Dark matter in the Universe: evidence, candidates and searches[*]

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Abstract

Contribution from the students of the 4th CERN–CLAF School of High-Energy Physics who participated in the Discussion Session addressing the issues of dark matter in the Universe.

1 Overview

Since the publication of Sir Isaac Newton's cornerstone work *Philosophiae Naturalis Principia Mathematica* in 1687, science has struggled towards the explanation of the motion of astrophysical objects in terms of the laws of gravitation. Deviations of observed motions from expected trajectories have proved very effective in deepening the understanding of the Universe. Whenever anomalies were observed in the motion of planets in the solar system, the question arose: should such anomalies be regarded as a refutation of the laws of gravitation or as an indication of the existence of unseen objects, or in a much modern expression: 'dark' objects? This second approach proved to be exactly the case of the anomalous motion of Uranus, which led to the existence of Neptune, but failed to explain the anomalies in the motion of Mercury. The latter had to wait for the advent of Einstein's theory of general relativity.

The nature and identity of the dark matter (DM) of the Universe is one of the most challenging problems facing modern cosmology. The problem is a long-standing one, going back to early observations of mass-to-light ratios by Zwicky [1]. This mysterious component that makes up about 22% of the Universe's energy contents is conceptually very similar to the old problem of unseen planets. Observations of some 'anomalies' in large astrophysical systems, with sizes ranging from galactic to cosmological scales, can only be explained either by assuming the existence of a large amount of unseen, dark matter, or by assuming a deviation from the known laws of gravitation and the theory of general relativity.

2 Evidence for dark matter

In this section we shall explore the main evidence for the existence of dark matter in our Universe. Although no direct detection of DM has been made, indirect observations indicate the need for dark, or weakly interacting matter. Such observations have been classified into three scales: galactic, galactic clusters and cosmological.

2.1 Galactic scale

The most direct and convincing evidence for DM comes at the galactic scale. The rotational curves of disk galaxies, namely the distribution of circular velocity of stars with respect to their distance from the centre of the galaxy, are obtained observationally. Usually the resulting behaviour of a flat profile at large distances from the galactic centre does not match the theoretical prediction, see Fig. 1.

In Newtonian dynamics, for a mass distribution $\rho(r)$, the total mass inside a radius r is given by $M(r) = 4\pi \int_0^r \rho(x)x^2 dx$, thus yielding a velocity profile of the form

$$v(r) = \sqrt{\frac{GM(r)}{r}}\,. \tag{1}$$

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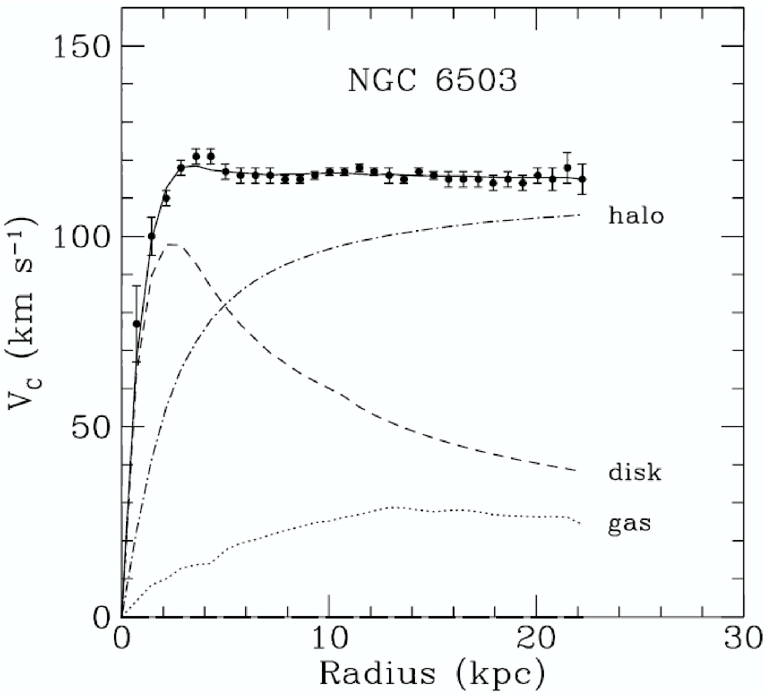
[*] Work performed as a student project under the supervision of R. Rosenfeld.



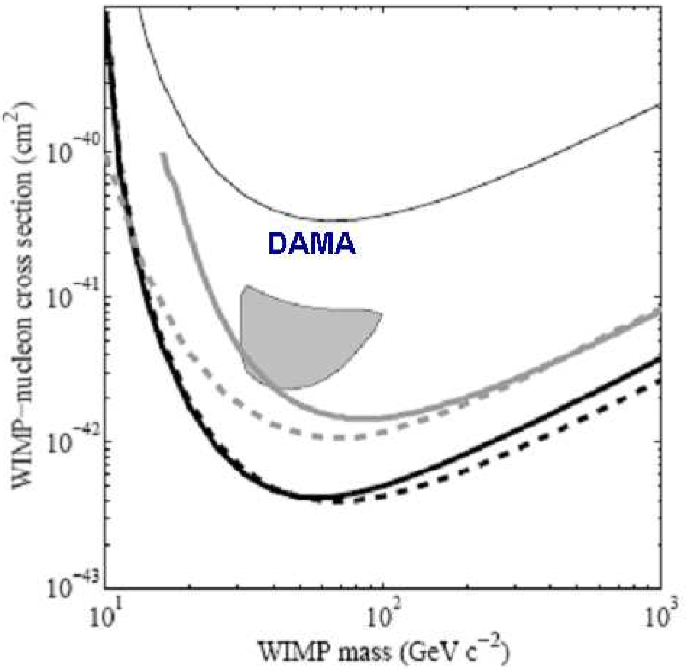


Fig. 1: Top: typical rotation curve of a galaxy. Bottom: experimental limits in the WIMP–nucleon cross-section versus WIMP mass parameter space for spin-independent interactions. The cross-section is normalized to a single nucleon. The region above the solid (dashed) black curves are excluded at 90% confidence level by current (initial) analysis of the CDMS-II Soudan WIMP search (Ge detectors) [7]. The upper thin black curve is the CDMS-II Soudan 90% C.L. exclusion limit for the Si detector [7]. The solid grey curve is the EDELWEISS exclusion limit [8]. The dashed grey curve is the ZEPLIN I exclusion limit [9]. The 3σ DAMA detection region is shown in light grey [6]. Plot from Ref. [10].

Hence at large distances we would expect a velocity falling as $1/\sqrt{r}$. The flatness of $v(r)$ could be explained by a mass distribution $M(r) \propto r$. But that extra mass does not seem to be there, or at least, we have not seen it yet. The solution is that galaxies have a spherical halo composed of electrically neutral matter that does have the usual gravitational properties.

Other important evidence found at this scale is the detection of DM through gravitational lensing. Light from stars or galaxies is bent when passing close to a massive object. Thus when observed, the light seems to come from a different place than its real source. Using this method, evidence has been found of DM surrounding elliptical galaxies. Other important evidence at this scale has been found, for more details see Ref. [2] and further references therein.

2.2 Galactic clusters scale

One of the several methods to calculate the mass of a cluster is treating it as a hydrostatic system at equilibrium. Roughly speaking, outside the core, the temperature of the cluster is constant and the density profile follows a power law with an index between –2 and –1.5. As early as 1933 Fritz Zwicky [1] compared the mass-to-light ratio of the galaxies at the Coma cluster with the Solar neighbourhood. The considerable discrepancy in the resulting temperatures among that cluster and the Solar neighbourhood suggests the existence of a large amount of DM.

2.3 Cosmological scale

Back in 1964 Arno Penzias and Robert Wilson observed an isotropic radiation coming from space. This radiation, the CMB (Cosmic Microwave Background) had already been predicted by George Gamow and his collaborators in the 1940s. After the Big Bang, as the Universe cooled down, it went through different stages: first baryogenesis, then the primordial nucleosynthesis followed by neutrino decoupling, etc. Through those epochs the Universe experienced the decoupling of certain particles, that is, their interactions at some point stopped being fast enough compared to the expansion of the Universe; hence they stopped being in equilibrium with the plasma. Particularly important is the decoupling of photons. Those photons constitute the CMB observed nowadays, and as they have been travelling essentially free ever since, they are imprinted with the characteristics of the Universe at the moment of their decoupling, the last scattering surface, see Refs. [3, 4].

From the study of these data, and using cosmological models, it is possible to infer the geometry and the mass content in the Universe. The latest analysis concludes that our Universe is flat and constrains the mass density parameter Ω_m to

$$\Omega_m h^2 = 0.135^{+0.008}_{-0.009} ,$$

where h is the Hubble parameter in units of 100 km/s/Mpc. However, if we now look at the prediction of the Big Bang nucleosynthesis, we have

$$\Omega_b h^2 = 0.0224^{+0.009}_{-0.009} ,$$

where Ω_b stands for the density parameter related to baryonic matter. Hence, baryonic matter is simply not enough to account for the geometry of the Universe. A significant amount of dark matter must exist.

3 Dark matter candidates

3.1 Properties of dark matter

There are some properties that a candidate for dark matter should have: it must be electrically neutral, massive, weakly interacting, and stable.

None of the known particles from the Standard Model (SM) have these characteristics; therefore DM is a signature of new physics. Many theoretical models have proposed candidates for DM, among them: sterile neutrinos, light scalar fields, axions, particles from Little Higgs models, Kaluza–Klein states, superheavy dark matter, Q-balls, CHAMPs, heavy fourth generation neutrinos, and within supersymmetry (SUSY) models there are sneutrinos ($\tilde{\nu}$), neutralinos ($\tilde{\chi}_1^0$), gravitinos ($\tilde{g}$), and axinos [2].

SUSY is a symmetry that relates bosonic with fermionic degrees of freedom. In practice it generates a new set of particles which are related to the particles we know (the SM particles), called the superpartners, which have half-spin difference from the SM ones.

3.2 The most likely candidate

The candidate for which we have more expectations and has been studied more is the neutralino, denoted by $\tilde{\chi}_1^0$. Neutralinos come from the mixture of the superpartner of the neutral gauge bosons $\tilde{W}^0$ (Wino), $\tilde{B}^0$ (Bino) and the neutral part of the two Higgs doublets (needed for MSSM) $\tilde{H}_1^0, \tilde{H}_2^0$ (Higgsinos), resulting in four different mass eigenstates named neutralinos (spin 1/2 fermions):

$$\tilde{W}^0, \tilde{B}^0, \tilde{H}_1^0, \tilde{H}_2^0 \quad \rightarrow \quad \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

where $\tilde{\chi}_i^0$ ($i = 1 \ldots 4$) are ordered from the lightest to the heaviest [5].

We see that $\tilde{\chi}_1^0$ have the three first properties needed for dark matter. The stability comes from the conservation of a new symmetry: R parity (which generalizes the conservation of baryonic and leptonic numbers). This new symmetry predicts that there is a superparticle which is not able to decay into any other sparticle: the Lightest Supersymmetric Particle (LSP). Assuming that the lightest neutralino $\tilde{\chi}_1^0$ is the LSP, it is a compelling candidate for non-baryonic dark matter.

3.3 Abundance

Once the candidate has the properties listed above, it has to be able to provide for the abundance needed in order to fulfil the observations. The abundance of the possible candidate can be estimated by solving the Boltzmann equation,

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = -\langle \sigma v \rangle \left(n^2 - (n^{eq})^2 \right),$$

where n is the particle number density, H is the Hubble parameter, $\langle \sigma v \rangle$ is the thermal averaged total annihilation cross-section multiplied by the velocity, and n^{eq} is the number density in thermal equilibrium. The present density of a generic relic, X, is simply given by $\rho_X = m_X n_X$. The relic density can be expressed in terms of the critical density as $\Omega_\chi \equiv \frac{\rho_\chi}{\rho_c}$.

The calculation of the abundance for any particle DM candidate is highly model dependent in two ways: it depends on the cosmological model and on the specific particle physics model (masses, couplings and cross-sections).

4 Direct search for dark matter

One of the most promising techniques to detect dark matter is by direct detection experiments. These experiments are based on the idea that the galaxy is filled with WIMPs and a fraction of them pass through the Earth. Therefore it is possible to look for the interaction of WIMPs with matter. To evaluate the rate of WIMP–nucleon scattering events, per unit of time and per unit detector material mass, we need to know the density, the velocity distribution and the WIMP–nucleon cross-section. In fact the rate can be written as:

$$R \approx \sum_i N_i \rho_W \langle \sigma_{iW} v \rangle , \tag{2}$$

where the index runs over the different nuclei species in the detector, N_i is the number of target nuclei, ρ_W is the local WIMP density and $\langle \sigma_{iW} v \rangle$ is the averaged cross-section times velocity for the scattering of WIMP-nucleon i. The local WIMP density ρ_W is assumed to be $\approx$ 0.3 GeV cm^{-3}.

4.1 Elastic scattering

In the elastic scattering of a WIMP with a nucleon of the detector, the WIMP interacts with a nucleus as a whole, causing it to recoil. If we assume that the velocity distribution of WIMPs is a Boltzmann distribution $f(v)$ centred in 270 km/s, the spectrum of the recoils is exponential with typical energies of 50 keV, depending of course on the WIMP mass. The detection is possible by measuring the recoil energy of the nucleon with ionization detectors (Ge and Si), with scintillation detectors (NaI, LXe and CaF_2), and with bolometers (Ge, Si, TeO_2).

4.2 The DAMA experiment

DAMA [6] is an observatory for rare processes based on the development and use of various kinds of radiopure scintillators. The main experimental set-ups are the $\approx$ 100 kg NaI(Tl) set-up, which completed its data taking in July 2002, the new 250 kg NaI(Tl) LIBRA (Large sodium Iodide Bulk for RAre process) set-up, the $\approx$ 6.5 kg liquid xenon (LXe) pure scintillator and the R&D installation for test on prototypes and small scale experiments. The location of the DAMA experiment is the Gran Sasso underground laboratory of INFN, Italy. The DAMA/NaI set-up has pointed out the presence of an annual modulation in the single-hit residual rate in the lowest energy interval 2–6 keV; the observed effect satisfies many peculiarities of the DM particle induced signature. This gives a 6.3 σ C.L. evidence over seven annual cycles for the presence of DM particles in our Galaxy.

The annual modulation of the DAMA event rate is consistent with the detection of a WIMP with a mass of $\approx$ 60 GeV and scattering cross-section of the order of 10^{-41} cm^2. Many other direct detection experiments have already produced quite strong limits on the elastic scattering cross-section of potential DM candidates. These results are not in agreement with the DAMA one, see Fig. 1. The reason for this discrepancy is not known.

5 Indirect search for dark matter through gamma-ray experiments

According to supersymmetry, neutralinos, even though stable, can annihilate each other, creating a cascade of particles and radiation that includes medium-energy gamma rays (see Fig. Fig. 2) . If neutralinos or WIMPs do exist, large-area telescopes will try to detect them through the products of their annihilation.

Indirect detection depends upon the squared density of WIMP particles in regions of the galaxy or beyond. Indirect DM detection via annihilation in the Galactic Centre region is an exciting possibility, although the prospects for the observation of gamma rays from that direction strongly depend on astrophysical parameters, such as the profile of dark matter in the innermost regions, which unfortunately are poorly known. Nevertheless, the development of next-generation gamma-ray telescopes, such as GLAST, will allow the test of many scenarios [12].

To observe gamma rays directly, observations must be made from space. This is because in the energy range in which experiments are interested (GeV to TeV), photons interact with matter via $e^+ \, e^-$ pair production, which leads to an interaction length of approximately 38 g cm^{-2}, which is much shorter than the thickness of the Earth's atmosphere (1030 g cm^{-2}). Thus at the these energies gamma rays cannot reach ground-based telescopes. Efforts have been developed, nevertheless, to observe gamma-rays indirectly with ground-based experiments. In this section we explore gamma-ray experiments and the status of both ground- and space-based telescopes.

5.1 Ground-based telescopes

The Earth's atmosphere is opaque to much of the electromagnetic spectrum. X-rays and gamma-rays are absorbed by the atmosphere and satellites are required for their direct detection. However, the atmosphere of Earth can be used as an enormous detector. When a very high energy gamma-ray photon interacts in

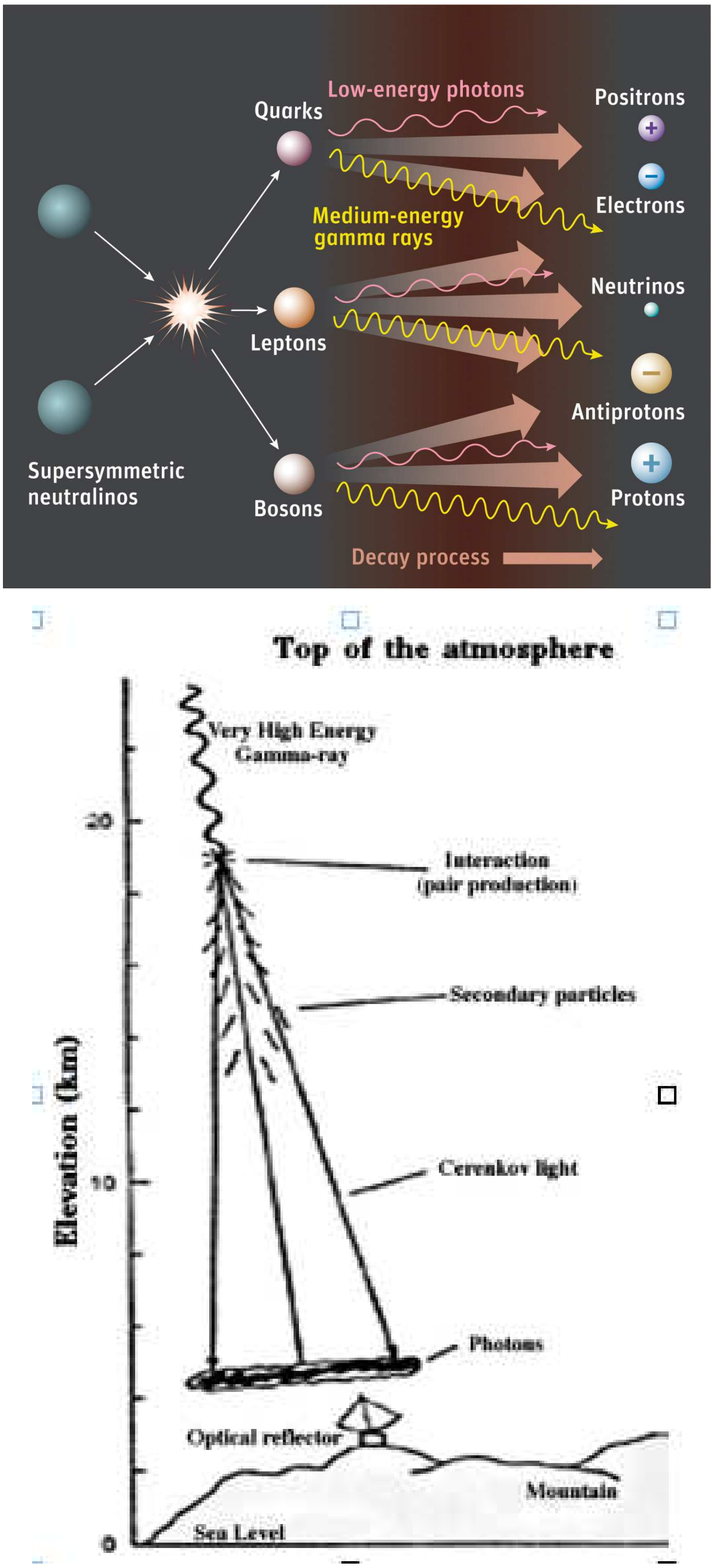


Fig. 2: Top: annihilation of neutralinos would give rise to a cascade of particles and radiation that includes medium-energy gamma-rays. Credit: Sky and Telescope & Gregg Dinderman [11]. Bottom: Gamma-rays interacting in the atmosphere create what is called an air shower.

Earth's atmosphere, it produces an electron–positron pair. Subsequent interaction of the electrons with the atmosphere results in gamma-ray production and a cascade of electrons and gamma-rays is produced. Because some of the electrons in the shower are moving faster than the speed of light in the atmosphere, they emit Cherenkov light, an electromagnetic shock-wave analogous to the sonic boom emitted by a supersonic jet. This light can be detected as a faint blue flash of short duration (a few milliseconds) at ground level (see Fig. 2). Atmospheric Cherenkov imaging observatories image this Cherenkov radiation. Though Cherenkov light is also produced by cosmic-ray showers, light from a gamma-ray shower can be discerned by its comparatively smooth shape, compact angular distribution, and through geometric considerations.

The first observation of Cherenkov light due to gamma-ray emission from an astrophysical source was the detection of the Crab Nebula with the Whipple Observatory [13]. Several sources of very high energy (TeV) gamma-rays energy have since been detected.

Among the experiments that were built to detect gamma-ray sources, are

- HESS (High Energy Stereoscopic System) is a project of four imaging atmospheric Cherenkov telescopes (IACT) used for TeV gamma astronomy in the GeV–TeV energy regime located near Gamsberg in Namibia. The whole array of four telescopes has an energy threshold of about 100 GeV and an angular resolution of less than 0.1 deg for a single event [14].
- The MAGIC Telescope Collaboration built a large atmospheric imaging Cherenkov telescope in 2001–2003, with a mirror surface of 236 m^2 and photomultiplier tubes of optimal efficiency, with a threshold of 70 GeV [15].
- CANGAROO III Project is an array of four 10 m Cherenkov telescopes in Woomera, Australia for efficient observation of celestial gamma-rays in the 100 GeV region [16].
- VERITAS (Very Energetic Radiation Imaging Telescope Array System) is a ground-based gamma-ray observatory with an array of four 12 m optical reflectors for gamma-ray astronomy in the GeV–TeV energy range located on Kitt Peak in Arizona, USA [17].

5.2 Space-based telescopes

- EGRET, the Energetic Gamma-Ray Experiment Telescope on Compton Gamma-Ray Observatory (CGRO) [18], detected gamma rays in the 20 MeV to 30 GeV range. The energy resolution of EGRET was 20–25% over most of its range of sensitivity. Absolute arrival times for photons were recorded with approximately 50 μs accuracy and bright gamma-ray sources can be localized with approximately 10-minute accuracy. Major discoveries with EGRET include the identification of blazars, a type of active galaxy classified from optical and radio observations, as prodigious gamma-ray emitters. EGRET has made a reliable measurement of the isotropic, presumably extragalactic diffuse emission.
- The GLAST (Gamma-ray Large Area Space Telescope) Large Area Telescope (LAT) consists of a tracking detector, calorimeter, and anti-coincidence detector [12]. The LAT is designed to present an effective area of 100 cm^2 with a field of view covering 1/6 of the full sky. The standard mode of operation will be continuous scan of the sky. The energy threshold is 20 MeV and gamma-ray energies up to 300 GeV can be measured. The angular resolution for the LAT is significantly better than EGRET, as is the energy resolution, especially above 10 GeV. The mission lifetime is designed for 5 years. With GLAST, one hopes to actually see individual dark-matter annihilations. Even though dark matter interacts much more weakly than ordinary matter, dark matter is not spread out evenly through space and should form clumps in and around galaxies. If dark matter is in fact composed of WIMPs, this clumping would improve the chances of these particles meeting and annihilating, producing steady streams of gamma rays detectable by GLAST's LAT. The trick will be distinguishing gamma rays produced by dark-matter annihilations from those generated

by numerous other sources in the Universe. To differentiate between the two, researchers have established a set of four guidelines [11]:

- SUSY predicts that WIMP annihilations will create gamma rays of particular wavelengths, distinct from those generated by other sources, such as black holes or supernovae.
- Dark-matter annihilations should produce gamma rays exclusively, ruling out interactions that involve other forms of radiation.
- These signals should appear to GLAST not as point sources, but as large patches in the sky - some nearly twice as big as the full Moon.
- These streams of gamma rays should be continuous, a marked difference from the fleeting explosions of gamma-ray bursts, which last only a few milliseconds to several minutes.

If a signal with all of these characteristics is found, chances are good that a source of WIMP annihilation has been found. For example, the Galactic Centre has long been considered to be one of the most promising regions of the sky in which to search for dark matter annihilations. The prospects for this depend, however, on a number of factors including the nature of the WIMP, the distribution of dark matter in the region around the Galactic Centre, and the presence of any astrophysical backgrounds [19].

Attempting to identify gamma rays from dark matter annihilations taking place near the Galactic Centre has been made more challenging by the discovery of a bright, very-high-energy gamma-ray source in that region [20]. This source appears to be coincident with the dynamical centre of the Milky Way (Sgr A*) and has no detectable angular extensions (less than 1.2 arc-minutes). Although speculations were initially made that this source could be the product of annihilations of very heavy ($\gtrsim$10 TeV) dark matter particles, this now appears to be very unlikely. The source of these gamma rays is more likely an astrophysical accelerator associated with our Galaxy central super-massive black hole [21, 22]. This gamma-ray source represents a formidable background for GLAST and other experiments searching for dark mater annihilation radiation from the Galactic Centre region [23].

The GLAST WIMP search programme has a number of potential search regions ranging from galactic substructure in the Milky Way all the way out to cosmological sources. If WIMP annihilation gamma rays are indeed collected by GLAST, then timing, spectral, and spatial signatures unique to WIMP annihilation are available which can facilitate rejection of other possible astrophysical sources of gamma rays. And if GLAST observes a point source with signatures of WIMP annihilation, then ground-based gamma-ray telescopes can view the point source and search for special signatures at or just below the mass of the WIMP.

6 Indirect search for dark matter through neutrino experiments

Neutralinos can also annihilate producing a flux of high-energy neutrinos. For instance, a possible annihilation process is $\chi + \bar{\chi} \to Z^0 \to W^+ + W^-$ followed by a W decay to (μ, ν_μ) or (e, ν_e). For a neutralino mass of around 200 GeV, the outcoming neutrinos are expected to have energies of around 100 GeV.

A high-energy neutrino interacts with matter (charge current interaction) transforming into its leptonic partner: e, μ or τ. When such a charged lepton moves in a medium faster than the local speed of light, it produces Cherenkov light which can be then detected by photomultiplier tubes. Experiments like Amanda and its upgrade, IceCube, use the South Pole ice as a medium in order to detect neutrinos crossing the Earth. In the Mediterranean Sea, several other neutrino detectors, such as Nestor and Antares, are deployed deep under the sea surface, recording up-going high-energy neutrinos. IceCube will be completed in 2011. Also, a large deep-sea structure with a volume of more than 1 cubic kilometre is being designed at the moment by the European collaboration KM3Net and will be located also on the bottom of the Mediterranean Sea.

6.1 The Antares experiment

The Antares Collaboration is constructing a large-area water Cherenkov detector in the deep Mediterranean Sea, optimized for the detection of muons from high-energy astrophysical neutrinos [24]. By construction, Antares is sensitive to up-going muon (anti)neutrinos with energies above 50–100 GeV.

The Antares Collaboration will look for neutrinos produced in neutralino anihilation inside the Sun by searching within a cone of 3 degree radius around the Sun position. It will be sensitive to a region of parameter space of mSUGRA models [24].

Neutrino detection is a growing field which will produce exciting results in the near future.

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References

[1] F. Zwicky, *Helv. Phys. Acta* **6** (1933) 110.

[2] G. Bertone, D. Hooper and J. Silk, *Phys. Rep.* **405** (2005) 279 `[arXiv:hep-ph/0404175]`.

[3] WMAP website - `wmap.gsfc.nasa.gov`

[4] J. Garcia-Bellido, *CERN 2004 European School of High-Energy Physics* (CERN 2006-003); V. A. Rubakov, *CERN 2001 European School of High-Energy Physics* (CERN 2002-002).

[5] For a review see: S.P. Martin, arXiv:hep-ph/9709356. See also Lectures of 2007 CERN Latin American School of High Energy Physics, Viña del Mar, Chile.

[6] R. Barnabei *et al.* (DAMA), *Phys. Lett.* **480** (2000) 23.

[7] D.S. Akerib *et al., Phys. Rev.* **D72** (2005) 052009.

[8] A. Benoit *et al., Phys. Lett.* **480** (2000) 23.

[9] G. Alner *et al., Astropart. Phys.* **23** (2005) 444.

[10] R.J. Gaitskell and V. Mandic, SUSY dark matter/interactive direct detection limit plotter, `http://dmtools.berkeley.edu/limitplots/`

[11] `www.nasa.gov/mission-pages/GLAST/science/dark-matter.html`

[12] GLAST LAT Collaboration (L. Wai for the Collaboration), *New Astron. Rev.* **49** (2005) 307.

[13] T.C. Weekes *et al., Astrophys. J.* **342** (1989) 379.

[14] `http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html`

[15] `http://wwwmagic.mppmu.mpg.de`

[16] `http://icrhp9.icrr.u-tokyo.ac.jp/index.html`

[17] `http://veritas.sao.arizona.edu/`

[18] `http://cossc.gsfc.nasa.gov/docs/cgro/egret/egret-doc.html`

[19] D. Hooper, G. Zaharijas, D.P. Finkbeiner and G. Dobler, `arXiv:0709.3114`.

[20] HESS Collaboration (F. Aharonian *et al.*), *Astron. Astrophys.* **425** (2004) L13;
MAGIC Collaboration (J. Albert *et al.*), *Astrophys. J.* **638** (2006) L101;
The VERITAS Collaboration (K. Kosack *et al.*), *Astrophys. J.* **608** (2004) L97;
CANGAROO-II Collaboration (Ken'ichi Tsuchiya *et al.*), *Astrophys. J.* **606** (2004) L115.

[21] F. Aharonian and A. Neronov, *Astrophys. J.* **619** (2005) 306.

[22] A. Atoyan and C.D. Dermer, *Astrophys. J.* **617** (2004) L123.

[23] G. Zaharijas and D. Hooper, *Phys. Rev.* **D73** (2006) 035010.

[24] G.M.A. Lim, on behalf of the ANTARES Collaboration, `arXiv:0710.3685`.