Dark Matter Introduction and Indirect Detection

Lecture Notes for a Basic Understanding of Dark Matter Research.

Haebarg Kang

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Abstract

This lecture note provide a concise foundation for understanding particle dark matter. Part I introduces the motivation for dark matter, observational evidence across cosmic scales, and the theoretical framework of thermal relics—emphasizing the origin and implications of the WIMP miracle. The section also reviews the limitations that have shifted research beyond the traditional WIMP paradigm. Part II focuses on indirect detection, covering the underlying concepts, flux calculations from annihilation and decay, cosmic-ray propagation, and major observational probes such as gamma rays, neutrinos, and the cosmic microwave background.

Contents

1 What is dark matter and why must it exist?

1.1 The necessity of dark matter proposed by Zwicky

When Fritz Zwicky (1933) measured the radial velocities of galaxies in the Coma Cluster, he found that the galaxies moved far faster than expected from the gravitational pull of their luminous matter. Assuming that the cluster was gravitationally bound and in dynamical equilibrium, he applied the virial theorem to estimate its total mass.

Virial theorem. For a stable, self-gravitating system, the time-averaged kinetic and potential energies satisfy

$$2\langle T\rangle + \langle U\rangle = 0.$$

For a cluster of N galaxies, each of typical mass m_g and velocity dispersion σ_v, the total kinetic energy is

$$\langle T\rangle = \frac{3}{2} N m_g \sigma_v^2.$$

Approximating the potential energy for a uniform spherical mass distribution of radius R,

$$\langle U\rangle \approx -\frac{3}{5}\frac{GM^2}{R},$$

the virial theorem implies

$$M_{\mathrm{vir}} \simeq \frac{5R\sigma_v^2}{G}.$$

Thus, the total (virial) mass is proportional to the product of the cluster's size and the square of its velocity dispersion:

$$M_{\mathrm{vir}} \propto R\sigma_v^2.$$

Luminous mass estimate. The luminous mass inferred from visible galaxies can be expressed as

$$M_{\mathrm{lum}} = \left(\frac{M}{L}\right)_{\mathrm{lum}} L_{\mathrm{tot}},$$

where $(M/L)_{\mathrm{lum}}$ is the stellar mass-to-light ratio and L_{tot} the total optical luminosity of the cluster.

The missing mass problem. Comparing these two estimates, Zwicky found that

$$\frac{M_{\mathrm{vir}}}{M_{\mathrm{lum}}} \sim 400,$$

implying that the visible galaxies contribute only a small fraction of the cluster's total mass. He proposed that most of the cluster's mass must be non-luminous, calling it *dunkle Materie* ("dark matter"). This was the first quantitative argument for the existence of dark matter, decades before the concept was confirmed cosmologically.

1.2 Core Evidence for Dark Matter

Beyond Zwicky's virial analysis, several independent lines of evidence across cosmic scales confirm the existence of a dominant, non-luminous matter component.

Galaxy rotation curves. The circular velocity of stars and gas at radius r in a galaxy is expected to follow

$$v_c(r) = \sqrt{\frac{GM(r)}{r}},$$

where $M(r)$ is the enclosed mass. If most mass were concentrated in the visible disk, one would expect $M(r) \approx \text{const}$ at large r, leading to a Keplerian decline $v_c(r) \propto r^{-1/2}$. However, Doppler measurements of optical (Hα) and radio (21 cm) lines show that

$$v_c(r) \approx \text{const} \quad \text{for large } r,$$

implying that $M(r) \propto r$ and thus the mass continues to rise well beyond the visible edge. This requires an extended, nearly isothermal halo with $\rho(r) \propto r^{-2}$—the hallmark of a dark matter distribution.

The Bullet Cluster. The merging cluster 1E 0657–56 ("Bullet Cluster") provides a striking astrophysical test of dark matter's collisionless nature. X-ray observations reveal a shock front where the intracluster gas (ordinary baryons) has been slowed by ram pressure, while weak and strong gravitational lensing maps show that the total mass peaks are offset from the X-ray gas and coincide with the galaxies themselves. Because galaxies and dark matter pass through the collision largely unaffected, the lensing-inferred mass traces a non-collisional component—direct empirical proof that most of the mass is not baryonic.

Large-scale structure formation. Galaxy redshift surveys (e.g., SDSS, DESI) reveal a filamentary "cosmic web" whose statistical properties match ΛCDM simulations containing cold, collisionless dark matter. In contrast, hot or warm dark matter would erase small-scale power through free-streaming, suppressing galaxy formation on sub-Mpc scales—inconsistent with observation. The agreement between N-body simulations and large-scale surveys therefore provides an independent and powerful confirmation of cold dark matter.

1.3 Cosmic Microwave Background and Cosmic Matter Budget

The relative amounts of ordinary matter, dark matter, and dark energy in the Universe can be precisely inferred from cosmological observables, particularly the Cosmic Microwave Background (CMB). The CMB encodes the conditions of the Universe at recombination ($z \simeq 1100$), when photons last scattered off electrons. Tiny temperature anisotropies at the level of $\Delta T/T \sim 10^{-5}$ reflect density fluctuations in the primordial plasma, from which the cosmic matter budget can be reconstructed.

Critical density and energy fractions. The total energy density required for spatial flatness is

$$\rho_c = \frac{3H_0^2}{8\pi G} \simeq 1.05 \times 10^{-5}\, h^2 \text{ GeV cm}^{-3}, \tag{1}$$

where H_0 is the present Hubble constant. The fractional contribution of a component i is defined as

$$\Omega_i = \frac{\rho_i}{\rho_c}.$$

Cosmic measurements yield:

$$\Omega_\Lambda \simeq 0.69, \qquad \Omega_\mathrm{m} \simeq 0.31, \qquad \Omega_\mathrm{b} \simeq 0.049, \qquad \Omega_\mathrm{DM} \simeq 0.26. \tag{2}$$

Thus, dark matter constitutes nearly

$$\frac{\Omega_\mathrm{DM}}{\Omega_\mathrm{b}} \approx 5,$$

meaning that about five times more mass is in dark matter than in baryons.

CMB acoustic peaks as a cosmic balance. Before recombination, photons and baryons formed a tightly coupled fluid undergoing acoustic oscillations. The gravitational pull of matter and the pressure of radiation generated standing waves whose imprints remain in the angular power spectrum of the CMB. The relative heights and spacings of the peaks encode the Universe's contents:

- The **first peak** fixes the total matter density $\Omega_{\rm m}h^2$ and overall curvature.
- The **second and third peaks** depend sensitively on the baryon fraction $\Omega_{\rm b}/\Omega_{\rm m}$.
- The **damping tail** constrains radiation density and small-scale diffusion.

Data from *WMAP* and *Planck* precisely measure these peaks, giving [**?**, 4]:

$$\Omega_{\rm DM}h^2 \approx 0.12, \qquad \Omega_{\rm b}h^2 \approx 0.022.$$

Without dark matter, the oscillations would be overdamped—baryons alone cannot reproduce the observed third-peak amplitude or small-scale power. The success of the ΛCDM model in matching the full CMB spectrum thus provides the strongest quantitative evidence that most of the Universe's matter is cold, non-baryonic, and gravitationally interacting.

The cosmic matter budget is not a speculative estimate but a precision measurement. By jointly fitting CMB anisotropies, large-scale structure, and supernova data, modern cosmology has established that dark matter comprises about 26% of the total energy density of the Universe—roughly five times the amount of ordinary baryonic matter.

2 Thermal Relics and the WIMP Paradigm

2.1 Thermal Relics and the Freeze-out Mechanism

In the early Universe, dark matter particles were part of the thermal bath, constantly annihilating and being produced through inverse reactions. The number density n_χ evolved according to the Boltzmann equation,

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\rm eq}^2\right), \tag{3}$$

where H is the Hubble expansion rate and $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section. It is convenient to rewrite this equation in terms of the yield $Y = n_\chi/s$ and $x = m_\chi/T$, with s the entropy density. During radiation domination,

$$H(T) \simeq 1.66\sqrt{g_*}\,\frac{T^2}{M_{\rm Pl}}.$$

At early times ($x \ll 1$), $n_\chi \approx n_{\chi,\rm eq}$, and the particle species stays in equilibrium. As the Universe expands and cools, the interaction rate $\Gamma = n_\chi\langle\sigma v\rangle$ eventually falls below H, and annihilations become inefficient. At this point, the comoving number density of dark matter freezes out:

$$n_\chi(T_f)\,\langle\sigma v\rangle \sim H(T_f), \qquad x_f \equiv \frac{m_\chi}{T_f} \approx 20\text{–}30. \tag{4}$$

Solving Eq. (3) through freeze-out yields an approximate relic abundance

$$\Omega_\chi h^2 \;\approx\; \frac{0.1}{\langle\sigma v\rangle/(3\times 10^{-26}\ {\rm cm^3\,s^{-1}})}, \tag{5}$$

where $\Omega_\chi = \rho_\chi/\rho_c$ is the fraction of the critical density $\rho_c = 3H_0^2/8\pi G$. Thus, the relic abundance is inversely proportional to the annihilation rate: larger $\langle\sigma v\rangle$ leaves fewer relics today.

The measured dark matter abundance,

$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001,$$

corresponds to a characteristic cross section

$$\langle \sigma v \rangle_{\rm thermal} \simeq 3 \times 10^{-26}\ {\rm cm^3\,s^{-1}},$$

remarkably close to weak-interaction strength.

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2.2 Hot, Warm, and Cold Relics

The relic's kinematic state at decoupling determines how it shapes cosmic structure. Thermal relics can be classified as:

- **Hot Dark Matter (HDM):** Relativistic at decoupling. Examples include active neutrinos with $m_\nu \lesssim 1$ eV. Their large free-streaming length,

$$\lambda_{\rm FS} \sim 40\ {\rm Mpc} \left(\frac{1\ {\rm eV}}{m_\nu}\right),$$

  smooths out fluctuations below galaxy scales, preventing early structure formation. HDM is therefore inconsistent with the observed bottom-up (hierarchical) growth of structure.

- **Warm Dark Matter (WDM):** Semi-relativistic at decoupling, typically with $m_\chi \sim$ keV. WDM suppresses small-scale structure (below dwarf-galaxy scales) and can alleviate some "small-scale crises," but Lyman-α forest data strongly constrain this regime.

- **Cold Dark Matter (CDM):** Non-relativistic at decoupling, with $m_\chi \gtrsim$ GeV. Its negligible free-streaming length allows structure to form hierarchically—from small halos to clusters—matching cosmological observations.

The dark matter inferred from the CMB and large-scale structure is consistent with *cold, collisionless* matter. Thermal relics that were non-relativistic when they froze out—such as WIMPs—naturally belong to this class.

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2.3 The WIMP Miracle

A remarkable coincidence arises when one considers a stable, weakly interacting particle at the electroweak scale. For $m_\chi \sim 10$–10^3 GeV and weak couplings $\alpha \sim 10^{-2}$,

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_\chi^2} \sim 10^{-26}\ {\rm cm^3\,s^{-1}},$$

precisely the value needed to reproduce $\Omega_{\rm DM} h^2 \simeq 0.12$ in Eq. (5). This numerical alignment—linking the weak interaction strength to the cosmic relic density—is known as the *WIMP miracle*.

From the late 1970s onward, this realization established Weakly Interacting Massive Particles (WIMPs) as the leading dark matter paradigm. The WIMP framework rests on four core assumptions:

1. **Neutral and stable:** survives to the present epoch and interacts gravitationally and weakly.
2. **Cold and collisionless:** non-relativistic during structure formation.

3. **Thermal origin:** initially in equilibrium, freezing out when $H \simeq n_\chi \langle \sigma v \rangle$.
4. **Weak-scale mass and couplings:** naturally yields the observed relic density.

This minimal, predictive picture connected particle physics and cosmology, providing a unified framework for direct, indirect, and collider searches.

3 Limitations of WIMP and Current Status

3.1 From the WIMP Miracle to Its Challenges

The *WIMP miracle* offered an elegant link between particle physics and cosmology: a weakly interacting particle at the GeV– scale naturally reproduces the observed dark matter relic density. For decades, this coincidence made the WIMP the dominant dark matter hypothesis, shaping the direction of both theoretical and experimental research. However, as null results have accumulated and theoretical motivations evolved, the WIMP picture has lost its once-central status.

Classic bounds shaping the WIMP window. Thermal reasoning and laboratory constraints defined an early "WIMP window" in parameter space:

- **Lee–Weinberg bound:** A light, neutrino-like species with weak-scale interactions would overclose the Universe unless $m_\chi \gtrsim$ 10–20 GeV.
- **Relic unitarity bound:** Partial-wave unitarity imposes $m_\chi \lesssim \mathcal{O}(100)$ for thermal s-wave relics, setting a robust upper limit on thermal WIMPs.
- **Precision electroweak limits:** LEP measurements of the Z-boson width exclude additional light active neutrino-like species ($m_\chi < m_Z/2$) as dominant dark matter.

These considerations established a theoretically motivated mass window—from a few GeV to several tens of TeV—guiding experimental design for decades.

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3.2 Why the WIMP Paradigm Lost Dominance

Despite its historical success, the WIMP paradigm has faced growing challenges, both theoretical and experimental.

Theoretical limitations.

- **Model dependence:** The WIMP concept emerged from frameworks such as supersymmetry, extra dimensions, and little Higgs models. The lack of new particles at the electroweak scale, even after years of LHC data, has weakened these theoretical motivations.
- **Loss of naturalness:** The absence of superpartners near 1 undermines the original link between WIMP dark matter and the electroweak hierarchy problem.
- **Degeneracy of relic solutions:** Detailed studies show that the observed $\Omega_\chi h^2 \simeq 0.12$ can arise across wide parameter ranges—via coannihilations, resonances, or velocity-dependent effects—reducing the uniqueness of the "miracle."
- **Emergence of non-thermal scenarios:** Mechanisms like freeze-in, asymmetric dark matter, and axion misalignment achieve the correct relic abundance without invoking weak-scale annihilation.

Experimental constraints. Over the past two decades, all three major experimental frontiers have reported null results in their WIMP searches:

- **Direct detection:** Experiments such as XENON1T, LUX, PandaX, and LZ have pushed spin-independent WIMP–nucleon limits below 10^{-47}–10^{-48} cm^2 for $m_\chi \sim 30$–50 GeV, approaching the so-called *neutrino floor*, where astrophysical neutrino backgrounds dominate.
- **Indirect detection:** Observations from *Fermi*-LAT, H.E.S.S., and *Planck* exclude the canonical thermal cross section $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1} across much of the sub-TeV mass range, with no confirmed annihilation or decay signal detected.
- **Collider searches:** Missing-energy and mono-jet searches at the LHC have found no evidence of weakly coupled new particles up to ~ 1 , severely constraining minimal SUSY WIMPs.

Taken together, these results suggest that the simplest WIMP scenarios—once considered inevitable—are now increasingly disfavored.

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3.3 Beyond the WIMP Paradigm

The current landscape of dark matter research reflects a paradigm shift: from a single thermal relic hypothesis to a broad spectrum of models that relax one or more of the WIMP assumptions.

- **Axions and Axion-like Particles (ALPs):** Light pseudoscalars emerging from the Peccei–Quinn solution to the strong-CP problem, produced non-thermally through vacuum misalignment.
- **Sterile Neutrinos:** keV-mass fermions mixing weakly with active neutrinos, leading to warm dark matter and X-ray line signatures.
- **Asymmetric Dark Matter:** The dark matter abundance arises from a particle–antiparticle asymmetry linked to baryogenesis, not from thermal freeze-out.
- **Hidden and Dark Sectors:** Dark photons, dark Higgs bosons, and other secluded states can interact feebly with the Standard Model, motivating fixed-target and low-energy collider experiments.
- **SuperWIMPs and Gravitinos:** Extremely weakly interacting relics that inherit their abundance from late decays of heavier WIMPs.

These alternatives extend the search to masses ranging from meV axions to ultramassive "WIMPzilla" states beyond the unitarity limit, forming a diverse and interconnected dark matter landscape.

In summary, Future experiments—covering sub-GeV thresholds, directional detection, and novel astrophysical probes—will continue to test both the surviving corners of WIMP parameter space and a wide range of non-WIMP candidates.// While the simple WIMP picture no longer monopolizes dark matter research, it remains a cornerstone framework that inspired the modern search program. Its legacy lies not only in what it predicted, but in the systematic, complementary strategy it established for uncovering the true nature of dark matter.

4 Dark Matter Indirect Detection

4.1 Definition and Motivation

Indirect detection aims to observe the *secondary Standard Model particles* produced when dark matter (DM) annihilates or decays in astrophysical environments. Unlike direct detection, which searches for scattering events in terrestrial detectors, indirect searches infer dark matter properties from excesses in cosmic γ rays, charged particles, or neutrinos.

This approach connects astrophysical observations to the microscopic properties of dark matter—its mass m_χ, annihilation cross section $\langle \sigma v \rangle$, decay lifetime τ_χ, and dominant final states. However, astrophysical backgrounds and the complex Galactic environment make interpretation challenging.

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4.2 Flux from Annihilation and Decay

For annihilating dark matter,

$$\frac{d^2\Phi}{dE\, d\Omega} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN}{dE} J_{\mathrm{ann}}, \tag{6}$$

where dN/dE is the particle spectrum per annihilation, and

$$J_{\mathrm{ann}}(\psi) = \int_{\mathrm{l.o.s.}} \rho^2(r(\ell, \psi))\, d\ell \tag{7}$$

is the *J-factor*, integrating the squared DM density ρ^2 along the line of sight.

For decaying dark matter,

$$\frac{d^2\Phi_{\mathrm{dec}}}{dE\, d\Omega} = \frac{1}{4\pi} \frac{1}{m_\chi \tau_\chi} \frac{dN}{dE} J_{\mathrm{dec}}, \qquad J_{\mathrm{dec}} = \int_{\mathrm{l.o.s.}} \rho(r)\, d\ell. \tag{8}$$

Why the J-factor matters. The J-factor encapsulates all astrophysical information—the geometry and density of the DM halo—while dN/dE and $\langle \sigma v \rangle$ or τ_χ encode the particle physics. This separation allows observational data to constrain DM properties independently of astrophysical uncertainties.

Astrophysical targets. Typical orders of magnitude:

$$J_{\mathrm{dwarf}} \sim 10^{18\text{–}20}, \quad J_{\mathrm{GC}} \sim 10^{22\text{–}23}, \quad J_{\mathrm{cluster}} \sim 10^{21} \ (\mathrm{GeV^2 cm^{-5}}).$$

Dwarf galaxies offer low backgrounds; the Galactic Center provides larger signals but with significant systematics.

Spectral signatures. The energy distribution dN/dE carries information about annihilation channels:

- **Continuum spectra:** from hadronization and decays (broad γ-ray or lepton spectra);
- **Sharp features:** from $\chi\chi \to \gamma\gamma$ or internal bremsstrahlung;
- **Secondary emission:** synchrotron, inverse Compton, or prompt neutrinos.

Spectral studies therefore test both the mass scale and annihilation mode of dark matter.

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4.3 Propagation of Charged Particles

Charged cosmic rays diffuse in the Galactic magnetic field and lose energy via synchrotron and inverse-Compton scattering. Their distribution $\psi(\vec{x}, E, t)$ satisfies the diffusion-loss equation,

$$\frac{\partial \psi}{\partial t} = D(E)\nabla^2\psi + \frac{\partial}{\partial E}[b(E)\psi] + Q(\vec{x}, E, t), \tag{9}$$

where Q is the source term from annihilation or decay, $D(E) = D_0(E/E_0)^\delta$ is the diffusion coefficient, and $b(E) \approx b_0 E^2$ encodes energy losses.

Regimes and scaling.

- **Diffusion-dominated:** protons and antiprotons ($\tau_{\rm diff} \ll \tau_{\rm loss}$);
- **Cooling-dominated:** electrons and positrons ($\tau_{\rm loss} \ll \tau_{\rm diff}$), yielding steep spectra.

A simple steady-state approximation gives

$$\psi(E) \propto \frac{1}{E^2} \int_E^{m_\chi} Q(E')\, dE', \tag{10}$$

demonstrating that high-energy leptons are strongly cooled. Numerical propagation codes such as GALPROP and DRAGON implement the full three-dimensional modeling.

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4.4 Observational Signatures and Current Constraints

CMB constraints. Energy injection from annihilation or decay at recombination alters the ionization history. The key parameter is

$$p_{\rm ann} = f_{\rm eff} \frac{\langle \sigma v \rangle}{m_\chi}, \tag{11}$$

where $f_{\rm eff}$ is the efficiency of energy deposition. *Planck* (2018) gives $p_{\rm ann} \lesssim 3\times10^{-28}\,\mathrm{cm^3\,s^{-1}\,GeV^{-1}}$ [4].

Gamma rays.

- **Dwarf spheroidals:** Cleanest targets; *Fermi*-LAT limits exclude the canonical $\langle \sigma v \rangle$ for $m_\chi \lesssim 100$ GeV.
- **Galactic Center:** Bright but background-dominated; the GeV excess can be explained by millisecond pulsars.
- **Line searches:** $\chi\chi \to \gamma\gamma$ gives narrow features; H.E.S.S. and *Fermi* constrain $\langle \sigma v \rangle_{\gamma\gamma} \lesssim 10^{-28}\ \mathrm{cm^3\,s^{-1}}$.

Charged cosmic rays.

- **Positrons:** The rising AMS-02 positron fraction requires cross sections $\gg$ thermal; disfavored by γ-ray and CMB bounds.
- **Antiprotons:** AMS-02 data consistent with secondary origin, limiting hadronic channels.
- **Antideuterons:** Low astrophysical backgrounds; future GAPS and AMS-100 experiments will provide sensitive tests.

Neutrinos. Dark matter can be gravitationally captured in the Sun or Earth, annihilating into neutrinos detectable at IceCube or Super-K. When capture–annihilation equilibrium holds, the neutrino flux depends mainly on the scattering cross section, providing an indirect probe of direct detection limits.

Other signatures. X-ray line emission from keV-scale sterile neutrinos (e.g. the debated 3.5 keV feature) and radio synchrotron emission from $e^{\pm}$ annihilation products constrain low-mass and decaying dark matter models.

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4.5 Summary of Indirect Constraints

Table 1: Representative indirect detection probes and current limits (approximate).

Observable	**Source / Target**	**Key Experiments**	**Current Limit or Status**
CMB anisotropies	Early Universe	*Planck*	$p_{\rm ann} \lesssim 3 \times 10^{-28}\ \mathrm{cm^3\,s^{-1}\,GeV^{-1}}$
γ rays	Dwarfs, GC, clusters	*Fermi*-LAT, H.E.S.S., CTA	Excludes thermal $\langle \sigma v \rangle$ up to ~ 100 GeV
Positrons	Galactic halo	AMS-02, PAMELA	Rising fraction; pulsar origin favored
Antiprotons	Galactic halo	AMS-02	Consistent with secondaries
Neutrinos	Sun, Earth	IceCube, Super-K	Limits on $\sigma_{\rm SD}$ from capture
X-rays	Clusters, GC	XMM-Newton, Chandra	3.5 keV line tentative

Overall status. No confirmed indirect detection of dark matter has been established. Joint limits from γ rays, cosmic rays, the CMB, and neutrinos rule out most simple s-wave thermal WIMPs below a few hundred GeV. Next-generation instruments (CTA, IceCube-Gen2, AMS-100) will extend coverage to multi-TeV masses and subdominant channels.

Acknowledgments

This note summarizes fundamental knowledge about dark matter based on text book and various lecture notes. For detailed information or calculation processes, please refer to the references listed below.
In addition to the listed references, the following books and notes are helpful for studying dark matter; (TASI2008-Dan Hooper, TASI2012-Profumo, TASI2014-Gelmini, Particle Dark Matter-Gianfranco Bertone, The Early Universe-Edward Kolb).
The preparation of these notes benefited from AI-assisted drafting and editing, with all physical interpretations and conclusions authored and reviewed by the lecturer.

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