Direct detection of non-baryonic dark matter

Gérard Nollez
Institut d'Astrophysique de Paris and Université Denis-Diderot

A dark universe

In 1933, Fritz Zwicky, observing the velocity distribution of galaxies in the Coma galactic cluster (Fig. 1), found a dynamic mass hundred times higher than could be inferred from its luminosity [1]. Far from vanishing in the light of more and more numerous and precise observations, this hidden mass problem has been confirmed as a key problem of contemporary cosmology. During two decades, a number of high precision observations, at various astronomical scales (rotation curves of spiral galaxies, dynamics of galaxies within clusters, X-ray emission of the hot intra-cluster gas, luminosity of distant type Ia supernovae, temperature anisotropies of the cosmic microwave background) have finally led to an impressive agreement on the mass-energy balance of our universe. We are now entering a new period of general consensus about a standard cosmological model (for a recent review see [2] for instance). The space is flat (rather than curved) which can be expressed by $\Omega = 1$, where Ω is a density parameter normalised to the critical density. The matter contribution to this density is about 30% ($\Omega_M = 0.27 \pm 0.05$), and most of the energy in the universe today appears as a gravitationally self-repulsive "dark energy" of totally unknown nature, accelerating the expansion of the universe ($\Omega_\Lambda = 0.73 \pm 0.05$). Baryonic matter, i.e. "ordinary" matter (protons and neutrons) which constitutes stars and galaxies, amounts to a few percent ($\Omega_B = 0.046 \pm 0.007$), in agreement with the theory of the Big Bang nucleosynthesis. Most of the matter in the universe (approximately 85%) is then non-baryonic and dark (since luminous matter only contributes to $\Omega_{lum} \cong 0.005$). The two dominant components in our universe, dark energy and dark matter, are presently not understood and are both of a very mysterious nature!

One of the most favoured hypothesis is that this non baryonic dark matter is constituted by a new type, still undiscovered, of elementary weakly interacting massive particle, which could explain the observed structures of our universe[1]. Generically called WIMPs, acronym for Weakly Interacting Massive Particles, these hypothetical particles would appear as thermal relics from the Big Bang era during which they were created, now trapped in the gravitational potential of galaxies and clusters of galaxies. It appears as a fascinating coincidence that, in order to develop a cosmologically relevant density parameter, of order unity, these WIMPs must have annihilation cross sections typical of the electroweak interactions. Fortunately enough a wealth of WIMP candidates are offered by Supersymmetry extensions of the Standard Model of Particle Physics [3], rather generically present in supergravity and superstring theories, that allow the unification of the four fundamental interactions. A rich spectrum of new elementary particles is predicted by Supersymmetry and in a large class of supersymmetric models, the lightest supersymmetric particle (generally supposed to be the neutralino) becomes stable. Note that this lightest superparticle, not observed at the LEP collider, must necessarily have a mass greater than 40 GeV. On the other hand, in order that its relic density remains consistent with the observed Ω_M, its mass must be < 1 TeV.

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This scenario is however still hypothetical since Supersymmetry has not been experimentally discovered. If the dark matter halo of our Milky Way is made of neutralinos, their detection in terrestrial detectors should be possible and the most satisfying proof of the WIMP hypothesis would be direct detection of these particles. The study of the rotation curve of our Galaxy indicates a dark matter density of about 0.3 GeV/cm^3 in the solar vicinity, the mass equivalent of 0.3 proton/cm^3. The contribution of baryonic dark matter to this halo, under the form of massive and compact halo objects, has been found to be negligible. As our solar system travels through this halo of neutralinos with a velocity of about 220 km/s, a flux of several millions of neutralinos per square meter and per second is crossing the Earth. This number is amazing, but, as we will see, the detection is not easy!

▲ **Fig. 1:** With a size of a few tens of millions of light-years, the Coma Berenices cluster of galaxies contains more than 1000 galaxies. From a measure of the kinetic energy of these galaxies, F. Zwicky showed that it is hundred times more massive than one can infer from its luminosity. (Image: Omar Lopez-Cruz & Ian Shelton/NOAO/AURA/NSF)

Direct detection principles

Neutralinos are coupled to matter through the weak interaction. This involves a (very low) probability for elastic scattering of a neutralino from nuclei of the material of a terrestrial detector [3]. Despite the huge number of dark matter particles crossing the detector in a time unit, the probability of scattering is so tiny that the detection rate is extraordinary low.

More quantitatively, for a given density and a given velocity distribution of neutralinos in the galactic halo and in the case of a dominant coupling independent of the nuclear spin, the event rate R is proportional to the product σA^2 where σ is the elastic scattering cross-section and A the nucleus mass number. The value of the cross section is predicted by the theory, but the values of many theoretical parameters are still unknown and the predictions allow a very broad domain of values: the allowed values of σ, normalised to the proton, spread over 7 orders of magnitude, from 10^{-48} to 10^{-41} cm^2. The corresponding event rate,

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[1] Neutrinos were once attractive candidates for non-baryonic dark matter. But recent experiments give evidence of a very low neutrino mass: they cannot significantly contribute to Ω_M. Moreover they are "hot" relativistic particles, and "hot" dark matter leads to much more diluted structures in the universe than can be observed.

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▲ **Fig. 2:** *(Left)* A 320 g phonon-ionisation Germanium cryodetector from EDELWEISS. *(Right)* A 100g phonon-ionisation Silicon cryodetector from CDMS. Note the photolithographically-fabricated thin film on the surface, which acts as the phonon sensor.

in a germanium crystal and for a neutralino mass of say 50 GeV varies from 5.10^{-7} to 5 event per kilogramme of detector and per day. At these ultra-low signal levels the task of the background reduction in the detector is a very demanding challenge: construction of shielding against external radioactivity, drastic selection of ultra-low radioactivity materials, protection against cosmic radiation in underground laboratories. Moreover, the recoil energy induced from galactic neutralinos is low, below 100 keV, and the shape of the recoil energy spectrum is exponentially decreasing. Most of the signal is lost if the detector energy threshold is > 10 keV and the usual shape of any detector background can easily mimic the signal.

Fortunately a number of signatures exist which can help to disentangle the signal from the background and to confirm its galactic origin. First of all neutralinos induce nuclear recoils in the detector, while most of the background particles (X and gamma photons, electrons from beta decays) create recoiling electrons in the detector through electromagnetic interaction. If the detector is able to discriminate between nuclear and electron recoils a drastic reduction of the background can be obtained. As we will see, most performing detectors (phonon and ionisation cryogenic detectors) presently achieve a background discrimination factor of more than 99.9 %, on an event by event basis. This discrimination is inefficient against neutrons which, as neutralinos, induce nuclear recoils through elastic scattering and mimic an eventual dark matter event. However neutrons will suffer multiple interactions in the detector with a high probability, which is not the case of the weakly coupled neutralinos.

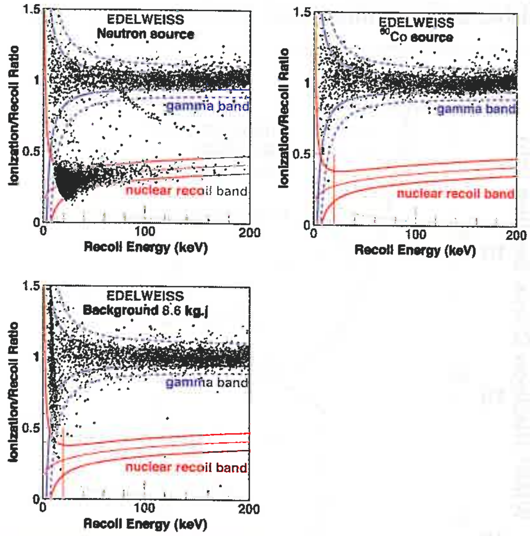
Discovering such a weak ripple requires robust statistics on the signal...

A direct signature of the astrophysical origin of a signal is given by its annual modulation: the Sun moves around the galactic centre with a velocity of about 220 km/s, while the Earth revolves around the Sun at a velocity of about 15 km/s that is added in summer and subtracted in winter, resulting in a sinusoidal modulation of the neutralino flux impinging on a terrestrial detector. The resulting event rate modulation is weak, of the order of 5% at most between June and December. Discovering such a weak ripple requires robust statistics on the signal and this type of detection is reserved to very massive detectors of the order of 100 kg or more. Moreover a number of key experimental parameters (energy calibration, detection efficiencies, possible seasonal modulation of the backgrounds, ...) must be maintained under control at a level much better than 5 % over very long periods, a very difficult task.

To conclude one can try to give a composite picture of the ideal dark matter detector. It is very massive (100 kg or more) to provide evidence of an eventual annual modulation of the signal, but constructed in a segmented form to eliminate multiple interactions which can not arise from neutralinos. Each detector module has a very low nuclear recoil energy threshold (10 keV or lower) and must discriminate, with a very high efficiency, the nuclear (signal) from electron (background) recoils. Ideally various target materials are used to take advantage of the event rate dependence on A^2 as an additional signature. The internal and environmental backgrounds must be maintained at very low levels, including the neutron background: a deep underground site insuring the most efficient suppression of cosmic muons is highly desirable, as well as vetoes to tag the few residual muons able to generate neutron showers. And, last but not least, the detector having to continuously work over very long periods of time in a rather inaccessible site, a very reliable technology is required. As one can suspect, this ideal detector does not yet exist, but various groups actively pursue this goal, using various approaches.

Experimental strategies

A first group of experiments use "classical" detectors of nuclear physics, Germanium semiconductor diodes or NaI scintillators. These techniques have been pushed to the highest technology and design standards, but an efficient nuclear recoil discrimination is missing. Germanium diode experiments (HDMS [4], IGEX [5], ...) have succeeded in operating under ultra-low background conditions (of the order of 0.05 event/keV/kg/day at 15 keV recoil energy) and HDMS has for a long time presented the highest sensitivity to neutralino dark matter. Large mass experiments are proposed, using new shielding designs and background reduction techniques. The DAMA [6] experiment uses a large mass of NaI

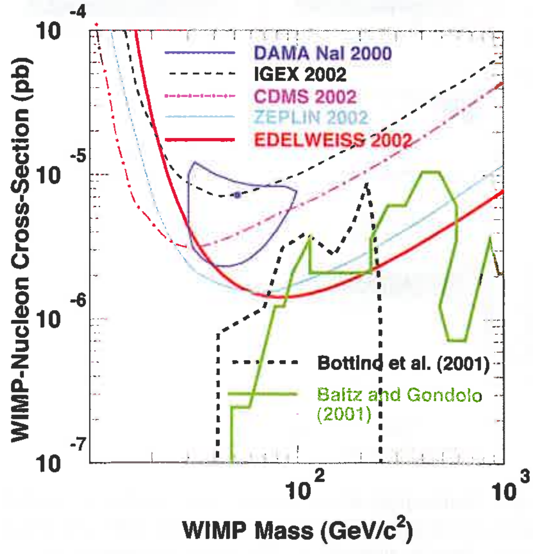


▲ **Fig. 3:** Distributions of the discrimination parameter (ratio of the ionisation signal to the recoil energy) from data collected in the centre fiducial volume of an EDELWEISS Ge detector. As expected no event is found in the nuclear recoil band when the detector is illuminated by a γ-photon source. The blue lines define the 90% and 99.9% efficiency bands for photons (centered on 1 by construction) and the red lines the 90% efficiency band for nuclear recoils. The hyperbolic green curve corresponds to a 3.5 keV ionisation energy threshold and the vertical red line to a 20 keV recoil energy threshold.

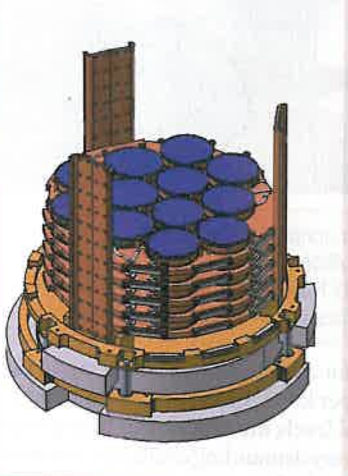
scintillators: nine modules for a total mass of about 90 kg. An upgrade to a total mass of 250 kg is under way. It is the only experiment that has claimed evidence for a WIMP detection. After 4 years of detector running (58000 kg.day of data accumulation) an annual modulation has been displayed in the signal and explained in terms of a WIMP of mass around 50 GeV and of (spin independent) cross section on the proton of 7.2 10^{-42} cm^2. This highly discussed result has not been confirmed by the other experiments which have recently reached the very high sensitivity level required.

NaI scintillators allow a limited nuclear recoil discrimination, the shape of the light pulses looking different for nuclear recoils and for electron recoils. But the effect is small at the energies of interest, near the threshold. Enhanced discrimination capability exists for liquid Xe scintillators, used also by the DAMA group and in the ZEPLIN [7] experiment; the pulse shape discrimination is however purely statistical. One has to extract from an experimental distribution of the decay times of the scintillation pulses the ones corresponding to nuclear recoils.

Efficient nuclear recoil discrimination, on an event by event basis, is only allowed by very recent technologies offering two readout channels for a single event. Cryogenic detectors, working at milli-Kelvin temperatures, have in common a phonon (or heat) channel that measures the energy deposition independently of the nature of the recoiling particle. For cryogenic phonon-ionisation experiments (CDMS [8], EDELWEISS [9]) the second channel measures the deposited charge (different for nuclear or electron recoils), accomplished by the use of semiconductor crystals, Germanium and also Silicon for CDMS (Fig. 2). These experiments have already produced physics results and are among the most sensitive dark matter searches. For cryogenic phonon-light experiments (CRESST [10], ROSEBUD [11]) the second channel is a scintillation measurement. A large range of scintillating materials is available, an interesting feature for the project of using targets with different mass numbers. First results of CRESST, using 300 g CaWO$_4$ modules, are expected in a few months. Also cryogenic but at a much higher temperature (165 K) the ZEPLIN-II experiment will use liquid Xenon as a target. In addition to the scintillation signal in the liquid phase the charges produced in the liquid (more efficiently by electron recoils) are drifted in the surrounding gas phase where they are detected. An experimental device with a target mass up to 30 kg is under construction.



▲ Fig. 4: The present spin-independent sensitivity limits of direct detection experiments. The limit cross-section on the proton (in pbarn, 1 pbarn=10^{-36} cm^2) is given as a function of the WIMP mass. Closed contour: allowed region at 3σ CL from the DAMA annual modulation data. Two regions spanned by some of the supersymmetric model calculations of [12, 13] are also shown.



◄ Fig. 5: Drawing of the EDELWEISS-II detector set-up. Up to 120 Ge detectors of mass 320 g (the blue plates) can be accomodated in a compact hexagonal arrangement at 10 mK. The grey plate, made of ultra-pure archeological lead, shields the detectors from the radioactivity of the dilution cryostat (not shown).

Edelweiss

As an illustration, a detailed description will now be given of the EDELWEISS experiment that represents to date the experiment with the best sensitivity for the spin-independent coupling and neutralino masses greater than about 50 GeV. The EDELWEISS collaboration, an association of seven French laboratories, has developed cryogenic phonon-ionisation Germanium detectors. The experimental site is the Laboratoire Souterrain de Modane in the Fréjus Tunnel under the French-Italian Alps. The 1780 m rock overburden results in a 2.10^6 reduction of the cosmic muon flux (4 muons/m^2/day).

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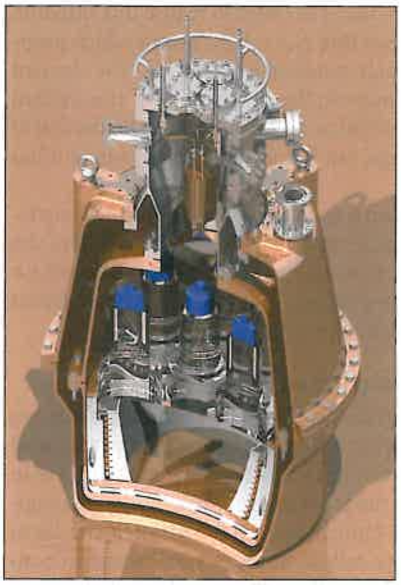
Three detectors are mounted in a dilution cryostat made of selected materials of very low radioactivity and protected from the radioactive environment by various shields. According to Monte Carlo simulations of these shields, based on the measured neutron flux in the experimental hall (1500 neutrons/m^2/day for $E > 1$ MeV), the rate of neutron scattering events above 20 kev is expected to be of the order of 0.04 per kg and per day. This number of nuclear recoils (which mimic true neutralino interactions) determines the ultimate sensitivity of the experiment in the present configuration.

Each detector is a 320g cylindrical Ge monocrystal, 70 mm in diameter and 20 mm in height (the most massive Ge cryodetector today), working at a temperature of about 20 mK. A very sensitive thermal sensor (Neutron Transmutation Doped germanium crystal) glued on the target measures the temperature rise induced by a particle interaction (phonon signal). The plane sur-



▲ **Fig. 6:** Drawing of the ZEPLIN-II scintillation detector. The liquid xenon is in the lower part of the thermally insulated vessel, surrounded by photomultipliers to detect the light pulses.

faces are metallized for simultaneous charge collection using a bias tension of a few volts (ionisation signal). The top electrode is divided into a central part (defining a fiducial volume) and a guard ring to identify and eliminate events occuring near the detector edges, whose charge collection is rather imperfect (electric field inhomogeneities).

As a nuclear recoil is much less ionising that an electron recoil, the ratio Q of the ionisation energy to the recoil energy is used as a discrimination parameter, on an event by event basis. A proper normalisation of the energies measured from the heat and ionisation channels leads the Q-values for gamma interactions to spread around 1 while the Q-values for neutrons are around 0.3. The scatter plots of Q versus the recoil energy E_R are presented in Fig. 3 for three cases: ^{252}Cf neutron (and also gamma ray) source, ^{60}Co γ-ray source and 54 days of low-background physics data. From the dispersion of the neutron data is obtained the *nuclear recoil band*, defined as the region in the (Q,E_R) plane where 90% of the nuclear recoils are expected. The Q-values recorded in the presence of a γ-ray source show that more than 99.9% of the gamma background is rejected (ie events lying out of the nuclear recoil band).

As to the low-background physics data, most of the events exhibit Q-values around 1 (as expected from gamma interactions) while no event is observed in the nuclear recoil band between 20 keV (the experimental threshold) and 100 keV (upper energy relevant for neutralino masses below 10 TeV) for a total exposure based on two different detectors of 11.7 kg.days. At 90% confidence level (CL), the experimental nuclear recoil rate is thus below 0.2 event/kg/day. The results are interpreted in terms of an upper limit (at 90% CL) on the neutralino-proton scattering cross-section shown in Fig 4. Using a somewhat idealised model of the galactic dark matter halo (spherical and isothermal) an event rate can be calculated. Comparison with the measured one gives the limit of the interaction cross-section above which a signal would become visible in the detector. In Fig. 4 the 3σ contour corresponding to the event detection in the DAMA experiment is shown: within this contour the blue point marks the central value of that measurement at $M = 52$ GeV and $\sigma = 7.2\ 10^{-42}$ cm^2. The EDELWEISS results are incompatible with the existence of such a neutralino. While 9.8 nuclear recoils should have beeen observed between 20 and 64 keV, none are observed. The Poisson probability of such a fluctuation is only 0.006%. Furthermore the EDELWEISS data start to probe some of the supersymmetric models predicting the highest interaction rates.

A look at the future

The direct detection story is obviously not concluded, and we have to explore more deeply the domain of the allowed cross-sections. Most of the future experiments aim to reach a sensitivity of about 10^{-44} cm^2. This limit does not imply only simple scaling of existing technologies but new advances in many fields.

A jump in the mass of the detectors is planned: CRESST-II, about 10 kg, using cryogenic phonon-light $CaWO_4$ modules of 300g; CDMS-II, about 7 kg, using cryogenic phonon-ionisation modules of Ge (250g) and Si (100g); DAMA with a new assembly of NaI scintillating crystals for a total mass of 250 kg; EDELWEISS-II, about 7 kg in a first phase, up to 30 kg in the final version, using cryogenic phonon-ionisation Ge modules of 320 g (Fig. 5); ZEPLIN-II with 30 kg of scintillating liquid Xe (Fig. 6). At present by far the best discriminating detectors, phonon-charge cryogenic detectors will attempt to further improve their rejection performances by identifying surface events, which might be confused with WIMPs by their incomplete charge collection. This is the strategy followed by the CDMS-II and EDELWEISS-II experiments, in proposing to use thin film thermal sensors to identify and reject surface interactions. On the other hand, the background rejection capabilities of the phonon-light rejection scheme will soon be explored by the CRESST-II and ROSEBUD experiments in real low background conditions; similarly, more efficient rejection capabilities of liquid Xe using a two-phase experiment will be tested in the ZEPLIN-II experiment. Finally a thorough understanding and control of the neutron background is required; large area active muon vetoes are therefore being studied, with the objective of limiting the residual neutron rate to about 10^{-3} evt/kg/day above 10 keV. At the European level, a collaborative effort is at present initiated to design a direct detection experiment at the one-ton scale, that is required to achieve a sensitivity to WIMP interactions at the 10^{-46} cm^2 level.

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