Experimental methods in astroparticle physics SS2020

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Contents

1. Lecture 2: Explanations and particle candidates

In this lecture, we discuss possible explanations to the various indications for dark matter explained in the first lecture. These include elementary particle candidates arising from different theories that will be discussed only briefly to have a general overview.

1.1. Modification of gravitational laws

A possible solution to explain some of the astronomical measurements is a modification of the gravitation laws. Such modified Newtonian dynamic models, like for instance MOND [1] or its relativistic extension TeVeS, can successfully describe rotational velocities measured in galaxies. Figure 1 shows as an example of fits of the MOND model (continuous line) to rotation curves. It can be seen that an excellent agreement between data and model is found.

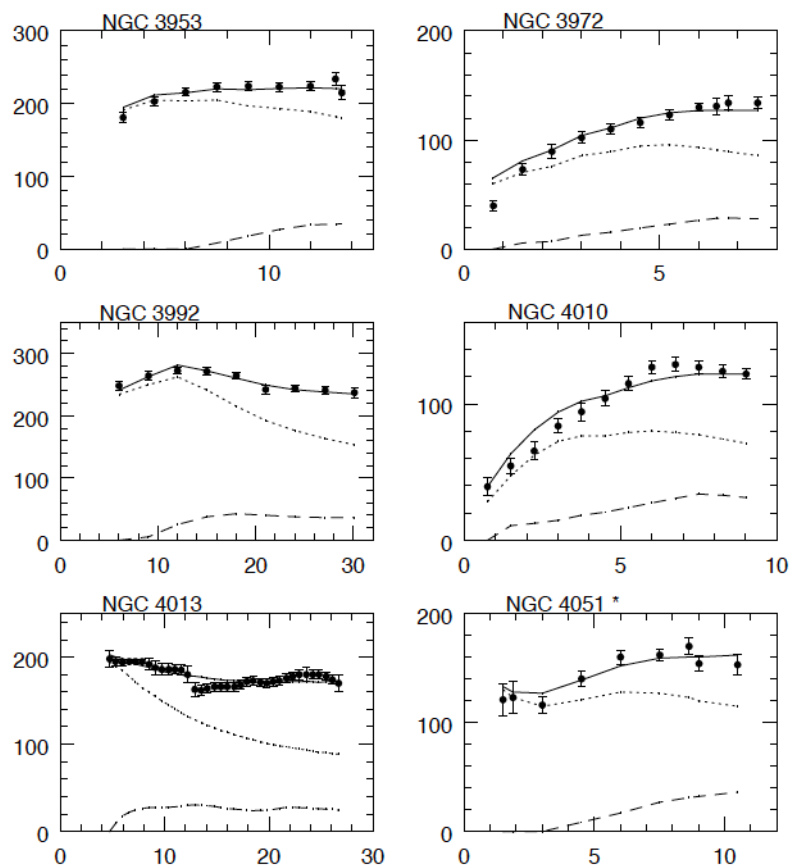

Figure 1. Fits of the MOND model (continuous line) to rotation curves data in Ursa Major galaxies. The dashed line represents the luminous disk and the dotted line the gaseous disk. Figure from Sanders & Verheijen, ApJ 503 (1998) 97.

The MOND theory was proposed in 1983 by M. Milgrom as a phenomenological approach. He modified Newton's second law in the limit of low acceleration to

$$\overline{F} = m_g \cdot \mu(a/a_0)\overline{a}, \tag{1}$$

with m_g the gravitational mass and a_0 a constant with dimensions of acceleration. The function μ is defined such that

$$\begin{aligned} \mu(x >> 1) &\sim 1 \\ \mu(x << 1) &\sim x \end{aligned} \tag{2}$$

with $x = a/a_0$ and $a_0 \sim 2 \times 10^{-10}$ m/s^2 is obtained from observations. MOND however, fails or needs unrealistic parameters to fit observations on larger scales such as structure formation or the CMB structure.

Exercise related to this topic

1.2. MACHOS and micro-lensing measurements

Massive astrophysical compact halo objects (called MACHOs) have also been considered as a plausible explanation for dark matter. These objects could be black holes, neutron stars, brown dwarfs or planets that would emit very little to no radiation. Searches for such objects have been carried out via gravitational microlensing, a technique suggested by Paczynski in 1986 [2]: the observed brightness of an object increases when a MACHO is aligned with the observed object, i.e. on its line of sight. Figure 2 shows examples of the microlensing events observed by the MACHO collaboration [3] when observing

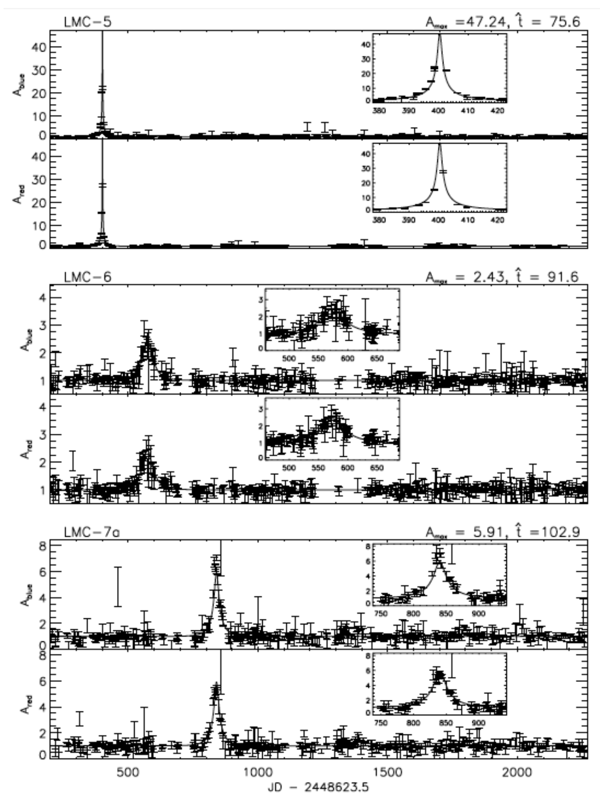

Figure 2. Examples of microlensing observations in the Large Magellanic Cloud. From C. Alcock *et al.* MACHO Collaboration [3].

towards the Large Magellanic Cloud. The inserts are a zoom into the signal region. A detection of an object using microlensing is a rare phenomenon and therefore, surveys typically monitor $O(10^7)$ stars.

The MACHO collaboration observed 12 million stars belonging to the Large Magellanic Cloud and detected $(13 - 17)$ microlensing events. Extrapolations to the Galactic dark matter halo showed that MACHOs could make up about 20% of the dark matter in our galaxy. A 100% MACHO-composition of the Milky Way's dark matter content is however ruled out at 95% C.L. [3] Actually, the baryonic nature of dark matter is meanwhile also ruled out by Big-Bang nucleosynthesis (BBN). The abundance of light elements predicted by BBN depends on the baryon density and, in fact, measurements constrain the baryon density to a value around Ω_b=0.04 close to the value derived from CMB.

Exercise on MACHOS

1.3. Primordial black holes

Besides the constrains from microlensing searches, MACHOS are ruled as explanation for dark matter also due to the effect they would cause on BBN and on the CMB. Black holes formed soon after the Big Bang [4] behave however, as if they would be non-baryonic and therefore, the constrains do not apply. Such primordial black holes (PBH) would form from the collapse of large over-densities in the early Universe. Several constrains on the fraction of mass that can be made up of black holes exist: from black hole evaporation, gravitational lensing, dynamical effects, CMB ... Figure 3 shows an overview of such constrains: with the x-axis the mass of the PBH or MACHO and in

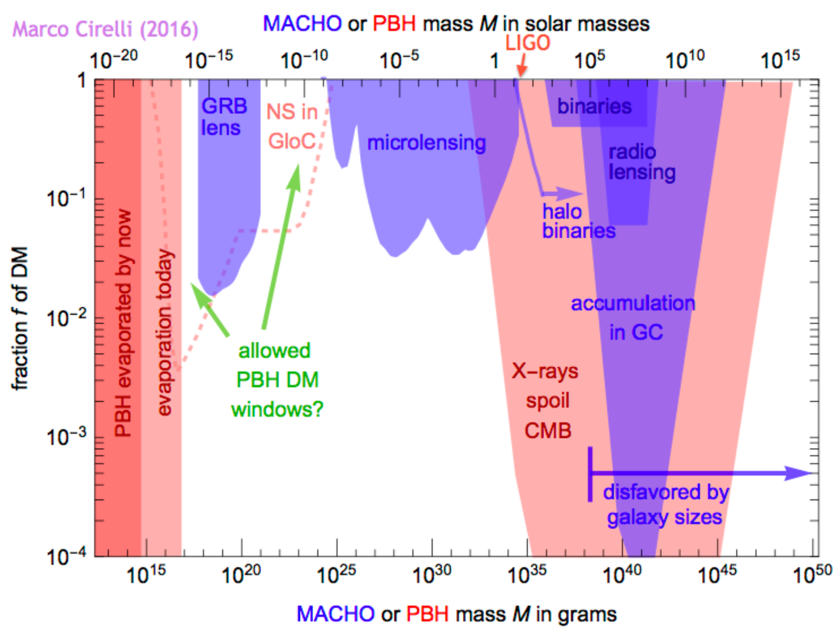

Figure 3. Constrains on the fraction of dark matter that is made up of black holes as a function of the black hole mass. Figure from M. Cirelli (2016).

the y-axis the fraction of dark matter for this given mass. Coloured regions represent the excluded regions in this parameter space. Although there are small windows for which all the dark matter would be allowed in a certain mass, most models predict that black holes are produced with some extended mass function (not all PBH would have the same mass).

1.4. Dark matter properties and the standard model particles

A common ansatz is to assume that dark matter is made out of massive neutral particles featuring a weak self-interaction. Under this hypothesis, we can summarize the properties that such elementary particles would need to fulfil.

- Massive $\rightarrow$ to explain the gravitational effects observed in lensing, dispersion velocities, rotation curves ...
- Neutral particle $\rightarrow$ no electromagnetic interaction, otherwise photons would be emitted/observed
- Stable or long-lived such that they didn't decay until today
- At most weak interaction $\rightarrow$ no strong interaction
- Cold or warm (cold are particles moving non-relativistic at the time when galaxies started forming, hot particles would be moving relativistic at that time, and warm is in-between)

Out of the standard model particles only the neutrino fulfills most of the properties above but not all. Neutrinos would have been produced thermally in the early Universe and due to their small masses would constitute hot dark matter. Cosmological simulations have shown, however, that a Universe dominated by neutrinos would not be in agreement with the observed clustering scale of galaxies [5]. Furthermore, due to the fermionic character of neutrinos, their occupation number is constrained by the Fermi-Boltzmann distribution, thus, they can not account for the observed dark-matter density in halos [6]. For these reasons, the neutrino is also excluded and no particle of the known standard model chart can account for the missing mass.

Exercise on this topic

The standard model is very successful in describing particles and their interactions but there are a few missing aspects. It does not include neutrino masses, it has no explanation for the matter-antimatter asymmetry in the Universe, no explanation for the 3 generations of particles, no unification of forces ... etc. Therefore, new models 'beyond the standard model' which ideally provide a new particle to account for dark matter are considered.

1.5. WIMPs and their production mechanism

If new hypothetical particles would be stable, neutral and have a mass from below GeV/c^2 to several TeV/c^2, they could be the weakly interacting massive particle (usually denoted WIMP). The standard production mechanism for WIMPs assumes that in the early Universe these particles were in equilibrium with the thermal plasma [7].

$$\chi\chi \leftrightarrow e^-e^+, \mu^-\mu^+, q\bar{q}, ZZ, W^-W^+ ... \tag{3}$$

As the Universe expanded, the temperature of the plasma became lower than the WIMP mass resulting in the decoupling of the WIMPs from the plasma. Figure 4 shows the evolution of the dark matter comoving abundance as temperature decreases. At

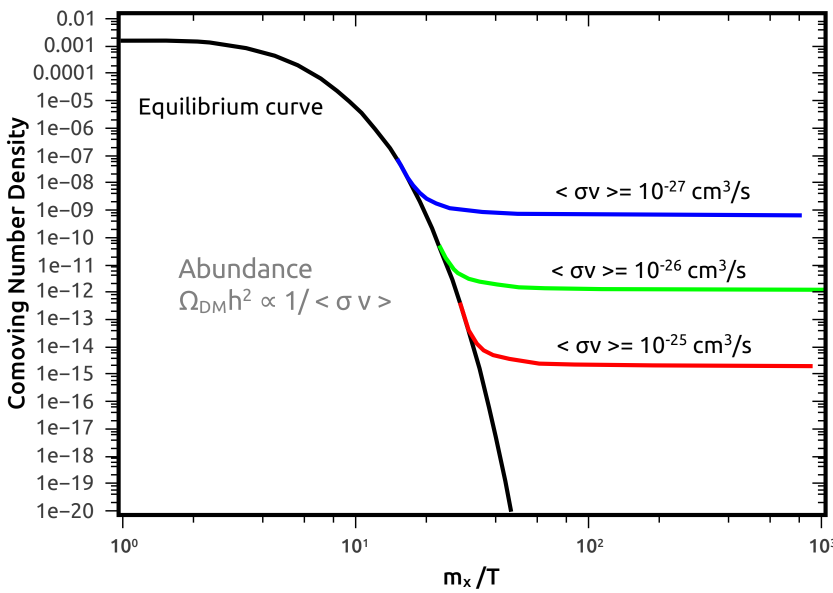

Figure 4. Evolution of the dark matter comoving abundance for different values of the thermally averaged annihilation cross section $\langle\sigma v\rangle$. The figure is taken from [8].

this freeze-out temperature, when the WIMP annihilation rate was smaller than the Hubble expansion rate, a dark matter relic density was reached. Interestingly, the cross-section necessary to observe the current dark matter density is of the order of the weak interaction scale. It appears as a great coincidence that a particle interacting via the weak force would produce the right relic abundance and, therefore, the WIMP is a theoretically well motivated dark matter candidate.

Figure 5 shows the landscape of dark matter candidates in the parameter space of particle mass (in logarithmic x-scale) and cross section with originally matter (also logarithmic y-scale) [9]. Besides WIMPs, the parameter space allowed for other candidates is marked in blue. Some of these new particles will be discussed briefly below or in upcoming lectures.

1.6. WIMPs in Supersymmetry (SUSY)

Supersymmetry models [10] were proposed already in 1973 as extensions of the standard model of particle physics to some of the issues of the standard model like the hierarchy problem or the unification of weak, strong and electromagnetic interactions. Figure 6

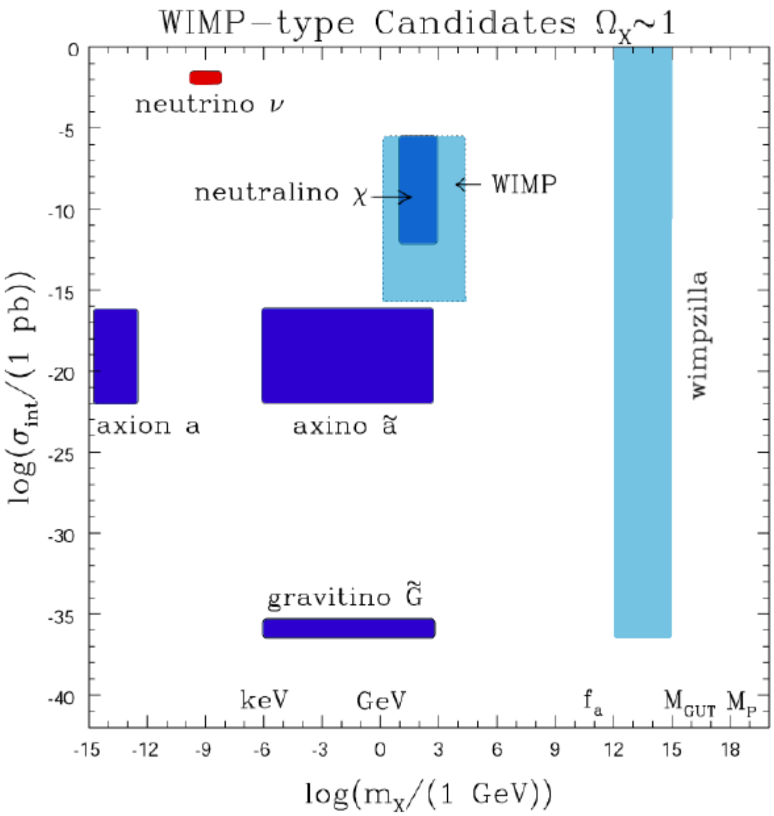

Figure 5. Dark matter particle candidates. Figure from L. Roszkowski arXiv:hep-ph/0404052 [9].

shows how by introducing new supersymmetric particles, the forces that do not meet at a single point when running through the energy in the standard model (left), do meet in Supersymmetry (right). In this model, a whole new set of particles are postulated such that for each particle in the standard model there is a supersymmetric partner. Each particle differs from its partner by 1/2 in spin and, consequently, bosons are related to fermions and viceversa. A new symmetry, the R-parity, is introduced in this model to prevent the decay of the proton. At the same time, it makes the lightest SUSY particle (LSP) stable constituting an ideal DM candidate. There are three possible dark matter candidates arising from supersymmetric models:

- the sneutrino ($s = 0$, partner of the neutrino),
- the neutralino ($s = 1/2$, superposition $\chi = \alpha\tilde{\gamma} + \beta\tilde{Z} + \gamma\tilde{H}_1 + \delta\tilde{H}_2$)
- and the gravitino ($s = 3/2$).

While the sneutrino is already ruled out by measurements, the gravitino, which appears only in supersymmetric models which include gravity, cannot be detected directly. The neutralino, the lightest neutral particle which appears as a superposition of the partners of the standard model bosons, constitutes an example of a new particle fulfilling the properties of a WIMP. The typical masses predicted for the neutralino range from few

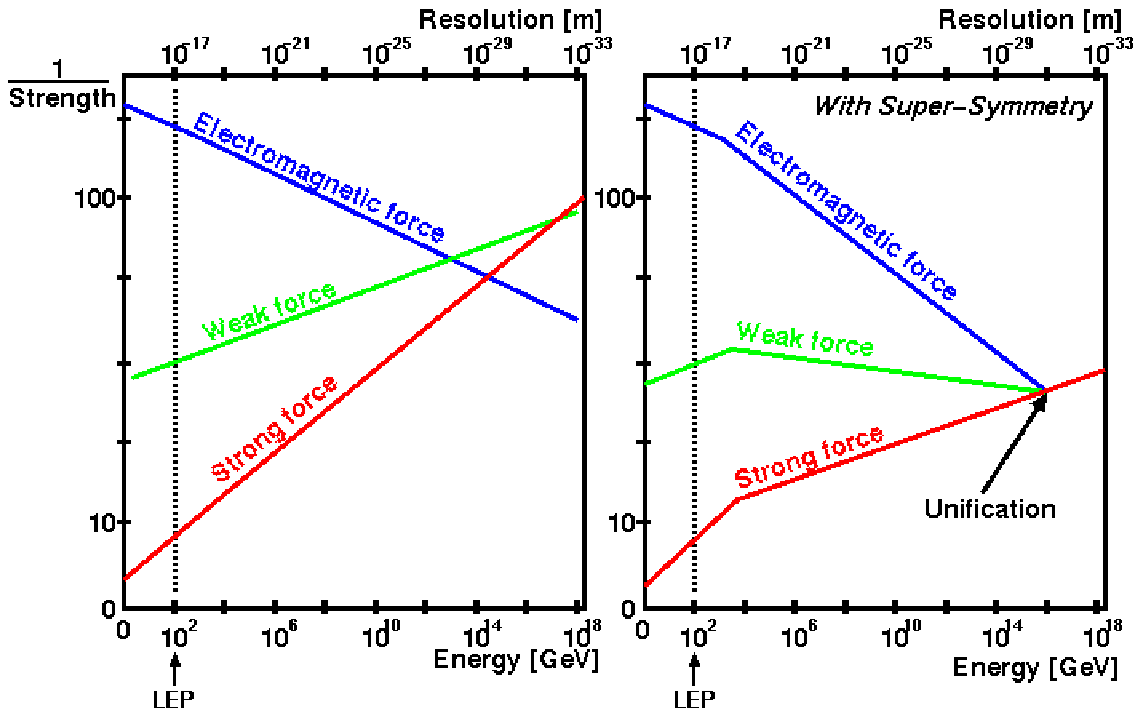

Figure 6. Unification of forces in Supersymmetry. Figure from CERN.

GeV/c^2 to several TeV/c^2.

There are several other models in which a WIMP candidate appear (extra dimensions, for instance) but here we have just discussed SUSY as a well known example for time reasons.

1.7. Superheavy WIMPs, sterile neutrinos and axions

This section gives only a very brief motivation for some other dark matter particle candidates: superheavy WIMPs, sterile neutrinos and axions as dark matter particles.

Among the non-WIMP candidates, 'superheavy dark matter' or 'WIMPzillas' (see figure 5) are postulated to explain the origin of ultra high-energy cosmic rays [11]. At energies close to 10^{20} eV, cosmic protons can interact with the cosmic microwave background and, thus, their mean free path is reduced resulting in a suppressed measured flux. Experimental results show, however, a few events above the expected cut-off, motivating a superheavy dark matter candidate. Decays of these non-thermally-produced superheavy particles with masses of $(10^{12} - 10^{16})$ GeV/c^2 could account for the observation of excess events, being at the same time responsible for the dark matter in the Universe.

Sterile neutrinos are hypothetical particles which were originally introduced to explain the smallness of the neutrino masses [12]. They are neutral leptons with no ordinary interactions (right-handed ν) besides mixing with neutrinos. Sterile neutrinos are present in many extensions of the standard model and in principle, almost any mass is allowed. Additionally, they provide a viable dark matter candidate. Depending on their production mechanism, they would constitute cold (non relativistic at all times) or a warm (relativistic only in an early epoch) dark matter candidate. A mass region, which is not yet constrained by X-ray measurements or the analysis of dwarf spheroidal galaxies, range from 1 keV to tens of keV. Given this very low mass, and the low interaction strength, the existence of sterile neutrinos is not tested by direct detection experiments. An indication could, for example, arise from the X-ray measurement of the sterile neutrino decay via the radiative channel $N \rightarrow \nu\gamma$ [13].

Finally, a very well motivated particle and dark matter candidate is the axion. In the standard model, there is no fundamental reason why QCD should conserve P and CP. However, from the experimental bound on the neutron electric dipole moment, very small values of P and CP violation are obtained. In order to solve this so-called 'strong CP-problem' [14], a new symmetry was postulated [15] in 1977. When this symmetry is spontaneously broken, a new massive particle, the axion, appears. The axion mass and the coupling strength to ordinary matter are inversely proportional to the breaking scale f_a which was originally associated to the electroweak scale (m_a, $g_{aii} \propto 1/f_a$). This original axion model is however ruled out by laboratory experiments [16]. Cosmological and astrophysical results provide also very strong bounds on the axion hypothesis. There exist, however, further 'invisible' axion models in which the breaking scale is a free parameter and still provide a solution to the CP-problem. Invisible axions or axion-like particles, would be produced non-thermally in the early Universe giving the right dark matter abundance. The resulting free streaming length would be small and, therefore, these axions are a "cold" candidate. Axion couple to matter in processes similar to Compton, Primakoff scattering and Bremstrahlung (g_{aNN}, $g_{a\gamma\gamma}$ & g_{aee}) and those are the interactions that are employed experimentally for their detection. Axions will be discussed in a dedicated lecture.

1.8. Summary and outlook

In this lecture we have reviewed briefly the most common explanations to the plethora of evidences for dark matter from Cosmology and Astronomy. We started discussing the modification of Newtonian dynamics but we realized that only a subset of the observations are satisfied by these theories. Next, we consider large massive objects like MACHOS or primordial black holes. While the MACHOS are ruled out by observations and BBN arguments, there is some parameter space available for primordial black holes. Most of the lecture was dedicated to new elementary particles arising from different models (which are usually not motivated by dark matter).

In the upcoming lectures we will discuss how to tests all these hypothesis. Figure 7 shows a scheme of possible detection ways. We will cover indirect and direct detection and also will discuss axion searches. Note that we are not covering searches at accelerators/LHC as this is a lecture focussing on detectors for astroparticle physics.

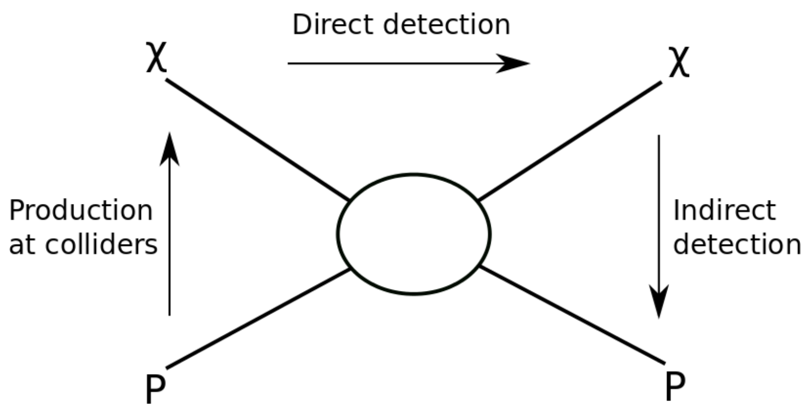

Figure 7. Schematic showing the possible dark matter detection channels. Figure from [17].

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