Particle Physicist's View on Indirect Detection of Dark Matter

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evidence:

Astrophysical and Cosmological observations have provided substantial evidence that point towards the existence of a new type of non-luminous, transparent matter.

Observations based on gravitational effects:

- dynamical effects → Bullet Cluster (galaxy cluster collision)
- deflection of light with gravitational lensing
- gravitational potential (of galaxy clusters)

By now, we know:

- DM makes up 85% of all matter in the universe
- interacts gravitationally

and if it is of particle nature:

- not part of SM → BSM physics
- became non-relativistic already early in the universe (at epoch of structure formation)
- electrically neutral (or very tiny charge)
- very long-lived (if not stable)

Challenges and Questions of particle physics:

If DM interacts with SM:

- how does the interaction look like?
- what is the mass and the spin of the DM candidate?
- what mechanism leads to the observed relic abundance of DM?
- only one DM particle or a whole sector?

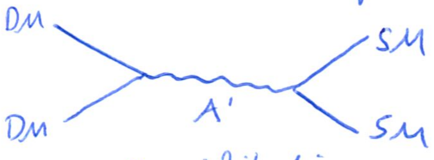
Different search strategies:

- collider-based experiments
- direct detection
- indirect detection ⇒ focus of the student lecture

Indirect Detection: (ID)

'Def.': study of possible visible products of DM interactions originating from the DM already present in the cosmos

in particular: Search for SM particles produced by decay or annihilation of DM (→ telescopes), or the secondary effect of those processes (→ i.e. on BBN, CMB)



annihilation

decay

Advantages:
- DM already there!
- huge amount of DM!
- telescopes sensitive to exotic sources of SM particles over huge range of energies

Challenges:
- DM only interacts weakly with SM → low rates
- huge backgrounds

⇒ might answer questions about DM that are hard or impossible to answer in direct detection or collider-based searches:

① Is DM perfectly stable? → lifetime of DM → decays

② What's the reason for the observed abundance of DM? → thermal relic → annihilation processes

Estimates for indirect detection:

① DM should be 'almost' stable to explain present large DM abundance without being enormously more abundant at recombination (→ would change well-measured CMB)

⇒ safe way: lifetime $\tau_{DM} \gg$ age of the universe $\sim 10^{10}\,\mathrm{yr} \sim 10^{17}\,\mathrm{s}$

↳ possible with operators that are highly suppressed at low energies, i.e. suppressed by GUT scale $M_{GUT} \sim 2 \cdot 10^{16}\,\mathrm{GeV}$

Lifetime estimates:

- dimension 5 operator, i.e. suppressed by $\frac{1}{M_{GUT}}$ $\Rightarrow$ decay rate scales like $|\mathcal{M}|^2$

$$\Gamma \sim \frac{m_{DM}^3}{M_{GUT}^2}$$

For $m_{DM} \sim 1\,\mathrm{TeV}$, we get

$$\tau = \frac{1}{\Gamma} \sim \frac{M_{GUT}^2}{m_{DM}^3} \sim \frac{(2\cdot 10^{16}\,\mathrm{GeV})^2}{(10^3\,\mathrm{GeV})^3} \sim 4\cdot 10^{23}\,\mathrm{GeV}^{-1} \sim 1\,\mathrm{s} \ll \text{age of universe}$$

$\Rightarrow$ too small

- dim. 6-operator suppressed by $\frac{1}{M_{GUT}^2}$ $\quad |\mathcal{M}|^2 \Rightarrow \Gamma \sim \frac{m_{DM}^5}{M_{GUT}^4}$

with $m_{DM} \sim 1\,\mathrm{TeV}$

$$\Rightarrow \tau \sim \frac{M_{GUT}^4}{m_{DM}^5} \sim 10^{50}\,\mathrm{GeV}^{-1} \sim 10^{26}\,\mathrm{s} \sim 10^9 \times \text{age of the universe}$$

$\Rightarrow$ no observable changes in history of the universe

$\Rightarrow$ no way that one can probe these DM decays at colliders for example

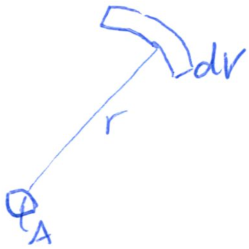
But do we actually observe these decays in ID?

Consider a DM number density n_χ within a volume element dV

The rate of DM decays is then given by $\frac{n_\chi dV}{\tau_{DM}}$

Assume that one observable particle is produced in every decay

$\hookrightarrow$ rate of observable particles reaching a detector with area A at distance r from dV is



$$\frac{dN}{dt} = \frac{A}{4\pi r^2}\frac{n\,dV}{\tau_{DM}}$$

Example: local DM halo with $n_\chi \sim \frac{0.4\,\mathrm{GeV}}{\mathrm{cm}^3}\frac{1}{m_{DM}}$ within $1\,\mathrm{kpc}$ and $dV = r^2 d\Omega\, dr$

$$\Rightarrow \frac{dN}{dt} = A\left(\frac{0.4\,\mathrm{GeV}}{\mathrm{cm}^3}\right)\left(\frac{d\Omega}{4\pi}\right)\frac{dr}{\tau_{DM} m_{DM}} \rightarrow A\left(\frac{0.4\,\mathrm{GeV}}{\mathrm{cm}^3}\right)\frac{1\,\mathrm{kpc}}{m_{DM}\tau_{DM}}$$

and with $\tau_{DM} \sim 10^{26}\,\mathrm{s}$ and $m_{DM} \sim 1\,\mathrm{TeV}$

$$\Rightarrow \frac{dN}{dt} \sim 10^{-4}\,\frac{1}{\mathrm{s}} \text{ for } A = 1\,\mathrm{m}^2 \Rightarrow \frac{\text{few thousand events}}{\text{year}}$$

$\Rightarrow$ visible: for example Fermi telescope (gamma) $\quad DM \to b\bar{b} \quad \tau_{DM} \sim 10^{27-28}\,\mathrm{s}$ ruled out

ICEcube (neutrinos) $\quad \hookrightarrow$ looking at dwarf galaxies $\quad$ from $\sim 10^2 - 10^{10}\,\mathrm{GeV}$

② Annihilating Dark Matter

Estimate of annihilation rate per unit volume per unit time

$$\Gamma_{ann} \sim \langle \sigma v_{rel} \rangle n_1 n_2 \overset{(1=2)}{\rightsquigarrow} \langle \sigma v_{rel} \rangle \frac{n_{DM}^2}{2} \quad \text{with } n_{DM} = \frac{\rho_{DM}}{m_{DM}}$$

n_1: number density of DM particle 1 — n_2: DM particle 2

Assuming again signal from a sphere of uniform DM density and 1 kpc surrounding the Earth

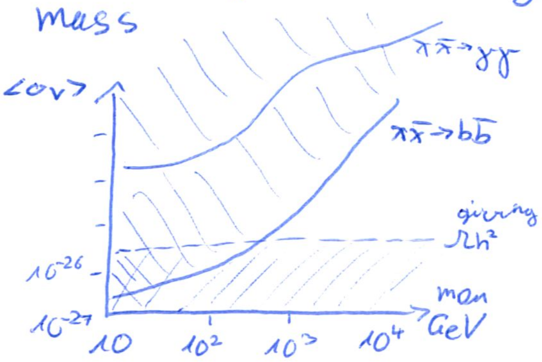
$$\Rightarrow \frac{dN}{dt} = \frac{A \langle \sigma v_{rel} \rangle}{2} (1\,\text{kpc}) \frac{\rho_{DM}^2}{m_{DM}^2} \sim 10^{-26} \frac{\text{cm}^3}{\text{s}} A\, (1\,\text{kpc}) \left(\frac{0.4\,\text{GeV}}{m_{DM}} \right)^2 \text{cm}^{-6}$$

with a weak-scale velocity-averaged cross-section $\langle \sigma v_{rel} \rangle \sim 10^{-26} \frac{\text{cm}^3}{\text{s}}$ $\sim 10^{-9}\,\text{GeV}^{-2}$ $(\approx G_F^2 m_{DM}^2)$

For $A = 1\,\text{m}^2$ and $m_{DM} \sim 1\,\text{TeV} \Rightarrow \frac{dN}{dt} \sim 5 \cdot 10^{-8} \frac{1}{s} \sim \frac{1\,\text{event}}{\text{year}}$

$m_{DM} \sim 100\,\text{GeV} \Rightarrow \frac{dN}{dt} \sim \frac{100\,\text{events}}{\text{year}}$ $\Rightarrow$ increasing with decreasing mass

even stronger for small masses if $\sigma \sim \frac{1}{m_{DM}^2}$



AMS-02 data (DM annihilations producing $\bar{p}$)

<u>But how is the relic abundance related to the annihilation cross-section?</u>
($\to$ in order to constrain thermal DM)

$\hookrightarrow$ focus on 2-to-2 processes $DM\,\overline{DM} \to SM\,\overline{SM}$

Freeze-out of DM

For a particle in kinetic equilibrium with occupancy number $f = \frac{1}{e^{(E-\mu)/T} \pm 1}$ the number density is given by

+ fermions
− bosons

$$n = \frac{g}{(2\pi)^3} \int f(\vec{p})\, d^3p$$

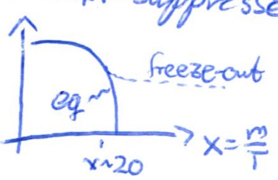
In the non-relativistic regime $T \ll m$, $m-\mu$ and $E = m + \frac{p^2}{2m}$, we have

$$e^{(E-\mu)/T} \pm 1 \approx e^{(E-\mu)/T} \quad \text{(fermions and bosons equal)}$$

↳ Maxwell-Boltzmann statistics

$$\Rightarrow n_{eq} = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T}$$

$\Rightarrow$ DM in equilibrium is Boltzmann-suppressed by $e^{-m/T}$



For number density that scales with $n \sim a^{-3}$

$$\frac{d}{dt}(na^3) = 0 \iff \frac{dn}{dt} + 3Hn = 0$$

if no processes that change number density take place

Including $\Gamma_{ann} \sim \langle \sigma v_{rel} \rangle n_\chi^2$

DM, DM → SM, SM 2-to-2 scattering

$$\Rightarrow \frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v_{rel} \rangle (n_\chi^2 - n_{eq}^2)$$

Introduce $Y = \frac{n}{s}$ with s entropy scaling like $\sim a^{-3}$ as well

$$\Rightarrow \frac{dY}{dx} = -\frac{s x \langle \sigma v_{rel} \rangle}{H x^2} (Y^2 - Y_{eq}^2) = -\frac{\lambda \langle \sigma v_{rel} \rangle}{x^2} (Y^2 - Y_{eq}^2)$$

with constant factor $\lambda = \frac{2\pi^2}{45} \frac{M_P}{1.66} \frac{g_{*s}}{g_*} m$

↳ no analytically closed form

But with $x \gg x_f$ for late times and $Y \gg Y_{eq}$

$$\frac{dY}{dx} \approx -\frac{\lambda \langle \sigma v_{rel} \rangle}{x^2} Y^2 \quad \text{(separable)}$$

x_f determined by
$\langle \sigma v_{rel} \rangle n^2 \sim Hn$, i.e. $\langle \sigma v_{rel} \rangle n \sim H$
↳ Hubble expansion rate comparable to time needed for DM particles to annihilate $\boxed{x_f \sim 20}$

Expanding $\langle \sigma v_{rel} \rangle = \langle a + bv^2 + \ldots \rangle = a + \frac{b}{x} + \ldots$

$$\Rightarrow \frac{1}{Y_\infty} = \frac{1}{Y_f} + \frac{\lambda}{x_f}\left(a + \frac{b}{2x_f}\right) \Rightarrow Y_\infty \approx \frac{x_f}{\lambda\left(a + \frac{b}{2x_f}\right)}$$

$$\Rightarrow \text{relic density } \Omega h^2 = \frac{m_\chi Y_\infty s_0}{\rho_c} h^2 \approx \frac{10^{-10}\,\text{GeV}^{-2}}{a + \frac{b}{2x_f}} \approx \mathcal{O}(10^{-1})$$

$\Rightarrow$ if a is leading term
↳ annihilation cross-sections 1-to-1 comparable from freeze-out → CMB → nowadays