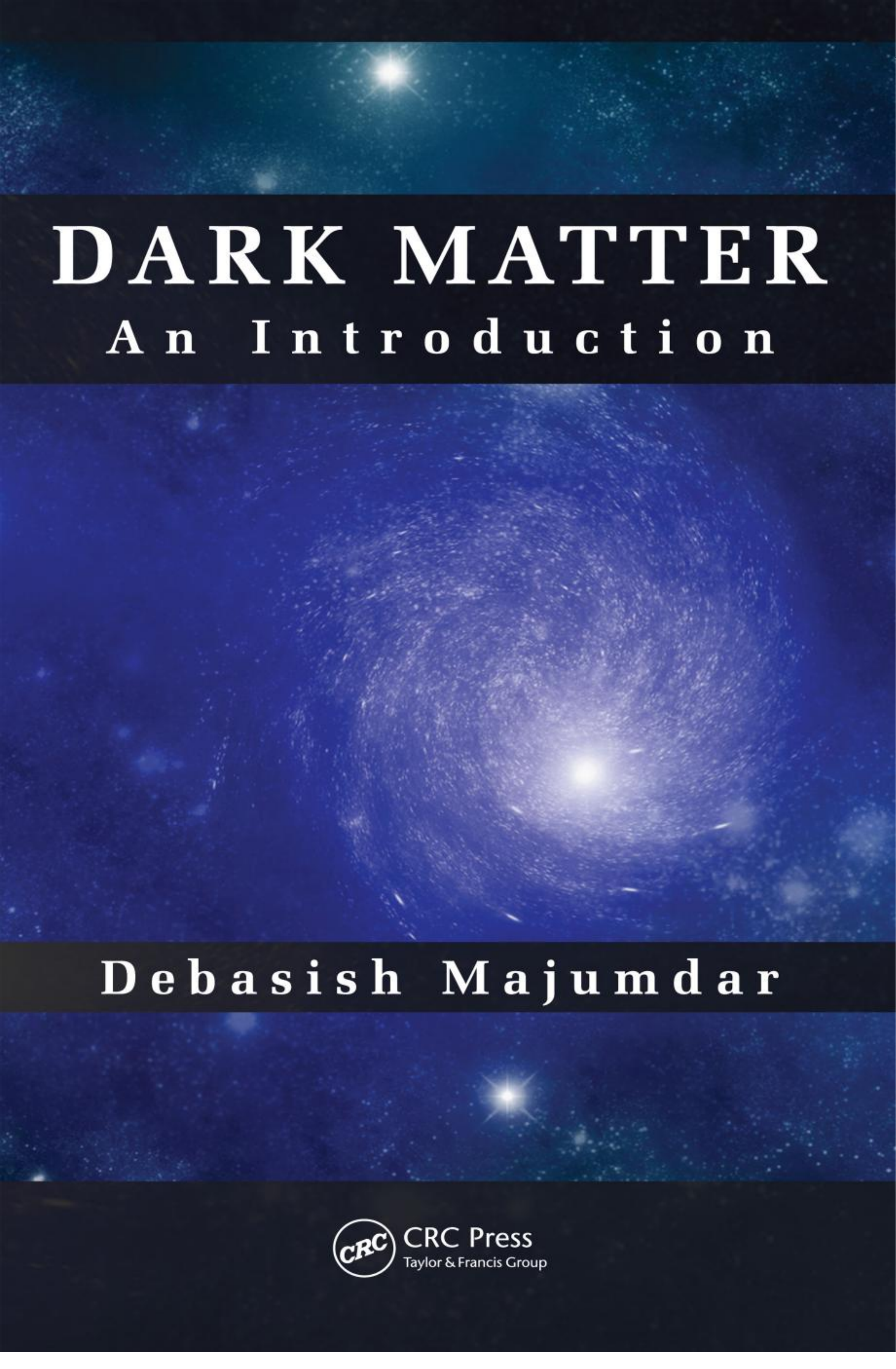
DARK MATTER
An Introduction
Debasish Majumdar
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## An Introduction

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# Contents

# Preface

A subject like dark matter encompasses as many as three main areas of fundamental physics, namely cosmology, particle physics, and astrophysics. Therefore a discussion on dark matter should encompass these three subjects with equal emphasis. This view is kept in mind throughout this book.

This book is intended to give an overview to a young researcher who will be pursuing a research career in dark matter in particular or astroparticle physics in general. A post-graduate student opting for a course in astroparticle physics, I hope, will also benefit from this book. It is my expectation that a general inquisitive reader will also gain an overview of the subject by going through the text of the book even though she/he does not go into the mathematical descriptions given in the book.

The discussion on the particle nature of dark matter requires a basic knowledge of particle physics. A chapter on particle physics, introductory in nature, is included in the book. The symmetries and the conservation laws that are fundamental to the theory of fundamental particles are discussed at a beginner's level. The theory of relativity plays an essential role in particle theory and cosmology as well. A brief discussion on relativity is therefore kept at the beginning. The basics of cosmology are discussed by explicitly deducing some of the equations related to cosmological parameters, cosmological measurements, etc. The existence of dark matter is primarily known through its gravitational effects. The inference came through several astronomical observations and through astrophysical calculations and insights. The astrophysical behavior of galaxies and galaxy clusters and the possible structure of dark matter distribution are discussed without going into very technical detail. Care has also been taken to include discussions that may be of interest to a more advanced reader interested in the astrophysical aspects of dark matter. Particle candidates for cold dark matter beyond the theory of the Standard Model are given with minimal details. Since a detailed discussion of theories like supersymmetry or theories of extra dimensions are not within the scope of this book, a very brief inroduction to these theories is included. Also given are a few examples of simple extensions of the Standard Model that may provide viable dark matter candidates. Dark matter is a relic particle and the process of its being "frozen out" after it is decoupled is a subject matter in which cosmology plays important roles. These include the evolution of the Universe, the calculation of the "freeze-out" temperature of a dark matter species and the subsequent calculation of its relic density. Chapters are devoted to these topics and attempts have been made to convey the matter in both simple text and mathematical formulations so that readers of different backgrounds get the flavor of the subject. With passing time, dark matter physics becomes more experimental than theoretical in nature. A number of experiments are either operational or will soon be operational and will look for direct evidence of dark matter. I have made sincere attempts to furnish a detailed account of various experimental techniques and the description of actual experiments in a manner that I hope will be understandable even for an informal reader.

I would sincerely consider my endeavor to be worthwhile if the readers find this book useful and if it invokes more interest in the subject of dark matter. Added to this, I would expect that a general reader will also find this book interesting reading.

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Kolkata

# Acknowledgments

At the very outset, it gives me immense pleasure to thank my students, whose continuous endeavors and support have made this work possible. I not only have gained a lot of insight while discussing various aspects of the subjects with them, but on several occasions they have suggested useful modifications of the contents. Their cooperation was not only limited to academic discussions. They proved to be a great support for me in the process of compiling proper LaTeX commands and even assisting me in generating some of the figures used in the book. I very humbly acknowledge the sincere efforts that my four students, namely, Debabrata Adak, Anirban Biswas, Amit Dutta Banik, and Kamakshya Prasad Modak extended to me.

I take this opportunity to thank my collaborators from whom I have learned a lot. They include Abhijit Bandyopadhyay, Arunansu Sil, and Subhendu Rakshit. I humbly acknowledge the favor of Palash Baran Pal that he extended to me overwhelmingly.

I am fortunate to have been associated with some of the very finest teachers and researchers during my research career. Their composure, their devotion and deep understanding, and their guidance have enriched me immensely. They not only imparted academic knowledge but motivated me at every up and down in my career. I tender my solemn acknowledgment of their support for my cause.

I wish to acknowledge my colleagues and close friends who not only thoroughly encouraged me in writing this book, but also ensured me a very relaxed state of mind with their exuberant company.

Last, but not the least, I gratefully acknowledge the relentless support of Radhanath Munshi. I also wish to profusely thank my wife and my little daughter who have tolerated me and my indifference with immense patience and sympathy during this work.

I feel privileged to humbly tender my deep respect for the blooming blessings showered upon me.

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# 1

# *Introduction*

From time immemorial the enigmatic Universe fascinates the human imagination and intellect. Humans wondered at the motion of the heavenly bodies in the vault of the sky and found resemblence between constellations of stars and earthly living beings. In the absence of any sophisticated instruments, the thinkers of those distant times used their diligent observations of the displacements of the heavenly bodies in the sky, their ascents and descents, to make various astronomical calulations. The advent of the telescope by Galileo Galilei heralded a new dawn in astronomical observations and calculations. Mathematician Johannes Kepler put forward the laws of planetary motion. The revolutionary discovery and mathematical formulation of gravitation – one of the fundamental forces of nature – by Sir Issac Newton paved the way for a more formidable understanding of the motion of the heavenly bodies. Any digression of the observed motion of the known astrophysical objects from the theory appears to indicate the presence of unknown objects.

This is indeed initially the study of galactic dynamics, the dynamics of galaxy clusters and the consequent application of cosmic virial theorem that led to the prediction of not only the existence of dark matter, but also its very substantial amount that appeared to far outweigh the visible Universe. The first indication to this effect in the past century came from the famous Dutch astronomer Jan Hendrik Oort in 1932 who, while measuring the velocities of the stars along the direction vertical to the plane of the galactic disk of our Milky Way galaxy, noticed that the vertical velocities of the stars are too high to have escaped the galactic influence. The Milky Way galaxy is a spiral galaxy having a disk-like structure with a central bulge of more concentrated matter. The extent of the disk is around 10 kpc (1 kpc $= 3.12 \times 10^{16}$ Km) from the galactic center and the disk itself has a thickness of $\sim 4$ kpc. The fact that the stars are confined within the galaxy, even though their vertical velocities are measured to be high enough, necessitates the presence of unseen mass in the galaxy. Oort reported his observations in the *Bulletin of the Astronomical Institutes of the Netherlands* in 1932 where he reported "*Integrating over a column perpendicular to the galactic plane I find that an average unit of photographic light corresponds to a mass of 1.8 (if both are expressed in the sun as unit), ...*"

Galaxies as noted by Herschell way back in 1780, are not distributed randomly in the Universe but rather they exist in separate groups or clusters. Galaxies in each such cluster form a gravitationally bound group. The famous astronomer Zwicky made his investigations in the galaxy cluster at Coma constellation 90 Megaparsecs away and also at the cluster in Virgo constellation and calculated its gravitational mass using the "virial theorem." He then used the mass-luminosity relation of the stars of the individual galaxies and estimated the mass of the luminous matter in each of the clusters. He came up with a huge discrepancy between these two masses and predicted the existence of dark invisible matter.

The galaxies of the clusters that are x-ray bright are contained within the x-ray emitting gas. These x-rays are produced when the gas that embeds the galaxies of the cluster is excited to a temperature (virial temperature $\sim$ keV) by the potential of the matter present inside the cluster. Observations of such x-ray bright clusters and the subsequent analysis of the observed data give a clear indication that only the galactic mass and the gas surrounding it is not sufficient to explain them – one would require the presence of unseen mass or dark matter in the cluster.

The study of the rotation curve of spiral galaxies shows more profound evidence of the overwhelming presence of dark matter in the galaxy. For the rotation curve analysis of a spiral galaxy, one measures the rotational velocity $v(r)$ of a star or gas in the galaxy as a function of their distance $r$ from the galactic center. These velocities will depend upon the mass enclosed by the sphere of radius $r$. Since for a spiral galaxy, one has a dense central region and the density of the visible mass is reduced as one goes away from the central region, one would expect a Keplerian decline of the rotation curve as one goes away from the dense central region of the galaxy. But instead, the observational measurements show not a Keplerian decline for $v(r)$ but rather a constant behavior with $r$. This is only possible if there is enormous unseen mass or rather a halo of unseen dark matter present at the galaxy.

The existence of huge unseen mass is also evident from the observed phenomenon of gravitational lensing. Gravitational lensing is a consequence of Einstein's theory of general relativity whereby the gravity of massive objects induces a curvature of the space-time in its vicinity. The more the influence of gravitation, the more distorted is the space-time geometry, suggesting the presence of larger mass. Light from a distant object (such as galaxy cluster) if it moves along such a curved space-time follows this local curvature of space-time giving rise to the lensing effect which is manifested as the appearence of multiple images of that object around the gravitational mass that causes the lensing. Astronomers found such a phenomenon (of multiple imaging) while observing certain galaxy clusters, when these kind of images appear surrounding such clusters. Needless to say, the light from the astronomical object that undergoes such lensing is behind the galaxy cluster that is being observed by the astronomers and the cluster is on the line of sight. The estimated mass that can produce a lensing effect is found to outweigh the mass of the target galaxy cluster around which such multiple images are observed. Thus there is certainly enormous mass in and around the galaxy cluster that remains invisible or "dark." Gravitational lensing is very useful for the search of dark matter even at the distant reaches of the Universe.

In discussions of evidence of dark matter, the observed phenomenon of bullet cluster needs mention. It was created in one of the most energetic events since the Big Bang when two gigantic galaxy clusters collided with each other some 4 billion light years away from the Earth at the constellation Carina. These two clusters collided with a speed of several million kilometers per hour. The x-ray images from these clusters reveal the shape of normal matter in the clusters after collision and the dark matter halos around them are known from the method of gravitational lensing. These observations suggest that due to collision, the smaller of the two clusters passes through the bigger cluster and the normal matter in the smaller cluster takes the shape of a bullet caused by the impact. But the dark matter halos of the two clusters pass through each other undistorted. It is also revealed that the normal matter in each of the clusters is dislocated away from their respective dark matter halos due to the impact of the collision. The event of "bullet cluster" is not only prolific evidence of the existence of dark matter but it also points to the fact that they have almost no interaction between them, as also with normal known matter.

Now the immediate question that arises is how much dark matter the Universe contains or in what ratio the dark matter exists with the known (luminous) visible matter such as the galaxies, clusters of galaxies, superclusters, innumerable stars, planets, and other objects. In other words, what fraction of the energy budget of the Universe is in fact dark matter. This is also important to understand: what role the dark matter plays in the formation of galaxies and galaxy clusters (structure formation), and how the dark matter influences the destiny of the Universe. The general wisdom supported by the experimental evidence suggests that the Universe (and hence the space-time) begins from a "singularity" with the so-called "Big Bang" and it is ever-expanding thereafter (with an initial rapidly accelerated inflationary phase). If the mass content of the Universe is very low, it would expand forever but on the other hand, if the mass content is very large, this would eventually collapse due to the gravitational pull of the matter. But the Universe appears to strike a very fine balance of maintaining a critical mass-energy density such that it will expand with a constant rate but the expansion is not infinite in time. *

The estimation of the energy budget of the Universe is made by measuring the anisotropies in the cosmic microwave background radiation (CMBR). The CMBR is the primordial radiation that last scatters from the Universe soup when the available free electrons were combined with the ions and atoms started appearing in the Universe. Thus no free electrons were available for the primordial photons by which the latter could undergo scattering, and therefore those photons started free-streaming and remained as background. The wavelengths of these photons suffer elongation with the expansion of the Universe (the scale

*Recent observations of Supernova Ia however suggest that the Universe is undergoing a late time (on cosmological time scale) accelerated expansion that is interpreted to have been caused by an unknown dark energy that works against the gravitational pull.

factor of the Universe also obviously changes with the expansion of the Universe) and in the present epoch, the wavelengths of these background photons are of microwave order (and hence the name CMBR). In principle the CMBR should be uniform from any direction in the sky but any non-uniformity (anisotropy) in CMBR, however small, is in fact indicative of the imprint of different concentration of mass of the last scattering surface from where the photons free-streamed. Thus anisotropies in CMBR contain enormous information regarding the mass-energy budget of the Universe. The analysis of observational data of the satellite-borne experiment, Wilkinson Microwave Anisotropy Probe or WMAP that look for such very tiny anisotropies in CMBR and more recently the data from another satellite-borne experiment, namely PLANCK, suggest that around 27% of the mass-energy content of the Universe is made of dark matter while a meager 4% accounts for the rest of the mass, which includes all the stars and galaxies, galaxy clusters, superclusters and all other known matters. This known matter is also called the “baryonic matter” and the above estimate follows from the requirement that the abundances of observed light elements such as H, D, $^3$He, $^4$He, and $^7$Li agree with the prediction of Big Bang nucleosynthesis that gives a theoretical understanding of the synthesis of light elements after the first minute of the Big Bang. The remaining 69% is a mysterious unknown energy called dark energy that is thought to be the cause of recently discovered late time accelerated expansion of the Universe. Therefore a huge 96% of the constituents of the Universe is totally unknown or “dark,” and the visible or “luminous” Universe accounts for only 4% of the total mass-energy content. The “luminous” matter signifies, in the microscopic domain, the fundamental particles or fundamental building blocks of matter such as quarks, leptons, the vector gauge bosons (the carrier of fundamental forces), and the scalar Higgs boson that follow the theory of the Standard Model of particle physics and in the macroscopic domain, the heavenly bodies like galaxies and galaxy clusters, superclusters and innumerable stars, novae and supernovae, pulsars and neutron stars, white dwarfs, planets, intersteller dust, etc.

In all probabilities, the total dark matter content or at least the major part of it is not made up of the known fundamental particles as otherwise they would have undergone the Standard Model interactions and therefore they could have been already probed by now. Therefore its constituents or at least a majority of its constituents do not supposedly follow the theory of the Standard Model of particle physics. For example, the invisibility of dark matter signifies that they do not emit any electromagnetic radiation and are incapable of undergoing any electromagnetic interaction, suggesting that they must be made up of neutral particles. Thus theories beyond Standard Model (BSM) may need to be invoked in order to predict a suitable particle candidate for dark matter. Such theories lead to the domain of new physics in the unchartered energy scale where new symmetries of nature may have to be envisaged.

The other important issue for understanding the dark matter in the Universe is its distribution in space, such as galaxies and galaxy clusters. The question is whether it is uniformly distributed throughout or its density varies in different regions in a galaxy. Rigorous astrophysical calculations indicate that the dark matter density is different in different regions. For example, the local (in the region of our solar system) dark matter density may be different from a more dense region such as the galactic center. Not only that their densities may vary at different locations in the galaxy, but their density profiles may also vary at different locations.

This is also a matter of concern of how massive the particles are that make up this huge quantity of dark matter. Experimental endeavors so far are suggestive of the dark matter candidate particles being massive ($\sim$GeV or tens of GeV). These particles were in chemical and thermal equilibrium in a very early epoch of the Universe. With the expansion of the Universe, when their interaction rate lagged behind the expansion rate of the Universe, they failed to interact with each other and as a result they decoupled from the content of the Universe and remained "frozen" thereafter with a relic density. The temperature at which this "freeze-out" occurs for the particle of a particular species is called the "freeze-out" temperature ($T_f$). If the dark matter candidate particle is massive enough so as to exceed the Universe temperature at the time of decoupling (both quantities are expressed in energy units), then that particle moves nonrelativistically and such a candidate for dark matter is called cold dark matter or CDM. A light particle (relativistic at the time of decoupling) candidate for dark matter is termed hot dark matter (HDM). This is not to suggest that there is no HDM in the Universe but it is perhaps the CDM that dominates the dark matter component of the Universe. The theoretical calculation of relic density requires the annihilation cross-section of the dark matter particles and comparing such calculations with the observed relic density (e.g., extracted from the observed CMBR anisotropy) reveals that the value of such cross-sections (multiplied by the relative velocity) should be around $\sim 10^{-26}$ $\text{cm}^3\ \text{sec}^{-1}$. This is clearly of weak interaction order and hence the CDM is often termed WIMP, or weakly interacting massive particles.

From the above discussions for the evidence of dark matter, a scenario of the dark matter properties seems to emerge. They can be naively summarized as follows:

- Dark matter is a nonluminous object. It has no interaction with photons and is incapable of emitting any electromagnetic radiation.

- The dark matter should consist of chargeless neutral particles, as it does not undergo any electromagnetic interaction.

- The dark matter is all pervading in the Universe and helps the formation of large-scale structure such as galaxy clusters by helping in accumulating gravitating mass.

- The dark matter particle is stable; otherwise it would perhaps decay to known fundamental particles and would have been detected in laboratory experiments.

- The interaction of dark matter with other Standard Model particles must be very weak.

- The known fundamental particles (Standard Model particles) like leptons and quarks cannot be dark matter candidates as they are mostly charged particles. The only exceptions are neutrinos, which are neutral particles but the relic density of neutrinos falls far too short of the observed relic density of dark matter. Although neutrinos cannot have mass within the framework of the Standard Model, various neutrino oscillation experiments have established that the neutrinos are indeed massive, however small

($\sim$eV) its mass may be. Neutrinos (active neutrinos) fall into the category of hot dark matter while a sterile neutrino, if exists, is thought to be in the "warm dark matter" (in between HDM and CDM) category and can contribute (however negligible) to the total dark matter content of the Universe.

Although dark matter is still by and large an enigma, attempts are being made to detect them directly or indirectly through various terrestrial and satellite-borne experiments. The direct detection of dark matter is attempted following the principle that, if a dark matter particle hits a nucleus of a detecting material, it suffers elastic scattering, as a result of which the target nucleus undergoes a recoil. As the interaction of dark matter with other particles is supposedly very feeble, the recoil energy of the target nucleus is very tiny ($\sim$ a few keV). In dark matter direct detection experiments, this tiny recoil energy is measured. In the absence of any convincing signature of detection of dark matter (there are however a very few claims from certain experiments), these experiments generally give an upper bound of the elastic scattring cross-section of the dark matter particle for different masses of the dark matter particle. The direct detection of dark matter should also exhibit a periodic annual variation of the detection due to the periodic revolution of Earth around the sun. The solar system, along with the sun, revolves about the galactic center (time for one revolution is $\sim$ 225 million Earth years). Since it is moving through the halo of dark matter (static halo), the sun (and the Earth as well) will encounter an apparent wind of dark matter impinging from a direction opposite to the direction of motion of the solar system. The ecliptic or the sun-Earth plane makes an angle of $60^{\circ}$ with the galactic plane. As the Earth revolves around the sun in a periodic motion, the parallel component $v_p$ of its velocity of revolution also changes its direction periodically over the year. Thus in the course of Earth's revolutionary motion around the sun, $v_p$ will be just oppositely aligned to the apparent dark matter wind at a certain time of the year while direction of $v_p$ will be aligned to the apparent dark matter wind direction at the other time around 6 months later, when the Earth is at a diametrically opposite location on its orbit of revolution. In the former event, Earth will encounter maximum dark matter flux while in the latter case, the Earth will embrace minimum dark matter flux. Thus there will be an expected modulation of detection of dark matter at an earthbound dark matter detection laboratory over the year. This phenomenon is known as annual modulation of dark matter signal and is a very powerful signature in dark matter direct detection experiments.

The dark matter can also trapped by the gravity of heavenly bodies. This happens when the dark matter passes through a body with high gravity such as the solar core or near the galactic center. In case the dark matter particles inside those bodies lose their velocities to values less than the velocities required to escape from these bodies, they are trapped inside them. When, by this process they accumulate inside such bodies in large numbers, and they can undergo pair annihilation among themselves to produce fermion-antifermion pairs and also photons by primary or secondary processes. The target objects for such annihilation products include galactic center, solar core, dwarf galaxies and galaxy clusters, galactic halo, and also extra-galactic sources. There are several earthbound experiments that are making attempts to detect such annhilation products, such as neutrinos from dark matter annihilations in heavenly bodies. Neutrino experiments such as ICE-CUBE (a 1 km$^3$ detector at the South Pole that uses Antarctic ice as detecting material and primarily meant for detecting high-enrgy neutrinos from heavenly sources like Gamma Ray Bursts or GRBs, Active Galactic Nuclei or AGN, etc.) also look for such neutrinos from sun or galactic center. The undersea neutrino detector such as ANTARES at the Mediterranian sea bed also can look at the galactic center for such neutrinos. Attempts are being made to detect photons from dark matter annihilations at the possible sites mentioned above through earthbound experiments like H.E.S.S., VERITUS, etc., and also the satellite-borne experiments like Fermi-LAT. There are extensive searches for excess positrons at cosmos that cannot be explained by cosmic ray sources. Satellite-borne experiments like PAMELA and more recently AMS experiment on-board the International Space Station or ISS have found an increasing trend of positron excess beyond 10 GeV energy, a phenomenon that cannot be explained by cosmic ray origins or other astrophysical processes. They may have originated from dark matter annihilation, and researchers are vigorously pursuing it.

Thus, understanding dark matter may perhaps unfold several unknown mysteries of the Universe. This will throw more insight into how the Universe evolved after the Big Bang and how the structure of the present Universe with all these galaxy clusters and superclusters came into being. Dark matter physics also has the potential to probe new unknown fundamental physics and perhaps new unknown symmetries of Nature that might predict new particles in Nature as yet unknown to us with which the dark matter may perhaps be constituted. Thus, the study of dark matter adresses three very important areas of fundamental physics, namely cosmology, particle physics, and astrophysics.

# 2

# *Brief Discussion on Relativity*

Relativity is an essential ingredient for the formulation of the theory of fundamental particles and interactions – the Standard Model of particle physics, for example. On the other hand, the subject of cosmology that helps us understand the evolution of our Universe, its energy budget, the particle density, etc., requires the application of Einstein's equation of gravity, which in turn based on the theory of relativity. The discussion of dark matter requires the theories of particle physics in order to predict its particle nature. Also, the cosmological ideas are very much essential for the estimation and evolution of dark matter density with the evolution of the Universe. Here we will touch upon essential ingredients of the theory of relativity that will be required for dark matter physics.

## 2.1 Galilean Transformation

In the theory of relativity any event point is described by four coordinates, three spatial coordinates and one time coordinate. That is to say that the space time manifold is a 4-dimensional continuum. It is also assumed in the theory of relativity that the laws of physics are same in any inertial frame. An inertial frame of reference is a frame that is moving with a constant velocity.

Thus if an event is designated as $(x,y,z,t)$ in a frame S, then in another frame $S'$ that is moving with respect to the unprimed frame $S$ with a velocity $v$ along the $x$-axis (measured in $S$) and the time in two reference frames are synchronized at $t = 0$, then the coordinates in primed