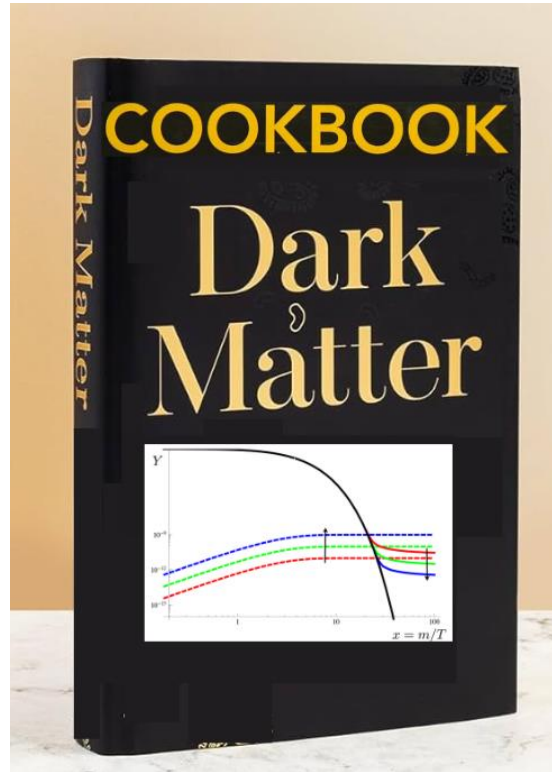


Dark Matter, Freeze-out and Freeze-in

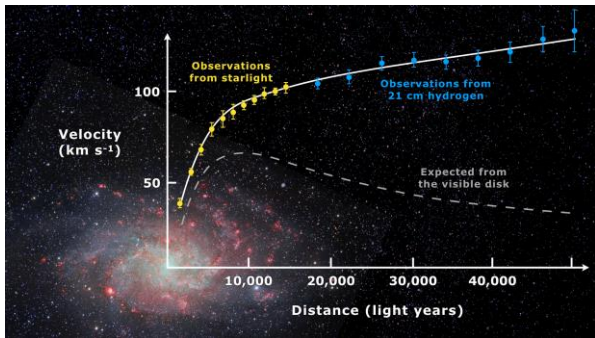
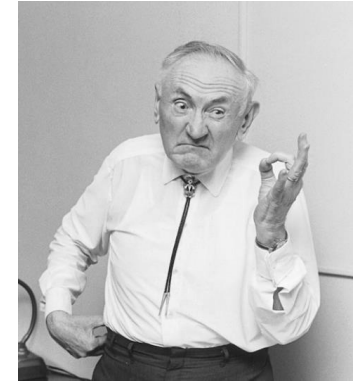


Rodrigo Capucha

Aula de METFOG, 2 de Maio de 2024

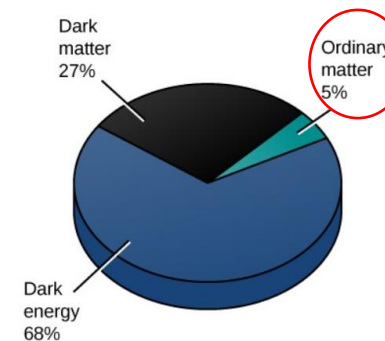
A (very) brief introduction to Dark Matter: evidence and properties

In 1933, **Fritz Zwicky**, while studying the **Coma Cluster**, estimated its mass based on the motion of galaxies near its edge. He concluded the cluster had about **400 times more mass than what was visually observable**. He called this unseen mass **dark matter** (more accurate estimations show that the **discrepancy is actually by a factor of 5**).

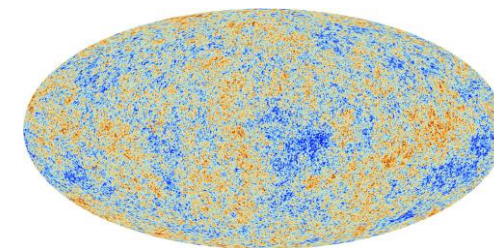


Vera Rubin's work in the 1960s and 1970s provided further evidence, using **galaxy rotation curves**. She showed that several galaxies contain about **six times as much dark as visible mass**.

Since then, many other observations with increasing precision confirmed these results: **gravitational lensing, cosmic microwave background (CMB), structure formation, bullet clusters**. The existence of dark matter is now widely accepted, and its amount known.



This is what we know!



Temperature fluctuations in the CMB

CMB are photons that decoupled from the thermal bath. The surface of last scattering is the one defined by the photons that could come freely to reach us today.

$$T_0 = (2.72548 \pm 0.00057)$$

The value of the variations is of the order $\delta T/T \leq 10^{-5}$ in the sphere of last scattering. If we study these variations in detail we can understand better the temperature fluctuations at that time. Temperature fluctuations on the sphere can be described via spherical harmonics, with the usual polar and azimuthal angles

$$\frac{\delta T(\theta, \phi)}{T_0} = \frac{T(\theta, \phi) - T_0}{T_0} = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}(\theta, \phi)$$

In order to analyse temperature fluctuations, the relevant measure is the variance of the temperature distribution

$$\frac{1}{4\pi} \int d\Omega \left(\frac{\delta T(\theta, \phi)}{T_0} \right)^2 = \frac{1}{4\pi} \sum_{m,l} |a_{lm}|^2$$

Temperature fluctuations in the CMB

The index m describes the angular momentum in a particular direction, but because there is no special direction in the sphere of last scattering the a_m coefficients do not depend on m . Thus, the sum over m yields $2l+1$ identical terms. The average of $|a_m|^2$ over m will be defined as the observed power spectrum

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2$$

The values of the coefficients c_l can be determined using

$$\frac{1}{4\pi} \int d\Omega \left(\frac{\delta T(\theta, \phi)}{T_0} \right)^2 = \frac{1}{4\pi} \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l$$

Temperature fluctuations measured by PLANCK allows to calculate c_l .

The peaks are generated by acoustic oscillations which occur in the baryon-photon fluid at the time of photon decoupling.

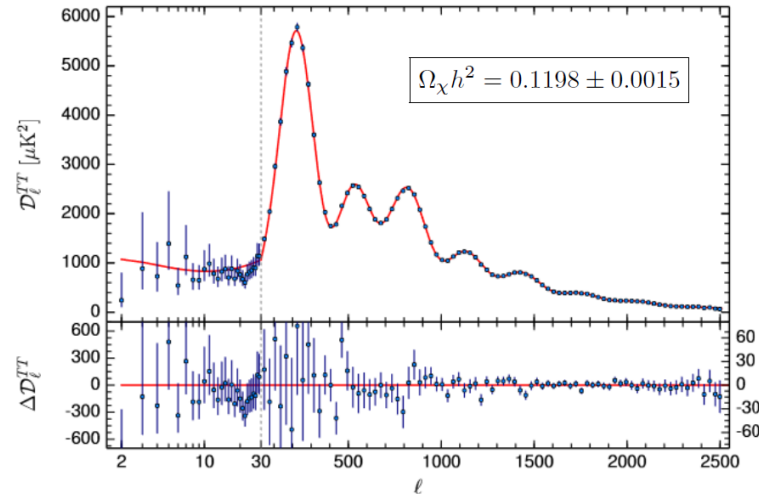
Regions with a large accumulation of DM form gravitational wells, which pull the baryon-photon fluid inside it resulting in a compression of the fluid.

At the same time the relativistic photons exert a pressure that counteracts the gravitational pull, which results in a rarefaction of the fluid.

These counteracting forces create oscillations in the baryon-photon fluid and lead to temperature fluctuations in the photon spectrum during decoupling.

Temperature fluctuations in the CMB

The odd numbered peaks correspond to the decoupling of photons during a compression phase, while even numbered peaks correspond to a decoupling during a rarefaction phase.



To fit the data points given in a model with 6 independent cosmological parameters is used under the assumption of a flat universe. This model is referred to as the "base Λ CDM", which includes the Hubble constant H , and the baryon and DM fraction

The first peak corresponds to the time of last scattering where the fluid compressed once. Determining its position gives information about the curvature of the universe.

The second peak corresponds to one compression and one rarefaction of the fluid. A large relative baryon content in the baryon-photon fluid would lead to an increase in amplitude of the compression peaks and at the same time to a decrease of the rarefaction peaks. Therefore, by measuring the ratio between the first and the second peak, the baryon content of the universe can be obtained.

The height of the third peak determines the amount of DM in the universe. Since, DM does not interact with photons, it only contributes to the strength of the compression peaks. Therefore, a large third peak is a sign of a sizeable DM component in the universe.

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

[Planck collaboration – 1807.06209](#)

Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\rho_c = \frac{3H^2}{8\pi G} = 1.8788 \times 10^{-26} h^2 \text{ kg m}^{-3}$$

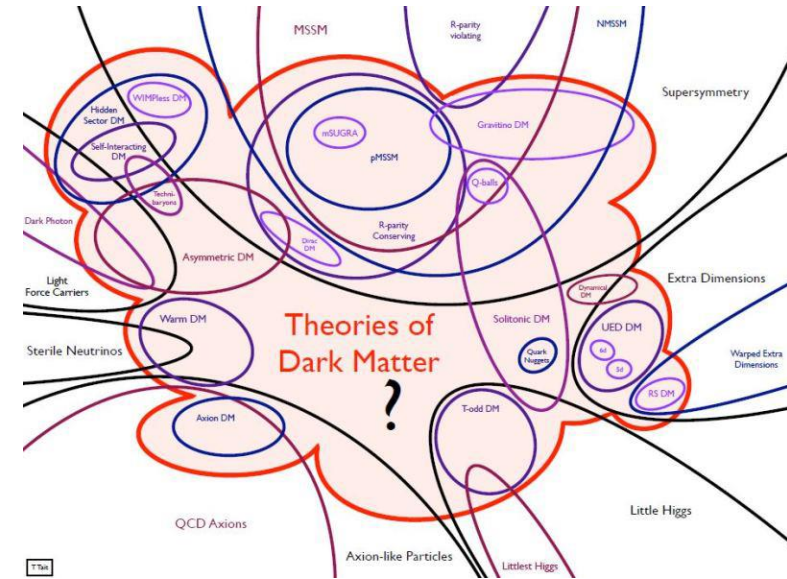
$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G \rho}{3H^2} \quad h \equiv \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}}$$

$$\Omega_{\text{m}} \sim 0.3, \Omega_{\Lambda} \sim 0.7, \Omega_{\text{r}} \sim 10^{-5}, \Omega_{\text{k}} < 10^{-2}$$

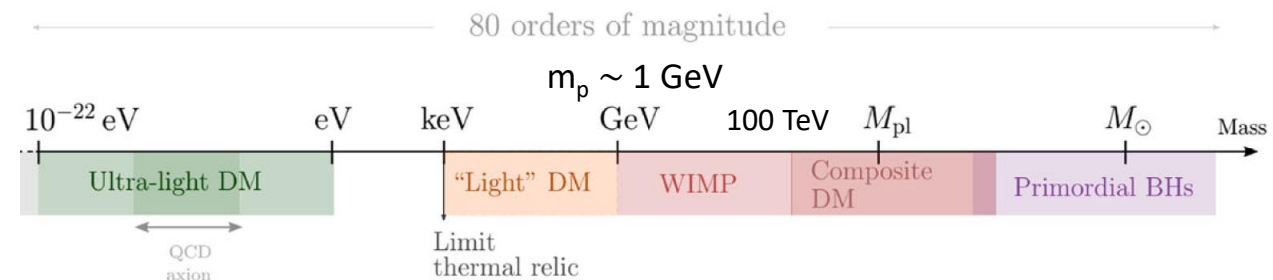
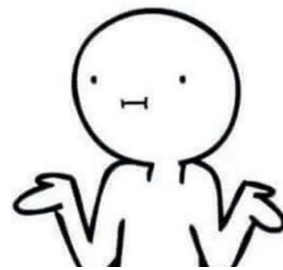
A (very) brief introduction to Dark Matter: evidence and properties

- **What we know about DM:**

- **Dark:** vanishing/suppressed coupling to photons;
- **Collisionless/weakly interacting** (mainly via gravity);
- **Non-baryonic;**
- **If thermal relic, must be cold** ($\lambda_{FS} < 10 \text{ Kpc}$);
- **Long-lived/stable**, with observed **relic abundance**;
- It is some type of **matter in the cosmological sense** ($\rho \sim a^{-3}$).



- **What is it then? Don't know!**



- No viable DM candidates in the SM. **New Particle?** What are its properties (spin, mass)?
- **MOND?** Something else?

The simplest DM model

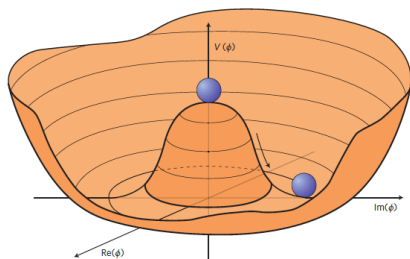
- We need a **“portal interaction”** which connects the **dark sector** to the **visible sector**, otherwise the DM particle cannot be detected.
- Coupling to photons suppressed -> **zero electric charge**.
- One of the simplest models is the **singlet model**, where a **real scalar singlet** field, **S**, is added to the SM. We impose that our theory is invariant under the transformation **S** → **-S** (this invariance is associated with the conservation of a **“darkness” quantum number**), which makes S **stable**.

singlet only part

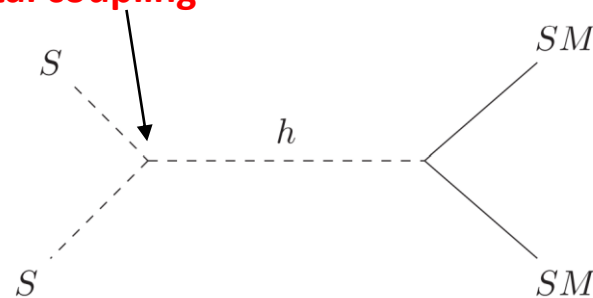
$$V_{\text{RxSM}} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h) \end{pmatrix}$$

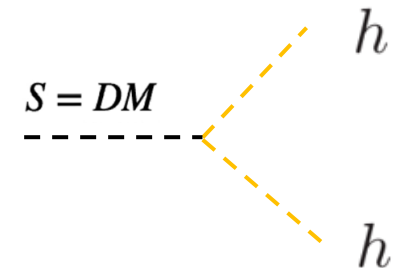
SM Higgs potential



Higgs portal coupling



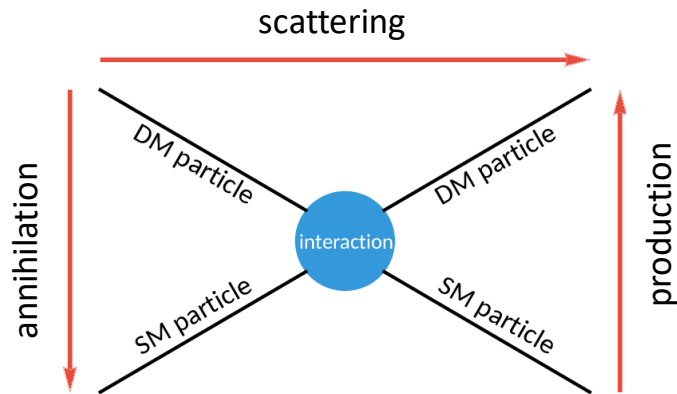
Z_2 : SM → SM, S → -S



Forbidden – darkness not conserved.

Mechanisms of thermal DM generation - Freeze-out

- Let us assume the existence of a **WIMP (Weakly Interacting Massive Particle)** which at some point in the early Universe is at **thermal equilibrium with the thermal bath**, interacting with it via scattering and annihilation/production processes, responsible for keeping this equilibrium.



How does $n(t)$, the number density of DM, evolves over time? This is described by the **Boltzmann equation**.

Assuming no interactions

$$0 = \frac{d}{dt}[n(t) a(t)^3] = \dot{n}(t)a(t)^3 + 3n(t)a(t)^2\dot{a}(t) \Rightarrow \dot{n}(t) + 3H(t)n(t) = 0$$

- Considering interactions, the Boltzmann equation becomes more involved. The general problem consists in determining how f_1 , the **distribution function of DM**, changes over time. Let us consider 2 to 2 processes of the type DM DM \leftrightarrow SM SM (annihilation/production), since only these result in changes in $n(t)$.

Liouville operator
(net rate of change in time of f)

$$\leftarrow \mathcal{L} [f_1] = \mathcal{C} [f_1] \rightarrow$$

Collision operator
(# particles gained/lost per phase-space volume and unit time under collisions)

Hubble parameter \leftarrow Known $\rightarrow \equiv n(t)$

$$\frac{d}{dt} \left[\int f_1(E, t) \frac{g_1 d^3 p_1}{(2\pi)^3} \right] + 3H \int f_1(E, t) \frac{g_1 d^3 p_1}{(2\pi)^3} =$$

$$- \sum_{\text{spins}} \int \left[f_1 f_2 (1 \pm f_3) (1 \pm f_4) |\mathcal{M}_{12 \rightarrow 34}|^2 - f_3 f_4 (1 \pm f_1) (1 \pm f_2) |\mathcal{M}_{34 \rightarrow 12}|^2 \right]$$

$$\times (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times \prod_{i=1}^4 \left(\frac{d^3 p_i}{(2\pi)^3 2E_i} \right)$$

Matrix elements \rightarrow 1, 2, 3, 4 distribution functions

Usually the quantity we're most interested in computing, although full distribution carries extremely useful information too.

- Pretty complicated problem to tackle in full generality! But it can be much simplified considering the following assumptions:

- $\mathbf{f}_1 = \mathbf{f}_1(\mathbf{E}, \mathbf{t})$ because of isotropy and homogeneity;
- No CP-violation: $|\mathbf{M}|^2$ is the same in both directions;
- In equilibrium, $\mathbf{f} \rightarrow \mathbf{MB}$, thus, $1 \pm \mathbf{f} \rightarrow 1$. Also, SM particles are always in equilibrium, thus $\mathbf{f}_3 \mathbf{f}_4 = \mathbf{f}_3^{\text{eq}} \mathbf{f}_4^{\text{eq}}$;
- DM is “almost” in equilibrium throughout most of the freeze-out, and $\mathbf{f}_1 = \mathbf{f}_1^{\text{eq}} \mathbf{n}_1 / \mathbf{n}_1^{\text{eq}}$

Mechanisms of thermal DM generation - Freeze-out

- After a bit of algebra, we end up with the known **Boltzmann equation for freeze-out**:

$$\dot{n}(t) + 3H(t)n(t) = -\langle\sigma v\rangle(n(t)^2 - n_{eq}^2)$$

Rate!

$$[\sigma v n] = m^2 \frac{m}{s} \frac{1}{m^3} = \frac{1}{s}$$



Internal dof (spin, color, particle/antiparticle)

$$n_{eq}(T) = g \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{E/T} \pm 1}$$

$$= \begin{cases} g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} & \text{non-relativistic states } T \ll m \\ \frac{\zeta_3}{\pi^2} g T^3 & \text{relativistic bosons } T \gg m \\ \frac{3}{4} \frac{\zeta_3}{\pi^2} g T^3 & \text{relativistic fermions } T \gg m. \end{cases}$$

non-relativistic states $T \ll m$

relativistic bosons $T \gg m$

relativistic fermions $T \gg m$.

Thermal averaged cross section (TAC)

$$\langle\sigma v\rangle = \frac{\int d^3p_1 d^3p_2 f_1(E_1) f_2(E_2) \sigma v_{12}}{\int d^3p_1 d^3p_2 f_1(E_1) f_2(E_2)}$$

f -> MB



$$\langle\sigma v\rangle = \frac{\int_{4m_{DM}^2}^{\infty} ds \sqrt{s} (s - 4m_{DM}^2) K_1(\sqrt{s}/T) \sigma}{8m_{DM}^4 T K_2^2(m_{DM}/T)}$$

$$v_{12} = \frac{\sqrt{(p_1 p_2)^2 - m_1^2 m_2^2}}{E_1 E_2}$$

$$\sigma = \sum_f \sigma_{12 \rightarrow f}$$

$$K_n(\tilde{x}) \sim \sqrt{\frac{\pi}{2x}} e^{-\tilde{x}} \left[1 + \frac{4n^2 - 1}{8\tilde{x}} + \frac{(4n^2 - 1)(4n^2 - 9)}{2!(8\tilde{x})^2} + \dots \right]$$

for very large x

Mechanisms of thermal DM generation - Freeze-out

- The number of **active degrees of freedom** in our system depends on the temperature. Above the electroweak scale $v = 246$ GeV the effective number of degrees of freedom includes all particles of the Standard Model.

$$\rho_{\text{eq}}(T) = g \int \frac{d^3p}{(2\pi)^3} \frac{E}{e^{E/T} \pm 1} = g 4\pi \int_m^\infty \frac{EdE}{(2\pi)^3} \frac{E\sqrt{E^2 - m^2}}{e^{E/T} \pm 1}$$

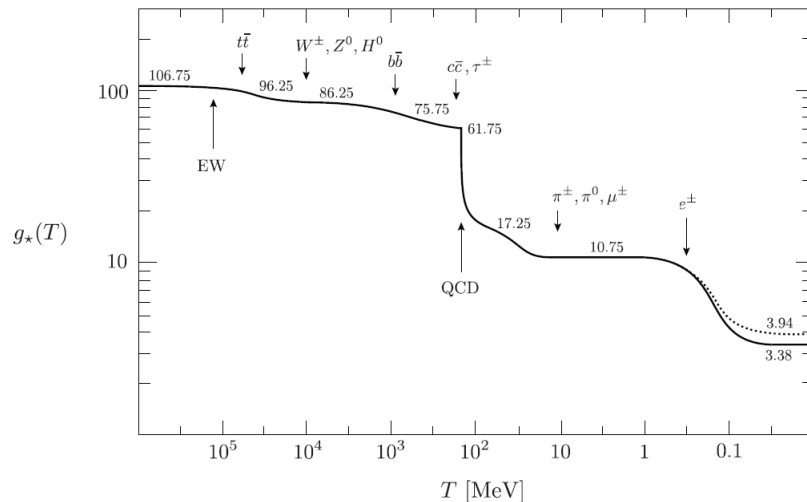
$$= \begin{cases} mg \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} & \text{non-relativistic states } T \ll m \\ \frac{\pi^2}{30} gT^4 & \text{relativistic bosons } T \gg m \\ \frac{7}{8} \frac{\pi^2}{30} gT^4 & \text{relativistic fermions } T \gg m. \end{cases}$$

$$\rho_r = \frac{\pi^2}{30} g_{\text{eff}}(T) T^4$$

$$g_{\text{eff}}(T) = \sum_{\text{bosons}} g_b \frac{T_b^4}{T^4} + \sum_{\text{fermions}} \frac{7}{8} g_f \frac{T_f^4}{T^4}$$

$$g_{\text{fermion}} = g_{\text{quark}} + g_{\text{lepton}} + g_{\text{neutrino}} = 6 \times 3 \times 2 \times 2 + 3 \times 2 \times 2 + 3 \times 2 = 90$$

$$g_{\text{boson}} = g_{\text{gluon}} + g_{\text{weak}} + g_{\text{photon}} + g_{\text{Higgs}} = 8 \times 2 + 3 \times 3 + 2 + 1 = 28.$$



$$g_{\text{eff}}(T > 175 \text{ GeV}) = 28 + 90 \cdot 7/8 = 106.75$$

When we reduce the temperature, this number changes whenever a particle species vanishes at the respective threshold $T = m$.

$$g_{\text{eff}}(T_0) = 3.4$$

$$S = h_{\text{eff}}(T) \frac{2\pi^2}{45} T^3$$

Figure 3.4: Evolution of relativistic degrees of freedom $g_*(T)$ assuming the Standard Model particle content. The dotted line stands for the number of effective degrees of freedom in entropy $g_{*S}(T)$.

Mechanisms of thermal DM generation - Freeze-out

- Further simplifications can be made to the Boltzmann equation, by defining $\mathbf{Y} = \mathbf{n}/\hat{s}$ and $\mathbf{x} = \mathbf{m}_{DM}/T$. Assuming that the **total entropy on the Universe remains constant** in time, and that freeze-out occurs during the **radiation-dominated era**, we have:

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}} \frac{g_*^{1/2} m_{DM}}{x^2} \langle \sigma v \rangle (Y^2 - Y_{eq}^2)$$

$$g_*^{1/2} = \frac{h_{\text{eff}}}{\sqrt{g_{\text{eff}}}} \left(1 + \frac{T}{3h_{\text{eff}}} \frac{dh_{\text{eff}}}{dT} \right) \quad Y_{eq} = \frac{45x^2}{4\pi^4 h_{\text{eff}} (m_{DM}/x)} gK_2(x) \quad \rho_r = \frac{3H^2}{8\pi G}$$

- Integrate Boltzmann equation between $x = 0$ and $x_0 = m_{DM}/T_0$, $T_0 = T_{\text{CMB}}$, to get $Y_0 = Y(T_0)$, and the relic density of DM.

$$\Omega_{DM} = \rho_{DM,0}/\rho_{\text{crit}} = m_{DM} \hat{s}_0 Y_0 / \rho_{\text{crit}}$$

$$\Omega_{DM} h^2 \approx 2.742 \cdot 10^8 \frac{m_{DM}}{\text{GeV}} Y_0$$

Mechanisms of thermal DM generation - Freeze-out

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}} \frac{g_*^{1/2} m_{DM}}{x^2} \langle \sigma v \rangle (Y^2 - Y_{eq}^2)$$

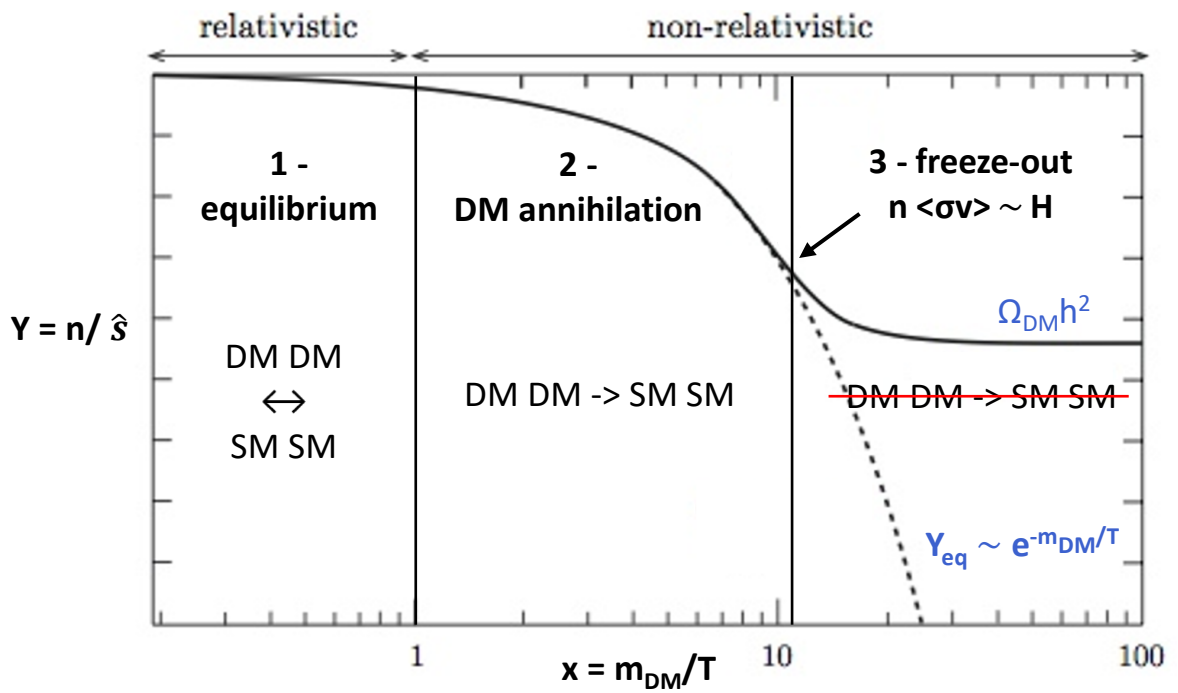


Image source: Daniel D. Baumann, Lecture notes on Cosmology

- 1 - $T > m_{DM}$, **equilibrium** between DM and SM particles.
- 2 - Universe cools off, DM production is disfavoured ($T \sim m_{DM}$). **DM annihilation dominates.**
- 3 - **freeze-out:** DM annihilation rate \sim Universe expansion rate. Annihilation heavily suppressed, DM number density "freezes-out".

- **DM is produced in the early Universe**, when in **thermal equilibrium with the thermal bath**. At some point, **DM decouples**, and its density remains frozen in time. The particles that survive this process (**thermal relics**) are the ones that contribute to the **relic density** observed today.

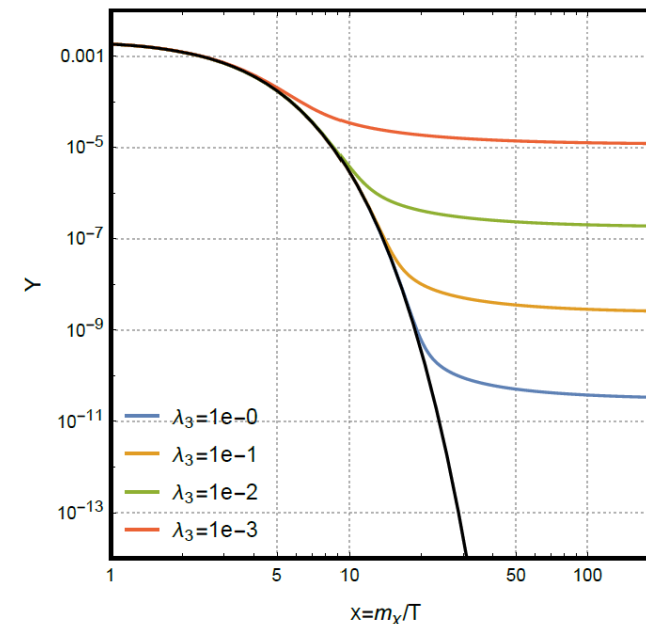
Mechanisms of thermal DM generation - Freeze-out

- Boltzmann equation has **no analytical solution** (must be solved numerically). However, an explicit solution can be obtained if we **start solving it from the freeze-out temperature** (we know the approximate solution before that!). Neglecting the Y_{eq}^2 term (**after freeze-out, $Y^2 \gg Y_{eq}^2$**), we get

$$\frac{1}{Y_0} = \frac{1}{Y_{FO}} + \int_{x_{FO}}^{\infty} C(x) \langle \sigma v(x) \rangle dx$$

- This is the **freeze-out approximation**. The above equation shows that the **Yield is inversely proportional to the thermal averaged cross section**.

DM annihilation into a final state with b-quarks, for the **real singlet model**. A **larger portal coupling** is equivalent to a larger TAC and a **more efficient annihilation rate**. Hence, this leads to a **smaller Yield/relic density**, as expected.



WIMP ~~“Miracle”~~ coincidence

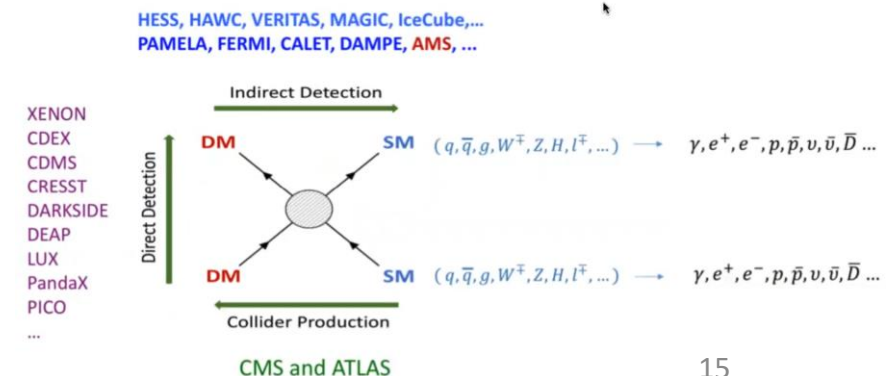
- **WIMPs (Weakly Interacting Massive Particles)** are by far the most studied candidate.
- The **“WIMP miracle”**: any DM particle with an **electroweak-scale mass** (GeV to TeV range) and an **annihilation process mediated by the weak interaction freezes-out with a relic density very close to the correct value**, which can be easily reached by slightly adjusting the relevant parameters of the model (DM mass and portal coupling).
- Assume a new (heavy) particle X which at some point in the early Universe is in thermal equilibrium with the thermal bath. Its relic density is:

$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right) \approx 0.1 \times \left(\frac{\alpha^2 / (200 \text{ GeV})^2}{\langle \sigma v \rangle} \right)$$

$$\frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$m_X = 200 \text{ GeV}, g_X = \alpha^{1/2} \implies \Omega_X h^2 \sim 0.1!$

- Many theories beyond the SM predict these WIMPs to exist, such as **Supersymmetry (SUSY)**. Experimental efforts to detect WIMPs via **direct detection (DD)**, **indirect detection (ID)** and **collider searches** have been **unsuccessful so far**.



Mechanisms of thermal DM generation - Freeze-in

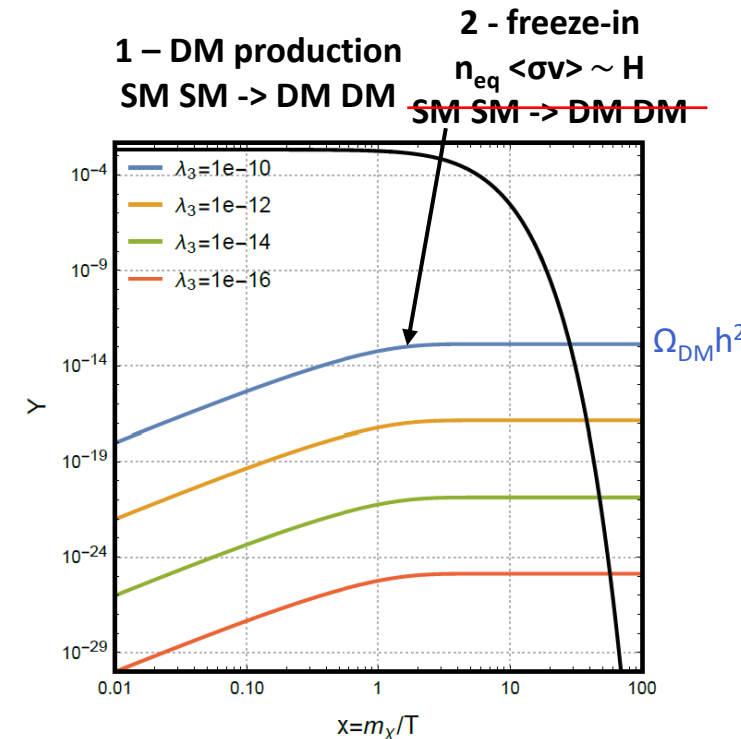
- Let us assume the existence of a **FIMP (Feebly Interacting Massive Particle)** which interacts so weakly with the SM (portal coupling $\sim 10^{-10}$ or smaller) that it **never reaches thermal equilibrium with the thermal bath**.
- Furthermore, we start with a **null initial DM abundance** ($Y(0) = 0$). Then, DM annihilation processes are extremely suppressed and can be neglected. **Only DM production from SM particles** is responsible for changing $n(t)$.

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}} \frac{g_*^{1/2} m_{DM}}{x^2} \langle \sigma v \rangle (Y^2 - Y_{eq}^2)$$

$$Y_0 = \int_0^\infty \lambda(x) \langle \sigma v(x) \rangle$$

At the **reheating temperature, DM starts being produced from SM particles**. Once the **DM production rate \sim Universe expansion rate**, production is heavily suppressed, and **DM “freezes-in”**. Usually **freeze-in happens earlier than freeze-out** (typical $x_{FI} = 2-5$).

DM production from an initial state with b-quarks, for the **real singlet model**. Opposite to the freeze-out, a **larger portal coupling leads to a larger Yield/relic density**, since now the Yield depends on the production rate.



Mechanisms of thermal DM generation - Freeze-in

It may appear that freeze-in is simpler than freeze-out, but that is not the case. The calculation of the relic density via freeze-in is in general more involved than for freeze-out.

We are still assuming $\mathbf{f} \sim \mathbf{MB}$, but this approximation is **not as good for the freeze-in** case, which happens earlier than freeze-out and through most of it, DM is relativistic. **Using the proper distributions (FD/BE) can induce a factor of 2 difference in the DM abundance**, depending on the model (but the integrations are more complicated).

Furthermore, **DM production from the decay of a heavier mediator** also plays a role. If the mediator is in thermal equilibrium with the bath, and decays into two DM particles, $Y \rightarrow \text{DM DM}$, the Boltzmann equation is:

$$\dot{n} + 3Hn = \langle D_{Y \rightarrow \text{DM DM}} \rangle n_Y^{eq} = 2N(Y \rightarrow \text{DM DM})$$

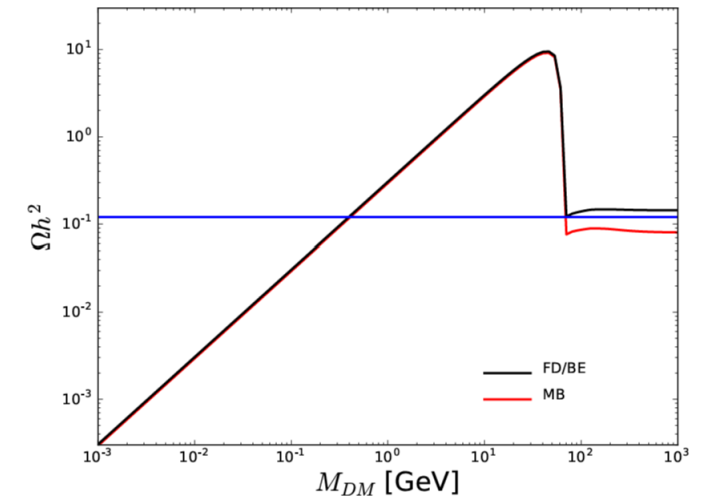
$$\mathcal{N}(Y \rightarrow \chi\bar{\chi}) = \frac{g_Y |\eta_Y|}{2\pi^2} m_Y^2 T \Gamma_{Y \rightarrow \chi\bar{\chi}} \tilde{K}_1(x_Y, 0, 0, \eta_Y, 0, 0)$$

$$\tilde{K}_1(x_1, x_2, x_3, \eta_1, \eta_2, \eta_3) \equiv \frac{1}{(4\pi)^2 p_{\text{CM}} T} \int \prod_{i=1}^3 \left(\frac{d^3 p_i}{E_i} \frac{1}{e^{E_i/T} - \eta_i} \right) e^{E_1/T} \delta^4(P_1 - P_2 - P_3)$$

In general, this decaying particle can belong to the dark sector. Also, it may not be in thermal equilibrium, in which case the calculations are a bit trickier (one needs to write down a Boltzmann equation for the decaying particle as well).

Image source: [arXiv:1801.03509v3](https://arxiv.org/abs/1801.03509v3)

Real singlet model for a portal coupling $\lambda_{\text{HS}} = 10^{-11}$



micrOMEGAs: a code for calculation of DM properties

- **Steps to compute the dark matter abundance predicted by your favourite model:**
 - 1 - Write down your Lagrangian and extract all vertices.
 - 2 - Figure out which processes are relevant for dark matter production/annihilation and compute all the cross-sections.
 - 3 – Compute the TAC and then write down the relevant Boltzmann equations and numerically solve them.
 - Do it all over again for a different model. **Sound pretty complicated!** (some models can have thousands of relevant processes).
 - Sophisticated programs have been developed to perform precise relic density computations for models with discrete symmetries (mainly for WIMPs). A certain level of automation is desirable, since this computation can involve the contribution of a large number of processes. **Major public codes capable of computing dark matter observables: SuperIso Relic, DarkSUSY, micrOMEGAs, MadDM.**
- [Arbey et al. - 1806.11489](#), [Bringmann et al. - 1802.03399](#), [Belanger et al. - hep-ph/0112278](#), [Arina et al. - 2012.09016, 2107.04598](#)
- Let us use micrOMEGAs to calculate the relic density for the real scalar singlet model, for both freeze-out and freeze-in.

micrOMEGAs: a code for calculation of DM properties

- Go to the micrOMEGAs website and download its latest version. On the website you can also find the online manual (download it too!), lectures and tutorials, several papers about micrOMEGAs, installation and how to use information, etc.

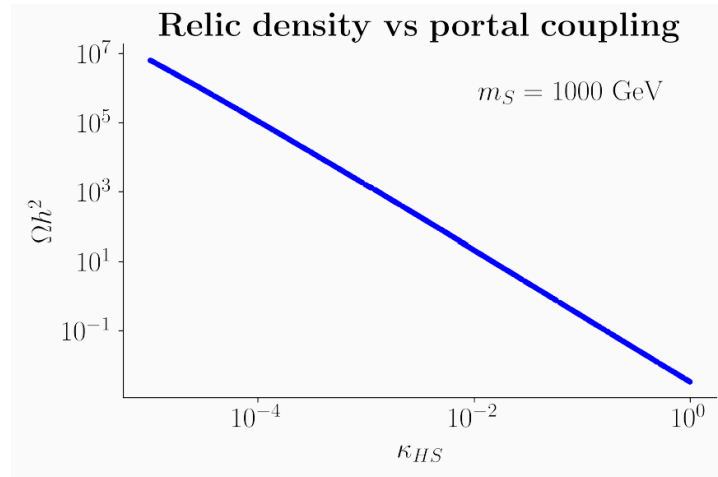
<https://lapth.cnrs.fr/micromegas/>

- Download and unpack micrOMEGAs: **tar -zxvf micromegas_6.0.tgz**
- Go to the micrOMEGAs directory and run make: **cd micromegas_6.0 && make**
- If everything goes smoothly, you are good to go. If you have compiling errors, check Section 3.2 of the manual.
- Go to the directory **micromegas_6.0/SingletDM/work/models** (this is the directory that contains the singlet DM model). Take a look at the files inside. Particles with a tilde before their name belong to the dark sector.
- Back to the directory SingletDM, it should contain a file called **main.c**, and another called **data.par**. The first one is the main file that tells micrOMEGAs what we want it to do. The second one can be used to change the free parameters of the model. Let us take a look at both.

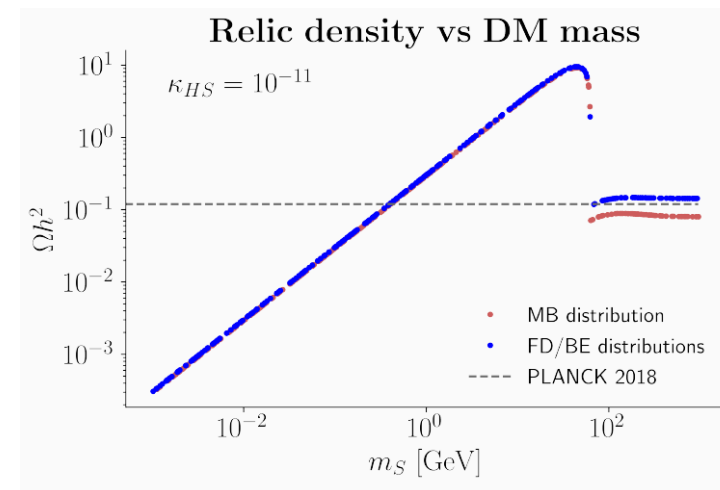
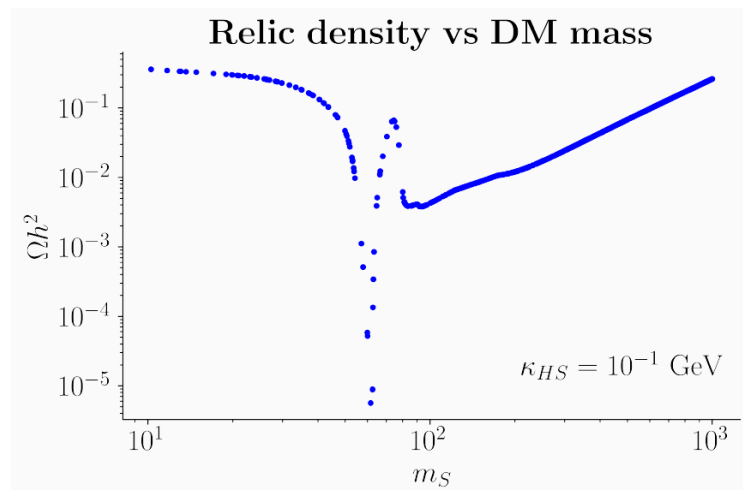
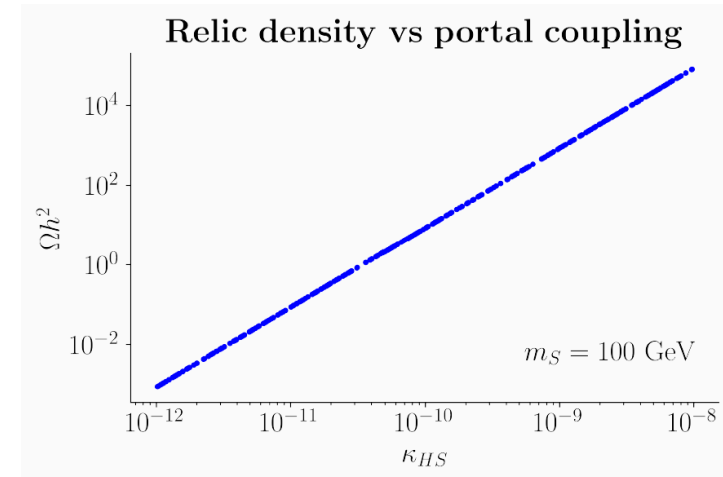
micrOMEGAs: a code for calculation of DM properties

- Let us modify the default main.c file to write a simple program to:
 - 1 – compute the freeze-out DM abundance and print the contributions of the main annihilation channels. Then, choose another value for the portal coupling. Did the relic density change as expected?
 - 2 – repeat step 1 for freeze-in (first go to the file sources/freezein.c. The first line of this file contains the statement `//#define NOSTATISTICS` which can be uncommented for micrOMEGAs to compute the relic density assuming a Maxwell-Boltzmann distribution. This option is faster).
 - 3 – changing the values of the DM mass and the portal coupling from within the code, using the `assignValW("var", val)` function, compute the freeze-out (and freeze-in) DM abundance for several masses and couplings.
- After editing the main.c file, to compile and run it do: **make main=main.c && ./main data.par**
- To create a new model, do in the micromegas_6.0 directory: **./newProject modelName**, and upload the CalcHEP mod files for your model to `modelName/work/models`.

Freeze-out



Freeze-in



Practical applications? What does ChatGPT has to say?

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You

could there be any practical applications for dark matter?

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ChatGPT

Dark matter, despite being one of the most enigmatic and elusive substances in the universe, could potentially have several practical applications, although many of them are still speculative at this point. Here are a few ideas:

1. **Advanced Propulsion:** Some theoretical physicists have proposed that dark matter could be harnessed for propulsion systems. If a way could be found to manipulate or interact with dark matter, it might be possible to use it as a fuel source for spacecraft, enabling faster and more efficient travel through space.
2. **Energy Generation:** If dark matter particles can be captured and converted into usable energy, it could provide a nearly limitless source of power. This could revolutionize energy production and address many of the world's energy needs without relying on finite resources like fossil fuels.
3. **Communications and Information Storage:** Dark matter interacts very weakly with regular matter, which means it could potentially be used in the development of highly secure communication systems or as a medium for information storage. Its properties could make it resistant to interference and eavesdropping.

4. **Medical Imaging:** Although speculative, some scientists have suggested that dark matter could be utilized in advanced medical imaging techniques. By developing technologies that can detect the interactions between dark matter and regular matter, it might be possible to create more detailed and accurate images of the human body, leading to better diagnosis and treatment of medical conditions.

5. **Fundamental Research:** Even if direct applications are not immediately apparent, studying dark matter could lead to breakthroughs in our understanding of the universe's fundamental laws. Technologies and applications that we cannot even imagine today may emerge from a deeper understanding of the nature of dark matter and its interactions with the rest of the cosmos.

However, it's essential to note that these potential applications are highly speculative, and significant scientific and technological advancements would be needed to realize them. Additionally, our current understanding of dark matter is still very limited, so it's challenging to predict with certainty what practical applications it might have in the future.