The search for astrophysical Dark Matter

Ori Friedman
Raymond and Beverly Sackler School of Physics and Astronomy, Tel – Aviv University, Tel Aviv, 69978, Israel

This short review summaries briefly some of the experiments conducted to find the elusive hypothetical Weakly Interacting Massive Particles (WIMPs) that are assumed to present at the solar system and across the universe. The WIMPs are, today, the main candidates for Dark Matter (DM). After a discussion about the DM gravitational anomaly, the term "the WIMP miracle" is introduced and along with the reasons WIMPs are the most promising explanation for the DM conundrum. The following discussion focuses on several experiments of direct detection through Dark Matter – Standard Model (DM-SM) recoil, which have all produced null results. After that are described a few indirect detection experiments which examine SM radiation from space that could have been produced or affected by several possible DM-DM or DM-SM interactions.

Introduction – in 1933, the Swiss astronomer, Fritz Zwicky, was the first to observe that the galaxies in the Coma Cluster were moving too fast to be able to hold themselves together in the cluster, considering their total observed mass as the source of the gravity that should be holding the cluster together [1]. He thus figured there should be a lot of "missing mass" in the cluster and was the one who coined the term "Dark Matter". Later, another famous astronomer, Vera Rubin, was the first to observe the gravitational anomaly in the form of rotational velocities of the outer stars in the spiral galaxy M31, not falling off as expected by Kepler's law, but remaining constant with increasing distance from the center of the galaxy [2]. An example for such a curve is shown in figure 1, for the galaxy NGC6503. Since then, the gravitational anomaly affecting rotational velocities of galaxies and galaxy clusters has been observed throughout the entire universe, encompassing galaxies and clusters of all kinds [2-3].

The missing matter is now considered to be about five times more abundant in the universe than baryonic matter, and its fingerprints are observed also through strong galaxy lensing [4] and in the Cosmic Microwave Background (CMB), the radiation which filled the universe after the epoch of recombination [5]. There are many theoretical models which attempt to explain the DM phenomena. Most of them assume it consists of exotic matter which can interact, weakly, with ordinary matter, while its properties change quite drastically from one model to another. Some theories suggest the gravitational anomaly has nothing to do with exotic matter at all, but rather a different behavior of gravity which has not yet been thought of (see ref [2] for a thorough review).

This review will shortly discuss the leading theories of DM, which assume it's an exotic form of matter, and some of the experiments conducted to verify or rule them out. The mentioned experiments attempt to observe "astrophysical WIMPs". Those are DM particles which travel through the earth or annihilate in space. The experiments conducted at the Large Hadron Collider (LHC) to "produce" DM particles during the different runs are not discussed here.

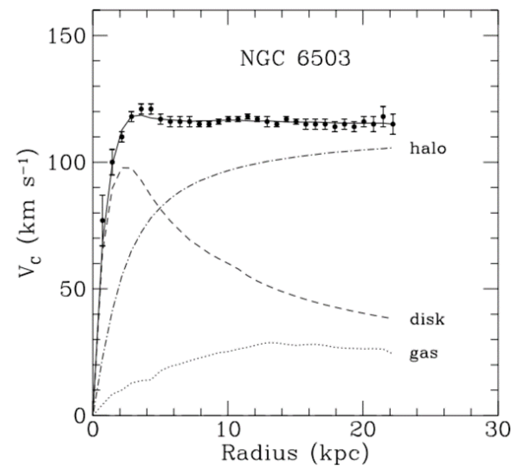

Figure 1 [6]: rotational velocity (V_c) as a function of the distance (Radius) from the center of the galaxy NGC6503. The dashed lines represent the contribution of each component of the galaxy to the observed curve according to DM models ('gas' is mostly hydrogen, 'disk' is the stars and non-luminous baryonic matter and 'halo' is the DM).

"The WIMP-miracle" – the main assumption today is that DM consists of Weakly-Interacting-Massive-Particles (WIMPs), which are non-baryonic (or leptonic), have null (or almost null) electric charge, stable (half-life > age of the universe) and do not appear in the Standard Model (SM). The motivation for this hypothesis in particle-physics comes from two of the main problems in the SM: the gauge hierarchy problem (why is there such a huge scale difference between gravity and the other forces) and the New Physics Flavor Problem/Puzzle (what creates the observed hierarchy between the different fermionic flavors) [3]. Several models of Super-Symmetry (SUSY), Unified Extra Dimensions (UED) and other theories try to solve these problems, and they

involve the existence of several yet unobserved particles (SUSY's main candidate is the 'neutralino' and UED main candidates are the 'KK bosons') that "naturally" have the properties and relic densities, Ω_{DM} (their abundance in the universe after the thermal freeze-out – see figure 3), that agree well with the astrophysical observations [2,3].
The WIMPs relic density, Ω_{χ} (χ for WIMPs), is calculated in those theories by [3]:

$$\Omega_{\chi} = \frac{m_{\chi} n_0}{\rho_c} \sim \frac{x_f T_0^3}{\rho_c M_{PL}} < \sigma_A v >^{-1} \qquad (1)$$

Where $< \sigma_A v > = \frac{k g_{weak}^4}{16\pi^2 m_{\chi}^2} \begin{cases} 1, & S\_ \ (wave\ annihilation) \\ v^2, & P\_ \ (wave\ annihilation) \end{cases}$,
$< \sigma_A v >$ is the annihilation cross section, i.e. the likelihood of the interaction through the weak force (hence g-weak), $x_f \equiv \frac{m_{\chi}}{T_f} \approx 20\ (typical\ value)$; m_{χ} is the WIMP's mass, T_f is the DM temperature at freezeout, ρ_c is the critical density for a flat universe (a universe with curvature equals to zero), as derived from Friedmann's equations, T_0 is the current (DM) temperature, $M_{PL} = \sqrt{\frac{hc}{G}} \cong 1.2 \cdot 10^{19} GeV$ is the Planck mass, $g_{weak} \cong 0.65$ is the coupling amplitude with the weak force and k is a varying parameter.
The natural range of parameters values in (1) for WIMPs (naturally arises from the theories) gives a well-approximated (relative to astrophysical observations) relic densities range as a function of the WIMPs mass, as shown in figure 2:

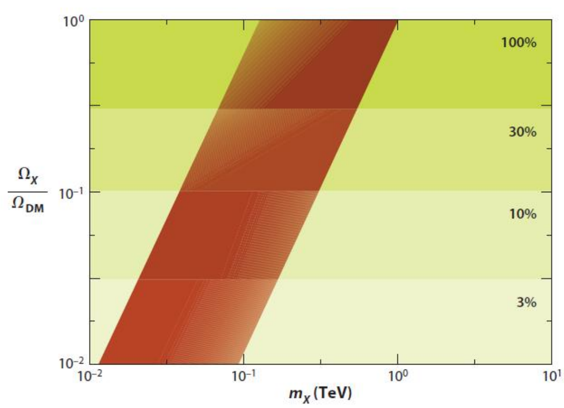

Figure 2 [3]: The parameters values for WIMP density (brown band) which come out of (1), taking $\Omega_{DM} = 0.227 \pm 0.014$ and varying the WIMP mass m_{χ}, taking both P- and S- wave annihilation channels into account and $0.5 \leq k \leq 2$. Note that $\frac{\Omega_{\chi}}{\Omega_{DM}} = 1$ for $100_{GeV} \leq m_{\chi} \leq 1_{TeV}$.

The "naturalness" of parameters values for WIMPs which give a good approximation to the observed DM relic density, is the "coincidence" which is called "the WIMP miracle" and is one of the strongest drive for many experiments around the globe aiming to find those elusive particles. The mass of the WIMPs is thought to be around the electroweak scale (10GeV – 1TeV) [3,7], and their main properties are listed in table 1. Note that neutrinos and axions were included, for they are possible candidates, though considered less likely for explaining the missing mass anomaly. For more details, see ref [3].
WIMPs in this review, as mentioned, refer to the particles which have the needed natural relic density: either the lightest of neutralinos in all SUSY models, which are a combination of several other SUSY particles as shown in table 1, or the UED particles (KK bosons) which are also stable.

Theory / properties	Candidate's name	mass	Main motivation	other properties
SUSY	Neutralino $\tilde{\chi} = \xi_{\gamma}\tilde{\gamma} + \xi_{Z}\widetilde{Z^0} + \xi_{h_1}\widetilde{h_1^0} + \xi_{h_2}\widetilde{h_2^0}$	$m_{\chi} \sim 100_{GeV}$	Gauge hierarchy	- neutral - fermions (spin 1/2) -majorana fermions
universal extra dimensions	Kaluza-Klein (KK) states $H_{kk}^0 ; \gamma_{kk} ; Z_{kk}^0$	$600_{GeV} < m_{B1} < 1.4_{TeV}$	Gauge hierarchy NPFP	- neutral - bosons
SM	Axion (less likely)	varies	-	-
SM	Neutrino (unlikely)	-	-	-

Table 1. leading DM candidates [3,7]

Looking for a direct impact – as previously mentioned, the most promising DM candidates are the neutralinos and KK bosons. Therefore, the focus of direct detection experiments around the globe are designed to be sensitive to the properties of these particles (mostly mass and cross section). According to theory, the neutralinos are majorana fermions (they are anti-particles of themselves), and the KK bosons may have anti-KK-bosons. Thus, they might annihilate, upon colliding, to form SM particles. These interactions might be observed (see mentioned experiments) [3,7]. Therefore, shortly after the Big Bang we'd expect their number to decline very rapidly (in fact, exponentially). In addition, the universe also expanded very fast at this early epoch. These caused the WIMPs density in the early universe to drop exponentially. Upon reaching the relic density, the DM particles are so diluted that in effect they barely ever meet each other at all, and thus their number and temperature are maintained roughly constant. This is called "the freezeout", and is shown as horizontal lines in figure 3:

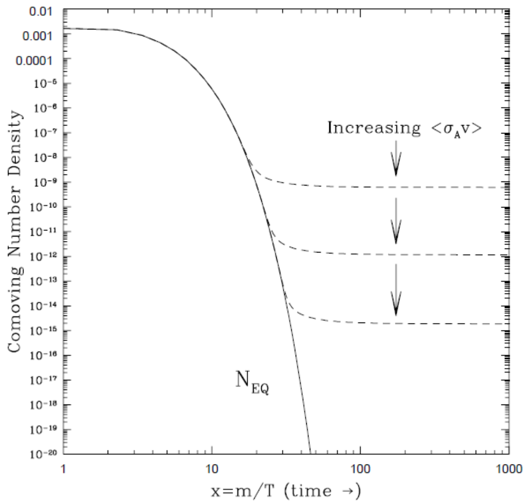

Figure 3 [7]: the comoving number density of WIMPs ($m_\chi \sim 100_{GeV}$) as a function of the Temperature of the universe. $N_{eq} \propto e^{-\frac{m_\chi}{T}}$ is the solid curve obtained for sustained thermal equilibrium and the dashed lines represent the freezeout caused by the expansion of the universe. The larger the cross section of the DM is, the more of it manages to annihilate before the thermal freezeout and thus results in lower comoving relic density. Astrophysical observations constrain the height of these lines.

That constant is expressed today in terms of energy density $\Omega_{DM} = 0.227 \pm 0.014$, which is about 5 times the energy density of all baryonic matter $\Omega_B = 0.0456 \pm 0.0016$ [3]. Being much more gravitationally-dominant than the baryonic matter, it dictates the formation of the largest scales of the universe, upon which the baryonic matter clumps to form galaxies [2-7]. The dominant astrophysical model for DM is known as ΛCDM (Λ Cold Dark Matter) which assumes that DM particles nearly never interact with baryonic matter or with themselves, just like in the SUSY/UED theories. Thus, it cannot cool down like regular matter and collapse, and therefore forms gigantic halo-like "bubbles" in which the galaxies are embedded. An example for a density profile of the DM halo is shown as dashed line in figure 1.

It can be deduced that the DM halo of the Milky-Way is present in the solar system as well, and so the DM particles are passing through the Earth continuously. However, because of the tiny WIMP-nucleon-cross-section, which is below $10^{-42} cm^2$ [8], and its interacting only by the weak force, a DM particle usually goes through the Earth without interacting with anything. However, there is a small chance for an interaction with SM particles, causing recoil (elastic spin independent scattering), $\chi\, SM \rightarrow SM\, \chi$, which can deposit energy at scales of 1-100 KeV (assuming WIMP mass range of 1-1000 GeV). Extremely sensitive underground detectors might detect this. Such detectors have been built but so far none has found a compelling evidence for DM scattering [8]. Although, null results from such sensitive experiments put further constrains on the DM cross section and mass, as shown in figure 4 for experiments conducted before 2017:

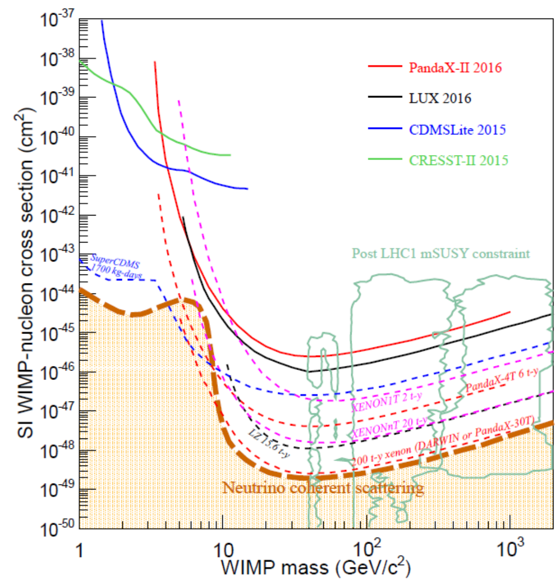

Figure 4 [8]: WIMPs-nucleon cross section – mass range experiments. The solid lines represent the constrains (upper limits) derived from the various experiments.
Dashed thin lines represent future experiments with greater sensitivity.
The broad dashed outline of the bottom part of the graph represents the sensitivity limit for any such experiment, as a result from neutrino noise background ("the neutrino floor"). The weak green bottom outlines are the constrains from Run1 at the LHC.

The latest null-result experiment, which is the most sensitive to date, is the XENON1T [9] (LUX2016 is almost as sensitive). The experiment looked for 34.2 days for any excess signals originated by nuclear recoils of DM from xenon atoms, in a cylinder of 1-meter high and 1-meter wide container filled with pure liquid xenon, which acted also as a large drifting chamber. The interactions of DM (and neutrinos) with the xenon atoms ionize them, causing the emission of scintillation photons and electrons, which are detected in the surrounding detectors. The experiment concluded there wasn't any excess of signals over the background noise which could indicate for DM interactions. The derived constrains from the experiment are shown in figure 5:

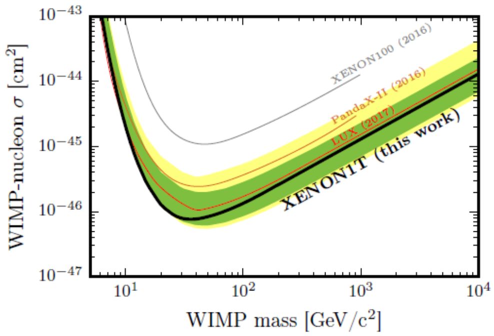

Figure 5 [9]: WIMPs cross section – mass constrains from XENON1T experiment. Black line for 90% confidence level, green for 1σ sensitivity and yellow for 2σ sensitivity bands.

However, despite the consistent null results, more experiments with greater sensitivity are being planned for the next decade, which will cover the whole theoretical range above the "neutrino floor" [8]. The planned experiments are shown in figure 4 as thin dashed lines.

Searches for clues in space – Despite profound astrophysical evidences for its existence, DM will remain controversial unless it will be observed to affect matter by means other than gravitational pull. In addition to measurements of its abundance throughout the universe by gravitational lensing [7] and fluctuations in the CMB [5], astrophysicists look for any sort of self-annihilation products which might occur in space, resulting in radiation which can't be explained by any other means. Such findings may strengthen the WIMPs hypothesis while weakening other theories which do not include DM. In general, WIMPs might be able to annihilate to any SM particles through many channels (until observed otherwise). An example of such annihilation through T, S and loop channel is shown in figure 6:

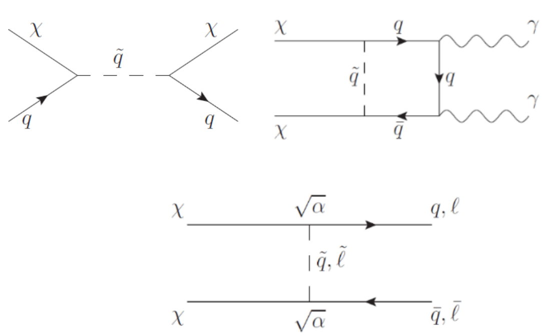

Figure 6 [7]: Possible Feynman diagrams for DM-SM interactions. top-left: possible scattering S channel for neutralinos (χ) with quarks (q).
Top-right: annihilation diagram to two photons with a quark-squark loop.
Bottom: possible annihilation T channel for DM (χ for neutralinos) to quarks / anti-quarks and/or leptons / anti-leptons.

One assumption of SUSY models is that annihilation of WIMPs produces neutrinos, among other particles. Given the gravitational potential well of the sun, one may expect an excess of WIMPs density within, from particles who did not have enough kinetic energy to escape it. Therefore, a relative excess of WIMPs annihilation products of neutrinos may be detected from the sun, with energies that match SUSY's predictions [3]. An extensive experiment ran by 'The Super-Kamiokande Collaboration' over 3903 days examined that expectation and found no evidence for excess of neutrinos flux (of any flavor), putting further constrains on spin-depended WIMPs (for masses below 200 GeV) and for spin-independent WIMPs (few GeV mass range) [10]. Similar experiments have been conducted, with the same results [3].

DM annihilation/decay process may result in final products of electron-positron pairs [2,3,5,7,10,12]. An excessive flux from space of either positrons or electron-positron pair, in the GeV-TeV range, may indicate on such processes. Such excess of electron – positron flux, at the corresponding energy range has indeed been observed raining down from space [3,12]. The data from various experiments and the expectation curves are shown in figure 7:

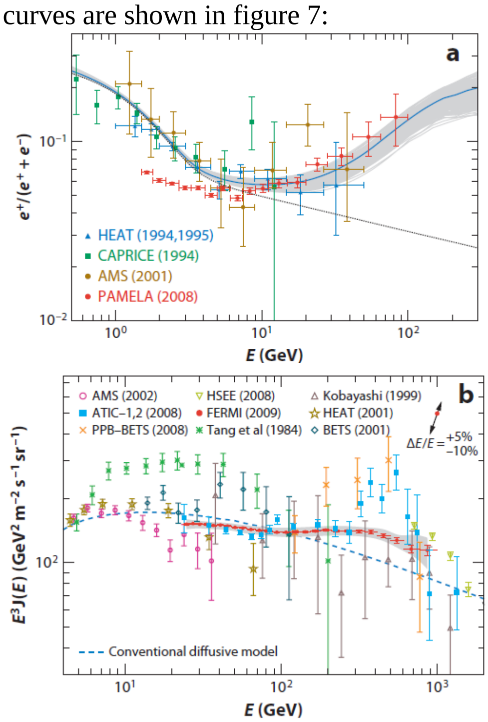

Figure 7 [3]: (a) positron portion as a function of the electron/positron energy. An excess flux can be seen at energies above 10GeV (blue line and data crosses) compared to expectations (lower grey curve). (b) total electron-positron radiation as a function of their energies. An excess flux can be seen at energies above 100GeV compared to expectations (blue dashed line).

There might be several adequate astrophysical explanations for the anomalies seen in figure 7, that do not require DM, and the properties of the WIMPs needed to make them possible is not compatible with theories [3]. Therefore, it is yet too early to conclude this as a solid indication to WIMPs annihilation.

In addition to electrons-positrons flux excess, there has been observed an excess of gamma rays flux from extragalactic sources, but after close examination of several possible annihilation channels for WIMPs, none could be pointed out as a viable source for the excess [11,12].

A recent discovery regarding radiation from the epoch of the formation of the first stars, might lead to a breakthrough in the whole Dark Matter business. During the epoch of 15<z<20 (z is the cosmological redshift), which corresponds to the range of about 180-280 million years after the big bang, radiation from the first stars began filling the universe. It is, therefore, expected to show strong absorption lines, due to photons interaction with hydrogen atoms (hydrogen was and is the most abundant baryonic element in the universe and is clumped in gigantic gas clouds). The strongest line absorption is expected to be in the 21cm wavelength, corresponding to the energy of the spin transition of the hydrogen's electron (from not excited to excited). The expected temperature of the hydrogen gas at this excited state, relative to the CMB temperature, with (in millikelvin) [14]:

$$T_{21} = 26.8x_{H1}\left(\frac{\rho_g}{\overline{\rho_g}}\right)\left(\frac{\Omega_b h}{0.0327}\right)\left(\frac{\Omega_\mathrm{m}}{0.307}\right)^{-\frac{1}{2}}\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(\frac{T_s-T_{CMB}}{T_s}\right) \qquad (2)$$

Where "x_{H1} is the mass fraction of neutral (that is, not ionized) hydrogen; ρ_g is the gas density and $\overline{\rho_g}$ is its cosmic mean value; Ω_m and Ω_b are the cosmic mean densities of matter and baryons, respectively, in units of the critical density (the mean density of a flat universe); h is the Hubble parameter in units of 100 $km \cdot s^{-1} Mpc^{-1}$; z is the redshift that corresponds to an observed wavelength of 21(1 + z) cm and an observed frequency of 1,420/(1+z) MHz; T_{CMB}= 2.725(1 + z) is the CMB temperature at z; and T_s is the spin temperature of hydrogen at z." (quoted from ref [14]).

The lowest expected gas relative-temperature to the CMB, at $z \approx 17.2$ and obtained by (2), which does not regard DM-baryons interactions, is $T_{21} = -0.209k$. Assuming black body radiation and Rayleigh jeans law, the brightness temperature is calculated by (in Kelvin) [15]:

$$T = \frac{\lambda^2 S}{2k_B\Omega} \qquad (3)$$

Where $\lambda = \frac{c}{v}$, Ω is the beam solid angle and S is the flux density of λ.

The absorptions lines were just recently observed, but, for the lyman-α (which corresponds to 21cm wavelength) the absorption was up to twice as deep as expected. at the same redshift (z), the flux measured lead to relative brightness temperature, obtained with the help of (3), of $T_{21} = -0.5^{+0.2}_{-0.5}\ k$ [14].

The main postulation for this anomaly of excessive cooling of the gas relative to the temperature of the CMB is that either the background radiation was hotter than expected or the hydrogen in the universe was colder. While there exists, for now, no explanation for a higher background radiation temperature [13], the simplest explanation for colder hydrogen is that it was scattered off by DM particles (which were much colder), depositing much of its energy to the colder DM [14]. The observed radiation's data and the DM-scattered/non-DM-scattered hydrogen fits are shown in figure 8:

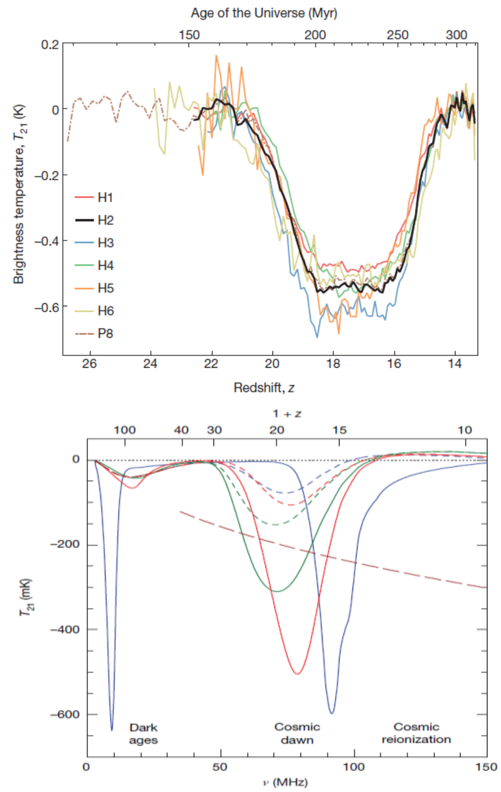

Figure 8. top [13]: Several analyses for the collected data (H1-H6, P8) of the brightness temperature of the 21cm radiation for different redshifts, where H2 gives the best fitting parameters. Bottom [13]: curves for hydrogen gas temperature as deduced from 21cm radiation at different red-shifts (and different frequencies) and different DM mass (m_χ) and cross-section (σ_1); dashed lines for models without DM-baryons scattering and the corresponding color solid lines for models with DM-baryons scattering. The red line is the best to fit the observed signal (bottom), with $m_\chi = 0.3_{GeV}$ and $\sigma_1 = 8 \cdot 10^{-20}$, where the fiducial velocity is $1_{km^{-1}}$, which is a typical velocity for matter in the cosmic dawn.

It is worth noting that the range of DM particles masses mentioned in [14] (which is below 4.3GeV at any fit) is lower, by about two orders of magnitude, than the theoretical WIMPs, which were discussed in the previous sections. The low mass (and cross sections) constrains derived from the fitting models can explain the null results in the direct-detection experiments.

Conclusions – The two leading theories for explaining the DM anomaly, SUSY and UED, were created for particle-physics needs. However, their associated particles, the WIMPs, happen to have the needed theoretical abundance in the universe to explain the Dark Matter anomaly. These theories predict the WIMPs have properties which enable them to be detected (directly or indirectly) in experiments that are sensitive enough to their parameter space. So far, however, those experiments have all produced null results, which cast a great doubt for the validity of these theories. If future direct and indirect detection experiments with higher sensitivities keep end up with null results, then most likely will these two theories be ruled out as possible explanations for DM, or completely discarded. Then there will be needed other, more exotic theories to explain the DM anomaly.

---

[1] F. Zwicky, Helvetica Physica Acta 6, 110 (1933).
[2] Dark Matter Self-interactions and Small Scale Structure; Sean Tulin & Hai-Bo Yu (2017).
[3] Dark Matter Candidates from Particle Physics and Methods of Detection; Jonathan L. Feng (2010).
[4] The dark matter of gravitational lensing; Richard Massey, Thomas Kitching, Johan Richard (2010).
[5] DARK MATTER AND DARK ENERGY; MARC KAMIONKOWSKI (2007).
[6] K. G. Begeman, A. H. Broeils and R. H. Sanders, Mon. Not. Roy. Astron. Soc. 249 (1991) 523.
[7] Dark Matter Astrophysics; Guido D'Amico, Marc Kamionkowski and Kris Sigurdson (2009).
[8] Current status of direct dark matter detection experiments; Jianglai Liu, Xun Chen, and Xiangdong Ji (2017).
[9] First Dark Matter Search Results from the XENON1T Experiment (2017).
[10] Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande (2015).
[11] Constraints on Dark Matter Annihilation/Decay from the Isotropic Gamma-Ray Background; Wei Liu, Xiao-Jun Bi, Su-Jie Lin, Peng-Fei Yin (2016).
[12] Explanations of the DAMPE high energy electron/positron spectrum in the dark matter annihilation and pulsar scenarios; Bing-Bing Wang, Xiao-Jun Bi, Su-Jie Lin, and Peng-fei Yin (2017).
[13] An absorption profile centred at 78 megahertz in the sky-averaged spectrum; Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh.
[14] Possible interaction between baryons and dark-matter particles revealed by the first stars; Rennan Barkana.
[15] https://science.nrao.edu/facilities/vla/proposing/TBconv