PARTICLE DARK MATTER
Observations, Models and Searches

Dark matter is among the most important open problems in modern physics. Aimed at graduate students and researchers, this book describes the theoretical and experimental aspects of the dark matter problem in particle physics, astrophysics and cosmology. Featuring contributions from 46 leading theorists and experimentalists, it presents many aspects, from astrophysical observations to particle physics candidates, and from the prospects for detection at colliders to direct and indirect searches.

The book introduces observational evidence for dark matter along with a detailed discussion of the state-of-the-art of numerical simulations and alternative explanations in terms of modified gravity. It then moves on to the candidates arising from theories beyond the Standard Model of particle physics, and to the prospects for detection at accelerators. It concludes by looking at direct and indirect dark matter searches, and the prospects for detecting the particle nature of dark matter with astrophysical experiments.

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Observations, Models and Searches

Edited by

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Preface

Dark matter (DM) is one of the pillars of the Standard Cosmological Model, but the nature of this elusive component of the matter budget of the Universe remains unknown, despite the compelling evidence at all astrophysical scales. The possible connection with theories beyond the Standard Model of particle physics makes DM one of the most important open problems in modern cosmology and particle physics, as witnessed by the enormous theoretical and experimental effort that is being put towards its identification.

Many different strategies have been devised to achieve this goal. First, the Large Hadron Collider, which is just starting operations, is expected to provide insights of paramount importance into possible extensions of the Standard Model of particle physics. Whether or not a specific candidate is "observed" at the LHC, any evidence for new physics (or lack thereof) will inevitably change our understanding of physics, and in particular our understanding of DM. If DM candidates are actually found, the question will arise of whether they actually are *the* DM in the Universe.

A convincing identification can probably be obtained only by combining the results of accelerator searches with astrophysical searches, based on the direct or indirect detection of DM particles in the local Universe. Direct DM searches are based on the measurement of the recoil energy of nuclei struck by DM particles in large detectors. This field has evolved dramatically in the past decade, and the different experimental strategies (cryogenic, liquid noble gases, superheated) developed over the years have led to a spectacular improvement of the constraints on DM–nucleon interactions. Alternatively, DM could be detected indirectly, through the detection of its annihilation or decay products. With this aim, many important instruments are currently taking data, in particular in the energy range between 1 GeV and 1 TeV, like the antimatter satellite PAMELA and the gamma-ray satellite Fermi, launched in June 2008.

The material is arranged in five parts: Dark matter in cosmology; Candidates; Accelerator searches; Direct detection; Indirect detection and astrophysical constraints. The interested reader will find an introduction to the DM problem and a detailed overview of the contents of the book in Chapter 1.

In brief, Part I is devoted to the astrophysical and cosmological aspects of the DM problem. The current understanding of the distribution of DM in the Universe, based on numerical simulations and astrophysical observations, is reviewed here, along with the most recent lensing observations that provide a 'direct' proof of the existence of DM, and a discussion of alternative theories that seek to dispense with DM. The chapters on DM distribution are particularly important for the reader interested in the indirect DM searches discussed in Part V.

The particle physics aspects of the DM problem are discussed in Part II. This part contains a discussion of the production mechanisms of DM in the early Universe, including among others thermal production, relevant for the broad class of candidates generically referred to as weakly interacting massive particles (WIMPs). The most widely discussed extension of the Standard Model of particle physics, supersymmetry (SUSY), and the most widely discussed DM candidate, the neutralino, are also introduced here. The discussion is, however, enlarged to include a systematic review of alternative extensions of the Standard Model, and alternative DM candidates, including non-SUSY WIMPs, and non-WIMP candidates.

Parts III, IV and V are dedicated to DM searches. Accelerator searches for new physics are discussed in Part III. Of particular importance for the reader interested in the DM problem are the chapters on strategies to discover and identify extensions of the Standard Model of particle physics at the LHC, and on the techniques that may allow, in case of detection, the identification of possible DM candidates. Part III also contains a chapter on DM 'tools', software that has been developed over the years by many different groups in an effort to allow systematic scans of the parameter space of new theories, along with the determination of physical quantities relevant for cosmology and accelerator, direct and indirect searches in each of the models explored in random scans.

Direct detection – the detection of DM through the measurement of the recoil energy of nuclei struck by DM in low-background detectors – is presented in Part IV. The main avenues in this field of research, cryogenic detectors and detectors using liquid noble gases, are presented here, along with a phenomenological overview and a discussion of 'directional' detectors currently under study.

Finally, Part V contains a discussion of the prospect for detecting DM 'indirectly', that is, through the observation of the products of its annihilation or decay. This is a field that is witnessing an explosion of interest, owing to the new data of the Fermi and PAMELA satellites, and it is anticipated that the excitement will remain high in the upcoming years, when a new generation of experiments will become available. A critical assessment of the possible DM interpretation of existing data is presented in this last part of the book, along with a discussion of the strategies that may provide the long-awaited smoking-gun signature for DM.

This book aims at presenting in a coherent way the state-of-the-art of the relevant aspects of the disciplines involved in the DM problem (astrophysics, cosmology and particle physics), along with the detection strategies, in order to build a common language among the different communities and, we hope, to prepare for the age of discoveries. It is more than a collection of review papers, in the sense that particular care has been taken to ensure a coherent and complete presentation of the DM problem, and to bear in mind as its eventual readers graduate students and researchers who want to obtain a better understanding of the many different aspects of the DM puzzle. The 46 authors who joined the project met the challenge of summarizing in chapters of 15 to 20 pages an entire field of research, in an effort to be at the same time accessible and complete. I thus believe that it can become a tool to increase exchanges among the different communities involved in DM searches, and to pave the road to a truly multidisciplinary approach to DM.

As is the case for all major endeavours, it is by no means certain that the search for DM will succeed. But this is how scientific research proceeds. If all our attempts fail, we will have to perform a radical revision of our understanding of Nature. But if one or more of the strategies so far devised turns out to be successful, the discovery of DM may well be remembered as one of the most exciting adventures in the history of science.

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Symbols and abbreviations

Symbols

Throughout the book, quantities describing the properties of DM particles are denoted with the subscript χ, unless otherwise specified. Here are some of the most frequently used symbols:

m_χ, mass of the DM particle
$\sigma_p^{\rm SI}$, spin-independent scattering cross-section off protons
$\sigma_n^{\rm SI}$, spin-independent scattering cross-section off neutrons
$\sigma_p^{\rm SD}$, spin-dependent scattering cross-section off protons
$\sigma_n^{\rm SD}$, spin-dependent scattering cross-section off neutrons
$\langle \sigma v \rangle$, thermal average of the annihilation cross-section
(σv), annihilation cross-section in the non-relativistic limit
$M_{\rm GUT}$, Grand-unification scale
$M_{\rm Pl}$, Planck scale
$M_{\rm SUSY}$, Supersymmetry scale
R_0, Galactocentric radius of the Sun
$\rho_{\rm crit}$, critical density of the Universe
ρ_χ, DM density
$\rho_\chi(R_0) \equiv \rho_0$, DM density in the solar neighbourhood
Ω_χ, relic abundance of DM (in units of $\rho_{\rm crit}$)
$\Omega_{\rm M}$, relic abundance of matter (same units)
$\Omega_{\rm b}$, relic abundance of baryons (same units)
$a_{\rm o}$, MOND parameter
$r_{\rm vir}$, virial radius
$M_{\rm vir}$, virial mass
$c_{\rm vir}$, virial concentration
$\delta_{\rm vir}$, virial overdensity

Acronyms and abbreviations

AQUAL, Aquadratic Lagrangian (theory)
BAO, Baryon Acoustic Oscillation
BBN, Big Bang Nucleosynthesis
BSM, (theories) Beyond the Standard Model
cMSSM, constrained MSSM
CDM, Cold Dark Matter
CMB, Cosmic Microwave Background
Crest, Collisionally Regenerated Structure
DM, Dark Matter
DSph, Dwarf Spheroidal Galaxy
EM, Electroweak
FP, Fokker–Planck (equation)
GEM, Gas Electron Multiplier
GC, Galactic centre
GR, General Relativity
IDM, Inert Doublet Model
IMBH, Intermediate Mass Black Hole
KK, Kaluza–Klein
LHC, Large Hadron Collider
LMC, Large Magellanic Cloud
LSP, Lightest supersymmetric particle
LKP, Lightest Kaluza–Klein particle
LTP, Lightest T-odd Particle
LZP, Lightest Z_3 Particle
LTR, Low-Temperature Reheating (models)
MOND, Modified Newtonian Dynamics
MSSM, Minimal Supersymmetric Standard Model
MW, Milky Way
NFW, Navarro, Frenk and White (profile)
NS, Neutron Star
mSUGRA, Minimal Supergravity
NTD, Neutron Transmutation Doped (germanium sensors)
SD, Spin-Dependent (coupling)
SDSS, Sloan Digital Sky Survey
SI, Spin-Independent (coupling)
SM, Standard Model
SMC, Small Magellanic Cloud
SMBH, Supermassive Black Hole

SNR, Signal-to-Noise Ratio
SQUID, Superconducting QUantum Interference Device
SUSY, Supersymmetry
TES, Transition Edge Sensors
TeVeS, Tensor Vector Scalar theory
TPC, Time Projection Chamber
UED, Universal Extra Dimensions
WD, White Dwarf
WDM, Warm Dark Matter
WIMP, Weakly Interacting Massive Particle