1 Cosmological Dark Matter Models

There is substantial evidence that most of the matter of the universe is dark and a compelling motivation to believe that it is mainly of non-baryonic origin \[1, 2, 3, 4, 5, 6, 7\]. The flat rotation curves in spiral galaxies indicate that most of their masses is in form of large Dark Matter (DM) halos of a mass ten times bigger than the visible mass. Dynamical evidence for the existence of DM at large scales comes from a variety of observation which leads to the conclusion that the luminous mass alone cannot explain the dynamics of the celestial bodies. Gravitational lensing, ROSAT data on X-ray from bremsstrahlung emission of fast electrons in the hot intergalactic gas provide evidence of DM at these scales. Clusters of galaxies velocity dispersion implies the existence of DM in the intercluster space \[8, 9\]. Finally, IRAS data and POTENT analysis on peculiar velocities of galaxies, COBE results on the Cosmic Microwave Background Radiation anisotropies, and high red-shift supernova data support the presence of DM at the largest scales of the universe.

The mean total energy density of the universe, \( \rho \), is currently expressed in units of the critical density \( \rho_c \), \( \Omega_0 \equiv \rho/\rho_c \) with \( \rho_c = 3H_0^2/8\pi G \) (= \( h^2 1.05 \times 10^4 \text{ eV cm}^{-3} \)), where \( H_0 \) is the Hubble parameter \( H_0 \equiv 100 \text{ h Kms}^{-1}\text{Mpc}^{-1} \), and \( G \) the gravitational constant. \( \Omega_0 \) consists of matter density \( \Omega_M \), a negligible part of radiation and, possibly, vacuum energy \( \Omega_\Lambda/3H_0^2 \). Values of \( h \) range \([7]\) between 0.4 and 1 with a long-standing preference for 0.5. Recent measurements, however, lead to higher values of \( h \) \([10, 11]\). Measures and estimates of the mean matter density, \( \Omega_M \), come from various sources, with values ranging from 0.01 to about 1. Luminous matter in galaxies (10 Kpc) accounts only for 1% or less. Galactic halos (50–100 Kpc) contribute up to a 10% to the matter density \( \Omega_h \sim 0.03 - 0.1 \). Mass-to-light ratios in clusters (\( \sim \text{Mpc} \)) \([12]\) suggest that \( \Omega_M > 0.2 \) in agreement with measurements derived from the dynamics of large scale structures and large scale velocity fields \([13, 14]\). At \( \sim 100 \text{ Mpc} \) and above, \( \Omega_M \) is measured by using the data on peculiar velocities of galaxies \([15, 16, 17]\) and red-shift surveys based on the IRAS catalogue. POTENT analysis \([18, 19]\) and IRAS data give a lower limit of \( \Omega_M > 0.3 \). As the scale of the observed cosmic structures increase, the value of \( \Omega_M \) becomes larger \([20]\), approaching the unity value predicted by inflationary cosmologies and supported by COBE results \([21]\).

Big-bang nucleosynthesis constrains \([22]\) the baryon fraction of a critical universe to be less than a few percent, \( \Omega_B h^2 = 0.01 - 0.02 \), and so baryonic dark matter is needed. On the other hand, the large values of \( \Omega \) at increasing scales, together with the smallness of \( \Omega_B \) imply that non-baryonic dark matter should be the main component of the universe. Dark baryons may be in form of black holes, jupiters, white dwarfs, brown dwarfs, or the generically so-called MACHOS (Massive Astrophysical Compact Heavy Objects). From the cosmological point of view, two big categories of non-baryonic DM candidates have been proposed: Cold Dark Matter (CDM) and Hot Dark Matter (HDM), according to whether they were slow- or fast-moving at the time of the galaxy formation. Their relative proportion is fixed to properly generate the observed cosmic structures by gravitational evolution of the scale-invariant primordial density.
fluctuations, as CDM produces structures earlier, whereas HDM erases density fluctuations at small scales \[20\]. The simple CDM \[21\] model leads to an excess of structure formation at small scales and need to be mixed \[7, 23\] with a small fraction of HDM to match the observed spectral power at all scales \[23\]. That mixed Cold plus Hot Dark Matter model \[22\] features \(\Omega_{CDM} \approx 0.75\), \(\Omega_{HDM} \approx 0.2\), \(\Omega_{\Lambda} \approx 0.05\) \((h = 0.5, \Omega = \Omega_{M} = 1)\). Recent values of the Hubble constant \((h \approx 0.7)\) might favour instead a Cold DM model with a non-zero cosmological constant \(\Omega_{\Lambda} = 0.7\) and \(\Omega_{M} = 0.3\) \[7\].

2 Dark Matter Candidates

2.1 Baryonic Dark Matter

Baryonic dark matter in form of MACHOS is actively searched for in on-going surveys of stars in the Large Magellanic Cloud by looking for possible microlensing effects produced by such objects when they pass near the line of sight between the observer and the stars \[24\]. The results of these observations (MACHO \[25\], EROS \[26\] and OGLE \[27\] experiments) indicate that MACHOS could account for a significant fraction of the dark halo. The results of MACHO, for instance after the first two years of data, conclude that the halo mass in form of MACHOS, within 50 Kpc, could be as much as 50% of the total halo mass, with MACHO masses in the range of 0.05 to 1 solar masses, its most probable mass being \(0.5^{+0.3}_{-0.2}\) M\(_{\odot}\). Brown dwarfs might be, then, good candidates to the baryonic dark matter of the galactic halo. However, the statistics is still too low (eight microlensing events in all MACHO plus EROS observations) to establish firm conclusions, as the results depend on the model of both visible and dark matter of the galaxy.

2.2 Non-Baryonic Dark Matter

Extensions of the Standard Model of Particle Physics provide non-baryonic dark matter candidates \[2, 6, 28\]. They should have non-zero masses, be electrically neutrals and interact weakly with ordinary matter. On the other hand, their present relic abundance must have the right values to fill the gap between \(\Omega_{B}\) and \(\Omega_{M}\).

2.3 Neutrinos as hot Dark Matter Candidates

Archetypical hot relics are the “standard” light \((m<\text{MeV})\) neutrinos \[4, 29\]. Their number density, for each flavor \(\nu_{e}, \nu_{\mu}, \nu_{\tau}\), \(n_{\nu} \sim 100\) cm\(^{-3}\) and, if endowed with a non-zero mass, they could provide by themselves the whole critical density. In fact, the Gerstein-Zeldovich bound \(\sum m_{\nu} \leq \Omega_{\nu}h^{2}92\) eV (where the sum extends over all species of light neutrinos with full weak interaction) would lead to the right relic density for various neutrino masses according to the fraction of hot dark matter contained in the model.

In the old, classical hot DM model, neutrinos (one or more species) of masses \(\sim 20 \text{ to } 30\) eV were supposed to constitute the whole DM, but being relativistic particles at freeze out, they cannot form galaxies (the so-called up-down scenario of galaxy formation where larger structures form earlier). Although cosmic strings would help, cold dark matter is required \[23\]. In the mixed CHDM model, where the hot DM is \(\Omega_{\nu} = 0.2\), the preferred total mass of the dark matter neutrino would be \(\sim 5\) eV \((h = 0.5)\) \[4, 22\] shared between the various neutrino species, according to the mass pattern used to solve, simultaneously, other neutrino puzzle (for instance neutrino oscillations). There is no known method proposed so far to directly detect the hot DM relic neutrinos and so terrestrial sources are used to explore this possibility. The discovery of a \(\nu_{\tau}\) mass in the few eV range would favor this form of DM and so several oscillation experiments are under way to explore that range \[50\].

2.4 Cold Dark Matter: Weak Interacting Massive Particles (WIMPs)

In the CDM sector, typical candidates are heavy Dirac or Majorana neutrinos in the GeV-TeV mass range or other heavy, weakly interacting neutral particles, generically called WIMPs \[2, 4, 23, 31, 32\]
2.5 Axions and their detection

Another celebrated CDM candidate is the axion [43], a non-thermal relic invented to solve the strong CP problem. The axion, a light neutral pseudo scalar Goldstone particle of very weak interaction, emerging from the spontaneous breaking of the Peccei-Quinn symmetry, could provide the universe critical density [4, 44, 45] for masses of about $10^{-9}$ GeV. Further improvements (a factor 10 in sensitivity) are foreseen by using ultralow noise DC SQUID amplifiers.

Energetic axions can be produced continuously in the interior of stars (red giants, supernovae), or in the Sun. Astrophysical (cooling rates of stars) and cosmological (overclosure of the universe) arguments, as well as laboratory experiments, require an axion mass in the range $10^{-6} \text{ eV} < m_a < 10^{-3} \text{ eV}$ [4, 44, 53]. Other masses are possible for hadronic axions, not coupled directly to leptons and interacting with matter through a two-photon vertex. The red giants bound stands at $g_{a\gamma\gamma} < 10^{-10} \text{ GeV}^{-1}$ [45].

The Sun is a powerful source of axions in the 1 - 15 keV energy range. The solar axion telescope experiment of the Rochester-BNL-FNAL collaboration [57] got the coupling limits: $g_{a\gamma\gamma} < 3.6 \times 10^{-9} \text{ GeV}^{-1}$ for $m_a < 30 \text{ meV}$ and $g_{a\gamma\gamma} < 7.7 \times 10^{-9} \text{ GeV}^{-1}$ for $30 < m_a < 110 \text{ meV}$. A method of detecting solar axions was proposed in Ref. [68] and extended recently in Ref. [69]. The axions convert coherently into photons in the lattice of a germanium crystal when the incident angle satisfies the Bragg condition. As shown in [70], the detection rates in various energy windows are correlated with the relative orientations of the detector and the sun. This correlation results in a temporal pattern which should be a distinctive, unique signature of the axion. A recent Ge detector experiment [71] has provided a new laboratory bound of $g_{a\gamma\gamma} < 2.7 \times 10^{-9} \text{ GeV}^{-1}$, independent of axion mass up to $\sim 1 \text{ keV}$.
3 Searches for Non-baryonic Dark Matter: General Features of the Detection. Strategies and Techniques [6, 2, 62]

Discovering the nature of the dark matter is one of the big challenges in Cosmology, Astrophysics and Particle Physics. There exists a large activity going on in non-baryonic dark matter searches through indirect or direct detection methods. No DM signal has been detected so far, but various kinds of candidates have already been excluded or constrained.

3.1 WIMPs Indirect detection. Large Underground Detectors and Neutrino Telescopes

Particle Dark Matter can be detected indirectly by searching in cosmic ray experiments for particles produced in the WIMP annihilation in the galactic halos [6, 54], like antiprotons, positrons or photons. The upcoming projects PAMELA [65] and AMS [66] will provide information on the antiproton component in cosmic rays and its implication on WIMPs annihilation in the halo. Dark Matter can also be detected by looking for the high energy neutrinos emerging as final products of WIMPs annihilation in celestial bodies [67] such as Sun [68, 69] or Earth [70, 71, 72], in deep underground detectors, or in running underwater (or underice) neutrino telescopes [73, 74, 75, 76, 77, 41].

WIMPs orbiting through the Earth or the Sun can be trapped inside these bodies when their velocity, as a result of a series of scatterings with the Earth or the Sun nuclei, drops below the escape velocity from the celestial body. The WIMPs sink gradually to the center where they accumulated and eventually annihilate each other into leptons, quarks, $Z^0$, $W^\pm$, Higgs..., which finally give rise to high energy muon neutrinos. By interacting with the surrounding medium of a detector (neutrino telescope), such neutrinos produce muons, which are the indirect signature of WIMPs.

Simple kinematics show that the average energy of the emitted neutrino is about 30% to 50% of the WIMP mass, i.e. significantly larger than that of other neutrinos coming from the Sun or Earth, a fact which permits distinguish the WIMP neutrinos [77]. Further subtraction of the atmospheric neutrino background leaves the way open for a most promising method of indirect WIMP identification,zeroing into the zone of GeV–TeV the search for neutrinos coming from the Sun or the Earth. This capability of the telescopes will be probably unmatched by the direct detection methods in the case of high mass WIMPs and spin-dependent couplings.

Multipurpose large underground detectors (MACRO [78], Frejus, Baksan [79], Soudan), and Neutrino Cerenkov telescopes (IMB [80], Kamiokande [81]), have been used to look for WIMPs neutrinos. We mention here the constrains to DM particle parameters obtained from Kamiokande, Baksan and MACRO. MACRO (Monopole Astrophysics and Cosmic Ray Observatory) in Gran Sasso has searched [79] for neutrino-induced upward-going muons coming from the direction of the Sun or of the Earth core collected with the lower part of the detector. No statistical significant signal has been discriminated over possible fluctuations of the atmospheric neutrinos background. The muon flux limit from non-atmospheric origin (in the 25° window) is $3.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (from the Earth) and of $6.6 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (from the Sun), after exposures of 1250 $\text{m}^2 \text{ yr}$ and 380 $\text{m}^2 \text{ yr}$ respectively. Indirect searches of neutrinos have been carried out at Baksan [79] (at 850 m.w.e.) with the scintillator telescope ($17 \times 17 \times 11 \text{ m}^3$). In 11.94 years of data, the upper bound on the muon fluxes produced by neutrinos of non-atmospheric origin are $2.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (90% C.L.) and $3.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (90% C.L.) (from the Earth and the Sun respectively), corresponding to exposures of 2954 $\text{m}^2 \text{ yr}$ and 1002 $\text{m}^2 \text{ yr}$. These results improve those of Kamiokande [81], $4.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (Earth) and $6.6 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ (Sun) obtained with exposures of 770 $\text{m}^2 \text{ yr}$ and 215 $\text{m}^2 \text{ yr}$. Predictions for the fluxes of such muons in supersymmetric models range in the case of the Earth from about $10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$ to $10^{-17} \text{ cm}^{-2} \text{ s}^{-1}$ (and somehow higher for the Sun case), and so bounds on the neutralino annihilation rate as a function of the neutralino mass have been obtained and regions of the neutralino parameter space excluded [73, 76, 11] as depicted in Figure 1 [74] corresponding to the scattered plots of the predicted WIMP muons coming from the Earth (Fig. 1a) and from the Sun (Fig. 1b), compared with the Baksan limit [79]. The above mentioned underwater neutrino telescopes project to enlarge the exposure areas to reach the $10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$ flux limit. Surfaces...
Figure 1: Predicted muon fluxes (from WIMPs annihilation) from the Earth (a) and from the Sun (b), Ref. [76] compared with the Baksan limit [79].

larger than $10^5 \text{m}^2$ would be suitable devices [6, 73, 74, 75, 76, 77, 83] to search for neutralinos in wide zones of their parameter space and so projects for larger deep underwater neutrino telescopes (1Km$^3$) are underway [77].

The main interest in the large neutrino telescopes [77, 84, 85, 86] is however motivated by their capability as high energy neutrino explorers of galactic and extragalactic sources [77, 85, 86]. They are expected to provide unique information about the astrophysical sources of cosmic rays of energies as high as $5 \times 10^{20}$ eV. The cosmic sources or “cosmic accelerators” which originate ultrahigh energy gamma rays (Active Galactic Nuclei, pulsars, X-ray binary systems, remnants of young supernovae) are supposed to be also copious sources of neutrinos through various mechanisms. Such neutrinos can be detected through the muons they produce in charge current interactions with the matter surrounding the detector. The higher the neutrino energy, the smaller the deflection of the outgoing muon from the neutrino incident direction, and so the emerging muon points back to the neutrino source. Neutrino telescopes will produce a “neutrino sky map” to complement the current sky image we have from other carriers, techniques and instruments (infrared, ultraviolet, macro and micro radio wave, CMBR, high and very high energy gamma rays...). They will allow also to explore regions not reachable through gamma observations due to the interstellar matter or to its absorption by the microwave cosmic background. Besides the indirect detection of WIMPs, neutrino telescopes could address also the exploration of other big-bang relics, cosmic strings, topological defects, which might emit, when collapsing, particles with energies up to $10^{25}$ eV, and the subsequent production of neutrinos. Needless to mention the usefulness of the telescope in the study of atmospheric neutrino oscillation or in long-baseline neutrino oscillation experiments.

Various estimates concluded that Neutrino Astronomy requires a mega-telescope of $\sim$1Km$^3$ [77, 74], which should be obviously placed deep underwater of under ice. A neutrino water Cerenkov telescope is a tridimensional array of optical modules (pressure vessel containing standard PM tubes and associated electronics) suspended on strings, which detects the Cerenkov light produced by the neutrino-induced muons. The measured light intensity—proportional to the muon energy—provides an upper limit to the neutrino energy. The muon trajectory is reconstructed from the time arrival of the Cerenkov wave front to the various PMs hit. Corresponding time resolution of the PMs are a few nanoseconds. Angular resolutions of about one degree can be obtained [$\theta_{\mu\nu} < 1.5^\circ \sqrt{E(\text{TeV})}$]. The position of the tridimensional set of optical sensors should be accurately monitored. Besides the technical challenges to be solved in the telescope construction, there exist many basic issues to be addressed, in particular, the determination of the physical parameters of the detector medium as well as the optimization of the geometry and instrumentation of the PM array for a given scientific objective. The net spacing, instrumentation
and fiducial volume of the neutrino telescope can be tailored according to the specific purpose of the instrument. A first stage (0.01 Km$^2$ of surface) of a modular, multipurpose telescope would be a very interesting tool for atmospheric neutrino experiments. Surface dimensions of 0.1 km$^2$, with a high energy threshold could be already useful for neutrino astronomy. A device of similar dimensions, with lower threshold and denser instrumentation would perform as WIMP indirect detector.

The pioneering contribution of DUMAND (Deep Underwater Muon and Neutrino Detector) [8], now abandoned, has settled the frame where the current telescopes or projects have been developed. Substantial progress in such projects has been accomplished in the past few years [57].

The AMANDA [89, 87] (Antarctic Muon and Neutrino Detector Array) detector deployed first four strings of optical modules at a depth from 810 to 1000 meters (Phase A) in the Antarctic polar ice, and then added seven more strings between 1520 to 1900 m deep (Phase B). A total of 290 optical sensors have been operating. Now AMANDA-II, featuring ten more strings around the A+B setup is in progress toward an effective exposure area of 60,000 m$^2$, and angular opening of one degree. Scattering lengths of Cerenkov light in AMANDA B are two orders of magnitude larger than in AMANDA A. The atmospheric muon flux has been measured to be 25 Hz in AMANDA B. Coincidence measurements between the sectors A and B have proved that up- and down-going events are well distinguished.

ANTARES [90, 87] (Astronomy with a Neutrino Telescope and Abyss Research) plans to place in a 2600 m deep abyss off-shore of the Toulon-Marseille Mediterranean coast a “demonstrator” consisting of three strings of 32 optical sensors each. In the future this instrument could be enlarged to the cubic kilometer scale with 49 strings (100 to 150 meters apart) and a total of 1500 PM. Supporting mechanical structures have been successfully deployed in a harbor basin and also at sea (2300 meters deep), 30 Km off shore. Optical background due to bioluminiscent and to $^{40}$K in water has been measured. A first step will be the development of 30 Benthos spheres (with various instrumented optical modules) connected by electro-optical cables to the shore station.

The Baykal [82, 91] lake neutrino telescope consists of a set of strings pending from an umbrella-like structure, instrumented with PM in large vessels, which has been operating since 1993 at a depth of 1366, 3.6 km off-shore. After the first instrument NT-36 (36 modules in three strings), which operated along 300 days in 1993-1994 and was successfully recovered, a larger set (NT-96) has been operating along 1996-1997. After analyzing $6.5 \times 10^7$ events in NT-36, two clear neutrino induced upward going muons events were detected (vs 1.2 expected from atmospheric neutrinos) and another three in NT-96. At the time of this writing, (fall of 1997), they have 144 modules and the NT-200 instrument is supposed to be completed by mid 1998.

NESTOR [84, 92] (Neutrinos from Supernova and TeV sources Ocean Range), will be installed at 3800 meters depth off-shore from Pylos (Greece). Successful deployments and recovery at 2600 meters deep of two mechanical structures of six articulated arms have been accomplished. The structure forms a star in aluminum (and in titanium), and the optical modules are pending at the end of each arm of the star. Each star constitutes one hexagonal floor (of 16 meters of diameter) in a projected tower of 12 floors, containing 168 PMTs per tower. A total of seven towers (1176 optical modules) is planned. Technical work on the deployment at deep sea, as well as measurement and characterization of the water physical properties have been accomplished.

The four collaborations are engaged in active R+D projects aiming to a future 1Km$^3$ neutrino telescope. The construction of the Km$^3$ scale instrument would likely proceed in several steps—scientifically interesting by themselves—to solve gradually the formidable technical tasks in its development and at the same time perform, at each step, relevant research on neutrino physics. A sequence of dimensions 0.01 Km$^3$–0.1 Km$^3$–1Km$^3$ has been suggested [57] corresponding to a significant research on neutrino oscillation, WIMP indirect searches and high energy neutrino astronomy respectively.

### 3.2 WIMP direct detection
3.2.1 General features.

Particle Dark Matter can also be detected through its direct interaction with ordinary baryonic dark matter \[ \text{[2, 62, 93, 94]} \]. The non-relativistic (\( \sim 0.001 \text{ c} \)) and heavy (TeV–GeV) dark matter WIMPs supposedly forming the galactic haloes could make a nucleus recoil with a few keV, from which only a fraction is visible in the detector. The detection rate depends on the halo model, on the type of WIMP and interaction, on the nuclear target and detector, as well as on the nuclear recoil relative efficiency in producing ionization, scintillation or heat (quenching factor). Semiconductor detectors of Ge and Si, scintillators—both solid (NaI, CaF\(_2\), LiF) and liquid (Xe)—and thermal (bolometer) detectors of Si, Ge and sapphire, have been used so far \[ \text{[95, 96, 97]} \].

The typical rates that would be produced, for instance, by WIMPs of Dirac neutrino-like type having spin-independent nuclear coherent interaction \[ \text{[93]} \] with Ge nuclei through \( Z^0 \) exchange reach a few hundred counts per Ge-detector kilogram and day, and so could be larger than the background achieved in the best ultralow background Ge detectors (0.1 to 2 counts per keV kg day), feature which has been used to exclude \[ \text{[104]} \] that type of candidates for a wide region of masses in various underground Ge experiments \[ \text{[98, 99, 100, 101, 102, 103]} \]. The rate that would be due to axial, spin dependent interactions \[ \text{[123]} \] (like that of Majorana neutrino-like particles) with detector nuclei having non-zero spin would be much smaller, and so more difficult to attain experimentally. Nevertheless, valuable exclusions for such spin-dependent couplings have been obtained in NaI \[ \text{[105, 106, 107, 108]} \], CaF\(_2\) \[ \text{[109, 132]} \] and Xe \[ \text{[110]} \] underground experiments.

More appealing candidates, such as the neutralino are starting to be at hand with the new generation of detectors, in particular in the case of the coherent neutralino nucleus spin-independent interaction through Higgs exchange, which might go up to a few counts per kg and day for some regions of their parameter space \[ \text{[33, 10, 11, 10]} \]. Some regions have already been excluded using Ge and NaI detectors data \[ \text{[40, 127]} \]. The spin-dependent contribution in the neutralino-nucleus scattering—through \( Z^0 \) or squark exchange—is still below the current background achieved.

The main features of the DM interaction—small energy deposits and small rates—settle the strategy of the DM direct searches: To use detectors of very low energy threshold and very low background (intrinsic and environmental), in particular in the low energy region where the nuclear recoil produced by the WIMP scattering is expected. The recorded background, sets the level of exclusion of the particle dark matter candidate and it must be reduced at its minimum level by employing passive and active shielding in a clean environment and using selected material of very low intrinsic radioactivity. An obvious requirement is to perform the experiment in an underground site.

A further step to reduce the background is the use of mechanisms distinguishing those events due to electron recoils (tracers of the background) from those due to nuclear recoils. Hybrid detectors measuring at the same time the ionization and heat (or the light and heat) produced in the detector, or the use of pulse shape discrimination techniques are successful attempts in the quest for the background reduction.

The possible presence of a particle CDM component in a spectrum is obtained by comparing the predicted CDM signal with the experimental spectrum. If the predicted WIMP-nucleus interaction rate is larger than the number of observed counts in a given energy region, the particle under consideration can be ruled out as a dark matter component for the values of masses and cross-sections—or for the corresponding regions of the parameter space defining the particle dark matter candidate—for which such rate was derived. The results are usually expressed as an exclusion plot in the plane of the WIMP-nucleus elastic scattering cross section, \( \sigma_{\chi N} \) versus the WIMP mass \( m_\chi \).

This conventional method of simply comparing the expected signal with the observed background spectrum (which may mimic itself the signal) is not supposed to detect the tiny imprint left by the dark matter particle, but only to exclude or constrain it. A convincing proof of the detection of CDM would be to find distinctive signatures in the data characteristic of the CDM, not faked by the background or by instrumental artifacts. Various DM identification signatures have been proposed: an annual modulation \[ \text{[111]} \] due to the seasonal June-December variation in the relative velocity Earth-halo; a very tiny daily modulation \[ \text{[112]} \] due to the Earth progressive eclipsing along the day of the DM halo particles in its way to the detector; a forward-backward asymmetry \[ \text{[113]} \] in the direction of the nuclear recoil due to
the Earth motion through the halo, and the nuclear target dependence of the rate \[^2^3\] . The search for annual modulation is by now the most extended and promising strategy of DM identification.

On the other hand, only a small fraction of the energy delivered by the WIMP goes to ionization, the main part being released as heat. More efficient excitation mechanisms, like Cooper pairs breaking in superconductors or phonons in thermal detectors (involving typical excitation energies of meV or \(\mu\)eV respectively), should be employed. Such cryogenic detectors \[^{114, 115, 116, 117, 151}\] will achieve lower energies threshold, almost 100% efficiency and have better energy resolution than the conventional detectors.

### 3.2.2 Detection rates.

WIMPs interact with quarks within nucleons inside a nucleus, and consequently the WIMP-nucleus cross-section depends on properties and parameters encompassing such three levels. In the non-relativistic approximation, the WIMP-nucleus cross-section has two components: a spin-independent part, and an axial, spin-dependent part, corresponding respectively to the coupling of WIMPs to the mass or to the spin of the nucleus \[^93, 6\].

The differential recoil energy spectrum produced by WIMPs interacting with nuclei is calculated straightforwardly \[^{93, 19}\] once the halo model and the type of WIMP and interaction have been defined. The spectrum should be properly corrected for the nuclear recoil relative efficiency in producing ionization, scintillation or heat, as well as for the loss of coherence (for momentum transfers larger than the inverse nucleus radius). The nuclear physics for the spin-independent case is well approximated by a simple form factor \[^{98, 119}\]. The axial case, however, requires detailed nuclear models \[^{120, 121}\]. The different values chosen for the parameters entering in the various levels of the WIMP-nucleus interaction, as well as the large parameter space defining the WIMP (say the relic neutralino), make the theoretical rate encompass various orders of magnitude.

The interaction rate of WIMPs producing a recoil \(T\) in the detector is given by

\[
\frac{dN}{dt=dT} = N_D \frac{\rho_h}{m} \int_{v_{\text{min}}(T)}^{v_{\text{max}}(T)} \frac{d\sigma}{dt}(v, T) f(\vec{v}) v d^3v
\]

where \(T\) is the recoil energy of the target nucleus, \(f(\vec{v})\) is the velocity distribution of the halo DM particle in the reference frame of the Earth, \(N_D\) is the total number of target nuclei, say per kilogram, \(\rho_h\) is the local galactic halo density, and \(d\sigma/dT\) is the WIMP-nucleus differential scattering cross section. The mass of the WIMP particle is denoted by \(m\). The measured deposited (electron equivalent or visible) energy \(E\) and the nuclear recoil energy \(T\) are related by a relative efficiency factor \(Q\) (or quenching) \(E = TQ\) (nuclear versus electron recoil efficiency in producing ionization). The quantity \(\tau_{\text{min}}(T)\) is the minimum relative velocity a particle must have in order to leave an energy \(T\) in the detector, i.e. \(\tau_{\text{min}}^2(T) = T(M + m)^2/2m^2M\), where \(M\) is the target nucleus mass, and \(\tau_{\text{max}}\) is the maximum velocity of WIMPs relative to the detector, i.e., the vectorial sum of the galactic escape velocity \(\vec{v}_{\text{esc}}\) and the velocity of the Earth through the halo, \(\vec{v}_E\). It is customarily assumed that the DM forms a non-rotating, isothermal, and spherically symmetric halo. In the galactic rest frame, the WIMPs are supposed to have a Maxwellian velocity distribution, with a velocity dispersion \(\nu_{\text{rms}}\). The local halo density is customarily taken \(\rho = 0.3\text{ GeV cm}^{-3}\) with the caution that this value could have an uncertainty of a factor \(2\) \[^{122}\]. In fact, a flattened halo distribution leads to \(\rho = 0.51^{+0.21}_{-0.17}\text{ GeV cm}^{-3}\) from microlensing data.

The WIMP interaction rate in counts per keV per kilogram and day reads

\[
S = 7.76 \times 10^{14}N_D \frac{1}{Q} \frac{(m + M)^2}{4Mm^3} \frac{\sigma_{W} \rho \eta}{\nu_{\text{rms}}}
\]

where \(\sigma_{W}\) is the elastic cross section of the WIMP-nucleus interaction (in \(\text{cm}^2\)), which includes the form factor correction for high momentum transfer, \(\sigma_{W} = \sigma F^2(T)\), \(\sigma\) being the point-like nuclear cross-section. The integral over the velocity distribution appears through the function \(\eta\) given in the simple case of an infinite escape velocity by \(\eta = erf(x+y)−erf(x−y)\) where \(x = \sqrt{3/2\nu_{\text{rms}}}/\nu_{\text{rms}}\) and \(y = \sqrt{3/2\nu_{\text{rms}}}/\nu_{\text{rms}}\) and \(erf(z)\) the usual error function \((erf(z) = 2/\sqrt{\pi} \int_0^z \exp(−t^2)dt)\).
The cross-section for the spin-independent heavy neutrino (or neutralino)-nucleus interaction, is strongly enhanced by the coherence factor \( \sigma_{SI} \sim N^2(A^2) \). In the case of Majorana WIMPs (like heavy Majorana neutrinos, neutralinos), the spin-dependent cross-section is proportional to the nuclear spin, \( \sigma_{SD} \sim \Lambda^2 J(J+1) \), where \( \Lambda = (a_p \langle S_p \rangle + a_n \langle S_n \rangle) / J \), \( \langle S_p,n \rangle \) are the contributions of the total proton and neutron spin in the nucleus and \( a_{p,n} \) the coupling constants WIMP-nucleon, depending upon the type of WIMP and interaction and on the quark spin distribution within the nucleon. Typical integrated rates for Ge are \( \sim 10^2 \) c/kg day, for the heavy Dirac neutrino spin-independent contribution; \( \leq 1 \) c/kg day for the coherent contribution neutralino-nucleus cross-section (due to Higgs exchange); and \( \leq 0.01 \) c/kg day for the spin-dependent contribution to the \( \chi \)-nucleus scattering (due to \( Z^0 \) exchange) for typical values of the parameters space 40 43.

### 3.2.3 WIMPs searches with Ge ionization detectors.

In the first generation of experiments, Si and Ge diodes were used. Various experimental groups have searched for WIMPs with Ge detectors as byproducts of double beta decay experiments: USC/PNL in Homestake 38 39; USCB / UCB / LBL in Oroville 100; Caltech/PSI/Neuchatel in Gothard 101; Zaragoza/USC/PNL in Canfranc 102; and Heidelberg/Moscow in Gran Sasso 103, with energy thresholds ranging from 1.6 keV to 12 keV (electron equivalent energy), and backgrounds at threshold of 0.2 to 5 c/keV.kg.day (lower backgrounds are obtained at a few keV above thresholds).

From these experiments, it was concluded that the heavy Dirac neutrino is excluded as a DM component for masses ranging from 9–10 GeV (Canfranc and Saint Gothard), up to 4.3 TeV (Homestake and HMDM Gran Sasso). The marginal presence of odd Ge isotopes in the Ge detectors lead to modest exclusions for the spin dependent interactions case. Figure 2 shows comparatively the exclusion plots obtained for spin-independent coupling in these experiments. Figure 3 shows the expected neutralino-Germanium interaction rates for some regions of the neutralino parameter space as computed by the Torino group 40 compared with the Homestake background limit. The performance of these Ge detectors in direct searches of neutralinos is compared in Figure 4 with that obtained in the indirect detection running experiments (for instance with the Baksan telescope bound on the WIMP muon flux).

### 3.2.4 WIMPs searches with scintillators.

Other nuclear targets used as WIMPs scatters are sodium and iodide. The 100% isotopic contents of A-odd isotopes of NaI scintillators (\(^{127}\)I and \(^{29}\)Na) make them sensitive to spin-dependent interactions with WIMPs and so significant experimental effort with sodium iodine scintillators are underway. The
level of background achieved with NaI scintillators, has been customarily about one order of magnitude worse than that of the best Ge detectors, as far as the bare spectra are concerned. R+D background reduction programs of the groups of BPRS [105] (Beijing/Paris/Rome/Saclay) UKDMC [106] (Imperial College/Oxford/Rutherford) and DAMA (Roma 2/Beijing/ENEA) [125], using selected components of very low radioactivity have achieved levels of \( \approx 1 - 2 \text{ c/keV.kg.day} \) in the relevant low energy region (bare spectra) vs \( (0.1 \sim 0.2) \text{ c/keV kg day} \) in the best Ge detectors. The BPRS collaboration [105] operated in a first step (in Gran Sasso and Frejus) NaI crystals of up to 7 kg achieving an (electron equivalent) energy threshold of \( E_{\text{thr}} = 4 \text{ keV} \) and a background of \( B_{\text{thr}} = 2 \text{ counts/(keV kg day)} \). Recently the DAMA [125] group in Gran Sasso has improved these performances with special NaI crystals of 9.7 kg. The UKDMC group [126], in the Boulby mine, has worked with NaI detectors of up to 6.2 kg, with similar remarkable results. Both collaborations have measured the quenching factors for nuclear recoils using neutrons. Other WIMPs searches with NaI were performed by the Zaragoza [107] and Osaka [108] groups in Canfranc and Kamioka respectively by using non-dedicated scintillators formerly employed in double beta decay searches.

The recent NaI background obtained in the UKDMC and DAMA experiments has been approaching, and even improving that of the traditionally ultralow background Ge diodes by incorporating pulse shape
techniques of background discrimination [25, 26]. To discriminate statistically the gamma background from the nuclear recoils, the timing behaviour of the pulses recorded for a data population—events falling in a given energy bin—is compared with that of a template produced by external gamma and neutron sources. It turns out that data and $\gamma$ background behavior are essentially identical, whereas nuclear recoils have, on average, a shorter time constant. The fraction of data which might be due to nuclear recoils (and so to neutrons or WIMPs) is then bounded to less than 10% to 1% (depending on the energy). The resulting background is accordingly reduced from its measured level [2–4 counts/(keV kg day)] to only a few $10^{-1}$ or $10^{-2}$ counts/(keV kg day). Mass targets used are 115 kg (DAMA) and 6 kg (UKDMC) and the energy thresholds achieved in these scintillators are 2–4 keV. The new $\sigma(m)$ (cross- section WIMP-nucleon versus WIMP mass) exclusion plots (see Figure 5) have already surpassed (DAMA) those obtained from the bare spectra of Ge detectors (spin independent interactions case) and are orders of magnitude more stringent than that of the Ge for spin-dependent couplings. There exists some favorable regions of the neutralino parameter space, which might be excluded [127] by these new spin-independent upper bounds, as depicted in Figure 6.

As large amounts of NaI crystals are economically affordable, sets of scintillators have been used to explore the annual modulation of WIMPs. The yearly modulation is originated because of the seasonal variation in the relative velocity of the Earth and the galactic halo due to the Earth’s rotation around the Sun. The resulting net speed of the Earth with respect to the halo reference frame oscillates between about 245 km s$^{-1}$ in June and 215 km s$^{-1}$ in December, and so the maximum amount of energy that can be deposited by the WIMPs in the detector, as well as their detection rates change accordingly.

The dimensionless Earth-halo relative velocity $y(t)$ is expressed as $y(t) = y_0 + \Delta y \cos \varpi (t - t_0)$, where $y_0 = 1.05$ and $\Delta y = 0.07$, according to the values $v_r = 232$ kms$^{-1}$, $v_{rms} = 270$ kms$^{-1}$ for the velocities, $\varpi = (2\pi/365)d^{-1}$, and $t_0 \sim$ June 2th. The expected signal can be expressed, at first order, as a constant term plus a modulated component of amplitude $S_m, S(t) = S_0 + S_m \cos \varpi(t - t_0)$ where $S_m = [\partial s/\partial y]_{y_0} \Delta y$. The modulated amplitude is only a few percent of the total DM signal. To search for the existence of a modulation in the data, one looks for a difference between the rates of June and December and derive the exclusion plots $\sigma(m)$ obtained by comparing such residuals with what was to be expected. Other, more elaborated methods of analysis which look for a possible periodic component in the data along the whole period of data taking (like the modulation significance method [128]) have

Figure 5: Exclusion plots for spin-independent couplings of WIMPs obtained in various experiments. Expected results for sapphire bolometers are also depicted. Predictions of typical MSSM models are illustrated (see text).
Figure 6: Regions of the neutralino parameter space which could be excluded \cite{127} by recent (NaI) spin-independent coupling bounds.

also been employed.

A search for annual modulation was carried out in Canfranc \cite{107} (Zaragoza University) along more than two years (1993–1995) with 32 kg of NaI scintillator corresponding to an effective exposure of 4613.6 kg day. The data did not show any seasonal modulation but imply constraints on cross-sections and masses of spin-dependent and spin-independent interactions of WIMPs more stringent than that obtained from the customary method of comparing the total expected rate with that experimentally measured. A larger experiment with seven NaI scintillators (a total of 75 kg), with upgraded PMs which use light guides and low background components is being installed at Canfranc (2450 m.w.e.), in a shielding with archaeological lead. Early experiments on WIMP signal modulation were also carried out with Ge detectors \cite{124}.

A liquid Xenon scintillator \cite{110} is being used by the DAMA Collaboration at Gran Sasso. An experiment with 6.5 kg. of liquid Xe (\sim 2 liters) isotopically enriched to 99.5\% in $^{129}$Xe with a background of $B \approx 3$ counts/(keV kg day) at threshold $E_{thr} \approx 10$ keV is looking for annual modulation. Preliminary results corresponding to an exposure of 31.4 days in winter and 66.1 days in summer did not find seasonal effects.

After these pioneering searches for WIMP annual modulation signals with NaI and liquid Xe scintillators, another experiment with a large mass of NaI scintillators (nine NaI crystals of 9.7 kg each) is presently running at Gran Sasso operated by the DAMA collaboration in a quest for seasonal modulations. The first reposted results \cite{129}, corresponding to an statistics of about 39 days in winter and 14 days in summer, bring forward an indication of a possible modulation effect $S_m = 0.034 \pm 0.008$ count/(keV kg day) in the 2–12 keV region, as analyzed by the modulation significance method. The analysis is extended to the whole relevant energy interval by using a maximum likelihood method to conclude that the reported annual modulation might be interpreted as due to a 60 GeV WIMP with an interaction cross-section on protons of $10^{-5}$ pb. The (preliminary) results of this work, however, do not allow any final statement on the presence of a signal and a larger statistics is needed, together with further effort in stability monitoring. Critical comments on these results can be found in \cite{130}. The data taking of the DAMA experiment continues with the purpose of configuring the modulation hint shown in the preliminary data. Possible implications of these data for relic neutralinos have been analyzed by the Torino group \cite{131}.
3.2.5 Searches with other techniques

There exist much more activity and projects on WIMP direct detection with conventional detectors. For instance, calcium fluorine scintillators are being explored for dark matter experiments by the groups of Roma 2, Osaka and Milan. The detector ELEGANT VI (Osaka) consisting of CaF$_2$(Eu) scintillators (a total of 3.5 kg of $^{19}$F), surrounded by CsI detectors as an active shield, is looking for WIMPs scattering on $^{19}$F (which has a favorable nuclear factor of merit for DM searches). After a preliminary test run at sea level, the set of calcium fluorine rods will go underground in the Otho Laboratory. On the other hand, the UCLA-UKDM collaboration is investigating the WIMP detection with liquid Xenon detectors. Nuclear recoil identification can be achieved in liquid Xenon either by scintillation pulse shape analysis or by drifting the ionization to produce a second proportional scintillation pulse. The ratio between the primary (liquid Xenon direct scintillation) and secondary pulses is different for electron and nuclear recoils and so the background can be efficiently discriminated. A 2-kg ICARUS-WIMP liquid Xenon device is operating at the Montblanc underground laboratory. A modular prototype of such ICARUS-like detector, called ZEPLIN, with 20 kg of liquid Xe, will be installed at Boulby.

Prototype detectors of moderately superheated microdroplets are being installed. Superheated Droplets Detectors (SDD) consist of a dispersion of droplets ($\varnothing \sim 10-100$ $\mu$m) (say of Freon-12) of a superheated liquid fixed in a viscous polymer or aqueous gel. These devices are insensitive to energetic muons, gamma rays, X-ray and beta particles, while responding to neutron recoils of only a few keV. The energy deposition in the droplet produces a phase transition from superheated to normal, causing its vaporization in a bubble of $\varnothing \sim 1$ mm, which can be optically recorded or detected with piezo-electric sensors. An experiment (SIMPLE) is being installed by a Paris Univ. VII/CFN Lisbon Univ. collaboration at a shallow depth near Paris, whereas a prototype projected by the Montreal/Chalk River collaboration is underway.

Large TPCs for DM are also in the prospective program of various groups (Saclay and San Diego), whereas the MUNU experiment will provide a device for developing methods in DM searches. In fact, low pressure gas detectors have been receiving attention for a long time because of their potential sensitivity to the nuclear recoil direction, a distinctive signature for WIMP identification. Direction-sensitive mechanisms and detectors have been proposed, among them, we mention the use of organic crystals (anthracene), the ejection of atoms from surfaces, the detection of the recoiling silicon atoms in the surface layers of silicon chips by means of thin film thermal detectors and the rotons in superfluid helium. Imprints left by WIMPs in old ancient mica are also being searched for, taking advantage of the fact that over long periods of time, WIMPs should have collided with underground mica ($^{16}$O, $^{28}$Sr, $^{27}$Al, $^{39}$K) and left tracks.

The Heidelberg/Moscow Collaboration is planning the use of a pure Ge detector, inside a set of Ge detectors. Preliminary results on background reduction obtained with a Ge detector embedded in a well of Ge in the same cryostat have already been obtained. This collaboration is planning a large dark matter and double beta decay experiment (Germanium Nitrogen Underground Search, GENIUS) with a cooled array of 300 enriched Ge detectors of a mass of 1 ton immersed in liquid nitrogen. We refer the reader to the recent reviews and topical Workshops on the subject.

3.2.6 Cryogenic Detectors.

In the WIMP scattering on matter, only a small fraction of the energy delivered by the WIMP goes to ionization, the main part being released as heat. Consequently, thermal detectors (quenching factor close to one) should be suitable devices for dark matter and other rare event searches. Moreover, the mechanisms and quanta involved in the detection imply that such detectors should have better energy threshold and energy resolution than conventional detectors. As a bonus, they will allow to enlarge the number of target nuclei (with various spin and nuclear masses) for WIMPs interactions. An important property is that they permit to discriminate backgrounds by simultaneously measuring the heat and the ionization (or scintillation). Some examples of cryogenic detectors are: bolometers (with various types of sensors); superconducting tunnel junctions; superheated superconducting grains (SSG), quasiparticle detectors, and cryogenic hybrid devices (i.e. detectors which are sensitive to both the heat and the ion-
ization produced by the DM particle). Two types of cryogenic detectors are being developed: bolometers (either pure thermal or thermal plus ionization hybrid detectors) and superconducting superheated grains. The development of bolometers along the past few years has been impressive.

Bolometers measure the increase of temperature produced by the recoiling nucleus hit by a WIMP, which is proportional to the ratio between the energy thermally released and the heat capacity of the crystal \( \Delta T = \Delta E/CV \), where \( C \) is the heat capacity, and \( V \) the volume of the bolometer. The temperature pulse is detected with a sensor in thermal contact with the absorber. An appealing feature of these detectors is that their energy resolution should be a priori much better than that of conventional detectors, as the energy deposition mechanism is made in terms of phonons (\( 10^{-4} - 10^{-6} \) eV). The energy resolution achieved is damped by several effects, but in the keV region, resolutions of the order of 100 to 300 eV have been achieved even for large mass crystals. Dielectric and diamagnetic materials—for which the heat capacity is proportional to the cube of the working to the Debye temperature ratio—have been widely used. That makes necessary to employ materials with large Debye temperature and work at temperatures as low as possible (of the order of tens of mK). The \(^3\text{He}/^4\text{He} \) dilution refrigerators (DR) needed for such searches, are not optimized for low background and so much work is being devoted recently to provide in the DR components the low radioactivity environment needed in rare event searches. Sensors used are neutron transmutation doped (NTD) thermistors (glued or bounded to the crystal), superconducting transition thermometers (SPT) and quasiparticle trapping assisted electrothermal feedback transition edge thermometers (QET).

The first bolometer operating underground (Gran Sasso) was that of the Milan group dedicated to double beta decay searches. Large bolometers of \( \text{TeO}_2 \) (334 g) with NTD Ge-sensors (Milan group, Gran Sasso), (resolution of 1% at 60 keV and background of \( \approx 12 \) counts/(keV.kg.day) at threshold, \( E_{\text{thr}} \approx 10 \) keV), although optimized for \( 2\beta \) decay searches, have produced data for constraining dark matter particle (see Figure) and have proved the sensitivity of these bolometers to nuclear recoils. The nuclear recoil quenching factor \( Q \) of these bolometers has been measured by using two 73 g tellurium oxide crystals at 22 mK, mounted face to face and measuring the energy of the \( \alpha \) and recoils signals produced by an implanted \( \alpha \) source. The result is \( Q_{\text{recoil}} = 1.025 \pm 0.01 \) (stat) \pm 0.02 (syst), practically independent of energy (from 10 to 200 keV). The current set-up of this experiment, four crystals of 334 g each, has been recently extended successfully to a set of 20 crystals. A new project to be installed in Gran Sasso, named CUORE (Cryogenic Underground Observatory for Rare Events) is a large extension of the Milan cryogenic array of twenty 340 g \( \text{TeO}_2 \) crystals with NTD Ge glued thermistors. CUORE will consist of an array of one thousand crystals of \( \text{TeO}_2 \) (750 g each) with NTD Ge sensors, cooled down to 10 mK, planned for double beta decay, direct detection of WIMPs, solar axion searches, low energy nuclear physics and, possibly, interactions of antineutrinos from artificial sources. Other absorbers can be also considered, like \( \text{Al}_2\text{O}_3 \), \( \text{PbWO}_4 \), Ge, CaF\(_2\), but the first step of CUORE—called CUORICINO—will choose the \( \text{TeO}_2 \) option. CUORICINO will consist of 100 crystals of \( \text{TeO}_2 \) of 5 cm side with a total mass of 75 kg, i.e. about 20 kg of \(^{130}\text{Te} \), an amount by far larger than in any running double beta decay experiment. That will allow a very significant experiment on double beta decay of \(^{130}\text{Te} \), as well as on WIMP annual modulation search.

The EDELWEISS (Experiment pour Decter les WIMPs en Site Souterraine) Collaboration (Saclay/IAS/Orsay/College de France/IAP/Lyon/Modane) has pioneered the operation at Frejus of a bolometer experiment dedicated to DM searches using a 24 g sapphire crystal endowed with an NTD Ge thermistor. Recent improvements of this experiment, have produced energy resolutions of \( \approx 3 - 4 \) keV at 60 keV, thresholds of 1–2 keV and backgrounds of 25 counts/(keV.kg.day) at low energy.

The CRESST (Cryogenic Rare Event Search with Superconducting Transition Thermometers) Collaboration (Munich/Garching/Oxford) has developed sapphire bolometers with superconducting phase transition thermometers SPT (in indium, indium/gold and tungsten). This Collaboration got with a 31 g sapphire bolometer (at 15 mK), an energy threshold of 0.3 keV and an energy resolution of \( \approx 100 \) eV for 1.5 keV X-rays FWHM, which is the best resolution obtained so far per unit of detector mass. The CRESST experiment employs four sapphire bolometers of 262 g each with tungsten SPT. The energy resolution is 250 eV at 1.5 keV and the expected energy threshold is 500 eV. After a successful
running test at Gran Sasso, a new improved set-up (with selected ultra-low background materials, cold box, copper frame) is being implemented. The CRESST predicted exclusion plot for a flat background of 1 count/(keV kg day) is also shown in Figure 5. The MSSM predictions (see for instance Refs. [6] and [39]) are also depicted to illustrate the sensitivity of these searches for neutralino dark matter.

On the other hand, small sapphire bolometers of $E_{th} \approx 0.3$ keV and energy resolution of 120 eV at 1.5 keV made by IAS (Orsay), are being explored in Canfranc at 2450 m.w.e. The ROSEBUD (Rare Objects Search with Bolometers Underground) experiment (IAS/IAP/Zaragoza) consists of two sapphire crystals of 25 g (and 50 g) each, cooled at 20 mK in a small DR shielded inside and outside with archaeological lead. Anticipated upper bounds for a background of 1 count/(keV kg day) are given in Figure 5.

A further step in the background discrimination has been recently achieved (CDMS [164] and EDELWEISS [165]) by measuring simultaneously the heat and ionization produced in the detector by the WIMP-nucleus scattering. The energy released by the recoiling nucleus impinged by the WIMP (or the recoiling electron impinged by a particle) appears in form of phonons and electron-hole pairs. Simultaneous measurement of both quantities for each event allows the discrimination of electron recoil events (tracers of the background) from nuclear recoil events (WIMP signal plus neutrons) because for a given deposited energy—measured as phonons—the ionization produced by the recoiling nucleus is less than that generated by electrons.

Low temperature hybrid devices [117, 151] have been developed by the CDMS (Cryogenic Dark Matter Search) [166] collaboration (UC Berkeley / CfPA / UCSB / Stanford) with Ge bolometers which also collect electron-hole pairs. The proof-of-principle of a 70 g hybrid Ge detector was successful and good discrimination efficiency between nuclear recoils and Compton background was obtained. Two BLIP [167] (Berkeley Large Ionization and Phonon based) Ge detectors (62 g and 165 g) with NTD Ge bounded thermistors have been operated at shallow depth in Stanford in the low background cold box of a DR at 20 mK. In another type of detector, called FLIP [168] (Fast Large Ionization and Phonon-based), the phonon sensors used are QETs (Quasiparticle trapping assisted Electrothermal feedback Transition edge thermometers) with aluminium phonon collector pads which absorb the phonons by breaking copper pairs and forming quasiparticles, which are trapped in tungsten. This trapping produces an increase in resistance showed up as a current pulse with a SQUID array. Both Ge-BLIP and Si-FLIP detectors have already produced results.

The BLIP 62 g Ge detector, for instance, has a gamma rejection ratio higher than 99% and a nuclear acceptance ratio greater than 95%. The FLIP 100 g Si detector has, respectively, the ratios 99% and 75% (at low energies). The phonon and ionization energy resolution FWHM of the 62 g Ge BLIP are respectively 500 eV and 1.5 keV. The recoil energy threshold is about 15 keV. The nuclear recoil background is already as low as 0.3 count/(keV kg day). The 165 g Ge BLIP has energy resolutions of about 1 keV FWHM in both channels, whereas the threshold is $\sim 2$ keV. On the other hand, the FLIP detector has 7 keV FWHM as phonon energy resolution and 2 keV as ionization energy resolution. The recoil energy threshold in this detector is $\sim 30$ keV. The background rate recorded in the above BLIP and FLIP detectors in anti-coincidence with the muon-veto stands, respectively, at about 4 counts/(keV kg day), 2 counts/(keV kg day) and 6 counts/(keV kg day). The corresponding nuclear recoil background—obtained after performing the phonon-ionization discrimination of events quoted above—goes down to 0.1–0.3 count/(keV kg day). These remarkable results give confidence in the method and techniques followed in the quest of the neutralino sensitive region. A tritium contamination is being removed. Problems concerning the drop in the discrimination efficiency at low energies due to the dead layer in the Ge detectors are being addressed. The exclusion plots obtained up to now by this Collaboration are shown in Figure 6, compared with those obtained in other running experiments. A next step will be the operation of these detectors in the SOUDAN underground facility.

The EDELWEISS Collaboration (Frejus) is now developing a 70 g Ge bolometer with simultaneous detection of heat and ionization, obtaining similar results to those of the BLIP Ge detector. An energy threshold of 4 keV (both phonons and ionization), an energy resolution of 1.25 keV FWHM for the phonon channel and of 1.3 keV for the ionization channel, both at $E = 122$ keV have been achieved [165]. A good separation of the neutron and gamma background has been obtained. A rejection efficiency of 98% for neutron
events from a source of $^{232}$Cf has been achieved relative to the gamma background of a $^{57}$Co source. This discrimination efficiency has allowed to reduce the effective background which could be attributed to WIMPs (nuclear recoils) to levels with an upper limit of 0.5 count/(keV kg day) in the 15 to 45 keV nuclear recoil energy. The preliminary results at a short running are reported in Ref. 163.

The proof-of-principle of simultaneous measurements of heat and light was made by the Milan group with a small (2g) CaF$_2$ scintillator bolometer and by the Lion and Tokyo groups with small LiF crystals, but these scintillating bolometers are still in a R+D stage.

The Superheated Superconducting Granules (SSG) detector proposal is about thirty years old 171. Proposed originally as neutrino detectors, they were then extended to other rare event processes like double beta decay or particle DM searches 153, 153. The signal produced in the SSG detectors, as response to the particle interaction, is due to the disappearance of the Meissner effect when the heat delivered by the particle energy deposition is able to trigger the superconducting to normal state phase transition (flip) of the grains. A suitable array of coils, embedded in the colloid measures the voltage drop produced by the local change of the magnetic flux over the flipped grains or region, in the external applied magnetic field. The SSG offer a fast (ns) timing capability; a unique background rejection (97%) (since only a single grain is expected to flip per WIMP interaction, in contrast to several grains with standard ambient radiation fields); a sensitivity to very low energy deposition (as proved in neutron irradiation experiments); and the advantage of having the readout and the SSG device thermally decoupled. The main disadvantage is the small instrumented mass and, consequently, the need for large-scale electronics. That small mass constraint is due to the small filling factor currently employed in these detectors, i.e. the majority of a SSG device is inert.

In particular, the Bern/PSI/Annecy group is constructing a Superconducting Superheated Grains (SSG) prototype detector (ORPHEUS experiment) 169, with 100 g of Sn (to be extended to 1-kg, and other targets) micrograins of 5 to 20 µm of diameter, to be operated at shallow depth. This group has proved the sensitivity of SSG detectors to nuclear recoils of only a few keV produced by elastic scattering of the PSI 70 MeV neutron beam with micrograins of Al (23 µm), Zn (19 µm) and Sn (17 µm). Phase transitions were also observed when these devices were exposed to radioactive sources or to the plain background. The Lisbon-Zaragoza-Paris Collaboration 170 is installing in Canfranc a pilot experiment (SALOPARD) also with an SSG suspension of 100 g of tin micrograins of 20 µm diameter. The gamma rejection predicted is about 95%, and the expected energy threshold of $\sim$ 2 keV. This group has proved that these devices can produce energy spectra by suitable sweeping of the applied magnetic field. Improvements in the radiopurity of the SSG detectors is a main question still to be solved by ORPHEUS and SALOPARD.

Other type of Superconducting detectors, like the Superconducting Tunnel Junction (STJ), made very important R+D progresses following the developments of the quasiparticle trapping technique 172 of the Oxford group, but there is not yet any planned STJ dark matter experiment.

4 Prospects of Future Experiments

The quest for the particle dark matter faces formidable tasks. To fulfill the requirements implied by the strategies indicated above, improvements in the radioactive background (both intrinsic and environmental), in detector efficiency and in energy threshold should be accomplished. The use of radiopure material need to be implemented by that of background discrimination techniques. New, suitable nuclear targets should be also tried. The search for modulated, distinctive signatures of WIMPs should be pursued. Most of these requirements will be hopefully fulfilled by sets of cryogenic/hybrid detectors, superconducting detectors or large masses of NaI scintillators or of other conventional detectors endowed with background discrimination, and this line of action is in the objective of the forthcoming or future experiments.

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