A Decaying Ultra Heavy Dark Matter (WIMPZILLA): Review of Recent Progress

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Abstract

Recent theoretical and observational motivations for existence of a decaying Ultra Heavy Dark Matter (UHDM) are reviewed. We show that present data from Ultra High Energy Cosmic Rays (UHECRs) and SN-Ia are compatible with a relatively short lifetime of UHDM.

1 Introduction

Particle Physics and Cosmology today are confronted with two principal mysteries: The nature of Dark Matter and the origin of UHECRs. Candidates for the first one are an ever-growing list of exotic particles from ultra light axions [1] to ultra heavy particles [2] and semi-particles like vortons [3]. Confirmation of one or a family of these candidates would be based on their observation in laboratory or through indirect detection.

For the second mystery various classical and exotic sources have been proposed (see [4] for review). Practically all of classical sources however fail to explain the highest energy tail of the cosmic rays spectrum [5]. Recently new born neutron stars and their wind have been proposed as an accelerator of charged particles to very high energies [6]. But they can accelerate only heavy nuclei like iron to $E \sim 10^{20}$ eV.

Another recent suggestion is the active galaxy M87 in Virgo Cluster as the unique nearby source of UHECRs [7]. In this case, to explain the uniform distribution of UHECRs, a large deflection of the particles in the galactic wind is necessary. This means that magnetic field of the wind must be much larger than observational limits. Even if we take this assumption for granted, primaries of the most energetic events must be $He$ or heavier nuclei to be originated from M87. However, increasing statistics of UHECR events confirms that primaries gradually change from heavy nuclei to light ones and most probably become protons for $E > 10^{17}$ eV [8].

The difficulty of accelerating charged particles to such extreme energies is not restricted to finding a source with enough large magnetic field and accelerating zone. It is also crucial for accelerated particles to escape the source without losing too much energy. In leaving a conventional acceleration zone i.e. when the magnetic field becomes gradually weaker at the boundary, charged particles lose energy by adiabatic expansion. The ejection energy becomes:

$$E_{ej} = E \left( \frac{B_{ej}}{B} \right)^{\frac{1}{2}}.$$  \hspace{1cm} (1)

where $E$ and $B$ are respectively energy of particle and magnetic field in the main part of the acceleration zone. The energy loss by this effect can be a few orders of magnitude.

The way out of this problem can be either an abrupt change of the magnetic field at the boundaries, or a change in the nature of charge particles [9]. The former solution needs a fine tuning of the source properties e.g. plasma density, geometry, distribution etc. The latter case needs that charge particles interact with environment and become neutral. In this case they lose also part of their energy. In both cases one has to consider the energy loss by other interactions as well. This is a factor which is not negligible in the sources with extreme conditions like AGNs, jets and atmosphere of neutron stars. On the other hand, energy loss during propagation also limits the possible sources of UHECRs. It has been suggested that UHE neutrinos originated from QSOs can interact with a halo of neutrinos around Milky Way and produce UHECRs [10]. The probability of such process however has been
challenged by other authors [11]. It has been proposed that due to Poisson distribution of interaction probability at short distances, a number of UHE protons can arrive on Earth without any loss of energy [12]. It has been argued that this can increases the possible distance to the source and thus the number of potential candidates. For a source at a few $M_{pc}$, the probability of non-interacting is $\sim 30\%$. But it decreases exponentially and for distances $\gtrsim 30M_{pc}$ it is only $\sim 10^{-8}$. Therefore this argument can be helpful if there are a number of nearby potential sources. If only AGNs and their jets are able to accelerate protons to ultra high energies, M87 is the only possible source and it is in a distance that non-interacting probability becomes very small.

Among exotic sources the first studies had been concentrated on topological defects like cosmic strings either as accelerator or as a source of ultra heavy particles (see [4] and references therein). In the latter case, defect decay produces UH particles which in their turn decay to Standard Model particles. The interest on topological defects is however declining as they have many difficulties to produce the spectrum of CMB and LSS fluctuations [13].

Neglecting other candidates like primordial black holes (which have their own difficulties), the decay of a meta-stable UHDM (or wimpzilla as it is usually called [2]) seems a plausible source for UHECRs. Below we review the particle physics models of UHDM and the observational consequence of their decay. Before doing this, we want to comment on an argument recently proposed against them as the source of UHECRs [14] [15]. The UHDM if exists must follow the distribution of dark matter and in this case the Halo of our galaxy is the dominant contributor in production of UHECRs as we will show it below. The off-symmetric place of the Earth with respect to the center of the Halo however must induce an anisotropy to the UHECRs distribution in the direction of center with respect to opposite one. This anisotropy has not been observed. The existence of a halo of MACHO type objects (presumably baryonic matter) up to $\sim 50kpc$ can be the answer to this argument. Smearing of anisotropies by the magnetic field also must be considered [16] [17]. Therefore, it is not evident that uniform distribution of UHECRs be an obstacle to UHDM hypothesis. A better understanding of the Halo geometry, content and magnetic field is necessary to quantify the expected anisotropy.

As for production of very heavy particles, our present knowledge about the physics after inflation, specially the preheating process shows that it is possible to produce large amount of extremely heavy particles, both bosons and fermions at this stage from a much lighter inflaton field [3] [18].

### 2 Particle Physics Models of UHDM

Many GUT scale theories include ultra heavy bosons of mass close to GUT scale i.e. $\sim 10^{16}GeV$ [19]. The challenge however is to make them meta-stable with a lifetime greater than present age of the Universe. Decay Lagrangian of a field $X$ can be written as:

$$\mathcal{L} \sim \frac{g}{M^2} X \phi^m \psi^n.$$  

$$p = d_x + m + \frac{3}{2} - 4.$$  

where $\phi$ and $\psi$ are respectively generic bosonic and fermionic fields. $g$ is a dimensionless coupling constant and $M_*$ is Plank mass scale or any other natural mass scale in the theory. This Lagrangian leads to a lifetime $\tau$:

$$\tau \sim \frac{1}{g^2 M_X (M_X^2)^2}.$$  

For $M_X \lesssim M_*$, the exponent $p$ must be large and (3) becomes non-renormalizable. The other possibility is an extremely suppressed coupling constant.
A number of models permit high order Lagrangian. Since early 90s, some compactification scenarios in string theory predict composite particles (e.g. cryptons) with large symmetry groups \[20\] and \( M \gtrsim 10^{14} \text{GeV} \). New class of string theories called M-theory \[21\] (heterotic strings and quantum gravity in 11-dim.) provides better candidates of large mass particles if the compactification scale is much larger than Standard Model weak interaction scale \[22\].

The general feature of this class of models is having a very large symmetry group of type \( G = \prod_i SU(N_i) \otimes \prod_j SO(2n_j) \). Their spectrum includes light particles with fractional charges which have not been observed. It is believed that they are confined at very high energies \( > 10^{10-12} \text{GeV} \). All of their decay modes are of type \( \mathcal{E} \) and their lifetime is in the necessary range.

Another group and probably less fine-tuned candidates are models with discrete symmetries. Particles can be elementary or composite. If massive neutrinos are Majorana, the discrete group is restricted to \( Z_2 \) and \( Z_3 \) by anomaly cancellation conditions \[23\]. These symmetries can happen quite naturally in Standard Model. The first one is matter parity. The second one is baryon parity and is proposed to be responsible for proton stability \[24\]. Dirac neutrinos are much less restrictive and permit that \( X \) particles (UHDM) decay directly to SM particles.

A subsets of these models in the contest of SUSY-GUTs consist of the decay of UH particles to at least one non-SM particle which we call \( Y \). In its turn \( Y \) can decay to SM particles. They are usually considered to be messenger bosons.

SO(10)-SUSY model presents an interesting example of this type of models because after SUSY breaking in hidden sector, it includes messengers with masses \( \gtrsim 10^{14} \text{GeV} \) \[19\]. In \[20\] messengers in representation \((8,1)_0\) and \((1,3)_0\) of Standard Model \( SU(3) \otimes SU(2) \otimes U(1) \) have been proposed as UHDM and \( Y \). However, in this case UHDM would have strong interaction and it would be difficult to explain the large observed bias between Dark Matter and baryons in present universe \[25\]. Moreover, in the early universe before nucleosynthesis, its large mass and strong interaction with quark-gluon plasma could create small scale anisotropies with important implication for galaxy formation. These perturbations has not been observed and in fact for explaining the distribution of galaxies today, it is necessary to wash out very small scale anisotropies. By contrast, \((1,3)_0\) representation for UHDM particles is a more interesting possibility because in this case they have only weak interaction with ordinary matter and no interaction with photons. This may explain some of features of galaxy distribution and CMB small scale anisotropies \[24\].

Two other scenarios for UHDM decay are suggested: decay through Quantum Gravity processes like wormhole production \[27\] and through non-perturbative effects like instanton production \[28\]. Even if they are plausible, their inclusion to known models is less straightforward than previous methods.

### 3 Comparison With Observations

A number of simulations have been performed to study the production and dissipation of UHECRs. Most of them consider topological defects as the source of UHECRs \[29\] \[30\] \[28\]. In \[31\] the decay of a UHDM has been studied without considering the effect of energy dissipation of remnants and they find a lifetime a few orders of magnitude larger than the age of the Universe.

Recently we have simulated the decay of UHDM and energy dissipation of remnants by including a large number of relevant Standard Model interactions in the simulation \[32\]. The spectrum of remnant protons and photons in a flat homogeneous universe with \( h_0 = 0.7 \) and \( \Omega_M = 0.3 \) is shown in Fig.1 and is compared with available data for UHECRs and high energy photons. It is evident that once all dissipation processes are taken into account, even a decaying UHDM with a lifetime as short as 5 times of the age of the Universe can not explain the observed flux of UHECRs. Nevertheless, the clumping of DM in the Galactic Halo provides enough flux and somehow increases this lifetime limit. Fig.2 shows the expected flux on Earth from the Galactic Halo calculated for a very simple halo model. A more realistic simulation is in preparation.
UHECRs are the most direct consequence of a decaying UHDM. But a decaying DM has other implications specially on the cosmic equation of state [36]. As part of CDM changes to Hot DM, this latter component along with cosmological constant appear in the cosmic equation of state like a quintessence matter with $w_q < -1$. Table 1 compares the fitting of simulations of a decaying DM to SN-Ia data [38, 37] (the mass of DM particles has a negligible effect on the cosmic equation of state). With present SN-Ia data, both decaying and non-decaying DM are compatible with observations but models with decaying DM systematically fit the data better than non-decaying ones.

4 Prospectives

A very important component of any source of UHECRs is high energy neutrinos. Until now no such component has been observed partly due to the lack of proper detectors. However, the new generation of neutrino telescopes like MACRO and Baikal Lake experiment should be able to detect such particles if they exist. The simulation described here is compatible with preliminary limits reported by MACRO Collaboration [39].

The detection of UHE neutrinos can give a hint on the decay spectrum of UHDM. If their cross-section with various matter and radiation components is as predicted by SM, most of them arrive on Earth without losing any energy. Nevertheless, if UHE neutrinos are not observed, it can not be considered as a very direct evidence against a decaying UHDM since conventional sources also must produce them.
through interaction of accelerated charged particles with ambient matter and radiation fields. This probably would be a sign that at high energies neutrinos have relatively strong coupling to one or a number of backgrounds and/or matter components.

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Table 1: Cosmological parameters from simulation of a decaying DM and parameters of the equivalent quintessence model. $H_0$ is in $km Mpc^{-1} sec^{-1}$.

| Stable DM | $\tau = 50\tau_0$ | $\tau = 5\tau_0$ |
|-----------|-------------------|-------------------|
| $\Omega_\Lambda^c = 0.68$ | 69.779 | 69.801 |
| $\Omega_\Lambda^c = 0.7$ | 69.798 | 68.301 |
| $\Omega_\Lambda^c = 0.72$ | 69.949 | 68.415 |
| $\Omega_\Lambda = 0.68$ | 0.684 | 0.714 |
| $\Omega_\Lambda = 0.7$ | 0.704 | 0.733 |
| $\Omega_\Lambda = 0.72$ | 0.724 | 0.751 |
| $\Omega_q = -1$ | -1.0066 | -1.0732 |
| $w_q = -1$ | -1.0060 | -1.0658 |
| $\chi^2$ | 62.34 | 62.22 |

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