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Dark matter at the LHC: WIMPs and beyond

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I discuss some aspects of current dark matter searches at the Large Hadron Collider. Using a few concrete dark matter models as examples, I illustrate how different ideas about the origin of the observed dark matter abundance in the Universe can lead to radically different phenomenological signatures and highlight the complementarity of different search channels in constraining the cosmologically viable parameter space.

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1. Introduction

Understanding the nature of dark matter constitutes a major task for contemporary high-energy physics, astrophysics and cosmology. The Cosmic Microwave Background (CMB) observations have provided us with several key measurements that can assist us in this endeavour, one of the most important being the total dark matter abundance in the Universe in ΛCDM cosmology [1]. Explaining the cosmic dark matter abundance is not only a question of theoretical interest. On the contrary, it is directly related to the question of whether we may hope to observe it non-gravitationally. In particular, although there are some ways to explain the observed cosmic dark matter density by relying only on gravity [2], most of our current ideas on the topic invoke non-gravitational interactions between dark matter and the Standard Model particles[1]. Then, if these interactions are strong enough, it may indeed be possible to observe dark matter as it scatters off ordinary matter (direct detection), to detect its annihilation and/or decay products in the galaxy and beyond (indirect detection), to produce it in association with other, more strongly interacting (and, hence, visible) particles at high-energy colliders such as the Large Hadron Collider (LHC) and so on.

Focusing on the LHC, and going a step further, the question of how exactly dark matter may manifest itself (*i.e.* the specific classes of signatures that should be considered) depends crucially on the general features of each dark matter generation mechanism. In other words, different dark matter generation mechanisms can lead to radically different observable signals. In this short presentation I will illustrate this point by focusing on two concrete ideas about dark matter genesis: thermal freeze-out, along with one of its variants that has been dubbed "conversion-driven freeze-out" or "co-scattering" and freeze-in. We will see that these ideas can give rise to a different dark matter phenomenology at the LHC, and all the corresponding signatures must be systematically looked for if we are to define a comprehensive dark matter search programme.

2. Thermal freeze-out

The majority of dark matter searches, both at the LHC and beyond, have been motivated by the so-called "WIMP miracle" which appears in the context of thermal freeze-out. In this picture dark matter interacts strongly enough with the Standard Model particles such that in the early Universe, which was sufficiently dense and hot, the two sectors were kept in thermodynamical (chemical + kinetic) equilibrium. As Hubble expansion caused the cosmic temperature to drop, dark matter could no longer be efficiently produced from annihilations of Standard Model particles and it started annihilating way, until its annihilation rate got superseded by the Hubble expansion rate. Beyond this point, the dark matter abundance "froze-out" to a roughly constant value. The "WIMP miracle" lies with the fact that if the mass of the dark matter particles is chosen to lie in the GeV-TeV scale and their interaction with the visible sector is of comparable strength as the electroweak interactions, this constant value roughly coincides with the one inferred from the CMB[2].

[1] At this point it would be good to also note that all existing dark matter models, even those that rely exclusively on gravity, require some extension of the Standard Model of particle physics.

[2] The literature on WIMPs is vast. For a computation of the dark matter annihilation cross-section required to match the observed value of the dark matter abundance *cf e.g.* [3].

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Three main approaches have been pursued in order to constrain WIMP dark matter models at the LHC. The first, and perhaps most celebrated one, is direct dark matter pair-production[3] in association with a visible particle (since dark matter itself is electrically neutral and cannot be directly detected). The corresponding signature is of the "mono-X" type, *i.e.* consisting of at least one visible object balancing a large amount of missing transverse energy. Mono-X searches can be considered to be among the most generic ones, as they try to replicate the annihilation processes that could have lead to dark matter freeze-out in the early Universe, only exchanging the initial and final state particles (*e.g.* $q\bar{q} \to \chi\chi$ instead of $\chi\chi \to q\bar{q}$) and demanding the presence of one additional visible object in the event, such as a jet (which could, in the example $q\bar{q} \to \chi\chi$, be easily generated through radiation of a gluon from one of the initial state quarks). They are, however, not always the most sensitive. For instance, if the dark matter particles χ are produced through an s-channel process involving some mediator S and $m_\chi > m_S/2$, then the reaction takes place with the mediator being off-shell and the corresponding cross-section is typically very small. In these cases, it is rather searches for the mediator itself that become relevant. Indeed, the mediator can be produced and decay on-shell into Standard Model particles giving rise, *e.g.*, to a dijet or dilepton signature similarly to the situation in traditional resonance searches. Lastly, in more complicated scenarios of physics Beyond the Standard Model (BSM) dark matter may be only one – typically the lightest – state of a much more extended "dark sector". In such models, the heavier dark sector particles can be produced and eventually decay into dark matter through a complicated decay chain involving numerous visible particles along with missing energy. Such searches can be very powerful, but their applicability is typically restricted to a relatively small number of models.

These three approaches are complementary between them but also complementary with other astrophysical and cosmological measurements. One example of their interplay can be seen in Figure 1, taken from Reference [4]. In this work, we considered an extension of the Standard Model by a fermionic dark matter candidate χ, which is a singlet under the Standard Model gauge group, and whose interactions with the Standard Model are mediated by a pseudoscalar particle A that couples with the ordinary fermions as

$$\mathscr{L} \supset -\frac{m_A^2}{2}A^2 - \frac{m_\chi}{2}\bar{\chi}\chi - i\frac{y_\chi}{2}A\bar{\chi}\gamma_5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} A\bar{f}_u\gamma_5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} A\bar{f}_d\gamma_5 f_d \tag{2.1}$$

where m_χ and m_A are the dark matter and mediator masses respectively, v is the Higgs vacuum expectation value and the sums run over all Standard Model quarks. In Figure 1 we overlay, in the (m_χ, m_A) plane, constraints stemming from searches for monojets (green hatched region), searches for resonances decaying into photons pairs (blue shaded region), $\tau^+\tau^-$ pairs (gray shaded region), $t\bar{t}$ pairs as well as the total $t\bar{t}$ cross-section measurement (gray hatched region). The black lines show (m_χ, m_A) combinations for which the correct relic density can be obtained in this model for a specific choice of $\chi - A$ and $\chi-$SM couplings, whereas the red lines represent constraints from searches for dark matter annihilations in dwarf spheroidal galaxies with the Fermi satellite (solid and dashed for constraints/projections respectively). We can indeed see that, depending on the masses of the exotic states, different LHC searches probe different regions of the cosmologically

[3] In most models dark matter stability is ensured by imposing a discrete $\mathbf{Z}_2$ symmetry under which dark matter is odd and the Standard Model particles are even. This symmetry implies that dark matter particles can only be produced in pairs or, eventually, in association with some other $\mathbf{Z}_2$-odd "dark sector" state.

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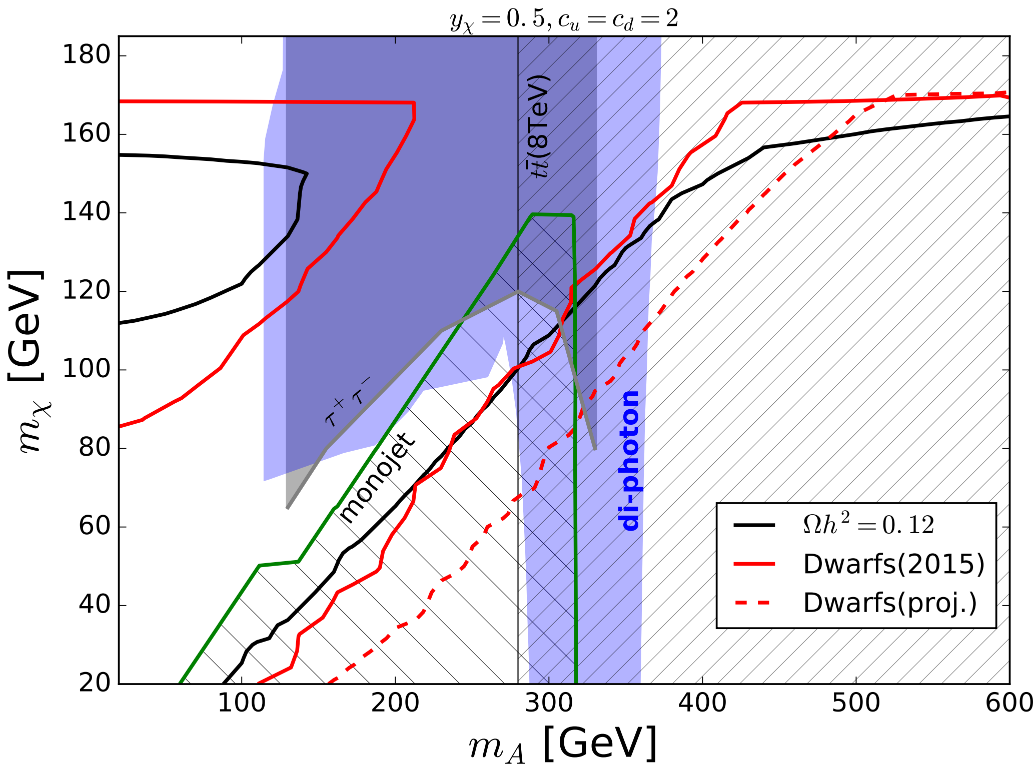

Figure 1: Indirect DM detection and collider constraints in the (m_A, m_χ) plane for $y_\chi = 0.5$ and $c_u = c_d = 2$. The cosmologically and astrophysically allowed region is located between the black and red lines. The shaded regions are excluded at the 95% CL by LHC searches for monojets (hatched green), $A \to \tau^+\tau^-$ systems (grey), diphoton resonances (blue), and deviations in $t\bar{t}$ events at 8 TeV (hatched grey). Figure taken from [4].

relevant parameter space: mono-X and mediator searches can constrain dark matter models in a complementary manner.

Besides, note that the Lagrangian of Equation 2.1 is not gauge invariant. It should be understood as an effective description of the low-energy limit of some more extended model. One possible UV completion is the so-called “2HDM + *a*” model, in which the Standard Model is extended by one additional Higgs doublet along with a pseudoscalar singlet. This setup indeed allows one to couple dark matter to the Standard Model in a fully consistent manner and gives rise to an even more extended phenomenology. This model is actually one of the benchmark models considered by the ATLAS and CMS collaborations, *cf e.g.* [5].

As a final remark, we should also note that if the dark sector of some model involves sufficiently small mass splittings between dark matter and heavier states, then dark matter can not only annihilate with these heavier particles in the early Universe (a process typically dubbed “coannihilation”) but also convert into them. In [6, 7] it was realised that there can be situations in which this conversion process, which was until recently ignored in freeze-out calculations, may actually be the dominant process through which cosmic dark matter is depleted. Interestingly, this “conversion-driven freeze-out” does not involve electroweak strength couplings between dark matter and the heavier particles, but rather couplings of the order of 10^{-7} or so. Note, however, that these heavier states can interact pretty strongly with the Standard Model particles, *i.e.* they could be produced copiously at the LHC and decay with a macroscopic lifetime into dark matter along with visible objects. This type of phenomenology differs drastically with respect to the one encountered in more conventional freeze-out scenarios. It brings dark matter into the realm of searches for long-lived particles (LLPs), which have recently been gaining popularity since they are motivated by numerous extensions of the Standard Model of particle physics [8]. These are the types of searches that will also be relevant in the second part of this presentation where we will discuss another dark matter generation mechanism, freeze-in.

3. Beyond WIMPs: freeze-in

As we already mentioned, one of the characteristic features of thermal freeze-out is that, given that dark matter is required to interact relatively strongly with the Standard Model particles, thermal equilibrium is established between the two sectors at some point during the cosmic evolution. As the strength of this interaction decreases, then typically we end up with candidates which would be overabundant and, hence, not viable (coannihilation and conversion-driven freeze-out being notable exceptions to this trend). But what if we kept decreasing the strength of this interaction? In a nutshell, below a certain value equilibrium between the two sectors would be impossible to establish. But then, what assumption should be made for the initial cosmic abundance of such Feebly Interacting Massive Particles (FIMPs)? It is reasonable to assume that if some particle species interacts extremely weakly with the Standard Model, as well as with all other particles belonging to the same thermal bath, then this species was likely completely absent in the very early Universe. These two elements constitute the basic premises of "freeze-in" dark matter production [9, 10]: first, that dark matter interacts extremely weakly with the Standard Model. Secondly, that the initial abundance of dark matter was negligible. Then, in the freeze-in picture, dark matter can be produced either in annihilation processes of Standard Model (or other bath) particles or from decays of heavier ones without annihilating back. The latter is due to the fact that the dark matter depletion rate scales as $n_\chi^2 \langle \sigma v \rangle$, where n_χ is the dark matter number density, σ its annihilation cross-section, v is the velocity and $\langle . \rangle$ denotes thermal averaging. Since all quantities involved in this expression are small, it is safe to neglect dark matter annihilation processes. Numerically, one finds that in the case of freeze-in through decays of a heavier bath particle into dark matter the relevant coupling must be of the order of 10^{-13} in order to obtain the correct relic abundance.

But how is it possible to probe such feebly interacting particles at the LHC? The crucial observation lies with the fact that, similarly to the case of the conversion-drive freeze-out, the heavier dark sector states can interact arbitrarily strongly with the Standard Model. As an example, in [11] we considered a model in which a scalar dark matter candidate s interacts with the Standard Model through a Yukawa-type interaction involving s, the right-handed component of the ordinary fermions f and the left-handed component of an $SU(2)_L$-singlet vector-like fermion F which may, nevertheless, be charged under $U(1)_Y$ ("heavy lepton" case) or even $SU(3)_c$ ("heavy quark" case). The relevant part of the Lagrangian reads

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{m_s^2}{2} s^2 + \bar{F} \left(i D_\mu \gamma^\mu \right) F - m_F \bar{F} F - \sum_f y_s^f \left(s \bar{F} \left(\frac{1+\gamma^5}{2} \right) f + \text{h.c.} \right), \quad (3.1)$$

where $f = \{e, \mu, \tau\}$, $\{u, c, t\}$ or $\{d, s, b\}$, depending on the $SU(3)_c \times U(1)_Y$ transformation properties of F. When the relic abundance Ω_s of s is dominated by decays of the heavy fermion F (which is typically the case for $m_F > m_s + m_f$), a relatively simple relation can be derived between Ω_s and the decay length of F, namely

$$c\tau[\mathrm{m}] \approx 9\, g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \mathrm{keV}}\right)\left(\frac{200\ \mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right], \tag{3.2}$$

where g_F are the internal degrees of freedom of F, M_{Pl} is the Planck mass, T_R is the reheating temperature of the Universe, T_0 is the temperature today, $K_1(x)$ is the modified Bessel function of the second kind of degree one and g_* are the effective degrees of freedom for the energy density.

From the expression 3.2 we can indeed see that F is expected to decay with a macroscopic decay length which, if s is light enough or if the reheating temperature T_R is sufficiently low[4], can be comparable to the size of the ATLAS and CMS detector components. We see, then, that such models of freeze-in tend to give rise to long-lived particles which can be produced at the LHC through Drell-Yan-like processes (lepton model) or even QCD (quark model). In [11] we considered three classes of LLP signatures. If F is a heavy lepton, we can employ constraints stemming from searches for Heavy Stable Charged Particles (HSCPs – when F decays outside the detector), displaced leptons (DLs – when F decays in the inner part of the tracker and the Standard Model lepton track can be reconstructed) and disappearing tracks (DTs – when F decays towards the outer parts of the tracker and the Standard Model lepton track cannot be reconstructed). In the heavy quark case, we can consider the HSCP and displaced vertex (DV) signatures. For more information on the concrete procedure followed in order to recast the relevant searches, as well as for a much more complete list of references, *cf* [11].

The results of this analysis can be seen in Figure 2, where we overlay the ensuing constraints (shaded regions) with the cosmologically relevant $(m_F, c\tau)$ combinations for different choices of m_s and T_R (lines) for the leptonic model (upper panel) and hadronic model (lower panel). In the lepton case, we can indeed see that searches for displaced leptons are efficient for decay lengths up to half a meter, excluding heavy lepton masses up to roughly 350 GeV, whereas searches for HSCPs provide powerful constraints extending up to masses of 600 GeV for $c\tau \gtrsim 1$m. Searches for disappearing tracks play a complementary role, probing the intermediate lifetime region for masses roughly up to 300 GeV. In the quark model, on the other hand, given the large production cross-section of F, searches for displaced vertices and HSCPs provide an impressive parameter space coverage, excluding heavy fermion masses even above 1 TeV for decay lengths spanning many orders of magnitude. In both cases, we can clearly see that the various LLP searches are highly complementary with each other as they probe different parent particle lifetimes, all of which can give rise to a viable cosmology: searches for HSCPs target larger dark matter masses and/or higher reheating temperatures, whereas searches for parent particles with shorter lifetimes can constrain scenarios of light frozen-in dark matter and/or with a lower reheating temperature. Let us also note that this is an example of freeze-in through an electrically charged and/or coloured parent particle.

[4]This would decrease the value of the integral in the last factor of Equation 3.2. Physically, it means that the abundance of F is Boltzmann-suppressed, *i.e.* that there are fewer F particles in the primordial plasma which can decay into dark matter.

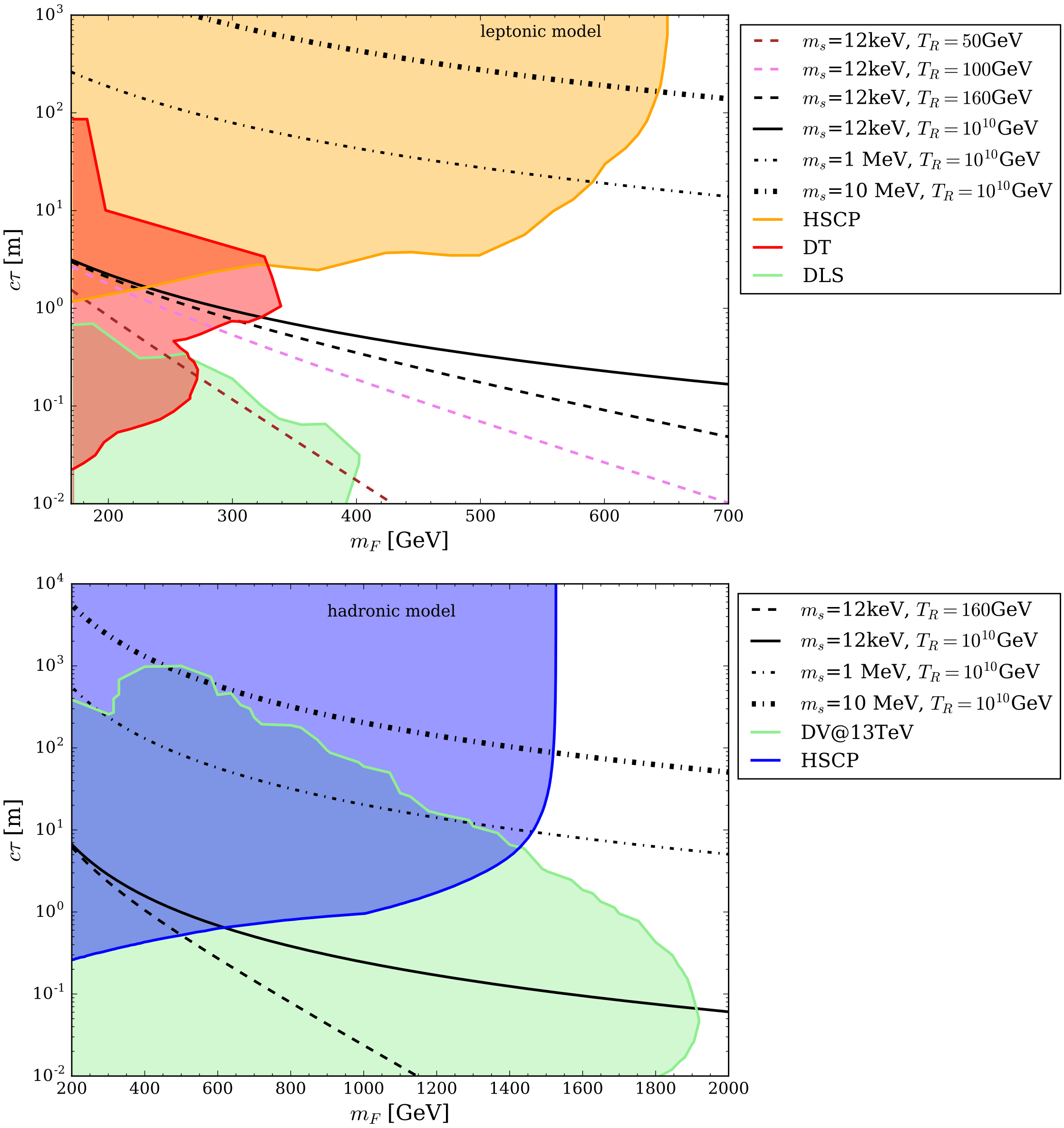

Figure 2: Summary of the LHC constraints for the lepton-like (upper panel) and the quark-like (lower panel) FIMP scenarios. The lines correspond to contours of $\Omega_s h^2 = 0.12$ for the values of m_s and T_R given in the legend.

A similar analysis with a neutral parent, which leads to different LLP signatures, can be found *e.g.* in [12].

All in all, the take-home message is that although cosmologically successful freeze-in requires feeble couplings between dark matter and the Standard Model, it can give rise to an exciting phenomenology at the LHC, in particular related to the flourishing activity in searches for long-lived particles. Note, also, that since these types of analyses often rely rather heavily on experimental issues such as track reconstruction efficiencies and instrumental backgrounds, they necessitate a close collaboration between theorists and experimentalists in order to obtain robust bounds on models of frozen-in dark matter.

4. Conclusions

So, what is the status of dark matter at the LHC? Very strong statements are quite hard to make and they typically don't do justice to the tremendous amount of effort that has been – and is being – devoted in order to detect dark matter particles at the Large Hadron Collider, but also to the creativity that has been demonstrated in the model-building arena. A few questions can, nevertheless, perhaps be given a tentative answer.

Has thermal freeze-out become more contrived? It is fair to say that the answer is yes. Concretely, given the plethora of constraints from the LHC, direct and indirect detection, today it is far less trivial to construct a consistent and viable model of frozen-out dark matter in the $\mathbf{O}(10^2)$ GeV mass region. Is thermal freeze-out excluded? Certainly not. In particular, it is still possible to construct viable models of WIMP-like dark matter by increasing or decreasing the dark matter mass, by judiciously choosing the types of DM-SM interaction and so on. Will we manage to completely exclude thermal freeze-out? I think that in the foreseeable future, no. For example, viable frozen-out dark matter can be accommodated for masses up to several hundreds of TeV [13], far beyond the reach of direct detection or the LHC. Then, are conventional (*e.g.* mono-X) searches obsolete? Certainly not. These searches are, for example, valuable especially for light (sub-GeV) dark matter, for which current direct detection technologies lose sensitivity (although there are many ideas about how to extend the direct detection mass range).

Given this situation, should we consider alternatives to conventional thermal freeze-out? I believe that the answer here is a resounding yes. First, because they are theoretically interesting possibilities which constitute perfectly viable cosmological scenarios. Secondly, because as we saw they can give rise to an exciting phenomenology at the LHC, predicting new signatures and motivating new experimental searches. During the past decade or so, dark matter physics provided some of the strongest motivation for new physics searches at the Large Hadron Collider. Thankfully, it continues to do so.

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