approx 0.3$. Inspired mostly by theoretical motivation (horizon problem, flatness problem and the beauty of the inflationary scenarios) $\Omega_0 = 1$ is usually assumed. This value is supported by IRAS data and POTENT analysis. No observational data significantly contradict this value.

There are several cosmological models based on the four types of DM described above (baryonic DM, HDM, CDM and vacuum energy). These models predict different spectra of fluctuations to be compared with data of COBE, IRAS, CfA etc. They also produce different effects for cluster-cluster correlations, velocity dispersion etc. The simplest and most attractive model for a correct description of all these phenomena is the so-called mixed model or cold-hot dark matter model (CHDM). This model is characterized by following parameters:

$$\begin{aligned} \Omega_\Lambda = 0, \Omega_0 = \Omega_b + \Omega_{CDM} + \Omega_{HDM} = 1, \\ H_0 \approx 55\ kms^{-1}Mpc^{-1}(h \approx 0.55), \\ \Omega_{CDM} : \Omega_{HDM} : \Omega_b \approx 0.75 : 0.20 : 0.05, \end{aligned} \tag{1}$$

Thus in the CHDM model the central value for the CDM density is given by $\Omega_{CDM}h^2 = 0.23$, with uncertaities within 0.1.

The best candidate for the HDM particle is τ-neutrino. In the CHDM model with $\Omega_\nu = 0.2$ mass of τ neutrino is $m_{\nu_\tau} \approx 4.7\ eV$. This component will not be discussed further.

The most plausible candidate for the CDM particle is probably the neutralino (χ): it is massive, stable (when the neutralino is the lightest supersymmeric particle and if R-parity is conserved) and the $\chi\chi$-annihilation cross-section results in $\Omega_\chi h^2 \sim 0.2$ in large areas of the neutralino parameter space.

Till recently the CHDM model was thought to face the *age problem.* The lower limit on the age of Universe $t_0 > 13$ Gyr (age of globular clusters) imposes the upper limit on the Hubble constant in the CHDM model $H_0 < 50\ kms^{-1}Mpc^{-1}$. This value was in contradiction with the observations of extragalactic Cepheids, which gave the Hubble constant $h = 0.73 \pm 0.1$. Now this problem disappeared in the light of the new Hipparcos estimate of the lower limit on the globular cluster age, 13 Gyr , which agrees well with $h \approx 0.6$ needed for the CHDM model.

Another successful cosmological model is ΛCDM. This model assumes that $\Omega_0 = 1$ is provided by the vacuum energy described by cosmological constant Λ and CDM. Using the limit on cosmological constant $\Omega_\Lambda < 0.7$ and the age of Universe one obtains $\Omega_{CDM} \geq 0.3$ and $h < 0.7$. Thus this model also predicts $\Omega_{CDM} h^2 \approx 0.15$ with uncertainties 0.1. Finally, we shall mention that the CDM with $\Omega_0 = \Omega_{CDM} = 0.3$ and $h = 0.8$, which fits the observational data, also gives $\Omega h^2 \approx 0.2$. Therefore $\Omega h^2 \approx 0.2 \pm 0.1$ can be considered as the value common for most models [6].

The further progress in cosmological environment of the DM models is connected with acoustic oscillations and determination of cosmological parameters from their observations.

The hot baryonic gas oscillates under the opposite forces of pressure and gravity, and the temperature fluctuations caused by this process at the epoch of radiation decoupling can be detected now as anisotropy of relic radiation.

The density fluctuations are produced in the Universe at the stage of inflation as quantum fluctuations of the scalar field which drives the inflation (inflaton). These primordial fluctuations occur on large superhorizon scales. When they reach the epoch of radiation decoupling (red shift $z \sim 1000$), they produce the regions of compression and rarefaction, seen in the relic microwave radiation as hot and cold spots. This anisotropy of microwave radiation corresponds to the large angles, larger than $\theta_{LS} \approx 2^\circ$, at which the whole last scattering surface (the horizon at $z \sim 1000$ is seen).

During the radiation dominated epoch the fluctuations in the baryonic gas grow on superhorizon scales where gravitation dominates over pressure. When a baryonic fluctuation enters the horizon in the *matter dominated* epoch it starts to oscillate under the forces of pressure and gravity. These oscillations are also left imprinted in the temperature fluctuations at the last scattering surface, but this time on subhorizon scale, i.e. at angles $\theta < \theta_{LS}$. At very small scales the fluctuations are damped because photons have enough time to diffuse out of overheated regions. Thus, we see that the evolution of the fluctuations are imprinted in the temperature distribution on the last scattering surface and we can observe it as anisotropy of relic microwave radiation.

The temperature distribution $T(\theta, \phi)$ can be expanded in spherical harmonics as

$$T(\theta, \phi) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta, \phi). \tag{2}$$

The anisotropy is determined as

$$C_l = < |a_{l,m}|^2 >, \tag{3}$$

where the brackets mean averaging over m. Small multipole moments l correspond to large θ. Monopole moment $l = 0$ gives the average temperature $T_0 = 2.725\ K$, the dipole moment $l = 1$ describes the dipole anisotropy caused by motion of the earth relative to microwave radiation. Quadrupole moment $l = 2$ gives anisotropy at the largest angular scales. At present COBE measurements extend only to large angles corresponding to $l \leq 20$. It reflects superhorizon scales, i.e. inflationary physics. The anisotropy C_l here is slowly varying funtion of l (so called the Sachs-Wolfe plateau).

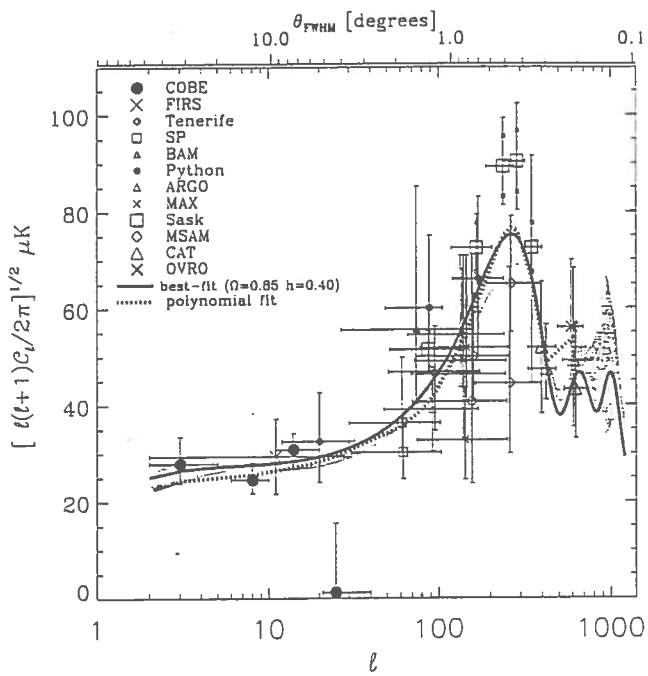

Figure 1: (from ref.[7]). Acoustic peak calculations in the best-fit model ($\Omega_0 = 0.85$ and $h = 0.40$) compared with recent microwave data.

An example of calculation of anisotropy C_l for the cosmological model with $\Omega_0 = 0.85$ and $h = 0.40$ is shown in Fig.1 [7]. One can observe there the first acoustic peak at $l \sim 200$ and smaller peaks at larger l. Anisotropy is damped at $l > 2000$ as predicted due to photon diffusion from overheated regions. The observational data presented in Fig.1 can be considered in agreement with calculations, giving the indication to the presence of the first acoustic peaks.

More discussion of acoustic peaks can be found in refs. [8] and [9]. The future satellite experiments MAP (NASA) to be launched in 2000 and Planck Explorer (ESA) to be launched in 2005, will map the sky with angular resolution better than $0.1°$. As calculations [9] show these measurements will allow to evaluate all basic cosmological parameters, namely Ω_0, Ω_b, H_0 and Λ with accuracy of a few percent. Thus, the cosmological part of DM model will be known precisely, but it cannot help to identify the elementary-particle nature of Dark Matter.

We shall analyze here the candidates for CDM which naturally arise from elementary particle physics. The best known solution for strong CP violation implies *axion*, which can serve as CDM particle. The supersymmetrization of the theory, which includes axion, results in *generalized neutralino* – a linear combination of five neutral spin 1/2 particles (wino, bino, two higgsinos and *axino*, the fermionic partner of axion). This generalized neutralino is most natural candidate for CDM particle. Some attention will be given to the baryonic DM in connection with observations of machos. The light gravitino will be shortly discussed.

2 Machos and Baryonic Dark Matter

The total number of microlensing events observed in the halo during last two years reached 10. Eight of them are observed by MACHO collaboration [10] and two – by EROS. The duration of lensing effect is determined by the lens mass. The distribution of observed durations yields the macho mass as [10] $M = 0.46^{+0.30}_{-0.17} M_\odot$. However, this value is model dependent. The most likely halo fraction of machos is [10] $f = 0.50^{+0.30}_{-0.20}$. The important result is observation [11] of 45 microlensing events in Galactic bulge. For a given rotation curve the heavy bulge implies the lighter halo and thus the *fraction* of machos increases for a given number of observed events.

The machos with these masses may be interpreted as white dwarfs. However, to escape from the Hubble Deep Field Search these objects must be very faint, two magnitudes fainter than the disc white dwarf sequence [12].

It was suggested [13] that the cool white dwarfs can be very old population, with an age about 16 *Gyr*, originated by early burst of star production. The rapid cooling might be provided due to crystallization and Debye cooling. The Hubble Deep Field search can discover these faint stars in the near future.

According to another suggestion [14], machos are cool compact objects, e.g. neutron stars or black holes. Again the early formation of these stars is needed. They are assumed to be produced by massive first generation stars with low metallicity. Their short lifetime provides the early generation of the compact objects and thus the efficient cooling.

Could machos be non-baryonic objects? An interesting idea of this kind was recently put forward in ref.[15]. These objects could be the neutralino stars, formed by neutralinos and baryons around singularities [16] in the distribution of neutralino gas. The neutralino stars are produced naturally and they do not meet any problems connected with the Hubble telescope observations. Unfortunatelly, as was demonstrated in ref.[17] these objects produce too high gamma-ray flux due to annihilation of neutralinos.

The DM in the halo of our Galaxy is found and most probably it is baryonic. Could be all DM in the Universe only baryonic? This question is often asked nowdays (e.g. see [18]).

Let us discuss shortly the problems arising in the baryonic-dominated Universe.

Nucleosynthesis requires $\Omega_B^{nucl} \leq 0.02h^{-2}$. On the other hand the clusters provide $\Omega_{DM}^{cl} \geq 0.2$. Therefore, the baryonic density is small ($\Omega_B^{nucl} < \Omega_{DM}^{cl}$), unless $h < 0.3$, which contradicts recent observations. If one arbitrary neglects this contradiction, the baryonic dominated Universe with $\Omega_B = \Omega_{DM}^{cl} \approx 0.2$ can be considered. Apart from IRAS data and POTENT analysis which give $\Omega \approx 1$, such model faces serious cosmological problems, including the horizon and flatness problem and observed spectrum of fluctuations, which is impossible to explain without CDM and HDM. Probably, these problems could be solved in some artificial models with Λ term and vacuum defects (e.g. strings), but at present the corresponding calculations do not exist.

3 Axion

The axion is generically a light pseudoscalar particle which gives natural and beautiful solution to the CP violation in the strong interaction [19] (for a review and references see[20]). Spontaneous breaking of the PQ-symmetry due to VEV of the scalar field $<\phi>= f_{PQ}$ results in the production of massless Goldstone boson. Though f_{PQ} is a free parameter, in practical applications it is assumed to be large, $f_{PQ} \sim 10^{10} - 10^{12}\ GeV$ and therefore the PQ-phase transition occurs in very early Universe. At low temperature $T \sim \Lambda_{QCD} \sim 0.1\ GeV$ the chiral anomaly of QCD induces the mass of the Goldstone boson $m_a \sim \Lambda_{QCD}^2/f_{PQ}$. This massive Goldstone particle is the *axion*. The interaction of axion is basically determined by the Yukawa interactions of field(s) ϕ with fermions. Triangular anomaly, which provides the axion mass, results in the coupling of the axion with two photons. Thus, the basic for cosmology and astrophysics axion interactions are those with nucleons, electrons and photons.

Numerically, axion mass is given by

$$m_a = 1.9 \cdot 10^{-3} (N/3)(10^{10}\ GeV/f_{PQ})\ eV, \tag{4}$$

where N is a color anomaly (number of quark doublets).

All coupling constants of the axion are inversely proportional to f_{PQ} and thus are determined by the axion mass. Therefore, the upper limits on emission of axions by stars result in upper limits for the axion mass. In Table 1 we cite the upper limits on axion mass from ref.[20], compared with revised limits, given recently by Raffelt [21].

Table 1: Astrophysical upper limits on axion mass

	1990 [20]	1996 [21]
sun	$1\ eV$	$1\ eV$
red giants	$1 \cdot 10^{-2}\ eV$	very uncertain
hor.–branch stars	not considered	$0.4\ eV$
SN 1987A	$1 \cdot 10^{-3}\ eV$	$1 \cdot 10^{-2}\ eV$

As one can see from the Table the strong upper limit, given in 1990 from red giants, is replaced by the weaker limit due to the horizontal-branch stars. The upper limit from SN 1987A was reconsidered taking into account the nucleon spin fluctuation in $N + N \to N + N + a$ axion emission.

There are three known mechanisms of *cosmological production* of axions. They are (i)thermal production, (i) misalignment production and (iii) radiation from axionic strings.

The relic density of thermally produced axions is about the same as for light neutrinos and thus for the mass of axion $m_a \sim 10^{-2}\ eV$ this component is not important as DM.

The *misalignment production* is clearly explained in ref.[20].

At very low temperature $T \ll \Lambda_{QCD}$ the massive axion provides the minimum of the potential at value $\theta = 0$,which corresponds to conservation of CP. At very high temperatures $T \gg \Lambda_{QCD}$ the axion is massless and the potential does not depend on θ. At these temperatures there is no reason for θ to be zero: its values are different in various casually disconnected regions of the Universe. When $T \to \Lambda_{QCD}$ the system tends to go to potential minimum (at $\theta = 0$) and as a result oscillates around this position. The energy of these coherent oscillations is the axion energy density in the Universe. From cosmological point of view axions in this regime are equivalent to CDM. The energy density of this component is approximately[20,22]

$$\Omega_a h^2 \approx 2 \cdot (m_a/10^{-5}\ eV)^{-1.18}. \tag{5}$$

Uncertainties of the calculations can be estimated as $10^{\pm 0.5}$.

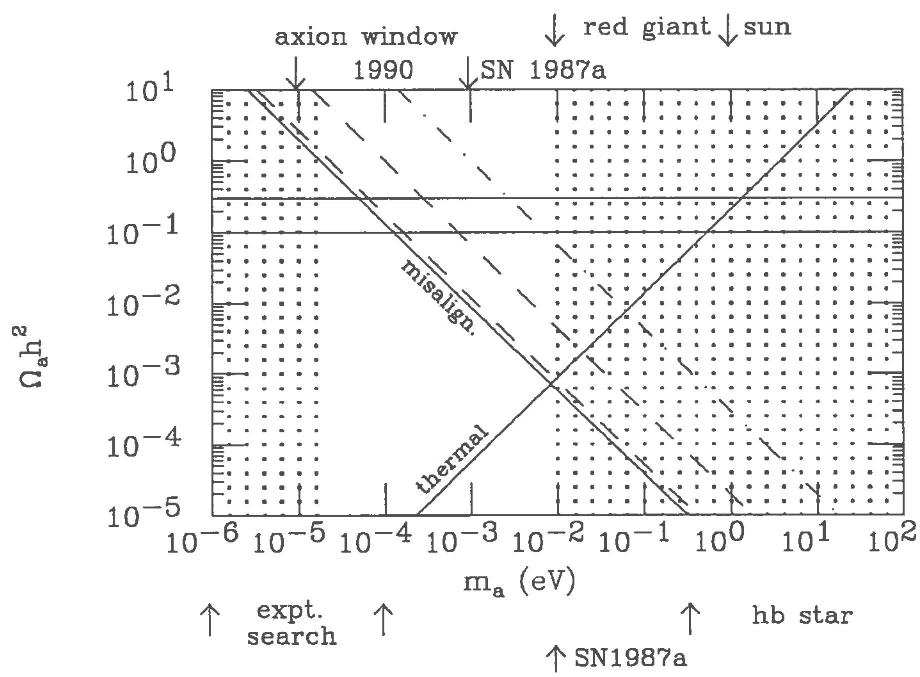

Figure 2: Axion window 1996. The curves "therm." and "misalign." describe the thermal and misalignement production of axions, respectively. The dash-dotted curve corresponds to the calculations by Davis[25] for string production. The recent refined calculations[23] are shown by two dashed lines for two extreme cases, respectively. The other explanations are given in the text.

Axions can be also produced by radiation of *axionic strings*[20,23]. Axionic string is a one-dimension vacuum defect $< \phi_{PQ} >= 0$, i.e. a line of old vacuum embedded into the new one. The string network includes the long strings and closed loops which radiate axions due to oscillation. There were many uncertainties in the axion radiation by axionic strings (see ref.[20] for a review). Recently more detailed and accurate calculations were performed by Battye and Schellard [23]. They obtained for the density of axions

$$\Omega_a h^2 \approx A(m_a/10^{-5}\ eV)^{-1.18} \tag{6}$$

with A limited between 2.7 and 15.2 and with uncertainties of the order $10^{\pm 0.6}$. The overproduction condition $\Omega_a h^2 > 1$ imposes lower limit on axion mass $m_a > 2.3 \cdot 10^{-5}\ eV$.

Fig.2 shows the density of axions $\Omega_a h^2$ as a function of the axion mass m_a. The upper limits on axion mass from Table I are shown above the upper absciss (limits of 1990) and below lower absciss (limits of 1996). The overproduction region $\Omega_a h^2 > 1$ and the regions excluded by astrophysical observations [21] are shown as the dotted areas.

The axion window of 1996 (shown as undotted region) became wider and moved to the right as compared with window 1990. The horizontal strip shows $\Omega_{CDM} = 0.2 \pm 0.1$ as it was discussed in Introduction. One can see from Fig.2 that string and misaligment mechanisms provide the axion density as required by cosmological CDM model, if axion mass is limited between $7 \cdot 10^{-5}\ eV$ and $7 \cdot 10^{-4}\ eV$. However, in the light of uncertainties, mostly in the calculations of axion production, one can expect that this "best calculated" window is between $3 \cdot 10^{-5}$ and 10^{-3} eV. This region is partly overlapped with a possible direct search for the axion in nearest-future experiments (see Fig.2 and refs.[24]).

4 Generalized neutralino

We shall consider now the supersymmetric theories where strong CP-violation is suppressed by PQ-symmetry (note, however, that in supersymmetric theories the new mechanisms for suppression of CP violation might appear, see e.g. [58]). In supersymmetric theory the PQ symmetry breaking results in the production of the Goldstone chiral supermultiplet which contains two scalar fields and their fermionic partner – axino ($\tilde{a}$). The scalar fields enter the supermultiplet in the combination $(f_{PQ} + s)\exp(a/f_{PQ})$, where s is a scalar field, saxino, which describes the oscillations of the initial field ϕ around its VEV value $<\phi> = f_{PQ}$, and a is the axion field. This phase transition in the Universe occurs at temperature $T \sim f_{PQ}$. As we saw in the previous section the axion is massless at this temperature and since supersymmetry is not broken yet, the axino and saxino are massless, too. The axion acquires the mass in the usual way due to chiral anomaly at $T \sim \Lambda_{QCD}$, while saxino and axino obtain the masses due to global supersymmetry breaking.

The saxino is not of great interest for cosmology: it is heavy and it decays fast (mostly into two gluons).

In the Minimal Supersymmetric Standard Model (MSSM) with broken PQ symmetry we have five spin 1/2 neutral particles: wino $\tilde{W}_3$, bino $\tilde{B}$, two Higgsinos ($\tilde{H}_1$ and $\tilde{H}_2$) and axino $\tilde{a}$. Generically the Lightest Supersymmetric Particle (LSP) is a linear superposition of these 5 fields:

$$\tilde{\chi} = C_1\tilde{W}_3 + C_2\tilde{B} + C_3\tilde{H}_1 + C_4\tilde{H}_2 + C_5\tilde{a} \tag{7}$$

Further on we shall consider two extreme cases: generalized neutralino $\tilde{\chi}$ is strongly dominated by the axino state and it is dominated by the first four terms in eq.(7). In the former case LSP is almost pure axino, in the latter– the usual neutralino.

5 Axino

How heavy the axino can be? The mass of axino is very model dependent. In the phenomenological approach, using the global supersymmetry breaking parameter M_{SUSY} one typically obtains (e.g. [27,28])

$$m_{\tilde{a}} \sim M_{SUSY}^2/f_{PQ} \tag{8}$$

For example, if global SUSY breaking occurs due to VEV of auxiliary field of the goldstino supermultiplet $< F >= F_g$, then the axino mass appears due to interaction term $(g/f_{PQ})\tilde{a}\tilde{a}F$ (F has a dimension M^2), and using $< F >= F_g = M_{SUSY}^2$ one arrives at the value (8).

The situation is different in supergravity. In ref.[29] the general analysis of the axino mass is given in the framework of local supersymmetry. It was found that generically the mass of axino in these theories is $m_{\tilde{a}} \sim m_{3/2} \sim 100\ GeV$. Even in case when axino mass is small at tree level, the radiative corrections raise this mass to the value $\sim m_{3/2}$. This result holds for the most general form of superpotential.The global SUSY result, $m_{\tilde{a}} \sim m_{3/2}^2/f_{PQ}$, can be reproduced in the local SUSY only if one of the superpotential coupling constants is very small, $\lambda < 10^{-4}$, which implies fine-tuning. Thus, the axino is too heavy to be a CDM particle.

The only exceptional case was found by Goto and Yamaguchi [30]. They demonstrated that in case of no-scale superpotential the axino mass vanishes and the radiative corrections in some specific models can result in the axino mass $10 - 100\ keV$, cosmologically interesting. This beautiful case gives essentially the main foundation for axino as CDM particle.

The cosmological production of axinos can occur through thermal production [32] or due to decays of the neutralinos [31,32]. The axion chiral supermultiplet contains two particles which can be CDM particles, namely axion and axino. In this section we are interested in the case when axino gives the dominant contribution. In particular this can take place in the range $2 \cdot 10^9\ GeV < f_{PQ} < 2.7 \cdot 10^{10}\ GeV$ where axions are cosmologically unimportant.

Since axino interacts with matter very weakly, the decoupling temperature for the thermal production is very high[32]:

$$T_d \approx 10^9\ GeV(f_{PQ}/10^{11}\ GeV). \tag{9}$$

Therefore, axinos are produced thermally at the reheating phase after inflation. The relic concentration of axinos can be easily evaluated for the reheating temperature T_R as

$$\Omega_{\tilde{a}} h^2 \approx 0.6 \frac{m_{\tilde{a}}}{100\ keV} \left(\frac{3 \cdot 10^{10}\ GeV}{f_{PQ}} \right)^2 \frac{T_R}{10^9\ GeV} \tag{10}$$

Reheating temperature $T_R \leq 10^9\ GeV$ gives no problem with the gravitino production. The relic density (10) provides $\Omega_{CDM} h^2 \sim 0.2$ for a reasonable set of parameters $m_{\tilde{a}}, f_{PQ}$ and T_R.

If the axino is LSP and the neutralino is the second lightest supersymmetric particle, the axinos can also be produced by neutralino decays[31,32,33]. According to estimates of ref.[33] the axinos are produced due to $\chi \to \tilde{a} + \gamma$ decays at the epoch with red-shift $z_{dec} \sim 10^8$. Axinos are produced in these decays as ultrarelativistic particles and the free-streaming prevents the growth of fluctuations on the horizon scale and less. At red-shift $z_{nr} \sim 10^4$ axinos become non-relativistic due to adiabatic expansion (red shift). From this moment on the axinos behave as the usual CDM and the fluctuations on the scales $\lambda \geq (1 + z_{nr}) c t_{nr}$ (which correspond to a mass larger than $10^{15} M_\odot$) grow as in the case of standard CDM. For smaller scales the fluctuations, as was explained above, grow less than in CDM model. Therefore, as was observed in ref.[33], the axinos produced by neutralino decay behave like HDM. It means that axinos can provide generically both components, CDM and HDM, needed for description of observed spectrum of fluctuations.

Unfortunatelly stable axino is unobservable. In case of very weak R-parity violation, decay of axinos can produce a diffuse X-ray radiation, with practically no signature of the axino.

6 Neutralino

The generalized neutralino can be dominated by the first four terms in eq.(7)

$$\chi = C_1 \tilde{W}_3 + C_2 \tilde{B} + C_3 \tilde{H}_1 + C_4 \tilde{H}_2 \tag{11}$$

i.e. by usual neutralino.

The neutralino is a Majorana particle. With a unitary relation between the coefficients C_i the parameter space of neutralino states is described by three independent parameters, e.g. mass of wino M_2, mixing parameter of two Higgsinos μ, and the ratio of two vacuum expectation values $\tan\beta = v_2/v_1$.

In literature one can find two extreme approaches describing the neutralino as a DM particle.

(i)*Phenomenological approach.* The allowed neutralino parameter space is restricted by the LEP and CDF data. In particular these data put a lower limit to the neutralino mass, $m_\chi > 20$ GeV. In this approach only the usual GUT relation between gaugino masses, $M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$, is used as an additional assumption, where α_i are the gauge coupling constants. All other SUSY masses which are needed for the calculations are treated as free parameters, limited from below by accelerator data.

One can find the relevant calculations within this approach in refs.[34,35] and in the review[36] (see also the references therein). There are large areas in neutralino parameter space where the neutralino relic density satisfies $\Omega_{CDM}h^2 \approx 0.2 \pm 0.1$. This is especially true for heavy neutralinos with $m_\chi > 100 - 1000$ GeV, ref.[37]. In these areas there are good prospects for *indirect* detection of neutralinos, due to high energy neutrino radiation from Earth and Sun (see [38,39] and references therein) as well as due to production of antiprotons and positrons in our Galaxy. The *direct* detection of neutralinos is possible too, though in more restricted parameter space areas of light neutralinos (see review [36]).

(ii) *Strongly constrained models.* This approach is based on the remarkable observation that in the minimal SUSY SU(5) model with fixed particle content, the three running coupling constants meet at one point corresponding to the GUT mass M_{GUT}. Because of the fixed particle content of the model, its predictions are rigid and they strongly restrict the neutralino parameter space. This is especially true for the limits due to proton decay $p \to K^+\nu$. As a result very little space is left for neutralino as DM particle. Normally neutralinos overclose the Universe ($\Omega_\chi > 1$). The relic density decreases to the allowed values in very restricted areas where $\chi\chi$-annihilation is accidentally large (e.g.due to the Z^0 exchange term - see ref.[40]. Thus, this approach looks rather pessimistic for neutralino as DM particle.

In several recent works [41–45] less restricted SUSY models were considered with more optimistic conclusions about detection prospects.

(iii)*Relaxed restrictions.* In some recent works the restrictions described in (ii) are relaxed. In particular, in [46] the large number of models with relaxed conditions were analysed. It was found that for many models neutralino can be discovered in the direct and indirect detection experiments [47]. This approach was recently further developed as described in presentations by R.Arnowitt [48] and L.Roszkowski [49] at this meeting.

In refs. [50,6] the SUSY models only with basic restrictions were considered.

7 SUSY models with basic restrictions

Following refs. [50,6] we shall consider here the restrictions to neutralino as DM particle, imposed by *basic* properties of SUSY theory. These restrictions are as follows:
(i)Radiative Electroweak Symmetry Breaking (EWSB), which is considered as fundamental element of the analysis, (ii) No fine-tuning stronger than 1%, which is natural but very powerful requirement; it results in the upper limit to neutralino mass $m_\chi < 200\ GeV$, (iii) Restrictions from Renormalization Group Equations (RGE) and from particle phenomenology (accelerator limits on the calculated masses and the condition that neutralino is LSP), (iv) Limits from $b \to s\gamma$ decay taken with the uncertainties in the calculations of the decay rate and (v) $0.01 < \Omega_\chi h^2 < 1$ as the allowed relic density for neutralinos.

At the same time some restrictions are lifted as being too model-dependent: (i) No restrictions are imposed due to $p \to K\nu$ decay, (ii) Unification of coupling constants at the GUT point is allowed to be not exact (it is assumed that new very heavy particles can restore the unification), (iii) unification in the soft breaking terms is relaxed. Following ref.[51] it is assumed that masses of Higgses at the GUT scale can deviate from the universal value m_0 as

$$m_{H_i}^2(GUT) = m_0^2(1+\delta_i) \qquad (i=1,2). \tag{12}$$

This non-universality affects rather strongly the properties of neutralino as DM particle: the allowed parameter space regions become larger and neutralino is allowed to be Higgsino-dominated, which is favorable for detection.

Some results obtained in ref.[50,6] are illustrated by Figs. 3 - 4.

In Fig.3 the regions excluded by the LEP and CDF data are shown by dots and labelled as LEP. The regions labelled "fine tuning" have an accidental compensation stronger than 1% and thus are excluded. No-fine-tuning region inside the broken-line box corresponds to a neutralino mass $m_\chi \leq 200$ GeV. The region "EWSB+particle phenom." is excluded by the EWSB condition combined with particle phenomenology (neutralino as LSP, limits on the masses of SUSY particles etc). In the region marked by rarefied dotted lines neutralinos overclose the Universe ($\Omega_\chi h^2 > 1$). The solid line corresponds to $m_0 = 0$. The regions allowed for neutralino as CDM particle ($0.01 < \Omega_\chi h^2 < 1$) are shown by small boxes. As one can see in most regions the neutralinos are overproduced. The allowed regions correspond to large $\chi\chi$ annihilation cross-section (e.g. due to Z^0-pole).

Fig. 3a and Fig. 3b differ only by universality: in Fig. 3a $\delta_1 = \delta_2 = 0$ (mass-unification), while in Fig. 3b $\delta_1 = -0.2$ and $\delta_2 = 0.4$. The allowed region in Fig. 3b becomes much larger and is shifted into the Higgsino dominated region.

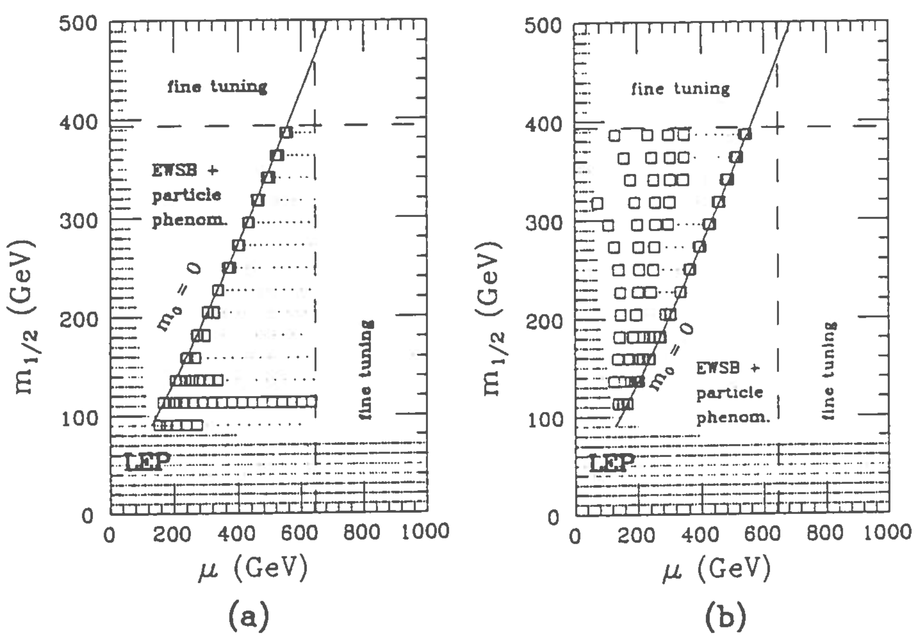

Figure 3: The neutralino parameter space for (a) mass–unification case $\delta_1 = \delta_2 = 0$ and (b) for non– universal case $\delta_1 = -0.2$, $\delta_2 = 0.4$. Both cases are given for $\tan\beta = 8$.

Let us discuss now the predictions of this model for direct and indirect detection of neutralinos. Direct detection is based on observarions of recoil nuclei from neutralino-nucleus scattering. As indirect detection we shall consider here the registration of high energy neutrinos from neutralino-neutralino annihilation in the center of Earth and Sun.

In Fig. 4a the scatter plot for the rate of direct detection with the *Ge* detector [52] is given for the non-universal case ($\delta_1 = 0, \delta_2 = -0.2$) and $\tan\beta = 53$. We notice that, for some configurations, the experimental sensitivity [52] is already at the level of the predicted rate.

In Fig. 4b we show predictions for the updoing flux of muons produced by neutrinos from neutralino-neutralino annihilation in the core of Earth. The muon flux from the direction of the Sun is shown in Fig. 4c. The horizontal solid curves in both cases present the observational upper limits [53]. One can see that in examples given above the muon fluxes can be reliably detected by future gigantic neutrino telescopes.

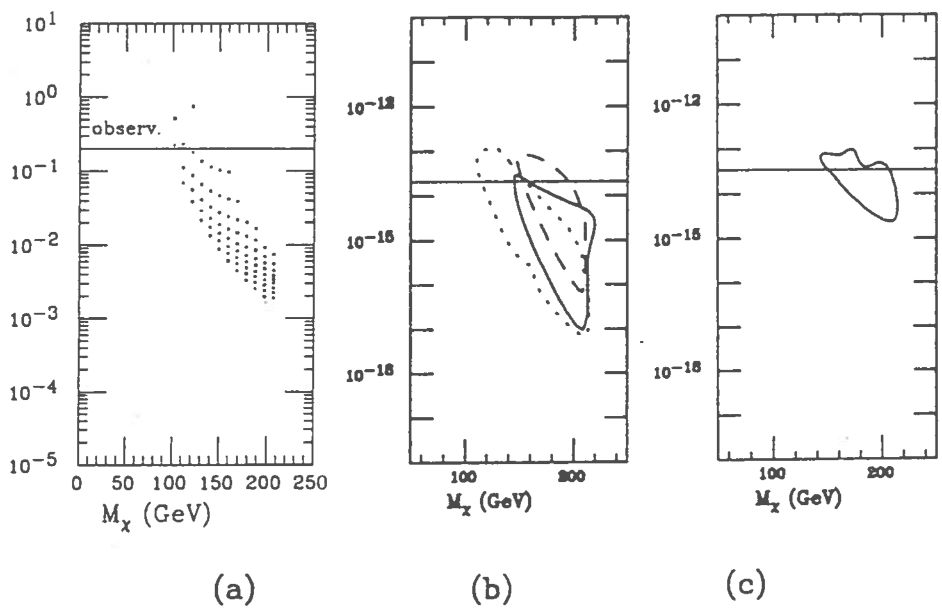

Figure 4: Direct (a) and indirect (b and c) detection of neutralinos for $\tan\beta = 53$ and different neutralino masses. Fig.4a presents counting rate in units $events/(kg \cdot day)$. Fig.4b gives the underground muon flux from the Earth-core direction for $\delta_1 = \delta_2 = 0$ (solid line), $\delta_1 = 0, \delta_2 = -0.3$ (dashed line), and $\delta_1 = 0.7, \delta_2 = 0.4$ (dotted line). Fig.4c gives the underground muon flux from the direction of the Sun for the case $\delta_1 = 0$ and $\delta_2 = -0.3$. ; the fluxes are given in units $cm^{-2}s^{-1}$.

8 Light gravitino

The great interest was recently given to the models with Dynamical Supersymmetry Breaking (DSB). In these models the global supersymmetry in the visible sector is broken by radiative corrections [54,55]. The typical models considered now have the hidden sector, where local supersymmetry is broken at low energy of order $1 - 1000\ TeV$. The fields from the second sector of the theory, *messenger sector*, connect the hidden and the visible sectors. The loop diagrams, containing the messenger fields, produce the mass difference between particles and their supersymmetric partners in the supermultiplets of the visible sector, providing thus the global supersymmetry breaking in the visible sector. The messenger sector may contain, as extreme, just one gauge supermultiplet. The realistic models, however, have more complicated messenger sector with with messenger gauge fields, messenger quarks and messenger leptons.

The DSB models with low-energy breaking supersymmetry have some advantages in comparison with the supergravity models: dangerous flavor-changing currents are automatically suppressed, no fine-tuning is needed for the hierarchy problem and all soft-breaking terms needed in the MSSM can be obtained with two-three free parameters. For the particular models see ref. [56,57] and citations therein.

Most important prediction of the low scale DSB models is that the LSP is gravitino. The mass of gravitino, $m_{3/2}$, is connected with the scale (F-term) of local supersymmetry breaking in the hidden sector:

$$m_{3/2} = \frac{F}{2\sqrt{3}M_{Pl}}, \tag{13}$$

where M_{Pl} is the Planck mass. For the lowest scale of local supersymmtry breaking $\sqrt{F} \sim 1\ TeV$, the mass of gravitino $m_{3/2} \sim 10^{-5}\ eV$.

The heavy gravitino interacts with matter multiplets mostly through its transverse component with spin 3/2. The coupling of this component is p/M_{Pl}, where p is characteristic momentum of the process. This interaction is very weak. In case of low mass, the longitudinal component with spin 1/2 (goldstino) interacts more strongly with coupling constant proportional to $1/m_{3/2}M_{Pl}$. For light gravitino and high energies this interaction can be much stronger than gravitational one.

For the cosmological applications the keV gravitinos are at interest. They form so called warm dark matter, with characteristic mass of the large scale structure larger than in case of CDM, but less than in neutrino case . This mass is given by

$$M \sim M_{Pl}^3/m_{3/2}^2 = 1.6 \cdot 10^{12} M_\odot (1\ keV/m_{3/2})^2, \tag{14}$$

which is of order of galactic mass.

In contrast to "standard" heavy gravitino, which never was in thermal equilibrium in the Universe, keV gravitino interacts strongly enough to be in equlibrium. Then the present density of neutralino can be easily estimated as

$$\frac{n_{3/2}(t_0)}{n_\gamma(t_0)} = \frac{43/11}{g_*} = 1.7 \cdot 10^{-2}, \tag{15}$$

where coefficient 43/11 takes into account reheating of photons and g_* is is the number of spin states at the moment of gravitino decoupling. The number in *rhs* of eq.(15) is obtained for $g_* = 915/4$ valid for all partciles of the MSSM. Using eq.(15) one obtains $\Omega_{3/2} = \rho_{3/2}/\rho_{cr} \approx m_{3/2}/1\ keV$, which provides that sub-keV gravitino can be warm dark matter particle.

One can worry about decay of the next lightest supersymmetric particle. In case it is the neutralino, it decays too fast with no observational consequences.

Very light gravitino can be seen in accelerator experiments or reveal itself in SN explosions[26]. It is easy to see that keV gravitino is too heavy to produce these signals.

The gravitino DM looks, unfortunatelly, undetectable.

9 Conclusions

The baryonic DM is discovered in the halo of our Galaxy. Machos have a mass between $0.1 - 1.2 M_\odot$ and comprise between $10 - 100\%$ of the total mass of galactic halo. However, the bulk of DM observed in the Universe can hardly be dominated by baryons.

The most successful cosmological models require CDM with density $\Omega h^2 \approx 0.2 \pm 0.1$. The minimal supersymmetric extension of SM, with strong CP violation suppressed by PQ-symmetry, predicts the generalized neutralino as a superposition of usual neutralino and axino. The Goldstone chiral supermultiplet contains axion and axino. Therefore, in this model there are three natural candidates for CDM particle: axion, axino and neutralino (or a linear superposition of the latter two).

The new *axion* window corresponds to axion masses between $3 \cdot 10^{-5}$ and $3 \cdot 10^{-3}\ eV$, i.e. it only partly overlaps with the range of search in microwave cavity experiments.

Axino can provide both CDM and HDM. The direct observation of this particle seems to be impossible.

Neutralino remains most attractive CDM candidate. In the models with radiative EW symmetry breaking the properties of neutralino are restricted, but there are many configurations where the neutralino can provide the required $\Omega_{CDM} h^2$ and can be found by direct and indirect methods.

Light gravitino can be the LSP in the models with the Dynamical Supersymmetry Breaking. In case the gravitino mass in sub-keV - keV range, these particles can form Warm Dark Matter with characteristic large-structure mass of order of galactic mass. The relic gravitino density which is needed for this scenario is naturally provided by the gravitino properties. Light gravitinos can be hardly detected directly.

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