

Dark Matter: Candidates and Searches

Zheng Cao^{1,*}

¹Beijing National Day School, No.66 Yuquan Road, Beijing 100039, China

*Corresponding author e-mail: willzheng_cao@protonmail.com

Abstract. Dark matter is an unknown field in astrophysics and cosmology. Various experiments to detect dark matter have already been done around the world since the hypothesis of dark matter was first proposed. In this article, several prevalent dark matter candidate theories have been reviewed, which will make contributions to the understanding of these theories, especially for beginners. The detections and methods, such as Weakly Interacting Massive Particles (WIMPs), have also been included.

1. Introduction

The constitution of the universe is very magical, and we can vividly simulate it using a chocolate cupcake, as shown in Figure 1. The matter in the universe comprises about 85% of dark matter, and the dark matter occupies about 25% of the universe's total energy density[1]. Scientists first come to realize the existence of dark matter from calculations indicating that many galaxies would fly apart[2], or that they would not form or move if they didn't contain a huge amount of invisible matter. There is also other evidence including discoveries in gravitational lensing and the cosmic microwave background[3], as well as observations of the universe's current structure, the formation and evolution of galaxies, mass location during galactic collisions, and the motion of galaxies in galaxy clusters. Planck satellite data, employed by Precision cosmology studies, suggest that the universe contains 4.9% of baryonic matter, 26.8% of cold dark matter (CDM), and 68.3% of a kind of mysterious energy known as dark energy [4]. Therefore, dark matter occupies about 85% of total mass, but dark energy and dark matter account for 95% of total mass-energy content[5].



Figure 1. Contents of the Universe, as illustrated by a chocolate cupcake [6].

Since we can't observe dark matter in a direct way, if it really exists, it will not interact with baryonic matter or cosmic radiation, unless through gravitational interaction. Baryonic Dark Matter exists the darkest matter yet is considered to be non-baryonic in essence; it may contain some as-yet-undiscovered subatomic particles. There are many hypothetical particle candidates, such as Massive Compact Halo Object (MACHOs), weakly-interacting massive particles (WIMPs), axions, and neutrinos. As shown in Figure 2, scientists are developing many ways to detect the Dark matter and search the probable particles.

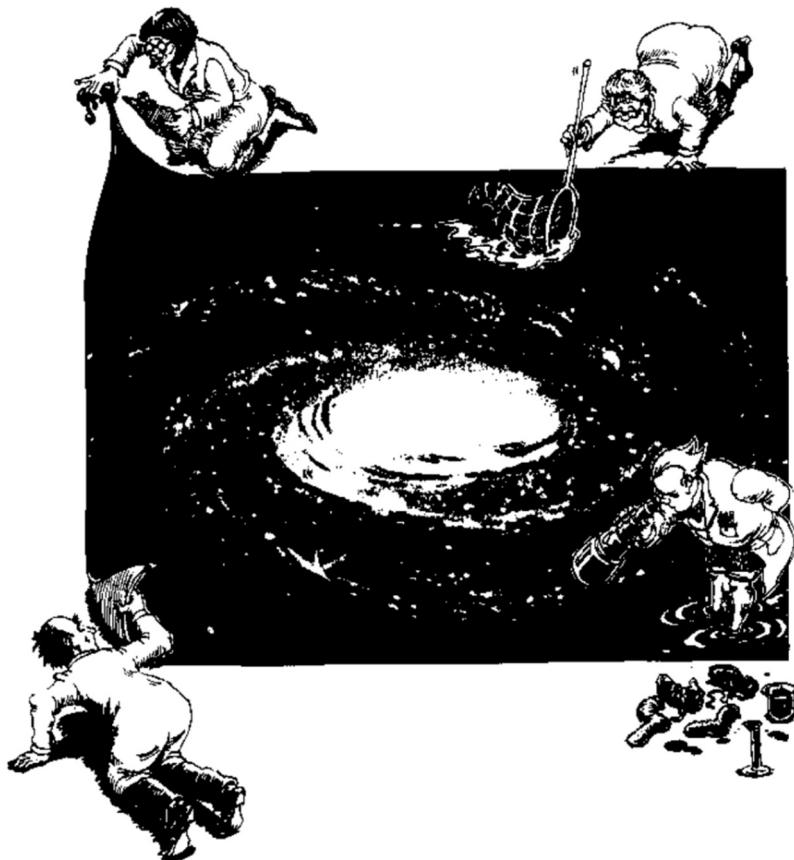


Figure 2. The search for dark matter in the Milky Way [7].

2. Dark Matter Candidates

2.1 Baryonic Dark Matter (MACHOs)

The Massive Compact Halo Object (Macho) class of candidates is the main baryonic candidates. They contain brown dwarf stars, Jupiters, and $100M_{\odot}$ Black holes. Brown dwarfs are spheres of H and He with masses below $0.08M_{\odot}$, so it is impossible for them to begin hydrogen nuclear fusion. Jupiters are similar to them but with masses near $0.001M_{\odot}$. Black holes with masses near $100M_{\odot}$ are the remnants of the early generation of stars, which were massive enough so that not many heavy elements were dispersed when they underwent the supernova explosions [8].

The MACHO and EROS experiments have already detected microlensing of stars in the Large Magellanic Cloud (LMC). Though the microlensing's number is small, it is several times more than would be expected from microlensing by the known stars. The MACHO data suggests that objects with a mass of $0.5M_{\odot}$ are probably responsible $-0.2M_{\odot}$ for this microlensing, with the total density equal to $\sim 20-50$ percent of the mass of Milky Way halo around ~ 20 kpc radius [9]. Both the EROS and the MACHO groups have not seen short duration microlensing events, suggesting strong upper limits for the possible contribution to the halo of the compact objects weighing less than $0.05M_{\odot}$. Though the

MACHO masses are expected for white dwarfs, strong observational limits and theoretical arguments that oppose white dwarfs being a significant fraction of the dark halo of our galaxy exist. Therefore it maintains unknown what objects are responsible for the observed microlensing toward LMC. Nonetheless, many microlensing events observed toward the galactic bulge are possibly explained by the existence of a bar aligned almost toward our position [10]. Probably the relatively small number of microlensing events toward the LMC is lensing by a tidal tail of stars that stretch toward us from the main body LMC. And even some data on the colors and luminosities of stars toward the LMC demonstrate that this is actually true [10].

2.2 Non-Baryonic Dark Matter

2.2.1 Weakly Interacting Massive Particles (WIMPs)

A critical distinction between the dark matter candidates is whether the particles were created thermally in the Early Universe or created non-thermally in a phase transition. Both of these two relics have a different relationship between their relic abundance Ω and their properties, including couplings and mass, so the difference is particularly crucial for dark matter detection. For instance, the WIMPs can be considered as the particles that are created thermally, but dark matter axions come mostly from non-thermal processes.

In thermal creation, when the universe was a very high temperature, thermal equilibrium reached, and the number density of WIMPs (or any other kind of particles) was about equal to the number density of photons. When the universe cooled, the number of WIMPs and photons decreased together as long as the temperature maintained higher than the WIMP mass. When the temperature eventually dropped under the WIMP mass, the creation of WIMPs would require being on the tail of the thermal distribution. Thus the number density of WIMPs would drop $\exp(-mWIMP/T)$ exponentially in equilibrium. If equilibrium was maintained until today, very few WIMPs left. Still, at some points, the WIMP density dropped low enough that the probability of WIMPs finding each other to annihilate became very small. (presume that an individual WIMP is relatively stable if it is to become the dark matter.) The WIMP number density froze out, and a significant number of WIMPs left today.

Solved by the new electroweak scale physics such as supersymmetry, many theoretical problems occur with the Standard Model of particle physics. So these theoretical problems can be evidence that the dark matter indeed consists of WIMPs. In other words, any stable particle that annihilates with electroweak scale cross-section is bound to contribute to the dark matter of the universe. The fact that theories such as supersymmetry, created for entirely different reasons, particularly predicts just this particle.

Also, Thermally created dark matter has weak scale interactions meaning that it may be within reach of accelerators, for instance, the LEP at CERN and the CDF at Fermilab. After all, these accelerators were established typically to detect the electroweak scale; as a result, many accelerators that search for exotic particles are also probing for the dark matter of the universe. In addition, because of the weak scale interactions, WIMP-nuclear interaction rates are within reach of a huge amount of both direct and indirect detection methods. Caldwell will go over these [11].

2.2.2 Axions

The axion would probably be the best example of a non-thermal particle dark matter candidate. In the quantum chromodynamics (QCD) Lagrangian, a term that allows important but as-yet unobserved CP violation in QCD and that contributes to the electric dipole moment of the neutron exists.

$$L_{QCD} = \sum_q \{ \bar{\Psi}_{qi} i\gamma^\mu [\delta_{ij} \partial_\mu + ig(G_\mu^\alpha t_\alpha)_{ij}] \Psi_{qj} - m_q \bar{\Psi}_{qi} \Psi_{qi} \} - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu} \quad (1)$$

$$L_{QED} = \bar{\varphi}_e i\gamma^\mu [\partial_\mu + ieA_\mu] \Psi_{qj} - m_e \bar{\Psi}_e \Psi_e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad (2)$$

where $G_{\alpha}^{\mu\nu} = \partial^{\mu}G_{\alpha}^{\nu} - \partial^{\nu}G_{\alpha}^{\mu} - gf^{\alpha\beta\gamma}G_{\beta}^{\mu}G_{\gamma}^{\nu}$ for color fields tensor, G_{α}^{μ} is the potential of the gluon fields, $f^{\alpha\beta\gamma}$ is the structure constants of the SU(3) color group, Ψ_i is the Dirac spinor of the quark field (i represents color) and $g = \sqrt{4\pi\alpha_s}(\hbar = c = 1)$ for the color charge (strong coupling constant); $t_{\alpha} 3 \times 3$ Gell-Mann matrices; generators of the SU(3) color group.

Upper limits on the neutron electric dipole moment indicate that the coefficient for the term should be 10^{-9} . Now, in principle, there's nothing wrong with a parameter having a small value—on the neutrino side, active neutrinos are at least six orders of magnitude lower in mass than the next-lightest Standard Model particle, the electron. However, normally, when a parameter which could potentially be big is nearly zero, This suggests that some protective symmetry is at work. The PecceiQuinn solution making this coefficient small, is to turn this coefficient into a dynamical field and plus a global symmetry that drives the offending term in the QCD Lagrangian to be precisely zero when broken. The field's fluctuations about the new vacuum of the broken theory are axions and the pseudo-Nambu-Goldstone bosons of the broken symmetry. Axions are, to some extent, less natural than WIMPs since they are tricky to get their co-moving number density to conform to the observed dark-matter density. A number of axion production mechanisms (they must be present) does exist; Nevertheless, the better way to produce dark matter axions is through non-thermal coherent oscillations of the axion field near the QCD phase transition. In this case, axions are light ($\sim 10 \mu$ eV) and born with zero momentum.

2.2.3 Neutrinos

The "standard" light ($m < \text{MeV}$) neutrinos are archetypical hot relics. Their number density, for each flavor $\nu_e, \nu_{\mu}, \nu_{\tau}$ is $n_{\nu} \sim 100 \text{ cm}^{-3}$ and, if given with a non-zero mass, they could offer by themselves the whole critical density. Factually, the Gerstein-Zeldovich bound $\sum m_{\nu} \approx \Omega_{\nu} h^2 92 \text{ eV}$ (where the sum extends over all species of light neutrinos with full weak interaction) can lead to the right relic density for various neutrino masses based on the fraction of hot dark matter involved in the model. In the old, classical hot DM model, neutrinos (one or more species) of masses $20 \sim 30 \text{ eV}$ should constitute the whole DM, but they cannot form galaxies (the so-called up-down scenario of galaxy formation where larger structures form earlier) being relativistic particles at freeze-out. Cold dark matter is still required even though cosmic strings would help. In the mixed CHDM model, the hot DM is $\Omega_{\nu} = 0.2$. So the preferred total mass of the dark matter neutrino should be $\sim 5 \text{ eV}$ (for $h = 0.5$) shared among the variety of neutrino species, based on the mass pattern used to solve another neutrino puzzle (for instance neutrino oscillations). No known method proposed so far to find the hot DM relic neutrinos directly, and thus terrestrial sources are used to explore this possibility. The discovery of a ν_{τ} mass in the few eV range would prefer this kind of DM, and thus several oscillation experiments are underway to explore that range [12].

3. Dark Matter Detection: General Features of the Detection and the Discovery of Chinese Scientific community

3.1 Detection for baryonic matter

There are some general astroparticle search strategies for both baryonic matter and non-baryonic matter, as shown in Figure 3. The search for galactic baryonic matter in the form of MACHOs has been launched following the demonstration that they may be a large part of the galactic DM and could be found using the microlensing effect. The MACHO, EROS, and OGLE collaborations have performed a program of observation by monitoring the luminosity of millions of stars in the Large and Small Magellanic Clouds for several years. EROS concluded that MACHOs couldn't contribute more than 8% to the mass of the galactic halo, but MACHO observed a signal at 0.4 solar mass and put an upper limit of 40%. Overall, this strengthens the need for non-baryonic DM, also supported by the arguments developed above [13].

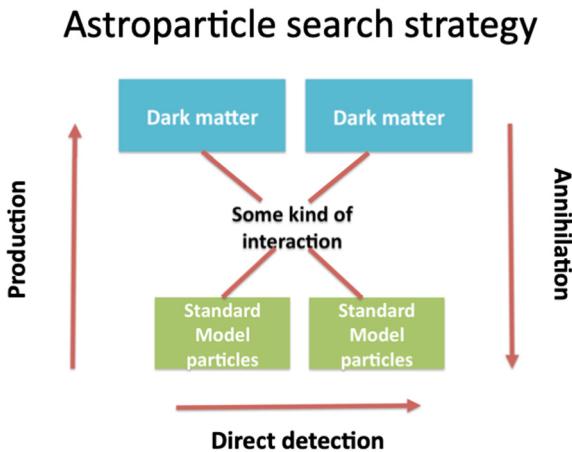


Figure 3. Sketch of the different types of astroparticle search strategies for dark-matter detection [14].

3.2 Detection for WIMPs

WIMPs will not be observed in a direct way if they are created at colliders because they are neutral and weakly interacting, and they are like huge neutrinos in terms of detection prospects. Nonetheless, we are able to realize WIMPs' existence. The quarks and gluons in the protons colliding together at the LHC usually do not annihilate directly to WIMPs, because WIMPs belong to all theories beyond the Standard Model. Quarks and gluons may annihilate a bunch of other extra particles (for example, colored particles like squarks and gluinos in the MSSM). These particles may finally transform to WIMPs inside the detector, the signature of which is missing energy when one tries to rebuild the chain of events. It takes a significant amount of efforts to determine which types of events (characterized by the number and types of jets, leptons, geometry, timing) may lead to the best limits for different WIMP models. No experimental evidence of physics beyond the Standard Model has evolved yet. Even if evidence for a WIMP is finally found, we cannot know whether that particle is stable on a time scale greater than a nanosecond or not.

Galactic WIMPs are possible to ram into nuclei in the laboratory, depositing tens to hundreds of keV of kinetic energy onto a single nucleus. This is of order 10^7 times smaller than the kinetic energy of fruit flies, and the event rate is many orders of magnitude smaller than the ambient flux of cosmic rays, which poses special challenges for detection. However, dozens of experiments planned or underway carried out to look for WIMPs in this method. The DAMA/LIBRA, CRESST, and CoGeNT experiments claim (sometimes in mild terms) WIMP detections. It would be good to say that these claims are not widely accepted, especially given the null detections of other experiments. Almost every experimentalist I have met has his or her own theory of the origin of the DAMA/LIBRA signal. The DM-Ice collaboration is performing a DAMA-like experiment in Antarctica, ingeniously using the IceCube Neutrino Observatory as a cosmic-ray veto. The best restrictions from experiments that do not find significant events above background are XENON100, CDMS-II, and COUPP, and are cutting through swaths of WIMP model space. Currently, experiments are making rapid gains in sensitivity because it is possible (through great effort!) to do nearly zero-background searches, but soon (in the next decade), experiments will hit the wall of irreducible astrophysical neutrino backgrounds.

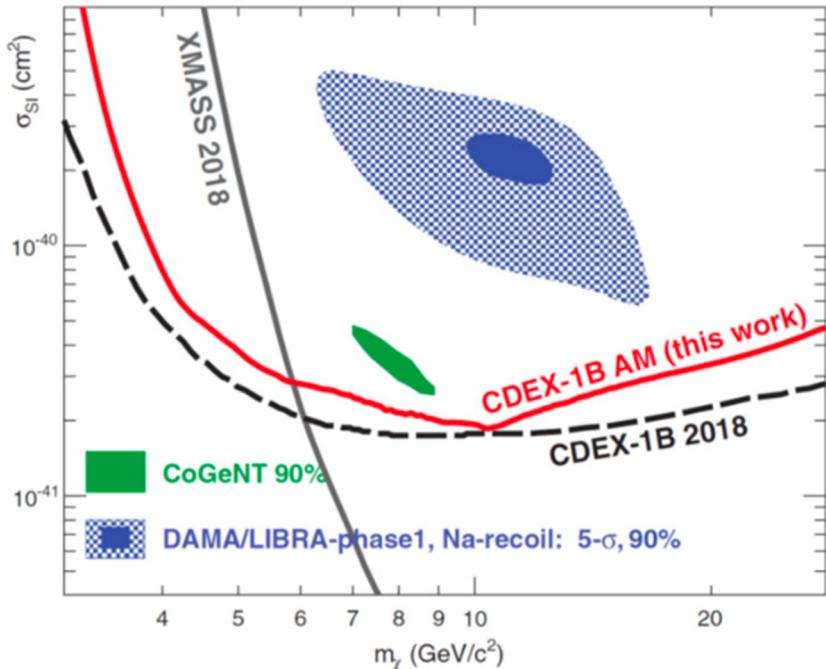


Figure 4. Limits at 90% C.L. from CDEX-1B AM-analysis (red) on spin-independent WIMP-nucleon cross-section [15].

3.3 CDEX experiment at CJPL

A wide range of astronomical and cosmological pieces of evidence show the existence of dark matter, which contributes about one-quarter of the energy density of the universe. Weakly interacting massive particles (WIMPs) could interact with the nuclei of normal matter through elastic scattering. This is because that it is the most desirable candidates of the dark matter, the recoil energy of which can be detected in extremely low background experiments at deep underground laboratories.

The location of China Jinping Underground Laboratory (CJPL) is in Sichuan Province, southwest of China. This laboratory is an ideal site for dark matter detections with a rock overburden of 2400 meters. Because of the low energy threshold and good energy resolution, p-type point contact (PPC) germanium detectors, sensitive to sub-keV recoil energy, were employed to searchlight WIMPs with masses 1 GeV/c^2 to 10 GeV/c^2 . The purpose of the China Dark Matter Experiment (CDEX) is to detect light WIMPs using PPC germanium detectors, which started to run at CJPL in 2010. As shown in Figure 4, We reported results from CDEX-1B with a single-element 994-gram PPC germanium detector and CDEX-10 consisting of three detector strings. [16].

3.4 PandaX experiment

As a staged experimental program, the PandaX (Particle AND Astrophysical Xenon observatory) is aiming at using the xenon as the target to conduct research on WIMP dark matter, and to probe into the nature of neutrinos. The first stage (PandaX-I, 120 kg) and the second stage (PandaX-II, 580 kg) experiments were finished in 2014 and 2019, respectively in CJPL-I. PandaX-I and PandaX-II used the so-called two-phase xenon time projection chamber (TPC) technology to detect the energy and position of the WIMP-nucleus scattering. The operation principle is displayed in Figure 5. A cryostat is full of liquid xenon, with two closely-packed arrays of the photomultipliers (PMTs), which are at the top (gas) and the bottom (liquid) parts of the chamber. The prompt scintillation photons that are collected by the PMTs are referred to as the S1 signal. In order to gather the ionization electrons, a drift electric field is applied between a light-transmitting cathode and gate electrodes located at the bottom and top of the liquid xenon, respectively. Then, a much stronger electrical field is built between the gate (in liquid)

and anode (in gas). This extraction field extracts the ionized electrons into the gaseous xenon, where region secondary electroluminescence photons are subsequently produced near the top PMT array. This delayed flash of photons is considered as the S2 signal. Three dimensional imaging of the interaction vertex can be gained with the pattern of S2 collected by the top PMT array (horizontal position), as well as the time separation between the S1 and S2 (vertical position). Peripheral background, which comes from the outside of the detector, can be largely suppressed by fiducialization. Events with multiple S2s from a multi scattering of the background gammas or neutrons are rejected as well. In terms of the remaining single-scatter events, owing to the differences between the ionization capabilities of the recoiling electron (stronger) and nucleus (weaker), the energy fraction that is carried by the ionized electrons is different between them. Therefore, the ratio S2/S1 is another powerful discriminant against the ER background. The superior potential of the liquid xenon TPC had been demonstrated by several experiments, including XENON10, XENON100, ZEPLIN, and LUX [17]. The results of different experiments are shown in Figure 6.

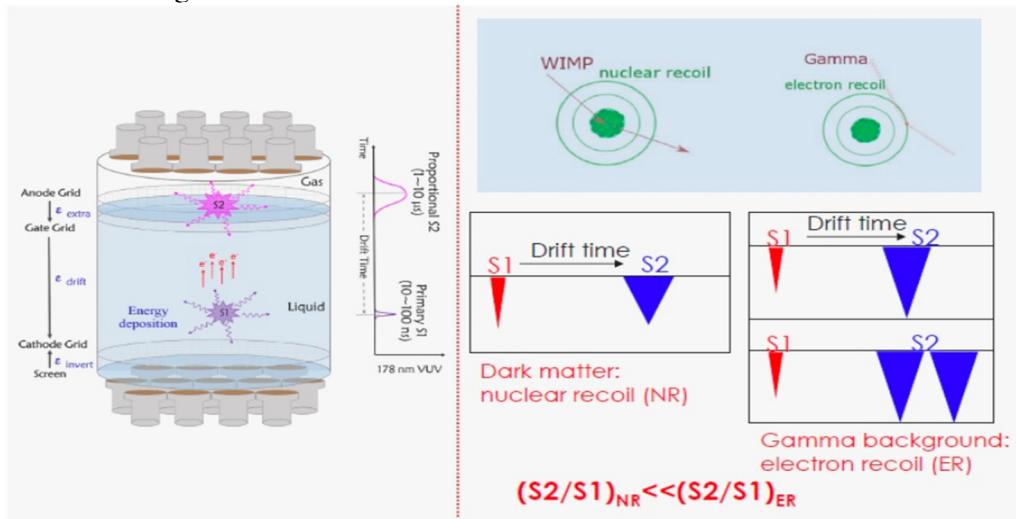


Figure 5. The schematics of a two-phase xenon time projection chamber [18].

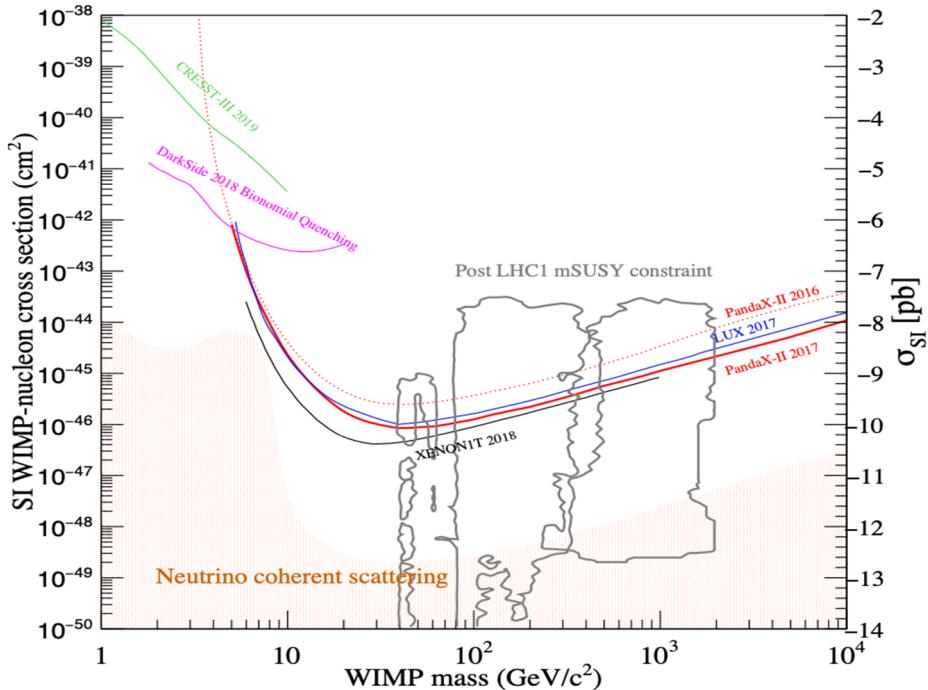


Figure 6. The current 90% upper limits on WIMP-nucleon SI cross-section [19].

4. Summary and Future Plans

After nearly a century, since it was initially proposed, the nature of dark matter remains mysterious. Until now, scientists have already proposed several dark matter candidates, as mentioned in the initial part of this paper. Many experiments have been carried out. People's curiosity towards the properties of Dark Matter evokes more and more further researches and experiments. Also, the Chinese community has increasing participation on the topic and has some high-value discoveries. As technology is advancing, the nature of Dark Matter will be clearer in the future.

References

- [1] Adam Riess, *Dark matter*, Encyclopedia Britannica Astronomy.
- [2] NASA, What is Dark Matter, <https://www.nasa.gov/audience/forstudents/9-12/features/what-is-dark-matter.html>.
- [3] Elizabeth Howell, *Cosmic microwave background: Remnant of the Big Bang*. (2018)
- [4] Plank|NASA website https://www.nasa.gov/mission_pages/planck
- [5] Wikipedia, *Dark matter*, https://en.wikipedia.org/wiki/Dark_matter.
- [6] Annika H.G.Peter, *Dark Matter*, Department of Physics and Astronomy at UCI. (2012)
- [7] G.G.Raffelt, *Dark Matter: Motivation, Candidates and Searches*, Max-Planck-Institute for physics. (1997)
- [8] Kim Griest, *The Nature of the Dark Matter*, Physics Department at University of California, San Diego. (1995)
- [9] G.Gyuk, N.Dalal, &K.Griest, Self-lensing Models of the LMC, Physics Department, University of California, San Diego. (1999)
- [10] G.G. Raffelt, *Dark matter: Motivation, Candidates and Searches*, Max-Planck-Institute for Physics. (1997)
- [11] Joel R. Primack, *Dark Matter and Structure Formation*, University of California, Santa Cruz.(1997)
- [12] Angel Morales, Particle Dark Matter and its Detection, Laboratory of Nuclear and High Energy Physics Faculty of Science at University of Zaragona, Spain. (1998)
- [13] Manuel Drees, Gilles Gerbier, *Mini-Review of Dark Matter: 2012*, Physikalisches Institute and Bethe Center for Theoretical Physics, University at Bonn, Nussallee 12, 53115 Bonn, Germany, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette Cedex, France. (2012)
- [14] Annika H.G. Peter, *Dark Matter*, Department of Physics and Astronomy at University of California, Irvine. (2012)
- [15] Hao Ma, Ze She, Zhongzhi Liu, Litao Yang, Qian Yue, Zhi Zeng, Tao Xue, *Results of direct dark matter detection with CDEX experiment at CJPL*, Key Laboratory of Particle and Radiation Imaging (Ministry of Education) and Department of Engineering Physics, Tsinghua University.
- [16] Lizhao, Jianglai Liu, *Experimental Search for Dark Matter in China*, Shanghai Jiao Tong University, Tsung-Dao Lee Institute. (2020)
- [17] Lizhao, Jianglai Liu, *Experimental Search for Dark Matter in China*, Shanghai Jiao Tong University, Tsung-Dao Lee Institute. (2020)
- [18] Lizhao, Jianglai Liu, *Experimental Search for Dark Matter in China*, Shanghai Jiao Tong University, Tsung-Dao Lee Institute. (2020)
- [19] Hao Ma, Ze She, Zhongzhi Liu, Litao Yang, Qian Yue, Zhi Zeng, Tao Xue, *Results of direct dark matter detection with CDEX experiment at CJPL*, Key Laboratory of Particle and Radiation Imaging (Ministry of Education) and Department of Engineering Physics, Tsinghua University.