LHC and models with antibaryonic dark matter

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Conventional Dark Matter (DM) models do not address the order-of-magnitude coincidence of visible (baryonic) matter and invisible (dark) matter contributions to the total energy density of the present Universe, $m_B \times n_B = \rho_B \sim \rho_{DM} = M_{DM} \times n_{DM}$. The models called asymmetric, (anti)baryonic DM are specifically designed to explain this coincidence by producing DM and generating Baryon Asymmetry of the Universe (BAU) via one and the same mechanism. If the latter involves scattering, which naturally implies similar number densities, $n_{DM} \sim n_B$, then DM particle mass is in GeV range, $M_{DM} \sim m_B$ and corresponding New Physics scale is high. Concentrating on a particular example of these models we show that, quite remarkably, the Large Hadron Collider has the best opportunity to probe this idea.

1 Introduction to Dark Matter

So far we have only gravitational evidences for the Dark Matter component of the Universe. That is what we actually observe indicates the lack of gravitational potentials: somewhat weaker force than expected in the framework of General Relativity (GR). Though not proved, it is widely accepted that not a modified gravity but some new *particle physics* is responsible for this phenomena. The point is that this lack of gravity happens at various spatial scales and during several cosmological epochs. New stable nonrelativistic particles emerged in the early Universe in a proper amount nicely fit to all the cosmological and astorphysical observations provided the standard gravitational interaction. To address the issue of DM phenomena without assistance, the GR must be modified at several different scales and times, while with the new matter component all the phenomena can be explained by its standard gravitational dynamics.

In astrophysics the DM manifests itself as a substance responsible for

- flatter rotational curves of galaxies
- stronger gravitational lensing by galaxy clusters
- hotter gas falling into the center in galaxy clusters

as compared to GR predictions with the visible matter only.

In cosmology the DM contribution is recognizable in

- observations of the standard candles like SN Ia
- measurements of angular size of cosmologically distant objects
- anisotropy picture of cosmic microwave background
- large scale structure formation

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• pattern of baryon acoustic oscillations

If dark matter phenomena are attributed to some new particles (there are no suitable candidates in the SM), they must be

• stable on cosmological time-scale

• nonrelativistic, $v \lesssim 10^{-3}$, already at equality epoch (the transition from radiation to matter domination happened in the early Universe when the plasma temperature was of about 1 eV)

• collisionless (immune to long range forces except gravity)

• electrically neutral (otherwise not dark!)

• heavier than $\sim 10^{-22}$ eV if bosons, to be confined within a galaxy; for fermionic dark matter the Pauli blocking places much stronger and very robust lower limit of about 500 eV

2 DM candidates and naturality

DM particles must be produced in the early Universe long before the equality epoch. One can assume that the dark matter particles emerge through scatterings of the SM particles in the primordial plasma and get thermalized. Later, while the Universe expands and all the particle densities decrease, dark matter freezes out. This is so-called thermal production mechanism, which suggests two options at the freezing out: dark matter particles X can be either relativistic or nonrelativistic by that moment. If dark matter particles freeze out being relativistic, one finds for their relative contribution to the present energy density of the Universe, see e.g. [1],

$$\Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} \approx 0.2 \times \left(\frac{M_X}{100\ \mathrm{eV}}\right) \cdot \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_f)}\right) ,$$

where g_X refers to the number of internal degrees of freedom of particle X (number of spin states, colors, etc) and $g_*(T_f)$ is the effective number of degrees of freedom in the primordial plasma at freezing out temperature T_f (in the SM all the particles relativistic at a given temperature contribute to $g_*(T)$ which thus can reach 106.75). One concludes that a dark matter particle of $\mathcal{O}(100)$ eV is a good candidate then, however it fails to fulfill the requirement on DM velocity at the equality epoch we mentioned above. Indeed, after becoming nonrelativistic at the temperature $T \sim M_X$ the velocity decreases further like $v \propto T$. At the equality, $T \approx 1$ eV, such a dark matter with $v \sim 10^{-2}$ is *too hot to produce the small scale structures* (e.g. dwarf galaxies) we observe in the Universe. This mechanism does not help, unless we flood the SM with new particles multiplying the effective number of degrees of freedom in the early Universe plasma by a factor of about 10, or cook the non-standard late-time cosmology with substantial entropy release in the plasma which dilute the number density of the decoupled DM component (e.g. a reheating-like stage after matter domination).

On the contrary, the "nonrelativistic" option at the freezing out provides with perfectly realistic dark matter candidates, which are very cold at the equality and hence their common name is *Cold Dark Matter*. In this case the dark matter particles stop to emerge from plasma because of kinematics rather than dynamics (the opposite case provided by very tiny coupling between the SM and dark matter particles is inherent in the unsuitable "relativistic" option considered above). Then dark matter particles annihilate. This process terminates as soon as their number density drops sufficiently to ensure that the dark matter lifetime with respect to annihilation, inversely proportional to the number density and the annihilation cross section σ_0, exceeds the age of the Universe at that time. In this case the dark matter relative contribution to the energy density of the Universe at present can be straightforwardly estimated as, see e.g. [1],

$$\Omega_X \approx 0.1 \times \left(\frac{(10\,\mathrm{TeV})^{-2}}{\sigma_0} \right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln \left(\frac{g_X M_{\mathrm{Pl}}^* M_X \sigma_0}{(2\pi)^{3/2}} \right) .$$

The required annihilation cross section is only by about two orders of magnitude smaller than the typical weak cross section. Hence, a new stable particle participating in weak interactions (WIMPs for weakly interacting massive particles) can serve as viable dark matter. The statement does not depend on the dark matter mass M_X and we only assume that the maximal temperature in the early Universe exceeds M_X. There are many realistic models with WIMP-like candidates, the mostly developed are supersymmetric extensions of the SM with the lightest superpartner (LSP) playing WIMP.

As to the thermal production, there are many alternatives provided by the well-motivated theoretical models which offer cosmologically viable dark matter candidates. In supersymmetric extensions LSP gravitino is produced in decays of superpartners and scatterings of SM particles and their superpartners in the primordial plasma. The same mechanism works for sterile neutrino, supplemented with production via active neutrino oscillations. Dark matter candidates, like Peccei-Quinn axion, Q-balls, stranglets, are produced at phase transitions in the early Universe. Dark matter particles can couple to inflaton field and hence emerge in inflaton oscillations, which in a number of cases get either classical or quantum enhancement. Finally, DM particles are produced by gravity while the Universe expands.

In many of these mechanisms not only a new stable particle must be introduced into the SM, but new interactions as well. In addition, new physical parameters (coupling constants and masses) must be specifically tuned to give the correct DM abundance. Hence *all these mechanism are considered as less natural than the thermal production, that favors WIMPs as DM.* Indeed, we need neither new interactions nor tuning of the DM mass to get the correct number, which is very attractive and hence *natural.* But this naturality is conditioned by the particle physics alone. On the contrary, cosmology itself rather disfavors WIMPs judging on the two assumptions inherent in the WIMP model: *(i)* they remain in thermal equilibrium at freeze out and *(ii)* there no asymmetry between DM particles and antiparticles, $n_X = n_{\overline{X}}$. Both the assumptions *seem unnatural* given the observation of the visible sector. Indeed, the two main well-understood processes in the early Universe—recombination and Big Bang Nucleosynthesis—are significantly out of equilibrium. The visible matter is asymmetric: there are no primordial antibaryons in the present Universe, $n_B \gg n_{\overline{B}}$.

3 Asymmetric DM

Let's suppose that the DM is asymmetric instead. When asymmetry is large, so that mostly one component (particles or antiparticles) dominates, we immediately find many differences with respect to the standard WIMP case, see e.g. [3]. In particular, many signatures change due to the absence of DM pair annihilation at present: *(i)* no any signals of DM annihilation inside the Sun (hence limits from the neutrino telescopes like ICECUBE, SuperK, Baksan are useless), *(ii)* no any signals of DM annihilation in the Galaxy halo (hence limits from satellite experiments like PAMELA, Fermi-LAT, etc are inapplicable either). There are also similarities to the WIMP case: say, the DM particles still may scatter off the ordinary matter, therefore the direct searches for the DM are relevant.

Stability of the DM particles can be naturally attributed to a new conserved charge. However, it is tempting to adopt the baryon charge instead. Indeed, it is in accordance with both the minimalistic approach—introducing as little new physics as possible—and absence of any hints in the searches for proton decay. In this setup the baryon number is conserved perturbatively, so that the total baryonic charge of the Universe is zero. The observed in the visible matter baryonic charge is compensated by the antibaryonic charge of the DM.

Now we can understand the order-of-magnitude coincidence $\rho_B \sim \rho_{DM}$. The DM particles carry the antibaryonic charge q_{DM} and if DM particles get produced by scattering of particles in plasma, so do the baryons,

$$X + Y \to \text{baryon} + \text{DM}\,,$$

and hence we expect similar number densities for the both components, $n_B \sim n_{DM}$. If DM particles remain mostly elementary in the late Universe (e.g. forming neither small scale objects like quarks form protons nor large scale objects like baryons form neutron stars), than the total baryon number conservation $q_B \times n_B + q_{DM} \times n_{DM} = 0$ implies the simple estimate of the DM mass,

$$M_{DM} = m_p \times \frac{n_B}{n_D M}\frac{\Omega_{DM}}{\Omega_B} \simeq 5\frac{-q_{DM}}{q_B}\,\text{GeV}\,.$$

It is worth to emphasize that the stability of the DM particle with respect to decay into SM antibaryons must be guaranteed by some means, e.g. kinematically.

The general phenomenological features of this setup are as follows:

• No annihilations like $X + X \to$ SM particles, hence no corresponding signals from the Sun, dwarf galaxies, Galactic center and galaxy clusters.

• DM particle mass is in the GeV range, so it seems quite a challenge for experiments performing direct searches for DM, where the energy deposit due to the DM elastic scattering is expected in the keV range.

• There can be DM annihilation with ordinary matter. The intensity of this source of the Galaxy cosmic rays is proportional to the product of baryon and DM densities, $I(\mathbf{r}) \propto n_{DM,Gal}(\mathbf{r}) n_B(\mathbf{r})$. However the signal is expected at energies $E \lesssim (M_X + m_p)/2 \sim$ a few GeV, which is difficult to recognize given presently unreliable predictions even for the solar modulation at these energies.

• DM particles can trigger the proton decay-like events, e.g. $X + p \to \pi +$ invisible. These processes, called *induced nucleon decays*, can be studied at the dedicated experimental facilities like SuperK. The signatures are very similar to those utilized in proton decay searches, albeit the energy release of the signal event is expected to be somewhat higher.

• DM particles can be pair produced in proton-proton scatterings at LHC. At the partonic level, quarks, antiquarks, gluons can emit partons or other particles before scattering, which yields the following signatures of DM production at LHC

$$p + p \to jet + \text{missing } P_T\,, \quad p + p \to \gamma + \text{missing } P_T\,, \quad p + p \to Z + \text{missing } P_T\,, \quad etc. \tag{1}$$

These signatures are adopted to probe models with extra spatial dimensions, supersymmetric models and generic models with WIMPs [2]. These searches are sensitive to the asymmetric DM models as well. The great advantage of the searches at LHC over the direct and other indirect searches is that the sensitivity does not depend on the mass of produced particles if they are reasonably light. Sensitivity of all other experiments drops dramatically with diminishing mass. For dark matter mass below about 10 GeV LHC is quite competitive and for masses below about 3 GeV superior [2] to all the other searches. For DM particle masses in GeV range, including the antibaryonic DM, the LHC seems the best experiment at present to check the models. This statement is illustrated below with a particular model of antibaryonic dark matter.

4 A working example: Hylogenesis

The model called Hylogenesis [4] (*hyle* for primordial matter and *genesis* for origin) introduces several new fields: two heavy Dirac fermions X_a, $a = 1, 2$ with masses $m_2 > m_1 \gtrsim 1\,\text{TeV}$, one Dirac fermion Y and one complex scalar Φ with masses $m_Y \sim m_\Phi \sim 1\,\text{GeV}$. The latter two form dark matter component, while the heavy fermions play the role of messengers between the dark and visible sectors with coupling through the *neutron portal*,

$$\mathcal{L}_{\text{int}} = \frac{\lambda_a}{M^2} \overline{X}_a d_R \overline{u}^C d_R + \zeta_a \overline{X}_a Y^C \Phi^* + \text{h.c.} \tag{2}$$

New particles carry baryon charge, so that $B_{X_a} = -(B_Y + B_\Phi) = 1$. Both dark matter particles and proton are stable provided by the following kinematic constraint on their masses,

$$|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi \, . \tag{3}$$

In the early Universe heavy fermions decay, producing the asymmetry both in dark and in visible sectors. Indeed, in the visible sector the interaction (2) violates baryon symmetry (by means of couplings λ_a), and complex dimensionless coupling constants λ_a, ζ_a break C- and CP-symmetries. If heavy fermions decay at the temperature T_d being nonrelativistic, $M_a \gg T_d$, the process is out-of-equilibrium, so that all three Sakharov's conditions of successful asymmetry generation are fulfilled. Assuming $M_{X_1} \ll M_{X_2}$ and that the decay $X_1 \to \overline{Y}\Phi^*$ dominates, one estimates the microscopic (quark) asymmetry [4]

$$\epsilon = \frac{\Gamma(X_1 \to udd) - \Gamma(\overline{X}_1 \to \overline{u}\overline{d}\overline{d})}{\Gamma(X_1 \to \overline{Y}\Phi^*) + \Gamma(\overline{X}_1 \to Y\Phi)} \approx \frac{m_1^5 \, \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\, \pi^3 \, |\zeta_1|^2 \, M^4 \, m_2} \, ,$$

that is related to the macroscopic baryon asymmetry as $\epsilon / g_* \sim \Delta_B = \frac{n_B}{s} \approx 10^{-10}$. The same asymmetry is generated between particles and antiparticles in the dark sector.

Then in the dark sector we obtain an asymmetry between relativistic particles and antiparticles. To make the DM contribution to the present energy density of the same order as the baryon contribution, all the CP-symmetric pairs (Y and $\overline{Y}$, Φ and Φ^*) must annihilate, when become nonrelativistic. Therefore, the CP-asymmetric relics form DM, and it is exactly the counterpart of baryon asymmetry in the visible sector. The baryon number conservation ensures $n_Y + n_\Phi = 2n_B$ and hence

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_Y + m_\Phi}{m_p} \, .$$

This relation together with bounds(3) constrain the DM masses to be inside the range

$$1.7\,\text{GeV} \lesssim m_Y, m_\Phi \lesssim 2.9\,\text{GeV}$$

And so the relation $\rho_B \sim \rho_{DM}$ *is natural.*

The model can be tested at LHC as discussed in [5, 6]. The direct production of X_a is initiated by the first term in (2), that without any need for the gluon bremsstrahlung yields the same WIMP-like signature as (1)

$$p + p \to jet + \text{missing } P_T \, .$$

The results of CMS analysis of the LHC events with a single and large missing-P_T [2] (the first run, c.m. energy $\sqrt{s} = 8\,\text{TeV}$, integrated luminosity $\mathcal{L} = 19.7\,\text{fb}^{-1}$) have been used [6] to place limits on the model parameters. If only one of the heavy fermions is kinematically available at LHC, for the light messenger in TeV mass range the limit on new-physics scale M reads,

$$\frac{M}{\text{TeV}} > 4 \times \sqrt{\lambda_1} \times \frac{\text{TeV}}{M_1}\,.$$

With two messengers available, the new-physics scale $M = 3.5\,\text{TeV}$ and $\lambda_{1,2}$ of about unity the messenger masses must exceed 1-3 TeV, see [6] for details.

Several other signatures have been put forward in [6]. They are associated with different final states, possible if u- or/and d-quarks in the lagrangian (2) are replaced with up- and down-type quark, respectively, of either the second or the third generations. Any such interaction plays the same role in cosmology as the neutron-portal (2), i.e. successfully produces DM and BAU. At LHC these operators induce *events with missing-P_T and a single heavy quark* (t, b, c). In particular, for $P_T > 40\,\text{GeV}$ the cross section of scattering $pp \to \bar{t}X$ for $\sqrt{s} = 8\,\text{TeV}$ was estimated [6] at the level of several fb with $M, M_1, M_2 \lesssim 1\,\text{TeV}$. More signatures emerge if the heavy messenger decays inside the LHC detectors into three quarks. Then generally one expects *events with 4 jets (and no missing-P_T), where three of them form a particle, i.e. the 3-jet invariant mass exhibits a peak at the messenger mass*. With heavy quark(s) replacing the light one(s) in the interaction (2) *some of the jets may be associated with the heavy quark(s) t, b, c*.

The neutron-portal interaction (2) and the similar one with s-quark(s) lead to induced nucleon decay events, when the DM particle $\Phi(Y)$ annihilates with proton(neutron) into $Y(\Phi)$ and the SM particles. The signatures are very similar to those of proton decays, like [4,5,7]

$$p \to K^+ + \nu\,, \quad n \to \nu + \gamma\,, \quad n \to \nu + e^+ + e^-\,, \quad p \to \eta\pi^+ \quad p \to \overline{\pi}^0\pi^+\,, \;\; etc$$

but with different kinematics in the final state. With $M_{1,2}, M \approx 1\,\text{TeV}$ the expected proton "lifetime" is of order $\tau \simeq 10^{32}$ yrs and longer. With account of the LHC bounds they exceed 10^{34} yrs [7]. Since the signal cross section at LHC scales as $\sigma \propto 1/M^4$, while $\tau \propto M^4 M_{1,2}^2$, *one observes that the LHC generally is much more sensitive to the model, than searches for the induced baryon decays*, that is the purpose of this talk.

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