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# Dark Matter and the Galactic Center

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**Abstract.** The question of the identity of dark matter is one of the most outstanding enigmas of contemporary cosmology and particle astrophysics. An overview is given of the subject, a brief history, some proposed particle candidates, and the several methods now available for finally solving this difficult problem. The galactic center is one of the most interesting places for the dark matter search using $\gamma$-rays, but also one that has challenging, maybe confusing, other sources of GeV-scale radiation.

**Keywords.** Dark matter, cosmology, elementary particles, galactic center

## 1. Introduction

With the recently published Planck Cosmic Microwave Background (CMB) measurements, the basic cosmological parameters are known with percent precision (see Planck Collaboration; Ade, P.A.R. *et al.* (2015) for details on how to combine the CMB data with Supernova cosmology and other data), namely

$$\begin{aligned}\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} &= 1.000 \pm 0.005 \\ \Omega_\Lambda &= 0.691 \pm 0.006 \\ \Omega_{CDM} &= 0.1199 \pm 0.0022 \\ \Omega_B &= 0.04911 \pm 0.0015 \\ h &= 0.6726 \pm 0.0098\end{aligned}$$

This defines the currently best parameter values of the ΛCDM model, which has been remarkably successful, being consistent with essentially all cosmological measurements at present. Here $\Omega_{tot}$ is the normalized total energy density (with $\Omega = 1$ indicating a geometrically flat universe, as predicted by models of cosmological inflation), $\Omega_\Lambda$ is the fraction in dark energy (parametrized in terms of its simplest possible component, Einstein's cosmological constant), $\Omega_{CDM}$ is the fraction of energy density in terms of (non-baryonic) cold dark matter, and $\Omega_B$ the fraction in baryonic, i.e., ordinary, matter. The Hubble parameter $h$ is scaled in units of 100 $\mathrm{kms^{-1}Mpc^{-1}}$.

The cold dark matter fraction is contributed by forms of dark matter that act as non-relativistic (slow) particles at the time of structure formation, and as can be seen from the Planck 2015 data, its existence is proven formally by some 50 standard deviations. In fact, nobody has yet found a way to describe the CMB data in alternative, reasonably simple, models that do not contain a large fraction of dark matter. (By observing gravitational lensing of the CMB by intervening structure, one can get confirming evidence on the order of 30 $\sigma$ of the existence of dark matter, The Planck Collaboration; Ade, P.A.R. *et al.* (2015a).)

The CDM has to be given by electrically neutral particles, as they will give structure formation a boost also between the epoch of matter-radiation equality in the early universe and the decoupling of baryons from the thermal plasma. Fluctuations in the CDM density then form potential wells that baryons can fall into once they decouple. This is one crucial ingredient in understanding how the observable structure may have formed despite the small ($\approx 10^{-5} - 10^{-4}$) angular anisotropies measured in the CMB.

The fact that the Standard Model of particle physics, containing quarks, leptons, gauge particles and the Higgs boson, does not have a suitable candidate for dark matter (i.e., electrically neutral, massive and long-lived - on the order of the age of the universe at least) means that we here have an interesting, cross-disciplinary problem, at the heart of what is generally known as astroparticle physics. From the figures in the table above, we see that the energy density in dark matter is about 5 times that of ordinary matter. (Dark energy is a completely different entity, being characterized by a negative pressure, and therefore a gravitational repulsion. It will not be discussed further here, but see e.g. Bergstrom & Goobar (2004).)

## 2. Early Indications of Dark Matter

Studying the velocities of galaxies in the Coma galaxy cluster, Fritz Zwicky in a seminal work used the virial theorem to conclude the existence of a large over-density of non-luminous matter Zwicky (1933). He stated that if this over-density were to be confirmed one would arrive at the "astonishing conclusion" that dark matter is present with a much greater density than luminous matter. Of course, at that time one did not think about non-baryonic matter; one had in mind non-luminous dust, gas, failed stars, etc. Babcock (1939) measured the optical rotation curve of M31 (Andromeda) and found very large rotation velocities in the outer parts. Knut Lundmark had already around 1925 to 1930 noted presence of "dunkle Materie" in nearby galaxies, see Lundmark (1930).

By the end of the 1970's accurate enough rotation curves were assembled (especially using 21 cm emission), the flatness of which was used to conclude that there was dark matter surrounding all galaxies in large "halos" so big, that one did not see the onset of decline of the flat rotation curves. (The optical rotation curves, like the pioneering one of Andromeda by Rubin & Ford (1970) did on the other hand not measure far enough from the center to conclude the existence of material beyond the baryons present in the exponential disk. For a thorough discussion of the history of dark matter, see Bertone & Hooper (2016).)

A key insight came in 1974, when, independently, Einasto, Kaasik & Saar (1974) and Ostriker, Peebles & Yahil (1974) argued for a large matter density $\Omega_M \sim 0.2$. As this is larger than the baryon density $\sim 5\%$ obtained in the beginning of the 1980's both from the analysis of the CMB (where the angular anisotropies were known to be smaller than around $10^{-4}$), and big bang nucleosynthesis, the notion of non-baryonic dark matter started to appear frequently in the literature. This coincided in time with the evolution in particle physics of new theories, such as Grand Unified Theories (GUTs) and especially supersymmetric (SUSY) theories which indeed contain neutral, heavy, long-lived particles, i.e. candidates for dark matter.

## 3. Particle Candidates for Dark Matter

There were a number of early suggestions of particles solving the DM problem, in particular:

• Massive neutrinos. Gershtein & Zel'dovich (1966) used for the first time the condition of not over-closing the universe to get a simple limit of 400 eV on the sum of neutrino masses, in particular important for the muon neutrino, whose mass was then poorly known from direct measurements. They did not propose neutrinos as dark matter, however, as the problem of non-baryonic dark matter was not known at the time. This upper limit was later refined to around 40 eV by Cowsick & McLelland (1972), and today Planck measurements (2015) put the limit around 0.23 eV.
Lee & Weinberg (1977) did the first "modern" calculation of the relic density of massive neutrinos, and found that besides the upper bound on light neutrinos, one could actually find a lower bound for more massive neutrinos of around 2 GeV, where neutrinos would no longer be hot dark matter (i.e., moving with relativistic velocities due to the tiny masses) but rather cold dark matter, moving non-relativistically after "freeze-out" in the early universe. To get this bound they solved the Boltzmann equation (which in this regime becomes the Riccatti equation), something that paved the way for all forthcoming analyses of cold dark matter.
Tremaine & Gunn 1979 were among the first to appreciate that these more massive neutrinos could in fact be the dark matter, and also showed that dynamical arguments could be used to limit the mass of light neutrinos to be less an 1 MeV, as otherwise they could not condense into small structures like dwarf galaxies.
After LEP at CERN measured the width of the $Z^0$ boson to limit the number of active neutrino species to 3, and direct detection experiments were setting stringent limits on massive neutrino dark matter up to the TeV range, neutrinos are not anymore seen as viable dark matter candidates, except if they do not couple directly to the weak gauge bosons - hypothetical so-called sterile neutrinos. Thus, it has since been realised that dark matter has to be related to physics beyond the Standard Model of particle physics.

• Axions. An early example of a particle beyond the Standard Model, still being very interesting as a dark matter candidate is given by the axion, introduced originally as a classical potential with $U(1)_{PQ}$ symmetry to solve the absence of CP violation (Peccei & Quinn (1977)). It was soon realised that the spontaneous breakdown of $U(1)_{PQ}$ leads to the existence of a light pseudo-Goldstone boson, the axion (Wilczek (1978), Weinberg (1978)). As various limits ruled out the simplest versions, an elegant solution was found (Kim (1979), Shifman, Vainshtein & Srednicki (1980), Dine, Fischler & Srednicki (1981)) involving fields of very high mass, meaning that the coupling strength and the axion mass were much smaller, and thought to be essentially "invisible".
It was Sikivie (1983)) who showed that the two-photon coupling still existing also in the invisible axion models, could, by a clever use of resonance, be used for axion detection. Some results exclude certain pieces of parameter space (for a review, see Raffelt (2014)), but a large range still exists to be explored. This is likely to be a main activity in the dark matter field during the coming years.
Axions, despite being so light, behave more like cold dark matter than hot dark matter due to their extremely weak coupling (they were never in thermal equilibrium).

We now turn to weakly interacting massive particles, WIMPs, that were in thermal equilibrium in the early universe, and the relic density which therefore can be reliably computed following the methods of Lee and Weinberg (1977). For a recent review of WIMP dark matter, see, e.g. Bergstrom (2012).

One finds that if the WIMPs (which we generally denote by $\chi$) interacted with regular electroweak gauge interaction strength with Standard Model particles in the primordial plasma, they would have followed the thermal distribution until roughly $k_B T_f \sim m_\chi c^2/20$, i.e., they were already quite non-relativistic at this "freeze-out" epoch. Moreover, to a good approximation, for particles annihilating through the $S$ wave the relic density only depends on the total annihilation cross section $\sigma_A$ times velocity (Jungman, Kamionkowski & Griest (1986)),

$$\Omega_\chi h^2 \simeq 0.11 \times \frac{2.8 \cdot 10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma_A |\mathbf{v}| \rangle}, \qquad (3.1)$$

where an average of velocities and angles is taken (the correct expression $\langle \sigma_A |\mathbf{v}| \rangle$ is often abbreviated as just $\sigma v$).

The value in Eq. (3.1) for $\sigma v$ evaluates to a cross section of 1 pb, i.e., a typical weak interaction cross section. In other words, if one gives ordinary gauge gauge couplings to the particle $\chi$, and a mass of typical weak interaction magnitude (to within an order of magnitude 250 GeV, say), then $\sigma v$ is such that the resulting relic density comes close to the measured value of $\Omega_\chi h^2 \sim 0.12$. This is peculiar to the WIMP scenario, sometimes called the "WIMP miracle". Of course, this may be nothing else than a coincidence, but is still an interesting fact.

The particle physics connection thus is particularly strong in the WIMP scenario. Namely, for typical gauge couplings to ordinary Standard Model particles and a dark matter particle mass at the ordinary weak interaction scale, the relic density is close to the measured one.

Although there is no completely convincing argument for WIMP dark matter – it may as said be a coincidence – it nevertheless gives WIMP candidates a flavor of naturalness. For non-WIMP candidates there is, on the other hand, usually a fine-tuning involved, or the use of non-standard early-universe cosmology, to obtain the correct relic density. Even limiting oneself to WIMP models for dark matter, the literature is extensive (see, e.g., Bertone (2010)).

Supersymmetry is a symmetry between particles differing half a unit of spin, such that, e.g., the lightest linear combination ("neutralino") of the spin-1/2 supersymmetric partners of the photon, the $Z^0$ and neutral Higgs particles would be a suitable dark matter candidate. Supersymmetric particles, although not yet found at accelerators, belong to the favored and most studied WIMPs (early work include Pagels & Primack (1982); Weinberg (1983); Goldberg (1983), Ellis *et al.* (1984), L.B. & Snellman (1986)). In supersymmetric models there is a multiplicatively conserved $Z_2$ quantum number, $R$-parity, which is $+1$ for all ordinary particles of the Standard Model and $-1$ for supersymmetric partners. It can be defined by

$$R = (-1)^{3(B-L)+2s}, \qquad (3.2)$$

with $B$ the baryon number, $L$ the lepton number and $s$ the spin of the particle. In supersymmetric models, $R$-parity conservation is natural to impose as it also forbids potentially catastrophically large baryon number violation to occur. Due to $R$-parity conservation, the lightest supersymmetric particle, generallly a neutralino, is stable, as it has no lighter particle to decay into. This gives the long (infinite) lifetime condition needed for a good dark matter candidate.

Relic density and other properties of supersymmetric theories for dark matter are nowadays readily computed (e.g., using the free DarkSUSY computer package, Gondolo *et al.* (2004)) once the (many) parameters of the model have been specified.

As CERN's LHC has now been running for about one year at record-high energy, 13 TeV, and luminosity of some 25 $\mathrm{fb}^{-1}$, and still no sign of supersymmetry has been found, SUSY models for dark matter, at least in the simplest scenario, are presently under some pressure. Indeed, "fine-tuned" models are still viable, but less attractive as the introduction of supersymmetry in particle physics was to a large extent motivated to avoid the fine-tuning needed to protect the low mass scale of weak interactions compared to the

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Planck scale. The DarkSUSY package, which was initially adapted to supersymmetric dark matter is currently being rewritten to handle generic WIMP candidates.

By now, probably hundreds of hypothetical dark matter candidate particles have been proposed, and many already being ruled out, but WIMPs (many non-supersymmetric) and axions still belong to the favoured ones. One way to circumvent the new LHC bounds is, for instance, to invoke coupling to leptons only (as the LHC is a hadron machine, with quarks and gluon being the main colliding constituents). This happens, for instance, in many models which seek a relation between the neutrino sector and dark matter.

## 4. Methods of WIMP detection

There are basically three different methods we may employ to detect dark matter particles , in particular WIMPs, and to gain insight on their mass and interaction strength. At the moment (in mid-2016), the LHC accelerator is gathering data at a very impressive pace, now at 13 TeV in the center of mass. The hope that the main experiments at the LHC, ATLAS and CMS, would discover events that do not fit into the current Standard Model of particle physics, has however not been realized. In particular, tentative evidence for a resonance of 750 GeV mass decaying into two photons turned out to be a statistical fluctuation (despite some 500 theoretical papers "explaining" its existence). Such a particle would not by itself constitute dark matter (because of the extremely short lifetime), but could have been a messenger coupling to the dark sector. The non-appearance of supersymmetry is another drawback for theory, and it would be fair to say that if this powerful idea fails, we are back to square one regarding the identity of dark matter.

The method of searching for direct detection of dark matter relies instead on the fact that dark matter particles should be present everywhere in the dark matter halo of the Milky Way. They should thus travel through the solar system and the earth with typical galactic velocities of $\sim$ 200 km/s, i.e., with $v/c \sim 10^{-3}$. From modeling of the Milky Way one finds that locally the mass density of dark matter should be of the order of 0.4 GeV/cm$^3$, within a factor of two or so. One can then estimate that, if the cross section is that of a WIMP, scattering on nuclei should take place with a cross section at or below below a few times $10^{-8}$ pb. In deep underground laboratories, there are a number of ingenious experiments taking data or being deployed with Xenon-100 (2014), LUX (2016) , and PandaX-II (2016) giving the best current bounds. These indirect detection experiments have seen an impressive gain of sensitivity during the last few years.

### 4.1. *Indirect Detection of Dark Matter through Gamma-rays from the Galactic Center*

In so-called indirect detection of dark matter, one instead registers products of dark matter self-annihilation from regions in the surrounding universe with a high dark matter density like the galactic center, dwarf spheroidal galaxies, or galaxy clusters. Knowing the halo density distribution, for instance by using numerical simulations one can estimate the annihilation probability. For one of the most promising targets, the galactic center, that is in fact a big problem, since its complex nature and formation history makes it essentially impossible to reliably calculate the interplay between dark and visible matter. It has been known for a long time (Bergstrom, Ullio & Buckley (1998)) that the unknown distribution of dark matter near the very center has a large influence on the detection rate of photons. In dark matter-only numerical simulations one finds a cuspy distribution (Navarro, Frenk & White (1996)),

$$\rho_{NFW} = \frac{\rho_c}{\left(\frac{r}{a}\right)\left[1+\left(\frac{r}{a}\right)^2\right]} \tag{4.1}$$

whereas a cored distribution behaving a a constant as $r \to 0$ is not excluded, and in fact preferred by some (for a review of the problem and possible solutions, see R. Teyssier *et al.*, (2013)). This difference at the very center of the Galaxy could mean several orders of magnitude difference in detected photon rate.

Even if the galactic center contains dark matter with a cuspy profile, there is still the difficulty of extracting the dark matter $\gamma$-ray signature against other possible sources. Indeed, it was stated in Bergstrom, Ullio & Buckley (1998), as a comment on the "GeV excess" of photons from the g.c. claimed by the EGRET satellite at the time "*In fact, present EGRET observations are not inconsistent with a continuum spectrum originating from dark matter annihilations, but other explanations are possible as well.*"

It turned out that the EGRET data had other, instrument-related problems, but the conclusion still stands: The diffuse emission from other sources, like millisecond pulsars or inverse Compton radiation from other electron positron sources (like episodes of activity of the central black hole) are very difficult to distinguish from dark matter annihilation radiation. This was why Bergstrom, Ullio & Buckley (1998) concentrated on processes with a distinctive signature, like $\chi\chi \to \gamma\gamma$, which do not have the corresponding background problem. To search for these, one would however need a larger detector than Fermi-LAT, and with better energy resolution. It seems that at present there is unfortunately no follow-up mission planned in the West. Both China and Russia, however, have missions (HERD (2016) and GAMMA-400 (2013), respectively) that may improve on the very high energy line search in the next decade.

An interesting episode occurred in 2012, when analyses of public Fermi-LAT data seemed to show a $\gamma$-ray line feature at around 130 GeV (Bringmann *et al.* (2012); Weniger (2012)), at the 3-4 $\sigma$ level. Subsequent analyses with more data did, however, not confirm the effect, the cause of which was probably a combination of instrument and statistical errors (see the most recent Fermi-LAT analysis (2015)).

D. Hooper, with various colleagues (see Hooper's contribution to these Proceedings), have made clever analyses (Hooper & Goodenough (2011), Daylan *et al.* (2016), for example) of Fermi-LAT data from the galactic center, and have shown that there is indeed a GeV excess, which can in principle be explained by annihilating dark matter. Recent analyses, however, (Bartels *et al.* (2016), Lee *et al.* (2016)) indicate that a point-source origin is more likely. It seems that millisecond pulsars could be a possible astrophysical source, but a definite answer is still lacking.

For $\gamma$-rays from dark matter annihilation, fore- and backgrounds from astrophysical processes may thus be large, and thus it may be advantageous to search in directions close to, but not exactly at, the galactic center (Baltz *et al.*, (2008)).

Interesting objects are the dwarf galaxies, where limits from Fermi-LAT are now getting into the parameter space of common WIMPs (Fermi-LAT Collaboration, Ackermann *et al.* (2015a)). In particular, WIMPs lighter than around 100 GeV, are disfavored in the simplest models. The relative abundance of DM in these dwarf galaxies is high, as star formation probably only occurs above some threshold mass, and the pressure from a few supernovae may be enough to completely empty a dwarf galaxy from baryons. This means that there may be bright spots in $\gamma$-rays in the sky, "dark matter clumps", that are not visible at all in any wavelength, except their possible annihilation to $\gamma$-rays.

Simulations indicate that DM clumps will be destroyed by tidal forces near the center of galaxies but can be very abundant in the outer regions (Springel *et al.* (2008)). When going to larger scale objects like galaxy clusters that are forming at the present epoch, the number of non-destroyed DM clumps may be even larger, making these clusters – in a perhaps unexpected agreement with the discovery of Zwicky (1933) – quite promising targets for indirect searches (Pinzke, Pfrommer & Bergstrom (2011) and references therein). However, with (probably) more realistic "boost factors" the present sensitivity of Fermi-LAT is an order of magnitude too small to give an observable signal (Anderson *et al.* (2015); Adams, Bergstrom & Spolyar (2016)).

Imaging air Cherenkov arrays like the future CTA (The CTA Collaboration (2013)) will have their peak sensitivity in the energy range between a few hundred GeV to a few TeV, which will be an interesting new energy region to probe. For the galactic center, it seems however that quite clever methods to avoid astrophysical sources have to be developed (see, e.g., Silverwood *et al.* (2015)).

### 4.2. *Indirect Detection of Dark Matter through Neutrinos from the Galactic Center*

Neutrinos could give an interesting signature as dark matter particles could scatter in the interior of the sun or the earth (and perhaps near the galactic center) and be gravitationally trapped there, enhancing the number density and thus the annihilation rate. The discovery of energetic neutrinos from the direction of the sun or the galactic center would be a spectacular verification of this process, and the mass of the dark matter particle could then be roughly estimated. The current large neutrino telescopes like IceCube (2016) and ANTARES (2015) have such dark matter searches in their scientific programs. For WIMPs captured and annihilating in the earth, the limits obtained from neutrino telescopes are not competitive with direct detection. To see a signal from the galactic center, a very cuspy profile would be needed. Gondolo and Silk (1999) showed that if the black hole at the g.c. would have formed in a monolithic manner, the subsequent accretion of dark matter, and the very cuspy profile so formed, would cause neutrinos to in fact dominate the detection rate. Very near the g.c. the gravitational field is dominated by the black hole and a stellar cusp is known to exist, with unknown effects on the dark matter density and therefore the annihilation rate into $\gamma$-rays (that may not get out of the very center) and neutrinos. Unfortunately, the contribution from dark matter to the rotation curve is much too small in the inner parts of the galaxy to enable to determine whether the halo density is cuspy or not. Also, even a very important concentration of dark matter very near the black hole could well influence the indirect detection rate Gondolo and Silk (1999) without having much dynamical effect otherwise.

### 4.3. *Conclusions*

There are good news and less good news concerning the identification of dark matter at present. The good news is that a powerful combination of cosmological data - foremost those of the CMB and structure formation in the early universe leaves no doubt about the existence of dark matter. The bad news is that, although current experiments searching for its detection have reached the sensitivity that could have made a definite detection possible, none has taken place. Indeed, there are some possible exceptions, like the current GeV excess detected by Fermi-LAT in the galactic center region, but the possibility of other sources remain. There is a also a long-standing claim by the DAMA/LIBRA experiment of an annual modulation (DAMA/LIBRA, Belli (2016)), but this is controversial since it has not been verified by other direct detection experiments. However, it is true that no directly comparable experiment has been done up to this date, so it is encouraging that at least one such experiment, SABRE, is currently being set up, with detectors both in the northern hemisphere (USA) and the southern (Australia), Froborg *et al.* (2016). This could convincingly check whether the modulation is indeed there, and if so, that it is not dependent on other environmental seasonal effects.

Of course, in the near future interesting phenomena may turn up as CERN's LHC continues to operate at record energy and luminosity. This could at least give us a glimpse of what lies beyond the Standard Model of particle physics, and thus lead us to a valid dark matter candidate particle. And future direct detection experiments will probe the available parameter space all the way down to the floor where coherent neutrino interactions become a difficult background. Even if nothing is found there, there is a possibility to probe even models with smaller direct detection cross section through indirect detection, as the annihilation cross section is in general very loosely correlated to that of direct detection (Bergstrom, Bringmann & Edsjo (2010)).

And if nature is kind to us, we could even get an unambiguous signal of dark matter from $\gamma$-rays in the planned new space experiments, or through neutrinos from the sun or earth in the large new neutrino detectors.

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