Università degli Studi di Studi di Padova

DIPARTIMENTO DI FISICA E ASTRONOMIA
Corso di Laurea triennale in Fisica

Tesi di laurea triennale

Testing phenomenological Dark Matter models using the Fermi LAT data

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Anno Accademico 2014–2015

To all the people who share the breathtaking daze
that so much is still unknown, out there, in our Universe.

Contents

Chapter 1

Introduction

In 1933, Swiss astronomer Fritz Zwicky, while studying clusters of galaxies at Caltech, first found a discrepancy between the visible mass and the gravitational effects of the Coma Cluster: since then, many proofs about the existence of much more matter than we can normally detect were reported (galaxy rotation curves and gravitational lensing, just to name two of them), leading to the nowadays solid hyphotesis that about the 25% of our Universe is made of “dark” matter, usually referred to as DM. Even though other hypothesis were formulated in order to explain these incongruities, throughout the last 80 years, especially from the 1970s, DM raised more and more interest, pushing scientists to introduce theories to explain the nature of this hidden matter and to develop more and more sophisticated experiments in order to detect it.

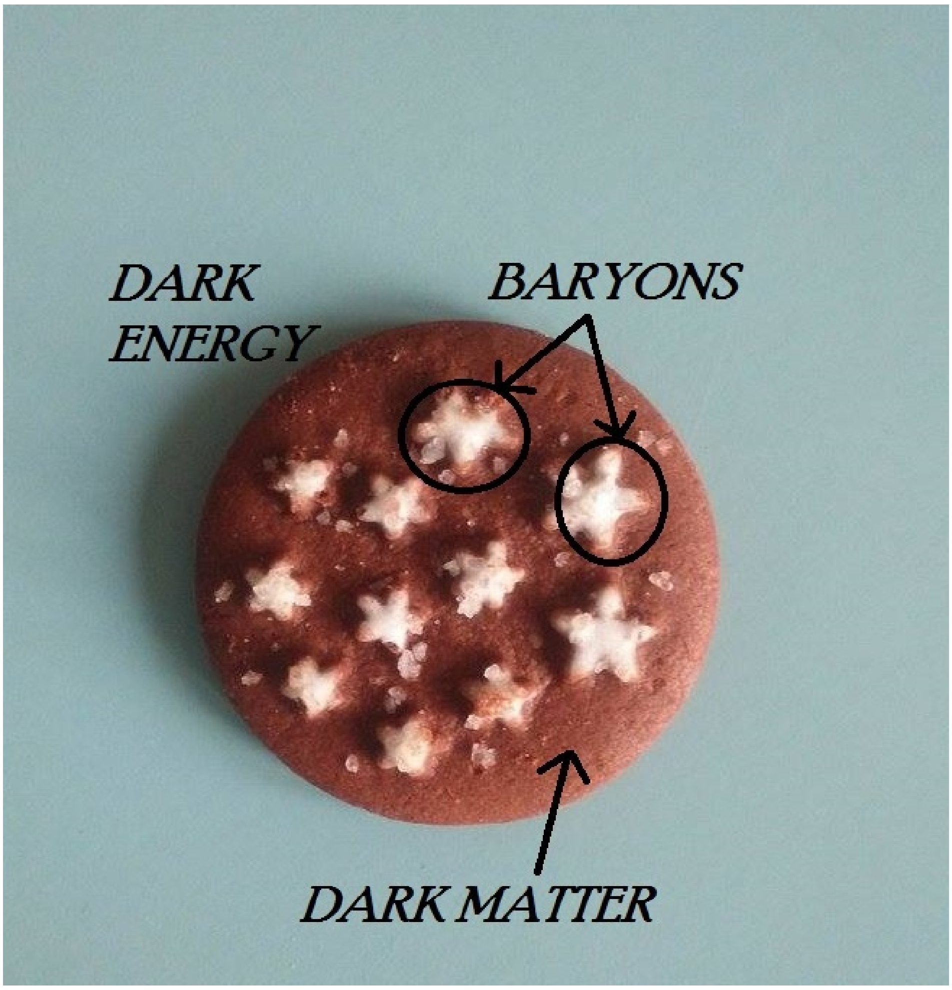

Figure 1.1: Contents of the Universe, as illustrated by a chocolate biscuit.

The models proposed for DM, listed below, usually conjugate particle physics and astrophysics: some exotic but cutting-edge theories, like SUperSYmmetry (SUSY) and Universal Extra Dimension (UED), naturally offer many candidates, that are introduced to solve problems of the Standard Model (SM) but satisfy some of the mass and relic density DM costraints as well. Anyway, DM candidates range from SM particles, like neutrinos or CHAMPs, to even particles emerging from String and M-Theory: this really broadens our perspective on the circus that surrounds the so-called SM zoo.

But in order to be a good candidate, a particle needs to be detected, or, at least, to be detectable: although the direct detection path is currently followed (see DAMA/LIBRA experiment at the Laboratori Internazionali del Gran Sasso as an example), in this work indirect DM detection through photon signals (γ-rays) is considered. In this chapter, a list of DM models is presented; in chapter 2 information about the Fermi LAT and data analysis method are reported, while in chapter 3 the expected flux calculation is performed and subsequent steps for future analysis are described; a small final section is dedicated to future possible paths that could be followed in order to finally uncover the DM mystery.

1.1 DM models

In this chapter, we are first going to enumerate and describe some of the DM models, along with some information about their origin and photon-annihilation cross section. A wide bibliography is reported. Candidates are divided in groups that share some characteristics.

- **NEUTRINO-LIKE PARTICLES**:

    1. **NEUTRINOS**: the first candidate we consider is an actual particle of the Standard Model[1], extensively studied and well-known. The advantage of considering the neutrino as the origin of Dark Matter definitely relies on the fact that we know it does exist, and has been first detected in 1956. On the other side, a disadvantage of this model comes from the observation that if the neutrino is the particle Dark Matter is made of, for sure it can't be *the only* particle constituting Dark Matter. Indeed, upper bounds on its mass constrain it not to be abundant enough to be the dominant component of Dark Matter. As far as the annihilation cross section is concerned, for example in the $\nu\overline{\nu} \to \gamma\gamma\gamma$ channel, we can write

        $$\sigma(\nu\overline{\nu} \to \gamma\gamma\gamma) = \frac{136}{91.125}\frac{G_F^2 a^2 \alpha^3}{\pi^4}\frac{w^8}{m_e^8}\omega^2, \tag{1.1}$$

        in which G_F is the Fermi coupling constant, ω is the photon energy, α is the fine-structure constant, and a is a related to θ_W, the Weinberg angle.

        Experimentally, while performing indirect observations of Dark Matter, we are only able to measure photons produced during the processes of annihilation of Dark Matter particles. This is indeed also the case of the Fermi/LAT satellite experiment, on which we are focusing on. Thus, since we are not able to distinguish among different processes of annihilation, in which one or more photons may be produced, we must take into account all the other process that yield one or more photons as final state, such as:

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[1] *"Numquam ponenda est pluralitas sine necessitate"*, *i.e.* Plurality is never to be posited without necessity *[2]*.

i) processes of photon-neutrino scattering, the total cross section of which reads

$$\sigma(\gamma\nu \to \gamma\nu) = \frac{3}{4}\frac{G_F^2\alpha^2}{\pi^3}\left[1+\frac{4}{3}\ln\left(\frac{m_W^2}{m_e^2}\right)\right]^2\left(\frac{\omega}{m_W}\right)^4\omega^2\,, \tag{1.2}$$

if there is no creation of extra photon, or the α-suppressed contribution

$$\sigma(\gamma\nu \to \gamma\gamma\nu) = \frac{262}{127.575}\frac{G_F^2\alpha^3 a^2}{\pi^4}\left(\frac{\omega}{m_e}\right)^8\omega^2\,, \tag{1.3}$$

when an extra photon is created;

ii) the channel, of order α^3, accounting for scattering of two photons and creation of a pair of $\nu\bar{\nu}$, with total cross section

$$\sigma(\gamma\gamma \to \gamma\nu\bar{\nu}) = \frac{2.144}{637.875}\frac{G_F^2\alpha^3 a^2}{\pi^4}\left(\frac{\omega}{m_e}\right)^8\omega^2\,. \tag{1.4}$$

We will have then to sum over the amplitudes of the processes that entail the same number of initial states, *i.e.* sum over the amplitudes of the process $\gamma\nu \to \gamma\nu$ and $\gamma\nu \to \gamma\gamma\nu$, and then calculate the cross section for them. This contribute must be then summed to the cross sections of the processes, namely $\nu\bar{\nu} \to \gamma\gamma\gamma$ and $\gamma\gamma \to \gamma\nu\bar{\nu}$, to be calculated separately, since they involve different physical initial states. Notice that, being the process $\gamma\nu \to \gamma\gamma\nu$ a radiative correction (brehmsstrahlung) to $\gamma\nu \to \gamma\nu$, we can also disregard it, and just sum the cross sections of the other processes. For further details, see [3].

2. **STERILE NEUTRINOS**: these are hypothetical particles, similar to SM neutrinos, but not affected by the weak-interactions that all the particles in the Standard Model are subjected to. These particle would then interact only through gravity. Furthermore, sterile neutrinos, as heavy massive particles, have been advocated in explaining the origin of neutrino masses in the neutrino Minimal Standard Model (νMSM). As shown in Ref. [5], massive sterile neutrinos mixed with ordinary neutrinos may represent a viable candidate for warm dark matter, since they could have been produced in the early Universe in the right amount. Theoretically, annihilation can't be contemplated, unless a coupling to a new light pseudoscalar ϕ (see e.g. Ref. [6]) is considered. Following Ref. [4] and Ref. [5], we rather characterize the lifetime and related decay of these particles in a lepton-antilepton pair, plus an active flavor of sterile neutrino. The lifetime can be then expressed as

$$\tau = \frac{10^5\ f(m)}{m(MeV)^5\sin^2(2\theta)}\,s\,, \tag{1.5}$$

where $f(m)$ takes into account the open decay channels (for $m <$ 1 MeV only the neutrino channels are open, and $f(m) = 0.86$, while for $m_s > 2m_e$ the $e^+ \, e^-$ channel is also open and $f = 1$), and θ is the mixing angle with the electron.

3. **HEAVY FOURTH GENERATION NEUTRINOS**: in most scenarios, these heavy neutrinos are excluded as a cold dark matter candidate by a combination of LEP (Large Electron-Positron Collider) and direct detection limits; in Ref. [22], anyway, a reaction like $N\overline{N} \to e^+ \, e^- \to \gamma\gamma$ had been admitted, but heavy neutrinos have more problems than the number of those they can be a solution of. Thus we will disregard this possibility in our investigation.

- **STRING, BRANE AND M-THEORY**:

  1. **AXIONS**: these are hypothetical particles, very-light and weakly-interacting. Theoretically, they have been postulated as a way to solve the problem of CP violation in quantum chromodynamics. Their framework is contiguous to the one of String Theory, and in analogy to this latter axions entail a huge number of parameters that depend on the details of the model. Their production mechanism is also crucial to derive observational consequences. No experimental evidence has been found so far, as the value of the photon-annihilation cross section depends on the model. Nevertheless, it's worth mentioning Ref. [7], in which the two-photon axion-decay lifetime is derived to be:

  $$\tau_a = \bar{\tau} \; \frac{\left(\frac{m_a}{eV}\right)^{-5}}{\left[\frac{\left(\frac{E}{N}-\alpha\right)}{\beta}\right]^2} \, . \tag{1.6}$$

     where $\bar{\tau} = 6.8 \cdot 10^{24}$ s, m_a denotes the mass of the axion (which ranges from 1 MeV to 10^{-12} eV, and is costricted to be lower than 10 keV by the latest experimental results), N and E are respectively the color and electromagnetic anomaly of the PQ simmetry, E/N ranges from 2 to 8/3 and the parameters $\alpha = 1.95$ and $\beta = 0.72$ have been considered. Anyway, a two-photon interaction that allows axion photon conversions in presence of an electromagnetic field can be investigated as well, and the expected flux of photons in presence of an electromagnetic field in the galaxy, or along their path towards us, may be calculated (see Ref. [47]). This investigation channel is not pursued here, though, as experimental and theoretical searches are still ongoing.

  2. **D-MATTER**: these are particle-like states originating from D-branes whose spatial dimensions are all compactified. Even though

techniques for calculation of full cross section are still under development, the annihilation of D-matter is expected to be small, but large enough to account for some of the events of ultra-high energy cosmic rays (UHECRs), provided that some special features of the local density of dark matter are satisfied (see Ref. [23]). No signal of their existence has been detected so far.

3. **CRYPTONS**: these are superheavy stable or metastable bound states of matter in the hidden sector, emerging from String and M- Theory. The literature on this subject is still under development. Nevertheless, few predictions have been provided, including the expected neutrino flux of the cryptons' decay, which, as reported in Ref. [13], corresponds to the number

   $$\Lambda = \frac{10^6 \text{ events}}{\text{km}^2 \cdot \text{year}} \,. \tag{1.7}$$

   In Ref. [14] it is shown that cryptons can be accommodated in String or M-Theory to have a definite mass, to undergo very weak interactions and have long lifetimes. These superheavy particles, with an abundance close to that required for a near-critical Universe, can be produced during inflation, and for some specific models popular in the literature, have been predicted to have an hidden-sector bound states weighing 10^{12} GeV. Finally, as reported in Ref. [15], cryptons' lifetime is expected to be

   $$\tau \simeq \frac{1}{m_x}\left(\frac{M}{m_x}\right)^{2(N-3)} , \tag{1.8}$$

   where $M \simeq 10^{18}$ GeV, m_x equals the energy-scale Λ_x of the specific instantiation of the theory taken into account[2] and N is the order of renormalization.

4. **BRANE WORLD DARK MATTER**: also known as branons, these hypothetical particles are "massive brane fluctuations" expected to be nearly massless and weakly interacting at low energies, emerging in brane-world models. According to Ref. [17] and Ref. [18], branons can interact with nucleons with a cross section

   $$\sigma = \frac{9M^2 m^2 \mu^2}{64\pi f^8} \,, \tag{1.9}$$

   where M is the branon mass, m the nucleon mass, $\mu = \frac{Mm}{M+m}$ and f is the tension scale; but they can be detected indirectly as

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[2] For instance, in the "flipped SU(5)" model, there are two confining non-abelian gauge factors: SO(10), whose coupling constant becomes strong at 10^{15} GeV, and SU(4), which becomes strong at 10^{12} GeV.

well: their annihilation can give rise to pairs of photons, directly or through branon annihilation into ZZ and W^+W^- (in which case, the produced high-energy gamma photons could be in the range 30 GeV-10 TeV). Another possibility is annihilation into the heaviest possible quarks, in which case the photon fluxes would be in the range detectable by space-based gamma ray observatories such as EGRET (energy range of 0.02-30 GeV) and FERMI (20 MeV-300 GeV). Going further, the Z,W annihilation cross section in the non-relativistic limit can be calculated (see *e.g.* Ref. [19]) to be

$$\langle \sigma v \rangle = \frac{M^2 \sqrt{1 - \frac{m_{Z,W}^2}{M^2}} (4M^4 - 4M^2 m_{Z,W}^2 + 3m_{Z,W}^4)}{64\pi^2 f^8} , \quad (1.10)$$

where f is the brane tension scale. Consequently, the flux predicted for the photons can be calculated using the well known photon annihilation cross section for Z and W. See also Ref. [20] for first order calculation, such as annihilation into massless gauge field, for which the leading order is

$$\langle \sigma v \rangle = 0 \, . \quad (1.11)$$

Last but not least, in Ref. [21] the photon-annihilation branons cross section is calculated, leading to

$$\sigma = \frac{1}{1920 N f^8 \pi} \frac{s(s - 4M^2)^2}{\sqrt{1 - \frac{4M^2}{s}}} , \quad (1.12)$$

where N is the number of branons and $s = (p_1 + p_2)^2 = 4\mathrm{E}^2$ is a Mandelstam variable (in the centre-of-mass reference frame). Considering N =1, in order to get a detectable particle (for this paper) we need to assume 10^6 GeV $> M > 10^2$ GeV and 1 GeV $< f < 10^6$ GeV. In this case, the cross section depends on the energy, so its value is not displayed here.

The problem with this candidate is that, for our analysis, DM particles are considered to be very slow, so that the energy E of the incoming photons is always smaller than the mass of the annihilating particle, namely $E < M_{DM}$, since all of the mass of the annihilating particles goes into the energy of photons, which may then lose energy because of non-kinematic effects (see formula 2.1 for further details). The cross section displayed above becomes a complex number: thus, this candidate will not be considered for data analysis.

- **SUSY, a.k.a. SUPERSYMMETRIC PARTICLES**: supersymmetry is one of the most elegant and promising theories beyond the Standard Model; it offers many DM candidates as well: looking for the LSP (Lightest Supersymmetric Particle) in the MSSM (Minimal Supersymmetric Standard Model), we find

  1. **NEUTRALINO**: "formed" by a wino, a bino and a couple of Higgsinos, the neutralino is the most considered and promising candidate. Many things could be said about this particle, but to be synthetic, let's get down to business: the neutralino interactions most relevant for the purposes of dark matter are self annihilation and elastic scattering off of nucleons. These are expected to be extremely non-relativistic in the present epoch, allowing to write

     $$\sigma v = a + bv^2 + \mathcal{O}(v^4) \simeq a\,. \tag{1.13}$$

     At low velocities, the leading channels for neutralino annihilation are annihilations to fermion-antifermion pairs (primarily heavy fermions, such as top, bottom and charm quarks and tau leptons), gauge bosons pairs (W^+W^- and Z^0Z^0) and final states containing Higgs bosons. Taking a look at the very complete Ref. [41], results for the W^+W^-, ZZ, Higgs boson, fermions and gluons annihilation cross section are reported, but the annihilation process to photons, the most complicated of the two-body annihilation channels, is considered as well. Referring to [42], the cross section is

     $$\sigma_{\gamma\gamma} v = \frac{\alpha^2 m_X^2}{16\pi^3} |\overline{\mathcal{A}}|^2, \tag{1.14}$$

     where many pages of calculation are needed to find the value of the amplitude $\overline{\mathcal{A}}$. Notice that in this work the annihilation channel $XX \to Z^0\gamma$, that gives a monoergetic photon line and was first examined in Ref. [58], is not taken into consideration; its cross section is estimated to be about 3.4 times as large as that for the process $XX \to \gamma\gamma$. Since in Ref. [59] a plateau value for the $Z\gamma$ cross section is calculated[3] to be $\sigma v = 0.6 \cdot 10^{-28}$ cm^3/s an arbitrary value of $\sigma_{\gamma\gamma} v = 1.8 \cdot 10^{-29}$ cm^3/s is set. As far as its mass is concerned, the value $m = 1$ TeV is chosen.

  2. **SNEUTRINO**: the sneutrino, the superpartner of the neutrino, evades some of the costraints for DM (for example, the scattering cross section with nucleons, see *e.g.* Ref. [1]). For this reason,

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[3] In Ref. [59] neutralino is considered as made only of one higgsino: literature about this topic is quite dispersive, and arbitrary assumptions need to be made.

not much can be found in literature, but in Ref. [43] the cross section is calculated for a Dirac right-handed sneutrino

$$\langle \sigma v \rangle = \frac{|\mathcal{M}|^2}{32\pi M^2_{sneutrino}} \simeq \frac{\alpha^2_{em}}{8\pi^3} \frac{y^4_\nu (A^2_\nu + \mu\text{'}^2)^2}{M_{\tilde{l}^4}} \frac{4}{M^2_{sneutrino}}\ , \quad (1.15)$$

where $\mathcal{M}$ is the Feynman amplitude of the annihilation, the expression of which can be recovered in reference [43] itself. Assuming $M_{sneutrino} = 130$ GeV, $\frac{y^4_\nu (A^2_\nu + \mu\text{'}^2)^2}{M_{\tilde{l}^4}} = 1.8$ and $\alpha_{em} = 1/127$, we get $\sigma v = 1.065 \cdot 10^{-10}\ \mathrm{GeV}^{-2} \cdot (\hbar \mathrm{c})^2 \cdot \mathrm{c} = 1.249 \cdot 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$. As in the neutralino case, an annihilation channel into a γZ couple is predicted, leading to a photon line signal; it will not be considered in this work, though. The predicted cross section is $\sigma v_{1\gamma} = \frac{\sigma v_{2\gamma}}{\cos^2 \theta_W} \left(1 - \frac{M^2_Z}{4M^2_{sneutrino}}\right)$ where θ_W is the Weinberg angle and M_Z is the mass of the Z boson. Taking $\cos^2 \theta_W = 0.77$ and $M_Z = 91$ GeV, we get $\sigma v_{1\gamma} \simeq 1.14 \sigma v_{2\gamma}$.

3. **GRAVITINO**: the superpartners of the graviton, with spin 3/2, gravitinos are very strongly theoretically motivated. With only gravitational interactions, however, they are very difficult to observe, they can pose problems for cosmology, and their presence can destroy the abundances of primordial light elements in some scenarios. Gravitinos may also be overproduced in the early universe if the temperature of the reheating epoch is not sufficiently low. As far as their annihilation cross section is concerned, nothing was found.

4. **AXINO**: the superpartner of axion, this particle is strongly motivated but quite neglected in literature as DM. It shares similar phenomenological properties with the gravitino. Decay and annihilation are predicted, but nothing “theoretical” was found (only lifetime decay into a gluon gluino pair, see Ref. [44]).

5. **QUINTESSINO**: contemplating quintessino as a dark matter particle allows to unify dark matter and dark energy in only one superfield, where the dynamics of the Quintessence drives the Universe acceleration and its superpartner, quintessino, makes up the dark matter of the Universe (see Ref. [45]). Also known as Quintessence boson, this particle is expected to decay into stau [45], whose detection is shown to be possible in the cosmic rays framework. We were able to find nothing more.

6. **PHOTINO**: the superpartner of the SM photon, it had been considered as a DM candidate, but in recent years it was neglected. Nevertheless, in Ref. [61], it is shown to decay in a $\gamma\gamma$

couple: assuming a photino mass $m_\lambda = 10$ GeV, the value of the annihilation cross section is

$$\sigma v = 4\frac{\alpha^4}{\pi}\frac{m_\lambda^2}{m^4}\left|\sum_f \mu_f^2 Q_f^4 F(1/\mu_f^2)\right|^2 . \tag{1.16}$$

The meaning of the parameters is in the paper itself, but another path is followed to perform the calculation: since in the paper the ratio between this cross section and the charm-anticharm annihilation cross section is reported, we find

$$\sigma v = R(10\text{ GeV}) \cdot \sigma v_{cc} \simeq 0.7 \cdot 10^{-4}\frac{128\pi\alpha^2 m_c^2 \beta_c}{27 m^4} \tag{1.17}$$

where $\alpha = 1/127$, $m_c = 1.29$ GeV is the mass of the quark charm, whose speed is assumed to be $\beta_c = 10^{-3}$, and m is the common mass for all squarks and sleptons[4], taken to be $m \simeq 300$ GeV (see Ref. [62]). Thus we find $\sigma v = 1.33 \cdot 10^{-20}$ GeV$^{-2} \cdot (\hbar c)^2 \cdot$ c $=$ $1.558 \cdot 10^{-37}$ cm^3/s.

7. **GOLDSTINO**: this is a Nambu-Goldstone fermion, superpartner of the Nambu-Goldstone boson, which is predicted to annihilate in many ways (see for instance Ref. [46]). The two-photon annihilation cross section can be then found to be

$$\begin{aligned}\sigma = \frac{1}{1728\pi}\frac{\kappa}{m_{3/2}^4} m_{\overline{\gamma}}^4 s\Bigg[1 + \frac{6x(1-2x-4x^2)}{1+x} + \\ + \frac{6x(-x+4x^2+8x^3)}{1+2x}\log\left(1+\frac{1}{x}\right)\Bigg] ,\end{aligned} \tag{1.18}$$

where $m_{3/2}$ is the gravitino mass (that can range from 10^{-6} eV to 1 TeV [60], so $m_{3/2} \simeq 100$ keV for us), $m_{\overline{\gamma}}$ is the photino mass, $s = 4E^2$ (E is the energy of the annihilating particles in the centre of mass frame reference), $x = m_{\overline{\gamma}}^2/s$ and $\kappa = 1/M_{PL}$ where $M_{PL} \simeq 1.22 \cdot 10^{22}$ GeV is the Planck mass. The quantity in square bracket is plotted in the quoted reference.

Anyway, in most scenarios Goldstino is massless, so it is not an eligible candidate for our investigation (see chapter 3).

8. **Q-BALLS**: a Q-ball is a nontopological soliton composed of a complex scalar field ϕ, predicted from the MSSM These particles are not reported to annihilate into photons, but rather decay into neutrinos, charged leptons, and their antiparticles (mainly positrons, see Ref. [16] for discussion about the charge and decay lifetime of Q-balls, as well as for the reasons for the impossibility for Q-balls to account for all the DM).

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[4] To this day, the hypothesis that sleptons and squarks share the same mass is abandoned, though.

- **DM FROM LITTLE HIGGS MODELS**: as an alternative mechanism (to supersimmetry) to stabilize the weak scale[5], many varieties of little Higgs models have been shown to contain possible DM candidates. In this paper we are going to study one of them, but others are found in literature (see, for instance, Ref. [1] and Ref. [34]).

  1. **FIRST VARIETY OF LITTLE HIGGS MODELS**: also called "theory space" little Higgs model, it predicts a particle called heavy photon, that is expected (see *e.g.* Ref. [32]) to produce γ rays through many channels:

     (a) monochromatic photons produced via direct annihilation into a two body final state ($\gamma\gamma$, hγ or Zγ);

     (b) photons radiated in the process of hadronization and fragmentation of strongly interacting particles produced either directly in WIMP annihilation or in hadronic decays of the primary annihilation products;

     (c) photons produced via radiation from a final state charged particle.

     Elaborated formulas about cross section values are reported in Ref. [32]; in this work we are going to consider only the $\gamma\gamma$ contribution to flux due to the direct DM annihilation. The particle is assumed to have a mass M between 100 GeV and 300 GeV: thus we get

$$\sigma v = \frac{g'^4 v^2}{72M^4} \frac{s^2 - 4sM^2 + 12M^4}{(s - m_h^2)^2 + m_h^2 \Gamma_h^2} \frac{\hat{\Gamma}(h \to \gamma\gamma)}{\sqrt{s}} \tag{1.19}$$

     where $m_h = 125.3$ GeV is the mass of the Higgs boson, Γ_h its width (a parameter related to its lifetime) and $v \simeq 246$ GeV its vev (vacuum expectation value, namely its average expected value in the vacuum), $s \simeq 4M^2$, g' is the U(1) gauge coupling parameter and finally $\hat{\Gamma}(h \to \gamma\gamma)$ is linked to the contributions from loops of particles of spin s. The value of the cross section here is obtained starting from the end, though: in Ref. [32], we find the values of the flux Φ as a function of the mass, namely

$$\Phi = (1.1 \cdot 10^{-9}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}) \left(\frac{\sigma_{\gamma\gamma} v}{1\mathrm{pb}}\right) \left(\frac{100\mathrm{GeV}}{M}\right)^2 . \tag{1.20}$$

     Furthermore, considering $m_h = 125.3$ GeV, we have $M \simeq 110$ GeV: for this value, we get $\log_{10} \Phi \simeq -13.3$, which means $\Phi \simeq$

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[5] It is not clear yet why the weak force is 10^{32} times stronger than gravity, as theory predicts it to be much weaker; furthermore, theoretical divergences to the mass of the Standard Model Higgs boson need to be explained.

$5.01 \cdot 10^{-14}$ cm^{-2} s^{-1}, that leads to $\sigma v = 5.51 \cdot 10^{-5}$ pb c $= 1.654 \cdot 10^{-30}$ cm^3/s.

The two additional processes that can produce monochromatic photons (*i.e.*, $B_H B_H \to Z\gamma$ or $B_H B_H \to h\gamma$) will be examined in a more detailed way elsewhere (see Ref. [33] for more details), together with (b) and (c) cases.

- **OTHERS**:

  1. **KALUZA-KLEIN STATES**: emerging in the Universal Extra Dimensions (UED) framework (first introduced by Kaluza around 1920, in an attempt to concile gravity and electromagnetism), this particle, also known as *pyrgon* or $B^{(1)}$ but LKP (which stands for Lightest Kaluza-Klein Particle) as well, is associated with the first Kaluza-Klein excitation of the photon (better, of the hypercharge gauge boson). If the LKP is to account for the observed quantity of dark matter, its mass should lie in the range of 400 GeV to 1200 GeV; moreover, following Ref. [1], the $B^{(1)}$ annihilation cross section is given by

     $$\sigma v \simeq \frac{0.6\text{pb}}{m^2_{B^{(1)}}[TeV]} \,. \tag{1.21}$$

     One expects to find as final states of the annihilation process pairs of fermion-antifermion, namely charged lepton pairs. Nevertheless, in Ref. [35] also the cross section for Higgs boson pair annihilation is reported. Direct detection does not appear the most promising way to probe $B^{(1)}$ LKP dark matter, but indirect detection has been considered: many channels are possible, but in particular gamma-ray flux has been predicted. In Ref. [36] the total annihilation cross section is provided

     $$\langle \sigma v \rangle \simeq \frac{1.7 \cdot 10^{26} cm^3/s}{(m_{LKP}/TeV)^2} \,, \tag{1.22}$$

     and the fact that couples of e^+e^- can produce gamma-rays is stressed.

     In Ref. [38] photons radiated from charged leptons have been considered, and the main Feynman diagrams have been written down. But the computation of the cross section has not been performed, since these processes are higher-order in perturbation theory.

     In Ref. [39] the fermionic one-loop cross section for the two photon annihilation of Kaluza Klein dark matter particles has been investigated. This process gives a nearly mono-energetic gamma-ray line, with energy equal to the mass of the KK dark matter particle. The calculated cross section is then

$$\sigma v = \frac{\alpha_Y^2 \alpha_{em}^2 g_{eff}^4}{144\pi m_{B^{(1)}}^2}\{3|B_1|^2 + 12|B_2|^2 + \\ +4|B_6|^2 - 4Re[B_1\ (B_2^* + B_6^*)]\}\,, \tag{1.23}$$

in which:
- $g_{eff}^2 = \frac{52}{9}$;
- $\alpha_Y = \frac{g_{eff}^2}{4\pi}$;
- $\alpha_{em} = \frac{e^2}{4\pi}$;
- $m_{B^{(1)}}^2$ is the mass of the particle;
- B_1, B_2 and B_6 are dimensionless scalars appearing in the decomposition of the polarization tensor, related to the mass shift between the $B^{(1)}$ and KK fermions, namely $\eta = \frac{m_{\chi^{(1)}}}{m_{B^{(1)}}}$.

Assuming $m_{B^{(1)}} = 0.8$ TeV and $\eta = 1.05$, we get $\sigma v = 130\text{c} \cdot 10^{-6}$ pb $= 3.9 \cdot 10^{-30}$ cm^3/s .

Finally, in Ref. [40] the cross section for the annihilation into fermions is reported, together with the expected gamma-ray and neutrino fluxes.

2. **WIMPZILLAS**: superheavy dark matter, relics from the Big Bang, must not have been in thermal-equilibrium during freeze-out to be allowed to evade the *unitary bound* (maximum annihilation cross section). Despite the attempt of developing many top-down cosmic-rays scenarios, in which wimpzillas may annihilate into ultra-high energy cosmic-ray particles (even though this interpretation is today problematic because it predicts a large photon component in the UEHCRs spectrum, in disagreement with the recent results of some experiments (see Ref. [47]), these particles, among which is the inflaton, do not seem to be able to annihilate into photons; numerical simulations were made to try to explain UHECRs,see Ref. [29]), but results were not positive. In Ref. [29], a discussion about the decay lifetime and experimental constraints can be found, but γ-rays fluxes have not been provided.

3. **LIGHT SCALAR DARK MATTER**: these are fermionic dark matter candidates with standard Fermi interaction, with sub-GeV mass. As explained in Ref. [30], the direct detection of LDM (Light Dark Matter) candidate particles is investigated considering the possible inelastic scattering channels either on the electron or on the nucleus target: in fact, since the kinetic

energy for LDM particles in the galactic halo does not exceed hundreds eV, the elastic scattering of such LDM particles both on electrons and on nuclei yields energy releases well below the energy thresholds of the detectors used in the field; this prevents the exploitation of the elastic scattering as detection approach for these candidates. Thus, the inelastic process is the only possible exploitable one for the direct detection of LDM: as an example, the LDM candidate may interact with the ordinary matter target, T, which can be either an atomic nucleus or an atomic electron depending on the nature of the colliding particle; as a result of the interaction a lighter particle is produced, and the target recoils with an energy which can be detected by suitable detectors. Moreover, LDM was suggested for being the responsible for the 511 keV gamma-ray line emission observed by the INTEGRAL satellite (annihilation into positrons, and subsequent gamma-ray line): even though other sources were considered, a small signature could be expected from dwarf spheroidal galaxies (dSph), and, as explained in Ref. [31], assumed that each annihilating pair of dark matter particles form a single positron which eventually annihilates producing two 511 keV gamma-rays, the flux of this gamma-ray line could be calculated. Anyway, since this line is out of the Fermi LAT range, this candidate needs to be ruled out from our list.

4. **MIRROR PARTICLES**: these strange and fascinating particles emerge from adding to the SM a mirror sector: the entire SM zoo is copied ad pasted, together with its interactions. These mirror particles have been introduced to alleviate the hierarchy problem, namely “the enormous difference between the weak and Planck scales in the presence of the Higgs field”; at the same time, they have been conjectured to conserve parity in weak interactions, too. Mirror particles can interact with ordinary matter both by mixing (for neutral colorless particles, like photons), but mainly through the gravitational force, which is exactly what DM naturally does. There have been many theoretical advancements in the literature. In Ref. [25], for a mirror atom of mass MA' and (mirror) atomic number Z' scattering on an ordinary target atom of mass MA and atomic number Z, the cross section is reported; in Ref. [26], we can even quote

   > *Only mirror matter-type dark matter is capable of explaining all six of these*[6] *desirable features.*

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[6] These are the basic properties of dark matter particles (mass, stability, darkness), the similarity in cosmic abundance between ordinary and non-baryonic dark matter, large scale structure formation, micro-lensing (MACHO) events, asymptotically flat rotation

In Ref. [26], we also find the $\gamma' + e^- \to \gamma + e^-$ cross section (γ' is the mirror particle of the γ)

$$\sigma \simeq 10^{-41}\left(\frac{\epsilon}{5 \cdot 10^{19}}\right)^2 cm^2 \,, \tag{1.24}$$

where ϵ is a factor of magnitude, namely $\epsilon \simeq 10^{-9}$ as suggested by the DAMA signal. In this work we decide to neglect this candidate, since studies are still ongoing and it is not the case of a flux generated by particles' annihilation or decay.

5. **CHAMPs**: according to Ref. [10], DM consists of very massive, charged particles, untedected so far because disguised as heavy isotopes of known chemical elements. In the paper, two estimates for annihilation σ are presented. The first one (*leptonic CHAMPs*) accounts for annihilation into two neutral weak intermediaries, for which the cross section, in the non-relativistic limit, is

$$\sigma v = \pi \alpha^2 M^{-2} \cos^{-4}\theta_W \,, \tag{1.25}$$

where v is the relative particles velocity, θ_W is the weak mixing angle, and M the mass of the CHAMP. The second one (*baryonic CHAMPs*) is simply given by

$$\sigma v = \left(\frac{m}{M}\right)^2 35 \text{ mb} \,, \tag{1.26}$$

where m is the mass of the nucleon (this is the case of nucleon-antinucleon low-energy annihilation). One of the most stringent bounds on the CHAMPs abundance comes from searches of anomalous heavy water. CHAMPs, being chemically identical to heavy hydrogen, can be trapped in oceans and lakes in the form of HXO, but so far, while the expected ratio is

$$\left(\frac{n_X}{n_H}\right) \simeq 10^{-5}$$

all the searches for anomalous hydrogen in sea water have failed, costraining

$$\left(\frac{n_X}{n_H}\right) \simeq 10^{-29}.$$

Furthermore, a combination of underground, baloon-satellites and other experiments excludes masses below 10^{18} GeV, basically ruling out CHAMPs as DM candidates (see Ref. [47]).

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curves in spiral galaxies, the impressive DAMA/NaI annual modulation signal.

6. **SELF INTERACTING DARK MATTER**: these particles, proposed, among the others, in Ref. [8], could solve the conflict between the prediction of weakly interacting CDM (Cold Dark Matter), which means overly dense cores in the centers of galaxies and clusters with an overly large number of halos within the Local Group, and actual observations. If DM particles are self-interacting, with a large scattering cross section but negligible annihilation or dissipation, this conflict can be resolved. Spergel and Steinhardt proposed a XX cross section in the form

   $$\sigma_{XX} = 8.1 \cdot 10^{-25}\ cm^2 \frac{m_x}{GeV} \frac{1Mpc}{\lambda}\,, \tag{1.27}$$

   where λ is DM particles' mean free path. Moreover, following Ref. [9], we must admit (without a complete formula) that the dark matter self interaction must have sufficiently large cross section, $\frac{\sigma}{m_X} \sim 0.1 - 10\ \frac{cm^2}{g}$, for velocities typical of dwarf galaxies, $v \sim 10^{-5}$, while having a smaller cross section for galaxy cluster velocities, $v \sim 10^{-3}$, where collisionless DM results are in good agreement. This is actually the self interaction cross section, and not the photon-annihilation cross section, which could not be recovered in the literature. For more information and examples about SIDM, see also Refs. [11, 12].

7. **SUPERWEAKLY INTERACTING DARK MATTER**: also called with the acronymous "superWIMPs", these particle preserve the WIMP miracle (the correct relic density, if $m_{SWIMP} = m_{WIMP}$), but are harder to detect, as they are even less interacting than WIMP. The prototypical example is the gravitino, the supersymmetric partner of graviton, but also other supersymmetric particles can be included in this list (axinos, for example) if a very weak interaction is considered: superWIMPs can consequently be seen as some of the particles mentioned above in a different scenario, in which no hypothesis on energy or similar have been made. They can hardly be detected, directly or indirectly, through classical DM experiments, but peaks in cosmic rays or photon flux can be observed. In Ref. [24] the expected flux of photons from WIMP-SWIMP decay for gravitons and gravitinos is reported, together with the maximum energy value

   $$E_\gamma^{max} = 680keV \left[\frac{GeV}{\Delta m}\right]\,, \tag{1.28}$$

   where $\Delta m = m_{WIMP} - m_{SWIMP}$.

8. **ADM**: asymmetric dark matter has recently emerged, among other models, for its prediction of gamma-ray flux. The model

is based on the idea of a DM–antiDM asymmetry (in a similar way to baryons), and even though in the simplest models of ADM annihilation signals are not expected (see *e.g.* Ref. [27]), recent models and predictions of late decays could generate a gamma-ray signal (detectable by FERMI-LAT, for example). Many heuristic bounds on various cross sections are found in Ref. [27], as well as annihilation cross sections into muons, positrons and taus (they could be useful in case of a cross data check). Moreover, in Ref. [28], we can read the formula of thermal annihilation cross section, which could give birth to a detectable gamma-ray flux; this investigation channel is not pursued here, though.

Now that the candidates are set, we need to understand which of them are the most promising, and to calculate the expected photon flux due to their annihilation.

Chapter 2

The Fermi Large Area Telescope

2.1 The Fermi LAT

Gamma-Ray Astronomy from space started with OSO-3, the third mission of the Orbiting Solar Observatory program. In 1967-68 it was able to detect the gamma rays coming form the Sun (most typically the Anderson line at 2.223 MeV) and mapped some sources at few tens of MeV, among them Scorpius X-1. Then it was the time of SAS-2 (Small Astronomy Satellite 2), launched in 1972 from the Italian exclave off the shore of Malindi, Kenya, and Cos-B launched in 1975 by ESA, but it was not until the launch of CGRO (the Compton Gamma-Ray Observatory, launched by NASA in 1991) that gamma-ray astronomy reached its full maturity. The Energetic Gamma Ray Experiment Telescope (EGRET), on board CGRO, was able to detect 271 provisional sources of γ-rays[63], providing a new understanding of the Universe and paving the way for the Fermi Gamma Ray Space Telescope spacecraft, that was launched on June 11$^{\text{th}}$, 2008 from the Kennedy Space Center (Florida, USA). Its principal scientific instrument is the Large Area Telescope (LAT), a pair conversion telescope detecting photons from about 20 MeV to more than 300 GeV and scanning the whole sky in about 3 h: it is an array of 4 towers (see figure 2.1) each composed by a tracker and a calorimeter covered by an anti-coincidence detector (to reject background events, mainly due to electrons, mimicking in their behavior gamma-rays). Collected data are publicly available in the framework of a scientific collaboration that includes more than 400 scientists and students of more than 90 universities and laboratories in 12 countries.

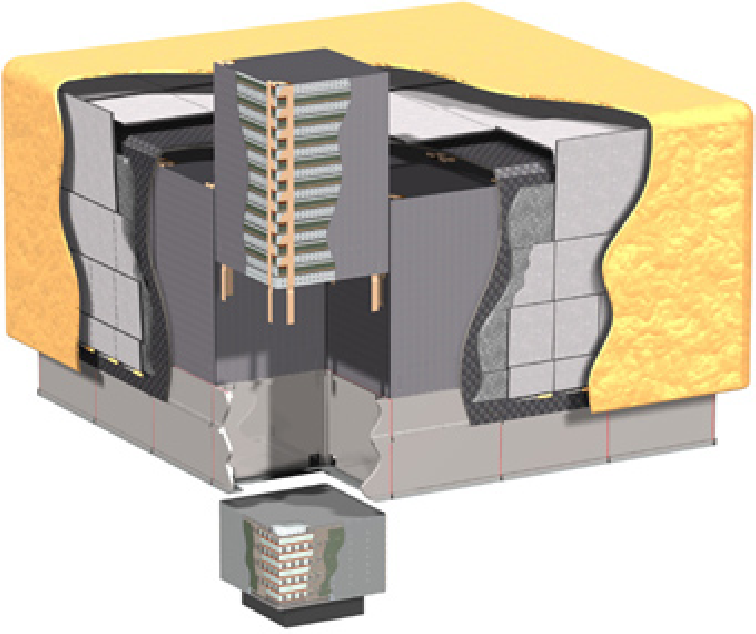

Figure 2.1: Schematic view of the Fermi LAT. A tower is shown for explanation: the protruding object on the bottom is the calorimeter, the one on top is the tracker, made of layers of Silicon strip detectors. The checked grey layer beneath the yellow cover is the anti-coincidence detector. The telescope's dimensions are 1.8 m × 1.8 m × 1.8 mfermi, for a total mass of 2789 kg. The entire satellite uses about 650 W, "less than a toaster", quoting Bill Atwood, namely one of its architects.

2.2 Data analysis method

2.2.1 The photon expected flux

The analysis is based on the calculation of the expected flux of photons from a DM source (annihilation or decay). The main formula, reported in Ref. [48], which provides the differential photon flux from DM annihilation and decay, per unit energy E and solid angle Ω is, at redshift $z = 0$:

$$\frac{d\Phi}{dEd\Omega}(E) = c\frac{1}{E}\int_0^\infty dz \frac{1}{H(z)(1+z)^4} j_{EG}(E,z)e^{-\tau_{EBL}(E,z)} \tag{2.1}$$

where

- c is the speed of light;
- $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$ is the Hubble function, $\Omega_m = \frac{8\pi G\rho}{3H^2}$ is the density parameter (ρ is the Universe density $\rho \simeq 3 \cdot 10^{-28}$

kg/m^3 so $\Omega_m \simeq 0.27$), $\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$ is the ratio between the energy density due to the cosmological constant and the critical density of the universe, $\Omega_\Lambda \simeq 0.73$, and $H_0 \simeq 68 \frac{km}{s\ Mpc}$ is the Hubble constant;

- $\tau_{EBL}(E, z)$ is a function that accounts for the γ-ray photon absorption due to Extragalactic Background Light (EBL);
- j_{EG} is the local emissivity for the annihilating/decay DM models, and consists of two contributions: the prompt one and the Inverse Compton (IC) one.

As far as the EBL attenuation is concerned, the processes relevant to the absorption of energetic photons in cosmological length scales and in the energy range roughly spanning from MeVs to TeVs are:

- pair production on baryonic matter,
- photon-photon scattering on ambient Photon Background Radiation (PBR),
- pair production on ambient PBR.

The basic kinematic requirement for this process is that there must be sufficient energy in the center-of-mass frame of the two-photon system to create the pair. The PBR is mainly composed by the CMB, the intergalactic stellar light and secondary infrared (IR) radiation. The intergalactic stellar light notably consists of the ultraviolet (UV) background produced in the low redshift Universe once the first (massive and hot) stars start to light up. Since this latter part is the most uncertain, we introduce three distinct modeling:

- *no UV* assumes that no UV background is present;
- *minimal UV* takes into account that recent studies suggest significantly lower values for the UV photon densities than estimated in many of the previous investigations;
- *maximal UV* assumes the UV background as given by *minimal UV* multiplied by a factor 1.5.

The choice of UV background affects the flux of very high energy extragalactic gamma rays. For further details, see always Ref. [48].

The parameters of the DM model make their appearance in the $j_{EG}(E, z) = j_{EG}^{prompt}(E, z) + j_{EG}^{IC}(E, z)$ term instead: let's study its two contributions. The first one reads:

$$j_{EG}^{prompt}(E, z) = E \begin{cases} \frac{1}{2} B(z) \left(\frac{\bar{\rho}(z)}{M_{DM}} \right)^2 \sum\limits_f \langle \sigma v \rangle_f \frac{dN^f}{dE}(E) & \text{(annihilation)} \\ \frac{\bar{\rho}(z)}{M_{DM}} \sum\limits_f \Gamma_f \frac{dN^f}{dE}(E) & \text{(decay)} \end{cases} \tag{2.2}$$

where $\overline{\rho}(z)$ is the average cosmological DM density, $\frac{dN^f}{dE}(E)$ is the spectrum of the prompt photons and $B(z)$ is a *cosmological boost factor*, which means an enhancing factor due to the effect of DM clustering. This term is calculated by adopting a halo model which approximates the matter distribution in the Universe as a superposition of DM halos [48]:

$$B(z, M_{min}) = 1 + \frac{\Delta_c}{3\overline{\rho}_{m,0}} \int_{M_{min}}^{\infty} dM \ M \frac{dn}{dM}(M, z) f[c(M, z)] \tag{2.3}$$

where $\overline{\rho}_{m,0}$ is the matter density at $z = 0$, $\Delta_c \simeq 200$ is the overdensity at which the halos are defined and M_{min} is the minimum halo mass. While M_{min} usually ranges from $10^{-3} M_{\odot}$ to $10^{-12} M_{\odot}$ (see Ref. [56]; $M_{\odot}$ is the solar mass), two typical values for M_{min} are (both will be taken into consideration in data analysis):

1. $M_{min} = 10^{-6} M_{\odot}$;
2. $M_{min} = 10^{-9} M_{\odot}$.

The term $\frac{dn}{dM}(M, z)$ is the halo mass function, that can be written in the form

$$\frac{dn}{dM}(M, z) = \frac{\overline{\rho}_{m,0}}{M^2} \nu f(\nu) \frac{d \log \nu}{d \log M} \tag{2.4}$$

where the parameter ν is defined as the ratio between the critical overdensity $\delta_c(z)$ and the quantity $\sigma(M)$ which is the variance of the linear density field in spheres containing a mean mass M. For the multiplicity function $f(\nu)$ it can be used

$$\nu f(\nu) = A \left(1 + \frac{1}{a\nu^p}\right) \left(\frac{a\nu}{2\pi}\right)^{\frac{1}{2}} e^{-a\nu/2} \tag{2.5}$$

where a and p have precise values, and A is determined by requiring the normalization of the $f(\nu)$ function. The last pieces of the puzzle, namely $f(c)$ and $c(M, z)$, represent the function for the halos with the Navarro-Frenk-White (NFW) density profile[1]

$$f(c) = \frac{c^3}{3} \left[1 - \frac{1}{(1+c)^3}\right] \left[\log(1+c) - \frac{c}{1+c}\right]^{-2} \tag{2.6}$$

and the halo concentration parameter function. The last one can be calculated assuming two different models:

1. the *Macciò* model;
2. the *power law* model, which gives a good fit within the mass range resolved by the simulations.

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[1] It is one of the most widely used DM density profile, originating from N-body simulations [57]; anyway, other models, such as Burkert or Einasto profile can be considered.

Information about these two models can be found in Ref. [54] and Ref. [55]; both of them will be tested in the following chapter.

We are not done yet. The emission coefficient for Inverse Compton radiation j_{EG}^{IC} can be approximated as

$$j_{EG}^{IC}(E,z) = 2\int_{m_e}^{M_{DM}(/2)} dE_e \frac{P_{IC}^{CMB}(E,E_e,z)}{b_{IC}^{CMB}(E_e,z)} \times$$

$$\times \int_{E_e}^{M_{DM}(/2)} dE_e \frac{dN_e}{dE_e} \begin{cases} \frac{1}{2}B(z)\left(\frac{\bar{\rho}(z)}{M_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f & \text{(annihilation)} \\ \frac{\bar{\rho}(z)}{M_{DM}} \sum_f \Gamma_f & \text{(decay)} \end{cases} \tag{2.7}$$

where the overall factor of 2 takes into account that equal populations of electrons and positrons radiate (the '(/2)' notation applies to decay). The functions $P_{IC}^{CMB}(E,E_e,z)$ and $b_{IC}^{CMB}(E_e,z)$ are the radiated power and the energy loss coefficient function for e$^{\pm}$: they can be computed in the full Klein-Nishina case or in Thomson limit. As the intergalactic medium is dominated by low energy CMB (Cosmic Microwave Background) photons, the Klein-Nishina formalism is needed only for the extreme mass region of DM, above $M_{DM} > 20$ TeV; in all other cases, the Thomson limit applies. Recall that the Thomson regime in electron-photon Compton scattering is identified by the condition $\epsilon'_{max} = 2\gamma\epsilon < m_e$, where ϵ denotes the energy of the impinging photon, ϵ' the same quantity in the rest frame of the electron, γ is the Lorentz factor of the electron and m_e is the electron mass.

Applying the recipe of equation 2.1, with all the ingredients discussed above, the fluxes of extragalactic gamma rays detectable by Fermi LAT are calculated, for every energy bin, ranging from 50 MeV to 300 GeV. The template found in the linked website[2] was used: it is a Mathematica® document, that allows the calculation of the flux by inserting the values of the minimal halo mass, the model, the UV model background, the mass of the DM candidate, its energy and annihilation cross section[3] (or lifetime).

The value must then be multiplied by the right value of the solid angle (see below for the Region of Interest (ROI) of the analysed data).

In the previous calculation nothing was said about the fact that the photon signal can have different origins: some particles are reported to decay, others to annihilate (through many channels) and finally others to do both of them. This problem emerges when considering the possibility of interaction of these different channels, that leads to interference additional terms, due to quantum effects. Anyway, since this contribution can be shown to be irrelevant, this phenomenon is actually neglected: the total flux of photons

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[2] http://www.marcocirelli.net/PPPC4DMID.html

[3] When available, $\langle\sigma v\rangle$ was used; else, relative velocity in the centre-of-masse reference frame was arbitrarily considered to be non relativistic, namely $v \simeq 10^{-3}c$

is the simple sum of the single photon fluxes. Finally, notice that in this paper only the annihilation into a couple of γ is considered.

2.2.2 Data from the Fermi LAT: origin and caveats

At this point, these values will be compared with available data. Events should be properly analyzed before becoming a good *γ-ray signal*: background signals and systematic uncertainties have to be considered and subsequently excluded from the analysis. Since studies about point-like sources have already been made (see Ref. [50] and Ref. [51]), the diffuse isotropic gamma-ray signal will have to be considered; before that, it is necessary to exclude the background and systematic contributes to signal: the first one is made up of many contributions (see Ref. [52]). The interstellar diffuse emission is due both to the interaction of cosmic rays with the cosmic medium, which is made of neutral gas, mainly atomic hydrogen, H_2 and CO, and ionized gas, and to other effects such as the bremsstrahlung emission (electrons scattering off ions), atoms excited by ultraviolet radiation of hot stars and interstellar dust, mainly consisting of heavy elements. All these factors contribute to the so-called galactic diffuse emission, depending on the sky region observed. Also, unresolved extragalactic discrete sources produce an additional diffuse component with almost isotropic distribution in the sky: blazars and radiogalaxies, interaction of cosmic rays in star-forming galaxies, nonthermal radiation from clusters of galaxies and Gamma-ray bursts (GRBs) not detected by the instrument may explain this contribution. The systematic error, instead, can be attributed to two factors: the effective area, namely instrumental effects that are conservatively evaluated by calculating the mismatch between the events collected from two parts (the *front* and the *back*) events, and different ways to build the diffuse interstellar emission model: eight different templates were developed, varying some of the parameters, resulting in different gas emissivities and CO-H_2 ratios.

Models for excluding these signals are based on years of observations and fitting attempts: they are freely available[4]. The data analysis will be performed using the LAT Science Tools package, available from the Fermi Science Support Center[5], and using the data accumulated from the beginning of scientific operations on 4 August 2008 to today. The region considered will consist of the whole sky: the solid angle will therefore be $\Omega = 4\pi$.

The full sky will be divided in pixels using the HEALPix (Hierarchical Equal Area isoLatitude Pixelization) algorithm[6]: as suggested by the name, this pixelization produces a subdivision of a spherical surface in which each pixel covers the same surface area as every other pixel. Figure 2.2 shows the partitioning of a sphere at progressively higher resolutions, from left to

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[4] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

[5] http://fermi.gsfc.nasa.gov/ssc

[6] http://healpix.jpl.nasa.gov/

right. The green sphere represents the lowest resolution possible with the HEALPix base partitioning of the sphere surface into 12 equal sized pixels. The yellow sphere has a HEALPix grid of 48 pixels, the red sphere has 192 pixels, and the blue sphere has a grid of 768 pixels ($\sim$ 7.3 degree resolution).

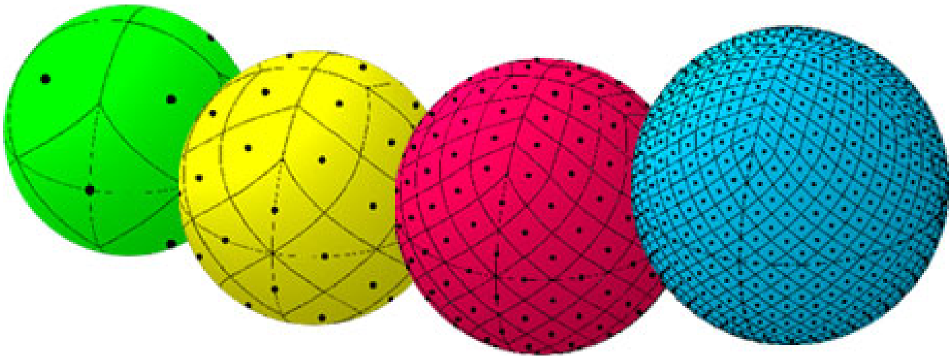

Figure 2.2: HEALPix algorithm.

The models will be fitted to the LAT data using a binned maximum-likelihood method based on Poisson statistics: to estimate the significance of a model, the likelihood ratio test will be used.

Chapter 3

Conclusions and future targets

3.1 Determining the candidates detectable by the Fermi LAT

To begin with, we can thin out the list: all the candidates that are predicted to produce a signal that is not contained in the detectable range, or that are predicted to produce no signal at all have to be excluded from this analysis. We must then consider that the Mathematica® document is set to have a mass range of $m_{DM} = 5$ GeV → 100 TeV for annihilation and $m_{DM} =$ 10 GeV → 200 TeV for decay, and energy E can range from 10^{-6} m_{DM} to m_{DM}[1]; the annihilation cross section must be inserted in cm^3/s and the DM decay rate in s^{-1}.

Of the 24 models proposed here, only 5 of them may be suitable for this analysis method. See Table 3.1 for a brief explanation for the exclusion for each of the 19 unlucky candidates. Of course these candidates are not completely ruled out, but other investigation methods need to be set, or other considerations about their origin or characteristics have to be made in order to fully reject (or accept) them. We must even precise again that only the annihilation or decay into a couple $\gamma\gamma$ is considered in this work; moreover, an avalanche process in which DM annihilates into some states that could then give "secondary" photons is not taken into consideration, as well as the possibility that DM is not made of only one single class of particles.

For the remaining candidates, the following figures account for the expected flux, on varying of some parameters: fluxes are given as $\log_{10}\left[\frac{d\Phi}{d\log_{10}E}\right]$

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[1] Anyway, no candidate exceeding these costraints may produce a signal detectable by the Fermi LAT

Candidate	**Reason for exclusion**
Neutrino	Mass too low
Sterile neutrino	Doesn't annihilate or decay into photons
Heavy fourth generation neutrino	Ruled out by experimental results
Axion	Mass too low
D-Matter	Studies are still ongoing
Crypton	Studies are still ongoing
Branon	Cross section unavailable for our software
Gravitino	Doesn't annihilate or decay into photons
Axino	Doesn't annihilate or decay into photons
Quintessino	Doesn't annihilate or decay into photons
Goldstino	Mass too low
Q-Ball	Doesn't annihilate or decay into photons
Wimpzilla	Ruled out by experimental results
Light Scalar Dark Matter	Out of Fermi LAT range
Mirror particle	No photon annihilation reference is found
CHAMP	Ruled out by experimental results
Self-interacting DM	Doesn't annihilate or decay into photons
SuperWIMP	Out of Fermi LAT range
Asymmetric DM	Doesn't annihilate or decay into photons

Table 3.1: List of excluded candidates for this investigation channel.

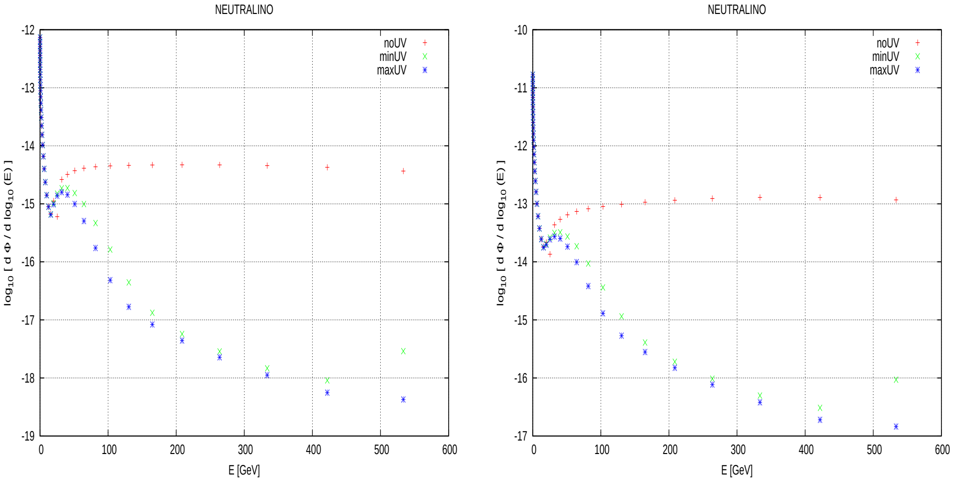
with E the energy in GeV. The units of $\left[\frac{d\Phi}{d\log_{10}E}\right]$ are photons/$(\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr})$.

In the comparison graphic, *6* and *9* indicate the possible values of the minimum halo mass, while m and p stand for *Macciò* and *power law* models.

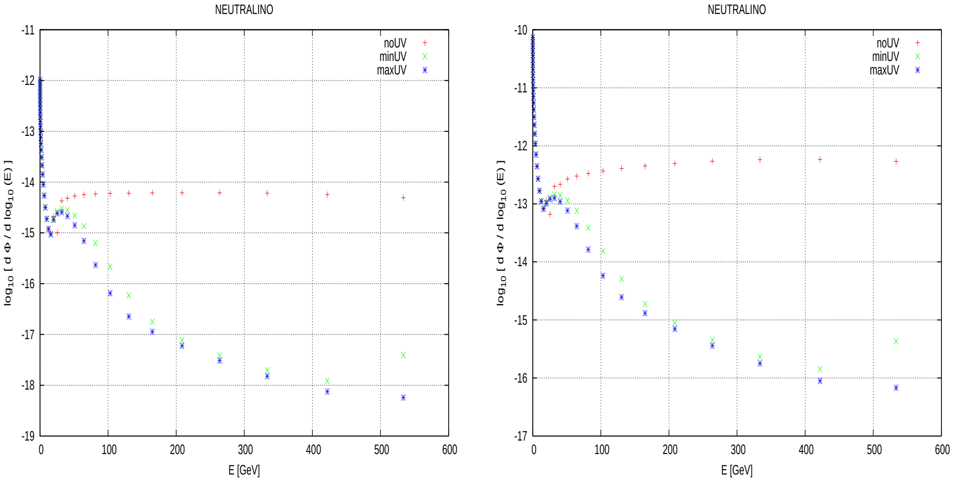
Fluxes range logarithmically from -7 to -20: the wider the cross section, the higher the expected flux. We can notice, then, that as expected noUV absorption hyphotesis leads to a larger number of photons (mainly for high energies), as well as the power law model with regards to the Macciò model. Different assumptions on the minimum halo mass value do not lead to big differences on the expected fluxes instead, so they may be neglected. Notice that for the photino, whose mass lies close to 10 GeV, different assumptions on the absorption model are absolutely unimportant (see figure 3.3).

As a general rule, the lower the energy, the higher the flux: the photino is an exception to this, but its values do not vary much with different energies. The most promising candidates, namely the one which leads to the higher expected flux, is the sneutrino, the particle with the larger cross section as well.

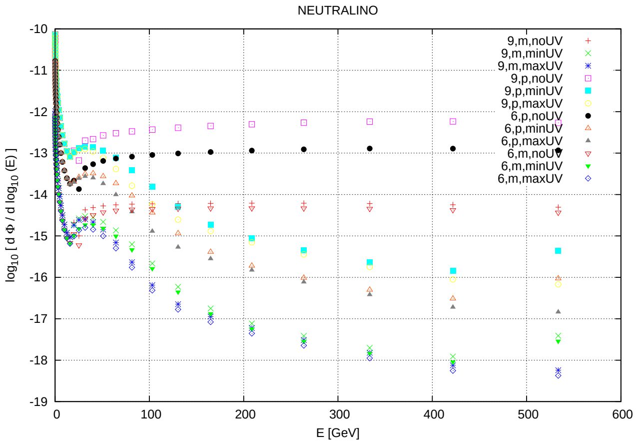
Finally, notice that fluxes were calculated as long as the energy of the particle was lower than its mass, as explained above.



(a) $M_{min} = 10^{-6} M_{\odot}$, Macciò model (b) $M_{min} = 10^{-6} M_{\odot}$, Power law model

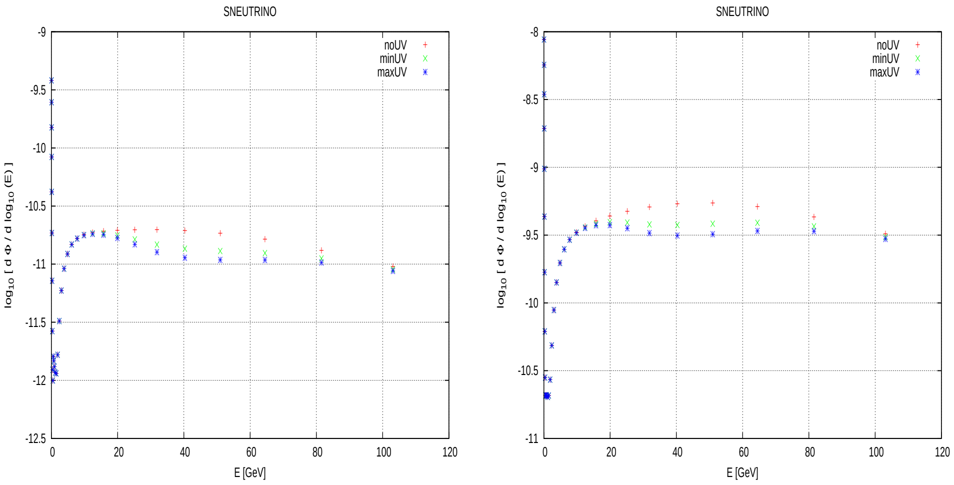


(c) $M_{min} = 10^{-9} M_{\odot}$, Macciò model (d) $M_{min} = 10^{-9} M_{\odot}$, Power law model

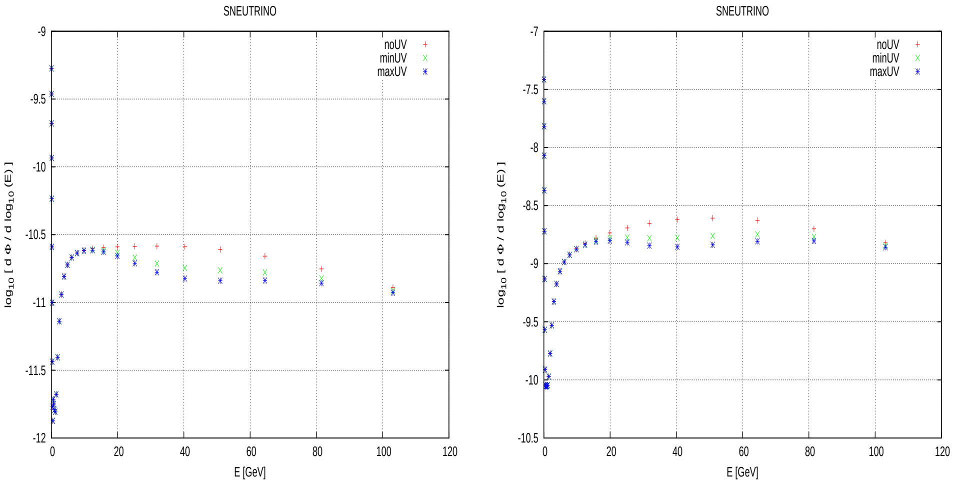


(e) Comparison

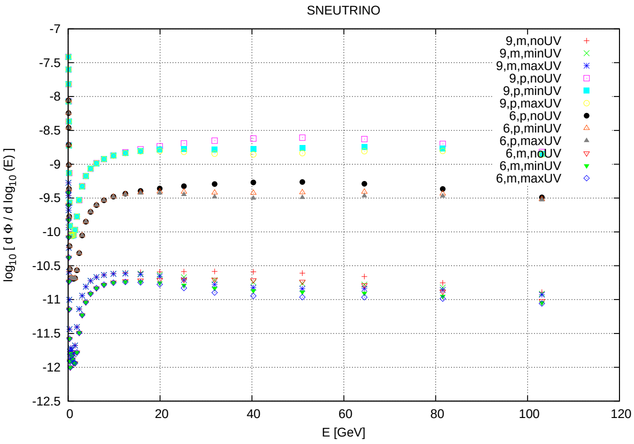
Figure 3.1: Neutralino expected flux on varying of some parameters.



(a) $M_{min} = 10^{-6} M_\odot$, Macciò model (b) $M_{min} = 10^{-6} M_\odot$, Power law model

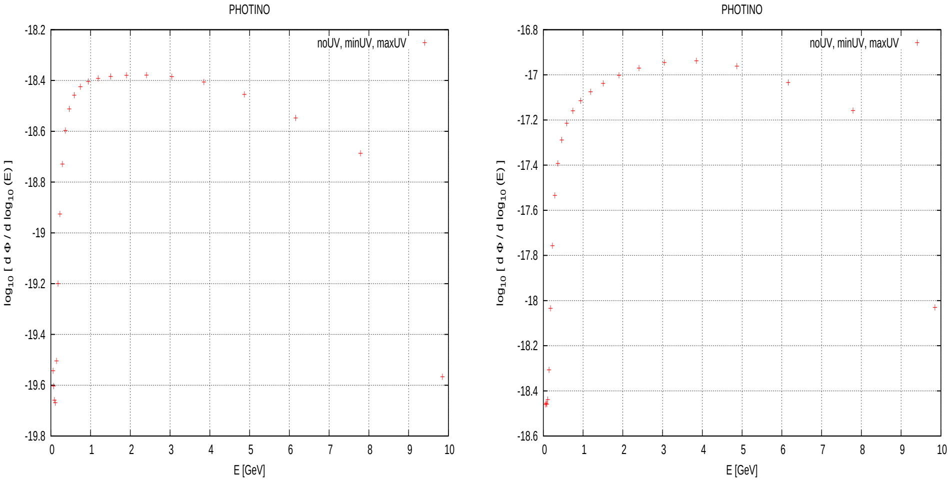


(c) $M_{min} = 10^{-9} M_\odot$, Macciò model (d) $M_{min} = 10^{-9} M_\odot$, Power law model

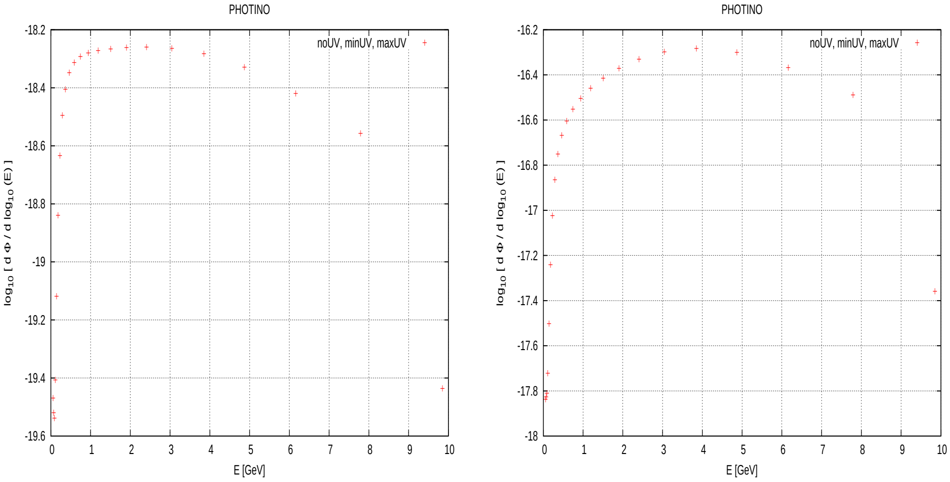


(e) Comparison

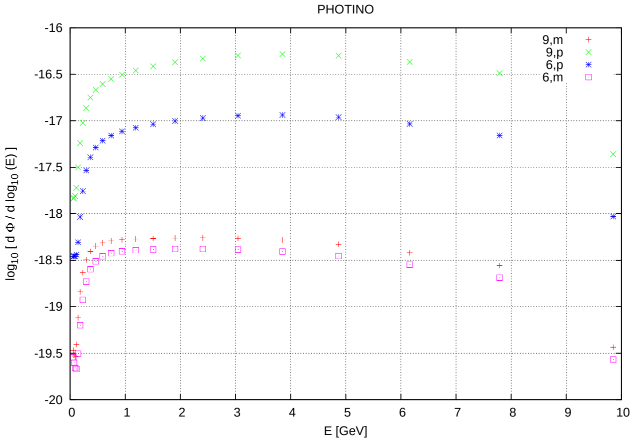
Figure 3.2: Sneutrino expected flux on varying of some parameters.



(a) $M_{min} = 10^{-6} M_{\odot}$, Macciò model (b) $M_{min} = 10^{-6} M_{\odot}$, Power law model

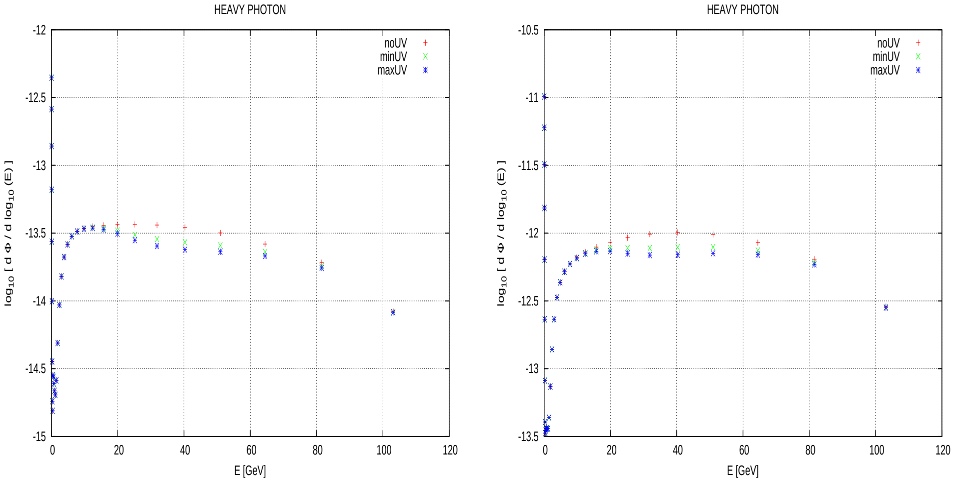


(c) $M_{min} = 10^{-9} M_{\odot}$, Macciò model (d) $M_{min} = 10^{-9} M_{\odot}$, Power law model

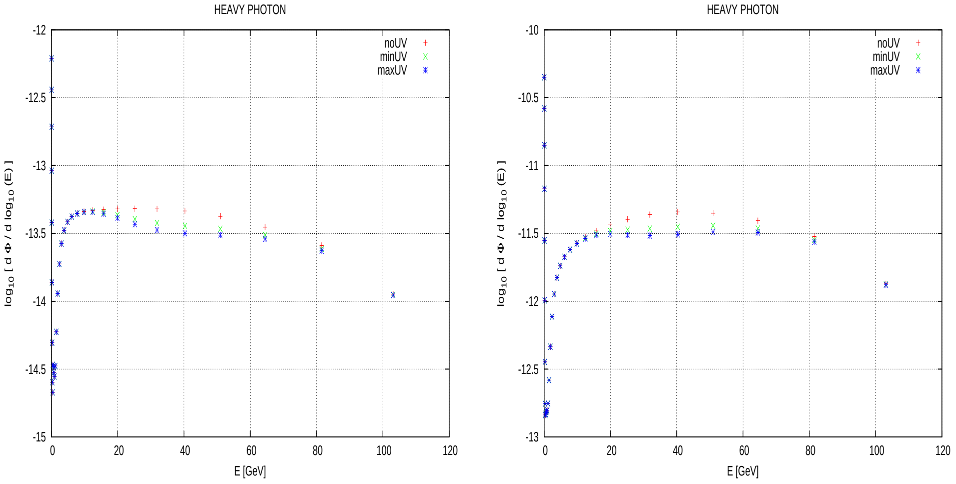


(e) Comparison

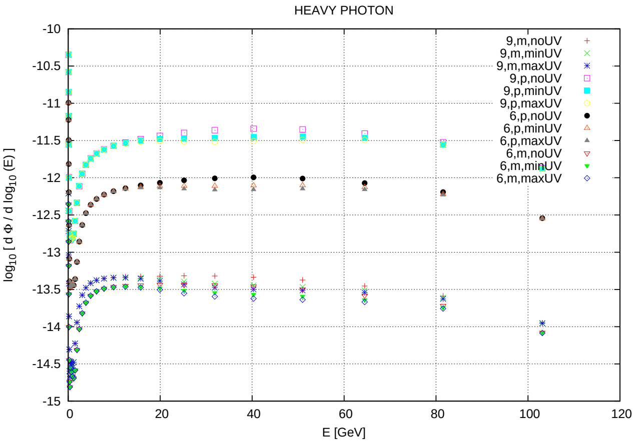
Figure 3.3: Photino expected flux on varying of some parameters.



(a) $M_{min} = 10^{-6} M_\odot$, Macciò model (b) $M_{min} = 10^{-6} M_\odot$, Power law model

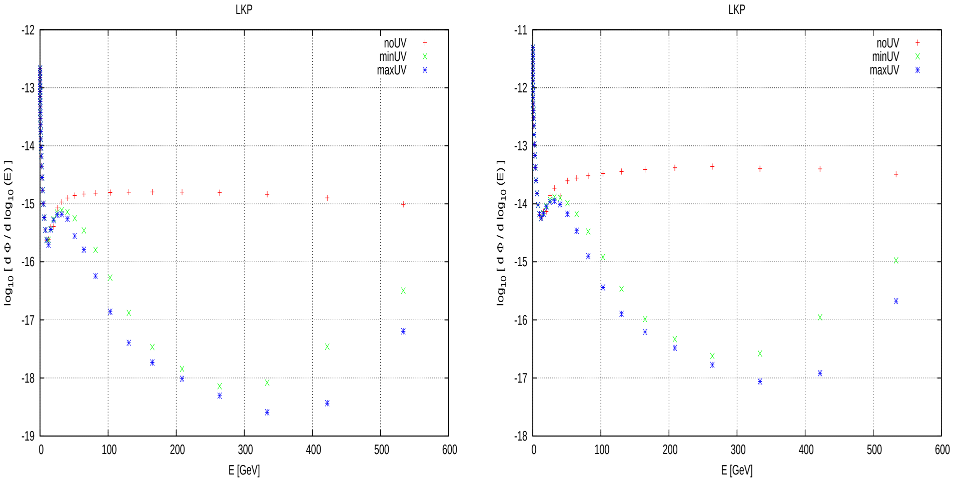


(c) $M_{min} = 10^{-9} M_\odot$, Macciò model (d) $M_{min} = 10^{-9} M_\odot$, Power law model

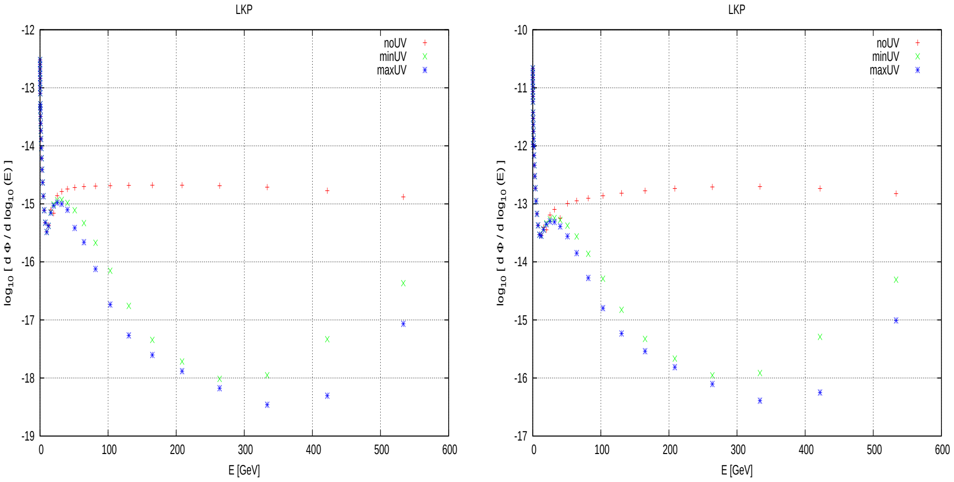


(e) Comparison

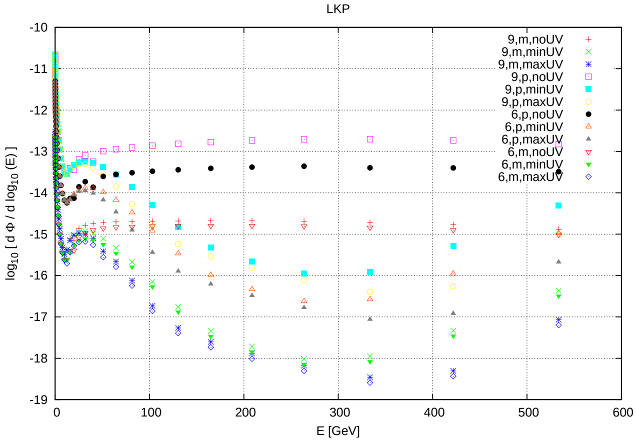
Figure 3.4: Heavy photon expected flux on varying of some parameters.



(a) $M_{min} = 10^{-6} M_{\odot}$, Macciò model (b) $M_{min} = 10^{-6} M_{\odot}$, Power law model



(c) $M_{min} = 10^{-9} M_{\odot}$, Macciò model (d) $M_{min} = 10^{-9} M_{\odot}$, Power law model



(e) Comparison

Figure 3.5: LKP expected flux on varying of some parameters.

3.2 Future targets

Now that the expected photon flux has been calculated, we need to start tha data analysis, following the instructions mentioned above: this is meant to be the next step in reaching a solid conclusion about Dark Matter and γ-ray flux.

As stated above, though, this work is not capable of determine the origin of DM, and can not account for all the DM models: that's why much more effort is needed. To begin with, in this sense, different hypothesis about the candidates' parameters can be made as a variation on the theme of this work: different assumptions about halo and EBL function models, mass, cross section or constant actual values may lead to different results. But other direct or indirect detection methods may be considered as well: just to name some of the experiments set up for the purpose, we can recall:

- **ADMX (Axion Dark Matter eXperiment)**, that uses a resonant microwave cavity within a large superconducting magnet to search for cold dark matter axions in the local galactic dark matter halo at the Center for Experimental Nuclear Physics and Astrophysics by the University of Washington;

- **EDELWEISS (Expérience pour DEtecter Les Wimps En Site Souterrain)**, located in the Modane Underground Laboratory, which uses cryogenic detectors, measuring both the phonon and ionization signals produced by particle interactions in germanium crystals;

- **DAMA/LIBRA (DArk MAtter experiment / Large sodium Iodide Bulk for RAre processes)**, that uses a scintillation detector to directly search for Weakly Interacting Massive Particles (WIMPs) in the galactic halo at the Laboratori Nazionali del Gran Sasso.

Future experiments are already on their way, though: the **Particle and Astrophysical Xenon Detector**, or **PandaX**, is a dark matter detection experiment at China Jinping Underground Laboratory in Sichuan, China, and occupies the deepest and largest underground laboratory in the world, planning to become the most sensitive such detector in the world; it is a direct-detection experiment, consisting of a dual-phase xenon time projection chamber detector, and plans to be fully operative by 2016.

The **European Underground Rare Event Calorimeter Array (EURECA)**, instead, is a planned dark matter search experiment using cryogenic detectors and an absorber mass, and it will be built in the Modane Underground Laboratory. But at **CERN** colliders are already working in order to help us reveal new particles (like supersymmetric particles) as well.

Industrios work is in progress: all of these experiments will gradually improve our degree of knowledge on the Universe, and could eventually help us shed light on the intriguing mystery of Dark Matter.

Acknowledgements

This work would have never seen the light of day without the thorough and patient help of Professor Antonino Marcianò, from Fudan University, and the experienced effort of Professor Denis Bastieri, from the University of Padua.

Thanks to Marco Cirelli for useful discussion about the Mathematica® software used above.

A special thank to Giancarlo, "stanco ma non stufo", to Nevia, who shows her motherly love by caring more than me, and to Gianluca, my wise firm brother.

A particular mention, then, must be made to all the people who supported me through all of this, and despite whom I was able to reach this goal; they don't need to be named, they already know they are important to me and that this work is partly theirs, too.

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