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**"DARK MATTER" IN OUR UNIVERSE**

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**"Dark matter" in our Universe**

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*Abstract: We summarize here the main topics of the dark matter problem. Presences of dark matter in galactic haloes and in clusters of galaxies are reviewed. The candidates to solve the problem and their implications are discussed together with the detection methods.*

*Riassunto: Riassumiamo in questo articolo i principali aspetti del problema della materia oscura. Sono evidenziate le presenze di materia oscura negli aloni galattici e nei cluster di galassie. Sono discussi i candidati per risolvere il problema, le loro implicazioni e i metodi di rivelazione.*

## 1. Introduction

Since the '20 years it was pointed out <sup>(1)</sup> that the average density of the Universe is greater than the evaluated one; but, only in the last few years there has been a strong evidence<sup>(2,3)</sup> that the "visible" matter in the Universe is about two orders of magnitude lower than the values given by the dynamical analysis of astrophysical objects. A candidate solution to this problem could be the presence of "dark matter" inside our visible Universe.

The standard cosmology is based on the assumption that our Universe arises from an initial singularity - Big Bang - and it is supported by the fact that the Universe goes on expanding. The theory of general relativity allows us to relate the evolution of the scale parameter,  $R(t)$ , of the Friedman, Robertson and Walker metric<sup>(4)</sup> to the average density of the Universe,  $\rho$ , by means of Friedman equation:

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = H^2(t) = \frac{8\pi G}{3} \rho - \frac{K}{R^2(t)} + \frac{\Lambda}{3}.$$

where  $K$  is a constant equal to 0, -1 or +1 respectively for a flat, open or closed Universe;  $\Lambda$  is the cosmological constant and the actual value of  $H(t)$  is the Hubble constant equal to  $(100 \times h)$  km s<sup>-1</sup> Mpc<sup>-1</sup> ranging the  $h$  value from  $\frac{1}{2}$  up to 1 (because of the experimental uncertainties).

An homogeneous isotropic Universe can be described by the density parameter  $\Omega = \rho/\rho_c$  and  $\rho_c = \frac{3H^2}{8\pi G} = (2 \times 10^{-29} \cdot h^2)$  g/cm<sup>3</sup> = (  $11h^2$  )

keV/cm<sup>3</sup> is named "critical density".

The case  $\Omega$  less, equal or greater than unit identifies respectively an open, flat or close Universe assuming  $\Lambda$  equal to zero.

By photometric methods it is possible to estimate the mean luminosities of the objects and systems in our Universe and, then, also their average densities; the quoted values <sup>(5,6)</sup> are  $\Omega \approx 0.002 \div 0.01$ . Of course, these methods cannot evaluate the whole average density of the Universe; in fact, non - luminous matter density can be estimated only by gravitational effects using the Virial method <sup>(2,3)</sup>, the deviation from the Hubble flow <sup>(7,8)</sup> and the space curvature <sup>(9,10)</sup> measurements.

To deduce the mass of a galaxy, the Virial method uses the measurements of halo velocities as a function of the distance from the galactic center. This is possible studying the optical emission of the stars in the haloes by means of modern spectroscopic techniques <sup>(2)</sup> or observing the Doppler shifts of the 21 cm line of neutral hydrogen present in the interstellar clouds <sup>(3)</sup>. For a stationary gravitational system, the Virial theorem allows us to obtain for the velocity,  $v$ , at  $r$  distance from the center of mass of the system:  $\langle v^2 \rangle = kG \langle \frac{M}{r} \rangle$ . The values within brackets are mean values,  $k$  is a geometrical constant (equal to 1 for a spherical symmetric system) and  $M$  is the mass inside the  $r$  radius. Experimental evaluations <sup>(2,3)</sup> of the velocity distributions for many galaxies give  $v$  values about constant even at distances greater than the optical dimension of the system; so that  $M(r) \propto r$  and the density  $\propto \frac{1}{r^2}$ . This can be justified by the presence of non-luminous matter far from the center.

Notice that big systems cannot be described by the Virial method because their ages are not larger than their rotation period and crossing times. However, special computer simulations - for these "non in equilibrium" systems - give results of the same order than those assuming virial equilibrium <sup>(5)</sup>.

Another relevant parameter - that can give additional suggestions on the existence of the "dark matter" - is the ratio between the mass ( $M$ ) and luminosity ( $L$ ) of a system,  $\frac{M}{L}$ . This parameter is conventionally assumed equal to one in the sun and - for a population of stars - is expected to range from 1 to 3 <sup>(5)</sup>. On the contrary, for spiral and elliptical galaxies an average value  $\frac{M}{L} \approx 20$  is found and this ratio increases quite linearly when increasing the mean distance,  $R$ , over which it is calculated (the scale): for instance some clusters and groups have an  $\frac{M}{L}$  value up to 200. This gives us another clear evidence about the presence of non-luminous matter in the Universe.

Another procedure is based on the deviations from the Hubble flow. In fact the velocity observed today should be equal to the acceleration due to density fluctuations multiplied by the time of growth of such fluctuations <sup>(8)</sup>. In the

linear theory:  $\vec{v} = \frac{1}{H} f(\Omega, H) \vec{\nabla} \int \frac{\delta(x')}{|x-x'|} d^3x'$ ; here the time,  $\frac{1}{H}$ , is corrected by

a function  $f(\Omega, H)$  and  $\delta = \Delta\rho/\rho$  is the density contrast between the galaxy and the underlying densities which are, in principle, detectable by the Hubble flow

measurements. Comparing the velocities of our group of galaxies with the cosmic microwave background, it is possible to evidence our infall to the Virgo cluster and to derive  $\Omega$  value. Davis and Peebles (7) found  $\Omega \approx 0.2$ , while Strauss and David (11) obtained a  $\Omega$  value ranging between 0.2 and 1.

Finally, the direct measurement of the space curvature - to obtain the  $\Omega$  value - is possible only at great distance (at least 1000 Mpc) when significant deviations from Euclidean geometry are present. From the detection of the space curvature (luminosity) vs the red-shift, Sandage e Tamman (10) obtained:  $\Omega \leq 2$ ; while Loh and Spillar (9), studying the densities of galaxies as a function of the red-shift, found  $\Omega = (1.2 \pm 0.3)$ .

In Table 1 we summarize the density values found with these various methods.

**Table 1**

A short summary of the Universe density observations with different methods(6,27).

	scale (kpc)	$\Omega$	References
Visible parts of galaxies (using photometric techniques)	10	0.002÷0.01	5,6
Haloes of galaxies (by Virial method)	100	0.02÷0.2	12,13
Clusters (by Virial method)	1000	$\approx 0.2$	12,14
Virgo infall	$10^4$	$\approx 0.2$	7
Large scale infall	$3 \times 10^4$	0.2÷1	11
Space curvature	$3 \times 10^6$	0.3÷2	9,10

Note that the actual value  $\Omega \approx 1$  implies that - at the beginning of the Universe ( $\cong 10^{-2}$  s) -  $\Omega$  was very close to 1 in a part over  $10^{15}$ . The

experimental measurements support this hypothesis and give rise to a basic cosmological problem, known as "flatness problem", that could be explained by new inflationary models <sup>(15)</sup>. The inflationary scenario expects an epoch of exponential expansion, followed by re-heating and nucleosynthesis. The structure of Einstein's equations implies that at the end of the exponential period,  $\Omega$  should be very close to unit. Furthermore, it is relevant that the inflationary models could explain also the "horizon problem" (i.e. the homogeneity and isotropy of 3 K background radiation) and the dilution of magnetic monopoles (created during the GUT phase transition).

Looking for possible solutions of this "dark matter" problem one has to take into account cosmological-, particle- and theoretical- physics, opening a large field of research. In the following we will discuss the "dark matter" candidates and the techniques to detect them.

### **3. What solutions to the "dark matter" problem?**

It is difficult to find a simple solution to the "dark matter" problem by conventional methods. This problem may be approached from astrophysical or cosmological points of view or following the hypotheses of the existence of non luminous objects or of a sea of stable elementary particles.

#### **3.1 Astrophysical and cosmological solutions**

Some possible astrophysical and cosmological explanations of the "dark matter" problem have been suggested, but they are ad-hoc and do not agree completely with other theoretical evaluations and experimental measurements (5,6).

An explanation may be the wrong evaluation of the distance ladder used by the astronomers to calculate the astronomical distances: in fact, the ladder is an overlapping of distance indicators, each one calibrated by the previous one. Therefore, the average density can be underestimated if the stars nearby the sun have a bigger luminosity than the estimated one. In addition if the rotational curves of spiral galaxies are due to outer gas in non circular and non permanent

orbits, one can underestimate the galaxy luminosity because the background luminosity is overestimated. Moreover, the velocities of globular clusters, companion galaxies and outlying stars may be perturbed by external very fast objects in non-permanent orbits.

Other possibilities are: a non-constant  $G$  values (increasing with the distance or varying with acceleration); a cosmological constant  $\Lambda$  different from zero (as an energy density of vacuum); a Hubble constant smaller than hypothesized; a non-zero lepton number and, finally, nucleosynthesis in presence of anti-matter or of decaying "dark matter" (12,16,17).

### 3.2 Existence of barionic "dark matter"

In the '30 years the astrophysicists (Jeans, Oort, Zwicky....) thought that the "dark matter" was made by dark and old stars, comets, planets, asteroids or intergalactic gas, produced by an inefficient process in the galaxy formation. But scientific progresses in the observation of X-, radio and infrared rays tend to exclude these possibilities. In fact, the number of neutron stars and black holes estimated by the X-ray emission is not enough to candidate them as "dark matter" source. On the other side, also the intergalactic gas does not give a solution because it is mainly constituted by neutral hydrogen that can be detected by the characteristic line of hyperfine structure at 21 cm and the measured quantity does not suffice.

Other suggestion may be that old and faint stars should have many non-detected heavy elements and more infrared emission than that observed in the haloes of the nearest galaxies. The possibility that the "dark matter" could be comets, asteroids or planets is, generally, ruled out because they are not frequent enough (1).

However, three other possibilities are open: existence of brown dwarfs (whose energy source is only the gravitational contraction) (12,18); very old, cold and faint white dwarfs (remnants of 2-8 solar masses stars) (19) and very massive black holes (20). Brown dwarfs have been widely searched, but only one candidate has been found: an infrared-emitting companion of the white dwarf G29-38 (21). The very massive black holes (masses between 10 and  $10^6$  solar masses) could be formed before galaxy formation and they could be detected by motion of nearby stellar objects.

### 3.3 Existence of non-barionic dark matter

A more popular solution suggests that the "dark matter" is made by stable non-barionic particles; this hypothesis is supported by three important astrophysical models: the cosmological inflation, the nucleosynthesis and the galaxy formation.

The inflationary models prefer  $\Omega \approx 1$ , as obtained observing dynamical effects; but taking into account only the barionic matter, one can find an average density about 2 orders of magnitude lower that could be explained by non-barionic matter.

Also the nucleosynthesis models widely support this solution; in fact, calculations of primordial abundances of the light isotopes  $^1\text{H}$ ,  $^2\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$  and  $^7\text{Li}$  in the early Universe (22,23) agree with the observed ones if the total density of the barions are:  $0.01 < \Omega_b h^2 < 0.025$  (22) or  $0.015 < \Omega_b h^2 < 0.15$  (23). More  $^4\text{He}$  nuclei and less  $^2\text{H}$  nuclei should give higher densities than those observed.

A further support to the non-barionic solution comes from the actual theories which do not provide the formation of the galaxies and larger structures; in fact, density fluctuations do not easily condensate in an homogeneous expanding Universe with  $\Omega < 1$  and without anisotropies into the 3 K microwave background radiation as observed ( $\Delta T/T \approx 10^{-5}$ ). This could be solved introducing topological singularities (cosmic strings) or non-barionic "dark matter" particles (13,24,25). They could be the origin of quantum fluctuations at the time of the inflation; therefore, the formation of the galaxies could be due to a gravitational collapse of such fluctuations (26).

Finally, note that if one considers the "dark matter" constituents as relativistic particles at the temperature of 1 keV ( "hot dark matter" particles), their energy transport would erase the density fluctuations up to medium scale(27); so superclusters should be formed before galaxies. But this is not compatible with the observations; so the hypothesis of "cold dark matter" particles with a non-relativistic energy at the time of galaxy formation is preferred. In Table 2 we summarize the massive particle candidates - by the most recent theories - as non-barionic "dark matter".



**Table 2**

Recent theories candidate particles for dark matter.

theories and models	candidate particles	references
GUT	massive neutrinos magnetic monopole	28
SUSY	$\tilde{\gamma}, \tilde{h}, \tilde{z}$ or their mixing (neutralino) $\tilde{\nu}$ gravitino gluino	29
Peccei-Quinn [1977]	axion	30
Simmetry breaking	Majoron; Goldstone boson	
exotics on galaxies formation	cosmic strings	13,24,25
exotics on matter constitution	quarks nuggets nuclearites	31

#### 4. Cold dark matter

The non-barionic "cold dark matter" density is directly related to the corresponding interaction cross section <sup>(32)</sup>. The thermodynamical equilibrium between the "cold dark matter" particles,  $\delta$ , and quarks (q) and leptons (l) - in the beginning of our Universe - can be described as:  $\delta \bar{\delta} \leftrightarrow q \bar{q}, l \bar{l}$ . Then, because of the expansion and of the subsequent temperature decreasing, we loose the equilibrium (the "freeze-out" time) and the particle-antiparticle pairs annihilate without re-formation.

If the rate of annihilation is greater than the rate of the Universe expansion, they will disappear and cannot survive up to now; otherwise, the expansion of the Universe will dilute them and they will constitute the "dark matter".

Therefore we may have a constraint on annihilation cross section. In the case of particles with  $M_{\delta} \geq 0.3$  GeV it is given by <sup>(27)</sup>

$$\sigma \times v = \frac{10^{-26}}{\Omega_{\delta} h^2} \text{ cm}^3 \text{ s}^{-1} \quad (1)$$

where  $v$  is the relative velocity of the particle-antiparticle pair; this cross section  $\sigma$  is about of the same order of the weak interaction cross section, as in the SUSY hypothesis. For this reason these particles are named WIMPs (Weakly Interacting Massive Particle). In particular for the Dirac massive neutrino as "dark matter" candidate, we obtain  $M_{\delta} \geq 2 \text{ GeV}$  knowing the interaction cross section. Note that experimental evaluations from accelerator experiments on the existence of scalar fermion particles, rule out mass smaller than 3-4 GeV (27). The relation (1) is obtained assuming that the  $\delta$  particles are stable and that the particles and antiparticles have identical initial density; in the case that the second hypothesis fails the value (1) is a lower limit. In case of non-stable particles the possibility that they could be "dark matter" particles is obviously related to their decay times.

To evaluate the expected flux of cold dark matter particles, one needs to take into account: the masses of dark matter particles, the galactic haloes density and the velocity distribution.

Using the data on the galactic halo density, Caldwell e Ostriker (33) estimated, near the Earth, a "dark matter" density with a factor 2 of uncertainty:  $\rho_{\text{halo}} \approx 7 \times 10^{-25} \text{ g cm}^{-3} \approx 0.4 \text{ GeV}/c^2 \text{ cm}^{-3}$ .

An estimate of the velocity distribution may be derived following the hypothesis that all the particles trapped in the gravitational field of Galaxy have an isothermal distribution with mean value  $v_{\text{rms}} = \sqrt{\frac{3}{2}} v_0 = 270 \text{ km/sec}$  (virial velocity of the Galaxy):  $\frac{dn}{dv} = n_0 (\pi v_0^2)^{-3/2} 4\pi v^2 \exp\left\{-\frac{v^2}{v_0^2}\right\}$ ; where:  $n_0 = \frac{\rho_{\text{halo}}}{M_{\delta}}$

Generally the velocity distribution is considered valid in case of velocity values less than the escape velocity from galactic gravitational field ( $v_{\text{esc}} \approx 550 \text{ km/sec}$ ) (34).

Using these evaluations one can obtain for the "dark matter" flux:

$$\begin{aligned} \varphi &\approx 10^{-17} \text{ g cm}^{-2} \text{ s}^{-1} & (2) \\ &\approx 5.4 \times 10^6 \times \left(\frac{1 \text{ GeV}}{M_{\delta}}\right) \text{ [particles cm}^{-2} \text{ s}^{-1}] \end{aligned}$$

Because of Earth's motion, the velocity of the Earth through the galactic halo has an annual modulation of  $\pm 30$  km/sec; so the flux will be also modulated.

## 5. Hot dark matter

In this section we consider as "dark matter" constituents, particles with relativistic energy at the decoupling time, named "hot dark matter" particles. The light neutrino is the most important candidate, being also the only dark matter candidate experimentally known.

To evaluate the density of each kind of neutrino,  $n_\nu$ , one has to take into account the observed density,  $n_\gamma$ , of 3 K background photons (35,36,37):  $n_\nu =$

$$\frac{3}{11} \times n_\gamma = 110 \text{ particles cm}^{-3} .$$

The abundance calculations predict a light massive neutrino with (38):  $\sum_\nu \frac{g_\nu}{2} m_\nu \approx 100 \times (\Omega h^2) \text{ eV}$  where  $g_\nu$  is the number of neutrino helicity states per specie.

Assuming  $0.15 \leq \Omega h^2 \leq 0.65$  (37) we can evaluate the neutrino mass in the hypothesis of one neutrino flavor domination and  $g_\nu=2$ :  $15 \lesssim m_\nu \lesssim 65 \text{ eV}$  .

Reliable experimental limits of neutrino masses are  $m_{\nu_e} \lesssim 10\text{-}20 \text{ eV}$  from SN1987a (39);  $m_{\nu_\mu} \lesssim 250 \text{ keV}$  from R. Abela et al.(40) and  $m_{\nu_\tau} \lesssim 35 \text{ MeV}$  from ARGUS (41).

These neutrinos are very hard to detect: in fact, their energy is of the same order of magnitude of background photon radiation, i.e. about 3 K ( $\approx 10^{-4} \text{ eV}$ ). Up to now few proposals are available to detect these light massive neutrinos (42). One uses the large cross section for coherent scattering considering a refractive index corresponding to a wavelength of about  $20 \mu\text{m}$  (43); the coherent reflection of neutrinos could give rise to measurable macroscopic forces on a target. Another possibility could be to evaluate the  $\nu_\mu$ - $\nu_\tau$  oscillations. As suggested by Harari (37), they could give us information on their roles in the dark matter problem, if  $\nu_\tau$  has mass in the range  $15 < m_{\nu_\tau} < 65 \text{ eV}$  and if we hold the "see-saw" mechanism (44), where  $m_{\nu_\tau} \gg m_{\nu_\mu} \gg m_{\nu_e}$  .

## 6. How to detect dark matter particles

As discussed above, the dark matter candidates are neutral and weakly interacting particles, they have a low energy and mean densities - nearby the earth - very small; so they are very difficult to detect.

The methods - proposed until now - to detect "dark matter" candidates can be classified (43) as "direct" or "indirect" measurements. In the "direct" experiments the interaction of dark matter candidates with a target and apparatus is observed; while the "indirect" measurements detect the secondary fluxes produced by the interactions of dark matter particles outside the Earth.

Note that in the "direct" method one has to distinguish between the case of light "dark matter" particle and heavy "dark matter" particle detection. In fact, the former are detectable only by means of macroscopical coherent effects on targets, while the heavy particles may interact with the nuclei in the target and they can be detected by observing the recoil nucleus.

## 7. Some ideas on heavy "dark matter" detection

The kinematics of the elastic scattering of WIMP's with  $M_\delta$  mass on a nucleus with  $M$  mass gives for the kinetic energy of the outgoing nucleus:

$$T = E_1 r \left( \frac{1 - \cos\theta^*}{2} \right)$$

where:  $r = \frac{4 \cdot M \cdot M_\delta}{(M + M_\delta)^2}$ ,  $E_1 = \frac{1}{2} M_\delta v^2$  and  $\theta^*$  is the CM scattering angle.

Assuming that:  $v \approx 10^{-3} c$  (typical virial velocity of our Galaxy) and  $r \approx 1$ , then  $T \approx 1 \div 10$  keV; so that the detector must be sensible to these energies of the recoil nucleus.

Assuming  $\frac{d\sigma}{d\cos\theta^*} \approx \cos\theta^*$  and the virial velocity distribution of the Galaxy, we derive the energy spectrum of the recoil nucleus from "dark matter" elastic

scattering:  $\frac{dR}{dT} = \frac{R_0}{E_0 T} \exp\left\{-\frac{T}{E_0 T}\right\}$ , where  $E_0 = \frac{1}{2} M_{\delta} v_0^2$  and  $R_0$  is the total rate.

In fig. 1 the calculated energy distribution of a recoil nucleus in Germanium detector from 10 GeV "dark matter" elastic scattering is shown in two different periods of a year, showing the annual modulation due to the Earth motion around the sun.

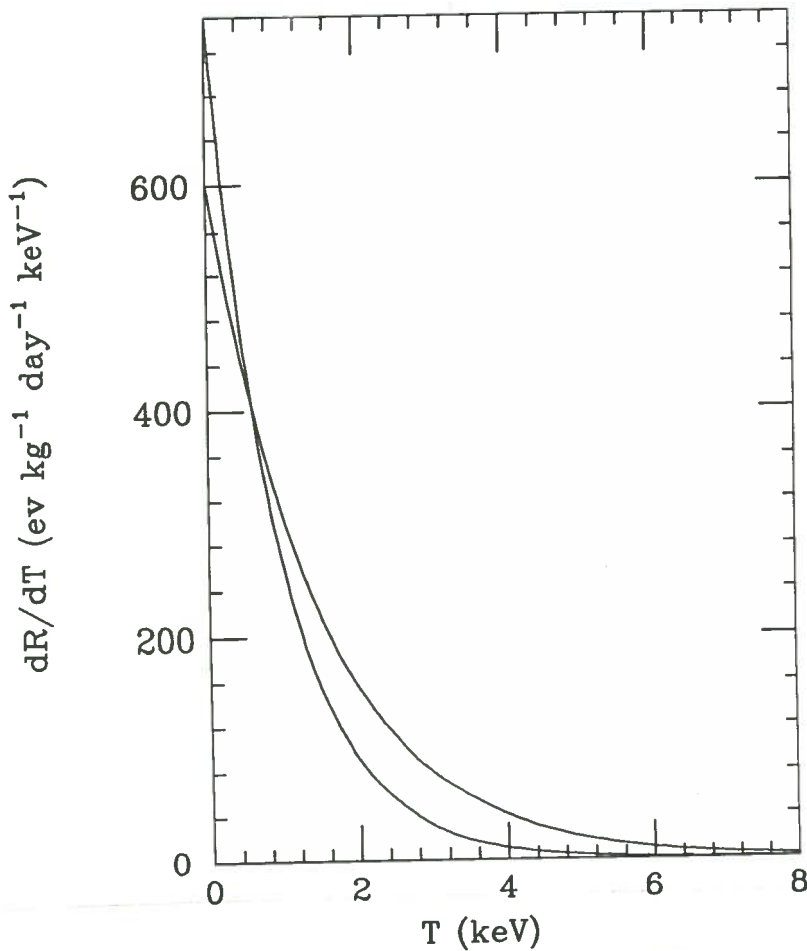


Fig. 1 - Recoil nucleus energy distribution from 10 GeV "dark matter" particles impinging a Germanium detector in two different periods of a year.

The actual annihilation rate of  $\delta \bar{\delta}$  pairs in the halo of galaxy or inside the sun, can be evaluated using the standard methods of the field theories and knowing the effective Lagrangian of the system. In particular, the constraint of the  $\delta$  particles annihilation cross section at the time of "freeze-out" (1), can be used

to study lower energy processes. Therefore the elastic scattering of  $\delta$  particles on quarks can be evaluated - by crossing - as:  $\sigma \approx \frac{10^{-38} \text{ cm}^2}{\Omega_\delta h^2}$ .

For instance, considering  $\Omega_\delta h^2 \approx 1$ , assuming  $v_{\text{rsm}}$  as the velocity of "dark matter" particles, a value of  $7 \times 10^{-25} \text{ gr/cm}^3$  for their density and a mass of 1 GeV, one obtains an interaction rate  $\approx 5.5 \text{ events day}^{-1} \text{ kg}^{-1}$  on the total energy spectrum to be compared with a background rate estimated of about  $3 \text{ events day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$  (45).

Many authors (34,46,47,48) pointed out the relevance of coherence effects for "dark matter" particles with mass  $\approx 10 \div 100 \text{ GeV}$  impinging on a nucleus. In this case, the average momentum - transferred from the  $\delta$  particle to the nucleus -  $\Delta p \approx \mu v = \frac{M M_\delta}{M + M_\delta} v \approx 0.02 \text{ GeV}$ , gives a characteristic coherence length,  $\lambda = 10^{-12} \text{ cm}$ ; so that coherence will be present when the nucleus radius is less than  $\frac{\lambda}{2\pi}$ .

As an example, we recall that the cross section scattering of lefthanded non relativistic neutrinos with vector coupling is:  $\sigma_T(\text{cm}^2) = (G_F^2/2\pi) \mu^2 K_N^2 = 2 \times 10^{-39} (M_\delta A r K_N^2)$  where  $K_N = (A-Z)/2$  is the coherence factor; its value enhances the expected event rate:  $R_0(\text{coherent}) \approx 1.2 r (N/2)^2 \text{ events kg}^{-1} \text{ day}^{-1}$  and one can obtain also rates of  $10 \div 1000 \text{ events kg}^{-1} \text{ day}^{-1}$  as shown in Table 3.

In case of the axial coupling interaction the coherence factor become:  $K_N = \lambda \sqrt{J(J+1)C}$  where:  $\lambda = \{[J(J+1) + s(s+1) - l(l+1)]/2J(J+1)\}^{1/2}$  and  $C = |H_{\delta n}|^2$  is the square matrix element which correlates the initial and final states of the  $\delta$  particles and unpaired nucleon; these values for many nuclei are tabulated in ref. 49. In this case the coherence factor is less than unit and there is no enhancement of the event rate. However, some authors (46,50,51) claim on increasing of 1 or 2 orders of magnitude in the cross section due to additional effects.

We summarize the expected rates in table 3. We want to notice that spin zero nuclei - used up to now in the experiments - are not good target nuclei for axially coupled particles.

**Table 3**

A brief review of typical orders of magnitude for the interaction rates <sup>(46,51)</sup>.

Interactions with nuclei	candidate particles	target nuclei	typical rates (kg <sup>-1</sup> day <sup>-1</sup> )
spin-independent: coherent weak interaction	sneutrino; heavy $\nu$ Dirac	Al	150 ( $M_\delta=10$ GeV)
		Ge	700 ( $M_\delta=10$ GeV)
		Sn	1400 ( $M_\delta=10$ GeV)
		Al	120 ( $M_\delta=100$ GeV)
		Ge	1400 ( $M_\delta=100$ GeV)
		Sn	4700 ( $M_\delta=100$ GeV)
spin-dependent	photino; z-ino; higgsino; heavy Majorana $\nu$	Hg	5 ( $M_\delta=5$ GeV)
		Ge	1.5 ( $M_\delta=5$ GeV)
		F	1 ( $M_\delta=5$ GeV)
		Hg	1 ( $M_\delta=17$ GeV)
		Ge	0.3 ( $M_\delta=17$ GeV)
		F	0.4 ( $M_\delta=17$ GeV)

In the following sections, we summarize the techniques for detecting "dark matter" particles by the observation of the elastic scattering recoil nuclei. The energy of recoil nucleus can be measured by well known ionization detectors, but with very low efficiency. Furthermore, being typical nucleus energy  $\approx 1-10$  keV, it is very important to detect the whole energy of the recoil nucleus. For this reason new experimental techniques are developed as: low temperature calorimetry, superconducting targets and direct detection of phonons produced by interaction of nuclei with crystalline lattice.

### 8. Low temperature calorimetry

The technique of particles detection by calorimetry<sup>(52,53,54)</sup> consists in measuring the temperature variation of a system when crossed by a particle that release energy to the lattice. Generally, a dielectric crystal at very low temperature - to have the smallest specific heat - is used. In this case the lattice specific heat can be evaluated by the following formula <sup>(55)</sup>:

$$C = 1940 \left( \frac{\rho}{A} \right) \left( \frac{T}{\Theta_D} \right)^3 \text{ J cm}^{-3} \text{ K}^{-1}$$

where  $\rho$  is the density of the medium,  $A$  is its atomic weight,  $T$  is the temperature and  $\Theta_D$  is the Debye temperature. When a particle goes through the detector of volume  $V$  the released energy  $E_R$  gives a temperature variation  $\Delta T = \frac{E_R}{C V}$ . For instance, using  $1 \text{ cm}^3$  of silicon  $\frac{\Delta T}{T} \approx 3 \times 10^{-10} \frac{E_R(\text{keV})}{T^4}$ .

To resolve and detect temperature variations  $\frac{\Delta T}{T} \lesssim 10^{-5}$ , the operating temperatures of these detectors must be about 20-40 mK <sup>(43)</sup>. Note that although actual dilution cooling techniques in principles can be used to reach  $T \approx 5 \text{ mK}$ , in practice it is very difficult to obtain  $T \leq 20 \text{ mK}$ , because of surface effects and material impurities.

The thermometer is obviously an essential part of the apparatus: generally, it consists either of a superconductor or of a semiconductor material. In the first case it works around the critical temperature and, when the temperature increases, its resistance varies sharply. However, because this kind of thermometer could work for a narrow range of temperature, it is preferable to use a semiconducting crystal. The thermometer sensitivity  $n = \frac{d \ln R}{d \ln T}$  must be as high as possible and, generally, can range from 1 to 10 <sup>(43)</sup>. A bias current,  $I$ , pass through these sensors and, when the temperature varies, the applied voltage varies. The thermal pulses have a characteristic rise times of about  $1 \mu\text{s}$  and slow fall time of about  $1-50 \text{ ms}$  due to the relaxation of the system when returning to the operating state. Of course, because of the long decay time, the low temperature detector have a long dead time and can be used only for low rate measurements as double beta decay, neutrino physics or "dark matter" detection.

The feasibility of this technique has been verified many times using either X-rays sources <sup>(56)</sup> or  $\alpha$  particles <sup>(57,58)</sup>. Good results have been obtained by Milan group <sup>(59)</sup>, who achieved an energy resolution  $\approx 100 \text{ keV}$  with  $0.7 \text{ g}$  of germanium and by WMI <sup>(60)</sup> who used  $7 \text{ g}$  of sapphire obtaining a resolution of  $70 \text{ keV}$ . Moreover, Milan group, implanting some radioactive nuclei of a  $\alpha$ -source ( $^{228}\text{Th}$ ) in the detector, has seen not only the energy of  $\alpha$ -particles but also the energy of the recoil nuclei <sup>(59)</sup>.



However, to obtain reliable results for the "dark matter" problem, the target mass should increase of almost two orders of magnitude without a sensible reduction of the energy resolution.

## 9. Superconducting targets

Low specific heat capacities can be obtained using superconductors below their transition temperature; they can be used both as target and temperature sensor. Because  $\Delta T = \frac{E_R}{C V}$ , to increase the accepted range of temperature variations the detector volume must decrease. This technique (52,61) uses an array of small spheres of superconducting material (5-10  $\mu\text{m}$  of diameter) in a dielectric medium. The array is inside a magnetic field, whose intensity is a function of the temperature that hold all the spheres close to the H-T transition boundary; by Meissner effect the magnetic field is excluded from each sphere. When an interaction inside a sphere releases an amount of energy larger than a threshold value, the granule switches to a resistive state and the magnetic field is included in the granule giving a flux variation which can be detected by a surrounding coil connected to a SQUID (Superconducting Quantum Interference Device) or a charge-sensitive amplifier. The best results were obtained using granules of 10  $\mu\text{m}$  in diameter and thresholds of few keV (62,63).

Unfortunately these experiments do not allow to detect the energetic spectrum of the incident particles. Some efforts are now performed to measure the relaxation time to return to the superconducting state (64); this time, in principle, should depend by the energy released in the granule. Another possibility may be to detect "micro - avalanches" of granules nearby the granule impinged by the particle; the subsequent signal should be proportional to the initial deposited energy (62).

Finally, note that - because all the granules are close to the H-T transition boundary - the switch to resistive state could even be induced by a variation of the magnetic field; so that this apparatus could be also sensible to magnetic monopoles.

## 10. Direct detection of phonons

Most of the energy deposited in a detector is converted to lattice vibrations, i.e. phonons. After the thermalization, this energy can be detected using the techniques previously discussed; however, it's also possible to detect directly the primary phonons. The process gives rise to primary phonons with a typical energy of about  $10^{-2}$  eV (43,65,66). The primary phonons at low temperature have a mean free path longer than the size of the crystal, therefore the wavefront reaches the phonon detector with the initial energy. This means that these apparatus can work at a temperature of about  $0.3 \pm 1$  K. Moreover, the phonon wavefront give rise a higher energy density than in the previously described detectors and it is possible to focus them inside the crystal. Furthermore, because it is possible to use large volume crystals these experiments are very attractive. The thermometric instrumentation is either superconductor sensors operating near to the critical temperature (67) or superconducting tunnel junctions.

The feasibility of such experiments has been confirmed by T. Peterreins et al. (68) using a silicon wafer as target.

This technique could even be used to detect X-rays (69) or solar neutrinos (70); but its main drawback is the drastic time and thermic dependance.

## 11. Ionization detection

Most of the existing detectors for "dark matter" are ionizing detectors, the most traditional ones. Generally, these detectors are used for other underground experiments as double beta decay: the elements used up to now are germanium and silicon and they are sensible to electrons with energy larger than  $\sim 3$  keV and to recoil nuclei with energy larger than  $\sim 12$  keV. The typical background rate of these experiments is (71,72):  $\sim 0.5 \pm 1$  events  $\text{kg}^{-1} \text{keV}^{-1} \text{day}^{-1}$ .

In fig. 2 it is shown the region (on the cross section vs mass plane) excluded by the experimental results obtained with 0.9 kg germanium spectrometer by Caldwell et al.(72). In fig.2 there is also shown the physical state for Dirac  $\nu$  when considered a "dark matter" particle. Caldwell excludes massive Dirac  $\nu$  with mass greater than 12 GeV and lower than 1.4 TeV. Another experiment by

Ahlen et al. (71) with 0.7 kg germanium, excludes masses greater than 20 GeV and lower than 1 TeV.

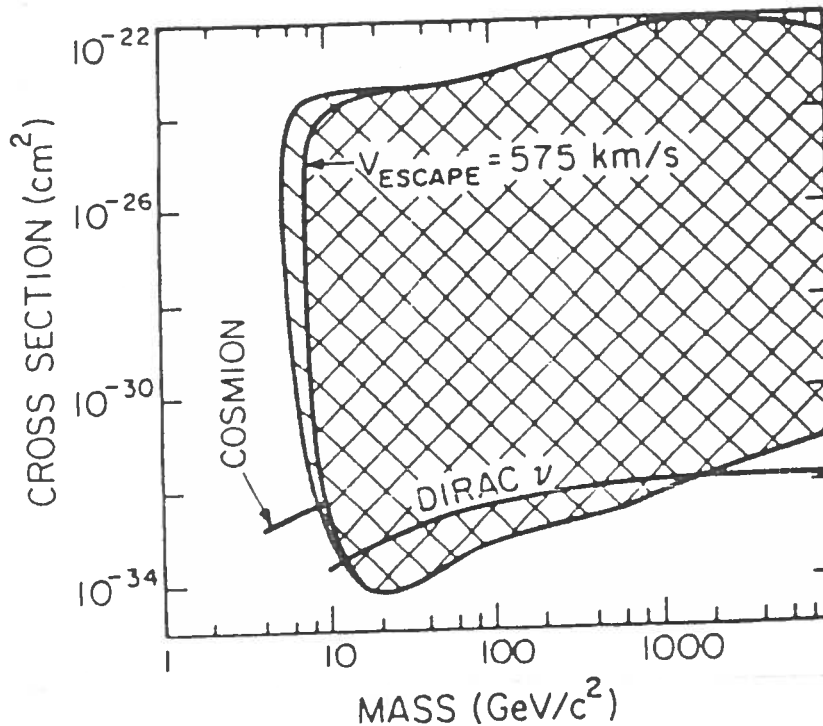


Fig. 2 - Region of plane interaction cross section vs mass excluded by the experiment of Caldwell et al. (72).

## 12. Axion detection

Another candidate as "dark matter" particle is the axion: a weakly interacting light boson of mass  $10^{-5} \div 10^{-2}$  eV hypotized by a CP simmetry breaking in according to the Peccei - Quinn model (30).

The detection technique takes into account that the axion can interact with a magnetic field producing a photon. This is possible because the axion can couple to two photons by fermion vacuum loops. Using the calculations by Schwinger (73) for the effective Lagrangian of pseudoscalar interactions (as in case of axion - fermions), one derives for the axion mass the range 0.18 eV -  $1.8 \times 10^{-5}$  eV in case of three fermion generations.

In the Sikivie (74) proposal the axion interacts with an external magnetic field and a photon with an average energy comparable with the axion mass ( $\approx 10^{-5}$  eV) has to be detected. Following this idea, the experiments of refs. 75,76,77

use high Q tuned resonant cavity in magnetic field: when the photons produced by axion interactions have the same frequency of the resonance frequency of the cavity, a detectable signal occurs. Therefore, it is necessary to scan all the frequency range to search for the signal. The width of the line is expected to be  $\frac{\Delta\nu}{\nu} = 10^{-6}$  and the frequency range 1÷200 GHz. The experimental limits set by S. De Panfilis et al. (77) rule out axions with a mass between 0.45 to  $1 \times 10^{-5}$  eV.

### 13. Indirect measurements

Another method to detect "dark matter" particles consists in the search for a component of the cosmic ray due to a secondary products of the "dark matter" interactions in the space. A suggestive hypothesis (78) could explain the solar neutrino puzzle (79) and the "dark matter" problem: the "cold dark matter" particles with a typical 4÷10 GeV mass (called Cosmions) could be captured and slowed down in the sun.

**Table 4**  
Excluded mass region from indirect measurements.

Dirac neutrinos	$M > 3 \text{ GeV}$
Majorana neutrinos	$5 < M < 25$ and $M > 60 \text{ GeV}$ KAM $M \approx 20 \div 40 \text{ GeV}$ (Frejus)
Electron sneutrinos	$M > 3 \text{ GeV}$
Muon sneutrinos	$M > 3 \text{ GeV}$
Tau sneutrinos	$M > 4 \text{ GeV}$

Therefore, these particles should cooled down the solar core explaining the solar neutrino puzzle and producing energetic neutrinos by annihilation. These high energy neutrinos could be detected by large underground detectors; FREJUS and KAMIOKANDE measuring the atmospheric background exclude with 90% C.L. the mass regions for "dark matter" candidates (80,81) reported in Table 4.

## 14. Other methods

The recoil nucleus direction is an important element to discriminate "dark matter" signals; but most of the experiments are not able to detect it. An experiment, proposed by Rich, Spiro and Tao (6,82), uses a Time Projection Chamber (TPC), filled with methane at very low pressure ( $\approx 3$  torr) to observe the recoil nucleus track and to determine its direction. The development of this technique is in progress.

Other proposals want to detect the inelastic scattering (46) on  $^{173}\text{Yb}$ ,  $^{155}\text{Gd}$ ,  $^{169}\text{Tm}$ ,  $^{187}\text{Os}$ ,  $^{159}\text{Tb}$  and  $^{183}\text{W}$  nuclei with a low excitation energy (about  $10\text{--}100$  keV); the subsequent decay gives a detectable photon.

Finally, a suggestive idea (83) - that needs technical improvements - suggests to detect the rotons produced by the recoil nuclei in superfluid helium.

## 15. Background reduction and signal identification

Being the interaction rate between "dark matter" particles and target nuclei expected extremely low, the most relevant problem for a "dark matter" detector is the rejection of the background events. In fact, the experiments to detect "dark matter" must be able to discriminate a few events in a day from the background mainly due to cosmic rays, to contaminations in the detector and to electronic noise.

To reduce countings from cosmic rays, these apparatuses are installed deeply underground where the radiation, mainly muons, is strongly suppressed as shown in fig. 3; for instance, in the underground Gran Sasso Laboratory, the muon flux is  $< 1 \text{ m}^{-2} \text{ h}^{-1}$  (84). The natural environmental radioactivity is also important: the use of shields may avoid the effect of short range particles as alpha, protons and electrons. Furthermore, the fast neutrons can induce nuclear reactions inside the detectors simulating "good" events; e.g., in the Gran Sasso Laboratory the fast neutrons flux is about  $0.30 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$  (85).

To avoid the countings from the contaminations inside the structural materials of the apparatus, one has to use extra-pure materials. Finally, the  $\gamma$  rays - i.e. mostly the Compton background - may be generally rejectable by means of the shape discrimination of the electronic pulse. Sometimes the

evaluation of the spatial distribution of the energy in the detector is used to identify background events taking into account only a "fiducial volume" as active detector. Moreover, crossed informations could be obtained using both ionization and heat measurements.

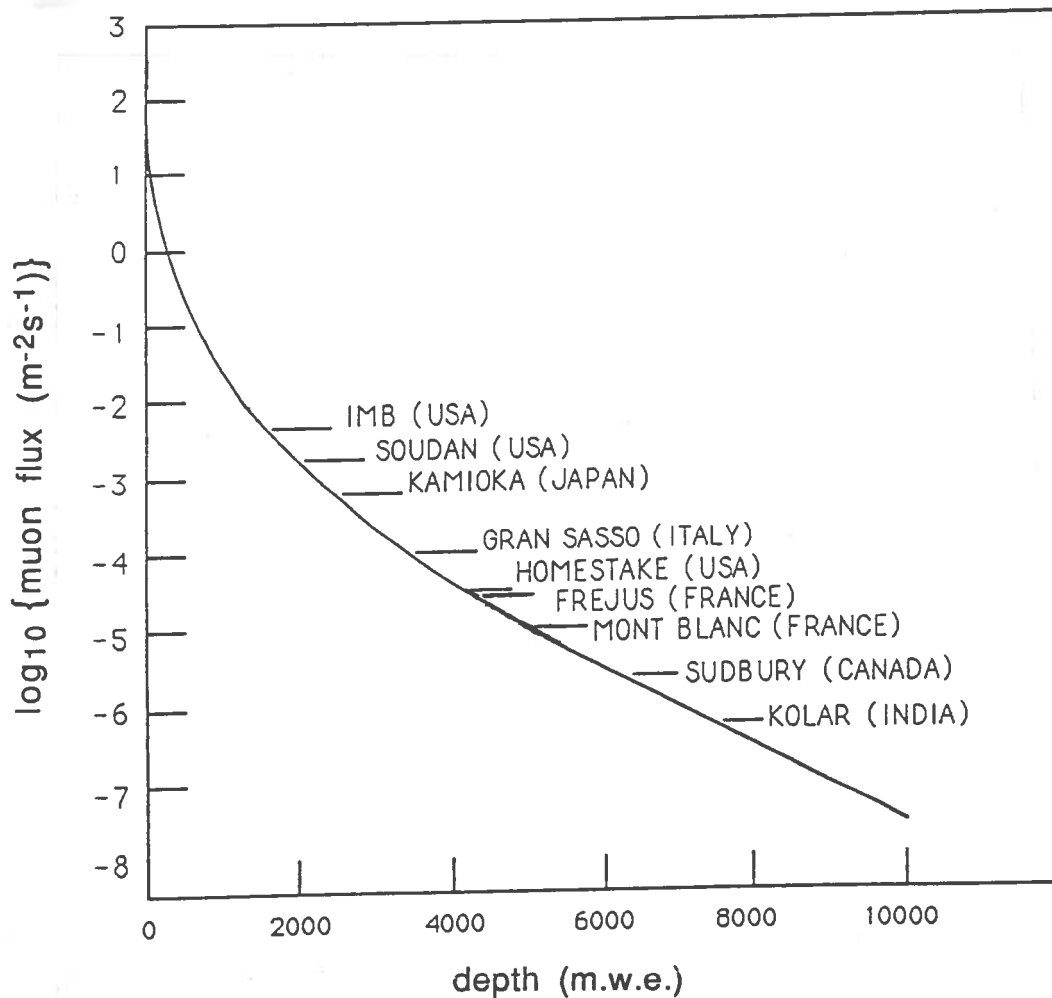


Fig. 3 - Muon flux as a function of laboratory depth (43).

However, four signatures may allow to distinguish a "dark matter" signal from the background: i) the annual rates and the energy spectrum modulations, that are expected to produce ~ a 1.5 factor between the maximum and the minimum rates in forward region (fig. 1); ii) the recoil nucleus direction, that holds the information of the primary "dark matter" direction; iii) the shape of the energy spectrum, that gives the  $E_{0r}$  value and, of course, an estimate of "dark matter" mass; iv) the possibility to use various materials as targets and, then, different interaction cross sections either for spin-dependent or for spin-independent.

## 16. Conclusions

As we have pointed out relevant problems are still open about "dark matter". The first one is to understand if it exists and if it may be considered the main constituent of the Universe. Nucleosynthesis, cosmological inflation and galaxy formation support the existence of non-barionic "dark matter" particles as the most reliable solution of missing mass problem. Furthermore even the last theoretical efforts give us a large number of candidates able to explain the problem, but they are not easy to detect. Therefore, a large number of experiments are needed to answer the question if the Universe will expand forever. However, many technical difficulties must be overcome also exploring possible new technologies.

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