IDPASC 2022 lecture notes for Dark matter detection

Suchita Kulkarni
suchita.kulkarni@uni-graz.at

Your takeaway messages:

1) Why do we think that DM exists?
2) What are the simplest DM relic density mechanisms and what are their caveats?
3) How do we detect dark matter? What are the basic principles and why are current experiments the way they are?

Literature

TASI lectures on dark matter: M. Lisanti
ArXiv: 1603.03797

TASI lectures on sub-GeV dark matter: T. Lin
ArXiv: 1904.07915

Introduction to cosmology and dark matter: A. De Simone
CERN CDS record 2702846

TASI lectures on Early universe cosmology
ArXiv: 1807.08749

Many excellent online lectures e.g. from
Francesco D'Eramo, Laura Baudis etc.

A history of dark matter: G. Bertone
ArXiv: 1605.04909

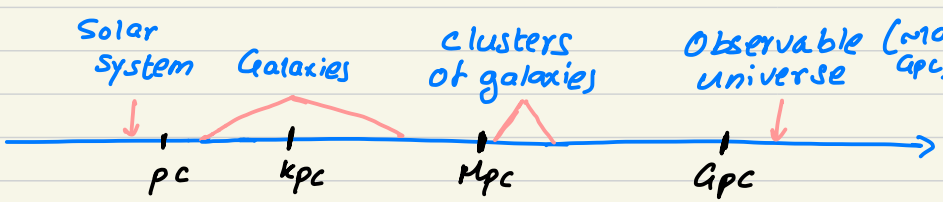
I have liberally taken many points from all these sources.

Dark matter evidences:

Dark matter exists, or to be precise the Universe contains a gravitational component which is not described by the Standard Model of particle physics neither by our current theory of gravity.

This statement is made confidently by astro-physicists and particle physicists because of the wealth of observational evidences at astrophysical scales. I will start with detailing few evidences.

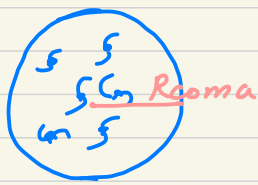
The earliest attempt to estimate the amount of dark matter in Milky-Way was by Lord Kelvin. He argued that if stars in the Milky Way can be described as gas of particles acting under the influence of gravity, then one can establish a relationship between size of the system and the velocity dispersion of stars. He made this argument in 1906 and used the French word to describe missing mass: Matière Obscure!



So how do we know that DM exists at all these scales? Let us do some back of the envelop estimates to check where the discrepancies historically arose

i) Coma cluster

This calculation is similar to that used by Zwicky in 1933.
The Coma cluster is a gravitationally stable system of collection of galaxies.
Since this system is stable we can consider it to be virialised, i.e. the kinetic and potential energy balance each other according to



$$2k + V \simeq 0$$

Now the kinetic energy of each galaxy is

$$k_i = \frac{1}{2} m_i v_i^2 \qquad v_i : \text{avg gal. velocity}$$

Thus $$k = \sum k_i = \frac{1}{2} \sum m_i v_i^2$$

$$= \frac{1}{2} v^2 \sum M_i$$ (let us assume all galaxies in clusture have same velocity, but each galaxy has diff. mass)

$$= \frac{1}{2} M_{coma} v^2$$

Let us now estimate the potential energy

$$V = - \sum_{i>j} \frac{G m_i m_j}{r_{ij}}$$ $i > j$ avoids double counting

For simplicity let us assume that galaxies are distributed uniformly over a sphere. You can estimate this yourself

$$V = -\frac{3}{5} G \frac{M_{coma}^2}{R_{coma}}$$

Virial theorm states that

$$2K + V = M_{coma} v^2 - \frac{3}{5} G \frac{M_{coma}^2}{R_{coma}} = 0$$

$$\Rightarrow v^2 \sim \frac{3}{5} G \frac{M_{coma}}{R_{coma}}$$

Given the avg galaxy velocity and size of the cluster, we can estimate the mass.
We can check this against the visible mass of the cluster obtained by mass to luminosity ratio.
When Zwicky did this calculation he found that the 'gravitational mass' of each galaxy is about

$$M_{avg} > 4.5 \times 10^{10} M_\odot$$

From Luminosity distance rela^n the mass is

$$M_{avg} > 8.5 \times 10^7 M_\odot$$

Thus there is a huge discrepancy showing a 'missing mass'

2) Rotational curves

Zwicky's calculations got a spotlight when his argument was augmented by an observation made by Vera Rubin.

Vera plotted the velocity of stars as a function of their distance from the centre of galaxy. This revealed surprises for the following reason:

The gravitational force felt by a star at distance r from centre of galaxy

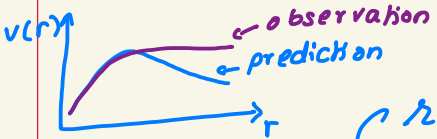
$$F = G\frac{M(r)\,m}{r^2} = \frac{mv^2(r)}{r} = \text{centrifugal force}$$

Thus $a = \frac{v^2(r)}{r}$ and

$$V(r) = \sqrt{\frac{GM(r)}{r}}$$

A galaxy typically shines upto 5-10 kpc for comparison our solar system is 8 kpc from the centre. Thus usually one can't get data much beyond this point But the advent of radio techniques allowed for this to be measured upto 200 kpc!

So what do we expect for limiting cases of velocity from our Newtonian dynamics?



$$v(r) \propto \begin{cases} r & r << r_c \quad \text{(Uniform spherical mass } M(r) \propto r^3\text{)} \\ \sqrt{\frac{1}{r}} & r >> r_c \quad (\mu = \text{const}) \end{cases}$$

However the observed behaviour was that at large distances the velocity remained more or less constant, indicating presence of additional gravitational mass.

3) Dark matter through x-ray emissions @ clusters

Clusters are galaxies + gas
Gas is gravitationally bound to the system.

Gas emits x-rays through ioniz^n and bremm.

$$\text{Gas} \rightarrow \text{x-ray} \propto n_{gas}^2$$

Thus measuring the x-ray emission helps establish the density and temperature $\rho(r)$ and $T(r)$ of the gas.

Now the gas is in hydrostatic eq. Thus

$$\underbrace{\frac{dP}{dr}}_{\text{pressure that wants to push gas out}} = \underbrace{-\frac{GM\,m(r)}{r}}_{\text{Gravity that keeps gas together}} = -\frac{G\rho(r)\,m(r)}{r^2}$$

From equation of state we know

$$P = nkT$$
$$= \frac{\rho}{m_p} kT \quad \text{(let's assume all gas is in protons)}$$

We get a relation between $T(r)$, $\rho(r)$, $M(r)$ within given radius.
We can also work out $M(r)$ through lensing.
The two estimates do not match with each other.

4) DM also exists on cosmological scales

CMB!

5) DM is responsible for perturbation/structure formation

We know e.g. from CMB that

$$\frac{\delta T}{T} \sim 10^{-5}$$ i.e. universe was very smooth/homogeneous

we think that the seed for these is inflation.
Also the fluctuation in the matter density was small

$$\frac{\delta \rho}{\rho} \sim 10^{-5}$$

Today we are very non-linear

$$\frac{\delta \rho}{\rho} \sim 10^{5}$$ for Milky-Way

How did we get here?

The universe is expanding and cooling. Thus density perturba^n grow with

$$\frac{\delta\rho}{\rho} \propto a$$

Since the Last Scattering surface the universe has grown by

$$\frac{a_{\text{Last scatt}}}{a_{\text{Today}}} \sim 10^{-3}$$

If universe contained only baryons then the corresponding

$\frac{\delta\rho_B}{\rho_B}$ couldnot have grown until after Last Scattering because universe was ionized the electrons and photons were coupled, any change in perturba^n was washed out

Thus using baryons only

$$\left.\frac{\delta\rho}{\rho}\right|_{\text{Today}} = \left.\frac{\delta\rho}{\rho}\right|_{\text{Last scatt}} \times 10^3$$

$$\sim 10^{-2}$$

we could not have achieved the non-linearity we do today.
Dark matter helped grow density perturba^n and form structure.

So how did dark matter survive?
I will sketch for you the WIMP dark matter w/o complicated math.

Before we proceed let's have some numbers handy. the fraction of DM energy density observed

$$\frac{\rho_{DM}}{\rho_{crit}} \sim 0.25$$

let us also remember $\xi_{DM} = \frac{\rho_{DM}}{s} \simeq 0.44\,eV$

ρ_{DM} = DM density s = entropy density

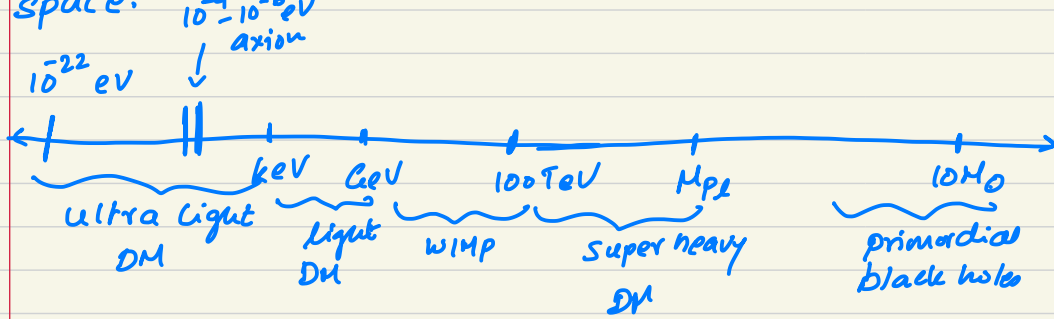
ξ_{DM}: after DM is produced, ξ_{DM} is const.

It is important to know at this point that apart from relic density we expect several things from DM.

1) Mostly SM color and electric charge neutral
2) Mostly cold
3) Mostly stable

But we do not know whether it is a particle. We do not know if and how it interacts with the Standard Model. we do not know the nature or the origin of DM. We do the best we can to understand this, we write theories!

I will not be able to review all (claimed) of DM candidates or their detection principles. But I will give you an idea of vastness of the space and review some part of the parameter space.



Now it is very important to remember that this is not a one dimensional parameter space. It is also an approximate cartoon. The other dimension of this cartoon is the strength and nature of DM-SM interactions. Finally it is also important to note that this entire discussion assumes a single particle being responsible for all of DM. We have no reason to expect this apart from its simplicity.

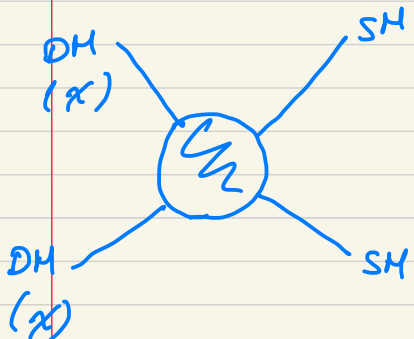
Ok! So how can we get 25% of energy density in DM?
Well we start with the most well explored class of DM candidates. The weakly interacting massive particle or WIMPs!

There are two very important conditions for WIMPs to work

The DM particle was in thermal equilibrium
AND
At some point there was a departure from the thermal equilibrium

How do we thermalize?

We assume very specific interaction mechanism with the SM.
We assume that in the early universe $2 \to 2$ DM-SM interactions kept DM in thermal eq.
Note that we assume nothing about the nature of DM (scalar, fermion..) or the nature of interaction at this point. We do assume that DM and it's anti-particle (if there is one) has same number density ie. the chemical potential of the system is zero.



$\chi\,\chi \longleftrightarrow SM\ SM$

This interaction has some rate Γ

$\Gamma(\chi\,\chi \to SM\ SM) = \Gamma(SM\ SM \to \chi\,\chi)$

How many of these interactions take place between some time interval t_1 & t_2?

$$N = \int_{t_1}^{t_2} \Gamma\, dt = \int_{T_1}^{T_2} \Gamma \frac{dt}{dT}\, dT = \int_{T_1}^{T_2} \frac{dT}{T} \frac{T}{\dot{T}}\, \Gamma$$

Another measure of temperature is entropy
we know that in standard cosmology entropy per unit volume is constant

$$sa^3 = \text{const.} \quad \text{we also know } s \propto T^3$$

$$\Rightarrow Ta = \text{const} \quad (\text{Not a precise eq}^n \text{ because there are factors of } g_* \text{ but for now it works})$$

Thus $\frac{\dot{T}}{T} = -H \qquad \frac{\dot{a}}{a} = H \qquad \boxed{\frac{d}{dt}(Ta) = 0}$

Thus $$N = \int_{T_2}^{T_1} \frac{\Gamma}{H} \frac{dT}{T}$$

Now let us estimate number of interactions when

$T_1 = 2T_2$ in other words when scale factor gets twice as big or volume goes by factor 8.
Assume

$$\frac{\Gamma}{H} \sim \text{const.}$$

$$N \sim \frac{\Gamma}{H} \ln(2)$$

$\Rightarrow$ within the time the universe doubles in size, the number of interactions $\sim \Gamma/H$

It makes sense because this problem has only two scales, the expansion rate of the universe and the SM-DM interaction rate.

If $\Gamma/H < 1$ not a single interaction is possible. Now we should remember that this is a qualitative result but it illustrates the argument beautifully.
Thus within the thermal history of the Universe to get WIMPs we need

$\Gamma/H > 1$ for thermalisation

$\Gamma/H < 1$ for departure from equilibrium

ok! Now we are interested in knowing what is the interaction strength necessary for this to happen? well for that, we should first get the number density because the interaction rate

$\Gamma \equiv \sigma \equiv$ probability for two particles to collide. If we have n_χ number of particles

$\Gamma = n_\chi \langle \sigma v \rangle$ where we have to remember to thermally avg the cross-section because the particles have a velocity distribution.

what is the number density distribution?

$$n_\chi = \begin{cases} \frac{\zeta(3)}{\pi^2} g_{eff} T^3 \sim T^3 & (T \gg m) \quad g_{eff} = \frac{3}{4} \text{ for Bos} \\ \left(\frac{m_\chi T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_\chi}{T}\right) & (T \ll m) \end{cases}$$

(Assume no chem pot)

In the relativistic regime the gas number density must scale as T^3 as it is the only scale in the problem.

If the DM particle remains in thermal eq. forever then the exponential suppression factor will kill all DM.
Thus it is very important that out of equilibrium is triggered.

This is also called freeze-out!

The condition for freeze-out is

$$\Gamma(T_F) = H(T_F) \quad \text{(Naive estimate)}$$

we need to evaluate two things
1) Compute T_F
2) Compute S_{DM}
Let's compute freeze-out-

$$H = \sqrt{\frac{\rho}{3M_{Pl}^2}} = \sqrt{\frac{8\pi G}{3}\rho} \quad \text{(from Friedmann eq')}$$

$$\simeq \frac{T^2}{M_{Pl}} \qquad \rho \propto T^4 \text{ for radiation dominated universe}$$

Now

$$\Gamma = n_\chi \langle \sigma v \rangle$$

Let's consider $\langle \sigma v \rangle = \sigma_0 = \text{const}$
This is applicable for many models with s-wave cross-section.
Ok, what do we use for n_χ?
We wrote two equations for n_χ, one for relativistic and another for non-relativistic regime. Which one of the two expressions we use, depends on

if at freeze-out

$$T_F > m_\chi \quad \text{(Hot relics)}$$
$$T_F < m_\chi \quad \text{(Cold relics)}$$

Both cases are possible, we will only consider cold relics.

Hot relics: can contribute to dark radiation, N_{eff} etc.

Cold relics: DM escapes thermal equilibrium with $m_\chi > T_F$.

Let's estimate this for now being careless about factors of 2π.

$$\sigma_0 (m_\chi T_F)^{3/2} \exp(-m_\chi/T_F) = \frac{T_F^2}{M_{Pl}} \qquad M_{Pl} = 2.4 \times 10^{18}\ GeV$$

This equation has two unknowns m_χ and σ_0.

There is no generic solution to this expression or computation of relic density.

So let's simplify: let's remember that temperature is synonymous with time.

Let's also define

$$x = \frac{m_\chi}{T} \quad \text{and} \quad x_F = \frac{m_\chi}{T_F}$$

Cold relics imply $x_F > 1$

$$\boxed{x_F^{1/2} \exp(-x_F) = \frac{1}{m_\chi M_{Pl} \sigma_0}}$$

Due to the exponential there is a weak dependence on m_χ and σ_0 when estimating x_F

$$x_f = \frac{1}{2}\ln(x_f) + \ln(m_\chi \sigma_0 m_{Pl})$$

$\Rightarrow$ the effect of changing m_χ and σ_0 on x_f is only logarithm.

Now we can do some calculations for WIMPs

$$m_\chi \sim 10\,GeV - 10\,TeV$$

$$\sigma_0 \sim \frac{\alpha_\omega^2}{32\pi} \frac{m_\chi^2}{m_{med}^4}$$

$$\sim \frac{\alpha_\omega^2}{32\pi} \frac{1}{m_\chi^2}$$

if m_χ and m_{med} are some order

$$\alpha_\omega \sim 0.01 \qquad m_\chi \sim 100\,GeV$$

If we plug these numbers in eq^n for x_f

$$x_f \sim 25$$

Note that changing m_χ or σ_0 does not change x_f a lot due to log dependence.
Having established x_f, let's compute relic density.

Since the relics are cold their energy density is

$$\rho_\chi = n_\chi m_\chi$$

$$\Omega_\chi = \frac{\rho_\chi}{\rho} = \frac{n_\chi}{s} m_\chi$$

At temperature below freeze-out

$$\Omega_\chi = m_\chi \frac{n_\chi a^3}{s a^3}$$ ← const let's evaluate it after freeze-out

$s a^3 \sim \text{const}$

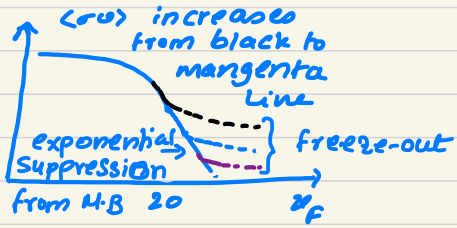
$n_\chi a^3 \sim \text{const}$ AFTER freeze-out

$$\Omega_\chi = m_\chi \underbrace{\frac{n_\chi^f}{s^f}}$$

Gets some small corrections if we solve Boltzmann eq correctly

$$n_f \sigma_0 = H(x_f) = \frac{T_f^2}{m_{Pl}}$$

$$s^f = \frac{2\pi^2}{45} g_* T_f^3 \sim T_f^3$$



$$\Omega_\chi = \frac{\rho_\chi^f}{s^f} = \frac{m_\chi n_\chi^f}{s^f} \sim m_\chi \frac{T_f^2}{m_{Pl}\sigma_0} \frac{1}{T_f^3} = \frac{x_f}{m_{Pl}\sigma_0}$$

$$\Rightarrow \sigma_0 \sim \frac{x_f}{m_{Pl}\Omega_\chi}$$

$x_f \sim 21$

$\Omega_\chi \sim 1\,eV$

$m_{Pl} \sim 10^{18}\,GeV \sim 10^{27}\,eV$

$$\frac{\alpha_\omega^2}{32\pi M_*^2} = \frac{21}{10^{27}\,eV^2}$$

if $\alpha_\omega \sim 10^{-2}$ and $M_* \sim 100\,GeV$ we get right equality

The WIMP miracle is not so much a miracle but careful arrangements of scales.

In deriving

$$\frac{\alpha_\omega^2}{32\pi m_\chi^2} \sim \frac{25}{10^{29}\,eV^2}$$

Assumes that $m_\chi \sim m_{med}$ assumes $\alpha_\omega \sim 0.01$.

It assumes that ii) $2m_\chi \neq m_{med}$ i.e. no resonance

iii) No entropy production

iv) That we know Hubble const through expansion history

v) Assumes DM DM $\to$ SM SM most dominant process

vi) Assumes that DM has no chemical potential / x $\neq$ asymmetry

When did dark matter freeze out in the cosmic evolution?

We can quantitatively estimate this

$$x_f = \frac{m_\chi}{T_f} \sim 25$$

Let's take $m_\chi \sim 100$ GeV $\Rightarrow$ $T_f = 4$ GeV

Now 1 eV $\sim$ 10k Kelvins

$\Rightarrow$ 1 GeV $\sim 10^4 \times 10^9$ Kelvin $= 10^{13}$ Kelvin

$\Rightarrow$ Dark matter freezes out $\sim 10^{13}$-10^{15} kelvin

CMB $\sim$ 3000 k

Neutrino decoupling $\sim 10^9$ K or 1 MeV

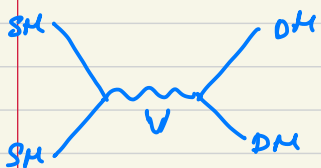
QCD phase transition $\sim$ few hundred MeV

$\Rightarrow$ Dark matter froze out much BEFORE anything in SM took place

Not covered in the lecture

Let us make some rough estimates about cross-sections. This is where particle physics is most important.

A simple process would be



$$|\mathcal{M}|^2 \sim g_\chi^2 g_f^2 \frac{32\, m_\chi^4}{(s-m_V^2)^2}$$

In the non-relativistic limit

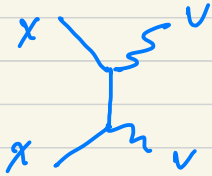
- $m_V > m_\chi$

$$\langle \sigma v \rangle \simeq \frac{16\pi \alpha_\chi \alpha_f m_\chi^2}{m_V^4}$$

$$\alpha_\chi \equiv g_\chi^2/4\pi \qquad \alpha_f \equiv g_f^2/4\pi$$

- $m_V < m_\chi \qquad \chi\chi \to f\bar{f} \qquad \langle \sigma v \rangle \simeq \frac{\pi \alpha_\chi \alpha_f}{m_\chi^2}$

But a new process is also possible



$$\langle \sigma v \rangle \simeq \frac{\pi \alpha_\chi^2}{m_\chi^2}$$

Sub-GeV DM

If we now compute the thermally avg. cross-sec

$$\langle \sigma v \rangle \simeq \frac{m_\chi^2}{\text{GeV}^2} \quad \frac{\alpha_\chi \alpha_f}{\alpha_\omega^2} \quad \frac{1}{10^9\ \text{GeV}^2}$$

where we take $m_V = 100$ GeV. If $\alpha_\chi \alpha_f \sim \alpha_W^2$
Then $\langle \sigma v \rangle$ drops below desired value for $m_\chi < $ GeV. weak interactions thus lead to over-abundance of sub-GeV DM. This is also commonly known as the Lee-Weinberg bound.

Thus typically sub-GeV DM requires new light-mediators to get correct relic density. One could use photons for this purpose, but that requires DM to be millicharged. The desired relic density can be obtained if

$$Q \simeq 10^{-3} \left(\frac{m_\chi}{\text{GeV}}\right)$$

Freeze-in DM

Finally there is an interesting limiting case for small interaction cross-sections where the DM never thermalizes. In this case the relic density is generated by so called freeze-in scenario rather than freeze-out.

Axions

Axions are an interesting dark matter candidate. Axions are formally not a part of Standard Model although they do help solve the Strong CP problem. Let us first understand what is the Strong-CP problem and how do axions help solve it.
The strong CP problem is related to the SM QCD Lagrangian. In the SM QCD lagrangian we can write the following term

$$\mathcal{L}_\theta^{CP} = \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

This term is CP-odd

$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} = \frac{1}{2}(E^2 - B^2) \qquad \underrightarrow{\begin{matrix} E \\ P\text{-odd} \quad T\text{-even} \\ B \\ P\text{-even} \quad T\text{-odd} \end{matrix}} \qquad \begin{matrix} P \text{ even} \\ T \text{ even} \\ P \text{ odd} \\ T \text{ odd} \end{matrix}$$

$$F_{\mu\nu} \tilde{F}^{\mu\nu} = -4 E \cdot B$$

$\Rightarrow$ CP odd

If we now write the QCD lagrangian

$$\mathcal{L} = i \bar{\psi} \not{D} \psi + \underbrace{\exp(i\theta_q) \lambda \bar{\psi}_L \psi_R}_{\text{we can not avoid a phase in mass matrix}} + \text{h.c.} + \frac{\theta g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$$

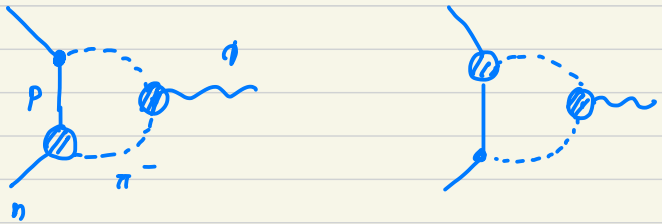
Usually we do not care about θ or θ_q because neither quantities enter perturbative physics. However they matter in non-perturbative physics in following way.
Suppose we decide to rotate away θ_q

$$\psi \to \exp(i\theta_q \gamma_5) \psi$$

$$\mathcal{L} \to \bar{\psi} \not{\partial} \psi + m \bar{\psi}_L \psi_R + (\theta + \theta_q) \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Let us call this $\theta + \theta_q = \bar{\theta}$. Such a term generates neutron electric dipole moment (and hence the importance of $\bar{\theta}$ for non-perturbative physics).

Neutron EDM



Experimental constraints on EDM $\Rightarrow \bar{\theta} \lesssim 10^{-11}$

Strong CP problem: why is $\bar{\theta} = \theta + \theta_q$ so small. Why do two unrelated quantities θ, θ_q balance each other so precisely?

The most popular solution to strong CP problem is introduction of so-called new U(1) Peccei-Quinn symmetry. This symmetry is broken at some high scale (f_A). Such broken symmetry has a pNGB associated with it. This is called axion.

$$\mathcal{L}_a \supset \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \frac{A}{f_A}$$

The neutron EDM $\propto \left\langle \frac{A}{f_A} \right\rangle$

The axion presents a soln to the CP problem because the potential is minimized for $\langle A \rangle = 0$, meaning the field will automatically evolve to generate small neutron EDM.

While we now explain the smallness of nEDM and

hence $\bar{\theta}$, this solu^ comes at the cost of an extra particle which is called axion.

In the ideal world the axion is massless however because it is NGB, it mixes with QCD pion and gains a small mass

$$m_A \sim 5.7 \times 10^{-6}\ eV \left(\frac{10^{12}\ GeV}{f_A}\right)$$

Depending on how the $U_{PQ}(1)$ is encorporated in the SM, several models of axions exist.

Finally the axion term enjoys a shift symmetry

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{A}{f_A}\, G\tilde{G} \qquad A \to A + k f_A$$

$$\delta S = \frac{k}{32\pi^2}\int d^4x\, G\tilde{G}$$

You can choose $k = -\bar{\theta}$ to remove term $\propto \bar{\theta}$ from $\mathcal{L}_{QCD}$. This also means that axion interactions should always be derivative to protect the shift symmetry.

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum \frac{C_{ff}}{2}\frac{\partial^\mu a}{\hat{}}\,\bar{f}\gamma_\mu\gamma_5 f$$

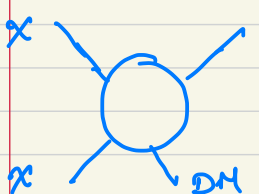
$$+ g_s^2 C_{aa}\frac{a}{\hat{}}\, G_{\mu\nu}\tilde{G}^{\mu\nu} + g_1 C_{ww}\frac{a}{\hat{}}\, W_{\mu\nu}\tilde{W}^{\mu\nu} + g^2 C_{BB}\frac{a}{\hat{}}\, B_{\mu\nu}\tilde{B}^{\mu\nu}$$

This Lagrangian characterizes axion interactions which are to be searched for at the experiments.

Lecture 2 Dark matter detection

We saw in the previous lecture that there are many different dark matter models with several different interactions and relic density generation mechanisms. Thus we need to have generic strategies for DM detection. The exact strategy is dependent also on the mass of DM. But the experiments keep in mind to be as model independent as possible.

In general there are several ways to search for dark matter. I will illustrate this and generic search strategies here.



In our 2-2 interaction mechanism the Feynmann diagram can be turned around to produce, scatter or annihilate DM. This can connect DM relic density mechanism to experiments. However this statement is extremely model dependent.

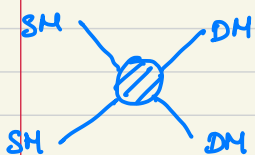
We should also remember that everything I describe below is applicable to look for DM-SM interactions. e.g. in a model where DM relic is generated entirely by interaction within DS (think $DM\ DM \to \nu\nu$ annihilation) the DM-SM interactions remain the only way to detect DM at the experiments.

Therefore, the connection between DM models and associated experimental searches is model dependent.

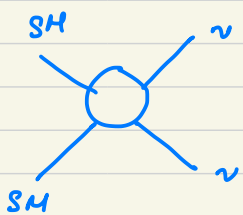
Let me start with one probe and explain the generic principles which are also applicable for other probes.

Let me start with <u>DM @ colliders.</u>

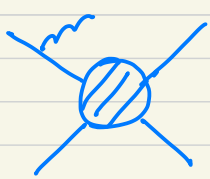
It is hoped that colliders can produce DM if the DM-SM interactions are strong enough. Such scenarios are not impossible specially for WIMP dark matter where DM-SM interactions are $\alpha_w \sim 0.01$ and have a scale of $\mathcal{O}(100)$ GeV.
However there is a problem- WIMP DM being charge and color neutral, if produced it will escape the detection.



$\Rightarrow$ nothing same as



So instead we look for events with



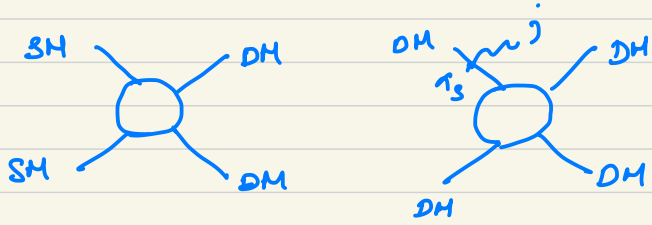
events which contain something visible + missing energy. Something visible = SM γ, ω, Z, jet
$\Rightarrow$ Mono-x searches.

So how do we know if this will work?
The first thing we do, is to estimate the number of events that can be produced at a collider.

Compute

$\sigma(SM\ SM \to DM\ DM\ j)$

This process has a penalty of α_s compared to $\sigma(SM\ SM \to DM\ DM)$ at some center of mass $\sqrt{s}$



IMPORTANT: Remember that this is a relativistic cross-section.

How many events are produced for this cross-section?

$N_{evts} = \mathcal{L} \times \sigma$ ← or integrated

where $\mathcal{L}$ is the total luminosity. (Remember our discussion of DM annihilation rate, which was $n_\chi \langle \sigma v \rangle$, the logic is similar here)

Now, in an ideal world this would be our number of events. Except, the detector is never ideal detector and it can only detect particles in certain angles. So we need to account for that.

$$N_{evts} = \underbrace{A \times \epsilon}_{\text{accounts for detector geometry and efficiency.}} \times \mathcal{L} \times \sigma$$

This means, in order to detect dark matter at collider we need to have a good production cross-section, as high as possible luminosity, but also a detector capable of detecting particles in large angular distribution. → Generic detectors are good!

For the LHC e.g. $\mathcal{L} \sim 3000\,fb^{-1}$

$\sqrt{s} \sim 13\,TeV - 14\,TeV$

$A \times \epsilon \sim 10^{-2} - 10^{-3}$

⇒ $\sigma \sim$ few fb can give a few events.

Note, for lower lumi and fixed $\sqrt{s}$ one can probe larger cross-section.

The second consideration is that of backgrounds. Even if the cross-section is large and can give sufficient number of events, they must have sufficiently different angular distribution than signal distribution so that we can detect signal. Another possibility is to have sufficiently small background events so that the signal 'sticks' above background.

We can have some idea of typical backgrounds at the LHC. For example the inclusive production crossections for some of the processes are as follows

	$j \geq 0$	$j \geq 1$
W production	10^4 pb	$\sim 10^3$ pb
Z production	10^3 pb	$\sim 10^2$ pb
$t\bar{t}$ production	10^3 pb	

Typical DM production has cross-section $\sim$ fb - 100 fb. Thus it is clear that

One needs to control backgrounds in order to discover events containing DM.

This is typically done by demanding events containing a hard jet

There is another aspect of probing DM at different colliders

Let's go back to Nevts

$$N_{evts} = A \times \epsilon \times \mathcal{L} \times \sigma$$

Let's forget about $A \times \epsilon$ for moment

If σ is small $\mathcal{L} \uparrow$ $\Rightarrow$ potential intensity frontier links

σ largish $\mathcal{L}$ ok $\Rightarrow$ Energy frontier

There is another very important aspect: trigger. Trigger determines which events to store and which to throw away. At the colliders we can record events only at a certain rate. If the trigger decides to store events faster than the speed of writing events then we will loose. This e.g. limits our ability to search for low resonances @ LHC.
Following event rates will give us some idea of the enormity of challenge.

Typical event rates

Inelastic $\sim 10^9$ Hz
$\omega \to l\nu$ ~ 100 Hz
$t\bar{t}$ ~ 10 Hz
$H(125\,GeV)$ ~ 0.1 Hz
$\chi(600\,GeV) \sim 0.01$ Hz

$\Rightarrow$ we need to select events at the 10^{11} level

Finally, the last consideration is the configuration of experiment.

Collider experiments can attain high energy but can not attain high lumi.

Fixed target experiment can reach high lumi but not so large energy.

We can estimate this:

Let us consider collision of two protons

$$P_1^\mu = (E_p, \vec{P}_1) \qquad P_2^\mu = (E_p, -\vec{P}_1)$$

for centre-of-mass configuration

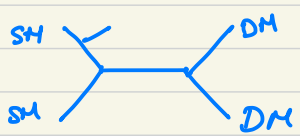
$$P_1^\mu = (E_p, \vec{P}_1) \qquad P_2^\mu = (m_p, 0)$$

for fixed-target configuration

$$s = (P_1^\mu + P_2^\mu)^2 = 2 \times E_p$$
$$= 2m_p^2 + 2E_p \times m_p$$

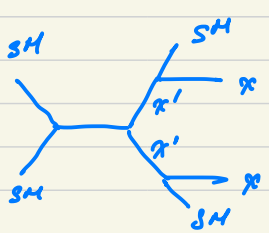
Comparing these two we notice that fixed target configuration needs much higher energy compared to the centre-of-mass configuration.

Looking for DM isn't the only way at colliders. We can also look for DM-SM interaction mediator.



Mono-X

Resonances



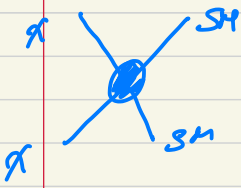
Finally colliders have distinct advantages

1) Colliders have controlled enviorment
2) We know the backgrounds much more precisely
3) The DM production is independent of its astrophysical abundance meaning we can probe underabundant DM
4) If/when we discover DM, we can measure the properties very precisely.

Disadvantages

1) We need DM to couple to SM, preferably to quarks
2) This role should be appreciable
3) If we detect a charge color neutral particle at collider we will not conclusively know if it is dark matter.
4) Interpreting a result from collider is a model dependent exercise.

Direct detection



DM-nucleus scattering: an incoming (astrophysically abundant) DM particle scatters off nucleus and produces nuclear recoil.

Measure this nuclear recoil in the form of heat, phonon or light in the detector.

How much recoil energy is deposited?

$$E_r = \frac{\mu^2 v^2}{2 m_N}(1-\cos\theta) \qquad \mu = \frac{m_\chi m_N}{(m_\chi + m_N)}$$

Mean WIMP velocity ~ 200 km/s

WIMP mass $\sim 1 - 1000$ GeV

Nucleus mass $\sim A \cdot m_p = 100$ GeV (e.g. xenon)

$\Rightarrow$ Typical recoil energies $\sim 1 - 100$ keV

$$m_\chi = m_N = 100\,\text{GeV} \cdot c^{-2}$$

$$\Rightarrow r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} = 1$$

$$v \sim 200\ \text{km/s} \sim (0.75 \times 10^{-3})\, c$$

$$\langle E_R \rangle = \frac{1}{2} m_\chi v^2 = \frac{1}{2} \cdot 100 \cdot \frac{\text{GeV}}{c^2} \cdot (0.75 \times 10^{-3} c)^2$$

$$= 30\ \text{keV}$$

What is the expected rate of events?

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

- $\langle v \rangle$ ← DM velocity
- $\sigma_{\chi N}$ ← DM-nucleus xse
- $\frac{\rho_\chi}{m_\chi}$ ← DM number density
- N ← no. of target nuclei in detector

$N \cdot \frac{\rho_\chi}{m_\chi} \cdot \langle v \rangle$ is like instantenious luminosity or flux

$\rho_\chi \sim 0.3$ GeV cm^{-3}

$\Rightarrow$ WIMP flux on Earth $\sim 10^5$ cm^{-2} s^{-1}

$$\frac{\rho_\chi}{m_\chi} \cdot \langle v \rangle \cdot \sigma = 10^5 \text{ cm}^{-2} \text{ s}^{-1} \times 10^{-39} \text{ cm}^2 = 10^{-34} \text{ s}^{-1}$$

$1 \text{ fb} = 10^{-15} \text{ barn} = 10^{-39} \text{ cm}^2$

Thus we need very large number of target nuclei to get appreciable rates and/or we need large exposures. This is the reson why we have order ton/yr exposures. We also need extremely low backgrounds, thus experiments are often underground.

A more careful analysis can be done as follows. We already established that the avg. no of events is given by

$$R \propto N \frac{\rho_0}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

However neither the cross-section nor the velocity is constant thus

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{min}}^{v_{max}} d^3v\, v\, \tilde{f}(v,t) \frac{d\sigma}{dE_R}$$

You should not that we don't know $\tilde{f}(v)$ very well.

$v_{min} = \sqrt{\frac{2 m_N E_R}{\mu^2}}$ is the minimum DM velocity that can be detected. Note that the minimum velocity increases (decreases) as m_N (m_χ) increases. This also means that for a given target typically there is a limiting case of DM mass below which the DM does not have enough velocity to be detected. This is a limit of DM-nucleus SD and leads to searches in the DM-electron scattering channel. The last job is to now establish $\frac{d\sigma}{dE_R}$

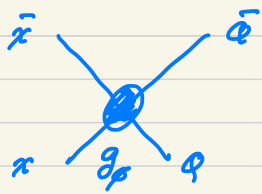
It is done by evaluating the cross-section in non-relativistic limit and by remembering that the nucleus is a composite object.
The procedure can be described as follows:

1) Map the quark operator to nucleon operator and use this to calculate DM-nucleus scattering amplitude
2) Take the non-relativistic limit of scattering amplitude
3) Relate this to differential cross-section by summing/averaging final/initial state spins

$$\frac{d\sigma}{dE_R} = \frac{2 m_N}{\pi v^2} \langle |\mathcal{M}_{NR}|^2 \rangle$$

Take as an example

$$\mathcal{L}_{eff} = g_{\phi} \bar{\chi} \chi \bar{Q} Q$$



This Lagrangian will allow us to compute

$\chi\bar{\chi} \to Q\bar{Q}$ scattering amplitude.

However we are interested in computing

$\chi\bar{\chi} \to n\,n$ when n = neutron or proton

In order to do this, we need to evaluate

$\langle n | Q\bar{Q} | n \rangle$ these operators are evaluated using the trace of energy momentum tensor

The fraction of proton mass accounted by a particular flavour of quark is defined by

$$m_p f_{T_q}^p = \langle p | m_q \bar{q} q | p \rangle$$

and the coupling of DM to protons is given by

$$f_p = \sum_{q=u,d,s} \frac{m_p g_{\phi}}{m_q} f_{T_q}^p + \frac{2}{27} f_{T_q}^p \sum_{q=c,b,t} m_p \frac{g_{\phi}}{m_q}$$

where $f_{T_q}^p = 1 - \sum_{q=u,d,s} f_{T_q}^p$

$f_{T_q}^{q}$ and $f_{T_q}^{p}$ is determined experimentally

The scattering amplitude thus is given by

$$M = f_p \bar{\chi} \chi \bar{p} p + f_n \bar{\chi} \chi \bar{n} n$$

Because $p\bar{p}$ and $n\bar{n}$ gives proton and neutron count we can write M in form of N.

$$M = [Z f_p + (A-Z) f_n] \chi \bar{\chi} \bar{N} \Gamma_N N$$

$$\bar{N} \Gamma_N = \bar{N} N \hat{F}_1(q) + \bar{N} \gamma_\mu N q^\mu \hat{F}_2(q) + \bar{N} \gamma_\mu N P^\mu \hat{F}_3(q)$$

$$\bar{N} \sigma^{\mu\nu} N q_\mu P_\nu \hat{F}_4(q)$$

However $\quad \gamma_\mu p^\mu N = m_N N$

$$N p'^\mu \gamma_\mu = m_N \bar{N}$$

which means the second term vanishes

$$\Rightarrow M = (Z f_p + (A-Z) f_n) \bar{\chi} \chi \bar{N} N F(q)$$

$F(q)$ is the form factor and is a linear combinⁿ of $\hat{F}$. It is usually given by Helm's form factor. $F(q)$ can depend on the exact nuclear physics details. Not all nuclei can be represented by Helm's form factor. Thus determining the correct form factor is an important part of direct detection experiments.

We still need to evaluate $\bar{N}N$ π x amplitude. This is done by deriving the non-relativistic limit of DM and nucleus spinors

$$N^s(p) = \begin{pmatrix} \sqrt{p\cdot\sigma}\,\xi^s \\ \sqrt{p\cdot\bar{\sigma}}\,\xi^s \end{pmatrix} \qquad \sqrt{p\cdot\sigma} \sim \sqrt{m_N - \bar{p}\cdot\sigma} \sim \sqrt{m_N}\left(1 - \frac{\bar{p}\cdot\sigma}{2m_N}\right)$$

and similary for DM spinor.

Leads to

$$\boxed{\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 f^2(q)}$$

Usually $f_p \sim f_n$ because of isospin symmetry. In this case

$$\frac{d\sigma}{dE_R} \propto A^2 \Rightarrow \text{heavier nuclei lead to larger enhancements.}$$

=> This is the reason why we have heavier elements at direct detection.

Not all particle physics interactions will lead to such A^2 enhancements. For example chirality flipping interactions $\propto \gamma^\mu\gamma^5$ do not lead to A^2 enhancements.

This can be explained as follows:
The effective interactions we considered are not

sensitive to the overall spin of the nucleus. Therefore the DM coherently scatters off the whole nucleus and thus gets an A^2 enhancement. Therefore these interactions are also known as DM spin-independent interactions.

In the opposite scenario, the DM-nucleus scattering is still coherent, but the DM couples to the overall spin of the nucleus and thus instead of A^2 it gets a factor of $J(J+1)$. These processes are called spin dependent interactions.

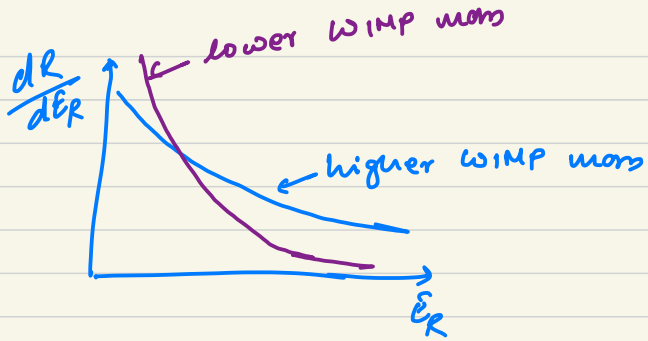
Let us understand the shape of signal processes at direct detection experiments
We already argued that $\frac{d\sigma}{dE_R} \propto \frac{1}{v^2}$

Thus
$$\frac{dR}{dE_R} \propto \int_{v_{min}}^{v_{esc}} d^3v \frac{f(v)}{v} \sim \int_{v_{min}}^{v_{max}} dv\, v \exp(-v^2/v_0^2)$$

$$\sim \exp(-E_R/E_0) \quad \text{where } E_0 \sim \frac{\mu^2 v^2}{m_N}$$

This means that the recoil spectrum at direct detection experiments is typically falling.

The recoil spectrum has a mean at E_0. E_0 typically decreases as DM mass decreases $\Rightarrow$ Recoil spectrum produces softer recoils



Typically reducing threshold ie. minimum detectable recoil energy helps gain sensitivity to lighter DM.

⇒ Ultimate aim:

Build as large dector as possible with as low threshold as possible.

For experimentalists this is a nightmare task. One can not lower threshold arbitrarily for very large exposures because it blows up backgrounds!

Unfortunaly just determining signal properties is not enough. We still need to worry about the shape and strength of backgrounds.

Backgrounds at direct detection

Primarily three sources (apart from potential Bananas which you should not carry near the expts)

1) Radioactivity of surroundings
2) Radioactivity of detector and shield material
3) Cosmic rays and secondary reactions

Remember: activity of a source

$$A = \frac{dN}{dt} = -\lambda N$$

Good to know numbers:

1) Amount of radioactivity in your body
   4000 Bq from ^{14}C
   4000 Bq ^{40}K
2) Number of Plutonium atoms in 1 kg of soil
   10 millions (transmutation of ^{238}U by fast CR neutrons)
   Soil: 1-3 mg U per kg

Reduce backgrounds at direct detection by

1) Active and passive shielding. Gain in suppressing natural radioactivity ~ 5 order magnitudes
2) Internal radioactivity: Make material as pure as possible or keep control on impurities.
   Unfortunately not much you can do about it.
3) Cosmic rays: Go underground!
   Backgrounds typically fall steeply after depth of 10 m water equivalent
4) Most problematic: muons and muon induced neutrons. The only way to suppress them
   Go underground!

Controlling radioactive backgrounds is hard, measuring/modelling them is even harder. Therefore ultra-sensitive direct detection experiments e.g. CRESST for low mass DM or XENONNT for high mass DM, need to be very careful in modelling the backgrounds.

Indirect detection

While I have no time to discuss indirect detection similar principles apply. Indirect detection relies on Dark Matter annihilation in the Universe today

$$\chi\chi \to SM\ SM$$

This process is very suppressed as $\Gamma < H$ today. However $\Gamma \propto n_\chi$ and hence if there are a large number of DM particles at one point then we may have some annihilat°.
This is the reason why we search for dark matter signals at the centre of galaxies where the dark matter density is high. We also observe e.g. dwarf galaxies which have little visible matter and larger DM content.

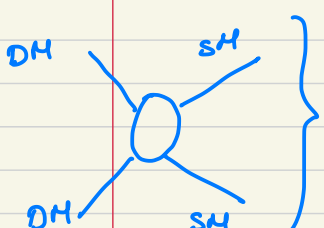
The SM final state particles propagate through the Universe and their detection principles are the same as most cosmic ray detection efforts: all charged SM particles get deflected in magnetic fields and hence magnetic field modelling is important.

The neutrino final states are interesting as

neutrinos don't get deflected and hence do not loose energy while propagating. DM $2 \to 2$ annihilā to neutrino final states can therefore lead to line spectrum with energy of m_χ. (As DM today is non-relativistic the centre of mass energy for DM DM → SM SM is 2DM mass, and thus each SM final state carries energy the same as DM mass). Neutrino lines if observed will be a very clean signal of DM. IceCube e.g. searches for such lines.

Finally DM might annihilatē to photons via loop processes. Although extremely suppressed in ratē they also lead to lines and hence are a clean signal.

A primary background in indirect detection searches is modelling of the source. If DM is being searched for at the centre of galaxy, we need to model the astrophysical i.e. SM processes at the centre very well. As no one precisely knows how to calculatē physics of such massive systems, this is done by observā/simulā.



Charged final states
Get deflected in magnetic fields
loose energy ⇒ diffuse signal
(these can also give diffuse photon radiā as charged particles emit photons)

Neutrinos and photons
Do not diffuse, lead to line spectrum, easier to search for